Constraining $b \to s\tau\tau$ & friends

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Beyond the Flavour Anomalies IV

April 2023

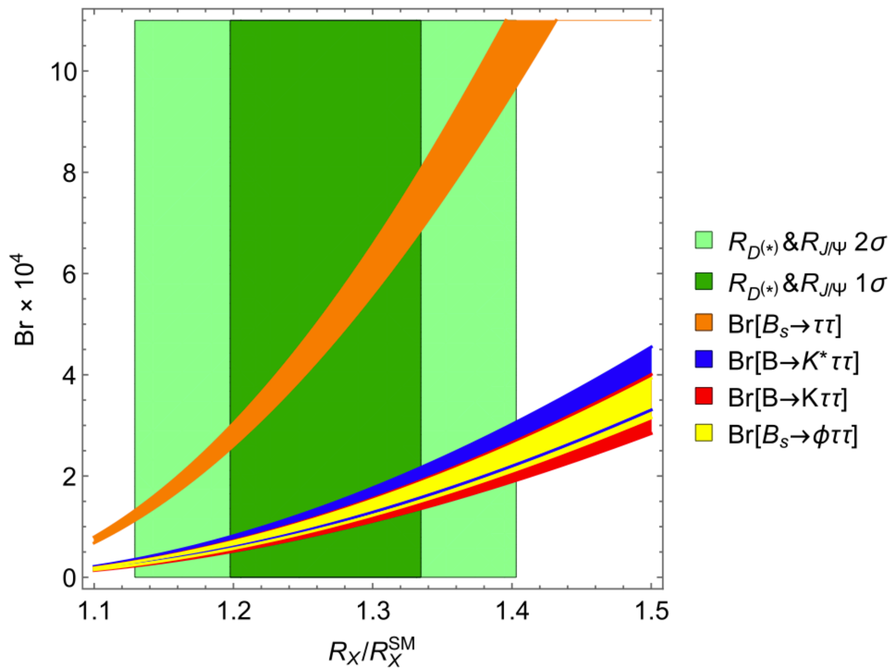
Why $b \to s\tau\tau$?

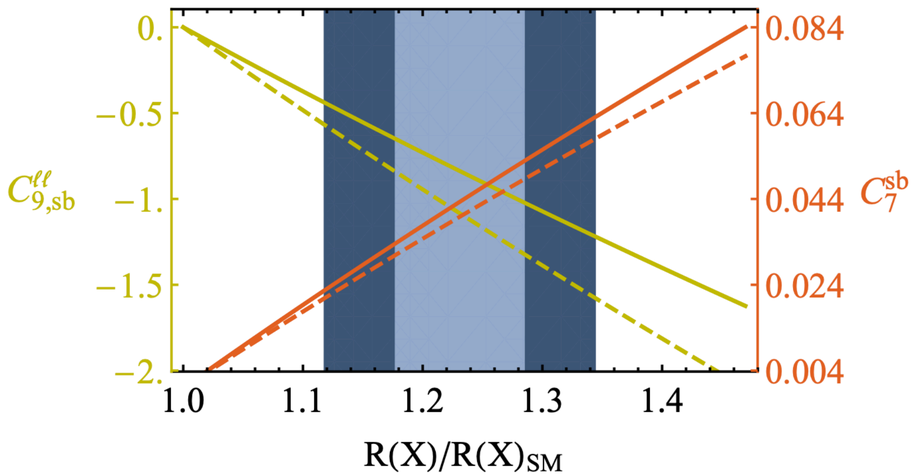
- Attempts to explain LFU violating effects in R(D)-R(D*) tend to enhance $b \to s\tau\tau$ couplings
- As a bonus, one obtains higher order corrections to $b \to s\ell\ell$, causing a LFU shift in C_9
  - In many models additional couplings to lighter leptons can be included to take care of e/μ LFnU

		SM prediction
$B_s \to \tau\tau$		$(7.73 \pm 0.49) \times 10^{-7}$
$B \to K\tau\tau$	$[15, 22]\mathrm{GeV}^2/c^2$	$(1.20 \pm 0.12) \times 10^{-7}$
$B \to K^*\tau\tau$	$[15, 19]\mathrm{GeV}^2/c^2$	$(0.98 \pm 0.10) \times 10^{-7}$
$B_s \to \phi\tau\tau$	$[15, 18.8]\mathrm{GeV}^2/c^2$	$(0.86 \pm 0.06) \times 10^{-7}$

Bobeth et al, PRL 112 (2014) 101801, Capdevila et al, PRL120 (2018) 181802

Capdevila et al, PRL120 (2018) 181802

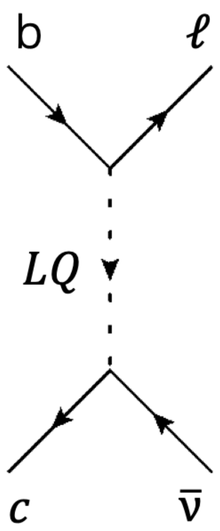


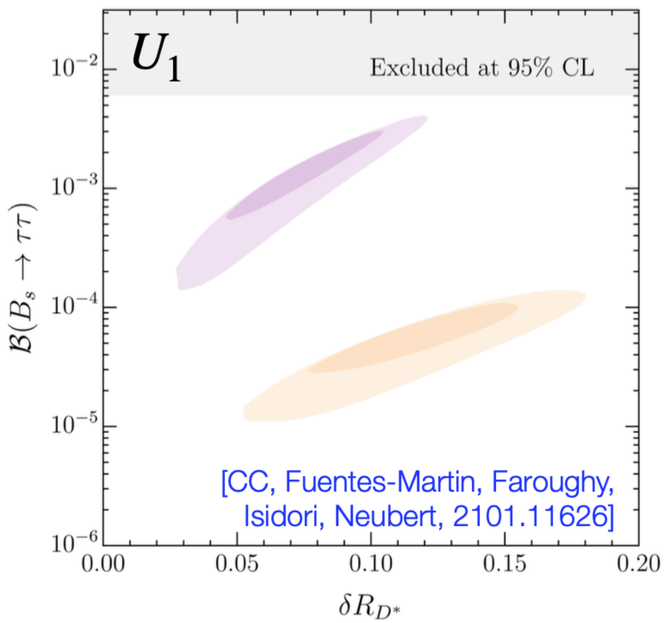


Crivellin et al, PRL 122 (2019) 011805

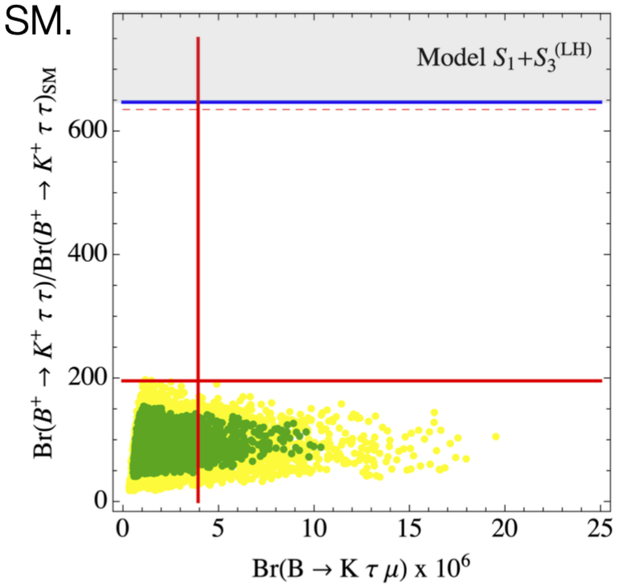
Leptoquarks?

- Natural good candidates to coherently address the anomalies while respecting other bounds
  - Constraints also from direct searches & high energy
  - Lepton flavour violation in B or tau decays





SM.



