Progress on $B^0 \to K^{*0}\tau^+\tau^-$ observables

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Motivations

- $b \to s$ **semileptonic decays** involving light leptons:
  $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$ show $\sim 2.6\,\sigma$ 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. @ low-$q^2_{\mu\mu}$ in tension w/ SM/QCD

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- The process $b \to s \tau^+ \tau^-$ has **not** been observed so far:
  $\mathcal{B}(B^+ \to K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3}$ @ 90 %; [BABAR]
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- **Here/FCC-ee:** investigation of $b \to s \tau^+ \tau^-$ physics,
  including asymmetries for the τ spin polarization

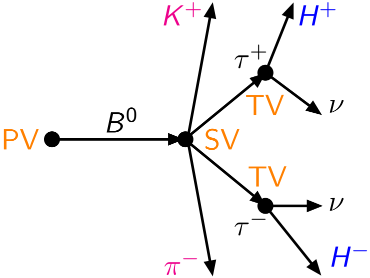
Reconstruction

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

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

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

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:

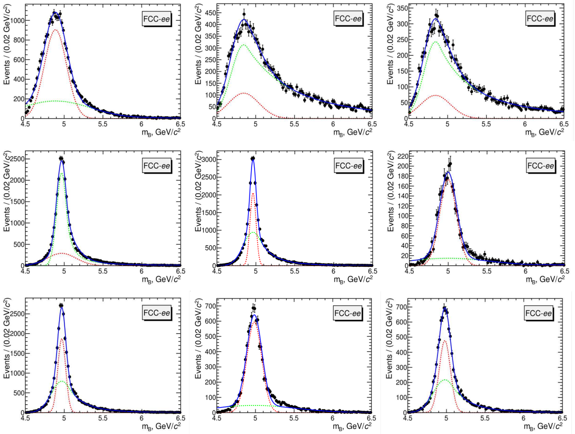
$$B^0 \to D_s^+ K^{*0} \tau^+ \nu_\tau \,, \quad \bar{B}_s^0 \to D_s^- D_s^+ K^{*0}$$

Channels:

$$D_s^+ \to \tau^+ \nu_\tau ,$$

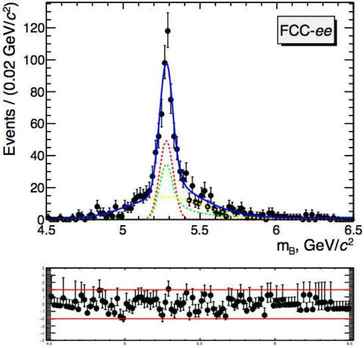
$$D_s^+ \to \pi^+ \pi^- \pi^+ K_L^0 ,$$

$$D_s^+ \to \pi^+ \pi^- \pi^+ \pi^0$$

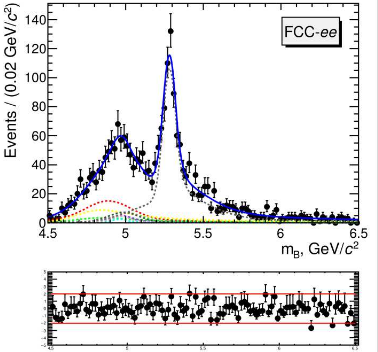


Signal and background fits

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



Signal model

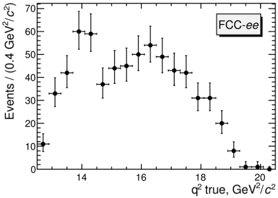


Full fit

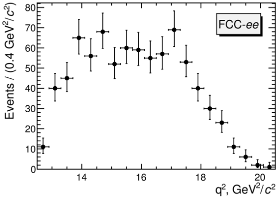
$\Rightarrow \mathcal{O}(10^3)$ reconstructed signal events

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

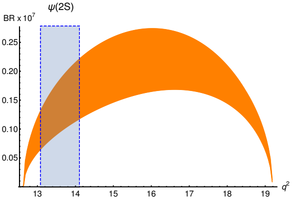
Reconstruction of the $\tau^+\tau^-$ inv. mass q^2, $4m_\tau^2 \le q^2 \le (m_B - m_{K^*})^2$



