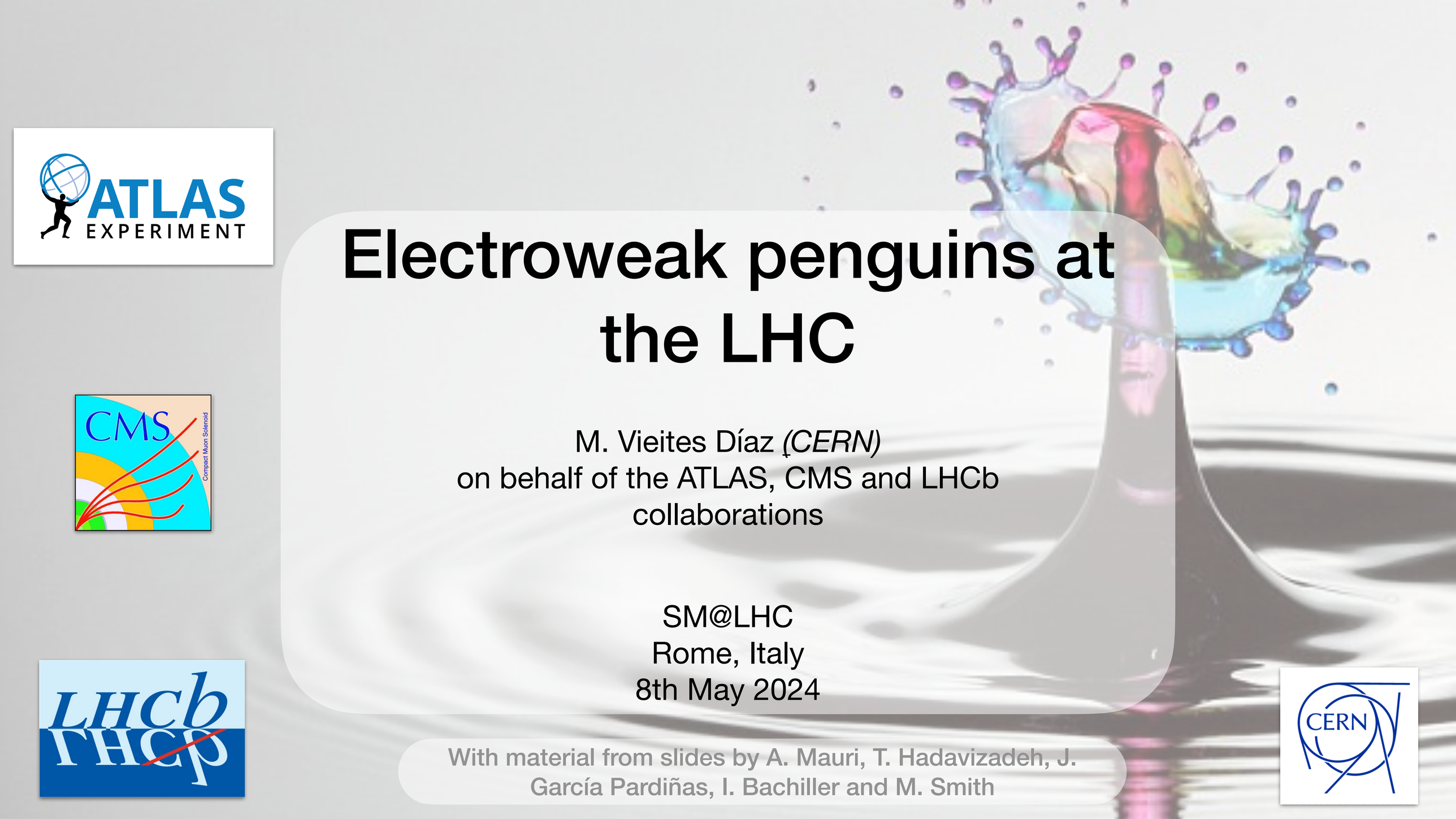


# Electroweak penguins at the LHC

M. Vieites Díaz *(CERN)*
on behalf of the ATLAS, CMS and LHCb collaborations

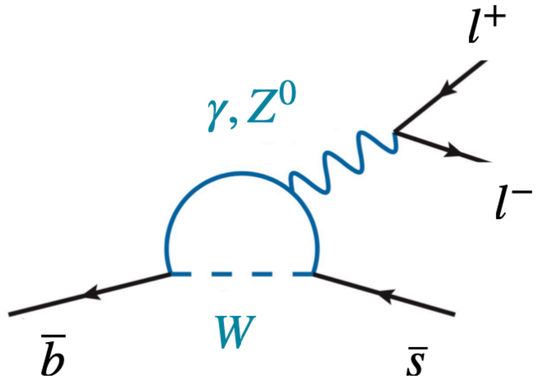
SM@LHC
Rome, Italy
8th May 2024

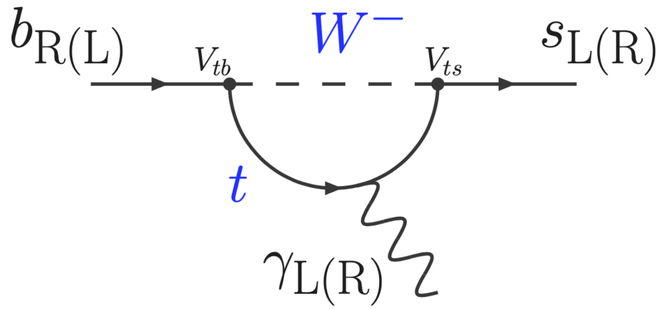
With material from slides by A. Mauri, T. Hadavizadeh, J. García Pardiñas, I. Bachiller and M. Smith

# Flavour Changing Neutral Currents

- Only allowed via loop (*aka* penguin) diagrams in the Standard Model
  - Clear experimental signatures
  - Extensive theory/phenomenology work on parameterisations of the decay rate
  - Long standing saga, lots of experience

Very good place to scrutinise the SM!




# The SM as an Effective Field Theory

**B** decays can be **described by an effective theory** by integrating out the heavy fields:

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$$

Wilson coefficients (*effective couplings*)

New particles?

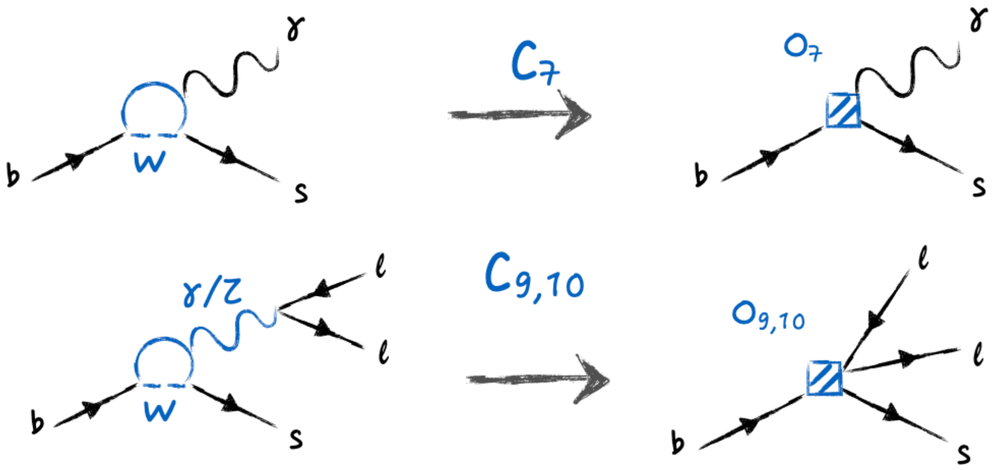
Local operators

Most relevant operators for FCNC:

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha, \qquad \textit{photon}$$

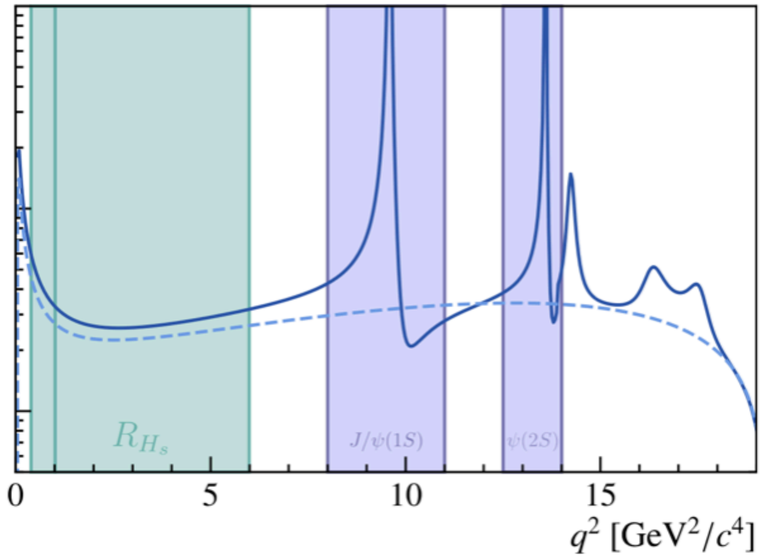
$$\mathcal{O}_{9V} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell} \gamma_\mu \ell, \qquad \textit{vector}$$

$$\mathcal{O}_{10A} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell} \gamma_\mu \gamma_5 \ell, \qquad \textit{axial-vector}$$

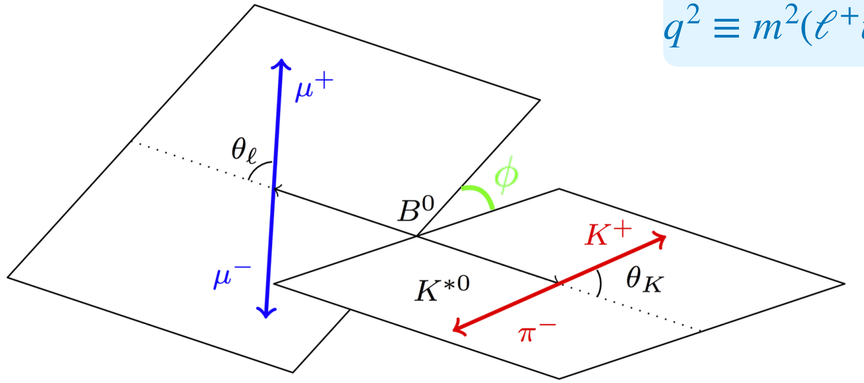


# Main observables in $b \to s\ell\ell$ decays

- Binned **branching ratios:** $q^2$-bins
  - **Double ratios** (Lepton Flavour Universality)
- **Binned angular** observables: $q^2$-bins, $f$(angles)
- **Amplitude** analyses: $f(q^2$ + angles)




$q^2 \equiv m^2(\ell^+\ell^-)$



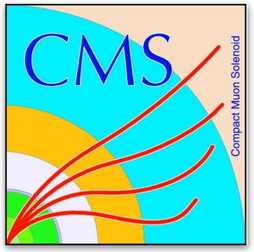
# Today


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

[Phys. Rev. Lett. 132 (2024) 131801]
[Phys. Rev. D 109 (2024) 052009]
[LHCb-PAPER-2024-011, in preparation]

$B^\pm \to K^\pm \ell^+\ell^-$

[arXiv:2401.07090]
[Phys. Rev. Lett. 131 (2023) 051803 ]
[Phys. Rev. D 108 (2023) 032002]






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

[Phys. Lett. B 842 (2023)]
[Phys. Rev. D105 (2022)]
[Phys. Rev. Lett. 128, (2022)]
[JHEP09(2023)199]

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

[arXiv:2404.03375]

# Today


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

[Phys. Rev. Lett. 132 (2024) 131801]
[Phys. Rev. D 109 (2024) 052009]
[LHCb-PAPER-2024-011, in preparation]

$B^\pm \to K^\pm \ell^+ \ell^-$

[arXiv:2401.07090]
[Phys. Rev. Lett. 131 (2023) 051803 ]
[Phys. Rev. D 108 (2023) 032002]










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

[Phys. Lett. B 842 (2023)]
[Phys. Rev. D105 (2022)]
[Phys. Rev. Lett. 128, (2022)]
[JHEP09(2023)199]

