Rare B decays

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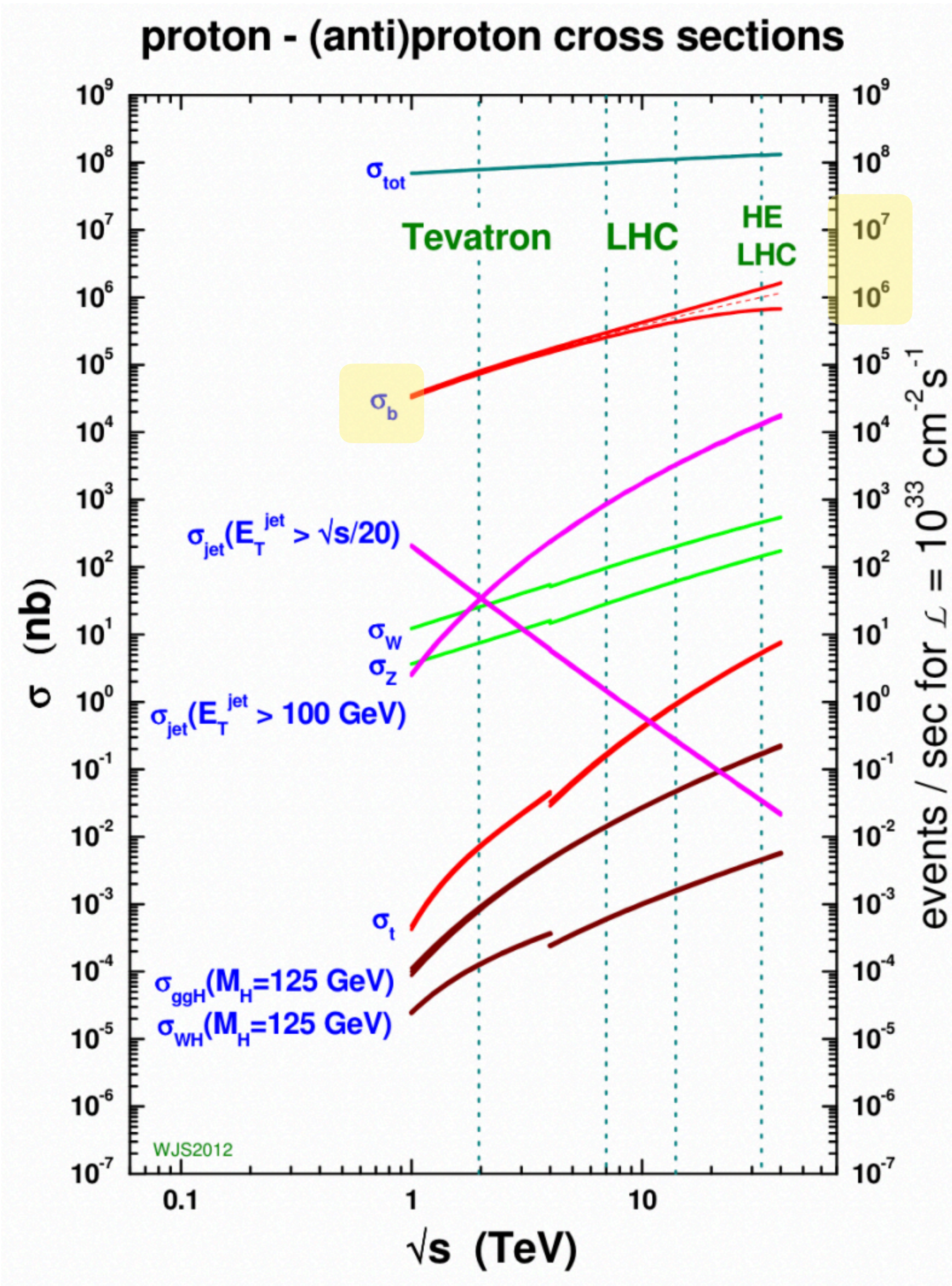
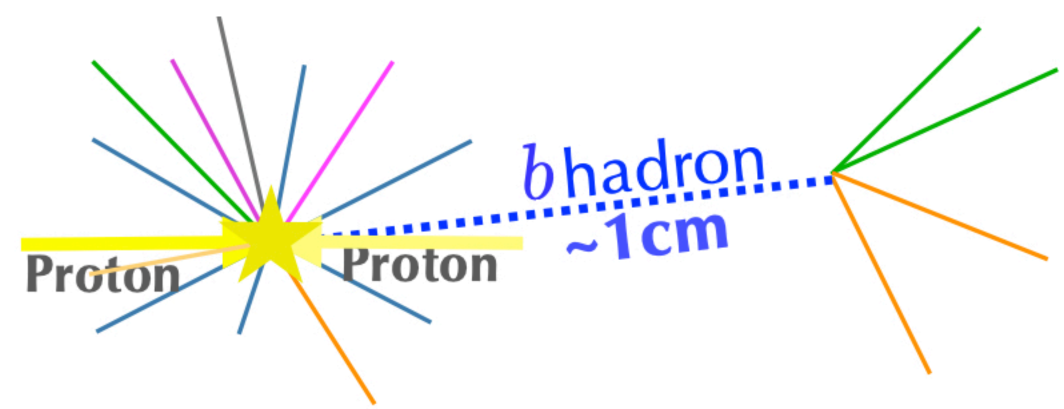
Disclaimer:

A selective set of results have been included in this talk.

b-quarks at the LHC

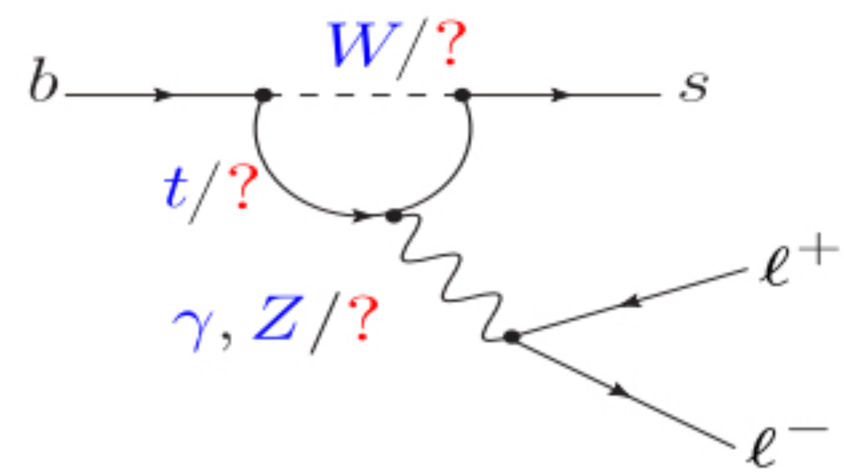


- Cross-section ~100 μb
- Millions of pairs produced per second
- **and they fly …**



Why Rare B decays ?

- Rare decays of heavy mesons are FCNC (forbidden at tree level and thus highly suppressed)
- New particles may appear in loops of rare FCNC decays, affecting branching ratios and angular distributions;
- These particles wouldn't need to be produced on mass shell in such diagrams ⇒ access to very large masses.



FCNC effective hamiltonian described as operator product expansion, C_i being the Wilson coefficients, that encode the short-distance physics, and O_i the corresponding operators.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}_i'(\mu)\mathcal{O}_i'(\mu)}_{\text{right-handed part suppressed in SM}}]$$

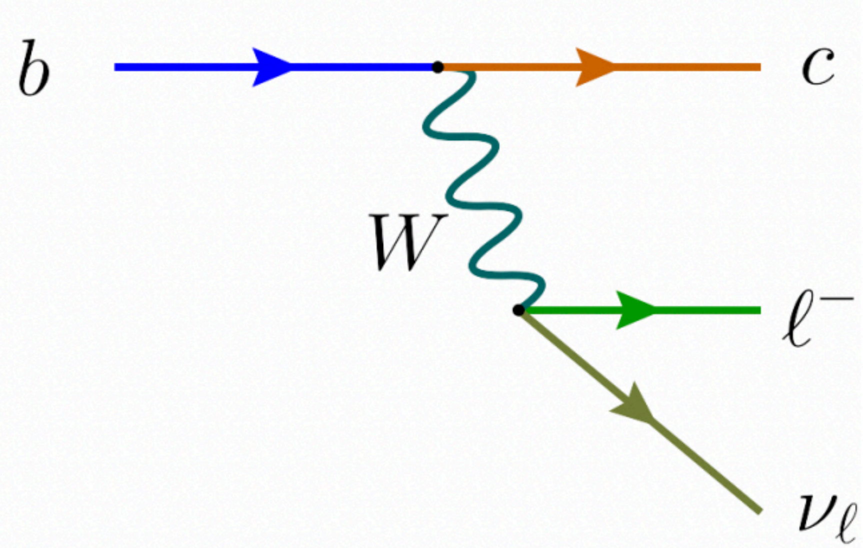
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

- Looking for deviation from SM prediction

$$\begin{cases} \mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP} \\ \mathcal{C}_i' = \mathcal{C}_i'^{NP} \end{cases}$$

Semi-leptonic b quark decays

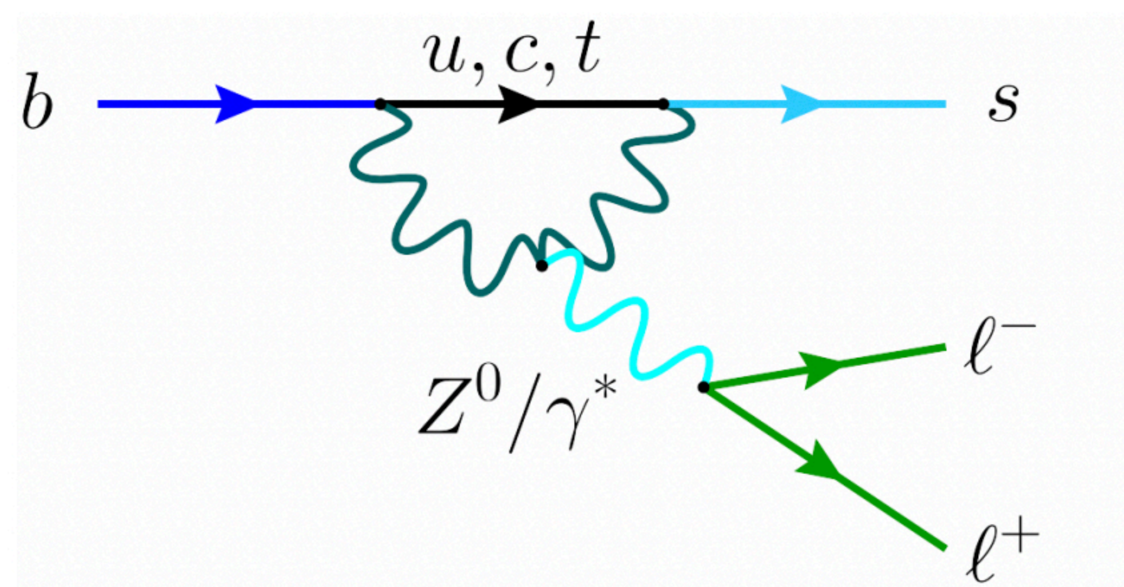
$b \to c\ell\nu$



Charged current:

- Tree-level
  - $\mathscr{B}$ order %
- Neutrino in final state (invisible)

$b \to s\ell\ell$

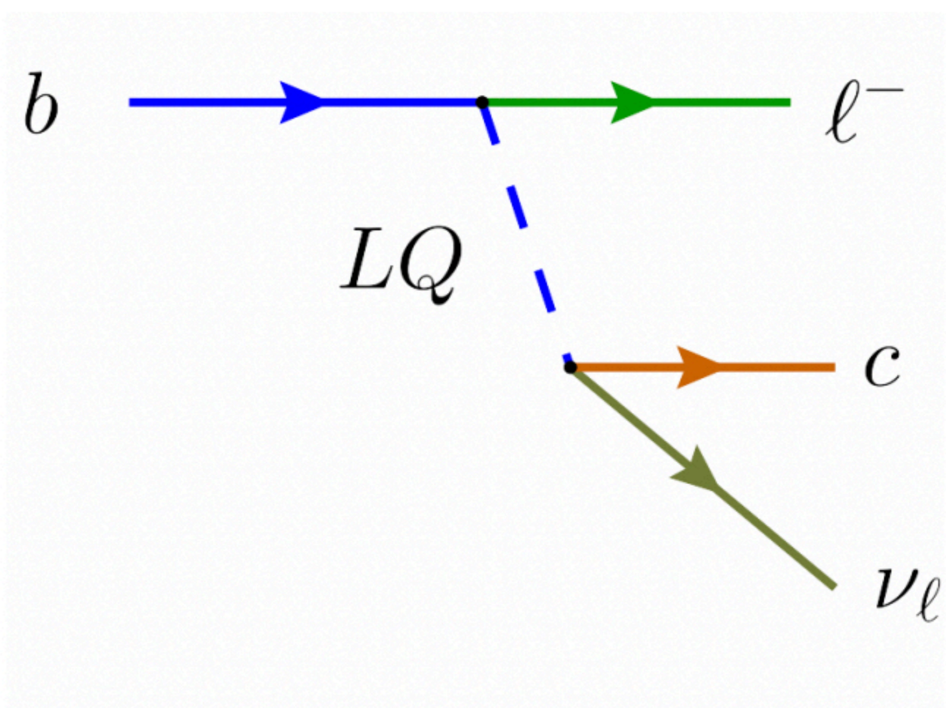


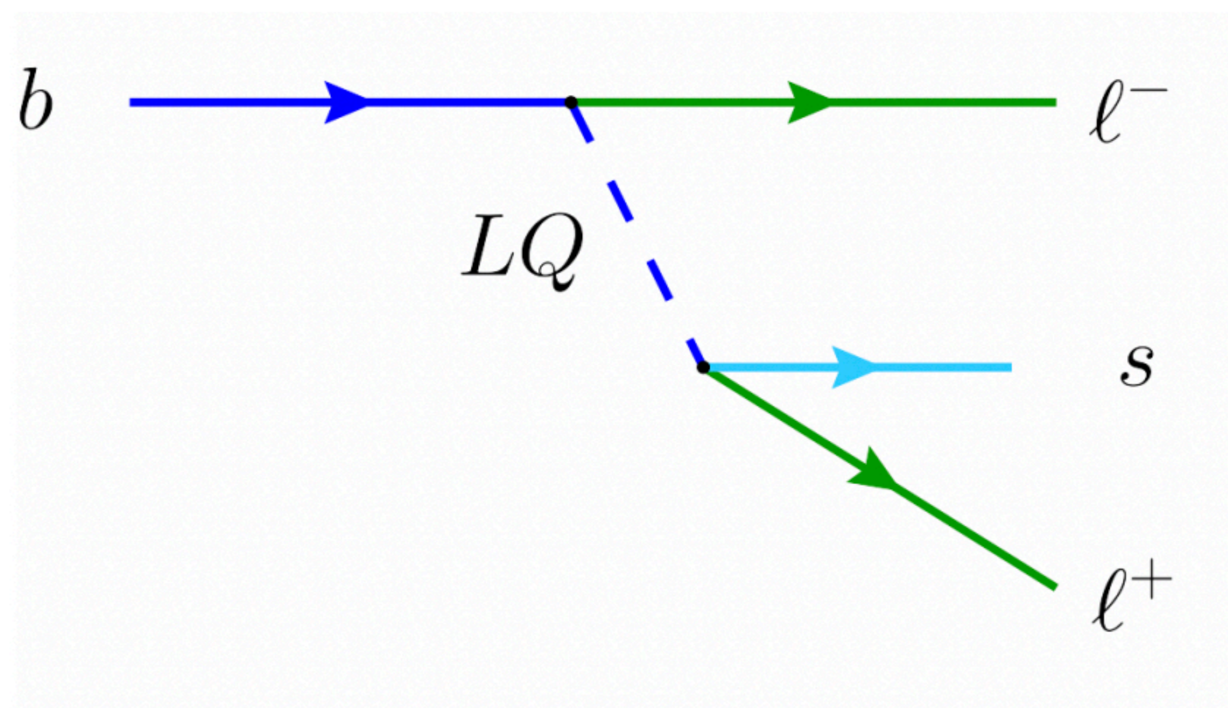
Neutral current:

- Loop-suppressed:
  - $\mathscr{B}$ order $10^{-7} - 10^{-9}$
- Full reconstructed final state

Semi-leptonic b quark decays

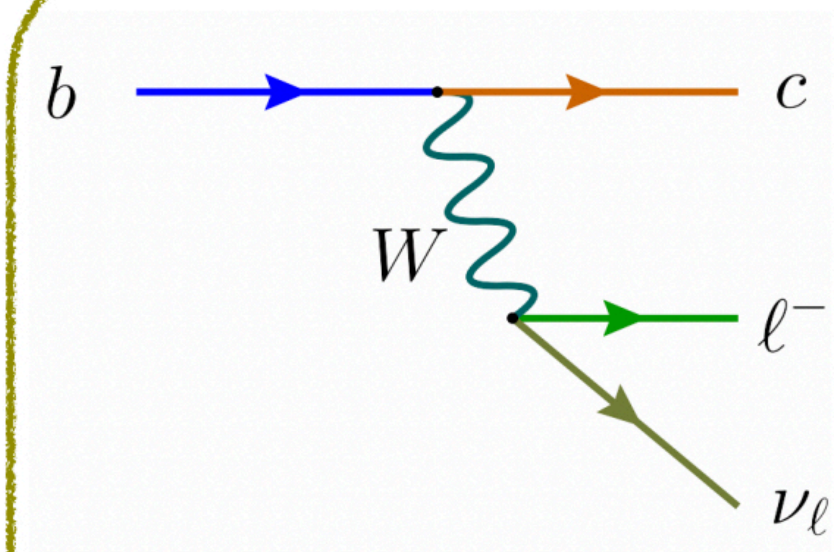
$b \to c\ell\nu$ $\qquad$ $b \to s\ell\ell$



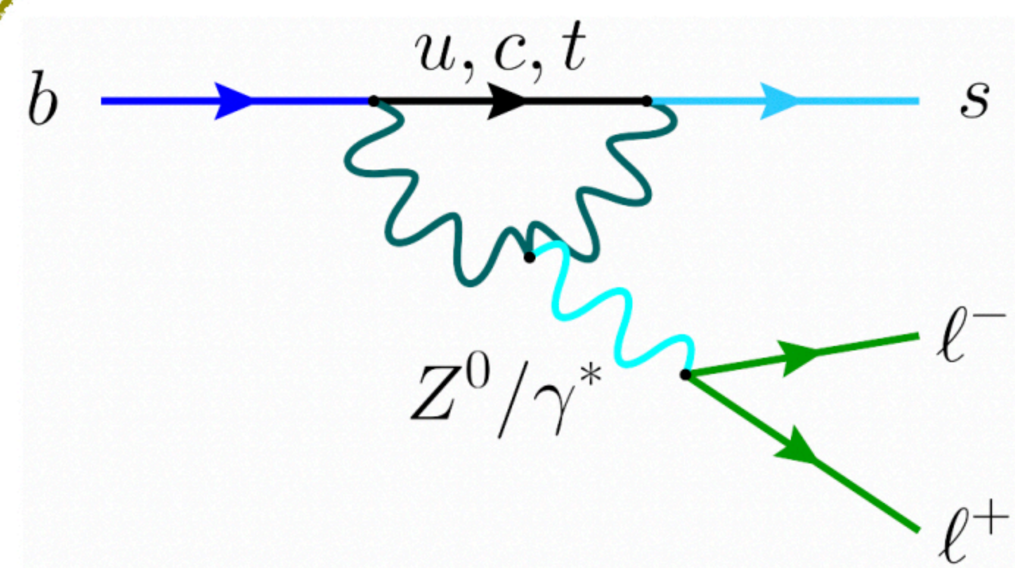


- NP particles having mass > TeV can modify the measured decay rate
- Leptoquark (LQ), Z' model