[Gherardi, Marzocca, Venturini 2008.09548]

$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)_{\rm SM}} \approx \frac{\mathcal{B}(B \to K\tau\tau)}{\mathcal{B}(B \to K\tau\tau)_{\rm SM}} \approx 1 \times 10^2$$

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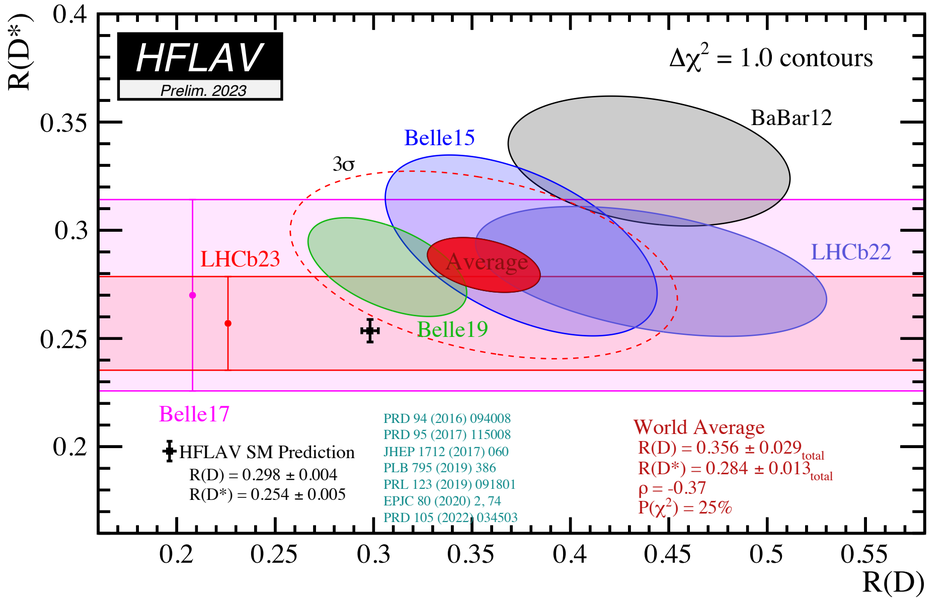
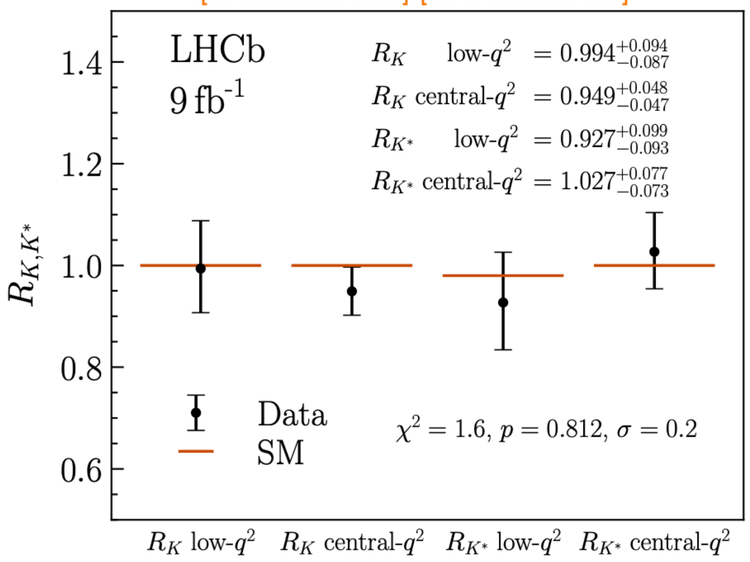
New since BFA III

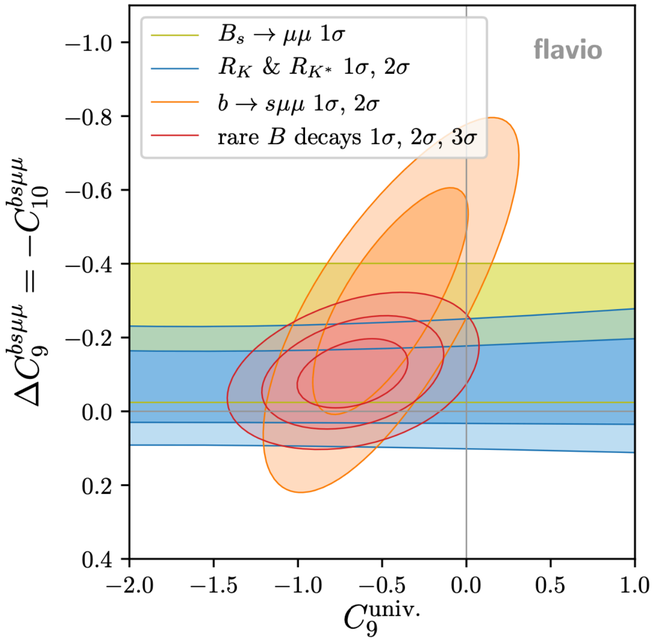
- LFU in Charged Currents
  - RD-RD* with leptonic τ
  - RD* hadronic with hadronic τ
- LFU in Neutral Currents
  - R_K and R_{K^*} at low and central q^2
  - Bs->mumu from CMS



[arXiv:2212.09152] [arXiv:2212.09153]



Greljo et al 2212.10497



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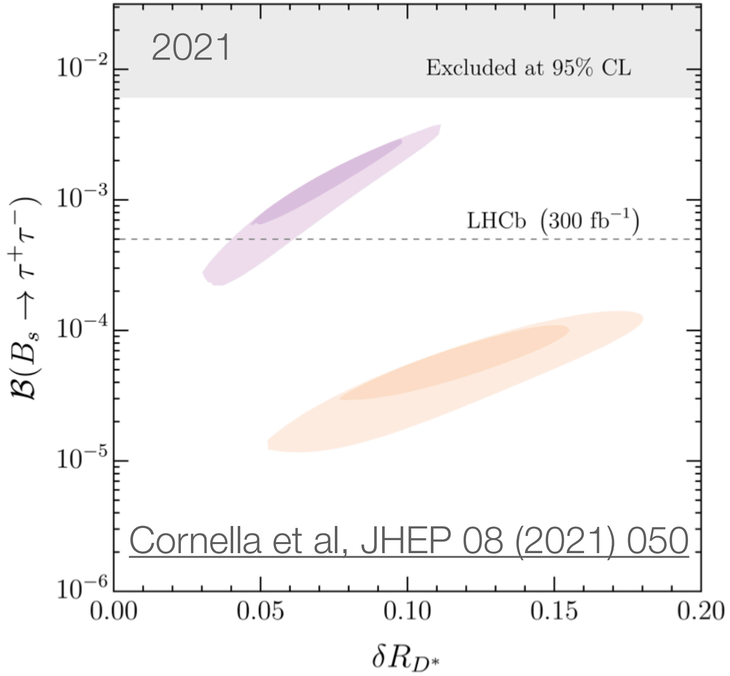
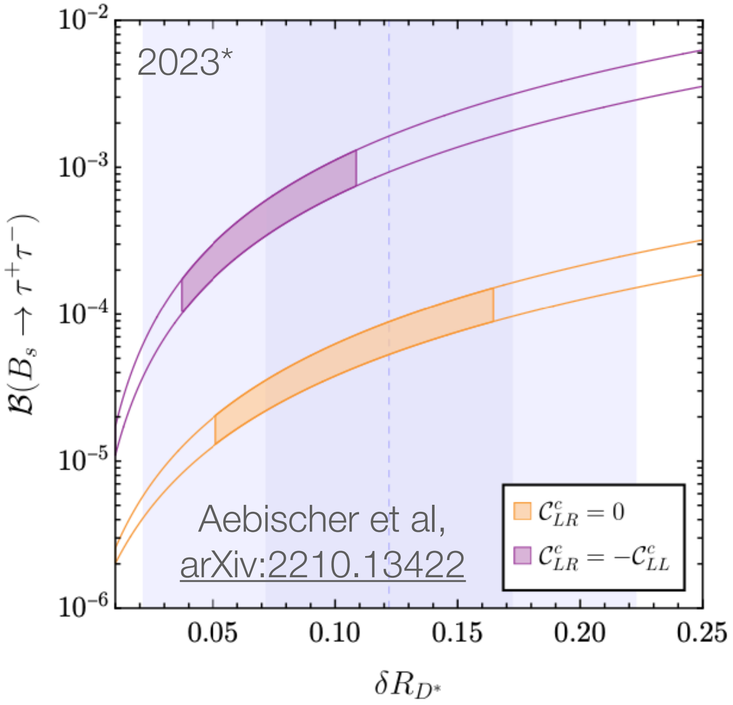


