# $b \to s\ell\ell$ transitions at LHCb

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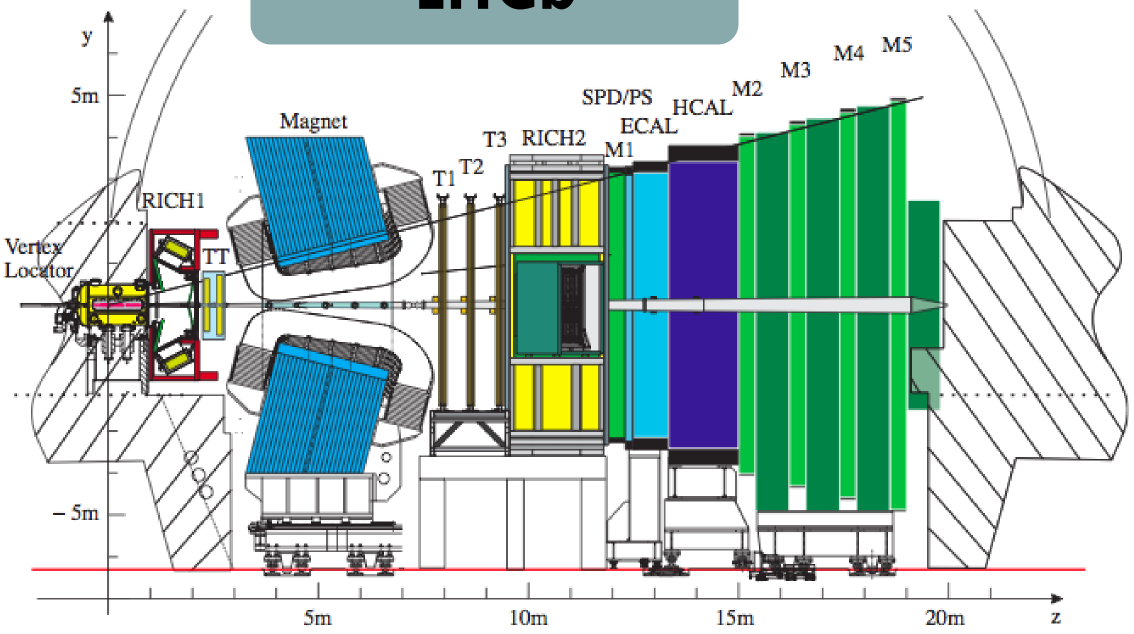
on behalf of LHCb collaboration

- Setting up the scene
- Branching Fractions results
- Angular analyses

# Setting up the scene

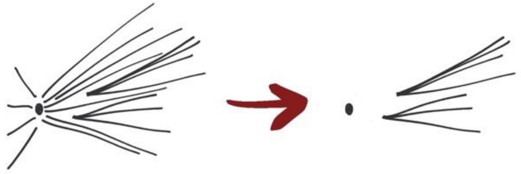
# The two LHCb incarnations

## LHCb



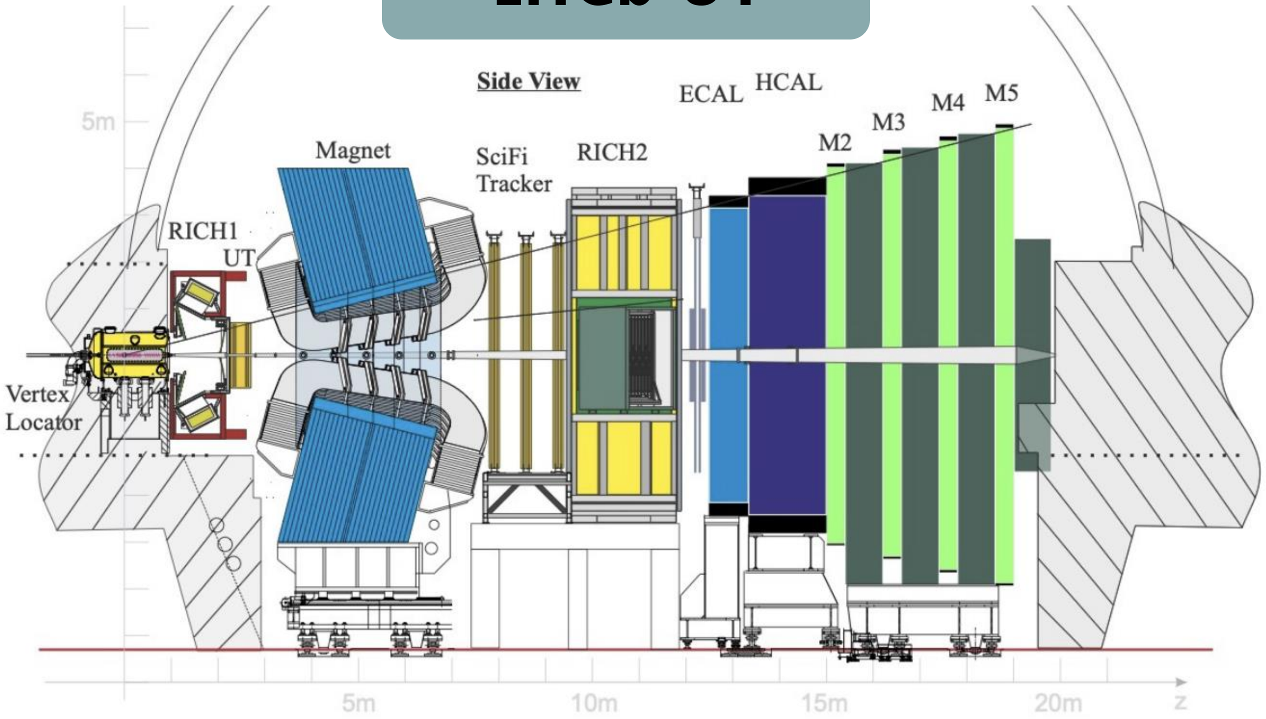

$\Delta p / p = 0.5 - 1.0\%$

$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$



Excellent PID (RICH detectors for $\pi$/K/p)

## LHCb-U1



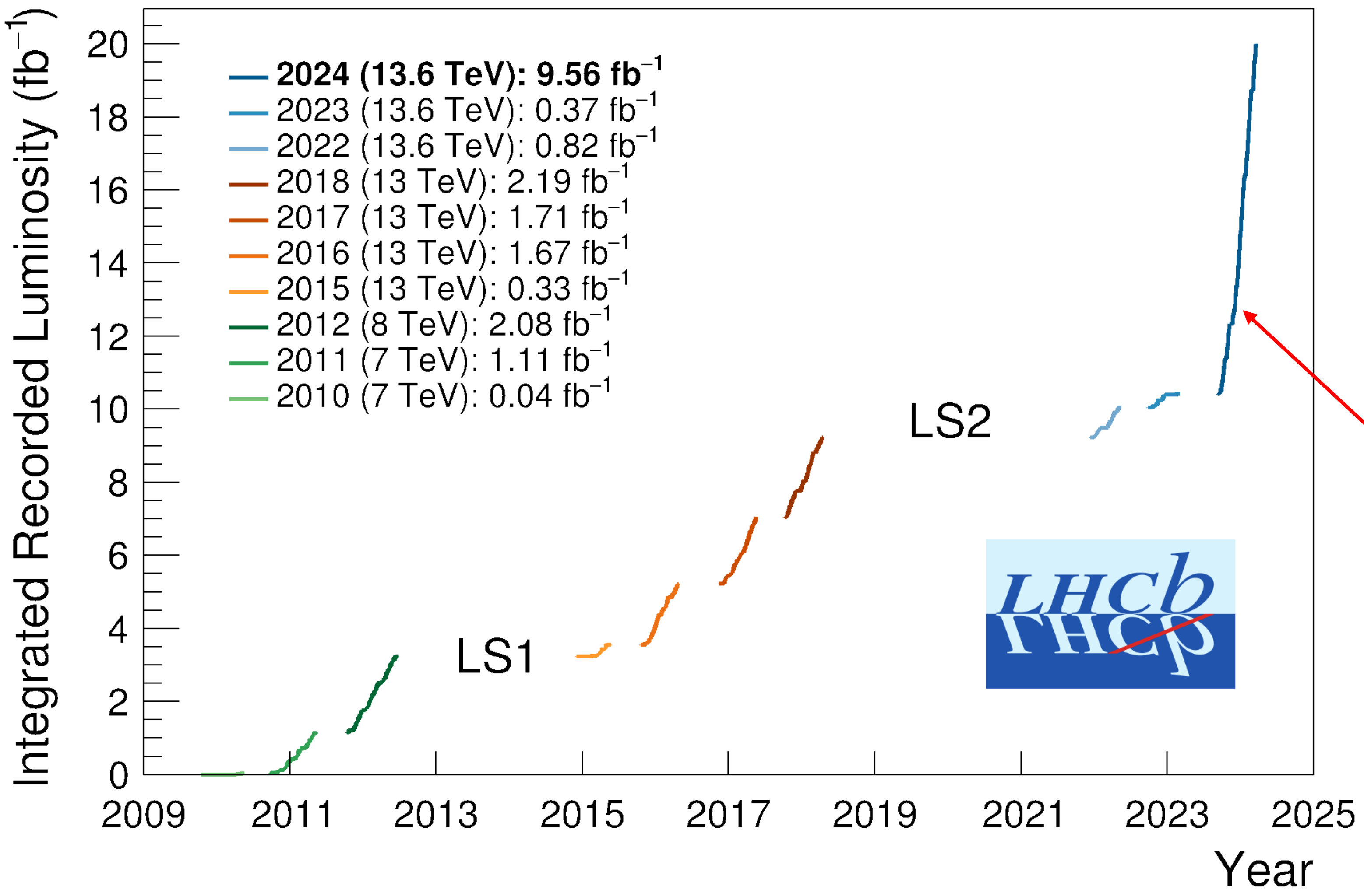

Peak luminosity ~ x 5

→ Readout at 40 MHz

→ Removal of the L0 hardware trigger

→ New tracking system

→ Real Time reconstruction & Alignement



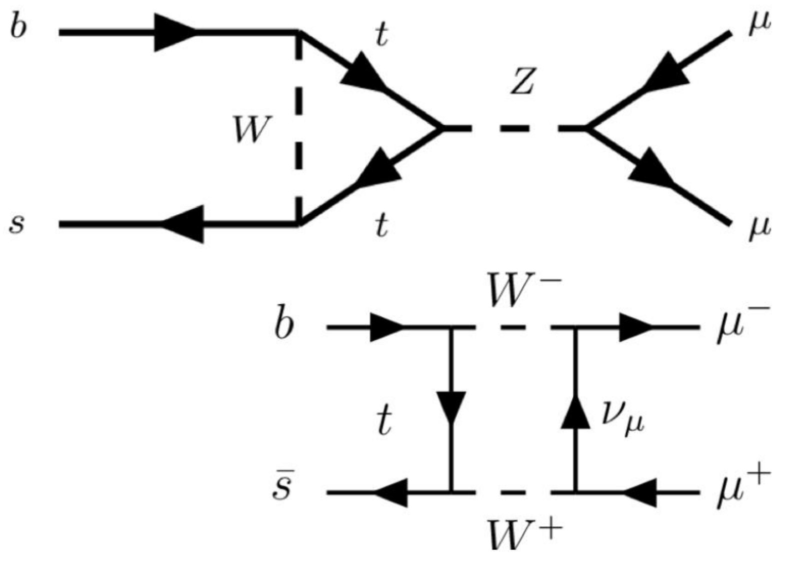

# Today's results

| 2011-2018 | |
|---|---|
| 7 & 8 TeV | 3 $fb^{-1}$ |
| 13 TeV | 6 $fb^{-1}$ |

| 2022-2026 | |
|---|---|
| 13.6 TeV | 9 $fb^{-1}$ (2024) |

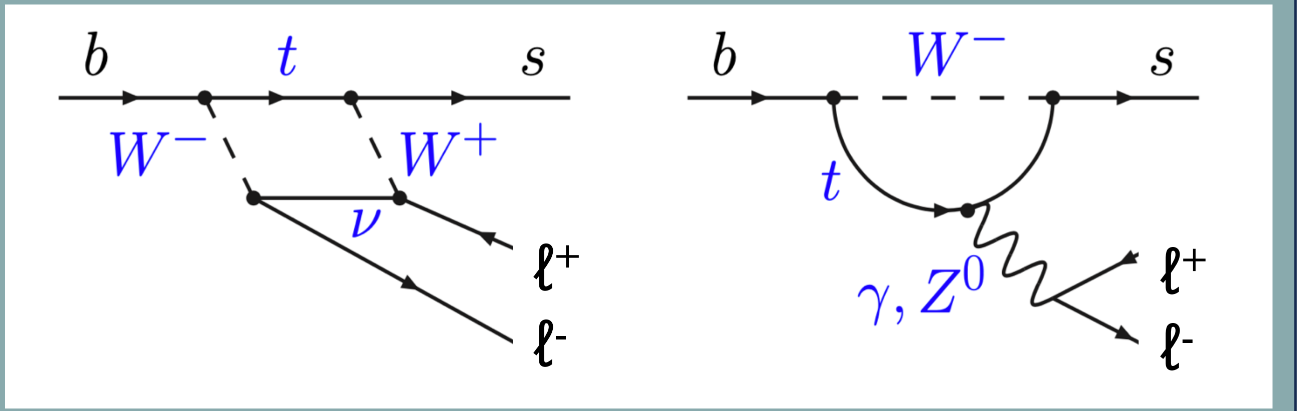
# Two main families of analyses for b⟶s $\ell^+\ell^-$ transitions

