Rare Decays at LHCb: Highlights of Recent Results

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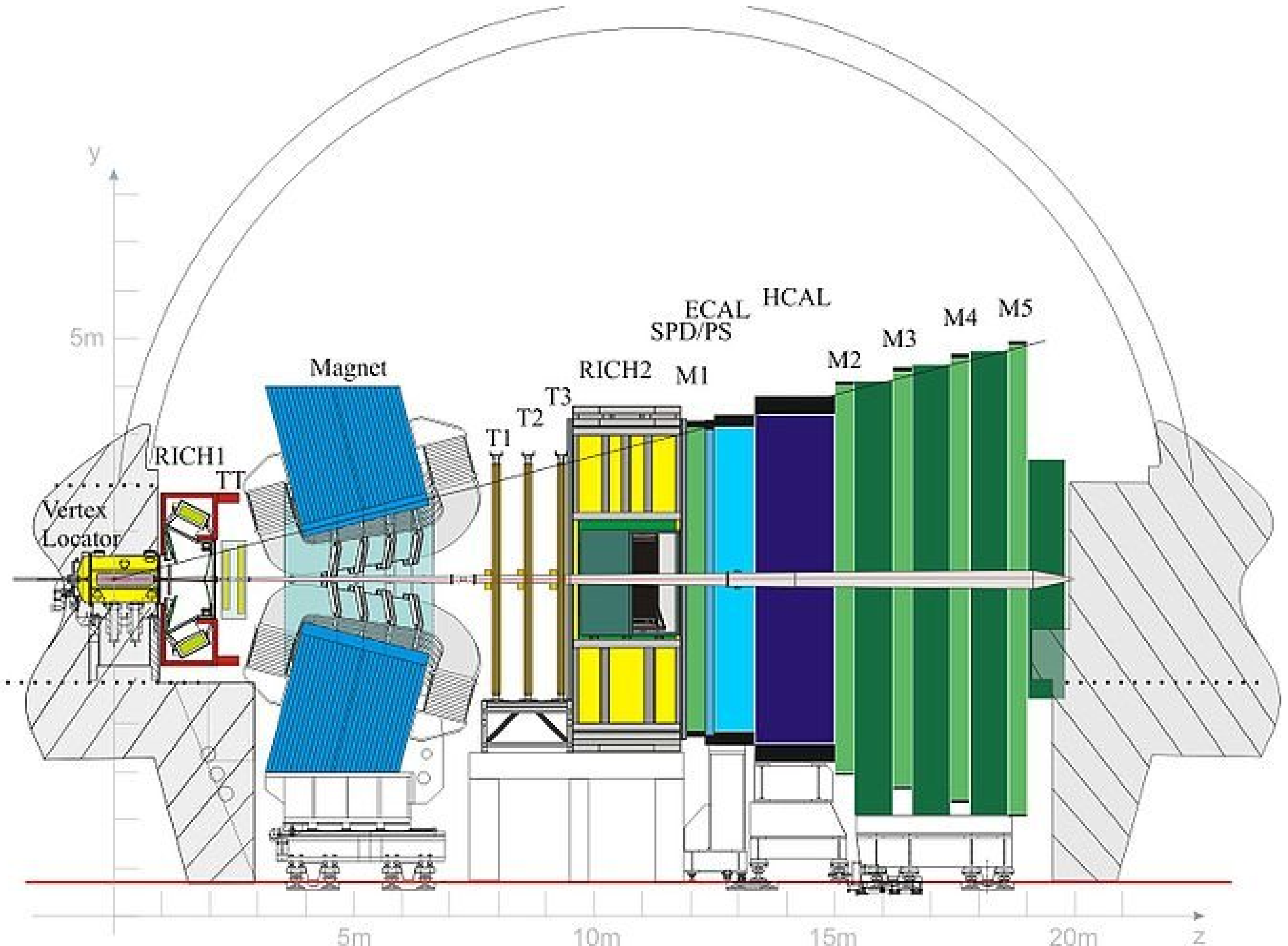
2024/11/09

Outline

- LHCb experiment in Runs 1-2
- FCNC b-hadron decays
  - Radiative decays
  - Angular observables
  - Amplitude analyses
  - LFU tests
- Other rare decays
  - Color suppressed, forbidden, rare charm/strange, 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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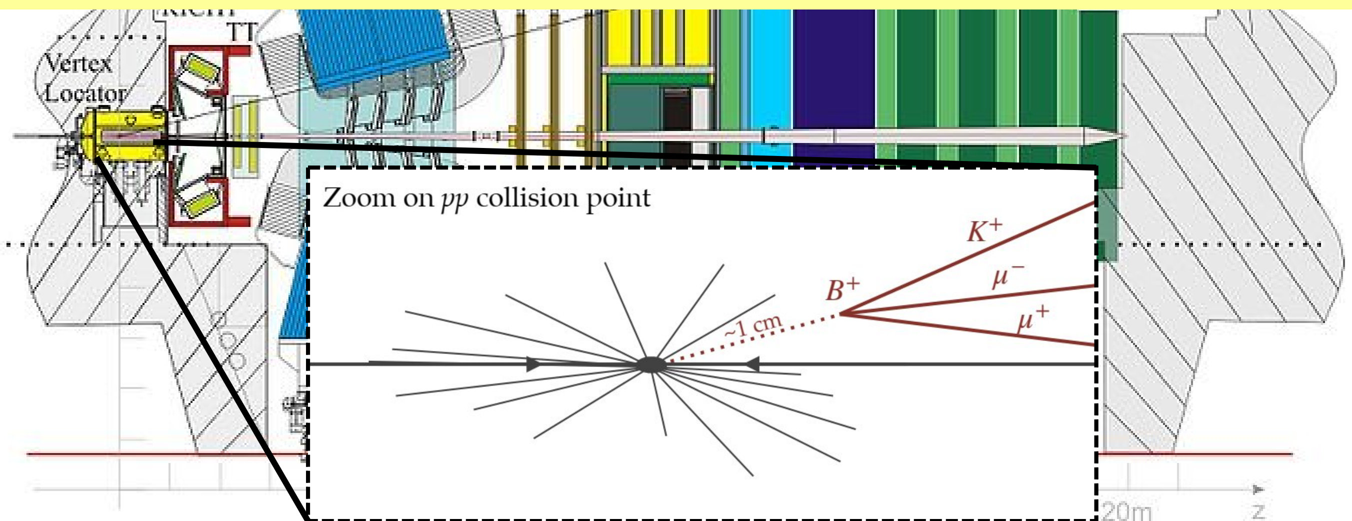
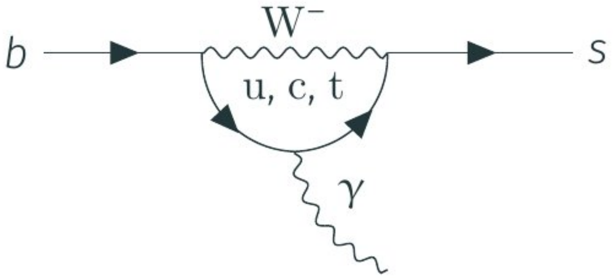


A list of recent LHCb $b \to s\gamma(\ell\ell)$ results

- Direct search of $B^0 \to \mu^+\mu^-\gamma$ [JHEP 07 (2024) 101]
- Amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$ [JHEP 06 (2024) 098]
- Amplitude analysis of $B_s^0 \to K^+K^-\gamma$ [JHEP 08 (2024) 093]
- Photon polarization in $B_s^0 \to \phi e^+e^-$, low q^2 [LHCb-PAPER-2024-030, prelim.]
- Angular analysis of $B^0 \to K^{*0}e^+e^-$, central q^2 [LHCb-PAPER-2024-022, prelim.]
- Angular analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ [arXiv:2409.12629]
- z-Expansion fit with $B^0 \to K^{*0}\mu^+\mu^-$ [PRD 109 (2024) 052009, PRL 132 (2024) 131801]
- Local & non-local amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 09 (2024) 026]
- LFU in $B_s^0 \to \phi\ell^+\ell^-$ [arXiv:2410.13748]
- LFU in $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ [LHCb-PAPER-2024-046, prelim.]

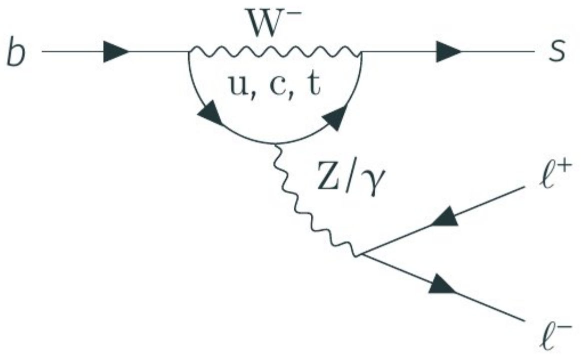
FCNC b decays

Radiative decays

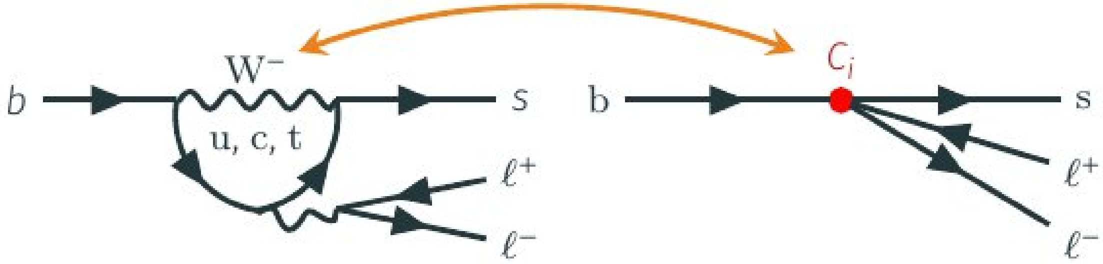


NP might manifest in the loops

Leptonic Decays



Effective Field Theory approach



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

+ chiral flipped

Wilson Coefficients: C_i

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

Operators: $\mathcal{O}_i$

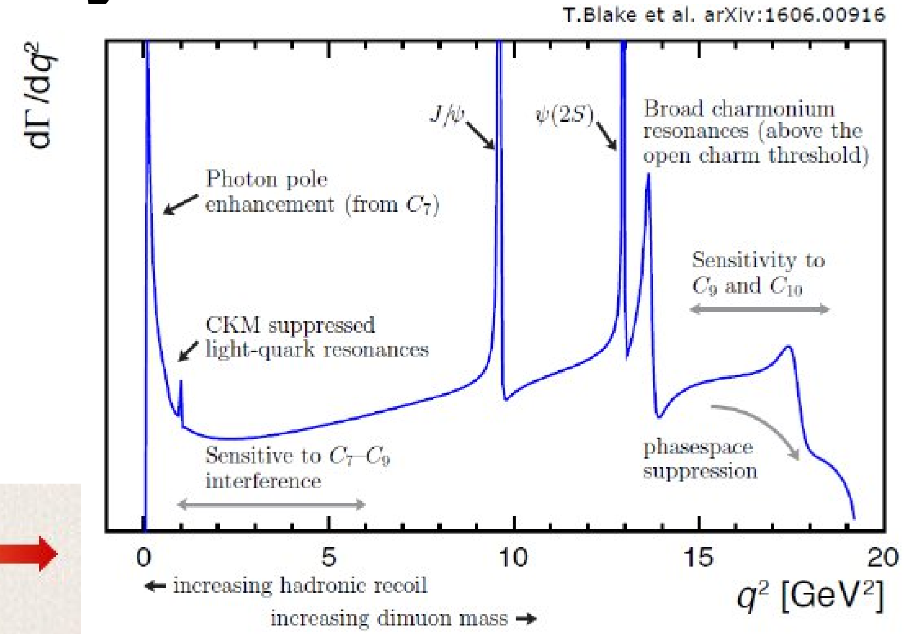
- → Non-perturbative, long distance physics
- → Strong interactions, difficult to calculate

