Multi-Curve Pricing of Non-Standard Tenor Vanilla Options in QuantLib

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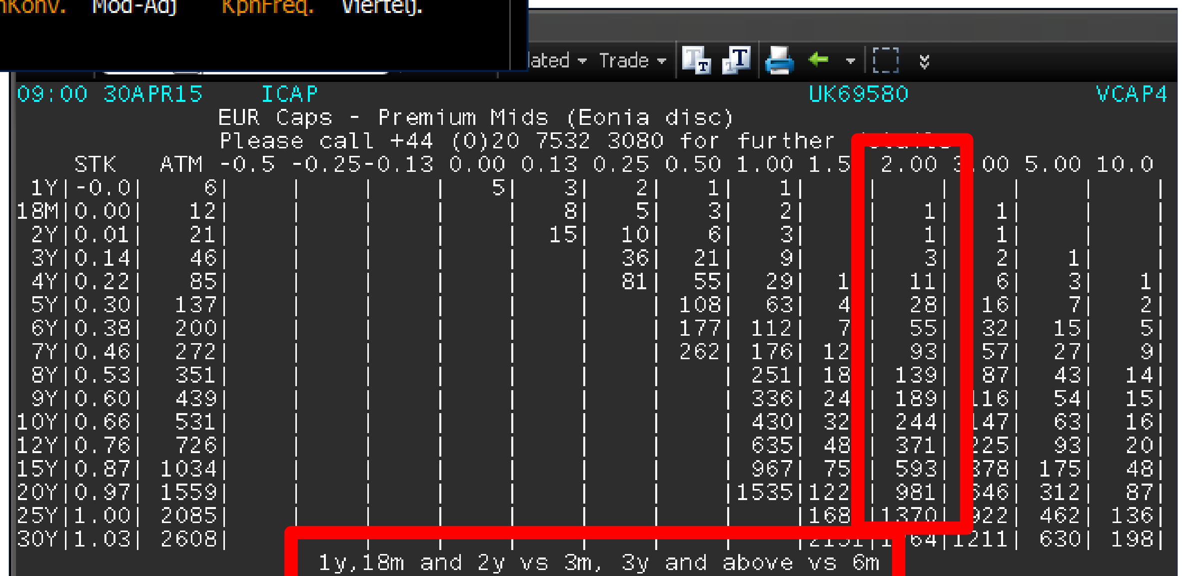
Swaption and caplet pricing w/ Black or Bachelier’s formula is trivial. So, why should we care?

Banco Popular Espanol SA, Oct. 2027, 3m Euribor +200bp, capped @ 400bp



	STK	ATM	-0.5	-0.25	-0.13	0.00	0.13	0.25	0.50	1.00	1.5	2.00	3.00	5.00	10.0
1Y	-0.0	6				5	3	2	1	1					
18M	0.00	12					8	5	3	2		1	1		
2Y	0.01	21					15	10	6	3		1	1		
3Y	0.14	46						36	21	9		3	2	1	
4Y	0.22	85						81	55	29	1	11	6	3	1
5Y	0.30	137							108	63	4	28	16	7	2
6Y	0.38	200							177	112	7	55	32	15	5
7Y	0.46	272							262	176	12	93	57	27	9
8Y	0.53	351								251	18	139	87	43	14
9Y	0.60	439								336	24	189	116	54	15
10Y	0.66	531								430	32	244	147	63	16
12Y	0.76	726								635	48	371	225	93	20
15Y	0.87	1034								967	75	593	378	175	48
20Y	0.97	1559								1535	122	981	546	312	87
25Y	1.00	2085									168	1370	922	462	136
30Y	1.03	2608									2151	[illegible]	1211	630	198

EUR long-term cap prices and vols quoted versus 6m Euribor

Non-standard tenor cap and swaption pricing requires consistent and theoretically sound volatility transformation from quoted standard-tenors to required non-standard tenors

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Agenda

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Notation, Normal Volatilities and Tenor Basis Modelling

Volatility transformation methodologies are already discussed in the literature and applied in the industry

- Classical approach for log-normal (ATM) volatilities based on Libor (or swap) rates

$$\sigma^{3m} = \frac{L^{6m}}{L^{3m}} \cdot \sigma^{6m}$$

- J. Kienitz, 2013
  - ATM Volatility transformation for caplets and swaptions
  - Translate between shifted log-normal and log-normal ATM volatilities to incorporate basis
  - Capture smile by exogenously specifying smile dynamics, e.g. (displaced diffusion) SABR

We elaborate an alternative view generalizing available results:

- Focus on implied normal volatilities as they become market standard quotations
- Consistent basis spread model for swaptions, caps (and exotic derivatives)
- Explicitely capture ATM as well as smile by the volatility transformation

Affine relation between underlying rates yields model-independent transformation of implied normal volatilities

- Implied normal volatilities $\sigma_S(K)$ for an underlying $S(T)$ with expectation $S(t)$ and strike K may be expressed by Bachelier's formula as

$$E[(S(T)-K)^+] = [S(t)-K]\cdot N\left(\frac{S(t)-K}{\sigma_S(K)\sqrt{T-t}}\right) + N'\left(\frac{S(t)-K}{\sigma_S(K)\sqrt{T-t}}\right)\cdot \sigma_S(K)\sqrt{T-t}$$

- Consider another underlying $U(T)$ with affine relation $\boldsymbol{U(T) = a\cdot S(T) + b}$. Then

$$E[(U(T)-K)^+] = a\cdot E\left[\left(S(T)-\frac{K-b}{a}\right)^+\right] = \cdots$$

$$= [U(t)-K]\cdot N\left(\frac{U(t)-K}{a\sigma_S\left(\frac{K-b}{a}\right)\sqrt{T-t}}\right) + N'\left(\frac{U(t)-K}{a\sigma_S\left(\frac{K-b}{a}\right)\sqrt{T-t}}\right)\cdot a\sigma_S\left(\frac{K-b}{a}\right)\sqrt{T-t}$$

- This yields model-independent relation between implied volatilities

$$\boldsymbol{\sigma_U(K) = a\cdot\sigma_S\left(\frac{K-b}{a}\right)}$$

We derive affine relations between Libor and swap rates and apply above normal volatility transformation

