Corroborating measurements

Claudia Cornella and Sam Cunliffe

Beyond the flavour anomalies, IP^3 Durham, 01.04.2020

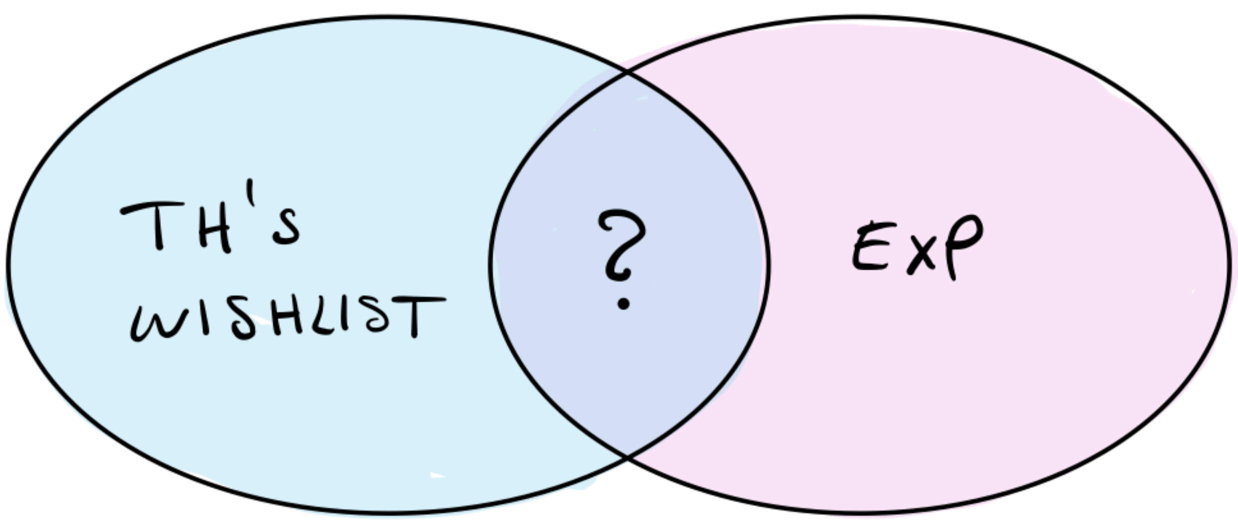
DESY.
Universität Zürich UZH

Intro

“Please talk about corroborating measurements for B anomalies”

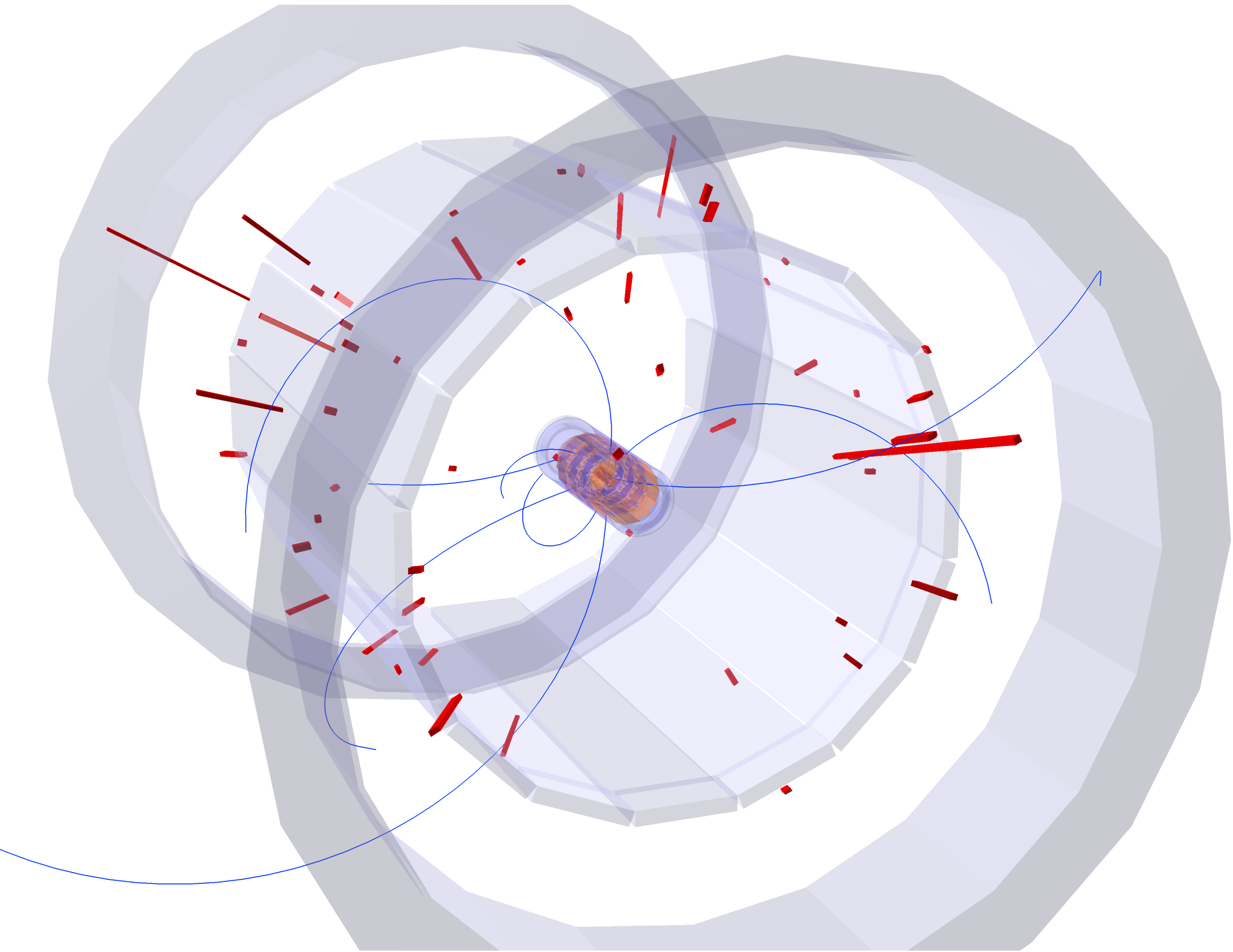
Our interpretation: answer two questions

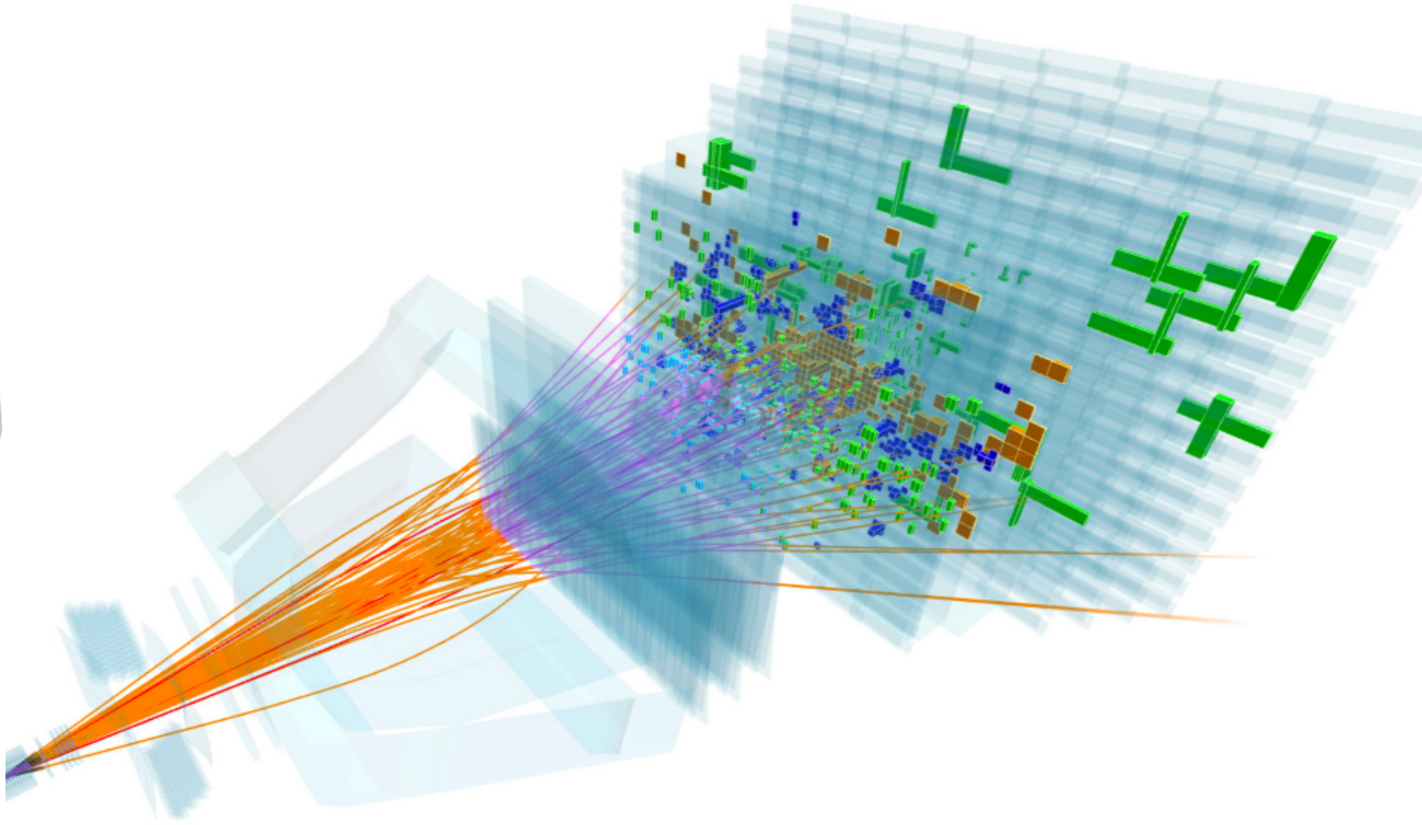
- If B anomalies are true NP signals, where else should we see something?
- What can Belle II and LHCb measure?



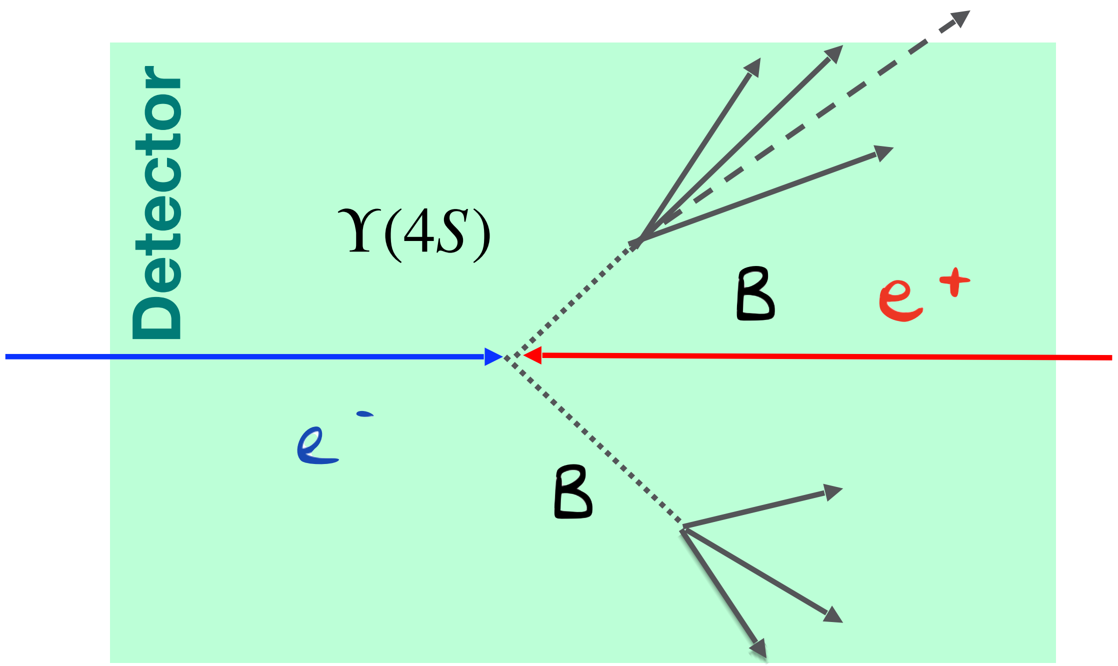
…and see if there’s some common ground.

