EUROPEAN CENTRAL BANK
EUROSYSTEM

Working Paper Series

Tomáš Adam, Marco Lo Duca

Modeling euro area bond yields using a time-varying factor model

No 2012 / February 2017

Abstract

In this paper, we study the dynamics and drivers of sovereign bond yields in euro area countries using a factor model with time-varying loading coefficients and stochastic volatility, which allows for capturing changes in the pricing mechanism of bond yields. Our key contribution is exploring both the global and the local dimensions of bond yield determinants in individual euro area countries using a time-varying model. Using the reduced form results, we show decoupling of periphery euro area bond yields from the core countries yields following the financial crisis and the scope of their subsequent re-integration. In addition, by means of the structural analysis based on identification via sign restrictions, we present time varying impulse responses of bond yields to EA and US monetary policy shocks and to confidence shocks.

Keywords: bond yield, sovereign debt crisis, factor model, stochastic volatility, Bayesian estimation
JEL Classification Codes: C11, G01, E58

Non-technical summary

Sovereign bond markets have been in the centre of attention of policy makers and academics in recent years. As the global financial crisis and the European banking and sovereign crisis demonstrated, understanding the pricing mechanism and the drivers of bond yields is essential to monitor risks, decide on policies and assess their effectiveness. On the one hand, a part of the literature suggests that at the peak of the sovereign debt crisis, euro area bond yields reflected fundamentals, in particular the expected deterioration of the macro environment and of fiscal positions. Another strand of the literature suggests that risk aversion, panic and irrational investors' behaviour drove bond yields.

Against this backdrop, this study contributes to the policy debate and the academic literature by presenting a new model to assess the pricing mechanism of euro area sovereign bond yields from a dynamic perspective. In particular, we use a factor model with time varying loading coefficients and stochastic volatilities to assess the drivers of sovereign bond yields in euro area countries. The time variation in factor loading coefficients allows for capturing changes in the pricing mechanism of bond yields, consistent with the evidence emerging from other empirical studies. Exploring both the global and local dimensions of bond yield determinants in individual euro area countries is one of our key contributions. Specifically, our model studies the drivers of country specific yields separating between (i) Euro area core and periphery factors to assess integration, spill-overs and contagion within the euro area (ii) US and Emerging Market Economies (EMEs) market factors to assess spill-overs to the euro area from the rest of the world. Finally, time varying impulse responses to monetary policy shocks and confidence shocks are identified via sign restrictions and studied.

The results support the view that the pricing mechanism of bond yields evolved during the European banking and sovereign crisis. The analysis identifies three distinct phases in euro area sovereign bond markets. In the first, initial phase, bond markets were almost fully integrated. In the second, when the crisis escalated, bond markets became dis-integrated. In this phase, the pricing of euro area sovereign bonds depended on different factors and the transmission of monetary policy shocks became heterogeneous across countries. Lastly, in the third phase of partial re-integration, the pricing mechanism of bonds approached the pre-crisis conditions, according to loading coefficients and structural impulse responses.

The results suggest a framework to assess the gravity of distress in bond markets based on the model presented in this paper. The framework could rely on benchmarking idiosyncratic volatilities, loading coefficients and impulse responses to the averages observed during the pre-crisis and during the crisis periods. Spiking idiosyncratic volatilities would be a first sign of market turbulence. The pricing of the periphery and the core factors across bond markets could be used to assess the degree of integration and spill-overs across countries. Generally, the dispersion of the loading coefficients for each factor and of the impact coefficients of impulse responses to structural shocks could be informative of anomalies in the pricing of bonds.

Our results have implications for the debate on the impact of unconventional monetary policy on sovereign bond markets in the euro area. While the literature predominantly quantifies the impact of unconventional monetary policy on bond yields and it assesses the transmission channels (e.g. the signalling channel vs the portfolio balance channel), our results also shed light on the impact of policies on the pricing mechanism of yields. Specifically, we highlight a link between euro area unconventional policies, the way different factors are priced into bond yields and the reaction of bond yields to monetary policy shocks. We find that the announcement of Outright Monetary Transactions by the ECB was a game changer leading to a gradual normalisation of the pricing mechanism of bond yields to the pre-crisis situation, when looking at loading coefficients and structural impulse responses. Finally, another interesting finding shows that yields in troubled euro area countries became more responsive to EA monetary policy shocks during the crisis periods. This suggests that ECB mix of unconventional monetary policy was particularly effective in those markets where monetary accommodation was needed.

1 Introduction

Sovereign bond markets have increasingly drawn the attention of policy makers and academics in recent years. As the global financial crisis and the European banking and sovereign crises demonstrated, understanding the pricing mechanism and the drivers of bond yields is essential to monitor risks, decide on policies and assess their effectiveness.

First, sovereign bonds are benchmark financial instruments used for pricing of a large variety of financial assets, including bank loans and derivatives. As a consequence, sovereign bond yields have implications for the broader macro financial environment and the transmission of monetary policy.

Second, as short term rates hit the zero lower bound across advanced economies, central banks resorted to unconventional monetary policies, including large purchases of sovereign bonds, with the aim of providing stimulus by lowering long term yields. This led the academic and policy communities to step up the efforts to analyse bond markets to assess the effectiveness, the transmission channels and international spill-overs of unconventional monetary policy ((Gagnon et al., 2011), (D'Amico and King, 2013), (Wright, 2012), (Joyce et al., 2011) for the UK; (Hancock and Passmore, 2011), (Stroebel et al., 2012), (Hattori et al., 2016), (Rosa, 2012), (Gilchrist et al., 2014), (Neely et al., 2010), (Chen et al., 2012), (Fratzscher et al., 2013), (Rogers et al., 2014), (Bowman et al., 2015), (Christensen and Rudebusch, 2012), (Bauer and Neely, 2014), (Krishnamurthy and Vissing-Jorgensen, 2011), (Bauer and Rudebusch, 2014)).

Finally, the European sovereign and banking crisis showed the importance of understanding signals from bond markets in order to assess the underlying pricing factors and design appropriate policy responses ((De Santis, 2012), (De Santis, 2015), (De Grauwe and Ji, 2013), (Beirne and Fratzscher, 2013)). On the one hand, a number of contributions suggest that, at the peak of the sovereign debt crisis, euro area bond yields reflected fundamentals, in particular the expected deterioration of the macro environment and of fiscal positions. On the other hand, a number of other contributions suggest that risk aversion, panic and irrational investors' behaviour drove bond yields.

Overall, the evidence presented on the European crisis supports the view that the pricing mechanism of sovereign bond yields might change over time, consistent with the existence of multiple equilibria and market imperfections.

Against the background of the importance of understanding the drivers of bond yields, especially in a crisis/post crisis environment, this study contributes to the policy debate and the academic literature by presenting a new model to assess the pricing mechanism of euro area sovereign bond yields from a dynamic perspective. In particular, we use a factor model with time varying loading coefficients and stochastic volatilities to assess the drivers of sovereign bond yields in euro area countries. The time variation in factor loading coefficients allows for capturing changes in the pricing mechanism of bond yields, consistent with the evidence emerging from other empirical studies. Exploring both the global and local dimensions of bond yield determinants in individual euro area countries is one of our key contributions. Specifically, our model studies the drivers of country specific yields separating between (i) Euro area core and periphery factors to assess integration, spill-overs and contagion within the euro area (ii) US and Emerging Market Economies (EMEs) market factors to assess spill-overs to the euro area from the rest of the world. Finally, time varying impulse responses to monetary policy shocks and confidence shocks are identified via sign restrictions and studied.

From a financial stability perspective, the model presented in this article allows for the detection of anomalies or rapid changes in the pricing mechanism of bonds. For example, the model can detect early signs of de-coupling among euro area bond markets when idiosyncratic volatilities increase and when the role of the loading coefficient of the core euro area factor decreases. It can detect early signs of contagion when the loading coefficient of the periphery euro area factor increases. It can also be used to monitor the intensity of the spill-overs from the rest of the world by looking at the loading coefficients on the external variables. Relevant benchmarks for assessing the level of anomalies in the pricing mechanism are provided by loading coefficients, volatilities and shape of impulse responses in the pre-crisis and crisis periods. From a monetary policy perspective, the model provides useful information on whether the pricing mechanism changes in response to policy actions.

From an academic perspective, this study improves on the existing literature ((Boysen-Hogrefe, 2013), (D'Agostino and Ehrmann, 2013)) by adding external factors (US and EMEs) and other variables into a dynamic factor model with time varying loading coefficients for euro area bond yields. Furthermore, the study presents new evidence based on time varying impulse responses to discuss how the transmission of EA and US monetary policy shocks has evolved during the crisis. In addition, from the econometric point of view, the study shows how a recently proposed precision-based simulator of state-space models by Chan and Jeliazkov (2009) can be used to sample factors in a FAVAR model after a correction of singularity in the transition matrix.

The empirical analysis presented in the paper shows that there is substantial time variation in the loading coefficients of factors and in the impulse responses of yields to different shocks. This supports the view that the pricing mechanism of bond yields is not stable across periods, suggesting the existence of multiple equilibria where the pricing factors for bonds differ. In particular, the model captures well the unfolding of the European sovereign and banking crisis as of 2010 and the subsequent re-integration of markets after 2012. As of 2010, when the crisis escalated, idiosyncratic volatilities in a number of euro area countries spiked, bond yields in the periphery gradually became more sensitive to the euro area periphery factor and less sensitive to the core factor. At the same time the impulse responses of bond yields in some countries changed shape, suggesting changes in the transmission of monetary policy shocks. After 2012, the pricing mechanism gradually approached the situation prevailing in the pre-crisis periods.

The results of the analysis have implications for the debate on the impact of unconventional monetary policy on sovereign bond markets in the euro area. Specifically, our results suggest a link between euro area unconventional policies, the way different factors are priced into bond yields and the reaction of bond yields to monetary policy shocks. A notable finding is that the announcement of Outright Monetary Transactions by the ECB appears to have led to the gradual normalisation of the pricing mechanism of bond yields towards the pre-crisis situation. Another interesting finding is that the ECB mix of unconventional monetary policy gained particular traction in those markets experiencing distress where accommodation was needed.

The remainder of the paper is organised as follows. The next section presents the model and the data used for the empirical analysis. The subsequent two sections discuss the results and their implications for financial stability surveillance and for the analysis of monetary policy. The final section concludes.

2 Methodology and data

2.1 Model setup

To study the dynamics of bond yields, we use a FAVAR model with time-varying loadings. In our benchmark model, first differences of bond yields of N euro area countries are assumed to be driven by two euro area factors, dynamics of bond yields in the United States and in emerging markets, by changes in USD/EUR exchange rate and finally by country-specific idiosyncratic shocks. The five driving factors in turn evolve according to a VAR(p) process, which allows us to study interactions between the factors themselves and also responses of each euro area government bond yields to these factors.

More formally, let $y_{i,t}$ denote bond yield of country i $(i = 1, ...N)$ at time t, i_t^{us}, i_t^{eme} denote the US and emerging market factors, s_t denote the USD/EUR exchange rate and $\lambda_{i,j,t}$ denote loading of i-th country on j-th factor at time t. This notation leads to the following measurement equation:

$$y_{i,t} = \lambda_{i,1,t} f_{1,t} + \lambda_{i,2,t} f_{2,t} + \lambda_{i,3,t} i_t^{us} + \lambda_{i,4,t} i_t^{eme} + \lambda_{i,5,t} s_t + v_{i,t}, \quad (1)$$

$$v_{i,t} \sim N(0, \sigma^2_{v_{i,t}}) \quad (2)$$

We assume that the loadings on the five factors driving euro area bond yields are time-varying. This allows us to study how the pricing mechanism changes over time. Another approach to allow for time-varying parameters in the FAVAR is taken by Mumtaz et al. (2011), who allow for changing parameters in the VAR part of the model. We opt for the first specification, since our emphasis is on the identification of drivers (factors) driving bond yields in each euro area country.