## $B_s \longrightarrow \ell^+\ell^-$




## $H_b \longrightarrow H_s\ \ell^+\ell^-$

**Most of the recent results**




Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

Eg : photon pole dominates when $q^2 \rightarrow 0$

# Flavour Changing Neutral Currents: a tool to search for NP

## Characteristics: rare !

$BR_{eff} < 10^{-7}$


## Rule of the game

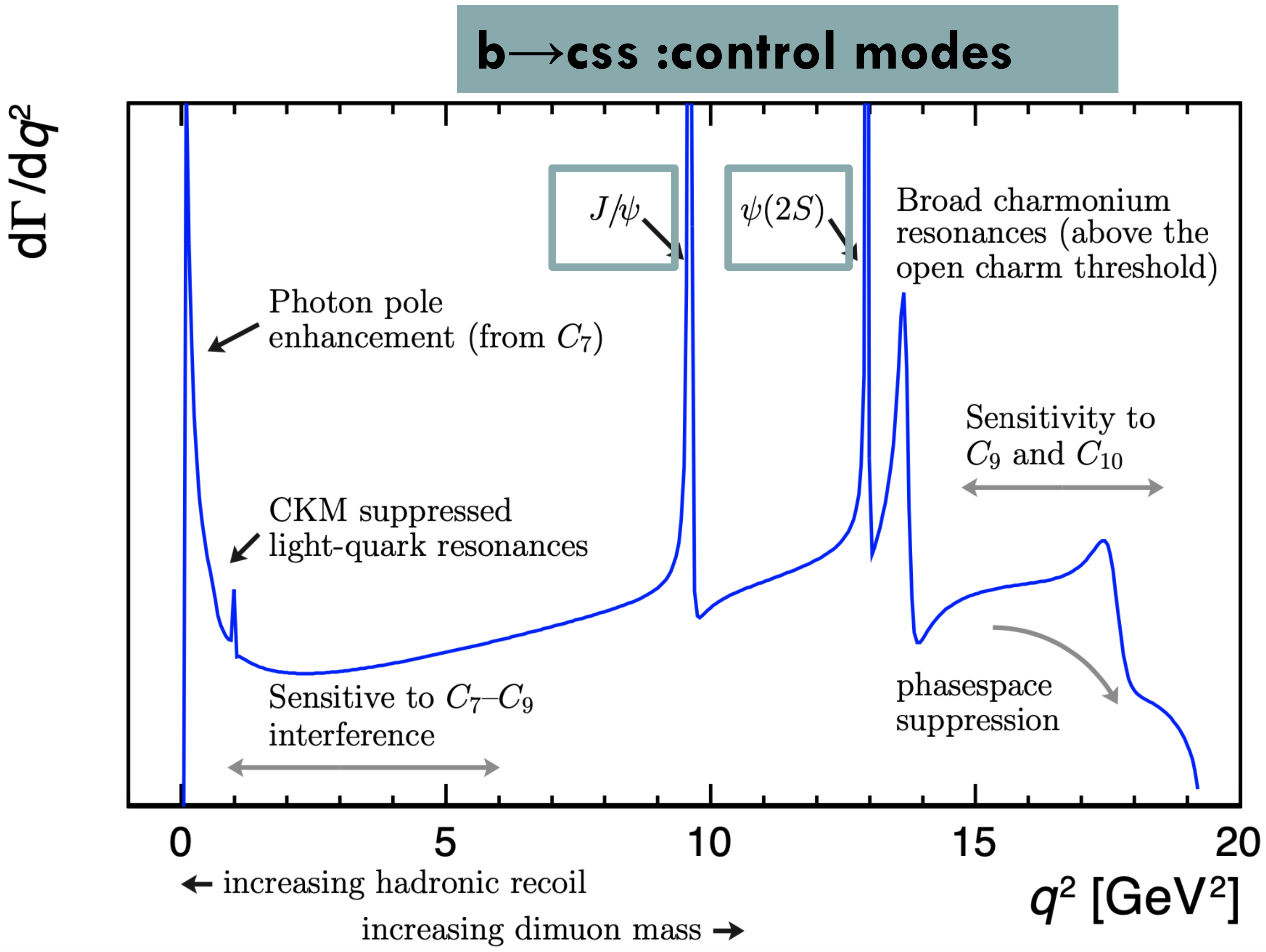
- Precisely predicted
- Precise measurements (as much as possible !)

## How NP would manifest ?

- **Modification of the decay rates ( ↑ or ↓ )**
- **Modification of the angular distributions**
- **New sources of CP violation**

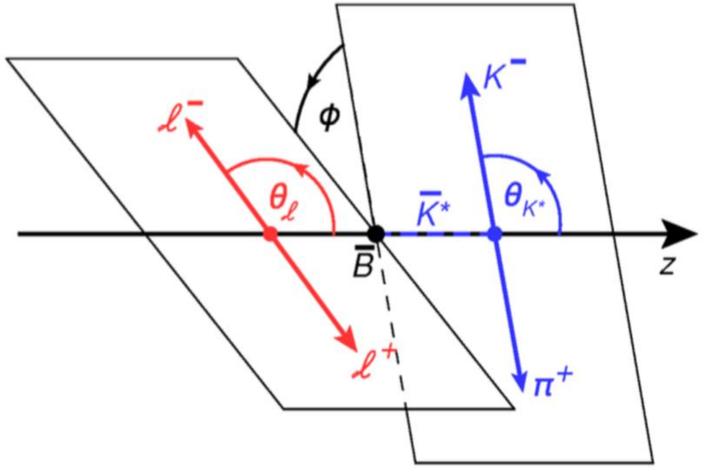
**Potentially different for $b \to s\mu^+\mu^-$ and $b \to s e^+ e^-$**

# Anatomy of the decays




Decay described by

- $q^2 = M^2(\ell^+\ell^-)$
- 3 angles (only one if B⟶Kℓℓ)



