LASH Risk and Interest Rates[☆]

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Abstract

In this paper, we first introduce a framework to understand and quantify a previously less-examined form of liquidity risk, *Liquidity After Solvency Hedging risk* or "LASH Risk". Unlike conventional forms of liquidity risk, LASH Risk is not linked to maturity transformation and callable claims, rollover risk, or insolvency. Using regulatory data on the universe of sterling repo and swap exposures, we document a rapid increase in liquidity risks from leveraged exposures in non-bank financial intermediaries (NBFIs). We construct a measure of aggregated LASH Risk across both instruments and show that solvency hedging in response to low-interest rates has "sowed the seeds" of future liquidity crises. We then link the pre-crisis liquidity risk exposures of NBFIs to their gilt trading activity during the UK LDI crisis and find that funds with larger exposures sold substantially higher quantities of gilts during the crisis, and thereby significantly contributed to the yield spike in the gilt market.

Keywords: Liquidity, Monetary policy, Non-Bank Financial Intermediaries, Hedging

JEL Codes: E44, G10, G22, G23

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1 Introduction

Liquidity crises have become increasingly common in the non-bank financial sector. Recent examples include the pandemic-era "dash for cash" in Spring 2020 and the UK LDI crisis in October 2022. A common and perhaps surprising feature of these events is that liquidity risk materialized even as solvency improved. These liquidity crises are linked to the surge in the use of hedging and funding instruments in the past decade — notably by pension funds, insurance companies, and alternative investment funds employing tools like interest rate swaps and repos. As such, the episodes are different from liquidity crises in the banking system, which arise from maturity transformation and callable liabilities.

In this paper, we first introduce a framework to understand and measure this previously less-examined form of liquidity risk, which we term *Liquidity After Solvency Hedging* risk or "LASH" risk. While hedging strategies lower solvency risks (Froot et al., 1993), hedging via derivatives requires the constant commitment of liquid assets in the form of margin requirements.[1] Similarly, borrowing in short-term money markets is only as valuable as the collateral pledged. Hence, hedging via derivatives and repo generates immediate liquidity aftershocks—even as the hedging largely eliminates the solvency risk associated with these shocks.

Our framework underscores the causal effects of interest rates on LASH Risk. Consider, as an example, a pension fund with long-duration liabilities (arising from its commitments to fund members) and a portfolio of relatively shorter-duration assets. A fall in interest rates is detrimental to solvency. The fund could hedge against rate risk by using a derivative that pays out when rates fall. The fund could also engage in shorter-term borrowing, which helps reduce the fund's duration gap (through shortening the duration of its liabilities) while allowing for additional investments in safe or risky assets. However, doing so exposes the fund to liquidity risk when rates rise—i.e. LASH Risk. At the same time, a low-rate environment also creates stronger incentives to hedge. A given basis point interest rate change leads to a greater impact on valuations when rates are lower. Moreover, low rates are associated with a less solvent fund. To the extent that the fund wishes to avoid a deficit, hedging risks to solvency becomes a priority when interest rates are low.

Opting for portfolio allocations that preserve solvency in low-interest rate environments

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[1] Following the Great Financial Crisis in 2007-09, to mitigate counterparty credit risk, regulatory reforms were put in place to promote greater use of central clearing, and to ensure minimum standards for margin requirements for both centrally and non-centrally cleared derivatives. The implicit trade-off between the mitigation of credit risk and the increased exposure to liquidity risks has been the subject of debate in policy circles in recent years (see, among others, Bank of England, 2018; Roberts-Sklar and Torrance, 2021).

requires hedging, inadvertently elevating LASH Risk. When financial institutions maintain sufficient liquidity buffers, small movements in interest rates will not lead to significant disturbances. The risk rather materializes during periods of sharply increasing interest rates, leading to liquidity crises as a direct result of investors' solvency hedging.[2] Unlike conventional forms of liquidity risk, LASH Risk is not directly linked to maturity transformation and callable claims (Diamond and Dybvig, 1983), rollover risk (Calvo, 1988), or the spiral between funding and market liquidity (Brunnermeier and Pedersen, 2009).

The paper's second key contribution is the introduction of a novel measure assessing the liquidity risk that financial institutions face, LASH Risk, from their exposure to derivatives and repo agreements, with an emphasis on NBFIs. Our framework reveals that such risk permeates various hedging instruments, from FX and inflation hedging to interest rate (IR) hedging. It also extends to collateralized debt instruments used for both funding and hedging, like repurchase agreements. In the case of rates, NBFIs predominantly use interest rate swaps and repo transactions secured by government bonds for hedging purposes. In this context, LASH Risk quantifies the sensitivity of the net present value of a hedging strategy to interest rate changes, which ties back to the underlying collateral posted for repos, and the present (discounted) value of the interest rate swap contract, as detailed in Bardoscia et al. (2021).

The third contribution is to measure LASH Risk for pound sterling interest rate contracts held by UK NBFIs. Our measure is available at high frequency and in real-time from 2019 onwards, and could therefore be a useful tool for regulators to monitor liquidity risks in the non-bank sector. To construct it, we collect regulatory data from the Bank of England on the universe of sterling repo transactions (Sterling Money Markets Database), the universe of pound sterling interest rate swap positions (UK EMIR Trade Repositories) and the universe of gilt (UK Government bonds) transactions (MiFID II database).

Figure 1 shows weekly LASH Risk estimates for NBFIs in the context of sterling interest rates (repos + swaps) to be large and rising over our sample period from 2019 to 2023. For example, in 2020, an increase of 100bps in interest rates would have led to liquidity claims that would have depleted the entire cash reserves of UK pension funds and insurers combined. The figure captures an evident "inverse U" relation co-moving with interest rates. We further document a sizeable cross-sectional dispersion, with the largest exposures concentrated in pension funds and alternative funds designated to match a pension plan's current and future liabilities (liability-driven investment (LDI) funds).

We then test the framework's predictive power regarding causes and consequences and

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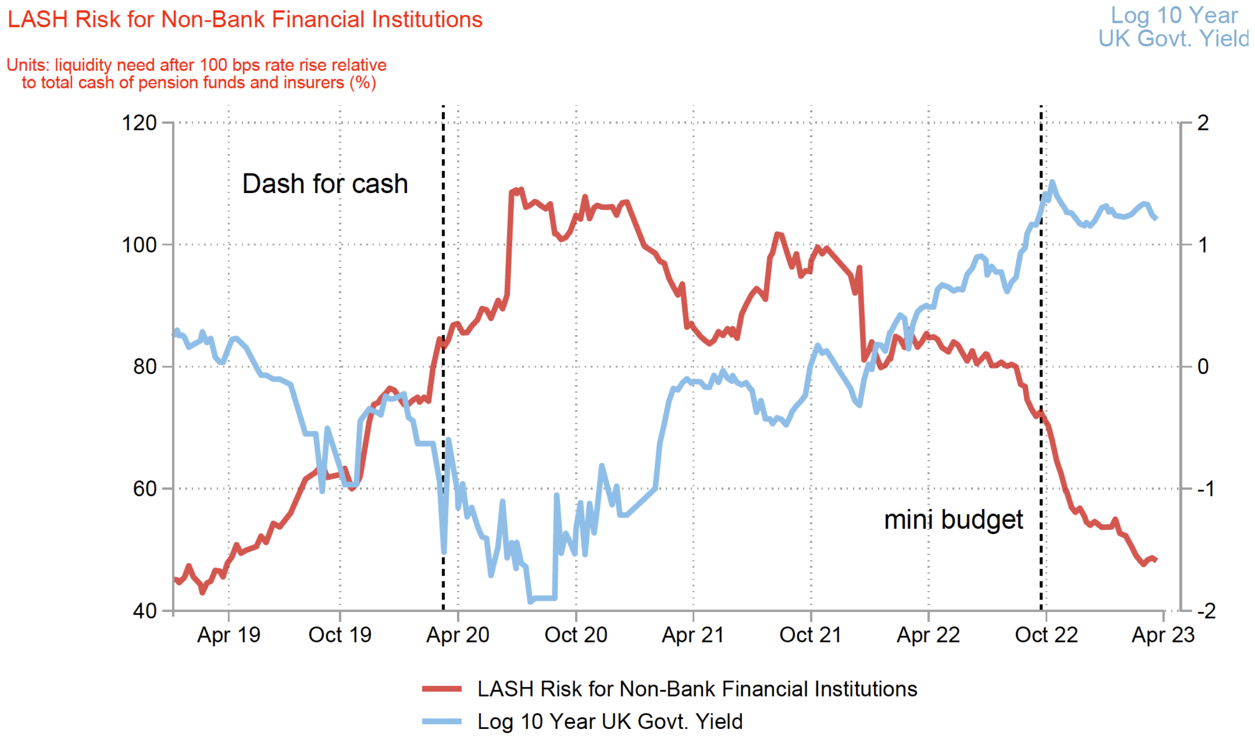
[2] It is worth noting that liquidity risks can, if not properly managed, transform into solvency risks if investors have to sell assets at large discounts to meet liquidity demands during periods of high volatility.

Figure 1 LASH Risk: Non-Bank Financial Intermediaries



NOTE. Estimated liquidity needs after 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 6 in Section 3.

show how the hedging behavior of NBFIs responds to interest rate changes. To do so, we first decompose aggregate LASH Risk into a behavioral and mechanical component with a standard first-order decomposition. The mechanical component captures market valuation adjustments: LASH Risk rises mechanically as rates fall due to the convexity of the underlying hedging strategy. The behavioral component abstracts from this mechanical effect and measures LASH Risk due to investors' discretionary changes of their hedging portfolio, holding the underlying convexity constant. We identify the causal effect of interest rates on our behavioral LASH Risk measure using a cross-sectional identification strategy. Specifically, we identify investors that are more severely exposed to a decline in interest rates, as they hold relatively short-duration assets. These investors experience deteriorating solvency as interest rates fall. Consistent with our framework, we find that these investors disproportionately take on LASH Risk relative to investors with higher-duration assets.

Having established the connection between low-interest rates and elevated LASH Risk, we then examine the link between NBFIs' pre-crisis liquidity risk exposures and UK government bond trading activities during the recent LDI stress episode in autumn 2022. We find that investors with larger LASH exposures sold substantially higher quantities of gilts during the LDI crisis: a one standard deviation increase in pre-crisis LASH Risk is associated with 15% higher daily sell volumes during the crisis. The effect is particularly pronounced for index-linked gilts, high-duration gilts, and gilts that are frequently used as repo collateral by these hedging entities. Due to these selling pressures, high LASH Risk investors significantly contributed to the yield spike in the gilt market: a one standard deviation increase in LASH-induced trading is associated with a 4.2bps daily increase in gilt yields (or 67bps over the entire 16-day crisis period).

In seeking solvency, NBFIs such as pension funds inadvertently reached for 'illiquidity' as outlined in our framework. Holding safe assets, which are traditionally considered protective measures for liability holders, coupled with a backdrop of low-interest rates and extensive quantitative easing, resulted in a transformation of their risk profiles. As a result, not only were NBFIs ill-equipped to absorb shocks pertaining to government bonds, but their actions also amplified those shocks. We contend that LASH Risk, a lesser-explored yet significant form of liquidity risk, can give rise to sizable pecuniary externalities. It originates from NBFIs' efforts to hedge against solvency risk, and it plays a pivotal and foretelling role during financial crises.

Related literature

We contribute to several strands of literature. First, we contribute to the literature on liquidity risk, which has traditionally centered on banks and liquidity risk stemming from maturity transformation or coordination failures (Diamond and Dybvig, 1983; Diamond and Rajan, 2001; Rochet and Vives, 2004; Morris and Shin, 2004). In the context of reducing banks' interest rate risk, the literature explores the use of financial instruments (McPhail et al. 2023, the role of maturity transformation as a hedge (Drechsler et al., 2021) and the trade-off between interest risk and liquidity risk (Drechsler et al., 2023). A related research strand focuses on the interactions between liquidity risk and claims arising from mark-to-market valuations (Brunnermeier and Pedersen, 2009; Adrian and Shin, 2010). Our paper, focusing on how NBFIs hedge solvency risks in the context of interest rates, adds a new dimension complementing these papers.

Second, our work adds to general theories of investment incentives by examining how NBFIs respond to monetary policy in their pursuit of solvency (Campbell and Sigalov, 2022).[3]

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[3] The relationship between interest rates and 'reach for yield' has been documented for insurers, pension funds, mutual funds, and banks (Becker and Ivashina, 2015; Martinez-Miera and Repullo, 2017; Lu et al., 2023; Aramonte et al., 2022).

Bertaut et al. (2023) highlight the significant influence of NBFIs on global capital markets through their long-term borrowing strategies. In their analysis, duration risk interacts and is amplified by FX risk via valuation changes, affecting sovereign bonds. Our paper focuses on the interaction of duration with solvency and liquidity risks. Regarding hedging interest rate risk, contemporaneous work studies the Dutch pension fund sector (Jansen et al., 2023), financial and non-financial sectors (Khetan et al., 2023), and non-bank entities in the UK (Pinter and Walker, 2023). We contribute to this literature by quantifying the liquidity implications associated with NBFIs' efforts to maintain solvency and strategies by exploiting high-frequency data across various instruments and different interest rate regimes.

Third, our paper links to the vast literature on the role of monetary policy, interest rates, and financial stability. Stein (2012) develops a framework that explains the nexus between financial stability, monetary policy, and the real economy. Theoretical and empirical studies study and document the risk-taking channel of monetary policy (Adrian and Shin, 2010; Jiménez et al., 2014) or the importance of credit creation in times of loose monetary policy on subsequent financial fragility (Grimm et al., 2023). Moreover, Greenwood et al. (2022) show how rapid credit and asset price growth predict financial crises.[4] We expand this literature by documenting how solvency hedging during in low-interest rate environments has "sowed the seeds" of future liquidity crises.

Lastly, we contribute to the liquidity and financial crisis literature. Brunnermeier (2009); Adrian et al. (2018); Bernanke (2018) document mechanisms, causes, and effects of the liquidity dry-ups during the Great Financial Crisis. More recent work analyzes the market liquidity shocks during the onset of the Covid-19 pandemic ("Dash for Cash") in the US (Haddad et al., 2021), the role of mutual funds liquidity transformation (Ma et al., 2022; Huang et al., 2021), and the role of holding dollar assets for UK investors (Czech et al., 2023). Pinter (2023) and Chen and Kemp (2023) dissect the market dynamics and responses during the UK LDI crisis of Autumn 2022. This paper sheds light on NBFIs' role in the run-up to and during the LDI crisis. More broadly, our paper is connected to the literature on the role of liquidity providers (Holmström and Tirole, 1998; Farhi and Tirole, 2012) with a more recent focus on monetary policy (Acharya and Rajan, 2023).

