LASH RISK AND INTEREST RATES[☆]

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Abstract

This paper studies a form of liquidity risk that we call *Liquidity After Solvency Hedging* or "LASH" risk. Financial institutions take LASH risk when they hedge against solvency risk, using strategies that require liquidity when the solvency of the institution improves. We focus on LASH risk relating to interest rate movements. Our framework implies that institutions with longer-duration liabilities than assets—e.g. pension funds and insurers—take more LASH risk as interest rates fall. Using UK regulatory data from 2019-22 on the universe of sterling repo and swap transactions, we measure, in real time and at the institution level, LASH risk for the non-bank sector. We find that at the peak level of LASH risk, a 100bps increase in interest rates would have led to liquidity needs close to the cash holdings of the pension fund and insurance sector. Using a cross-sectional identification strategy, we find that low interest rates caused increases in LASH risk. We then find that the pre-crisis LASH risk of non-banks predicts their bond sales during the 2022 UK bond market crisis, contributing to the yield spike in the market.

Keywords: Liquidity, Monetary policy, Financial crisis, Hedging
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1 Introduction

Liquidity crises have become increasingly common in the non-bank financial sector. Recent examples include the pandemic-era liquidity crisis of Spring 2020, the 2022 commodity market turmoil following Russia's invasion of Ukraine, and the 2022 UK bond market crisis. These liquidity crises are linked to the rising use of hedging instruments—such as swaps and repos—by pension funds, insurers, and alternative investment funds. This paper relates these crises to an understudied form of liquidity risk related to hedging. We label this risk *Liquidity After Solvency Hedging* or "LASH" risk. Institutions take LASH risk when they hedge against losses, using strategies that lead to liquidity needs when the institution's solvency improves. As such, LASH is distinct from other forms of liquidity risk, which typically materialize when solvency deteriorates.[1]

As a preamble to the empirical contributions of the paper, we develop a simple framework to define LASH risk and differentiate it from other forms of liquidity risk. As an example, consider a fund, such as a life insurer or pension fund, with long-duration liabilities and shorter-duration assets. A fall in interest rates lowers solvency since the value of liabilities rises more than the value of assets. The fund can hedge this solvency risk using an interest rate swap, whose value rises when rates fall. This hedging strategy creates liquidity needs when rates rise. As rates rise, the value of the swap falls, and the fund must pay liquid assets ("margin") to their counterparty equal to the fall in the swap's value. The margin requirement represents LASH risk, which materializes even if the solvency of the fund improves with rising rates.

We formalize LASH risk using a simple model of portfolio choice. There is a fund endowed with long-duration liabilities, which faces duration risk from shocks to interest rates. The model has four empirically grounded ingredients. First, the fund faces costs from insolvency—defined as negative net worth—and these costs generate risk aversion and a desire for hedging. One interpretation of these costs is regulatory penalties from insolvency, but costs other than regulation may also matter. Second, the fund can hedge duration risk only by using interest rate derivatives, which require margin and so generate liquidity risk. The derivative is best interpreted as a swap, but we discuss how LASH risk applies to other hedging instruments such as repo. The fund does not have access to assets of long enough duration to hedge the liability. The third ingredient is that holding liquid assets is costly as

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[1] For work on the disruption in bond markets during the pandemic-era liquidity crisis, see Haddad, Moreira and Muir (2021). For the 2022 commodity market turmoil, see Avalos and Huang (2022); for the UK bond market crisis in the same year, see Breeden (2022). An earlier instance of LASH risk is the 1993 bankruptcy of the Germany energy conglomerate Metallgesellschaft (Culp and Miller, 1994).

they command a premium, this prevents the fund from self-insuring liquidity risk. Fourth, the fund can hold medium-duration assets, which have a higher return than liquid assets but incur a liquidity cost when sold. With these four ingredients, the fund optimally chooses its hedging strategy.

The model generates three predictions that guide our empirical contributions. First, the optimal strategy partially hedges solvency risk from falling rates, i.e. risks to net worth, at the cost of some liquidity risk from rising rates, i.e. the risk of margin calls. The fund's solvency improves after a shock that increases rates. However, the fund may need to liquidate assets to pay variation margin on the swap—which is liquidity risk materializing. This liquidity-solvency trade-off is what motivates the fund to hedge only partially. Second, incentives to take LASH risk are higher in a low interest rate environment. Since the fund is only partially hedged against interest rate risk, net worth is low when rates are low, meaning the fund is closer to insolvency. Since insolvency is costly and nearer, the fund has a greater incentive to hedge against interest rate risk—at the cost of more LASH risk. Third, a large enough positive shock to rates leads to a "liquidity crisis". Funds exhaust their holdings of short-term and liquid assets, requiring costly sales of medium-term assets to pay margin. However, the fund's solvency improves during the liquidity crisis.

The simple framework clarifies that LASH risk is different from some other common forms of liquidity risk. LASH risk relates neither to maturity transformation and callable claims (Diamond and Dybvig, 1983; Farhi and Tirole, 2012), nor to rollover risk (Calvo, 1988; Cole and Kehoe, 2000; Aguiar, Chatterjee, Cole and Stangebye, 2022). Moreover, in our example, the fund is exposed to LASH risk precisely when their solvency improves due to rising rates. Therefore, LASH risk differs from the feedback between funding and market liquidity (Brunnermeier and Pedersen, 2009), which arises when solvency deteriorates. In the example, LASH risk applies to institutions with long-duration liabilities and short-duration assets, the opposite maturity structure of a typical bank. While our example and empirical analysis focus on interest rates, we also discuss how the same principles apply to other asset prices, such as commodities or exchange rates, which are relevant for different sectors in the financial system.

We then make three empirical contributions that match the predictions of the model. In our first empirical contribution, we show that non-banks take on LASH risk to partially hedge solvency risk. We measure LASH risk for pound sterling interest rate contracts held by UK non-banks. In this context, LASH risk measures the liquid assets an institution must pay as a margin for a given change in interest rates. For instance, suppose an investment fund holds an interest rate swap to hedge against falling rates. We measure the liquid assets the fund must pay to its counterparty when the value of the swap falls because rates have risen. We apply the measure to regulatory data from the Bank of England on the universe of sterling repo transactions, the universe of pound sterling interest rate swap positions and the universe of UK government bond transactions. Our measure is available at the institution level and in real time, starting from 2019. LASH risk from interest rates concentrates in the pension fund and life insurance sector—i.e. financial institutions with long-duration liabilities. We find that LASH risk is large: at the peak level of risk, a 100bps rise in interest rates would have generated liquidity needs close to the liquid asset holdings of the entire UK pension fund and insurance sector. During some crisis episodes, such as the 2022 UK bond market crisis that we will discuss shortly, rates have risen significantly more than 100bps in a short time window. We also show that pension funds are partially, but not fully hedged against interest rate changes—their solvency improves when interest rates rise.

Our second empirical contribution is to argue that low interest rates cause LASH risk. To start, we find that in the aggregate time series, low interest rates associate with high LASH risk. LASH risk increases from 2019 through 2022 as interest rates fall; and then falls as interest rates rise. However, other factors could have caused these patterns. For instance, macroeconomic conditions could have affected both rates and LASH risk. Therefore, we pursue a cross-sectional identification strategy to identify the causal effect of interest rates on LASH risk. We identify institutions that are particularly exposed to a decline in interest rates, as they hold relatively short-duration assets. These institutions experience a particularly large fall in solvency as interest rates fall. Our framework predicts these institutions should hedge more against interest rate risk to avoid costly insolvency and, in doing so, raise LASH risk. Consistent with our framework, the exposed institutions raise their LASH risk more as interest rates fall relative to institutions with higher-duration assets.

Our third empirical contribution is to show that when rates rise sharply, the LASH risk caused by the previous decline in rates leads to liquidity crises. LASH risk is not itself the "root cause" of crises. Instead, LASH amplifies the root cause—a sudden, initial rise in rates. Due to margin calls, pension funds must sell bonds to raise liquid assets, which leads rates to rise even more. We study the liquidity crisis in the UK pension fund sector in September and October 2022. That period was characterized by sharply rising interest rates, margin calls, and gilt sales by UK pension funds. We find that institutions with ex-ante larger LASH risk sold substantially higher quantities of gilts during the crisis: a one standard deviation increase in pre-crisis LASH risk is associated with 15% higher daily sell volumes during the crisis. Gilt sales due to LASH risk exacerbated the crisis further. High LASH risk institutions significantly contributed to the yield spike in the gilt market: a one standard deviation increase in gilt sales due to LASH risk leads to a 4.1bps daily increase in gilt yields (or 66bps over the entire 16-day crisis period).

Consistent with our framework, the solvency of the pension fund sector *improved* during the liquidity crisis. Could pension funds have used their improving solvency to raise liquid assets and avert the crisis? Liquidity needs from LASH risk are hard to fulfill for three reasons. First, the improvement in solvency comes from a fall in the value of liabilities, which cannot be pledged as collateral. Second, the aggregate liquidity needs of the pension fund sector may have been too large to fulfill. In general, liquidity supply in secured credit markets is often constrained during crises (see, e.g., Afonso, Cipriani, Copeland, Kovner, Spada and Martin, 2021; Duffie, 2022). During the 2022 crisis, repo rates spiked, suggesting supply constraints. Funds that borrowed from ex ante supply-constrained repo lenders sold particularly many bonds during the crisis. Third, the institutions that took LASH risk did not have sophisticated liquidity strategies. In one form of a lack of sophistication, only about half of the institutions that were active in the swap market also participated in the repo market. Accessing liquidity for these funds was challenging, and they sold particularly many bonds. As a second form of a lack of sophistication, many institutions hedged their liquidity risk by pooling together with other funds into specialized entities. The pooled structure slowed the transfer of liquidity to where it was scarce. We show that LASH risk had a particularly large impact on these pooled entities.

While our evidence and the corresponding liquidity crisis is from the UK, LASH risk matters in other settings. Czech et al. (2023) show that non-banks that held dollar assets financed with foreign currency liabilities were forced to liquidate assets at the onset of the Covid pandemic in spring 2020. The reason was margin calls due to foreign exchange hedges, even as the US dollar appreciated and solvency improved. A classic case of LASH risk is the 1993 failure of energy conglomerate Metallgesellschaft, which offered customers long-term price guarantees for fuel and heating. These guarantees would lead to solvency risk if energy prices rose, which Metallgesellschaft hedged with derivatives. When the energy price fell, the company's solvency improved, but it faced margin calls that led to its failure (Culp and Miller, 1994). Regarding interest rate risk, Jansen et al. (2023), show that Dutch pension funds liquidated assets in response to the recent rise in interest rates due to the funds' use of interest rate swaps, with consequences for Dutch bond prices. Broadly, what unites these episodes is that sharp swings in asset prices, which should have improved solvency, also provoked costly asset sales and even failure due to the liquidity needs arising from hedging.

Given that LASH risk is different from other forms of liquidity risk, there are also different policy implications. Typically, policymakers worry about providing liquidity support during crises. For instance, Bagehot's Dictum states that policymakers should only provide liquidity support during a crisis at a penalty rate. The reason is that institutions often require liquidity support when their solvency deteriorates. Providing liquidity support ex-post encourages solvency risk and moral hazard ex-ante (Farhi and Tirole, 2012). LASH risk is different. Institutions increase LASH risk when they hedge against solvency risk. Therefore, mitigating the adverse effects of LASH risk ex post—for instance, by providing liquidity support during crises—may *reduce* solvency risk by encouraging hedging ex ante. Therefore, the policy trade-offs for preventing LASH risk are different from other liquidity crises. A full exploration is beyond the scope of the paper, but policymakers are actively debating these questions (e.g., Hauser, 2023a).

Related literature. This paper relates to three literatures. First, we contribute to the literature on liquidity risk, which has traditionally centered on banks and illiquidity stemming from maturity transformation or coordination failures (Diamond and Dybvig, 1983; Diamond and Rajan, 2001; Rochet and Vives, 2004; Morris and Shin, 2004; Farhi and Tirole, 2012; Castiglionesi, Feriozzi and Lorenzoni, 2019; Cooperman, Duffie, Luck, Wang and Yang, Forthcoming). Closer to our work, Drechsler, Savov, Schnabl and Wang (2023) study how interest rates affect the trade-off between liquidity and solvency in the context of the banking system. In their model, low rates reduce solvency by reducing the value of banks' deposit franchises. High rates create liquidity risk because the deposit franchise becomes a runnable asset.[2] Our setting shares the feature that interest rates affect the trade-off between liquidity and solvency. However, with LASH risk, the source of liquidity risk does not relate to the deposit franchise or to banks specifically. Instead, LASH risk applies to non-banks or, more generally, any institution that hedges solvency risks with strategies that raise liquidity risk.

In studying liquidity risk, we contribute to the broader literature on liquidity crises. Brunnermeier (2009), Adrian, Kiff and Shin (2018), and Bernanke (2018) document mechanisms, causes, and effects of the liquidity crises during the Great Financial Crisis. Borio, Claessens, Schrimpf and Tarashev (2023) link liquidity crises to collateral use. Recent papers analyze the "Dash for Cash" liquidity crisis during the onset of the Covid-19 pandemic (Haddad, Moreira and Muir, 2021), including the role of mutual funds' and life insurers' liquidity transformation (Ma, Xiao and Zeng, 2022; Huang, Jiang, Liu and Liu, 2021; Foley-Fisher, Heinrich and Verani, 2023), and the role of holding dollar assets for UK investors (Czech, Huang, Lou and Wang, 2023; Cesa-Bianchi, Czech and Eguren-Martin, 2023). Pinter (2023)

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[2] The extent to which banks bear interest rate risk from their deposit franchises (Krishnamurthy et al., 2024), securities holdings (Jiang et al., 2023) or derivative positions (McPhail et al., 2023) is still a topic of debate in the literature. For the non-banks exposed to LASH risk, we find that even after accounting for hedging, rates and solvency have a clear negative association.

and Chen and Kemp (2023) dissect the market dynamics and policy response during the UK bond market crisis in autumn 2022. Pinter, Siriwardane and Walker (2024) provide a forensic account of how fire sales of safe assets, abetted by slow-moving capital, was a key feature of the UK crisis. Our paper shows that solvency hedging is an important cause of certain liquidity crises, which implies distinct policy implications.

Some research focuses on how deteriorating solvency raises liquidity risk via margin calls (e.g., Brunnermeier and Pedersen, 2009). LASH risk also operates via margin calls. However, LASH risk happens when solvency improves. As such, LASH risk is an instance of what is known to practitioners as "right-way risk": when a counterparty's solvency improves as its payment obligations increase (Canabarro and Duffie, 2003). The liquidity risk arising from falling solvency, as in Brunnermeier and Pedersen (2009), is an instance of "wrong-way risk". In principle, these comovements with solvency should alter the optimal margining embedded in the hedging contract. The theoretical literature has studied optimal margining in the presence of counterparty risk and moral hazard (e.g., Biais et al., 2020). We take the presence and degree of variation margining as a primitive, motivated by a regulatory framework that requires the suppliers of derivatives to eliminate all counterparty risk through the full margining of their positions.

A second literature to which our paper contributes studies interest rates and financial stability. Various papers document how lower interest rates raise risk-taking (e.g., Adrian and Shin, 2010; Jiménez, Ongena, Peydró and Saurina, 2014) and lead to credit creation and subsequent financial instability (e.g., Grimm, Jordà, Schularick and Taylor, 2023). Other papers document the relationship between interest rates and risk-taking through 'reach for yield' behavior, in the context of insurers, pension funds, mutual funds, and banks (Becker and Ivashina, 2015; Domanski, Shin and Sushko, 2017; Martinez-Miera and Repullo, 2017; Lu, Pritsker, Zlate, Anadu and Bohn, 2023; Aramonte, Lee and Stebunovs, 2022) and the interaction with FX risk (Bertaut, Bruno and Shin, 2023).[3] We contribute to this literature by studying a specific mechanism: how low interest rates raise liquidity risk via hedging solvency risk with derivatives.

Third, we contribute to the literature studying pension funds and related non-bank institutions (see Scharfstein (2018) for an overview).[4] A closely related paper is Klingler and

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[3] Adrian and Liang (2018) and Boyarchenko, Favara and Schularick (2022) provide comprehensive reviews.

[4] Lucas and Zeldes (2009) and Lucas (2017) investigate how reforms to the discount rates applied to pension funds' liabilities affect the asset allocation of pension funds. Greenwood and Vayanos (2010), Greenwood and Vissing-Jorgensen (2018) and Jansen (2021) provide sharp evidence that pension funds' behavior affects interest rates and spills over to other sectors. Koijen and Yogo (2022) investigate how risk-based capital regulation affects the portfolio choice of life insurers. Foley-Fisher, Narajabad and Verani (2020) document self-fulfilling runs within the life insurance industry.

Sundaresan (2019), who show that under-funded pension funds have a higher demand for hedging via swaps. We build upon their work by providing evidence of a link between interest rates and the demand for hedging that operates through a general relationship with solvency. Beyond their paper, we connect pension fund hedging to liquidity risk, which has various additional implications. A second related paper is Jansen, Klingler, Ranaldo and Duijm (2023), who study hedging with swaps in the Dutch pension fund sector. They explore how regulation leads pension funds to use swaps, creating liquidity risk when interest rates rise. We complement the paper in various ways. Our paper points out that falling interest rates are another cause of liquidity risk from hedging instruments. We also connect pension funds' hedging strategies to a salient liquidity crisis, the 2022 UK bond market crisis. Most significantly, we emphasize how improving solvency accompanies the liquidity risk from these hedging strategies—which is crucial for regulation.

Outline. The paper is organized as follows. Section 2 develops a simple framework that will guide our empirical analysis, which predicts that (i) funds partially hedge solvency risk by taking on LASH risk, (ii) incentives to take on LASH risk are greater in a low-rate environment, and (iii) a large enough positive shock to rates generates a liquidity crisis. Section 3 presents the context, data, and strategy to measure LASH risk. Section 4 shows that pension funds partially hedge solvency risk at the cost of taking on LASH risk. Section 5 shows that low rates cause higher LASH risk. Section 6 shows how LASH risk contributed to the UK bond market crisis in 2022. Section 7 concludes.

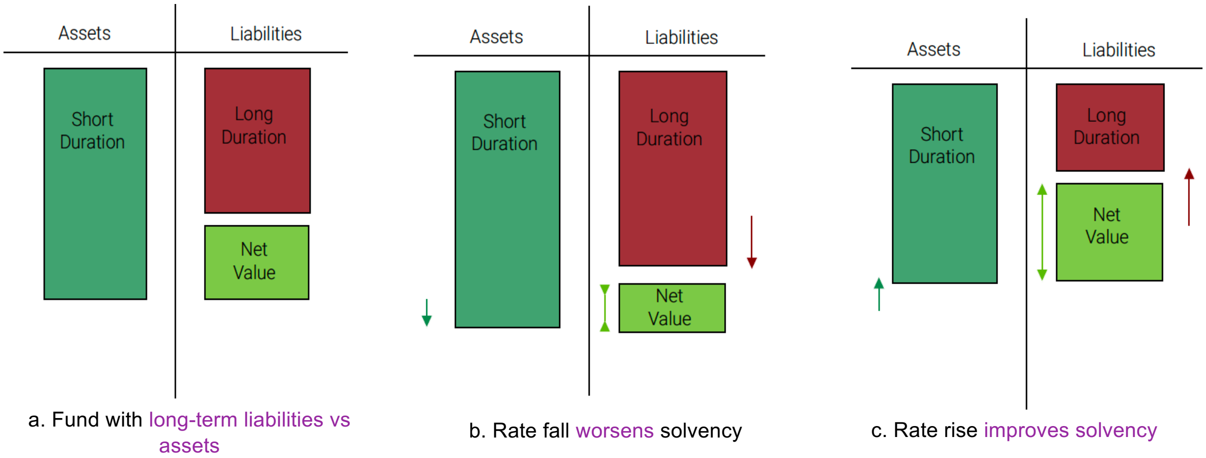
2 LASH Risk: A Simple Framework

As a preamble to the empirical contributions of the paper, this section fixes ideas about LASH risk with a simple model. The model generates three predictions that will structure our empirics: (i) funds partially hedge solvency risk by taking on LASH risk, (ii) incentives to take on LASH risk are greater in a low rate environment, and (iii) a large enough positive shock to rates generates a liquidity crisis, even as solvency improves.

2.1 LASH Risk Mechanics

We start with the mechanics of LASH risk for interest rates. Consider a financial institution with a portfolio of short-duration assets and long-duration liabilities, as in Figure 1.a. This institution could be a pension fund or insurer, with liabilities to its members that are far in the future. Due to the duration mismatch, a decline in interest rates increases the value

Figure 1 Non-Bank Financial Intermediaries and Interest Rates



a. Fund with long-term liabilities vs assets

b. Rate fall worsens solvency

c. Rate rise improves solvency

of the institution's liabilities more than the value of its assets. Net worth falls—that is, its solvency worsens (Figure 1.b). In contrast, when rates increase, the value of liabilities falls by more than assets, and its solvency improves (Figure 1.c).

