Journal of Banking and Finance 77 (2017) 35–52

Contents lists available at ScienceDirect

Journal of Banking and Finance

journal homepage: www.elsevier.com/locate/jbf

Assessing the effects of unconventional monetary policy and low interest rates on pension fund risk incentives

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ARTICLE INFO

Article history:
Received 31 July 2015
Accepted 13 December 2016
Available online 14 December 2016

JEL classification:
G11
G23
E52

Keywords:
Pension funds
Unconventional monetary policy
Asset allocation
Interest rates

ABSTRACT

This study quantifies the effects of persistently low interest rates near to the zero lower bound and unconventional monetary policy on pension fund risk incentives in the United States. Using two structural vector autoregressive (VAR) models and a counterfactual scenario analysis, the results show that monetary policy shocks, as identified by changes in Treasury yields following changes in the central bank's target interest rates, lead to a substantial increase in pension funds' allocation to equity assets. Notably, the shift from bonds to equity securities is greater during the period where the US Federal Reserve launched unconventional monetary policy measures. Additional findings show a positive correlation between pension fund risk-taking, low interest rates and the decline in Treasury yields across both well-funded and underfunded public pension plans, which is thus consistent with a structural risk-shifting incentive.

1. Introduction

"More than half of the largest local governments in the U.S. have liabilities from pension underfunding that exceed 100% of their revenues" (Moody's Investors Service, Global Credit Research, 26 September 2013).

The public finance community has become more concerned than ever before about underfunded pension obligations that could cause a broad retirement crisis. The rise in life expectancy, which significantly increases liabilities, and the immense challenges in the asset allocation landscape render the financing of these liabilities more difficult than ever (Cocco et al., 2005).[1] Official estimates of US public pension fund shortfalls range from \$700 billion to \$1 trillion, while the financial meltdown of 2008 exacerbated the underfunding problem.[2] In the aftermath of the recent financial crisis, the average ratio of pension assets to liabilities (the funding ratio) plummeted from 95% as of fiscal year-end 2007 to 64% by fiscal year-end 2009, and only recovered modestly to 74% for the 2013 fiscal year.[3]

The severe funding gap has triggered increased interest among academics, practitioners, and policymakers in understanding the investment strategy and the risk-taking behavior of the public pension fund industry. While US public pension funds have evidently been investing an ever-increasing proportion of their assets in risky investments and equities, the empirical literature on determining long horizon optimal asset allocation has not settled this issue hitherto.[4] For instance, Rauh (2009) finds that private

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[1] See also Cocco and Gomes (2012) for the role of longevity risk on saving and retirement decisions.

[2] This figure is obtained using the calculation and actuarial method of the US Census Bureau.

[3] Appendix A describes the pension funds used in the analysis. Appendix B (Appendix C) provides information on (most underfunded) State pension funds used in the sample.

[4] The US Public Fund Boards, which govern public pension funds, decide on the allocation of assets. Pension funds are largely unconstrained in the proportion of funds that can be invested in risky assets and in their assumptions on the expected rate of return of the various asset classes. Therefore, they have significant latitude to choose their assets and their liability discount rate.

http://dx.doi.org/10.1016/j.jbankfin.2016.12.007
0378-4266/

pension plans have departed from traditional investments such as government bonds, and have heavily invested in risky securities such as equities and in alternative assets such as hedge funds, private equities and real estate investment trusts in order to achieve higher return. Notably, the author also finds that changes in the allocation of pension fund assets seem to be motivated by risk management rather than risk-shifting incentives. By contrast, Mohan and Zhang (2014) find that risk-shifting incentives dominate the US public pension funds asset allocation decisions. Some studies such as Campbell and Viceira (2001) and Cochrane (2014) show that investments in stocks can be less risky and more profitable for long horizon portfolios while other studies advocate a more conservative approach (e.g., Bader and Gold, 2007). According to Lucas and Zeldes (2009), the accounting rules for public pensions create an irregular incentive to invest in equities since projected liabilities are discounted and calculated on the basis of expectations for investment return instead of discounting them at a rate that reflects the risk of their liabilities. Similarly, Novy-Marx and Rauh (2011) document that pension funds exploit a loose regulation to camouflage their deficits by investing in the stock market, which results in a higher discount rate for their liabilities.[5] Altogether, these findings contrast those of Rauh (2009) and indicate that pension fund asset allocation decisions are driven by risk-shifting rather than risk management incentives.[6]

Additionally, the dramatic changes in the US monetary policy framework can also be one of the factors that have serious impacts on pension fund risk-taking and asset allocation decisions. More precisely, the sharp reductions in interest rates to overcome the stock market crash of 2001 and the Federal Reserve's unconventional monetary policy adopted to mitigate the financial crisis of 2008 might also incentivize changes in pension fund asset allocation decisions.[7] The literature consistently provides evidence that the expansionary monetary policy successfully led to the reduction of long-term interest rates, as expected by the US Federal Reserve (see e.g., Gagnon et al., 2010; Wright, 2012), but also created financial constraints and provoked an increase in the risk-taking behavior for financial institutions. More concretely, Bernanke (2013, 2015) predicts that investors and portfolio managers dissatisfied with low returns may "reach for yield" by taking on more credit risk, duration risk, or leverage, while Chodorow-Reich (2014) finds evidence of increased risk-taking for some private pension funds, starting in 2009 and dissipating in 2012. To date, little is known about how unconventional monetary policy affects investment policy decisions of US public pension funds, despite an extensive literature focusing on the economic and the financial sector effects (e.g., financial asset prices, interest rates, long-term yields, and the value of dollar) and the effectiveness of this policy (Adam and Billi, 2007; D'Amico et al., 2012; Gali, 2014; Neely, 2015). Instead, the pension funds literature emphasizes endogenous factors affecting asset allocation decisions including, among others, the level of underfunding, fiscal and regulatory constraints, and effective risk management skills (Rauh, 2006; Aglietta et al., 2012; Blake et al., 2013; *inter alia*).

This article contributes to the related literature by assessing the impact of unconventional monetary policy and low interest rates on the risk incentives and the asset allocation decisions of US public pension funds. More precisely, our study goes one step further from the recent works of Rauh (2009), Lucas and Zeldes (2009) and Mohan and Zhang (2014), since it explicitly accounts for exogenous factors that affect pension fund risk-taking behavior. We also extend these works by using a large sample and by offering new evidence on the discrimination between risk-shifting and risk management incentives in US public pension funds. The empirical literature on this issue is particularly thin and shows mixed results. For instance, Rauh (2009) finds no evidence that pension funds and especially financially distressed funds engage in risk-shifting behavior. The observed correlation between asset allocation and lagged investment returns implies that changes in the allocation of assets are prompted by an incentive for efficient risk management. On the contrary, Mohan and Zhang (2014) suggest that public pension undertake more risk when underfunded, which is consistent with the risk transfer hypothesis.

At the empirical level, we initially use a regression analysis to identify how asset allocation changes over time and across monetary policy regimes (expansionary and contractionary) with different interest rate levels. In order to quantify the role of monetary policy, as in Kapetanios et al. (2012), we identify monetary policy shocks by the changes in government bond yields following the changes in the US Federal Reserve policy interest rate. We employ a Bayesian vector autoregressive (BVAR) model, estimated over rolling windows, to capture the complex interrelationships between Treasury yields, interest rates, and asset and risk management decisions. This model allows for structural changes and takes into account uncertainty about the probability distributions of the system's variables when investigating the impulse response functions. To ensure the robustness of the findings, we also use a Markov-switching structural VAR (MS-SVAR) model that relaxes the assumption of constant parameters over time and thus enables us to incorporate a more sophisticated treatment of potential structural changes across different regimes (see also Waggoner and Zha, 2003; Primiceri, 2005). The MS-SVAR underlying structural shocks are identified through restrictions on the impulse responses, as in Kapetanios et al. (2012). Notably, the use of different models that vary in their emphasis increases the robustness of our findings. Finally, we conduct a counterfactual analysis to show that Treasury yields would have been higher, *ceteris paribus*, in the absence of drastic changes in the monetary policy framework. This intuition is built on the link between government bond yields and interest rates proposed by Estrella (2005).

Our results indicate that interest rates at the zero lower bound and the launch of unconventional monetary policy prompted a gradual increase in equity assets and in pension fund risk-taking behavior. Additionally, risk-shifting incentives to avoid low-yield investments (such as Treasury bonds) in favor of riskier investments (such as equities and alternative assets) dominate pension fund asset allocation decisions. More precisely, the results over the whole sample period suggest that asset allocation is correlated with short-term lagged investment returns, and higher returns precede higher equity allocation. Given that from 2001 till 2007 the equity market increased considerably, this provides evidence for procyclicality since an increase in the stock market triggers an increase in equity holdings. However, our sub-period analysis uncovers the absence of correlation between asset allocation and short-term lagged investment returns. The slump of the stock market in 2008 was not followed by a reduction in equity assets, implying that there is a structural shift out of bond assets and that the risk

[5] There are typically minimum funding requirements imposed by regulation in the US pension fund industry. In particular, the required minimum contributions are calculated on the basis of amortizing existing underfunding over a time period of 30 years, while the higher the assumed investment return, the lower the required contribution by pension fund members.

[6] Following Rauh (2009, p. 2689), a risk management incentive occurs when well-funded pension funds invest in riskier securities, while underfunded pension funds invest in less risky assets.

[7] The unconventional monetary policy measures (also called "quantitative easing"), conducted by the Federal Reserve's Federal Open Market Committee (FOMC), comprises a mix of instruments such as the zero lower bound target policy rate, repurchases of Treasury and agency bonds, and asset-backed securities. They have also been adopted by other central banks (e.g., Japan, the Eurozone, and the United Kingdom). There is also evidence to suggest that these unconventional measures improve economic and financial conditions (e.g., Kapetanios et al., 2012; Joyce et al., 2012; Chen et al., 2012; Gambacorta et al., 2014).

management incentive is not the primary reason for the reduced allocation to bonds.

Moreover, we find a positive correlation between the increase in equity allocation and monetary policy shocks associated with lower interest rates and lower Treasury yields, across well-funded and underfunded pension funds, which is consistent with a structural risk-shifting incentive in favor of risky investments. A reduction in interest rates which is followed by a decline of 5% in the 10-year Treasury yield over the period 1999–2014 is associated with an 18% decrease in the allocation of bond securities and a 17% increase in the allocation to equity assets, across well-funded and underfunded plans. Finally, the results from the counterfactual analysis suggest that the risk-taking behavior of pension funds is affected by low interest rates and unconventional monetary policy. Particularly, in a higher interest rate environment without significant declines in Treasury yield, the investment return from bond securities would have been significantly larger, from 6.56% to 7.19% for a 100 basis point rise in the 10-year Treasury yield and to 7.68% for a 200-basis-point appreciation in the yield.

Consistent with Lucas and Zeldes (2009), we find that pension plans assume an unrealistically high expected rate of return, which they fail to reach on average. Concretely, the mean investment return across the group of pension funds is close to 8% and it is also used as the typical liability discount rate. A high expected return protects pensioners from having to increase their contributions. If risky assets perform well then the subsequent improvement in pension funding reduces the need for increased contributions. In many cases, the assumed higher level of interest rates would have helped many funds to achieve their planned return of 8%, since the results indicate that in a higher interest rate environment the return increases significantly from 6.56% to 7.74% on average. Simultaneously, portfolio risk would have been substantially lower. Therefore, the low interest rate environment and the use of unconventional monetary policy prompt a re-allocation of pension fund assets, leading to increased allocations to risky investments. However, it is worth noting that conclusions are drawn cautiously as monetary policy is only one of the possible explanations for the risk-taking behavior of pension plans and that other factors which might have an important role on pension fund asset allocation decisions are not examined in our study.

The remainder of this paper proceeds as follows. Section 2 discusses the relevant literature. Section 3 describes the methodological approach. Section 4 depicts the dataset and analyzes the results. Section 5 presents robustness checks. Section 6 concludes.

2. Literature review

2.1. Pension fund asset allocation strategy

The determination of an optimal asset allocation policy for public pension funds is an important but unsettled task. At a theoretical level, Sharpe (1976) and Treynor (1977) describe a pension liability as a contract between two parties with a put option exercisable in the event of bankruptcy and a strike price equal to the value of pension liabilities. The literature on the optimal portfolio choice for retirement savings starts with the argument that under specific assumptions (e.g., returns are normally distributed), the goal of shareholder maximization is achieved when pension funds invest in bonds (see, e.g., Black, 1980; Tepper, 1981; Bodie, 1990; *inter alia*). These studies argue that long-term portfolios for retirement savings should be encouraged to hold more bonds than stocks. However, several recent studies observe that more than 50% of US pension fund assets are, on average, invested in stocks (Rauh, 2009; Mohan and Zhang, 2014; *inter alia*). This shift in the allocation of assets can be explained by two main reasons.

