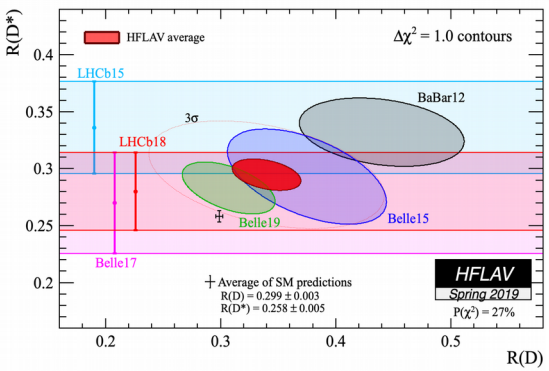
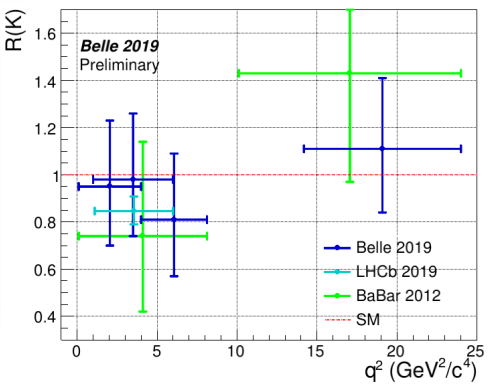
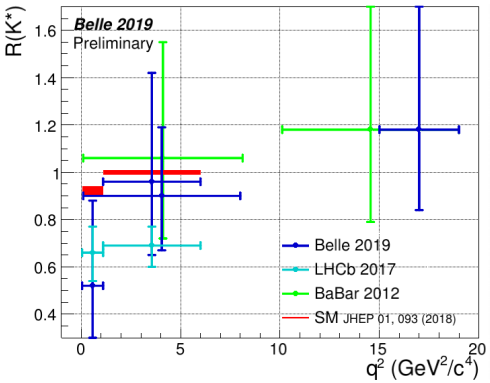
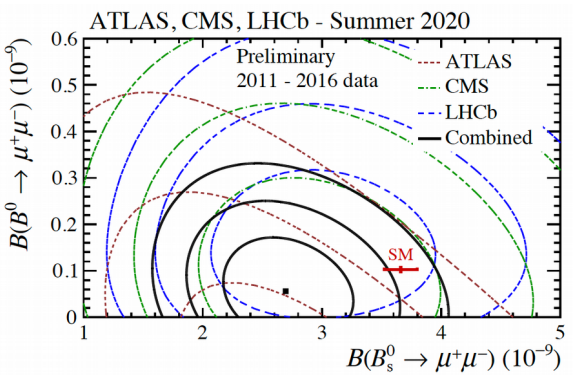
Anomalies in Flavour Physics

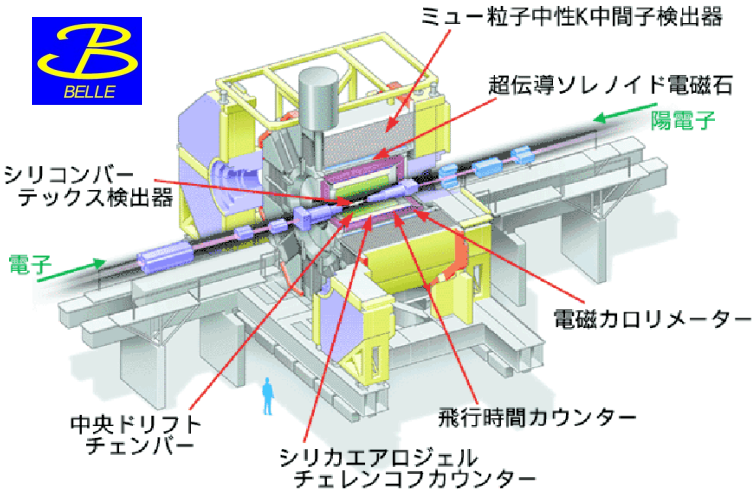
''Experimental overview''

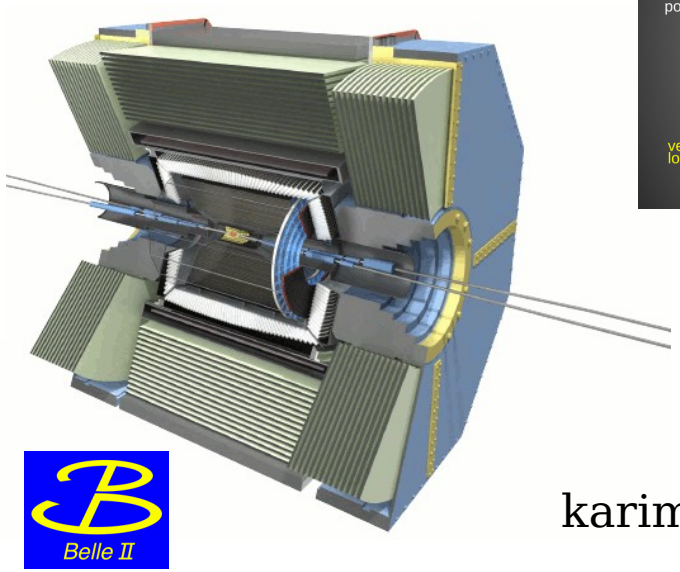


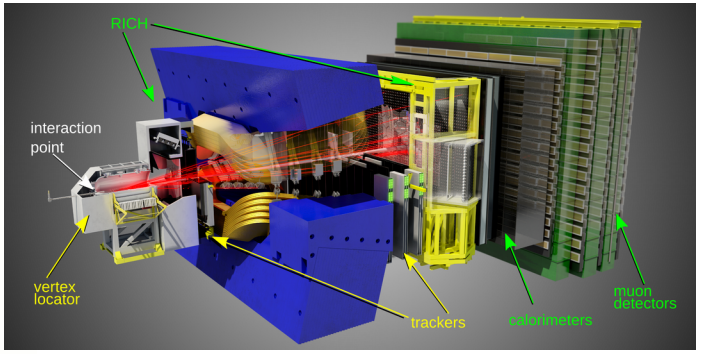












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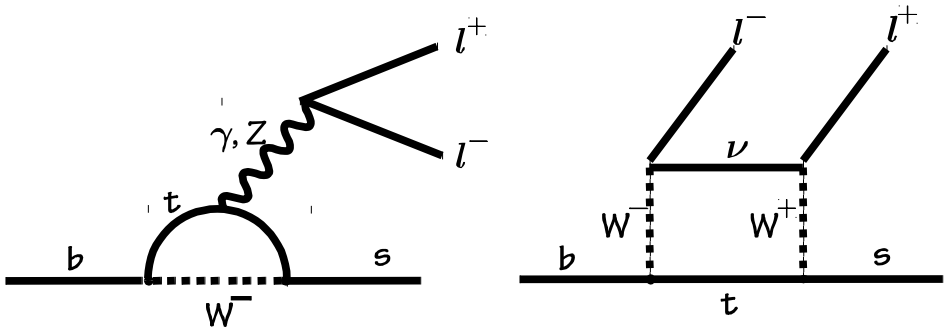
2020/10/07

