LFU Violation in B decays in light of FCC-ee

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Based on 2nd FCC workshop *(and references quoted herein)*

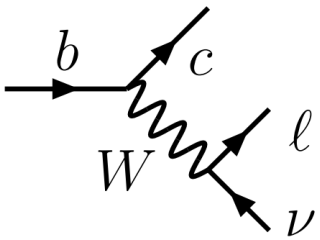
Outline

Outline

B-physics anomalies

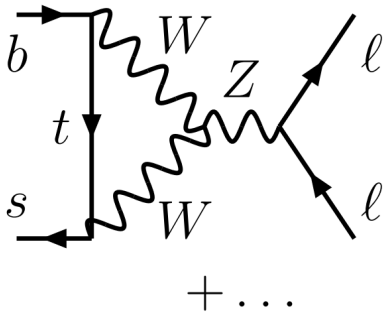
SM $\sim$ respects LFU (Lepton Flavor Universality) $\Rightarrow R_X \simeq 1$

Charged Currents



$R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu)}{\mathcal{B}(B^0 \to D^{(*)-}(e^+,\mu^+)\nu)}$	$R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to (J/\psi)\tau^+\nu)}{\mathcal{B}(B_c^+ \to (J/\psi)\mu^+\nu)}$
[R_D: BaBar,Belle; R_{D^*}: BaBar,Belle,LHCb]	[LHCb]
$\sim 2 - 3.4\sigma$ (w/ SM)	$\sim 2\sigma$ (w/ SM)

Neutral Currents



$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$	BRs and angular obs. in $b \to s\mu^+\mu^-$
[R_K: BaBar,Belle,LHCb; R_{K^*}: LHCb]	[LHCb, Belle, ATLAS, CMS]
$\sim 2.1 - 2.6\sigma$ (w/ SM)	$\sim 2.2 - 2.9\sigma$ (w/ SM)

Pattern of deviations w.r.t. the SM $\rightarrow$ NP sources of LFUV

Close horizon

LHCb and Belle II

year		2012	2020	2024	2030
LHCb	$\mathcal{L}$ [fb^{-1}]	3	8	22	50
	n($b\bar{b}$)	0.3×10^{12}	1.1×10^{12}	37×10^{12}	87×10^{12}
	$\sqrt{s}$	7/8 TeV	13 TeV	14 TeV	14 TeV
Belle (II)	$\mathcal{L}$ [ab^{-1}]	0.7	5	50	-
	$n(B\bar{B})$	0.1×10^{10}	0.54×10^{10}	5.4×10^{10}	-
	$\sqrt{s}$	10.58 GeV	10.58 GeV	10.58 GeV	-

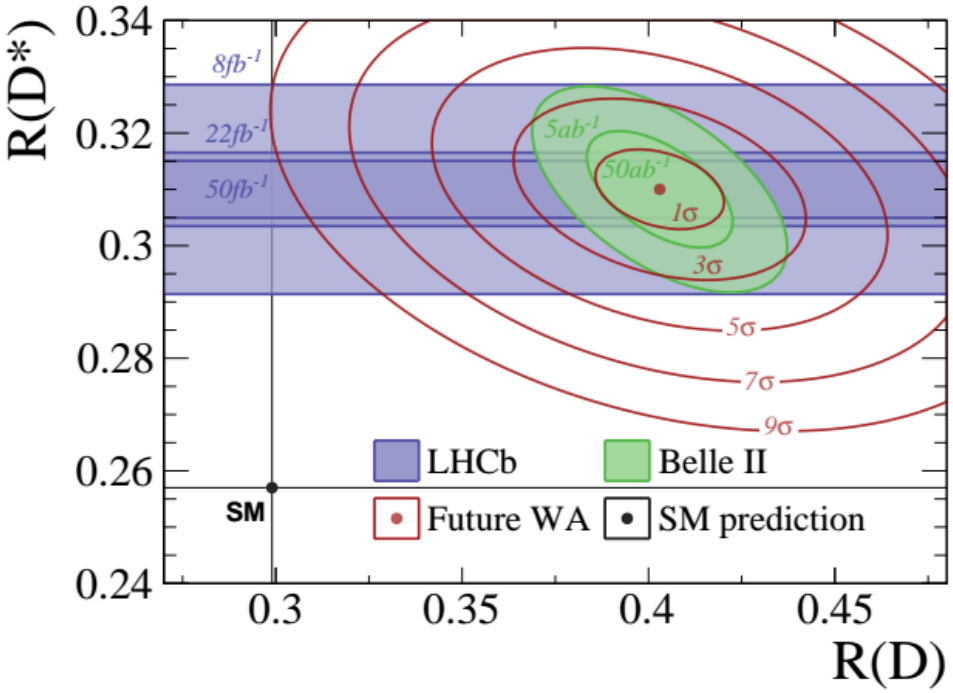
[Albrecht+'17 (and refs. therein)]

- **More data** on the already measured channels
- **New channels** (with different backgrounds) &
  new observables $\Rightarrow$ test the *consistency* of the LFUV picture

LHCb and Belle II - FCCC

arXiv:1709.10308: J. Albrecht, F. U. Bernlochner, M. Kenzie, S. Reichert, D. M. Straub, A. Tully

Measurement	SM prediction	Current World Average	Current Uncertainty	Projected Uncertainty[1]				
				Belle II		LHCb		
				$5ab^{-1}$	$50ab^{-1}$	$8fb^{-1}$	$22fb^{-1}$	$50fb^{-1}$
				2020	2024	2019	2024	2030
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%



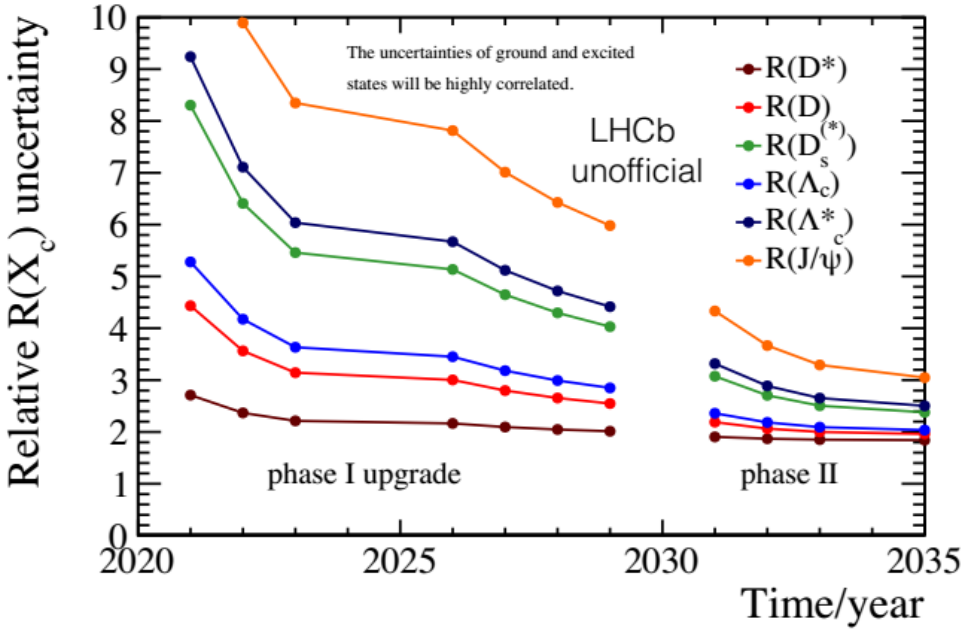
← assuming unchanged central values

Combined Belle II and LHCb should be able to **establish** $\gg 5\sigma$ **in** $R_{D^{(*)}}$

LHCb and Belle II - FCCC

$R_{D^{(*)}}$, $R_{D_s^{(*)}}$, $R_{\Lambda_c^{(*)}}$, $R_{J/\psi}$ w/ relative uncertainties **below** $\sim 5\%$:

[P. Owen @ Elba. Theo: Bernlochner+'16, Monahan+'16,'17]



Phase-II will substantially benefit $R(X_c)$ measurements of B_s,Λ_b^0,B_c hadrons.

Not accessible by Belle-II.

