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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

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How QE changes the nature of sovereign risk

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Abstract

We examine the effect of Quantitative Easing (QE) by the ECB on the sovereign bond risks of Italy, Ireland, Spain and Portugal. First, outcomes of panel regression models suggest that QE lowered the effect of volatility on sovereign bond spreads by 1 to 2 percentage points. Compared to asset purchases aimed at easing the monetary stance, purchase programmes supporting monetary transmission by countering financial market stress most clearly reduced the effect of volatility on spreads. Second, using a contingent claims model (CCM), the values of the implicit put options provided by QE as a backstop to investors are calculated to be substantial. Our results guide policymakers on the use of backstop facilities for sovereign bond markets.

JEL classification: E52, E58, G12
Keywords: Quantitative Easing, Sovereign risk, Sovereign spreads, Contingent Claims Model

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1. Introduction

Since the Global Financial Crisis (GFC), central banks have used large scale asset purchase programmes. These Quantitative Easing (QE) programmes are regularly aimed at easing the monetary stance, by lowering interest rates to prevent downward inflation spirals. Some QE programmes also aim at supporting the monetary transmission process, for instance by countering financial market stress. A rich literature documents the effects of asset purchases on bond yields and credit spreads (see for instance Van den End and Titzck (2021) for an overview). These effects relate to the signaling channel, the duration extraction channel and the portfolio rebalancing channel. There is however less research about the effectiveness of QE as an instrument to stabilize markets by providing a backstop for some tail risks in sovereign bond markets, in support of monetary transmission. This tail risk relates to sovereign default risk and associated risk aversion and to disorderly market conditions in public debt markets such as market illiquidity, fire sales, and asset price volatility. In the Economic and Monetary Union (EMU) such risks came to the fore during the sovereign debt crisis in 2010-2012 and the start of the COVID-19 pandemic.

Following Costain et al. (2021) we relate the credit risk extraction channel to the backstop function that is provided by sovereign bond purchases of the central bank. This backstop can be explicit, if asset purchases are conducted to stabilize financial markets. The backstop can also be implicit if asset purchases, conducted for the purpose of maintaining price stability or supporting monetary transmission, make interest payments on sovereign debts more sustainable by lowering sovereign bond yields (while the interest payments to the central bank will return to the treasury as dividends). Our paper contributes to the literature by examining the effect of the backstop function of QE on the relation between bond market volatility and sovereign bond spreads. This enables us to distinguish the effects of market stabilization programmes from the effects of regular asset purchase programmes aimed at the monetary stance, which related studies usually do not distinguish.

The prime QE programme of the ECB to ease monetary and financial conditions is the Public Sector Purchase Programme (PSPP), which was activated in 2015. By purchasing government bonds of EMU countries the PSPP's purpose is to address the risks of a prolonged period of too low inflation, by lowering long-term bond yields. While this supports the fiscal position of EMU governments, the PSPP is not a market stabilization instrument. Nonetheless, the PSPP has changed the character of the sovereign bond market, since the ECB holds a significant amount of sovereign debt of EMU countries.

In addition, over the last decade, the ECB has increasingly used QE as a market stabilization instrument to reduce the fragility of EMU sovereign bond markets. De Grauwe and Ji (2013) show that in countries where QE is applied as a market stabilization instrument there is less evidence for overshooting credit spreads. The ECB activated the Securities Markets Programme (SMP) in 2010 to ensure the depth and liquidity in malfunctioning segments of the sovereign bond markets. This classifies it as a market stabilization instrument. Similarly, the Outright Monetary Transactions programme (OMT) was announced by the ECB in 2012 "to address severe distortions in government bond markets which originate from, in particular, unfounded fears on the part of investors of the reversibility of the euro. Hence, under appropriate conditions, OMTs are an effective backstop to avoid destructive scenarios with potentially severe challenges for price stability in the euro area" (Draghi, 2012). The purpose of OMT to avoid bad equilibria classifies it also as a market stabilization instrument. The announcement of OMT effectively calmed financial markets and the actual use of this instrument was not needed. In March 2020, the Pandemic Emergency Purchase Programme (PEPP) was introduced as a non-standard monetary policy measure with both a monetary stance and a market stabilization objective (Lane, 2020). This programme had to provide investors the reassurance that self-fulfilling market instability risks will be contained by the stabilizing presence of the central bank liquidity provision. The PEPP successfully contributed to stabilize sovereign bond markets, as the level and volatility of bond yields returned to pre-crisis levels within several months after the start of the pandemic.

The market stabilization role of the central bank supports the low-risk status of sovereign debt. Brunnermeier et al. (2020) relate this to the central bank's role as market-maker of last resort, which guarantees the possibility of trading sovereign bonds by keeping bid-ask spreads low. In principle, the market stabilization function is only needed in situations where the market fails to coordinate a good equilibrium. De Grauwe and Ji (2013) hypothesize that sovereign bond markets in the EMU are more vulnerable to this than in stand-alone countries because there is no single national central bank that can act as a monetary back-stop for sovereign default risk. This can lead to a bad equilibrium with rising sovereign spreads, capital outflows and increasing sovereign default risk. Therefore the asset purchases by the ECB have an important signaling function for the low-risk status of EMU sovereign bonds.

By acting as market-maker of last resort the central bank changes the nature of sovereign risk. The central bank backstop in fact removes some tail risks from the market. This shares features with a put option written by the central bank to investors. The option can be exercised by investors in extreme market conditions through selling the sovereign bonds that they hold in their portfolio to the central bank. These extreme market conditions refer to a common shock that affects all countries in the EMU. This option protects these investors against some tail losses on their bond holdings. Consequently, the existence of the implicit put option will induce investors to change their expectations about the safety of sovereign bonds, i.c. their assessment of liquidity and sovereign default risk.

Against this backdrop, we investigate how QE changes the nature of sovereign risk. Our research question is to determine to what extent the ECB's asset purchases have effectively lowered sovereign risk spreads of crisis-prone EMU countries through reducing the effect of volatility on sovereign bond markets. We analyze this question through the lens of the credit risk extraction channel, for which we use the volatility of sovereign bond returns as indicator. High volatility reflects high uncertainty about debt sustainability, for which investors will require a risk premium. This premium is a compensation for default risk and related liquidity risk on sovereign bonds and is a component of the credit spread.

Because excessive volatility usually reflects distressed market conditions, the central bank may try to stabilize markets by activating a QE programme. By lowering sovereign bond yields, QE contributes to the sustainability of public debt, because lower yields enable sovereigns to borrow at more favorable conditions. To test this we focus on a number of key crisis-prone EMU countries which were eligible for the PSPP, in particular Italy, Ireland, Spain, Portugal. These countries likely benefit more from the market stabilization effect of QE than the less crisis-prone countries.

We use two modelling approaches to examine the market stabilization effect of QE. Both approaches link volatility of sovereign bond returns to sovereign credit spreads. We assume that this volatility is an indicator for uncertainty about sovereign bond values. Sovereign credit spreads include a compensation for tail risks in sovereign bond markets, associated with default risk, liquidity risk and exchange rate or redenomination risk. First we estimate a panel regression model, following De Haan et al. (2014). We extend their model by including a monetary policy variable to assess to what extent the volatility-reducing effects of QE lowered sovereign spreads. The outcomes of the panel regression show that the market stabilization effect of QE lowered the spreads for the four EMU countries in our sample by 1 to 2 percentage points since the start of the PSPP in 2015. The programmes with a market stabilization objective, i.e. SMP, OMT and PEPP, reduced the effect of volatility on spreads most clearly. The SMP and PEPP contributed to lower spreads through the flow of bond purchases (the flow effect could not be tested for the OMT since this programme was never activated). This effect is not found to be significant for the PSPP programme.

Second, as a complementary approach we use a structural credit risk model to assess the market stabilization function of QE on sovereign risk. Based on a contingent claims model (CCM) we postulate that QE features as a put option written by the central bank to bond holders which protects them against tail risk. It resembles the market stabilization function of QE, through which the central bank purchases bonds from investors in stressed market conditions that directly or indirectly affect all EMU countries. The implicit central bank put option provides investors with a backstop to sell their bonds to the central bank when the bond value drops and sovereign risk spreads increase. The central bank will step up its purchases at spread levels that are associated with dysfunctioning bond markets. In such conditions, the value of the put option will increase as simulated with the CCM. The CCM provides a framework to quantify the value of the market stabilization function of QE. An important parameter that determines this value is the volatility of the return on the underlying bonds. Since the market stabilization function of QE particularly influences bond market volatility, we conduct counterfactual simulations for the option value, based on the volatility parameter. The simulations show that the market stabilization policy by the ECB was valuable to investors in the sovereign bonds of the four countries in our sample.

The remainder of the paper is structured as follows. Section 2 provides the context of the market stabilization function of QE. Section 3 presents the panel regression model, and discusses the results. Section 4 presents the Contingent Claims model (CCM) and discusses the results. Section 5 concludes.

2. The market stabilization function of QE: concept and measurement

In this section, we first elaborate on different components of credit risk and then describe the quantitative easing (QE) programmes.

2.1 Credit risk components

Credit risk measures the probability and size of economic losses resulting from a borrower defaulting on its contractual obligations towards a debtor. There are several degrees of a loss that can be treated as separate credit risk components. First, investors require a compensation for the expected loss. This measure is forward-looking and conditional on, for instance, the firm's current value, leverage, volatility, debt structure and the risk-free interest rate. Second, risk-averse investors will also require a compensation for the unexpected loss. Typically the unexpected loss also serves as the basis for determining the economic capital that a financial institution or firm needs to allocate to absorb the risk. Third, when risk aversion is very high investors also want to be compensated for losses that go beyond the unexpected loss (i.c. stress loss embedded in the tail of a loss distribution; Figure 1).

[insert Figure 1]

Measures of credit risk therefore take into account tail risks, which are associated with default risk, which in turn may interact with liquidity or exchange rate risk. Such tail risks will show up in extreme values of the variance of asset returns, or peaks in volatility. In credit risk models, tail risk is usually expressed in terms of a number of standard deviations of a certain loss amount (see Chatterjee, 2015 for an overview). It captures the likelihood that a credit related loss exceeds the expected loss, measured by the number of standard deviations by which the actual loss deviates from the expected loss at a certain confidence level

Empirical literature finds that the compensation and risk premiums required for these credit risk components is time-varying (e.g., Heynderickx et al., 2016). Tail risk can be difficult to diversify by investors due to the high correlation existing between defaults on individual assets in stressed market conditions. Correlated defaults are associated with systemic risk and financial instability (see for instance Ibragimov et al., 2011 and Patro et al., 2013). Central banks try to mitigate this risk by providing a backstop to financial markets, e.g., by extending liquidity provision to counterparties and/or by asset purchases.

In structural credit risk models, like the CCM, the credit or default risk is driven by uncertainty in the assets value (A) of a firm, or a debtor in general, relative to its debt obligations (i.e. the default barrier). The CCM is useful for deriving risk-neutral default measure estimates. For that the CCM assumes that the value of assets evolves through time by a stochastic process in the form of a geometric Brownian motion, which is driven by a drift term (μ) and a random or stochastic term ($\sigma_A dZ$).

$$\frac{dA_t}{A_t} = \mu dt + \sigma_A dZ_t \qquad (1)$$

The drift term μ represents the instantaneous expected growth rate of the asset value, σ_A represents the instantaneous standard deviation expected growth rate, dt an infinitesimal time interval and Z_t is a Wiener process. Eq. (1) assumes that the instantaneous change in the asset value has a normal distribution with mean μ and standard deviation σ_A and that returns are identically and independent distributed over time (assuming informational efficiency of markets). Assuming complete and frictionless markets (no arbitrage), the value of a contingent claim on a firm's assets can be calculated as the discounted expected value of future payoffs, using a risk-neutral probability measure. This measure is based on the risk-free rate (replacing μ). It postulates that the contingent's claim value is independent of investors' risk aversion and the risk premium.