Lepton flavour (non) universality using $B^+ \to K^{(*)} l^+ l^-$ decays

no evidence of New Physics in a series of ''clean'' flavor-changing observables, such as $\Delta F=2$, $b \to s\gamma$ **but** ...

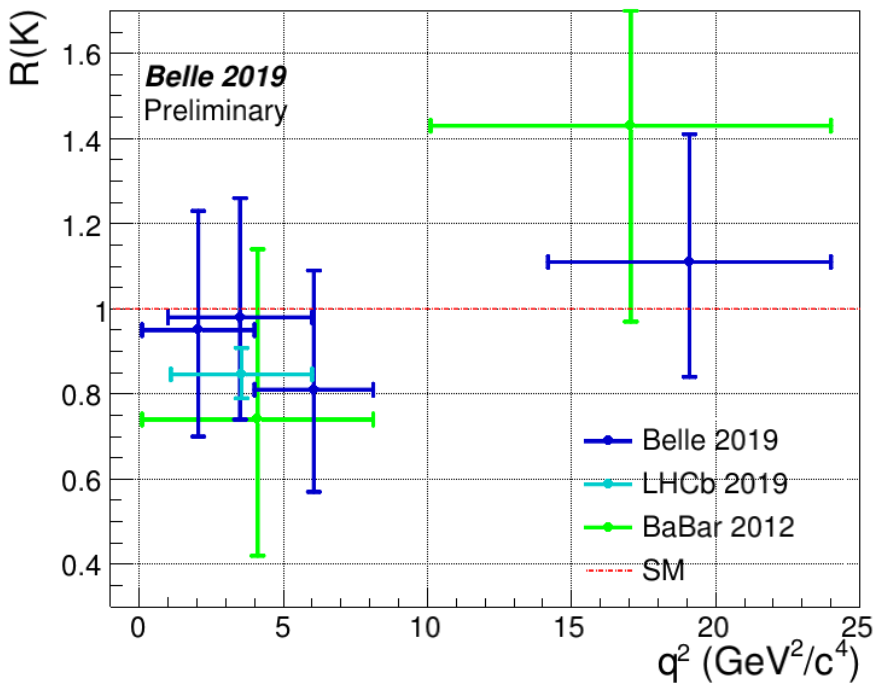


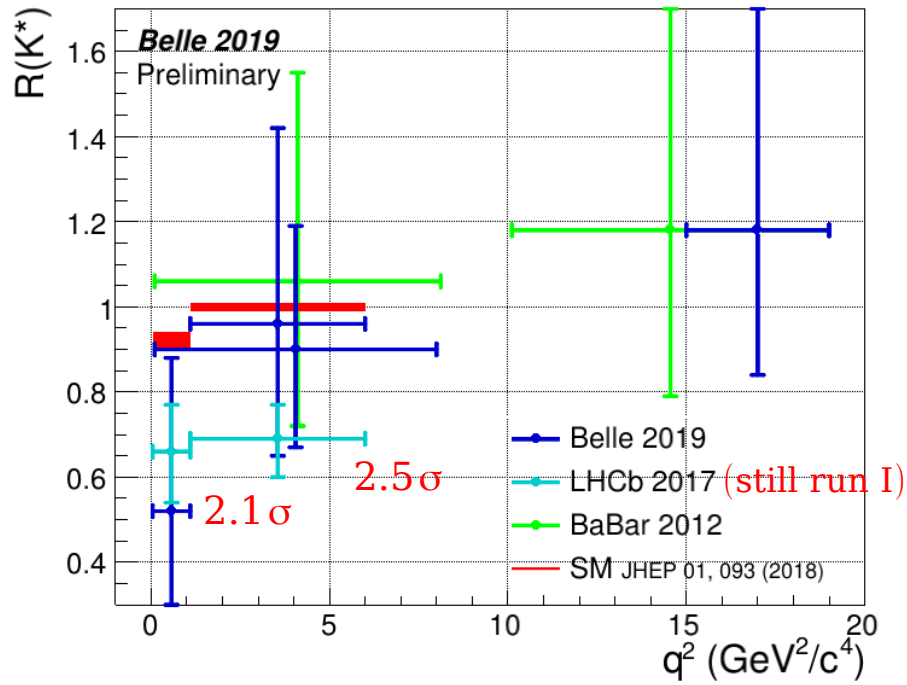
The ''clean'' Lepton Flavor Universality ratios:

$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)} \mu\mu)}{Br(B \to K^{(*)} ee)}$$

SM prediction very robust: $R_K(SM) = 1$

[up tiny QED and lepton mass effects]





LHCb: $R_K = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$ [2.5σ]

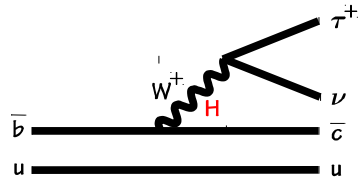
LHCb: $R_{K^*} = 0.66^{+0.11}_{-0.07}{}^{+0.03}_{-0.05}$ [2.1σ]

$= 0.69^{+0.11}_{-0.07}{}^{+0.05}_{-0.05}$ [2.5σ]