For V_{ub} and V_{cb}, see talk by D. Bečirević

LHCb and Belle II - FCNC

[Albrecht+'17 (and refs. therein)]

Belle II

Observable	q^2 interval	Measurement $0.7\,\mathrm{ab}^{-1}$	Extrapolations $5\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$R(K)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	-	11%	3.6%
$R(K)$	$q^2 > 14.4\,\mathrm{GeV}^2$	-	12%	3.6%
$R(K^*)$	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2$	-	10%	3.2%
$R(K^*)$	$q^2 > 14.4\,\mathrm{GeV}^2$	-	9.2%	2.8%

LHCb

Observable	q^2 interval	Measurement $3\,\mathrm{fb}^{-1}$	Extrapolations $8\,\mathrm{fb}^{-1}$	$22\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$
$R(\phi)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	-	0.159	0.086	0.056
$R(\phi)$	$15.0 < q^2 < 19.0\,\mathrm{GeV}^2$	-	0.137	0.074	0.048
$R(K)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	$0.745^{+0.090}_{-0.074} \pm 0.036$ [17]	0.046	0.025	0.016
$R(K)$	$15.0 < q^2 < 22.0\,\mathrm{GeV}^2$	-	0.043	0.023	0.015
$R(K^*)$	$0.045 < q^2 < 1.1\,\mathrm{GeV}^2$	$0.66^{+0.11}_{-0.07} \pm 0.03$ [18]	0.048	0.026	0.017
$R(K^*)$	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2$	$0.69^{+0.11}_{-0.07} \pm 0.05$ [18]	0.053	0.028	0.019
$R(K^*)$	$15.0 < q^2 < 19.0\,\mathrm{GeV}^2$	-	0.061	0.033	0.021

~ 2 % stat.

Combined Belle II and LHCb should be able to **establish** $\gg 5\sigma$ **in** $R_{K^{(*)}}$

LHCb and Belle II - FCNC

- LFU Violating obs. $P_5'^{\mu} - P_5'^{e}$ by LHCb, and Belle II
- $B_q \to \mu\mu$: e.g., discovery of $B_d \to \mu\mu$ by CMS (>2030)
- $b \to d\ell\ell$: e.g., $\frac{\mathcal{B}(B^+ \to \pi^+ \mu\mu)}{\mathcal{B}(B^+ \to \pi^+ ee)}$ by LHCb (300 fb^{-1})
- $B_s^0 - \overline{B}_s^0$ mixing

[CKMfitter'13: see talk by S. Monteil]

Sensitivities of modes with $\nu\bar{\nu}$ in the final state

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	25%	9.3%
$f_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.079
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$\mathcal{B}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5

B2TiP Report (in progress)

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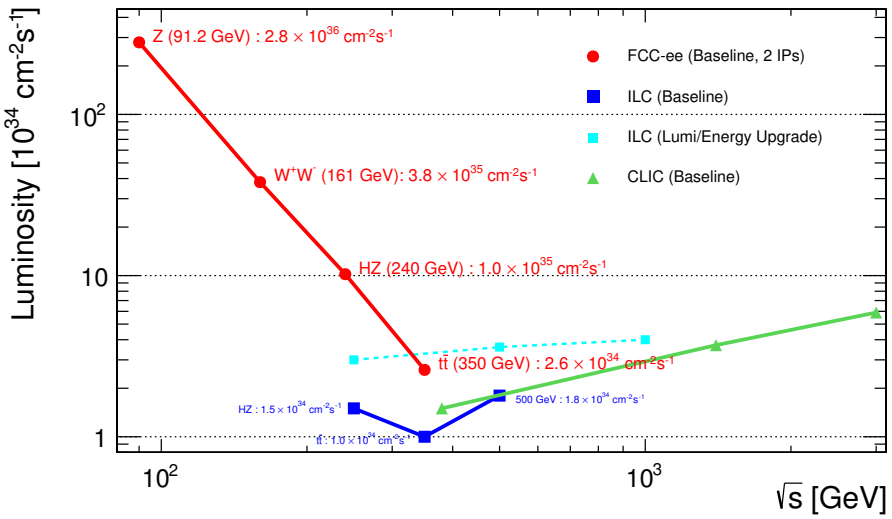
B2TiP Report (in progress)

FCCC & FCNC: exciting times ahead w/ Belle II and LHCb

Outline

Future Circular Collider @ CERN

- e^+e^- collider stage:
  $\sqrt{s} = 90, 160, 240, 350$ GeV
- Clean experimental environment
- All species of heavy flavors
- Large boosts
- Excellent vertexing
- **Unique opportunities for Flavor Physics**



In total, 10^{13} Z bosons

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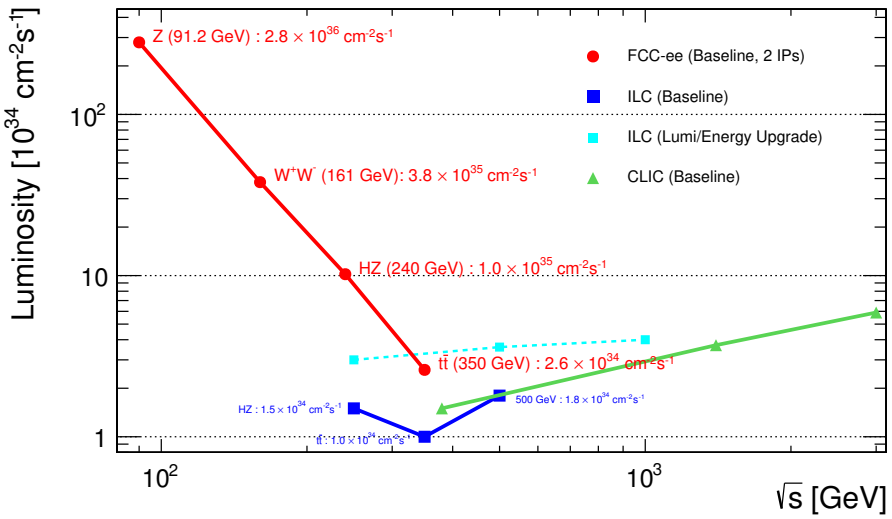

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HERE: review of (at least a few) flavor physics cases

Possible EFT interpretations

$$\text{C.C.}: \mathcal{L}_{b\to c\ell\nu} \supset -\frac{2G_F}{\sqrt{2}} V_{cb}\left[\left(C_{CC}^{SM} + \epsilon_L^{\ell}\right) \underbrace{\bar{c}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho(1-\gamma_5)\nu_\ell}_{SM:\, tree-level}\right] + \text{h.c.}$$

[X.-Q. Li+'16, Alonso+'16, Celis+'17]

$$\text{N.C.}: \mathcal{L}_{b\to s\ell\ell} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2}\left[\left(C_{NC}^{SM} + \delta_L^{\ell}\right) \underbrace{\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho(1-\gamma_5)\ell}_{SM:\, 1-loop}\right] + \text{h.c.}$$

(in fact, $c_9^{SM}(\mu_b) \simeq -c_{10}^{SM}(\mu_b)$) [Altmannshofer+'17, Capdevila+'17, L.-S. Geng+'17]

$\rightarrow$ *Possibilities other than* $\delta_L^{\mu}(\mu_b)$ *and* $\epsilon_L^{\tau}(\mu_b)$ **not** *excluded!*

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δ_L^{μ} and ϵ_L^{τ} at the level of $\sim \mathcal{O}(10\% - 20\%)$ of the SM,

with very different meanings: SM loop vs. SM tree

Common framework

[cf. di Luzio, Nardecchia'17]

$\Lambda_{NP} \sim \mathcal{O}(1-100)$ TeV $\Rightarrow$ direct searches, [Allanach, Greljo, Zupan: talks on FCC-hh]
low-energy (precision) observables

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low-energy (precision) observables

At energies $\Lambda_{NP} \gg v_{EW}$,
and assuming no new light d.o.f. below $\sim \Lambda_{NP}$:

[Glashow+'14,Feruglio+'16,'17]

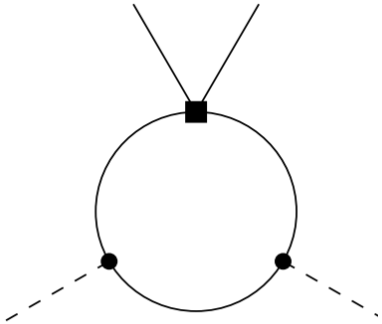
$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\left(C_1\, \bar{q}'_{3L}\gamma^\mu q'_{3L} \cdot \bar{\ell}'_{3L}\gamma_\mu \ell'_{3L} + C_3\, \bar{q}'_{3L}\gamma^\mu \tau^a q'_{3L} \cdot \bar{\ell}'_{3L}\gamma_\mu \tau^a \ell'_{3L}\right)$$

