$b \to s\tau\tau$: BSM model correlations and what we can learn from stronger bounds on the BRs.

Claudia Cornella and Sam Cunliffe

Beyond the flavour anomalies II, 20-22.04.2021

Corroborating measurements II

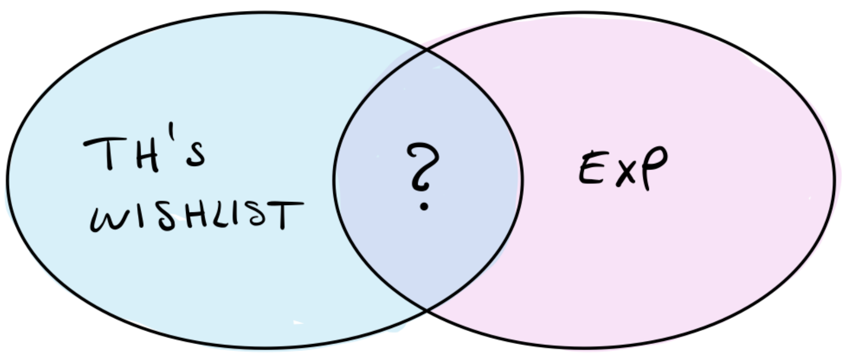
Claudia Cornella and Sam Cunliffe

Beyond the flavour anomalies II, 20-22.04.2021

Intro

We want to analyze possible measurements **complementary** to B anomalies:

- If B anomalies are NP signals, where else should we see something?
- What can Belle II and LHCb measure?



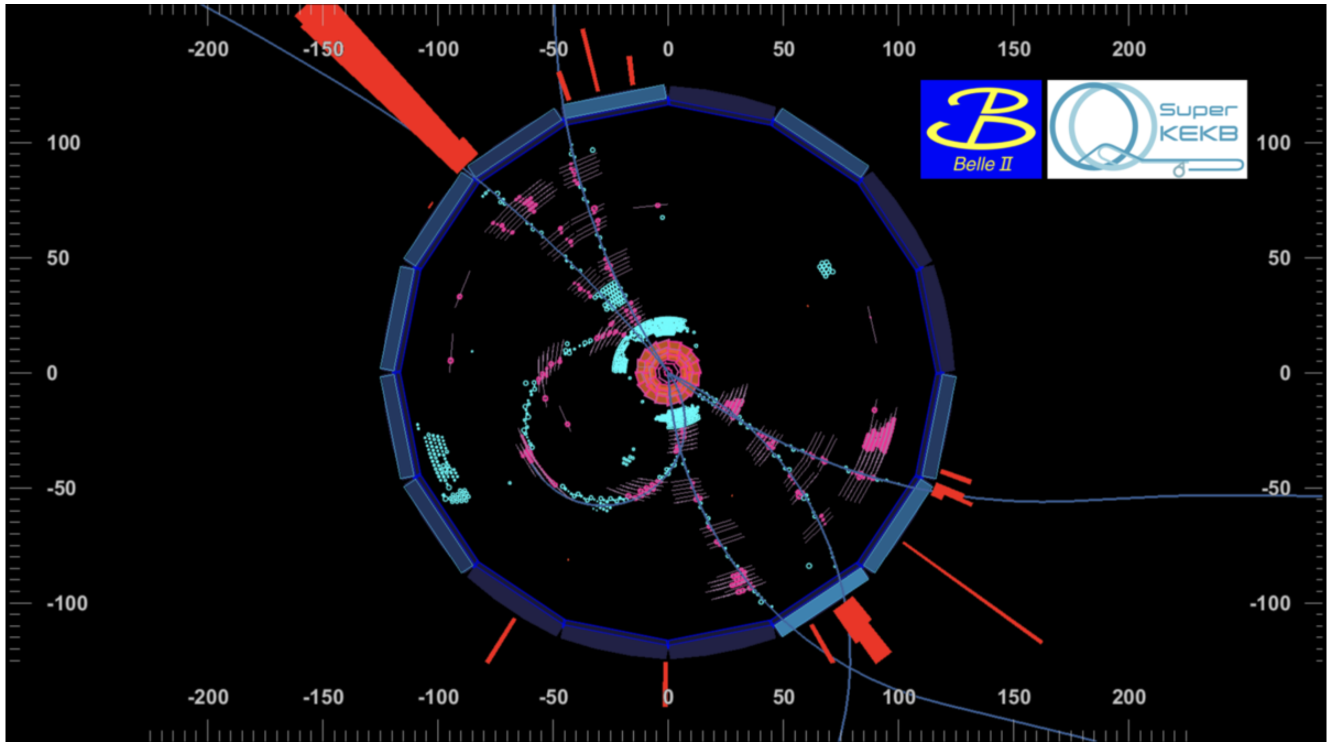
Disclaimer:

- The aficionados of the workshop *won't* find big news with respect to last year:

  LHCb update on R_K and $B_s \to \mu\mu$ consolidates the picture in $b \to sll$,

  but $R_{D^{(*)}}$ drives the size of most of the signatures considered here.

The experiments



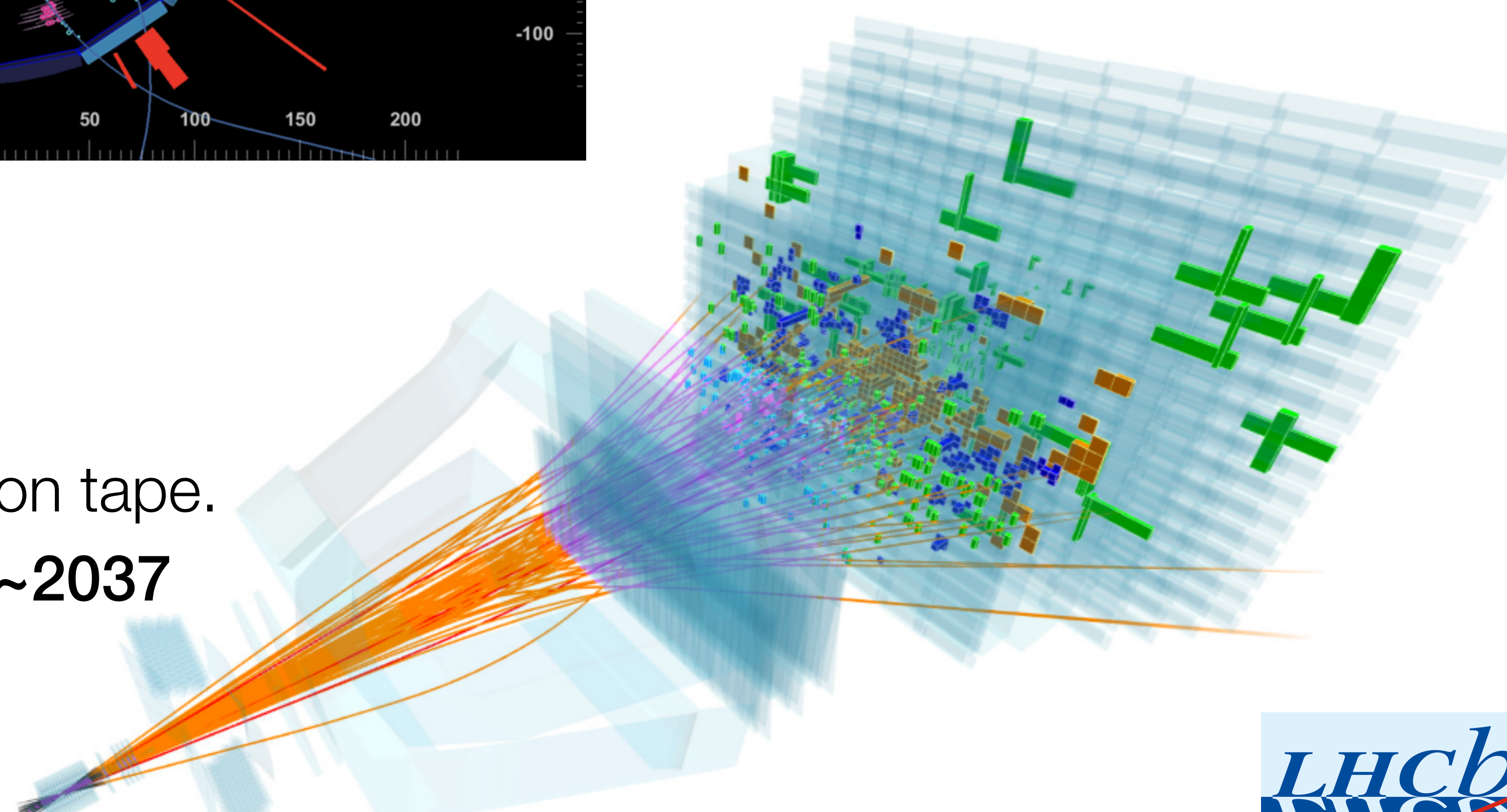
Belle II

Near term goal: **0.5–1 ab^{-1}** over the next two years.

5 ab^{-1} ~2024
50 ab^{-1} 2031

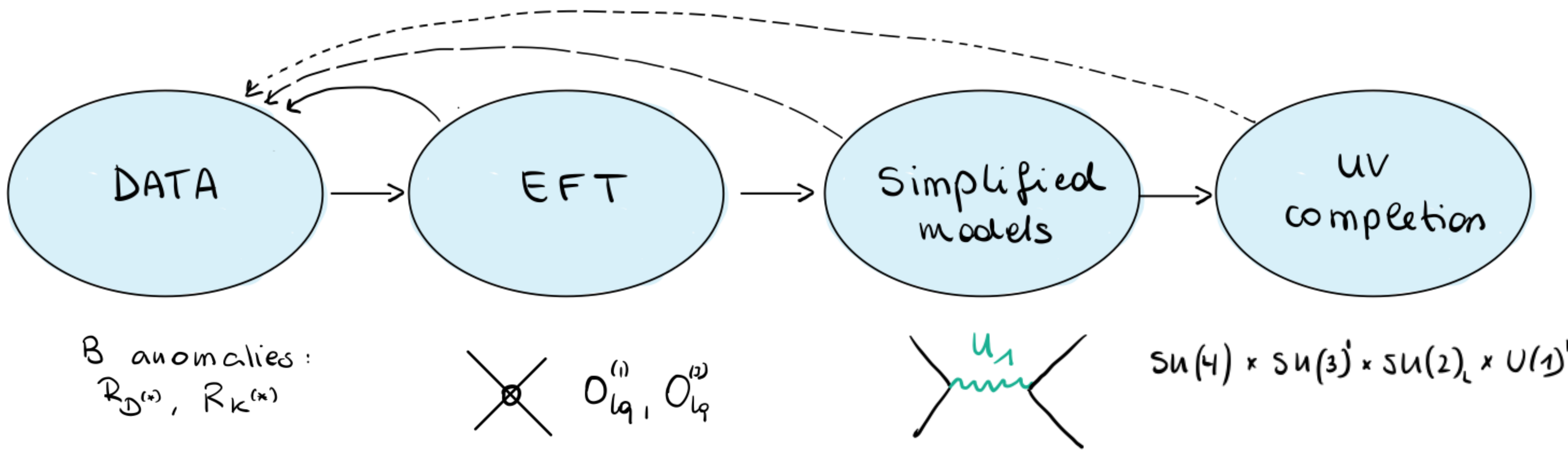
LHCb

3+6 fb^{-1} on tape.
300 fb^{-1} ~2037



The theory tools

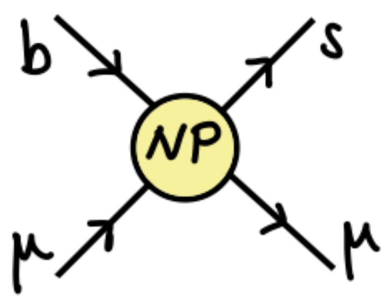
We work in a bottom-up approach:



- These steps are complementary, not unidirectional.
- At each step we can investigate connections with other observables.
- Strength of connections can vary a lot (more or less dependent on theory assumptions).

Where to go from $b \to s\mu\mu$?

Assume **there is NP in $\boldsymbol{b \to s\mu\mu}$** (and electrons are SM-like)



$$\mathcal{L}_{\rm NP} = \frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha}{4\pi} \left[\mathcal{C}_9 (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) + \mathcal{C}_{10} (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)\right]$$

$$\sim 10^{-5}\, G_F$$

We want to explore the **flavor structure** of this interaction:

…in quark space: $b \to d\mu\mu$ (almost) indifferent to $R_{D^{(*)}}$

…in lepton space: $b \to s\tau\tau$, $b \to s\nu\nu$, $b \to s\tau\mu$ expected NP effect depends **heavily** on whether we add $R_{D^{(*)}}$

$b \to d\mu\mu$

A priori, no "obvious" relation between NP in $b \to s$ and $b \to d$.

In NP models with a min. broken $U(2)_q$ symmetry (motivated by $\Delta F = 2$) , $b \to s$ and $b \to d$ are connected:

$$\frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\mathrm{SM}} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx 10^{-2}$$

(modulo phase space)

$B \to \pi\mu\mu$

$B_d \to \mu\mu$

We can **test LFU** in $b \to d$ via

$$R_\pi[q^2_{\min}, q^2_{\max}] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\mathcal{B}}{dq^2}(B^+ \to \pi^+\mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\mathcal{B}}{dq^2}(B^+ \to \pi^+e^+e^-)} \overset{U(2)}{\approx} R_K^{(*)}$$

✓ It's **clean**: pollution from long distance effects < 10% in large q^2 regions

[Bordone, CC, König, Isidori, 2101.11626]

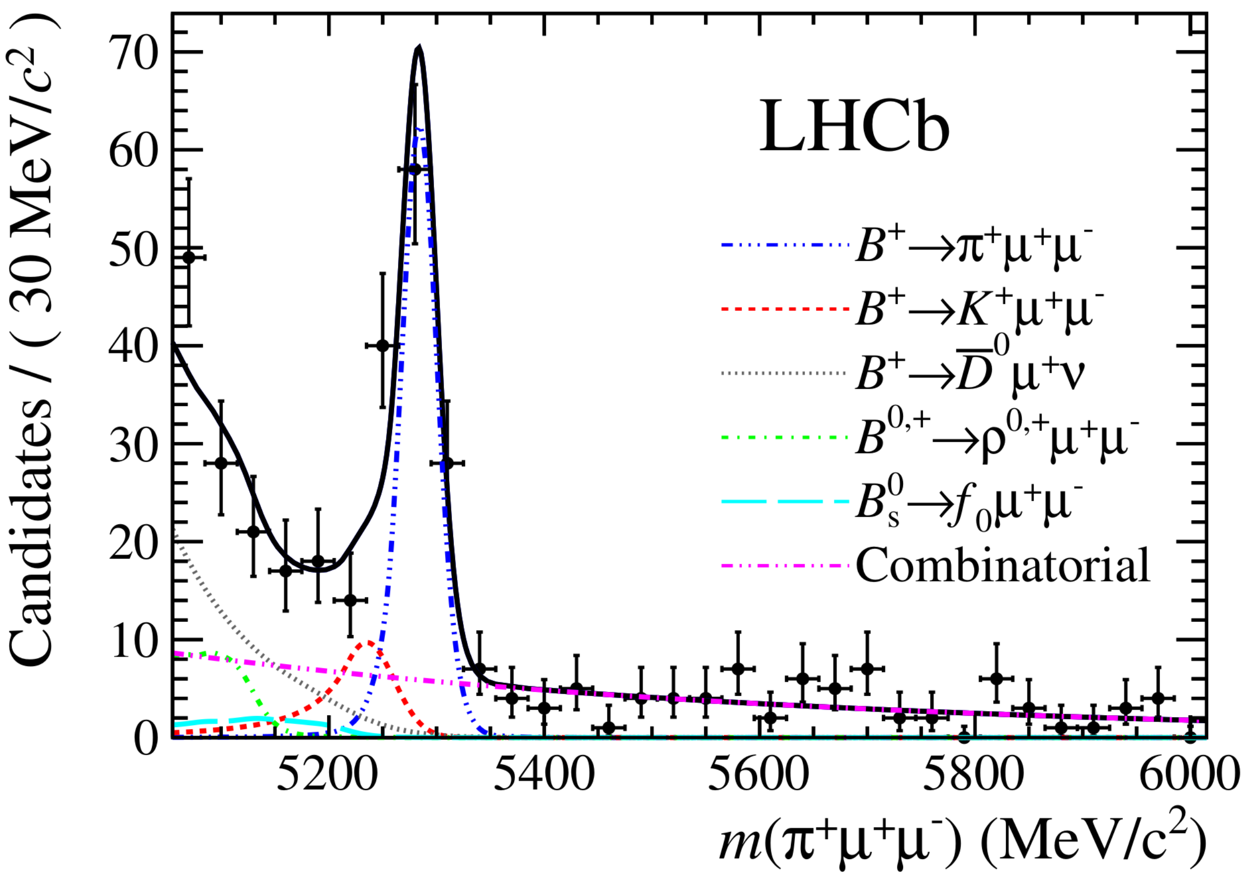
Experimental $b \to d\mu\mu$

A beautiful peak
(but now 6 years old)

Aside from the updated $B_d \to \mu\mu$
(let's not forget this excellent work)

LHCb: $B \to \pi\mu\mu$
[LHCb, JHEP10(2015)034]

According to the upgrade note, LHCb needs 300 fb^{-1} to be able to form R_π



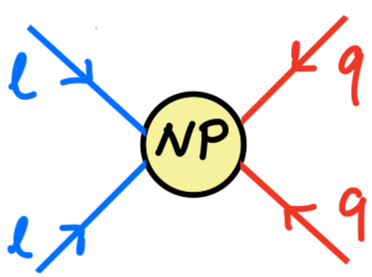
Sam's rough and unofficial number puts Belle II at ~300 $B \to \pi\ell\ell$ events in 50 ab^{-1}… looks like we could measure that ratio too…

Explaining both sets of anomalies: a recap

B anomalies fit nicely together in the **SMEFT.** [see talk by Peter and Quim]

Minimal setup
(NP coupled to LH fields only)

$$\mathscr{L} = \frac{C_{\ell q}^{(3)}}{\Lambda^2}(\bar{\ell}\gamma^\mu \tau^a \ell)(\bar{q}\gamma^\mu \tau^a q) + \frac{C_{\ell q}^{(1)}}{\Lambda^2}(\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma^\mu q)$$



- ✓ $C_9^\mu = - C_{10}^\mu$
- ✓ V_L solution to $b \to c\tau\nu$
- ✓ ΔC_9^U via RGE mixing

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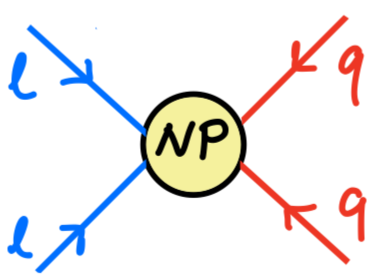