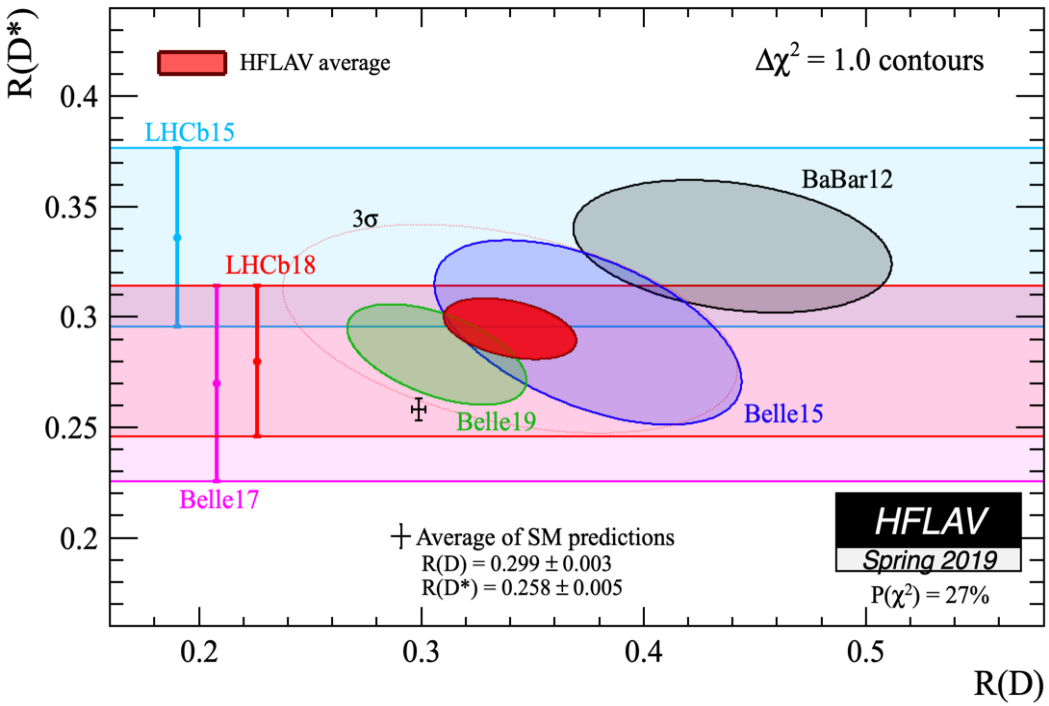
+ angular analysis (P_5')

⇒ Explained in SM effective field theory by having $C_9 \sim -1$ instead of 0

Summary for $B \to D^{(*)} \tau \nu$



$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$



BaBar

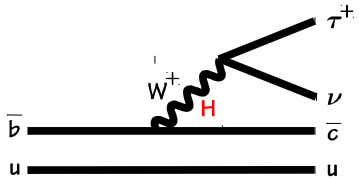
$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

average

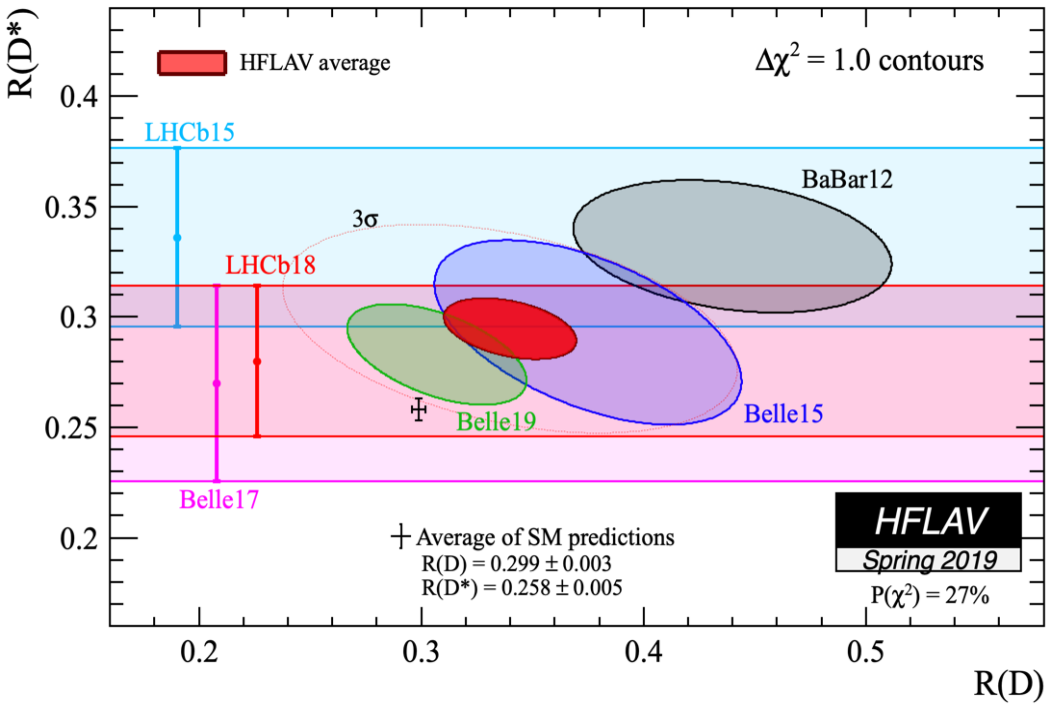
$$R(D) = 0.340 \pm 0.027 \pm 0.013$$
$$R(D^*) = 0.295 \pm 0.011 \pm 0.008$$