Experimental tools





Belle II



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

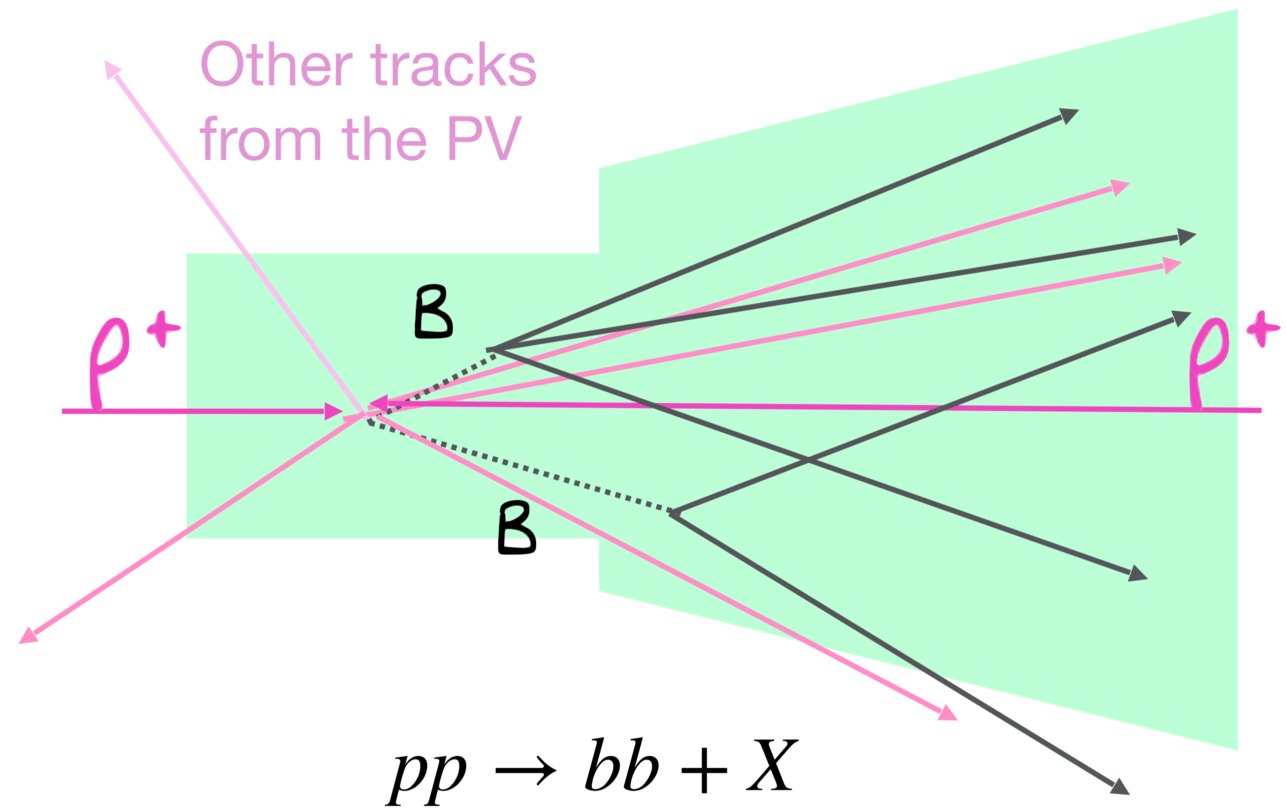
$$\sqrt{s} = 2\sqrt{7 \times 4}\ \mathrm{GeV} = 10.58\ \mathrm{GeV}$$

Collision energy known → boost to CM.

Full event contained.

Good at missing energy and neutrals ($\gamma, K_S^0, K_L^0, \pi^0, \nu, \nu\nu$).

LHCb



$$pp \to bb + X$$

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

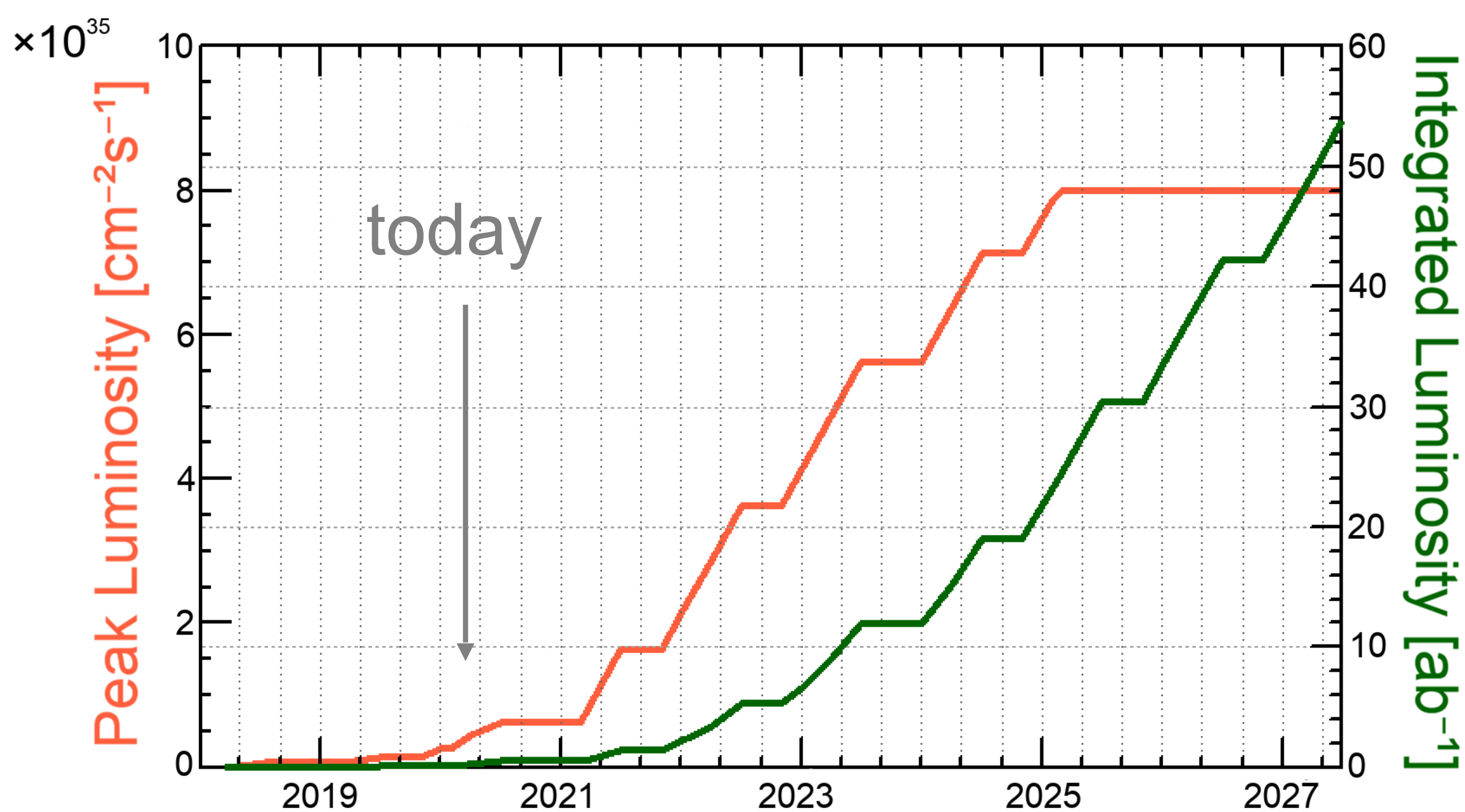
Collision energy not known precisely.

Abs. luminosity not known precisely*.
Significantly more data.

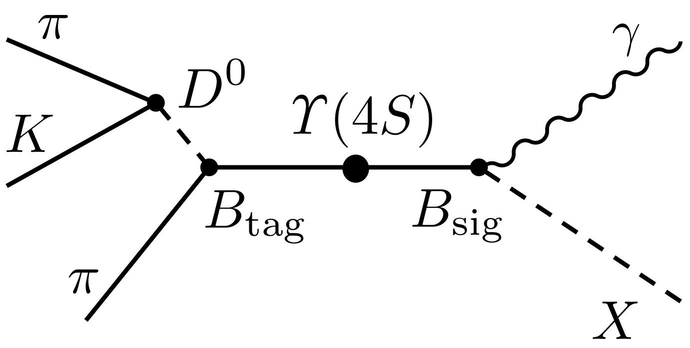
Access to $B_s, B_c, \Lambda_b \ldots$.