First, the portfolio-management landscape has changed radically. While equities have traditionally been classified as risky assets, there is now evidence suggesting that excess stock returns are actually less volatile over long holding periods and, thus, stocks are relatively safe assets for long-term investors (see, Campbell and Viceira, 2002, Chapter 4). Moreover, Campbell and Viceira (2001) show that volatility shocks in the US stock market is not sufficiently persistent and negatively correlated with stock returns to justify a large negative intertemporal hedging portfolio demand for stocks with bond-related assets. Similarly, Cochrane (2014) documents that, in a dynamic intertemporal environment, investments in stocks can be less risky and more profitable for long horizon portfolios. In particular, the author proposes a dynamic trading strategy based on time-varying state variables as a different way of constructing long-horizon portfolios of stocks. Some other works on long-term portfolio choice provide strong evidence that a long-term investor with a conservative attitude (i.e., risk averse) should hedge interest rate risk and respond to mean-reverting stock returns by increasing the average allocation to equity securities (Campbell et al., 2003).

A second reason for the shift in the asset allocation to equity securities is supported by the US regulatory environment. While the financial theory suggests that "*the discount rate used to value future pension obligations should reflect the riskiness of the liabilities*" (Brown and Wilcox, 2009), pension funds practically set their discount rates based on the characteristics of the assets held in their portfolios, rather than the characteristics of the pension liabilities. As a result, Lucas and Zeldes (2009) show that underfunded pension funds prefer to invest heavily in higher yielding, but riskier assets, such as equities because they expect a higher average return to reduce underfunding over time. More precisely, the accounting rules for public pension funds set by the Government Accounting Standard Board create an irregular incentive to invest in equities since projected liabilities are discounted at the expected return on assets rather than at a rate that reflects the risk of liabilities.[8] Hence, investing in stocks leads to a higher allowed discount rate for the liabilities, and this, in turn, allows pension funds to present lower degrees of underfunding and to camouflage their shortfalls as well as helps to postpone any increase for pension contribution to the future generations.

2.2. Risk shifting versus risk management incentive

As described above, recent developments in the empirical asset allocation literature and the accounting rules set for pension funds provide two arguments for the practice of investing in equity securities in long horizon portfolios. This investing approach is also largely in parallel with private sector practices. Blake et al. (2013) document that over the last two decades there is a shift from centralized to decentralized pension fund management, since funds replace managers with "better-performing" specialists. However, in most cases, pension plans are severely underfunded and their investments underperform. Munnell et al. (2008) report that the increased exposure to equity securities, from an average of about 40% in the early 1990s to about 70% in 2000s, and the slump of stock markets in 2008 led to a loss of about US $1 trillion. In a similar vein, Franzoni and Marin (2006) argue that the combination of a deep stock market downturn and the fall in interest rates from 2000 to 2002 led to a $400billion loss on the funding status of US pension plans. Bader and Gold (2007) propose a more conservative approach by investing in bonds in order to reduce the volatility of funding levels and the likelihood of severe shortfalls during financial slumps. In a related study, Brown and Wilcox

[8] The Government Accounting Standard Board is an independent organization that establishes standards of accounting for public (state and local) pension funds.

(2009) suggest that pension funds should use risk-free real interest rates to discount their pension promises and direct an increased proportion of investment to bond-related securities. Ebrahim et al. (2014) argue that the asset allocation puzzle is purely a partial equilibrium phenomenon feasible only in the absence of capital constraints. Hence, the risk-aversion attitude (such as investments in bond yields) allows for wealth smoothing. Therefore, in spite of the new developments analyzed in the previous studies, the ongoing literature clearly does not reach a consensus on the management practices of pension fund portfolios.[9]

Rauh (2009) raises an additional critical issue regarding whether the shift in the risk-taking behavior of pension funds is dominated by risk management or by risk-shifting incentives. In particular, a risk management incentive suggests that well-funded pension funds could invest in riskier securities (such as equities) while underfunded pension funds would, on the contrary, invest in less risky assets (such as bonds). The author finds that the risk-taking behavior of US pension plans is consistent with a risk management incentive. The findings of Rauh (2009) are lately contradicted by Mohan and Zhang (2014), who test the risk management hypothesis and document that public pension funds undertake more risk when they are underfunded, indicating that the risk-shifting incentive dominates the risk-taking behavior of US pension plans.

Overall, our literature review shows that the question of optimal portfolio choice for pension funds is still open to debate, while there is evidence to support the increase of the allocation to equity securities. Moreover, the literature remains inconclusive on whether this shift in the pension fund risk-taking behavior is due to risk management or risk-shifting incentives given the underfunding problem faced by many state pension plans. This lack of consensus motivates our empirical investigation on these issues, particularly in the context of the US expansionary monetary policy and low interest rate environment, which renders the path to performance of pension funds more challenging.

3. Methodological framework

As stated earlier, our study examines whether the new monetary policy framework is one of the factors that affects risk incentives and asset allocation decisions of US public pension funds. More precisely, we investigate whether low interest rates and unconventional monetary policy create an incentive for pension funds to invest their assets in risky securities. Besides the low interest rate environment since the early 2000s, unconventional monetary policy can also provide an additional incentive for investors to search for high yields by taking on more credit risk, duration risk, or leverage, as noted by Bernanke (2013). We also examine whether the new monetary policy era, marked by low interest rates and unconventional policy measures, encourages a risk management or a risk-shifting incentive for pension fund asset allocations.

To assess these issues, we split our sample into four periods: *i*) Period 1 (1998–2000) when interest rates were between 4%–7% and the 10-year US Treasury yield was about 7% and, hence, investments in safe assets were attractive; *ii*) period 2 (2001–2005) when stock markets collapsed and interest rates reached historical low levels to promote a gradual economic recovery; *iii*) period 3 (2006–2007) is characterized by improvements in economic conditions and significant credit expansion, which caused a moderate increase in interest rates; and finally *iv*) period 4 (2008–2013) corresponds to the reduction of the interest rate near the zero lower bound, while also the US Federal Reserve announced a large program of asset purchases and other unconventional monetary measures. In order to quantify the role of different monetary policy regimes on pension fund risk-taking behavior, we use two structural VAR models (BVAR and MS-SVAR) and follow Kapetanios et al. (2012) to define monetary policy shocks as changes in bond yields following changes in interest rates. This definition is supported by the link between Treasury bond yields and interest rates (Estrella, 2005). In addition, we examine several counterfactual scenarios in which monetary policy shocks are less persistent (i.e., interest rates decline modestly and therefore Treasury yields are higher) to investigate the effects on portfolio risk (i.e., beta) and how the allocation of assets to risky investments could be affected.

3.1. The BVAR model

Vector autoregressive models, as introduced in the pioneering works of Sims (1972, 1980) represent a standard benchmark for the analysis of dynamic monetary policy experiments. Our study builds on two macroeconometric models to analyze the effects of monetary policy shocks on the risk-taking behavior of pension funds. We also conduct a counterfactual analysis with respect to monetary policy shocks. More precisely, we simultaneously use a Bayesian VAR model estimated over rolling windows where parameters are treated as random and a reduced-form MS-SVAR model, in which parameters are allowed to change over time. While the former enables us to reduce parameter uncertainty and improve forecast accuracy, the latter offers the possibility to capture the potential of regime changes.

Lenza et al. (2010) and Kapetanios et al. (2012) provide a basic framework for capturing the effects of monetary policy shocks on macroeconomic variables. Motivated by these studies, we define the monetary policy shock and then we build a similar BVAR-based model:

$$Q_t = di_t + db_t \tag{1}$$

where Q_t is the monetary policy shock (i.e. a change in interest rates that leads to a larger or smaller change in bond yields), di_t represents the change (d) in interest rates (i), and db_t is the change (d) in Treasury bond yields (b).

$$Y_t = \Theta_0 + \Theta_1 Y_{t-1} + \ldots + \Theta_p Y_{t-p} + e_t \tag{2}$$

where Y_t represents a vector of six variables (the monetary policy shock, the pension funds allocation to equities, its allocation to cash and bonds, its allocation to other assets, pension fund portfolio beta and its return on investments), Θ_0 is a vector of constants, Θ_1 to Θ_p are parameter matrices, and e_t is the vector white-noise error term.

We use a univariate AR(1) process with high persistence as our prior for each of the variables in the BVAR model.[10] Hence, the expected value of the matrix Θ_1 is $E(\Theta_1) = 0.99 \times I$. We assume that Θ_1 is normal conditionally on Σ, with first and second moments given by

$$E\left[\Theta_1^{(ij)}\right] = \begin{cases} 0.99 & if\ i = j \\ 0 & if\ i \neq j \end{cases}, \quad Var\left[\Theta_1^{ij}\right] = \varphi\sigma_i^2/\sigma_j^2 \tag{3}$$

[9] For an in-depth analysis and observation on this issue, see also Benzoni et al. (2007).

[10] We use a Likelihood Ratio (LR) test to obtain the most suitable number of lags. In particular, we let R(a)=0 to represent a set of restrictions and $\int^{(}\alpha,\ \Sigma_e)$ the likelihood function. Then the $LR = 2[ln \int \alpha^{un},\ \Sigma_e^{un}) - ln \int \alpha^{re}, \Sigma_e^{re})]$, becomes $(R(\alpha^{un})'[\frac{dR}{d\alpha^{un}} \Sigma_e^{re} \otimes (X'X^{-1})(\frac{dR}{d\alpha^{un}})']^{-1})(R(\alpha^{un}))$ and we maximize the likelihood function with respect to α subject to R(α)=0. We test a VAR $(\hat{q}-1)$ against VAR $(\hat{q})$ and then a VAR $(\hat{q}-2)$ against VAR $(\hat{q}-1)$ to obtain the correct number of lags. In order to compare the results obtained by LR with other testing procedures we calculate: $T(ln|\Sigma_e^{re}| - ln|\Sigma_e^{un}|) \underset{\rightarrow}{D} x^2(\nu)$, where $X_t = (y'_{t-1}, \ldots, y'_{t-q})'$, and $X' = (X_0, \ldots, X_{T-1})$, is a (4×4) matrix (i.e. mq*T) and $\nu = 2$, which represents the number of restrictions.

where Θ_0 contains a diffuse normal prior, $\Theta_1^{(ij)}$ represents the element in position (i,j) in the matrix Θ_1, and the covariances among the coefficients in Θ_1 are zero. Also, the prior scale and the matrix of disturbances have an inverted Wishart prior as explained in Appendix D so that $\Sigma \sim iW(v_0, S_0)$, where v_0 and S_0 are the prior scale and shape parameters, and with the expectation of Σ equal to a fixed diagonal residual variance $E(\Sigma) = diag(\sigma_1^2, \ldots, \sigma_N^2)$. Our BVAR model is similar to Bańbura et al. (2010) and Kapetanios et al. (2012) since it is estimated using rolling windows to account for structural changes in monetary policy. Consequently, the shrinkage parameter φ determines the tightness of the prior which indicates the extent to which the data affects the estimates.

3.2. The MS-SVAR model

Our sample identifies four regimes: *i*) relatively high interest rates (and thus Treasury yields) between 1998 and 2000 (regime 1); *ii*) the stock market crash of 2001 (regime 2), which led to a dramatic decline in interest rates and in Treasury yields; *iii*) the 2007 to 2008 period, in which the federal funds target rate increased modestly and Treasury yields followed with a modest increase (regime 3); and *iv*) the period from mid-2008 until the end of our sample period in 2013 (regime 4), in which the Federal Reserve decreased interest rates near to the zero lower bound (and Treasury yields collapsed) and adopted unconventional monetary measures (i.e., quantitative easing) to promote financial stability and economic development in the US. This pattern of frequent changes in the US monetary policy over recent years led us to consider a regime switching structural VAR model with the following form:

$$Y_t = c + Z(A)Y_{t-1} + u_t \tag{4}$$

where Y_t is a vector of endogenous variables, c is a vector of intercepts, $Z(A)$ is a matrix of autoregressive coefficients of the lagged value of Y_t and u_t is a vector of residuals. The reduced-form error terms are related to the uncorrelated structural errors ε_t as follows:

$$\varepsilon_t = \mathrm{B}^{-1} u_t \tag{5}$$

The vector of endogenous variables (Y_t) includes the following six variables in the VAR system:

$$Y_t = [PFEA_t,\ PFBA_t,\ \ PFTA_t,\ PFAB_t,\ PFR_t,\ Q_t] \tag{6}$$

where $PFEA_t$ represents the pension fund's allocation to equities, $PFEB_t$ its allocation to cash and bonds, $PFTA_t$ its allocation to other assets, $PFAB_t$ its asset beta, and PFR_t its return on investments, and Q_t the monetary policy shock.

