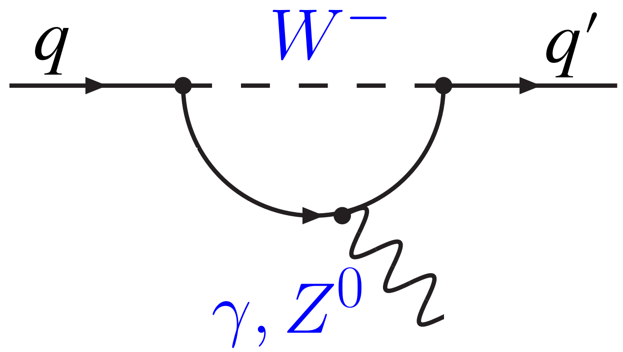
29 Sep 2025 - FCCP - Capri

Rare heavy-flavour decays at LHCb

Martino Borsato

On behalf of the LHCb Collaboration



LHCb

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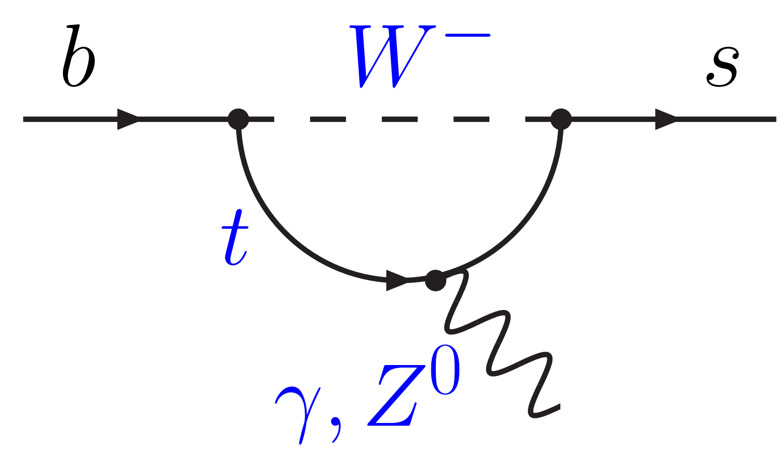
Electroweak FCNC in $b \to s$

- Electroweak $b \to s$ transitions
  - Suppressed by loop and V_{CKM} $\to$ decay rates of order 10^{-6} or less
  - Tiny BSM contributions can enter at the same order as SM amplitude
  - Sensitive up to few(several) TeV depending on BSM flavour structure

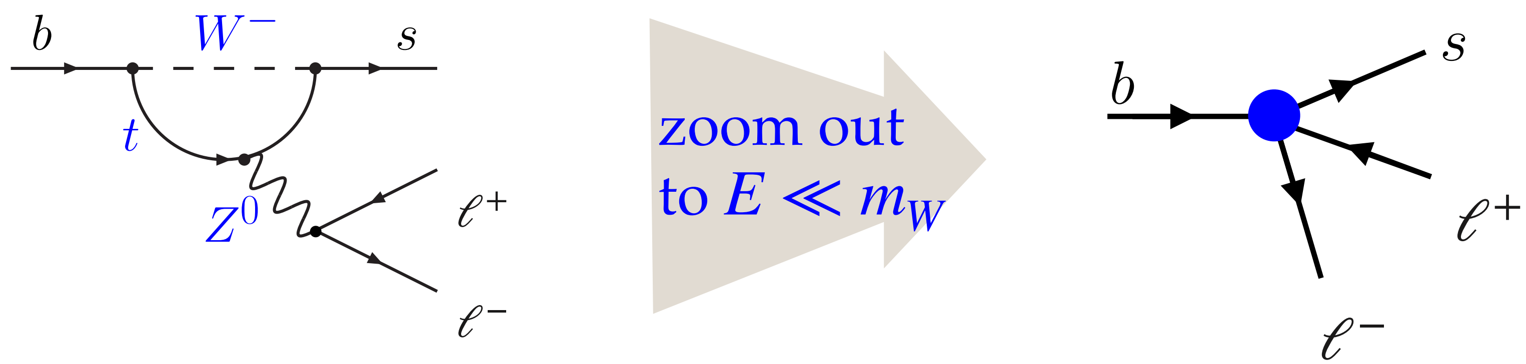


$b \to s\gamma$, $b \to s\ell^+\ell^-$, $B_s \to \ell^+\ell^-$

- Excellent experimental probe
  - $m_b \gg \Lambda_{\text{QCD}} \Rightarrow$ perturbative calculations
  - B is narrow and long-lived ($\tau_B \simeq 1.5$ ps)
  - No neutrinos involved!
  - Several complementary observables
  - Several complementary decay channels

$\longrightarrow$ Branching ratios, angular analyses, SM symmetry tests

Effective theory interpretation



EFT below EW scale:

$$\mathcal{H}_{\text{eff}} = \frac{1}{(34\ \text{TeV})^2} \sum_i C_i O_i$$

$O_7^{(\prime)} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{\text{R(L)}} b) F^{\mu\nu}$ **dipole ($b \to s\gamma$)**

$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{\text{L(R)}} b)(\bar{\ell}\gamma^\mu \ell)$ **vector**

$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{\text{L(R)}} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$ **axial-vector**

$O_S^{(\prime)} = (\bar{s}\gamma_\mu P_{\text{R(L)}} b)(\bar{\ell}\ell)$ **scalar**

$O_P^{(\prime)} = (\bar{s}\gamma_\mu P_{\text{R(L)}} b)(\bar{\ell}\gamma_5 \ell)$ **pseudo-scalar**

Experimental probes

	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
Radiative $b \to s\gamma$	✓			
Leptonic $B_s \to \ell^+\ell^-$			✓	✓
Semileptonic $b \to s\ell^+\ell^-$	✓	✓	✓	✓

- Wilson coefficients are complex valued
- SM quark current mostly left-handed, but need to constrain BSM right-handed Wilson coefficients C'
- SM is LFU but one should consider the lepton-flavour dimension $C^e \neq C^\mu \neq C^\tau$

See previous talk by Paula Alvarez Cartelle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BRASILIA
CANCRI
CAPRICORNI

$$b \to s\gamma$$

Radiative $b \to s\gamma$

Left handed $C_7 = C_7^{SM} + C_7^{NP}$

- $\mathcal{B}(B \to X_s\gamma) \propto C_7^2 + C_7'^2$
  - 5% precise prediction [1]
  - 5% precise from B-factories (Very hard at LHCb) [2]
- $\text{Im}(C_7)$ measured with A_{CP}
  - $B \to K_S\pi^0\gamma$ at B-factories [2]
  - Tagged time-dep. analysis of $B_s \to \phi\gamma$ at LHCb [3]

Right handed $C_7' \simeq C_7'^{NP}$

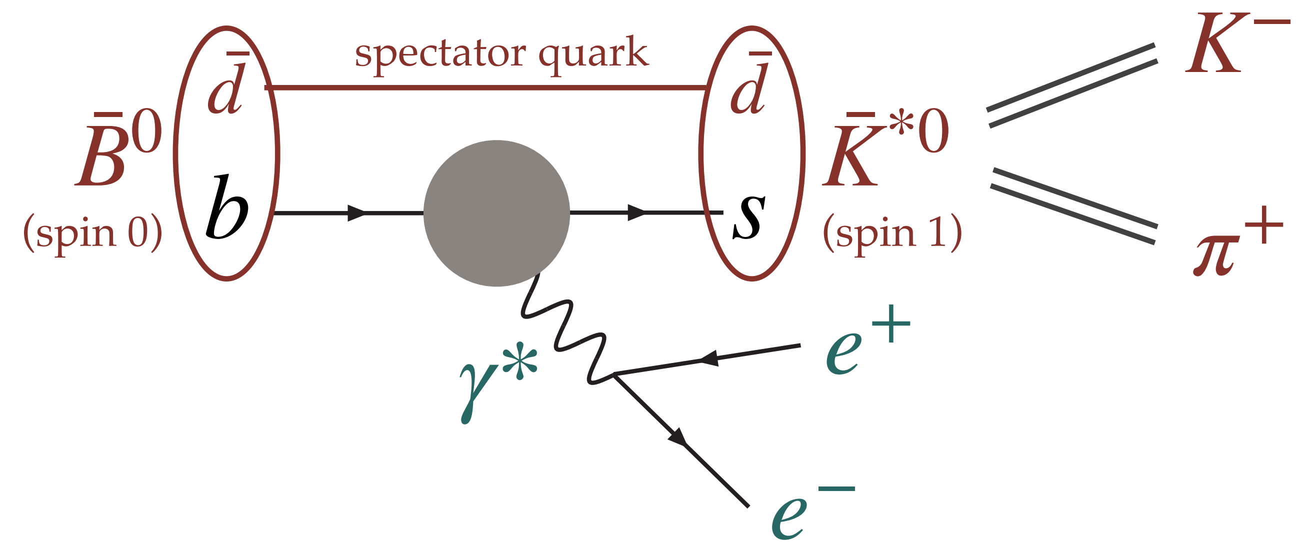
- Mixing-induced CPV in $B \to K_S\pi^0\gamma$ at B-factories [2]
- $\Delta\Gamma_s$ induced rate asymmetry in $B_s \to \phi\gamma$ at LHCb [3]
- Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb [4]
- Transverse asymmetries in $B \to Ve^+e^-$ at LHCb [5]

-> the most sensitive

[1] M. Misiak et al JHEP 06(2020)175
[2] HFLAV average of BaBar and Belle
[3] LHCb PRL 123 (2019) 081802
[4] LHCb PRD 105 (2022) L051104
[5] LHCb JHEP 12 (2020) 081 and JHEP 03 (2025) 047

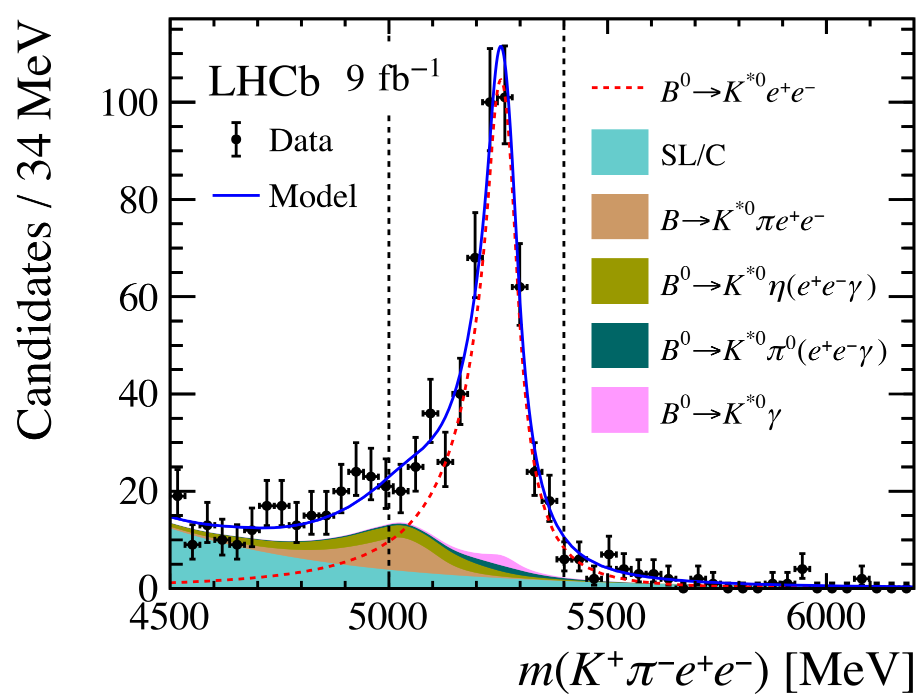
$b \to s\gamma$ in $B \to Ve^+e^-$

- ✓ Use $\gamma^* \to e^+e^-$ to measure photon polarisation!
- ✓ Get nice $h^-h^+e^-e^+$ final state
- ◉ Rate lower by $\alpha_{\text{e.m.}}$

