TUPIFP workshop
2-4 April 2019, Durham

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LATEST RESULTS AND PROSPECTS FOR LFV SEARCHES IN B DECAYS

LEPTON FLAVOUR VIOLATION

Lepton Flavour Violation (LFV): non-conservation of lepton flavour

- Conservation well established (e.g. $\mu \to e\gamma$, $\mu \to 3e$) …
- … but not supported by strong theoretical reasons
- Observation of neutrino oscillation implies LFV in loops (BR < 10^{-40})
- LFV signatures: searches for forbidden decays in the SM

At LHCb:

b DECAYS: $B \to e\mu$, $B \to Ke\mu$, $B \to \tau\mu$, $B \to K^{(*)}\tau\mu$, $\Lambda_b \to \Lambda e\mu$
c DECAYS: $D^0 \to e\mu$
τ DECAYS: $\tau \to \mu\mu\mu$

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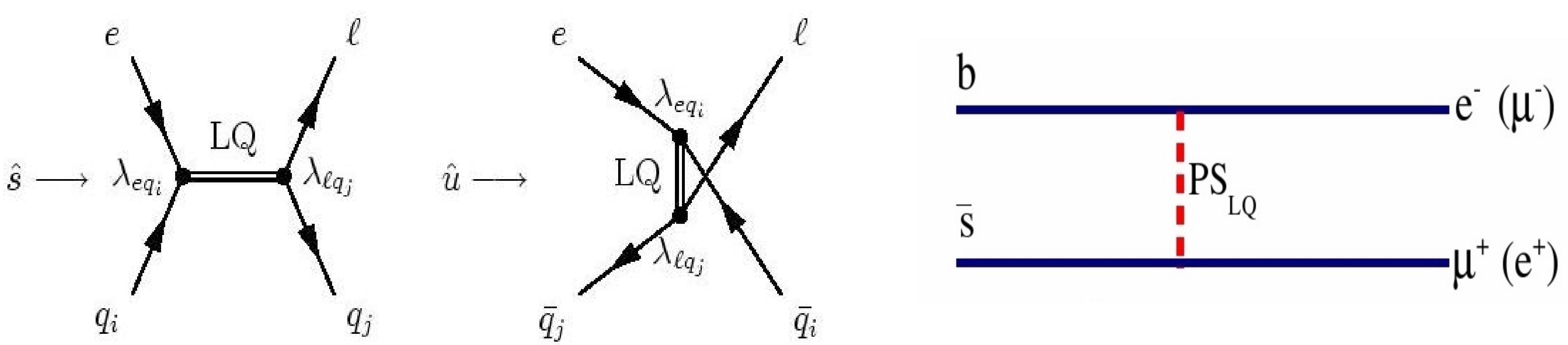
METHOD

- Processes that are strongly suppressed (forbidden) in the SM might be enhanced by new mediating particles
- LFV predicted by a large variety of alternative models (Leptoquarks, new gauge Z'… [PRD94(2016)115021] [PRD92 (2015) 054013] [Phys.Rev.D94(2016)115021] [JHEP 06 (2015) 072])
- Such particles can enter SM diagrams as virtual particles ⇒ can indirectly observe mediators unaccessible to direct searches (> TeV)



CURRENT SCENARIO

[1] Phys. Rev. Lett. 115, 111803
[2] JHEP 08 (2017) 055
[3] arXiv:1903.09252
[4] arXiv: 1609.08895v2
[5] Phys. Rev. Lett. 114, 091801

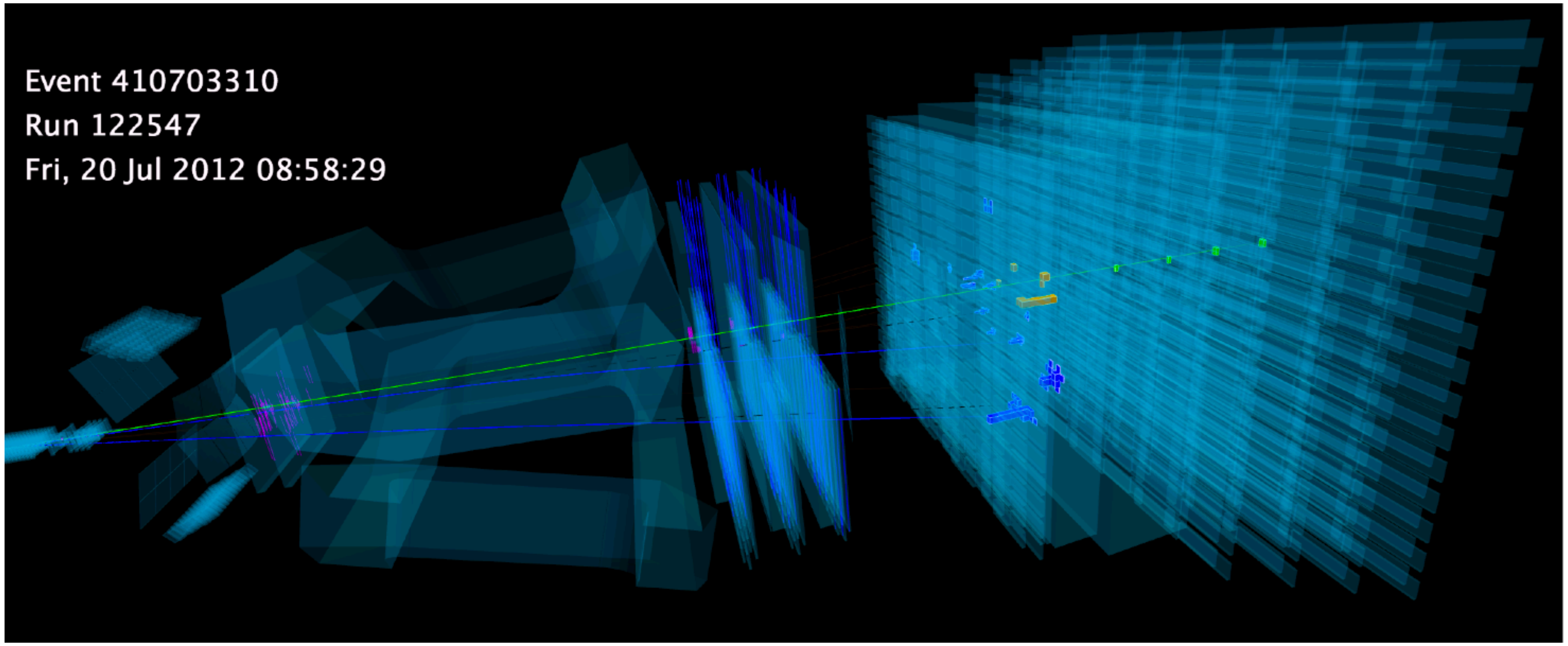
- Potential LNU effects [1,2,3] open to new scenarios
- Potential links between LNU and LFV in some models [4,5] entail a renewed interest on the subject

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

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

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

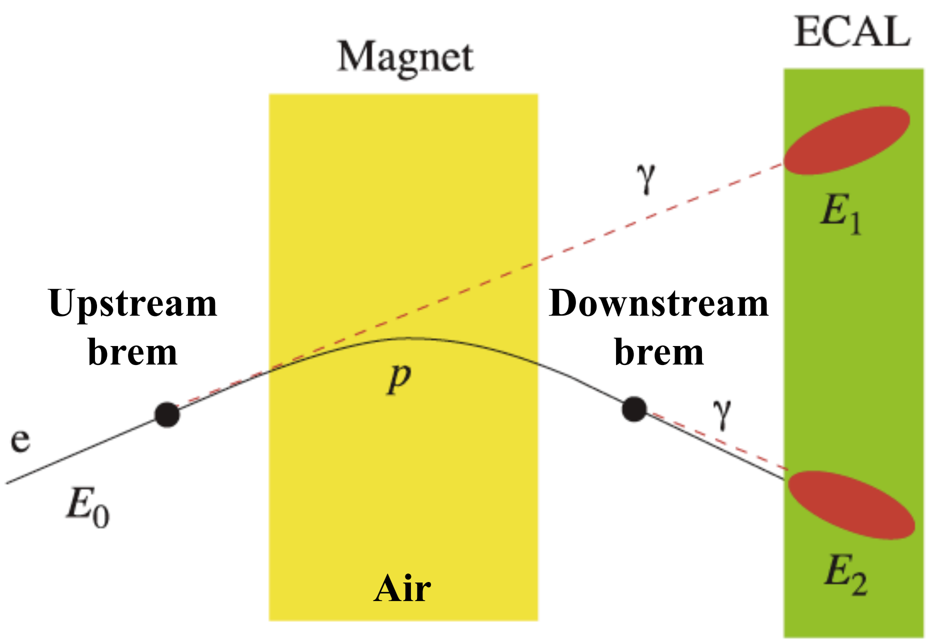
[JHEP 1803 (2018) 078]



- Forbidden decay from both B_d and B_s mesons
- Trigger on muon or electron
- Primary background: $B^0 \rightarrow h^+h'^-$ with both hadrons misidentified
  - Particle IDentification cuts play important role
- Reject combinatorial background with MVA
- Need to deal with bremsstrahlung (see next slide)

BREMSSTRAHLUNG RECOVERY

[JHEP 1803 (2018) 078]



- Need to deal with bremsstrahlung
  - Brem improves electron ID → helps with background
  - Need to split in categories

Selection efficiencies and mass shapes depend on whether or not a brem photon was added to the electron in the reconstruction (brem categories)

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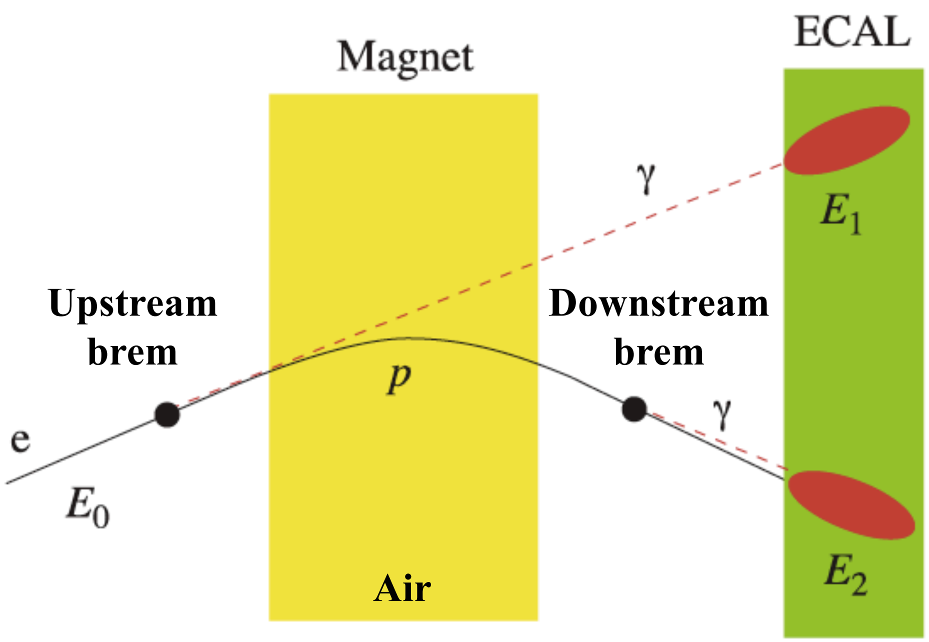