Against this backdrop, we use the realized volatility of sovereign bond price returns as an indicator for sovereign default risk, since this is associated with tail risk related to uncertainty about the value of sovereign bonds. Realized volatility is time-varying and driven by risk aversion and thereby addresses the limitation of the CCM of assuming Gaussian distributed probability distributions with fixed parameters. Figure 2 shows the realized volatility of sovereign bond price returns of the EMU countries in our sample. Volatility here is measured as the annualized standard deviation of daily bond returns calculated over a 45-day horizon. Volatility was low until the Great Financial Crisis in 2008, which was a wake-up call for investors that sovereign bonds of EMU countries are risky. Volatility has peaked occasionally since then, most strongly during the European sovereign debt crises of 2010-2012. In that period the ECB introduced QE. At the start of the pandemic, in March 2020, volatility peaked again and the ECB implemented additional monetary policy measures.

[insert Figure 2]

2.2 QE programmes

The ECB has conducted sovereign bond purchases via several programmes since the sovereign debt crisis of 2010-2012 (Figure 3). We jointly define them as QE programmes, while acknowledging that an individual programme may have a specific objective. The ECB activated the Securities Markets Programme (SMP) in 2010 and announced the Outright Monetary Transactions (OMT) programme in 2012. While the latter has never been used, the SMP resulted in ECB purchases of Greek, Irish, Portuguese, Italian and Spanish sovereign bonds. The programme aimed at addressing the malfunctioning of these sovereign bond markets to support the monetary transmission process. This qualifies the SMP as a market stabilization instrument, targeting stressed market segments to reduce severe market tensions. Empirical studies show that the SMP had a downward effect on targeted sovereign bond yields (see, for instance, ECB, 2015).

[insert Figure 3]

Since 2015 the ECB purchases government bonds of EMU countries with the Public Sector Purchase Programme (PSPP), which is the largest programme in terms of assets purchased (Figure 3). The purpose of the PSPP is to contribute to the monetary stance by addressing the risks of a too prolonged period of low inflation. The bonds purchased under the PSPP are guided by the Eurosystem's national central banks' capital key, subject to issue share and issuer limits. These rules aim to preserve market functioning and price discovery and to ensure the purchases would not be perceived as circumventing the euro area's monetary financing prohibition. While the PSPP was not introduced as a market stabilization instrument, it contributed to reduce sovereign bond yields by several tens of basis points at announcement (Altavilla et al., 2015). The long-term stock effects of the PSPP on euro area bond yields are estimated to range from 50 to 100 basis points (Eser et al., 2019).

In March 2020, the Pandemic Emergency Purchase Programme (PEPP) was introduced as a programme with a dual role for market stabilization and delivering the monetary accommodation required for price stability (Lane, 2020). This programme provides investors the reassurance that self-fulfilling market instability risks will be contained by the stabilizing presence of the ECB's liquidity provision. The PEPP successfully contributed to stabilize sovereign bond markets in the beginning of the pandemic, as the level and volatility of bond yields returned to pre-crisis levels within several months.

[insert Table 1]

3. Panel regression model

This section first discusses related studies on the effect of central bank asset purchases on bond spreads, followed by our panel regression model, respectively.

3.1 Related literature

Our panel regression model is an extension of De Haan et al. (2014). They examine the extent to which large swings of sovereign yields in peripheral EMU countries during the euro debt crisis of 2010-2012 can be attributed to fundamentals, focusing on the inherent uncertainty in bond yield models. They estimate different models for 11 euro countries plus 6 non-euro countries (for comparison purposes) over the period 2001-2013 and show that the outcomes are strongly affected by modelling choices which affect the explanatory power of macro fundamentals and the extent of mispricing. We extend the approach of De Haan et al. by focusing on the dampening effect of QE on the relation between sovereign bond volatility and spreads. Their panel regression approach is more appropriate for our research question than an affine term structure model, since we focus on one particular component in the bond yield (i.c. the compensation for sovereign default, or tail risk) and we do not model the complete yield curve.

A common conclusion in the literature is that the OMT mitigated sovereign related risks. Krishnamurthy et al. (2017) find that the OMT, like the SMP reduced market segmentation, redenomination and default risk in crisis-prone EMU countries. Gilbert (2019) shows that the

OMT broke the negative feedback loop between EMU member states by limiting negative spill-overs. Other research finds that sovereign bond purchases by the PSPP were associated with positive spill-overs to crisis-prone countries that benefitted from lower bond yields due to rebalancing of investors towards higher yielding government bonds (Mudde et al., 2021).

The recent empirical literature on the effect of QE on bond markets indicates that QE is particularly effective in reducing credit spreads in distressed market conditions. Bailey et al. (2020) relate this to the liquidity channel of QE, which depends on market or informational frictions, to which the central bank responds by asset purchases that encourage trading and reduce liquidity premia. As a result, QE particularly has a strong effect on risk spreads in times of financial turbulence, implying that the impact is state contingent. Vissing-Jorgensen (2020) provides evidence for the Fed's market-stabilization role of QE during the Covid crisis. The outcomes of her regression model show that the liquidity providing effect of the Fed's asset purchases led to a substantial reduction of Treasury yields.

Hondroyiannis and Papaoikonomou (2021) estimate the effect of the ECB's sovereign bond purchases in the Covid crisis, based on a time-varying parameter model which includes macroeconomic and financial market variables. They find stronger effects of asset purchases on bond yields of peripheral countries and generally diminishing marginal effects over time. They explain the effect of QE on bond yields by the commitment of the ECB to the integrity of the common currency that reduces systemic risk, similar to the role of QE as backstop for tail risk that we examine. Costain et al. (2021) show that the announcement of PEPP in March 2020 created a (parallel) downward shift in the Italian yield curve. The authors argue that this is due to 'credit risk extraction', caused by the expected absorption of peripheral bonds by the PEPP and by an endogenous decrease in the default probability of Italy.

A related study is Monteiro and Vasicek (2019) who estimate the effect of QE on sovereign bond spreads with a panel regression model. They conclude that unconventional monetary policy has played an important role in stabilizing sovereign debt markets since 2012. Paniagua et al. (2017) use a time-varying unobserved components model to disentangle the role of fundamental variables and market risk perception to explain changes in sovereign spreads in EMU countries during crises. They find that risk-aversion of creditors, fiscal indebtedness and liquidity variables are important determinants of bond spreads.

Our approach contributes to the literature by using the relation between the sovereign spread and bond return volatility as indicator for the effectiveness of market stabilization by QE. This helps to distinguish the effects of market stabilization programmes on sovereign spreads from the effects of more regular asset purchase programmes. Related studies use more generic financial market indicators to measure the effect of asset purchases and usually do not distinguish between the different types of asset purchase programmes. Next to that, our application of the CCM model contributes to the literature by providing a structural representation for the backstop function of central bank asset purchases.

3.2 Panel model

We estimate the relationship between sovereign bond spreads and macroeconomic variables and financial market conditions by means of a panel regression model, similar to De Haan et al. (2014). The baseline model is specified as:

$$r_{it} - rf_t = \alpha_{0i} + \alpha_1 cpi_{it} + \alpha_2 gdp_{it} + \alpha_3 debt_{it} + \alpha_4 vol_{it} + \alpha_5 car_{it} + \alpha_6 nfa_{it} + \alpha_7 rs_t + \alpha_8 ru_t + \alpha_9 hilo_{it} + \varepsilon_{it} \quad (2)$$

The dependent variable is the sovereign bond spread, defined as the 10 year sovereign bond yield (*r*) minus the risk-free rate (*rf*) for which we use the 10 years OIS (euro overnight index) swap rate. The subscripts *i* and *t* refer to country *i* and month *t* respectively. The explanatory variables are the expected inflation rate (*cpi*), expected real gdp growth rate (*gdp*), expected government debt ratio in percent of gdp (*debt*), expected current account balance in percent of gdp (*car*), net foreign assets in percent of gdp (*nfa*), and the bond return volatility (*vol*). The latter is an indicator for market stress, which, amongst others, may be related to risk aversion and reduced market liquidity (see further Section 3.3 for variable definitions). Since QE as market stabilization instrument is most likely activated in stressful market conditions, we control for the state of the market. This is done by including variable *hilo*, which is a non-parametric measure for extreme movements in sovereign bond prices, i.c. the monthly average of daily differences between the highest and lowest sovereign bond price.[1] As another extension of the De Haan et al. (2014) model, two proxy variables for monetary

[1] Being a non-parametric measure for tail movements in sovereign bond prices, variable *hilo* is distinct from variable *vol*, which is a parametric measure based on the standard deviation of log bond price returns (see Appendix A). The correlation between *hilo* and *vol* across the panel of countries is +0.59.

policy are added as controls: the shadow rate (rs) and the unexpected response of the risk-free rate to monetary decisions (ru). The former controls for the anticipation of monetary measures by market participants as the shadow rate is based on yield curve data. The shadow rate has been negative since January 2012 (Figure 4).

[insert Figure 4]

Our priors for the coefficients of the macroeconomic and volatility variables are: $\alpha_1, \alpha_3, \alpha_4, \alpha_9 > 0$ and $\alpha_2, \alpha_5, \alpha_6 < 0$. We have no prior on the effect of the shadow rate on the sovereign risk premium α_7. Finally, the effect of monetary surprises on the spread α_8 is a priori unclear. Figure 5 shows the time series for these surprises.

[insert Figure 5]

Our assumption is that unconventional monetary policy in general, and QE in particular, changes the link between bond market volatility and sovereign spreads. Whereas normally a high bond market volatility contributes to a high sovereign bond spread, this relation may be less strong or even disappear due to QE. We postulate that the relationship between volatility and spreads changed as a result of QE. Therefore, we estimate this relationship for two episodes or regimes, the first before and the second after the start of large-scale asset purchases by QE. Specifically, to analyze to what extent QE affects the component of the credit spread that compensates investors for volatility, we interact the bond return volatility (vol_{it}) in two alternative ways: (1) with a QE dummy (D_t^{QE}) which has value 1 for the period since January 2015 when the ECB announced the PSPP and 0 otherwise,[2] (2) with the shadow rate (rs_t) which became increasingly negative in the PSPP period. The methods are complementary, as the first method shows how the relationship changes between periods without and with large-scale QE while the second method gives an estimate of the effect of monetary policy on the relationship between market stress and bond spreads. By introducing these interaction terms, we allow for non-linearities in the relationship between spreads and volatility.

[2] We also formally tested whether 2015m1 is a breakpoint for the relationship between spreads and volatility. The absence of such a breakpoint was strongly rejected by the breakpoint test of Ditzen (2021).

We date the QE dummy similar to the PSPP period because since then the ECB has become an increasingly dominant investor in the sovereign bond market (Figure 3). With its almost continuous market presence the PSPP is the largest programme in terms of assets purchased. This implies that the QE dummy does not capture the effect of market stabilization per se, given that the PSPP primarily aims at the monetary stance. The effect of pure market stabilization programmes is estimated in Eq. (5)-(6).