How can the institution in Figure 1 hedge duration risk? One approach is to lengthen the duration of its assets. However, a pension fund's or life insurer's liabilities can extend beyond three decades, exceeding the maturity of most outstanding bonds. The fund needs a hedge. One option is to write a derivative contract—such as an interest rate swap—where the institution pays a floating rate in exchange for a fixed rate (as in Figure 2.a). Such a contract will appreciate in value when rates fall, partly offsetting the loss on the rest of the institution's portfolio (Figure 2.b).

Hedging with interest rate swaps generates liquidity risk as solvency improves—which is LASH risk. When the value of a swap falls, the institution must pay liquid assets to its counterparty equal to the fall in value. This payment is "variation margin".[5] When interest rates rise, the institution will become more solvent if some of the duration mismatch remains after hedging. However, rising interest rates lower the value of the swap. Consequently, the institution must make payments to its counterparty (Figure 2.c). Therefore, the hedging strategy generates a need for liquidity even as solvency improves. This coincidence of deteriorating liquidity and improving solvency due to hedging with derivatives is LASH risk materializing.

When LASH risk materializes, liquidity crises can happen. Financial institutions may

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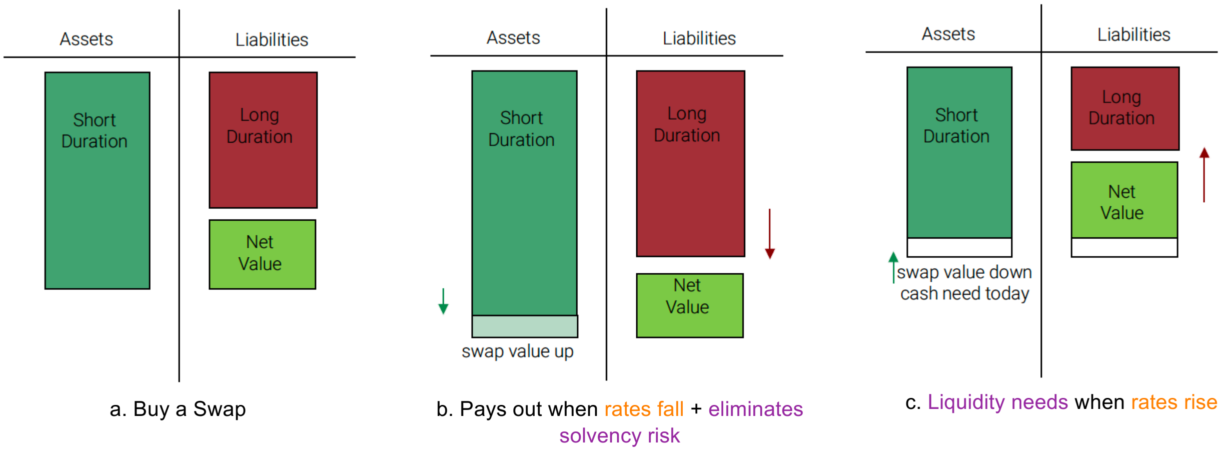
[5] We discuss the institutional details of variation margin in Appendix Section C.

Figure 2 Non-Bank Financial Institutions and Hedging



a. Buy a Swap

b. Pays out when rates fall + eliminates solvency risk

c. Liquidity needs when rates rise

have enough liquid assets to pay variation margins after small interest rate increases. However, large rate rises could require margin calls that are greater than liquid asset holdings. In this case, institutions may have to sell less liquid assets to raise cash and meet the margin call. If the asset sales include bonds, then interest rates may increase more—further improving solvency and deteriorating liquidity, and amplifying the liquidity crisis.

2.2 LASH Risk Formalization

We now formalize LASH risk with a model, which generates predictions that will structure our empirical work.

2.2.1 Environment

We consider the investment problem of a non-bank financial institution, or “fund”. Time runs from $t = 0, 1, \dots, \infty$. The fund is endowed with a perpetual liability that requires paying a fixed l in every period. A natural example is a pension fund or a life insurer, which typically have long-duration commitments to their members.

The fund can invest in three assets. First, the fund holds a_t units of a one-period bond, which pay total coupons a_t in period $t+1$. Second, there is a medium-duration asset, which we model as a geometrically decaying multi-period bond with a decay rate $\delta \in (0,1)$. The fund holds b_t units of the bond, with coupon b_t in $t+1$. Absent sales or purchases of the bond, there is a passive equation of motion for bond holdings $b_{t+1} = \delta b_t$. Third, the fund holds s_t units of interest rate swaps. The fund cannot short bonds, meaning $a_t \geq 0$ and $b_t \geq 0$. However, the swap position, s_t, can be positive or negative.

Asset prices. All assets are priced by a deep-pocketed marginal investor active in the bond and swap markets. The investor is competitive, risk-neutral and discounts the future at rate R_t^{-1}. The marginal investor values the liquidity service from one period bond at rate η, which is non-pecuniary. The fund does not share this non-pecuniary value.

Let q_t^b denote the price of the geometric bond. The investor values the bond at $q_t^b = \mathbb{E}_t \left[\sum_{j=0} \delta^j \prod_{s=0}^{j} R_{t+s}^{-1} \right]$. Let q_t^l denote the price of a perpetuity paying one every period: $q_t^l = \mathbb{E}_t \left[\sum_{j=0}^{\infty} \prod_{s=0}^{j} R_{t+s}^{-1} \right]$. Last, the liquidity service implies that the price of the short-term bond is given by $q_t^a = R_t^{-1}(1+\eta)$. We assume that the medium-term bond is costly to sell. The fund bears a liquidation cost of c per unit sold. The marginal investor does not discount the value of the bond due to the liquidation cost.

Interest rate swaps last for one period and are priced fairly. There is a fixed leg associated with a realized cash-flow in period $t+1$ of $\mathbb{E}_t \left[R_{t+1}^{-1} \right]$—which depends on markets' expectations of interest rates at time t when the contract is traded. There is a floating leg associated with a realized cash-flow in period $t+1$ of R_{t+1}^{-1}.[6] When the swap is realized, the buyer receives the floating cash-flow and pays the fixed cash-flow. Therefore the realized cash-flows from a swap position s_t are given by $s_t \left(R_{t+1}^{-1} - \mathbb{E}_t \left[R_{t+1}^{-1} \right] \right)$, i.e. the difference between the floating and the fixed leg. Clearly, a unit of swap holdings yields a cash flow $\left(R_{t+1}^{-1} - \mathbb{E}_t \left[R_{t+1}^{-1} \right] \right)$ when the interest rate unexpectedly falls between t and $t+1$. Therefore holding swaps hedges against falls in interest rates. When the interest rate rises, the swap buyer must pay cash-flows, because $\left(R_{t+1}^{-1} - \mathbb{E}_t \left[R_{t+1}^{-1} \right] \right)$ is negative. The loss on the swap position can be interpreted as the "variation margin" associated with the swap.[7]

Fund Value. We can define the net asset value of the fund as $w_t = q_t^a a_t + q_t^b b_t - q_t^l l$, i.e. the value of the medium term and the one period bond holdings, deducting the value of the liability. Accounting for liquidity costs, w_t evolves according to

$$w_t = a_{t-1} + b_{t-1} - l + q_t^b \delta b_{t-1} + s_{t-1} \left(R_t^{-1} - \mathbb{E}_{t-1} \left[R_t^{-1} \right] \right) - c \underbrace{\max \{0, \delta b_{t-1} - b_t\}}_{\text{sales of the geometric bond}} - q_t^l l. \quad (1)$$

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[6] We have assumed that the swap is written on the inverse of the interest rate for analytical convenience. Buying the swap and receiving the floating leg insures against low rates. In practice, interest rate swaps are written on the level of the rate, and so receiving the fixed leg hedges against low rates.

[7] Note that a multi-period swap that is fully margined would require an exchange of cash flows proportional to the gain or loss on the single period swap. So the assumption of single-period swaps is a simple way to capture variation margin.

In this equation, net asset value is: coupons from the short- and medium-term bonds; deducting the payment associated with the long-term liability; the continuation value of the previous holding of the medium term bond; the payoff from the previous period's swap position; the liquidation costs associated with possible sales of the medium term bonds; and deducting the continuation value of the liability.

Liquidity needs. The fund must have sufficient resources in order to cover any losses on its swap position. It is useful to define $m_t \equiv a_{t-1} + b_{t-1} + s_{t-1}\left(R_t^{-1} - \mathbb{E}_{t-1}\left[R_t^{-1}\right]\right) - l$ as liquid resources available to the fund—i.e. coupons from the short- and medium-term bond and the payoff from the swap position, deducting the payment associated with the long-term liability. If liquid resources are positive, then the fund can cover its liabilities including a potential loss on the swap position. If liquid resources are negative, then the fund must sell medium-term bonds. As such, liquid resources and medium-term bonds must satisfy

$$(1-c)\max\{0, \delta b_{t-1} - b_t\} \geq -\min[m_t, 0]. \tag{2}$$

This equation states that the value of sales of the medium-term bond must exceed the liquidity needs of the fund, should these liquidity needs be negative.

Fund objective. There is a fund manager in charge of the fund until an exogenous period T.[8] The manager is risk neutral, does not enjoy limited liability and receives compensation in period T (that is negligible compared to the value of the fund) proportional to

$$\pi_T = (1 + \kappa \mathbf{1}\left(w_T < 0\right)) w_T. \tag{3}$$

Here, the marginal value to the fund manager of increasing wealth is linear. The marginal value is greater when the fund is in deficit, since $\kappa > 0$. The fund manager maximizes their objective (3) by choosing holdings of swaps, short and medium-term bonds $\{s_t, a_t, b_t\}_{t=0}^{T}$, subject to the law of motion for net worth (1), the liquidity constraint in (2), and the no-shorting requirement that $a_t, b_t \geq 0$.

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[8] The fixed investment horizon is helpful for tractability. An infinite horizon model where the fund manager discounts the future and is compensated in proportion to the current value of the fund every period delivers similar results.

2.2.2 Discussion of Main Ingredients

Our model contains four necessary ingredients to obtain our main results. These ingredients are empirically grounded and will combine to produce the predictions of the model.

1. **Costs from insolvency.** For the fund, reducing a deficit by \$1 is more beneficial than increasing a surplus by \$1, since $\kappa > 0$ in equation (3). This asymmetry could represent a regulatory penalty. In the UK, for example, pension funds are taxed if they have deficits. These costs could also represent economic factors, such as companies' unwillingness to commit resources to their insolvent pension funds. Finally, the objective resembles "reference dependent" preferences, which may capture relevant behavioral factors (Lian, Ma and Wang, 2019).

2. **Funds can only use swaps to hedge duration risk.** The fund cannot hold assets with long enough duration to hedge duration risk, because the medium-duration asset has lower duration than the perpetual duration liability. This assumption captures the notion that long-duration assets such as 30-year government bonds are scarce and command high premia (e.g., Greenwood and Vayanos, 2010). The fund can only hedge interest rate risk using swaps.[9]

3. **Liquid assets command premia.** The fund can insure against liquidity risk by holding short-duration assets. However, these assets command a liquidity premium captured by η in the model. Empirically, liquidity premia are common (see e.g., Nagel, 2016).

4. **Illiquidity of the medium-term asset.** The medium-term asset has a higher return than the short-term asset but incurs liquidation costs when sold. A reason for these costs could be the constrained broker-dealer balance sheets (Duffie, 2022).

Costs from insolvency lead to risk aversion, which encourages the firm to hedge interest rate risk. Moreover the fund must use swaps to hedge the risk. Liquidity needs generated by the hedge cannot be offset without a cost: either the fund must hold expensive liquid assets, or risk liquidating a portion of its long-duration portfolio.

To obtain analytical results we make simplifying assumptions about the interest rate process and the fund's problem that we relax in a numerical analysis. First, we assume the interest rate follows a process $R_{t+1}^{-1} = R_t^{-1} + \varepsilon_{t+1}$, where ε_{t+1} is a mean-zero shock to

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[9] As we will discuss in Section 2.4, an equivalent hedging strategy involves borrowing short-duration assets to buy the medium-duration asset, i.e. a form of repo contract.

the interest rate with bounded support $[\varepsilon^l, \varepsilon^h]$. ε^l is large enough so that the gross interest rate is positive. The density of ε_{t+1} converges to zero at its bounds. Finally $R_{t+j} = \bar{R}$ for all $j \geq 2$. That is, interest rate risk is present only in period $t+1$. It is useful to define $t+1$ net worth if the fund neither hedges nor holds short-term bonds, as $y_{t+1}(\varepsilon_{t+1}) = b_t - l + q^b_{t+1}(\varepsilon_{t+1})\delta b_t - q^l_{t+1}(\varepsilon_{t+1})l$. Here, we make explicit that net worth depends on the shock ε_{t+1}. We then make the following assumptions on the fund's problem:

Assumption 1. *(i)* $y_{t+1}(0) > 0$ *and* $y_{t+1}(\varepsilon^h) < 0$*; (ii)* $c < \frac{y_{t+1}(0)}{y_{t+1}(0) - y_{t+1}(\varepsilon^h)}$*; and (iii)* $T = t + 1$.

The first part of the assumption requires that, absent hedging, the fund is solvent if rates equal their expected value, whereas the fund is insolvent if rates fall sufficiently far. As such, fund value is neither too great nor too small to render hedging irrelevant. The second and third assumptions are made for tractability. The second ensures that liquidation costs are never large enough at the optimal level of hedging to lead to insolvency. The third assumption, combined with the process for interest rates, allows us to ignore inter-temporal aspects by focusing on a single-period investment horizon.

2.2.3 Predictions of the Model: Liquidity vs. Solvency Risk

The key feature of this model is that the fund uses swaps to trade off solvency risk from falling rates versus liquidity risk from rising rates. We define solvency risk as the likelihood that the fund's net asset value w_t is negative. We define liquidity risk as the likelihood that the fund's liquid resources m_t are negative, meaning they must sell medium-duration bonds. Unless the fund fully hedges solvency risk, the fund loses value from falling interest rates—since the liability has longer-duration than assets. As such, the fund should hedge interest rate risk. However, hedging solvency risk also has a cost, namely the risk of costly liquidations.

To elaborate on the trade-off between solvency and liquidity risk, in Appendix A.1 we derive the first order necessary condition for the choice of swaps, s_t, associated with the fund manager's objective (3). The first order condition is:

$$\kappa Pr\left\{w_{t+1} < 0\right\}\left(\mathbb{E}_t\left[\varepsilon_{t+1} | w_{t+1} < 0\right]\right) = \frac{c}{1-c} Pr\left\{m_{t+1} < 0\right\}\left(\mathbb{E}_t\left[-\varepsilon_{t+1} | m_{t+1} < 0\right]\right). \tag{4}$$

The first order condition shows the fund's incentive to trade off solvency risk against liquidity risk. The term before the equality is the marginal value of holding swaps in states of the world in which the fund has a negative solvency so that $w_{t+1} < 0$. These states occur after unexpected interest rate falls. Therefore, this term represents the benefit of holding swaps, by reducing insolvency when rates fall. The term after the equality is the marginal cost of holding swaps in states of the world where the fund has negative liquidity, so that $m_{t+1} < 0$. In these states, the cost of swaps is the liquidation of medium-term assets. These states happen when interest rates rise, in which case the fund has a loss on its swap position. In these states solvency may improve: the coincidence of better solvency and worse liquidity with rising rates is LASH risk materializing.

We now derive the main three predictions of the model, which we collect in the following proposition.

Proposition 1. *If Assumption 1 holds, the liquidity premium η on the short run asset is sufficiently high, and the maximum realization of the interest rate shock ε_l is sufficiently large, then*

(i) *The fund will partially hedge interest rate risk: the fund will choose an optimal level of hedging $s_t > 0$; but the risk of solvency will be positive, so that $Pr(w_{t+1} < 0) > 0$.*

(ii) *If the interest rate R_t is lower, then the optimal level of hedging s_t increases.*

(iii) *There exists a positive threshold realization of the interest rate shock ε_{t+1}, such that if the shock exceeds that threshold, the fund will sell medium-duration assets. At this threshold, net worth w_{t+1} is positive and greater than if rates equal their expected level.*

Proof. See Appendix A.1

The intuition for the first part of the proposition is straightforward. As we have discussed, the fund holds swaps in order to trade off the solvency risk from falling interest rates against the liquidity risk from rising rates. The proposition establishes that, under our assumptions, the fund does not resolve this trade-off by hedging all of the solvency risk. Since the liquidity premium is large, the fund cannot self-insure with short-term assets. As such, the fund must liquidate medium-term bonds when the loss on the swap is sufficiently large. Since liquidation is costly, the fund does not hold too many swaps, which prevents complete hedging.

The intuition for the second part of the proposition is as follows. By the first part, the fund only partially hedges against interest rate risk. Therefore falling interest rates lower the solvency of the fund. Since insolvency is costly and nearer, the fund has a greater incentive to hedge against interest rate risk by raising its holdings of swaps. Formally, for a given s_t lower rates raise the left hand side of equation (4) but have no impact on the right hand side. As such, low rates make the fund raise its swap holdings.

The third part of the proposition is also simple. A large increase in interest rates implies a large payment is required to cover the loss on the swap position. This necessarily exhausts the fund's holdings of liquid assets. As such, the fund must sell medium-term bonds to satisfy the margin call. Liquidation of the medium-term asset is what we term a "liquidity crisis". However, the underlying solvency of the fund will have improved—in the sense that the fund has higher value than if interest rates had not increased.

Last, our analytical results make strong assumptions for tractability. In Appendix A.2, we explore a calibrated version of the model with $T > t + 1$ and interest rate risk at all horizons and show that with reasonable liquidity premia, swaps holdings and LASH risk indeed rises as interest rates fall. For numerical results we simply assume the rate is i.i.d. Our result also hinges on hedging taking place using swaps, or other *linear* hedging strategies. We elaborate on this aspect of the model in Appendix A.3. In the coming sections, we will confront the three predictions of our model with data.

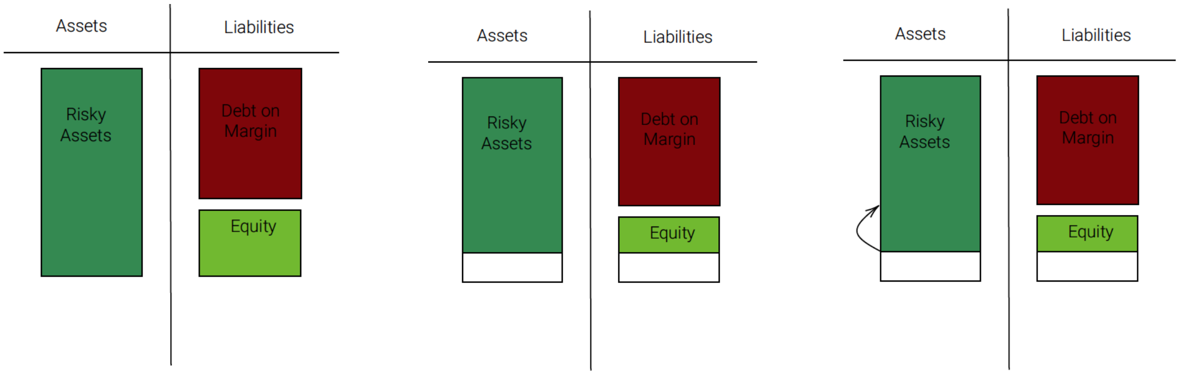
2.3 LASH vs. Other Liquidity Risk

Our framework shows that LASH risk is different from other forms of liquidity risk. Consider, for instance, liquidity risk from maturity transformation and bank runs (Diamond and Dybvig, 1983). In this case, the risk of a bank run is linked to the bank's long-term and illiquid assets versus their short-term and callable liabilities to savers. However, LASH risk is independent from callable claims. In our example of a pension fund, liabilities are long term and assets are shorter term—the opposite pattern of the traditional bank.

LASH risk is also distinct from liquidity risks associated with rolling over short-term debt (e.g., Calvo, 1988; Cole and Kehoe, 2000; Morris and Shin, 2004; He and Xiong, 2012; Aguiar et al., 2022). In our example, LASH risk occurs even though liabilities are long term and debt is not rolled over.