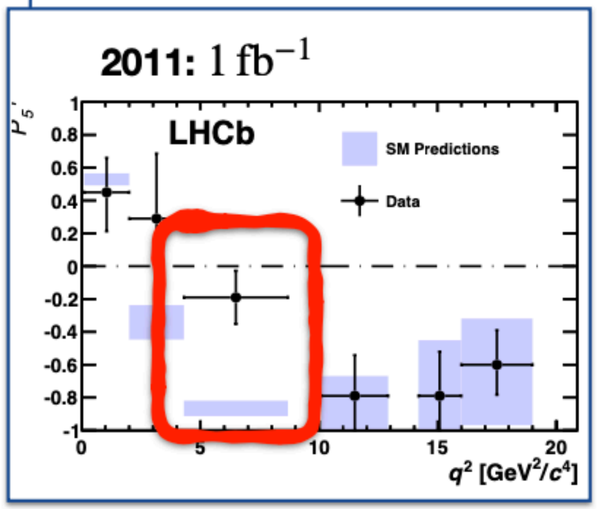
$B_s^0 \to \mu^+\mu^-\gamma$

[arXiv:2404.03375]

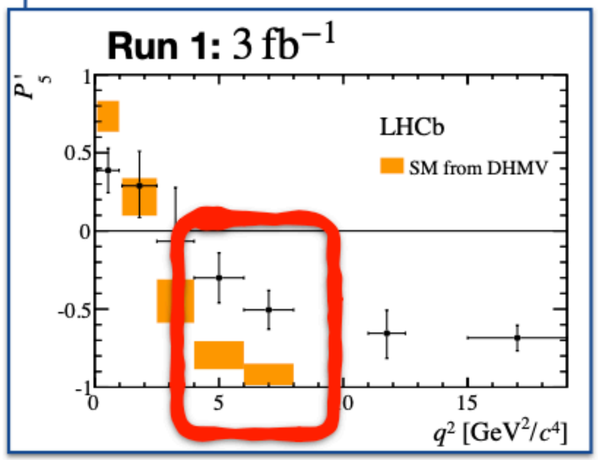
# Intriguing pattern…

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

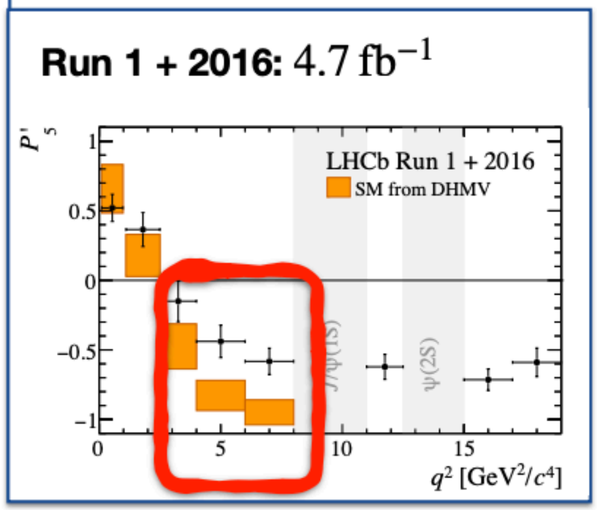
Tensions have remained for ~10 years




[LHCb-PAPER-2013-037]




[LHCb-PAPER-2015-051]



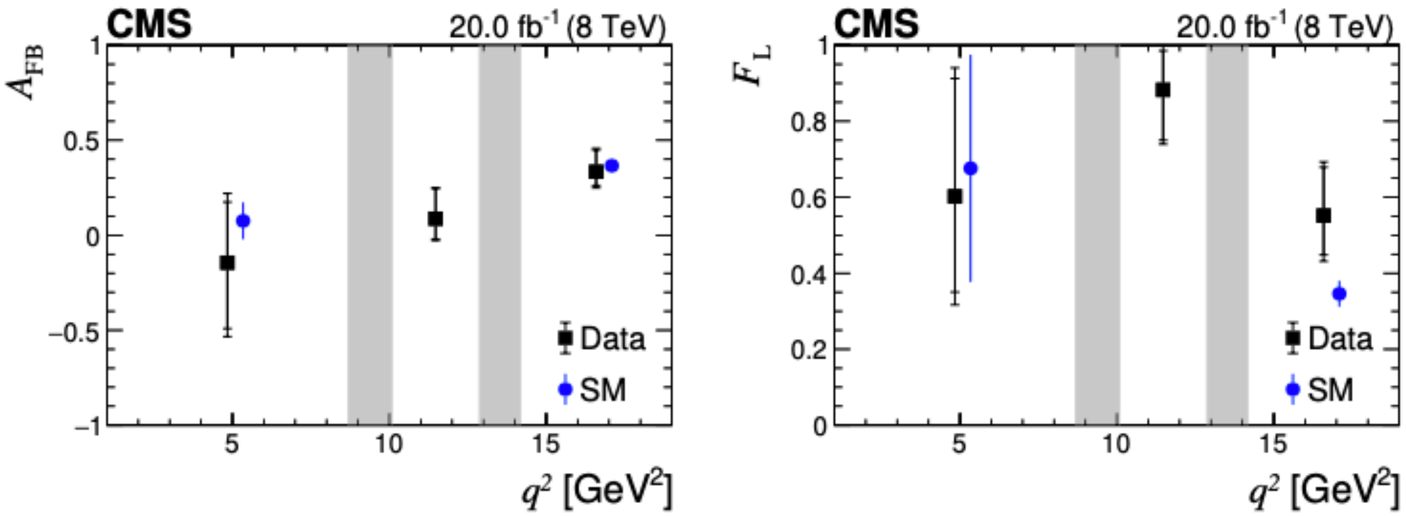

[LHCb-PAPER-2020-002]

$P_5'$ : a particular combination of helicity amplitudes built to be quasi-independent of form factors (~theory uncertainties)

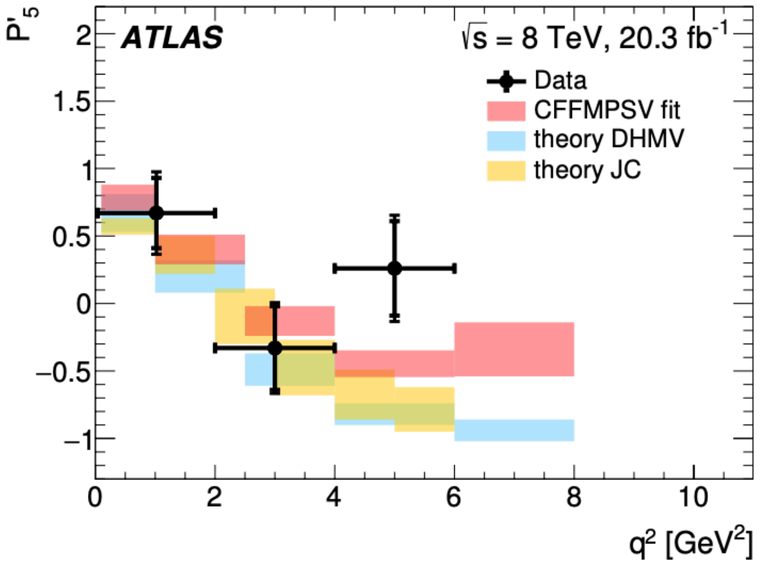
# which can still be investigated further

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

[JHEP04(2021)124]



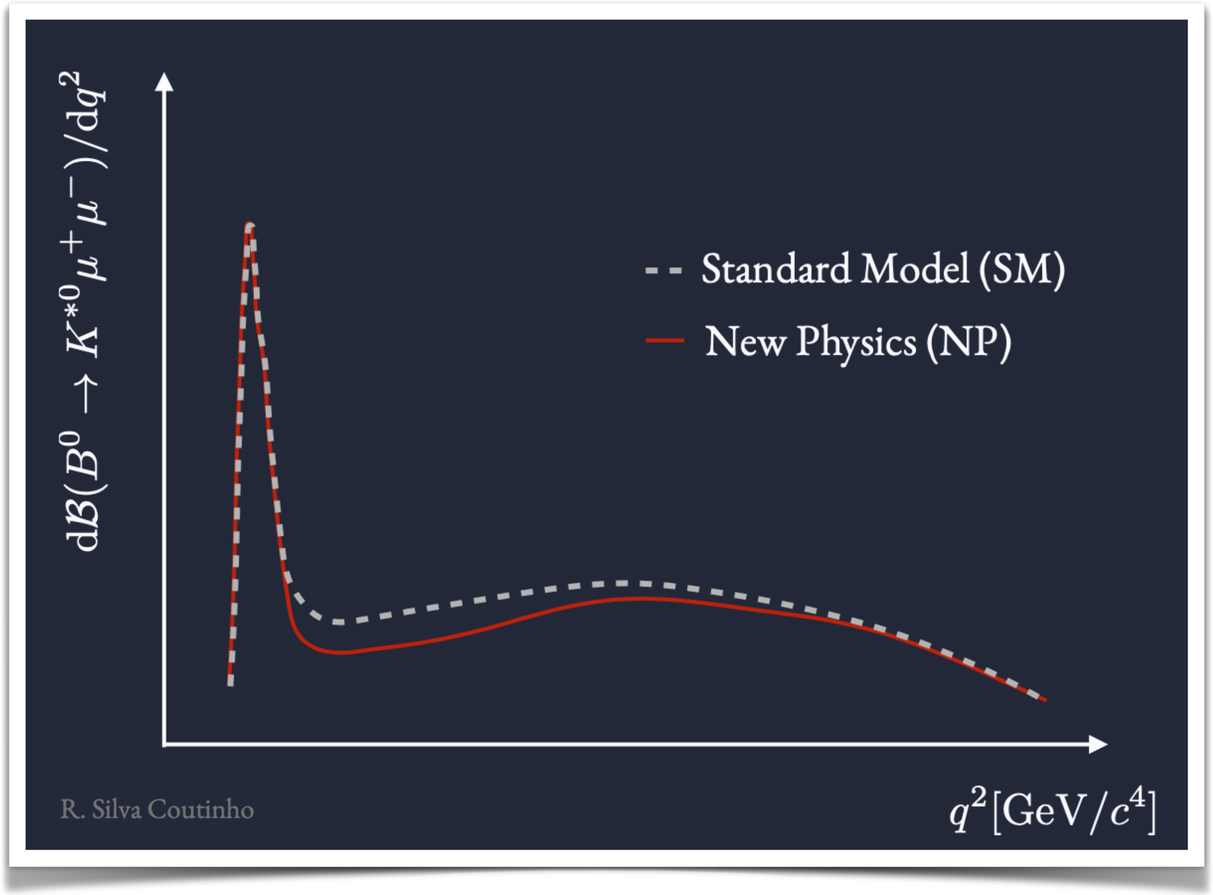

[JHEP10(2018)047]