In line with the literature (e.g., Primiceri (2005)) and in order to reduce dimensionality of the model, we assume that time-varying loadings follow a random walk process:

$$\lambda_{i,j,t} = \lambda_{i,j,t-1} + \epsilon_{i,j,t}, \quad \epsilon_{i,j,t} \sim N(0, \sigma^2_{\epsilon_{i,j}}), \quad (3)$$

where shocks $\epsilon_{i,j,t}$ are uncorrelated across equations, explanatory variables and time (indices i, j, t, respectively).

In addition to loadings, idiosyncratic shocks to the measurement equation are allowed to be time-varying and follow a random walk stochastic volatility process:

$$\log \sigma^2_{v_{i,t}} = \log \sigma^2_{v_{i,t-1}} + \epsilon_{v_t}, \quad \epsilon_{v_t} \sim N(0, \sigma_{\epsilon^2_v}) \quad (4)$$

The common factors and "exogenous" variables evolve according to a standard VAR process:

	EA core	EA periphery	US	EME	USD/EUR
EA monetary policy shock	+	+		+	+
US monetary policy shock			+	+	-
Risk aversion shock			-	+	-

Table 1: Sign restrictions on responses (on impact) to structural shocks. The plus sign in the USD/EUR column denotes the appreciation of euro vis-a-vis the US dollar.

$$Y_t = \Phi(L)Y_t + e_t, e_t \sim N(0, \Sigma), \qquad (5)$$

where $Y_t = \{f_{1,t}, f_{2,t}, i_t^{us}, i_t^{eme}, s_t\}$, $\Phi(L)$ is a multivariate lag polynomial (which includes an intercept in each VAR equation) and Σ is a general covariance matrix, i.e., we allow for non-zero correlation between shocks to the VAR equations.

2.1.1 Identification of factors

The factors $f_{1,t}$ and $f_{2,t}$ are identified using the strategy suggested by Bernanke et al. (2005) by assuming restrictions on the first two rows of matrix L_t, which stacks the row vectors $(\lambda_{i,1,t}, \lambda_{i,2,t}, \lambda_{i,3,t}, \lambda_{i,4,t}, \lambda_{i,5,t})$ across index i. Specifically, we assume that $\lambda_{i,j,t} = 1$ for $i = j$ and $\lambda_{i,1,t} = 0$ otherwise, for $i = 1, 2$.

This identification strategy allows us to interpret the common factors, when ordering of variables is chosen properly. In our case, we choose the first two bond yield series to represent bond yields of Belgium and Greece, respectively. This means that bond yield dynamics of Belgium is contemporaneously unaffected by movements in the second factor, bond yields in the US and emerging markets. Similarly, in other words, movements in Greek government bond yields are contemporaneously driven only by the second factor and idiosyncratic shocks. As a result of this identification, we can loosely interpret the first euro area factor as the core factor ($\lambda_{i,t}^{core} \equiv \lambda_{i,1,t}$) and the second euro area factor as the periphery factor ($\lambda_{i,t}^{periphery} \equiv \lambda_{i,2,t}$).

One may argue why German yields were not chosen to be ordered first, instead of Belgian. We do not opt for this possibility, since due to safe haven effects observed in the recent years, it is not reasonable to assume that $\lambda_{DE,t}^{periphery}$ would be always zero. Instead, one can expect $\lambda_{DE,t}^{periphery}$ to be often negative. In addition, a robustness check for this alternative identification strategy did not yield substantially different results[1].

2.1.2 Identification of structural shocks

In order to identify structural shocks in the model and draw impulse responses, we use an identification scheme based on contemporaneous sign restrictions (see Table 1). We focus on three structural shocks.

[1] It is worth noting that the first factor estimated using the baseline setup is mostly correlated with changes in yields in Finland (91%) and Germany (90%), while the correlation coefficients with changes in yields in Belgium is 75%. The second factor is mostly correlated with yields in Italy (43%), Greece (38%) and Spain (37%). This confirms that the chosen normalization of factors does not predetermine the shape of the estimated factors and also motivates the names of the factors (core / periphery). The correlations are also depicted in Figure D.1.

The tightening EA monetary policy shock is characterized by an increase in the euro area core and periphery factors, by an appreciation of the euro vis-a-vis the US dollar and by an increase in bond yields in emerging markets. This set of sign restrictions is motivated by standard assumptions on the impact of monetary policy on quasi-risk free yields, as captured by the core factor, and on the exchange rate [2]. In addition, we impose that the periphery factor, which prices in sovereign risk in troubled euro area countries, and emerging market yields, which prices in other risk factors, increase with monetary policy tightening, consistent with the findings on the impact on monetary policy on risk (Fratzscher et al. (2016), Bekaert et al. (2013)). Similarly to the euro area monetary policy shock, the tightening US monetary policy shock is characterized by an increase in the US and EME yields and by an appreciation of the US dollar. Finally, the risk aversion shock (or negative shock to market confidence) leads to higher yields in emerging markets, US dollar appreciation and lower US yields, reflecting safe haven flows. For the risk aversion shock, we leave responses in the euro area core and periphery factors unrestricted. We discuss the identified structural shocks and potential alternative approaches in Section 5.

2.1.3 Estimation

The model is estimated using Bayesian techniques, where posterior distributions of parameters are approximated by the Gibbs sampler. Technical details of the estimation are provided in the Appendix. Worth to note is that the dimension of the model is large, both in terms of the number of observations and parameters. The unobserved variables (factors, factor loadings and stochastic volatilities of idiosyncratic shocks) are usually estimated using simulation algorithm, such as that proposed by Carter and Kohn (1994). In contrast, we use a relatively recent precision-based simulator suggested by Chan and Jeliazkov (2009), which significantly reduces the computational burden in that it avoids the Kalman filtering step used in the standard algorithms. We run the Gibbs sampler 55,000 times and discard the first 50,000 draws as a burn-in sample. The subsequent 5,000 draws of parameters are used to compute posterior quantities.

2.2 Data

We use weekly data on 10 year government bond yields for the analysis, starting in October 2005 and ending at the end of August 2016. The data are plotted in Figure 1. We difference the data to achieve stationarity required for the factor analysis and subsequently standardize them [3] for computational purposes.

[2] Yields are expected to increase and the exchange rate to appreciate in response to monetary tightening

[3] We use a common standardization, i.e., demeaning and dividing by a standard deviation.

		Levels					Differences				
Variable	n	min	max	mean	median	sd	min	max	mean	median	sd
AT	559	0.24	4.84	2.83	3.24	1.27	-0.28	0.39	-0.01	-0.01	0.08
BE	559	0.37	5.41	3.11	3.58	1.28	-0.65	0.57	0.00	-0.01	0.10
DE	559	0.00	4.64	2.48	2.67	1.30	-0.30	0.27	-0.01	-0.01	0.08
EME	559	5.24	8.48	6.59	6.58	0.51	-0.48	0.44	0.00	-0.01	0.08
ES	559	1.20	7.25	3.99	4.10	1.27	-1.22	0.62	0.00	0.00	0.14
FI	559	0.22	4.89	2.71	2.93	1.28	-0.31	0.30	0.00	-0.01	0.08
FR	559	0.39	4.81	2.87	3.22	1.19	-0.27	0.35	-0.01	-0.01	0.08
GR	559	3.39	38.35	9.61	7.65	6.97	-19.60	5.11	0.01	0.01	1.11
IE	559	0.68	14.02	4.51	4.32	2.40	-1.89	1.59	0.00	-0.02	0.21
IT	559	1.19	7.05	4.00	4.25	1.23	-1.00	0.57	0.00	-0.01	0.12
NL	559	0.23	4.82	2.72	2.92	1.28	-0.25	0.28	-0.01	-0.01	0.08
PT	559	1.65	15.60	5.43	4.44	2.81	-2.26	1.91	0.00	0.00	0.29
US	559	1.44	5.21	3.08	2.88	1.05	-0.41	0.31	0.00	-0.01	0.10
USDEUR	559	1.06	1.59	1.31	1.32	0.11	-0.06	0.10	0.00	0.00	0.02

Table 2: Descriptive statistics for sovereign bond yields and euro/dollar exchange rate (USDEUR). Source: Datastream

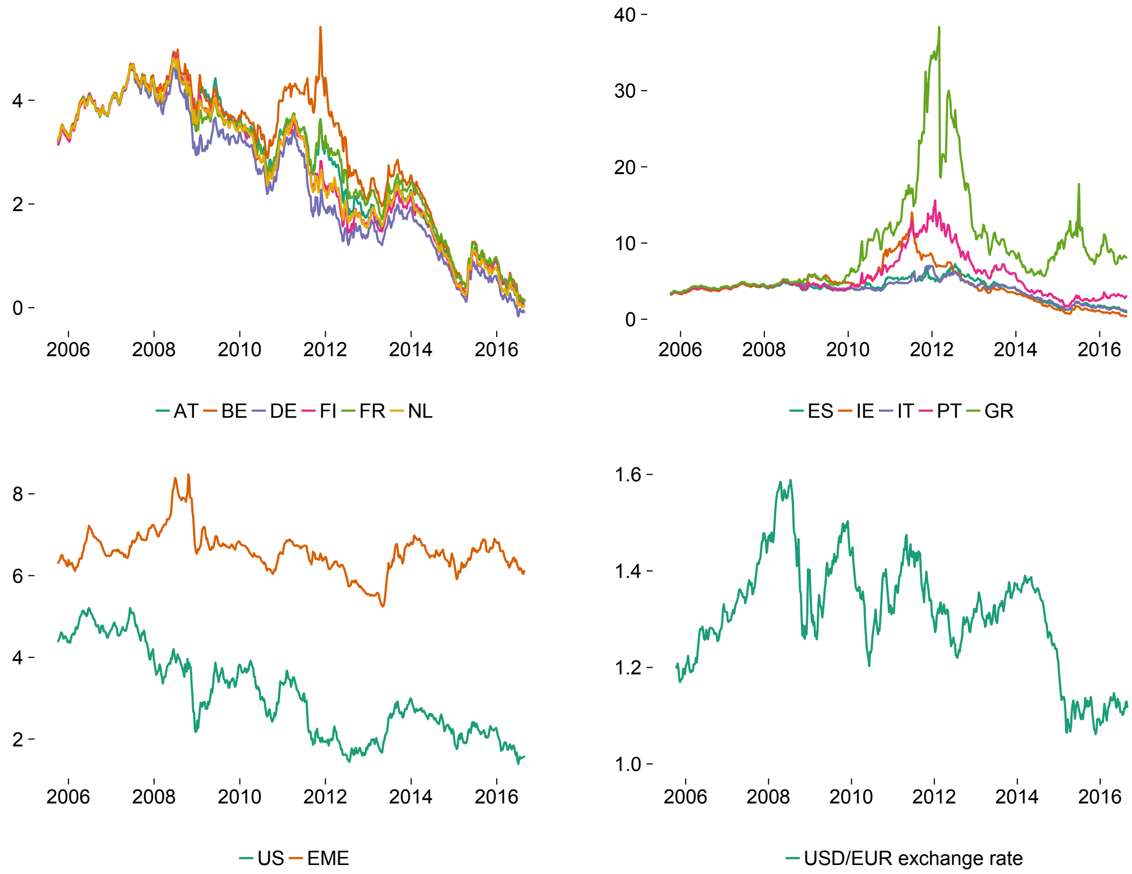

Figure 1: Sovereign bond yields and euro/dollar exchange rate (USDEUR). Source: Datastream

3 Results

The model described in the previous section yields several outputs, which we study subsequently.

