Lepton Flavor Violation in rare B decays

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On behalf of the LHCb Collaboration,
with contributions from BaBar, Belle, Belle II

SM@LHC
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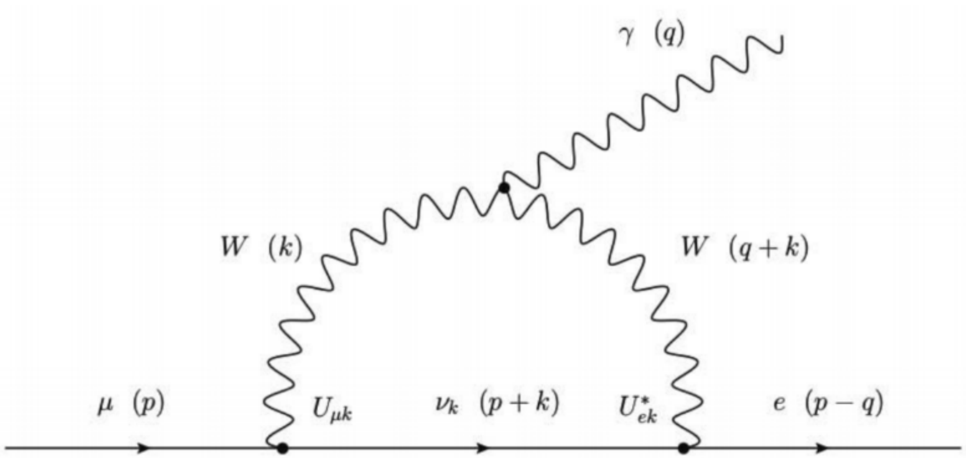
LFV in rare B decays

- **Lepton Flavor** is essentially (and accidentally...) conserved in the Standard Model
  - But not supported by strong theoretical reasons (e.g. underlying symmetry)
  - Neutrino oscillations → LFV → extension of SM (O(10^{-40}) → unobservable)… worse, 10^{-54}, in the charged lepton sector



$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M_W^2}\right|^2$$

$$\simeq 10^{-55} - 10^{-54}$$

  - LFV observation in the charged sector → New Physics

LFU → LFV

- While interest in lepton-flavour violation has been there for a long time, there is renewed interest, especially in the HF sector
  - Recent convincing (?) and coherent evidences of Lepton Flavor Universality violations in measurements by LHCb/Belle/BaBar
    - b → c charged currents: τ vs. light leptons (μ, e) [R_D , R_{D*} ,$R_{J/\psi}$]
    - b → s neutral currents: μ vs. e [R_K , R_{K*} (+ P_5' etc)]
  - LFU maybe just a low-energy property:
    - the different families may well have a very different behavior at high energies (explanation for their very different masses?).
  - Most BSM → allow (large) charged LF[U]V (exp 3rd generation)
    - SUSY, Extended Higgs, little Higgs, LQ, Z' [JHEP09(2017)040, Phys.Rev.D 59, 034019 (1999), Phys.Rev.Lett. 114 (2015) 091801, Phys.Rev.D 92, 054013 (2015), arXiv:1211.5168v3 JHEP12(2016)027(*), Phys.Rev.D86 (2012) 054023,arXiv:1505.05164, Phys.Rev.Lett. 118 (2017), 011801, JHEP11(2017)044, Phys.Rev.D 98, 115002 (2018), JHEP10(2018)148, arXiv:1903.11517 etc...]
  - LFUV → LFV

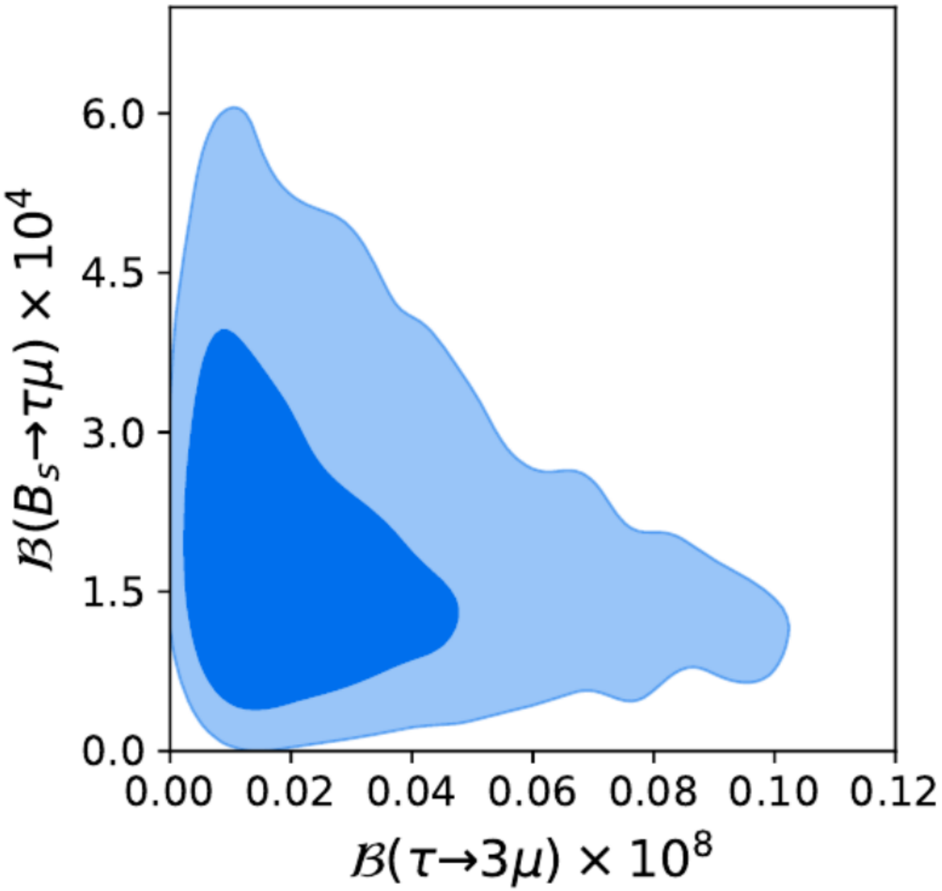
$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \sim 3 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2 , \; \mathcal{B}(B \to K(e^{\pm},\mu^{\pm})\tau^{\mp}) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2 ,$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 0.01 \left(\frac{1-R_K}{0.23}\right)^2 , \quad \frac{\mathcal{B}(B_s \to \tau^+(e^-,\mu^-))}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 4 \left(\frac{1-R_K}{0.23}\right)^2 .$$

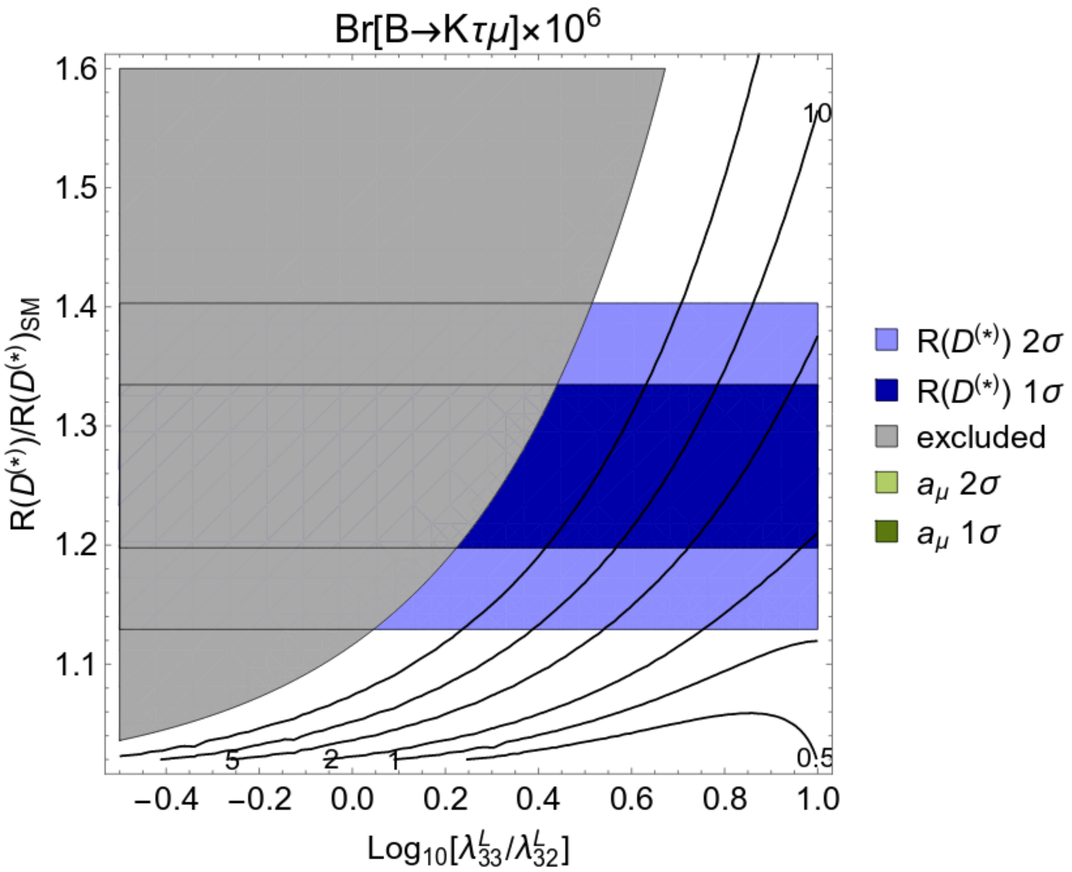
(*) Hiller Loose Schonwald

Exciting times

- If the anomalies are due to NP, we should expect to see several other BSM effects in LFV modes:



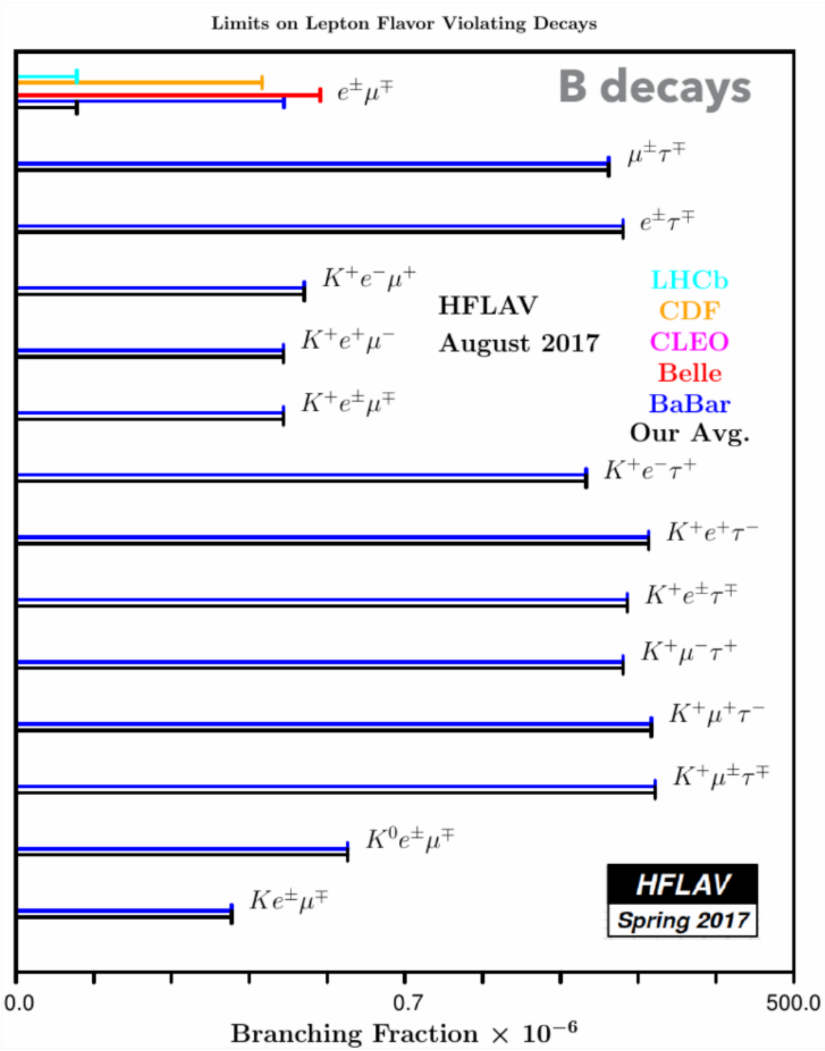
Bordone et al.
JHEP10(2018)148
(2018)



Crivellin, Mueller, Ota
JHEP09(2017)040

Summary of relevant modes

Decays	Experimental (**january 2018**) upper limit (90% CL)
$B_d \to \tau e$	$2.8\ 10^{-5}$ [2]
$B_s \to \tau e$	-
$B_d \to \tau\mu$	$2.2\ 10^{-5}$ [2]
$B_s \to \tau\mu$	-
$B_d \to e\mu$	$2.8\ 10^{-9}$ [3]
$B_s \to e\mu$	$1.1\ 10^{-8}$ [3]
$B_u \to K\tau\mu$	$4.8\ 10^{-5}$ [1]
$B_d \to K^*\tau\mu$	-
$B_u \to K\tau e$	$3.0\ 10^{-5}$ [1]
$B_d \to K^*\tau e$	-
$B_u \to K\mu e$	$9.1\ 10^{-8}$ [4]
$B_d \to K^*\mu e$	$5.8\ 10^{-7}$ [4]



[1] BaBar Phys. Rev. D 86, 012004 (2012)

[2] BaBar Phys.Rev.D77:091104 (2008)

[3] LHCb Phys.Rev.Lett. 111 (2013) 141801

[4] BaBar Phys. Rev. D73, 092001 (2006).

