Rare B Decays at LHCb: Highlights of Recent Results

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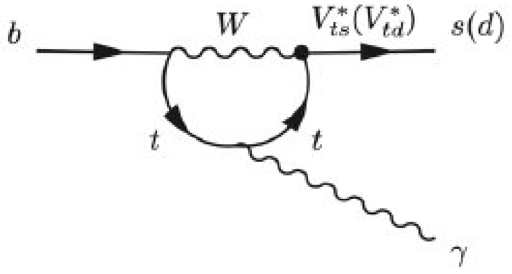
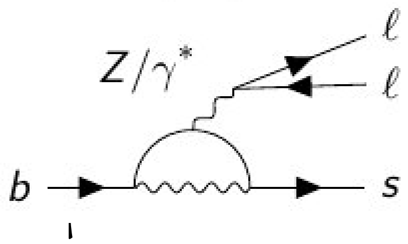
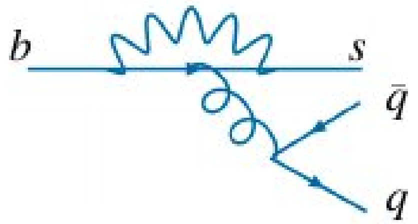
2025/09/20

Outline



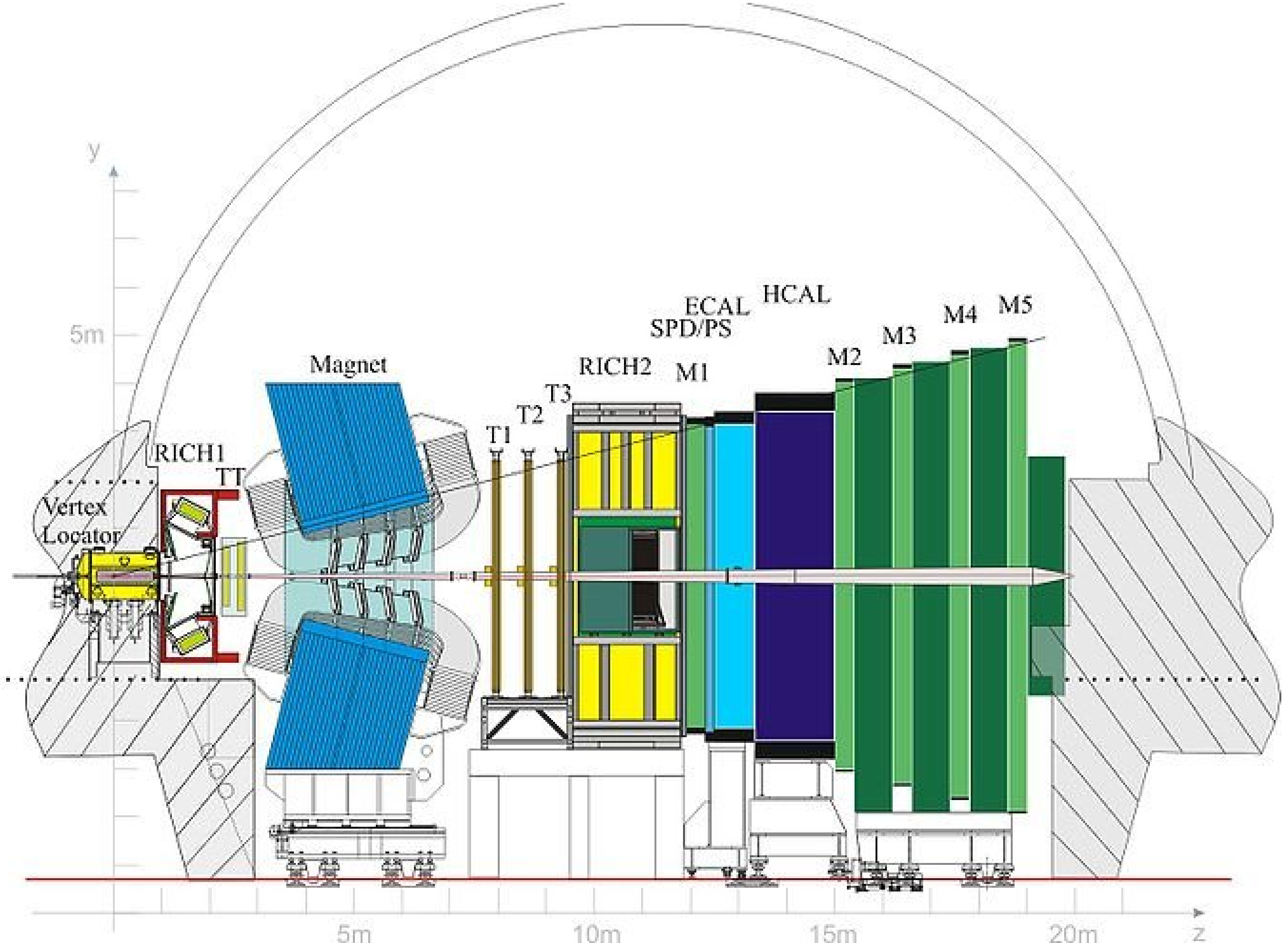
- LHCb experiment in Runs 1-2
- Recent results on
  - Radiative B decay $B^0 \to \rho^0(770)\gamma$
  - LFU tests in FCNC decays: $B^+ \to K^+e^+e^-$, $B^0 \to K^{*0}e^+e^-$, B_s^0
  - Comprehensive analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decay
  - $B^0 \to K\pi\tau^+\tau^-$, $B_s^0 \to KK\tau^+\tau^-$
  - LFV decay $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$
  - Charmless baryonic B decays: $B^0 \to K_S^0 p\bar{p}$, $B^+ \to \bar{\Lambda}p\bar{p}p$, etc.
- Summary & outlook





LHCb detector in Runs 1-2

By design: study *CP*-violating processes and rare *b*-hadron decays

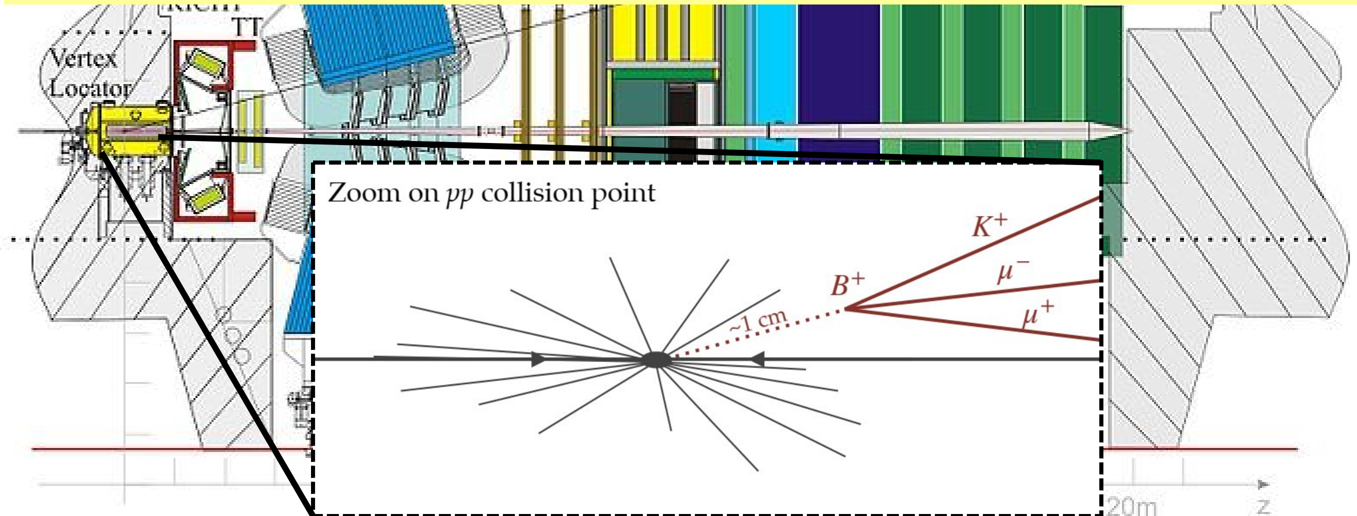


- can profit from the large $b\bar{b}$ and $c\bar{c}$ cross-sections and from the larger production at high pseudorapidity
- $\sigma(pp \to b\bar{b}X) = 144 \pm 1 \pm 21\,\mu\text{b}$ at 13 TeV in the LHCb acceptance $\Rightarrow \sim$ 25% of the total inside LHCb [Phys.Rev.Lett. 118, 052002]
- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance [JHEP 05 (2017) 074]

LHCb detector in Runs 1-2

By design: study *CP*-violating processes and rare *b*-hadron decays

- Particle detection in the forward region (down to the beam-pipe)
- Excellent resolution for localization of decay vertices (Vertex Locator) → Excellent time resolution, enough to resolve $B_s - B_s$ oscillation
- Excellent momentum resolution ($\sigma(m_B) \sim 25$ MeV for 2-body decays)
- Excellent particle identification to distinguish p, $K^\pm$, $\pi^\pm$, $\mu^\pm$
- Excellent leptonic and hadronic triggers



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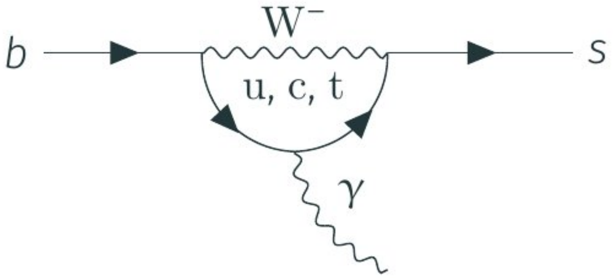
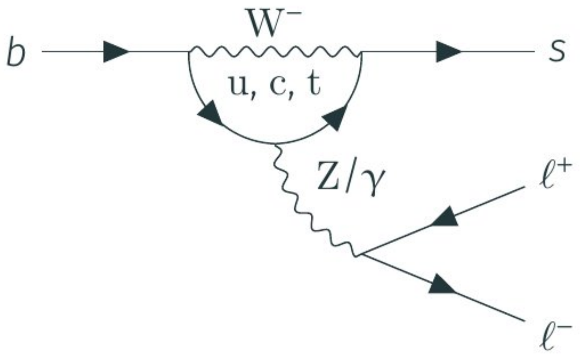
FCNC b decays

Radiative decays

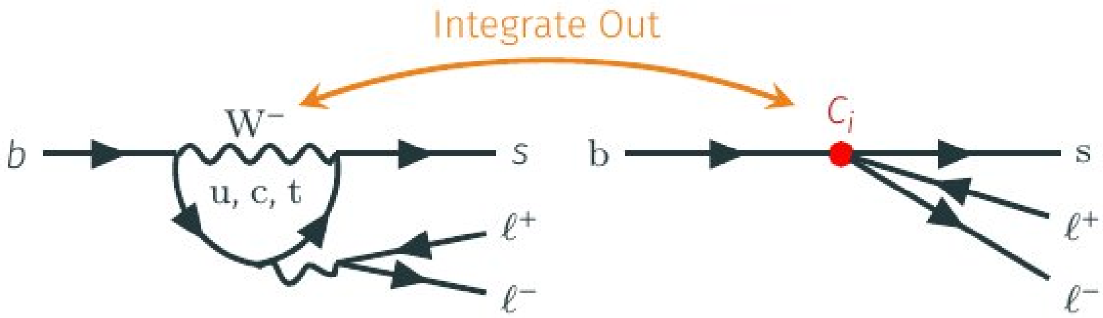


NP might manifest in the loops

Leptonic Decays



Effective Field Theory approach



$$\mathcal{H}_{SM} \longrightarrow \mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i (C_i^{SM} + C_i^{NP}) \mathcal{O}_i$$

+ chiral flipped

Wilson Coefficients: C_i

- → Perturbative, short distance physics
- → Describes heavy SM+NP effects

Operators: $\mathcal{O}_i$

- → Non-perturbative, long distance physics
- → Strong interactions, difficult to calculate

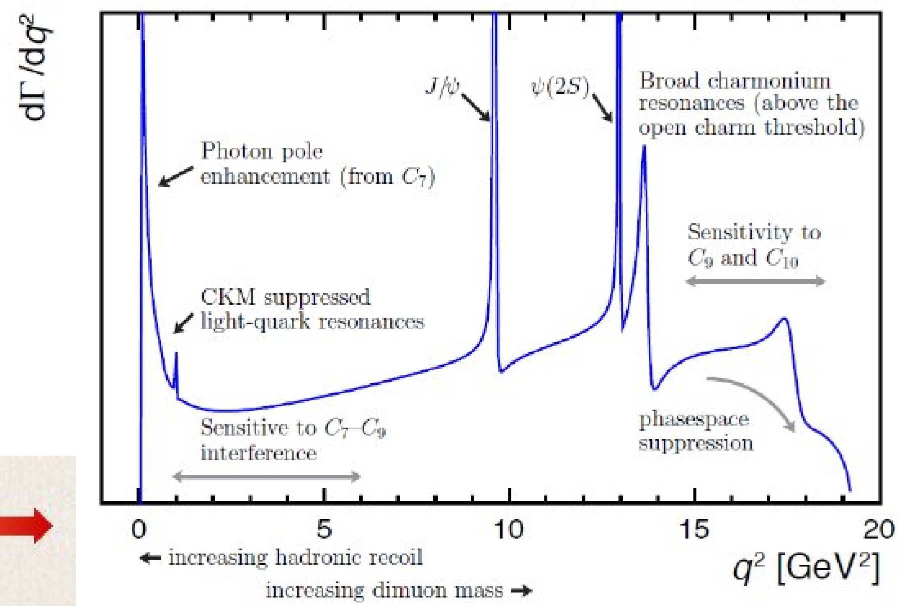
$\mathcal{O}_7$ EM
$\mathcal{O}_9$ Vector dilepton
$\mathcal{O}_{10}$ Axial-vector dilepton

