Smoking guns involving measurements of tau couplings

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Beyond the Flavour Anomalies
26/04/22

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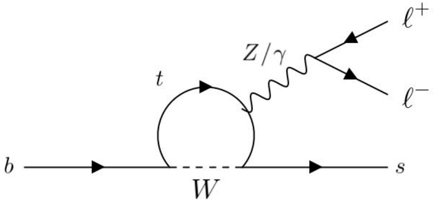
b decays

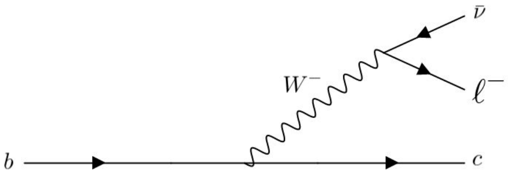


$b \to sll$

loop-level

$b \to cl\nu$

tree–level



$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{i=1..10,S,V,T,T5} V_{qb}V_{qs}^* C_i \mathcal{O}_i$$

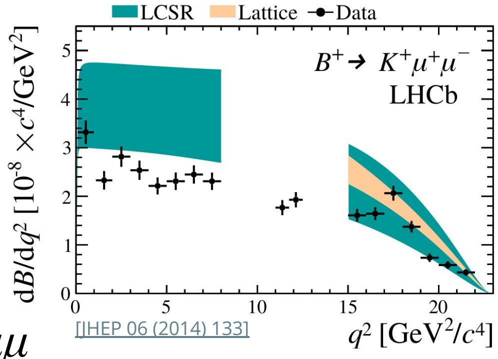
$$l = e, \mu, \tau$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} [(1 + g_V)\mathcal{O}_V + (-1 + g_A)\mathcal{O}_A + g_S\mathcal{O}_S + g_P\mathcal{O}_P + g_T\mathcal{O}_T + g_{T5}\mathcal{O}_{T5}]$$

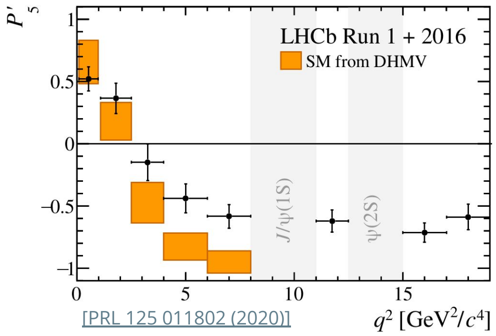
- SM gauge sector does not differentiate between lepton flavours
- Studied using an Effective Field Theory (EFT) approach, short-distance (and heavy NP) encoded in Wilson coefficients and couplings (C_i and g_i)
- The operators $\mathcal{O}_i$ describe long-distance physics

: NP

The Anomalies

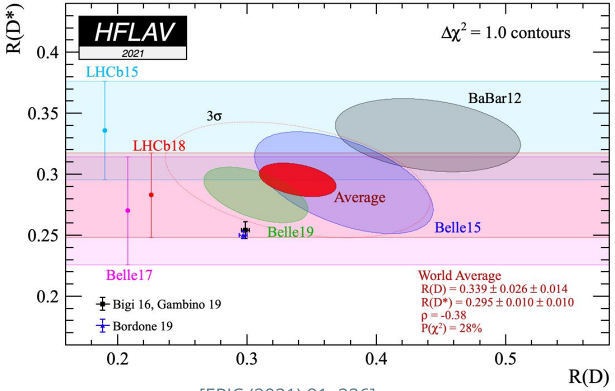


[JHEP 06 (2014) 133]



[PRL 125 011802 (2020)]

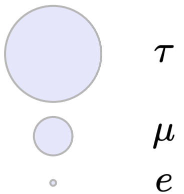
- ➢ Deviations from SM seen in $b \to s\mu\mu$
  - Branching fraction and angular observables
  - Lepton Flavour Universality (LFU) test using R_K shows anomalies at ~3σ
- ➢ Also in $b \to c\ell\nu$
  - LFU test using $R(D^{(*)})$ and $R(J/\psi)$ show discrepancies at the 2-3σ level.



[EPJC (2021) 81: 226]

Combined interpretation

PRL 120 181802 (2018)



- Hints at a hierarchical NP effect
- $b \to s\ell\ell$ anomalies suggest NP contribution to SM V – A operator, which change the normalisation of $b \to c\ell\nu$ transitions

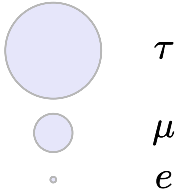
$$\frac{R_{J/\psi}}{R_{J/\psi}^{SM}} = \frac{R_D}{R_D^{SM}} = \frac{R_{D^*}}{R_{D^*}^{SM}}$$

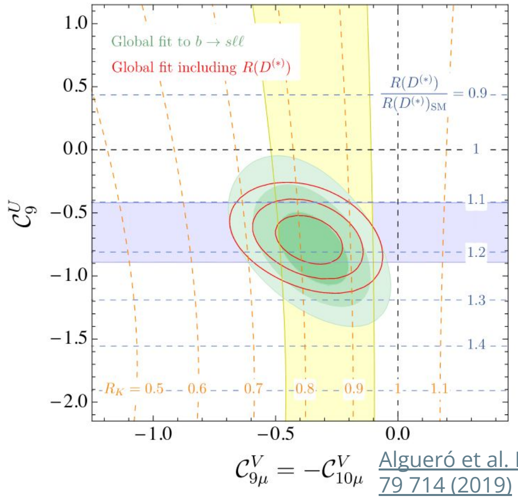
(in line with experimental observations)

- $SU(2)_L$ invariance of dim-6 operators for left-handed fermions generates similar contributions for $b \to s\tau\tau$ and $b \to c\tau\nu$

$$[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma_\mu\nu_\tau] + [\bar{s}_L\gamma_\mu b_L][\bar{\tau}_L\gamma_\mu\tau_L]$$

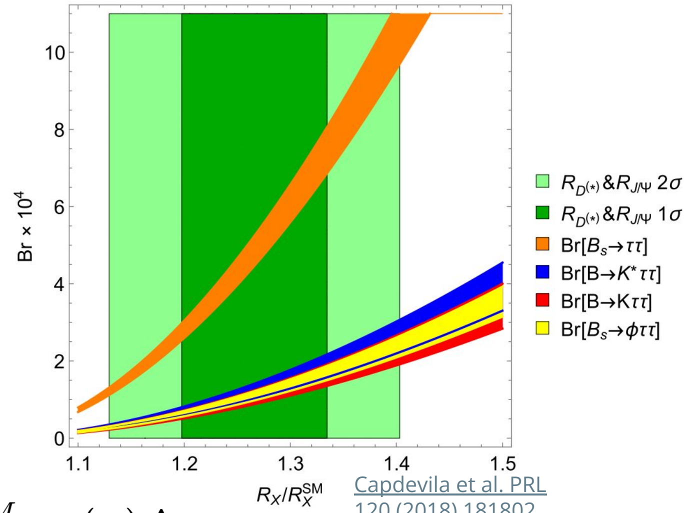
Combined interpretation





Algueró et al. EPJC 79 714 (2019)

Capdevila et al. PRL 120 (2018) 181802



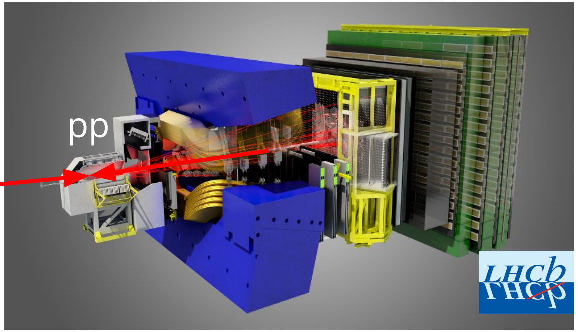
Capdevila et al. PRL 120 (2018) 181802

$R(D^{(*)})$ measurements predict a large enhancements to rare $b \to s\tau\tau$ decays.