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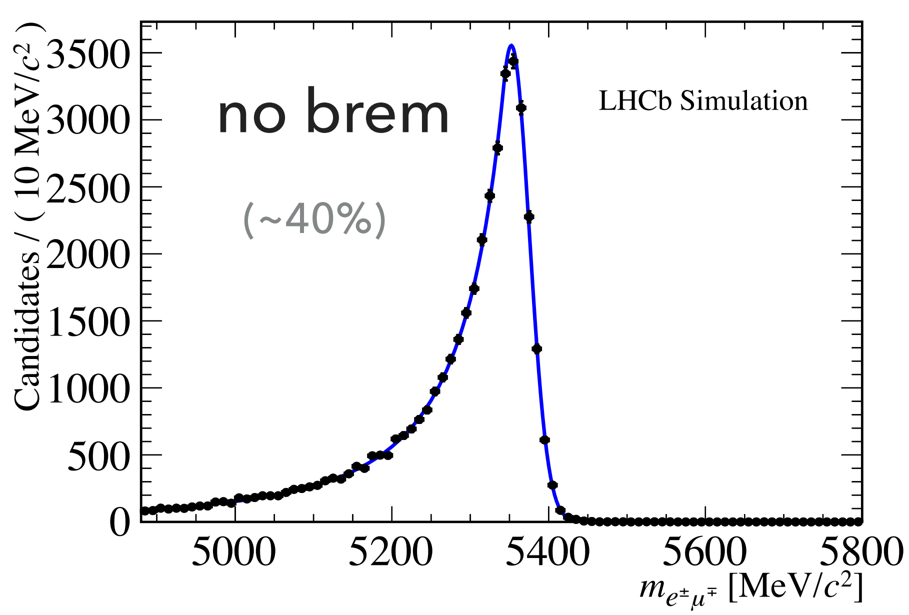
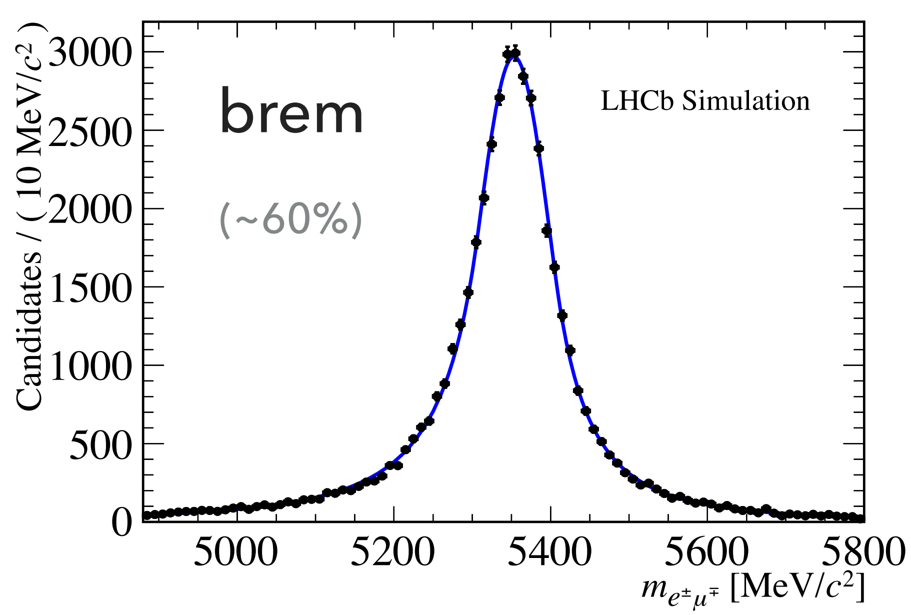
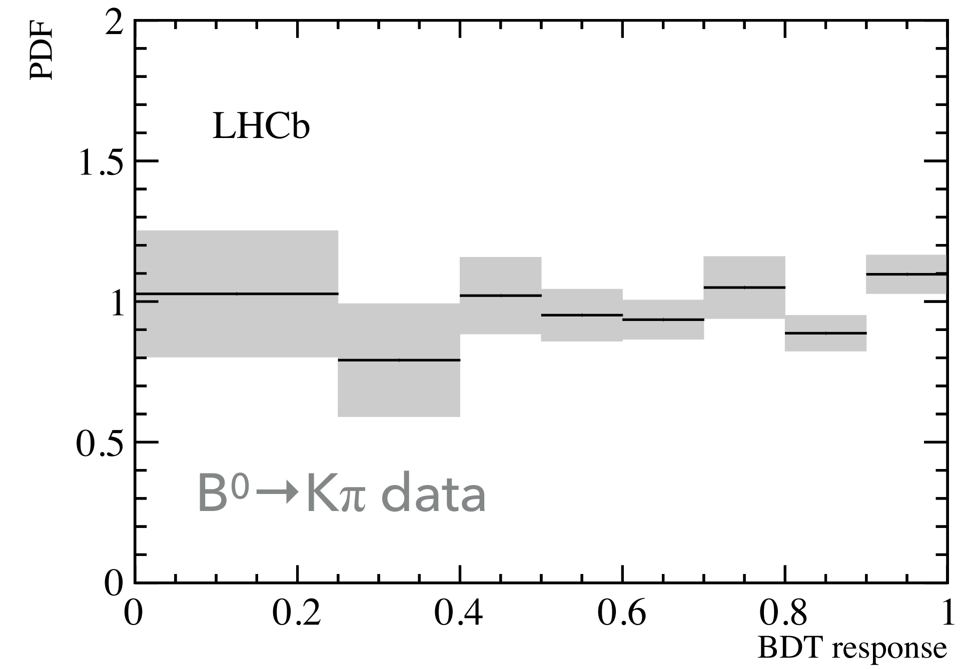


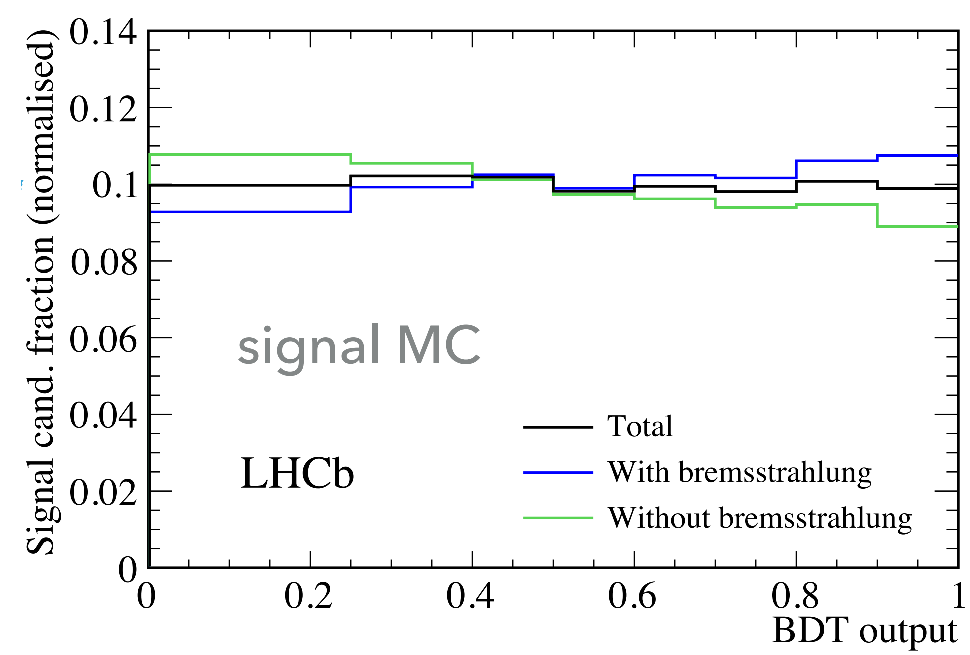


$B_{(s)} \rightarrow e\mu$

[JHEP 1803 (2018) 078]

- BDT against combinatorial. Response modelled to be flat on signal (MC) (and peaked on zero for bkg)
- Response on data evaluated on $B^0 \rightarrow K\pi$, as a proxy channel
  - Unbiased for trigger selection
  - Corrected for selection efficiency
  - Corrected for brem category



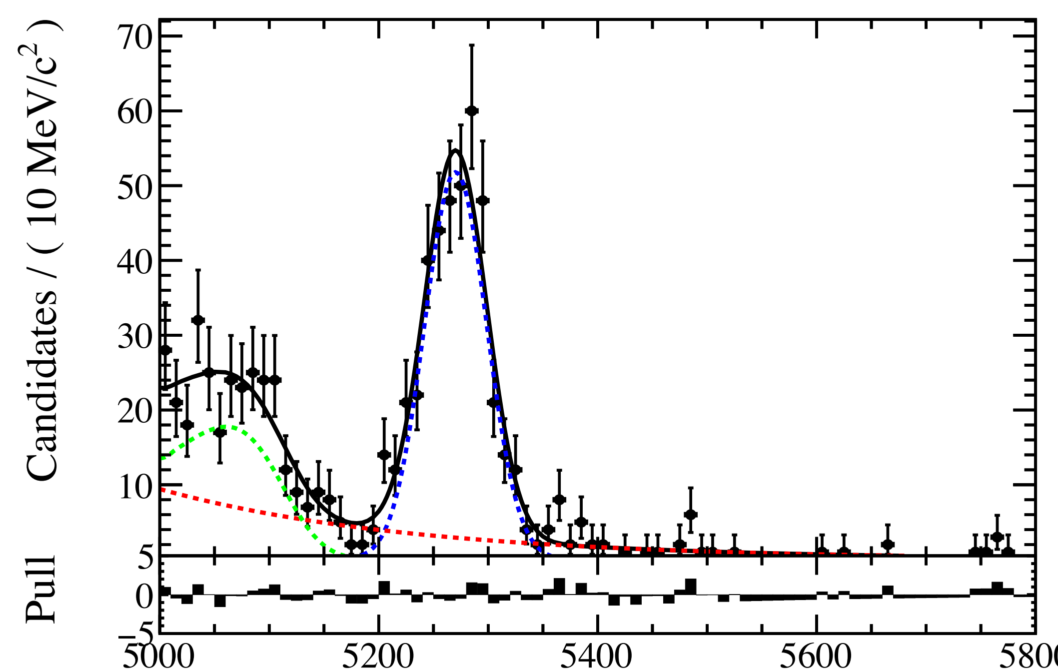


- Analysis binned in 8 BDT bins x 2 brem categories

$B_{(s)} \to e\mu$ – Peaking background

[JHEP 1803 (2018) 078]

- $B \to h^+h'^-$ ($h,h' = K,\pi$) double-misID only peaking background
- Yield estimated in two independent ways:
  - Efficiencies from MC, PID calibrated on data
  - Normalisation to $B^+ \to J/\psi(\to \mu\mu)K^+$
  - Directly from $B \to h^+h'^-$ data, fitting single-misID candidates and multiplying by additional misID probability from first method