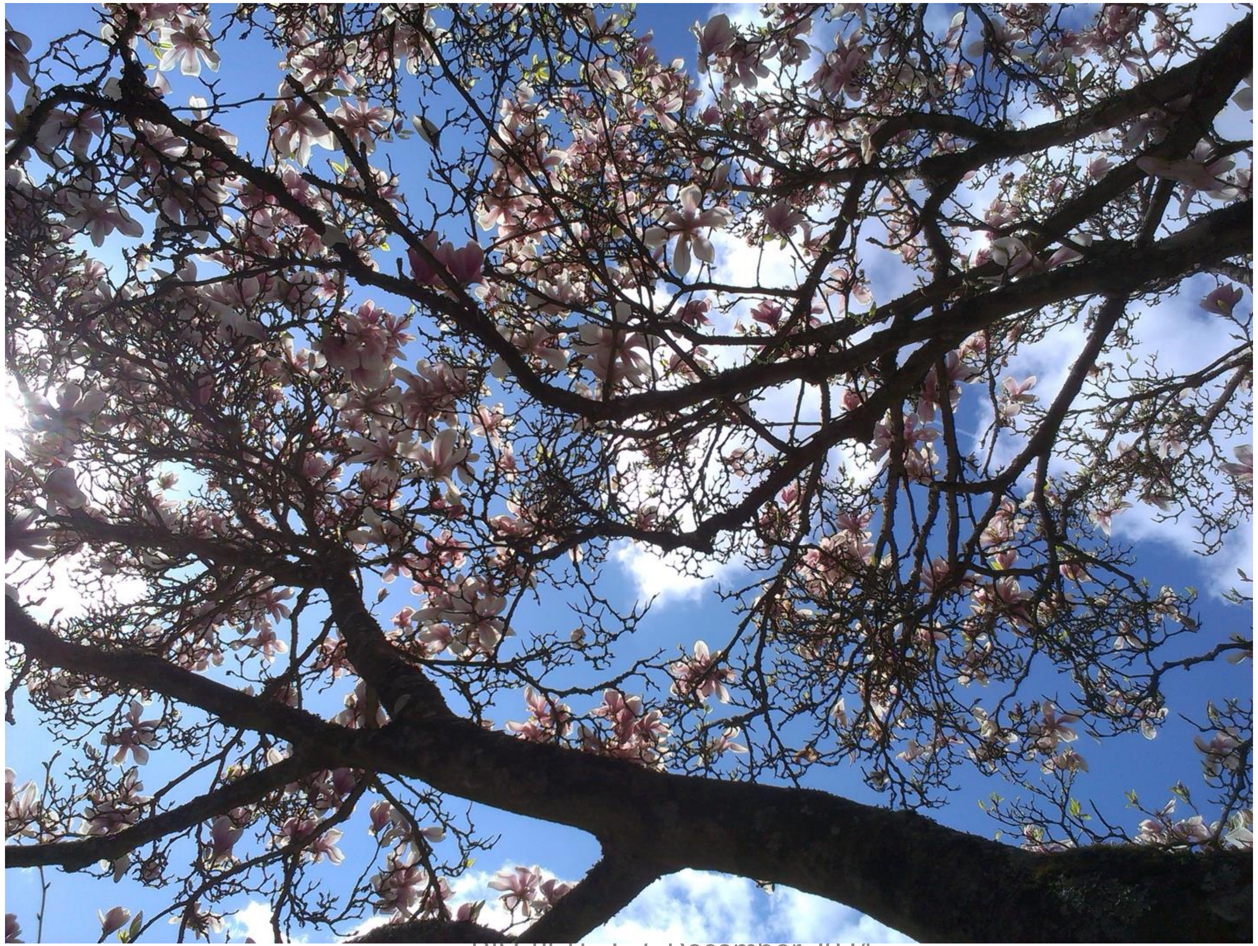

Branching Ratios

Angular observables

LFU observables :
R-ratios
angular observables differences

\- th. clean +

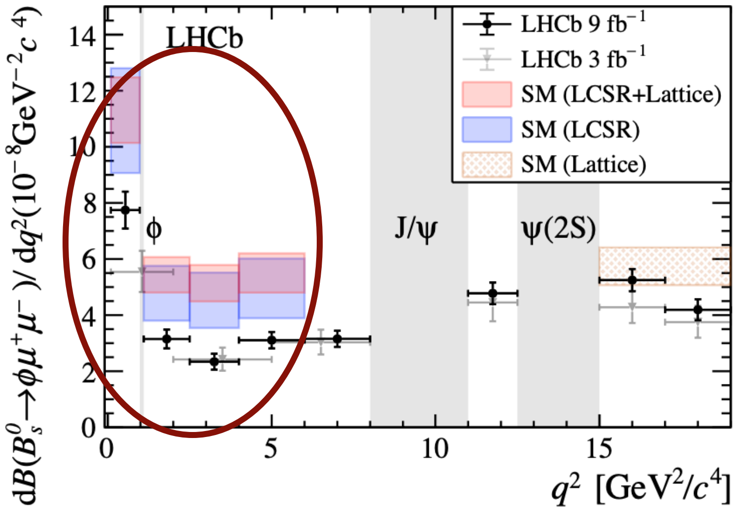
# Branching fractions measurements



# BF measurements

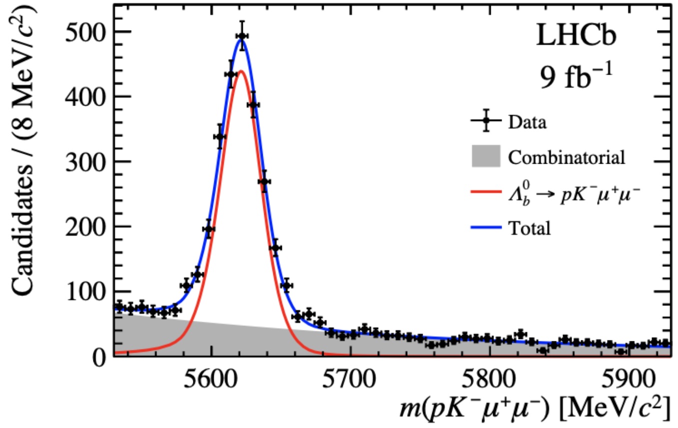
$B_s \to \phi\, \mu\mu$

PRL 127 (2021) 151801

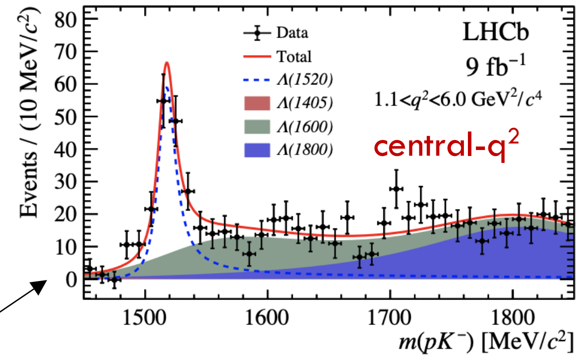


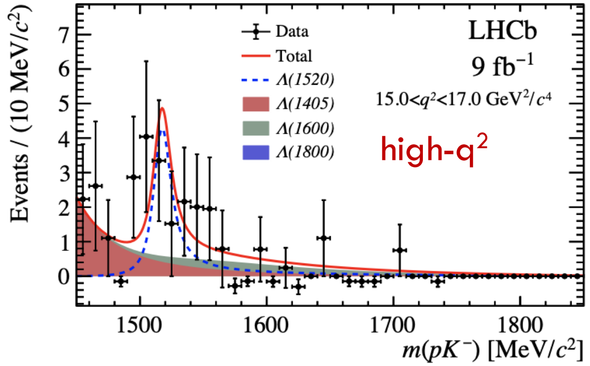

$\Lambda_b \to \Lambda(1520)\, \mu\mu$

PRL 131 (2023) 151801




$N(\Lambda_b \to pK^-\mu^+\mu^-) = 2250 \pm 57(\text{stat})$

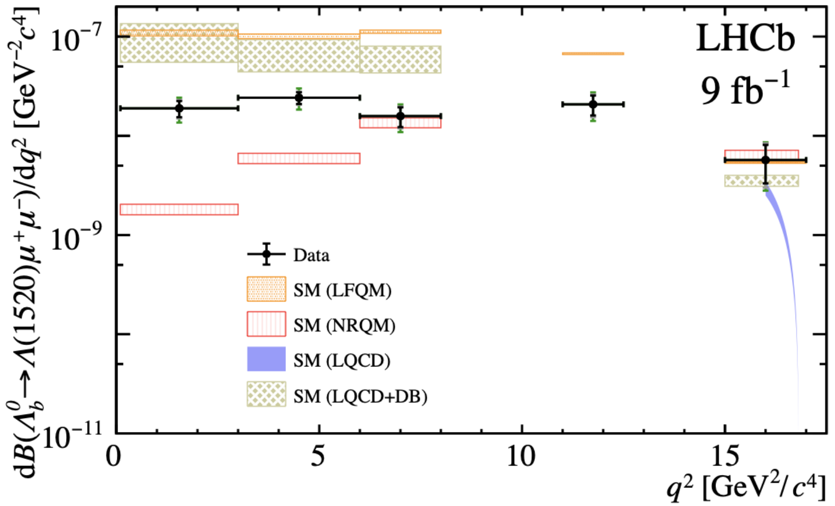



***b*-mesons: a tendency to measure BF lower than predictions (low and central q$^2$).**

***b*-baryons: BF in agreement with LQCD (high-q$^2$). Lack of precise predictions in the rest of phase space.**

**Predictions uncertainties correlated between bins**



# LFU tests using Branching Ratios

Analyses in bins of $q^2$

$B^{+,0}$, $B_S$, $\Lambda_b$ → ; $K, K^*, \phi, pK \ldots$ →

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H_s e^+ e^-)}{dq^2} dq^2} \overset{SM}{\cong} 1$$

Double ratio ⇒ cancels out most of the systematics due to e/μ differences

$$= \frac{BR(B \to H_s \mu\mu)}{BR(B \to H_s ee)} \times \frac{BR\left(B \to H_s J/\psi(ee)\right)}{BR\left(B \to H_s J/\psi(\mu\mu)\right)}$$

$$\frac{\Gamma(J/\psi \to e^+ e^-)}{\Gamma(J/\psi \to \mu^+ \mu^-)} = 1 \text{ [PDG]}$$

$$= \frac{\mathcal{N}_{H_S\mu\mu}}{\mathcal{N}_{H_SJ/\psi(\mu\mu)}} \times \frac{\varepsilon_{H_SJ/\psi(\mu\mu)}}{\varepsilon_{H_S\mu\mu}} \times \frac{\mathcal{N}_{H_SJ/\psi(ee)}}{\mathcal{N}_{H_See}} \times \frac{\varepsilon_{H_SJ/\psi(ee)}}{\varepsilon_{H_See}}$$

Yields obtained from mass fits

Efficiencies obtained from corrected MC using data-driven techniques

Use of $r_{J/\psi} = \frac{BR\left(B \to H_s J/\psi(\mu\mu)\right)}{BR\left(B \to H_s J/\psi(ee)\right)}$ and $R_{\psi(2S)}$ as cross-checks

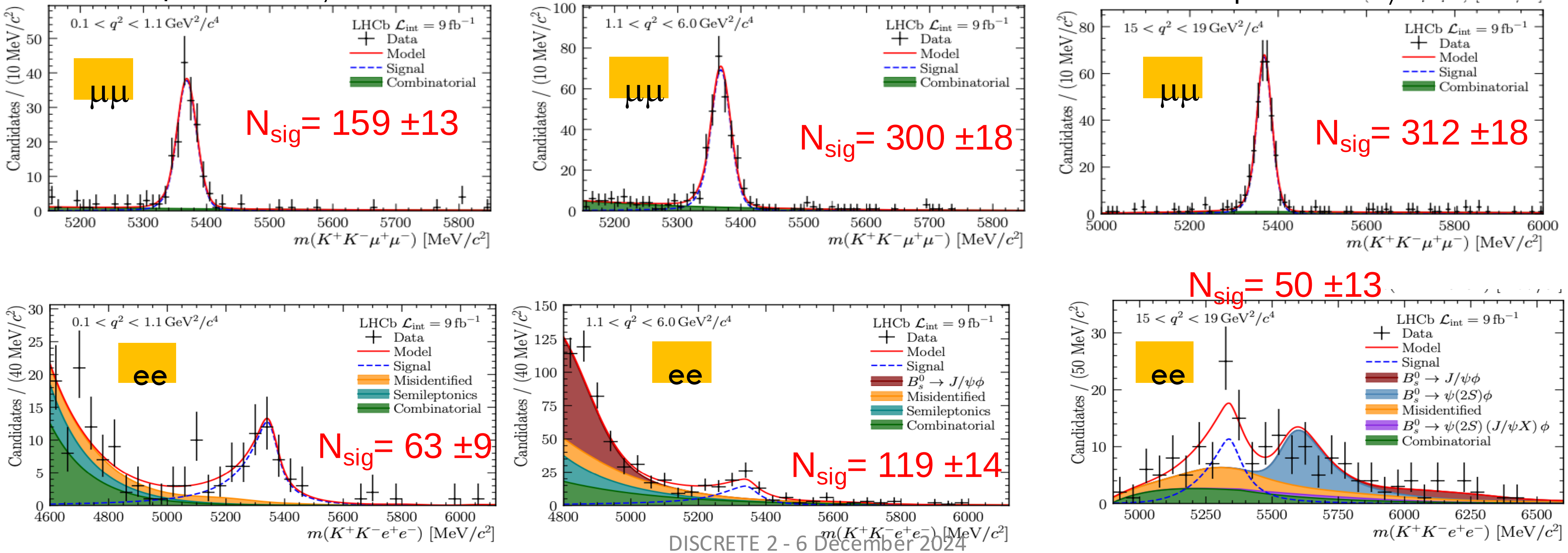
# $B_s \to \phi \ell\ell$

[2410.13748](https://arxiv.org/abs/2410.13748) submitted to PRL

**NEW**

- Blind analysis in 3 $q^2$ regions
- Narrow $\phi$ resonance, no partially reconstructed hadronic background ("$\phi^{**}$")
- Combinatorial & double semi-leptonic backgrounds suppressed using multivariate classifiers
- Residual hadron→e mids-ID background measured from data

Low-$q^2$ $0.1<q^2<1.1\ \mathrm{GeV}^2/c^4$ | Central-$q^2$ $1.1<q^2<6\ \mathrm{GeV}^2/c^4$ | High-$q^2$ $15<q^2<19\ \mathrm{GeV}^2/c^4$



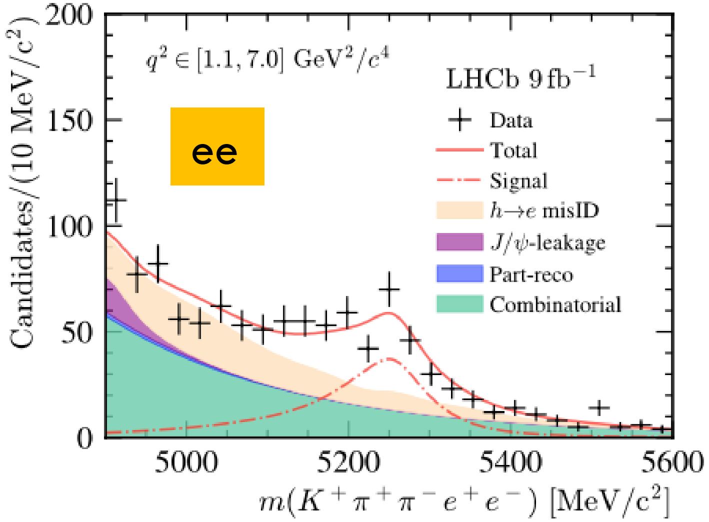
# Similar analysis but using $B^{\pm} \to K\pi\pi\,\ell\ell$

NEW

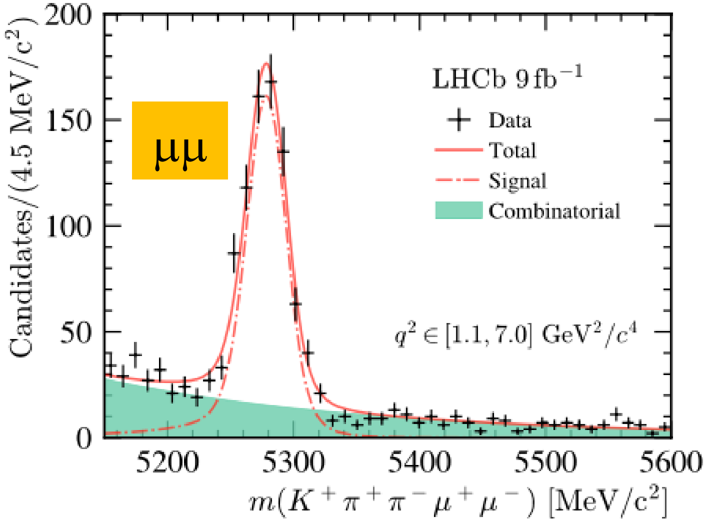
LHCb-PAPER-2024-046
in preparation

One kinematic region $1.1<q^2<7$ GeV$^2$/c$^4$

$N_{sig}$= 264 ±21




$N_{sig}$= 731 ±31




Larger background due to the $K\pi\pi$ system instead of the $\phi$

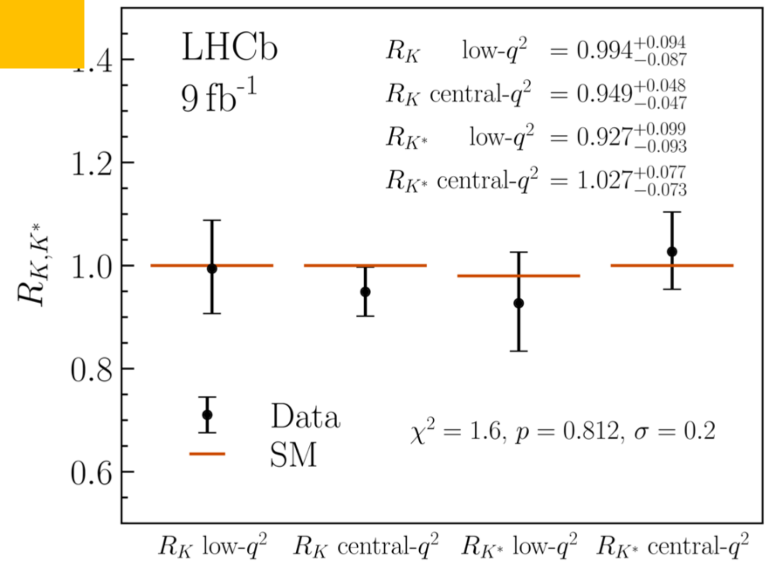
Systematic uncertainty dominated by the modelling of mass distribution of the hadron→e mids-ID background