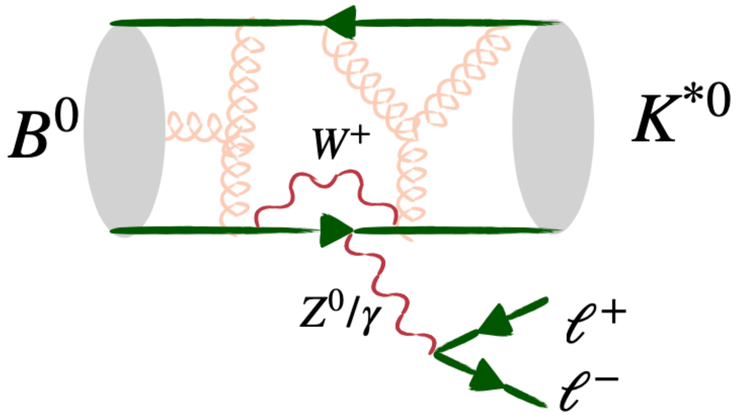



Angular observables, built from combination of helicity amplitudes

ATLAS and CMS public results based on part of Run1 data only

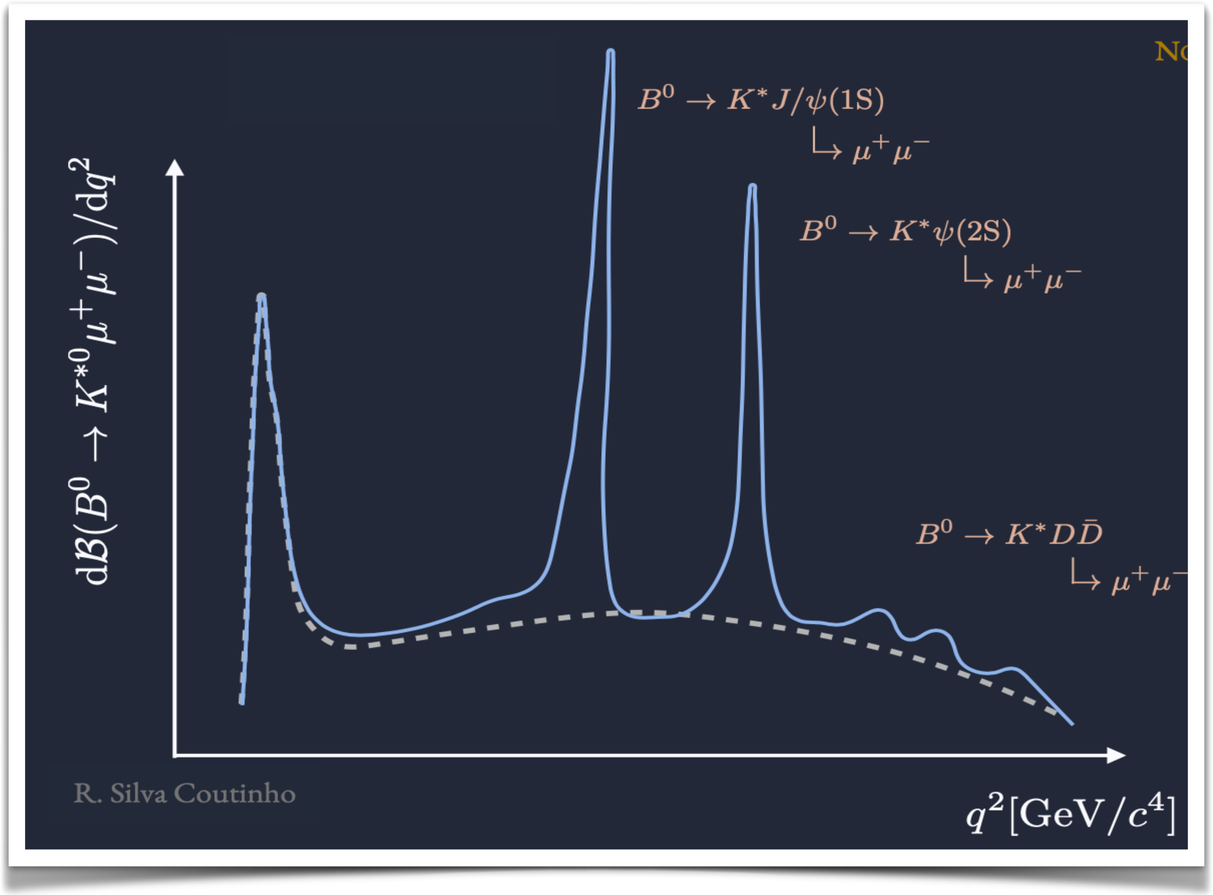
# The tension: New Physics ?

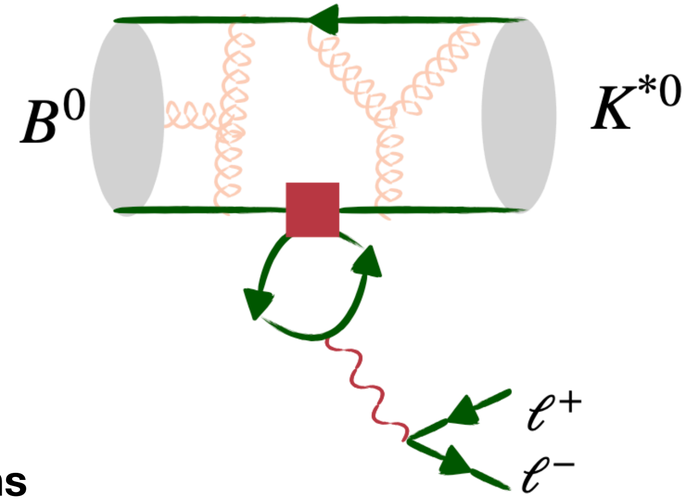



- **Local contributions**

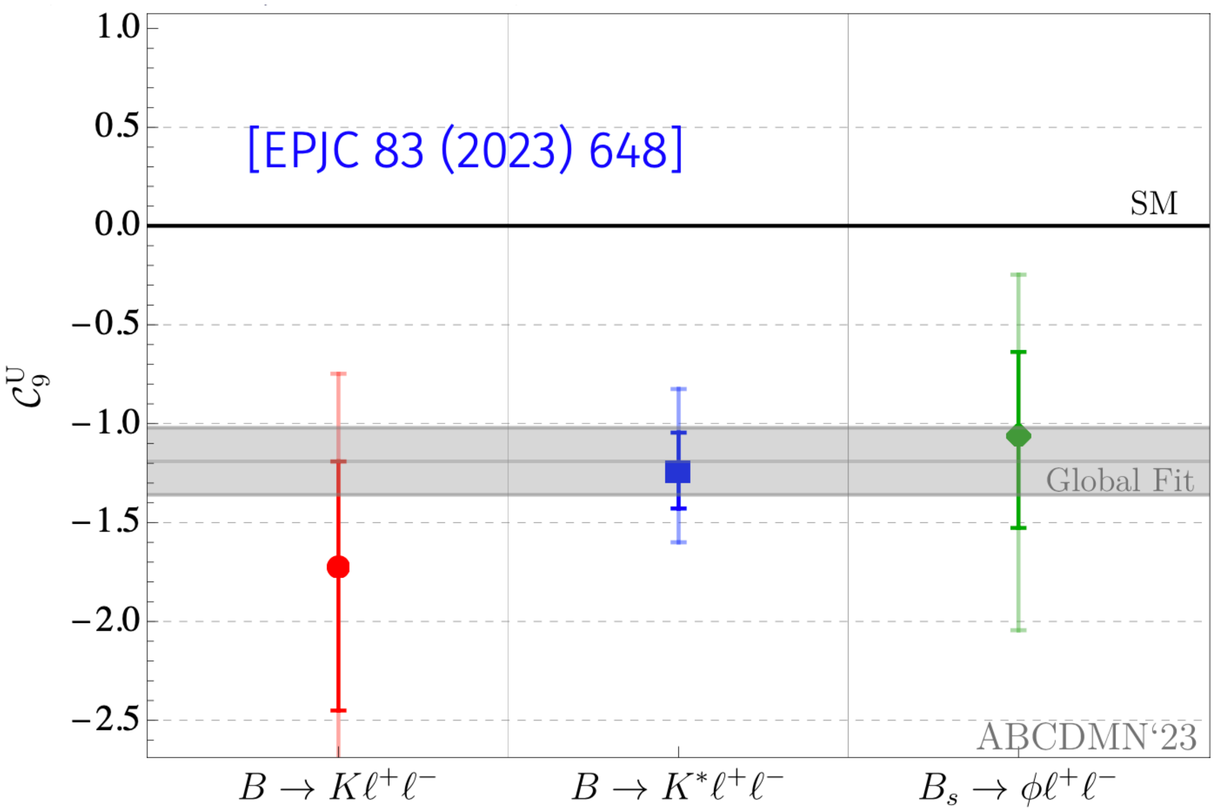
# The tension: New Physics or QCD?




- **Local contributions**
- **Non-local contributions**
  - One-particle (1P) contributions, seen as resonances and able to cause interferences far away from the poles
  - Two-particle (2P) contributions, from “charm-loops” ($D^{(*)}\overline{D}^{(*)}$) and $\tau^+\tau^-$ rescattering

# Global fits




Fit for $C_9$, assuming SM for other WCs

- Current preferred solution from the global fits: shift in $C_9$
  - Many long-distance contributions (vector-like) mimic this
- Current goal: could these be modelled, and therefore disentangled in a fit to data?

# To bin or not to bin

**Model independent** ⟵ ⟶ **Model dependent**

**Binned** | **Unbinned**

**Binned fit**

[PRL 125, 011802] **(2020)**

[JHEP 02, 104] **(2016)**

[PRL 111, 191801] **(2013)**

Binned angular observables

**Z-expansion**

[PRL 132, 131801] **(2024)**

[PRD 109, 052009] **(2024)**

$C_{9,10}^{(\prime)}$ + non-local polynomial

**Today**

**Dispersion relation**

[LHCb-PAPER-2024-011, in preparation] **(2024)**

$C_{9,10}^{(\prime)}, C_9^{\tau}$ + non-local magnitudes and phases


# Z-expansion vs Dispersion relation

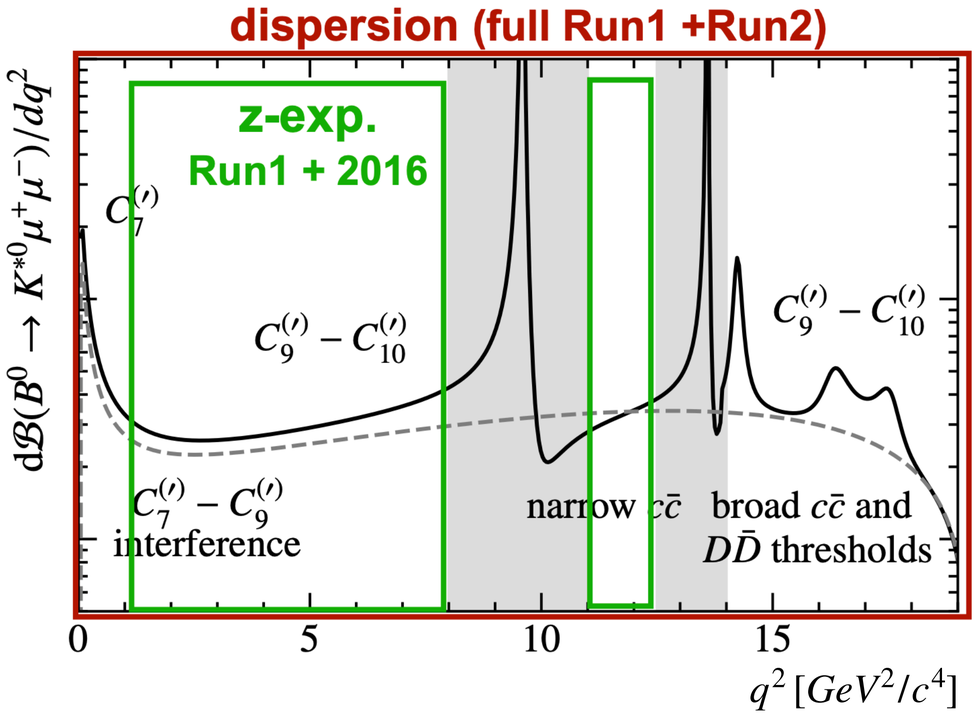
**Similar:**

- **Experimental methodology** (selection, combinatorial background, acceptance…)
- **Local Form Factors**, constrained to:
  - Light-cone sum rules
  - Lattice QCD

[JHEP 01 (2019) 150]
[PoS (LATTICE2014) 372]

**But different:**

- Modelling of the **non-local** contribution
- $q^2$ range
- Dataset



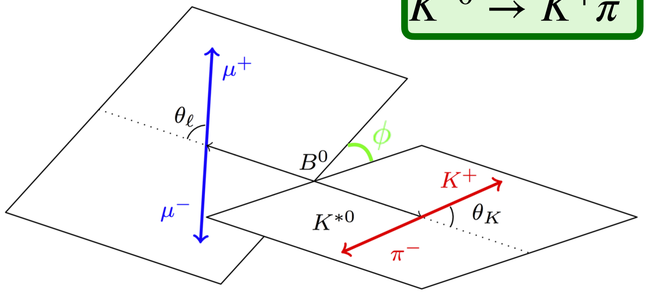
# Z-expansion

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

Decay rate: $$\frac{\mathrm{d}^5\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}k^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2,k^2) f_i(\vec{\Omega})$$

