Search for new physics in b→sll transitions at LHCb

Stefania Ricciardi
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on behalf of LHCb

b→sll transitions

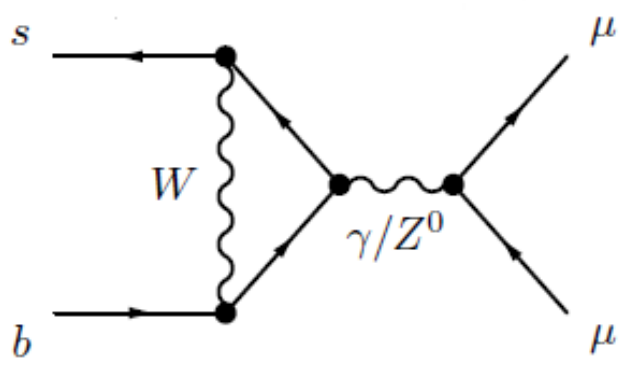
- Decays mediated by b→sll are FCNC
- Proceed in the SM only via loops

Rare processes (BF $\leq 10^{-6}$)

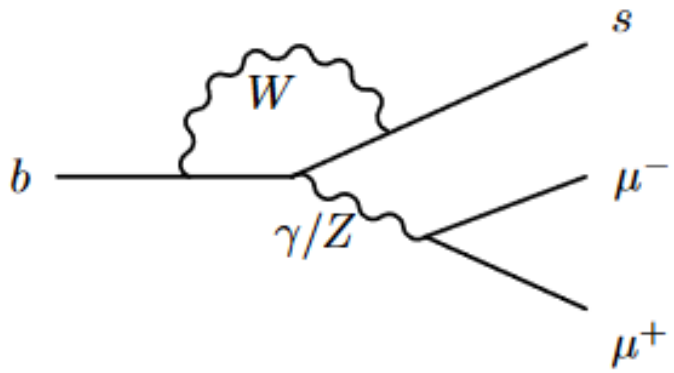
- New (virtual) particles may significantly alter decay amplitudes
- Sensitive to new physics at high scales, that are inaccessible to direct production searches

Rich laboratory

- Many channels:
  - *b* mesons or baryons
  - *l* = *e*, μ or τ
  - leptonic or semi-leptonic decays
- Many observables, depending on final state



Pure leptonic



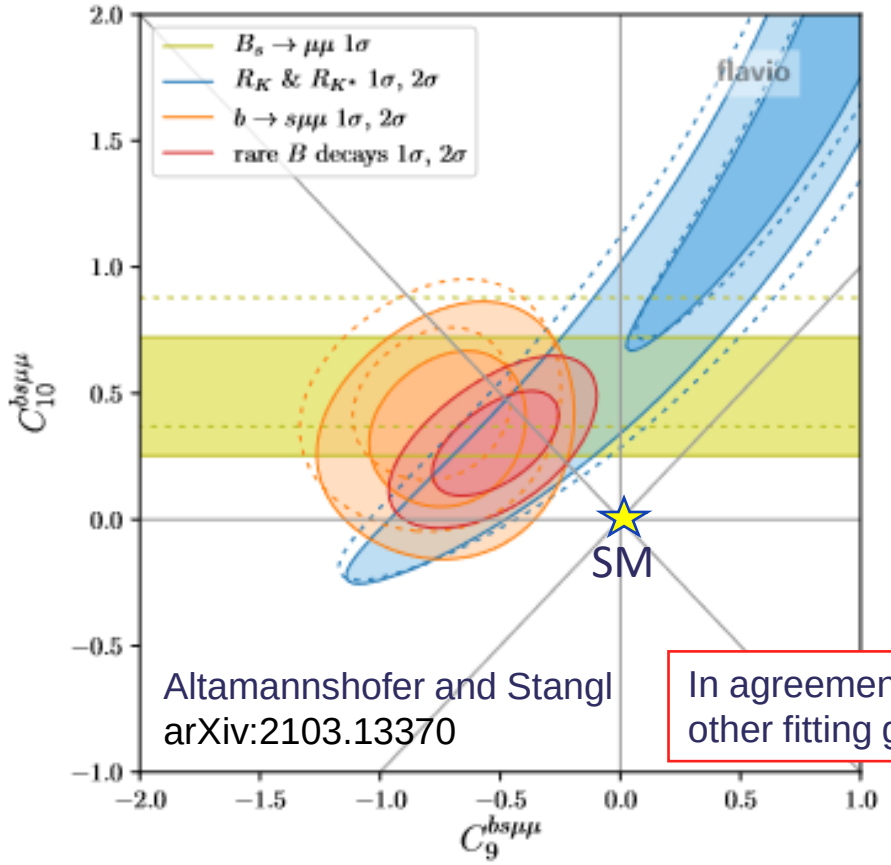
Semi-leptonic:
add spectator quark(s)

Outline

- **$b \to s\mu\mu$**
  - Branching fractions
  - Angular observables
- **$b \to s\mu\mu$ / $b \to see$**
  - Lepton Flavour Universality tests
- **$b \to sll'$, $l \neq l'$**
  - Lepton Flavour Violating decays searches
- **Outlook**

❖ Anomalies: discrepancies with SM in several observables

- 1-3.6 σ in semi-leptonic branching fractions and angular observables
- 3.1 σ in LFU tests (R_K)
- >4 σ discrepancy in global fits



Altamannshofer and Stangl
arXiv:2103.13370

In agreement with other fitting groups

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$b \to s ll$ anomalies

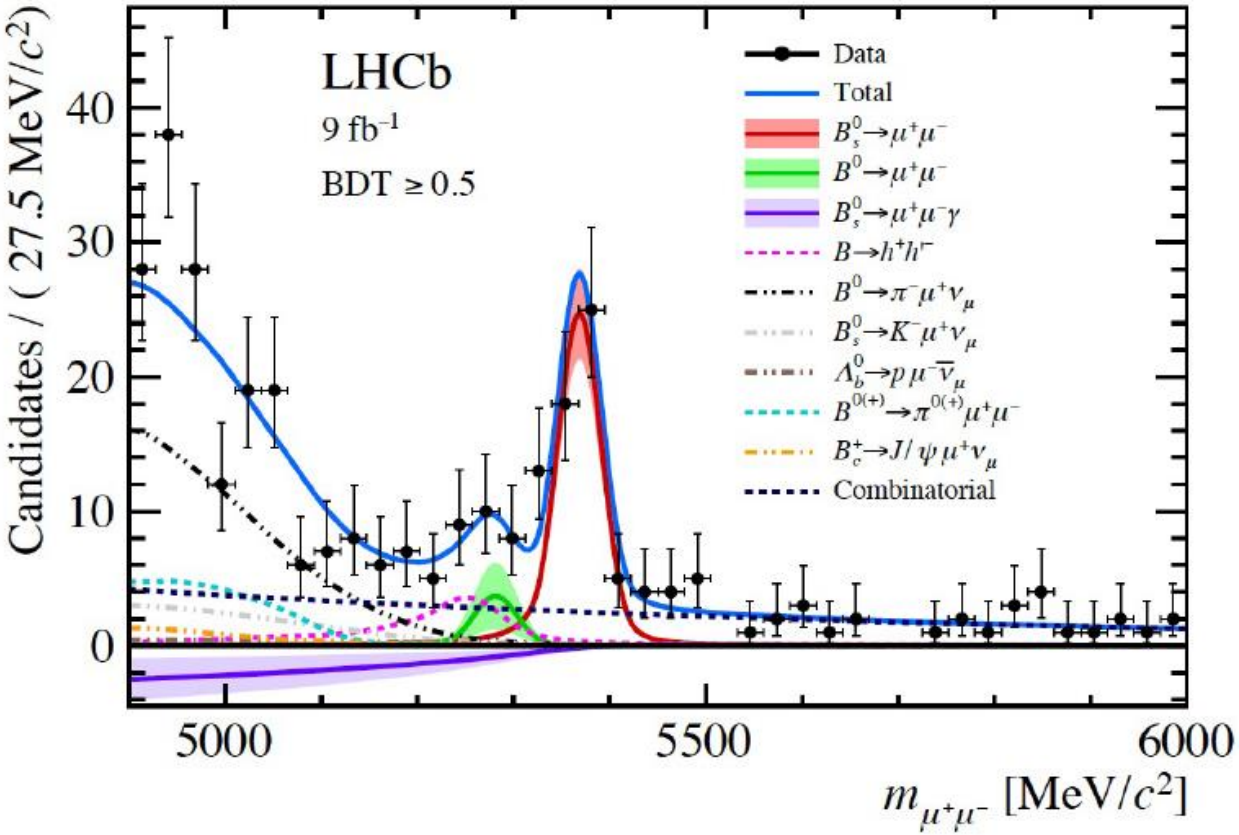
$B^0_s \to \mu\mu$

- Unique decay, very sensitive to new physics
  - helicity suppressed $\Rightarrow$ very rare (BF 10^{-9})
  - B^0_s decay constant well-known from lattice QCD $\Rightarrow$ precise (4%) BF predictions

