Liquidity, Government Bonds and Sovereign Debt Crises[1]

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Abstract

This paper analyzes the Eurozone financial crisis through the lens of sovereign bond liquidity. Using novel data we show that repo haircuts on peripheral government bonds sharply increased during the crisis reducing their liquidity and amplifying the rise in their yields. We study the systemic impact of a liquidity shock to sovereign securities on the business cycle and asset prices through a DSGE model with financial frictions. The model predicts a drop in economic activity, deflation and a fall in the value of illiquid government bonds. We show that liquidity facilities can alleviate the contractionary effect of this shock. Impulse response functions of VAR models are the empirical confirmation the negative impact of a liquidity shock on the value of government bonds.

"Italian bonds are in the perfect storm at the moment. Real money investors are running away and those using Italian bonds to finance will also be clearing the desk now".

"LCH Clearnet SA raises margin on Italian bonds", Financial Times 9th November 2011.

1 Introduction

Why did countries in the periphery of the Eurozone pay higher interest rates on public debt than countries in the core during the recent financial crisis? Since the creation of a monetary union has integrated the sovereign debt markets and eliminated the exchange rate risk, two main factors may answer this question: credit risk and liquidity.

Credit risk derives from the government's probability of default. Weak fiscal and macroeconomic fundamentals of a country induce investors to ask higher compensation for holding government debt because of the possibility of suffering losses. In addition, fears of default and self-validating expectations may also drive up yields of government securities issued by those countries that cannot press new currency as predicted by Calvo (1988), Cole and Kehoe (2000) and Corsetti and Dedola (2012).

Liquidity is a broad concept that the traditional theories of Keynes (1936) and Hicks (1962) refer to as the capacity of an asset to store wealth and protect its owner from a shortage of revenue. Modern corporate finance distinguishes between market liquidity and funding liquidity. Market liquidity is the facility to obtain cash by selling an asset; when some impediments make it difficult to find a buyer the market liquidity is low and the price of the asset deviates from its fundamentals. Recent empirical literature disentangles the impact of credit risk and market liquidity risk in the evolution of European government bond yields (Favero, Pagano, and von Thadden (2010); Monfort and Renne (2011); Manganelli and Wolswijk (2009)).

This paper instead focuses on the role of funding liquidity, which is the ease with which investors can obtain funding (Brunnermeier and Pedersen (2009)). As they typically borrow against an asset, I consider funding liquidity as the

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capacity of an asset to serve as collateral. I show that government bonds are the prime collateral securities in the European repo market, which is becoming an essential source of funding for the banking system.[3] In particular, the increase in counterparty credit risk during the crisis led to a shift from unsecured to secured funding forcing borrowing banks to post securities in the interbank market, whose value exceeds the loan by a certain amount, the haircut or initial margin, which is the metric that I employ to measure funding liquidity. Given the value of an asset, the lower the haircut the larger the amount of cash that the borrower can obtain by pledging the asset.

Before the crisis the perceived safety of government bonds made them good collateral to back banks' debt and their repo haircuts were low. Hence they inherited some of the medium of exchange of money offering lower returns relative to other assets.[4] Nevertheless, I show that during the crisis the emergence of sovereign risk led to a rise in repo haircuts on peripheral government bonds, reducing their liquidity and capacity to serve as collateral for secured borrowing. The funding of investors shrank along the lines of the mechanism emphasized by Gorton and Metrick (2012) for the US liquidity crisis in 2007 - 2008, leading to a drop in investment. In order to reduce the contraction of their funding, leveraged investors shifted their portfolios towards more liquid bonds of the core with lower haircuts, contributing to the widening of the yield spreads.[5]

Building on Del Negro, Eggertsson, Ferrero, and Kiyotaki (forthcoming) I explore this liquidity channel of the Eurozone crisis through a DSGE model with financial frictions calibrated for Ireland.[6] Similarly to European banks, investors choose to hold sovereign bonds as a way to store liquidity for financing future investment. Since they cannot completely pledge the future returns of investment, the liquidity of their asset portfolio is crucial to determine the amount of investment that can be funded. Thus, even if the returns on public bonds are lower than those on private assets, investors can ease their funding constraint by borrowing against them.[7]

However, a liquidity shock calibrated to match the dynamic of repo haircut can suddenly reduce the amount of funding that investors can obtain by pledging government bonds and investment falls. In addition, nominal frictions and the zero lower bound (ZLB) prevent the real interest rate to decline and consumption also falls.

Several papers incorporate the liquidity friction proposed by Kiyotaki and Moore (2012) into general equilibrium models, such as Kurlat (2013), Bigio (2015), Shi (2015), Ajello (forthcoming), Del Negro, Eggertsson, Ferrero, and Kiyotaki (forthcoming).[8] They assume that government bonds are not subject to this constraint and are perfectly liquid. I depart from this assumption and introduce two types of government bonds with di_erent degrees of liquidity, in the spirits of Hicks (1939, pag. 146): long-term bonds which are subject to a liquidity constraint and short-term bonds which are not. A liquidity shock tightens the constraint of long-term bonds, which increases the premium that investors are willing to pay for holding short-term bonds. Furthermore, while previous studies interpret the liquidity shock as a change in market liquidity and a dry-up of liquidity in the secondary market, in this model it is equivalent to a rise in the repo haircut capturing a change in funding liquidity.

I analyze the impact of a policy experiment which consists of swapping illiquid government bonds for highly liquid papers (short-term debt or money) through direct purchases or collateralized loans in response to the liquidity shock. This intervention can be thought as the Expanded Asset Purchase Programme and 3-year Long Term Refinancing Operations implemented by the European Central Bank. The liquidity friction in long-term bonds breaks the irrelevance principle of Wallace (1981) and Eggertsson and Woodford (2003) for open market operations since the government exchanges liquid bonds for illiquid bonds, thus modifying the composition of aggregate portfolio holdings and mitigating the drop in consumption and investment. Reis (2015) also evaluate the effect of Quantitative Easing,

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[3] Gennaioli, Martin, and Rossi (2014a) finds empirical evidence that in a large panel of countries banks hold a sizable amount of government bonds because of their liquidity service.

[5] Banks could alternatively pledge government bonds for ECB refinancing operations, especially after the introduction of fixed-rate full allotment tender procedures, but paying a higher interest rate than the rate in the private repo market (see Boissel, Derrien, Ors, and Thesmar (2014) and Mancini, Ranaldo, and Wrampelmeyer (2013)). This opportunity cost of borrowing from the ECB may explain why the share of government bonds on total pledged assets reduced during the crisis (Cassola and Koulisher (2013)).

[6] The model abstracts from the risk of sovereign default to focus on a pure liquidity channel. Bi (2012); Bi and Traum (2012); Bocola (2015); Coimbra (2015) and Uribe (2006) introduce the probability of default in DSGE model.

[7] This echoes Holmstrom and Tirole (1998) who show that firms that cannot pledge any of their future income are willing to pay a premium on assets that are able to store liquidity and help them in state of liquidity shortage.

[8] The literature proposes alternative ways to incorporate liquidity in macroeconomic models. In Gertler and Kiyotaki (2010) liquidity shocks affect interbank funds and variations in haircuts are modeled as tightening of the incentive constraint of banks. In Jermann and Quadrini (2012) the financial shock is equivalent to a reduction in the market liquidity of terms capital which tightens its enforcement constraint, limiting the borrowing capacity of the firm. Jaccard (2013) considers a liquidity shock as the destruction of a fraction of the safe asset produced by the financial sectors which provide liquidity services to firms and households. In Calvo (2012) liquidity is a parameter that enters the utility function making the land more valuable. Benigno and Nisticò (2013) define liquidity as the property of an asset to be exchanged for consumption goods.

assuming that short-term bonds are more liquid than long-term bonds since they can be used as collateral in the interbank market together with reserves. In his model the unconventional monetary policy relaxes the constraint of banks by exchanging illiquid long-term bonds for liquid reserves. One main difference to my paper is that the source of the disturbance is a fiscal shock and not a financial shock.

Finally, I assess empirically the impact of a liquidity shock on Irish government bond yield with a structural VAR model. The liquidity shock is identified via a narrative approach by reading the variations in haircuts published through the Circulars of LCH Clearnet, the largest European clearing house. The impulse response function shows a positive reaction of yield and lends support to the predictions of the model. Furthermore, this result is confirmed with impulse response functions estimated by local projections that allow for regime shifts in autoregressive coefficients for states of high and low levels of sovereign risk.

The structure of the paper is as follows. Section 2 provides a picture of the European repo market and the funding liquidity of government bonds. Section 3 presents the model. Section 4 shows the results of the numerical simulation. Section 5 examines empirically the impact of a liquidity shock and Section 6 concludes.

2 Funding liquidity of government bonds

This section presents evidence of the importance of government bonds for the funding of European banks, since they are the main collateral securities of the repo market which is becoming essential for banks to meet their liquidity needs. Figure 1 exhibits the extraordinary expansion of the European repo market in the last decade as reported by the the European Repo Market Surveys.[9] Repos tripled in the run-up to the crisis and after a short contraction between 2008 and 2009 recovered to their pre-crisis level, reaching around e3 trillion. The size of the European repo market is close to that of the US market, estimated to be about $4.4 trillion in 2009 based on the average daily amount outstanding of the primary dealers repo financing (See Acharya and Oncu (2012)).

Figure 1: European repo market (billions of euros)
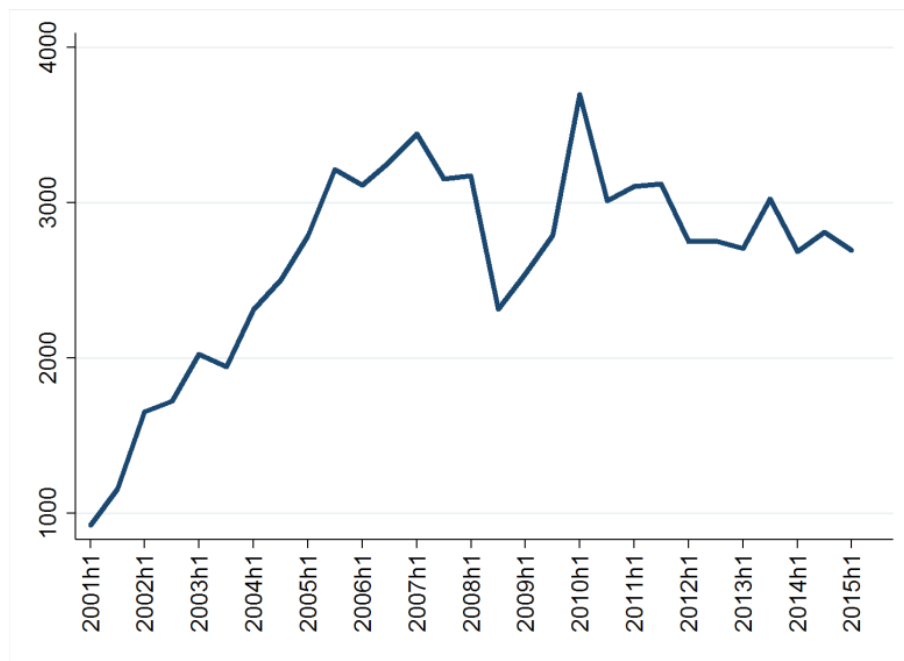
Note: repos reported by banks which participated continuously in all the (borrowing activity).
Source: Eurpean repo survey (ICMA)

Figure 2 compares the dynamics of secured and unsecured borrowing using data from the European Money Market Survey of the European Central Bank. There is a massive shift of banks' funding from the unsecured to the secured segment, in particular after the onset of the global financial crisis following the rise in counterparty credit risk. Furthermore, decomposing the repo market by types of arrangements we can observe that bilateral CCP-cleared repos

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[9] See the Appendix A.1 and A.2 for definitions employed for repo contracts and description of the data sources.

steadily increased, while over-the-counter bilateral repos declined and the tri-party repos account for a little share of the market. Thus, changes in haircuts applied by clearing houses strongly affect funding conditions in the European repo market.

