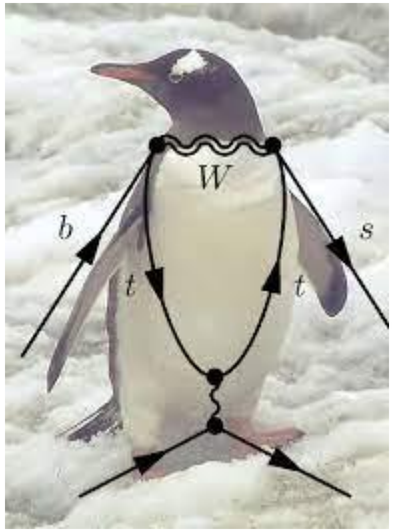
# Highlights of Recent LHCb Results on NP Searches in Rare Decays




Liang Sun
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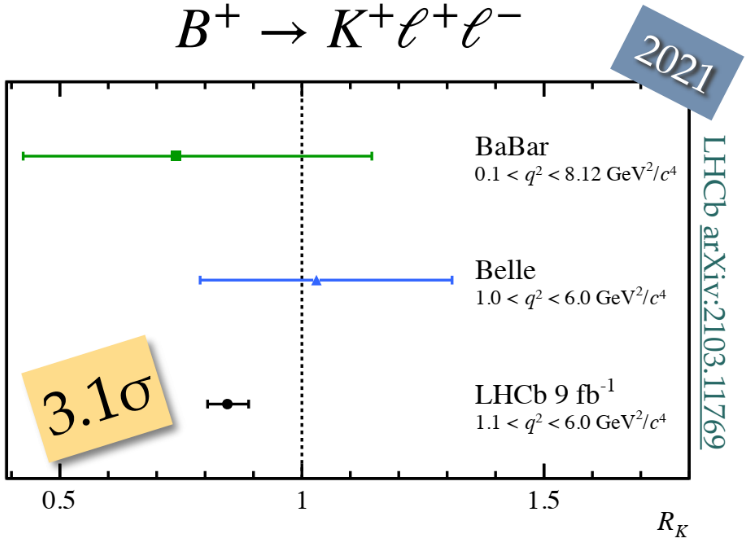



NPG Workshop 2021

Nov. 07 2021, Qingdao (Virtual), China

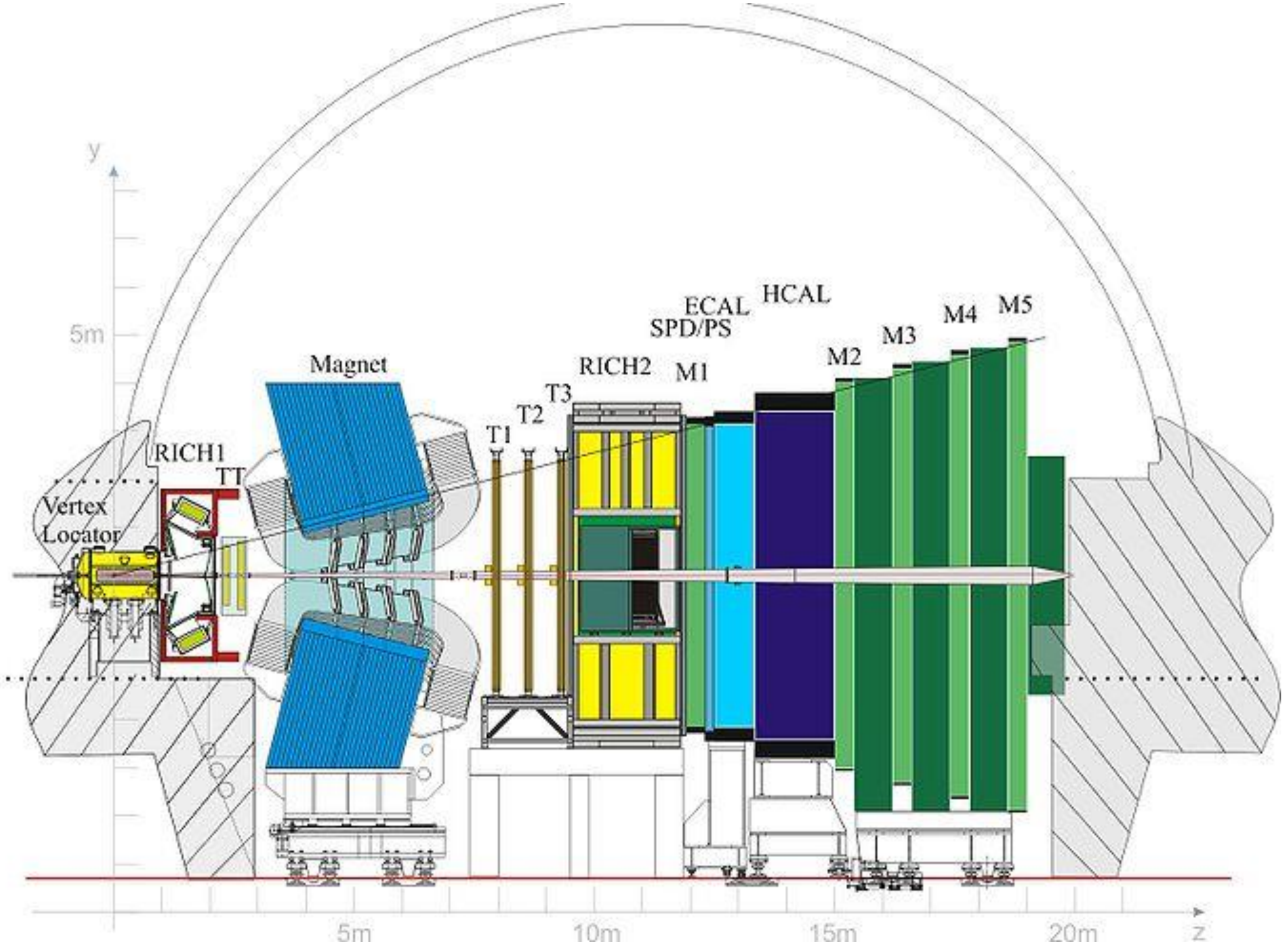
# Outline

- LHCb experiment
- (Very!) Recent results in $b$-sector:
  - **LU in $B^0 \to K_S^0 \ell^+ \ell^-$ and $B^+ \to K^{*+}(\to K_S^0 \pi^+)\ell^+\ell^-$ (10.2021)**
  - **LU in $B^+ \to K^+ \ell^+ \ell^-$ (03.2021)**
  - **Angular analyses of $B^0 \to K^{*0}\mu^+\mu^- / B^+ \to K^{*+}\mu^+\mu^- / B_s^0 \to \phi\mu^+\mu^-$ (05.2020/12.2020/07.2021)**
  - **BFs of $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'(1525)\mu^+\mu^-$ (05.2021)**
  - **BFs of $B_{(s)}^0 \to \mu^+\mu^-(\gamma)$ (08.2021)**
  - **Radiative decays of $\Xi_b^- \to \Xi^- \gamma$ / $\Lambda_b^0 \to \Lambda\gamma$ (08.2021/*prelim.*)**
- (Very!) Recent results in charm sector:
  - **Search for 25 decays of $D_{(s)}^+ \to h^\pm \ell^+ \ell^{(\prime)\mp}$ (10.2020)**
  - **CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$ (*prelim.*)**
- Run3 and beyond
- Summary and discussions

✓ See LHCb Public results (cern.ch) for a complete list on rare decay searches.
✓ For exotic new particles such as LLP, see here

# LHCb detector in a nutshell

**By design: study CP-violating processes and rare $b$-hadron decays**




- can profit from the large $b\bar{b}$ and $c\bar{c}$ cross-sections and from the larger production at high pseudorapidity
- $\sigma(pp \to b\bar{b}X) = 144 \pm 1 \pm 21\,\mu\text{b}$ at 13 TeV in the LHCb acceptance $\Rightarrow \sim$ 25% of the total inside LHCb **[Phys.Rev.Lett. 118, 052002]**
- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance **[JHEP 05 (2017) 074]**

# LHCb detector in a nutshell

**By design: study CP-violating processes and rare *b*-hadron decays**

- Particle detection in the forward region (down to the beam-pipe)
- Excellent resolution for localization of decay vertices (Vertex Locator) → Excellent time resolution, enough to resolve $B_s - B_s$ oscillation
- Excellent momentum resolution ($\sigma(m_B)$~25 MeV for 2-body decays)
- Excellent particle identification to distinguish p, $K^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$
- Excellent leptonic and hadronic triggers