B anomalies

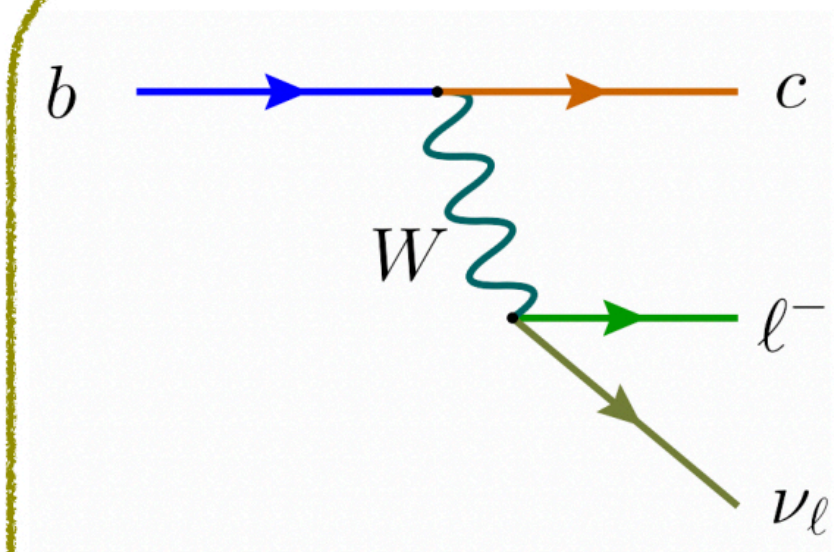


Charged current $\sim 3\sigma$

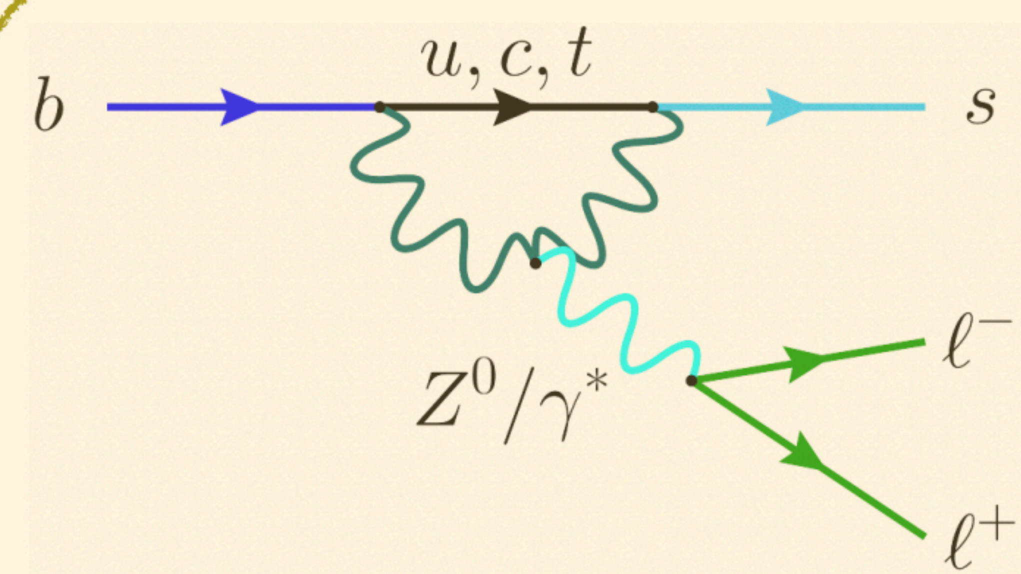


Neutral current $\sim 4 - 5\sigma$

B anomalies



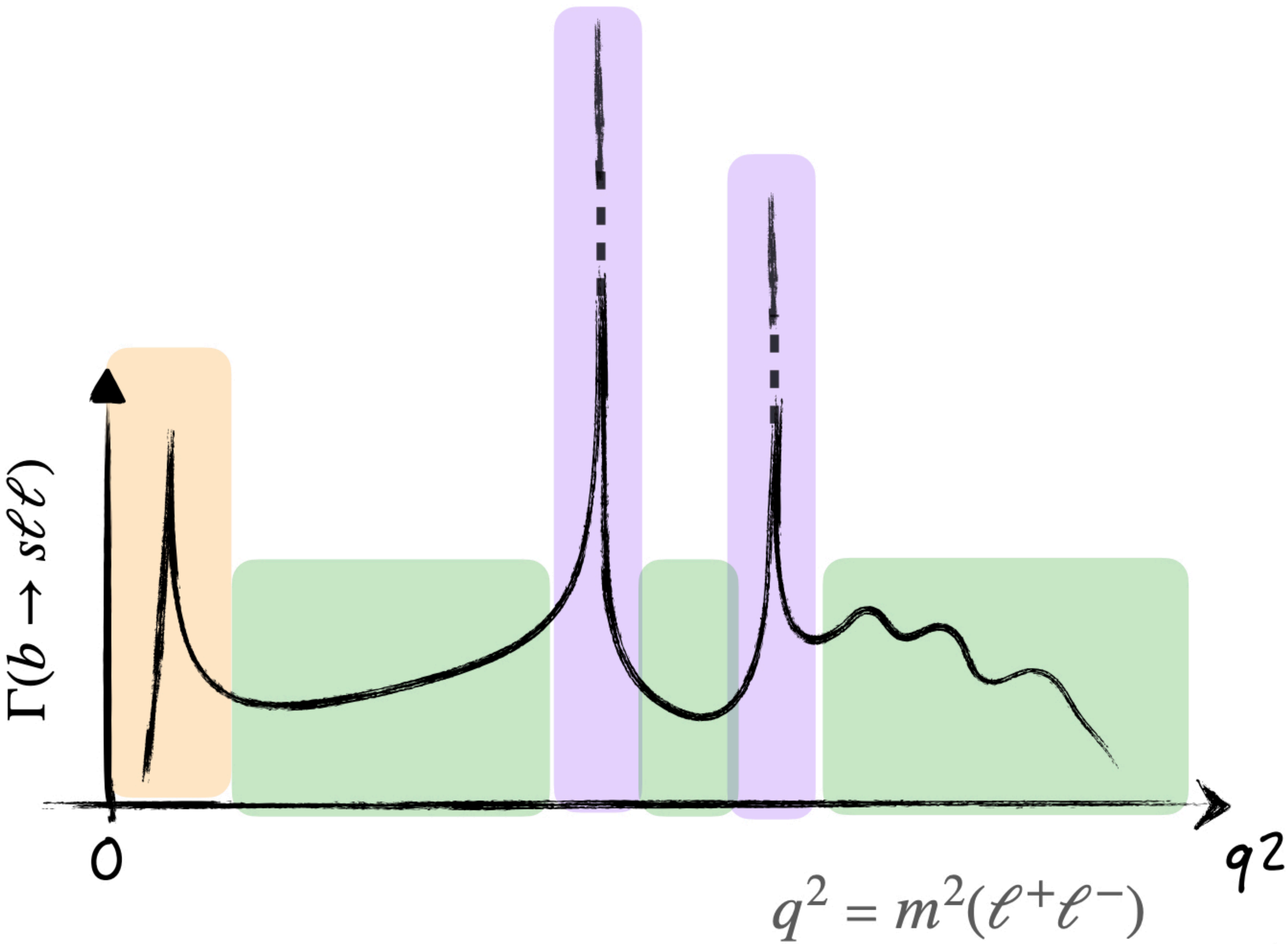
Charged current $\sim 3\sigma$



Neutral current $\sim 4 - 5\sigma$

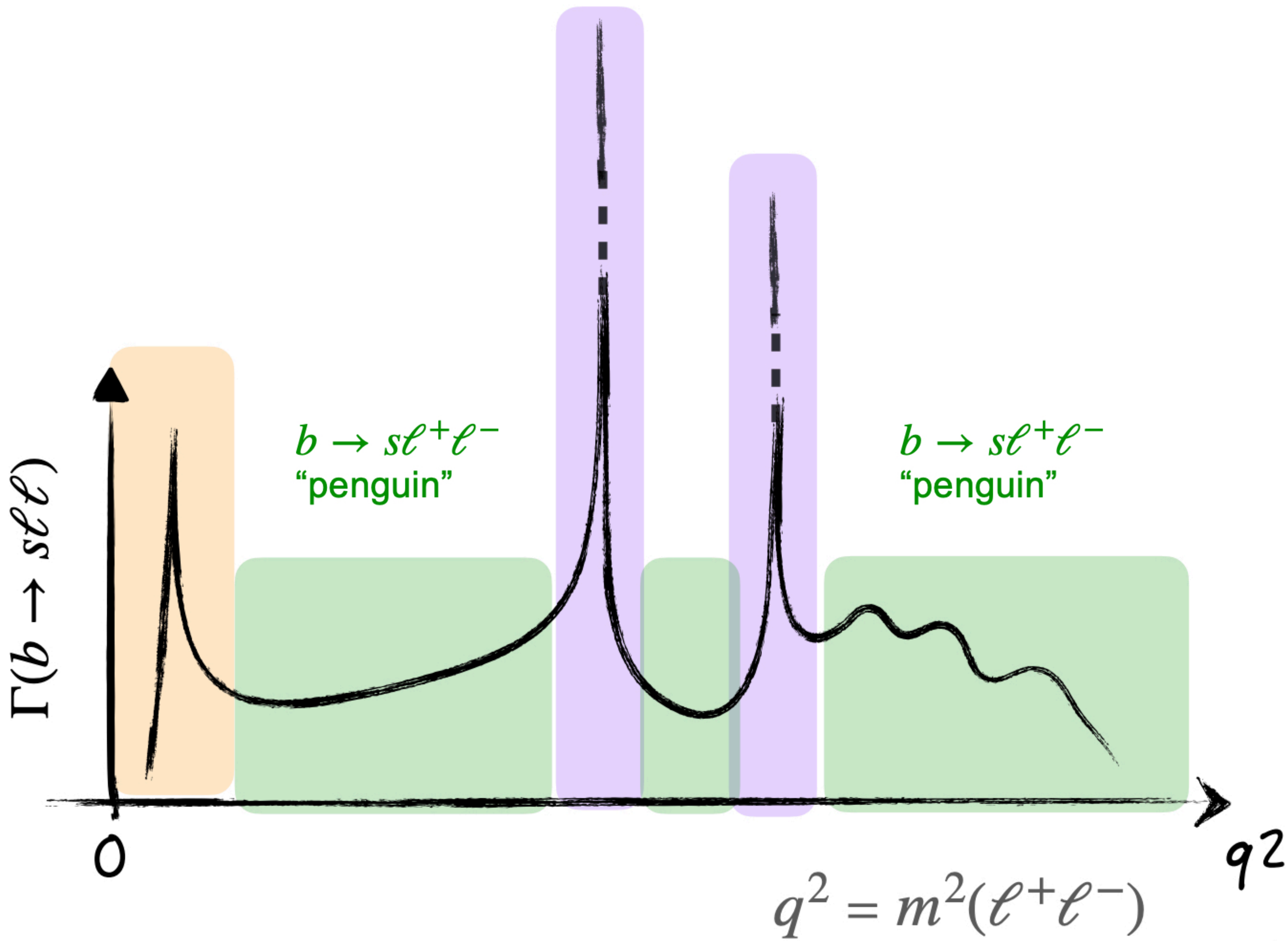
Focus of this talk

q^2 spectrum in $b \to sll$ transition



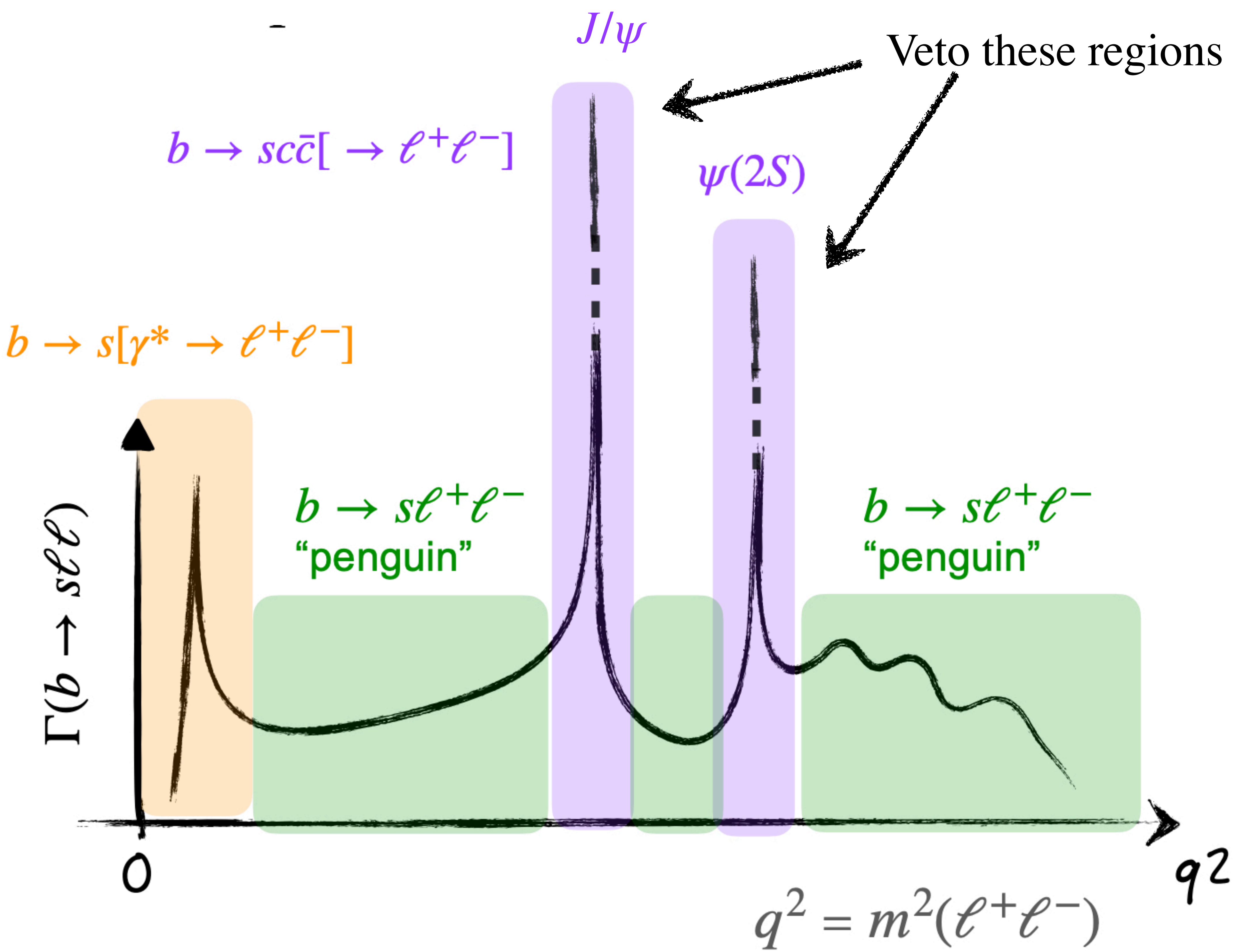
E. Smith

q^2 spectrum in $b \to sll$ transition



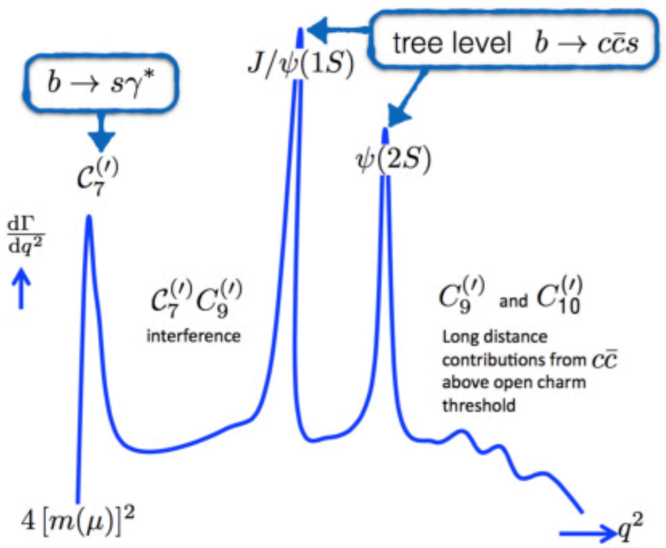
E. Smith

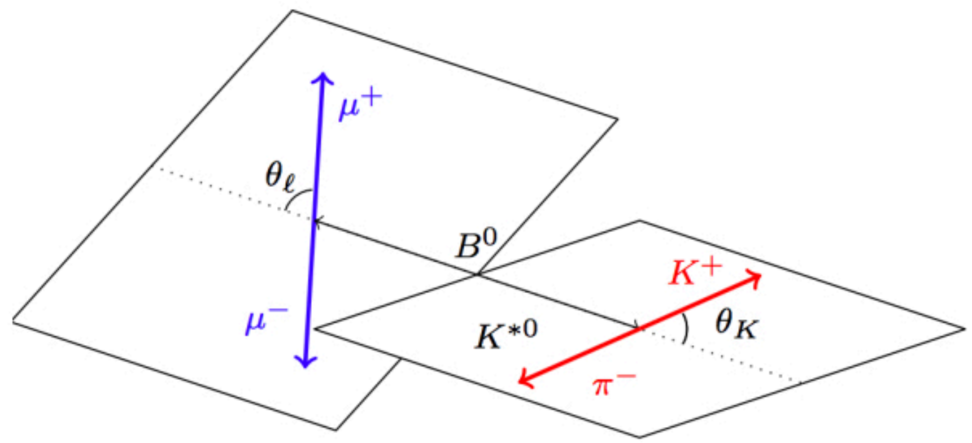
q^2 spectrum in $b \to sll$ transition

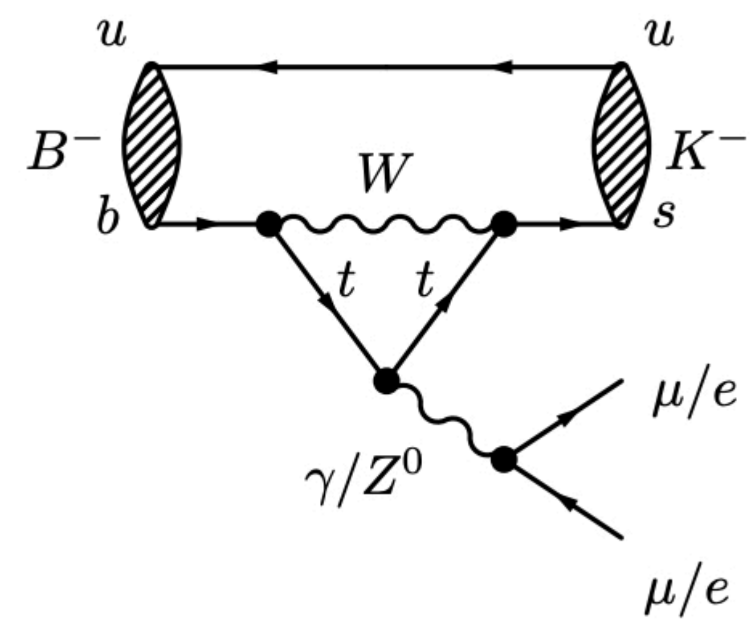


E. Smith

Experimental observables







Branching fractions
Simpler for LHC (focus on μ), but large theory uncertainties

Angular observables
Minimal FF uncertainties, though sensitive to charm loops

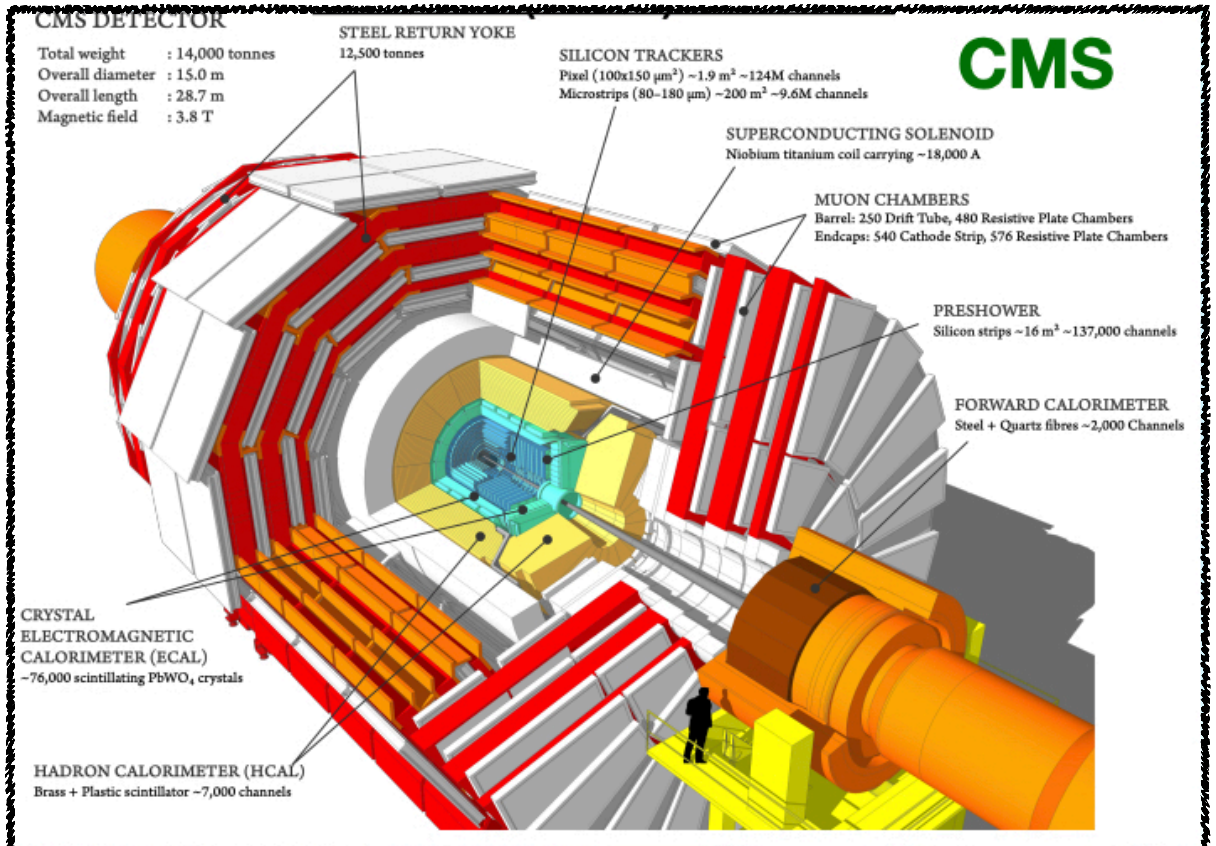
LFU ratios
Clean!
Theory uncertainties ~ 1%, but electrons harder at the LHC

Increasing precision of the SM prediction

Experiments

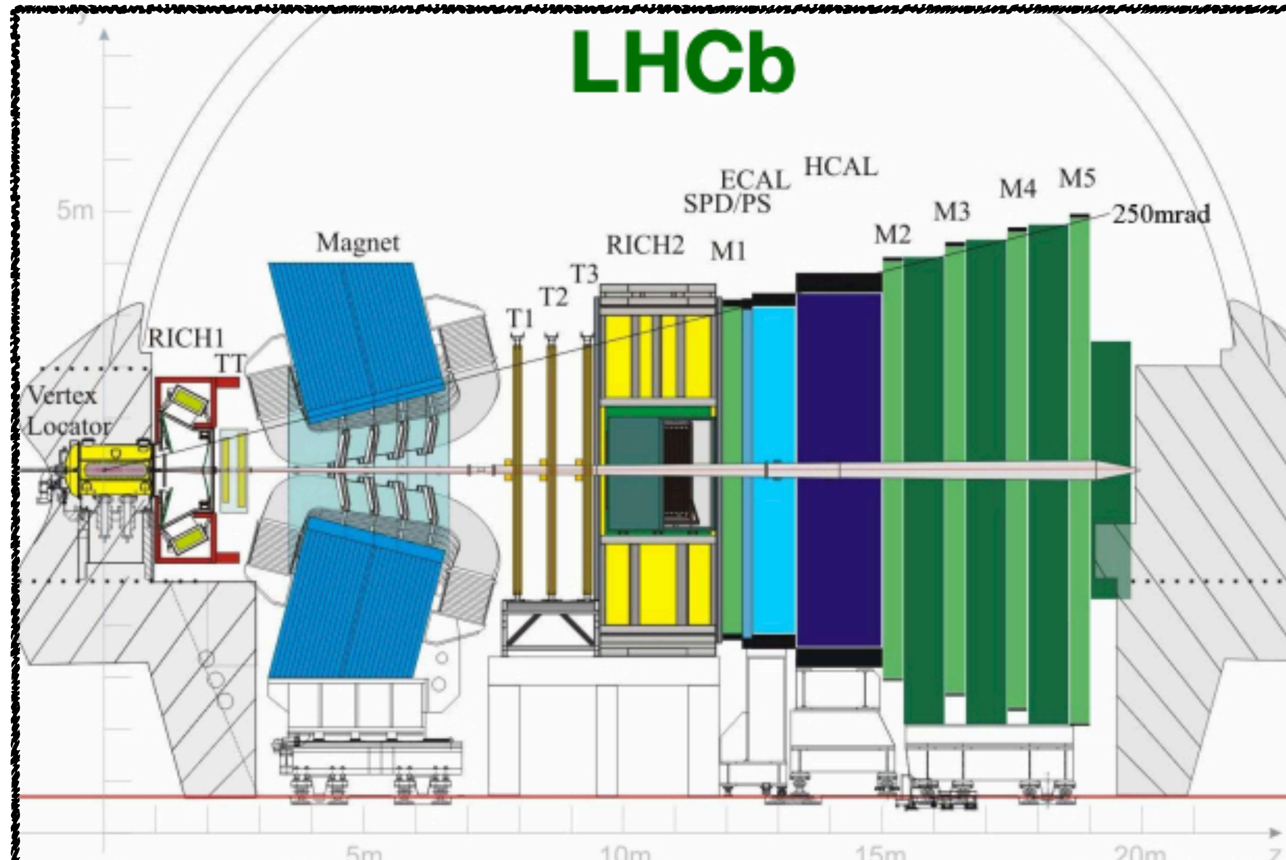
pp collisions at 7, 8, 13 TeV

JINST **3** (2008) S08004



- Accelerator: LHC
- General purpose detector
- Period: 2011 till now
- Collected 165 fb^{-1} data (Run 1 + 2)
- All species of B hadrons
- Plan: 3000 fb^{-1} (by end of HL-LHC)
- Very busy environment
- Low trigger efficiency
- Better with muons
- No charged hadron PID

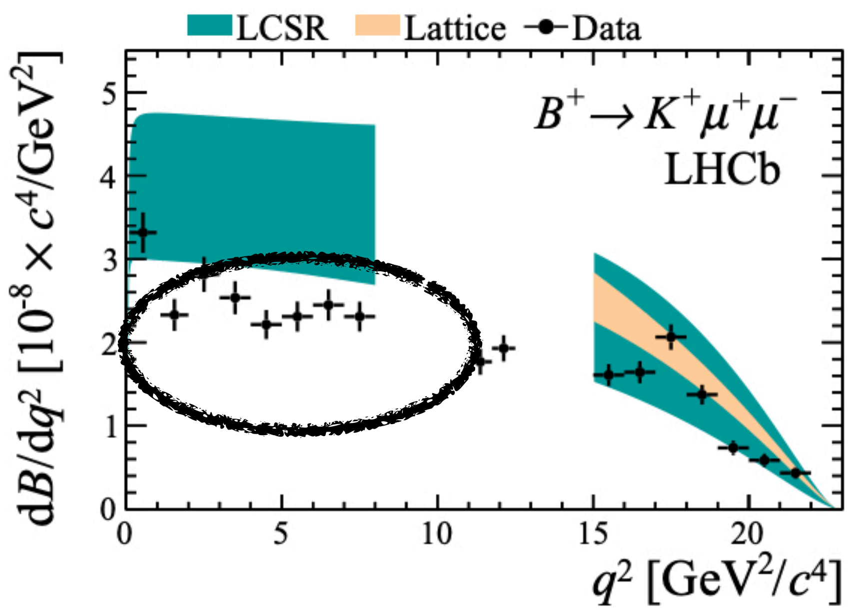
JINST **3** (2008) S08005



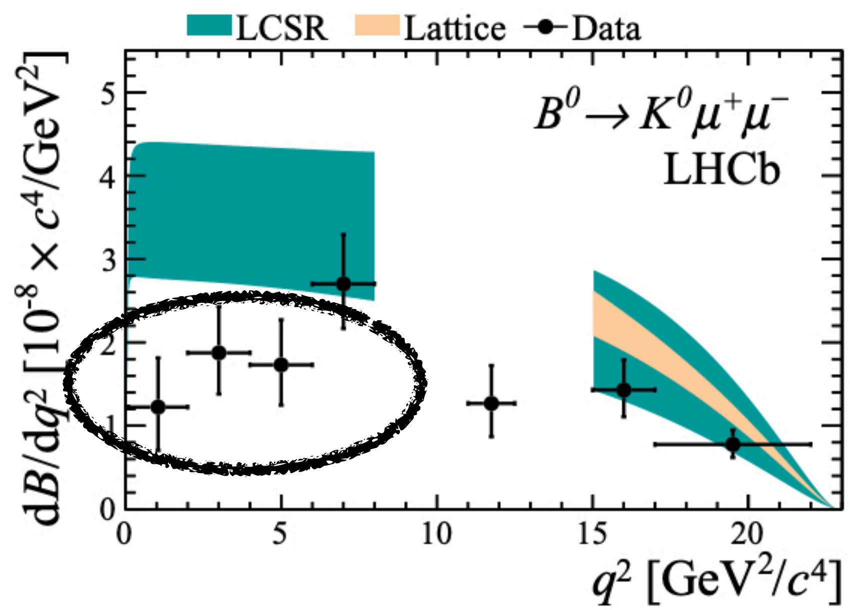
- Accelerator: LHC
- Forward-looking spectrometer
- Period: 2011 till now
- Collected 9 fb^{-1} data (Run 1 + 2)
- All species of B hadrons
- Plan: 300 fb^{-1} (by end of HL-LHC)
- Less busier environment than CMS
- Low trigger efficiency
- Better with tracks
- Excellent charged hadron PID

