Search for New Physics @ LHCb

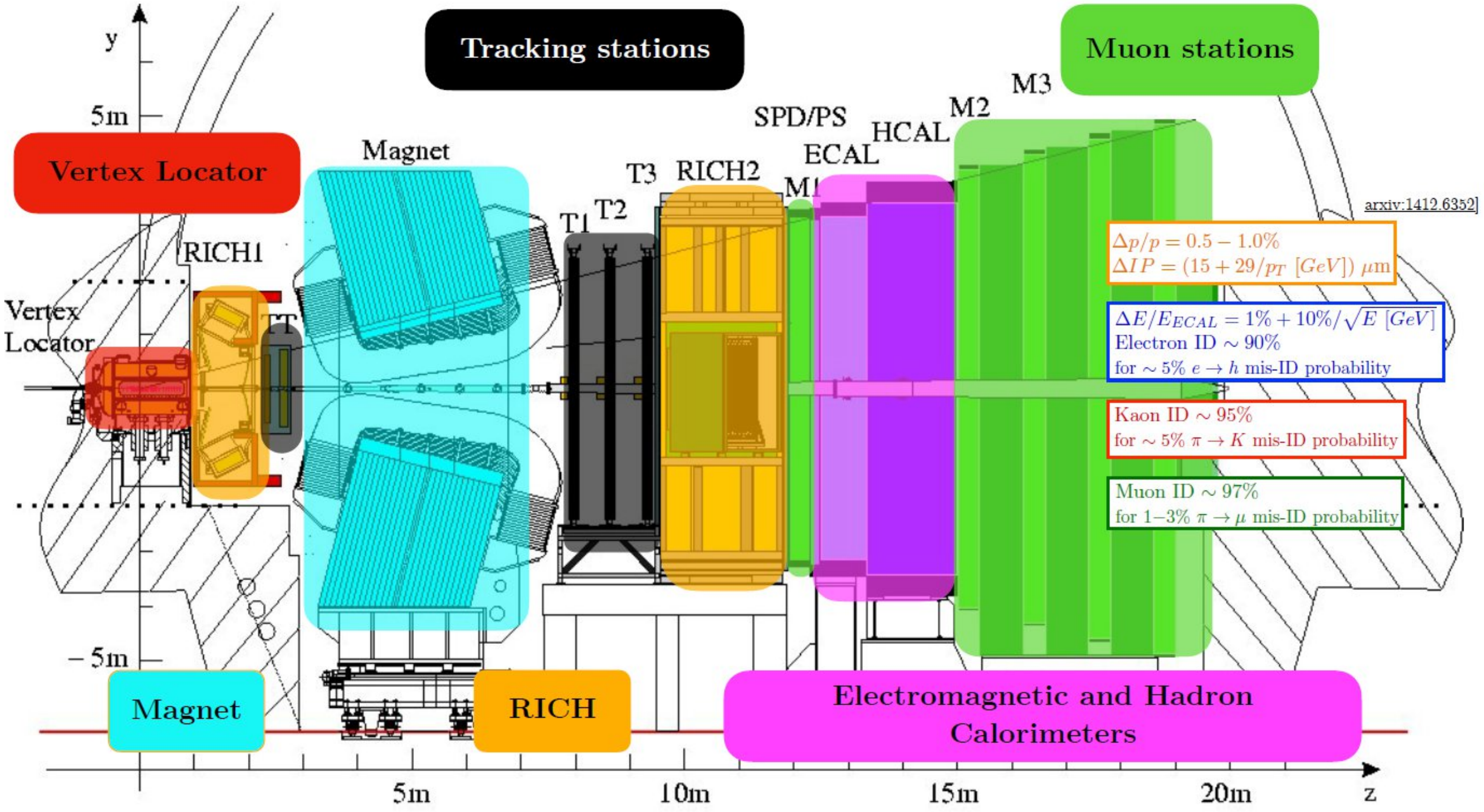
Liang Sun
Wuhan University
2025/12/12

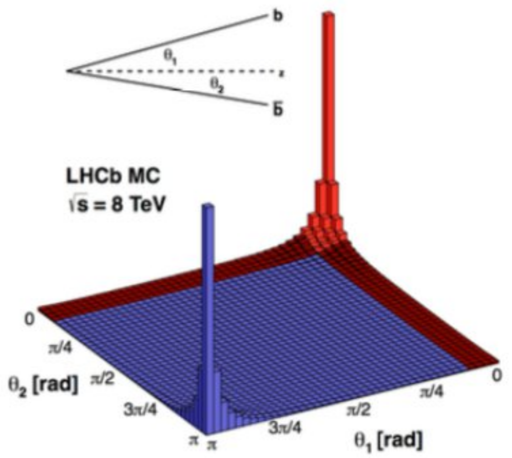
CAP2025, Beijing

Outline

- LHCb experiment in Runs 1-2,3
- Highlights of recent results on
  - Rare B decays ($b \to d\gamma$, $b \to s\ell\ell$)
  - Very rare B decays
  - Rare decays of light hadrons & τ
- A complete list of published results here
- Summary & outlook

LHCb in Runs 1-2 (2011-2018)

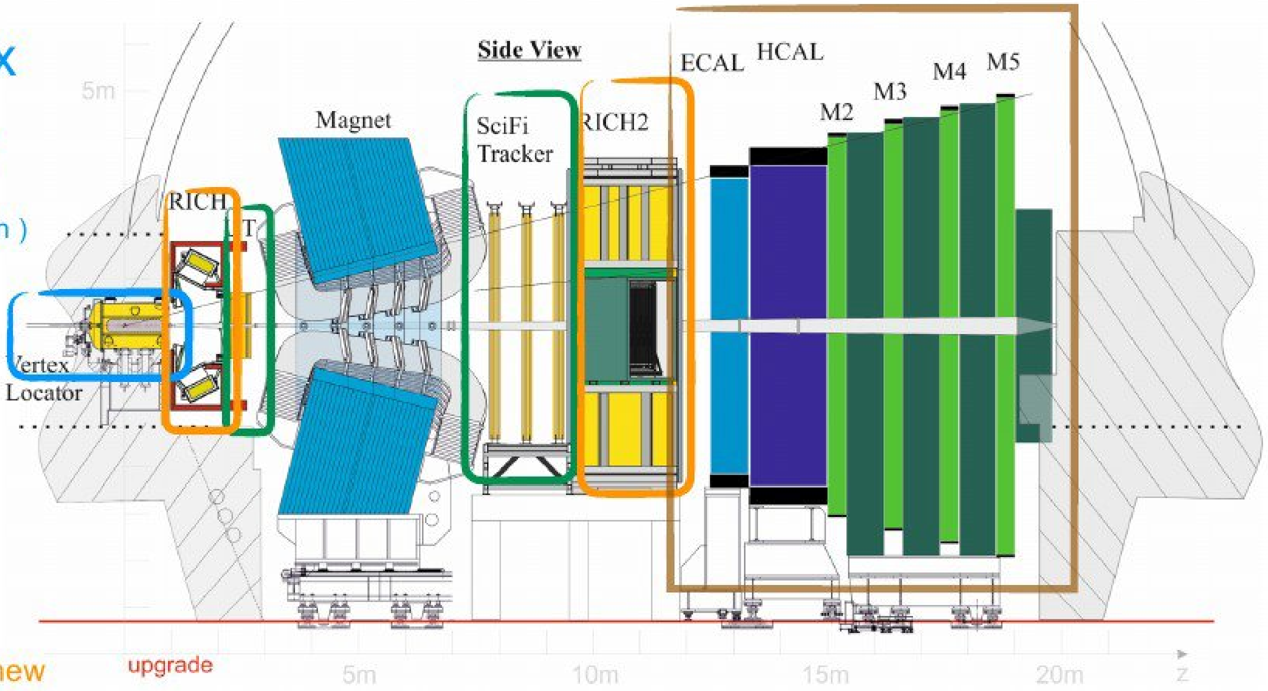




LHCb is designed and optimized for HF & CPV

LHCb in Run3 (2022-)

New Vertex detector (Si-microstrip-> Si-pixel, closer to beam, improved IP resolution)

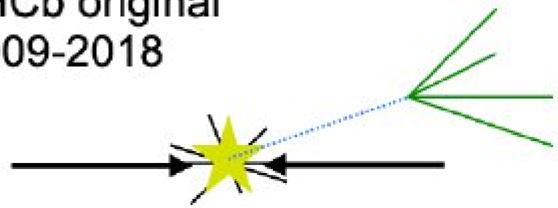


New PID detector, new photon detectors, readout + modified optics/mechanics

New tracking system (Si-strip + straw-tubes ->Scintillating fibres,+ Si-strip UT > granularity)

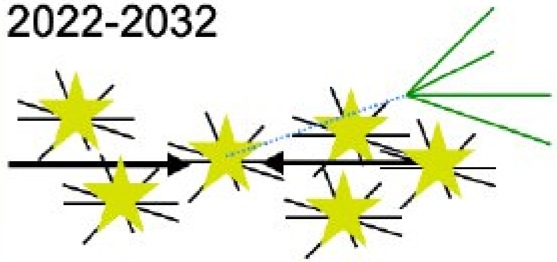
New read out

LHCb original 2009-2018



~1 pp collision per bunch-crossing

LHCb Upgrade I 2022-2032



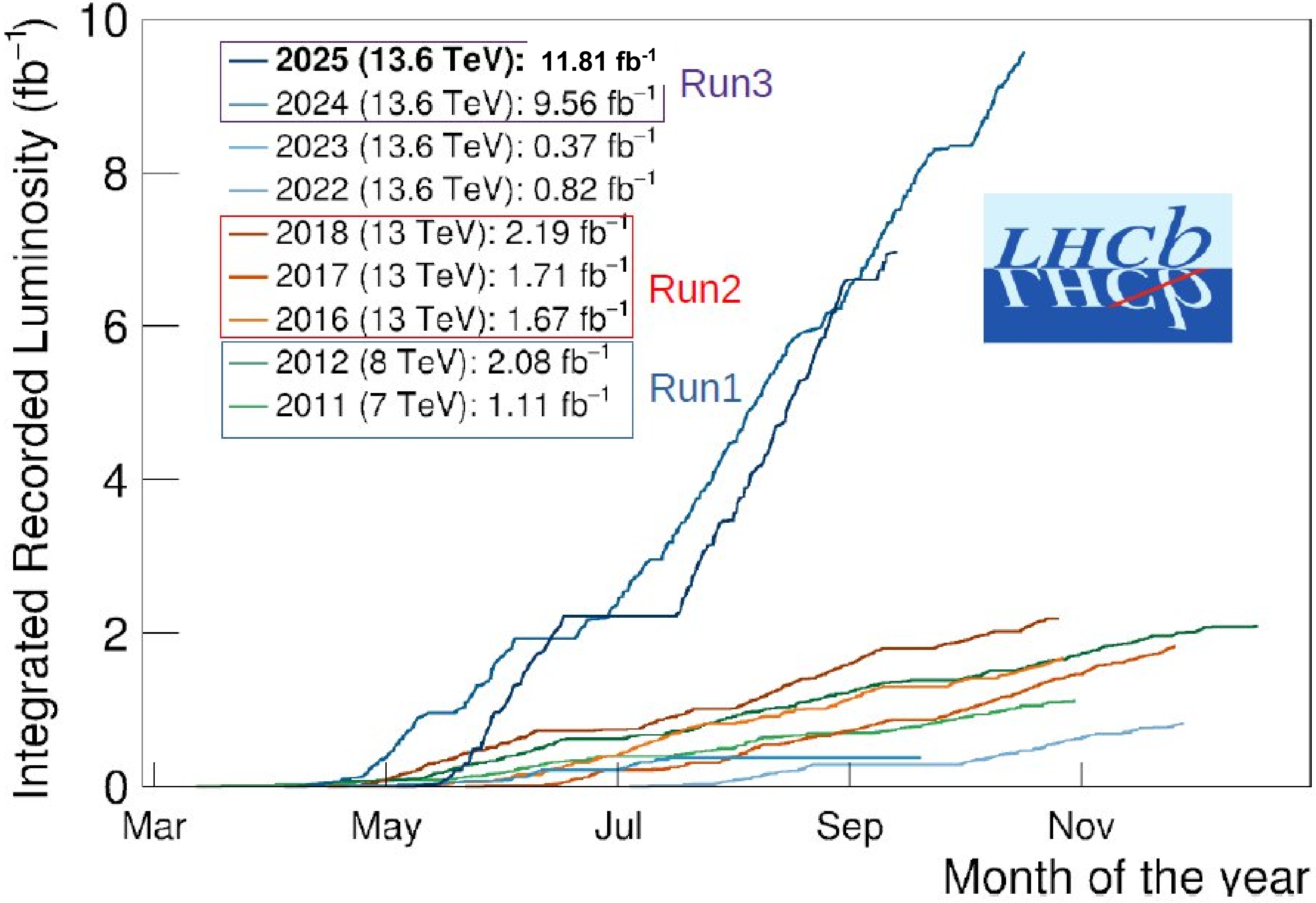
~6 pp collisions per bunch-crossing

Running with 5x higher instantaneous luminosity!

+ new DAQ/data centre

Excellent detector performance since 2024!