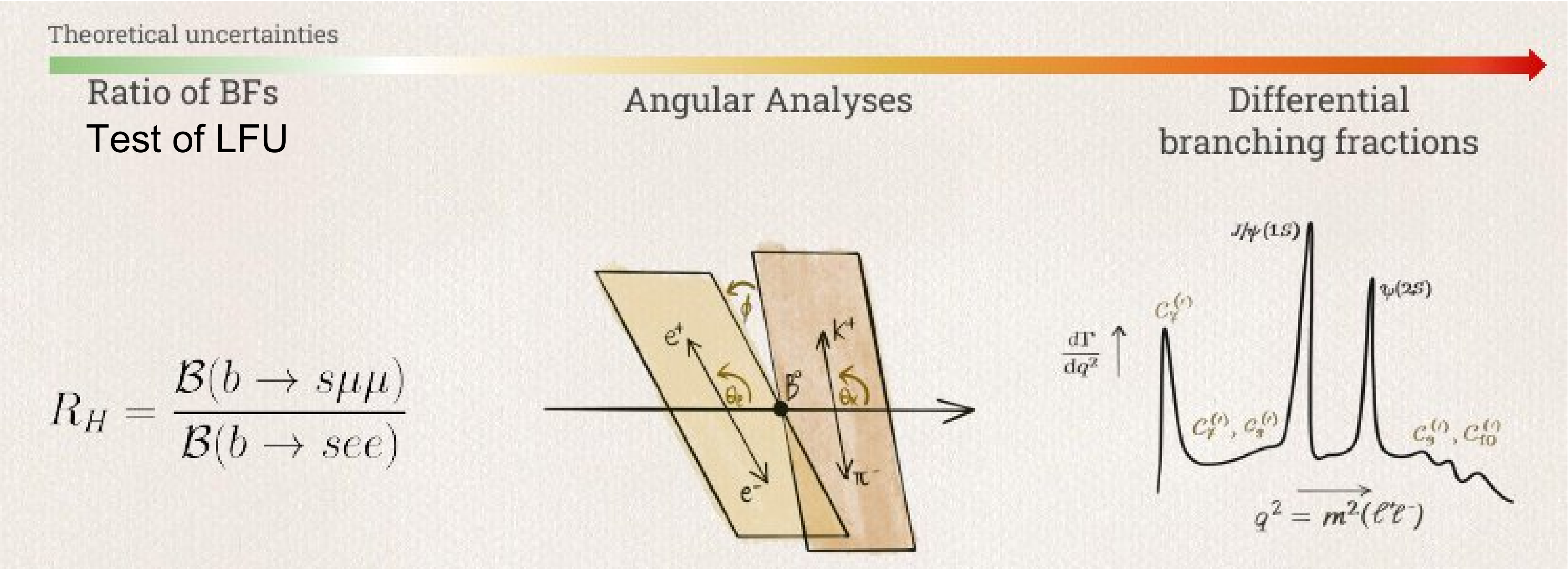
Observables in FCNC b decays

Physics depends on $q^2 = m^2_{ll}$:

- Resonances (e.g. J/ψ, ϕ)
- Photon pole at low q^2
- Vector or axial vector current

T.Blake et al. arXiv:1606.00916

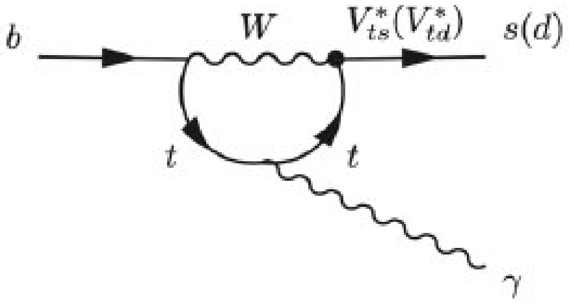


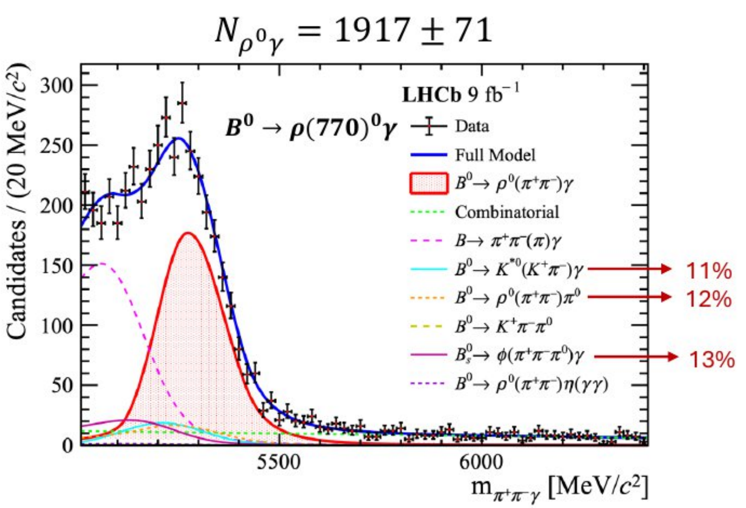


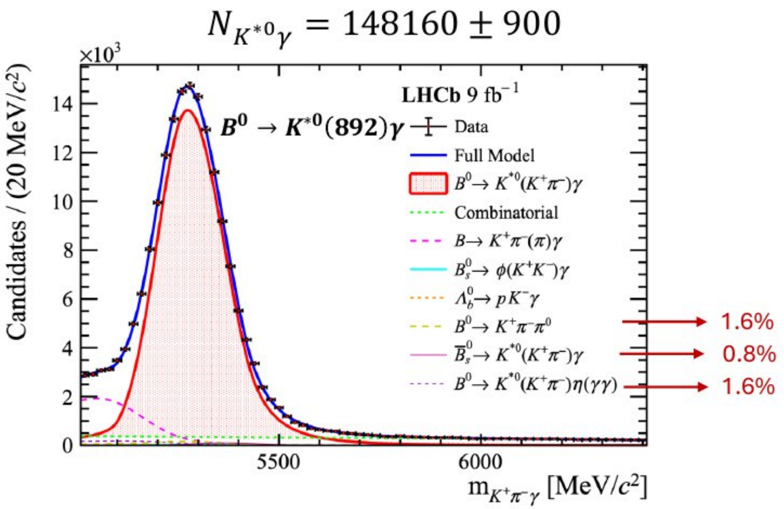
Radiative $B^0 \to \rho^0(770)\gamma$ decays

- Using full 9 fb^{-1} Runs1-2 data
- Normalization channel $B^0 \to K^{*0}\gamma$
- Offering independent & direct constraint on $|V_{td}/V_{ts}|$

$$\frac{\mathcal{B}(B^0 \to \rho^0(\pi^+\pi^-)\gamma)}{\mathcal{B}(B^0 \to K^{*0}(K^+\pi^-)\gamma)} \propto |V_{td}/V_{ts}|^2$$







$$\frac{\mathcal{B}(B^0 \to \rho(770)^0\gamma)}{\mathcal{B}(B^0 \to K^*(892)^0\gamma)} = 0.0189 \pm \underset{\text{(stat.)}}{0.0007} \pm \underset{\text{(sys.)}}{0.0005},$$

arXiv:2507.14401

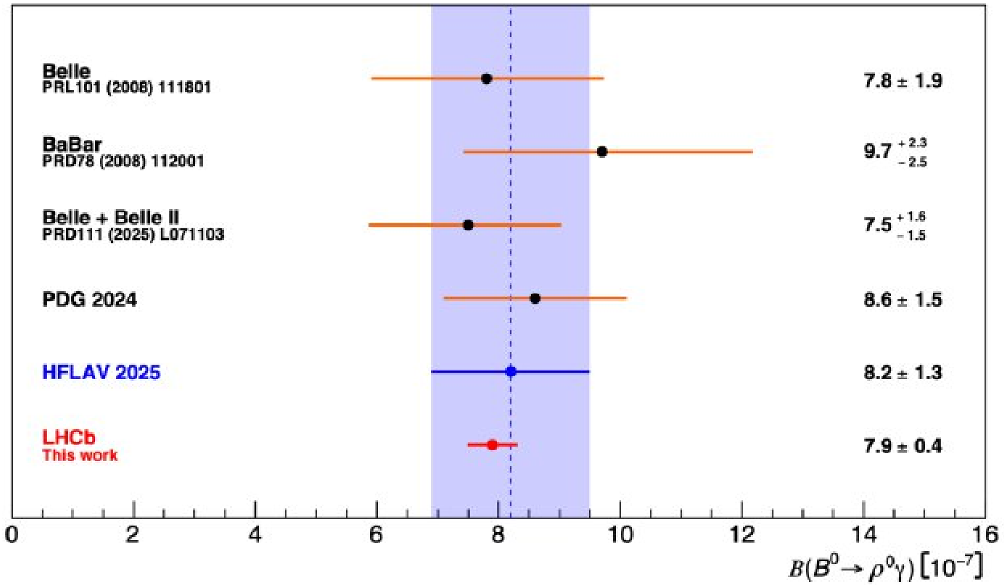
Radiative $B^0 \to \rho^0(770)\gamma$ decays

Combining with the known branching fraction for the $B^0 \to K^{*0}\gamma$

$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.9 \pm \underset{\text{(stat.)}}{0.3} \pm \underset{\text{(sys.)}}{0.2} \pm \underset{\text{(BF norm.)}}{0.2}) \times 10^{-7}$$

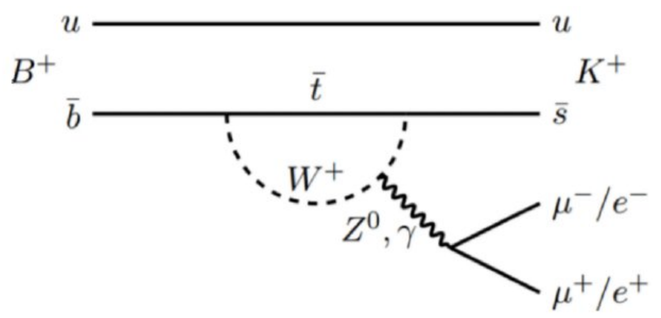
Most precise measurement to date

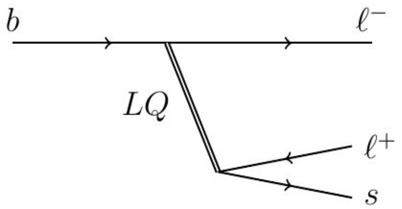
- Assuming $\rho^0 \to \pi^+\pi^-$ decay dominates the dipion spectrum in [630,920] MeV/c^2
- Assuming $K^{*0} \to K^+\pi^-$ decay dominates the $K^+\pi^-$ spectrum in [795.5,995.5] MeV/c^2
- Contribution from wide resonances at higher masses or from nonresonant are neglected



Good agreement with the current world average but with lower uncertainty

LFU tests in $b \to s l^+ l^-$ decays



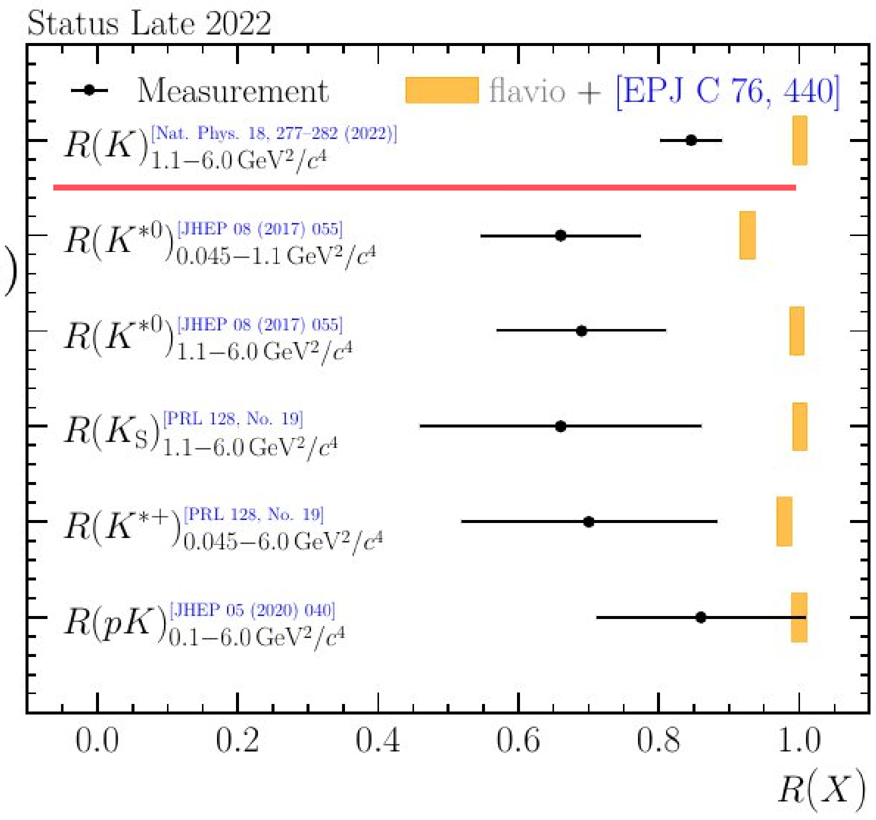


- FCNC processes highly suppressed in SM
- NP may manifest in the loops and cause LFU violation
- LFU tests use

$$q^2 = m(\ell^+\ell^-)^2$$

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

  - Cancellation of hadronic uncertainties in the ratio => precise prediction of R_X

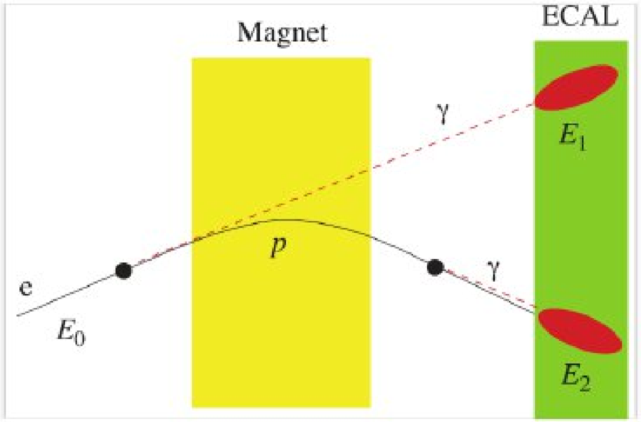


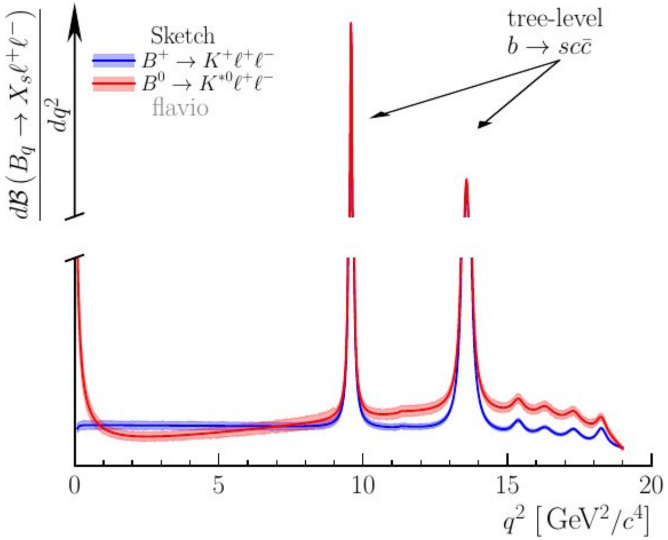
R(K$^{(*)}$) measurements @ LHCb

- Electrons & muons behave quite differently in the LHCb detector
- Lower efficiencies & worse resolution (energy loss) for electrons
- Double-ratio of branching fractions:

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

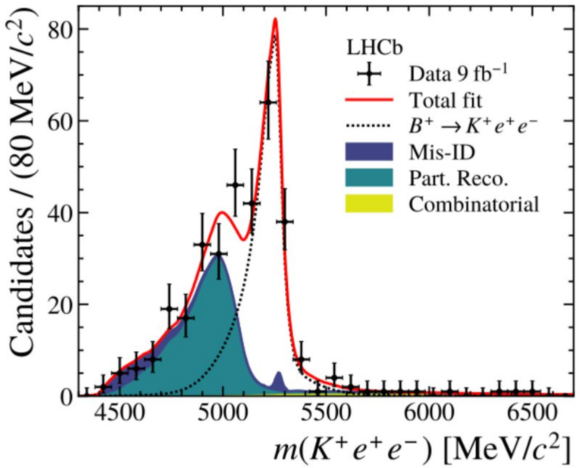
  - Most of systematic uncertainties cancel to 1st order
  - LFU in $J/\psi \to l^+ l^-$ well established at ‰ level [BESIII, PRD 88, 032007 (2013)]
  - Validated in ψ(2S) mode

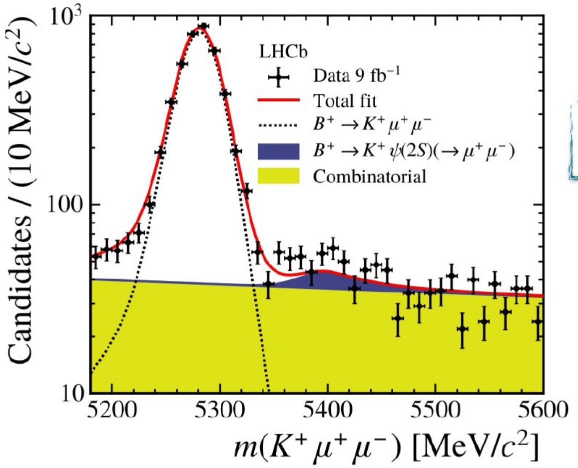




R(K) result at high q^2

- First LHCb result at high q^2 region above $\psi(2S)$ (q^2 > 14.3 GeV^2)
- Full Runs1-2 9 fb^{-1} analysis



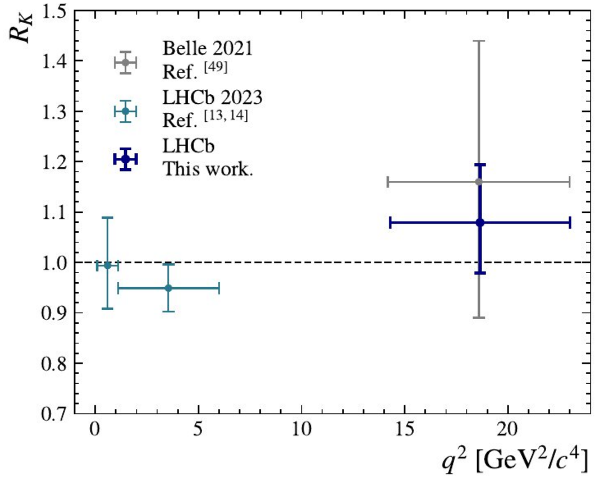


$N(K^+\mu^+\mu^-) = 4008 \pm 71$

Most precise to date:

$$R_K(q^2 > 14.3\ \mathrm{GeV}^2/c^4) = 1.08^{+0.11}_{-0.09}{}^{+0.04}_{-0.04}$$

- Compatible with the SM



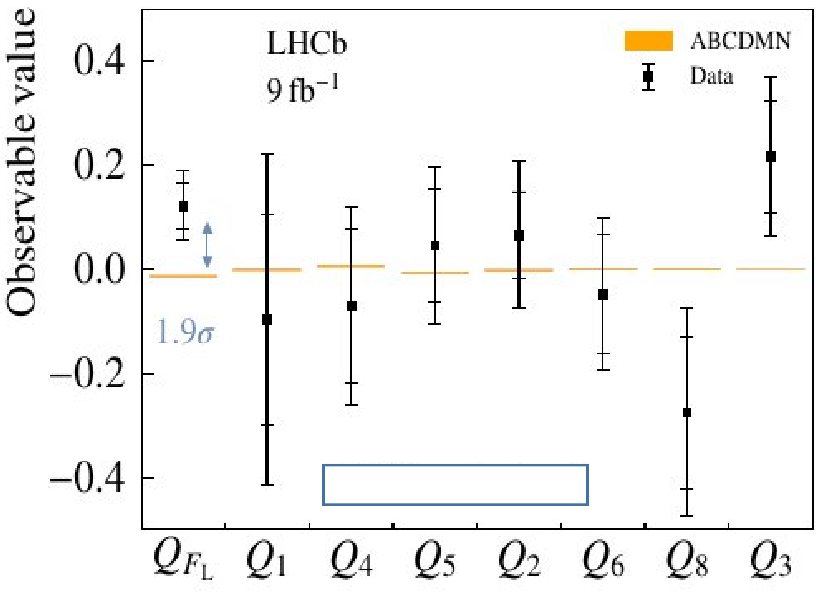
$$R_K = \frac{N(K^+\mu^+\mu^-)}{N(K^+e^+e^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{1}{r_{J/\psi}}$$

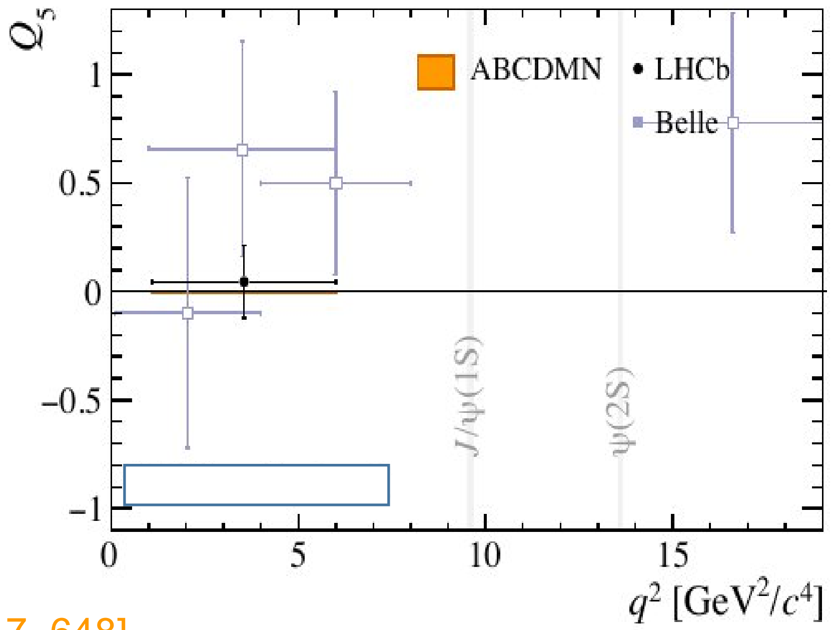
JHEP 06 (2025) 140

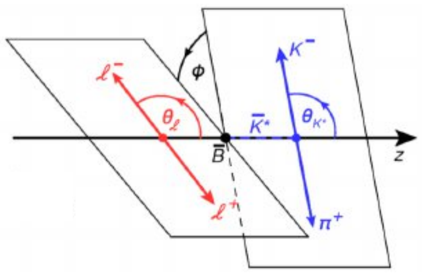
LFU in angular analysis of $B \to K^{*0} e^+ e^-$

- First angular analysis at central q^2 region
- Full Runs1-2 9 fb^{-1} analysis with 5D unbinned weighted fit
- LFU quantities derived by comparing e^+e^- to $\mu^+\mu^-$ results in [PRL 132 (2024) 131801]

$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$







Results are all consistent with LFU conservation hypothesis

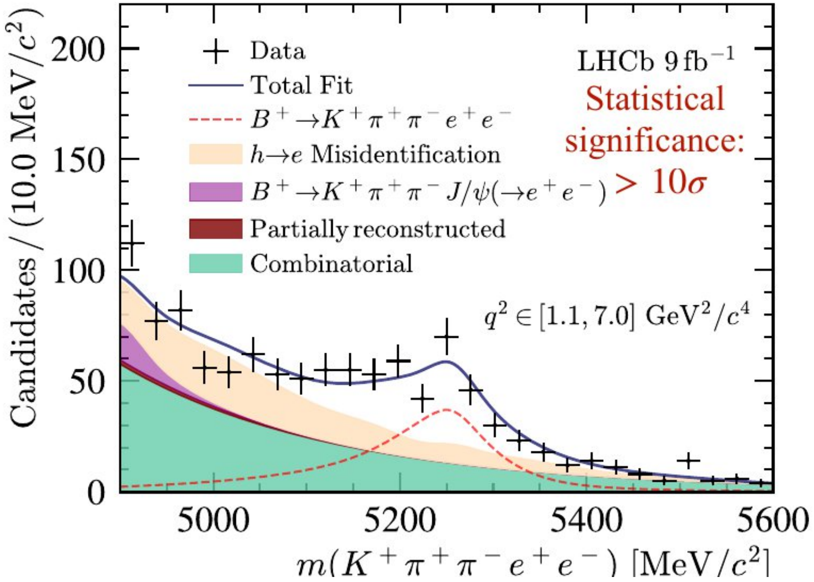
[M. Algueró et al., EPJC 83 (2023) 7, 648]

PRL 134 (2025) 181803

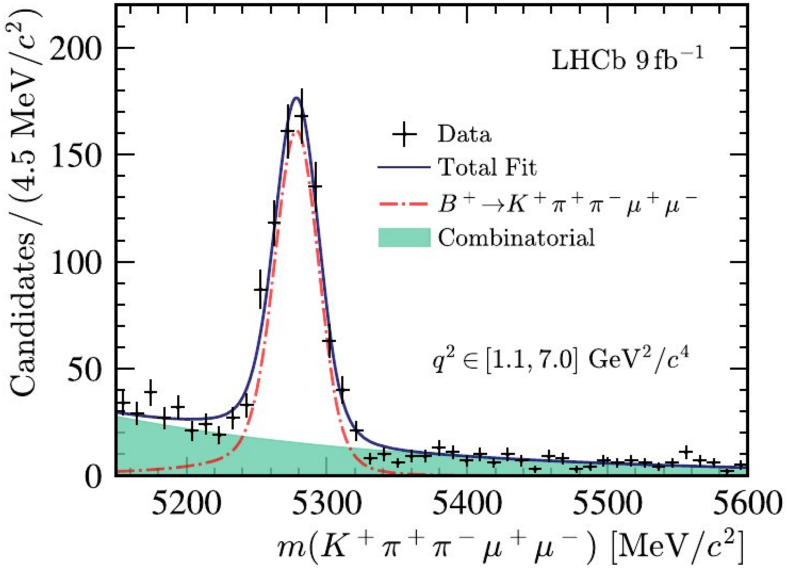
R(Kππ): LFU in $B \to K\pi\pi l^+ l^-$

- First LFU test in this channel, inclusive $K\pi\pi$ system
- In central q^2 region: $1.0 < q^2 < 7.0$ GeV^2
- First observation of $B^+ \to K^+\pi^+\pi^- e^+ e^-$
- Cross-checks: $r_{J/\psi} = 1.033 \pm 0.017, R_{\psi(2S)} = 1.040 \pm 0.030$

$$R^{-1}_{K\pi\pi} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^+ \to K^+\pi^+\pi^- e^+ e^-)}{\frac{\mathcal{N}}{\varepsilon}[B^+ \to K^+\pi^+\pi^- J/\psi\,(\to e^+e^-)]} \Big/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^+ \to K^+\pi^+\pi^- \mu^+ \mu^-)}{\frac{\mathcal{N}}{\varepsilon}[B^+ \to K^+\pi^+\pi^- J/\psi\,(\to \mu^+\mu^-)]}$$



