INFN PERUGIA
Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

LHCb

Status and prospects of rare decay searches at LHCb

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On behalf of the LHCb collaboration

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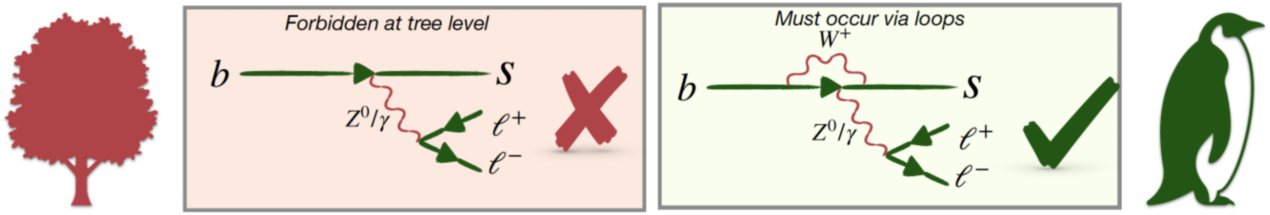
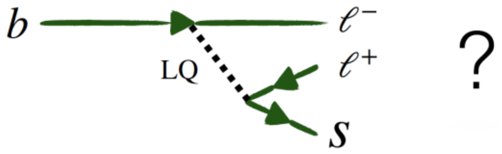
WIFAI 2024: Workshop Italiano sulla Fisica ad Alta Intensità

Why search for rare decays?

- Flavour Changing Neutral Currents (FCNC)
  - Forbidden at **tree level** in the SM
  - Allowed only at **loop level**
  - New Physics (NP) contributions may enter in loops





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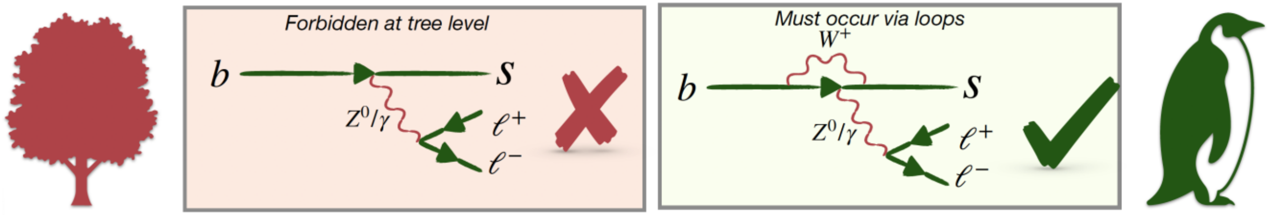

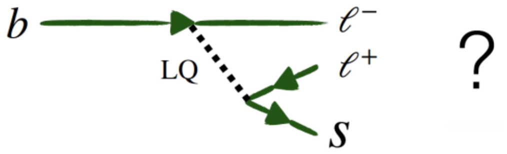

Look for deviations from SM predictions

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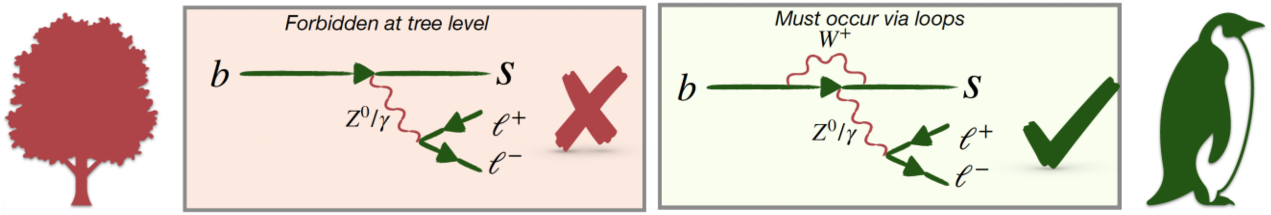
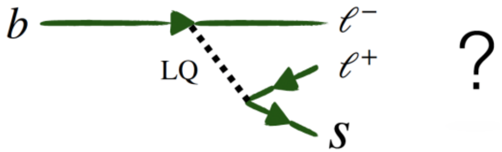
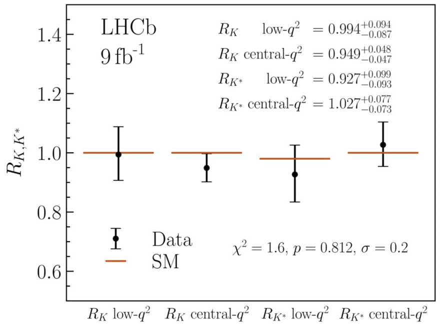


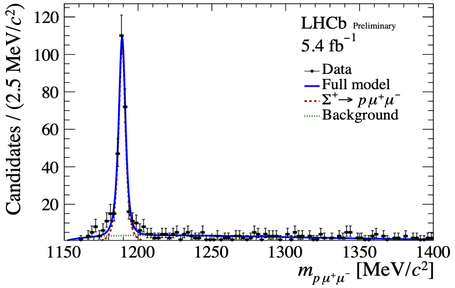


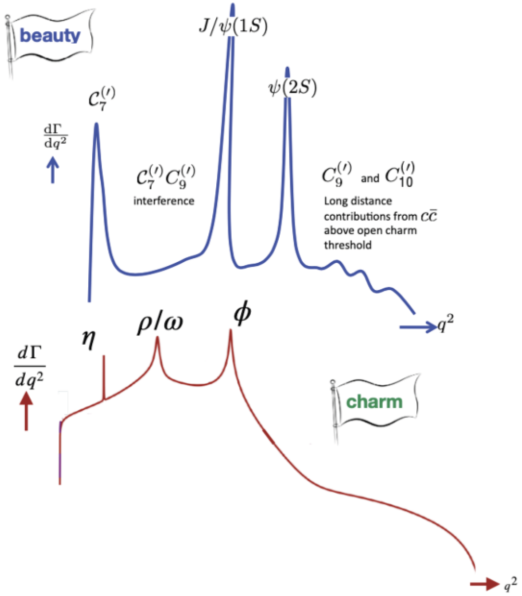
Look for deviations from SM predictions

- Exstensive programme at *LHCb*
  - Search for (very) rare or forbidden modes
  - Branching Fractions ($\mathcal{B}$) measurements
  - Amplitude and angular analyses
  - CP violation
  - Null tests in the SM

https://lbfence.cern.ch/alcm/public/analysis





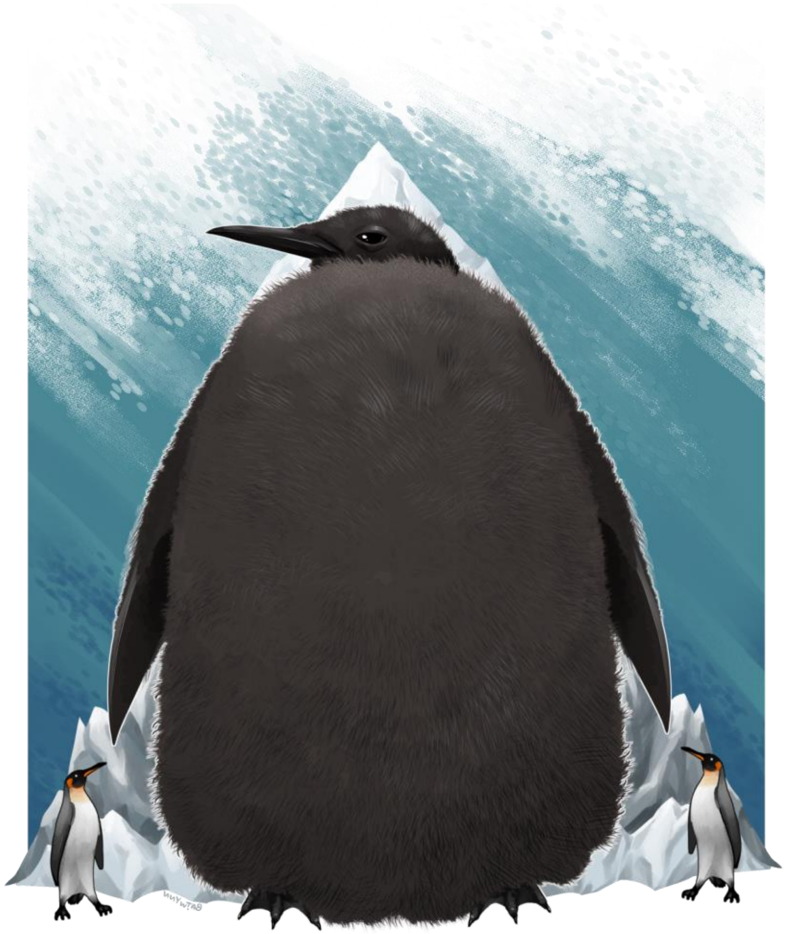


Today’s talk – New results

- **Amplitude measurements in *B* decays**
  - *"Amplitude analysis of the radiative decay $B_s^0 \to K^+K^-\gamma$"* [JHEP 08 (2024) 093]
  - *"Comprehensive analysis of local and non local amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay"* [JHEP 09 (2024) 026]

- **Null tests in *B* decays: LFU and LFV**
  - LFU - *"Test of lepton flavour universality with $B_s \to \phi_{(\to K^+K^-)}\ell^+\ell^-$ decays"*
    [arXiv:2410.13748]
    "Test of lepton flavour universality with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays"
    [LHCb-PAPER-2024-046] – Paper in preparation
  - LFV – *"Search for the lepton-flavor violating decay $B_s^0 \to \phi\mu^\pm\tau^\mp$"*
    [arXiv:2405.13103]

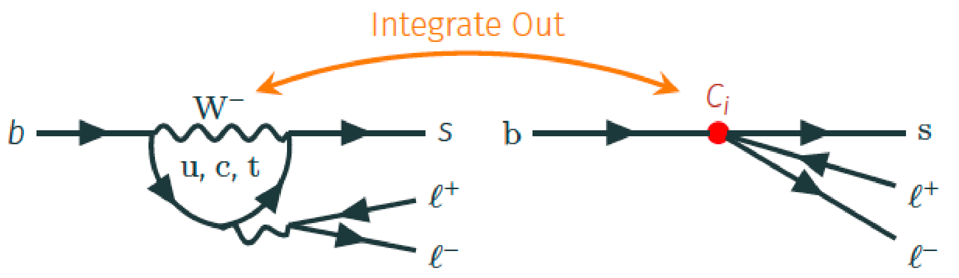
- **Rare charm and strange decays**
  - *"Search for the rare decay of charmed baryon Λ_c^+ into the $p\mu^+\mu^-$ final state"* [PRD 110 (2024) 5, 052007]
  - *"Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb"* [LHCb-CONF-2024-002]



Amplitude measurements in B decays

Studying $b \to s\ell^+\ell^-$ transitions

- Effective Field Theory (EFT)
  - **Short distance physics** parametrised via effective couplings



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

Wilson Coefficients C_i
- Perturbative, short distance physics
- Describes heavy SM+NP effects

Operators $\mathcal{O}_i$
- Non-perturbative, long distance physics
- Strong interactions, difficult to calculate

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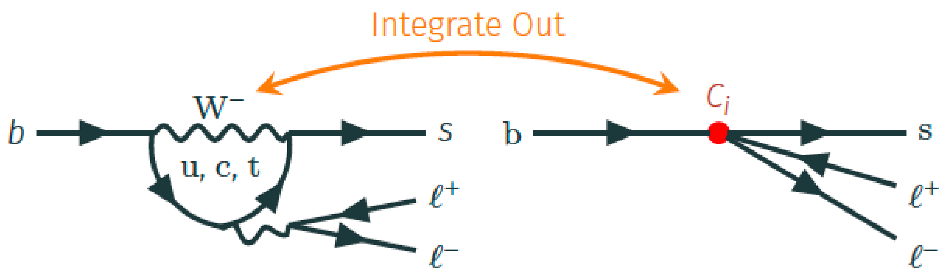

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Operators $\mathcal{O}_i$
- Non-perturbative, long distance physics
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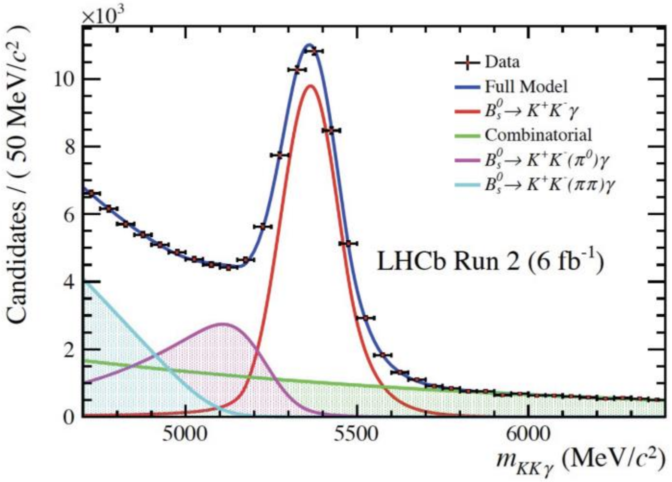
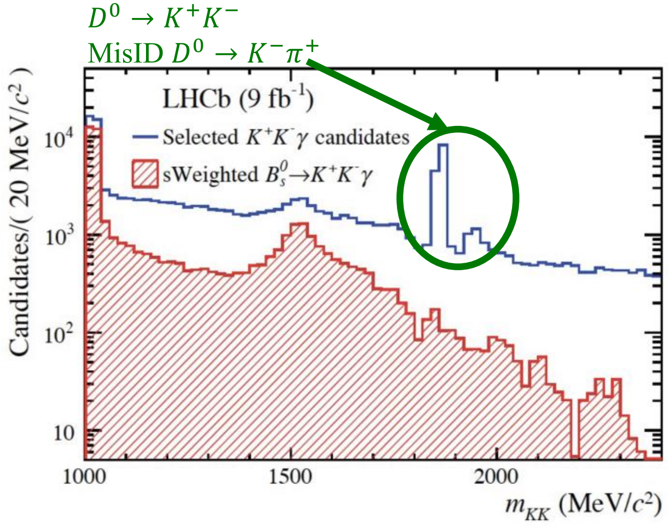
- RD mostly sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$