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- ✓ ΔC_9^U via RGE mixing

scalar/tensor contributions also possible
(NP coupled also to RH fermions)

$$+\frac{C_{\ell edq}}{\Lambda^2}(\bar{\ell}d)(\bar{e}q) \quad \text{or}$$

$$+\frac{C_{\ell equ}^{(1)}}{\Lambda^2}(\bar{\ell}e)\sigma_2(\bar{q}u) + \frac{C_{\ell equ}^{(3)}}{\Lambda^2}(\bar{\ell}\sigma_{\mu\nu}e)\sigma_2(\bar{q}\sigma^{\mu\nu}u)$$

- ✓ $V_L + S_R\,/\,S_L, T$ solution to $b \to c\tau\nu$

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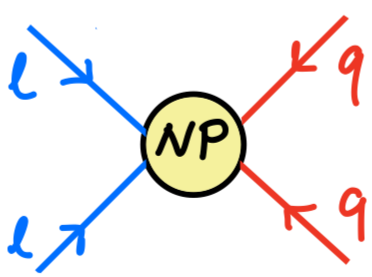

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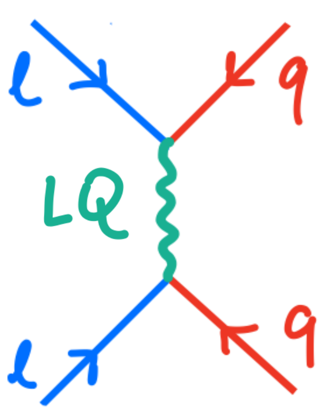


Leptoquarks are the best candidates
(no 4-lepton and 4-quark processes at tree level)

[far too many papers to be cited]

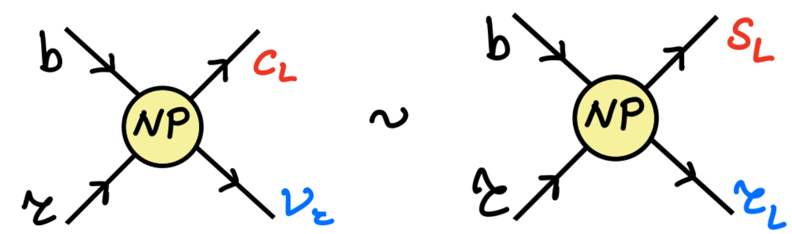
Three possibilities: $U_1 \qquad S_1 + S_3 \qquad (S_3 + R_2)$

[(*)Exception: R2 + S3]

$b \to s\tau\tau$

- With the NC anomaly only there's no reason to expect sizable NP in $b \to s\tau\tau$.
- If we add $R_{D^{(*)}}$, $b \to s\tau\tau$ has(*) to be large: [see e.g. Crivellin et al. 1703.09226]

$\ell_L^3 = \begin{bmatrix} \nu_\tau \\ \tau_L \end{bmatrix} \quad q_L^2 = \begin{bmatrix} c_L \\ s_L \end{bmatrix} \quad \overset{SU(2)_L \text{ invariance}}{\Longrightarrow}$



$\Rightarrow B \to K\tau\tau$ and $B_s \to \tau\tau$ enhanced over the SM.

How much?

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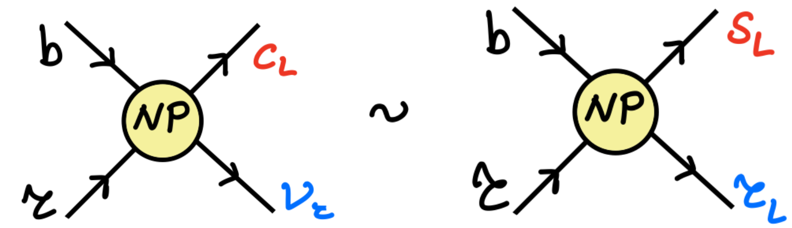
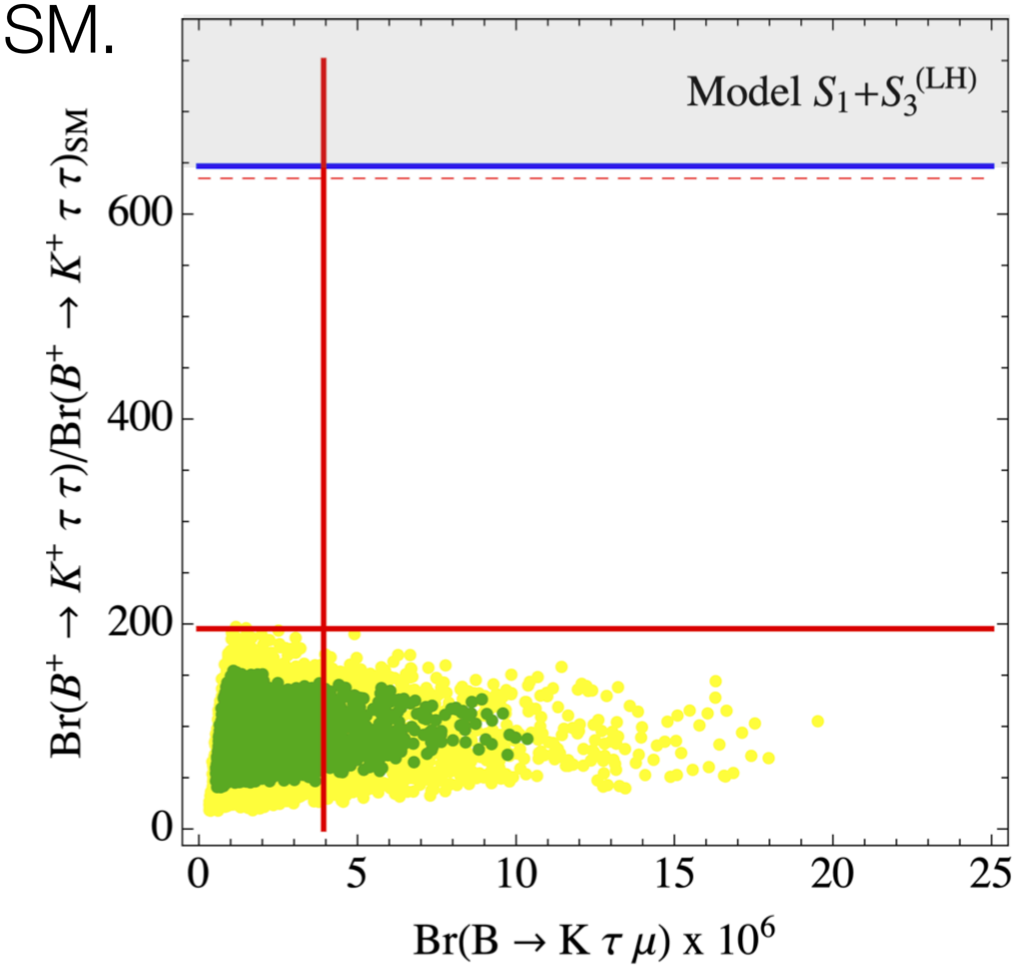


$\Rightarrow B \to K\tau\tau$ and $B_s \to \tau\tau$ enhanced over the SM.

How much?

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



[Gherardi, Marzocca, Venturini 2008.09548]

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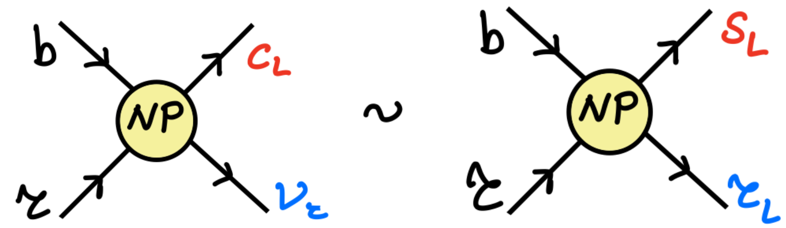

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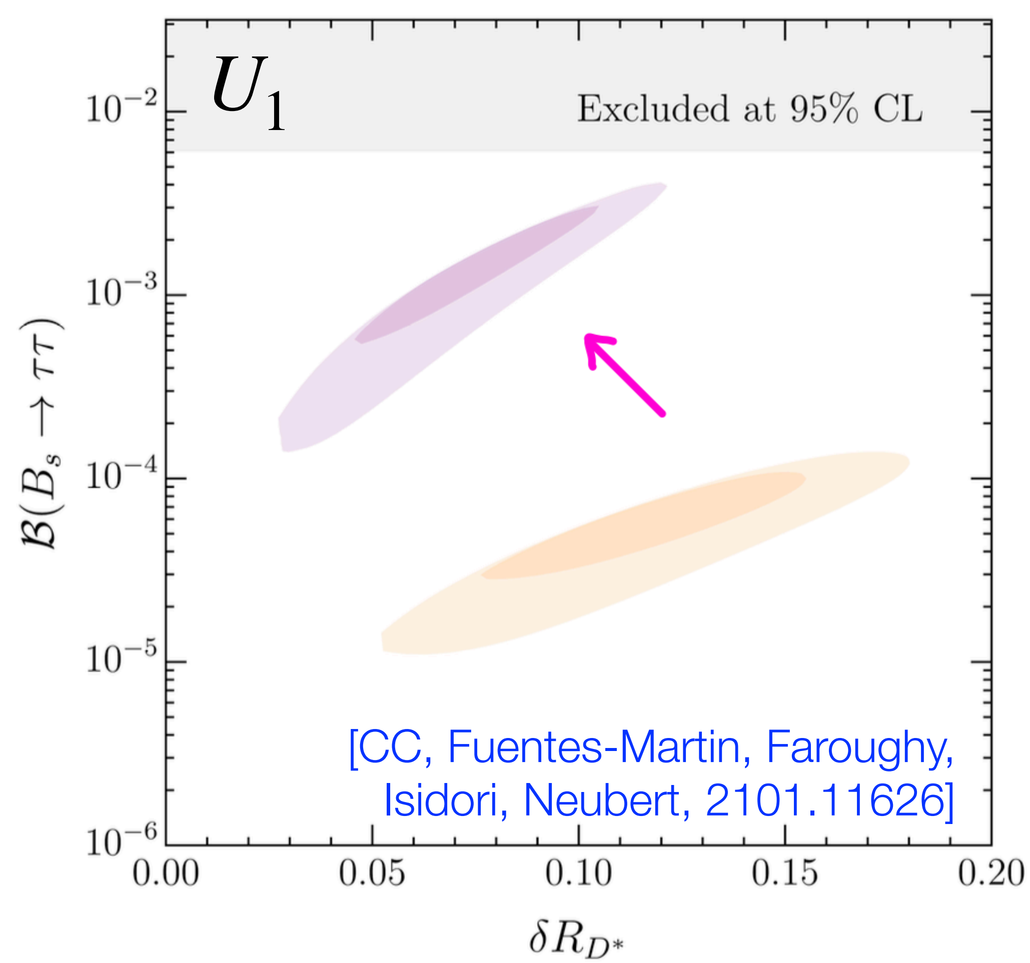
$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)_{\rm SM}} \approx \frac{\mathcal{B}(B \to K\tau\tau)}{\mathcal{B}(B \to K\tau\tau)_{\rm SM}} \approx 1 - 2 \times 10^3$$

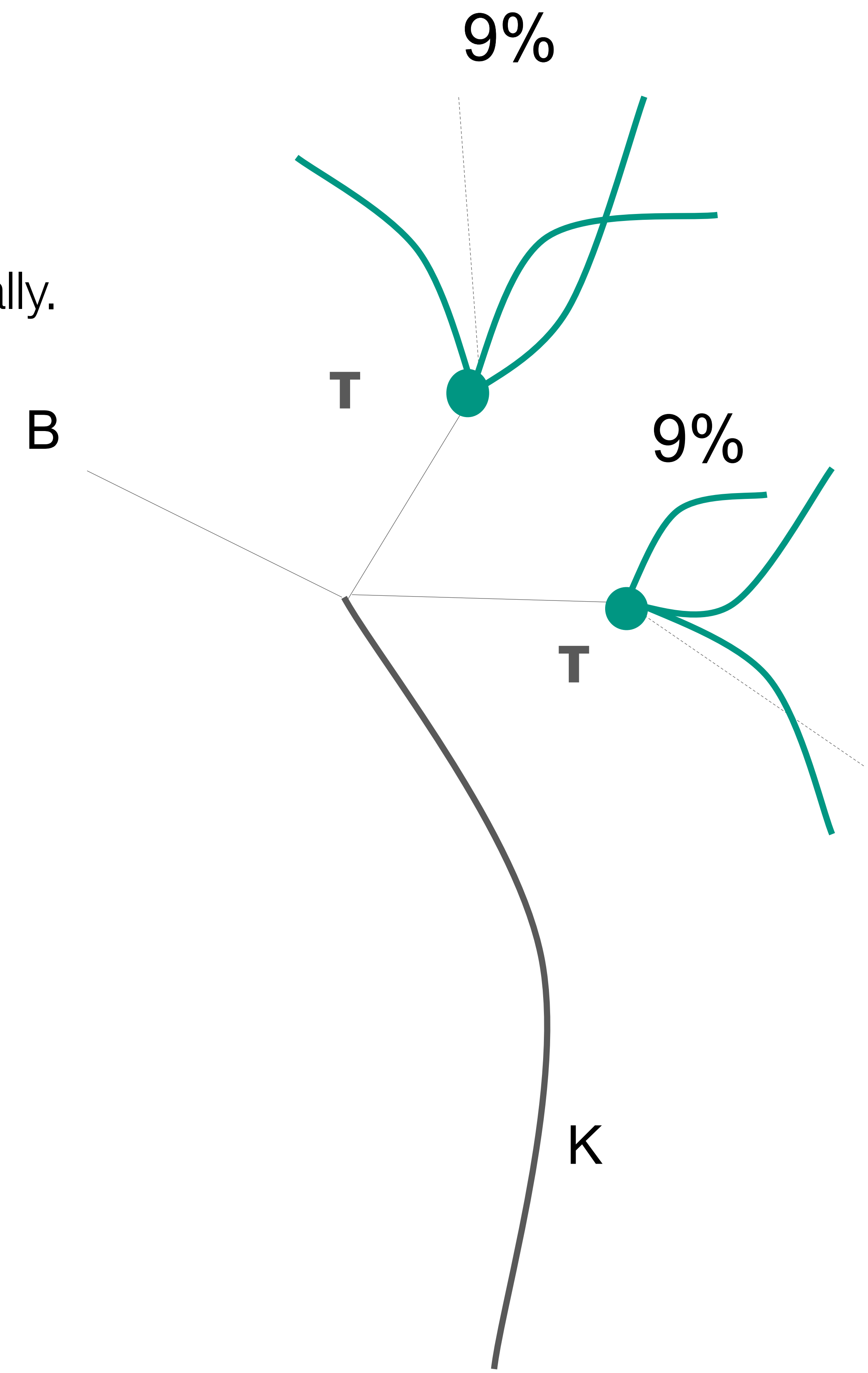


Why are ditaus limits so weak?

Di taus from a B decay: not trivial experimentally.
For either of us.

- LHCb : two neutrinos.

- Experimentally preferred the 3-prong-3-prong topology: take a hit from tau branching fraction.



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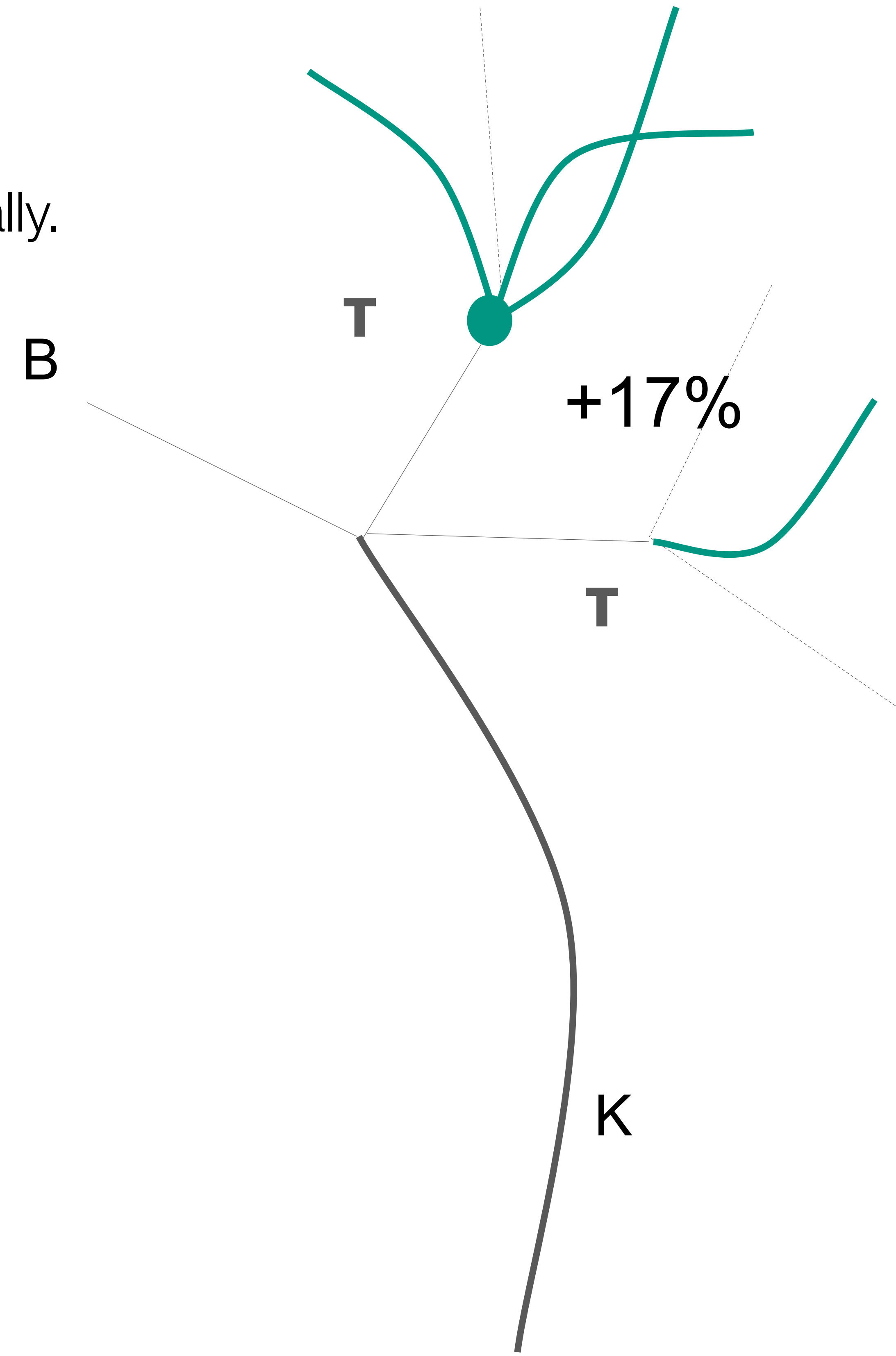