SM: Beneke, Bobeth, Szafron, arXiv:1908.07011

$$B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Phys Rev D 105 (2022) 012010



- ~2 σ tension between ATLAS+CMS+LHCb combined measurement of B^0_s results (2020) and SM prediction
- 2022: new results from LHCb

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$$

Upper limits at @95% CL

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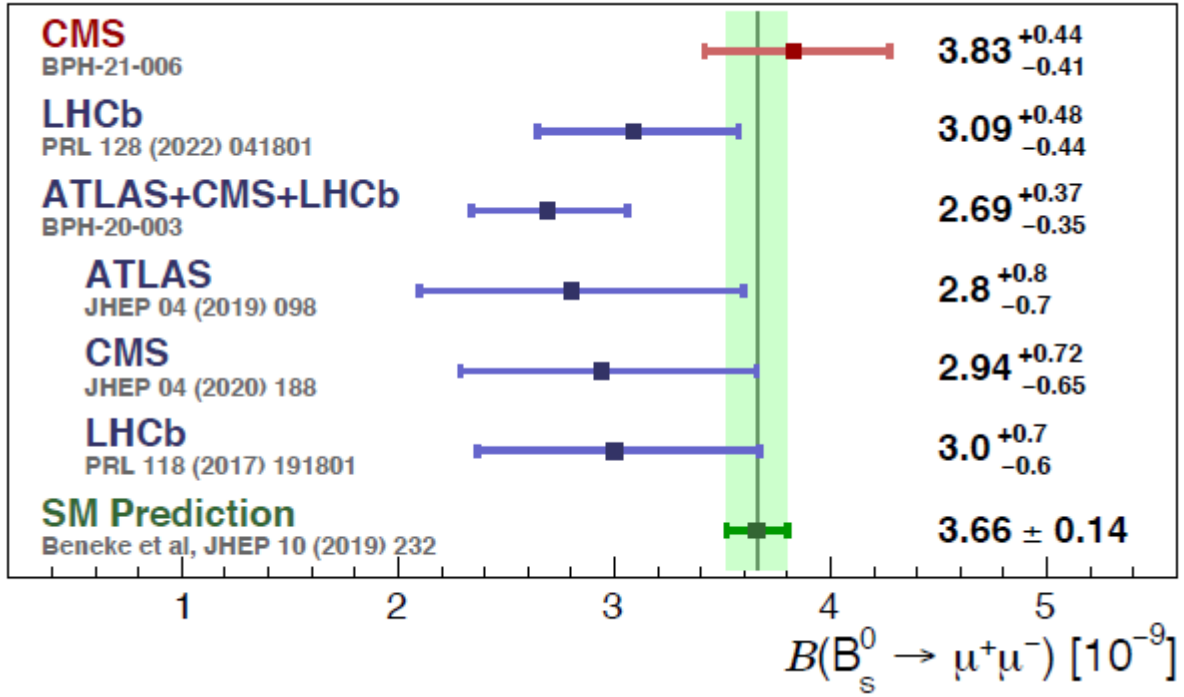
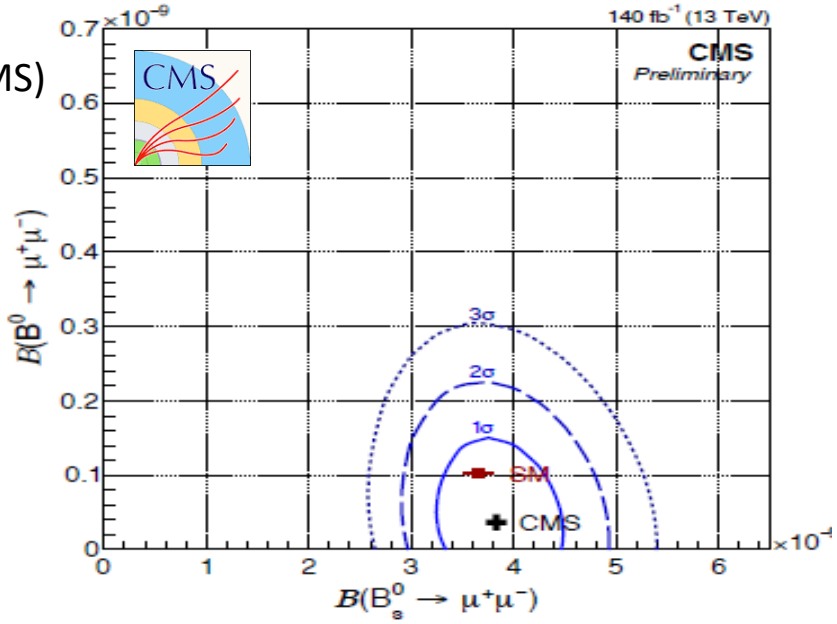
$B^0_s \to \mu\mu$

D.Kovalskyi (CMS)
CERN seminar,
26/07/22





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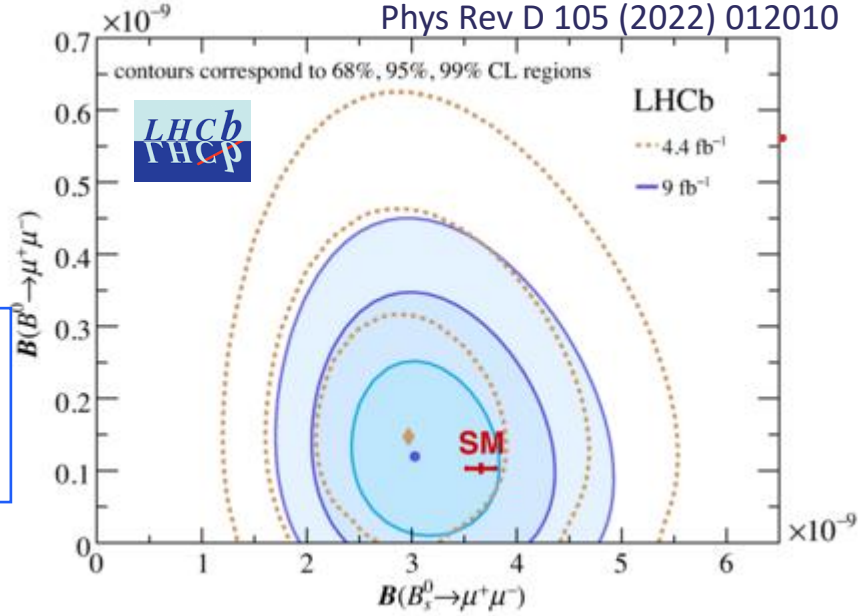

- New preliminary results presented @ICHEP22 by CMS (currently best precision)
- Both LHCb and CMS results in good agreement with SM