difference with SM predictions is at **3σ** level

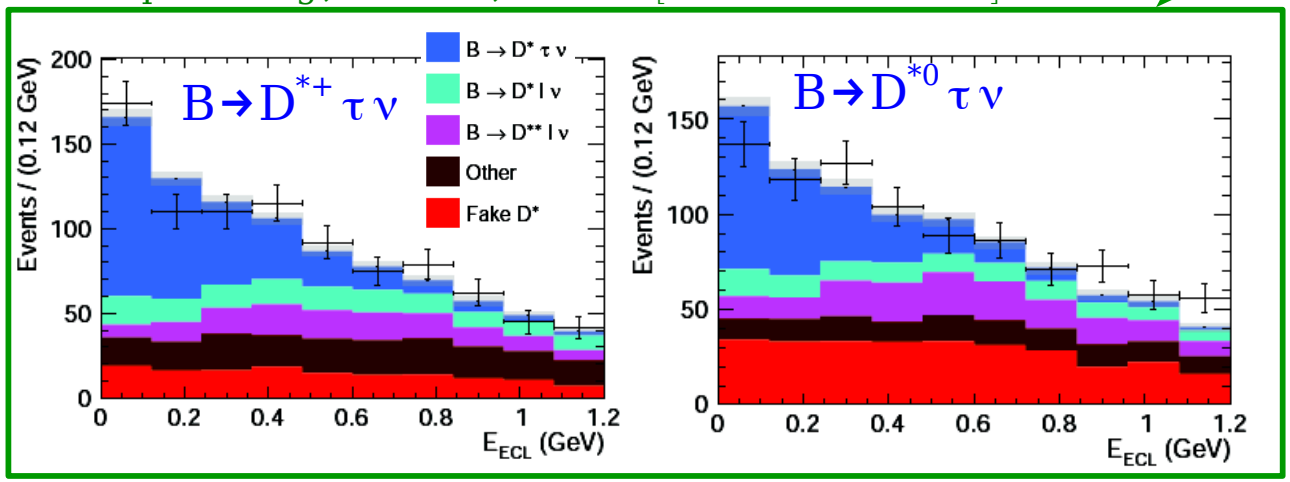
Summary for $B \to D^{(*)} \tau \nu$



$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$



semi-leptonic tag, PRL 124, 161803 [arXiv:1904.08794]



Belle 19 SL tag

BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle 15 (had tag)

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

$R(D^*) = 0.270 \pm 0.035 \,^{+0.028}_{-0.025}$

$R(D) = 0.307 \pm 0.037 \pm 0.016$
$R(D^*) = 0.283 \pm 0.018 \pm 0.014$

LHCb 15 (muonic τ decay)

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

LHCb 18 (hadronic τ decay)

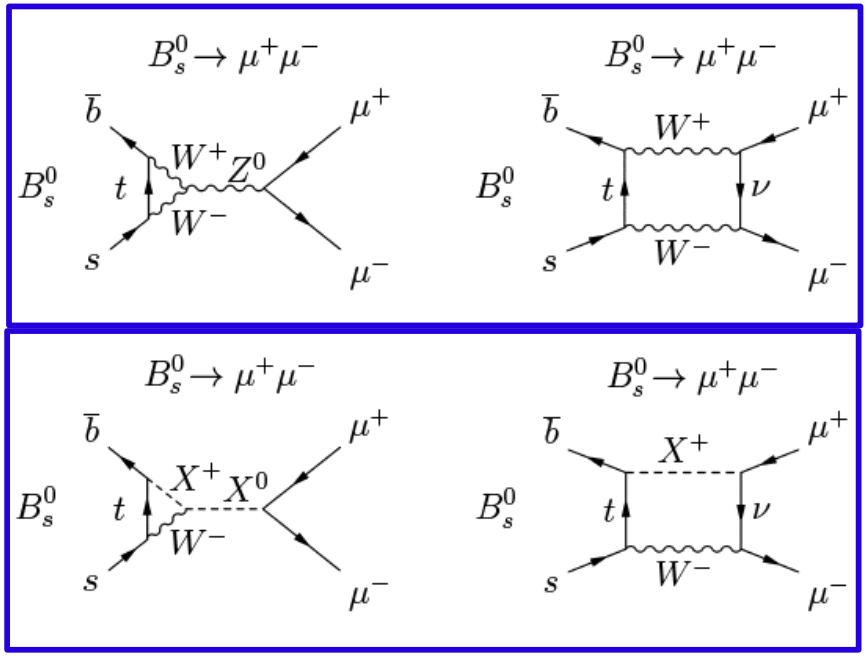
$R(D^*) = 0.280 \pm 0.018 \pm 0.029$

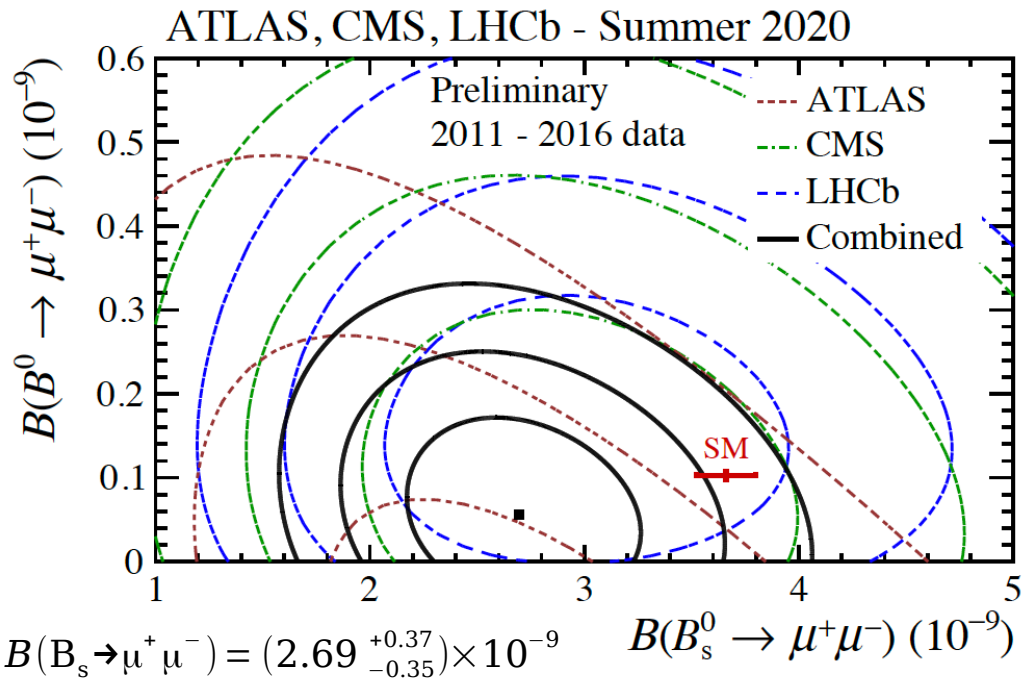
average

$R(D) = 0.340 \pm 0.027 \pm 0.013$
$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

difference with SM predictions is at **3σ** level

$B_{s(d)} \to \mu^+\mu^-$





$B(B_s \to \mu^+\mu^-) = (2.69\ ^{+0.37}_{-0.35}) \times 10^{-9}$

$B(B_d \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10}$

higher-order FCNC allowed in SM

$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]

Some difference with SM ~ 2.1 σ in direction expected by if $B \to K^{(*)}\mu^+\mu^-$ deviations are real