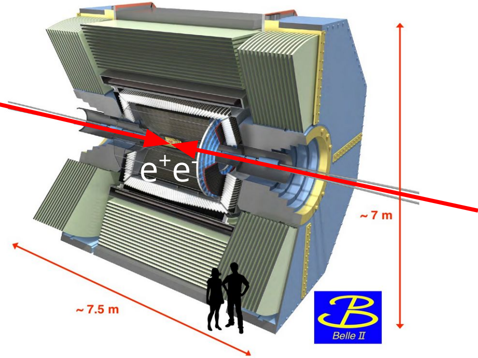
$$C_{9(10)}^{\tau\tau} \approx C_{9(10)}^{SM} - (+)\,\Delta$$

$$\Delta = \underbrace{\frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}}_{\approx 860}\left(\sqrt{\frac{R_X}{R_X^{SM}}} - 1\right) \approx O(100)$$

Within reach of current experimental capabilities



Experimental tools



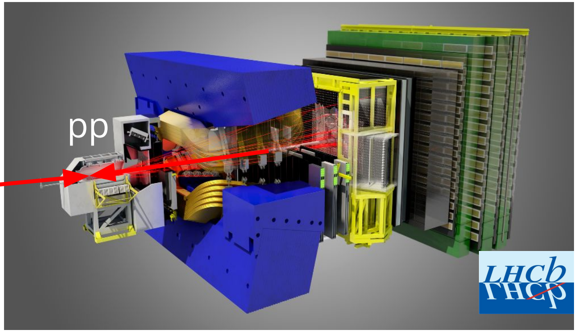
- τ is short-lived
- Neutrinos in final state
- Harder to reconstruct
- More sources of background

LHCb

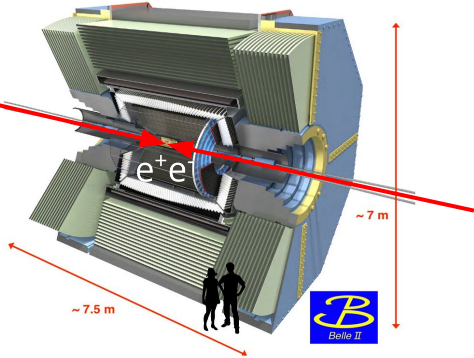
- Forward detector, lacks precise knowledge of production energies
  - Issues with neutrinos
- Large number of collected B decays
- Experimentally challenging to account for backgrounds
- Access to baryonic decay modes

Belle II

- 4π detector, precise knowledge of production energies
  - Missing momentum more easily reconstructible
- Lower statistics
- Cleaner collisions with less background



Experimental tools



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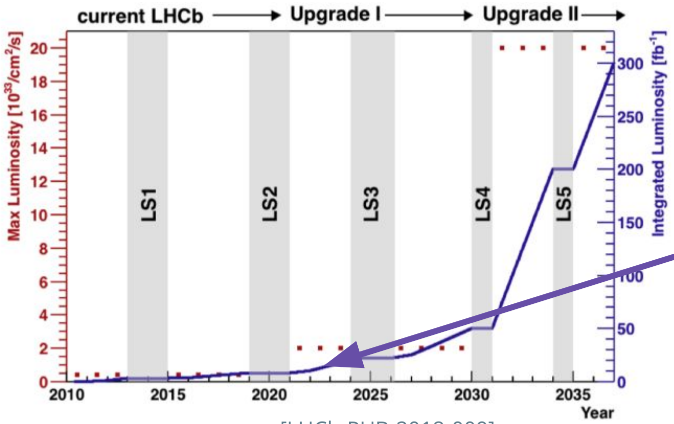
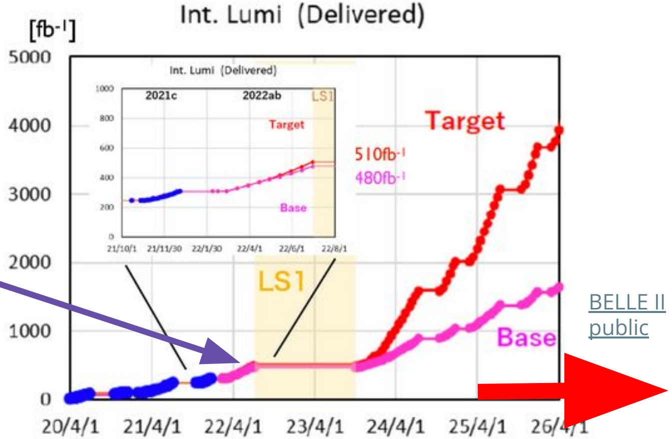


[LHCb-PUB-2018-009]

Today

Belle II



BELLE II public

7

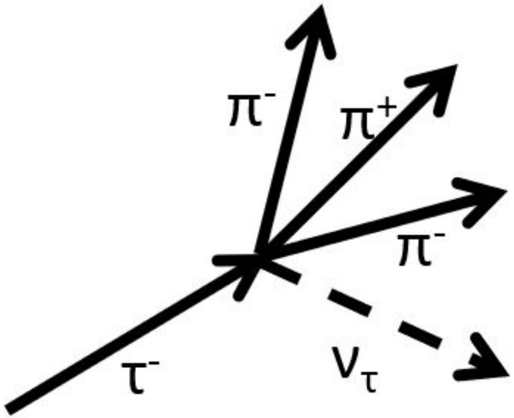
Tau decay modes

Pionic (3-prong) decay mode

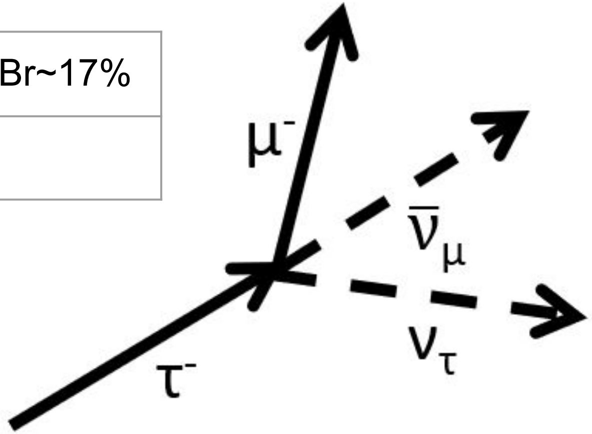
- ➢ Can easily reconstruct tau end-vertex
- ➢ Presence of pions ⇒ lots of background

Muonic decay mode

- ➢ Only specific topologies allow to reconstruct tau decays
- ➢ Less background associated with muons



3-prong Br~14%	Muonic Br~17%
$\tau \rightarrow \pi\pi\pi\nu_\tau\ (+\pi^0)$	$\tau \rightarrow \mu\nu_\mu\nu_\tau$