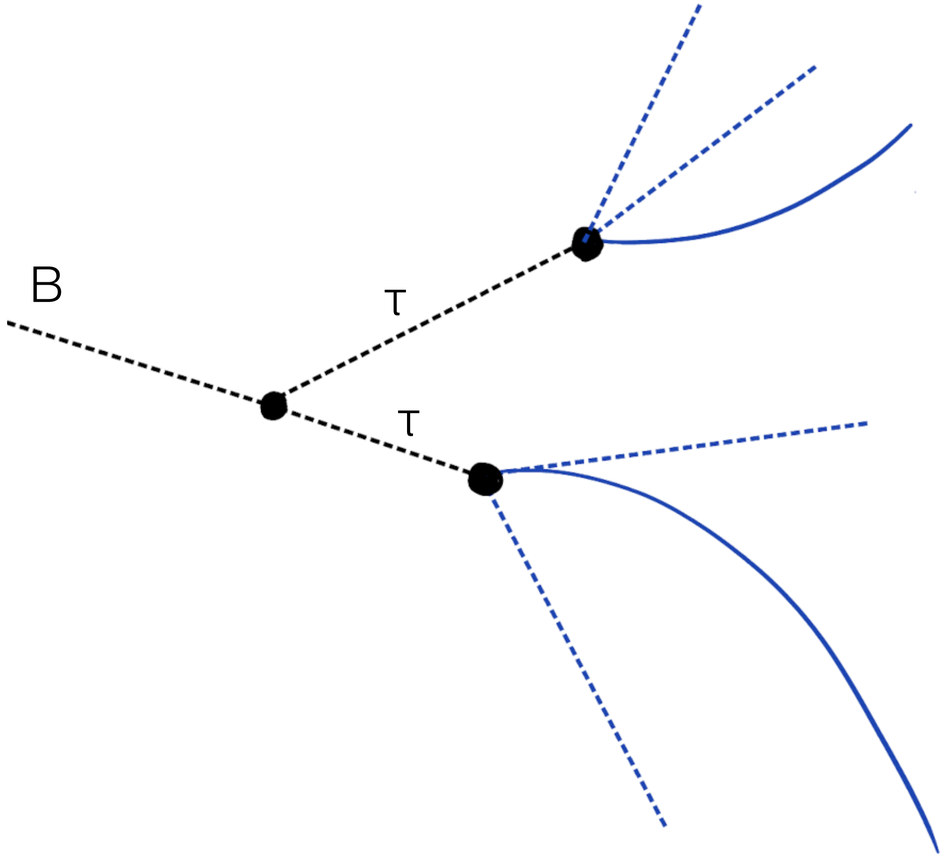


Given the effect is driven by R(D) - R(D*), the enhancements in $b \to s\tau\tau$ still favoured

* Also includes new CMS result in $\sigma(pp \to \tau\tau)$

Experimental challenges of $b \to s\tau\tau$

- At least two undetected neutrinos in the final state:
  - challenging for both Belle II and LHCb
- Several options for τ reconstruction
  - One prong $\tau \to \mu\nu_\mu\nu_\tau$ [Br ~ 17%]
    - Less background (muon ID)
    - More neutrinos
    - Add $\tau \to \pi^+\nu_\tau$ [BR ~ 10%] and $\tau \to \pi^+\pi^0\nu_\tau$ [BR ~ 25%]?
  - Three prong $\tau \to \pi^+\pi^-\pi^+\nu_\tau$ [Br ~ 9%]
    - Use vertex and mass to constraint the decay kinematics
    - Usually more background
- Peaking backgrounds affect both - specially $B \to DDX$



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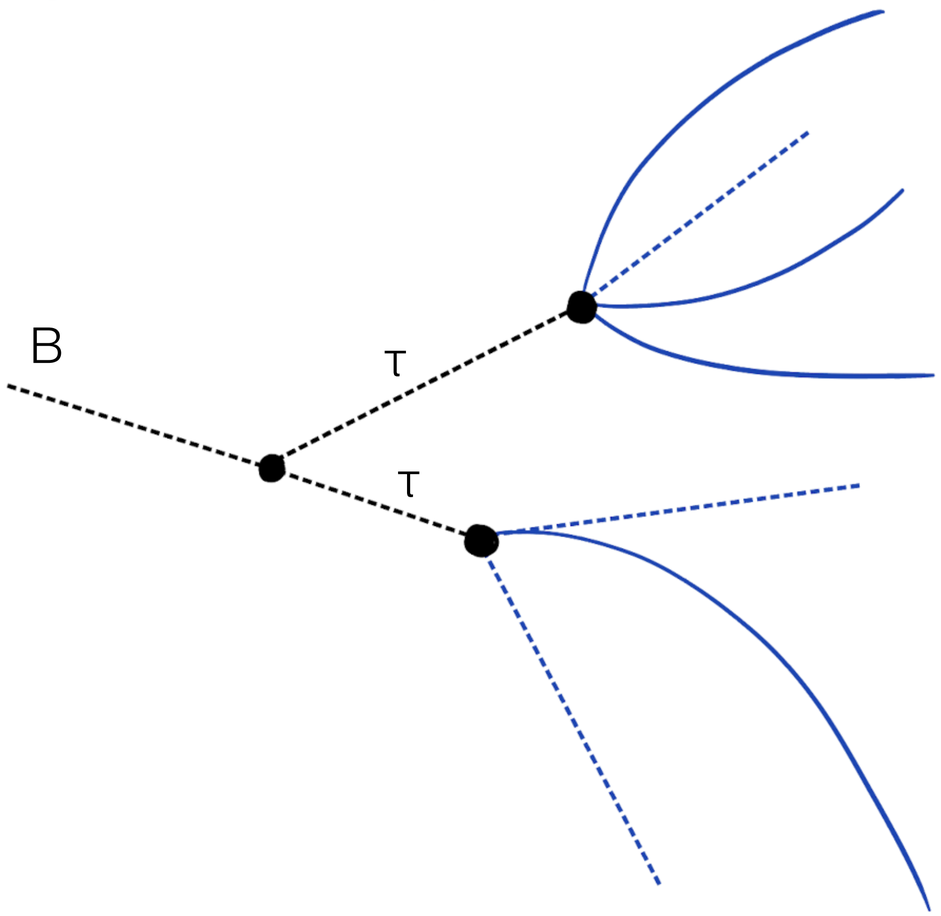