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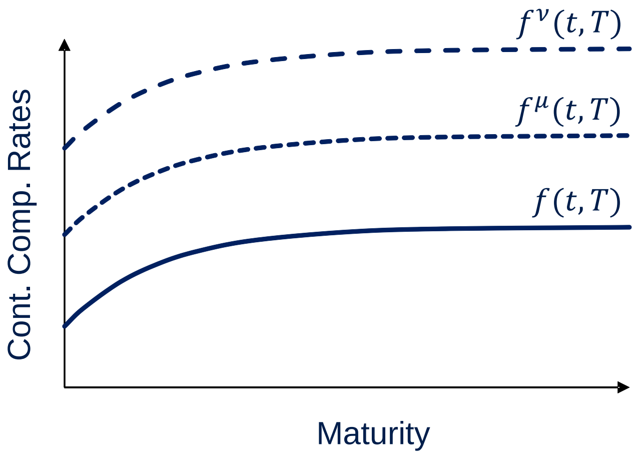
Tenor basis is modelled as deterministic spread on continuous compounded forward rates



Long tenor curve with forward rates $L^{\nu}(t;T_1,T_2)$

Short tenor curve with forward rates $L^{\mu}(t;T_1,T_2)$

OIS discount curve with discount factor $P(t,T)$

Deterministic spread relation between forward rates

$$f^{\nu}(t,T) = f(t,T) + b^{\nu}(T)$$

$$f^{\mu}(t,T) = f(t,T) + b^{\mu}(T)$$

Deterministic Relation between forward Libor rates and OIS discount factors

$$1 + \tau_{1,2} \cdot L^{\nu}(t;T_1,T_2) = D^{\nu}(T_1,T_2) \cdot \frac{P(t,T_1)}{P(t,T_2)} \text{ with } D^{\nu}(T_1,T_2) = e^{\int_{T_1}^{T_2} b^{\nu}(s)ds}$$

$$1 + \tau_{1,2} \cdot L^{\mu}(t;T_1,T_2) = D^{\mu}(T_1,T_2) \cdot \frac{P(t,T_1)}{P(t,T_2)} \text{ with } D^{\mu}(T_1,T_2) = e^{\int_{T_1}^{T_2} b^{\mu}(s)ds}$$

We use the multiplicative terms D^{ν} and D^{μ} to describe tenor basis

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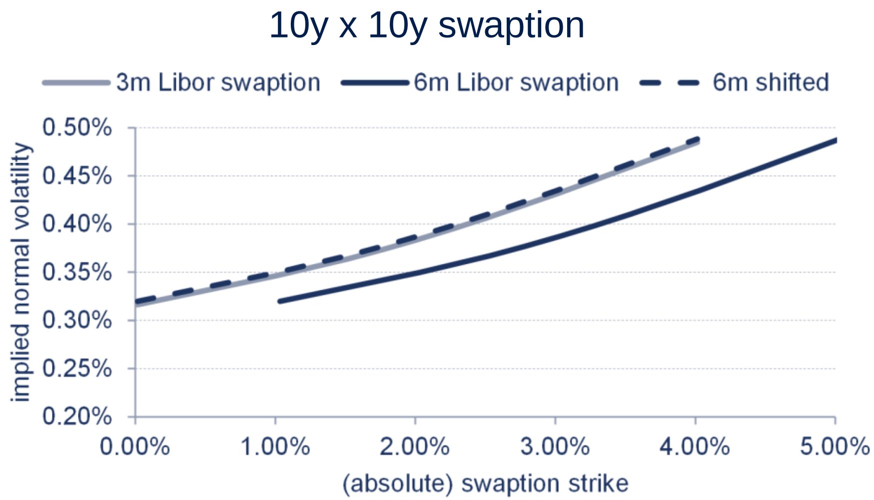
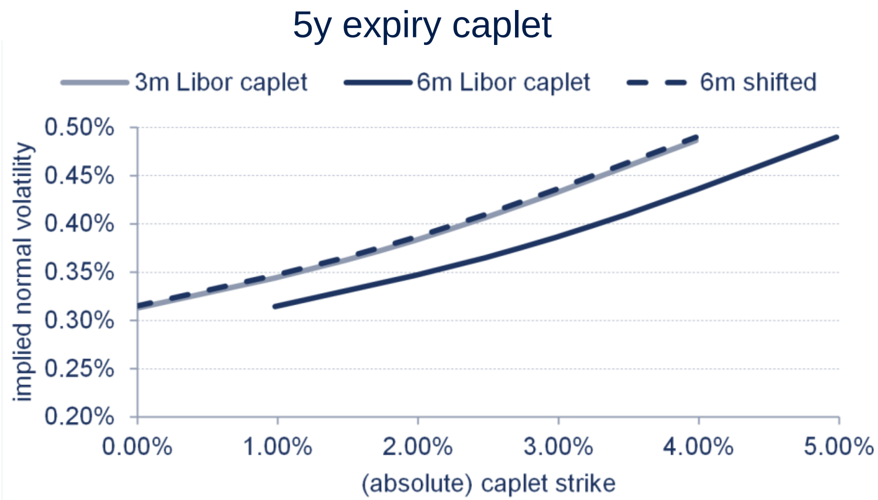
Term structure model w/ basis spreads provides benchmark for volatility transformation methodology

» Set up Quasi-Gaussaian short rate model (4 factors, local/stochastic volatility, basis spreads)

» Compare implied normal volatilities for swaptions and caplets based on 3m and 6m Libor