# Cross-checks and results

| | $B_s \to \phi\ell\ell$ | $B^{\pm} \to K\pi\pi\,\ell\ell$ | |
|---|---|---|---|
| $r_{J/\psi}$ | 0.997 ±0.013 | 1.033 ±0.017 | (stat [data + MC]) only |
| $R_{\psi(2S)}$ | 1.010 ±0.026 | 1.040 ±0.030 | (stat [data + MC]) only |
| $R^{-1}_{1.1-6\ \mathrm{GeV}/c^2}$ | $0.91^{+0.20}_{-0.19} \pm 0.05$ | $1.31^{+0.18}_{-0.17} \pm 0.12$ | |

**In agreement with previous measurements and SM prediction**

Phys. Rev. D 108 (2023) 032002
Phys. Rev. Lett. 131 (2023) 051803




- 5 to 10 % precision
- dominated by statistical uncertainty

# Angular analyses

# Angular analyses

$$\frac{d\Gamma(B \to V\mu\mu)}{d\Omega dq^2} = \sum_i J_i(q^2) f_i(\Omega)$$

+ additional nuisances parameters (S-wave)

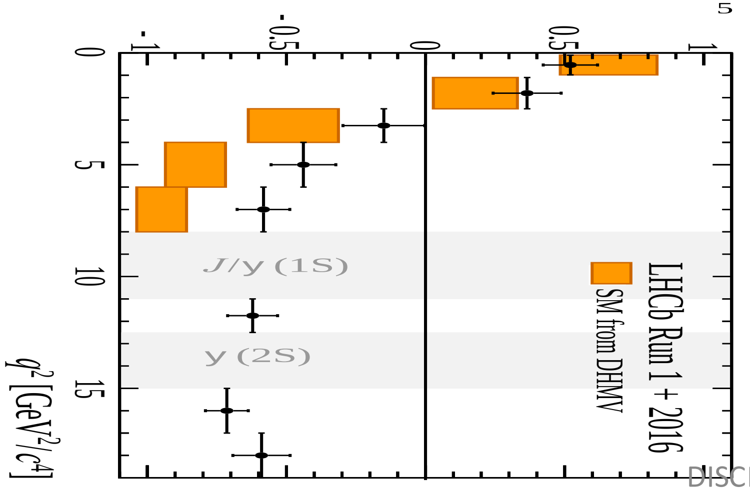
EPJS 233, 409-428 (2024)

Amplitudes, Wilson coefficients, Form Factors (FF)

8 parameters
Could be optimised to reduce the sensitivity to FF

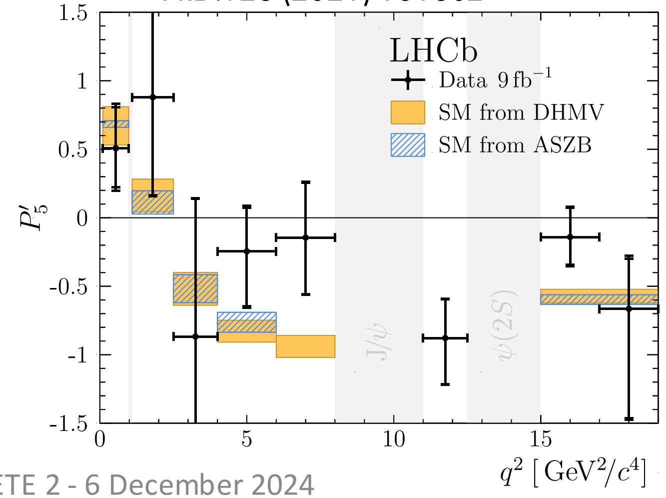
$B^0 \to K^{*0} \mu\mu$

PRL. 125 (2020) 011802



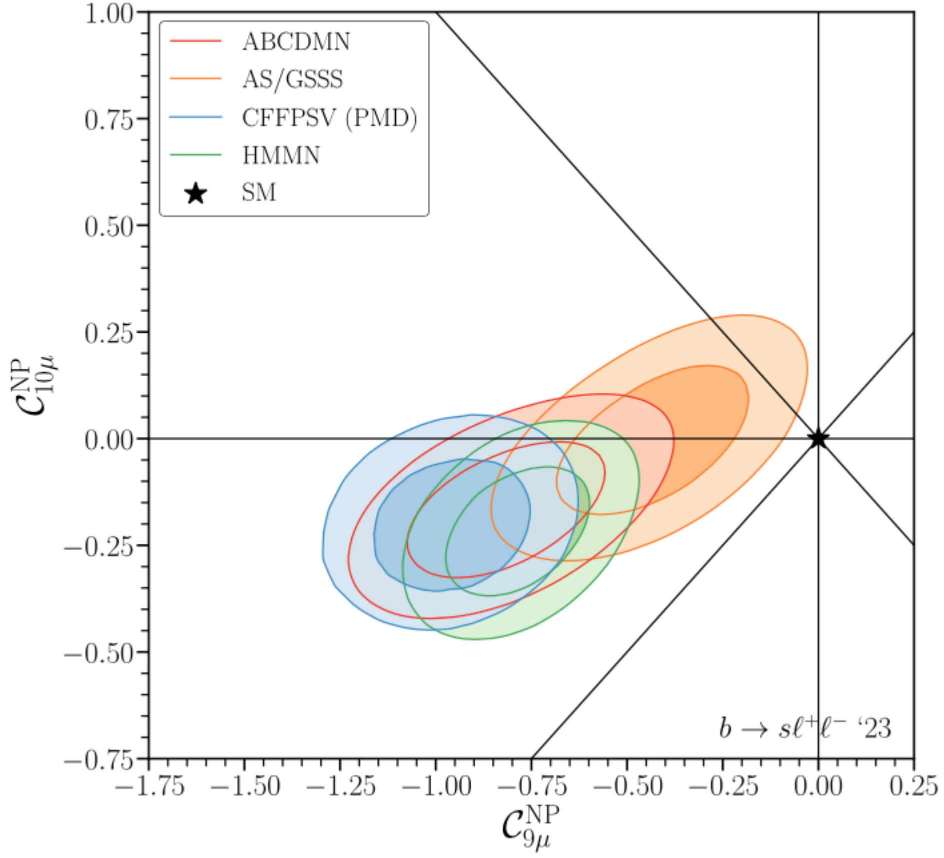

$B^+ \to K^{*+} \mu\mu$

PRL .126 (2021) 161802

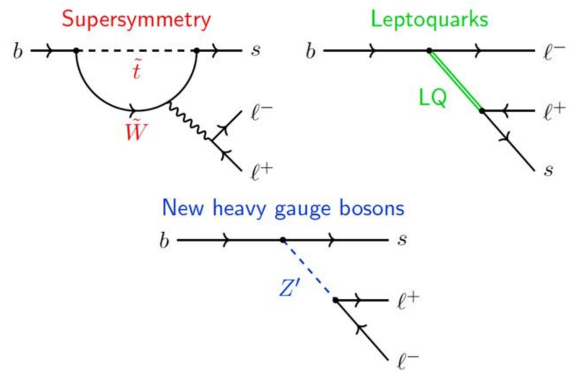


# Global fits using results from branching ratios & angular analyses:

EPJS 233, 409-428 (2024)

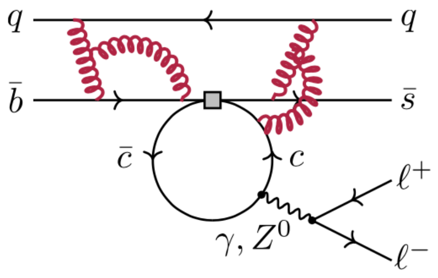


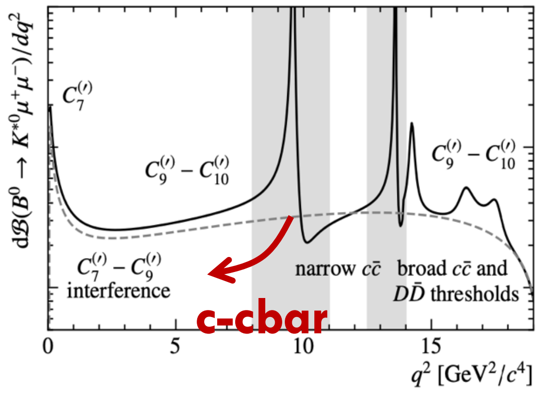

## New Physics showing up




or

## Mismodelling of SM (non perturbative QCD) predictions



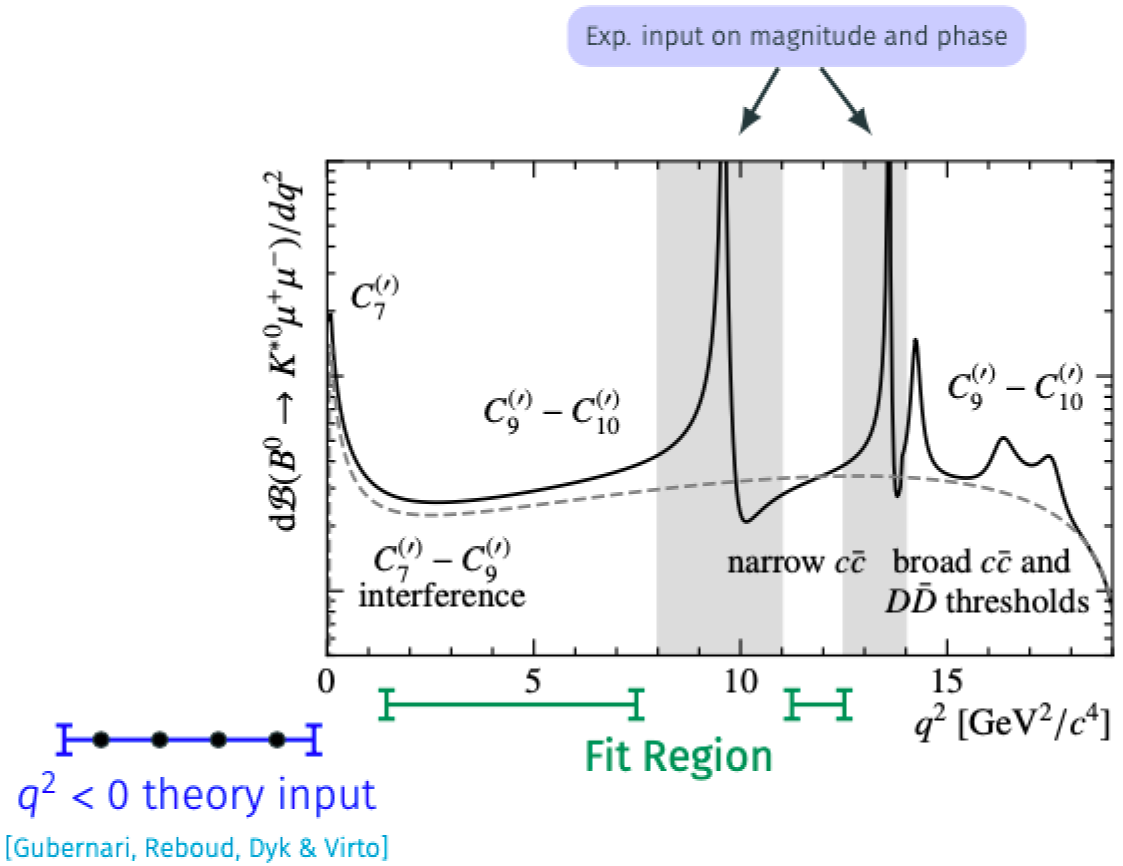

?