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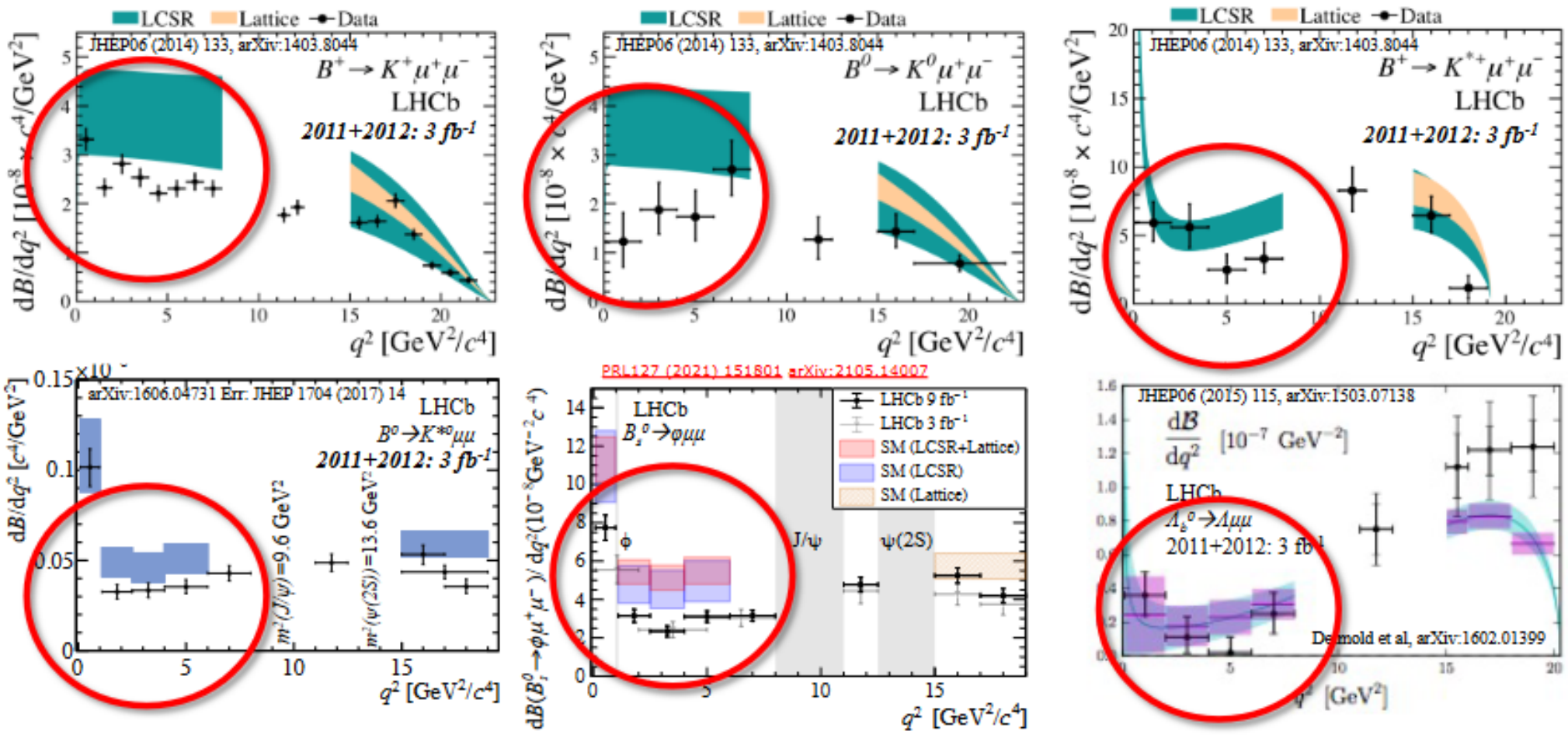
Semi-leptonic: differential branching fractions



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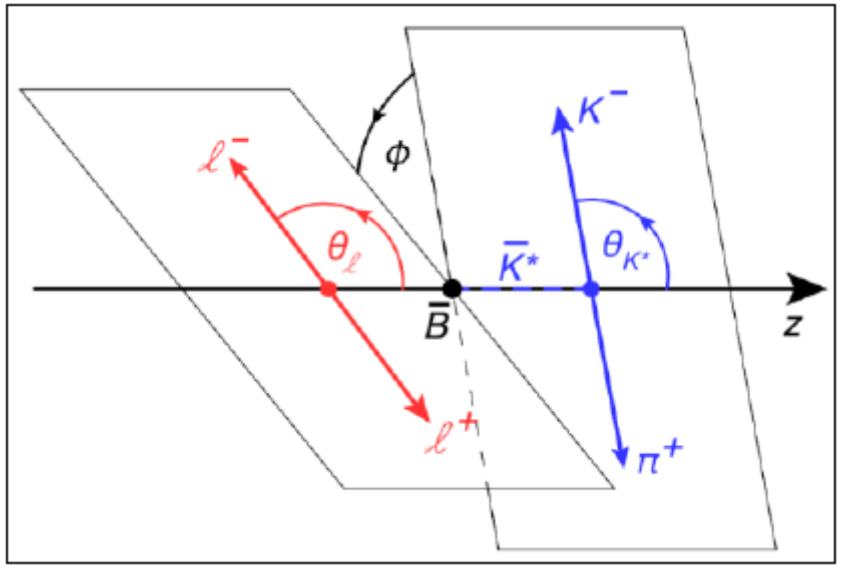
All semi-leptonic BFs lower than SM predictions at low q^2 (~1-4σ)
[comparison limited due to large theory uncertainties on form factors]

4-body decays: angular observables

- Prototype:
  $B^0 \to K^{*0}\,\mu\mu$
- Differential decay rate described by 3 angles and di-muon invariant mass squared (q^2)
- Rich structure of observables in the angular coefficients [functions of q^2]



Optimised observables can be formed out of the angular coefficients which are robust against form-factors uncertainties (e.g. , P_5')

Descotes-Genon et al., JHEP 01 (2013) 048

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$\sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

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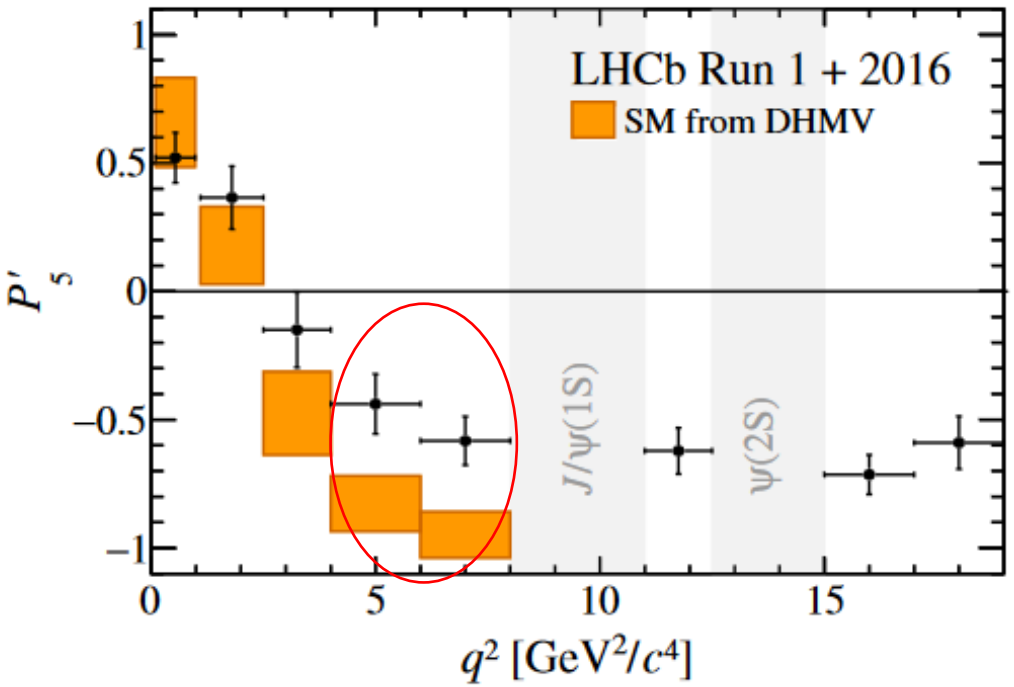
P'_5

- Anomaly in P'_5 found in $B^0 \to K^{*0}\mu\mu$ for $4<q^2<8$ GeV^2
- Recently observed also in B^+ isospin partner
- Deviations from SM predictions also in other angular observables

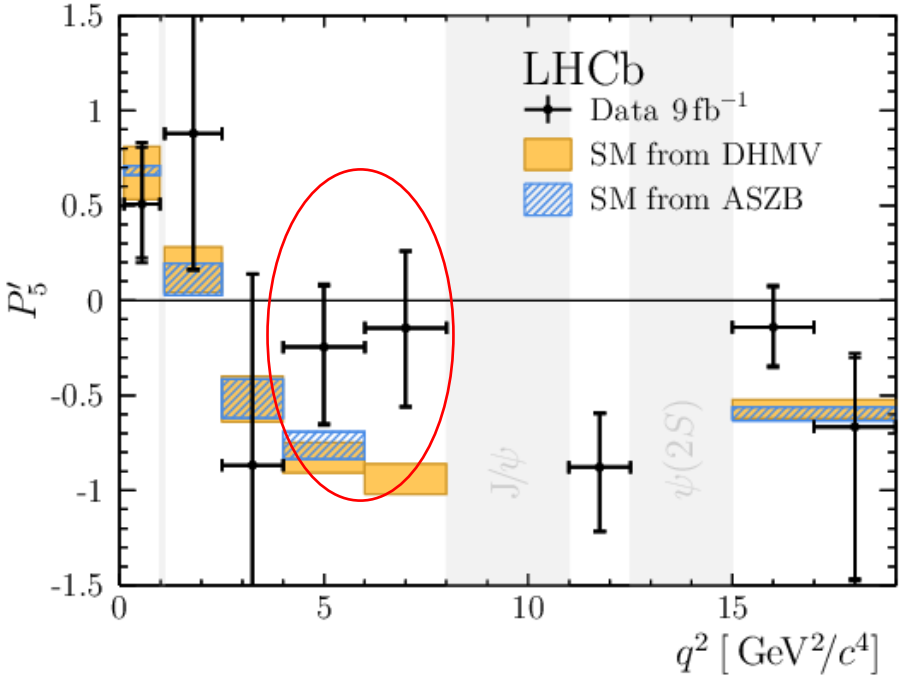
$B^0 \to K^{*0}\mu\mu$

PRL 125 (2020) 011802



$B^+ \to K^{*+}\mu\mu$

PRL 126 (2021) 161802



Extent of hadronic contributions still matter of debate (particularly charm-quark loops)

