University of Zurich

Department of Economics

Working Paper Series

ISSN 1664-7041 (print)
ISSN 1664-705X (online)

Working Paper No. 170

The Swiss franc's honeymoon

Rahel Studer-Suter and Alexandra Janssen

August 2014

The Swiss franc's honeymoon*

Rahel Studer-Suter   Alexandra Janssen†

August 13, 2014

Abstract

To counter the sharp appreciation of the Swiss franc that set in in the wake of the European sovereign debt crisis, on September 6, 2011, the Swiss National Bank announced to enforce a minimum EUR/CHF exchange rate of CHF 1.20. We find that the simple, though elegant model for the exchange rate within a target zone proposed by Krugman (1991) describes the behavior of the Swiss franc since the inception of this lower bound. Being a prime example of a safe haven currency, the Swiss franc systematically appreciates when global market conditions tighten. But as Krugman's model predicts, the sensitivity of the Swiss franc exchange rate to state variables that indicate such risky times declines as it approaches its lower bound. In particular, the Swiss franc is well described as an S-shaped function of the option prices implied probability for EUR/CHF exchange rate realizations below the lower bound. This state variable not only indicates times of increased global risk, but also quantifies appreciation pressure on the Swiss currency at the lower bound. We conclude that the Swiss franc lower bound helps stabilizing the value of the Swiss currency.

JEL Classification Numbers: E52, E58, F31, G01

Keywords: exchange rate target zone, safe haven currency, volatility smile

*We thank Mathias Hoffmann for very helpful discussions and comments. We are also grateful to seminar participants at the University of Zürich, and to suggestions we received from participants at the SNB-UZH workshop on Asset Prices and Exchange Rates that took place on May 20-21, 2014, in Zürich.

†Both authors are at the University of Zürich, Department of Economics, International Trade and Finance Group. Mail address: Zuerichbergstrasse 14, CH-8032 Zürich, SWITZERLAND. E-mail: alexandra.janssen@uzh.ch and rahel.suter@econ.uzh.ch Web: http://www.econ.uzh.ch/itf

1 Introduction

During summer 2011, when the European sovereign debt crisis was escalating dramatically and debt-ceiling negotiations in the Unite States made investors feel uncertain about global economic prospects, the Swiss franc appreciated rapidly against all major currencies. In August 2011, the Swiss franc noted near parity to the euro which corresponds to a nominal appreciation of the Swiss currency of more than thirty percent since September 2008 when the bankruptcy of Lehman Brothers marked the global outbreak of the financial crisis of 2008/2009. After the Swiss National Bank was not successful in halting the unchecked appreciation of the Swiss franc by massively expanding the monetary base in August 2011, on September 6, 2011, it announced to introduce a minimum exchange rate of 1.20 Swiss francs against the euro. On that day, the Swiss National Bank unequivocally declared to enforce this minimum rate with the "utmost determination", and to stand ready to "buy foreign currencies in unlimited quantities".[1] After the Swiss National Bank's policy rate already was at the lower bound as a result of the central bank's response to the global financial crisis of 2008/2009, the enforcement of a minimum exchange rate was left as an option to combat the restrictive monetary conditions that the Swiss economy was confronted with in the wake of the European sovereign debt crisis.

A central bank, which is confronted with an overvalued currency, enforcing a one-sided currency target zone, has hardly ever been seen before.[2] In this paper, we throw light on this quite unique attempt of the Swiss National Bank to put a ceiling on the value of the Swiss franc by explicitly announcing a lower bound. To do so, we retrieve the model for the exchange rate behavior within a target zone developed by Paul Krugman (1991). But different from Krugman, who described the exchange rate as a function of money supply and velocity shocks, we propose state variables for the exchange rate that come from a risk-based view of currency prices. This approach is particularly suitable for the Swiss franc since it is the epitome of a safe haven currency: while paying low returns on average, the Swiss franc systematically appreciates when global markets perform badly. Paul Krugman's model predicts that the exchange

[1] SNB press release, September 6, 2011:
http://www.snb.ch/en/mmr/reference/pre_20110906/source/pre_20110906.en.pdf

[2] In a certain respect comparable to the case of the Swiss franc, to face appreciation pressure on its currency, Hong Kong's currency board moved from pegging the Hong Kong dollar unilaterally to the US dollar (strong-side commitment only) to a two-sided exchange rate target zone in 2005. This allowed to implement a weak-side commitment for the value of the HKD against the USD.

rate within a target zone is an S-shaped function of the fundamentals that determine its value: a credible[3] commitment of the monetary authority to always enforce the target zone mutes the sensitivity of the exchange rate to its fundamentals as it approaches the margins of its band. We find that state variables that indicate times of increased global market risk co-move with the franc/euro exchange rate accordingly.

Describing the Swiss franc as a safe haven currency, we find that global market risk – as measured for example by the VIX index[4] – drives the value of the Swiss currency in particular if market conditions tighten. But besides global market uncertainty, there are other global and country-specific factors that influence the Swiss franc/euro exchange rate. For example, the euro gained in value against the Swiss franc with the launch of the OMT-program in September 2012,[5] or comparably robust growth prospects for the Swiss economy might have contributed to regaining strength of the franc against the euro during 2013. A state variable that unites all global and country-specific fundamentals and market sentiments which determine the Swiss franc/euro exchange rate is given by the option prices implied density function for the future value of the Swiss franc. As it is derived from prices that emerge from trade in highly liquid markets, this state variable should incorporate all information that is relevant for the expected path of the value of the Swiss franc against the euro. In line with the prediction of Krugman's model, we find that the Swiss franc/euro exchange rate is well described as a curved function of the option prices implied probability that the franc will note below 1.20 to the euro in the near future.

A further important aspect of this option state variable is that it allows to quantify appreciation pressure on the Swiss franc at the lower bound. We find that the risk-neutral probability for the Swiss franc noting below 1.20 to the euro one month in the future is as high as 25% at certain days during summer 2012. This could indicate that markets doubted the Swiss National Bank's willingness to continue the Swiss franc lower bound exchange rate regime at any event during these tumultuous months. But as Krugman (1991) explains, the exchange rate remains an S-shaped function of its fundamental even if markets put some doubt on the continuation of the

[3] A target zone is called "credible" if its sustainability is not questioned by markets.

[4] Volatility S&P 500 (VIX) index provided by the Chicago Board Option Exchange.

[5] On September 6, 2012, the European Central Bank announced technical details concerning the Outright Monetary Transaction program. Under certain conditions, the OMT-program allows the ECB to buy government issued bonds on secondary markets. http://www.ecb.europa.eu/press/pr/date/2012/html/pr120906_1.en.html

target-zone regime. Also, Bertola & Svensson (1993) presented a version of the model in which the exchange rate is a S-shaped function of a state variable that measures the the probability with which the market expects a realignment of the exchange rate band of a particular size. These contributions provide the theoretical background for our finding that the sensitivity of the Swiss franc/euro exchange rate to the option prices-based state variable we suggest is well described as a function of the Swiss national bank's monetary policy stance: the correlation of the value of the Swiss franc with the implied probability for EUR/CHF$<$1.20 is weaker the closer to its lower bound the franc notes.

Krugman's (1991) model requires that the monetary authorities intervene in foreign exchange markets only if the exchange rate threatens to surpass the limits of its band. The development of reserve holdings of the Swiss National Bank suggest that this condition is fulfilled in the case of the Swiss franc one-sided target zone regime: most probably, the Swiss National Bank has suspended the correlation between the value of the Swiss franc and market fundamentals by currency market interventions only when the franc noted at its lower bound. However, we find that the sensitivity of the Swiss franc to its fundamentals is already muted above this lower bound where no central bank interventions have taken place. In the light of Krugman's model, we conclude that the sole announcement of the Swiss franc lower bound has helped the Swiss National Bank to stabilize the value of its currency: the Swiss franc is in honeymoon.

The remainder of this paper is organized as follows. Section (2) first presents a version of Krugman's (1991) model for the exchange rate within a target zone and then proceeds to assess the behavior of the Swiss franc/euro exchange rate within the framework of this model. Section (3) starts with a brief overview of pricing conventions in over-the-counter currency option markets and then discusses the behavior of the Swiss franc/euro exchange rate volatility smile during different currency market intervention regimes implemented by the SNB, and around days on which the central banks took action. Section (4) proposes the option prices implied probability for future Swiss franc/euro exchange rate realizations below 1.20 as a state variable for the exchange rate, and Section (5) incorporates this variable into the Krugman (1991) model. Section (6) continues to present an option price interpretation of the value of the Swiss franc directly. Section (7) concludes.

2 A model for the behavior of the exchange rate within a target zone

Since September 2011, the Swiss National Bank (SNB) prevents the franc from appreciating beyond 1.20 Swiss francs to one euro. Since then, the EUR/CHF exchange rate is allowed to float freely only at levels above this lower bound. The economics of such exchange rate target zones has intensively been discussed in the context of the European exchange rate mechanism of the European monetary system, which exhorted its members to keep their exchange rate fluctuating only in a given band around a central parity over the years prior to the introduction of the euro as the single common currency.[6] Thereby, Paul Krugman's (1991) elegant target zone model became the starting point for much research that followed. Under the assumption that markets expect monetary authorities to keep their exchange rates within the announced target zone at any events, and under the assumption that central banks intervene in money markets only when exchange rates threaten to touch an edge of the band, the model predicts that the logarithm of the exchange rate should be an S-shaped function of market fundamentals. Also, economic reasoning requires that the exchange rate is insensitive to the fundamentals at the edges of the band. However, empirical tests failed to confirm these predictions of the Krugman (1991) model: firstly, interest rate differentials often suggest that investors are skeptical about the sustainability of the bands, and secondly, exchange rates hardly cluster near the edges of the band, where the model predicts they should, but are rather found to float more or less tightly around the central parities – most probably so because central banks are reluctant to intervene only if an exchange threatens to surpass its band.[7] But the elegance of Krugman's model for the behavior of the exchange rate within target zones motivates us to assess the EUR/CHF exchange rate in the light of this model anew. Different from most exchange rate target zones that have ever existed, the SNB installed only a one-sided target zone for the Swiss franc. Thereby, the SNB aims at preventing its currency from appreciating without bounds. Historical evidence on the contrary suggests that exchange rate target zones mostly got into disturbing situations because central banks, running out of reserves, became unable to fight depreciation pressure

[6]The European exchange rate mechanism (ERM) was introduced in March 1979 to achieve monetary stability in Europe in preparation for the introduction of a single currency, the euro, in 1999. Within this system, exchange rates were based on central rates against the European currency unit ecu, which was the European unit of account and consisted of a weighted average of the participating currencies. Currency fluctuations within this multilateral exchange rate grid had to be contained within a margin of ± 2.25 percent on either side of bilateral rates, which the exception of the Italian lira that was allowed a margin of ± 6 percent, and in August 1993, fluctuation margins were widened to ± 15 percent (except for the mark-Dutch guilder exchange rate).

[7]See for example Flood *et al.* (1991) or the evidence cited by Garber & Svensson (1995).

on their currencies and eventually devalued below the limiting target rate.[8] Stability of the Swiss franc exchange rate target zone in contrast rests upon the willingness of the SNB to accumulate foreign exchange reserves in unlimited quantities when markets put upward pressure on the Swiss franc, and to stand firm against political pressure to rise or lower the exchange rate bound. While domestic policy conflicts can urge the central bank to abandon or realign the Swiss franc lower bound in the medium run, short-run speculative attacks on the Swiss franc exchange rate regime are impossible. The fact that the Swiss case is unique in this respect motivates us to retrieve Paul Krugman's (1991) target zone model.

2.1 Krugman's (1991) model

2.1.1 Model

Krugman (1991) considers a log-linear model of the exchange rate. Expressing all variables in natural logarithms, the exchange rate s equals

$$s_t = m_t + v_t + \gamma \frac{E_t(ds_t)}{dt} \tag{1}$$

where s is the spot price of foreign exchange and $E_t(\cdot)$ denotes expectation conditional on information available at time t. Further, there are two fundamentals in (1), the domestic money supply m and a shift term v. Monetary policy is passive; in the case of the Swiss franc, the central bank is prepared to increase m to prevent s from falling below the announced minimum level $\underline{s}$, but as long as s lies above $\underline{s}$, money supply remains unchanged. The only exogenous source of exchange rate dynamics is the shift term v. In Krugman's exposition of the model, v represents a velocity shock, but other interpretations of v allow for alternative models for the exchange rate. As we describe the Swiss franc as a safe haven currency, which means that it appreciates systematically when global asset markets are in turmoil, we will consider variables that indicate global market conditions and sentiments as state variables for the Swiss

[8] Following the German unification which required a tightening of monetary policy in Germany, the European exchange rate mechanism came into crisis: in September 1992, the lira was devalued and the UK saw itself unable to halt depreciation pressure on the pound sterling and suspended its participation in the ERM. Until mid-1993, several currencies within the ERM were devalued. Eventually, after the Banque de France attempted to cut interest rates to sub-German levels, ERM fluctuation margins were widened from ±2.25 percent to ±15 percent in August 1993. Other prominent examples for dramatical devaluations of currencies within more or less fixed exchange rate systems include the 1994 economic crisis in Mexico, the 1997 Asian financial crisis, the Russian ruble crisis in 1998, or the Argentine economic crisis 1998-2002.

franc/euro exchange rate. In particular, we set $\nu = -\kappa$, where a high κ indicates increased market risk. This leads to the following equation for the exchange rate

$$s_t = m_t - \kappa_t + \gamma \frac{E_t(ds_t)}{dt}. \tag{2}$$

Higher market risk κ now implies a lower s which corresponds to a more appreciated Swiss franc against the euro in our case. To solve the model, the market risk variable κ is assumed to follow a continuous-time random walk

$$d\kappa_t = \mu dt + \sigma dW_t$$

where μ is a constant predictable change in κ, dW is a standard Wiener process, and σ is a constant. This assumption implies that if markets expect no changes in m, that is, if there are no specific monetary policy rules in place, there will be no predictable changes in s. Using Itô's lemma and equation (2), depreciation during such a free float can be written as

$$\frac{1}{dt}E_t(ds_t) = s'(m_t - \kappa_t)\mu + s''(m_t - \kappa_t)\frac{1}{2}\sigma^2.$$

This leads to the following functional equation for the exchange rate:

$$s(m_t, \kappa_t) = (m_t - \kappa_t) + \gamma s'(m_t - \kappa_t)\mu + \gamma s''(m_t - \kappa_t)\frac{1}{2}\sigma^2. \tag{3}$$

The general solution to (3) is

$$s(m_t, \kappa_t) = (m_t - \kappa_t) + \gamma\mu + A\exp(\lambda_1(m_t - \kappa_t)) + B\exp(\lambda_2(m_t - \kappa_t)) \tag{4}$$

where $\lambda_1 > 0$ and $\lambda_2 < 0$.[9] A and B are constants of integration. If the exchange rate is allowed to float freely, s would simply equal the fundamental $(m - \kappa)$ and thus follow a random walk process, and we may set $A = B = 0$.

However, if the central bank announces to impose a lower limit $\underline{s}$ on the price of foreign exchange, the constants A and B are determined by the requirement that the exchange rate is

[9] λ_1 and λ_2 are the roots of the quadric equation in λ, $\lambda^2\gamma\sigma^2/2 + \lambda\gamma\mu - 1 = 0$, and are given by $\lambda_1 = \frac{-\mu+\sqrt{\mu^2+2\sigma^2/\gamma}}{\sigma^2} > 0$, and $\lambda_2 = \frac{-\mu-\sqrt{\mu^2+2\sigma^2/\gamma}}{\sigma^2} < 0$.

insensitive to its fundamentals at the lower bound. This is required to preclude arbitrage opportunities as the exchange rate can move in one direction only once it notes at $\underline{s}$. Hence, while $s'(m-\kappa) \geq 0$ for $s > \underline{s}$, the boundary condition $s'(\underline{m-\kappa}) = 0$ implies $B > 0$.[10] With A equal zero and B being positive, equation (4) describes the exchange rate as a non-linear function of κ, whereby it is more sensitive to changes in κ the further away from the lower bound $\underline{s}$ it notes. At the lower bound, the expected change of s is positive, and because expected depreciation enters the basic exchange rate equation, this affects the exchange rate itself. The relationship between κ and s must be bent as s approaches its lower bound.

2.1.2 Essential conditions

Three conditions are essential to the Krugman (1991) model: First, variables that affect demand and supply of foreign exchange follow a random walk. Second, interventions to influence the exchange rate occur only at the bands. Third, market participants expect that the monetary authority will impose the exchange rate bands with very high probability. We will consider the first condition later. As concerns the second condition, Figure (1) shows the foreign exchange reserves of the Swiss National Bank together with the Swiss franc to euro exchange rate. In accordance with the model assumption, this figure suggests that currency market interventions predominantly have taken place when the Swiss franc noted very close to its lower bound. This contrasts with the experience from other exchange rate target zones where intra marginal interventions have taken place frequently thus rejecting the basic version of the Krugman (1991) model.[11] While this condition - only marginal intervention - is fulfilled for the Swiss franc exchange rate target zone, the third condition, which is the assumption that markets expect that monetary authorities will prevent the exchange rate from moving outside the target zone at any event, is more critical.

Svensson (1990) proposed a "simple test of target zone credibility". He noted that if markets believe that monetary authorities will always prevent the exchange rate from moving out of

[10] A and B are determined by the requirement that the exchange rate function be tangent to its upper and lower bound: In the case of a one-sided target zone, there is no upper bound on the fundamental $(m-\kappa)$, i.e., $(\overline{m-\kappa}) \to \infty$. This implies $A \to 0$. B then is determined by $s'(\underline{m-\kappa}) = 0$, i.e. $0 = 1 + \lambda_2 B \exp(\lambda_2(\underline{m-\kappa}))$. With $\lambda_2 < 0$, this implies $B > 0$. Further, to preclude arbitrage opportunities, the exchange rate must spend no time on its lower bound. But as concerns the assumption that central bank interventions are infinitesimal at the bounds, Flood and Garber (1991) extend the model to allow for intra marginal discrete intervention policies; the behavior of the exchange rate within such a modified model remains almost unchanged.

[11] See the evidence cited in Garber & Svensson (1995), p.1878

the target zone, that is, if markets perceive the exchange rate regime as completely credible, forward exchange rates must never lie outside the band. For the Swiss franc to euro exchange rate, this condition holds true for one month forward exchange rates, which suggests to conclude that at the one-month horizon, investors never expected the Swiss franc to appreciate beyond CHF 1.20 – forward exchange rates suggest that at the one month horizon, the Swiss franc exchange rate regime has always been credible. However, forward rates at longer maturities noted well below this lower bound on several occasions. Between Mai and August 2012, three month forward rates lie below CHF 1.20 on 55 out of 67 trading days. Figure (5) shows that forward rates at longer horizons noted even more distinctly below the lower bound of the Swiss franc that the Swiss National Bank announced to enforce with the "utmost determination". During 2012, annual forward rates suggest that markets expected the Swiss franc to appreciate against the euro beyond CHF 1.20 within one year on two thirds of all trading days. However, since Svensson's (1990) simple test of target zone credibility fails to reject credibility of the Swiss franc exchange rate regime at short horizons, we proceed to asses the implications of Krugman's (1990) target zone model for the behavior of the Swiss franc to euro exchange rate.