Operator $\mathcal{O}_i$	$B_{s(d)} \to V_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to V_{s(d)}\gamma$
$\mathcal{O}_7$ EM	✓		✓
$\mathcal{O}_9$ Vector dilepton	✓		
$\mathcal{O}_{10}$ Axial-vector dilepton	✓	✓	
$\mathcal{O}_{S,P}$ (Pseudo-)Scalar dilepton	(✓)	✓	

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

- *"Amplitude analysis of the radiative decay $B_s^0 \to K^+K^-\gamma$"*
  - $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 9.0\ \text{fb}^{-1}$
  - [JHEP 08 (2024) 093]
- Nice features
  - Free of the S-wave amplitude
  - Interferences of odd- and even-spin resonances cancel out
  - Detector asymmetries cancelled out by folding over θ_{KK}
    $\cos\theta_{KK} \to |\cos\theta_{KK}|$





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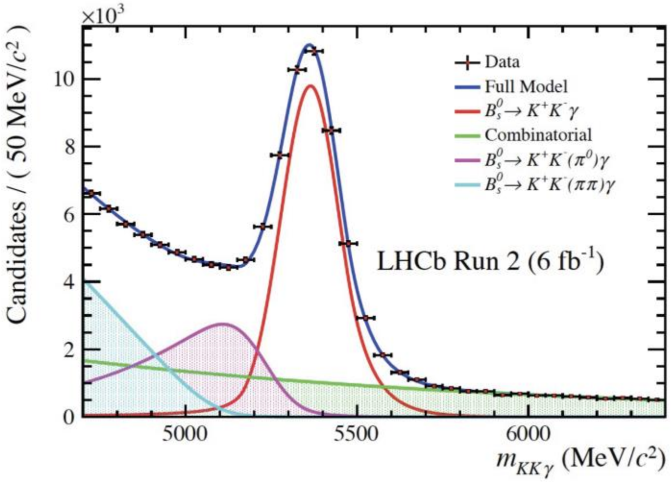
    $\cos\theta_{KK} \to |\cos\theta_{KK}|$

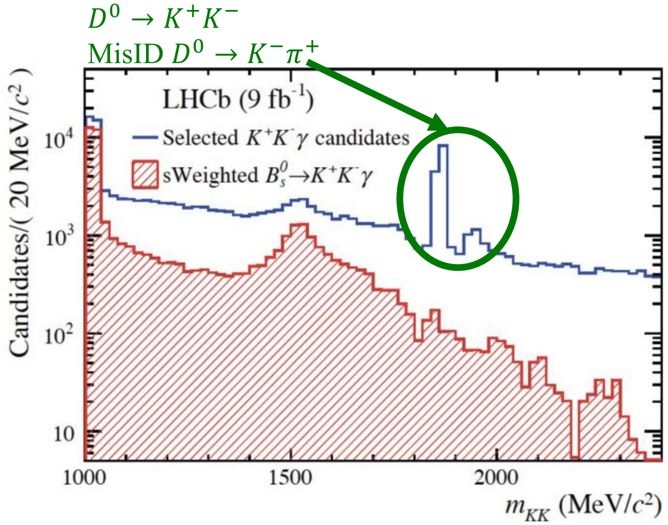
- Amplitude fit

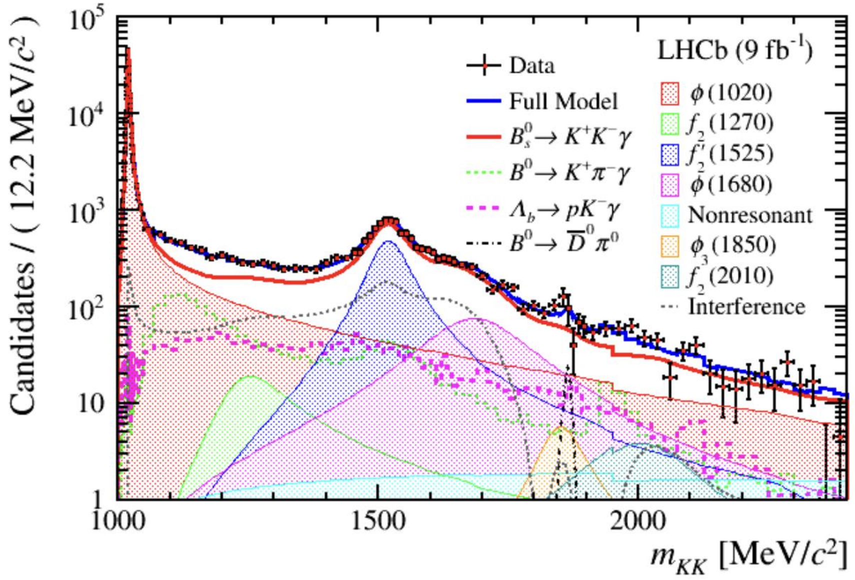
$$\mathcal{P}_s(m_{KK}, \theta_{KK}) = \varepsilon(m_{KK}, \theta_{KK}) \cdot \left|\sum_R c_R \cdot \mathcal{F}_R \mathcal{F}_B \mathcal{BW}_R(m_{KK}; \mu_R, \Gamma_R) \cdot d_{10}^{J_R}(\vartheta_{KK})\right|^2$$

PDF — Acceptance — Isobar KK model

20 free parameters
- Yields, isobar factors, phases
- $\phi(1020), f_2'(1525)$ - mass and width
- $\phi(1020)$ - radius







Results on $B_s^0 \to K^+K^-\gamma$

➤ Fit fractions, relative $\mathcal{B}$ and overall tensor contribution reported for the preferred fit solution

State	Fit fraction [%]	Relative fit fraction [%]	Phase [deg.]
$\phi(1020)$	$70.3^{+0.9}_{-1.0}{}^{+1.0}_{-1.2}$	100	0 (fixed)
$f_2(1270)$	$0.8\pm0.3^{+0.2}_{-0.3}$	$1.2^{+0.4}_{-0.3}{}^{+0.3}_{-0.5}$	$-55^{+13}_{-17}{}^{+25}_{-17}$
$f_2'(1525)$	$12.1^{+0.6}_{-0.5}{}^{+0.9}_{-0.4}$	$17.3^{+0.8}_{-0.7}{}^{+1.3}_{-0.5}$	0 (fixed)
$\phi(1680)$	$3.8^{+0.6}_{-0.5}\pm0.7$	$5.4^{+0.9}_{-0.6}{}^{+1.0}_{-1.1}$	$137^{+5}_{-6}\pm8$
$\phi_3(1850)$	$0.3^{+0.2}_{-0.1}{}^{+0.2}_{-0.1}$	$0.4^{+0.3}_{-0.2}{}^{+0.3}_{-0.2}$	$-61^{+16}_{-13}{}^{+13}_{-12}$
$f_2(2010)$	$0.4\pm0.2^{+0.2}_{-0.1}$	$0.6^{+0.3}_{-0.2}{}^{+0.3}_{-0.2}$	$43^{+30}_{-24}{}^{+52}_{-59}$
$(KK)_{NR}$	$0.5^{+0.4}_{-0.2}{}^{+0.3}_{-0.2}$	$0.6^{+0.5}_{-0.3}{}^{+0.5}_{-0.3}$	$165^{+6}_{-16}\pm9$

$$\mathcal{F}_{\{f_2\}} = 16.8 \pm 0.5\,(\text{stat}) \pm 0.7\,(\text{syst})\%,$$

$$\frac{\mathcal{B}(B_s^0 \to f_2'(1525)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.194^{+0.009}_{-0.008}\,(\text{stat.})^{+0.014}_{-0.005}\,(\text{syst.}) \pm 0.005\,(\mathcal{B})$$

$$\frac{\mathcal{B}(B_s^0 \to f_2(1270)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.25^{+0.09}_{-0.07}\,(\text{stat.})^{+0.06}_{-0.10}\,(\text{syst.}) \pm 0.03\,(\mathcal{B}),$$

$$\frac{\mathcal{B}(B_s^0 \to \phi(1680)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} \times \mathcal{B}(\phi(1680) \to K^+K^-) = 0.026^{+0.004}_{-0.003}\,(\text{stat.}) \pm 0.005\,(\text{syst.}).$$

➤ Conclusions

- **First amplitude analysis** of the dikaon resonant structure in $B_s^0 \to K^+K^-\gamma$ decay
  - ✓ $m_{KK} = 2400\ \text{MeV}/c^2$
- **First observation** of the radiative $B_s^0 \to f_2'(1525)\gamma$ decay

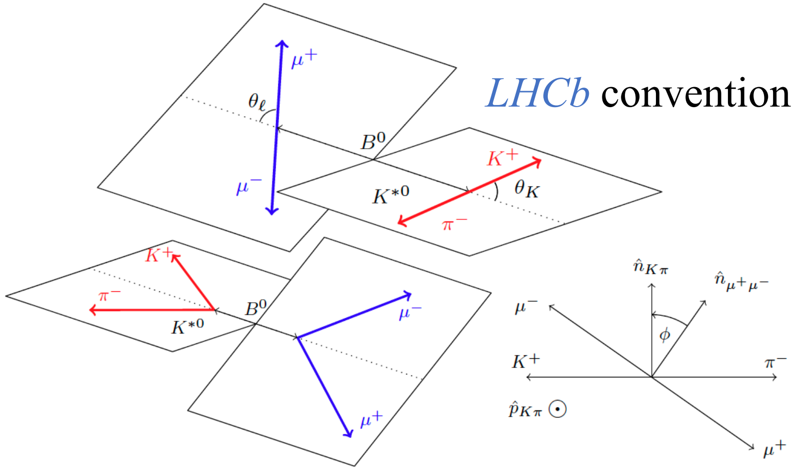
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

- Phase space described by θ_ℓ, θ_k, ϕ, $m_{K\pi}$ and $q^2 = m^2(\mu^+\mu^-)$

$$\frac{d\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) g_i(m^2_{K\pi})$$

Angular observables (J_i) → $P'_5 = \frac{J_5}{2\sqrt{-J_{2c}J_{2s}}}$ Less affected by theoretical uncertainties

Angular distributions (f_i)



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$$P_5' = \frac{J_5}{2\sqrt{-J_{2c}J_{2s}}}$$

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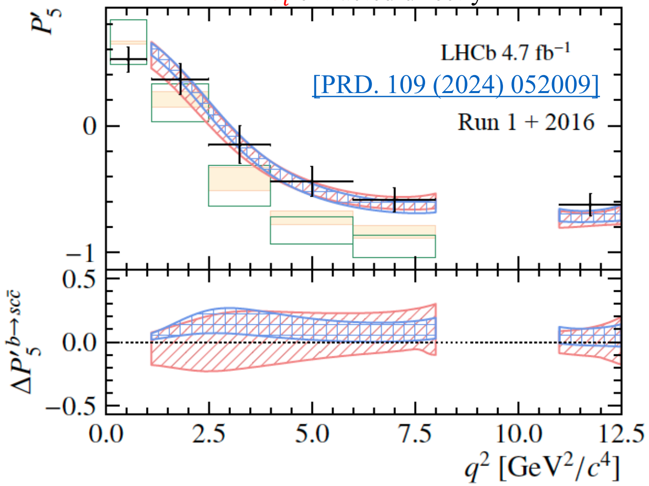
Angular observables

$$\frac{d\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega} dm_{K\pi}^2} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) g_i(m_{K\pi}^2)$$

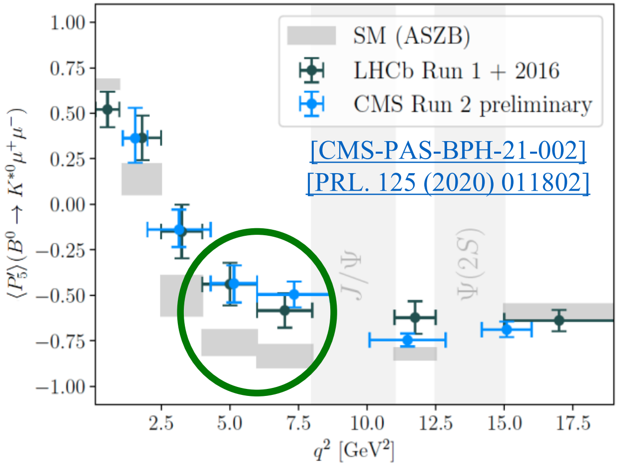
Angular distributions

- Long standing tensions with the SM

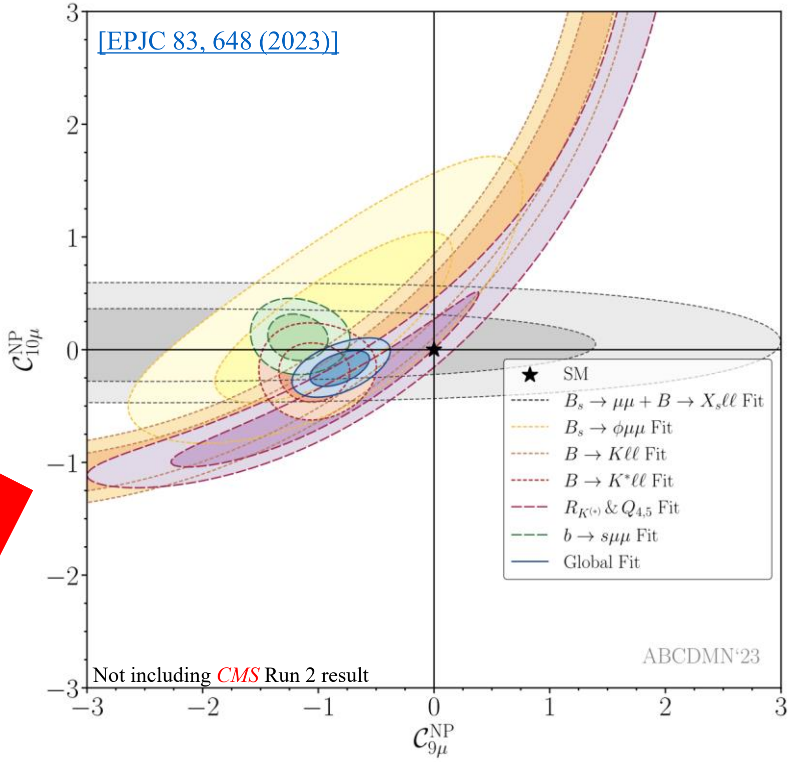
Model dependence
NL contributions modelled by polynomial expansion
C_i extracted directly