$b \to s\tau\tau$ decays

$$\mathcal{B}(B \to K\tau\tau)^{[15,22]}_{SM} = (1.2 \pm 0.12) \times 10^{-7} < 2.25 \times 10^{-3} \text{ at } 90\% \, CL \, (\text{BaBar})$$ [PRL 118, 031802 (2017)]

$$\mathcal{B}(B \to K^*\tau\tau)^{[15,19]}_{SM} = (0.98 \pm 0.10) \times 10^{-7} < 2.0 \times 10^{-3} \text{ at } 90\% \, CL \, (\text{Belle})$$ [arXiv: 2110.03871]

Capdevila et al. PRL 120, 181802 (2018)

- ➢ Large enhancements $\mathcal{O}(10^3)$ driven by $R(D^{(*)})$ anomalies

Improving these sensitivities is one of the most important experimental tasks for the near future

- ➢ Measurement will allow determination of lepton non-universal $C^{\tau\tau}_{9(10)}$
- ➢ Hadronic effects less of a concern due to potentially large NP effects
- ➢ Will also be able to set bounds on scalar, vector and tensor NP Wilson coefficients

Bobeth et al. APPB Vol. 44 (2013) 127-176

b → sττ: B→K$^{(*)}$ττ

$$\mathcal{B}(B \to K\tau\tau)^{[15,22]}_{SM} = (1.2 \pm 0.12) \times 10^{-7} < 2.25 \times 10^{-3} \text{ at } 90\% \, CL \text{ (BaBar)}$$ [PRL 118, 031802 (2017)]

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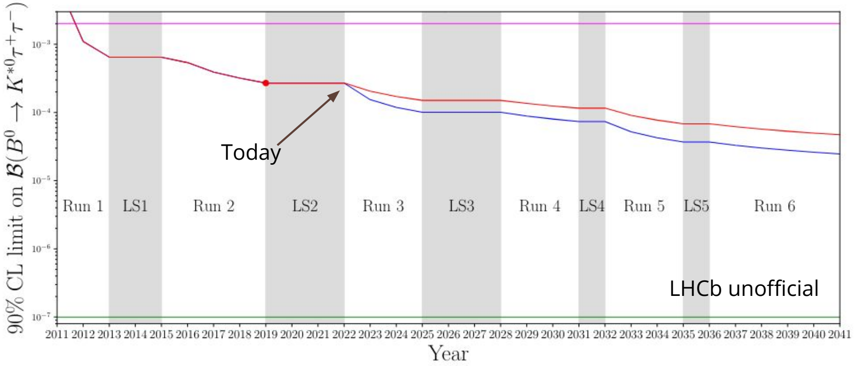
Capdevila et al. PRL 120, 181802 (2018)

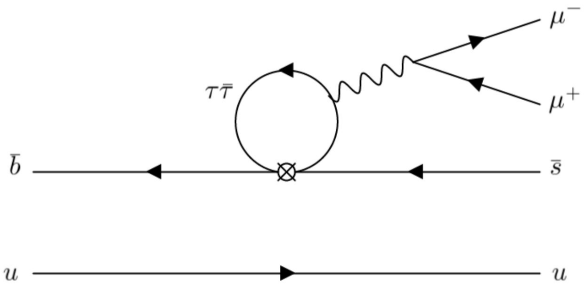
- ➢ Current expected experimental sensitivities are at the level of expected enhancements
- ➢ New experimental ideas are imperative to further improve precision

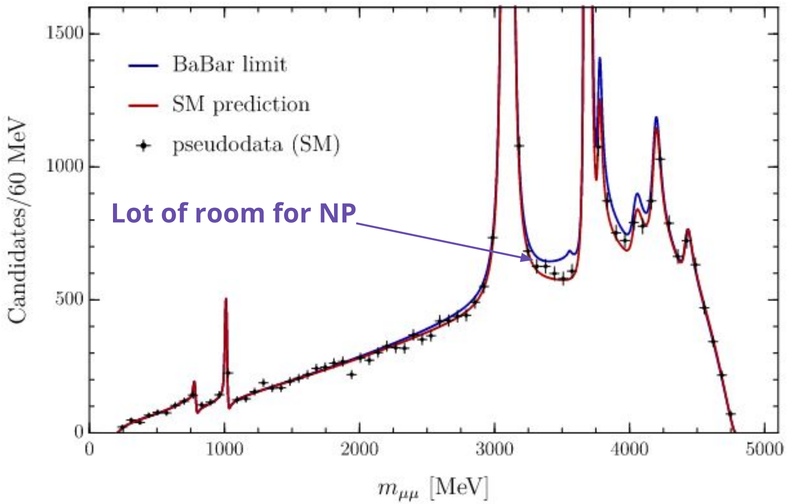


[CERN-THESIS-2022-17]

Discovery would be a smoking gun of NP

B→Kττ imprints in B→Kμμ [Cornella et al. EPJC **80** 1095 (2020)]





Caveat: Large destructive phase for the 2 particle charm states (DD, DD*, D*D*) would dilute sensitivity to the tau loop

LHCb sensitivities

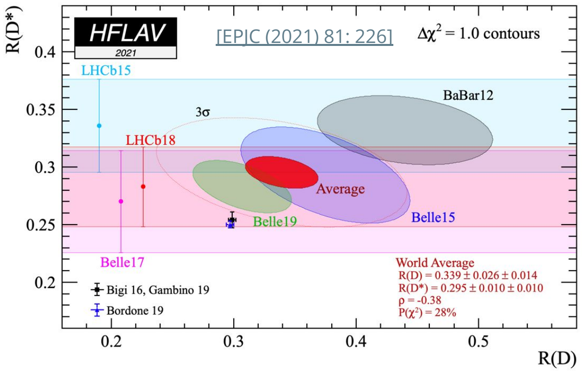
Scenario	$\mathcal{C}_9^\tau$ (90% CL)	$\mathcal{B}$ ($C_{10\tau} = -C_{9\tau}$)	$\mathcal{B}$ ($C_{10\tau} = 0$)
Run I-II dataset	533	2.7×10^{-3}	0.8×10^{-3}
Run I-V dataset	139	1.8×10^{-4}	0.5×10^{-4}
Run I-II dataset, improved form factors	533	2.7×10^{-3}	0.8×10^{-3}
Run I-V dataset, improved form factors	127	1.5×10^{-4}	0.5×10^{-4}

Br. indirectly constrained by determining Wilson coefficients from data

LFU tests with b→cℓν

$$R_H = \frac{\mathcal{B}(B \to H\tau\nu)}{\mathcal{B}(B \to Hl\nu)} \; ; H = D^{(*)}, J/\psi$$

- $R(D)$, $R(D^*)$ and $R(J/\Psi)$ away from SM
  [PRL 120 (2018) 121801] [EPJC (2021) 81: 226]
  - LFU tests with W bosons SM-like
    [Nature Phys. 17 (2021) 813–818] [EPJC 77 (2017) 367] [EP 10 (2016) 030]
  - BF ratios between e and μ modes close to unity
    ⇒ new physics could be hierarchical
    [arXiv:1702.01521]

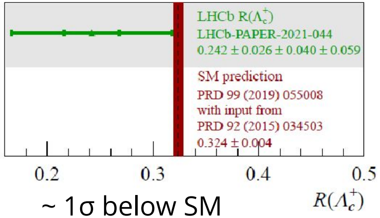


~ 3σ from SM

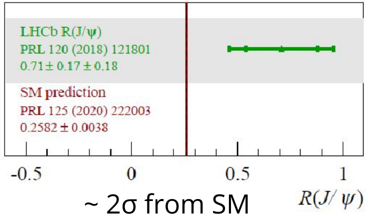
- Baryonic LFU test at LHCb

$$R(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c \mu \bar{\nu})} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