The paper is organized as follows. Section 2 advances the framework and the definition of LASH Risk. Section 3 describes the measurement of LASH Risk for sterling rate exposures of NBFIs. Section 4 presents the institutional background of NBFIs' hedging strategies and describes our data in more detail. Section 5 shows stylized facts on LASH Risk in the context

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[4] Adrian and Liang (2018) and Boyarchenko et al. (2022) provide comprehensive reviews of the research at the intersection of monetary policy and financial stability.

of sterling rates. Section 6 analyzes the causal effect of interest rates on our behavioral LASH Risk measure. Section 7 analyzes the consequences and the whiplash during the recent LDI crisis episode. Section 8 concludes.

2 LASH Risk: A Framework

This section provides an overview of our conceptual framework, which introduces "LASH Risk" — the liquidity risk following hedging against solvency risk. A detailed technical discussion is presented in Appendix A for those seeking further information.

Consider a financial institution with a portfolio characterized by short-duration assets and long-duration liabilities, as illustrated in Figure 2. This could represent a pension fund or insurer with liabilities to its members that will realise after much of the existing stock of bonds matures. An asset with a longer duration will experience a greater decline in its value when interest rates increase and, similarly, a more significant increase when interest rates fall.[5] Conversely, the value of an asset with a shorter duration is less susceptible to changes in interest rates. Hence, when interest rates fall, the value of the institution's liabilities increases more than its assets due to this duration mismatch, as illustrated in 2.b, and solvency worsens. In contrast, in scenarios where interest rates undergo an increase, there is a consequential depreciation in the value of the institution's longer-term liabilities, which is greater than the depreciation of its short-duration assets, as depicted in 2.c, and solvency improves.

How can financial institutions hedge duration mismatches and interest rate risk? Consider the same financial institution with a portfolio of short-duration assets. One option is to contract in financial hedging instruments such as an interest rate swap where the institution pays a floating rate in exchange for a fixed rate (as in Figure 3). Such a contract will appreciate in value when rates fall. Hence, the swap contract can be used to offset the changes in the relative value of the institution's liabilities when rates change. The derivative acts as a hedge, neutralizing part of the risk to the institution's solvency (Figure 3.b). However, such a strategy generates an exposure to liquidity risk. Derivative contracts such as swaps are constantly revalued. The contract requires the frequent transfer of liquid assets or cash between counterparties to keep the contract net present value at zero based on prevailing market prices (a practice known as variation margining). Hence, when interest rates increase,

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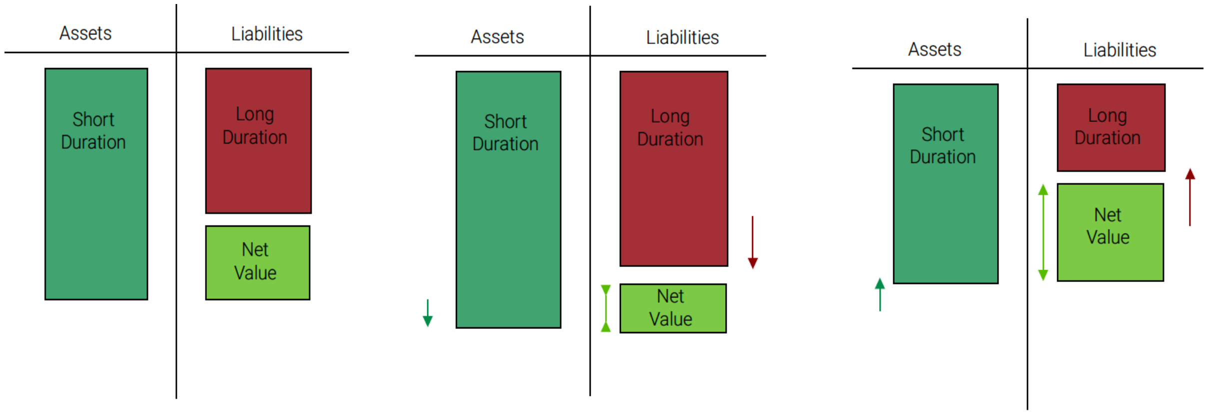
[5] The present value of an instrument relates to the interest rate the investment may earn. For example, the simplest form of discounting an asset value is using the risk-free rate - as interest rates increase, the expected future payments of the asset are worth less from today's perspective.

Figure 2 Non-Bank Financial Intermediaries and Interest Rates



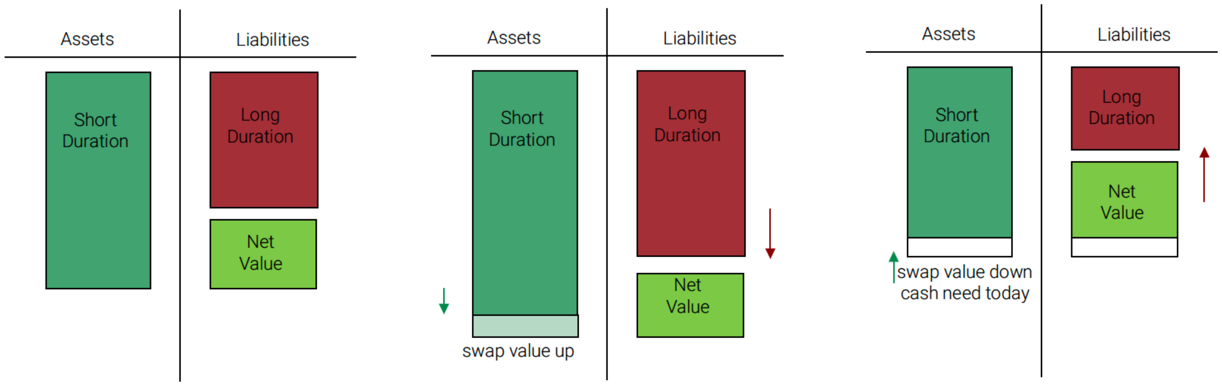
a. Fund with long-term liabilities vs assets

b. Rate fall worsens solvency

c. Rate rise improves solvency

the institution may become more solvent, but there is simultaneously a decline in the value of the hedging derivative contract. Consequently, the institution must make payments today to its derivatives counterparty (Figure 3.c). In such a case, the hedging strategy generates an immediate demand for liquidity even if the underlying improvement in the institutions' solvency position has yet to be realized (Froot et al., 1993).

Figure 3 Non-Bank Financial Intermediaries and Hedging



a. Buy a Swap

b. Pays out when rates fall + eliminates solvency risk

c. Liquidity needs when rates rise

The financial institution does not need to rely solely on financial derivatives to hedge. It could also manage interest rate risk by using leverage and shortening the duration of its liabilities by borrowing short-term. Specifically, the institution could use a repurchase agreement (repo), as illustrated in Figure 4.a, to hedge against interest rate risk. A repo is a form of short-term borrowing where the borrower sells a financial security to a lender with the contractual agreement to buy it back at a later date at a specified price. This strategy allows the institution to borrow short-term while using the funds to invest in longer-term assets. Borrowing short-term to lend long-term effectively replicates an interest rate swap as the institution pays a short-term rate on its borrowing and receives the fixed, long-term rate on the assets it purchases. However, repurchase agreements are also subject to margin requirements. A fall in the value of the underlying collateral needed to secure the borrowing either requires further assets (or cash) to be pledged or the borrowing to be repaid. Again, interest rates rise, and the subsequent fall in asset valuations generates, therefore, immediate liquidity needs.

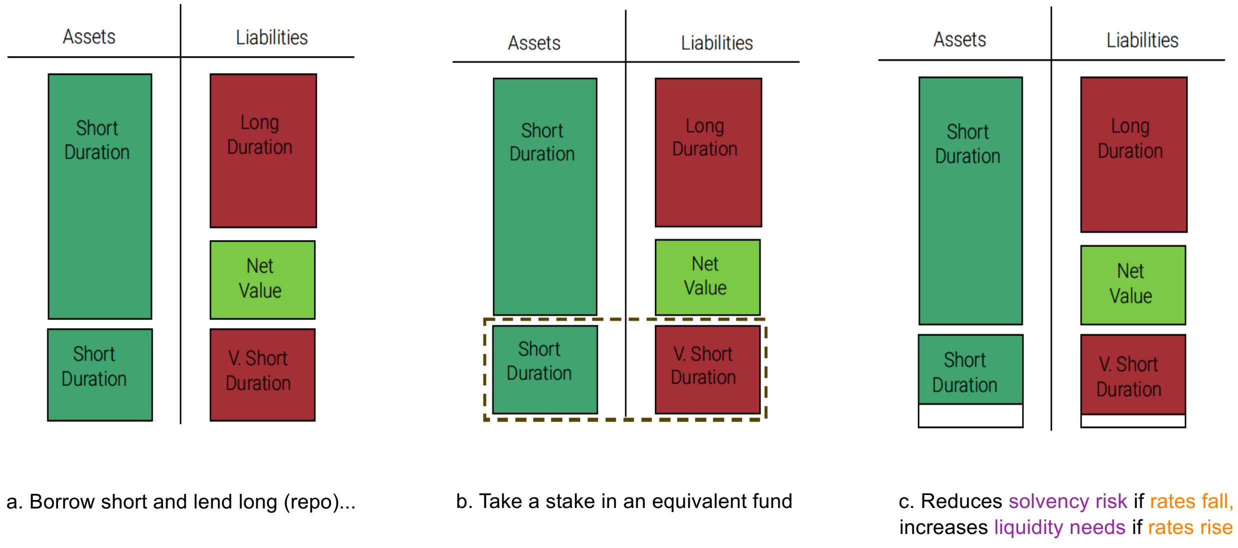
The financial institution does not even have to engage in the borrowing itself. It could instead take an equity stake in an fund that uses the equivalent repo contracts to leverage up and buy longer-dates assets, as shown in Figure 4.b. Payoff from the stake in the fund replicates the hedging strategy. Still, lower interest rates reduce the solvency risk for the institution, while liquidity needs increase with higher interest rates.

In the case of minor market fluctuations, this adjustment in liquidity needs is unlikely to cause significant operational disturbances. Financial institutions typically maintain liquidity buffers, enabling them to liquidate small portions of their portfolio without precipitating a fire sale. However, substantial market shocks or policy changes that trigger significant asset price movements can potentially disrupt financial stability. This leads to a semiparadoxical situation when it is the asset price movements that, in the absence of hedging, are associated with large gains in solvency that generate liquidity crises.

Interest rate risk is one application, a sizeable one, but generalizable, as mentioned, to other financial instruments and hedging strategies. An institution that has an FX mismatch on its balance sheet can use of FX derivatives (e.g., swaps or forwards) to hedge movements in exchange rates. Again this reduces solvency risk, but at the expense of increasing liquidity risks as these derivatives are also margined. Large swings in exchange rates can then lead to costly fire sales (e.g., "dash for cash" in Spring 2020, see Czech et al. 2023) which share the same features.

For NBFIs engaged in liquidity transformation and risk-taking, as depicted in the prior examples, striving for solvency can paradoxically precipitate a 'reach for illiquidity' during prolonged periods of low-interest rates. Pursuing protective measures (safe assets and/or financial instruments) to hedge ex-ante insolvency unintentionally alters their risk profiles. We show that LASH Risk, a sizeable type of liquidity risk, arises from NBFIs hedging

Figure 4 Non-Bank Financial Intermediaries: Additional Examples



a. Borrow short and lend long (repo)...

b. Take a stake in an equivalent fund

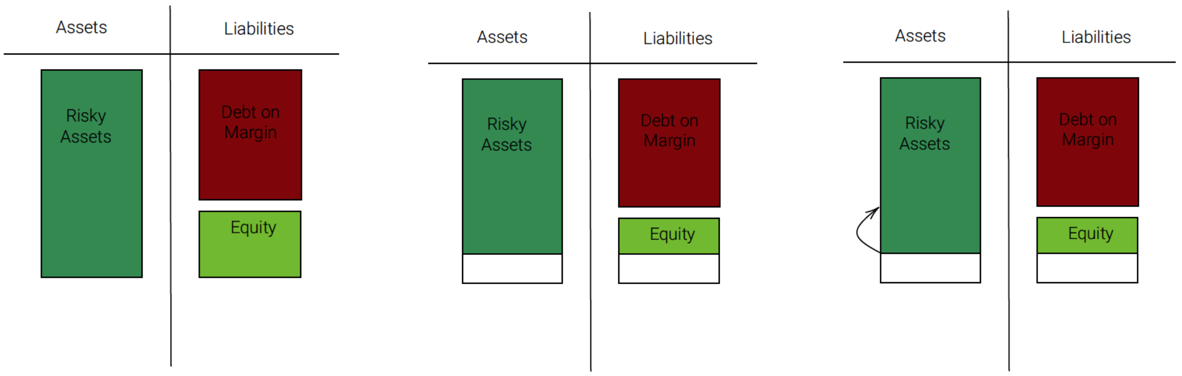
c. Reduces solvency risk if rates fall, increases liquidity needs if rates rise

solvency risk, with important and predictive effects during crises.

The discussion — and the link between risk in financial institutions and crises — reveals distinct mechanisms. LASH Risk differs from the traditional maturity transformation and run-risk (Diamond and Dybvig, 1983). In this case, the risk of a bank run is linked to the mismatch between financial intermediaries' engagement in long-duration projects and the provision for savers to withdraw funds on demand. This creates a mismatch where intermediaries are engaged in long-term assets through their investments, yet they are accountable for meeting short-term liabilities to their savers. However, our model focuses on risks not associated with callable or short-term debt liabilities and considers institutions with longer-term liabilities actively trying to hedge solvency risk. Our model stands apart from those studies that feature multiple equilibria and self-fulfilling crises, such as (Calvo, 1988), where a cycle of high-interest rates that increases the likelihood of default, which then perpetuates higher interest rates, is observed. Our mechanism differs from scenarios where rollover risks are spawned by 'sunspots' that exacerbate underlying bad fundamentals (Cole and Kehoe, 2000). Furthermore, our mechanisms are separate from rollover crises stemming from creditors' coordination failures (Morris and Shin, 2004).