Branching Fractions

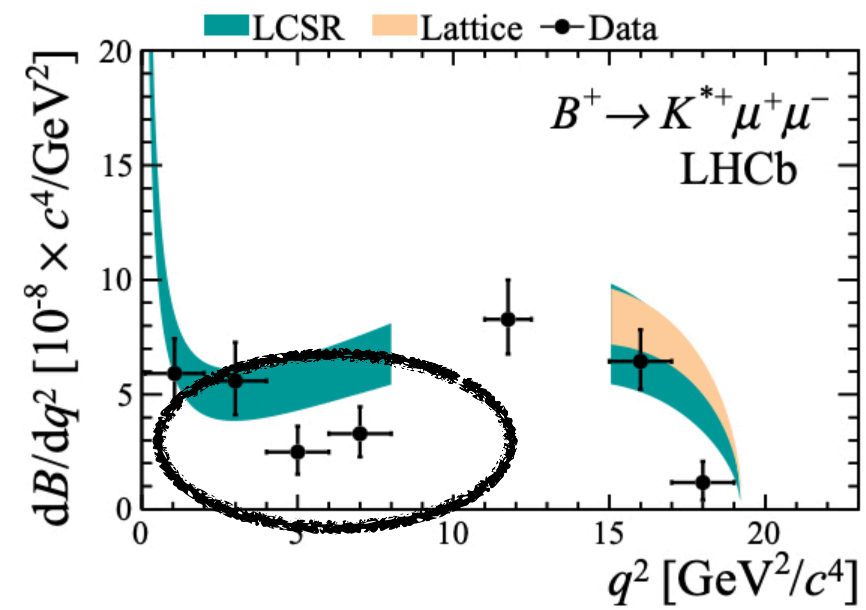
JHEP 06(2014) 133



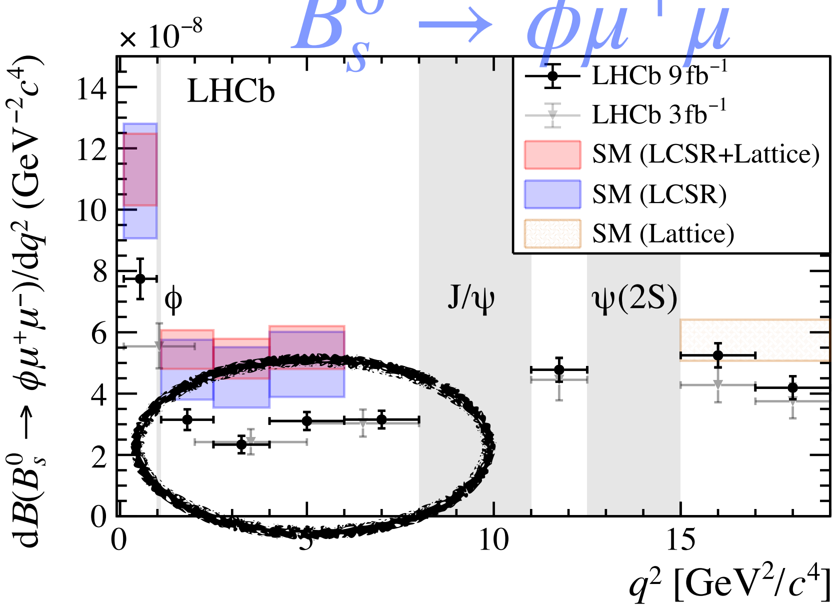
JHEP 06(2014) 133



JHEP 06(2014) 133

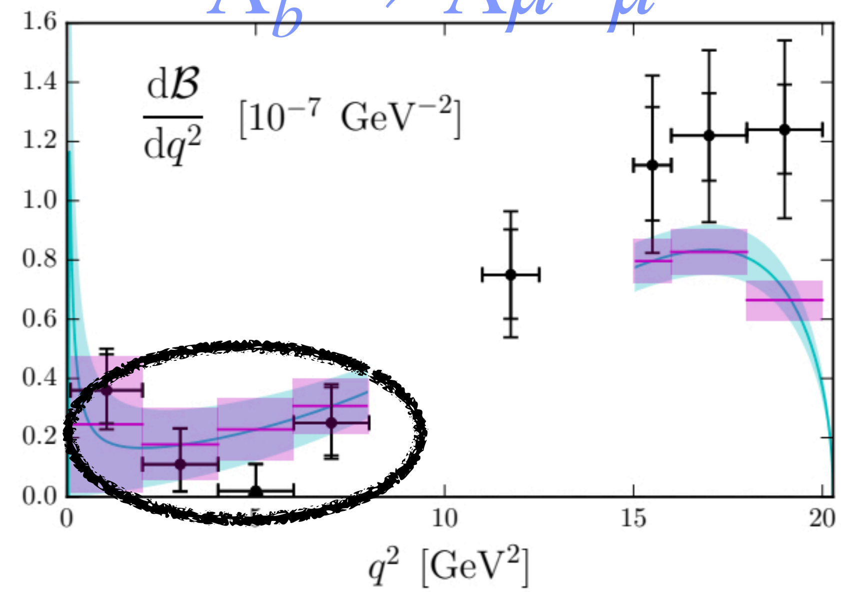


$B_s^0 \to \phi\mu^+\mu^-$



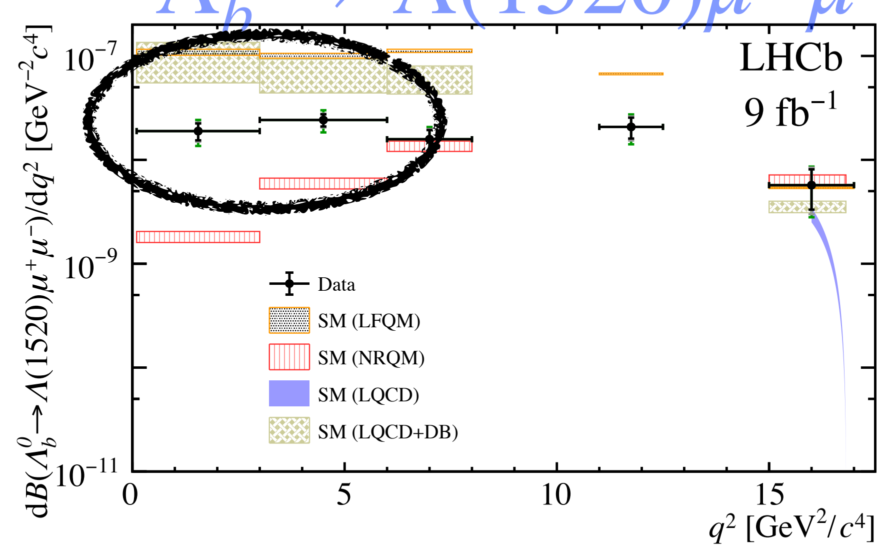
PRL 127(2021) 151801

$\Lambda_b \to \Lambda\mu^+\mu^-$



JHEP 06(2015) 115

$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

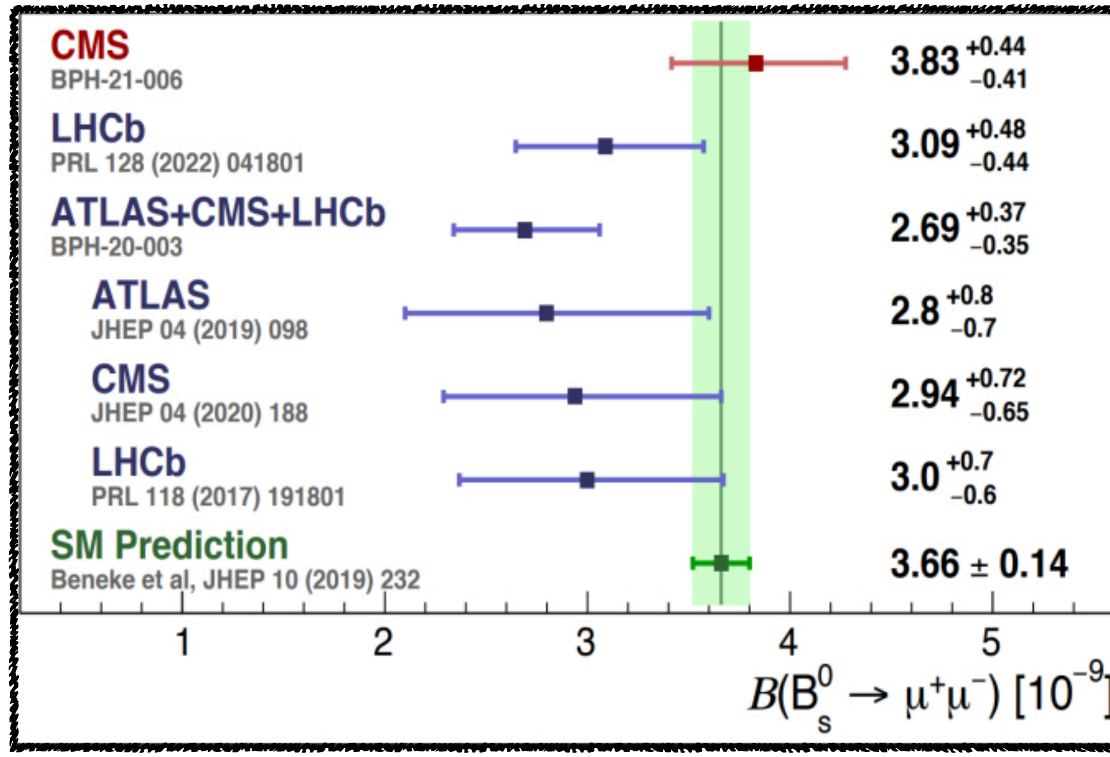


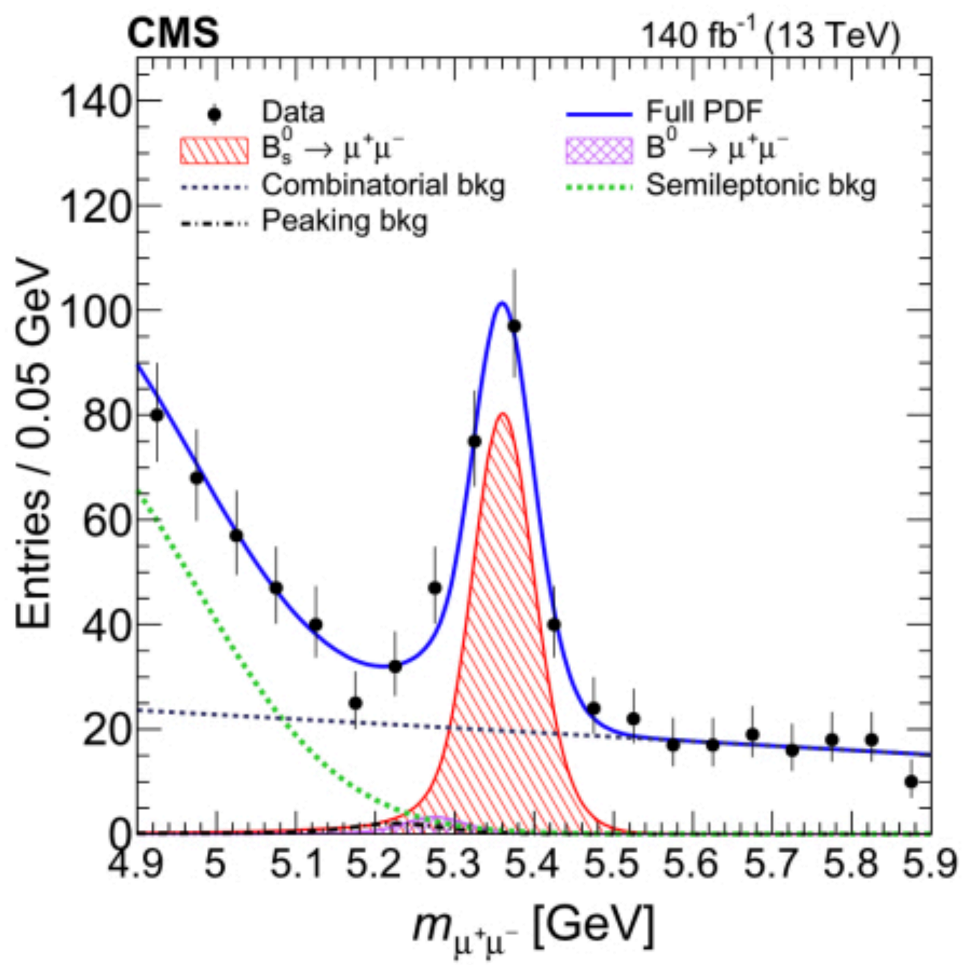
PRL 131(2023) 151801

Similar pattern observed, decay rate too low!!

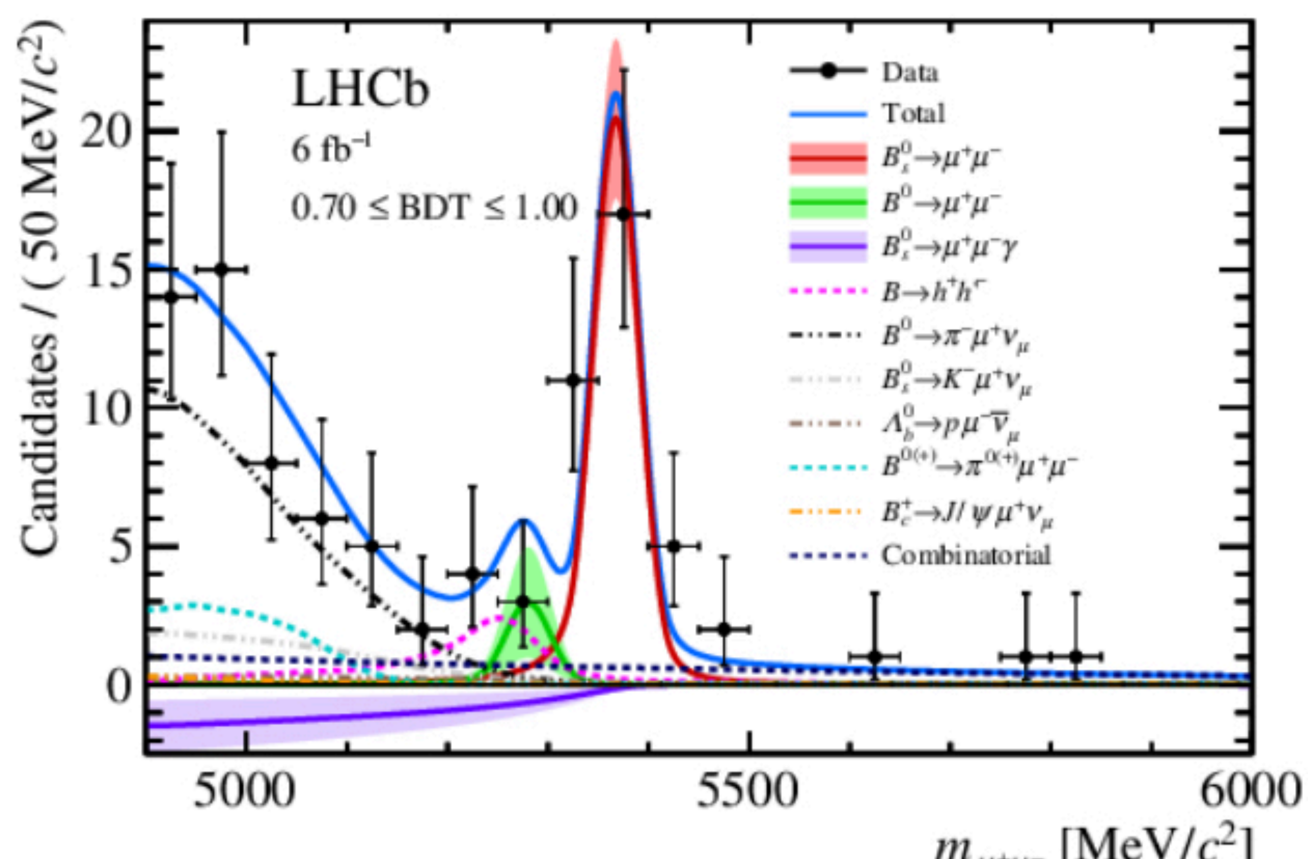
Fully leptonic decay $B_s^0 \to \mu^+\mu^-$

- Golden channel for searching New Physics
  - FCNC, highly suppressed in SM (helicity suppressed)
  - Hadronic contributions are clear and well known from Lattice QCD
- BF results are consistent with SM predictions





[Phys. Lett. B 842 (2023)]

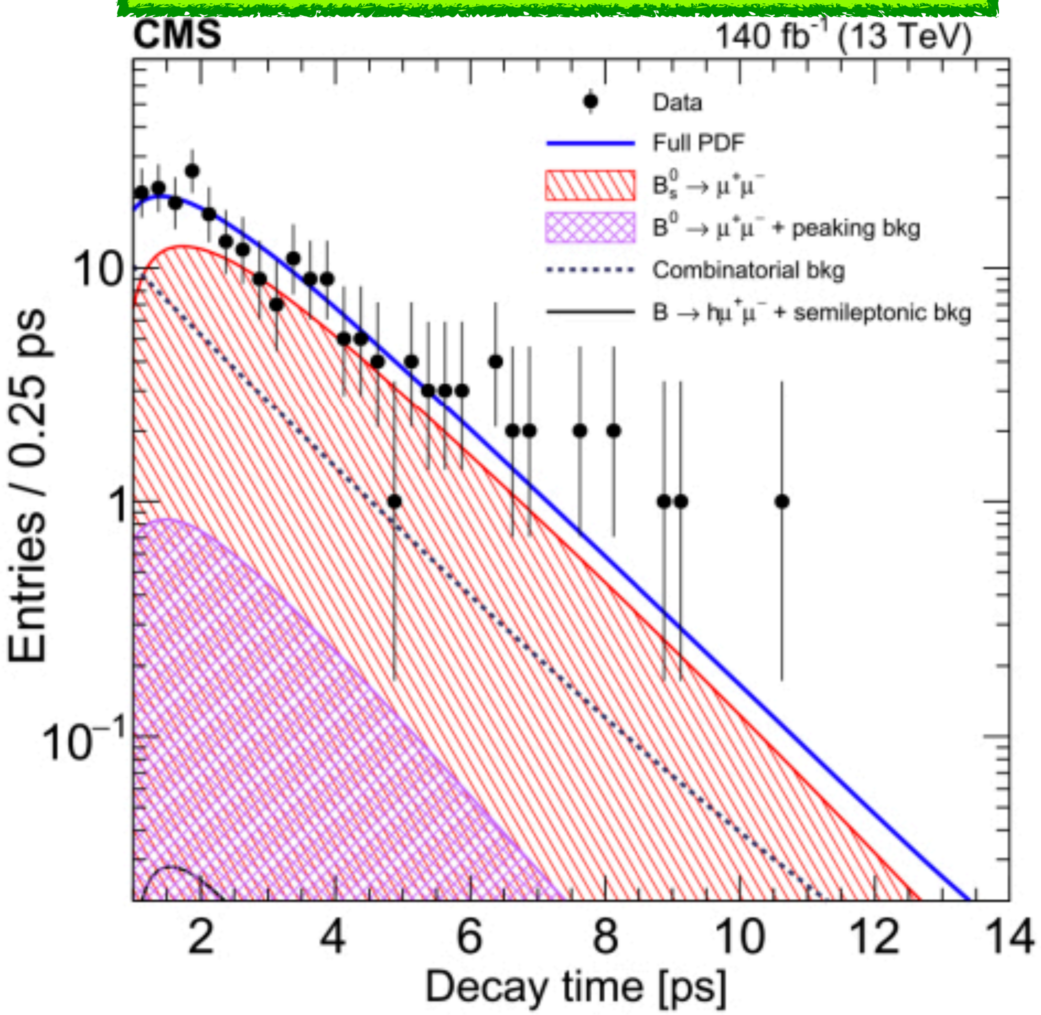


[Phys. Rev. D105 (2022)]
[Phys. Rev. Lett. 128, (2022)]

Well behaved $B_s^0 \to \mu^+\mu^-$

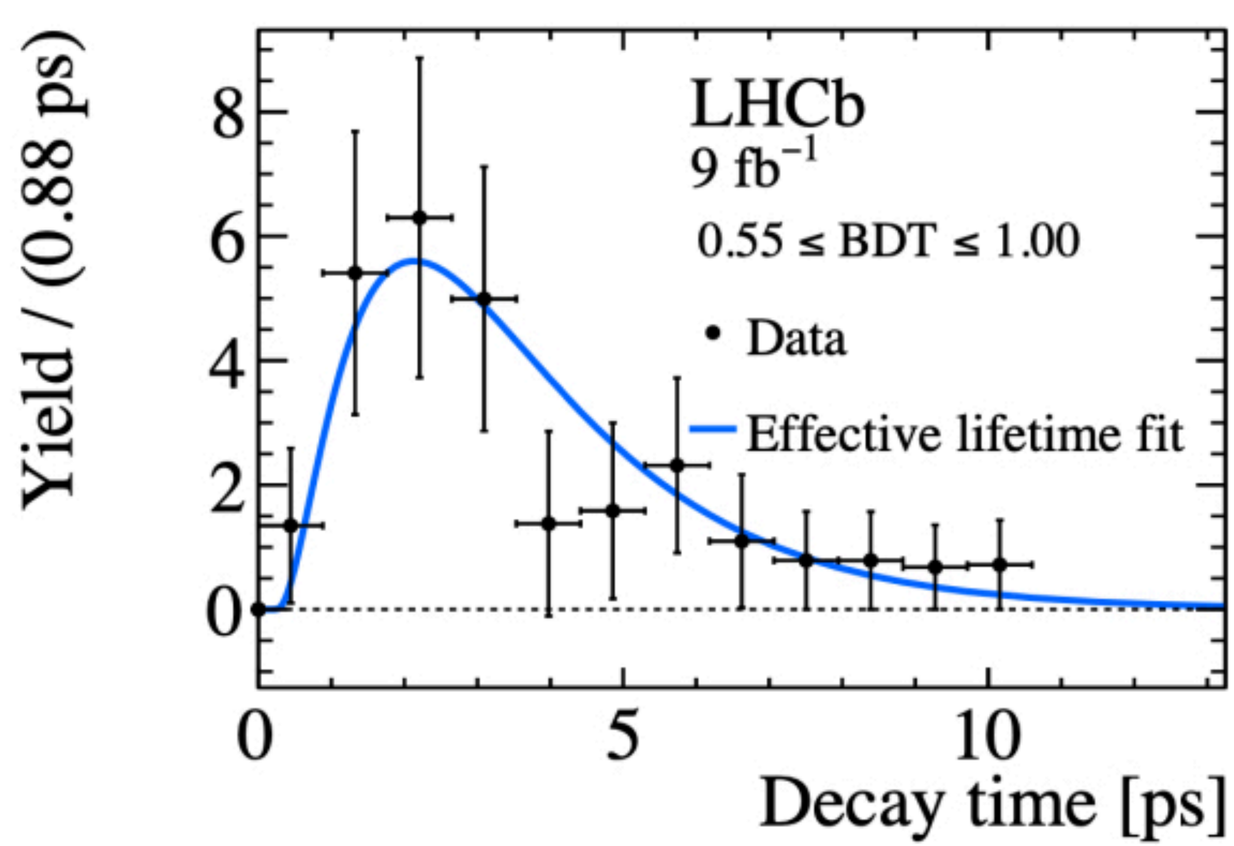
- Effective lifetime: in the SM, only the heavy mass eigenstate of the B_s^0 can decay to the $\mu^+\mu^-$ final state
- SM prediction $\tau_H = 1.624 \pm 0.009$ ps [PDG, PTEP 2022 (2022) 083C01]
- Overall, results well compatible with the SM predictions → stability of C_{10}

$\tau = 1.83^{+0.23}_{-0.20}(stat.) \pm 0.04(syst.)$ ps



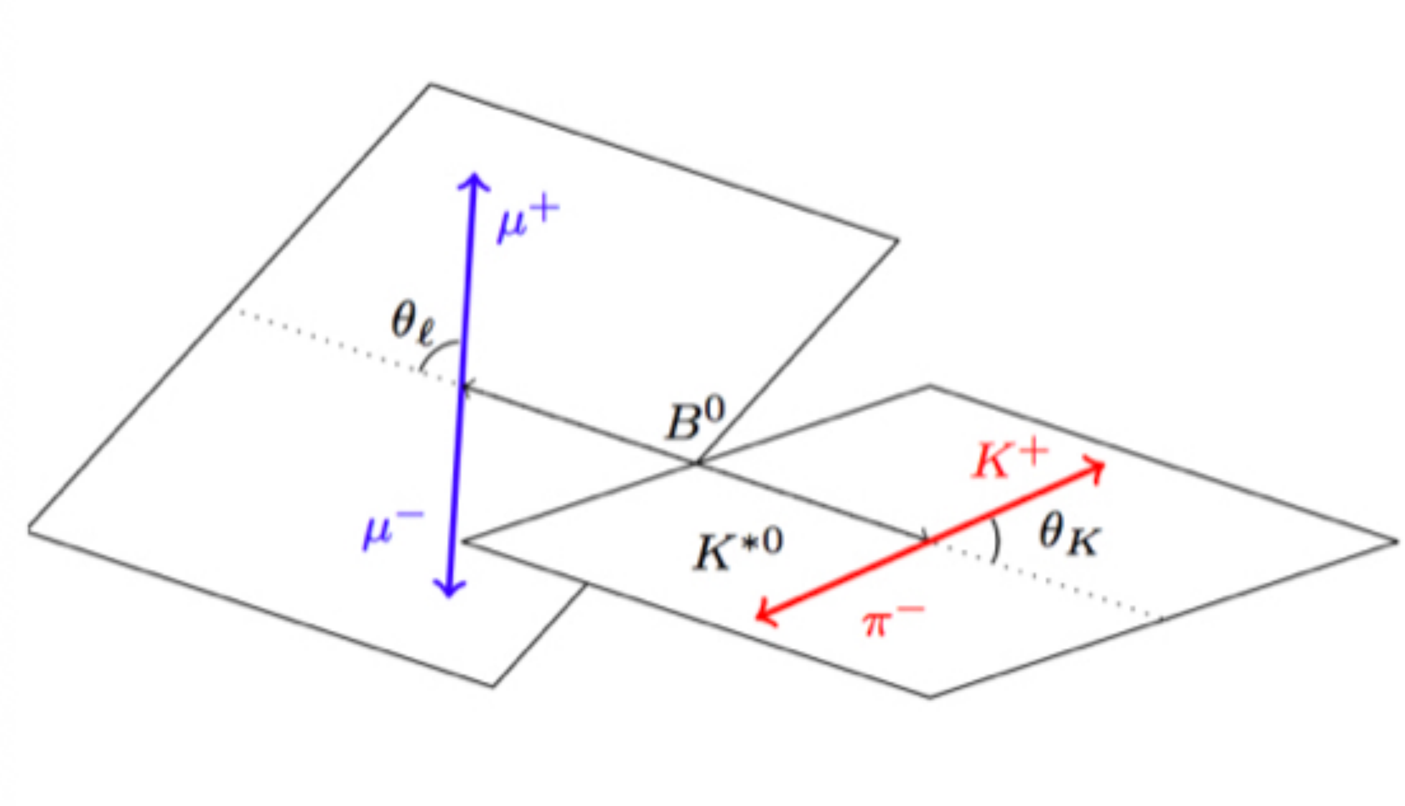
[Phys. Lett. B 842 (2023)]

$\tau = 2.07 \pm 0.29(stat.) \pm 0.03(syst.)$ ps



[Phys. Rev. D105 (2022)]
[Phys. Rev. Lett. 128, (2022)]

Angular Analysis $B \to V(\to h^+h^-)\mu^+\mu^-$



Vector (spin 1)

- 3 polarisation amplitudes

Measure decay rate across three angles (Ω) and q^2

- perform in the bins of q^2

angular coefficients - function of amplitudes

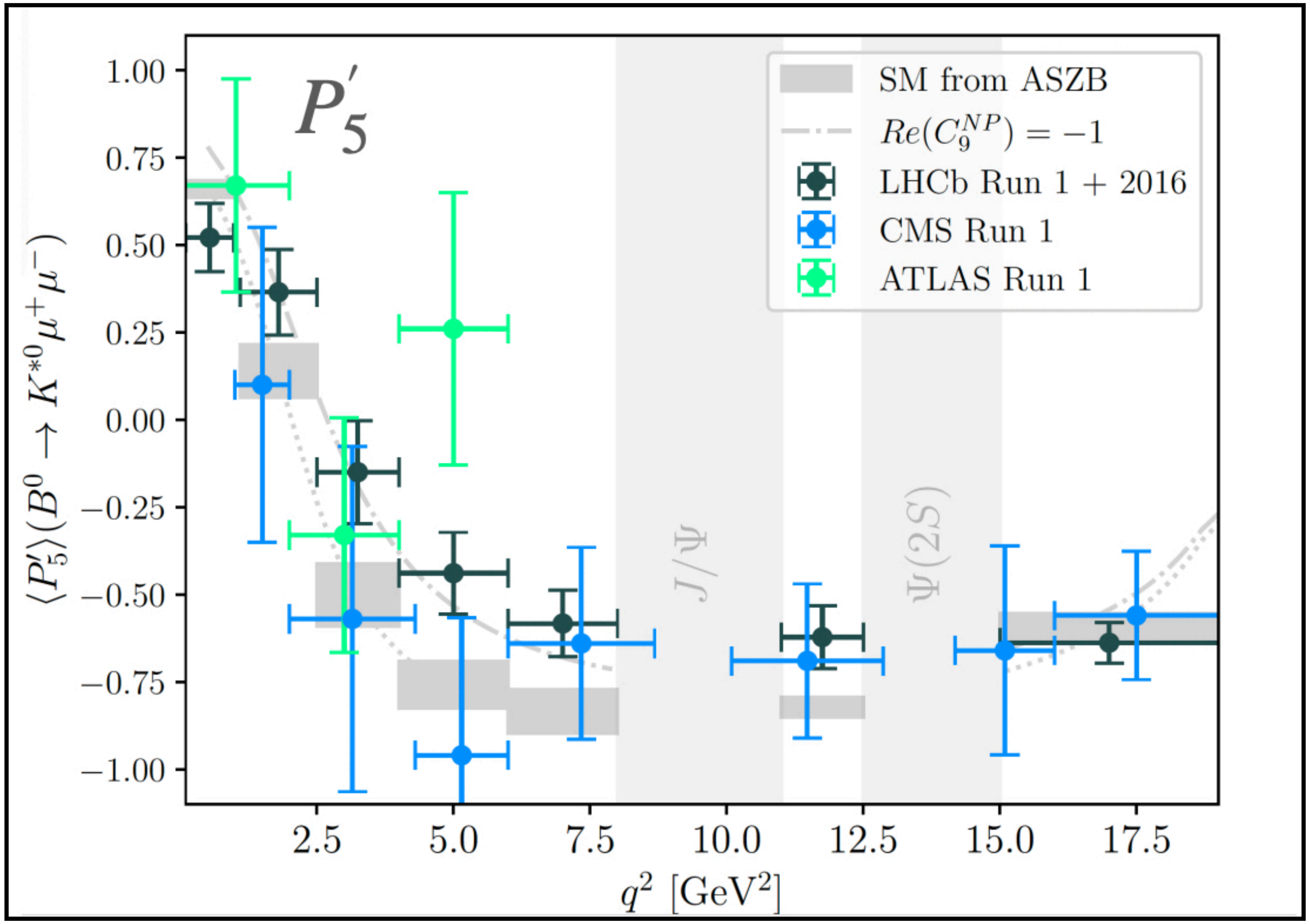
$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i I_i(q^2) f_i(\Omega)$$