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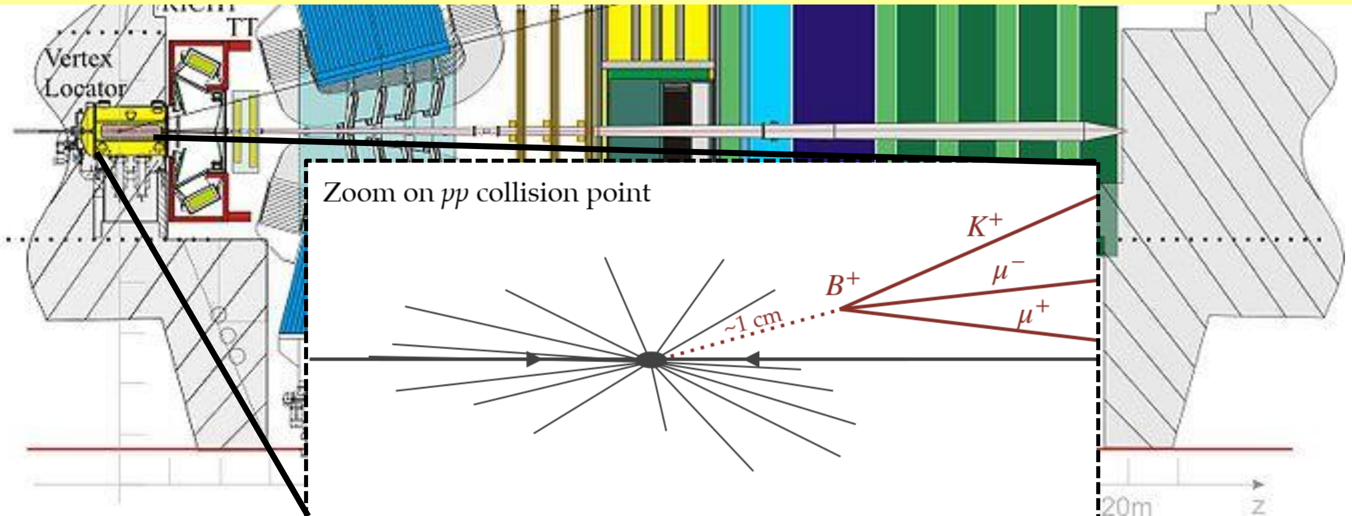
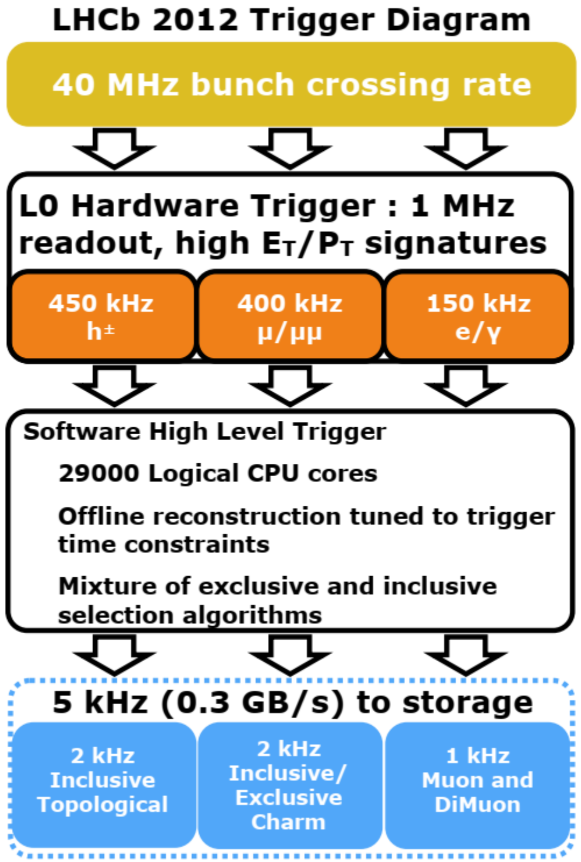
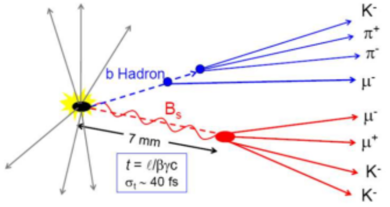
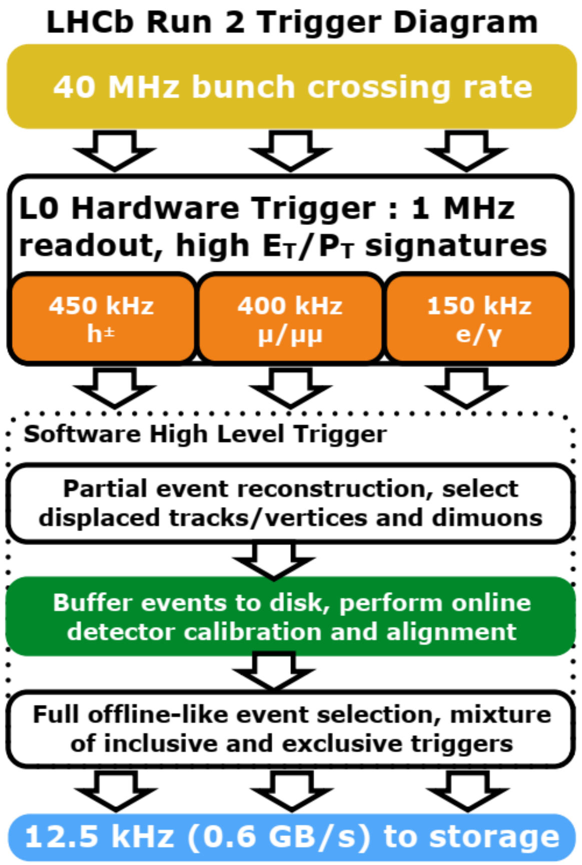
- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance [JHEP 05 (2017) 074]



# LHCb trigger scheme



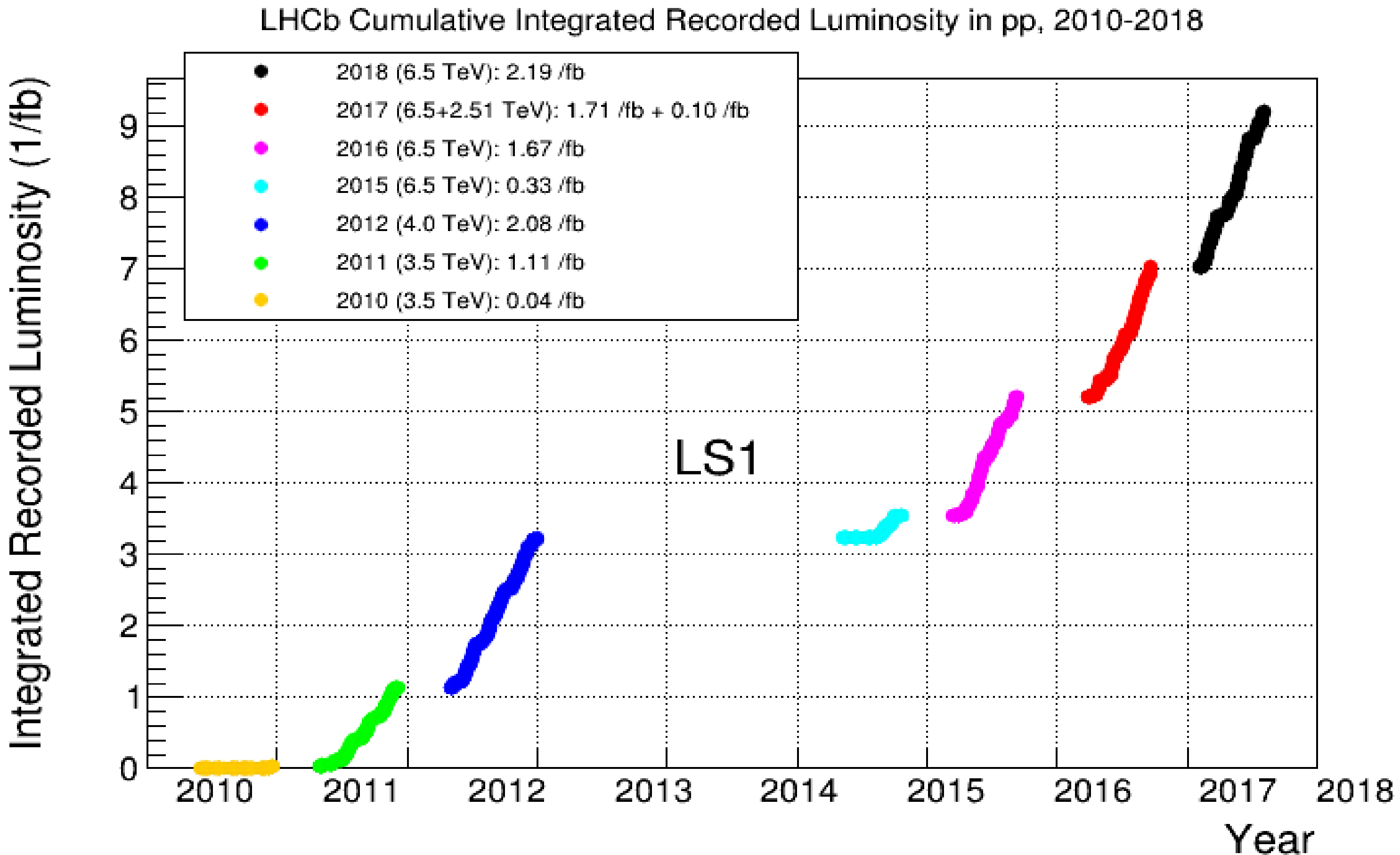




trigger efficiency: $\sim$ 90% on muons, $\sim$ 30% for multi-body hadronic final states