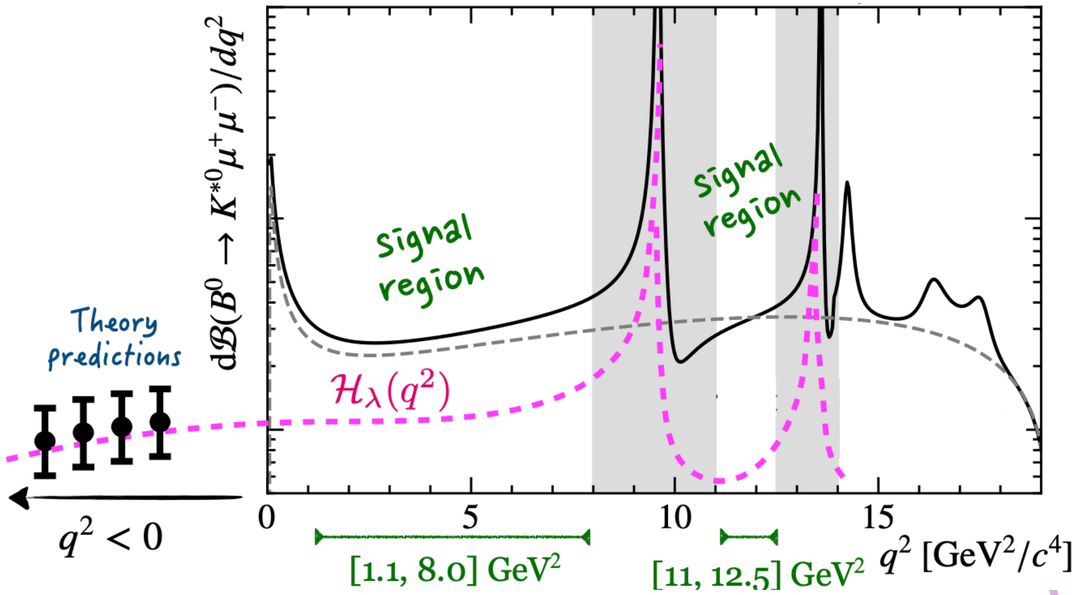
$$B^0 \to K^{*0}\mu^+\mu^-$$

$$K^{*0} \to K^+\pi^-$$




$$I_i \propto (\mathcal{A}_{\lambda_1}\mathcal{A}^*_{\lambda_2})$$

$$\mathcal{A}^{L,R}_\lambda = \mathcal{N}_\lambda\left\{[\underbrace{(C_9 \pm C_9')}_{\text{WCs}} \mp \underbrace{(C_{10} \pm C_{10}')}_{\text{WCs}}]\overbrace{\mathcal{F}_\lambda(q^2)}^{\text{FFs}} + \frac{2m_b M_B}{q^2}[\underbrace{(C_7 \pm C_7')}_{\text{WCs}}\overbrace{\mathcal{F}^T_\lambda(q^2)}^{\text{FFs}} - 16\pi^2\frac{M_B}{m_b}\underbrace{\mathcal{H}_\lambda(q^2)}_{\text{non-local}}]\right\}$$



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[Phys. Rev. D 109 (2024) 052009]

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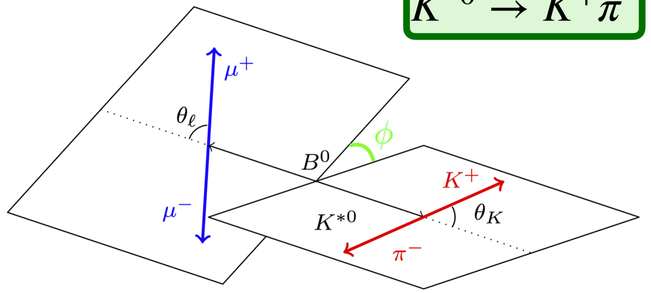
$B^0 \to K^{*0}\mu^+\mu^-$

$K^{*0} \to K^+\pi^-$

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- $C_9 \pm C_9'$, $C_{10} \pm C_{10}'$: WCs — Fit params.
- $\mathcal{F}_\lambda(q^2)$: FFs — Constrained ext. inputs.
- $C_7 \pm C_7'$: WCs — Fixed to SM
- $\mathcal{F}^T_\lambda(q^2)$: FFs — Constrained ext. inputs.
- $\mathcal{H}_\lambda(q^2)$: non-local

Map $q^2$ into $z(q^2)$, remove the poles and expand into a converging series

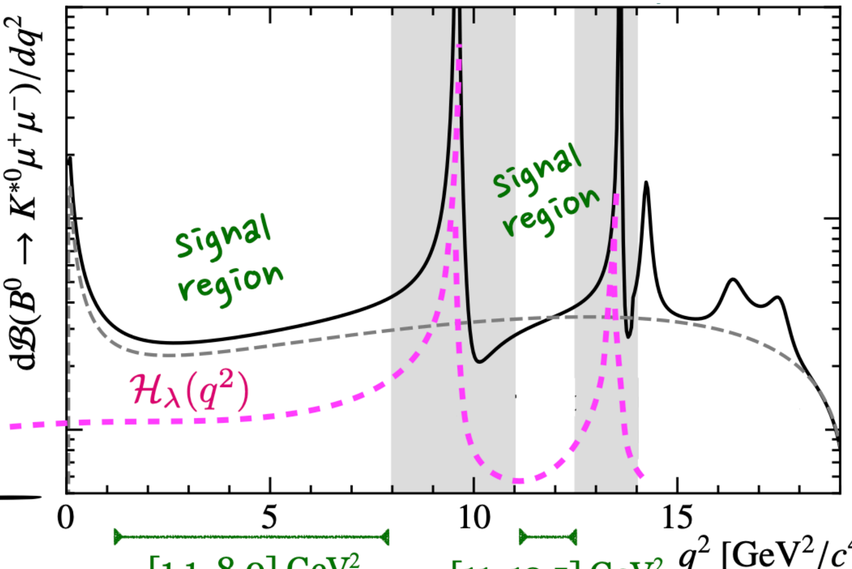
$$\mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}}\frac{1 - zz^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda.n} z^n$$

Fit params.

Theory predictions

$q^2 < 0$

[JHEP 02 (2021) 088]



New 2024!

# Dispersion relation

[LHCb-PAPER-2024-011, in preparation]

→ **Amplitudes** parameterised in terms of **effective Wilson Coefficients** and local form factors

**Dispersion Relation**

$$C_9^{\text{eff},\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{\text{light}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

Local | Non-local contributions

$$C_7^{\text{eff},\lambda}(q^2) = C_7^{\mu} + \epsilon^{\lambda} e^{i\omega^0}$$

$\Delta C_7^{\lambda}$

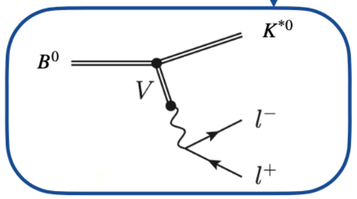
**Polarisation dependent shift to $C_7$**

This is determined theoretically at negative $q^2$ values

**Subtraction term**

Asatrian, Greub, Virto [JHEP 04 (2020) 012]

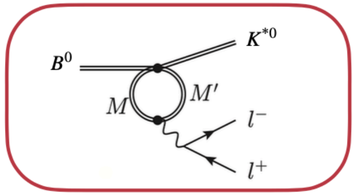
*Negligible impact from light quarks*




**1-particle contributions**

**Includes:**

| | |
|---|---|
| $\omega(782)$, | $\psi(2S)$, |
| $\rho(770)$, | $\psi(3770)$, |
| $\phi(1020)$, | $\psi(4040)$, |
| $J/\psi$, | $\psi(4160)$ |

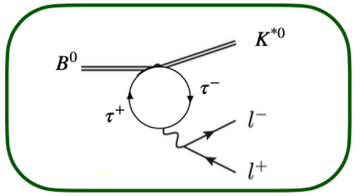



**2-particle contributions**

**Includes:**

$D\bar{D}$,
$D^*\bar{D}$,
$D^*\bar{D}^*$

C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]




**Tau loop contribution**

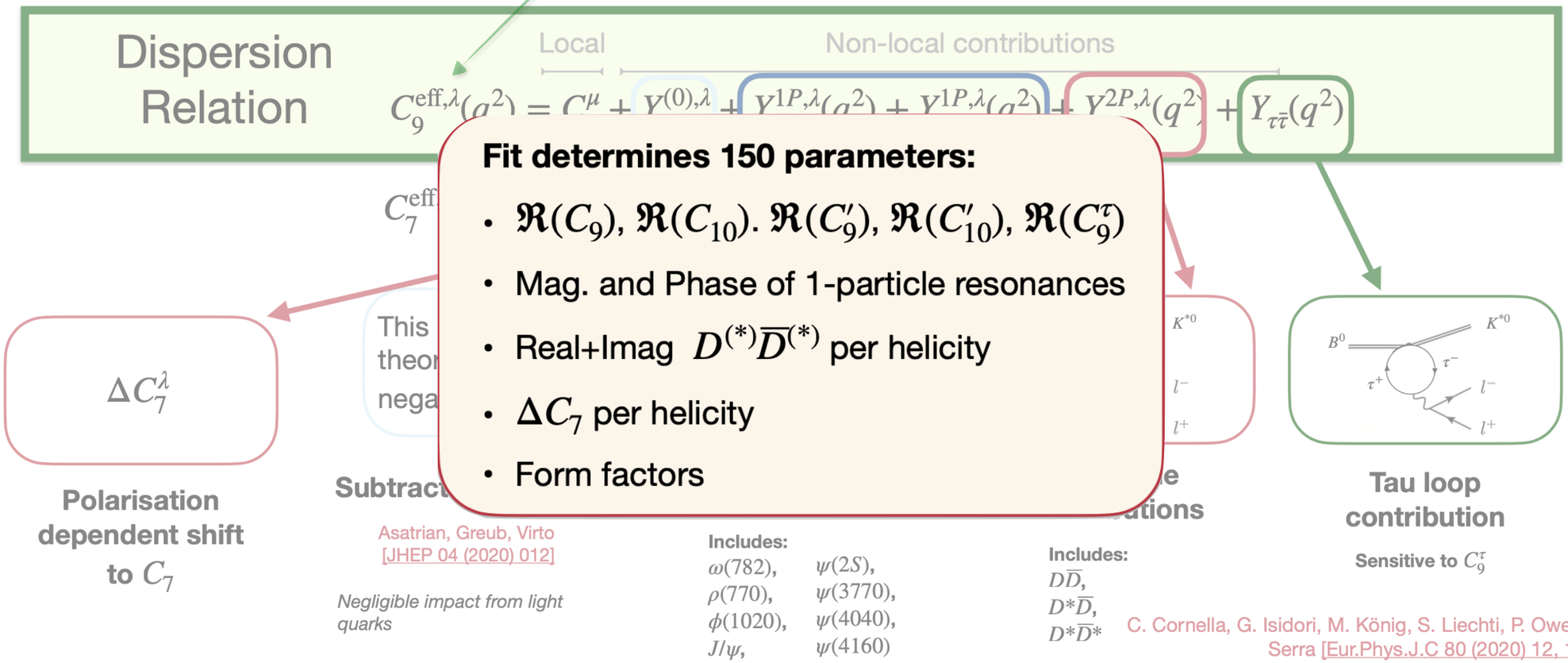
**Sensitive to $C_9^{\tau}$**

New 2024!