$\rightarrow$ *Here, illustrative only!*

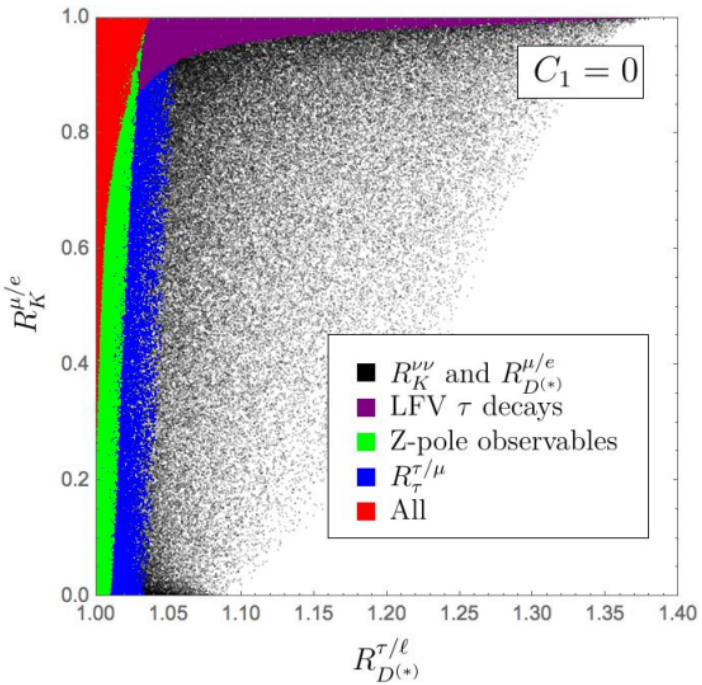
Correlations w/ other processes

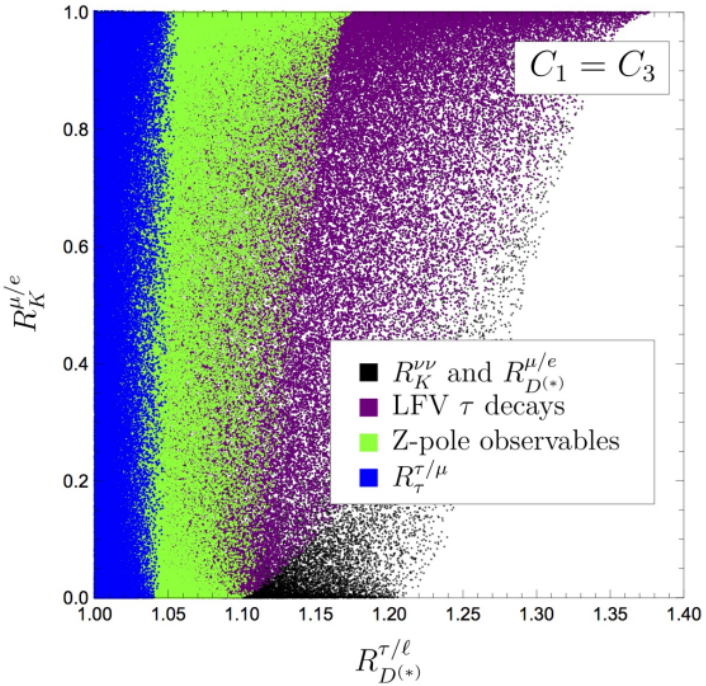
$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\left(C_1(\Lambda_{NP})\,\bar{q}'_{3L}\gamma^\mu q'_{3L}\cdot\bar{\ell}'_{3L}\gamma_\mu\ell'_{3L} + C_3(\Lambda_{NP})\,\bar{q}'_{3L}\gamma^\mu\tau^a q'_{3L}\cdot\bar{\ell}'_{3L}\gamma_\mu\tau^a\ell'_{3L}\right)$$

ψ^4



$\psi^2 H^2 D$





EW corrections: LNV four-lepton ops., coupling of Z to leptons, etc.

[Feruglio+'17]

Correlations w/ other processes: Z decays

Vector + axial neutral couplings from $R_f = \frac{\Gamma_{\rm had}}{\Gamma_{f\bar{f}}}$, $\mathcal{A}_f = \frac{2\, g_v(f)\, g_a(f)}{g_v^2(f)+g_a^2(f)}$

[R. Tenchini]

fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10^{-2}
c	2×10^{-3}	1×10^{-2}

Relative precisions

Improvements 1 – 2 orders of magnitudes with respect to LEP, depending on the fermion

Important also for some **concrete models** (e.g., involving Z' or LQs)

Correlations w/ other processes: LNV Z decays

- Lepton Flavour-Violating Z decays in the SM with lepton mixing are typically

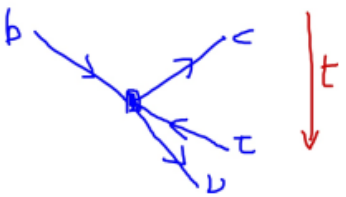
$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

- Current limits at the level of ~10^{-6} (from LEP and more recently Atlas, *e.g.* [DELPHI, Z. Phys. C73 (1997) 243] [ATLAS, CERN-PH-EP-2014-195 (2014)])

- Following study by M. Dam on LNV:

$$\mathcal{B}(Z \to \tau^{\pm}\mu^{\mp}) < 10^{-9} - 10^{-10}$$

B_c lifetime (cf. talk by J.M. Camalich)



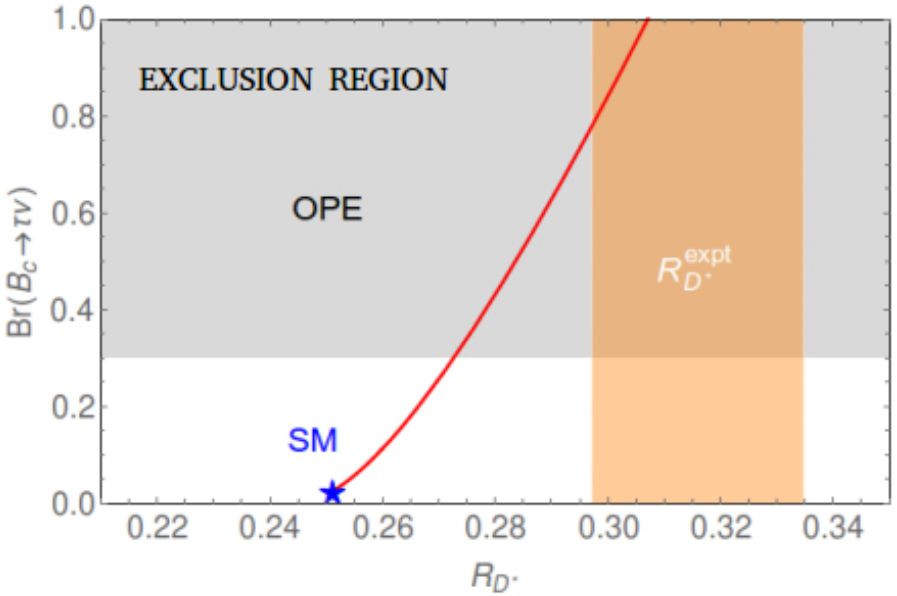
$$\frac{\mathrm{BR}(B_c\to\tau\nu)}{\mathrm{BR}(B_c\to\tau\nu)^{\mathrm{SM}}} = \left|1+\epsilon_L^\tau + \frac{m_{B_c}^2}{m_\tau(m_b+m_c)}\epsilon_P^\tau\right|$$

$$\tau_{B_c}^{\mathrm{OPE}} \overset{SM}{=} 0.52^{+0.18}_{-0.12}\ \mathrm{ps} \Rightarrow$$

[Bigi'95,Beneke+'96,C.-H. Chang+'00]

$$\mathcal{B}(B_c^- \to \tau\nu) \lesssim 30\%$$

Suppressed coupling ϵ_P^τ



[Alonso+'16; see also, Akeroyd+'17]

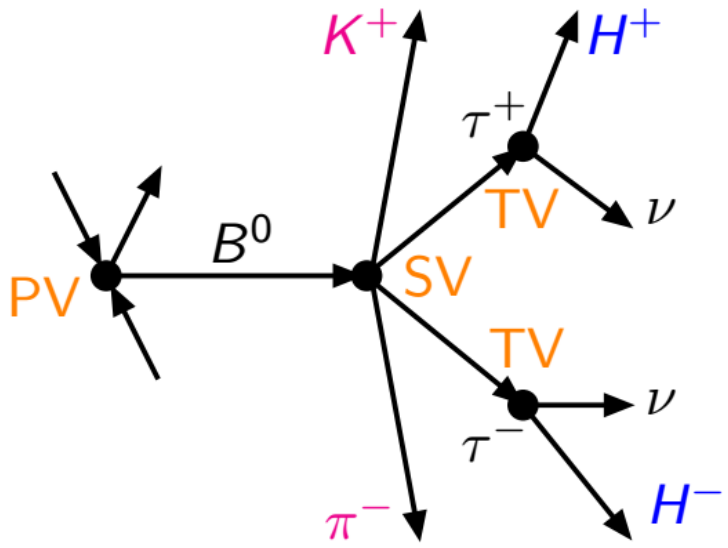
$$\overbrace{\mathrm{BR}_{\mathrm{eff}}}^{\mathrm{FCC-ee}} = \overbrace{\mathrm{BR}(B\to\tau\nu)}^{\mathrm{Belle\ \&\ BaBar}} + \overbrace{\frac{f_c}{f_u}}^{\mathrm{TH.input}}\ \mathrm{BR}(B_c\to\tau\nu)$$

$b \to s\tau\tau$ transitions

- $b \to s$ **semileptonic decays** involving **light leptons**: **tension** of data with the SM
- Processes $b \to s$ with **taus** have not been observed so far:
  $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ @ 90 %; [BaBar]
  expected sensitivity at Belle II of $\mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-5})$; [S. Wehle]
  also, $\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ [LHCb]
- LFU violation suggested by μ, e (to mention only FCNC), room for LFU violation in taus