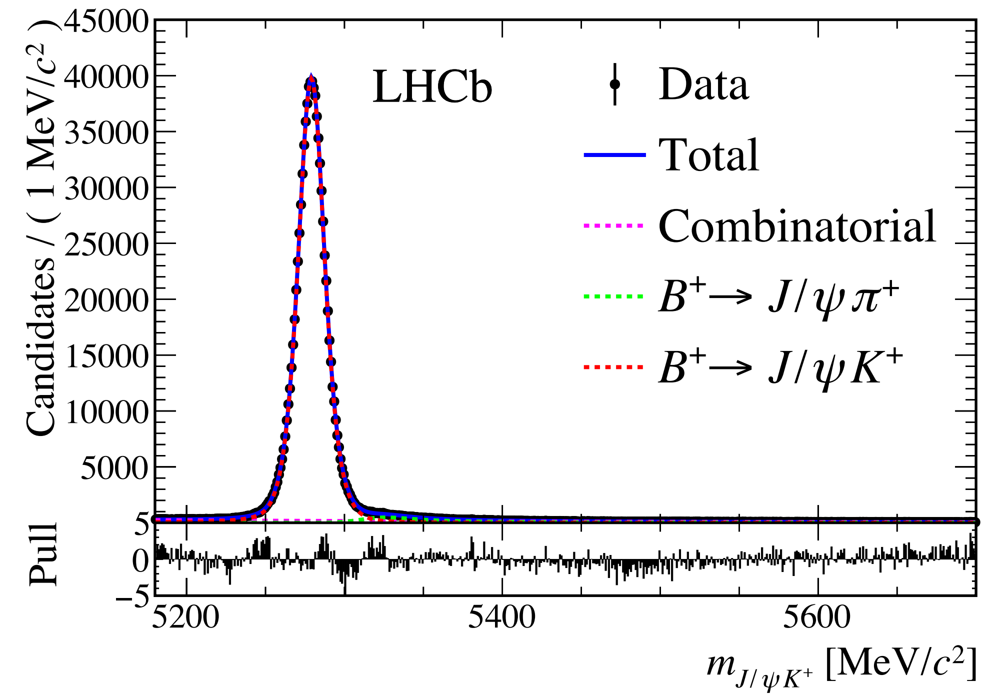


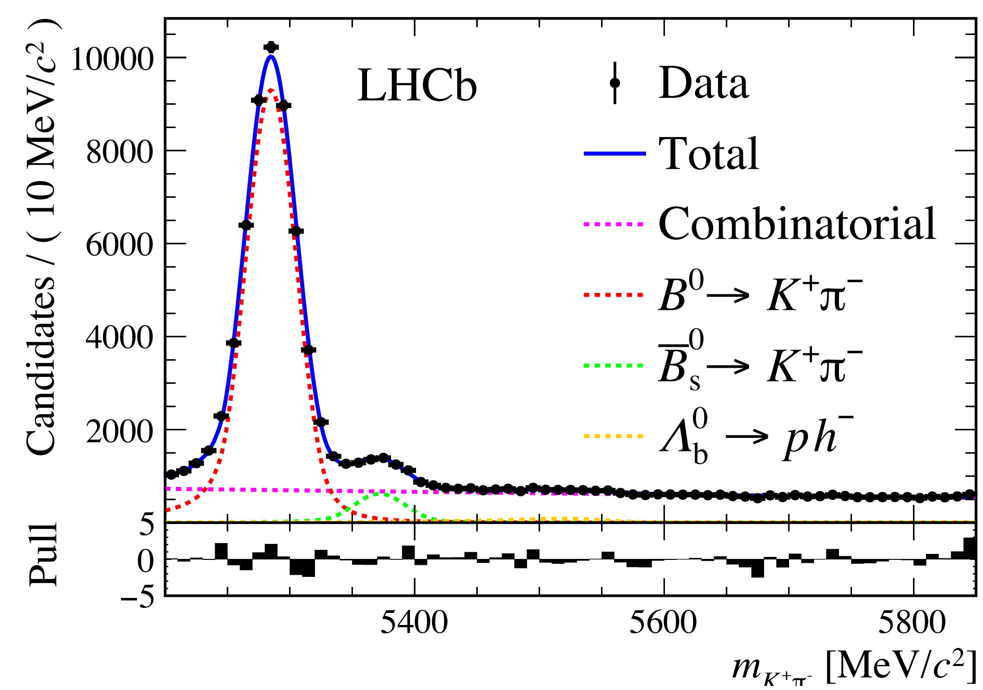
Compatible results: <<1 candidates surviving

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

[JHEP 1803 (2018) 078]

- Normalise simultaneously to two channels:
  - $B^+ \to J/\psi(\to \mu\mu)K^+$, chosen for the large yield, allowing a precise fit
  - $B^0 \to K^+\pi^-$, chosen for the similar topology to the signal (i.e. similar reco efficiencies)





Relative yield cross-checked:

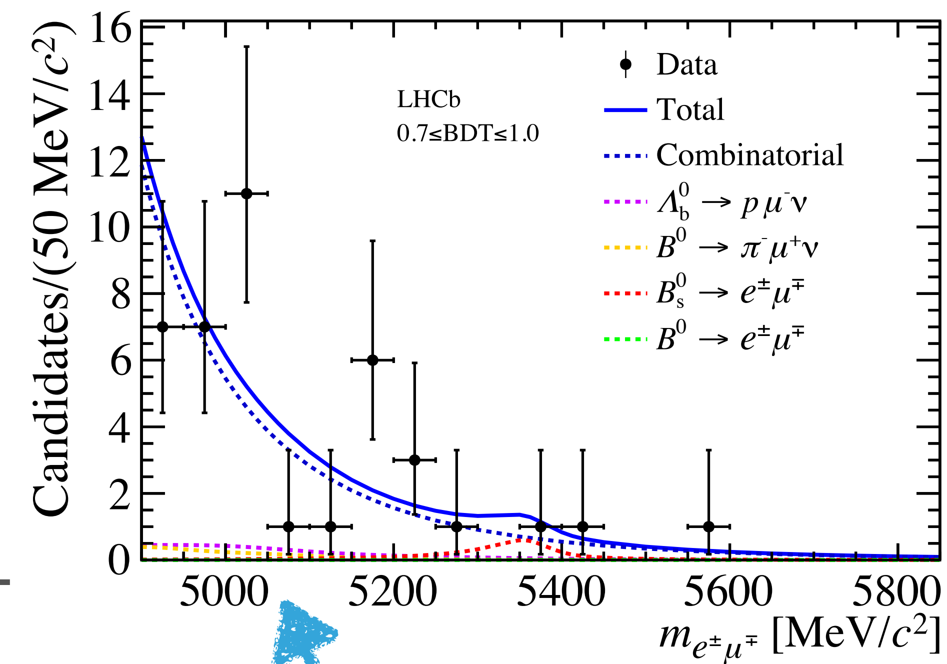
$R^{PDG} = 0.321 \pm 0.013$ [PDG]

$$R_{\rm norm} = \frac{N_{B^0\to K^+\pi^-} \times \varepsilon_{B^+\to J/\psi K^+}}{N_{B^+\to J/\psi K^+} \times \varepsilon_{B^0\to K^+\pi^-}} = 0.332 \pm 0.002\,(\text{stat}) \pm 0.020\,(\text{syst}),$$

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

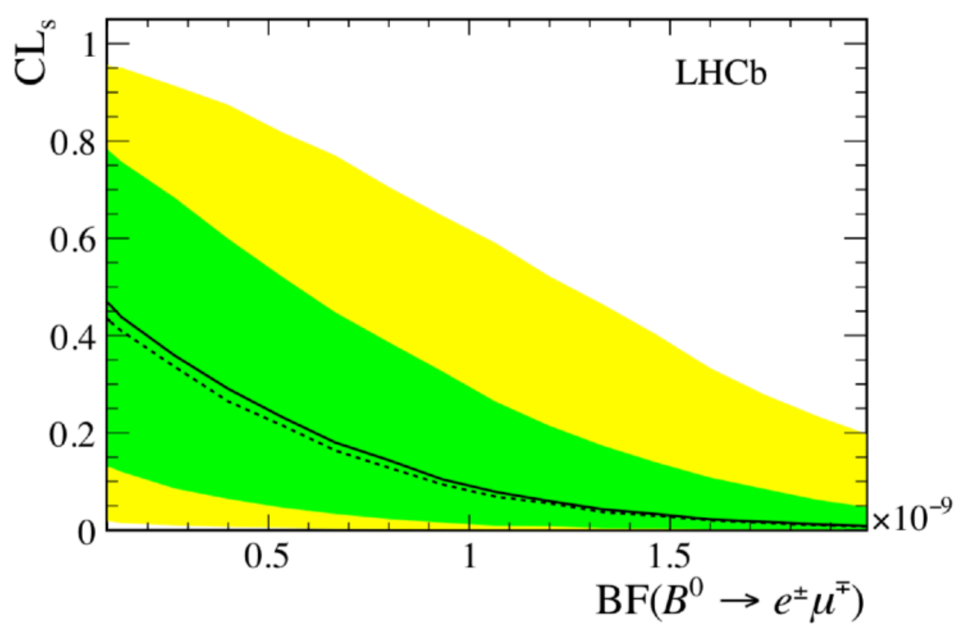
[JHEP 1803 (2018) 078]

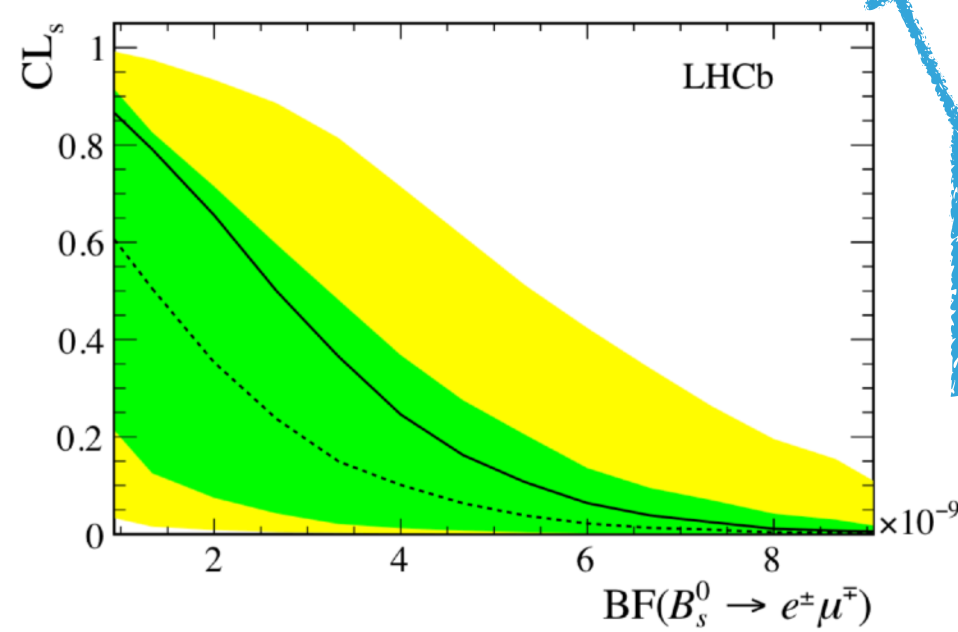
- $B \rightarrow e\mu$ on full Run I: $3 fb^{-1}$
- Fit to m(eμ): no excess → limits with CLs



$\mathcal{B}(B^0 \rightarrow e^\pm\mu^\mp) < 1.3\,(1.0) \times 10^{-9}$ @90(95)% CL

Two exclusive backgrounds surviving B0→πμν and Λ0b→pμν





$\mathcal{B}(B_s^0 \rightarrow e^\pm\mu^\mp) < 6.3\,(5.4) \times 10^{-9}$ if B_s light eigenstate dominates

$\mathcal{B}(B_s^0 \rightarrow e^\pm\mu^\mp) < 7.2\,(6.0) \times 10^{-9}$ if B_s heavy eigenstate dominates