Model-independence
Observables measured in bins of q^2 and translated into C_i



Shift in C_9 favoured ($\sim 4\sigma$)



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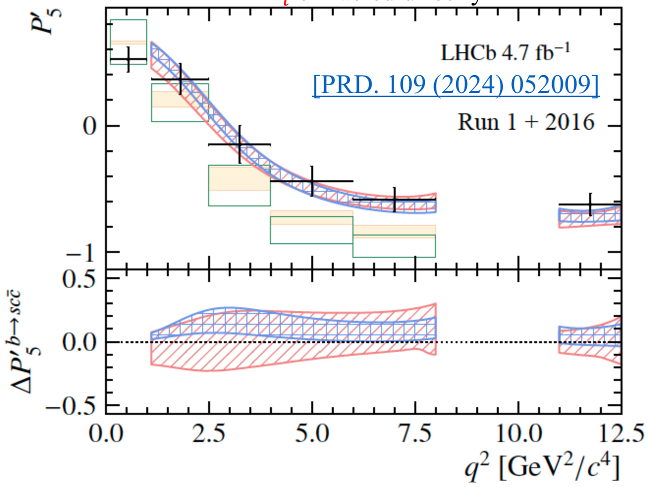

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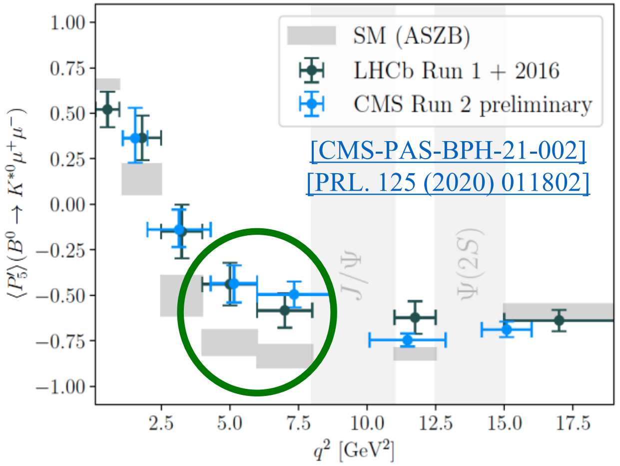

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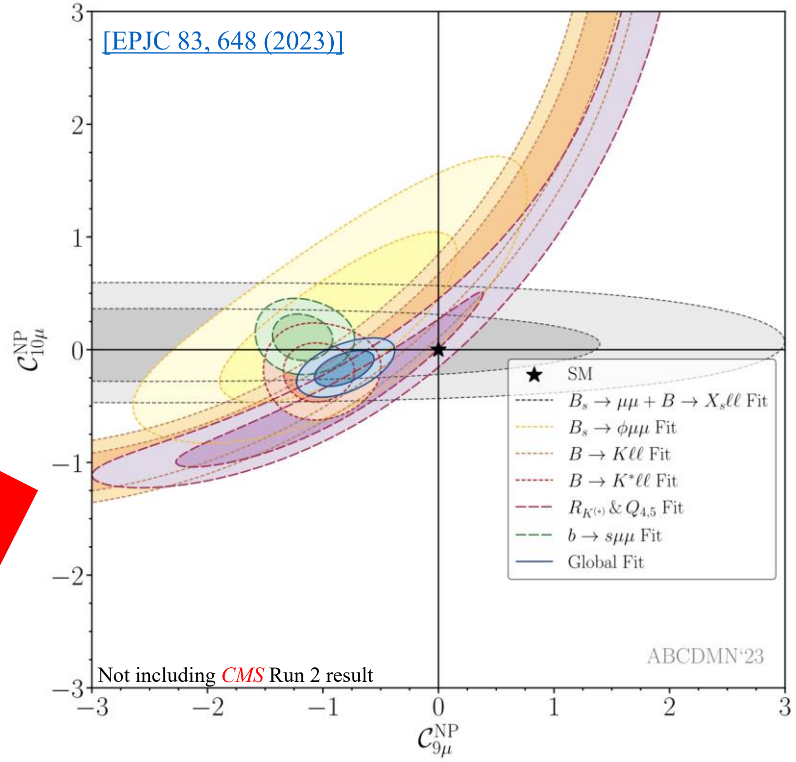


Intepretation of the anomaly

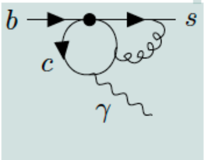
NL contribution from $c\bar{c}$ resonances impact the rare mode regions
NP or underestimated SM QCD?
Amplitude analysis to separate local and non-local contributions

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

- *"Comprehensive analysis of local and non local amplitudes in the $B_0 \to K^{*0}\mu^+\mu^-$ decay"*
  - $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 8.4\ \text{fb}^{-1}$
  - [JHEP 09 (2024) 026]
- Non-local effects described as corrections to C_9

$$C_9^{eff,\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0)}(q_0^2) + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{eff,\lambda} = C_7 + \zeta^{\lambda} e^{i\omega^{\lambda}}$$



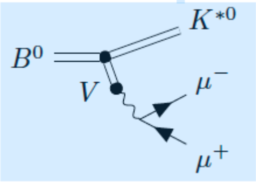
C_7 vertex correction

Polarisation dependent shift to C_7

Determined theoretically at negative q^2

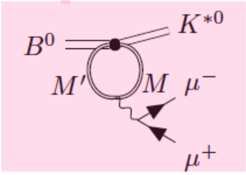
Constant term

Negligible impact from light quarks
[JHEP 04 (2020) 012]



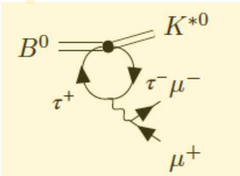
1-particle contributions

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



2-particle contributions

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

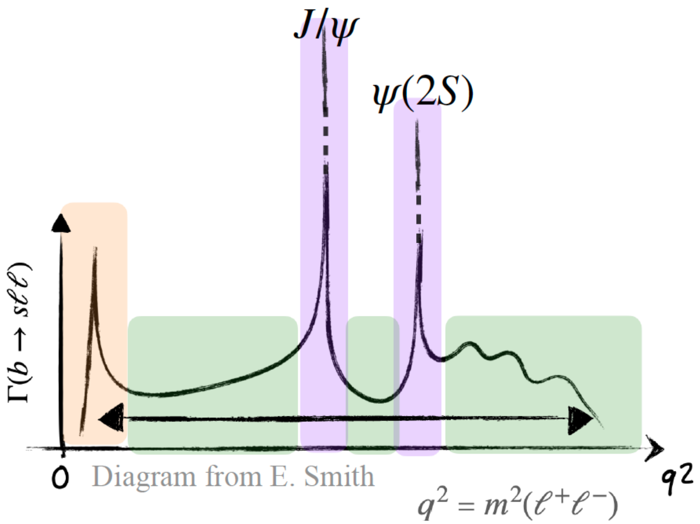


$B^0 \to K^{*0}\tau^+\tau^-$ contribution

Sensitive to C_9^{τ}
[EPJC 80 (2020) 12, 1095]

High model dep.

Full q^2 spectrum parametrised
- Wilson coefficients
- Form factors
- Non-local contributions



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

- Unbinned maximum likelihood fit to the four-dimensional distribution
  - $\cos\theta_\ell, \cos\theta_K,\ \phi$ and q^2

Signal fractions — Differential decay rate — Acceptance — Resolution — Combinatorial background

$$\mathscr{P}^i_{Tot}(\overline{\Omega}, q^2) = f^i_{sig}\Big((\mathscr{P}_{sig}(\overline{\Omega}, q^2) \times \epsilon(\overline{\Omega}, q^2)) \circledast R^i(q^2)\Big) + (1 - f^i_{sig})\mathscr{P}_{bkg}(\overline{\Omega}, q^2)$$

High model dep.

Simulation
- Acceptance

Data
- Resolution
- Background model

Theory
- Local $B^0 \to K^{*0}$ form factors
- Gaussian constrained

150 parameters determined in fit

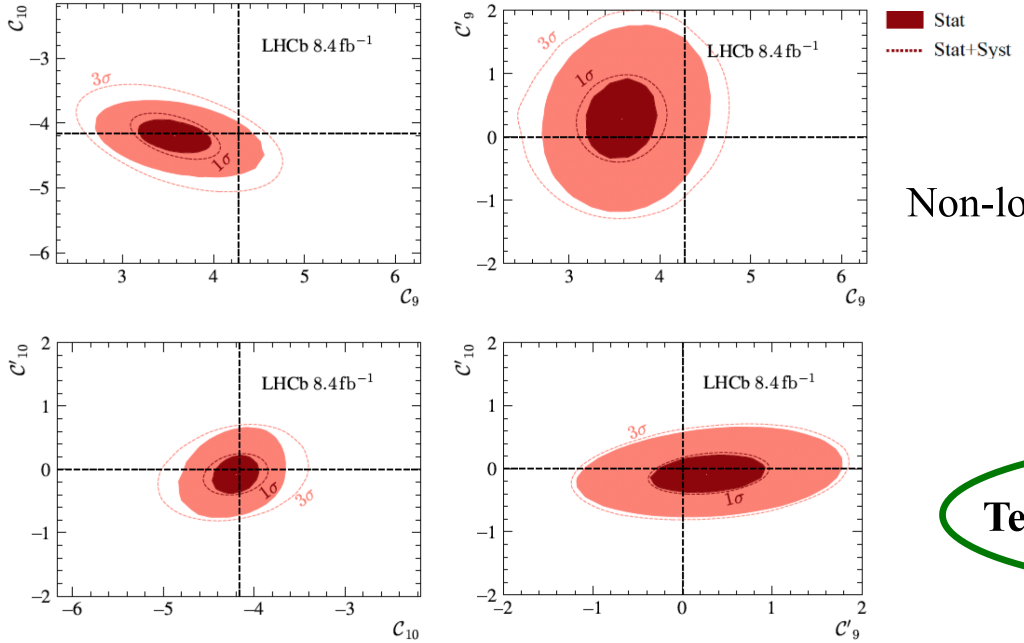
- $\mathscr{R}(C_9)$, $\mathscr{R}(C_{10})$, $\mathscr{R}(C_9')$, $\mathscr{R}(C_{10}')$, $\mathscr{R}(C_9^\tau)$
- Mag. & phase of 1P contributions
- Real & Imag. of $D^{(*)}\bar{D}^{(*)}$ per helicity
- ΔC_7 per helicity
- Form Factors

Results from the amplitude fit

High model dep.

- **Wilson coefficients**
  - Global significance of $\mathbf{1.5\sigma}$
  - Largest local deviation in C_9 at $\mathbf{2.1\sigma}$
  - **First** direct measurement of $C_{9\tau}$

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



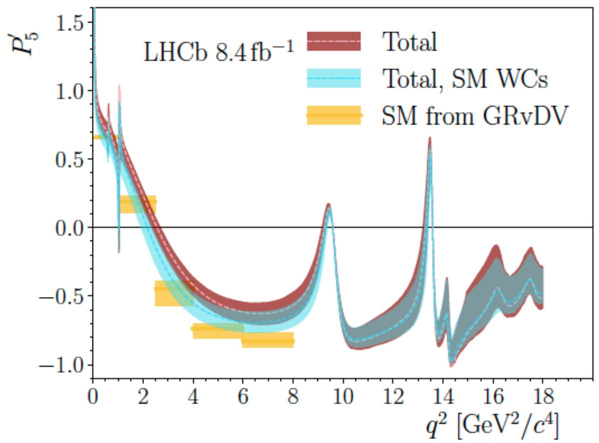
Non-local contributions larged than expected
C_9 still shifted down from C_9^{SM}
More data needed

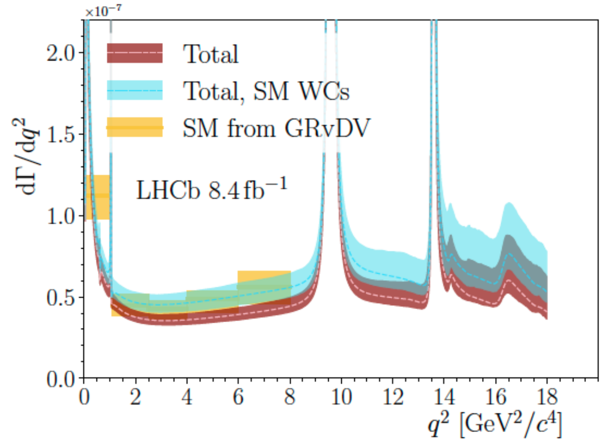
Tension still persist in observables

- **New** limit on $\mathcal{B}$ at 90% CL
  - From measurement of $C_{9\tau}$
  - Assuming value of $C_{10\tau}$

$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \sim [0.8 - 2.5] \times 10^{-3}$

Best 90% limit from direct measurements by Belle
$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \sim 3.1 \times 10^{-3}$
[Phys. Rev. D108 (2023) L011102]



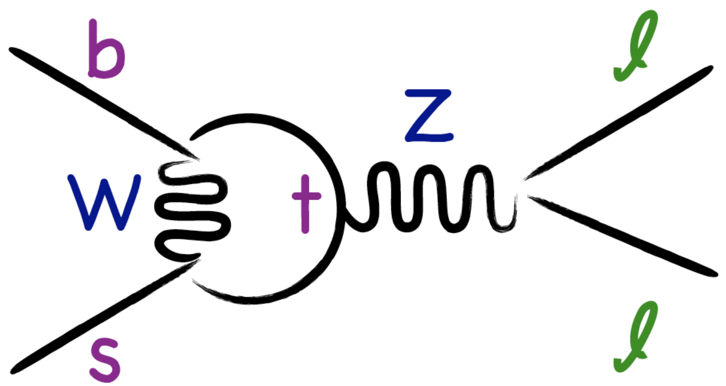


Null tests in B decays
LFU and LFV

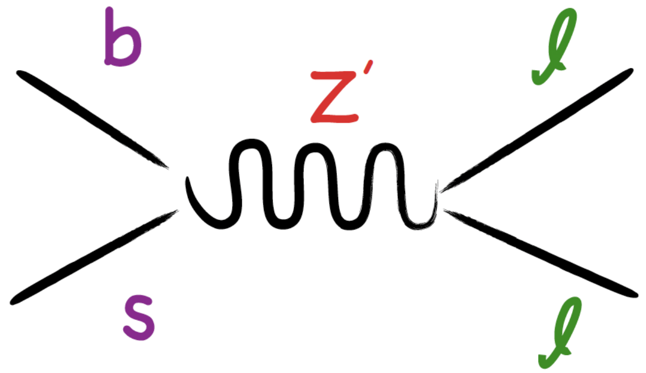
Lepton Flavour Universality

- $b \to s\ell^+\ell^-$ transitions happen only via **loop** or **boxes**
  - $\mathcal{B} \sim 10^{-7} - 10^{-6}$
  - Used to test the Lepton Flavour Universality (LFU) in the SM
  - Non-LFU physics mediators may contribute in the amplitudes