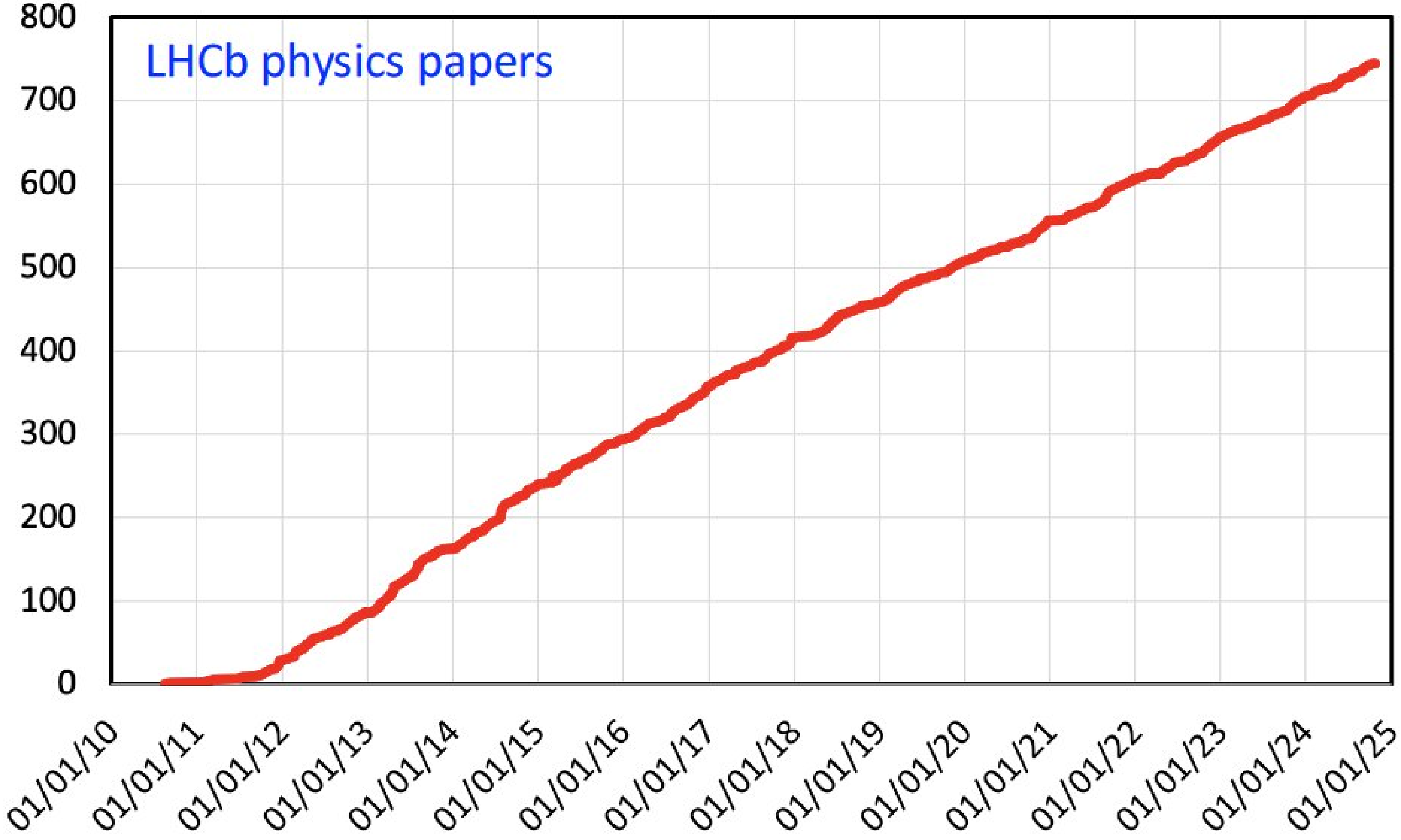
LHCb datasets

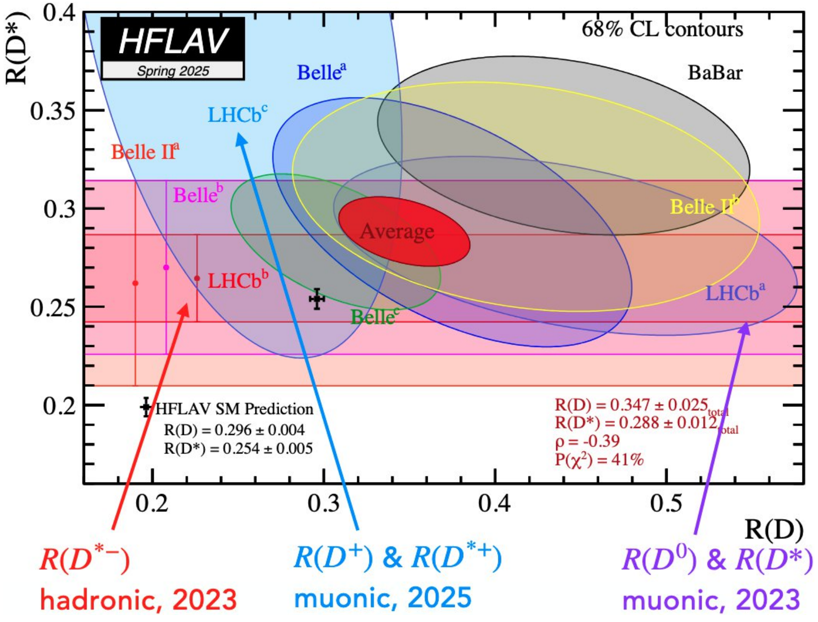


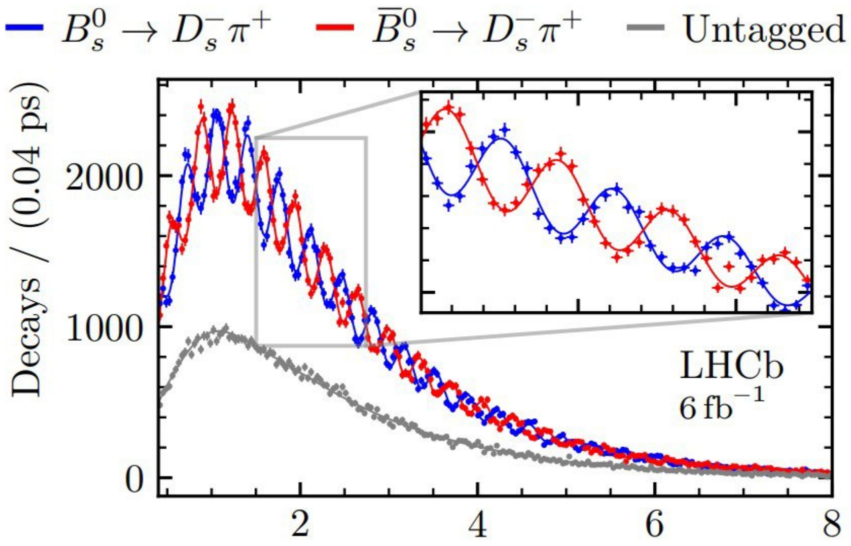
All results shown today are based on Runs 1-2 datasets

LHCb physics program

Publication luminosity

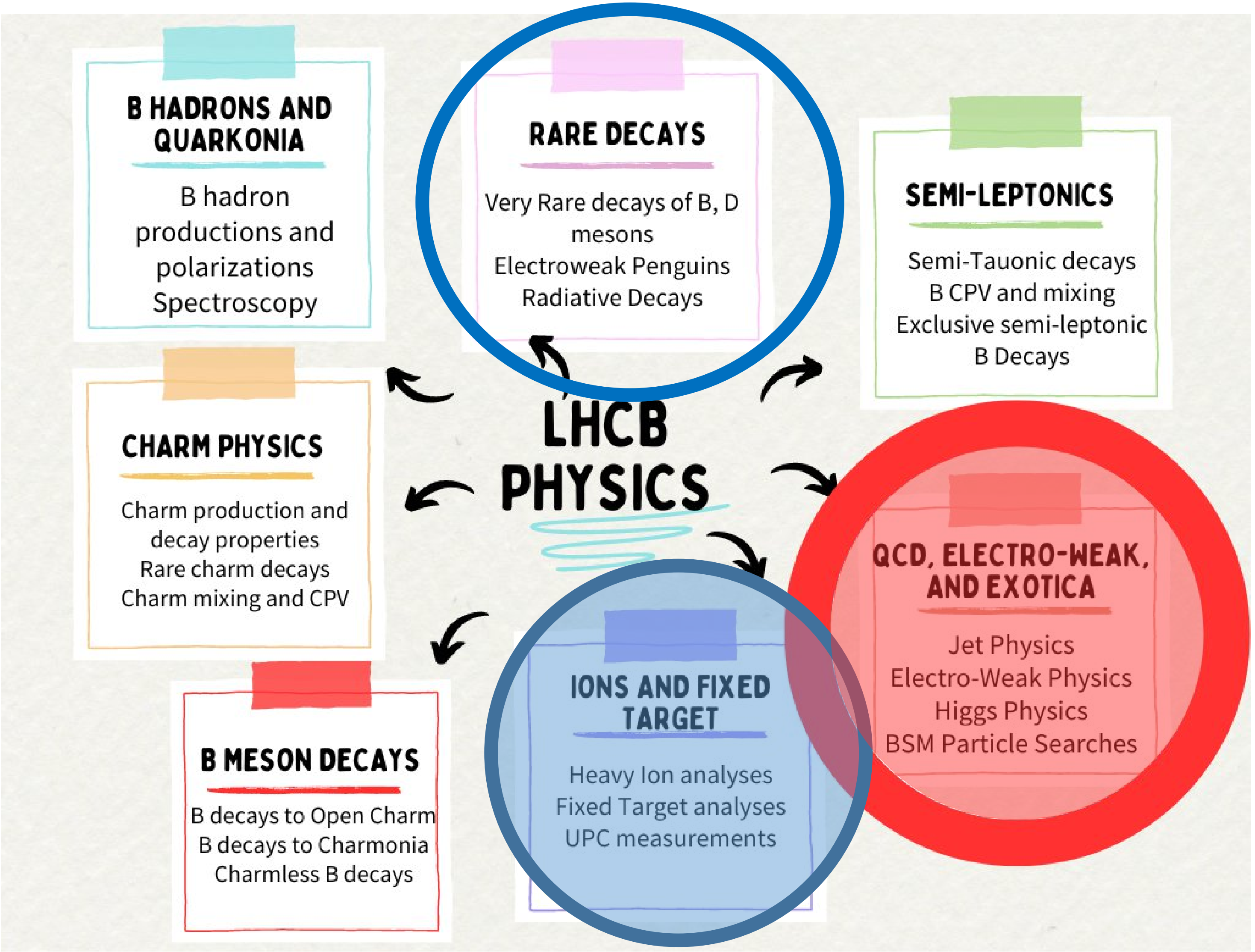


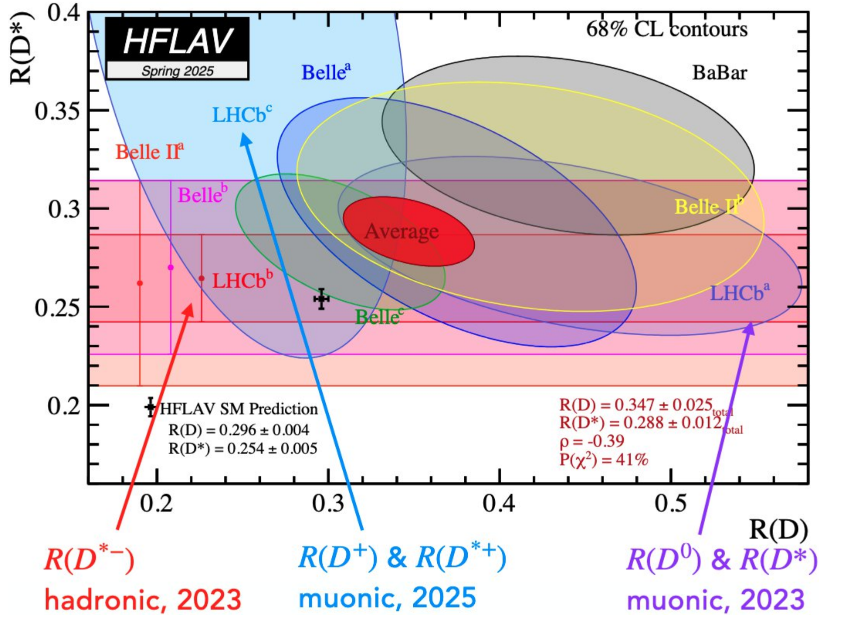


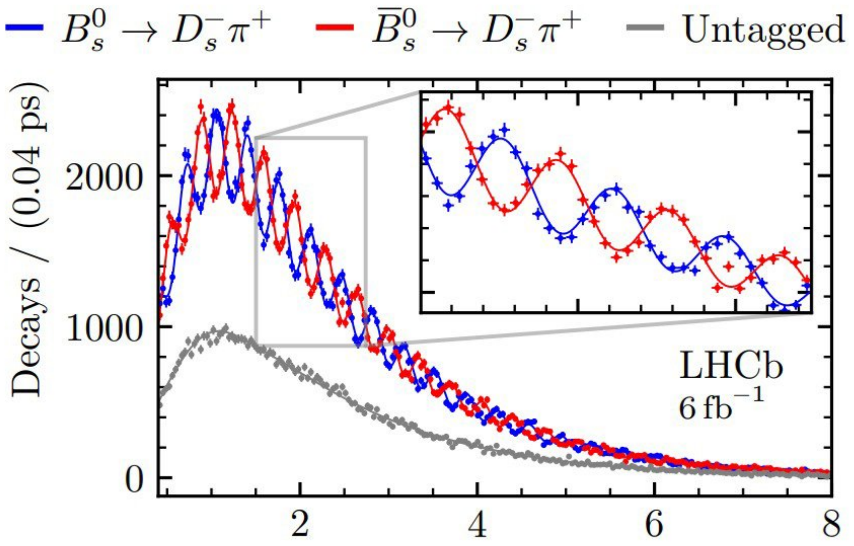


Nat. Phys. 18, 1–5 (2022)

LHCb physics program



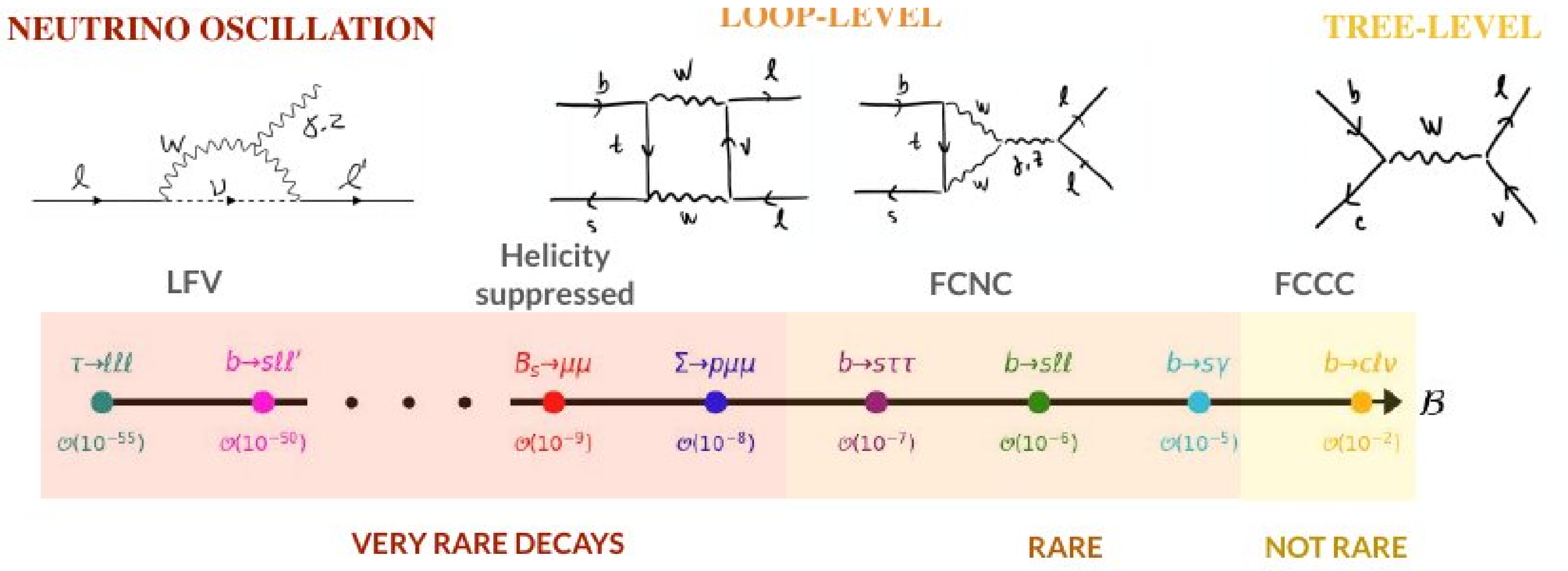




Nat. Phys. 18, 1–5 (2022)

Rare decays and very rare decays

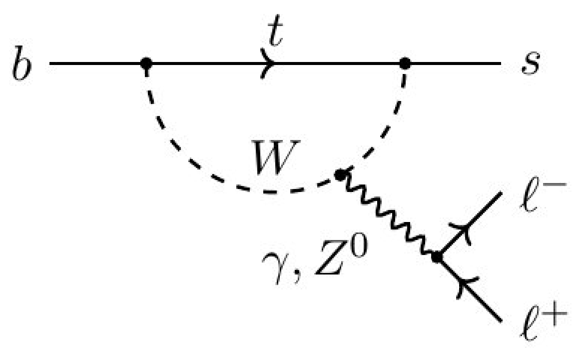
- Rare decays are processes mediated by flavor-changing neutral currents (FCNC)
- Very rare decays involve other highly suppressed processes that are usually out of reach experimentally

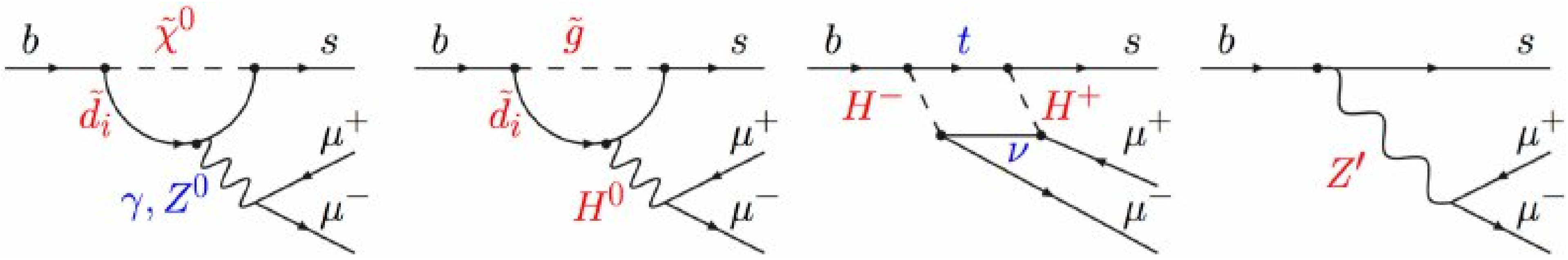


Rare decays as a probe for New Physics

- FCNC processes suppressed in SM
- New physics particles with energy scale up to $O(100)$ TeV could manifest in the loops