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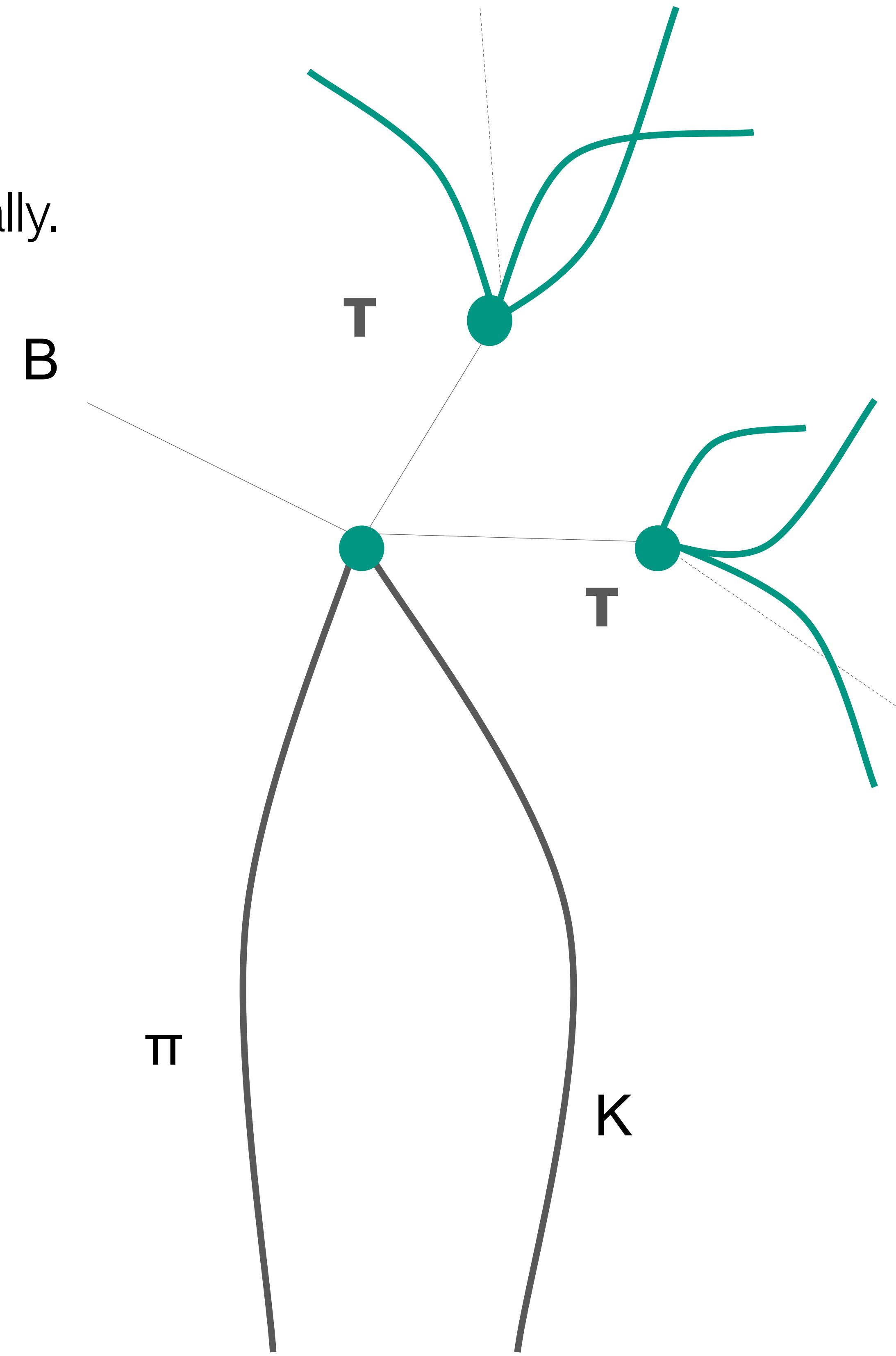
The K^* can help by providing the B decay vertex at the cost of an extra track and $K^* \to K\pi$.



Experimental $B \to K\tau\tau$

Experimentalists have noticed your papers!

- Enthusiasm in Belle II given predicted enhancements.
- Rumors from LHCb too? Yes, Kostas we were listening to the R_K seminar.
- Nothing is ready yet. You have to imagine behind-the-scenes fun.

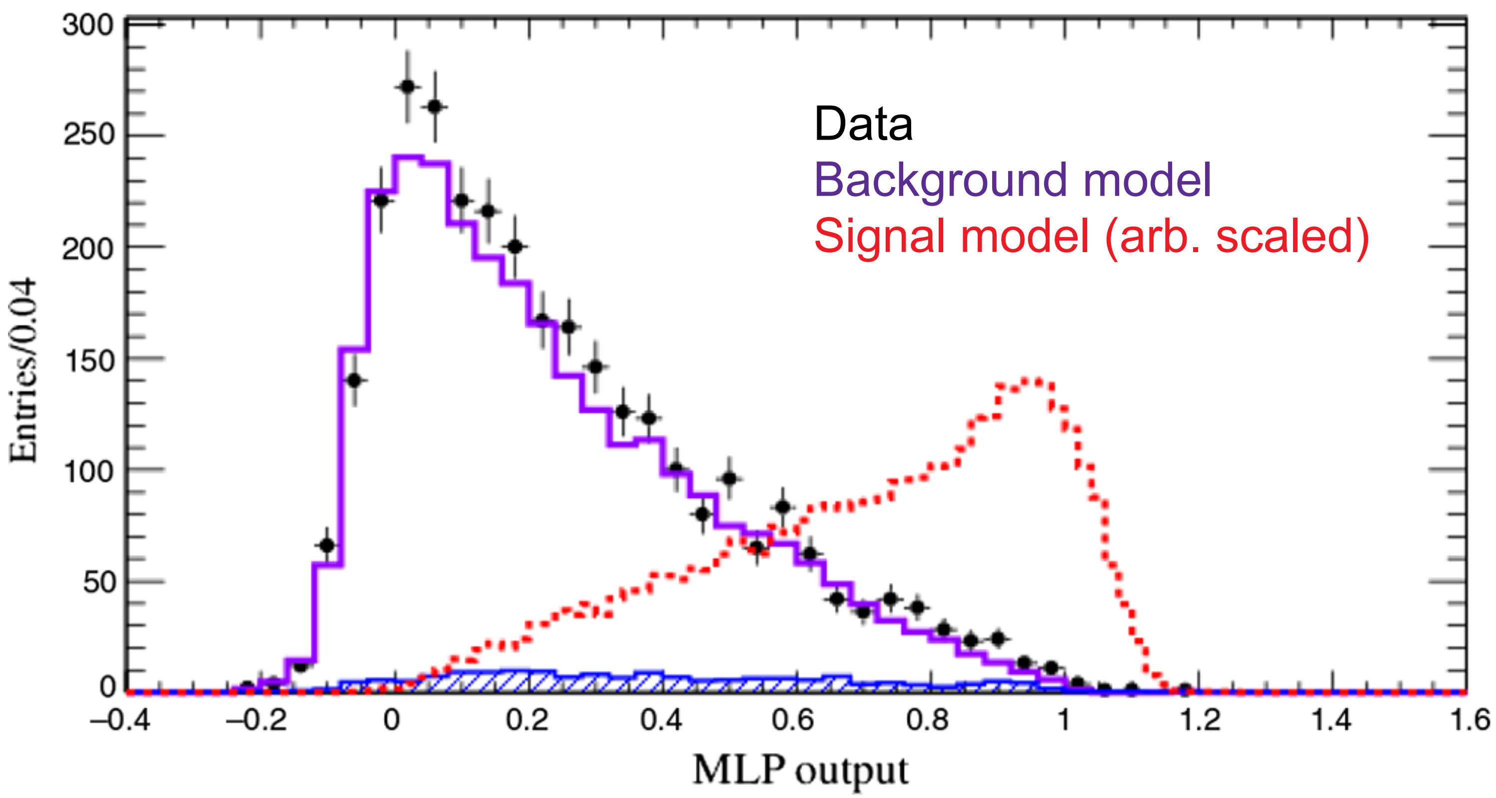
Only BaBar has published: $\mathscr{B}(B \to K\tau\tau) < 2 \times 10^{-3}$

[Babar, PRL.118.031802]

$\varepsilon_{\text{tag}} \sim 0.1\,\%$

Belle II can soon reach 10^{-4} (ab⁻¹).

[Belle II, PTEP(2019)123C01]



Experimental $B_s \to \tau\tau$

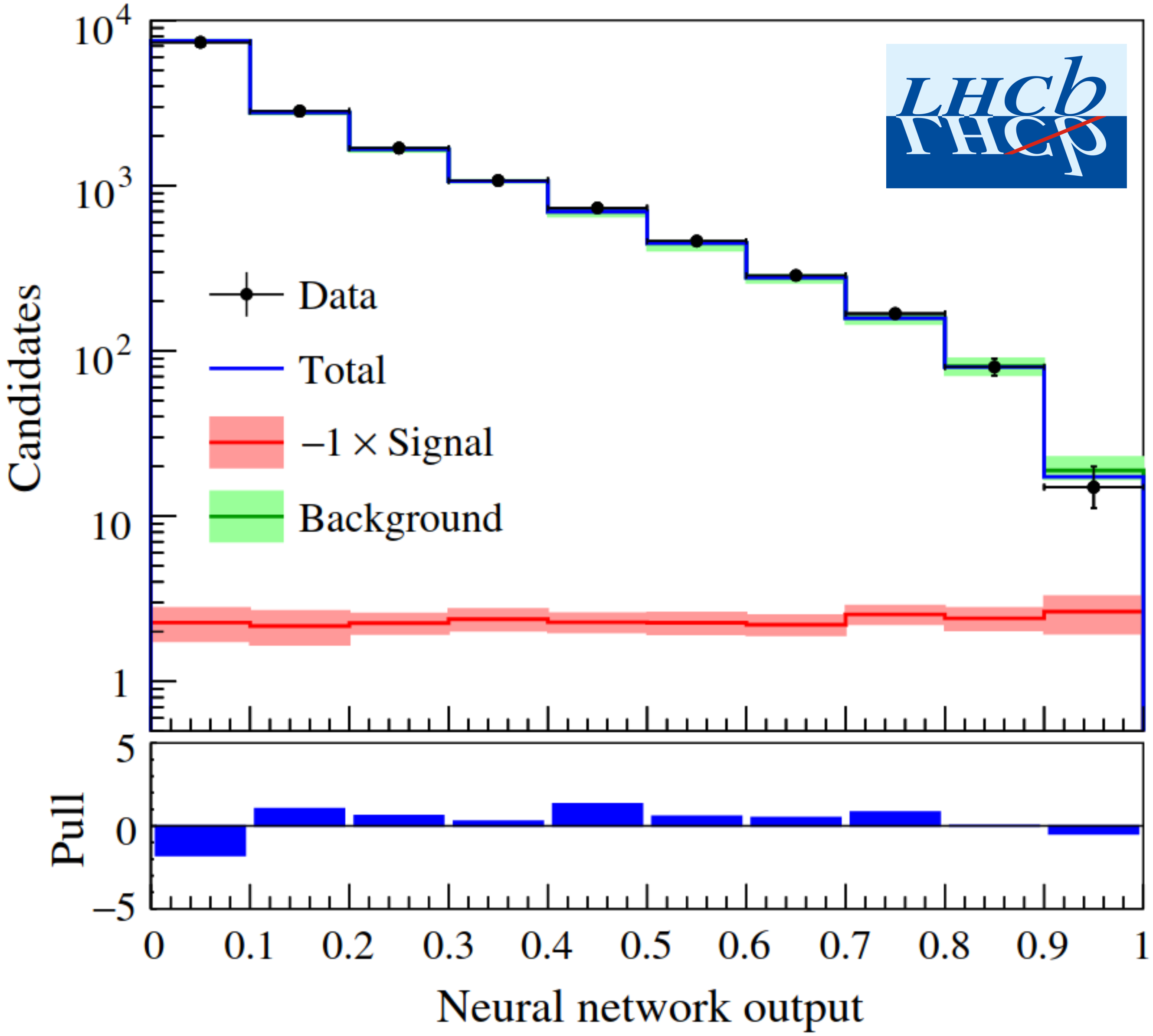
Belle II for sure plans a run at $\Upsilon(5S)$. But this will not happen soon. No Belle II B_s's for some time. Belle II: ~10^{-4} w/ 5 ab^{-1}.

LHCb rules the game.
[LHCb, PRL.118.251802]

$$\mathscr{B}(B_s \to \tau\tau) < 7 \times 10^{-3}$$

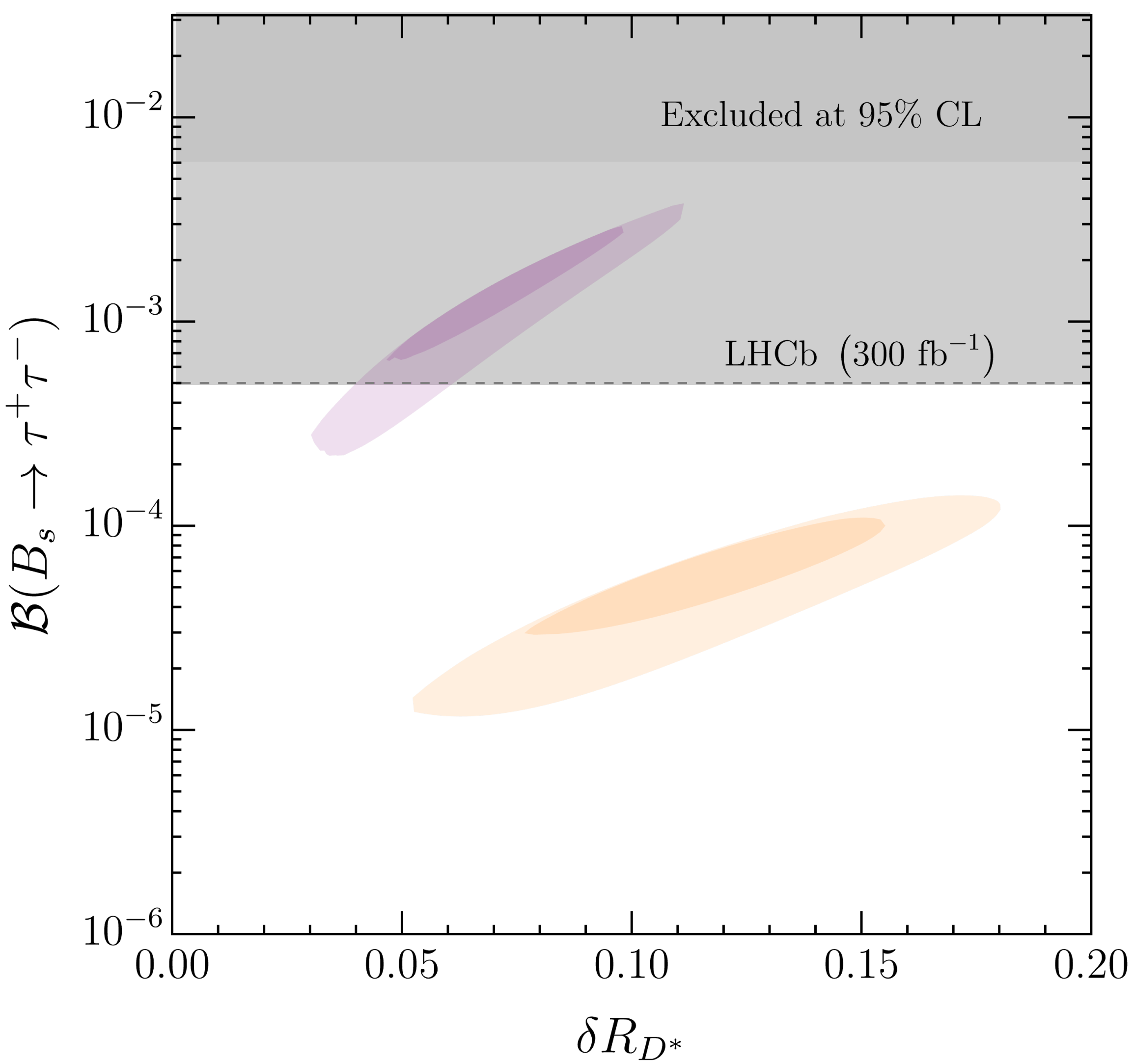
via 3prong-3prong (so they have the di-vertex) but that means the τ branching fraction also gives a hit.

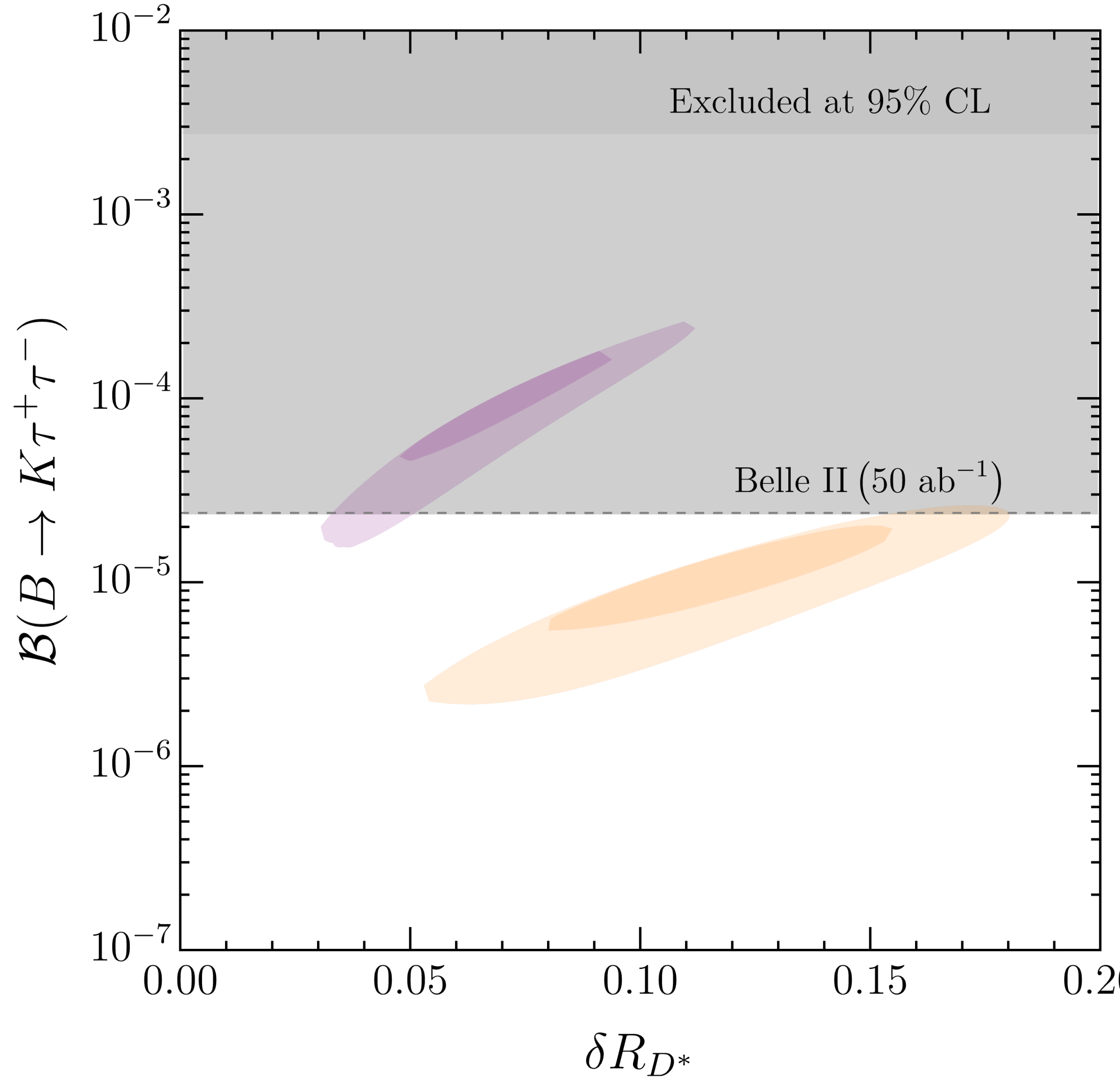
+ the other 6 fb^{-1} ?
Pretty please.