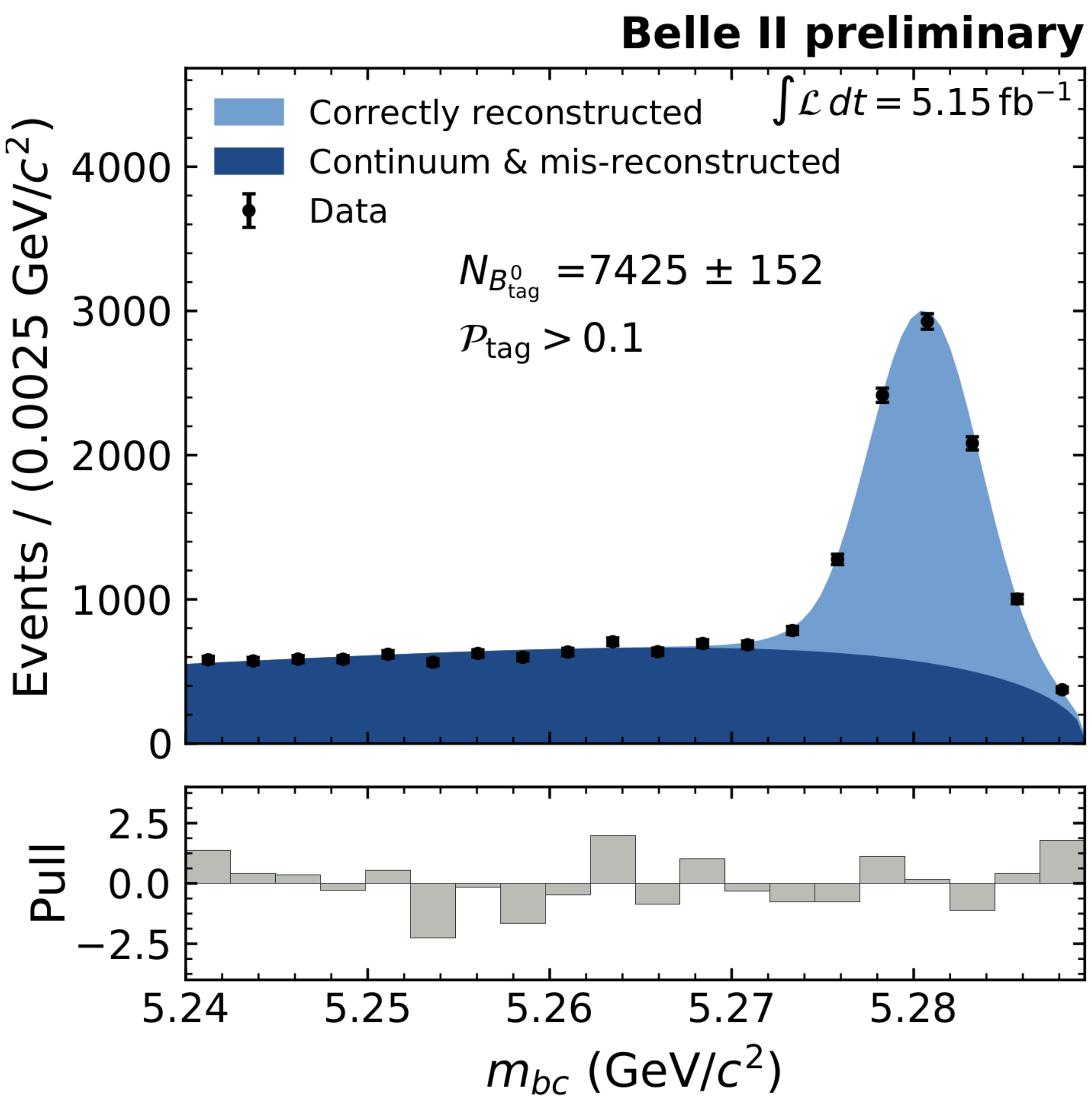
Misc. facts of interest for Belle II

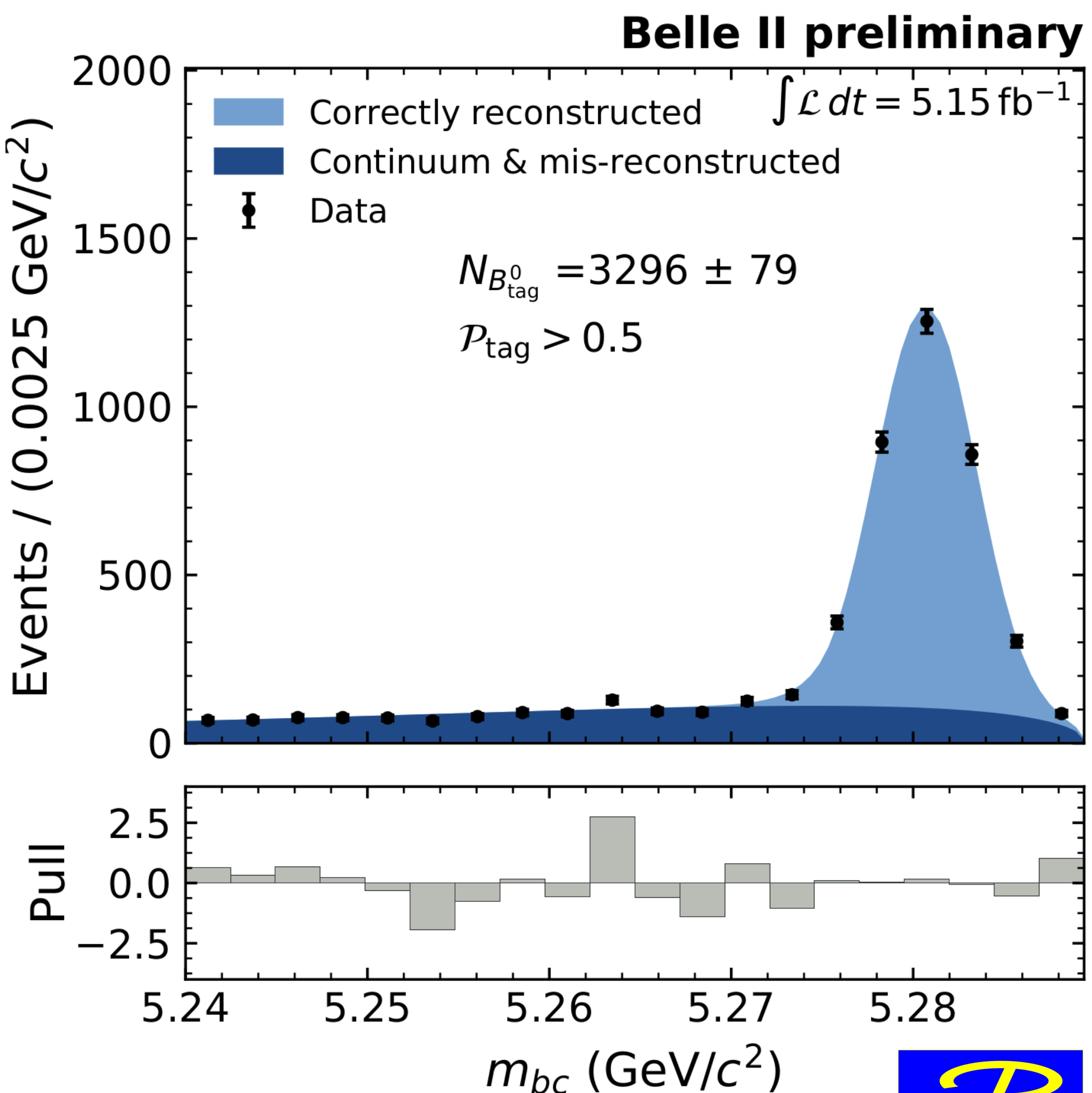
- Data rate: $\mathbf{10^9}$ $\boldsymbol{BB}$ per $\mathbf{ab^{-1}}$ $\rightarrow$ Lifetime dataset $\mathbf{50\ ab^{-1}}$ $\rightarrow 2 \times 5 \times 10^{10}$ B's.
- Access to B_s ***is*** possible but need dedicated runs at $\Upsilon(5S)$.
- Take any B_s projections/predictions from Belle II with a grain of salt.
- Full event reconstruction.
- Flavour tagging.
- $ee \rightarrow \tau\tau$.



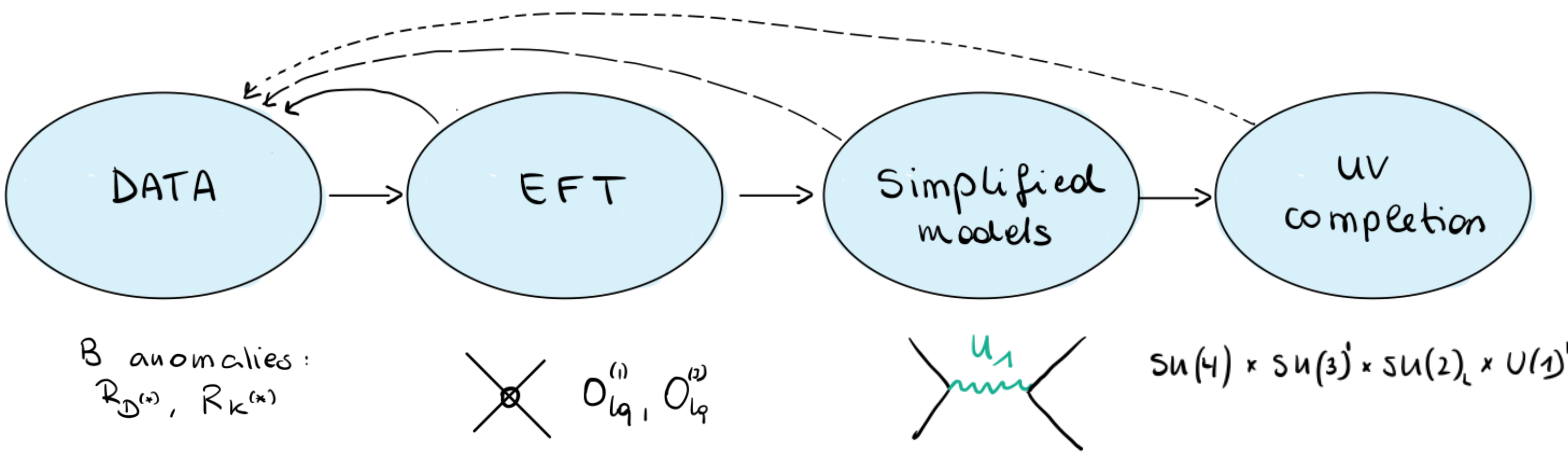
Full event interpretation







Theory tools



- 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).

We would like to be as model independent as possible, without forgetting all the lessons we learnt along the way!

Outline

Goal: identifying corroborating measurements, assuming:

- Almost nothing (B anomalies are there, NP is heavy).

  observables in the same partonic transition, $b \to s\mu\mu$ and $b \to c\tau\nu$

  $\to$ discriminate the Lorentz structure of NP

- NC and CC anomaly have a common NP origin

  $b \to s\nu\nu$, $b \to s\tau\tau$, τ/μ LFV

- and are connected to the SM flavour hierarchies ($U(2)$ flavour symmetry)

  relate $b \to c$ and $b \to u$, $b \to s$ and $b \to d$

  $\to$ discriminate the flavour structure of NP

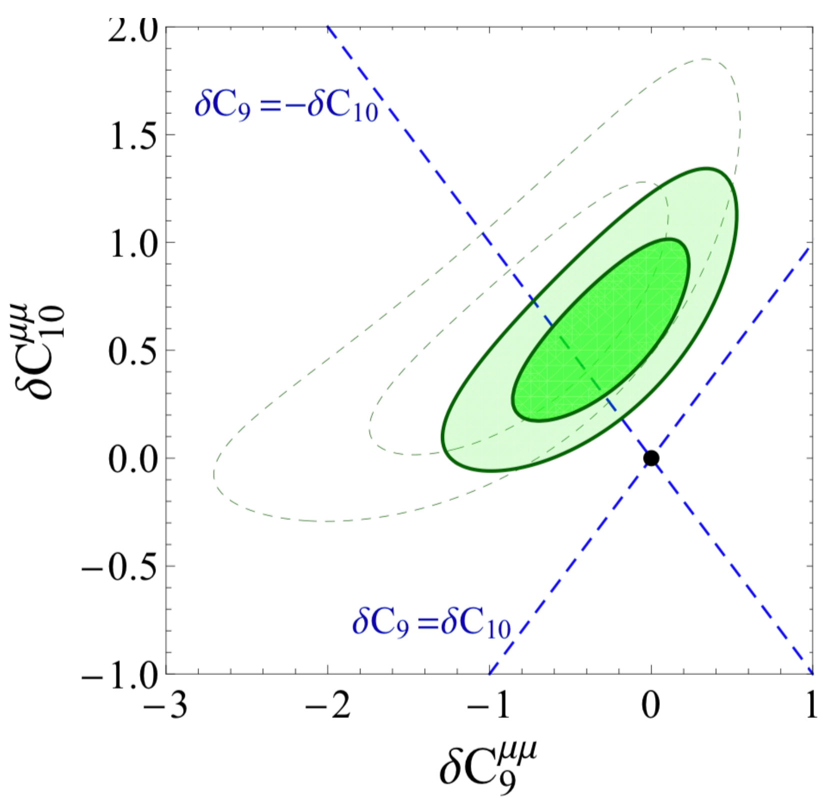
Observables in $b \to s\mu\mu$

[see talks by Paula Alvarez Cartelle and Francesco Polci, Peter Stangl and Sébastien Descotes-Genon]

$$\mathscr{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[C_9(\mu)\,(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}\gamma_\mu \mu) + C_{10}(\mu)\,(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}\gamma_\mu \gamma_5 \mu) \right] + \ldots$$

Different observables are complementary in pinning down NP structure.