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 $\tau \to H\,\nu$



Conservation laws + vertexing:

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

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

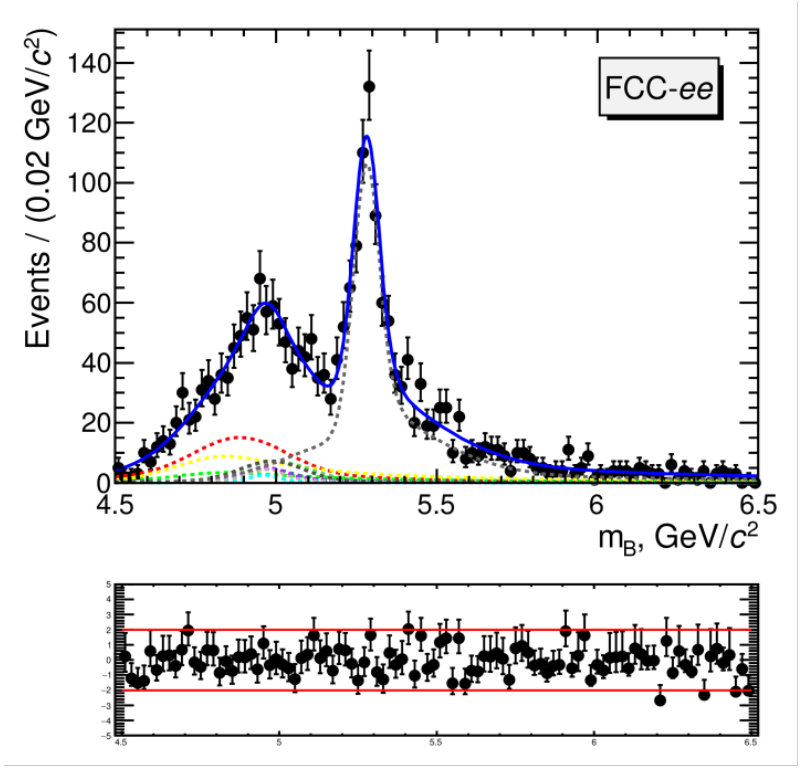
See talk by S. Monteil; similar technique for $B_s \to \tau\tau$ (ongoing?)

SM simulation: parameters from ILD detector, for $H^\pm = \pi^\pm \pi^- \pi^+$

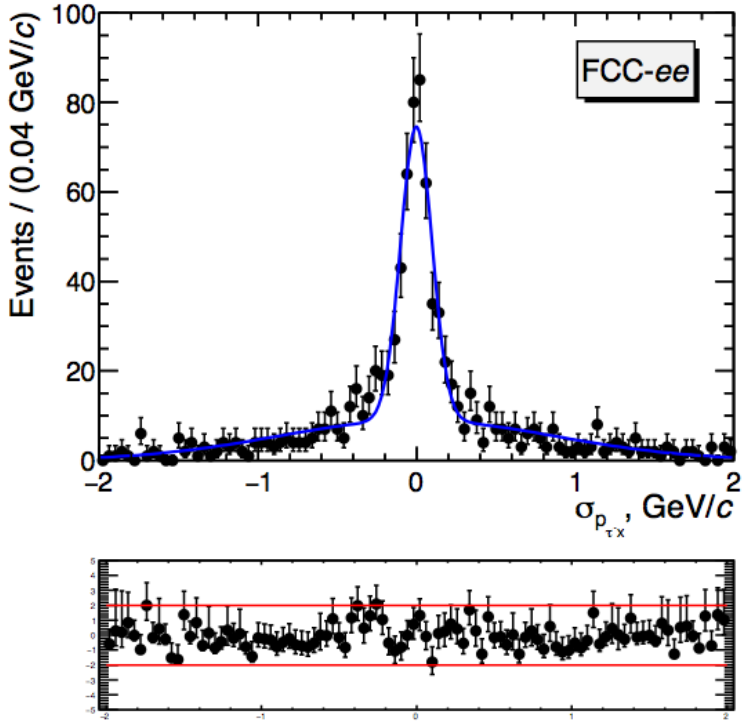
Signal and background fits

(Most relevant background comes from D mesons in $b \to c$)
Results for baseline luminosity (10^{13} Z bosons)

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



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

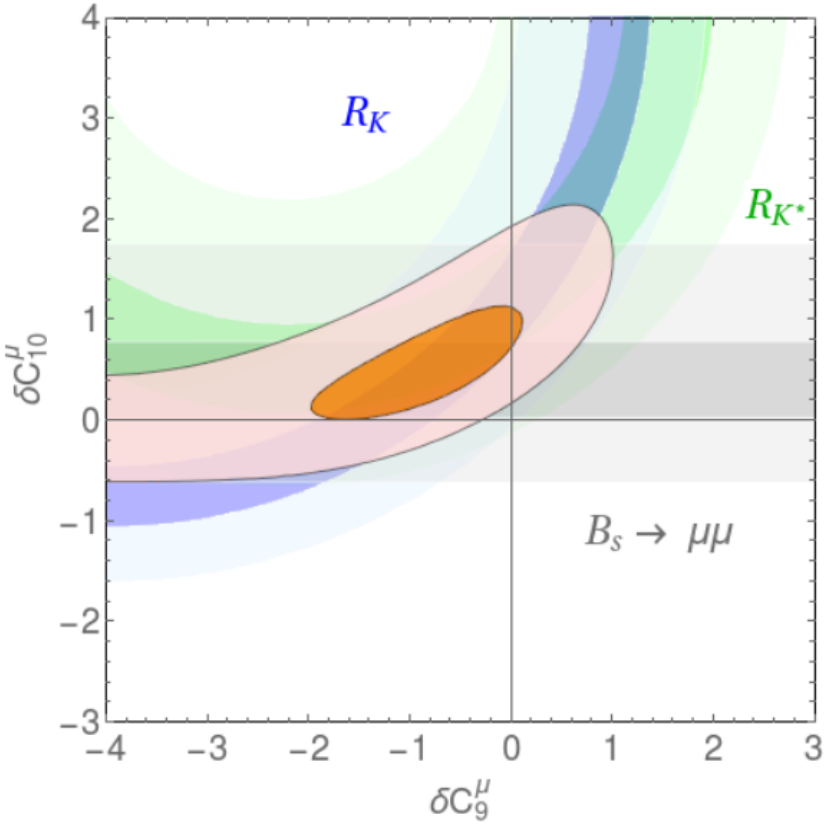


τ kin.: $\gtrsim$ 50% events w/ a precision better than 0.2 GeV

Set of $b \to s\tau\tau$ transitions

$R_{K^{(*)}} \equiv R^{\mu/e}_{K^{(*)}}$ and $B_s \to \mu\mu$

BaBar, Belle, LHC



[L.-S. Geng+'17]

FCC-ee:

Plane $R^{\tau/\ell}_{K^{(*)}}$ and $B_q \to \tau\tau$

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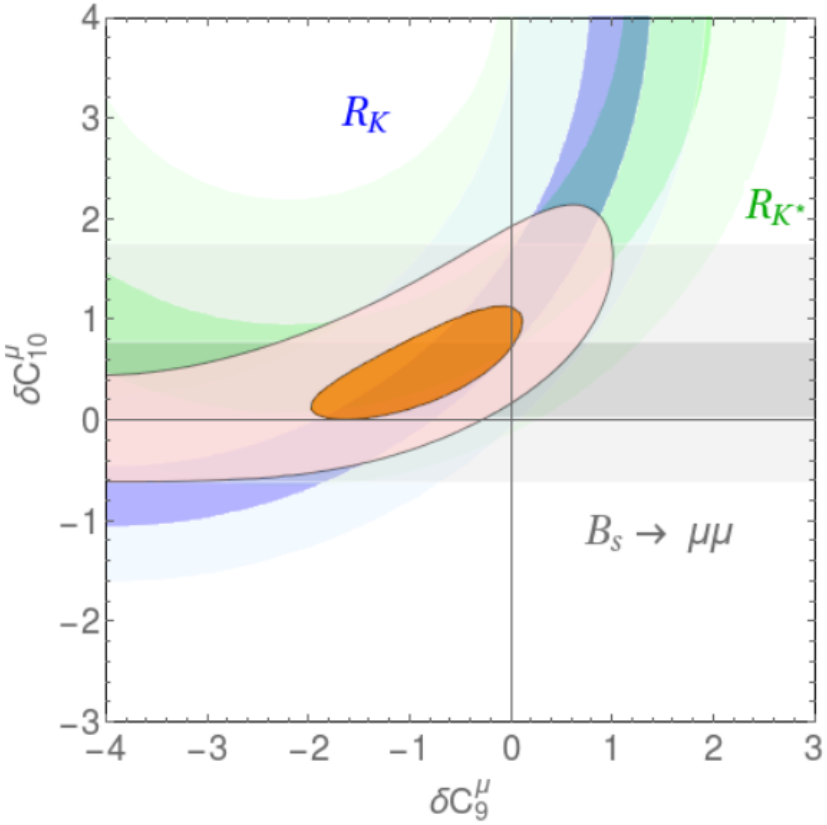