In doing so, we introduce a nuanced perspective, distinct from the framework proposed by Brunnermeier and Pedersen (2009), which stresses the feedback between funding and market liquidity. In particular, their model delineates the interplay between an asset's market liquidity and a trader's funding liquidity, with traders' provision of market liquidity contingent on their funding conditions. The authors elaborate on the dependency of traders' funding requirements — such as capital and margin calls — on the liquidity of assets in the market. In their analysis, margin requirements can, under specific circumstances, contribute to financial instability, and a symbiotic reinforcement exists between market liquidity and funding liquidity that can incite liquidity spirals. To further illustrate the difference, consider a fund that has entered a leveraged bet on a risky asset with a margin requirement as in Figure 5. A shock leads to an initial loss, which wipes out some of the bank assets/net worth, which leads to margin calls (Figure 5.b). The financial institution sells assets to meet margin calls, which pushes down asset prices, further raising margin requirements and causing further asset sales (Figure 5.c), leading to a "liquidity spiral" as explained by the authors (see Figure 2 in their paper). A fundamental difference is that in our case, there are no losses; instead, as explained, solvency improves.

Figure 5 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.

3 Measurement: LASH Risk for Non-Banks and Sterling Rates

3.1 Measurement: General Concept

In its most general form, LASH Risk measures the liquidity needs derived from the sensitivity of the net present value of a financial hedging contract with respect to changes in the hedged instrument — for example, FX, inflation, or interest rates. Contracts of longer maturity will have a higher sensitivity to changes in the underlying rates, leading to a higher weight in LASH, as long as the contract implies positive liquidity demands. LASH Risk from interest rate sensitivity for contract i at time t reads:

$$LASH_{i,t} \approx \Lambda \times \frac{\partial NPV_{i,t}}{\partial R_t} \tag{1}$$

where $NPV_{i,t}$ is the net present value of the hedging strategy, and R_t is the interest rate related to the underlying contract. One can interpret $\frac{\partial NPV_{i,t}}{\partial R_t}$ as the effect of an upward shift in the yield curve. Λ captures liquidity needs per unit of NPV change, which may differ based on the contract type. We assume Λ to be a constant $\left(\frac{\partial \Lambda}{\partial R_t} = 0\right)$, and hence we abstract from second-order effects from R to liquidity needs, which may for instance arise from margin spirals or an increase in repo haircuts.

Aggregate LASH Risk in the system across all contracts is defined as:

$$LASH^A_{i,t} = \sum_i Q_{i,t} \text{LASH}_{i,t} \tag{2}$$

where $Q_{i,t}$ captures the total quantity of contract i, e.g. notional or borrowing size. The equation can be re-written in a way that accounts for investor-level j hedging portfolios as:

$$LASH^A_{i,j,t} = \sum_j \sum_i Q_{i,j,t} \text{LASH}_{i,j,t}. \tag{3}$$

3.2 Measurement: Across Markets

Next, we apply equation (1) to repos and interest rate swaps.

Repos

Repos are short-dated contracts where a counterparty borrows cash against (typically high-quality) collateral. The majority of repo transactions are overnight, but pension funds and other liability-driven hedgers predominantly use term repos with a maturity of one month or more. LASH Risk arises via price changes of the underlying collateral and the associated discounted value of the expected cash flows. As collateral value decreases, a counterparty would need to pledge more collateral (or cash) to be able to borrow the same amount of cash, everything else equal. In repo, similar to variation margining in derivative contracts, margins are typically calculated to eliminate the net exposure outstanding between two parties.

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. 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:

$$LASH_{i,t}^{Repo} = \frac{Q_{i,t}}{100} \times \frac{\sum_{k=1}^{c \cdot m} (1 + R_{k,t})^{-k} \cdot (T_k - t)}{P_{b,t}} \times \left(1 + \frac{YTM_{b,t}}{c_b \cdot m_{b,t}}\right)^{-1} \tag{4}$$

where $P_{b,t}$ is the market price of bond b, $T_k - t$ is the time to each cash flow k from time t perspective, 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 $\Lambda = 1$.

Interest Rate Swaps

A fixed-to-floating interest rate swap is a (long-dated) derivative contract where two counterparties agree to exchange a fixed cash flow with a variable one, e.g., LIBOR, SOFR, SONIA, c times a year, for a duration of m years. The interest rate exchange between the fixed and floating leg is based on a notional size Q, but the notional is never swapped. A swap also requires a pledge of usually highly liquid collateral in the form of initial and variation margin.

LASH Risk arises in swaps via the cash flow sensitivity to changes in interest rates. In practice, this risk materialises in the form of variation margin requirements, which are daily (cash) margin calls that reflect the mark-to-market price of the contract. For example, from the perspective of an investor who receives the fixed rate and has to pay the floating one, the value of the swap decreases as interest rates increase. The other counterparty will then demand a margin payment to bring the swap back to a net zero value.[6]

We use a swap's variation margin demands to approximate LASH Risk, and we employ the methodology by Bardoscia et al. (2021) to calculate these demands. LASH Risk from a 100bps increase in interest rates for contract i with maturity m based on notional Q and with c cash flow swaps a year reads:

$$LASH_{i,t}^{IRS} = \frac{Q_{i,t}}{100} \times \sum_{k=1}^{c \cdot m} e^{-R_{k,t} \cdot (T_k - t)} \tag{5}$$

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[6] 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 non-cash collateral.

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 $T_k - t$ evaluated from time t perspective. 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 $\Lambda = 1$.

3.3 Measurement: Mechanical versus Behavioral LASH Risk

We now introduce a simple decomposition of aggregate LASH Risk into two separate parts, which we term its "behavioral" and "mechanical" components.

Consider aggregate LASH Risk as $\text{LASH}_t^A = \sum_i Q_{i,t}\text{LASH}_{i,t}$. That is, aggregate LASH Risk sums across the LASH Risk of individual contracts. Therefore LASH Risk can comove with interest rates for two reasons. First, there are behavioral factors: the financial system might reallocate funds $Q_{i,t}$ towards contracts i with higher LASH Risk. Second, there are mechanical factors: as interest rates fall, the LASH Risk of any given contract will rise. The reason is convexity. As interest rates fall, the duration of any given contract increases. With greater duration, the value of contracts and the associated liquidity needs become more sensitive to interest rate changes, i.e., greater LASH Risk, as described in Appendix A.

We can separate the behavioral and mechanical components via a standard first-order decomposition. In particular, we can write the change in aggregate LASH Risk as:

$$\overbrace{\Delta \sum_i Q_{it}\text{LASH}_{it}}^{\text{aggregate change}} = \underbrace{\sum_i Q_{it}\Delta\text{LASH}_{it}}_{\text{mechanical change}} + \overbrace{\sum_i \text{LASH}_{i,t-1}\Delta Q_{it}}^{\text{behavioural change}} \tag{6}$$

The terms on the right-hand side are the mechanical and the behavioral components, respectively. In particular, the behavioral 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.

The equivalent measure expressed at institution level j is:

$$\overbrace{\Delta \sum_j \sum_i Q_{ijt}\text{LASH}_{ijt}}^{\text{aggregate change}} = \underbrace{\sum_j \sum_i Q_{ijt}\Delta\text{LASH}_{ijt}}_{\text{mechanical change}} + \overbrace{\sum_j \sum_i \text{LASH}_{ij,t-1}\Delta Q_{ijt}}^{\text{behavioural change}} \tag{7}$$

Both the mechanical and the behavioral components of LASH Risk are important. However, the behavioral component is of special interest. The response of the behavioral component to interest rate changes will measure the so-called "reach for illiquidity" behavior, that is, whether firms reallocate towards hedging strategies with greater LASH Risk in a low-rate environment.

4 Institutional Background and Data Sources

4.1 NBFIs and their Hedging Behavior

Derivatives and repurchase agreements have become increasingly important in recent years for hedging and funding purposes. Firms can hedge their balance sheet mismatch, and in particular their duration gap, using instruments such as repos and interest rate swaps.

Among NBFIs, pension funds and insurance companies traditionally have the largest duration gap between their assets and liabilities. Their liabilities consist of long term payment promises to pensioneers or contingent insurance beneficiaries. To reach the desired returns, these NBFIs will invest in shorter term and riskier assets, examples including stocks, government and corporate bonds, or real estate.

Defined benefit pension funds promise a guaranteed return to their beneficiaries upon retirement, while defined contribution funds have variable returns. By construction, defined benefit funds have higher hedging needs, as they need to meet a certain guaranteed return. 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.[7]

Hedging strategies are not always the same—even for similar balance sheet structures—and depend not only on the duration gap and the pension fund type, but also on the way future liabilities are discounted. 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 calculation, and US pension funds take a more bespoke approach and use a so-called asset-led discounting approach. 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.

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

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 clients.

The UK had over 5,300 defined benefit pension schemes in 2022, making it a very fragmented market.[8] 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, emphasizing the frequent use of repo leverage in this market segment.

Other NBFIs include insurance companies, hedge funds, and money market funds, amongst others. Insurance companies traditionally have a smaller duration gap than pension funds and tend to exhibit lower interest rate hedging positions compared to the PFLDI sector.[9] Hedge funds and money market funds have a very small duration gap, and are hence unlikely to build up substantial exposures to hedge solvency risks (in the context of interest rate risk).

Hedging Sensitivities to Interest Rates and Liquidity Needs

Long-tenor swaps and repos with long-maturity collateral are particularly sensitive to interest rate changes via the discounting of future cash flows. Hence, following a rate rise, investors face the largest liquidity needs for these types of contracts (if they are net borrowers in the repo market and receivers of the fixed leg in a swap contract). We therefore expect pension funds, LDIs and insurers to face the largest liquidity needs given their long-dated repo collateral portfolio and their long-tenor swap contracts. By contrast, all other NBFIs, even though they can be large players in gross terms (such as hedge funds), have relatively small net exposures when accounting for maturity (Khetan et al., 2023), and therefore low expected liquidity needs when rates rise sharply.

As described in the previous section, when interest rates increase, long-duration liabili-

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[8] See Pension Regulator Annual report.

[9] For instance, in the UK, insurance companies are regulated by the Prudential Regulation Authority. We note that UK insurers use almost exclusively interest rate swaps (and not repos) to hedge their interest rate risk.

ties decrease in value by more than short-duration assets. The solvency of a pension fund is measured via its funding ratio, which is defined as the fraction of assets to the value of discounted liabilities. The ratio is lower in low-interest rate environments and will mechanically improve as interest rates rise. This effect is evident in the UK, as average funding ratios increased from approx. 90% in 2017 to more than 130% at the beginning of 2023 — see the left panel of Figure 10.

At the same time, when interest rates rise, swaps and repos become more expensive as funding costs increase. The combination of improved funding ratios and costly hedging during periods of higher rates should lead to a decrease in hedging and hence also to an implicit decrease in liquidity needs in crises. By contrast, low interest rate environments should be associated with substantial hedging, and the build-up of high liquidity risks.

4.2 Data Sources and Coverage

To test our theoretical framework and apply it to the interest rate hedging exposures of UK NBFIs, we construct a database consisting of: i) the universe of UK gilt transactions; ii) the universe of pound sterling repo transactions based on government gilts; and iii) the universe of pound sterling interest rate swap positions.

The overall data coverage varies among datasets: gilt market transaction from January 2018 to March 2023; daily repo flows and stocks between January 2017 to March 2023; and weekly outstanding IRS positions between January 2019 to October 2023.

Bond Market (Gilts) To analyze trading in the gilt market, we use the transaction-level MiFID II database maintained by the UK's Financial Conduct Authority (FCA). The MiFID 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 gilt dealers are UK-domiciled and hence FCA-regulated institutions, our data cover virtually all transactions in the gilt market. Each transaction report contains information on the transaction date and time, ISIN, execution price, transaction size, and the legal identities of the buyer and seller.[10]

Secured Money Market (Repos) We use the Bank of England's Sterling Money Market data collection (SMMD). This transaction-level dataset covers 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

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[10] ISIN stands for International Securities Identification Number, and each bond issuance will have a unique ISIN.

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.

Financial Hedging Instruments (Swaps) To analyse the interest rate swap positions, we leverage transaction-level data from two 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 for the period between January 2019 and October 2023.[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, the paper retrieves daily OIS curves from the Bank of England FAME platform to construct the discount rates and LASH Risk for interest rate swaps, as well as daily modified duration measures for gilts from Bloomberg. We also use the yield curves from the publicly available Bank of England database.

5 LASH Risk from Interest Rates: Descriptive Facts

This section presents four descriptive stylized facts about our measure of LASH Risk, for NBFIs 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 behavioral 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 PFLDI sector.

Overall, these descriptive facts invite two questions. First, what are the drivers of LASH Risk—and do low interest rates induce investors to take on more LASH Risk? Second, can LASH Risk lead to financial market turmoil, such as distress in the PFLDI sector after the

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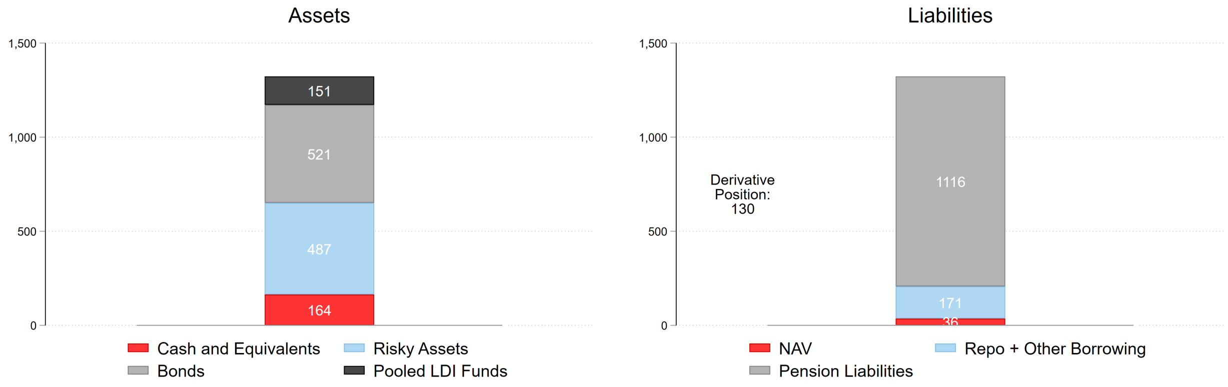
[11] We retrieve the data via the Bank of England's access to the mandatory reporting of the UK European Markets Infrastructure Regulation (UK EMIR). More details on the reporting obligation can be found here. For pre-2021 data (reported under EU EMIR), the Bank of England had access to (i) trades cleared 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.