# Dispersion relation

[LHCb-PAPER-2024-011, in preparation]

→ **Amplitudes** parameterised in terms of **effective Wilson Coefficients** and local form factors




**Fit determines 150 parameters:**

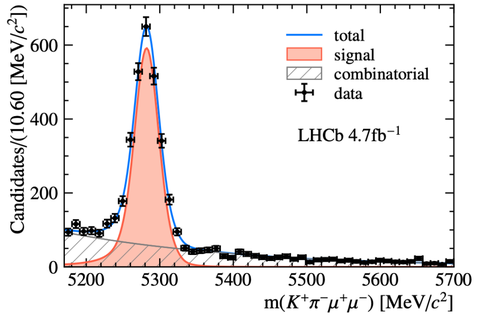
- $\Re(C_9)$, $\Re(C_{10})$. $\Re(C_9')$, $\Re(C_{10}')$, $\Re(C_9^{\tau})$
- Mag. and Phase of 1-particle resonances
- Real+Imag $D^{(*)}\overline{D}^{(*)}$ per helicity
- $\Delta C_7$ per helicity
- Form factors

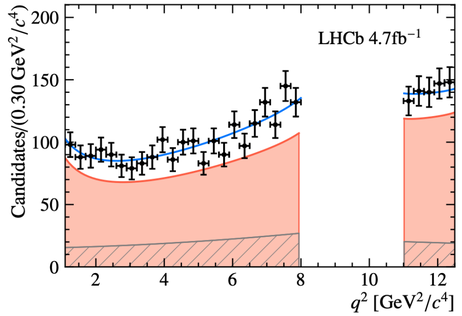
[Phys. Rev. Lett. 132 (2024) 131801]
[Phys. Rev. D 109 (2024) 052009]

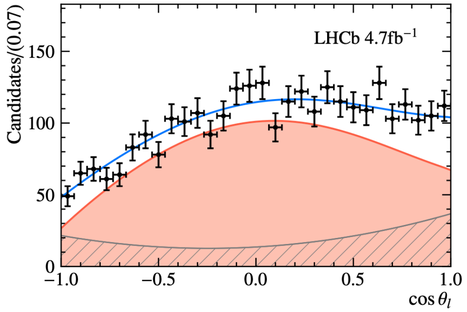
[LHCb-PAPER-2024-011, in preparation]

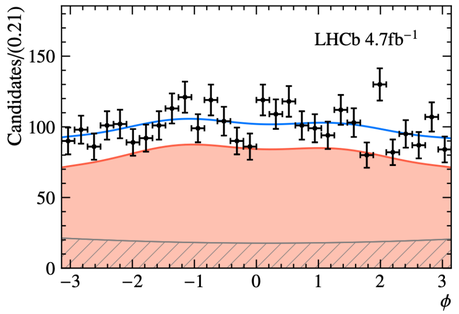
# Z-expansion | Dispersion relation

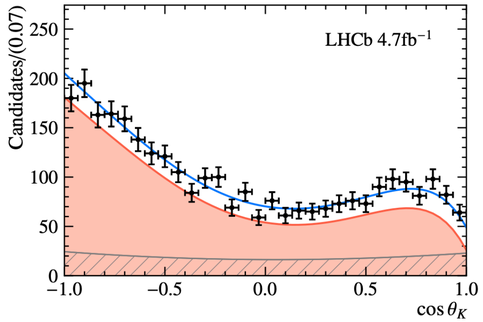
→ 5D fit using Run 1 + 2016 data, with charmonium vetoes

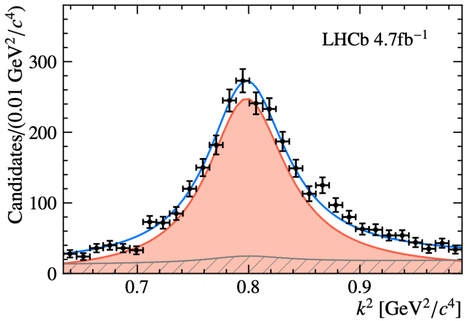


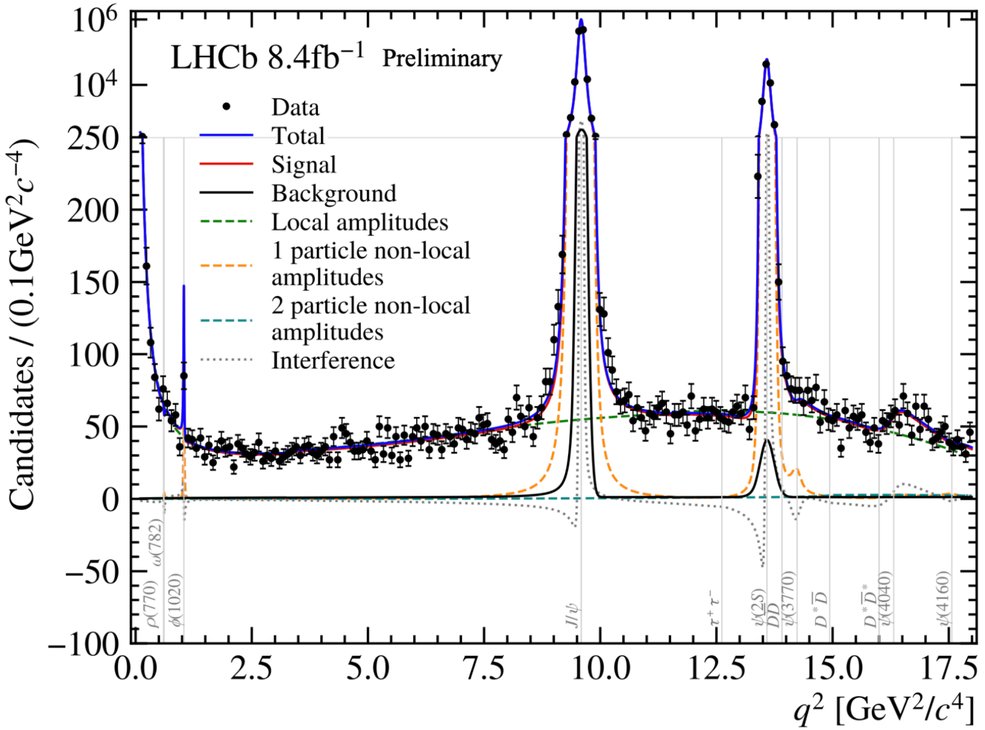



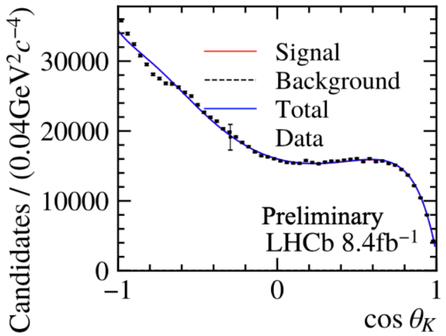



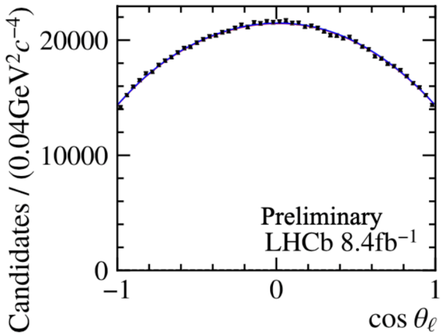



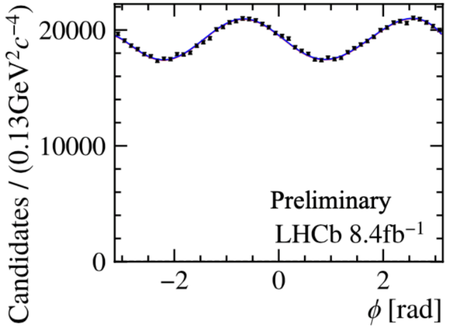




→ 4D fit to Run 1 + Run 2 data, full $q^2$ spectrum



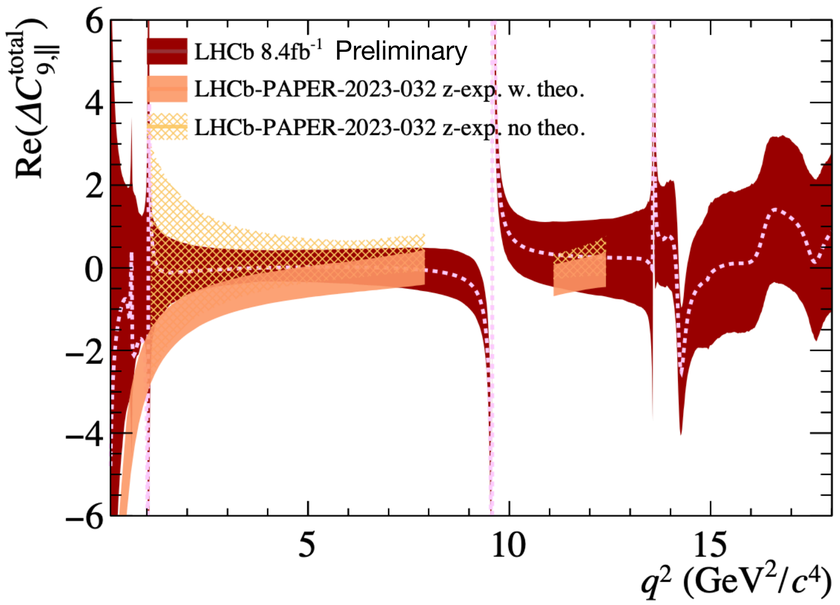



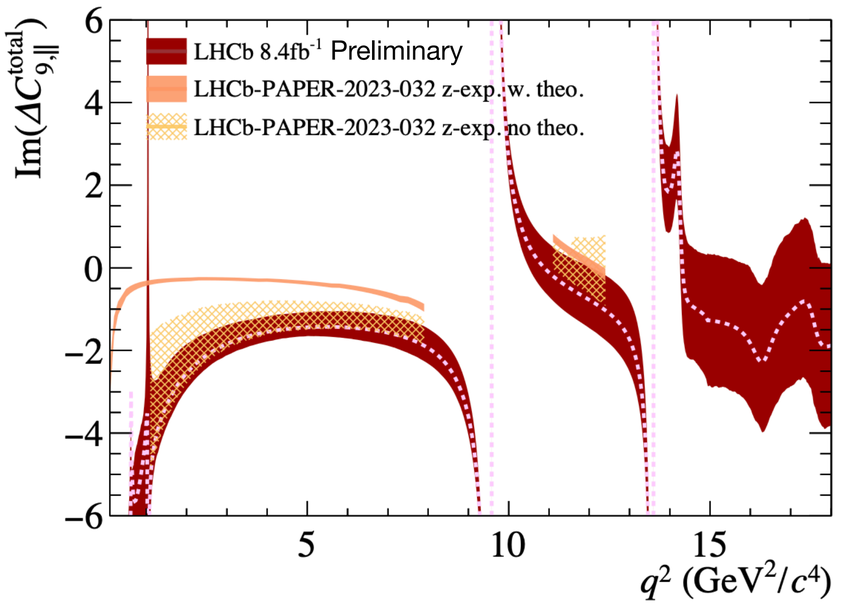



New 2024!