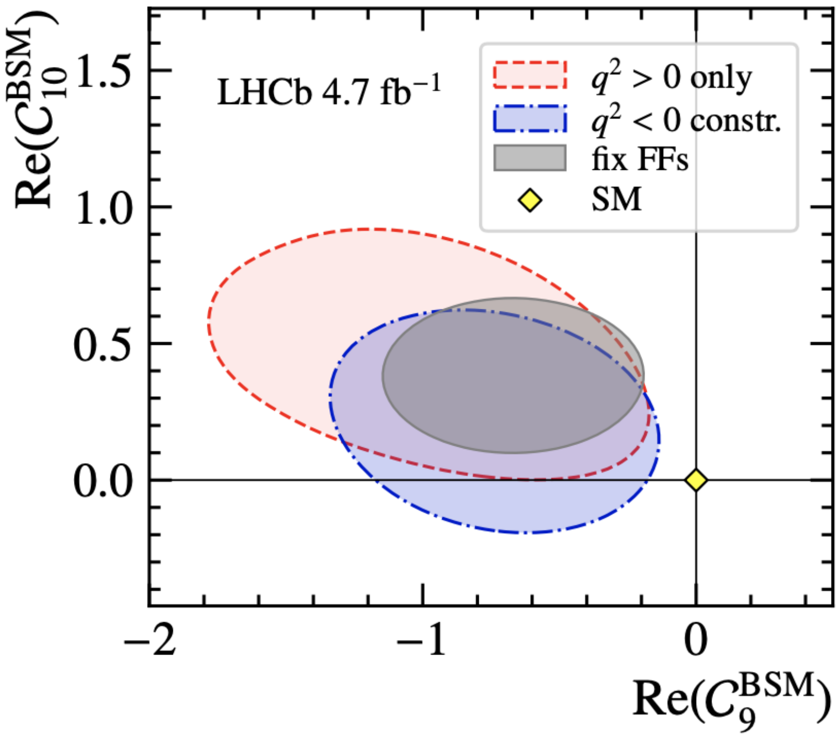
# Two analyses aiming at constraining non-local contributions from data

Analysis with 6D fit $\left(M(K\pi\mu\mu), M(K\pi), q^2, \vec{\Omega}\right)$

Extract $C_{9,10}^{(\prime)}$ + non-local contributions modelled by polynomials

Sketch from Lakshan@IW2024

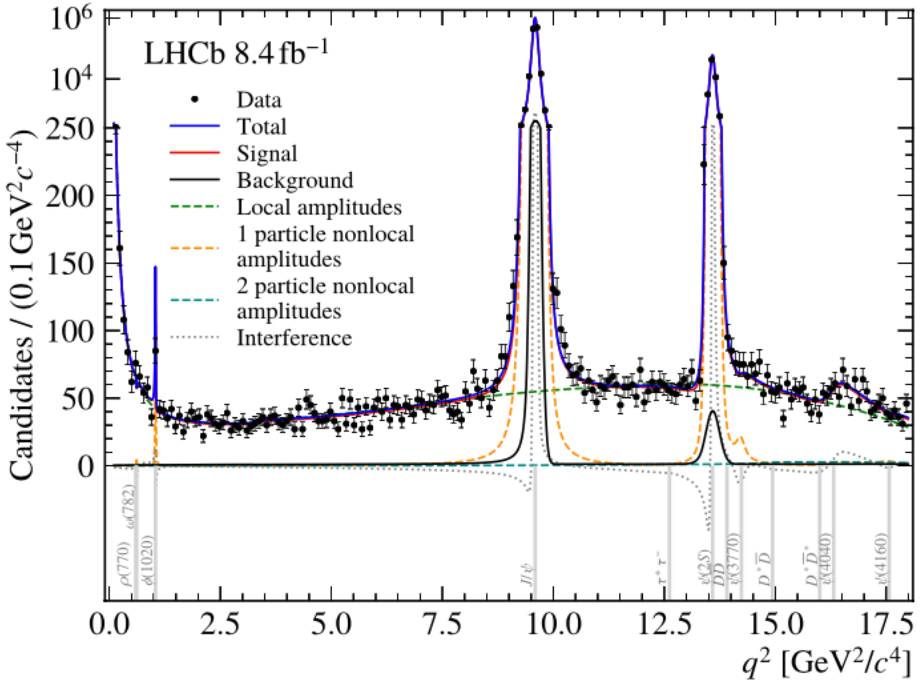


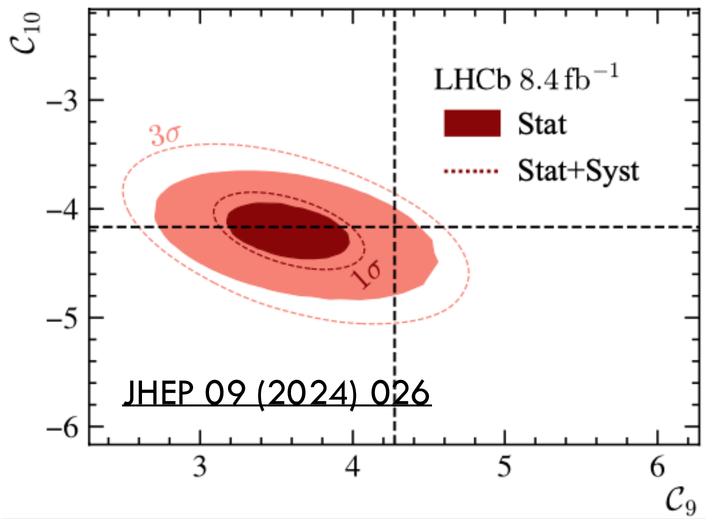

Phys. Rev. Lett. 132 (2024) 131801
Phys. Rev. D 109 (2024) 052009

# Analysis with 5D fit $\left(M(K\pi\mu\mu), q^2, \vec{\Omega}\right)$ over the whole $q^2$ spectrum

JHEP 09 (2024) 026




Extract $C_{9,10}^{(\prime)}$ $C_9^{\tau}$ + non-local contributions (shift to $C_9$ )




JHEP 09 (2024) 026

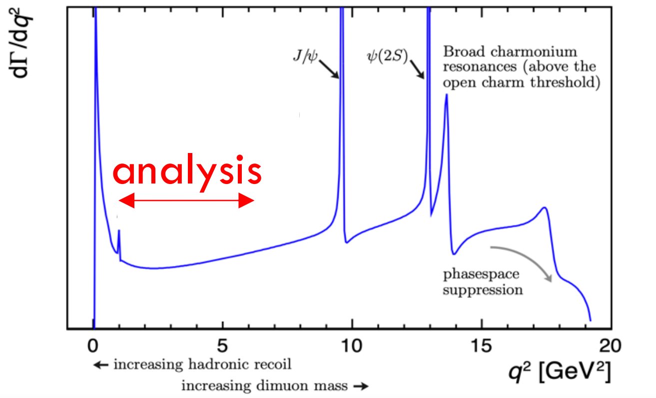
Take-away message from these 2 analyses:

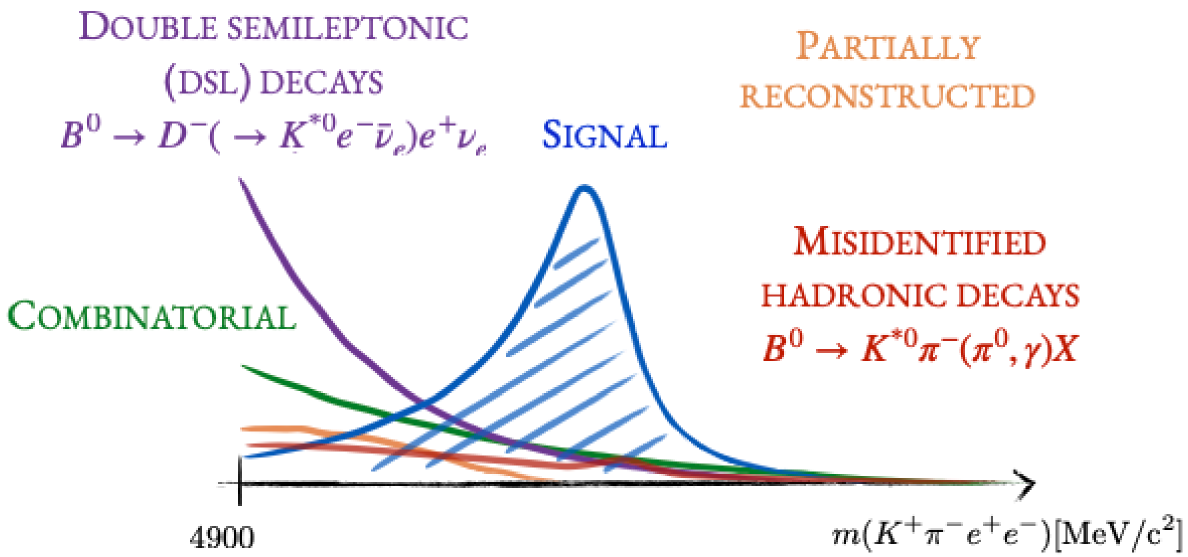
- **Non-local contributions seem larger than what has been assumed so far**
- **$C_9$ still shifted from SM**
- **More data is needed**

# Angular analysis of $B^0 \to K^{*}ee$ in the central $q^2$ region

NEW

LHCb-PAPER-2024-022
in preparation

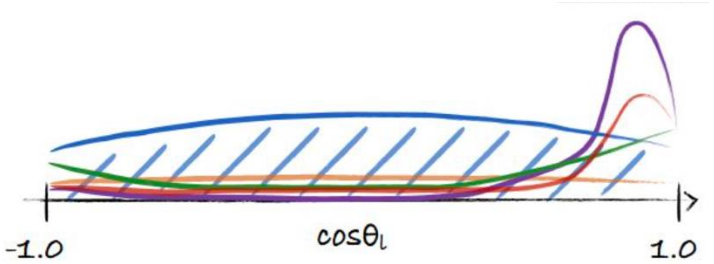



Modelling of the mass and angular distributions of all the components

⇒ Data-driven methods

Angular acceptance modelled in $(\cos\theta_\ell, \cos\theta_K, \varphi, q^2)$, used as a per-event weight

