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The Swiss franc's honeymoon

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Abstract

Starting from the stylized fact that the Swiss franc is a safe haven currency, this paper focuses on the determinants of the Swiss franc during the lower bound regime from September 2011 to January 2015. We describe the Swiss franc as a function of global market risk fundamentals and find that the macroeconomic model outlined by Krugman (1991) describes the EUR/CHF exchange rate well during this particular time. We show that, as predicted by Krugman's model, the sole expectation that the Swiss National Bank would prevent the Swiss franc from appreciating beyond 1.20 to the euro muted the sensitivity of EUR/CHF to global market risk. An important assumption for the model prediction to hold is that the central bank's commitment to the exchange rate target is credible. We thus use EUR/CHF option prices together with the global market risk fundamental to assess the credibility of the lower bound. We find that the only true credibility issue was in November 2014. After November 2014 the Swiss National Bank could convince markets anew from its target-zone policy and suspend the lower bound unexpectedly a few weeks later.

JEL Classification Numbers: E52, E58, F31, G01

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

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1 Introduction

The Swiss franc is a safe haven currency: during the last hundred years, the Swiss franc has been appreciating whenever markets have been volatile and declining worldwide (see for example Baltensperger & Kugler, 2016). Likewise, the franc rapidly gained in value against all major currencies in the aftermath of the Global Financial Crisis of 2008/2009. In the wake of the subsequent European sovereign debt crisis, low interest rates and a massive expansion of the Swiss monetary base could not halt the unchecked appreciation of the Swiss franc against all major currencies. As the strength of the Swiss franc started to severely challenge the Swiss economy, on 6 September 2011, the Swiss National Bank (SNB) took action and declared to enforce a minimum exchange rate of 1.20 Swiss francs per one euro for an indefinite period of time. Markets were surprised by this sudden policy change, but probably even more so when the SNB abruptly declared the end of this lower bound regime on 15 January 2015.

Taking the safe haven property of the Swiss franc as a given, this paper follows a macroeconomic approach and describes the Swiss franc as a function of fundamentals that mirror global market sentiment, such as for example the VIX.[1] In particular, this paper focuses on the determinants of the Swiss franc during the lower bound regime over September 2011 to January 2015. We find that the Krugman (1991) model for the behavior of exchange rates within target zones describes the Swiss franc/euro exchange rate well during this particular time. In Krugman's model, the market's expectation that a central bank will intervene once its exchange rate is about to surpass the announced bounds is sufficient to stabilize exchange rates everywhere. Accordingly, we find that no actual Swiss National Bank interventions were needed to shield the Swiss franc from worldwide market turbulences, with two exceptions, one during spring 2012, and a second one during fall 2014. As Krugman's (1991) model predicts, the sensitivity of the Swiss franc to its global risk fundamentals — the Swiss franc's safe haven property — declined as the franc approached the EUR/CHF $= 1.20$ lower bound. Further, we contrast this result to the behavior of the Swiss franc during periods characterized by either a freely floating exchange rate, or by substantial Swiss National Bank interventions independent of an explicitly communicated exchange rate target.

[1]Throughout this paper, VIX denotes the CBOE Volatility Index which is derived from the traded option contracts on the S&P500 index.

In this paper, we show that Krugman's (1991) simple, though elegant model can illustrate how powerful the SNB's monetary policy experiment has been. This result is remarkable since many empirical research on exchange rate target zones have rather rejected version of Krugman's (1991) approach. The most crucial model assumption is that the central bank's commitment to the exchange rate target is *credible*. Applied to the Swiss-franc-lower-bound-regime, the model requires that *markets put no probability on exchange rate realizations below* EUR/CHF $=$ 1.20. The second part of this paper qualifies our results through the lens of this strong prerequisite. We crystallize a Swiss-franc specific *mistrust-factor* from EUR/CHF currency option prices and from global option prices – from the VIX in particular – and conclude that the Swiss National Bank's credibility with respect to the lower bound regime has severely been put into question only over November 2014. We think that the strong appreciation pressure on the Swiss franc over spring 2012 was rather related to fear of a break-up of the Eurozone which, obviously, would have ended the Swiss franc lower bound regime, than to mistrust in the SNB's lower-bound commitment. We assert that the SNB suspended the "Swiss franc's lower-bound honeymoon" a few weeks after true mistrust towards the SNB's exchange rate policy announcement had arisen for the first time.

The next section introduces the global market risk state variable VIX as a macroeconomic fundamental for EUR/CHF. It unveils that the explanatory power of this VIX-global-market-risk-fundamental for the Swiss franc varies over episodes characterized by different Swiss National Bank monetary policy regimes. Section (3) presents the Krugman (1991) exchange-rate-target-zone model and shows that it describes the behavior of EUR/CHF well during the Swiss franc lower bound episode. Krugman's (1991) macroeconomic model describes exchange rates as a function of macroeconomic fundamentals, K. Whenever we refer to the VIX in its particular role as such an exchange rate fundamental, K, we refer to it as K_{VIX}. Section (4) uses currency option prices to assess the credibility of the SNB's lower-bound commitment. This is not only a crucial condition in the Krugman model, but also interesting per se. Section (5) relates the analysis in this paper to the recent literature, and Section (6) concludes.

2 Episodes of different Swiss franc regimes

To begin with, Figure (1) plots the Swiss franc/euro spot exchange rate together with the VIX, and with the Swiss National Bank's foreign currency reserves, over 2008 to 2016. Vertical lines separate five episodes of different Swiss franc exchange rate policy regimes. These episodes are identified by the SNB's officially announced policy stance in the Quarterly Bulletins,[2] together with the evolution of the central bank's foreign currency reserves.[3] Interestingly, these episodes also differ by the volatility of EUR/CHF conditional on the VIX- volatility of global markets. This observation forms the starting point of our analysis.

First, we identify two "free-float-periods" the first of which stops in April 2009, and the second reaches from June 2010 to September 2011. Over these episodes, the SNB had not communicated any exchange rate target and its foreign currency reserves remained broadly unchanged. When floating freely, the Swiss franc is volatile and co-moves strongly with the VIX: global market sentiment, as indicated by this index, importantly determines the value of the Swiss franc. This stands in sharp contrast to the franc's behavior during two "intervention-periods": between April 2009 and June 2010, and since January 2015, the SNB announced to prevent the Swiss franc from appreciating,[4] and increasing foreign currency reserves in its balance sheet indicate that it traded accordingly — with limited success over spring 2010 however. During these intervention-periods, the Swiss franc's volatility is muted. Note that these intervention-periods are not shaped by an explicitly communicated exchange rate target, which importantly distinguishes them from the unique "lower-bound-period" over September 2011 to January 2015. As regards the volatility of the exchange rate, it is only during the lower-bound regime that it is level-dependent: it is higher whenever EUR/CHF notes further above the lower bound of 1.20. This is exciting, because it corresponds exactly to what Krugman's (1991) model will predict.

Table (1) confirms the above conclusions concerning the different exchange rate regimes. The

[2]https://www.snb.ch/en/iabout/pub/oecpub/id/pub_oecpub_quartbul

[3]https://data.snb.ch/en

[4]After the franc had appreciated sharply against the euro in the wake of the Global Financial Crisis in 2008, the SNB announced to *prevented the Swiss franc from appreciating further against the euro* – see the SNB's quarterly assessments of March, June, September, and December 2009, and of March 2010. Since the suspension of the Swiss franc lower bound, the SNB communicates to *take account of the exchange rate situation*, and *therefore remain active in the foreign exchange market, as necessary*: see the SNB's quarterly assessments over 2015 and 2016, https://www.snb.ch/en/iabout/pub/oecpub/id/pub_oecpub_quartbul.

table shows least square estimates from regressing percentage changes of EUR/CHF on percentage changes of the VIX. As expected, changes in the VIX are negatively correlated with changes in the Swiss franc's price during the free-float periods. Higher global market risk implies a higher value of the Swiss franc. During the intervention-periods in contrast, VIX cannot explain EUR/CHF. Last, the VIX does explain EUR/CHF during the lower-bound-period, but coefficient estimates and R^2-measures are lower than during the free-float episodes. This conforms with the predictions of Krugman's 1991 model.

Important explanatory power of global risk factors for the Swiss franc, such as the VIX, is also documented in Griesse & Nitschka (2013), who further document increasing sensitivity of the Swiss franc to global risk in times of high uncertainty. Similarly, Ranaldo & Soderlind (2010) find that the Swiss franc appreciates systematically against the euro when global equity markets, bond markets, and currency markets signal difficult economic conditions. Kugler & Weder di Mauro (2005) document that the Swiss franc pays high returns if unexpected events that increase world-wide political uncertainty happen. Taking an asset pricing approach, Verdelhan (2011) and Hoffmann & Suter (2010) construct a global risk factor from a large cross-section of currency returns and find that this factor has important explanatory power for excess returns of the Swiss franc. All this evidence challenges the conclusion put forward by Meese & Rogoff (1983) whereby exchange rates basically are unpredictable,[5] and it supports the macroeconomic explanation of EUR/CHF we suggest in this paper within Paul Krugman's (1991) model.