3.1 Reduced-form results: estimated factors, idiosyncratic volatilities and loading coefficients

The raw estimated factors are not very informative on their own, since they are estimated on stationary time series and therefore capture co-movements of weekly bond yield changes, which can be very noisy. To obtain a more informative insight from the factors, we focus on their cumulative sums (Figure 2), which show general directions of bond yield movements. A number of stylised facts are worth noting. First, the euro area core factor displays a similar pattern to core euro area countries bond yields, as observed in Figure 1. Second, the euro area periphery factor captures well the evolution of sovereign tensions across the euro area. In particular, the periphery factor started to follow an upward trend in 2010 reaching a peak in 2012. It stabilised in early 2012, following the three year ECB long-term refinancing operations (LTROs) and reverted in the second part of the year after the ECB announced the possibility of Outright Monetary Transactions (OMT). After the summer of 2012, the periphery factor followed a generally declining trend. This evidence suggests a role of ECB policies in bringing the pricing mechanism of bond yields to normal times. Another interesting finding is that the downward trend in the periphery factor did not revert during the summer 2015, the period of large uncertainty related to the extension of the macroeconomic adjustment programme in Greece. This suggests that the latter episode of turmoil remained largely contained. A last finding is that one can observe a decoupling of the euro area core factor from US yields after 2013, when monetary policy in the euro area and in the US started diverging.

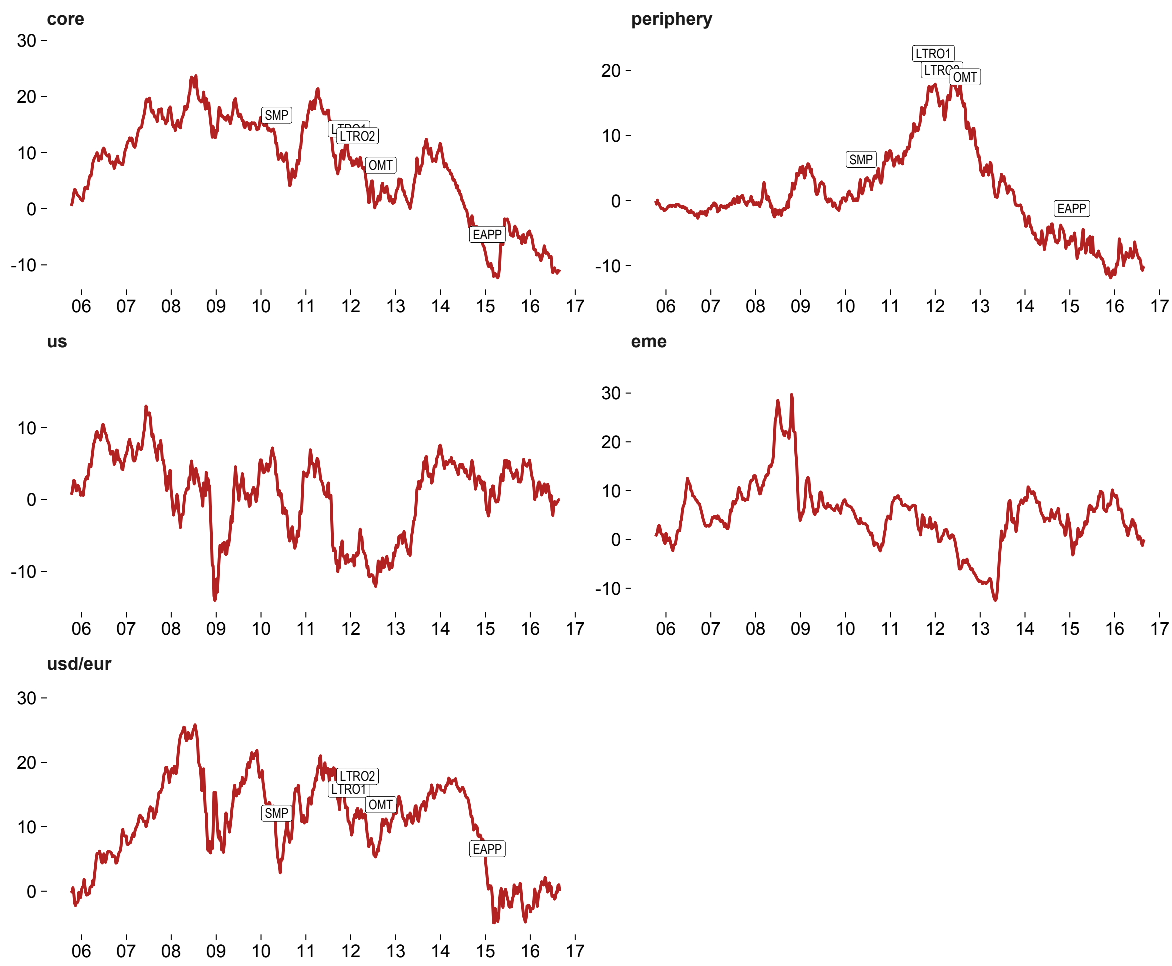

Figure 2: Cumulative sums of estimated factors and exogenous variables used for the analysis (which were stationarized and standardized, subsequently).

Turning to the stochastic volatility of idiosyncratic shocks (Figure 3), it was generally elevated during the peak of the financial crisis of 2008, reflecting the turmoil in financial markets. Another generally observed peak coincides with the beginning of 2012, i.e. around the peak of the sovereign debt crisis. Interestingly, stochastic volatility in Greece evolves relatively smoothly compared to other countries. This reflects the high standard deviation of changes in Greek bond yields on which the model is estimated and additionally its loading on the periphery factor, which explains Greek bond movements relatively well on average. Nevertheless, stochastic volatility of idiosyncratic shocks of Greek bonds was elevated during the summer 2015, reflecting the uncertainty around the extension of the adjustment programme.

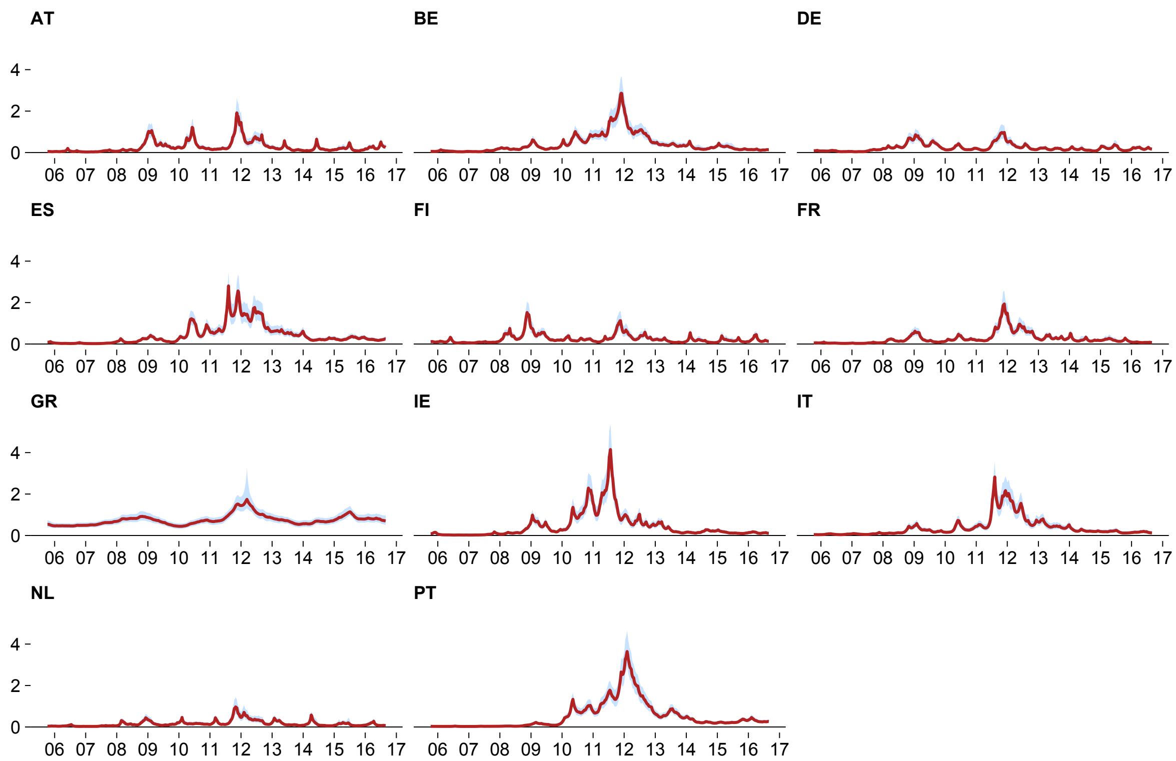

Figure 3: Stochastic volatility of idiosyncratic shocks to bond yields: posterior median, 16th and 84th quantiles.

Turning to factor loadings (Figures 4 and B.1 - B.3), there are a number of interesting findings. First, at the beginning of the sample, loadings on both the core and the periphery factors were homogeneous, reflecting the integration of the euro area bond markets. Second, following the financial crisis of 2008, loadings of all countries on the core factor generally declined. Third, the loadings of IT, PT, IE, ES started decoupling from the loadings of other countries in 2009. Their loadings on the core factor declined significantly, while the loading on the periphery factor substantially increased. Consistently with the dynamics of the periphery factor, the decoupling reached its peak in 2012, after which countries became again more homogeneous (as measured by the similarity of loading coefficients). It is worth noting that the reversal in the dispersion among loading coefficients coincides with the announcement of the OMT programme in summer 2012 (denoted in figures in the Appendix)[4]. The OMT brought about a change in the pricing mechanism of sovereign bonds, leading to re-integration between the periphery and the core of the euro area. Nevertheless, at the end of the sample, loadings on the core factor were still lower than at the beginning of the sample, while loadings on the periphery factor were higher (particularly in the case of Portugal, Spain, and Italy). Interestingly, the loadings of Germany and Finland on the periphery factor are generally negative, which reflects their safe haven status. The safe haven status of these two countries is further reflected by periods of large positive loadings on the exchange rate (Figure B.1), which signals that depreciation of the euro tends to be associated with declining yields in Germany and Finland on average.

[4]On July 26 2012, the ECB president hinted to the imminent adoption unconventional monetary policy measure during his speech in London. The OMT was finally announced in August 2012.