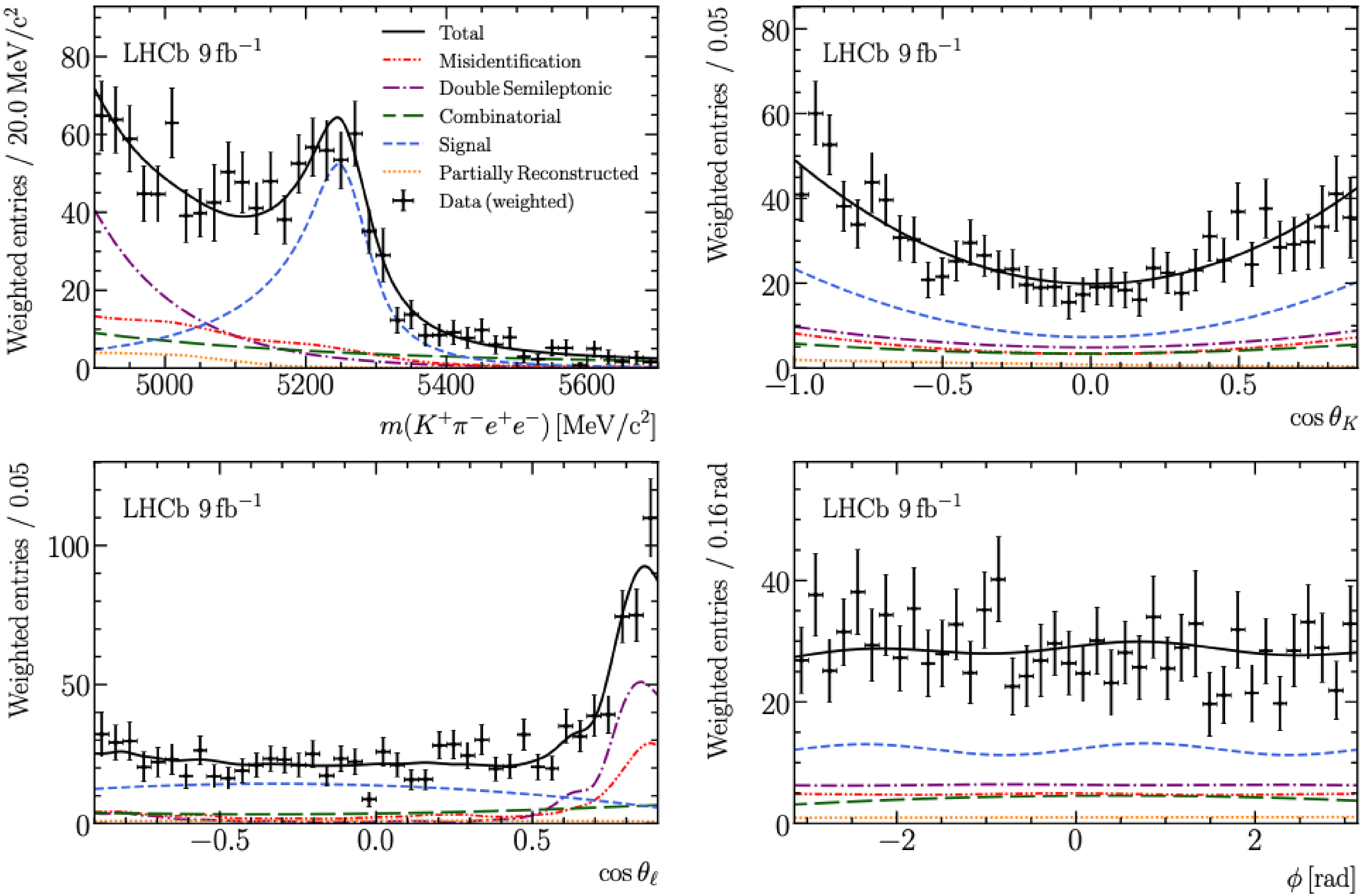




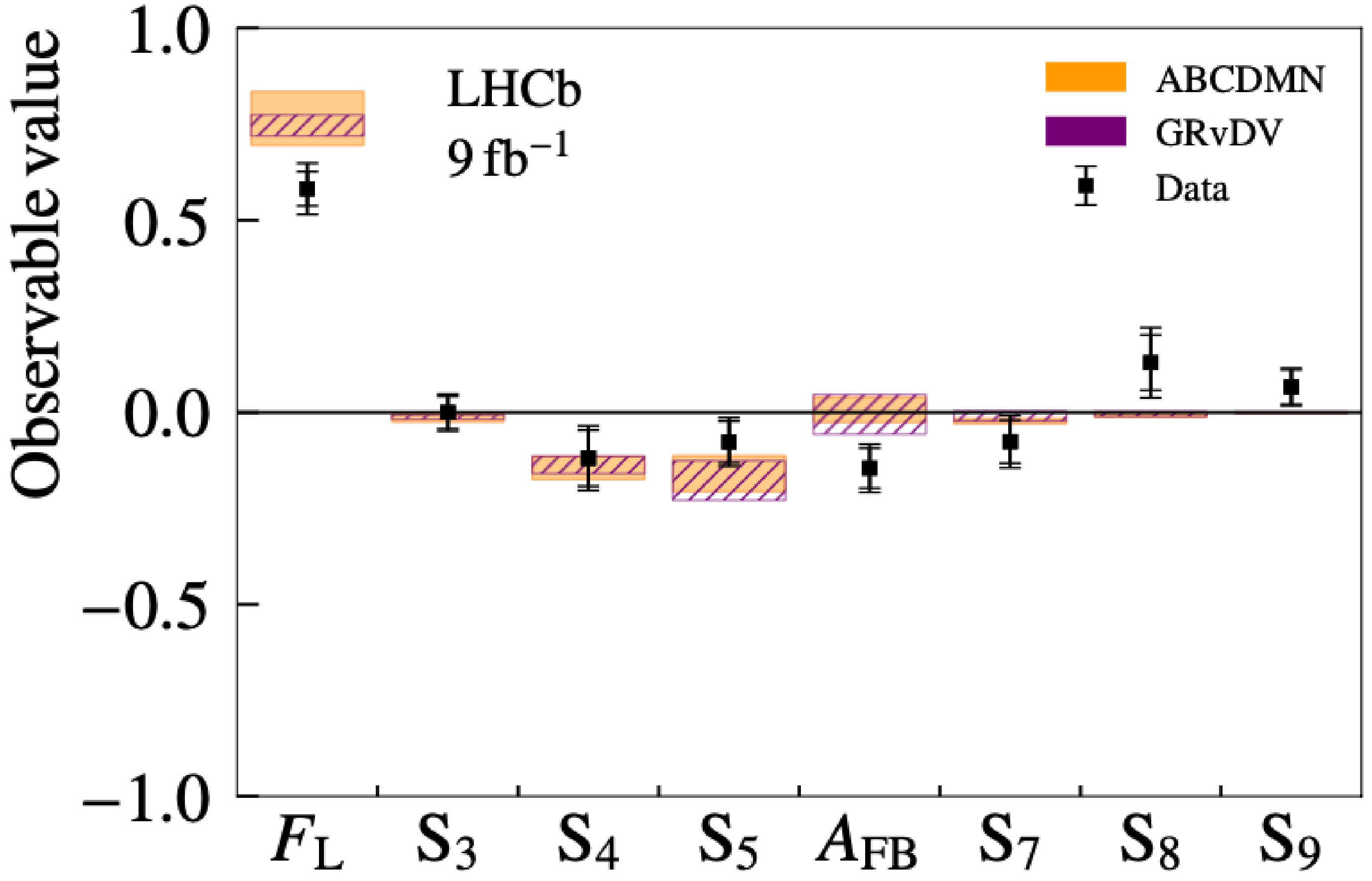

Drawings: Zenzi Wang

# Fit projections:





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




Main sources of systematics:

- Double semi-leptonic & combinatorial backgrounds parametrisation
- Acceptance modeling

**In agreement with SM prediction**

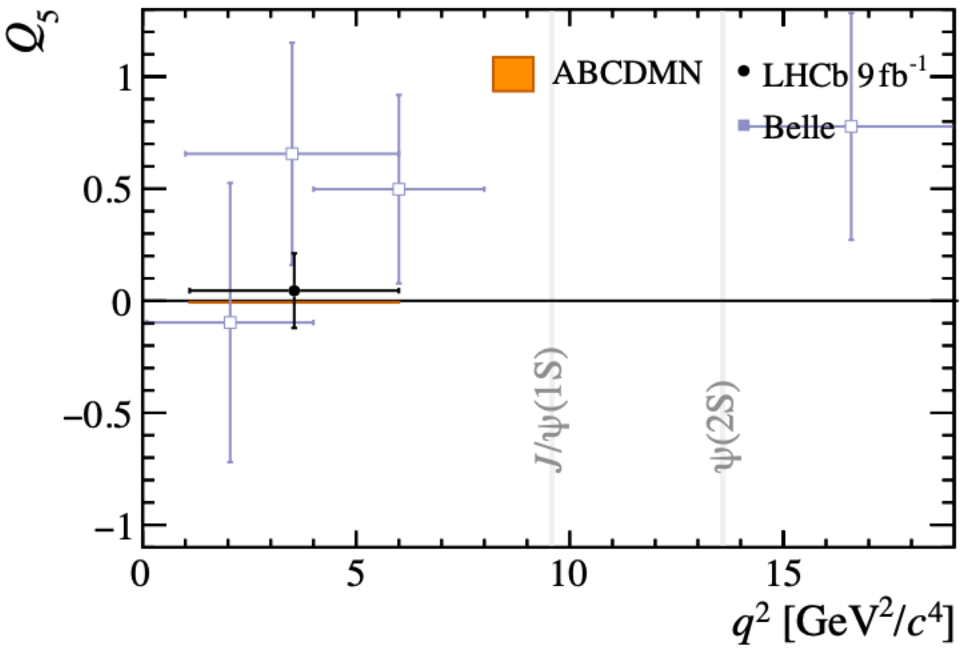
GRvDV → [N. Gubernari, M. Reboud, D. Van Dyk, J. Virto, JHEP 09 (2022) 133] 25
ABCDMN → [M. Algueró, A. Biswas, B.Capdevila, S. Descotes-Genon, J. Matias, EPJC 83 (2023) 7, 648]

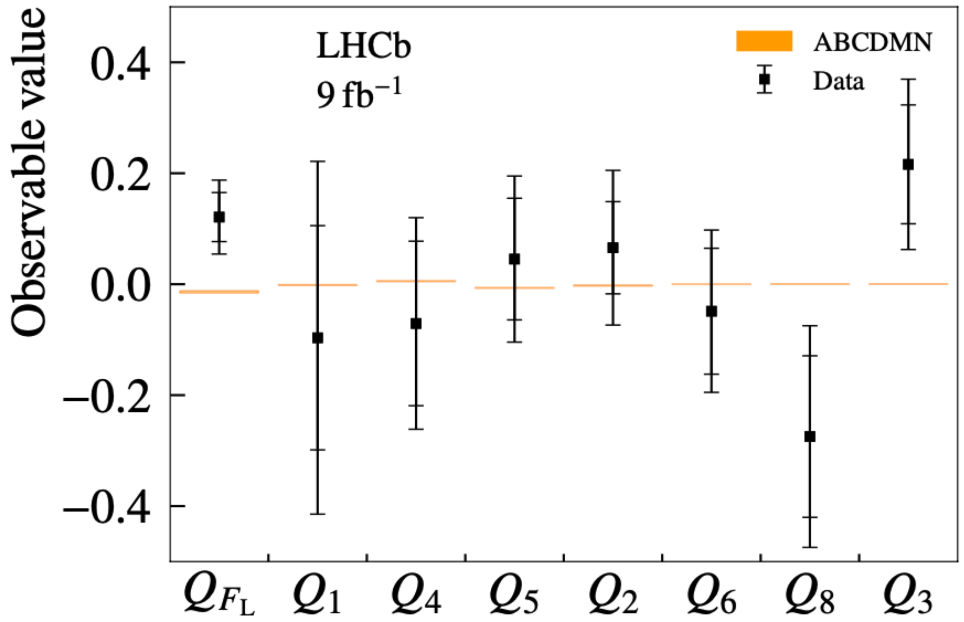
# LFU test

- 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 but without S-wave for overall coherence)

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

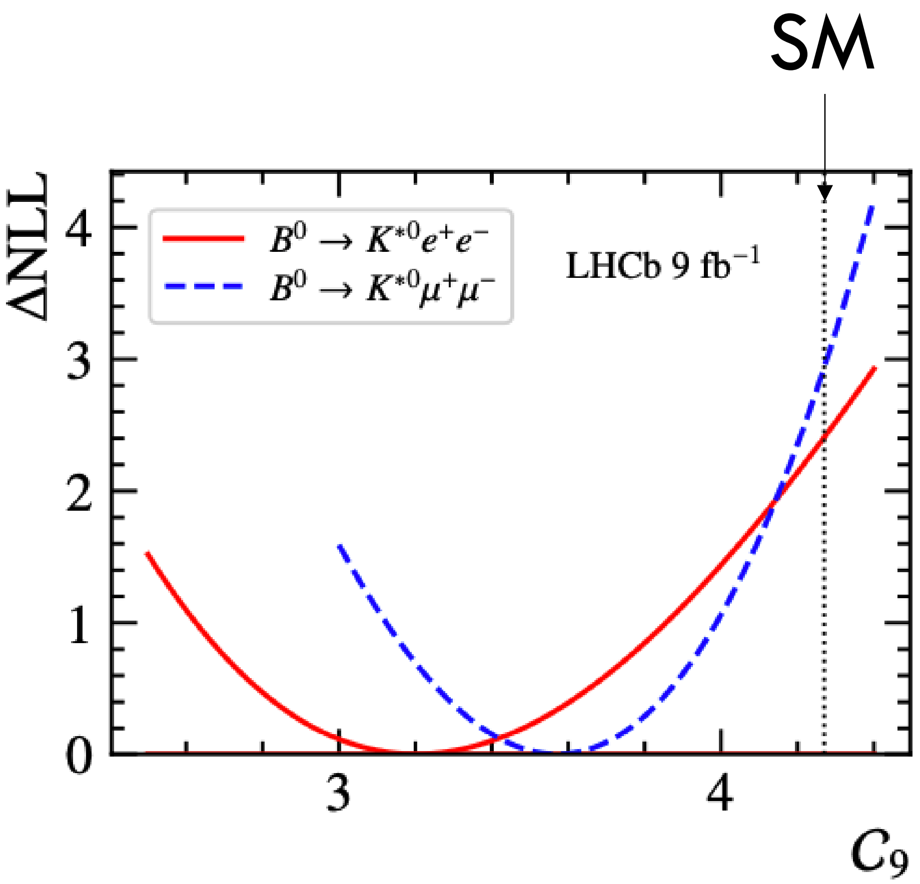
$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$