2.1.3 Honeymoon effect

The simplest version of Krugman's (1991) model outlined so far predicts that within a target zone, the exchange rate is a smoother function of foreign exchange market fundamentals than it would be under a free float. Even though market interventions by the central bank cease once the exchange rate moves above its lower bound, market participants' expectation that the central bank will prevent the Swiss franc from appreciating beyond CHF 1.20 has a stabilizing effect everywhere on the exchange rate: equation (4) with $A = 0$ and $B > 0$ suggests that the relationship between the fundamental and the exchange rate is flatter than it would be under a free float. Thereby, for values of the spot rate "not too far" above 1.20, the exchange rate should be less sensitive to market fundamentals the closer to its lower bound it just notes. We will consider this implication next.

2.2 Market fundamentals: the Swiss franc as a safe haven currency

The Swiss franc is commonly perceived as a safe haven currency: when worldwide markets are in turmoil, the Swiss franc tends to appreciate and thus provides investors with a hedge against losses on other assets that decrease in value during such times. Hence, variables that indicate such risky times should have strong explanatory power for the Swiss franc. Challenging the conclusion put forward by Meese & Rogoff (1983) whereby exchange rates basically are unpredictable, a growing literature argues in favor of such a risk-based explanation of currency returns.[12] For the Swiss franc, Hoffmann & Suter (2010) and Verdelhan (2011) find that a slope factor constructed from the cross-section of currency portfolio returns predicts changes in the Swiss franc exchange rate conditional on bilateral interest rate differentials, and Griesse & Nitschka (2013) show that the Swiss franc tends to appreciate against the euro when global risk as measured by changes in the CBOE option implied volatility index VIX spikes, whereby this relationship is likely to be more pronounced during times of high market uncertainty. Using data at daily and higher frequency, Ranaldo & Soderlind (2010) find that the Swiss franc appreciates systematically against the euro when equity markets fall, when bond prices increase/ bond returns fall, and when foreign exchange volatility spikes, which all signals difficult market conditions. Kugler & Weder di Mauro (2005) eventually find that the Swiss franc pays high returns if unexpected events that increase world-wide political uncertainty happen.

This evidence that the Swiss franc tends to appreciate when global market conditions tighten motivates us to use variables that measure such risk as the fundamental variables κ in the exchange rate equation (2). In particular, we follow Ranaldo & Soderlind (2010) who showed that stock market and bond market returns predict daily movements in the Swiss franc/euro exchange rate. We use the EURO STOXX 50 index (ESTX50), which is the most important Blue-chip index for the Eurozone, to measure conditions on the stock market, and Barclay's euro aggregate government bond index (BOND) for the fixed income market. In addition,

[12] Lustig & Verdelhan (2007), Burnside (2011) and Lustig & Verdelhan (2011) discuss the association of currency returns with consumption growth. Menkhoff *et al.* (2013) show that currency returns are predictable conditioning on several standard macro fundamentals such as interest rate differentials, real GDP growth, real money growth, and real exchange rates, Hoffmann & Suter (2013) show that the cross-section of consumption growth rates predicts currency portfolio returns, and Jorda & Taylor (2009) find that a fundamental equilibrium exchange rate explains carry trade returns. Burnside *et al.* (2011b), Burnside *et al.* (2009) Burnside *et al.* (2011a), and Burnside *et al.* (2011c) focus on explanations of the carry trade such as investor overconfidence and peso problems. Lustig *et al.* (2011) show that currency portfolios that covary more heavily with global carry trade returns earn higher excess returns on average, thus compensating investors for large losses during times of global market turmoil. Menkhoff *et al.* (2012) find that innovations in exchange rate volatility have explanatory power for currency portfolio returns.

we consider three variables that capture market uncertainty more directly: the SPX VIX index which is an index of the implied volatility of 30-day options on the S&P 500 calculated from a wide range of calls and puts, JP Morgan's FX VXY option implied volatility index for the G7 currencies (VXY), and the Credit Suisse First Boston Risk-Appetite Index (CSFB), which is a very broad measure of market sentiments capturing both, equities and fixed income markets in developed and emerging markets. The summary statistics presented in table (1) suggest that except for the VIX index, all these variables have a unit root which satisfies the model assumption that the exchange rate fundamentals follow a random walk.

2.3 Non-linear relationship between market fundamentals and the Swiss franc/euro exchange rate

2.3.1 Swiss franc lower bound regime

To test whether the sensitivity of the Swiss franc/euro exchange rate with respect to the market fundamentals declines as the Swiss franc approaches its lower bound, we regress percentage changes in the EUR/CHF spot rate S on percentage changes in the market fundamentals K described above, interacted with the percentage deviation of the spot rate from its lower bound. In particular, we run the following regression

$$\Delta s_t = \alpha + \beta_1 s_{\Delta 1.20,t} \times (\kappa_t \mid \kappa_t \geq 0) + \beta_2 s_{\Delta 1.20,t} \times (\kappa_t \mid \kappa_t < 0) + \beta_3 \kappa + \beta_4 s_{\Delta 1.20,t} + \epsilon_t \quad (5)$$

where $\Delta s_t = \ln(S_t/S_{t-1})$ and $\kappa_t = \ln(K_t/K_{t-1})$. The distance of the spot exchange rate from its lower bound at time t is measured as $s_{\Delta 1.20,t} = \ln(S_t/\underline{S}) = \ln(S_t/1.20)$. The regression equation (5) estimates separate slope coefficients $\beta = \{\beta_1, \beta_2\}$ for upward movements and downward movements of the fundamental. This specification is motivated by Lettau *et al.* (2013) who show that currency returns covary more strongly with aggregate market returns conditional on bad market returns than they do conditional on good market returns. In line with this conclusion, we find that the Swiss franc appreciates more significantly when global markets become turbulent than it depreciates when markets run well. This suggests that the Swiss franc not only acts as a safe haven currency on average, but particularly so in difficult market conditions: investors long in Swiss francs and short in euro will earn positive returns in particular when market risk spikes.

Tables (2) and (3) present the results from estimating equation (5) for the time since the introduction of the Swiss franc lower bound by the Swiss National Bank in September 2011. Estimates for β_1 and β_2 that are significantly different from zero suggest that, in accordance with the prediction of Krugman's (1990) model for the exchange rate, the Swiss franc/euro exchange rate is more sensitive to changes in fundamentals the further away from its lower bound it notes. This is what we find if we use the European blue-chip stock market index ESTX50 or the VIX index as foreign exchange market fundamentals κ: the more depreciated the Swiss franc against the euro is, the more it appreciates when stock markets plummet or when stock market volatility increases.[13] Although not statistically different from zero, we find that the Swiss franc has a strong tendency to appreciate as government bond prices decline, which, in the context of the European sovereign debt crisis, supports the interpretation of the Swiss franc as a safe haven currency. The currency market volatility index VXY and the risk appetite index CSFB have no explanatory power for the Swiss franc/euro exchange rate over the period from September 2011 to January 2014. To summarize, we find that the equity market variables have a stronger effect on the Swiss franc/euro exchange rate, the farther away from its lower bound of EUR/CHF=1.20 the Swiss franc notes. The scatter plot shown in figure (3) supports this finding: in particular since January 2012, the value of the Swiss franc against the euro appears to be a S-shaped function of the ESTX50 index as sketched in figure (2). Thereby, values for the spot exchange rate cluster near the lower bound value of the Swiss franc which is what the Krugman (1991) model predicts: since exchange rates are expected to move slowly near the edge of the target zone, they will appear there often (see for example Garber & Svensson (1995), p.1877).

Further evidence that the sensitivity of the Swiss franc/euro exchange rate increases in the distance of the spot rate from its lower bound is provided by figure (4). Applying the methodology proposed by Elliott & Mueller (2006) and Mueller & Petalas (2010), this figure plots a

[13] The positive exposure of currency returns to equity market risks is also documented by Jurek (2014) who finds that different carry trade strategies load positively on equity market factors, and in particular so on the return of a S&P 500 index put-writing strategy which is explicitly short equity volatility risk. Caballero & Doyle (2012) report that carry trade returns are highly correlated with the returns of a strategy which shorts VIX futures. Further, Lustig *et al.* (2011) report that high (low) interest rate currencies tend to offer low (high) returns when equity volatility increases.

time-varying estimate for the β_t coefficient obtained from regressing percentage changes of the spot rate on percentage changes in the ESTX50 index

$$\Delta s_t = \alpha + \beta_t \kappa_t + \epsilon_t. \quad (6)$$

Not only does the quasi-local-level test (qLL test) prosed by Elliott & Mueller (2006) indicate strong parameter instability for β_t, but the estimate for β_t also increases substantially with the weakening of the Swiss franc against the euro: the further away the Swiss franc notes from its lower bound, the stronger the Swiss franc covaries with equity market returns. To conclude, these results suggest that indeed, announcing an explicit exchange rate target has helped the Swiss National Bank to mute the effect of negative shocks to market fundamentals on the Swiss currency when the Swiss franc already is relatively strong. The behavior of the Swiss franc/euro exchange rate since the introduction of the lower bound of the Swiss franc is relatively well explained by Krugman's (1990) simple model for the exchange rate.

2.3.2 Other Swiss franc policy regimes

Since the outbreak of the global financial crisis in 2008, the Swiss National Bank's reaction to the massive appreciation of the franc against all major currencies can be described by three periods of different foreign exchange market intervention regimes: between April 2009 and May 2010, the SNB heavily intervened in the foreign exchange market to prevent the Swiss franc from appreciating a lot, in May 2010, the SNB stopped these interventions, but in September 2011 it decided to intervene in the foreign exchange market anew and announced to defend the Swiss franc euro exchange rate at CHF 1.20 per 1 EUR. Hence, the behavior of the Swiss franc during this last one-sided target zone period can be contrasted with its behavior over the period between May 2010 and September 2011 when the Swiss franc was freely floating, and with its behavior between April 2009 and May 2010 when the SNB was intervening in the foreign exchange market without announcing a lower bound on the Swiss franc price of foreign currencies. To do so, we run a version of regression (5) again for the three different SNB foreign exchange policy periods whereby we interact the market fundamental variables with the log level of the Swiss franc/euro spot exchange rate

$$\Delta s_t = \alpha + \beta_1 \kappa_t \times \ln(S) + \beta_2 \kappa + \beta_3 \ln(S) + \epsilon_t$$

Tables (4) and (5) present the results. It is only during the period of the exchange rate target zone regime that a non linear relationship between the stock market variables and the value of the Swiss franc is significant: in contrast to the time prior to the announcement of the Swiss franc lower bound, a declining EURO STOXX 50 index or an increasing VIX index now predict an appreciation of the Swiss franc that is increasing in the log level of the spot rate. For the other time periods, such a conditional relationship is not found. Strikingly, it is only during the target zone period that the uninteracted log level of the exchange rate predicts changes in the spot rate: during that period, a higher level of the spot rate predicts a subsequent appreciation of the Swiss franc, which signals reversion of the Swiss franc towards its lower bound.

During June 2010 to August 2011, when the Swiss franc was freely floating, a declining stock market index, an increasing bond price index, and a declining risk appetite index all go along with an appreciation of the Swiss franc against the euro, but unconditional on the level of the exchange rate. This again supports the view that the value of the Swiss franc increases when financial markets stumble, but there is no evidence for a non-linear relationship between these market fundamentals and the value of the Swiss currency for the time in which the Swiss National Bank refrained from intervening in foreign exchange markets. The relationship of currency market volatility and the Swiss franc/euro exchange rate is ambiguous. Finally, over the period from April 2009 to May 2010, which is when the Swiss National Bank attempted to halt the appreciation of the Swiss franc by massively intervening in currency markets, all market fundamentals have no explanatory power for the EUR/CHF exchange rate; except the bond price index for which the effect is ambiguous. To conclude, the strong non-linear relationship between the stock market and the value of the Swiss franc against the euro is unique to the period since the introduction of the Swiss franc lower bound in September 2011, and variables that explain the behavior of the Swiss franc if it is floating freely lose explanatory power once monetary authorities intervene in the markets.

2.4 Safe haven demand at the Swiss franc lower bound

Within the framework of Paul Krugman's (1991) model for the exchange rate, we have described the Swiss franc as a safe haven currency and argued that the sole announcement of the Swiss National Bank to always defend the Swiss franc lower bound has created a "target zone honeymoon"(Krugman 1987): without the need for actual market intervention, the traders' expectation that the value of the Swiss franc will never surpass its ceiling value mutes the sensitivity of the Swiss franc to global market risk. Hence, we argue that the price of the Swiss franc is driven by global risk, whereby the sensitivity of the franc to this risk is determined by the market on the one hand – the Swiss franc tends to appreciate in tumultuous times – and by the Swiss National Bank's commitment to defend a minimum price of 1.20 Swiss francs per one euro on the other hand. Thereby, this latter mechanism gains the upper hand if the Swiss franc approaches the lower bound. We have provided evidence that such a target zone honeymoon is in effect for the Swiss franc since the Swiss National Bank announced to defend a lower bound of the franc price of one euro in September 2011.

Between January and August 2012 however, the Swiss franc virtually noted at its lower bound. During that time, increasing reserve holdings of the Swiss National Bank indicate that foreign exchange market interventions were needed to defend the Swiss franc target zone. Also, EUR/CHF forward exchange rates at three months and longer maturities frequently noted below 1.20. This raises the question of how firm markets perceived the SNB's commitment to defend the Swiss franc lower bound to be, which further entails the question of how importantly the SNB's policy stance has determined the value of the Swiss franc relative to global market forces. A state variable that combines both of these driving forces would be given by a measure for appreciation pressure on the Swiss franc against the euro: by the Swiss franc being a safe haven, increasing appreciation pressure mirrors increasing global risk, but by the presence of the Swiss franc lower bound regime, appreciation expectations should decline as the franc approaches its lower bound. Thus, the extent to which safe haven demand at the lower bound nevertheless triggers appreciation pressure quantifies the market's perceived uncertainty about the continuation of the Swiss franc lower bound regime.[14]

[14]Note that even if markets put positive probability on the possibility that the monetary authority could give up defending the exchange rate target zone once the exchange rate threatens to surpass its bound, Krugman's (1991) model still implies that the exchange rate is a S-shaped function of its fundamentals (see Krugman, 1991, section V).

A powerful indicator for appreciation pressure on the Swiss franc against the euro is given by the density function for the future value of the Swiss franc that currency option prices imply. This state variable should incorporate all information that is relevant for the expected path and uncertainty of the future value of the Swiss franc, since it is derived from prices that are set in highly liquid markets. Svensson (1990) proposed a simpler approach to assess how stable markets expect an exchange rate target zone to be and focused on interest rate differentials and forward exchange rates directly: if a monetary authority's commitment to defend a fluctuation band for the exchange rate is completely credible, forward rates must never lie outside the band such that no arbitrage opportunities arise. However, starting with Fama (1984), a broad literature documents how poorly forward rates predict spot rates, and markets are aware of this stylized fact. The advantage of using option prices, that is, the prices of derivatives on forward exchange rates, is that they allow to derive higher moments of the expected exchange rate distribution in addition. The skewness and kurtosis of the implied exchange rate distribution might be highly informative to gauge market sentiment. For example, if a call option, that gives its holder the right to buy foreign currency for a predetermined price at a specific date in the future, trades at a higher price than the corresponding put option, this signals that markets are eager to insure against the risk of an appreciation of the foreign currency. Such insight motivated for example Campa & Chang (1996), (1998) or Malz (1996) to use currency option prices to assess the credibility of exchange rate target zone regimes. We follow in these tracks and analyze the prices of EUR/CHF options to further assess the determinants of the Swiss franc exchange rate since the announcement of its lower bound in September 2011. The next section starts with a brief description of currency option price quotes in over-the-counter markets. The paper then proceeds to describe the behavior of the option prices implied density function for the Swiss franc to euro exchange rate around specific events. In section (5), we argue that the option prices implied probability that the Swiss franc will note below 1.20 to the euro qualifies as a powerful state variable for the exchange rate within the framework of Krugman's (1991) target zone model. In addition to this, section (6) explains how the target zone model allows for an option price interpretation of the Swiss franc directly. The last section will conclude.

Hence, considering that markets could have been uncertain about the continuation of the Swiss franc lower bound regime at some events is in accordance with the results presented in the first part of this paper.

3 EUR/CHF option prices

3.1 Option prices in over-the-counter currency markets

This section first shows how option prices are quoted in over-the-counter (OTC) currency markets. Then, the section proceeds to introduce three option portfolios that are frequently traded in these markets: at-the-money straddles, risk reversals, and strangles summarize the position and the shape of the density function that option prices imply for the future exchange rate.

3.1.1 Pricing conventions

For our analysis, we download daily currency option price quotes from Blomberg for the Swiss franc/euro exchange rate. Over-the-counter markets in which most currency option dealing takes place use conventions based on the Black-Scholes model to express the terms and prices of currency options.[15] The Black-Scholes formula for the value of a European currency call options is[16]

$$C(F, \tau) = \left(FN(d_1) - KN(d_2)\right) e^{-r\tau} \tag{7}$$

and the value of a put is

$$P(F, \tau) = \left(F\left[N(d_1) - 1\right] - K\left[N(d_2) - 1\right]\right) e^{-r\tau} \tag{8}$$

where τ is the time remaining until maturity expressed in years, F denotes the forward price of the deliverable currency, K is the strike price of the option, r is the domestic risk-free rate of interest, and $N(\cdot)$ denotes the cumulative normal distribution, and

$$d_1 = \frac{\ln(F/K) + \sigma^2\tau/2}{\sigma\sqrt{\tau}}$$
$$d_2 = \frac{\ln(F/K) - \sigma^2\tau/2}{\sigma\sqrt{\tau}}$$

[15] The original exposition of the Black-Scholes model is Black & Scholes (1973). A very similar model was developed independently by Merton (1976). The application of the model to foreign currency options is also called the Garman-Kohlhagen model, after its publication by Garman & Kohlhagen (1983). (see Malz (1996), footnote 11.)

[16] See Garman & Kohlhagen (1983), or, for a textbook version, Hull (2012), chapter 14.

In currency markets, the only unobserved variable in equations (7) and (8) is the volatility of the price of the foreign currency σ. Alternatively, replacing the left-hand side of equations (7) and (8) with an observed option price allows to extract volatility as an implicit function of C_t or P_t, and F_t, τ, and K. In this context, σ is called the option implied volatility. The Black-Scholes values increase monotonically in σ, so the implied volatility is a unique inverse function of $C_t(F,\tau)$ or $P(F,\tau)$.

In over-the-counter currency markets, option quotes are made on implied volatilities rather than option prices denominated in currency units. Also, options are not specified by strike prices K, but by the option delta Δ which measures the degree to which options are in- or out-of-the-money. The delta of a put and a call is given by the derivative of the Black-Scholes option values with respect to the forward rate

$$\begin{aligned} \Delta_C &= \frac{\partial C(F,\tau)}{\partial F} \\ &= e^{-r\tau}N(d_1) \qquad (9) \\ \Delta_P &= \frac{\partial P(F,\tau)}{\partial F} \\ & -e^{-r\tau}N(-d_1) \qquad (10) \end{aligned}$$

Hence, the delta of an option measures the sensitivity of the option price to the forward exchange rate and it takes on values between 0% and 100%. The delta of an at-the-money forward option, that is, the delta of an option of which the exercise price is set equal to the forward exchange rate of the same maturity as the option, is approximately 50 percent. Frequently traded are further options with a delta of 25, whereby a 25-delta call (put) corresponds to an option with a strike above (below) the strike of an at-the-money option.

3.1.2 Volatility smile

The Black-Scholes model would imply that all options on the same currency have the same implied volatility, regardless of time to maturity and moneyness. However, it turns out that σ differs across deltas and maturities for options on a given foreign currency. When regarding implied volatilities for a specific maturity only, one typically finds that the implied volatility is higher for options with a delta further away from 50 percent, that is, for options that are more deeply in-the-money or out-of-the-money. This pattern is referred to as the “volatility smile”, an example is shown in Figure (7).

