$b \to s\tau^+\tau^-$ @ FCC-ee and $\tau^\pm$ polarizations

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Motivations

- $b \to s$ **semileptonic decays** involving **light leptons**:
  $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$ shows $\sim 2.6\,\sigma$ tension w/ SM; [LHCb]
  $B \to K^{(*)} \mu^+ \mu^-$ and $B_s \to \phi \mu^+ \mu^-$ branching ratios, and [LHCb]
  $B \to K^* \mu^+ \mu^-$ ang. obs. in tension w/ SM/QCD, [LHCb, Belle, ATLAS]
  together w/ R_{K^*}: certainly an exciting picture [LHCb] [cf. Marco's talk]

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- The process $b \to s$ with **taus** has not been observed so far:
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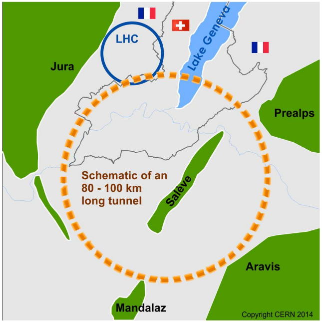
  still far above SM-branching ratio of $\mathcal{O}(10^{-7})$
- LFU violation suggested by μ, e (to mention only FCNC),
  room for LFU violation in taus [cf. Andreas' talk]

Future Circular Collider @ CERN

- Design stage
- e^+e^- collider
  (formerly known as TLEP)
- $\sqrt{s} = 90, 160, 240, 350$ GeV
- Clean experimental environment
- Flavor physics cases
  remain unexplored



Here: **1.** $B \to K^* \tau^+ \tau^-$ reconstruction @ FCC-ee
2. Polarization asymmetries of the τ [$\bar{B} \to D^* \tau^- \bar{\nu}$: see Martin's talk]
3. Anatomy of $\tau-$LFUV through polarization asyms.

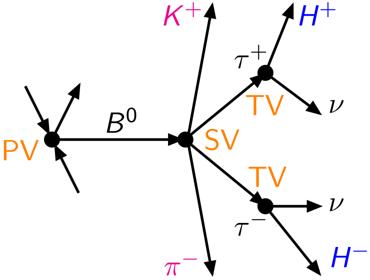
Reconstruction of $B \to K^* \tau^+ \tau^-$ events

Challenge: reconstruct events (m_B, kinematics) where information is missing due to the final-state neutrino in $\tau \to H\,\nu$

Primary Vertex (**PV**) $\to$ production of the B meson

Secondary Vertex (**SV**) $\to$ the decay $B \to K^* \tau^+ \tau^-$

Tertiary Vertexes (**TV**) $\to$ decays of the τ leptons



Conservation laws + vertexing:

$$\{m_\tau, E_H, \vec{p}_H, \mathrm{SV}, \mathrm{TV}\} \Rightarrow \vec{p}_\tau,\ \vec{p}_\nu$$

$$\{\vec{p}_{K^*} = \vec{p}_{K\pi}, \mathrm{PV}, \mathrm{SV}\} \Rightarrow m_B,\ \vec{p}_B$$

(In what follows, $H^\pm = \pi^\pm \pi^- \pi^+$)

Simulation: chosen performances [from ILD detector]

MC generated data: true values smeared due to finite resolutions

Momentum resolution: ($p_\perp = p \sin\theta$)

$$\frac{\sigma_{p_\perp}}{p_\perp^2} = 10^{-5}\,[\mathrm{GeV}^{-1}] \oplus \frac{5\times 10^{-4}}{p_\perp \sin\theta}$$

Vertex resolution: (considering nb. of tracks out of a vertex)

- Primary Vertex → 1.5 um
- Secondary Vertex → 3.5 um
- Tertiary Vertex → 2.5 um

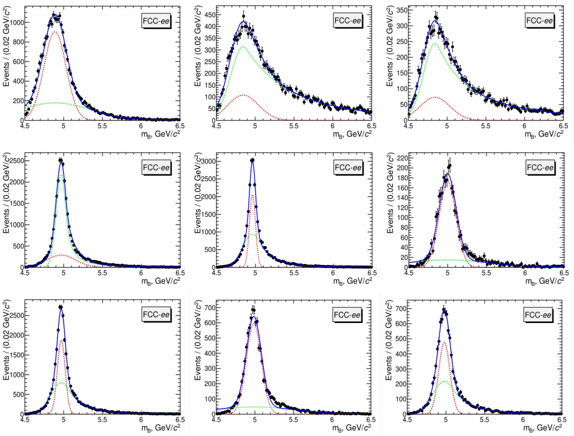
Background

Most relevant background comes from D mesons in $b \to c$:

$$B^0 \to D_s^+ K^{*0} \tau^+ \nu_\tau \,, \quad \bar{B}_s^0 \to D_s^- D_s^+ K^{*0}$$