Fit to $\mathscr{B}(B_s \to \mu\mu)$ and $R_K^{(*)}$ only:



[Sumensari @ Implications 2019]

- $C_9^\mu = -C_{10}^\mu$: $R_K = R_{K^*} = R_\phi = R_{pK}$
- $R_K \neq R_K^* \quad \to \quad C_{9,10}^{(\prime)} \neq 0$

Wishlist: updates on R_{K^*}

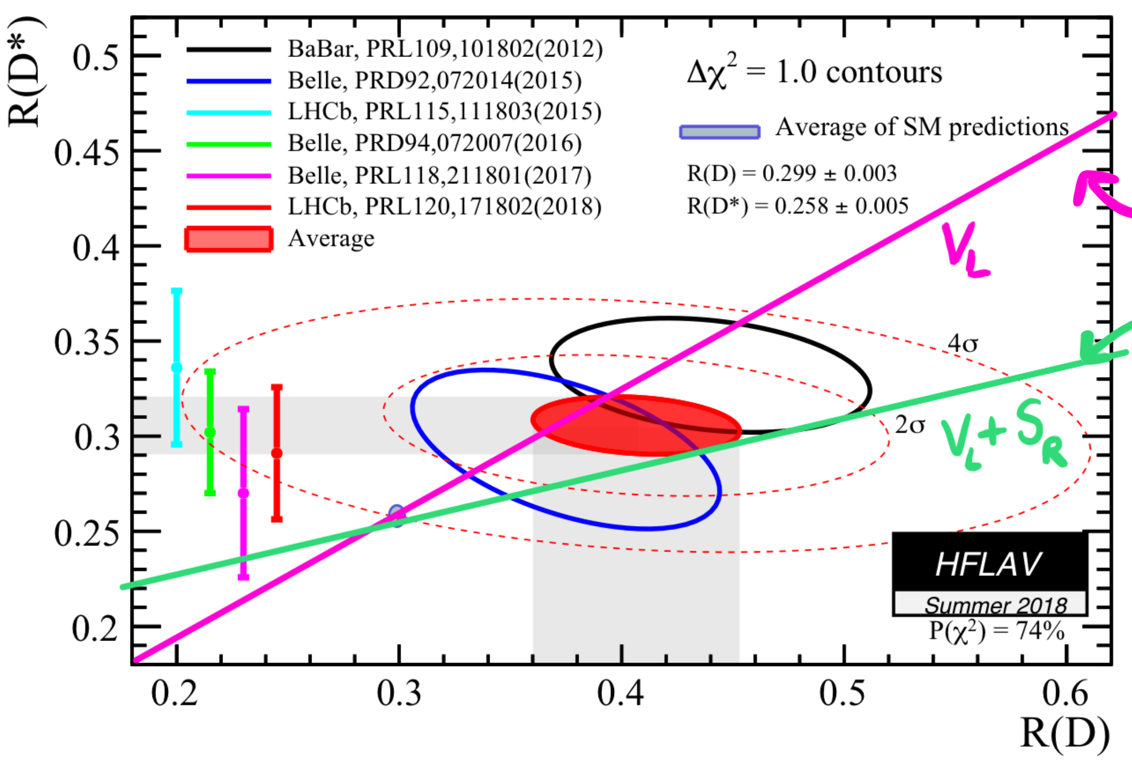
other LFU ratios, e.g. R_ϕ, R_{pK}

Observables in $b \to c\tau\nu$

[talks by Mark Smith and Rodrigo Alonso]

$$\mathscr{L}_{\text{eff}} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)+g_{V_R}(\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_L)+g_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R\nu_L)+g_T(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)\Big]$$

Also here, obs. in the same partonic transition give complementary info:



- NP in LFU ratios:

V_L only $\quad \Delta R_D = \Delta R_D^* \; (= \Delta R_{J/\Psi} = \Delta R_{\Lambda_c})$

$S, T \neq 0 \quad \Delta R_D \neq \Delta R_{D*}$

- Angular observables: largely insensitive to V_L, powerful probe of S, T

Wishlist: updates on $R_{D*}, R_{J/\Psi}$, ang. obs. in $B \to D^{(*)}\tau\nu$, other LFU ratios: R_{D^+}, R_{Λ_c}

Combined explanation of $b \to c\tau\nu$ and $b \to s\mu\mu$

[talks by Gino Isidori and Joe Davighi]

B anomalies fit nicely together in the SMEFT.

Minimal solution with $SU(2)_L$ triplet + singlet,

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

Additional scalar/tensor contributions possible and realised in explicit models (e.g. $U_1 \sim (3,1)_{2/3}$ with couplings to RH fermions).

In this setup:

- direct matching gives $C_9^\mu = -C_{10}^\mu$
- V_L (+ S_R) solution to $b \to c\tau\nu$ anomaly
- large $b \to s\tau\tau$ generates $\Delta C_9^{\mathrm{uni}}$ via RGE mixing

! $b \to s\nu_{(\tau)}\bar{\nu}_{(\tau)}$ sets tight constraint on $|C_{\ell q}^{(3)} - C_{\ell q}^{(1)}|$

$\to$ need to enforce $C_{\ell q}^{(1)} \approx C_{\ell q}^{(3)}$ (automatically satisfied for U_1)

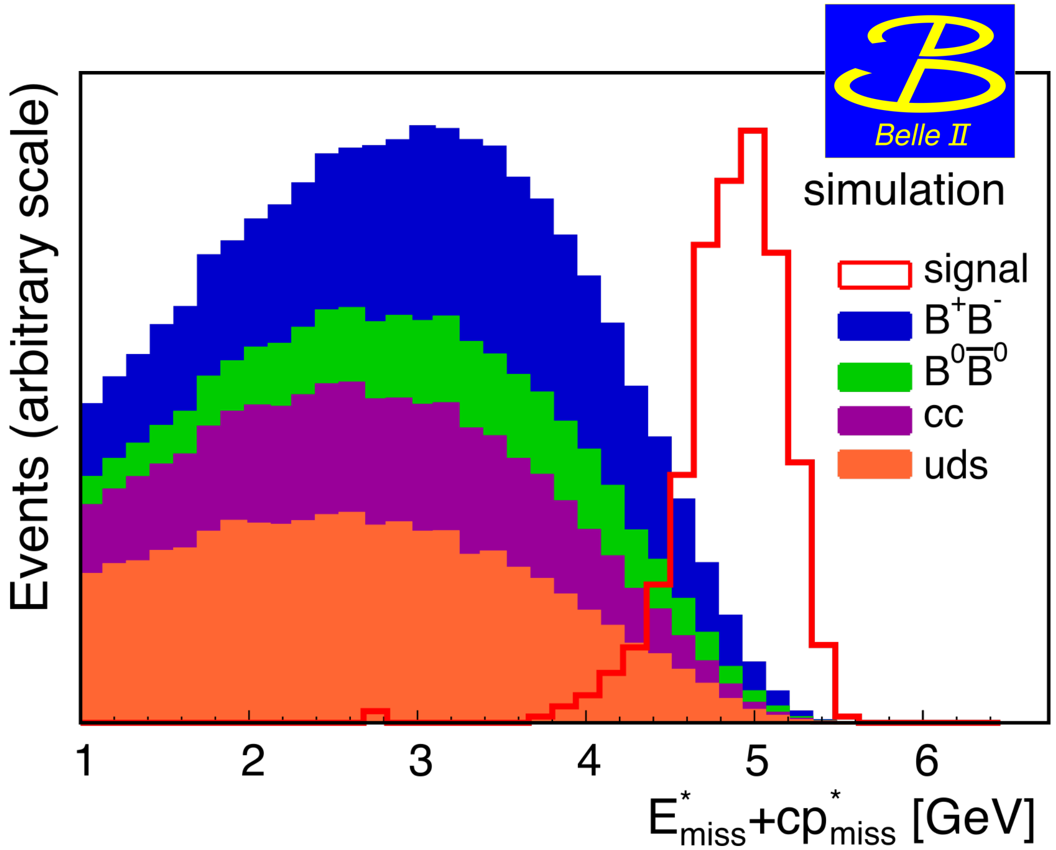
$B \to K\nu\nu$

- Assuming SM rate, this will be observed at Belle II

- $10\,\%$ uncertainty on $\mathscr{B}$ with $50\ \mathrm{ab}^{-1}$
  PTEP(2019)123C01

- First observation in couple of years (assuming the schedule doesn't drag too much) or a couple of ab^{-1}.

- Can form $E^{*}_{\mathrm{miss}} + cp^{*}_{\mathrm{miss}}$ to give a peaking "mass" distribution.



$b \to s\tau\tau$ and $b \to s\tau\mu$

Two main consequences:

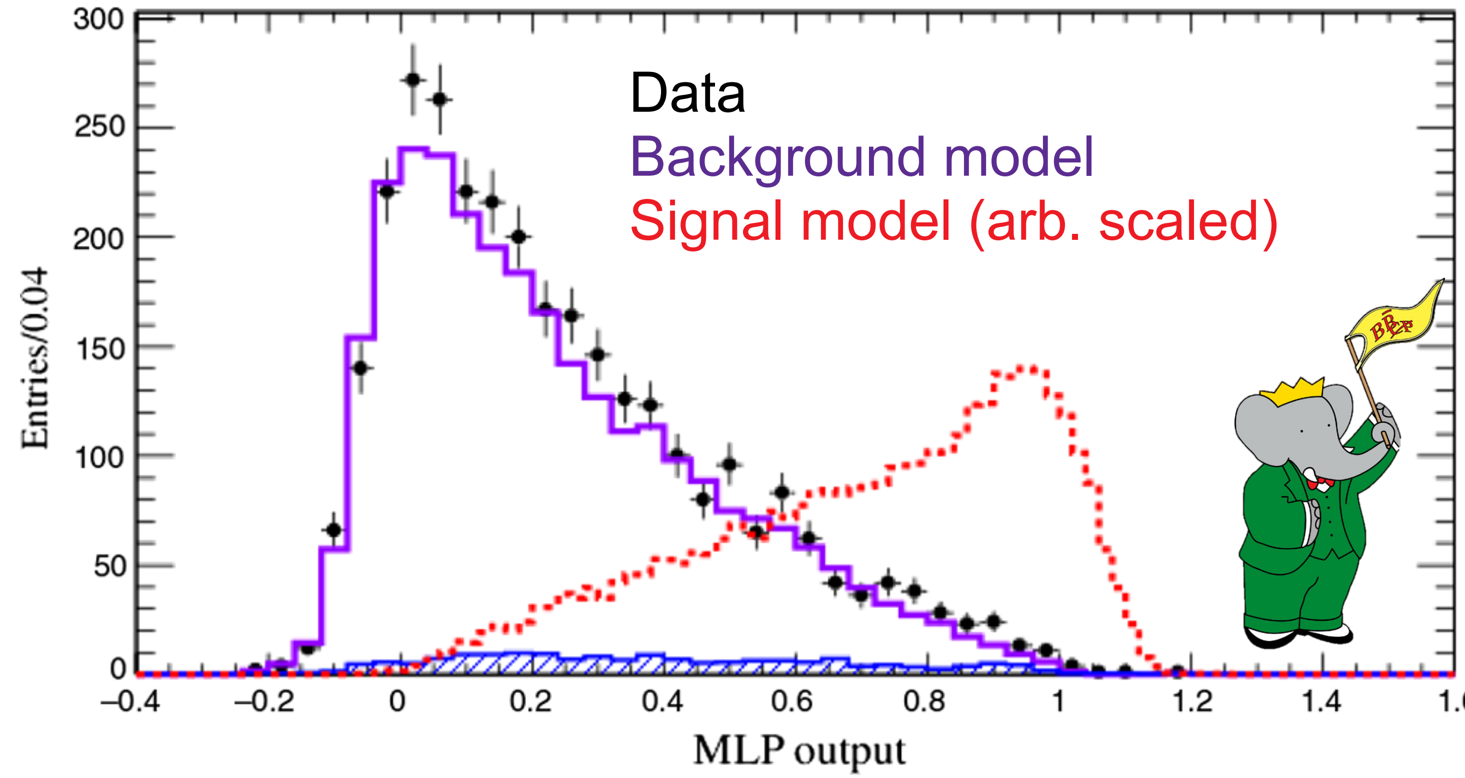
- Huge enhancement in $b \to s\tau\tau$ (size driven by $R_{D^{(*)}}$)
- Large $\tau\mu$ LFV (size driven by $R_{K^{(*)}}$)

	$C_{\ell edq} = 0$	$C_{\ell edq} \neq 0$	SM	Exp
$B_s \to \tau^+\tau^-$	10^{-5}	10^{-4}	10^{-7}	$< 3.4 \cdot 10^{-3}$
$B^+ \to K^+\tau^+\tau^-$	10^{-5}	10^{-4}	$1.2 \cdot 10^{-7}$	$< 2.25 \cdot 10^{-3}$
$B_s \to \tau^\pm\mu^\mp$	10^{-7}	10^{-6}	-	$< 2.1 \cdot 10^{-5}$
$B^+ \to K^+\tau^+\mu^-$	10^{-8}	10^{-7}	-	$< 1.7 \cdot 10^{-5}$
$\tau \to \mu\gamma$	-	10^{-9}	-	$< 3.0 \cdot 10^{-8}$
$\tau \to \mu\phi$	10^{-11}	10^{-11}	-	$< 5.1 \cdot 10^{-8}$

$B \to K\tau\tau$

- Only Babar has published: PRL.118.031802.
- Belle search is in preparation (but expect a similar sensitivity)
- Belle II can't see SM with $50\ \mathrm{ab}^{-1}$, we can get to $\mathbf{10^{-5}}$