Neutral Current



New Physics

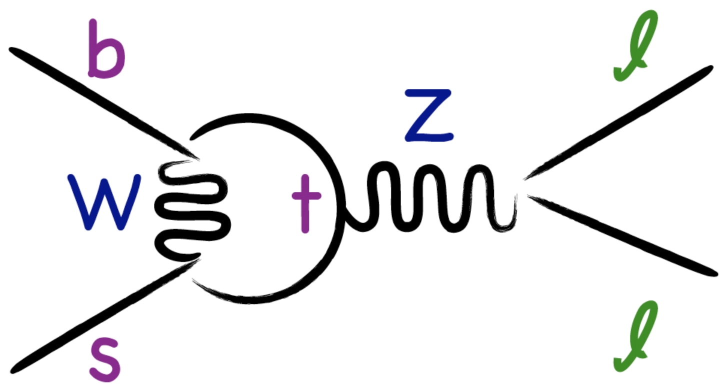


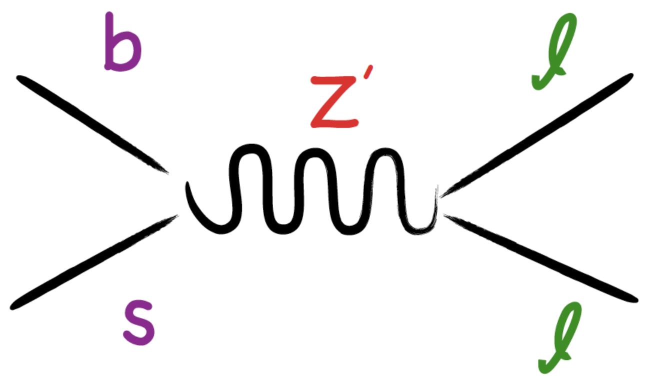
Lepton Flavour Universality

- $b \to s\ell^+\ell^-$ transitions happen only via **loop** or **boxes**
  - $\mathcal{B} \sim 10^{-7} - 10^{-6}$
  - Used to test the Lepton Flavour Universality (LFU) in the SM
  - Non-LFU physics mediators may contribute in the amplitudes
- LFU test by measuring relative rates
  - Hadronic uncertainties cancels out
  - Predicted with very high precision by the SM

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

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathcal{B}(B \to Xe^+e^-)}{dq^2} dq^2} \overset{\text{SM}}{\equiv} 1 \quad \text{if } m_\ell^2 \ll q^2$$

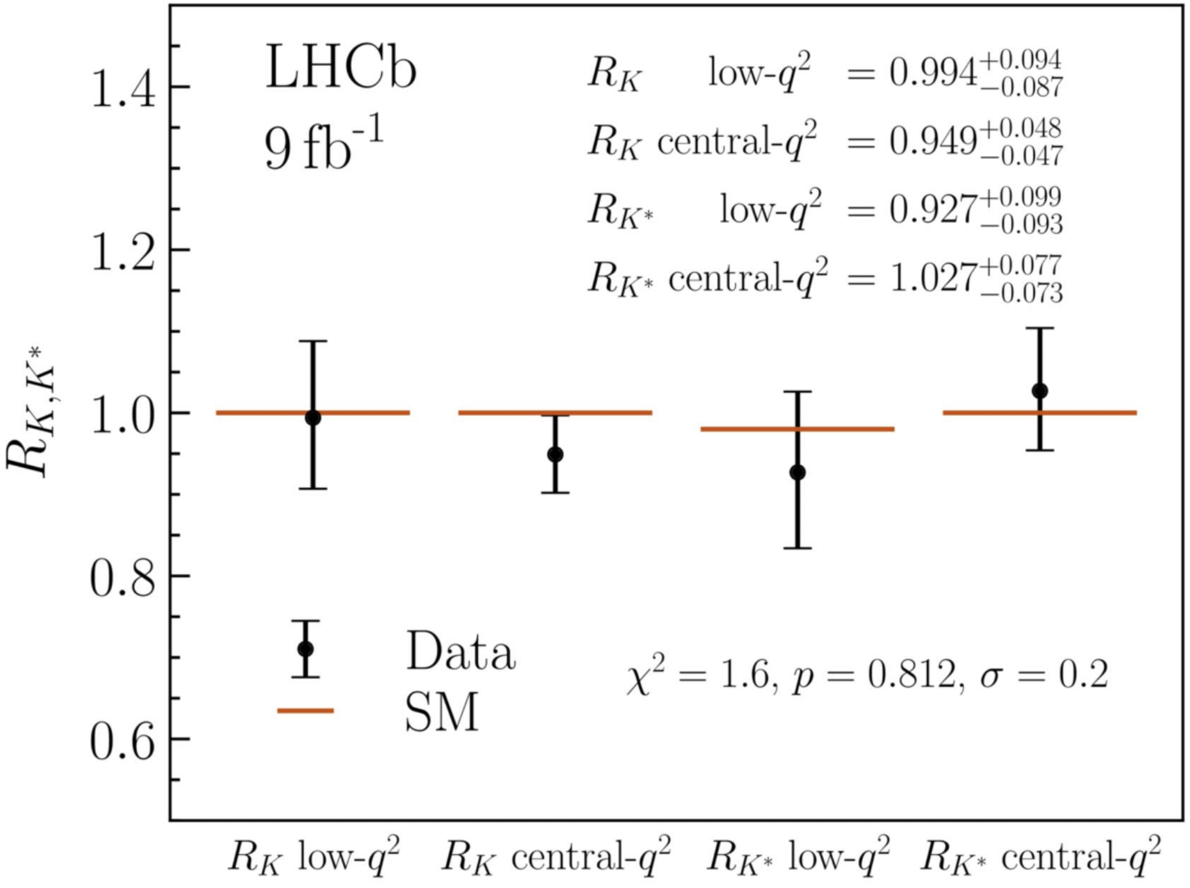




LFU at LHCb

- *LHCb* dominates the precision of LFU tests
  - Investigated different hadronic systems $X = K, K^*, pK$ ...
- Latest results
  - LFU test with $B_s \to \phi_{(\to K^+K^-)}\ell^+\ell^-$ decays
    - ✓ First LFU test with a B_s decay
    - ✓ First *LHCb* high-q^2 LFU test
    - ✓ First observation of $B_s \to \phi e^+e^-$ decay
  - LFU test with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays
    - ✓ First inclusive LFU test with 5-body decays
    - ✓ First observation of $B^+ \to K^+\pi^+\pi^- e^+e^-$

[PRD 108 (2023) 032002]



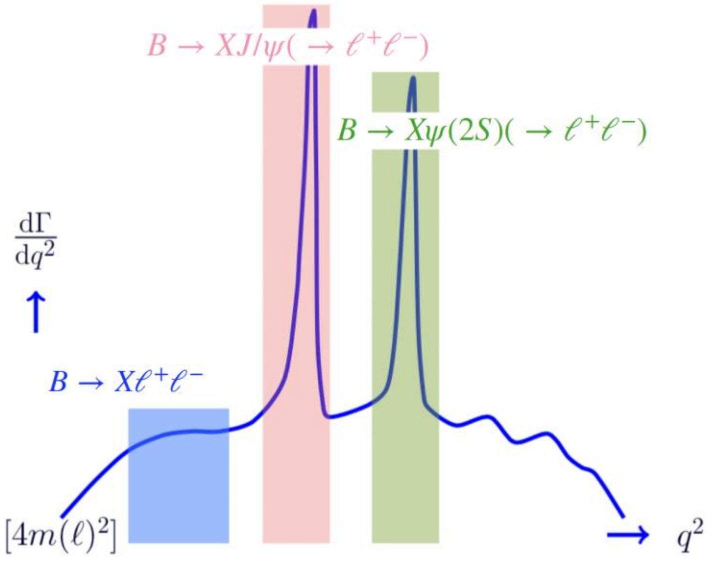
Experimental strategy

- R_X measured as double ratios
  - Mitigate e/μ reconstruction differences

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

Yields: Unbinned maximum-likelihood fits to the B invariant mass

Efficiencies: Simulation corrected for data/MC differences



- Resonant channels used for checks/data driven studies

$$r_{J/\psi} = \frac{\mathcal{B}(B\to XJ/\psi(\to\mu^+\mu^-))}{\mathcal{B}(B\to XJ/\psi(\to e^+e^-))} \equiv 1 \to \text{Sensitive to } e, \mu \text{ differences}$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B\to X\psi(2S)(\to\mu^+\mu^-))}{\mathcal{B}(B\to XJ/\psi(\to\mu^+\mu^-))} \cdot \frac{\mathcal{B}(B\to XJ/\psi(\to e^+e^-))}{\mathcal{B}(B\to X\psi(2S)(\to e^+e^-))} \equiv 1 \to \text{Efficiency related systematics cancel in double ratio}$$

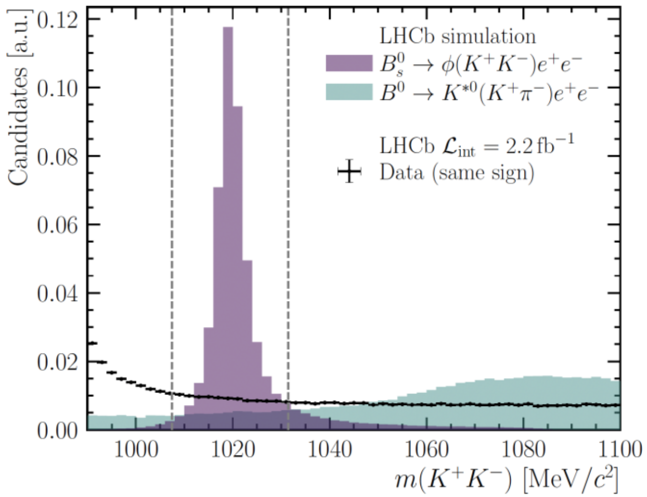
$R_\phi(X = \phi)$

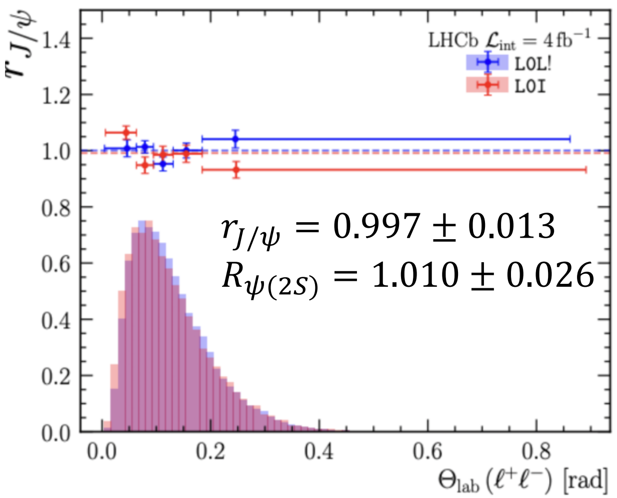
➤ *"Test of lepton flavour universality with $B_s \to \phi_{(\to K^+K^-)}\ell^+\ell^-$ decays"*

- $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 9.0$ fb^{-1}
- [arXiv:2410.13748]

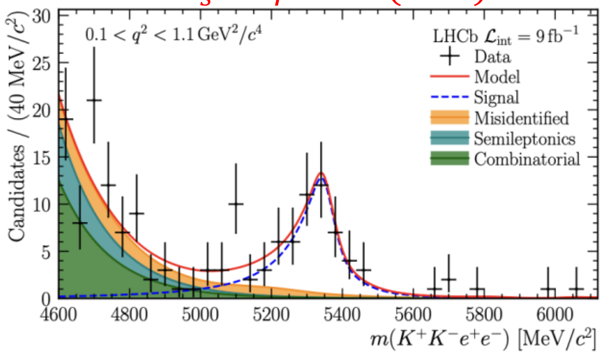
➤ Analysis

- Measurement performed in three q^2 regions
  - ✓ Low-q^2 - $0.1 < q^2 < 1.1$ GeV$^2/c^4$
  - ✓ Central-q^2 - $1.1 < q^2 < 6.0$ GeV$^2/c^4$
  - ✓ High-q^2 - $15.0 < q^2 < 19.0$ GeV$^2/c^4$
- Narrow ϕ resonance and excellent $m(K^+K^-)$ resolution at *LHCb*

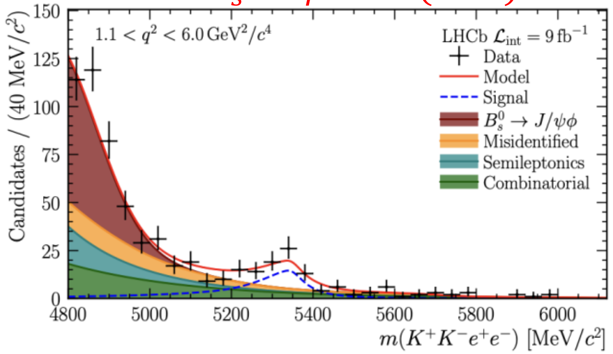




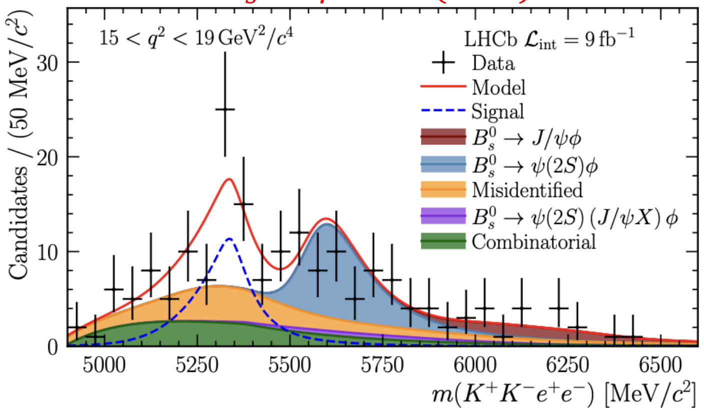
Observation
$B_s \to \phi e^+e^-$ (6.8σ)