Finally, LASH risk is different from the liquidity risk studied by Brunnermeier and Pedersen (2009) and others. The key feature of this form of liquidity risk is that liquidity and solvency deteriorate at the same time. With LASH risk, liquidity deteriorates as solvency improves. To elaborate, the Brunnermeier-Pedersen model studies how traders' funding liquidity—which relates to margin calls—depends on the liquidity of assets in the market. In their analysis, margin requirements mean that market liquidity and funding liquidity interact to create adverse liquidity spirals. To illustrate the mechanism and how it differs from LASH risk, consider a fund that has entered a leveraged bet on a risky asset with a margin requirement as in Figure 3.a. A shock leads to an initial loss, which wipes out some of the bank assets/net worth, which leads to margin calls (Figure 3.b). The financial institution sells assets to meet margin calls, which pushes down asset prices, further raising margin

Figure 3 Comparison: Funding Liquidity (Brunnermeier and Pedersen, 2009)



a. Fund has leveraged bet on a risky asset with a margin requirement.

b. Initial loss wipes out some of bank assets/net worth..
- Leads to margin calls...

c. Leads to margin calls...
- ... leading to asset sales...
- ... pushing down asset prices...
- ... raising margin requirements...
- ... add causing further asset sales.

requirements and causing further asset sales (Figure 3.c), leading to a "liquidity spiral" (see Figure 2 of Brunnermeier, 2009). With LASH risk there is no fall in solvency; instead, solvency improves as liquidity risks materialize.

2.4 Beyond Swaps and Interest Rate Risk

We now discuss LASH risk more broadly, for other hedging instruments and other risks to solvency. The fund could also manage interest rate risk with other strategies. One strategy is to shorten the duration of the fund's liabilities by borrowing using short-term debt. In doing so, the fund's interest rate exposure falls as the gap between the duration of liabilities and assets narrows. Specifically, the institution could use a repurchase agreement (repo) for short-term borrowing, and use the proceeds to invest in longer-duration assets. This strategy replicates an interest rate swap. The institution pays a short-term floating rate on its borrowing and receives the fixed, long-term rate on the assets it purchases.

Repo borrowing requires variation margin to be paid when interest rates rise—which again results in LASH risk. With repo, the borrower sells a financial security to a lender, and agrees to buy it back at a later date and typically a higher price. The security serves as collateral and is usually a long-term bond. If the collateral falls in value, the borrower must pay liquid assets equal to the fall in value. Again, interest rate rises, and falling bond prices, generate liquidity needs.

The pension fund can hedge the risk from long-term liabilities and short-term assets with another strategy. The pension fund can hold a stake in a second fund that has the opposite duration structure, that is, short-term liabilities and long-term assets. In the context of pensions, particularly in the UK, this latter fund is known as a Liability-Driven Investment (LDI) fund. The LDI fund borrows with repo to buy longer-duration assets (or engages in equivalent interest rate swap transactions). The payoff from holding an equity stake in the LDI fund replicates the payoff from employing the hedging strategy directly. Again, lower interest rates raise solvency risk, while higher interest rates raise liquidity risk.[10]

Interest rate risk is one important application of LASH risk, but the concept applies to other forms of risk. An institution that wishes to hedge a foreign exchange (FX) mismatch can use similar instruments to do so (e.g., swaps or forwards). For example, a fund with dollar denominated assets and euro denominated liabilities would like a derivative that pays off in the Euro appreciates – specifically, it would swap euros for dollars. Again, this strategy reduces solvency risk but raises liquidity risk due to margin calls from the FX swap. Large movements in exchange rates can then lead to liquidity needs when the solvency of the institutions improves. This pattern contributed to the pandemic-era liquidity crisis of Spring 2020 (Czech et al., 2023).

3 Data and Measurement of LASH Risk

This section discusses our data sources and how we use the data to measure LASH risk.

3.1 Data Sources and Coverage

To measure LASH risk for interest rates, we construct a database of: i) the universe of UK government bond (gilts) transactions; ii) the universe of gilt repo transactions; iii) the universe of sterling interest rate swap positions and iv) hand-collected UK pension fund balance sheet data. The consolidated sample period across all datasets is January 2019 to March 2023.

Bond market. To analyze trading in the UK bond market, we use the transaction-level MiFID II database maintained by the UK's Financial Conduct Authority (FCA). The MiFID

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[10] LDI funds benefit smaller pension funds, which lack the scale to manage hedging strategies in-house, and thus outsource hedging to the LDI funds, often in "pooled" entities that include assets from several pension funds. Pension funds are subject to cash calls to provide liquidity to LDI funds that they own in the case of margin calls that the LDI fund cannot cover itself. We discuss institutional details of the UK pension fund system in Appendix Section B.

II data provide detailed reports of all secondary-market trades of UK-regulated firms or branches of UK firms regulated in the European Economic Area (EEA). Given that all bond dealers are UK-domiciled and hence FCA-regulated institutions, our data cover virtually all transactions in the market. Each transaction report contains information on the transaction date and time, ISIN (a unique identifier for each bond), execution price, transaction size, and the legal identities of the buyer and seller. We will focus on the UK government bond (gilt) segment of the wider bond market, and from now on, the term bond refers to those issued by the UK government (unless stated otherwise).

Repo Market. The Bank of England's Sterling Money Market data (SMMD) is a transaction-level dataset covering the sterling unsecured and secured (gilt repo) money markets. The data are obtained from dealers in the respective money markets and have been collected since 2016. The data cover 95% of activity in which a bank or dealer is a counterparty, but the data do not capture the small segment of non-bank to non-bank repo transactions. We are again able to identify the identity of the counterparties, the collateral ISINs associated with each transaction, the transaction size, and the execution price.

Interest Rate Swap Market. To analyze the interest rate swap positions, we use transaction-level data from two European Markets Infrastructure Reporting (EMIR) Trade Repositories, DTCC and LSEG Regulatory Reporting Limited (previously Unavista). We collect weekly positions on outstanding over-the-counter (OTC) GBP interest rate swap (IRS) and overnight index swap (OIS) trades where at least one of the counterparties is a UK entity.[11] The IRS dataset contains trade-level information on the counterparties' identities, notional, currency, floating rate, the direction of trade, maturity, and execution date. The cleaning process of the database is largely based on Khetan et al. (2023), with several additions that allow us to better exploit and understand the outstanding positions of these entities.

In addition, to compute discount rates and construct our measure of LASH risk, we use Bank of England data on OIS and yield curves as well as daily data on gilts' modified duration from Bloomberg.

Pension Fund Balance Sheets. We construct, to the best of our knowledge, the largest dataset detailing individual UK pension fund balance sheets. We hand-collect data

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[11] We retrieve the data via the Bank of England's access to the mandatory reporting of the UK European Markets Infrastructure Regulation (UK EMIR). More details on the reporting obligation can be found here. For pre-2021 data (reported under EU EMIR), the Bank of England had access to (i) trades cleared by a CCP supervised by the Bank, (ii) trades where one of the counterparties is a UK entity, (iii) trades where the derivative contract is referencing an entity located in the UK or derivatives on UK sovereign debt, (iv) trades where the Prudential Regulation Authority (PRA) supervises one of the counterparties. For post-2020 data, the Bank of England has access to all data reported to trade repositories under UK EMIR.

from annual reports and newsletters for 100 individual pension funds from 2017 to 2022, covering more than 40% of the UK pension sector by asset size in 2020.[12] Our database includes information on net investments, cash, bonds and derivative holdings. Tables E.1 and E.2 summarize the cross-section of actuarial assets and liabilities, and the evolution of funding ratios over time.

3.2 Measurement: Interest Rate LASH Risk for Non-Banks

We now describe how to measure LASH risk arising from interest rate hedging. Similar methods can be used, for instance, to measure LASH risk from FX hedging.

General Concept. We wish to measure how margin calls of a given contract change after a shock to interest rates. As such, given a shock to interest rates R_t, LASH risk for hedging contract i is

$$LASH_{i,t} \approx \Lambda_i \times \frac{\partial NPV_{i,t}}{\partial R_t}, \tag{5}$$

where $NPV_{i,t}$ is the net present value of the hedging contract. For a swap, $NPV_{i,t}$ is the present value of the floating leg minus the fixed leg. For a repo contract, $NPV_{i,t}$ is the value of the repo collateral. One can interpret $\partial NPV_{i,t}/\partial R_t$, sometimes referred to as dollar duration or DV01, as the effect of a uniform shift in the yield curve on the present value of the hedging contract. Λ_i captures by how much margin increases as the NPV of the contract changes, which may differ based on the contract type. For both swaps and repos on government debt, the typical contract features $\Lambda_i \approx 1$, so we use this value.[13] Setting Λ_i as a constant abstracts from changing margin requirements or in repo haircuts in response to a change in rates. Appendix D elaborates on how the specific steps to compute (5) for repos and interest rate swaps.

For a given institution j that holds $Q_{i,j,t}$ of a given hedging contract, its aggregate LASH risk is given by

$$LASH_{j,t} = \sum_i Q_{i,j,t} \text{LASH}_{i,t}. \tag{6}$$

Letting $Q_{i,t}$ denote the aggregation of contracts across institutions, aggregate LASH risk is

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[12] There is limited fund-level data on UK pension fund balance sheets. The closest exercise in collecting UK data is done by Konradt (2023), covering 12 UK pension funds worth \$300bn in asset size. In 2020, we observe 65 pension funds worth £1046.9bn in actuarial assets, out of the total average of £2497bn in the UK pension fund sector that year. Our sample also includes 20 out of the largest 25 pension funds by asset size.

[13] Margin requirements on interest rate swaps are typically set so that the variation margin equals the change in the value of the swap, while repo haircuts on government debt are fairly close to zero (for example, the average gilt repo haircuts for LDI funds were only around 25 basis points in the first three quarters of 2022, see Ivan, Lillis, Maqui and Salazar, 2024). So long as Λ_i is homogeneous across investors its exact value will not play an important role in our empirical analysis.

given by

$$LASH_t^A = \sum_i Q_{i,t}\text{LASH}_{i,t} = \sum_j LASH_{j,t}^A, \tag{7}$$

where $LASH_{j,t}^A$ is LASH risk held by institution j.

Two observations are in order. First, contracts with long maturity have higher LASH risk, since their NPV is more sensitive to changes in interest rates. Second, LASH risk goes in both directions—firms can receive or pay liquidity, depending on the direction of their exposure and the price change of the underlying instrument. If the contract value $Q_{i,t}$ decreases (increases) from the perspective of institution j, then the firm is obliged to post (receive) margin. For example, pension funds are exposed to liquidity demands when yields rise, whereas their counterparties (mainly dealer banks) have to post margin when rates fall.

Therefore, given that each contract involves two counterparties, the aggregate measure of $LASH_t^A$ for all institutions in the economy is close to zero. When we document positive LASH risk for the non-bank financial sector, it implies that another set of agents in the economy has negative LASH risk exposures (in the UK, for example, that would be the banking sector—see, e.g., Khetan et al., 2023).

Mechanical versus Discretionary LASH risk. The term $\partial NPV_{i,t}/\partial R_t$ in equation (5) is not constant at the contract level and depends on the level of interest rates. By convexity, the value of a bond or the fixed leg of a long-dated swap both become more sensitive to interest rate movements when rates are lower. One goal of the paper is to explore how funds choose different levels of LASH risk as interest rates vary. Therefore, we must account for this automatic link. We introduce a simple decomposition of LASH risk into two separate parts, which we label its "mechanical" and "discretionary" components. The mechanical component captures convexity. The discretionary factor captures how the financial institutions shift their allocation of hedging, $Q_{i,j,t}$, towards contracts i with ex ante higher or lower LASH risk.

Consider the definition of aggregate LASH risk in equation (7). We can separate the discretionary and mechanical components via a standard first-order decomposition. In particular, we can write the change in aggregate LASH risk as

$$\overbrace{\Delta \sum_i Q_{it}\text{LASH}_{i,t}}^{\text{aggregate change}} = \underbrace{\sum_i Q_{i,t}\Delta\text{LASH}_{i,t}}_{\text{mechanical change}} + \overbrace{\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}}^{\text{discretionary change}}. \tag{8}$$

The discretionary component measures how LASH risk changes as firms' holdings of different hedging contracts change, holding fixed the duration and convexity of the hedging contracts themselves. One can obtain a similar measure of discretionary LASH risk at the institution level.

4 LASH Risk from Interest Rates: Descriptive Facts

This section shows that, consistent with our model, institutions with long-dated liabilities like pension funds and insurers take on significant LASH risk. We provide additional descriptive facts about the nature of this LASH risk. Finally, we show that despite LASH risk, pension funds are partially hedged, meaning their net worth rises with interest rates.

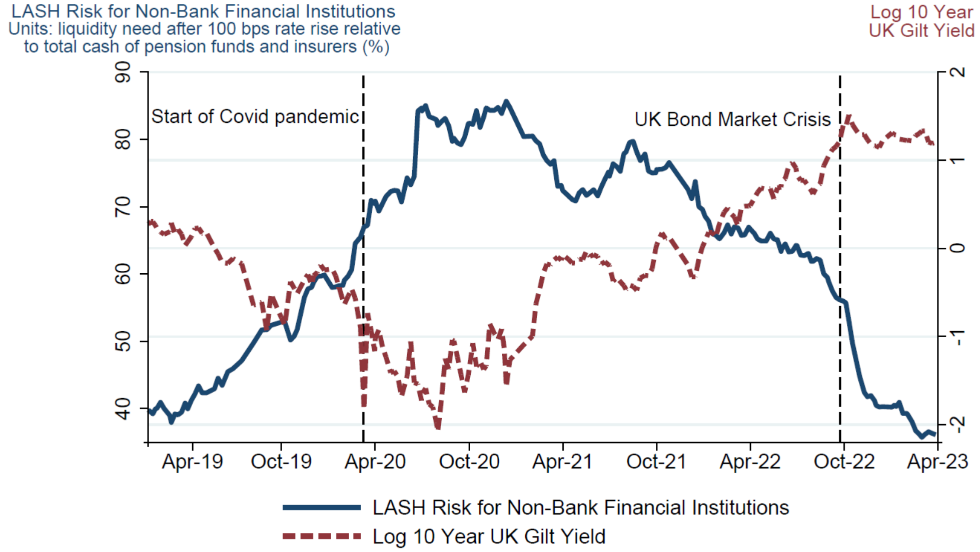
4.1 LASH Risk—Descriptive Facts

This section presents four descriptive facts about our measure of LASH risk for non-bank financial institutions and sterling rates. In brief, we find that (i) LASH risk is large and higher when interest rates are low; (ii) movements in LASH risk are largely due to discretionary rather than mechanical reasons; (iii) LASH risk is large for both interest rate swaps and repo contracts; and (iv) LASH risk is concentrated in the pension fund sector, including LDI funds.

i. LASH risk is large, and higher when interest rates are low. Figure 4 demonstrates this fact, by reporting aggregate LASH risk at weekly frequency, in the non-bank financial sector, from 2019 to 2023. To give a sense of scale, we normalize LASH risk by the cash holdings of UK pension funds and insurers (who, as we will see, are the main holders of LASH risk). The units indicate that at the peak, a 100bps increase in interest rates would have induced liquidity needs that would almost deplete the entire cash positions of both sectors—in other words, LASH risk is very large. For context, although a 100bps interest rate increase is significant, it is smaller than the 130bps trough-to-peak increase in the 30-year gilt yield during the 2022 UK bond market crisis. Moreover, as predicted by our framework, LASH risk moves inversely with interest rates. The figure plots the log of the 10-year gilt yield. When long-dated government bond yields are relatively low, as in 2020, LASH risk is relatively high. Our framework predicts this pattern.

ii. Movements in LASH risk are largely due to discretionary rather than mechanical reasons. Recall that LASH risk can vary for two reasons: first, institutions might reallocate funds towards instruments with higher LASH risk; and second, the LASH risk of individual contracts mechanically rises as interest rates fall due to convexity. Appendix

Figure 4 LASH RISK: NON-BANK FINANCIAL INSTITUTIONS



NOTE. Estimated liquidity needs after a 100bps rise in interest rates relative to total cash holdings of UK pension funds and insurers (%). The measure corresponds to $LASH^{A}_{i,t}$ as defined in equation 8 in Section 3.2. Cash is from the UK flow of funds and cash is defined as currency, deposits of any sort and holdings of money market fund liabilities.

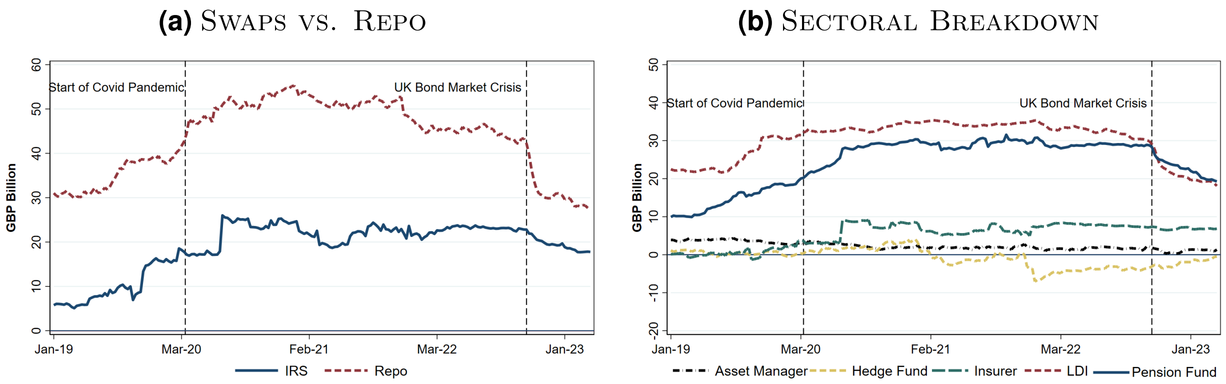
Figure E.8 demonstrates that discretionary effects dominate—the total LASH risk is shown in blue, and the discretionary component in red. The two series co-move closely. Therefore, movements in LASH risk over time primarily reflect how institutions reallocate funding and hedging towards instruments with higher LASH risk.

The third and fourth facts describe where LASH risk concentrates.

iii. LASH risk is large for both interest rate swaps and repo contracts. These are the two primary hedging strategies that we consider, both prevalent throughout the non-bank financial system. In practice, both strategies generate significant LASH risk. Figure 5a reports this result. In the figure, the blue line captures LASH risk for repo contracts, whereas the red line is LASH risk for swaps. Both swap and repo exposures are large, and the LASH risk from repo tends to be £20-30bn higher than the LASH risk from swaps.

iv. LASH risk is concentrated in the pension fund and, to a lesser extent, the insurance sector. Figure 5b displays this result. In the figure, we disaggregate LASH risk across five sectors, namely regular pension funds, LDI funds, insurers, asset managers, and hedge funds. Broadly defined, LDI funds belong to the pension fund sector. Considering LDI funds and regular pension funds jointly, it is apparent that the broad pension fund sector is the primary holder of LASH risk for interest rates. Insurers have a smaller but positive amount of LASH risk. Traditionally life insurers also have a smaller duration gap

Figure 5 LASH: Swaps vs. Repo and Sectoral Breakdown



(a) Swaps vs. Repo

(b) Sectoral Breakdown

NOTE. Panel (a) shows the evolution of the discretionary LASH risk by instrument in £bn for all non-banks, separately for swaps versus repo. Panel (b) shows the evolution of the discretionary LASH risk across different sectors in £bn, for pension funds, insurers, LDI funds, hedge funds and asset managers, respectively.

than pension funds. Hedge funds and asset managers have a very small duration gap, and are unlikely to use swaps to hedge interest rate risk.

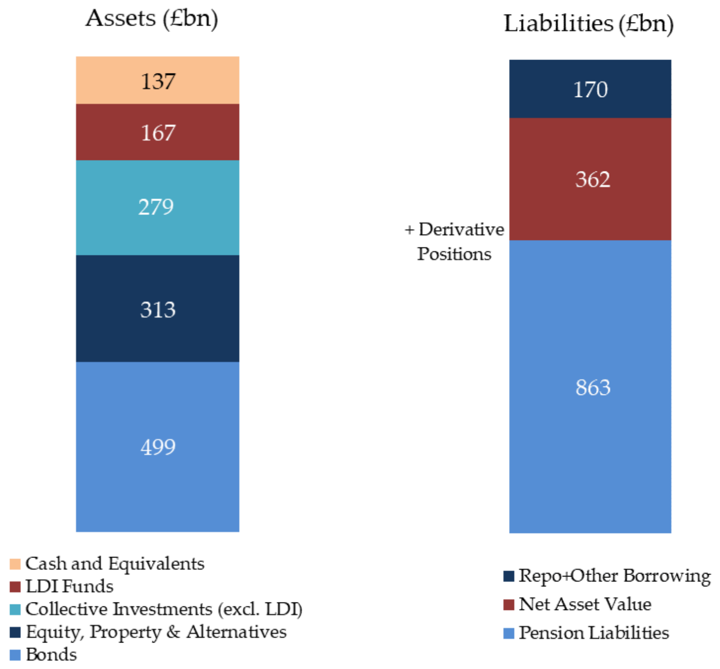
Figure 6 puts this finding in context by presenting the aggregate balance sheet of UK defined benefit private pension funds at the end of 2022 (see Appendix B for additional institutional details). Major assets include equity, property, alternatives, and government bonds, which tend to have shorter duration than pension liabilities. The also shows significant interest rate hedging. Liabilities include repo and assets include LDI funds. As we have discussed, both LDI and short term borrowing hedge interest rate risk. Swaps, the third hedging strategy, are held off-balance sheet. We plot notional interest rate swap positions of the pension fund sector in Appendix Figure E.5. In total, hedging against interest rate risk is large. Combining swaps, repo, and LDI investments, the UK pension fund sector has interest rate hedges with a notional value equivalent to more than 50% of pension liabilities, and three times the aggregate cash holdings of the pension fund sector.