We modify the regime-switching structural VAR model in Eq. (4) to allow for changes in the policymaker's reaction (i.e., regime changes) and to study how pension funds are affected. Therefore, we propose an MS-SVAR model with non-recurrent states where transitions are allowed in a sequential manner. Hence, to move from regime 1 to regime 4, the process has to consider regime 2 and regime 3. Similarly, transitions to past regimes are not allowed. In particular:

$$Y_t = c_s + \sum_{j=1}^{k} B_{j,S} Y_{t-j} + A_{0,S}\varepsilon_t \tag{7}$$

Following Jin et al. (2006) and Mohan and Zhang (2014), we measure the pension asset beta as the weighted average of individual asset betas, i.e., $Pension\ Asset\ Beta = \sum_{i=1}^{n} W_i \times \beta_i$, where W_i is the weight of each asset class with $\sum_{i=1}^{n} W_i = 1$, and β_i is the estimated beta of each asset class. We extend the SVAR model in Eq. (4) to the case of an MS-SVAR with non-recurrent states to account for the regime-dependent reaction of pension funds to changes in monetary policies.[11]

As in Chib's (1998) study, the break dates of the regime changes in the model are unknown and they are modeled through the latent state variable S, which is assumed to follow an M-state Markov chain process (where M refers to the dates of the regimes) with restricted transition probabilities, such that:

$$\begin{cases} p_{ij} = p(S_t = j | S_{t-1} = i)\ with \\ p_{ij} > 0\ if\ i = j \\ p_{ij} > 0\ if\ j = i+1 \\ p_{MM} = 1 \\ p_{ij} = 0\ otherwise \end{cases} \tag{8}$$

Given the number of policy regime changes as described above, M is equal to 4 and the transition matrix is defined as:

$$\tilde{P} = \begin{pmatrix} p_{11} & 0 & 0 & 0 \\ 1 - p_{11} & p_{22} & 0 & 0 \\ 0 & 1 - p_{22} & p_{33} & 0 \\ 0 & 0 & 1 - p_{33} & 1 \end{pmatrix}$$

Alternative modeling techniques provide different relative weights to the sample and prior information. Specifically, unrestricted VARs use information very sparsely in choosing the variables, in selecting the correct lag length of the model, and in imposing identification restrictions. As a result, unrestricted VAR models may lead to poor forecasting due to overfitting the dataset (see, Koop, 2013). Structural and Bayesian methods provide a reliable solution for these problems as identified by De Mol et al. (2008) and George et al. (2008). By using Bayesian inference, we allow informative priors so that prior knowledge and results can be used to inform the current model. We also avoid problems with model identification by manipulating prior distributions. Therefore, this is the most suitable technique to employ for statistical regions of flat density. Moreover, an important assumption in Bayesian inference is that the data are fixed and the parameters are random. Hence, with restricted structural regimes, we do not depart from reality. An additional advantage of the use of structural regimes and Bayesian inference is that these models include uncertainty in the probability model, yielding more realistic suggestions. Also, our structural models employ prior distributions and hence, more information is used along with 95% probability intervals for the posterior distributions.

3.3. Counterfactual scenario

To produce counterfactual forecasts, we base our analysis on the empirical work of Kapetanios et al. (2012) and assume that under a different monetary policy framework, interest rates would have been higher and therefore, the 10-year US Treasury yield would have been 100, 120, or 200 basis points higher, for the whole sample period, *ceteris paribus*. In practice, we implement this impact on yields by changing the 10-year US Treasury yield spread to identify the effect of the simulations on the risk and asset allocation behavior of pension plans. Therefore, the effects of monetary policy are captured solely through lower government bond yields. We simulate two scenarios: (i) Monetary policy interventions lower interest rates and this in turn causes a downward shift in Treasury yields (i.e. monetary policy shocks); and (ii) in contrast to scenario (i) monetary policy does not change over time,

[11] Note that transitions between regimes are allowed in a sequential manner, and thus to move from regime 1 to regime 4, the process must visit regime 2 and regime 3. Transitions to past regimes are also not allowed and, in a similar way to the BVAR model and Equation (5), the vector Y_t contains annual data on pension funds, and $B_{j,S}$ and $A_{0,S}$ are regime-dependent autoregressive coefficients and structural shock loading matrices respectively.

monetary policy shocks are not identified, interest rates are higher and hence Treasury yields are higher. Notably, scenario (i) mimics the real monetary policy adopted by the Federal Reserve while capturing the effect of unconventional policies and low interest rates on pension fund asset allocation decisions. Accordingly, scenario (ii) assumes that interest rates and Treasury yields would have been higher and thus we adjust government bond spreads and the overnight repo rate. To identify the impact of monetary policy shocks, we compare the effect of the two scenarios on pension fund performance.

In a similar vein, Wright (2012) uses a structural VAR model to provide ample evidence that long-term interest rates and Treasury yields lowered significantly since the federal funds rate has been stuck at the zero lower bound. Using a similar model, Christensen and Rudebusch (2012) find that government bond yields declined, following announcements by the Federal Reserve and the Bank of England to buy long-term debt. Also, Weale and Wieladek (2016) use a Bayesian VAR model and document that the announcement of 1% of GDP of large-scale purchases of government bonds led to a rise of 0.58% and 0.25% in real GDP for the US and the UK, respectively. The counterfactual approach employed in this paper is similar in spirit to Kapetanios et al. (2012) and goes one step further from the existing literature because it does not simply quantify the effects of the policy on pension funds, but it also examines a “what if” scenario, hypothesizing that interest rates and Treasury yields would have been higher in a different monetary policy framework.

4. Empirical results

4.1. Data analysis and descriptive statistics

We collect detailed information about the characteristics, pension plans, and asset allocations for 151 US pension funds from January 1998 to December 2013 from the Public Plans Database (PPD) obtained from the Center for Retirement Research at Boston College. The full sample includes 2416 observations and consists of the historical yearly asset allocation in various asset classes for each pension fund and the yearly return by asset class from 1998 to 2013, the latest year for which all data are available. Moreover, we collect, from Bloomberg database, yearly data for the 10-year US Treasury yield and the federal funds target rate (upper bound).[12] Our sample includes at least one pension fund from each state, while also it contains the largest plans based on their assets. More precisely, Table 1 shows that there are 224 state pension plans, with 151 included in our sample. In addition, there are 3761 local pension plans.[13] The total number of assets for all the state and local plans is about $3,2 billion, while our sample contains information for about $3,0 billion of assets, which is approximately 92% of the total assets invested in the US public pension fund industry. Fig. 1 shows the dynamics of the federal funds target rate and the 10-year US Treasury yield. Throughout the 1998–2013 period the Treasury yield continuously declined from 6.82% in 2000 to 1.49%. Similarly, the federal funds rate decreased from 6.5% in 2000 to 0.25% in 2013.

Table 2 depicts the summary statistics with information on asset allocation for all pension funds during the entire sample period. More precisely, Panel A presents the assumption for annual investment return on a yearly basis as reported by the pension funds. It contains the 1-, 3-, 5-, and 10-year realized investment

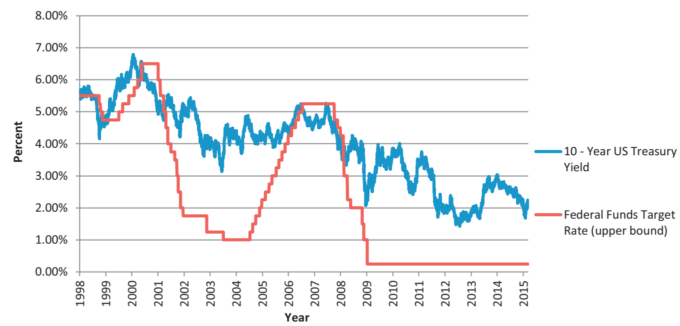

Fig. 1. Nominal yields on 10-year Treasury bonds and the federal funds target rate, Notes: The figure shows nominal yields from 1998 to 2013 on 10-year Treasury bonds for the U.S. and the federal funds target rate set by the Federal Open Market Committee. The data has been collected from Bloomberg database.

returns, and the funding gap ratio, which represents assets divided by actual liabilities. Any value which is lower than 1.0 implies that assets fall short of liabilities and thus the pension fund is underfunded, while a value higher than 1.0 indicates that assets exceed liabilities, and thus the pension fund is overfunded. Panel B provides the asset allocation for the pension funds and the estimated betas (i.e., the systematic risk) for the overall period for each investment.

Panel A shows that pension funds assume a high expected rate of return, but, on average, fail to reach that expectation. Hence, our descriptive summary statistics show that funds were, on average, underfunded during the sample period. Specifically, the mean investment return assumption (henceforth, the performance benchmark) is 7.86%, while the standard deviation for the assumed rate of return is 0.42%, indicating a very small variation in the return assumption within and across pension funds. This means that, if interest rates are below 5%, all investments allocated to government bonds and cash will underperform on an annual basis. The realized return for pension funds is much lower than the assumed rate of return. We provide the results for the average 1-, 3-, 5-, and 10-year returns and observe that pension funds underperform their expectations in each case. Indeed, the average returns are 5.58%, 5.22%, 5.36%, and 6.87%, respectively. While pension funds in some years achieved returns that were higher than their assumed returns, they usually failed to meet their target over longer investment periods.

It is worth noting that, over the 16-year period, the funds suffered several disastrous returns compared to the 8% benchmark. For instance, the low level of interest rates drove their returns much lower than the performance benchmark, while stock market crashes, which occurred in 2001 and in the financial meltdown of 2007–2008, further depressed their investments in equities. Therefore, our statistics suggest that public pension funds are assuming unrealistic investment returns, which leads to underfunding with annual contributions being based on the assumption of an 8% annual return on investment. Again, the majority of pension funds are underfunded. The mean actuarial funding ratio for 1998–2013 is 82.4% with half of the observations lying in the range of 70.0%–90.0%. The minimum (19.6%) and the maximum (197.3%) ratios suggest a high variability of pension funding status. Furthermore, the average actuarial funding ratio declines from 98.9% in 1998 to 70.61% in 2013, suggesting that underfunding worsens over the years, which is consistent with the failure to reach the benchmark return.

Table 3 compares asset allocation and portfolio beta by period. We observe that investments in equities and alternative assets increase meaningfully over the years. In particular, the average allocation to equities is 42.5% in period 1, and rises to 45.9% in period 2, 50.0% in period 3, and 59.6% in period 4. This in-

[12] Please see Appendix A and B for detailed information on the pension funds used in the analysis.

[13] Analytical data for the surplus or deficit and for the allocation of assets is available only for the 151 pension plans included in our sample, due to restrictions on data availability.

Table 1
Data analysis
This table presents the total number of state and local pension funds in the US. The number of states that is included in our sample is in parenthesis. Also, the table presents total assets for all the pension schemes (i.e. state and local) offered from each State, and assets that are included in our sample (i.e. assets in-sample). The total number of state pension plans is 224, while 151 are included in our sample. The total number of local pension plans is 3761. Our sample contains the biggest pension plans by assets, and therefore it represents about 92% of the total assets of the public (state and local) pension fund industry. The source of this data is from the U.S. Cencus Bureau.