$B_{(s)} \to \tau\mu$

- Many BSM explaining the anomalies predict large $B(B_{(s)} \to \tau^{\pm}\mu^{\mp})$
  - Z': 10^{-8} [1] to 10^{-5} [2]
  - LQ: 10^{-9} [3] to 10^{-6} [4] to 10^{-5} [5]
  - PS 3 : 10^{-4} [6]
- Experimental status
  - $B(B^0 \to \tau^{\pm}\mu^{\mp}) < 2.2\ 10^{-5}$ [7]
  - $B(B_s^0 \to \tau^{\pm}\mu^{\mp})$: no limit yet

[1] Bečirević et al. [EPJ C76(2016)134]

[2] Crivellin et al. [PRD 92 (2015) 050413]

[3] Bečirević et al. [JHEP 11(2016)035]

[4] Bhattacharya et al [JHEP 01(2017)15]

[5] Smirnov [MPLA 33(2018)1550019]

[6] Bordone et al. [JHEP10(2018)148]

[7] BaBar, Phys.Rev.D77,091104(2008)

$B_{(s)} \to \tau\mu$

- Challenging search: at least a missing neutrino in the final state
- Tau decay modes
  - one-prong decays
    - $\tau^- \to e^- \nu_e \nu_\tau$: B =~17%
    - $\tau^- \to \mu^- \nu_\mu \nu_\tau$: B =~17%
    - $\tau^- \to \pi^- \nu_\tau$: B =~11%
    - $\tau^- \to \rho^- \nu_\tau$: B =~22%
  - three-prong decays
    - $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$: B =~9%
    - $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$: B =~5%
- BaBar & Belle (II)
  - can constraint the kinematic of the decay using the information of the other B and the centre of mass energy of the beam
  - can use the one-prong decays, accessing ~ 70% of the τ decays
- Not possible in hadron collider, even less with a forward detector
  - in LHCb: focus on the 3-prong mode → reconstruct the τ decay vertex

$B_{(s)} \to \tau\mu$

LHCb-PAPER-2019-016

NEW!

- **LHCb** analysis with Run 1 data (3 fb^{-1})
- Reconstruct $B_{(s)} \to \tau^{\pm}\mu^{\mp}$ candidates using the 3-prong τ decay
  - optimised for $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ (B=~9%)
    - $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ also contributes to some level ~7%)
- Compute corrected B invariant mass
  - blind signal region in data
- Background rejection
  - multivariate techniques, isolation variables, …
  - use same-sign data ($\tau^{\pm}\mu^{\pm}$) + simulation for qualitative studies
- Signal yields extraction
  - simultaneous fit to the mass distributions in bins of a final BDT
    - bins have different signal over background ratios
  - independently for B_s^0 and B^0
- Branching fractions normalised to the $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$ mode

$B_{(s)} \to \tau\mu$

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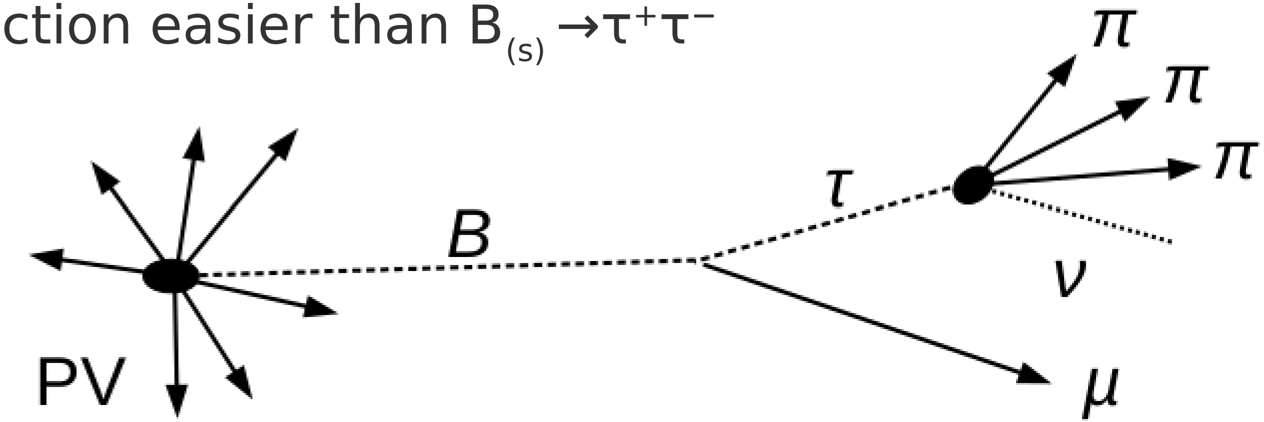
- Mass reconstruction easier than $B_{(s)} \to \tau^+\tau^-$



  - only one missing neutrino
  - only 4 tracks
  - the muon points to the B vertex
  - enough constraints to compute the neutrino momentum
  - hence the B mass with a 2-fold ambiguity

$$\begin{cases} {m_\tau}^2 = (E_{3\pi} + |\vec{p}_\nu|)^2 - (\vec{p}_{3\pi} + \vec{p}_\nu)^2 \\ \vec{x}_B \in (\mathrm{d}_\mu) \\ (\vec{p}_{3\pi} + \vec{p}_\nu) \parallel (\vec{x}_\tau - \vec{x}_B) \\ (\vec{p}_{3\pi} + \vec{p}_\mu + \vec{p}_\nu) \parallel (\vec{x}_B - \vec{x}_{\mathrm{PV}}) \end{cases}$$

$$M_B = \sqrt{(E_{3\pi} + E_\mu + |\vec{p}_\nu|)^2 - (\vec{p}_{3\pi} + \vec{p}_\mu + \vec{p}_\nu)^2}$$

$B_{(s)} \to \tau\mu$

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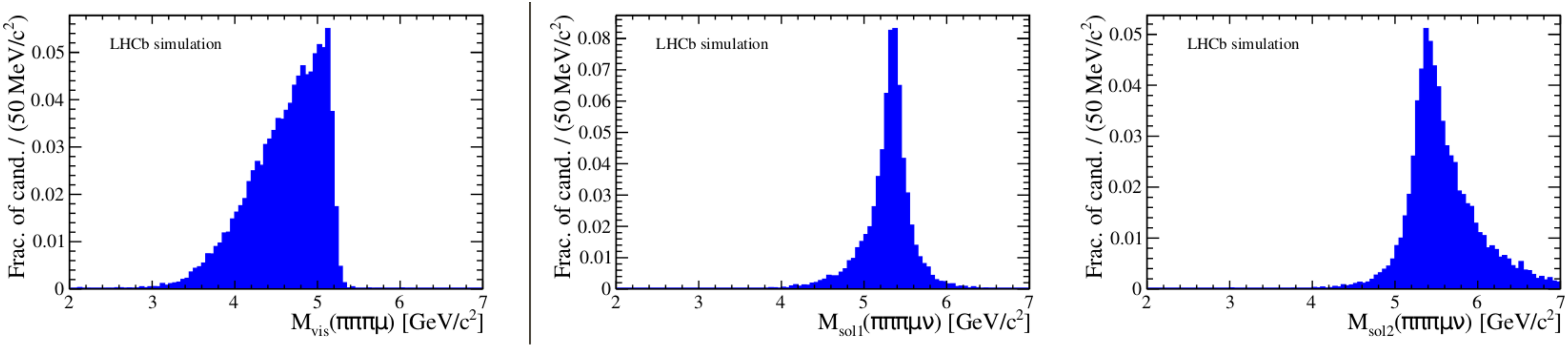
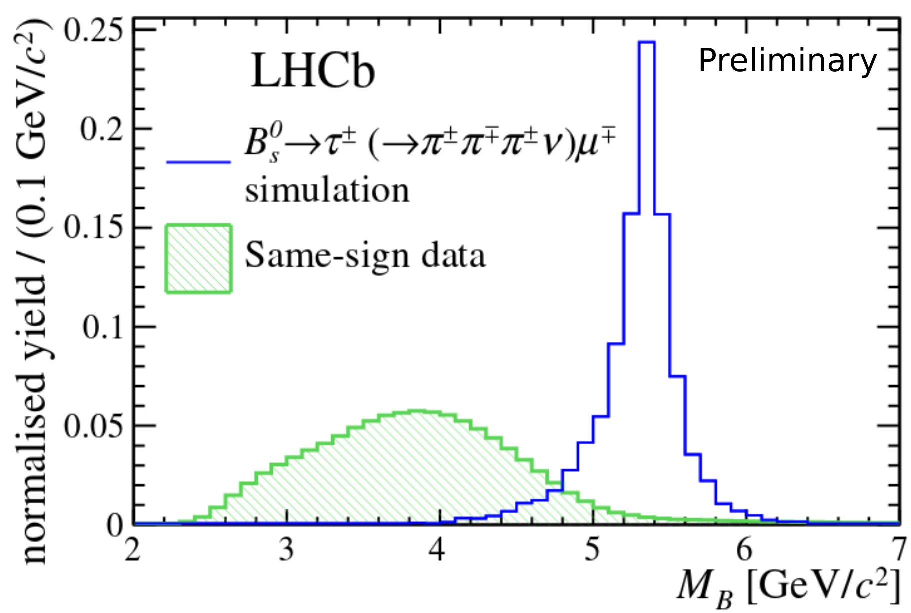


- ~70% of physical solutions for signal ($B_{(s)} \to \tau^{\pm}(\to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu)\mu^{\mp}$)
- less for background (<50%)
- use solution with largest signal -vs- background separation
- opposite sign data blinded in the B mass range 4.9−5.8 GeV/c²



$B_{(s)} \to \tau\mu$

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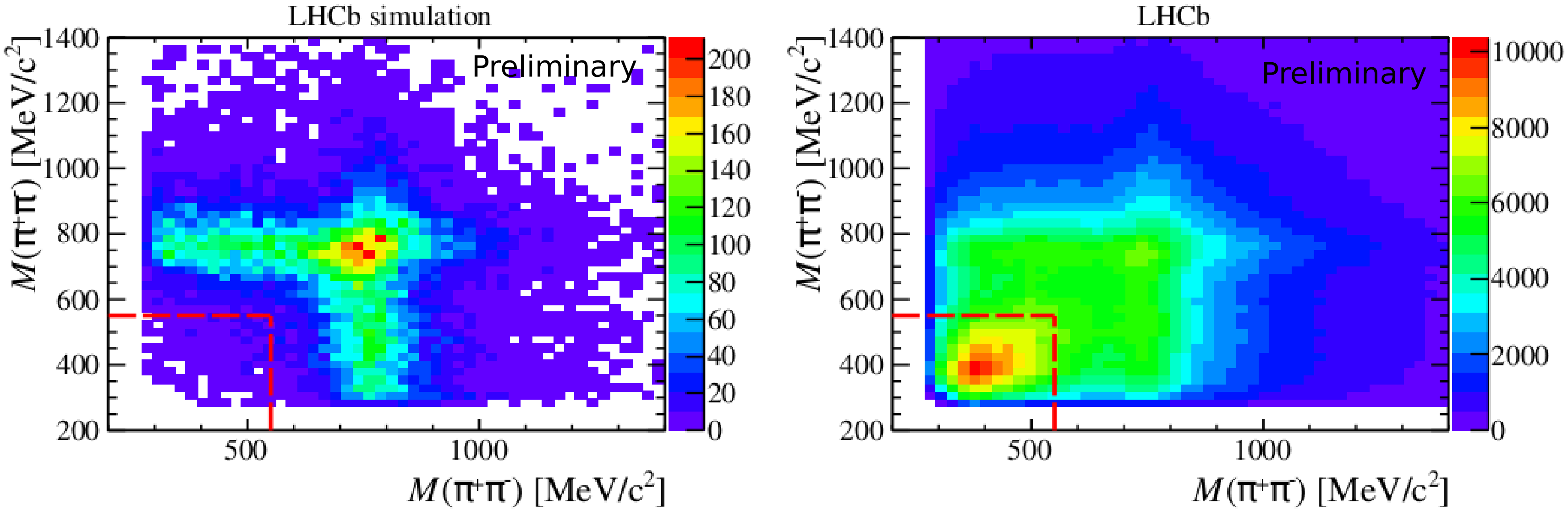
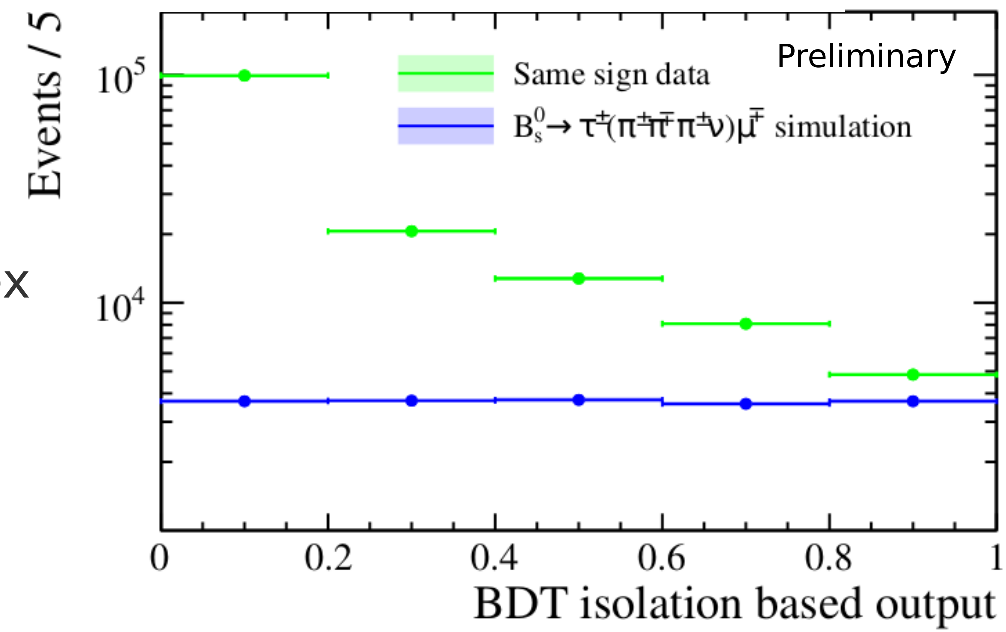
- Preselection