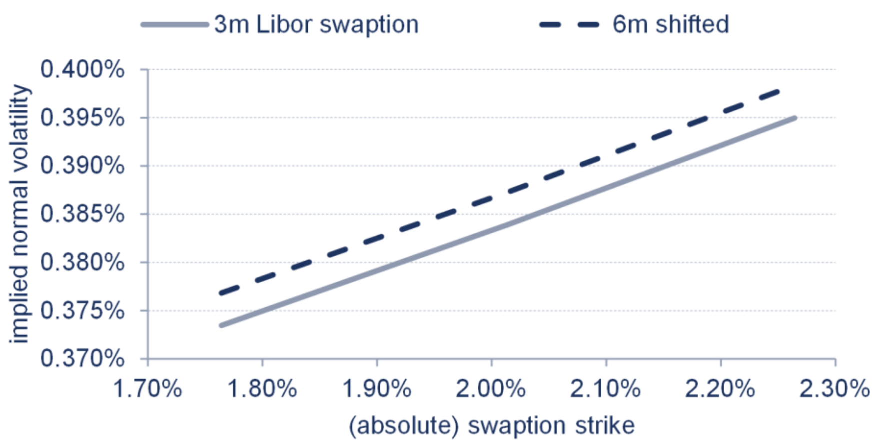
‚6m shifted' smile represents 6m smile horizontally shifted by difference in 3m vs. 6m forward rates

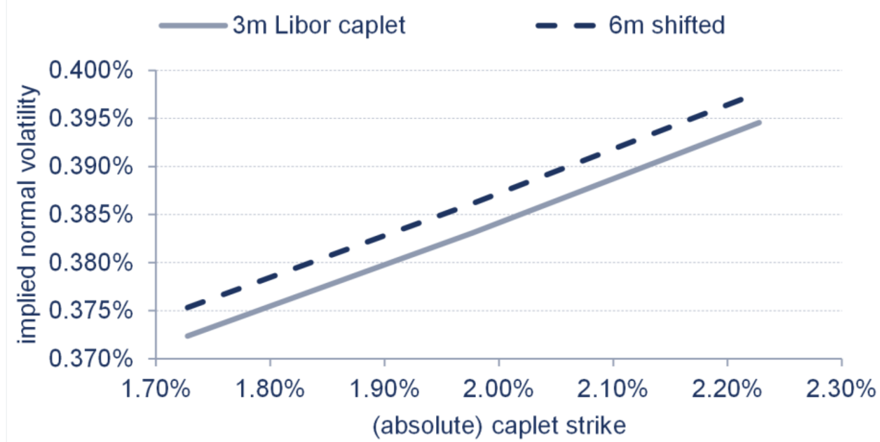
For a high-level view on volatility transformation just shift the smile by the difference in forwards

However, a closer look reveals additional variances in volatilities for different tenors

» Same Quasi-Gaussian model and swaption/caplet instruments as before

» Zoom in around ATM volatilities





What are the reasons for the additional variances?

» 3m versus 6m tenor basis

» Differences in payment frequency for 3m and 6m Libor legs for swaptions

» Interest rate de-correlation for caplets

We derive volatility transformation methodologies that capture basis, pay schedules and de-correlation

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Constant Basis Point Volatility Approach for Swaptions

Forward swap rates are expressed in terms of OIS discount factors and tenor basis spreads

» Consider forward swap rates based on short and long tenor Libor rates S^{μ} and S^{ν} with equal annuity

$$An(T) = \sum_{j=1}^{M} \tau_j \cdot P(T, \bar{T}_j)$$

» Applying deterministic basis model yields

$$S^{\mu}(T) = \frac{P(T, \bar{T}_0) - P(T, \bar{T}_M)}{An(T)} + \frac{1}{An(T)} \cdot \sum_{i=1}^{N^{\mu}} \left[D^{\mu}\left(T_{i-1}^{\mu}, T_i^{\mu}\right) - 1\right] P(T, T_{i-1}^{\mu})$$

$$S^{\nu}(T) = \frac{P(T, \bar{T}_0) - P(T, \bar{T}_M)}{An(T)} + \frac{1}{An(T)} \cdot \sum_{i=1}^{N^{\nu}} [D^{\nu}(T_{i-1}^{\nu}, T_i^{\nu}) - 1] P(T, T_{i-1}^{\nu})$$

» Thus S^{μ} and S^{ν} are related by

$$S^{\nu}(T) - S^{\mu}(T) = \frac{1}{An(T)} \cdot \left[\sum_{i=1}^{N^{\nu}} [D^{\nu}(T_{i-1}^{\nu}, T_i^{\nu}) - 1] P(T, T_{i-1}^{\nu}) - \sum_{i=1}^{N^{\mu}} \left[D^{\mu}\left(T_{i-1}^{\mu}, T_i^{\mu}\right) - 1\right] P(T, T_{i-1}^{\mu})\right]$$

Given our basis model, the swap rate spread is stochastic and depends on quotients $P(T, T_{i-1}^{\mu/\nu})/An(T)$

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Terminal Swap Rate (TSR) models developed for CMS pricing provide the ground for swap rate spread modelling

» Consider annuity mapping function expressed as linear terminal swap rate model

$$\alpha(s,T_p) = E\left[\frac{P(T,T_p)}{An(T)} \mid S^\mu(T) = s\right] \approx a(T_p)[s - S^\mu(t)] + \frac{P(t,T_p)}{An(t)}$$

- function $a(T_p)$ is derived satisfying additivity and consistency condition with basis spreads
- for more details on CMS pricing subject to basis spreads, see e.g. S. Schlenkrich, 2015
- we may replace terms $P(T,T_p)/An(T)$ by $a(T_p)[S^\mu(T) - S^\mu(t)] + P(t,T_p)/An(t)$

» Applying TSR model to swap rate spread yields

$$S^\nu(T) - S^\mu(T) = \frac{1}{An(t)} \cdot \left[\sum_{i=1}^{N^\nu}[D^\nu(T_{i-1}^\nu,T_i^\nu) - 1]P(t,T_{i-1}^\nu) - \sum_{i=1}^{N^\mu}[D^\mu(T_{i-1}^\mu,T_i^\mu) - 1]P(t,T_{i-1}^\mu)\right]$$

$$+[S^\mu(T) - S^\mu(t)] \cdot \underbrace{\left[\sum_{i=1}^{N^\nu}[D^\nu(T_{i-1}^\nu,T_i^\nu) - 1]a(T_{i-1}^\nu) - \sum_{i=1}^{N^\mu}[D^\mu(T_{i-1}^\mu,T_i^\mu) - 1]a(T_{i-1}^\mu)\right]}_{\lambda^{\mu,\nu}}$$

$$= S^\nu(t) - S^\mu(t) + [S^\mu(T) - S^\mu(t)] \cdot \lambda^{\mu,\nu}$$

Spread component $\lambda^{\mu,\nu}$ captures tenor basis and differences in payment schedules