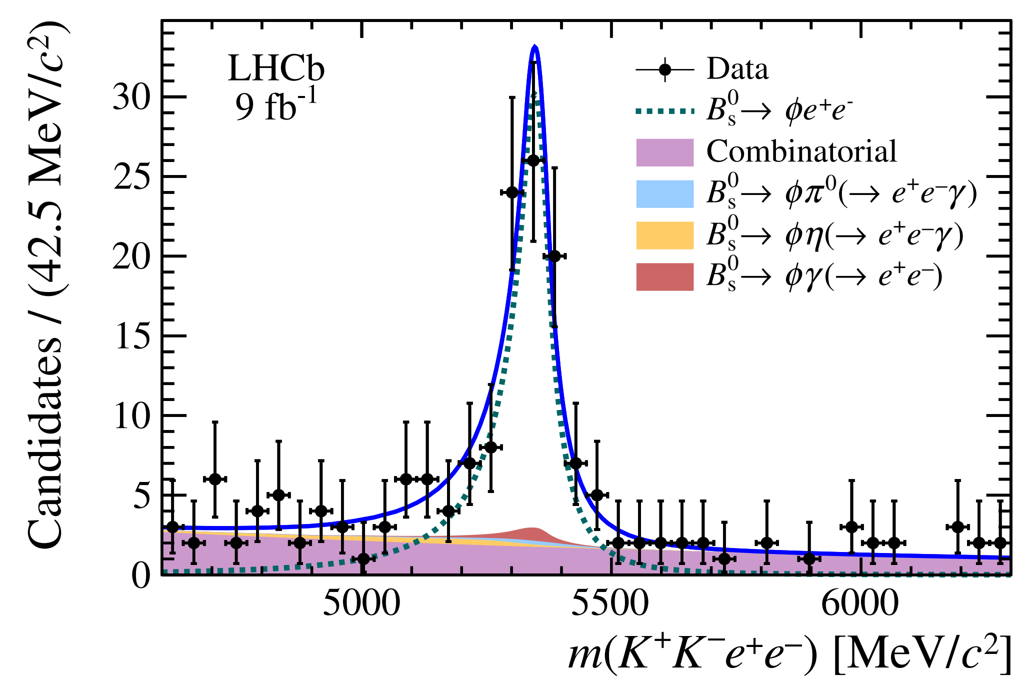


- ✓ About 500 $B^0 \to K^*ee$
- ✓ About 100 $B_s^0 \to \phi ee$

LHCb JHEP 12 (2020) 081

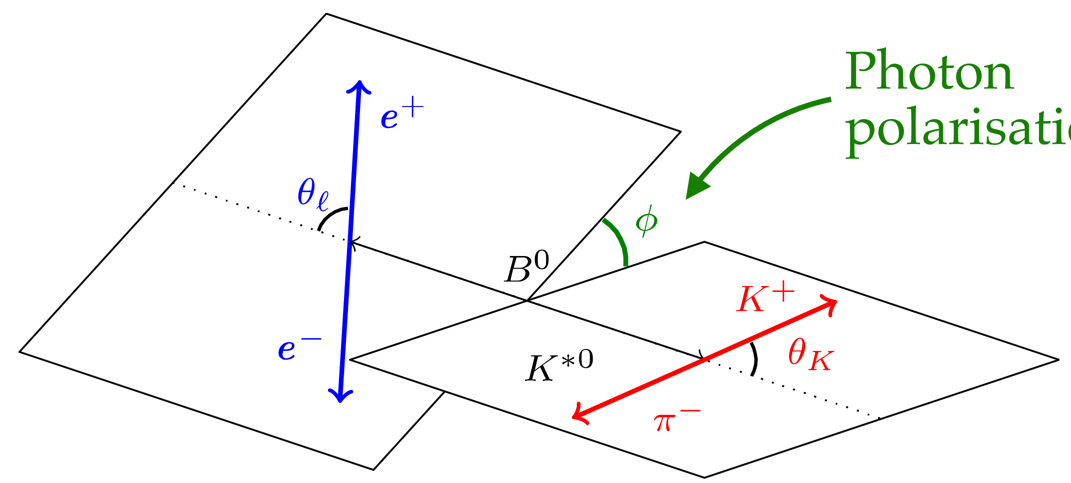


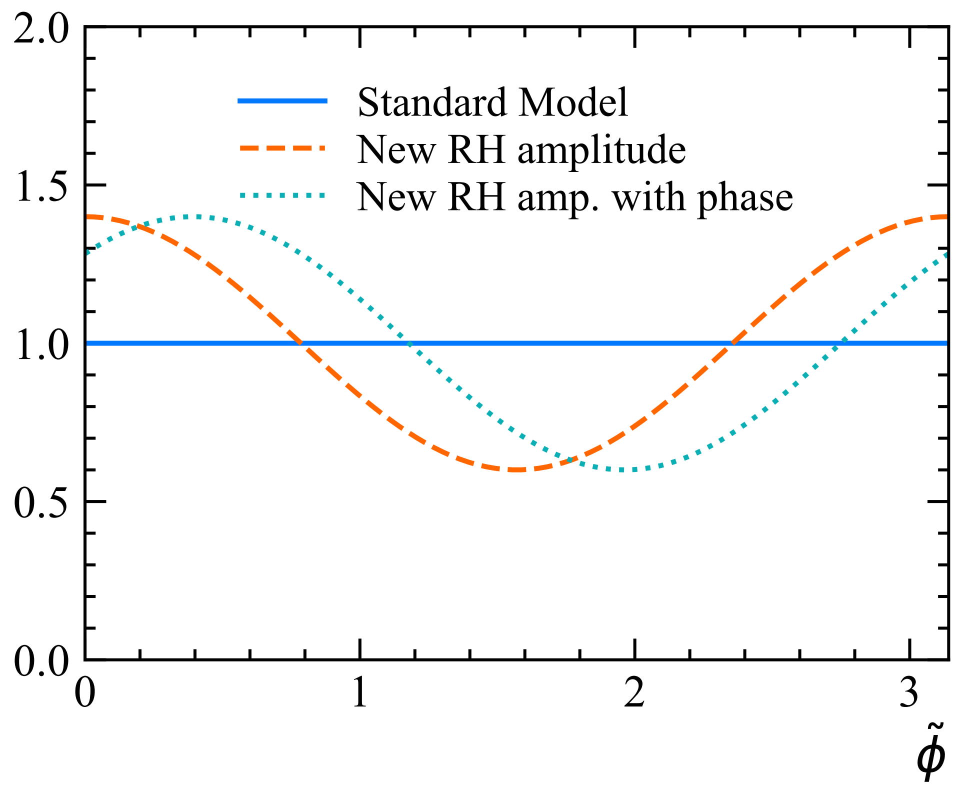
LHCb JHEP 03 (2025) 047



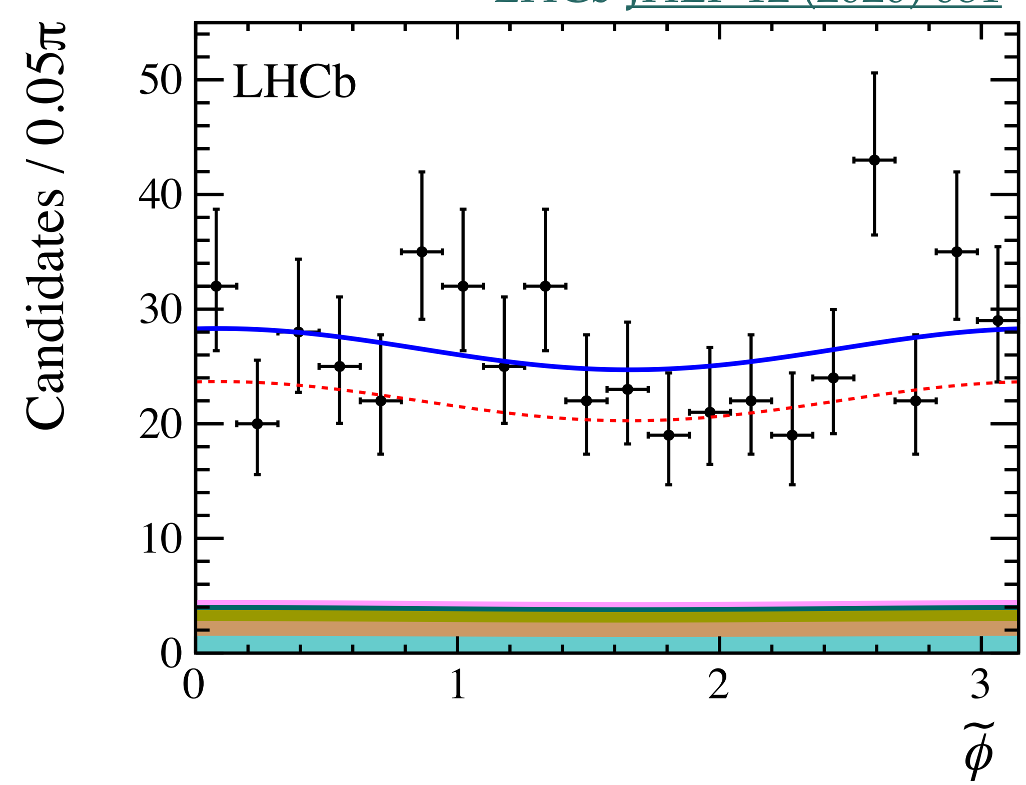
$b \to s\gamma$ in $B \to Ve^+e^-$

- $B^0 \to h^+h^-e^+e^-$ described by 3 angles
- Photon polarisation measured with ϕ
  - $\cos 2\phi$ or $\sin 2\phi$ modulation would signal right-handed contribution





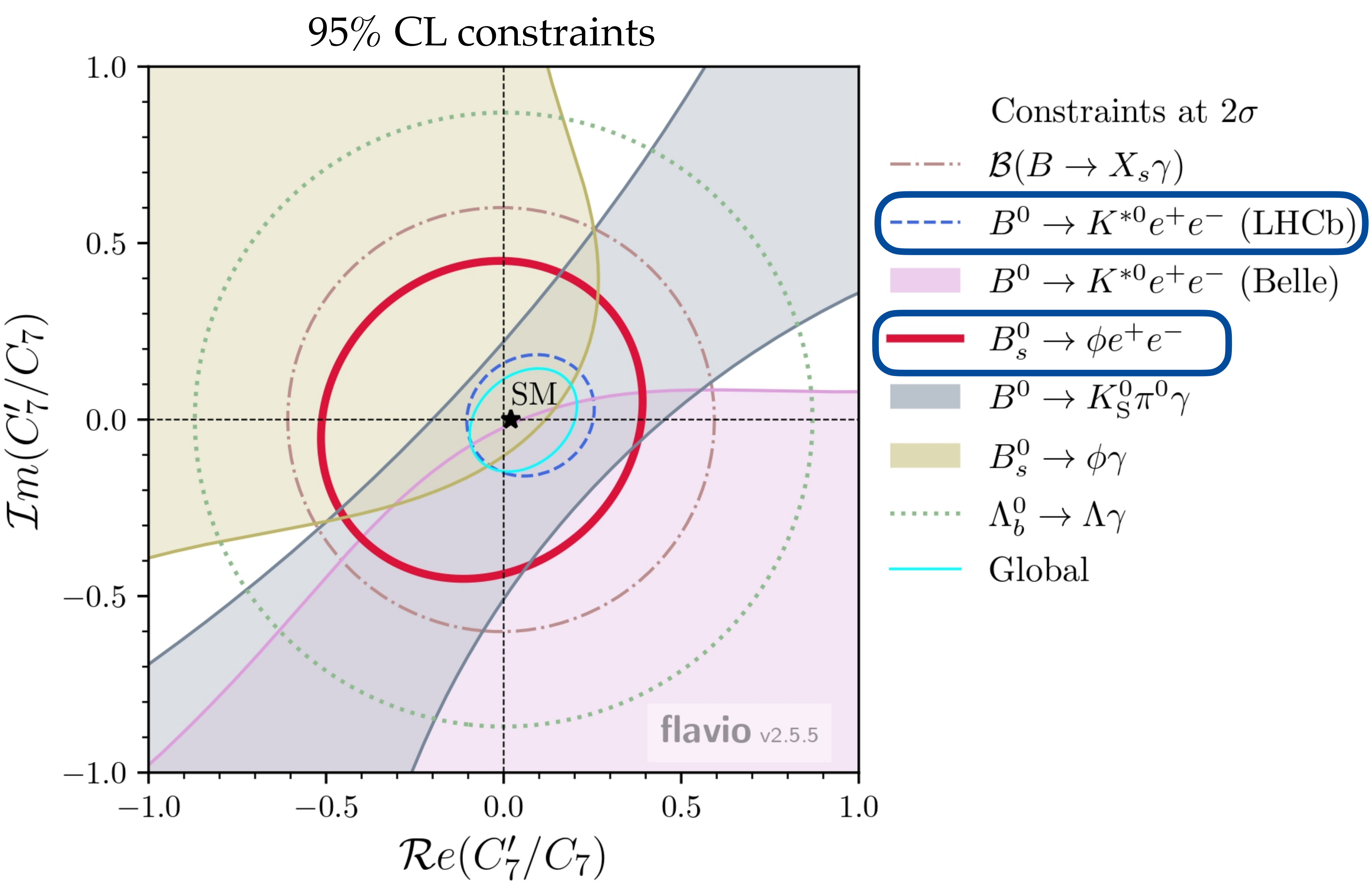
LHCb JHEP 12 (2020) 081



No significant modulation observed

$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$

LHCb JHEP 03 (2025) 047

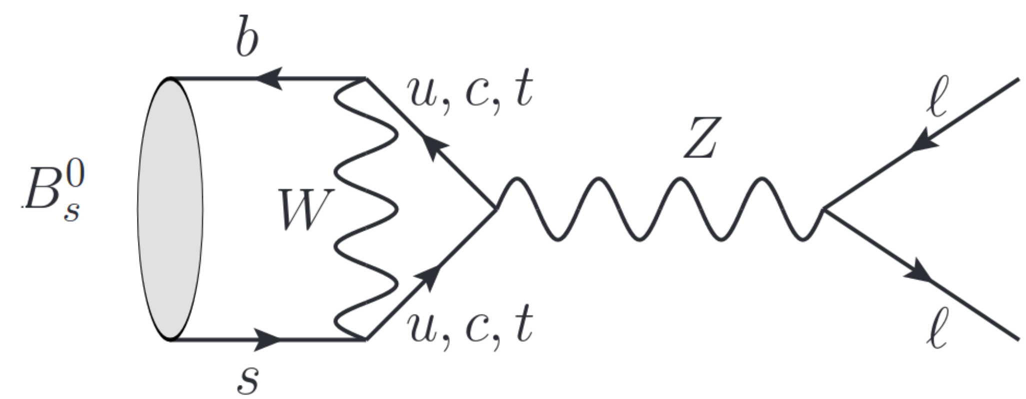


Leptonic $B_s \rightarrow \ell\ell$

Leptonic $B_s \to \mu^+\mu^-$

- A golden flavour physics channel
  - Very rare 10^{-9} BR (helicity suppression)
  - Precise 4% BR prediction (fully leptonic)

  Beneke et al. JHEP 10 (2019) 232
  Kozachuk et al., PRD 97 (2018) 053007



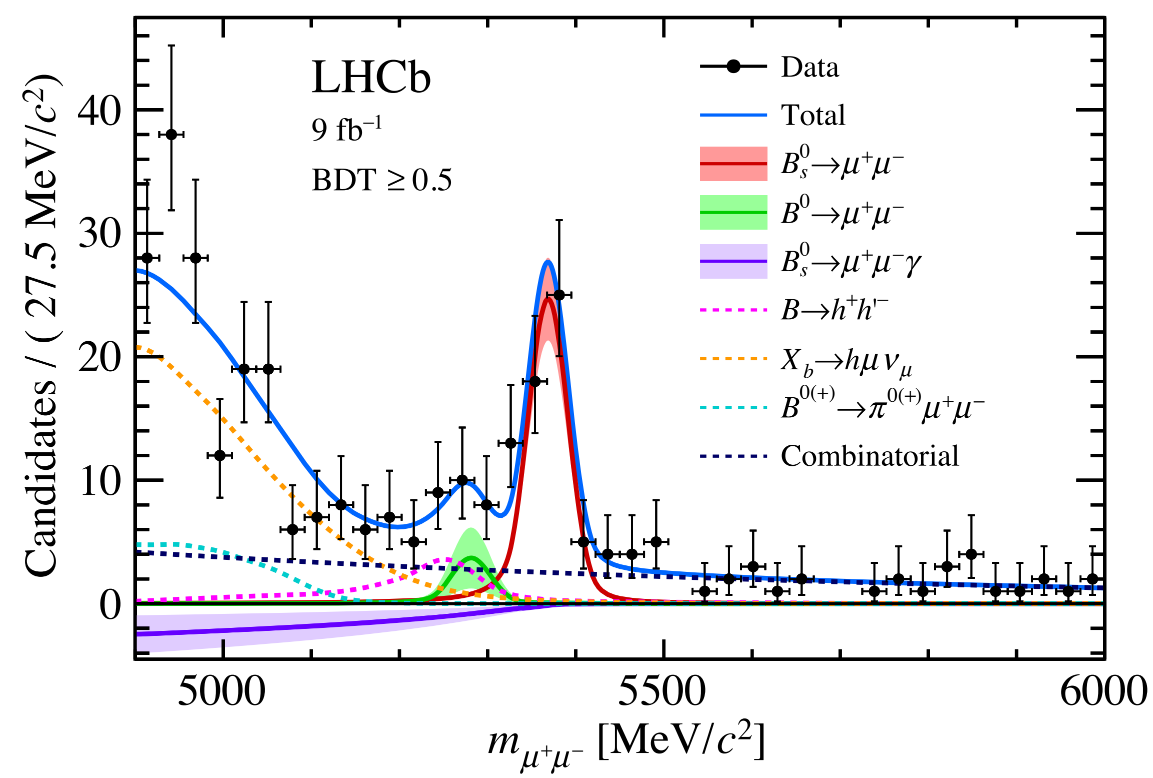
+ box diagram involving neutrinos

- Searched since the 80's and firstly observed in 2014 by LHCb+CMS (Nature 522 (2015) 68)

- Current world average dominated by LHCb+CMS

- Measurements compatible with SM
  → strong constraints on C_{10}, C_S and C_P but cannot disentangle them

PRL 128, (2022) 041801

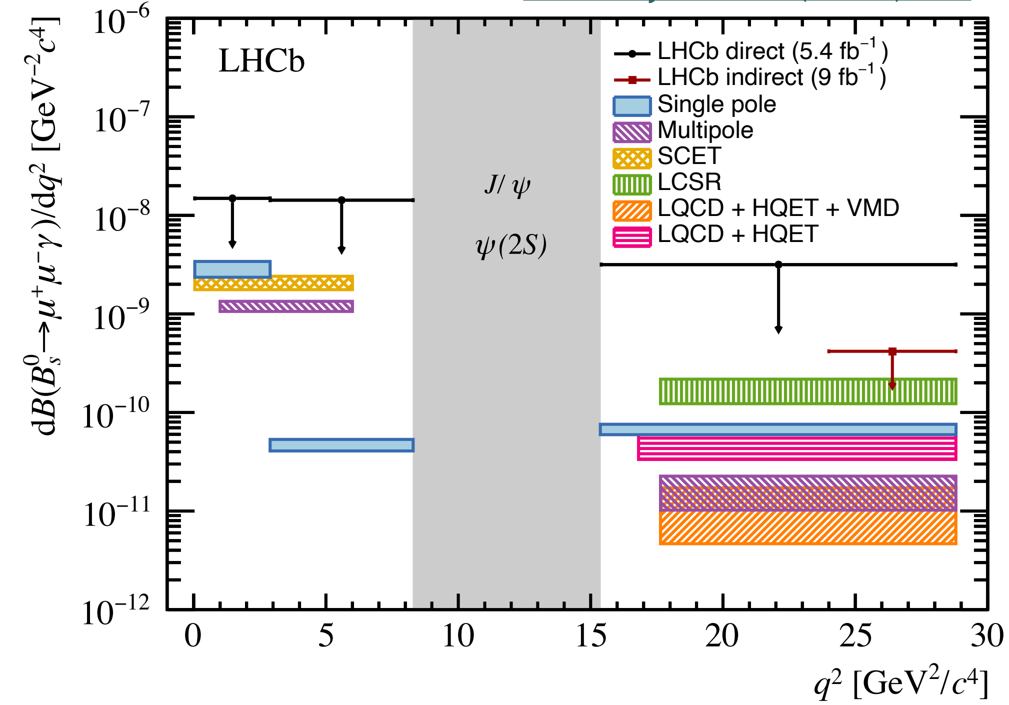


LHCb: PRL 128, (2022) 041801
CMS: *PLB* 842 (2023) 137955
ATLAS: *JHEP* 04 (2019) 098

Other leptonic decays

- Search for $B_s \to \mu\mu\gamma$
  - Lifted helicity suppr, but pay α_{em}
  - Sensitive to C_9 and C_{10}
  - Searched in both $\mu\mu$ (part-reco) and $\mu\mu\gamma$ (full-reco)

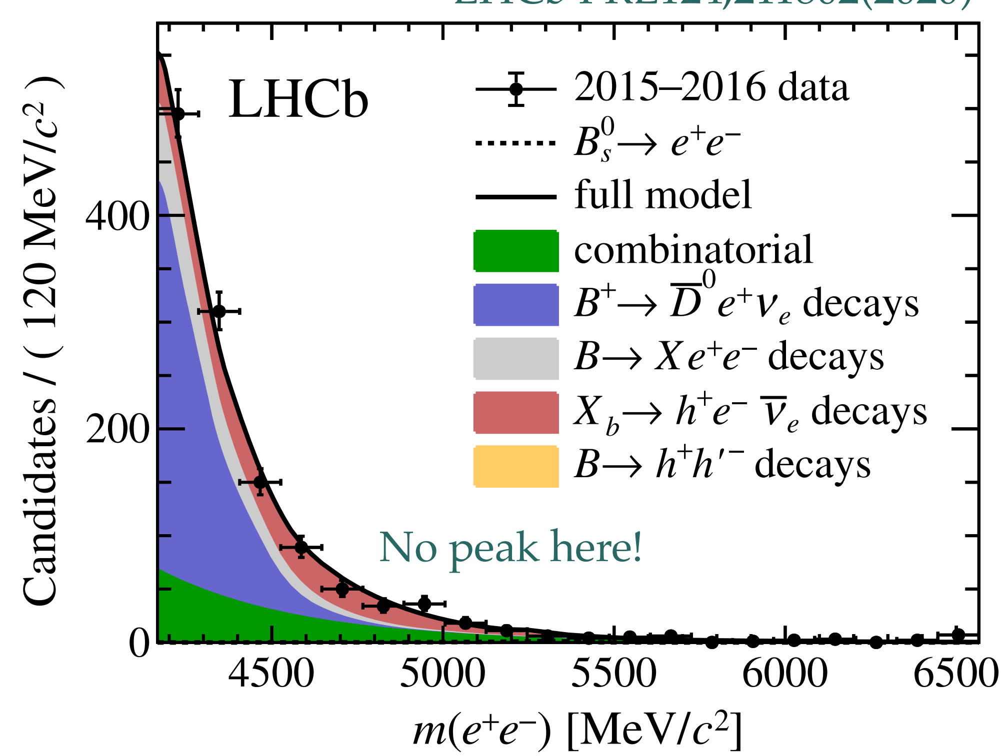
LHCb JHEP07(2024)101



- Search for $B_s \to ee$
  - Further suppressed by $(m_e/m_\mu)^2$
  - Constrains (pseudo)scalars C_S and C_P
  - Could help disentangle $C_{S,P}$ from C_{10} in the measurement from $B_s \to \mu\mu$ (assuming lepton universality holds)

$$BR\left(B_s^0 \to e^+e^-\right) < 9.4 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