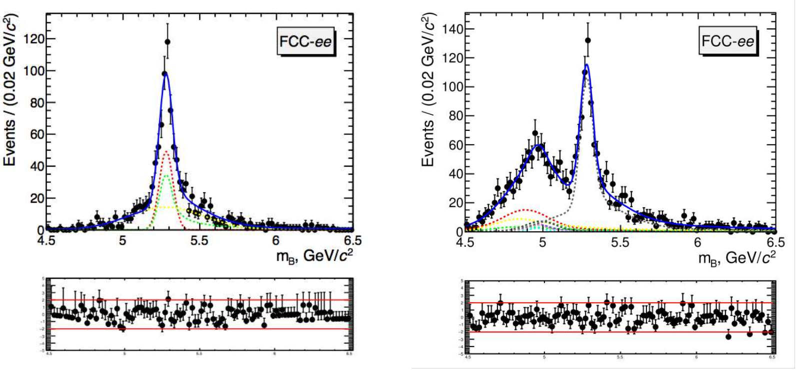
Channels:

$$D_s^+ \to \tau^+ \nu_\tau ,$$
$$D_s^+ \to \pi^+ \pi^- \pi^+ K_L^0 ,$$
$$D_s^+ \to \pi^+ \pi^- \pi^+ \pi^0$$



Signal and background fits

Results for baseline luminosity (10^{13} Z bosons)



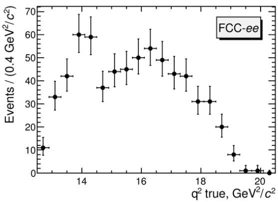
Signal model

Full fit

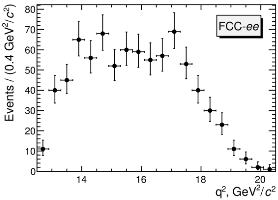
$\Rightarrow \mathcal{O}(10^3)$ reconstructed signal events

Invariant mass of the $\tau^+\tau^-$ pair

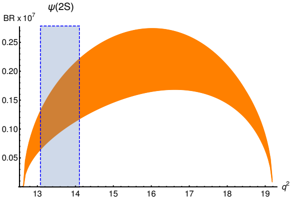
Reconstruction of the $\tau\tau$ inv. mass q^2, w/ $4m_\tau^2 \leq q^2 \leq (m_B - m_{K^*})^2$



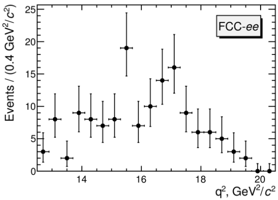
Simulated



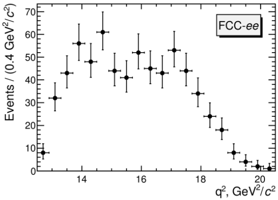
Signal+background



SM prediction



Background

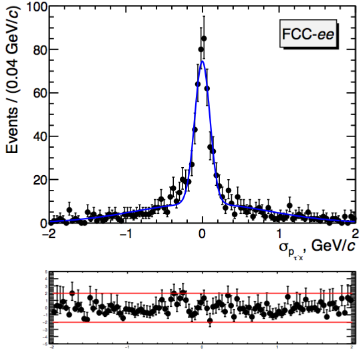


Signal only

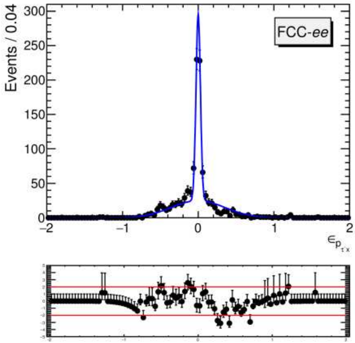
Reconstructed τ momentum

Efficiency in the τ momentum reconstruction:

$\sigma_{p_\tau} = (p_{reconstructed} - p_{true})$



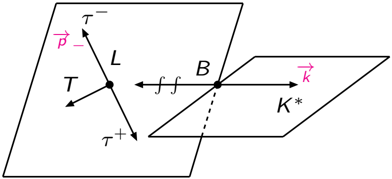
$\epsilon_{p_\tau} = (p_{reconstructed} - p_{true})/p_{true}$



Asymmetries in the τ polarization

Decay products in $\tau \to H\nu$ act as a self-analyzer [cf. Susanne's talk in $\sim$ 15 min]

[Tsai '71, T. Hagiwara et al. '77, Kühn et al. '84, Aurenche et al. '85, K. Hagiwara et al. '90, Rougé '90, Davier et al. '93]



Rest frame of the τ^-

Longitudinal: $e_L = \widehat{\vec{p}}_-$

Normal: $e_N = \dfrac{\vec{k} \times \vec{p}_-}{|\vec{k} \times \vec{p}_-|}$

Transverse: $e_T = e_N \times e_L$

[Hewett '95, Krüger and Sehgal '96]

[Aliev et al., Bensalam et al. '02, P. Colangelo et al. '06 '14]

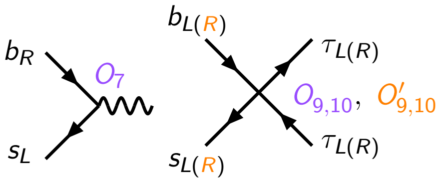
$$\mathcal{P}_X^\pm = \frac{d\Gamma(\tau^\pm \text{ w/ spin along } +e_X) - d\Gamma(\tau^\pm \text{ w/ spin along } -e_X)}{d\Gamma(\tau^\pm \text{ w/ spin along } +e_X) + d\Gamma(\tau^\pm \text{ w/ spin along } -e_X)}$$

$m_\tau \to 0^+$: $\mathcal{P}_L^\pm$ reduce to $\tau^\pm$ Left/Right chirality asymmetries, while $\mathcal{P}_{T,N}^\pm$ vanish

SM operators and Wilson coefficients

Below EW scale, $H_{weak:\, b\to s} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} c_i(\mu_b) O_i(\mu_b)$

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$
$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma^\mu b_L) \bar{\tau}\gamma_\mu \tau$$
$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma^\mu b_L) \bar{\tau}\gamma_\mu \gamma_5 \tau$$



In the SM, $\mathcal{P}^{\pm}_{L,T,N}$ depend on c_7^{eff}, c_9^{eff}, c_{10}, where "eff" includes loop contributions from $O_{1,2,3,4,5,6,8}$ [Buchalla et al. '95, Beneke et al. '01, Seidel '04]

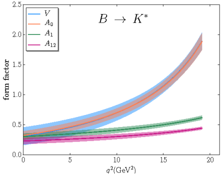
Muon data: δc_9^μ, δc_{10}^μ, c'^{μ}_9, c'^{μ}_{10} [Altmannshofer et al., Descotes-G. et al., Hurth et al.]

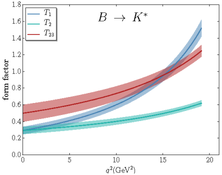
Sources of uncertainty

Lattice extraction of the Form Factors (FF) $\rightarrow$ low recoil of the $K^{(*)}$, ϕ, or high $(p_{\tau^+} + p_{\tau^-})^2 = q^2$

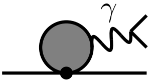
[Horgan et al. '13 '15: $B \rightarrow K^*$, $B \rightarrow \phi$]

[Bailey et al. '15: $B \rightarrow K$]





Correction for $\bar{\tau}\gamma_\mu\tau$: ops. of higher dimension $\oplus$ charm resonances $\Rightarrow$ $\sim 10\ \% \times c_9^{\text{eff}}$, times arbitrary phases for the different helicities



[Grinstein et al. '04, Beylich et al. '11]

Uncertainty of c_7^{eff}, c_9^{eff}, c_{10} (ren. scale, α_s value, etc.): $\mathcal{O}(2\ \%)$

[e.g., QED: Bobeth et al. '03]