$B(B_s \to e^+e^-) = (8.35 \pm 0.39) \times 10^{-14}$

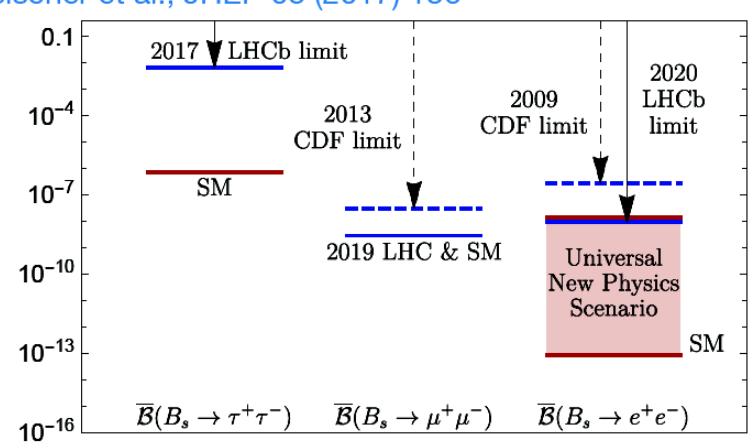
$B(B_d \to e^+e^-) = (2.39 \pm 0.14) \times 10^{-15}$

[M. Beneke et al, JHEP 10 (2019) 232]

$B(B_s \to e^+e^-) < 11.2 \times 10^{-9}$ @ 95% CL

$B(B_d \to e^+e^-) < 3.0 \times 10^{-9}$ @ 95% CL

Fleischer et al., JHEP 05 (2017) 156

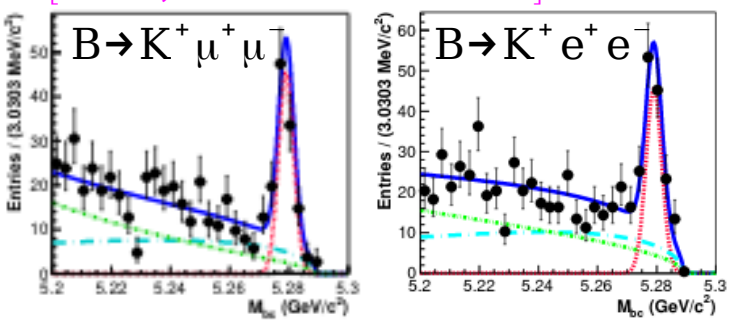


Expected results for $R(K^{(*)})$ and $R(D^{(*)})$

LHCb should update soon R_{K^*} (Run I +II expected reduce uncertainty by ~ 2), R_{D^*}, and also include R_D

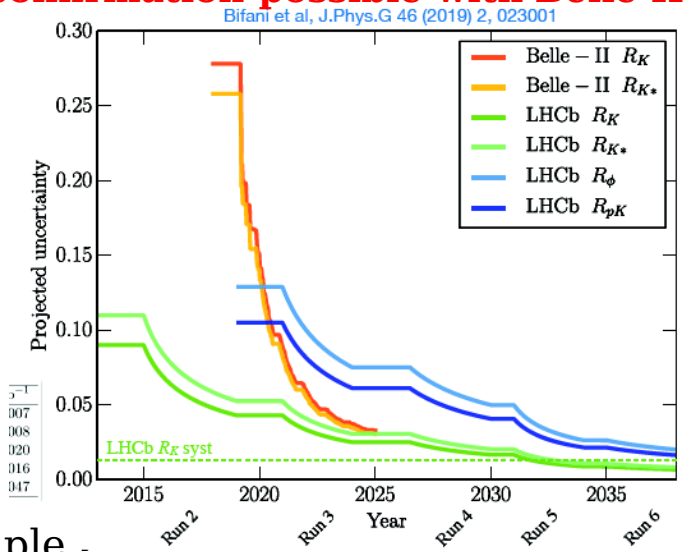
Upgrade I (50 fb^{-1}), Upgrade Ib & II (300 fb^{-1})

[Belle, arXiv:1908.01848]



5σ confirmation possible with Belle II 20 ab^{-1}

Bifani et al, J.Phys.G 46 (2019) 2, 023001



Belle II aiming for 50 ab^{-1} by 2031, so 100 × Belle data sample
⇒ room for B−tagging improvement

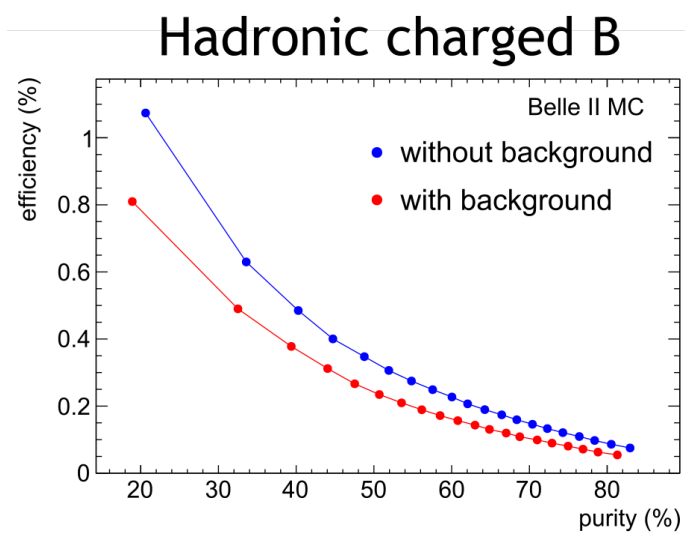
- More modes used for tag-side hadronic B than Belle, multiple classifiers

Particle	# channels (Belle)	# channels (Belle II)
$D^+/D^{*+}/D_s^+$	18	26
D^0/D^{*0}	12	17
B^+	17	29
B^0	14	26

Algorithm	MVA	Efficiency	Purity
Belle v1 (2004)	Cut based (Vcb)		
Belle v3 (2007)	Cut based	0.1	0.25
Belle NB (2011)	Neurobayes	0.2	0.25
Belle II FEI (2017)	Fast BDT	0.5	0.25

Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:



Lepton flavour (non) universality using $B^+ \to K^{(*)} l^+ l^-$ decays

Model candidates

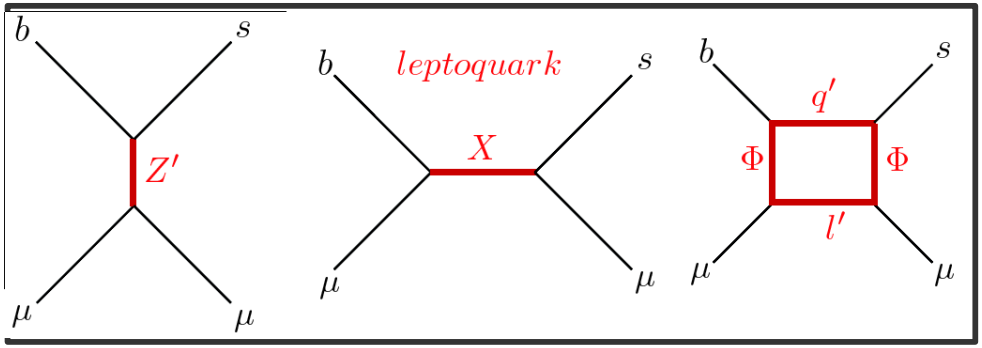
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **Models with leptoquarks**

- ✓ Effective operator from LQ exchange
- ✓ Yukawa interaction with LQs provide flavor violation

✧ **Models with loop induced effective operator**

- ✓ With extended Higgs sector and/or vector like quarks/leptons
- ✓ Flavor violation from new Yukawa interactions



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV $b \to s e\mu$, $b \to s e\tau$, ...

G. Isidori, FPCP 2020: correlations among $b \to s(d) ll'$ within the U(2)-based EFT

	μμ (ee)	ττ	νν	τμ	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ → 10^{-6}	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

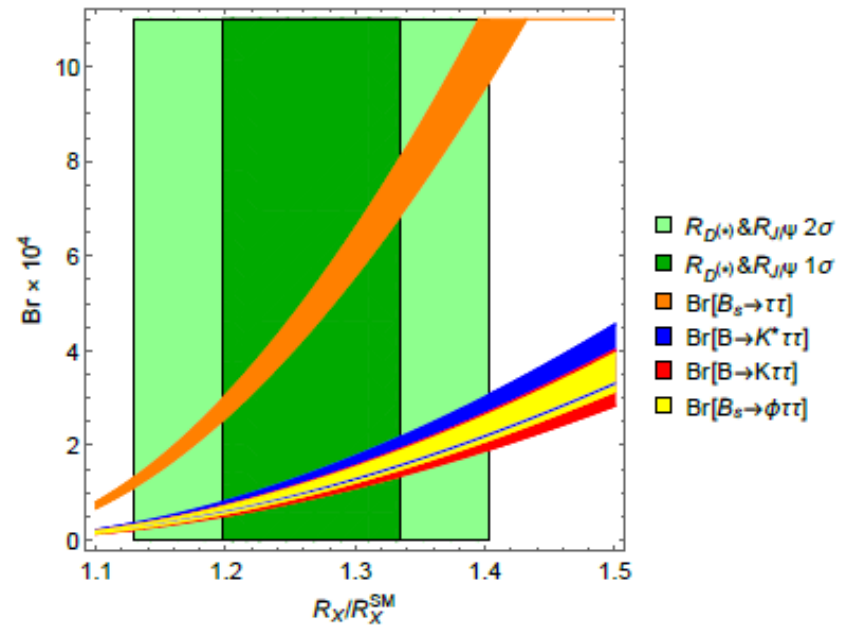
$B \to K^{(*)} \tau\tau$

[B. Capdevila et al, arXiv:1712.01919]

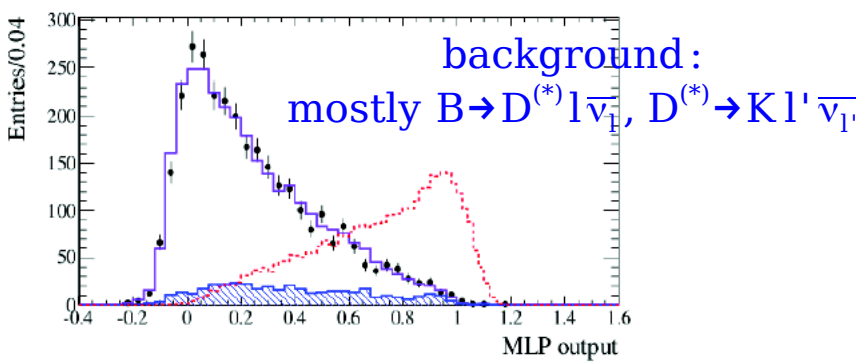
q^2 range for predictions for $B \to H \tau^+ \tau^-$: from $4\, m_\tau^2$ ($\sim 12.6\ \mathrm{GeV}^2$) to $(m_B - m_H)^2$
to avoid contributions from resonant decay
through $\psi(2S)$, $B \to H \psi(2S)$, $\psi(2S) \to \tau^+ \tau^-$
predictions restricted to $q^2 > 15\ \mathrm{GeV}^2$:

greatly enhanced in NP models...

$$B(B \to K \tau^+ \tau^-)_{SM} = (1.2 \pm 0.1)\ 10^{-7}$$
$$B(B \to K^* \tau^+ \tau^-)_{SM} = (1.0 \pm 0.1)\ 10^{-7}$$



strategy used: [BaBar, arXiv:1605.09637]
B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$