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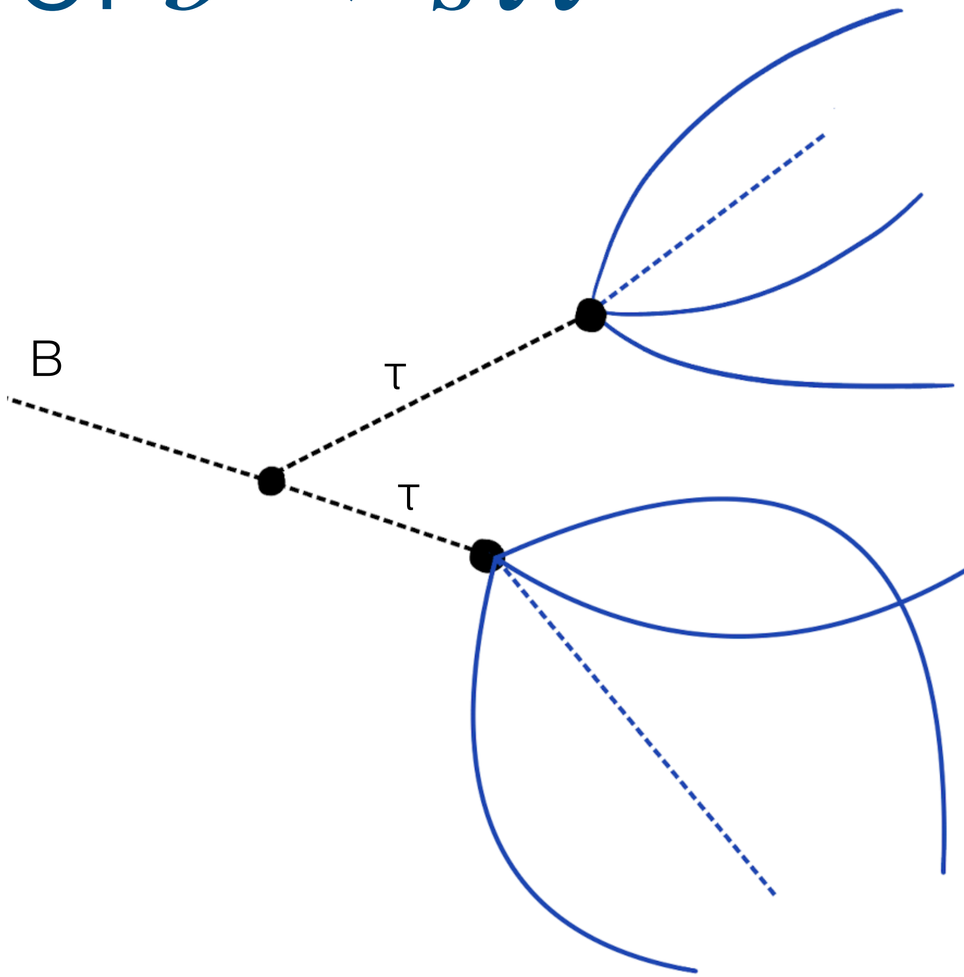

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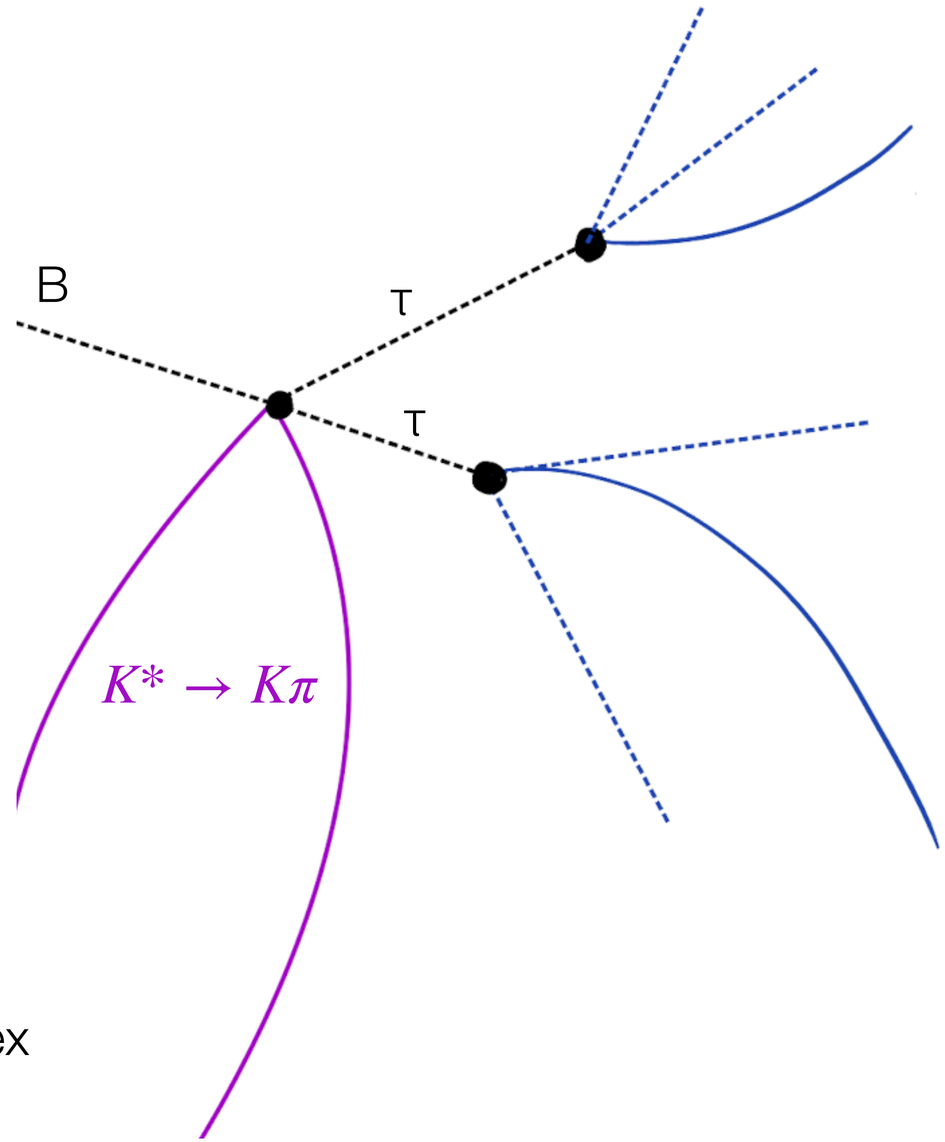
- Additional tracks from the B decay can help constraining the vertex



$B_s \to \tau\tau$

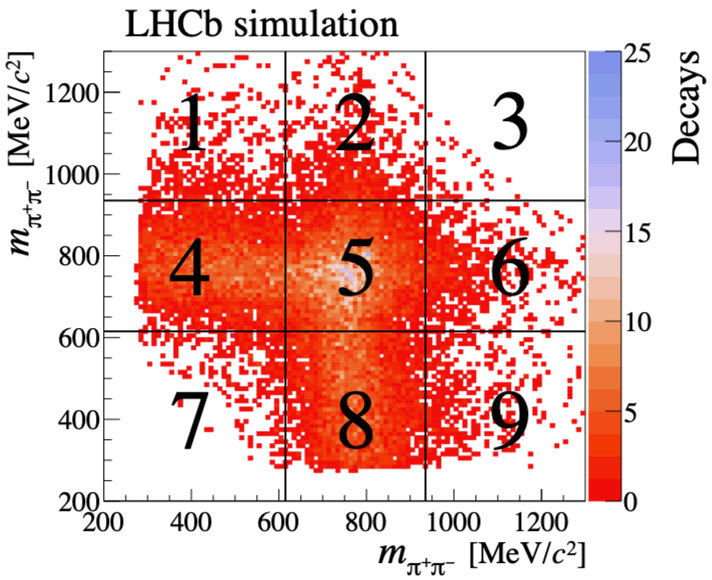
- Only limit coming from LHCb Run1, using hadronic τ decays

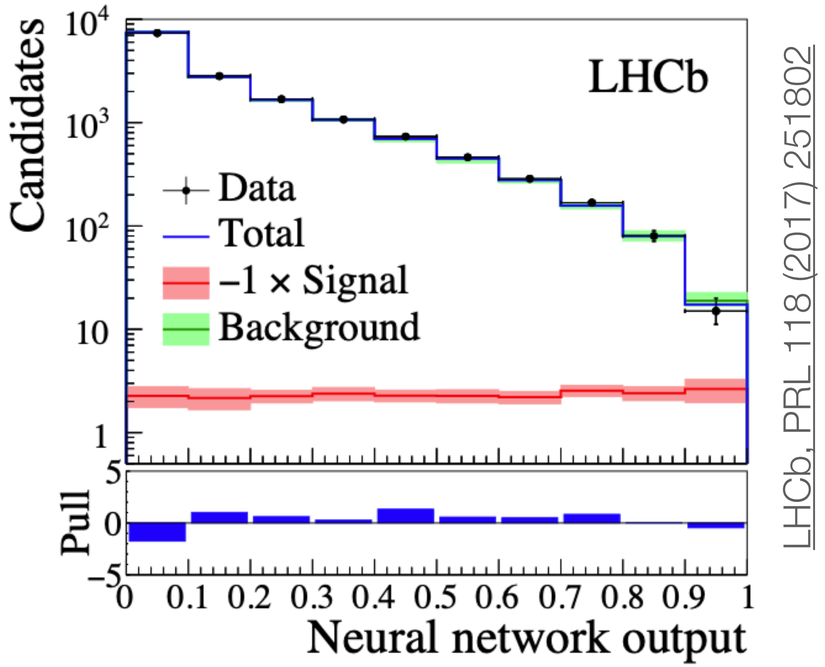
$$Br(B_s \to \tau\tau) < 6.8 \times 10^{-3} \quad @95\% \ \ \mathrm{CL}$$
$$Br(B_d \to \tau\tau) < 2.1 \times 10^{-3} \quad @95\% \ \ \mathrm{CL}$$