# LHCb data samples

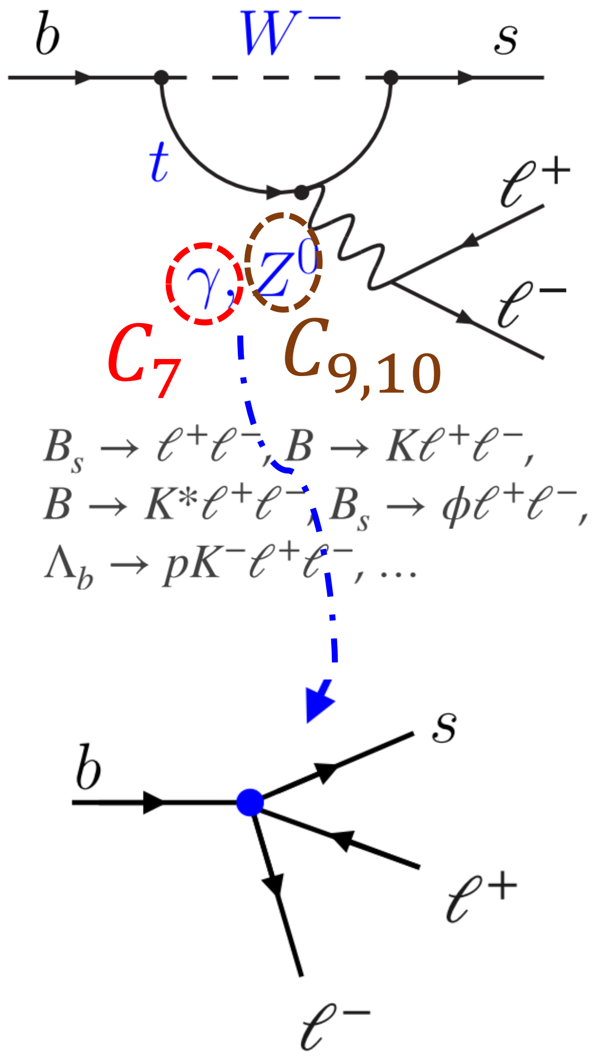
- **levelled** instantaneous luminosity of $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Run 1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run 2: $\sim 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
- $\sigma(pp \to Q\bar{Q}X) \propto \sqrt{s} \Rightarrow$ 4x $b$- and $c$-hadrons in Run 2

Total ~$10^{12}$ $b\bar{b}$ in the acceptance



# Why $b \to s\ell^+\ell^-$?

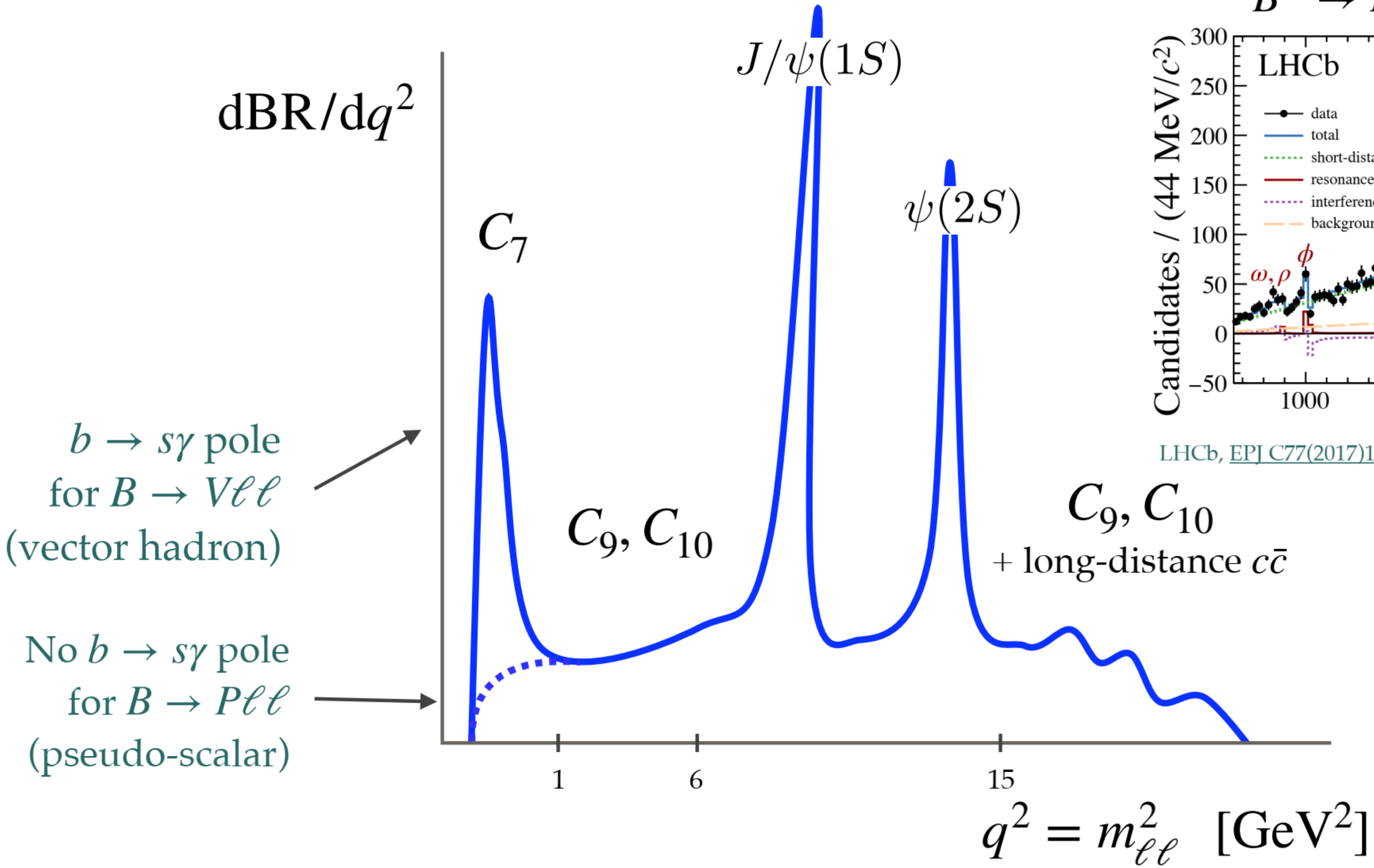
- **F**lavor **C**hanging **N**eutral **C**urrents
- Forbidden at tree level (Rare decays with BF <$10^{-6}$)
- NP could enter the loop at the same order as SM
- Small LD contribution, can be interpreted with Effective Theory
- Effective couplings from loops parameterized by **Wilson Coefficients** => Sensitive to NP!
- SM contributions:
  - Vector ($C_9$) and Axial-vector ($C_{10}$) leptonic currents
  - $C_7$ well constrained from radiative $b \to s\gamma$ processes

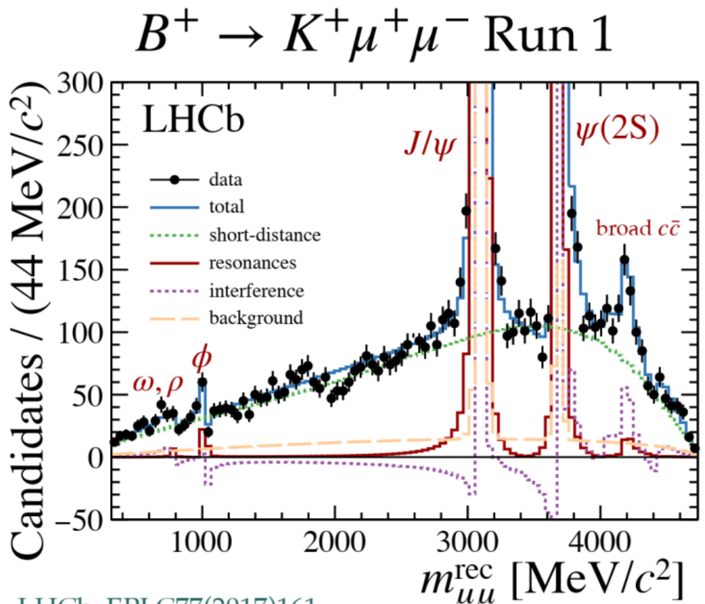



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

# Dilepton mass (q²) spectrum of $b \to s\ell^+\ell^-$




LHCb, EPJ C77(2017)161

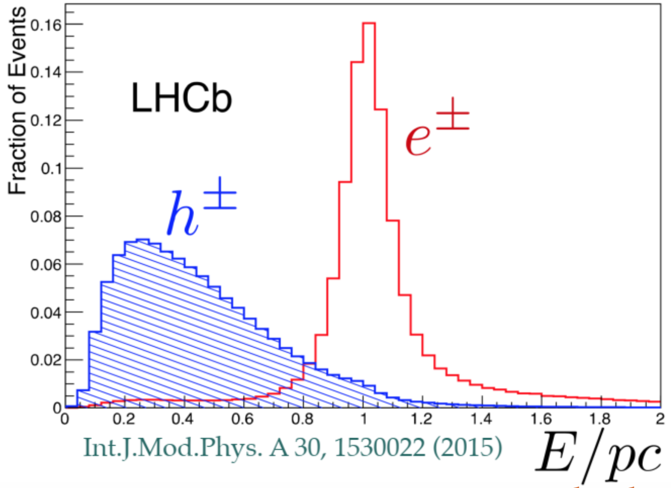
# Electrons at LHCb

- Efficiency bottleneck at hardware trigger:
  - $p_{\mathrm{T}}(\mu^{\pm}) > 1.5 - 1.8$ GeV
  - $E_{\mathrm{T}}(e^{\pm}) > 2.5 - 3.0$ GeV
- Electron ID based on ECAL and tracking (harder and slower than $\mu$ ID)