@90(95)% CL

$B^+ \rightarrow K^+ e\mu$

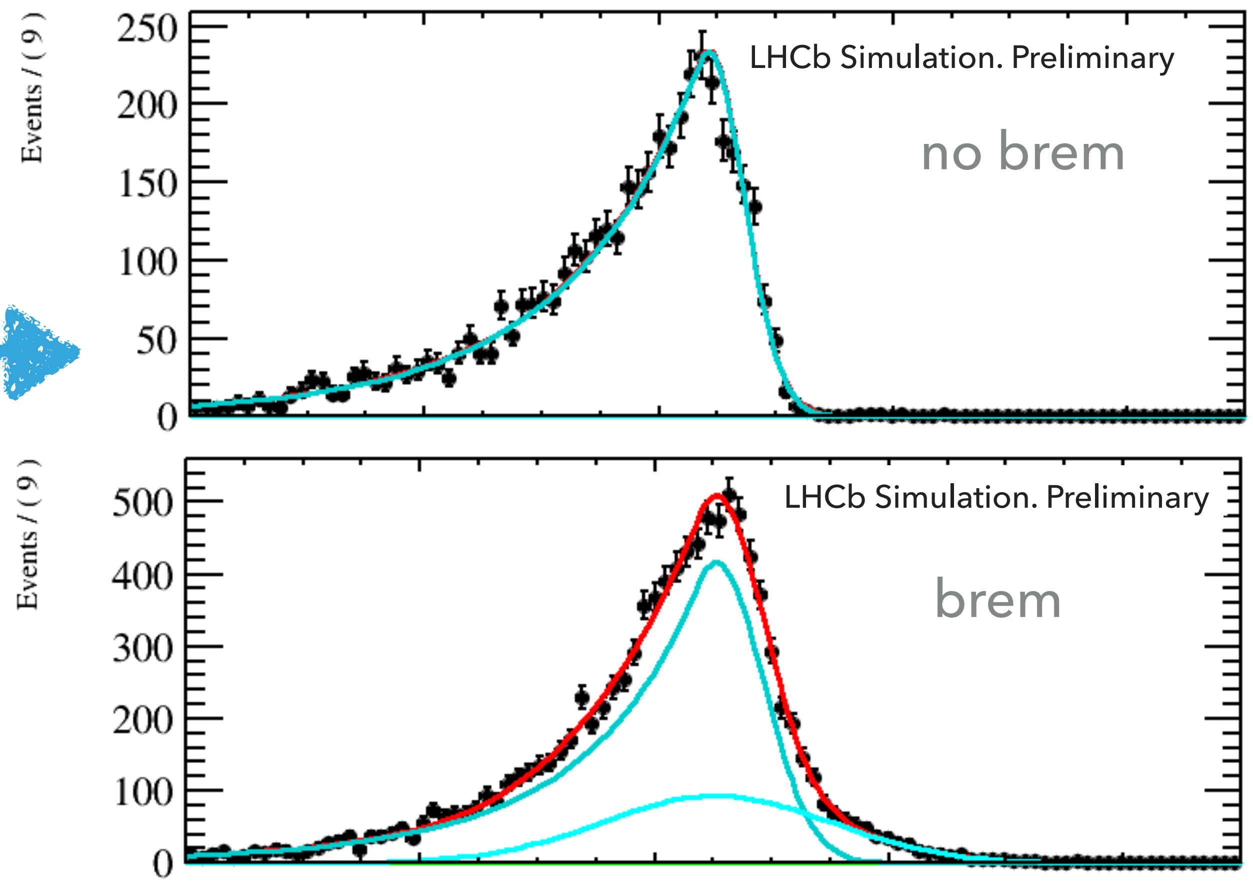
LHCb UNOFFICIAL!

- 3-body → lower helicity suppression than B→eμ
- New Physics predictions (almost) within reach:

$$\mathscr{B}(B^+ \rightarrow K^+ e^\pm \mu^\mp) \in [0.043,3] \cdot 10^{-8}$$

[PRD 97 (2018) 015019, JHEP 06 (2015) 072, JHEP 12 (2016) 027 with κ=1, JHEP 08 (2015) 123, PRD 92 (2015) 054013, PL B750 (2015) 367, PLB 751 (2015) 54]

- Trigger on muon
- Normalise to $B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+$
- Fit in brem categories
- Analysis still blind…!



$B^+ \to K^+ e\mu$ – Backgrounds

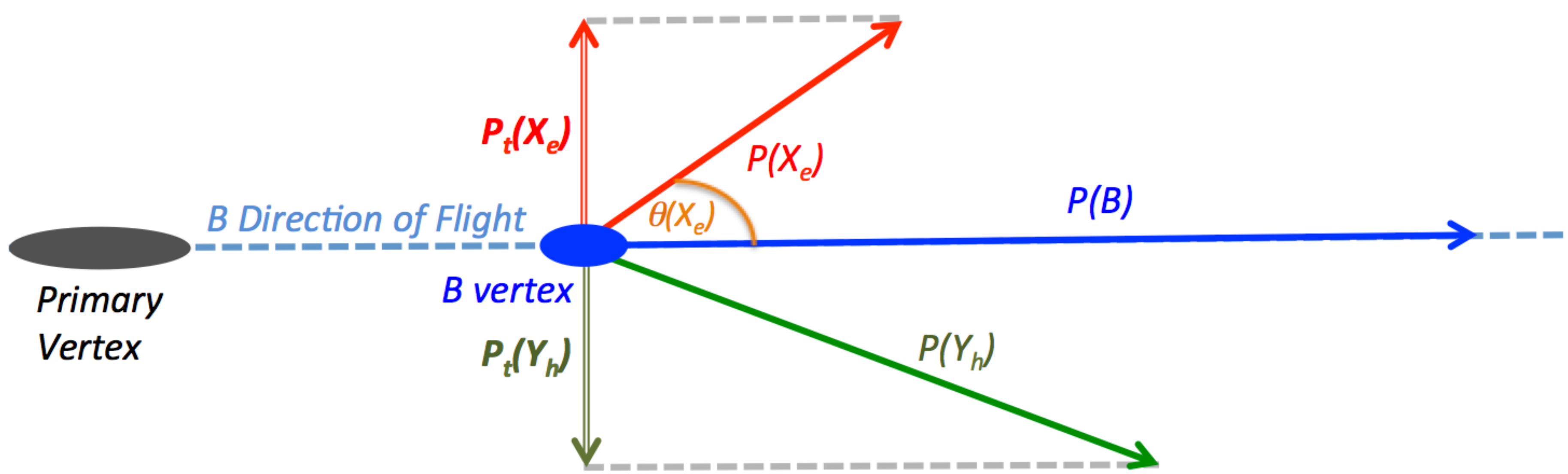
LHCb UNOFFICIAL!

- Two categories of partially-reconstructed (PR) backgrounds explicitly vetoed:
  - $B^+ \to \ell^+ \nu \overline{D}^0(\to K\ell'\nu)$ or $\mathrm{B}^+ \to \ell^+ \nu \overline{\mathrm{D}}^0(\to \mathrm{K}\pi)$ removed with $m(K^\pm \ell^\mp) > 1885\ \mathrm{MeV/c^2}$
  - Charmonium decays with misID: $B^+ \to J/\psi(\Psi(2S))K^+$ removed with cut depending on type of misID
- Very small contributions from non-resonant decays.

$B^+ \to K^+ e\mu$ – Backgrounds

LHCb UNOFFICIAL!

- First, topological, BDT against combinatorial, trained on upper sideband
- Second BDT (BDTHOP) against part-reco, trained on lower sideband
  - Same features as first BDT, with the addition of HOP mass, ideal for rejecting PR in decays with electrons
- Cut on both BDTs



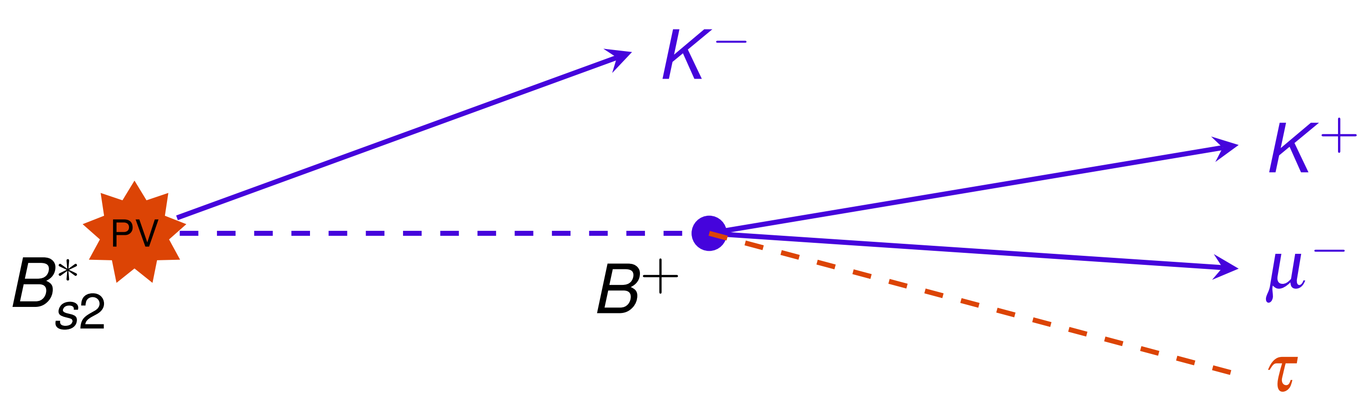
$$\alpha_{\rm HOP} = \frac{P_t^h}{P_t^e},$$

$$\vec{P}^{\rm corr}(e^+e^-) = \alpha_{\rm HOP}\vec{P}^{\rm meas}(e^+e^-).$$

$B^+ \to K^+ \tau\mu$ from B_{s2}^* decays

LHCb UNOFFICIAL!

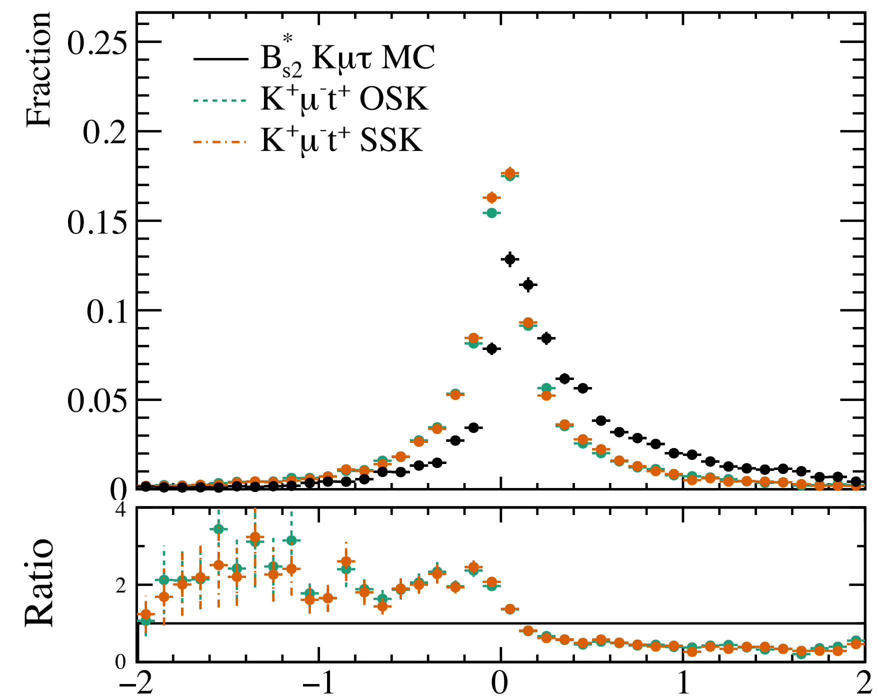
- τ modes are important as LFU suggests hierarchical couplings
- Using B^+ from B_{s2}^* decays allows to constrain kinematics of PR candidates
  - Strategy: tag $B^+ \to K^+\mu X$ decays and look for τs in missing mass



- Model signal and bkg missing mass shapes from MC and same-sign (SSK) $B_{s2}^* \to BK$ data
- Normalise to $B^+ \to J/\psi(\to \mu\mu)K^+$ with and without B_{s2}^* contribution
- Exclude $\tau \to 3\pi$, subject to separate analysis

LHCb UNOFFICIAL!

$B^+ \to K^+\tau\mu$ from B_{s2}^* decays - Backgrounds



Distance from K μ vertex to τ – track closest approach

- BDT against combinatorial
  - Trained against SSK
  - Bin in classifiers' response
- Other peaking backgrounds:
  - Vetoes on Kμ mass to remove J/ψ and Φ contributions
  - Non-B^+ decays must have combinatoric prompt kaon, and this contribution is present in SSK too, thus it is already accounted for!
  - Peaking missing mass must be produced from single missing particle. Only candidate is D meson, but not much SM background with $B^+ \to D\mu K$...
  - misID very low, combined with low background BF...