	State	State	Local	Total Assets	Assets in-sample
1	Alabama	4 (2)	6	$ 33,251,180	$ 31,688,375
2	Alaska	4 (2)	2	$ 10,406,246	$ 9,573,746
3	Arizona	4 (4)	3	$ 41,443,164	$ 40,655,744
4	Arkansas	6 (2)	27	$ 22,219,051	$ 19,019,508
5	California	5 (5)	58	$ 657,647,900	$ 639,233,759
6	Colorado	2 (2)	65	$ 46,530,078	$ 42,500,573
7	Connecticut	6 (3)	55	$ 32,522,521	$ 29,562,972
8	Delaware	1 (1)	7	$ 8,642,790	$ 8,020,509
9	Florida	1 (1)	471	$ 163,785,916	$ 138,890,457
10	Georgia	10 (8)	24	$ 82,222,704	$ 73,918,211
11	Hawaii	1 (1)	0	$ 12,051,078	$ 12,051,078
12	Idaho	2 (1)	2	$ 12,272,952	$ 11,413,845
13	Illinois	6 (5)	650	$ 135,110,275	$ 119,302,373
14	Indiana	8 (6)	61	$ 28,263,756	$ 25,550,435
15	Iowa	4 (2)	5	$ 27,525,334	$ 25,075,579
16	Kansas	1 (1)	7	$ 15,918,274	$ 14,660,730
17	Kentucky	6 (3)	15	$ 28,043,843	$ 25,211,415
18	Louisiana	14 (8)	21	$ 39,936,873	$ 34,026,216
19	Maine	1 (1)	0	$ 11,432,765	$ 11,432,765
20	Maryland	2 (1)	17	$ 54,432,962	$ 49,697,294
21	Massachusetts	14 (9)	86	$ 64,984,732	$ 58,746,198
22	Michigan	6 (5)	130	$ 76,494,465	$ 67,468,118
23	Minnesota	8 (4)	137	$ 53,136,559	$ 44,634,710
24	Mississippi	4 (2)	0	$ 23,017,265	$ 21,337,005
25	Missouri	10 (5)	56	$ 58,748,518	$ 51,169,959
26	Montana	9 (4)	0	$ 9,060,965	$ 7,819,613
27	Nebraska	5 (3)	8	$ 12,748,146	$ 11,090,887
28	Nevada	2 (2)	0	$ 29,002,144	$ 29,002,144
29	New Hampshire	2 (1)	2	$ 6,450,662	$ 5,812,046
30	New Jersey	7 (4)	3	$ 74,449,190	$ 66,706,474
31	New Mexico	5 (2)	0	$ 23,139,872	$ 19,946,570
32	New York	2 (2)	6	$ 382,206,781	$ 358,127,754
33	North Carolina	6 (6)	2	$ 79,986,718	$ 77,747,090
34	North Dakota	2 (2)	9	$ 4,074,364	$ 3,675,076
35	Ohio	5 (4)	1	$ 159,749,953	$ 142,337,208
36	Oklahoma	6 (3)	6	$ 26,611,420	$ 21,927,810
37	Oregon	1 (1)	5	$ 59,390,416	$ 54,639,183
38	Pennsylvania	3 (3)	1577	$ 95,888,331	$ 80,450,310
39	Rhode Island	1 (1)	12	$ 8,511,634	$ 7,583,866
40	South Carolina	4 (3)	2	$ 27,627,880	$ 24,837,464
41	South Dakota	2 (1)	2	$ 9,571,530	$ 8,537,805
42	Tennessee	1 (1)	14	$ 45,050,770	$ 42,708,130
43	Texas	7 (7)	125	$ 213,473,749	$ 192,553,322
44	Utah	6 (3)	1	$ 22,991,422	$ 20,048,520
45	Vermont	3 (2)	2	$ 3,613,701	$ 2,901,802
46	Virginia	1 (1)	17	$ 70,627,037	$ 65,895,026
47	Washington	6 (6)	20	$ 65,919,198	$ 61,436,693
48	West Virginia	1 (1)	40	$ 12,330,864	$ 11,147,101
49	Wisconsin	1 (1)	2	$ 89,813,290	$ 87,388,331
50	Wyoming	6 (3)	0	$ 6,851,026	$ 5,713,756
	Total	224(151)	3761	$3,279,182,264	$3,014,875,552

creased allocation to risky assets implies an increase in risk-taking behavior by public pension funds. Accordingly, allocation to government bonds declines from 39.1% in period 1 to 22.9% in period 4. Pension funds allocating a high percentage to equities are apparently most affected by severe market downturns. More importantly, we observe that the funding gap ratio increases over the years at the same level as the proportion of equity investments increases, leading to an increased number of underfunded pension funds from period 1 to period 4. This is more evident in late 2008 and early 2009, when pension funds with large allocations in stocks were more adversely affected. Equity allocation peaked in period 4 (2008–2013) when the Federal Reserve launched unconventional monetary measures and lowered its policy rates close to the zero lower bound, confirming that these policies affect pension funds and cause an incentive for riskier investments. Fig. 2 also presents in detail changes in the allocation of assets from 1998 to 2013.

Similarly, portfolio beta follows an upward trend, but increases less than the equity allocation due to the increased investments in alternative assets. The allocation to short-term cash also declines over these time periods, since lower interest rates offer an unattractive alternative to pension funds, which expect a high annual return. Although the average alternative allocation over the entire period is 1.84%, it increases significantly over the period and ranges from 1.83% (period 1) to 6.3% (period 4). In summary, compared to the mean values for the entire period, bond and cash allocations are lower, while allocations in equities, alternative assets, and real estate assets are higher. Pension funds' portfolio beta, as

Table 2
Descriptive statistics
This table presents the descriptive statistics for the 151 US pension funds from 50 states, with 2416 observations. Panel A provides the summary statistics for pension plan return assumption, investment returns and the funding ratio, from 1998 to 2013. Panel B provides the summary statistics for the allocation of assets for the whole time period. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

	Mean *(%)*	Standard deviation *(%)*	Minimum *(%)*	Median *(%)*	Maximum *(%)*
Panel A: pension funds characteristics					
Return Assumption	7.86	4.19	5.75	8.00	9.00
1 Year Inv. Return	5.58	12.04	−30.70	8.84	31.65
3 Years Inv. Return	5.22	6.27	−13.70	5.21	17.90
5 Years Inv. Return	5.36	3.61	−3.54	4.20	25.66
10 Years Inv. Return	6.87	2.54	−1.47	7.20	13.90
Funding Gap Ratio	82.44	19.62	19.10	82.50	197.39
Panel B: pension asset allocation, average for the overall sample period (1998–2013)					
Equities	53.87	12.27	0.00	56.10	75.40
Domestic Equities	36.21	12.42	0.00	38.50	71.57
International Equities	16.44	6.39	0.00	16.81	36.04
Bonds	27.32	9.70	0.00	26.30	100.00
US Govern. Bonds	25.98	11.31	0.00	25.00	100.00
International Bonds	2.44	2.41	0.00	0.30	9.90
Real Estate	6.07	4.15	0.00	5.96	28.40
Cash	2.44	2.99	0.00	0.17	22.50
Alternative Invest.	1.84	7.56	0.00	4.40	56.62
Pension Asset Beta	0.5743	0.1938	0.3839	0.5042	0.6988

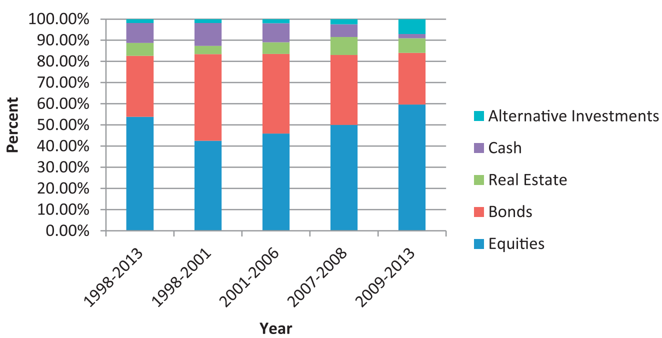

Fig. 2. The average pension funds asset allocation, Note: The figure presents the asset allocation of pension funds for the following time-periods: from 1998–2013 (overall sample period), from 1998–2000 (period 1), from 2001–2006 (period 2), from 2007–2008 (period 3), and from 2009–2013 (period 4). The sample contains 151 pension funds from 50 states.

of 2013, is higher than the sample period average, due to the increase in equity assets and the drop in bond assets.

Moreover, Panel A of Table 3 shows that during period 1 (1998–2000) pension funds, on average, invested more in government bonds compared to all other periods. As a result, government bonds represented a higher annual required contribution in pension fund investments. However, the lowering of policy rates close to zero and the associated decrease in the level of interest rates triggered a shift in asset allocations, from government bonds to equities and alternative investments. This is evident from the figures for period 2 in Panel B (2001–2005), period 3 in Panel C (2006–2007) and period 4 in Panel D (2008–2013). Note that average funding ratios declined over the years, and this is related with low interest rates and the unconventional monetary policy. However, conclusions are drawn cautiously as other factors which might have an important role on pension fund asset allocation decisions are not examined in this study, and therefore, monetary policy is one of the factors affecting the risk taking behavior of pension plans.

Panel A of Table 4 presents the top 15 pension funds by liabilities. The funding coverage ratio ranges from 40% to 99%. The 5-year investment return is lower than the return assumption of 8% for all pension funds and ranges from 1.7% to 6.8%, confirming the funds' underperformance. However, while the 10-year return presents an improved picture, only two funds achieved a rate of return exceeding the return assumption of 8%. Notably, the majority of pension funds allocate more than 50% of their investments to equities and less than 25% to bonds. Panel B depicts the funds with the higher coverage ratio. It shows that the 5- and 10-year returns are substantially higher when compared with the fund performance in Panel A. It is also evident that these funds allocate a much lower proportion of their assets to equities (32% on average) and a higher proportion to bonds (27%), suggesting that investing in equities does not imply better long-term performance.

4.2. Risk determinants of asset allocation

To shed light on the effects of low interest rates and unconventional monetary policy on pension funds, we examine the relationship between monetary policy shocks, defined as changes in interest rates which lead to larger or smaller changes in Treasury bond yields, with: *i*) the return on pension assets during the fiscal year; and *ii*) the portfolio's risk (beta). Table 5 shows the regression results using pension fund asset allocation as the dependent variable, during the four different time periods. Specifically, a 10% increase in the investment return reduces the percentage of assets allocated to Treasury bonds and to short-term cash by 2.06% during period 1, and systematic risk increases by 0.42% as a result of the reduction of assets allocated to safe investments. By contrast, a 10% increase in the investment return increases the percentage of assets allocated to equities by 4.81%. This in turn increases the systematic risk of the portfolio by 0.68%.

We also find that a similar correlation exists during period 2, where a 10% increase in the investment return prompts a decrease in assets allocated to safe securities by 3.03%, while the percentage of assets invested in equity increases significantly by 6.94%. This relation implies that asset allocation is correlated with short-term lagged investment returns, with higher returns preceding higher equity and lower bond allocation. Interestingly, for pension funds with weak funding ratios (Panel B), the correlation between asset allocation and short-term lagged returns is meaningfully smaller, implying a risk-shifting behavior. Notably, in periods 3 and 4, there is an increase in the proportion of alternative assets. The effect of lagged returns is statistically significant at the 5% level. As a result, the allocation of assets is not correlated with short-term lagged

Table 3
Pension fund asset allocation
This table depicts the detailed asset allocation and the portfolio beta for 151 pension funds from 50 US States, with 2416 observations. Panel A provides the allocation from 1998 to 2000. Panel B presents the allocation of assets from 2001 to 2006. Panel C shows the allocation of assets from 2007 to 2008 and Panel D exhibits the allocation of assets from 2009 to 2013. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

	Mean *(%)*	St. deviation *(%)*	Minimum *(%)*	Median *(%)*	Maximum *(%)*
Panel A: pension asset allocation, Period 1: 1998–2000					
Equities	42.52	9.88	0.00	42.76	57.81
Domestic Equities	34.73	6.59	0.00	34.01	94.22
International Equities	7.79	3.82	0.00	4.28	19.35
Bonds	40.94	9.60	0.00	36.07	100.00
US Govern. Bonds	39.10	6.34	0.00	46.87	100.00
International Bonds	1.84	1.16	0.00	1.21	3.80
Real estate	3.85	3.61	0.00	3.90	8.74
Cash	10.86	5.73	0.00	10.06	30.69
Alternative Invest.	1.83	2.04	0.00	1.62	8.77
Pension Asset Beta	48.46	10.53	0.00	44.93	56.25
Panel B: pension asset allocation, period 2: 2001–2006					
Equities	45.98	11.73	0.00	49.22	60.02
Domestic Equities	38.06	8.21	0.00	38.86	91.66
International Equities	7.92	5.05	0.00	9.40	25.80
Bonds	37.58	10.08	0.00	39.79	98.00
US Govern. Bonds	36.23	6.47	0.00	46.35	100.00
International Bonds	1.35	1.55	0.00	1.60	5.00
Real Estate	5.50	5.74	0.00	8.62	12.08
Cash	9.03	5.31	0.00	10.11	24.64
Alternative Invest.	1.91	2.26	0.00	1.64	10.93
Pension Asset Beta	50.96	12.07	0.00	46.83	60.30
Panel C: pension asset allocation, period 3: 2007–2008					
Equities	50.02	11.98	0.00	52.76	72.40
Domestic Equities	32.07	10.36	0.00	40.45	79.82
International Equities	17.95	7.02	0.00	20.71	40.83
Bonds	33.06	9.98	0.00	30.60	100.00
US Govern. Bonds	32.50	5.31	0.00	30.05	100.00
International Bonds	0.56	1.07	0.00	0.24	4.00
Real Estate	8.45	6.03	0.00	6.29	33.56
Cash	6.02	2.21	0.00	6.84	14.77
Alternative Invest.	2.45	10.04	0.00	1.66	12.14
Pension Asset Beta	54.33	14.82	0.00	48.83	66.71
Panel D: pension asset allocation, period 4: 2009–2013					
Equities	59.64	13.88	0.00	58.76	76.50
Domestic Equities	36.02	13.52	0.00	38.99	73.79
International Equities	23.62	8.93	0.00	23.01	42.87
Bonds	24.41	9.25	0.00	21.75	100.00
US Govern. Bonds	22.98	10.69	0.00	18.33	100.00
International Bonds	2.53	2.63	0.00	0.49	11.02
Real Estate	6.92	4.85	0.00	6.54	29.50
Cash	2.01	3.91	0.00	0.17	22.50
Alternative Invest.	6.35	6.40	0.00	6.12	59.84
Pension Asset Beta	0.6881	0.1539	0.0000	0.4902	0.7409

investment returns, since higher returns precede lower equity and bond allocation.