Three instruments that are actively traded in over-the-counter currency option markets, *delta-neutral straddles*, *risk reversals*, and *strangles* or *butterfly spreads*, summarize the position and shape of the volatility smile. Straddles and strangles both consist of buying or selling an equal number of call and put options on the same currency with the same time to maturity. A delta-neutral *straddle* consists of a portfolio in which both, the put and the call option are at-the-money. The price of this portfolio gives the at-the-money (atm) implied volatility, and it indicates the overall level of the volatility smile. A *strangle* is a portfolio of an out-of-the-money put and an out-of-the-money call with the same delta; most frequently, strangles with a delta of 25 percent are traded. Strangle prices are quoted as the spread of the average implied volatility at which the options are bought or sold over the at-the-money implied volatility:

$$str25 = \frac{\sigma(C25) + \sigma(P25)}{2} - atm$$

The strangle implied volatility indicates the degree of curvature of the volatility smile; hence, a strangle is a bet on a large move of the underlying currency either upwards or downwards. Eventually, the *risk reversal* also consists of an out-of-the-money put and call, but in contrast to the strangle, the dealer exchanges one of the options for the other with the counterpart. Because the put and the call generally have different implied volatilities, the dealer pays or receives a premium for exchanging the options. The premium is expressed as the implied volatility spread at which a 25-delta call is exchanged for a 25-delta put and indicates the skewness of the volatility smile

$$rr25 = \sigma(C25) - \sigma(P25)$$

If a 25-delta call trades at a higher price than a 25-delta put such that the risk reversal is positive, this indicates that the market favors the foreign currency.

For our analysis, we download implied volatility quotes from Blomberg for Swiss franc options on the euro in the form of at-the-money implied volatilities, 10- and 25-delta risk reversals and 10- and 25-delta strangles. Given these quotes, we obtain the implied volatility of 25-delta put and call options as $\sigma(C25) = atm + str25 + \frac{1}{2}rr25$ and $\sigma(P25) = atm + str25 - \frac{1}{2}rr25$, and accordingly for 10-delta put and call options. Considering put-call parity,[17] Blomberg hence provides us with implied volatility quotes for five levels of moneyness, namely for $\Delta = \{10, 25, 50, 75, 90\}$.

3.2 Swiss franc/euro exchange rate volatility smile

The option price quotes that are readily available in over-the-counter markets, the at-the-money implied volatility (atm), the risk-reversal (rr) and the strangle (str), summarize the distribution of option prices across option deltas or, accordingly, strike prices. Since currency option contracts might be used to insure against – or to bet on – particular future spot price realizations, the option price distribution is indicative for the market's expected future distribution of spot exchange rates. The at-the-money implied volatility indicates the overall level of option prices thus informing about traders' eagerness to profit from currency fluctuations. Out-of-the-money strangles provide large gains if the spot price at the expiration date notes far away from the strike price specified in the option contract, hence, high strangle prices signal that traders potentially expect currency prices to move far either upwards or downwards. A negative risk reversal implied volatility realizes if put options, that are out-of-the-money because they have a strike price below the current spot price of the foreign currency, trade at higher prices than call options with the same degree of moneyness. This signals that traders are keen to insure against appreciation of the home currency.

Figure (6) shows time series of the Swiss franc/ euro spot exchange rate, the at-the-money implied volatility, the 25-delta risk reversal, and the 25-delta strangle implied volatility. Vertical lines indicate the dates around which the Swiss National Bank changed its foreign exchange market intervention policy regime. Between April 2009 and May 2010, the SNB heavily intervened in the foreign exchange market to halt the appreciation of the Swiss franc against all major currencies in the wake of the outbreak of the global financial crisis in 2007/2008. In May 2010, the SNB stopped these interventions, but resumed intervening in summer 2011, and eventually announced the Swiss franc lower bound in September 2011. The at-the-money implied volatility was highest during the period between May 2010 and summer 2011, in which the

[17] Put-call parity implies that puts and calls with the same exercise price have identical implied volatilities, so the volatility of an x-delta put equals that of an $(1 - x)$-delta call.

Swiss franc was freely floating against the euro, and decreased sharply with the announcement of the Swiss franc lower bound. This suggests that markets anticipated that the volatility of the Swiss franc/euro exchange rate was to decline with the SNB acting against an appreciation of the Swiss franc beyond CHF 1.20 to the euro. In contrast, the strangle implied volatility increased distinctly with the announcement of the Swiss franc lower bound and remained at high levels until the end of July 2012 when Mario Draghi, president of the European Central Bank, unambiguously stated that the ECB will be "...ready to do whatever it takes to preserve the euro".[18] This suggests that over the first year of the one-sided Swiss franc target zone regime, markets nevertheless put increased probability on large movements of the Swiss franc/euro exchange rate in either direction. The risk reversal however increased from negative to positive values when the SNB announced the Swiss franc lower bound. This indicates that markets no longer expected the Swiss franc to appreciate against the euro, but to depreciate. Appreciation pressure on the Swiss franc set in during summer 2012 anew, when the European sovereign debt crisis was escalating dramatically, but declined again after President Draghi's "whatever-it-takes" statement in July 2012 and the launch of the Outright Monetary Transaction (OMT) program[19] at the beginning of September 2012. Table (6) presents summary statistics for these currency option price quotes for the three different SNB foreign exchange policy periods, and figure (7) shows average volatility smiles for these three regimes. While the volatility smile for the period in which the Swiss franc was freely floating against the euro indicates strong appreciation pressure on the Swiss currency, on average, the volatility smile over the Swiss franc lower bound exchange rate regime period is less asymmetric and signals depreciation expectations of the Swiss franc against the euro.

3.3 Interpolating the risk neutral distribution

Over the first year of the Swiss franc lower bound regime, 25-delta EUR/CHF strangle prices were distinctly higher than before the inception of the Swiss franc lower bound, and in summer 2012, 25-delta risk reversal prices were as low as during the period before the inception of the Swiss franc lower bound when the franc was on an appreciating trend against the euro. These option prices indicate that during the most tumultuous months of the European sovereign debt

[18] Follow for example this link: http://www.youtube.com/watch?v=Pq1V0aPEO3c

[19] `http://www.ecb.europa.eu/press/pr/date/2012/html/pr120906_1.en.html`

crisis, the commitment of the Swiss National Bank to stabilize the Swiss franc at values above 1.20 to the euro was not sufficient to dispel the markets fear of sharp movements in EUR/CHF. To question how strongly market's doubted the stability of the Swiss franc lower bound, we proceed to interpolate the risk-neutral EUR/CHF density function from the option price quotes that are readily available in over-the-counter markets. To a certain extent, this function will allow to quantify appreciation and depreciation expectations of the franc of any given size. For example, it provides a measure of the probability that the Swiss franc will note below its lower bound of CHF 1.20 to the euro one month in the future.

Note that the distribution that option prices imply for future exchange rates is a risk-neutral distribution: if for example traders fear much that the Swiss franc could appreciate, calls with high exercise prices might trade at higher prices than if they represented a fair bet on CHF appreciation. In that case, the risk-neutral probability of a CHF appreciation is higher than the probability that the market effectively assigns to it. Nevertheless, changes in the implied density function can inform about the market's altering view of future currency prices, and in the end, it is the quoted option prices which represent the costs at which investors can hedge their foreign exchange exposure.

To obtain this risk-neutral EUR/CHF density function, we follow the approach proposed by Malz (1997) and interpolate the volatility smile.[20] His approach bases on the insight promoted by Breeden & Litzenberger (1978) according to which the discounted risk-neutral density function of the time T asset price equals the second derivative of the call option price function with respect to the exercise price

$$\frac{\partial^2 C(F,\tau;K,\sigma,r)}{\partial K^2} = e^{-r\tau}\pi(K) \tag{11}$$

To obtain a closely spaced series of call option prices with different exercise prices, which is needed to empirically implement equation (11), Malz proposes to first interpolate the volatility smile to obtain a series of implied volatility quotes across deltas, and then to use the Black-Scholes call option price formulas (7) and (9) to transform the option prices from the volatility-delta space to the cash price - strike price space. With the at-the-money implied volatility (*atm*),

[20]The literature has presented a large number of techniques to estimate the option implied density function for future asset prices. Jackwerth (1999) for example provides an extensive survey.

the risk reversal (*rr*), and the strangle (*str*) volatility price quotes indicating the level, the skewness and the kurtosis of the volatility smile respectively, Malz (1997) proposes to approximate the implied volatility function by

$$\hat{\sigma}(\Delta) \quad = \quad b_0 atm_t + b_1 rr_t(\Delta - 0.50) + b_2 str_t(\Delta - 0.5)^2. \tag{12}$$

Imposing the condition that the at-the-money volatility and the risk reversal and the strangle price lie exactly on $\hat{\sigma}(\Delta)$ allows to solve for $(b_1, b_2, b_3) = (1, -2, 16)$. Since delta itself is a function of the implied volatility, substitute equation (9) into equation (12) and solve for σ as a function of K. Having obtained implied volatilities for given strike prices, the call pricing function (7) eventually allows to substitute out cash call prices for given strike prices. The last step to obtain the risk-neutral probability distribution of strike prices at maturity requires to differentiate the call price function with respect to the strike prices. This is easiest done numerically by calculating simple finite differences. The estimated cumulative distribution function at point K is

$$\hat{\Pi}(K) \quad = \quad e^{-r\tau}\left(\frac{C(K) - C(K-h)}{h} + 1\right)$$

and the estimated probability density function is

$$\hat{\pi}(K) \quad = \quad \frac{\hat{\Pi}(K) - \hat{\Pi}(K-h)}{h}$$

where h is the step size between adjacent strike prices K. This is done for each K to draw the entire cumulative distribution or density function.

3.4 Swiss franc risk-neutral probability distribution and central bank actions

Since the payoffs of currency options are conditional on the future value of the underlying currencies, option prices inform about the expected (risk-neutral) probability distribution of future exchange rates. This section describes the behavior of the EUR/CHF implied density function during the Swiss franc lower bound monetary policy regime with a particular focus on the evolution of skewness and kurtosis around days on which the Swiss- and the European central bank took action.

In general, policy actions undertaken by either the Swiss National Bank (SNB) or the European Central Bank (ECB) should increase the skewness of the option prices implied EUR/CHF density function and lower its kurtosis. A positive skewness indicates that markets expect the Swiss franc to depreciate against the euro: weakening the Swiss franc is a direct objective of the SNB, whereas the ECB works towards a more stable Eurozone and thus a more valuable euro. The lower the kurtosis of the EUR/CHF implied density function, the less probability markets put on a large move of the exchange rate. Central bank interventions should aim at reducing such tail risk.

Figure (8) depicts the behavior of the kurtosis and the skewness of the EUR/CHF risk-neutral density function since the introduction of the Swiss franc lower bound, and vertical lines mark particular events. On September 15, 2011, the SNB published its first monetary policy assessment after it had unambiguously announced to prevent the Swiss franc from appreciating beyond 1.20 francs to the euro. In this statement, the Swiss central bank repeatedly emphasized its will to defend the franc/euro minimum exchange rate.[21] Thereafter, the skewness increased sustainedly and remained positive until the end of the year, suggesting that the SNB's policy statement successfully eased smoldering appreciation pressure on the Swiss currency. At the beginning of 2012, appreciation pressure on the Swiss franc set in again, but the loosening of the criteria for eligible collateral in Eurosystem credit operations[22] that the ECB approved on February 9, 2012, temporally suspended depreciation expectations of the euro against the franc. But over the month that preceded the Greek legislative elections on June 18, 2012, skewness and kurtosis of the implied EUR/CHF density function indicate sharp appreciation pressure on the Swiss franc again, combined with a high probability for large movements of the exchange rate. Eventually, it was only after the ECB announced the technical details concerning the Outright Monetary Transaction (OMT) program[23] on September 6, 2012, that ended depreciation expectations of the euro against the franc and induced markets to expect a smooth path for EUR/CHF. The launch of this program, possibly together with Daghi's "whatever-it-takes"

[21] http://www.snb.ch/en/mmr/reference/pre_20110915_1/source/pre_20110915_1.en.pdf

[22] http://www.ecb.europa.eu/press/pr/date/2012/html/pr120209_2.en.html

[23] The Outright Monetary Transaction (OMT) program allows the ECB to buy government-issued bonds on secondary markets to provide liquidity to countries that face problems selling their debt. For details, follow http://www.ecb.europa.eu/press/pr/date/2012/html/pr120906_1.en.html

statement at the end of July 2012, marks a turning point in the fortunes of the Eurozone: the skewness of the implied EUR/CHF probability distribution permanently increased to slightly positive levels no longer indicating appreciation pressure on the Swiss franc, and the kurtosis suggests that uncertainty about large movements in the exchange rate declined to pre-crisis levels.

Figure (9) presents the results from a more systematic analysis of the interrelation between SNB and ECB policy actions and the moments of the EUR/CHF implied probability distribution function. The figure depicts the average behavior of the mean, skewness and kurtosis of this probability function around days on which statements or policy interventions of either of the two central banks became public. Table (7) provides a detailed description of this event-dummy variable. It emerges that it is only after September 2012, which marks the beginning of a calmer period in the EUR/CHF market, that central bank interventions are systematically followed by higher skewness and lower kurtosis of the risk-neutral EUR/CHF density function. Over the first year of the Swiss franc lower bound regime in contrast, central banks seem to have difficulty to calm markets, since their policy interventions as listed in Table (7) are followed by lower skewness and increasing kurtosis on average. Even though the SNB was able to halt the Swiss franc from appreciating beyond CHF 1.20 to the euro, the two central banks have been unable to clearly control appreciation expectations of the franc against the euro and stop markets from betting on large jumps in EUR/CHF over the most tumultuous year of the Swiss franc lower bound regime. But since about September 2012, they are.

4 Stability of exchange rate target zones

Research about the behavior of the exchange rate within target zones had its golden age when the first European Exchange Rate Mechanism (ERM I) was in operation, which exhorted its members to stabilize their currencies within admitted fluctuation limits around predetermined central parities over the twenty years prior to the introduction of the euro in 1999. At various events during that time, markets had good reason to doubt the credibility of these exchange rate target zones since realignments – adjustments of central parities or of the width of fluctuation limits around these parities – were frequent.

An obvious extension of the Krugman (1991) target zone model was therefore to incorporate such time-varying realignment risk. Bertola & Svensson (1993) presented a model in which the expected size and the probability of a realignment act as a state variable next to the market fundamental κ for the exchange rate, and for example Rose & Svensson (1995), Svensson (1993) or Lindberg *et al.* (1993) provide empirical implementations. Thereby, their assessment of the credibility of the ERM relied on the uncovered interest rate parity condition by which interest rate differentials or forward discounts should be unbiased predictors of future exchange rates. Such predicted exchange rate changes are decomposed into the sum of expected depreciation within the existing exchange rate band and expected adjustment of the limits of the band. Within-band depreciation is estimated using macroeconomic and financial variables like past exchange rates and interest rates. Eventually, the interest rate differential minus the estimated within-band depreciation constitutes the expected realignment. Conditional upon a given expected size of the realignment, this *intensity of realignment* measure allows to deduce the probability of the realignment within a given time horizon. For example, a realignment intensity of 10 percent over some fixed horizon is consistent with a 0.5 probability of a 20-percent devaluation, or a 0.4 probability of a 25-percent devaluation over that horizon.

Following this notion of realignment expectations, Campa & Chang (1996) calculate an intensity of realignment measure from currency option prices. Defining the size of realignment by $S_t - \overline{S}$, which is the difference between the spot rate at time t and the upper bound of the exchange rate band, the realignment intensity is given by $G(t) = \int_{\overline{S}}^{\infty}(S_t - \overline{S})f(S_t)dS_t$ where $f(S_t)$ is the density function of exchange rate realizations at time t. This definition of realignment intensity implies that $(1+i)$ times the risk-neutral value of a call option with strike price $\overline{S}$ constitutes a lower bound of the realignment intensity.[24] Campa and Chang find that such call option prices indicate a high intensity of realignment for the lira and the pound sterling in the month before they each left the European exchange rate mechanism (ERM) in 1992, indicating that markets expected the depreciation of these currencies against the mark that followed. Further qualifying this intensity of realignment measure, Campa & Chang (1998) find that macroeconomic variables such as real exchange rates, trade balances, foreign reserves, money supply,

[24]The risk-neutral value of a call option is given by its expected discounted payoff at maturity of the option: $C(K,\tau) = \frac{1}{1+i_\tau}\int_K^{\infty}(S_\tau - K)f(s_\tau)dS_\tau$, where i_τ denotes the risk-free rate of interest over timeτ, K denotes the strike price, and S_τ the spot price of the foreign currency at maturity of the option contract. $f(s_\tau)$ is the density function of exchange rate realizations at maturity of the option contract.

inflation and output are unable to explain patterns in realignment intensities, which is in line with the results that Rose & Svensson (1994) obtained using deviations from uncovered interest rate parity as a measure of the realignment intensity.

While these approaches allow to estimate an intensity measure of realignment, they are unable to endogenously estimate both, the expected size of a realignment and its probability. Doing so requires a model for the behavior of the exchange rate. Malz (1996) therefore assumes a jump-diffusion model for the stochastic process of the exchange rate which leads to formulas for call and put options that are averages of the Black-Scholes option values given a jump, weighted by the probability of a jump, and the Black-Scholes values absent a jump, weighted by the probability of no jump. Estimating the parameters of this model yields estimates for the jump size and the probability with which it might occur. However, Malz states that even in this framework, it is difficult to distinguish sharply between the contribution of the two components of the realignment intensity, jump size and jump probability.

In the case of the Swiss franc, political and economic groups have required for a rise of the franc's lower bound at several events, and during summer 2012 there seem to have been market rumors that the SNB could lower the minimum Swiss franc price of the euro. But much more of an issue than such a realignment of the lower bound is the possibility that the SNB could give up the target zone regime altogether and let the Swiss franc float freely. Our "intensity of realignment" state variable will therefore just quantify appreciation pressure on the Swiss franc beyond the boundary value of EUR/CHF=1.20.

4.1 Stability of the one-sided Swiss franc target zone

The risk-neutral density function of the Swiss franc/ euro exchange rate can inform about the probability that markets assign to the Swiss franc noting below its lower bound on a given day in the future. For each date since the announcement of the Swiss franc lower bound in September 2011, Figure (10) therefore plots the option implied probability that the Swiss franc will note below CHF 1.20 to the euro; the figure shows $\hat{\Pi}(K, \tau)$ with $K = 1.20$ and $\tau = 1$ month, whereby $\hat{\Pi}(K, \tau)$ has been derived from daily price quotes of EUR/CHF currency options with one month time to maturity as described in section (3). It is natural to interpret this measure as the market's time-varying expectation of the persistence of the Swiss franc lower bound monetary policy regime. This relates to the concept of the "intensity of realignment" which the target zone literature has established. Especially during the year 2012, the risk-neutral probability for EUR/CHF lower than 1.20 was strikingly high on many occasions and quite volatile, fluctuating between 10 percent and over 30 percent. Such high implied probabilities indicate that traders have been eager to insure against CHF appreciation beyond EUR/CHF=1.20, or to bet on EUR depreciation, thus driving up the prices of out-of-the-money EUR/CHF put options for example. The risk-neutral distribution hence suggests that markets casted doubt on the Swiss National Bank's willingness to defend the Swiss franc lower bound in any event. Even if these risk-neutral probabilities might well differ from the subjective probabilities that market participants assigned to a Swiss franc appreciation beyond its lower bound, they nevertheless mirror traders' ability to pay for insurance against CHF appreciation thus providing a measure of market pressure that the Swiss National Bank had to withstand.