SM predictions for $B^0 \to K^{*0}\tau^+\tau^-$ and $B \to K\tau^+\tau^-$

$$\text{Binned obs.}: \quad \langle \mathcal{P}_X^{\pm}(K^{(*)}) \rangle = \frac{\int_{14.18\,\mathrm{GeV}^2}^{q^2_{\max}} dq^2 \left(\frac{d\Gamma}{dq^2}(e_X) - \frac{d\Gamma}{dq^2}(-e_X) \right)}{\int_{14.18\,\mathrm{GeV}^2}^{q^2_{\max}} dq^2 \left(\frac{d\Gamma}{dq^2}(e_X) + \frac{d\Gamma}{dq^2}(-e_X) \right)}$$

$$\begin{aligned}
\mathcal{B}(K^*) \times 10^7 &= 1.30\,(09)\,(\mathbf{22})\,(10) \\
\langle \mathcal{A}_{FB}(K^*) \rangle &= 0.203\,(15)\,(\mathbf{25})\,(04) \\
|\langle \mathcal{P}_L^{\pm}(K^*) \rangle| &= 0.560\,(07)\,(\mathbf{28})\,(12) \\
|\langle \mathcal{P}_T^{-}(K^*) \rangle| &= 0.533\,(18)\,(\mathbf{39})\,(02) \\
|\langle \mathcal{P}_T^{+}(K^*) \rangle| &= 0.03\,(04)\,(\mathbf{11})\,(01) \\
|\langle \mathcal{P}_N^{\pm}(K^*) \rangle| &= 0.013\,(01)\,(\mathbf{12})\,(00)
\end{aligned}$$

$$\begin{aligned}
\mathcal{B}(K) \times 10^7 &= 1.61\,(07)\,(\mathbf{12})\,(09) \\
\langle \mathcal{A}_{FB}(K) \rangle &= 0 \\
|\langle \mathcal{P}_L^{\pm}(K) \rangle| &= 0.246\,(4)\,(\mathbf{6})\,(2) \\
|\langle \mathcal{P}_T^{\pm}(K) \rangle| &= 0.744\,(00)\,(\mathbf{17})\,(06) \\
\langle \mathcal{P}_N^{\pm}(K) \rangle &= 0
\end{aligned}$$

Uncertainties: form factors, **OPE** $\oplus$ **charm resons.**, Wilson coefs.

$$\frac{\mathcal{P}_L^{\pm}(K)}{\mathcal{P}_T^{\pm}(K)}(q^2) = \frac{F_1(q^2)}{F_0(q^2)} \times f(m_{B,K,\tau}, q^2) \quad \Rightarrow \quad \frac{|\langle \mathcal{P}_L^{\pm}(K) \rangle|}{|\langle \mathcal{P}_T^{\pm}(K) \rangle|} = 0.330\,(5)\,(0)\,(0)$$

$$\frac{\mathcal{P}_L^{\pm}(K^*_{\mathrm{long.}})}{\mathcal{P}_T^{\pm}(K^*_{\mathrm{long.}})}(q^2) = \sum_{i=1}^{2} \frac{A_i(q^2)}{A_0(q^2)} \times f_i(m_{B,K^*,\tau}, q^2) \Rightarrow \frac{|\langle \mathcal{P}_L^{\pm}(K^*_{\mathrm{long.}}) \rangle|}{|\langle \mathcal{P}_T^{\pm}(K^*_{\mathrm{long.}}) \rangle|} = 0.68\,(3)\,(0)\,(0)$$

Double polarizations

Also possible to define the correlated $\tau^\pm$ polarization:

$$\mathcal{P}_{AB}(q^2) = \frac{\left[\frac{d\Gamma}{dq^2}(e_A^-, e_B^+) - \frac{d\Gamma}{dq^2}(-e_A^-, e_B^+)\right] - \left[\frac{d\Gamma}{dq^2}(e_A^-, -e_B^+) - \frac{d\Gamma}{dq^2}(-e_A^-, -e_B^+)\right]}{\frac{d\Gamma}{dq^2}(e_A^-, e_B^+) + \frac{d\Gamma}{dq^2}(-e_A^-, e_B^+) + \frac{d\Gamma}{dq^2}(e_A^-, -e_B^+) + \frac{d\Gamma}{dq^2}(-e_A^-, -e_B^+)}$$

$$|\langle \mathcal{P}_{LL}(K^*) \rangle| = 0.35\ (1.7)\ (\mathbf{2})\ (0.7)$$

$$|\langle \mathcal{P}_{TT}(K^*) \rangle| = 0.05\ (3)\ (\mathbf{9})\ (1)$$

$$|\langle \mathcal{P}_{NN}(K^*) \rangle| = 0.09\ (2)\ (\mathbf{8})\ (1)$$

$$|\langle \mathcal{P}_{LT}(K^*) \rangle| = 0.00\ (2)\ (\mathbf{3})\ (0.7)$$

$$|\langle \mathcal{P}_{TL}(K^*) \rangle| = 0.28\ (0.9)\ (\mathbf{3})\ (1)$$

$$|\langle \mathcal{P}_{LN,NL}(K^*) \rangle| = 0.05\ (0.2)\ (\mathbf{2})\ (0.1)$$