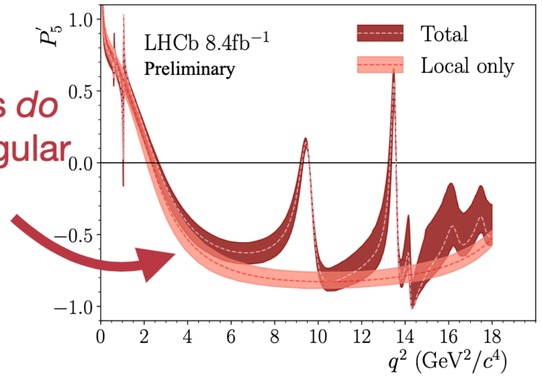
# Non-local amplitudes

[LHCb-PAPER-2024-011, in preparation]




Nonlocal contributions *do* influence angular observables




- Results shown per helicity
- Overall, **good agreement with z-expansion** analysis

LHCb-PAPER-2023-032 == [Phys. Rev. D 109 (2024) 052009]

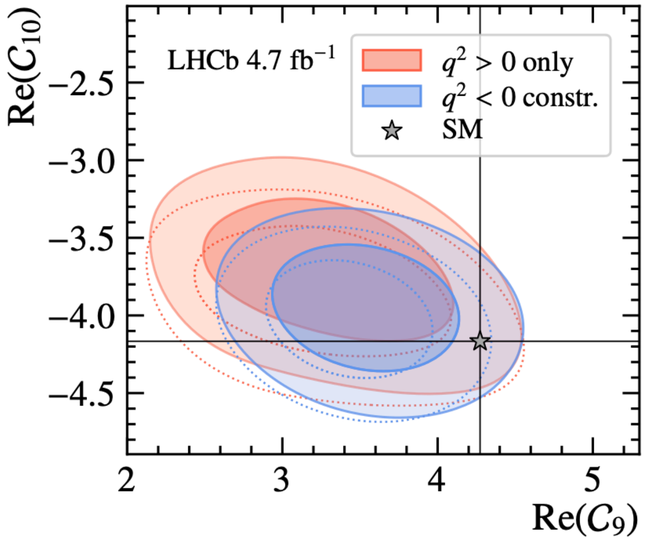
[Phys. Rev. Lett. 132 (2024) 131801]
[Phys. Rev. D 109 (2024) 052009]

[LHCb-PAPER-2024-011, in preparation]

# Wilson Coefficients in 2D

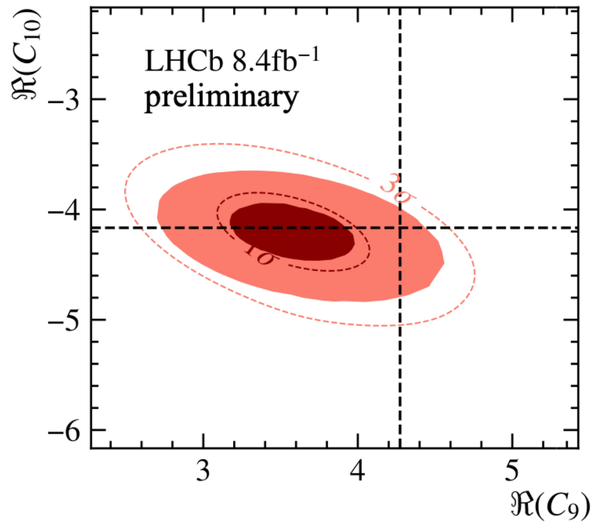
New 2024!

→ Both analyses give a consistent picture, also with global fit from the binned analyses and other $b \to s\mu^+\mu^-$ decays




| | | | |
|---|---|---|---|
| $C_9$ | $3.34^{+0.53}_{-0.57}$ | $(\ 3.59^{+0.33}_{-0.46}\ )$ | $1.9\,(1.8)\,\sigma$ |
| $C_{10}$ | $-3.69^{+0.29}_{-0.31}$ | $(-3.93^{+0.27}_{-0.28})$ | $1.5\,(0.9)\,\sigma$ |
| $C'_9$ | $0.48^{+0.49}_{-0.55}$ | $(\ 0.26^{+0.40}_{-0.48}\ )$ | $0.9\,(0.5)\,\sigma$ |
| $C'_{10}$ | $0.38^{+0.28}_{-0.25}$ | $(\ 0.27^{+0.25}_{-0.27}\ )$ | $1.5\,(1.0)\,\sigma$ |

Global significance $1.3\,(1.4)\,\sigma$




| | | |
|---|---|---|
| $C_9$ | $3.56 \pm 0.28 \pm 0.18$ | $2.1\sigma$ |
| $C_{10}$ | $-4.02 \pm 0.18 \pm 0.16$ | $0.6\sigma$ |
| $C'_9$ | $0.28 \pm 0.41 \pm 0.12$ | $0.7\sigma$ |
| $C'_{10}$ | $-0.09 \pm 0.21 \pm 0.06$ | $0.4\sigma$ |
| $C_9^\tau$ | $-116 \pm 264 \pm 98$ | $0.4\sigma$ |

Global significance $1.5\,\sigma$

Largest shift w.r.t. the SM

First time measured!

Systematic uncertainty dominated by $\mathcal{B}(B^0 \to J/\psi K^{*0})$, used in the overall scale of the local and non-local amplitudes.

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

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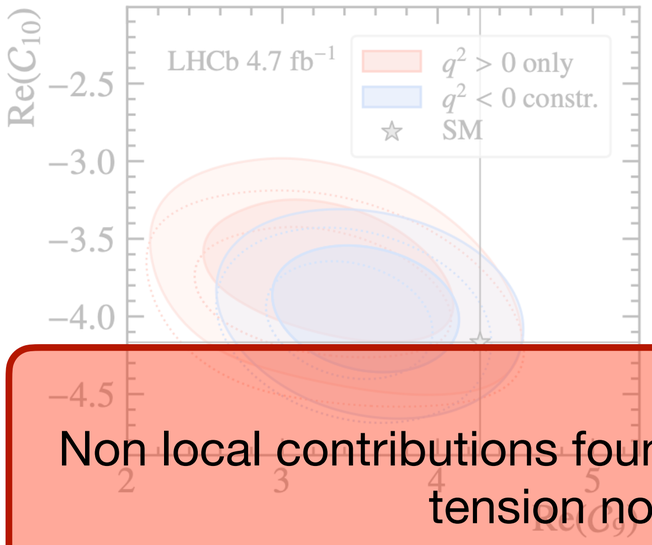


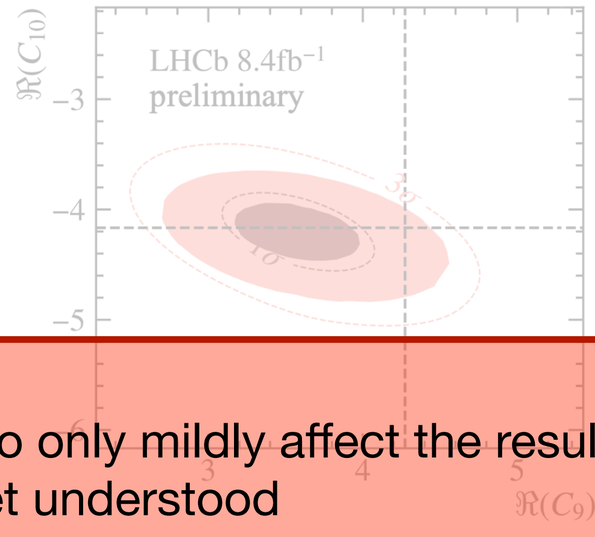


Non local contributions found to only mildly affect the results, tension not yet understood

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# Today

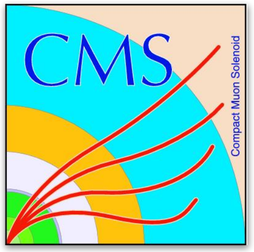



$B^0 \to K^{*0}\mu^+\mu^-$

[Phys. Rev. Lett. 132 (2024) 131801]
[Phys. Rev. D 109 (2024) 052009]
[LHCb-PAPER-2024-011, in preparation]

$B^\pm \to K^\pm \ell^+\ell^-$

[arXiv:2401.07090]
[Phys. Rev. Lett. 131 (2023) 051803 ]
[Phys. Rev. D 108 (2023) 032002]






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

[Phys. Lett. B 842 (2023)]
[Phys. Rev. D105 (2022)]
[Phys. Rev. Lett. 128, (2022)]
[JHEP09(2023)199]

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

[arXiv:2404.03375]

# Ratios of $\mathscr{B}(B^{\pm} \to K^{\pm}\ell^{+}\ell^{-})$

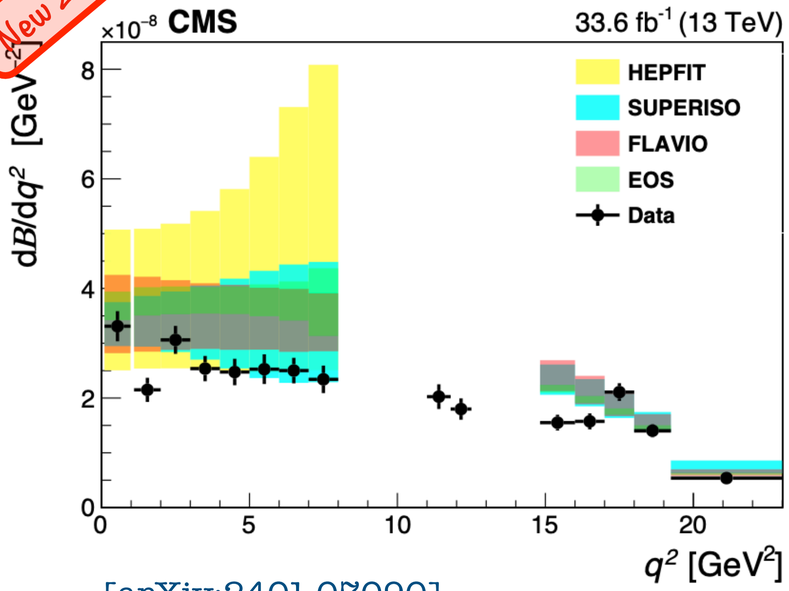
- **Robust test of Lepton Flavour Universality**
- LHCb's double determination in the $K$ and $K^*$ modes is leading in precision
  - Extensive checks with single $r_{J/\psi}$ ratio, $R(\psi(2S))$ double ratio and numerous data/MC corrections
- **New CMS analysis** (with B-parking data):
  - Similar extensive crosschecks, using same two control regions, $J/\psi$ and $\psi(2S)$
  - Muon mode used to also extract differential branching ratio

$$R_{H_s} \equiv \frac{\mathcal{B}(B^+ \to H_s\mu^+\mu^-)}{\mathcal{B}(B^+ \to H_s e^+e^-)} \Big/ \frac{\mathcal{B}(B^+ \to H_s J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to H_s J/\psi(\to e^+e^-))}$$

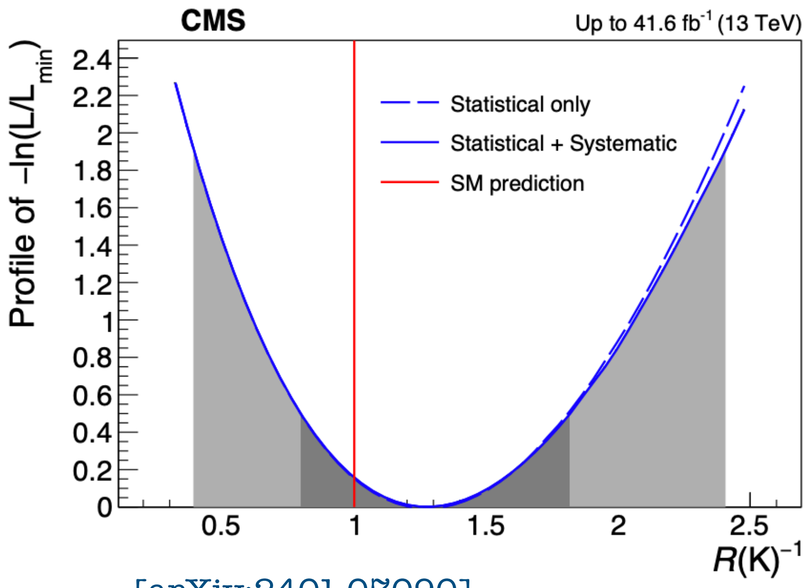
LFU test compatible with SM

$\mathrm{d}B/\mathrm{d}q^2$ systematically below theory predictions

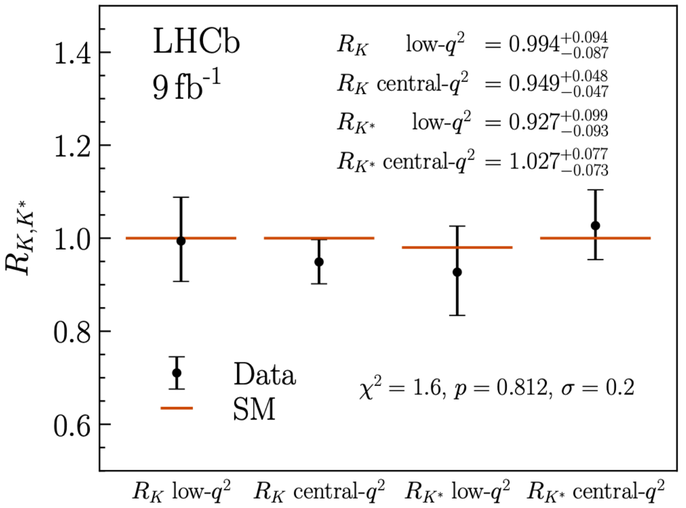
New 2024!