$b \to s\ell\ell$ decays in the SM

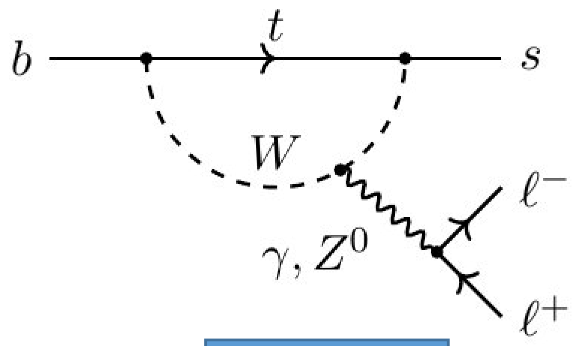




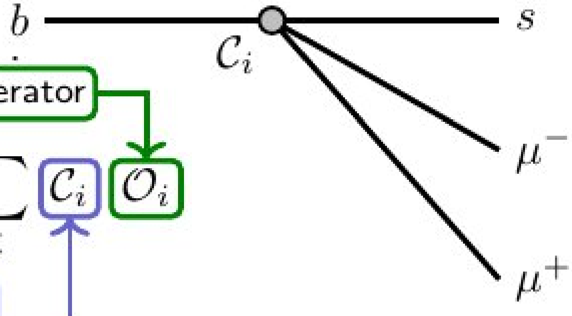
Rare decays as a probe for New Physics

- FCNC processes suppressed in SM
- New physics particles with energy scale up to *O*(100) TeV could manifest in the loops
- This could cause deviation of Wilson coefficients from SM values

$b \to s\ell\ell$ decays in the SM



Effective description



Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

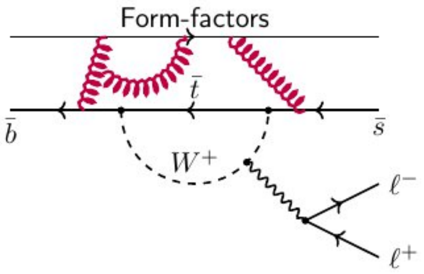
$b \to s\gamma$ ($\mathcal{C}_7^{(\prime)}$); $b \to s\ell\ell$ ($\mathcal{C}_7^{(\prime)}$ – $\mathcal{C}_S^{(\prime)}$); $B_s^0 \to \mu^+\mu^-$ ($\mathcal{C}_{10}^{(\prime)}$ – $\mathcal{C}_P^{(\prime)}$)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

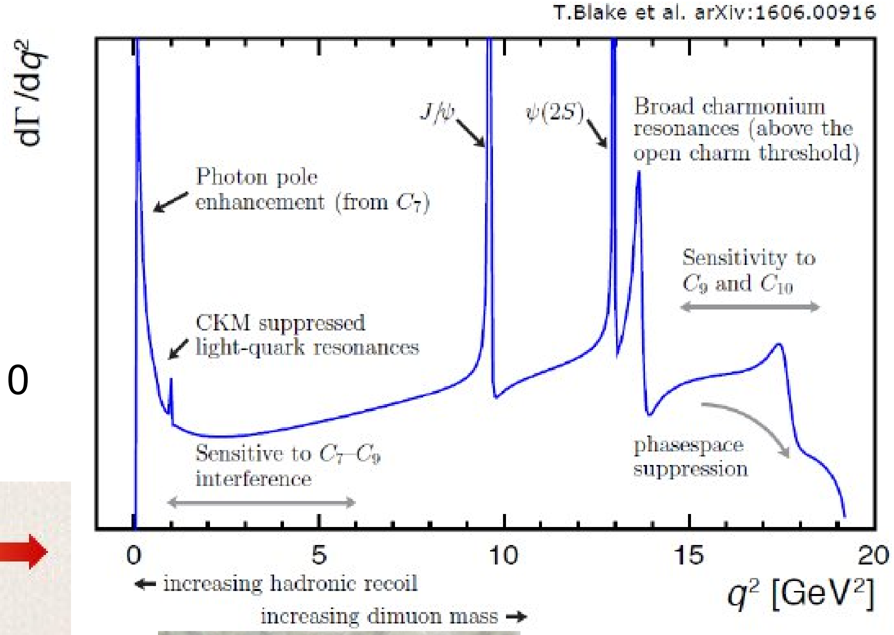
Local operator ($\mathcal{O}_i$)

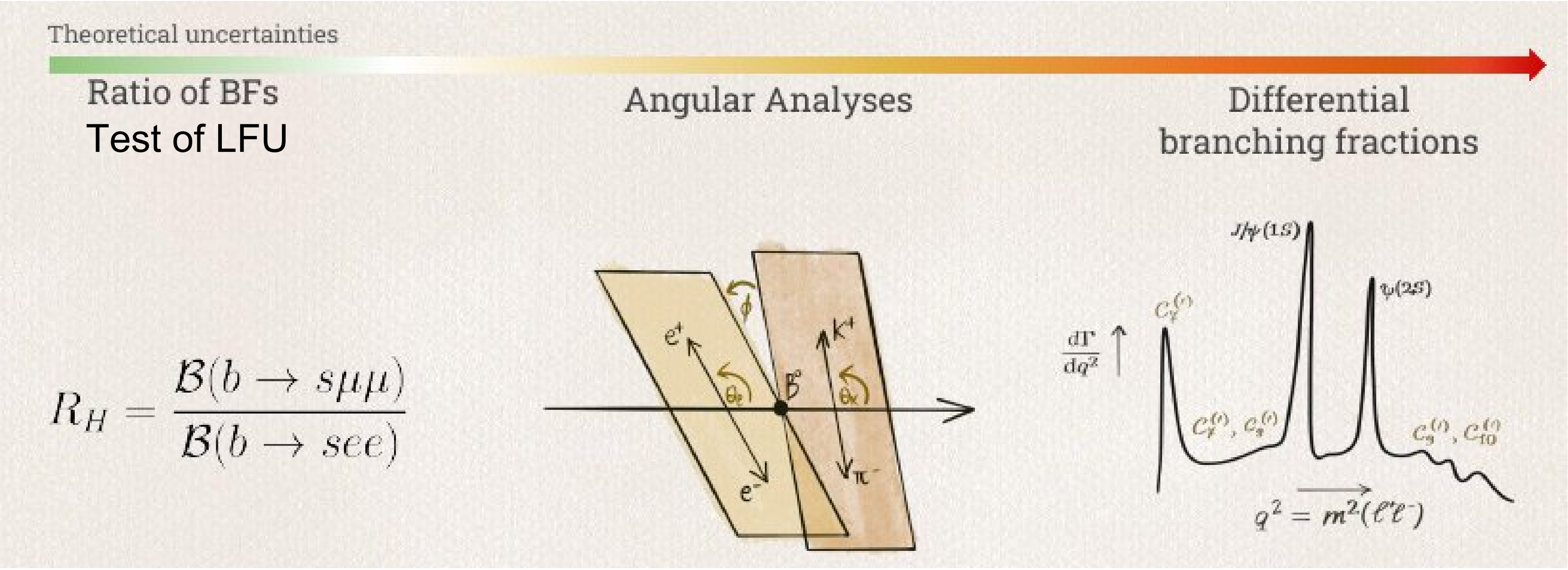
Wilson coefficient ("effective coupling") ($\mathcal{C}_i$)

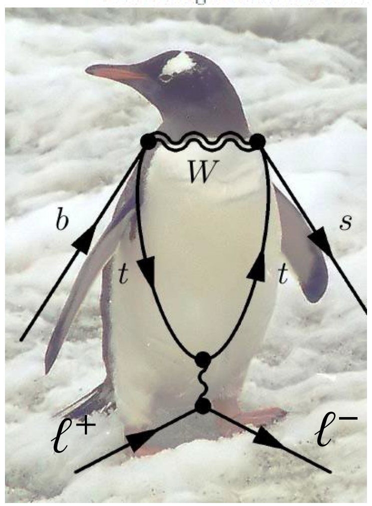
Observables in FCNC $b \to s\ell\ell$ decays



Physics depends on $q^2 = m^2_{ll}$:
- Resonances (e.g. J/ψ, ϕ)
- Photon pole at low q^2: C_7
- Vector or axial vector current: $C_{9,10}$



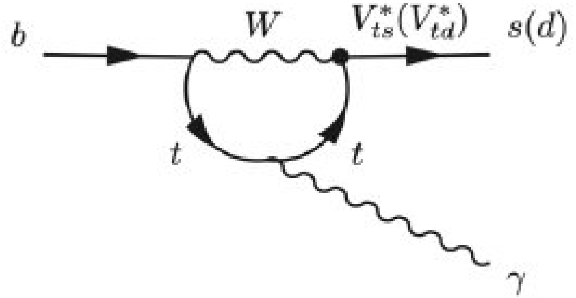


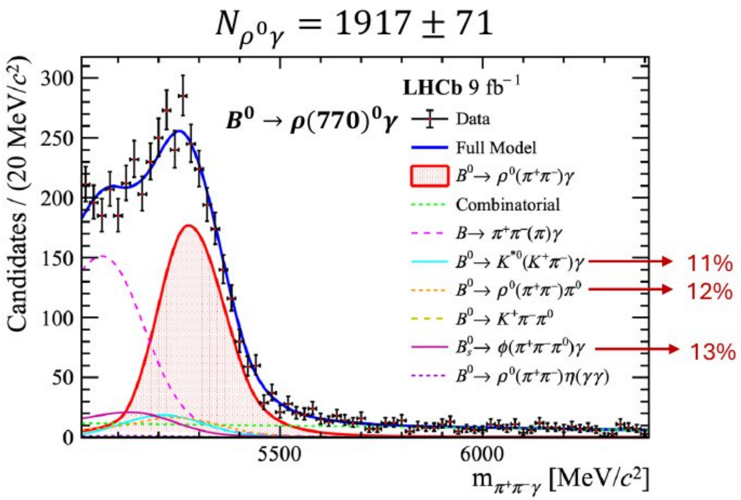


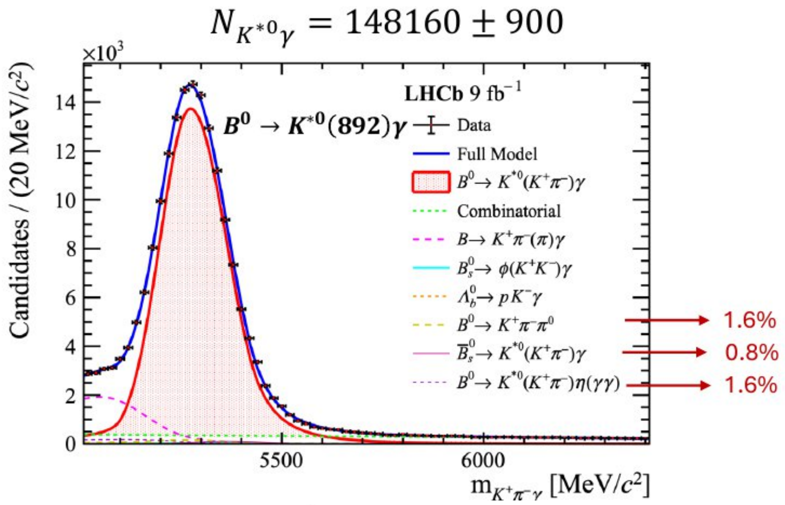
Radiative $B^0 \to \rho^0(770)\gamma$ decays

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

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





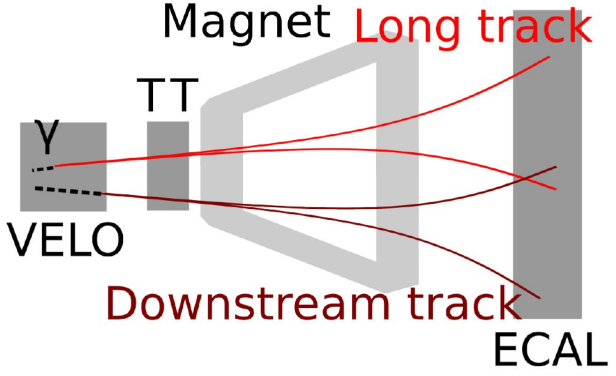


$$\frac{\mathcal{B}(B^0 \to \rho(770)^0\gamma)}{\mathcal{B}(B^0 \to K^*(892)^0\gamma)} = 0.0189 \pm 0.0007 \pm 0.0005,$$
(stat.) (sys.)

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

Most precise measurement to date

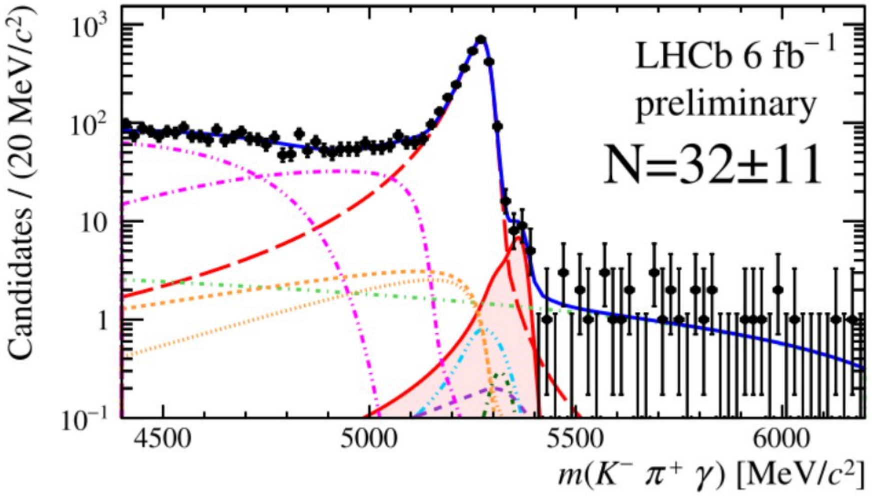
First evidence of $B_s^0 \to K^- \pi^+ \gamma$



- Using full 9 fb^{-1} Runs1-2 data
- Normalization channel $B^0 \to K^{*0}\gamma$
- Using photons converting to e^+e^-
  - Long & downstream tracks
- Observing 38 ± 18 signals with 3.5σ significance
- BF results in good agreement with SM predictions:

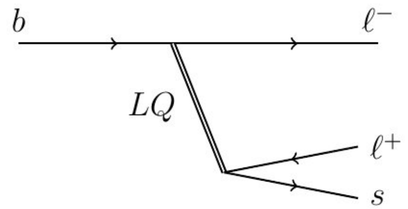
$$\frac{\mathcal{B}(B_s^0 \to K^-\pi^+\gamma)}{\mathcal{B}(\overline{B}^0 \to K^-\pi^+\gamma)} = (3.7 \pm 1.2 \pm 0.4) \times 10^{-2} \quad \text{(stat., sys.)}$$
$$\text{for} \quad 796 < \mathrm{m}(K^-\pi^+) < 996\,\mathrm{MeV}/c^2$$

$$\frac{\mathcal{B}(B_s^0 \to K^-\pi^+\gamma)}{\mathcal{B}(\overline{B}^0 \to K^-\pi^+\gamma)} = (0.2 \pm 2.7 \pm 1.3) \times 10^{-2}$$
$$\text{for} \quad 996 < \mathrm{m}(K^-\pi^+) < 1800\,\mathrm{MeV}/c^2$$