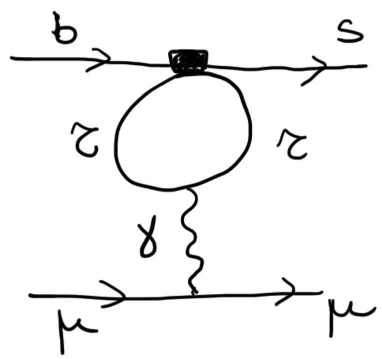
PTEP(2019)123C01



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

Probing $B \to K\tau\tau$ in $B \to K\mu\mu$

[CC et al., 2001.04470]



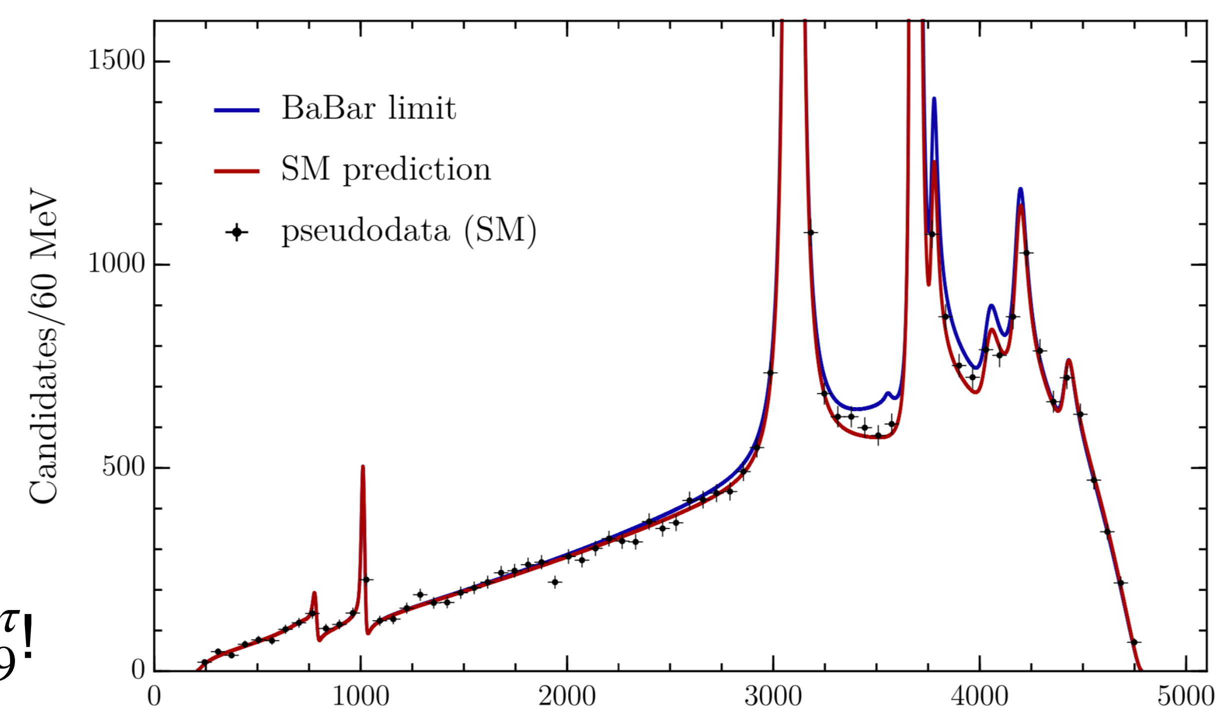
EW loop, but room for large NP in $b \to s\tau\tau$.

Non-local effect, distinct from O_9^μ -O_9^τ mixing.

Unique imprint on the $B \to K\mu\mu$ dimuon spectrum:

- cusp at $\tau\tau$ threshold
- q^2-distortion above/below

$\to$ model independent extraction of C_9^τ!



Sensitivity @ LHCb:	$\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 2.7 \cdot 10^{-3}$	Run I-II
	$< 1.5 \cdot 10^{-4}$	LHCb upgrade II

…competitive with direct bound!

$\tau \to \mu\gamma$

- Can use event shape variables to get relatively clean tau event selection.
  - Still “tagging”, but more efficient
  - Beam background is potential issue

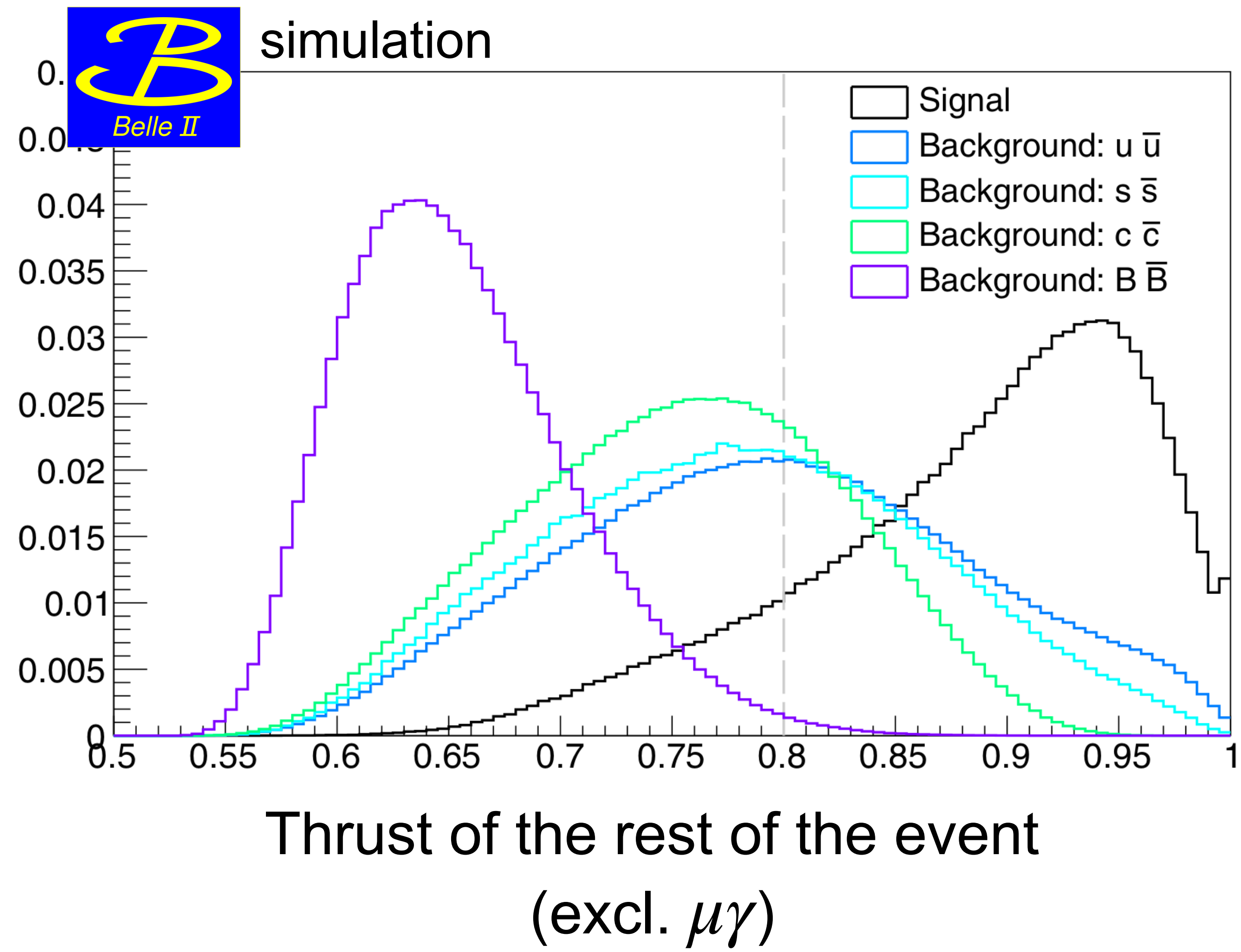
- Belle & BaBar published

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

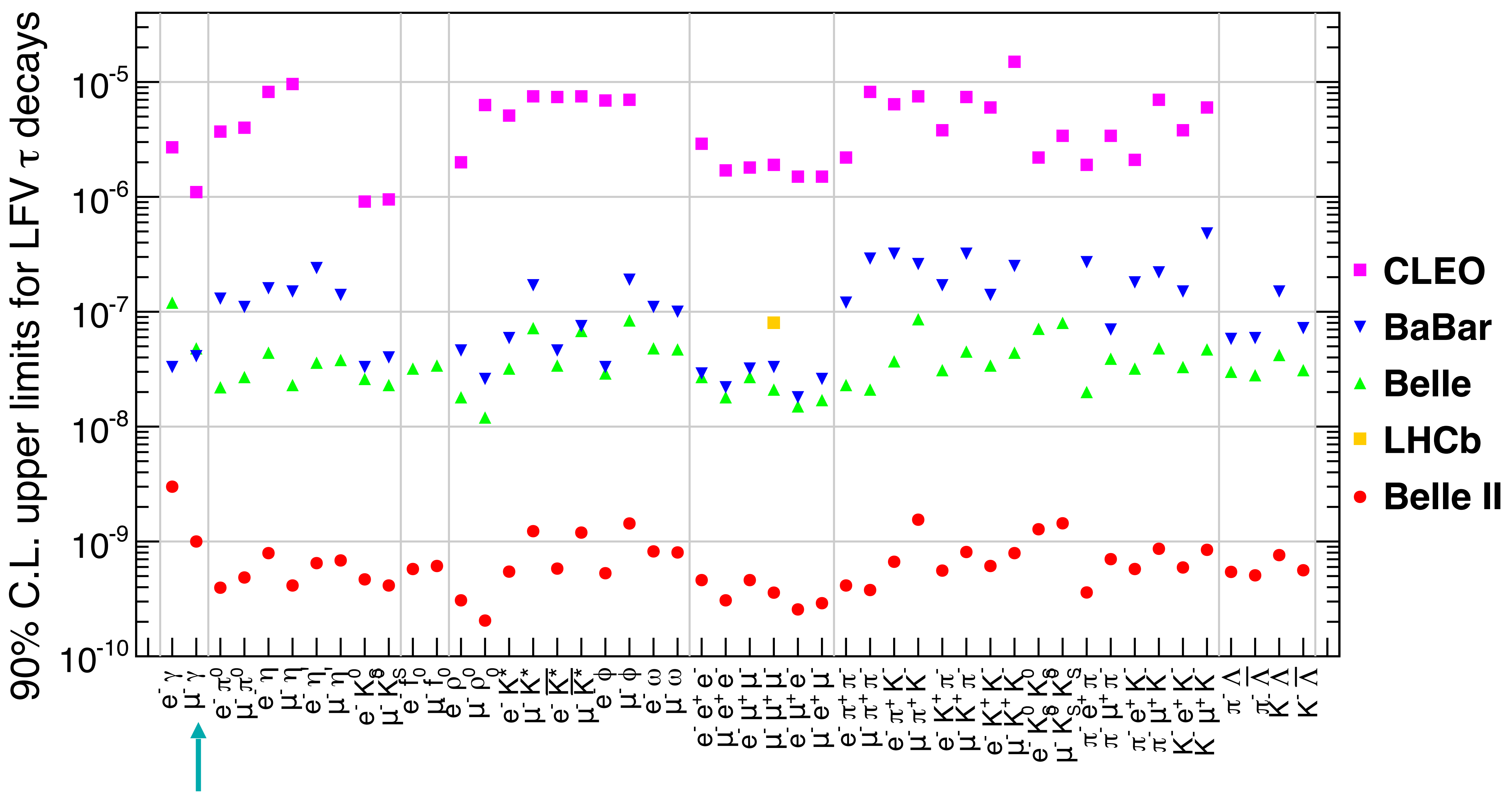
  PRL104(2010)021802
  Phys.Lett.B666(2008)

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

  PTEP(2019)123C01



$\tau \to \mu\gamma$



B anomalies and SM hierarchies

Combined explanation requires NP with a non-trivial flavour structure: large couplings to 3rd gen., smaller couplings to light families.

This resembles the SM Yukawa couplings!

? Is there an underlying flavour symmetry? Can we test it?

Flavour hierarchies <u>and</u> anomalies can be described by a [minimally broken] $U(2)^5$ flavour symmetry!