Figure 6 UK Pension Funds: Aggregate Balance Sheet



announcement of the "Mini-Budget" in autumn 2022? We will tackle both questions in the sections to come.

As a precursor to the descriptive facts, and as a reminder of how LASH Risk works, we review the balance sheet of the UK pension fund sector. Figure 6 reports the liabilities (right panel) and assets (left panel) of UK pension funds.[12] There are two key features of the UK pension fund sector. First, there are relatively large and long duration pension liabilities. These liabilities create solvency risks because as interest rates fall, long duration liabilities significantly increase in value. Pension funds can hedge these solvency risks through swaps or repo contracts—both strategies are important, as the information on repo borrowing and other derivative positions in the right panel indicates. However, as we have discussed, these hedging strategies create liquidity needs when interest rates rise. The second key feature of the UK pension fund sector is its relatively small share of assets in cash or cash equivalents, as the left panel shows. Thus, when interest rates rise, the liquidity demands on pension funds may exceed the cash available on their balance sheets.

We now present our descriptive stylized facts.

i. *LASH Risk is large, and higher when interest rates are low.*

Figure 1 in the introduction demonstrates this fact. As aforementioned, the figure reports the aggregate LASH Risk in the NBFI sector from 2019 to 2023. LASH Risk is normalized by the cash holdings of UK pension funds and insurers. The units indicate that at the peak, a 100bps increase in interest rates would have induced liquidity needs that are greater than the cash positions of the entire sector—in other words, LASH Risk is very large. Moreover, LASH moves inversely with interest rates. When long-dated government bond yields are relatively low, as in 2020, LASH Risk is relatively high.

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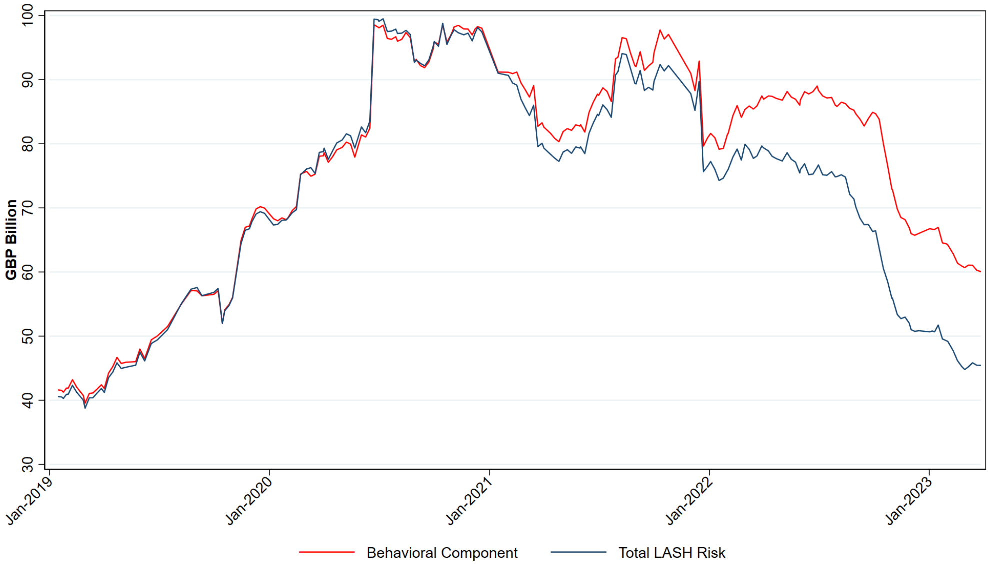
[12] Calculations based on 2023 ONS data.

ii. *Movements in LASH Risk are largely due to behavioral 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. In practice, behavioral effects dominate.

Figure 7 demonstrates this result—the total LASH Risk is shown in blue, and the behavioral component in red. The two co-move closely in the first three years of our sample. Therefore, movements in LASH Risk over time primarily reflect how institutions reallocate funding and hedging towards instruments with greater LASH Risk. The divergence in the last two years of the sample is due to mechanical effects—as interest rates rose over this period, the duration of hedging strategies fell. The first two findings indicate that LASH Risk is an important financial stability concern and may be related to the level of interest rates. In the following sections, we analyze this hypothesis in greater detail.

Figure 7 LASH RISK: BEHAVIORAL COMPONENT



NOTE. This figure shows the evolution of the total LASH Risk and the behavioral LASH Risk component in £bn for all NBFIs. The *Behavioral Component* is defined as $\sum_i \mathrm{LASH}_{i,t-1}\Delta Q_{i,t}$ for interest rate swaps and repos, respectively, as shown in equation 6 in Section 3.

The third and fourth descriptive facts are centered around the concentration of LASH Risk within the financial system.

iii. *LASH Risk is large for both interest rate swaps and repo contracts.*

These are the two primary funding and hedging strategies that we consider, both prevalent throughout the non-bank financial system. In practice, both strategies generate significant LASH Risk. Figure 8 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 £10-20bn higher than the LASH Risk from swaps. However, towards the end of our sample, the LASH Risk from swaps actually exceeds the one from repo as PFLDIs sought to de-lever in the aftermath of the LDI crisis.

Figure 8 BEHAVIORAL LASH RISK: SWAPS VS. REPO

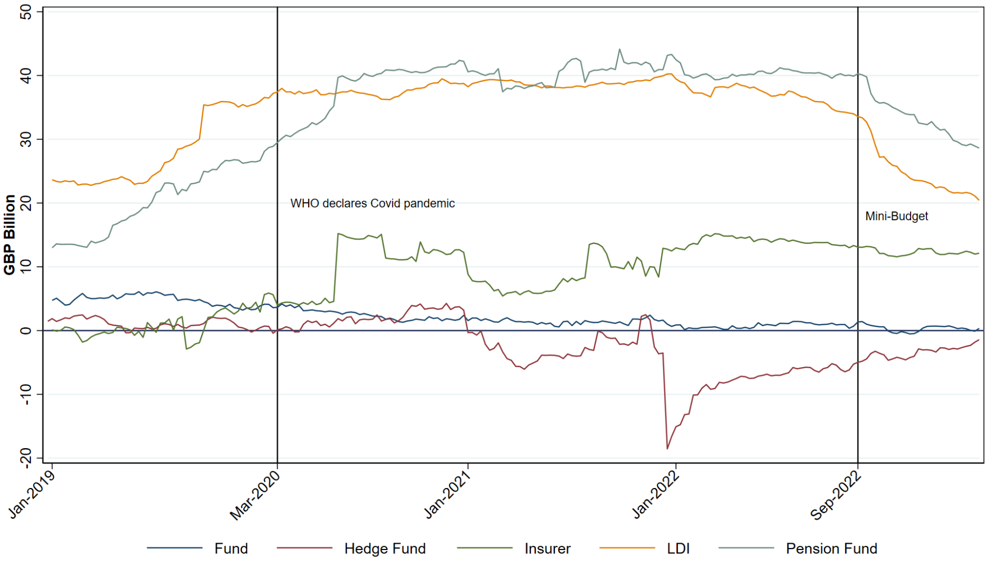
NOTE. This figure shows the evolution of the behavioral LASH Risk by instrument in £bn for all NBFIs. The *Behavioral Component* is defined as $\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}$ for interest rate swaps and repos, respectively, as shown in equation 6 in Section 3.

iv. *LASH Risk is concentrated in the pension fund sector.*

Figure 9 displays this result. In the figure, we disaggregate LASH Risk across five sectors, namely regular pension funds, LDI funds, insurers, funds, and hedge funds. Broadly defined, LDI funds belong to the pension fund sector. Thus, the overall pension fund sector is the primary holder of LASH Risk.

The third and fourth descriptive facts reinforce that LASH Risk is likely an important determinant of financial stability, particularly in the case of pension funds. To emphasize this point, the following sections will link LASH Risk to the episode of financial instability in the aftermath of the 2022 UK "Mini-Budget."

Figure 9 Behavioral LASH Risk: Sectoral Breakdown



NOTE. This figure shows the evolution of the behavioral LASH Risk across different sectors in £bn. The *Behavioral Component* is defined as $\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}$ for pension funds, insurers, LDI funds, hedge funds and funds, respectively, as shown in equation 6 in Section 3.

6 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 section argues that low interest rates are associated with high LASH Risk using a cross-sectional identification strategy.

The simple framework of Section 2 provides a mechanism through which low interest rates cause high LASH Risk. Suppose that on net, many NBFIs (especially PFLDIs) are short duration—i.e., the duration of the investor's liabilities is longer than the duration of its assets. Then, when interest rates fall, NBFIs' solvency deteriorates. Since their solvency risk has increased, investors should hedge more—so that LASH Risk rises.[13]

However, testing this mechanism is challenging. Other factors might explain the aggregate correlation between LASH Risk and interest rates. For instance, investors might increase hedging for other reasons, and in doing so increase their demand for long duration bonds—a form of reverse causality. Or, omitted variables could cause both LASH Risk and low interest rates—for instance a macro shock, such as a growth slowdown, could lower both

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[13] We formalize this argument in Appendix Section A, using a standard "reach for yield" model of the pension fund sector following Lian et al. (2019).

NBFIs' solvency and interest rates. These factors are hard to disentangle using time series data alone.

Therefore, to examine causality, we exploit cross-sectional variation from our rich regulatory data. Our identification strategy analyzes how the assets held at the beginning of the sample influence solvency afterwards. Specifically, investors holding relatively high duration assets experience lower capital losses as interest rates fall, relative to investors holding low duration assets. Therefore, as interest rates fall, solvency should deteriorate more for investors holding low duration assets. Since low duration investors face greater solvency risk, they require more hedging. As such, our simple framework predicts that low duration investors 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.

To implement our cross-sectional strategy, we assume that investors rebalance their portfolios each quarter, and hence estimate the following quarterly panel regression:

$$\Delta LASH_{j,t}^{Behavioral} = \alpha + \alpha_j + \beta_1 \Delta Yield_t + \beta_2 \left(AD_{j,t=0} \times \Delta Yield_t \right) + \varepsilon_{j,t}, \tag{8}$$

where $\Delta LASH_{j,t}^{Behavioral}$ measures the quarterly change in the behavioral LASH Risk of investor j at the end of quarter t. $AD_{j,t=0}$ is a snapshot of the modified duration of investor j's assets (as proxied by investor j's repo collateral portfolio) at the beginning of the sample, and $\Delta Yield_t$ is the quarterly change in the yield of the S&P U.K. Gilt Index or the quarterly change in the 10-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 duration variable is standardized. We include investor fixed effects, and cluster standard errors at the quarter and investor level. We also include time fixed effects in an alternative specification to control for all time-varying macroeconomic trends. These fixed effects therefore absorb both macroeconomic and investor characteristics and hence most of the aggregate variation.

Our framework predicts that β_1 is negative and that β_2 is positive. That is, as bond prices rise and interest rates fall, investors with low duration assets suffer disproportionately. Therefore, the LASH Risk of these investors increases more relative to investors with high duration assets.[14]

Our identification assumption is that investors with initial short asset duration would not have experienced capital losses relative to investors with initial long duration, for reason other than their initial asset holdings. Though this assumption is difficult to verify, it is certainly plausible. Investors hold long duration assets for many reasons that are orthogonal to the other determinants of solvency such as fund manager skill.

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 117% increase in the behavioral LASH Risk of investor j. Importantly, the coefficient of the interaction term reveals that this effect is reduced to a 19% increase (=-1.17+0.98) when the initial asset duration of investor j increases by one standard deviation. Therefore, when yields decrease, the LASH Risk of low-duration investors increases more compared to the one their high-duration counterparts. We obtain qualitatively similar results when including time fixed effects, or when using the 10-year gilt yield instead of the index.

Therefore, falling interest rates lead to an economically and statistically significantly greater LASH Risk taken by low duration investors—consistent with our mechanism. Therefore our cross-sectional identification strategy suggests that low interest rates are associated with high LASH Risk—reassuringly, using a different source of variation from the descriptive time series patterns of the previous section.

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[14] Technically, $AD_{j,0}$ measures gross asset duration, whereas net asset duration is what matters for solvency. In ongoing work, we correlate pension funds' net and gross asset durations using hand-collected balance sheet data.

Table 1 Rates and Investor-level LASH Risk

	(1)	(2)	(3)	(4)
	$\Delta LASH^{Behavioral}$			
$\Delta Yield^{Index}$	-1.17**			
	(0.51)			
$\Delta Yield^{Index}$ × Initial Duration	0.98**	0.99**		
	(0.44)	(0.45)		
$\Delta Yield^{10Y}$			-0.92**	
			(0.35)	
$\Delta Yield^{10Y}$ × Initial Duration			0.80***	0.80**
			(0.27)	(0.27)
Observations	10304	10304	10304	10304
R squared	0.030	0.033	0.030	0.034
Time FE	no	yes	no	yes
Investor FE	yes	yes	yes	yes

Note. For each investor, we calculate the quarterly change in the behavioral LASH Risk. The independent variable is the quarterly change in the S&P U.K. Gilt Index or the 10-year gilt yield, interacted with the modified duration of investor 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 investor and quarter level are reported in parentheses. We include investor and quarter fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

7 Consequences: Backlash During Crises

7.1 LASH Risk and Investor Selling Pressure

Having established the pronounced build-up of LASH Risk in recent years, we now examine the link between NBFIs' pre-crisis liquidity risk exposures and their UK government bond trading activities, and the subsequent impact on yields during recent stress episodes. To do so, we examine the recent 2022 UK LDI crisis, when the yields of long-dated gilts spiked by more than 100bps (right panel of Figure 10).

On 23 September 2022, the then Chancellor, Kwasi Kwarteng, presented a "Mini-Budget" proposal to the UK Parliament. The abrupt change in the fiscal stance initiated a self-reinforcing spiral in government bond prices, which was amplified by the vulnerabilities — LASH Risk — in the pension fund and LDI sector (Figure 9). 30-year gilt yields rose by 130bps in a matter of days, as investors had to sell their holdings to obtain cash to meet

Figure 10 LDI Crisis: Pension Funds' Funding Ratios and Gilt Yields

NOTE. Left Panel: Aggregate funding ratio (defined as total assets divided by total liabilities) of UK pension in %. Source: Pension Protection Fund 7800 Data. Right Panel: Yields of UK government bonds (gilts) at different maturities in %.

margin calls on their term repo and IRS positions.[15] Importantly, these liquidity demands occurred against the backdrop of pension funds' improving funding ratios, as the present value of their liabilities decreased due to higher discount rates (i.e. gilt yields, see Figure 10). As the liquidity crisis intensified, the Bank of England was required to intervene 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 PFLDIs to adjust their portfolios by reducing their repo leverage (Hauser, 2023; Alexander et al., 2023). In total, PFLDIs sold nearly £30bn in the period between September 23 and October 14 (see Figure 11 and Pinter 2023).