$$\tau^- \to a_1^- \nu_\tau \to \rho\pi^-\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$$



- Isolation based BDT
  - trained on same-sign data and simulated signal
  - uses charged, neutral, and vertex isolation variables
    - 40% of signal efficiency
    - more than 90% BG rejection



$B_{(s)} \to \tau\mu$

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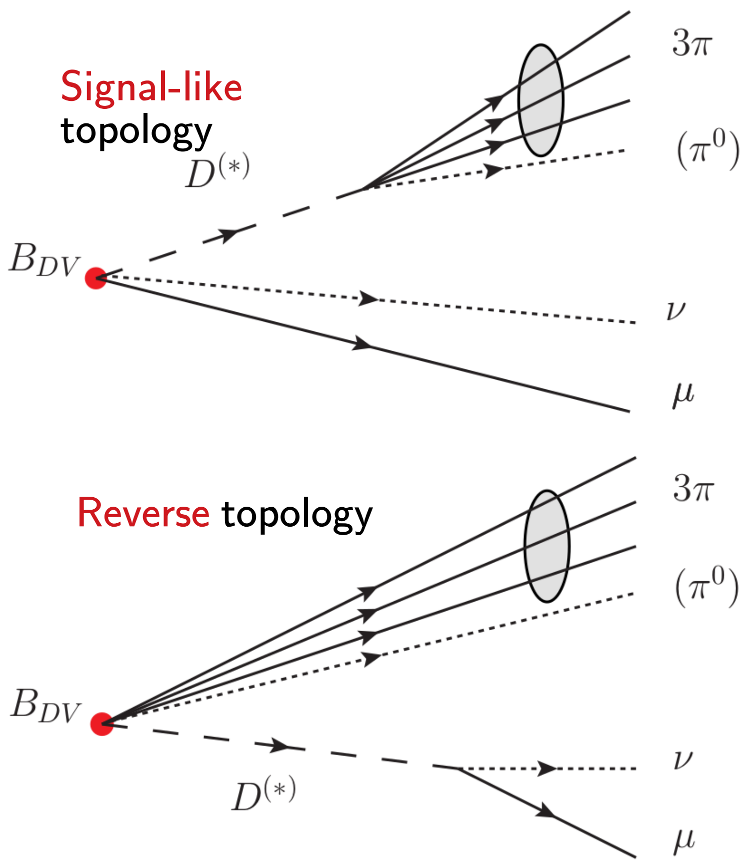
- Main backgrounds:
  - combinatorics
  - partially reconstructed B decays
- Background samples
  - same-sign candidates ($\tau^{\pm}\mu^{\pm}$)
    - → selection optimization
  - simulation
    - → qualitative studies
    - exclusive decays - non-exhaustive list
    - inclusive b-samples - statistically limited
- Backgrounds rejection:
  - multivariate classifiers
    - including isolation variables
  - dedicated selection against peaking background
    - τ decay time for, e.g., $B_{(s)} \to D_{(s)}(\to \mu^- \nu_\mu)\pi^+\pi^-\pi^+$



$B_{(s)} \to \tau\mu$

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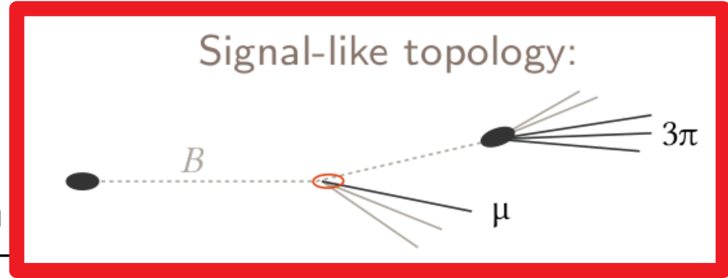
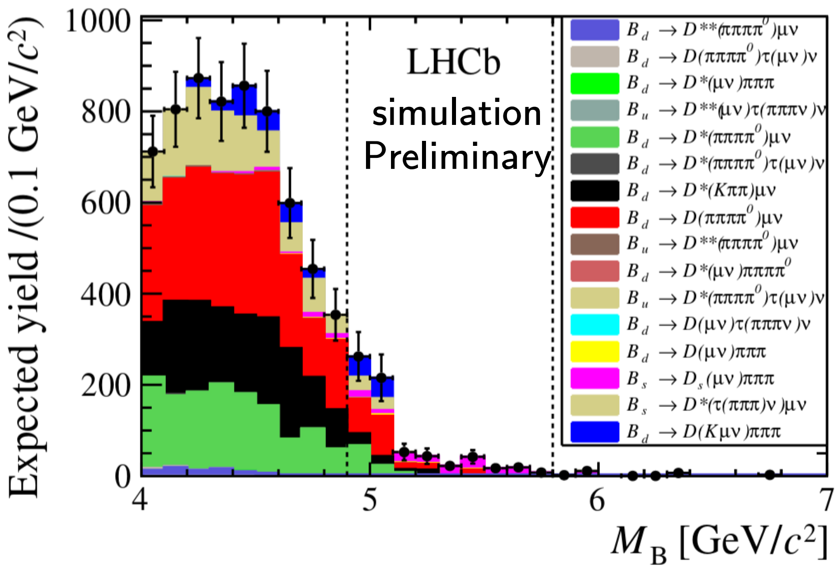
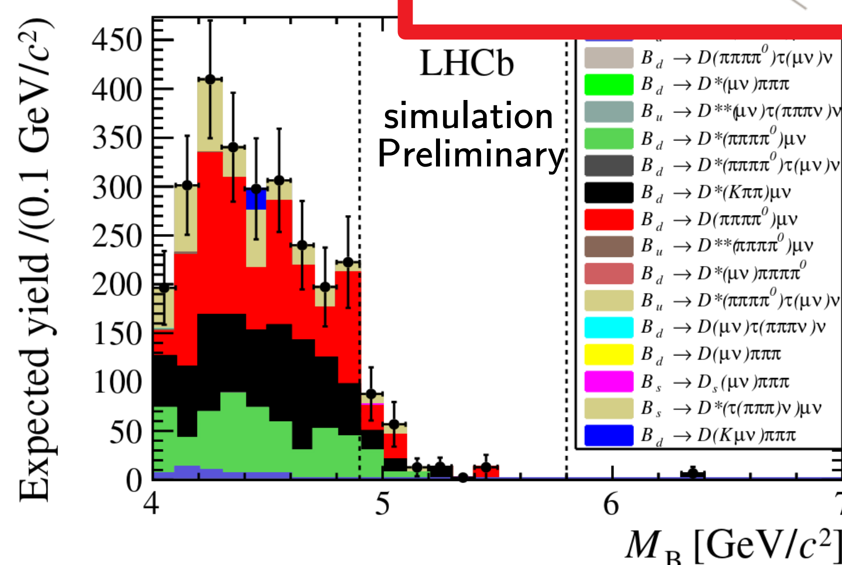
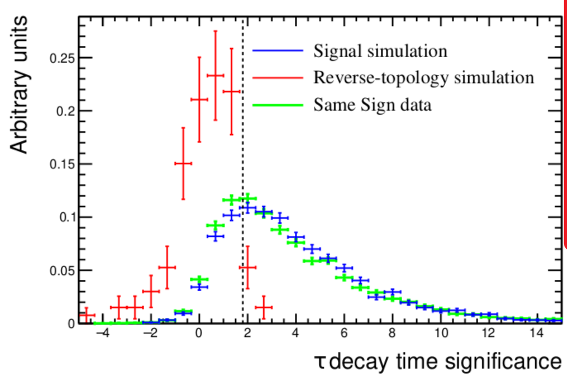
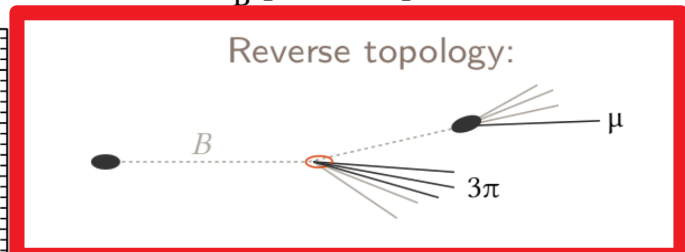