$\mathcal{N}(B^+ \to K^+\pi^+\pi^- e^+ e^-) = 264 \pm 21$



$\mathcal{N}(B^+ \to K^+\pi^+\pi^- \mu^+ \mu^-) = 731 \pm 31$

$$R^{-1}_{K\pi\pi} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

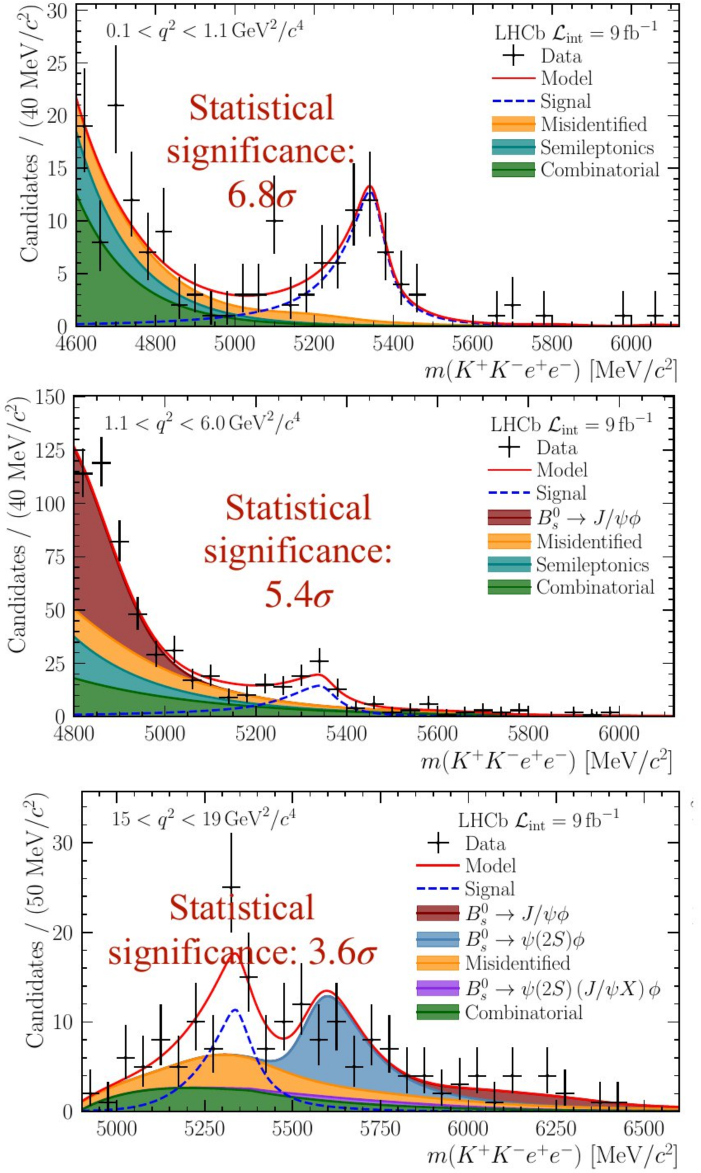
- Compatible with the SM

R(ϕ): LFU in $B_s^0 \to \phi l^+ l^-$

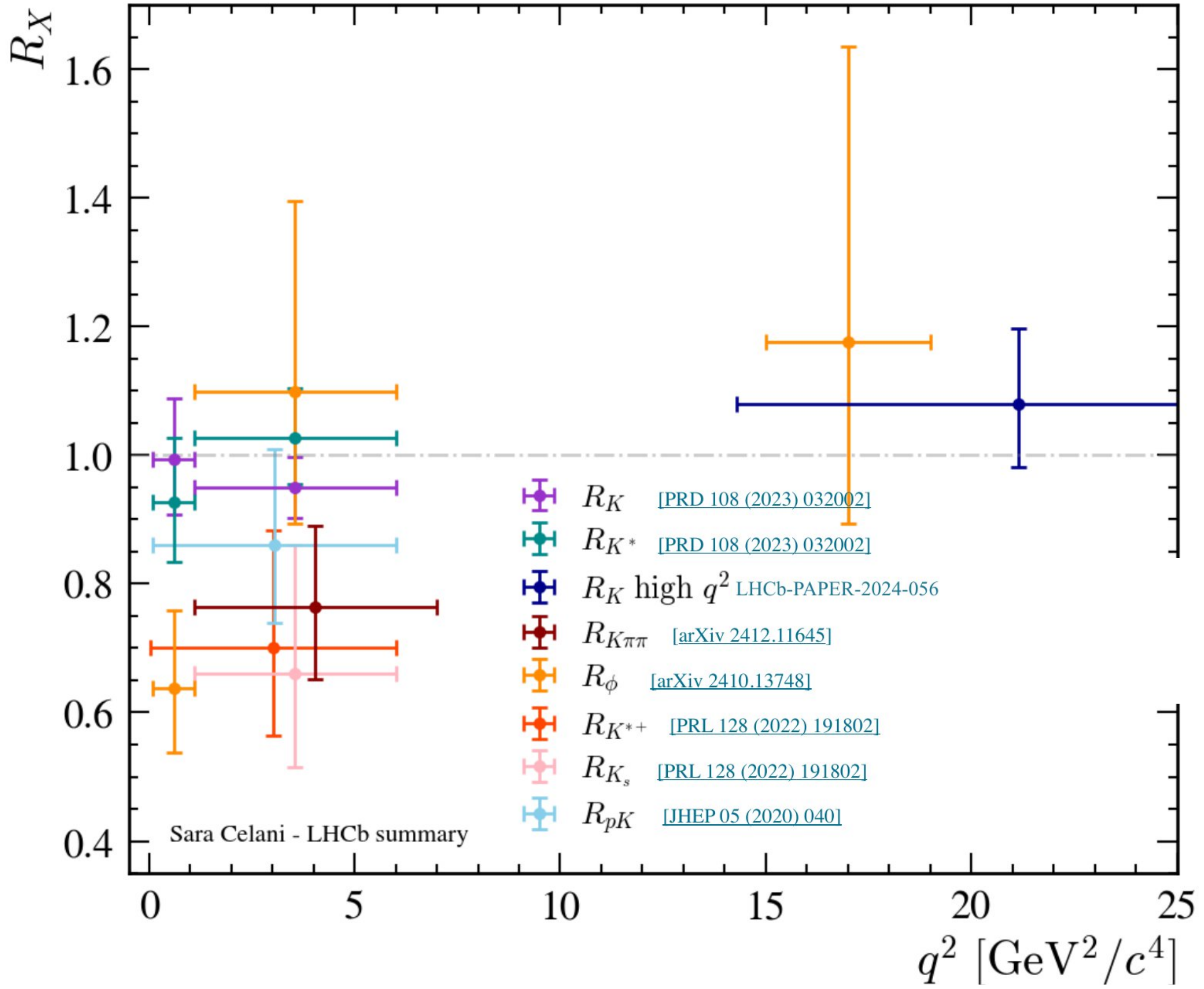
- First LFU test for B_s^0 decays
- In three q^2 regions: [0.1, 1.1], [1.1, 6.0], [15, 19] GeV^2
- Cross-checks: $r_{J/\psi} = 0.997 \pm 0.013, R_{\psi(2S)} = 1.010 \pm 0.026$
- Results in agreement with SM:

q^2 [GeV^2/c^4]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

$$R_\phi = \left(\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi)}\right) \Big/ \left(\frac{\mathcal{B}(B_s^0 \to \phi e^+ e^-)}{\mathcal{B}(B_s^0 \to J/\psi(\to e^+ e^-)\phi)}\right)$$



Summary of LHCb FCNC LFU results



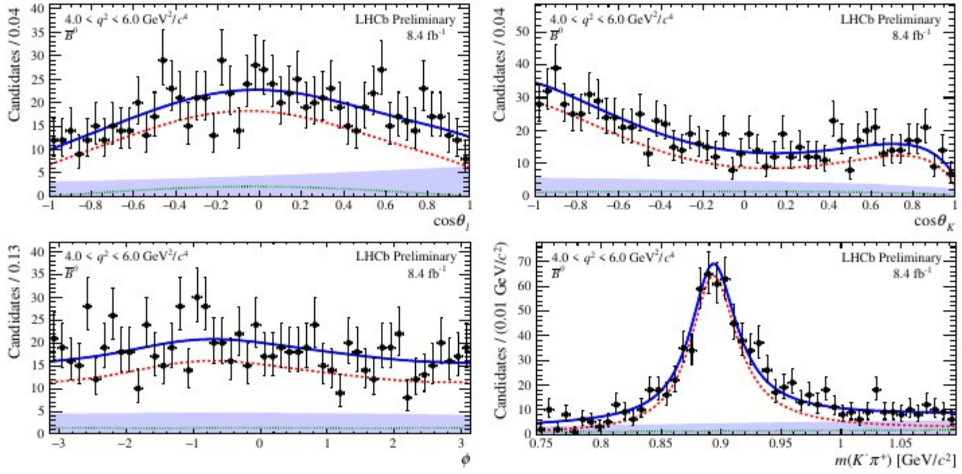
Moriond QCD 2025 - Flavour changing neutral currents decay at LHCb

LHCb-PAPER-2025-041
In prep.

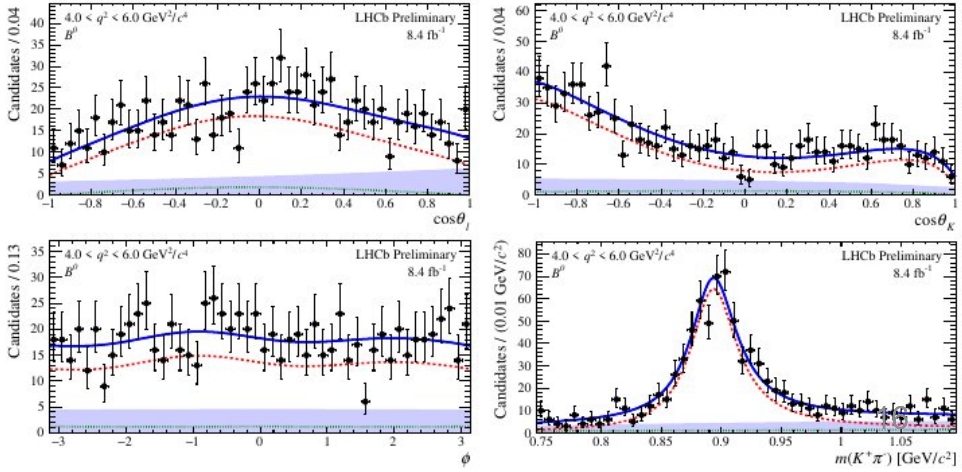
Legacy Runs1-2 $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ measurement

- 5D (3 decay angles, m_B, $m_{K\pi}$) unbinned ML fit in bins of q^2
  - Improved selection, more observables (CPV, dBF)
  - Finer q^2 binning
  - Lepton mass accounted for
  - Full suite of S-wave and P-/S-wave interference observables
  - 2x statistics
  - Data split into B^0 and $\overline{\mathrm{B}}^0$, and fit simultaneuously

$\overline{B}^0$:

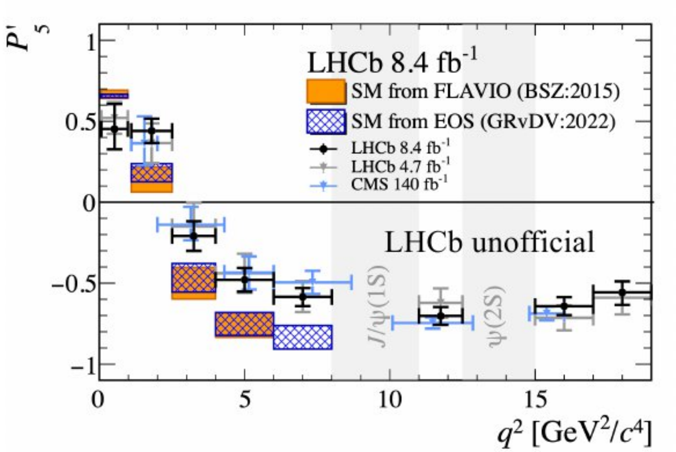


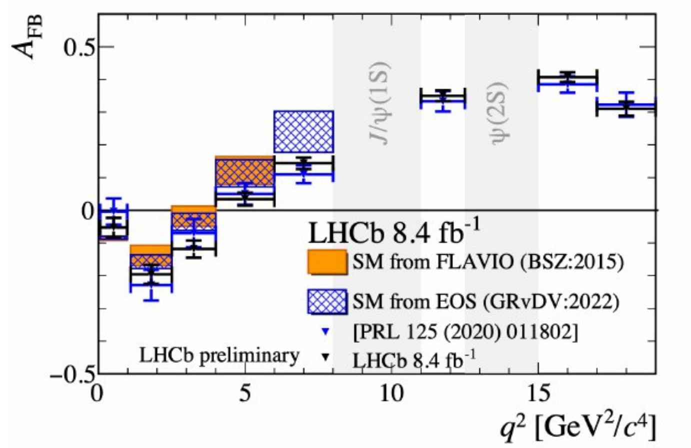
B^0:

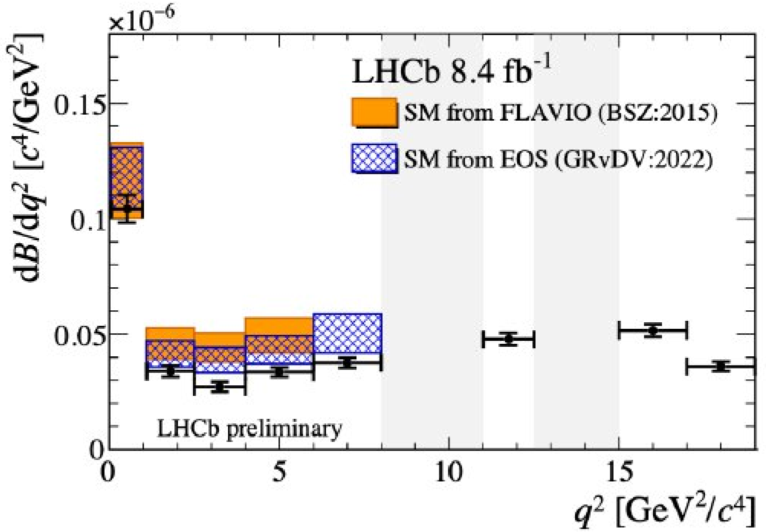


LHCb-PAPER-2025-041
In prep.

Legacy Runs1-2 $B^0 \to K^{*0}\mu^+\mu^-$ measurement



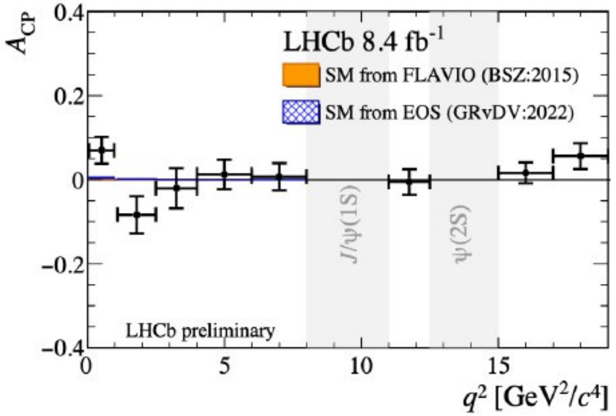


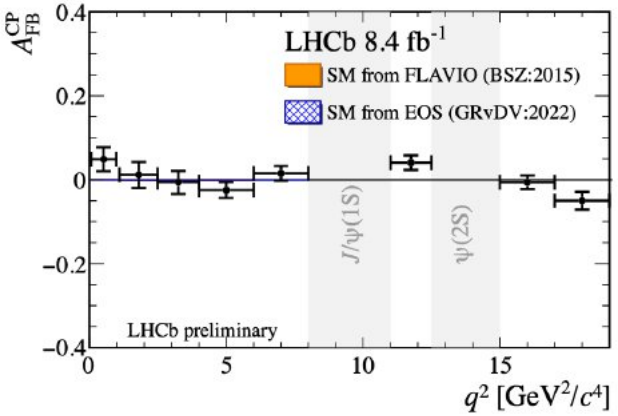


- Results in P'_5 excellent agreement with both CMS and previous LHCb
- Deviations of 2.6 and 2.7 σ in 4-6 and 6-8 GeV^2 bins

The forward-backward asymmetry, A_{FB}, also now shows marked disagreement with improved statistics

- The branching fraction is consistently below SM predictions



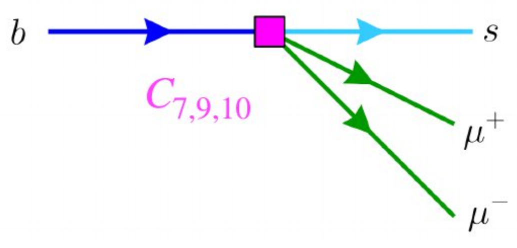


LHCb-PAPER-2025-041
In prep.