Against this backdrop, we now analyze whether NBFIs' pre-crisis LASH exposures can predict their gilt selling activities during the market turmoil. Our hypothesis is that insti-

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[15] During the 2020 "Dash for Cash", in contrast to the LDI crisis, the principal shock was a rapid depreciation of pound sterling against the dollar, triggering large margin calls on investors' FX hedging positions (Czech et al., 2023).

Figure 11 LDI Crisis: PFLDIs' Gilt Trading Volumes

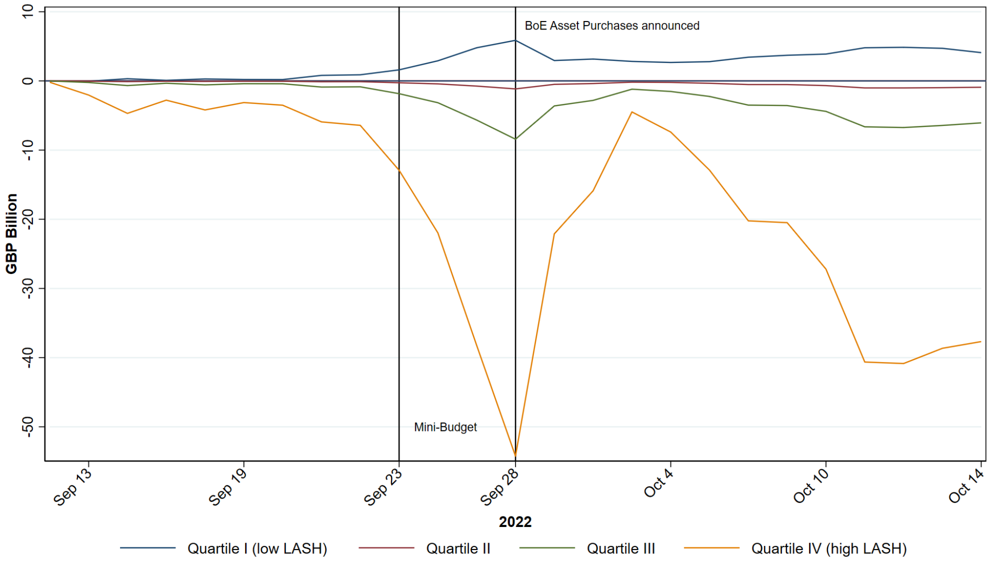
NOTE. Total net gilt trading volumes of UK NBFIs following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

tutions with larger pre-crisis LASH Risk, and hence a more pronounced risk of facing large liquidity demands (i.e. margin calls) during the crisis, sold relatively higher quantities of gilts than investors with low pre-crisis LASH exposures.

To analyze the link between LASH Risk and the liquidity demands and gilt trading during the LDI crisis, we first divide the NBFIs in our sample into four groups based on their pre-crisis LASH exposures, calculated from both their repo and IRS positions. We measure the investor-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.

At the peak of the crisis, as shown in Figure 12, the estimated cumulative change in the value of repo collateral—which can be interpreted as an upper bound for repo variation margin calls (in the absence of haircuts)—likely exceeded £50bn across NBFIs. Figure 12 also demonstrates how the group of NBFIs with particularly large pre-crisis LASH exposures (Quartile 4) was most severely affected by the sharp drop in the value of the posted repo collateral, with an estimated decrease of more than £50bn. Unsurprisingly, this group of NBFIs mainly consists of PFLDIs, who had large net exposures in term repo borrowing (see Figures B.3 & B.5). Consistent with this notion, we observe a similar pattern when plotting the same graph for PFLDIs only, as shown in Figure B.12 of the Appendix. Conversely, the group with the lowest LASH Risk was likely a net *receiver* of repo variation margin during the crisis, with an estimated increase in the value of their repo collateral of around £6bn before the BoE intervention on September 28. It is worth emphasizing at this point that the link between pre-crisis LASH exposures and liquidity needs (implied by the change in the value of repo collateral) is mechanical; and the striking difference between the low- and high LASH quartiles documented in Figure 12 confirms the initial premise of our LASH measure.

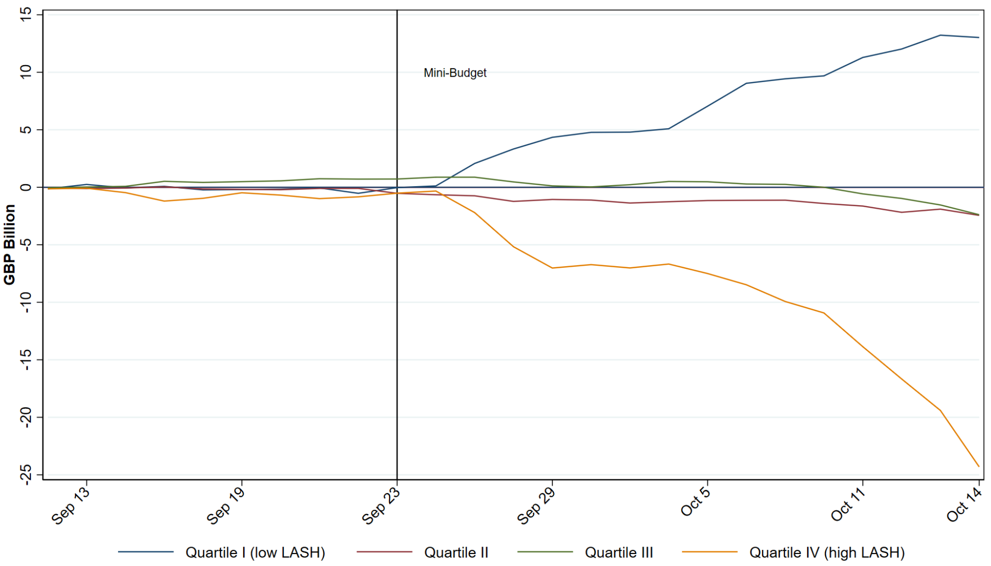
Figure 12 ESTIMATED CUMULATIVE CHANGE IN THE VALUE OF REPO COLLATERAL BY PRE-CRISIS LASH EXPOSURE



NOTE. Aggregate estimated changes in the value of repo collateral posted by UK non-bank financial intermediaries (NBFIs) in £bn during the 2022 LDI Crisis, by quartile of their pre-crisis LASH Risk: Quartile I captures the NBFIs 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.

Having documented the link between LASH Risk and liquidity demands, we now turn our attention to the impact of LASH Risk on investors' gilt trading behavior. As shown in Figure 13, the group of NBFIs with the highest pre-crisis LASH exposure (Quartile IV) sold substantially higher quantities of gilts compared to the other three groups. In total, this group sold almost £25bn worth of gilts during the crisis, while the group with the lowest LASH Risk (Quartile I) was in fact buying around £13bn worth of gilts. It is worth noting that before the crisis, the net volumes are very similar for all four groups, which mitigates concerns about any unobserved pre-crisis trends. We again observe a similar pattern when plotting the same graph for PFLDIs only: as shown in Figure B.11 of the Appendix, the net sales of the PFLDI 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 for any of the four groups.

Figure 13 Cumulative Gilt Trading Volumes by Pre-crisis LASH Exposure



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

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

$$Vol_{j,t} = \alpha + \alpha_{s,t} + \beta_1 LASH_{j,t=0} + \varepsilon_{j,t}, \tag{9}$$

where $Vol_{j,t}$ measures the net trading volume of institution j at time t, including all NBFIs 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 investors’ sell volumes, which capture whether investor j was a net seller on a given day. The net and sell volumes are transformed using the inverse hyperbolic sine transformation. Therefore, the regression coefficient β_1 again approximately measures the percent change in volumes when LASH Risk increases by one standard deviation, even if volumes are negative (see, e.g., Czech et al. 2023). We include sector-day fixed effects and use standard errors clustered on the day and sector level.

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	0.045	0.046
Sector-Day FE	yes	yes	yes	yes

Note. For each investor, as defined in equation 3 in Section 3, "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 investor's daily gilt net trading volume on day t in Columns (1) and (2), and the investor'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.

The results are shown in Table 2. Consistent with Figure 13, we find that investors with larger pre-crisis LASH exposures sold substantially higher quantities of gilts during the UK LDI 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 fund and LDI fund (PFLDI) sector in Table C.1 of the Appendix. Consistent with our baseline results, a one standard deviation increase in LASH Risk is associated with a 12% increase in PFLDIs' daily sell volumes.

An important feature of the LDI crisis was the pronounced selling by "pooled" LDI funds, in which multiple (often smaller) pension funds invest together — in contrast to segregated arrangements, where the assets of a single pension scheme are invested in a separate account.[16] The speed and scale of the moves in yields following the Mini-Budget announcement outpaced the ability of pooled funds' smaller clients — who typically rebalance their positions only on a weekly or monthly frequency — to provide new funds (Breeden, 2022). As a result, pooled funds became forced sellers and liquidated large quantities of gilts (see Figure B.10 in the Appendix). To test this more formally, we use the following specification:

$$Sell\ Vol_{j,t} = \alpha + \alpha_{s,t} + \beta_1 LASH_{j,0} + \beta_2 \left(LASH_{j,0} \times Type\ Fund_j\right) + \varepsilon_{j,t}, \tag{10}$$

where $Type\ Fund_j$ is an indicator variable for segregated and pooled LDI funds, respectively. The remaining variables are defined as in Equation (9). We again include sector-day fixed effects and use standard errors clustered on the day and sector level.

Table 3 LASH RISK AND POOLED LDI FUNDS

	(1)	(2)	(3)
		Sell Volume	
LASH	0.13***	0.14***	0.11***
	(0.03)	(0.02)	(0.02)
LASH × Segregated Fund	0.04		0.06*
	(0.05)		(0.03)
LASH × Pooled Fund		0.87***	0.90***
		(0.04)	(0.05)
Observations	8875	8875	8875
R squared	0.046	0.049	0.049
Sector-Day FE	yes	yes	yes

NOTE. For each investor, as defined in equation 3 in Section 3, "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 investor's daily sell volume on day t. "Segregated Fund" and "Pooled Fund" indicate segregated and pooled LDI funds, respectively. 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.

The results are presented in Table 3. We find that the effect is indeed substantially more pronounced for pooled LDI funds: a one standard deviation increase in LASH Risk is associated with 90% higher daily sell volumes for pooled LDI funds relative to other NBFIs.

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

Intriguingly, the coefficient for segregated LDI funds is only weakly significant, emphasizing that the coordination frictions in pooled LDI funds — in combination with elevated LASH Risk — was a particularly strong driver of gilt sales during the crisis.

7.2 Bond-level Liquidation Choices

An important question at this point is whether the selling pressure was concentrated in bonds with particular characteristics. As investors with pronounced LASH Risk exposures frequently invest in high-duration assets, our hypothesis is that the selling pressure increases with the duration of a bond. Furthermore, we hypothesize that the selling pressure is also more pronounced for gilts that are frequently used as repo collateral as well as for inflation-linked gilts. To test these hypotheses, we exploit the granularity of our data and run the following regression on the investor-bond-day level:

$$Sell\,Vol_{j,b,t} = \alpha + \alpha_{s,t} + \alpha_{b,t} + \beta_1 LASH_{j,0} + \beta_2 \left(LASH_{j,0} \times Bond\,Characteristics_b\right) + \varepsilon_{j,b,t} \tag{11}$$

where $Vol_{j,t}$ measures the net trading 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 gilt's usage as repo collateral (as measured by the total pre-crisis repo borrowing amount for each bond across all NBFIs), and iii) index-linked gilts. $LASH_{j,0}$ is defined as in equation (9). We include both sector-day and bond-day fixed effects and use standard errors clustered on the day, sector and maturity-bucket level.

The results are presented in Table 4. Consistent with our baseline results, we find that higher pre-crisis LASH Risk predicts heightened gilt selling pressure, even when controlling for sector-day and bond-day fixed effects. Importantly, confirming our hypotheses, we find that the effect is particularly pronounced for high-duration gilts and index-linked gilts. For example, a one standard deviation increase in LASH is associated with 8% higher daily sell volumes in index-linked gilts (relative to 5% higher sales in nominal bonds). Moreover, the effect is weakly statistically significant for gilts that are frequently used as repo collateral.

7.3 Impact of Selling Pressure on Yields

The previous analyses have shown that NBFIs with higher pre-crisis LASH Risk indeed sold significantly higher quantities of gilts during the LDI crisis, particularly in the case of longer-maturity gilts and gilts frequently used as repo collateral. An important question at this point is whether and by how much this selling pressure contributed to the yield spike during

Table 4 LASH Risk and Bond-level Liquidation Choices

	(1)	(2)	(3)	(4)
	Sell Volume			
LASH	0.06***	0.05***	0.05***	0.05***
	(0.01)	(0.01)	(0.00)	(0.01)
LASH × Frequent Collateral Use		0.02*		
		(0.01)		
LASH × Low Duration			0.01	
			(0.01)	
LASH × High Duration			0.01***	
			(0.00)	
LASH × Inflation-linked				0.03**
				(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 investor, as defined in equation 3 in Section 3, "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 investor'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 market turmoil in September and October 2022.

An obvious concern with this exercise is that NBFIs' selling of gilts may be driven by many factors, including private information. To isolate the impact of LASH Risk on NBFI trading and, in turn, on gilt yield movements, we follow Czech et al. (2023) and construct a measure of *LASH-induced trading (LASH-IT)*. Specifically, we calculate each investor's LASH-induced trading in bond b assuming that each investor proportionally scales up or down its holdings in response to liquidity demands. Due to the lack of complete information on bond holdings of individual pension funds, we approximate the weight of bond b in investor j's portfolio, $w_{j,b}$, by measuring the weight of the given bond in investor's j pre-crisis repo collateral portfolio. LASH-induced trading (LASH-IT) in bond b on day t is then defined as:

$$LASH\text{-}IT_b = \frac{\Sigma_j LASH_{j,t=0} \times w_{j,b,t=0}}{Amount\ Outstanding_{b,t=0}} \tag{12}$$

where $LASH_{j,t=0}$ is the estimated pre-crisis LASH exposure of NBFI j, and $w_{j,b}$ is the weight of bond b in investor'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 LDI crisis:

$$\Delta Yield_{b,t} = \alpha + \alpha_{m,t} + \alpha_{g,t} + \beta_1 \times LASH\text{-}IT_b + \varepsilon_{b,t} \tag{13}$$

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

Table 5 presents the results. The effect is statistically and economically highly significant. In most conservative specifications with maturity bucket-day and type gilt-day fixed effects (Column 4), a one standard deviation increase in LASH-IT is associated with a 4.2bps daily increase in gilt yields. Over the entire 16-day crisis period, this would attribute around 67bps of the yield spike to LASH-induced trading. For comparison, 30-year gilt yields spiked by 103bps over the same period — therefore, LASH-induced trading accounts for around two thirds of the yield spike during the LDI crisis.