4.2 Partial Hedging of Interest Rate Risk

Our framework predicts that pension funds partially hedge interest rate risk by taking on LASH risk. We have established the presence of LASH risk and that the funds hedge. We now show that the hedging is partial—as rates rise, pension fund solvency improves.

The solvency of a pension fund is typically measured via its funding ratio, which is defined as the fraction of the market value of its assets to the market value of its liabilities, discounted with UK government bond yields. Figure 7 shows that the aggregate funding

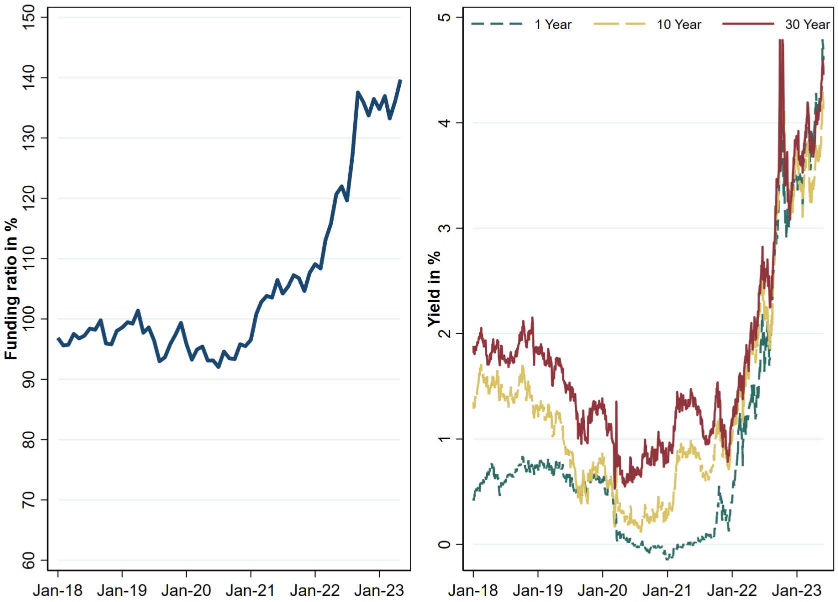
Figure 6 UK Pension Funds: Aggregate Balance Sheet



NOTE. Calculations based on 2023 ONS data and 2023 PPF 7800 data.

ratio rose from around 90% in 2020 to almost 140% at the end of 2022. Over this period, interest rates rose. As such, despite hedging against some interest rate risk, pension funds are not fully hedged.

Figure 7 Pension Funds' Funding Ratios and Bond Yields



NOTE. The left panel shows the aggregate funding ratio (defined as total market value of assets divided by total market value of liabilities) of UK pension funds in %. Source: Pension Protection Fund 7800 Data. The right panel displays the yields of UK government bonds (gilts) at different maturities in %.

5 Low Interest Rates and High LASH Risk

Our descriptive evidence shows a striking pattern: in aggregate, LASH risk is high when interest rates are low. This pattern matches our conceptual framework, which predicts that a decline in rates lowers solvency for pension funds, which raises hedging demand and LASH risk. This section tests and confirms that low interest rates cause an increase in LASH risk using a cross-sectional identification strategy.

To support our claim, we exploit the cross-sectional variation from our regulatory data. Our identification strategy analyzes how the assets held at the beginning of the sample influence solvency afterwards. Specifically, institutions that hold relatively long-duration assets will experience lower capital losses as interest rates fall, relative to institutions holding shorter-duration assets. Therefore, as interest rates fall, solvency should deteriorate more for institutions holding short-duration assets.

Since short-duration institutions face greater solvency risk following a decrease in interest rates, they require more hedging. As such, our simple framework predicts that short-duration institutions should disproportionately increase LASH risk after interest rate falls. Appealingly, the cross-sectional variation captures the same mechanism that we conjecture should operate at the aggregate level. That is, LASH risk increases because falling interest rates reduce solvency.

Technically, it is *net* duration that matters for solvency, rather than our measure of *gross* asset duration. However, asset duration will be a proxy for net duration, unless within each institution asset duration is very strongly negatively correlated with liability duration. The supervisory data does not record pension funds' net duration. However we can study the relation between asset duration and net duration in a subsample of institutions in our hand-collected balance sheet data. As we describe in Appendix F, we measure net duration using the sensitivity of a pension fund's individual funding ratio to changes in interest rates. Appendix Figure F.1 shows the comparison between net duration and asset duration. The figure confirms that there is a negative correlation between the two, i.e. institutions with short asset duration have net worth that is more sensitive to rate changes.

To implement our cross-sectional strategy, we estimate the following quarterly panel regression:

$$\Delta LASH^{Disc.}_{j,t} = \beta_1 \Delta Yield^{10Y}_t + \beta_2 \Delta Yield^{10Y}_t \times \left(\sum_i^I \omega_{j,i,t=0} \times AD_{i,t}\right) + \text{fixed effects} + \varepsilon_{j,t}, \quad (9)$$

where $\Delta LASH^{Disc.}_{j,t}$ measures the quarterly change in the discretionary LASH risk of institution j at the end of quarter t. $\sum_i^I \omega_{j,i,t=0} \times AD_{i,t}$ is the weighted modified duration of institution j's assets, calculated from the institution's holdings of each gilt at the beginning of the sample and multiplying these with the given gilt's duration.[14] $\Delta Yield^{10Y}_t$ is the quarterly change in the ten-year gilt yield. To facilitate the interpretation of the coefficients, the dependent variable is transformed using the Inverse Hyperbolic Sine method. Therefore, the regression coefficients measure the percent change in LASH risk, even if LASH risk is negative (see, e.g., Czech et al. 2023). The yields are denoted in percentage points, and the weighted duration variable is standardized. We cluster standard errors at the quarterly level and include various combinations of fixed effects, described below, to control for how different institutions respond to time-varying macroeconomic trends.

Our framework predicts that β_2 is positive. That is, as interest rates fall, institutions with long-duration assets take on less LASH risk. These institutions have lower falls in solvency as rates fall, and less of a need for more hedging. Our framework also predicts that β_1 is negative. Overall, as rates fall and solvency declines, LASH risk rises.

The identification assumption is that institutions with short-duration assets would not have altered their hedging behavior in response to interest rate movements for reasons other

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[14] We do not observe institutions' gilt holdings directly. However, we can approximate them with the institution's repo collateral portfolio, which is observable.

Table 1 RATES AND INSTITUTION-LEVEL LASH RISK

	(1)	(2)	(3)	(4)
	$\Delta LASH^{Discretionary}$			
$\Delta Yield^{10Y}$	-1.33***			
	(0.37)			
$\Delta Yield^{10Y}$ × Duration	0.89**	0.95**	1.08***	0.87**
	(0.37)	(0.35)	(0.35)	(0.37)
Observations	4657	4657	4657	4657
R squared	0.016	0.024	0.040	0.063
Time FE	no	yes	yes	yes
Institution FE	yes	yes	yes	yes
Institution-Yield Level FE	no	no	yes	no
Institution-Yield Slope FE	no	no	no	yes

NOTE. For each non-bank financial institution, we calculate the quarterly change in the discretionary LASH Risk. The independent variable is the quarterly change in the 10-year gilt yield, interacted with the modified duration of institution j's assets at the beginning of the sample. The dependent variable is transformed using the Inverse Hyperbolic Sine method; the yield change is denoted in percentage points; and the modified duration is standardized. Clustered standard errors on the quarter level are reported in parentheses. We include institution, quarter, institution-yield level (ten-year gilt yields) and institution-yield slope (ten-year minus two-year gilt yields) fixed effects. fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Coefficients corresponding to the constant, control variables and fixed effects not reported.

than how rate movements affect solvency. To probe this identification assumption, in various specifications, we also include institution, institution times yield level (ten-year gilt yields) and institution times yield slope (ten-year minus two-year gilt yields) fixed effects. These fixed effects absorb, for instance, differences in how funds respond to interest rate changes—which could reflect differences in fund manager style.

Table 1 presents the results. We find that the effect is statistically and economically significant and, as predicted, β_1 is negative and β_2 is positive. Column (1) shows that a 100bps quarterly decrease in the gilt yield index is associated with a 133% increase in the discretionary LASH risk of institution j. Importantly, the coefficient of the interaction term reveals that this effect is reduced to a 44% increase ($= -1.33 + 0.89$) when the initial asset duration of institution j increases by one standard deviation. Therefore, when yields decrease, the LASH risk of short-duration institutions increases more compared to the one of their long-duration counterparts. The estimate of β_2 is similar in columns (2)-(4), as we progressively add time and institution times yield curve fixed effects.

Overall, falling interest rates lead to significantly higher LASH risk taken by short-duration institutions, consistent with our framework. Our cross-sectional identification strategy suggests that low interest rates lead to high LASH risk—using a different source of variation from the descriptive time series patterns of the previous section.

6 Consequences: LASH Risk and Liquidity Crises

We now show that, consistent with our conceptual framework, when LASH risk materializes, it can lead to liquidity crises. These crises materialize even if solvency rises at the same time. We focus on the 2022 UK bond market crisis. We emphasize that LASH risk was not itself the "root cause" of this crisis. Instead, the root cause was a sudden, initial rise in rates—which was then amplified by LASH risk.

6.1 Background: 2022 UK Bond Market Crisis

Background. On 23 September 2022, the Chancellor at the time, Kwasi Kwarteng, presented a "Mini-Budget" proposal to the UK Parliament. The abrupt change in the fiscal stance initiated a sharp, initial rise in interest rates.

Over the subsequent days, there was a combination of (i) margin calls on term repo and swap positions, (ii) sales of bonds in order to raise liquidity, and (iii) further rises in interest rates and then further margin calls. These three factors collectively characterized the liquidity crisis. From trough-to-peak during the crisis, 30-year gilt yields rose by 130bps in a matter of days. In total, pension and LDI funds sold nearly £30bn in the period between September 23 and October 14 (see Appendix Figure E.9 and Pinter, 2023).

As the liquidity crisis intensified, the Bank of England intervened to safeguard financial stability. The Bank's temporary and targeted backstop, announced on September 28 and scheduled to end on October 14, proved effective in ending the fire-sale dynamic and helped pension funds to adjust their portfolios by reducing their repo leverage (Hauser, 2023b; Alexander et al., 2023). Importantly, liquidity needs arose even as the solvency of the pension fund sector improved—the present value of pension liabilities decreased with higher discount rates (i.e. gilt yields, see Figure 7).

6.2 LASH Risk and the Liquidity Crisis

We argue that LASH risk amplified the initial rise in interest rates from the "Mini-Budget". As such, LASH risk led to the liquidity crisis—the combination of margin calls, gilt sales, and further rises in rates. We proceed in three steps. First, we show that as expected, institutions with higher ex-ante LASH risk indeed faced more margin calls. Second, we show that institutions with higher LASH risk sold larger quantities of bonds. Third, we show that the sales induced by LASH risk seem to have caused higher interest rates.

To analyze the link between LASH risk, the liquidity demands and bond trading during the 2022 UK bond market crisis, we first divide the non-banks in our sample into four groups based on their pre-crisis LASH exposures, calculated from both their repo and swap positions. We measure the institution-specific LASH exposure on August 30, hence well in advance of the onset of the crisis and before the election of Liz Truss as Prime Minister. Our main sample includes all non-banks, and not just pension and LDI funds. The choice of sample is natural—other non-banks such as hedge funds are not endowed with long-term liabilities, and do not have incentives to take on LASH risk. These institutions serve as natural "control" observations. However, as we discuss, the results in this section remain robust even when focusing exclusively on pension funds.

LASH risk and margin calls. First, Figure 8 shows that institutions with greater ex-ante LASH risk, indeed had greater liquidity needs due to their margin calls. We plot the cumulative change in repo collateral as a proxy for margin calls in the repo market, analyzed separately for each quartile of the ex ante LASH risk distribution.[15] A more negative number indicates greater margin calls. The plot goes from the start to the end of the liquidity crisis. Funds with the highest LASH risk faced the largest margin calls. This group mainly consists of pension and LDI funds, who had large net exposures in term repo borrowing (see Appendix Figures E.1 & E.2). Consistent with this notion, we observe a similar pattern when plotting the same graph for pension funds only, as shown in Appendix Figure E.11. As such, funds who were hedging solvency to a greater extent, indeed had greater liquidity needs as rates rose. The figure also shows that in aggregate repo margin calls increased—though disproportionately driven by high LASH risk funds.

LASH risk and bond sales. Second, we show that funds with higher ex ante LASH risk sold more bonds—in order to raise liquid assets and meet their margin calls. Figure 9 shows that the institutions with the highest pre-crisis LASH exposure (Quartile IV) sold many more government bonds compared to the other three groups. In total, this group sold more than £25bn during the crisis, while the group with the lowest LASH risk (Quartile I) was, in fact, buying around £15bn worth of bonds. Before the crisis, the net volumes are very similar for all four groups. We again observe a similar pattern when plotting the same

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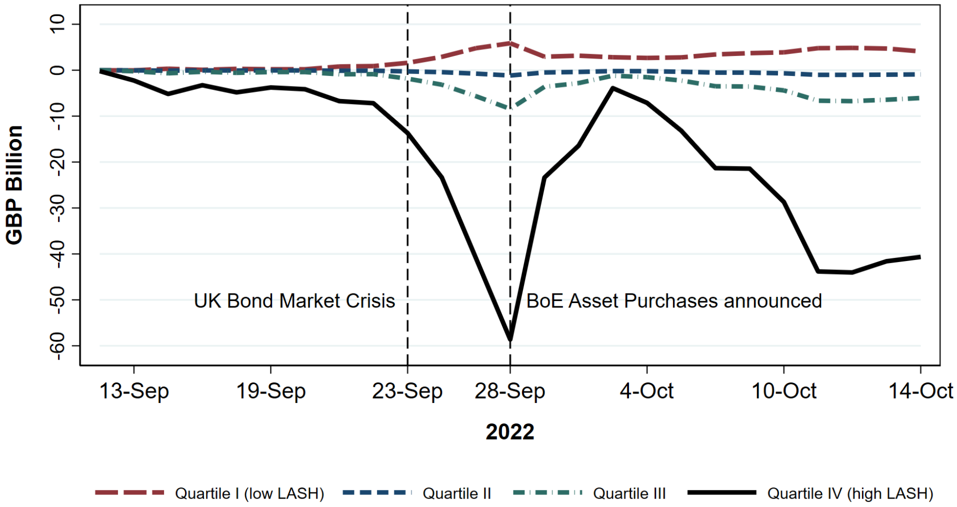
[15] This proxy for repo margin calls is exactly correct if haircuts do not change and there are no bilateral agreements to avert the margin call.

Figure 8 CHANGE IN REPO MARGIN CALLS BY PRE-CRISIS LASH EXPOSURE



NOTE. Aggregate estimated changes in the value of repo collateral posted by UK non-bank financial institutions in £bn during the 2022 UK bond market crisis, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures. Source: Sterling Money Market data collection.

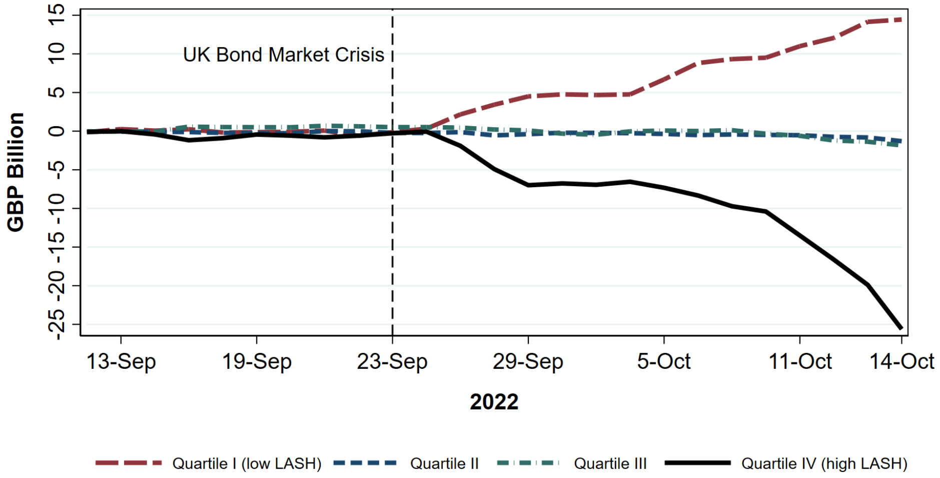
graph for pension and LDI funds only: as shown in Figure E.12 of the Appendix, the net sales of the pension fund sector were concentrated in the group of funds with the largest pre-crisis LASH exposures (Quartile IV). Again, we do not observe any differential pre-crisis trends.

To test the link between LASH risk and gilt selling pressures more formally, we use the following regression specification:

$$Vol_{j,t} = \alpha + \alpha_{s,t} + \beta_1 LASH_{j,t=0} + \varepsilon_{j,t}, \tag{10}$$

where $Vol_{j,t}$ measures the net trading volume of institution j at time t, including all non-banks in our sample. We define the crisis period as the sixteen trading days between September 23 and October 14 (see Pinter, 2023). We calculate a "combined" LASH measure, which captures the LASH risk from both repo and IRS exposures, but we also run separate regressions for these two individual LASH risk components. The LASH variable is standardized to facilitate the interpretation of the coefficients. Furthermore, we also run separate regressions for institutions' sell volumes, which capture whether institution j was a net seller on a given day. Again, net and sell volumes are transformed using the inverse hyperbolic sine transformation to give the regression coefficient β_1 an approximate percent change interpretation

Figure 9 Cumulative Gilt Trading by Pre-crisis LASH Exposure



NOTE. Total net bond trading volumes of UK non-banks, by quartile of their pre-crisis LASH risk: Quartile I captures the banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures.

even if volumes are negative. We include sector-day fixed effects and use standard errors clustered on the day and sector level.

The results are shown in Table 2. Consistent with Figure 9, we find that institutions with larger pre-crisis LASH exposures sold substantially higher quantities of gilts during the UK bond market crisis: a one standard deviation increase in pre-crisis LASH risk is associated with 15% higher daily sell volumes during the crisis period (Column 3). Importantly, this effect is robust to the inclusion of sector-day fixed effects, hence not driven by time-varying sector characteristics. Furthermore, the effect is economically and statistically more significant for the LASH risk from repo exposures, consistent with the larger magnitude of overall LASH risk in the repo market. As a robustness check, we also conduct our analysis exclusively for the pension and LDI fund sector in Table E.5 of the Appendix. Consistent with our baseline results, a one standard deviation increase in LASH risk is associated with a 10% increase in pension fund daily sell volumes.