  - Analysis of the full Run2 data ongoing (at least x2)
  - Expected to reach 10^{-3} at the end of Run4 [50/fb]
  - And 5×10^{-5} by the end of Upgrade II [300/fb]
  - Tau decay model will become limiting

- Belle II, assuming will collect 5/ab at the ϒ(5S), would reach 8×10^{-3}

Belle II, PTEP(2019)123C01





LHCb, PRL 118 (2017) 251802

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

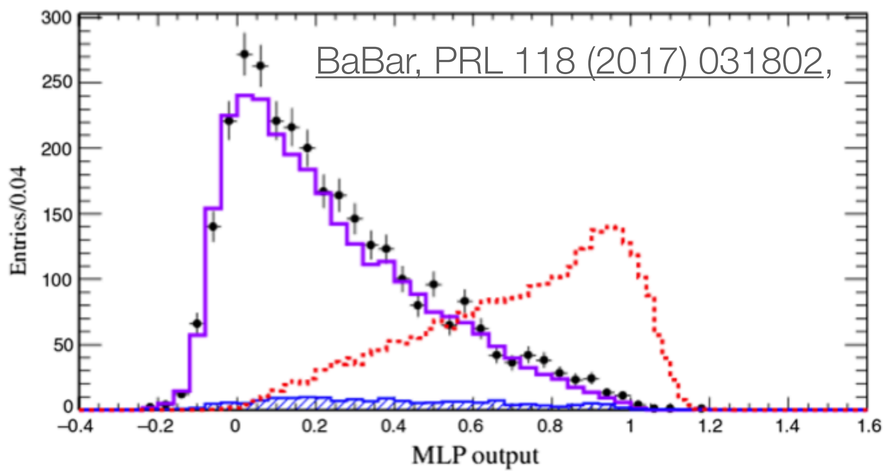
- Only limit coming from BaBar, using leptonic τ decays (μμ, ee, eμ)

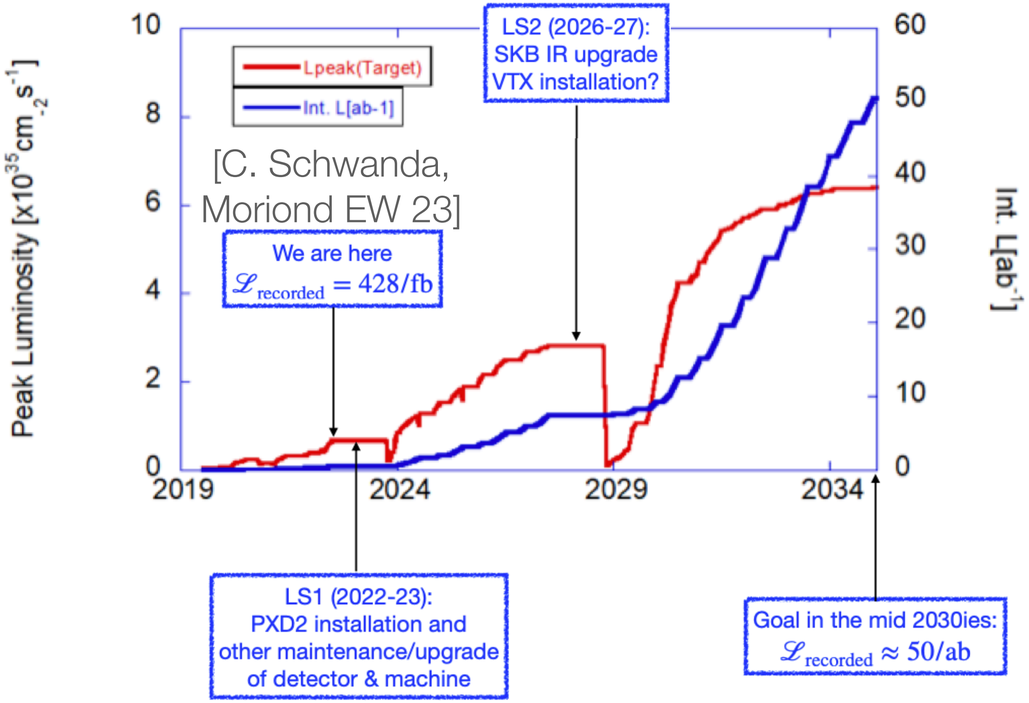
$$Br(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3} \quad @90\% \ \ \mathrm{CL}$$

  - Fully reconstructed Btag, gives access to missing momentum from Bsig

- At Belle II, soon reach 10^{-4} [1/ab] and 10^{-5} by the end of data taking [50/ab]
  Belle II, PTEP(2019)123C01

- At LHCb, $B \to h^+h^-\tau\tau$ has better prospects, e.g. $B \to K^{*0}\tau\tau$ expected to reach 10^{-4} [Run1+2]
  - Also $B_s \to \phi\tau\tau$ or $\Lambda_b \to pK\tau\tau$ being pursued both in the hadronic and leptonic modes





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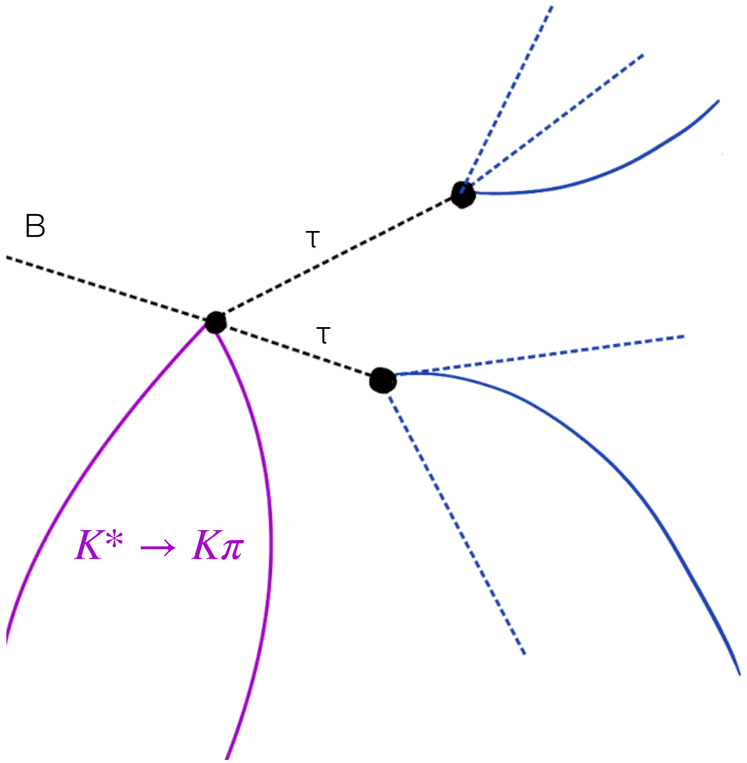
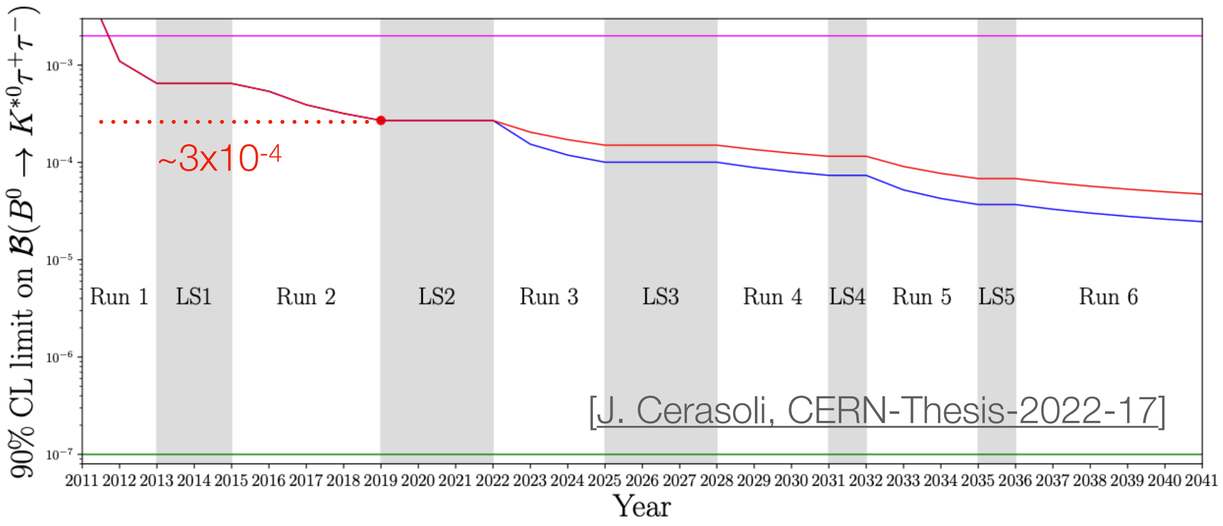
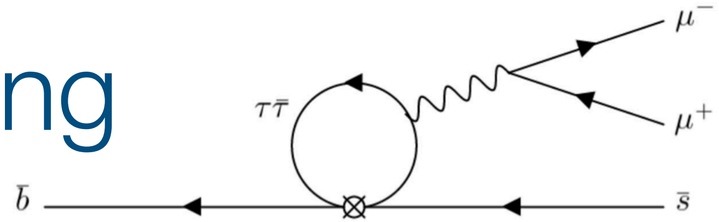