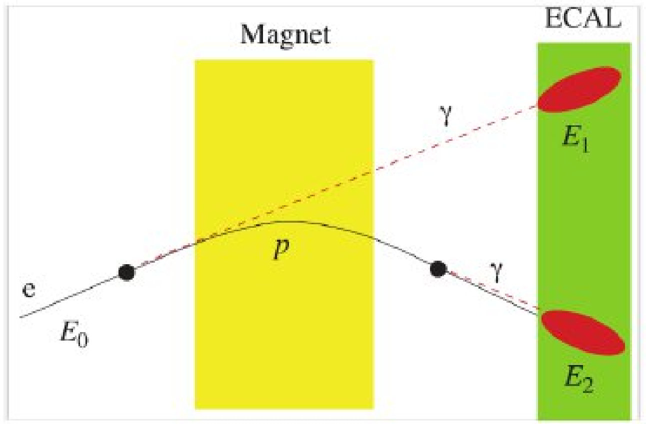


Run2 Downstream low-m(Kπ)
Better resolution due to less bremsstrahlung

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



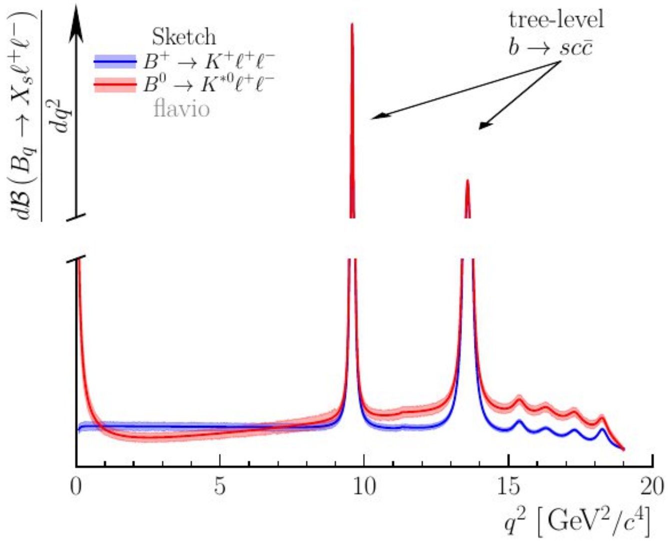
- Electrons & muons behave quite differently in the LHCb detector
- Lower efficiencies & worse resolution (energy loss) for electrons



- Double-ratio of branching fractions:

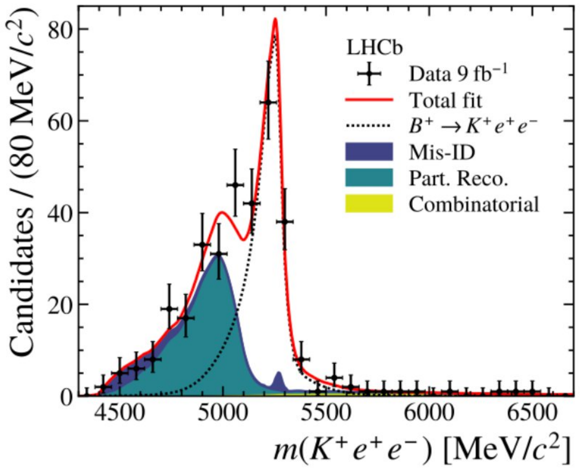
$$R_X = \frac{\mathcal{B}\left(B_q \to X_s \mu^+ \mu^-\right)}{\mathcal{B}\left(B_q \to X_s J/\psi(\mu^+ \mu^-)\right)} \cdot \frac{\mathcal{B}\left(B_q \to X_s J/\psi(e^+ e^-)\right)}{\mathcal{B}\left(B_q \to X_s e^+ e^-\right)}$$

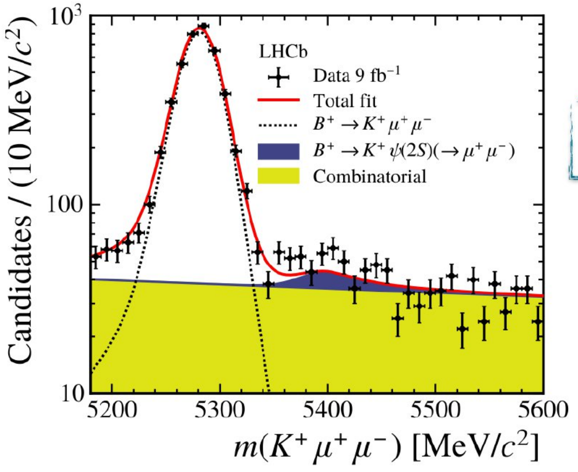
  - Most of systematic uncertainties cancel to 1st order
  - LFU in $J/\psi \to l^+ l^-$ well established at ‰ level [BESIII, PRD 88, 032007 (2013)]
  - Validated in ψ(2S) mode



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



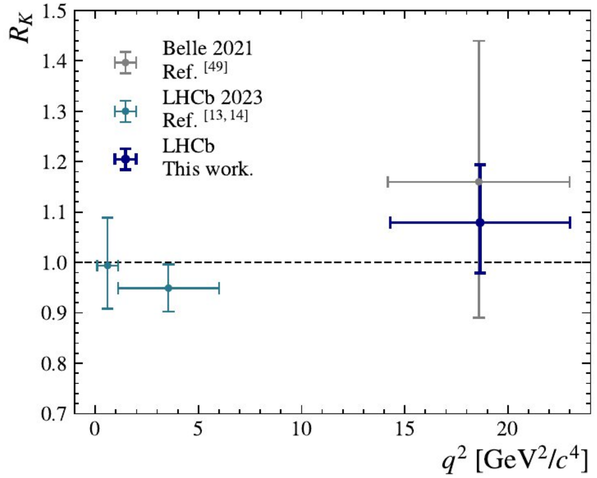


$N(K^+\mu^+\mu^-) = 4008 \pm 71$

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

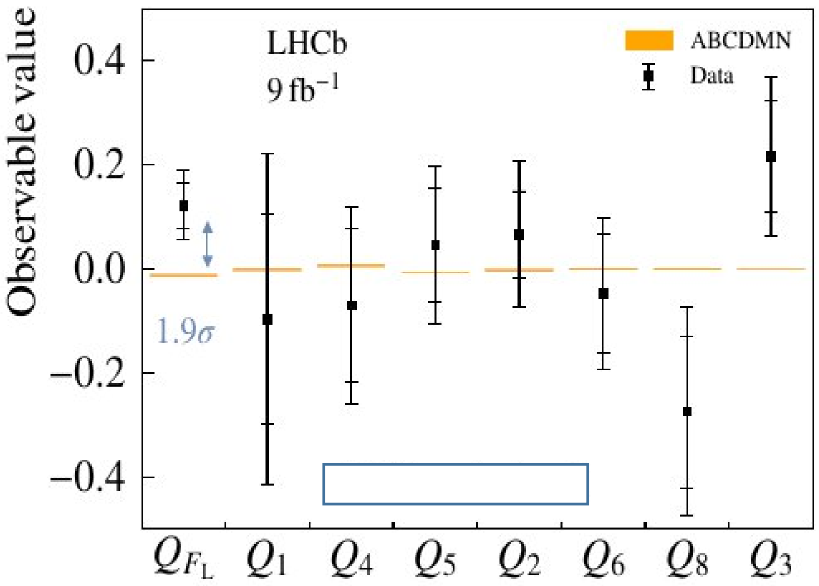


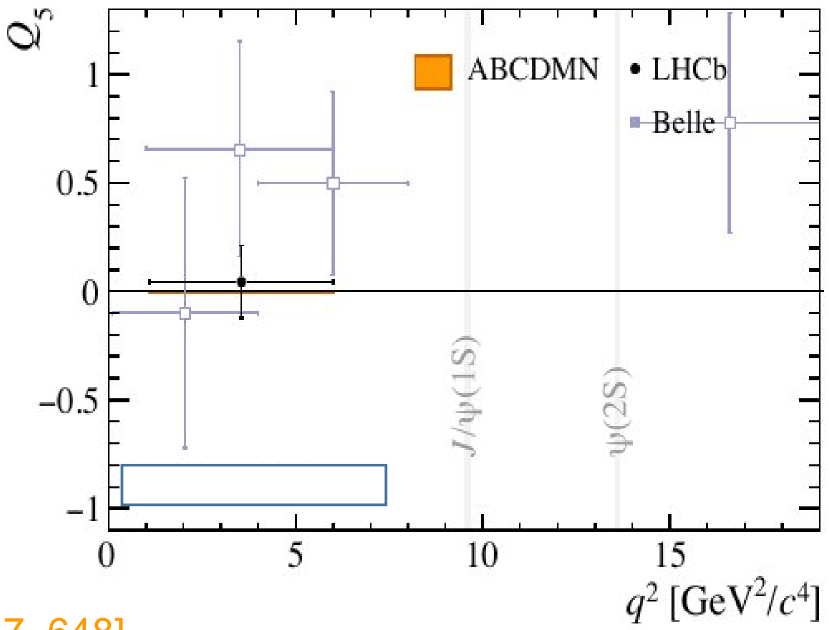
$$R_K = \frac{N(K^+\mu^+\mu^-)}{N(K^+e^+e^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{1}{r_{J/\psi}}$$

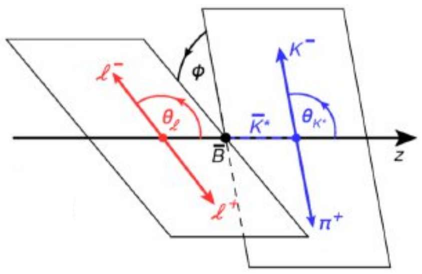
LFU in angular analysis of $B \to K^{*0} e^+ e^-$

- 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]

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







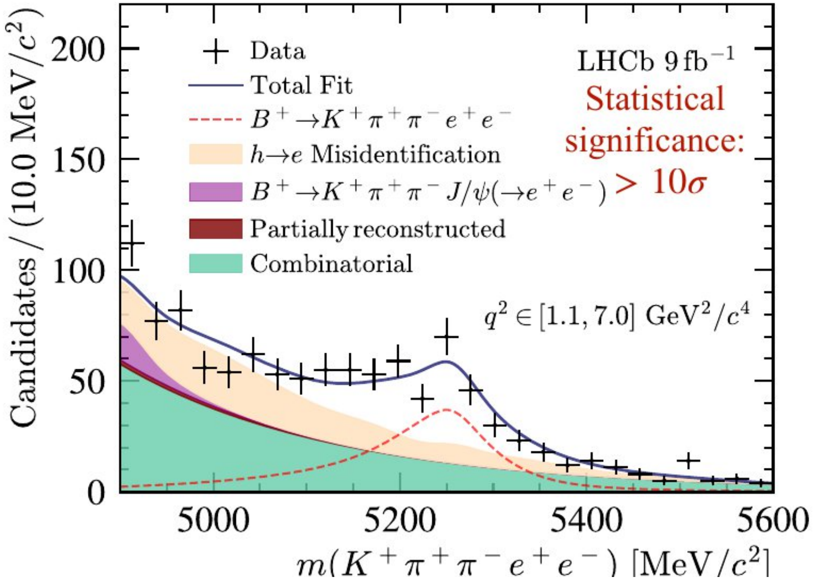
Results are all consistent with LFU conservation hypothesis

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

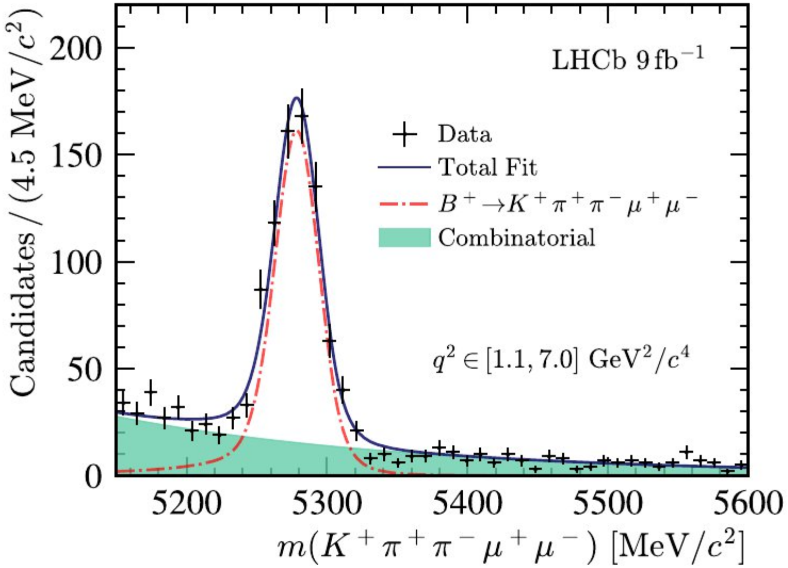
R($K\pi\pi$): LFU in $B \to K\pi\pi l^+ l^-$

- 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: $r_{J/\psi} = 1.033 \pm 0.017, R_{\psi(2S)} = 1.040 \pm 0.030$