The model including the interaction of bond return volatility with the QE dummy (D_t^{QE}) is specified as:

$$r_{it} - rf_t \ = \alpha_{0i} + \alpha_1 cpi_{it} + \alpha_2 gdp_{it} + \alpha_3 debt_{it} + \alpha_4 vol_{it} + \alpha_5 car_{it} + \alpha_6 nfa_{it} + \alpha_7 rs_t + \alpha_8 ru_t + \alpha_9 hilo_{it} + \alpha_{10} D_t^{QE} vol_{it} + \alpha_{11} D_t^{QE} + \varepsilon_{it} \qquad (3)$$

The model including the interaction of bond return volatility with the shadow rate is specified as:

$$r_{it} - rf_t \ = \alpha_{0i} + \alpha_1 cpi_{it} + \alpha_2 gdp_{it} + \alpha_3 debt_{it} + \alpha_4 vol_{it} + \alpha_5 car_{it} + \alpha_6 nfa_{it} + \alpha_7 rs_t + \alpha_8 ru_t + \alpha_9 hilo_{it} + \alpha_{10} rs_t vol_{it} + \varepsilon_{it} \qquad (4)$$

To compare the market stabilizing effect of the different asset purchase programs we replace D_t^{QE} in Eq. (3) by separate dummy variables for the SMP, OMT, PSPP and PEPP:

$$r_{it} - rf_t \ = \alpha_{0i} + \alpha_1 cpi_{it} + \alpha_2 gdp_{it} + \alpha_3 debt_{it} + \alpha_4 vol_{it} + \alpha_5 car_{it} + \alpha_6 nfa_{it} + \alpha_7 rs_t + \alpha_8 ru_t + \alpha_9 hilo_{it} + \alpha_{10} D_t^{SMP} vol_{it} + \alpha_{11} D_t^{OMT} vol_{it} + \alpha_{12} D_t^{PSPP} vol_{it} + \alpha_{13} D_t^{PEPP} vol_{it} + \alpha_{14} D_t^{SMP} + \alpha_{15} D_t^{OMT} + \alpha_{16} D_t^{PSPP} + \alpha_{17} D_t^{PEPP} + \varepsilon_{it} \qquad (5)$$

The QE programme dummies are 1 for the period since the ECB announced or introduced the particular programme (SMP: May 2010, OMT: July 2012, PSPP: January 2015, PEPP: March 2020). We estimate the model with different windows for the QE programme dummies, i.c. windows ending 3, 6, 12 and 18 months from the start of the programme, respectively. This makes the effect of the programmes comparable, taking into account that they have a different length in practice. Moreover, the relatively short windows contribute to identify the effect of the QE programmes, separate from other monetary measures such as targeted long term refinancing operations (TLTRO) for which banks can pledge sovereign bonds as collateral.

To examine the potentially different effects of the flows of asset purchases on sovereign spreads, we interact the QE programme dummies with a variable for the flows of purchased sovereign bonds (*flow*, as in Eq. (6)). We exclude the OMT in this equation since no bonds were actually purchased under this programme.

$$r_{it} - rf_t = \alpha_{0i} + \alpha_1 cpi_{it} + \alpha_2 gdp_{it} + \alpha_3 debt_{it} + \alpha_4 vol_{it} + \alpha_5 car_{it} + \alpha_6 nfa_{it} + \alpha_7 rs_t + \alpha_8 ru_t + \alpha_9 hilo_{it} + \alpha_{10} flow_{it} + \alpha_{11} D_t^{SMP} flow_{it} + \alpha_{12} D_t^{PSPP} flow_{it} + \alpha_{13} D_t^{PEPP} flow_{it} + \alpha_{14} D_t^{SMP} + \alpha_{15} D_t^{PSPP} + \alpha_{16} D_t^{PEPP} + \varepsilon_{it} \quad (6)$$

The flow effect could be related to the liquidity channel of QE (Bailey el al., 2020), which would imply that the programmes with a market stabilization objective mainly have an effect on bond spreads through the flow of asset purchases.[3] Hence, our priors for the SMP and PEPP (the two explicit market stabilization programmes) interaction terms are: $\alpha_{11}, \alpha_{13} < 0$.

A potential problem of the panel model, which it shares with all regression models, is endogeneity. Technically, endogeneity occurs when an explanatory variable in a regression model is correlated with the error term. This can occur under a variety of conditions, but two cases are especially common: (1) when important variables are omitted from the model (called "omitted variable bias") and (2) when there is feedback from explanatory variables to the dependent variable and, hence, the outcome variable is not simply a response to the explanatory variables (called "simultaneity bias"). The second case may be especially relevant in our setting. Sovereign bond spreads affect countries' macro-economic fundamentals and financial market conditions. Concerning the main regressor – volatility (*vol*) – endogeneity is addressed in the single equation models by an instrumental variable approach, which constructs an instrument for *vol* based on lags of all the internal variables (i.c. the regressors) including the lag of *vol*. Moreover, the central bank likely takes into account sovereign bond spreads in its monetary policy. This makes the model prone to the omitted variable bias. This bias is partly addressed by the control variables, variable *hilo* in particular. *Hilo* controls for the state of the market and so takes into account that the activation of QE as market stabilization instrument is dependent

[3] For this reason we focus on the flow of asset purchases and disregard the stock effects.

on the market conditions, which also reflect in bond spreads. As an alternative method we apply the structural credit risk model (CCM), which does not suffer from endogeneity issues, as the parameters of the model are not estimated. We discuss this model in Section 4.

3.3 Data

The data we use for the panel regressions cover four periphery EMU countries which were hit by the sovereign debt crisis in 2010-2012: Italy, Ireland, Portugal, Spain. We do not include Greece, due to too many missing observations and outliers, next to the fact that Greece is not eligible for the PSPP. The unbalanced panel covers the 2000m1 – 2021m3 period and the data are monthly with some gaps due to missing values. The key variables are as follows.

In the panel regression model, the dependent variable is the sovereign bond spread, defined as the 10 year sovereign bond yield (*r*) minus the risk-free rate (*rf*) for which we use the 10 years OIS (euro overnight index) swap rate. The sovereign bond spread reflects various risk components which may be mitigated by a market stabilization programme, i.c. credit, liquidity, redenomination (exchange rate) risk and general risk aversion. Since these risks raise the uncertainty about the value of sovereign bonds, they will also be reflected in bond return volatility. The choice for the 10 years maturity is motivated by the average maturity of the ECB sovereign bond holdings, which is 7 to 8 years on average (ECB, 2021).

An alternative risk-free rate is the German 'bund yield', which is similar in value to the OIS swap rate in most of the sample period. However, since 2015 the bund yield has a negative premium with regard to the OIS rate, reflecting the safe-haven status of Germany and that QE contributed to a scarcity premium in the bund yield (Schlepper et al., 2017). By taking the OIS rate as risk-free rate, our results are not influenced by this scarcity premium. As a robustness test, in Section 3.5 we do however include the bund yield as risk-free rate as a replacement of the OIS. Another alternative spread measure is the credit default swap (CDS) spread. However, for the purpose of our paper the CDS spread is less useful, since central banks do not operate in the CDS market with their QE programmes.

The bond return volatility variable (*vol*) is defined as the end of month annualized standard deviation of daily sovereign bond price returns, calculated over a 45-day horizon. These variables are country specific and taken from Bloomberg.

We use two proxy variables for monetary policy: the shadow rate (rs as determined in Krippner, 2015) and the unexpected response of the risk-free rate to monetary decisions (ru). The latter is defined as the first principal component of OIS rate surprises, cumulative per month, based on Altavilla et al. (2019). While rs is a proxy for anticipated monetary policy measures, variable ru captures the surprise effect of monetary policy. Both variables are for the euro area as a whole.

As additional monetary policy variable in the panel regressions we take the flow of sovereign bond purchases by the ECB of individual EMU countries. These are published by the ECB in terms of net purchases in the PSPP (monthly basis) and the PEPP (bimonthly basis; we calculate monthly data by interpolation). Data on SMP purchases are only available on a stock basis; we take first differences to calculate monthly flows.

As in De Haan et al. (2014), for most macroeconomic variables in the panel regressions we use Consensus forecasts taken from Consensus Economics, which are available for each month m of a particular year for the current year y and the next year $y+1$. We derive average forecasts for the coming 12 months. This acknowledges that interest rates reflect market expectations about future developments. If F_m^y is the Consensus forecast in month m for the current year y, and F_m^{y+1} is the Consensus forecast for $y+1$, then the weighted average for the next 12 months is defined as:

$$\frac{F_m^y \cdot (12-m) + F_m^{y+1} \cdot m}{12}, \text{ with } m = 1,...,12 . \qquad (7)$$

Appendix A gives the definitions and sources of all variables and Table 1 presents summary statistics. The outcomes of a panel unit root test suggested by Levin et al. (2002) show that, when suppressing panel-specific means, the presence of a unit root in all panels can be rejected for all panel variables except for the expected current account balance in percent of gdp (car), expected debt ratio (debt) and net foreign assets (nfa) (Appendix B).

3.4 Results panel regression

Table 2, column (1), presents the estimation results for the baseline model (Eq. (2)). The fit is good, with a within R^2 of 0.87. The coefficients for inflation, real GDP growth, debt and financial conditions (*vol* and *hilo*) are statistically significantly different from zero and have the expected signs. Net foreign assets unexpectedly has a positive sign and the current account variable is not statistically significant. Neither is the coefficient for the monetary policy surprise. The shadow rate has a significantly negative coefficient.

[insert Table 2]

Column (2) shows the results for Eq. (3), i.e. when interacting bond return volatility (*vol*) with the QE dummy (which is 1 since January 2015 and 0 otherwise). The statistically significant coefficient for this interaction term is -0.054, indicating that the effect of bond market volatility on the spread was smaller in the QE episode. This is illustrated by the average marginal effect of volatility on the spread for the two different values of the QE dummy, in Figure 6. A one percentage point increase of bond return volatility raises the spread by around 0.09 percentage point in normal times, while the volatility effect on the spread is around 0.04 during the QE episode.

[insert Figure 6]

Column (3) shows the results for Eq. (4), i.e. when interacting bond return volatility (*vol*) with the shadow rate during the whole sample period, instead of the QE dummy. The statistically significant coefficient for this interaction term is 0.016, which means that when the shadow rate is negative the effect of volatility on the spread is lower than when the shadow rate is positive. This is illustrated by the average marginal effect of financial market conditions on the spread for values of the shadow rate between -1% and -4% (Figure 7). The positive effect of a 1 percentage point increase in bond return volatility on the spread is 0.075 percentage point at a shadow rate of -1% and decreases to 0.025 percentage point at a shadow rate of -4%. The 95% confidence bands indicates moreover that the latter effect is not statistically significant from zero.

[insert Figure 7]

How do the results translate in terms of the contribution of monetary policy to lower the sovereign bond spreads of the countries concerned? To visualize this, we calculate the predicted spread according to the estimated Eq. (3), first using the actual QE dummy and second using a counterfactual QE dummy which is zero during the whole sample period. Figure 8 shows the differences in outcomes. These differences range from -1 (Ireland) to -2 percentage points (Italy). Similarly, we calculate the predicted spread according to the estimated Eq. (4), first using the actual shadow rate and second using a counterfactual shadow rate which is zero instead of negative as from 2012m1. There are negative differences ranging from -0.3 (Spain, Portugal) to -0.7 percentage points (Italy), but there are also positive differences (Figure 9).

[insert Figures 8, 9]

Table 3 presents the coefficient estimations of the dummy variables for the SMP, OMT, PSPP and PEPP interacted with the volatility variable (Eq. (5)). It shows that the coefficients for the interaction terms for the SMP, OMT and PEPP are most significant with a negative sign, implying that the (upward) effect of bond return volatility on the spread was smaller during these specific programmes. The coefficients for the PEPP are significant for all windows ending 3, 6, 12 and 18 months from the start of the PEPP announcement. In the robustness section below we test to what extent the effects of PEPP can be distinguished from the effect of the Next Generation EU (NGEU) programme on bond spreads. The coefficients for the OMT are significant for windows ending 3, 6 and 12 months from the start of the programme. This outcome confirms our priors for the SMP, OMT and PEPP interaction terms. It indicates that these market stabilization programmes clearly diminished the (upward) effect of volatility on sovereign spreads. The interaction terms for the PSPP are only weakly significant for the 12 months window. These results indicate that the market stabilization programmes reduced the effect of volatility on spreads and not the regular bond purchases by the PSPP.

[insert Table 3]

The estimation outcomes of Eq. (6) including the flow of asset purchases, confirm our priors for the coefficients (see Table 4). The significantly negative coefficients of the interaction terms for the flow of asset purchases under the SMP and PEPP indicate that these market stabilization programmes increased the (downward) effect of purchase flows on sovereign spreads. This indicates the effect of the liquidity channel of QE on sovereign spreads. The flow of asset purchases under the PSPP did not significantly contribute to lower the spreads over windows of 6 to 12 months from the start of the programme.

[insert Table 4]

3.5 Robustness tests

As a first robustness test we take the German 10 years bund yield as an alternative risk-free rate. While the bund yield is similar to the OIS swap rate in most of the sample period, it has a negative premium with regard to the OIS rate since 2015. This reflects that QE contributed to a scarcity premium in the bund yield. To test whether this alternative risk-free rate would influence our results, we estimate the baseline model (Eq. (1)) and the model including the interaction of bond return volatility with the QE dummy (Eq. (3)) with the sovereign bond spread defined as the 10 year sovereign bond yield minus the 10 years bund yield. Since the QE dummy (D^{QE}) has value 1 for the period since January 2015, it overlaps with the period in which the premium in the bund became negative.