[5]There exists a growing literature that documents that currency returns are predictable from economic fundamentals. 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 conditional on several standard macroeconomic 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.

3 A model for exchange rates within a target zone

Paul Krugman's (1991) elegant model became the starting point for much research on the economics of exchange rate target zones which was of high interest during the European Exchange Rate Mechanism (ERM) of the European Monetary System (EMS). In this system, introduced in 1979, member countries of the European Economic Community (EEC) agreed to peg their bilateral exchange rates within fluctuation bands of no more than ± 2.25 percent around central parities. However, these exchange rate bands have frequently been realigned, and after speculative attacks have urged the British pound and the Italian lira to leave the system, the German Reunification eventually triggered the collapse of the system in 1993.

For operating exchange-rate target-zones, Krugman (1991) describes a macroeconomic model in which the exchange rate is an S-shaped function of fundamentals. This function obtains under two important model assumptions. First, a central bank's commitment to the target-zone must be *credible*. Credible in this context means that *markets never doubt the continuation of the lower bound*. Second, central banks must intervene in currency markets only when exchange rates effectively threaten to touch one of the edges of the band. Probably because these conditions did not hold in reality, empirical tests mostly rejected Krugman's model. In the ERM, central bank interventions were frequent also inside the band,[6] and realignments of the currency bands happened on several occasions thus rationalizing doubt on the continuation of existing currency bands. All around the world, speculative attacks frequently made exchange-rate target-zones collapse.[7]

For the Swiss franc, the situation is different. First, the Swiss National Bank has announced to defend a strong-side bound for its currency. This implies that no speculative attacks are possible that would urge a sudden realignment or a suspension of the exchange-rate bound, because a central bank can expand the monetary base of its currency without limits. Because of this, a strong-side exchange rate commitment is likely to be more credible than any weak-side

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

[7] 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.

commitment. Hence, a central bank can be more relaxed to let its currency float very closely to the edge of the band. Figure (1) suggests that the SNB did so because foreign currency reserves never increase when EUR/CHF noted above 1.20. The stability of the Swiss franc exchange rate target zone solely rests upon the willingness of the SNB to accumulate foreign exchange reserves in unlimited quantities when necessary, and to stand firm against political pressure to rise or lower the exchange rate bound. In these respects, the Swiss case is unique — the *credibility condition* (as we will argue later in more detail) and the *no-interventions-above-the-bound condition* are fulfilled such that Krugman's (1991) model applies.

3.1 Krugman's (1991) model

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

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

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 the exchange rate equation (1), the domestic money supply m and a shift term κ. 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 notes above $\underline{s}$, money supply remains unchanged. The only exogenous source of exchange rate dynamics is the shift term κ. In Krugman's exposition of the model, κ represents a velocity shock. As we focus on the Swiss franc in its role as a safe haven currency, we specify κ to be a state variable for global market risk, whereby higher κ indicates tighter markets: higher κ implies a lower s which corresponds to a more appreciated Swiss franc against the euro.

To solve the model, assume that κ follows a continuous-time random walk

$$d\kappa_t = \mu dt + \sigma dW_t \tag{2}$$

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.

If the monetary authority announces to impose a lower limit on s, we show in the Appendix that the following general solution for the exchange rate function obtains:

$$s(m_t, \text{K}_t) \quad = \quad (m_t - \text{K}_t) + \gamma\mu + B\exp(\lambda(m_t - \text{K}_t)) \tag{3}$$

$\lambda > 0$ is a parameter and $B > 0$ is a constant of integration. Figure (2) sketches this function: given m, s falls in K. Intuitively, since market's expectation that s will increase once it notes at $\underline{s}$ enters the basic exchange rate equation (1), the sensitivity of s on K declines in K. Once persistent increases in K have nevertheless driven the exchange rate to the lower bound, one has to impose that s becomes insensitive to K. Otherwise, changes in s conditional on K would be predictable as the central bank will allow for increases in s only. This would give rise to arbitrage profits. Assuming central bank credibility and considering this no-arbitrage condition, the "bended" fundamental exchange rate function (3) results that Figure (2) depicts.

3.2 The Swiss franc's honeymoon

Figure (3) presents an empirical implementation of the Krugman (1991) exchange rate function (3) with $s =$ EUR/CHF and the VIX as the exchange rate fundamental K_{VIX}. The scatterplot of Figure (3) unveils the model-implied negative, non-linear relationship between K_{VIX} and EUR/CHF: the Swiss franc can be described as a falling, concave function of K_{VIX}. The figure suggests that the Swiss franc becomes less sensitive to K_{VIX} closely above the bound which is also where it clusters: in Krugman's model, exchange rates are expected to move slowly near the edge of the target zone such that – intuitively – they will appear there often.

Table (2) presents the results from testing the Krugman exchange rate function econometrically. The table shows least square coefficient estimates $\{\beta, \gamma, \delta\}$ and corresponding t-statistics for the following regression

$$\Delta s_t \quad = \quad \alpha + \beta\left(\hat{S}_t \Delta \text{K}_t\right) + \gamma \Delta \text{K}_t + \delta \hat{S}_t + \epsilon_t$$

$$\Delta s_t \quad = \quad \alpha + \beta_1\left(\hat{S}_t \Delta \text{K}_{\text{up},t}\right) + \beta_2\left(\hat{S}_t \Delta \text{K}_{\text{down},t}\right) + \gamma \Delta \text{K}_t + \delta \hat{S}_t + \epsilon_t$$

where $\Delta s_t = \ln(S_t) - \ln(S_{t-1})$ are percentage changes in the EUR/CHF spot rate, and $\kappa_t = \kappa_{\text{VIX},t}$. The term $\hat{S}_t = (S_t - \underline{S}) = (S_t - 1.20)$ denotes the level of the actual exchange rate above its lower bound. Eventually, the above regression allows for separate slope coefficients $\beta = \{\beta_1, \beta_2\}$ for upward movements (κ_{up}) and downward movements (κ_{down}) 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 conditional on good market returns. In line with this conclusion, Table (2) shows that the coefficient estimate for the interaction terms, β, are significantly positive, whereby this relationship is more distinct during market downturns. The regression analysis confirms that the "loading" ($= \beta\hat{S}_t$) of the exchange rate on κ_{VIX} is time-varying and increases in the actual exchange rate's distance from the lower bound, $\hat{S}_t$.

Complementary 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 time-varying estimate for the β_t coefficient obtained from regressing percentage changes of the spot rate, Δs_t, on $\Delta\kappa_{\text{VIX},t}$.

$$\Delta s_t \quad = \quad \alpha + \beta_t \Delta\kappa_{\text{VIX},t} + \epsilon_t. \tag{4}$$

By the safe-haven property of the Swiss franc, we expect $\beta_t < 0$, and Krugman's (1991) model predicts lower β_t if EUR/CHF is higher. This is what we find. The quasi-local-level test (qLL test) prosed by Elliott & Mueller (2006) indicates strong parameter instability (time-variation) for β_t, and graphical inspection suggests that β_t falls in EUR/CHF: the elasticity of the Swiss franc to κ_{VIX} is higher the further away EUR/CHF notes from its lower bound.

To conclude, Krugman's (1991) model finds support by the behavior of the Swiss franc/euro exchange rate conditional on a global market risk fundamental: the SNB has sent its currency into honeymoon where it relaxed under the sunshade of market expectations that provided protection against crazy fundamentals.

4 Credibility

While the condition that a central bank does not change the monetary base as its exchange rate stays inside the band is easily verified and holds for the Swiss franc, the credibility condition is more difficult to assess. Because this condition is not only crucial in the framework of Krugman's model, but also interesting per se, this section examines the credibility assumption for the Swiss franc lower bound regime using financial market data.

4.1 forward exchange rates

A "simple test of target zone credibility" has been proposed by Svensson (1990). Svensson noted that forward exchange rates represent expected appreciation or depreciation of exchange rates, and they must never lie outside the band in a credible target-zone regime. Otherwise, arbitrage opportunities would arise.[8] Applied to the Swiss case, Figure (5) visualizes that EUR/CHF forward exchange rates never importantly noted below EUR/CHF = 1.20, in particular not at levels as low as 1.10 that realized when the SNB ended the lower-bound era. Hence, in retrospect, Svensson's (1990) test broadly confirms that markets have taken the SNB's lower-bound-commitment for granted. But qualifying this result, Campa & Chang (1996, 1998), or Malz (1996, 1997a) noted that higher moments of the exchange rate distribution are more informative about market's expectations. Currency option prices not only inform about the mean, but also about the variance, skewness and kurtosis of the expected exchange rate distribution function. This can inform about the probability which markets assign to the continuation of an exchange-rate target zone in place.