CP-averaged observables

Angular coefficients   Spherical harmonics

Example: $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

LHCb PRL 125, 011802 (2020)
ATLAS: JHEP 10 (2018) 047
CMS:PLB 781 (2018) 517541



$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+ (\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l$$
$$+ \frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+ \sqrt{(1-F_L)F_L}(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi)$$
$$- \sqrt{(1-F_L)F_L}(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi)$$
$$+ 2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi)\Big]$$

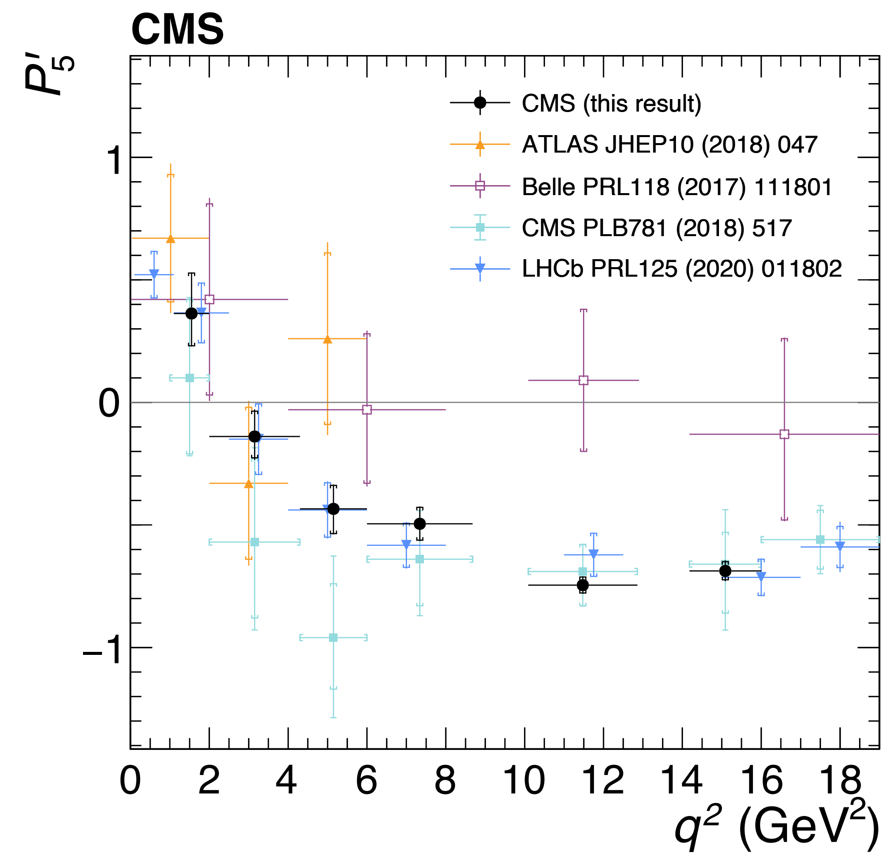
One of the clean angular observables

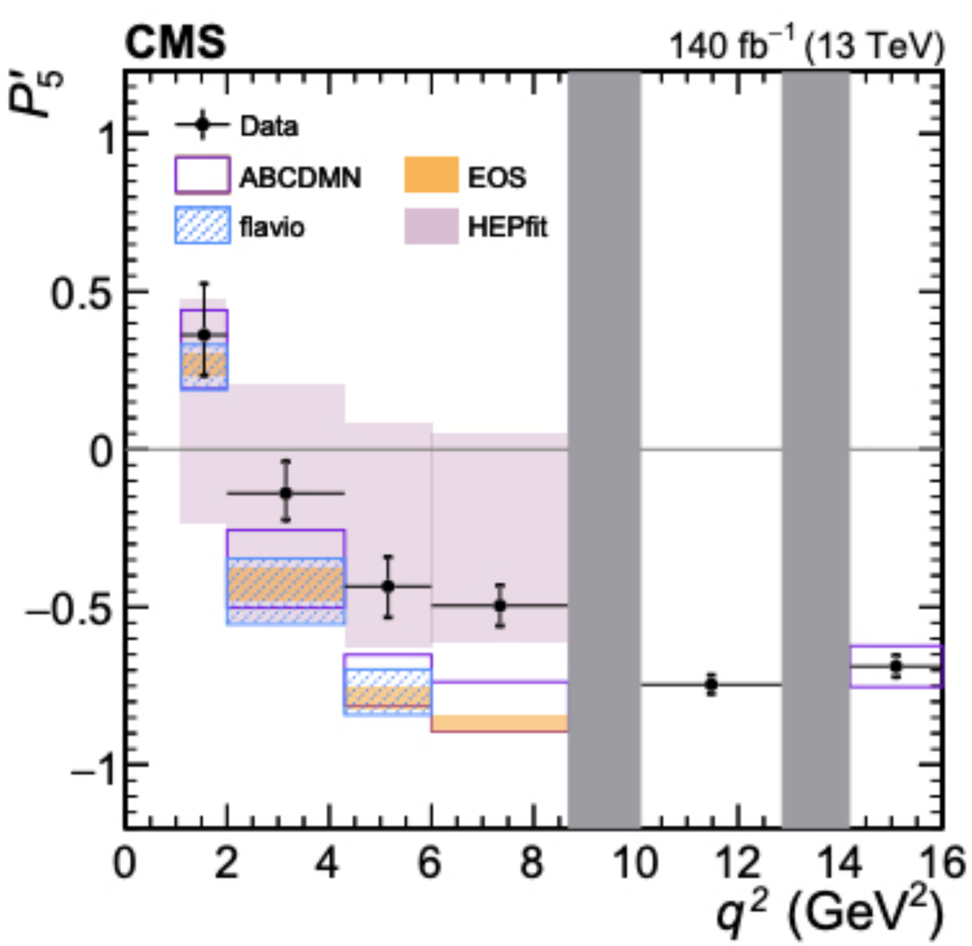
$B^0 \to K^{*0}\mu^+\mu^-$ from CMS

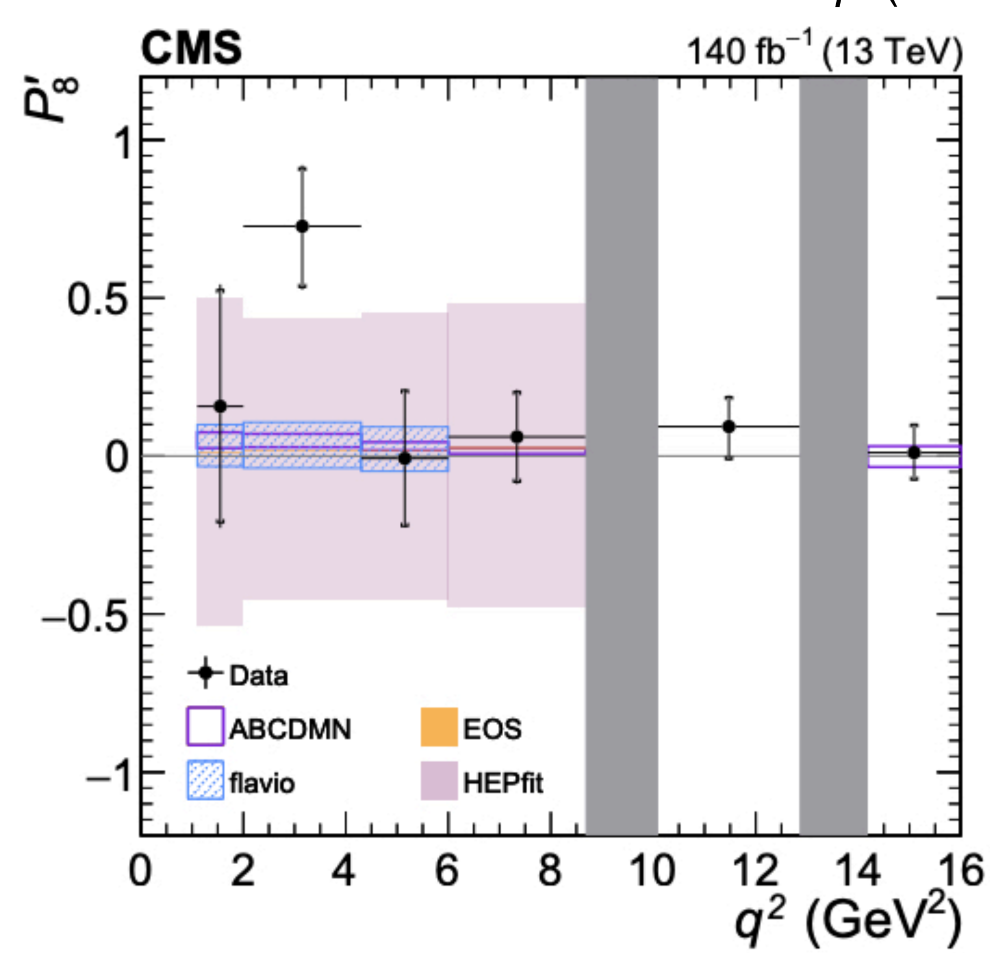
PLB 864 (2025) 139406

NEW

- Measurement updated with 140 fb^{-1} data
- Six bins over range $1.1 < q^2 < 16.0$ GeV^2/c^4
- Few observables (e.g P_2, P_5' and P_8') still in tension with SM prediction



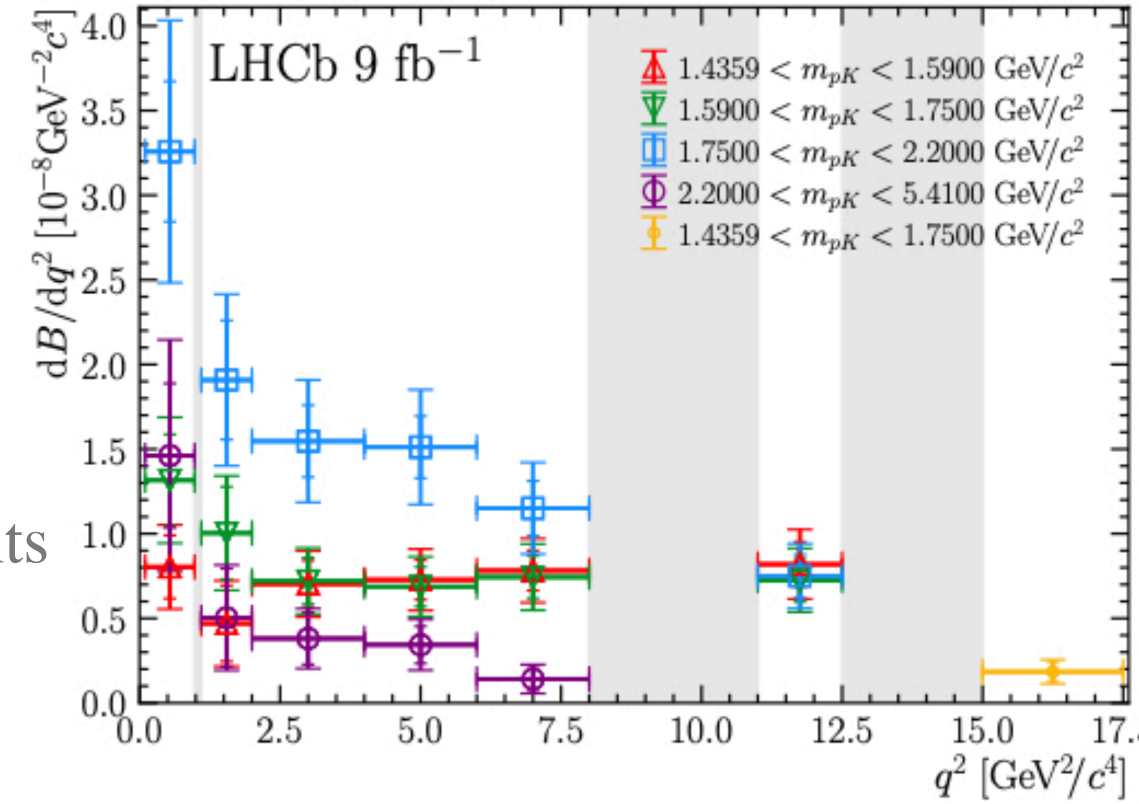


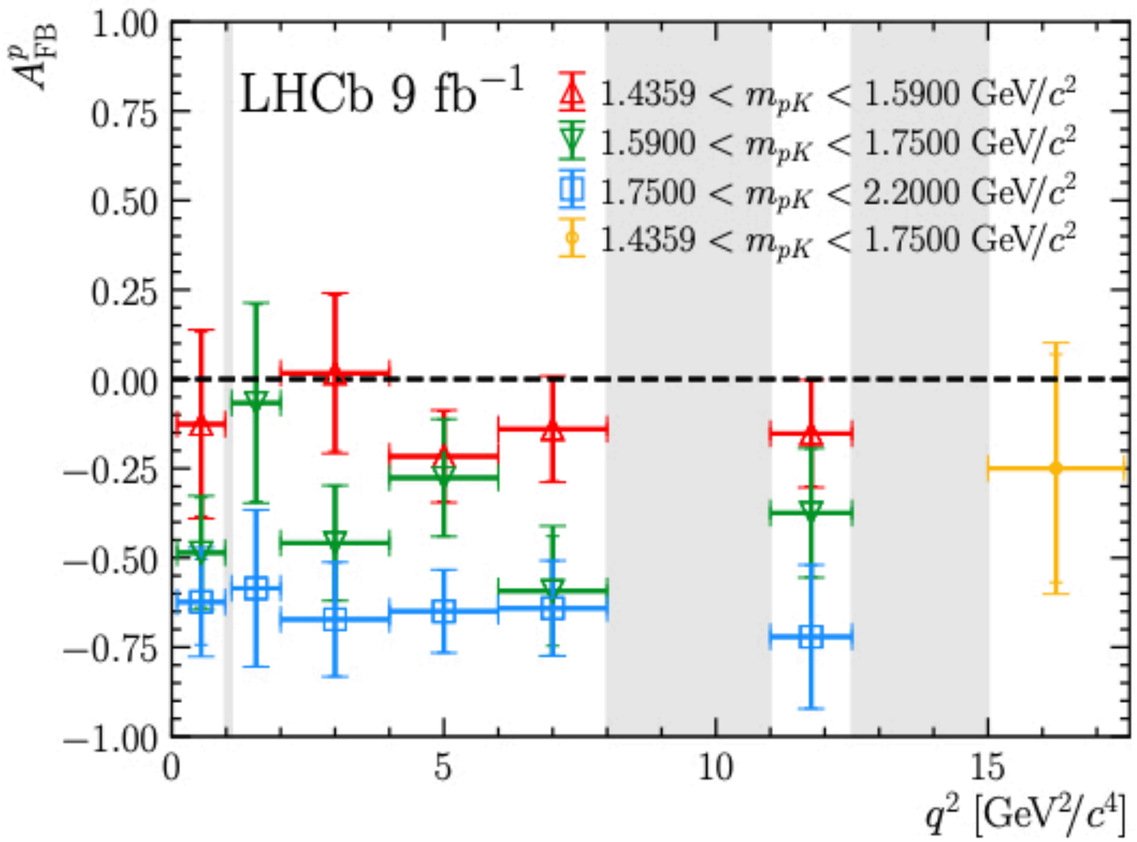


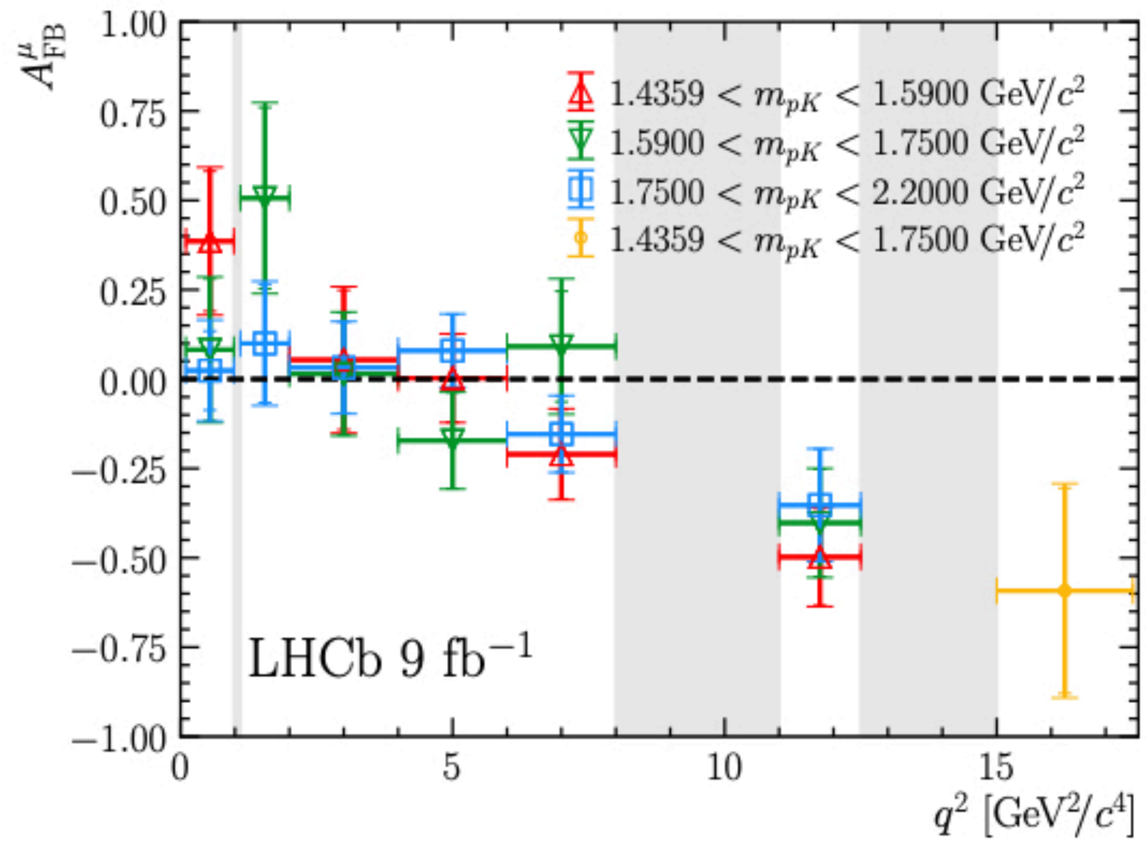
Angular analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$

JHEP 12 (2024) 147

- Measurement of branching fraction and angular observables in q^2 and m_{pK}
- $\Lambda_b^0 \to J/\psi pK^-$ used as normalisation mode
- Decay rate fully described by 46 angular moments
- Results compatible with SM







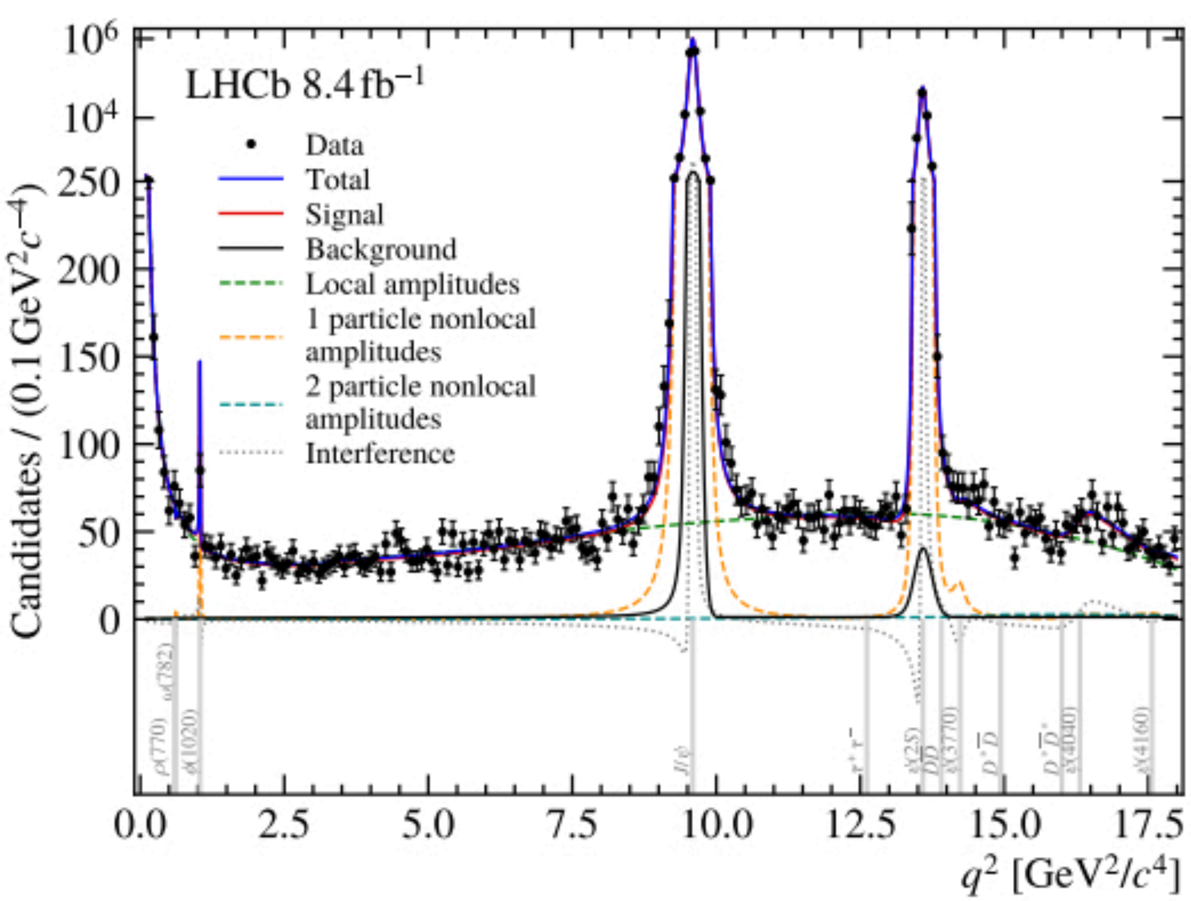
Amplitude analysis in $B^0 \to K^{*0}\mu^+\mu^-$

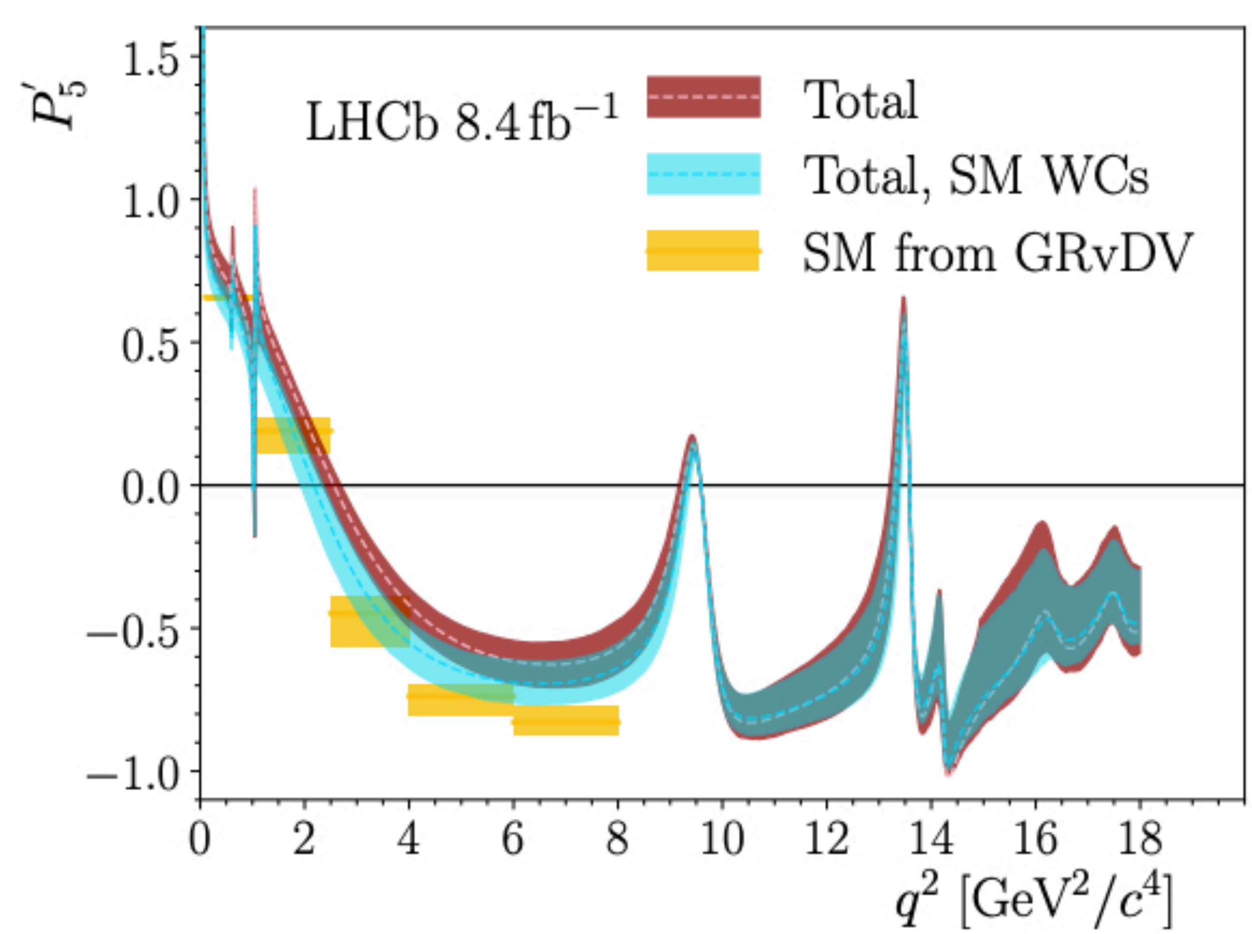
JHEP 09 (2024) 026

- Fit spectrum continuously to disentangle long (non-local) and short distance contributions
- Explicitly model non-local effects as a shift in $C_9^{eff,\lambda} = C_9 + Y_{q\bar{q},\lambda}(q^2)$
- $Y_{q\bar{q},\lambda}$ includes one-particle states i and two-particles states j

$i = \{\rho(770), \omega(782), \phi(1020), J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160)\}$
$j = \{D\bar{D}, D^*\bar{D}, D^*\bar{D}^*\}$