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Lepton Flavour Universality (LFU)

- Equal gauge coupling of electroweak bosons to all leptons in SM $\Rightarrow$ LFU
- R_X ratios test LFU in $b \to sll$
  - Theoretically pristine
  - QCD uncertainties cancel in the ratio, small uncertainty O(1%) from QED

[Eur. Phys. J. C (2016) 76:440, JHEP 12(2020)104]

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B_q \to X_s e^+e^-)}{dq^2} dq^2} = 1 \pm \mathcal{O}(1\,\%)$$

- Five different ratios published so far by LHCb: $X_s = K^+, K^0_S, K^{*0}, K^{*+}$ and pK^-

LFU results: R_X all below SM

R_K (9/fb) 3.1 σ from SM

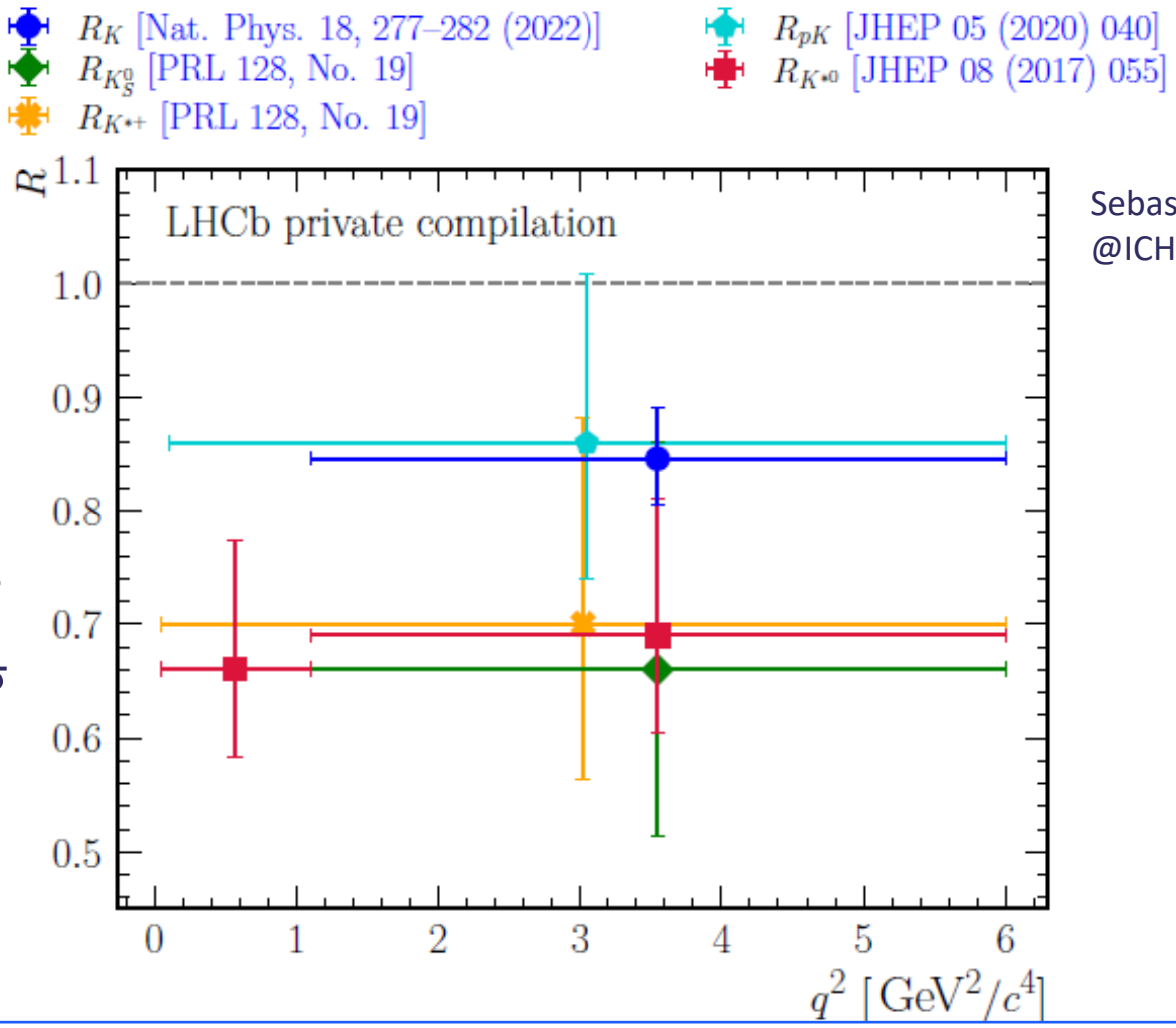
$R_{K^{*+}}$ (9/fb) 1.4 σ

R_{Ks} (9/fb) 1.5 σ

$R_{K^{*0}}$ low-q^2 (3/fb) 2.1 σ

$R_{K^{*0}}$ central-q^2 (3/fb) 2.4 σ

R_{pK} (5/fb) <1 σ

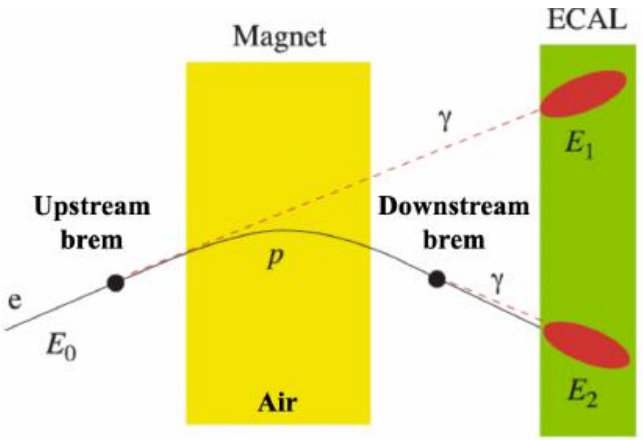


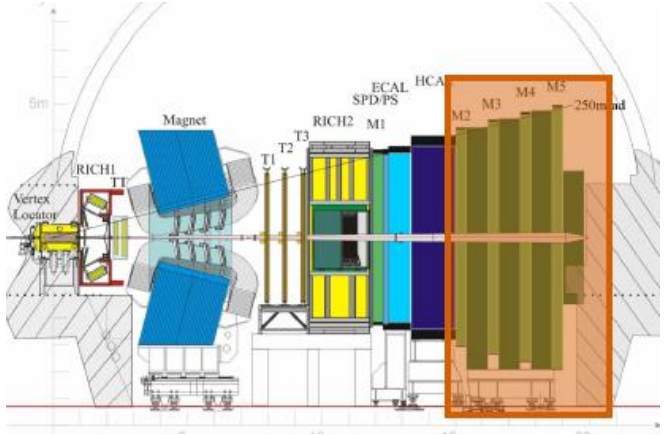
Sebastian Schmitt @ICHEP22

LFU: theoretically cleanest anomaly, experimentally challenging

LFU: experimental challenge

Trigger and reconstruction differences between electrons and muons





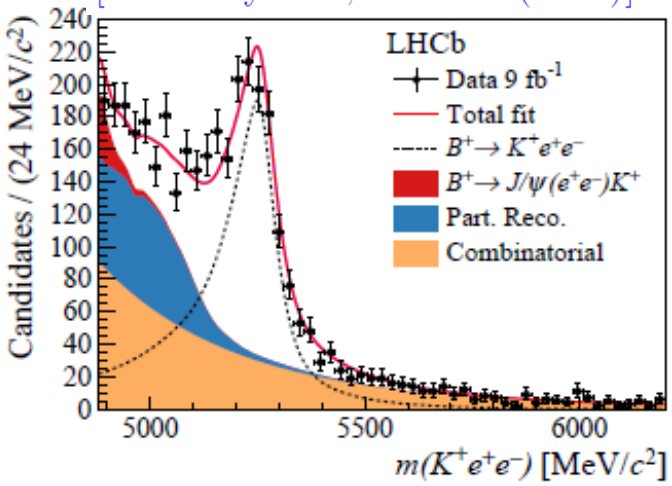
Electrons:

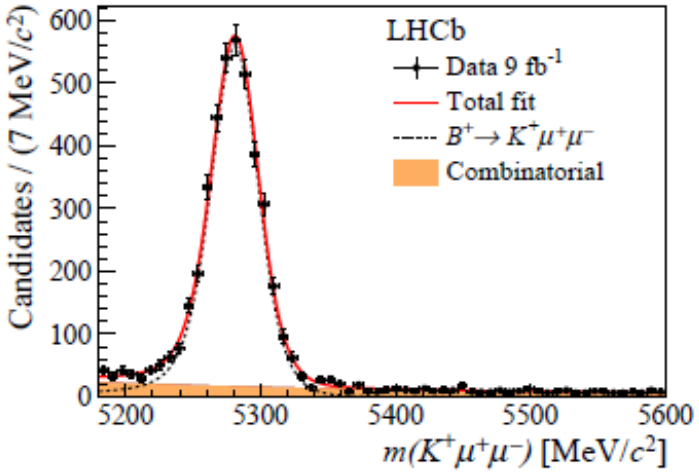
- Calorimeter trigger
- Higher trigger thresholds than muons (E_T >3 GeV)
- Challenging PID: $e \to e$ ~90%, $h \to e$ ~5%
- Bremsstrahlung:
  - Degradation of *B* mass resolution
  - Higher background than muons

Muons:

- Triggered by muon end-system
- Lower threshold: p_T >1.5 GeV
- Good p-resolution and PID $\mu \to \mu$ ~97%, $h \to \mu$ 1-3%

[Nat. Phys. 18, 277–282 (2022)]





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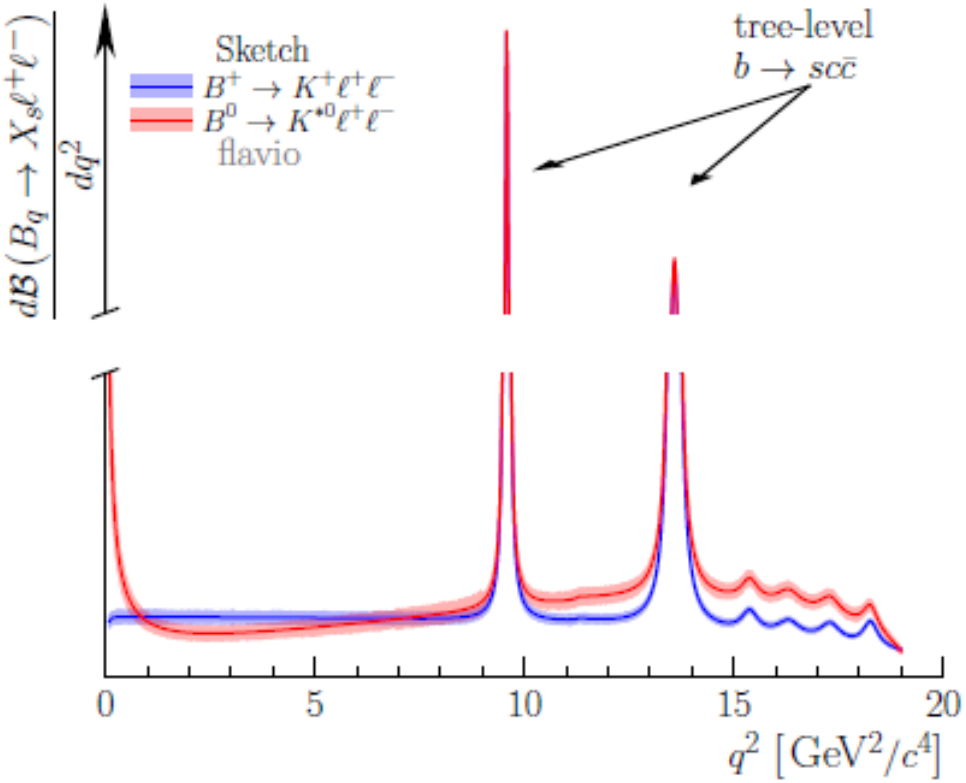
LFU tests: experimental strategy

Double ratios to reduce systematics uncertainties:

$$R_X = \frac{\mathcal{B}\left(B_q \to X_s \mu^+\mu^-\right)}{\mathcal{B}\left(B_q \to X_s J/\psi(\mu^+\mu^-)\right)} \cdot \frac{\mathcal{B}\left(B_q \to X_s J/\psi(e^+e^-)\right)}{\mathcal{B}\left(B_q \to X_s e^+e^-\right)}$$

- Ratios determined using yields and efficiencies
  - Efficiencies calibrated using control data
  - Yields extracted with fits to the data
- Blind analysis to minimise analysts' bias
- Procedure validated using resonant decays:
  - $B_q \to X_s\, J/\psi(l^+l^-)$ and $B_q \to X_s\, \psi(2S)(l^+l^-)$
  - LFU for $J/\psi \to l^+l^-$ established at ‰ level [PDG 2022]



LFU: analysis validation

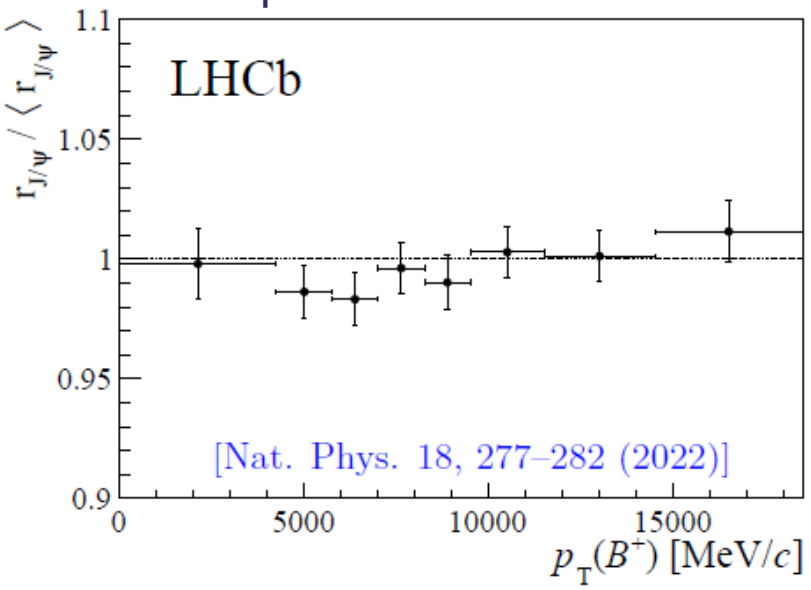
Single ratio of BFs:

- Limited cancellation of systematics
- Probes directly electrons vs muons

⇒ Stringent validation

$$r_{J/\psi} = \frac{\mathcal{B}(B_q \to X_s J/\psi(\mu^+\mu^-))}{\mathcal{B}(B_q \to X_s J/\psi(e^+e^-))}$$

Independent of kinematics



X_s	$r_{J/\psi}$	$R_{\psi(2S)}$
K^+	0.981 ± 0.020	0.997 ± 0.011
K^{*+}	0.965 ± 0.032	1.017 ± 0.050
K^0_S	0.977 ± 0.028	1.014 ± 0.036
K^{*0}	1.043 ± 0.045	within 1σ from 1
pK^-	0.96 ± 0.05	within 1σ from 1

$$R_{\psi(2S)} = \frac{\mathcal{B}(B_q \to X_s \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B_q \to X_s \psi(2S)(e^+e^-))} \cdot r^{-1}_{J/\psi}$$

Double ratio of BFs:

- Cancellation of systematics similar to R_X
- "Rehearsal" of R_X

$r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity within 1σ for all modes