Notably, for all four periods, the allocation of assets is correlated with monetary policy shocks - changes in interest rates which lead to larger or smaller changes in bond yields -since a 1% decline in bond yields leads to higher equity and lower bond allocation, as it is evident from Panels A and B of Table 5. During period 4, when the Federal Reserve announced a large program of asset purchases and at the same time lowered policy rates close to the zero lower bound, the effects are greater in magnitude. Specifically, the percentage of assets invested in bonds for a 1% decline in Treasury yields is associated with a 10.52% decrease in the percentage of assets allocated to bond securities. The effect of changes in Treasury yields is statistically significant at the 5% level.

Overall, our results are consistent with the patterns shown in Figs. 1 and 2, where a reduction in interest rates that was followed by a 5% decline in the 10-year Treasury yield over the period is associated with an 18% decrease in the allocation to bond securities and a 17% increase in the allocation to equity assets. This is observed for well-funded and underfunded pension plans, indicating a structural risk-shifting behavior. Consequently, a lower interest rate environment and the use of unconventional monetary policy measures prompt pension funds to change their strategic asset allocation from safe to riskier investments.

4.3. Results from the BVAR model

We estimate the BVAR model using one lag order and a rolling approach for the entire sample period. Similar to Kapetanios et al. (2012), we assume that the use of unconventional monetary policy tools, from 2008 until 2011, and the sharp drop in interest rates near to the zero lower bound may have depressed government bond yields by about 100 basis points. To assess the impact of monetary policy shocks on the asset allocation and the risk taking behavior of pension funds, we compare actual returns with those of the counterfactual scenario (i.e., government bond yields would have been 100 basis points higher than actual yields in the absence of monetary policy shocks) and take the difference between the two as our estimate. Moreover, we increase the asset allocation to government bonds and decrease the allocation to equities to

Table 4
Top-fifteen pension funds by liabilities and funding coverage ratio
This table provides detailed characteristics for the top fifteen pension funds based on their liabilities (Panel A) and the fifteen best-funded pension plans (Panel B) as of 2013. In addition, it provides the 5- and the 10-year investment return, the percentage of assets allocated to equities and bond securities, and the systematic risk for each pension plan (i.e. portfolio beta). The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Pension fund	Liabilities (U.S. $)	Funding coverage ratio (%)	Inv. 5 year return (%)	Inv. 10 year return (%)	% of investment in equities	% of investment in bonds	Portfolio beta
Panel A: top-fifteen pension funds by liabilities							
California Teachers	222,280,992	67.0	3.72	7.53	53.6	16.79	0.57
Florida RS	154,125,952	85.4	5.04	7.44	59.09	22	0.62
Texas Teachers	150,666,000	80.8	5.4	7.2	49.7	14.3	0.64
New York State Teachers	94,538,800	87.5	5.2	7.5	58.89	18.99	0.52
Ohio Teachers	94,366,696	66.3	4.87	8.08	52.78	20.19	0.61
Illinois Teachers	93,886,992	40.5	4.2	7.2	43.9	24.79	0.60
Pennsylvania School Emp.	89,951,816	63.8	2.5	7.72	21.1	18.2	0.62
Wisconsin Retirement Sys	85,328,704	99.9	1.7	4.8	36.28	14.83	0.58
Virginia Retirement Sys	79,077,592	65.9	4	7.6	47.49	21.69	0.52
Georgia Teachers	72,220,864	81.0	6.27	6.55	73.5	26.49	0.56
Michigan Public Schools	63,839,728	59.5	6.8	7.4	41.79	12.1	0.62
North Carolina Teachers and State Employees	63,630,280	94.1	5	6.6	46.4	33.79	0.63
Oregon PERS	60,405,200	90.6	5	8.33	36.9	21.89	0.61
University of California	57,380,960	75.9	4.67	6.62	47.99	23.99	0.57
New Jersey Teachers	53,645,476	57.0	5.32	7.26	39.2	15.37	0.61
Panel B: top-fifteen pension funds by funding coverage ratio							
Washington LEOFF Plan 2	6,859,000	114.6	3.81	8.29	37.7	22.62	0.63
DC Police & Fire	3,644,085	110.09	7.19	6.8	52.99	28	0.65
Washington Teachers Plan	8,016,000	104.9	3.81	8.29	37.7	22.62	0.66
Washington PERS 2/3	23,798,000	102.3	3.81	8.29	37.709	22.62	0.60
Washington School Employees Plan 2/3	3,273,000	101.9	3.81	8.29	37.7	22.62	0.62
South Dakota PERS	8,803,700	100	7.11	8.72	50.7	19.7	0.64
Wisconsin Retirement Sys	85,328,704	99.9	4.6	8.39	48.29	21.03	0.63
North Carolina Local Gov	20,338,784	99.8	5	6.59	46.4	33.79	0.65
TN Political Subdivisions	7,789,873	94.96	5.33	6.15	56.59	28.49	0.67
North Carolina Teachers and State Employees	63,630,280	94.19	5	6.59	46.4	33.79	0.69
TN State and Teachers	34,123,560	93.33	5.33	6.15	56.59	28.49	0.61
Louisiana State Parochial	3,217,464	92.5	13.65	7.28	37.4	26.71	0.67
Delaware State Employees	8,257,270	91.1	5.5	9.39	54.1	21.7	0.62
Oregon PERS	60,405,200	90.69	5	8.33	36.9	21.89	0.68
DC Teachers	1,759,043	90.09	7.2	6.8	52.99	28	0.67

Table 5
Relationship between lagged investment returns and Treasury yields on pension fund asset allocation
This table presents the results of the regression of the change in the percentage of allocation to bond securities, short-term cash and equity assets on the mean investment return per period. It also provides the change in the portfolio's beta and Treasury yield based on the percentage of changes in the allocation of assets, for 151 US pension funds from 50 States resulting in 2416 observations. Panel A exhibits results for well-funded pension plans. In contrast, Panel B presents results for the most underfunded pension plans, from 1998 to 2013. The major data source is the Public Plans Database obtained from the Center for Retirement Research at Boston College and the Bloomberg database. R-square is expressed in percentage.

	Percentage of assets invested in bond securities and cash			Percentage of assets invested in equities		
	Investment return (%)	Portfolio beta	Decline in treasury yield (%)	Investment return (%)	Portfolio beta	Decline in treasury yield (%)
Panel A: funding status decile 1 (best funding ratio)						
Period 1: 1998–2000	−2.06	0.42	3.67	4.81	0.68	2.89
Period 2: 2001–2006	−3.03	0.57	6.81	6.94	1.73	7.22
Period 3: 2007–2008	−5.91	0.85	7.36	−0.87	1.06	6.36
Period 4: 2009–2013	−8.20	1.36	10.52	−2.39	0.41	7.61
Probability > x^2	0.48	–	0.52	0.59	–	0.53
Pension funds	151	151	151	151	151	151
R–squared: Period 1	1.60	1.67	1.58	2.10	2.15	2.22
R–squared: Period 2	2.33	2.40	2.31	2.29	2.25	2.53
R–squared: Period 3	2.34	2.47	2.44	1.32	1.29	1.57
R–squared: Period 4	2.40	2.49	2.52	2.38	2.36	2.61
Panel B: funding status decile 2 (worst funding ratio)						
Period 1: 1998–2000	−1.90	0.31	2.04	2.66	0.49	1.80
Period 2: 2001–2006	−2.03	0.38	3.88	3.92	1.08	3.11
Period 3: 2007–2008	−2.97	0.40	5.92	1.80	0.53	4.87
Period 4: 2009–2013	−3.13	0.48	6.96	−0.94	0.21	5.05
Probability > x^2	0.49	–	0.51	0.53	–	0.51
Pension funds	151	151	151	151	151	151
R–squared: Period 1	1.28	1.27	1.19	2.10	2.08	2.02
R–squared: Period 2	2.14	2.11	2.10	2.47	2.30	2.53
R–squared: Period 3	2.21	2.24	2.22	1.90	1.82	1.91
R–squared: Period 4	2.22	2.43	2.78	2.59	2.41	1.98

Table 6
Bayesian VAR counterfactual results
This table reveals the effects of monetary policy shocks on pension fund asset allocation decisions and risk-taking behavior. The time periods are split based on the drastic changes in monetary policy to capture the full effects and the changes in the characteristics of the pension funds. Three scenarios are simulated: i) 100 basis point increase in the Treasury yield; ii) 120 basis point increase in the Treasury yield; and iii) 200 basis point increase in the Treasury yield, for 151 US pension funds from 50 States, making 2416 observations. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Estimate	Bond securities (%)	Short-term cash (%)	Portfolio total return (%)	Systematic risk
Overall sample period (1998–2013)				
Mean	3.62	1.44	6.56	0.55
100bp	4.48	2.16	7.19	0.52
120bp	4.97	2.28	7.25	0.51
200bp	5.63	2.51	7.68	0.46
Period 1: 1998–2000				
Mean	5.03	3.01	7.86	0.49
100bp	5.92	3.85	8.51	0.45
120bp	6.06	3.97	8.64	0.44
200bp	7.01	4.30	9.28	0.40
Period 2: 2001–2005				
Mean	3.84	1.97	7.12	0.52
100bp	4.51	2.39	7.70	0.50
120bp	4.64	2.45	7.83	0.49
200bp	5.29	2.91	8.33	0.43
Period 3: 2006–2007				
Mean	2.97	1.29	5.87	0.57
100bp	4.48	2.16	6.51	0.53
120bp	4.97	2.28	6.70	0.52
200bp	5.63	2.51	7.49	0.48
Period 4: 2008–2013				
Mean	1.96	1.01	5.10	0.61
100bp	2.73	1.42	5.62	0.55
120bp	2.88	1.59	5.75	0.54
200bp	3.46	1.73	6.34	0.50

identify the return to pension fund investments. This procedure is also used in Lenza et al. (2010) and Kapetanios et al. (2012) when they examine the effects of unconventional monetary policy on the macroeconomy, and in Ait-Sahalia et al. (2012) when they address the effect of monetary policy shocks on financial markets. We also use two additional tests by simulating the effects of a 120-basis-point and a 200-basis-point increase in government bond yields and short-term overnight rates for cash holdings, while allowing the size of adjustment on the yields to vary over the entire sample period.

Table 6 reports the estimated effects of monetary policy shocks on pension fund investment return and asset allocation. The mean return results reveal that monetary policy shocks substantially decreased the return on bond investments, making bond assets unattractive. The largest impact occurred in period 4 (2008–2013), when the Federal Reserve launched a large program of asset purchases and at the same time reduced the official US bank rate to 0.25%. While stock markets underperform, plans do not reduce their equity holdings, indicating that there is a structural risk-shifting incentive to riskier securities, such as equities and alternative investments, as a result of the policy rate cut-off to the zero lower bound. This evidence suggests that the funding status of a given pension plan changes in accordance with developments in monetary policy. Under this scenario, pension funds tend to invest more in equities and less in safe assets, such as government bonds.