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



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



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

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

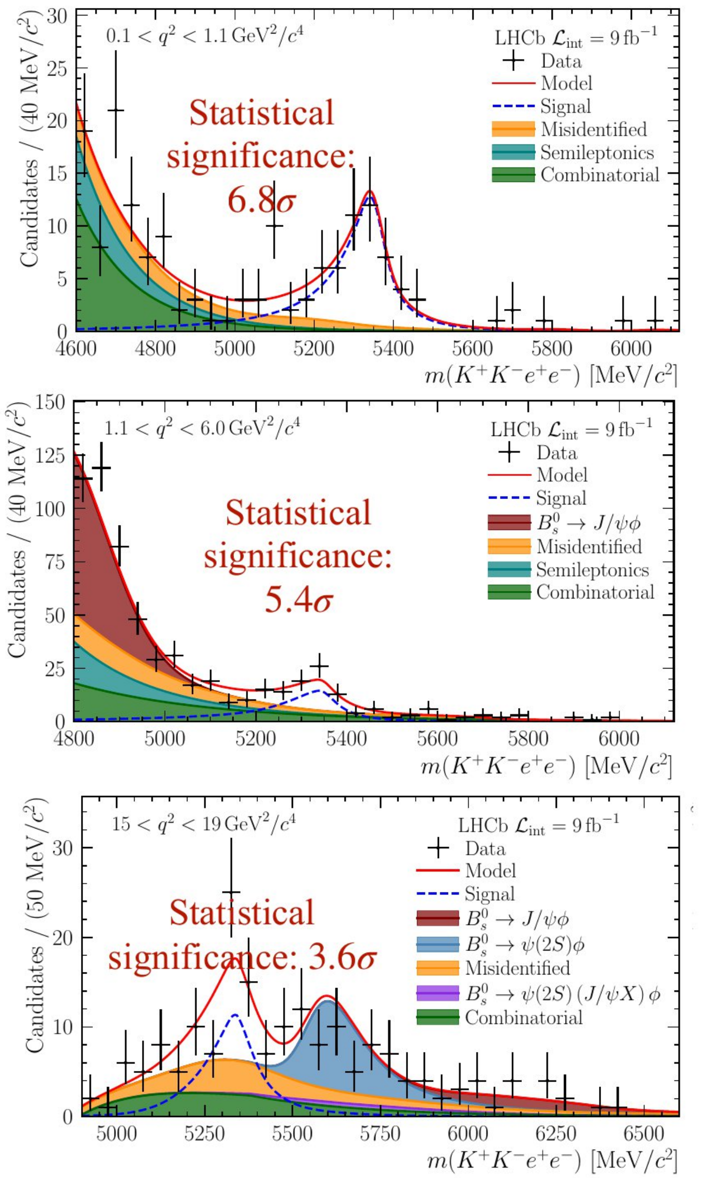
- Compatible with the SM

R(ϕ): LFU in $B_s^0 \to \phi l^+ l^-$

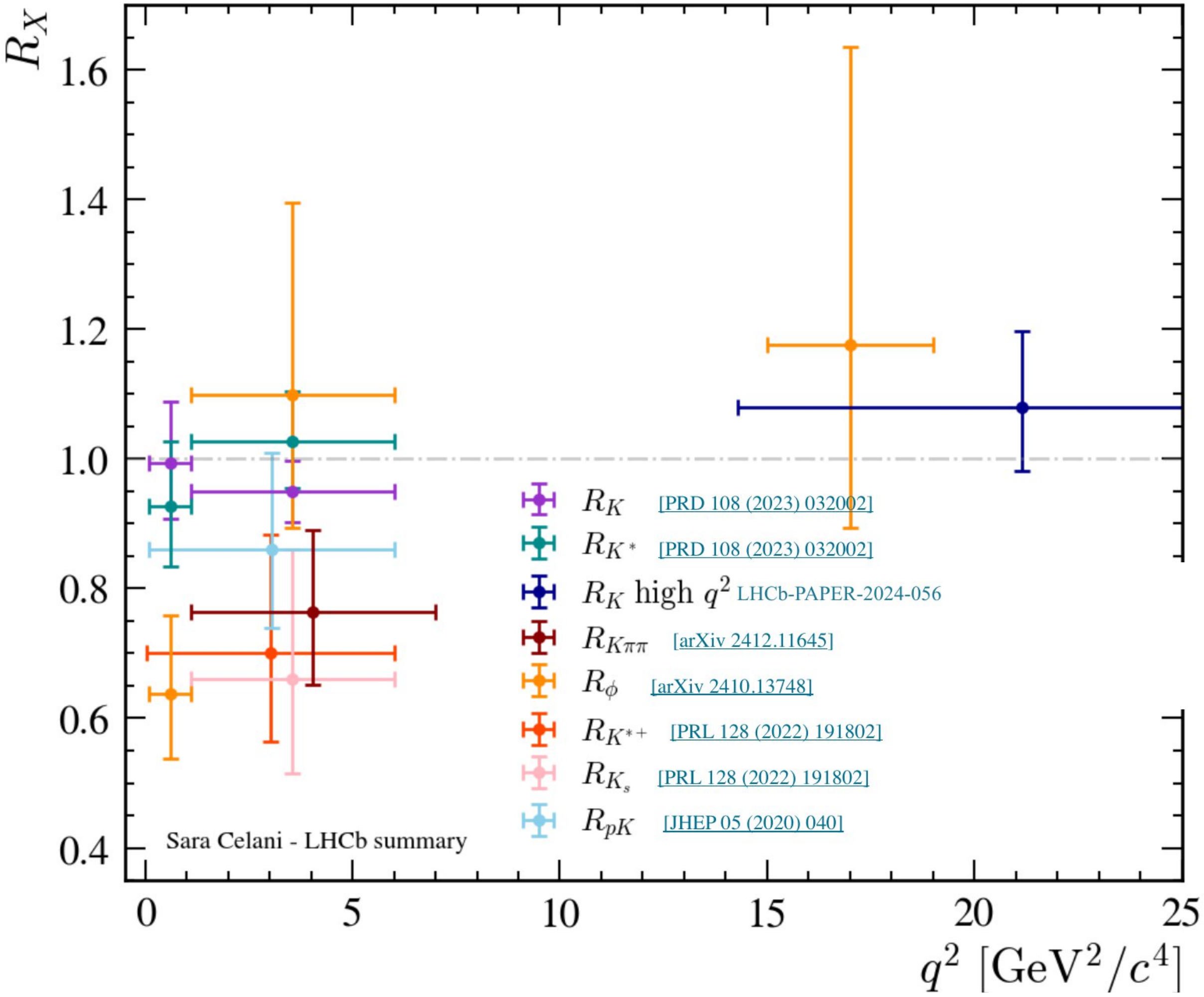
- First LFU test for B_s^0 decays
- In three q^2 regions: [0.1, 1.1], [1.1, 6.0], [15, 19] GeV^2
- Cross-checks: $r_{J/\psi} = 0.997 \pm 0.013, R_{\psi(2S)} = 1.010 \pm 0.026$
- Results in agreement with SM:

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

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



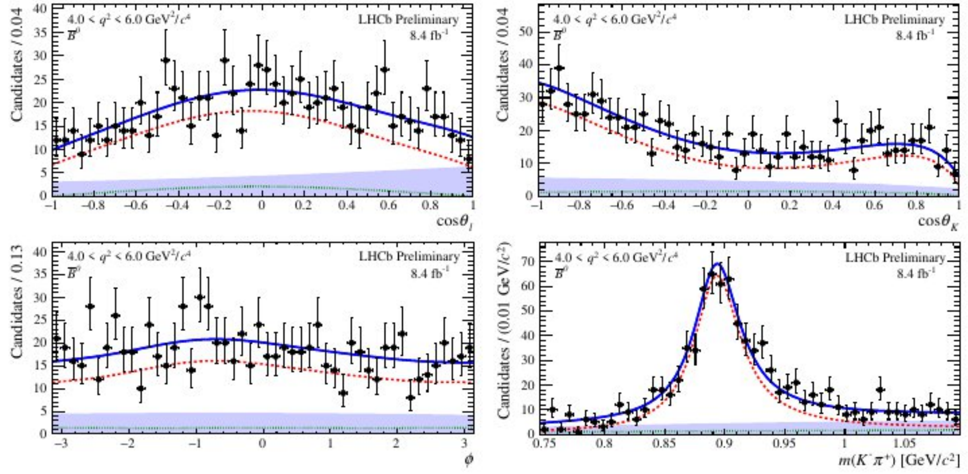
Summary of LHCb FCNC LFU results



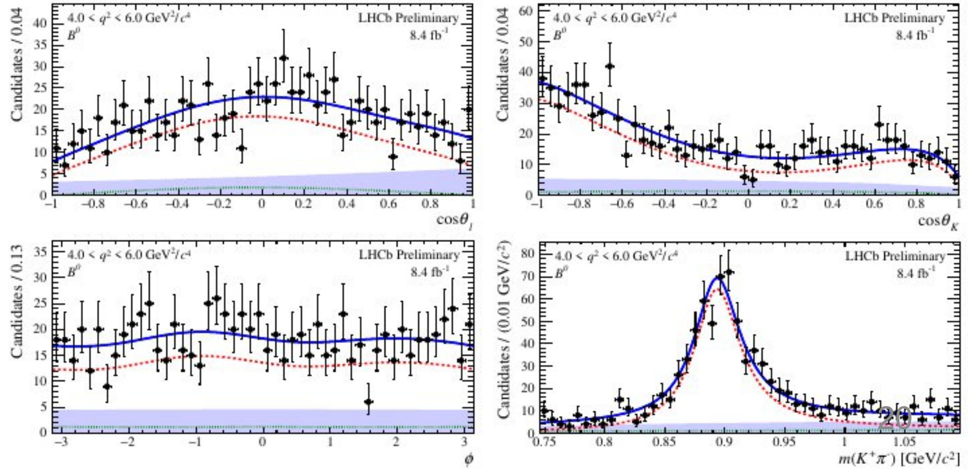
Legacy Runs1-2 $B^0 \to K^{*0}\mu^+\mu^-$ measurement

- 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 ~1 GeV^2
  - Lepton mass accounted for
  - Full suite of S-wave and P-/S-wave interference observables
  - 2x statistics: ~12k signals
  - Data split into B^0 and $\overline{B}^0$, and fit simultaneously

$\overline{B}^0$:

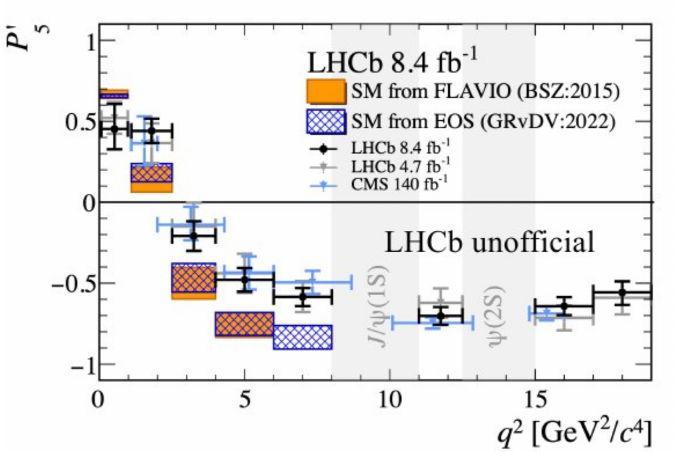


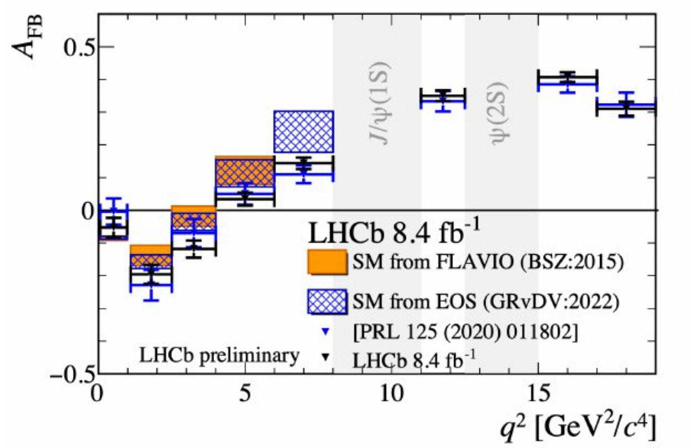
B^0:

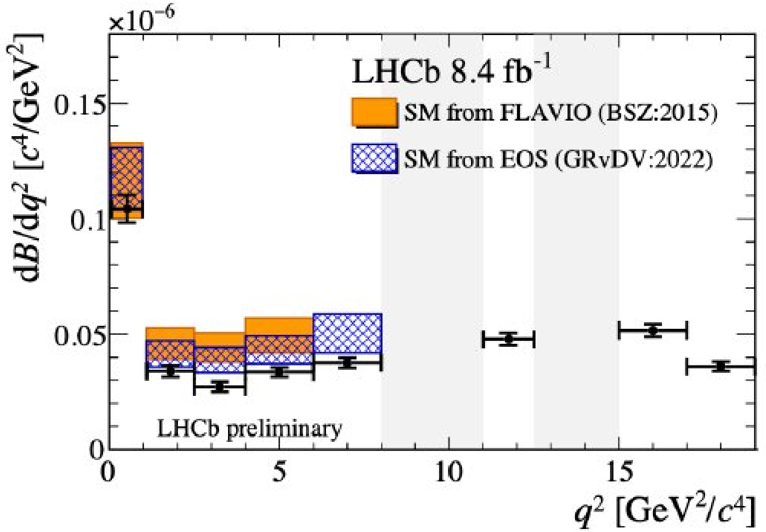


LHCb-PAPER-2025-041
In prep.

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



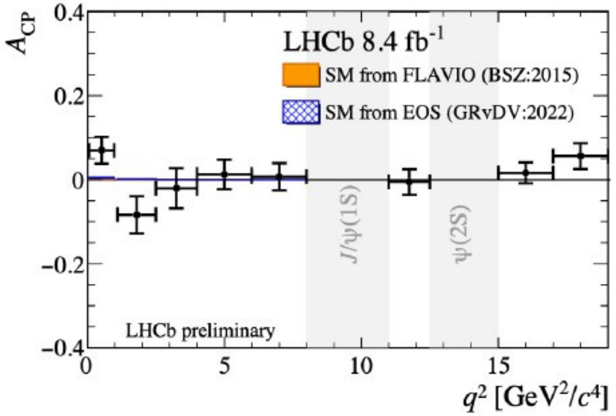


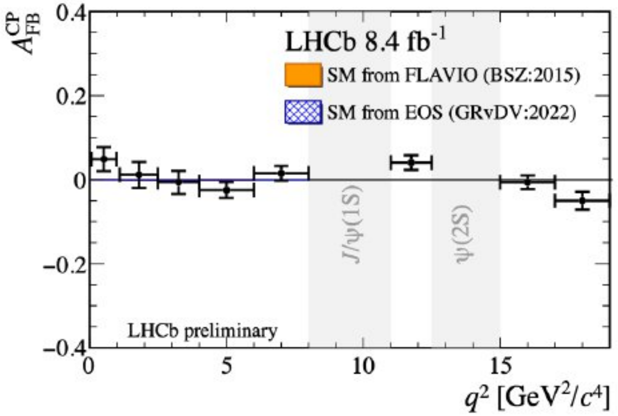


- Results in P'_5 excellent agreement with both CMS and previous LHCb
- Deviations of 2.6 and 2.7 σ in 4-6 and 6-8 GeV^2 bins

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

- The branching fraction is consistently below SM predictions

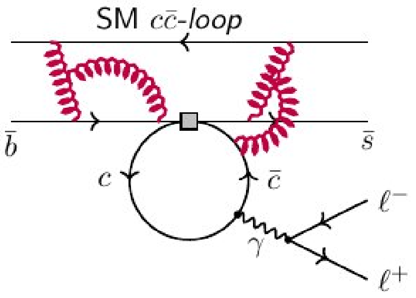


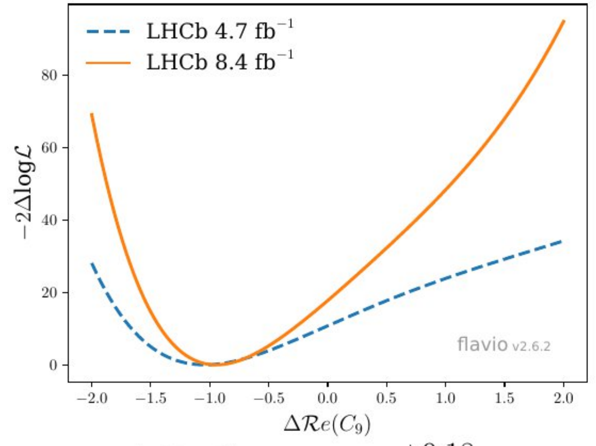


LHCb-PAPER-2025-041
In prep.

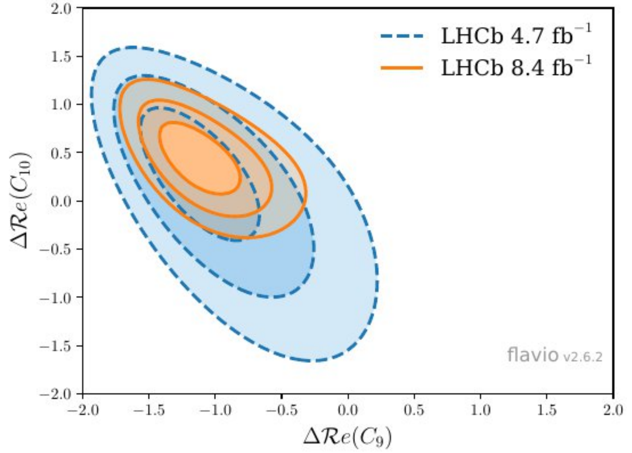
Legacy Runs1-2 $B^0 \to K^{*0}\mu^+\mu^-$ measurement

- Interpretation in terms of Wilson coefficients, by combining angular observables and BFs up to 8 GeV^2
- Alternative theory packages with different approaches on (non-local) FFs, with consistent results
- Tension most pronounced in Re(C_9), with shifts consistent across q^2 bins
- NP or underestimated hadronic (charm-loop) contributions?