LFV AT LHCb

Summary of LHCb LFV analyses and prospects:

published:

$B^0 \to e\mu$	JHEP 1803 078	2018	limit $\mathcal{O}(10^{-9})$
$D^0 \to e\mu$	PLB 754 167	2017	limit $\mathcal{O}(10^{-8})$
$\tau \to \mu\mu\mu$	JHEP 02 121	2015	limit $\mathcal{O}(10^{-8})$

coming soon:

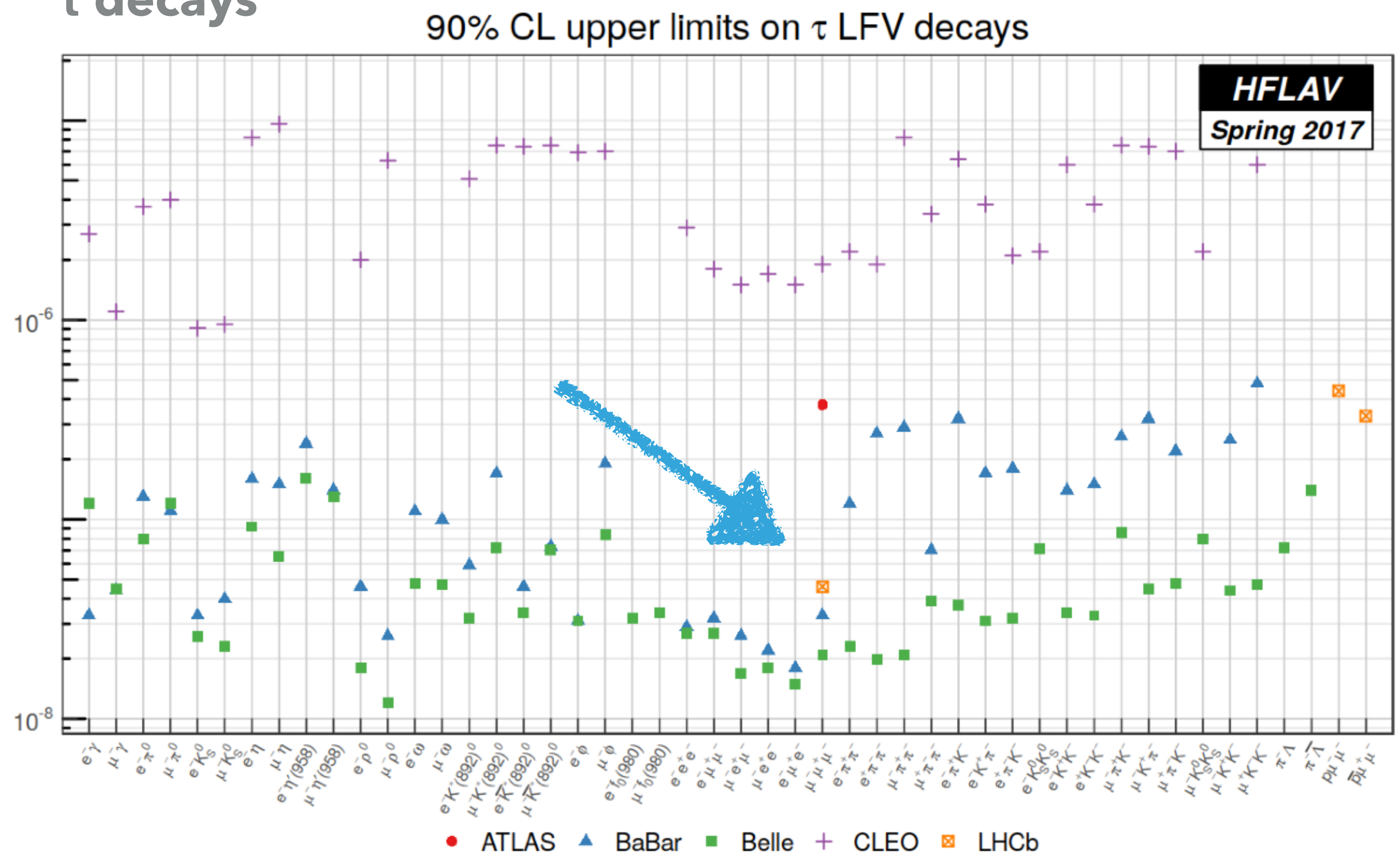
$B^0 \to K e\mu$	no helicity suppression
$\Lambda_b \to \Lambda e\mu$	baryon sector
$B \to K/K^* \tau\mu$	LFU suggests hierarchical couplings
$B \to \tau\mu$	

+ analyses of previously published channels adding new data

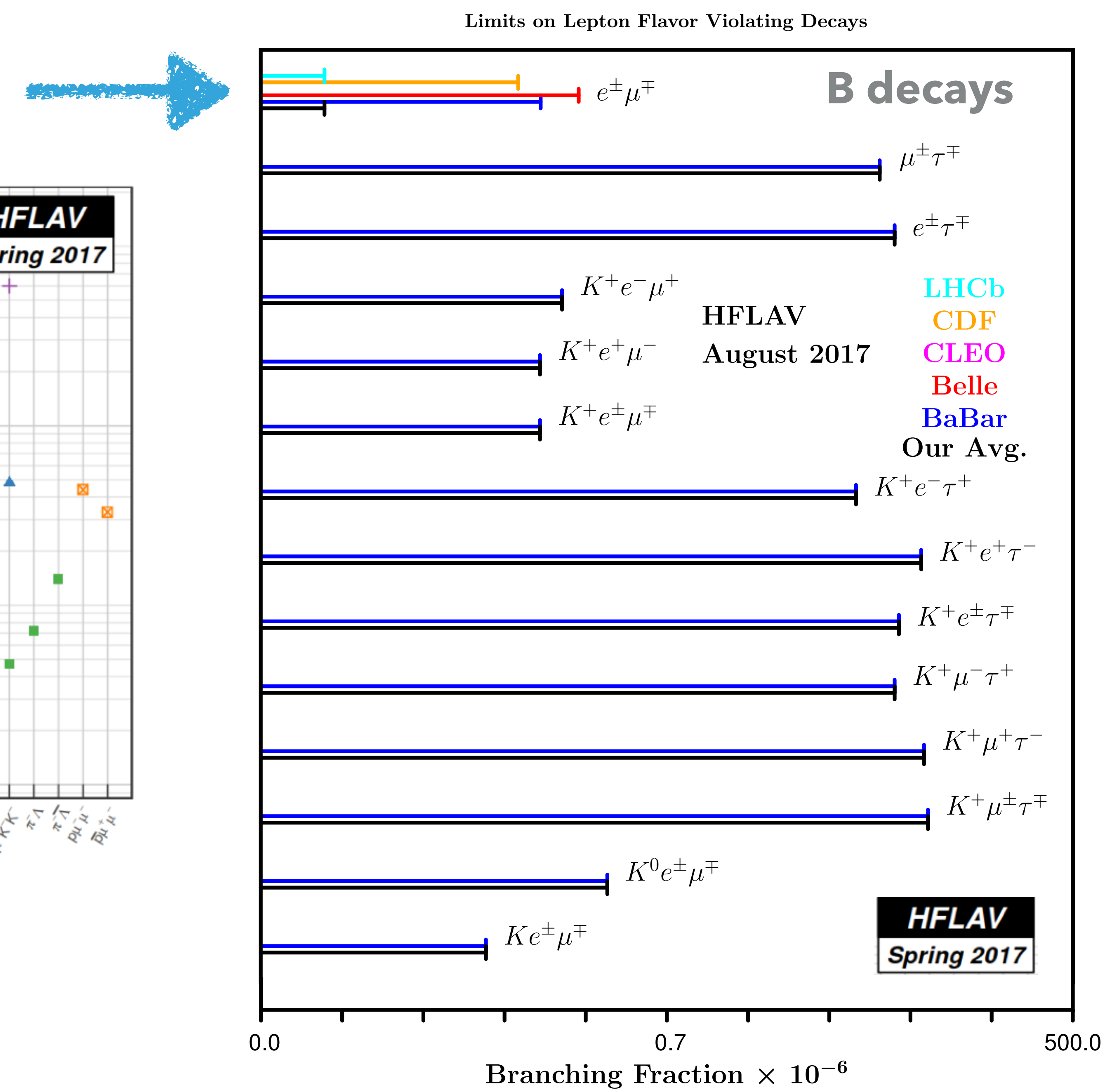
LFV AT LHCb

LHCb is significantly contributing to constrain new physics

τ decays



B decays



SUMMARY AND CONCLUSIONS

- Observation of LFV would be a clear sign of new physics
- Anomalies in LFU would make LFV searches also interesting
- No LFV observed yet:
  - In many channels we are reaching the level of BSM predictions
  - Statistically limited: analysing Run 2!
  - New modes will be analysed