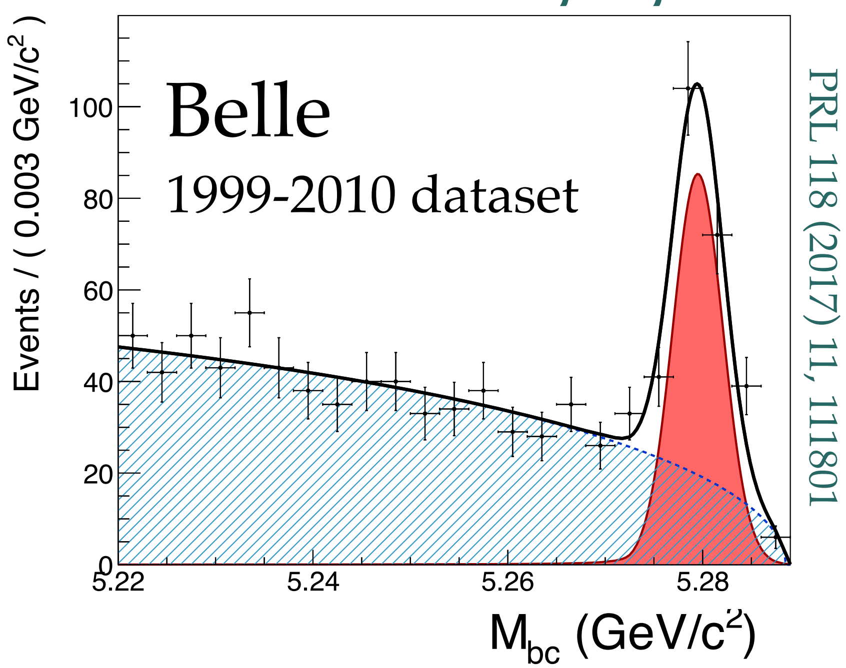
LHCb PRL124,211802(2020)



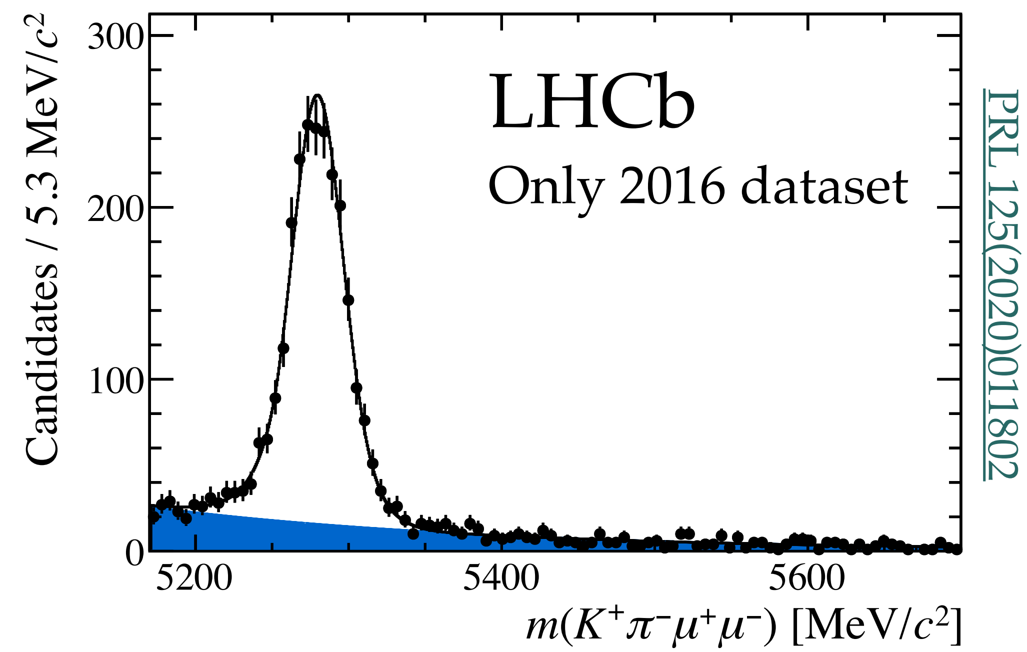
Semileptonic $b \to s\ell\ell$

LHCb's **strength**

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



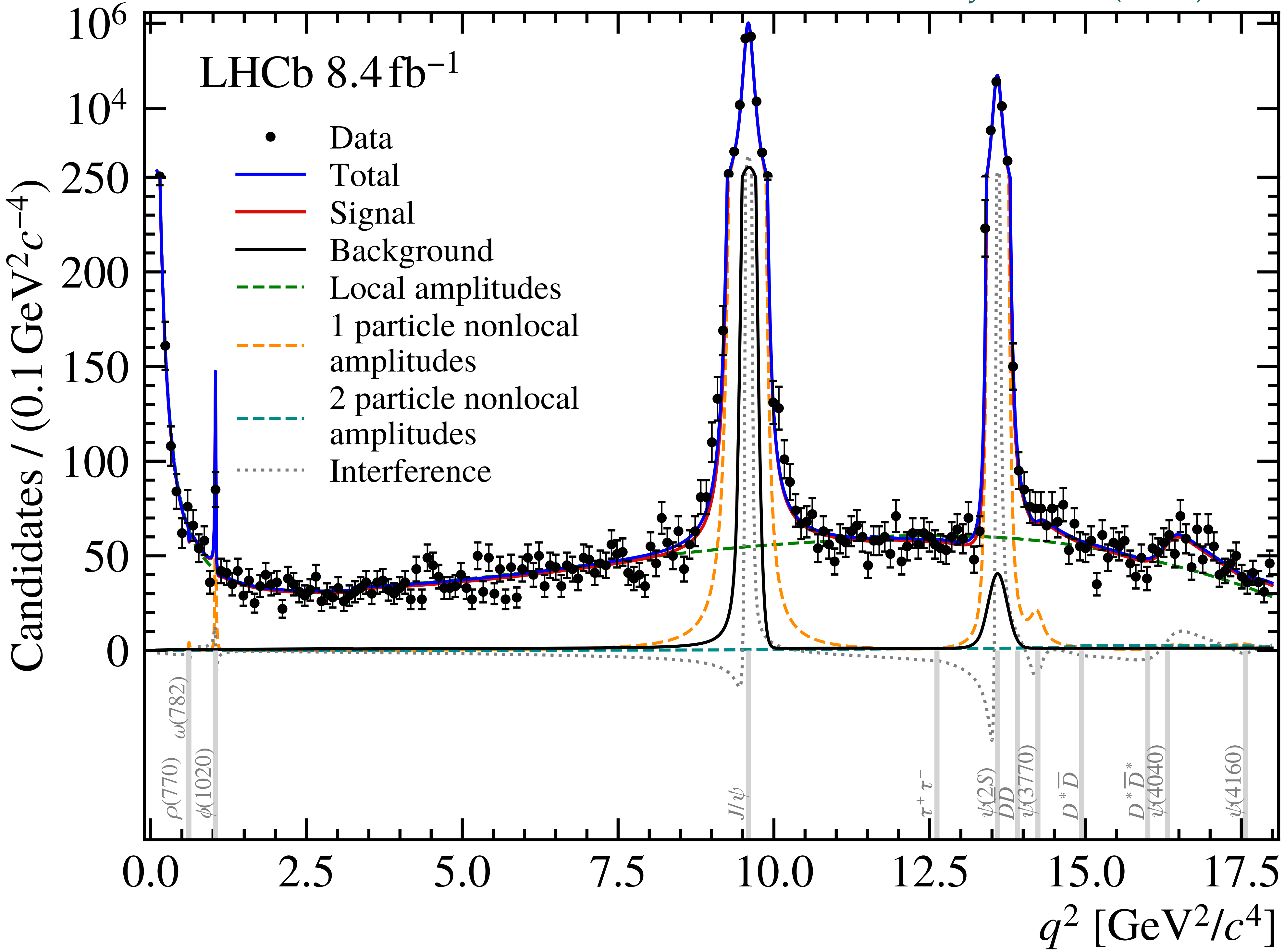
$B^0 \to K^* \mu^+ \mu^-$



But probably impossible
to do $B \to K\nu\bar{\nu}$ at LHCb
(see Belle2 talk by Meihong Liu)

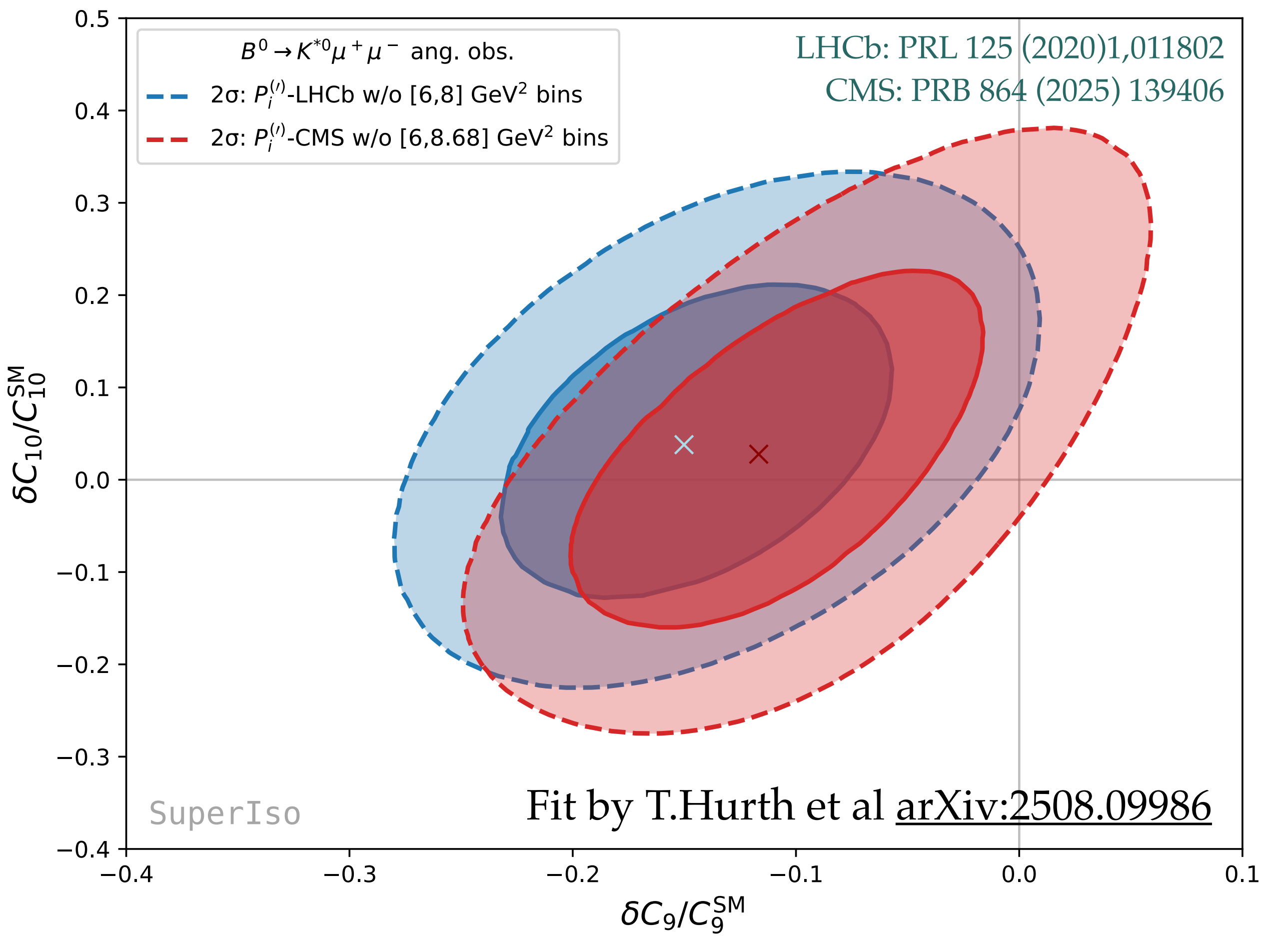
The $B^0 \to K^*\mu\mu$ dataset

JHEP 09 (2024) 026



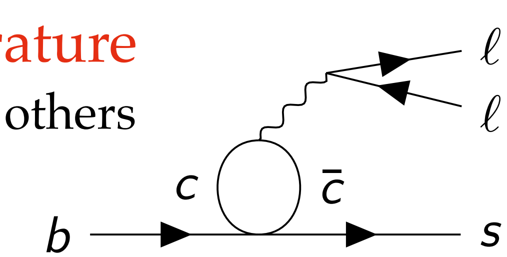
The $B^0 \to K^*\mu\mu$ dataset

Deviation in C_9 Wilson coeff confirmed by CMS



Long distance effects from $b \to sc\bar{c}$ under debate in the literature

[arXiv:2507.17824] and many others



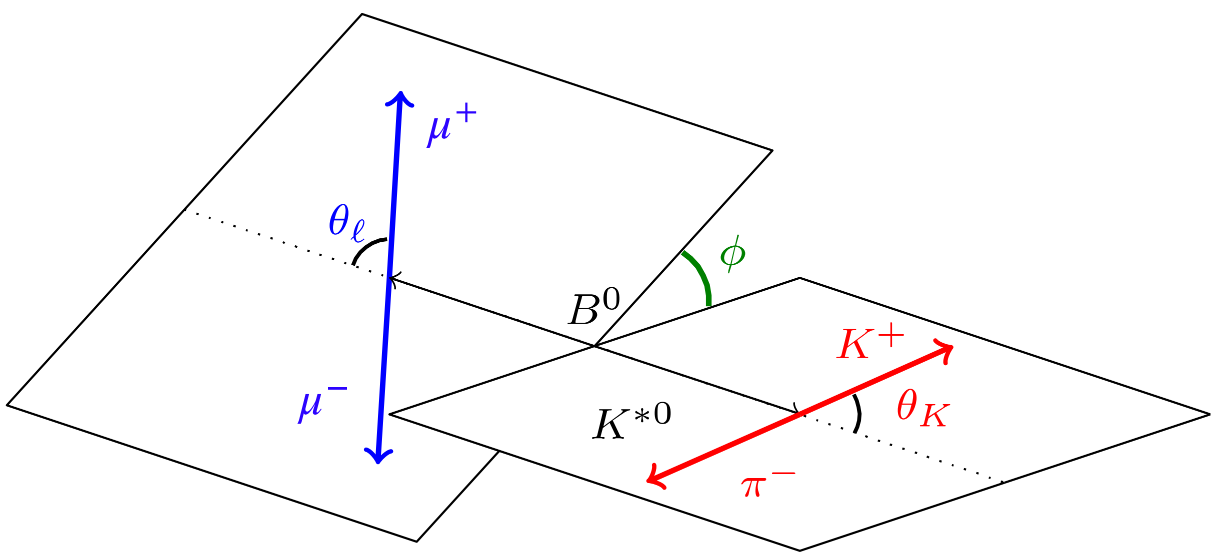
- LHCb has performed several angular analyses with different levels of model dependence
  - 4.7/fb Binned CP-averaged observables [PRL 125 (2020)1,011802]
  - 4.7/fb **Ampl.Ana** based on z-expansion [PRL 132 (2024) 131801]+ [PRD 109 (2024) 052009]
  - 8.4/fb **Ampl.Ana** with dispersion model [JHEP 09 (2024) 026]
- Anomaly in C_9 not covered by fit models allowing for long-distance effects

$B^0 \to K^*\mu\mu$ angular analysis

LHCb-PAPER-2025-041 (in preparation)

- New comprehensive analysis measuring model-indep angular observables in q^2 bins
- Using full Run 1+2 dataset (8.4 / fb) → doubled stat compared to previous analysis

See CERN talks by L.Carus and M.Smith

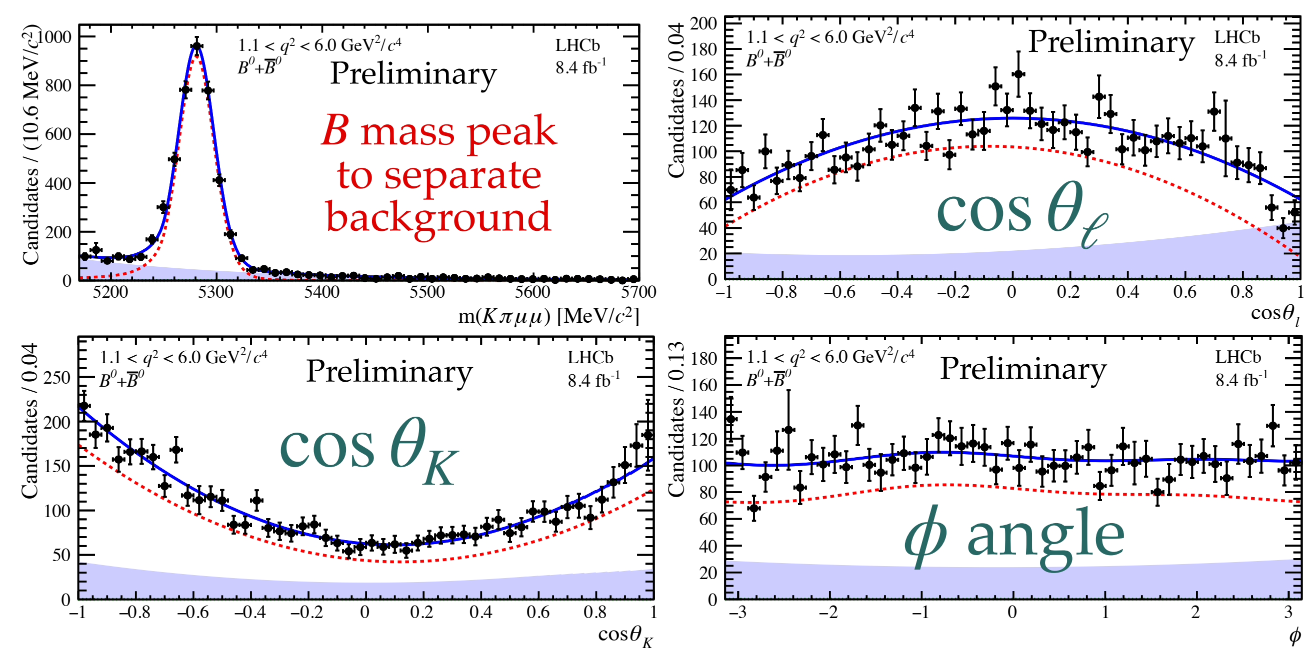


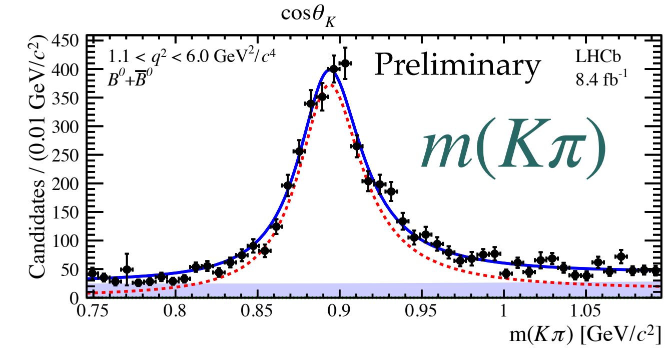
$$\frac{d^4\Gamma}{dq^2\, d\vec{\Omega}\, dm_{K\pi}} \frac{1}{\Gamma + \bar{\Gamma}} \propto \sum_i S_i(q^2) f_i(\vec{\Omega}) \left|\mathrm{BW}(m_{K\pi})\right|^2$$