Legacy Runs1-2 $B^0 \to K^{*0}\mu^+\mu^-$ measurement

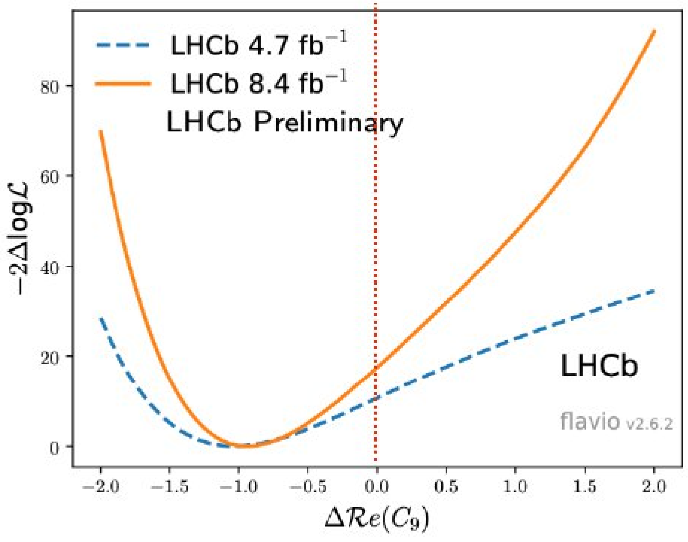
- Two different theory packages are used, which take different approaches, e.g. different non-local form factors

$$H_{eff} \propto \sum_i \mathcal{O}_i C_i$$

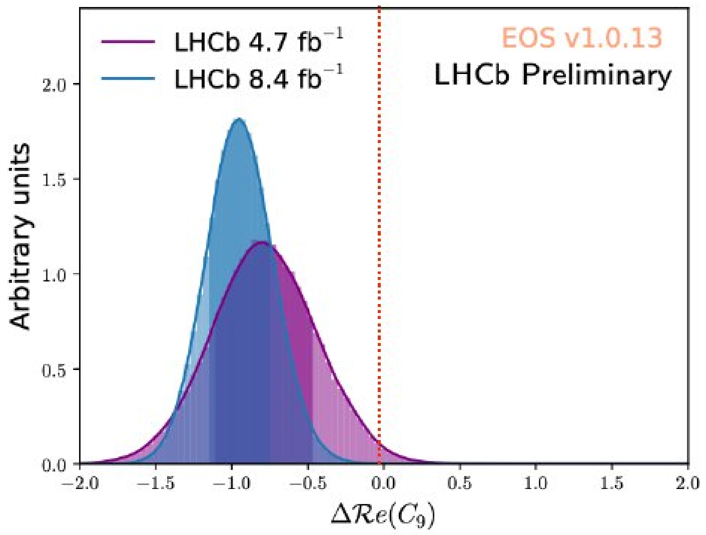


C_9 = vector-coupling

$$\Delta Re(C_9) = -0.93^{+0.18}_{-0.16}$$
Significance: 4.1σ



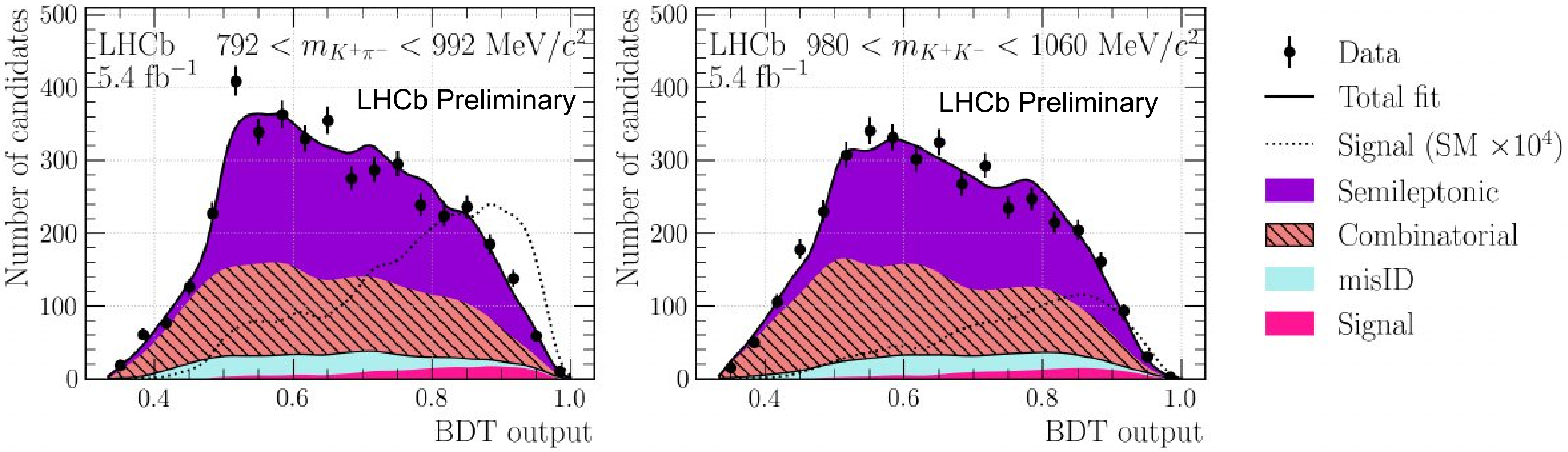
$$\Delta Re(C_9) = -0.94^{+0.22}_{-0.22}$$
Significance: 4.0σ



LHCb-PAPER-2025-048
In prep.

Search for $B^0 \to K^+\pi^-\tau^+\tau^-$ & $B_s^0 \to K^+K^-\tau^+\tau^-$

- Using Run2 5.4 fb^{-1} data
- Reconstructing taus with muonic channel
- Decays are searched in bins of dihadron masses



Searches in the lowest Kπ and KK bins

LHCb-PAPER-2025-048
In prep.

Search for $B^0 \to K^+\pi^-\tau^+\tau^-$ & $B_s^0 \to K^+K^-\tau^+\tau^-$

- Using Run2 5.4 fb^{-1} data
- Reconstructing taus with muonic channel
- Decays are searched in bins of dihadron masses
- No signal founds, upper limits are set:

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.8 \times 10^{-4}\ (2.5 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \phi\tau^+\tau^-) < 4.7 \times 10^{-4}\ (4.1 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL}.$$

One order of magnitude improvement!
First search!

LHCb Preliminary

Upper limit on the shift Δ in the $\mathcal{C}_{9(10)}^{\tau\tau}$ Wilson coefficient at 90% and 95% CL.

Confidence level	$B^0 \to K^+\pi^-\tau^+\tau^-$	$B_s^0 \to K^+K^-\tau^+\tau^-$
90%	1.6×10^2	2.4×10^2
95%	1.8×10^2	2.8×10^2

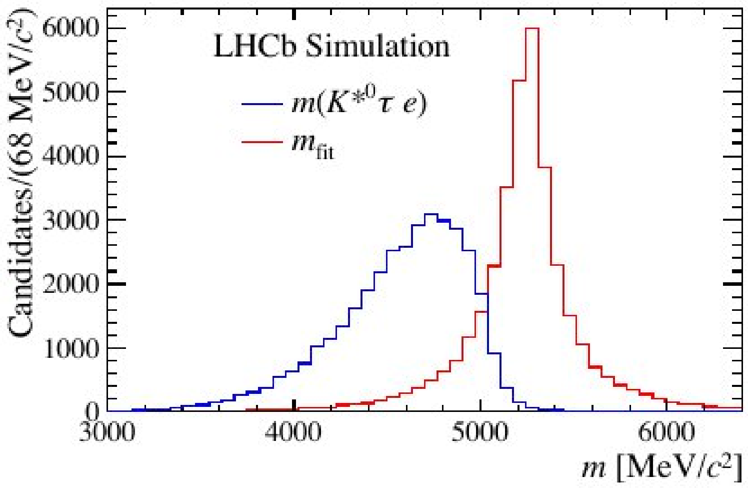
LHCb Preliminary

arXiv:2506.15347

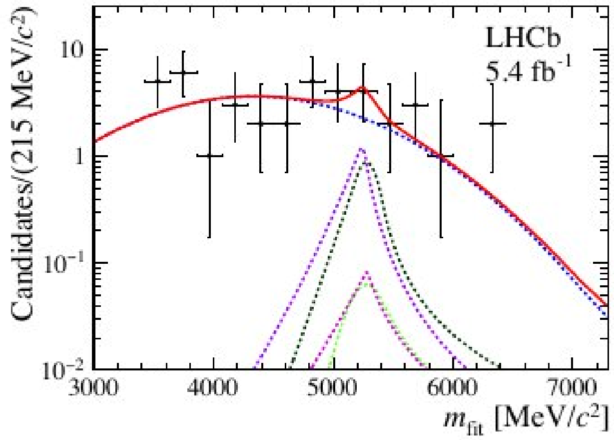
Search for LFV decay $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

- Lepton Flavour Violating decays would be enabled/enhanced by leptoquarks or Z' models
- New search for the lepton-flavour-violating decays $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$ at LHCb
  - first direct LFV search at LHCb with $e\tau$ combination (Run2 data)
  - New Physics models predict branching ratio up to 10^{-6} for this decay
  - 3-prong τ hadronic decay ⇒ decay vertex available, kinematic constraints with dedicated Decay Tree Fit gives much improved resolution!
  - $B^0 \to D^- D_s^+$ ($D^- \to K\pi\pi$, $D_s^+ \to KK\pi$) used as normalisation and control channel, and 3 multivariate discriminators to suppress background:
    - topologies of the signal decays and the combinatorial background
    - Isolation (simulation + Same Sign data)
    - Charm vs τ-lepton rejection
  - Limits on two decay channels at 90%(95%) CL:

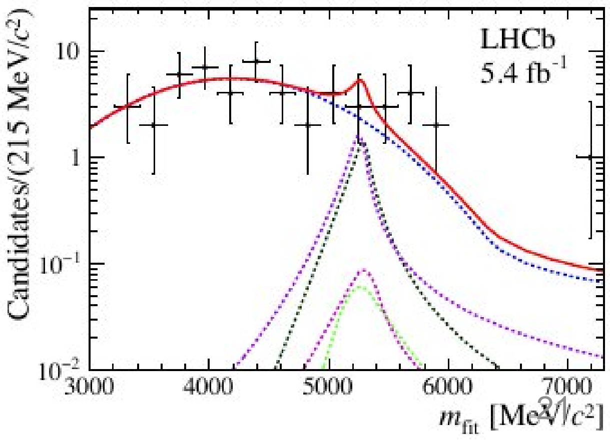
$$\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.9(7.1) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 4.9(5.9) \times 10^{-6}$$



$B^0 \to K^{*0}\tau^- e^+$

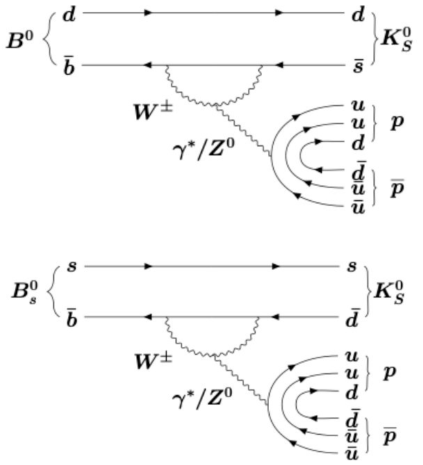


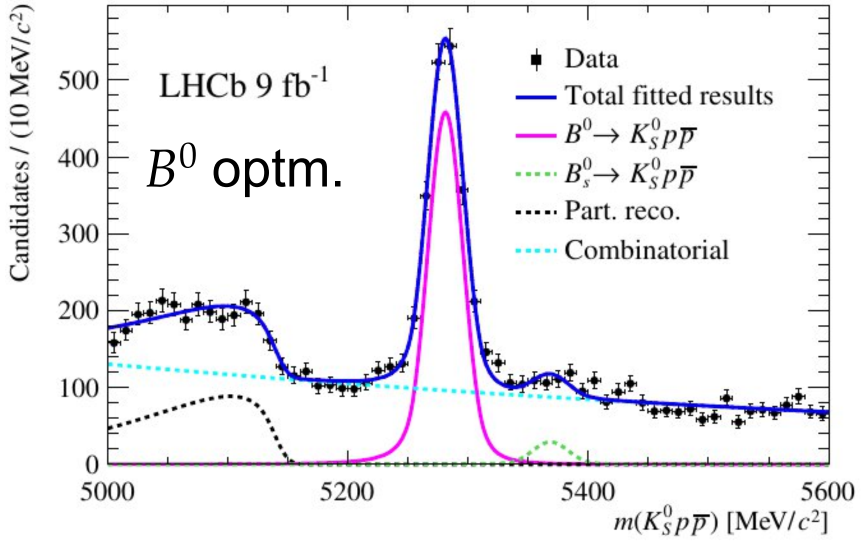
$B^0 \to K^{*0}\tau^+ e^-$



$B^0_{(s)} \to K^0_S p\bar{p}$ BF measurements

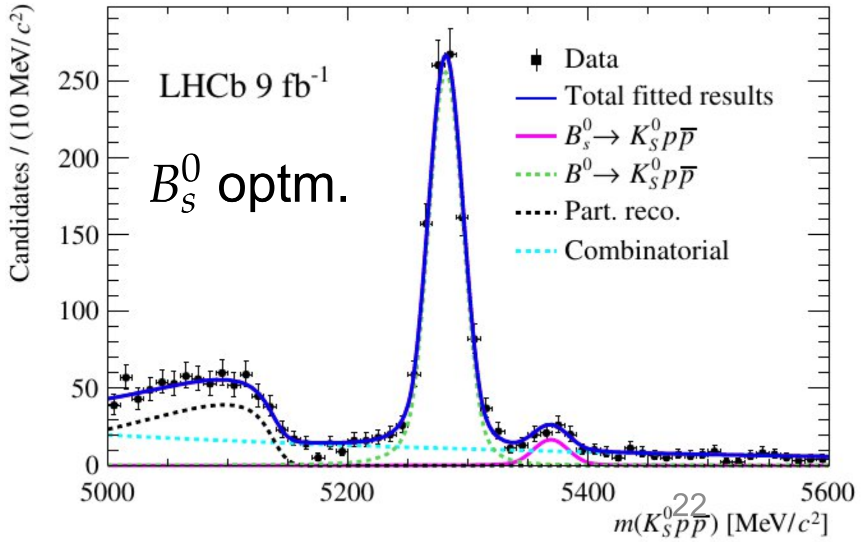
- BF($B^0 \to K_S p\bar{p}$) more precise and consistent with world average value $(2.66 \pm 0.32) \cdot 10^{-6}$ [PDG].
- $B_s^0 \to K_S p\bar{p}$ discovery at 5.6σ.