Table 5 IMPACT OF LASH-IT ON GILT YIELDS

	(1)	(2)	(3)	(4)
	$\Delta Yield_{t-1,t}$			
LASH-IT	8.83*** (1.04)	8.88*** (1.13)	3.66*** (1.33)	4.22*** (1.32)
Observations	1253	1253	1253	1253
R squared	0.260	0.317	0.618	0.657
Day FE	yes	-	-	-
Type Gilt-Day FE	no	no	yes	yes
Maturity Bucket-Day 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 12. 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.

8 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", either from active forms of financial hedging or changes in the funding strategy and operational hedges. We document a rapid increase in liquidity risks from NBFIs' leveraged exposures linked to low-interest rate periods, which have "sowed the seeds" of future liquidity crises.

Paradoxically, purchasing protective measures (safe assets and/or financial instruments) to hedge ex-ante insolvency unintentionally creates liquidity risks further down the line. Therefore, this sizeable type of liquidity risk arises from investors — particularly NBFIs — hedging solvency risk, and can give rise to sizable pecuniary externalities during crises.

Financial markets have grown and deepened due to increased 'transactional' finance practices such as lending against collateral, requiring margins for derivative transactions, and the general rise in secured transactions (Borio et al., 2023; Duffie, 2022). These trends, which gained momentum following regulatory responses addressing counterparty and credit risks during the Global Financial Crisis (GFC), may have inadvertently heightened financial stability risks, mainly through increased liquidity risks.

As a point in case, during the recent UK LDI crisis, investors with more pronounced pre-crisis LASH exposures sold substantially higher quantities of gilts during the crisis. Furthermore, LASH-induced trading accounts for around two-thirds of the yield spike during the market turmoil in autumn 2022.

What are the implications of LASH Risk? 'Responsible' institutions trying to hedge solvency risks find themselves vulnerable to LASH Risk—i.e. akin to a transformation of risk in the financial system. While it seems that LASH Risk is not directly connected to moral hazard concerns associated with risky investments, it nonetheless leads to pecuniary externalities, which warrant further consideration. We leave the analysis of LASH Risk and its implications in other market segments (e.g. FX or inflation) for future research.

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Appendix

A A Model: Net Asset Values and Hedging Demand

This appendix presents a concise model that forms the basis of the conceptual framework discussed in Section 2, mainly focusing on 'LASH Risk' — the liquidity risk that arises from hedging against solvency risk. The model considers the interest rate risk management problem of a non-bank financial institution, which we refer to as a fund and is best thought of as a pension fund or an insurer.

This fund has a given perpetual liability that it needs to cover with a portfolio of assets. It can use interest rate derivatives, effectively a swap contract, alongside manipulating the duration of it is portfolio to manage interest rate risk. The model has four important ingredients that makes the analysis interesting and serve to highlight the mechanisms we have in mind:

1. **Asymmetric payoffs.** For the fund reducing a deficit by \$1 is more beneficial than increasing a surplus by \$1. Practically, this asymmetry in payoffs might represent a regulatory penalty (e.g. in the UK, for example, pension funds are explicitly taxed via a risk-based levy if they fall into deficit, see here.), but broadly, it could encompass various reputational or behavioural explanations (see Lian et al. 2019).
2. **Duration mismatch.** The perpetual liability cannot be hedged by a perpetual bond, the fund only has access to a financial assets of shorter duration. Swaps can be used to hedge (perfectly) but they generate the need for liquidity in the following period.
3. **Liquid assets are expensive.** The fund can self insure against liquidity needs by holding short duration assets but those assets require paying a convenience premium.
4. **Illiquidity of the long duration asset.** holding only long term assets generates liquidity costs in the case where the swap contract is out of the money and short term debt holdings are insufficient.

The net effect of the first ingredient is to introduce a kink in the objective of the fund. This generate effective risk aversion and that motivates the hedging of interest rate risk. The second ingredient guarantees that the fund will choose to the hedge interest rate risk partly through the use of derivatives. The third and fourth ingredients insure that liquidity needs generating by the hedge cannot be offset without a cost: either the fund must hold expensive liquid assets or run the risk of liquidating a long duration portfolio. Hence there is an interior solution where the fund holds a combination holding illiquid long duration assets, expensive liquid assets and engaging in a hedging strategy

This liquidity-solvency trade-off means that the fund is imperfectly hedged. Therefore, lower rates worsen the funds financial position. This pushes the fund closer to the kink in its objective function which in turn raises effective risk aversion. Higher risk aversion raises hedging demand and encourages the fund to take more liquidity risk.

A.1 Environment

We consider the investment problem of a non-bank financial institution ("the fund"). Time runs from $t = 0, 1, \ldots, \infty$. The fund has liabilities structured as a perpetuity that require paying a fixed l in every period. The pension fund can invest in (i) a one period bond, a_t, (ii) a geometrically decaying multiperiod bond, b_t, with decay rate δ: i.e. the bond has a coupon b_t in $t+1$ with passive equation of motion $b_{t+1} = \delta b_t$ and (iii) an interest rate swap s_t. The fund cannot go short: $a_t \geq 0$ and $b_t \geq 0$, but the swap position, s_t, can be positive or negative.

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}. We assume R_t^{-1} involves according to a first order Markov process, $F(R'|R)$. This discount factor is also used to value the fund's liabilities. For analytical results we will sometimes treat R_t^{-1} as i.i.d with mean $\bar{R}^{-1}$. The marginal investor values the liquidity service from one period bond at rate η. This is non-pecuniary. The fund does not share this service, instead the fund will receive an endogenous liquidity benefit to one period debt.

Asset prices Let q_t^b denote the price of the geometric bond, the investor values the bond at $q_t^b = \mathbb{E}_t \left[\sum_{j=0} \delta^j \prod_{s=0}^{j} R_{t+s}^{-1}\right]$,and in the i.i.d. case the price becomes $q_t^b = \left(1 - \delta \bar{R}^{-1}\right)^{-1} R_t^{-1}$. Let q_t^l denote the price of a perpetuity paying one every period. We have $q_t^l = \sum_{j=0}^{\infty} \prod_{s=0}^{j} \mathbb{E}_t \left[R_{t+s}^{-1}\right]$. From here it is clear that the perpetuity has longer duration than the geometric bond. In the i.i.d case, this price is $q_t^l = \left(1 - \bar{R}^{-1}\right)^{-1} R_t^{-1}$. Last the liquidity services implies that the price of the short term bond is given by $q_t^a = R_t^{-1} (1 + \eta)$.

Interest rate swaps are priced fairly and have a fixed leg $\mathbb{E}_t \left[R_{t+1}^{-1}\right]$ and floating leg R_{t+1}^{-1}: buying the swap means paying fixed and receiving floating. So the cashflows from the realised swap position are given by $s_t \left(R_{t+1}^{-1} - \mathbb{E}_t \left[R_{t+1}^{-1}\right]\right)$.

We assume that the geometric bond is costly to sell, liquidation cost: $q_t^b c$ per unit sold. The investor does not discount the value of the bond due to the liquidation costs.

Fund value We can define the net asset value of the fund as $w_t = q_t^a a_t + q_t^b b_t - q_t^l l$. Accounting for liquidity costs, w_t evolves according to

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

In addition, the no shorting constraint implies that the fund must have sufficient cash on hand from the payments it receives on its assets and bond liquidations to cover its swap position. That is

$$a_{t-1} + b_{t-1} - l + (1-c)q_t^b \max\left\{0, \delta b_{t-1} - b_t\right\} \geq s_{t-1}\left(\mathbb{E}_t\left[R_t^{-1}\right] - R_{t-1}^{-1}\right).$$

Fund manager's objective The fund manager is risk neutral, does not enjoy limited liability and receives period compensation (that is negligible compared to the value of the fund) proportional to

$$\pi_t = w_t + \kappa \mathbf{1}\left(w_t < 0\right) w_t,$$

where in line, with the above, $\kappa > 0$ is a penalty term that incentivises the manager to avoid deficits. For simplicity, we assume the fund manager discounts the future at rate a fixed rate β rather than R_t^{-1}. How the manager discounts plays a limited role in the model and so the assumption of a fixed rate is innocuous.

A.2 The fund manager's problem

Let $\mathcal{S}_t = \{R_t, R_{t-1}\}$ denote the state of the world at time t. The fund manager's problem can be expressed recursively as

$$\max_{a_t, b_t, s_t} V(a_{t-1}, b_{t-1}, s_{t-1}; \mathcal{S}_t) = \left(1 + \kappa \mathbf{1}\left[w_t < 0\right]\right) w_t + \beta \mathbb{E}\left(V(a_t, b_t, s_t; \mathcal{S}_{t+1})\right)$$

subject to

$$w_t + q_t^l l = a_{t-1} + \delta b_{t-1} - l + q_t^b (1-\delta) b_{t-1} + s_t\left(R_t^{-1} - \mathbb{E}_{t-1}\left[R_t^{-1}\right]\right) - c q_t^b \max\left\{0, (1-\delta) b_{t-1} - b_t\right\}.$$

Using the fact that the manager will only liquidate by necessity we have

$$(1-c) q_t^b \left((1-\delta) b_{t-1} - b_t\right) \geq \max\left\{s_t\left(\mathbb{E}_{t-1}\left[R_t^{-1}\right] - R_{t-1}^{-1}\right) - a_{t-1} - \delta b_{t-1} + l, 0\right\}.$$

When the left hand side of the model is positive, we have the model analogue to LASH risk materialising: the fund is forced to sell assets at a cost to cover losses on its hedges.

The flow budget constraint is therefore:

$$q_t^a a_t + q_t^b b_t = a_{t-1} + \delta b_{t-1} - l + q_t^b (1-\delta) b_{t-1} + s_{t-1}\left(R_t^{-1} - \mathbb{E}_{t-1}\left[R_t^{-1}\right]\right) - \frac{c}{1-c} \max\left\{s_{t-1}\left(\mathbb{E}_t\left[R_t^{-1}\right] - R_t^{-1}\right) - a_{t-1} - \delta b_{t-1} + l, 0\right.$$

A.3 Analysis

We start by illustrating the fund's exposure to interest rate risk, then discuss its optimal hedging strategy before discussing how the level of rates affect the demand for hedging.

The fund's exposure to interest rate risk (excluding hedging). Now imagine that the fund never hedges ($s_t = 0$) then

$$\frac{dw_t}{dR_t^{-1}} = b_{t-1}\frac{dq_t^b}{dR_t^{-1}} - l\frac{dq_t^l}{dR_t^{-1}}.$$

Assuming the discount factor is i.i.d. with unconditional mean $\bar{R}^{-1}$, then

$$\frac{dq_t^b}{dR_t^{-1}} = \frac{1}{1-\delta\bar{R}^{-1}}.$$

$$\frac{dq_t^l}{dR_t^{-1}} = \frac{1}{1-\bar{R}^{-1}} > \frac{dq_t^b}{dR_t^{-1}}.$$

So unless we have $w_t \gg 0$, we know $\frac{dw_t}{dR_t^{-1}} < 0$ (i.e. a fall in interest rates hurts the fund). The fund therefore should try to set $s_t > 0$.

Optimal hedging strategy. Consider the Fund's first order condition with respect to s_t is:

$$\beta\mathbb{E}_t\left[\frac{d}{ds_t}\left(1+\kappa\mathbf{1}\left[w_{t+1}<0\right]\right)w_{t+1}\right] = 0.$$

Define the following conditional expectations

$$\mathbb{E}_t\left[.\right] \equiv \mathbb{E}_t\left[.|w_{t+1}<0\right],$$

$$\mathbb{E}_t\left[.\right] = \mathbb{E}_t\left[.|s_t\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right]-R_{t+1}^{-1}\right)-a_t-\delta b_t+l>0\right],$$

$$\mathbb{E}_t^{\ominus}\left[.|s_t\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right]-R_{t+1}^{-1}\right)-a_t-\delta b_t+l, w_{t+1}<0\right].$$

These correspond to the expectations conditional on the Fund having a deficit, having to liquidate and having to do both. Define p_t, p_t and $p_t^{\ominus}$ the corresponding probabilities. By Leibnitz's rule, we can ignore the affect of decisions on probabilities at the margin.

Splitting along the dimension of whether the fund pays liquidity costs yields the following first order condition

$$\frac{\beta c p_t}{1-c}\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right]-\mathbb{E}_t\left[R_{t+1}^{-1}\right]\right)+p_t\beta\kappa\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right]-\mathbb{E}_t\left[R_{t+1}^{-1}\right]\right)+\frac{p_t^{\ominus}\beta\kappa c}{1-c}\left(\mathbb{E}_t^{\ominus}\left[R_{t+1}^{-1}\right]-\mathbb{E}_t\left[R_{t+1}^{-1}\right]\right)=0.$$

Now, note that absent liquidity costs, the fund would be perfectly hedged against interest rate risk and either set $p_t = 0$ or $\mathbb{E}_t\left[R_{t+1}^{-1}\right] = \mathbb{E}_t\left[R_{t+1}^{-1}\right]$. But assuming $p_t > 0$, this is not optimal as insuring all interest rate risk ignores the cost liquidity risk.

Since the Fund is imperfectly hedged, we know that $\frac{dw_t}{dR_t^{-1}} < 0$ and s_t. This means that

$$\left(\mathbb{E}_t\left[R_t^{-1}\right] - \mathbb{E}_t\left[R_t^{-1}\right]\right) > 0,$$

the states of the world where the fund is in deficit are ones where the discount factor is higher than expected (rates lower than expected). In contrast, the fund will have a liquidity deficit if

$$s_t\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right] - R_{t+1}^{-1}\right) - a_t - \delta b_t + l > 0.$$

So

$$\mathbb{E}_t\left[R_{t+1}^{-1}\right] - \mathbb{E}_t\left[R_{t+1}^{-1}\right] < 0,$$

the discount rate is low (interest rate high) when the fund faces a liquidity shortfall.