$b \to s\tau\tau$: low-energy projections for the U_1

LHCb (300 fb^{-1}) and Belle II (50 fb^{-1}) will almost exclude the U_1 (LH + RH) (or see one!), U_1 (LH) will be still alive and kicking!



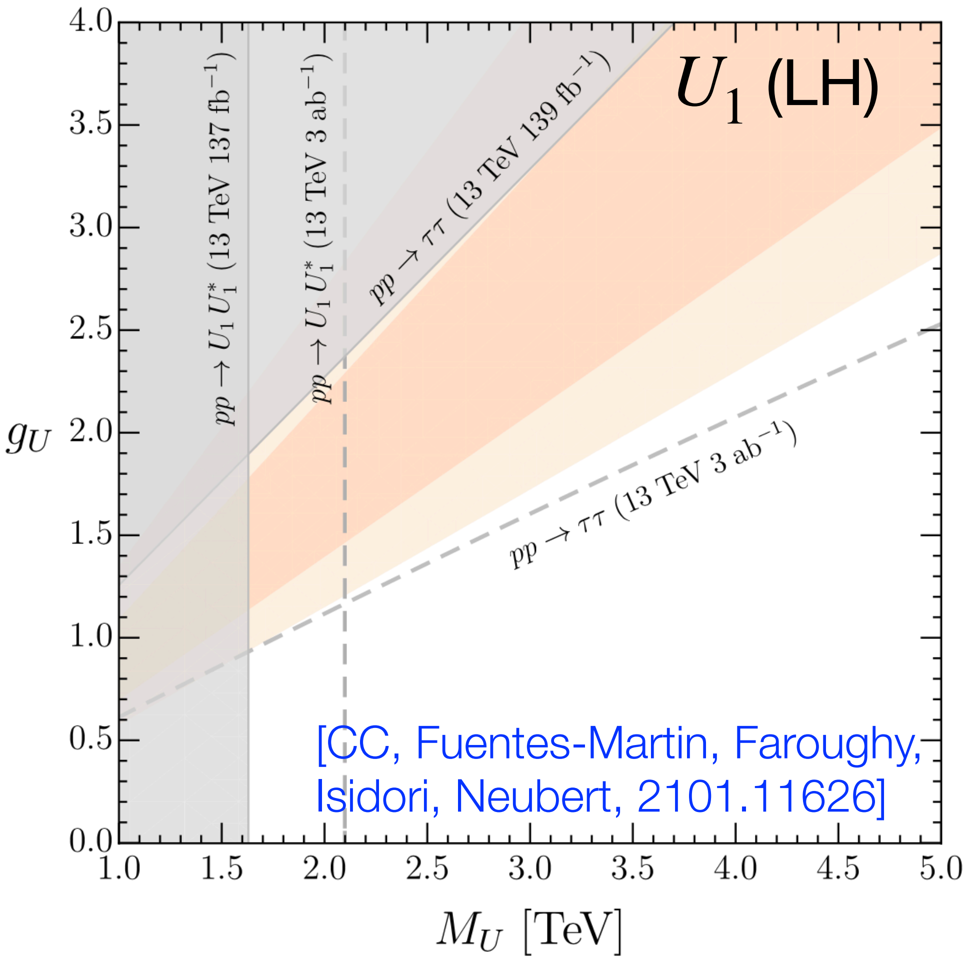


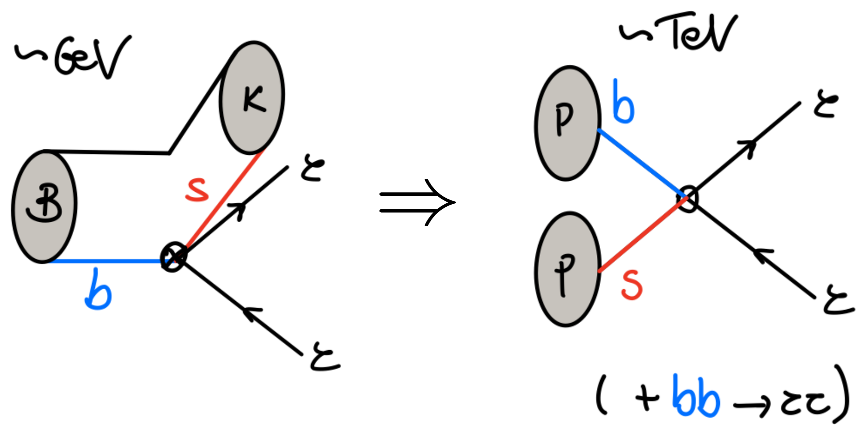
[CC, Fuentes-Martin, Faroughy, Isidori, Neubert, 2101.11626]

High-pT bounds from $pp \to \tau\tau$

The same interaction can be probed in **di-tau tails** at the LHC. Generally **stronger** than low-E bounds!

[Faroughy, Greljio, Kamenik, 1609.07138; Fuentes-Martin et al. 2003.12421]





- U_1 solution is completely falsifiable at HL-LHC (or we will find a U_1!)
- same for $R_2 + S_3$,
- still space left for $S_1 + S_3$

Two more remarks:

Models for $R_D^{(*)}$ only yield similar enhancements in $B \to K\tau\tau$,$B_s \to \tau\tau$ and $pp \to \tau\tau$.

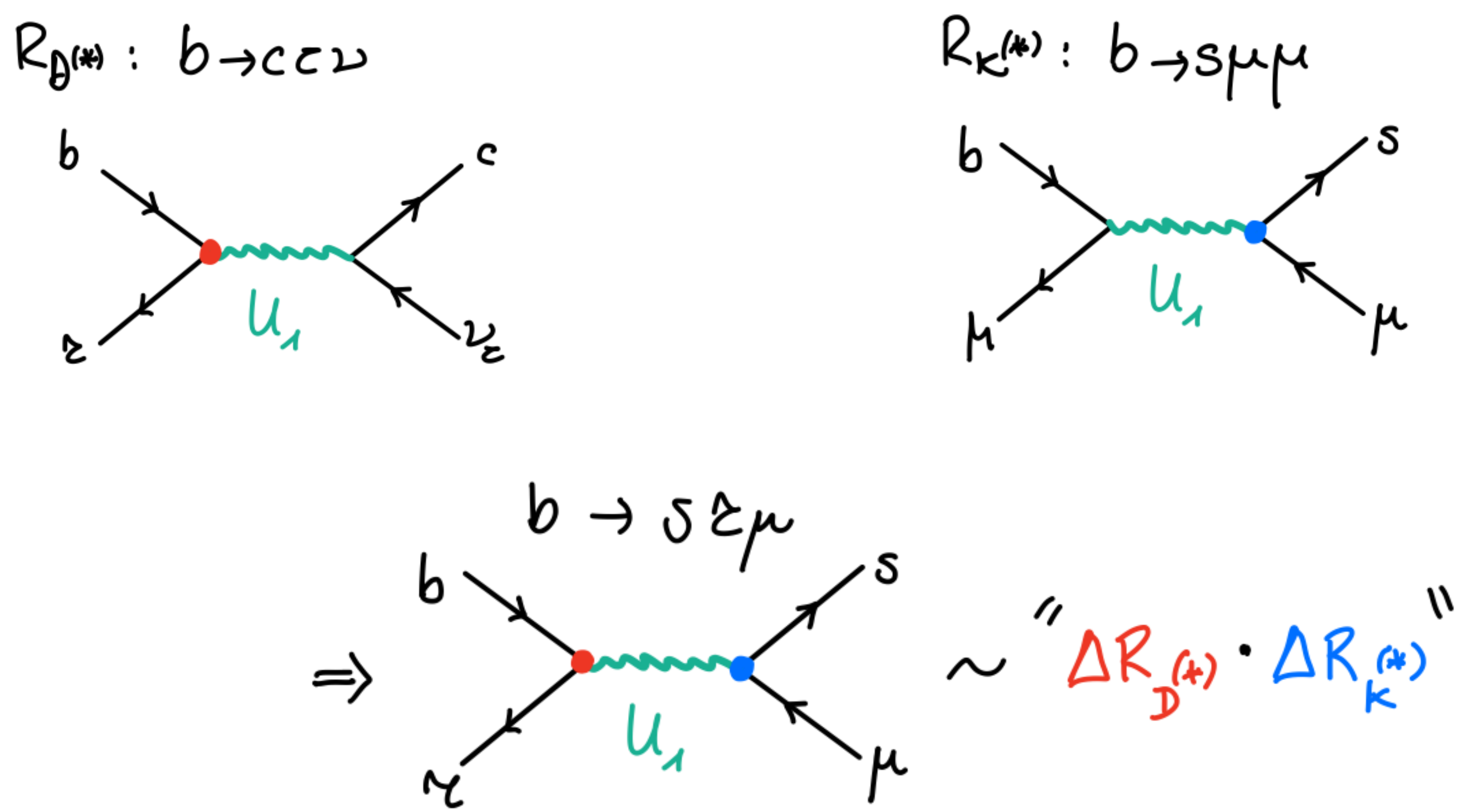
Any change in $R_D^{(*)}$ will alter these conclusions significantly.

Lepton Flavour Violation in $b \to s\tau\mu$ and τ decays

large τ/μ LFV

$b \to s\tau\mu$ ($B_s \to \tau\mu$, $B \to K\tau\mu$) $\leftrightarrow$ **both** CC and NC anomalies are there

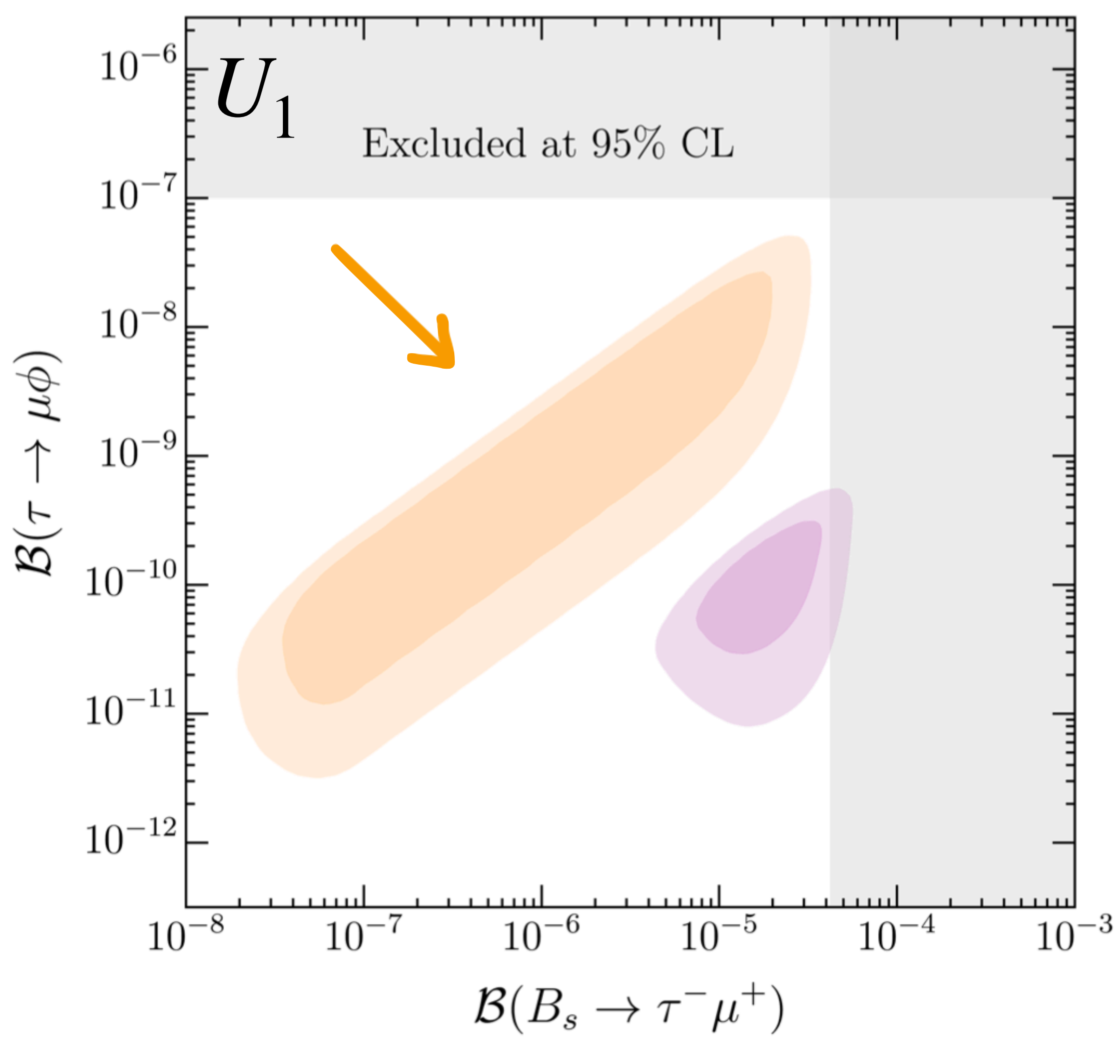
τ decays ($\tau \to \mu\phi, \tau \to \mu\gamma$)



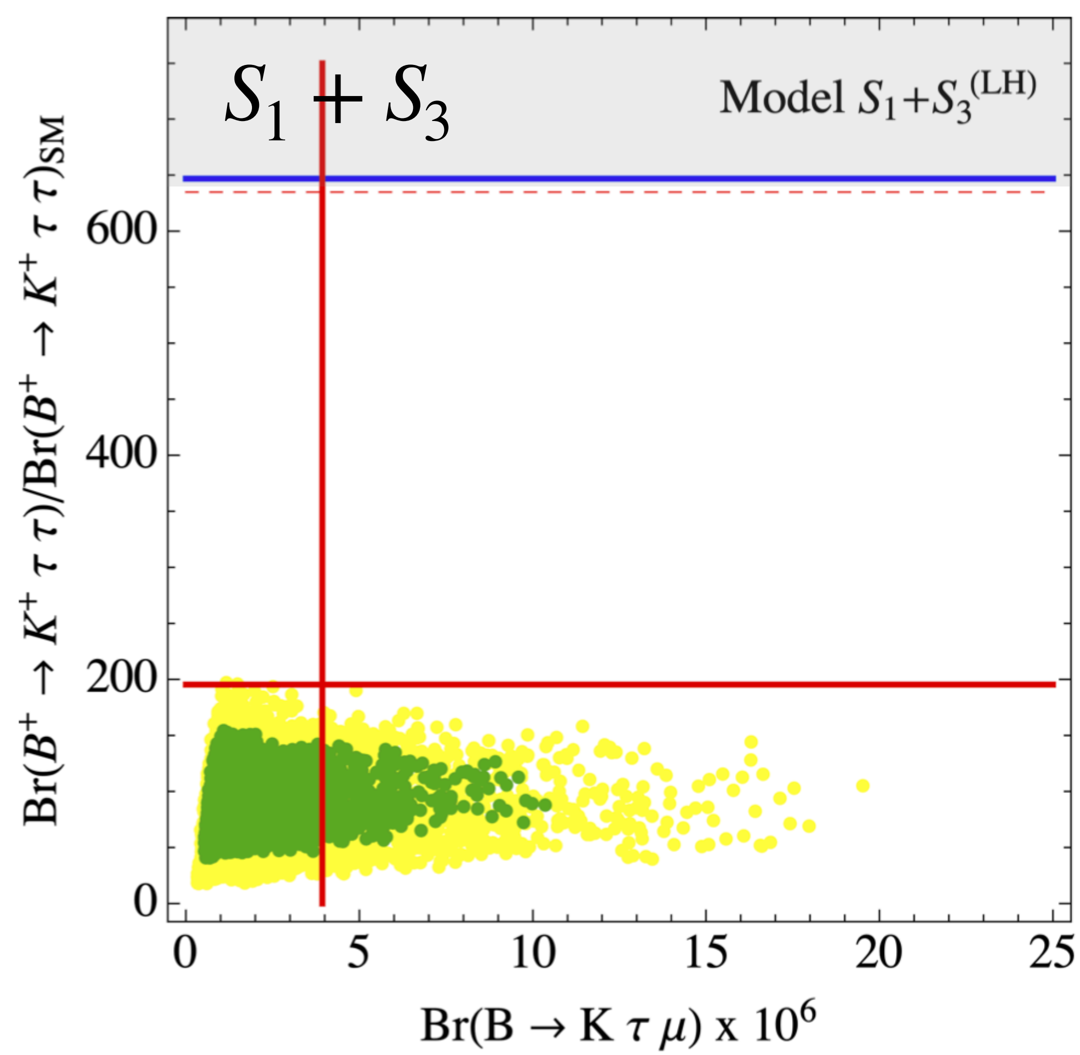
Lepton Flavour Violation in $b \to s\tau\mu$ and τ decays

$$\mathcal{B}(B_s \to \tau\mu) \approx \mathcal{B}(B \to K\tau\mu) \approx 10^{-7} - 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\phi) \approx 10^{-10} - 10^{-8}$$



[CC, Fuentes-Martin, Faroughy, Isidori, Neubert, 2101.11626]