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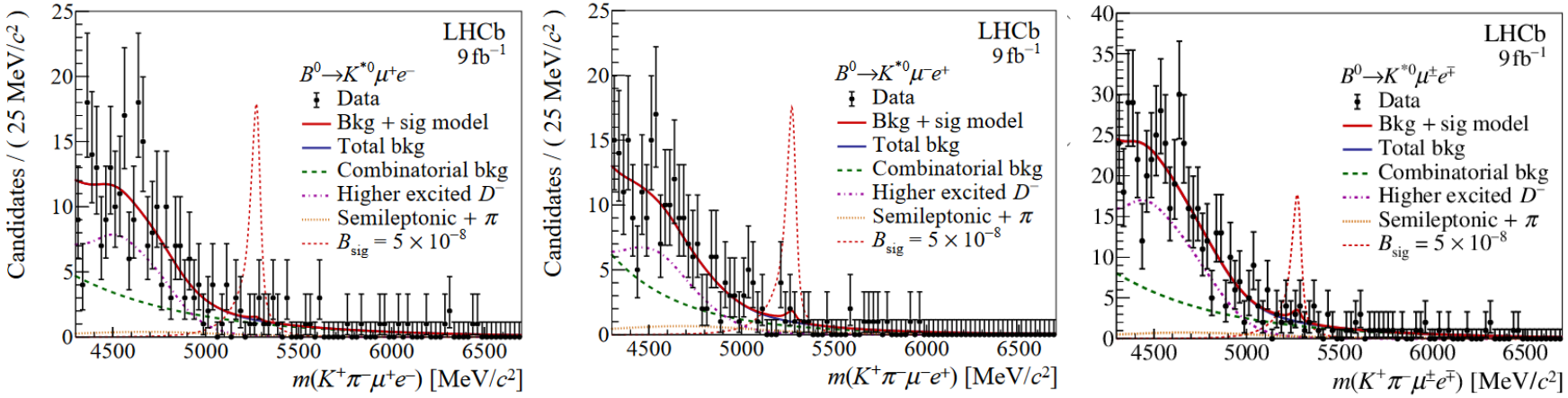
Lepton Flavour Violation

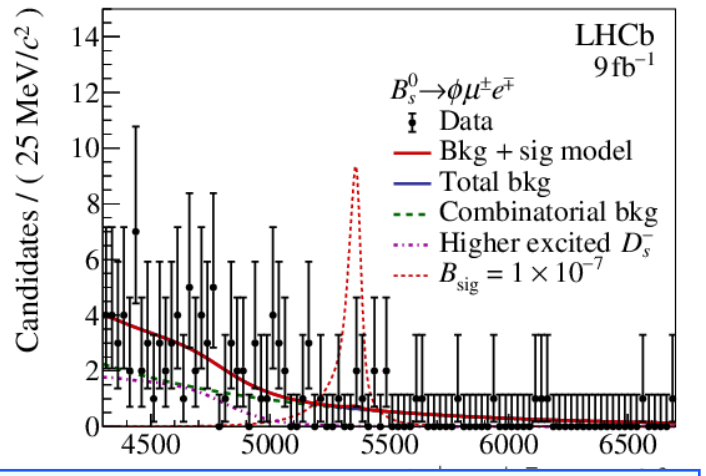
- Lepton Flavour Violation (LFV) closely connected to LFU violation [Glashow, Guadagnoli, Lane, PRL 114(2015)091801]
  - LFV forbidden in SM (occurring only via ν oscillation, with BFs ~10^{-50}, much below detection), signal would be unequivocal proof of new physics
  - Several BSM models predict LFV within reach if LFU violation is as large as measured (e.g., leptoquark [Hiller et al., JHEP 12 (2016)027], Z' models [Crivellin et al, PRD 92(2015)054013])
- Searches conducted in many decay modes @LHCb, only two most recent ones shown here

arXiv:2207.04005

LFV: $B^0 \to K^{*0}\mu e$ and $B_s \to \phi\mu e$

$B^0 \to K^{*0}\mu e$ results separated by charge as new physics may contribute differently to "same-sign" and "opposite-sign" kaon/muon





- No significant signal
- Upper limits @90% (95%) C.L.

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (6.9 \times 10^{-9})$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9}\ (7.9 \times 10^{-9})$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}\ (11.7 \times 10^{-9})$$

$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}\ (19.8 \times 10^{-9})$$

- $B^0 \to K^{*0}\mu e$ limits improved by ~x10 over previous best results
- World's first constraint of a semi-leptonic LFV B^0_s decay.

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LFV: $B^0 \to K^{*0}\tau\mu$

- If new physics hierarchically coupled, as data suggest, modes with τ particularly sensitive
- Generally, loose bounds for modes with τ in final states [missing energy from neutrinos]

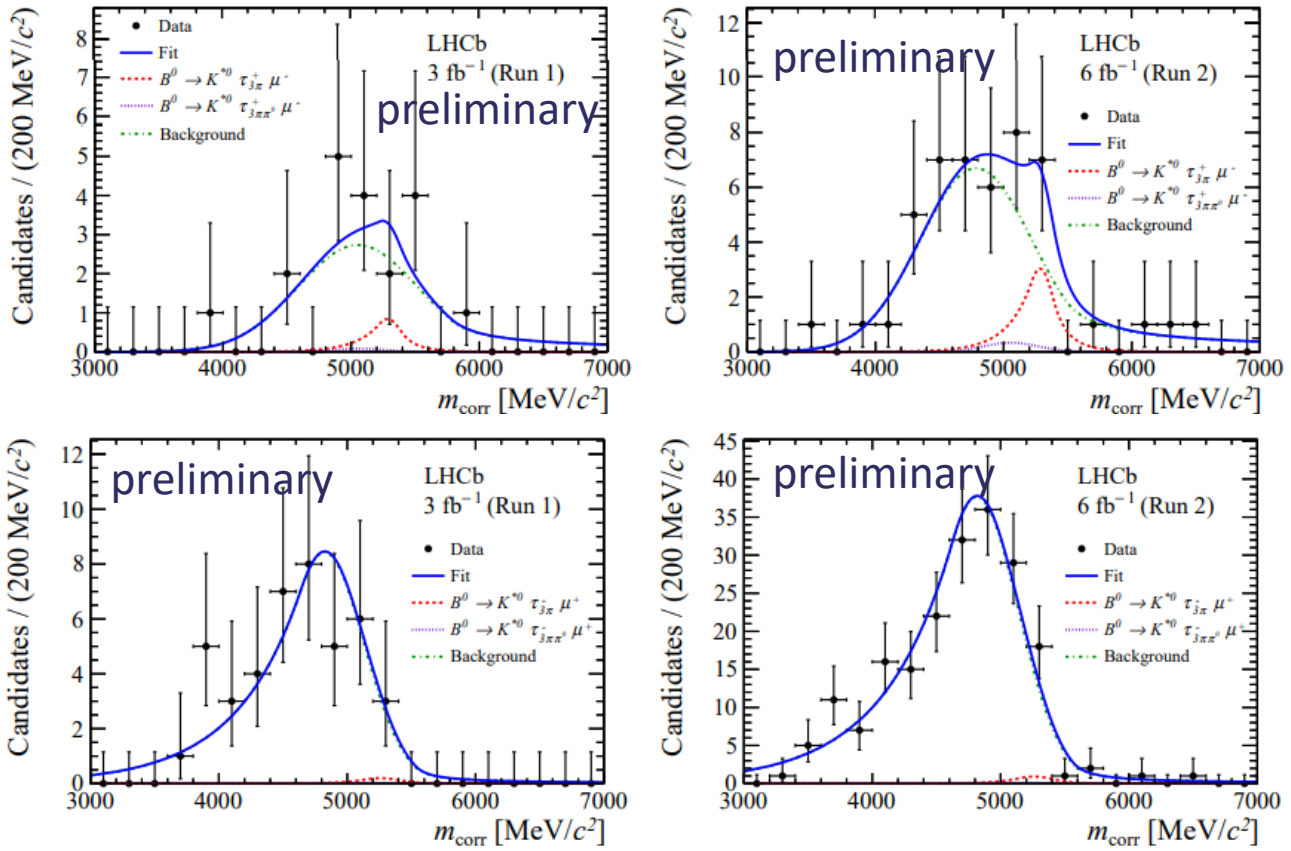
LHCB-PAPER-2022-021
in preparation

NEW

$$m_{\rm corr} = \sqrt{p_\perp^2 + m^2_{K^*\tau\mu}} + p_\perp$$

$K^+\tau^+$

$K^+\tau^-$



- Here:
  $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
  $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\ (1.2) \times 10^{-5}$$

@90% (95%) C.L.