4.2 over-the-counter (OTC) option price quotes

Prices of different option contracts imply a probability density function for future exchange rate realizations. The option price quotes that are readily available in over-the-counter markets

[8]Bertola & Svensson (1993) presented an extension of the Krugman (1991) model in which a state variable in addition to the exchange rate fundamental K accounts for market's expected probability and size of a realignment of the edges of an exchange rate target-zone in operation, and for example Rose & Svensson (1995), Svensson (1993) or Lindberg *et al.* (1993) provide empirical implementations for different currency pairs of the ERM. Thereby, their assessment of credibility relies on the uncovered interest rate parity condition by which interest rate differentials or forward discounts should be unbiased predictors of future exchange rates.

are the at-the-money implied volatility price, the risk-reversal price, and the strangle price. These are prices of particular option portfolios which are described in the Appendix. It is convenient to focus on these three prices, because they summarize the distribution of the exchange rate function which they imply. In particular, the at-the-money implied volatility indicates the overall level, the risk-reversal indicates the skewness, and the strangle volatility price indicates the kurtosis of the option-prices implied exchange rate distribution. Note that this distribution is a risk-neutral distribution, which means that it puts more weight on exchange rate values which markets fear.[9] But even if — or rather because — this option-implied exchange rate distribution function does not mirror "true" expectations, but "feared" expectations, it importantly informs about market sentiment.

Figure (6) shows time series of the EUR/CHF at-the-money implied volatility (ATM), the 25-delta risk-reversal (RR), and of the 25-delta strangle (STR) over the lower-bound regime.[10] Negative risk-reversal prices indicate appreciation pressure on the Swiss franc against the euro, and high strangle prices indicate that markets put high probability on a large jump of the exchange rate in either direction.

For the days during spring 2012 when EUR/CHF was sticky at 1.20, the 25-delta RR-prices allow for a direct assessment of the perceived stability of the Swiss franc minimum exchange rate. During these days, this RR prices would have been zero or positive if all market participants would have expected that one euro will always be exchangeable for 1.20 Swiss francs in the spot market. Alas, Figure (6) unveils that this did not hold true. In addition, high STR prices indicate that some market participants indeed expected a large move of EUR/CHF. When the banking crisis and the sovereign debt crisis hit Europe unprepared in spring 2012, RR-prices unveil that even the SNB's market interventions could not halt appreciation pressure on the franc beyond 1.20 to the euro. However, it is not clear whether this appreciation pressure has primarily been driven by doubt of whether the SNB was truly "prepared to buy foreign currencies in unlimited quantities",[11] or whether increasing global risk aversion and fear of a

[9] As an example, consider a EUR/CHF call option with a relatively high exercise price. A long position in such a contract insures against a loss from a Swiss franc appreciation. If markets fear such an appreciation, demand for this option contract will be high which increases its price. In that case, the risk-neutral probability for a Swiss franc appreciation will turn out to be higher than the probability that traders effectively assign to it.

[10] The option delta indicates how far an option is in-the-money, or out-of-the money. See the Appendix for further explanation.

[11] SNB Quarterly Bulletin of March 2012

break-up of the Eurozone rather explain it. Support for this latter interpretation is given by the fact that it was actions taken by the European Central Bank that eased appreciation pressure on the franc, and not policy steps undertaken by the SNB. Following Draghi's "whatever-it-takes" statement at the end of July 2012[12] and the launch of the Outright Monetary Transaction (OMT) program[13] on 6 September 2012, prospects for the euro improved and EUR/CHF RR-prices increased.

The EUR/CHF spot exchange rate and RR-prices fell again over November 2014. While the above narrative suggests that appreciation pressure on the franc during 2012 sourced in demand for insurance that Swiss francs could provide when the future of the euro was uncertain, this time, appreciation pressure is likely more related to markets expecting a soon end of the lower-bound policy. This was triggered by rumors that the ECB was considering large-scale open market transactions, which inevitably induces appreciation pressure on the franc vis-à-vis the euro.[14] But in December, the SNB started to target negative LIBOR rates and could convince markets again that it will always defend EUR/CHF $= 1.20$.[15] Having regained credibility, the SNB's suspension of the lower bound one month later came as a surprise — option prices, together with the sharp fall of EUR/CHF on 15 January 2015, tell that markets didn't anticipate this to happen.

4.3 appreciation pressure on the franc at 1.20: "global risk aversion" vs "lack of credibility"?

While risk-reversal prices and strangle prices with constant delta indicate appreciation pressure and uncertainty for EUR/CHF independent of the actual level of the exchange rate, the trajectory of the price of EUR/CHF option contracts with a constant strike of $K = 1.20$ can inform about appreciation expectations of the franc beyond 1.20 to the euro also when EUR/CHF noted above

[12] In July 2012, 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". Follow for example this link: `http://www.youtube.com/watch?v=Pq1V0aPEO3c`. At the beginning of September 2012, the publication details for the Outright Monetary Transaction (OMT) program further calmed markets, `http://www.ecb.europa.eu/press/pr/date/2012/html/pr120906_1.en.html`.

[13] 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`

[14] see for example this Reuters news: http://uk.reuters.com/article/uk-ecb-qe-idUKKCN0IT0KX20141109

[15] See the SNB Quarterly Bulletin of 11 December 2014, https://www.snb.ch/en/iabout/pub/oecpub/id/pub_oecpub_quartbul

1.20. Option prices for given strike prices are not quoted in the market, but the Appendix shows how to obtain them from ATM, RR, and STR prices with constand delta.

Consider the price of an European EUR/CHF put options that entitles its holder to sell one euro for $K = 1.20$ Swiss francs in $\tau =$one month time:[16]

$$P(K,\tau) \quad = \quad \frac{1}{1+i_\tau}\int_0^K (K - S_\tau(\kappa_\tau))f(S_\tau)dS_\tau \tag{5}$$

In the following, the price of this put contract is denoted by P(1.20). This option contract is in-the-money (has a positive price) only if $E(S_\tau) < K$, that is, if $E(\text{EUR/CHF}_\tau) < 1.20$. Strictly speaking, in a credible lower-bound exchange rate regime, such a put option contract must never have a positive price. But the panel in the middle of Figure (7) unveils that P(1.20) has been high at various instances. Figure (9) in the Appendix suggests that the probability for $S_\tau < 1.20$ has repeatedly been as high as $30\% - 40\%$, and even positive for $S_\tau < 1.10$ over spring 2012. But in the above section, we have argued that the then observed high prices for put contracts with strikes below EUR/CHF $= 1.20$ likely resulted from fear of the euro falling apart. In contrast, we argue that over November 2014, the SNB was indeed confronted with a credibility problem. The following paragraphs elaborate on this presumption.

This paper describes the Swiss franc as a safe haven currency, that is, as a function of global risk fundamentals such as the VIX. Credibility of the lower bound implies that the sensitivity of the franc to its global risk fundamentals is zero at the bound and increases in the distance of the spot rate from the bound: the announcement to always defend EUR/CHF $= 1.20$ has muted the safe haven property of the Swiss franc. This obtains without any foreign exchange market transactions by the SNB, as long as EUR/CHF notes above 1.20. Over spring 2012 and fall 2014 in contrast, EUR/CHF was sticky at 1.20, and it did not fall further because the SNB enforced it. By trading to stabilize EUR/CHF at 1.20, the SNB completely suspended the safe haven behavior of the Swiss franc spot exchange rate because it let not market forces determine its price. But in contrast to the spot exchange rate, this central bank trading could not suspend

[16]Hanke *et al.* (2016) summarize that because short-term interest rates on the Swiss franc have been close to zero and consistently below euro interest rates, an American EUR/CHF put option should never be exercised early, which makes its price equal to that of a European put option (see Hanke *et al.* (2016) on page 10, or the argumentation in Hanke *et al.* (2015)).

the safe haven characteristics of EUR/CHF option prices, as Figure (7) unveils. The middle and the lower plot of this figure show that P(1.20) strongly co-moves with VIX, also when EUR/CHF noted at the bound. This safe haven behavior of EUR/CHF option prices, which apparently is not (completely) suspended by the Swiss franc lower bound, allows to shed light on whether *global*, or *Swiss franc specific* factors lie at the source of Swiss franc appreciation pressure. Whenever P(1.20) and VIX-global-risk-aversion spike at the same time, appreciation pressure on the Swiss franc is likely driven by global market risk and not by Swiss franc specific issues such as "SNB credibility". Confirming the conclusion derived from RR prices, P(1.20) sharply increased absent a corresponding peak in VIX only over fall 2014. We conclude that this identifies the single severe instance of low SNB credibility.