LASH risk and rising rates. The third factor characterizing the liquidity crisis was a continued rise in rates after the initial shock of the Mini-Budget. We show that LASH risk contributed to the subsequent rise in rates. To isolate the impact of LASH risk on non-bank trading and, in turn, on yield movements, we follow Czech et al. (2023) and construct a measure of *LASH-induced trading (LASH-IT)*. Specifically, we calculate each

Table 2 LASH Risk and Gilt Trading Volumes

	(1)	(2)	(3)	(4)
	Net Volume		Sell Volume	
LASH combined	-0.21***		0.15***	
	(0.04)		(0.02)	
LASH Repo		-0.16***		0.12***
		(0.04)		(0.02)
LASH IRS		-0.13*		0.08***
		(0.05)		(0.02)
Observations	8875	8875	8875	8875
R squared	0.035	0.035	0.046	0.046
Sector-Day FE	yes	yes	yes	yes

Note. For each non-bank financial institution, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, either for repo and IRS exposures combined, or separately for both instruments. The dependent variable is the institution's daily gilt net trading volume on day t in Columns (1) and (2), and the institution's sell volumes on day t in Columns (3) and (4). The dependent variables are transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Double-clustered standard errors on the day and sector level are reported in parentheses. We include sector-day fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

institution's LASH-induced trading in bond b assuming that each institution proportionally scales up or down its holdings in response to liquidity demands. Due to the lack of complete information on bond holdings of individual institutions, we approximate the weight of bond b in institution j's portfolio, $w_{j,b}$, by measuring the weight of the given bond in institution's j pre-crisis repo collateral portfolio. LASH-induced trading (LASH-IT) in bond b on day t is then defined as:

$$LASH\text{-}IT_b = \frac{\Sigma_j LASH_{j,t=0} \times w_{j,b,t=0}}{Amount\ Outstanding_{b,t=0}} \tag{11}$$

where $LASH_{j,t=0}$ is the estimated pre-crisis LASH exposure of institution j, and $w_{j,b}$ is the weight of bond b in institution's j pre-crisis repo collateral portfolio, and *Amount Outstanding*$_{b,t=0}$ is the bond's amount outstanding before the crisis. We then employ the following regression specification to measure the impact of LASH-induced trading on gilt yields during the crisis:

$$\Delta Yield_{b,t} = \alpha + \alpha_{m,t} + \alpha_{g,t} + \beta_1 LASH\text{-}IT_b + \varepsilon_{b,t} \tag{12}$$

where $\Delta Yield_{b,t}$ is the daily change in yields. Again, we define the crisis period as the sixteen trading days between September 23 to October 14. We also include maturity bucket-day fixed effects ($\alpha_{m,t}$) as well as type gilt-day fixed effects ($\alpha_{g,t}$), which control for differential

Table 3 IMPACT OF LASH-IT ON GILT YIELDS

	(1)	(2)	(3)	(4)
	$\Delta Yield_{b,t}$			
LASH-IT	9.29*** (0.91)	9.72*** (1.06)	3.21** (1.49)	4.13** (1.60)
Observations	1253	1253	1253	1253
R squared	0.261	0.321	0.616	0.649
Day FE	yes	-	-	-
Day × Type Gilt FE	no	no	yes	yes
Day × Maturity Bucket FE	no	yes	no	yes

NOTE. As the dependent variable, we measure the daily change in yields for each bond. The independent variable is the bond's LASH-induced trading ("LASH-IT") in bond b on day t as defined in equation 11. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The independent variable is standardized. Standard errors clustered on the bond level are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant and fixed effects not reported.

effects for nominal and index-linked gilts. Standard errors are clustered on the bond level.

Table 3 presents the results. The effect is statistically and economically highly significant. In the most conservative specification with maturity bucket-day and type gilt-day fixed effects (Column 4), a one standard deviation increase in LASH-IT is associated with a 4.1bps daily increase in gilt yields.

6.3 Sources of Illiquidity

During the liquidity crisis, pension fund solvency improved (see Figure 7). What prevented pension funds from using their improving solvency to raise liquid funds and avert the crisis? This section presents three reasons why pension funds were illiquid despite better solvency.

Improvements in solvency came from falling liabilities. Securing liquidity against a decline in liabilities is difficult. A declining value of liabilities cannot be pledged as collateral and used for secured lending. In principle, funds might be able to access liquidity via unsecured lending. However, in practice unsecured lending is uncommon in the pension fund sector. In particular, pension funds do not seem to borrow unsecured via credit lines. Stress test data from year-end 2021, i.e. the last period before the crisis, reveals no UK pension funds with available credit commitments from the listed exposures of major UK banks. Instead, the main source of liquidity for UK pension funds is secured against collateral in the repo market.

Unsophisticated liquidity management. Many pension funds were relatively unsophisticated in managing liquidity. For instance, many funds were not active in secured repo markets. As the right panel of Appendix Figure E.13 shows, only around half of the institutions that were active in the swap market also engaged in repo borrowing before the crisis. Even if a fund had adequate assets to secure financing, arranging liquidity at short notice in a market where the fund had not previously participated is challenging.

The cross-sectional behavior of fund-level sales suggests that unsophisticated liquidity management was partly responsible for bond sales. One proxy for unsophisticated funds, available in the cross-sectional data, is to identify funds that did not access repo markets for liquidity before the crisis. A second proxy for unsophisticated liquidity management is "pooled LDI funds". As we discussed in Section 2.4, pension funds often hold stakes in LDI funds, which hedge against pension funds' duration risk by borrowing with repo to buy longer-duration assets. Small and unsophisticated funds tend to hold stakes in "pooled" LDI funds, which invest money from several pension funds—in contrast to segregated arrangements, where the assets of a single pension scheme are invested in a separate account. Transferring liquidity from the multiple owners of pooled LDI funds to the LDI fund itself was time-consuming—in part due to coordination problems among the various fund owners, and in part because the small and unsophisticated pension funds typically rebalanced their positions only on a weekly or monthly frequency (Breeden, 2022). By contrast, "segregated" LDI funds had a single owner who tended to be more sophisticated, making it easier to transfer liquidity from the owner to the LDI fund.[16]

To test for the role of unsophisticated liquidity management, we employ a version of the regression model in equation (10). In one specification, we add an indicator variable called "Swap Only" that captures whether a given non-bank accessed only the swap market (and hence not the repo market) in the quarter prior to the crisis. In a second specification, we interact with indicators for whether the fund is a pooled or segregated LDI fund.

Table 4 shows that our proxies for unsophisticated liquidity management predict bond sales during the crisis. Regarding access to swap markets, non-banks that only accessed the swap market in the quarter prior to the crisis have 15% higher sell volumes compared to other investors who also have access to the repo market (Column 2). We also find that bond sales are larger for pooled LDI funds: a one standard deviation increase in LASH risk is associated with 93% higher daily sell volumes for pooled LDI funds relative to other non-banks (Column 3). The coefficient for segregated LDI funds is insignificant (Column 4). It

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[16] At the end of 2021, approximately £200bn of the £1.4tn in UK LDI assets were invested in multi-institution pooled funds (Breeden, 2022).

is worth noting that pooled LDI funds' sales account for only around 15% of the total bond sales by pension funds and LDI funds during the crisis (Appendix Figure E.10) so pooled funds cannot alone account for the bond sales.

Constraints on supply of liquidity. The UK bond market experienced a market-wide increase in the demand for liquidity. The increase in aggregate demand for liquidity may have exhausted supply. In particular, there may be limits on whether secured lending markets could have supplied the necessary liquidity. The left panel in Appendix Figure E.13 makes this point by showing the evolution of overnight repo spreads during the crisis. The sharp spike of more than 30bps is indicative of constraints on the supply of liquidity via the repo market.

The cross-sectional behavior of fund-level sales also suggests that constrained supply was important. To show this point, we develop a measure of which funds were most exposed to constrained supply. We exploit the fact that in repo markets, relationships between pension funds and their counterparties tend to be "sticky". Appendix Figure E.14 shows that trades between newly formed counterparties only account for around 4% of all repo trades. The counterparties of pension funds in repo markets are dealer banks. We then develop a measure of whether dealer banks were relatively supply-constrained before the crisis. Specifically, we identify banks who charged higher repo spreads prior to the crisis, and were thus likely closer to regulatory limits. With this measure, we can identify pension funds who were particularly exposed to ex-ante supply constrained banks.

Using our measure, we revisit the regression model in equation (10). We add another indicator variable that measures whether a given non-bank obtained the majority (more than 50%) of its funding from "high-spread" dealers—that, on average, charge their clients more than the market median for term repo borrowing—in the quarter prior to the crisis. With this measure, sell volumes are 14% higher for non-banks that are more exposed to high-spread dealer banks prior to the crisis (Column 5). We infer that constraints on the supply of liquidity in the repo market was an important reason for bond sales.

Overall, there were at least three reasons why pension funds could not raise liquidity despite their improving solvency—namely improvements in solvency from falling liabilities, unsophisticated liquidity management and constraints on the supply of liquidity. This discussion emphasizes that the distribution of LASH risk across sectors matters. Banks tend to have better access to liquidity via central bank facilities. Therefore, LASH risk in the banking system may be less likely to lead to a liquidity crisis. LASH risk for non-banks is more problematic—because non-banks, such as pension funds, have worse access to liquidity.

Table 4 LASH RISK AND SOURCES OF ILLIQUIDITY

	(1)	(2)	(5)	(4)	(3)	(6)
	Sell Volume					
LASH	0.15***	0.14***	0.14***	0.20***	0.14***	0.12**
	(0.02)	(0.01)	(0.02)	(0.05)	(0.01)	(0.04)
LASH × Swap-only		0.15***				0.17*
		(0.04)				(0.07)
LASH × Pooled LDI Fund			0.93***			0.95***
			(0.02)			(0.09)
LASH × Segregated LDI Fund				-0.08		0.00
				(0.06)		(0.05)
LASH × High Spread Exposure					0.14***	0.16*
					(0.03)	(0.08)
Observations	8875	8875	8875	8875	8875	8875
R squared	0.046	0.047	0.050	0.047	0.047	0.051
Sector-Day FE	yes	yes	yes	yes	yes	yes

NOTE. For each non-bank financial institution, LASH is measured as the potential liquidity needs following a 100bps shift in gilt yields for repo and IRS exposures combined. The dependent variable is the institution's daily sell volume on day t. Segregated LDI Fund and Pooled LDI Fund indicate segregated and pooled LDI funds, respectively. Swap-only indicates institutions that have no activity in the repo market in the quarter prior to the crisis. High Spread Exposure indicates whether the majority (more than 50%) of repo borrowing of a given institution is with high-spread dealers (that charge more than the market median on average) in the quarter prior to the crisis. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Double-clustered standard errors on the day and sector level are reported in parentheses. We include sector-day fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

6.4 Bond Level Characteristics

We close the paper by asking whether sales were concentrated in bonds with particular characteristics. We run the following regression at the institution-bond-day level:

$$Sell\ Vol_{j,b,t} = \alpha + \alpha_{s,t} + \alpha_{b,t} + \beta_1 LASH_{j,b,t=0} + \beta_2 \left(LASH_{j,b,t=0} \times Bond\ Characteristics_b\right) + \varepsilon_{j,b,t} \tag{13}$$

where $Sell\ Vol_{j,b,t}$ measures the sell volume of institution j in bond b at time t. *Bond Characteristics* includes: i) three duration buckets (low, medium, high), ii) two groups measuring the frequency of the bonds's usage as repo collateral (as measured by the total pre-crisis repo borrowing amount for each bond across all non-banks), and iii) an indicator variable for index-linked bonds. $LASH_{j,t=0}$ is defined as in equation (10). We include both sector-day and bond-day fixed effects and use standard errors clustered on the day, sector and maturity-bucket level.

Table 5 LASH RISK AND BOND-LEVEL LIQUIDATION CHOICES

	(1)	(2)	(3)	(4)
	Sell Volume			
LASH	0.05***	0.04***	0.04***	0.04***
	(0.00)	(0.00)	(0.00)	(0.00)
LASH × Frequent Collateral Use		0.01*		
		(0.00)		
LASH × Low Duration			0.01	
			(0.01)	
LASH × High Duration			0.01*	
			(0.00)	
LASH × Inflation-linked				0.02**
				(0.01)
Observations	42481	42382	41667	42481
R squared	0.115	0.115	0.114	0.115
Bond-Day FE	yes	yes	yes	yes
Sector-Day FE	yes	yes	yes	yes

NOTE. For each non-bank financial institution, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, for repo and IRS exposures combined. The dependent variable is the institution's daily gilt sell volume in bond b on day t. "Frequent Collateral Use" indicates the frequent use of bond b as repo collateral, i.e. the top 50% of bonds based on their use as repo collateral. "Duration" indicates the duration bucket of bond b (long, medium, short). "Inflation-linked" indicate index-linked gilts. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Clustered standard errors on the day, sector and maturity-bucket level are reported in parentheses. We include sector-day fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Coefficients corresponding to the constant, control variables and fixed effects not reported.

The results are presented in Table 5. Consistent with our baseline results, we find that higher pre-crisis LASH risk predicts bond selling pressure, even when controlling for sector-day and bond-day fixed effects. We find that the effect is particularly pronounced for high-duration bonds, bonds that are frequently used as repo collateral and index-linked bonds. For example, a one standard deviation increase in LASH is associated with 6% higher daily sell volumes in index-linked gilts (relative to 4% higher sales in nominal bonds).

7 Conclusion

In this paper, we introduce a framework to understand and measure the liquidity risk that arises from financial institutions' actions to mitigate solvency risk. *Liquidity After Solvency Hedging risk*, or "LASH risk", arises when institutions use certain hedging strategies to reduce solvency risk, which leads to higher liquidity needs when the value of the hedge falls and solvency improves. We focus on LASH risk for non-banks, such as pension funds, with long-duration liabilities and shorter-duration assets. For these non-banks, LASH risk ought to rise as rates fall, because solvency deteriorates which requires more solvency hedging. Our framework has focused on interest rate risk. However, it can be generalized to other asset prices and, indeed, the literature has highlighted similar episodes in different market segments and jurisdictions.

We make three empirical contributions. First, we measure LASH risk for the universe of non-banks' sterling interest rate exposures, from interest rate swaps and repo, in the UK from 2019 onwards. LASH risk is large—at peak, a 100bps increase in interest rates leads to liquidity needs that would nearly deplete the entire cash holdings of the combined pension fund and insurance sector. While LASH risk is large, funds are partially but not fully hedged against interest rate risk. Second, we show that low rates increase LASH risk. In the time series, LASH risk is high when rates are low. We then exploit our granular data using a cross-sectional identification strategy, comparing funds with different exposures to falling interest rates. Funds who are more exposed, due to having shorter-duration assets, increase LASH risk by more. Third, we show that the LASH risk caused by low rates leads to liquidity crises, even as solvency improves. In particular, during the 2022 bond market crisis in the UK, fund-level LASH risk is a strong predictor of bond sales by pension funds. As such, LASH risk contributed to the spike in yields during the crisis.

The implications of LASH risk are different from some other forms of liquidity risk. LASH risk arises from 'responsible' institutions trying to hedge solvency risks, and the risk materializes precisely when solvency improves. LASH risk is thus different from other forms of liquidity risk that materialize when solvency deteriorates. Therefore, mitigating the adverse effects of LASH risk ex post—through measures such as liquidity support during a crisis—may not encourage solvency risk ex ante. As such, the policy trade-offs from intervening during a crisis may be different from conventional liquidity crises. We leave a full investigation of these ideas to future work. Likewise, we leave the analysis of LASH risk and its implications in other market segments (e.g., foreign exchange or inflation) for future research.

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Appendix

A Additional Theoretical Results

A.1 Proof of Proposition 1

Proof preliminaries To start, we reformulate the problem and define some notation. Under our described process for the interest rate, the asset prices in period $t+1$ follow:

$$q^l_{t+1}(\varepsilon_{t+1}) = \frac{\varepsilon_{t+1} + R_t^{-1}}{1 - \bar{R}^{-1}},$$

$$q^b_{t+1}(\varepsilon_{t+1}) = \frac{\varepsilon_{t+1} + R_t^{-1}}{1 - \delta \bar{R}^{-1}}.$$

The shock, ε_{t+1}, has support $\varepsilon_{t+1} \in (\varepsilon^l, \varepsilon^h)$ with ε^h positive and finite so the gross rate cannot fall to zero, and $\varepsilon^l \geq -R_t^{-1}$ with an upper bound that we will define below. Denote the cumulative density of the shock $F(\varepsilon)$, with corresponding p.d.f. $f(\varepsilon)$. The initial level of the R_t^{-1} can be treated as a primitive of the problem.

The proposition assumes a sufficiently high liquidity premium on the short-run asset. For simplicity, we set $\eta \to \infty$, so $a_t = 0$. To ease notation we occasionally drop function dependencies on ε_{t+1} and s_t. The problem can then be recast as simply choosing the optimal amount of hedging at time t (with b_t given):

$$\max_{s_t} \mathbb{E}_t \left[\left(1 + \kappa \mathbf{1}\left[w_{t+1} < 0\right]\right) w_{t+1} \right], \tag{A.1}$$

subject to:

$$w_{t+1}(\varepsilon_{t+1}, s_t) = b_t - l + q^b_{t+1} \delta b_t + s_t \varepsilon_{t+1} + \frac{c}{1-c} \min\left\{m_{t+1}, 0\right\} - q^l_{t+1} l,$$

$$m_{t+1}(\varepsilon_{t+1}, s_t) = b_t + s_t \varepsilon_{t+1} - l.$$

It is useful to define:

$$y(\varepsilon_{t+1}) = b_t - l + q^b_{t+1} \delta b_t - q^l_{t+1} l,$$

This represents the unhedged value of the fund. From assumption 1, the fund is solvent in period t in the sense that $y(0) > 0$ but $y(\varepsilon^h) < 0$. Given the definitions of q^b_{t+1} and q^l_{t+1}, it is straightforward to see that solvency condition requires $b_t > l$. We also have:

$$\frac{dy}{d\varepsilon_{t+1}} = \frac{\left(\delta - \delta\bar{R}^{-1}\right) b_t - \left(1 - \delta\bar{R}^{-1}\right) l}{\left(1 - \delta\bar{R}^{-1}\right)\left(1 - \bar{R}^{-1}\right)}.$$

This is negative so long as $\frac{b_t}{l} < \frac{\left(1-\delta\bar{R}^{-1}\right)}{\delta\left(1-\bar{R}^{-1}\right)}$, and this is required by the first part of assumption 1. This means the fund is not so wealthy that the gain on its medium-duration assets from lower rates offsets the duration mismatch from its longer-duration liabilities. A negative value for the derivative implies, absent hedging, that the fund loses out the more positive the shock and the lower the rate.

Given the function $y(\varepsilon_{t+1})$ is exogenous and linear, it is useful to parameterize it as:

$$y = y_0 + y_1\varepsilon_{t+1}, \tag{A.2}$$

where $y_0 \equiv y(0) > 0$ and $y_1 \equiv \frac{dy}{d\varepsilon_{t+1}} < 0$. At this point, it is worth noting that y_0 is decreasing in R_t^{-1} at rate y_1 and y_1 is invariant to R_t^{-1} as this will be used later.

The proposition states that the upside risk on the interest rate is sufficiently high. We now define the upper bound on ε^l which pins down how far interest rates could rise. We impose:

$$\varepsilon^l < \frac{b_t - l}{\left(\frac{y_0}{\varepsilon^h} + y_1\right)}. \tag{A.3}$$

As we shall see, this condition will ensure that if the fund hedges sufficiently to remove all risk of insolvency when rates fall, it will face a liquidity crisis if there is a sufficiently large rise in rates.

Hedging choices absent liquidity costs. Define s_t^{**} as a value of s_t that solves problem (A.1) when $c = 0$. Since $\mathbb{E}_t\left[\varepsilon_{t+1}\right] = 0$ this is is equivalent to:

$$s_t^{**} = \max_{s_t} \mathbb{E}_t\left[\mathbf{1}\left[y_0 + (s_t + y_1)\,\varepsilon_{t+1} < 0\right]\left(y_0 + (s_t + y_1)\,\varepsilon_{t+1}\right)\right].$$

Note the maximand is weakly negative with a maximum at zero. From the linearity of $y_0 + (s_t + y_1)\,\varepsilon_{t+1}$, the objective is maximized, for any s_t where both $y_0 + (s_t + y_1)\,\varepsilon^h_{t+1} \geq 0$ and $y_0 + (s_t + y_1)\,\varepsilon^l_{t+1} \geq 0$. Selecting

$$s^{**}_t = -y_1, \tag{A.4}$$

fully insures the fund against interest rate risk and hence guarantees the objective is at the maximum given $y_0 > 0$. However, there is a complete set of solutions given by $s^{**}_t \in [\underline{s}, \bar{s}]$ where

$$\underline{s} = -\left(\frac{y_0}{\varepsilon^h} + y_1\right) \leq |y_1|\,,$$
$$\bar{s} = -\left(\frac{y_0}{\varepsilon^l} + y_1\right) > |y_1|\,.$$

If $s^{**}_t = \underline{s}$, the fund does not remove all interest rate risk but hedges sufficiently to ensure its solvency in the worst-case scenario. If $s^{**}_t = \bar{s}$, the fund over-hedges so that its net worth is decreasing in the interest rate but not so much that at the highest possible value of the rate, the fund is insolvent.

Last, for any $s_t < \underline{s}$, the probability of insolvency is positive, and the fund's payoff can always be improved by increasing s_t towards $\underline{s}$. This implies that absent liquidity costs, $s_t < 0$ is not optimal either.

Hedging choices with liquidity costs. Define, s^*_t as a value of s_t that solves problem (A.1) when $c > 0$. Conjecture that there exists an s^*_t that is unique, positive and less than $\underline{s}$. We will first characterize s^*_t under this conjecture, proving points $(ii) - (iii)$ in the proposition. Then, we will confirm that the conjecture is correct, proving point (i).