Figure 2: Interbank transactions in the European money market

Repos and unsecured borrowing (total turnover)   Shares of bilateral and tri-party repos (in percent of total)
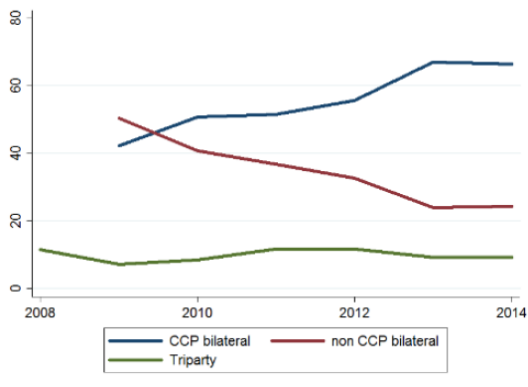
Source: European Money Market Survey (ECB)

Concerning the collateral posted in repo transactions, Figure 3 shows that government bonds are the predominant securities, accounting for around 80% of the total collateral pool. This share was stable during the crisis and represents a structural characteristics of the European repo market, different to the US market where securities issued by the private sector account for a larger share (Krishnamurthy, Nagel, and Orlov (2014)) Looking at the composition of sovereign securities, German bonds are the largest share, although their supply is lower than French and Italian bonds (Eurostat (2013)). In addition, the share of Italian bonds dropped substantially during the Eurozone crisis, from 10% in December 2010 to 7% in December 2011.

Figure 3: Share of collateral in the European repo market
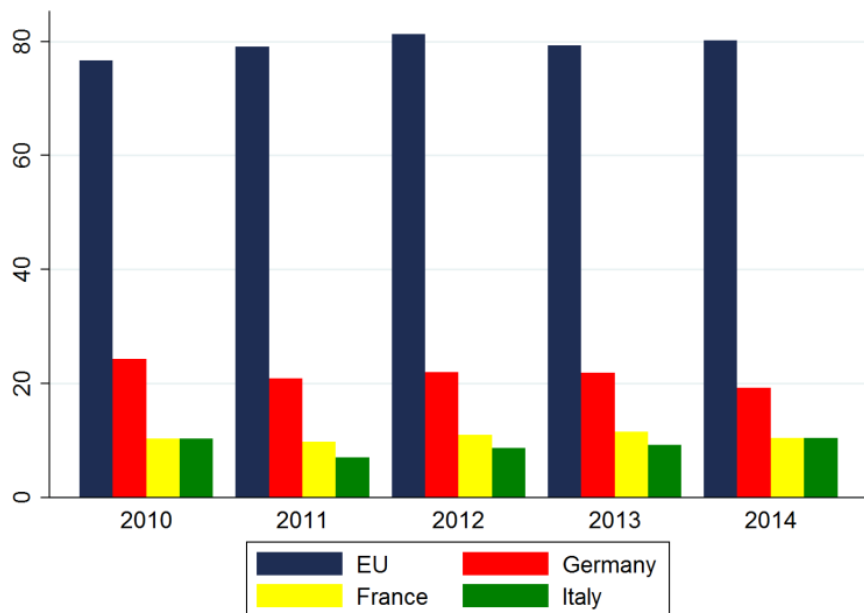
*Source: Eurpean repo survey (ICMA.)*

The collateral composition of the European repo market reflects not only the safety of securities but also their liquidity. Figure 4 shows the evolution of 10 year government bond yields of peripheral countries (Ireland, Portugal, Italy and Spain) and the haircuts applied on these securities by LCH Clearnet, the largest European clearing house. Following the

rise in bond yields and sovereign risk, haircuts on Irish and Portuguese bonds surged up to 80%. Italian and Spanish bonds also experienced rises in haircuts but these were more mitigated. However, it is worth noting that the increase in haircuts on Italian bonds is associated with their decrease in the share of collateral in the repo market (Figure 3).[10]

Figure 4: Yields (LHS) and haircuts (RHS) on 10-year government bonds
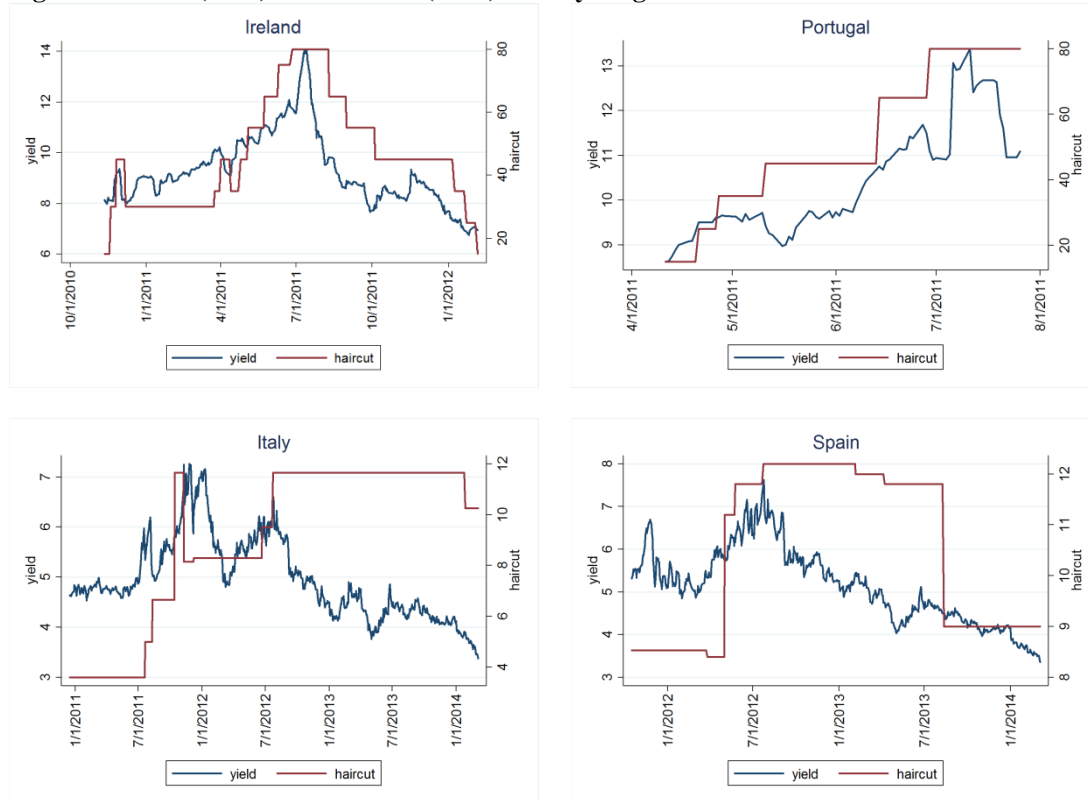
To summarize, European government bonds have become an essential liquid instrument for banks, especially after the onset of the financial crisis, since they are needed to pledge collateral securities as guarantee of repayment in order to borrow on the interbank market. Therefore, their value incorporates a premium reflecting their capacity to serve as collateral. Nevertheless, repo haircuts sharply increased on peripheral government bonds reducing their funding liquidity. In the next section I study the impact of this liquidity shock and the transmission mechanism to the real economy in a DSGE model.

3 The model

The model is an infinite horizon economy populated by a continuum of households of measure one. The members of each household are either entrepreneurs or workers. The model incorporates nominal rigidities, since prices and wages are set in staggered contracts, and real rigidities with capital adjustment cost along the lines of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007). The Appendix B1 through B4 reports the equations for the production process. Households allocate saving across three risk-free financial assets characterized by different degrees of liquidity: equity, long-term and short-term sovereign bonds. The government conducts fiscal policy - collecting taxes and conventional monetary policy by setting the nominal interest rate. Long-term bonds are subject to a liquidity shock which is the only shock perturbing the economy. In response to this shock the government may implement an unconventional policy which consists of increasing the supply of one-period bonds that are more liquid than long-term bonds.

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[10] In Armakola, Douady, Laurent, and Molteni (2016) we show that a similar pattern is observed for haircuts applied by other major European clearing houses.

3.1 Households

Structure. Each household has a unit measure of members indexed $j \in [0,1]$. At the beginning of each period all members are identical and hold an equal share of the household's assets. They receive an idiosyncratic shock, iid across members and across time, which determines their profession: entrepreneurs or workers. With probability γ they are entrepreneurs and with probability $1-\gamma$ they are workers. By the law of large number γ and $1-\gamma$ also represent respectively the fraction of entrepreneurs and workers in the economy. Each entrepreneur $j \in [0, \gamma)$ invests and each worker $j \in (\gamma,1]$ supplies labor; both types return their earnings to the household. At the end of each period, all members share consumption goods and assets, but resources cannot be reallocated among members within the period.

Preferences. The household's objective is to maximize the utility function

$$\mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} U(C_s, H_s(j)) = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\frac{C_s^{1-\sigma}}{1-\sigma} - \frac{\xi}{1+\eta} \int_{\gamma}^{1} H_s(j)^{1+\eta} dj \right] \qquad (1)$$

where $\mathbb{E}_t$ denotes the conditional expectation, β is the subjective discount factor, σ measures the degree of relative risk aversion, ξ is a scaling parameter that can be chosen to match a target value for the steady state level of hours and η is the inverse of the Frisch elasticity of the labor supply. Utility depends positively upon the sum of the consumption good bought by household members C_t and negatively upon the workers' labor supply $H(j)_t$.