[arXiv: 2201.03497]



~ 1σ below SM



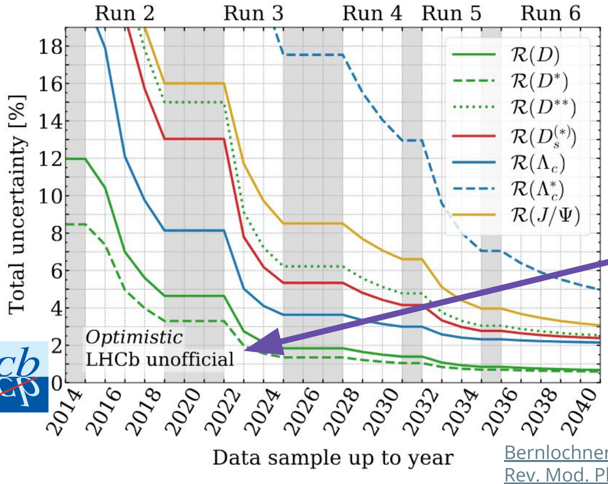
~ 2σ from SM

Guy Wormser@LP2021

$R(\Lambda_c)_{exp} < R(\Lambda_c)_{SM}$ interpretation?

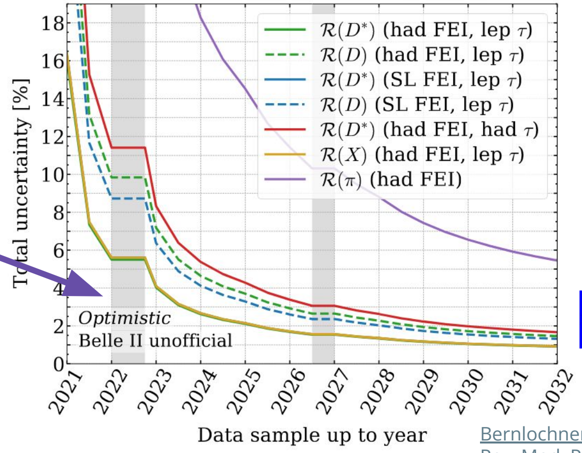
b→cℓν decays - future prospects

➢ Future holds promising results for $b \to c\ell\nu$ LFU tests



Bernlochner et al. Rev. Mod. Phys. 94, 015003

Today



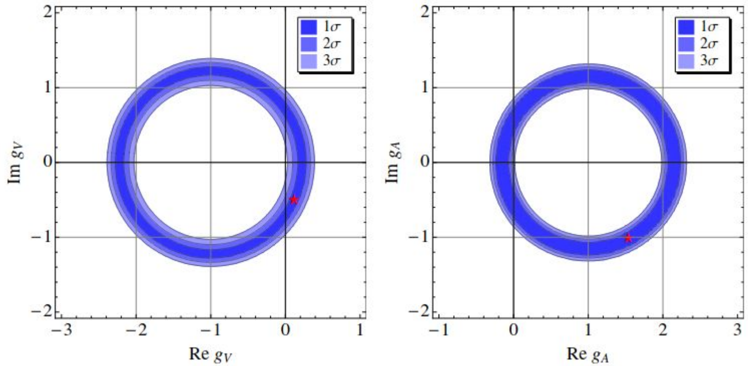
Bernlochner et al. Rev. Mod. Phys. 94, 015003

➢ Br. recovered from fit from kinematic information

➢ Polarization of τ and D^* obtained from angular analysis of $B \to D^*\tau\nu$ will provide crucial information

B→D$^{(*)}$τν angular observables

Allowed NP regions and best fit point from measured $R(D)$ and $R(D^*)$ as of 2016

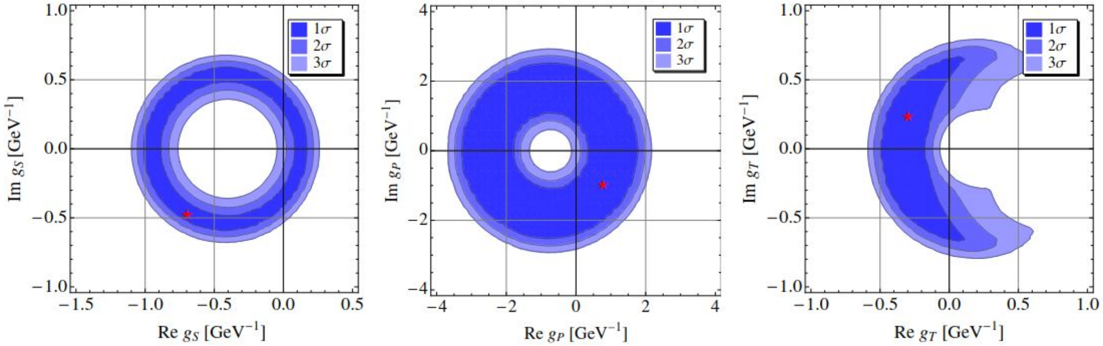


★ Best fit point

SM at $(Re[g_i], Im[g_i]) = (0,0)$

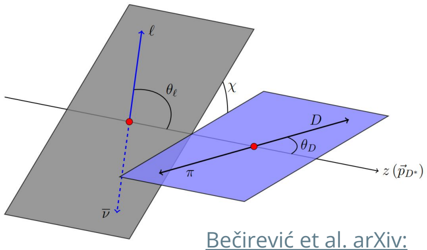
Bečirević et al. arXiv: 1602.03030

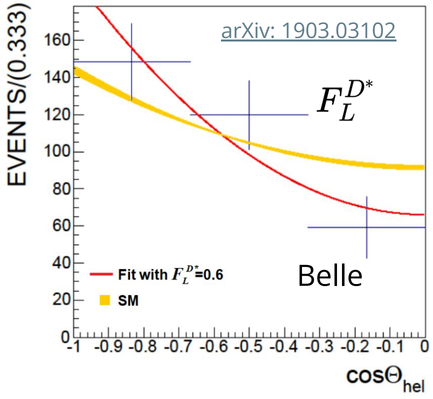
One coupling at a time



B→D(*)τν angular observables

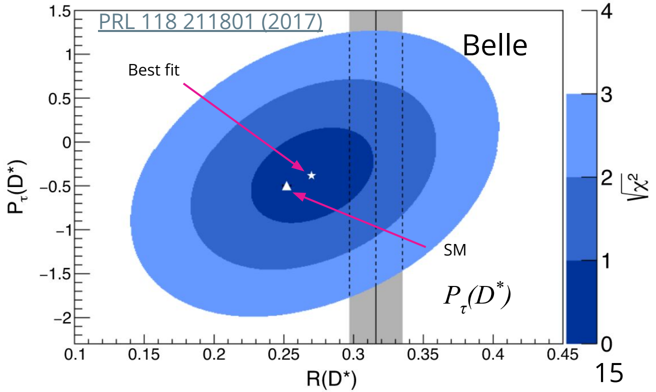
Not a smoking gun…





- Angular analysis extracts couplings (g_i) and form factor parameters directly from fit to data