- Direct access to C_{9_τ} for the first time due to tau-scattering contribution



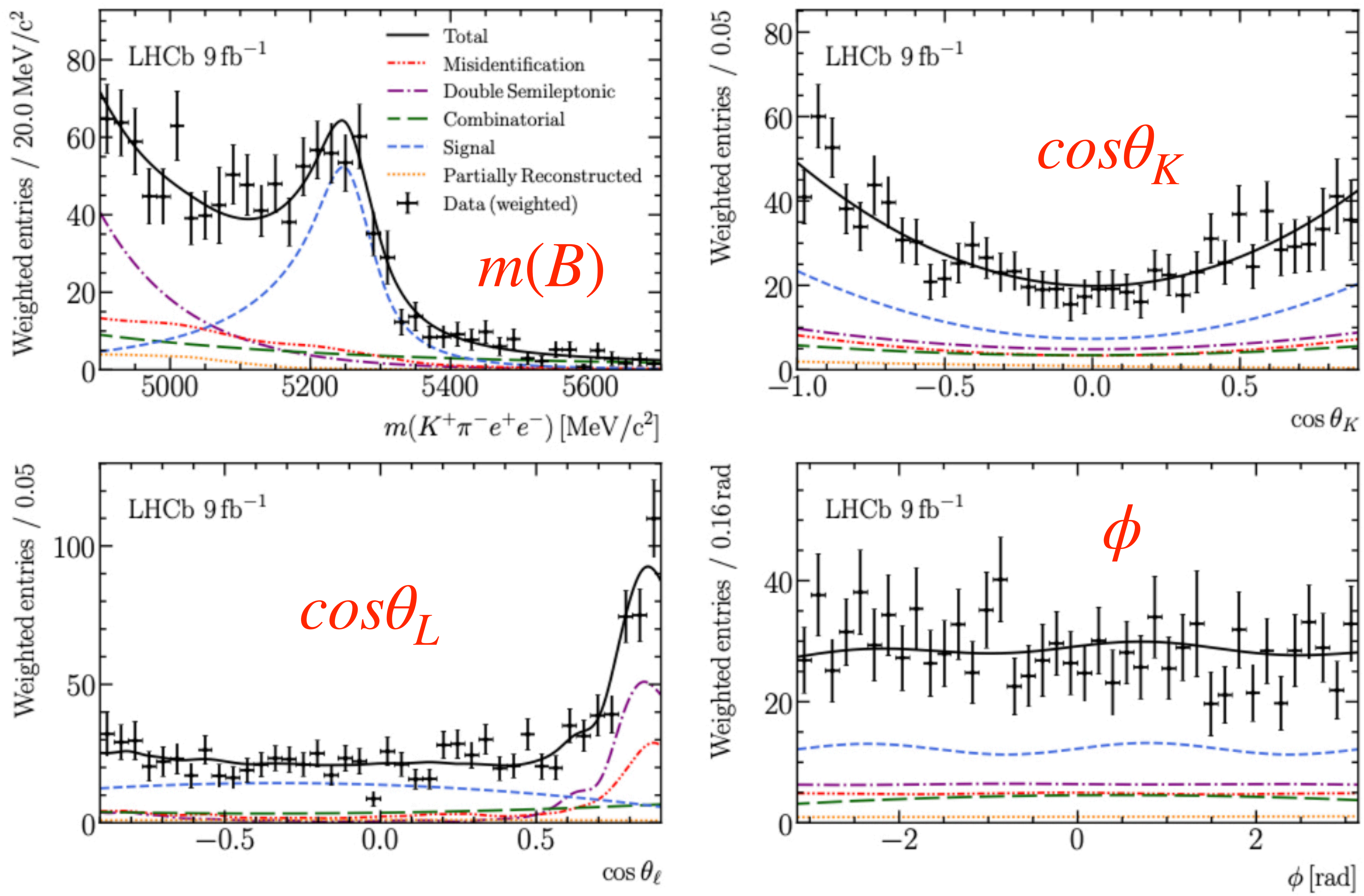


Angular Analysis $B^0 \to K^{*0}e^+e^-$

arXiv.2502.10291

- Angular observables extracted from 4D fit in central q² bin
- General good agreement with SM predictions ▸ most precise measurement till date

$q^2 \in [1.1, 6.0]$ GeV²/c⁴



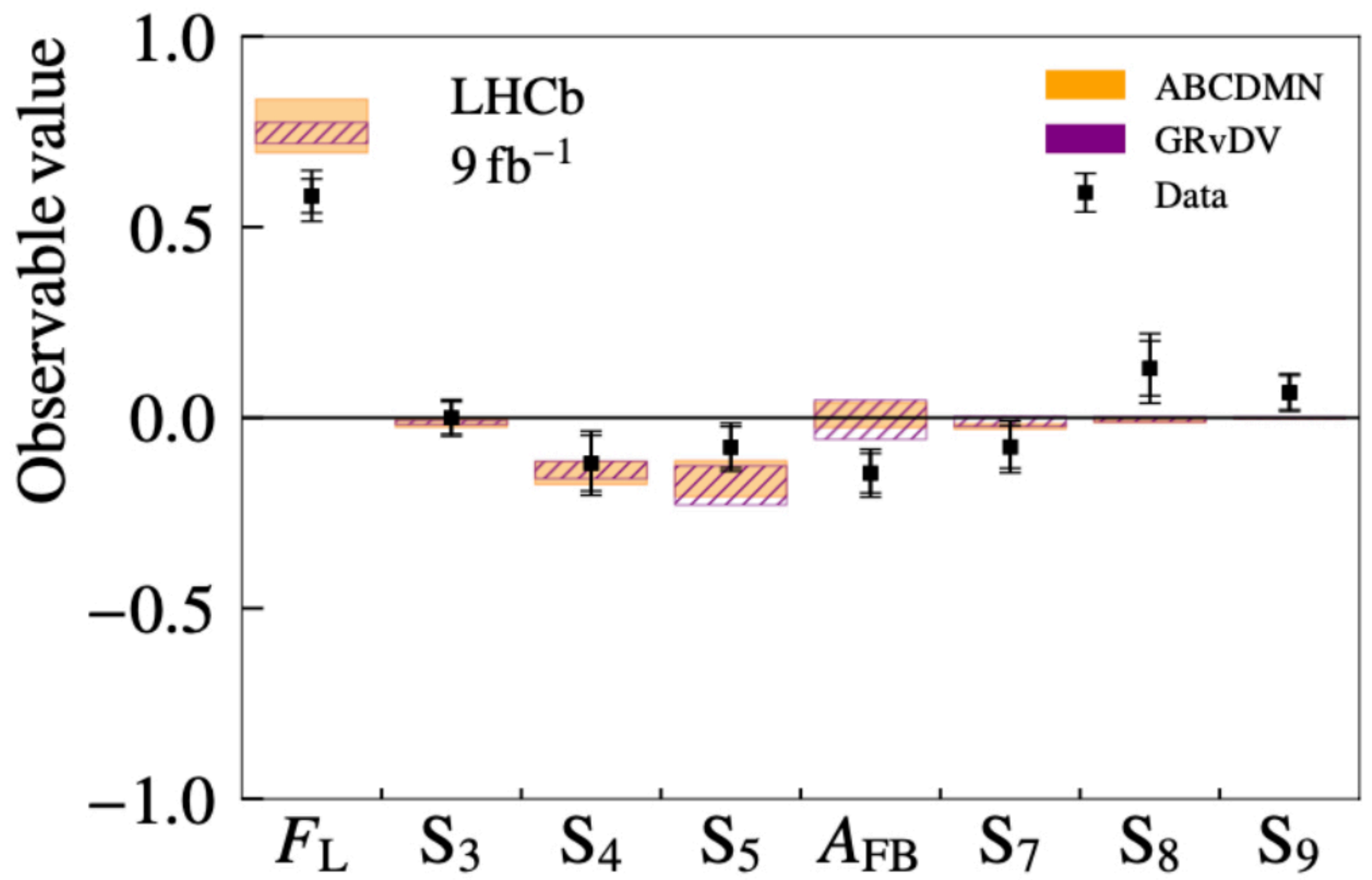
Result summary

arXiv.2502.10291

F_L	$0.582 \pm 0.045 \pm 0.050$
S_3	$-0.000 \pm 0.042 \pm 0.023$
S_4	$-0.119 \pm 0.073 \pm 0.042$
S_5	$-0.077 \pm 0.054 \pm 0.033$
A_{FB}	$-0.146 \pm 0.052 \pm 0.035$
S_7	$-0.077 \pm 0.056 \pm 0.038$
S_8	$0.129 \pm 0.072 \pm 0.056$
S_9	$0.066 \pm 0.045 \pm 0.020$

[N. Gubernari, M. Reboud, D. Van Dyk, J. Virto, JHEP 09 (2022) 133

[M. Algueró, A. Biswas, B.Capdevila, S. Descotes-Genon, J. Matias, EPJC 83 (2023) 7, 648



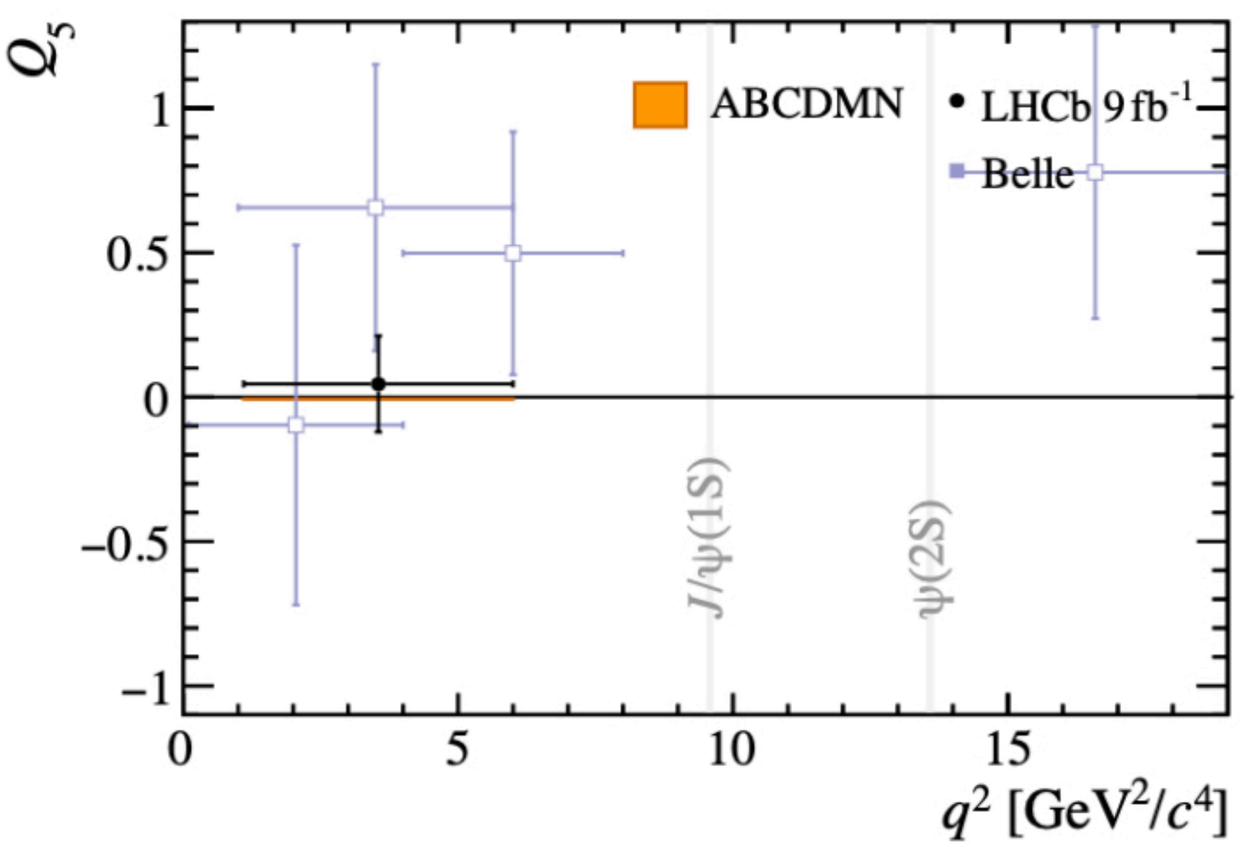
- Results in agreement with SM

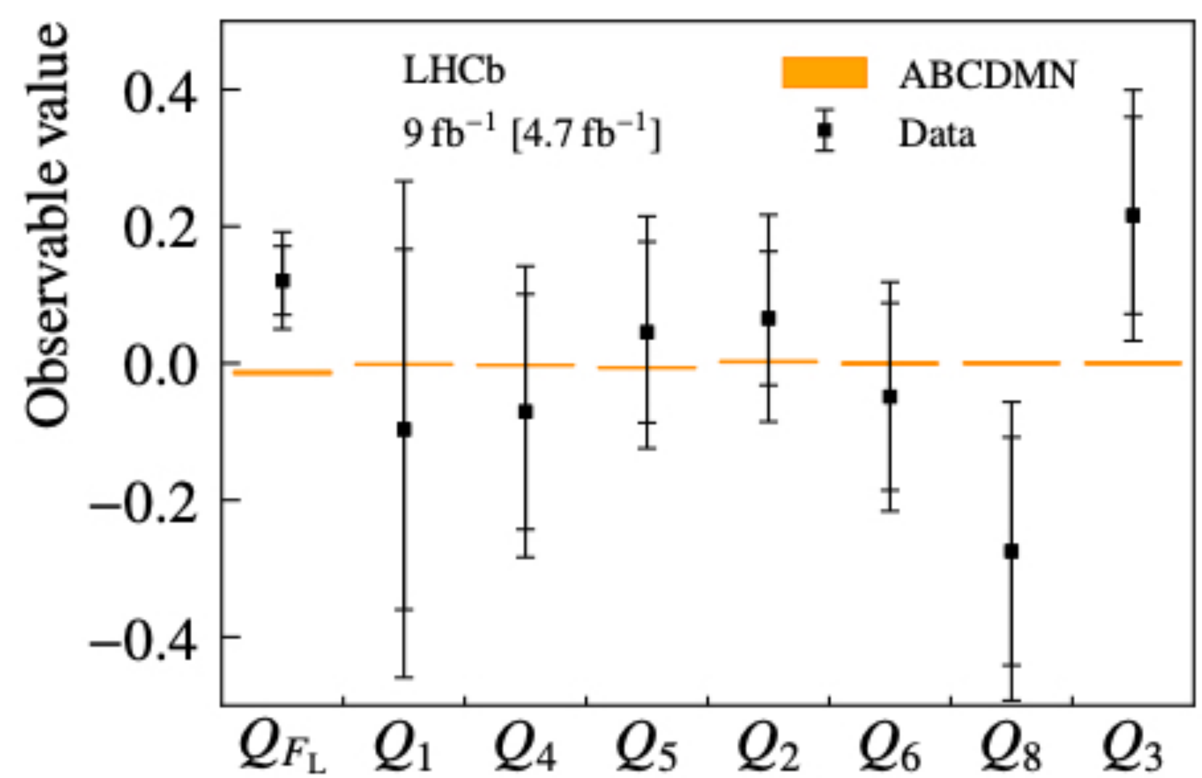
LFU test

arXiv.2502.10291

- Use the set of observables which are less sensitive to Form Factors
- Compare with the results from the muon fit (as in PRL 132 (2024) 131801)
- Construct LFU observables $Q_i = P_i^\mu - P_i^e$
    - Good agreement with SM predictions
    - No strong sign of LFU violation observed

$$P_1 = \frac{2S_3}{(1-F_L)},$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)},$$
$$P_3 = \frac{-S_9}{(1-F_L)},$$
$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



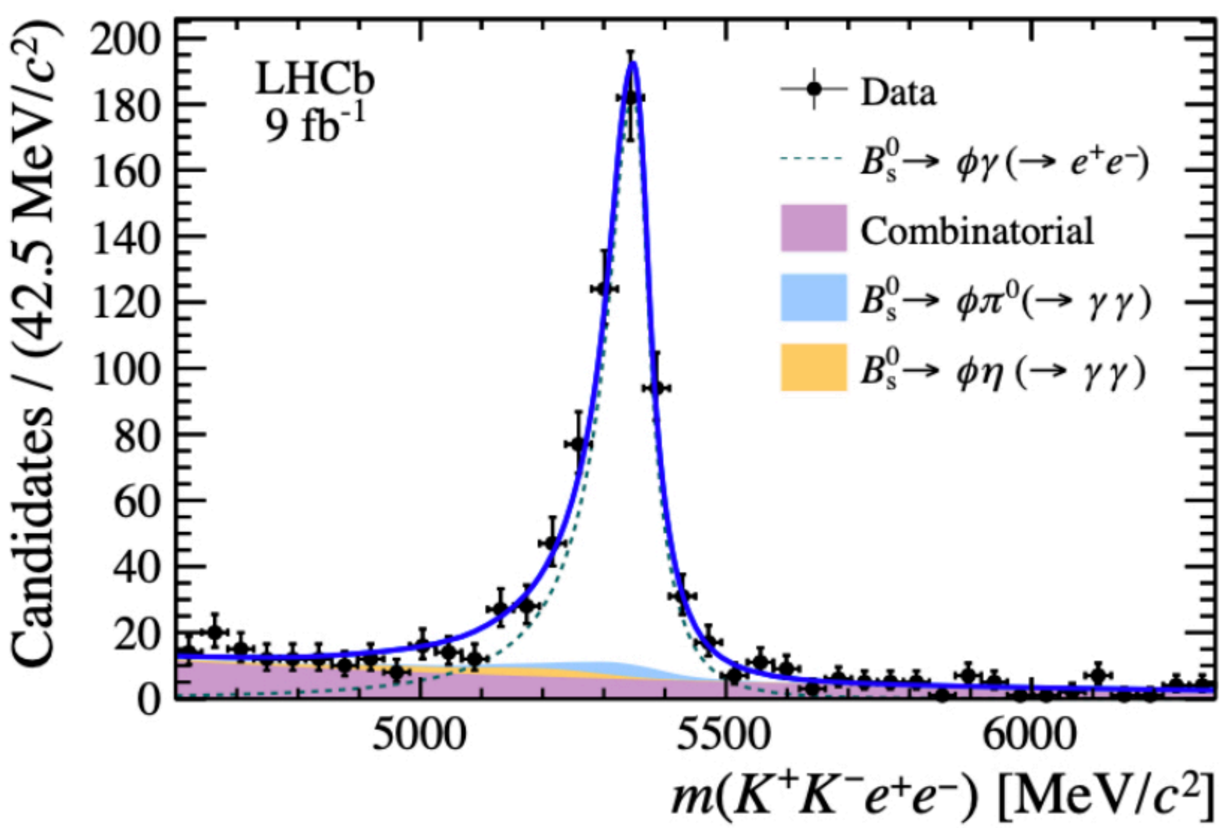


Photon polarisation constraints from $B_s^0 \to \phi e^+ e^-$

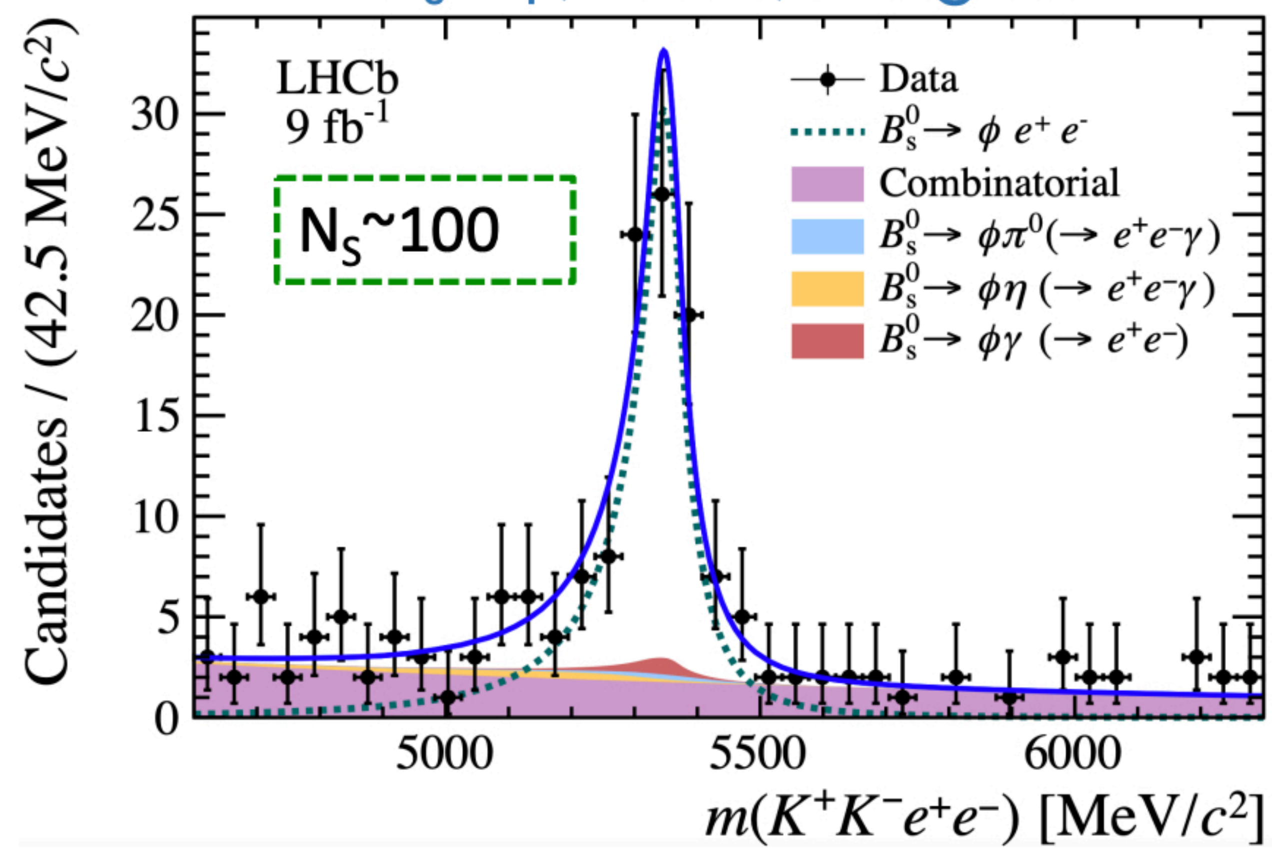
[JHEP 2025 (2025) 47]

- Very low q^2, angular observable sensitive to C_7, C_7'
- First observation of $B_s^0 \to \phi e^+ e^-$

$B_s \to \phi(\to K^+K^-)\gamma_{ee}$ control channel

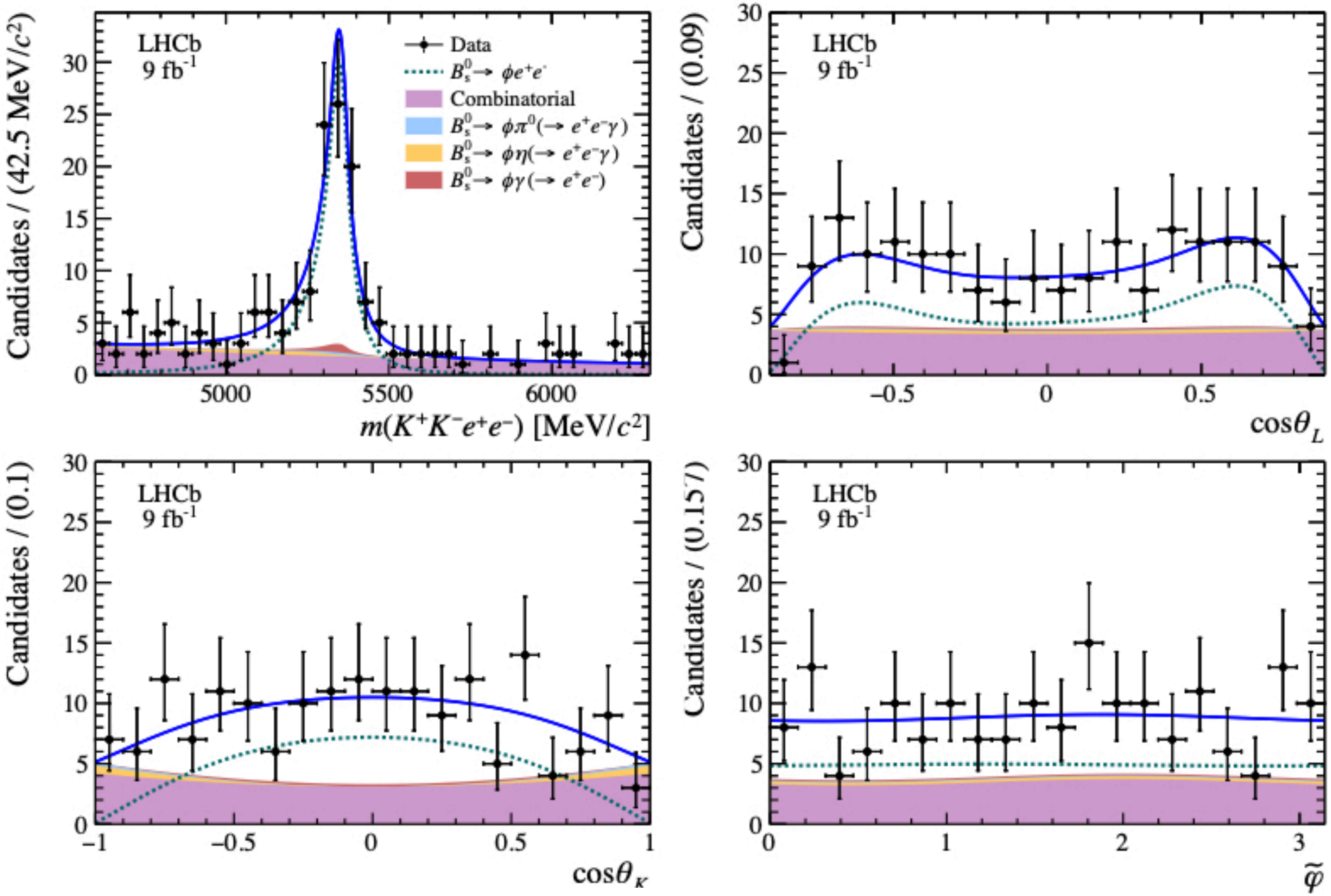


$B_s \to \phi(\to K^+K^-)ee$ signal



4D fit

[JHEP 2025 (2025) 47]