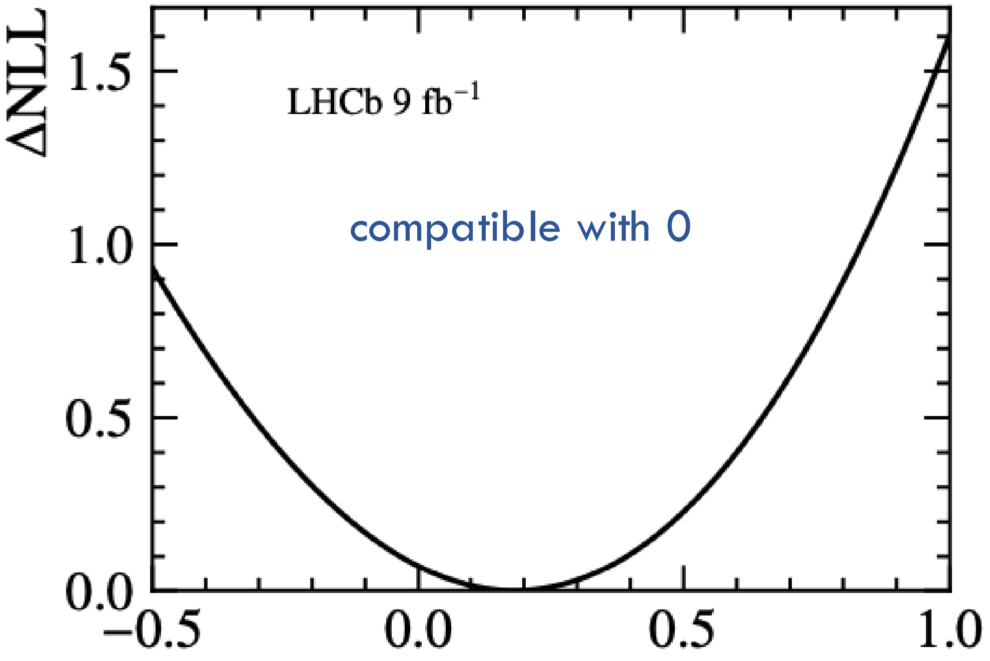



- **more precise than previous Belle measurement**
- **consistent with LFU conservation**

**in agreement with the SM but also with the K*$\mu\,\mu$ results.**




$\Delta C_9 = C_9^{(\mu)} - C_9^{(e)}$

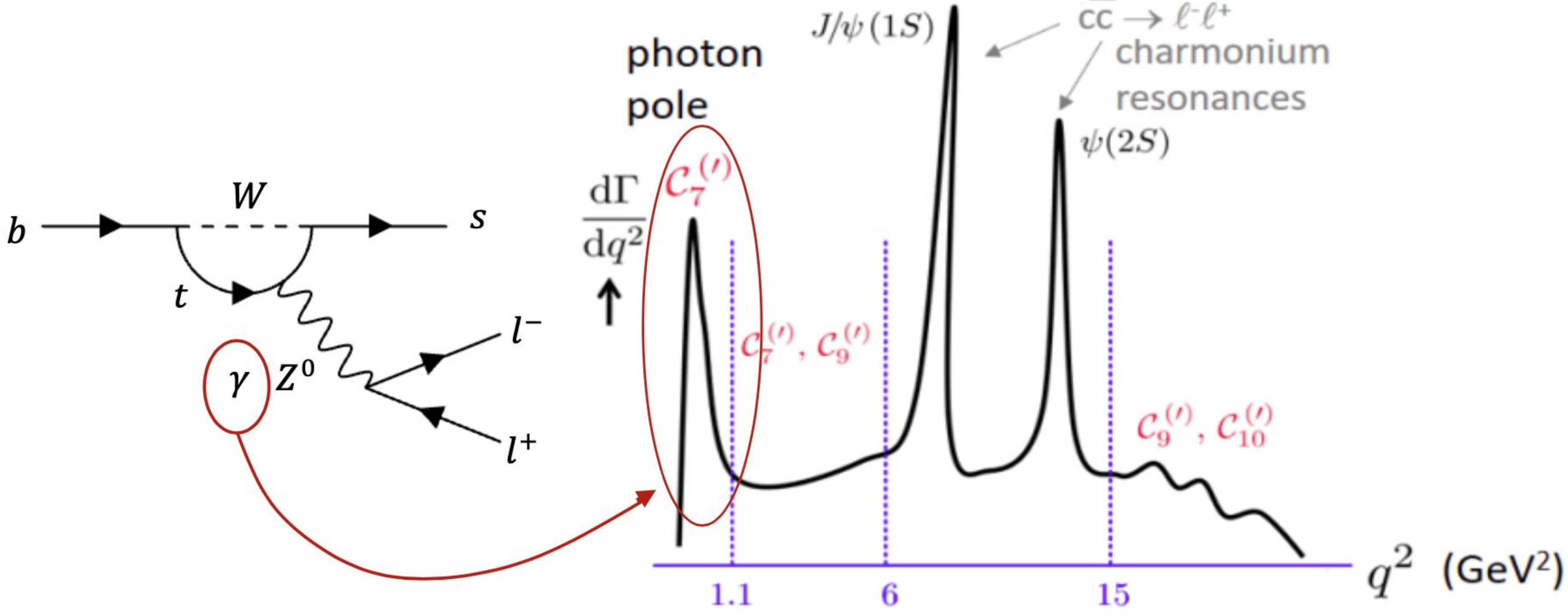
Similar shift in K*μμ and K*ee

Form factors constrained from [JHEP 12 (2023) 153] and non-local QCD terms from [JHEP 02 (2021) 088, JHEP 09 (2022) 133]
Hadronic contributions shared between K*μμ and K*ee

# Measurement of the photon polarisation using $B_s \to \phi(\to KK)ee$

**NEW**

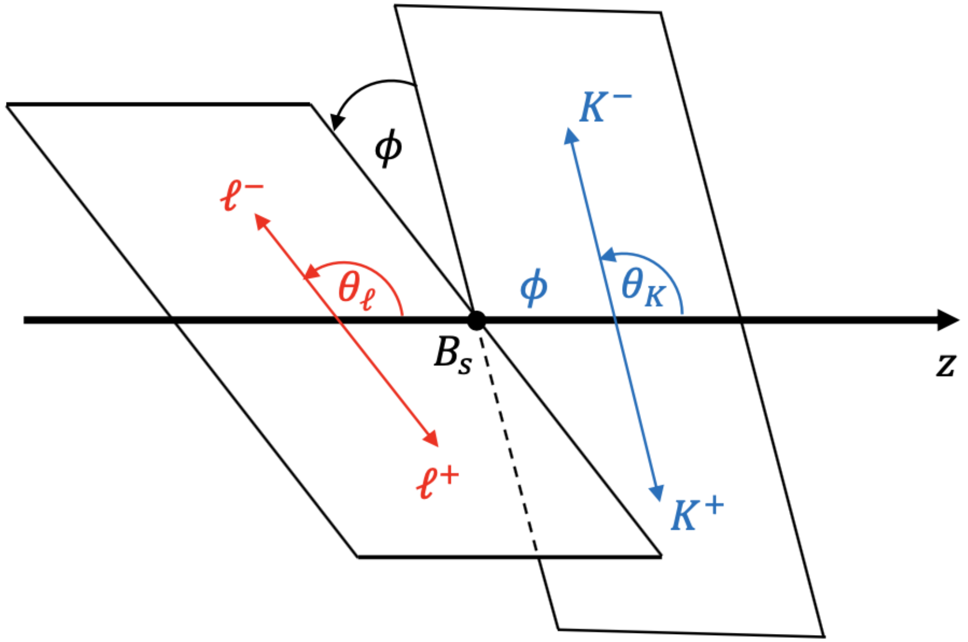
2411.10219 submitted to JHEP




®virtual photon: go for $q^2$ as low as possible

®use electrons : 10 MeV< $m_{ee}$ <500 MeV

3 angles to describe the decay (valid for all $q^2$) :




+ some folding:

$$\tilde{\phi} = \phi \text{ if } \phi > 0, \text{ and } \tilde{\phi} = \phi + \pi \text{ if } \phi < 0$$

$$\frac{1}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\tilde{\phi}^1}$$

$$= \frac{9}{32\pi} \left\{ \frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \right.$$

$$+ \left[\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right]\cos 2\theta_l$$

$$+ \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_l\cos 2\tilde{\phi}$$

$$+ (1-F_L)A_T^{ReCP}\sin^2\theta_k\cos\theta_l$$

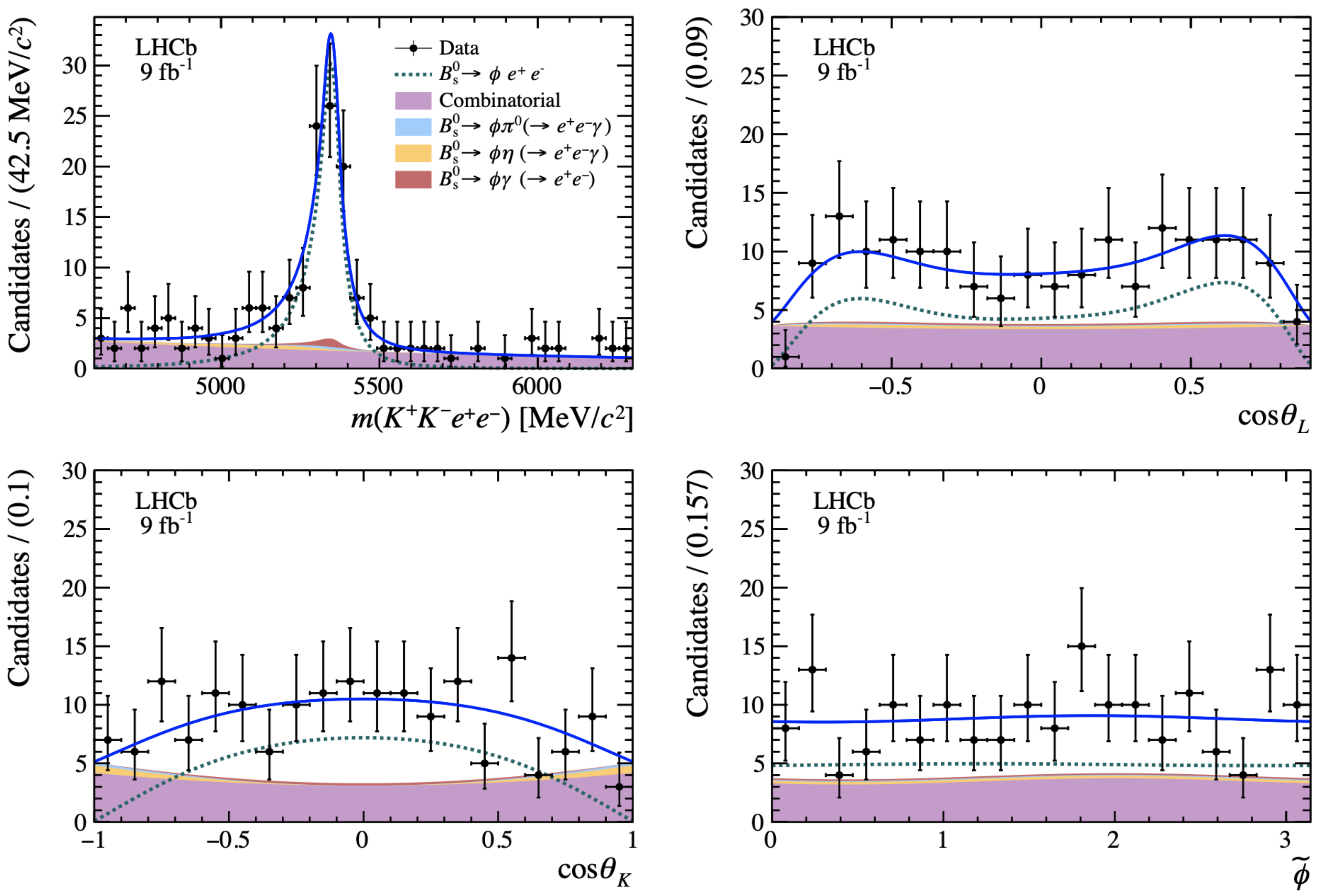
$$\left. + \frac{1}{2}(1-F_L)A_T^{ImCP}\sin^2\theta_k\sin^2\theta_l\sin 2\tilde{\phi} \right\}$$

$$A_T^{(2)}(q^2\to 0) = \frac{2Re(C_7C_7^{\prime *})}{|C_7|^2+|C_7^\prime|^2} + {\Delta_1}^2$$

$$A_T^{ImCP}(q^2\to 0) = \frac{2Im(C_7C_7^{\prime *})}{|C_7|^2+|C_7^\prime|^2} + {\Delta_2}^2$$