[arXiv:2401.07090]




[arXiv:2401.07090]

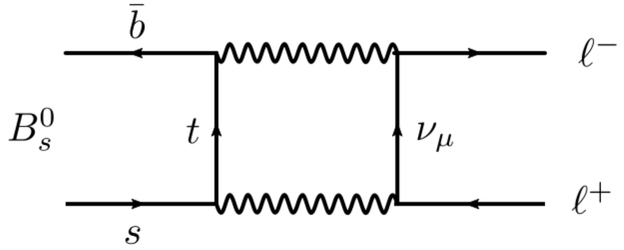



[Phys. Rev. Lett. 131 (2023) 051803 ]
[Phys. Rev. D 108 (2023) 032002]

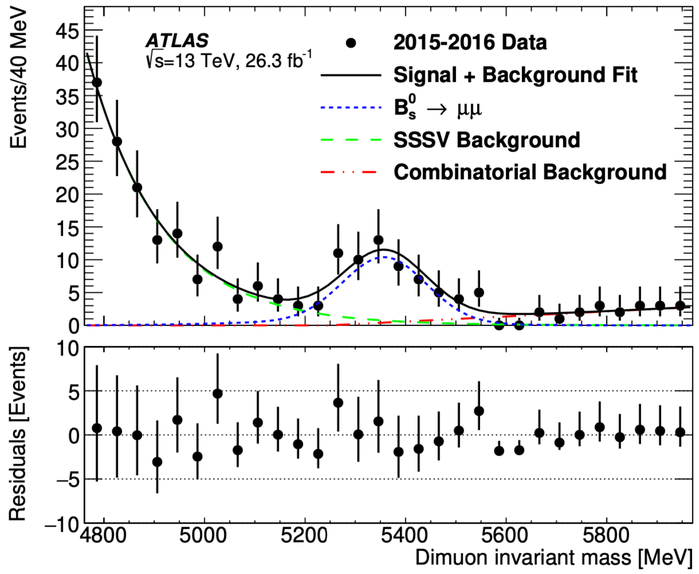
# Fully leptonic: $B_s^0 \to \mu^+\mu^-$

- Only **hadronic** contributions from the **decay constants**, $f_{B_{(s)}}$ : **well known from the lattice**

- Effective lifetime: in the SM, only the *heavy* mass eigenstate of the $B_s^0$ can decay to the $\mu^+\mu^-$ final state




[JHEP09(2023)199]

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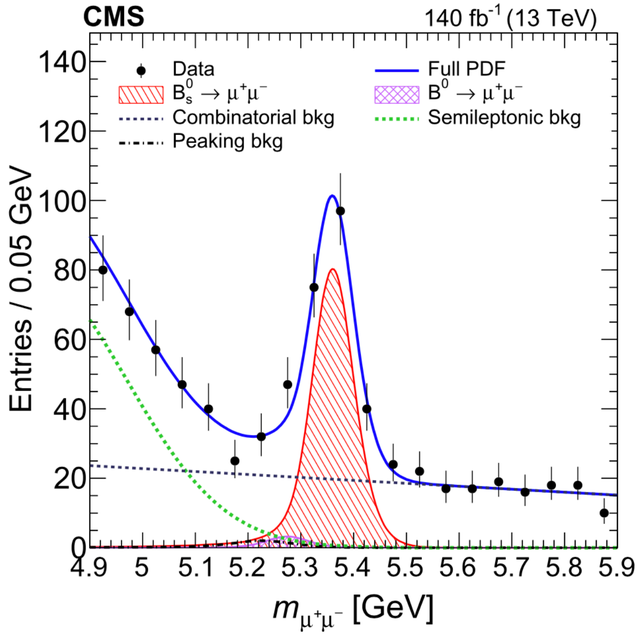


[Phys. Rev. D105 (2022)]
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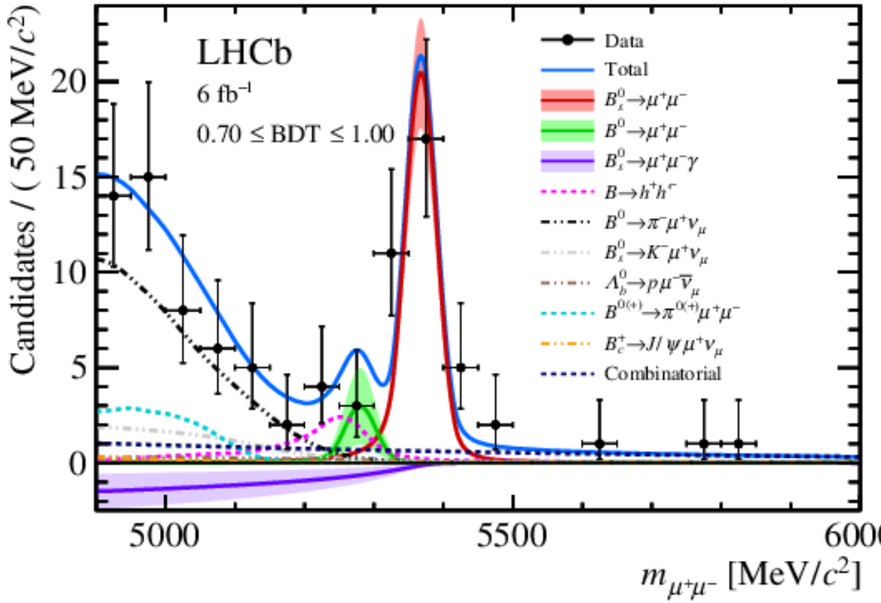
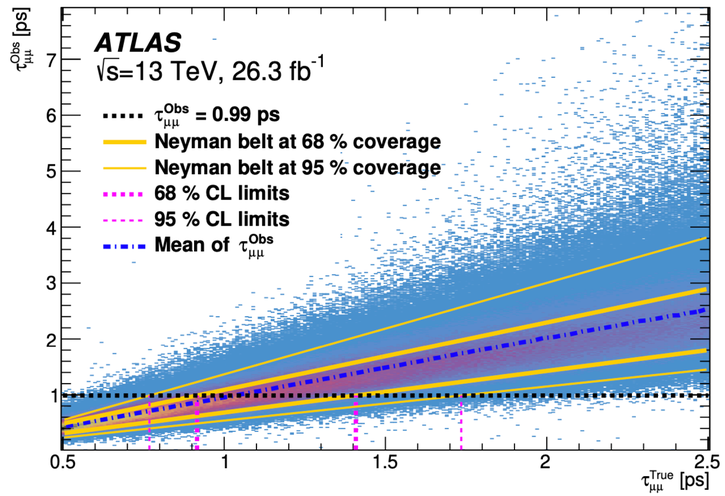


# Well behaved $B_s^0 \to \mu\mu$

- 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 $C_{10}$

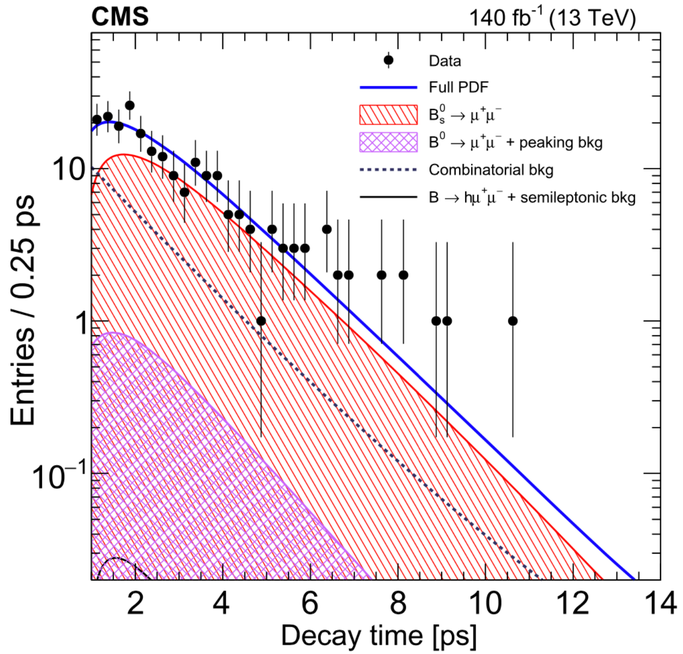
$\tau_{\mu\mu}^{\text{Obs}} = 0.99^{+0.42}_{-0.07}$ (stat.) $\pm 0.17$ (syst.) ps

[JHEP09(2023)199]



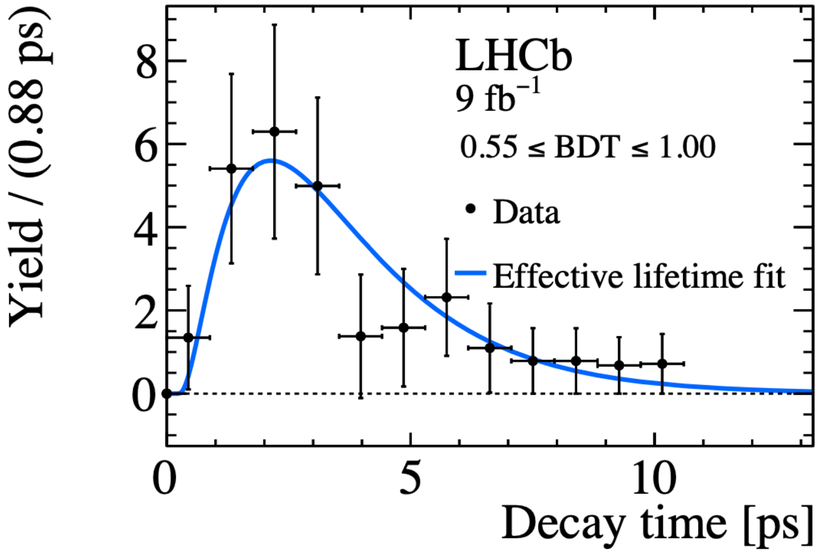

$\tau = 1.83^{+0.23}_{-0.20}$ (stat.) $\pm 0.04$ (syst.) ps

[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)]



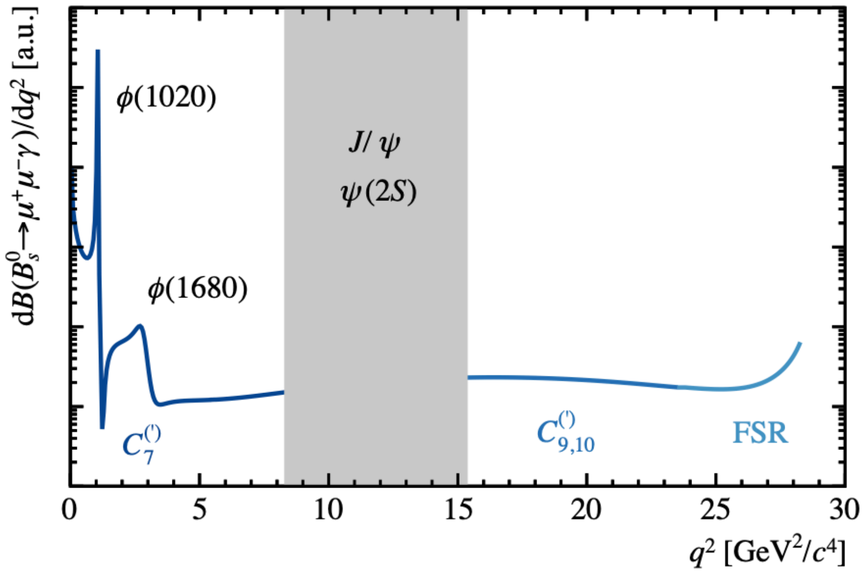
New 2024!