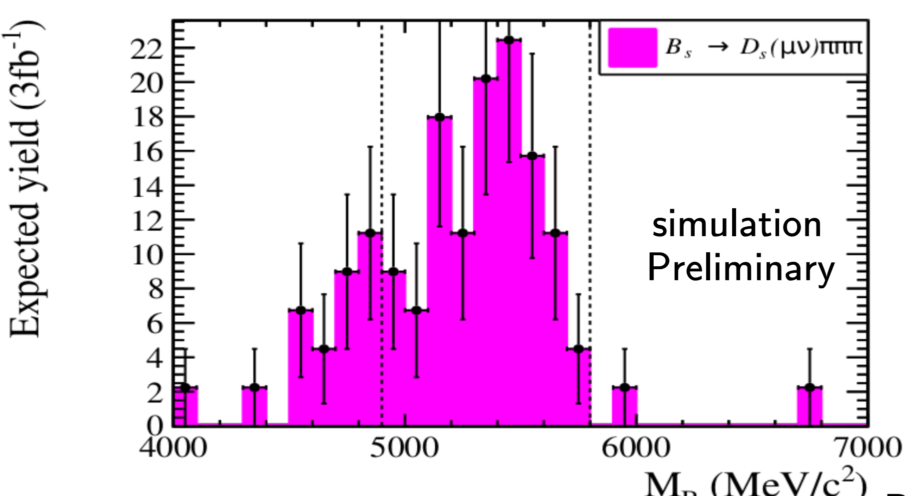
Before and after full selection

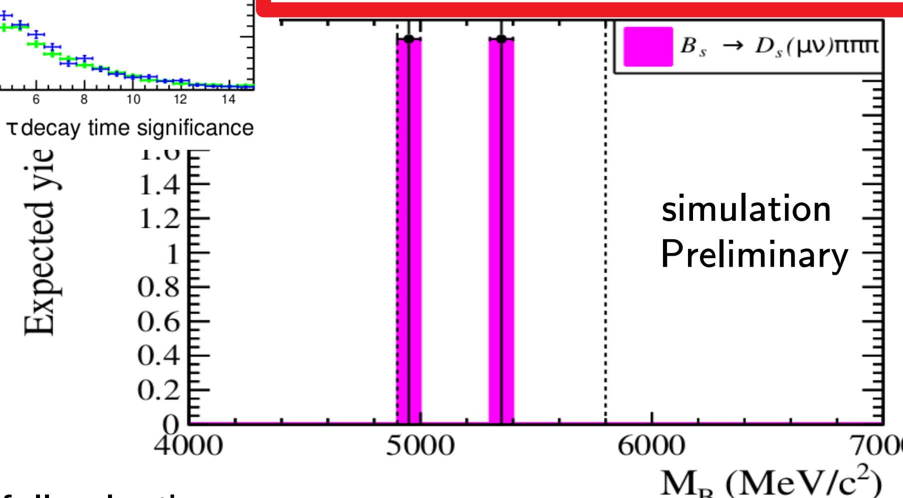












Before and after full selection

$B_{(s)} \to \tau\mu$

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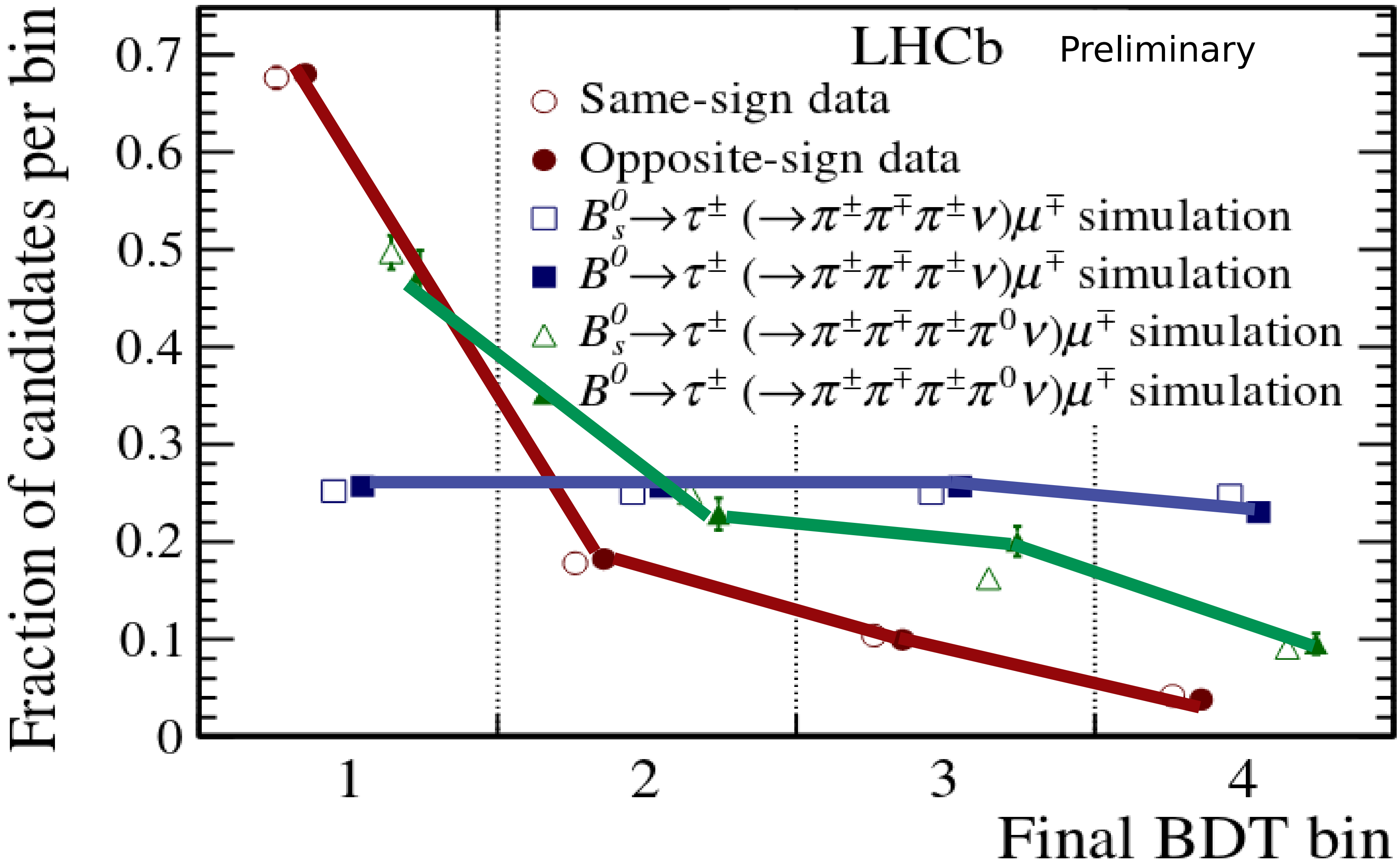
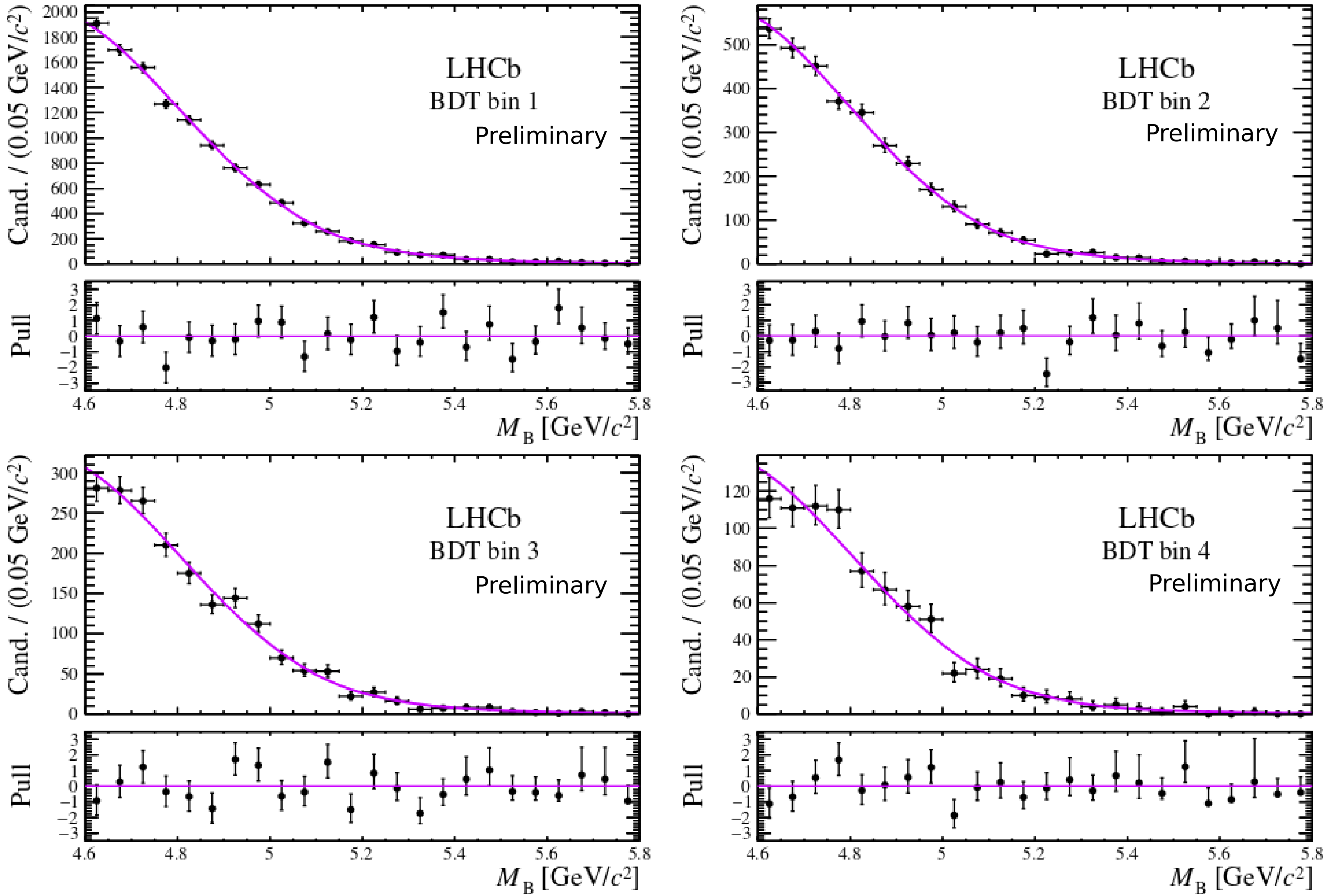


$B_{(s)} \to \tau\mu$

Limited B_s and B_d signal separation
→ B_s signal fit, assuming no B_d contribution



B_s^0 yield = −19 ± 38
[B^0 yield = −70 ± 58]

$B_{(s)} \to \tau\mu$

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- Normalisation

$$\mathcal{B}\left(B^0_{(s)} \to \tau^{\pm}\mu^{\mp}\right) = \alpha_{(s)} \cdot N^{\text{sig}}_{(s)}$$

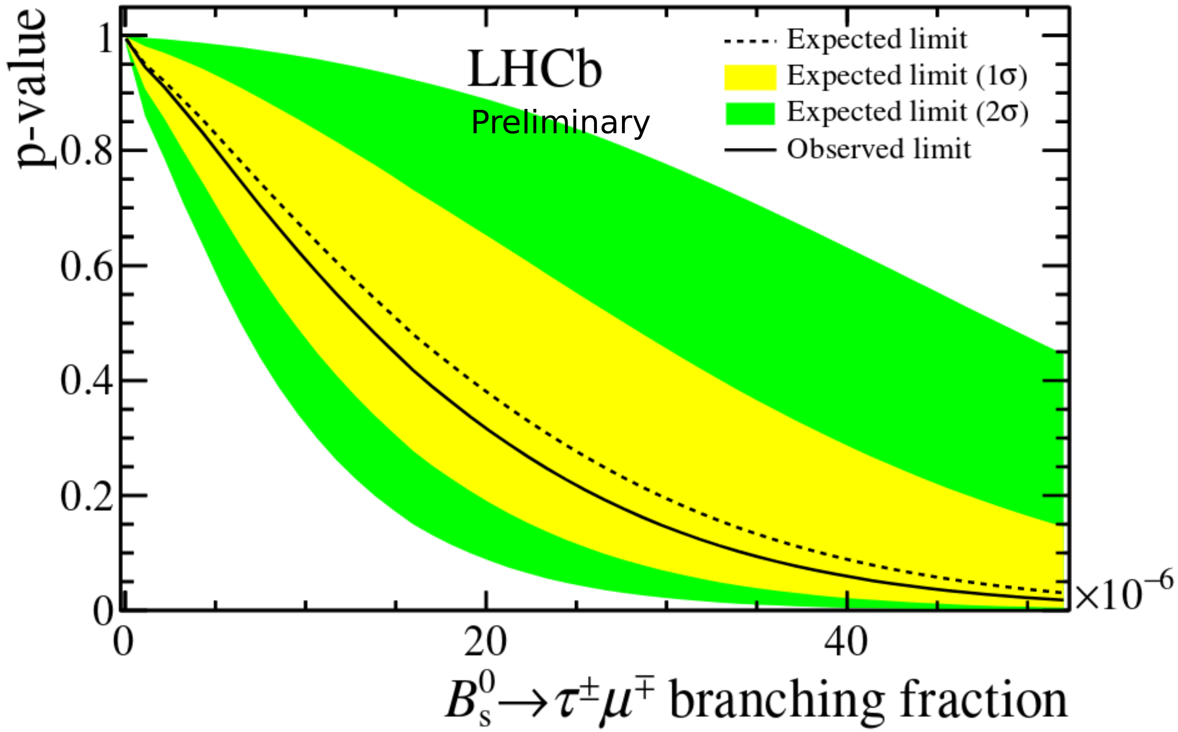
$$\alpha_{(s)} = \frac{f_{B^0}}{f_{B^0_{(s)}}} \cdot \frac{\mathcal{B}\left(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+\right)}{\mathcal{B}\left(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau\right)} \cdot \frac{\varepsilon_{B^0 \to D\pi}}{\varepsilon_{B^0_{(s)} \to \tau\mu}} \cdot \frac{1}{N^{\text{norm}}}$$

$\alpha_s = (4.32 \pm 0.61) \cdot 10^{-7}$ and $\alpha = (1.25 \pm 0.16) \cdot 10^{-7}$

	$\varepsilon_{B \to \tau\mu}$	$\varepsilon_{B \to D\pi}$	External inputs
rel. uncertainty	$\sim 2\%$ (data-vs-MC)	$\sim 11\%$ (trigger)	B^0: 6.0% – B^0_s: 8.4%

$B_{(s)} \to \tau\mu$

- Includes fit systematics
  - background shape systematics worsen the limit by ~35% (largest contribution)



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}

FIRST MEASUREMENT

BEST WORLD LIMIT

- Caveat :
  - Inclusion of $B \to a_1 \mu\nu$ mode (currently unmeasured) would improve the B_s limits by $\sim 16\% \times (\mathcal{B}(B^0 \to a_1(1260)^- \mu^+ \nu_\mu)/10^{-4})$