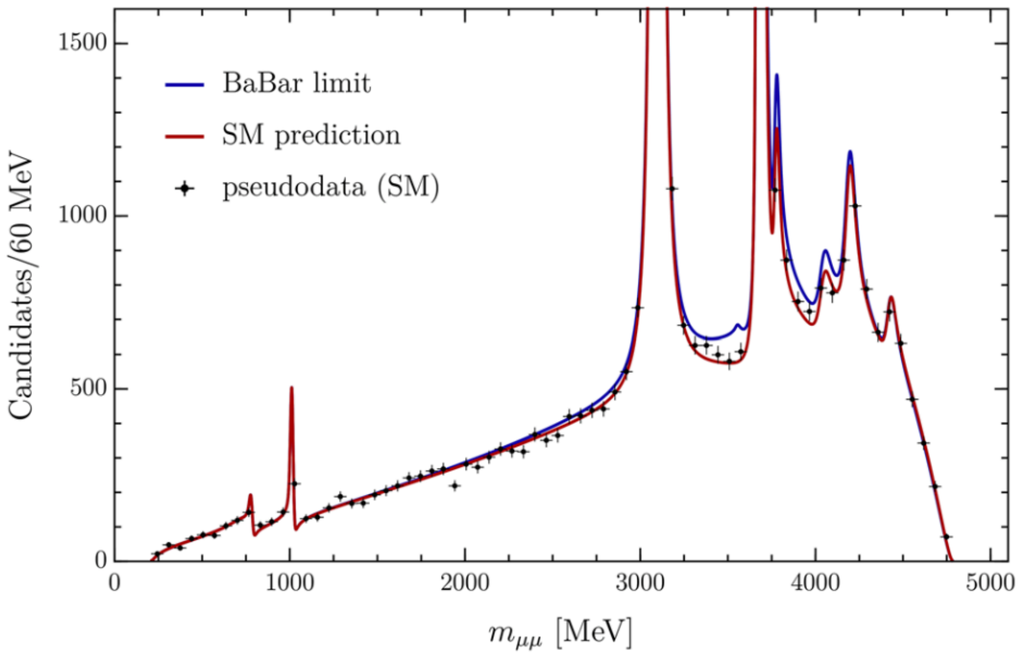


$B \to K^{(*)}\tau\tau \to K^{(*)}\mu\mu$ re-scattering

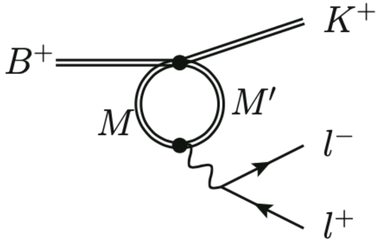


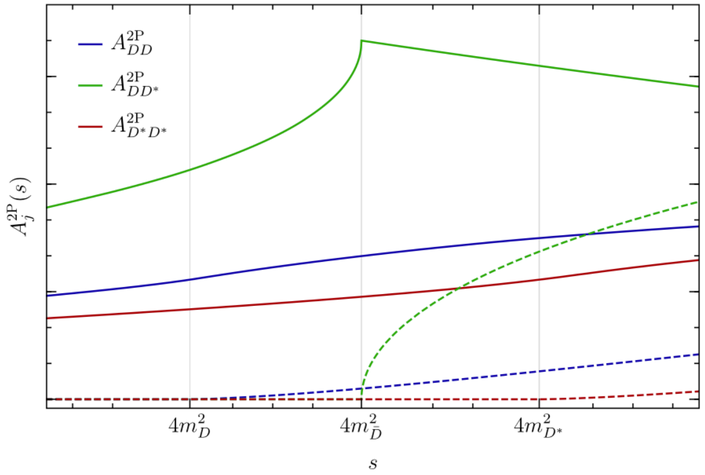
- Indirect limit to $B \to K\tau\tau$ from the precise study of the $B \to K\mu\mu$ di-μ mass spectrum
  - cusp in-between the J/ψ and ψ(2S) resonances (2xm_τ)
  - distortion in the shape of the spectrum before the resonances

Cornella et al, EPJC 80 (2020) 1095



- Requires to experimentally distinguish the $b \to s\tau\tau$ amplitude from long distance hadronic contributions also with q2-dependence



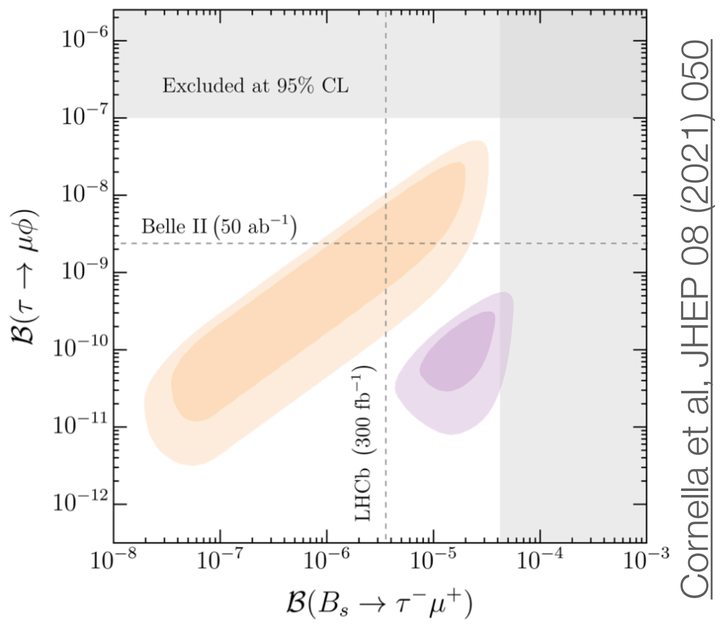


Scenario	$\mathcal{C}_9^\tau$ (90% CL)	$\mathcal{B}\,(\mathcal{C}_{10}^\tau = -\mathcal{C}_9^\tau)$	$\mathcal{B}\,(\mathcal{C}_{10}^\tau = 0)$
Run I–II dataset	533	2.7×10^{-3}	0.8×10^{-3}
Run I–V dataset	139	1.8×10^{-4}	0.5×10^{-4}