How about $p_t^{\ominus}$? This means that the fund faces a deficit and a liquidity shortfall at the same time. This is only possible if the fund's initial deficit (i.e. $w_t \ll 0$) is so big that even a positive interest rate surprise which causes a liquidity shortfall still has the fund in a deficit. So we still have

$$\mathbb{E}_t^{\ominus}\left[R_{t+1}^{-1}\right] - \mathbb{E}_t\left[R_{t+1}^{-1}\right] < 0.$$

However, for simplicity consider the case where $p_t^{\ominus} = 0$ (i.e. $w_t \approx 0$). Then the optimal hedging strategy sets

$$p_t \kappa \left(\mathbb{E}_t\left[R_{t+1}^{-1}\right] - \mathbb{E}_t\left[R_{t+1}^{-1}\right]\right) = p_t \frac{c}{1-c}\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right] - \mathbb{E}_t\left[R_{t+1}^{-1}\right]\right).$$

The fund trades off the fact that a swap transfers cashflows to states of the world where the fund is in deficit against the fact the swap transfers cashflows away from states of the world where the fund has a liquidity shortfall.

Low rates and LASH risk. Only a verbal reasoning for the moment. The unhedged cashflows generated by the fund are given by

$$a_{t-1} + \delta b_{t-1} - l,$$

these are independent of R_t, where as we have

$$w_t = q_t^a a_t + q_t^b b_t - q_t^l l,$$

which are linked to current and future interest rates.

It follows that p_t, the probability of a deficit, is more sensitive to rates than the current cashflows (over time the two will converge). Holding s_t fixed a fall in rates raises p_t, (via lower w_t) but it does not have much impact on p_t. Hence, the left hand side of the hedging optimality condition rises more than the right hand side in response to a fall in rates, assuming $p_t \to 1$ such that $\left(\mathbb{E}_t\left[R_{t+1}^{-1}\right] - \mathbb{E}_t\left[R_{t+1}^{-1}\right]\right) \to 0$. So a fall in rates raises hedging demand.

B Data: Additional Information & Summary Statistics

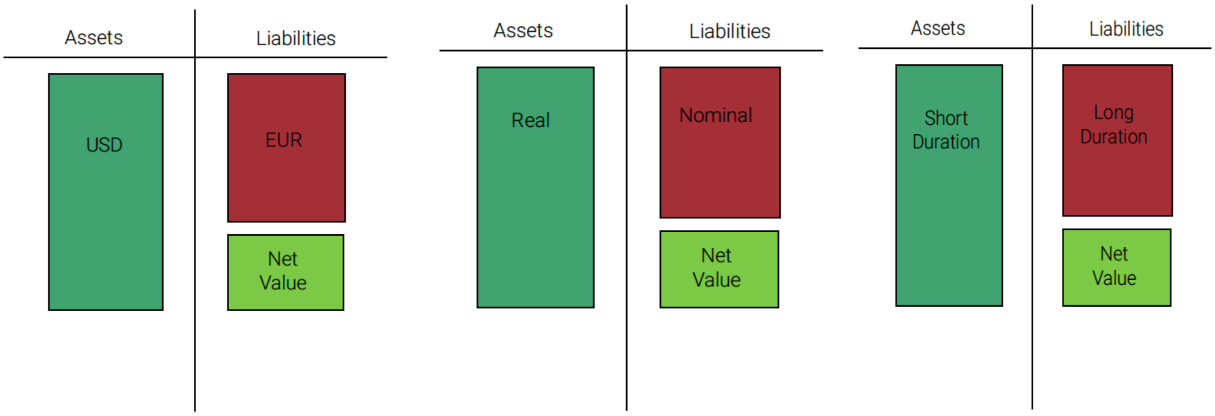
This section of the Appendix provides additional information and summary statistics for the various data sources used in the empirical analysis.

Table B.1 SUMMARY STATISTICS: AVERAGE NET POSITIONS AND LASH RISK

	Repo net borrowing					IRS net receive fixed					Repo behavioral LASH					IRS behavioral LASH				
Sector	2019	'20	'21	'22	'23	2019	'20	'21	'22	'23	2019	'20	'21	'22	'23	2019	'20	'21	'22	'23
Pension fund	38	64	74	69	48	66	98	103	133	113	8	15	18	16	11	11	21	23	23	20
LDI	99	121	130	113	73	17	37	40	38	23	22	28	30	26	17	4	9	9	9	5
Insurer	0	0	0	0	0	9	20	21	70	58	0	0	0	0	0	0	9	9	14	12
Hedge Fund	-7	11	-3	-34	-15	48	74	-38	-137	-71	0	1	-1	-3	-1	1	0	-3	-4	-3
Fund	9	7	7	4	4	20	15	2	5	5	2	1	1	1	1	3	1	0	0	0
Other financial	7	20	18	10	5	-8	-11	-3	-9	-14	2	4	3	2	1	-3	-3	-1	-1	-1

NOTE. Sample: Summary statistics on repo and IRS positions in the period from 2019 to 2023. 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.

Figure B.1 LASH RISK: ADDITIONAL EXAMPLES

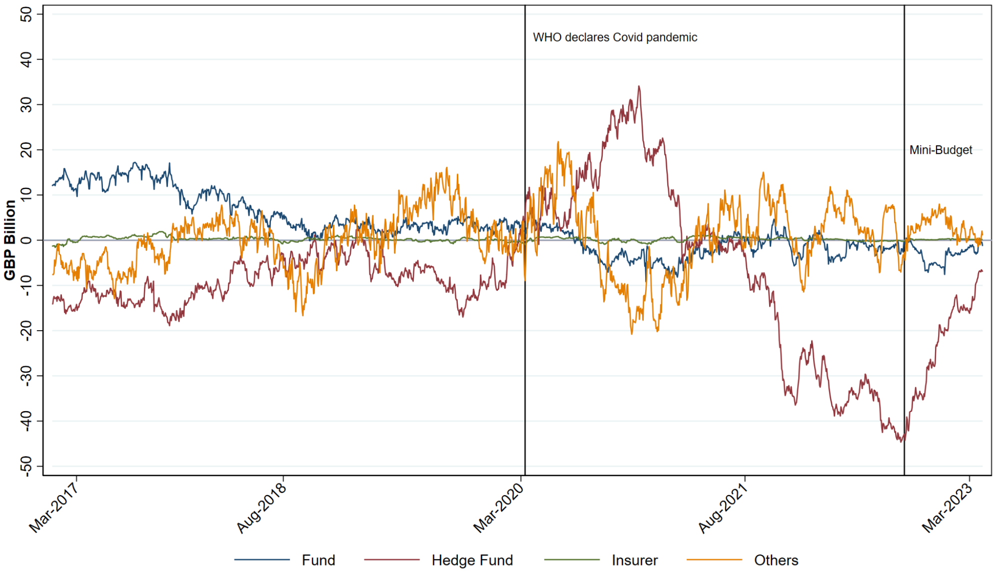


a. FX Swaps

b. Infrastructure fund with indexed-linked assets

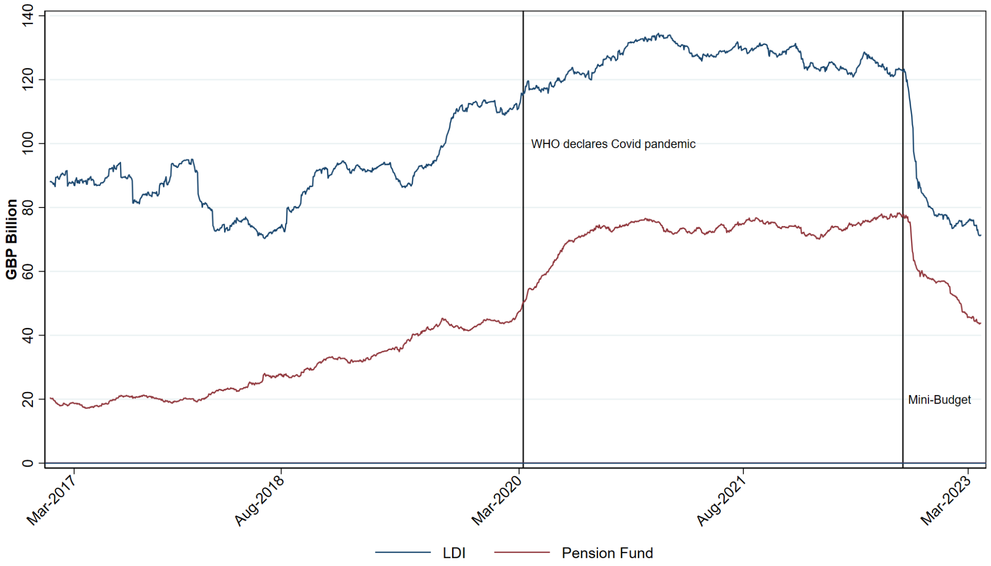
c. Reduce solvency risk but increase Liquidity Risk

Figure B.2 Repo Net Borrowing Stocks Across Sectors



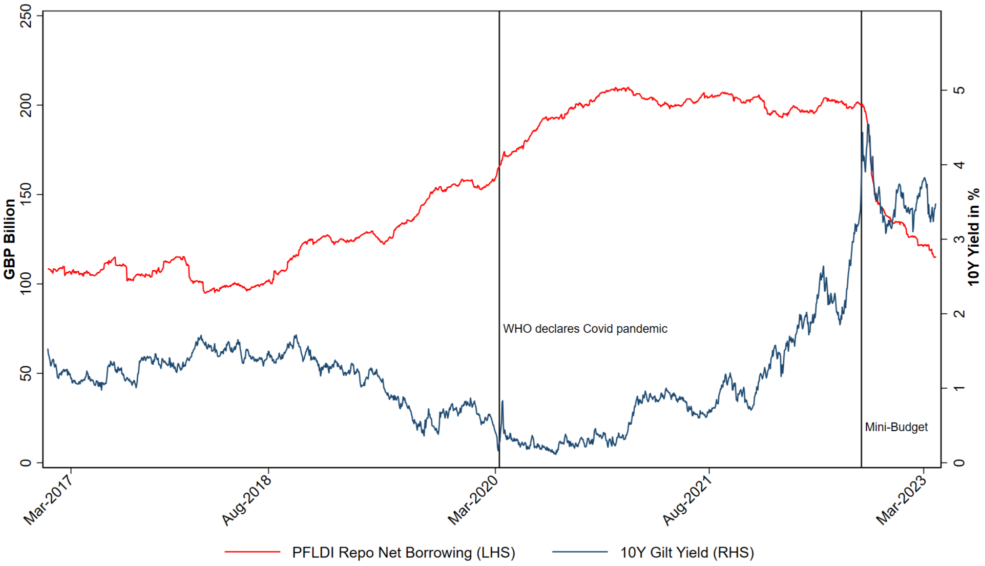
NOTE. Aggregate repo net borrowing across all sector types in £bn. "Others" include sovereign entities and other financials. Source: Sterling Money Market data collection.

Figure B.3 PFLDI Repo Net Borrowing Stocks by Sector



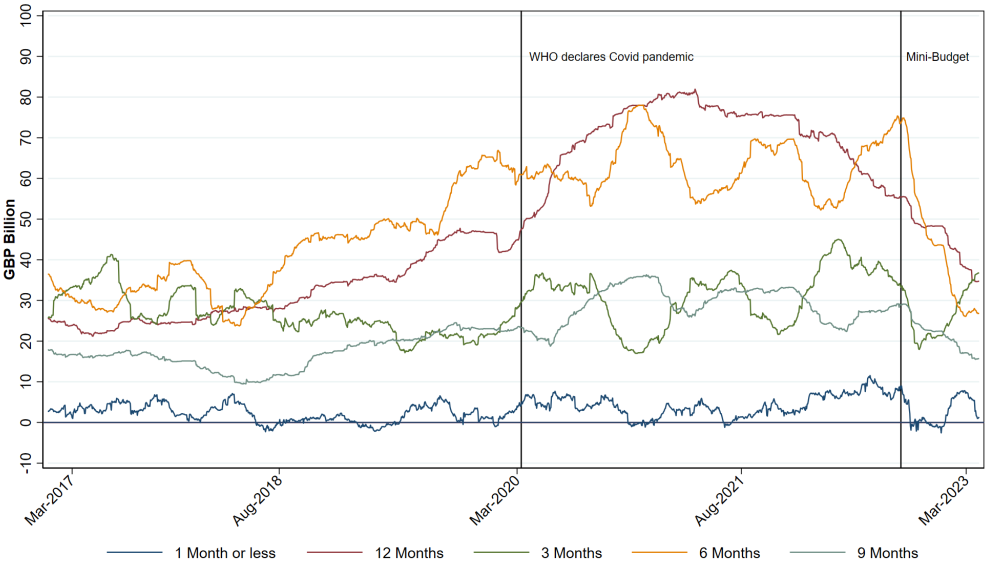
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds (PFLDIs) in £bn. Source: Sterling Money Market data collection.

Figure B.4 PFLDI REPO NET BORROWING STOCKS & 10Y GILT YIELDS



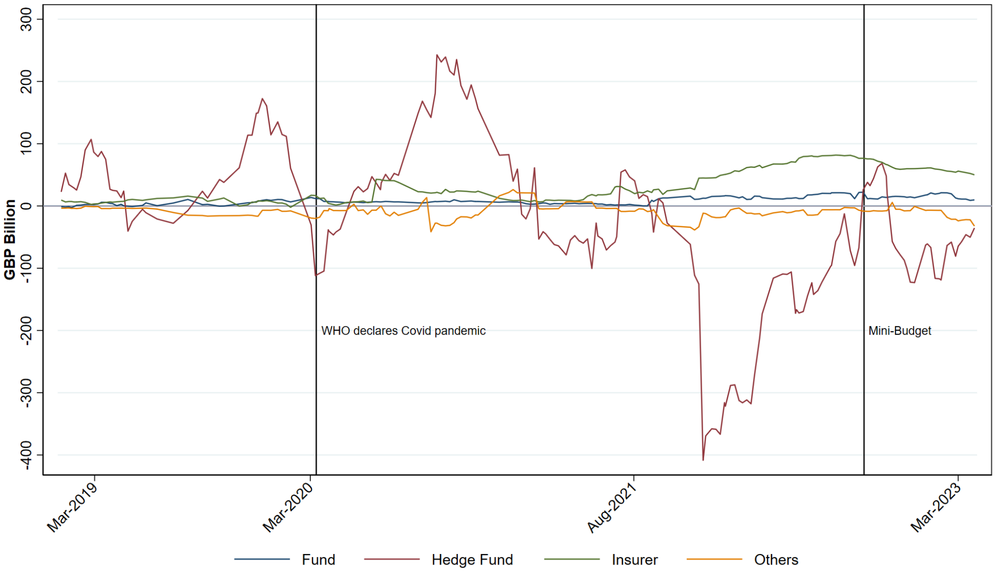
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds (PFLDIs) in £bn and 10Y gilt yields in %. Source: Sterling Money Market data collection & Bank of England.