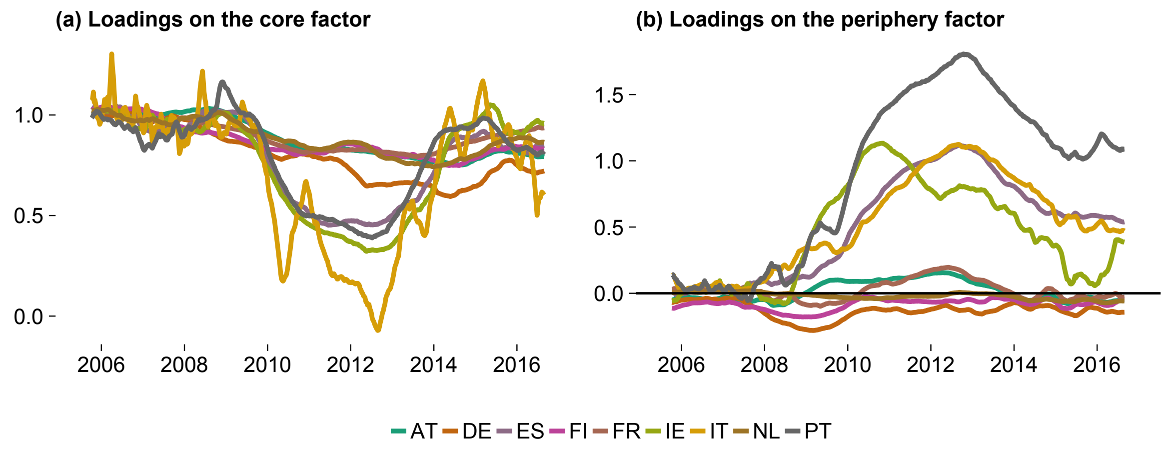

Figure 4: Evolution of loadings of bond yields on factors

3.2 Structural form results

Regarding the structural analysis, it is worth checking the evolution of structural shocks in order to assess the plausibility of the imposed sign restrictions. To facilitate the identification of periods of prevailing monetary accommodation, Figure 5 plots semi-annually cumulated euro area and US monetary policy shocks. In the euro area, significant loosening of monetary policy occurs in the second half of 2008 and 2011, in the first half of 2010 and during 2012 and 2014. All of these periods coincide with important monetary policy actions. The detected accommodation in the second half of 2008 corresponds to aggressive rate cuts and provision of liquidity in the aftermath of the collapse of Lehman Brothers. Accommodation in 2010 and 2011 corresponds to the introduction and the re-activation of the Security Market Program (SMP). Easing in 2012 reflects the unprecedented provision of long term loans via the three year long term refinancing operations and the announcement of Outright Monetary Transactions (OMT). Finally, accommodation in 2014 reflects the progressive building up of expectations and the final announcement of the Extended Asset Purchase Program (EAPP). Turning to the US monetary policy shocks, one can observe loosening in the second half of 2008, and 2011 in response to the introduction of different rounds of bond purchases. On the other hand, the model correctly captures the announcement of tapering of bond purchases in 2013 and the build-up of expectations of monetary policy tightening in 2015.

To validate our identification scheme, we also check the largest identified shocks. For euro area the largest accommodative monetary policy shocks occurred in the weeks when the SMP (May 2010) and the EAPP (January 2015) were announced. The largest accommodative US monetary policy shocks coincided with the initial announcement of the LSAP programme (November 2008) and its expansion to government securities (March 2009). On the other hand, one of the largest tightening shock for the US was in June 2013, when the "tapering" of the QE programme by the Fed was anticipated.

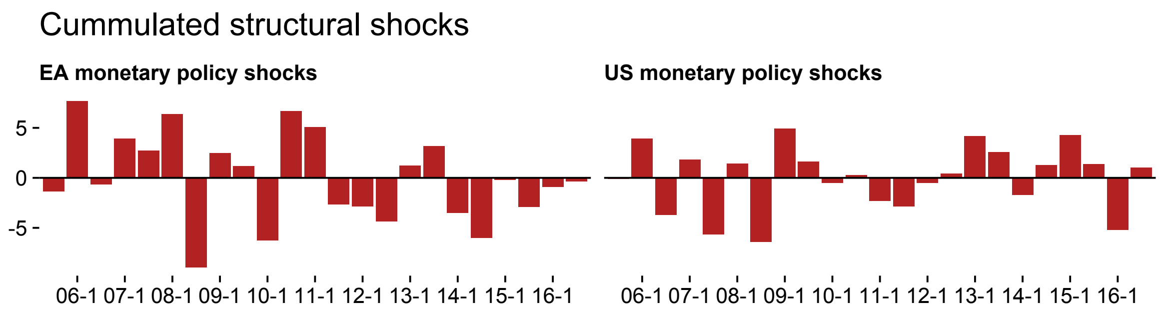

Figure 5: Semiannually cumulated structural shocks

Figure 6 depicts responses to the identified shocks described in the methodology section (euro area and the US monetary policy shocks, respectively, and the risk aversion shock). The shocks are priced in quickly, reflecting the fast behaviour of financial markets. In addition, the speed of responses is lowest in emerging market economies.

The responses to the euro area (tightening) monetary policy shock are significant for the core and periphery factors, as well as for the exchange rate, leading to an appreciation of the euro vis-a-vis the US dollar. The same shock leads to positive responses of the US (not specified by the sign restrictions) and emerging market yields, although the reaction is statistically insignificant in the first two weeks in case of the United States. A tightening US monetary policy shock leads to a significant positive response in emerging markets and to a significant appreciation of the dollar vis-a-vis the euro. The same shock leads to a positive, significant, response in the euro area core factor, which is not implied by the sign restrictions. Finally, increasing risk aversion, which by definition leads to the appreciation of the dollar accompanied by rising yields in the EMEs and declining yields in the United States, leads to a decrease in yields in the core and an increase in the periphery, although the responses in the periphery are insignificant. This can be explained by a various nature of the risk aversion shocks (global vs local, for example).

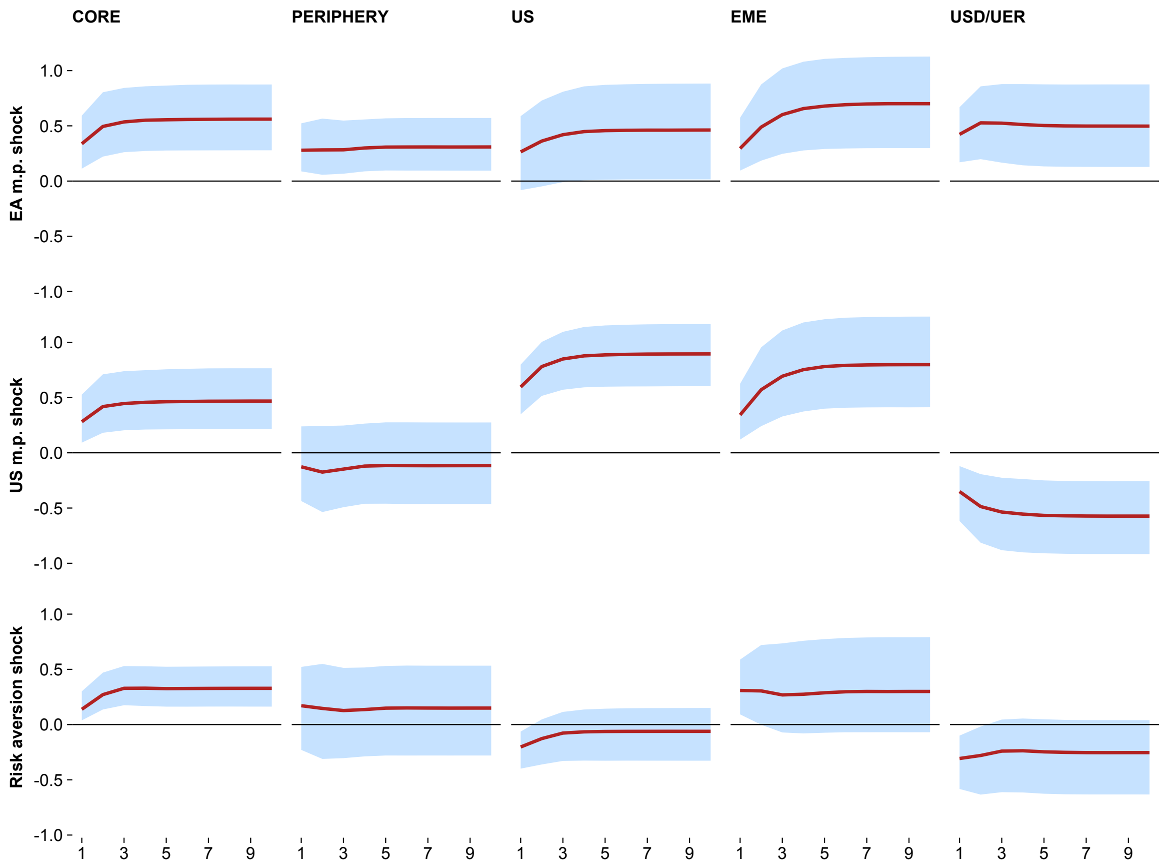

Figure 6: Cumulative impulse responses to structural shocks: posterior median, 16th and 84th quantiles. x-axis: weeks

The impulse response functions presented so far have been computed using the VAR equation of the FAVAR model based on the assumption of constant coefficients. These results can be transformed using time-varying loadings into time-varying impact responses of each country to each structural shock, which are depicted in Figures 7. The time varying impulse responses provide interesting insights on how the transmission of monetary policy has evolved during recent years, reflecting market conditions and different policy mixes.

The results suggest that at the beginning of the sample, the responses of sovereign yields to all shocks were relatively homogeneous across countries, consistent with a high degree of financial integration in Europe. Focusing on the euro area monetary policy shock, the responses of PT, ES, IT and IE started decoupling from the other countries in 2008. Overall, between 2008 and 2014 impulse responses remained dispersed across euro area countries. At the end of the sample, responses were homogenous again across the euro area, with the exception of PT, IT and ES. The latter result suggests at least partial normalisation of the transmission mechanism of monetary policy to bond yields in the euro area.

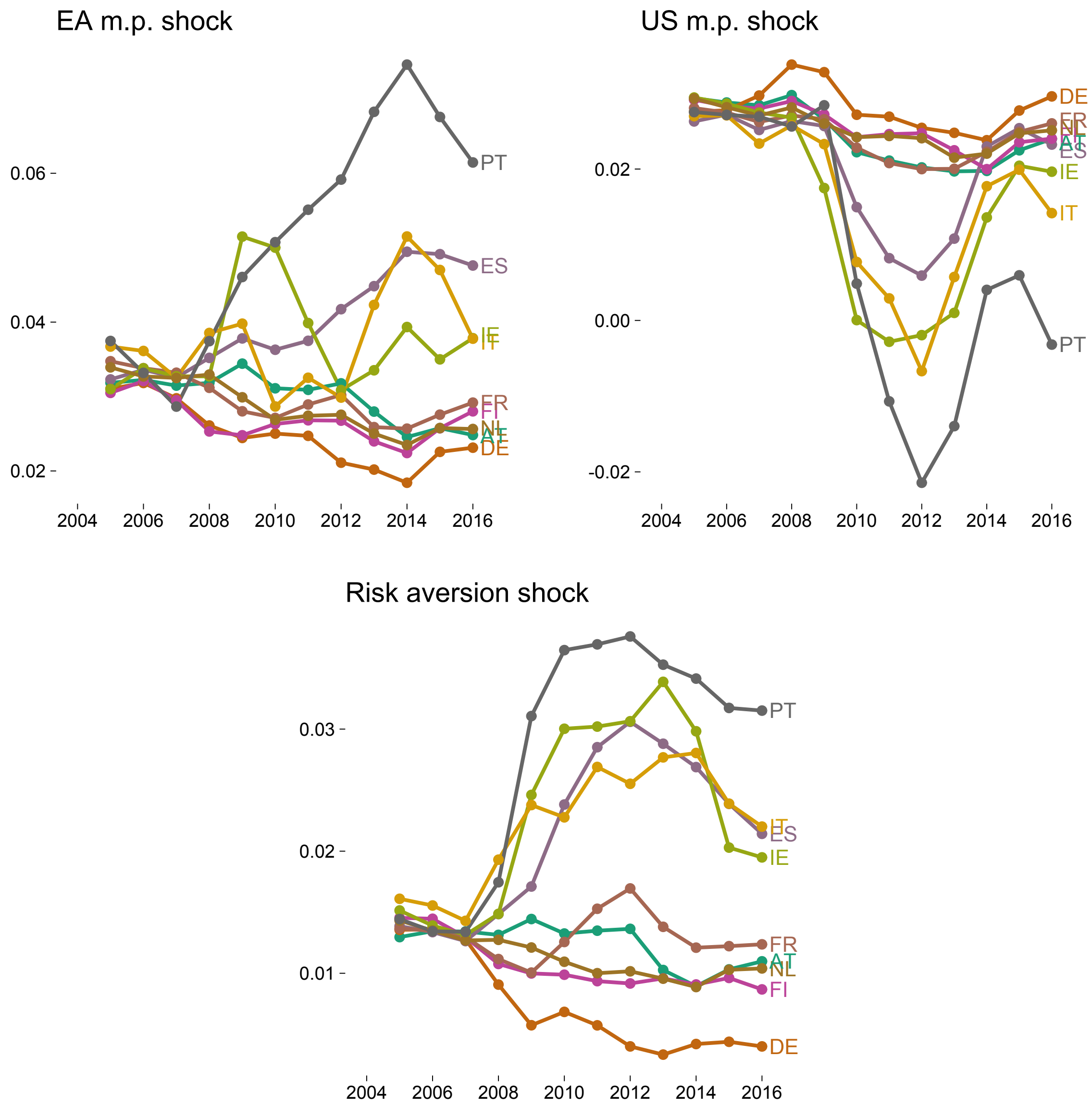

Figure 7: Impact coefficients to the euro area and US monetary policy shocks - annual averages