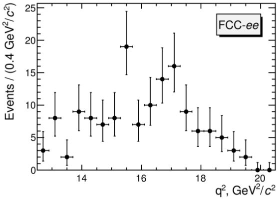
Simulated



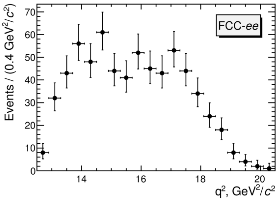
Signal+background



SM prediction



Background

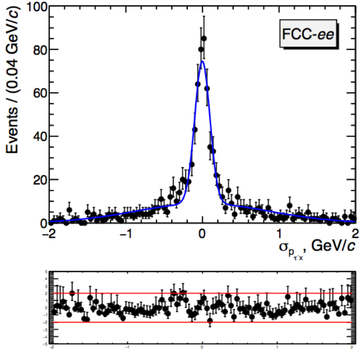


Signal only

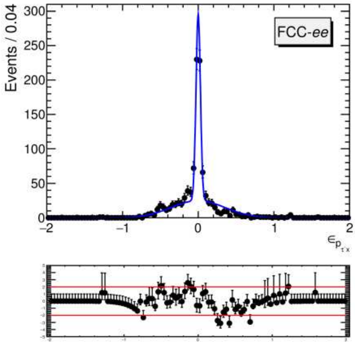
Reconstructed τ momentum

Efficiency in the τ momentum reconstruction:

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



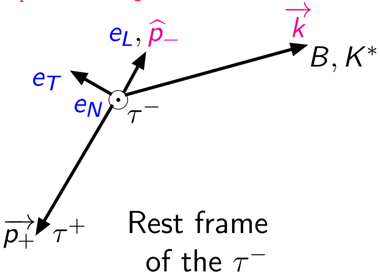
$\epsilon_{p_\tau} = (p_{reconstructed} - p_{true})/p_{true}$



Asymmetries in the τ polarization

$\tau \to H\nu$ polarization reconstruction for $H^\pm = \pi^\pm\pi^+\pi^-$ (under implementation)

[Tsai '71, T. Hagiwara et al. '77, Kühn et al. '84, Aurenche et al. '85, K. Hagiwara et al. '90, Rougé '90, Schade '09]



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

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

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]

$$\mathcal{A}_X^- = \frac{(\#\ \tau^-\ \text{w/ spin along } +e_X) - (\#\ \tau^-\ \text{w/ spin along } -e_X)}{(\#\ \tau^-\ \text{w/ spin along } +e_X) + (\#\ \tau^-\ \text{w/ spin along } -e_X)}$$

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

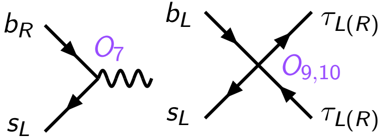
SM operators and Wilson coefficients

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, $\mathcal{A}^{\pm}_{L,T,N}$ depend on $c_7^{\rm eff}$, $c_9^{\rm eff}$, c_{10}, known up to the NNLL

[Buchalla et al. '95, Seidel '04, Beneke et al. '01]

$\mathcal{A}^{\pm}_N$ is odd under time reversion, thus requiring complex phases.
In the SM, $\mathrm{Im}\{c_7^{\rm eff}\}, \mathrm{Im}\{c_9^{\rm eff}\}$ come at higher orders $\Rightarrow \mathcal{A}^{\pm}_N \ll \mathcal{A}^{\pm}_{L,T}$

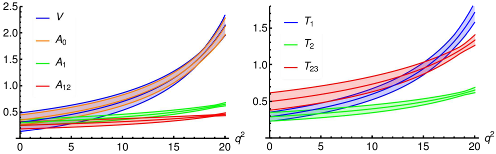
[cf. Krüger and Sehgal '96]

Sources of uncertainty

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

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

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

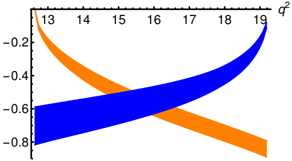


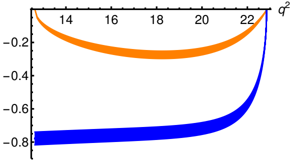
Ops. of higher dimension (power counting in $1/Q$, $Q = (m_b, \sqrt{q^2})$): contributions amount ~ 5 % [Grinstein et al. '04, Beylich et al. '11]

Other uncertainties (renormalization scales, top mass) are subleading

QED effects not calculated ($\mathcal{O}(2$ %) for $B \rightarrow X_s \ell^+ \ell^-$, $\ell = e, \mu$) [Bobeth et al. '03]