The outcomes in Table 5 show that the alternative risk-free rate has little influence on the outcomes of the baseline and the interaction model. The signs and the significance levels of the coefficients are similar. The interaction of bond return volatility with the QE dummy remains significant with a negative sign, although the significance and magnitude of the coefficient is somewhat higher in the model with the bund yield as risk-free rate than in the model with the OIS rate.

[insert Table 5]

As a second robustness test we investigate to what extent the effects of PEPP can be distinguished from the effect of the Next Generation EU (NGEU) programme on bond spreads.[4] The NGEU was agreed on 21 July 2020. It is a recovery instrument that allows the European

[4] Between 2011 and 2014 Ireland, Portugal and Spain received funds from the European Financial Stability Facility (EFSF) and the European Stability Mechanism (ESM). We do not control for these programmes since they are a necessary condition for the OMT. This implies that the impact of the OMT – announced mid-2012 – on sovereign bond spreads implicitly includes expectations about an EFSF or ESM programme. This complicates isolating the effects of OMT and EFSF/ESM on spreads.

Commission to borrow EUR 750 bn on the capital markets, for the purpose of addressing the consequences of the pandemic. The NGEU is limited in time and new net borrowing activity will stop at the latest at the end of 2026. Since the crisis-prone countries receive a relative large share of the NGEU loans and grants (EU, 2021), the NGEU may have had a downward effect on the sovereign spreads in particular of these countries.

We find that the PEPP had a significant effect on spreads independent from the NGEU. To separate the effect of the PEPP from the NGEU we restrict the QE dummy for PEPP to 1 for the period between the start of PEPP and the NGEU agreement, implying that the dummy equals 0 from July 2020 onward. First, we replace D^{PEPP} in Eq. (5) with this restricted dummy. The outcomes in Table 6 show that the coefficient for the interaction of the restricted PEPP dummy with the volatility variable remains significant, although the significance level is somewhat lower than for the original dummy. Second, we interact the restricted PEPP dummy with the flow of purchased sovereign bonds (*flow*, as in Eq. (6a)). This interaction term is significantly negative, indicating that PEPP reinforced the downward effect of purchase flows on bond spreads in the months preceding the NGEU.

[insert Table 6]

4. Contingent claims model

In this section we use a contingent claim model (CCM) to assess the market stabilization function of QE for sovereign risk. Key features of this model are its structural specification and the independence of economic agents' preferences or return expectations. The CCM allows us to analyze QE as a put option written by the central bank to protect bond holders against some tail risks. We assume that this put option reflects the market stabilization function of QE, by which the central bank shows that it is prepared to purchase bonds from investors in stressed market conditions that directly or indirectly affect all EMU countries. Compared to the regression analysis in the previous section the CCM approach does not suffer from potential endogeneity issues (see Section 3.2) because CCM is a structural model.

In a situation without QE an investor is fully exposed to the default risk of a sovereign bond. In this case the observed spread of a bond is a compensation for the expected loss on the bond plus the risk premium that risk-averse investors require to hold the bonds. This risk premium is a compensation for the unexpected loss. In stressed market conditions, the risk premium may overshoot due to high risk aversion of investors who also require a compensation for a possible stress loss (see also Figure 1).

In a situation with QE as a market stabilization instrument, the bondholder is protected from negative tail outcomes owing to the central bank put. Note that the investor does not directly pay a premium for this protection, because the central bank considers market stability to be a public good. The central bank finances the central bank put by creating money (i.c. central bank reserves) when buying bonds. The put premium is implicit and actually accrues to the sovereign which issues the bond that is eligible for QE, since the put option for tail risk reduces the risk premium component in the bond spread. This is the case for newly issued bonds. With regards to existing bonds that become eligible for QE, the windfall of the put option accrues to the bondholder (investor) to the extent that the put premium (which does not have to be paid) is larger than the reduction in the bond spread at the moment the put is written.[5] In that case existing bond holders earn a windfall due to the central bank put option.

Our motivation to use the CCM to assess the effect of the central bank backstop on sovereign risk is the important role of volatility in the model. By including realized bond return volatility in the CCM this market stabilizing effect of QE is then taken into account in the valuation of the put option. The option value is proxied by performing counterfactual simulations from 2015 onwards. Moreover, since realized volatility is time-varying and driven by risk aversion it also addresses some of the limitations of the CCM. The CCM assumes Gaussian distributed probability distributions, while actual default probability distributions are fat tailed. In the literature various methods are proposed to remedy the assumption of a Gaussian distribution for the underlying asset returns, such as alternative volatility models or adjustments of the default probability (see Aboura et al., 2014 for an overview). We apply the latter method by mapping between the risk-neutral default probabilities and actual sovereign default data. The mapping is based on data of sovereign default rates per credit rating bucket, as collected by Moody’s for the 1983-2020 period. We use those actual default rates to adjust the risk-neutral

[5] Note that the sovereign is typically the single shareholder of the central bank. So the sovereign also benefits from the profits that the central bank makes on its QE programme. The expected profit is a function of the bond yield relative to the funding costs of creating bank reserves. The profits are over time distributed to the sovereign in the form of dividends. Similarly, the sovereign may receive less benefits if the QE programme is loss-making.

default probability as specified in Eq. (8) in Section 4.2. This adjustment ensures that the default probability used in the CCM exhibits the fat tail characteristics of real world sovereign default risk.

4.1 Literature

A contingent claim is a derivative contract whose future payoff depends on the value of another asset. The CCM deals with the valuation of these derivative contracts and is a generalization of the option pricing theory founded by Black and Scholes (1973) and Merton (1973). The CCM has been applied to a wide variety of settings, ranging from corporate default risk (Merton, 1974) to financial stability (Gray et al., 2010).

We apply the CCM to sovereign credit risk. The CCM is usually called the "Merton model" when it is applied to measure credit risk (Merton, 1974). The Merton model takes a balance sheet perspective and is based on the following three guiding principles: (i) the value of liabilities is derived from the values of assets; (ii) asset values follow a stochastic process similar to Eq. (1), and (iii) different types of liabilities have different priority, i.e., senior and junior claims on the assets. These principles also apply when analyzing sovereign credit risk. Gray et al. (2007b) introduce the CCM to sovereign credit risk assessment. Gapen et al. (2008), Brière et al. (2016) and Gómez-Puig et al. (2018) follow similar approaches to derive forward-looking indicators of sovereign risk. To the best of our knowledge, the CCM has not been applied to central bank bond purchases in the literature.

The starting point for the CCM is a sovereign's balance sheet, where both assets and liabilities are marked-to-market. Whereas the outstanding amounts of sovereign debt, both in local and in foreign currencies, can be easily observed, this is not the case for the market value and the volatility of sovereign assets. The CCM is however effective in getting an "implied" estimate of both variables using the observable market price dynamics of sovereign liabilities.

Here an assumption is necessary to distinguish between junior and senior sovereign debt. Gray et al. (2007b) define local currency sovereign debt and base money to be junior and foreign currency debt to be senior. The main argument is that sovereign local-currency liabilities have "equity-like features" because governments can easily issue local-currency debt and base money in large amounts even if this causes a dilution in their value.

However, individual EMU countries have no control over the currency in which their debt is denominated, since the ECB controls the monetary base at the level of the euro area. Therefore, in this case foreign currency debt cannot be assumed to be senior to local currency debt. Gómez-Puig et al. (2018) deal with this by assuming that the priority structure of (euro denominated) sovereign debt distinguishes junior from senior debt in EMU countries. We follow their approach.

4.2 Model

Similar to Gómez-Puig et al. (2018) we define junior sovereign debt (E) to be equal to total sovereign debt held by domestic investors excluding domestic banks. This assumes that although the government may default on its debt held by domestic investors, it will try to avoid defaulting on the part held by domestic banks to prevent that the banking sector collapses as a consequence. This is particular relevant for the vulnerable countries that we analyse because commercial banks in these countries banks typically hold significant amounts of government debt. We define senior sovereign debt (B) to be equal to total sovereign debt plus the interest payments minus junior sovereign debt. We assume that the bonds purchased by QE are part of the senior sovereign debt and the strike price of the put option is equal to the default-free value of senior debt (B).

Both junior and senior debt are a claim on the sovereign's assets. The value of junior sovereign debt in the CCM is given by,

$$E_t = A_t\, N(d_1) - B_t e^{-rT} N(d_2) \tag{8}$$

where A is the unobserved market value of sovereign assets, r the long-term risk-free market interest rate derived from collateralized interest rate swaps, T the duration of the sovereign debt, $d_1 = \frac{\ln\left(\frac{A_t}{B_t}\right)+\left(r+\frac{1}{2}\sigma_A^2\right)T}{\sigma_A\sqrt{T}}$, $d_2 = d_1 - \sigma_A\sqrt{T}$, σ_A is the unobserved volatility of the return on sovereign assets and $N()$ the cumulative standard normal distribution function. $N(d_1)$ is the risk-neutral probability of the value of the assets at maturity exceeding the default-free value of senior debt. Variable d_2 is the distance to distress and $N(d_2)$ reflects the risk-neutral probability of default. We take a long-term risk-free market interest rate because the average duration of the outstanding debt is also long-term. From the CCM we further know that the value of junior sovereign debt is also equal to

$$E_t = A_t \frac{\sigma_A}{\sigma_E} N(d_1) \tag{9}$$

where σ_E is the volatility of the sovereign bond returns as observed in financial markets. We assume that the volatility of senior debt (B) is a proxy for the volatility of junior debt (E). Our assumption is that the difference between junior and senior debt is determined by the bond ownership. The bonds themselves have similar characteristics and will have the same price regardless for instance the residency of the bond holder. This implies that we can assume that the volatility of senior debt (in the hands of domestic banks and foreign investors) is similar to the volatility of junior debt (domestically held bonds by non-bank investors). Eqs. (8) and (9) together can be used to numerically solve for the two unknowns: sovereign asset value (A) and sovereign asset volatility (σ_A).[6] The numerical procedure involves an iterative procedure were σ_E is taken as the initial value for σ_A and the initial value of A being guessed. The procedure repeats until the values of σ_A and A converge to values that simultaneously solve for Eqs. (8) and (9) in the successive iterations (for the procedure see Tabbae and Van den End, 2005).

Based on this we can determine the value of the implicit put option,

$$P_t = B_t e^{-rT} N(-d_2) - A_t N(-d_1) \tag{10}$$

The value of put option P reflects the expected loss (related to the risk-neutral default probability), which is covered by the debt guarantee (Gray et al., 2007a).[7] The value of B determines the strike price of the put option, since the seller of the option (or guarantor) provides protection against default on the senior debt. Applying this concept to QE as market stabilization instrument, the strike price of the put option on sovereign bonds is implicit, as its level is not communicated by the central bank to the market.

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[6] A theoretical proxy for the value of A is the present discounted value of the net fiscal surpluses (see for instance Gapen et al., 2007). However, calculating this proxy is problematic as it requires estimating future economic performance, the political commitment to a variety of programs including social security and other entitlement programs, and the use of an appropriate discount rate.

[7] We follow the approach taken by other papers in this field and use the pricing formula in (10) which is applicable to European options on non-dividend paying assets and which can only be exercised at expiration. Pricing formulas that do take into account early exercise make the valuation procedure more complicated without materially changing the outcomes.