For point (iii), note that:

$$m_{t+1} = b_t + s_t\varepsilon_{t+1} - l.$$

Hence, we can define a threshold realization $\varepsilon_0(s_t) = \frac{l-b_t}{s_t} < 0$, such that if the rate is sufficiently high ($\varepsilon_{t+1} < \varepsilon_0$) then $m_{t+1} < 0$ and the fund will be forced to sell assets. The threshold is increasing in s_t. The condition in equation (A.3) guarantees $\varepsilon_0(\underline{s}) > \varepsilon^l$. What is left to show is that $\varepsilon_0(s_t^*) > \varepsilon^l$ such that a sufficient rate rise will cause selling given the optimal choice s_t^*. If that is the case, for any positive s_t^* that is less than less than $\underline{s}$, the firm will have net worth greater than y_0 if the realized shock is at the threshold $\varepsilon_0(s_t^*)$. Liquidation costs are infinitesimal at the threshold and the fund imperfectly hedged so benefits from higher rates.

As $s_t < \underline{s}$, there is also a threshold realization,

$$\varepsilon_1(s_t) = \frac{y_0}{-\left(y_1 + s_t\right)},$$

such that if the rate is sufficiently low $(\varepsilon_{t+1} > \varepsilon_1(s_t))$ then $w_{t+1} < 0$. Note that $\varepsilon_1(s_t) > 0$ as $y_0 > 0$ and $y_1 + s_t$ is negative for $s_t \leq \underline{s}$.

At this point, it is useful to distinguish between two cases. *Case (i)*: $w_{t+1}(\varepsilon^l, \underline{s}) > 0$; *Case (ii)*: $w_{t+1}(\varepsilon^l, \underline{s}) < 0$. In *Case (i)*, if the fund hedges sufficiently to avoid insolvency when rates fall, the losses from illiquidity when rates rise are never sufficient for it to also become insolvent for very large interest rate rises. In *Case (ii)*, the liquidation costs on the hedge can be sufficiently large that in the case of high rates such that fund is insolvent.

We will first with complete the proof assuming *Case (i)* holds, and then show that *Case (ii)* is ruled out by assumption 1. In *Case (i)*, problem (A.1) can be expressed as:

$$\max_{0<s_t<\underline{s}} \mathbb{E}_t \left[\kappa \int_{\varepsilon_1(s_t)}^{\varepsilon^h} \left(y_0 + \left(s_t + y_1\right)\varepsilon_{t+1}\right) dF(\varepsilon) + \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t)} \left(b_t + s_t \varepsilon_{t+1} - l\right) dF(\varepsilon) \right].$$

Noting the first integrand above is zero evaluated at $\varepsilon_1(s_t)$, and the second integrand is zero evaluated at $\varepsilon_0(s_t)$, the relevant first order condition is:

$$\kappa \int_{\varepsilon_1(s_t^*)}^{\varepsilon^h} \varepsilon_{t+1} dF(\varepsilon) + \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t^*)} \varepsilon_{t+1} dF(\varepsilon) = 0. \tag{A.5}$$

The first term in equation (A.5) is strictly positive for $s_t < \underline{s}$ and is the marginal benefit of an additional unit of hedging in terms of reducing the risk of insolvency. The second term is weakly negative for $s_t < \underline{s}$, strictly if $\varepsilon_0(s_t^*) > \varepsilon^l$, and is the marginal cost of an additional unit hedging in terms of extra liquidation costs.

The corresponding second order condition is (noting $\varepsilon_0 < 0$, $\varepsilon_1 > 0$ and $y_1 + s_t^* < 0$):

$$\kappa \frac{\varepsilon_1^2}{(y_1 + s_t^*)} f(\varepsilon_1) - \frac{c}{1-c} \varepsilon_0^2 f(\varepsilon_0) < 0,$$

hence s_t^* corresponds to an interior maximum where the probability $\varepsilon_0(s_t^*) > \varepsilon^l$ of insolvency is positive. Now imagine that $\varepsilon_0(s_t^*) < \varepsilon^l < 0$, then the fund could increase s_t and reduce the probability of insolvency with no corresponding costs of illiquidity. Hence, we must have that s_t^* is sufficiently large $\varepsilon_0(s_t^*) > \varepsilon^l$. This proves point (*iii*).

We now prove point (*ii*) under *Case (i)*. Note that R_t^{-1} enters first order condition (A.5) solely through the definition of y_0 in ε_1. Recalling $\frac{dy_0}{dR_t^{-1}} = y_1$, and applying the implicit function theorem, we obtain:

$$\frac{ds_t^*}{dR_{t-1}^{-1}} = \underbrace{\left(\frac{1}{\frac{c}{1-c}\varepsilon_0^2 f(\varepsilon_0) - \kappa \frac{\varepsilon_1^2}{(y_1+s_t^*)} f(\varepsilon_1)} \right)}_{>0} \underbrace{\frac{\kappa \varepsilon_1 y_1}{(y_1 + s_t^*)} f(\varepsilon_1)}_{>0}.$$

Hence, the equilibrium level of hedging is decreasing in the initial level of the interest rate. This proves point (*ii*).

We now confirm that the conjectures regarding the equilibrium level of hedging s_t^* are true. Consider the bounds $0 < s_t^* < \underline{s}$. Start with the conjecture $s_t^* > 0$. Imagine, instead that s_t^* was mildly negative such that there was no liquidity risk from the swap position. This is equivalent to the $c = 0$ case, and a marginal increase in the fund's swap position would add

$$\kappa \int_{\varepsilon_1(s_t)}^{\varepsilon^h} \varepsilon_{t+1} dF(\varepsilon) > 0$$

to the expected payoff. Expanding a negative swap position to the point where liquidity risk emerges only introduces an additional benefit of increasing s_t through reducing liquidation costs if rates rise. The same argument holds at $s_t = 0$. There is no liquidity risk at $s_t = 0$, so raising s_t unambiguously raises the expected payoff.

Now consider the conjecture $s_t^* < \underline{s}$. At the point $s_t^* = \underline{s}$, solvency risk is nil and s_t comes with a marginal cost of illiquidity of $\frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(\bar{s})} (-\varepsilon_{t+1}) dF(\varepsilon)$. Further increases in s_t from $\bar{s}$

would raise $\varepsilon_0(\bar{s})$ and hence liquidity costs further without any benefit in terms of reduced insolvency. Now a marginal reduction in s_t from $\underline{s}$ generates a cost of insolvency equal to $\kappa\varepsilon^h f(\varepsilon^h)$. However, as the probability density was arbitrarily small at the bounds this increase insolvency less than the marginal cost of illiquidity. Hence, $s_t^* = \underline{s}$ is not optimal.

Last consider the conjectured existence and uniqueness of s_t^*, note that first order condition can be expressed as:

$$\kappa \int_{\varepsilon_1(s_t^*)}^{\varepsilon^h} \varepsilon_{r,t+1} dF(\varepsilon) = \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t^*)} (-\varepsilon_{r,t+1}) dF(\varepsilon).$$

For all $0 < s_t < \underline{s}$, the left hand side is positive and decreasing in s_t and from the assumptions on $F(\varepsilon)$ the left hand converges smoothly to 0 as $s_t \to \underline{s}$. For the right hand side, first note $\varepsilon_0(s_t)$ is increasing in s_t. For sufficiently low s_t, $\varepsilon_{r,0}(s_t) < \varepsilon^l$ then the right hand is zero and unaffected by a change in s_t. We know $\varepsilon_{r,0}(\underline{s}) > \varepsilon^l$, hence, for sufficiently large s_t, we will have $\varepsilon_{r,0}(s_t) > \varepsilon^l$ and the right hand side will be positive. Since, in the interval $s_t \in (0, \underline{s})$, the left hand side starts positive, is decreasing and tends to zero and the right hand side starts at zero, is weakly increasing and in positive at the upper end of the interval there exists a single crossing.

We now turn to ruling out *Case (ii)*. If $w_{t+1}(\varepsilon^l, \underline{s}) < 0$, there exists a potential third threshold $\varepsilon_2(s_t) < \varepsilon_0(s_t)$ whereby $y_0 + \left((1 + \frac{c}{1-c})s_t + y_1\right)\varepsilon_2(s_t) + \frac{c}{1-c}\left(b_t - l\right) = 0$ and $w_{t+1} < 0$ if $\varepsilon_{t+1} < \varepsilon_2(s_t)$. Now,

$$\varepsilon_2(s_t) = -\frac{\frac{c}{1-c}\left(b_t - l\right) + y_0}{\left((1 + \frac{c}{1-c})s_t + y_1\right)},$$

for this region to exist $s_t > \frac{-y_1}{(1+\frac{c}{1-c})} = -(1-c)y_1$. We also have $\underline{s} = -\left(\frac{y_0}{\varepsilon^h} + y_1\right)$. If $-(1-c)y_1\varepsilon^h > -\left(y_0 + y_1\varepsilon^h\right)$ this region cannot exist. This condition is satisfied by assumption 1.

A.2 Numerical Results with Model

Here we illustrate numerically that for a reasonable parameterization, as interest rates fall LASH risk increases, which is result (ii) from Proposition 1. We solve the model numerically using value function iteration, assuming an i.i.d. interest rate and parameterizing the model as described in Table A.1.

Table A.1 Summary of Parameters

Parameter	Description	Value
c	Cost of liquidation	0.015
δ	Decay rate of long-term bond	0.91
l	Fund payment to its members at each period	0.04
η	Short-term bond premium	0.014
κ	Penalty for fund's deficit	0.3

We choose δ such that the duration of the long-term bond is equal to 10 years. The values for c and η are from Harris and Piwowar (2006) and Nagel (2016), respectively. To show that funds are incentivized to increase their swap holdings after decreases in interest rates, we solve the model for $T = 10$ across a range of interest rates, assuming that R^{-1} has different uniform distributions. These distributions have varying means ranging from 0.9 to 0.98 while maintaining the same variance.

Figure A.1 displays the results, plotting the average s_t against against R^{-1}. As can be clearly seen, low rates (high R^{-1}) are clearly correlated with more demand for hedging.

Figure A.1 Optimal swap holdings across different average values for R^{-1}

A.3 The Linear Hedging Assumption

In our model, the fund is only able to hedge interest rate risk with swaps. This means the hedging strategy is linear. The fund is unable to hedge using non-linear derivatives such as interest rate options. This has important implications for the model's outcomes which we elaborate on here.

Equation (4) is also beneficial as it provides an insight into the importance of the restricting attention to linear hedging strategies. We repeat here for convenience:

$$\kappa Pr\left\{w_{t+1}<0\right\}\left(\mathbb{E}_t\left[\varepsilon_{t+1}|w_{t+1}<0\right]\right)=\frac{c}{1-c}Pr\left\{m_{t+1}<0\right\}\left(\mathbb{E}_t\left[-\varepsilon_{t+1}|m_{t+1}<0\right]\right). \qquad \text{(A.6)}$$

The fund does not care about the payoff from the swap contract in the states of the world where it is neither illiquid nor insolvent. Hence, essentially, what buying the swap does is endow the fund with a valuable put option that pays out when rates fall and the fund has a deficit. This is what the left hand side of equation (4) captures. The right hand side captures that buying the swap also forces the fund to sell a call option that is costly to cover in states where the fund is illiquid. Therefore, if the fund could trade the appropriate interest rate options it could, effectively, buy the put without selling the call and so would be able to hedge solvency risk in a manner that avoids illiquidity.

The justification for limiting our attention to linear strategies is twofold. First, implementing an option based strategy to avoid liquidity risk requires a high degree of financial sophistication and the ability to accurately forecast c (which is problematic if c rises sharply when there is correlated selling). Second, as we show, in practice, hedging strategies are linear. Interest rate options trade in a thin market, are expensive and thus have very limited trading volumes.

B Institutional Background on UK Pension Funds

The pension fund sector, along with specialized funds servicing it, constitutes a major source of LASH risk in the non-bank sector. Pension funds can be categorized as defined benefit (DB) or defined contribution (DC) funds. Defined benefit pension funds promise a guaranteed return to their beneficiaries upon retirement, while defined contribution funds provide returns that vary based on market performance. By construction, defined benefit funds have higher hedging needs, as they need to meet certain guaranteed payments in the far future. For the UK pension fund system, out of the total £2.2tn of assets under management in Q1 2023, £1.8tn can be attributed to public and private defined benefit funds.[17]

Hedging strategies differ even among pension funds with similar balance sheet structures. They depend on the duration gap, fund type, and the method used to discount future liabilities. Differences in regulations and discounting practices across jurisdictions lead to diverging optimal hedging strategies. For instance, UK pension funds predominantly use gilt yields to discount their liabilities, while Dutch pension funds include the euro interest rate swap rate in their calculations, and US pension funds take a more bespoke approach and use a so-called asset-led discounting methodology. As a consequence, Dutch pension funds almost exclusively hedge using interest rate swaps (Jansen et al., 2023), US pension funds have higher incentives to take on riskier assets as a hedging strategy (Andonov et al., 2017), and in our paper, we find that UK pension funds more frequently use repos than swaps as part of their hedging strategy.

Pension fund market fragmentation also impacts the hedging landscape. In countries with a concentrated market, funds have sufficiently large balance sheets and in-house expertise to design and implement their individual hedging strategies. By contrast, in a fragmented pension fund system, small pension schemes would not have the size or capacity to make in-house hedging a viable solution, giving rise to alternative strategies. A solution is to delegate a part of the portfolio to alternative investment funds, which are designed to attract funds from one (segregated fund) or multiple pension funds (pooled fund). These funds then select their assets, derivatives, and repo leverage based on the desired duration profile of their

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[17] See The Office for National Statistics (2023) dataset for details.

clients.

The UK had over 5,300 defined benefit pension schemes in 2022, making it a highly fragmented market.[18] It is, therefore, perhaps unsurprising that the UK saw a rapid rise in alternative investment funds in the recent decade, such as Liability Driven Investment funds (LDIs). In fact, we find that the LASH risk from repo exposures is mainly concentrated in the LDI sector (see Figure E.1), emphasizing the frequent use of repo leverage in this market segment.

C UK Margin Requirements and Market Standards

Margin practices in derivative and repo market changed dramatically following the 2008 financial crisis, driven by wide-reaching regulatory reforms. One of these reforms targeted collateral backing of derivative exposures to mitigate counterparty credit risk. Other reforms aimed to improve credit risk management through better collateral management in securities financing transactions, and so, short-term money markets.

Interest rate risk can affect both derivatives and repo transactions through different channels. The value of an interest rate swap contract changes as the underlying market rate of the specified index (e.g., LIBOR, SONIA) changes, implicitly affecting counterparty credit risk. In addition, in a collateralized transaction, when the value of the underlying collateral changes as interest rates change (e.g., a government bond), the credit risk of the transaction changes as well. A common practice to mitigate these two risks—by regulation or choice—is regular margin posting.

Definition – initial margin and variation margin

In derivatives trading, margin requirements were introduced as part of post-GFC reforms to mitigate systemic risk. There are two types of margining: initial margin (IM) and variation margin (VM). Initial margin serves to protect parties from potential future exposure that may arise between a counterparty's default and the subsequent closing out of positions. It is recalculated regularly to account for changing risks. Typically, IM includes a core component

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[18] See Pension Regulator Annual report.

related to market risk and factors in additional risks, such as liquidity and concentration risk (BCBS and IOSCO, 2022).

Additionally, derivative users are required to settle changes in the trade's market value at least once daily through VM. Therefore, VM reflects the mark-to-market process, ensuring that positions are reset to a net value of zero after each payment (BCBS and IOSCO, 2020).

Margin practices for centrally and non-centrally cleared derivatives

Both centrally cleared and non-centrally cleared (bilateral) trades are subject to margin requirements. Since mid-2016, interest rate derivatives in certain currencies, including the pound sterling, have been subject to mandatory clearing, with phase-ins based on firm classifications and derivative volumes. The majority of trades in our sample fall under these mandatory clearing requirements. Globally, over 75% of all interest rate derivatives were centrally cleared in 2023 (BIS, 2023).

Both IM and VM are mandatory for centrally cleared trades, with specific requirements determined by central counterparties' (CCP) margin models. In UK clearing houses, variation margin is generally required to be posted in cash, though there are exceptions based on CCP-specific rules. For example, at LCH, intraday VM requirements can be met using excess pre-positioned initial margin. Unlike the stricter VM rules, there is more flexibility regarding initial margin. IM can be posted in cash or highly liquid non-cash collateral, depending on the rules of the specific CCP (BCBS and IOSCO, 2022).

Cash collateral offers advantages, such as lower haircuts (Benos et al., 2022). During periods of high market volatility, the preference for cash increases further due to rising haircuts and greater price volatility in other assets. While VM is typically exchanged at the end of the trading day, CCPs have the discretion to issue margin calls more frequently, especially in times of heightened volatility. For example, intraday margin calls surged during the "Dash for Cash" episode in March 2020 (BCBS and IOSCO, 2022).

For non-centrally cleared (bilateral) trades, counterparties may choose not to clear trades through a central counterparty if the derivatives and counterparty types do not fall under mandatory clearing requirements. In such cases, the Basel Committee on Banking Supervision (BCBS) and the International Organization of Securities Commissions (IOSCO) require that all financial counterparties and systemically important non-financial counterparties exchange VM for new trades initiated after March 1, 2017. Additionally, they must exchange IM if both counterparties are part of groups with a month-end average gross notional amount of non-centrally cleared derivatives of at least EUR 8 billion (BCBS, 2013).

This IM requirement was phased in and applies only to contracts entered into once the counterparties' outstanding gross notional exceeds the phased-in threshold for that month (see PS14/21 for details). The UK implementation specifies a list of eligible assets that financial and non-financial counterparties within scope can use to meet VM and IM requirements, including cash and specific assets subject to haircuts. However, for vanilla derivatives and standard agreements, it is likely that cash will be the preferred collateral for VM due to its frequent exchange requirements.[19]

Is the exchange of VM mandatory?

The obligation to post VM is always mandatory, with no discretion to waive this requirement. For centrally cleared trades, this includes the additional obligation to post VM exclusively in cash.

Where does the cash go?

Collateral collected by central counterparties (CCPs) is subject to strict and limited redeployment rules. IM is paid by both counterparties to the CCP, as required under Article 47 of EMIR, and is segregated in clearing member and client accounts. This ensures that, in the event of a CCP default, members will recover exactly the IM collateral they initially provided. In contrast, VM is passed directly through the CCP to the end-users. The counterparty that is out of the money pays VM to the CCP, which then transfers it to the counterparty that is in the money.

UK EMIR regulations require that at least 95% of cash positions in a CCP's margin account held overnight must be invested in safe and liquid assets. In the UK, CCPs are permitted to invest only in reverse repos, government bond purchases, and central bank deposits (Article 43 of UK EMIR). Given the short-term nature of margin calls, CCPs

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[19] For rules on OTC derivatives not cleared by a CCP, see UK EMIR Art 11, and for eligible non-financial counterparties, see UK EMIR Art 10. The asset classes subject to mandatory clearing are outlined in the Technical Standards referenced in UK EMIR Art 5(2).

primarily invest in reverse repos (for a detailed discussion on CCP collateral usage, see Benos et al., 2022). In contrast, there are no specific restrictions on how VM transferred to end-users can be used, to the best of our knowledge.

For non-centrally cleared trades, regulation mandates that IM must be segregated with a third-party holder or custodian, and the collecting counterparty is generally prohibited from rehypothecating, repledging, or reusing the collected IM, with a few exceptions (see Articles 19 and 20 of BTS 2016/2251). Similar to centrally cleared trading, VM can be redeployed and is only required to be segregated if the posting counterparty requests it (see Article 19.5 BTS 2016/2251). However, since VM is exchanged daily and counterparties may need it for liquidity purposes to meet future VM calls, it is likely that cash is used for limited investment opportunities, such as reverse repos.

Magnitudes: VM outweighs IM

Daily VM calls are typically much larger in magnitude than IM calls for both centrally cleared and non-centrally cleared trades, making VM the primary driver of liquidity needs. For example, aggregate VM calls across clearing members can be up to six times higher than IM calls (Czech et al., 2021).

During periods of stress, such as the onset of the COVID-19 pandemic, daily VM calls by CCPs surged from $25 billion in February 2020 to $140 billion on March 9, 2020, while the peak for IM calls was only half of that (BCBS and IOSCO, 2022). Similarly, at UK clearing houses, non-bank financial intermediaries faced VM calls exceeding £13 billion, while their IM demand rose by only £2.4 billion (Czech et al., 2023).

Differences with repo margining practices

Repurchase agreements are a type of Securities Financing Transaction (SFT) and are not subject to mandatory margining requirements like derivative contracts. Instead, they fall under Credit Risk Mitigation regulations, and counterparties are expected to adhere to best margining practices established by industry bodies (see, e.g., ICMA, 2023).

Best practices for repo margining align closely with those for derivatives, though they are generally less stringent. The International Capital Market Association (ICMA) recommends at least daily re-evaluation of net exposures, exchanges of VM, and delivery of cash margin on the same day that a margin call is made. Additionally, firms are encouraged to clear existing margin accounts (either paid or received) before issuing new margin calls.

These calls can be satisfied with cash or securities that are acceptable as general collateral in the repo market, or with securities that possess equal or superior characteristics to the original collateral posted. In practice, this often limits the options to High-Quality Liquid Assets (HQLA). Furthermore, counterparties have the option to delegate collateral and margin management to a third party, allowing custodians to handle margin calls in a manner similar to derivatives practices.