How persistent are monetary policy shocks? We answer this question by examining the sensitivity of pension fund returns under the assumption that government bond yields would have been higher if there were no major changes in the Federal Reserve's policy over the sample period. The results, reported in Table 6, indicate that the portfolio return for the pension funds increases significantly from 6.56% to 7.19% for a 100-basis-point rise in yield, and to 7.68% for a 200-basis-point increase in yield. It is notable

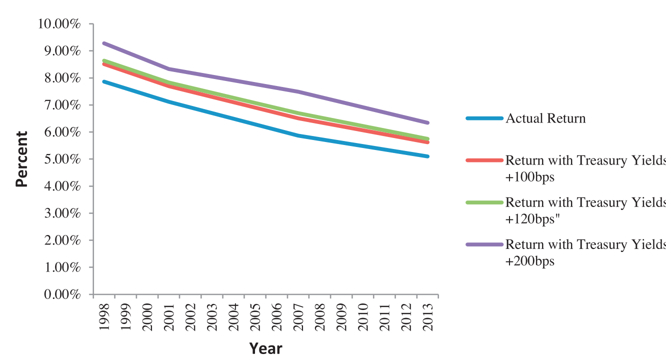

Fig. 3. BVAR counterfactual analysis, Note: The figure shows the persistence of monetary policy shocks on pension funds risk-taking behavior. The actual return refers to the achieved investment return in pension assets from 1998 to 2013. Three scenarios are simulated, where the Treasury yield is higher by 100 basis points, 120 basis points, and 200 basis points, respectively, to assess the portfolio return.

that, in many cases (i.e., in period 1 and in period 2) the assumed higher level of interest rates helps pension funds to achieve their planned return of 8%. Fig. 3 evidences the difference in return under the three counterfactual scenarios where the percentage of pension fund assets allocated to equities could be lower since investments in safer assets would be more attractive.

In the scenario with higher interest rates, we add the assumption that investments in government bonds would be more attractive for pension funds and that they would allocate their assets accordingly. For a more meaningful comparison, the allocation to government bonds is kept constant at the proportion allocated during period 1. Table 7 presents the effects of the monetary policy on pension fund returns under these assumptions. The results indicate that the portfolio return would have been higher

Table 7
Bayesian VAR estimation of portfolio effects with higher allocation of assets for bond securities
This table presents the effects of monetary policy shocks on pension fund asset allocation decisions and risk-taking behavior, based on the scenario that the allocation of assets in bond securities and short-term cash does not change from period 1 to period 4. The mean portfolio return represents 151 US pension funds from 50 States, making 2416 observations. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Estimate	Bond securities (%)	Short-term cash (%)	Portfolio total return (%)	Systematic risk
Overall sample period (1998–2013)				
Mean return	3.62	1.44	6.64	0.55
100bp	4.48	2.16	7.48	0.51
120bp	4.97	2.28	7.57	0.50
200bp	5.63	2.51	7.86	0.45
Period 1: 1998–2000				
Mean return	5.03	3.01	7.86	0.49
100bp	5.92	3.85	8.51	0.44
120bp	6.06	3.97	8.64	0.43
200bp	7.01	4.30	9.28	0.38
Period 2: 2001–2005				
Mean return	3.84	1.97	7.53	0.52
100bp	4.51	2.39	7.91	0.50
120bp	4.64	2.45	7.94	0.49
200bp	5.29	2.91	8.52	0.42
Period 3: 2006–2007				
Mean return	2.97	1.29	5.91	0.57
100bp	4.48	2.16	6.77	0.52
120bp	4.97	2.28	6.82	0.51
200bp	5.63	2.51	7.62	0.47
Period 4: 2008–2013				
Actual return	1.96	1.01	5.28	0.61
100bp	2.73	1.42	5.80	0.54
120bp	2.88	1.59	5.91	0.53
200bp	3.46	1.73	6.63	0.49

Table 8
Shocks, regimes and effects – MS-SVAR model.

Regime/Shock	Effect on G. B yields	Effect on asset allocation for G.B	Effect on allocation in equities/Alt. Inv.	Effect on portfolio risk
Peak level for I.R.	Positive (>)	Positive (>)	Negative (<)	Positive (lower risk)
Decrease in I.R.	Negative (<)	Negative (<)	Positive (>)	Negative (higher risk)
Moderate increase in I.R.	Slightly positive (≥)	Positive (>)	Slightly negative (≤)	Positive (lower risk)
ZLB and QE	Negative (<)	Negative (<)	Positive (>)	Negative (higher risk)

Note: G.B. denotes government bonds, Alt. Inv. denotes alternative investments, I.R. is the interest rate, ZLB is the Zero Lower Bound level for the interest rate, and QE denotes the launch of unconventional monetary policy with the Quantitative Easing program.

by 122 basis points, increasing from 6.64% to 7.86%, while the portfolio beta (systematic risk) would be substantially lower.

4.4. Results from the MS-SVAR model

We test for the number of regimes by prior knowledge and carry out robustness checks by using the marginal likelihood criterion as introduced by Chib (1998). Fig. 4 illustrates the estimated regime pattern for pension asset allocation, while Table 8 identifies monetary policy shocks through the changes in the interest rates and the associated change in Treasury yields. In particular, Table 8 presents the effects during the four monetary policy regimes: i) during period 1 (1998–2000), when interest rates increase and reach their peak levels for the entire sample period; ii) during period 2 (2001–2005), when interest rates decrease; iii) during period 3 (2006–2007), when interest rates increase moderately; and iv) during period 4 (2008–2013), when interest rates are set at the zero lower bound and unconventional monetary tools emerge. Similar to Kapetanios et al. (2012), the shocks are identified using a sign. A positive monetary policy shock that increases interest rates is expected to trigger an increase in the yield curve. On the other hand, a negative shock is expected to cause a compression in the yield curve.

Fig. 5 shows the impulse response functions to Treasury bonds and equity allocation following a monetary policy shock. From the figure it is clear that the monetary policy regime affects substantially the allocation of assets to equities and bonds. Specifically, the response from pension funds was to increase the proportion of equities and to decrease accordingly the proportion of assets allocated to government bonds. This finding suggests that pension funds risk taking meaningfully increases with a decline in the level of interest rates and with the launch of unconventional tools.

Additionally, to capture the effects of monetary policy shocks, we follow the scenarios studied using the BVAR model, where we assume that government bond yields would have been 100, 120, or 200 basis points higher, if there had been no dramatic changes in monetary policy. Table 9 describes the effects on pension fund asset allocation and investment return from these simulations. For a 100-basis-point increase in Treasury yields, the maximum impact occurs in period 2 (2001–2005) and period 4 (2008–2013), since during these two periods the unconstrained policy rate declines. Specifically, as illustrated in Fig. 6, the investment return increases significantly from 6.56% to 7.74% for a 200-basis-point rise in yield. Similar to the results of the BVAR model, in many cases, the assumed higher level of interest rates helps pension funds to achieve their planned return of 8% (in periods 1 and 2). Moreover, the MS-SVAR model indicates that, if monetary policy shocks had been less persistent, the portfolio risk (i.e., beta) would be smaller and the allocation to bond securities meaningfully higher.

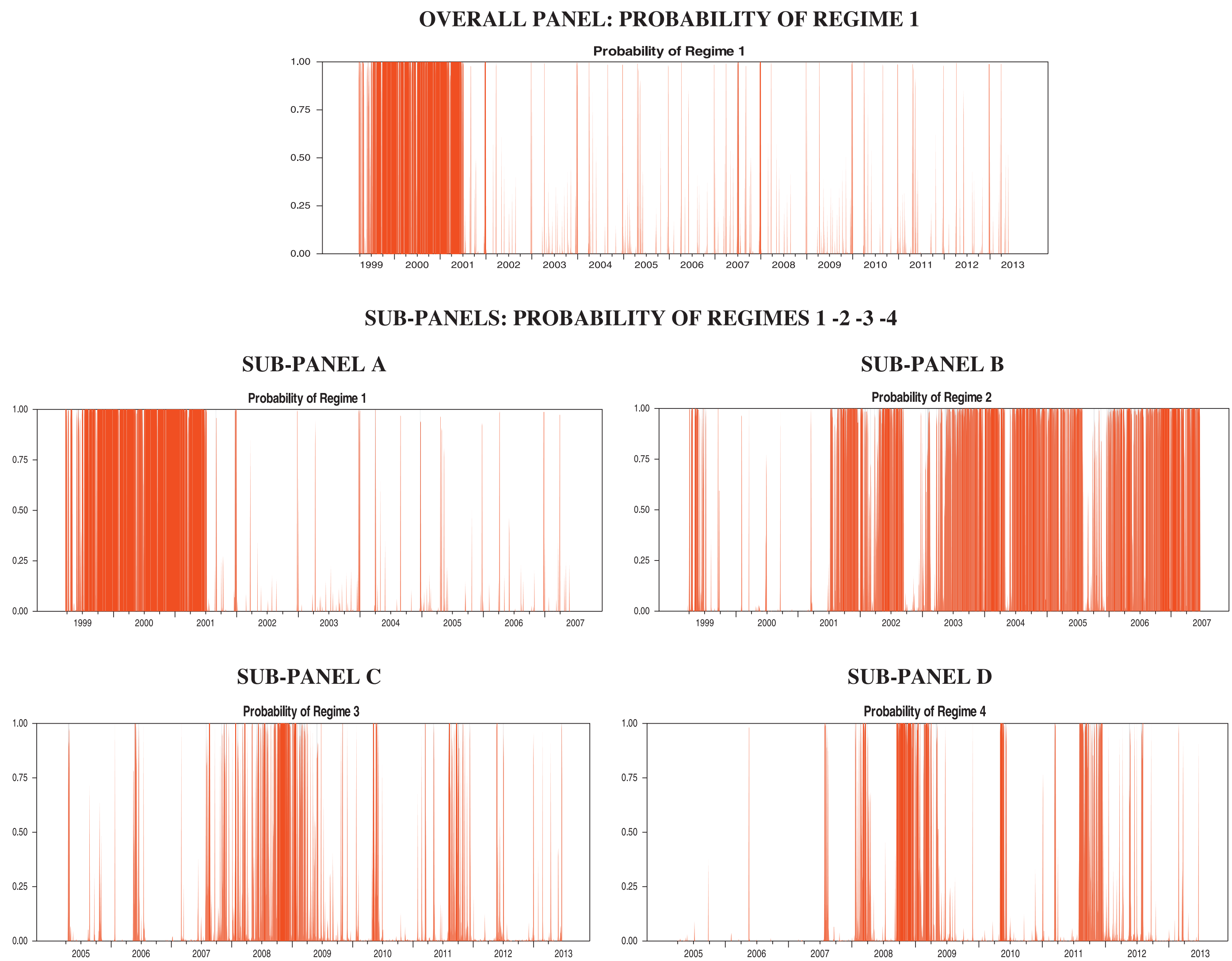

Fig. 4. MS-SVAR switching regimes, Note: The figure illustrates the four Markov switching regimes, estimated using the MS-SVAR model. The Overall Panel exhibits the whole sample period and shows the identification of Regime 1. There are also four Sub-Panels which focus mainly on the period when the Regime is identified. Sub-Panel A shows regime 1 (1998–2000) where interest rates increased. Sub-Panel B displays regime 2 (2001–2006) where interest rates declined. Sub-Panel C exhibits regime 3 (2007–2008) where interest rates increased moderately. Sub-Panel D reveals regime 4 (2009–2013) where interest rates declined near the Zero Lower Bound.

Similarly, we also assume that pension funds would allocate their assets according to a scenario in which investments in bond securities would be more attractive and that the allocation to government bonds would stay constant at the proportion allocated during period 1. The results obtained under this scenario, reported in Table 10, reveal that the investment return would have been higher by 122 basis points, changing from 6.70% to 7.92%, while the portfolio beta would be substantially lower.

5. Robustness check

The main finding of our study is that low interest rates and the launch of unconventional monetary policy (i.e., quantitative easing) trigger a risk-shifting behavior for pension funds to invest in riskier securities, such as equity assets. The allocation of assets to government bonds decreased meaningfully as pension funds invested on assets with higher yield, to finance their liabilities. We test the sensitivity of our results by using different scenarios for the effect of changes in government bond yields on pension asset allocation, portfolio risk, and investment return. In this section, we adopt the Chib (1998) approach and use a particle Markov Chain Monte Carlo (MCMC) simulation to test for the number of possible regimes, since less than four, or more than four, regime switches in principle can occur. We also allow the regime to grow exponentially with time t, creating robust dependence between the state variables.

More precisely, the posterior MCMC approach, with a limit of 5000 observations is used to compute the marginal log-likelihood values with the conditional variance depending only on past shocks.[14] A high value of the log-likelihood (i.e., a value closer to zero) indicates better fitting. Table 11 presents the results estimated by bridge sampling. The differences between bridge sampling and Chib's method are very small. Similarly, the alteration between the marginal log-likelihood values increases substantially from regimes 1 to 4, but decreases in regime 5 for all the pairs considered, as is evident in Table 11. The increased value in regime 5 implies that the four-regime model fits the data best.