4.3.1 identifying credibility independent of global risk aversion

We have argued that P(1.20) can be driven by both, global risk aversion and expectation of a soon end of the Swiss franc lower bound regime. The upper plot of Figure (7) attempts to distinguish these two sources of appreciation pressure on the Swiss franc. The figure presents the scores of the two principal components constructed from the global risk exchange rate fundamental $K_{VIX} = VIX$, and P(1.20). While building principal components is a purely technical method to separate orthogonal factors from correlated variables, we can assign both factors an obvious interpretation here. The first principal component loads positively on both, VIX and P(1.20), and it explains three quarters of the total variance. Clearly, this factor mirrors broad global market sentiment. The trajectory of the second factor however suggests an interpretation in terms of credibility or *mistrust*. By construction, and by the obvious interpretation of the first principal component, this factor is unrelated to overall market risk. In more detail, this factor is high over 2012, but a clear single spike is also visible in fall 2014. To conclude, this factor analysis adds evidence that doubt in the continuation of the lower bound regime, that sourced in a potential decision of the SNB in the first place (and not in a break-up of the Eurozone for example), only arose during November 2014.

4.3.2 macroeconomic explanation of EUR/CHF option prices

In the Krugman (1991) model, appreciation pressure on the franc beyond 1.20 to the euro never occurs. This framework predicts that the safe haven property of the Swiss franc — its systematic co-movement with variables that mirror global market tension — gradually vanishes as the franc approaches the lower bound. But evidence presented above suggests that the model-conform behavior of EUR/CHF was on hold during spring 2012 and November 2014, as the Swiss franc was insensitive to K_{VIX} only because the SNB enforced it, and not because of model-conform expectations. In particular, EUR/CHF option prices (P(1.20)) display a safe haven behavior over the spring 2012 episode. But during the other months of the lower bound regime, P(1.20) should be a non-linear function of K_{VIX} too, because it is monotone in the value of the underlying EUR/CHF exchange rate. This finds support in Figure (8) that plots the negative of P(1.20) against VIX: most observations align on a Krugman (1991) model type "bended honeymoon curve" in the P(1.20) and K_{VIX} space. The spring 2012 interruption of the Swiss franc's honeymoon is clearly visible by the observations marked as red dots which lie as outliers "far below the bended curve". The same is observed for the November 2014 episode (green circles). Both episodes are characterized by doubt about the continuation of the lower bound, which — as we argue — is due to high global market risk in the first case, and to effective doubt on the SNB's readiness to continue the lower bound regime in the second case. Interestingly, the observations of P(1.20) and VIX for the final days of the lower bound regime are perfectly in line with the predictions of Krugman's model. Table (3) shows least square coefficient estimates from regressing percentage changes of P(1.20) on percentage changes of K_{VIX}, interacted with the level of EUR/CHF above the lower bound. As for the EUR/CHF spot rate, the results confirm that the safe haven behavior of P(1.20) declines as the spot rate approaches the lower bound. The further above the lower bound the Swiss franc notes, the more does P(1.20) increase if global risk, VIX, increases.

5 related literature

The present paper continues our earlier working-paper version available as Studer-Suter & Janssen (2014); to the best of our knowledge, we were the first to relate to Paul Krugman's

(1991) ideas to describe the Swiss franc lower bound episode. But meanwhile, our approach and our results are closely related to the findings of a series of recent papers: in a nutshell, the literature concludes that EUR/CHF tends to be distributed as Krugman's (1991) model predicts (Hertrich, 2016b), and credibility of the SNB's regime has been low over the initial months of the lower-bound regime, but increased until summer 2014, when it started to decline again. All studies agree that EUR/CHF would have been much lower than 1.20 during the 2012 outbreak of the European sovereign debt crisis, but only two papers (Hertrich, 2016a and Hertrich & Zimmermann, 2015) conclude that the SNB's credibility was weak during that time. Eventually, the literature concludes that the SNB ended the lower-bound regime at a point in time when markets' doubt was high.

A log-linear model for the exchange rate forms the starting point of most studies on exchange rate target zones, which is also common in finance. But in this framework, the only recent publication that takes our way and uses macroeconomic fundamentals to explain EUR/CHF is Hui *et al.* (2016): these authors find that the drift coefficient in the equation for the fundamental — that corresponds to μ in equation (2) of this paper — increases in foreign exchange reserves which pushes EUR/CHF away from the strong-side limit. Time-variation in μ can be interpreted as variability in credibility.

A series of papers decomposes the log-linear process for the exchange rate into a "fundamental" or "latent" exchange rate, that is, the exchange rate that would have prevailed in absence of the lower bound, plus a "guarantee"[17] which is the value of the SNB's commitment to prevent the franc from appreciating beyond 1.20 to the euro. Jermann (2016) describes a model in which this guarantee is determined by the expected continuation probability of the lower-bound regime at a given horizon, and he applies his model to price currency options conditional on the model-implied exchange rate process. Hanke *et al.* (2015) and Hanke *et al.* (2016) view the SNB's guarantee as a put option to sell euros for 1.20 Swiss francs, and in addition to a latent process for the exchange rate, they derive measures for the market's expected remaining lifetime of the lower-bound regime: they find that credibility increased between summer 2012 and summer 2014, but then started to fall again which suggests that markets had anticipated the end of the lower-bound era. Hertrich (2016a) proposes to model EUR/CHF as a reflected geomet-

[17] we like this term which is borrowed from Hanke *et al.* (2016)

ric Brownian motion, as in Veestraeten (2013). His estimate of the process for the latent EUR/CHF exchange rate resembles those of the contributions cited above, but he interprets the difference between the latent (implied by their option pricing model) and the observed exchange rate as a measure of the costs the SNB had to bear to sustain the lower bound regime. This suggests to conclude that credibility has been low during the 2012 outbreak of the European crisis, which stands in contrast to the interpretations of the other papers cited above.

Hertrich (2016b) adapts the target-zone model by Chen and Giovannini (1992) to allow for estimates of the unconditional distribution of EUR/CHF in its one-sided target-zone. He finds that EUR/CHF is asymmetric and right-skewed which corresponds to what the Krugman (1991) model predicts, and which reaffirms that the SNB intervened in currency markets only at the lower bound, and not above it. The second crucial assumption of Krugman's (1991) model, which is the credibility assumption, is the main focus of Hertrich & Zimmermann (2015). These authors specify a currency option pricing model which applies to exchange rates in one-sided target zones; in this model, the exchange rate follows a Brownian motion as in the standard Garman & Kohlhagen (1983) model, which our qualitative results are based on, but the process has a reflecting barrier in addition. If correctly specified, this model allows for quantitative estimates of option-implied probabilities for future EUR/CHF rates below the bound. While the evolution of credibility corresponds to the finding of other papers — low at the beginning, potentially low during spring 2012, and falling since summer 2014 — these authors conclude that the SNB's policy stance has never been credible: they state that in a credible lower-bound regime, EUR/CHF put option prices must not trade at any positive price. Our paper responds to this by arguing that much of the appreciation pressure on the Swiss franc was rather not related to speculation on a suspension of the lower bound, but related to safe haven demand during times of high global market uncertainty. This is the strength of the macroeconomic approach to the exchange rate — it allows for interpretations.

The macroeconomic approach of this paper starts from the notion of the Swiss franc as a safe haven currency, and it documents high explanatory power of the VIX for EUR/CHF, which is a common measure of global market sentiment.

6 Conclusion

Starting from the stylized fact that the Swiss franc is a safe haven currency, this paper retrieves the macroeconomic model outlined by Krugman (1991) to describe the EUR/CHF exchange rate as a function of global market risk fundamentals, which is the VIX in particular. During most of the Swiss franc lower bound regime, that was in operation between September 2011 and January 2015, EUR/CHF behaved conforming with the predictions of Krugman's model: the sole expectation that the Swiss National Bank will prevent the Swiss franc from appreciating beyond 1.20 to the euro has muted the sensitivity of EUR/CHF to global market risk. The Swiss franc was in honeymoon. In the model, this obtains because the central bank is assumed to be credible. The second part of this paper assesses this crucial assumption. Analyzing the co-movement of EUR/CHF option prices and global market risk, we conclude that though markets doubted the continuation of the existing EUR/CHF exchange rate policy when the European sovereign debt crisis put the continuation of the euro into question during spring 2012, SNB credibility was a true issue only in November 2014. Alas, after markets had doubted the SNB's willingness to continue the lower bound regime for the first time, the Swiss central bank could convince markets anew from its target-zone policy in December 2014. A few weeks later, the SNB unexpectedly suspended the lower bound. To conclude, this paper supports Krugman's (1991) model for EUR/CHF during the Swiss franc lower bound episode. This is remarkable since a large literature rather rejected versions of this model. But here, this simple, though elegant approach can explain how the Swiss franc's value was determined by its global risk fundamentals inside the recent target-zone.