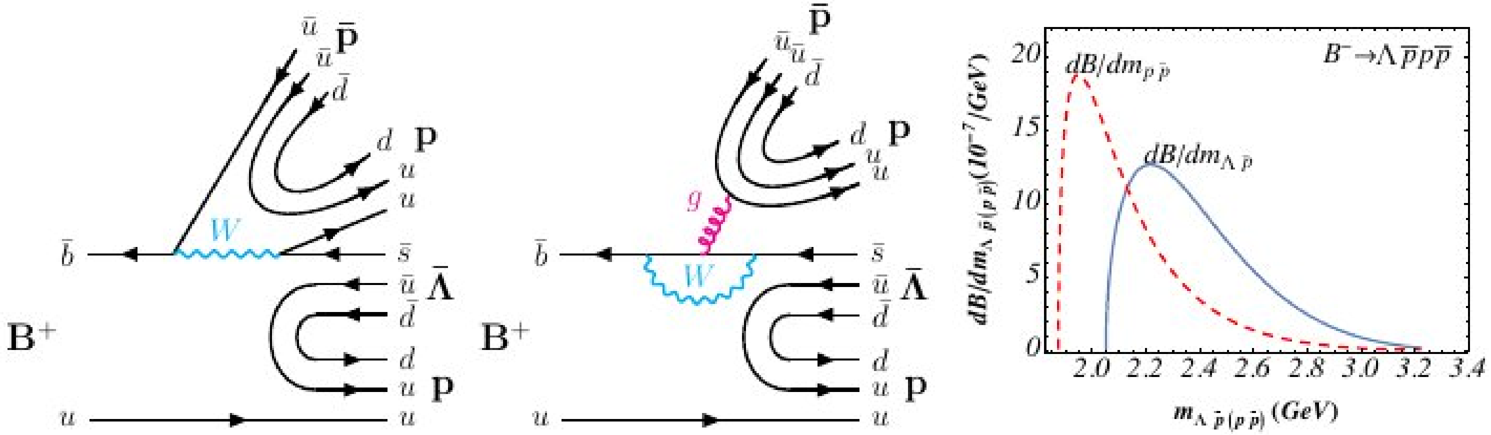
	$B^0 \to K_S\pi^+\pi^-$	$B^0 \to K_S p\bar{p}$	$B_s^0 \to K_S p\bar{p}$
Yield	32145 ± 230	1791 ± 52	66 ± 12

$$\mathcal{B}(B^0 \to K^0 p\bar{p}) = (2.82 \pm 0.08 \pm 0.12 \pm 0.10) \times 10^{-6},$$
$$\mathcal{B}(B_s^0 \to K^0 p\bar{p}) = (9.14 \pm 1.69 \pm 0.90 \pm 0.33 \pm 0.20) \times 10^{-7}$$



Study of $\mathrm{B}^+ \to \overline{\Lambda} p \bar{p} p$

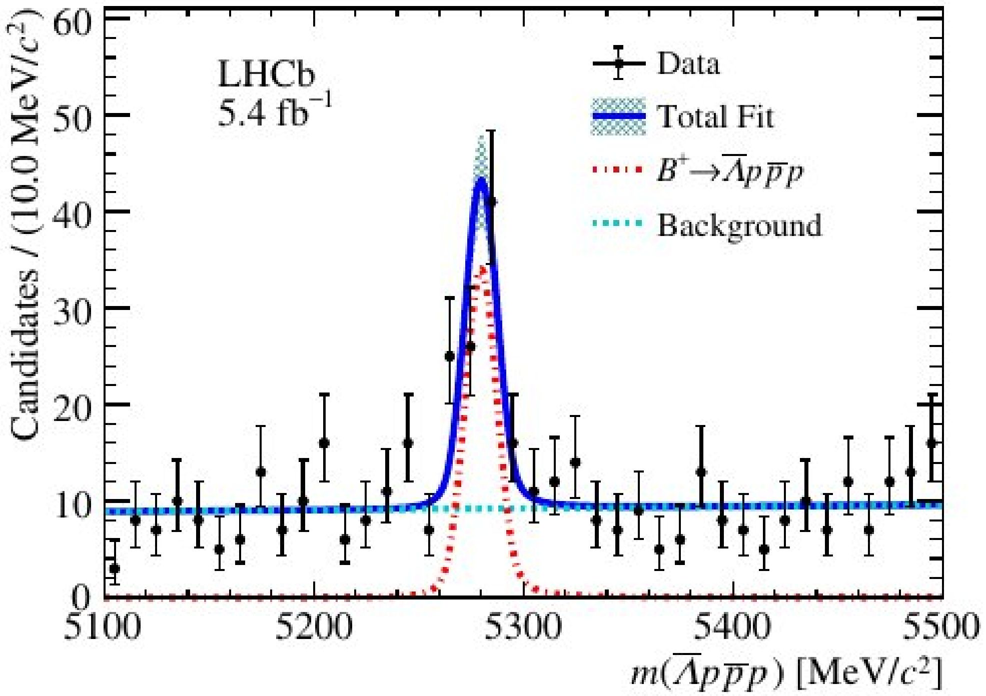
- Counterpart of recently observed decay $B^0 \to p\bar{p}p\bar{p}$ [PRL**131**(2023)091901]
- $B^+ \to \bar{\Lambda}^0 p\bar{p}p$ is dominated by $b \to s$ transition[*] at loop level, and $b \to u$ transition at tree level are color suppressed
- Prediction of $\mathcal{B}(B^+ \to \bar{\Lambda}^0 p\bar{p}p) = (7.4^{+0.6}_{-0.2} \pm 0.03^{+3.6}_{-2.6}) \times 10^{-7}$[*]
- Explore the mass spectra (double threshold effect) and extend the study of baryonium-like bound states such as the $X(1835)$ and $X(2085)$



*[PLB**845**(2023)138158]

Study of $B^+ \to \overline{\Lambda} p\bar{p}p$

- The signal yield is $N(B^+ \to \bar{\Lambda}^0 p\bar{p}p) = 78 \pm 12$, with a significance greater than 5 standard deviations



LHCb measurement : $\mathcal{B}(B^+ \to \bar{\Lambda}^0 p\bar{p}p) = (2.08 \pm 0.34 \pm 0.12 \pm 0.26) \times 10^{-7}$

Theory prediction : $\mathcal{B}(B^+ \to \bar{\Lambda}^0 p\bar{p}p) = (7.4^{+0.6}_{-0.2} \pm 0.03^{+3.6}_{-2.6}) \times 10^{-7}$

PLB845(2023)138158

arXiv:2508.16259

Study of $B^+ \to \bar{\Lambda} p \bar{p} p$

- The background-subtracted invariant-mass spectra of $\bar{\Lambda}p$ and $\bar{p}p$, exhibit clear **threshold enhancement** near both the baryonantibaryon mass thresholds:

Figure 1: $m(\bar{\Lambda}p_1) < m(\bar{\Lambda}p_2)$

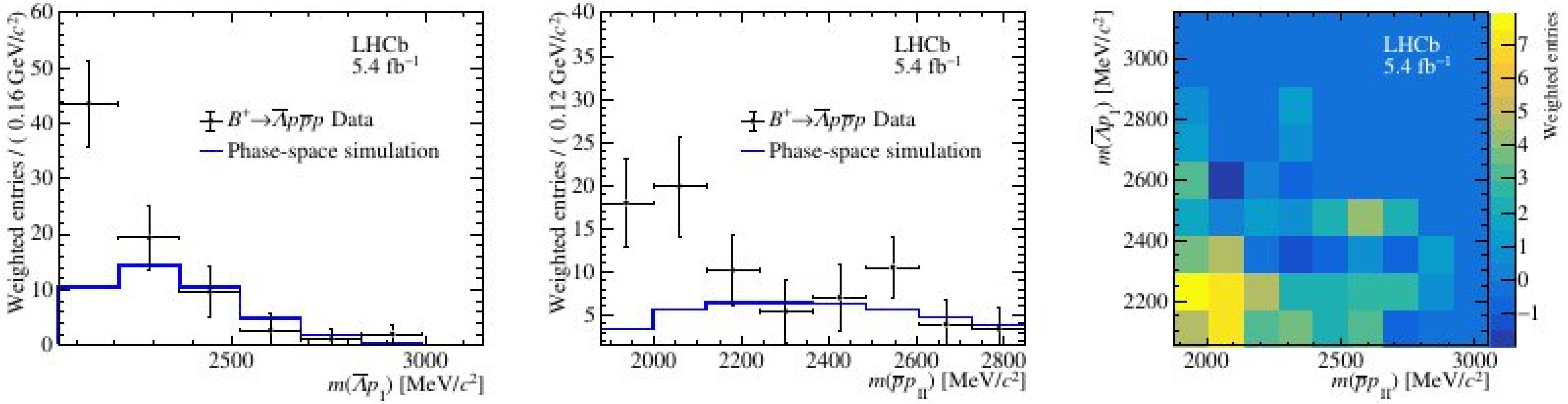
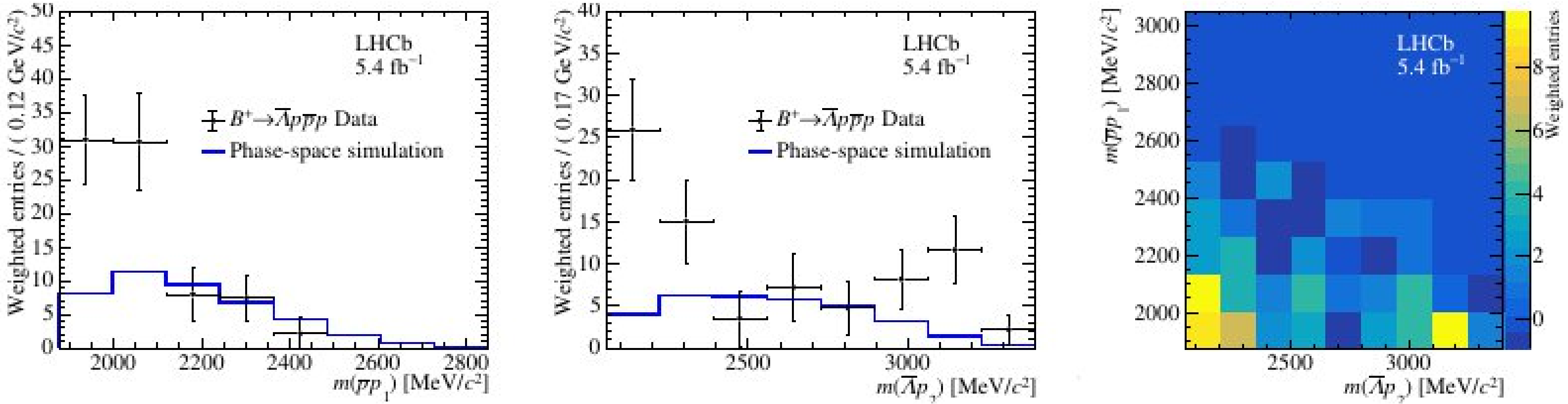


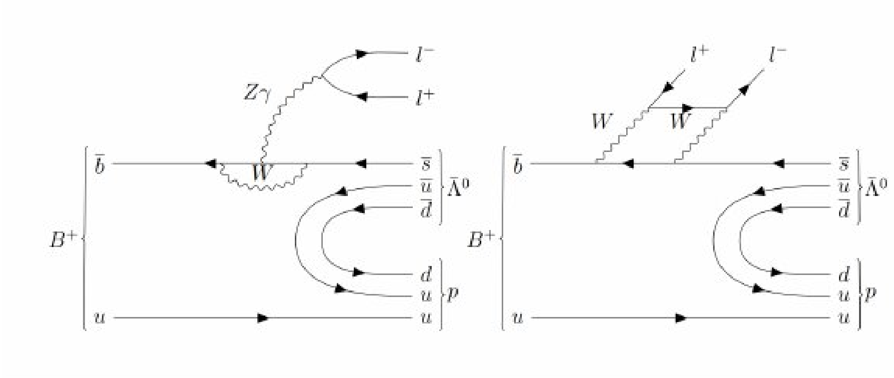
Figure 2: $m(\bar{p}p_1) < m(\bar{p}p_2)$

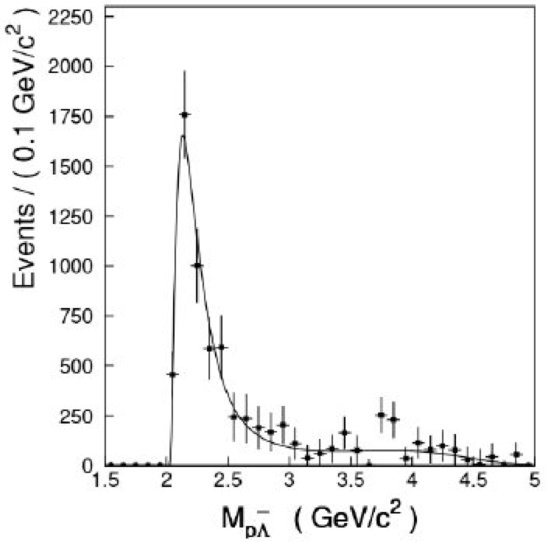


Search for $\mathrm{B}^+ \to \overline{\Lambda} p \mu^+ \mu^-$: Work-in-progress

- Essentially a $b \to s\ell^+\ell^-$ process
- EWP baryonic decays, sensitive to both NP and $\bar{\Lambda}^0 p$ threshold enhancement effects
- SM based prediction puts BF of $B^+ \to \bar{\Lambda}^0 p\mu^+\mu^-$ at about **1.08×10^{-7}** [J. Phys.G 41 (2014) 065002]
- BABAR measured $\mathcal{B}(\mathrm{B}^+ \to \bar{\Lambda}^0 p\nu\bar{\nu}) < 3.0 \times 10^{-5}$ [PRD 100 (2019) 111101], given expected BF of **7.9×10^{-7}**. However a recent paper claimed that the prediction on $B^+ \to \bar{\Lambda}^0 p\nu\bar{\nu}$ should be **20x smaller** [EPJC 83 (2023) 4, 300].
- Threshold enhancement effects, observed significantly near the $\bar{\Lambda}^0 p$ invariant mass threshold, play a crucial role in four-body baryonic B decays, as confirmed by Belle's study of $B^+ \to \bar{\Lambda}^0 p\pi^+\pi^-$ [PRD 80 (2009) 111103(R)].