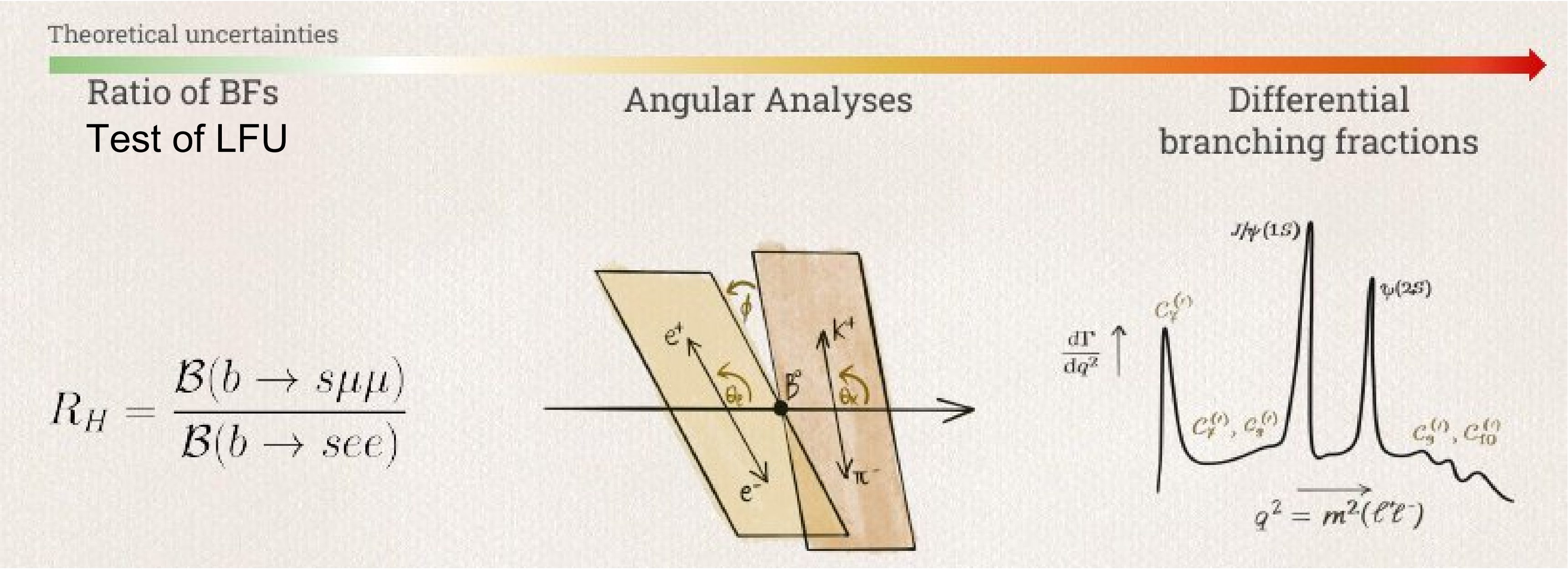
$\mathcal{O}_7$ EM
$\mathcal{O}_9$ Vector dilepton
$\mathcal{O}_{10}$ Axial-vector dilepton

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



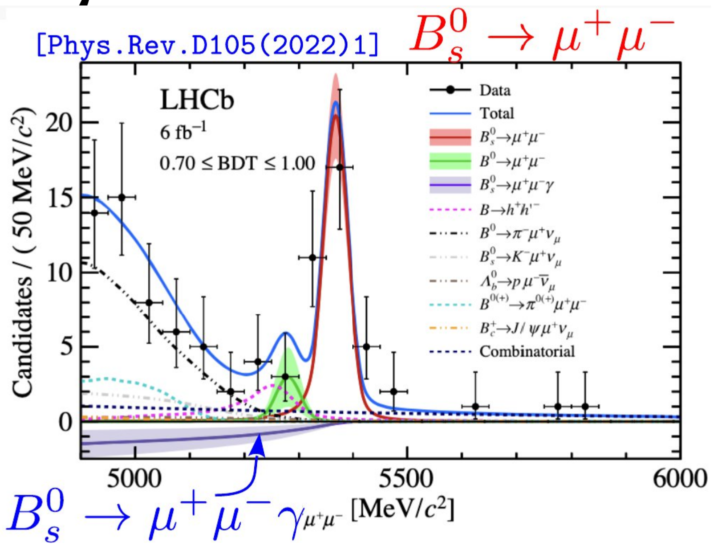


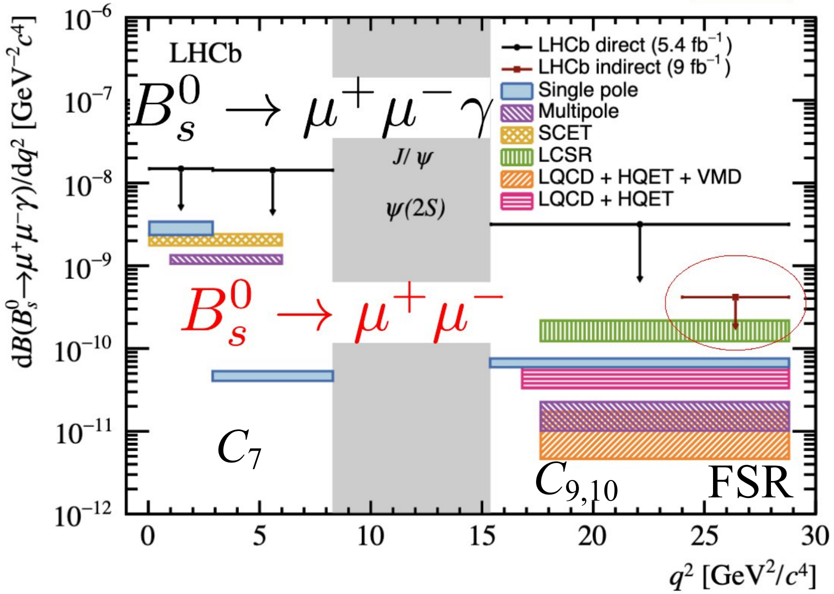
[JHEP 07 (2024) 101]

First direct search on $B_s^0 \to \mu^+\mu^-\gamma$

- Previously Indirect limit from high-q² ISR in $B^0 \to \mu^+\mu^-$
- Now, reconstruct γ, with 5.4 fb^{-1} Run 2 data
- Sensitivity to $C_{7,9}$ in addition to C_{10} . Theory Br$\sim 10^{-9}$ to 10^{-10} depends on $B_s^0 \to \gamma$ FF
- Upper limits are set:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I} < 3.6\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm II} < 6.5\,(7.7) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm III} < 3.4\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I,\ with\ \phi\ veto} < 2.9\,(3.4) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm comb.} < 2.5\,(2.8) \times 10^{-8},$$