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Affine relation between swap rates yields implied normal volatility transformation

» We have from basis model and Linear TSR model the affine relation

$$S^\nu(T) = S^\mu(T) + S^\nu(t) - S^\mu(t) + [S^\mu(T) - S^\mu(t)] \cdot \lambda^{\mu,\nu}$$
$$= [1 + \lambda^{\mu,\nu}] \cdot S^\mu(T) + [S^\nu(t) - [1 + \lambda^{\mu,\nu}] \cdot S^\mu(t)]$$

» Combination with the general volatility transformation result yields

$$\boldsymbol{\sigma^\nu(K) = [1 + \lambda^{\mu,\nu}] \cdot \sigma^\mu\left(\frac{K - [S^\nu(t) - [1 + \lambda^{\mu,\nu}] \cdot S^\mu(t)]}{1 + \lambda^{\mu,\nu}}\right)}$$

» Moreover, for two swap rates $S(T)$ and $\tilde{S}(T)$ based on the same Libor tenor but with different annuities $An(T)$ and $\widetilde{An}(T)$ we may derive the following approximate relation

$$\tilde{S}(T) \approx \frac{An(t)}{\widetilde{An}(t)} \cdot S(T) \text{ and thus } \boldsymbol{\tilde{\sigma}(K) = \frac{An(t)}{\widetilde{An}(t)} \cdot \sigma\left(\frac{\widetilde{An}(t)}{An(t)} \cdot K\right)}$$

Tenor basis and payment frequency have a slight effect on ATM and skew

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Swaption transformation methodology is confirmed by benchmark term structure model

- Keep 3m curve fixed and mark 3m vs. 6m basis from 0bp to 300bp
- Leave remaining parameters (in particular volatilities) unchanged
- Analyse resulting implied normal ATM volatilities

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Caplet Volatility Transformation

Basis model yields relation between short and long tenor forward Libor rates

- Consider a long tenor period $[T_0, T_n]$ with forward Libor rate $L^\nu(t) = L^\nu(t; T_0, T_n)$
- Decomposition into n short tenor periods $[T_0, T_1], \dots, [T_{n-1}, T_n]$ with forward Libor rates $L_i^\mu(t) = L_i^\mu(t; T_{i-1}, T_i)$
- Deterministic spread model yields

$$1 + \tau^\nu \cdot L^\nu(t) = D^\nu(T_0, T_n) \cdot \frac{P(t, T_0)}{P(t, T_n)}$$

$$1 + \tau_i^\mu \cdot L_i^\mu(t) = D^\mu(T_{i-1}, T_i) \cdot \frac{P(t, T_{i-1})}{P(t, T_i)}, i = 1, \dots, n$$

- Fundamental relation between forward Libor rates

$$1 + \tau^\nu \cdot L^\nu(t) = D^{\mu,\nu} \cdot \prod_{i=1}^{n} \left[1 + \tau_i^\mu \cdot L_i^\mu(t)\right]$$

with

$$D^{\mu,\nu} = \frac{D^\nu(T_0, T_n)}{\prod_{i=1}^{n} D^\mu(T_{i-1}, T_i)} = \exp\left\{\int_{T_0}^{T_n} [b^\nu(s) - b^\mu(s)] ds\right\}$$

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First order approximation of Libor rate dynamics…

- Use vector notation $L^{\mu}(t) = \left[L_i^{\mu}(t)\right]_{i=1,\dots,n}$ and define $C(L^{\mu}(t)) = \prod_{i=1}^{n}\left[1 + \tau_i^{\mu} \cdot L_i^{\mu}(t)\right]$
- Long tenor Libor returns become

$$L^{\nu}(T) - L^{\nu}(t) = \frac{D^{\mu,\nu}}{\tau^{\nu}} \cdot [C(L^{\mu}(T)) - C(L^{\mu}(t))]$$

$$\approx \frac{D^{\mu,\nu}}{\tau^{\nu}} \cdot \nabla C(L^{\mu}(t)) \cdot [L^{\mu}(T) - L^{\mu}(t)]$$

- The elements of the gradient $\nabla C(L^{\mu}(t))$ are

$$\nabla C(L^{\mu}(t)) = \left[\frac{\tau_j^{\mu} \cdot \prod_{i=1}^{n}\left[1 + \tau_i^{\mu} \cdot L_i(t)\right]}{1 + \tau_j^{\mu} \cdot L_j^{\mu}(t)}\right]_{j=1,\dots,n} = \left[\frac{\tau_j^{\mu} \cdot [1 + \tau^{\nu} L^{\nu}(t)]}{D^{\mu,\nu} \cdot \left[1 + \tau_j^{\mu} \cdot L_j^{\mu}(t)\right]}\right]_{j=1,\dots,n}$$

- This yields the relation between Libor rates as

$$L^{\nu}(T) - L^{\nu}(t) = \sum_{i=1}^{n} \underbrace{\left[\frac{\tau_i^{\mu} \cdot [1 + \tau^{\nu} L^{\nu}(t)]}{\tau^{\nu} \cdot \left[1 + \tau_i^{\mu} \cdot L_i^{\mu}(t)\right]}\right]}_{v_i} \cdot \left[L_i^{\mu}(T) - L_i^{\mu}(t)\right]$$

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(Co-)Variance approximation yields relation for ATM volatilities

- From $L^\nu(T) - L^\nu(t) = \sum_{i=1}^{n} v_i \left[L_i^\mu(T) - L_i^\mu(t)\right]$ follows

$$Var[L^\nu(T) - L^\nu(t)] = \sum_{i,j=1}^{n} v_i \cdot v_j \cdot Cov\left[L_i^\mu(T) - L_i^\mu(t), L_j^\mu(T) - L_j^\mu(t)\right]$$

with $v_i = \left(\tau_i^\mu \cdot [1 + \tau^\nu L^\nu(t)]\right) / \left(\tau^\nu \cdot \left[1 + \tau_i^\mu \cdot L_i(t)\right]\right)$

- Approximate variances by implied normal ATM volatilities and correlations as

$$Var[L^\nu(T) - L^\nu(t)] \approx [\sigma^\nu(L^\nu(t))]^2$$

$$Cov\left[L_i^\mu(T) - L_i^\mu(t), L_j^\mu(T) - L_j^\mu(t)\right] \approx \rho_{i,j}^\mu \cdot \sigma_i^\mu\left(L_i^\mu(t)\right) \cdot \sigma_j^\mu\left(L_j^\mu(t)\right)$$

- This yields ATM volatility transformation formula

$$[\sigma^\nu(L^\nu(t))]^2 = \sum_{i,j=1}^{n} v_i \cdot v_j \cdot \rho_{i,j}^\mu \cdot \sigma_i^\mu\left(L_i^\mu(t)\right) \cdot \sigma_j^\mu\left(L_j^\mu(t)\right)$$

- ATM transformation formula has the same general structure as elaborated in J. Kienitz, 2013 for log-vols.