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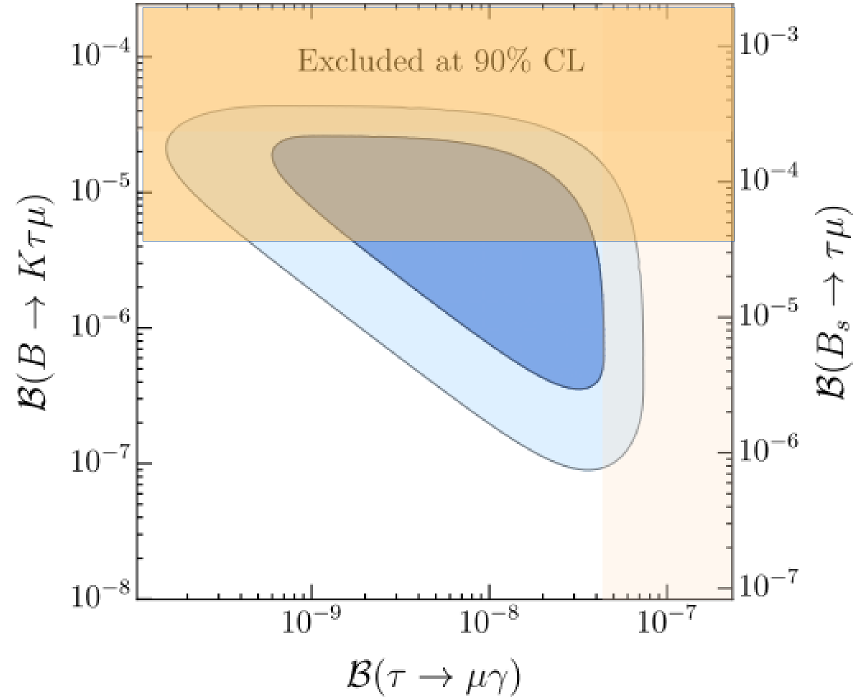
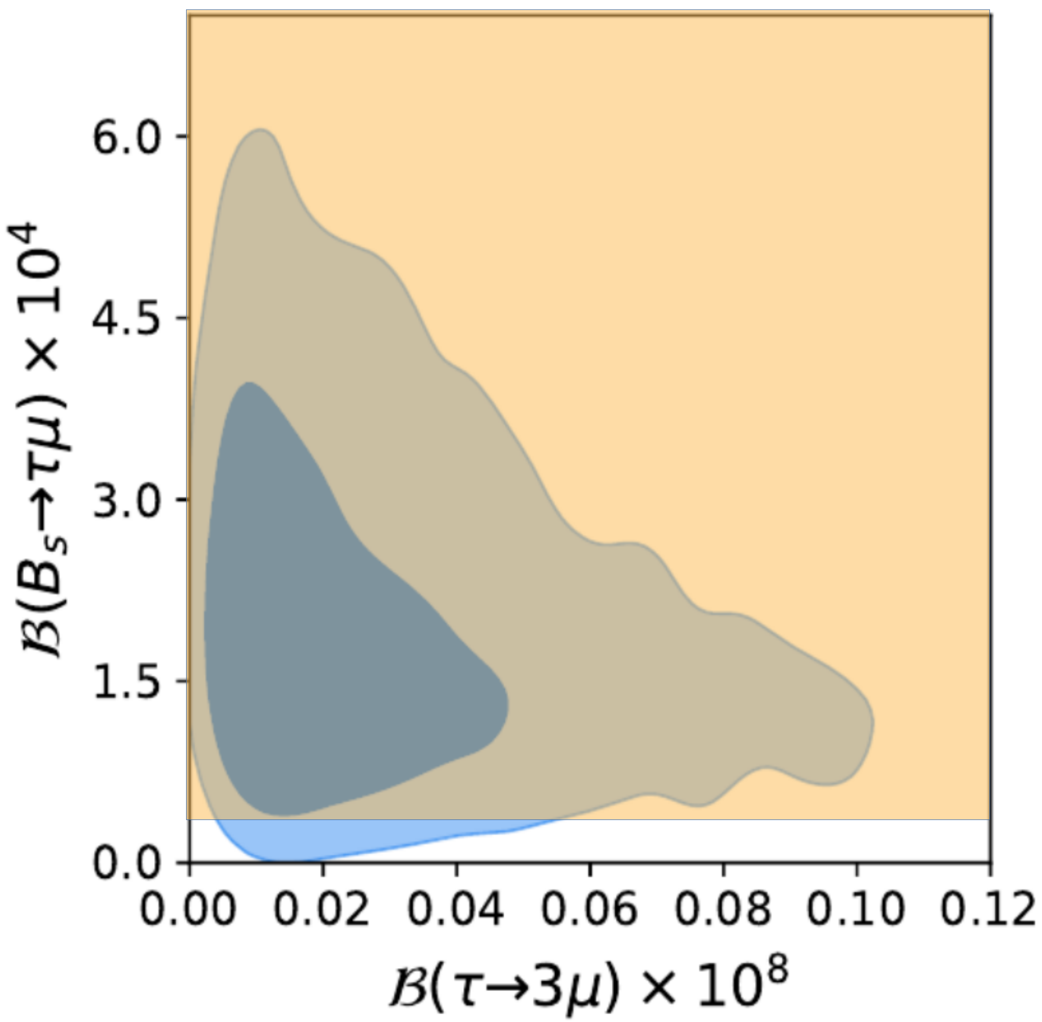
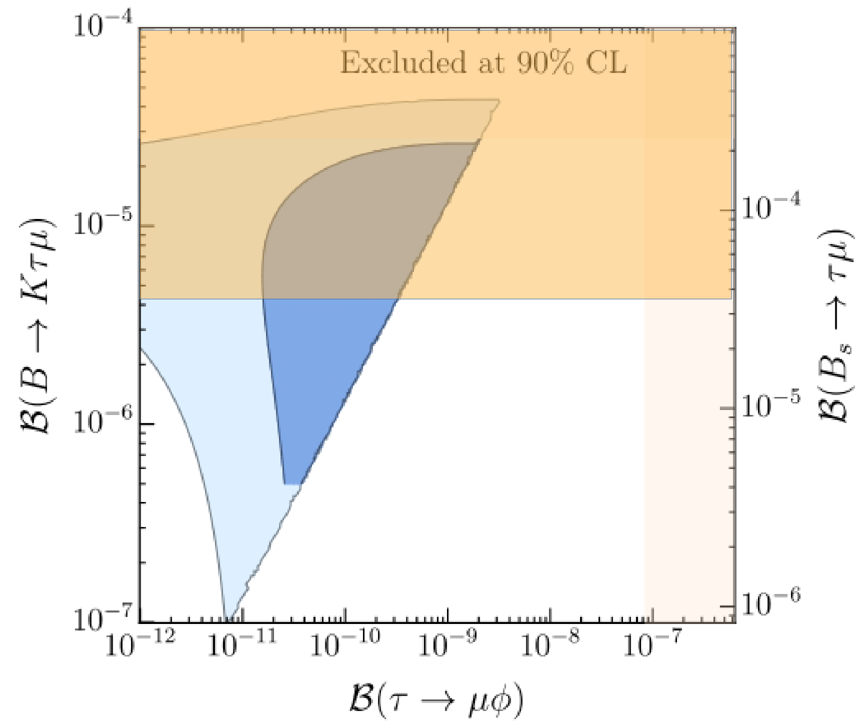
$B_{(s)} \to \tau\mu$

Cornella, Fuentes-Martin, Isidori, [arXiv:1903.11517]



Bordone et al. [JHEP10(2018)148]





$B_{(s)} \to e\mu$

LHCb JHEP 1803 (2018) 078

- In LFV models, BR enhanced up to $O(10^{-11})$
- Recent LHCb update
  - follows [Phys.Rev.Lett. 111 (2013) 141801], performed with 1 fb^{-1}

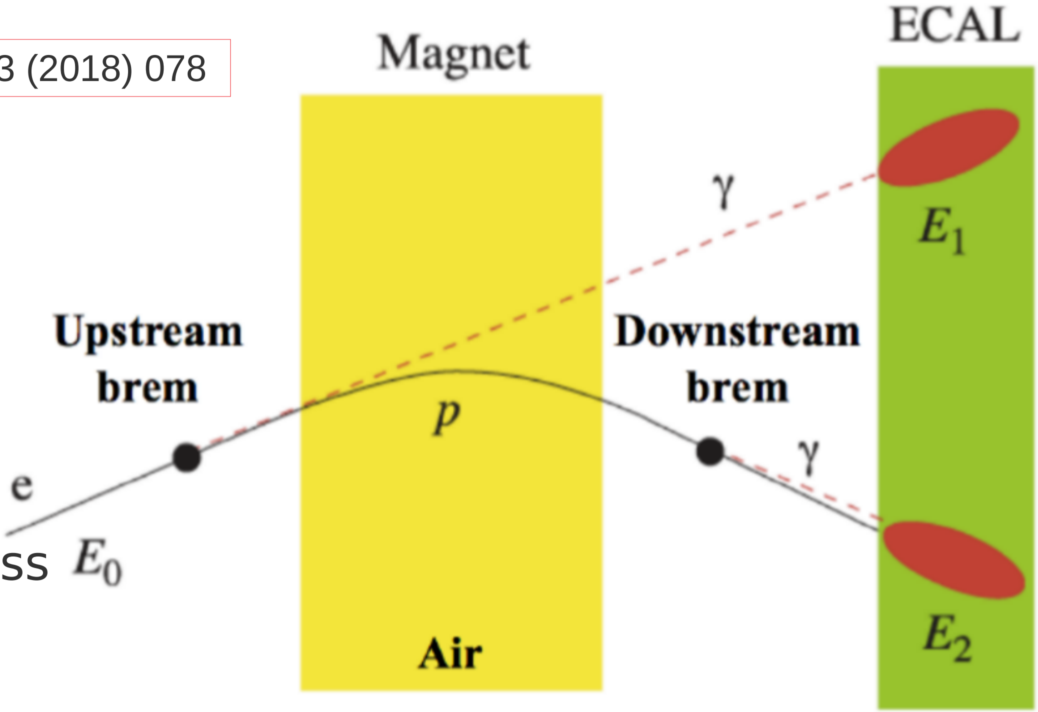
$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 2.8 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$
$$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 1.1 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$

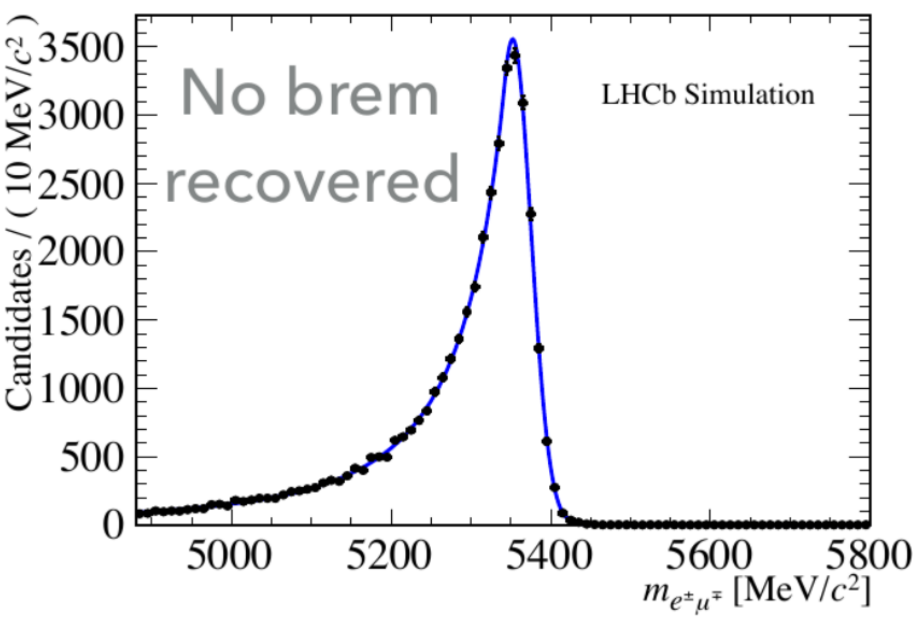
- Using all Run1 data (3 fb^{-1})
  - improvements
    - more triggers used, hence higher efficiency
    - improved and dedicated BDT

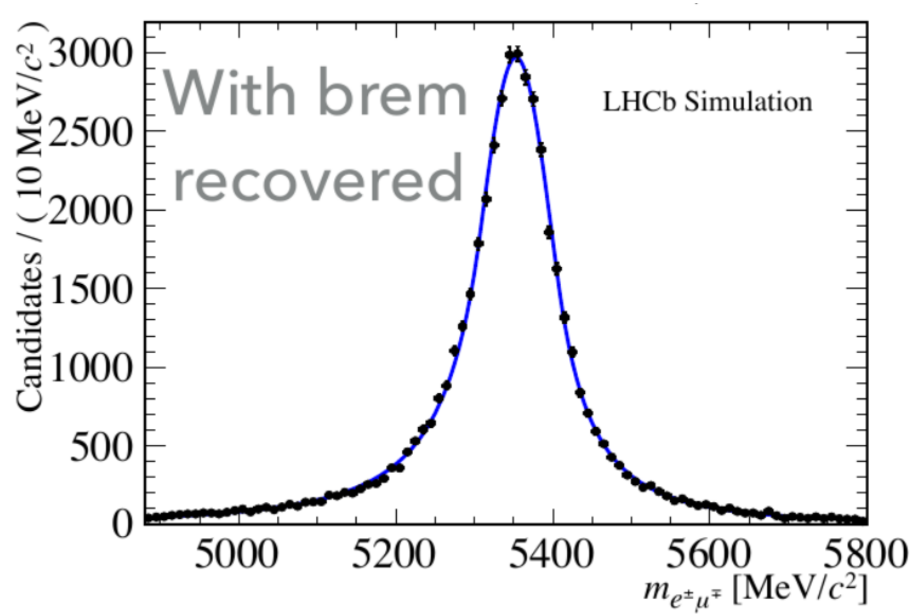
$B_{(s)} \to e\mu$

JHEP 1803 (2018) 078

- Clean trigger signature
- Muon reconstruction extremely performant in LHCb
- Electron reconstruction
  - resolution degraded by energy loss from bremsstrahlung
  - signal divided in sets with and without bremsstrahlung photons