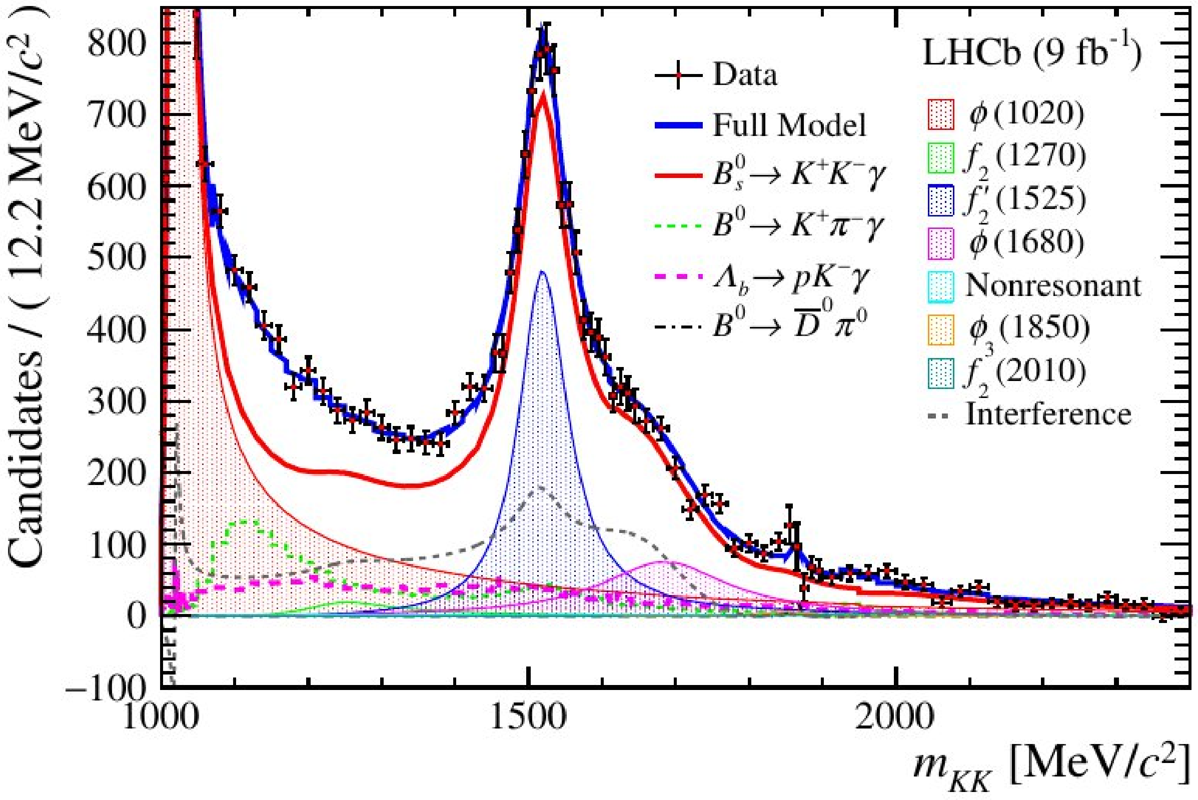


Radiative $b \to s\gamma$ decays

Amplitude analysis of $B_s^0 \to K^+K^-\gamma$

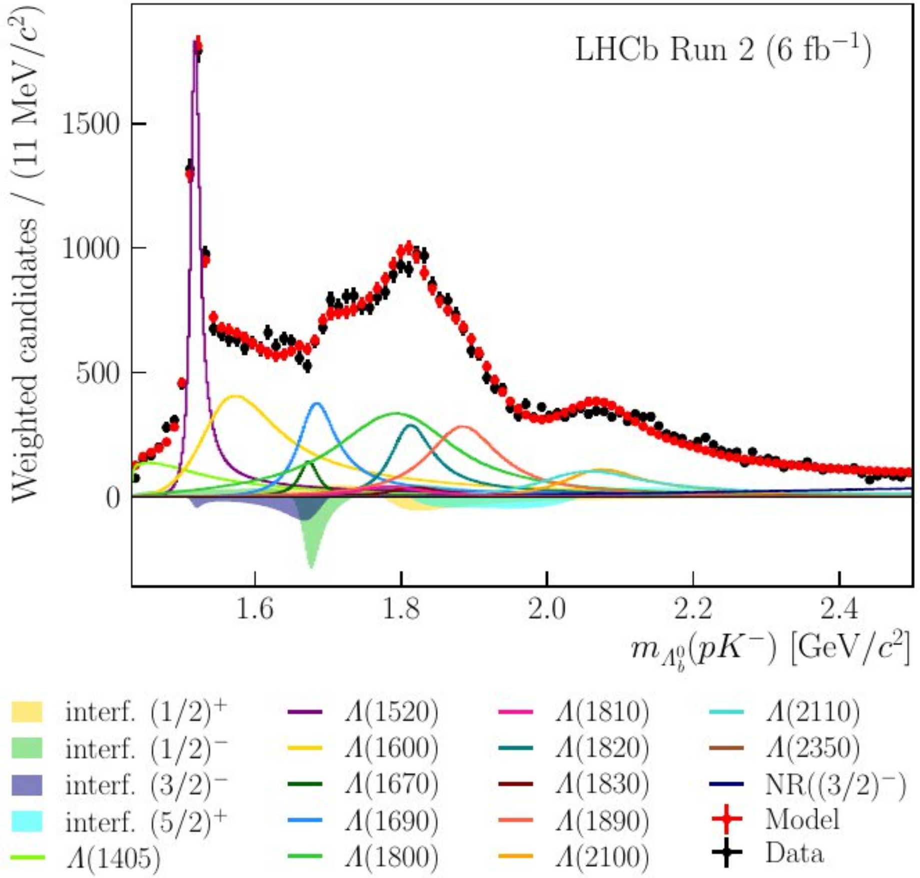
[JHEP 08 (2024) 093]

First observation of $B_s^0 \to f_2'(1525)\gamma$ decay



Amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$

[JHEP 06 (2024) 098]



Photon polarization in $B_s^0 \to \phi e^+ e^-$

- First angular analysis in the low q^2: [0.0009, 0.2615] GeV^2
- Decay rates described as:

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_L \mathrm{d}\cos\theta_K \mathrm{d}\tilde{\varphi}} = \frac{9}{32\pi}\Big\{ & \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\
& + \left[\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right]\cos 2\theta_L \\
& + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde{\varphi} \\
& + (1-F_L)A_T^{ReCP}\sin^2\theta_K\cos\theta_L \\
& + \frac{1}{2}(1-F_L)A_T^{\mathcal{I}mCP}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde{\varphi}\Big\}\,.
\end{aligned}
$$

F_L : Longitudinal polarisation of ϕ meson

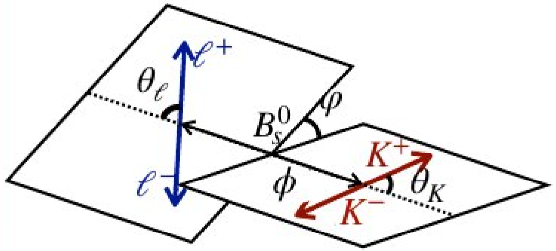
A_T^{ReCP}: related to the forward-backward asymmetry

$A_T^{(2)}$ and A_T^{ImCP} are sensitive to photon polarisation

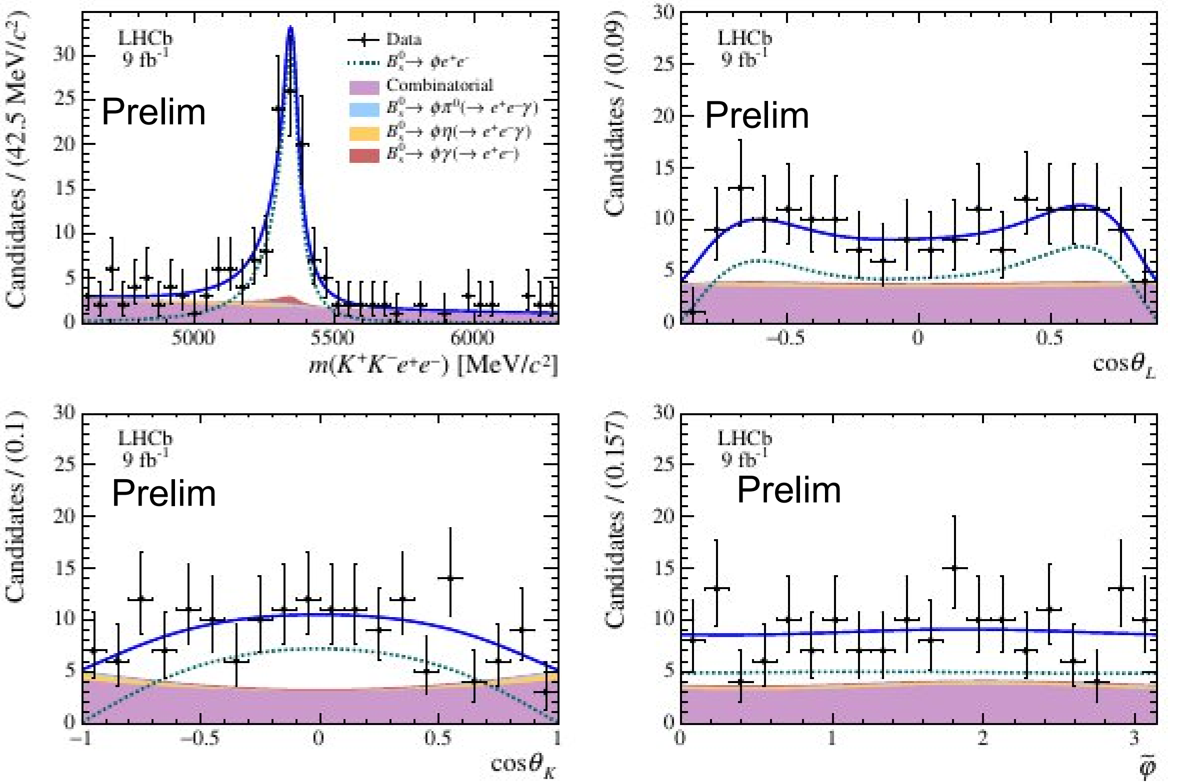
$$A_T^{(2)}(q^2 \to 0) = \frac{2Re(C_7 C_7^{\prime *})}{|C_7|^2 + |C_7^{\prime}|^2} + \Delta_1^2,$$

$$A_T^{ImCP}(q^2 \to 0) = \frac{2Im(C_7 C_7^{\prime *})}{|C_7|^2 + |C_7^{\prime}|^2} + \Delta_2^2,$$

Δ_i due to Δm_s and $\Delta\Gamma_s$



4D unbinned ML fit to mass and angular variables



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F_L : Longitudinal polarisation of ϕ meson

A_T^{ReCP}: related to the forward-backward asymmetry

$A_T^{(2)}$ and A_T^{ImCP} are sensitive to photon polarisation

$$A_T^{(2)}(q^2\to 0) = \frac{2Re(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2} + \Delta_1^2,$$

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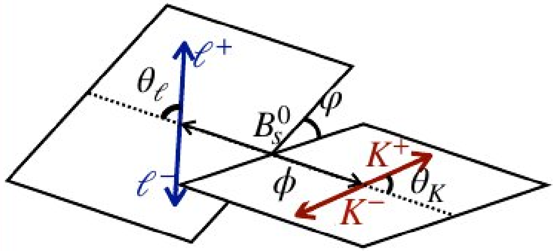
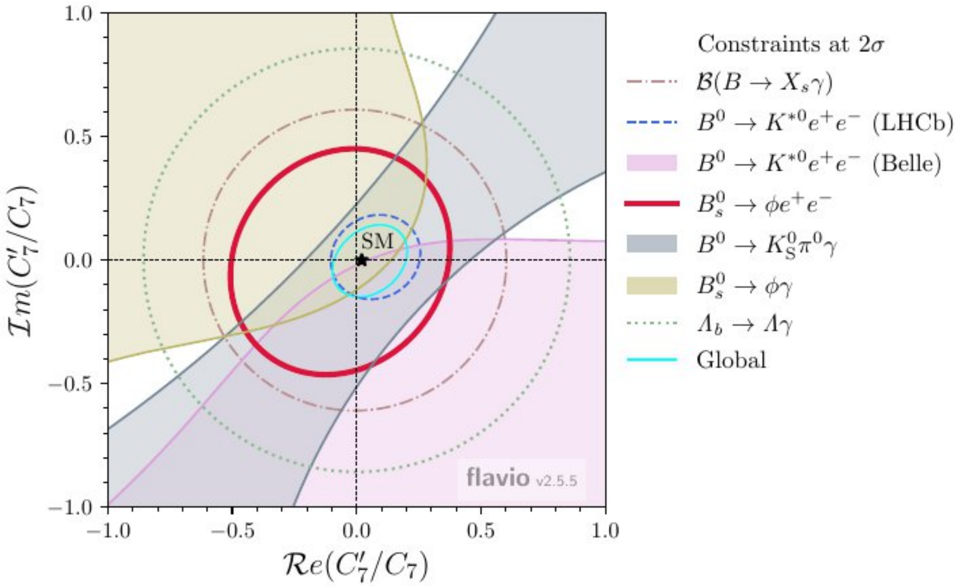
Δ_i due to Δm_s and $\Delta\Gamma_s$