Portfolio. Households buy physical capital K_t at price q_t and they lend it to intermediate good producers earning a constant dividend stream r_t. They also own government securities B^L_t with price Q^L_t defined as perpetuities with coupons which decay exponentially as in Woodford (2001). A bond issued at date t pays λ^{k-1} at date t+k, where $\lambda \in [0, \beta]$ is the coupon decay factor that matches the parameter of the duration of government securities, corresponding to $(1 - \lambda \beta)^{-1}$.[11] I define this bond as long-term to differentiate it from the short-term bond B^S_t which is a one-period bond with zero coupon, i.e. $\lambda = 0$, with price Q^S_t. I assume that the supply of short-term sovereign debt is very limited and accounts for a small share of the households' portfolio.[12] In addition, families hold N^O_t claims on their other households' capital and sell claims on own capital to other households' N^I_t. The financing structure implies the households' balance sheet at the beginning of period t in the table below.

Household's balance sheet (financial assets)

Asset		Liability	
Capital stock:	$q_t K_t$	Equity issued:	$q_t N^I_t$
Other's equity:	$q_t N^O_t$		
Long-term bonds:	$Q^L_t \frac{B^L_t}{P_t}$		
Short-term bonds:	$Q^S_t \frac{B^S_t}{P_t}$	Net worth:	$q_t N_t + Q^L_t \frac{B^L_t}{P_t} + +Q^S_t \frac{B^S_t}{P_t}$

I assume that equity issued by the other households (N^O_t) and the unmortgaged capital stock ($K_t - N^I_t$) yield the same returns, have the same value and depreciate at the same rate, so they are perfect substitutes and can be summed together and defined as equity.

$$N_t = N^O_t + K_t + N^I_t \qquad (2)$$

At the end of each period households also receive profits D_t and D^I_t from intermediate goods producers and capital producers, respectively. The budget constraint of the typical household member j can be written as follows

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[11] An alternative interpretation of the long-term debt is that λ is the fraction of the outstanding bonds paying a constant coupon of 1 and $(1 - \lambda)$ is the fraction of bonds which mature at each period and for which the government pays back the principal to the bond holder Chatterjee and Eyigungor (2012).

[12] This assumption avoids household members holding government bonds with only a short maturity because they are more liquid. It is consistent with the evidence supported by Eurostat (2013): in Europe one-year bonds account for just 5% of the total outstanding public debt, the average maturity is between 6 and 7 years, which is matched in the calibration of the model. In equilibrium the returns on long-term and short-term bonds are linked by a non-arbitrage condition. Most of New Keynesian models present only a one-period bond rolled over every period. In Leeper and Zhou (2013) the government may find it optimal to issue bonds with a long maturity because they facilitate the intertemporal smoothing of inflation and output gap. Cochrane (2001) analyses long-term debt and optimal policy in the fiscal theory of price level.

$$C_t(j) + p_t^I I_t(j) + q_t[N_{t+1}(j) - I_t(j) - \lambda N_t] + Q_t^L \left[\frac{B_{t+1}^L(j)}{P_t} - \lambda \frac{B_t^L}{P_t} + Q_t^S \frac{B_{t+1}^L(j)}{P_t} \right]$$
$$= r_t N_t + \frac{B_t^L}{P_t} + \frac{B_t^S}{P_t} + \frac{W_t(j)}{P_t} H_t(j) + D_t + D_t^I - T_t \tag{3}$$

where P_t denotes the price level, p_t^I is the cost of one unit of new capital in terms of the consumption goods, differing from 1 because of capital adjustment cost, $H_t(j)$ and $W_t(j)$ are the working hours and nominal wage for workers j as discussed in the next section. According to the left side of the budget constraint, the household members allocate resources between purchase of non-storable consumption good, investment in new capital - if they are entrepreneurs - and net purchase of equity, long-term bonds and short-term bonds. They finance their activities on the right side of the budget constraint with returns on equity, long-term bonds, short-term bonds, wages of differentiated labor - if they are workers - and the dividends net to taxes.

A key assumption of the model is the presence of the following funding constraints which limit the financing of new investments by entrepreneurs and determine the different degree of liquidity of the assets

$$N_{t+1}(j) \geq (1-\theta)I_t(j) + \lambda N_t \tag{4}$$

$$B_{t+1}^L(j) \geq (1-\phi_t)B_t^L \tag{5}$$

$$B_{t+1}^S(j) \geq 0 \tag{6}$$

Inequality 4 means that the entrepreneur can issue claims on the future output of investment but only for a fraction $\theta \in [0, 1]$. This borrowing constraint implies that investment is partially funded internally and entrepreneurs have to retain 1 - θ as own equity. In addition, equity is assumed to be completely illiquid since entrepreneurs cannot sell it to obtain more resources to invest. Hence, the entrepreneurs' equity holding at the start of the period t+1 must be at least the sum of the downpayment $(1 - \theta)I_t$ and depreciated equity λN_t, where λ is the inverse depreciation rate.[13]

The entrepreneur can acquire additional resources by disposing of a fraction $\phi_t \in [0, 1]$ of long-term bonds, so a resaleability constraint imposes to keep the residual $(1 - \phi_t)$ of bonds in his portfolio (inequality 5). $(1 - \phi_t)$ is equivalent to the haircut in a repo transaction since it determines the amount of liquidity that the entrepreneur can obtain by pledging sovereign securities in secured borrowing. In other words, the entrepreneur cannot borrow against the value of the entire bond holding because of the presence of the haircut. The assumption on the diverse resaleability of equity and bonds reflects the different liquidity of privately issued securities, which are scarcely used as collateral, and sovereign bonds, which are largely pledged by European banks for repo transactions.

Inequality 6 implies that short-term bonds are not subject to resaleability constraint and are fully liquid, but entrepreneurs cannot borrow from the government.[14] ϕ_t is the key parameter of the model characterizing the liquidity of financial assets. We can think that it takes value 0 for equity, value 1 for short-term bonds and an intermediate value for long-term bonds. The dynamic of the model follows a reduction in ϕ_t, which is paramount to a rise in the repo haircut on sovereign bonds.

At the end of the period, the assets of households are given by

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[13] Nezafat and Slavik (2011) model a financial shock as a tightening in the credit conditions and a drop in θ and assume that equity/capital is completely liquid. In our set-up the assumption that equity is illiquid means that entrepreneurs cannot issue equity on the unmortgaged capital stock and cannot sell any of others' equity remained.

[14] Similarly, inequalities 4 and 5 ensure that receipts from trading equity and long-term bonds are strictly positive, which prevents the entrepreneur from going short on these securities.

$$N_{t+1} = \int N_{t+1}(j)\, dj \qquad (7)$$

$$B_{t+1}^S = \int B_{t+1}^S(j)\, dj \qquad (8)$$

$$B_{t+1}^L = \int B_{t+1}^L(j)\, dj \qquad (9)$$

$$K_{t+1} = K_t + \int I_t(j)\, dj \qquad (10)$$

Next, the specific functions of entrepreneurs and workers are taken into account.

3.1.1 Entrepreuneurs

The entrepreneur $j \in [0, \gamma)$ does not supply labor, so $H_t(j) = 0$ in equation 3 to get his budget constraint. In order to acquire new equity he can either produce it at price p_t^I or buy it in the market at price q_t. For the rest of the model I assume that $q_t > p_t^I$ in order to focus on the economy where the liquidity constraints bind, thus limiting the ability of the entrepreneur to finance investments. In this case, the entrepreneur will use all the available liquidity for new investment projects to maximize the households' utility. Accordingly, they minimize the equity holding by issuing the maximum amount of claims on the investment return to reduce the size of the downpayment as implied by constraint 4. The entrepreneur also sells the maximum amount of bonds as allowed by constraint 5, because their expected returns are lower than those on new investment. As a result, in equilibrium the liquidity constraints all bind and the entrepreneur does not consume goods within the period:

$$N_{t+1}(j) = (1 - \theta)I_t(j) + \lambda N_t \qquad (11)$$

$$B_{t+1}^L(j) = (1 - \phi)B_t^L \qquad (12)$$

$$B_{t+1}^S(j) = 0 \qquad (13)$$

$$C_t(j) = 0 \qquad (14)$$

Given the solutions for entrepreneurs, $N_{t+1}(j)$, $B^L_{t+1}(j)$, $B^S_{t+1}(j)$, C_t for $j \in [0, \gamma)$, equations 11, 12, 13 and 14 can be plugged into equation 3 to derive the function of investment for entrepreneurs

$$I_t(j) = \frac{r_t N_t + [1 + \lambda \phi_t Q_t^L]\frac{B_t^L}{P_t} + Q_t^S \frac{B_t^S}{P_t} + D_t + D_t^I - T_t}{p_t^I - \theta q_t} \qquad (15)$$

The nominator represents the maximum liquidity available for the entrepreneurs deriving from the return on papers (equity and long-term bonds), sales of the resaleable fraction of long-term bonds after depreciation, sales of short-term bonds and the dividends net to taxes. The denominator is the difference between the price of one unit of investment goods and the value of equity issued by the entrepreneur, which indicates the amount of own resources necessary to finance one unit of investment. Equation 15 shows that a drop in φ_t not only increases the haircut to long-term bonds but also reduces the leverage of entrepreneurs and impacts directly on their investment. Aggregating by entrepreneurs total investment is

$$I_t = \int_0^\gamma I_t(j)\, dj = \frac{r_t N_t + [1 + \lambda \phi_t Q_t^L] \frac{B_t^L}{P_t} + Q_t^S \frac{B_t^S}{P_t} + D_t + D_t^I - T_t}{p_t^I - \theta q_t} \qquad (16)$$

3.1.2 Workers

Workers $j \in [\gamma, 1]$ do not invest, so $I_t(j) = 0$. They supply labor as demanded by firms at a fixed wage; the union who representing each type of worker sets wages on a staggered basis. To determine the asset and consumption choices of workers, I first derive the household's decision for $N_{t+1}; B^L{}_{t+1}; B^S{}_{t+1}$ and C_t, taking W_t and H_t as given. Knowing the solution for entrepreneurs, $N_{t+1}(j); B^L{}_{t+1}(j); B^S{}_{t+1}(j)$ and $C_t(j)$ can be determined for workers, given the aggregate consumption and asset holding.