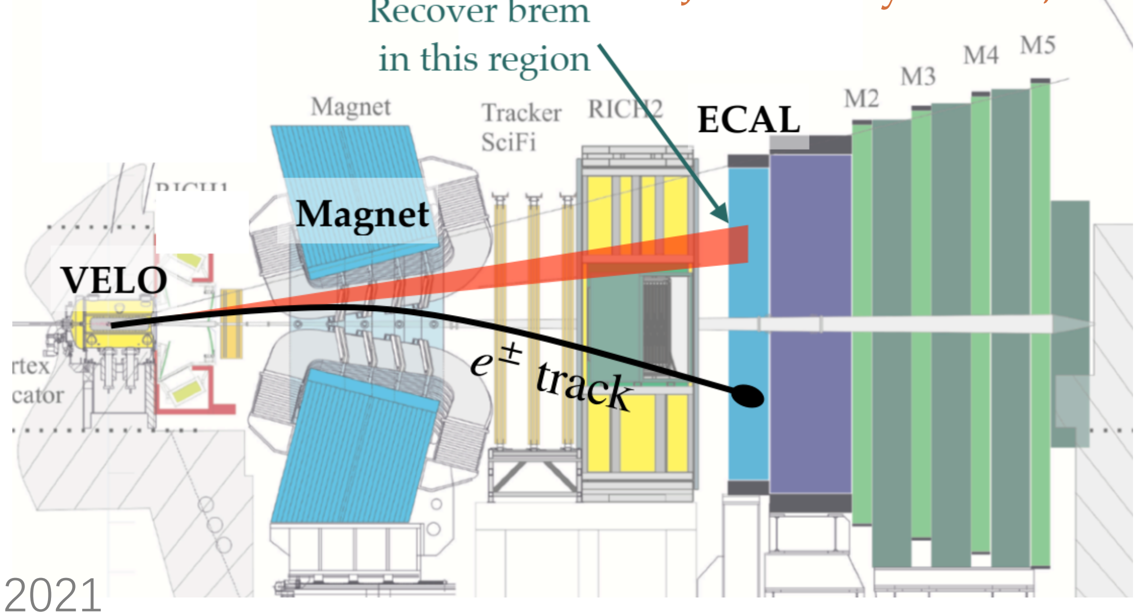
$$\frac{\epsilon(B^+ \to K^+\mu^+\mu^-)}{\epsilon(B^+ \to K^+e^+e^-)} \simeq 2.8$$

- Measurement of $p(e^{\pm})$ affected by bremsstrahlung emission before magnet
- Bremsstrahlung photon recovery procedure has limited efficiency

Electron ID




Int.J.Mod.Phys. A 30, 1530022 (2015)




From M. Borsato's talk @ Flavour Anomaly Workshop 2021

# Lepton universality test: R(K)

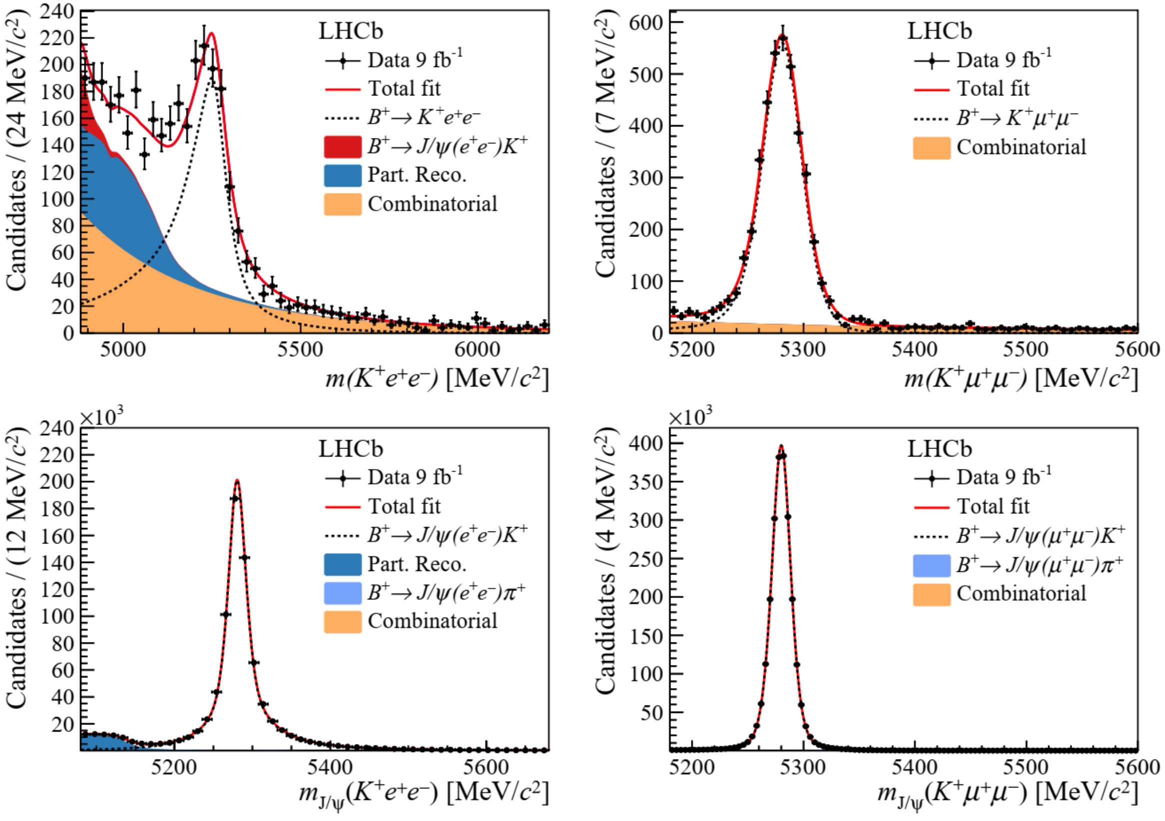
- SM predicts R(K) to be very close to one:

$$R(K^{(*)}) = \frac{BR(B \rightarrow K^{(*)} \mu\mu)}{BR(B \rightarrow K^{(*)} e e)} = 1 \pm \underbrace{O(10^{-3})}_{\text{neglect lepton mass}} \pm \underbrace{O(10^{-2})}_{\text{QED}}$$

[EPJ C76 (2016) 8, 440]

- Experimentally, double-ratio used to cancel systematic uncertainties

$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B \to K^{(*)} \mu^+\mu^-)}{\mathcal{B}(B \to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$




$$R_{K^+} = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst}) \text{ in } [1.1, 6.0]\ \text{GeV}^2$$

**→ 3.1σ deviation from the SM**

# Lepton universality tests: R(K*+)

- SM predicts R(K*) to be very close to one:

$$R(K^{(*)}) = \frac{BR(B \to K^{(*)} \mu\mu)}{BR(B \to K^{(*)} ee)} = 1 \pm \underbrace{O(10^{-3})}_{\text{neglect lepton mass}} \pm \underbrace{O(10^{-2})}_{\text{QED}}$$

[EPJ C76 (2016) 8, 440]

- Experimentally, double-ratio used to cancel systematic uncertainties

$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to J/\psi\,(e^+e^-)\,K^{(*)})} \Bigg/ \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$

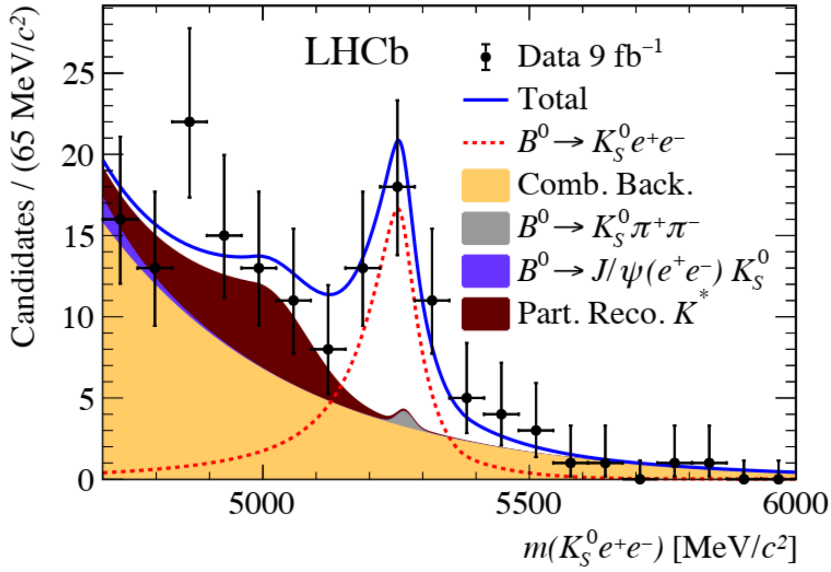
$$\frac{d\mathcal{B}(B^0 \to K^0 e^+ e^-)}{dq^2} = 2.6 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.}) \times 10^{-8}\,\text{GeV}^{-2}$$

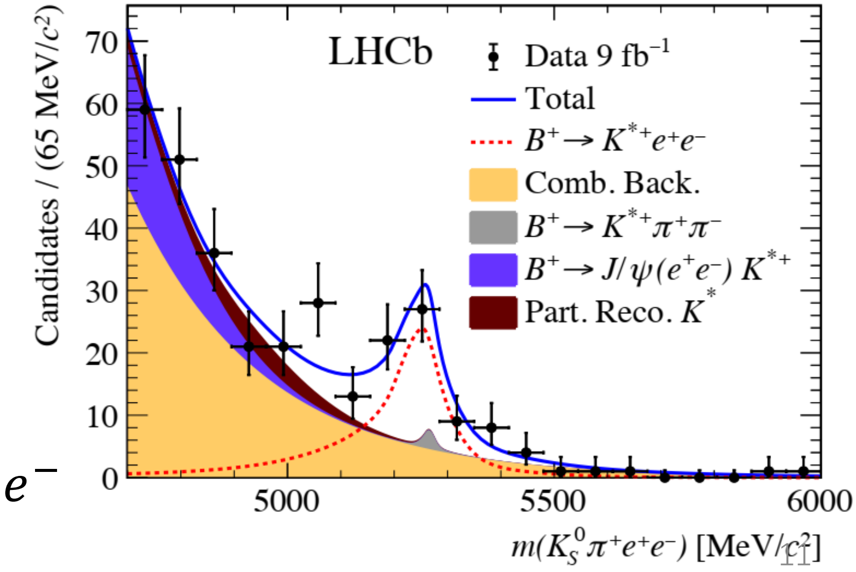
for $q^2 \in [1.1, 6.0]$ GeV$^2$

$$\frac{d\mathcal{B}(B^+ \to K^{*+} e^+ e^-)}{dq^2} = 9.2^{+1.9}_{-1.8}\,(\text{stat.})^{+0.8}_{-0.6}\,(\text{syst.}) \times 10^{-8}\,\text{GeV}^{-2}$$