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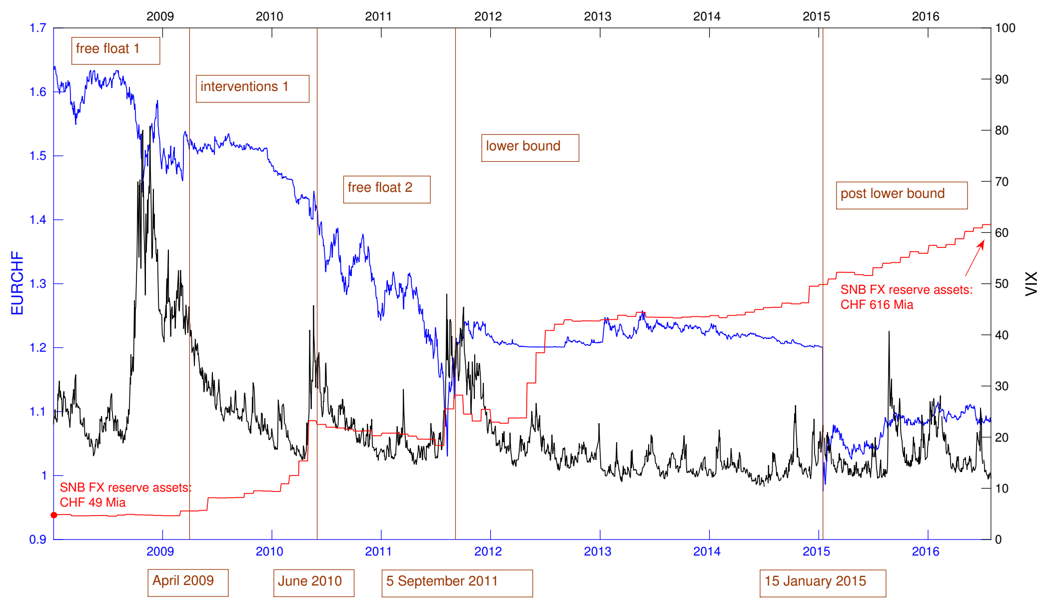
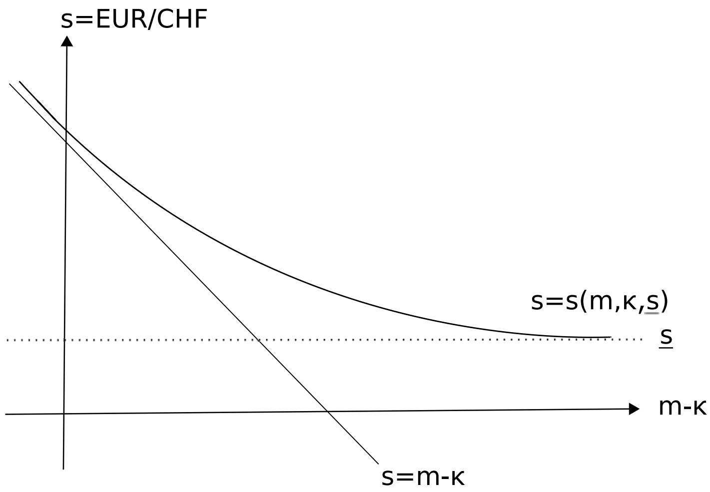
Figure 1: EUR/CHF, VIX, SNB foreign currency reserve assets



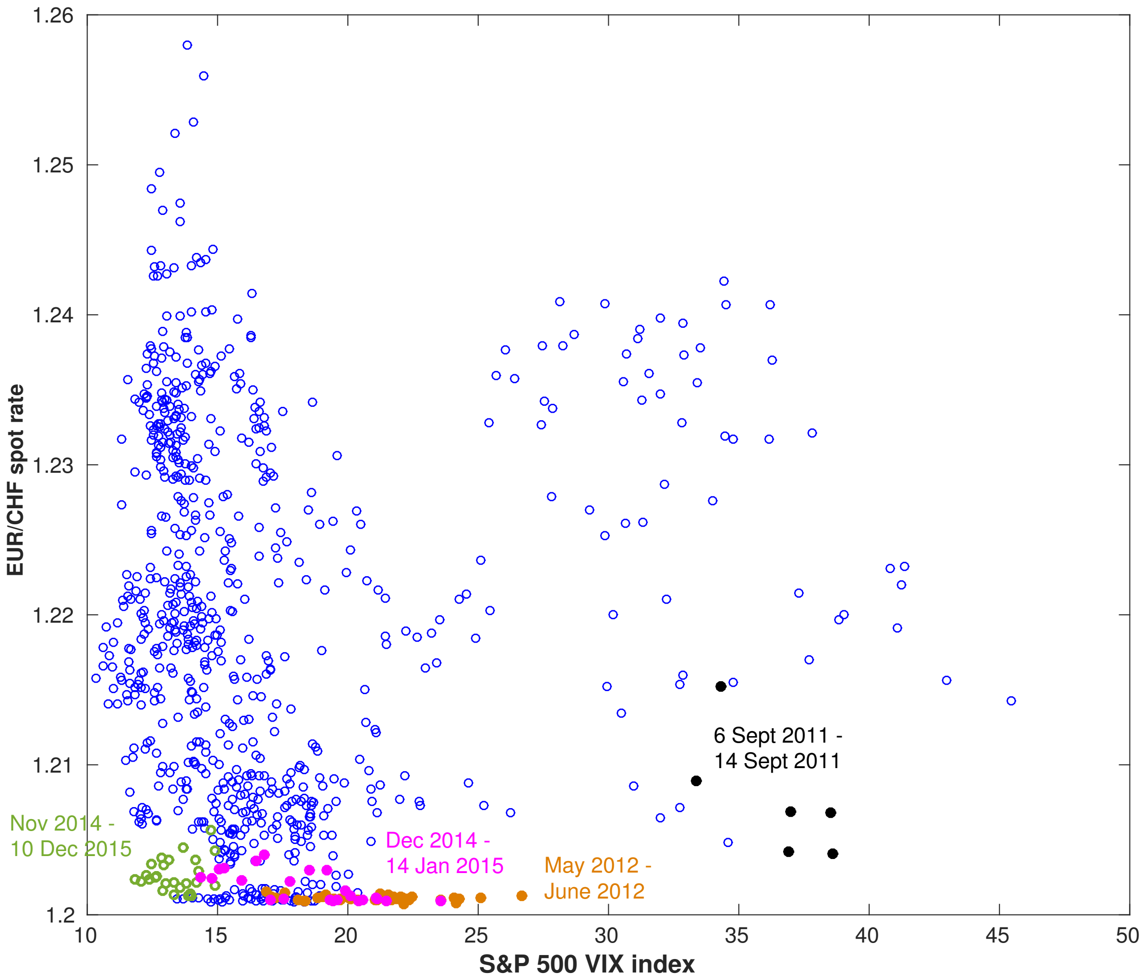
The blue graph (left axis) shows the Swiss franc/euro spot exchange rate expressed in numbers of Swiss francs per one euro, and the black graph (right axis) shows the S&P 500 options implied volatility index VIX. The red graph (right axis) indicates the Swiss National Bank's foreign currency reserve assets measured in 10 Mia of Swiss francs. Based on the SNB's communicated policy stance and on the evolvement of its foreign currency reserves, the figure distinguishes five different monetary policy regimes which are characterized by the volatility of the EUR/CHF exchange rate, given the volatility of global markets as measured by the VIX index. Exchange rate observations and the VIX index are daily, SNB reserve holdings are reported monthly.