Supervisory market intelligence suggests that the best practice rules for margining are largely followed, particularly for gilt-based repos.

D LASH Risk from Interest Rates: Measurement for Repo Contracts and Interest Rate Swaps

In this section, we apply equation (5) to repos and interest rate swaps.

Repos As explained in the previous section, repos are short-dated collateralized borrowing arrangements that allow institutions to shorten the duration of their liabilities. The majority of repo transactions are overnight, but pension funds and other interest rate hedgers predominantly use term repos with a maturity of one month or more. LASH risk arises via price changes of the underlying collateral. As the collateral value decreases, ceteris paribus, a counterparty would need to pledge more collateral (or cash) to be able to borrow the same amount.

We approximate LASH risk for repos using the modified duration of the underlying collateral, which measures the impact of a 100bps change in interest rates on the value of the bond. Therefore, in the context of repo, LASH risk resembles the conventional DV01 (or “dollar duration”). For each contract i with bond collateral b of maturity m years and coupon payments c times a year, LASH risk for a 100bps increase in interest rates at time t

reads:

$$LASH^{Repo}_{i,t} = \frac{Q_{i,t}}{100} \times \underbrace{\frac{\sum_{k=1}^{K}(1+r_t)^{-k_b} \cdot CF_{b,k} \cdot k_b}{P_{b,t}} \times \left(1 + \frac{YTM_{b,t}}{c_b}\right)^{-1}}_{\text{Modified duration of bond } b} \tag{D.1}$$

where $Q_{i,t}$ is the borrowing amount of a given repo contract. $P_{b,t}$ is the market price of bond b, k_b is the time to each cash flow $CF_{b,k}$ of bond b from time t perspective (in years), and $YTM_{b,t}$ is the bonds' yield to maturity. We assume zero haircuts as most of the LASH risk in our sample is due to longer-term repos, which are, of course, less frequently rolled over compared to overnight contracts (where haircuts play a bigger role, e.g., during the Great Financial Crisis). This implies a one-to-one liquidity need with respect to the cash flow sensitivity to interest rates, hence $\Lambda_i = 1$.

Interest Rate Swaps An interest rate swap is a contract where two counterparties agree to exchange a fixed interest rate for a variable one, e.g., LIBOR, SOFR, SONIA, c times a year, for a duration of m years. The interest is calculated on a notional amount, Q, but only the difference in interest payments is exchanged. The fixed interest rate is set so that the NPV of the contract is zero at initiation; that is, neither side needs to pay the other to enter the agreement. To mitigate counterparty credit risk, parties entering a swap must pledge liquid collateral as initial margin.

LASH risk arises in swaps mainly due to variation margin. The counterparties are required to exchange variation margin on a daily basis to maintain the zero net present value of the contract as interest rates change. The floating rate payer will post variation margin to the fixed rate payer when rates rise (and vice versa when rates fall). In practice, this is implemented through daily (cash) margin calls that reflect the change in the mark-to-market price of the contract.[20]

The size of the margin calls, and the demand for liquidity, depend on the sensitivity of the swap's fixed versus floating cash flows to changes in interest rates. We extend the methodology proposed by Bardoscia et al. (2021) to calculate the liquidity needs from a given interest rate move and hence to obtain an estimate of LASH risk. Imagine an interest

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[20] Variation margin is a regulatory requirement, and the requirements may differ between centrally-cleared and bilateral swaps. A centrally cleared swap requires daily cash pledges for variation margin, while bilateral swaps can have more bespoke conditions if permitted by regulation, e.g., the use of non-cash collateral.

rate swap of net notional value Q. We are at time zero and the swap matures at year T, and makes c coupon payments per year. Let k index coupon periods. There is a swap curve which defines the time zero sequence of annualized forward floating rates given by $r_{k,k-1}$, and a fixed rate $\bar{r}$ (for an at the money swap $(\bar{r} \equiv r_{T,0})$). Cash-flows are discounted at rate:

$$d_k = (1 + \frac{r_{k,0}}{c})^{-k} \approx e^{-\frac{r_{k,0}}{c}k}$$

The present value of the floating and fixed leg of the swap is given by:

$$PV_{floating} = Q \sum_{k=1}^{cT} d_k \frac{r_{k,k-1}}{c}$$

$$PV_{fixed} = Q \sum_{k=1}^{cT} d_k \frac{\bar{r}}{c}$$

Now the NPV of the contract for the floating rate payer is given by:

$$NPV = PV_{fixed} - PV_{floating} = \frac{Q}{c} \sum_{k=1}^{cT} d_k (\bar{r} - r_{k,k-1}).$$

For a ex post shift upwards of the swap curve, the sensitivity reads:

$$\frac{\partial NPV}{\partial r} = -\frac{Q}{c} \sum_{k=1}^{cT} \left[\underbrace{d_k + \frac{\partial d_k}{\partial r} r_{k,k-1}}_{\text{change in value of floating leg}} - \underbrace{\frac{\partial d_k}{\partial r} \bar{r}}_{\text{change in value of fixed leg}} \right]. \tag{D.2}$$

Solving in continuous time yields:

$$\frac{\partial NPV}{\partial r} = -\frac{Q}{c} \sum_{k=1}^{cT} \left[d_k + \frac{k}{c} d_k (\bar{r}_i - r_{k,k-1}) \right].$$

Hence, LASH risk from a 100bps increase in interest rates for a swap contract i with maturity T based on notional Q and with c cash flow swaps a year reads:

$$LASH^{IRS}_{i,t} = \frac{Q_i}{100c} \sum_{k=1}^{cT} \left[d_k + \frac{k}{c} d_k (\bar{r}_i - r_{k,k-1}) \right]. \tag{D.3}$$

where the discount rate for cash flow k, $e^{-R_{k,t}\cdot(T_k-t)}$, is evaluated based on the daily Overnight Index Swap (OIS) yield curve for maturity $T_k - t$ from time t perspective. We derive the forward rates $r_{k,k-1}$ as implied by the OIS curve. We assume the fixed rate to be the prevailing OIS rate at the start of contract i corresponding to the trade maturity. Lastly, standard contracts have semi-annual coupons, so $c = 2$, without loss of generality.The LASH risk for swaps via variation margin implies a one-to-one liquidity need with respect to the cash flow sensitivity to interest rates, hence $\Lambda = 1$.

E Data: Additional Information & Summary Statistics

This section of the Appendix provides additional information and summary statistics for the various data sources used in the empirical analysis.

Table E.1 SUMMARY STATISTICS: UK PENSION FUND BALANCE SHEETS

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
N	10	22	50	65	68	69	10
Total assets (£bn)	115.0	553.7	801.3	1046.9	956.5	876.9	55.1
Total liabilities (£bn)	117.2	560.7	815.2	1099.9	900.0	807.9	50.8
Actuarial assets (£m)							
Min	907	933	179	62	145	177	916
Mean	11501	25170	15711	15863	14066	12709	5513
Median	3600	4360	3767	3676	3611	3029	2364
Max	60000	358175	395867	444167	463022	406597	23500
Std deviation	18973	75692	55560	55490	56579	49732	7605
Actuarial liabilities (£m)							
Min	1074	1044	193	95	125	162	835
Mean	11724	25485	15985	16665	13235	11709	5078
Median	3673	4501	3499	3642	3511	2960	2195
Max	67500	368981	404974	475130	418665	366574	20300
Std deviation	20615	78046	56894	59416	51396	45031	6659

NOTE. Cross-sectional dispersion and total actuarial values and liabilities for the UK pension funds in our hand-collected sample. Values are reported in £m, unless otherwise stated, and N denotes the total number of pension funds in each year of our sample.

Table E.2 SUMMARY STATISTICS: UK PENSION FUND FUNDING RATIOS

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
N	13	23	52	70	76	74	11
Underfunded PFs	0.62	0.52	0.56	0.60	0.33	0.27	0.27
Pension fund funding ratios							
Min	0.81	0.78	0.81	0.65	0.80	0.91	0.91
Mean	0.98	1.02	1.00	0.98	1.04	1.06	1.07
Median	0.94	1.00	0.99	0.98	1.04	1.05	1.07
Max	1.31	1.39	1.40	1.49	1.54	1.42	1.23
Std. deviation	0.13	0.12	0.11	0.12	0.10	0.10	0.09

NOTE. Cross-sectional dispersion of funding ratios for the UK pension funds in our hand-collected sample. N denotes the total number of pension funds in each year of our sample, and the underfunded PFs denotes the share of pension funds with a negative funding ratio (so assets<liabilities) in the given year. A ratio of 1 indicates that the actuarial value of assets exactly matches the actuarial value of liabilities.

Table E.3 SUMMARY STATISTICS: AVERAGE NET POSITIONS AND LASH RISK

	Repo net borrowing					**IRS net receive fixed**				
Sector	2019	’20	’21	’22	’23	2019	’20	’21	’22	’23
Pension fund	38	64	74	69	48	65	96	101	132	112
LDI	99	121	130	113	73	17	37	40	38	23
Insurer	0	0	0	0	0	10	23	27	72	60
Hedge Fund	-7	11	-3	-34	-15	59	82	-14	-108	-81
Fund	9	7	7	4	4	23	21	11	18	15
Other financial	7	20	18	10	5	-8	-11	-3	-9	-14
	Repo discretionary LASH					**IRS discretionary LASH**				
Sector	2019	’20	’21	’22	’23	2019	’20	’21	’22	’23
Pension fund	8	15	18	16	11	5	11	12	12	10
LDI	22	28	30	26	17	2	5	5	5	3
Insurer	0	0	0	0	0	0	6	6	8	7
Hedge Fund	0	1	-1	-3	-1	1	0	-1	-1	-1
Fund	2	1	1	1	1	2	1	1	0	0
Other financial	2	4	3	2	1	-2	-2	-1	-1	-1

NOTE. Sample: Summary statistics on repo and IRS positions from 2019 to 2023. Values reported in £bn. Repo net borrowing captures the daily average cash borrowing per sector in a given year. The IRS net position captures the average holding of net receive fixed positions (negative values read as net pay fixed) per sector in a given year. Behavioural LASH risk captures the average for each sector in a given year.

Table E.4 Summary Statistics: Cross-sectional variation of Net positions and LASH risk

		Repo net borrowing			Repo discretionary LASH		
Sector	N	Mean	Median	Std dev	Mean	Median	Std dev
Pension fund	273	259.3	144.3	388.3	59.4	31.5	89.3
LDI	337	360.6	113.6	1275.5	82.6	25.5	300.6
Insurer	16	45.2	36.7	205.3	6.3	3.6	43.4
Hedge Fund	284	-59.7	-0.6	561.4	-4.0	0.0	65.6
Fund	203	117.6	3.7	626.6	22.9	0.6	143.7
Other financial	13	-10.5	0.0	116.7	-1.1	0.0	21.1
		IRS net receive positions			IRS discretionary LASH		
Sector	N	Mean	Median	Std dev	Mean	Median	Std dev
Pension fund	450	297.9	32.0	1372.2	29.9	2.6	183.9
LDI	231	199.3	48.2	477.1	24.9	3.0	72.6
Insurer	76	971.4	17.0	4034.6	139.2	0.2	691.3
Hedge Fund	149	-231.0	10.0	19493.3	-7.4	0.0	186.4
Fund	869	54.2	0.8	565.0	2.6	0.0	29.4
Other financial	217	-148.8	-6.5	1266.4	-14.1	-0.2	107.3

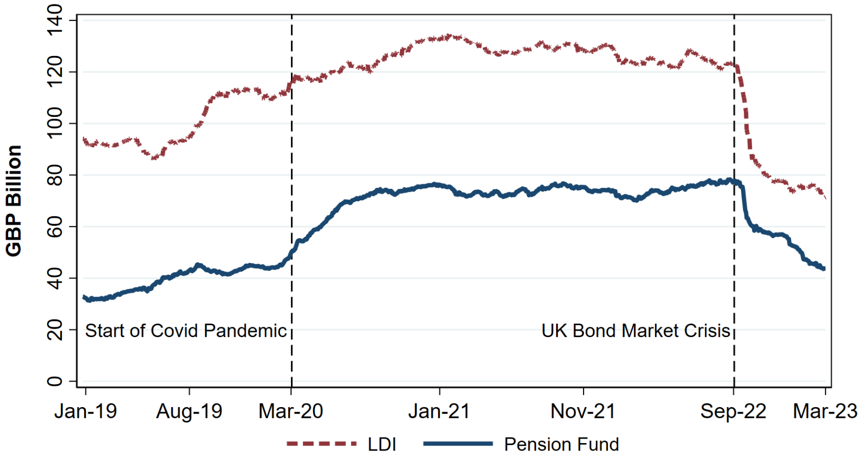
Note. Sample: Firm level summary statistics for repo (2017-2023) and IRS positions (2019-2023). Values are reported in £m, and N denotes the number of firms in each sector of our sample. The mean and median of repo net borrowing capture the total daily cash borrowing in the cross-section, and the IRS net position captures the outstanding net receive fixed positions (negative values read as net pay fixed). Behavioural LASH risk measures the outstanding LASH exposure at firm level in a given day.

Table E.5 LASH risk and Gilt Trading Volumes - Pension & LDI Funds only

	(1)	(2)	(3)	(4)
	Net Volume		Sell Volume	
LASH combined	-0.12**		0.10***	
	(0.05)		(0.02)	
LASH Repo		-0.10***		0.08***
		(0.03)		(0.02)
LASH IRS		-0.04		0.05
		(0.07)		(0.04)
Observations	2325	2325	2325	2325
R squared	0.036	0.036	0.044	0.044
Day FE	yes	yes	yes	yes

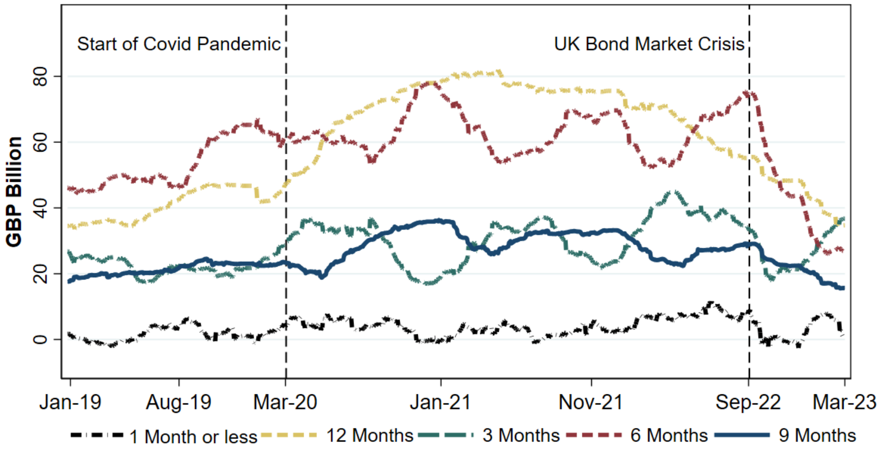
Note. For each pension & LDI fund, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, either for repo and IRS exposures combined, or separately for both instruments. The dependent variable is the institution's daily gilt net trading volume on day t in Columns (1) and (2), and the institution's sell volumes on day t in Columns (3) and (4). The dependent variables are transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Clustered standard errors on the day level are reported in parentheses. We include day fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

Figure E.1 Pension & LDI Funds' Repo Net Borrowing Stocks



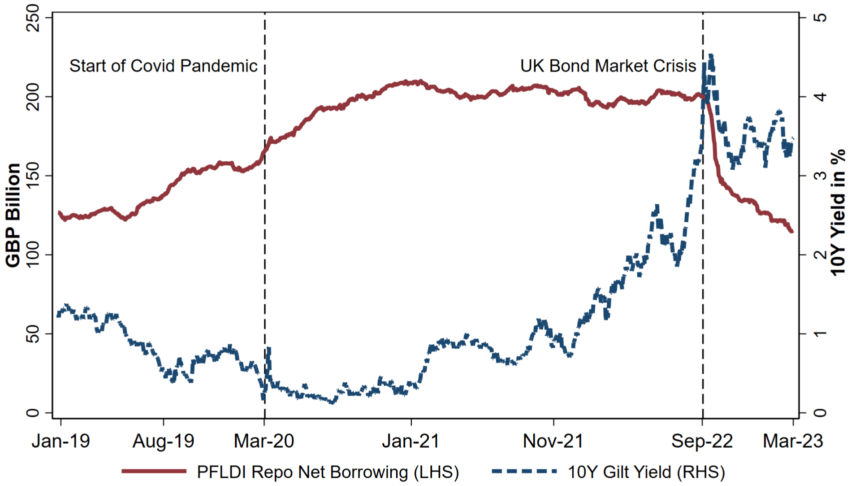
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds in £bn. Source: Sterling Money Market data collection.

Figure E.2 Pension & LDI Funds' Repo Net Borrowing Stocks by Maturity



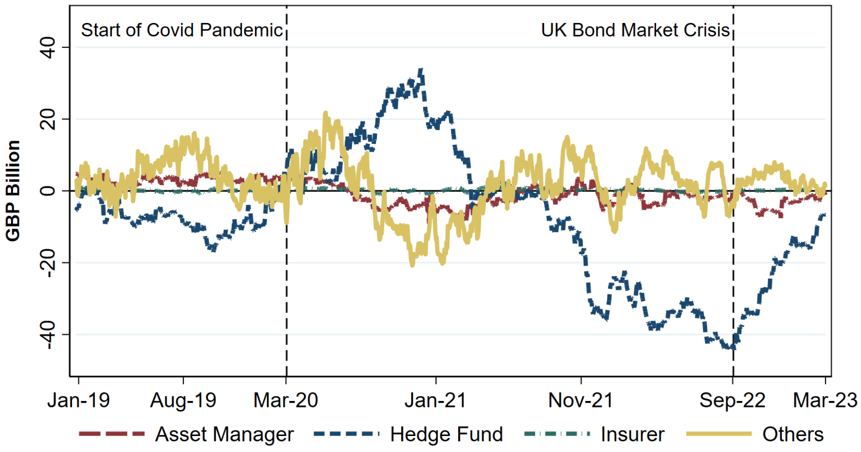
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds by the maturity bucket at initiation in £bn. Source: Sterling Money Market data collection.

Figure E.3 Pension & LDI Funds' Repo Net Borrowing Stocks & 10Y Gilt Yields



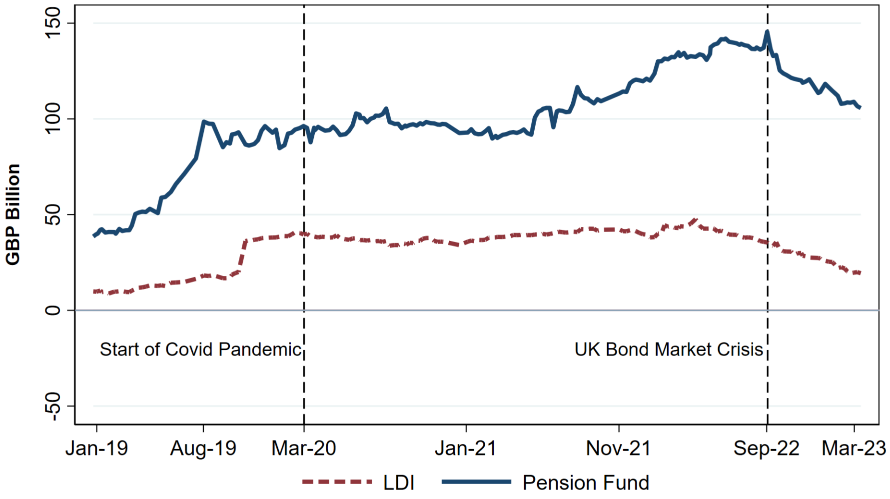
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds in £bn and 10-year gilt yields in %. Source: Sterling Money Market data collection & Bank of England.

Figure E.4 Repo Net Borrowing Stocks Across Other Non-Bank Sectors



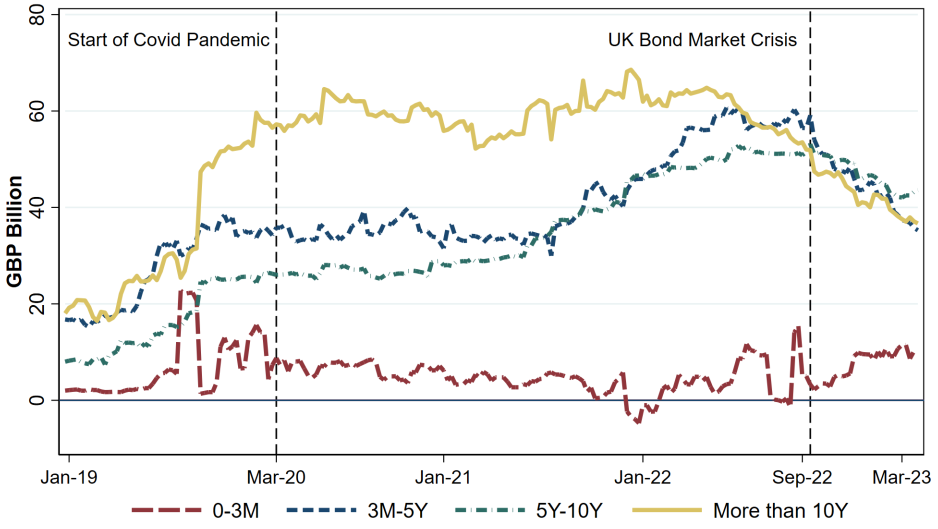
NOTE. Aggregate repo net borrowing across all sector types in £bn. "Others" include sovereign entities and other financials. Source: Sterling Money Market data collection.