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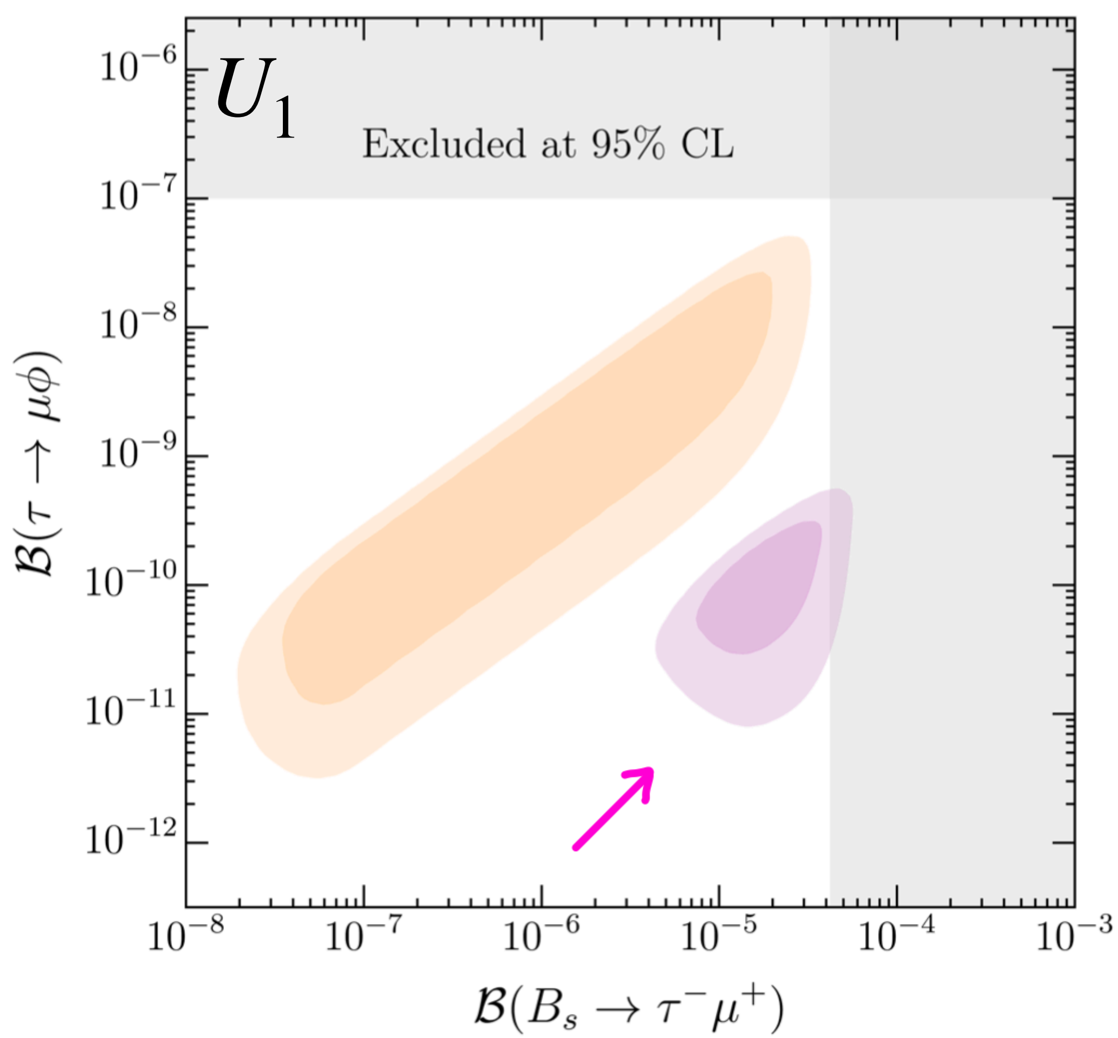
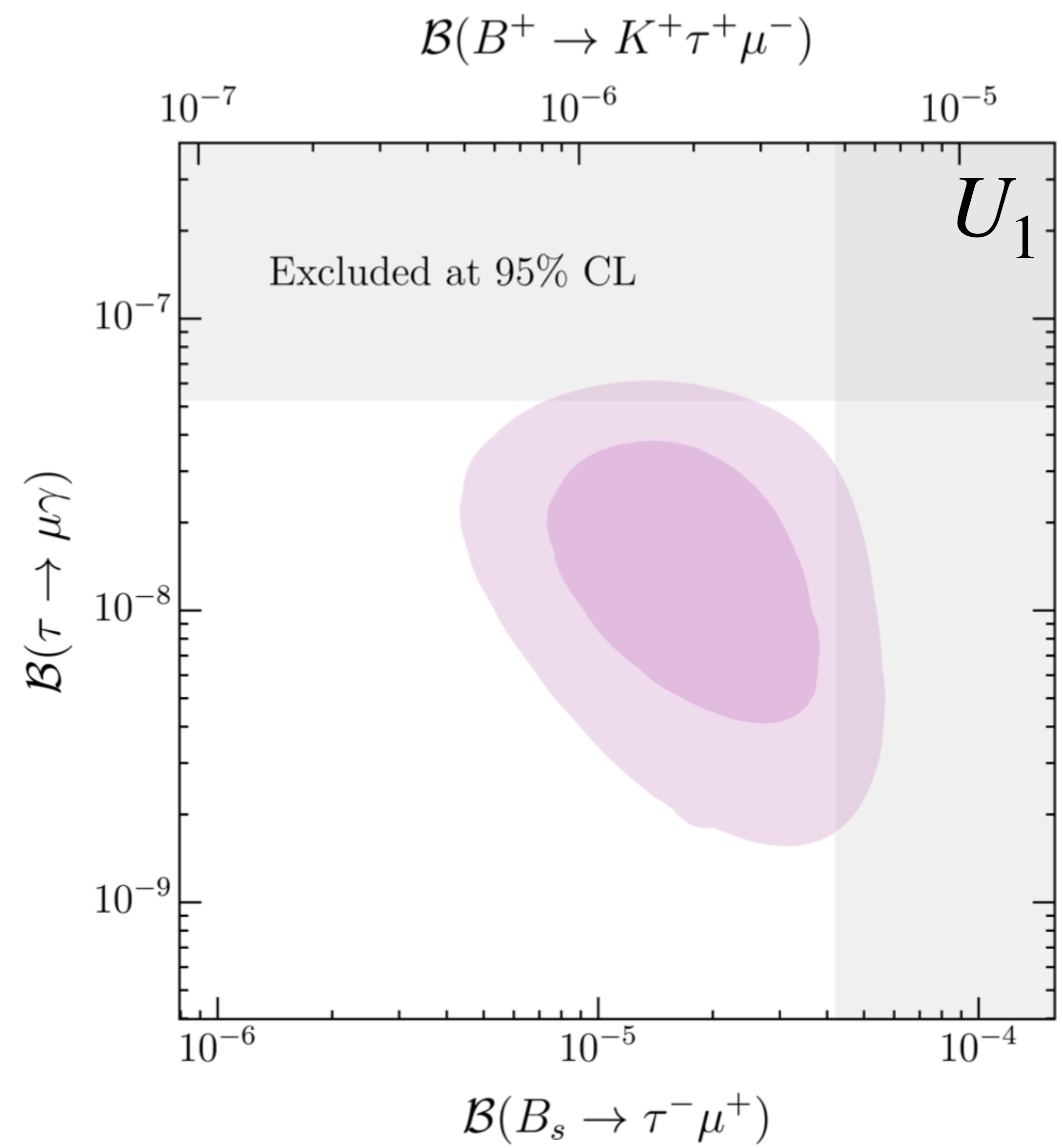
$$\mathcal{B}(B_s \to \tau\mu) \approx 1 \times 10^{-5}$$

$$\mathcal{B}(B \to K\tau\mu) \approx 1 \times 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\gamma) \approx 1 \times 10^{-8}$$





[CC, Fuentes-Martin, Faroughy, Isidori, Neubert, 2101.11626]

Experimental $B \to K\tau\mu$

"Easier" than $\tau\tau$ for both because only one neutrino (and fewer soft tracks). Similarly some excitement in Belle II.

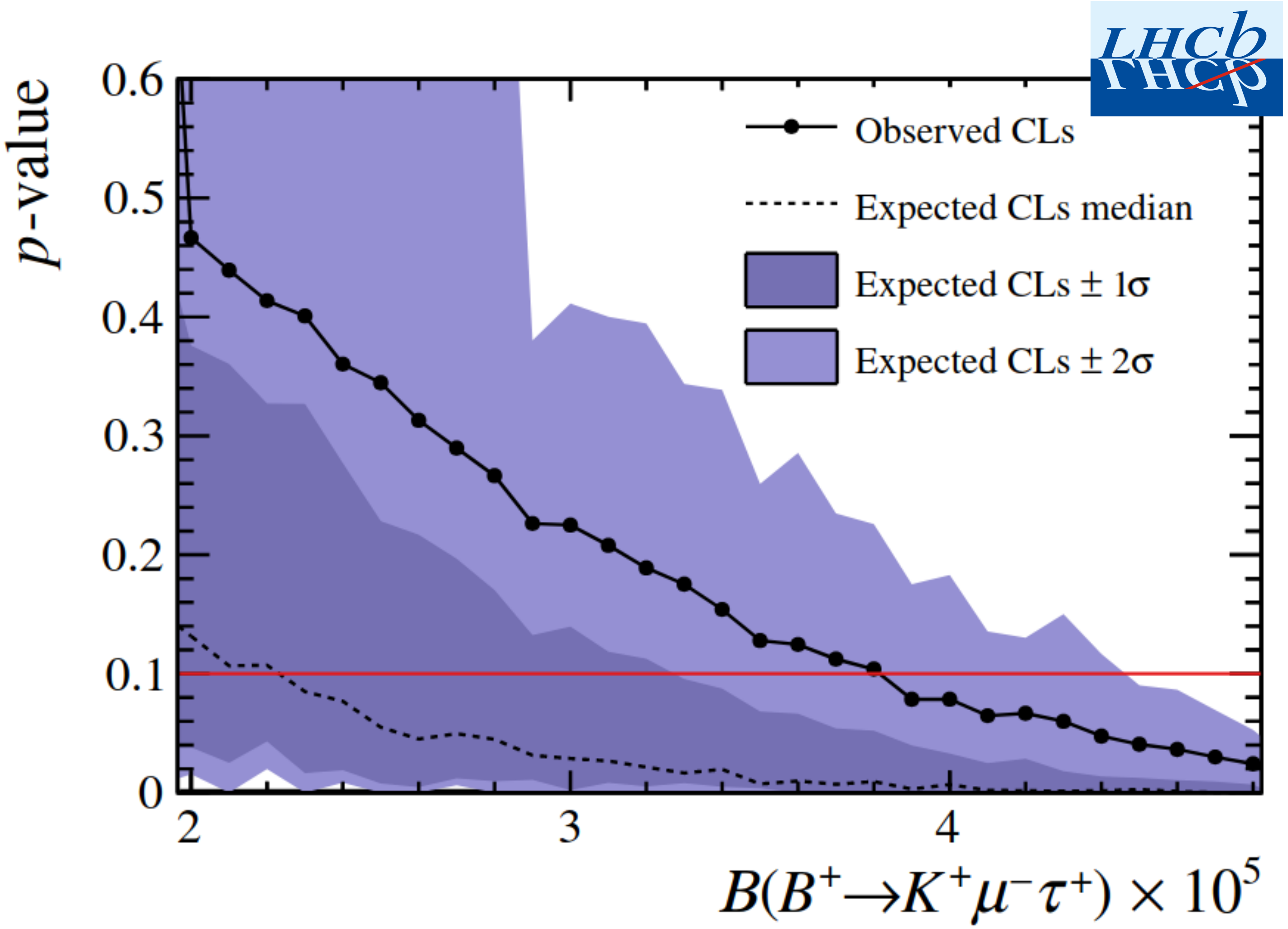
LHCb already have (cool tagging with $B^*_{s2} \to BK$)

$$\mathscr{B}(B \to K\mu^-\tau^+) < 3.9 \cdot 10^{-5}$$

[LHCb,JHEP06(2020)129]

Only just miss out on "worlds best BaBar:

$$\mathscr{B}(B \to K\mu^-\tau^+) < 2.8 \cdot 10^{-5}$$



Experimental $\tau \to \mu\gamma, \tau \to \mu\phi$

Belle II is also a tau factory!

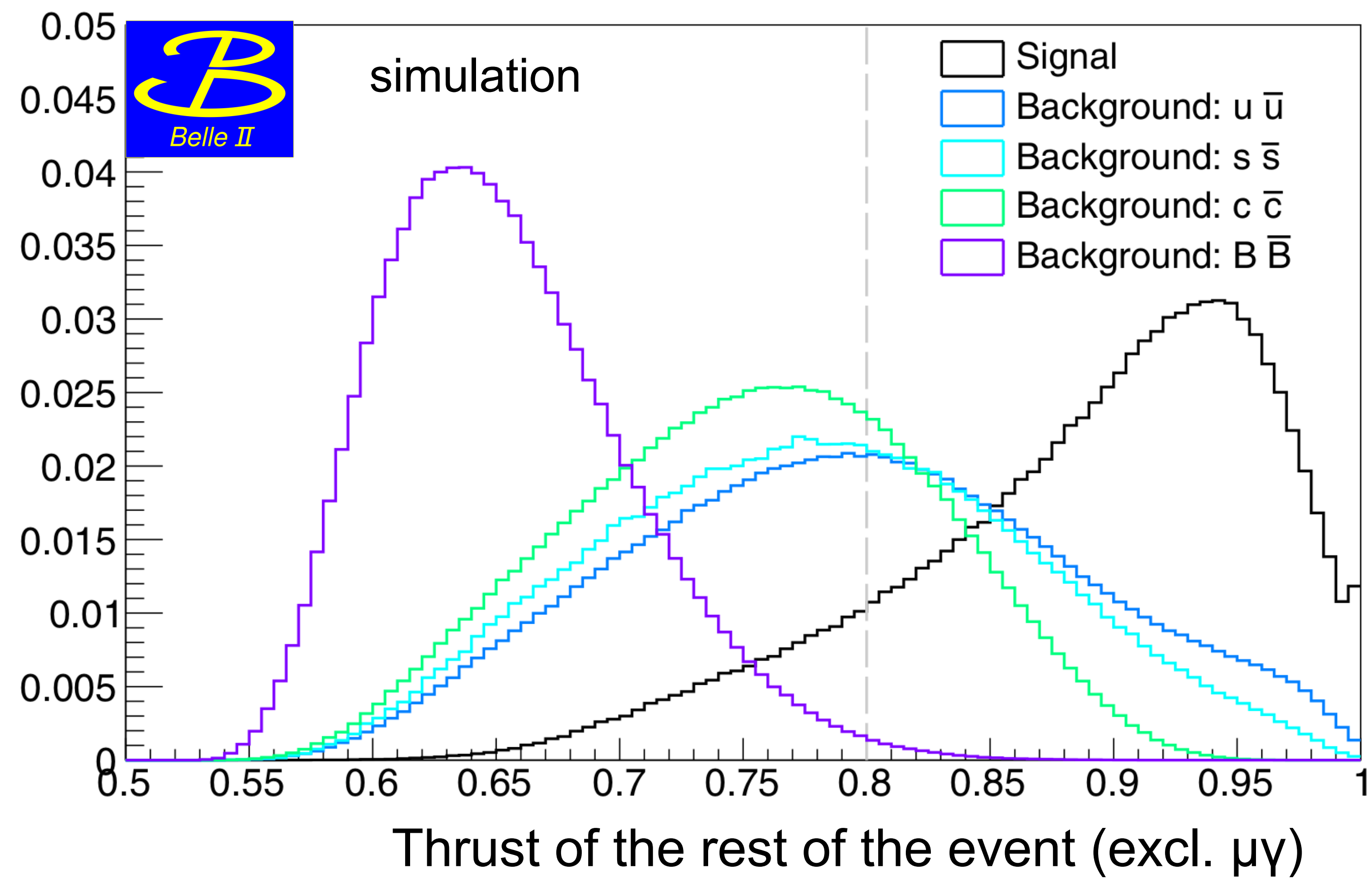
Another “free” benefit of ee machine.

$$\sigma(ee \to \Upsilon(4S)) = 1.11 \text{ nb}$$
$$\sigma(ee \to cc) = 1.3 \text{ nb}$$
$$\sigma(ee \to \tau\tau) = 0.92 \text{ nb}$$

Belle & BaBar published:

$$\mathscr{B}(\tau \to \mu\gamma) < 4 \times 10^{-8}$$

[Babar, PRL104(2010)021802]
[Belle, Phys.Lett.B666(2008)]