Figure (10) also depicts the implied probabilities for EUR/CHF noting below 1.10, as well as above 1.25 and 1.30. The implied probability for EUR/CHF below 1.10 peaked prior to the Greek legislative elections in June 2012, which is a time that was characterized by heavy uncertainty as regards the future of the EMU, but were also relatively high over the first four month of the Swiss franc lower bound monetary policy regime. It is also over these initial months that markets put increased porbability for EUR/CHF noting above 1.25 or even 1.30. This large variance of implied future exchange rates suggests that right after the inception of the Swiss franc lower bound regime, markets were uncertain what price the Swiss National Bank truly was going to impose on its currency. Option prices not only casted doubt on the central bank's willingness to defend the lower bound it hat set, but probably also mirror the political pressure for an even weaker Swiss franc. Over 2011 and 2012, the SNB was confronted with trading associations and political committees requiring for a minimum exchange rate of CHF 1.30 or even 1.40 to the euro.[25] Since the franc probably would have traded at much more appreciated levels than that in the absence of the lower bound regime, the observations that markets put relatively high probability on a such a depreciated Swiss franc suggests that at least some traders doubted whether the Swiss central bank wasn't to rise the Swiss franc lower bound.

[25]Labor unions represented by the "Schweizerischer Gewerkschaftsbund SGB" or the "UNIA", representatives of the catering industry, export oriented firms, the "Schweizerischer Arbeitgeberverband" which is an employers' association, the think-tank economiesuisse, or the "Wirtschaftskommission des Nationalrats" which is the economic council of the National Assembly would all have welcomed a weaker Swiss franc.

The interpolated EUR/CHF put and call option prices[26] shown in figure (11) suggest the same description of market sentiments towards the one-sided Swiss franc target zone regime. If the Swiss National bank always imposes the Swiss franc minimum exchange rate, any EUR/CHF put option with a strike price below $K = 1.20$ never finishes in-the-money. Hence, if markets believe that the SNB will enforce the Swiss franc lower bound, put options that entitle to sell euro against francs for prices above 1/1.20 euro per franc should be worthless. However, EUR/CHF put options with a strike price of $K = 1.20$ traded at positive prices throughout the year 2012, and put options prices with an exercise price of $K = 1.10$ peaked during summer 2012. This suggests that markets were ready to pay for example a positive price for a bet on the Swiss franc noting below its lower bound within one month time. On the other hand, during the first four month of the Swiss franc target zone regime, not only EUR/CHF put options with $K = 1.20$ traded at positive prices, but also call options with a strike price of $K = 1.25$ or $K = 1.30$ were relatively expensive. However, the price of EUR/CHF call options that entitle to buy euro for 1.25 Swiss francs turned to almost zero around January 2012. This suggests to conclude that at that moment, markets no longer suspected that the Swiss National Bank could attempt to loose monetary conditions by rising the Swiss franc lower bound.

To summarize, EUR/CHF option prices allow to quantify to a certain extent how determined markets perceived the SNB to stick to the Swiss franc lower bound of 1.20 to the euro: while market's put high probability on both, a weaker or a stronger Swiss franc during the first couple of month of the lower bound regime, market expectations were clear-cut during 2012 in that the SNB had to withstand quite pronounced appreciation pressure.

5 Option price state variable in the Krugman model

In the first part of this paper, we have argued that the simplest version of Krugman's (1991) model for the behavior of exchange rates within a target zone describes the behavior of the Swiss franc reasonably well: a decline in the stock market or a spike in its option implied volatility VIX both correlate with an appreciation of the Swiss franc against the euro, whereby this correlation is stronger the farther away from its lower bound the Swiss franc exchange rate

[26]The put and call prices depicted in figure (11) have been constructed from the interpolated volatility smile and the Black-Scholes formula for put options as described by Malz (1997).

notes. However, the analysis of EUR/CHF option prices challenges an important assumption of Krugman's (1991) target zone model: the model requires that markets cast no doubt on the monetary authority's power to keep the exchange rate within the determined target zone at any event. But negative 25-delta risk-reversal implied volatilities indicate appreciation pressure on the Swiss franc even though the Swiss franc already noted at its lower bound, and 25-delta strangle implied volatilities indicate that markets took into consideration that the Swiss franc exchange rate could jump far either upwards or downwards, particularly so around monetary policy events such as the publication of the quarterly bulletin of the Swiss National Bank. Eventually, the one month forward-looking risk-neutral density function for the Swiss franc price of one euro shows that markets put relatively high probability on the possibility that the Swiss currency could note below 1.20 francs to the euro. Correspondingly, EUR/CHF put option with strike prices of 1.20 or lower traded at positive prices.

Given these results, an obvious next step is to follow in the target zone literature's tracks and allow within the Krugman (1991) model that market's doubt the continuation of existing exchange rate bands. In the last section of his contribution, Krugman (1991) argues that the exchange rate remains an S-shaped function of its fundamentals even if markets expect that the monetary authority could give up defending a target zone once the exchange rate threatens to surpass its bound.[27] Also, Bertola & Svensson (1993) present an extension of the Krugman model in which investors take into consideration that a central bank might change the position and size of the exchange rate band for its currency, but which nevertheless generates a honeymoon effect for the exchange rate. In their approach, the probability with which markets expect a shift of the exchange rate bounds of a particular size acts as a state variable next to the market fundamental κ. Like κ, this "intensity of realignment" state variable is assumed to follow a Brownian motion process. The increments in this process are allowed to be correlated with those in κ. Further, the intensity of realignment state variable may depend linearly on the current value of the exchange rate $s(t)$. In the literature, empirical estimates of this "intensity of realignment" state variable commonly base on interest rate differentials and other market

[27] Krugman (1991) discusses the case in which markets expect with some positive probability ϕ that once the exchange rate threatens to surpass its bound, monetary authorities will abandon the exchange rate target zone regime such that the exchange rate goes over to floating freely. Krugman argues that this kind of imperfect credibility may reduce, but not eliminate, the stabilizing effect of the exchange rate target zone. Bertola & Caballero (1992) however present a model in which markets expect with some probability that instead of giving up the exchange rate target zone, exchange rate bands will be realigned. In their setting, a honeymoon effect results only if this probability is very low.

fundamentals.[28]

We propose to use the option implied probability for a Swiss franc price of one euro below 1.20 as a state variable for the exchange rate within the Krugman (1991) model, and we denote it by $g(t) = \Pi(K = 1.20, \tau = 1)$, which is the risk-neutral probability for exchange rate realizations below $K = 1.20$ Swiss francs per one euro derived from option prices with $\tau = 1$ month time to maturity. This variable relates to the "intensity of realignment" measure from the literature explained above because it quantifies appreciation pressure on the Swiss franc at the lower bound. Our state variable $g(t)$ can indicate how much markets doubted the continuation of the Swiss franc lower bound regime at different points in time. In addition, this option price-based state variable nicely embeds the interpretation of the Swiss franc as a currency that is highly sensitive to global market risk into the Krugman (1991) model, since appreciation pressure on the Swiss franc systematically sets in if global risk spikes: table (10) shows that the increments of $g(t)$ are significantly correlated with the increments of the global risk factors we have used as exchange rate fundamentals in the first part of this paper. Global market risk importantly impacts on the Swiss franc, but the systematic behavior of EUR/CHF option prices around particular SNB- and ECB-specific events further suggest that also uncertainty that is rather related to Switzerland and the EMU than to the whole world economy is important for the price of the Swiss franc. Lastly, our option-price based state variable for the exchange rate should mirror such region-specific information as well. Since it is derived from prices that emerge from trade in highly liquid markets, this state variable should incorporate all information that is relevant for the expected path of the value of the Swiss franc against the euro.

As the Krugman (1991) model predicts, the scatter-plot presented in figure (12) reveals a clear non-linear relationship between EUR/CHF and the option prices implied probability for EUR/CHF < 1.20: as it approaches its lower bound, the Swiss franc/euro exchange rate co-moves less with appreciation pressure on the Swiss franc. Within the model, this results because markets expect that the Swiss National Bank will suspend the impact of appreciation pressure on the actual value of its currency once it threatens to surpass its ceiling value with high probability.

Obviously, $g(t)$ is not only driven by stochastic fluctuations in global market sentiment, but it is also determined by the actual level of the Swiss franc/euro exchange rate $s(t)$ which it is sup-

[28] See for example Rose & Svensson (1995), Svensson (1993), Lindberg *et al.* (1993)

posed to explain: clearly, the lower EUR/CHF is, the higher is the probability for EUR/CHF $<$ 1.20. In fact, regressing $g(t)$ on $s(t)$ reveals a positive and highly significant estimate.[29] To control for this dependency, the scatter-plot in figure (13) plots all EUR/CHF realizations against the residuals obtained from regressing $g(t)$ on a constant, the current level of the exchange rate $s(t)$, and on its lagged value $g(t-1)$. As for the market fundamentals in the first part of this paper, and as for $g(t)$, we observe that the Swiss franc/euro exchange rate is well described as a bended function of these residuals. The sensitivity of EUR/CHF on innovations in $g(t)$ unrelated to the current level of the exchange rate declines as the Swiss franc approaches its lower bound, which validates Krugman's (1991) target zone model.

Following Bertola & Svensson (1993) to integrate our new state variable for the exchange rate into the Krugman (1991) model, the equation for the exchange rate becomes

$$s(t) = g(t) + \gamma \frac{E_t d(s_t)}{dt} \tag{13}$$

$$g(t) = g_1(t) + a + bs(t) \tag{14}$$

$$dg_1(t) = \mu_g dt + \sigma_g dW_g(t), \qquad dW_g(t)dW_\kappa(t) = \rho dt, \qquad |\rho| \leqq 1$$

where $dW_g(t)$ and $dW_\kappa(t)$ are potentially correlated standard Wiener processes related to $g(t)$ and other exchange rate fundamentals $\kappa(t)$ like the global risk factors we used in the first part of this paper. While it is difficult to solve the model with an arbitrary functional form of the dependence of $g(t)$ from $s(t)$, Bertola & Svensson (1993) note that the linear case we assumed so far is easy to handle. Substituting equation (14) into (13) leads to the following equation for the exchange rate

$$s(t) = \frac{a}{1-b} + \left(\frac{1}{1-b}\right) g_1 + \left(\frac{\gamma}{1-b}\right) E_t \left[\frac{ds(t)}{dt}\right]$$

which is of the same functional form as (2) such that a solution to the model exists that leads to an S-shaped exchange rate function $s(g)$.

[29] Regressing $g_t = \Pi(K = 1.20, \tau)$ on a constant a and the EUR/CHF spot exchange rate S_t

$$g_t = a + b(S_t) + \epsilon_t$$

yields the following OLS estimates: $\hat{a} = 7.7$ and $\hat{b} = -6.2$. Allowing for autocorrelation and heteroscedasticity in the error term, both estimates are highly significantly different from zero. Hence, the closer to its lower bound the Swiss franc notes, the higher is g_t.

Given this theoretical foundation of our option-based state variable $g(t)$, the regression results presented in table (11) confirm the non-linear relationship between $g(t)$ and $s(t)$ depicted in the scatter-plots of figures (12) and (13). Regressing percentage changes in the Swiss franc/euro exchange rate on first differences of our intensity of realignment state variable interacted with the percentage deviation of the Swiss franc from its lower bound yields a negative OLS-estimate that, after allowing for autocorrelation and heteroscedasticity in the error term, is highly significant:

$$\Delta \log(S_t) \quad = \quad const + \beta_1 \Delta g_t \times (S_t - 1.20) + \beta_2 \Delta g_t + \beta_3 (S_t - 1.20) + \beta_4 \Delta \log(S_{t-1}) + \epsilon_t$$

While the estimates for β_2 and β_3 are not statistically different from zero, the estimate for β_1 is significantly negative. Thus, a given increase in the state variable $g(t)$ goes along with a relatively higher appreciation of the Swiss franc against the euro the weaker the Swiss currency is. But as the Swiss franc/euro exchange rate approaches its lower bound, the negative relation between increases in appreciation pressure and actual Swiss franc appreciation fades out. To conclude, this paper describes the Swiss franc as an asset whose price is explained by it's sensitivity to global or systematic risk, that is, risk which investors cannot hedge. Thereby, this sensitivity is a function of the monetary policy regime which markets believe that the Swiss National Bank is implementing.

6 Option price interpretation of EUR/CHF

The Krugman (1991) target-zone model not only allows for a risk-based interpretation of the Swiss franc by the corresponding choice of the state variables, but it also embeds an asset-pricing view of exchange rates directly. In particular, Krugman's (1991) model suggests to interpret the Swiss franc/euro exchange rate as the price of an asset portfolio that consists of two positions, a long position in a fundamental asset whose value is determined by the expected path of the risky exchange rate fundamental, plus a short position in an EUR/CHF put option with a strike price of 1.20. To see this, note that the equation for the exchange rate (2) can be solved forward to obtain

$$
\begin{aligned}
s_t &= \frac{1}{\gamma}\int_{\tau=t}^{\infty}(m_\tau-\kappa_\tau)e^{-\left(\frac{\tau-t}{\gamma}\right)}d\tau \\
&= \frac{1}{\gamma}\int_{\tau=t}^{\infty}(m_0-\kappa_\tau)\,e^{-\left(\frac{\tau-t}{\gamma}\right)}d\tau+\frac{1}{\gamma}\int_{\tau=t}^{\infty}(m(\kappa_\tau)-m_0)\,e^{-\left(\frac{\tau-t}{\gamma}\right)}d\tau
\end{aligned} \tag{15}
$$

where m_0 is the monetary base which is held constant as long as the exchange rate remains above the lower bound.

The first term on the right hand side of equation (15) represents the fundamental part. In our implementation, higher global market risk κ_t implies a lower $s(\kappa_t)$, that is, a higher value of the Swiss currency. Since κ_t is assumed to follow a random walk, its expected value increases in its actual level κ_t. Thus, the "fundamental" value of the Swiss currency increases in κ. If however κ_t moves to values that would imply $s(\kappa_t) < 1.20$, the Swiss National Bank has committed itself to increase m above m_0 such that $s(m(\kappa_t), \kappa_t)$ does not fall below EUR/CHF=1.20. Hence, by the random walk property of κ again, the expected Swiss franc monetary base $(m(\kappa_\tau))$ increases in κ_t, leading to a higher s_t. Together with the "fundamental" term, this "option pricing term" leads to the now familiar bended relationship between the exchange rate and its fundamental.

The option pricing interpretation of the second term in the above exchange rate equation arises because it represents the obligation of the SNB to sell Swiss francs against euros on demand at EUR/CHF=1.20. Selling Swiss francs against euros increases the monetary base and prevents the Swiss franc from falling below its lower bound. This obligation corresponds to a short position in a CHF/EUR call option or, equivalently, to a short position in a EUR/CHF put option with a strike price of $K = 1.20$.[30] Focusing on the EUR/CHF put option, the risk-neutral value of such a contract is given by

$$
P(K,\tau) = \frac{1}{1+i_\tau}\int_0^K (K - S_\tau(\kappa_\tau))f(S_\tau)dS_\tau \tag{16}
$$

where we again assume that the expected exchange rate at maturity of the option contract, $S_\tau(\kappa_\tau)$, is a declining function of the actual level of the fundamental κ_t. Clearly, the value of this put option increases as κ_t increases so that a *short* position in this contract loses in value for

[30] A CHF/EUR call option entitles its holder to buy Swiss francs paying with euros for a given strike price, and a EUR/CHF put option gives its holder the right to sell euros against Swiss francs at a predetermined price. Since we use EUR/CHF option prices in this paper, we will focus on the EUR/CHF put option contract.

higher κ. In sum, the value of the Swiss franc asset portfolio, which consists of a fundamental asset position whose value increases in κ_t and an option position whose value declines in κ_t, is a bended function of the market fundamental κ_t as the basic Krugman (1991) model suggests.

To refer to the analysis of the Swiss franc presented in the preceding sections of this paper, the option price-based state variable for the exchange rate we suggested directly relates to the option pricing position of the "Swiss franc portfolio": a higher implied probability for EUR/CHF < 1.20 monotonically translates into a higher price of an EUR/CHF put option with a strike price of $K = 1.20$. Given the stylized fact that the Swiss franc tends to appreciate in globally risky times, that is, given that S_t falls in κ_t, equation (16) visualizes how increasing systematic risk rises the price of EUR/CHF put options. Since the "Swiss franc portfolio" includes a short position in such an option contract, the Swiss franc should appreciate less in κ the higher this global risk already is, possibly implying a Swiss franc/euro exchange rate far below 1.20. Figure (14) plots this new variant of the option price-based state variable $\tilde{g}(t) = P(K, \tau)$ against all EUR/CHF realizations. Clearly visible, the Swiss franc can be described as a bended function of $\tilde{g}(t)$. [31]

To draw the big picture and to summarize our results, the two variants of the option price-based state variables for the exchange rate $g(t) = \Pi(K, \tau)$, and $\tilde{g}(t) = P(K, \tau)$ with $K = 1.20$ and $\tau = 1$ month a) quantify appreciation pressure on the Swiss franc against the euro at the Swiss franc lower bound and thus indicate the "credibility" of the Swiss franc target zone, b) reflect increasing latent global market risk, c) further mirror EUR/CHF exchange rate specific uncertainty, and d) directly describe the value of the Swiss currency against the euro. The Swiss franc/euro exchange rate is well described as a nonlinear function of these state variables.[32]

Think about the following: Veestraeten (2013) finds an s-shaped option pricing function for options on currencies in two-sided target zone regimes. The option price function tangentially nears the boundaries of its band. In fact, absence of arbitrage opportunities require the option to have zero movement upon reflection. Non-zero movement would indeed allow for predictable gains if the option were bought just prior to intervention. Or, the first derivative of the price

[31] Veestraeten (2013) presents a model for currency option pricing within credible exchange rate target zone regimes. In his model, the option price is an S-shaped function of the exchange rate that tangentially nears the boundary of its band.

[32] Dumas *et al.* (1995) and Veestraeten (2013) present a model for currency option pricing within exchange rate target zone regimes.

function to the exchange rate is equal to zero at the boundaries.

7 Summary and concluding remarks

The introduction of a one-sided exchange rate target zone regime for the Swiss franc in September 2011 has helped the Swiss National Bank not only to halt the strong appreciation of the Swiss currency that set in in the wake of the global financial crisis and during the tumultuous months of the European sovereign debt crisis, but also to mute the sensitivity of the Swiss franc to spikes in global market risk. In line with the predictions of Paul Krugman's (1991) simple, though elegant, model for the behavior of the exchange rate within a target zone, we conclude that declines in the stock market and increases in stock options implied volatility go along with a smaller appreciation of the Swiss franc against the euro, the closer to its lower bound of EUR/CHF=1.20 the Swiss currency already notes. Such a non-linear relationship between variables that capture global market risk and the value of the Swiss franc is not found for the time before the inception of the Swiss franc lower bound, when the Swiss currency was freely floating (between June 2010 and August 2011), or when the Swiss National Bank was heavily intervening in foreign exchange markets to depreciate the value of its currency without having announced a lower bound (between April 2009 and May 2010).