Figure B.5 PFLDI REPO NET BORROWING STOCKS BY MATURITY



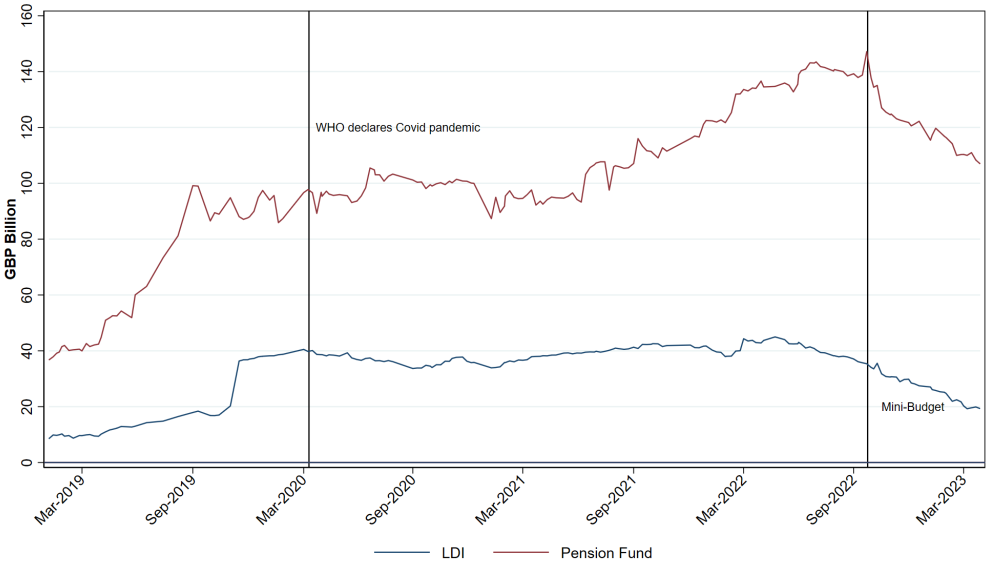
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds (PFLDIs) by the maturity bucket at initiation in £bn. Source: Sterling Money Market data collection.

Figure B.6 IRS NET NOTIONALS ACROSS SECTORS



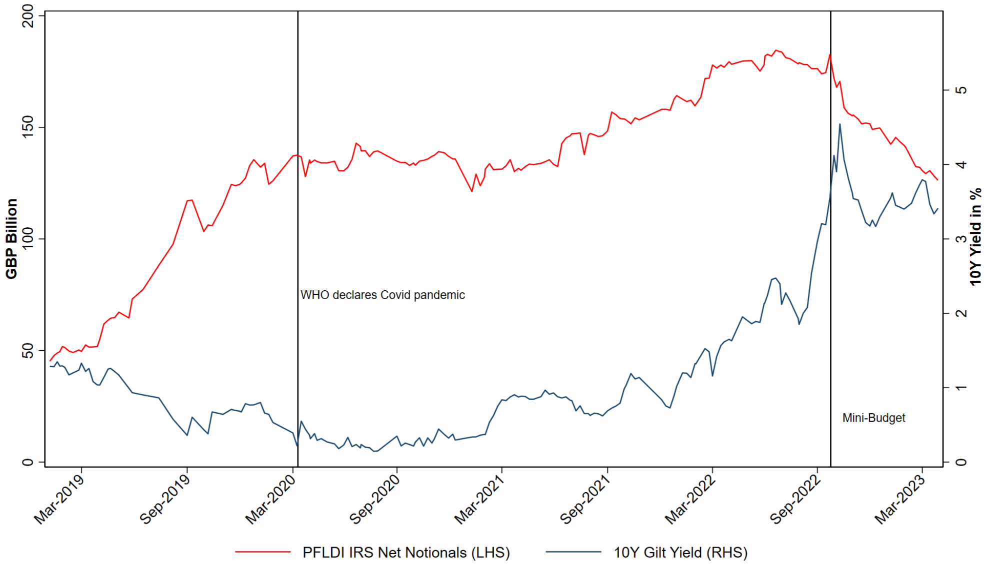
NOTE. Aggregate IRS net notionals across all sector types in £bn. "Others" include sovereign entities and other financials. Source: EMIR Trade Repository Data.

Figure B.7 PFLDI IRS NET NOTIONALS BY SECTOR



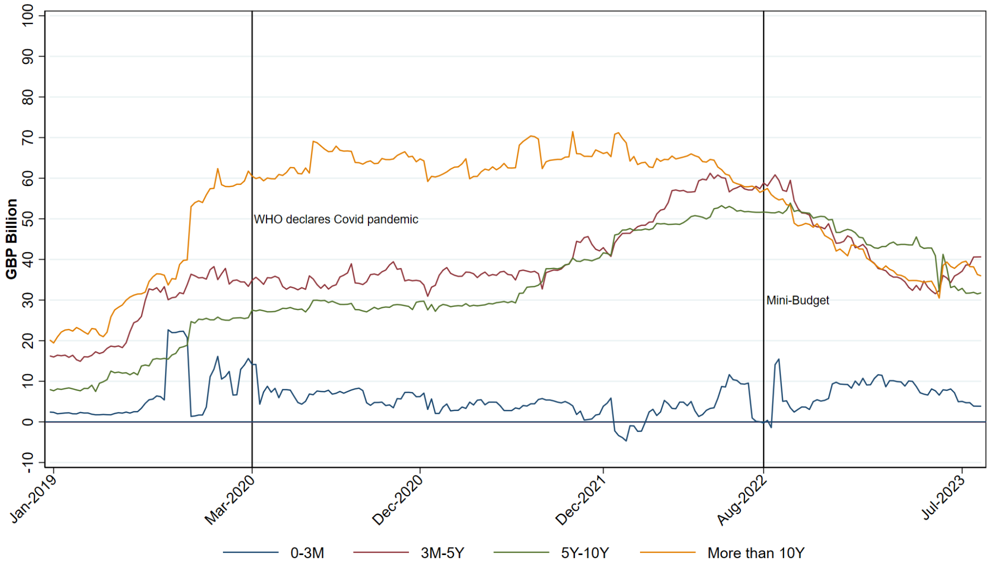
NOTE. Aggregate IRS net notionals of UK pension and LDI funds (PFLDIs) in £bn. Source: EMIR Trade Repository Data.

Figure B.8 PFLDI IRS Net Notionals & 10Y Gilt Yields



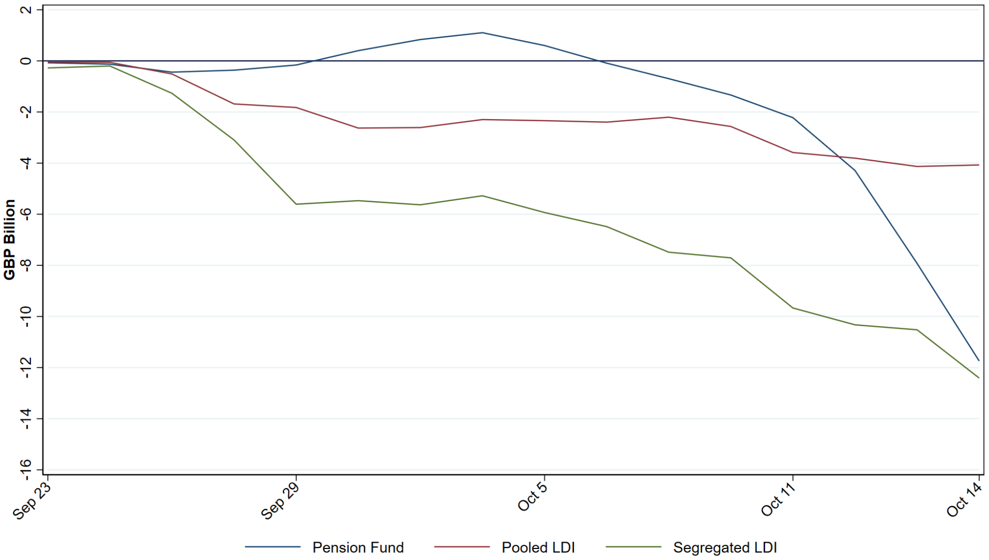
NOTE. Aggregate IRS net notionals of UK pension and LDI funds (PFLDIs) in £bn and 10Y gilt yields in %. Source: EMIR Trade Repository Data & Bank of England.

Figure B.9 PFLDI IRS Net Notionals by Maturity



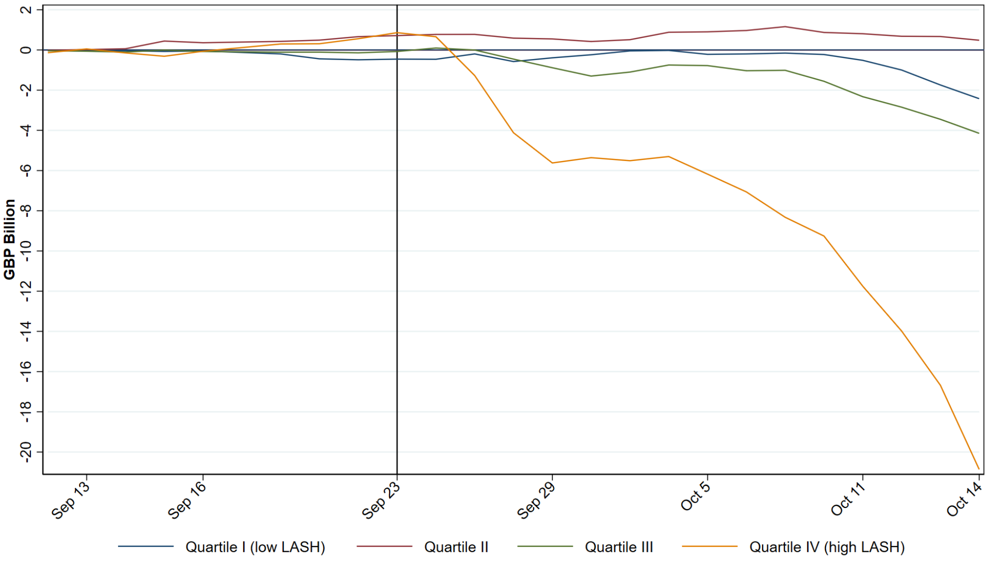
NOTE. Aggregate IRS net notionals of UK pension and LDI funds (PFLDIs) by maturity bucket in £bn. Source: EMIR Trade Repository Data.

Figure B.10 LDI Crisis: PFLDIs' Gilt Trading Volumes



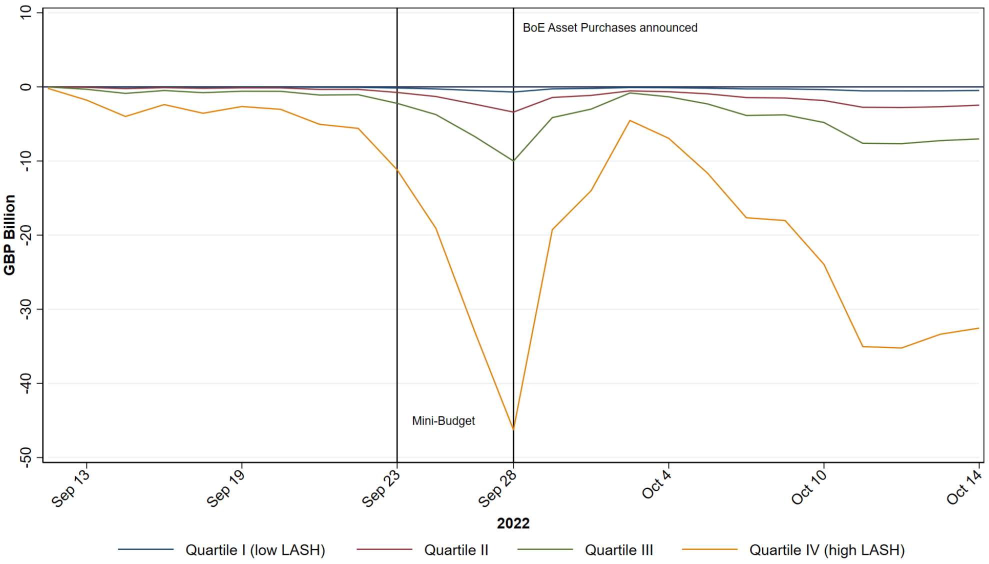
NOTE. Total net gilt trading volumes of UK PFLDIs (split into pension funds, segregated LDI funds and pooled LDI funds) following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

Figure B.11 LDI Crisis: PFLDIs' 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 NBFIs with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures.

Figure B.12 LDI CRISIS: ESTIMATED CUMULATIVE CHANGES IN THE VALUE OF REPO COLLATERAL POSTED BY PFLDIS



NOTE. Aggregate estimated changes in the value of repo collateral posted by UK pension and LDI funds (PFLDIs) in £bn during the 2022 LDI Crisis, by quartile of their pre-crisis LASH Risk: Quartile I captures the NBFIs 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.

C Additional Results

This section of the Appendix provides additional results for the regression analyses in our empirical section.

Table C.1 LASH RISK AND GILT TRADING VOLUMES - PFLDI ONLY

	(1)	(2)	(3)	(4)
	Net Volume		Sell Volume	
LASH combined	-0.15**		0.12***	
	(0.06)		(0.03)	
LASH Repo		-0.11***		0.08***
		(0.03)		(0.02)
LASH IRS		-0.07		0.07*
		(0.07)		(0.04)
Observations	2346	2346	2346	2346
R squared	0.036	0.036	0.044	0.045
Day FE	yes	yes	yes	yes

NOTE. For each investor, as defined in equation 3 in Section 3, "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 investor's daily gilt net trading volume on day t in Columns (1) and (2), and the investor'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.