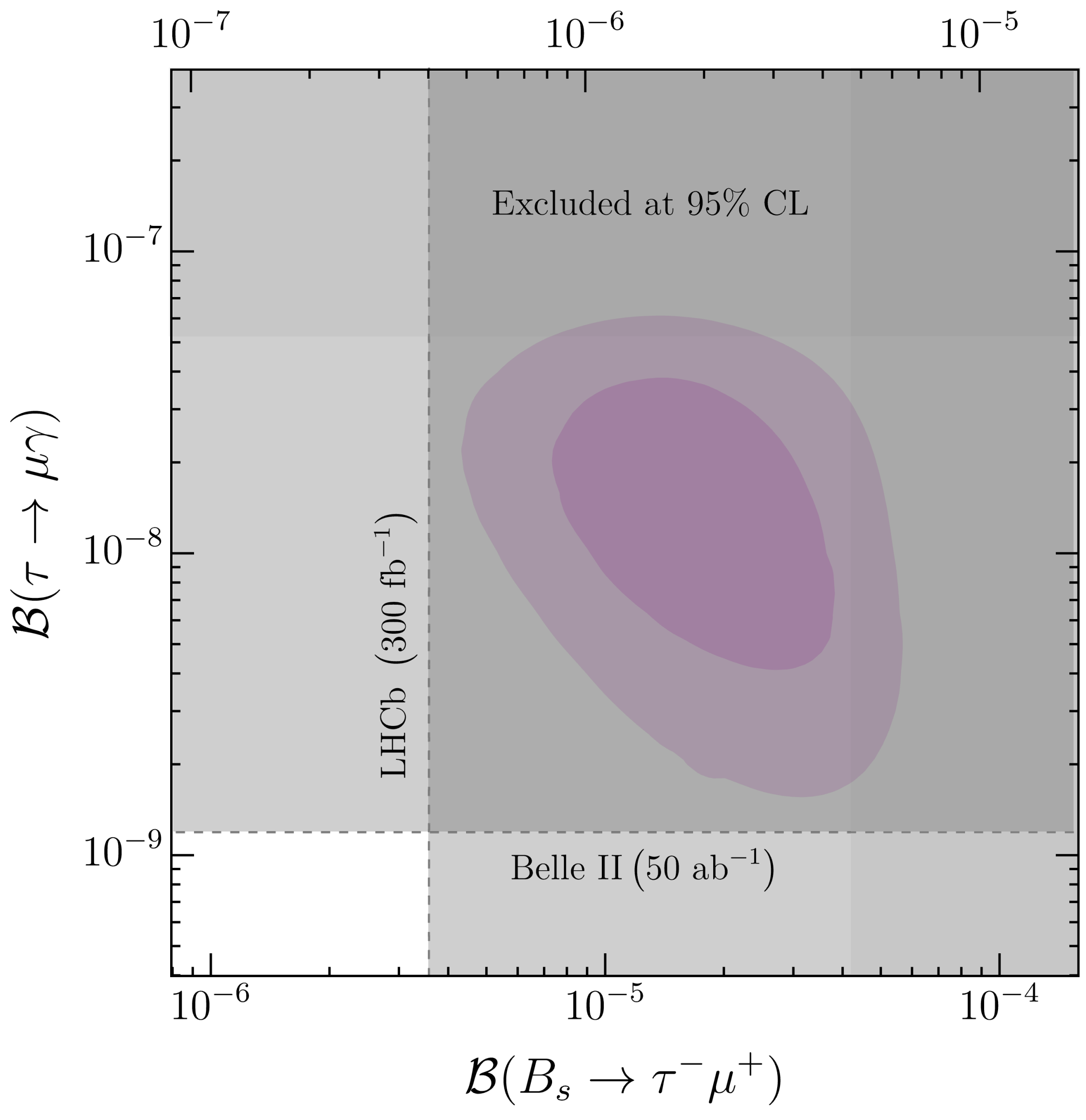


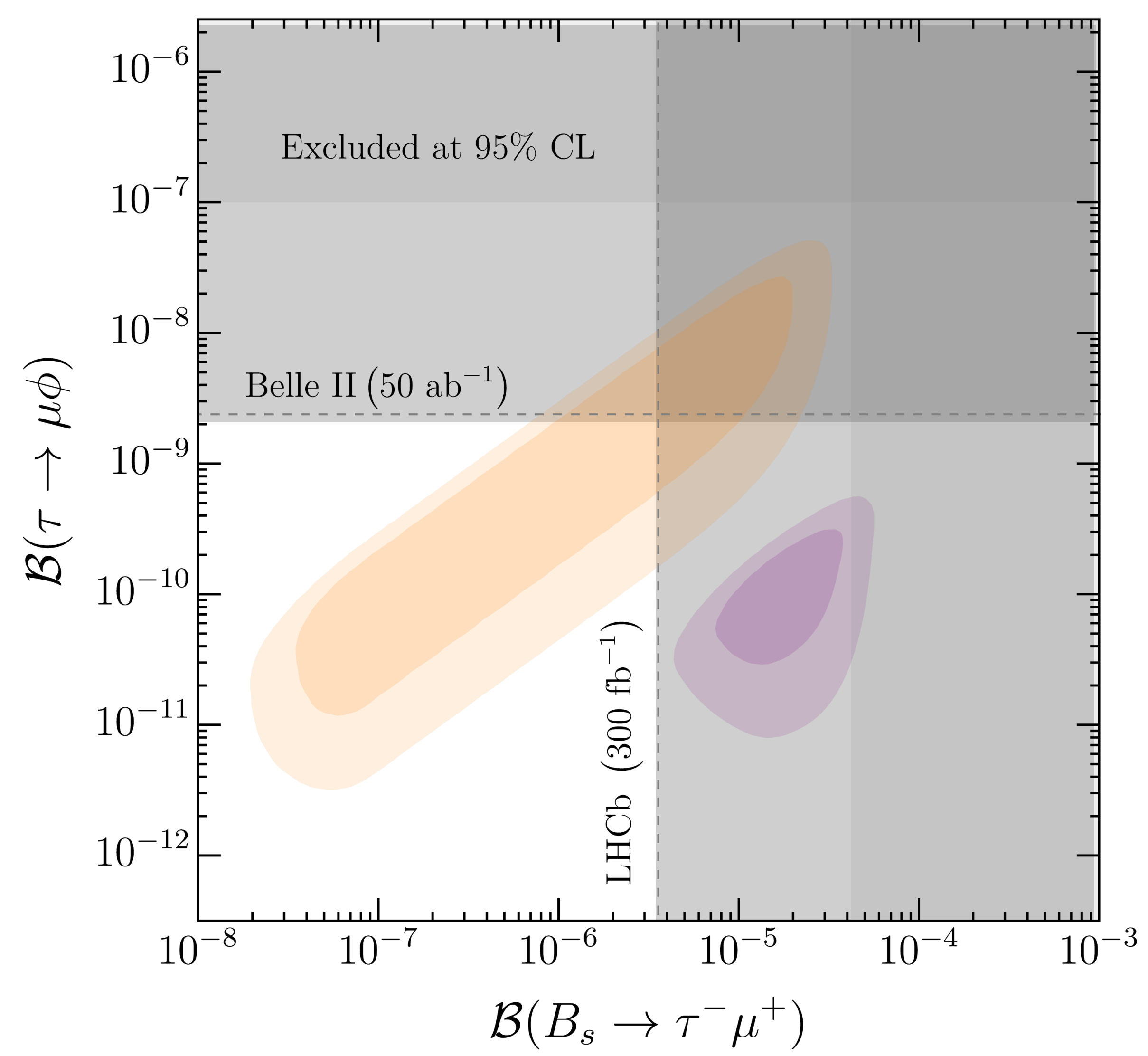
Belle II can improve by a factor ~2 c.f. Belle per ab^{-1}.

[Belle II, PTEP(2019)123C01]

τ/μ LFV: low-energy projections for the U_1

LHCb (300 fb^{-1}) and Belle II (50 fb^{-1}) will exclude the U_1 (LH + RH) (or see something!), U_1 (LH) will still be in good shape!





[CC, Fuentes-Martin, Faroughy, Isidori, Neubert, 2101.11626]

$B \to K\nu\nu$

One of the toughest constraints for model building. All combined solutions **enhance** it.

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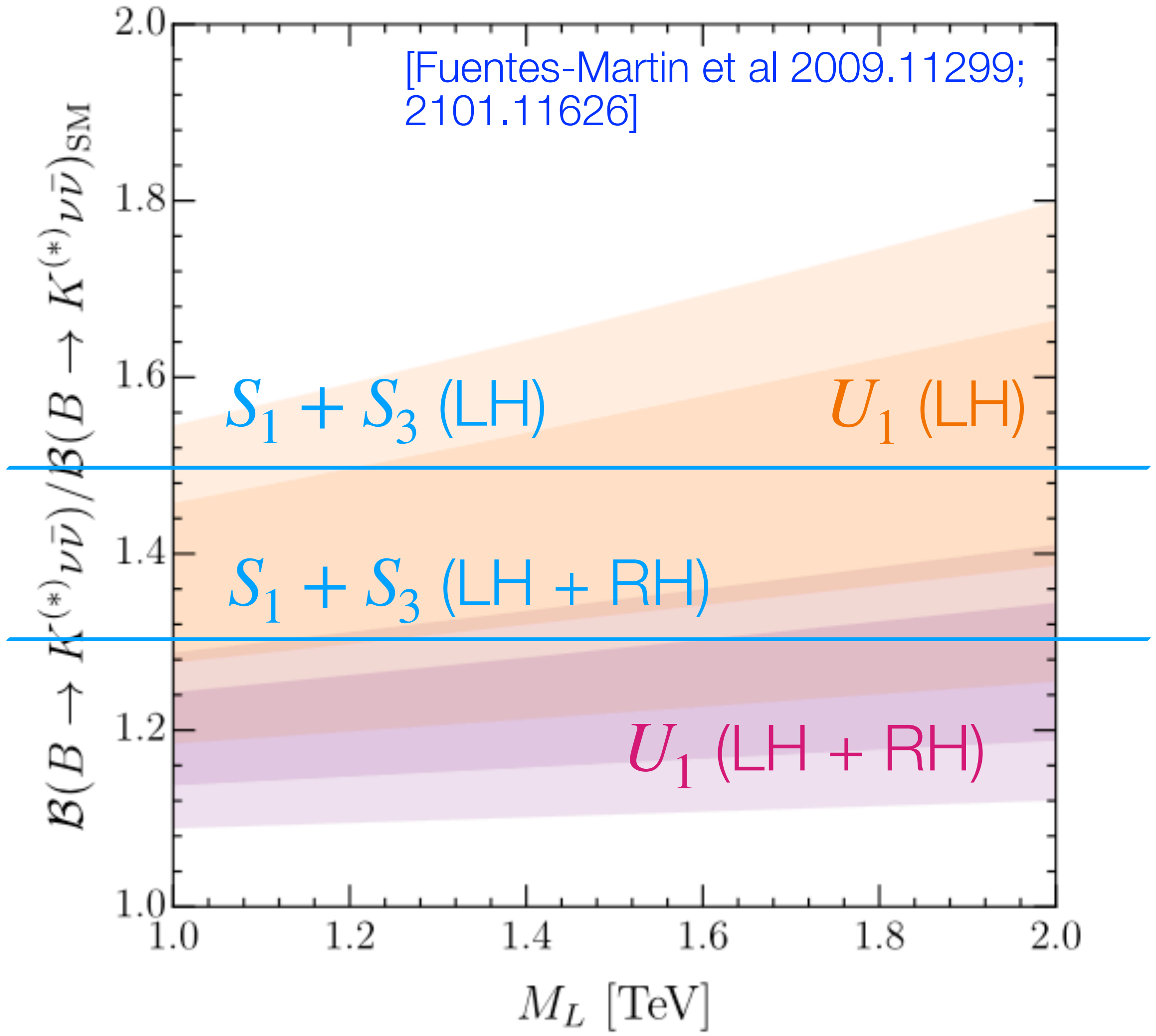

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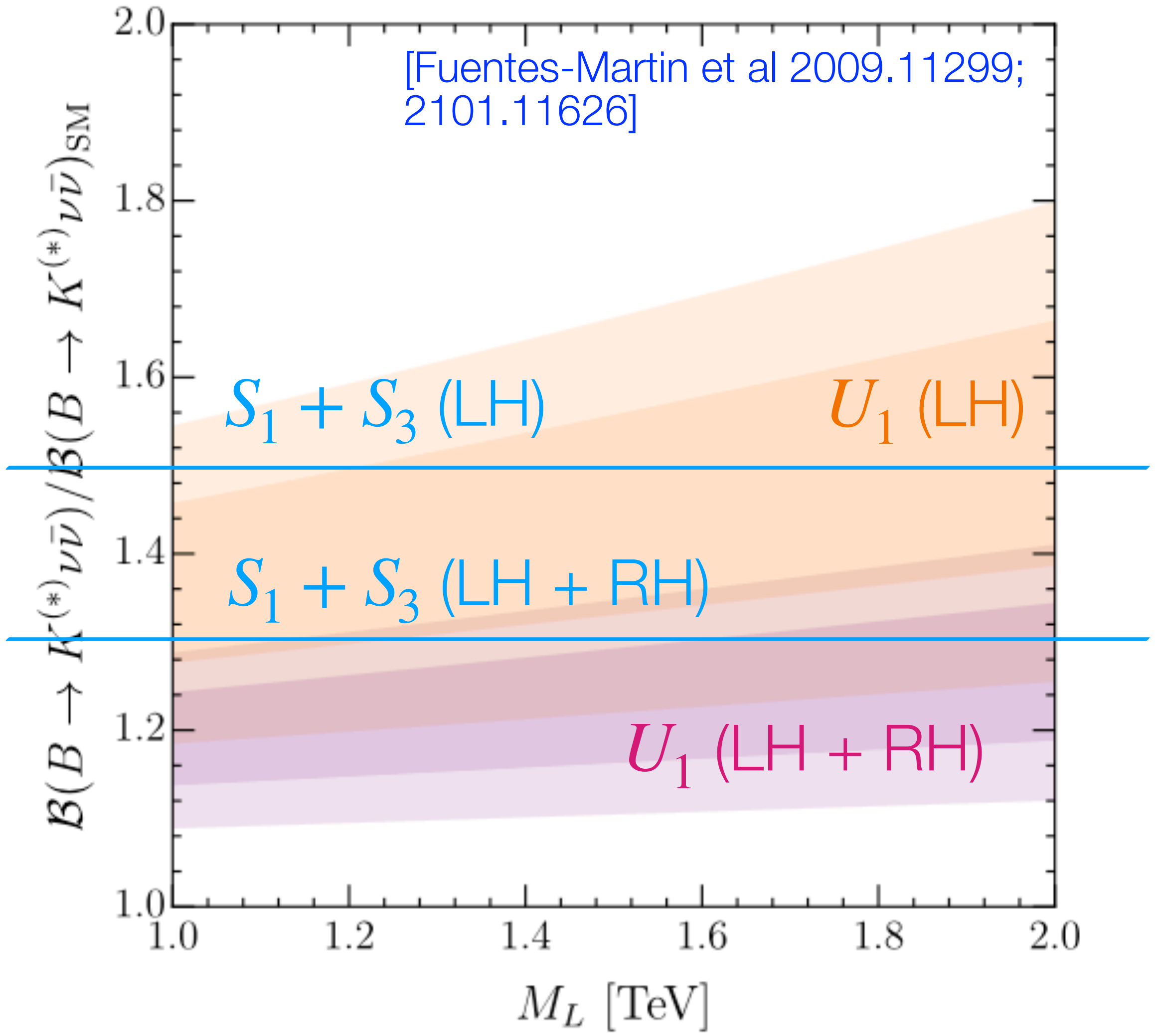

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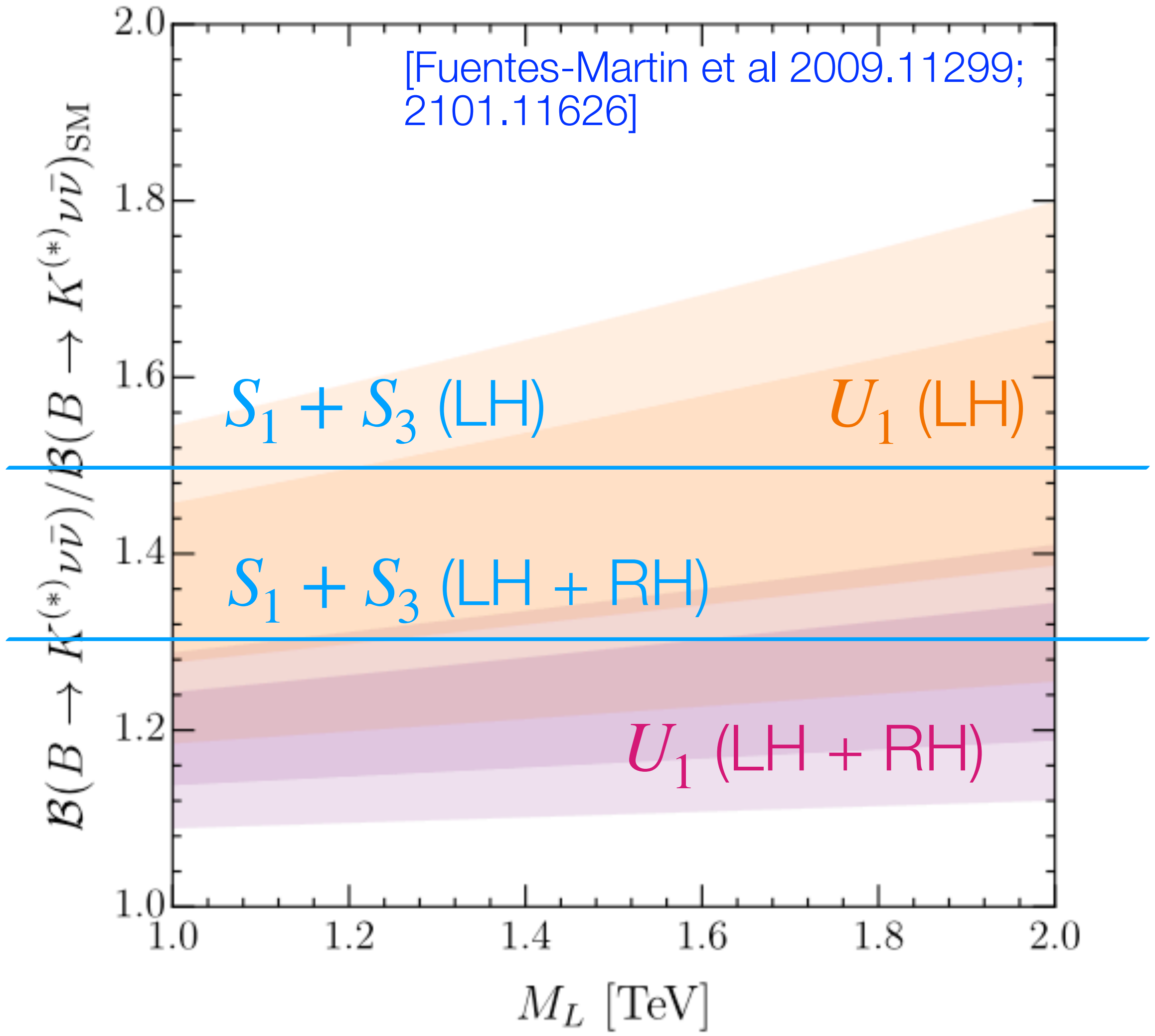