Price quotes of option portfolios that are commonly traded in over-the-counter markets indicate that over the first few months after the SNB announced to prevent the Swiss franc from appreciating beyond 1.20 francs to the euro, markets were uncertain about how the Swiss central bank was going implement this new policy regime: option prices not only suggest that markets doubted whether the central bank will truly defend this lower bound, but they also indicate doubt about whether the central bank will give way to political pressure and rise the Swiss franc lower bound to 1.25 or even 1.30 to the euro. In contrast, over 2012, when the European sovereign debt crisis was escalating dramatically, market expectations were more clear-cut and option prices now put considerable porbability on the Swiss franc noting below 1.20 to the euro in the near future. Also, option prices suggest that the central banks were unable to convince the market of a stable future exchange rate path during the first year of the Swiss franc lower bound regime. To allow for such uncertainty about the continuation of the Swiss franc lower bound monetary policy regime within the framework of Krugman's (1991) model, we consider the risk-neutral probability that the Swiss franc will note below EUR/CHF=1.20 in the near future as a fundamental variable that drives the value of the Swiss franc. This state variable for the exchange rate not only quantifies doubt about the Swiss franc lower bound, but it also indicates surges in global market risk because safe haven demand for Swiss francs spikes in such tumultuous times. Again, we are able to describe the sensitivity of the Swiss franc to this option price-based state variable as a function of the Swiss central bank's monetary policy stance: the closer to its lower bound the Swiss franc already notes, the less it appreciates as appreciation pressure, indicated by option prices, surges. To conclude, the Swiss franc is in honeymoon.

Since the inception of the Swiss franc lower bound, economic conditions in Switzerland and the euro area have been changing: the discussion about the euro break up, that was striking in the media during summer 2012, has virtually vanished and the euro crisis is subsiding. As of January 2014, the global economy is recovering and major central banks consider normalizing their monetary policy stances. However, the franc is still trading close to its lower bound. Since EUR/CHF has reached a peak in May 2013, the franc has steadily been appreciating against the euro and even dropped below 1.21 to the euro at the end of February 2014 when armed men occupied government buildings in the Ukrainian region of Crimea and raised the Russian flag. Against the hope that the Swiss franc lower bound would become irrelevant as safe haven demands for the franc reverse once the euro crisis subsides, in spring 2014, the Swiss franc lower bound still importantly frames the Swiss National Bank's monetary policy decisions. The value of the Swiss franc is influenced by this one-sided exchange rate target zone regime, and a version of Krugman's (1991) model for the behavior of exchange rate within target zones describes aspects of its behavior considerably well.

References

Bertola, Giuseppe, & Caballero, Ricardo J. 1992. Target Zones and Realignments. *The American Economic Review*, **82**(3), pp. 520–536.

Bertola, Giuseppe, & Svensson, Lars E. O. 1993. Stochastic Devaluation Risk and the Empirical Fit of Target-Zone Models. *The Review of Economic Studies*, **60**(3), pp. 689–712.

Black, Fischer, & Scholes, Myron S. 1973. The Pricing of Options and Corporate Liabilities. *Journal of Political Economy*, **81**(3), 637–54.

Breeden, Douglas T, & Litzenberger, Robert H. 1978. Prices of State-contingent Claims Implicit in Option Prices. *The Journal of Business*, **51**(4), 621–51.

Burnside, Craig. 2011. The Cross Section of Foreign Currency Risk Premia and Consumption Growth Risk: Comment. *American Economic Review*, **101**(7), 3456–76.

Burnside, Craig, Eichenbaum, Martin, & Rebelo, Sergio. 2009. Understanding the Forward Premium Puzzle: A Microstructure Approach. *American Economic Journal: Macroeconomics*, **1**(2), 127–54.

Burnside, Craig, Eichenbaum, Martin, & Rebelo, Sergio. 2011a. Carry Trade and Momentum in Currency Markets. *Annual Review of Financial Economics*, **3**(1), 511–535.

Burnside, Craig, Eichenbaum, Martin, Kleshchelski, Isaac, & Rebelo, Sergio. 2011b. Do Peso Problems Explain the Returns to the Carry Trade? *Review of Financial Studies*, **24**(3), 853–891.

Burnside, Craig, Han, Bing, Hirshleifer, David, & Wang, Tracy Yue. 2011c. Investor Overconfidence and the Forward Premium Puzzle. *The Review of Economic Studies*, **78**(2), 523–558.

Caballero, Ricardo J., & Doyle, Joseph B. 2012 (December). *Carry Trade and Systemic Risk: Why are FX Options so Cheap?* Working Paper 18644. National Bureau of Economic Research.

Campa, Jose M., & Chang, P. H. Kevin. 1998. ERM Realignment Risk and its Economic Determinants as Reflected in Cross-rate Options. *The Economic Journal*, **108**(449), 1046–1066.

Campa, Jose Manuel, & Chang, P. H. Kevin. 1996. Arbitrage-Based Tests of Target-Zone Credibility: Evidence from ERM Cross- Rate Options. *The American Economic Review*, **86**(4), pp. 726–740.

Dumas, Bernard, Jennergren, L. Peter, & Naeslund, Bertil. 1995. Realignment risk and currency option pricing in target zones. *European Economic Review*, **39**(8), 1523 – 1544.

Elliott, Graham, & Mueller, Ulrich K. 2006. Efficient Tests for General Persistent Time Variation in Regression Coefficients -super-1. *Review of Economic Studies*, **73**(4), 907–940.

Fama, Eugene F. 1984. Forward and spot exchange rates. *Journal of Monetary Economics*, **14**(3), 319 – 338.

Flood, Robert P., Rose, Andrew K., & Mathieson, Donald J. 1991. An empirical exploration of exchange-rate target-zones. *Carnegie-Rochester Conference Series on Public Policy*, **35**(0), 7 – 65.

Garber, Peter M., & Svensson, Lars E.O. 1995. Chapter 36 The operation and collapse of fixed exchange rate regimes. Handbook of International Economics, vol. 3. Elsevier.

Garman, Mark B., & Kohlhagen, Steven W. 1983. Foreign currency option values. *Journal of International Money and Finance*, **2**(3), 231 – 237.

Griesse, Christian, & Nitschka, Thomas. 2013. *On financial risk and the safe haven characteristics of Swiss franc exchange rates*. Tech. rept. Swiss National Bank Working Papers.

Hoffmann, Mathias, & Suter, Rahel. 2010. The Swiss Franc Exchange Rate and Deviations from Uncovered Interest Parity: Global vs Domestic Factors. *Swiss Journal of Economics and Statistics*, **146**(1), 349–371.

Hoffmann, Mathias, & Suter, Rahel. 2013. *Systematic Consumpiton Risk in Currency Returns*. Tech. rept. Available at SSRN: http://ssrn.com/abstract=2289234 or http://dx.doi.org/10.2139/ssrn.2289234.

Jackwerth, Jens Carsten. 1999. Option Implied Risk-Neutral Distributions and Implied Binomial Trees: A Literature Review. *Journal of Derivatives*, **7**(2), 66.82.

Jorda, Oscar, & Taylor, Alan M. 2009. *The Carry Trade and Fundamentals: Nothing to Fear But FEER Itself*. Working Paper. National Bureau of Economic Research.

Jurek, Jakub W. 2014. Crash-Netural Currency Carry Trades. *Jornal of Financial Economics, forthcoming*.

Krugman, Paul R. 1987 (Dec.). *Trigger Strategies and Price Dynamics in Equity and Foreign Exchange Markets*. NBER Working Papers 2459. National Bureau of Economic Research, Inc.

Krugman, Paul R. 1991. Target Zones and Exchange Rate Dynamics. *The Quarterly Journal of Economics*, **106**(3), pp. 669–682.

Kugler, Peter, & Weder di Mauro, Beatrice. 2005 (Aug.). *Why Are Returns on Swiss Franc Assets So Low? Rare Events May Solve the Puzzle*. CEPR Discussion Papers 5181. C.E.P.R. Discussion Papers.

Lettau, Martin, Maggiori, Matteo, & Weber, Michael. 2013 (February). *Conditional Risk Premia in Currency Markets and Other Asset Classes*. Working Paper 18844. National Bureau of Economic Research.

Lindberg, Hans, SÃ¶derlind, Paul, & Svensson, Lars E. O. 1993. DEVALUATION EXPECTATIONS: THE SWEDISH KRONA 1985-92. *Economic Journal*, **103**(420), 1170 – 1179.

Lustig, Hanno, & Verdelhan, Adrien. 2011. The Cross-Section of Foreign Currency Risk Premia and Consumption Growth Risk: Reply. *American Economic Review*, **101**(7), 3477–3500.

Lustig, Hanno N., & Verdelhan, Adrien. 2007. The Cross Section of Foreign Currency Risk Premia and Consumption Growth Risk. *American Economic Review*, **97**(1), 89 – 117.

Lustig, Hanno N., Roussanov, Nikolai L., & Verdelhan, Adrien. 2011. Common Risk Factors in Currency Markets. *The Review of Financial Studies*, **24**(11), 3731–3777.

Malz, Allan M. 1996. Using option prices to estimate realignment probabilities in the European Monetary System: the case of sterling-mark. *Journal of International Money and Finance*, **15**(5), 717 – 748.

Malz, Allan M. 1997. Estimating the probability distribution of the future exchange rate from option prices. *Journal of Derivatives*, **5**(2), 18–36.

Meese, Richard A., & Rogoff, Kenneth. 1983. Empirical exchange rate models of the seventies: Do they fit out of sample? *Journal of International Economics*, **14**(1-2), 3 – 24.

Menkhoff, Lukas, Sarno, Lucio, Schmeling, Maik, & Schrimpf, Andreas. 2012. Carry Trades and Global Foreign Exchange Volatility. *Journal of Finance*, **67**(2), 681 – 718.

Menkhoff, Lukas, Sarno, Lucio, Schmeling, Maik, & Schrimpf, Andreas. 2013. *Currency Risk Premia and Macro Fundamentals*. Tech. rept. Available at SSRN: http://ssrn.com/abstract=2282480 or http://dx.doi.org/10.2139/ssrn.2282480.

Merton, Robert C. 1976. The Impact on Option Pricing of Specification Error in the Underlying Stock Price Returns. *Journal of Finance*, **31**(2), 333–50.

Mueller, Ulrich K., & Petalas, Philippe-Emmanuel. 2010. Efficient Estimation of the Parameter Path in Unstable Time Series Models. *The Review of Economic Studies*, **77**(4), 1508–1539.

Newey, Whitney K, & West, Kenneth D. 1987. A Simple, Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. *Econometrica*, **55**(3), 703–08.

Ranaldo, Angelo, & Soderlind, PaulT. 2010. Safe Haven Currencies. *Review of Finance*, **14**(3), 385–407.

Rose, Andrew K., & Svensson, Lars E. O. 1994. European exchange rate credibility before the fall. *European Economic Review*, **38**(6), 1185–1216.

Rose, Andrew K., & Svensson, Lars E.O. 1995 (Oct.). *Expected and Predicted Realignments: The FF/DM Exchange Rate During the EMS*. NBER Working Papers 3685. National Bureau of Economic Research, Inc.

Svensson, Lars E. O. 1993. Assessing target zone credibility : Mean reversion and devaluation expectations in the ERM, 1979-1992. *European Economic Review*, **37**(4), 763–793.

Svensson, Lars E.O. 1990 (June). *The Simplest Test of Target Zone Credibility*. Working Paper 3394. National Bureau of Economic Research.

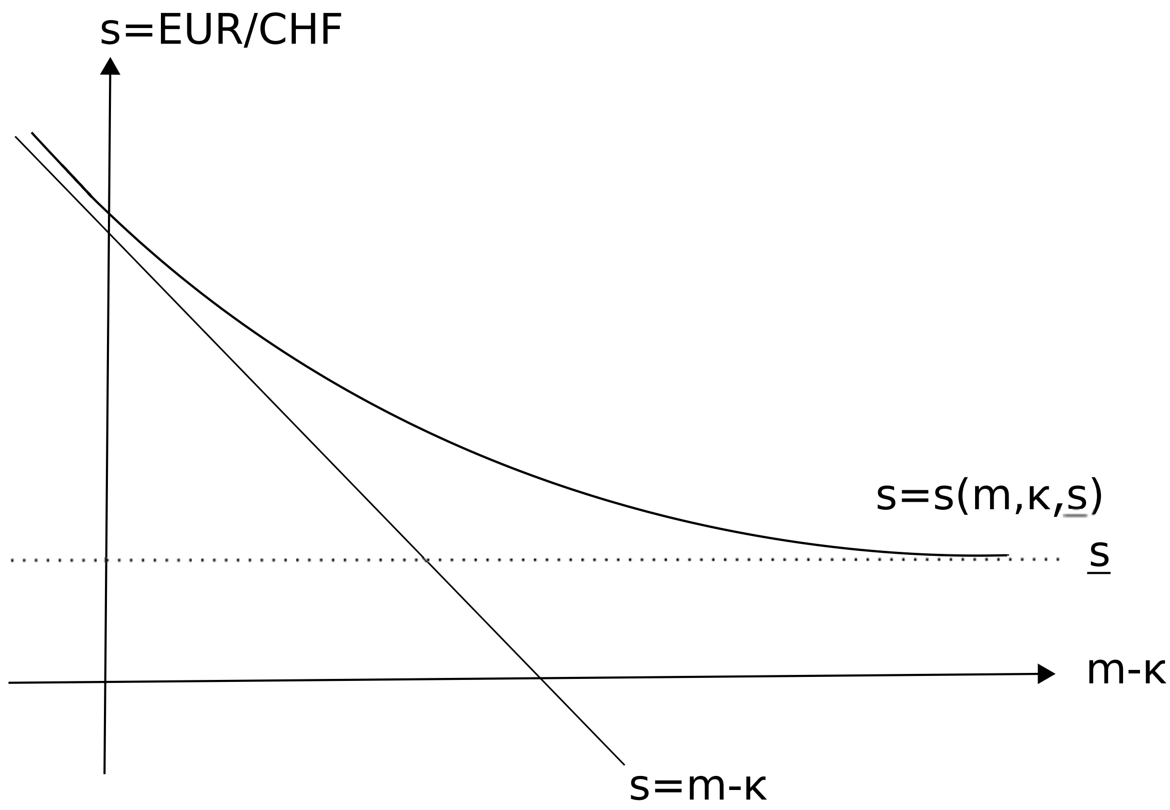
Veestraeten, Dirk. 2013. Currency option pricing in a credible exchange rate target zone. *Applied Financial Economics*, **23**(11), 951–962.

Verdelhan, Adrien. 2011. *The Share of Systematic Risk in Bilateral Exchange Rates*. Working Paper. available at SSRN: http://ssrn.com/abstract=1930516.

Figure 1: SNB reserves and EUR/CHF 1month forward exchange rate

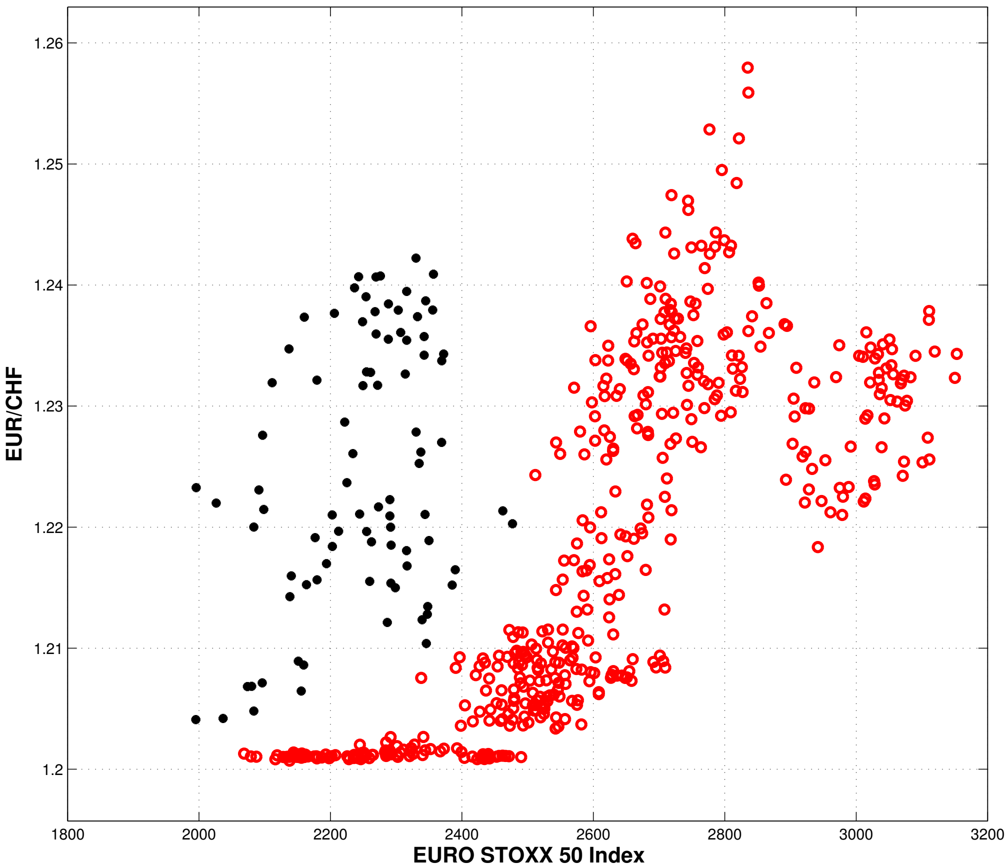
The figure shows the Swiss National Bank's foreign exchange reserves measured in millions of Swiss francs, and the Swiss franc/euro spot exchange rate expressed in Swiss francs per one euro. The data for the foreign exchange reserves is at monthly frequency, the spot exchange rate is measured daily.

Figure 2: Krugman (1991) exchange rate function



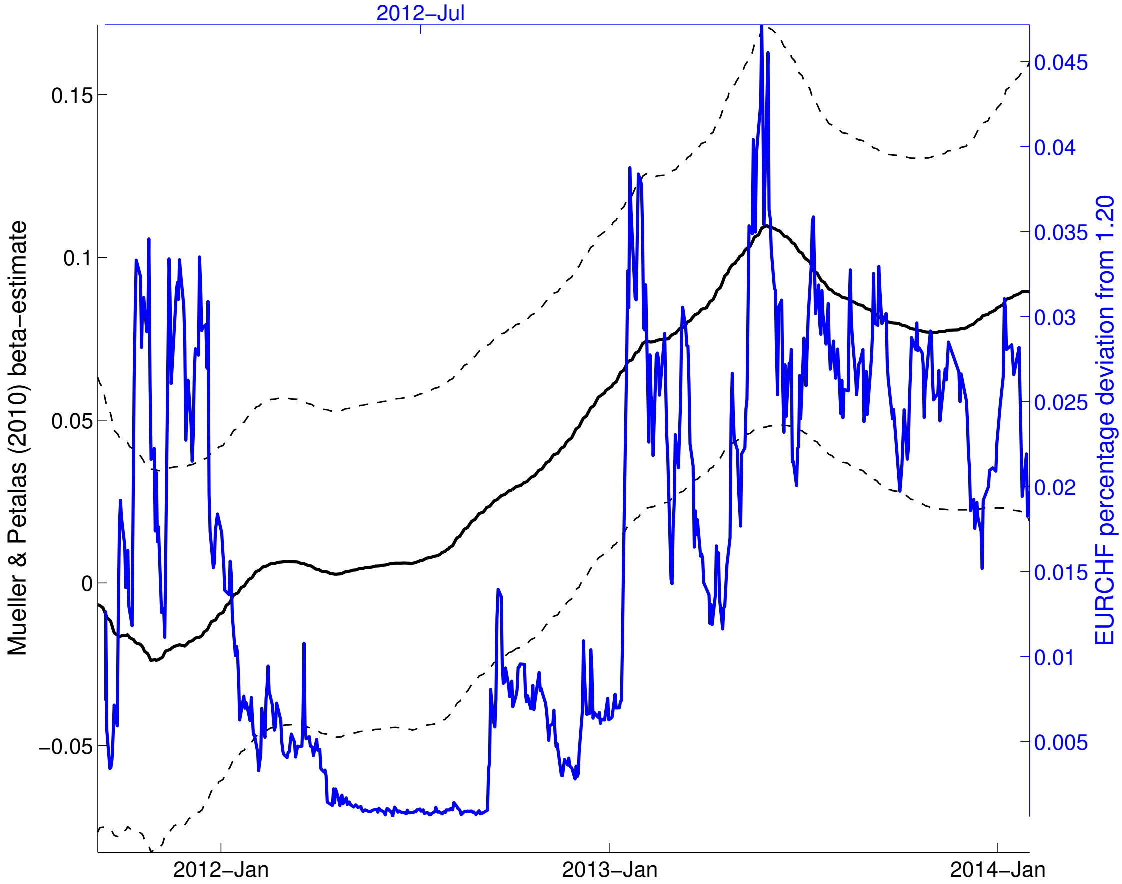
This graph sketches the exchange rate s as a function of currency market fundamentals κ. Applied to a one-sided target zone exchange rate regime, the graph depicts the behavior of the exchange rate that the Krugman (1991) model implies: as it approaches its lower bound, the exchange rate should become insensitive to changes in the market fundamentals; $\underline{s} = s(\underline{m-\kappa})$ denotes this lower bound.