- Results in agreement with SM

$$A_T^{(2)} = -0.045 \pm 0.235 \pm 0.014$$ Sensitive to photon polarisation

$$A_T^{\mathcal{I}mCP} = 0.002 \pm 0.247 \pm 0.016$$

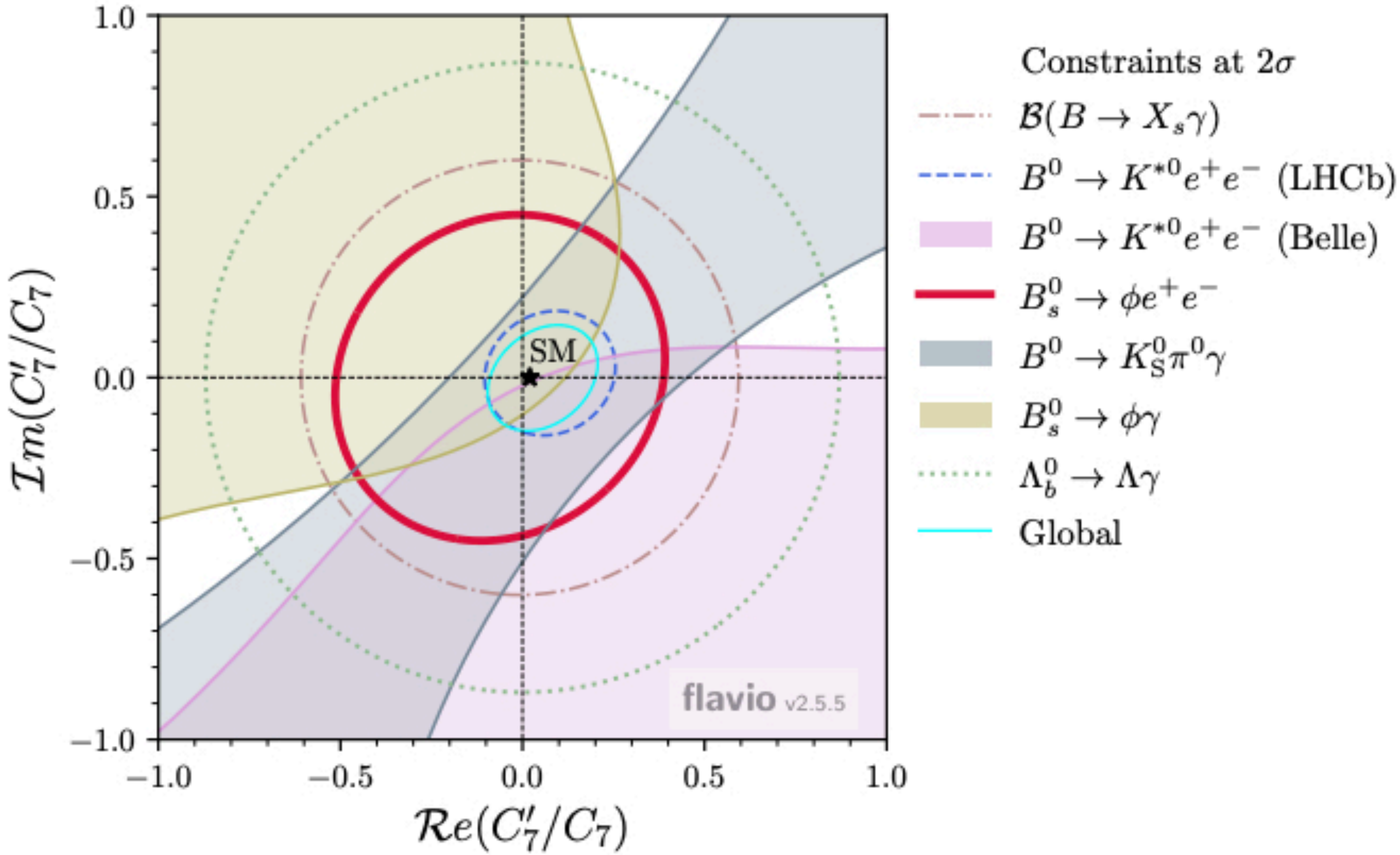
$$A_T^{\mathcal{R}eCP} = 0.116 \pm 0.155 \pm 0.006$$ Forward-backward asymmetry

$$F_L = (0.4 \pm 5.6 \pm 1.2)\%,$$ Longitudinal polarisation

Photon polarisation summary

[JHEP 2025 (2025) 47]

- Results in agreement with SM

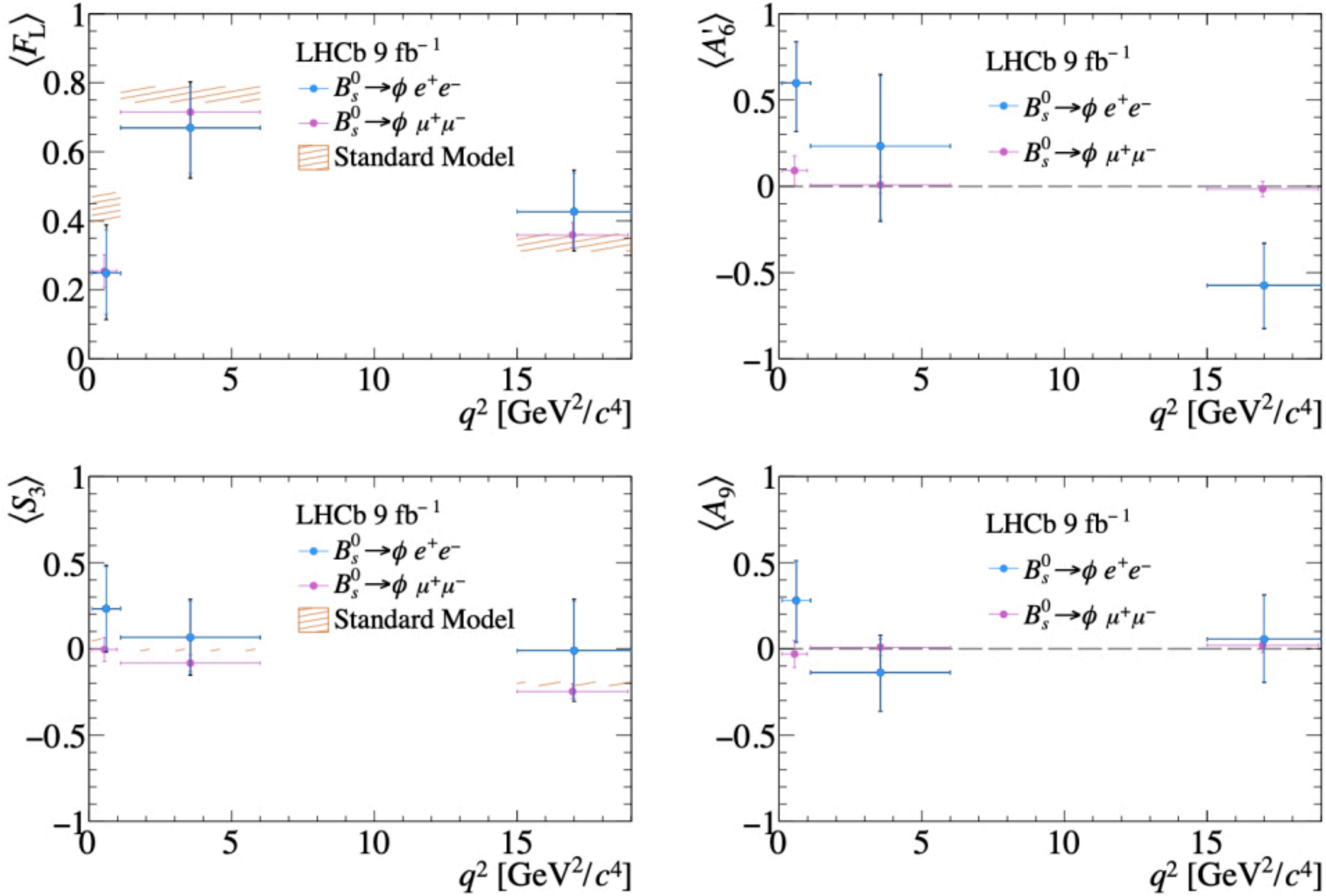


Angular analysis of $B_s^0 \to \phi e^+ e^-$

NEW

[LHCb-PAPER-2025-006, in preparation]

- Angular analysis of same decay mode in the ***low, central and high*** q^2 regions
- Results compatible with SM predictions and previous measurements on $B_s^0 \to \phi\mu^+\mu^-$

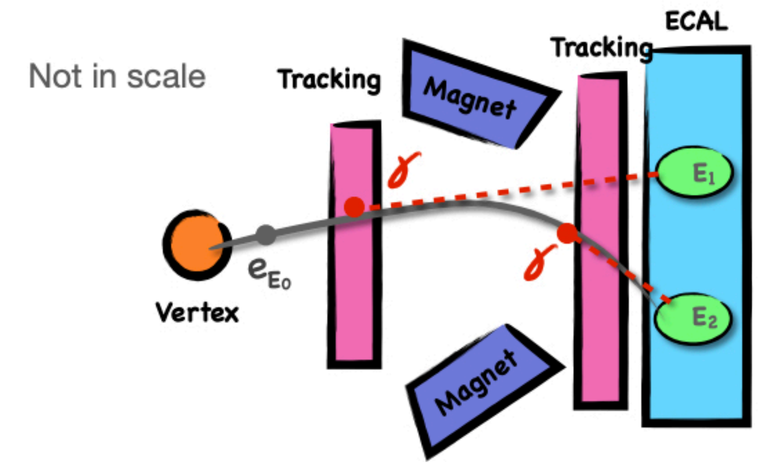


LFU ratio: Experimental Strategy

S. Celani

$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$

- Precisely predicted to be ~1 in SM

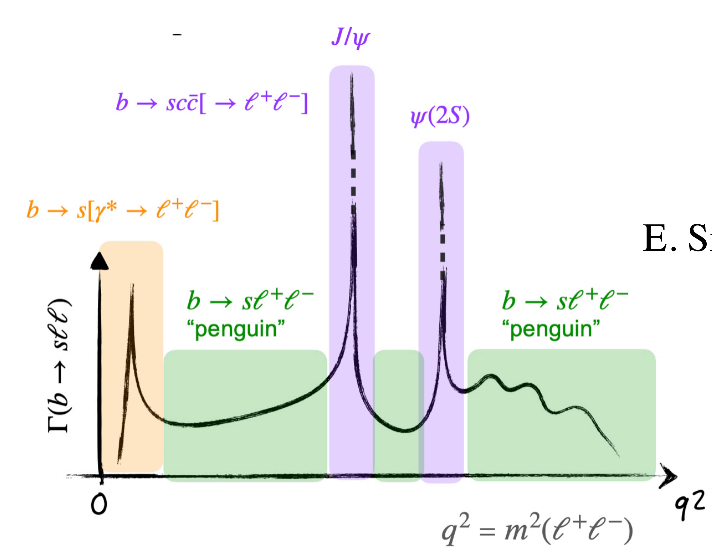


- R_X are measured as double ratios

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

  - **Yields:** obtained from mass fit
  - **Efficiencies:** obtained from corrected MC using data-driven techniques

- Validate LFU using resonant channels
  - Single ratio: $r_{J/\psi} = 1$, double ratio: $R_{\psi(2S)} = 1$



E. Smith

LFU ratio with $B_s^0 \to \phi l^+ l^-$ (R_ϕ)

PRL 134 (2025) 121803

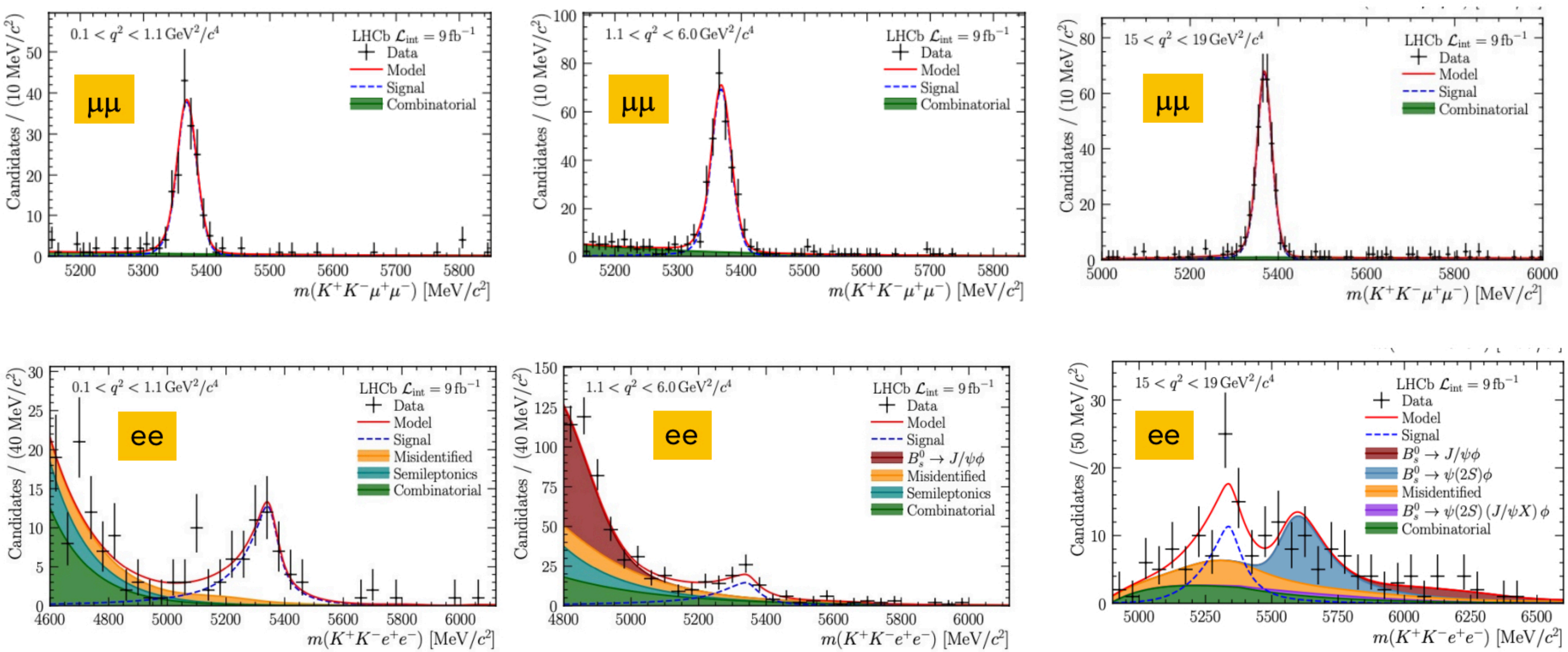
- First LFU ratio in B_s^0 decays, using 9 fb-1 data
- Blind analysis, measurement performed in three q^2 regions
  - *Low* q^2 : $0.1 < q^2 < 1.1$ GeV2/c4
  - *Central* q^2 : $1.1 < q^2 < 6.0$ GeV2/c4
  - *High* q^2 : $15.0 < q^2 < 19.0$ GeV2/c4 ☞ FIRST TIME
- Validation: $r_{J/\psi} = 0.997 \pm 0.013, R_{\psi(2S)} = 1.010 \pm 0.026$
- Results in agreement with the SM predictions

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

- $\mathcal{B}(B_s \to \phi e^+ e^-)$ agrees with SM and the measured $\mathcal{B}(B_s \to \phi \mu^+ \mu^-)$

Mass fits

PRL 134 (2025) 121803



Statistical significance: 6.8σ

Statistical significance: 5.4σ

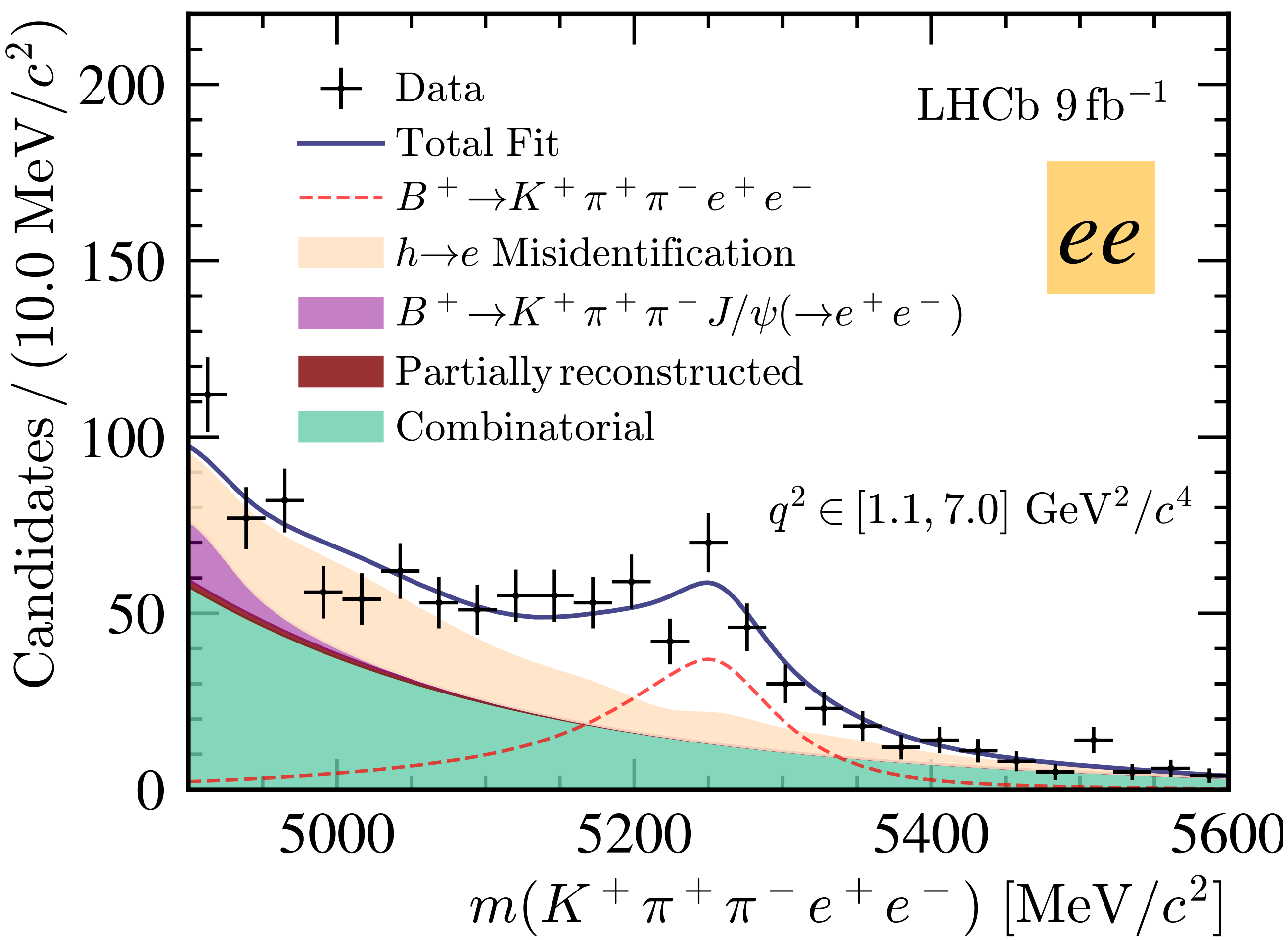
Statistical significance: 3.6σ

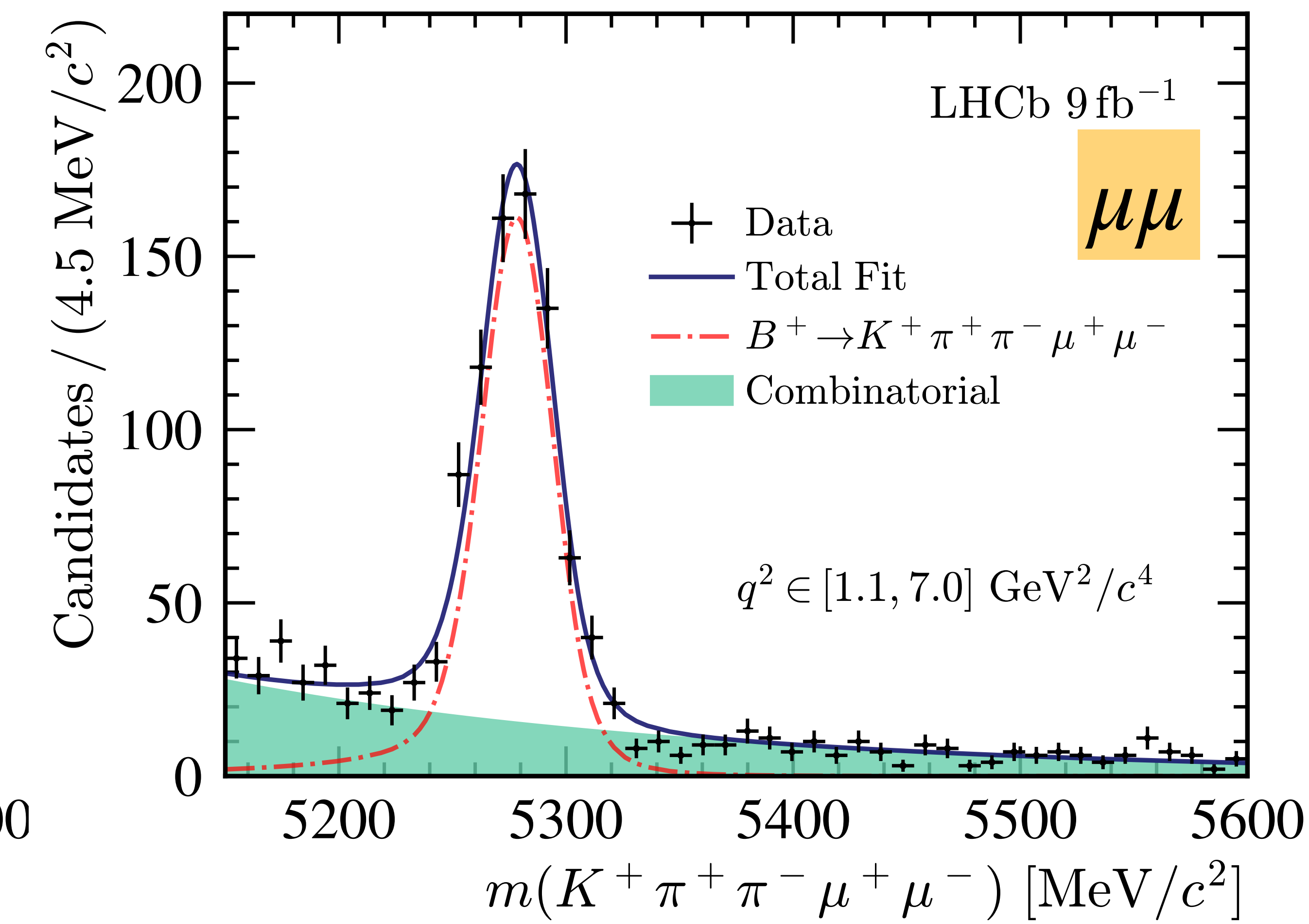
Another LFU ratio but using $B^+ \to K^+\pi^+\pi^- l^+ l^-$ ($R_{K\pi\pi}$)

arXiv.2412.11645

- Measurement performed in *central* q^2 : $1.1 < q^2 < 7.0$ GeV²/c⁴
- First observation of $B^+ \to K^+\pi^+\pi^- e^+ e^-$ mode (significance > 10σ)
- Validation: $r_{J/\psi} = 1.033 \pm 0.017$, $R_{\psi(2S)} = 1.040 \pm 0.030$
- Results compatible with the SM predictions

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



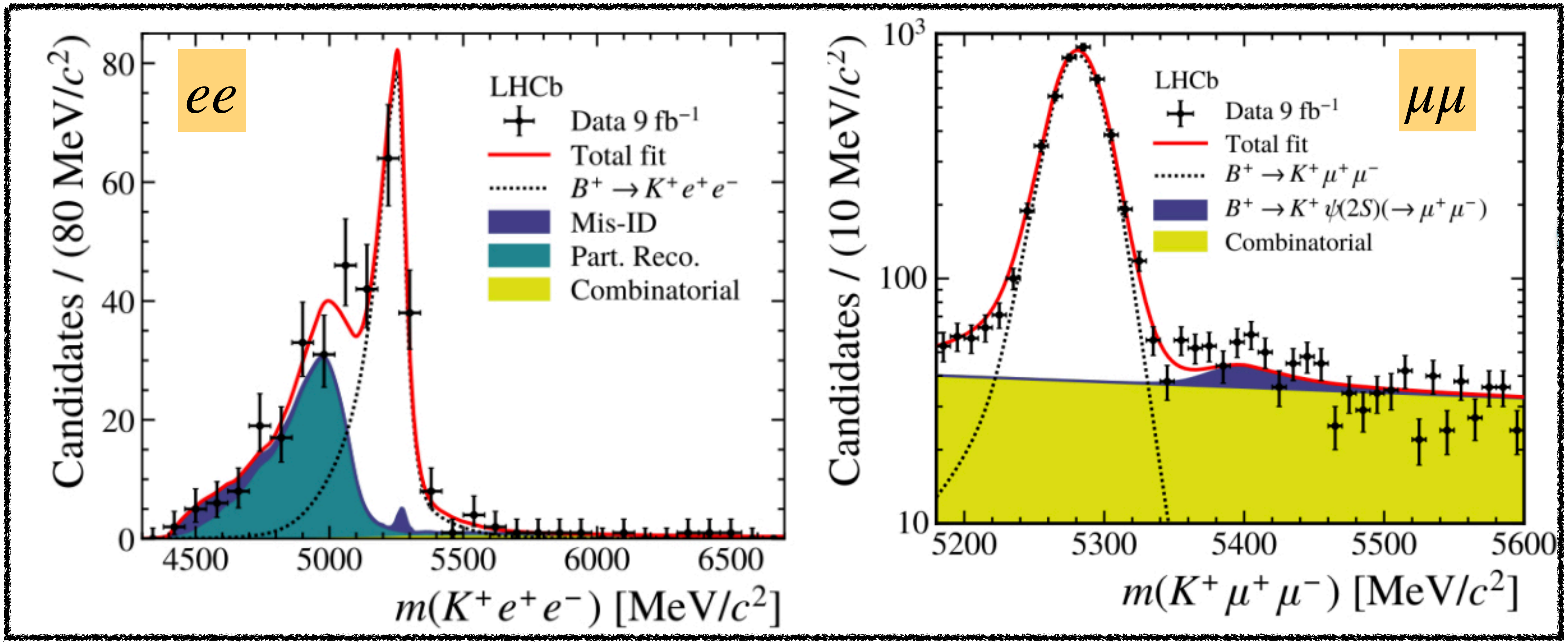


Another LFU ratio but with $B^+ \to K^+ l^+ l^-$ at high q^2 (R_K^{high})

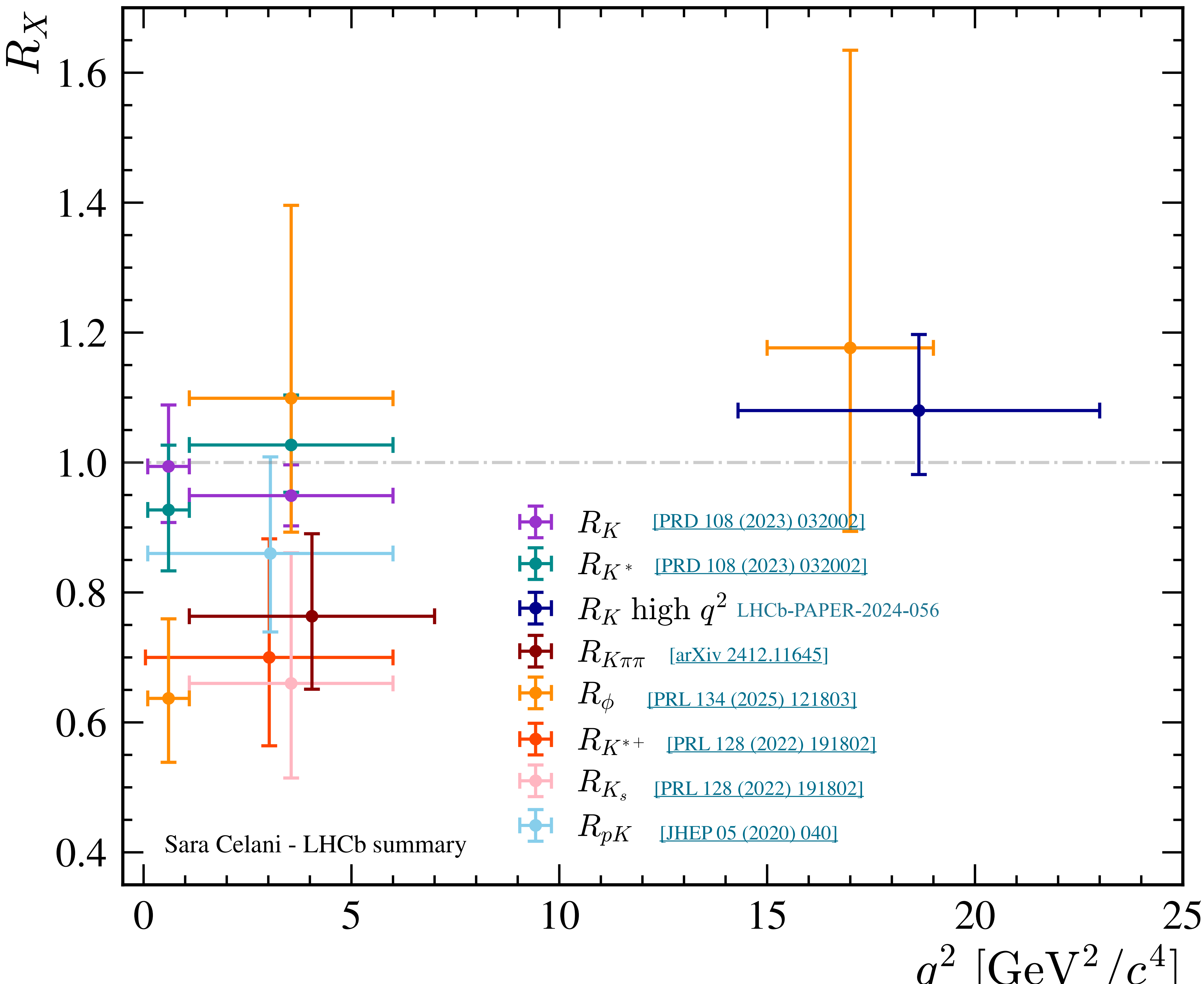
LHCb-PAPER-2024-056, in preparation

NEW

- Measurement performed in high q^2 : $q^2 > 14.3$ GeV²/c⁴
- Most precise LFU test above the $\psi(2S)$ mass
- Validation: $r_{J/\psi} = 0.977 \pm 0.003 \pm 0.055$, $R_{\psi(2S)} = 1.002 \pm 0.009 \pm 0.004$
- Results compatible with the SM predictions