Observation
$B_s \to \phi e^+e^-$ (5.4σ)



Evidence
$B_s \to \phi e^+e^-$ (3.6σ)

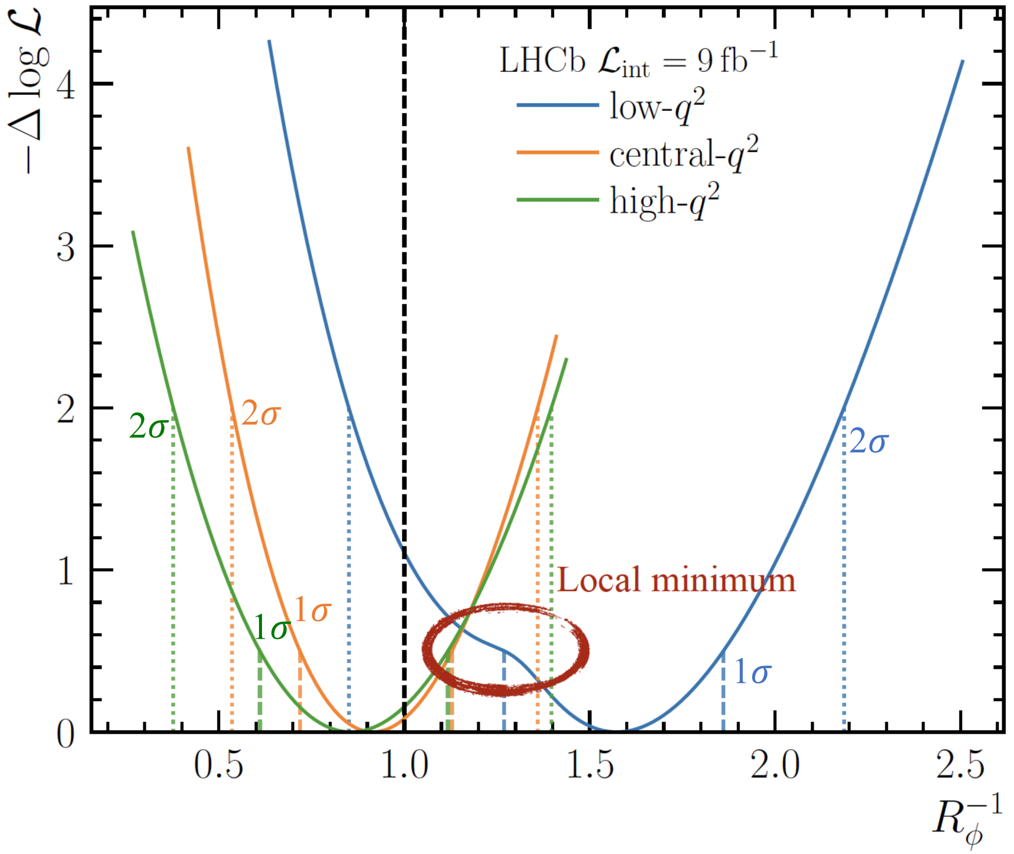


Results on R_ϕ

➤ Measurements in agreement with SM predictions

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

- Dominated by **statistical** uncertainty
- Main **systematics** - Signal and background modelling shapes



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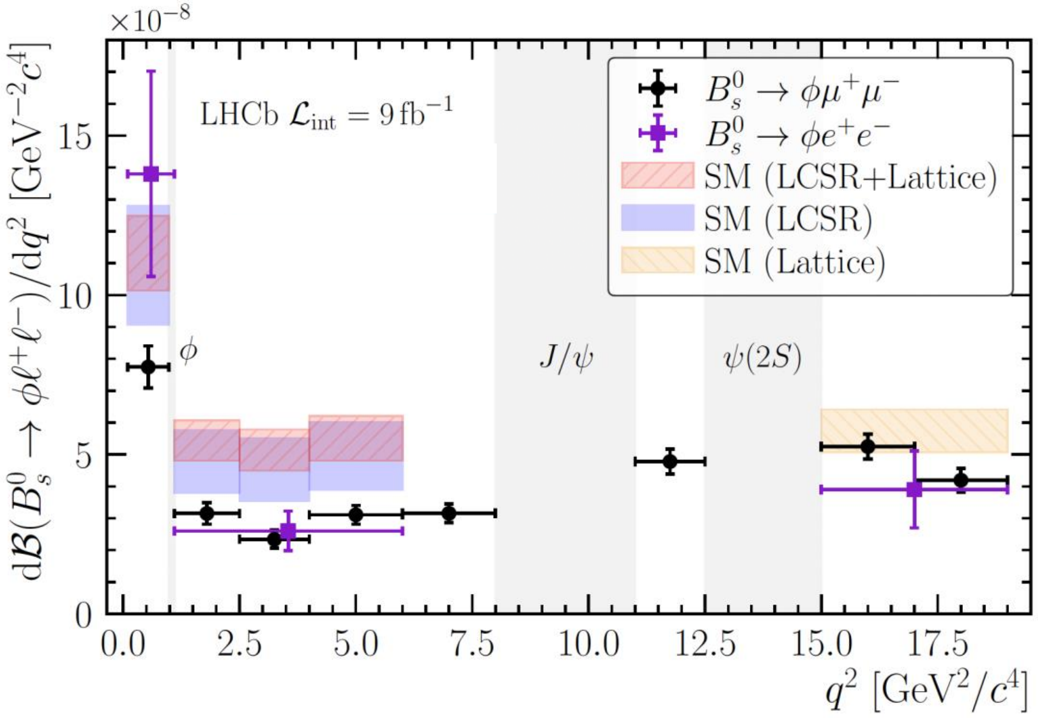
- Dominated by **statistical** uncertainty
- Main **systematics** - Signal and background modelling shapes

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

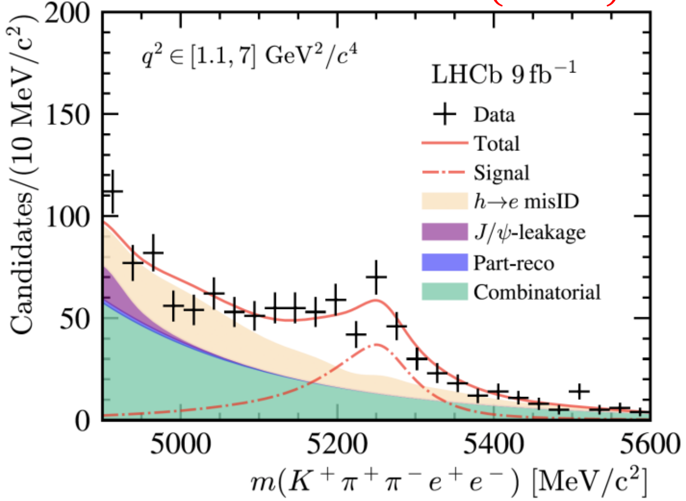
q^2 [GeV$^2/c^4$]	$d\mathcal{B}(B_s^0 \to \phi e^+e^-)/dq^2$ [10^{-7} GeV$^{-2}c^4$]
$0.1 < q^2 < 1.1$	$1.38\,^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$

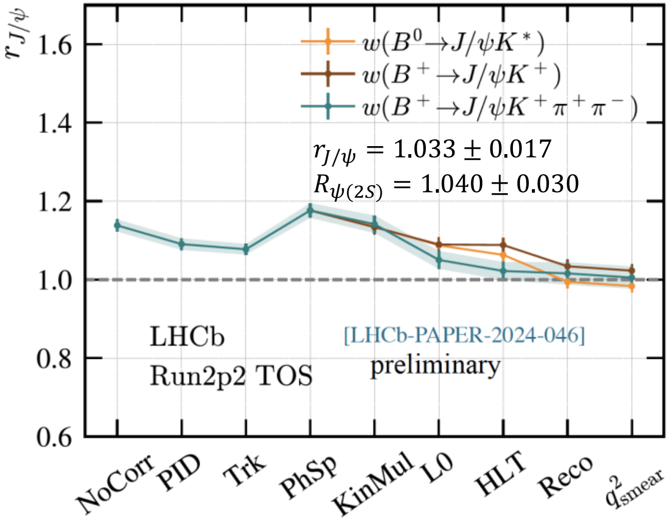


Observation
$B^+ \to K^+\pi^+\pi^-e^+e^-$ ($> 10\sigma$)

$R_{K\pi\pi}(X = K\pi\pi)$

- *"Test of lepton flavour universality with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays"*
  - $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 9.0$ fb^{-1}
  - [LHCb-PAPER-2024-046] – paper in preparation
- Analysis
  - Measurement performed in **one** q^2 region
    - ✓ Central-q^2 - $1.1 < q^2 < 7.0$ GeV$^2/c^4$
  - Decay simulated with PS model





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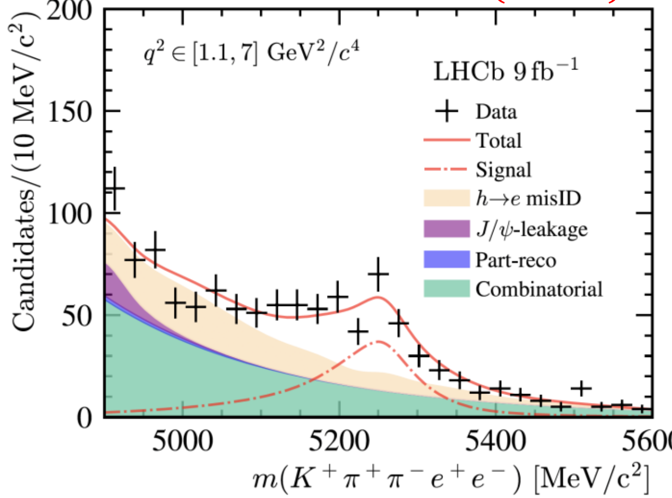
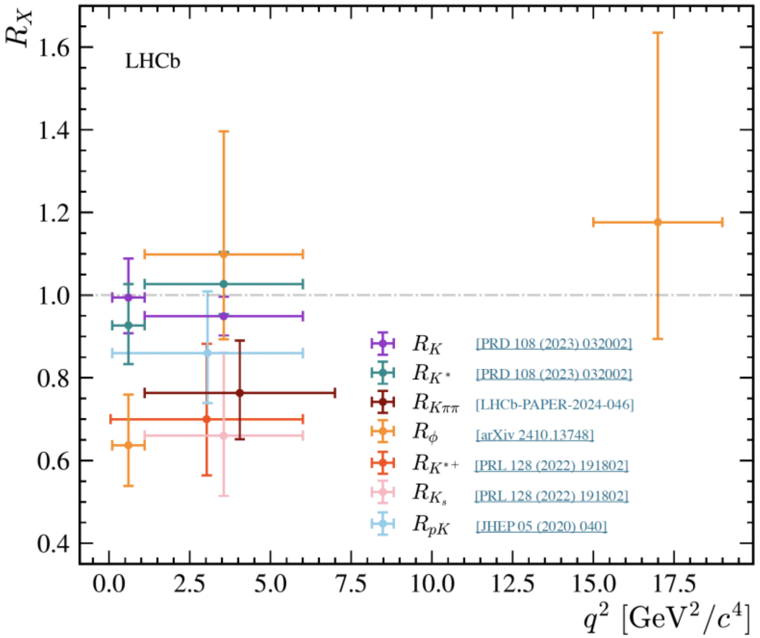
- Analysis
  - Measurement performed in **one** q^2 region
    - ✓ Central-q^2 - $1.1 < q^2 < 7.0\ \text{GeV}^2/c^4$
  - Decay simulated with PS model
- Measurement in agreement with SM predictions

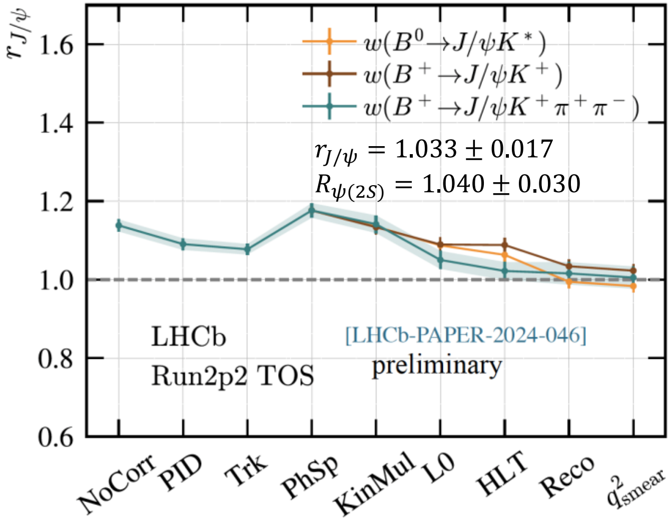
$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

Main **systematics**
Background modelling
Reweighting of the simulated phase-space

Observation
$B^+ \to K^+\pi^+\pi^-e^+e^-$ ($> 10\sigma$)