[L.-S. Geng+'17]

FCC-ee:

Plane $R^{\tau/\ell}_{K^{(*)}}$ and $B_q \to \tau\tau$

Also:

Angular observables

for $b \to s\tau\tau$

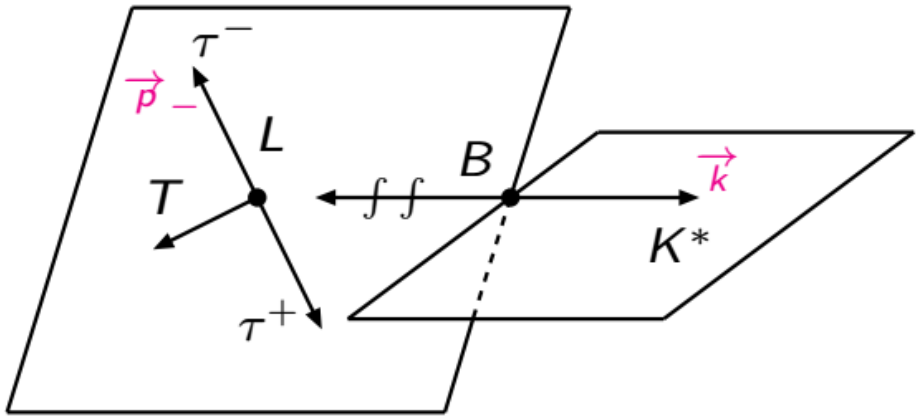
and τ **polarizations**

Outline

Asymmetries in the τ polarization

Decay products in $\tau \to H\nu$ act as a self-analyzer

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

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 predictions for $B \to K^{(*)}\tau^+\tau^-$

[Kamenik,Monteil,Semkiv,VS'17]

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

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

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

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

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

Clean *differential* quantities:

$$\frac{\mathcal{P}_L^{\pm}(K)}{\mathcal{P}_T^{\pm}(K)}(q^2) = \frac{F_1(q^2)}{F_0(q^2)} \times f(m_{B,K,\tau}, q^2) \quad \Rightarrow \quad \frac{|\langle \mathcal{P}_L^{\pm}(K)\rangle|}{|\langle \mathcal{P}_T^{\pm}(K)\rangle|} = 0.330\,(05)\,(\mathbf{10})\,(00)$$

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

Back to the B anomalies

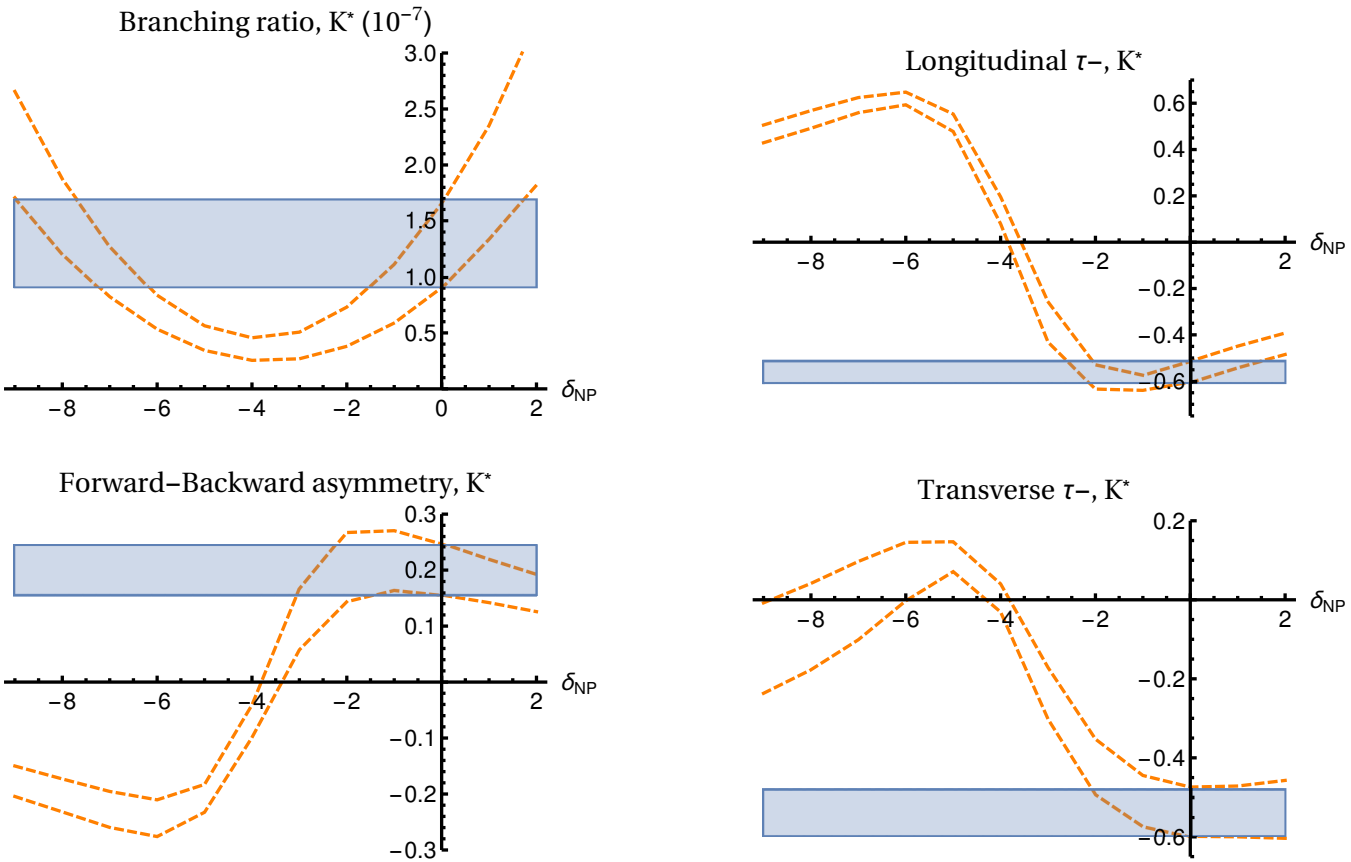
- Generally: bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ imply [BaBar, Belle]
  $|\delta c_9|, |c_9'|, |\delta c_{10}|, |c_{10}'| \lesssim \mathcal{O}(10)$ [Buras+ '14, Alonso+ '15; cf. Bobeth and Haisch '11]
- New dim=6 operators much beyond the EW scale:

Ex. $\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l]$, $\mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\sigma^A Q_j][\bar{L}_k\gamma^\mu\sigma^A L_l]$

For $C^{(1)}_{2333} \approx C^{(3)}_{2333} \equiv C \;\Rightarrow\; \frac{2\times C}{\Lambda^2_{NP}}([\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau] \;+\; [\bar{s}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\tau_L])$

Correlate $R_{D^{(*)}}, R_{J/\psi}$ anomalies to $b \to s\tau^+\tau^-$: [BaBar, Belle, LHCb]
enhance $b \to s\tau^+\tau^-$ rates to $\mathcal{O}(10^{-4})$ [Buttazzo+'17]

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

Outline

Overview

- LHCb and Belle II will verify/rule out the B-anomalies
- Direct searches: a case for FCC-hh
- Low-energy observables: a case for FCC-ee
- Associated effects are likely in Z decays to leptons
- Channels accessible only to FCC-ee include $B_c \to \tau\nu$
- Much to explore in $b \to s\tau\tau$: angular observables; clear NP signatures in tau polarizations

Thanks!