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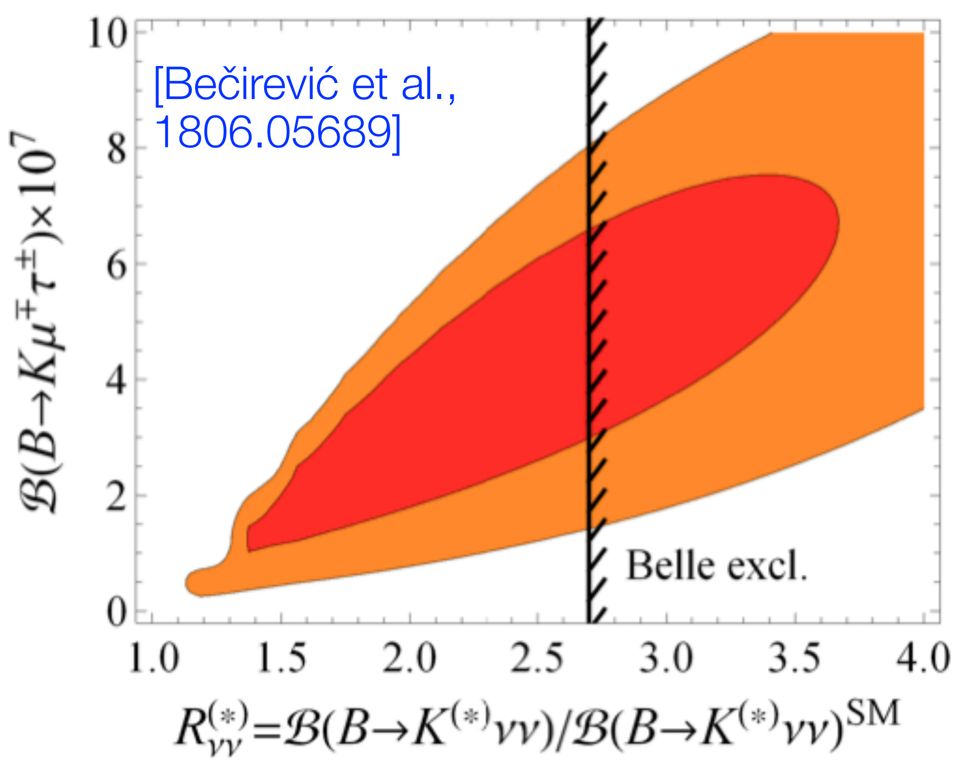
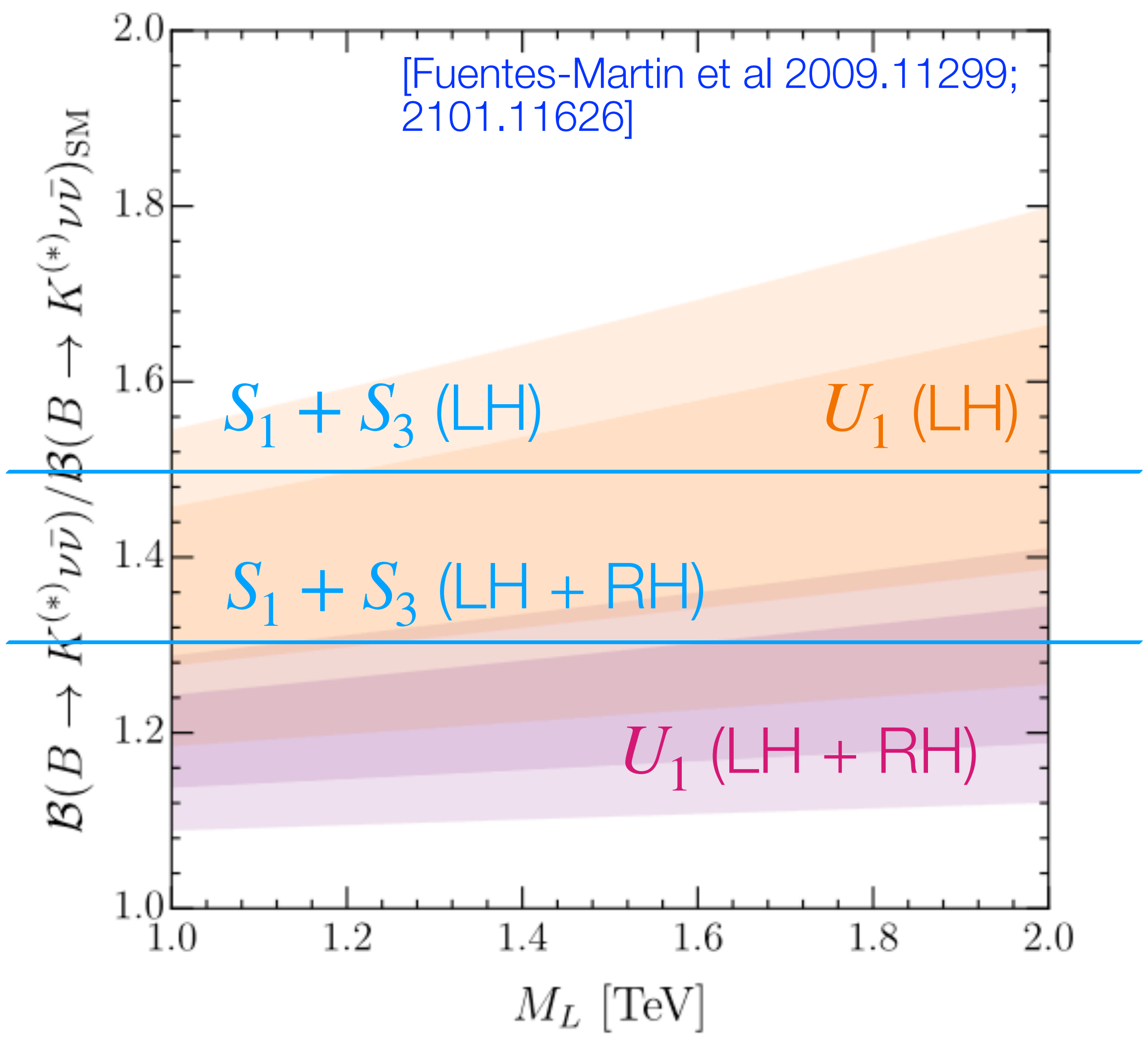




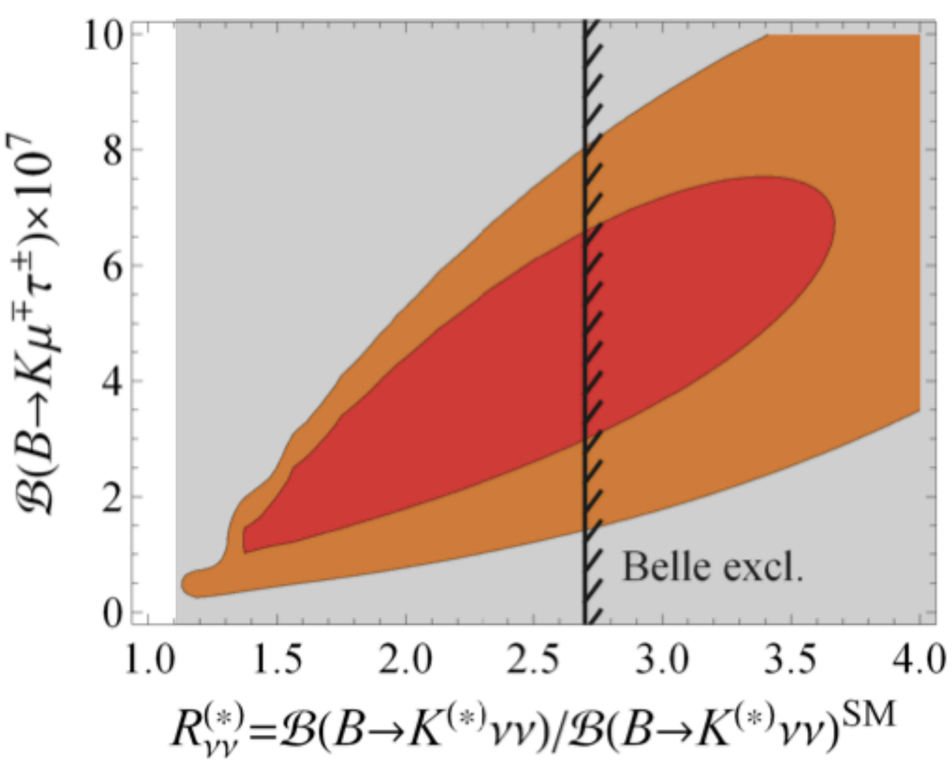
$R_2 + S_3$ $$\frac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}(B \to K\nu\nu)_{\rm SM}} \gtrsim 1.5$$

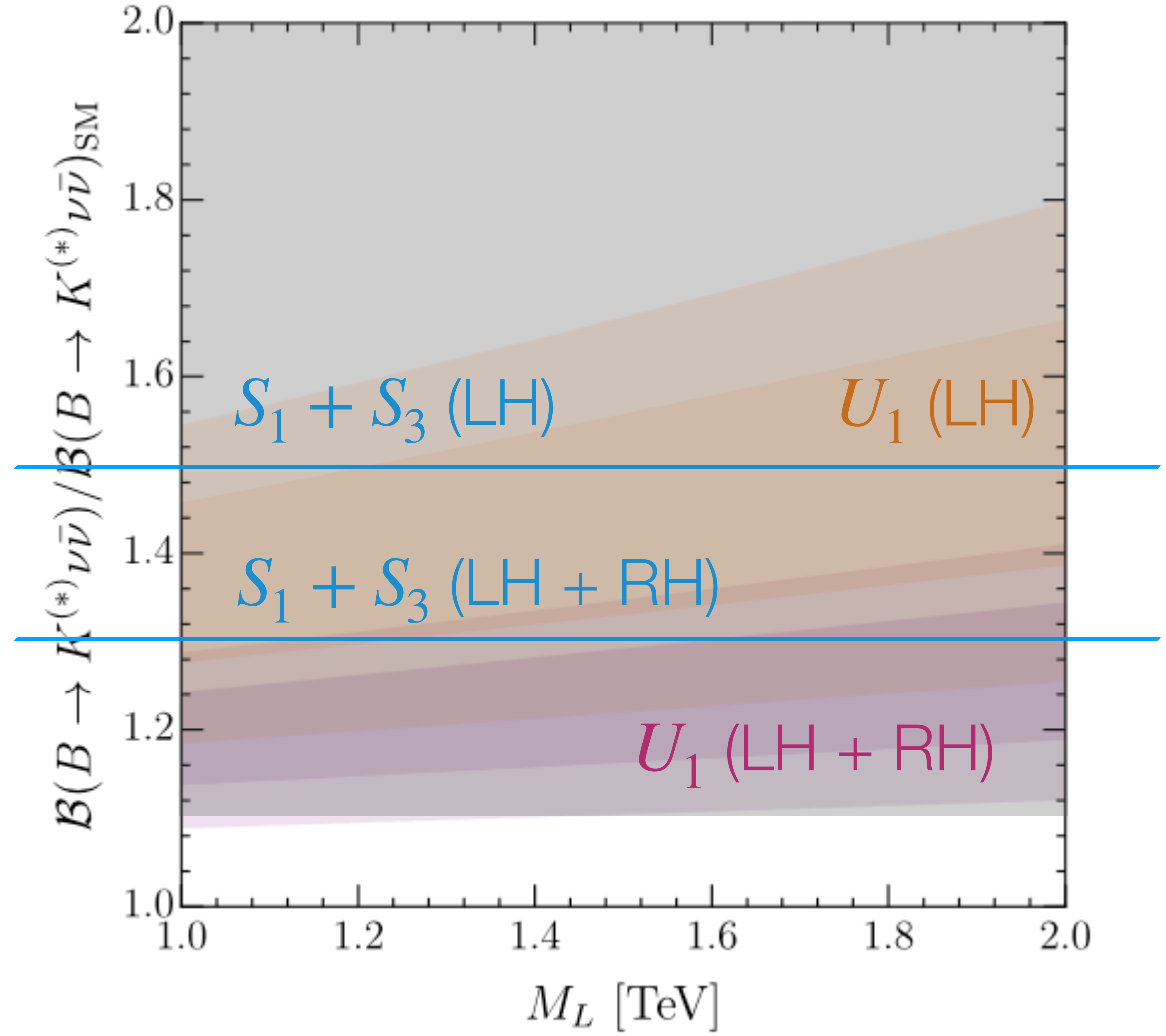
Experimental $B \to K\nu\nu$

It's cool.
Both tagged and untagged.

I will not spoil Sally's talk here.

(she actually worked on it so you can ask her all of your tough questions)





[(*) on top of observables in $b \to s\mu\mu$ and $b \to c\tau\nu$]

Conclusions

B anomalies	corroborating measurements*
$b \to s\mu\mu$	$b \to d\mu\mu$ u(2) (+ possibly μ/e LFV - not discussed here)
$R_{D^{(*)}}$ & $b \to s\mu\mu$ (or $R_{D^{(*)}}$ only)	large $b \to s\tau\tau$ and $pp \to \tau\tau$ rock solid
$R_{D^{(*)}}$ & $b \to s\mu\mu$	large τ/μ LFV in $b \to s\tau\mu$ and τ decays explicit model
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  → it's a team game, both low and high E can help!
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If you want us to give a more interesting talk next, please update R_D/R_{D*}!
[CMS bailed us at Moriond, and LHCb are missing the 6 fb^{-1}…]

(Rough) experimental time-ordering

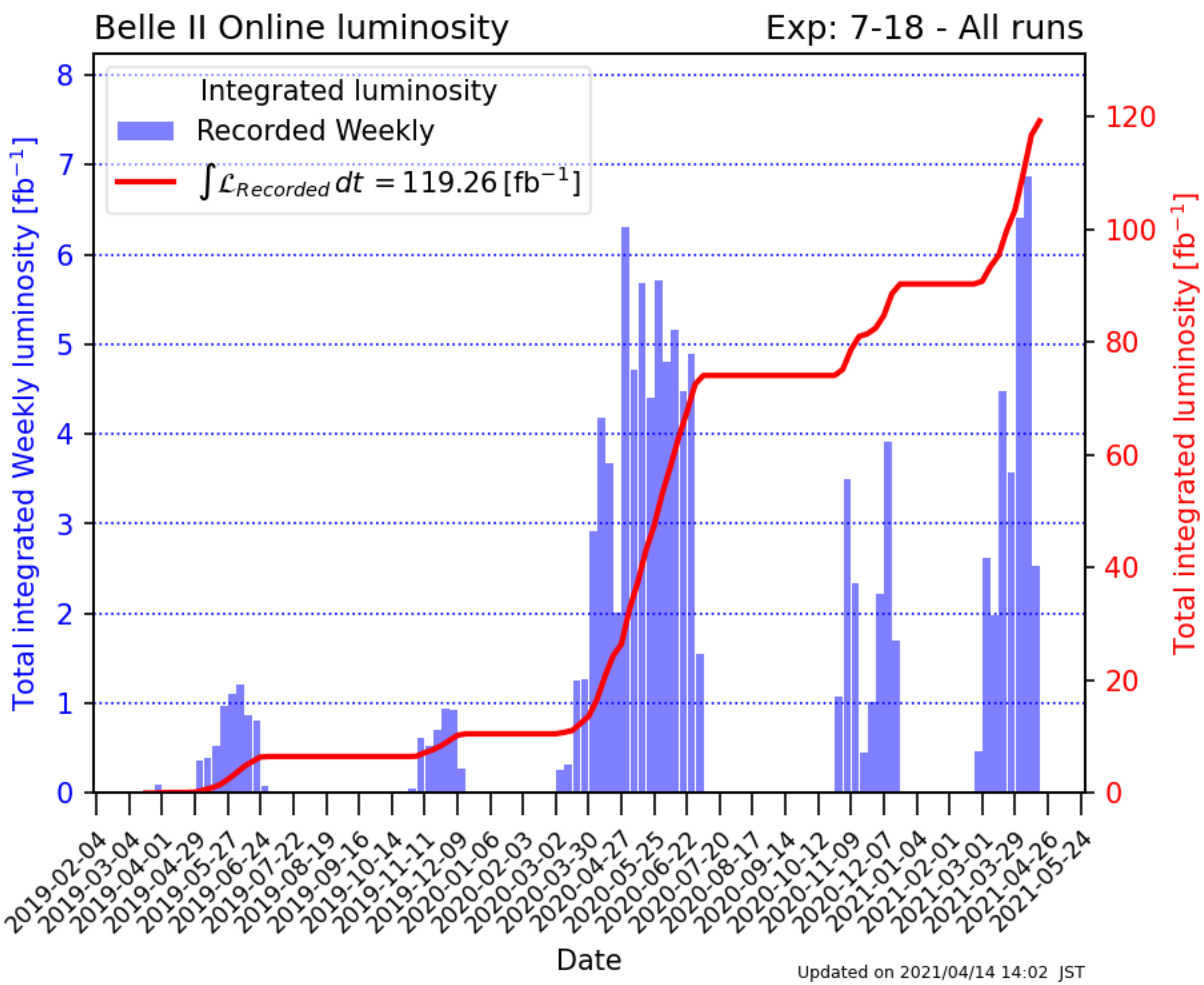
1. R_K update! $(g-2)_\mu$. Belle II demonstrator untagged $B \to K\nu\nu$.
   Flavour physics is cool again.
2. Incremental update to some τ LFV searches at Belle I.
   Belle II starts to make τ measurements.
3. LHCb finishes analysing Run2 data.
   - Wishlist R_ϕ, $B_s \to \tau\mu$, $B \to \pi\mu\mu$, $B_s \to \tau\tau$…
4. Belle II collects enough data to say something in B physics (~ab^{-1})
5. LHC startup
   - CMS & ATLAS high-PT
   - LHCb updates (?)
6. Belle II approaches 50 ab^{-1} and delivers on all of its promises.

Intermediate projections?

Slides for backup

How is Belle II doing right now?