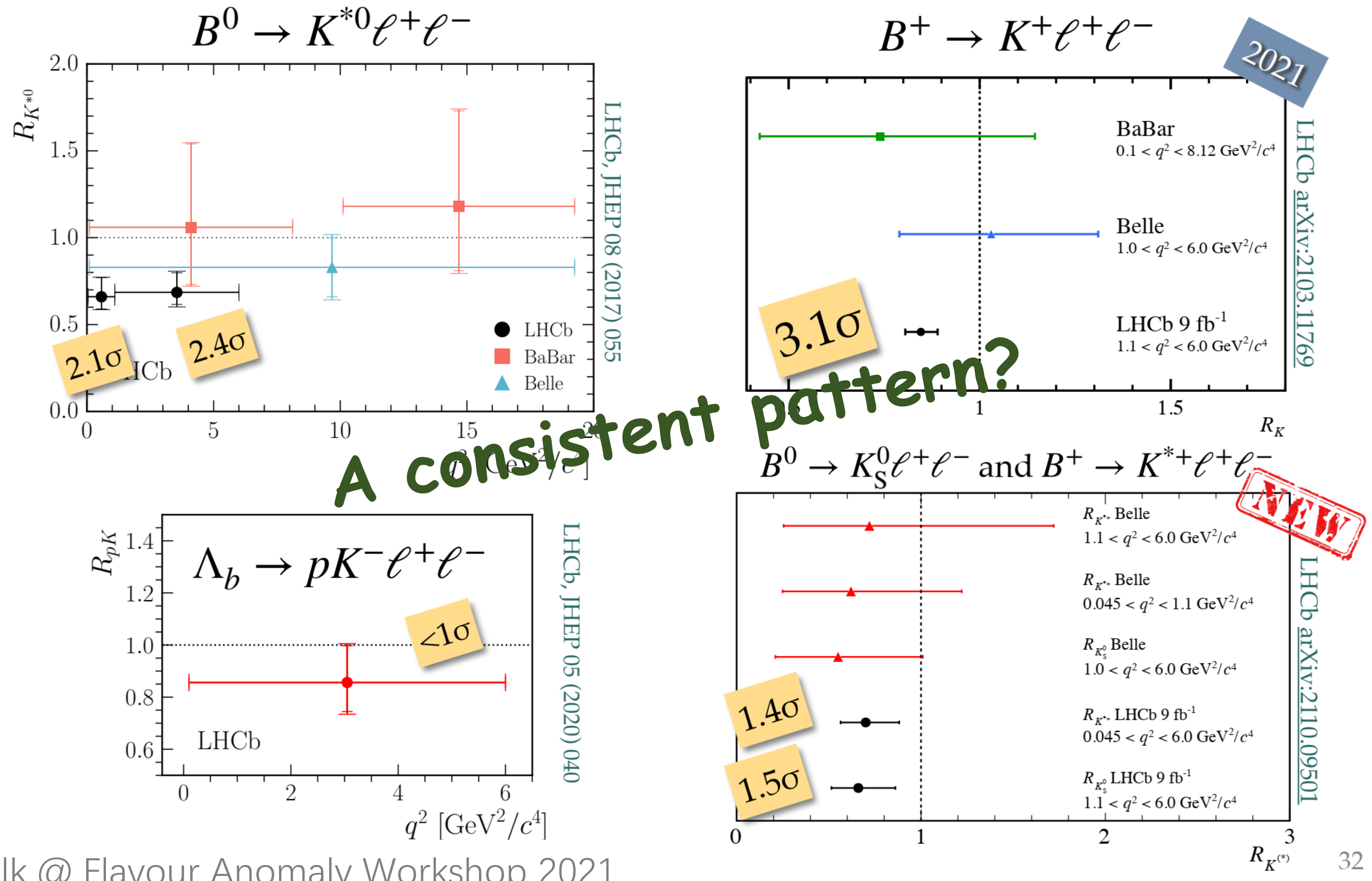
for $q^2 \in [0.045, 6.0]$ GeV$^2$

First observation of $B^0 \to K^0_S e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$



# Summary of LU tests @ LHCb

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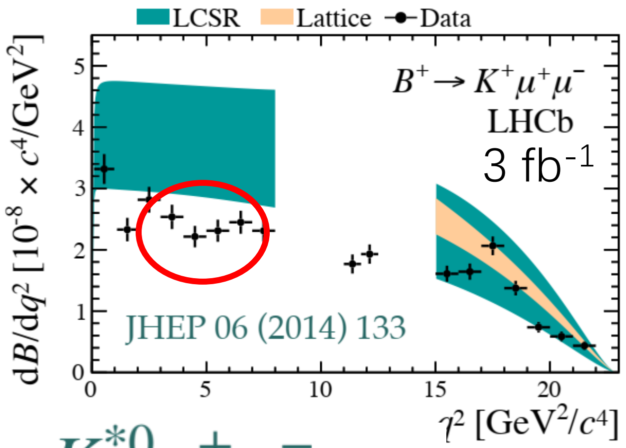
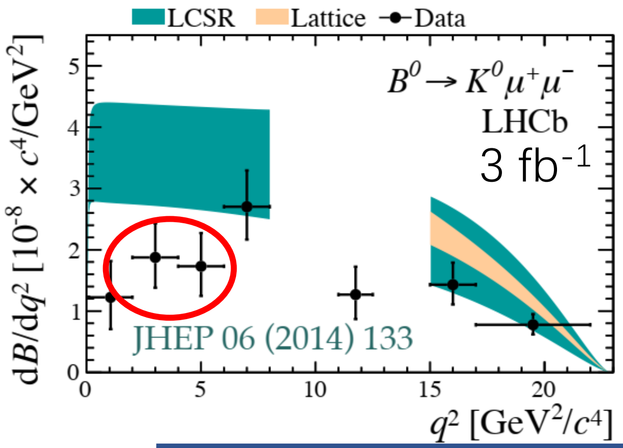
# Partial BFs of $b \to s\mu^+\mu^-$ @ LHCb

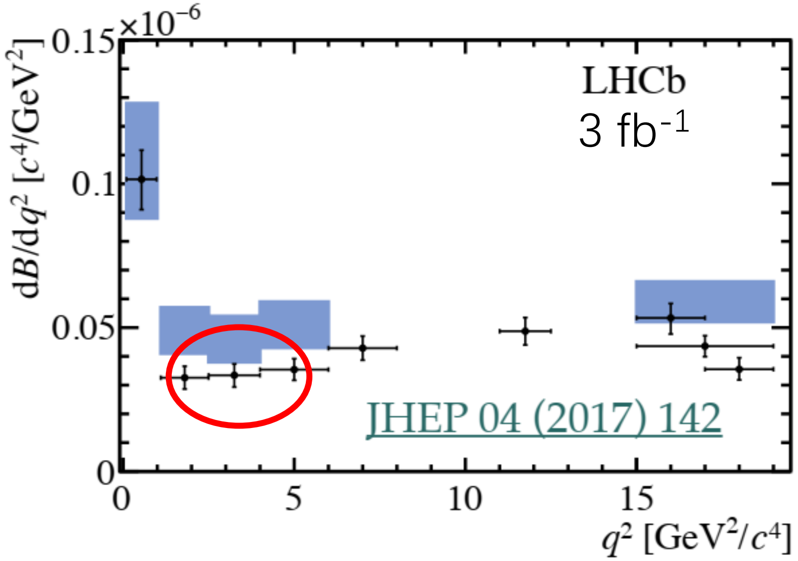
$B^+ \to K^+\mu^+\mu^-$




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

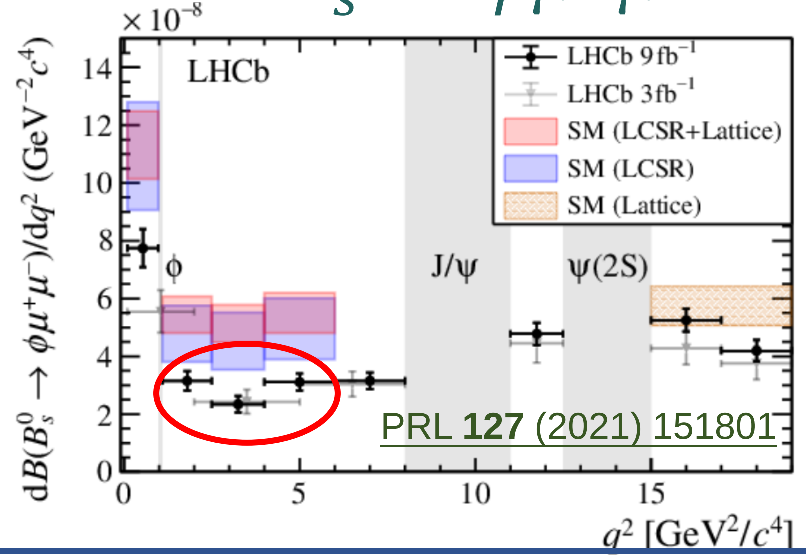



$B^0 \to K^{*0}\mu^+\mu^-$

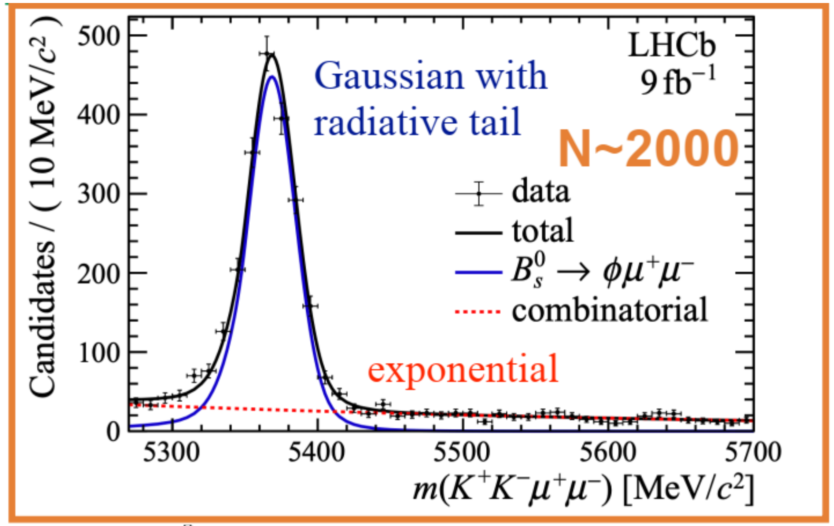



An update of Run1 results

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



# Measuring $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$




**$q^2 \in [1.1, 6.0]$** $\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/\mathrm{d}q^2 = (2.88 \pm 0.21) \times 10^{-8}\,\mathrm{GeV}^2/c^4$