The value of the risky senior debt *D* equals the value of a default-free bond with similar duration minus the value of the put option:

$$D_t = B_t e^{-rT} - P_t \tag{11}$$

Gray et al. (2007a) relate the yield to maturity (*y*) of risky debt (*D*) to the credit spread (*s*), which is defined as the compensation for the risk-neutral default probability,

$$\exp(-y_t) = \frac{D_t}{B_t} = \frac{B_t e^{-rT} - P_t}{B_t} \tag{12}$$

which can be rewritten to get the spread *s* written in terms of *P*,

$$s_t = y_t - r_t = -\frac{1}{t} ln\left(1 - \frac{P_t}{B_t e^{-rT}}\right) \tag{13}$$

The strike price in terms of the sovereign debt level is related to a reference level of the credit spread at which the central bank will intervene by asset purchases to prevent disorderly market conditions.[8]

By its extensions of QE programmes over time the ECB has (implicitly) shown an increased willingness to provide protection against tail risk in sovereign bond markets. In the CCM model this implies that the strike price of the central bank put option is reduced, or in other words, the central bank is prepared to intervene at an increasingly lower level of sovereign debt and associated spread level. A reason for this might be that the central bank assesses that the monetary transmission process is distorted at a lower level of spreads than it was before.

To reflect this time-varying nature of the strike price we extend the CCM model by adding to the option equation for the strike price S_t, which is the time-varying level at which the central bank activates the option,

$$P_t = (B_t + (B_0 - S_t))\, e^{-rT}\, N(-d_2) \; - \; A_t\, N(-d_1) \tag{14}$$

[8] The reference level of the spread is inversely related to the bond price, as central bank interventions at a lower spread level mean that the central bank is prepared to buy at a higher bond price level and vice versa.

In the steady state at $t = 0$ it holds that $B_0 = S_0$, with P_t being equal to the put option value in Eq. (10). In Eq. (14), however, the value of the option increases if the default-free debt B_t increases relative to a constant strike price ($S_t = S_0$). A higher sovereign debt level implies higher sovereign default risk and so the put option written by the central bank is increasingly more valuable for investors.

The option value also rises if the debt level B_t remains constant ($B_t = B_0$), while the strike price S_t is lowered by the central bank. A lower strike price implies that the central bank is prepared to purchase sovereign bonds for market stabilization reasons at lower levels of sovereign debt, which is associated with a lower reference level of the bond spread. This would raise the value of the put option for investors, if the actual debt level B_t remains constant or increases.

4.3 Data

For the CCM we use quarterly data on sovereign debt taken from the ECB's Statistical Data Warehouse. This source provides data on total government debt, interest payments, domestic government debt, short term debt and government debt securities held by domestic banks. Data on the duration of government debt is taken from Bloomberg. Total government debt, or public debt includes the debt of the central, local and government sub-sectors. While actually only central government debt is sovereign debt, we use this broader concept of public debt, since this debt is eligible for the public sector purchase programmes of the ECB.

4.4 Outcomes of the CCM

We conjecture that the central bank effectively provides investors with a put option on sovereign bonds (which are part of senior debt *B*) via QE. The central bank backstop will lower the option value if it reduces the default risk on senior debt. A likely channel for this is the downward effect of asset purchases on bond return volatility, which is a driving factor of A, $N(-d_1)$ and of the put option value P in Eq. (10) (bearing in mind that σ_A drives A and d_1). We apply the numerical procedure from the previous section to derive the put option values for Italy, Spain, Ireland and Portugal, see Box 1 for a numerical example.

Figure 10 shows the evolution of the put option value (in billion euros) over time for the different countries.[9] The option value is based on the time-varying realized bond return volatility σ_A, which is amongst others derived from volatility of the sovereign bond returns σ_E. The option values increased sharply following the EMU sovereign debt crisis and decreased after March 2012, in tandem with the decline of volatility in sovereign bond markets (see Figure 2). In 2020 the put value spiked again as a reflection of the impact of the pandemic on sovereign risk. After the start of the PEPP the put option value decreased again sharply. Note that the development of the put option closely follows the credit spread on long-term government bonds, in line with Eq. (13). This indicates that the option value is influenced by the volatility reducing effect of QE, which hides the underlying effect of QE on sovereign default risk.

[insert Figure 10]

Box 1. Numerical example

As an example we apply the CCM model to sovereign risk data for Italy as of December 2011. Junior sovereign debt (E) at that time was EUR 1,038 bn (EUR 1,283 bn local sovereign debt minus EUR 245 bn local sovereign debt held by local banks). Senior sovereign debt (B) was at EUR 957 bn (EUR 1,973 bn total sovereign debt plus EUR 22 bn interest payments minus EUR 1,038 bn junior sovereign debt). Furthermore, the 10-year Overnight Index Swaps rate (r) was at 2.05%, the duration (T) of the government debt 8.44 years and the sovereign debt volatility (σ_E) 34.74%. Based on this input we numerically determine by the iterative process the sovereign asset value (A) to be EUR 1,813 bn and sovereign asset volatility (σ_A) to be 20.9%. Based on this we can determine the value of the put option ($P_t = B_t e^{-rT} N(-d_2) - A_t N(-d_1)$) embedded in senior debt that reflects the default risk to be equal to EUR 30 bn. Note that total assets equal total liabilities in the following standard way,

$$A_t = E_t + B_t e^{-rT} - P_t$$

$$1{,}813 = 1{,}038 + 957 e^{-0.0205*8.44} - 30$$

[9] For calculating the put option's value we first calculate $d_1 = \frac{\ln\left(\frac{A_t}{B_t}\right) + \left(r + \frac{1}{2}\sigma_A^2\right)T}{\sigma_A \sqrt{T}}$ and $d_2 = d_1 - \sigma_A \sqrt{T}$. Next, we transform these variables in the following way $d_1' = \ln(1.7d_1 + 1)$ and $d_2' = \ln(1.1d_2 + 0.9)$. Note that $N(-d_2)$ represents the risk-neutral default probability which overstates the actual default probability (Gray et al., 2007a). In the application to corporate credit risk, the standard adjustment mechanism for this is to map firm risk-neutral default probabilities against a database of actual corporate defaults (Moody's KMV). Similarly we map the rating based sovereign default probabilities of Moody's on the distance to distress. The parameters α and β in $\ln(\alpha d_1 + \beta)$ are calibrated by minimising the difference between the actual default probabilities and $1 - \ln(\alpha d_1 + \beta)$. The outcomes are sensitive to calibration of the mapping.

To gauge the underlying effect of QE on default risk and hence on the value of the put option, we perform a counterfactual simulation from 2015 onwards. In the simulation we assume that the sovereign bond return volatility (σ_E) in 2015-2020 remained at the constant (high) level observed in 2015, the year in which the PSPP was introduced. The counterfactual assumes that since 2015 there has been no volatility reducing effect of QE. The difference between the shadow put value and the actual put value then indicates the value of the central banks' commitment to support market stability assuming that QE has reduced bond return volatility from 2015 onward.

The dashed lines in Figure 10 shows the shadow values of the put option, assuming the counterfactual high bond return volatility (σ_E) from 2015. The value of the QE programmes that expresses the protection against tail risk is reflected in the difference between the bold lines (actual put value) and the dashed lines (shadow put value), as plotted in Figure 11. This difference clearly widened in 2015-2019, except for Italy, where bond return volatility increased again in 2018 even though the PSPP was active. The widening difference between the shadow and actual put value indicates that QE was valuable to investors.

At the start of the pandemic (March 2020) the actual bond market volatility spiked again and only declined after the PEPP programme was introduced. It suggests that the PSPP programme alone did not provide investors sufficient protection against tail risk in sovereign bonds. Otherwise volatility would not have increased that much. The PEPP programme however seemed to offer such protection, as reflected in the widening difference between the shadow and actual put value in the course of 2020 plotted in Figure 11. It indicates that the market stabilization function of PEPP was valuable for investors in sovereign bonds.

[insert Figure 11]

4.5 Discussion and interpretation of the CCM results

The assumed central bank put differs from a regular put option in various ways. First, the central bank put is not traded as a separate instrument in financial markets and therefore it is an implicit option. Hence, the central bank does not communicate the reference levels (strike price) to the market in advance. The conditions of the central bank put are therefore not fully clear to investors.

A second difference with a regular put option concerns the right to exercise the option. In a regular option contract, the right to exercise lies with the buyer of the option. When announcing QE, the central bank takes the initiative to write the option and, during the purchases of government bonds itself, the central bank facilitates the exercise of the option by investors. Investors decide to (not) sell their bonds to the central bank based on their preferences and market expectations. The central bank put changes the behavior of the bond price with respect to the underlying fundamentals. The combination of the bond plus the put option means that the bond price itself responds less strongly to negative scenarios compared to a situation without a central bank put.

Finally, investors do not directly pay a premium for the put option to the central bank, whereas a direct premium is paid for a regular put option to the writer of the option. Despite these differences, it is conceptually possible to analyze the central bank put using the CCM. After all, the central bank put is an option for investors to sell their bonds to the central bank and the value of this option depends on the value and risk profile of the underlying bonds in the QE programme and the reference level of the bond spread.

Central bank interventions in bond markets can contribute to resolve market instability and prevent bad equilibria, as the OMT announcement and the PEPP programme showed. For this reason central banks and regulators are considering liquidity backstop facilities to support the functioning of the sovereign bond markets in stress conditions (Group of Thirty, 2021). Such interventions can, similar to QE as market stabilization instrument, be welfare improving if they result in financial markets responding more rationally to macro fundamentals and contribute to lower sovereign spreads by reducing bond market volatility.

However, if financial markets are normalized again while the central bank continues to purchase assets, the risk of unintended side effects and moral hazard increases. If sovereign debt levels remain high or other macroeconomic imbalances persist, the related risks shift from investors to the central bank, who offers an implicit put option against tail risk through QE. It also reduces incentives for governments to pursue structural reforms to improve the economy.

These risks can be avoided by relating the strike price of the central bank put option more closely to the risk of disorderly market conditions. For a QE market stabilization programme this means that the reference level of credit spreads, which determines or triggers the sovereign bond purchases, is increased if the risk of a bad equilibrium diminishes (and vice versa). This pleas for a time-varying strike price of the central bank put, which is countercyclical to spread developments in financial markets.

5. Conclusions

Over the last decade, the ECB has increasingly used QE as a market stabilization instrument. In principle, the market stabilization function is only needed in situations where the market fails to coordinate a good equilibrium. However, by acting as market maker of last resort the central bank also changes the nature of sovereign risk. The central bank backstop in fact removes tail risks from the market. We contribute to the literature by examining the effect of the backstop function of QE on bond market volatility and sovereign spreads. Our results can guide policymakers on the use of backstop facilities for sovereign bond markets.

We examine how QE changes the nature of sovereign risk. Our research question is to what extent the asset purchases by the ECB have lowered sovereign risk spreads of crisis-prone EMU countries through reducing the volatility effect on sovereign bond markets. We focus on four EMU countries (Italy, Ireland, Spain, Portugal) and use two modelling approaches to examine the relationship between macro-fundamentals, bond market volatility and sovereign bond spreads.

The outcomes of a panel regression model show that the market stabilization effect of QE lowered sovereign bond spreads by 1 to 2 percentage points. The market stabilization programmes SMP, OMT and the hybrid PEPP reduced the effect of volatility on spreads most clearly, with the SMP and PEPP also contributing to lower spreads through the flow of bond purchases. This effect is not found for the PSPP programme that is focused on the monetary stance.

As a complementary second approach we use a contingent claims model (CCM) to assess the effect of QE on sovereign risk. We postulate that QE features as a put option written by the central bank to bond holders which protects them against tail risk. It resembles the market stabilization function of QE, through which the central bank purchases bonds from investors in stressed market conditions. The implicit central bank put option provides investors a backstop to sell their bonds to the central bank when the bond value drops and sovereign risk spreads increase.

The central bank will step up its purchases at spread levels that are associated with dysfunctioning bond markets. In such conditions, the value of the put option will increase as simulated with the CCM. Hence, the CCM provides a framework to quantify the value of the market stabilization function of QE. An important parameter that determines this value is the volatility of the returns on the underlying bond. Since the market stabilization function of QE particularly influences bond market volatility, we conduct counterfactual simulations for the option value, based on the volatility parameter. The simulations show that the market stabilization policy by the ECB was valuable to investors in the sovereign bonds of the four countries in our sample.