  However, $v_i = \frac{\tau_i^\mu \cdot [1+\tau^\nu L^\nu(t)]}{\tau^\nu \cdot \left[1+\tau_i^\mu \cdot L_i(t)\right]}$ differ and already capture tenor basis

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Derive smile transformation from boundary argument

» Consider special case that

$$\bar{L}^{\mu}(t) = L_1^{\mu}(t) = \cdots = L_n^{\mu}(t) \text{ for all } t \text{ and thus } \rho_{i,j}^{\mu} = 1$$

» Then

$$L^{\nu}(T) - L^{\nu}(t) = \left[\sum_{i=1}^{n} v_i\right] \cdot \left[\bar{L}^{\mu}(T) - \bar{L}^{\mu}(t)\right]$$

and we get the affine relation

$$L^{\nu}(T) = \left(\sum_{i=1}^{n} v_i\right) \bar{L}^{\mu}(T) + \left[L^{\nu}(t) - \left(\sum_{i=1}^{n} v_i\right) \bar{L}^{\mu}(t)\right]$$

» This yields the implied volatility smile transformation (for that special case)

$$\sigma^{\nu}(K) = \left(\sum_{i=1}^{n} v_i\right) \cdot \sigma^{\mu}\left(\frac{K - \left[L^{\nu}(t) - \left(\sum_{i=1}^{n} v_i\right)\bar{L}^{\mu}(t)\right]}{\left(\sum_{i=1}^{n} v_i\right)}\right)$$

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Combine structure of ATM and (boundary case) smile transformation

» ATM volatility transformation

$$[\sigma^\nu(L^\nu(t))]^2 = \sum_{i,j=1}^{n} v_i \cdot v_j \cdot \rho_{i,j}^{\mu} \cdot \sigma_i^{\mu}\left(L_i^{\mu}(t)\right) \cdot \sigma_j^{\mu}\left(L_j^{\mu}(t)\right)$$

» Smile transformation for $\bar{L}^{\mu}(t) = L_1^{\mu}(t) = \cdots = L_n^{\mu}(t)$

$$\sigma^\nu(K) = \left(\sum_{i=1}^{n} v_i\right) \cdot \sigma^{\mu}\left(\frac{K - [L^\nu(t) - (\sum_{i=1}^{n} v_i)\bar{L}^{\mu}(t)]}{(\sum_{i=1}^{n} v_i)}\right)$$

» ATM and skew condition represent neccessary conditions for volatility transformation.

» We propose the general transformation that complies with ATM and smile condition:

$$[\boldsymbol{\sigma}^{\boldsymbol{\nu}}(\boldsymbol{K})]^{2} = \sum_{i,j=1}^{n} \boldsymbol{v}_i \cdot \boldsymbol{v}_j \cdot \boldsymbol{\rho}_{i,j}^{\mu} \cdot \boldsymbol{\sigma}_i^{\mu}(\boldsymbol{K}_i) \cdot \boldsymbol{\sigma}_j^{\mu}(\boldsymbol{K}_j) \;\; \boldsymbol{with} \; \boldsymbol{K}_i = \frac{\boldsymbol{K} - \left[\boldsymbol{L}^{\nu}(\boldsymbol{t}) - (\sum_{i=1}^{n} \boldsymbol{v}_i)\boldsymbol{L}_i^{\mu}(\boldsymbol{t})\right]}{(\sum_{i=1}^{n} \boldsymbol{v}_i)}$$

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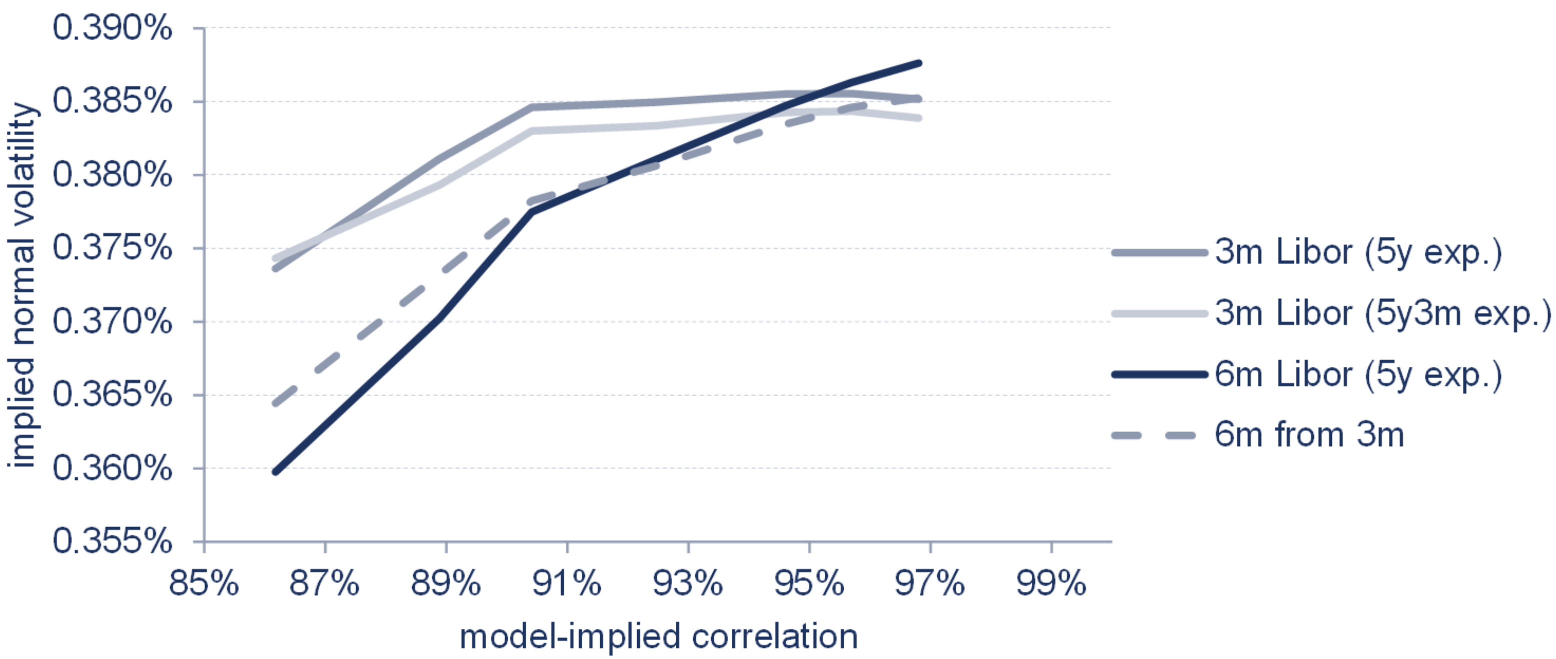
Caplet volatility transformation methodology yields good match with term structure model benchmark