[14] The marginal likelihood is computed in the Markov-switching models in a similar way to Hamilton and Susmel (1994).

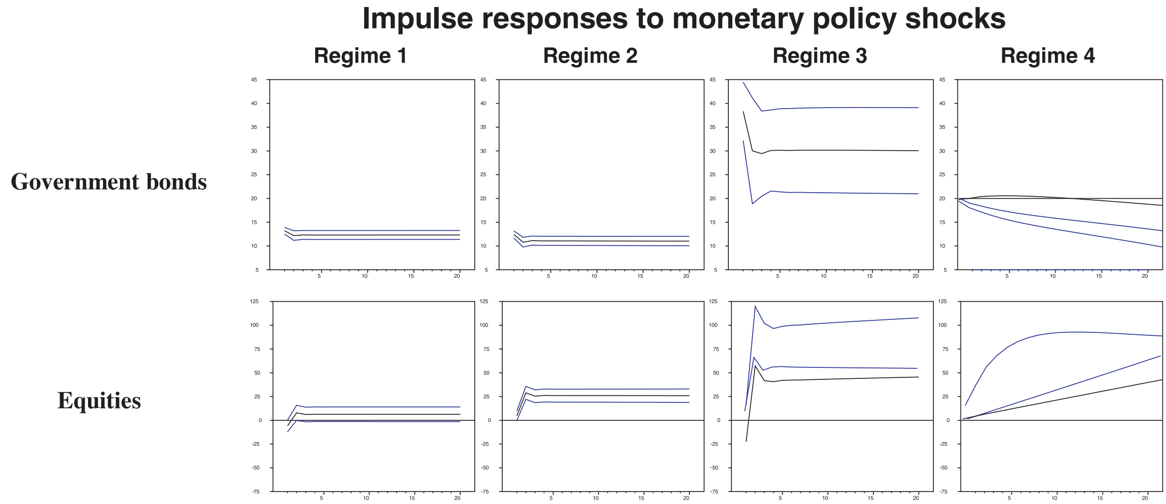

Fig. 5. Generalized impulse response functions to monetary policy shocks, Note: This figure depicts the generalized impulse response functions of the endogenous variables of the MS-SVAR model during four different monetary policy environments (Regimes 1, 2, 3, and 4 respectively). The four regimes represent the identification of the shocks (i.e. changes in the interest rates that lead to larger or smaller changes to bond yields). The figure summarizes responses by pension funds regarding the allocation of assets to government bonds and to equities following monetary policy shocks. The Y axis represents changes in the allocation and the X axis represents the time period. During Regime 1, the monetary policy shock causes a slight negative response to government bonds and a positive response (i.e. increase in the allocation) in equities. During Regime 2, when interest rates decline government bonds respond negatively (i.e. downward slope), while equities respond positively. During Regime 3, the monetary policy shock initially causes a negative response to the allocation of government bonds (downward slope), but later the response of government bonds recovers to higher levels, indicating allocation to bond assets increased slightly, which might be due to the increase in interest rates. On the contrary, the response of equities is initially positive, but later it becomes slightly negative. Finally, during Regime 4 (i.e. interest rates at historically low levels) the response of government bonds is overly negative, while allocation to equities increases substantially.

Table 9
MS–SVAR counterfactual results
This table exhibits conditional forecasting for the effects of monetary policy shocks on pension fund asset allocation decisions and risk-taking behavior. The time periods are divided based on the drastic changes in monetary policy to capture the full effects and the changes in the characteristics of pension funds. Three scenarios are simulated: i) 100 basis point increase in the Treasury yield; ii) 120 basis point increase in the Treasury yield; and iii) 200 basis point increase in the Treasury yield, for 151 US pension funds from 50 States, making 2416 observations. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Estimate	Bond securities (%)	Short-term cash (%)	Portfolio total return (%)
Overall sample period			
Mean return	3.62	1.44	6.56
100bp	4.51	2.19	7.23
120bp	4.98	2.28	7.29
200bp	5.72	2.59	7.74
Period 1: 1998–2000			
Mean return	5.03	3.01	7.86
100bp	5.98	3.87	8.54
120bp	6.11	3.99	8.67
200bp	7.16	4.38	9.35
Period 2: 2001–2005			
Mean return	3.84	1.97	7.12
100bp	4.63	2.48	7.89
120bp	4.69	2.51	7.92
200bp	5.40	3.01	8.55
Period 3: 2006–2007			
Mean return	2.97	1.29	5.87
100bp	4.53	2.18	6.54
120bp	4.98	2.28	6.72
200bp	5.72	2.59	7.60
Period 4: 2008–2013			
Actual return	1.96	1.01	5.10
100bp	2.79	1.44	5.68
120bp	2.90	1.61	5.77
200bp	3.55	1.76	6.48

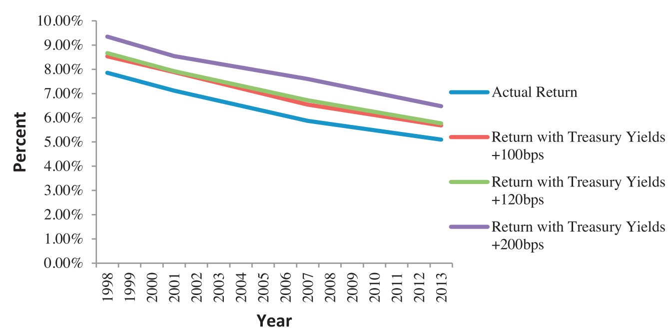

Fig. 6. MS-SVAR counterfactual analysis, Note: The figure shows the persistence of monetary policy shocks on pension fund risk-taking behavior. The actual return refers to the achieved investment return in pension assets from 1998 to 2013. Three scenarios are simulated, where the Treasury yield is higher by 100 basis points, 120 basis points, and 200 basis points, respectively, to assess the portfolio return.

6. Conclusion

US public pension funds suffer from severe funding shortfalls, triggered, at least partially, by the stock market downturns experienced during the financial crisis of 2008–2009. Pension plans have clearly been investing an ever-increasing proportion of their assets in risky investments. In an important departure from the existing literature, this study provides new evidence on the effects of unconventional monetary policy and low interest rates on the US public pension funds. Our empirical analysis is based on counterfactual scenarios, a BVAR model and a MS-SVAR model. The MS-SVAR model, in particular, allows us to analyze the complex relationships between Treasury yields, interest rates, and pension fund asset and risk management decisions, while relaxing the assumption of constant parameters over time to allow for capturing structural changes in pension fund asset allocation strategy. We find that monetary policy shocks, defined as changes in Treasury yields following changes in interest rates, are associated by an increase in equity and a decrease in bond assets.

Table 10
MS-SVAR estimation of portfolio effects with higher allocation of assets for bond securities
This table presents the effects of monetary policy shocks on pension fund asset allocation decisions and risk-taking behavior based on the scenario that the allocation of assets in bond securities and short-term cash does not change from period 1 to period 4. The mean portfolio return represents 151 US pension funds from 50 States, making 2416 observations. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Estimate	Bond securities (%)	Short-term cash (%)	Portfolio total return (%)
Overall sample period			
Mean return	3.62	1.44	6.70
100 bp	4.51	2.19	7.53
120 bp	4.98	2.28	7.59
200 bp	5.72	2.59	7.92
Period 1: 1998–2000			
Mean return	5.03	3.01	7.86
100 bp	5.98	3.87	8.54
120 bp	6.11	3.99	8.67
200 bp	7.16	4.38	9.35
Period 2: 2001–2005			
Mean return	3.84	1.97	7.58
100 bp	4.63	2.48	7.94
120 bp	4.69	2.51	7.97
200 bp	5.40	3.01	8.61
Period 3: 2006–2007			
Mean return	2.97	1.29	5.95
100 bp	4.53	2.18	6.79
120 bp	4.98	2.28	6.83
200 bp	5.72	2.59	7.84
Period 4: 2008–2013			
Actual return	1.96	1.01	5.33
100 bp	2.79	1.44	5.84
120 bp	2.90	1.61	5.92
200 bp	3.55	1.76	6.68

More precisely, a decrease in interest rates, which is followed by a decline of 5% in the 10-year Treasury yield over the study period, decreases the allocation to bond securities by 18% but increases the allocation to equity assets by 17%. The greater impact occurs during the unconventional monetary policy period with the launch of quantitative easing and the zero lower bound policy. These results imply that a lower interest rate environment and the use of unconventional monetary policy measures prompted pension funds to change their strategic asset allocation from safe to riskier investments, and thus constitute an explanation for the risk-taking behavior of pension plans.

Moreover, our counterfactual analysis shows consistent results on the reaction of pension fund investment return to monetary policy shocks, whatever the model used. For example, the portfolio return in pension funds increases significantly from 6.56% to 7.19% for a 100-basis-point rise and to 7.68% for a 200-basis-point increase in the Treasury yield using the BVAR approach. For the MS-SVAR model, the portfolio return increases from 6.56% to 7.74% for a 200-basis-point increase in the yield. Notably, in many cases the assumed higher level of interest rates helps pension funds achieve their benchmark return of 8% (i.e., in period 1 and in period 2). Finally, we document that the risk management incentive is not the primary reason for the reduced allocation to bond investments in pension funds. Well-funded and underfunded pension funds invest the largest proportion of their assets in equity securities, indicating that the risk-shifting incentive dominates the risk taking behavior of US public pension funds.

Acknowledgments

The authors are grateful to the former Minister of State for Pensions Steven J. Webb, to Carol Alexander (The Editor), Michael Arghyrou, Alan Collins, M. Shahid Ebrahim, Mauricio Fiaschetti, Christopher Geczy, Benjamin Guin, Rhys ap Gwilym, Christos Floros, Michael Haliassos, Renatas Kizys, Alexandros Kontonikas, Alexander Michaelides, Steven Ongena, Thien Nguyen, Gioia Pescetto, Andy Thorpe, Ania Zalewska, Jan Zimmerman, the participants at the 2015 Conference on "Institutional and Individual Investors: Saving for Old Age" at the University of Bath (Bath, United Kingdom), the Vietnam 2015 International Conference on Finance (Ho Chi Minh City, Vietnam), seminar participants at the University of Sussex and three anonymous reviewers for helpful comments and suggestions. All errors are our own responsibility.

Appendix A. Data analysis

In the US, public sector pensions are offered by three sources: The federal, state and local levels of government. Pension plans are divided into two categories namely defined benefit and defined contribution pensions. The former has been more widely used over the last years by public agencies in the US. Each state administers at least one pension system and each system has at least one pension plan. A state government usually establishes

Table 11
Marginal log-likelihood for 5.000 simulations
This table displays results for bridge sampling and Chib's method for the marginal likelihood value for bridge sampling and Chib's method. The shortest distance from zero indicates the most appropriate the number of regimes. The most suitable number of regimes appears in **bold**. The sample period is from 1998 to 2013 and contains a total of 2416 observations. The major data sources are the Public Plans Database, obtained from the Center for Retirement Research at Boston College and the Bloomberg database.

Filtered probability of regimes	1	2	3	**4**	5
Overall sample					
Bridge sampling	−853.82	−844.76	−833.09	**−822.23**	−829.70
Chib	−849.21	−841.04	−831.71	**−820.85**	−830.63
Period 1					
Bridge sampling	−938.03	−930.60	−920.33	**−909.75**	−921.44
Chib	−936.42	−931.93	−921.15	**−910.06**	−919.10
Period 2					
Bridge sampling	−855.73	−849.01	−840.19	**−829.37**	−840.62
Chib	−842.88	−834.26	−824.25	**−813.65**	−824.77
Period 3					
Bridge sampling	−972.11	−963.08	−953.02	**−941.24**	−951.94
Chib	−956.07	−947.63	−937.19	**−926.16**	−935.29
Period 4					
Bridge sampling	−968.79	−960.48	−950.42	**−939.92**	−948.67
Chib	−951.40	−943.85	−934.16	**−923.10**	−931.80

Appendix B
State pension funds used in the sample.