3.1.3 The problem of households

To solve the model for the household, I aggregate the workers' and entrepreneurs' budget constraint

$$C_t + p_t^I I_t + q_t[N_{t+1} - I_t - \lambda N_t] + Q_t^L \left[\frac{B_{t+1}^L}{P_t} - \lambda \frac{B_t^L}{P_t} + Q_t^S \frac{B_{t+1}^L}{P_t} \right]$$
$$= r_t N_t + \frac{B_t^L}{P_t} + \frac{B_t^S}{P_t} + \int_\gamma^1 \frac{W_t(j)}{P_t} H_t(j) + D_t + D_t^I - T_t \qquad (17)$$

Households maximize the utility function (2) by choosing $C_t, N_{t+1}, B^L{}_{t+1}$ and $B^L{}_{t+1}$ subject to the aggregate budget constraint and the investment constraint. The first order conditions for equity, long-term bonds and short-term bonds are respectively

$$U'_{c,t} = \beta \mathbb{E}_t \left\{ U'_{c,t+1} \left[\frac{r_{t+1} + \lambda q_{t+1}}{q_t} + \frac{\gamma(q_{t+1} - p_t^I)}{p_t^I - \theta q_{t+1}} \frac{r_{t+1}}{q_t} \right] \right\} \qquad (18)$$

$$U'_{c,t} = \beta \mathbb{E}_t \left\{ \frac{1}{\pi_{t+1}} U'_{c,t+1} \left[\frac{1 + \lambda Q_{t+1}^L}{Q_t^L} + \frac{\gamma(q_{t+1} - p_t^I)}{p_t^I - \theta q_{t+1}} \frac{1 + \lambda \phi_{t+1} Q_{t+1}^L}{Q_t^L} \right] \right\} \qquad (19)$$

$$U'_{c,t} = \beta \mathbb{E}_t \left\{ \frac{1}{\pi_{t+1}} U'_{c,t+1} \left[\frac{1}{Q_t^S} + \frac{\gamma(q_{t+1} - p_t^I)}{p_t^I - \theta q_{t+1}} \frac{1}{Q_t^S} \right] \right\} \qquad (20)$$

where π_t is the inflation rate defined as $\pi_t = P_{t+1}/P_t$. The choice of sacrificing one unit of consumption today to purchase a paper gives a payoff which is composed of two parts. The first is the returns on the asset: $(r_{t+1} + \lambda q_{t+1})/q_t$ for equity, $(1 + \lambda Q^L{}_{t+1})/Q^L{}_t$ for long-term bonds and 1 for short-term bonds. The second part is a "liquidity premium", deriving from the fact that papers in the entrepreneurs' portfolio relax their investment constraint. This premium is a function of the leverage $\gamma/(p^I{}_t - \theta q_t)$, the distance between the price of equity and the price of capital goods, and the liquid returns of each asset. Thus, the bond holding eases the financing constraints more than the equity holding, which makes bonds more valuable for entrepreneurs.

3.2 The government

The government conducts monetary and fiscal policy separately, following exogenous policy rules, and faces the following intertemporal budget constraint

$$Q_t^L \frac{B_t^L}{P_t} + Q_t^S \frac{B_t^S}{P_t} + T_t = (1 + \lambda Q_t^L) \frac{B_t^L}{P_t} + \frac{B_t^S}{P_t} \qquad (21)$$

The debt repayment is financed by the issue of new debt and net taxes T_t. A solvency condition links taxes with the outstanding beginning-of-period government debt in term of deviation from the steady state

$$T_t - T = \psi_T \left(\frac{B_t^L}{P_t} - \frac{B^L}{P} \right) \tag{22}$$

where $T > 0$ measures the elasticity of fiscal policy to variations in the size of the debt. The government sets the nominal interest rate following the feedback rule constrained by the zero lower bound condition

$$R_t = \max \left(\pi_t^{\psi_\pi}, 1 \right) \tag{23}$$

where $\psi_\pi > 1$. Unconventional policy consists of purchasing illiquid long-term bonds by issuing liquid short-term bonds. The supply of one-period bonds (in term of equity) is a function of the proportional deviations of liquidity from the steady state

$$\frac{B_{t+1}^S}{N} = \psi_B \left(\frac{\phi_t}{\phi} - 1 \right) \tag{24}$$

The price of the nominal short-term bond is the inverse of the nominal rate, so the government by setting the nominal interest rate, also sets the price of short-term bonds.

$$Q_t^S = \frac{1}{R_t} \tag{25}$$

4 Numerical simulation

4.1 Calibration

I calibrate the model at quarterly frequency to match the economy of Ireland because of the rich dynamic of the haircuts on Irish bonds, which is used to calibrate the process of the liquidity parameter ϕ_t (see Figure 4). Table 1 reports the calibrated values. The steady state of liquidity ϕ is 0.75, equivalent to one minus the haircut on 10 year Irish bonds before the crisis. I estimate the stochastic process for ϕ_t as an AR(1) process from the dynamics of the Irish haircut during the period of crisis. The autoregressive coefficient ρ^ϕ is found to be 0.99 and the standard deviation of the residuals σ^ϕ is 1.3. These values measure respectively the persistence of the freeze in the repo market and the size on the liquidity shock. The other parameter characterizing the financial frictions θ describes the fraction of investment financed externally. Since entrepreneurs represent broadly the banking system in channeling resources to the production sector of the economy, I consider θ as the ratio of banks' external finance, defined as the sum of deposits, long-term debt and equity, over total assets. I construct the average of this ratio for the 18 largest financial institutions for which Bankscope reports information on repos which is 0.5 (Table 2 in the Appendix A.3). The liquidity share in this economy is defined as:

$$ls_t = \frac{\phi Q_t^L B_{t+1}^L}{\phi Q_t^L B_{t+1}^L + q_t P_t K_{t+1}} \tag{26}$$

The nominator is the liquid part of public debt computed as the total of Irish government gross liabilities times the liquidity parameter. The denominator is equal to the value of the total productive capital (OECD (2013)). The average of this ratio during the period 2000 and 2011 is 0.43, which is taken as the steady state value of the liquidity share. The parameter λ pins down the duration of long-term bonds given by $(1 - \lambda)^{-1}$. I set $\lambda = 0.973$ to match the average maturity of the Irish debt, which is 6.9 years (Eurostat (2013)).

Other parameters are standard in the literature: the discount factor $\beta = 0.99$, the inverse Frish elasticity of labor supply $\eta = 1$, the capital share $\alpha = 0.4$, the arrival rate of investment opportunity in each quarter $\gamma = 0.05$. The degree of monopolistic competition in labor and product markets is calibrated symmetrically assuming a steady state markup of 10% ($\delta_p = \delta_w = 0.1$). The average duration of price and wage contracts is 4 quarters $\zeta_p = \zeta_w = 0.1$). Concerning the policy rules, the feedback coefficient on inflation in the monetary policy rule _ is 1.5 in order to guarantee a uniquely determined equilibrium. The government finances most of the intervention through issuance of new short term debt and transfers slowly adjust to the government net wealth position ($\psi_T = 0.1$). The coefficient for the intensity of the government intervention ψ_B is -0.127, the same value used by Del Negro, Eggertsson, Ferrero, and Kiyotaki (forthcoming).

Definition	Parameter	Value
Preferences		
Household discount factor	β	0.99
Realtive risk aversion	σ	1
Inverse Frish elasticity	η	1
Production and investment		
Capital share of output	α	0.4
Adjustment cost parameter	Γ	1
Probability of investment opportunity	γ	0.05
Inverse depreciation rate / Bond maturity parameter	λ	0.973
Nominal frictions		
Price and wage calvo probability	$\zeta_\pi = \zeta_w$	0.75
Price and wage steady-state markup	$\delta_\pi = \delta_w$	0.5
Financial frictions	θ	0.5
Borrowing constraint	θ	0.5
Resaleability constraint	ϕ	0.75
Autoregressive coefficient of liquidity	ρ^ϕ	0.99
Size of liquidity shock	σ^ϕ	1.3
Steady-state of liquidity share	ls	0.43
Policy rule		
Monetary policy rule coefficient	ψ_π	1.5
Transfer rule coefficient	ψ_T	0.1
Government intervention coefficient	ψ_B	-0.127

4.2 Results

4.2.1 The impact of a liquidity shock

I first analyze the economy in which the government does not respond to the negative liquidity shock. Figure 5 shows the response of real and financial variables to a drop in φ_t for the first twelve quarters. Output, consumption and investment simultaneously fall by 8.78%, 8.03% and 10.92%, respectively. The magnitude of the reduction in investment is close to that observed in the Irish economy in 2011 (-7.21%). The contraction of liquidity impacts directly on investments by tightening the entrepreneurs' funding constraint, shrinking the funds they can obtain from borrowing against bonds. Moreover, it is amplified by the fall in the value of equity that increases the required downpayment, reducing the leverage of entrepreneurs. The drop in the price of equity (-14.23%) and long-term bonds (-8.42%) has a negative wealth effect on consumption.

In particular, the presence of nominal rigidities is a key element for the fall in consumption, because with a flexible price the contraction in the economic activity would generate deflationary expectations leading to negative real interest rate and boosting consumption, as observed in the model of Kiyotaki and Moore (2012). The liquidity shock results in a large and persistent decline in the price of final goods.

Concerning asset prices, the liquidity contraction of long-term bonds leads to a "flight to liquidity" towards the more liquid short-term bonds, as indicated by the jump in the liquidity spread (13.78%), defined as the difference between the price of short-term and long-term bonds. In addition, the strong persistence of the shock induces entrepreneurs to anticipate lower future liquidity, thus reinforcing this mechanism. Shi (2015) notes that when equity is subject to liquidity constraint (reselability constraint), a negative liquidity shock in the Kiyotaki and Moore (2012) setting leads to an increase in equity price. A reduction in the resaleability reduces the supply of equity, while the demand is not affected since there is no change in the quality of investment projects. In this model, the fall in the demand for long-term bonds more than offsets the contraction of their supply following the reduction in their resaleability, bringing about the drop in their price, consistent with the widening of yield spreads of less liquid peripheral bonds.

Figure 5: Impulse response function to a negative liquidity shock
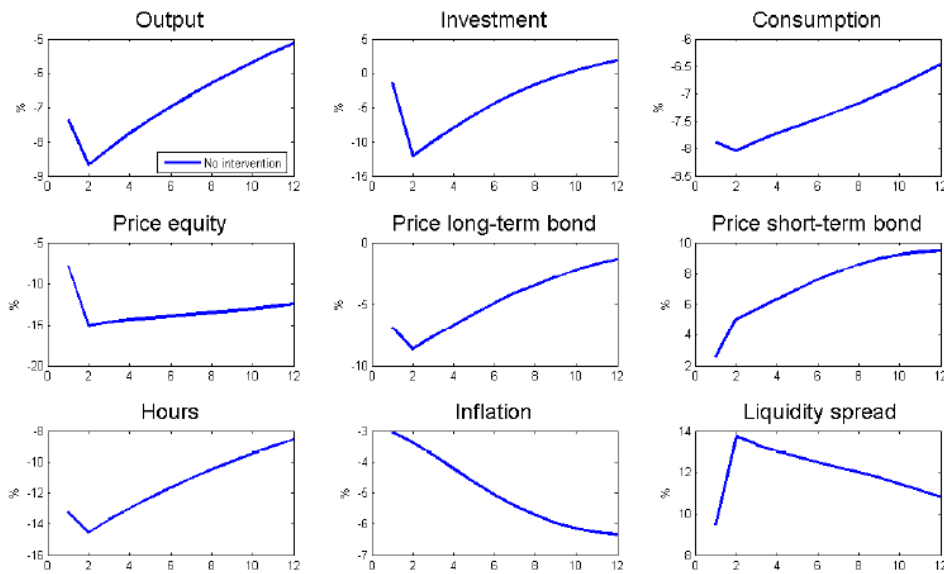
4.2.2 The effects of the policy intervention

I consider now the scenario in which the government reacts to the drop in φ_t by issuing more public liquidity. Figure 6 compares the impulse responses to a negative liquidity shock in the case that the government does not intervene (blue line) and in the case in which it does react (red line). The model predicts that this unconventional policy alleviates the contractionary effect of the shock substantially. Output decrease by 5.73%, consumption by 6.17% and investment by 5.35%. The fall in consumption drastically lessens, mainly because the reduction in the price of equity is less pronounced, which also reduces the deleveraging of entrepreneurs. The increased supply of liquid short-term bond relaxes the funding constraint of entrepreneurs. Moreover, the implemented policy succeeds in reducing the deflationary effect of the liquidity shock (- 2.89%). Regarding financial variables, the impact of the unconventional measure on the liquidity premium is very limited, as shown by the response of the liquidity spread.