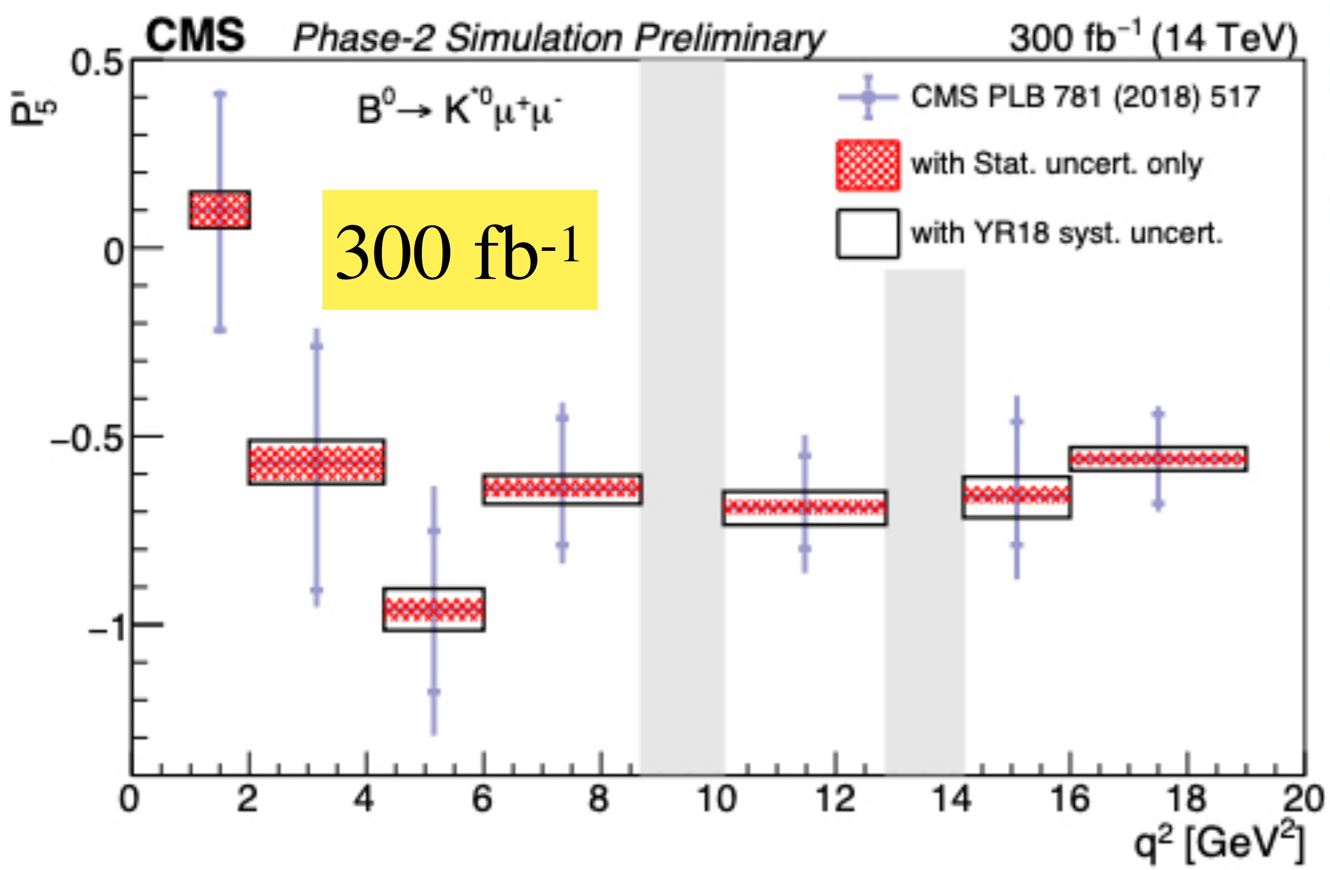
LFU status summary

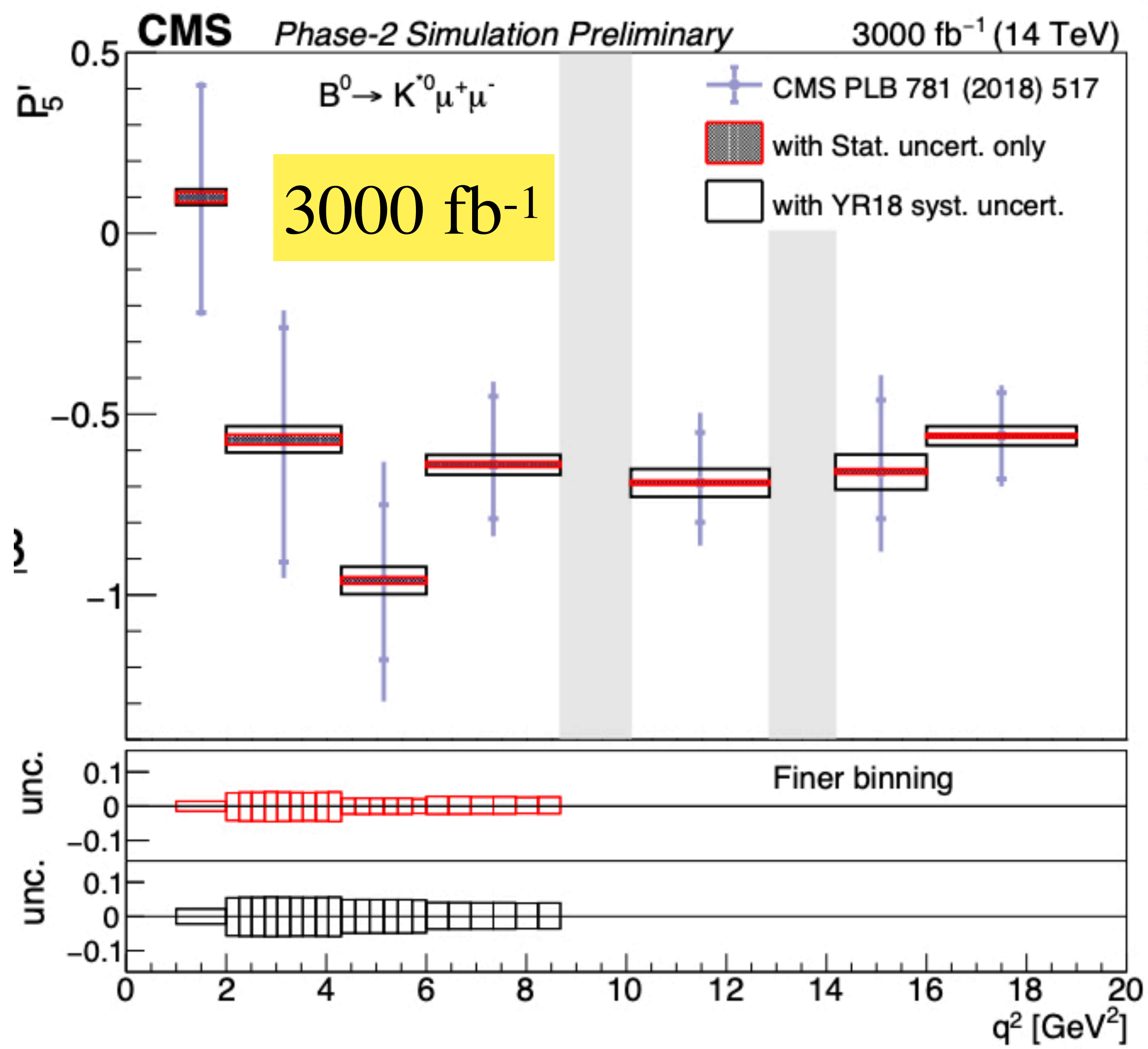


Future prospects (CMS)

$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

FTR-18-033

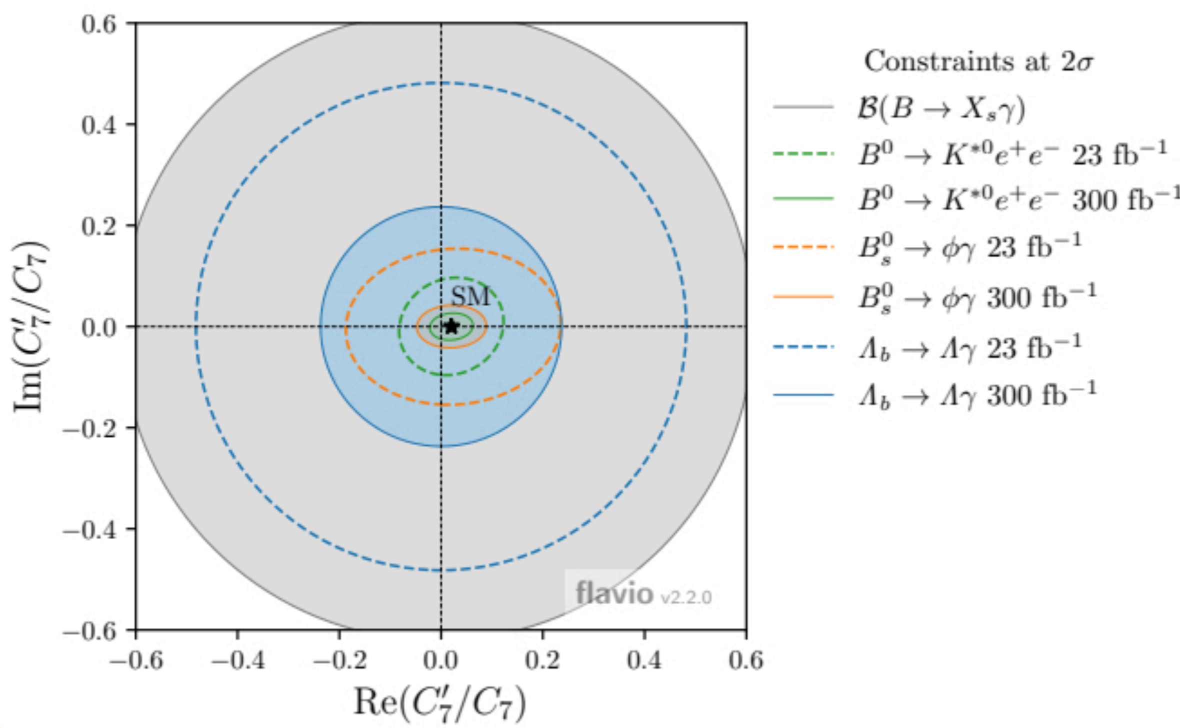




Future prospects (LHCb)

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 ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	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
α_γ($\Lambda^0_b \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[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



Conclusions & Outlook

- Rare B decays provide ***stringent tests*** of NP beyond SM
- Latest results with better precision ***can neither confirm nor deny*** them
- Updates with ***more data and new modes*** under development
- Most of the measurements are still statistically limited
  - LHC Run 3 and beyond will tell us more!

Stay Tuned !

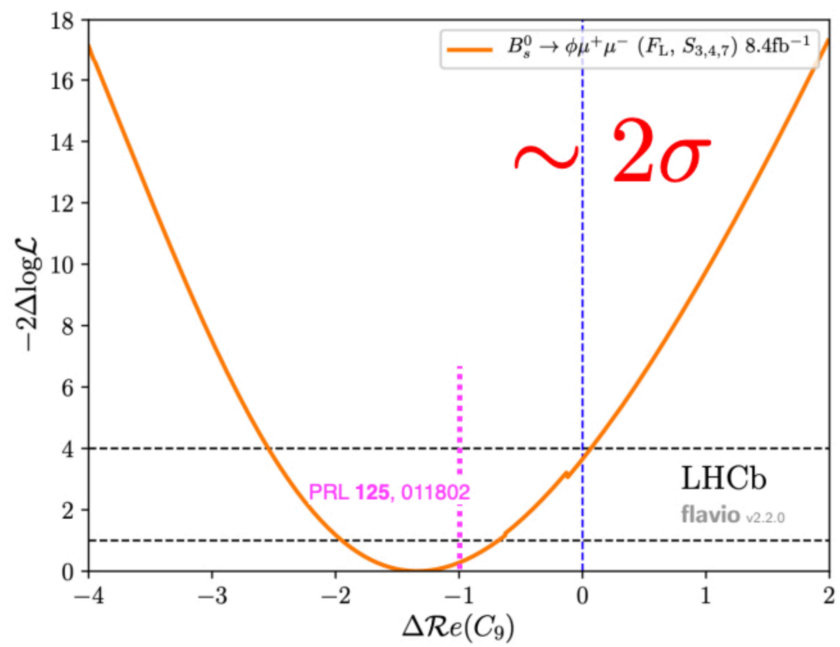
Spare Slides

Other angular analysis measurements

$B_s^0 \to \phi\mu^+\mu^-$

$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.3\,^{+0.7}_{-0.6}$

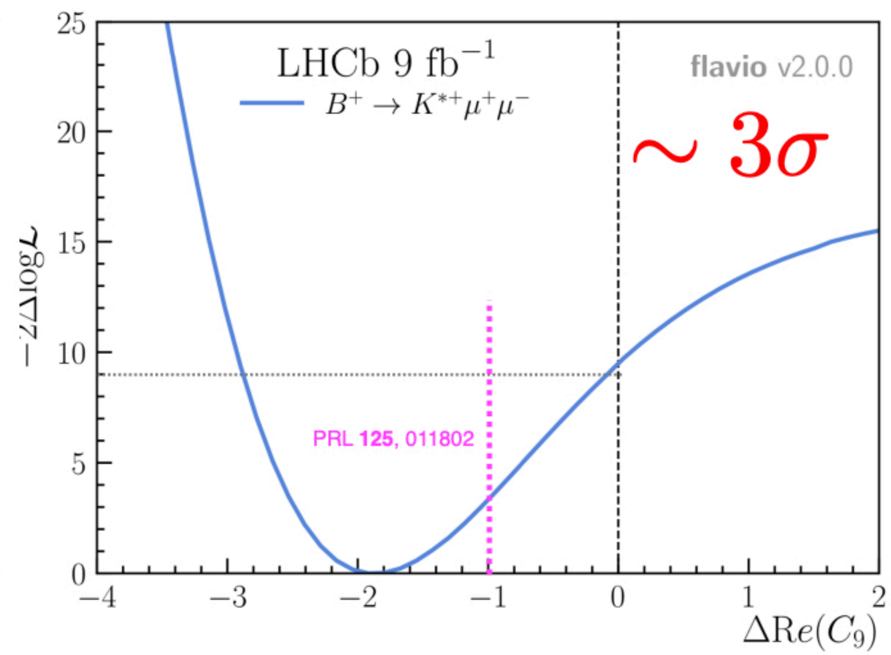
JHEP 11 (2021) 043



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

$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.9$

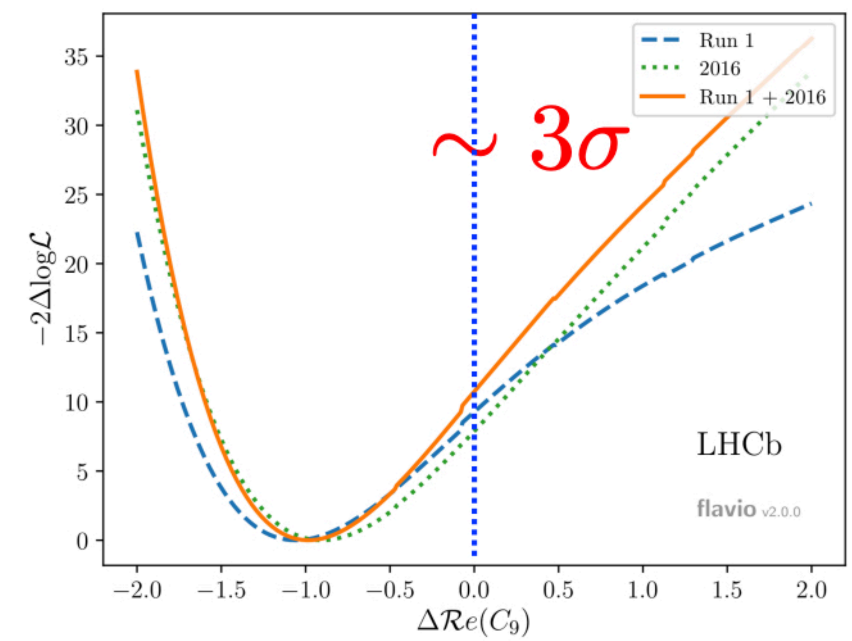
Phys. Rev. Lett. **126**, 161802



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

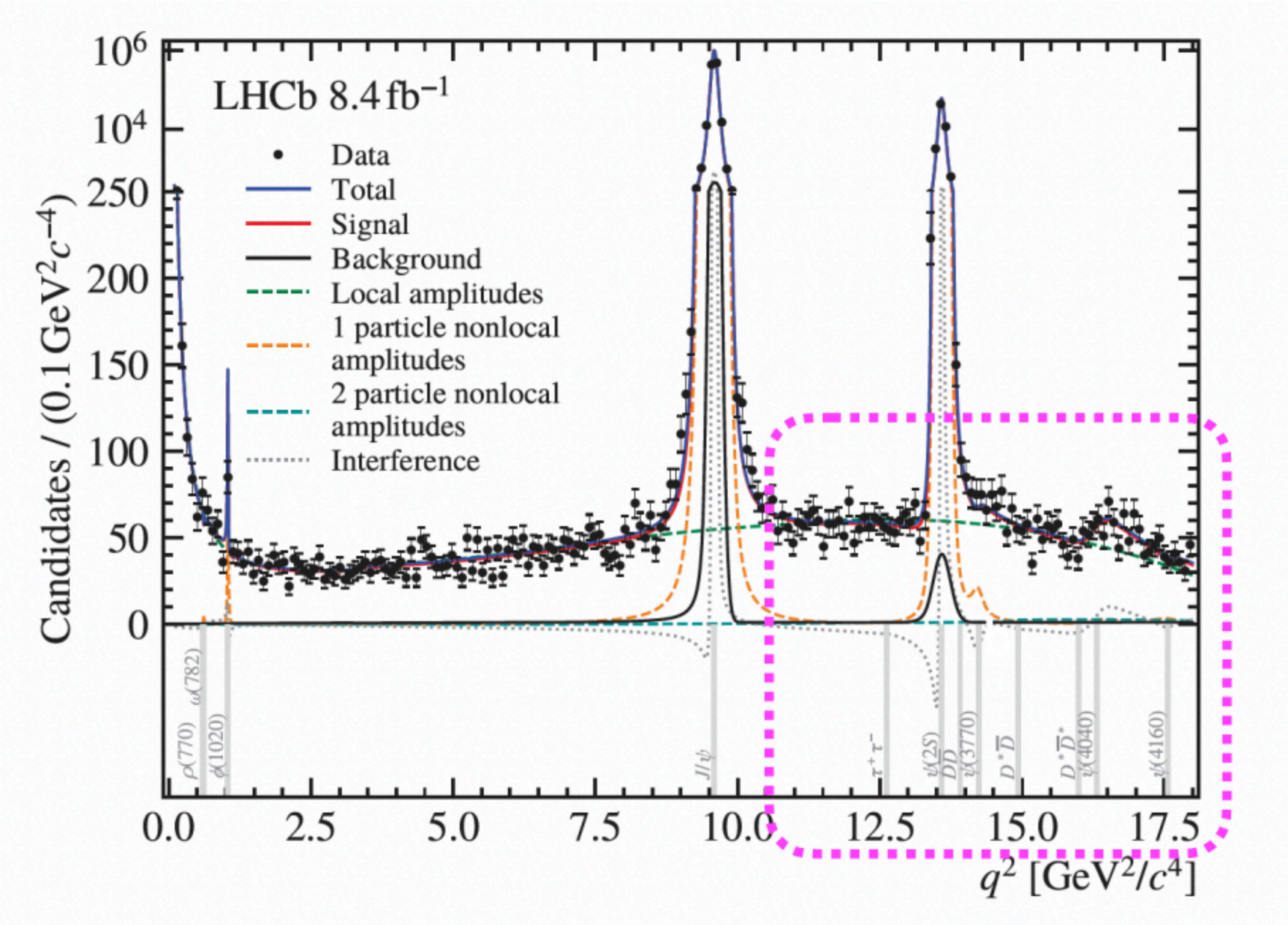
$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$

Phys. Rev. Lett. **125**, 011802

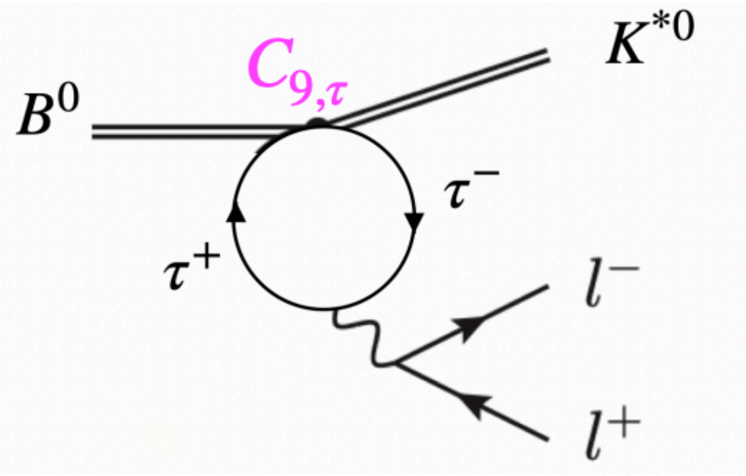


Same pattern, negative definitions in effective modelling

Bonus: worlds first direct measurement of $C_{9\tau}$



LHCb-PAPER-2024-011



Muon analysis is sensitive to $C_{9,\tau}$ via

$B^0 \to K^{*0}[\tau^+\tau^- \to \gamma^* \to \mu^+\mu^-]$

$\propto C_{9,\tau}$

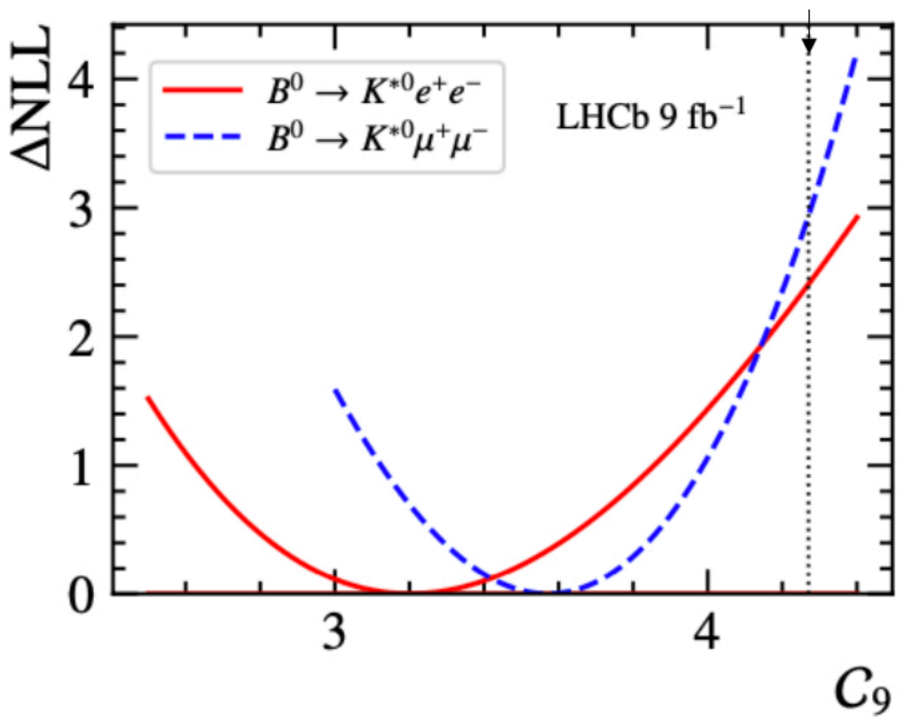
Worlds first direct measurement of $C_{9,\tau}$

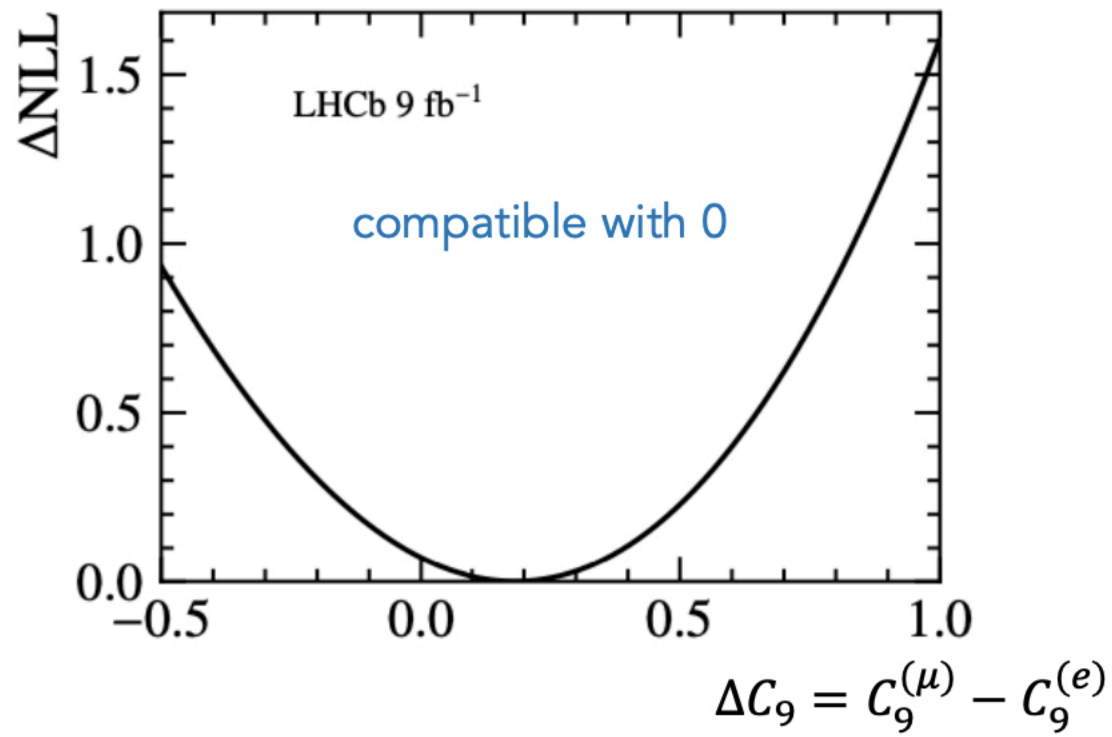
$$C_{9,\tau} = (-1.0 \pm 2.6 \pm 1.0) \times 10^2$$