Interestingly, bond yields in troubled euro area countries (PT, IT, IE and ES) became more sensitive to euro area monetary policy as the crisis escalated. This finding apparently contradicts the narrative that the transmission mechanism of monetary policy in the euro area became impaired during the crisis. While this may indeed be the case for the transmission of conventional monetary policy via short term rates, other forms of unconventional monetary policy were introduced during the crisis specifically to overcome the lack of grip of conventional monetary policy. By relying on the identification scheme based on sign restrictions on the movement of factors and the exchange rate, our approach captures the impact of the overall mix of monetary policy on bond yields. Against this backdrop, the finding that yields in troubled euro area countries react more to the mix of monetary policy is not surprising. This supports the view that new forms of monetary policy were most effective where they were needed, i.e. in bond markets of troubled euro area countries.

Turning to US monetary policy shocks, the responses of euro area bond yields were also homogeneous at the beginning of the sample, suggesting strong integration in European sovereign bond markets. Similarly to the responses to euro area monetary policy shocks, the dispersion of responses increased significantly starting from 2010, when the euro area banking and sovereign crisis escalated, and peaked in 2012. At the end of the sample, responses were homogenous again across the euro area, with the exception of IE, IT and PT. It is worth noting how countries largely driven by the periphery factor during the acute phase of the European crisis (PT, IT, IE, ES) were "isolated" from the US monetary policy shocks. The higher and more stable impact coefficients of the euro area other countries could be related to substitutability of their bonds with US Treasuries in portfolios of global bond investors. The impulse response analysis suggests that this substitutability was lost by troubled euro area countries after the financial crisis of 2008. At the same time, yields of these countries started to react more sensitively to risk aversion shocks and this sensitivity diminished somewhat only after 2012.

The impulse response analysis described so far suggests how yields of each country react over time to shocks of the same size. In order to assess the drivers of changes in bond yields, one can employ an historical decomposition (plotted in Figure 8). The results show that the euro area core factor was driven to a large extent by euro area monetary policy shocks, which led to declines in yields particularly in 2008, 2012 and 2014, i.e. years when the ECB either cut interest rates or announced programmes to further ease monetary conditions. Furthermore, one can observe the opposite effect of expectations of tightening the US monetary policy in 2013 and 2015. Changes in the periphery factor were largely driven by unexplained shocks, which plausibly capture the local risk aversion and worsening fundamentals, i.e. effects we are not able to identify using our relatively parsimonious model. On the other hand, loosening of the euro area monetary policy in 2012, 2014 and 2015 was successful in driving down the periphery factor.

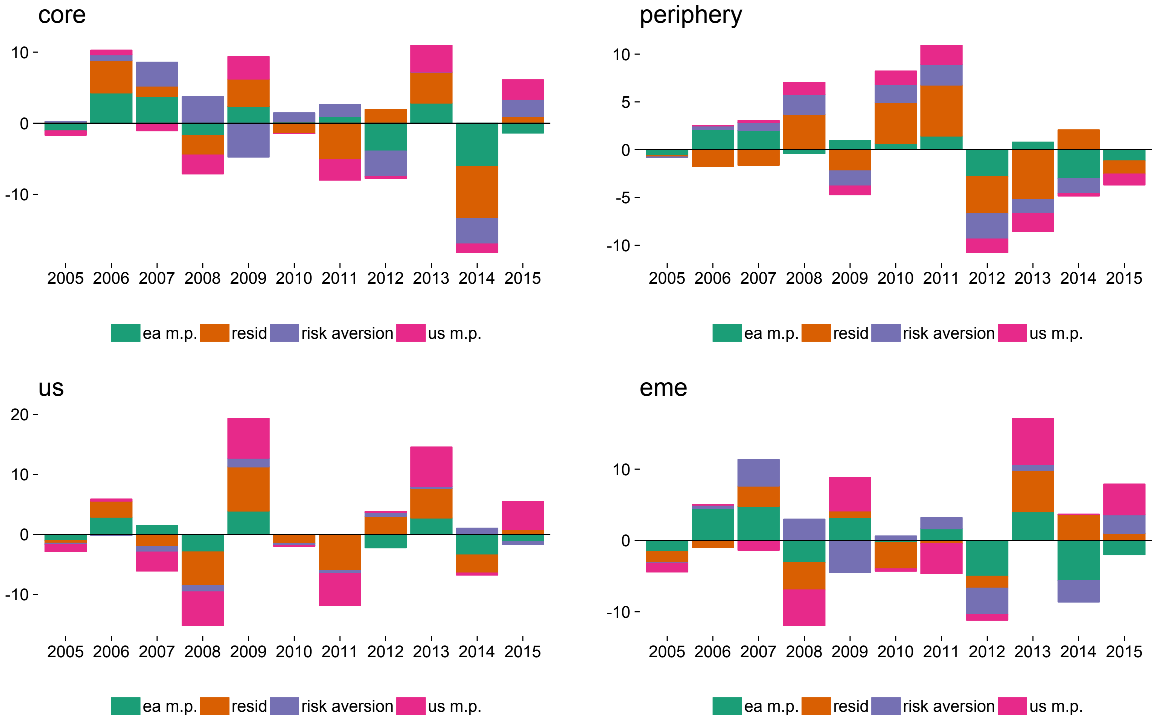

Figure 8: Historical decomposition of annual changes in bond unobserved factors, bond yields in the US and EMEs.

Regarding the US factor, one can observe that changes in the euro area monetary policy had relatively small impact on its changes. In addition, the model identifies significant loosing in 2008 and 2011 and tightening in 2013 and 2015. Finally, the US monetary policy had a significant loosening effect on EME yields in 2011 and 2012, reflecting portfolio rebalancing effect of unconventional monetary policy. On the other hand, the tapering announcement in 2013 and expectations of tightening the US monetary policy in 2015 contributed to an increase in EME bond yields.

3.3 Robustness analysis

We check the robustness of our findings along several dimensions. Regarding the reduced form analysis, we test alternative assumptions to identify the core and periphery factors. In our benchmark specification, we identify the signs and magnitudes of the factors by assuming that changes in the Belgian sovereign yields on the core factor have loading equal to one and zero elsewhere. Symmetrically, the Greek sovereign bond yield loads only on the periphery factor by the coefficient equal to one. In the robustness check, we replace the Belgian bond yields by German bond yields, while we replace the Greek bond yields with Portuguese yields. The results are substantially unaffected by this change [5]. Generally the results are broadly stable as long as the core factor is identified by mean of a non-troubled euro area sovereign bond yield and the periphery factor by one euro area troubled country. While the shape of the factors might slightly change across specifications, the key results about time variation in loading coefficients and impulse response functions remain stable.

[5] The correlation between the first factors (core factor) in the two different specifications is 0.98, while the correlation between the second factors (periphery factor) is 0.9.

Regarding the identification of structural shocks and the related impulse responses, we perform two additional robustness checks. In the first one, we want to check how restrictive our assumption on fixed coefficients in the VAR part of the model is (i.e., $\Phi(L), \Sigma$ in Equation 2.1). Our motivation for this is that one may expect that the transmission mechanism has changed due to the introduction of non-standard measures of monetary policy. Therefore, we estimate (endogenously in one model) two sets of system matrices ($\Phi(L), \Sigma$), where the first set is used for filtering the state variables in the first part of the sample (up to the end of 2010) and the second set is used for the filtering in the remaining sample. The resulting factors are highly correlated with the baseline results (with correlation coefficients of the two factors of 0.99, 0.93, respectively). Also the impulse responses that we obtain in this setting confirm the findings of our benchmark specification.

Second, we extend the model to include an additional exogenous variables which helps identifying shocks. We note that demand shocks might results in similar effects to US monetary policy shocks in the set of variables that we include in the model and use for identification. Essentially, a demand shock in the US might push US yields and the US dollar up, the same conditions that we use for identifying US monetary policy shocks[6]. In order to disentangle between the two type of shocks, we include US breakeven inflation [7] among the variables in the model. While a demand shock would push inflation up, a tightening monetary policy shock would push it down. The results in this setting confirm a large part of our benchmark specification. However, this alternative model specification identifies monetary policy tightening in the US in 2009, which is not very plausible. In order to keep the model parsimonious, we decided to drop the measure of break-even inflation from the baseline model.

4 Discussions of the results

4.1 Implications for financial stability surveillance

The results discussed in the previous section support the view that the pricing mechanism of bond yields evolved during the European banking and sovereign crisis. First, a new pricing (periphery) factor associated to the euro area troubled countries emerged during the acute phase of the crises. Second, loading coefficients of bond yields on the different factors changed substantially during the crisis. Specifically, the loading coefficients of troubled countries on the periphery factor increased, while those on the core factor decreased. The opposite was true for other euro area countries. Third, the reaction of yields to US and Euro area monetary policy shocks also evolved according to market conditions.

The results support the view of three distinct phases in euro area sovereign bond markets between 2006 and early 2016. In an initial phase of almost full integration, only one pricing factor mattered for euro area sovereign bond yields (i.e. the core factor). Also, loading coefficients and impulse responses to shocks where homogeneous across sovereign bond markets in this period. In the second phase, when the crisis escalated, bond yields decoupled: some bond yields remained tightly linked to the core factor, while others became linked to the periphery factor. During this phase, also the transmission of monetary policy

[6] In our view, this is less of a problem in the euro area, where a demand shock would most likely lead to a decrease in risk and therefore to a decrease in the periphery factor, which is the opposite of a tightening monetary policy shock.

[7] Measured as 10-year breakeven inflation rate, downloaded from Federal Reserve Economic Data (ticker T10YIE).

was heterogeneous across countries. Lastly, in the third phase of partial re-integration of bond markets, the pricing mechanism appeared to approach the pre-crisis conditions according to loading coefficients and impulse responses.