(and apologies for any omission)

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]

Background

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

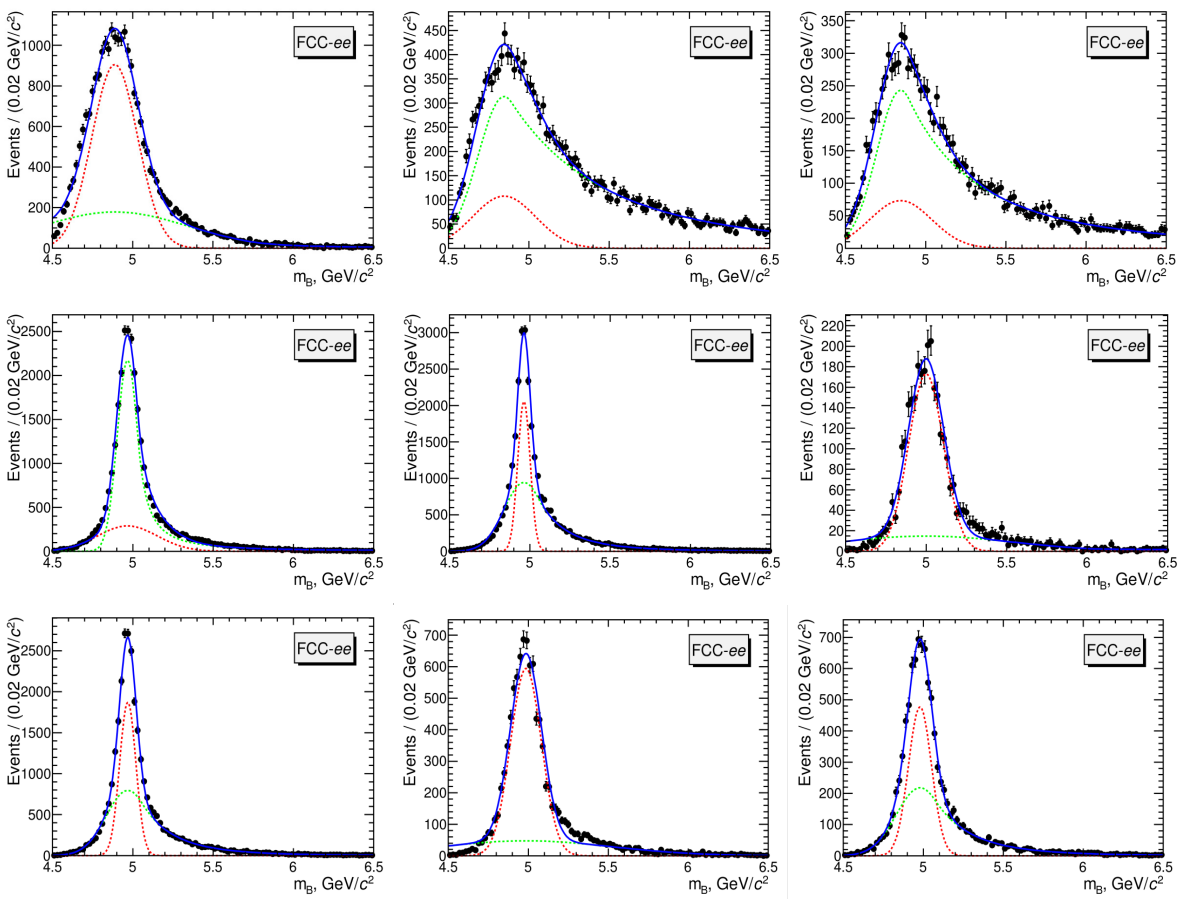
$$B^0 \to D_s^+ K^{*0} \tau^+ \nu_\tau \,, \quad \bar{B}_s^0 \to D_s^- D_s^+ K^{*0}$$

Channels:

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

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

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



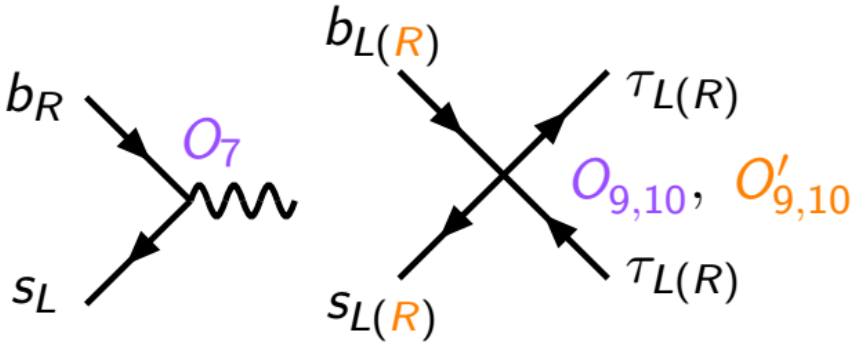
SM operators and Wilson coefficients

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

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma^\mu b_L) \bar{\tau} \gamma_\mu \tau$$

$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma^\mu b_L) \bar{\tau} \gamma_\mu \gamma_5 \tau$$



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]

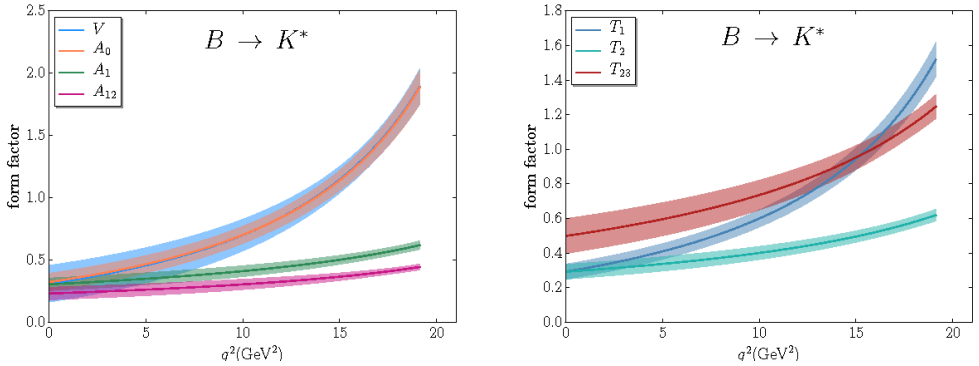
Muon data: δc_9^μ, δc_{10}^μ, c'^μ_9, c'^μ_{10} [Altmannshofer et al., Descotes-G. et al., Hurth et al.]

Sources of uncertainty

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

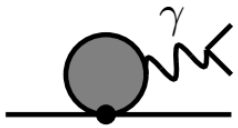
[Horgan et al. '13 '15: $B \rightarrow K^*$, $B \rightarrow \phi$]

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



Correction for $\bar{\tau}\gamma_\mu\tau$: ops. of higher dimension & charm resonances $\Rightarrow$ for quantities defined over large bins, $\sim 10\ \% \times c_9^{\mathrm{eff}}$

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



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

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

Double polarizations

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

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

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

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

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

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

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

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

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

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

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

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

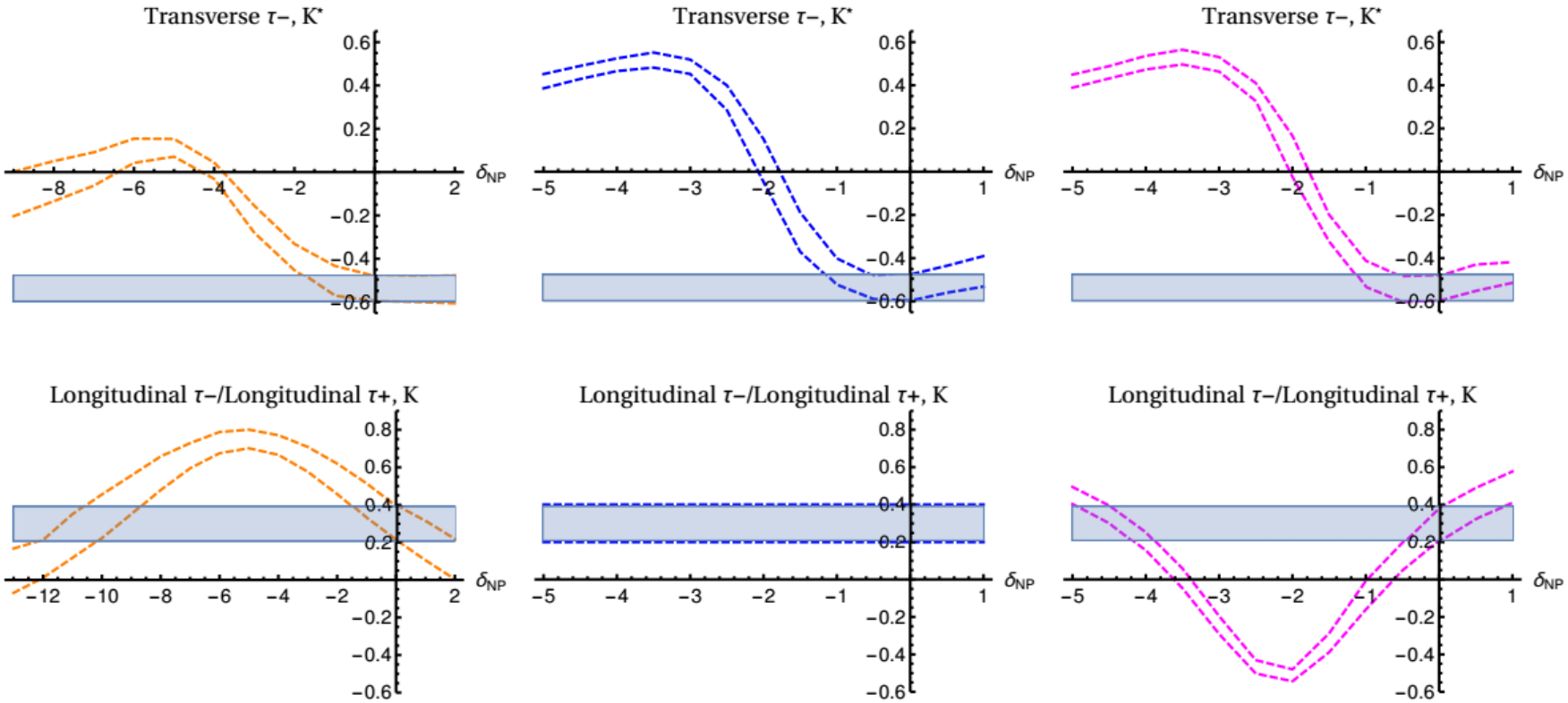
$|\langle \mathcal{P}_{LT,TL}(K)\rangle| = 0.33\ (0)\ (\mathbf{3})\ (1)$