Results consistent with SM

$$A_T^{(2)} = -0.045 \pm 0.235 \pm 0.014\,,$$
$$A_T^{\mathcal{I}mCP} = 0.002 \pm 0.247 \pm 0.016\,,$$
$$A_T^{\mathcal{R}eCP} = 0.116 \pm 0.155 \pm 0.006\,,$$
$$F_L < 11.5\% \text{ at } 90\% \text{ CL}$$

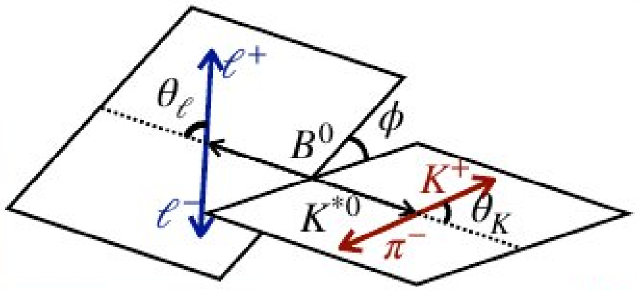
Prelim



Angular analysis of $B^0 \to K^{*0} e^+ e^-$

- First angular analysis in the central q^2: [1.1, 6.0] GeV^2
- Decay rates described as:

$$\frac{d^4\Gamma[B^0 \to K^{*0}e^+e^-]}{dq^2 d\cos\theta_K d\cos\theta_l d\phi} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\theta_K, \theta_l, \phi)$$



angular observables

- F_L — Fraction of longitudinal polarization of K^{*0}
- S_i — CP-averaged
- A_{FB} — Forward-backward asymmetry of the dielectric system

F_L, A_{FB}, and S_i are sensitive to Wilson coefficient ($C^{(\prime)}_{7,9,10}$) and form factors

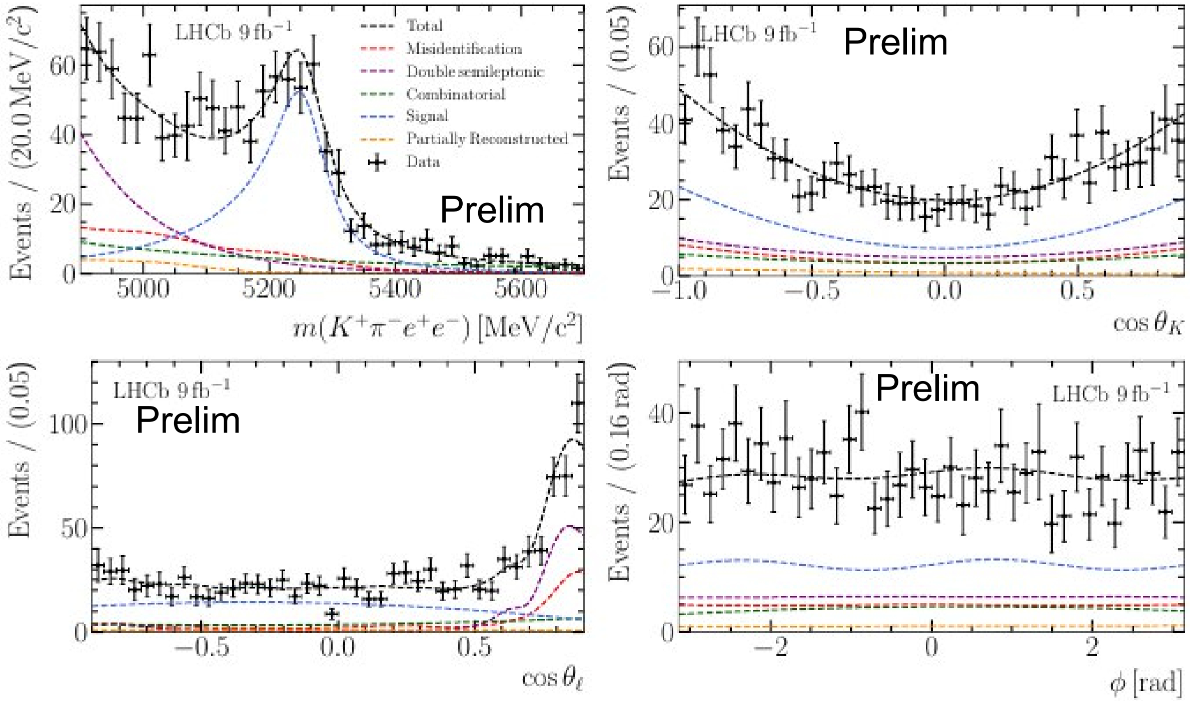
Perform ratio of observables ($e.g.\, P'_5$) where form factors cancels

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

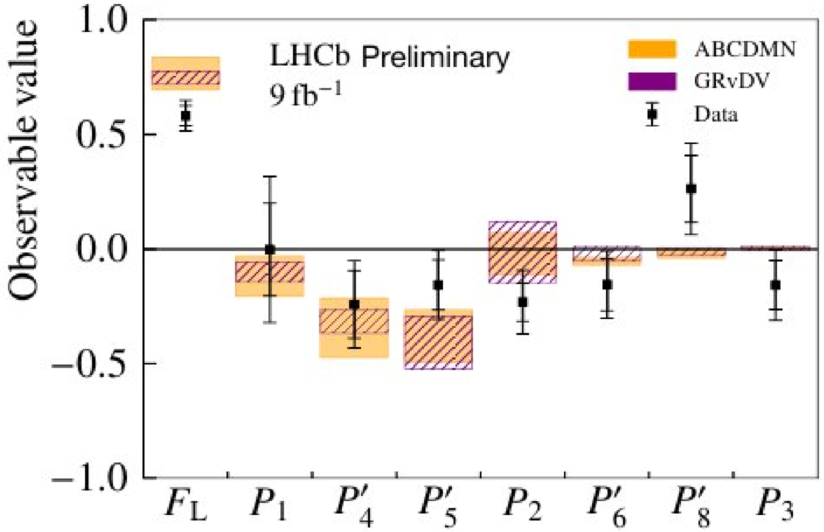
JHEP, 05 (2013) 137

Angular analysis of $B^0 \to K^{*0} e^+ e^-$

4D unbinned ML fit to mass and angular variables

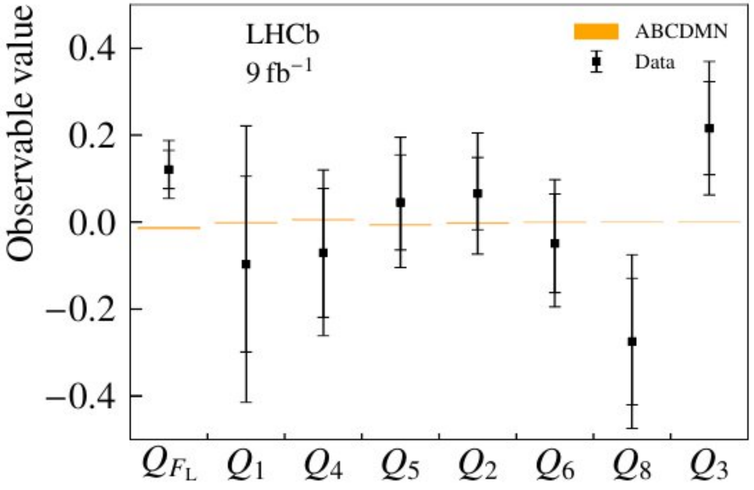


Angular observables measured in $q^2 \in [1.1, 6.0]$ GeV^2



LFU observables derived using

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



Generally good agreement with SM predictions and LFU

[arXiv:2409.12629]

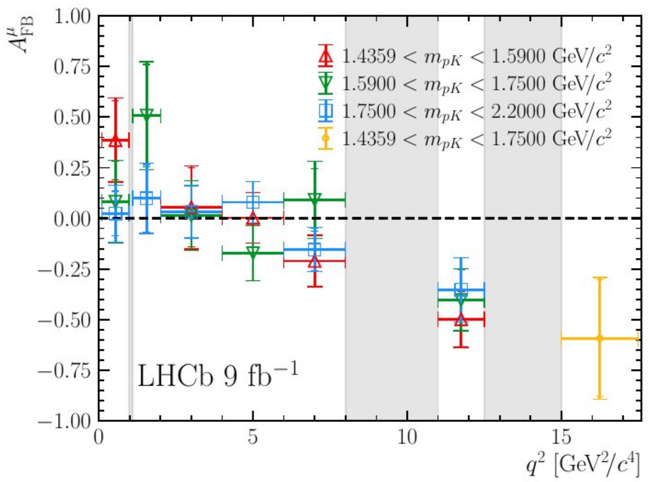
Angular analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$

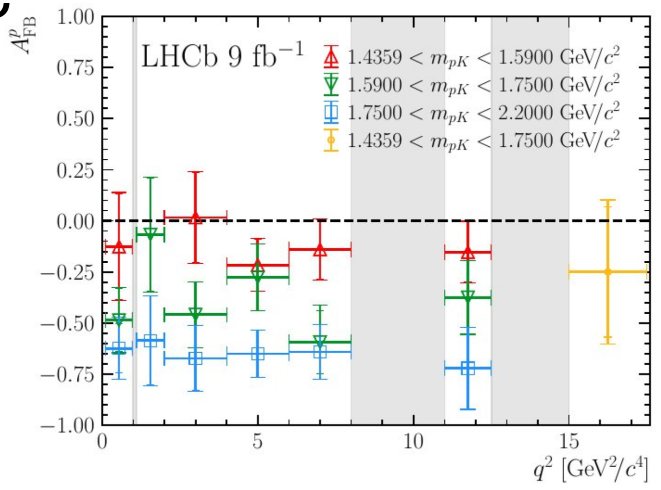
$$A_{\mathrm{FB}}^{\mu} = \frac{3}{2}\overline{K}_2$$

- Measured branching fractions and angular moments in bins of q^2 and m_{pK}^2 and normalized with J/ψ
- Decay rate described by 46 angular moments:

$$\frac{d\Gamma^5}{d\vec{\Phi}} = \frac{3}{8\pi}\sum_{i=0}^{46} K_i(q^2, m_{pK}^2) f(cos\theta_\mu, cos\theta_p, \phi)$$

- Forward-background asymmetry (A_{FB}) of $\mu^+\mu^-$ sensitive to $C_{9,10}$ (same sign-flip pattern as seen in $B^0 \to K^{*0}\mu^+\mu^-$)
- Large A_{FB} observed in hadron is the effect of interference of resonances with different parity