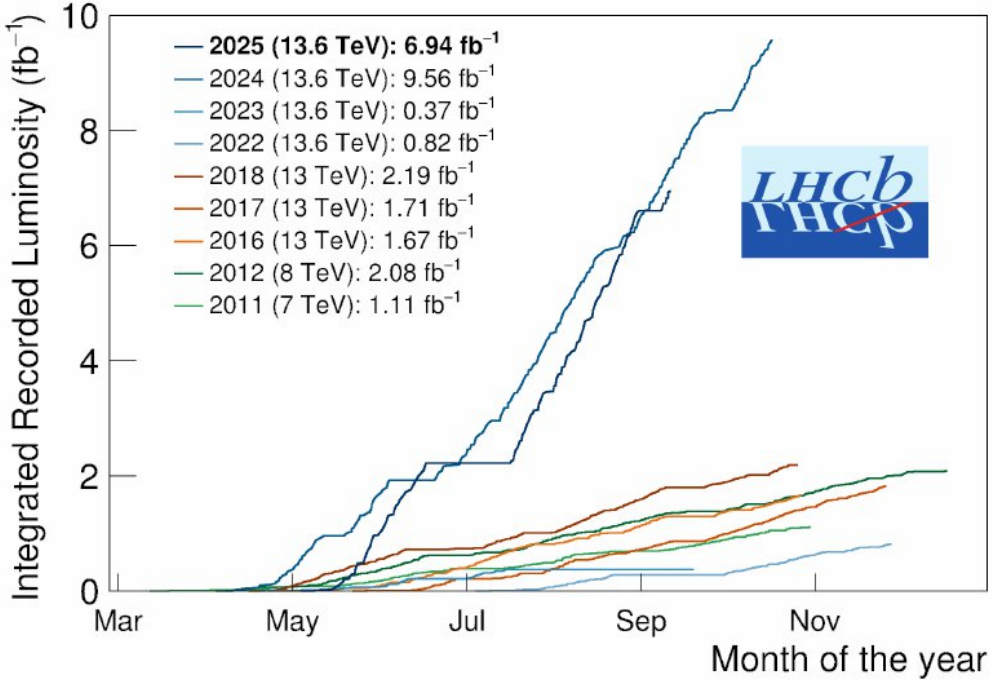
Stay tuned for our results!

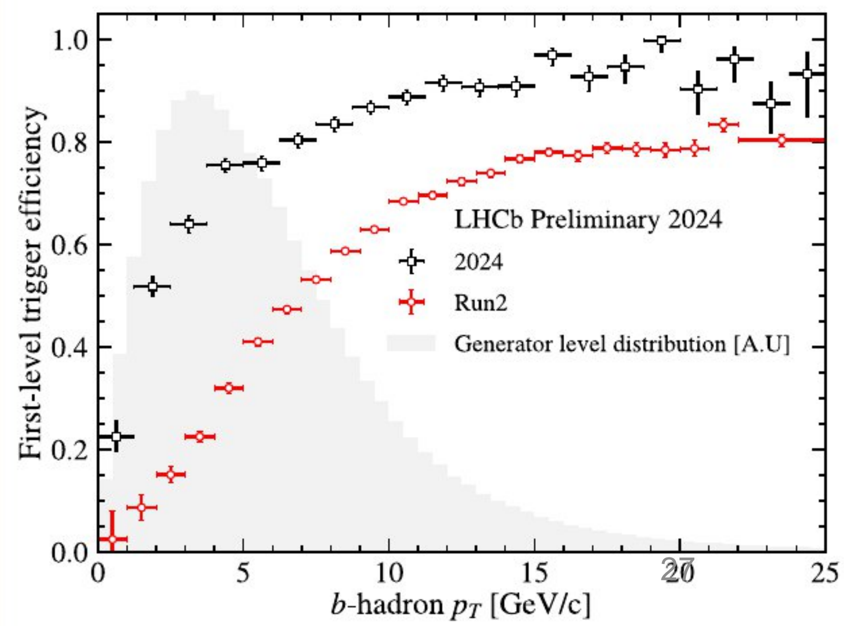




Summary

- Studies on rare b decays are key to searches for BSM
- Many first searches, LFU tests, and angular analyses, esp. with electron channels
- So far, no surprises, but tensions still persist (C_9?)
- Studies in four-body baryonic decays ongoing, stay tuned!
- Now a new detector and improved hadron trigger: higher efficiency per fb^{-1}
- And we will have Run4 and Upgrade-II!
  - 50 fb^{-1} by 2033, > 300 fb^{-1} by 2041



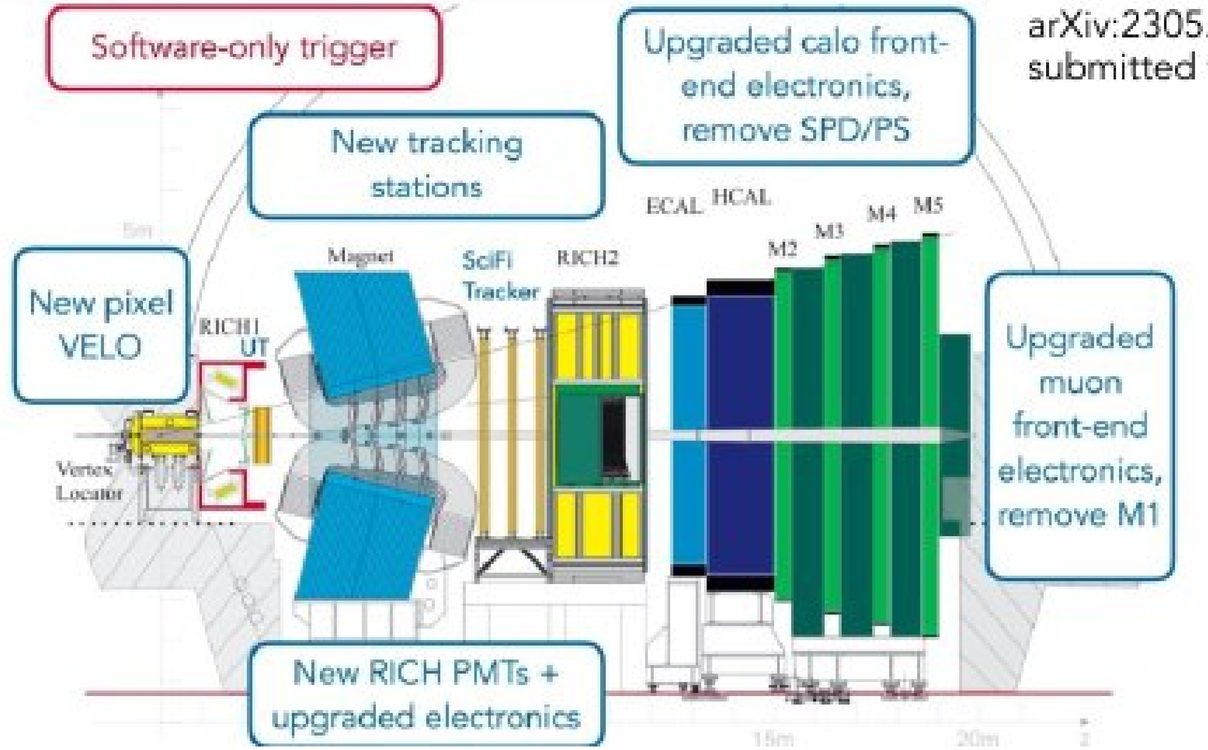


Backup Slides

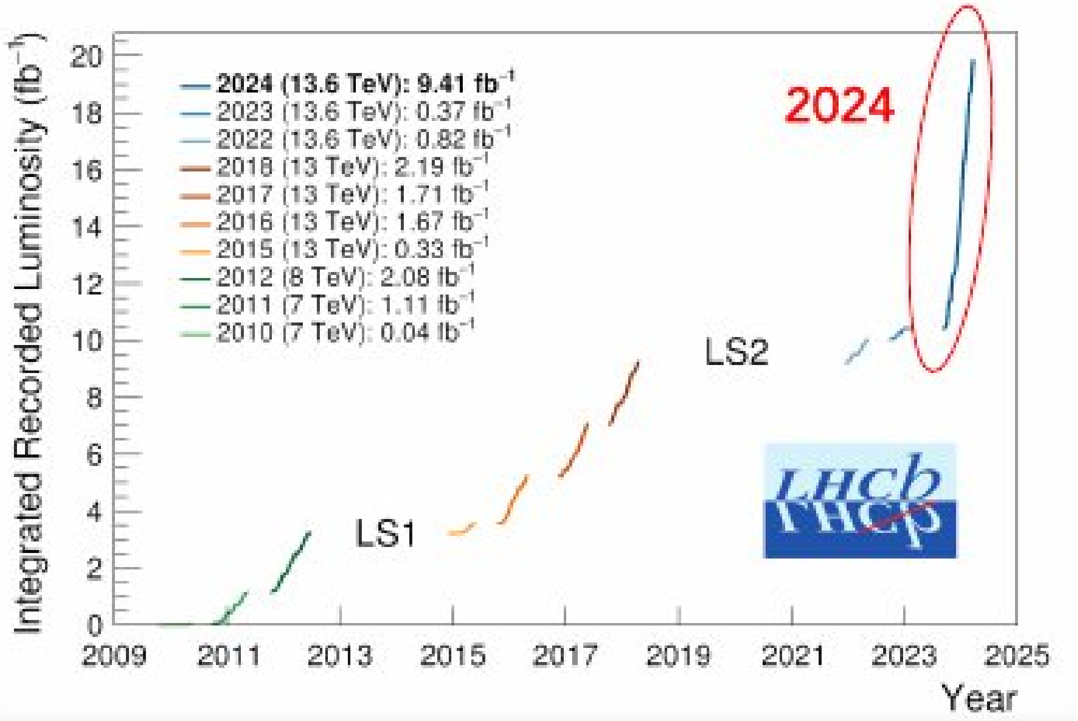
LHCb-Upgrade I

Luminosity x5 wrt Run2
5.5 visible interactions/crossing
Higher track multiplicity from ~<70> to ~<180>)

No more hardware trigger (full detector readout at 40 MHz)
Tracking & PID detectors modified/replaced
Higher granularity



arXiv:2305.10515, submitted to JINST

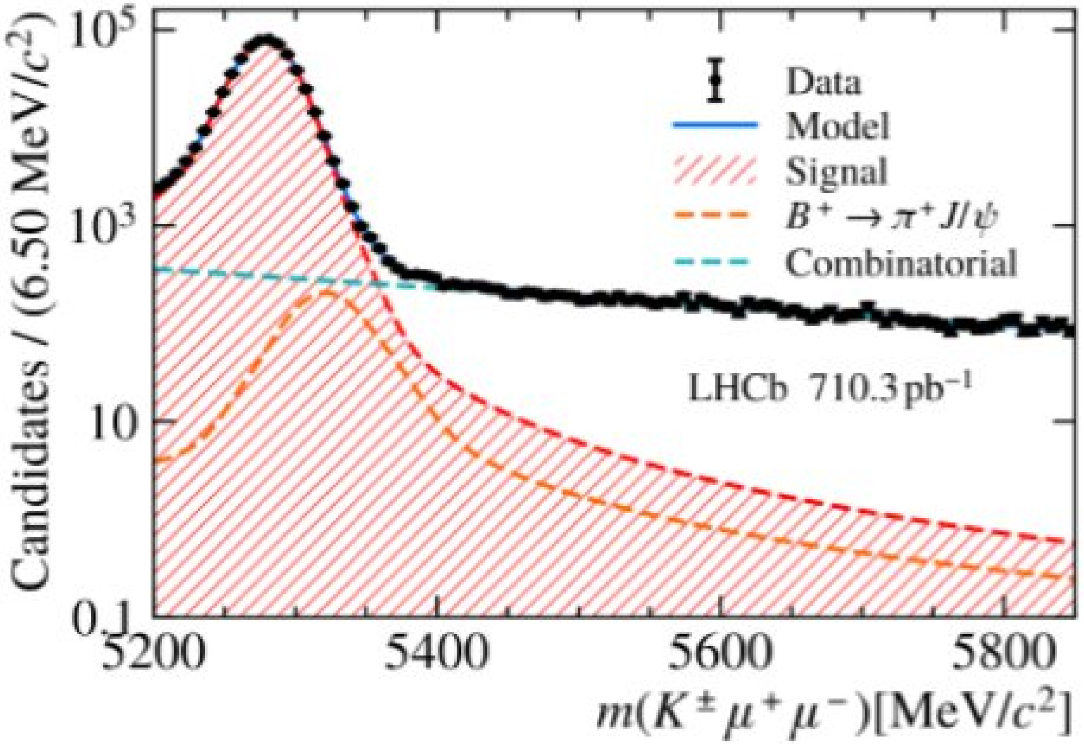


In January 2023, a loss of control of the LHC primary vacuum system
⇒ plastic deformation of the RF foil separating VELO from LHC.
⇒ significant impact on 2023 physics programme

2022 – 2023 : commissioning and understanding the new detector

2024 : a lot of data !