- Theoretically fascinating [more in Gino Isidori's talk]
- Experimentally testable: equipping EFT with flavour symmetry & breaking terms leads to testable predictions, both in CC and NC.

$U(2)^5$ symmetry & breaking terms

[Barbieri et al.,Eur.Phys.J.C 71 (2011) 1725]

The Yukawa couplings in the SM respect an approximate

$$U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e,$$

minimally broken to recover SM mass matrices:

$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad U(2)_{q,\ell} \quad U(2)_{u,d,e}$$

$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} \boldsymbol{\Delta_{u,d,e}} & \boldsymbol{V_{q,\ell}} \\ 0 & 1 \end{pmatrix} \quad |\boldsymbol{V_q}| \sim V_{cb} \quad |\boldsymbol{\Delta_{u,d,e}}| \sim y_{c,s,\mu}$$

Unbroken symmetry

Minimally broken symmetry

Idea: NP Lagrangian respects the same symmetry, broken only by $V_{q,\ell}$

This gives a good fit to B anomalies for $|V_{q,\ell}| \sim \mathcal{O}(10^{-1})$

SMEFT + $U(2)^5$

[Fuentes-Martín et al., Phys.Lett.B 800 (2020) 135080]

Taking (semileptonic) SMEFT + minimally broken $U(2)^5$, few operators survive:

$$\mathscr{L}_{\rm EFT} \supset \mathscr{L}_{\rm SM} - \frac{1}{v^2}\left[C_V\,\Lambda_V^{[ij\alpha\beta]}\left(\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right)^{[ij\alpha\beta]} + \left(2\,C_S\,\Lambda_S^{[ij\alpha\beta]}\,\mathcal{O}_{\ell edq}^{[ij\alpha\beta]} + \mathrm{h.c.}\right)\right]$$

NP parameters: C_V, C_S [NP strength] $\Lambda_V = \Gamma_L^\dagger \times \Gamma_L$, $\Lambda_S = \Gamma_L^\dagger \times \Gamma_R$ [Flavor structure]

- $U_1 \sim (3,1)_{\frac{2}{3}}$ is the only single mediator with one to one matching to this structure
- $S_1 + S_3$ also works, with $C_S = 0$

At lowest order in the symmetry breaking terms ($V_{q,\ell}$),

$$\Gamma_L \approx \begin{array}{c} \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\ \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ 0 & \lambda_\ell^\mu & 1 \end{pmatrix} \end{array} \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \qquad \lambda_q^s, \lambda_\ell^\mu \sim O(10^{-1}) \qquad \Delta_{q\ell}^{s\mu} \sim O(10^{-2})$$

$$\Gamma_R \approx \begin{array}{c} \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_b}{m_s}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_b & 1 \end{pmatrix} \end{array} \begin{array}{c} d_R \\ s_R \\ b_R \end{array}$$

Testing the $U(2)^5$ ansatz

$b \to c$ and $b \to u$, $b \to s$ and $b \to d$ transitions are connected, because they depend on the same breaking term!

$$\frac{b \to c\ell\nu}{b \to u\ell\nu} = \left.\frac{b \to c\ell\nu}{b \to u\ell\nu}\right|_{\mathrm{SM}}$$

$$\frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\mathrm{SM}}$$

$$\frac{R_\pi^{(*)}}{R_\pi^{\mathrm{SM}}} \approx 0.75\,\frac{R_D}{R_D^{\mathrm{SM}}} + 0.25\,\frac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}}$$

$$\frac{\mathcal{B}(\bar{B}_u \to \tau\bar{\nu})}{\mathcal{B}(\bar{B}_u \to \tau\bar{\nu})_{\mathrm{SM}}} \approx \frac{\mathcal{B}(\bar{B}_c \to \tau\bar{\nu})}{\mathcal{B}(\bar{B}_c \to \tau\bar{\nu})_{\mathrm{SM}}}$$

$$R_K \approx R_{K^*} \approx \frac{\mathcal{B}(B \to \pi\mu\bar{\mu})}{\mathcal{B}(B \to \pi e\bar{e})}$$

$$\frac{\mathcal{B}(B_s \to \mu\mu)}{\mathcal{B}(B_s \to \mu\mu)_{\mathrm{SM}}} \approx \frac{\mathcal{B}(B_d \to \mu\mu)}{\mathcal{B}(B_d \to \mu\mu)_{\mathrm{SM}}}$$

$$^{(*)}R_\pi \equiv \frac{\mathcal{B}(B \to \pi\tau\nu)}{\mathcal{B}(B \to \pi\ell\nu)}$$

[see talk by Aleksey Rusov]

$B \to \pi \ell \nu$

- Belle has set a limit

$$\mathscr{B}(B \to \pi \tau \nu) < 2.5 \cdot 10^{-4}$$

Phys.Rev.D93(2016)032007

- Ratio $\dfrac{\mathscr{B}(B \to \pi \tau \nu)}{\mathscr{B}(B \to \pi \ell \nu)}$

- At Belle II with a few ab^{-1} can measure the ratio to $30\,\%$

- Full $50\ \mathrm{ab}^{-1}$ can get to $10\,\%$
  PTEP(2019)123C01

$B \to \pi \ell \ell$

- LHCb has observed $B \to \pi \mu \mu$

JHEP10(2015)034

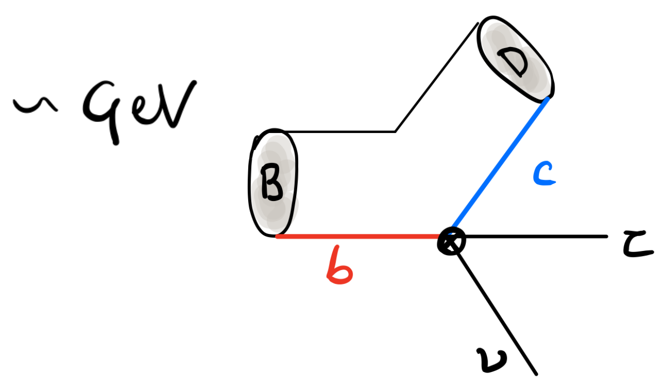
- According to the upgrade note, LHCb needs $300\ \mathrm{fb}^{-1}$ to be able to form

$$\frac{\mathscr{B}(B \to \pi \mu \bar{\mu})}{\mathscr{B}(B \to \pi e \bar{e})}$$

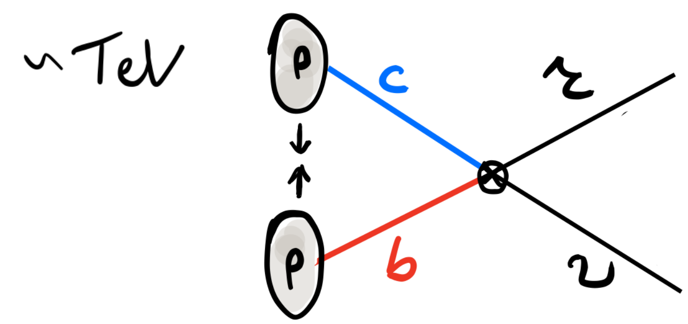
- Very rough and unofficial number puts Belle II at $\sim 300\ \ B \to \pi \ell \ell$ events in $50\ \mathrm{ab}^{-1}$ ….looks like we could measure that ratio too.

Probing flavour at high-p_T

“ traditional” flavour searches



flavour searches at high-p_T



- are complementary: test the same underlying NP in different kin. regimes
- can compete:

e.g. in $pp \to \ell\nu$

$$\frac{\mathcal{L}_{ij} \times |V_{ij}|^2 \times \left(\frac{M_W^2}{\hat{s}} - \epsilon_L\right)^2}{\mathcal{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{M_W^2}{\hat{s}}\right)^2}$$

energy enhancement of NP cross section

$(\hat{s}/M_W^2)^2 \sim \mathcal{O}(10^5)$

PDF suppression

$\mathcal{O}(10^{-5})$ for bc

[Javier Fuentes-Martin @ CAFPE 2019]

High-p_T vs low energy

Low energy	High - p_T	How well does high-p_T?	
$b \to s\mu\mu$	$pp \to \mu\mu$	[Unless large couplings to valence quarks] [Greljo et al, Eur.Phys.J.C 77 (2017) 8, 548]	
$b \to s\tau\mu$	$pp \to \tau\mu$	[Angelescu et al., 2002.05684]	
$b \to c\tau\nu$	$pp \to \tau\nu$	[Greljo at al.,1811.07920]	
$b \to s\tau\tau$	$pp \to \tau\tau$	[Faroughy et al., 1609.07138] [Fuentes-Martin et al., 2003.12421]	

Conclusions

- $B \to K\tau\tau$ is ***cool***.
  - Nice interplay between experiments:
    - direct @ Belle II
    - vs. indirect @ LHCb via $B \to K\mu\mu$,
    - vs. bounds from high p_T.
  - Discussion point: **could LHCb do $B \to K^{(*)}\tau\tau$ directly?**
  - Do you prefer the K^{*0} for the $K\pi$ vertex? Should be equally interesting.
  - $B_s \to \tau^+\tau^-$ is also cool. Will there be an update?

- If we allow [min. broken] $U(2)^5$ **symmetry**, then we also expect corroboration from $B \to \pi\tau\nu$ and $B \to \pi\ell\ell$.
  - Maybe some fun competition Belle II vs. LHCb regarding R_π.

- LFU ratios and $b \to c\tau\nu$ measurements are also corroborating!
  - Didn't focus on them because of previous talk, and the session tomorrow.
  - To be discussed then?

	th.	LHCb	B2		th.	LHCb	B2		th.	LHCb	B2
$b \to s\mu\mu$ only				**Combined**				**$b \to c\tau\nu$ only**			
R_K, R_{K^*}	**	✓ **	**	$B \to K\tau\tau$	**	?	**	R_D, R_{D^*}	**	✓ *	**
R_φ	**	*	✗	$B_s \to \tau\tau$	**	?		$R_{\Lambda c}$	**		✗
R_{pK}	*	*	✗	$B \to K\tau\mu$	**	✓ *	*	$R_{J/\psi}$	**	✓	
$B \to K\mu\mu$	*	✓ **	**	$B_s \to \tau\mu$	**	U *		$B_c \to \tau\nu$	**	?	✗
$B_s \to \mu\mu$	**	✓ **		$B \to K\nu\nu$	**	✗	**	$B \to D\tau\nu$ (angular)	**		**
				$\tau \to \mu\gamma$	**		**				
$pp \to \mu\mu$	*	[high p_T]		$pp \to \tau\mu$	*	[high p_T]		$pp \to \tau\nu$	**	[high p_T]	
$b \to d\mu\mu$ only								**$b \to d\tau\nu$ only**			
								$\mathcal{B}\,[B \to \pi\tau\nu]$ / $\mathcal{B}\,[B \to \pi\mu\nu]$	*	?	**
R_π	*	U *	*	$B \to \pi\tau\tau$	*						
$B_d \to \mu\mu$	*	✓ **	**	$B \to \pi\nu\nu$	*			$\mathcal{B}\,[\Lambda_b \to p\tau\nu]$ / $\mathcal{B}\,[\Lambda_b \to p\mu\nu]$	*		✗
				$B \to \pi\tau\mu$	*						
								$\mathcal{B}\,[B_s \to K^*\tau\nu]$ / $\mathcal{B}\,[B_s \to K^*\mu\nu]$	*		✗

Key:

✓	paper exists
U	need upgrade [LHCb-PUB-2018-009]
✗	cannot be done
?	I wasn't sure

Backup

Full event interpretation

- $\Upsilon(4S) \rightarrow BB$ events can be split.
- "Tag" side object reconstructed from generic B decays.
- Train a fast BDT to return a tag *candidate* and probability.
- Trade-off: constraint + purity vs. efficiency.
- Can have a fully constrained hadronic decay, but take a hit in efficiency.
- This isn't new: was done at Belle (BaBar did something similar). Improvements due to speed + adding generic decay modes.