Tension with SM at **3.6$\sigma$ (LCSR+Lattice)** and **1.8$\sigma$ (LCSR)**

**$q^2$-integrated** $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \underbrace{\pm 0.21}_{\text{stat.}} \underbrace{\pm 0.16}_{\text{syst.}} \underbrace{\pm 0.39}_{\text{norm.}} \underbrace{\pm 0.03}_{q^2\ \text{extrap.}}) \times 10^{-7}$

[JHEP 09 (2015) 179], [arXiv:2103.06810]

SM LCSR:

[Bharucha et al., JHEP 08 (2016) 098],

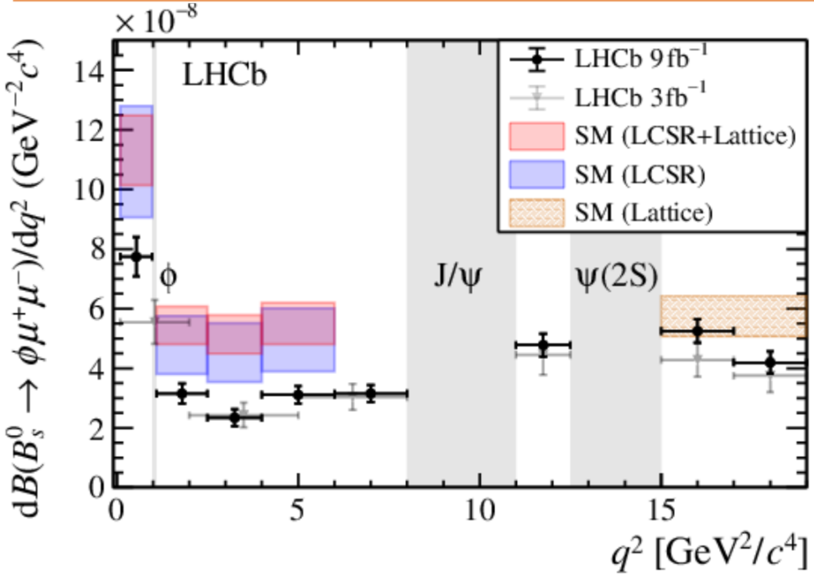
[Altmannshofer et al., EPJ C 75 (2015) 382],

[Straub, arXiv:1810.08132]

SM LCSR+Lattice:

+[Horgan et al., PRL 112 (2014) 212003],

+[Horgan et al., PoS LATTICE2014 (2015) 372]



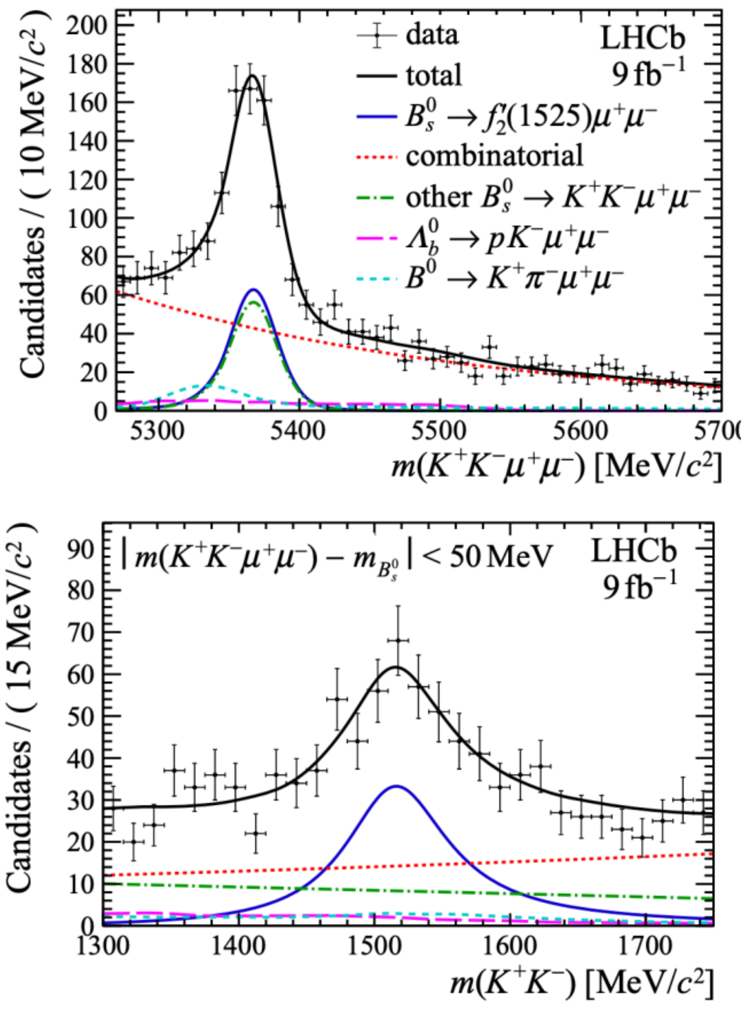
# Observation of $B_s^0 \to f_2'(1525)(\to K^+K^-)\mu^+\mu^-$

- First observation of a spin-2 FCNC mode!

$$\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$

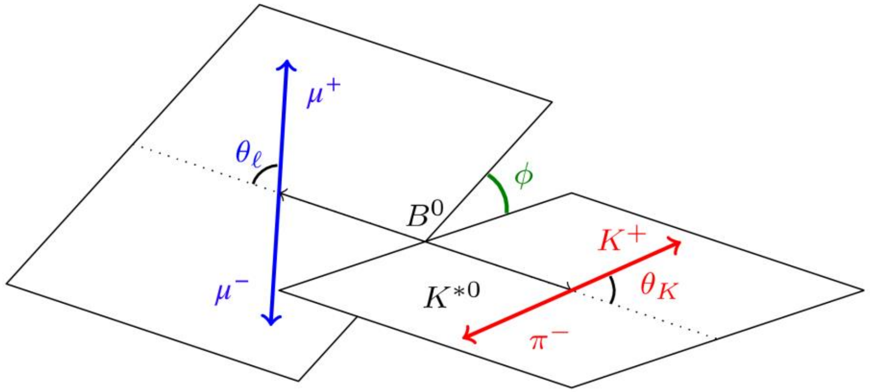
SM: $1.2 - 1.7 \times 10^{-7}$

[PRD 83 (2011) 034034, EPJC 81 (2021) 30, arXiv:2009.06213v2]

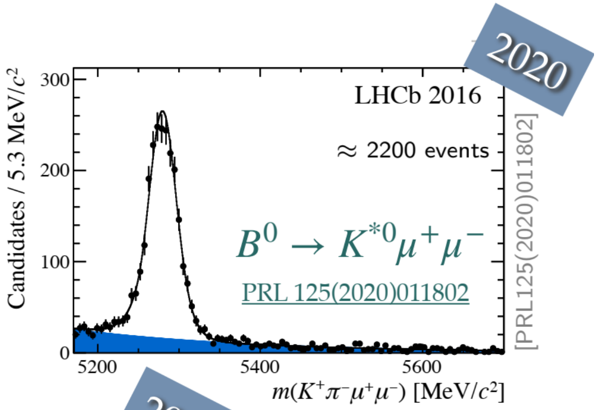


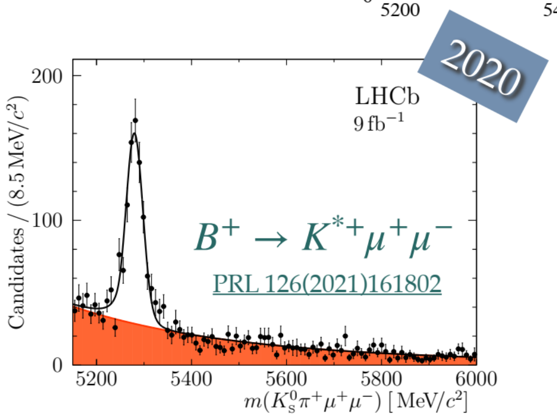
# Angular analyses of $B^0_{(s)} \to V(hh)\mu^+\mu^-$

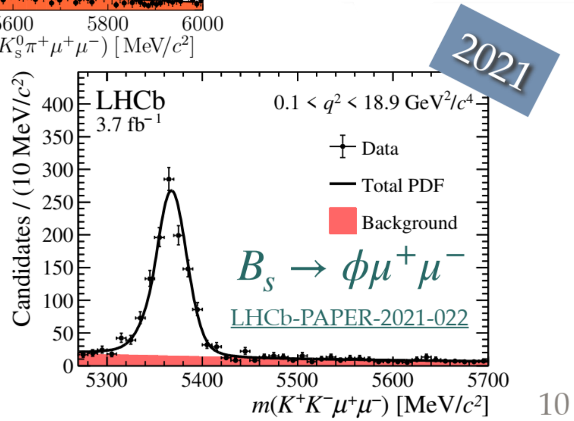
- $B \to V\mu^+\mu^-$ 4-body decay has rich kinematic structure
- Described by 3 angles and $q^2$