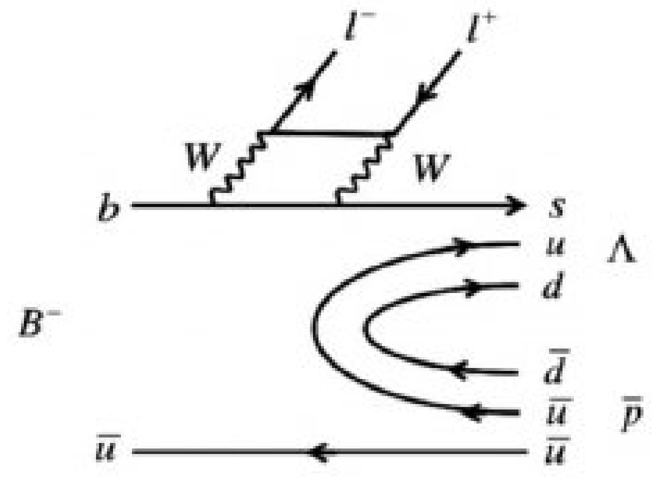


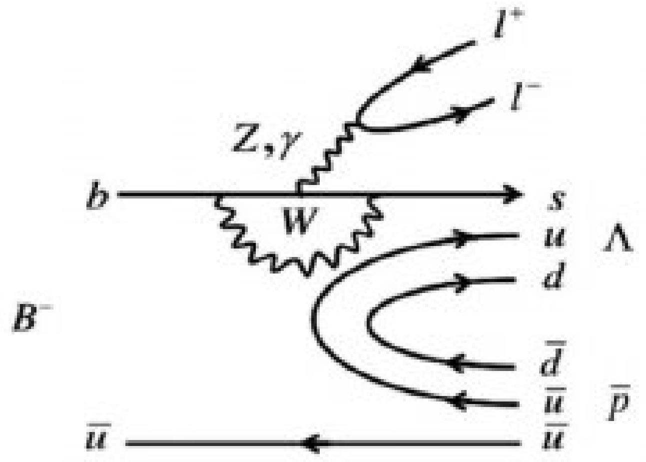
$\Delta\mathcal{R}eC_9 = -0.93^{+0.18}_{-0.16}$
Significance $4.1\,\sigma$



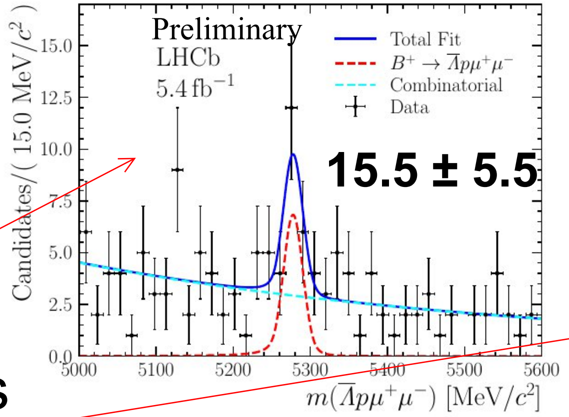
First evidence of $B^+ \to \overline{\Lambda} p \mu^+ \mu^-$

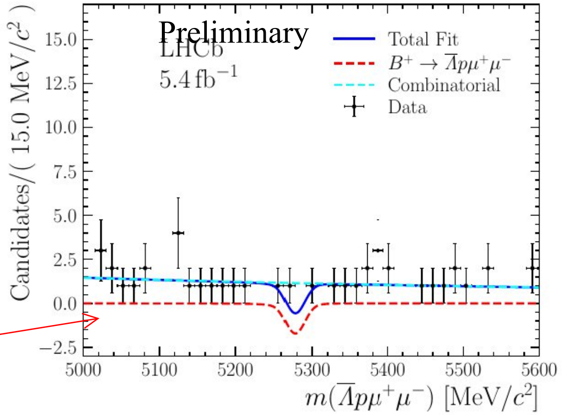
- Mediated via $b \to s\mu^+\mu^-$, baryonic final state less explored to mesonic counterparts
  - Phenomenology of hadronization
  - Rich dynamics in hadronic system
  - Clean access to exotic states such as X(2085)
- Threshold enhancement effects in $\overline{\Lambda} p$ system observed in other mutibody decays, e.g. $B^+ \to \overline{\Lambda} p \pi^+ \pi^-$ [link] and $B \to \overline{\Lambda} pKK$ [link]
- SM based BF prediction at ~1.08×10^{-7} [link]
- Expecting significantly lower BF if FFs from a more recent paper [link] are used instead



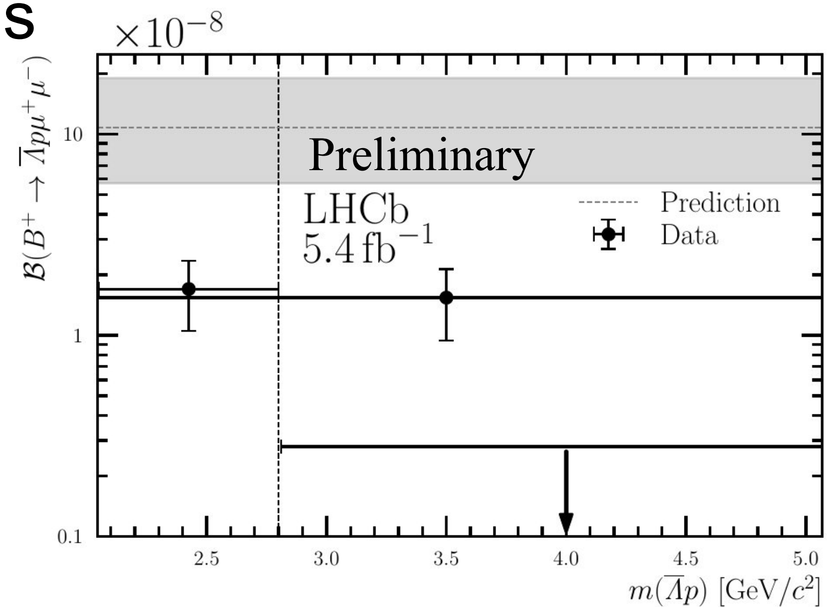


First evidence of $B^+ \to \overline{\Lambda} p \mu^+ \mu^-$





- Using 5.4 fb^{-1} Run2 data
- Normalization channel: $B^+ \to J/\psi\, \overline{\Lambda} p$
  - Also used for signal shape calibration & correction for data/simulation differences
- Signal searched for in low & high $m(\overline{\Lambda} p)$ regions



- Evidence for the decay found in the $m(\overline{\Lambda} p) < 2.8$ GeV region with significance of 3.5σ
- The total branching fraction is measured:

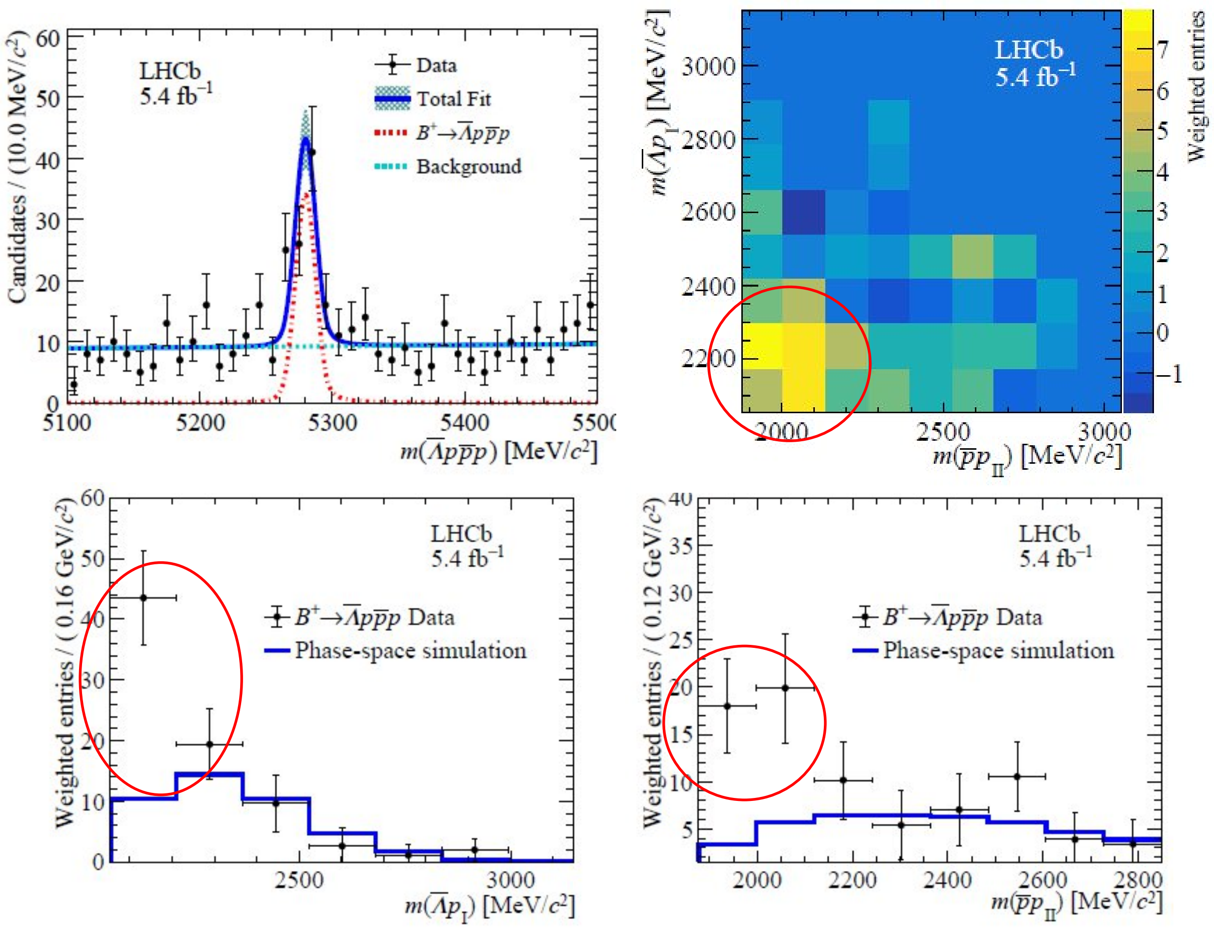
$$\mathcal{B}(B^+ \to \overline{\Lambda} p \mu^+ \mu^-) = (1.54 \pm 0.65_{\text{stat}} \pm 0.18_{\text{syst}} \pm 0.13_{\text{ext}}) \times 10^{-8}$$

arXiv:2508.16259
Accepted by PRL

First observation & CPV in $B^+ \to \overline{\Lambda} p \bar{p} p$

- Dominated by $b \to s$ transition, sensitive to NP
- Using Run2 5.4 fb^{-1} data
- First observation with BF measured:
  - $\mathcal{B}\left(B^+ \to \overline{\Lambda} p \bar{p} p\right) =$
    $(2.15 \pm 0.35 \pm 0.12 \pm 0.28) \times 10^{-7}$
- Direct CP asymmetry measured:

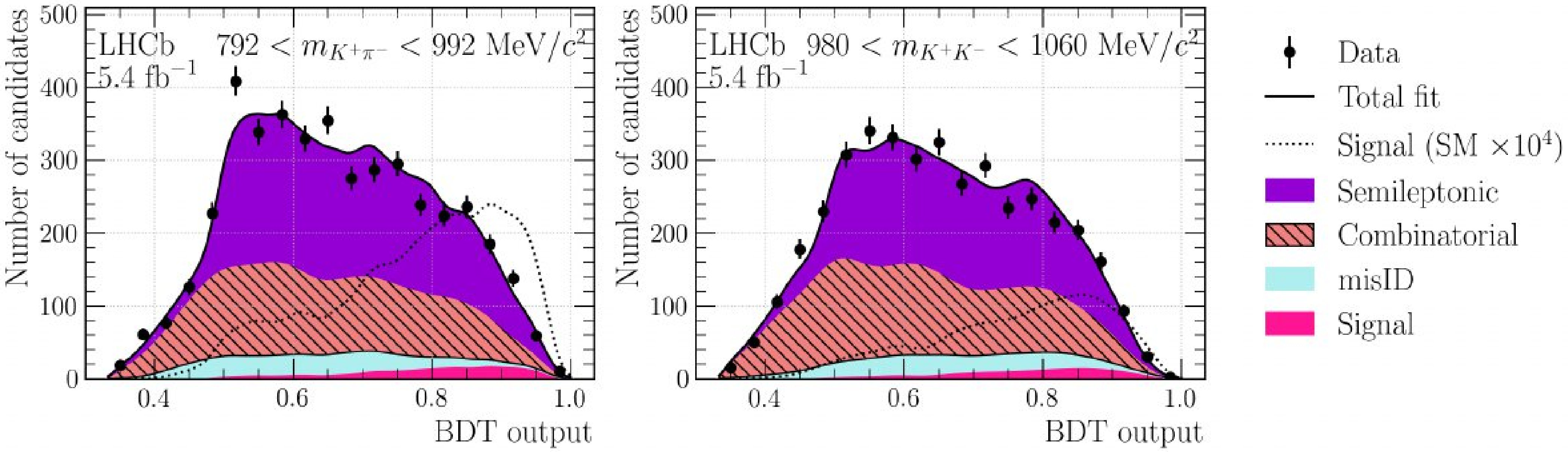
$$\mathcal{A}_{CP} = (5.4 \pm 15.6 \pm 2.4)\%$$



Pronounced enhancements at both kinematic thresholds

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 for in bins of dihadron masses



Searches in the lowest Kπ and KK bins

arXiv:2510.13716

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 for in bins of dihadron masses
- No signal founds, upper limits are set:

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

One order of magnitude improvement!

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

First search!

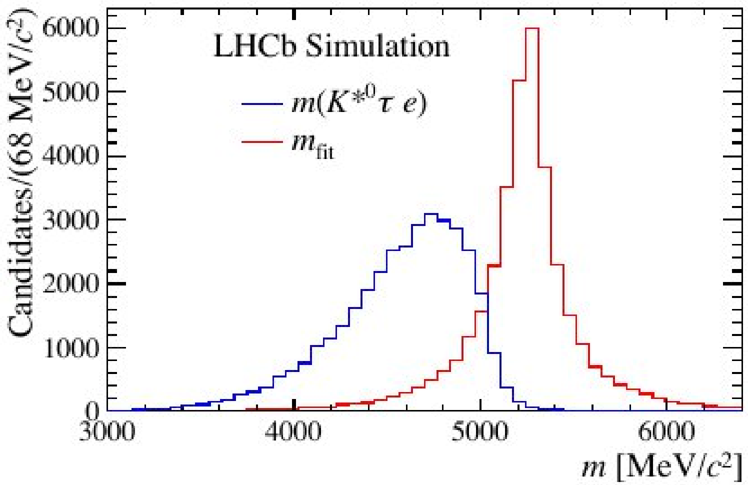
Upper limit on the shift Δ^2in the $\mathcal{C}_{9(10)}^{\tau\tau}$ Wilson coefficient at 90% and 95% CL.

$$\mathcal{C}_{9(10)}^{\tau\tau} = \mathcal{C}_{9(10)}^{\mathrm{NP}} - (+)\Delta$$

Confidence level	$B^0 \to K^+\pi^-\tau^+\tau^-$	$B_s^0 \to K^+K^-\tau^+\tau^-$
90%	2.5×10^4	4.5×10^4
95%	2.9×10^4	5.2×10^4

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

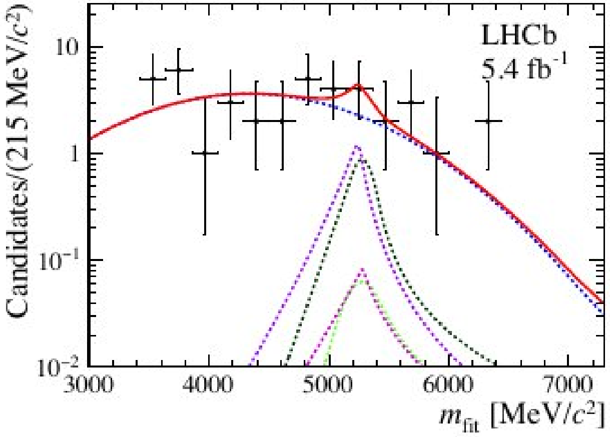
- Lepton Flavour Violating decays would be enabled/enhanced by leptoquarks or Z' models
- New search for the lepton-flavour-violating decays $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$ at LHCb
  - first direct LFV search at LHCb with $e\tau$ combination (Run2 data)
  - New Physics models predict branching ratio 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!