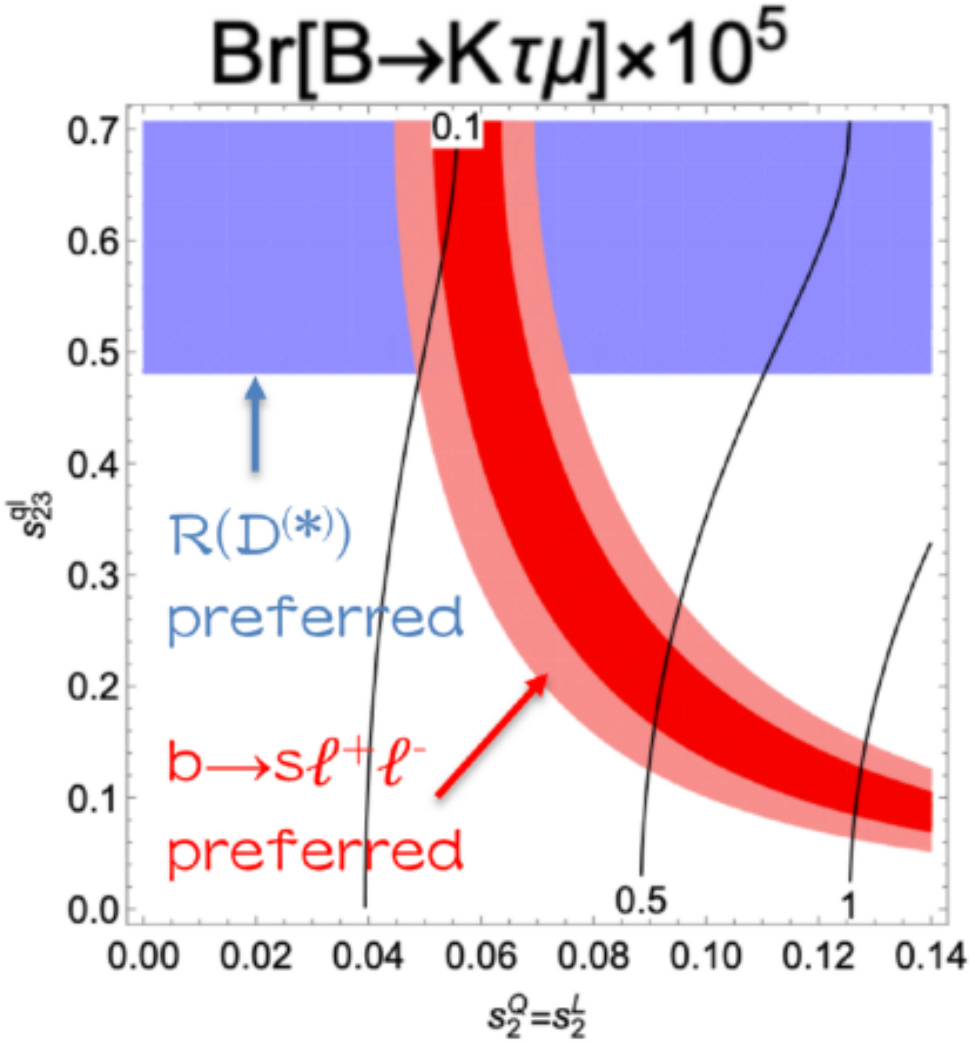


BaBar's result with had tag: $B(B^+ \to K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3}$ at 90% CL

[Belle II, arXiv:1808.10567]

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+ \tau^+ \tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0

$R(D^*)$ and $b \to s\mu\mu \Rightarrow B \to K\tau\mu$



[L. Calibbi et al, arXiv:1709.00692]

- $R(D^{(*)})$ 2σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 2σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 1σ

Key Features of PS^3

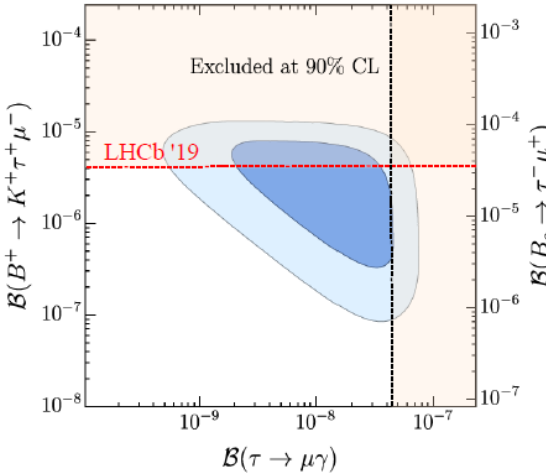
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

common to all PS-type models

- TeV-scale LQ, colour-octet vector and Z'
- decent fit to low-energy data
- large $\tau \to \mu$ LFV effects

specific to PS^3

- hierarchical symmetry breaking pattern relates flavour-dependent LQ couplings to Yukawa hierarchies
- LQ coupling also to right-handed fermions



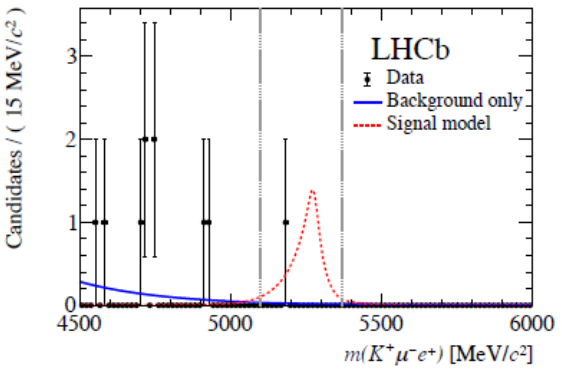
LFV $B \to K l l'$ ($l = e, \mu, \tau$) decays

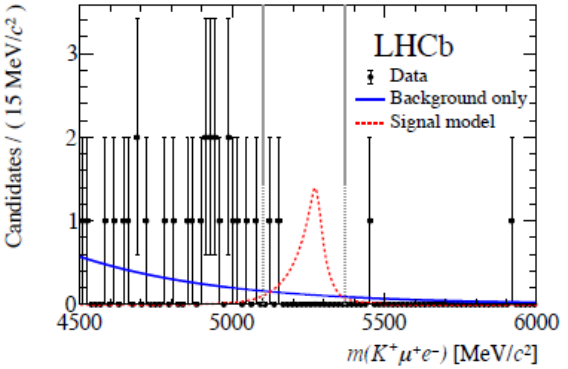
[LHCb, arXiv:1909.01010]

$B \to K^+ \mu^\pm e^\mp$

$B(B^+ \to K^+ \mu^+ e^-) < 8.8 \times 10^{-9}$ at 95% CL

$B(B^+ \to K^+ \mu^- e^+) < 9.5 \times 10^{-9}$ at 95% CL



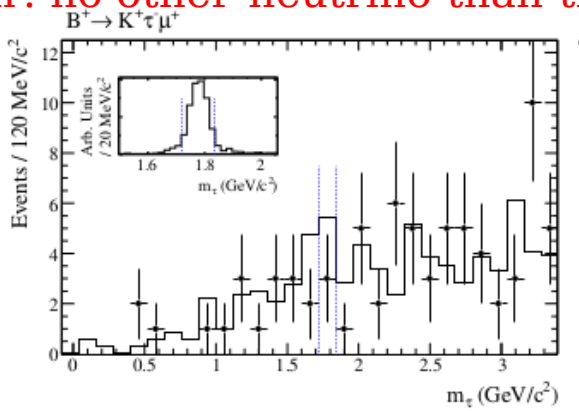


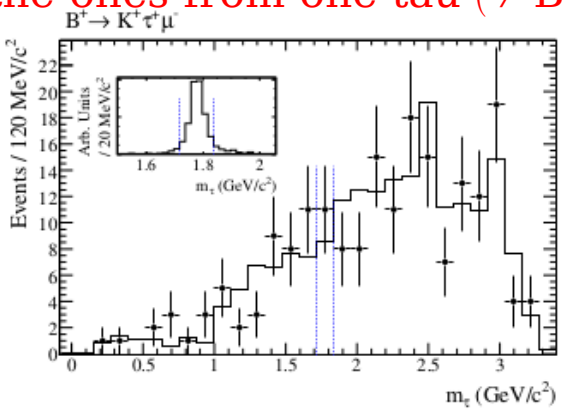
$B \to K \tau l$ ($l = e, \mu$)