Ang. observables

Spherical harmonics

5D fit in large q^2 bin 1-6 GeV^2



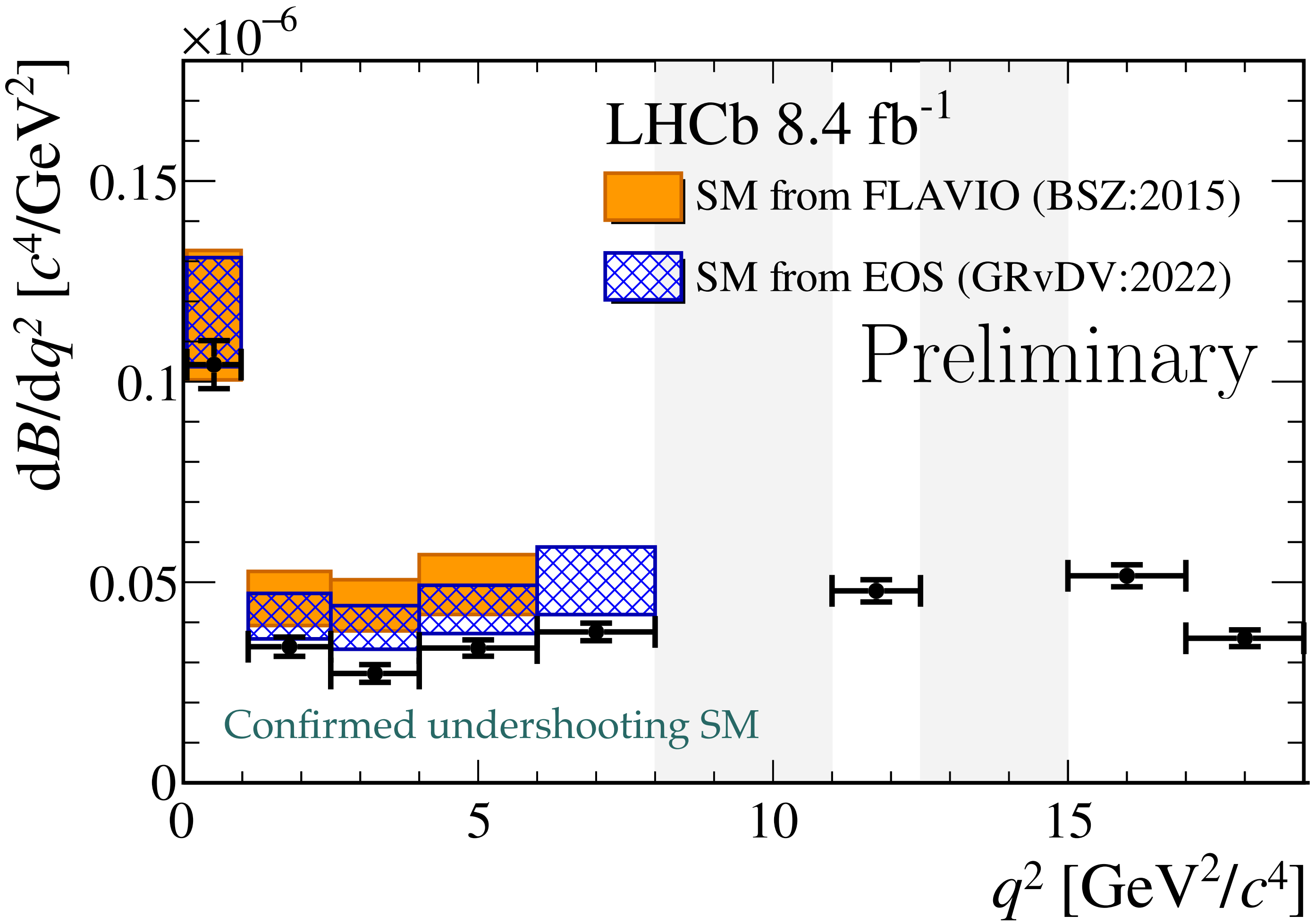


$m(K\pi)$ explicitely included in the model

$B^0 \to K^*\mu\mu$ angular analysis

NEW

LHCb-PAPER-2025-041 (in preparation)



- dBr/dq^2 determined simultaneously with the angular shape
- Allows result to be independent on the angular distribution
- Also provides full correlation matrix for global fits of Wilson coeffs

BSZ:
[arXiv:1810.08132]
[JHEP 08 (2016) 098]
GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]

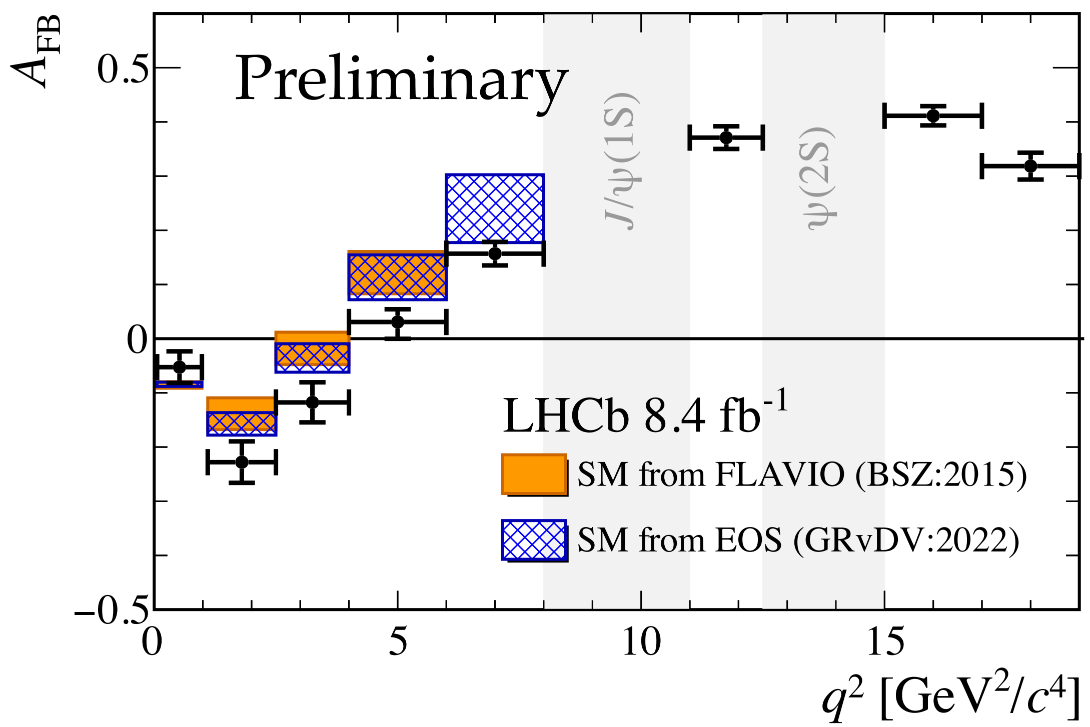
Check CERN seminar for all preliminary results (plots, tables)

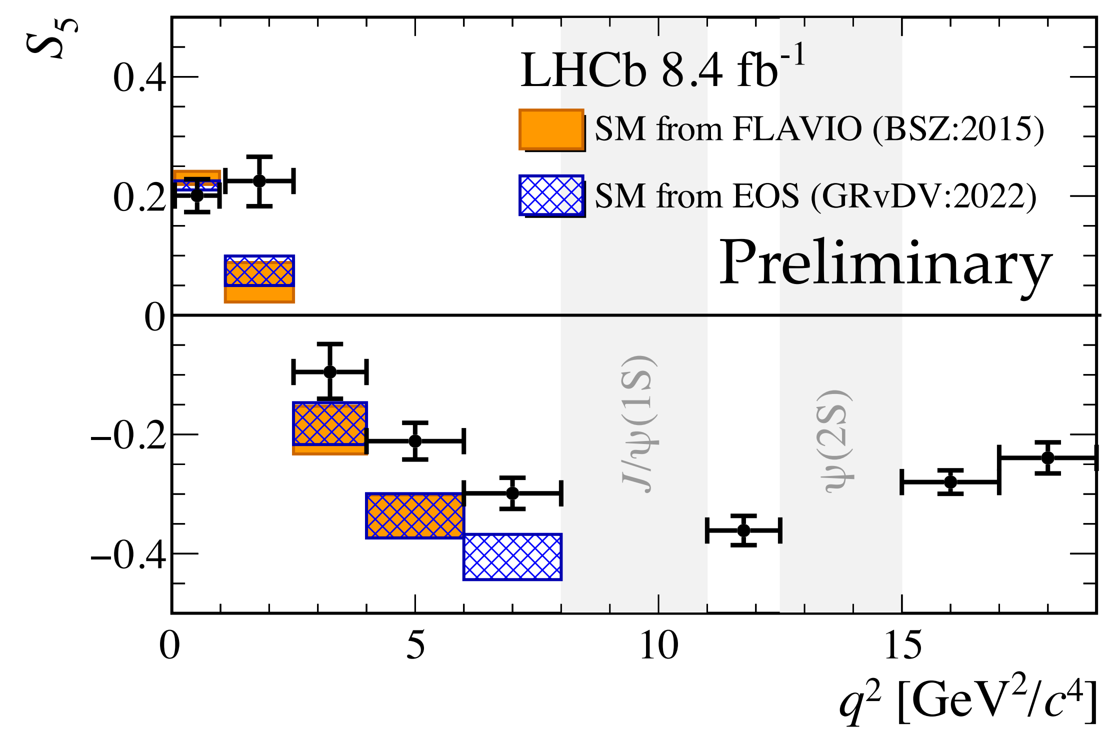
$B^0 \to K^*\mu\mu$ angular analysis

NEW

LHCb-PAPER-2025-041 (in preparation)

Here a couple of examples of the fitted angular observables





- Several fit configurations to extract max information with best sensitivity (e.g. assuming or not $m_\mu = 0$, allowing or not A_{CP})
- Also fitting optimised observables (e.g. P_5')
- Shown here: fit with "partially massive model" ($S_1^s = 3S_2^s$ but $S_2^c \neq -S_1^c$) and no CP assymmetries

Check CERN seminar for all preliminary results (plots, tables)

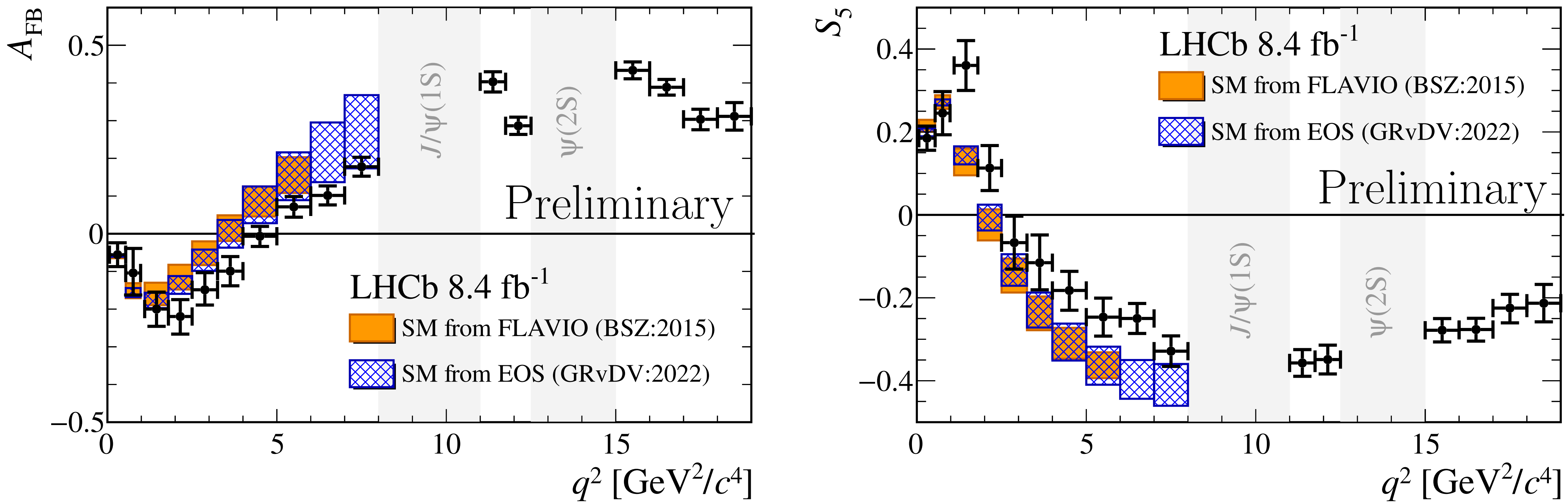
BSZ:
[arXiv:1810.08132]
[JHEP 08 (2016) 098]
GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]

$B^0 \to K^*\mu\mu$ angular analysis

NEW

LHCb-PAPER-2025-041 (in preparation)

Halved q^2 bins to have better resolution on observables q^2 dependence



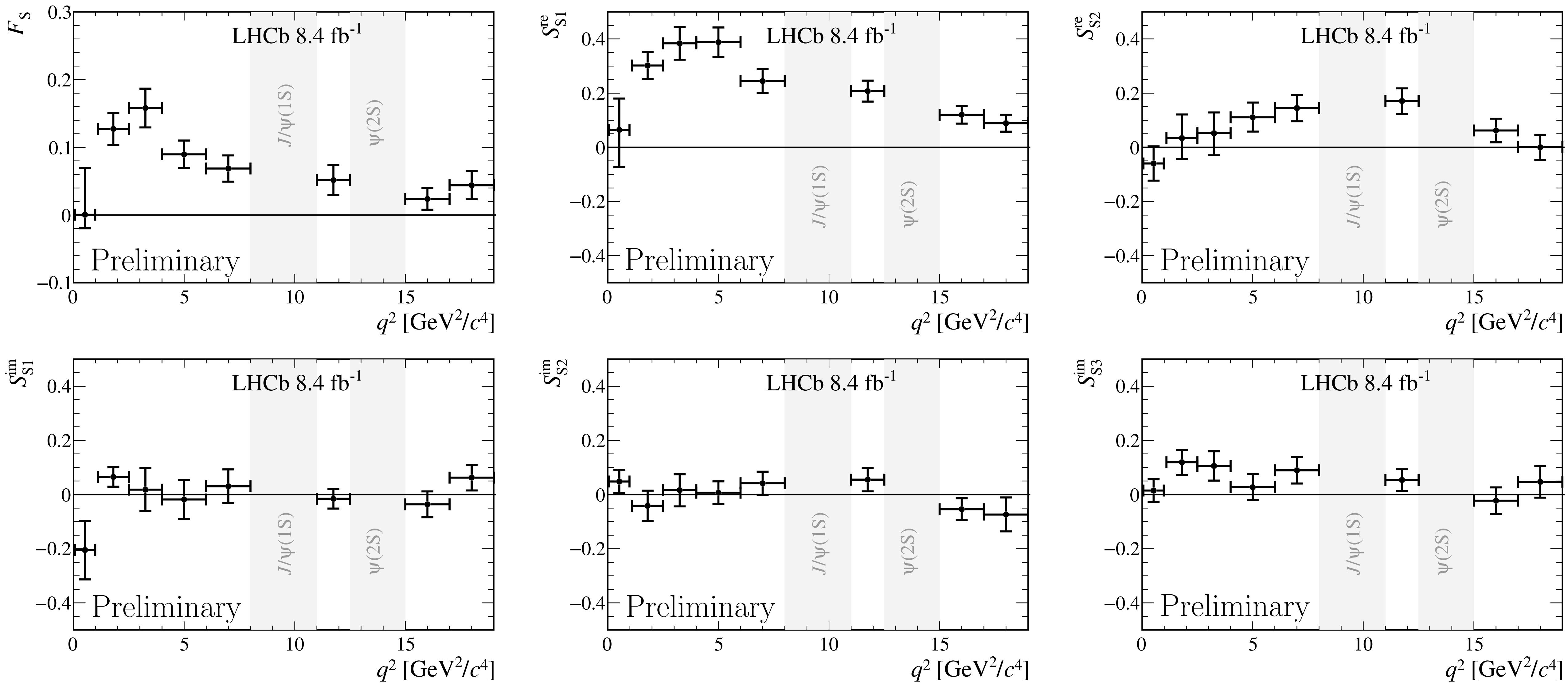
BSZ:
[arXiv:1810.08132]
[JHEP 08 (2016) 098]
GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]

Check CERN seminar for all preliminary results (plots, tables)

$B^0 \to K^*\mu\mu$ angular analysis

LHCb-PAPER-2025-041 (in preparation)

- Fitting also S-wave component and S/P interference observables for the first time