	$B^{\pm}$ (%)	B^{0} (%)
Hadronic		
FEI	0.76	0.46
FEI w/ Belle channels	0.53	0.33
Belle	0.28	0.18
BaBar	0.4	0.2
Semileptonic		
FEI	1.08	2.04
Belle	0.31	0.34
BaBar	0.3	0.6

Comput.Softw.Big Sci. 3 (2019)

Belle II status

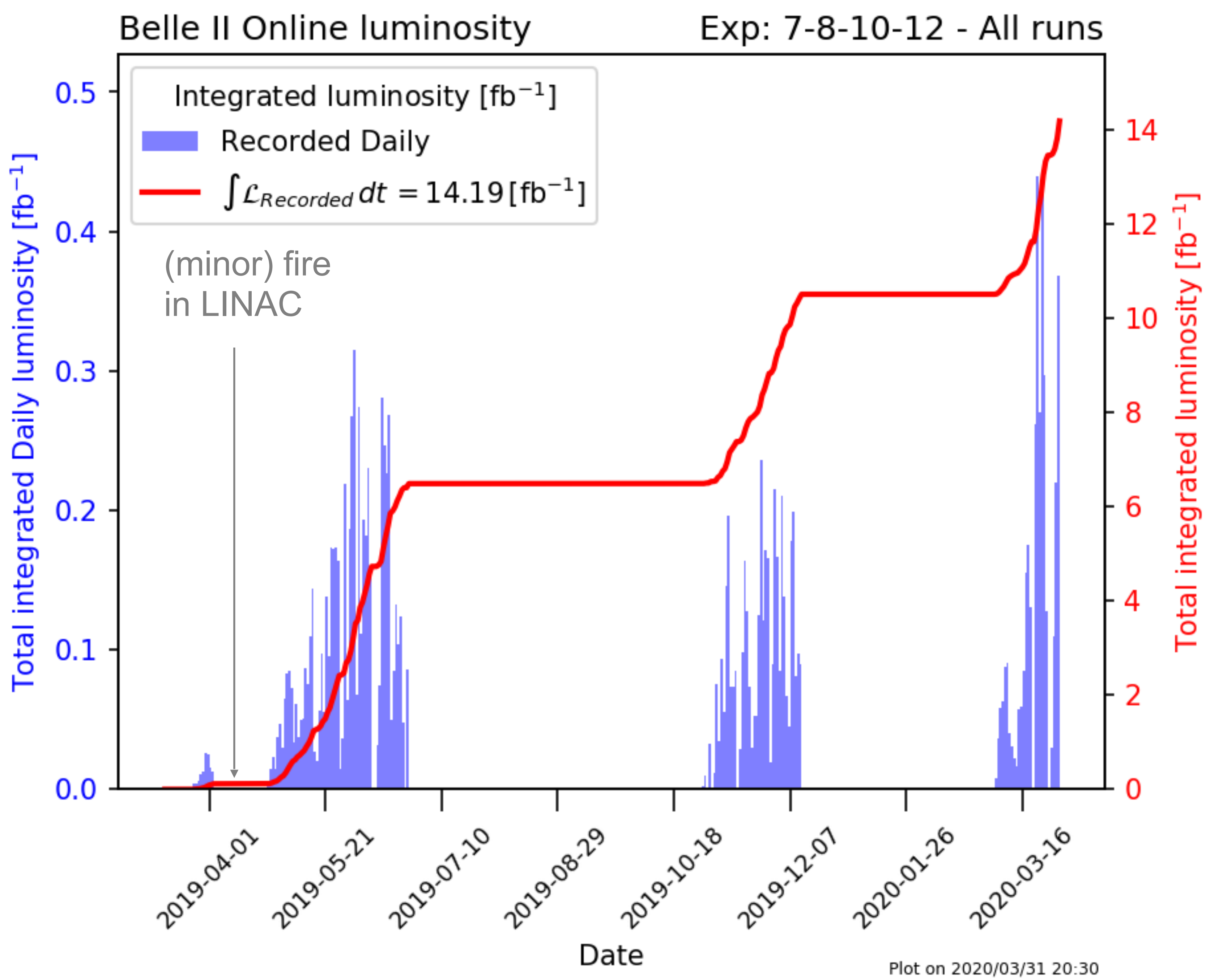
Taking data right now!

2018: $0.5\ \text{fb}^{-1}$
w/o vertex detector.

2019: $10\ \text{fb}^{-1}$.

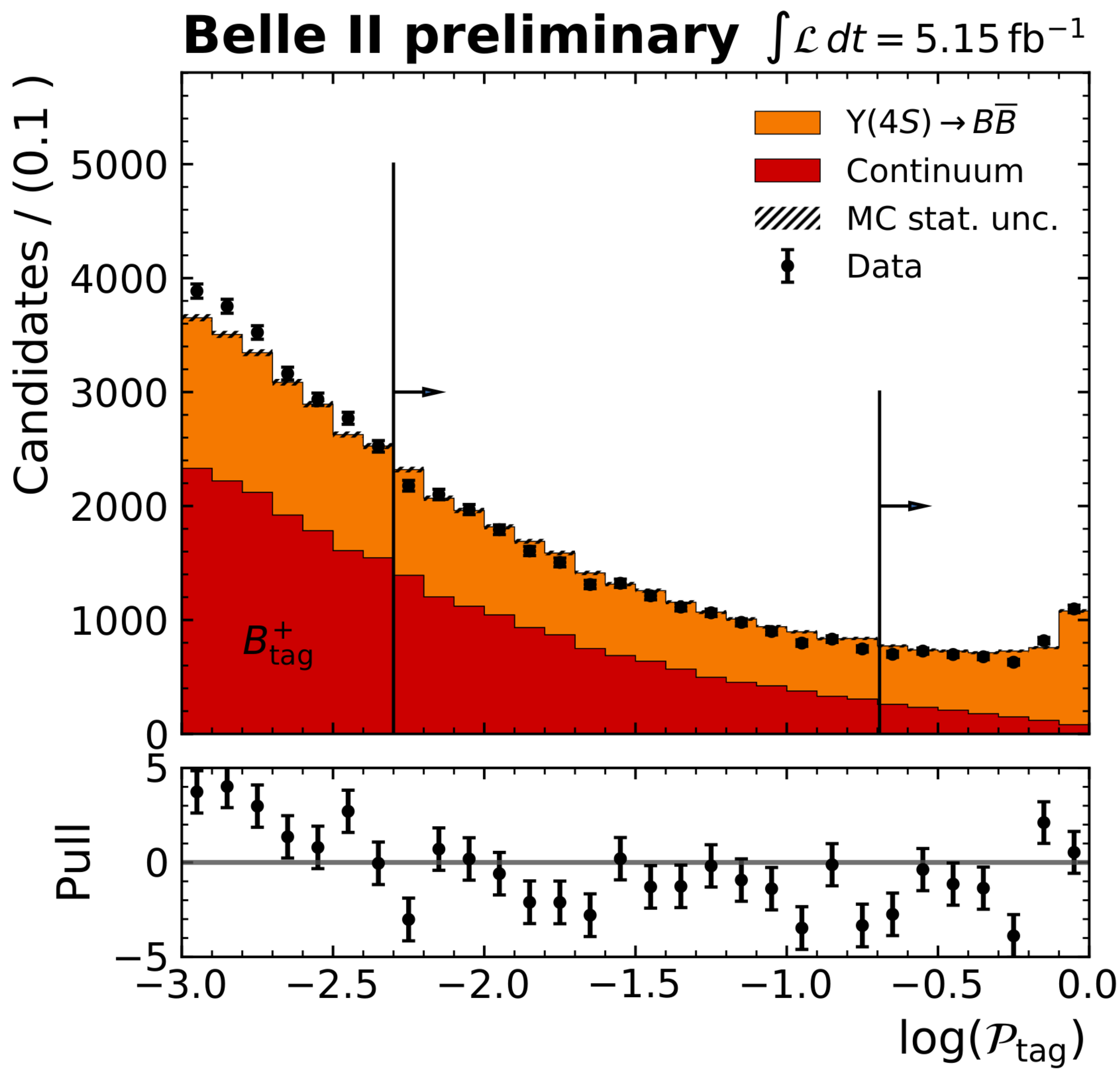
2020: $\sim 3\ \text{fb}^{-1}$ so far!

2±1 papers on **2018** data.
#0 ChinPhys.C41021001.
#1/2 is arXiv:1912.11276.
#2/2 is < a little delayed >.



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

More details about the FEI



More details about $B \to K\nu\bar{\nu}$ and friends

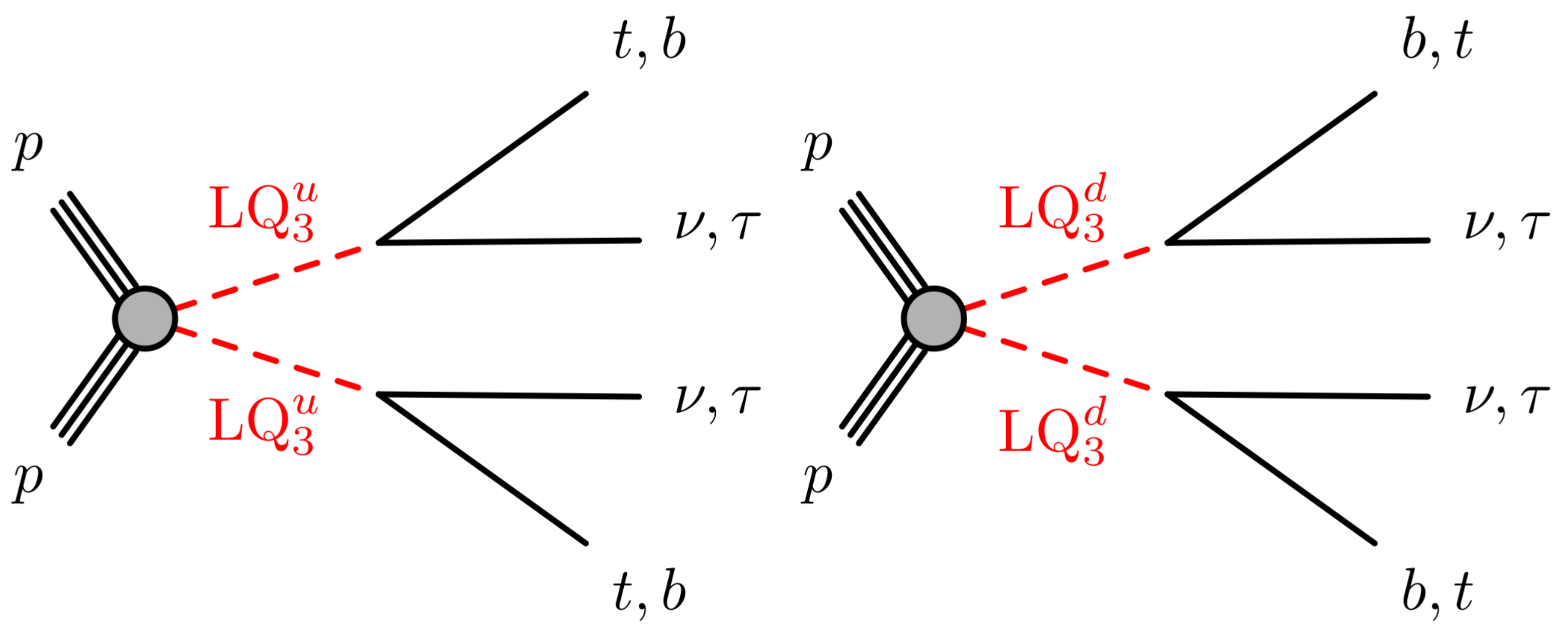
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	—	—	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	—	—	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	—

PTEP(2019)123C01

Belle II

ATLAS and CMS LQ searches

- Most recent limits are 2016 data $\sim \mathbf{36\ fb^{-1}}$
- CMS is Eur.Phys.J.C78(2018)707 (s), Phys.Rev.D.98.032005 (v)
- ATLAS JHEP06(2019)144.
- (*c.f.* $137\ \mathrm{fb}^{-1}$ that they have 2016-18).
- Search for, eg. $2\tau + 2b$ jets.
- Excluded up to $\sim \mathbf{1400\ GeV}/c^2$