Figure 2: Sketch of the Krugman (1991) exchange rate function



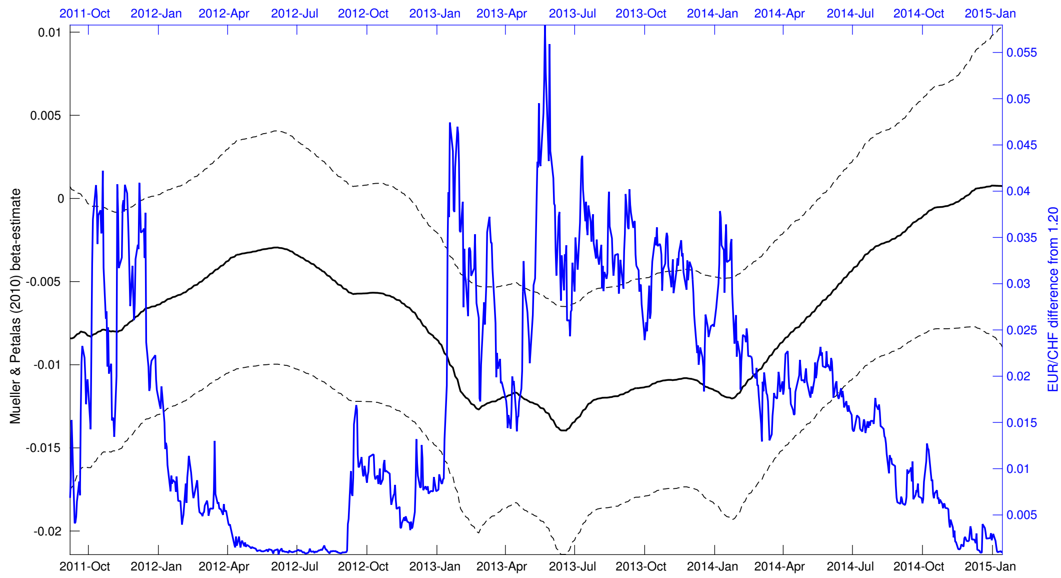
This figure sketches the Krugman (1991) functional relationship of the spot exchange rate s and currency market fundamentals κ, m applied to the one-sided target zone regime of the sort that the Swiss National Bank enforced for the Swiss franc against the euro between September 2011 and January 2015. The existence of the lower bound $\underline{s}$ implies a lower bound for the fundamental $(\underline{m-\kappa})$, where m is the monetary base and κ are other currency market fundamentals reflecting foreign exchange supply and demand. As s approaches the lower bound, it becomes insensitive to changes in the fundamentals.

Figure 3: EUR/CHF, a function of κ_{VIX}



The figure plots each observation of the Swiss franc/euro exchange rate against the same day's value of the S&P 500 options implied volatility index VIX. The data is at daily frequency and includes all days that were trading days in Switzerland and the US, and for which observations of the VIX index are available.

Figure 4: Time-varying sensitivity (β) of EUR/CHF on K_{VIX}

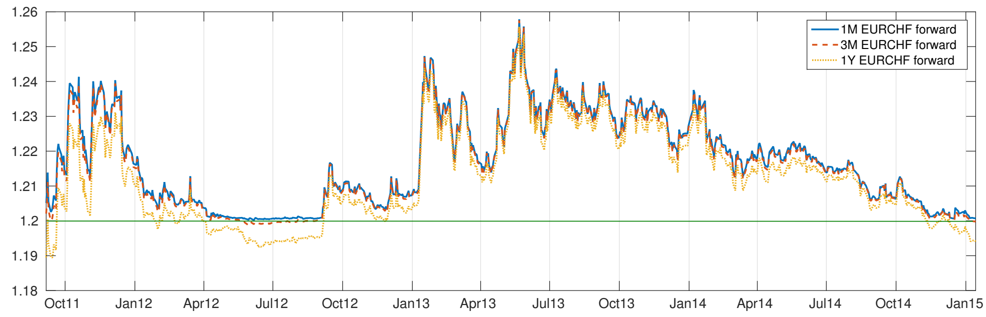


Applying the method proposed by Elliott & Mueller (2006) and Mueller & Petalas (2010), the black line (left axis) shows time-varying estimates of the β_t- coefficient of the following regression equation

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

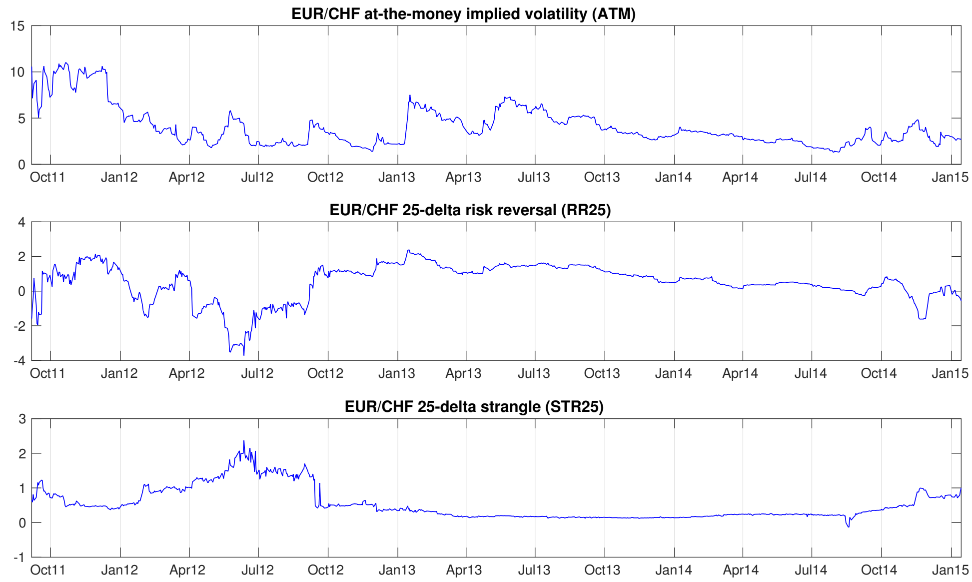
where Δs_t denote percentage changes in the EUR/CHF spot exchange rate, α denotes a constant and $K_t = \ln(\text{VIX}_t) - \ln(\text{VIX}_{t-1})$ is the exchange rate fundamental. The thin, dotted lines depict 95% confidence intervals for the β_t-estimates. The blue line (right axis) shows the distance of EUR/CHF_t from the lower bound of 1.20. The data is at daily frequency and includes all days that were trading days in Switzerland as well as in the US, and for which the VIX is available.

Figure 5: EUR/CHF outright forward exchange rates



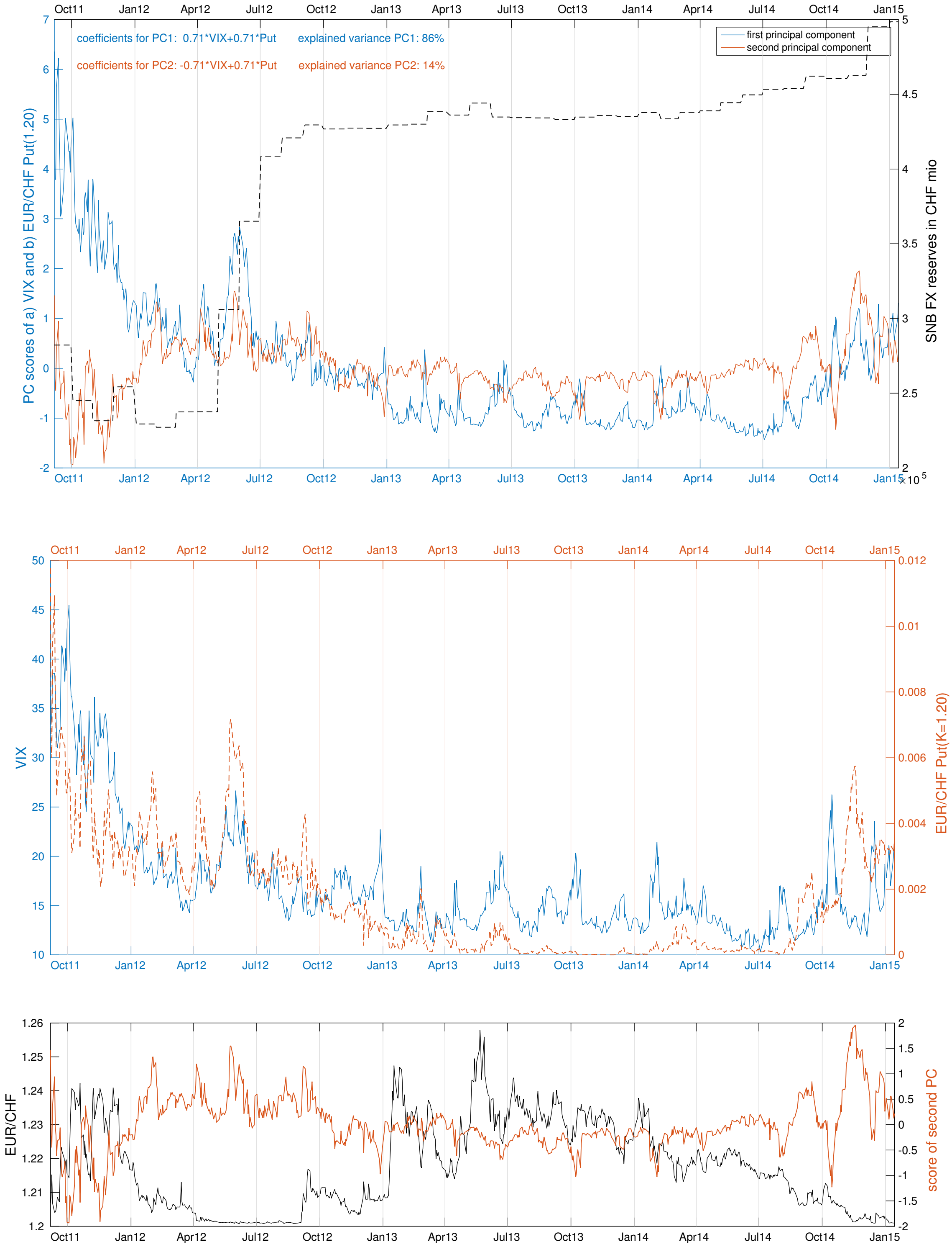
The figure shows EUR/CHF forward outright exchange rates for 1 month, 3 months, and 12 months maturity. The data is daily and encompasses all days that were trading days in the US and Switzerland between mid September 2011 and mid January 2015.