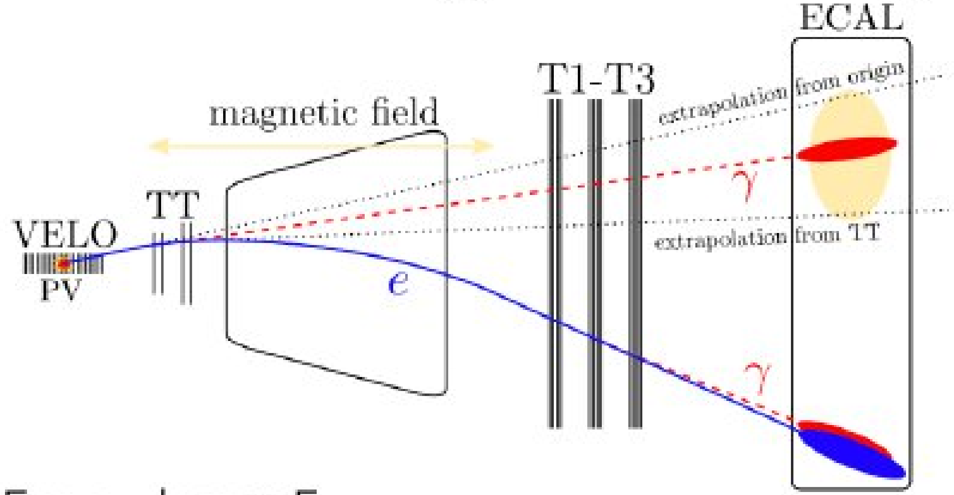
$1\,\text{fb}^{-1}$ collected during October 2024

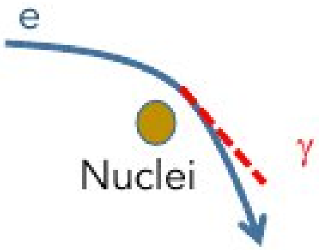


LHCb_TDR_023

Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)	Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests				
γ ($B \to DK$, *etc.*)	4° [9,10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [29,30]	3%	2%	1%
a^d_{sl} ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a^s_{sl} ($B^0_s \to D^-_s\mu^+\nu_\mu$)	33×10^{-4} [35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5} [38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K^0_s\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—	—	—	0.2
$A^{(2)}_{\text{T}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
A^{Im}_{T} ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12 [61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62,64]	0.007	0.005	0.002

Bremsstrahlung emission is significant for electrons





Before the magnet

- electron can be swept out (=lost !)
- kinematics are "wrong"

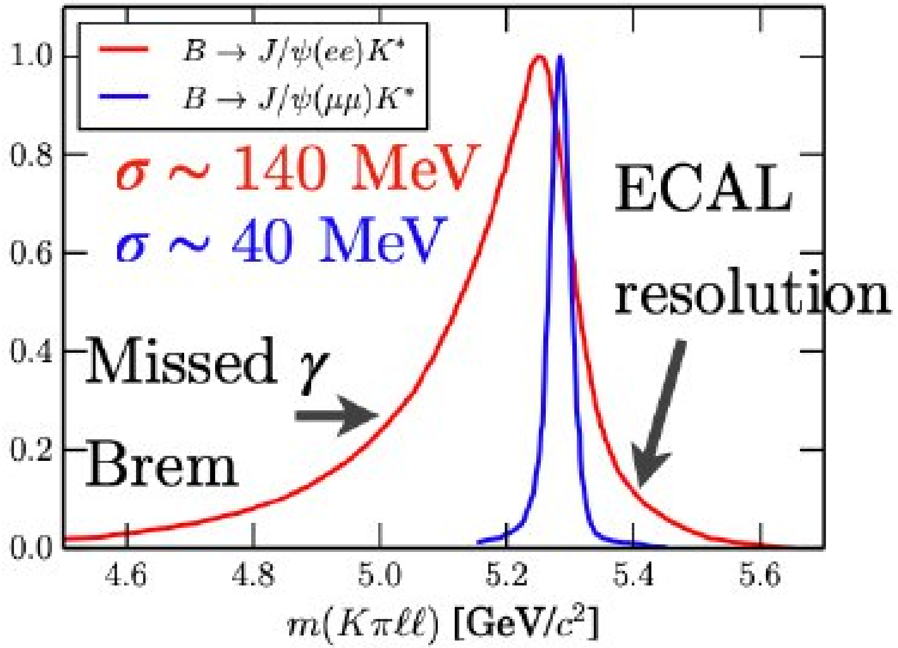
After the magnet

- not an issue

In both cases E/p is correct

Energy loss ∝ E_e
Energy loss ∝ material

⇒ Use of a recovery algorithm

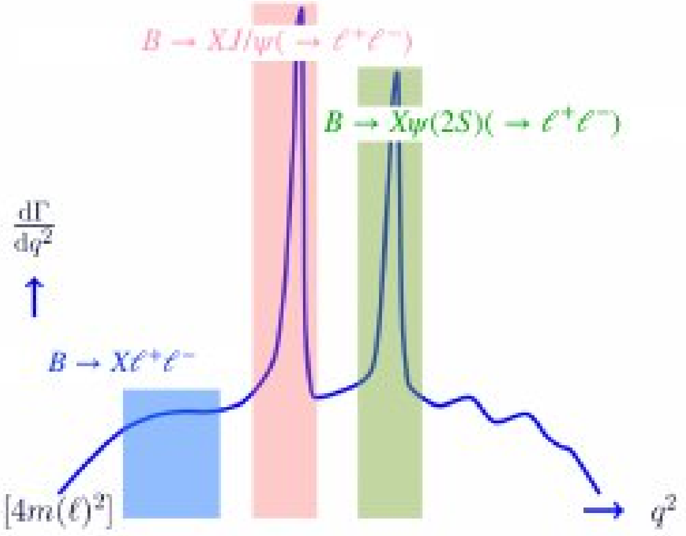


LFU ratio: Experimental strategy

- R_X are measured as double ratios, to mitigate e/μ reconstruction differences

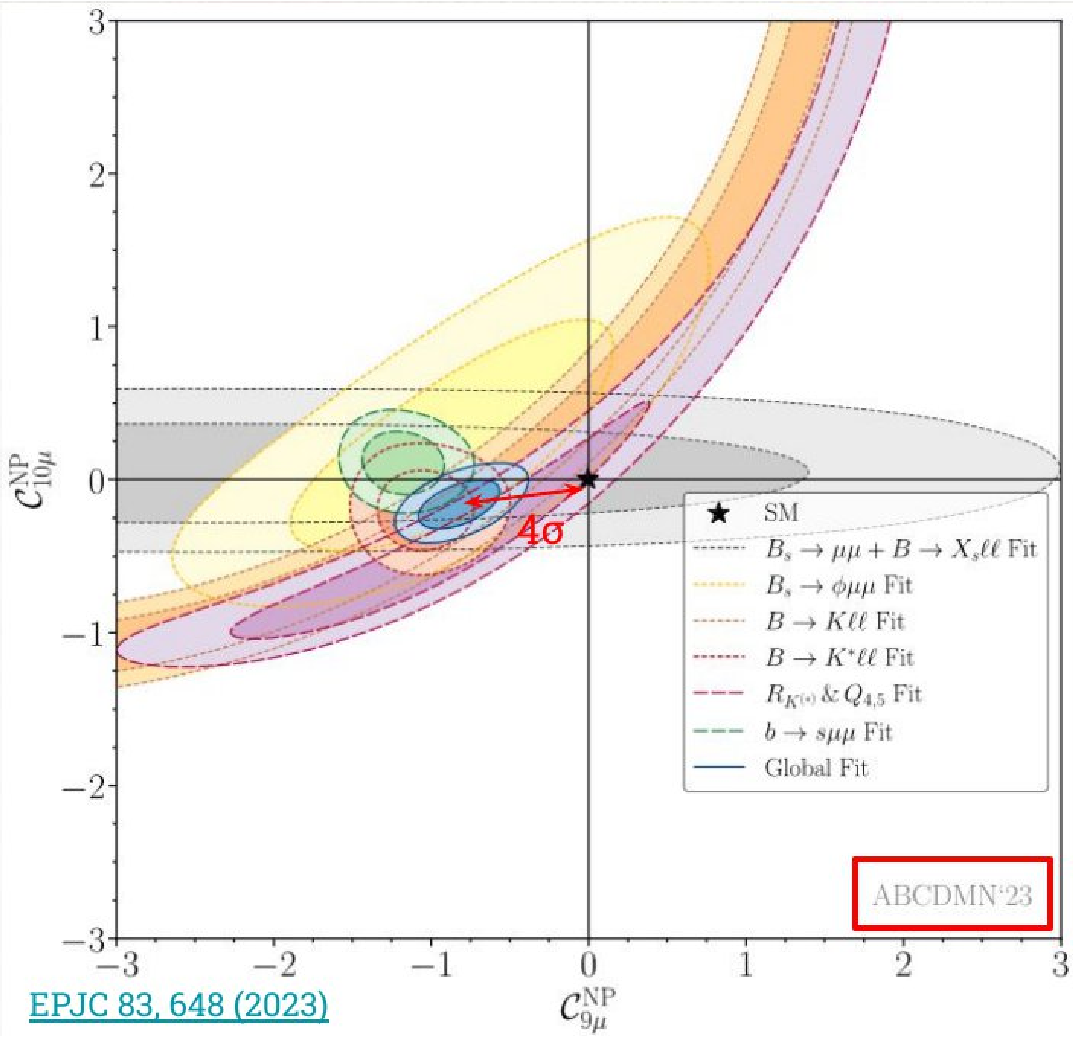
$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to XJ/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to XJ/\psi(\to e^+e^-)}}$$

  - Yields: unbinned maximum-likelihood fits to the B invariant mass
  - Efficiencies: simulation corrected for well-known MC/data differences

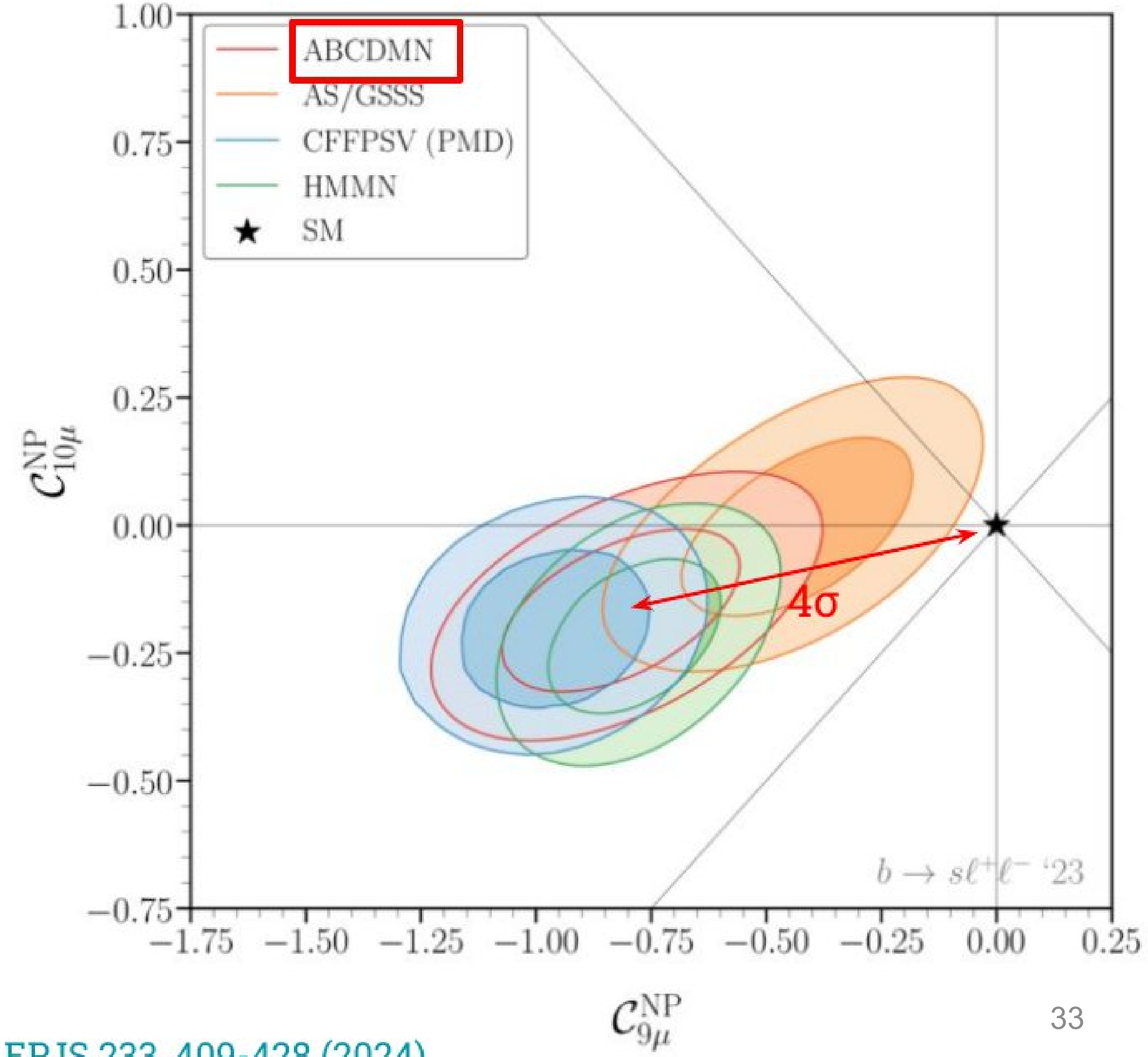


- Resonant channels also used for checks/data driven studies
  - J/ψ and $\psi(2S)$ satisfy LFU, not mediated by $b\to s\ell\ell$
    - $r_{J/\psi} = \dfrac{\mathcal{B}(B\to XJ/\psi(\to\mu\mu))}{\mathcal{B}(B\to XJ/\psi(\to ee))} \equiv 1$ Sensitive to e,μ differences
    - $R_{\psi(2S)} = \dfrac{\mathcal{B}(B\to X(\psi(2S)\to\mu\mu))}{\mathcal{B}(B\to X(J/\psi\to\mu\mu))} \cdot \dfrac{\mathcal{B}(B\to X(J/\psi\to ee))}{\mathcal{B}(B\to X(\psi(2S)\to ee))} \equiv 1$ Efficiency related systematics cancel in double ratio

Wilson Coefficients global fits



EPJC 83, 648 (2023)



EPJS 233, 409-428 (2024)