Concerning potential explanations of the above findings, as discussed in ((Lo Duca, 2012)), there are several reasons why the determinants of asset prices could change across periods. First, during turbulent periods, information asymmetries could prevent the market to clear at a given price ((Stiglitz and Weiss, 1981)). Second, heterogeneous investors have different allocation strategies, therefore pricing changes across periods are reflecting the mix of active investors. The latter is likely to have changed substantially during the crisis, especially for sovereign bonds in troubled euro area countries. In particular, evidence suggests that the pool of active investors in these bond markets shrank and liquidity got much thinner. Third, during periods of market turbulence, investors might face binding constraints as, for example, margin calls, or the need to sell certain assets to preserve the risk profile of their portfolios. In this context, investment decisions are either increasingly influenced by certain events, as rating actions, or become increasingly related to the dynamic of certain variables as, for example, the price or the volatility of certain benchmark assets. As pointed by Adrian et al. (2010), this can generate self-enforcing de-leveraging cycles that increase the sensitivity of prices and flows to common factors. Fourth, the information set that investors use to price assets might change over time. This might have been the case during the European banking and sovereign crisis when ex-ante unlikely fears of euro break up started being priced into sovereign bonds (Draghi (2012), De Santis (2015)).

The above results suggest a framework to assess the gravity of distress in bond markets based on the model presented in this paper. First, spiking idiosyncratic volatilities are a first sign of market turbulence. Although, as demonstrated by the 2015 Greek episode, a spike in the idiosyncratic volatility in one market does not necessarily transmit to other markets. Idiosyncratic volatilities could be benchmarked to average levels in the pre-crisis and in the crisis periods. Second, looking at the pricing of the periphery and the core factors across bond markets is important to assess the degree of integration and spill-overs across countries. Significant turbulence would be detected when the loading on the periphery factor increases in one country. A dangerous situation of contagion would emerge when the loading coefficient of the periphery factor increases in more countries. Generally, the dispersion of the loading coefficients for each factor could be benchmarked to the levels observed during the acute phase of the crisis.

4.2 Impact of monetary policy on the pricing mechanism of sovereign bond yields

Our results have implications for the debate on the impact of unconventional monetary policy on bond markets. While the literature predominantly quantifies the impact of unconventional monetary policy on bond yields and it assesses the transmission channels (e.g. signalling channel vs portfolio balance channel), our results shed light on the impact of policies on the pricing mechanism of yields. Specifically, our results suggest an intriguing link between euro area unconventional policies, the way different factors are priced into bond yields and the reaction of bond yields to monetary policy shocks. While it is extremely difficult to formally test the link between unconventional monetary policy and changes in the pricing mechanism of sovereign bond yields, a number of stylised facts appear to support the view that the announcement of Outright Monetary Transactions by the ECB was a game changer leading to a turning point in several indicators of markets stress. Conversely, several other unconventional monetary policy actions, including the Security Market Programme (SMP), other purchases programmes and liquidity injections, while having visible positive effects (Fratzscher et al. (2016)), only temporarily halted the escalation of the crisis. Specifically, the OMT announcement coincides (i) with turning points in the cumulated dynamics of the periphery factor which started decreasing the second half of 2012, (ii) with a gradual normalisation of the loading coefficients of bond yields on the core and periphery factors towards pre-crisis levels and (iii) with gradual normalisation of the reaction of euro area bond yields to monetary policy shocks.

Another interesting finding relates to the dynamic response of sovereign yields to euro area monetary policy shocks. In particular, over time, yields in troubled euro area countries became more responsive to EA monetary policy shocks. At the same time, the response of yields in other euro area countries did not display substantial changes. This suggests that ECB mix of unconventional monetary policy was particularly effective in those markets in distress where risk premia rose and where accommodation was needed.

5 Conclusion

The paper studies movements in euro area sovereign bond yields using a factor model with time-varying loadings, which capture potential changes in the pricing mechanism of bond yields. Impulse responses to three structural shocks (EA monetary policy, US monetary policy and risk aversion) are also analysed over time. The structural identification strategy based on sign restrictions yields overall plausible results when assessed against key monetary policy actions during the period under review.

The results support the view that the pricing mechanism of bond yields evolved during the European banking and sovereign crisis. The analysis identifies three distinct phases in euro area sovereign bond markets. First, an initial phase when bond markets were almost fully integrated. A second phase of dis-integration in bond markets when the crisis escalated. In this phase the pricing of euro area sovereign bonds depended on different factors and the transmission of monetary policy shocks became heterogeneous across countries. Lastly, a third phase of partial re-integration, when the pricing mechanism of bonds approached the pre-crisis conditions, according to loading coefficients and structural impulse responses.

The above results suggest a framework to assess the gravity of distress in bond markets based on the model presented in this paper. The framework could rely on benchmarking idiosyncratic volatilities, loading coefficients and impulse responses to the averages observed during the pre-crisis and during the crisis periods. Spiking idiosyncratic volatilities would be a first sign of market turbulence. The pricing of the periphery and the core factors across bond markets could be used to assess the degree of integration and spill-overs across countries. Generally, the dispersion of the loading coefficients for each factor and of the impact coefficients of impulse responses to structural shocks could be informative of anomalies in the pricing of bonds.

Our results have implications for the debate on the impact of unconventional monetary policy on sovereign bond markets in the euro area. While the literature predominantly quantifies the impact of unconventional monetary policy on bond yields and it assesses the transmission channels (e.g. the signalling channel vs the portfolio balance channel), our results also shed light on the impact of policies on the pricing mechanism of yields. Specifically, our results suggest a link between euro area unconventional policies, the way different factors are priced into bond yields and the reaction of bond yields to monetary policy shocks. We find that the announcement of Outright Monetary Transactions by the ECB was a game changer leading to a gradual normalisation of the pricing mechanism of bond yields to the pre-crisis situation, when looking at loading coefficients and structural impulse responses. Finally, another interesting finding shows that yields in troubled euro area countries became more responsive to EA monetary policy shocks during the crisis periods. This suggests that ECB mix of unconventional monetary policy was particularly effective in those markets where accommodation was needed.

References

Adrian, T., Shin, H. S., et al. (2010). The changing nature of financial intermediation and the financial crisis of 2007–2009. *Annual Review of Economics*, 2(1):603–618.

Bauer, M. D. and Neely, C. J. (2014). International channels of the Fed's unconventional monetary policy. *Journal of International Money and Finance*, 44:24–46.

Bauer, M. D. and Rudebusch, G. D. (2014). The signalling channel of Federal Reserve bond purchases. *International Journal of Central Banking*, 10:233–89.

Beirne, J. and Fratzscher, M. (2013). The pricing of sovereign risk and contagion during the european sovereign debt crisis. *Journal of International Money and Finance*, 34:60–82.

Bekaert, G., Hoerova, M., and Duca, M. L. (2013). Risk, uncertainty and monetary policy. *Journal of Monetary Economics*, 60(7):771–788.

Bernanke, B., Boivin, J., and Eliasz, P. (2005). Factor augmented vector autoregressions (FAVARs) and the analysis of monetary policy. *Quarterly Journal of Economics*, 120(1):387–422.

Bowman, D., Londono, J. M., and Sapriza, H. (2015). US unconventional monetary policy and transmission to emerging market economies. *Journal of International Money and Finance*, 55:27–59.

Boysen-Hogrefe, J. (2013). A dynamic factor model with time-varying loadings for euro area bond markets during the debt crisis. *Economics Letters*, 118(1):50–54.

Carter, C. and Kohn, R. (1994). On Gibbs sampling for state space models. *Biometrika*, 81(3):541–553.

Chan, J. C. and Jeliazkov, I. (2009). Efficient simulation and integrated likelihood estimation in state space models. *International Journal of Mathematical Modelling and Numerical Optimisation*, 1(1-2):101–120.

Chen, Q., Filardo, A. J., He, D., and Zhu, F. (2012). International spillovers of central bank balance sheet policies. *BIS Papers No. 66, Bank for International Settlements, Basel (2012).*

Christensen, J. H. and Rudebusch, G. D. (2012). The response of interest rates to US and UK quantitative easing. *The Economic Journal*, 122(564):F385–F414.

D'Agostino, A. and Ehrmann, M. (2013). The pricing of G7 sovereign bond spreads: The times, they are a-changin. ECB Working Paper Series, No. 1520.

D'Amico, S. and King, T. B. (2013). Flow and stock effects of large-scale treasury purchases: Evidence on the importance of local supply. *Journal of Financial Economics*, 108(2):425–448.

De Grauwe, P. and Ji, Y. (2013). Self-fulfilling crises in the eurozone: An empirical test. *Journal of International Money and Finance*, 34:15–36.

De Santis, R. A. (2012). The euro area sovereign debt crisis: safe haven, credit rating agencies and the spread of the fever from Greece, Ireland and Portugal. ECB working paper series (1419).

De Santis, R. A. (2015). A measure of redenomination risk. ECB working paper series (1785).

Draghi, M. (2012). Speech at the global investment conference in London (26 July 2012).

Fratzscher, M., Duca, M. L., and Straub, R. (2016). ECB unconventional monetary policy: Market impact and international spillovers. *IMF Economic Review*, 64(1):36–74.

Fratzscher, M., Lo Duca, M., and Straub, R. (2013). On the international spillovers of US quantitative easing. *ECB Working Paper Series, No. 1557.*

Gagnon, J., Raskin, M., Remache, J., and Sack, B. (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking*, 7(1):3–43.

Gilchrist, S., Yue, V., and Zakrajsek, E. (2014). The response of sovereign bond yields to US monetary policy. Technical report, Tech. rep., Mimeo.

Hancock, D. and Passmore, W. (2011). Did the Federal Reserve's MBS purchase program lower mortgage rates? *Journal of Monetary Economics*, 58(5):498–514.

Hattori, M., Schrimpf, A., and Sushko, V. (2016). The response of tail risk perceptions to unconventional monetary policy. *American Economic Journal: Macroeconomics*, 8(2):111–136.

Joyce, M., Lasaosa, A., Stevens, I., Tong, M., et al. (2011). The financial market impact of quantitative easing in the United Kingdom. *International Journal of Central Banking*, 7(3):113–161.

Kim, S., Shephard, N., and Chib, S. (1998). Stochastic volatility: likelihood inference and comparison with ARCH models. *The Review of Economic Studies*, 65(3):361–393.

Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). The effects of quantitative easing on interest rates: channels and implications for policy. Technical report, National Bureau of Economic Research.

Lo Duca, M. (2012). Modelling the time varying determinants of portfolio flows to emerging markets. ECB Working Paper Series, No. 1468.

Mumtaz, H., Zabczyk, P., and Ellis, C. (2011). What lies beneath? A time-varying FAVAR model for the UK transmission mechanism. ECB Working Paper Series (1320).

Neely, C. J. et al. (2010). *The large scale asset purchases had large international effects.* Federal Reserve Bank of St. Louis, Research Division.

Primiceri, G. (2005). Time varying structural vector autoregressions and monetary policy. *The Review of Economic Studies*, 72(3):821–852.

Rogers, J. H., Scotti, C., and Wright, J. H. (2014). Evaluating asset-market effects of unconventional monetary policy: a multi-country review. *Economic Policy*, 29(80):749–799.

Rosa, C. (2012). How "unconventional" are large-scale asset purchases? the impact of monetary policy on asset prices. Technical Report 560, Staff Report No. 560, Federal Reserve Bank of New York.

Stiglitz, J. E. and Weiss, A. (1981). Credit rationing in markets with imperfect information. *The American economic review*, 71(3):393–410.