$$|\langle \mathcal{P}_{TN,NT}(K^*) \rangle| = 0.00\ (0.2)\ (\mathbf{3})\ (0)$$

$$|\langle \mathcal{P}_{LL}(K) \rangle| = 0.30\ (1)\ (\mathbf{6})\ (2)$$

$$|\langle \mathcal{P}_{TT}(K) \rangle| = 0.68\ (0.5)\ (\mathbf{2})\ (0.7)$$

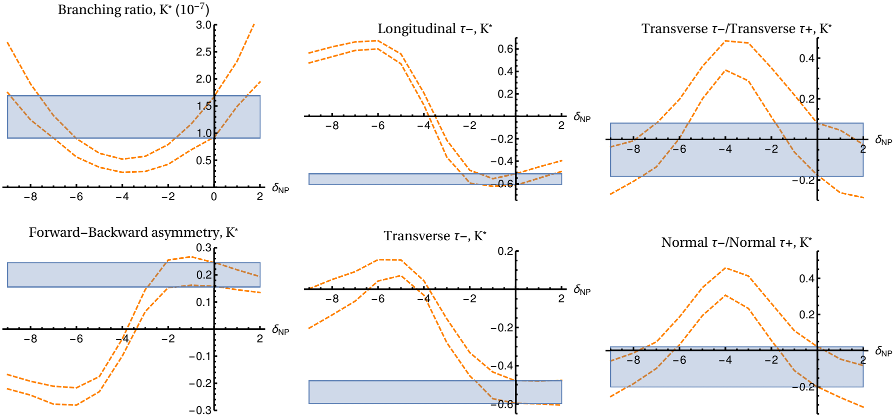
$$|\langle \mathcal{P}_{NN}(K) \rangle| = 0.20\ (1)\ (\mathbf{9})\ (4)$$

$$|\langle \mathcal{P}_{LT,TL}(K) \rangle| = 0.33\ (0)\ (\mathbf{3})\ (1)$$

$$|\langle \mathcal{P}_{LN,NL}(K) \rangle| = 0.11\ (0)\ (\mathbf{7})\ (0.2)$$

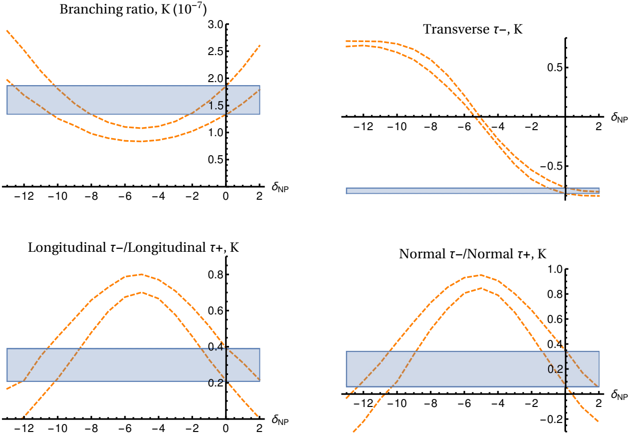
$$|\langle \mathcal{P}_{TN,NT}(K) \rangle| = 0.03\ (0)\ (\mathbf{3})\ (0)$$

Case of real $\delta c_9 \equiv \delta_{\rm NP}$: $B \to K^* \tau\tau$



- Ranges chosen for $\approx$ SM-like $\mathcal{B}$ (SM: $c_9^{\rm eff} \simeq 4$)
- SM-like asyms. exclude a large set of $\delta_{\rm NP}$ values
- The double asyms. give a complementary picture