- Recent results:
  - $B^0 \to K^{*0}\mu^+\mu^-$with 6/fb (~4600 events)
  - $B^+ \to K^{*+}\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi\mu^+\mu^-$ with 9/fb (~1900 events)



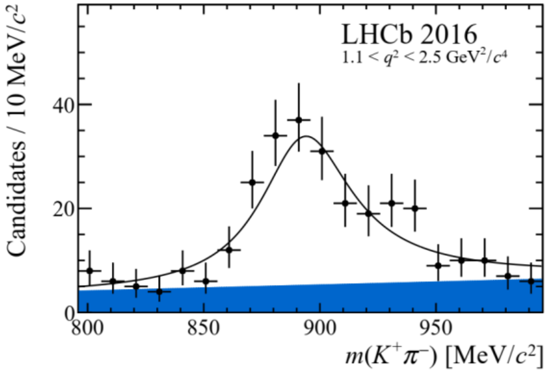
PRL **125** (2020) 011802

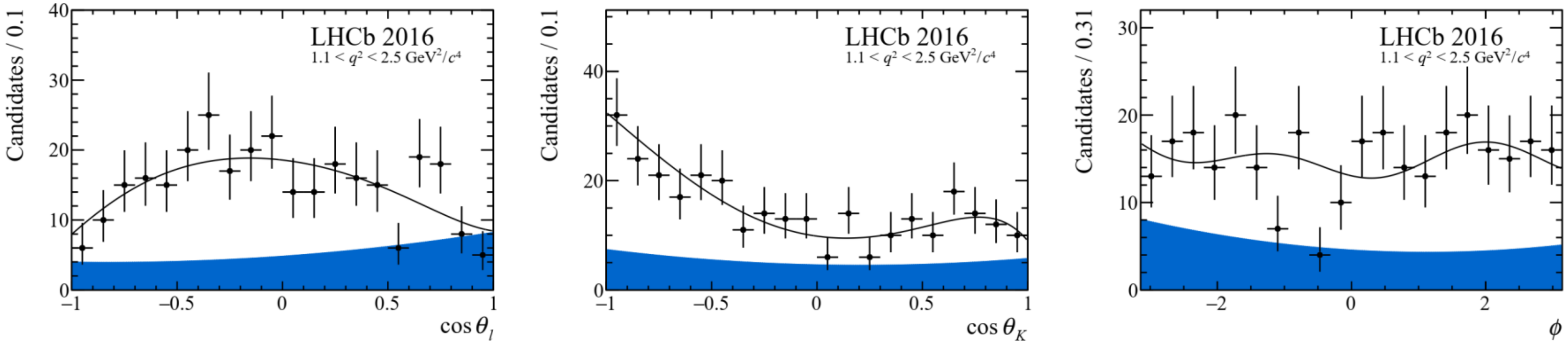
# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

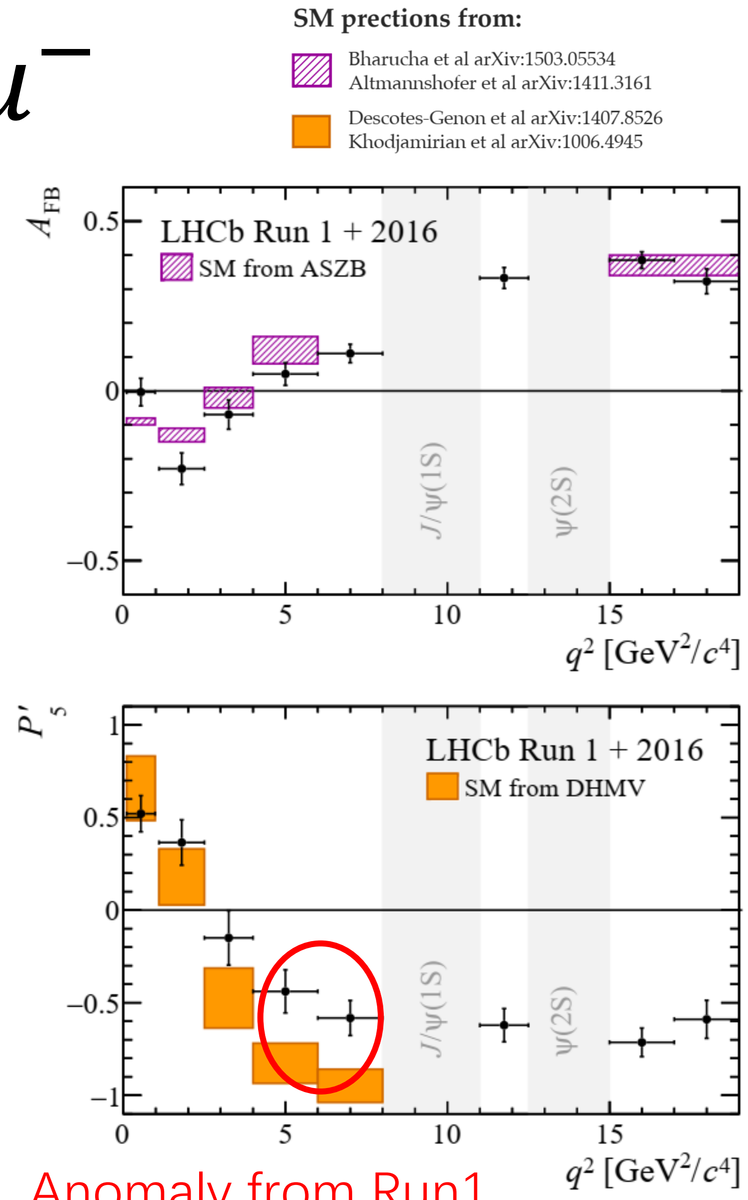
P-wave formulism:

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

- **8 independent CP-averaged observables: $F_L$, $A_{FB}$, $S_{3,4,5,7,8,9}$**
- **Form factors cancel at leading order: $P_i' = S_i/\sqrt{F_L(1-F_L)}$**



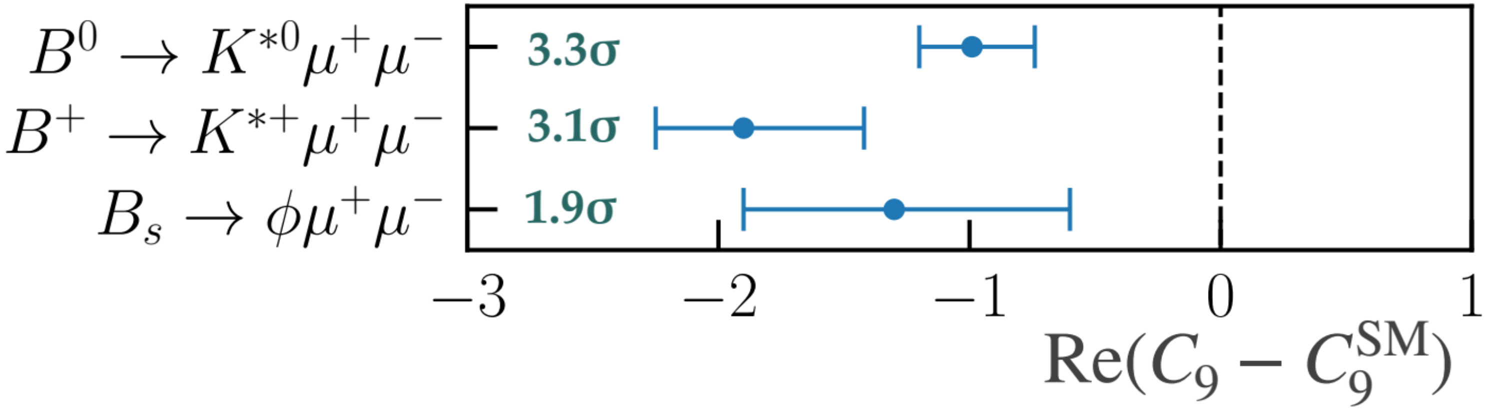




Anomaly from Run1 persists

# Angular analyses of $B^0_{(s)} \to V(hh)\mu^+\mu^-$

- Simple fits of vector coupling $\boldsymbol{C_9}$ based on different LHCb analyses give consistent results

Private compilation of the Flavio fits results presented in from PRL 125(2020)011802, PRL 126(2021)161802, LHCb-PAPER-2021-022