Stroebel, J., Taylor, J. B., et al. (2012). Estimated impact of the federal reserves mortgage-backed securities purchase program. *International Journal of Central Banking*, 8(2):1–42.

Wright, J. H. (2012). What does monetary policy do to long-term interest rates at the zero lower bound? *The Economic Journal*, 122(564):F447–F466.

A Estimation of the FAVAR with time-varying loadings and stochastic volatility

The model given by Equations 2, 3 gives rise to the following blocks of parameters:

- Factors $f_{1,t}, f_{2,t}$
- Time-varying factor loadings $\lambda_{i,j,t}$, $i = 1, \ldots, N$, $j = 1, 2, 3, 4$
- Idiosyncratic shocks volatilities $\sigma^2_{v,t}$
- VAR model parameters B and Σ

A.1 Gibbs sampling

The marginal posterior distributions and their quantiles are approximated using the Gibbs sampler by drawing parameters from their conditional posterior distributions, most of which are standard in the literature. Time-varying loadings were sampled by applying the algorithm by Chan and Jeliazkov (2009); the VAR model parameters were drawn from their conditional posterior distributions which are standard in the Bayesian VAR literature. Variances of the idiosyncratic shocks were sampled using the approach by Kim et al. (1998). What deserves a deeper explanation is sampling of factor themselves.

Conditional on other parameters of the model, factors can be routinely extracted as an unobserved variable in a state space model, which can be written in the following way: [8]

The observation equation relates the observed variables to unobserved state variables:

$$\underbrace{\begin{bmatrix} y_{1,t} \\ y_{2,t} \\ \vdots \\ y_{N,t} \\ i_t^{us} \\ i_t^{eme} \end{bmatrix}}_{y_t} = \underbrace{\begin{bmatrix} \lambda_{1,1} & \lambda_{1,2} & \lambda_{1,3} & \lambda_{1,4} \\ \lambda_{2,1} & \lambda_{2,2} & \lambda_{2,3} & \lambda_{2,4} \\ \vdots & \vdots & \vdots & \vdots \\ \lambda_{N,1} & \lambda_{N,2} & \lambda_{N,3} & \lambda_{N,4} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{H_t} \underbrace{\begin{bmatrix} f_{1,t} \\ f_{2,t} \\ \widetilde{i}_t^{us} \\ \widetilde{i}_t^{eme} \end{bmatrix}}_{\beta_t} + \underbrace{\begin{bmatrix} e_{1,t} \\ e_{2,t} \\ \vdots \\ e_{N,t} \\ e_{us,t} \\ e_{eme,t} \end{bmatrix}}_{e_t} \tag{A.1}$$

where

$$R = \mathbf{cov}(e_t) = \mathbf{diag}\{\sigma_{1,t}, \sigma_{2,t}, \ldots \sigma_{N,t}, 0, 0\} \tag{A.2}$$

The transition equation describes the dynamics of state variables:

[8] In this appendix, we focus on the case of a VAR(1) process, however higher order processes can be incorporated by re-defining the F matrix.

$$\underbrace{\begin{bmatrix} f_{1,t} \\ f_{2,t} \\ \widetilde{i}_t^{us} \\ \widetilde{i}_t^{eme} \end{bmatrix}}_{\beta_t} = \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}}_{\mu} + \underbrace{\begin{bmatrix} \phi_{11,1} & \phi_{12,1} & \phi_{13,1} & \phi_{14,1} \\ \phi_{21,1} & \phi_{22,1} & \phi_{23,1} & \phi_{24,1} \\ \phi_{31,1} & \phi_{32,1} & \phi_{33,1} & \phi_{34,1} \\ \phi_{41,1} & \phi_{42,1} & \phi_{43,1} & \phi_{44,1} \end{bmatrix}}_{F} \underbrace{\begin{bmatrix} f_{1,t-1} \\ f_{2,t-1} \\ \widetilde{i}_{t-1}^{us} \\ \widetilde{i}_{t-1}^{eme} \end{bmatrix}}_{\beta_{t-1}} + \underbrace{\begin{bmatrix} v_{1,t} \\ v_{2,t} \\ v_{us,t} \\ v_{eme,t} \end{bmatrix}}_{v_t} \tag{A.3}$$

$$\mathbf{cov}(v_t) = \Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix}, \tag{A.4}$$

where Σ_{ii} is a 2x2 block of matrix Σ.

Note that exogenous variables (i_t^{us} and i_t^{eme}) are both in the observation and transition equations and the relationship between them is achieved by imposing ones in Equation A.1 and zero variances in Equation A.2.

The unobserved factors can be relatively easily sampled, for example, using the algorithm by Carter and Kohn (1994), which is, however, prohibitively slow for our purposes. Therefore we use the ideas from the algorithm by Chan and Jeliazkov (2009), whose variant adjusted for our purposes is described subsequently.

First, in order to correct for singularity of matrix R we reduce the number of our state variables only to the number of factors. As a result, we can write our observation equation as:

$$\widetilde{y}_t = \begin{bmatrix} y_{1,t} - \lambda_{1,3} i_t^{us} - \lambda_{1,4} i_t^{eme} \\ y_{2,t} - \lambda_{2,3} i_t^{us} - \lambda_{2,4} i_t^{eme} \\ \vdots \\ y_{N,t} - \lambda_{N,3} i_t^{us} - \lambda_{N,4} i_t^{eme} \end{bmatrix} = \begin{bmatrix} \lambda_{1,1,t} & \lambda_{1,2,t} \\ \lambda_{2,1,t} & \lambda_{2,2,t} \\ \vdots & \vdots \\ \lambda_{N,1,t} & \lambda_{N,2,t} \end{bmatrix} \begin{bmatrix} f_{1,t} \\ f_{2,t} \end{bmatrix} + \underbrace{\begin{bmatrix} e_{1,t} \\ e_{2,t} \\ \vdots \\ e_{N,t} \end{bmatrix}}_{e_t} \tag{A.5}$$

and the transition equation as:

$$\begin{bmatrix} f_{1,t} \\ f_{2,t} \end{bmatrix} = \widetilde{\mu}_t + \begin{bmatrix} \phi_{11,1} & \phi_{12,1} \\ \phi_{21,1} & \phi_{22,1} \end{bmatrix} \begin{bmatrix} f_{1,t-1} \\ f_{2,t-1} \end{bmatrix} + \widetilde{v}_t \tag{A.6}$$

where

$$\mathbf{cov}(\widetilde{v}_t) = \widetilde{\Sigma} = \Sigma_{11} - \Sigma_{12}\Sigma_{22}^{-1}\Sigma_{21} \tag{A.7}$$

and

$$\widetilde{\mu}_t = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \Sigma_{12}\Sigma_{22}^{-1} \begin{bmatrix} v_{1,t} \\ v_{2,t} \end{bmatrix} \tag{A.8}$$

,

which follows from the properties of conditional normal distributions.

Let

$$L_t = \begin{bmatrix} \lambda_{1,t,1} & \lambda_{1,t,2} \\ \lambda_{2,t,1} & \lambda_{2,t,2} \\ \vdots & \\ \lambda_{N,t,1} & \lambda_{N,t,2} \end{bmatrix} \tag{A.9}$$

and

$$\widetilde{f_t} = (f_{1,t}, f_{2,t})^T \tag{A.10}$$

We can rewrite the measurement equation as

$$\begin{bmatrix} \widetilde{y_1} \\ \widetilde{y_2} \\ \vdots \\ \widetilde{y_T} \end{bmatrix} = \begin{bmatrix} L_1 & 0 & 0 & 0 \\ 0 & L_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & L_T \end{bmatrix} \begin{bmatrix} \widetilde{f_1} \\ \widetilde{f_2} \\ \vdots \\ \widetilde{f_T} \end{bmatrix} + \begin{bmatrix} \widetilde{e_1} \\ \widetilde{e_2} \\ \vdots \\ \widetilde{e_T} \end{bmatrix} \tag{A.11}$$

or, in line with Chan and Jeliazkov (2009), as

$$y = G\eta + \epsilon \tag{A.12}$$

The stacked version of the transition equation can be written as:

$$H\eta = Z\gamma + \nu \tag{A.13}$$

where

$$H = \begin{bmatrix} I_2 & & & & \\ -\widetilde{F} & I_2 & & & \\ & -\widetilde{F} & I_2 & & \\ & & \ddots & \ddots & \\ & & & -\widetilde{F} & I_2 \end{bmatrix} \tag{A.14}$$

and

$$Z\gamma = \begin{bmatrix} \widetilde{a_1} \\ \widetilde{a_2} \\ \widetilde{a_1} \\ \widetilde{a_2} \\ \vdots \end{bmatrix} \tag{A.15}$$

This specification of the model is now in line with (Chan and Jeliazkov, 2009) and their algorithm can be used to sample the unobserved factors.

B Time-varying loadings on factors and exogenous varibales

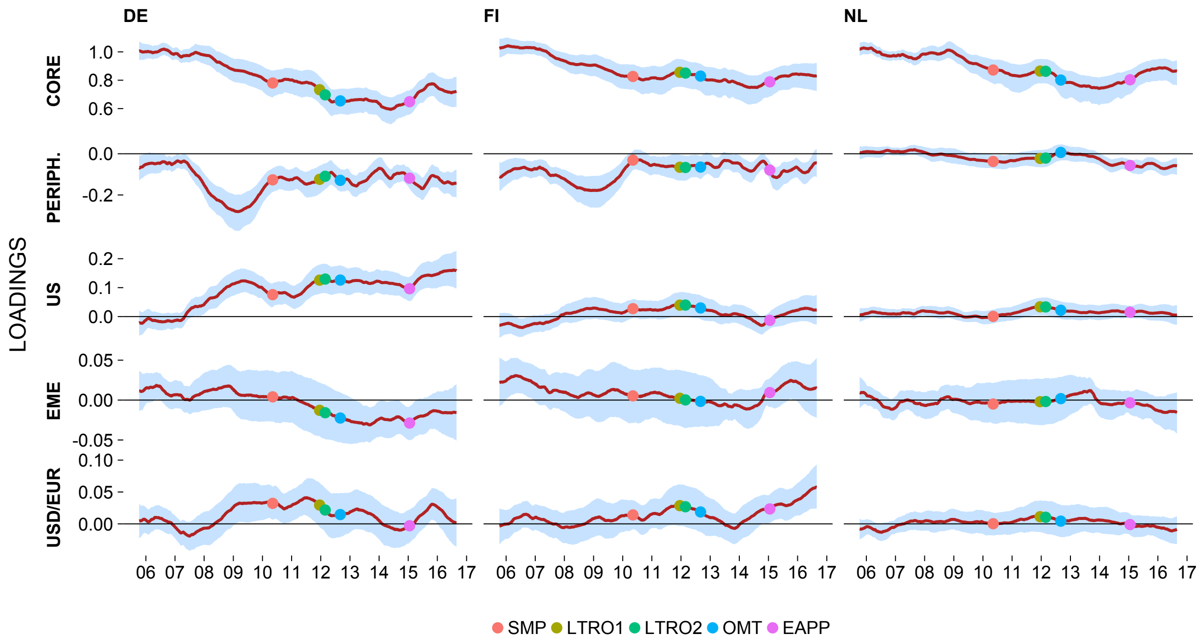

Figure B.1: Evolution of loadings of bond yields on factors: posterior median, 16th and 84th quantiles.