» Mark several scenarios for model correlation in Quasi-Gaussian model

» Leave remaining parameters unchanged

» Analyse model-implied normal ATM volatilities versus model-implied correlations (both evaluated by Monte-Carlo simulation)



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Estimating Forward Rate Correlation

Consider volatility transformation for caplets as (an invertable) mapping from short tenor volatilities and correlations to long tenor volatilities

» Caplet volatility transformation for ATM and smile may be written as

$$\psi: (\sigma^{\mu}, \rho^{\mu}) \mapsto \sigma^{\nu}$$

» For two long tenor volatilities σ^{ν_1} and σ^{ν_2} with $\mu < \nu_1 < \nu_2$ we also have

$$\begin{bmatrix} \sigma^{\mu} \\ \rho^{\mu} \end{bmatrix} \mapsto \begin{bmatrix} \sigma^{\nu_1} \\ \sigma^{\nu_2} \end{bmatrix} = \begin{bmatrix} \psi^1(\sigma^{\mu}, \rho^{\mu}) \\ \psi^2(\sigma^{\mu}, \rho^{\mu}) \end{bmatrix}$$

Consequences (provided reasonable regularisation for ρ^{μ})

» If ATM short and long tenor volatilities σ^{μ} and σ^{ν} are available then we can imply correlations ρ^{μ}

» If ATM long tenor volatilities σ^{ν_1} and σ^{ν_2} are available then we can imply short tenor volatility σ^{μ} and correlation ρ^{μ}

Once correlations are derived we can apply caplet volatility transformation for the whole smile

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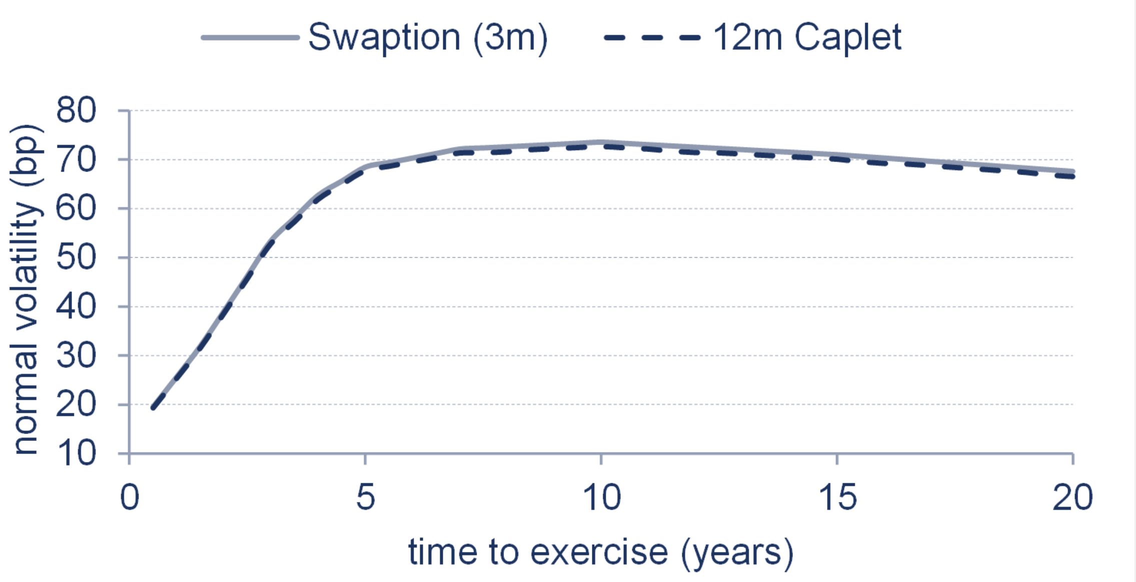
As a starting point transform 1y ATM swaption volatilities to 12m Euribor caplet volatilities

» 1y EUR swaption volatility: 3m Euribor (Act/360) versus semi-annual fixed (30/360)

› Use swaption transformation methodology to convert 3m Euribor to 12m Euribor ATM vols

› Use annuity transformation to convert semi-annual, 30/360 to annual Act/360 payments