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

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

Distinction of NP models

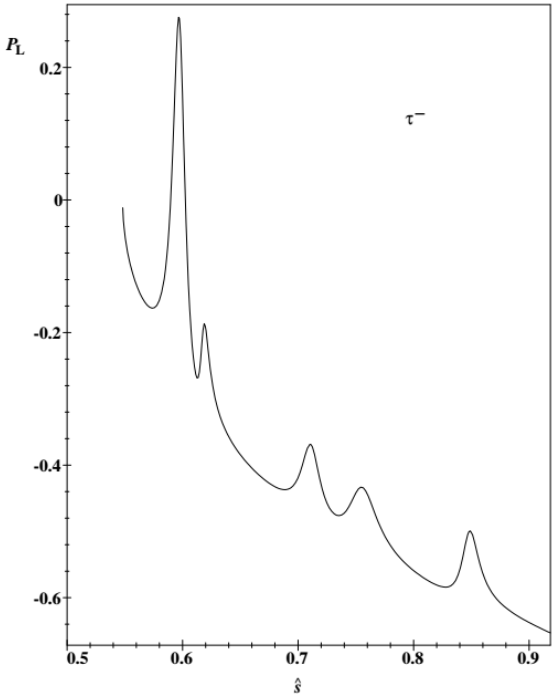
- $\delta c_9 \equiv \delta_{\rm NP}$,
- $\delta c_9 = -c_9' \equiv \delta_{\rm NP}$, and
- $\delta c_9 = -c_9' = -\delta c_{10} = -c_{10}' \equiv \delta_{\rm NP}$

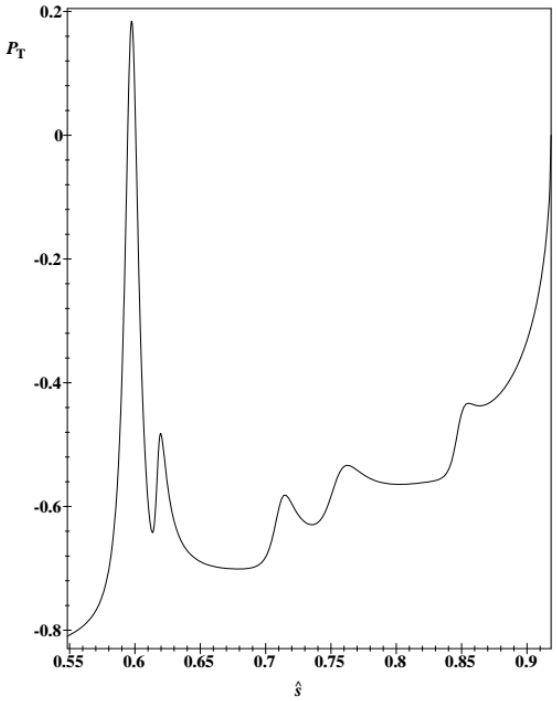


Clean differential quantities

$$\frac{\mathcal{P}_L^{\pm}(K)}{\mathcal{P}_T^{\pm}(K)}(q^2) = \frac{F_1(q^2)}{F_0(q^2)} \times f(m_{B,K,\tau}, q^2) \quad \Rightarrow \quad \frac{|\langle \mathcal{P}_L^{\pm}(K)\rangle|}{|\langle \mathcal{P}_T^{\pm}(K)\rangle|} = 0.330\,(05)\,(\mathbf{10})\,(00)$$

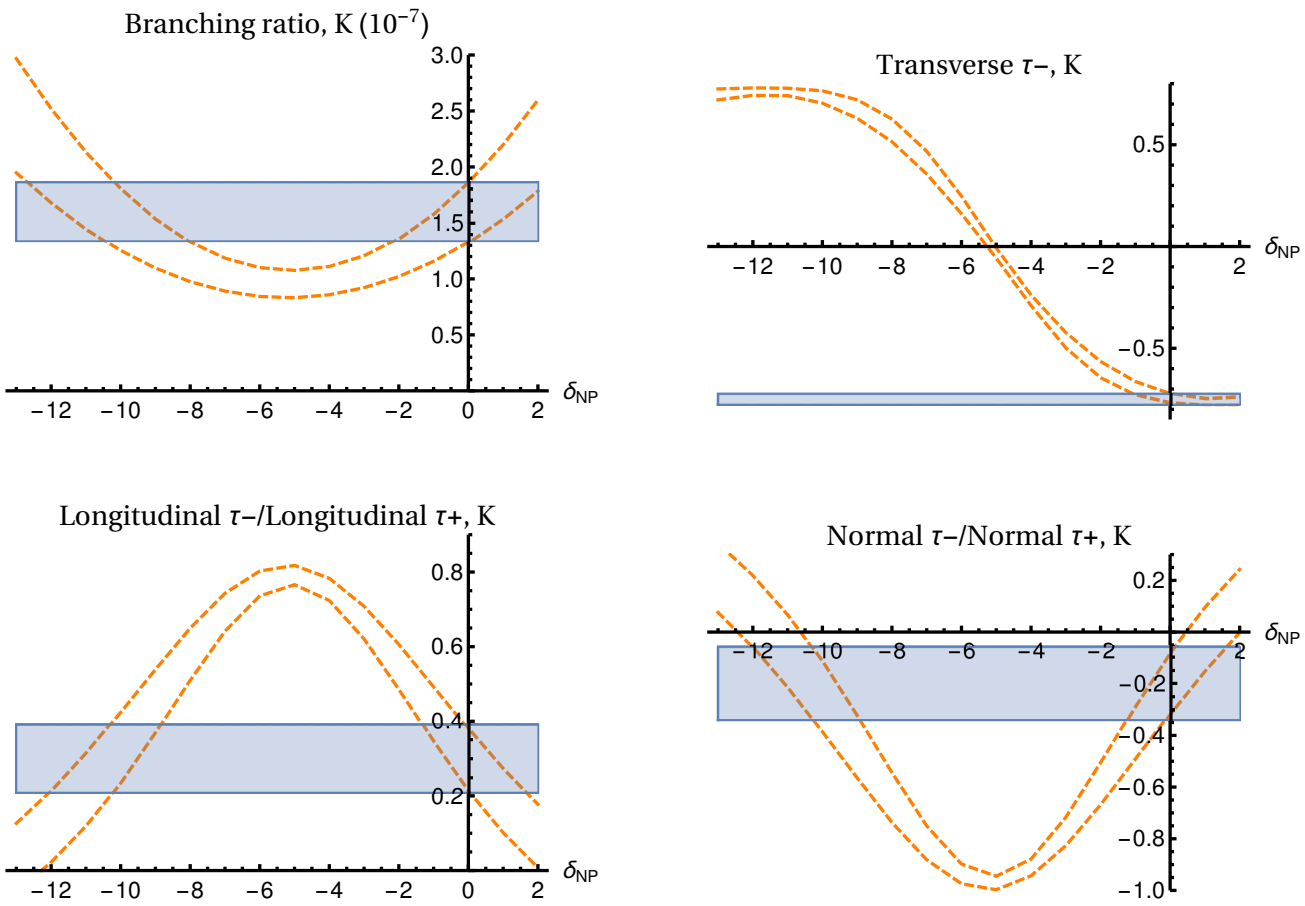
$$\frac{\mathcal{P}_L^{\pm}(K^*_{\text{long.}})}{\mathcal{P}_T^{\pm}(K^*_{\text{long.}})}(q^2) = \sum_{i=1}^{2} \frac{A_i(q^2)}{A_0(q^2)} \times f_i(m_{B,K^*,\tau}, q^2) \Rightarrow \frac{|\langle \mathcal{P}_L^{\pm}(K^*_{\text{long.}})\rangle|}{|\langle \mathcal{P}_T^{\pm}(K^*_{\text{long.}})\rangle|}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





(Polarizations for $B \to X_s \tau^+ \tau^-$) [Kruger and Sehgal '96]