Plan name	Plan name	Plan name
Alabama ERS	Alabama Teachers	Alaska PERS
Alaska Teachers	Arizona Public Safety Personnel	Arizona SRS
Arkansas PERS	Arkansas Teachers	California PERF
California Teachers	City of Austin ERS	Chicago Firefighters
Colorado School	Colorado State	Colorado Municipal
Connecticut Teachers	Connecticut SERS	Contra Tennessee County
DC Teachers	DC Police & Fire	Delaware State Employees
Denver Employees	Denver Schools	Florida RS
Georgia County Schools	Georgia ERS	Georgia Teachers
Georgia Municipal	Hawaii ERS	Idaho PERS
Illinois Municipal	Illinois SERS	Illinois Teachers
Indiana PERF	Indiana Teachers	Iowa PERS
Kansas PERS	Kentucky County	Kentucky ERS
Kentucky Teachers	LA County ERS	Louisiana SERS
Louisiana Teachers	Maine Local	Maryland PERS
Massachusetts State and Teachers	Massachusetts SERS	Massachusetts Teachers
Massachusetts ERF	Michigan Public Schools	Michigan SERS
Michigan Municipal	Minnesota PERF	Minnesota State Employees
Minnesota Teachers	Mississippi PERS	Missouri DOT and Highway Patrol
Missouri Local	Missouri PEERS	Missouri State Employees
Missouri Teachers	Montana PERS	Montana Teachers
Nebraska Schools	Nevada Police Officer and Firefighter	Nevada Regular Employees
New Hampshire Retirement System	New Jersey PERS	New Jersey Police & Fire
New Jersey Teachers	New Jersey PERF	New Mexico Teachers
New Mexico PERF	New York City ERS	New York State Teachers
North Carolina Local Government	North Dakota PERS	North Dakota Teachers
North Carolina State & Local ERS	North Carolina State & Local Police & Fire	Ohio PERS
Ohio Police & Fire	Ohio School Employees	Ohio Teachers
Oklahoma PERS	Oklahoma Teachers	Oregon PERS
Pennsylvania School Employees	Pennsylvania State ERS	Phoenix ERS
Rhode Island ERS	REPS Louisiana	San Diego County
San Francisco City & County	South Carolina Police	South Carolina RS
South Dakota PERS	St. Louis Indiana School Employees	St. Paul Indiana Teachers
Texas County & District	Texas ERS	Texas LECOS
Texas Municipal	TN Political Subdivisions	TN State and Teachers
University of North Carolina	Utah Noncontributory	Vermont State Employees
Vermont Teachers	Virginia Retirement System	Washington LEOFF Plan 2
Washington PERS 2/3	Washington School Employees Plan 2/3	Washington Teachers Plan 2/3
West Virginia PERS	West Utah Teachers	Wisconsin Retirement System
Wyoming Public Employees	Massachusetts State Corrections Officers Retirement Plan {CORP}	Connecticut Municipal Employees Retirement System {MERS}
Iowa Municipal Fire and Police Retirement System {MFPRSI}	Louisiana Municipal Police Employees Retirement System {MPERS}	Louisiana School Employees Retirement System {LSERS}
Louisiana State Parochial Employees Retirement System {PERS}	Minnesota Public Employees Retirement Association {MPERA}[Police and Fire Retirement Fund]	Oklahoma Police Pension and Retirement System {Police System}
Utah Public Safety	Montana County Employee's Retirement Association {ACERA}	Wyoming County Employees Retirement Association {KCERA}
North Carolina City Employees Retirement System {LACERS}	North Carolina Fire and Police Pension System {Pensions}	Montana Water and Power Employees Retirement Plan {DWP}
Massachusetts County Employees Retirement System {ERS}	Massachusetts County Employees Retirement System {The System}	Georgia City Employees Retirement System {SDCERS}
Georgia Municipal Employees Annuity Benefit Fund {"The Plan"}	Louisiana Police Annuity Benefit Fund {"The Fund"}	Wyoming County Employees Annuity Benefit Fund {CEABF}
Boston Retirement Board	Massachusetts Fire Dept Article 1B Pension Fund	Georgia Police Pension Fund Article 2
Georgia Municipal Pension Plan	Louisiana Police and Fire Pension System	Pennsylvania Municipal Retirement System
Massachusetts City Employees Retirement System {The System}	Chicago Teachers	South Carolina Municipal Retirement System
Missouri Fire Employees Retirement System		

multiple pension plans within one pension system for employees with different job qualifications and tenure of service. In particular, our dataset contains: i) Public Employees' Retirement System (PERS) plans –also called Employees' Retirement System (ERS) plans– offered to all state police officers, as well as all other qualifying state government employees; ii) the Teachers' Retirement System (TRS) plan, which is offered for employees of state-sponsored educational institutions; iii) the State Retirement System (SRS), which is offered to public servants, including teachers, municipal workers, and other government employees; iv) plans for public safety personnel (PSP); and v) plans for police officers and firefighters. The number of pension systems in each state ranges from one to six – California and Texas each have six pension systems.

The major data source for the study is the Public Plans Database (PPD) obtained from the Center for Retirement Research at Boston College.[15] The PPD data are collected from plans, annual reports, and actuarial valuations. The sample period includes fiscal years from 1998 to 2013, and covers 151 pension systems from 50 states. (Appendix B)

[15] More information is available from the Centre for Retirement Research at Boston College at: http://crr.bc.edu/data/public-plans-database/

Appendix C

Most underfunded pension funds in the post-credit crisis period

Rank	State	Funding ratio 2013 (%)	Funding ratio 2012 (%)	Funding ratio 2011 (%)	Funding ratio 2010 (%)	Funding ratio 2009 (%)	Funding ratio 2008 (%)	Median funding ratio (2008–2013, %)
1	Illinois	39.3	40.4	43.4	45.4	50.6	54.3	44.4
2	Kentucky	44.2	46.8	50.5	54.3	58.2	63.8	52.4
3	Connecticut	49.1	49.1	55.1	53.4	61.6	61.6	54.3
4	Alaska	54.7	59.2	59.5	60.9	75.7	74.1	60.2
5	Kansas	56.4	59.2	62.2	63.7	58.8	70.8	60.7
6	New Hampshire	56.7	56.2	57.5	58.7	58.5	68.0	58.0
7	Mississippi	57.6	57.9	62.1	64.0	67.3	72.8	63.1
8	Louisiana	58.1	55.9	56.2	55.9	60.0	69.6	57.2
9	Hawaii	60.0	59.2	59.4	61.4	64.6	68.8	60.7
10	Massachusetts	60.8	65.3	71.4	68.7	63.8	80.5	67.0
11	North Dakota	61.0	63.5	68.8	72.1	83.4	87.0	70.5
12	Rhode Island	61.1	62.1	62.3	61.8	64.3	59.7	62.0
13	Michigan	61.3	65.0	71.5	78.8	83.6	88.3	75.2
14	Colorado	61.5	63.2	61.2	66.1	70.0	69.8	64.7
15	West Virginia	63.2	64.2	58.0	56.0	63.7	67.6	63.5
16	Pennsylvania	64.0	65.6	71.7	77.8	85.5	86.9	74.7
17	New Jersey	64.5	67.5	68.1	66.0	71.3	76.0	67.8
18	Indiana	64.8	61.0	64.7	66.5	72.3	69.8	65.7
19	Maryland	65.3	64.2	64.5	63.9	64.9	77.7	64.7
20	South Carolina	65.4	67.9	66.5	68.7	70.1	71.1	68.3
21	Virginia	65.4	69.5	72.0	79.7	83.5	81.8	75.9
22	Alabama	66.2	66.9	70.1	73.9	75.1	79.4	72.0
23	Oklahoma	66.5	64.9	66.7	55.9	57.4	60.7	62.8
24	New Mexico	66.7	63.1	67.0	72.4	76.2	82.8	69.7
25	Vermont	69.2	70.2	72.5	74.6	72.8	87.8	72.7
26	Nevada	69.3	71.0	70.1	70.5	72.4	76.2	70.8
27	Ohio	71.9	65.1	67.8	67.2	66.8	86.0	67.5
28	Montana	73.3	63.9	66.3	70.0	74.3	83.4	71.7
29	Arizona	74.1	74.5	73.2	77.0	79.9	80.8	75.7
30	Arkansas	74.5	71.4	72.5	74.8	77.5	87.2	74.6
31	Minnesota	74.7	75.0	78.4	79.8	77.1	81.4	77.7
32	Utah	76.5	78.3	82.8	85.7	84.1	100.8	83.4
33	Missouri	76.6	78.0	81.9	77.0	79.4	82.9	78.7
34	California	76.9	77.4	78.4	80.7	86.6	87.6	79.5
35	Wyoming	78.7	79.6	83.0	85.9	88.8	79.3	81.3
36	Nebraska	79.2	78.2	81.9	83.8	87.9	92.0	82.8
37	Maine	79.6	79.1	80.2	70.4	72.6	79.7	79.3

Appendix D. The likelihood function

Following Sims (1980), Eq. (2) in 3.1 becomes:

$$Y = XA + E \tag{C1}$$

and

$$y = (I_m \otimes X)a + e,\ \ e \sim 0,\ \Sigma_e \otimes I_T \tag{C2}$$

where Y and E are (4×4) matrices and X is a (4×1) matrix, $X_t = [y'_{t-1}, \dots, y'_{t-q}, \hat{y}'_t)$; y and e are (4×1) vectors, I_m is the identify matrix, and $a = vec(A)$ is a (4×1) vector.

Thus, the likelihood function of Eq. (C2) is

$$\int (a,\ \Sigma_e) \infty |\Sigma_e \otimes I_T|^{-0.5} \exp \times \left\{ -0.5 \Big((y - (I_m \otimes X)a)' \big(\Sigma_e^{-1} \otimes I_T \big) (y - I_m \otimes X)a \Big) \right\} \tag{C3}$$

where

$$\begin{aligned}
&(y - (I_m \otimes X)a)'(\Sigma_e^{-1} \otimes I_T)(y - (I_m \otimes X)a) \\
&= (\Sigma_e^{-0.5} \otimes I_T)(y - (I_m \otimes X)a)'(\Sigma_e^{-0.5} \otimes I_T)(y - (I_m \otimes X)a) \\
&= [(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a]'(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a
\end{aligned}$$

and also

$$\begin{aligned}
&(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a) \\
&= (\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a_{ols} + (\Sigma_e^{-0.5} \otimes X)(a_{ols} - a)
\end{aligned}$$

where $a_{ols} = (\Sigma_e^{-1} \otimes X'X)^{-1}(\Sigma_e^{-1} \otimes X)'y$

Therefore, we have

$$\begin{aligned}
&(y - (I_m \otimes X)a)' \big(\Sigma_e^{-1} \otimes I_T \big) (y - (I_m \otimes X)a) \\
&= \Big(\big(\Sigma_e^{-0.5} \otimes I_T \big) y - (\Sigma_e^{-0.5} \otimes X) a_{ols} \Big)' \\
&\quad \times \Big(\big(\Sigma_e^{-0.5} \otimes I_T \big) y - \big(\Sigma_e^{-0.5} \otimes X \big) a_{ols} \Big)
\end{aligned} \tag{C4}$$

$$+ (a_{ols} - a)' \big(\Sigma_e^{-1} \otimes X'X \big)\ (a_{ols} - a) \tag{C5}$$

We derive the likelihood function of a VAR (q = 1) as the product of a Normal density for a, conditional on the OLS estimate (i.e. a_{ols}) and on Σ_e, and a Wishart density for Σ_e^{-1}, conditional on a a_{ols} from the decomposition of Eqs. (C4) and (C5) as follows:

$$\begin{aligned}
&\int (a,\ \Sigma_e) \infty |\Sigma_e \otimes I_T|^{-0.5} \exp\{-0.5(a_{ols} - a)'(\Sigma_e^{-1} \otimes X'X) \\
&\quad \times (a_{ols} - a)(-0.5(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a_{ols})' \\
&\quad \times [(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a_{ols}]\} \\
&= |\Sigma_e|^{-0.5k} \exp\{-0.5(a_{ols} - a)'(\Sigma_e^{-1} \otimes X'X)(a_{ols} - a)\} \\
&\quad \times |\Sigma_e|^{-0.5(T-k)} \exp\{-0.5tr[(\Sigma_e^{-0.5} \otimes I_T)y - ((\Sigma_e^{-0.5} \otimes X)a_{ols})' \\
&\quad \times [(\Sigma_e^{-0.5} \otimes I_T)y - (\Sigma_e^{-0.5} \otimes X)a_{ols}]\} \infty \mathbb{N}(a | a_{ols},\ \Sigma_e, X, y) \\
&\quad \times \mathbb{W}(\Sigma_e^{-1} | y, X, a_{ols}, T - k - m - 1)
\end{aligned} \tag{C6}$$

where tr is the trace of the scale matrix $[(y - (I_m \otimes X)a_{ols})'(y - (I_m \otimes X)a_{ols})]^{-1}$. The conditional posterior for a will be normal and the conditional posterior of Σ_e^{-1} will be Wishart.

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