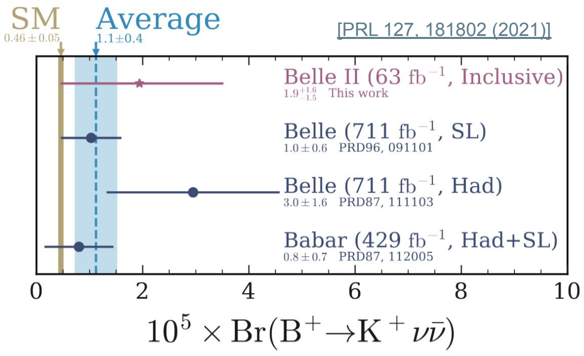
- D^{*-} meson polarization F_L^{D*} sensitive to $g_{P,T}$
- τ polarization asymmetry $P_\tau(D^*)$ sensitive to $g_{P,T}$
- τ polarization asymmetry $P_\tau(D)$ sensitive to $g_{S,T}$
- and other observables Bečirević et al. arXiv: 1602.03030



Improved measurements important to better understand b → sττ enhancements

b → sνν decays: $B^+ \to K^{(*)}\nu\nu$

Decay	SM prediction Buras et al. arXiv:1409.4557	90% CL upper limit	
		Belle (II)	BaBar [PRD 87 (2013) 112005]
$\mathscr{B}(B^+ \to K^+\nu\nu)$	$(3.98\pm0.43\pm0.19)\times10^{-6}$	$<4.1\times10^{-5}$ (Belle II) [PRL 127, 181802 (2021)]	$<3.7\times10^{-5}$
$\mathscr{B}(B^0 \to K^{*0}\nu\nu)$	$(9.19\pm0.86\pm0.50)\times10^{-6}$	$<5.5\times10^{-5}$ (Belle) [PRD 87 (2013) 111103]	$<9.3\times10^{-5}$



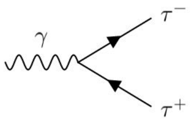
- ➢ All neutrino flavours included in $B^+ \to K^{(*)}\nu\nu$ decays ⇒ stringent limits will constrain expected size of NP effects in $b \to s\tau\tau$ decays Buras et al. arXiv:1409.4557
- ➢ Expect much better sensitivity with Belle II using inclusive tagging approach [Prog. Theor. Exp. Phys. 2019, 123C01]
  - Observation expected from Belle II soon
  - With 50 ab^{-1} absolute precision expected to be ~5×10^{-7}

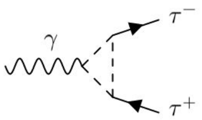
Current limits close to SM suggest NP effects are small in $b \to s\nu\nu$ decays

$(g-2)_\tau$ and τ EDM

$$\mu = g\,\frac{q}{2m}\,\mathbf{S}$$

Magnetic moment of
spin ½ particle



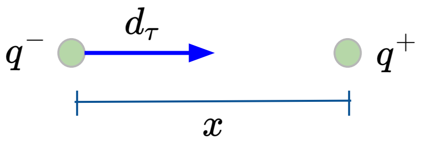


g = 2 + loop corrections **+ NP**

$$a_\tau = (g-2)_\tau/2$$

$$a_\tau^{\mathrm{SM}} = 0.00117721(5)\,;\; a_\tau^{\mathrm{exp}} = -0.018\,(17)$$

Eidelman et al. MPL A22 (2007) 159-179 DELPHI, [EPJC 35 (2004) 159-170]



$$d_\tau = qx$$

Electric dipole moment (EDM) describes the distribution of charge in a system

Non-zero EDM (d_τ) implies **CP violation**

$$|d_\tau|_{SM} \approx 10^{-33}$$

Beresford et al. PRD 102 (2020) 113008

$$Re(d_\tau)_{exp} = (1.15 \pm 1.7) \times 10^{-17}\, e\,cm$$

$$Im(d_\tau)_{exp} = (-0.83 \pm 0.86) \times 10^{-17}\, e\,cm$$

BELLE, [PLB 55 1-2 (2003)]

Small τ lifetime makes these difficult to measure

$(g-2)_\tau$ and τ EDM Belle II prospects

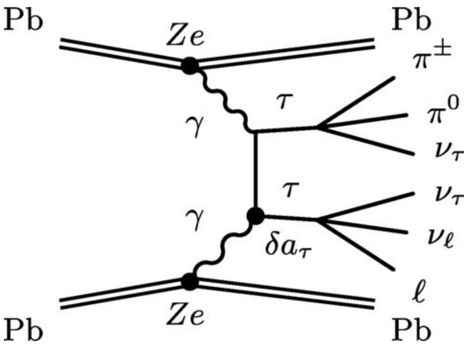
- $(g-2)_\tau$
  - Belle II expected to reduce absolute uncertainty from 0.017 (DELPHI) to 0.012
    [JHEP 03 (2016) 140]

- τ EDM competitive:
  - 40 times gain compared to current results, leading to $[Re, Im(d_\tau)] < 10^{-18}$–$10^{-19}$
    [Prog. Theor. Exp. Phys. 2019, 123C01]

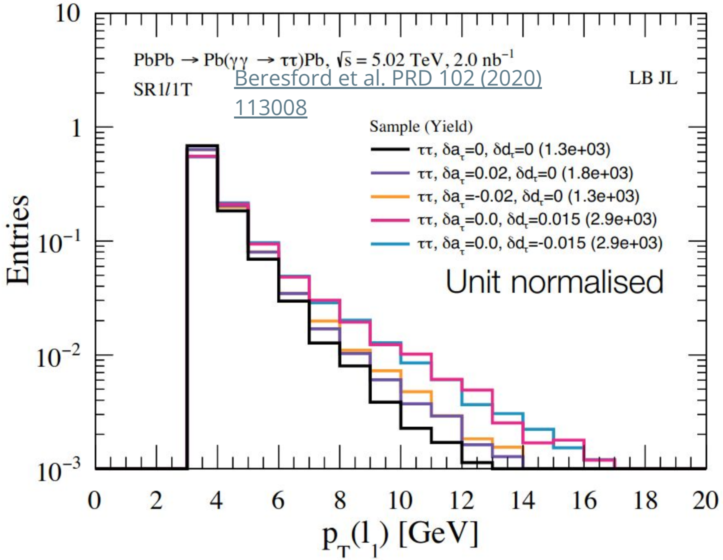
$(g-2)_\tau$ and τ EDM at LHC

New technique to measure $(g-2)_\tau$ from ultraperipheral Pb-Pb collisions at LHC