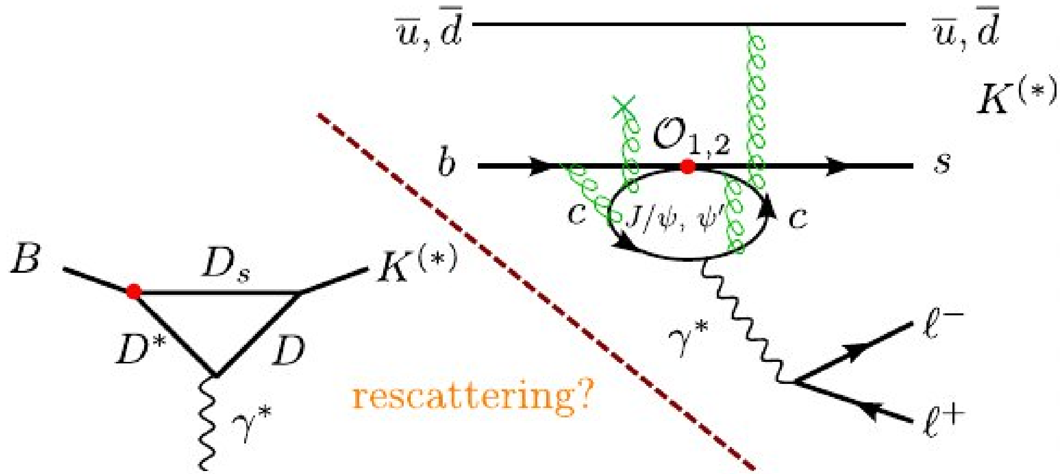


$$A_{\mathrm{FB}}^{p} = \frac{3}{2}\overline{K}_4 - \frac{\sqrt{21}}{8}\overline{K}_{10} + \frac{\sqrt{33}}{16}\overline{K}_{16}$$

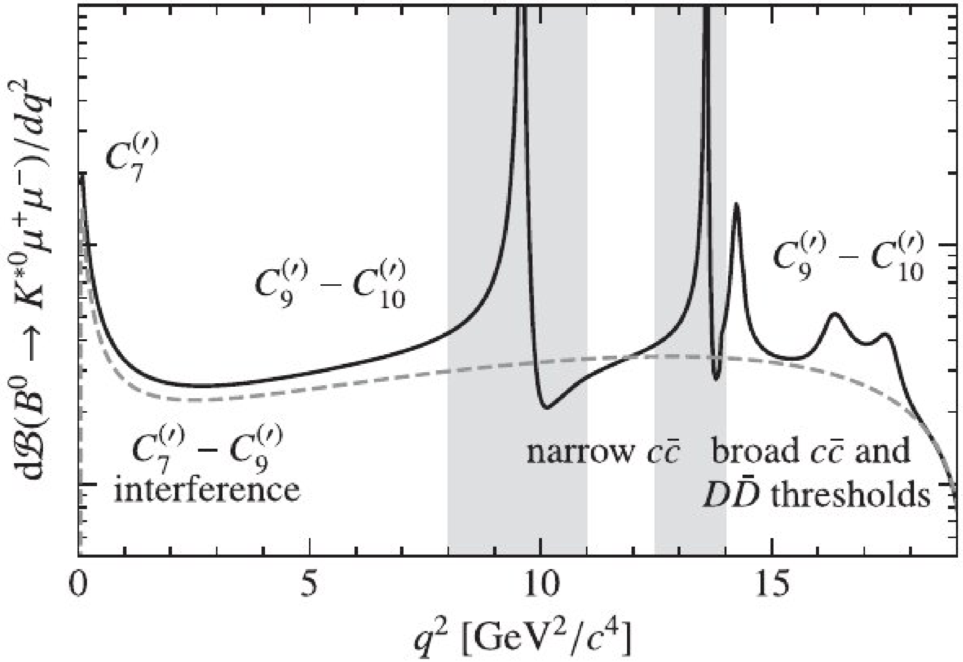
[PRL 132 (2024) 131801]

Data-driven approaches for $B^0 \to K^{*0}\mu^+\mu^-$

- Non-local (charm loop) hadronic contributions bring in large theoretical uncertainties, and can mimic BSM effects
- Data-driven approaches are needed here!
  - z-expansion
  - Dispersion



[PRL 132 (2024) 131801]

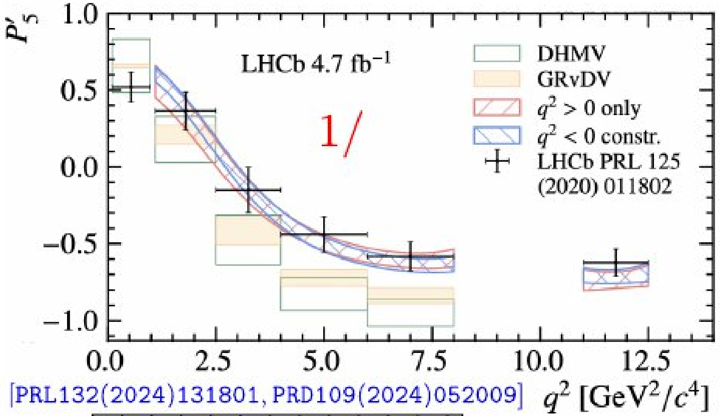


Data-driven approaches for $B^0 \to K^{*0}\mu^+\mu^-$

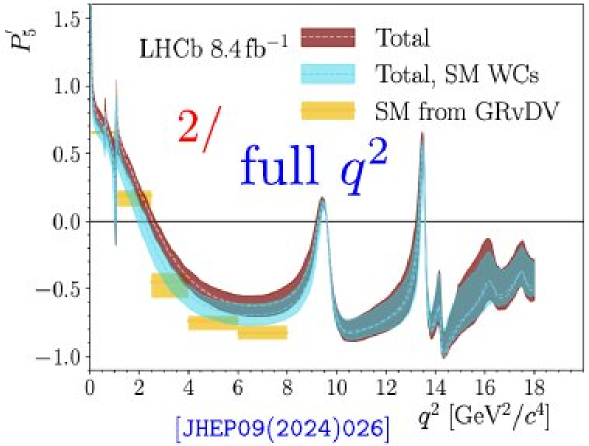
1/ Fit to long-distance $\mathcal{H}_\lambda(q^2)$ as model-independent z-expansion:

$$\mathcal{A}^{L,R}_{\lambda=0,\|,\perp} = \mathcal{N}_\lambda \left\{ \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}') \right] \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[(C_7 \pm C_7')_{\rm SM} \mathcal{F}^T_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right]\right.$$

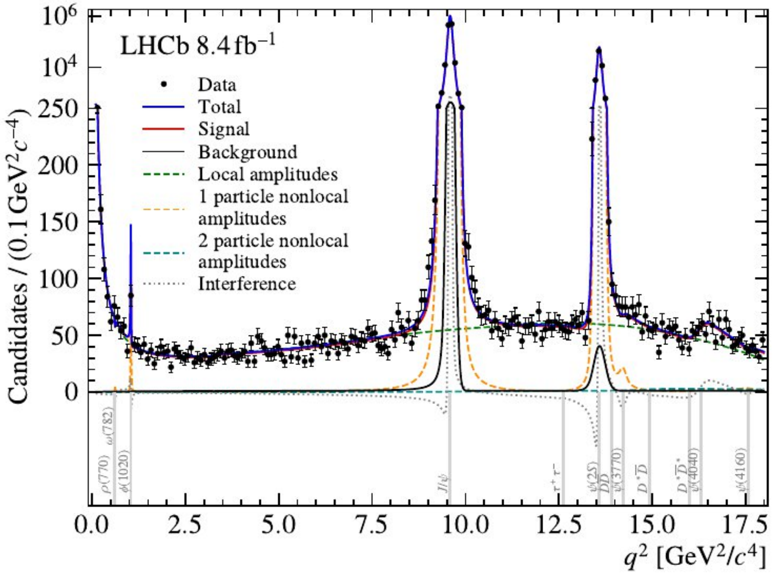
2/ $C^{(\rm eff)}_{9,\lambda} \to C_9 + Y_{q\bar{q},\lambda}(q^2)$. $Y_{q\bar{q}} \in$ sum $\{\rho,\, \omega,\, \phi,\, J/\psi,\, ...,\, D^{(*)}\overline{D}^{(*)}\}$

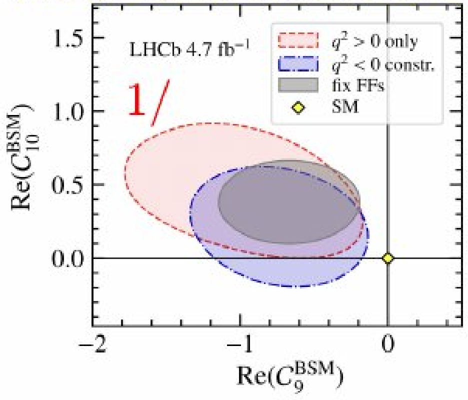


[PRL132(2024)131801, PRD109(2024)052009]



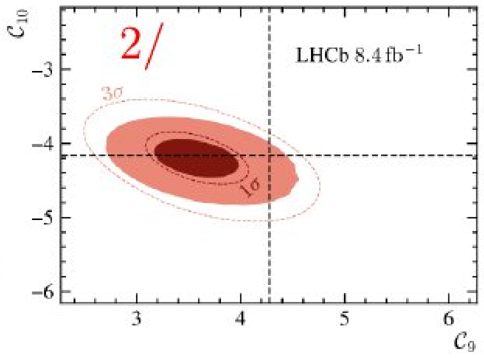
[JHEP09(2024)026]