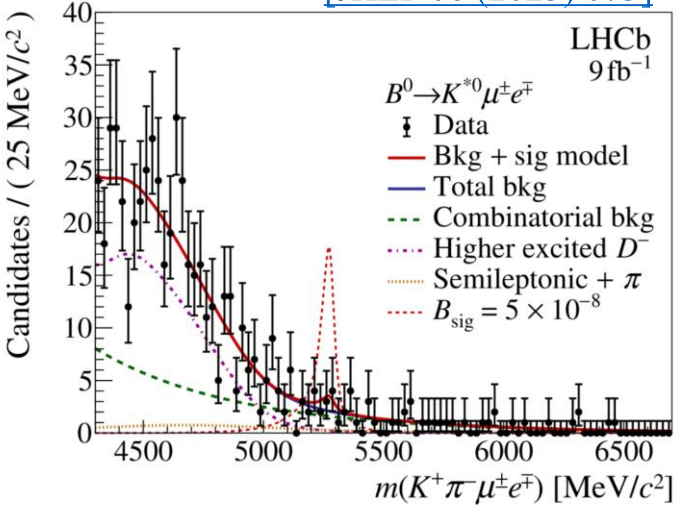
Lepton Flavour Violation

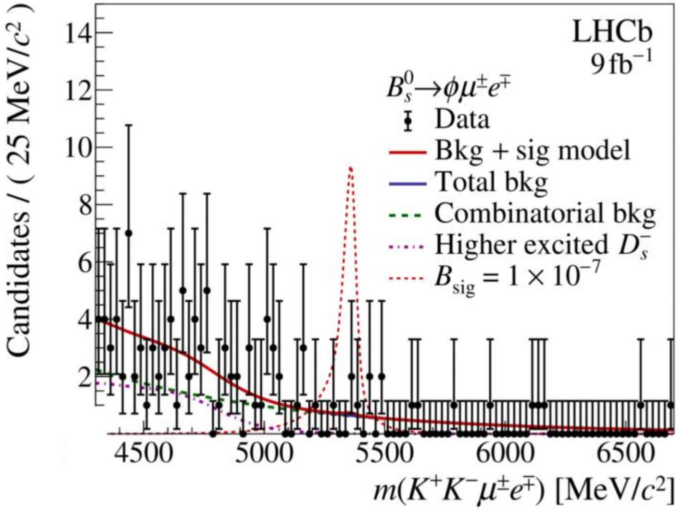
[JHEP 06 (2023) 073]

- $b \to s\ell^+\ell^-$ transitions to look for Lepton Flavour Violation (LFV) decays
  - Related to possible LFUV
  - Way to constrain NP models
- $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$ decays at *LHCb*
  - No signicant signals observed
    - ✓ Best limits set so far at 90% (95%) CL
    - ✓ Most stringent limits on a semileptonic LFV b-hadron decays

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (6.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9}\ (7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}\ (11.7 \times 10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}\ (19.8 \times 10^{-9})$$

World first limit

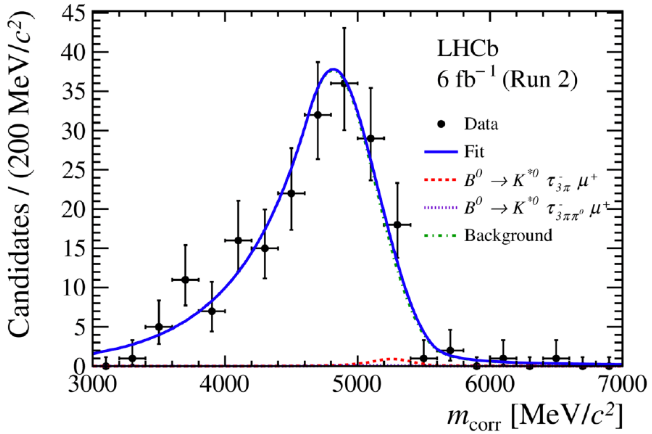


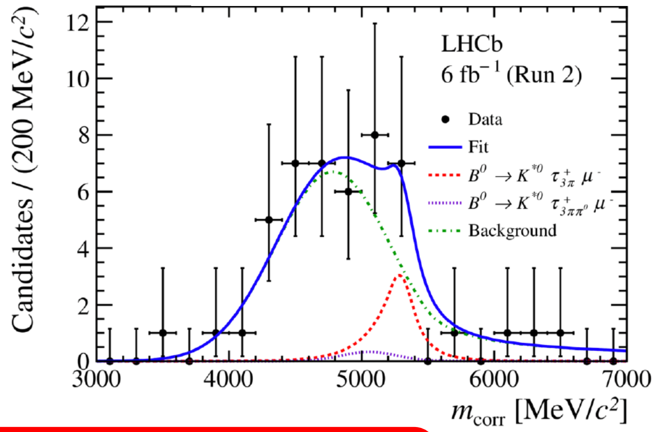


LFV with τ

- *"Search for the lepton-flavour violating decays $B^0 \to K^{*0}\tau^\pm\mu^\mp$"*
  - $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 9.0$ fb^{-1}
  - [JHEP 06 (2023) 143]
- Analysis
  - $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Separated treatment for charged combinations
  - Corrected mass to recover neutrinos energies

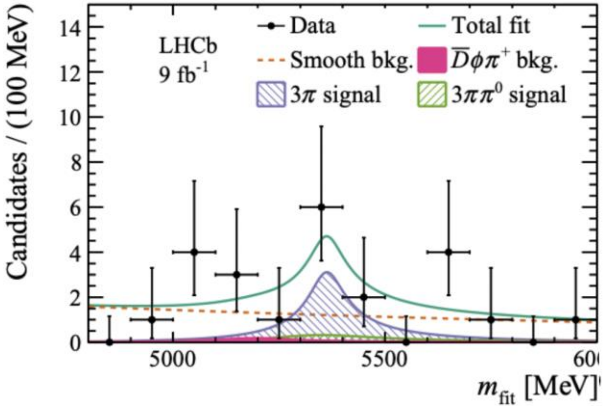
$$m_{corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$$

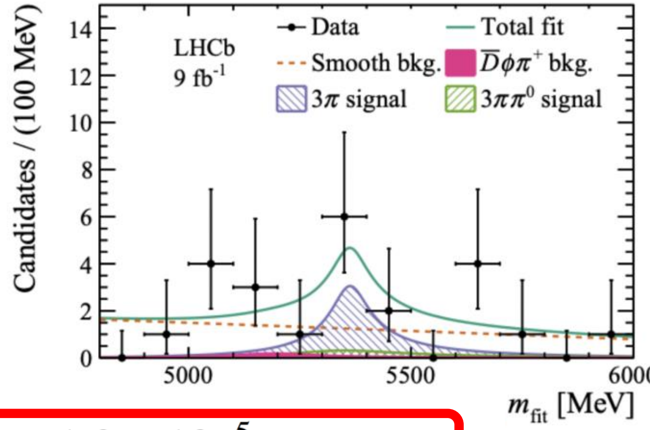




$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6}$ at 90% CL

- *"Search for the lepton-flavor violating decay $B_s^0 \to \phi\mu^\pm\tau^\mp$"*
  - $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 9.0$ fb^{-1}
  - [arXiv:2405.13103]
- **New** measurement with τ
  - Mass re-fitted
    - ✓ Missing υ momentum and kinematic constraints
  - No charge separation possible
  - See Simone's talk this afternoon



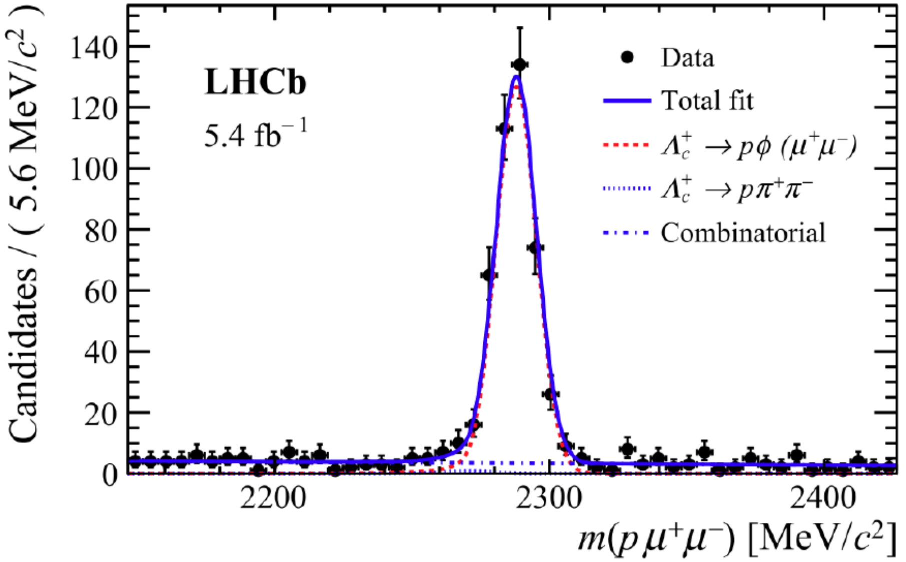


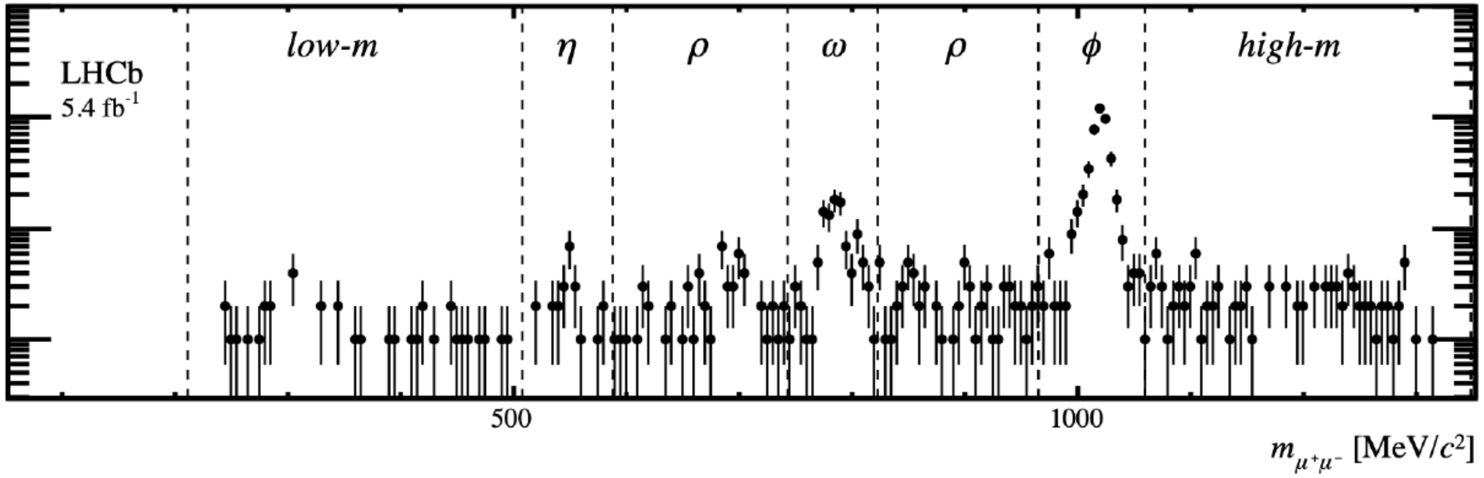
$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.0 \times 10^{-5}$ at 90% CL

Rare charm and strange decays

Search for $\Lambda_c^+ \to p\mu^+\mu^-$ decays

- $c \to u\mu\mu$ transition
  - Non-resonant short-distance ($\mathcal{B}\sim10^{-8}$)
  - ϕ, ρ, η, ω intermediate resonances
- *"Search for the rare decay of charmed baryon Λ_c^+ into the $p\mu^+\mu^-$ final state"*
  - $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4\ \text{fb}^{-1}$
  - [PRD 110 (2024) 5, 052007]
- Analysis
  - Study in both **resonant** and **non-resonant** dimuon regions
  - Normalised to ϕ region - $\Lambda_c^+ \to p\phi(\to \mu^+\mu^-)$



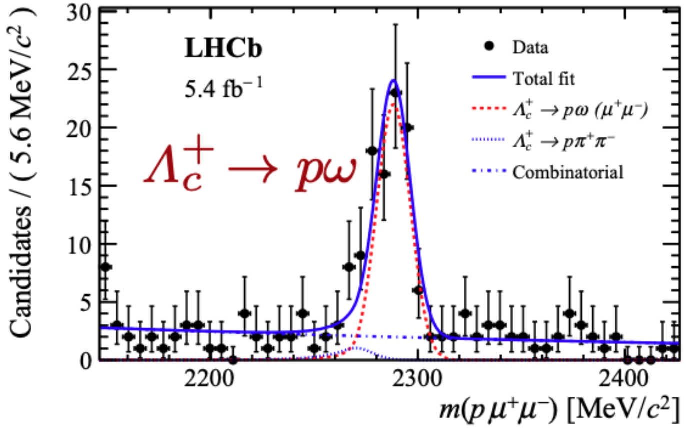


Region	Range [MeV/c^2]
low-m region	$211.32 < m_{\mu^+\mu^-} < 507.86$
high-m region	$1059.46 < m_{\mu^+\mu^-} < 1348.13$
η region	$507.86 < m_{\mu^+\mu^-} < 587.86$
ω region	$742.65 < m_{\mu^+\mu^-} < 822.65$
ρ region	$587.86 < m_{\mu^+\mu^-} < 742.65$
	or $822.65 < m_{\mu^+\mu^-} < 965.20$
ϕ region	$979.46 < m_{\mu^+\mu^-} < 1059.46$

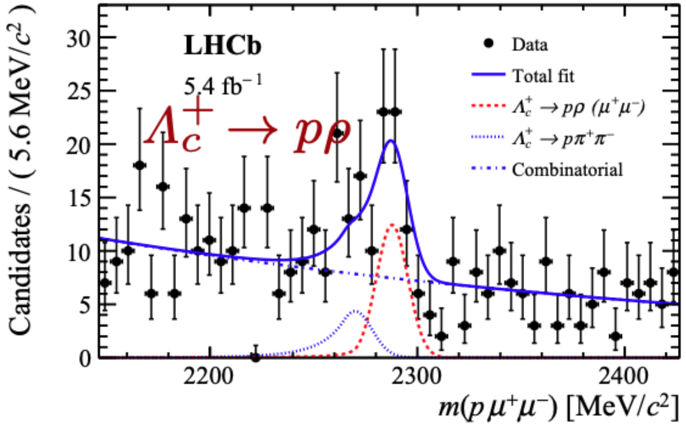
Λ_c^+ resonant decays

- **Three** distinct results

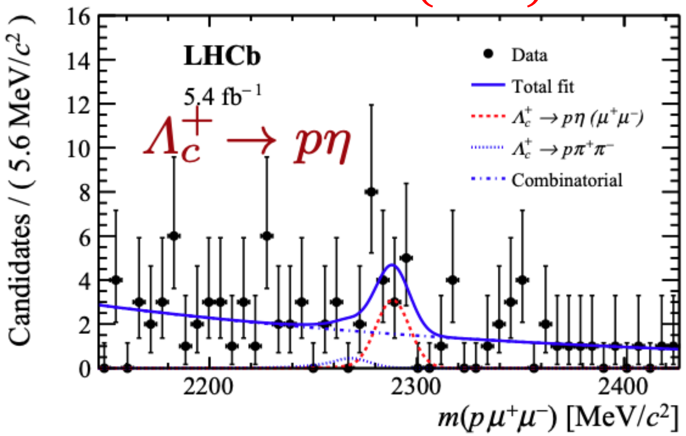
Observed ($> 7.0\sigma$)