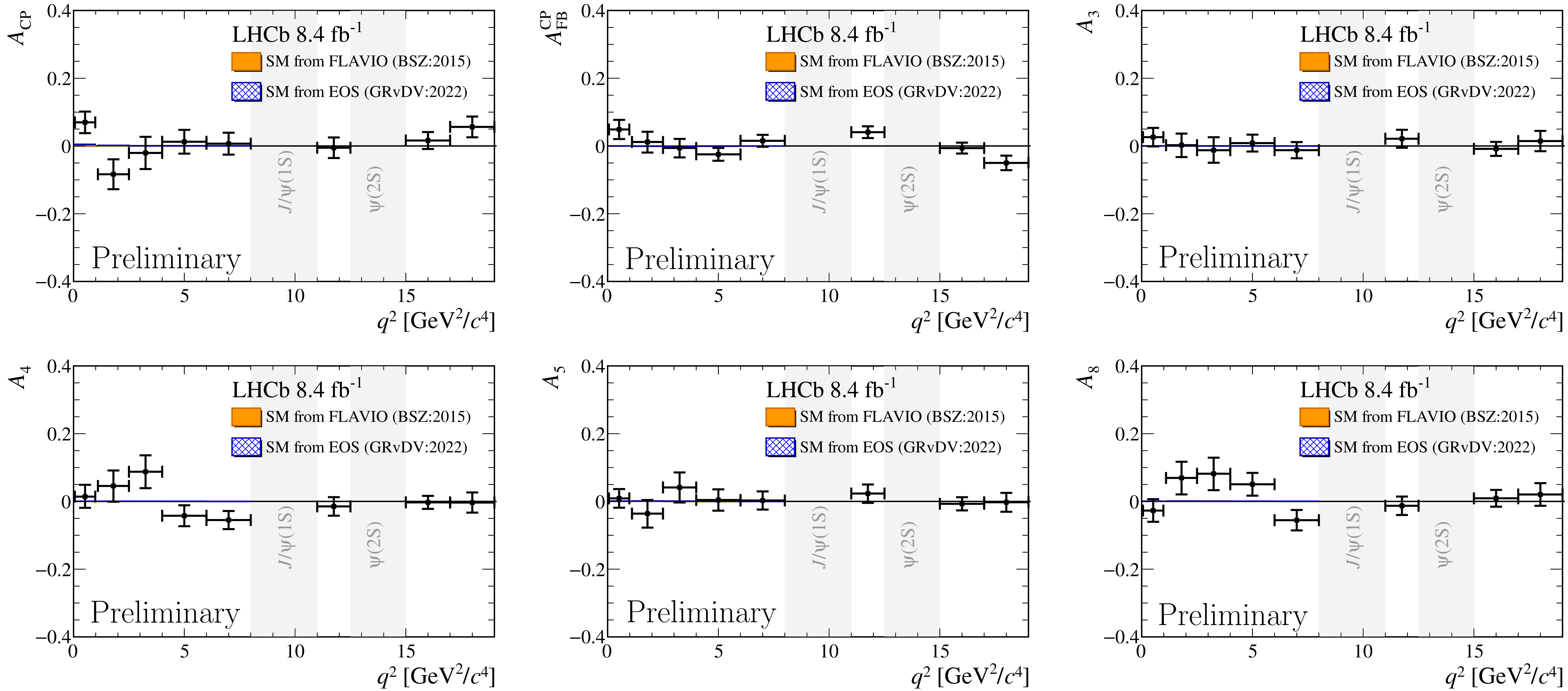


Check CERN seminar for all preliminary results (plots, tables)

$B^0 \to K^*\mu\mu$ angular analysis

LHCb-PAPER-2025-041 (in preparation)

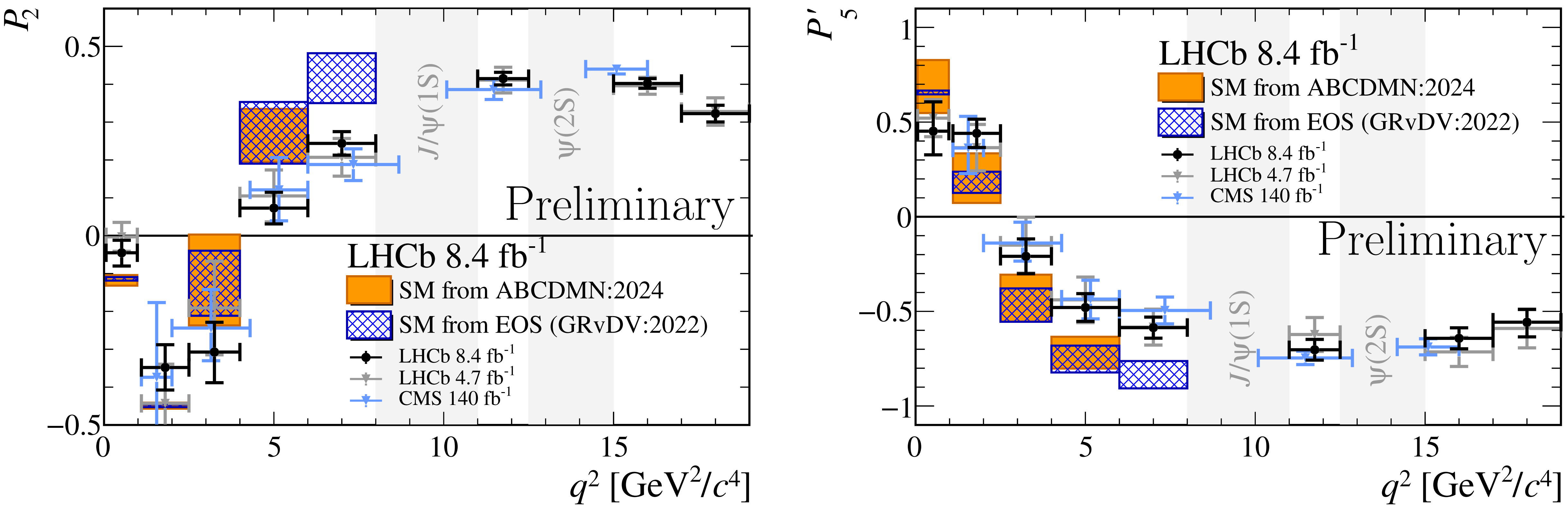
- CP asymmetric angular observables measured: no significant CP asymmetry observed



Check CERN seminar for all preliminary results (plots, tables)

Comparison to previous results

LHCb-PAPER-2025-041 (in preparation)

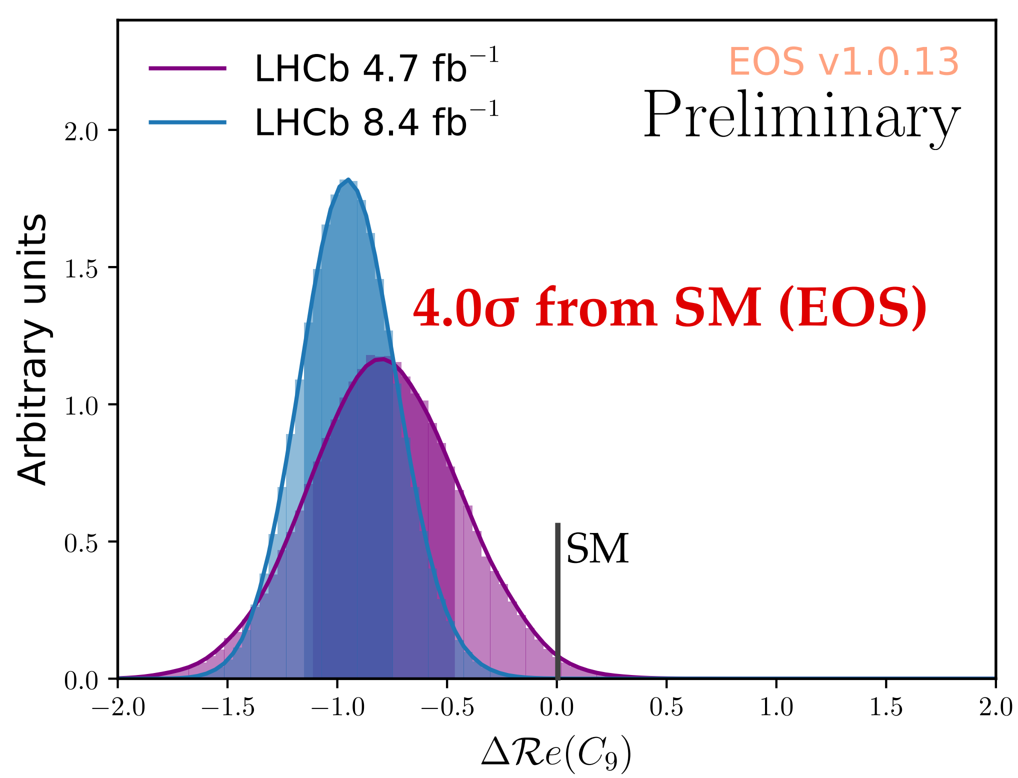


- New result consistent with previous LHCb measurement (superseded)
- Also consistent and more precise than latest CMS measurement (140 fb^{-1})

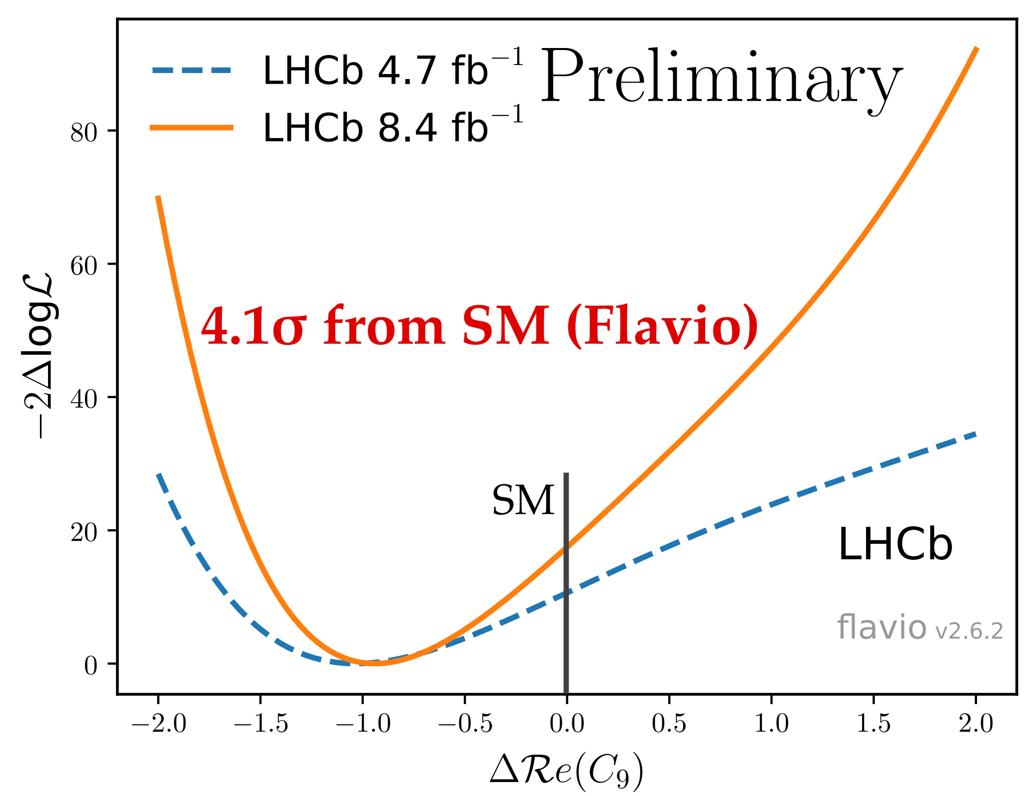
Wilson coefficients fits

LHCb-PAPER-2025-041 (in preparation)

- Can fit C_9 Wilson coefficient to angular observables and Br
  - Precise results depend on fit setup and treatment of non-local effects → take it with a grain of salt
  - Many predictions available, just two sets compared here
- **Anomaly wrt SM persists and gets more significant**

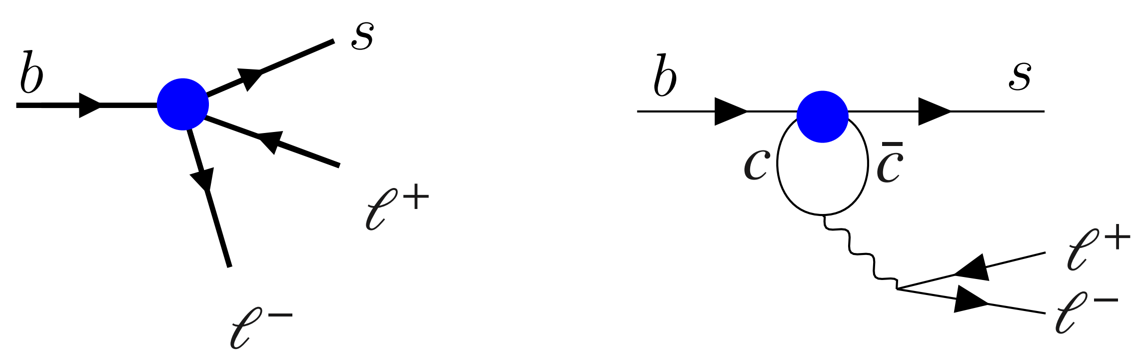


EOS: EPJC 82 (2022) 569



Flavio: arXiv:1810.08132

Comparison to unbinned LHCb analyses



$$C_{9,\lambda}^{\text{eff}}(q^2) = C_9^{\text{SM}} + \Delta C_9 + H_\lambda(q^2)$$

- Flavio fit to binned analysis (8.4/fb): $\Delta C_9 = -0.94^{+0.21}_{-0.17}$ (i)
- Model with z-expansion (4.7/fb): $\Delta C_9 = -0.93^{+0.53}_{-0.57}$ (ii)
- Local/non-local amplitudes (8.4/fb): $\Delta C_9 = -0.71 \pm 0.33$ (iii)

- Differences in ΔC_9 value and significance expected
- Non-local contributions effect very degenerate with ΔC_9

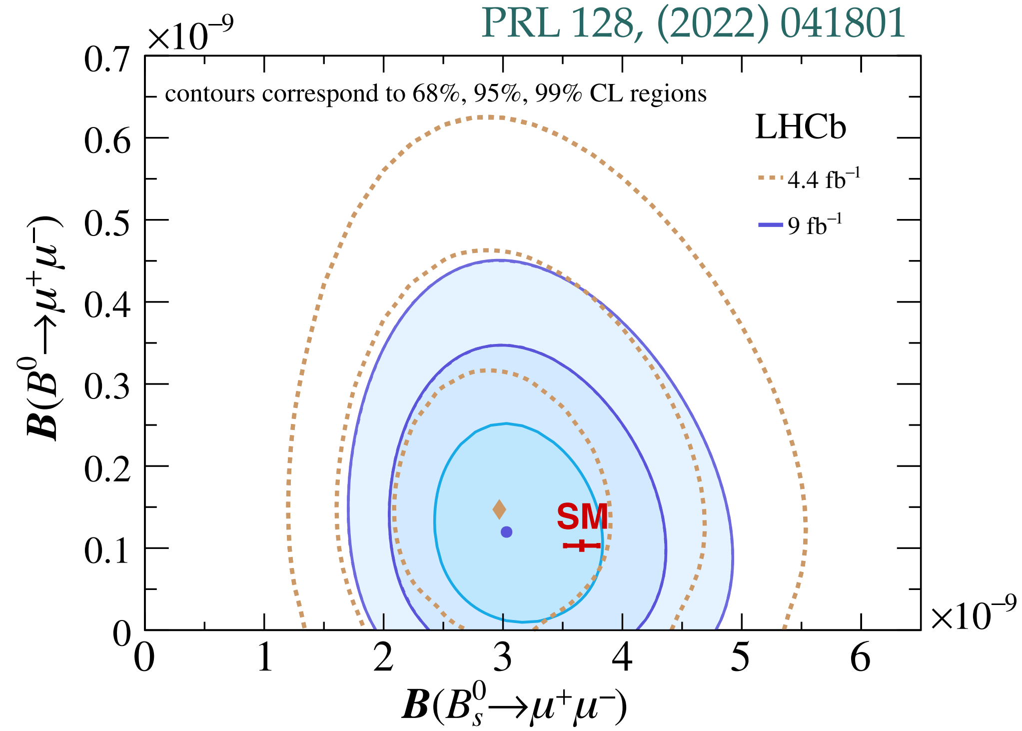
(i) LHCb-PAPER-2025-041 (in preparation)
(ii) [PRL 132 (2024) 131801]+ [PRD 109 (2024) 052009]
(iii) [JHEP 09 (2024) 026]

Electroweak FCNC in $b \to d$

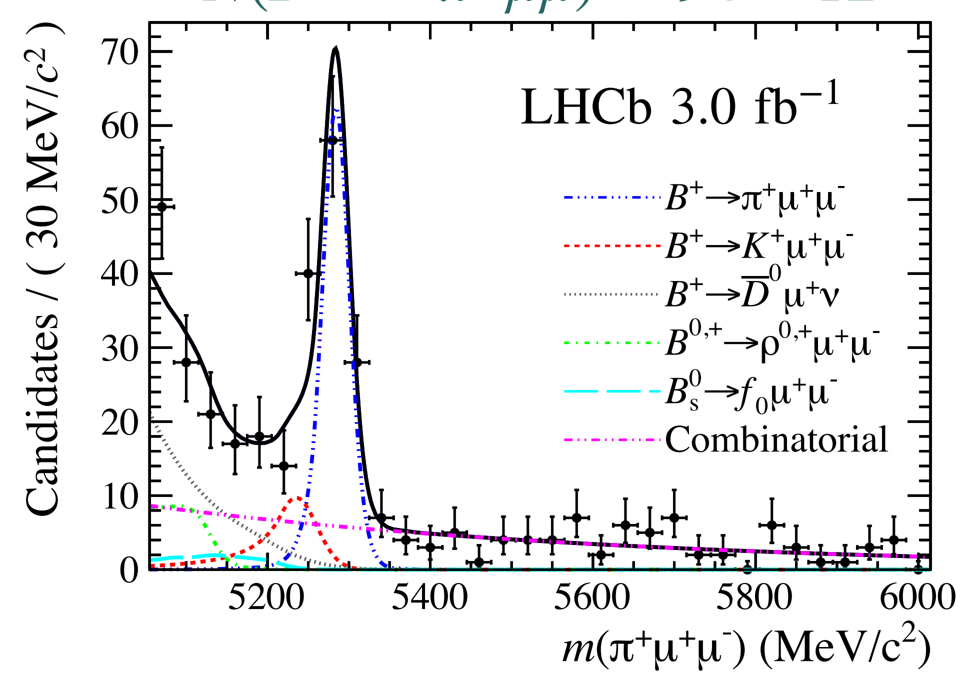
$b \to d$ FCNC decays

- A further $|V_{td}/V_{ts}|^2 = \simeq 0.05$ suppresion of decay rates w.r.t. $b \to s$
  - Starting to explore the $b \to d$ frontier
- Leptonic $B_d \to \mu\mu$ is almost at reach of experimental sensitivity
- $B^+ \to \pi^+\mu\mu$ measured with Run 1 dataset at 13% stat precision
- Many ongoing $b \to d\ell\ell$ analyses. We are about to enter the precision regime (time-dep, angular, …)
  → **Stay tuned for upcoming results**