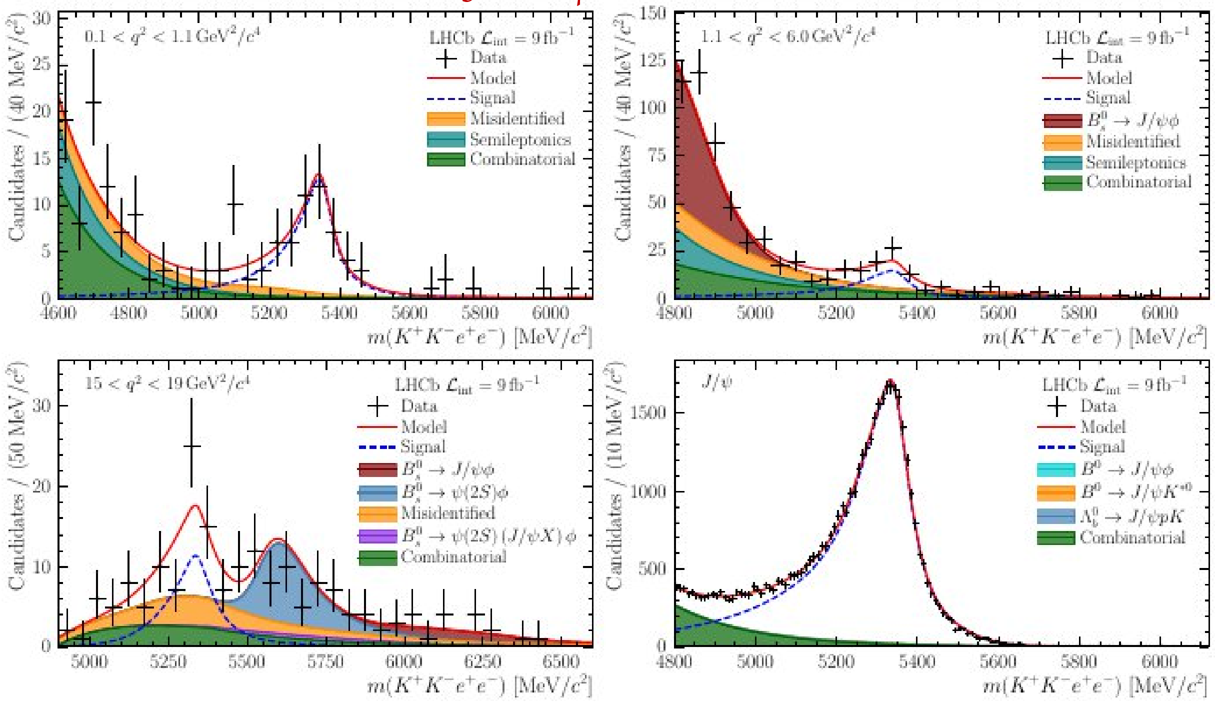
$\Delta C_9 < 0$ preferred but overall tension reduced

both exp. and theory improvements in future



LFU tests in $b \to s\ell\ell$

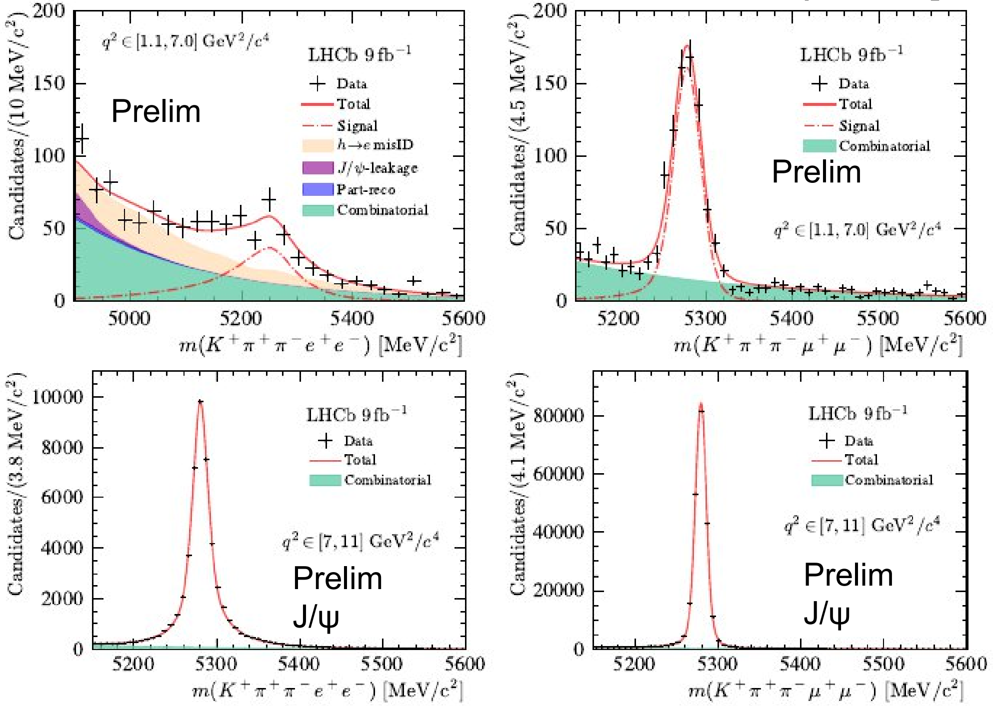
First observation of $B_s^0 \to \phi e^+ e^-$
and first LFU test of $B_s^0 \to \phi \ell^+ \ell^-$ [arXiv:2410.13748]



q^2 [GeV$^2/c^4$]	R_ϕ^{-1}	$\mathrm{d}\mathcal{B}(B_s^0 \to \phi e^+ e^-)/\mathrm{d}q^2$ [10^{-7} GeV$^{-2}c^4$]
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$	$1.38\,^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$

First LFU test of $B^+ \to K\pi\pi\ell^+\ell^-$

LHCb-PAPER-2024-046, prelim.]



$$R_{K\pi\pi}^{-1} = \frac{\int_{1.1\,\mathrm{GeV}^2/c^4}^{7\,\mathrm{GeV}^2/c^4} \frac{\mathrm{d}\Gamma(B^+ \to K^+\pi^+\pi^-e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2/c^4}^{7\,\mathrm{GeV}^2/c^4} \frac{\mathrm{d}\Gamma(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

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

$q^2 \in [1.1, 7.0]$ GeV$^2/c^4$

Searches for other rare decays

- $B_c^+ \to \pi^+\mu^+\mu^-$ [EPJC 84 (2024) 468]
- $B_s^{*0} \to \mu^+\mu^-$ [LHCb-CONF-2024-003]
- $B \to D\mu^+\mu^-$ [JHEP 02 (2024) 032]
- $B_s^0 \to \phi\tau\mu$ [arXiv:2405.13103]
- $D^0 \to hhe^+e^-$ [LHCb-PAPER-2024-047, prelim.]
- $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 110 (2024) 052007]
- $\Sigma^+ \to p\mu^+\mu^-$ [LHCb-CONF-2024-002]

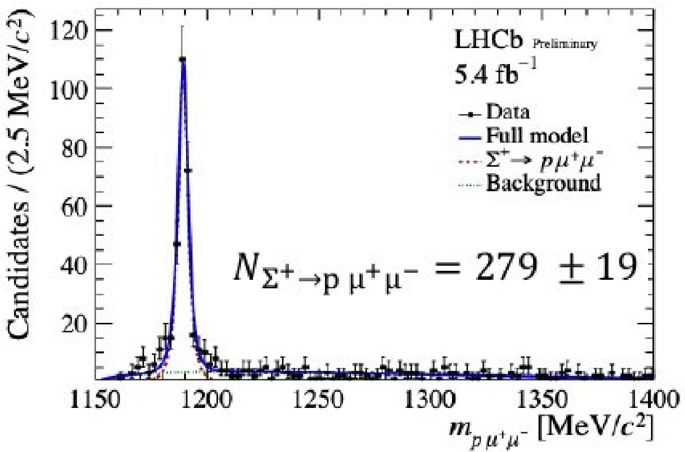
First observation!

$D^0 \to \pi^+\pi^-e^+e^-$

m(e^+e^-) region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
Low mass	211–525	$< 4.81\ (5.39)$
η	525–565	$< 2.27\ (2.74)$
ρ^0/ω	565–950	$4.53 \pm 1.00 \pm 0.72 \pm 0.62$ *
ϕ	950–1100	$3.84 \pm 0.70 \pm 0.39 \pm 0.53$ *
High mass	> 1100	$< 2.00\ (2.17)$

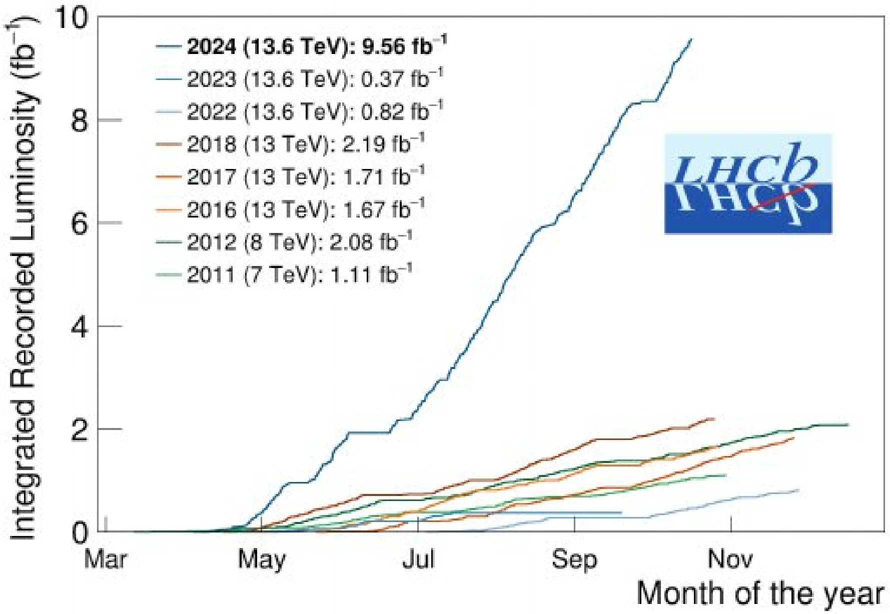
First observation!

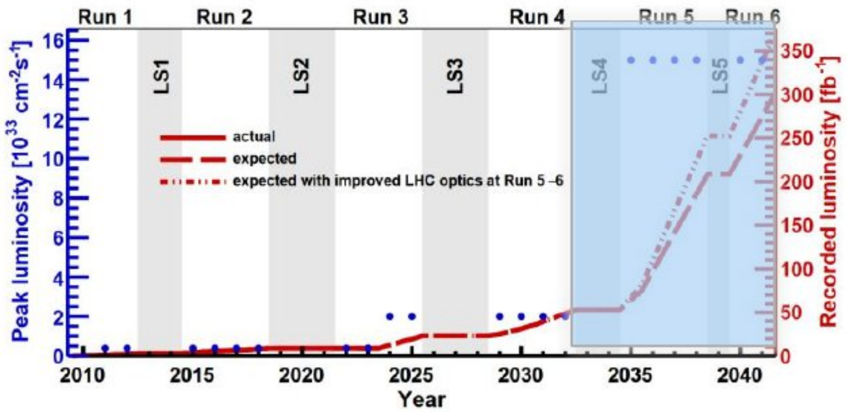
* Statistical, systematic and uncertainties related to norm. BF



Summary

- Studies on rare b decays are key to searches for BSM
- Many first searches, LFU tests, and angular analyses, esp. with electron channels
- Data-driven approaches improve our understanding of non-local effects in $B^0 \to K^{*0}\mu\mu$
- So far, no surprises, but tensions still persist (C_9?)
- Now a new detector and improved hadron trigger
    - 9.6 fb^{-1} already collected for Run3
- And we will have Run4 and Upgrade-II!