Our results can guide policymakers on the use of backstop facilities for sovereign bond markets. The outcomes indicate that market stabilization programmes lower sovereign spreads by reducing bond market volatility. This will be welfare improving, provided that unintended side effects such as moral hazard risk and reduced fiscal discipline are mitigated by the design of the programme.

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Tables

Table 1**.** Summary statistics

	Mean	*Median*	*Standard deviation*	*Minimum*	*Maximum*	*Number of obs.*
spread	1.56	1.01	1.89	-0.32	11.89	716
cpi	1.62	1.57	0.88	-1.06	3.68	716
gdp	1.23	1.35	1.83	-7.47	6.06	716
debt	95.97	102.91	33.31	20.05	170.17	716
vol	9.45	7.00	7.84	2.77	78.04	716
car	-1.91	-1.39	4.48	-14.49	10.22	716
nfa	-73.74	-81.85	48.24	-226.70	2.00	716
rs	0.37	0.34	2.28	-3.92	4.36	716
ru	-0.10	-0.19	3.36	-12.91	11.95	716
hilo	0.11	0.06	0.17	0.00	1.49	716

Explanatory note. *Spread* = yield on 10 year government bond (*r*) minus risk free rate (*rf*) in percentage points, *cpi* = expected inflation rate, *gdp* = expected real gdp growth, *debt* = expected debt ratio, *vol* = financial market conditions, *car* = expected current account ratio, *nfa* = net foreign assets, *rs* = shadow rate, *ru* = unexpected monetary policy, *hilo* = high minus low. Average per country, except for *rf*, *rs* and *ru* which are on a euro area level. Variable definitions are given in Appendix A.

Table 2. Estimation results. Relationship between sovereign bond spreads (dependent variable) and macroeconomic and financial market variables

	Baseline model	*vol* interacted with *QE dummy*	*vol* interacted with *rs*
	(1)	(2)	(3)
Inflation expectations (*cpi*)	0.400*** (0.063)	0.322*** (0.060)	0.420*** (0.063)
Growth expectations (*gdp*)	-0.238*** (0.024)	-0.173*** (0.024)	-0.246*** (0.024)
Debt forecast (*debt*)	0.026*** (0.003)	0.025*** (0.002)	0.026*** (0.003)
Bond return volatility (*vol*)	0.088*** (0.08)	0.089*** (0.007)	0.091*** (0.008)
Volatility x QEdummy		-0.054** (0.021)	
Volatility x Shadow rate (*rs*)			0.016*** (0.005)
Current account forecast (*car*)	0.011 (0.014)	0.021 (0.013)	0.025* (0.014)
Net foreign assets (*nfa*)	0.007*** (0.001)	0.008*** (0.001)	0.009*** (0.001)
Shadow rate (*rs*)	-0.070*** (0.025)	-0.158*** (0.026)	-0.193*** (0.043)
Monetary policy surprise (*ru*)	0.005 (0.008)	0.001 (0.008)	0.007 (0.008)
High-low (*hilo*)	4.061*** (0.264)	4.025*** (0.252)	4.107*** (0.262)
QE dummy = 1		-0.448** (0.205)	
R^2 – within	0.873	0.887	0.875
Number of observations	622	622	622

Explanatory note. Based on the model in Eq. (2). Fixed country effects included (not reported). Volatility has been instrumented, using all the internal variables including the lag of volatility. Standard errors, robust to cross-sectional heteroskedasticity and within-panel serial correlation, within parentheses. ***, **, * denote *p*-values less than or equal to 1%, 5%, 10%, respectively. Variable definitions are given in Appendix A.

Table 3. Estimation results for interaction terms. Dependent variable is Spread

	window 1..3 months	window 1..6 months	window 1..12 months	window 1..18 months
	(1)	(2)	(3)	(4)
Vol	0.100*** (0.008)	0.099*** (0.008)	0.091*** (0.008)	0.069*** (0.009)
Vol x SMP dummy	-0.034 (0.023)	-0.058*** (0.020)	-0.033** (0.016)	0.006 (0.010)
Vol x OMT dummy	-0.109*** (0.039)	-0.081*** (0.023)	-0.044*** (0.017)	-0.014 (0.012)
Vol x PSPP dummy	-0.082 (0.152)	-0.105 (0.134)	-0.116* (0.064)	-0.059 (0.045)
Vol x PEPP dummy	-0.122** (0.060)	-0.113*** (0.042)	-0.129*** (0.032)	-0.105*** (0.030)

Explanatory note. Fixed country effects included (not reported). Volatility has been instrumented, using all the internal variables including the lag of volatility. Standard errors, robust to cross-sectional heteroskedasticity and within-panel serial correlation, within parentheses. ***, **, * denote *p*-values less than or equal to 1%, 5%, 10%, respectively. Variable definitions are given in Appendix A.

Table 4**.** Estimation results for flow effects.
Dependent variable is *Spread*

	window 1..6 months	window 1..12 months
	(1)	(2)
Flow	-18.167* (9.755)	-7.980 (9.656)
Flow x SMP dummy	-38.384** (16.113)	-55.320*** (14.885)
Flow x PSPP dummy	10.324 (130.065)	-38.734 (92.263)
Flow x PEPP dummy	-87.969 (76.522)	-140.376** (68.702)

Explanatory note. Fixed country effects included (not reported). Volatility has been instrumented, using all the internal variables including the lag of volatility. Standard errors, robust to cross-sectional heteroskedasticity and within-panel serial correlation, within parentheses. ***, **, * denote *p*-values less than or equal to 1%, 5%, 10%, respectively. Variable definitions are given in Appendix A.

Table 5**.** Robustness test with dependent variable Spread based on German bund yield

	Baseline model	*vol* interacted with *QE dummy*
	(1)	(3)
Inflation expectations (*cpi*)	0.351*** (0.057)	0.316*** (0.056)
Growth expectations (*gdp*)	-0.187*** (0.021)	-0.163*** (0.023)
Debt forecast (*debt*)	0.030*** (0.002)	0.030*** (0.002)
Bond return volatility (*vol*)	0.092*** (0.07)	0.094*** (0.007)
Volatility x QEdummy		-0.059** (0.021)
Current account forecast (*car*)	-0.013 (0.012)	0.011* (0.012)
Net foreign assets (*nfa*)	0.004*** (0.001)	0.005*** (0.001)
Shadow rate (*rs*)	-0.071*** (0.021)	-0.101*** (0.023)
Monetary policy surprise (*ru*)	-0.006 (0.008)	-0.009 (0.007)
High-low (*hilo*)	4.169*** (0.243)	4.077*** (0.243)
QE dummy = 1		0.116 (0.196)
R^2 – within	0.891	0.894
Number of observations	693	693

Explanatory note. Fixed country effects included (not reported). Volatility has been instrumented, using all the internal variables including the lag of volatility. Standard errors, robust to cross-sectional heteroskedasticity and within-panel serial correlation, within parentheses. ***, **, * denote *p*-values less than or equal to 1%, 5%, 10%, respectively. Variable definitions are given in Appendix A.

Table 6**.** Robustness test for effect of NGEU. Dependent variable is *Spread*

	vol interacted with *SMP dummy*	*vol* interacted with *OMT dummy*	*vol* interacted with *PSPP dummy*	*vol* interacted with *PEPP dummy*[1]
	(1)	(2)	(3)	(4)
Vol x QE dummy (window 1..6 months)	-0.058*** (0.020)	-0.091*** (0.026)	-0.100 (0.136)	-0.120** (0.060)
Estimation results for flow effect. Dependent variable is *Spread*				
Flow x QE programme dummy (window 1..6 months)	-31.642** (16.054)		16.318 (130.590)	-160.442** (83.349)

[1] The PEPP dummy equals 1 in March-June 2020 and equals 0 from July 2020 onward. Explanatory note. Fixed country effects included (not reported). Volatility has been instrumented, using all the internal variables including the lag of volatility. Standard errors, robust to cross-sectional heteroskedasticity and within-panel serial correlation, within parentheses. ***, **, * denote *p*-values less than or equal to 1%, 5%, 10%, respectively. Variable definitions are given in Appendix A.

Figures

Figure 1 – Credit loss distribution (source: Chatterjee, 2015)

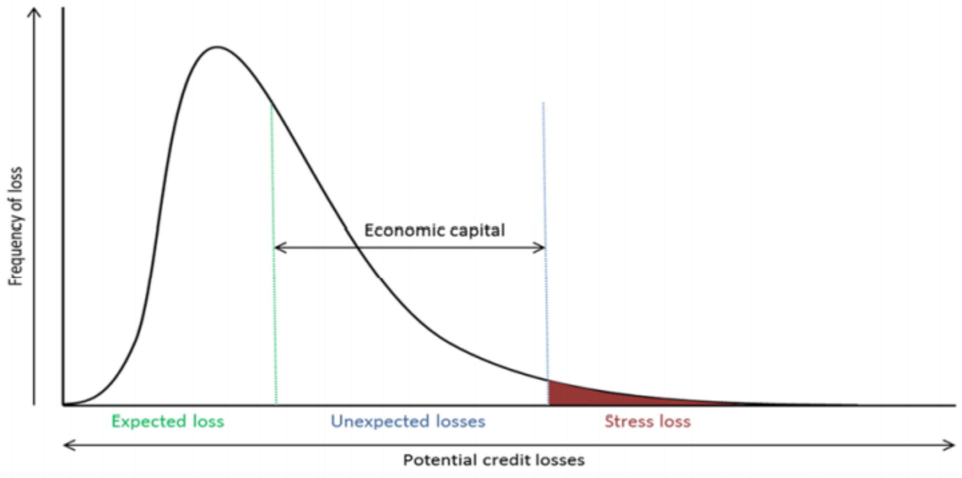


Figure 2 – Bond return volatility (end-of quarter annualized standard deviation of daily bond returns, calculated over 45-day horizon; percentage)

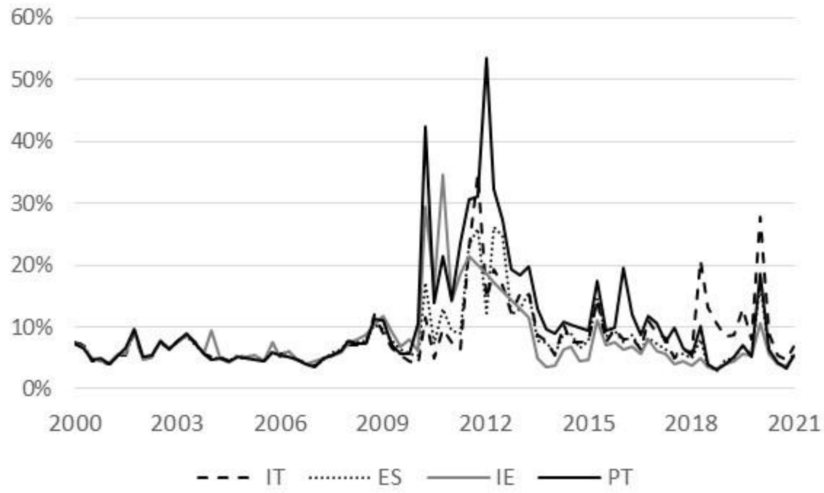


Figure 3 – Sovereign bond purchase programmes ECB (Eur billions)