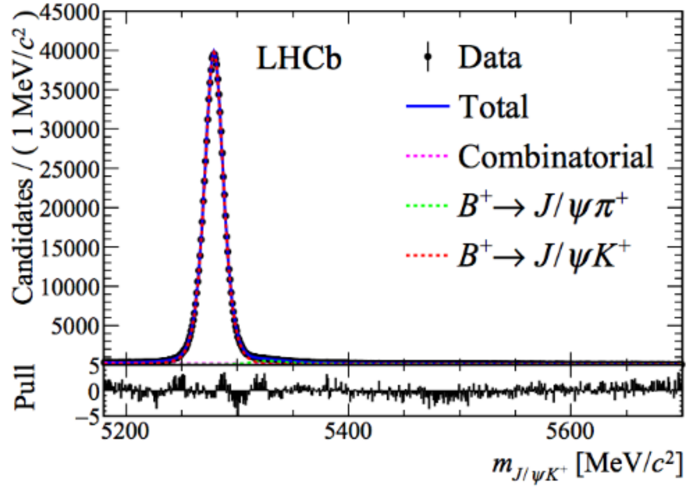


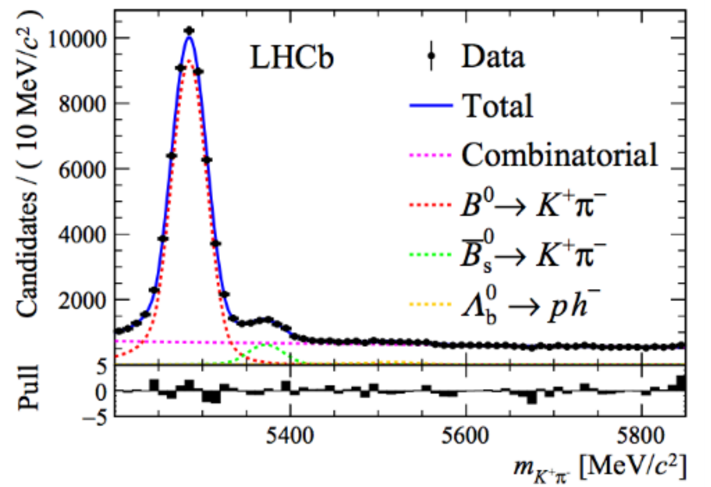


$B_{(s)} \to e\mu$

JHEP 1803 (2018) 078

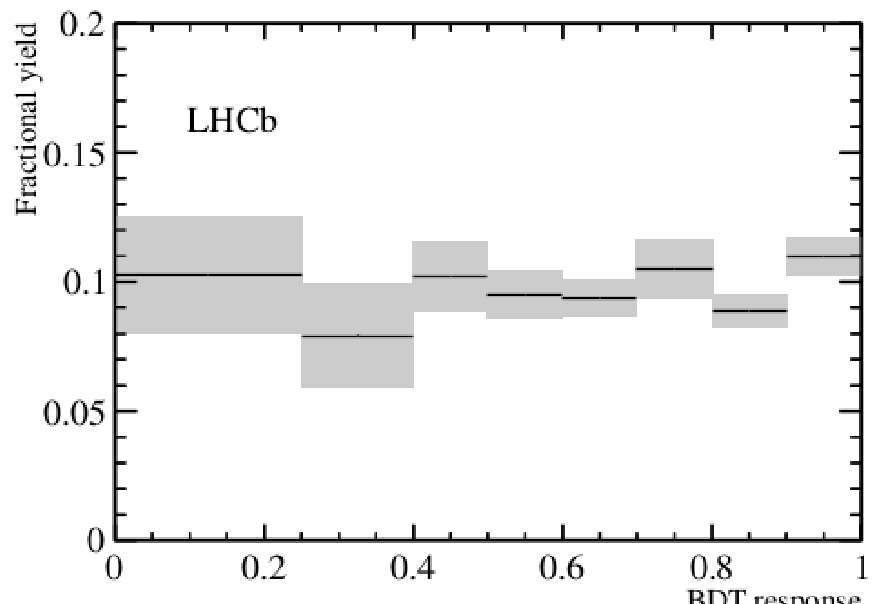
- Two normalisation channels used:
  - $B^+ \to J/\psi K^+$ (clean final state)
  - $B^0 \to K^+\pi^-$ (same topology as the signal)





- Backgrounds
  - Main (peaking) background is $B^0 \to K^+\pi^-$
  - PID reduces it to negligible amounts (0.1 events)

- BDT
  - trained on MC for signal, same-sign data for BG
  - no PID information used, therefore response determined on data with $B^0 \to K^+\pi^-$

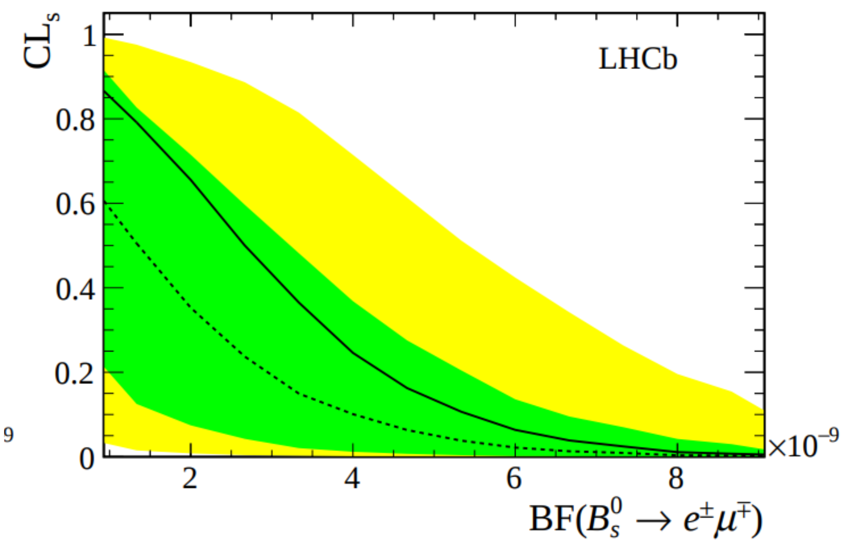


$B_{(s)} \to e\mu$

Candidates split by number of Bremsstrahlung photons (0 left, > 1 right)

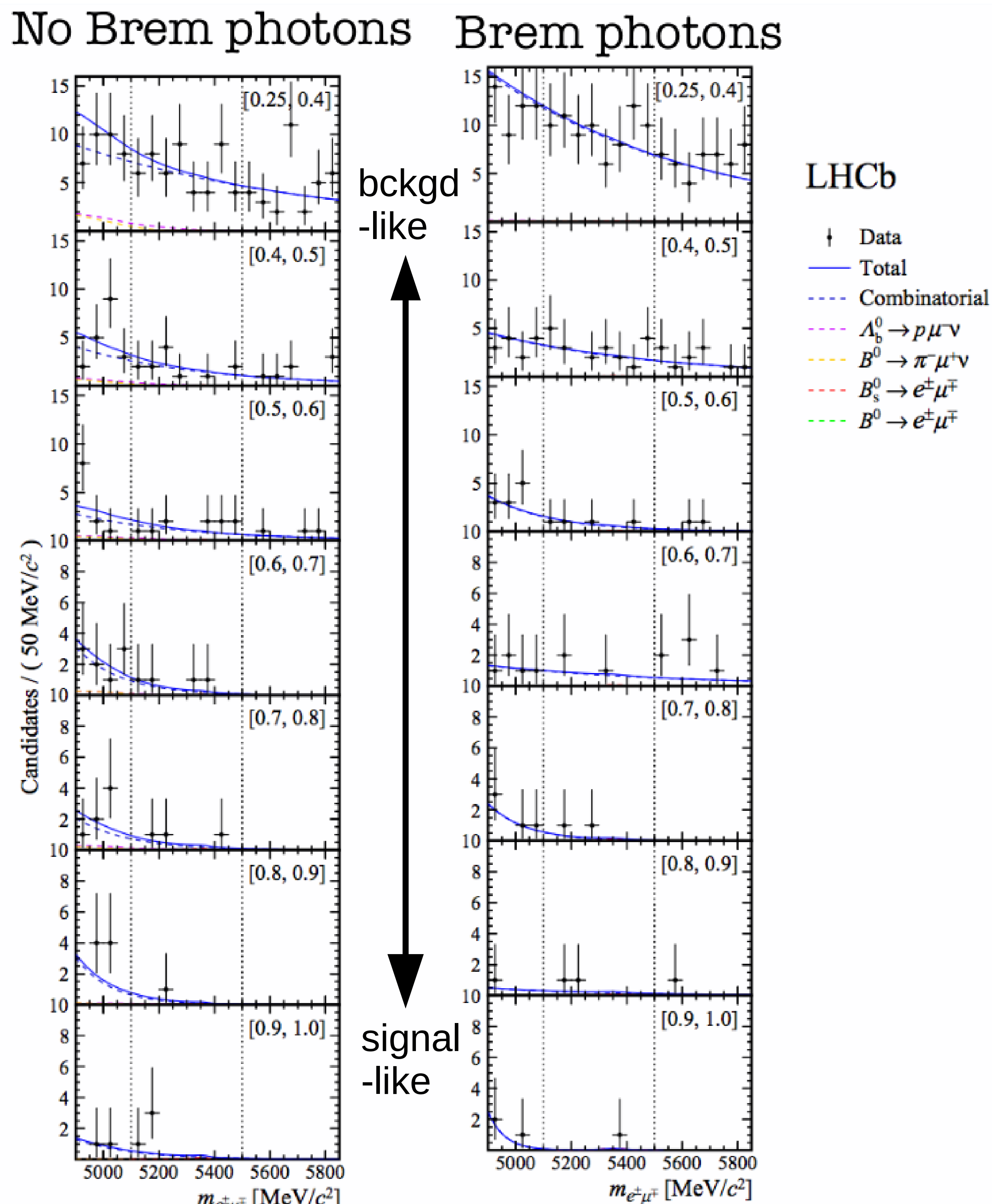
Simultaneous fit to 7 bins of BDT classifier

Best World's limits set



$$\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 5.4(6.3) \times 10^{-9}$$
@90%(95%) C.L.

$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.0(1.3) \times 10^{-9}$$
@90%(95%) C.L.