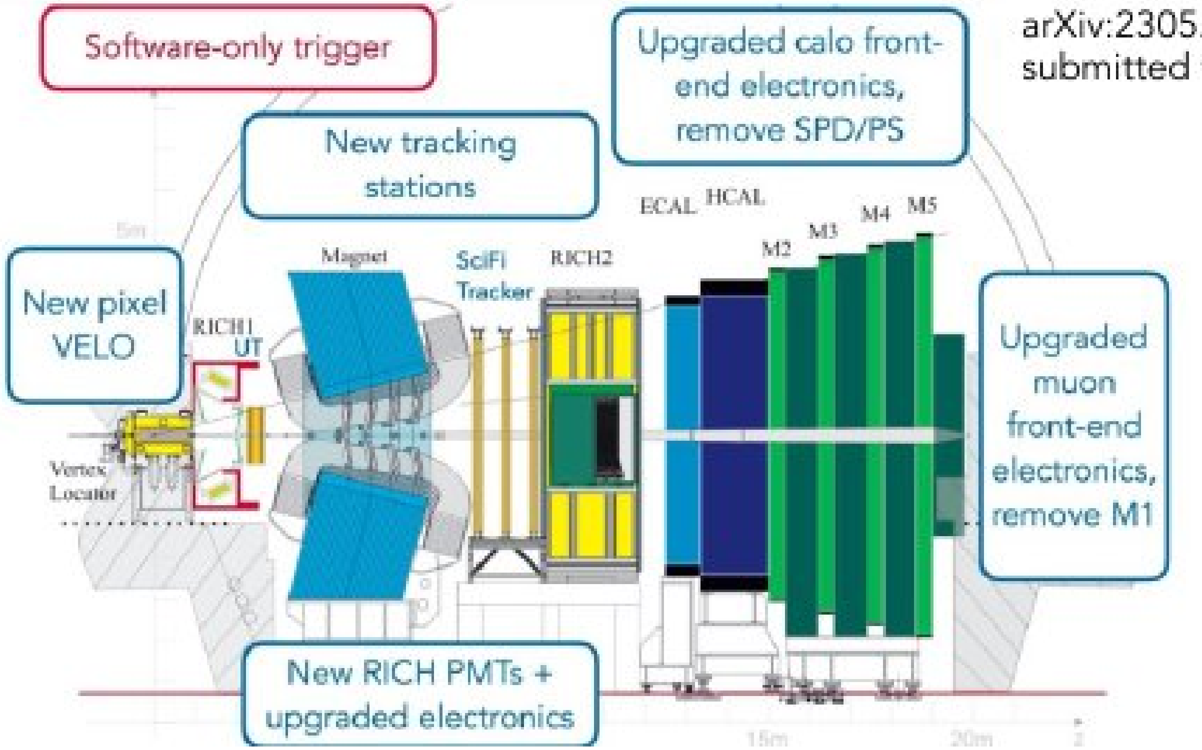


Backup Slides

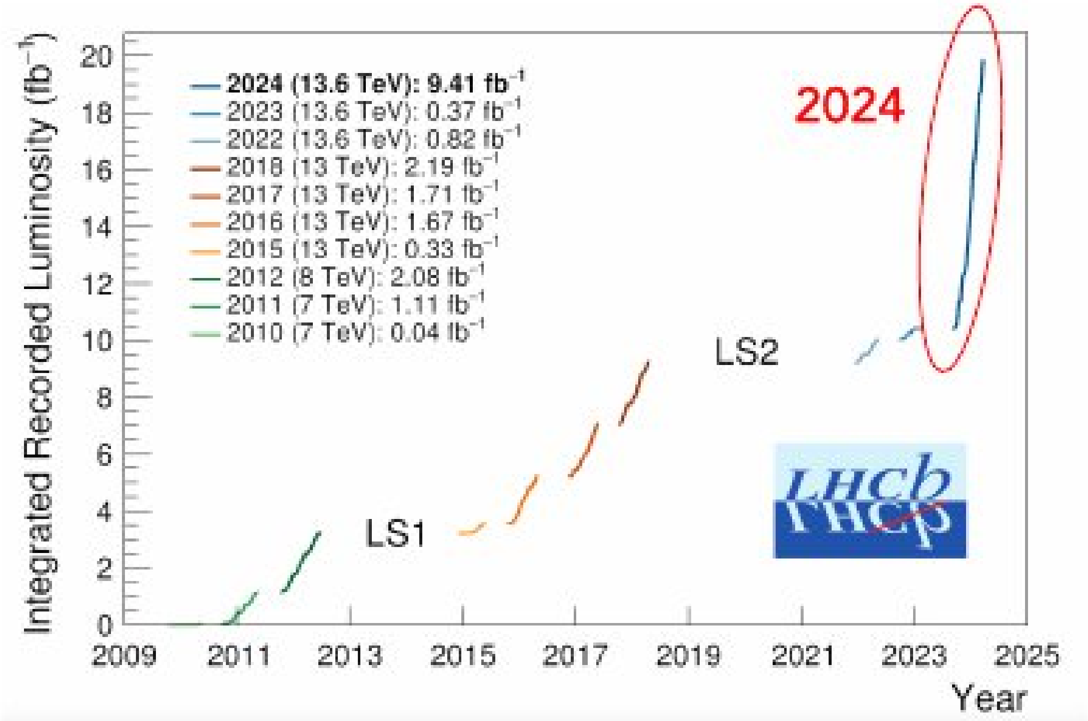
LHCb-Upgrade I

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



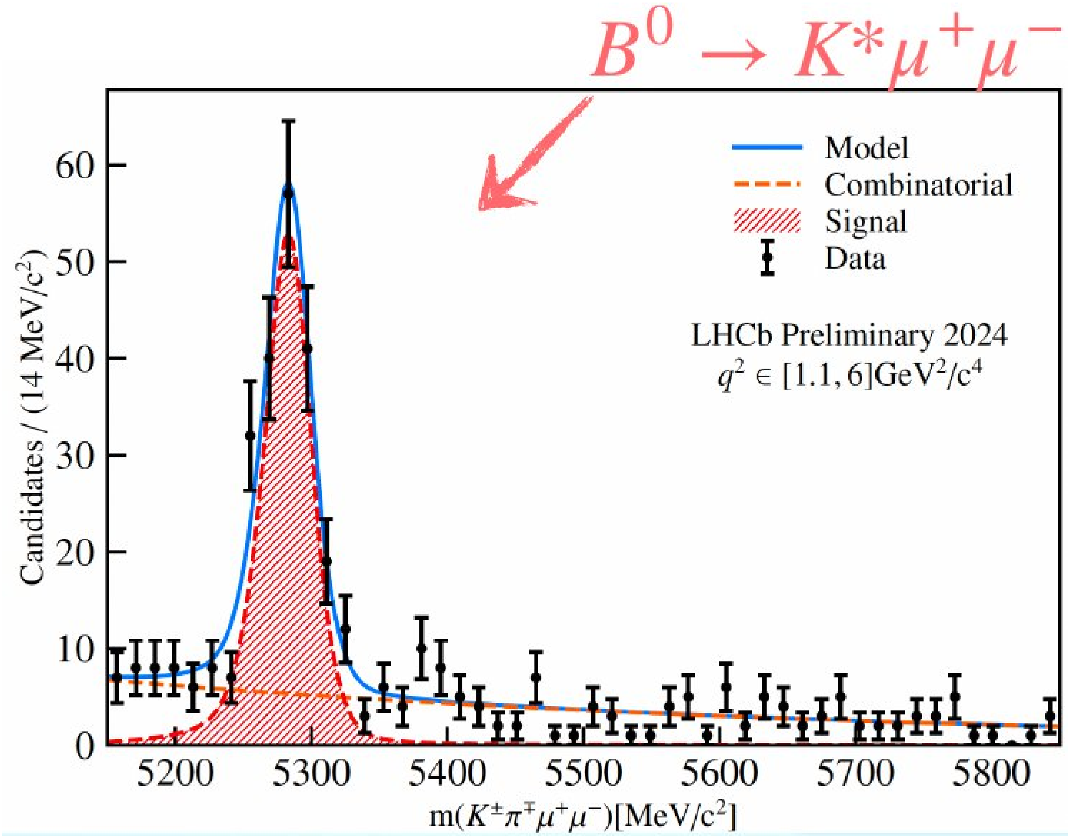
arXiv:2305.10515, submitted to JINST



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

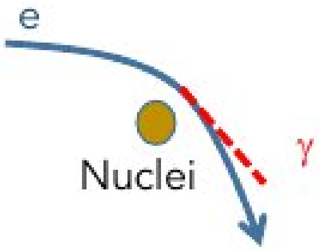
2024 : a lot of data !

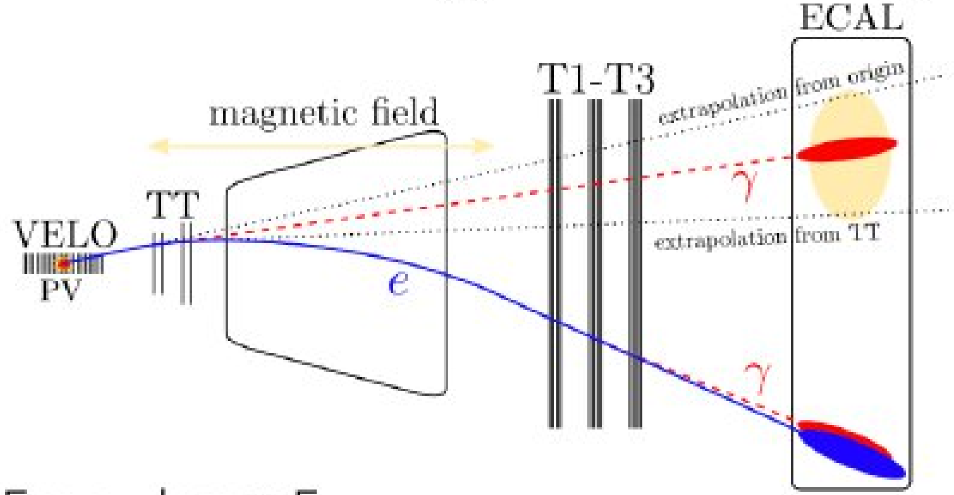


LHCb_TDR_023

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 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%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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"