Figure 6: The effects of policy intervention
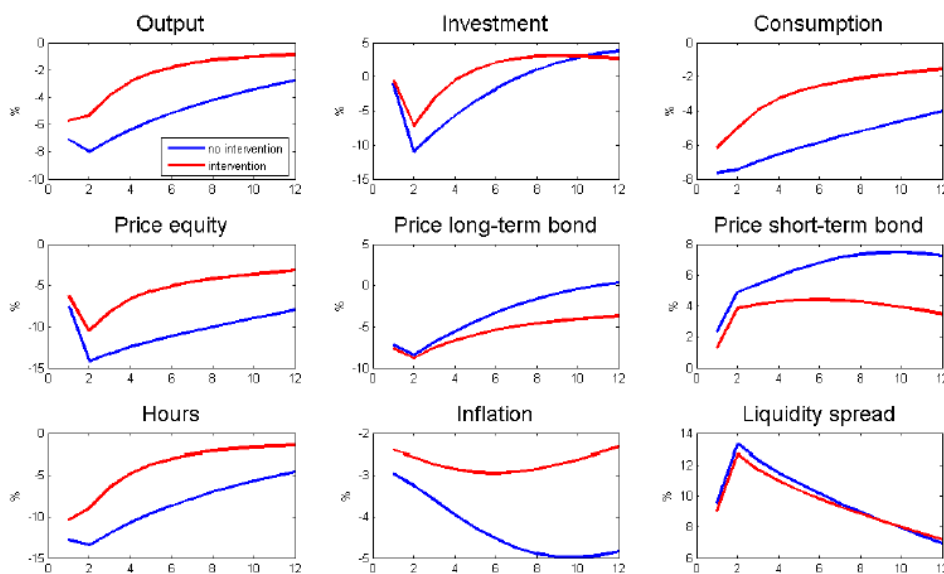
4.2.3 The zero lower bound

I show that when monetary policy is constrained by the zero lower bound the impact of the liquidity shock and the effect of unconventional policy are both amplified. Figure 7 displays the impulse response to the liquidity shock if the zero lower bound is binding with (red dashed line) and without (blue dashed line) the policy intervention. On impact, the drop in output and consumption is similar to what I obtain ignoring the zero lower bound, as shown by Figure 7 (-8.55% and -7.19%, respectively), but is far more persistent. The nominal interest rate cannot reach the negative region and conventional monetary policy cannot boost consumption expenditure through a reduction in the real interest rate, mitigating the impact of the liquidity shock, as in the case in which the zero lower bound does not bind. This in part explains the strong deflationary pressure following the liquidity shock. The fall in investment is deeper (-15.80%) and also more persistent. Concerning asset prices, the price of equity falls more steeply following the stronger reduction in the demand for new capital, while the magnitude of the liquidity spread is similar to the scenario without zero lower bound. Because of the zero lower bound constraint, the effectiveness of unconventional policy is greater than it would be if it were possible for the government to lower the policy rate below zero. In particular, this measure avoids that the economy remaining in a region of low consumption and deflation.

Figure 7: The zero lower bound
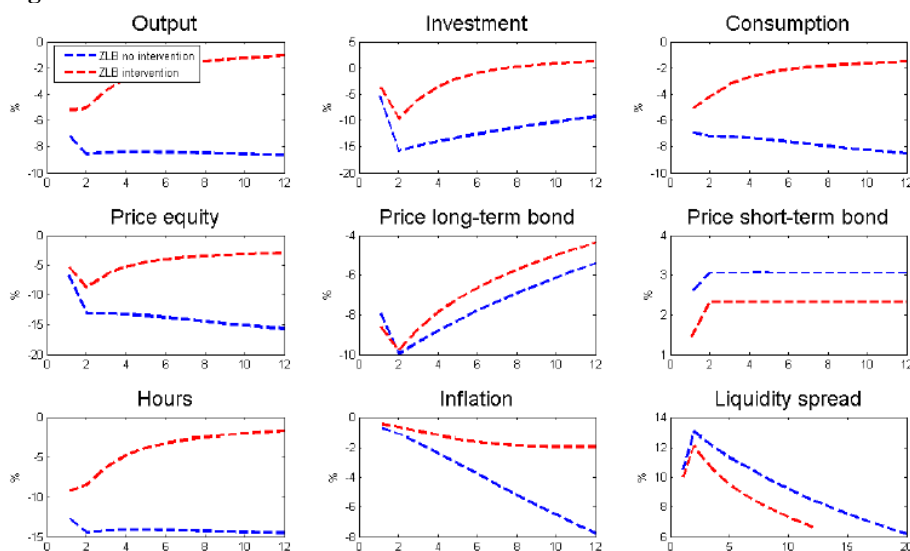
5 Confronting the theory with the data

This section analyzes empirically the impact of a funding liquidity shock on the value of government bonds. To do so, I study the impulse response function of a structural vector autoregressive model (VAR), including haircuts applied by LCH Clearnet Ltd (h_t), CDS spreads (CDS_t) and yields (yd_t) of 10 year Irish government bonds in order to deal with endogeneity problems and reverse causality issues. In the theoretical model I abstract from the probability of government default, but two main reasons motivate the inclusion of CDS spreads as a measure of credit risk. First, it allows to disentangle the funding liquidity channel from the credit risk channel. Second, it helps identify a funding liquidity shock since the clearing house LCH Clearnet Ltd takes into account the evolution of CDS spread to set the repo haircuts on government bonds. Methodologically, this exercise is close to the study of Pelizzon, Subrahmanyam, Tomio, and Uno (2016), which analyzes the dynamic relation between credit risk and market liquidity.

Data are at daily frequency and cover the period from 01-11-2010 to 01-12-2011. The sample is right censored to take into account the first 3-year Long Term Refinancing Operation (LTRO) implemented on 08-12-2011, which altered the relationship between the variables as confirmed by the Chow test implemented on the regression of yd_t on h_t and CDS_t. Other unconventional monetary policies, such as the Security Market Programme and refinancing operations with full

allotment, were already active during this period, but their inception, which is likely to have an impact on market sentiments, precedes the beginning of the sample.[15]

Let $\mathbf{y}_t = [h_t, CDS_t, yd_t]$' and consider the reduced form VAR

$$\mathbf{y_t} = B(L)\mathbf{y_t} + \mathbf{u_t} \qquad (27)$$

where $E_t \mathbf{u_t u_t}' = V$. The number of lags (p) is 4 but results are robust to a longer lag length. Coefficient matrices and variance-covariance matrix are estimated with Bayesian techniques using non-informative priors (Canova (2007)). I impose limited prior information given the ignorance about the properties of a funding liquidity shock.

The identification of a funding liquidity shock is based on the narrative approach and the timing of the implementation of announced variations in haircuts.[13] The series of changes in haircuts is constructed by reading the Repo Clear Margin Rate Circulars from the website of LCH Clearnet Ltd through which the Risk Management of the clearing house communicates to its members the revisions of the risk parameters for government bonds. These documents provide information on the date of the announcement, date of implementation and variations in additional margins required. To give a sense of how I proceed, Figure 11 in Appendix A.2 reports an example of the Circular.

LCH Clearnet Ltd communicates to its members all modifications in haircuts at the close of business and their revision is applied one day after the publication of the circular. The delay between the announcement and the implementation of changes in haircut is crucial for the identification of structural shocks which are recovered via recursive zero restrictions. More formally, reduced form residuals can be expressed as a linear combination of structural shocks $\mathbf{u}_t = A_0 \mathbf{e}_t$ with $E \mathbf{e}_t \mathbf{e}_t' = I$ and $A_0' A_0 = V$. I restrict A_0 to a lower triangular matrix with diagonal elements equal to one and I apply the Choleski decomposition to the estimated variance covariance matrix. The ordering structure of the variables implies the following assumptions. First, h_t is predetermined relative to CDS_t and yd_t, so financial shocks relative to CDS_t and yd_t do not affect h_t during the same day. Second, a shock to h_t instantaneously impacts yd_t as predicted by the theoretical model. The procedure of placing the narrative variable first in the recursive order is also adopted for the identification of fiscal policy shocks (Ramey and Shapiro (1998) and Romer and Romer (2010)), based on the assumption that within the same quarter fiscal policy instruments do not respond contemporaneously to macroeconomic variables. In our case h_t is endogenous to CDS_t and yd_t since they are part of the information set used by the Risk Management of LCH Clearnet Ltd to settle the haircut. Nevertheless, the implementation lag of variations in haircuts ensures that CDS_t and yd_t do not affect h_t within the same business day. In this regard, the identification strategy shares the approach of the High Frequency Identification (HFI) for the effect of monetary policy surprises.[16]

A possible issue for the identification of a funding liquidity shock is that market participants may anticipate variations in haircuts. In particular, LCH Clearnet Ltd published indicative thresholds at 450 basis point spread at the 10 year maturity to AAA benchmark, or at 500 basis point at 5 year CDS spread as risks indicators.[17] However, it also states that they are key indicators to judge the credit risk of a security but do not trigger automatic actions for increases in haircuts and margin calls.[18] Anecdotal evidence suggests that changes in haircuts partly followed discretionary criteria and were to a large extent unexpected (See Bank of Italy (2013)).

In order to confirm that changes in haircut were not anticipated, I perform two statistical tests. First, I run a Granger causality test of CDS spread and yield spread to 10 year German bonds on variations in haircut at the date of the announcement of their revision. If they help predict changes in haircuts, market participants could anticipate their modifications by looking at these indicators of sovereign risk. Table 3 in the Appendix C shows that CDS spread and yield spread fail to predict announced changes in haircuts. Second, I run the Hansen (2000) test to assess the presence of a threshold regressing CDS_t on h_t.[19] Figure 12 in the Appendix C displays the graph on the normalized likelihood ratio sequence as a function of the threshold in CDS spread. The graph provides evidence of a threshold at 569 basis points, substantially higher than the 500 basis point threshold published by LCH Clearnet Ltd as a key indicator of risk.

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[15] Pelizzon, Subrahnmanyam, Tomio, and Uno (2016) show that following the implementation of 3 year LTROs the sensitivity of market liquidity to credit risk reduced. Boissel, Derrien, Ors, and Thesmar (2014) find that this policy was effective in disconnecting repo rates from CDS spreads.