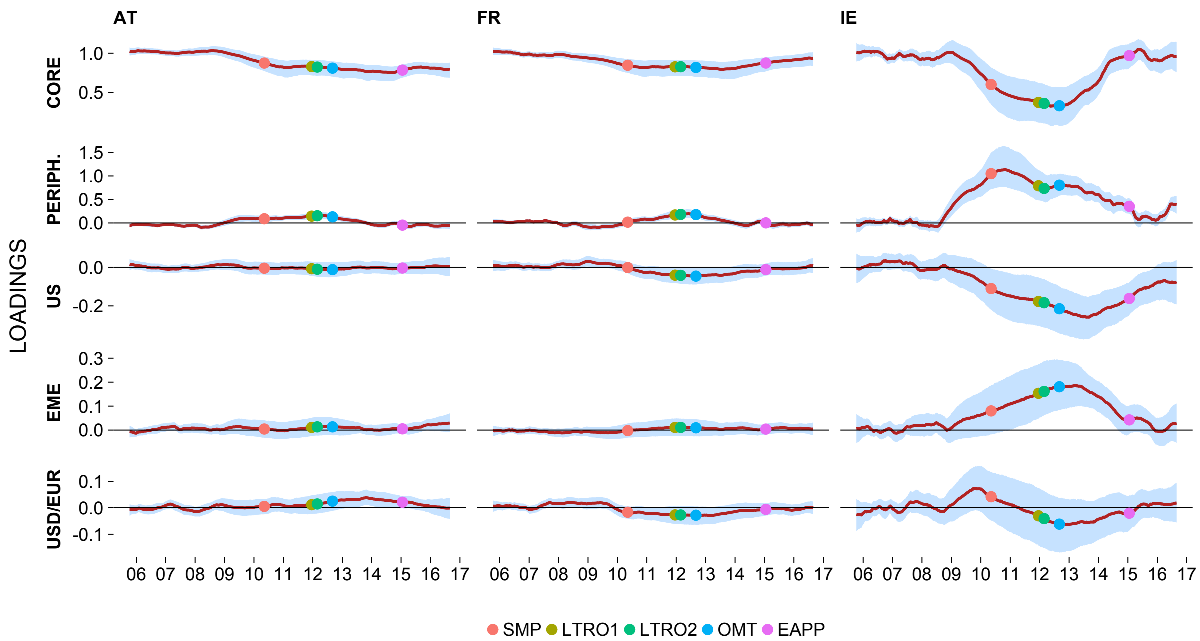

Figure B.2: Evolution of loadings of bond yields on factors: posterior median, 16th and 84th quantiles.

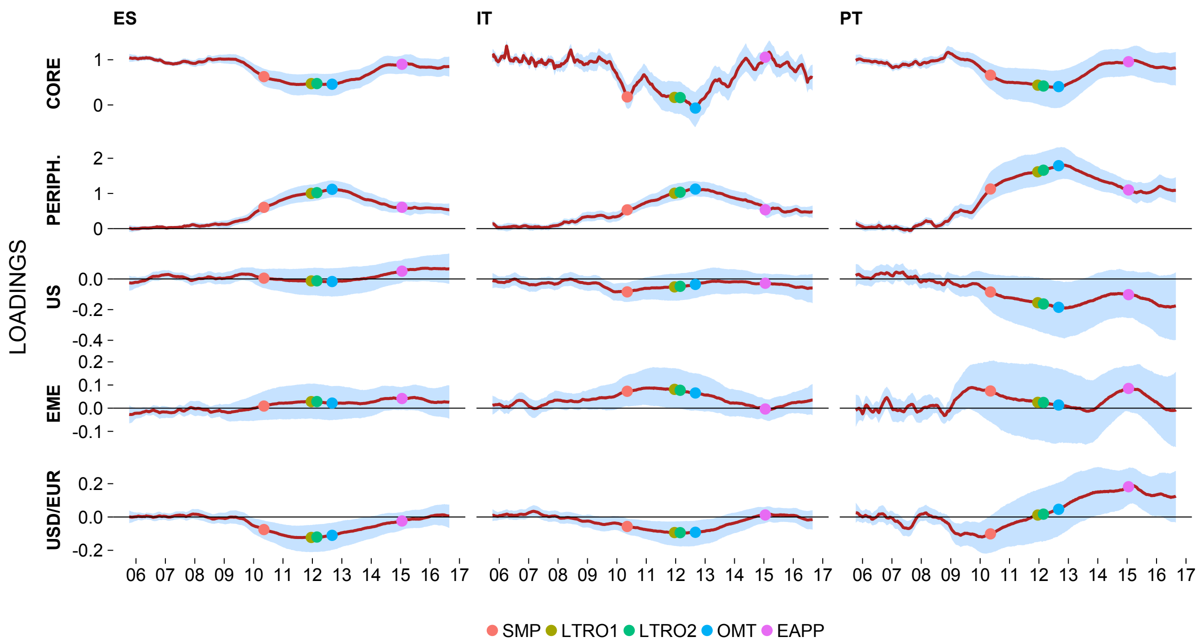

Figure B.3: Evolution of loadings of bond yields on factors: posterior median, 16th and 84th quantiles.

C Time-varying impact responses to structural shocks

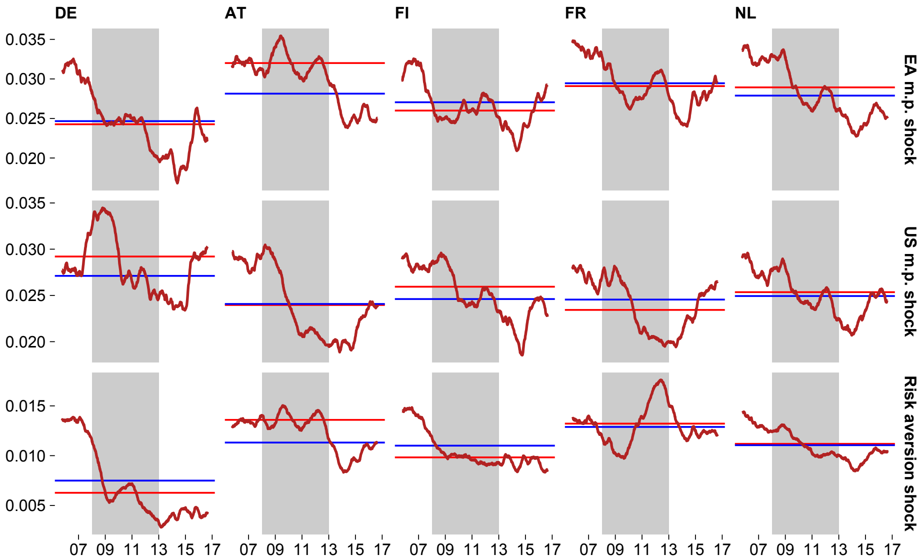

Figure C.1: Posterior median responses (on impact) of bond yields to structural shocks over time.

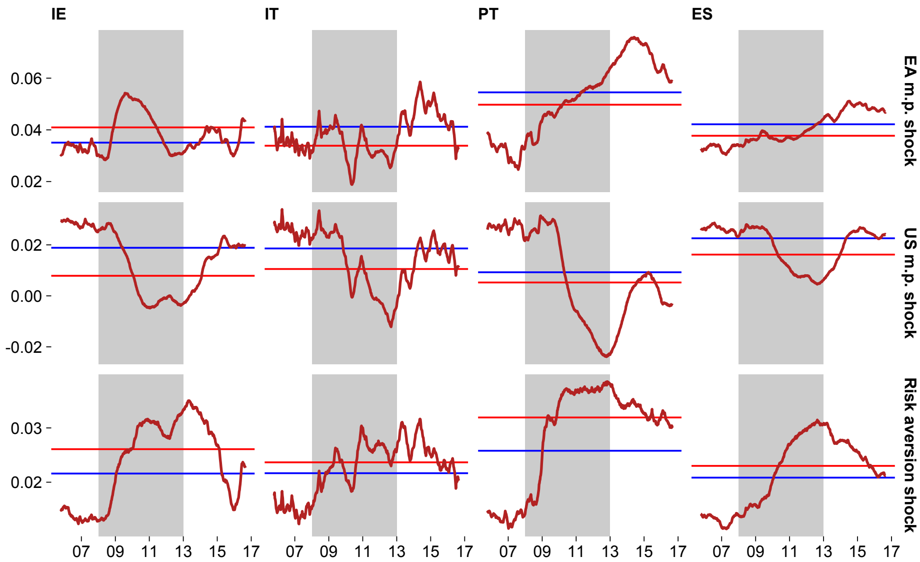

Figure C.2: Posterior median responses (on impact) of bond yields to structural shocks over time.

D Correlations with factors

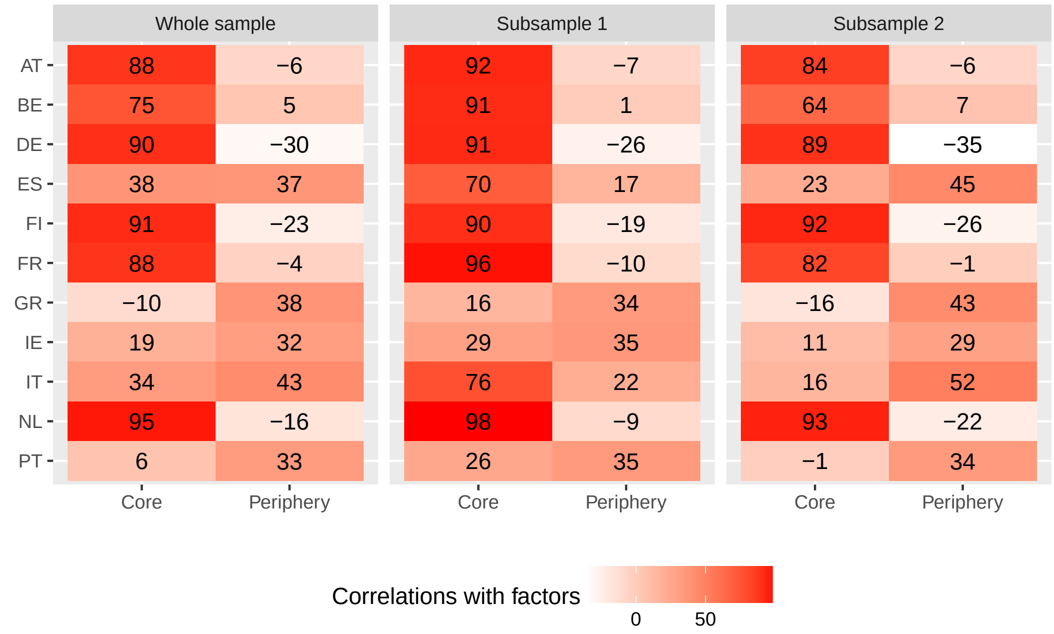

Figure D.1: Correlations of each country with factors. Subsample 1: October 2005 - December 2010. Subsample 2: January 2011 - August 2015.

Acknowledgements

The authors would like to thank for helpful discussions and valuable feedback to: Giorgio Primiceri, Fabio Canova, Roberto De Santis, Giulio Nicoletti, Mahir Binici, Marek Jarocinski, Joshua Chan, participants to the INFINITI 2016 Conference, participants to internal seminars of the European Central Bank.

Tomáš Adam
European Central Bank; Institute of Economic Studies; Charles University; Prague; Czech Republic; email: Tomas.Adam@cnb.cz

Marco Lo Duca
European Central Bank; Frankfurt am Main; Germany; email: marco.lo_duca@ecb.int

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

ISSN	1725-2806 (pdf)	DOI	10.2866/557042 (pdf)
ISBN	978-92-899-2734-5 (pdf)	EU catalogue No	QB-AR-17-024-EN-N (pdf)