» Transformed volatility is equivalent to 12m Euribor ATM caplet volatility



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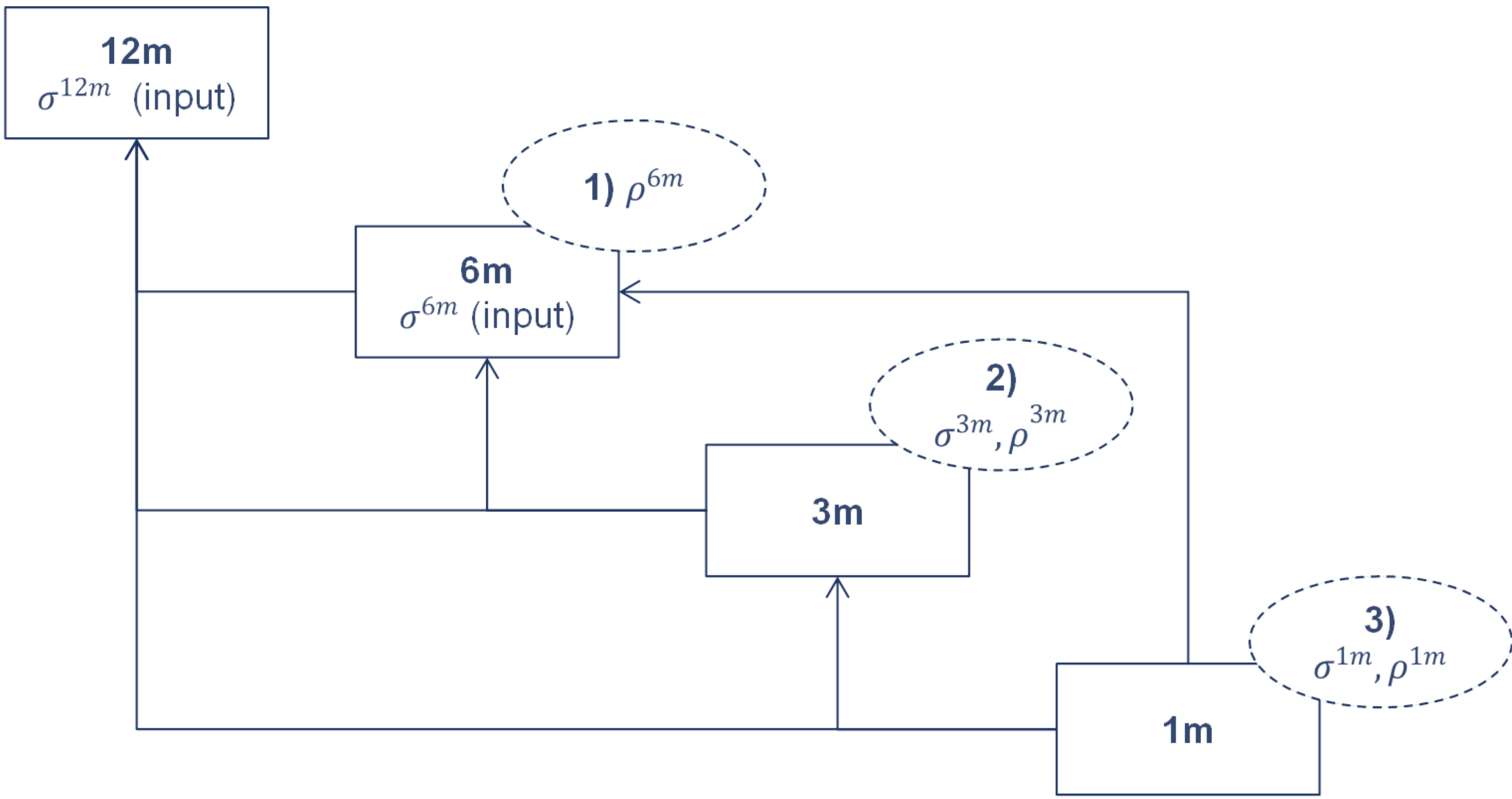
Use 6m and 12m caplet volatilities and sukzessively derive further ATM volatilities and correlations



Procedure yields consistent setting of volatilities and correlations for all relevant tenors

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We use a classical correlation parametrisation

- Correlation structure depending on Libor rate start dates T_i and T_j

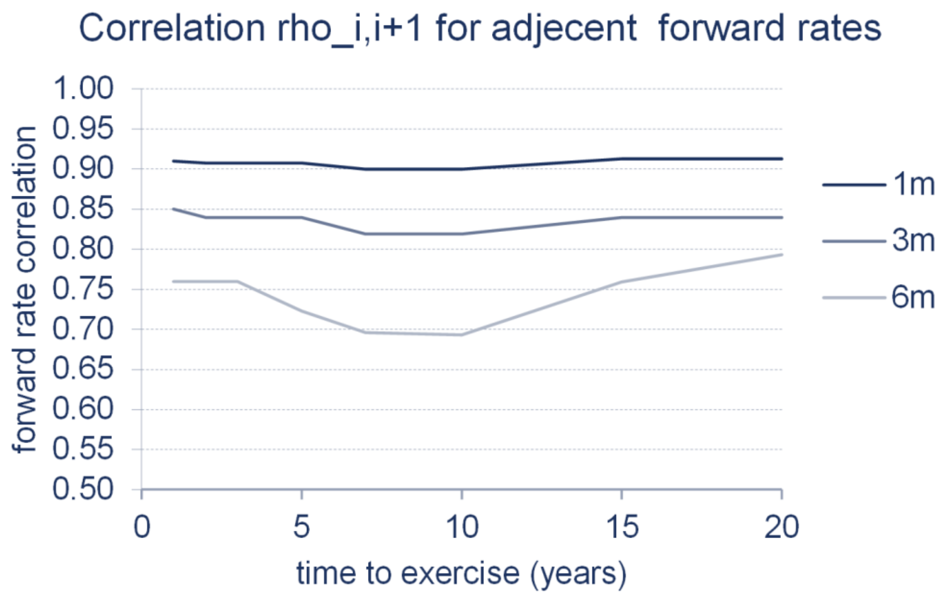
$$\rho_{i,j} = \rho_\infty(T_i) + [1 - \rho_\infty(T_i)] \exp\{-\beta(T_i)(T_j - T_i)\}, T_j > T_i$$

- For 3m and 6m correlations mark $\rho_\infty(T_i) = 0$ and only fit $\beta(T_i)$
- For 1m correlation include $\rho_\infty(T_i)$ in calibration to improve fit