Figure 3: Krugman (1991) exchange rate function: EUR/CHF and Stock market



The figure plots values of the EURO STOXX 50 index against the Swiss franc/euro exchange rate which is measured in units of Swiss francs per euro. Black dots denote data points that lie between September 6, 2011 and January 13, 2012, and red circles mark data points between January 2012 and January 2014. This break point in January 2012 is motivated by the observation that around that date, the Swiss franc noted at its lower bound for the first time since the SNB announced to defend a Swiss franc lower bound of EUR/CHF=1.20. The data is at daily frequency and includes all days that were trading days in Switzerland and in the US.

Figure 4: Mueller and Petalas (2006) time-varying beta estimates

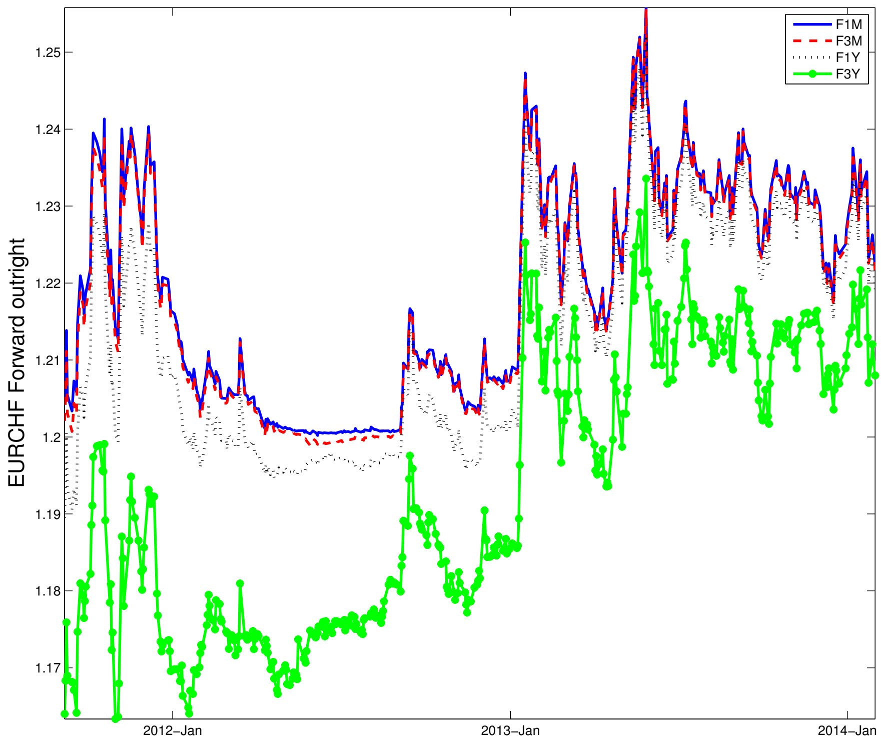


Applying the method proposed by Elliott & Mueller (2006) and Mueller & Petalas (2010), the black line (left axis) shows time-varying estimates of the β_t- coefficient of the following regression equation

$$\Delta s_t \quad = \quad \alpha + \beta_t \kappa_t + \epsilon_t$$

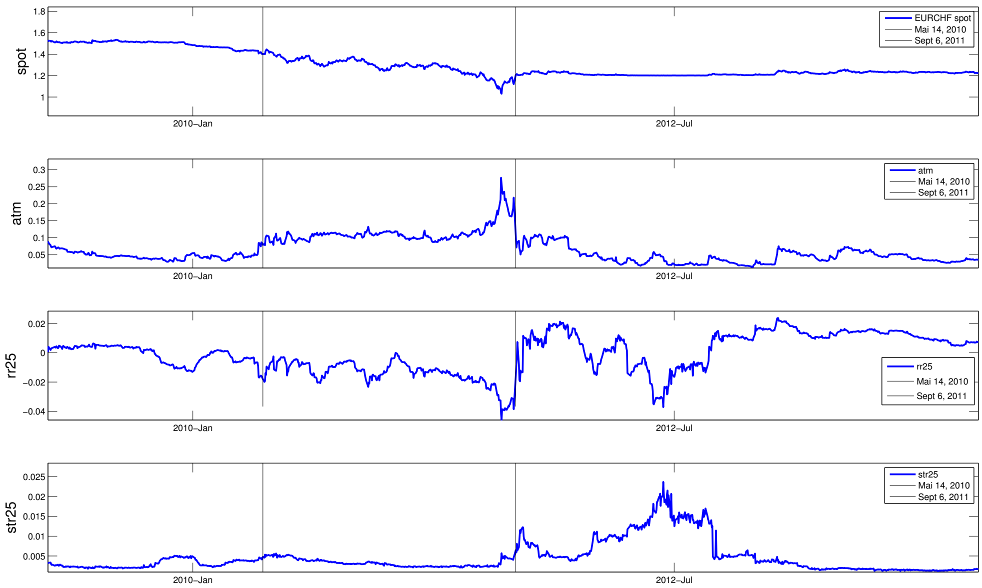
where Δs_t denote percentage changes in the EUR/CHF spot exchange rate, α denotes a constant and κ_t is a foreign exchange market fundamental. Here, κ_t equals percentage changes of the EURO STOXX 50 index. The thin, dotted lines depict 95% confidence intervals for the β_t-estimates. The blue line (right axis) shows percentage deviations of the EUR/CHF spot exchange rate from its lower bound which equals EUR/CHF=1.20. The data is at daily frequency and encompasses all days that were trading days in Switzerland as well as in the US.

Figure 5: EUR/CHF forward exchange rate



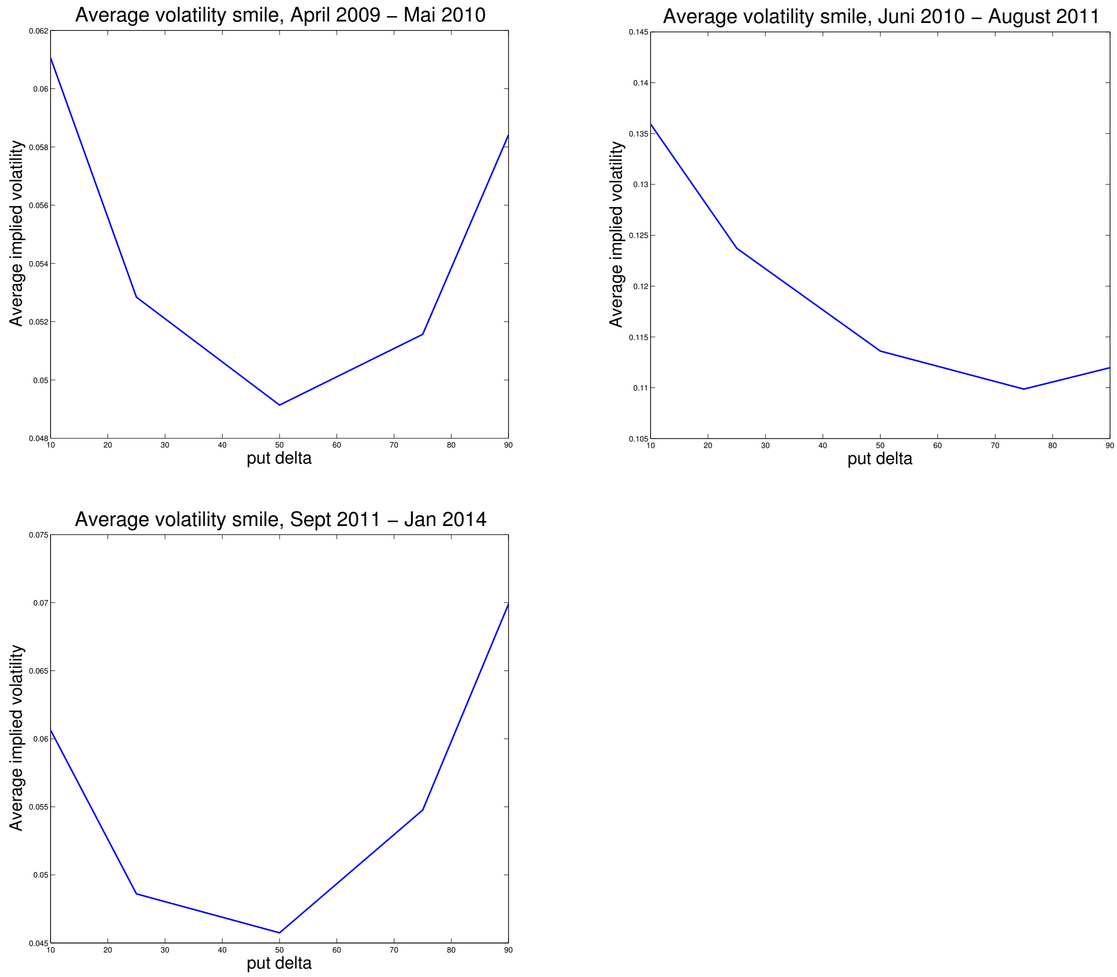
The figure shows EUR/CHF forward outright exchange rates for different maturities. The data is at daily frequency and encompasses all days that were trading days in the US and in Switzerland between September 2011 and January 2014.

Figure 6: EUR/CHF spot exchange rate and currency option implied volatility



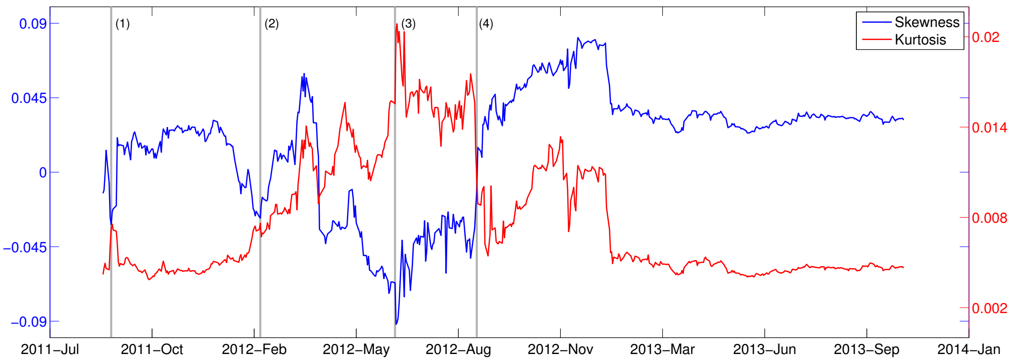
The figures show time-series plots of the EUR/CHF spot exchange rate, and currency option volatility price quotes: *atm* denotes the at-the-money implied volatility, *rr25* is the volatility price quote for a risk-reversal with a delta of 25, and *str25* denotes the 25-delta strangle volatility price. The option contracts have a maturity of one month, the data is at daily frequency and encompasses all days that were trading days in Switzerland and in the US. The vertical lines indicate dates around which the Swiss National Bank changed its foreign exchange policy regime: between April 2009 and Mai 2010, the SNB heavily intervened in the foreign exchange market to prevent the Swiss franc from appreciating a lot. In May 2010, the SNB stopped these interventions, but in September 2011 it decided to intervene in the foreign exchange market anew and announced to defend the Swiss franc euro exchange rate at CHF 1.20 per 1 EUR.

Figure 7: Average volatility smile for different SNB foreign exchange policy regimes



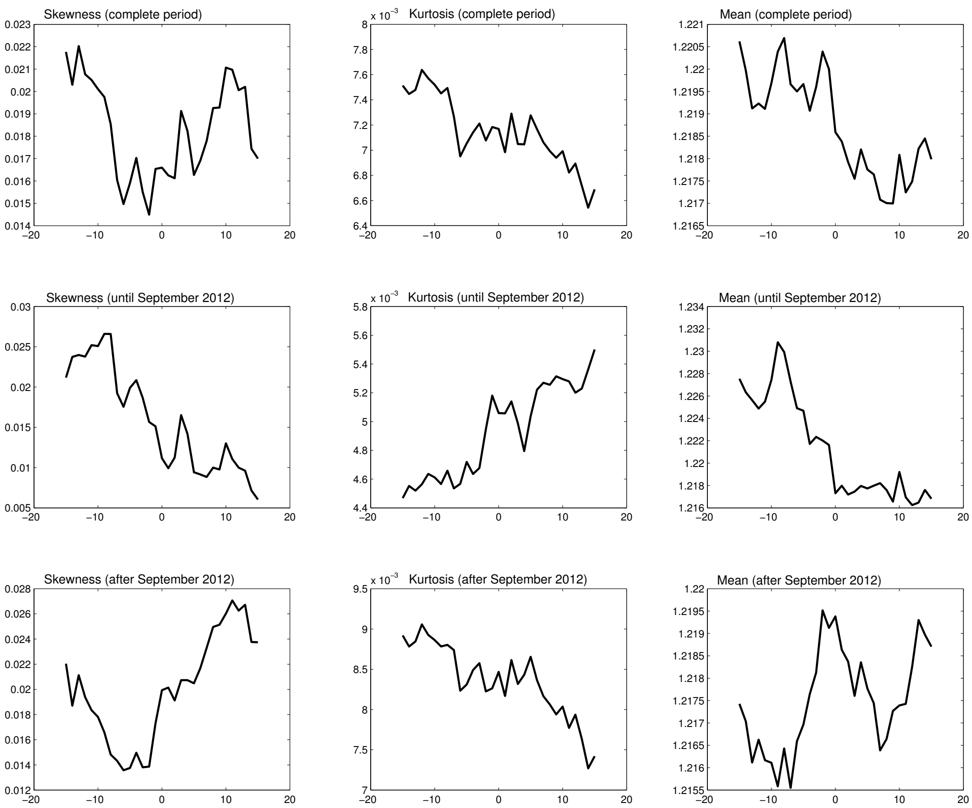
The figure shows average EUR/CHF option volatility smiles for three periods which are characterized by different SNB foreign exchange market intervention regimes: between April 2009 and Mai 2010, the SNB heavily intervened in the foreign exchange market to prevent the Swiss franc from appreciating a lot. In May 2010, the SNB stopped these interventions, but in September 2011 it decided to intervene in the foreign exchange market anew and announced to defend the Swiss franc euro exchange rate at CHF 1.20 per 1 EUR. Lines plot the time-series average of the implied volatility quotes in percentage points against the put delta of the currency option. Currency options have a time to maturity of one month. The data is at daily frequency and encompasses all days that were trading days in Switzerland and in the US.

Figure 8: Skewness and Kurtosis of implied EUR/CHF density function



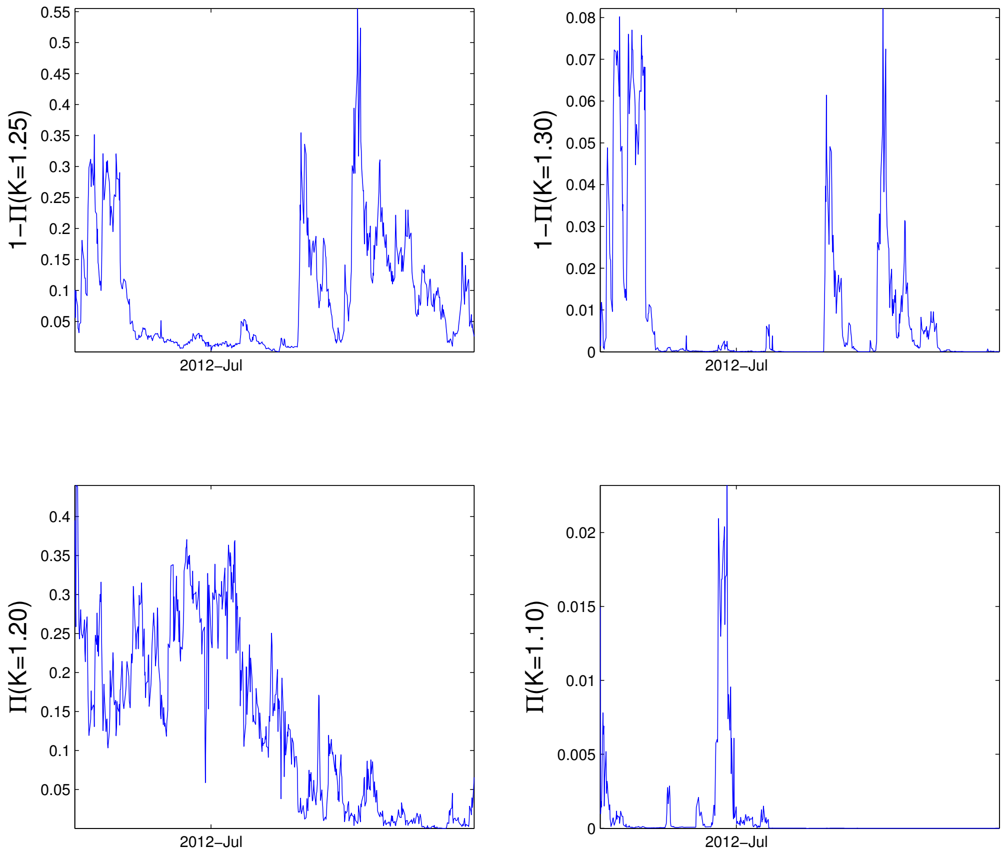
The blue dotted line (left axis) shows the skewness of the option implied EUR/CHF density function, and the red line (right axis) shows its kurtosis. The data is at daily frequency and covers all days that were trading days in the US as well as in Switzerland. Vertical lines indicate dates at which influential events took place. On September 15, 2011 (1), the first SNB monetary policy assessment after the inception of the Swiss franc lower bound was published. On February 9, 2012 (2), the ECB approved eligibility criteria for additional credit claims. On June 18, 2012 (3), Greek legislative elections took place, and on September 6, 2012 (4), details of the ECB's OMT program became public.