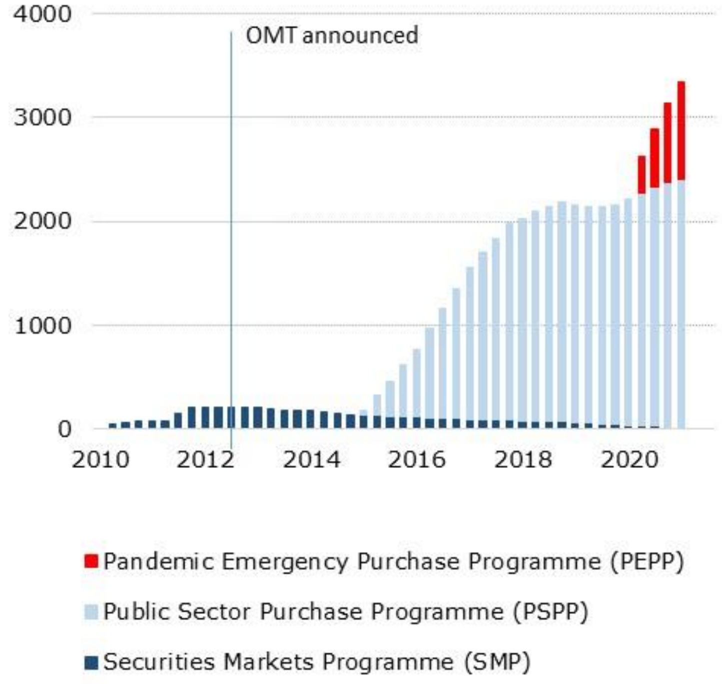
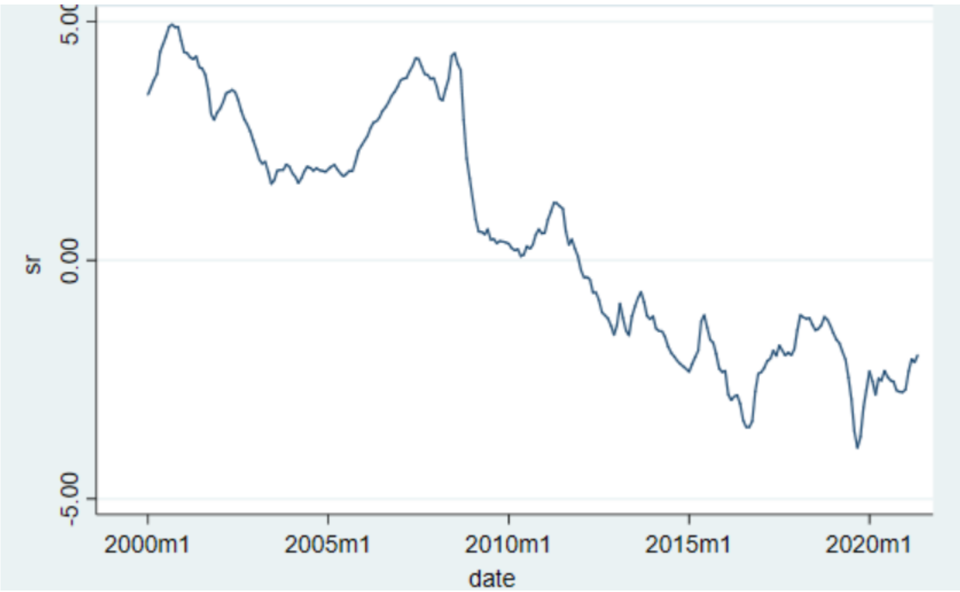
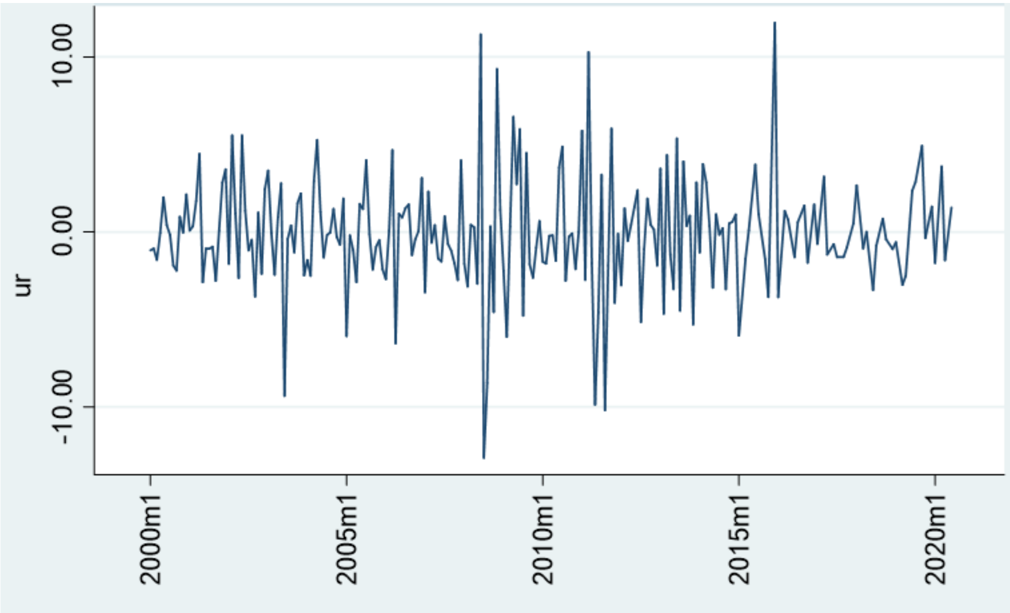


Figure 4 - Shadow rate



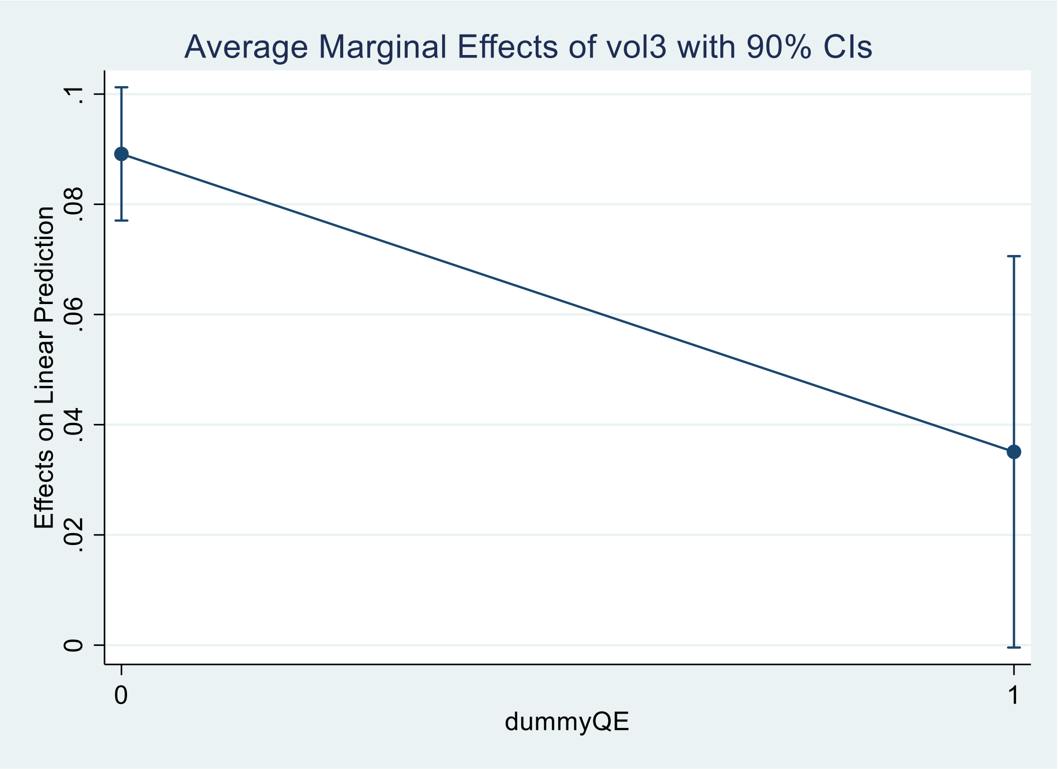
Source: shadow rate: Krippner (www.ljkmfa.com)

Figure 5 – Monetary policy surprises



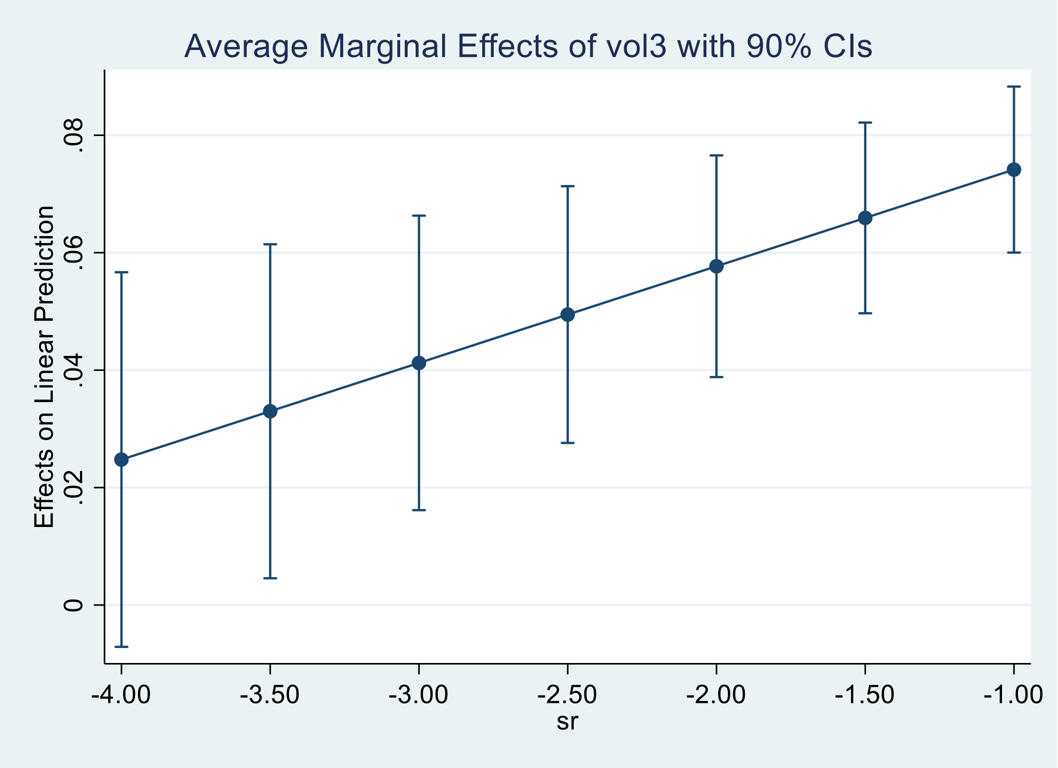
Source: own calculations based on Altavilla et al. (2019)

Figure 6 – Average marginal effect of *vol* on *spread*, for dummy QE = 0, 1



Note: vertical bars represent 95% confidence bands.

Figure 7 – Average marginal effects of *vol* on *spread*, for values of *rs* between -1% and -4%



Note: vertical bars represent 95% confidence bands.