Figure E.5 Pension & LDI Funds' IRS Net Notionals



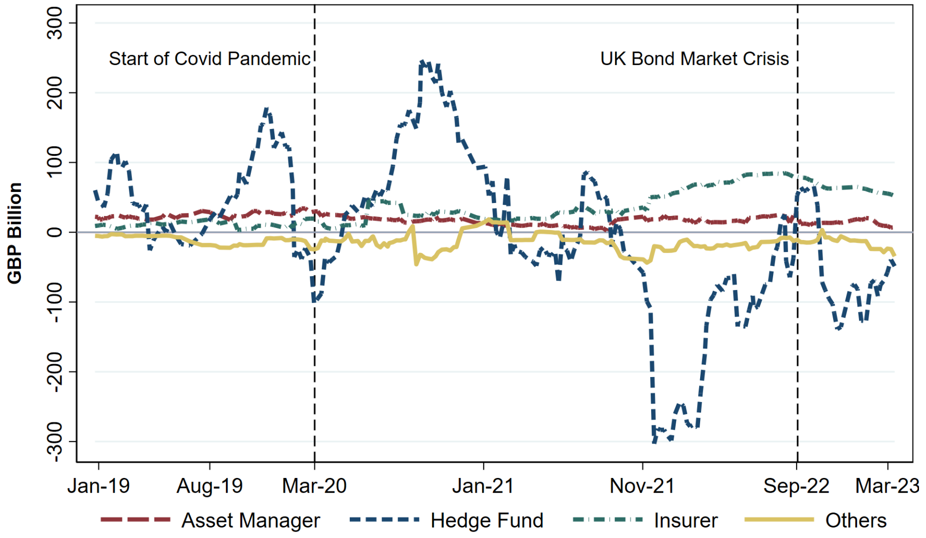
NOTE. Aggregate IRS net notionals of UK pension and LDI funds in £bn. Source: EMIR Trade Repository Data.

Figure E.6 Pension & LDI Funds' IRS Net Notionals by Maturity



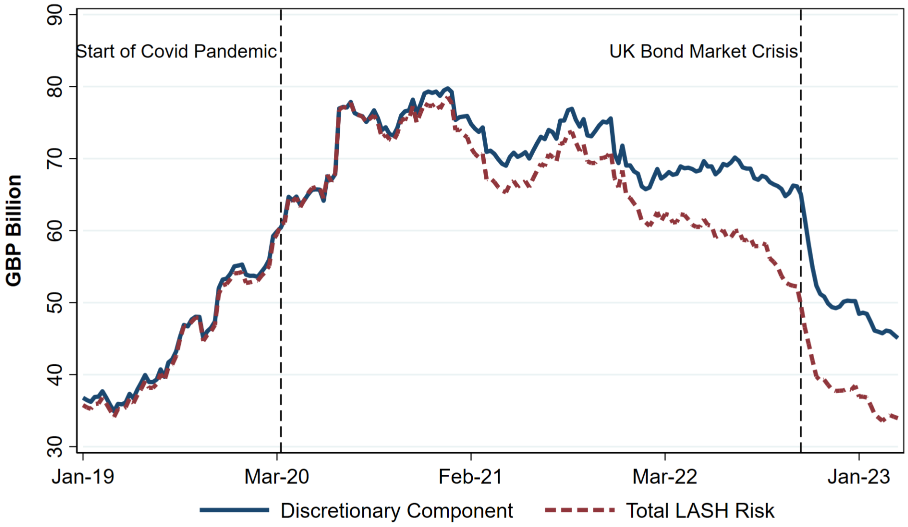
NOTE. Aggregate IRS net notionals of UK pension and LDI funds by maturity bucket in £bn. Source: EMIR Trade Repository Data.

Figure E.7 IRS Net Notionals Across Other Non-Bank Sectors



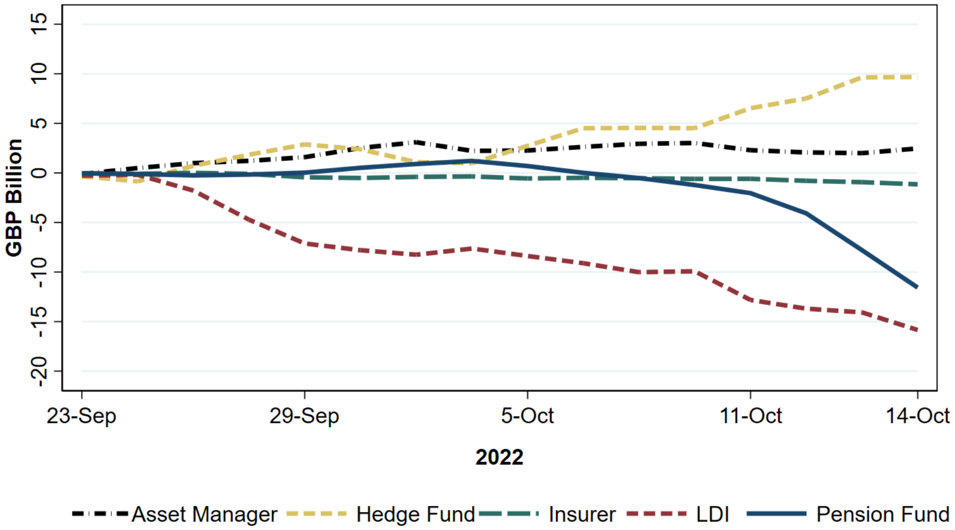
NOTE. Aggregate IRS net notionals across all sector types in £bn. "Others" include sovereign entities and other financials. Source: EMIR Trade Repository Data.

Figure E.8 LASH: DISCRETIONARY COMPONENT



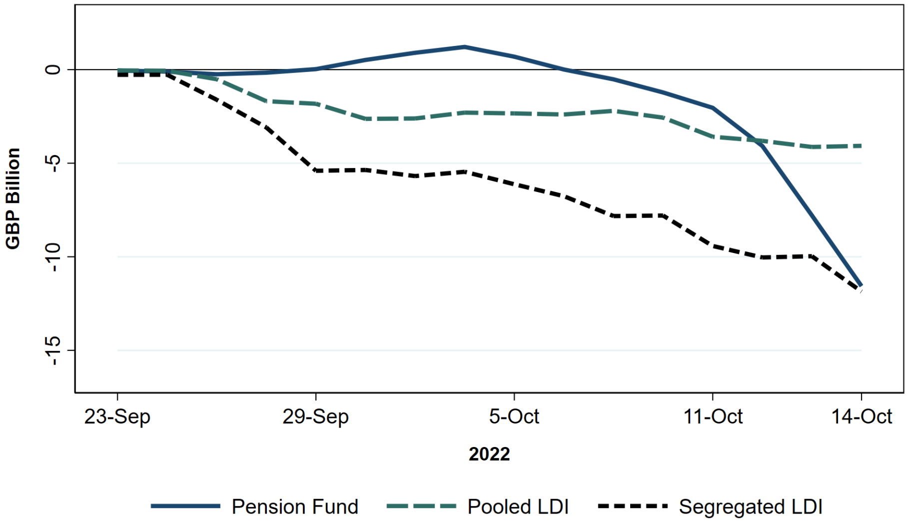
NOTE. This figure shows the evolution of the total LASH risk and the discretionary LASH risk component in £bn for all non-banks. The *Discretionary Component* is defined as $\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}$ for interest rate swaps and repos, as shown in equation 8 in Section 3.2.

Figure E.9 UK BOND MARKET CRISIS: NON-BANKS' BOND TRADING VOLUMES



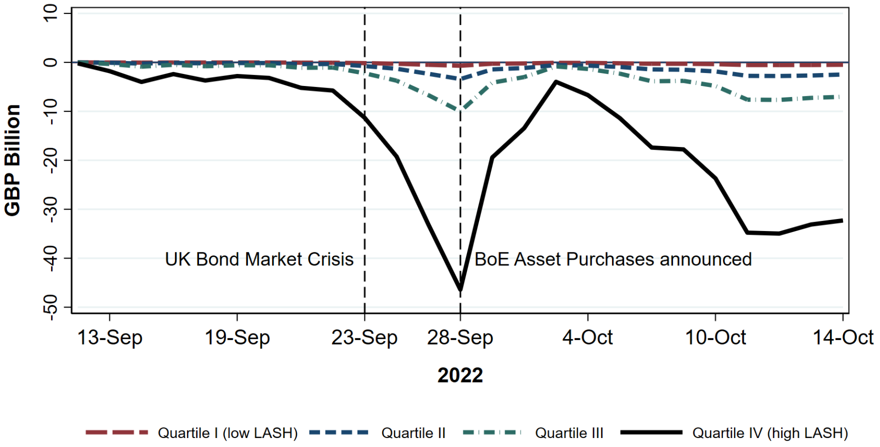
NOTE. Total net gilt trading volumes of UK non-bank financial institutions following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

Figure E.10 UK Bond Market Crisis: Pension & LDI Funds' Gilt Trading Volumes



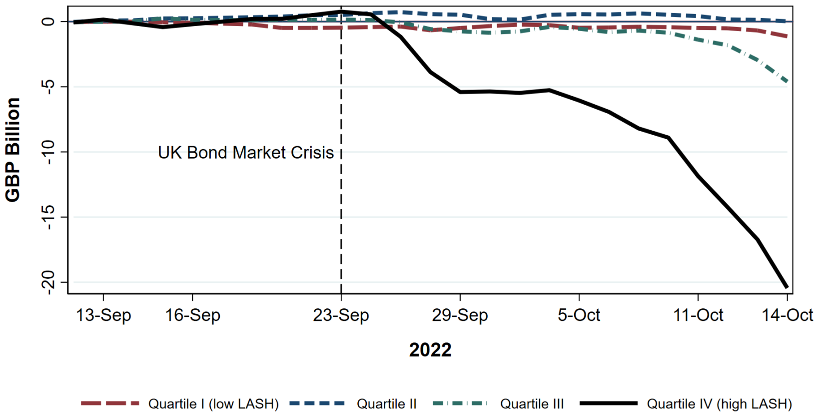
NOTE. Total net gilt trading volumes of UK pension & LDI funds' (split into pension funds, segregated LDI funds and pooled LDI funds) following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

Figure E.11 UK Bond Market Crisis: Estimated Cumulative Changes in the Value of Repo Collateral posted by Pension & LDI Funds



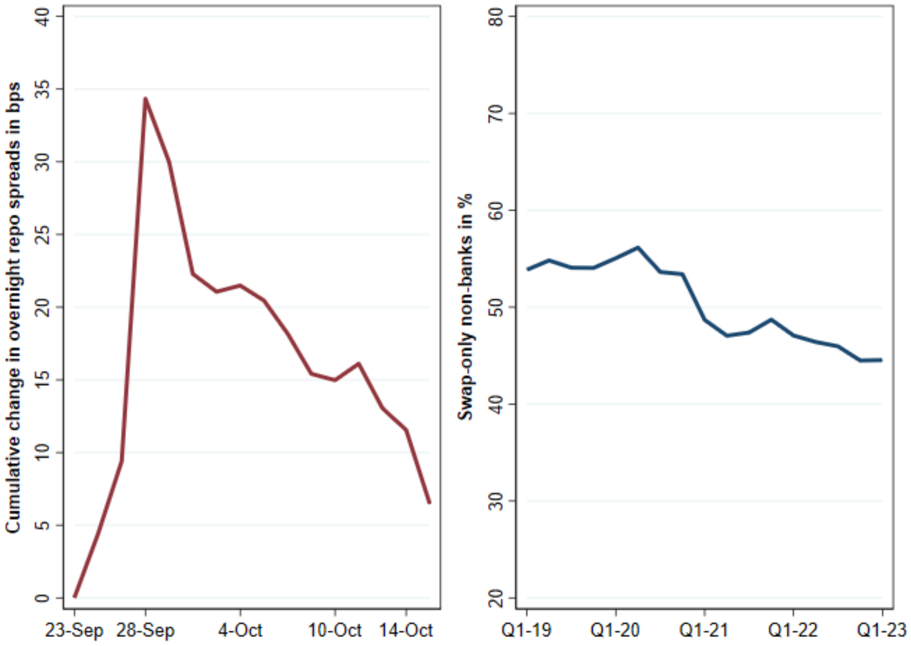
NOTE. Aggregate estimated changes in the value of repo collateral posted by UK pension and LDI funds in £bn during the 2022 UK bond market crisis, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures. Source: Sterling Money Market data collection.

Figure E.12 UK Bond Market Crisis: Pension & LDI Funds' Cumulative Gilt Trading Volumes based on pre-crisis LASH exposure



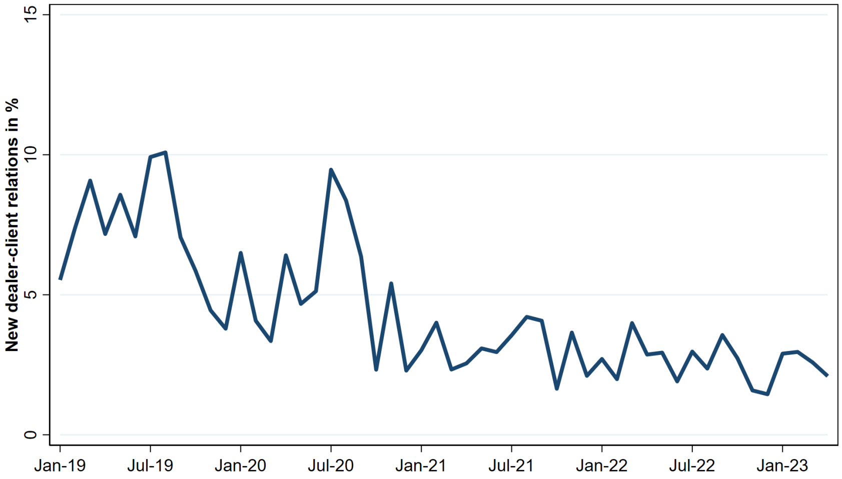
NOTE. Total net gilt trading volumes of UK pension funds and LDI funds, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures.

Figure E.13 Overnight Repo Spreads and Limited Access to Repo Market



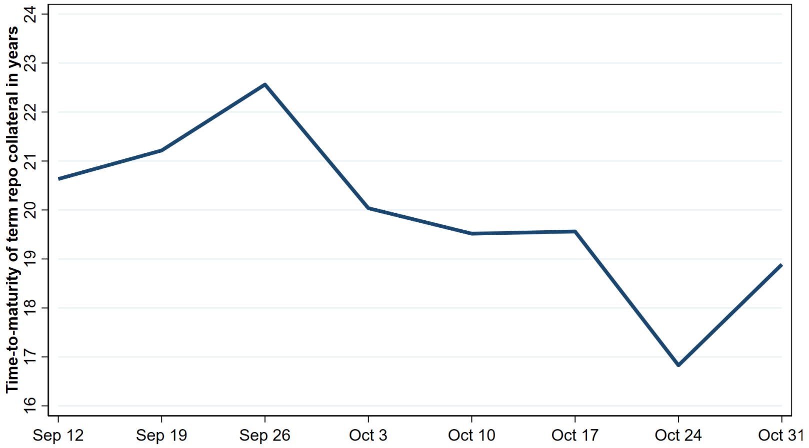
NOTE. Left Panel: Cumulative change in overnight gilt repo spreads (in bps) during the 2022 UK bond market crisis. Right Panel: Share of non-banks that only hold interest rate swaps in their portfolios, and are not borrowing or lending via the repo market, measured quarterly for the period from Q1 2019 to Q1 2023. Source: Sterling Money Market data collection & EMIR Trade Repository Data.

Figure E.14 Repo Market: New Dealer-Client Relationships



NOTE. Average monthly share of trades in the repo market that constitute a newly formed relation between a dealer and a non-bank client. Source: Sterling Money Market data collection.

Figure E.15 UK Bond Market Crisis: Average Time-to-maturity of Gilt Repo Collateral



NOTE. Weekly average of the time-to-maturity of gilt collateral in term repo trades of pension funds and LDI funds during the 2022 UK bond market crisis. Source: Sterling Money Market data collection.

F Pension Funds' Gross Asset Duration and Solvency

In Section 5, we show that falling interest rates lead to an economically and statistically significantly higher LASH risk taken by institutions with short asset duration. Technically, rather than gross asset duration, the duration gap between assets and liabilities (i.e. net duration) is what matters for solvency. In the absence of granular information on the duration of institutions' liabilities, however, we use institutions' initial gross asset duration (measured via the bonds in their repo collateral portfolio) as a proxy for their duration gap. To test the correlation between net and gross duration, we use our hand-collected balance sheet data for UK pension funds.

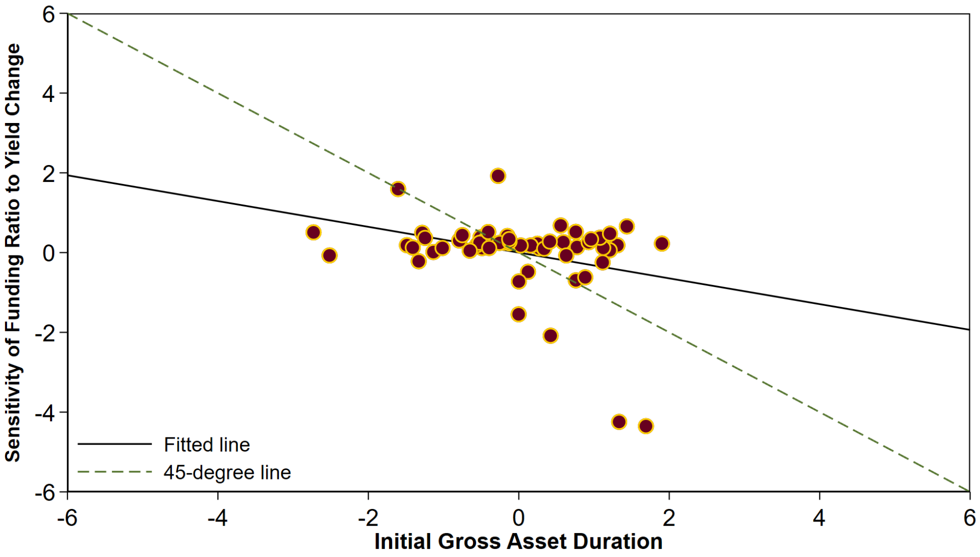
First, we measure the net duration of pension funds. To do so, we estimate the sensitivity of the funding ratios of individual pension funds to changes in the ten-year UK gilt yield using seemingly unrelated regressions:

$$\Delta FundingRatio_{j,t} = \alpha + \beta_f \Delta Yield_t + \varepsilon_{j,t}, \tag{F.1}$$

where $\Delta FundingRatio_{j,t}$ measures the annual change in the natural logarithm of pension fund j's funding ratio—which is defined as the value of the fund's assets over liabilities— in year t. $\Delta Yield_t$ is the annual change in the ten-year UK gilt yield. β_f is our measure of the funds' net duration.

Appendix Figure F.1 shows a scatter plot relating our estimate of fund-level net duration to the gross asset duration of these funds. Each are in standardized units, the funding ratio sensitivities on the vertical axis, and the gross asset duration on the horizontal axis. The association is clearly negative, even though the number of matched funds is relatively small. In other words, the funding ratio of funds with shorter asset duration is more sensitive to a change in yields—and hence the solvency of these funds will decrease more sharply in response to lower interest rates relative to funds with longer asset duration. Therefore, the results emphasize the negative correlation between gross and net duration, and support our choice of gross asset duration as a viable proxy for institutions' duration gap.

Figure F.1 Sensitivity of Pension Funds' Funding Ratios to Yield Changes and Gross Asset Duration



NOTE. This figure shows a scatter plot of the sensitivity of individual pension funds' annual change in log funding ratios to changes in the yield of the ten-year UK gilt yield, and the funds' gross asset duration. Each are in standardized units, the funding ratio sensitivities on the vertical axis, and the gross asset duration on the horizontal axis. Funding ratios are the ratio of the market value of assets to liabilities.