$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\ (9.8) \times 10^{-6}$$

@90% (95%) C.L.

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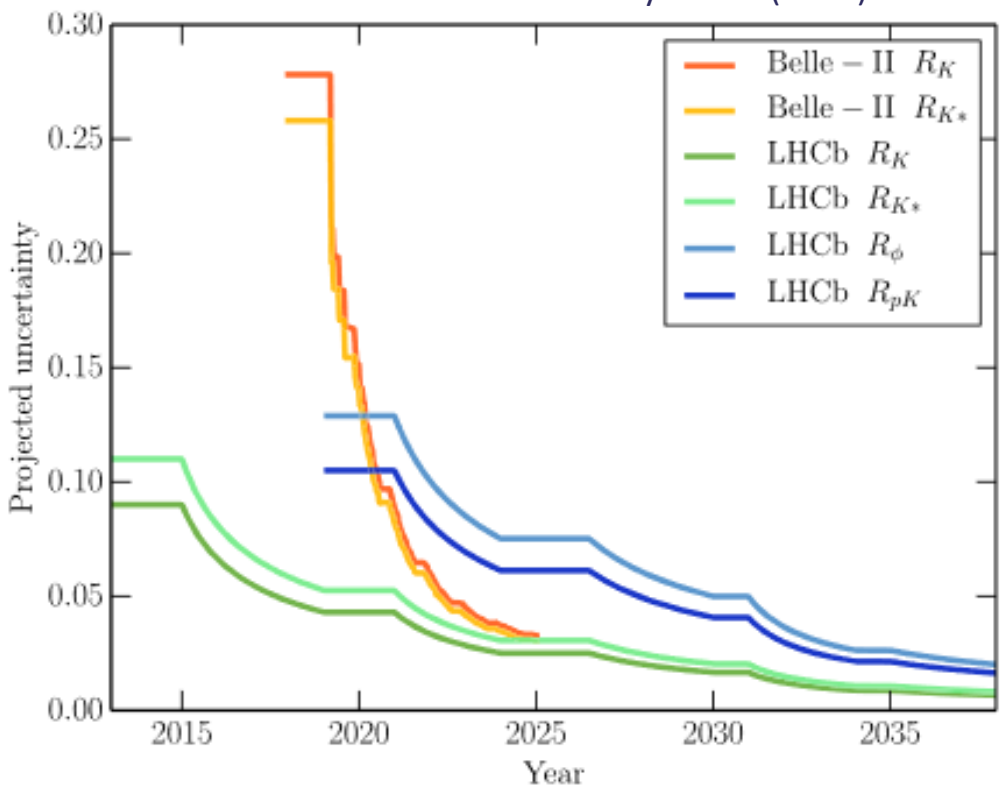
These are the most stringent limits to date on $b \to s\tau\mu$ transitions

Summary and outlook

"Cautious" excitement!

- Intriguing tensions between experimental results and SM predictions have appeared in many decays mediated by b→sll
- Consistent new physics solution favoured when results are fitted within EFT framework
- Anomalies under close scrutiny by theory and experimental communities:
  - Easier experimental observables (differential branching fractions, angular observables) not theoretically clean
  - Theory clean observables (LFU) experimentally more challenging
- All results limited by statistical uncertainties
  - More data will allow to clarify situation

J. Phys. G 46 (2019)023001



LHCb (50 fb^{-1} during Run3 and Run4), Belle II expected to achieve similar precision with 50 ab^{-1}. >5σ LFU violation if central values don't change

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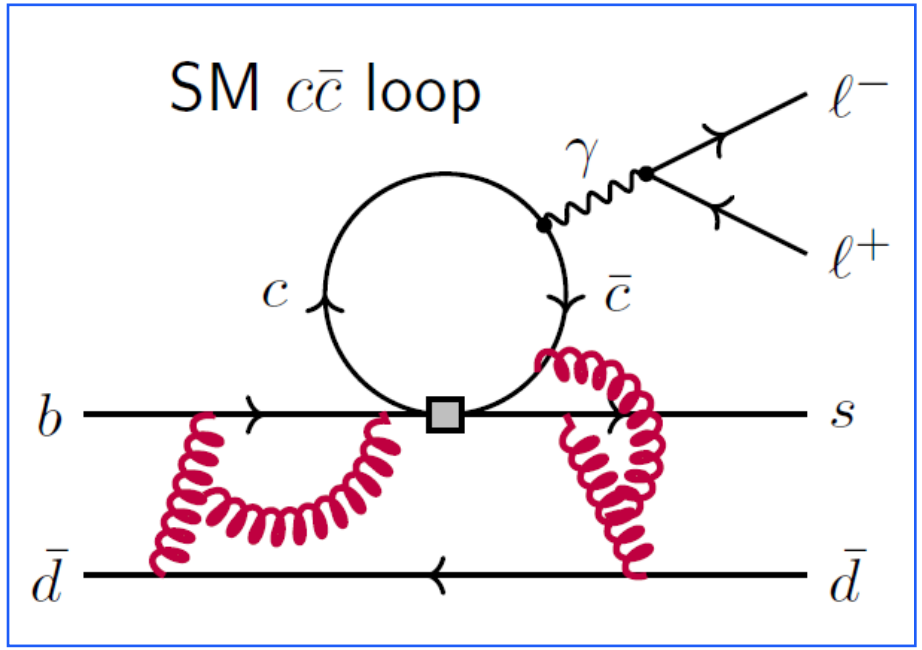
Thank you

Additional material

Charm-loops in $B^0 \to K^{*0}\mu^+\mu^-$



New physics effects in the short-distance coefficients can be disentangled from non-local hadronic effects (charm loops) via an amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$. Two different approaches pursued at LHCb (Bobeth et al. Eur.Phys.J. C (2018) 78:451 and Egede et al. Eur.Phys.J. C (2018) 78:453) using Run 1 and Run 2 data.

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R_X numerical results

Run1 3fb^{-1} JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 \end{cases}$$

$2.1\sigma,\ 2.4\sigma$

Run1 + 2016 4.7fb^{-1} JHEP 05 (2020) 040

$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

1σ

Run1+2 9fb^{-1} Nat.Phys.18, 277-282 (2022)

$$R_K = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst})$$

3.1σ

Run1+2 9fb^{-1} PRL 128 (2022) 191802

$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})^{+0.02}_{-0.04}\,(\text{syst.})\,,$$

$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})^{+0.03}_{-0.04}\,(\text{syst.})$$

$1.5\sigma,\ 1.6\sigma$

- Statistical uncertainty dominates
- Main sources of systematic uncertainties:
  - Fit model
  - Limited size of control samples used to calibrate simulation

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LFU planned future measurements

- High priority work ongoing:
  - Unified analysis of R_K and R_{K*0} will provide final results with Run 1 and Run 2 full data sample
  - Efforts lead to a deeper understanding of the LFU measurements that will be reflected in the results
- In parallel also measurements of R_{pK} with full 9/fb dataset, R_ϕ and $R_{K\pi\pi}$ (new)

We appreciate your patience until results become available

Expected stat. uncertainty on some of the planned measurements [extrapolation uses Run1 results, from "Physics case for an LHCb Upgrade II", arXiv: 1808.08865]

R_X	$9\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$
R_K	0.043	0.017
$R_{K^{*0}}$	0.052	0.020
R_ϕ	0.130	0.050
R_{pK}	0.105	0.041
R_π	0.302	0.117

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Future schedule

N. Tuning @ ECFA meeting, 22 July 2022

2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035+
	Run III				Run IV									Run V
LS2						LS3						LS4		
LHCb 40 MHz UPGRADE I	$L = 2 \times 10^{33}$				LHCb Consolidate			$L = 2 \times 10^{33}$ $50\ fb^{-1}$				LHCb UPGRADE II		$L=1\text{-}2\times10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$				ATLAS Phase II UPGRADE			HL-LHC $L = 5 \times 10^{34}$						HL-LHC $L = 5\times10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$				CMS Phase II UPGRADE									$3000\ fb^{-1}$
Belle II	$L = 3 \times 10^{35}$				$7\ ab^{-1}$					$L = 6 \times 10^{35}$			$50\ ab^{-1}$	

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

LHC schedule:

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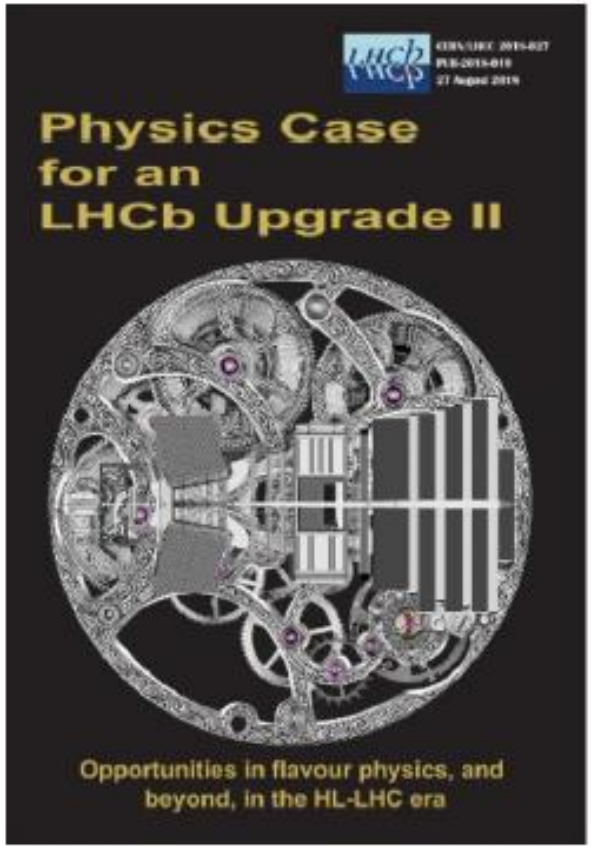
b→sll prospects with LHCb Upgrade II

- European Strategy Update 2020

"The full potential of the LHC and HL-LHC, including the study of flavour physics, should be exploited"

- Upgrade II will realise the full physics potential

March 2022: LHCC approved R&D programme, followed by subsystem TDRs



LHCC-2018-027

LHCC-2021-012

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R_X: projected yield and uncertainties

LHCC-2018-027

Yield	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pK e^+ e^-$	–	120	360	820	5 000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

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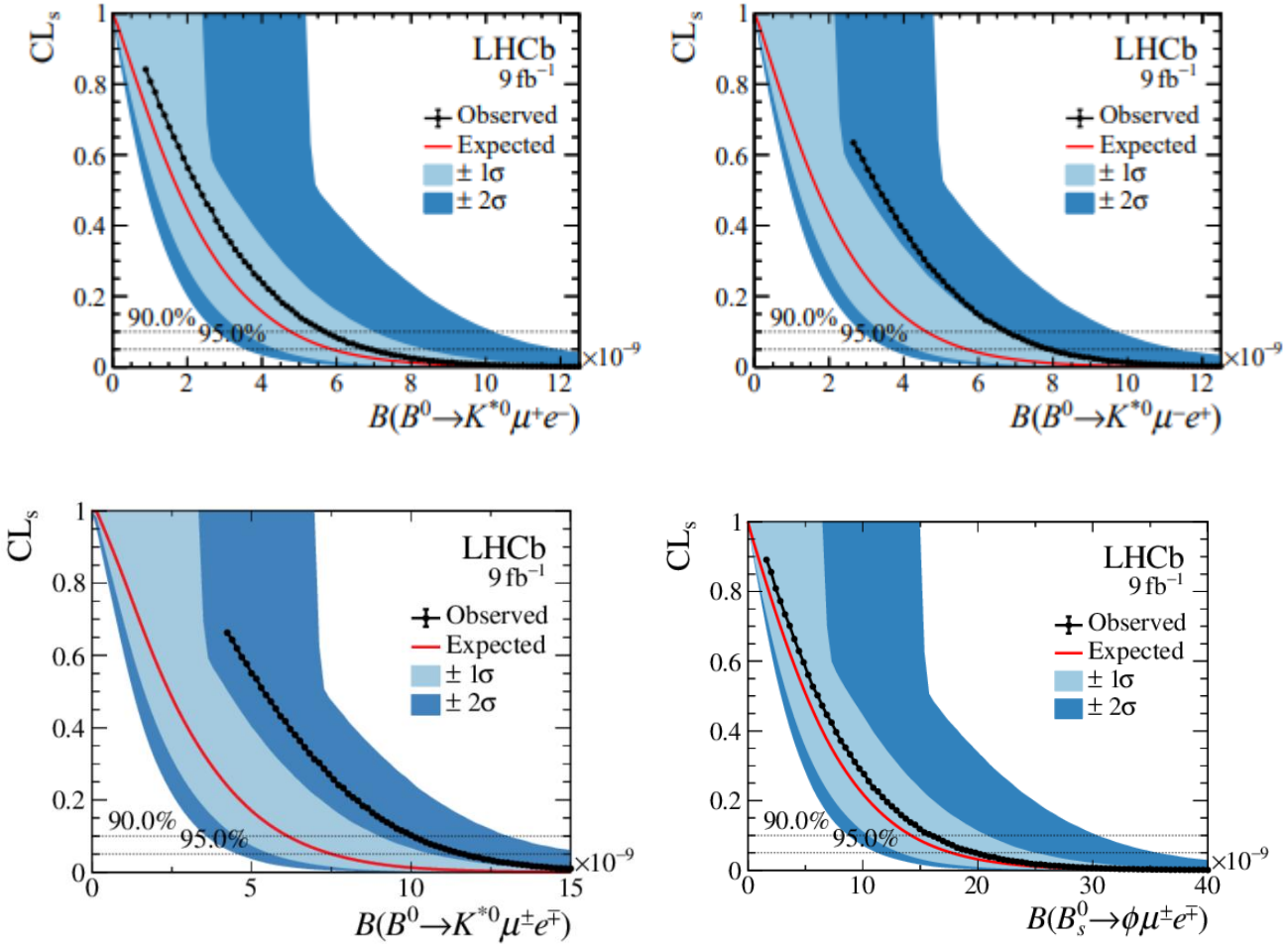
LFV: CLs

arXiv:2207.04005



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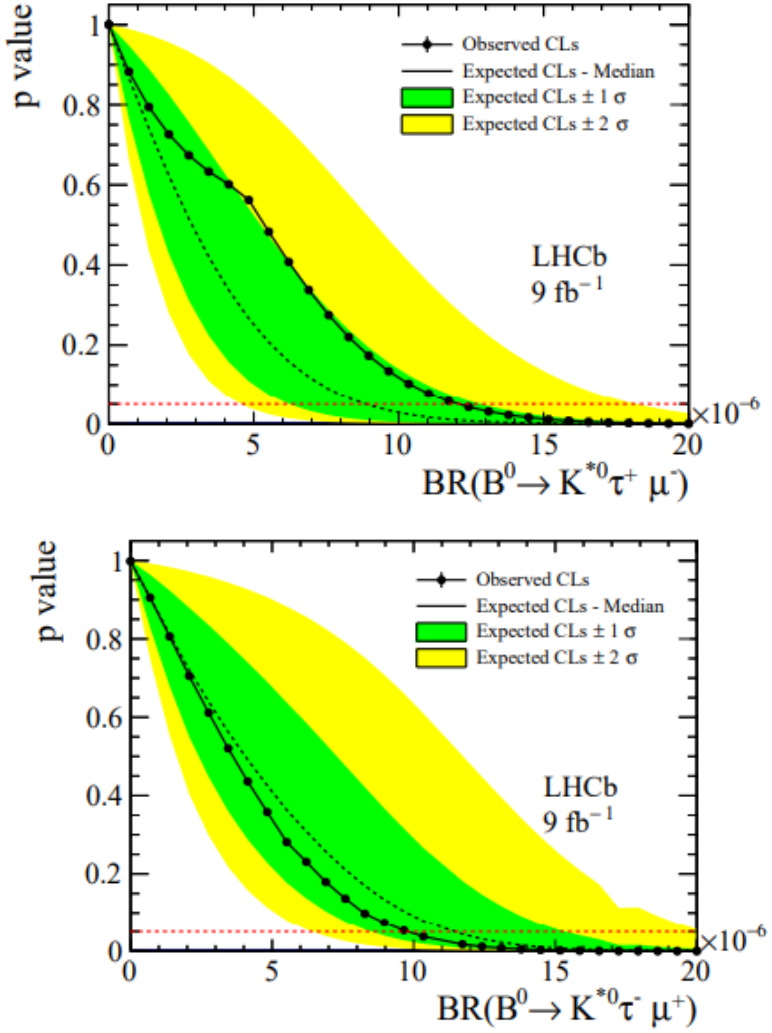

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