Figure 9: average behavior of option implied EUR/CHF density function around central bank events



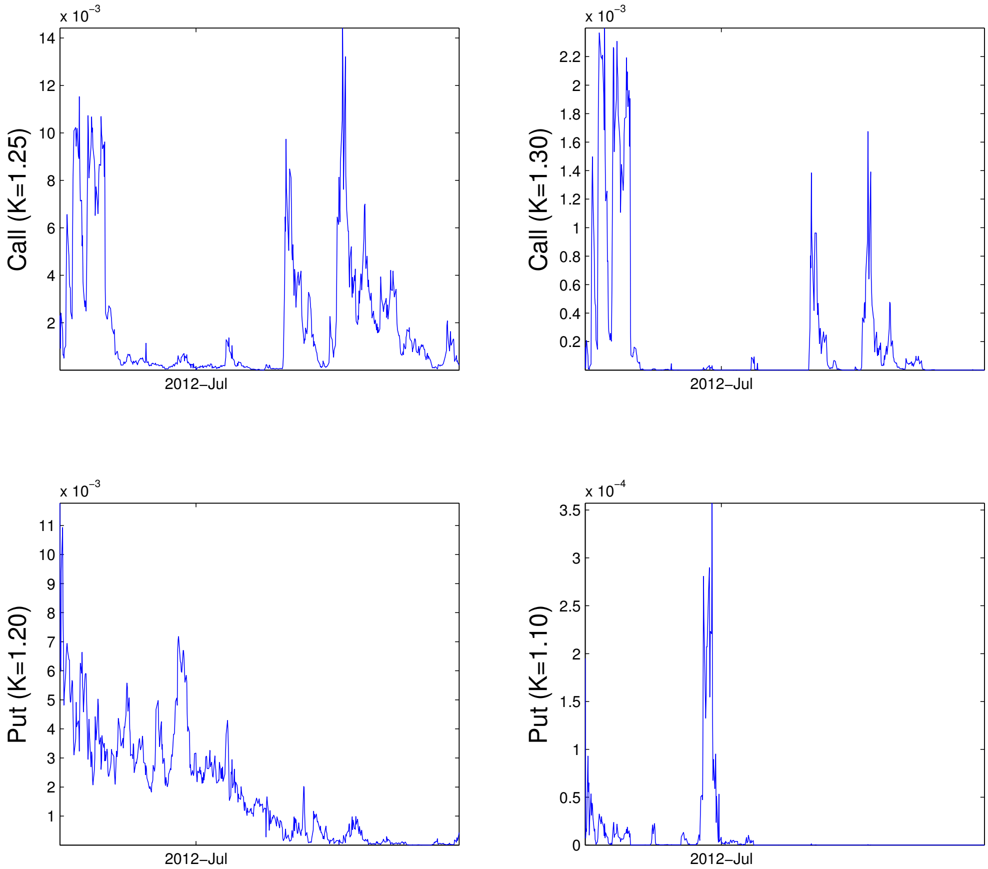
The figures show the average behavior of the skewness, the kurtosis, and the mean of the option implied EUR/CHF density function on the days that precede and follow central bank events. All events are listed in table (7). The data starts on September 6, 2011 – which is when the Swiss franc lower bound regime was installed – and reaches through to January 2014. This period is divided into two sub-periods, the period prior to Mario Draghi's spirited speech in August 2012 in which he clearly stated the ECB's willingness to support the euro at any event and the subsequent launch of the ECB's Outright Monetary Transaction program (OMT) in September 2012, and the period thereafter.

Figure 10: Risk-neutral cumulative density function



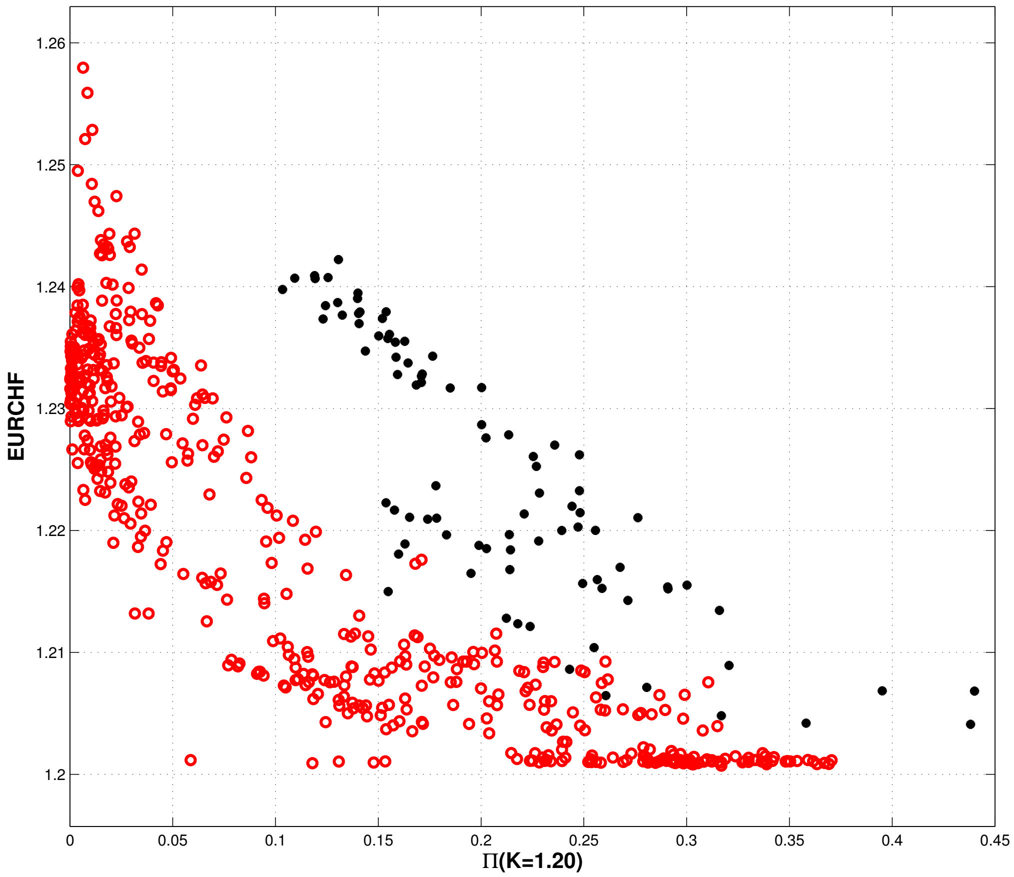
The figures show the cumulative risk-neutral density function that option prices with one month time to maturity imply for particular values of the EUR/CHF exchange rate at the expiration date of the option contracts. Risk-neutral density functions have been obtained by interpolating the volatility smile as Malz (1997) suggested, details are described in section (3.3). The upper left plot shows the option implied probability for a exchange rate above EUR/CHF=1.25, and the upper right plot depicts the probability for an exchange rate above EUR/CHF=1.30. The lower plot on the left shows the risk-neutral probability that EUR/CHF will note below 1.20, and the lower plot on the right shows the probability that EUR/CHF will trade below 1.10 in one month time. The data is at daily frequency and includes all days that were trading days in the US as well as in Switzerland and spans the period from September 6, 2011 to January 31, 2014.

Figure 11: Put and Call option prices



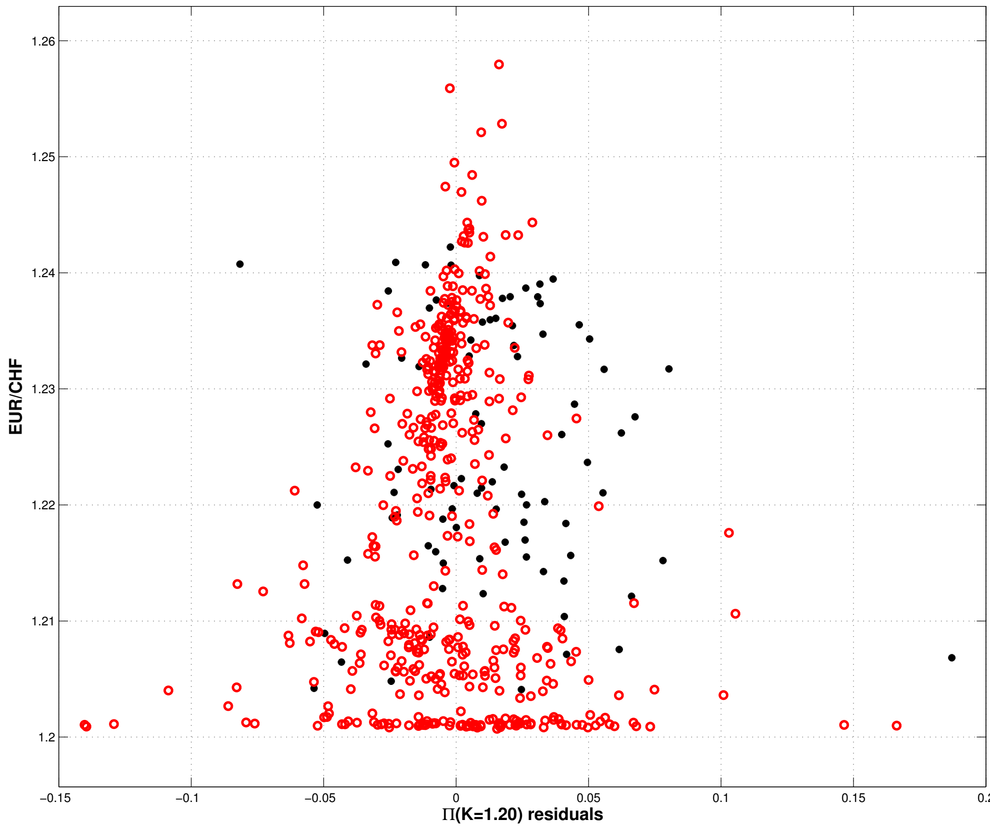
The figure shows time-series of call and put option prices with given strike prices *K*. These option prices are constructed from the interpolated volatility smile as Malz (1997) suggested and the Black-Scholes formulas for put and call option prices. The data is at daily frequency and includes all days that were trading days in the US as well as in Switzerland and spans the period from September 6, 2011 to January 31, 2014.

Figure 12: Krugman (1991) exchange rate function: EUR/CHF and implied probability for EUR/CHF<1.20



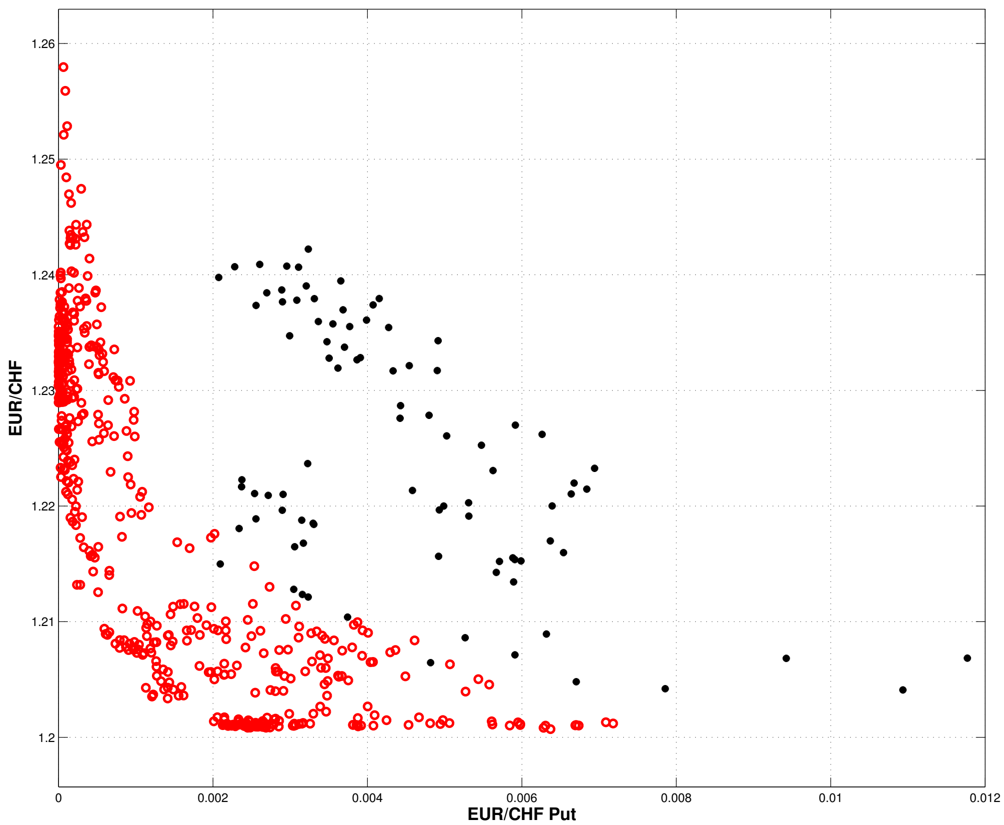
The figure plots the risk-neutral probability that the Swiss franc will note below 1.20 to the euro at the expiration dates of option contracts, which lies one month in the future, against the Swiss franc/euro exchange rate that is measured in units of Swiss francs per euro. The risk-neutral density function for Swiss franc prices of one euro is obtained by interpolating the volatility smile as suggested by Malz (1997), details are described in section (3.3). Black dots denote data points that lie between September 6, 2011 and January 13, 2012, and red circles mark data points between January 2012 and January 2014. This break point in January 2012 is motivated by the observation that around that date, the Swiss franc noted at its lower bound for the first time since the SNB announced to defend a Swiss franc lower bound of EUR/CHF=1.20. The data is at daily frequency and includes all days that were trading days in Switzerland and in the US.

Figure 13: Krugman (1991) exchange rate function: EUR/CHF and implied probability for EUR/CHF<1.20 residuals



The figure plots the residuals from regressing the risk-neutral probability that the Swiss franc will note below 1.20 to the euro one month in the future on a constant, the level of the EUR/CHF spot exchange rate and the lagged risk-neutral probability against the Swiss franc/euro exchange rate that is measured in units of Swiss francs per euro. The risk-neutral density function for Swiss franc prices of one euro is obtained by interpolating the volatility smile as suggested by Malz (1997), details are described in section (3.3). Black dots denote data points that lie between September 6, 2011 and January 13, 2012, and red circles mark data points between January 2012 and January 2014. This break point in January 2012 is motivated by the observation that around that date, the Swiss franc noted at its lower bound for the first time since the SNB announced to defend a Swiss franc lower bound of EUR/CHF=1.20. The data is at daily frequency and includes all days that were trading days in Switzerland and in the US.

Figure 14: Krugman (1991) exchange rate function: EUR/CHF and EUR/CHF put price with strike 1.20



The figure plots the price of an EUR/CHF put option with a strike of EUR/CHF=1.20 and one time to maturity against the Swiss franc/euro exchange rate that is measured in units of Swiss francs per euro. Put prices are obtained from the interpolated risk-neutral density function for the Swiss franc prices of one euro as suggested by Malz (1997), details are described in section (3.3). Black dots denote data points that lie between September 6, 2011 and January 13, 2012, and red circles mark data points between January 2012 and January 2014. This break point in January 2012 is motivated by the observation that around that date, the Swiss franc noted at its lower bound for the first time since the SNB announced to defend a Swiss franc lower bound of EUR/CHF=1.20. The data is at daily frequency and includes all days that were trading days in Switzerland and in the US.

Table 1: Summary statistics of exchange rate fundamentals

	ESTX50	BOND	VIX	FX VXY	CSFB	Prob(EUR/CHF<1.20)	P(K=1.20)
mean	2648	106	20.77	11.11	24.4457	0.1333	0.0019
st.dev	254	2.75	6.7970	2.0629	4.6871	0.1127	0.0019
skewness	-0.4127	-0.1913	1.1320	0.0039	-0.1224	0.4104	1.1938
kurtosis	2.2647	2.2952	3.8778	2.2256	2.2588	1.9041	4.6271
ADF constant, trend	-2.6	-1.8923	-5.2	-4.1255	-0.56	-0.44	-0.49
ADF constant,	-2.6	-1.3875	-4.5	-2.6402	-0.35	-0.26	-0.31
nobs	1162	1186	1186	1186	1186	588	589
time span	2009(4) - 2014(1)	2009(4) - 2014(1)	2009(4) - 2014(1)	2009(4) - 2014(1)	2009(4) - 2014(1)	2011(11) - 2014(1)	2011(11) - 2014(1)

The table shows summary statistics for the variables that serve as state variables for the EUR/CHF exchange rate. $ESTX50$ and $BOND$ are the EURO STOXX 50 Index and Barclay's euro aggregate government bond index, VIX, $FX\ VXY$, and $CSFB$ denote the VIX index of implied volatility in S&P index options provided by the CBOE, JP Morgan's FX VXY option implied volatility index for the G7 currencies, and the Credit Suisse First Boston Risk Appetite Index respectively. $Prob(EURCHF) < 1.20$ is the option implied probability for an EUR/CHF exchange rate below 1.20, and $P(K = 1.20)$ is the price of an EUR/CHF put with a strike of 1.20 and a time to maturity of one month. The data is at daily frequency, and the dataset includes all days that were trading days in the USA and in Switzerland. Augmented Dickey-Fuller test statistics are computed including a constant and either a trend or not. Asymptotic critical values are given by -3.96 (1%), -3.41 (5%) for the case with a linear time trend and by -3.43 (1%), -2.86 (5%) for the case without linear time trend. The number of lags is chosen according to the AIC information criterion.

Table 2: Relationship between EUR/CHF and market fundamentals

$(\Delta ESTX50 : \Delta ESTX50 > 0) \times s_{\Delta 1.20}$	1.4342		1.4079		
	(1.0268)		(0.9674)		
$(\Delta ESTX50 : \Delta ESTX50 < 0) \times s_{\Delta 1.20}$	**5.5210**		**5.6474**		
	(4.5208)		(4.0749)		
$(\Delta BOND : \Delta BOND > 0) \times s_{\Delta 1.20}$		-1.6837	-1.3723		
		(-0.2624)	(-0.2336)		
$(\Delta BOND : \Delta BOND < 0) \times s_{\Delta 1.20}$		8.0344	-1.1097		
		(1.3821)	(-0.2020)		
$(\Delta ESTX50) \times s_{\Delta 1.20}$				**3.5949**	
				(3.6766)	
$(\Delta BOND) \times s_{\Delta 1.20}$					4.3190
					(0.9755)
$\Delta ESTX50$	-0.0086		-0.0081	-0.0110	
	(-0.8209)		(-0.7622)	(-1.0273)	
$\Delta BOND$		-0.0743	-0.0359		-0.0883
		(-1.3192)	(-0.7719)		(-1.4964)
$s_{\Delta 1.20}$	-0.0046	-0.0151	-0.0049	**-0.0233**	**-0.0239**
	(-0.4343)	(-1.6669)	(-0.5086)	(-3.2757)	(-3.1350)
$const$	**0.0004**	**0.0004**	**0.0004**	**0.0004**	**0.0004**
	(3.2988)	(3.2540)	(3.3216)	(3.1583)	(3.3072)
$\overline{R}$	0.13	0.01	0.13	0.11	0.01
nobs	563	587	563	563	587

The table reports coefficient estimates as well as t-statistics from regressing percentage changes in the Swiss franc to euro exchange rate on the covariates listed in the first column of the table. The covariance matrix of the error term has been estimated following Newey & West (1987) and Newey and West (1994). $\Delta ESTX50$ and $\Delta BOND$ denote log differences of the EURO STOXX 50 Index and Barclay's euro aggregate government bond index respectively. $s_{\Delta 1.20}$ denotes the percentage deviation of the Swiss franc to euro exchange rate from its lower bound which has been set by the Swiss National Bank at CHF 1.20 per on EUR. The data is at daily frequency and covers all days that were trading days in the US and Switzerland over the period from September 6, 2011 to January 31, 2014.