Beresford et al. PRD 102 (2020) 113008, Dyndał et al. PLB 809 (2020) 135682



τ pairs from photon fusion

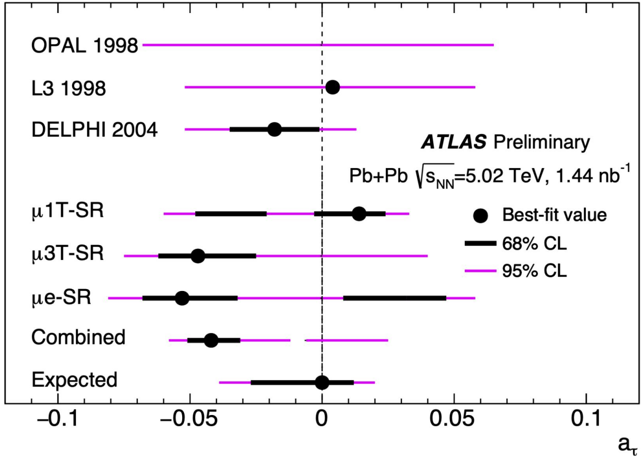


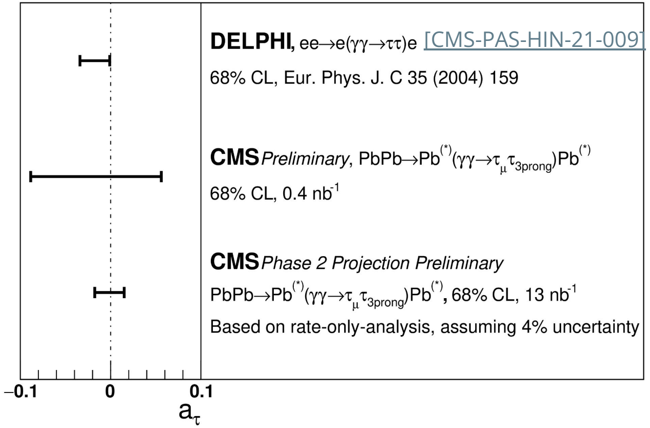
Beresford et al. PRD 102 (2020) 113008

Different moments modifies lepton p_T distribution

$(g-2)_\tau$ and τ EDM: current results

Two intervals from interference of SM and BSM





$a_\tau \in (-0.058,\ -0.012) \cup (-0.006,\ 0.025)$ at 95% CL limits

Latest ATLAS result, Jakub Kremer@QM2022

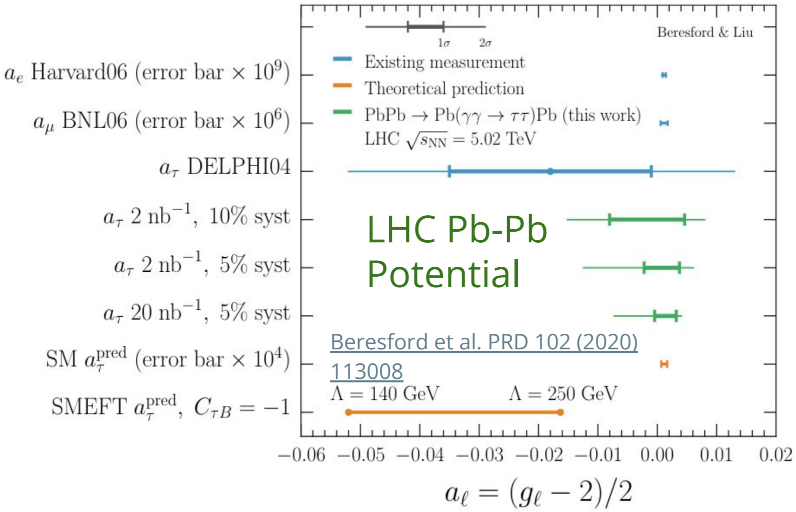
CMS result: $(-8.8 < a_\tau < 5.6) \times 10^{-2}$ at 68%

[CMS-PAS-HIN-21-009]

- ➢ Latest measurements by CMS and ATLAS do not include τ EDM
- ➢ τ EDM measured by Belle [PLB 551 (2003) 16-26]

$$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17} e\,\text{cm},$$
$$Im(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17} e\,\text{cm}$$

$(g\text{–}2)_\tau$ and τ EDM: LHC prospects

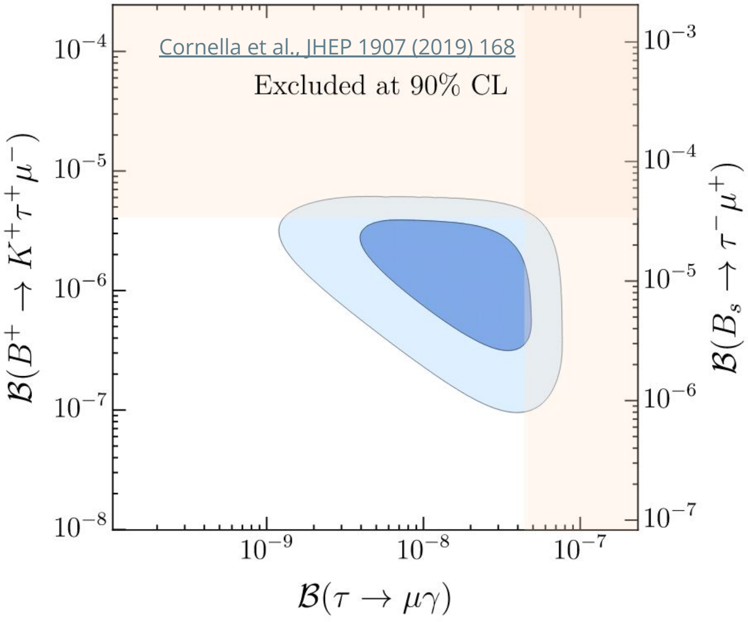


- Analyses with Pb-Pb collisions at the LHC expected to Beresford et al. PRD 102 (2020) 113008
  - 10-fold enhancements compared to DELPHI for $(g\text{-}2)_\tau$ (20 nb^{-1})
  - $|d_\tau| < 3.4 \times 10^{-17}$ e cm at 95% CL assuming a_τ SM-like (2 nb^{-1})

Possibility of simultaneous measurement of a_τ and d_τ?

LFV decays

- Lepton flavour violating decays not necessary for NP to exist
- Measurements help reduce spectrum of NP models
- $\mathscr{B}(B^+ \to K^+ \mu^- \tau^+) < 3.9 \times 10^{-5}$ at 90% CL [JHEP 06 (2020) 129]
- $\mathscr{B}(B_s \to \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}$ at 95% CL assuming no contributions from $B^0 \to \tau^\pm \mu^\mp$ decays [PRL 123 (2019) 211801]



Limits close to predictions from some NP scenarios, any signal would be proof of NP

BELLE II and LHCb expected to improve sensitivities by an order of magnitude

[Prog. Theor. Exp. Phys. 2019, 123C01] [LHCb-PUB-2022-012]

Concluding remarks

- BELLE II and LHCb expect promising increase in precision of $b \to c\tau\nu$ LFU tests
  - Differential information of the decays offering complimentary information
- Large NP enhancements expected in $b \to s\tau\tau$
  - Enhancements make observation within experimental reach
  - The large enhancements also reduce importance of hadronic uncertainties
- $(g-2)_\tau$ and tau EDM accessible at BELLE II and LHC
  - Precision expected to improve at least by an order magnitude
- LFV measurements also improving to reduce NP parameter space

Tau modes are the frontier of flavour physics for the next decade

https://www.pinterest.com/pin/655696026976436346/

Discussion points

- $R(\Lambda_c)_{exp} < R(\Lambda_c)_{SM}$ interpretation

- LHC wide combination of $(g-2)_\tau$ and τ EDM
  - Complementarity with high p_T taus in ATLAS/CMS and low p_T taus in LHCb
  - Simultaneous measurement of both values?

- Complementarity to CP observables
  - Usefulness of measuring CP asymmetries through imaginary Wilson coefficients in $b \to s\tau\tau$
  - Link to tau EDM?