Case of real $\delta c_9 \equiv \delta_{\rm NP}$: $B \to K\tau\tau$

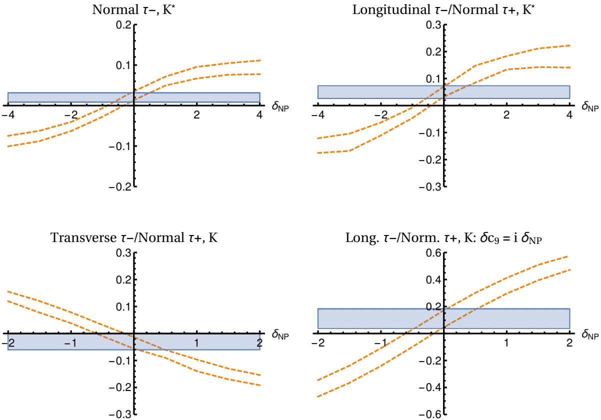


- Enhancement of LL, NN asymmetries to values $\gtrsim 0.8$
- T vanishes in the untagged case ($B^0 \to K^0, \bar{B}^0 \to \bar{K}^0$)

Pure imaginary $\delta C_9 \equiv i\,\delta_{\rm NP}$

In the SM, $\mathrm{Im}\{c_7^{\rm eff}\}, \mathrm{Im}\{c_9^{\rm eff}\}$ come at higher orders $\Rightarrow \mathcal{P}_N^{\pm} \ll \mathcal{P}_{L,T}^{\pm}$

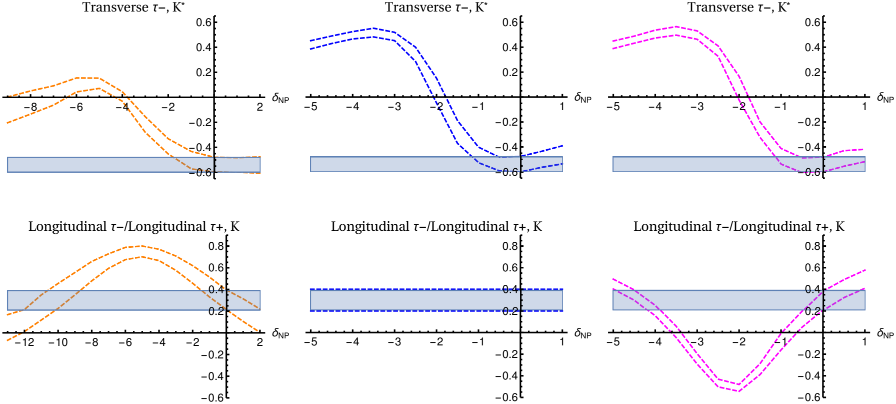
[cf. Krüger and Sehgal '96]



Similar modulations are also found for $\delta C_{10} \equiv i\,\delta_{\rm NP}$

Distinction of NP models

- $\delta C_9 \equiv \delta_{\rm NP}$,
- $\delta C_9 = -C_9' \equiv \delta_{\rm NP}$, and
- $\delta C_9 = -C_9' = -\delta C_{10} = -C_{10}' \equiv \delta_{\rm NP}$



Overview and ongoing work

- Proof of viability of the reconstruction of $B \to K^* \tau\tau$ events
- SM: good theoretical control of some polarization asymmetries, $\delta \langle \mathcal{P}^{\pm}_{L,T}(K^{(*)}) \rangle_{SM} \lesssim \mathcal{O}(10~\%)$
  (smaller for the long./transv. ratios)
- Clear NP signatures

- Ongoing work:
  experimental reconstruction of the L, T, N polarizations,
  for in principle $\tau^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}\nu$

Hvala*

*Thanks

Constraints on $(\bar{b}\Gamma s)(\tau^+\Gamma'\tau^-)$

- Indirect information from $\Gamma_d/\Gamma_s \Rightarrow \mathcal{B}(B_s \to \tau^+\tau^-) < 0.03$,
- $B \to X_s\tau^+\tau^-$ mimicking $b \to u\ell\bar{\nu}$, $\ell = e, \mu$,
- Direct bounds from $B^+ \to K^+\tau^+\tau^-$:
  constraints $|c_{S,AB}, c_{V,AB}, c_{T,AB}| \lesssim 10^3$ $(A, B = L, R)$

[Bobeth and Haisch '11; cf. Grossman et al. '96]

- With the direct bound, $\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$: [LHCb]
  $|c_{S,AB}, c_{V,AB}|$ bounds roughly improved by a factor ~ 2

- $SU(2)_L$ symmetry: exploit $B \to K^{(*)}\nu\bar{\nu} \Rightarrow c_{V,AL} \lesssim \mathcal{O}(10)$

[Buras et al. '14, Alonso et al. '15]