Observed ($> 5.6\sigma$)



Evidence (3.0σ)



- Branching fractions measurements
  - No attempt to disentangle the resonant components to account for interference effects

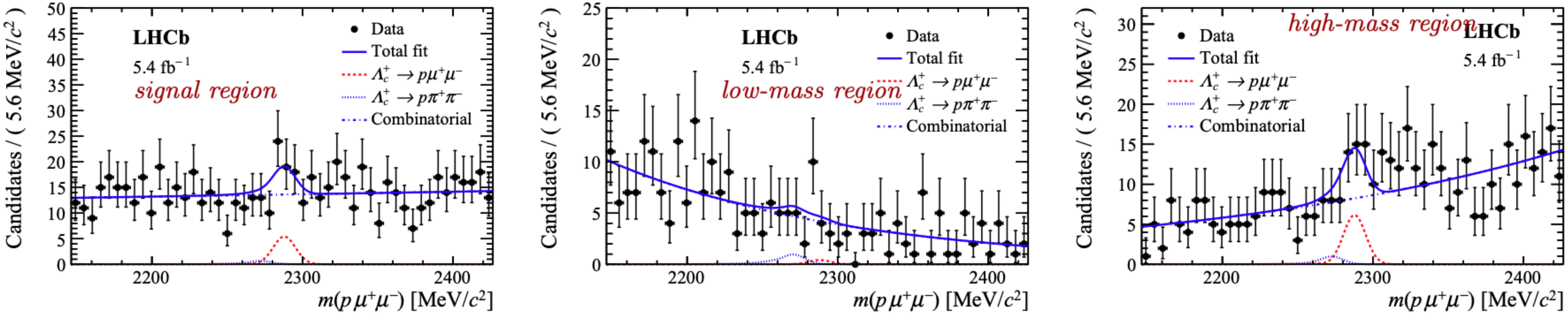
$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.73\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4},$$

$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3},$$

Λ_c^+ non-resonant decays

➤ No evidence for $\Lambda_c^+ \to p\mu^+\mu^-$ decays in the **non-resonant** regions



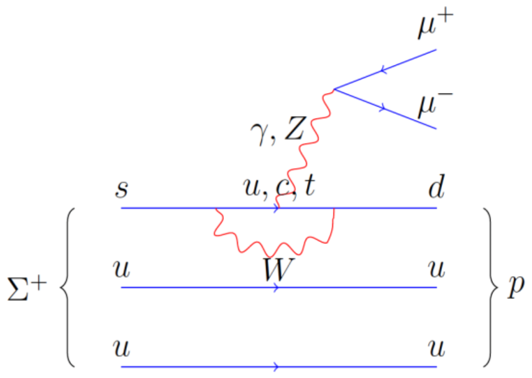
$$\frac{\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi \to \mu^+\mu^-)} < 0.09\ (0.10) \quad \text{at} \quad 90\%\ (95\%)\ \text{CL}.$$

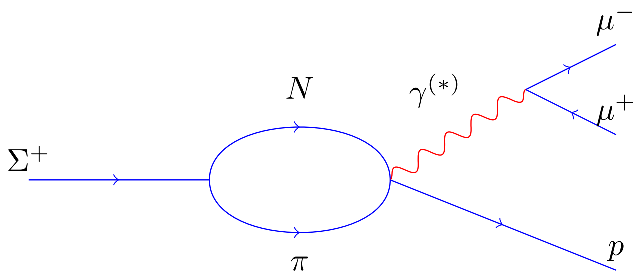
➤ **New** upper limit using $\mathcal{B}(\Lambda_c^+ \to p\phi)$ and $\mathcal{B}(\phi \to \mu^+\mu^-)$ from the PDG

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL}.$$

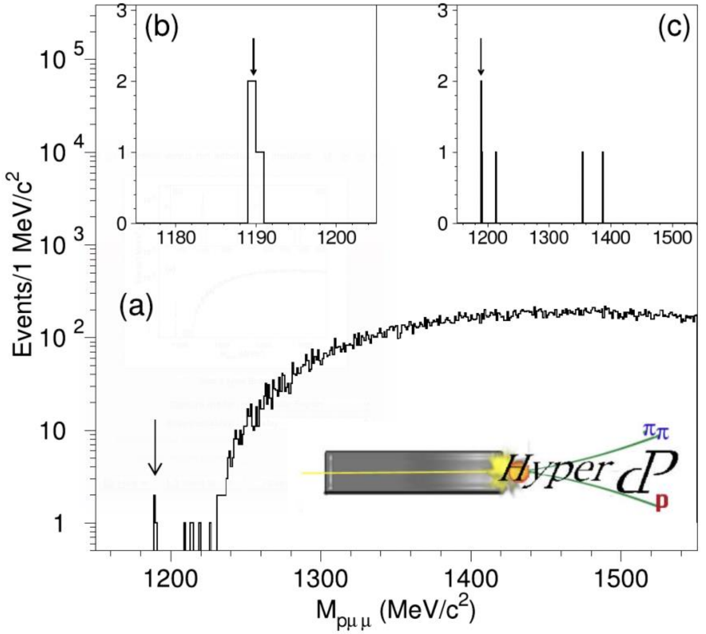
$\Sigma^+ \to p\mu^+\mu^-$

- $s \to d\mu\mu$ transition
  - Short distance SM $\mathcal{B} \sim \mathcal{O}(10^{-12})$
  - Dominated by long distance contributions from $\Sigma^+ \to (N\pi)^+$ decays
    $1.6 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.1 \times 10^{-8}$
    [Phys. Rev. D72 (2005) 074003]
    [JHEP 1810 (2018) 040]





- First evidence from the *HyperCP* experiment
  - Three candidates observed in absence of background
  - Measured branching fraction:
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$
    [Phys. Rev. Lett. 94 (2005) 021801]



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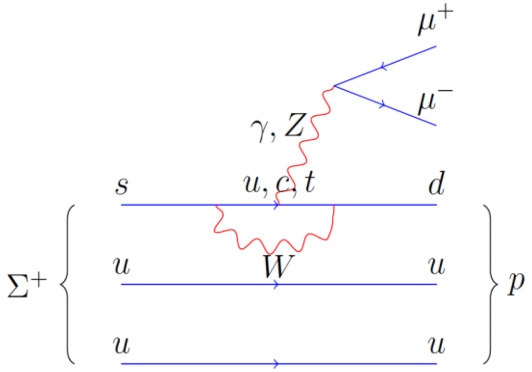
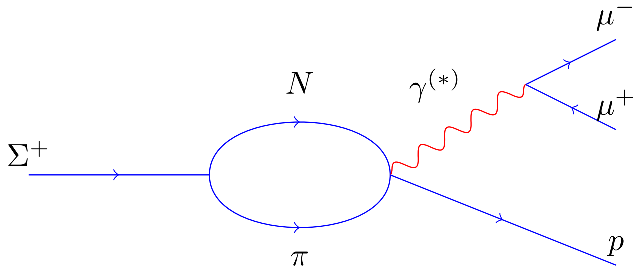
    [JHEP 1810 (2018) 040]





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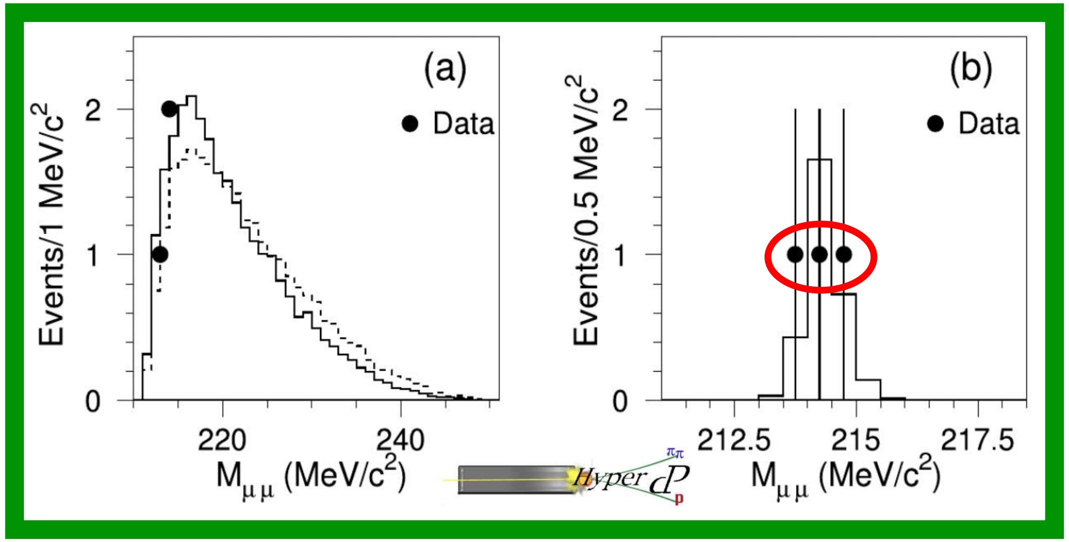
    [Phys. Rev. Lett. 94 (2005) 021801]

- The Anomaly
  - **Same** dimuon invariant mass for the observed candidates
  - Possible $\Sigma^+ \to pX^0(\to\mu^+\mu^-)$ decay
    $m_{X^0} = 214.3 \pm 0.5$ MeV
    $\mathcal{B}(\Sigma^+ \to pX^0(\to\mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5)\times10^{-8}$



First search at LHCb

- *"Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$"*
  - Run 1 dataset
    $\sqrt{s} = 7, 8$ TeV, $\mathcal{L} = 3.0\ \text{fb}^{-1}$
    [Phys. Rev. Lett. 120 (2018) 221803]

- **Stronger** evidence by *LHCb*
  - Excess of signal candidates w.r.t. background
    $N_{\Sigma^+ \to p\mu^+\mu^-} = (10.2^{+3.9}_{-3.5})$
  - Measured branching fraction:
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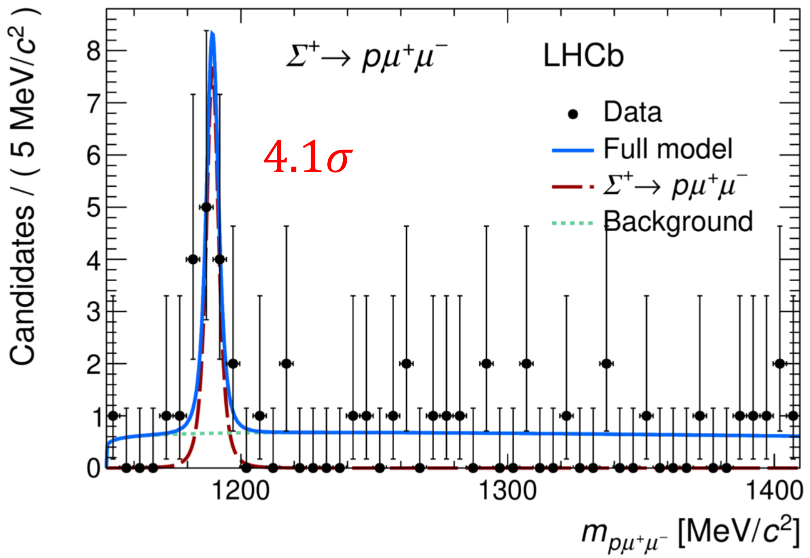

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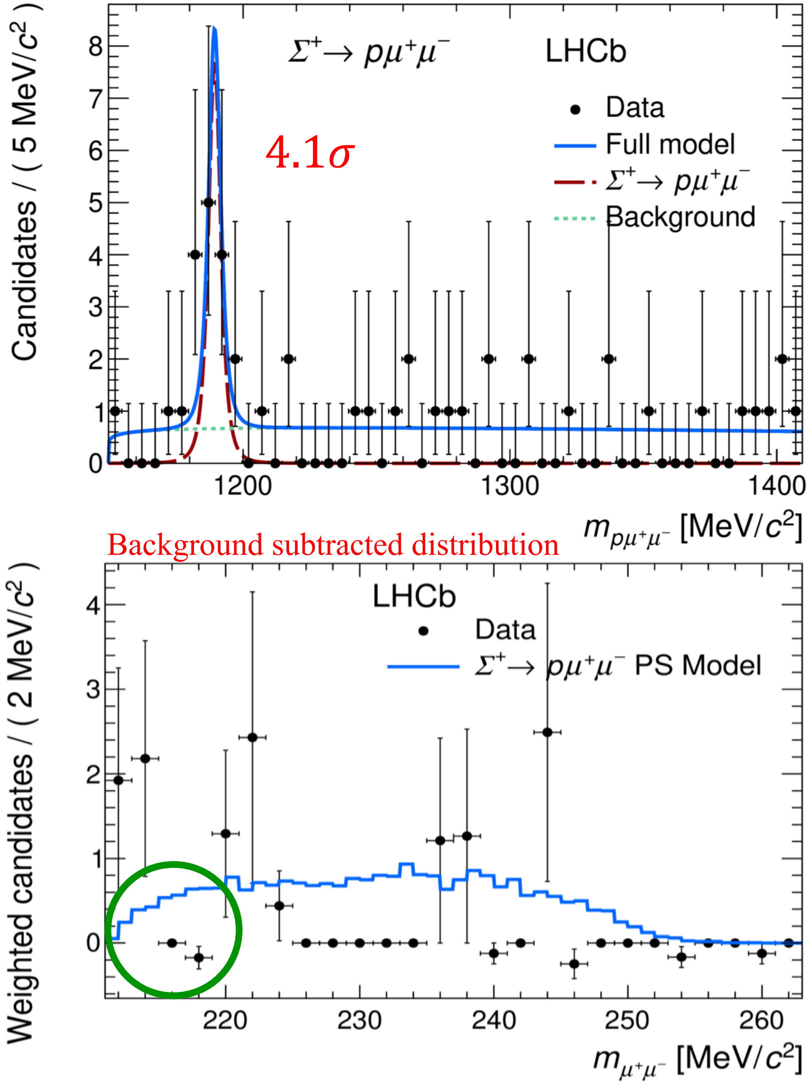
- Search for the X^0 resonance
  - No significant peak found in the $m_{\mu^+\mu^-}$ distribution
  - Upper limit at 90% C.L.
    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$
  - HyperCP result central value excluded