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





$\mathcal{B}(K^*) \times 10^7 = 1.0 \times (1 \pm \mathbf{20}\ \% \ \pm 5\ \%)$
$\langle \mathcal{A}_{\mathbf{L}}^{-}(\mathbf{K^*}) \rangle = -0.59 \times (1 \pm 2\ \% \ \pm \mathbf{5}\ \%)$
$\langle \mathcal{A}_{\mathbf{T}}^{-}(\mathbf{K^*}) \rangle = -0.52 \times (1 \pm \mathbf{12}\ \% \ \pm 5\ \%)$

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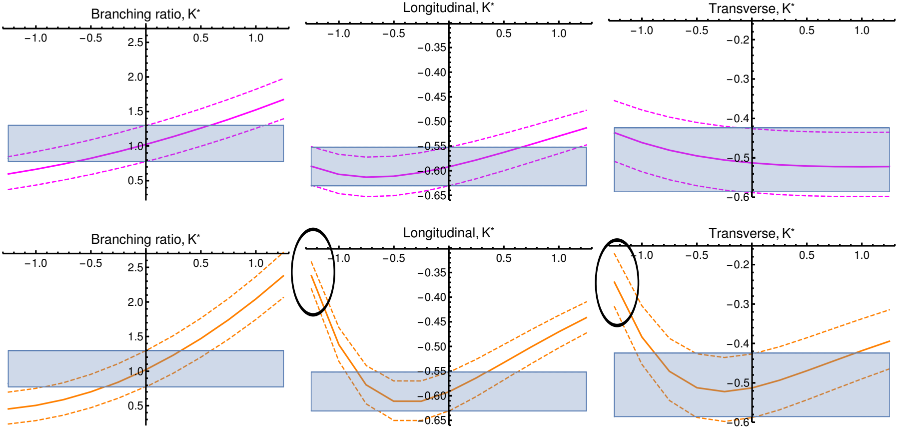
$\langle \mathcal{A}_{\mathbf{T}}^{-}(\mathbf{K}) \rangle = -0.76 \times (1 \pm 0.1\ \% \ \pm \mathbf{5}\ \%)$

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

First errors come from Form Factors, while the second ones from OPE (taken as a universal 5 % at the moment)

Different NP scenarios favored by muon data

Two NP cases: $\delta c_9 \approx -1$ (top), and $\delta c_9 = -c_9' \approx -1$ (bottom)
(in the SM: $c_9^{\text{eff}} \approx 4,\ c_9' = 0$) [Descotes-G. et al., Hurth et al., Altmannshofer et al.]



($B \to K$ cannot distinguish these two NP cases)

Conclusions and ongoing work

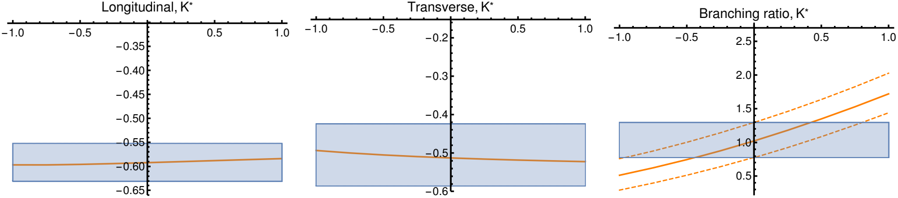
- Process $B^0 \to K^{*0}\tau^+\tau^-$:
  BR not yet measured, $b \to s\tau\tau$ couplings not much constrained;
  complementary information (assuming LFU),
  e.g., δc_9 vs. $\delta c_9 = -c_9'$;
  new observables from τ polarizations, $\mathcal{A}^{\pm}_{L,T,N}$
- Proof of viability of the reconstruction of events, m_B, $\overrightarrow{p_\tau}$
- Good theoretical control of polarization asymmetries,
  $\delta\langle\mathcal{A}^{\pm}_{L,T}\rangle = \mathcal{O}(10\ \%)$

- Reconstruction of the spin polarization
- Other obs. defined from both, τ^+ and τ^-, spin polarizations
- New CP violating phases ($\to$ normal polarization)

Many thanks

Other NP cases

Another case favored by muon data is $\delta c_9 = -\delta c_{10} \approx -0.7$



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

- Indirect information from $\Gamma_d/\Gamma_s \Rightarrow B_s \to \tau^+\tau^-$, and
- $B \to X_s\tau^+\tau^-$ mimicking $b \to u\ell\bar{\nu}$, $\ell = e, \mu$, and
- 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]

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

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