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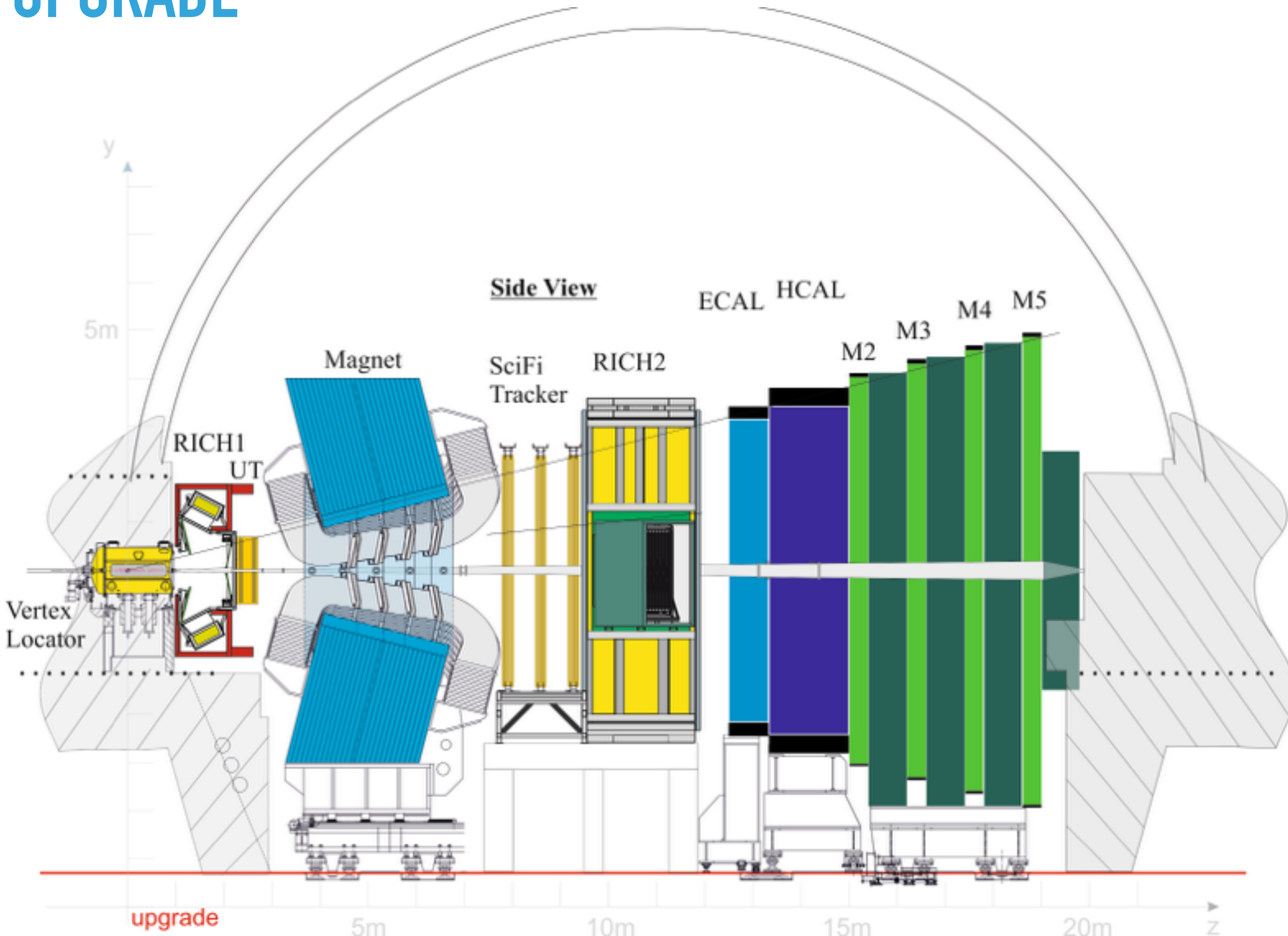
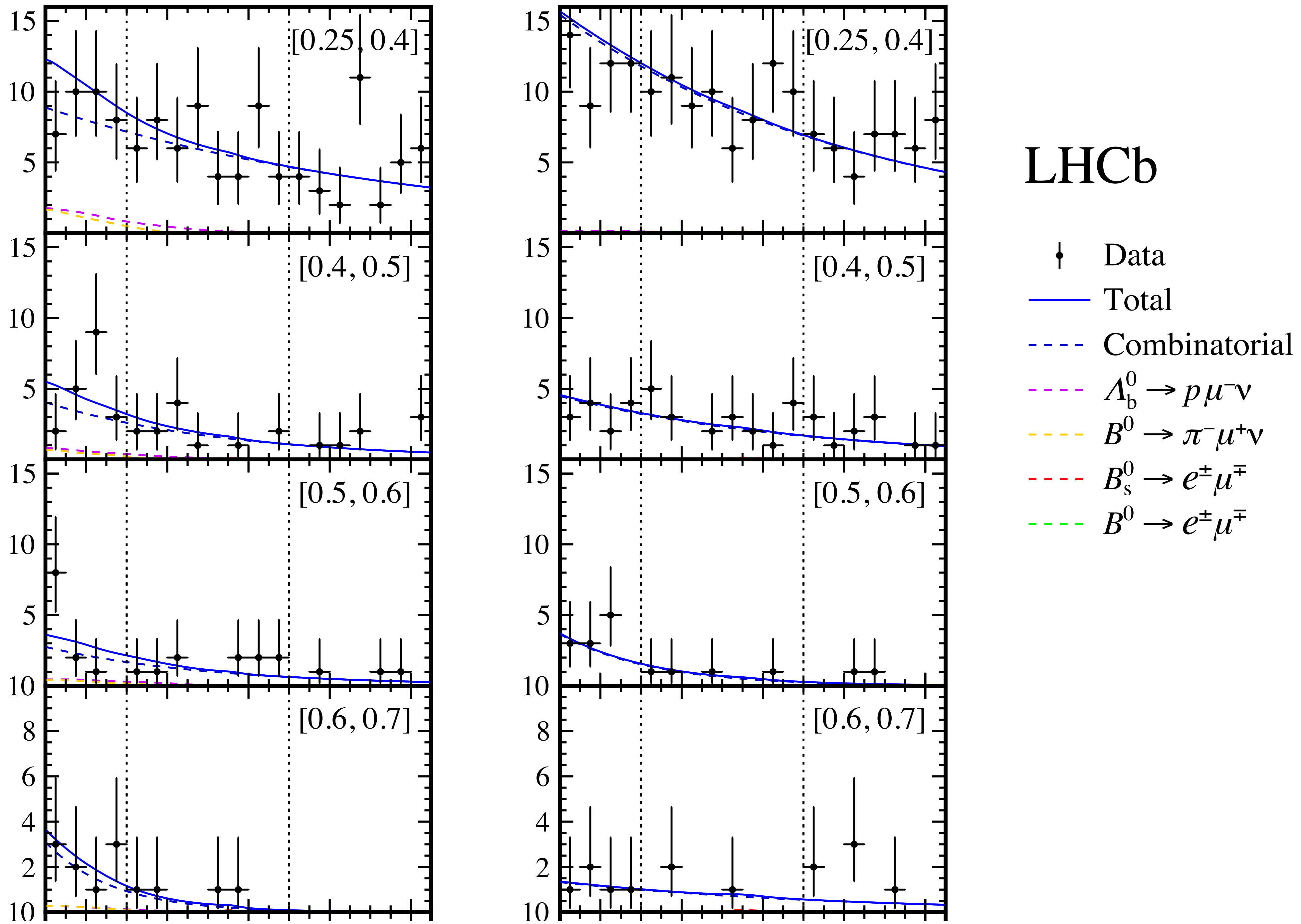
BACKUP

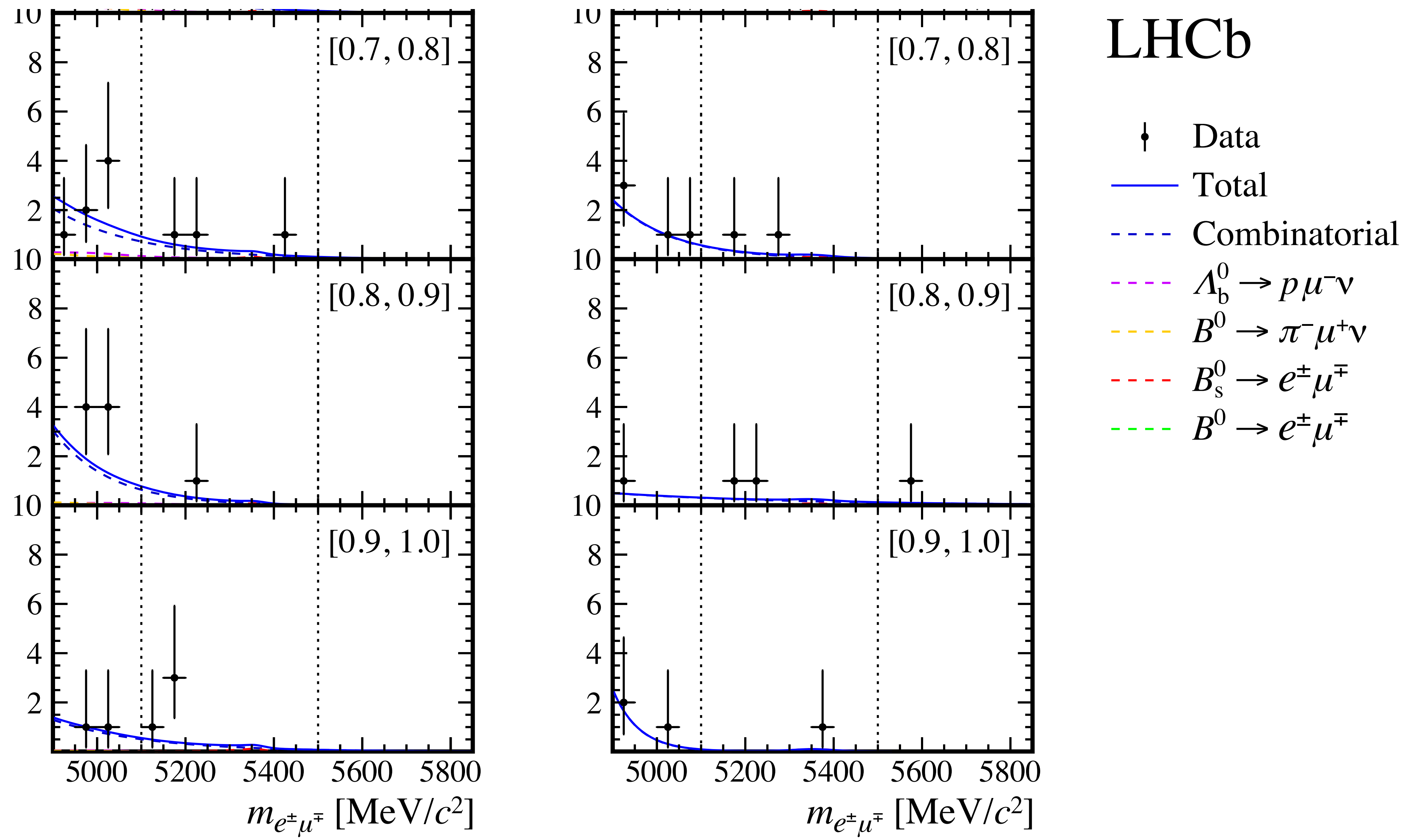
LHCB UPGRADE



MASS FITS


LHCb
Data
Total
Combinatorial
$\Lambda_b^0 \to p\mu^-\nu$
$B^0 \to \pi^-\mu^+\nu$
$B_s^0 \to e^\pm\mu^\mp$
$B^0 \to e^\pm\mu^\mp$
[0.25, 0.4]
[0.4, 0.5]
[0.5, 0.6]
[0.6, 0.7]

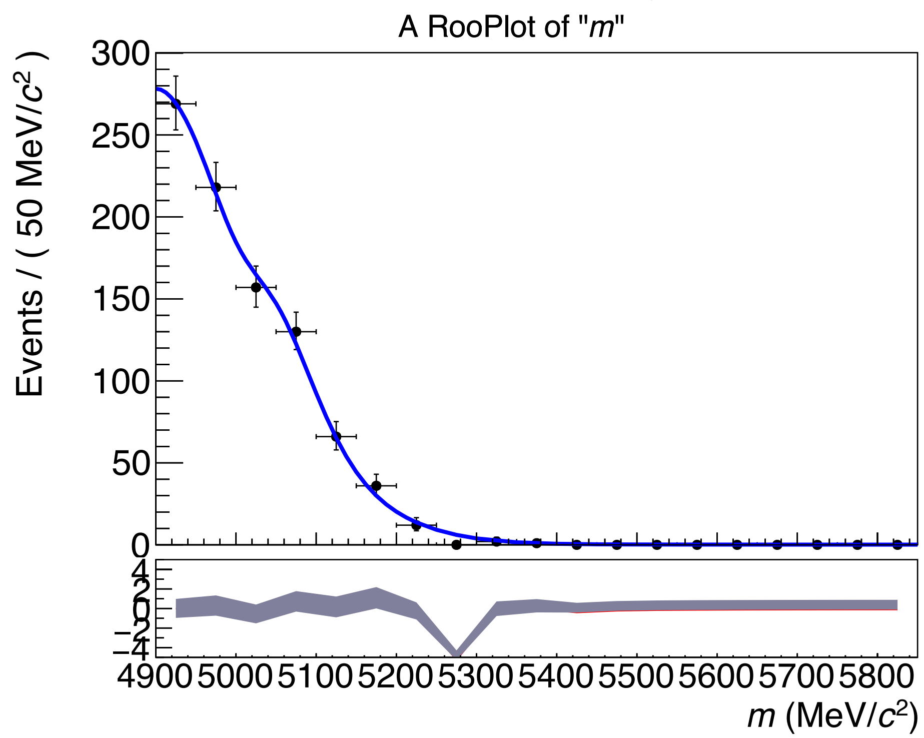
MASS FITS (2)