[16] See Bagliano and Favero (1999), Faust, Rogers, Swanson, and Wright (2003), Nakamura and Steinsson (2013), Gertler and Karadi (2015).

[17] See http://secure-area.lchclearnet.com/member_notices/circulars/2010-10-05.asp and http://www.ecb.europa.eu/paym/groups/pdf/mmcg/Item_1_LCH_Margining.pdf?0fe79f1cef93461dc22566a4e165db44

[18] See http://ftp.lch.co.uk/risk_management/sovereign_risk_framework_faqs.asp. Furthermore, ICMA (2015) argues that \Although CCPs apply more rigorous risk management practices than many market users, their methodologies are often proprietary and therefore opaque, and it is not possible for members to scrutinize these methodologies, despite their critical dependence on them" (pag 25).

[19] The yield spread to 10 year German bonds was above 450 basis points for the whole period of the sample.

Figure 14 in the Appendix C, which compares episodes when the CDS spread exceeded 500 basis points with changes in haircuts, shows that only one increase in haircuts took place the same day when the CDS spread breached the threshold. Overall, these tests suggest that variations in haircuts were to a large extent liquidity surprises.

Figure 8 plots the response of government bond yield to one standard deviation shocks to haircut and CDS spread. The reaction of yield to a liquidity shock is positive and significant up to 3%. The impact of a credit risk shock is stronger up to 6.5%. During the crisis, credit risk accounts for a large variation in Irish government bond yields, but funding liquidity was also an important determinant for their evolution.

Figure 8: Impulse response function of government bond yields
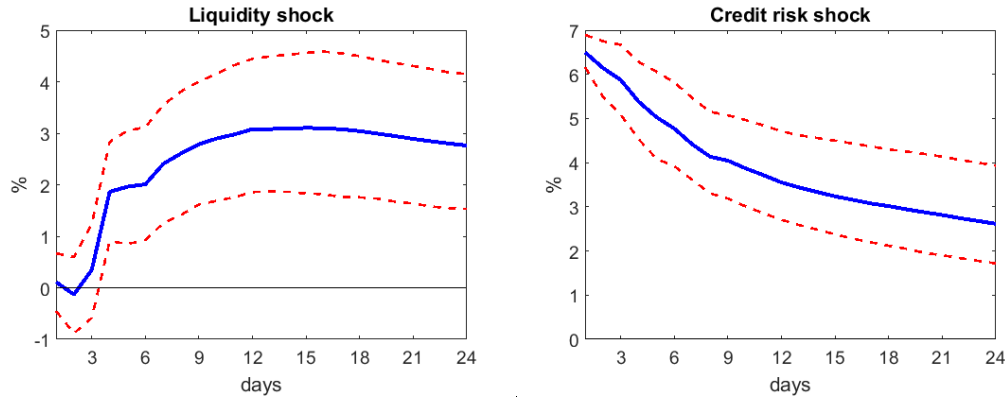
Note: This figure shows the responses of 10 year government bond to one standard deviation shocks to haircuts (LHS) and to CDS spread (RHS). The solid blue line plots the posterior median and the red dash lines are the 10th and 90th percentiles with 50000 draws for which the first 20000 are discarded as burn-in draws.

As a robustness test, I estimate impulse responses by local projections (Jordà (2005)). This approach has the advantage that it does not require transforming the VAR model into a vector moving average model for the impulse response function using estimated parameters for horizon 0 to iterate forward. The model is the following

$$yd_t = \delta' X_{t-1} + \beta shock_t + u_t \tag{28}$$

where X_{t-1} include the first four lags of the variables yd_t, CDS_t, h_t; δ collects the coefficients; $shock_t$ corresponds to the series of haircut. I use the Newey-West corrections for standard errors because of the serial correlation in the error terms induced by the successive leading of the dependent variable. The local projections method allows for a non linear model and state dependent impulse response function. Figure 15 in the Appendix C displays a non linear relationship between the variables in the VAR and Tables 4 in the Appendix C reports the results of the Hansen (2000) test for the coefficients showing the presence of a threshold for the CDS spreads. I define an economy to be in a stress state if the CDS spread is above 600 basis points as indicated by Table 4. Consider the non linear model along the lines of Owyang, Ramey, and Zubairy (2013).

$$yd_t = \delta'_L X_{t-1} + \beta_L shock_t + u_t^L \qquad \text{if } CDS_t \leq \gamma$$
$$yd_t = \delta'_H X_{t-1} + \beta_H shock_t + u_t^H \qquad \text{if } CDS_t > \gamma \tag{29}$$

where δ_k with k = L;H collects the coefficients and L stands for low and H stands for high. Figure 9 plots the impulse response function for the linear and the non linear model. Quantitatively, the impact of a liquidity shock on yield is stronger with the impulse response estimated by local projections. Figure 9 reveals some important differences between the responses in a high stress state and in a low stress state. In the first case, the high level of sovereign risk exacerbates the effect of a liquidity shock on sovereign bond yield. In particular, on impact the response is more pronounced and instantaneous. In the second case, the response is delayed.

Figure 9: Responses of government bond yields to a liquidity shock in a linear model (LHP) and a state-dependent model (RHP)
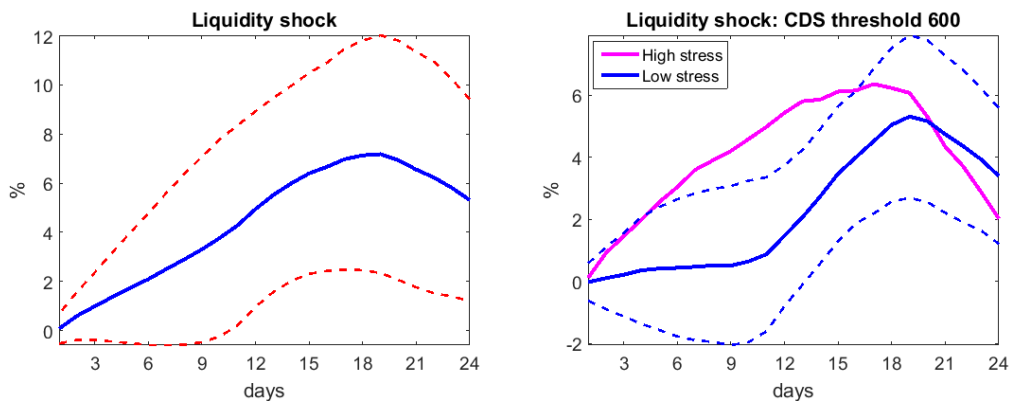
Note: These figures show the impulse response of 10 year government bond yields to a one shock of haircut. The left hand panel shows the impulse response of a linear model. The right hand panel shows the impulse response of a state-dependent model, with blue line representing the response in the regime of low CDS spread and the magenta line the response in the regime of high CDS spread. The dash lines represent 95 percent bands that are based on Newey-West standard error.

These results suggest the presence of a liquidity premium on government bonds according to their capacity to serve as collateral, in line with Bartolini, Hilton, Sundaresan, and Tonetti (2011) who find that in the US differences in the collateral values across asset classes contributes to explain yield spreads. Since the high frequency of financial series is essential for the identification of a liquidity shocks, I do not consider the impact on macroeconomic variables in the empirical analysis.[20] However, the literature finds that during the crisis surges of government bond yields were transmitted to the real economy through the banks' lending channel. Acharya, Eisert, Eufinger, and Hirsch (2014) show that banks' exposures to impaired sovereign debt explains the negative real effects suffered by European firms and their reduction in capital expenditures. This is consistent with the negative impact of a liquidity shock on investment as a result of a tightening in financial conditions, as displayed by the theoretical model in Section 4.

6 Conclusions

This paper has explored the liquidity channel of the Eurozone sovereign debt crises. It has shown that government securities play a key role as collateral in the secured interbank market, which is a primary source of funding for banks to meet their liquidity needs. Nevertheless, during the crisis repo haircuts on peripheral government bonds grew substantially following the rise in sovereign risk.

I studied the consequences of a reduction in sovereign bond liquidity with a model incorporating liquidity frictions to simulate the impact of a rise in haircuts. The model exhibits a fall in output, investments, consumptions and a rise in the liquidity spread, suggesting a flight-to-liquidity from the less liquid to the more liquid bonds. The contractionary effects of this shock can be alleviated by a policy response consisting of issuing more short-term bonds to provide investors with more liquid assets that relaxes their funding constraint. This measure is more effective when the monetary policy is constrained by the zero lower bound.

I have assessed empirically the impact of a shock to haircuts on government bond yields by estimating the impulse response function of a SVAR model and the regime-dependent impulse response function by local projections. A liquidity shock increases the yield significantly, especially in the state of high stress in the sovereign debt market, confirming the prediction of the model.

The joint escalation of sovereign bond yields and haircuts suggest an alternative channel for the European "twin crises" - the combination of sovereign weakness and banking fragility – in addition to the balance sheet channel (Gennaioli, Martin, and Rossi (2014b)) and the bail-out channel (Acharya, Drechsler, and Schnabl (2014)). Before the crisis, banks accumulated government bonds to store liquidity and use them as collateral to lever up, increasing their exposure on foreign bonds as a result of European financial integration (Bolton and Jeanne (2011)). Nevertheless, the emergence of sovereign risk on peripheral countries triggered repo haircuts to their government bonds drying up interbank

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[20] The mixed frequency VAR approach creates a bridge between high frequency financial variables and low frequency macroeconomic variables but cannot keep the daily frequency of financial variables that I exploit for the identification strategy (see Foroni and Marcellino (2014) for a survey).

liquidity. Banks in the core reduced simultaneously their position on peripheral bonds to avoid a contraction in their funding, depressing the value of these securities even more and resulting in further increases in haircuts.

The theoretical model can be extended in several dimensions. One is to introduce the risk of government default to endogenize the liquidity parameter as a function of the sovereign default, following the literature on fiscal limit (see Bi (2012) and Bi and Traum (2012)). When the level of the debt approaches the fiscal threshold the probability of default increases and the liquidity of government bond falls. A second extension would be to consider an open economy with two countries conducting independent fiscal policy and sharing monetary policy in the typical framework of a monetary union in order to study the impact of a liquidity shock on the bond issued by one country and the possible policy responses of the central bank. I leave these extensions for further research.

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A Data appendix

A.1 Definitions for repos

A repo transaction is an agreement between two parties on the sale and subsequent repurchase of securities at an agreed price. It is equivalent to a secured loan, with the main difference that legal title of securities passes from the cash borrower to the cash lender which may re-use them as collateral in other repo transactions. In order to protect the lender from the risk of a reduction in the value of collateral, repos involve overcollateralization and the difference between the value of the loan and the value of collateral is the haircut or initial margin. The haircut takes account of the unexpected loss that the lender may face due to the difficulty of selling the collateral security in response to a default by the borrower. Accordingly, it provides a measure of market liquidity of collateral from the standpoint of the lender and a measure of from the standpoint of the borrower since determines the amount of cash that can be raised given the value of collateral.