Table 3: Relationship between EURCHF and market fundamentals

$(\Delta VIX : \Delta VIX > 0) \times s_{\Delta 1.20}$	**-0.6445**					
	(-4.2307)					
$(\Delta VIX : \Delta VIX < 0) \times s_{\Delta 1.20}$	-0.1263					
	(-0.6906)					
$(\Delta VXY : \Delta VXY > 0) \times s_{\Delta 1.20}$		-0.2817				
		(-0.2935)				
$(\Delta VXY : \Delta VXY < 0) \times s_{\Delta 1.20}$		0.4809				
		(0.7030)				
$(\Delta CSFB : \Delta CSFB > 0) \times s_{\Delta 1.20}$			-0.5775			
			(-1.6168)			
$(\Delta CSFB : \Delta CSFB < 0) \times s_{\Delta 1.20}$			0.1357			
			(0.2842)			
$(\Delta VIX) \times s_{\Delta 1.20}$				**-0.4462**		
				(-3.3889)		
$(\Delta VXY) \times s_{\Delta 1.20}$					0.1225	
					(0.2027)	
$(\Delta CSFB) \times s_{\Delta 1.20}$						-0.2468
						(-0.7816)
ΔVIX	-0.0021			-0.0018		
	(-1.2815)			(-1.1410)		
ΔVXY		-0.0051			-0.0055	
		(-0.8896)			(-0.9429)	
$\Delta CSFB$			0.0056			0.0057
			(1.6736)			(1.5786)
$s_{\Delta 1.20}$	-0.0110	-0.0168	-0.0124	**-0.0216**	**-0.0238**	**-0.0237**
	(-1.2380)	(-1.6807)	(-1.0264)	(-2.9254)	(-3.0553)	(-3.0346)
const	**0.0004**	**0.0004**	**0.0004**	**0.0004**	**0.0004**	**0.0004**
	(3.2651)	(3.2401)	(3.2875)	(3.1452)	(3.2687)	(3.3187)
$\overline{R}$	0.09	0.01	0.02	0.08	0.01	0.01
nobs	587	587	587	587	587	587

The table reports coefficient estimates as well as t-statistics from regressing percentage changes in the Swiss franc to euro exchange rate on the covariates listed in the first column of the table. The covariance matrix of the error term has been estimated following Newey & West (1987) and Newey and West (1994). ΔVIX, ΔVXY, and $\Delta CSFB$ denote log differences of the VIX index of implied volatility in S&P index options provided by the CBOE, of JP Morgan's FX VXY option implied volatility index for the G7 currencies, and of the Credit Suisse First Boston Risk Appetite Index respectively. $s_{\Delta 1.20}$ denotes the percentage deviation of the Swiss franc to euro exchange rate from its lower bound which has been set by the Swiss National Bank at CHF 1.20 per on EUR. The data is at daily frequency and covers all days that were trading days in the US and Switzerland over the period from September 6, 2011 to January 31, 2014.

Table 4: Relationship between EURCHF and market fundamentals

	Sept 2011 - Jan 2014		Jun 2010-Aug 2011		Apr 2009 - May 2010	
$\Delta ESTX50 \times S$	**3.5949**		-1.0169		0.5107	
	(3.6766)		(-2.3577)		(0.9391)	
$\Delta BOND \times S$		4.3190		3.4622		**-12.2105**
		(0.9755)		(1.1352)		(-4.4241)
$\Delta ESTX50$	**-0.6664**		**0.4998**		-0.1565	
	(-3.5889)		(4.3201)		(-0.7209)	
$\Delta BOND$		-0.8757		**-1.7055**		**4.7528**
		(-1.0324)		(-2.0786)		(4.2347)
S	**-0.0233**	**-0.0239**	-0.0204	-0.0168	-0.0052	0.0005
	(-3.2757)	(-3.1350)	(-1.7102)	(-0.9596)	(-0.5153)	(0.0507)
$const$	0.0046	0.0048	0.0051	0.0035	0.0018	-0.0004
	(3.3668)	(3.2386)	(1.6435)	(0.7480)	(0.4368)	(-0.1030)
$\overline{R}$	0.11	0.01	0.21	0.06	0.05	0.06
nobs	563	587	311	311	283	283

The table reports coefficient estimates as well as t-statistics from regressing percentage changes in the Swiss franc to euro exchange rate on the covariates listed in the first column of the table. The covariance matrix of the error term has been estimated following Newey & West (1987) and Newey and West (1994). $\Delta ESTX50$ and $\Delta BOND$ denote log differences of the EURO STOXX 50 Index and Barclay's euro aggregate government bond index respectively. S denotes the log level of the Swiss franc to euro exchange rate. The data is at daily frequency.

Table 5: Relationship between EURCHF and market fundamentals

	Sept 2011 - Jan 2014			Jun 2010-Aug 2011			Apr 2009 - May 2010		
$\Delta VIX \times S$	**-0.4462**			0.0041			-0.0863		
	(-3.3889)			(0.0370)			(-0.7715)		
$\Delta VXY \times S$		0.1225			**1.2477**			0.0733	
		(0.2027)			(5.0144)			(0.1260)	
$\Delta CSFB \times S$			-0.2468			-0.3021			-0.2763
			(-0.7816)			(-1.4044)			(-1.0668)
ΔVIX	**0.0795**			-0.0500			0.0252		
	(3.1539)			(-1.7880)			(0.5613)		
ΔVXY		-0.0278			**-0.4101**			-0.0511	
		(-0.2431)			(-6.8264)			(-0.2164)	
$\Delta CSFB$			0.0507			**0.1298**			0.1227
			(0.8372)			(2.2897)			(1.1867)
S	**-0.0216**	**-0.0238**	**-0.0237**	-0.0150	-0.0123	-0.0105	-0.0041	-0.0048	-0.0020
	(-2.9254)	(-3.0553)	(-3.0346)	(-1.1002)	(-1.1504)	(-0.7773)	(-0.4246)	(-0.4910)	(-0.1744)
const	**0.0043**	**0.0047**	**0.0047**	0.0031	0.0024	0.0020	0.0014	0.0017	0.0005
	(3.0215)	(3.1531)	(3.1369)	(0.8418)	(0.8471)	(0.5408)	(0.3533)	(0.4233)	(0.1167)
$\overline{R}$	0.08	0.01	0.01	0.17	0.24	0.12	0.02	0.03	0.03
nobs	587	587	587	311	311	311	283	283	283

The table reports coefficient estimates as well as t-statistics from regressing percentage changes in the Swiss franc to euro exchange rate on the covariates listed in the first column of the table. The covariance matrix of the error term has been estimated following Newey & West (1987) and Newey and West (1994). ΔVIX, ΔVXY, and $\Delta CSFB$ denote log differences of the VIX index of implied volatility in S&P index options provided by the CBOE, of JP Morgan's FX VXY option implied volatility index for the G7 currencies, and of the Credit Suisse First Boston Risk Appetite Index respectively. S denotes the log level of the Swiss franc to euro exchange rate. The data is at daily frequency.

Table 6: Summary statistics of currency option implied volatilities

		ATM		RR25		BF25		RR10		BF10	
		mean	std	mean	std	mean	std	mean	std	mean	std
EURCHF	Apr 1, 2009 - Mai 31, 2010	4.9139	1.4305	-0.1278	0.6151	0.3065	0.1027	-0.2636	1.0771	1.0597	0.3416
	July 1, 2010 - Sept 5, 2011	11.3609	2.7969	-1.3852	0.8157	0.3184	0.0922	-2.3953	1.4210	1.0341	0.4216
	Sept 6, 2011- January 31, 2014	4.57485	2.2755	0.6162	1.1970	0.5940	0.5086	0.9277	2.3724	1.9525	1.6073

The three columns under each contract report the mean (mean) and the standard deviation (std) of the contract on risk reversal (RR), butterfly spread (BF), and delta-neutral straddle implied volatilities (ATM). The numbers following the RR and BF denote the delta of the contract. Data are daily, for each series, the starting date of each series is indicated in tiny letters. All data series end on July 25, 2013. Weekends and non-trading days excluded.

Table 7: Central bank variable

Date	Central Bank	Event	Source
06.09.11	SNB	Swiss National Bank sets minimum exchange rate at CHF 1.20 per euro	*
08.09.11	ECB	Monetary policy decision	***
15.09.11	ECB	ECB announces additional US dollar liquidity-providing operations.	**
15.09.11	SNB	Monetary policy assessment of 15 September 2011	*
15.09.11	SNB	Central banks extend provision of US dollar liquidity.	*
30.09.11	ECB	Results of the Euro Money Market Survey 2011	***
06.10.11	ECB	ECB announces second covered bond purchase program. ECB announces details of refinancing operations.	**
11.10.11	ECB	Statement by EC, ECB and IMF on fifth review mission to Greece	**
01.11.11	ECB	New European Central Bank president	**
03.11.11	ECB	ECB lowers interest rates by 25 basis points. ECB announces details of its second covered bond purchase program.	**
16.11.11	ECB	Statement by EC, ECB and IMF on second review mission to Portugal.	**
21.11.11	SNB	New agreement on the distribution of the SNB profit	*
30.11.11	ECB	Coordinated central bank action to address pressures in global money markets	***
30.11.11	SNB	Coordinated central bank action to address pressures in global money markets	*
08.12.11	ECB	ECB lowers interest rates by 25 basis points. ECB announces measures to support bank lending and money market activity.	**
15.12.11	SNB	Monetary policy assessment of 15 December 2011	*
16.12.11	ECB	ECB announces two one-day liquidity-providing fine-tuning operations.	***
22.12.11	ECB	ECB allots €489 billion to 523 banks in first 36-mont longer-term refinancing operation.	**
23.12.11	SNB	Announcement by the Bank Council of the Swiss National Bank: Rumors concerning Chairman of SNB Governing Board prove to be without foundation.	*
07.01.12	SNB	Bank Council of the Swiss National Bank tightens control.	*
09.01.12	SNB	Swiss National Bank Chairman, Philipp Hildebrand, resigns with immediate effect.	*
13.01.12	SNB	Swiss National Bank expects annual profit of CHF 13 billion and will be able to make distribution.	*
19.01.12	ECB	Statement by European Commission, ECB, and IMF on review mission to Ireland.	**
09.02.12	ECB	ECB approves eligibility criteria for additional credit claims.	**
12.01.12	ECB	Monetary policy decision	***
28.02.12	ECB	ECB temporarily suspends eligibility of Greek bonds as collateral. Statement by European Commission, ECB and IMF on review mission to Portugal.	**
01.03.12	ECB	ECB allots €530 billion to 800 banks in second 36-month longer-term refinancing operation.	**
08.03.12	SNB	Annual result of the Swiss National Bank for 2011	*
15.03.12	SNB	Monetary policy assessment of 15 March 2012	*
04.04.12	ECB	Monetary policy decision	***
05.04.12	ECB	Assessment of a new direct link between securities settlement systems in the euro area.	***
18.04.12	SNB	New SNB Governing Board: Thomas Jordan becomes Chairman, Jean-Pierre Danthine becomes Vice Chairman and Fritz Zurbrügg joins Board.	*
03.05.12	ECB	Monetary policy decision	***
04.06.12	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal	**
06.06.12	ECB	ECB announces details of refinancing operations with settlement in the period from 11 July to 15 January 2013.	***
14.06.12	SNB	Monetary policy assessment	*
22.06.12	ECB	ECB takes further measures to increase collateral availability for counterparties.	***
25.06.12	SNB	Swap agreement between the Swiss National Bank and the National Bank of Poland	*
05.07.12	ECB	ECB lowers rates.	**

Table 8: central bank variable cont'd

Date	Central Bank	Event	Source
12.07.12	ECB	Statement by European Commission, ECB and IMF on review mission to Ireland	**
20.07.12	ECB	ECB suspends Greek bonds as collateral.	**
02.08.12	ECB	Monetary policy decision	***
27.08.12	SNB	Swiss National Bank: No proposal for activation of countercyclical capital buffer	*
06.09.12	ECB	ECB announces technical features of Outright Monetary Transactions.	**
11.09.12	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal. Greek Prime Minister visits the ECB.	**
12.09.12	ECB	ECB extends the swap facility agreement with the Bank of England.	***
13.09.12	SNB	Monetary policy assessment	*
28.09.12	ECB	ECB welcomes Spanish authority's announcement on bottom-up stress test.	**
04.10.12	ECB	Monetary policy decision	***
25.10.12	ECB	Statement by European Commission and ECB on first review of financial assistance program for Spain.	**
31.10.12	ECB	Ending of covered bond purchase program 2 (CBPP2)	***
08.11.12	ECB	Monetary policy decision	***
19.11.12	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal.	**
27.11.12	ECB	ECB announces rescheduling of loan-level data reporting requirements.	**
06.12.12	ECB	ECB announces details of refinancing operations with settlement in the period from 16 January to 9 July 2013.	***
13.12.12	ECB	ECB extends the existing swap arrangements with other central banks. Mario Draghi welcomes agreement on SSM.	***
13.12.12	SNB	Monetary policy assessment	*
13.12.12	SNB	Central banks extend swap arrangements until February 2014	*
18.12.12	SNB	Swiss National Bank opens branch in Singapore.	*
19.12.12	ECB	ECB reinstates Greek bonds as collateral.	**
20.12.12	SNB	Decrees issued by the Swiss National Bank concerning systemic importance.	*
10.01.13	ECB	Monetary policy decision	***
17.01.13	SNB	Swiss National Bank expects annual profit of CHF 6 billion	*
04.02.13	ECB	Statement by European Commission and ECB on second review of financial assistance program for Spain	**
07.02.13	ECB	Statement by European Commission, ECB and IMF on review mission to Ireland.	**
13.02.13	SNB	Countercyclical capital buffer: proposal of the Swiss National Bank and decision of the Federal Council	*
21.02.13	ECB	Details on securities holdings acquired under the Securities Markets Program	***
07.03.13	ECB	Monetary policy decision	***
14.03.13	SNB	Monetary policy assessment	*
15.03.13	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal	**
22.03.13	ECB	ECB announces changes to the use as collateral of certain uncovered government-guaranteed bank bonds.	***
04.04.13	ECB	Monetary policy decision	***
05.04.13	SNB	Revision of financial market infrastructure oversight: Swiss National Bank launches consultation phase.	*
15.04.13	ECB	Statement by the European Commission, ECB and IMF on the conclusion of the review mission to Greece.	**
18.04.13	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal	**
02.05.13	ECB	ECB reinstates Cypriot bonds as collateral. ECB lowers rates.	**
09.05.13	ECB	Statement by European Commission, ECB and IMF on review mission to Ireland.	**
31.05.13	ECB	ECB welcomes the introduction of separate EONIA and EURIBOR panels.	**
03.06.13	ECB	Cypriot President visits the ECB.	**
06.06.13	ECB	Monetary policy decision	***
20.06.13	SNB	Monetary policy assessment	*

Table 9: central bank variable cont'd

Date	Central Bank	Event	Source
25.06.13	SNB	Partial revision of National Bank Ordinance enters into force.	*
28.06.13	ECB	Eligibility of marketable debt instruments issued or guaranteed by the Republic of Cyprus.	***
04.07.13	ECB	ECB says that it expects key interest rates to remain at present or lower levels for an extended period of time.	**
05.07.13	ECB	ECB reactivates eligibility of Cypriot bonds as collateral.	**
18.07.13	ECB	ECB strengthens its risk control framework. Statement by European Commission, ECB and IMF on the 11th review mission to Ireland.	**
01.08.13	ECB	ECB welcomes Cypriot authority's decision to conclude the resolution of the country's major bank.	**
16.08.13	SNB	SNB StabFund repays Swiss National Bank loan	*
05.09.13	ECB	Monetary policy decision	***
12.09.13	ECB	ECB welcomes European Parliament vote to create single supervisory mechanism.	**
19.09.13	SNB	Monetary policy assessment of 19 September 2013	*
27.09.13	ECB	ECB adopts decisions to follow up on the review of its risk control framework.	***
30.09.13	ECB	Statement by European Commission and ECB on the fourth review of the financial sector assistance program for Spain	**
02.10.13	ECB	Monetary policy decision	***
03.10.13	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal	**
10.10.13	ECB	ECB and the People's Bank of China establish a bilateral currency swap agreement.	***
31.10.13	ECB	ECB establishes standing swap arrangements with other central banks.	***
07.11.13	ECB	ECB lowers rates. Statement by European Commission, ECB and IMF on review mission to Cyprus.	**
20.11.13	ECB	ECB nominates Danièle Nouy as Chair of the Supervisory Board of the SSM.	**
21.11.13	ECB	ECB suspends early repayments of the three year LTROs during the year end period.	***
05.12.13	ECB	Monetary policy decision	***
16.12.13	ECB	Statement by European Commission, ECB and IMF on review mission to Portugal.	**
09.01.14	ECB	Monetary policy decision	***
24.01.14	ECB	US dollar liquidity-providing operations as of 1 February 2014	***

The table lists the events that build the central bank event variable. These events consist of important actions or statements by either the ECB or the SNB. The events concerning the SNB are collected from press releases available at `http://www.snb.ch/en/ifor/media/id/media_releases?dsrp_446ddb0d.page=1` (*). ECB events are collected from `http://www.ecb.europa.eu/ecb/html/crisis.en.html` (**), and from `http://www.ecb.europa.eu/press/pr/activities/mopo/html/index.en.html` (***).

Table 10: Correlation of changes in $g(t)$ and other exchange rate fundamentals

	$\Delta(ESTX50)$	$\Delta BOND$	ΔVIX	ΔVXY	$\Delta CSFB$
$\Delta(\Pi(K=1.20,\tau)$	-0.2433	0.0221	0.2443	0.1700	-0.1329
p-value	4.9693e-09	0.5933	2.0093e-09	3.4525e-05	0.0013

The table shows correlation coefficients between changes in the risk-neutral probability that the Swiss franc notes below CHF 1.20 to the euro with first differences of other potential exchange rate fundamentals, as well as p-values for testing the hypothesis of no correlation against the alternative that there is a non-zero correlation. If the p-value is small, say less than 0.05, then the correlation is significantly different from zero. $\Delta\Pi(K,\tau)$ denotes first differences of the probability that the Swiss franc notes below 1.20 to the euro implied from the prices of currency options with one month time to maturity. $\Delta ESTX50$ and $\Delta BOND$ denote differences of the EURO STOXX 50 Index and Barclay's euro aggregate government bond index, and ΔVIX, ΔVXY, and $\Delta CSFB$ denote first differences of the VIX index of implied volatility in S&P index options provided by the CBOE, of the JP Morgan's FX VXY option implied volatility index for the G7 currencies, and of the Credit Suisse First Boston Risk Appetite Index respectively. The data is at daily frequency and spans the period from September 2011 to January 2014.

Table 11: Nonlinear relationship between EURCHF and "intensity of realignment"

$(\Delta g : \Delta g > 0) \times (S_t - 1.20)$	**-3.6640**	
	(-10.0732)	
$(\Delta g : \Delta g < 0) \times (S_t - 1.20)$	**-5.6926**	
	(-11.3800)	
$\Delta g \times (S_t - 1.20)$		**-4.3598**
		(-11.9619)
Δg	0.0042	0.0031
	(1.8460)	(1.3202)
$(S_t - 1.20)$	**-0.0122**	-0.0054
	(-3.1246)	(-1.4204)
$\Delta \log(S_{t-1})$	**0.1108**	**0.1074**
	(2.6213)	(2.5221)
const	0.0001	**0.0002**
	(1.2738)	(2.8293)
$\overline{R}$	0.63	0.61
nobs	586	586

The table reports coefficient estimates as well as t-statistics from running the following regression

$$\Delta \log(S_t) \quad = \quad const + \beta_1 \Delta g_t \times (S_t - 1.20) + \beta_2 \Delta g_t + \beta_3 (S_t - 1.20) + \beta_4 \Delta \log(S_{t-1})$$

where S_t denotes the EUR/CHF spot exchange rate observed at date t, and $g_t = \Pi(K = 1.20, \tau)$ is the risk-neutral probability implied by the prices of options with one month time to maturity that the Swiss franc notes below EUR/CHF=1.20. Δ denotes first differences. The covariance matrix of the error term has been estimated following Newey & West (1987) and Newey and West (1994). The data is at daily frequency and covers the period from September 2011 to January 2014.