Figure 6: OTC EUR/CHF option price quotes



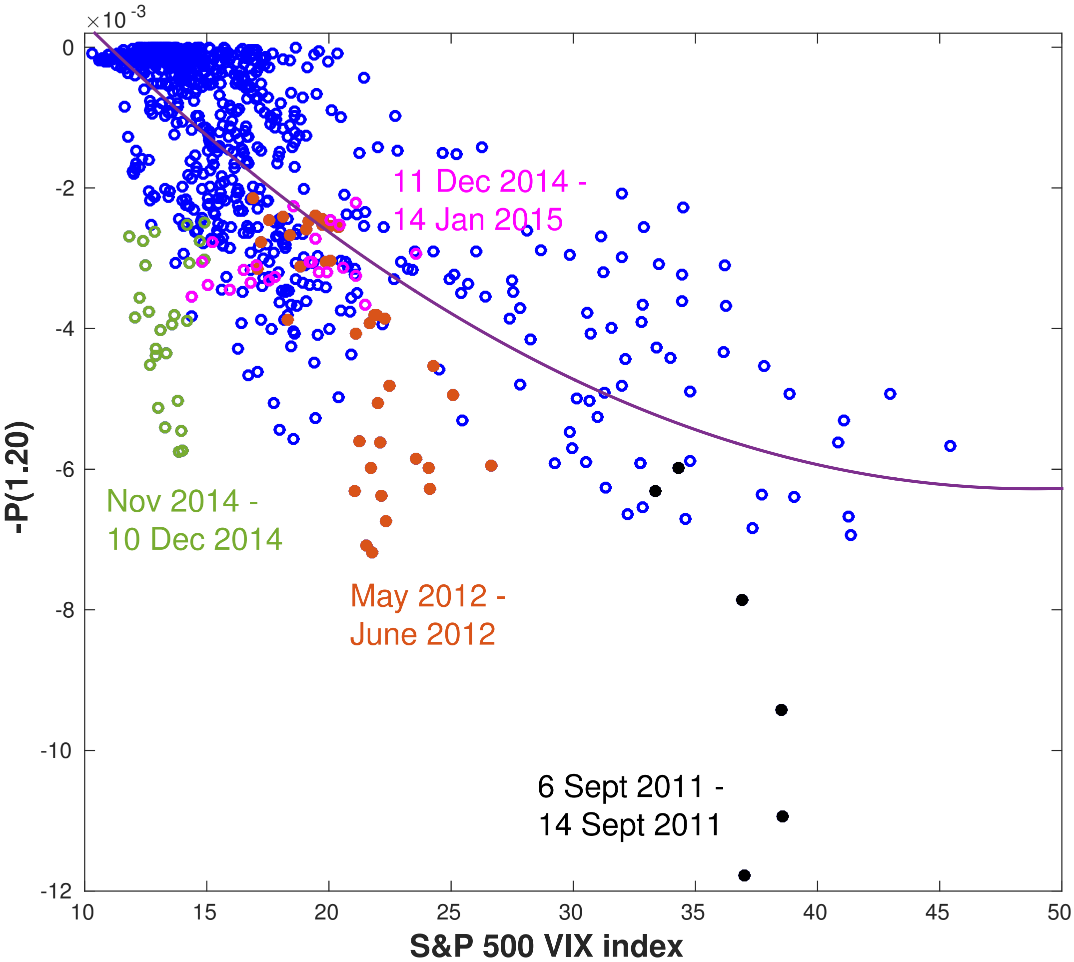
The figure shows time-series plots of the volatility price of three different EUR/CHF option contracts. A description of these contracts is given in the Appendix. All option contracts have a maturity of one month, the data is at daily frequency and encompasses all days that were trading days in Switzerland and the US.

Figure 7: A factor for global risk and a credibility-factor



The upper figure plots the scores of the two principal components of the a) S&P 500 options implied volatility index VIX and of b) the price for an EUR/CHF put option with a strike price of 1.20 and a time-to-maturity of one month, denoted P(1.20) in this paper. Principal components are constructed from the correlation matrix of the two variables. The put option price is obtained by interpolating the volatility smile, the Appendix describes further details. The blue graph shows the score of the first principal component which explains 85% of the variance in the data, and the red graph depicts the score of the second principal component (both left axis). The black, dotted graph indicates the Swiss National Bank's currency reserve assets in CHF millions (right axis). The middle plot shows the two variables the principal componends are derived from, the VIX and P(1.20). The plot at the bottom shows the score of the second principal component again together with EUR/CHF.

Figure 8: P(1.20)against its global risk fundamental K_{VIX}



The figure plots ths S&P 500 options implied volatility index VIX against the negative of the price of an EUR/CHF put option with a strike of 1.20 and one month time to maturity, denoted by P(1.20) in this paper. Put prices are obtained from the interpolated risk-neutral density function for the Swiss franc prices of one euro as suggested by Malz (1997b), details are described in the Appendix. The purple line displays the best fitting quadric polynomial with y = P(1.20) and x = VIX. The data is at daily frequency and includes all days that were trading days in Switzerland and the US.

Table 1: EUR/CHF explained by VIX-measured global market risk

	JAN 2008 - MAR 2009	APR 2009 - MAY 2010	JUN 2010-AUG 2011	SEPT 2011 - JAN 2015	JAN 2015 -JUL 2016
ΔVIX	-0.0429^*	-0.0072	-0.0488^*	-0.0072^*	-0.0057
	(-10.6546)	(-1.7326)	(-7.2298)	(-6.0061)	(-1.7347)
CONST	-0.0000	-0.0002	-0.0005	0.0000	0.0002
	(-0.0517)	(-1.4239)	(-1.0799)	(0.1391)	(1.1680)
R^2	0.30	0.03	0.19	0.06	0.01
NOBS	302	279	304	814	380

The table reports coefficient estimates and corresponding t-statistics from regressing percentage changes in EUR/CHF on percentage changes in the VIX. T-statistics are calculated from a HAC-consisten covariance matrix according to Newey & West (1987) and Newey & West (1994). Generally speaking, an increasing VIX indicates "bad days". The Swiss franc is a safe haven currency because it systematically appreciates against the euro (and other currencies) whenever VIX increases. The data is at daily frequency and covers all days that were trading days in the US and Switzerland, and for which the VIX is available (some few dates are missing). The complete sample spans the period from 3 January 2008 to 29 July 2016.

Table 2: EUR/CHF as a function of K_{VIX} during the lower bound regime (SEPT 2011 - JAN 2015)

$(\Delta\text{VIX} : \Delta\text{VIX} > 0) \times \hat{S}$	-0.4708^*	$(\Delta\text{VIX}) \times \hat{S}$	-0.3816^*
	(-4.6191)		(-4.0971)
$(\Delta\text{VIX} : \Delta\text{VIX} < 0) \times \hat{S}$	-0.1984		
	(-1.3620)		
ΔVIX	-0.0009		-0.0008
	(-0.7610)		(-0.6559)
$\hat{S}$	-0.0094		-0.0149^*
	(-1.3958)		(-2.6345)
CONST	0.0003^*		0.0003^*
	(3.2080)		(3.0755)
R^2	0.09		0.09
NOBS	814		814

The table reports coefficient estimates and corresponding t-statistics from regressing percentage changes in EUR/CHF on percentage changes of the S&P 500 options implied volatility index VIX. T-statistics are calculated from a HAC-consisten covariance matrix according to Newey & West (1987) and Newey & West (1994). $\hat{S} = S - 1.20$ denotes the deviation of EUR/CHF from the lower bound. The data is at daily frequency and covers all days that were trading days in the US and Switzerland, and for which data for the VIX is available (some few days are missing). The data covers the period from 6 September 2011 to 14 January 2015.