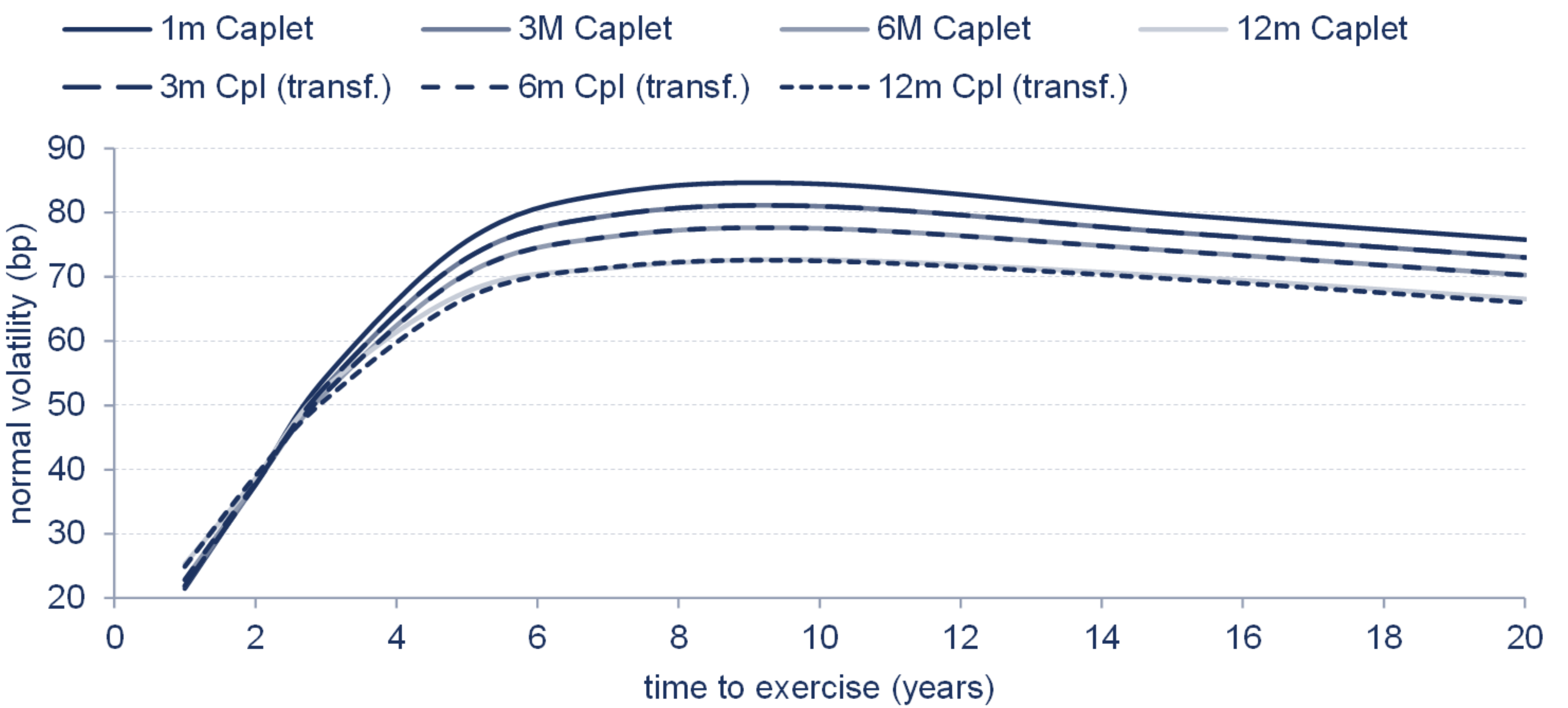
correlation

calibration

results



Example calibration of 1m volatilities to (already) available 3m, 6m, and 12m volatilities



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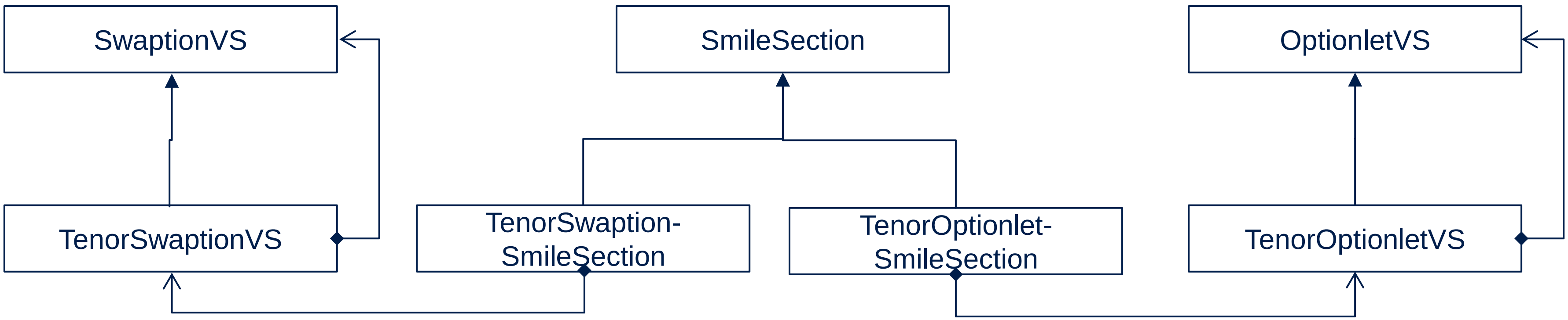
Implementation in QuantLib

Use decorator design pattern to implement volatility transformation



- Store short/long tenor index
- Reference to base volatility
- Reference to discount curve
- Create TenorSwapttion-SmileSection and pass on volatility evaluation

- Set up TSR model
- Derive $\lambda^{\mu,\nu}$
- Implement volatility transformation

- Set up short tenor smile sections
- Calculate v_i
- Implement volatility transformation

- Store short/long tenor index
- Reference to base volatility
- Reference to discount curve
- Create TenorOptionlet-SmileSection and pass on volatility evaluation

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Summary and Conclusion

Summary and Conclusion

- Shifting normal volatilities by difference in forward rates provides a reasonable approach for volatility transformation
- If more accuracy is desired we elaborated an approach for ATM and smile capturing
  - Tenor basis
  - Payment frequency and day count conventions for swaptions
  - De-correlation for caplets
- Combining swaption and caplet volatility transformation allows full specification of correlations and volatilities of non-standard tenors
- More details may be found in the literature

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