Convert to 90% CL on
$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim [1.7 - 2.2] \times 10^{-3}$

Best direct measurement of $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) =$
3.1×10^{-3} 90% CL Belle, Phys. Rev. D108 (2023) L011102

SM prediction $\mathcal{O}(10^{-7})$, NP models $\mathcal{O}(10^{-4})$


ΔNLL
$B^0 \to K^{*0}e^+e^-$
$B^0 \to K^{*0}\mu^+\mu^-$
LHCb 9 fb^{-1}
0
1
2
3
4
3
4
C_9


ΔNLL
LHCb 9 fb^{-1}
compatible with 0
0.0
0.5
1.0
1.5
−0.5
0.0
0.5
1.0
$\Delta C_9 = C_9^{(\mu)} - C_9^{(e)}$

Photon polarisation constraints from $B_s^0 \to \phi e^+ e^-$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\varphi}} = \frac{9}{32\pi}\left\{\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K \right.$$
$$+\left[\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\right]\cos 2\theta_L$$
$$+\frac{1}{2}(1-F_{\mathrm{L}})\,A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde{\varphi}$$
$$+(1-F_{\mathrm{L}})\,A_{\mathrm{T}}^{\mathcal{R}eCP}\sin^2\theta_K\cos\theta_L$$
$$\left.+\frac{1}{2}(1-F_{\mathrm{L}})\,A_{\mathrm{T}}^{\mathcal{I}mCP}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde{\varphi}\right\}.$$

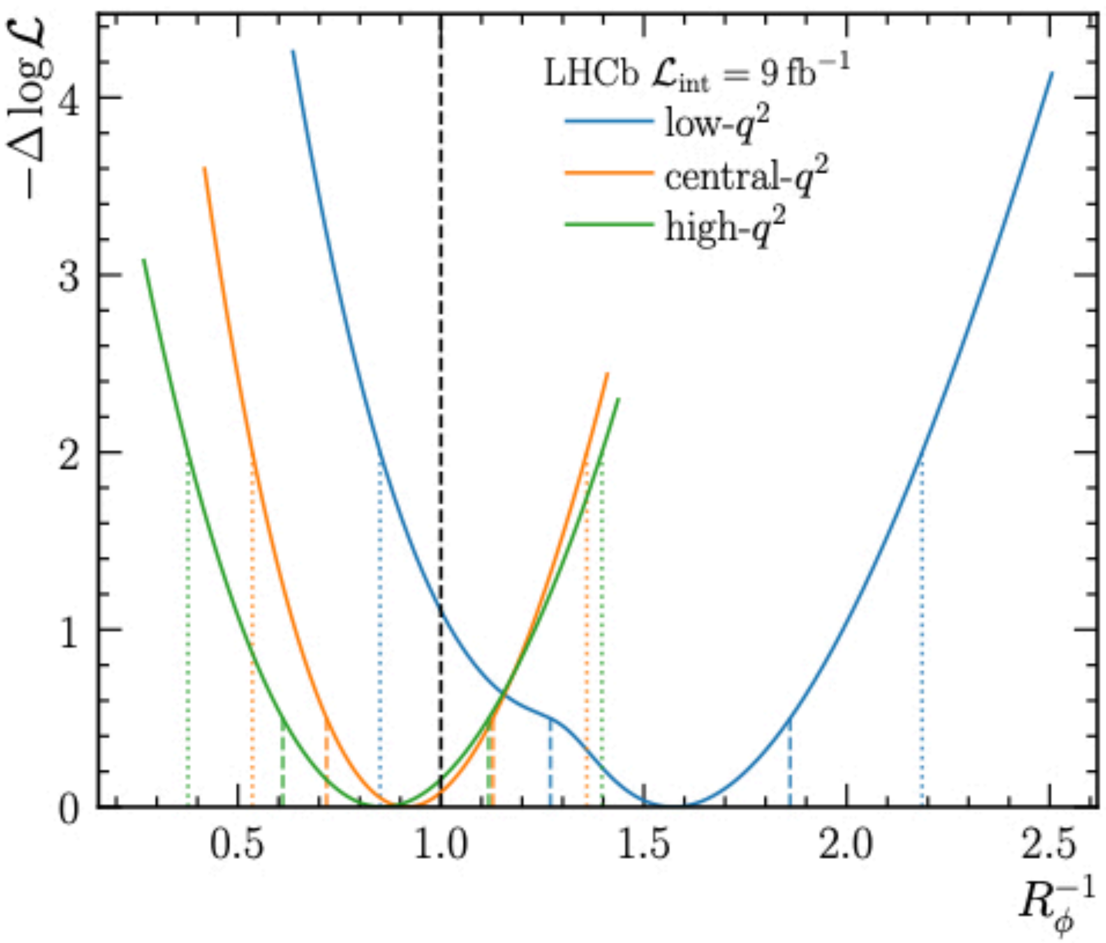
$$\lim_{q^2\to 0} A_{\mathrm{T}}^{(2)}(q^2) = \frac{2\left[\mathcal{R}e[C_7]\mathcal{R}e[C_7'] + \mathcal{I}m[C_7]\mathcal{I}m[C_7'] + \frac{y}{2}[(\mathcal{R}e[C_7])^2 - (\mathcal{I}m[C_7])^2]\right]}{(\mathcal{R}e[C_7])^2 + (\mathcal{I}m[C_7])^2},$$

$$\lim_{q^2\to 0} A_{\mathrm{T}}^{\mathcal{I}mCP}(q^2) = \frac{2\left[\mathcal{R}e[C_7]\mathcal{I}m[C_7'] - \mathcal{I}m[C_7]\mathcal{R}e[C_7'] - y\mathcal{R}e[C_7]\mathcal{I}m[C_7]\right]}{(\mathcal{R}e[C_7])^2 + (\mathcal{I}m[C_7])^2},$$

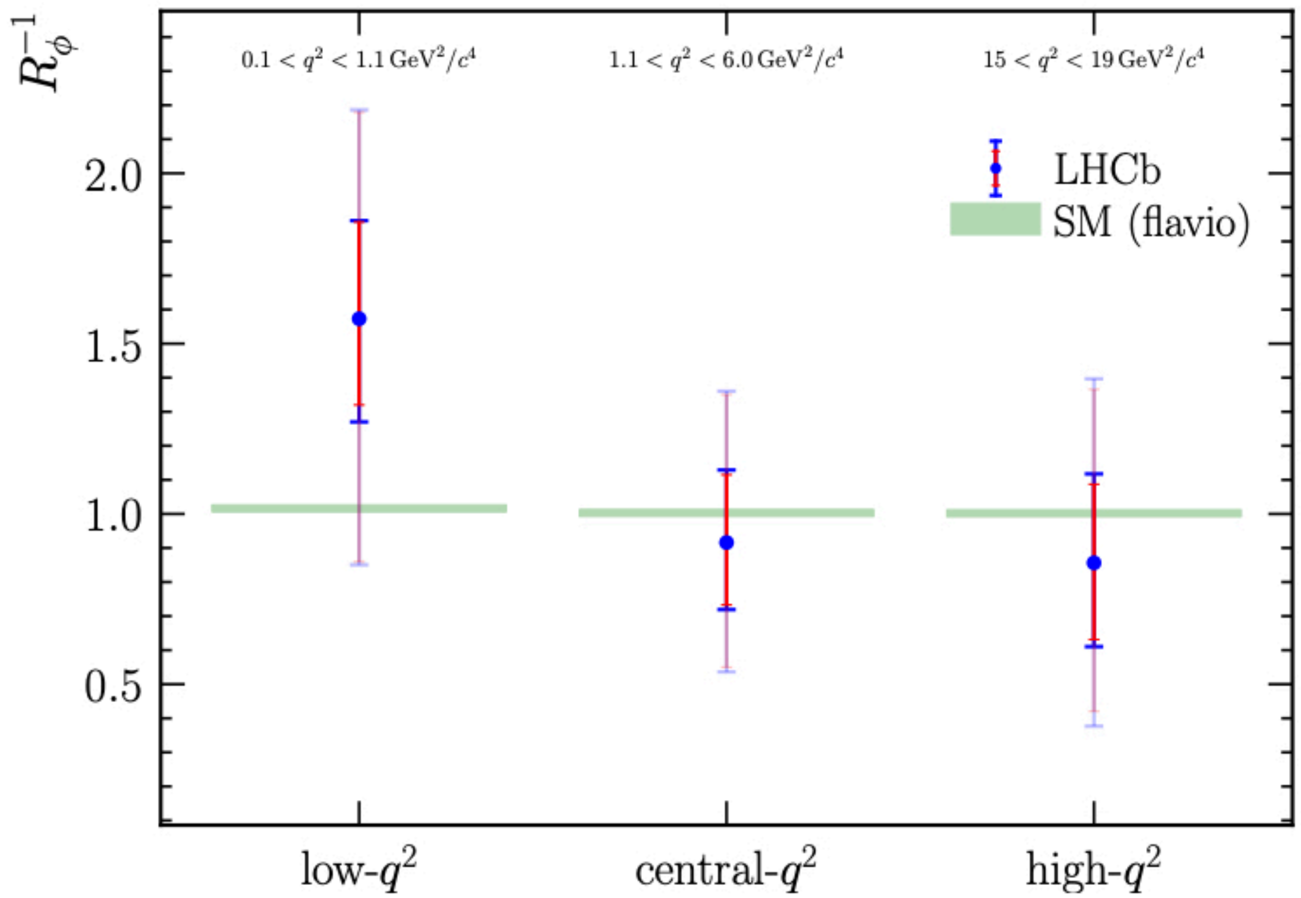
$$y = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

Source of systematic	$A_{\mathrm{T}}^{(2)}$	$A_{\mathrm{T}}^{\mathcal{I}mCP}$	$A_{\mathrm{T}}^{\mathcal{R}eCP}$	F_{L}
$\Delta\Gamma_s/\Gamma_s$	0.008	<0.001	<0.001	<0.001
Corrections to simulation	0.002	<0.001	<0.001	0.010
Acceptance function modelling	<0.001	<0.001	0.001	0.002
Simulation sample size for acceptance	0.006	0.008	0.005	0.002
Background contamination	0.009	0.014	0.004	0.006
Angles resolution	−0.005	<0.001	—	—
Total systematic uncertainty	0.014	0.016	0.006	0.012
Statistical uncertainty	0.235	0.247	0.155	0.056

R_ϕ



$-\Delta \log \mathcal{L}$
LHCb $\mathcal{L}_{\text{int}} = 9\,\text{fb}^{-1}$
low-q^2
central-q^2
high-q^2
R_ϕ^{-1}



R_ϕ^{-1}
$0.1 < q^2 < 1.1\,\text{GeV}^2/c^4$
$1.1 < q^2 < 6.0\,\text{GeV}^2/c^4$
$15 < q^2 < 19\,\text{GeV}^2/c^4$
LHCb
SM (flavio)
low-q^2
central-q^2
high-q^2

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

□

$$\frac{1}{\mathrm{d}(\Gamma+\overline{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\overline{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+ \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Source	F_L	P_1	P_4'	P_5'	P_2	P_6'	P_8'	P_3
Comb and DSL backgrounds	0.69	0.87	0.49	0.61	0.95	0.24	0.81	0.71
Part. reco. background	0.21	0.17	0.14	0.22	0.20	0.06	0.07	0.16
Misid. had. background	0.38	0.57	0.18	0.26	0.34	0.41	0.17	0.36
Effective acceptance	0.39	0.49	0.52	0.51	0.55	0.62	0.50	0.40
Signal mass modelling	0.26	0.16	0.14	0.18	0.31	0.06	0.06	0.15
J/ψ backgrounds	0.18	0.13	0.06	0.11	0.29	0.04	0.04	0.12
S-wave component	0.35	0.10	0.18	0.11	0.29	0.21	0.01	0.20
B^+ veto	0.50	0.41	0.28	0.37	0.52	0.22	0.21	0.37
Fit bias	0.01	0.00	0.04	0.03	0.08	0.02	0.02	0.02
Total	1.14	1.25	0.84	0.97	1.38	0.84	0.99	1.02

□

Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathcal{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathcal{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e$, (LHCb only μ)

Isospin

$R(D^0) = R(D^+)$

$R(D^{*0}) = R(D^{*+})$

Hadronic

$\tau \to \nu_\tau \pi X$

Semi-leptonic (SL)

$\tau \to \nu_\tau \ell \nu_\ell$

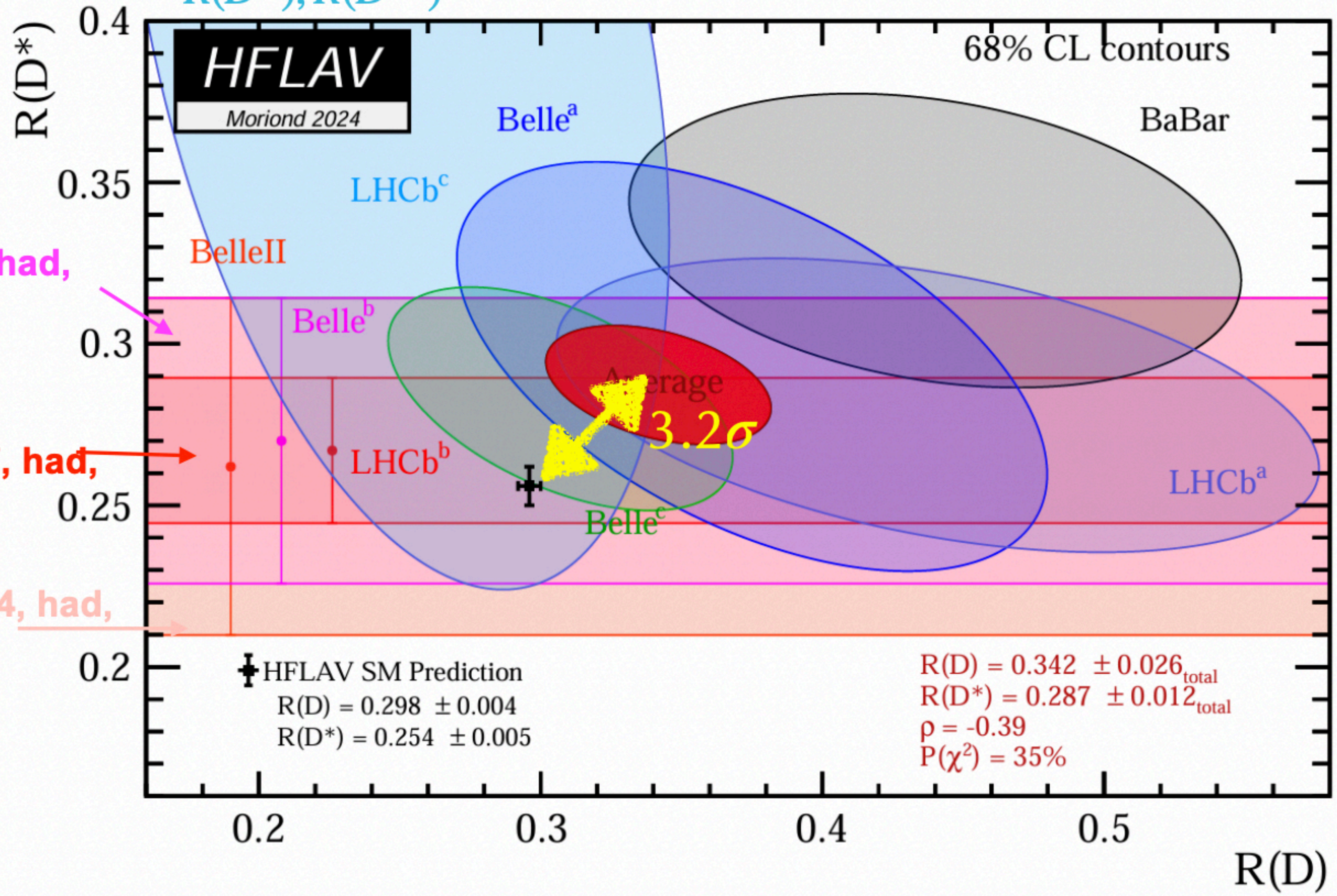
LHCb 2024, SL,
$R(D^+), R(D^{*+})$ $D^{*(+)} \to D^+(\to K^-\pi^+\pi^+)\pi^0$

Belle 2017 had, $R(D^{*+})$

LHCb 2017, had, $R(D^{*+})$

Belle II 2024, had, $R(D^*)$

LHCb 2023, SL $R(D^0), R(D^{*(+)})$ $D^{*(+)} \to D^0 X$

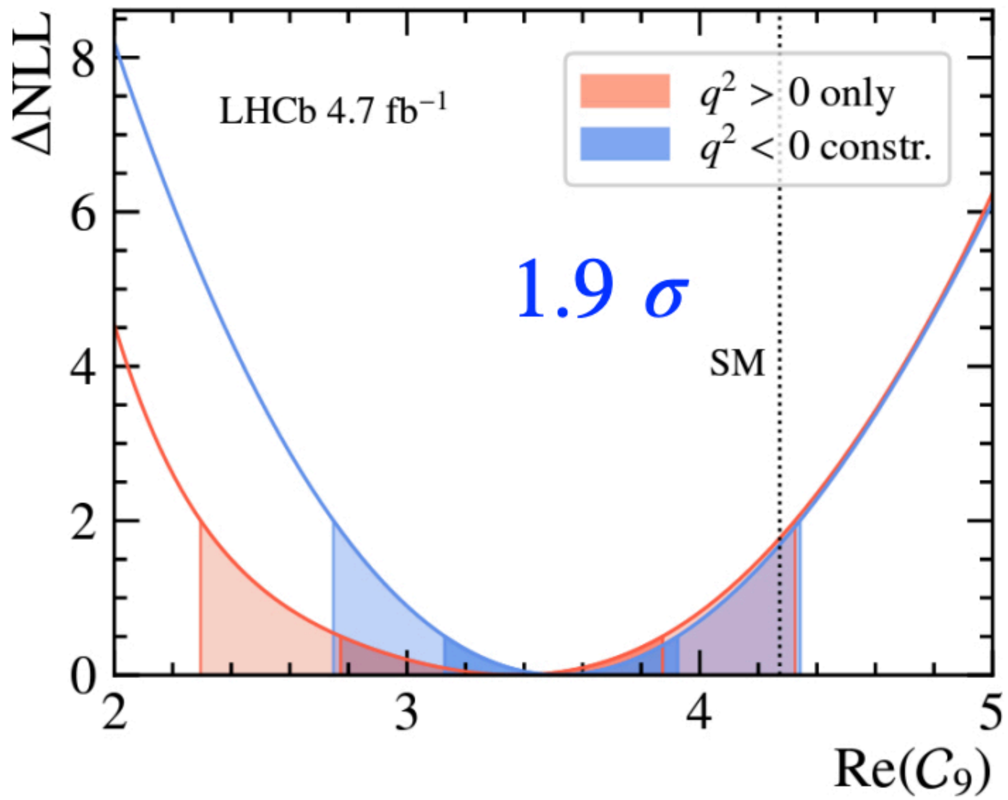


16

Measured values of C_9 ?

LHCb-PAPER-2023-032

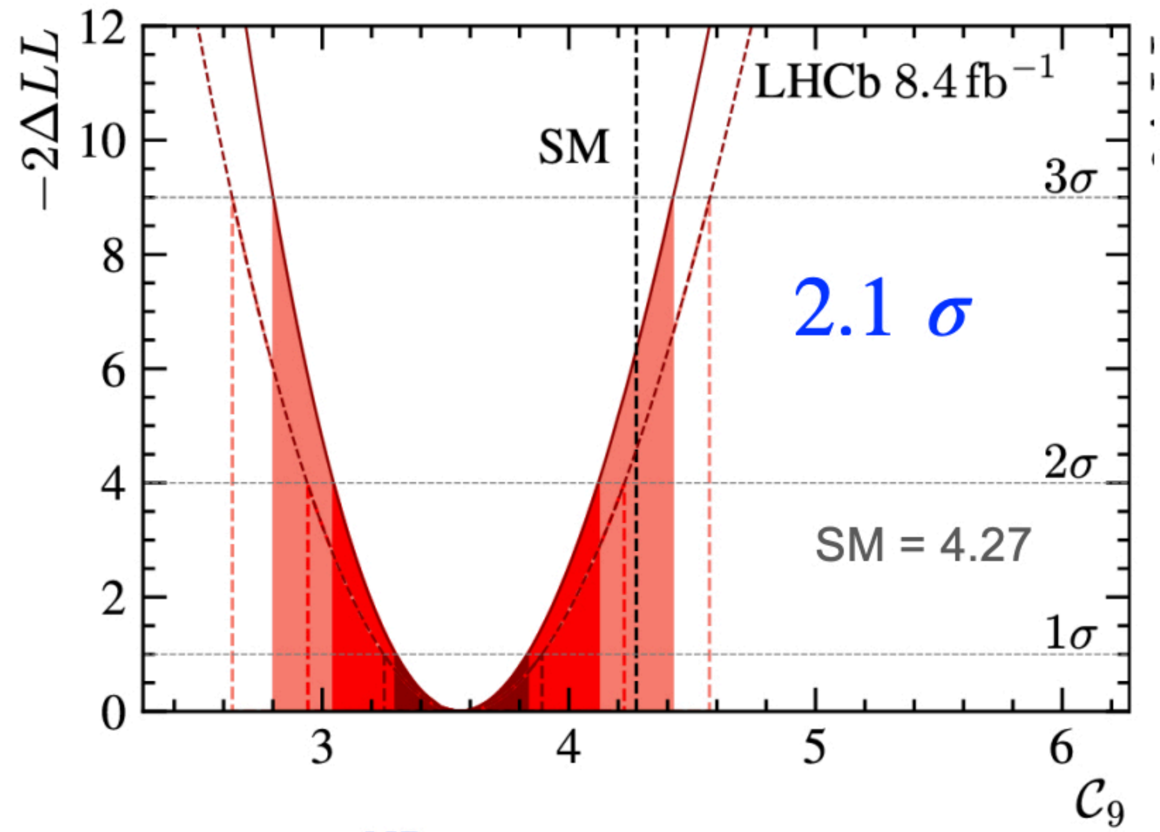
Z-expansion



$$\Delta C_9^{NP} = -0.93^{+0.53}_{-0.57}$$

LHCb-PAPER-2024-011

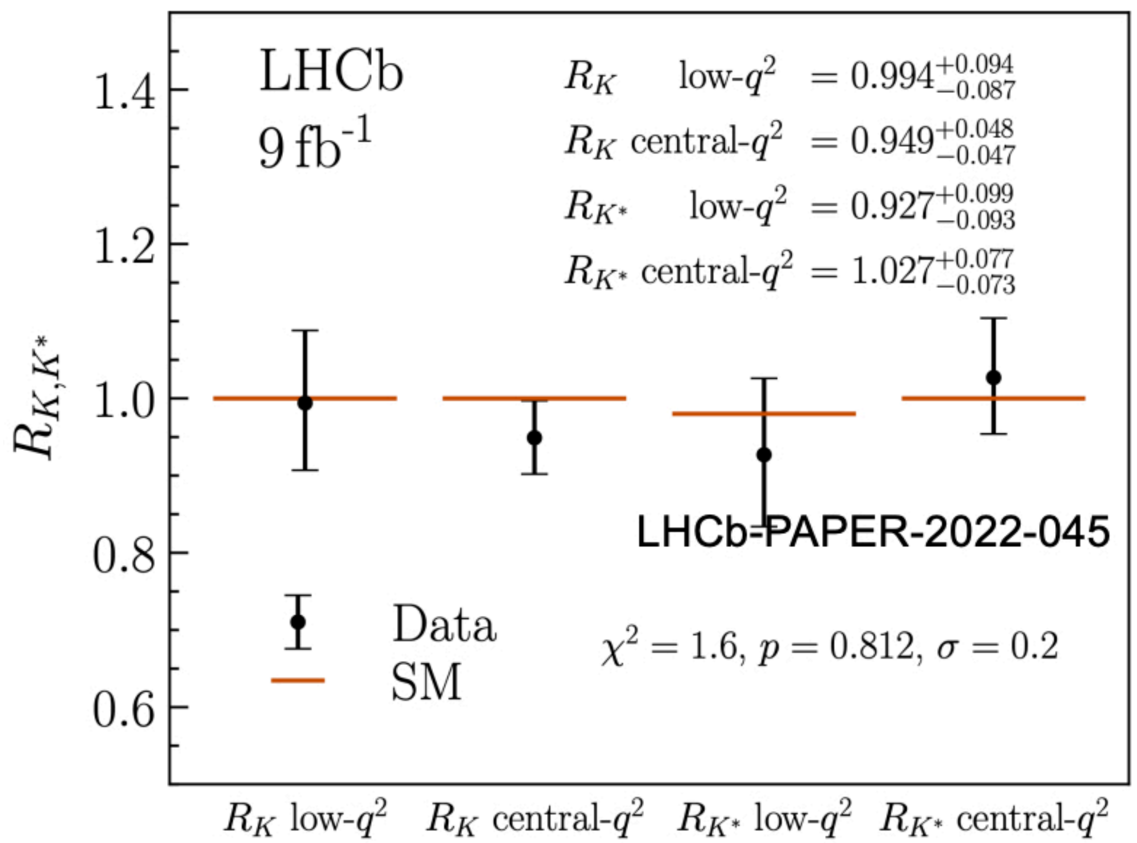
Amplitude model



$$\Delta C_9^{NP} = -0.71 \pm 0.33$$

	$q^2 > 0$ only				
	best fit value	68% C.I.	95% C.I.	SM value	deviation from SM
$\mathcal{C}_9$	3.34	[2.77, 3.87]	[2.30, 4.33]	4.27	1.9 σ
$\mathcal{C}_{10}$	−3.69	[−4.00, −3.40]	[−4.33, −3.12]	−4.17	1.5 σ
$\mathcal{C}'_9$	0.48	[−0.07, 0.97]	[−0.62, 1.45]	0	0.9 σ
$\mathcal{C}'_{10}$	0.38	[0.13, 0.66]	[−0.14, 0.92]	0	1.5 σ

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$



Precisely predicted to be ~1 in SM

New CMS result

$$R(K) = 0.78^{+0.47}_{-0.23}$$