JHEP 1803 (2018) 078

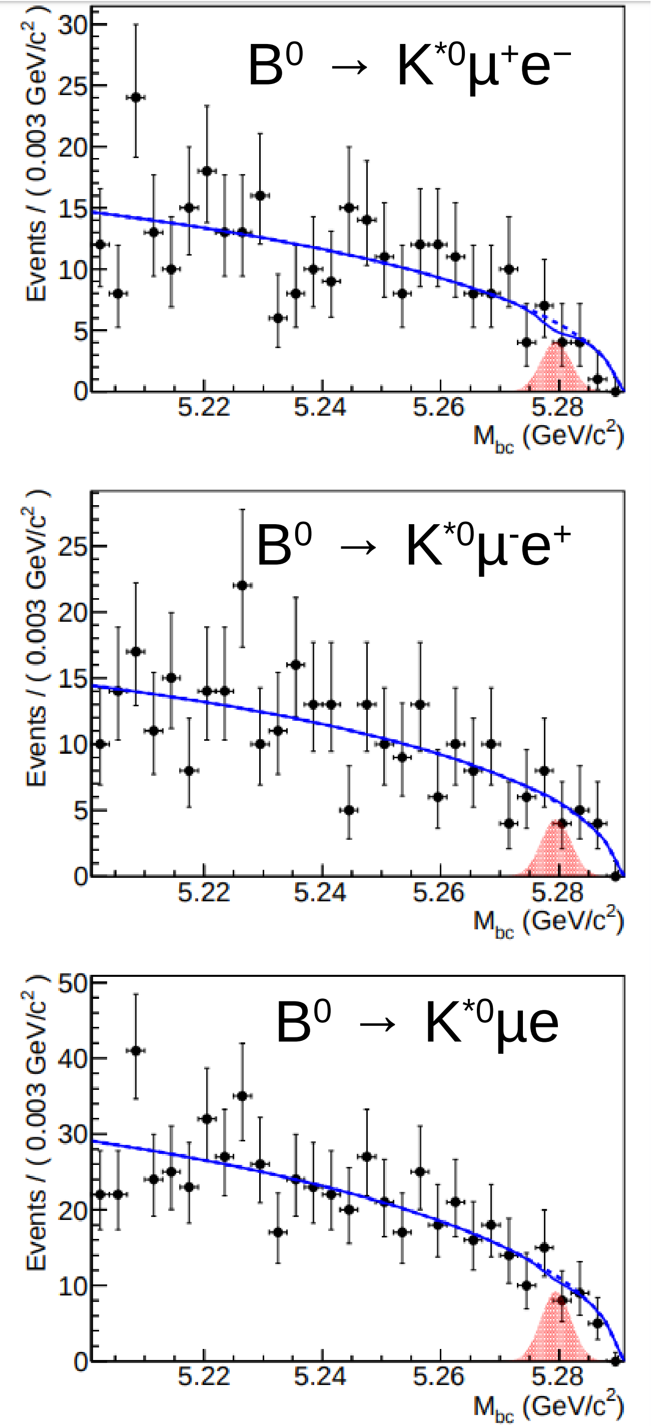
$B_d \to K^* e\mu$

Belle

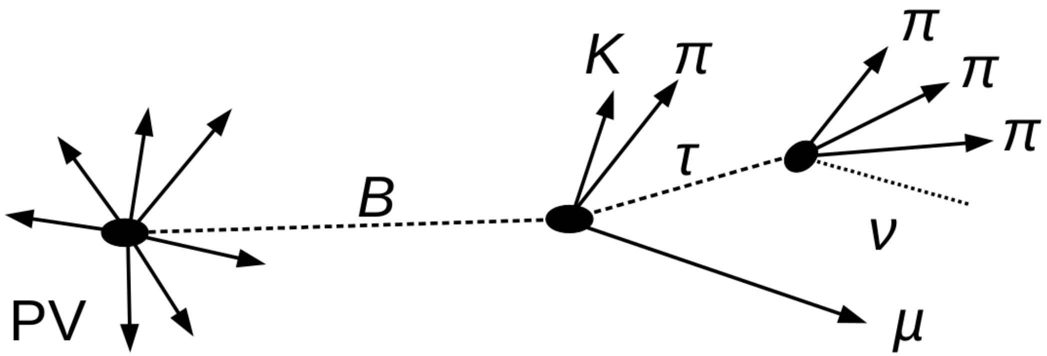
Phys. Rev. D 98, 071101 (2018)

- (772 ± 11) × 10^6 BB events (711 fb^{-1})
- Signal/continuum discrimination from:
  - a multivariate analyzer: neural network
- Signal/double lepton background
  - combinatorics and cascade SL decays
  - Another NN devised
- Vetoes on J/Ψ
- Blind analysis
- Upper limits (90% CL)

Mode	ε (%)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ (10^{-7})
$B^0 \to K^{*0}\mu^+ e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*0}\mu^- e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8



$B_d \to K^* \tau\mu$



Ongoing analysis in LHCb

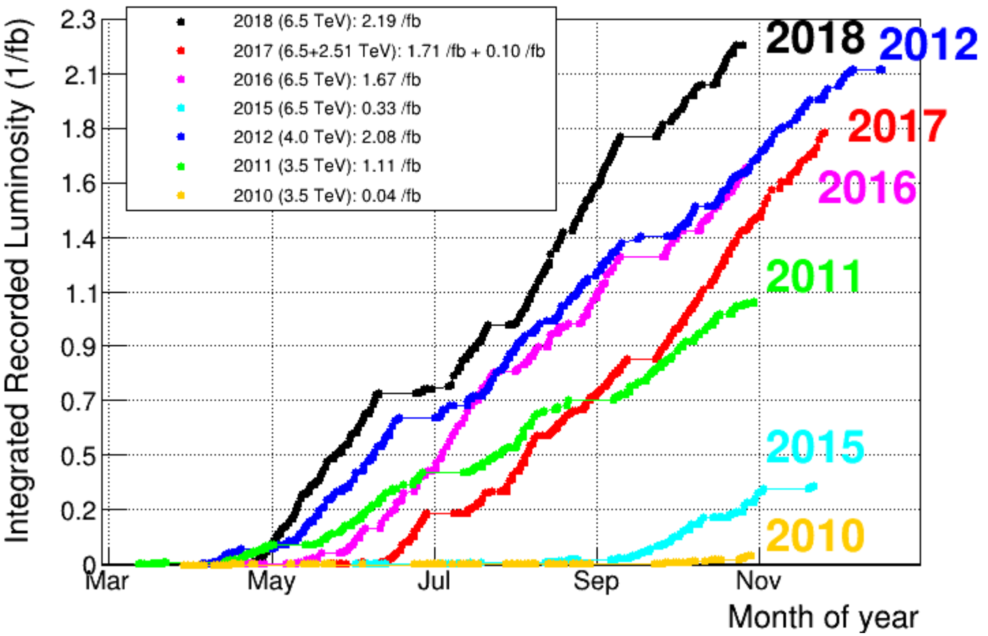
- Comparison with $B_{(s)} \to \tau^{\pm}\mu^{\mp}$
  - 6 tracks ! But:
    - only one missing neutrino
    - the B decay vertex is reconstructed
  - Reconstructed mass
    - corrected mass

$$\sqrt{P_T^2 + M_{ch}^2} + P_T$$

  - Background
    - combinatorics + partially reconstructed
    - suppressed using multivariate techniques
  - Expect limits ~ few 10^{-6} (Run 1&2)
- Work in progress (LHCb) as well on **$(B_s^{**} \to K)B_u \to K\tau\mu$**
  - BR~10^{-6} possible (BaBar already published a 90% C.L. limit of 4.8 10^{-5})
  - exploits B^{**} chain: full mass reconstruction in principle

Prospectives : LHCb

- A whole family to be searched for:
  - $B_{(s)} \to \tau\mu$,
  - $B_{(s)} \to e\mu$,
  - $B^+ \to K\tau\mu$,
  - $B^0 \to K^{*0}\tau\mu$,
  - $B^+ \to Ke\mu$,
  - $B^0 \to K^{*0}e\mu$,
  - $B_s \to \varphi\tau\mu$,
  - $B_s \to \varphi e\mu$, etc...



- Exploit data already accumulated
  - LFV public results currently use Run1 dataset (2011/2012), 3 fb^{-1} of pp collisions at (7/8) TeV
  - LHC Run2 ~6fb^{-1} of pp collisions at 13 TeV! So much more data to analyze

- Upgrades:

2018-2021	Run 3 (2021-2023)	2023-2025	Run 4 (2025-2028)	2028-2030	Run 5 (2030-2035+)
Shutdown	~23fb^{-1}	Shutdown	~50fb^{-1}	Shutdown	~300fb^{-1}
LHCb upgrade PhaseI				LHCb upgrade PhaseII	

Perspectives : LHCb +Belle II

Decays	LHCb RUN3 (95% CL)	LHCb RUN5 (95% CL)
$B \to \tau\mu$	$1\text{-}2 \; 10^{-6}$	$4\text{-}7 \; 10^{-7}$
$B_s \to \tau\mu$	$5\text{-}9 \; 10^{-6}$	$1\text{-}3 \; 10^{-6}$
$B \to e\mu$	$2 \; 10^{-10}$	$9 \; 10^{-11}$
$B_s \to e\mu$	$8 \; 10^{-10}$	$3 \; 10^{-10}$

Adding $\pi\pi\pi\pi^0$ mode and improved upgrade trigger and tracking and better analysis

Decays	BELLE II limit reach 50 ab-1 (90% CL)
$B \to \tau e$ / $B \to \tau\mu$	$1.6 \; 10^{-5}$ / $1.3 \; 10^{-5}$
$B \to K\tau e$ / $B \to K\tau\mu$	$2.1 \; 10^{-6}$ / $3.3 \; 10^{-6}$

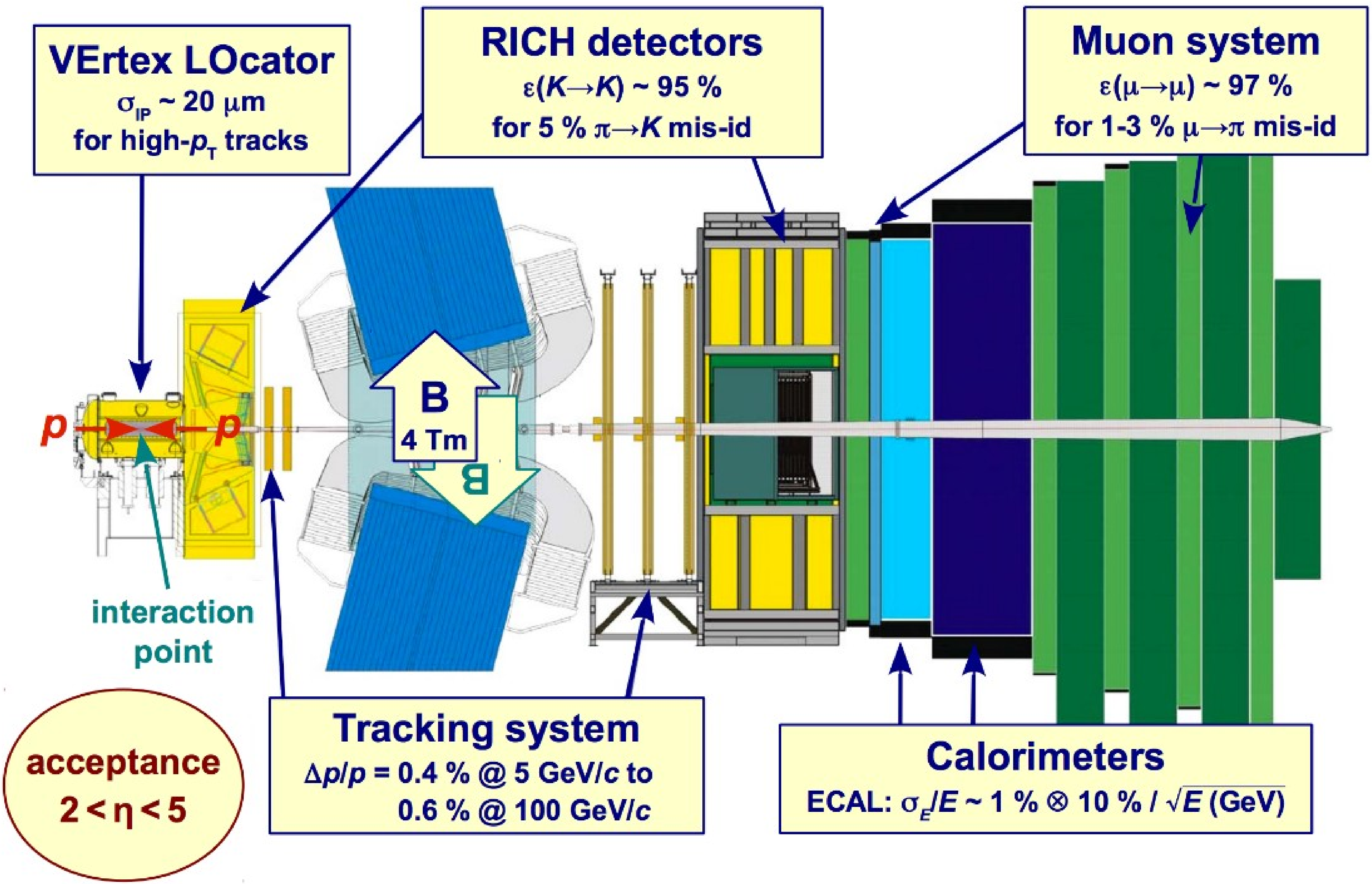
Synergy in $B \to \tau X$: BELLE II → better understanding of intermediate resonance structure of the $\tau \to \pi\pi\pi\nu$ decay

Conclusions

- **Lots of work on B meson LFV decays**
- **Motivated by...**
  - LFUV anomalies, but not only...
- **Very challenging at LHCb**
  - Missing energy (neutrinos)
  - Electron ID
  - High level and variety of (exclusive) backgrounds
- **Not possible to just turn the crank**
  - Handmade (work of artisans!) analyses, made from scratch
  - Longer time, published results are extensively scrutinized
  - Small groups of people. Highly formative
  - Isolations and other tools/selections, MVAs, creative control samples
- **New gamers coming: interplay among experiments**
- **Analysis improvements & detector upgrades needed to get to much more interesting regimes**

BACKUPS

THE LHCb DETECTOR



Other LFV measurements

$\tau^- \to p\mu^-\mu^-$	$\mathcal{B} < 4.4 \times 10^{-7}$ @ 90% CL	[Physics Letters B 724 (2013)]
$\tau^- \to \bar{p}\mu^+\mu^-$	$\mathcal{B} < 3.3 \times 10^{-7}$ @ 90% CL	[Physics Letters B 724 (2013)]
$\tau \to \mu\mu\mu$	$\mathcal{B} < 4.7 \times 10^{-8}$ @ 90% CL	[JHEP 02 (2015) 121]
$D^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 1.3 \times 10^{-8}$ @ 90% CL	[Phys. Lett. B754 (2016) 167]
$B^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 1.0 \times 10^{-9}$ @ 90% CL	[JHEP 1803 (2018) 078]
$B_s^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 5.4 \times 10^{-9}$ @ 90% CL	[JHEP 1803 (2018) 078]
$H^0 \to \mu^\pm\tau^\mp$	$\mathcal{B} < 26\%$ @ 95% CL	[arXiv:1808.07135]