# A new player: $B_s^0 \to \mu^+\mu^-\gamma$

[arXiv:2404.03375]

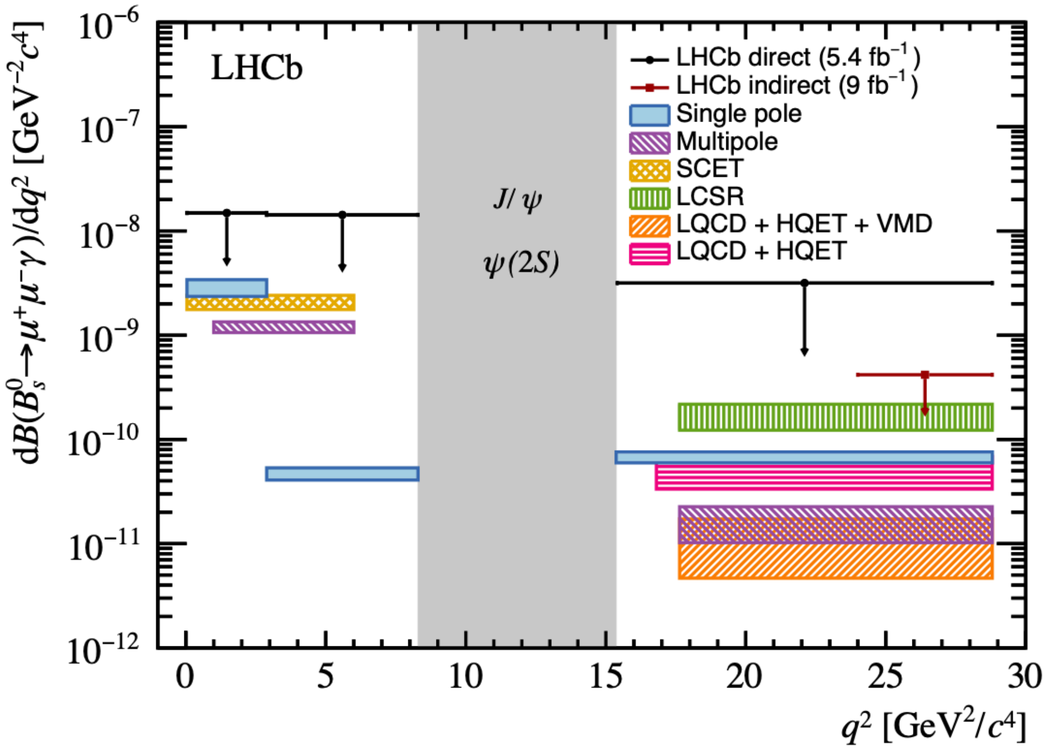
- **Sensitive to $C_7$ and $C_9$** (in addition to $C_{10}$) and **photon lifts helicity suppression** $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \sim \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$
- Poor knowledge of the $B_s^0 \to \gamma$ **form factors** and **neutral in final state** → mass resolution driven by calorimeter instead of tracking (worse for LHCb)

**Phys. Rev. D70 (2004) 114028**
**CERN-THESIS-2020-303**




Search performed with LHCb Run 2 (2016-2018) data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.8 \times 10^{-8}\,[95\,\%\ \text{CL}]$$



# Conclusions

- With **enough data** and **good analysis and interpretation** of it, we will be able to disentangle its different contributions and, hopefully, **understand them at a fundamental level.**

- First analysis of $B^0 \to K^*\mu\mu$ with full Run 1+2 data sample.
- Data prefers larger non-local contributions than the formal SM calculations, regardless of the treatment of the non-local effects.
- First direct measurement of $C_9^\tau$
- Global compatibility with the SM at 1.3 (z-expansion) and 1.5 (dispersion relation)

- First direct search of the $B_s^0 \to \mu^+\mu^-\gamma$ decay, sensitive to $C_7$, $C_9$ and $C_{10}$

- $B_s^0 \to \mu\mu$ branching ratio compatible with SM
- Effective lifetime measurements getting as precise as $\Delta(\tau_H, \tau_L)$

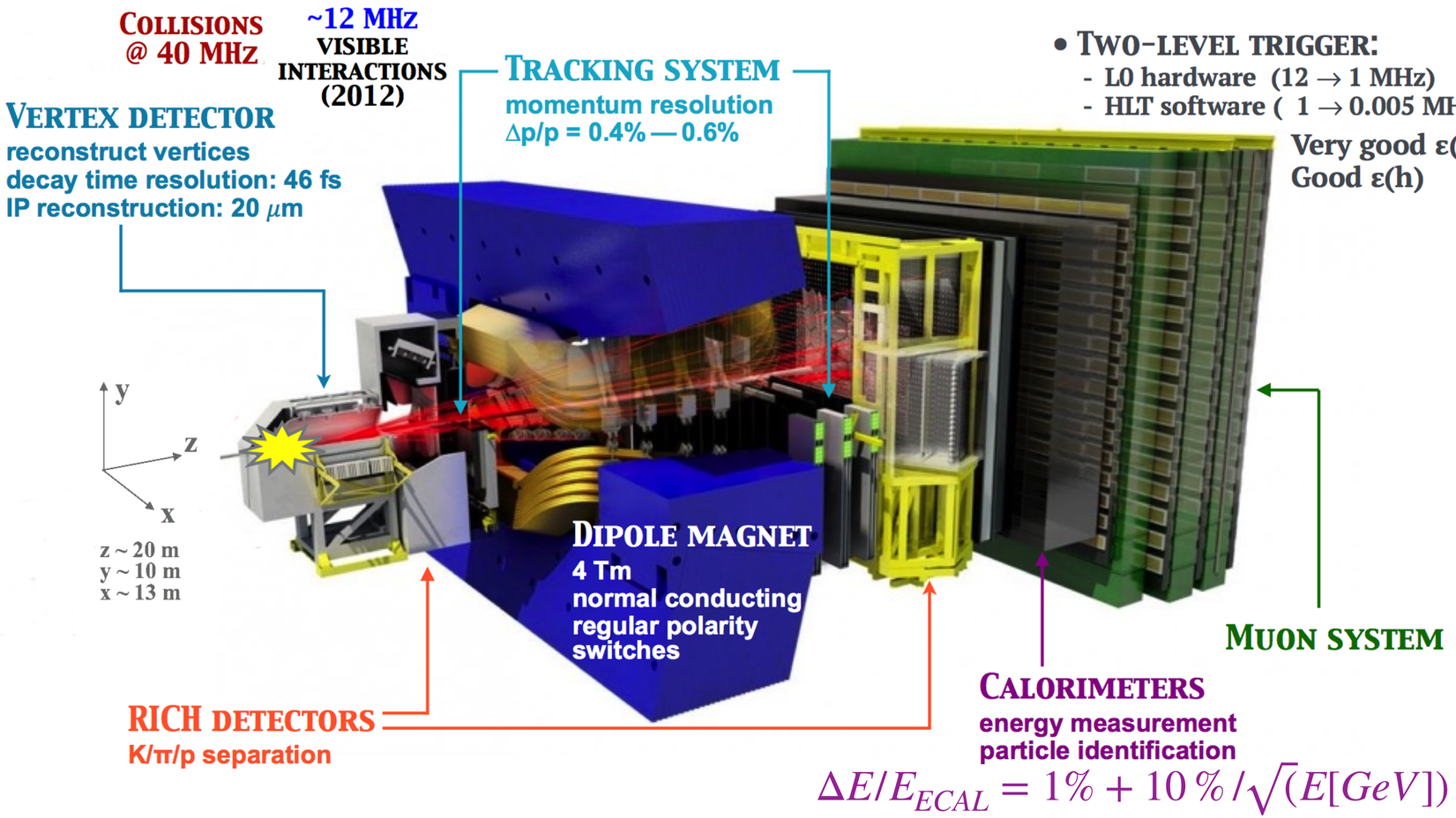
- LFU ratios ($e/\mu$) in agreement with the SM
- $B^0 \to K\mu\mu$ differential branching ratio systematically below SM in the low $q^2$ region

➡**Keep working** on squeezing the available data and on **increasing the available data samples**!


DETAILS

# The LHCb detector*

- ✓ Excellent tracking and vertexing
- ✓ Excellent Particle identification
- ✓ Very good momentum resolution
- ✴ Complicated geometry
  - ✴ Not hermetic



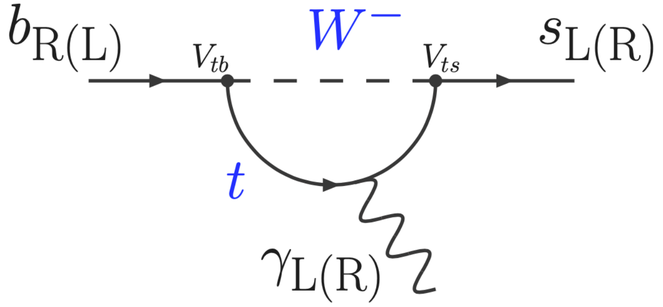

LHCb Detector Performance

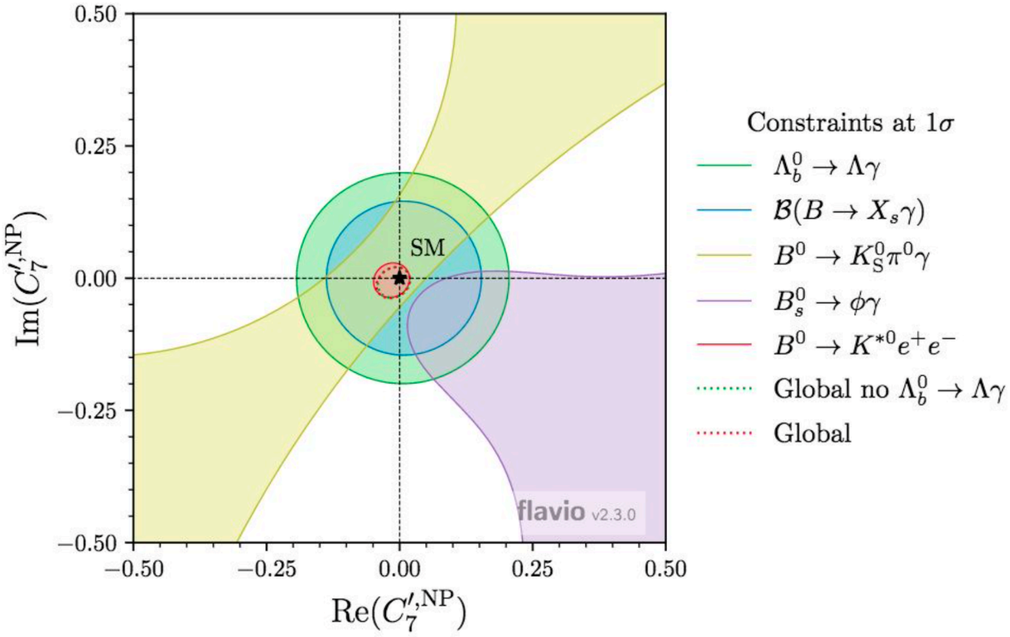
International Journal of Modern Physics A
Vol. 30, No. 7 (2015) 1530022

*Runs 1&2 Edition

# More on $C_7^{(\prime)}$?

- **The territory of the radiative penguins**
- **Radiative decays:** described with a single operator! **(clean)**
  - $\mathscr{H}_{eff} \propto V_{ts}^* V_{tb}(C_7 O_7 + C_7' O_7')$
  - Right-handed currents very suppressed in the SM: $C_7' \propto \frac{m_s}{m_b} C_7$
  - Photon polarisation: $\lambda\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$, constrained by
    - Time-dependent analysis of $B_s^0 \to \phi\gamma$ **arXiv:1905.06284**
    - Self-analysing decay of the $\Lambda_b^0 \to \Lambda\gamma$ **arXiv:2111.10194**
    - [virtual photon] angular $B^0 \to K^* e^+ e^-$ **arXiv:2010.06011**
  - New/updated LHCb analyses in preparation!
  - Large impact expected from Belle II




A. Paul and D. M. Straub, JHEP 04 (2017) 027 D.
M. Straub, "flavio", arXiv:1810.08132