Figure 10 shows an example of bilateral repo. At time t, the cash borrower (securities dealer, commercial bank, hedge fund) posts e100 securities as collateral and receives a e90 loan from the cash lender (commercial bank, investment fund, money market fund) with a haircut of 10%. At time t+k, the borrower returns the cash with an interest of 1.1% (the repo rate) and receives back the collateral. If repo is used to finance the purchase of a security, the haircut is equivalent to the inverse of the leverage. In order to hold e100 securities the investor can borrow up to e90 from the repo lender and must come up with e10 of its own capital, so the maximum leverage is 10. A rise in haircut by 10 percentage points reduces the borrower's funding to e80 and its leverage to 5.

According to the involvement of intermediaries between the lender and the borrower, repos can be distinguished in two types. In bilateral repos, the lender and the borrower transact directly with each other, selecting the collateral, initiating the transfer of cash and securities, and conducting collateral valuation. In tri-party repos, a third party intermediates the transaction providing operational services to the parties, in particular the selection and valuation of collateral securities, but does not participate in the risk of transaction. The determinants of haircuts vary according to the repo structure. In repos that are not cleared by a Central Clearing Counterparty (CCP), the haircut reflects mainly the creditworthiness of the borrower. Instead in repos involving a CCP which bears the counterparty credit risk, haircuts are settled on the basis of the CCP's internal rules and depend on the market risk of collateral.

Figure 10: Bilateral repo contract

Time T   Time T+K
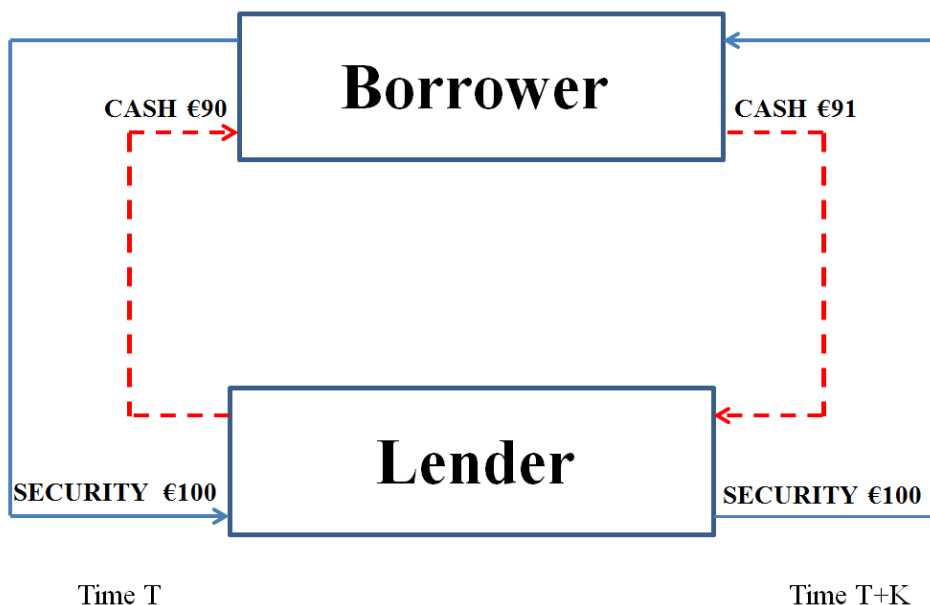
A.2 Data

Because of the lack of comprehensive information on the European repo market, we use different sources. First, Bankscope, which provide banks' balance sheet data at annual frequency showing the amount of repos and reverse repos held by credit intermediaries. It allows to compare different funding instruments, but lacks important breakdowns (such as counterparty, maturity and currency) preventing a more granular analysis and does not distinguish between repos in the interbank market from ECB monetary policy operations. Second, the European Repo Market Survey published semi-annually by the International Capital Market Association (ICMA) since 2001, which asks a sample of 67 banks in Europe for the value of their repo contracts that were still outstanding at close of a certain business date excluding repos transacted with central banks. From the data of the European Repo Market Survey we subtracted reverse repos in order to focus the analysis on the liability side of banks' balance sheets.

It reports information on the size and composition of the European repo market, including the type of repo traded, the rates, the collateral, the cash currency and the maturity. Third, the Euro Money Market Survey, an yearly survey published by the ECB since 2002 covering 101 banks, which decomposes the repo market in three segments: CCP-based, over-the-counter bilateral, and triparty. We collected data on haircuts to 10-year government bonds applied by the LCH Clearnet Ltd and LCH Clearnet SA, which are the largest European clearing houses (see Armakola, Douady, Laurent, and Molteni (2016)), and we identi_ed changes in haircuts with a narrative approach by reading the RepoClear Margin Rate Circulars through which they communicate the variation to its members. Finally, data on yields, CDS spreads and bid-ask spread come from Bloomberg.

Figure 11: Example of Repo Clear Margin Rate Circular

A.3 Banks' balance sheet

I use information on banks' balance sheet from Bankscope in order to measure the share of repos compared to other sources of funding. Since Bankscope does not distinguish repos in the private interbank market from the refinancing operations of central banks we consider 2010 in order to avoid the 3 year LTROs implemented in 2011 and 2012. Repos account for a large share of banks' liabilities especially for the largest five banks for which Bankscope report data on repos. I use banks' balance sheet in order to calibrate the parameter θ for the borrowing constraint.

Table 2: Funding structure of European commercial banks in percentage of total liabilities (2010)

Bank	Deposits	Interbank	LT debt	Repos
BNP Paribas	26.62	7.07	6.19	10.48
Barclays Bank Plc	23.41	5.89	9.89	13.26
Banco Santander	45.04	4.69	16.92	9.60
Société Generale	24.47	7.62	8.74	9.58
UBS AG	24.13	2.13	10.04	12.52
UniCredit SpA	42.99	10.83	16.96	3.39
Credit Agricole Corporate	14.43	10.63	0.70	5.61
Intesa Sanpaolo	30.84	10.32	27.99	1.99
Banco Bilbao	43.79	6.01	14.16	8.89
Commerzbank AG	34.32	12.01	13.72	7.13
Danske Bank	23.22	5.19	27.66	7.87
Skandinaviska Enskilda Banken	35.5	7.42	14.01	2.14
Bankia SA	36.78	3.43	29.6	11.56
Svenska Handelsbanken	29.21	8.06	30.27	0.49
Fortis Bank	41.18	7.68	5.50	4.30
Abbey National Treasury Services Plc	52.99	13.42	13.85	2.79
KBC	50.76	7.35	10.58	8.53
Banca Monte dei Paschi	32.35	9.41	24.56	9.86

Note: Deposits = costumer deposits; Interbank = interbank deposits; LT debt = long-term debt

Source: Bankscope

Note: Deposits = costumer deposits; Interbank = interbank deposits; LT debt = long-term debt
Source: Bankscope

B Additional Model Details and Derivations

B.1 Firms

Competitive final good producers combine differentiated intermediate goods Y_{it}, for i ∈ [0,1] into a single homogeneous final good Y_t, using a constant return to scale technology in the form of Dixit and Stiglitz (1977)

$$Y_t = \left[\int_0^1 Y_{it}^{\frac{1}{1+\lambda_f}} di \right]^{1+\lambda_f} \qquad (30)$$

where $\lambda_f > 0$. They take input prices P_{it} and output prices P_t as given and their demand for the generic ith intermediate good is

$$Y_{it} = \left[\frac{P_{it}}{P_t} \right]^{-\frac{1+\lambda_f}{\lambda_f}} Y_t \qquad (31)$$

The zero profit condition for competitive final-goods producers implies that the aggregate price level is

$$P_t = \left[\int_0^1 P_{it}^{-\frac{1}{\lambda_f}} di \right]^{-\lambda_f} \qquad (32)$$

The monopolist firm i hires labor services and rent capital from households to produce the intermediate good using the following technology

$$Y_{it} = K_{it}^{\alpha} H_{it}^{1-\alpha} \tag{33}$$

where $\alpha \in (0; 1)$. K_{it} denotes the capital services and H_{it} the quantity of labor hired by the ith intermediate-good producer, which sets prices P_{it} subject to Calvo (1983) scheme frictions, taking the rental rate of capital r_t and the real wage W_t/P_t as given. With probability $1 - \zeta_p$, the firm can reset its price and with probability ζ_p cannot. By the law of large numbers, the probability of changing the price corresponds to the fraction of firms that rest the price, so each period a randomly selected fraction of firms $1 - \zeta_p$ can reoptimize the price to maximize the present discount value of profits.

B.2 Labor market

The labor markets mirrors the structure of the good market along the lines of Erceg, Henderson, and Levin (2000). Competitive labor agencies aggregate differentiated j labor inputs into a homogeneous single labor service H_t according to the technology

$$H_t = \left[\left(\frac{1}{1-\gamma} \right)^{\frac{\lambda_w}{1+\lambda_w}} \int_{\gamma}^{1} H_t(j)^{\frac{1}{1+\lambda_w}} \right]^{1+\lambda_w} \tag{34}$$

where $\lambda_w > 0$. Labor agencies sell labor services H_t to intermediate good producers for the nominal wage rate W_t. The first order condition for labor services determines the demand curve for the jth labor type:

$$H_t(j) = \frac{1}{1-\gamma} \left[\frac{W_t(j)}{W_t}^{-\frac{1+\lambda_w}{\lambda_w}} \right] H_t \tag{35}$$

Labor unions represent all types of workers and set the wage rate $W_t(j)$ for the specific labor input j taking as given the demand for their specific labor input and subject to the Calvo scheme frictions on a staggered basis, taking as given the demand for their specific labor input.

Each period, labor agencies are able to reset the wage $W_t(j)$ with probability $1 \ \square \ \_w$ and with probability $\_w$ they cannot and the wage remains fixed. By the law of large number, the probability of changing the wage corresponds to the fraction of workers whose wages change. Households supply whatever labor is demanded at that wage. If labor agencies can modify the wage, they will choose the wage W_t to maximize their utility function.

B.3 Capital-good producers

The creation of new capital is delegated to competitive capital-good producers who transform consumption goods into investment goods. They choose the amount of investment goods to maximize the profits taking the price of investment goods p_t^I as given

$$D_t^I = \left\{ p_t^I - \left[1 + \Gamma \left(\frac{I_t}{I} \right) \right] \right\} I_t \tag{36}$$

The price of investment goods differ from the price of consumption goods because of the adjustment costs, which depends on the deviations of actual investment from its steady-state value. $\Gamma(.)I_t$ reflects the adjustment cost and $\Gamma(.)$ is a measure of technology illiquidity, capturing the difficulty to undo investment. We assume that $\Gamma(1) = \Gamma'(1) = 0$ and $f''(1) > 0$. The first order condition for this problem is

$$p_t^I = 1 + \Gamma \left(\frac{I_t}{I} \right) + \Gamma \left(\frac{I_t}{I} \right) \frac{I_t}{I} \tag{37}$$

C Empirical tests

Table 3: Granger causality tests

| Hypothesis test	Result	F statistics	Critical value
Do CDS spreads Granger-cause variations in haircut ?	No	2.25	3.88
Do yield spreads Granger-cause variations in haircut ?	No	0.40	3.88

Note: The number of lags is selected using the Bayesian Information Criterion (BIC) considering a maximum of 10 lags. Tests are performed at the significance level of 0.05. If the F-statistics is lower than the critical value, we accept the null hypothesis that variable X does not Granger causes variable Y.