Other LFV Measurements

μ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \nu_e \overline{\nu}_\mu$	LF	[f] < 1.2 %	90%	53
$e^- \gamma$	LF	$< 4.2 \times 10^{-13}$	90%	53
$e^- e^+ e^-$	LF	$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	LF	$< 7.2 \times 10^{-11}$	90%	53

$$\mathcal{B}(Z^0 \to e^{\pm}\mu^{\mp}) < 7.5 \times 10^{-7} \text{ (@95\%CL)}$$

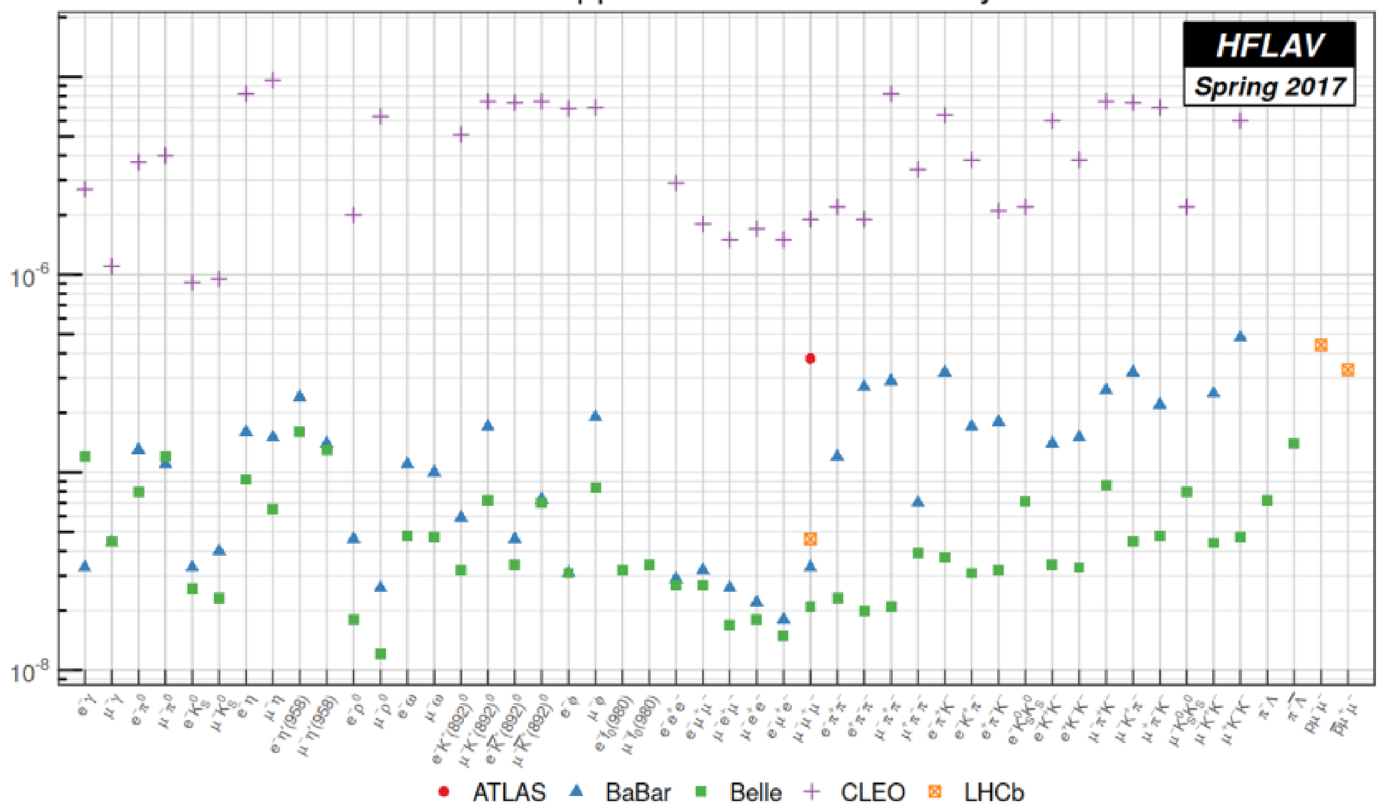
$$\mathcal{B}(Z^0 \to e^{\pm}\tau^{\mp}) < 9.8 \times 10^{-6} \text{ (@95\%CL)}$$

$$\mathcal{B}(Z^0 \to \mu^{\pm}\tau^{\mp}) < 1.2 \times 10^{-5} \text{ (@95\%CL)}$$

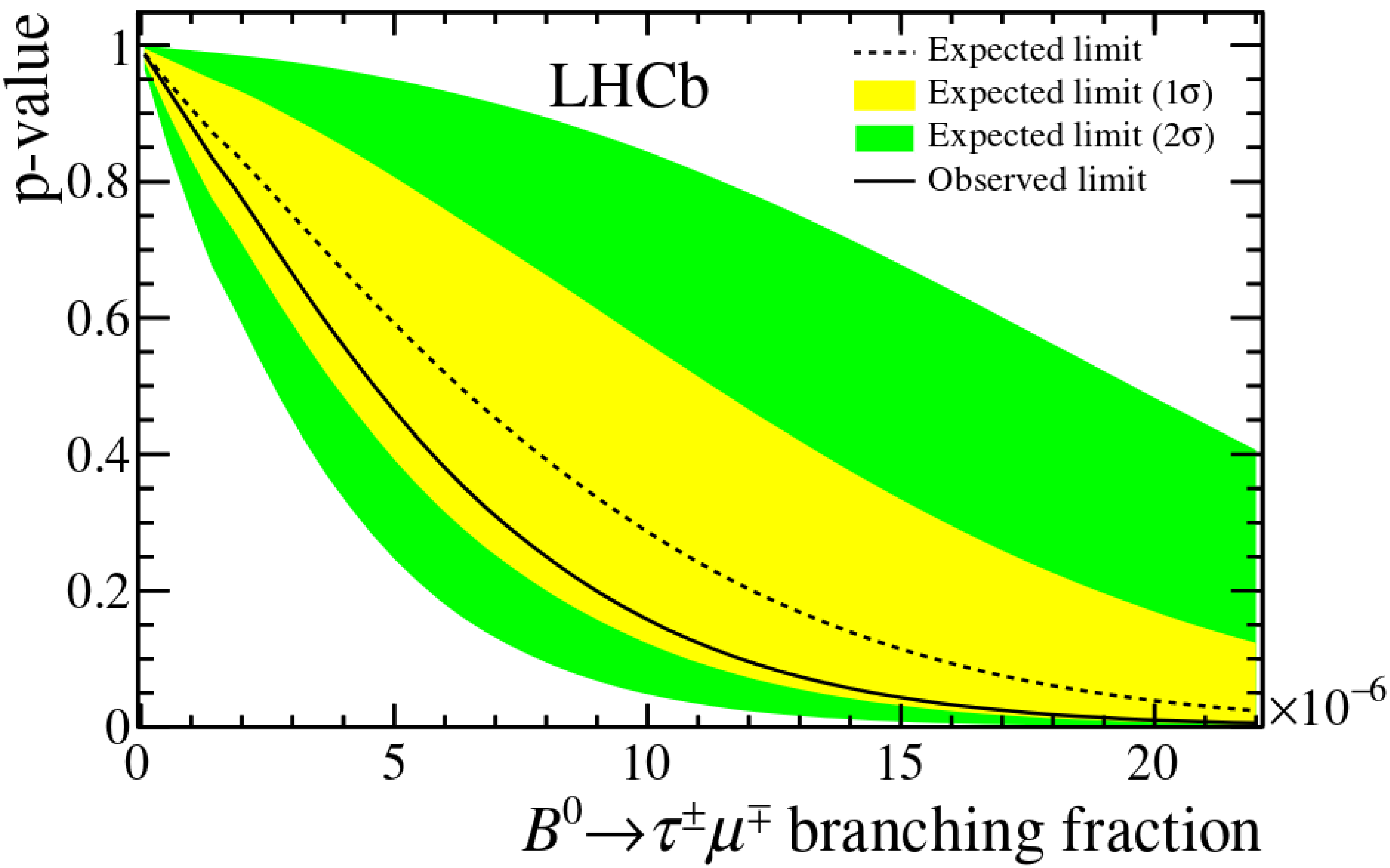
$$\mathcal{B}(H^0 \to \mu\tau) < 0.25\% \text{ (@95\%CL)}$$

$$\mathcal{B}(H^0 \to e\tau) < 0.61\% \text{ (@95\%CL)}$$

90% CL upper limits on τ LFV decays

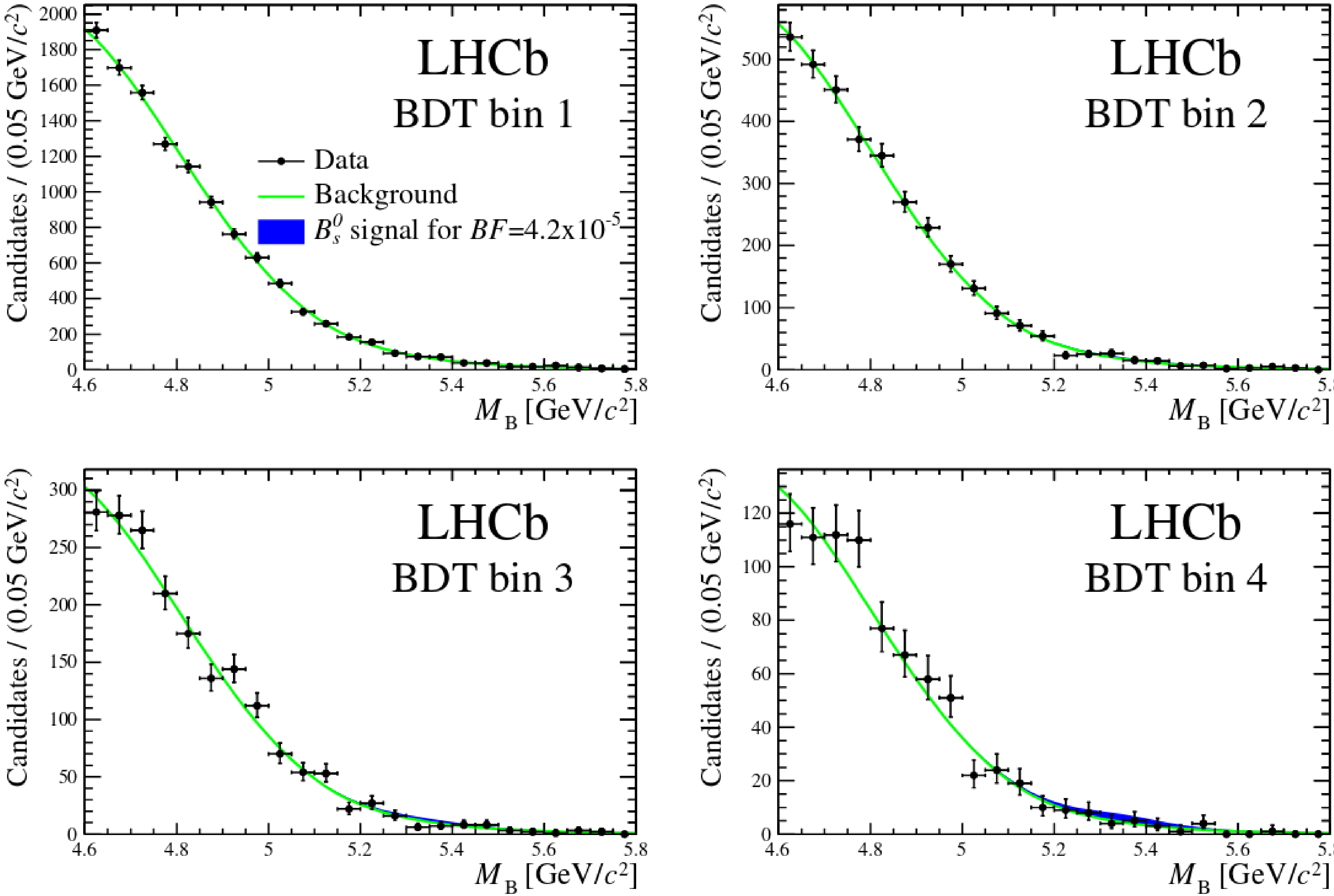


Limit B→τμ



LHCb
Expected limit
Expected limit (1σ)
Expected limit (2σ)
Observed limit
p-value
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
×10⁻⁶
B⁰→τ±μ∓ branching fraction

Fit with added signal Bs



Fit with added signal Bd