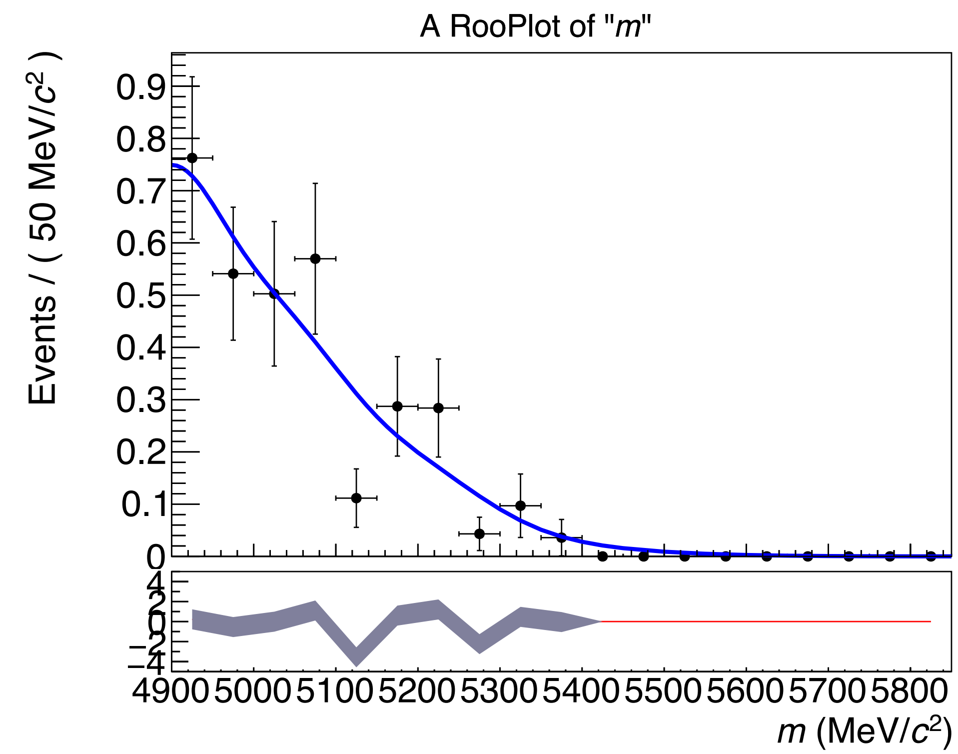
[0.7, 0.8]
[0.8, 0.9]
[0.9, 1.0]
5000 5200 5400 5600 5800
$m_{e^\pm\mu^\mp}$ [MeV/c^2]
LHCb
Data
Total
Combinatorial
$\Lambda_b^0 \to p\mu^-\nu$
$B^0 \to \pi^-\mu^+\nu$
$B_s^0 \to e^\pm\mu^\mp$
$B^0 \to e^\pm\mu^\mp$

EXCLUSIVE BACKGROUNDS

$$\mathbf{B^0 \rightarrow \pi\mu\nu}$$



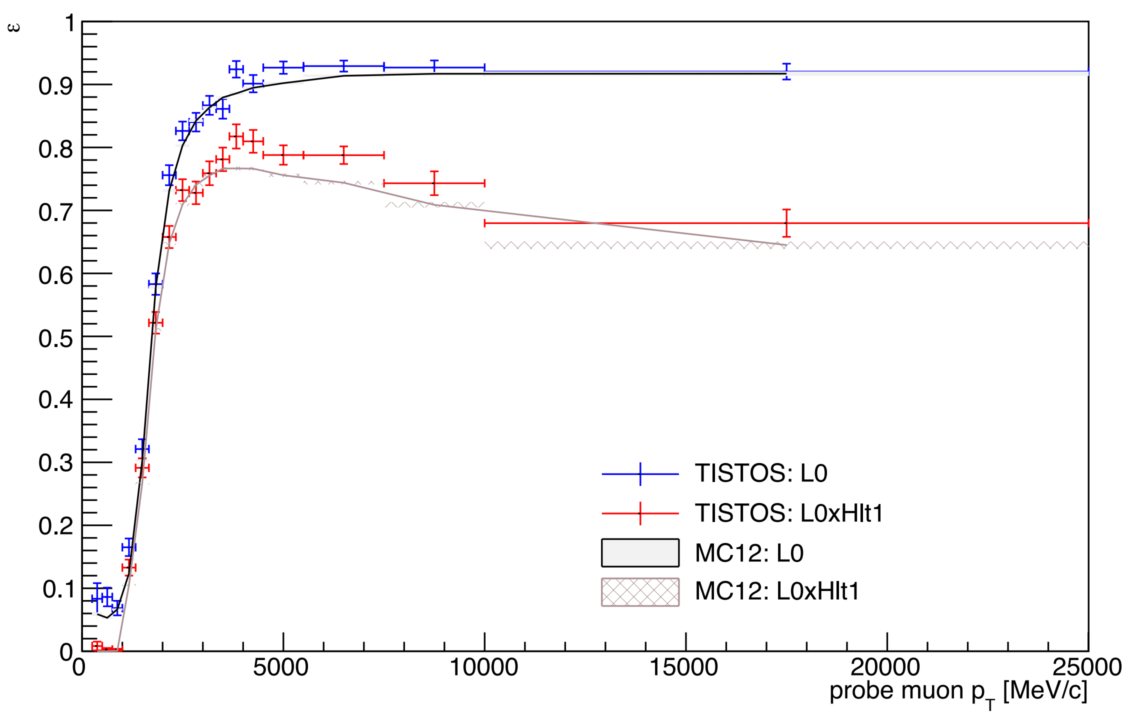
$$\mathbf{\Lambda_b^0 \rightarrow p\mu\nu}$$

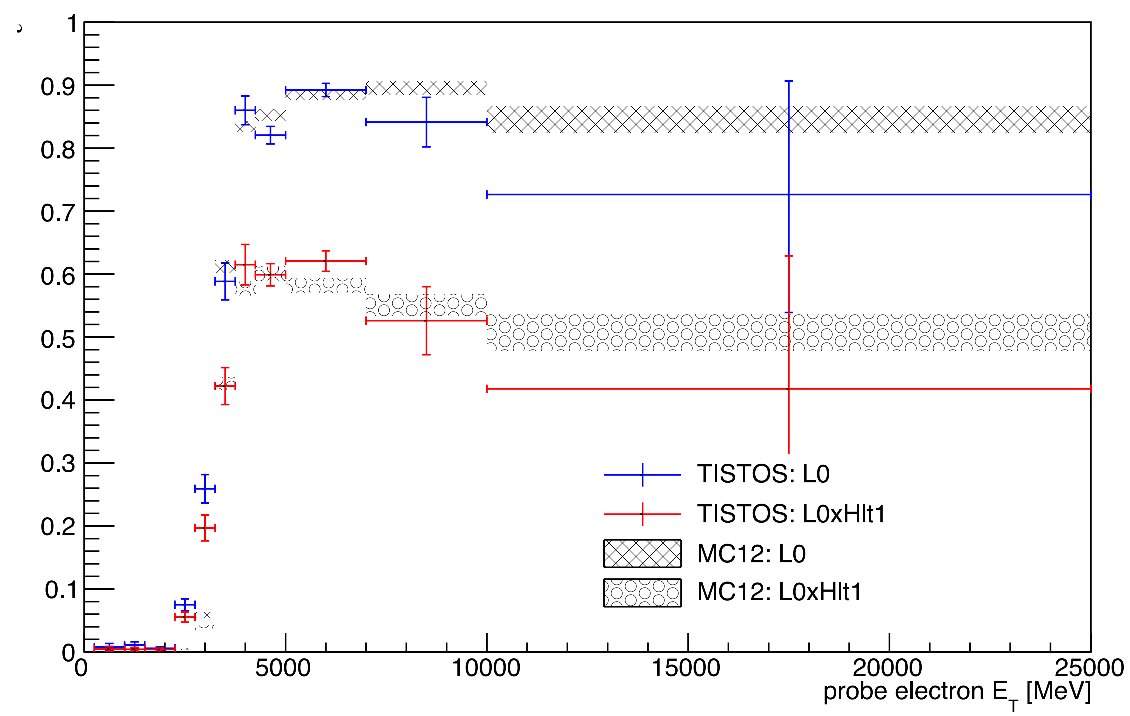


- Shapes shown are BDT bin 2 $[0.25, 0.4]$, without brem recovery

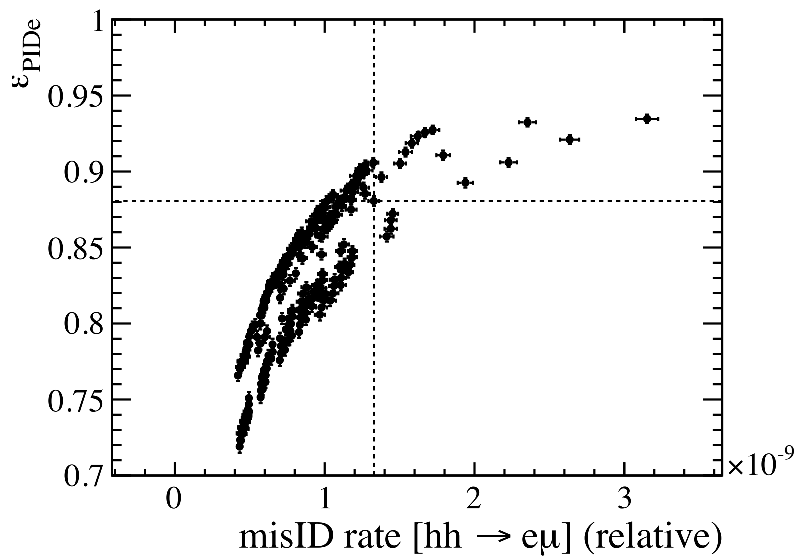
TRIGGER STRATEGY AND EFFICIENCIES

$B^0_{d,s} \to e^{\pm}\mu^{\mp}$ (HasBremAdded == 0)	$0.726 \pm 0.002\,(\mathrm{stat}) \pm 0.015\,(\mathrm{syst})$
$B^0_{d,s} \to e^{\pm}\mu^{\mp}$ (HasBremAdded == 1)	$0.621 \pm 0.002\,(\mathrm{stat}) \pm 0.015\,(\mathrm{syst})$
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	0.758 ± 0.006
$B^0 \to K^+\pi^-$	0.212 ± 0.002