PRL 128, (2022) 041801



$N(B^+ \to \pi^+\mu\mu) = 94 \pm 12$

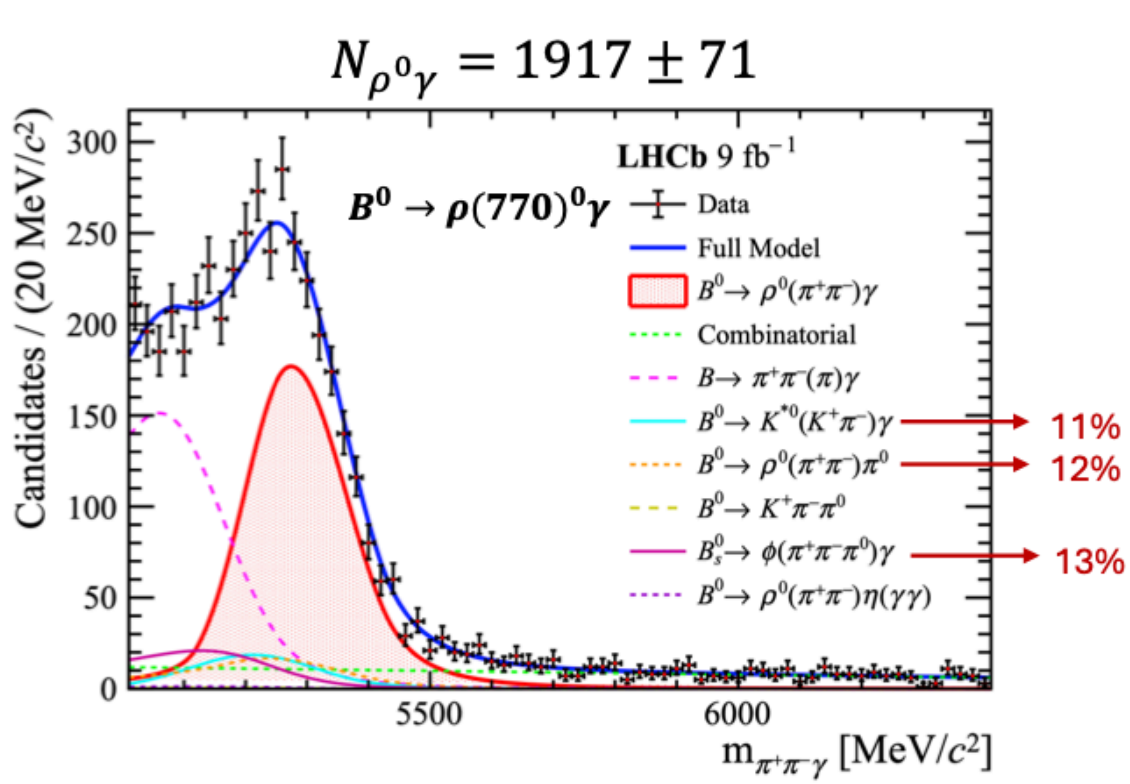


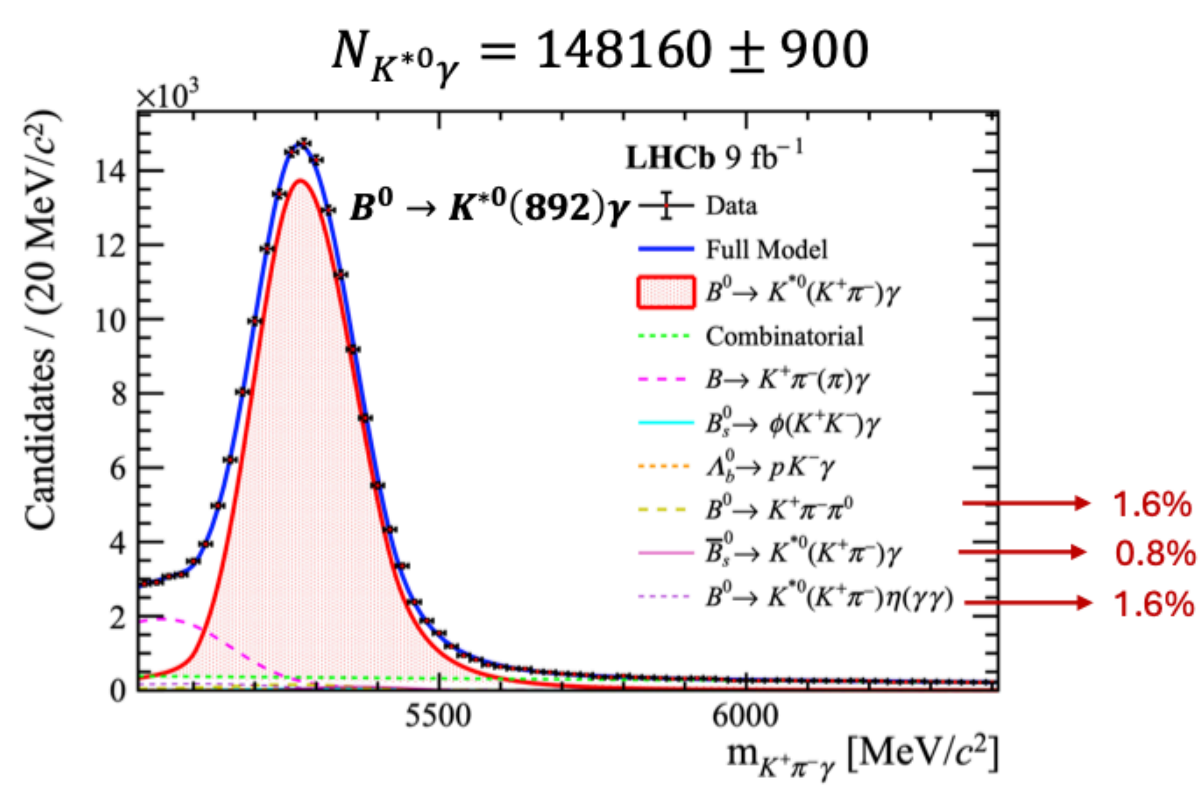
Measurement of $Br(B^0 \to \rho^0\gamma)$

NEW

JHEP 10 (2015) 034

- At LHCb we are starting to have $O(10^3)$ events of $b \to d\gamma$ decays
- **NEW**: ~2000 events of $B^0 \to \rho\gamma$ using the Run 1+2 dataset (9/fb)
  $\mathrm{Br}(B^0 \to \rho\gamma) = (7.9 \pm 0.3 \pm 0.2 \pm 0.2) \times 10^{-7}$
  with the last uncertainty stemming from $\mathrm{Br}(B^0 \to K^*\gamma)$



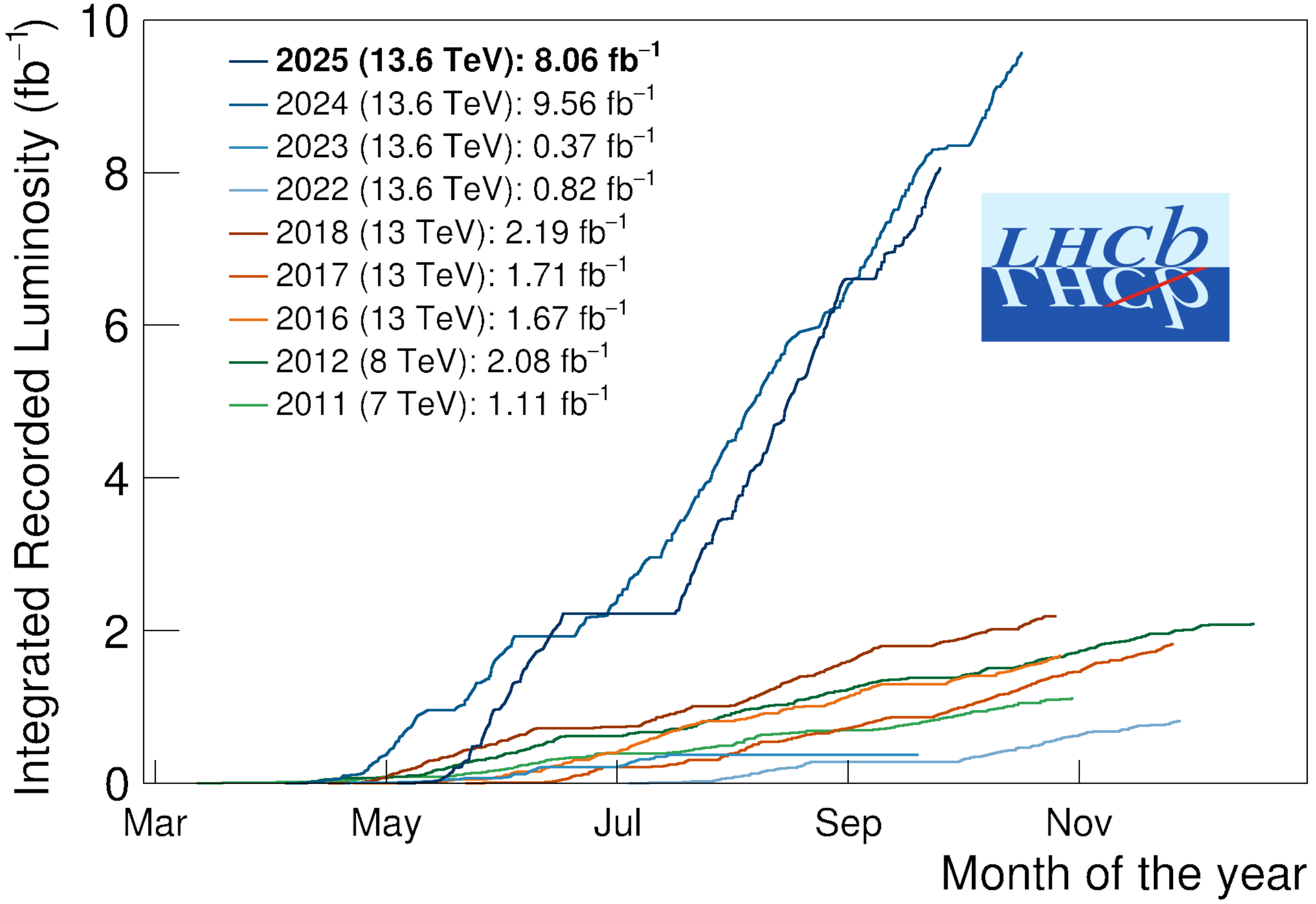


LHCb Upgrade I

Current LHCb detector

- Upgraded to run at 5 × luminosity
  - Removed hardware trigger: reading out full detector in real time (30 MHz)
  - Real time analysis allows more precise and efficient triggering
- **Upgrade II** aims to collect 300/fb by end of HL-LHC, installation by 2036

https://lbgroups.cern.ch/online/OperationsPlots/index.htm

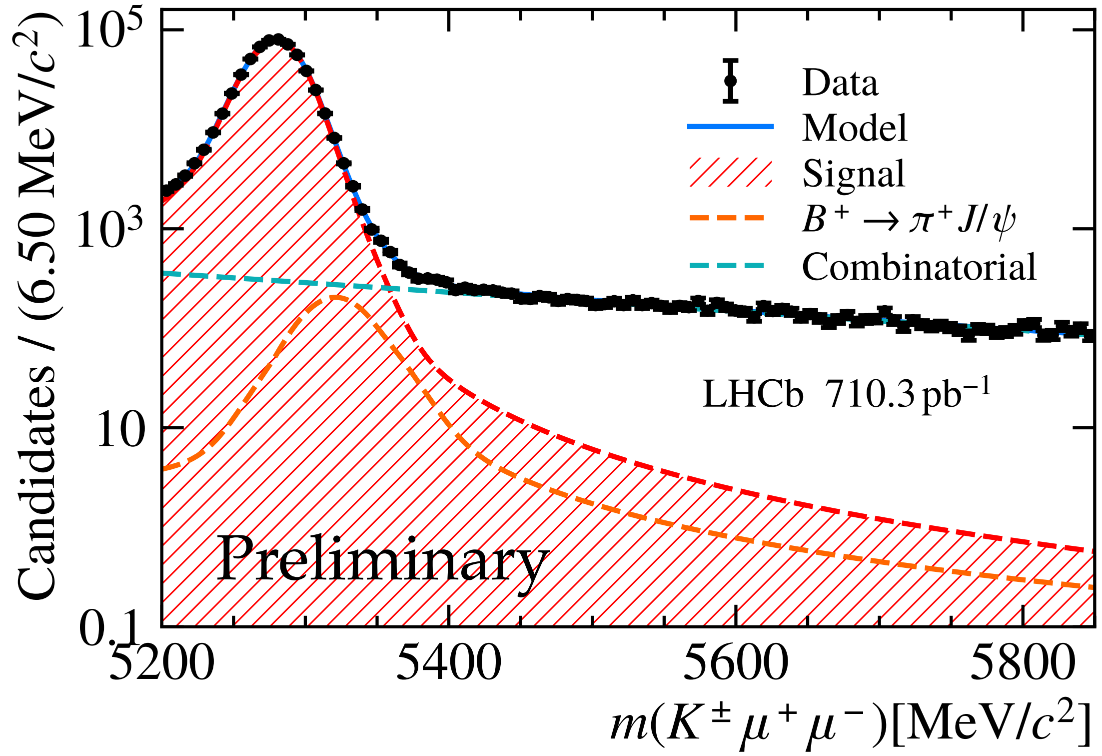


$B^+ \to K^+ J/\psi$ to validate Run3 data

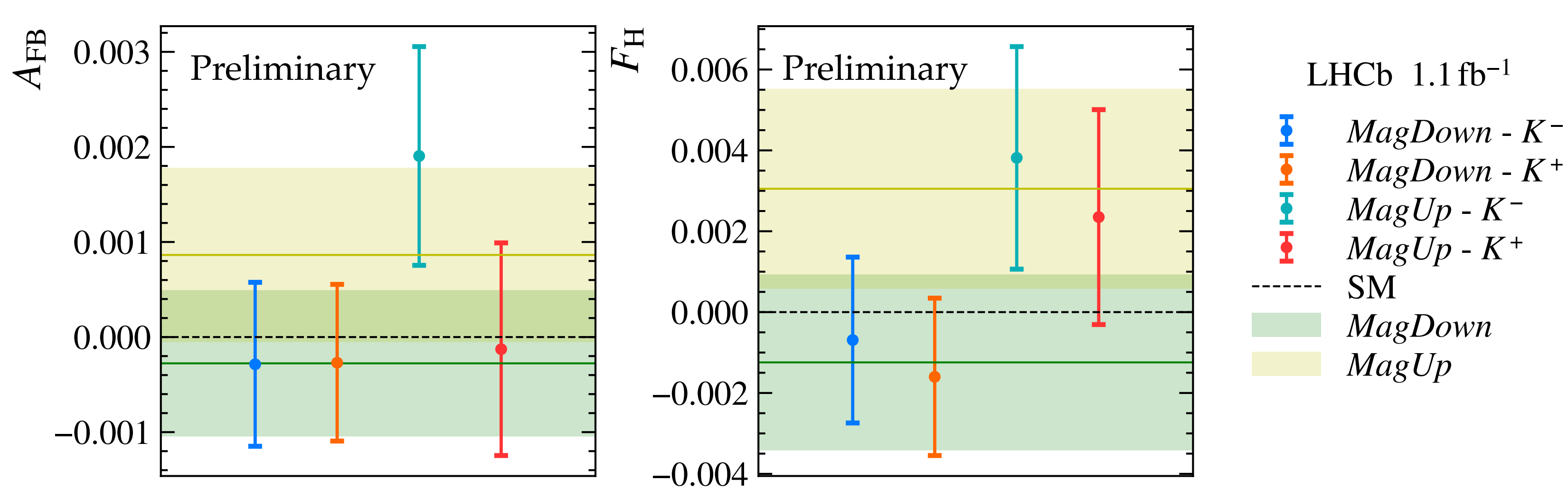
NEW

LHCb-PAPER-2025-040, in preparation

- SM candle with no new physics expected and large stat
- Measured A_{FB} and F_H differentially across kinematic using data from 2024 run with pileup μ=5.3
- Validated $b \to s\mu\mu$ analyses with Run3
- Systematics 5-10 times smaller than stat