New analysis with Run 2

- *"Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb"*
  - $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4\ \text{fb}^{-1}$
  - [LHCb-CONF-2024-002]

- What's new?
  - **Increase in statistics**
    - ✓ Factor ~4 larger w.r.t. previous analysis
    - ✓ Larger MC samples
  - **Increase in performances**
    - ✓ Run 1 → Highly prescaled minimum bias data
    - ✓ Run 2 → Dedicated trigger lines
      - ✓ Gain of a factor ~13 in signal efficiency
    - ✓ Improved PID performance on protons and muons

New analysis with Run 2

First observation with overwhelming significance

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  - [LHCb-CONF-2024-002]

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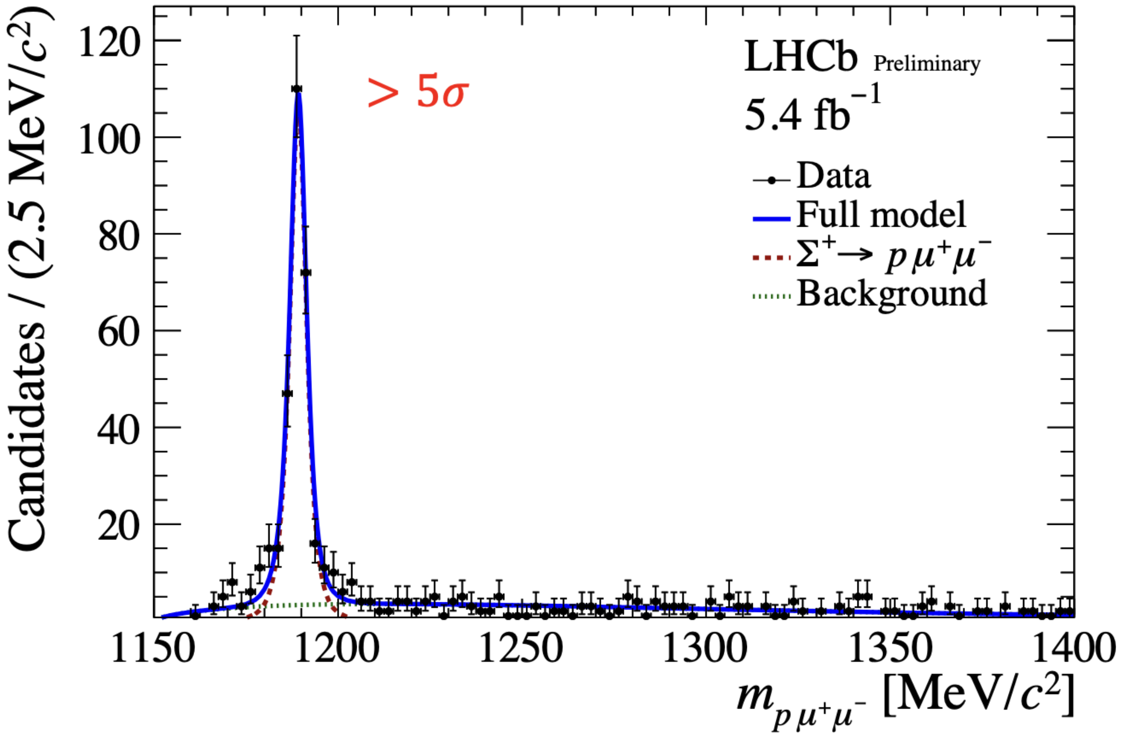
- Results
  - $N_{\Sigma^+\to p\mu^+\mu^-} = 279 \pm 19$
  - **Rarest hyperon decay ever observed**
  - Paper in preparation with integrated BF measurement

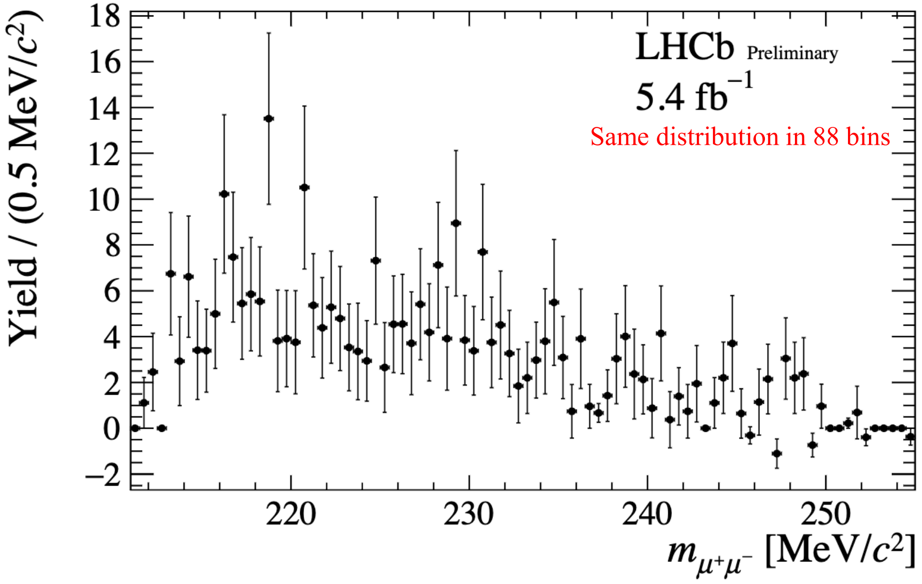


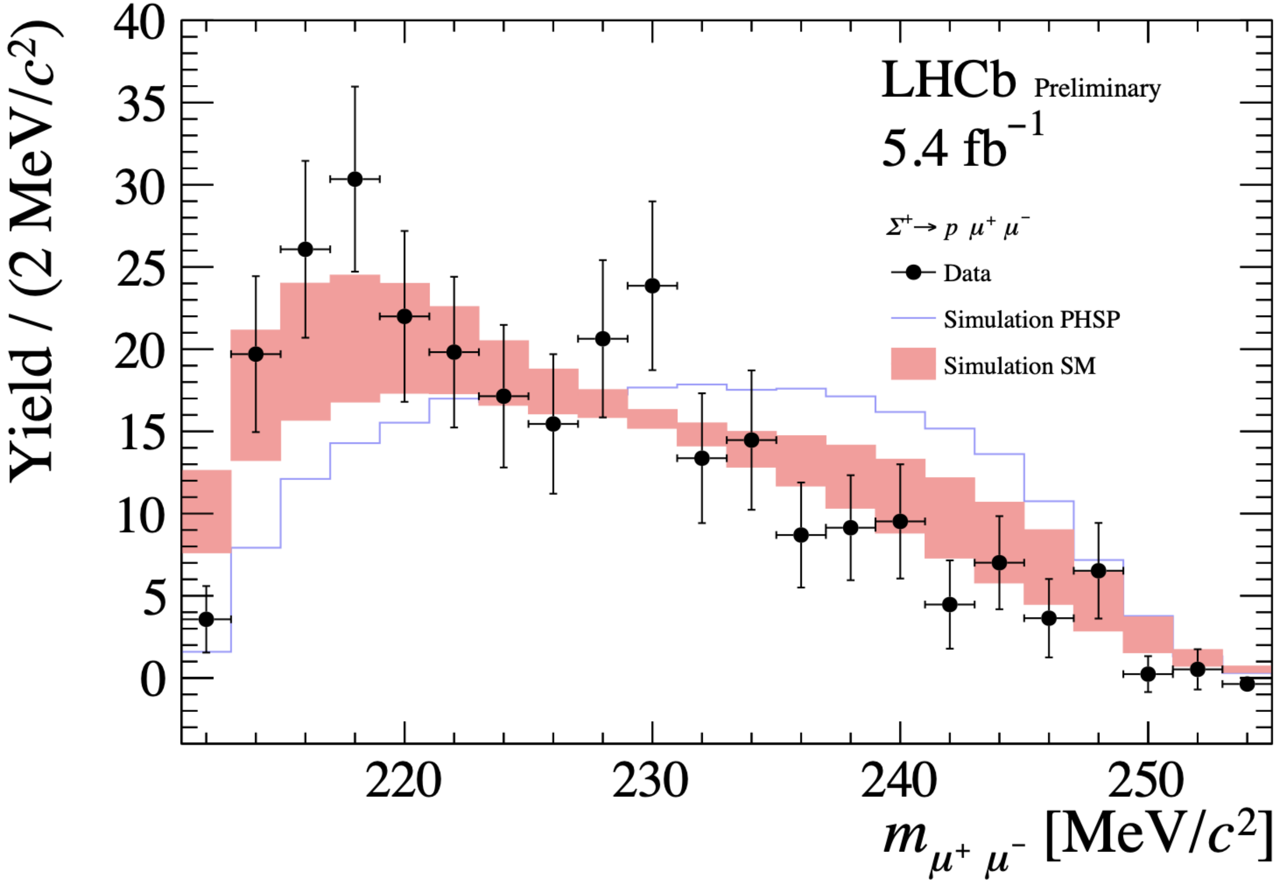
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} \cdot N_{\Sigma^+\to p\mu^+\mu^-}$$

Search for HyperCP-like signals

- Background subtraction
  - *sPlot* method using $m_{p\mu^+\mu^-}$ as discriminant variable
    - ✓ Event-by-event signal re-weight

- No significant peaking structure is visible
  - Data compared with simulated phase space
    - ✓ Simulation re-weighted according to SM amplitude
  - Good agreement found in the full $m_{\mu^+\mu^-}$ distribution





Conclusions

- Rare decays at *LHCb*
  - A way to investigate on (possible) NP hints
  - b-sector, but also c- and s-modes
  - Major (and some world's best) contributions "from our side"

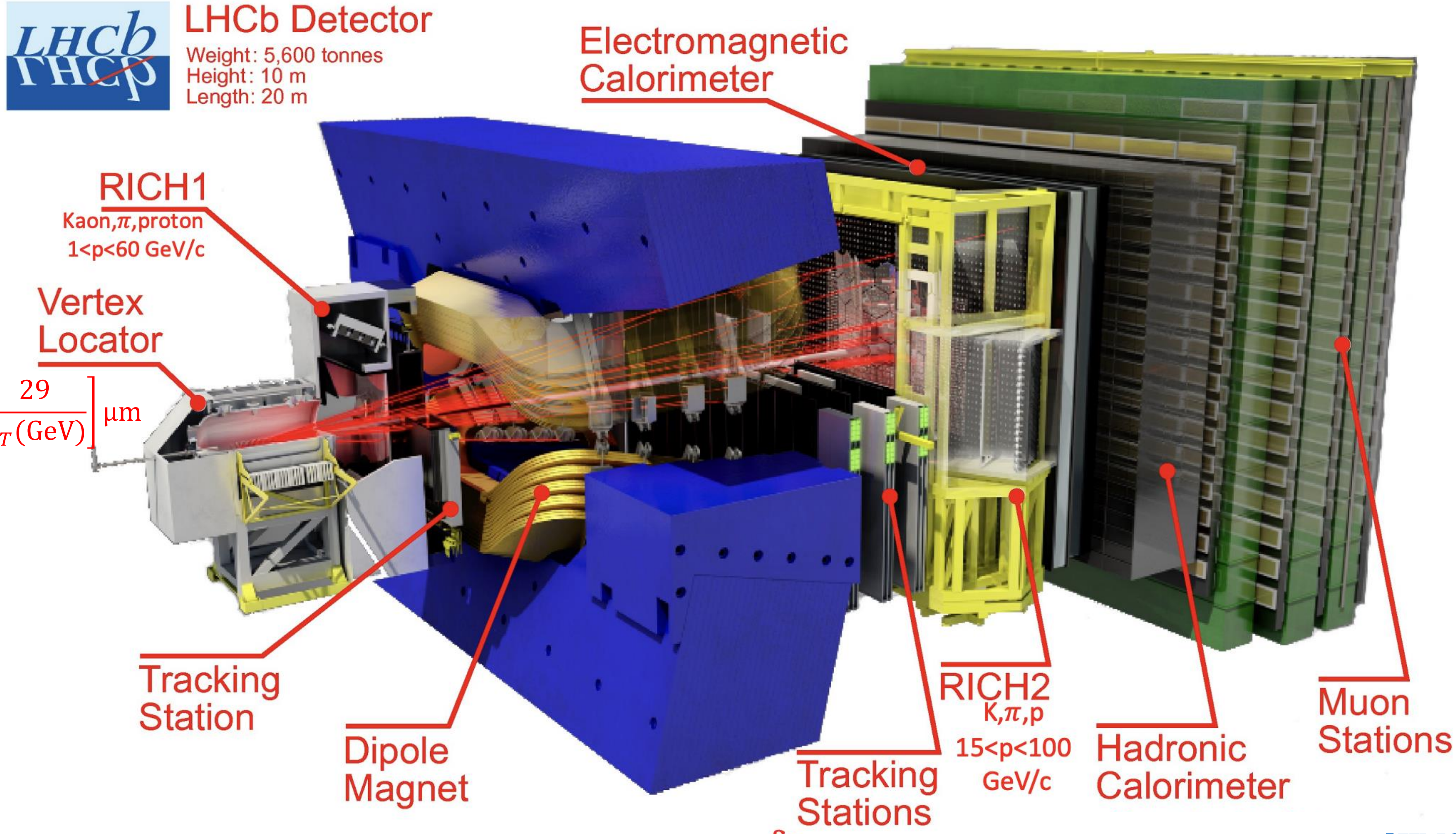
- Today's talk (Run 1 + Run 2 dataset)
  - Amplitude analyses
  - LFU and LFV null tests
  - Searches for (very) rare charm and strange decays

- What's next?
  - Run 3 is happening **right now** with LHCb Upgrade 1, however …
  - … rare modes measurements still expected to be statistically limited
  - Full potential in flavour physics will be exploited with Upgrade II
    - ✓ Run 5 and beyond

On behalf of the LHCb collaboration thank you for your attention

Backup slides

The LHCb Run 2 detector



$$\sigma_{IP} = \left[15 + \frac{29}{p_T(\mathrm{GeV})}\right] \mu\mathrm{m}$$

$$\frac{\delta p}{p} < 0.5 - 1\%$$

[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]