Backup

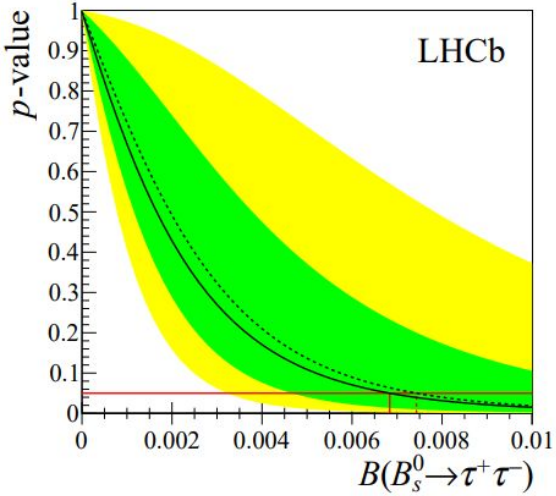
b → sττ decays: $B_s \to \tau\tau$

$$\mathcal{B}(B_s \to \tau\tau)_{\rm SM} = (7.73 \pm 0.49) \times 10^{-7} \ll 6.8 \times 10^{-3} \text{ at } 90\% \text{ CL}$$

PRL 112, 101801 (2014) [PRL 118 251802 (2017)]

Assumption: no contribution from $B^0 \to \tau\tau$

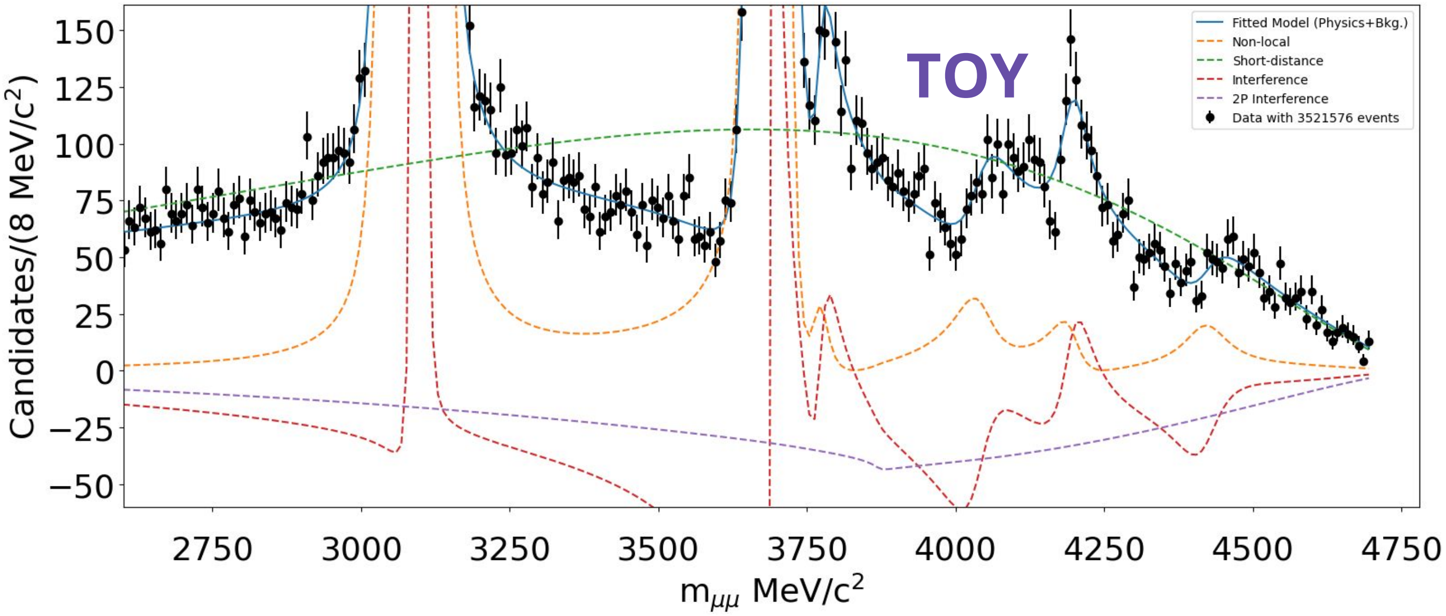
[PRL 118 251802 (2017)]



- Expect large NP enhancements $\mathcal{O}(10^3)$ driven by $R(D^{(*)})$ anomalies
- LHCb Run 2 result expected soon
- BELLE II projected to have sensitivities of $\mathcal{O}(10^{-4})$ with 50 ab^{-1} [Prog. Theor. Exp. Phys. 2019, 123C01]
- LHCb with 300 fb^{-1} will give a 5-fold increase in sensitivity [LHCb-PUB-2022-012]

No hadronic uncertainties

B→Kττ imprints in B→Kμμ [Cornella et al. EPJC **80** 1095 (2020)]



Caveat: If a huge destructive phase exists for the 2 particle charm states (DD, DD*, D*D*) sensitivity to the tau loop could be diluted.

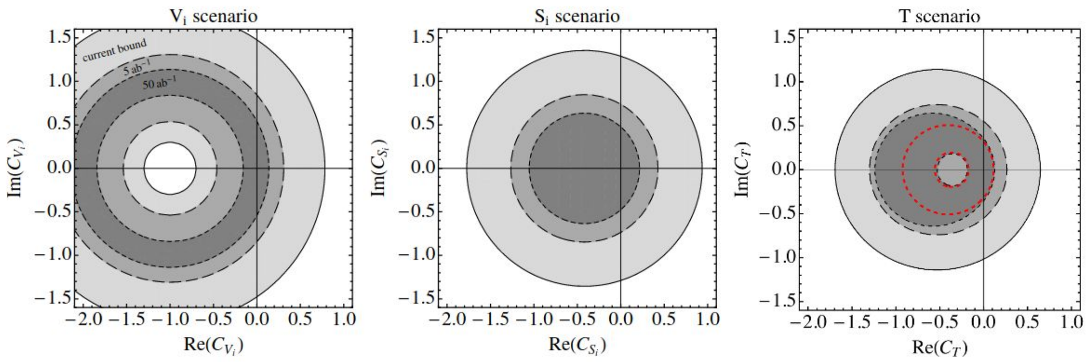
b→uτν transitions

- ➢ Doubly Cabibbo-suppressed, very sensitive to NP
- ➢ $\mathcal{B}(B^+\to\tau\nu)$ HFLAV result in agreement with SM predictions [EPJC (2021) 81: 226]
  - ○ Expect 8-fold increase in precision with 50 ab^{-1} BELLE II [Prog. Theor. Exp. Phys. 2019, 123C01]
  - ○ Offers information on scalar Wilson coefficients
- ➢ Upper limit obtained for $\mathcal{B}(B^0\to\pi\tau\nu)$ by Belle also in agreement with the SM [PRD 93 (2016) 032007]

Construct

$$R_\pi = \frac{\mathcal{B}(B\to\pi\tau\nu)}{\mathcal{B}(B\to\pi l\nu)}$$

BELLE II hopes observation of the tau mode and measurement of R_π

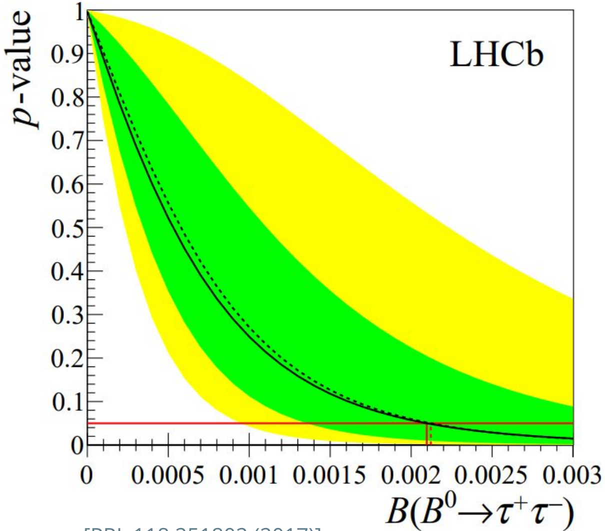


[Prog. Theor. Exp. Phys. 2019, 123C01]