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$



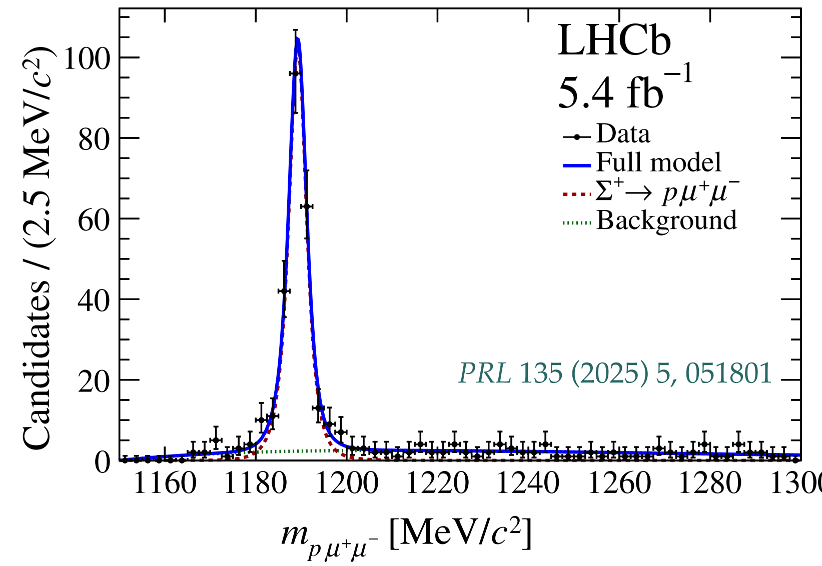
Rare Kaon decays

Rare Kaon decays at LHCb

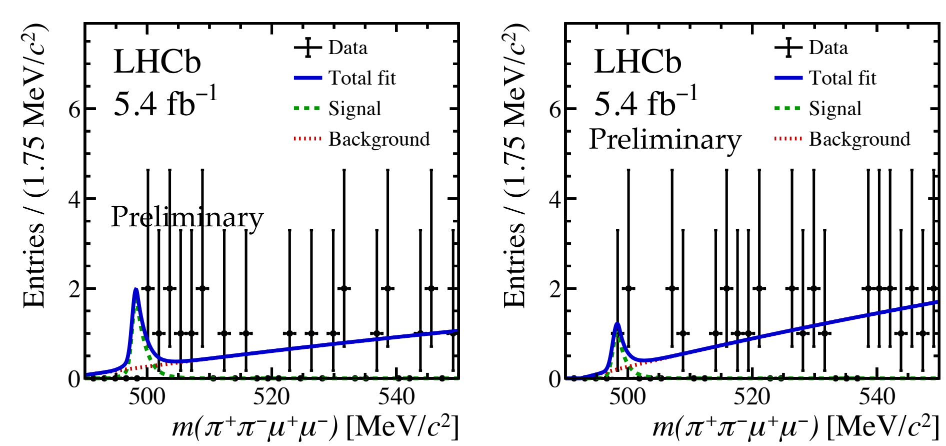
- At LHC pp collisions the kaon cross section is $\sim$ 2400 times larger than that of the b-quark
- LHCb trigger not designed for kaons, but huge improvements with Run2 and Run3
- LHCb now at the forefront of rare kaon:
  - (i) $Br(K_S \to \mu\mu) < 2.2 \times 10^{-10}$ at 90% CL
  - (ii) $Br(K_S \to \mu\mu\mu\mu) < 5.1 \times 10^{-12}$ at 90% CL
  - (iii) **New!** **Observation** of $\Sigma^+ \to p\mu\mu$ with $Br = (1.08 \pm 0.17) \times 10^{-8}$
  - (iv) **Very new!** $Br(K_S \to \pi\pi\mu\mu) < 1.4 \times 10^{-9}$ at 90% CL
  - (v) Also anomalous decays of η and η' to $\mu\mu$ and $\pi\pi\mu\mu$

(i) PRL 125 (2020) 231801
(ii) PRD108 (2023) L031102
(iii)PRL 135 (2025) 5, 051801
(iv)LHCb-PAPER-2025-045 in preparation
(v) LHCb-CONF-2025-002

Observation of $\Sigma^+ \to p\mu\mu$

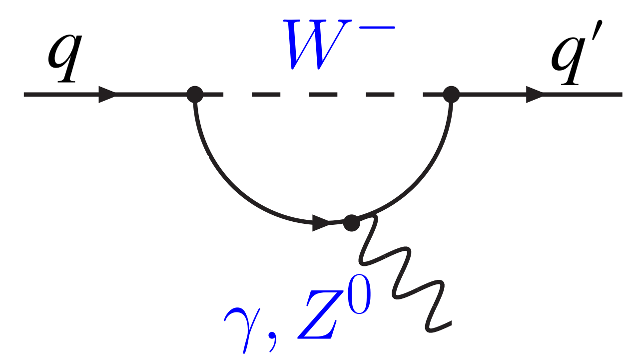


Search for $K^0 \to \pi^+\pi^-\mu^+\mu^-$



Conclusions

- The LHCb experiment marked **a new era for rare B decays**
  - Very large yields allowing more and more sophisticated analyses
  - Persistent anomaly in $b \to s\mu\mu$ decays under scrutiny



NEW

- Preliminary results presented today:
  - Comprehensive model-independent analysis of $B \to K^*\mu\mu$
  - Precise measurement of $B \to \rho^0\gamma$ branching ratio
  - Validation of Run3 data with $B \to KJ/\psi(\mu\mu)$ analysis
  - Search for $K^0_S \to \pi\pi\mu\mu$

"Extraordinary claims require
extraordinary evidence"
Carl Sagan

"Discovery commences with
the awareness of anomaly"
Thomas Kuhn

BACKUP

WC dependence of $Br(B_s \to \ell\ell)$

$$\bar{\mathcal{B}}r(B_s \to \ell^+\ell^-)_{\rm SM} = \frac{1}{1-y_s}\frac{G_F^2\alpha^2}{16\pi^3}\tau_{B_s}|V_{ts}V_{tb}^*|^2 f_{B_s}^2 M_{B_s} m_\ell^2 \sqrt{1-4\frac{m_\ell^2}{M_{B_s}^2}}|C_{10}^{\rm SM}|^2.$$

$$P_{\ell\ell} \equiv \frac{C_{10}^{\ell\ell}-C_{10'}^{\ell\ell}}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_P^{\ell\ell}-C_{P'}^{\ell\ell}}{C_{10}^{\rm SM}}\right],$$

$$S_{\ell\ell} \equiv \sqrt{1-4\frac{m_\ell^2}{M_{B_s}^2}}\frac{M_{B_s}^2}{2m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_S^{\ell\ell}-C_{S'}^{\ell\ell}}{C_{10}^{\rm SM}}\right].$$

$B^0 \to K^*\mu\mu$ angular analysis

NEW

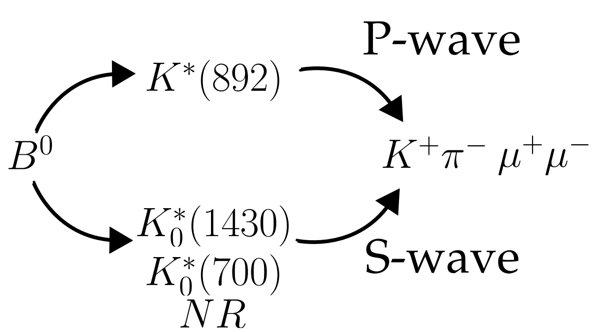
LHCb-PAPER-2025-041 (in preparation)

Angular observables
S_i : CP average
A_i : CP asymmetries

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}\,\mathrm{d}m_{K\pi}}\frac{1}{\Gamma+\bar{\Gamma}} = \left(1-\hat{\Gamma}_{\mathrm{S}}\right)\frac{9}{64\pi}\sum_i \left(S_i - A_i\right) f_i(\vec{\Omega})\left|\mathcal{BW}_{\mathrm{P}}\left(m_{K\pi}\right)\right|^2$$
$$+\frac{1}{8\pi}\sum_{1ac,2ac}\left(\tilde{S}_i-\tilde{A}_i\right) f_i(\vec{\Omega})\left|\mathcal{BW}_{\mathrm{S}}\left(m_{K\pi}\right)\right|^2$$
$$+\frac{1}{8\pi}\sum_{1bc,\ \mathrm{S1-S5}}\mathcal{R}e/\mathcal{I}m\left[\left(\tilde{S}_i-\tilde{A}_i\right) f_i(\vec{\Omega})\mathcal{BW}_{\mathrm{S}}\left(m_{K\pi}\right)\mathcal{BW}_{\mathrm{P}}\left(m_{K\pi}\right)^*\right]$$

$m(K\pi)$ explicitely included

Measured also all S-wave and P-/S-wave interference observables



- Large number of parameters: 25 S_i if allowing for massive leptons and scalar+tensor amplitudes
- **Several fit configurations** to extract max information with best sensitivity (e.g. assuming or not massless leptons, allowing or not CP asymmetries)

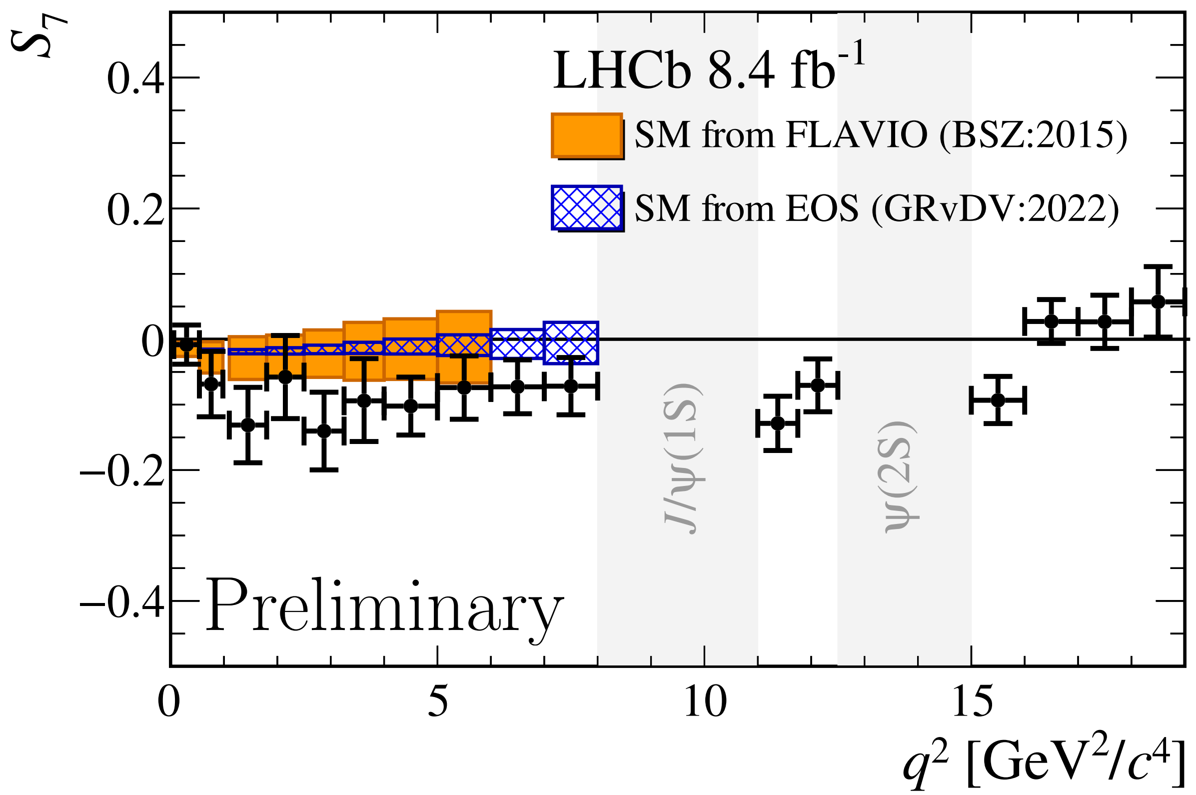
Check CERN seminar for more details

$B^0 \to K^*\mu\mu$ angular analysis

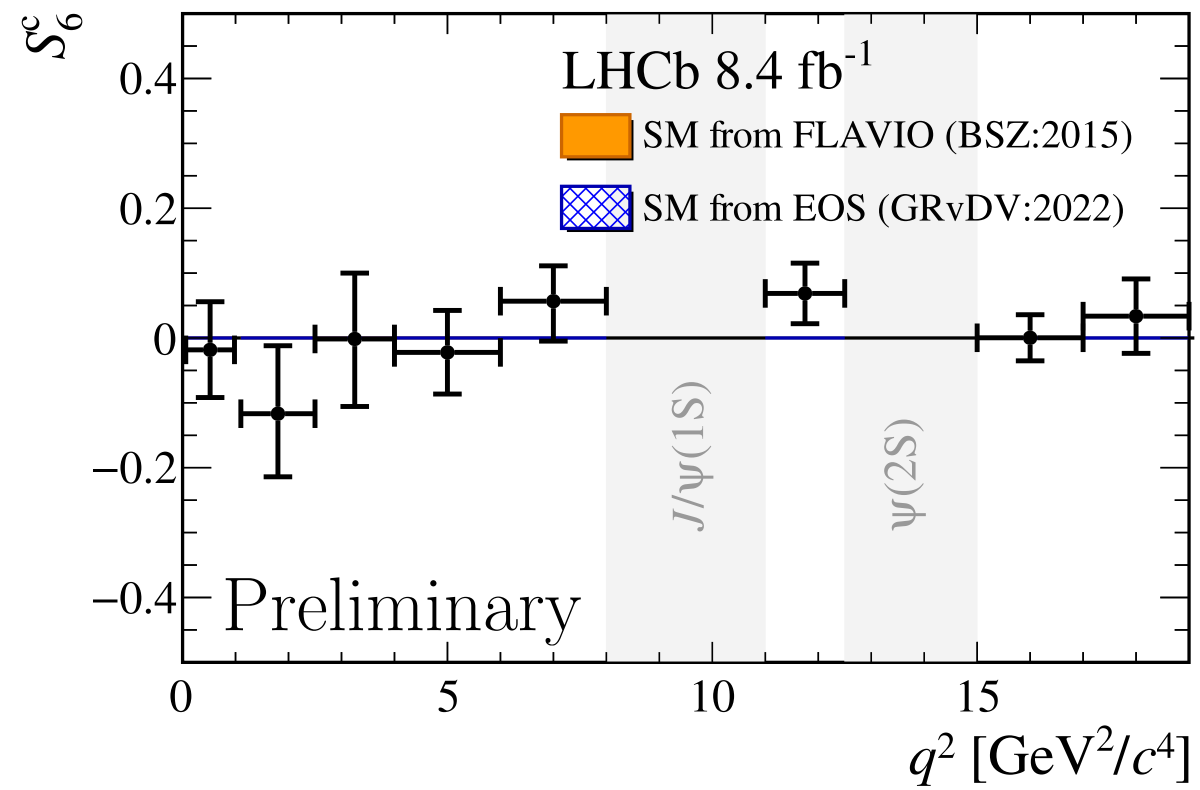
NEW

LHCb-PAPER-2025-041 (in preparation)

S_7 is sensitive to strong phases



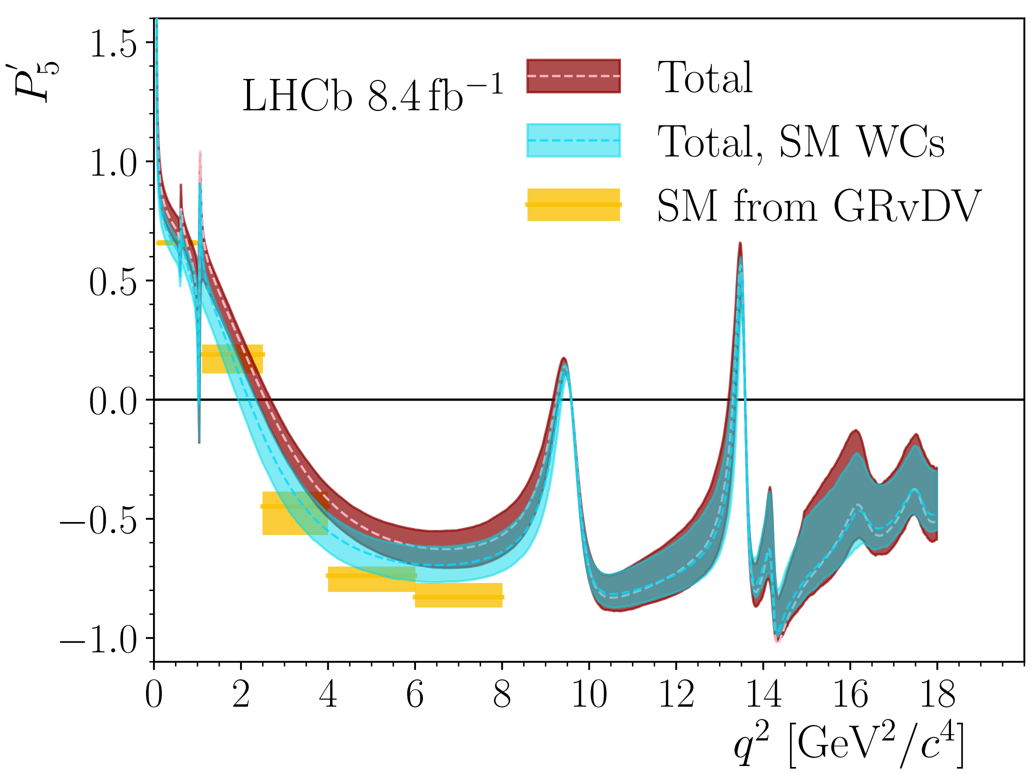
S_6^c is sensitive to NP tensor or scalar