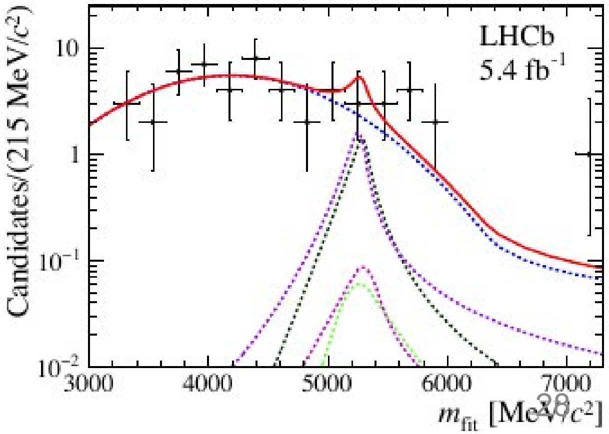
  - $B^0 \to D^- D_s^+$ ($D^- \to K\pi\pi$, $D_s^+ \to KK\pi$) used as normalisation and control channel, and 3 multivariate discriminators to suppress background:
    - topologies of the signal decays and the combinatorial background
    - Isolation (simulation + Same Sign data)
    - Charm vs τ-lepton rejection
  - Limits on two decay channels at 90%(95%) CL:

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

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

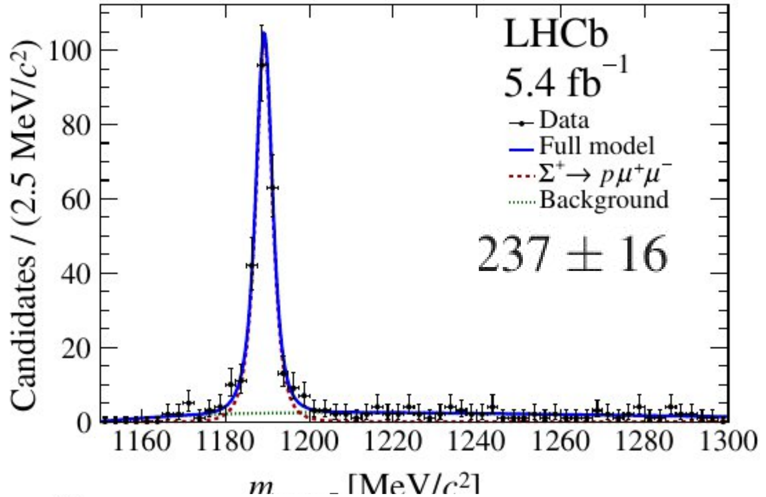


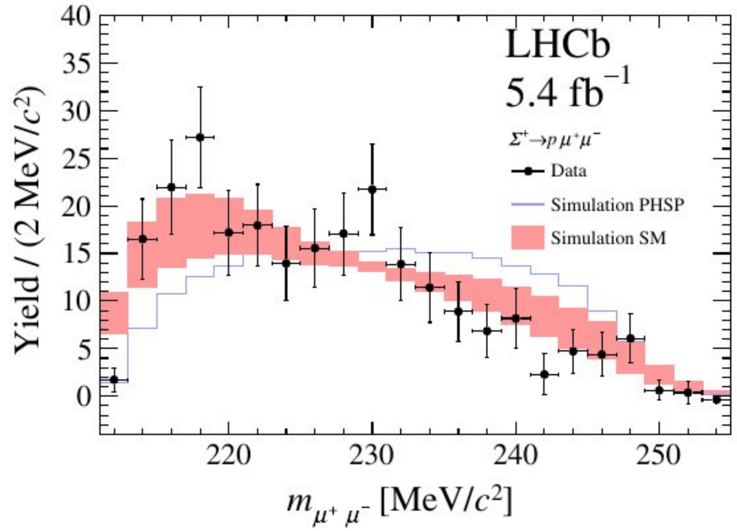
$B^0 \to K^{*0}\tau^+ e^-$



Other rare decays: recent results

- First observation of $\Sigma \to p\mu^+\mu^-$ [PRL 135 (2025) 051801]
    - $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.08 \pm 0.17) \times 10^{-8}$
    - Rarest baryon decay ever observed
    - No structure found in the dimuon mass spectrum, compatible with SM
- Search for $K^0_{S(L)} \to \pi^+\pi^-\mu^+\mu^-$ [arxiv:2511.02619]
- Search for $\eta^{(\prime)} \to (\pi^+\pi^-)\mu^+\mu^-$ [LHCb-CONF-2025-002]
- Search for $\tau \to \mu\mu\mu$ [LHCb-PAPER-2025-052, in prep.]

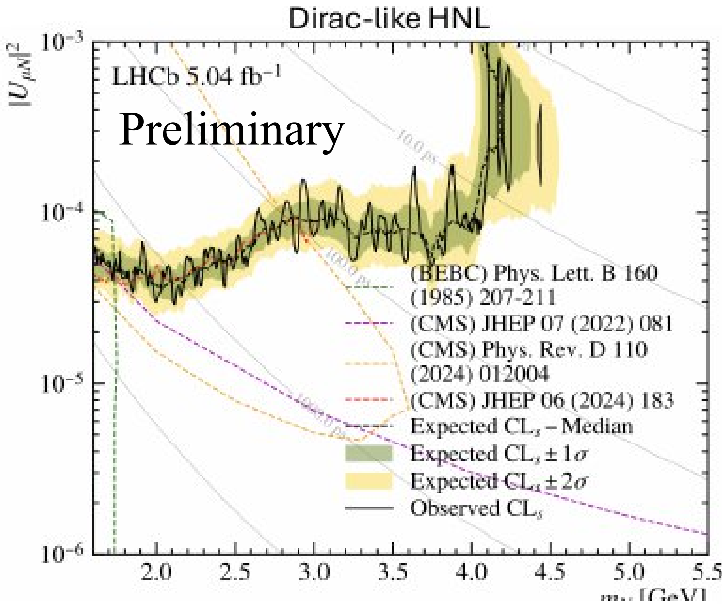


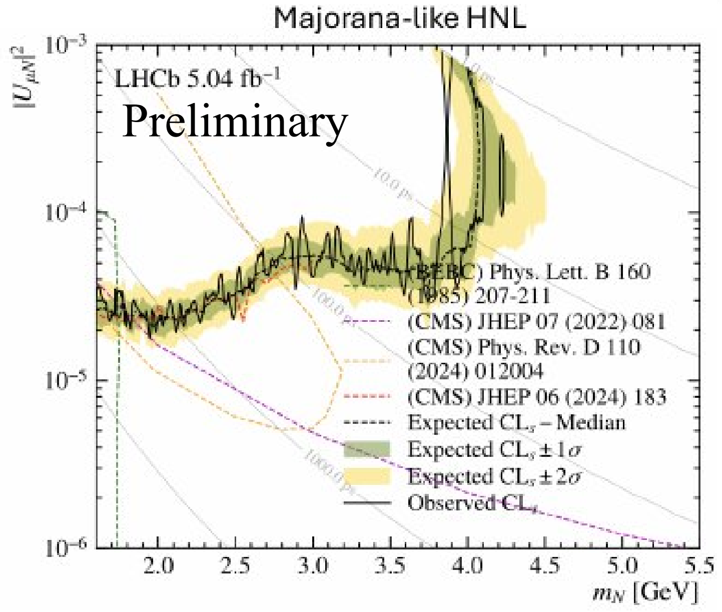


LHCb-PAPER-2025-042
In prep.

Search for HNLs in B decays

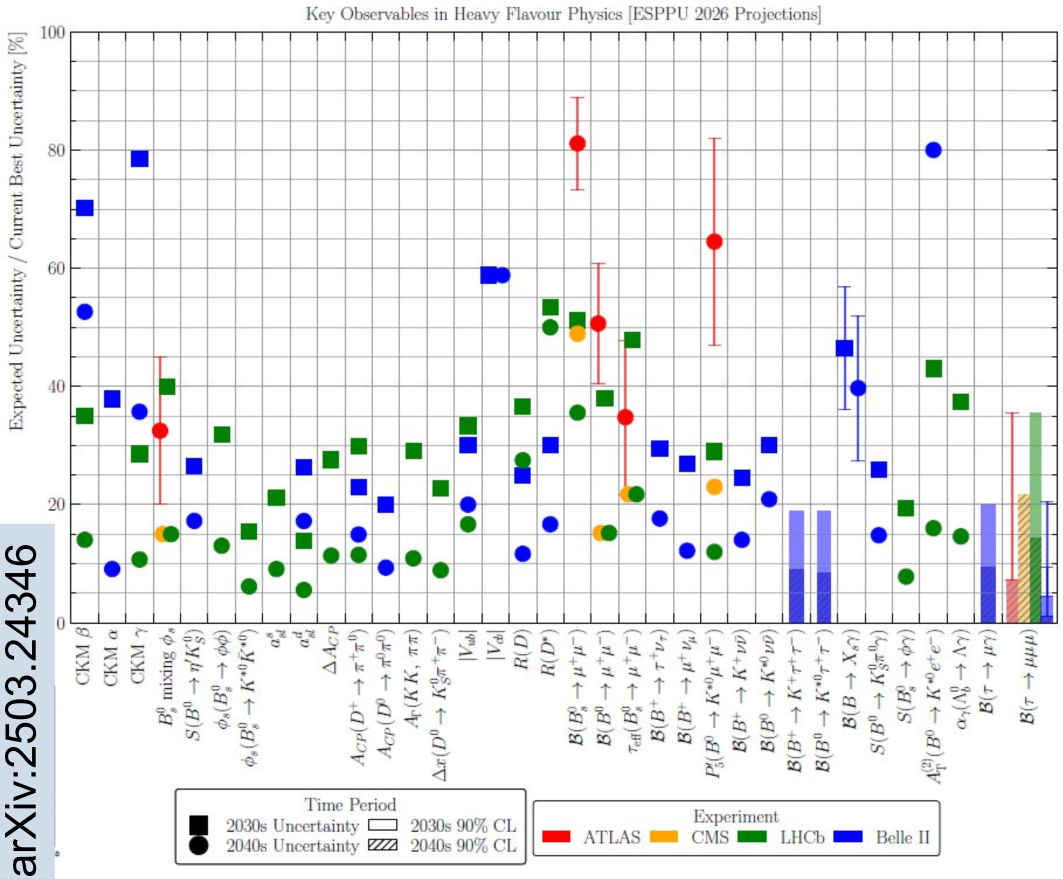
- Heavy Neutral Leptons are right-handed counterparts to SM neutrinos, and interact with SM particles as massive neutrinos
- Production of HNLs between 1.6 and 5.5 GeV largely through (semi-)leptonic B meson decays
- Based on 5.04 fb^{-1} Run2 data, using decay $N \to \mu\pi$
- Global significance of 0.6σ after accounting for look-elsewhere effect
  - Compatible with the no-HNL hypothesis



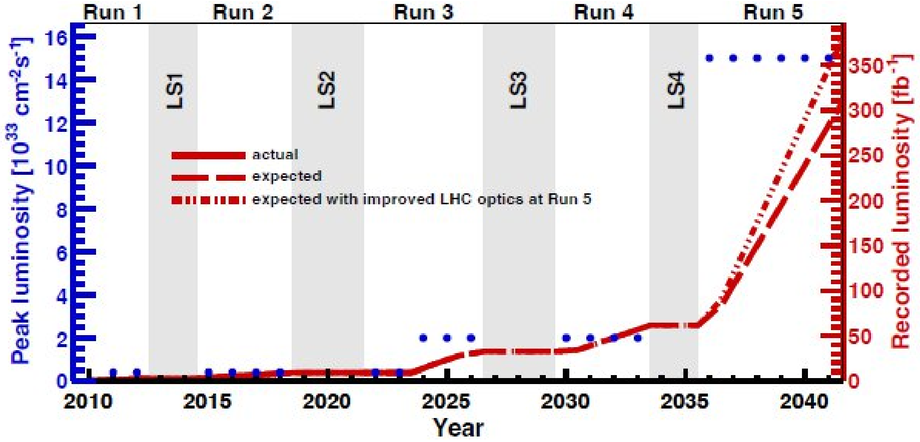


Summary & outlook

- Broad & rich flavor physics programs at LHCb
- Rare decays sensitive to NP effects, with LHCb taking a leading role
- So far, no surprises, but tensions still persist (C_9?)
- Now a new detector and improved hadron trigger: higher efficiency per fb^{-1}
- A huge Run3 data sample available for analysis, while understanding of new detector ongoing [arXiv:2511.16564]
- And we will have Run4 and Upgrade-II!
    - 50 fb^{-1} by 2033, > 300 fb^{-1} by 2041