Tight constraints expected for Wilson coefficients

b→dττ transitions

- $b \to d\ell\ell$ more suppressed than $b \to s\ell\ell$ ($V_{td} < V_{ts}$)
- $\mathcal{B}(B^0 \to \tau\tau)$ predicted to be (2.22±0.19)×10^{-8} in the SM [PRL 112 (2014) 101801]
  - $\mathcal{B}(B^0 \to \tau\tau)$ < 2.1×10^{-3} at 95% CL (LHCb) [PRL 118 (2017) 251802]
    - Much looser than limits for muonic mode [PRL 118 (2017) 191801]
    - Belle II expected to improve sensitivities by 2 orders of magnitude [Prog. Theor. Exp. Phys. 2019, 123C01]
    - LHCb with 300 fb^{-1} will give a 5-fold increase in sensitivity [LHCb-PUB-2022-012]



[PRL 118 251802 (2017)]

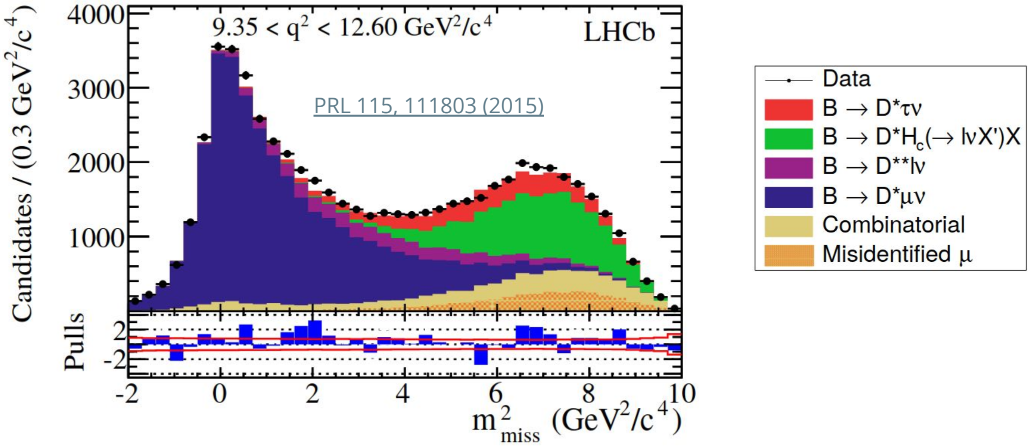
- $B^{0,+} \to \pi^{0,+}\tau\tau$ SM branching fraction of $\mathcal{O}(10^{-9})$ [JHEP 06 (2014) 040]
  - Theoretical input from Lattice QCD exists [PRL 115(15) 152002 (2015

$b \to d\mu\mu$ currently SM-like, tau mode still work in progress

Backgrounds in b→cℓν decays

➢ Larger sources of background associated with tau/semi-leptonic decays because of invisible particles

$$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$$



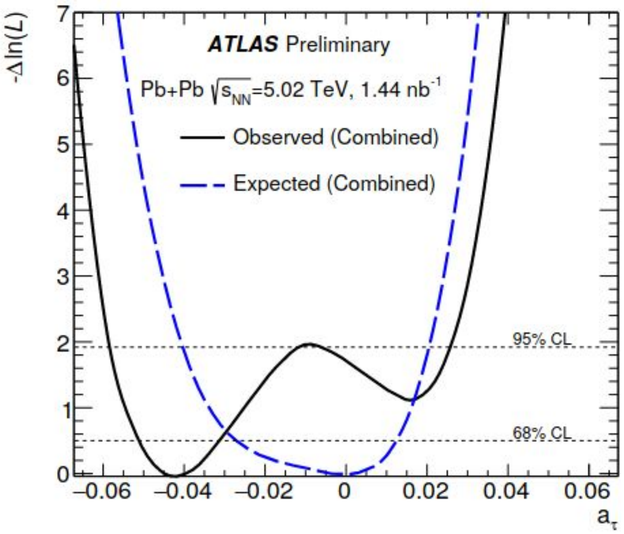
Coupling dependence on angular observables in b→cℓν decays

Quantity	g_V	g_A	g_S	g_P	g_T
A_{FB}^{D}	×	–	⋆⋆⋆	–	⋆
$A_{\lambda_\tau}^{D}$	×	–	⋆⋆⋆	–	⋆⋆
$A_{FB}^{D^*}$	⋆	⋆⋆⋆	–	⋆⋆⋆	⋆
$A_{\lambda_\tau}^{D^*}$	×	×	–	⋆⋆	⋆
$R_{L,T}$	×	×	–	⋆⋆	⋆⋆
A_5	⋆⋆	⋆⋆	–	⋆	⋆⋆⋆
C_χ	⋆	×	–	⋆⋆	⋆⋆
S_χ	⋆⋆⋆	⋆⋆⋆	–	×	⋆⋆⋆
A_8	⋆⋆	⋆⋆	–	⋆⋆	⋆⋆⋆
A_9	⋆	⋆	–	⋆⋆	⋆⋆
A_{10}	⋆⋆	⋆⋆	–	×	⋆⋆
A_{11}	×	×	–	⋆⋆	⋆⋆

[arXiv: 1602.03030]

$(g-2)_\tau$ double interval

➢ Interference of SM and BSM amplitudes results in double interval in observed limits [Jakub Kremer@QM2022]



Jakub Kremer@QM2022

LFU measurements of τ decays

- Some NP models explaining B anomalies suggest changes in W couplings to taus [PLB 826 (2022) 136903]
  - Current results in agreement with SM prediction of 1

$$\left.\frac{\mathcal{A}\left[\tau \rightarrow \mu \nu \bar{\nu}\right]}{\mathcal{A}\left[\mu \rightarrow e \nu \bar{\nu}\right]}\right|_{\mathrm{EXP}}=1.0029 \pm 0.0014 \qquad \left.\frac{\mathcal{A}\left[\tau \rightarrow \mu \nu \bar{\nu}\right]}{\mathcal{A}\left[\tau \rightarrow e \nu \bar{\nu}\right]}\right|_{\mathrm{EXP}}=1.0018 \pm 0.0014 \qquad \left.\frac{\mathcal{A}\left[\tau \rightarrow e \nu \bar{\nu}\right]}{\mathcal{A}\left[\mu \rightarrow e \nu \bar{\nu}\right]}\right|_{\mathrm{EXP}}=1.0010 \pm 0.0014$$

[arXiv: 2201.08170] [EPJC (2021) 81: 226]

  - NP models suggest shifts of around 0.1%, potentially accessible with future experiments [PLB 826 (2022) 136903]

- Tau mass and lifetime come in as parameters in SM
  - Important for many precision measurements and predictions
  - Current PDG averages [Prog. Theor. Exp. Phys. (2020) 083C01 and 2021 update]:
    - m_τ: 1776.86±0.12 MeV (6.8×10^{-5} relative uncertainty compared to 2.3×10^{-8} for muons)
    - t_τ : $(290.3\pm0.5)\times10^{-15}$ s (1.7×10^{-3} relative uncertainty compared to 1.0×10^{-6} for muons)
  - More statistics in the future ⇒ reduction in uncertainties