strategy used: B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$, $(n\pi^0)\pi\nu$, with $n \geq 0$

using momenta of K, l and B, **can fully determine the τ four-momentum**

unique system: no other neutrino than the ones from one tau ($\neq B \to \tau\nu$, $D^{(*)}\tau\nu$...)





[BaBar, arXiv:1204.2852]

$B(B^+ \to K^+ \tau^- \mu^+) < 4.5 \times 10^{-5}$ at 90% CL, $B(B^+ \to K^+ \tau^+ \mu^-) < 2.8 \times 10^{-5}$ at 90% CL

(also results for $B \to K^+ \tau^\pm e^\mp$, $B \to \pi^+ \tau^\pm \mu^\mp$, $B \to \pi^+ \tau^\pm e^\mp$ modes)

[LHCb, arXiv:2003.04352]

Search for the lepton favour violating decay $B^+ \to K^+ \mu^- \tau^+$ using B_{s2}^{*0} decays, $B_{s2}^{*0} \to B^+ K^-$

$Br(K^+ \tau^+ \mu^-) < 3.9 \times 10^{-5}$ at 90% CL

(provides an extra kinematic constraint)

⇒ **Belle has yet to provide a result here (potential looser & more efficient B-tagging)**

⇒ **LHCb (upgrade), Belle II will have stat for one order of magnitude improvement**

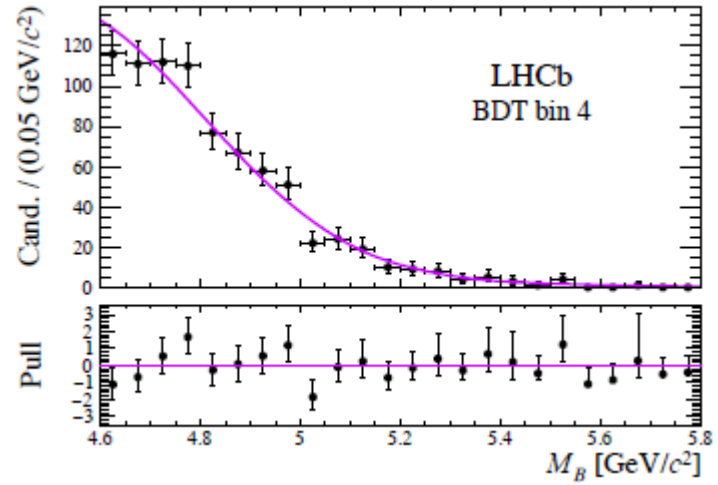
LFV $B_{(s)} \to ll'$ decays

$B_{(s)} \to \tau^{\pm}\mu^{\mp}$

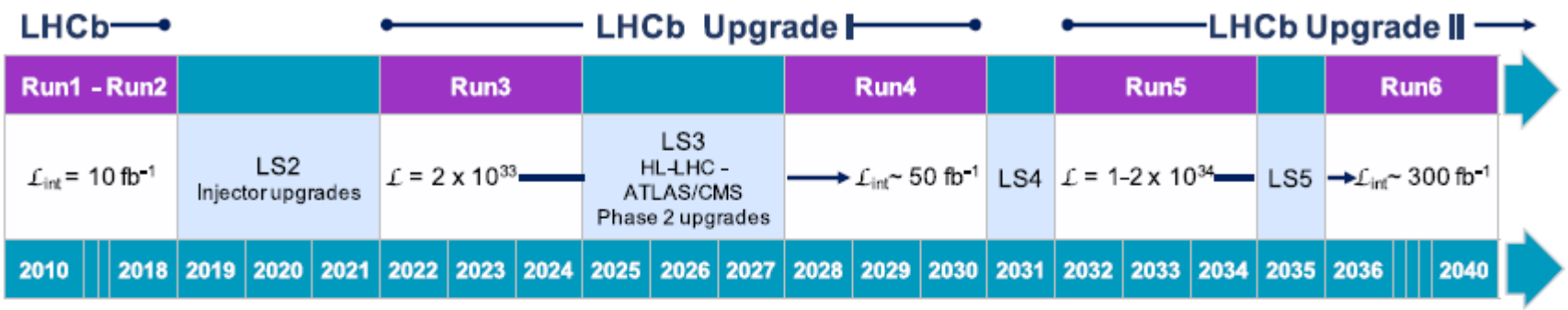
[Run I data (3 fb^{-1}) using 3-prong τ decays]

Mode	Limit	90% CL	95% CL
$B_s^0 \to \tau^{\pm}\mu^{\mp}$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^{\pm}\mu^{\mp}$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

[LHCb, arXiv:1905.06614]



[CERN-LHCC-2018-027]



	LHCb Run1	Upgrade I	Upgrade II
$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp})$	$< 1.3 \times 10^{-9}$	$< 2 \times 10^{-10}$	$< 9 \times 10^{-11}$
$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp})$	$< 6.3 \times 10^{-9}$	$< 8 \times 10^{-10}$	$< 3 \times 10^{-10}$
$\mathcal{B}(B^0 \to \tau^{\pm}\mu^{\mp})$	$< 1.4 \times 10^{-5}$	–	$< 3 \times 10^{-6}$

projections @95% CL

⇒ **Belle II at 10^{-6} sensitivity with 50 ab^{-1}**

Summary

- Current anomalies suggest possible NP
  ⇒ Update of LFU could show an evidence of NP already with LHCb full run 2 data
- Belle II and LHCb upgrade(s) will provide ''soon'' much more…
  ⇒ stat → much more precise measurements
  ⇒ more observables : q^2 , angular distributions
- LFV searches will strongly constraints the parameters space several BSM models