arXiv:2503.24346

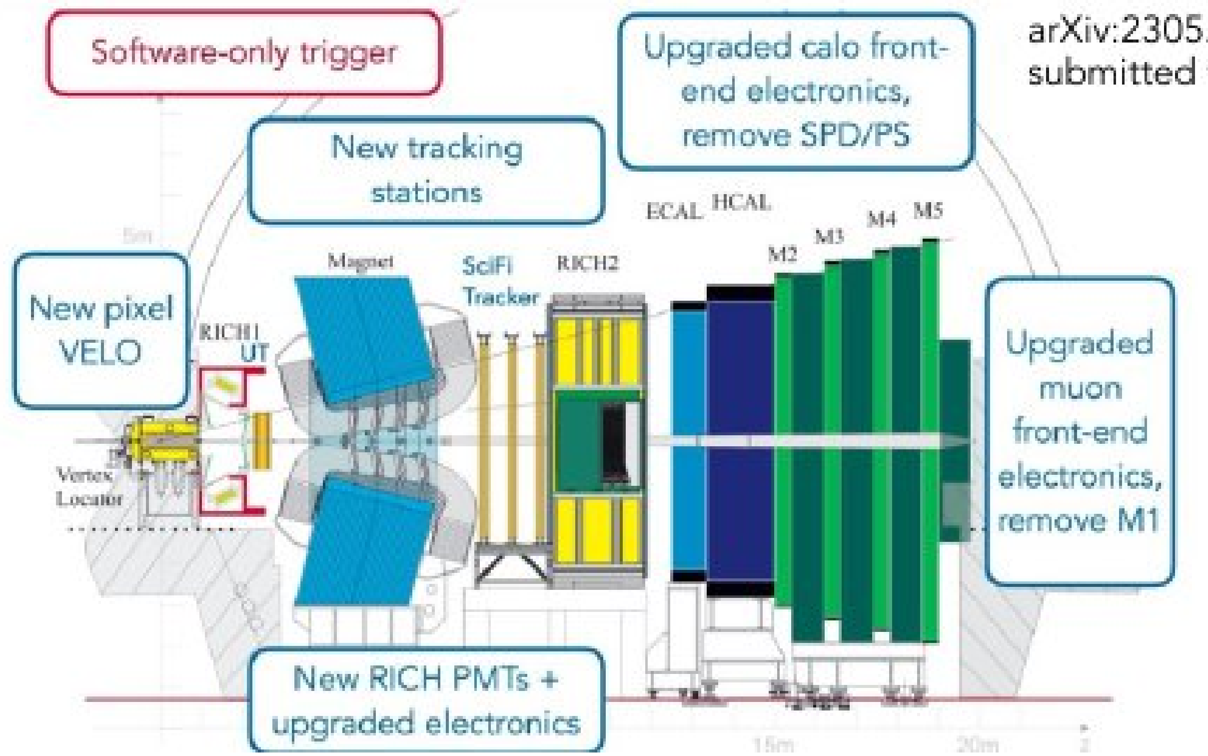


Backup Slides

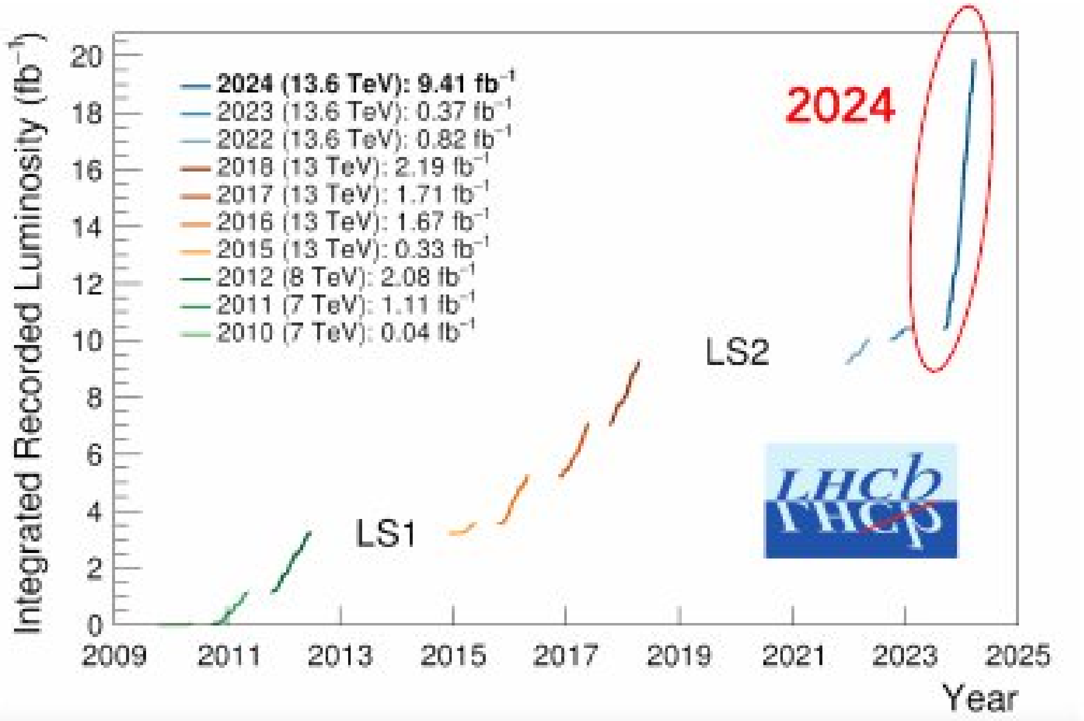
LHCb-Upgrade I

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

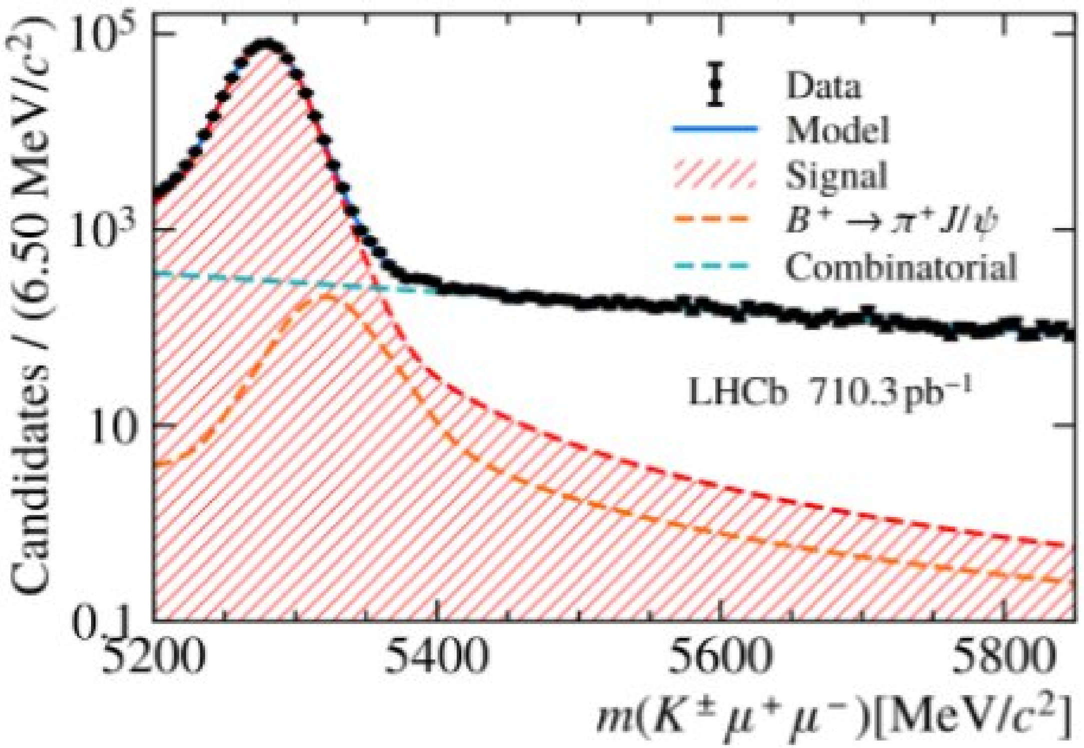


In January 2023, a loss of control of the LHC primary vacuum system
⇒ plastic deformation of the RF foil separating VELO from LHC.
⇒ significant impact on 2023 physics programme

2022 – 2023 : commissioning and understanding the new detector

2024 : a lot of data !

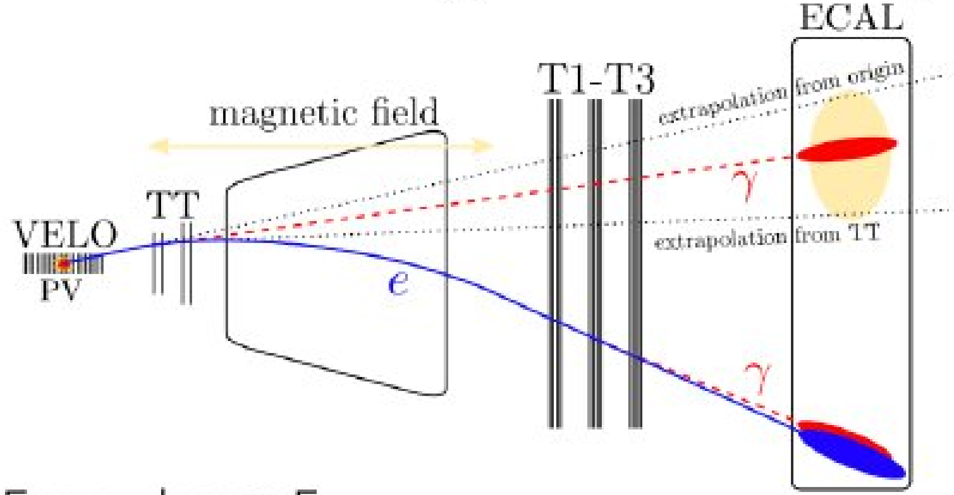
$1\,\mathrm{fb}^{-1}$ collected during October 2024

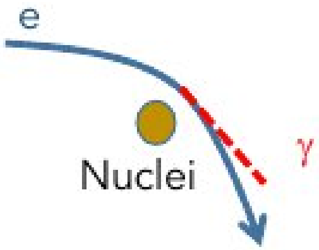


LHCb_TDR_023

Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9,10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29,30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_s^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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"

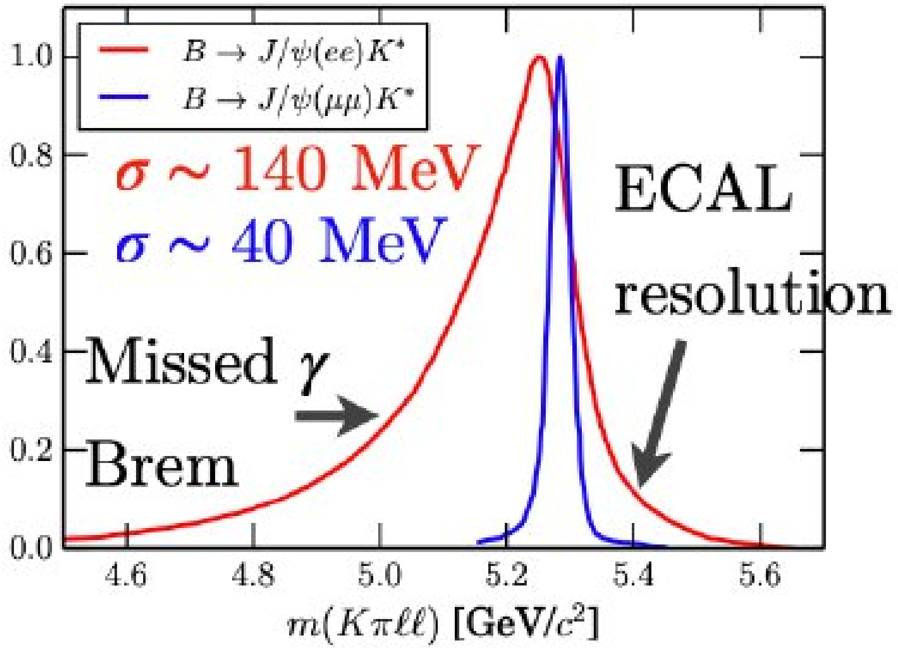
After the magnet

- not an issue

In both cases E/p is correct

Energy loss ∝ E_e
Energy loss ∝ material

⇒ Use of a recovery algorithm

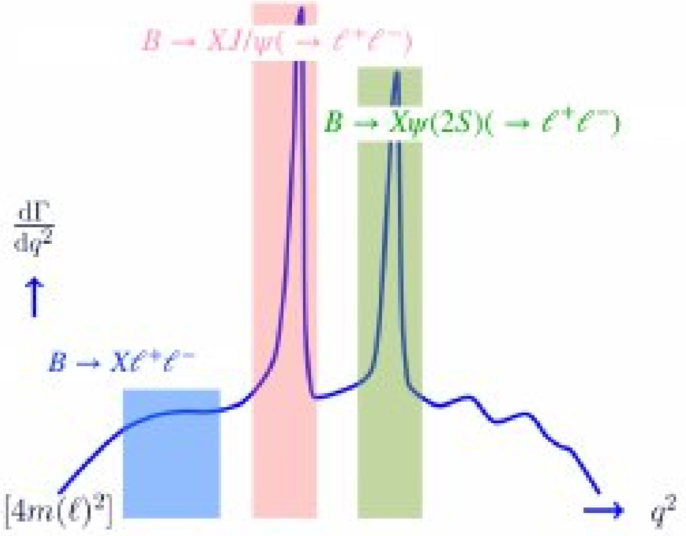


LFU ratio: Experimental strategy

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

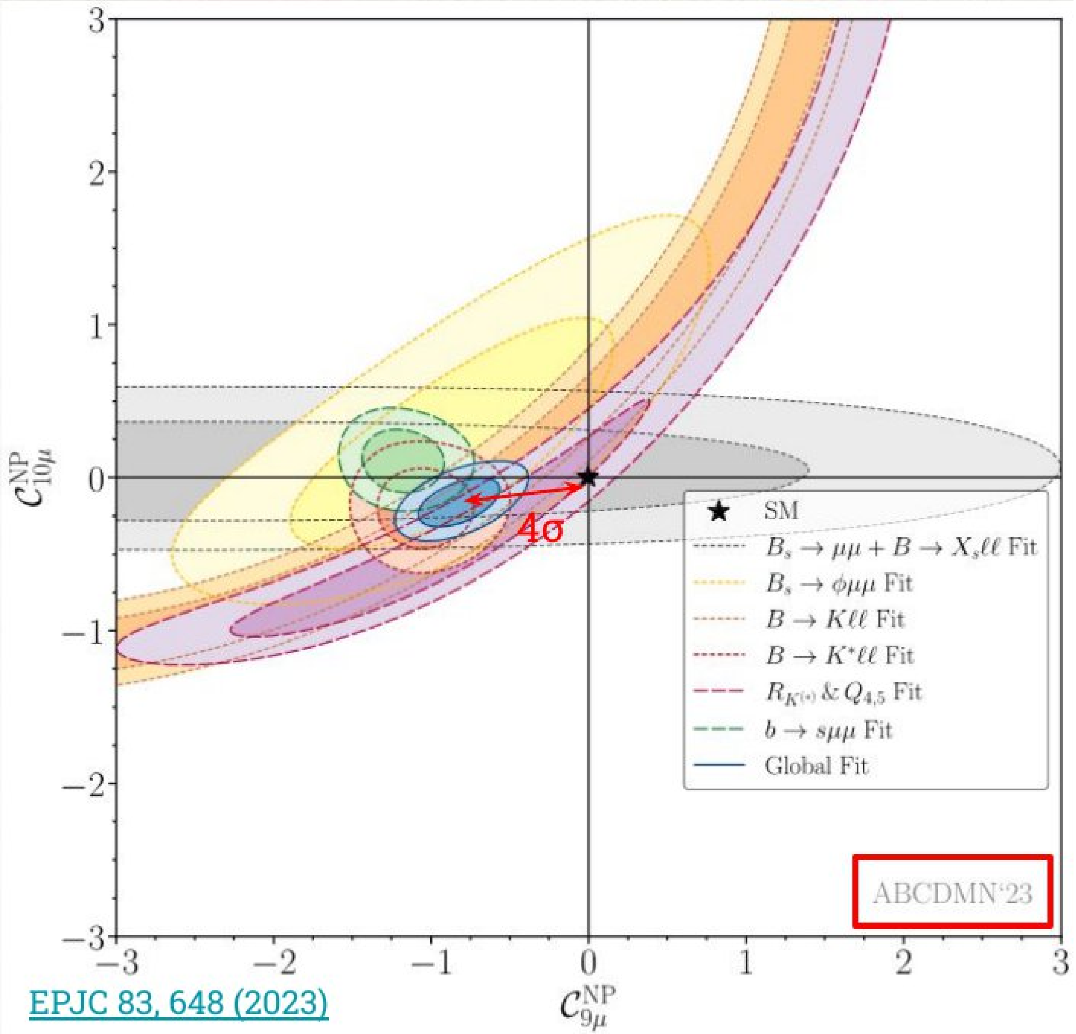
$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to XJ/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to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

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

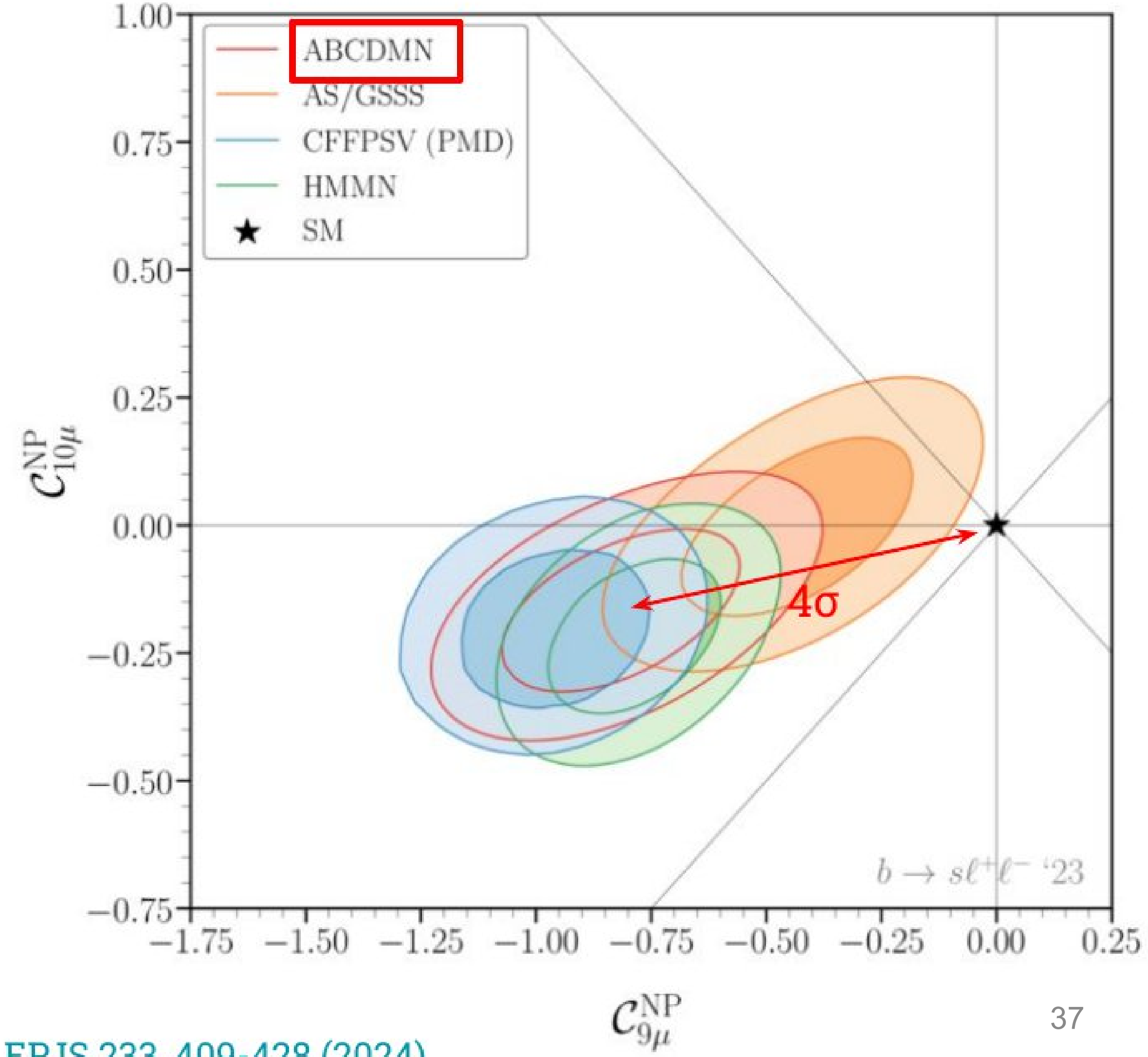


- Resonant channels also used for checks/data driven studies
  - J/ψ and $\psi(2S)$ satisfy LFU, not mediated by $b \to s\ell\ell$
    - $r_{J/\psi} = \frac{\mathcal{B}(B \to XJ/\psi(\to \mu\mu))}{\mathcal{B}(B \to XJ/\psi(\to ee))} \equiv 1$ Sensitive to e, μ differences
    - $R_{\psi(2S)} = \frac{\mathcal{B}(B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

Wilson Coefficients global fits



EPJC 83, 648 (2023)



EPJS 233, 409-428 (2024)