Competitive with current direct searches

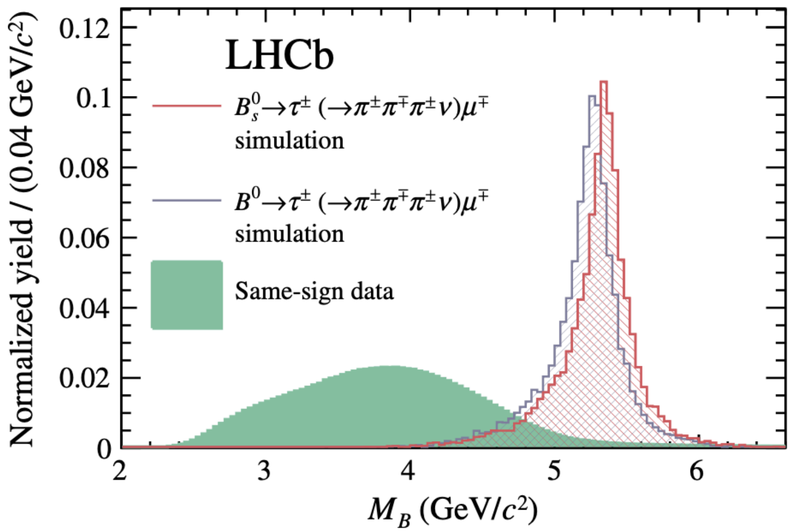
LFV decays: $b \to s\tau\mu$

- Without NC LFU anomalies, enhancement in $b \to s\tau\mu$ not as favoured?
  - Tiny in the SM (neutrino oscillation), null test of SM
- Experimentally look for $B_s \to \tau\mu$, $B \to K\tau\mu$, etc
  - With only one τ things get a bit easier:
    - Reconstruct full kinematics for the hadronic decay (up to ambiguities)
    - Use additional constraints from beam energy (B-factories) or $B^*_{2s} \to BK$ (LHCb)



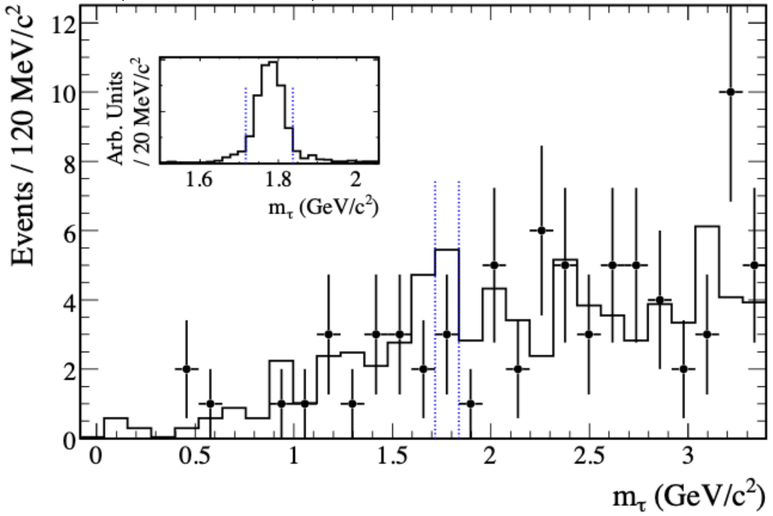
Cornella et al, JHEP 08 (2021) 050

$Br(B_s \to \tau\mu) < 3.4 \times 10^{-5}$ @90% CL



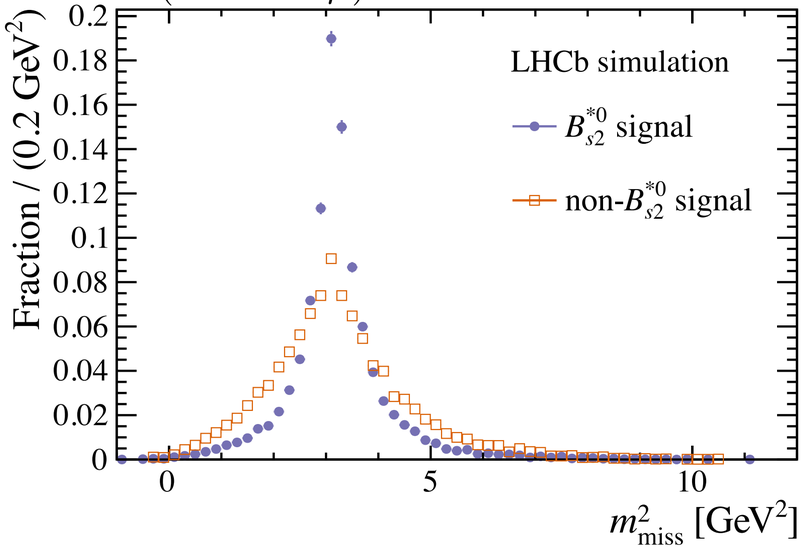
LHCb, PRL 123 (2019) 211801

$Br(B \to K\tau\mu) < 2.8 \times 10^{-5}$ @90% CL



BaBar, PRD 86 (2012) 012004

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



LHCb, JHEP 06 (2020) 129

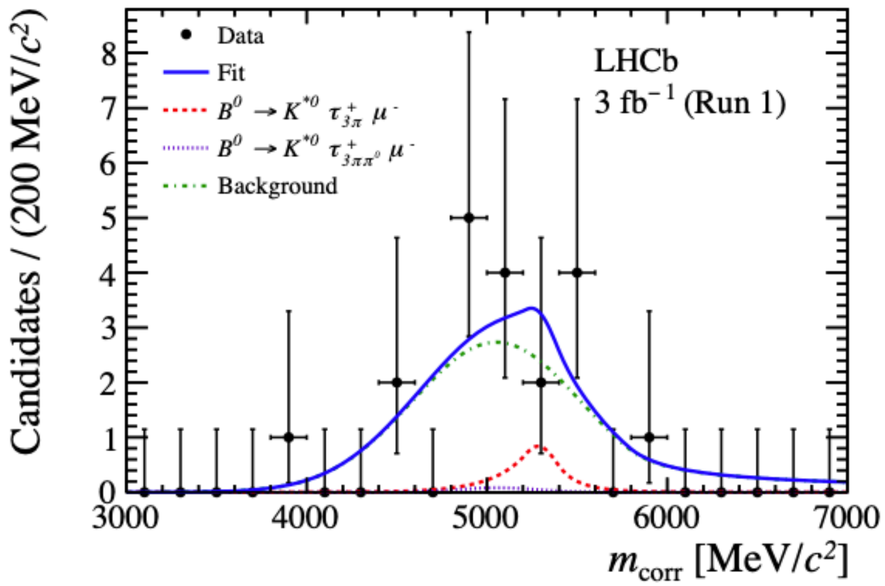
New limit on $B \to K^* \tau\mu$

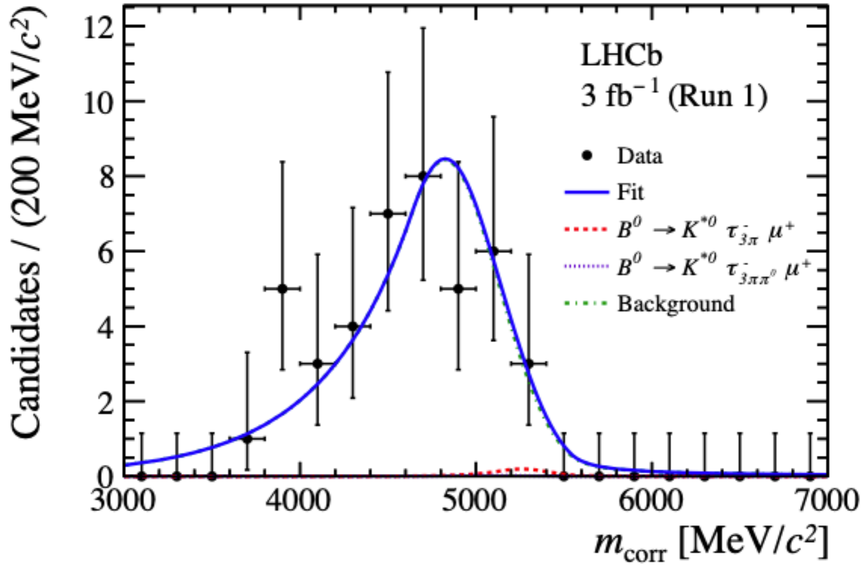
- Using full Run1+Run2 dataset & hadronic τ's
  - Separate $\tau^+\mu^-$ from $\tau^-\mu^+$, due to different mix of backgrounds
  - Fit the corrected mass: $m_{\text{corr}} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$
- Best experimental limit in $b \to s\tau\mu$

$$Br(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5} \quad @90\% \ \text{CL}$$
$$Br(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6} \quad @90\% \ \text{CL}$$