Table 3: P(1.20) as a function of K_{VIX}

dependent variable: ΔP(1.20)						
ΔVIX $\times \hat{S}$	ΔVIX	$\hat{S}$	Δs	CONST	R^2	NOBS
88.3188*	−0.3816	6.1467*	−121.9785*	−0.0167	0.33	814
(3.5119)	(−1.4336)	(4.2790)	(−6.4099)	(−0.8877)		
	1.0452*	6.4437*	−127.7677*	−0.0204	0.31	814
	(3.8589)	(4.3005)	(−6.4993)	(−1.0428		

The table shows least square coefficient estimates from regressing percentage changes of P(1.20), which denotes the price of a EUR/CHF put option contract with a strike of 1.20 and a time-to-maturity of 1 month, on percentage changes in the VIX. In the model presented in the first two rows (coefficient estimates and t-statistics below), changes in VIX are also interacted with the distance of EUR/CHF from the lower bound, $\hat{S}$ = EUR/CHF − 1.20. The put prices are obtained by interpolating the volatility smile as suggested by Malz (1997b), details are described in the Appendix. T-statistics for the least squares estimates are calculated from a HAC-consisten covariance matrix according to Newey & West (1987) and Newey & West (1994). The data is at daily frequency and covers all days that were trading days in the US and Switzerland, and for which data for the VIX is available (some few days are missing). The data covers the period from 6 September 2011 to 14 January 2015.

A The Krugman (1991) model

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

$$s_t = m_t + \nu_t + \gamma \frac{E_t(ds_t)}{dt} \tag{6}$$

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 the exchange rate equation (6), the domestic money supply m and a shift term ν. 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 notes above $\underline{s}$, money supply remains unchanged. The only exogenous source of exchange rate dynamics is the shift term ν. In Krugman's exposition of the model, ν represents a velocity shock, but other interpretations of ν allow for alternative models for the exchange rate. As we focus on the Swiss franc in its role as a safe haven currency, we chose variables that mirror global market sentiment as the exchange rate fundamentals. In particular, we set $\nu = -\kappa$, where a high κ indicates increased market risk. This leads to the following equation for the exchange rate

$$s_t = m_t - \kappa_t + \gamma \frac{E_t(ds_t)}{dt}. \tag{7}$$

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, assume that κ follows a continuous-time random walk

$$d\kappa_t = \mu dt + \sigma dW_t \tag{8}$$

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 (7), depreciation during such a free float can be written as

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

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

$$s(m_t, \kappa_t) \quad = \quad (m_t - \kappa_t) + \gamma s'(m_t - \kappa_t)\mu + \gamma s''(m_t - \kappa_t)\frac{1}{2}\sigma^2. \tag{9}$$

The general solution to (9) is

$$s(m_t, \kappa_t) \quad = \quad (m_t - \kappa_t) + \gamma\mu + A\exp(\lambda_1(m_t - \kappa_t)) + B\exp(\lambda_2(m_t - \kappa_t)) \tag{10}$$

where $\lambda_1 > 0$ and $\lambda_2 < 0$.[18] 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 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 $B > 0$.[19] With A equal zero and B being positive, equation (10) 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.

[18] 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 $\lambda_2 = \frac{-\mu - \sqrt{\mu^2 + 2\sigma^2/\gamma}}{\sigma^2} < 0$.

[19] 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.

B Currency option prices

B.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.

B.1.1 Pricing conventions

For our analysis, we download daily currency option price quotes from Bloomberg 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.[20] The Black-Scholes formula for the value of a European currency call options is[21]

$$C(F,\tau) = (FN(d_1) - KN(d_2))\, e^{-r\tau} \tag{11}$$

and the value of a put is

$$P(F,\tau) = (F\,[N(d_1)-1] - K\,[N(d_2)-1])\, e^{-r\tau} \tag{12}$$

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

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

[20] 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.)

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

In currency markets, the only unobserved variable in equations (11) and (12) is the volatility of the price of the foreign currency σ. Alternatively, replacing the left-hand side of equations (11) and (12) 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

$$\begin{aligned}
\Delta_C &= \frac{\partial C(F,\tau)}{\partial F} \\
&= e^{-r\tau}N(d_1) \qquad (13) \\
\Delta_P &= \frac{\partial P(F,\tau)}{\partial F} \\
& -e^{-r\tau}N(-d_1) \qquad (14)
\end{aligned}$$

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.

B.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".

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 Bloomberg 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,[22] Bloomberg hence provides us with implied volatility quotes for five levels of moneyness, namely for $\Delta = \{10, 25, 50, 75, 90\}$.

B.2 Interpolating the risk neutral distribution

To obtain the risk-neutral EUR/CHF density function, we follow the approach proposed by Malz (1997b) and interpolate the volatility smile.[23] 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

$$\frac{\partial^2 C(F, \tau; K, \sigma, r)}{\partial K^2} \quad = \quad e^{-r\tau} \pi(K) \tag{15}$$

To obtain a closely spaced series of call option prices with different exercise prices, which is needed to empirically implement equation (15), 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 (11) and (13) 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), 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 (1997b) proposes to approximate the implied volatility function by

$$\hat{\sigma}(\Delta) \quad = \quad b_0 atm_t + b_1 rr_t (\Delta - 0.50) + b_2 str_t (\Delta - 0.5)^2. \tag{16}$$

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, one can substitute equation (13) into equation (16) and solve for σ as a function of K. Having obtained implied volatilities for given strike prices, the call pricing function (11) eventually allows to substitute out cash call prices for given strike prices. The last

[22]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.

[23]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.

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

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

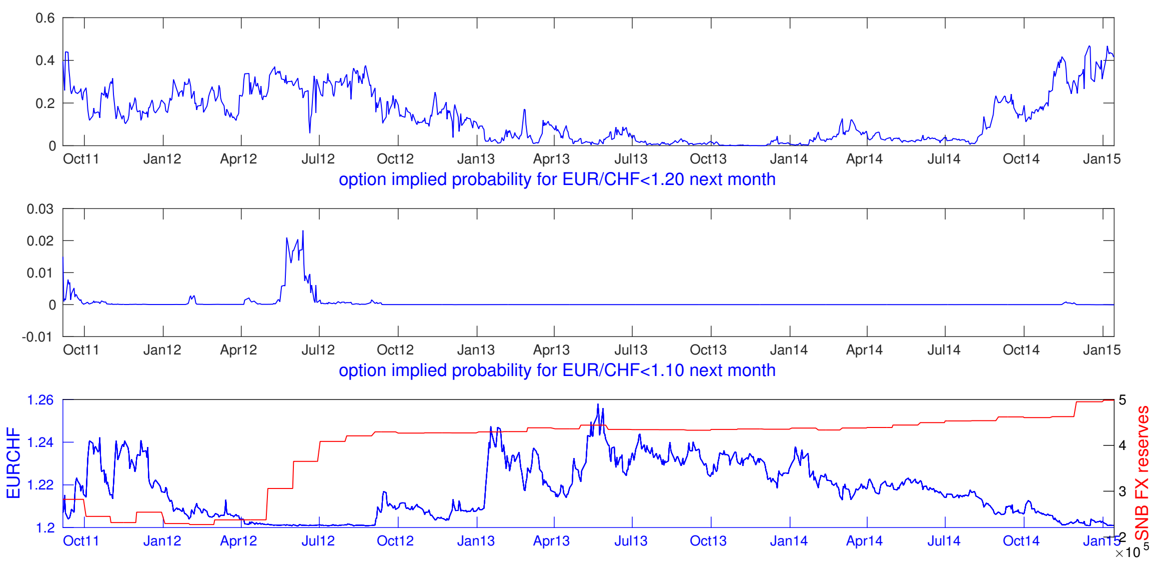
and the estimated probability density function is

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

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.

B.3 option implied probability for EUR/CHF < 1.20

Figure 9: Option prices implied probability for EUR/CHF < 1.20 (1.10) one month in the future



The figure plots the risk-neutral probability that the Swiss franc will note below 1.20 (1.10) to the euro at the expiration dates of European option contracts, which lie one month in the future. The risk-neutral density function for the Swiss franc price of the euro is obtained by interpolating the volatility smile as suggested by Malz (1997b).