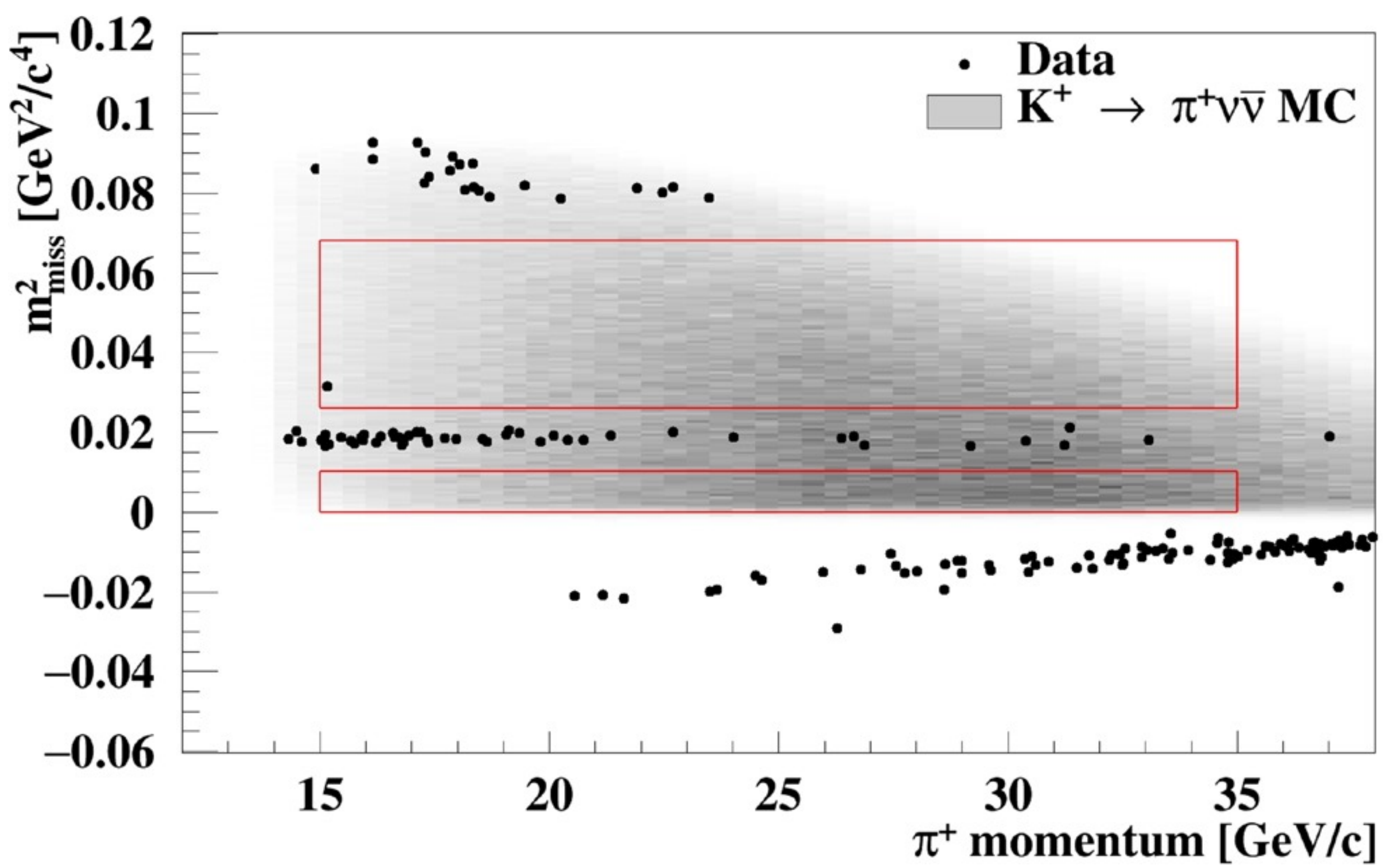


$K^+ \to \pi^+ \nu \bar{\nu}$ @ NA62

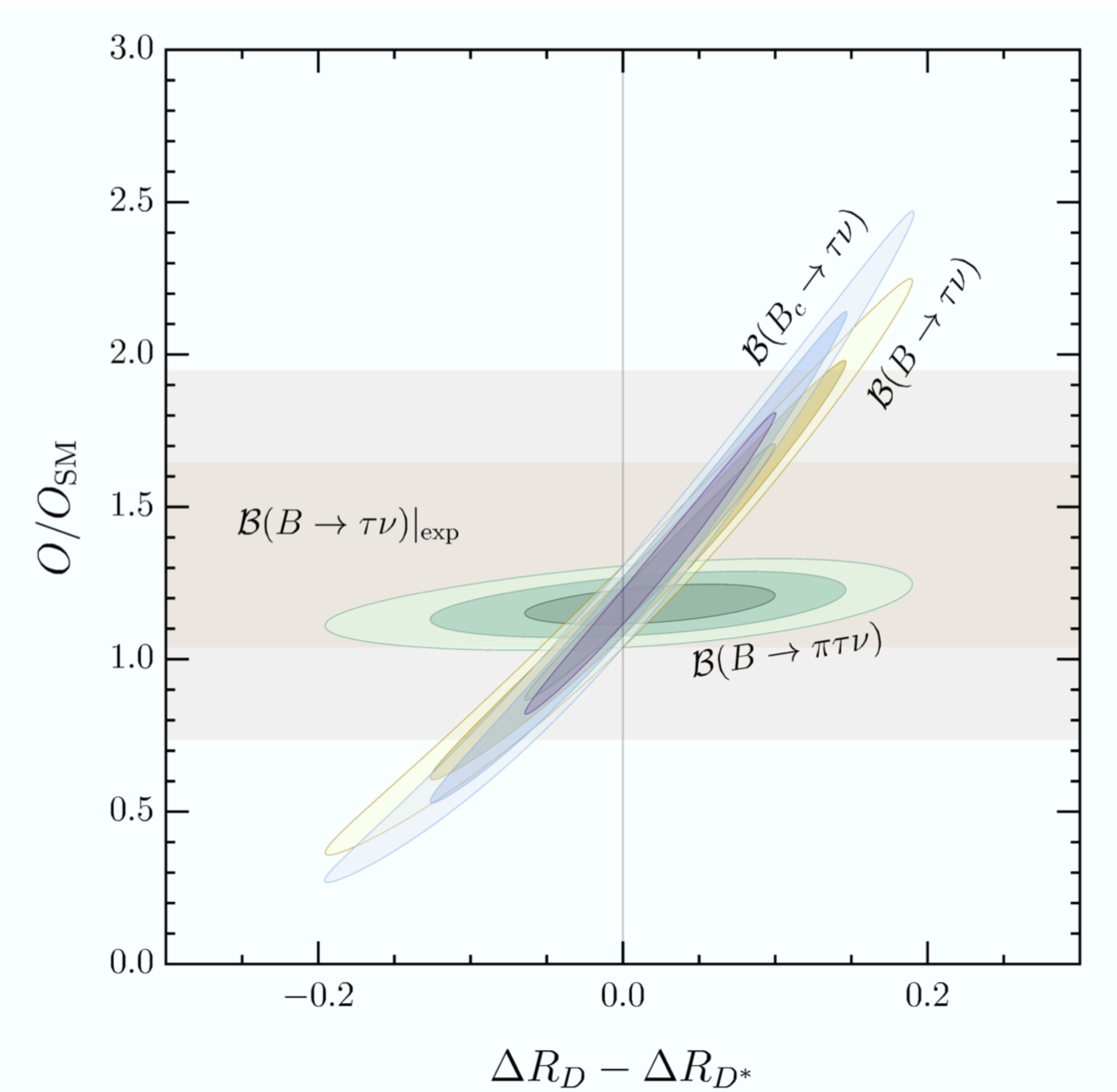
- Buras et al say $(9.11 \pm 0.72) \cdot 10^{-11}$ JHEP11(2015)33.
- NA62 performed a first search w/ combined 2016 & 17 dataset.
  Limit is at $18.5 \cdot 10^{-11}$ Phys.Lett.B791(2019)156.
- They talk in terms of a "Single Event Sensitivity", SES := 1 / (N_K, $\varepsilon_{\pi\nu\nu}$)

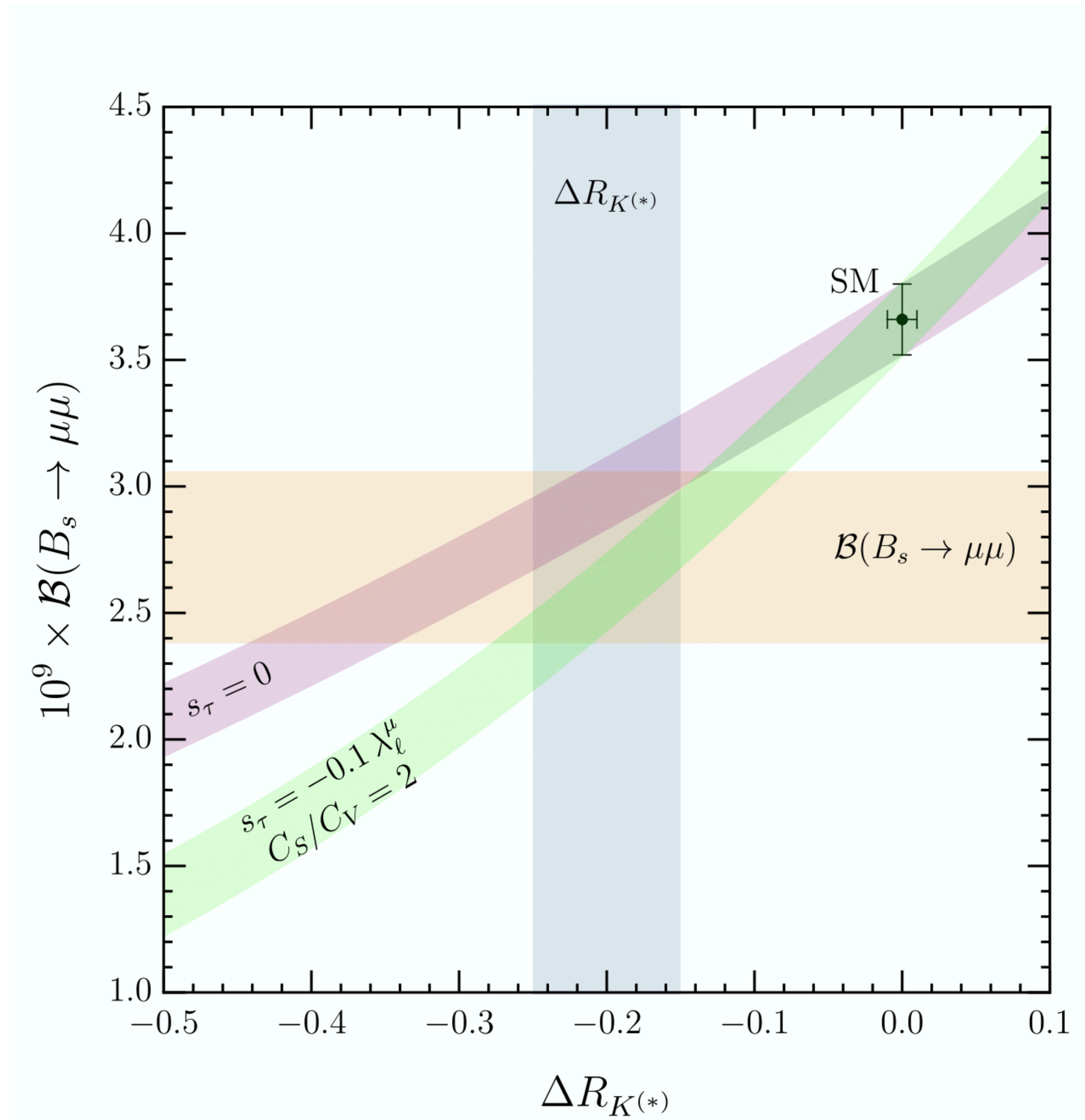
- Nice way to think about it. Express sensitivity in a FoM.

- Leading order effect is how well they know the acceptance.



Testing $U(2)^5$





$$\frac{b \to c\ell\nu}{b \to u\ell\nu} = \left.\frac{b \to c\ell\nu}{b \to u\ell\nu}\right|_{\rm SM}$$

$$\frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\rm SM}$$