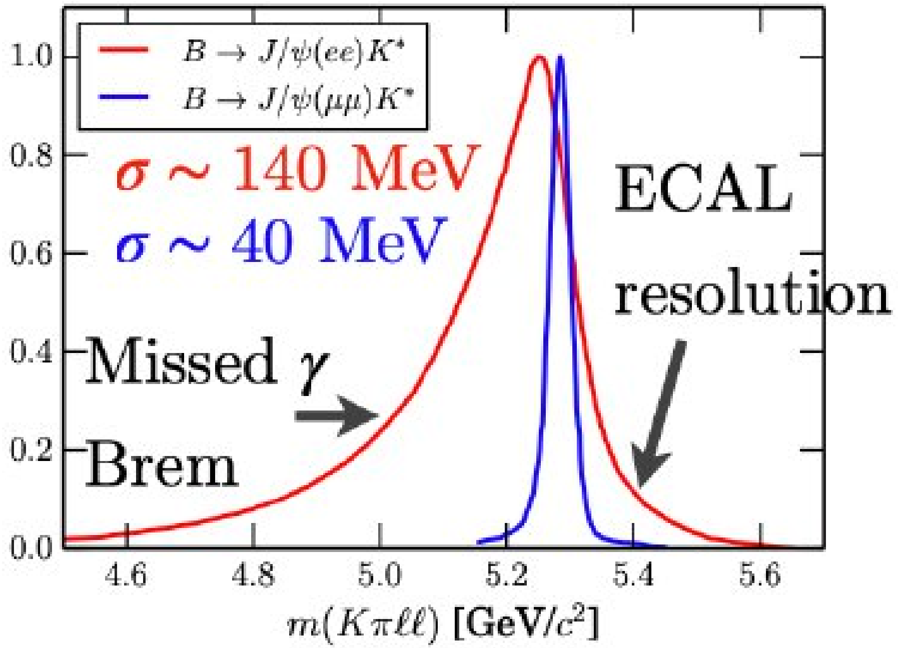
After the magnet

- not an issue

In both cases E/p is correct

Energy loss ∝ E_e
Energy loss ∝ material

⇒ Use of a recovery algorithm

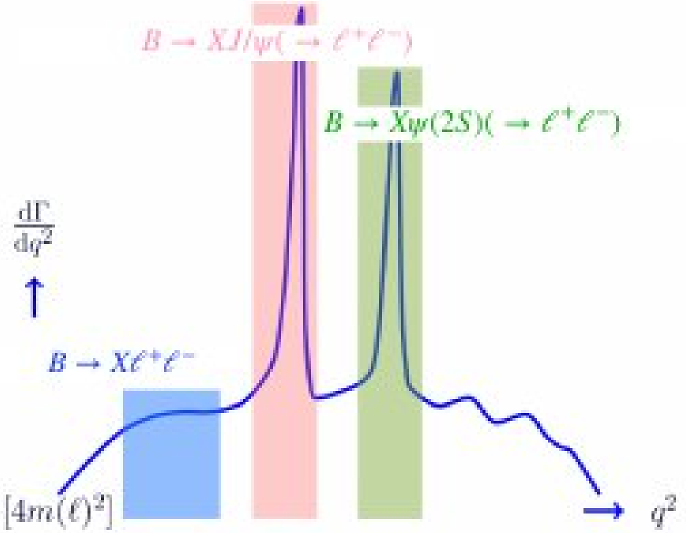


LFU ratio: Experimental strategy

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

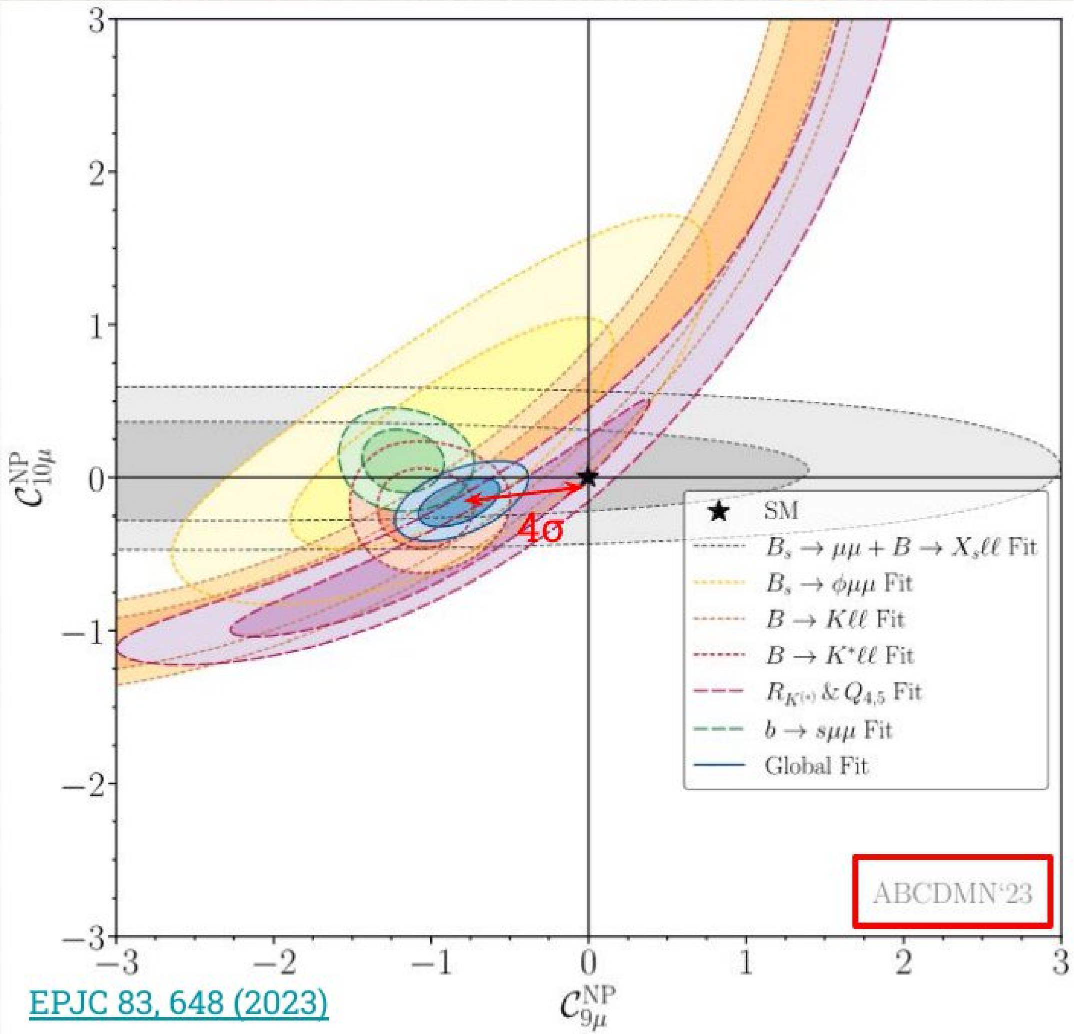
$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to XJ/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to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

  - 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 $b\to s\ell\ell$
    - $r_{J/\psi} = \dfrac{\mathcal{B}(B\to XJ/\psi(\to\mu\mu))}{\mathcal{B}(B\to XJ/\psi(\to ee))} \equiv 1$ 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 Coeffients global fits



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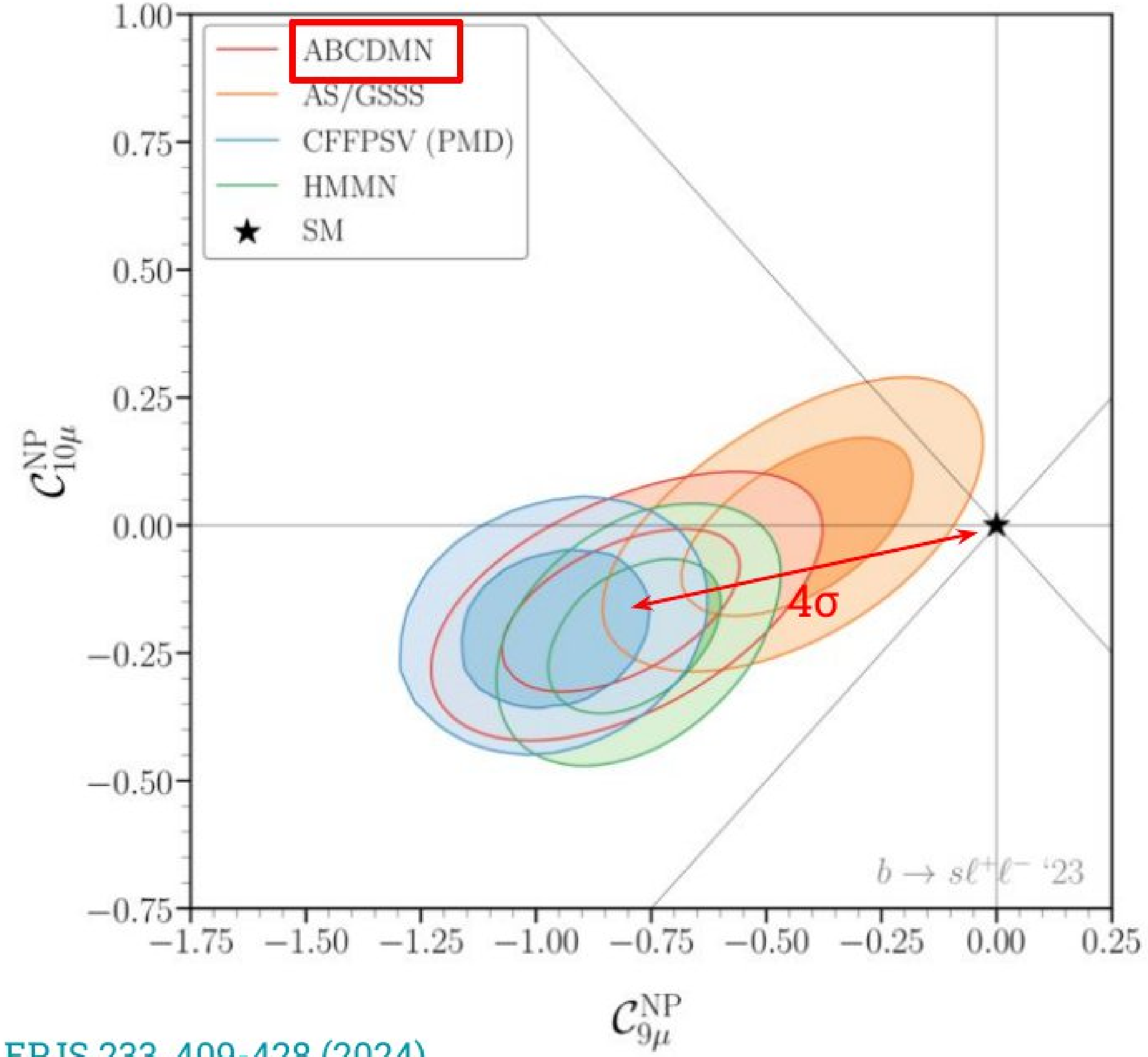

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