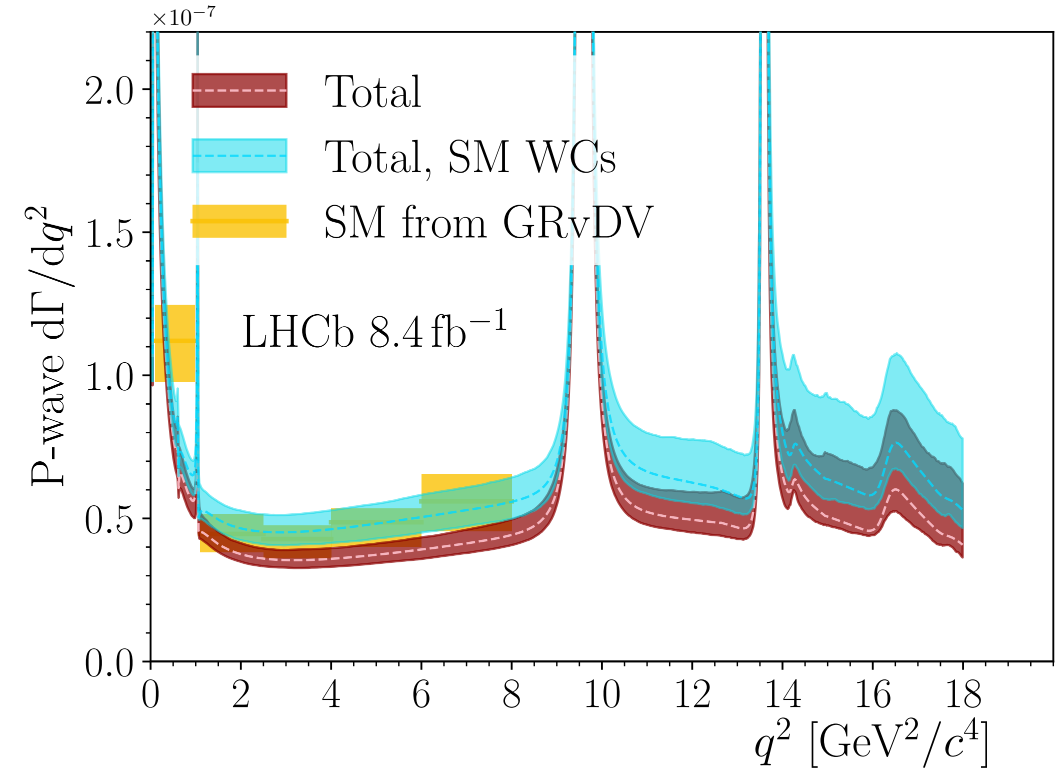


Check CERN seminar
for all preliminary
results (plots, tables)

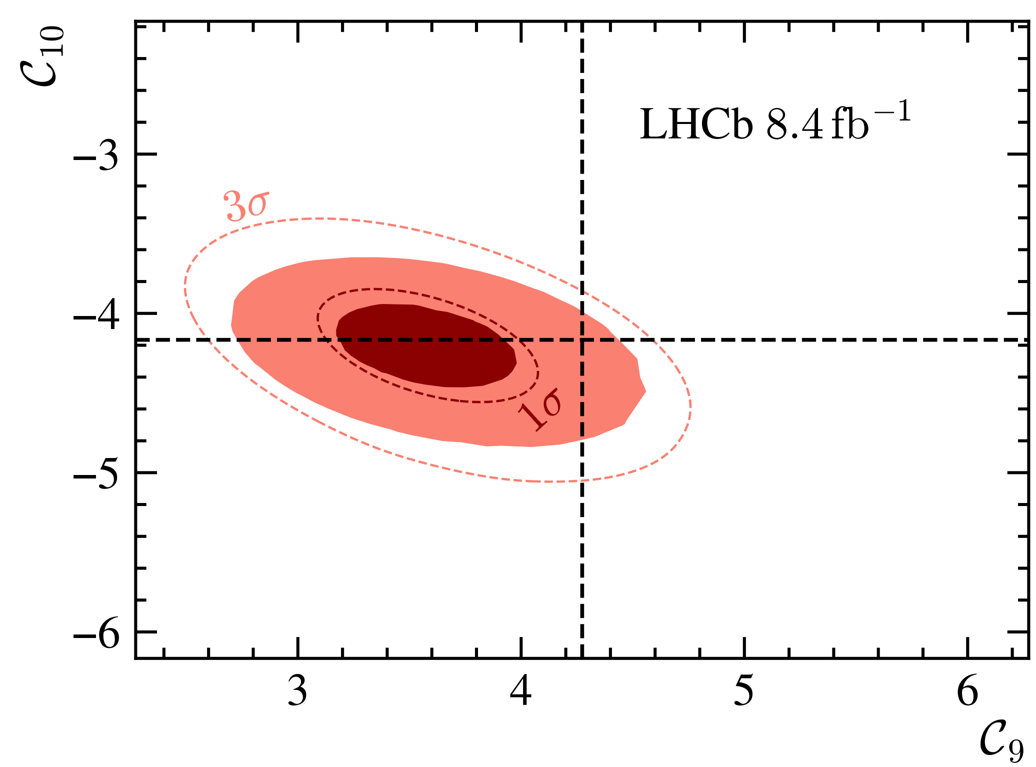
Amplitude analysis of $B^0 \to K^* \mu\mu$

JHEP 09 (2024) 026



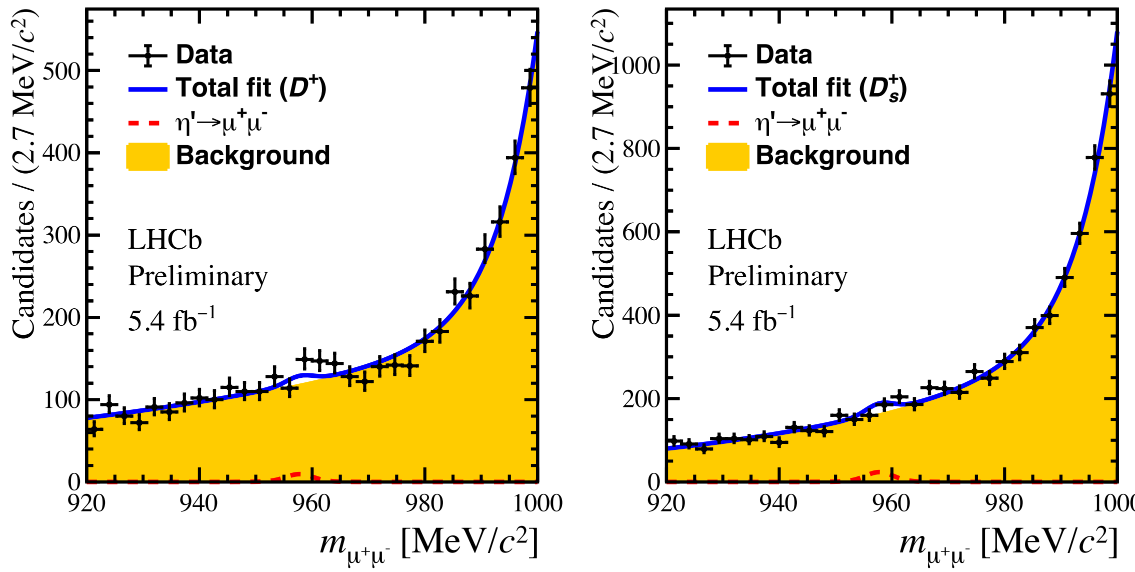


Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$



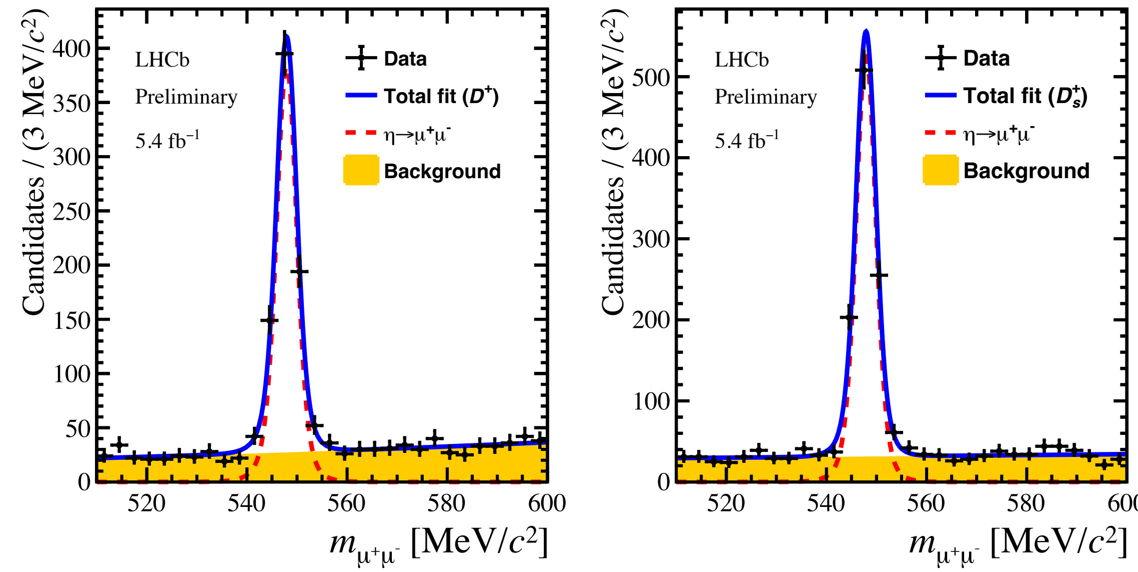
Anomalous decays of η and η'

LHCb-CONF-2025-002



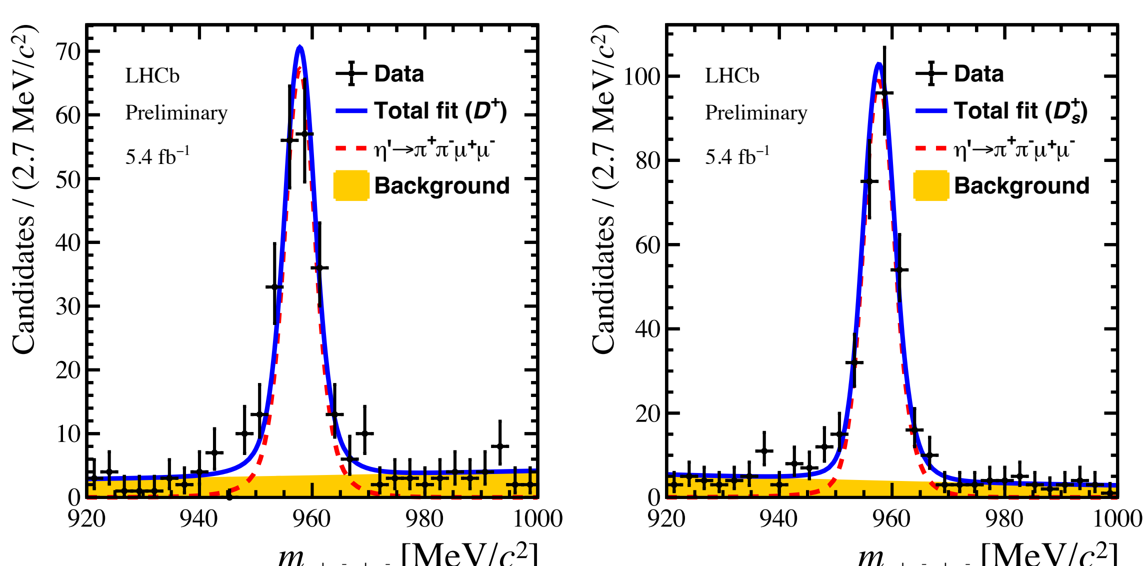
$\mathcal{B}(\eta' \to \mu^+\mu^-) < 1.9 \times 10^{-7}$,

First ever search

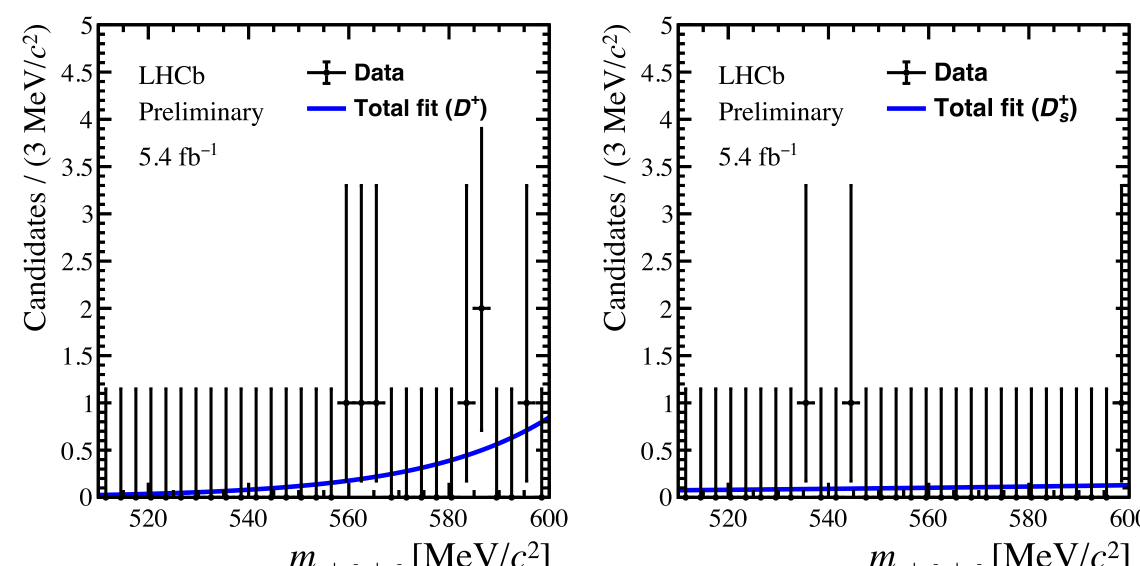


$\mathcal{B}(\eta \to \mu^+\mu^-) = (5.30 \pm 0.14\,_{(\mathrm{stat})} \pm 0.18\,_{(\mathrm{syst})} \pm 0.26_{\phi}) \times 10^{-6}$

Most precise value

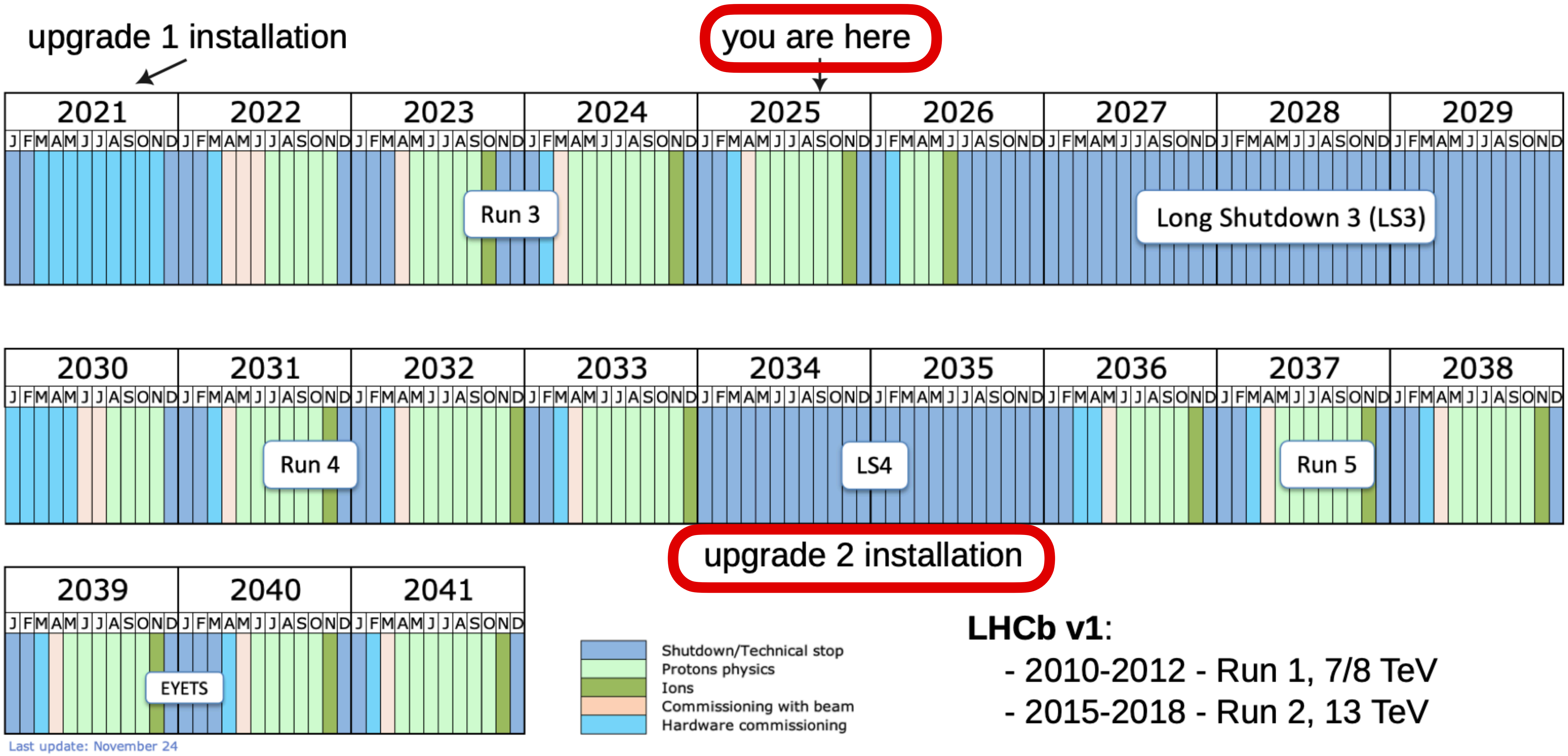


$\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) = (2.80 \pm 0.14\,_{(\mathrm{stat})} \pm 0.13\,_{(\mathrm{syst})} \pm 0.14_{\phi}) \times 10^{-5}$.



$\mathcal{B}(\eta \to \pi^+\pi^-\mu^+\mu^-) < 6.0 \times 10^{-7}$

Future runs and Upgrade II



LHCb v1:

- 2010-2012 - Run 1, 7/8 TeV
- 2015-2018 - Run 2, 13 TeV

The LHCb experiment in Run 1-2

LHCb detector design

- Huge $\sigma(pp \to b\bar{b}X)$ at the LHC $\to 10^{12}$ b-hadrons in LHCb acceptance in Run 1+2

- Hardware trigger on object with p_{T} exceeding 2-3 GeV
- Displaced vertex identification in software trigger stage
- Dipole magnet with precise tracking detectors $\sigma_p/p \sim 0.5\,\%$
- Particle ID with calorimeters, muon system and Cherenkov detectors (RICH)