- For similar performances, can expect limits around 10^{-7} for the end of LHCb Upgrade II
- At Belle II, expect limits around 10^{-6} with 50/ab [naive extrapolation of BaBar result]

LHCb-PAPER-2022-021

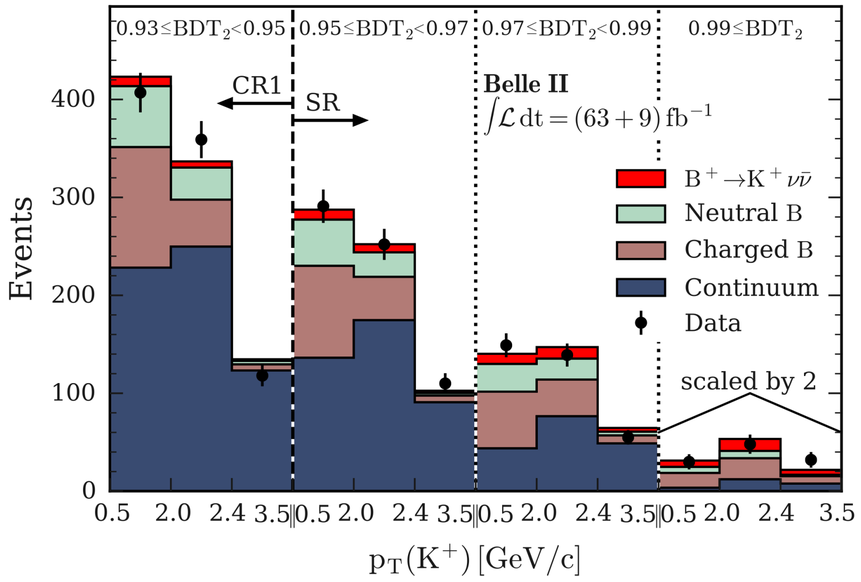


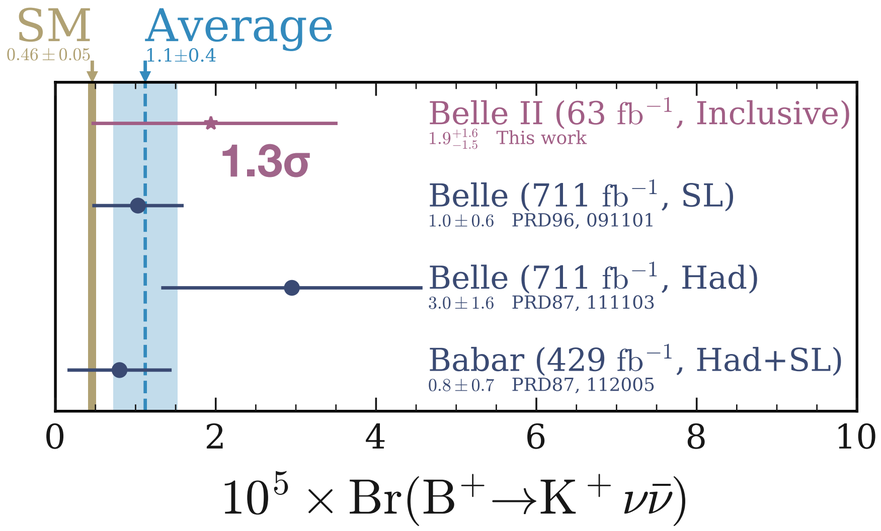


$b \to s\nu_\tau\nu_\tau$: Search for $B^+ \to K^+\nu\bar{\nu}$

- One of the most important constraints for all these models comes from limits to $B \to K\nu\nu$
  - Very challenging experimentally, Belle II territory
- First encouraging limit with a fraction of the new Belle II data, and observation at the SM (if not earlier!) expected with 5/ab for both $B \to K^{(*)}\tau\tau$

[Belle II, PRL 127 (2021) 181802]





Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$	$< 19 \times 10^{-6}$	30%	11%

Belle II, PTEP(2019)123C01

Conclusions

- A lot to explore in τ final states
  - If LFU in CC stays with us, expect significant enhancement in $b \to s\tau\tau$
  - They are challenging, that's why progress is slower
- Experiments are putting effort into these analyses
  - Using LFV decays to pave the way to the di-τ analyses
  - Exploring new techniques for τ reconstruction, and more favourable final states
- Expect new results not too far in the future!

Backup

What about $b \to s\tau e$?

- Would this also be expected if electrons have NP couplings too?
- Best experimental limit comes from BaBar
  - Belle II: sure
  - LHCb: Once you have missing energy carried away by the neutrinos, mass resolution is no longer that different between e and μ, OK!
- Similar scaling as in previous slide would take us to:
  - 10^{-6} with 50/ab from Belle II
  - 10^{-7} with LHCb Upgrade II

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Mode	τ channel	$N_{sb,i}$	$R_{b,i}$	b_i	n_i	$\epsilon_{h\tau\ell,i}$	$\mathcal{B}(B \to h\tau\ell)$ $(\times 10^{-5})$ central value	90% C.L. UL
$B^+ \to K^+\tau^-\mu^+$	e	22	0.02 ± 0.01	0.4 ± 0.2	2	$(2.6 \pm 0.2)\%$	$0.8\ ^{+1.9}_{-1.4}$	< 4.5
	μ	4	0.08 ± 0.05	0.3 ± 0.2	0	$(3.2 \pm 0.4)\%$		
	π	39	0.045 ± 0.020	1.8 ± 0.8	1	$(4.1 \pm 0.4)\%$		
$B^+ \to K^+\tau^+\mu^-$	e	5	0.03 ± 0.01	0.2 ± 0.1	0	$(3.7 \pm 0.3)\%$	$-0.4\ ^{+1.4}_{-0.9}$	< 2.8
	μ	3	0.06 ± 0.03	0.2 ± 0.1	0	$(3.6 \pm 0.7)\%$		
	π	153	0.045 ± 0.010	6.9 ± 1.5	11	$(9.1 \pm 0.5)\%$		
$B^+ \to K^+\tau^-e^+$	e	6	0.095 ± 0.020	0.6 ± 0.1	2	$(2.2 \pm 0.2)\%$	$0.2\ ^{+2.1}_{-1.0}$	< 4.3
	μ	4	0.025 ± 0.010	0.1 ± 0.1	0	$(2.7 \pm 0.6)\%$		
	π	33	0.045 ± 0.015	1.5 ± 0.5	1	$(4.8 \pm 0.6)\%$		
$B^+ \to K^+\tau^+e^-$	e	8	0.10 ± 0.06	0.8 ± 0.5	0	$(2.8 \pm 1.1)\%$	$-1.3\ ^{+1.5}_{-1.8}$	< 1.5
	μ	3	0.045 ± 0.020	0.1 ± 0.1	0	$(3.2 \pm 0.7)\%$		
	π	132	0.035 ± 0.010	4.6 ± 1.3	4	$(8.7 \pm 1.2)\%$		