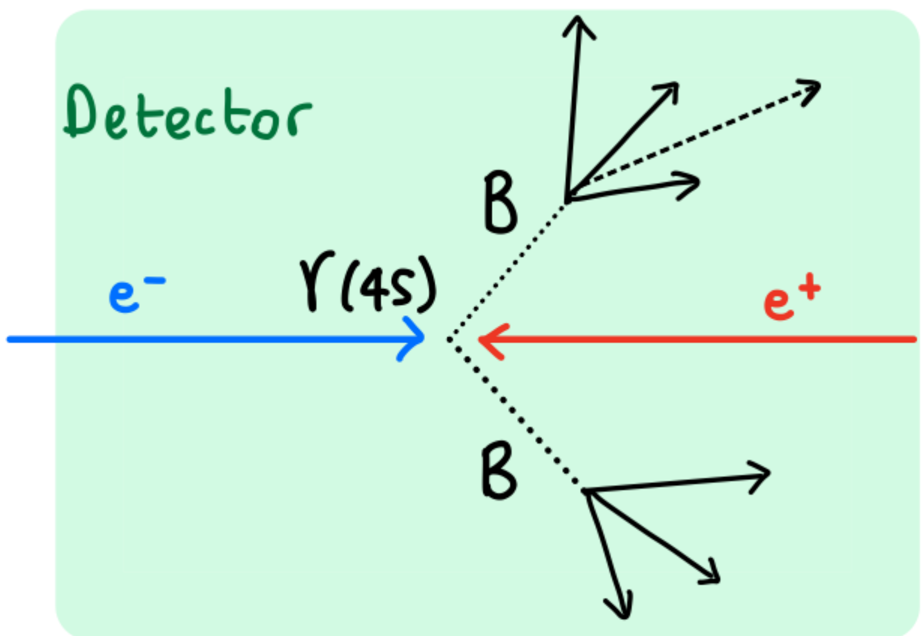
For more details: see Sally's talk on Thursday.



https://confluence.desy.de/display/BI/Belle+II+Luminosity

The experiments

Belle II

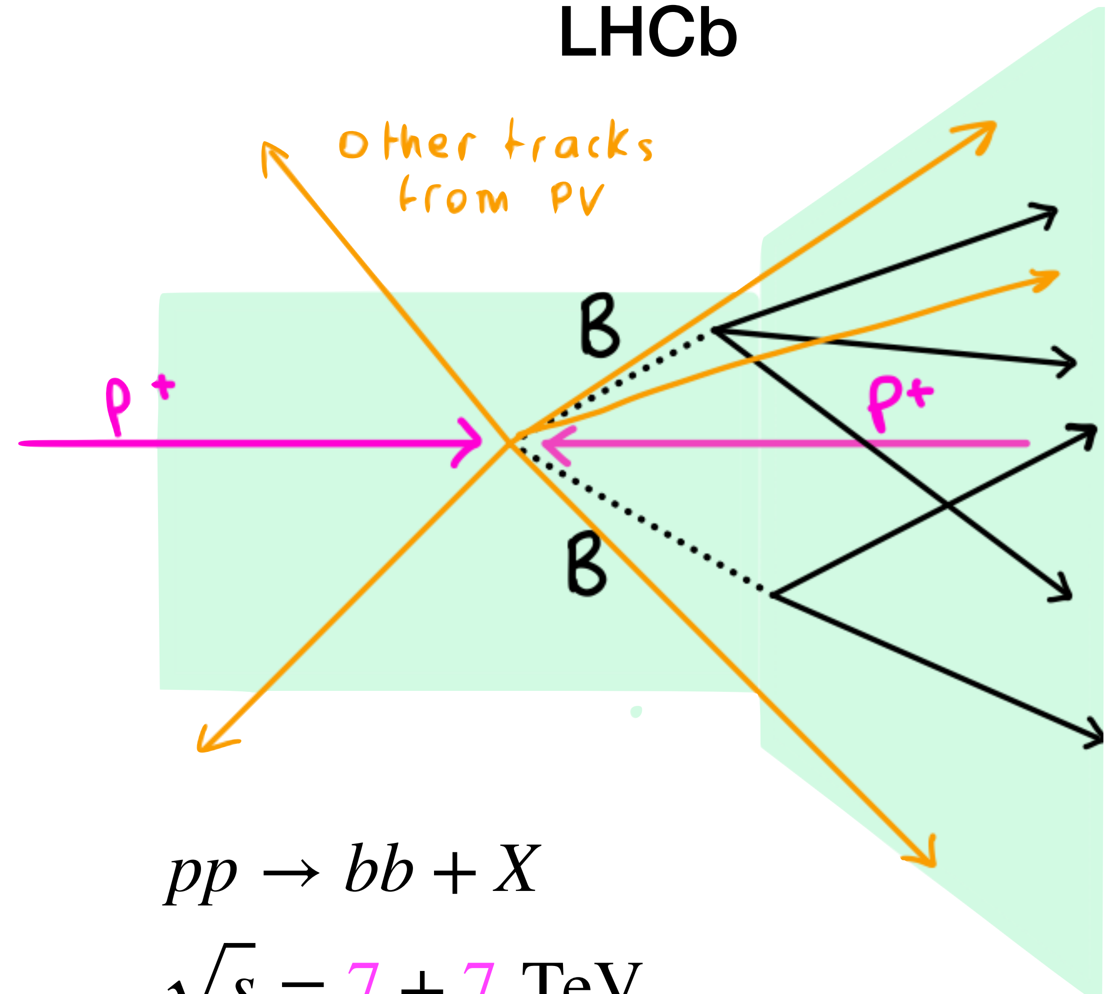


$ee \to \Upsilon(4S) \to BB$

$\sqrt{s} = 2\sqrt{7 \times 4}\ \mathrm{GeV} = 10.58\ \mathrm{GeV}$

- Collision energy known → boost to CM.
- Full event contained.
- Good at missing energy and neutrals (γ, K_S^0, K_L^0, π^0, ν, $\nu\nu$).

LHCb



$pp \to bb + X$

$\sqrt{s} = 7 + 7\ \mathrm{TeV}$

- Collision energy not known precisely.
- Abs. luminosity not known precisely*.
- Significantly more data.
- Access to B_s, B_c, Λ_b ….

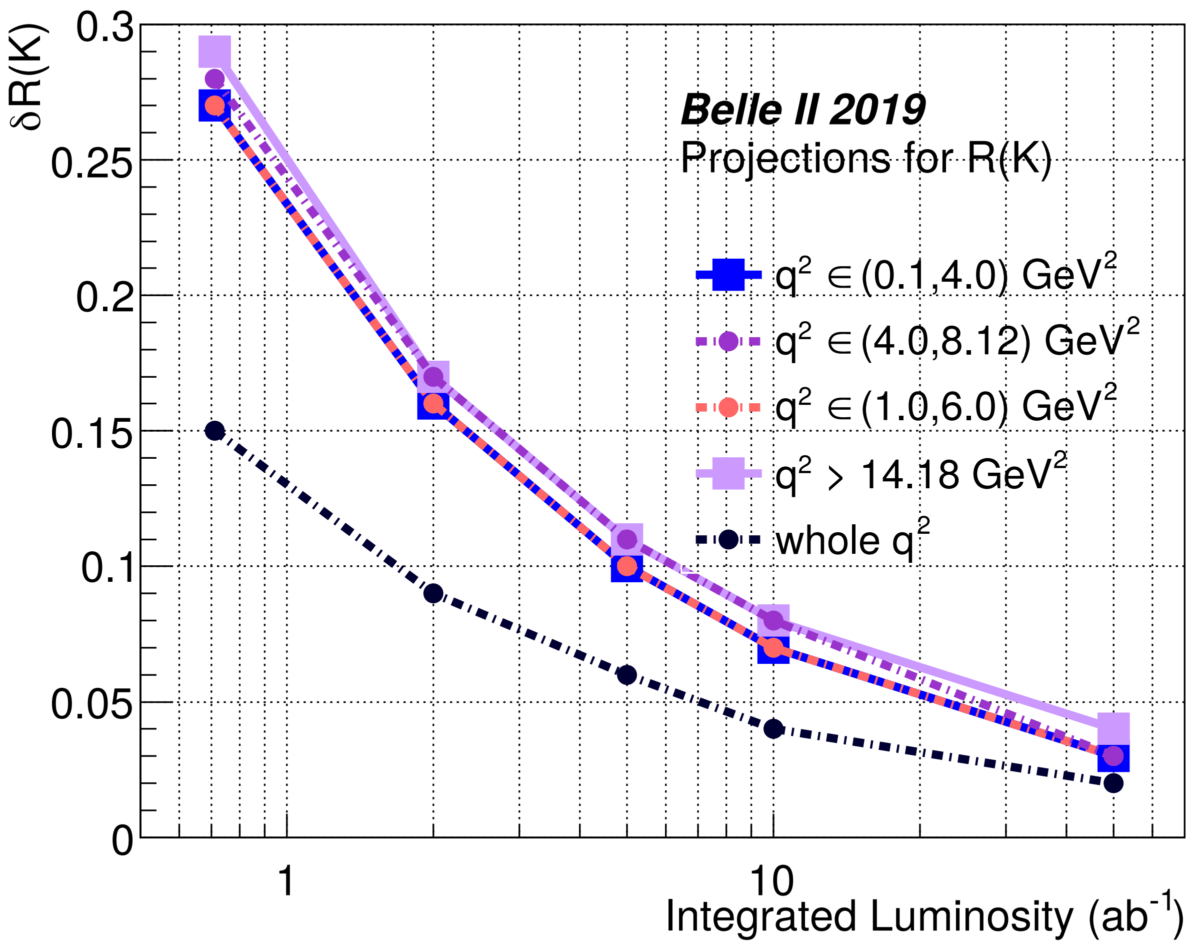
“So when can Belle II confirm R_K?”

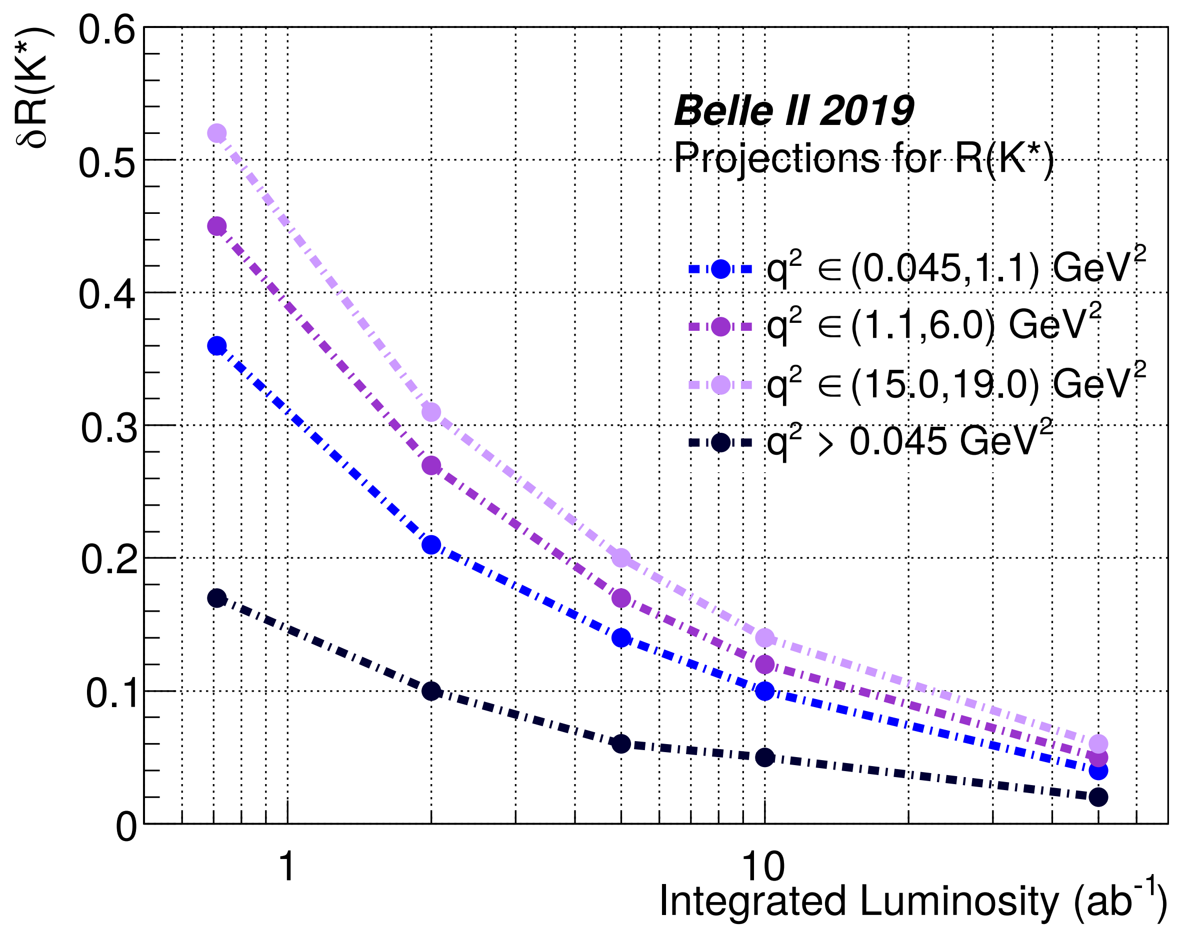
You are making us spoil Sally’s talk.

Belle has analysed the full dataset (R_K and R_{K^*}).

Safe answer: 20 ab^{-1} to get to the same size error bars.

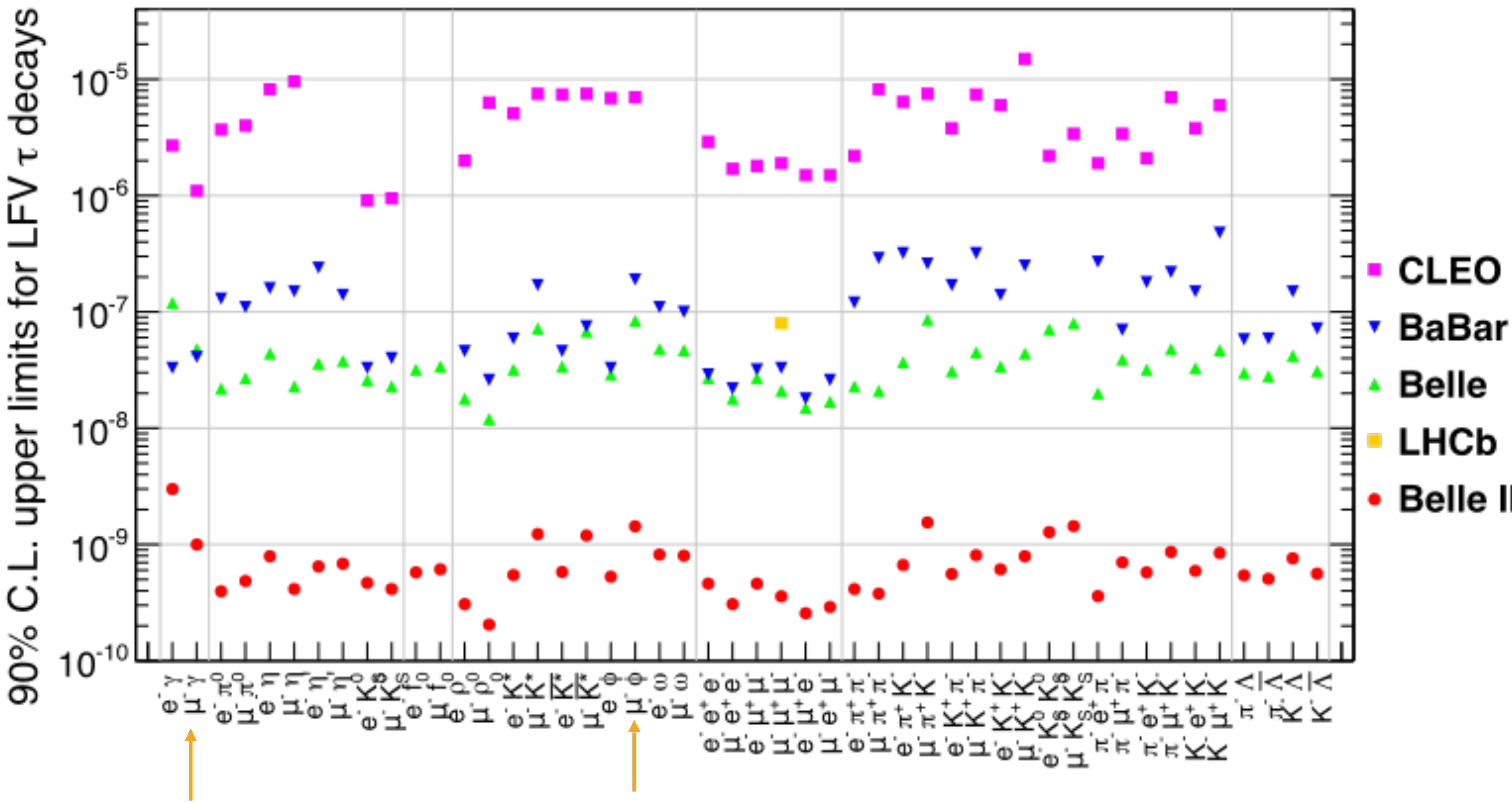
Unsafe answer: ~5 ish years.





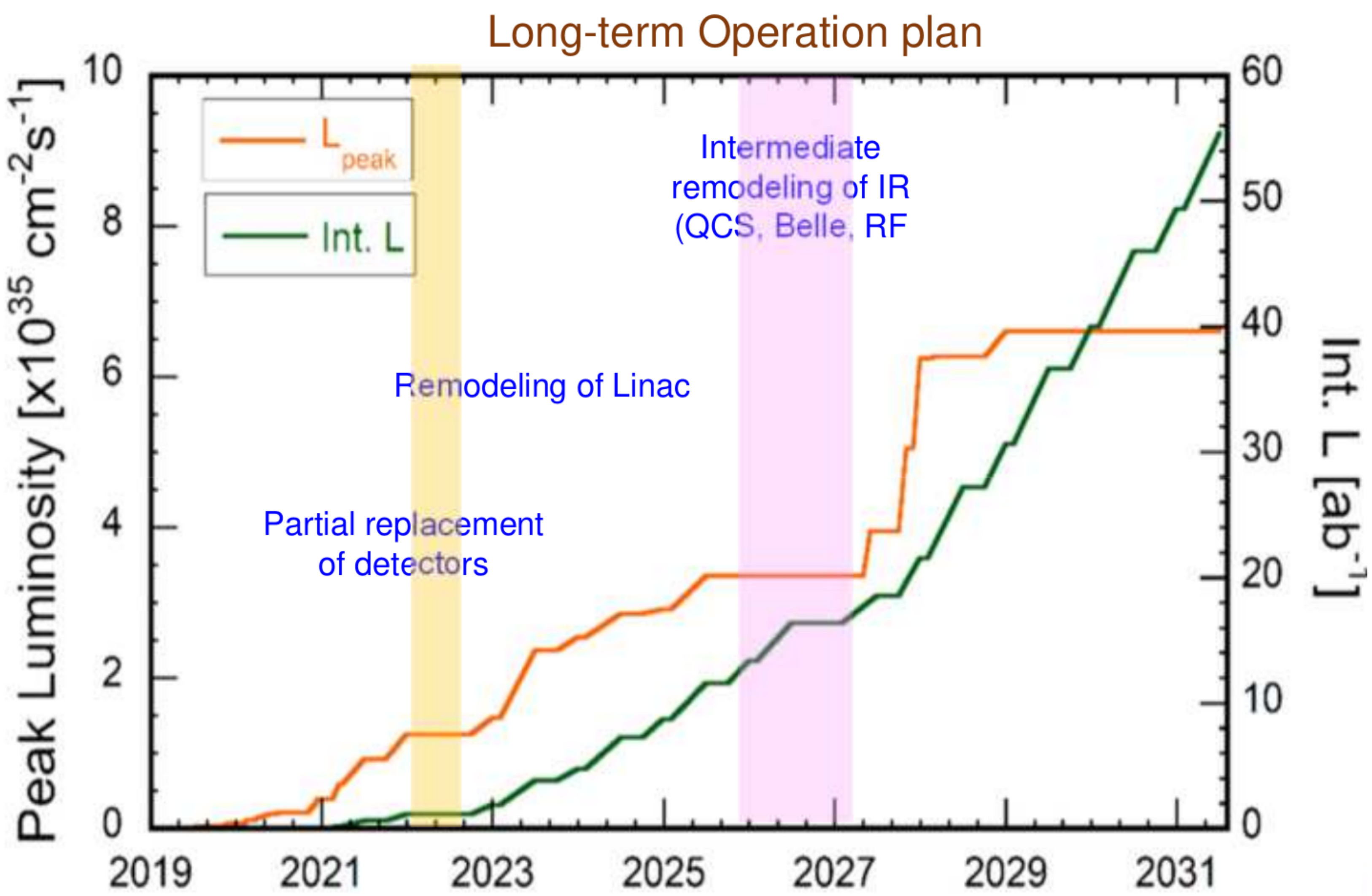
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	—
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	—	—	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	—	—	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp) \cdot 10^6$	—	—	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp) \cdot 10^6$	—	—	< 1.3

Experimental $\tau \to \mu\gamma$ and $\tau \to \mu\phi$



Belle II schedule (updated)

5 ab^{-1} ~2024
50 ab^{-1} 2031



Schedule changes quite often.
Probably not sensible to keep showing them (or talking in terms of years).