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

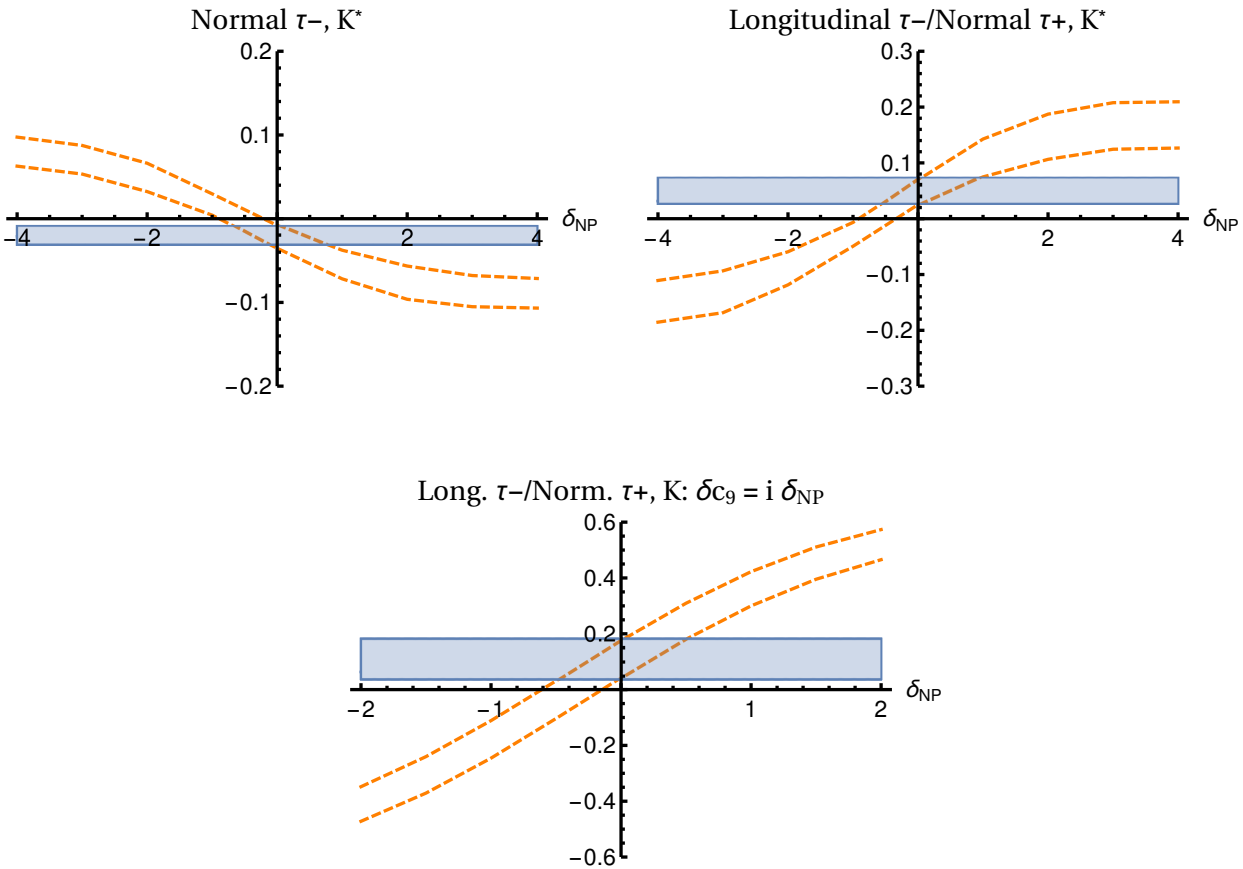


- Enhancement of LL, NN asymmetries to values $\gtrsim 0.8$
- T vanishes in the untagged case ($B^0 \to K^0$, $\bar{B}^0 \to \bar{K}^0$)

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 $\Rightarrow \mathcal{P}_N^{\pm} \ll \mathcal{P}_{L,T}^{\pm}$

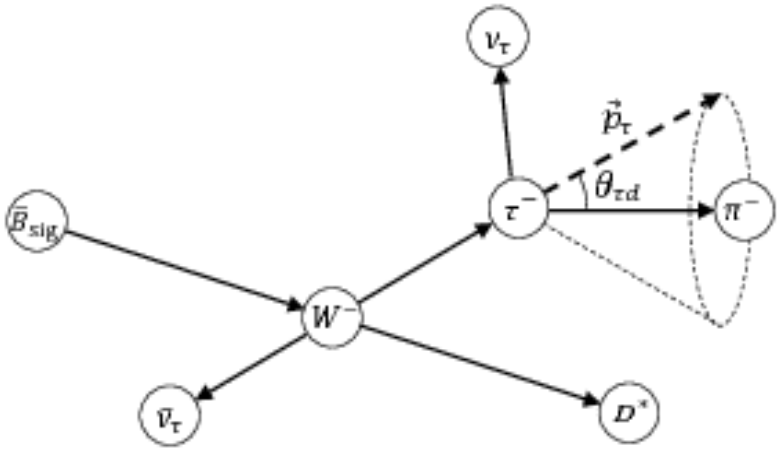
[cf. Krüger and Sehgal '96]



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

τ-lepton polarization in $\bar{B}^0 \to D^* \tau^- \bar{\nu}_\tau$

- First meas. of the τ longitudinal polarization in $\bar{B}^0 \to D^* \tau^- \bar{\nu}$ through $\tau^- \to \pi^- \nu_\tau$, $\tau^- \to \rho^- \nu_\tau$ [Belle'16,'17]



- The distribution of $\cos(\theta_{\tau d})$ gives the polarization
- SD information carried out by the polarizations of the τ-lepton

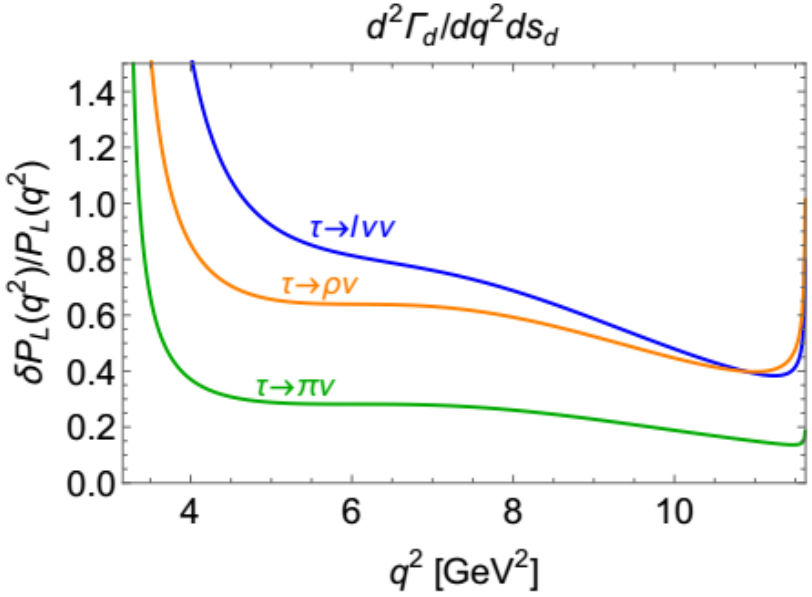
[Ivanov+'17]

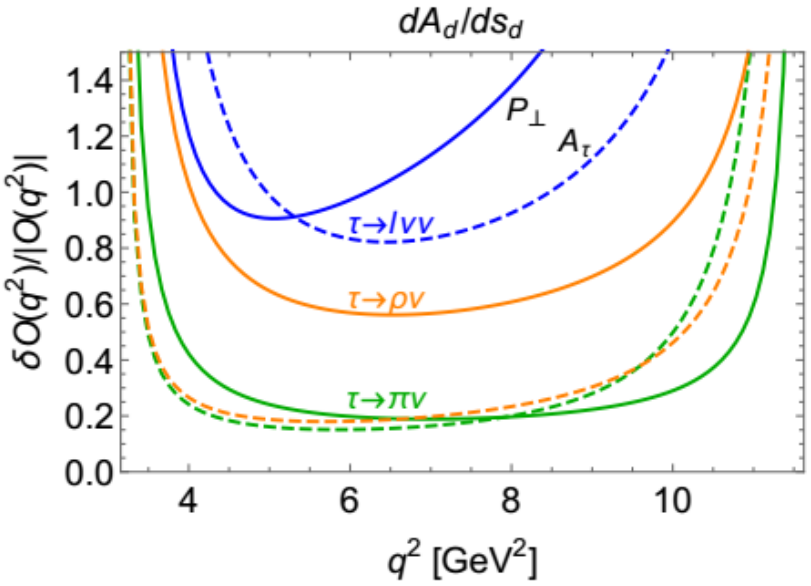
τ-lepton polarization in $B \to D\tau\nu$

- Final-state $\tau \to d\nu_\tau(\bar{\nu}_\ell)$, $d = \{\pi, \rho, \ell\}$: **self-analyzer** [Alonso+'17]

  $\Gamma_d(\tau \to d) \Rightarrow P_L$, and $A_d(q^2) = F_A^d A_\tau(q^2) + F_\perp^d P_\perp(q^2)$

  A_τ: FB asym.; $P_\perp$: perpendicular pol. (e.g. in the plane $\pi\nu_\tau$)
- **Belle II** (full operation): $\tau \to \pi\nu_\tau$, uncertainties $\lesssim \mathcal{O}(10\ \%)$





$s_d = E_d/\sqrt{q^2}$ (in the $\tau\bar{\nu}_\tau$ rest-frame)