$\Delta_i$ due to $\Delta m_s$ and $\Delta\Gamma_s$

# 4D fit : m(KKee), $\cos\theta_K$, $\cos\theta$ $\tilde{\phi}$




$$A_T^{(2)} = -0.045 \pm 0.235 \pm 0.014\,,$$
$$A_T^{ImCP} = 0.002 \pm 0.247 \pm 0.016\,,$$
$$A_T^{ReCP} = 0.116 \pm 0.155 \pm 0.006\,,$$
$$F_L < 11.5\% \text{ @ } 90\% \text{ CL}\,.$$

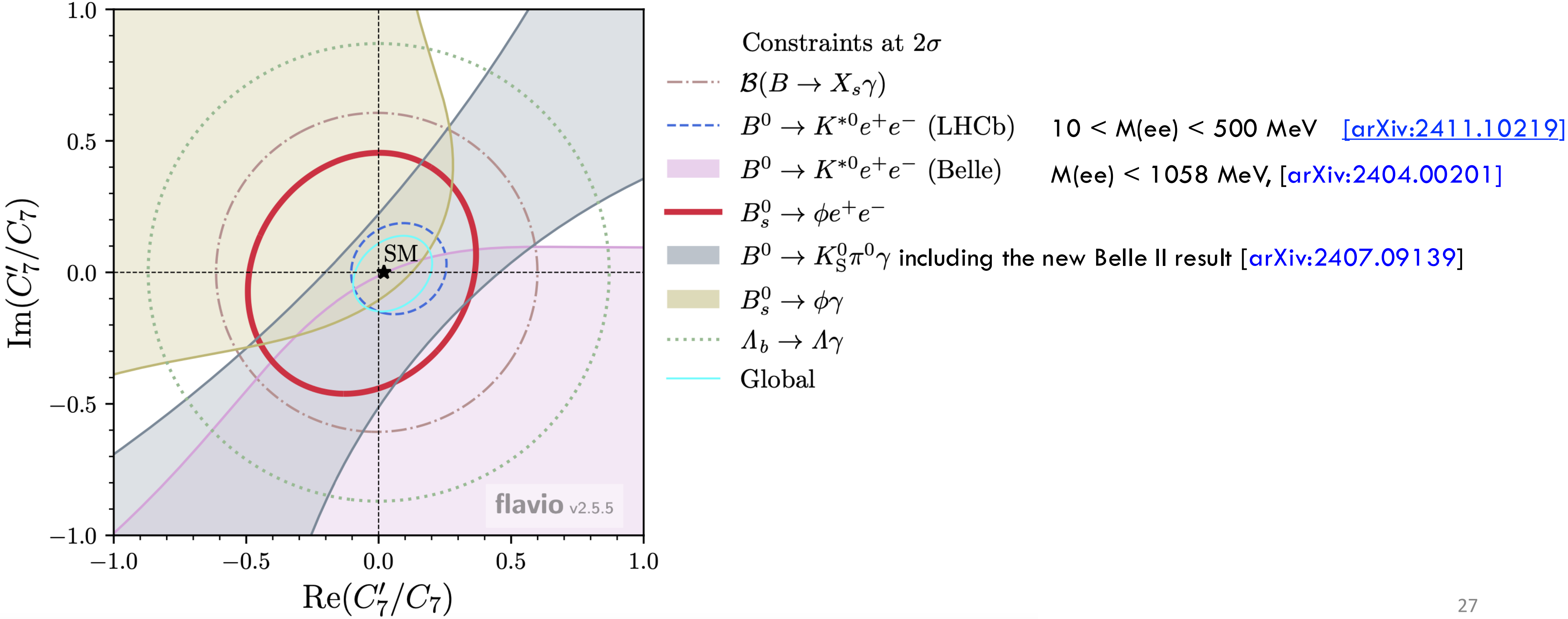
effective region:
$0.0009 < q^2 < 0.2615$ GeV$^2$/c$^4$

**in good agreement with the SM**

## The photon polarisation in $b \to s\gamma$ transitions is known with a precision of ~ 4%

## All measurements are in good agreement

[LHCb-PAPER-2024-030, in preparation]



# Summary

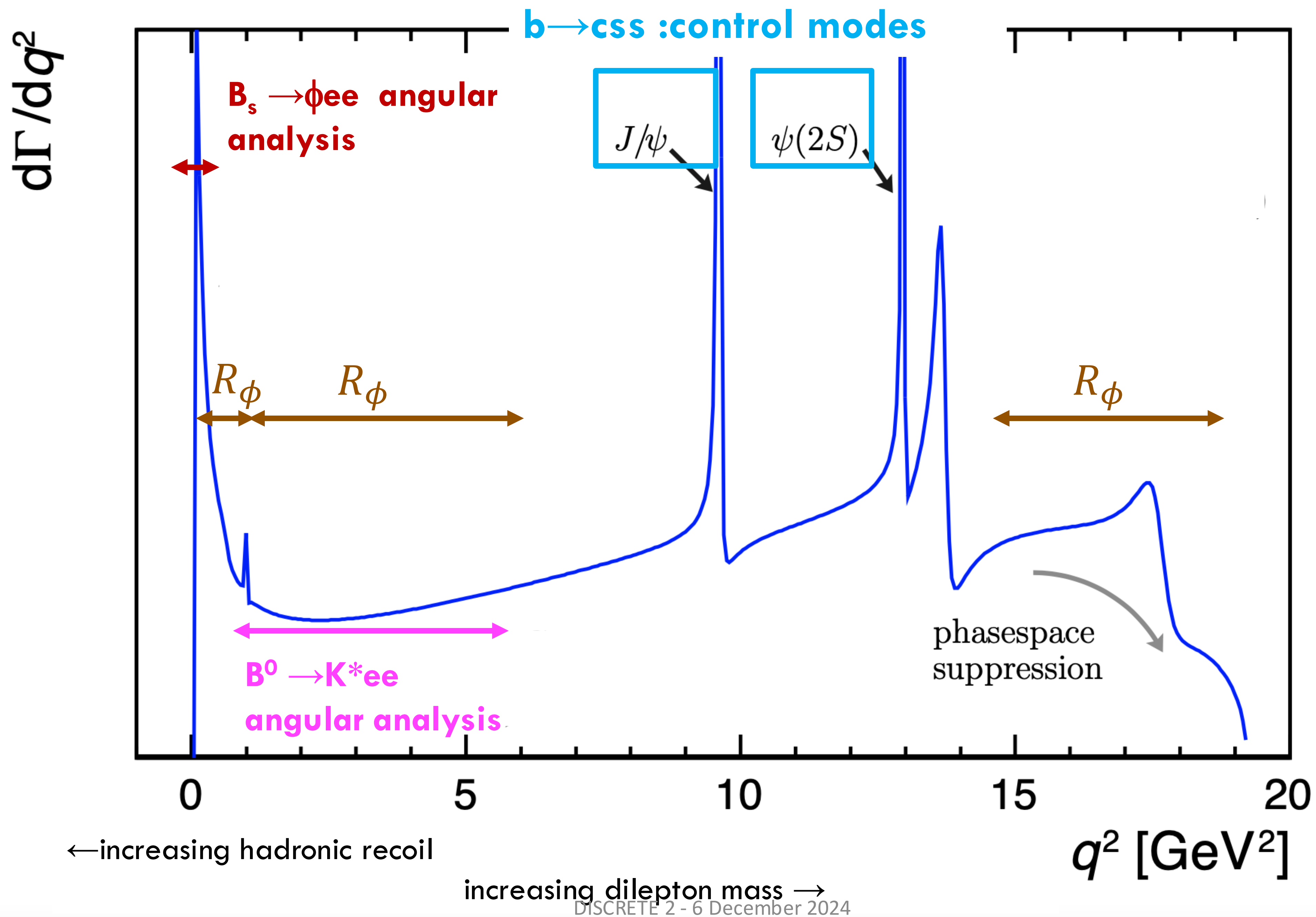
- **Branching ratio measurements :**
  - tensions still present in b→s $\mu\ \mu$
  - LFU holds at the few % level

- **Angular analyses:**
  - tensions still present in b→s $\mu\ \mu$ – origin not yet clarified
  - First $B^0 \rightarrow K^{*0}$ ee angular analysis in the central $q^2$ region for the first time: in agreement both with the SM and $B^0 \rightarrow K^{*0}\ \mu\ \mu$
  - First use of $B_s \rightarrow \phi$ee to measure the photon polarisation in b→s$\gamma$ transition with is entering the few % precision era.

Stay tuned !

**We need (and have) more data**

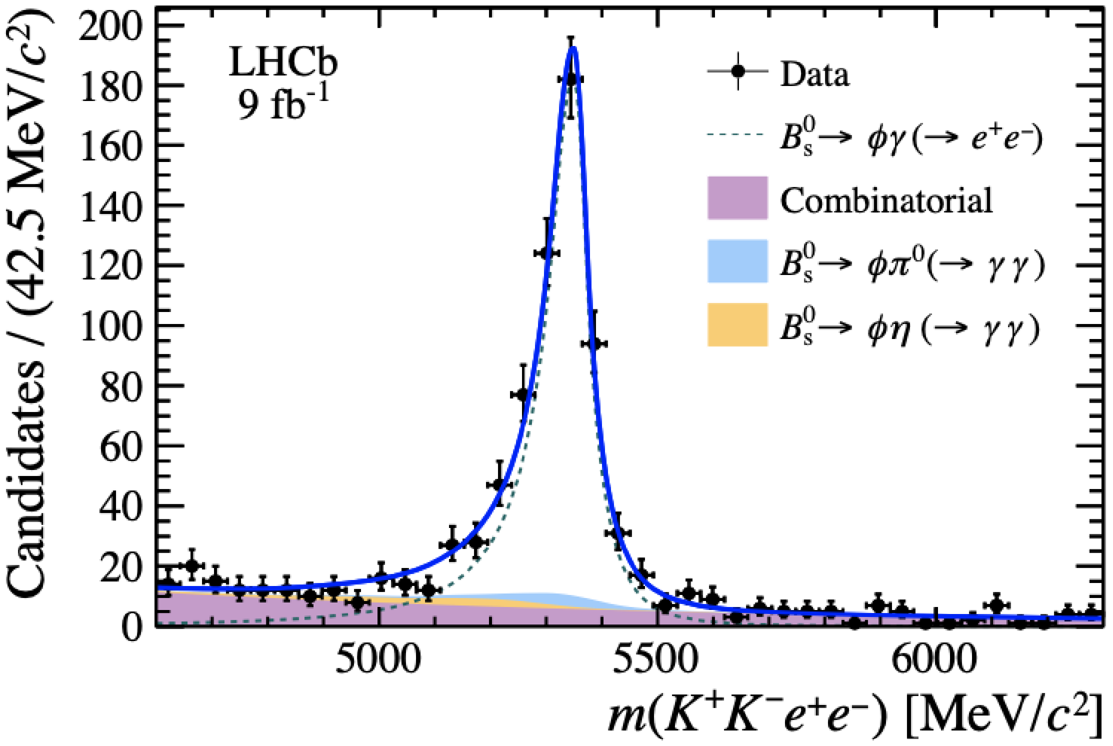
# Back-up slides


b→css :control modes
dΓ/d$q^2$
$B_s$ →ϕee angular analysis
$J/\psi$
$\psi(2S)$
$R_\phi$
$R_\phi$
$R_\phi$
$B^0$ →K*ee angular analysis
phasespace suppression
0
5
10
15
20
$q^2$ [GeV$^2$]
←increasing hadronic recoil
increasing dilepton mass →

Background mostly of combinatorial nature due to the very specific kinematical region and $\phi$ **resonance**

The radiative decay with a converted photon is a nice control channel : $B_s \to \phi(\to K^+K^-)\gamma_e$

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




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