Figure 8 – Counterfactual for predicted spread: Predicted spread minus predicted spread calculated with counterfactual QE Dummy equal to 0 instead of 1 as from 2015m1

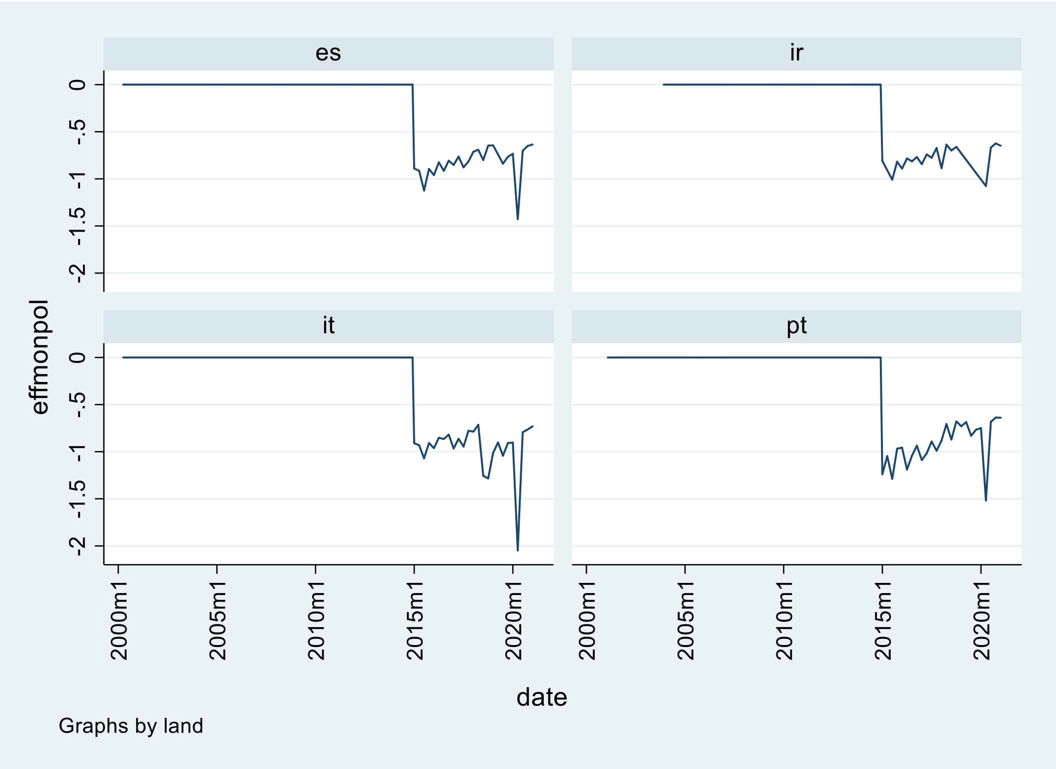


Figure 9 – Counterfactual for predicted spread: Predicted spread minus predicted spread calculated with counterfactual shadow rate equal to zero instead of negative as from 2012m1

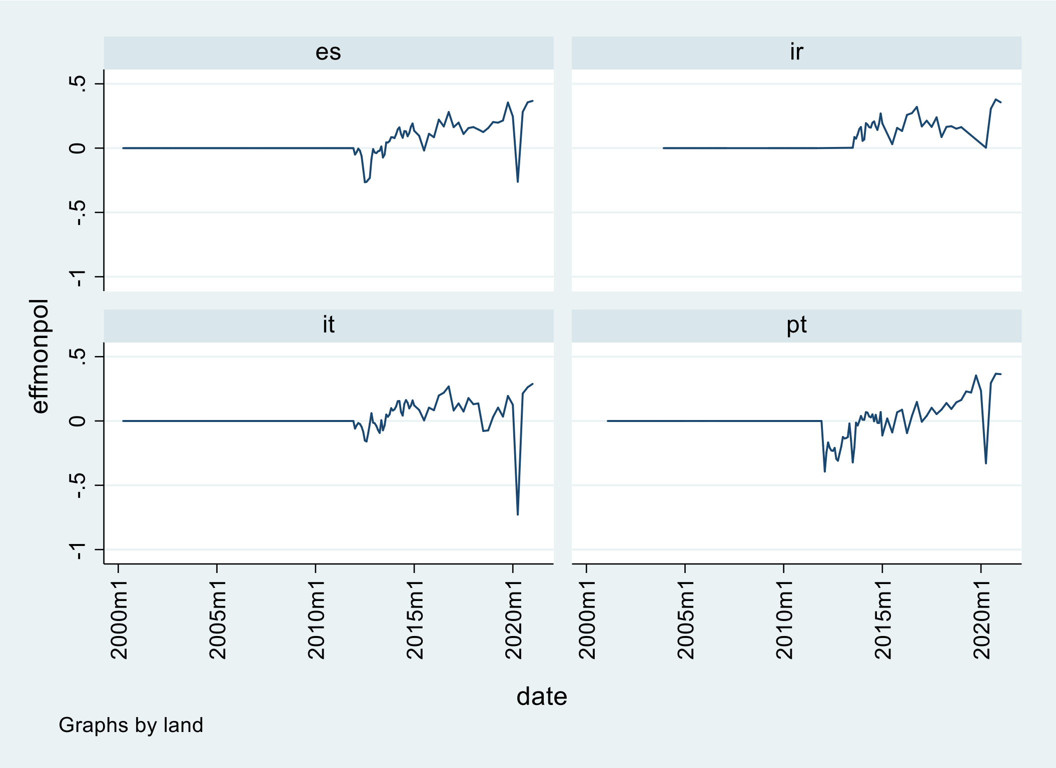
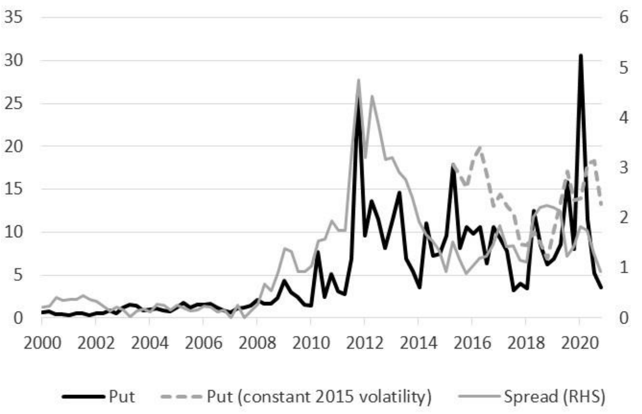
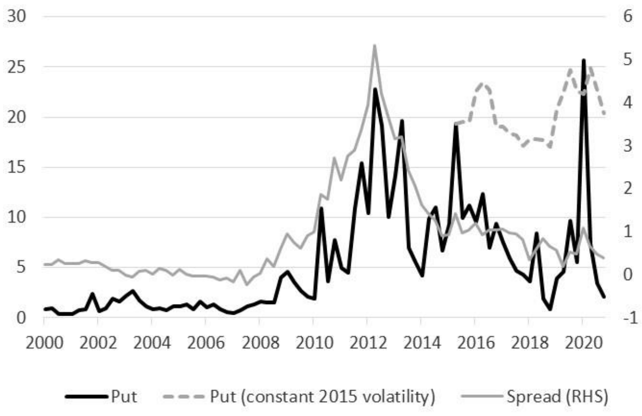


Figure 10 – Put option value (left-hand axis in EUR bn) and credit spread (right-hand axis in percentage points)

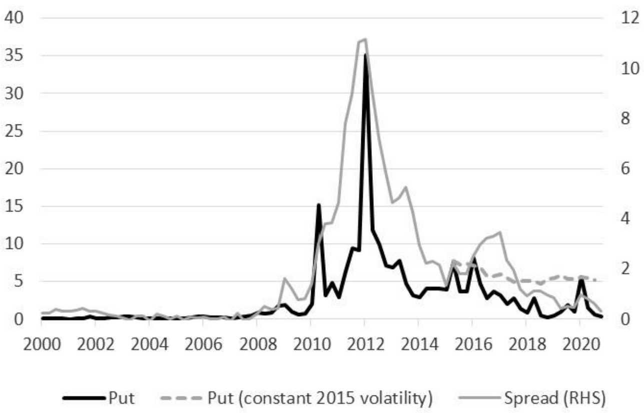
Italy



Spain



Portugal



Ireland

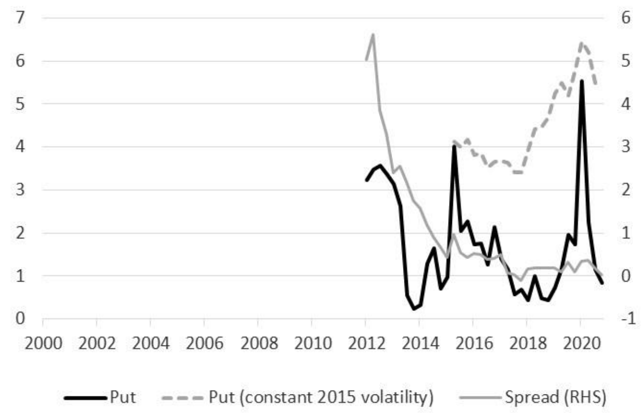
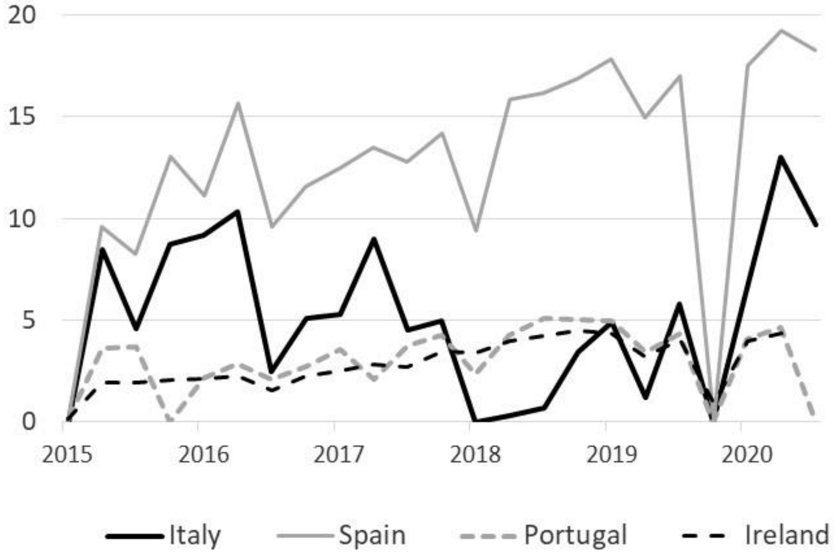


Figure 11 – Underlying value of QE reflected in put option value

(difference between shadow put value and actual put value, EUR bn)



Appendix A. Data definitions and sources

Variable name	*Description*	*Definition*	*Sources*
r	Yield on 10 year government bonds	Monthly average	Datastream
rf	Euro overnight index swap rate	Monthly average	Datastream
cpi	Inflation rate, Consensus forecast	Monthly, weighted average for next 12 months [a]	Consensus Economics
gdp	Real GDP growth rate, Consensus forecast	Monthly, weighted average for next 12 months [a]	Consensus Economics
debt	Debt ratio, % GDP, expected	Debt ratio minus *bal*; debt ratio seasonally adjusted and interpolated from quarterly figures [b]	OECD, Consensus Economics
bal	Budget balance, % GDP, Consensus forecast	Monthly, weighted average for next 12 months [a]	Consensus Economics
vol	Realized sovereign bond market volatility, by country	End of month annualized standard deviation of daily log bond price returns calculated over 45-day horizon	Own calculations based on Bloomberg
hilo	Highest minus lowest daily sovereign bond price, indicator of market liquidity	Monthly average of daily differences between the highest and lowest sovereign bond price	Own calculations based on Bloomberg
car	Current account ratio, % GDP, Consensus forecast	Monthly, weighted average for next 12 months [a]	Consensus Economics
nfa	Net foreign assets, % GDP	Monthly, end of period	IMF
rs	Shadow rate	Monthly, average	Krippner (www.ljkmfa.com)
ru	Monetary policy surprise	Monthly. First principal component of OIS rate surprises	Own calculations based on Altavilla et al. (2019)
flow	Net sovereign bond purchases	Monthly, end of period. This includes bonds issued by sovereigns, public agencies and regionals state entities.	ECB
B	Total sovereign debt	Quarterly, end of period	ECB

B short-term	Total short-term sovereign debt (residual maturity ≤ 1 year)	Quarterly, end of period	ECB
E	Total sovereign debt held by domestic investors excluding domestic banks	Quarterly, end of period	ECB
interest payments	Interest expenses of government	Quarterly, end of period	ECB
T	Duration government debt	Quarterly, end of period	Bloomberg

[a] If F_m^y is the Consensus forecast made in month *m* for the current year *y*, and F_m^{y+1} is the Consensus forecast for the coming year *y*+1, then the weighted average for the next 12 months is defined as: $\frac{F_m^y \cdot (12-m) + F_m^{y+1} \cdot m}{12}$, with $m = 1,\ldots,12$.

[b] If *bal* Consensus forecasts were not available, actual figures have been used.

Appendix B. Levin, Lin and Chu panel unit root tests

Ho: Panels contain unit roots		
Ha: Panels are stationary		
Panel means:	Not included	
Time trend:	Not included	
Panel variable	*Adjusted t*	*p-Value*
r-rf	-1.816	0.034
cpi	-2.521	0.005
gdp	-3.077	0.001
debt	2.342	0.990
vol	n.a.	n.a.
car	-1.027	0.152
nfa	0.385	0.650
hilo	n.a.	n.a.

Note: ADF regressions: 1 lag; Common AR parameter.
LR variance: Bartlett kernel, 20 lags average (chosen by LLC).
LLC test results for *vol* and *hilo* could not be calculated as these variables are weakly balanced.

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