PID STRATEGY AND EFFICIENCIES

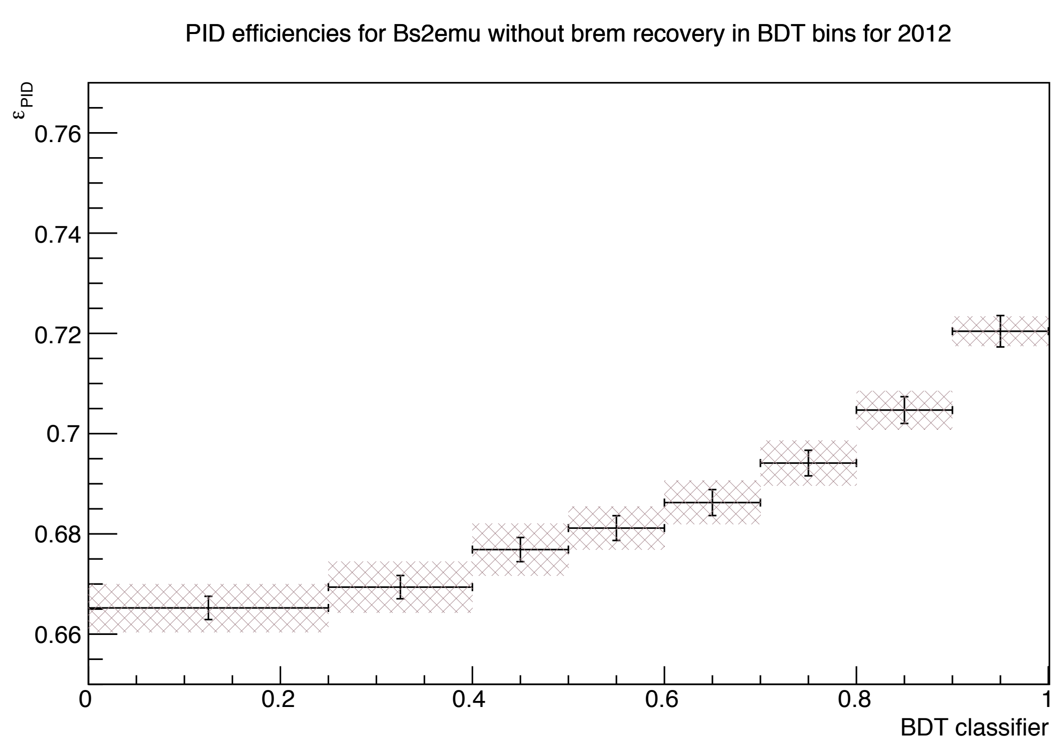


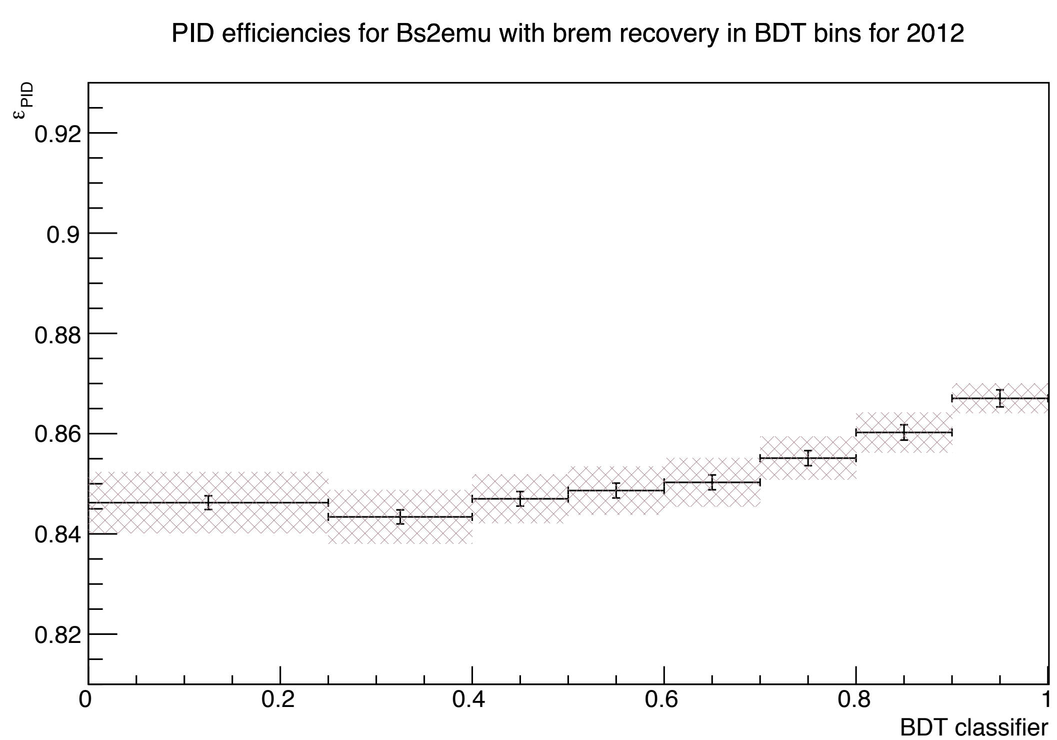
- Optimisatised with respect to $B^0_{(s)} \to h^+h^-$ double misID, with figure of merit (FOM):

$$\text{FOM} = \sum_{B^0_{d,s}\to \text{hh}} \frac{f_{d,s}}{f_d} \mathcal{B}(B^0_{d,s} \to \text{hh}) \epsilon^{\text{PID}}_{\text{hh}\to e\mu}$$

- Same signal PID efficiency ($\simeq$ 80%), but lower misID rate

wrt old LHCb analysis





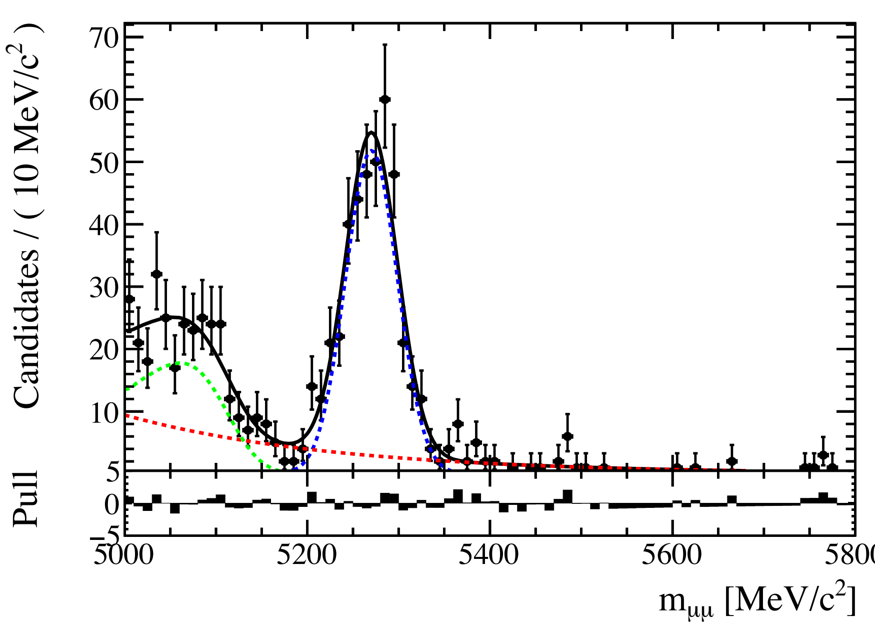
PEAKING BACKGROUNDS - B→HH

Main method

- Estimation of expected amount of $B^0_{(s)} \to h^+h^-$ is determined using $B^0_{(s)} \to h^+h^-$ MC weighted with `PIDCalib` efficiencies
- Normalise with respect to $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
- Expected result shown here in full mass, BDT and `HasBremAdded` range and is negligible

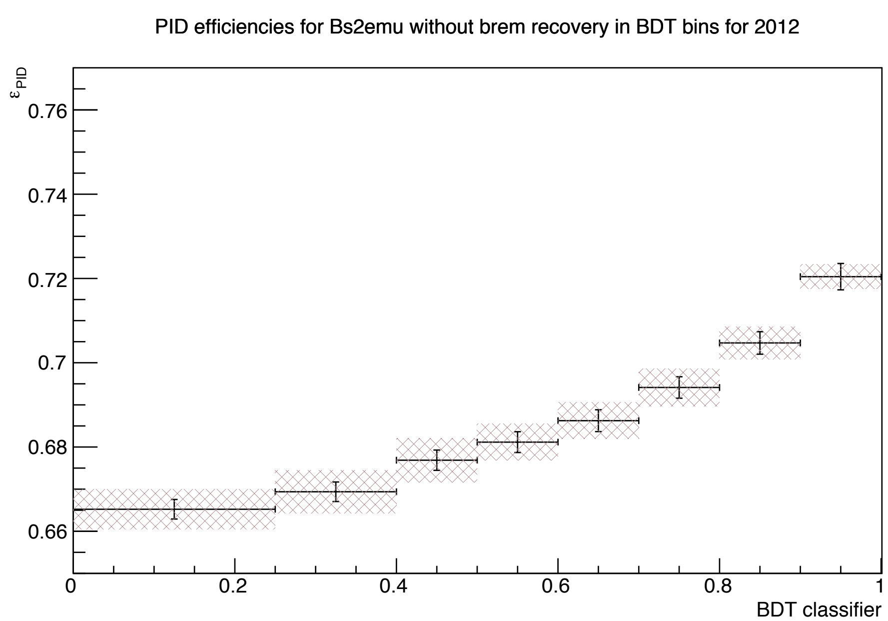
Cross-check

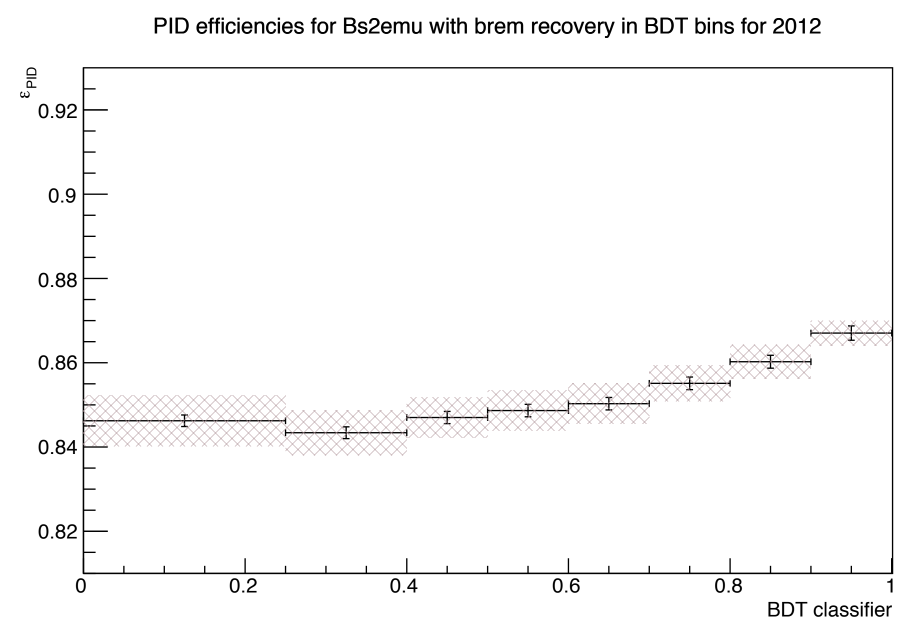
- Single misID determined in $B^0_{(s)} \to h^+h^-$ data
- Electron PID on one of the tracks and hadron PID on other
- Additional misID efficiency with main method
- Result compatible



EFFICIENCIES – PID

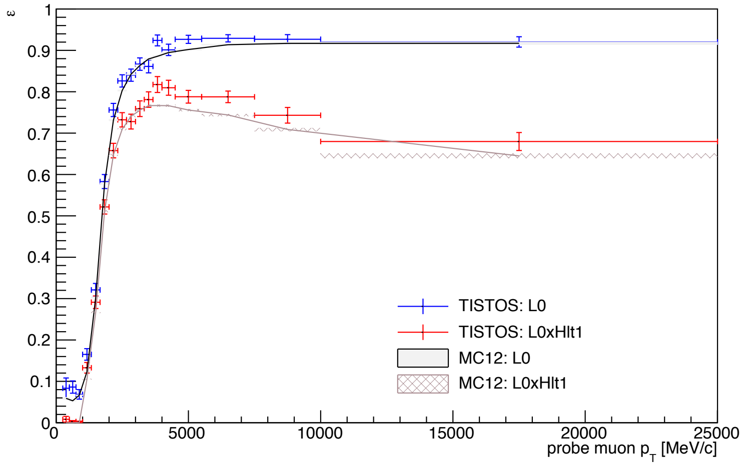
- Determined using `PIDCalib`
- Reweighting to signal MC in bins of BDT and `HasBremAdded` with track p_T, η (and nSPDHits for electron to data nSPDHits distribution)
- $B^0 \to K^+\pi^-$ uses p and η binnings

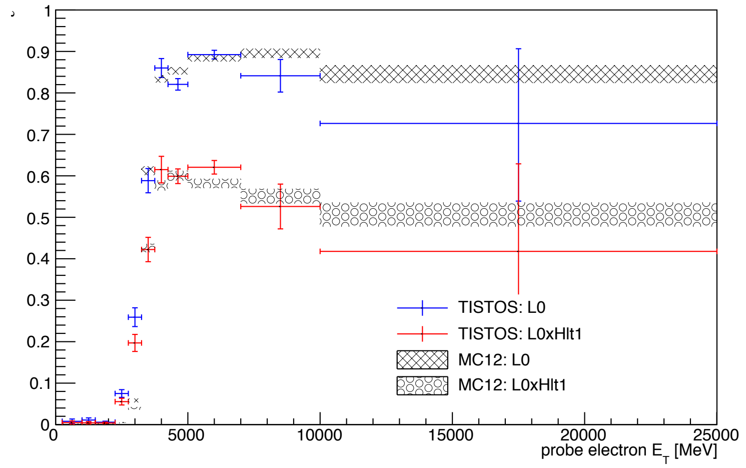




	Run 1
$B^+ \to J/\psi\ (\to\mu^+\mu^-)K^+$	$0.9781 \pm 0.0002\,(\mathrm{stat})$
$B^0 \to K^+\pi^-$	$0.3850 \pm 0.0001\,(\mathrm{stat})$

EFFICIENCIES - TRIGGER





- TISTOS for L0xHlt1
- Using TIS sample of
- Reweight efficiencies to IP and E_T (for electron) or p_T (for muon) to account for biases
- Hlt2 efficiencies from MC
- Systematics from TISTOS binning and MC reweighted for B p_T and nSPDHits

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B2EMU - LQ MASS