## Figure 12: Confidence interval construction for threshold
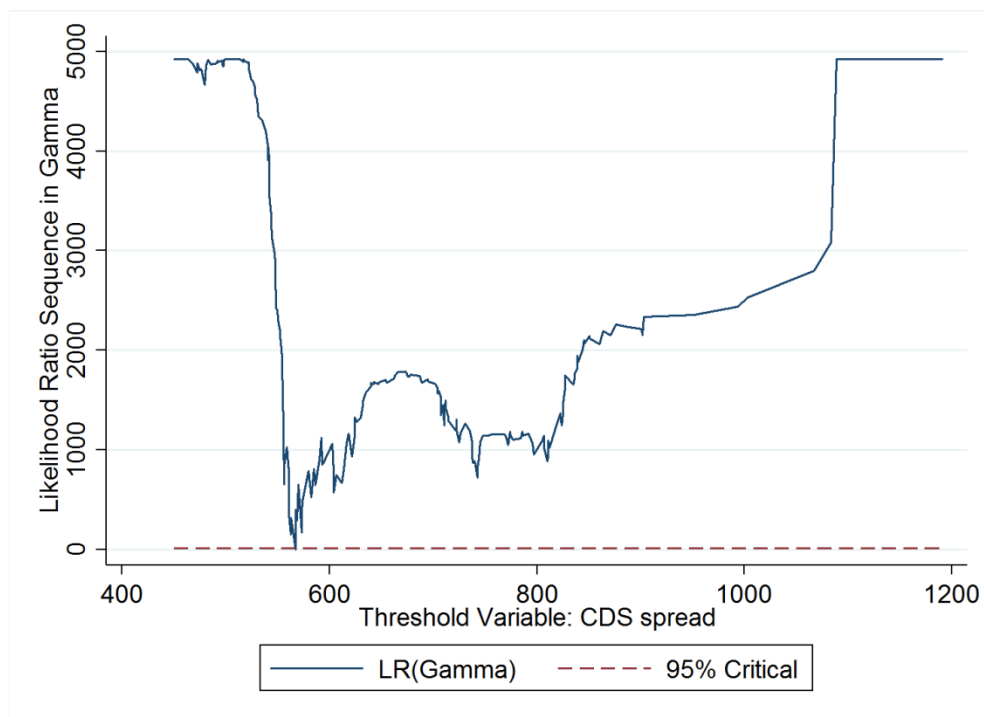
Note: The threshold test statistics is plotted for the regression $h_t = \alpha_0 + \alpha_1 CDS_t$ The figure displays a graph of the normalized likelihood sequences as a function of the threshold (CDS_t). The dotted line plots the 95% critical value.

**Figure 13: Repo haircut and 500 bp threshold of CDS spread**
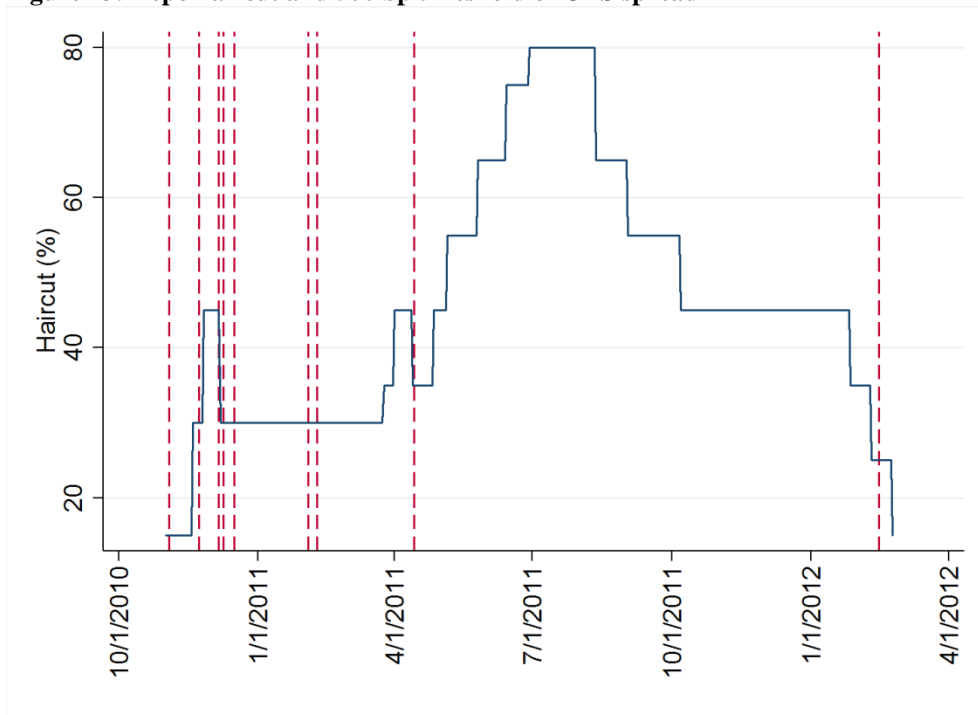
Note: The blue line plots the haircuts on 10-year Irish government bonds applied the LCH Clearnet Ltd. The dash red vertical lines represent the episodes when the CDS spread of Irish government bonds breached the 500 basis point threshold.

Figure 14: CDS spread and thresholds
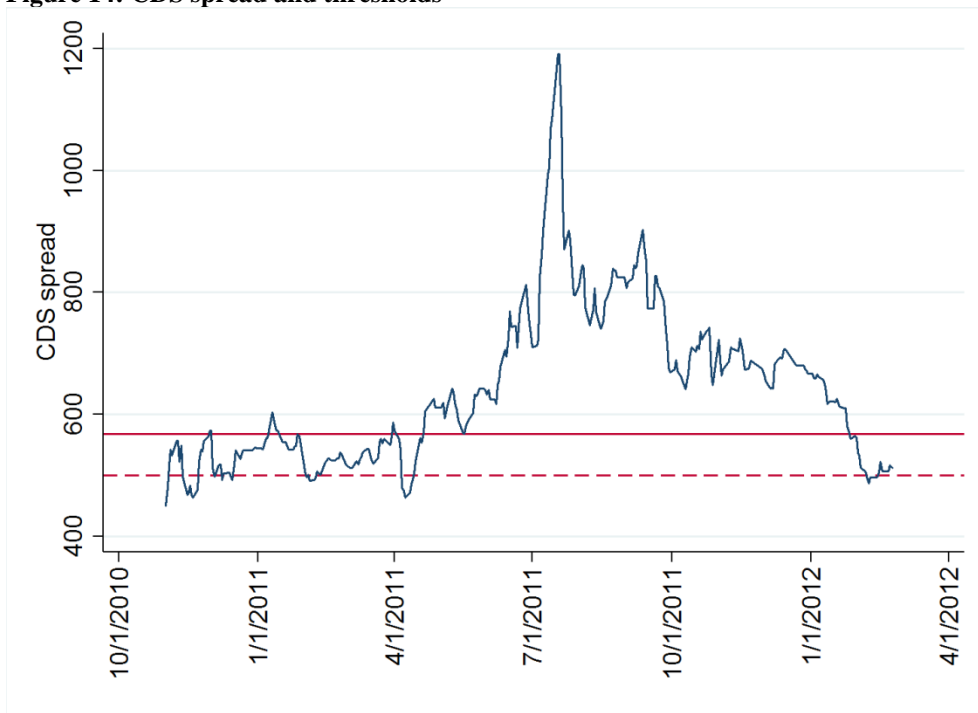
Note: The blue line plots the CDS spread. The red dash line shows the announced threshold of 500 basis points and the solid red line the threshold suggested by the Hansen test in Figure12.

Figure 15: 3D scatter chart
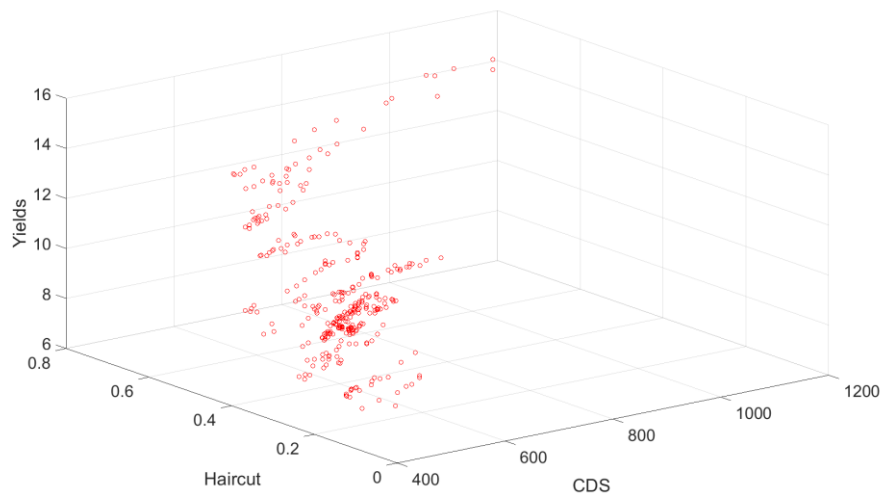
Note: This figure shows the 3D scatter chart for yields, haircut and CDS spread.

Table 4: Hansen's (2000) test for the presence of threshold effects

Threshold variable	A	B	p-value
yd_{t-1}	**8.76**	25.76	0.02
yd_{t-2}	8.879	25.38	0.08
yd_{t-3}	8.999	23.62	0.16
yd_{t-4}	8.91	24.42	0.08
CDS_{t-1}	**585.22**	27.47	0.01
CDS_{t-2}	**593.93**	23.32	0.04
CDS_{t-3}	**568.86**	23.28	0.02
CDS_{t-4}	616.55	24.99	0.06
h_{t-1}	**0.45**	23.74	0.04
h_{t-2}	0.55	18.47	0.34
h_{t-3}	0.35	20.79	0.2
h_{t-4}	0.35	19.82	0.14

Notes: The equation contains four lags. The test is an LM-type test for the null hypothesis that there is no threshold effect. The table reports the estimate of the optimal threshold value estimate, the LR test, and a bootstrap-based p-value calculated with 1,000 draws and a 15% trimming value of the sample to allow for sufficient degrees of freedom. The test corrects for left-over heteroskedasticity. Entries in bold signify evidence of a threshold at the conventional 95-percent confidence level.