- However $C_9^{\mathrm{SM}}$ could be altered by non-local $c\bar{c}$ loops

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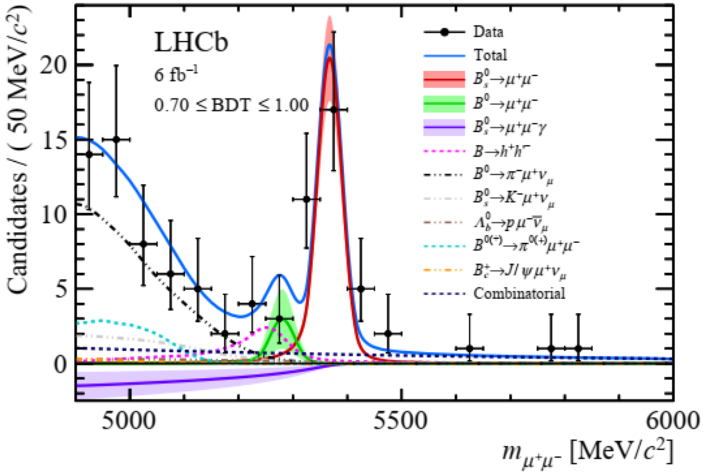
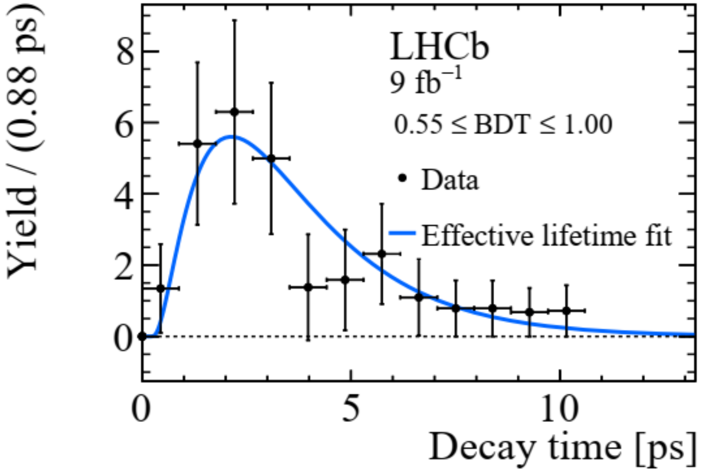
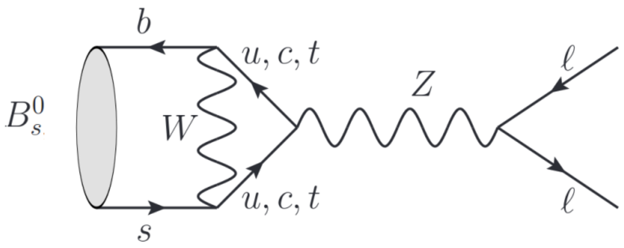
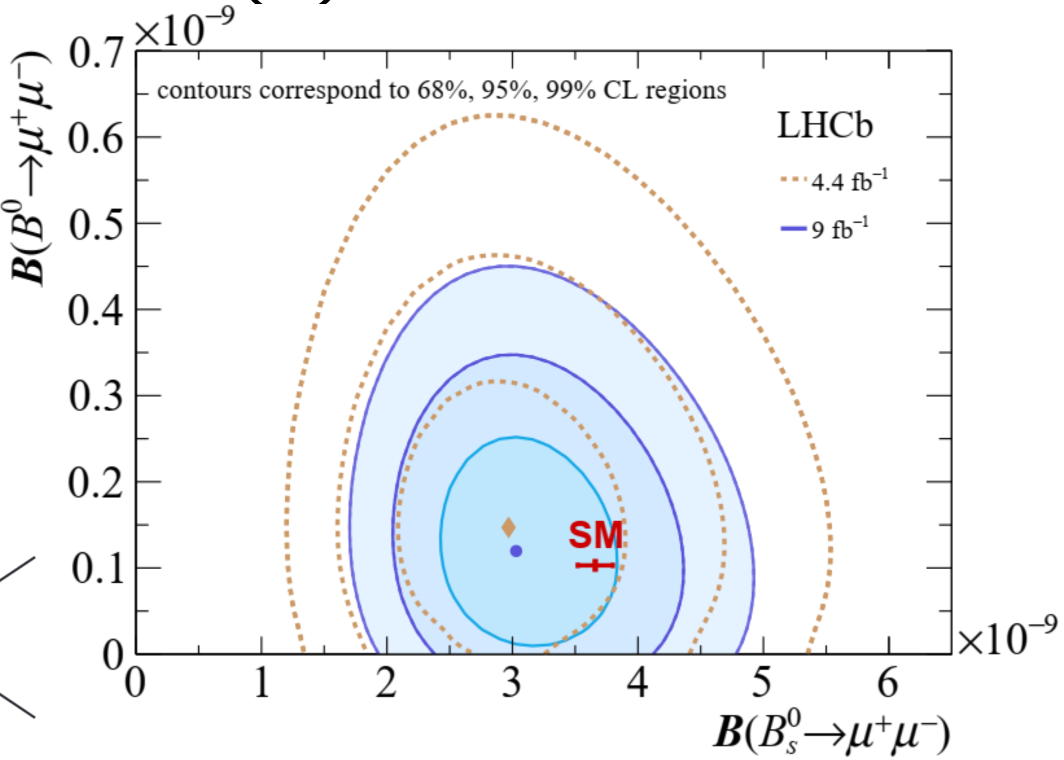
# $B_s^0 \to \mu^+\mu^-$ and search for $B_{(s)}^0 \to \mu^+\mu^-(\gamma)$




$\tau = 2.07 \pm 0.29 \pm 0.03$ ps




$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}\,{}^{+0.15}_{-0.11}) \times 10^{-9}$$

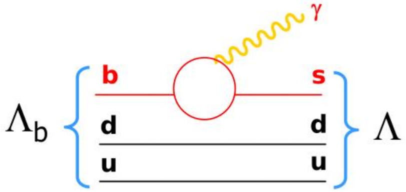
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

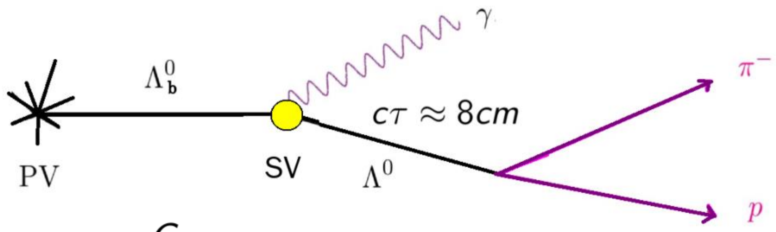
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9} \text{ with } m_{\mu\mu} > 4.9 \text{ GeV}$$

# Photon polarization in $\Lambda_b \to \Lambda\gamma$

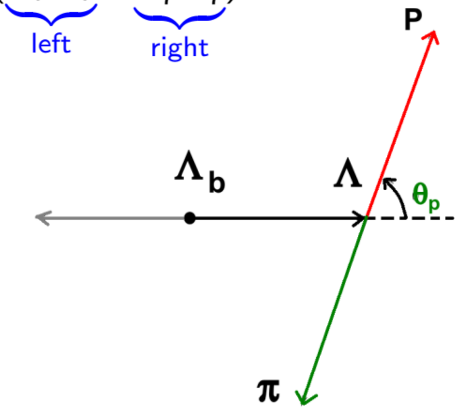
- First angular analysis of radiative b-baryon decays

$N_{\Lambda_b^0\to\Lambda\gamma} = 440 \pm 40$



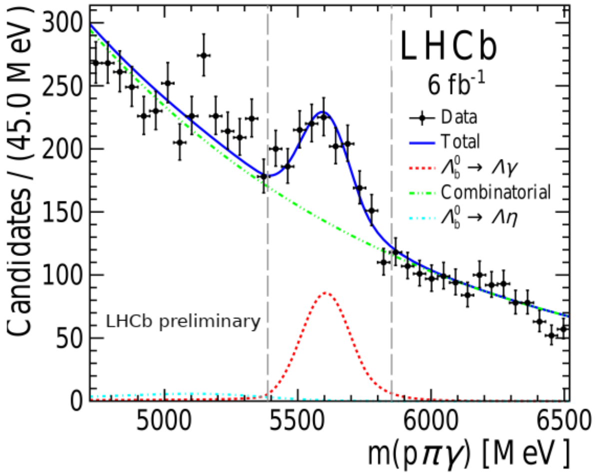



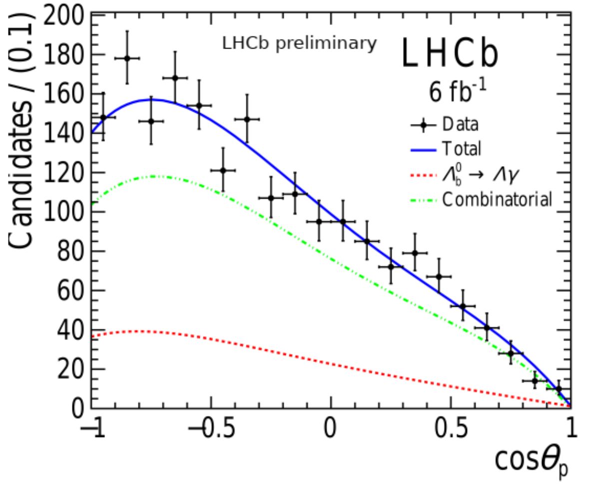

$$\mathcal{H}_{eff} = -4\frac{G_F}{\sqrt{2}}V_{ts}^{*}V_{tb}(\underbrace{C_7O_7}_{\text{left}}+\underbrace{C_7'O_7'}_{\text{right}})$$




$$\Gamma_{\Lambda_b}(\theta_p) = \frac{1}{4}\left(1 - \alpha_\gamma\alpha_\Lambda\cos\theta_p\right)$$

$\alpha_\Lambda$ = 0.754 ± 0.004 [BESIII: NP 15 (2019) 631]

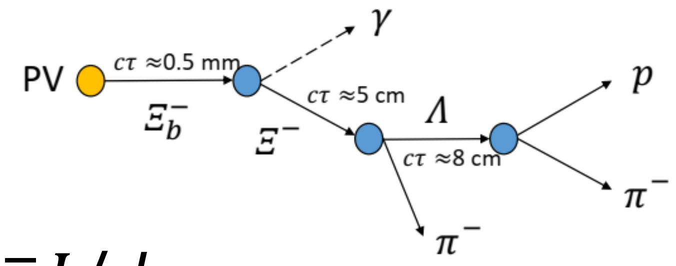



$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\;{}^{+0.04}_{-0.13}$$

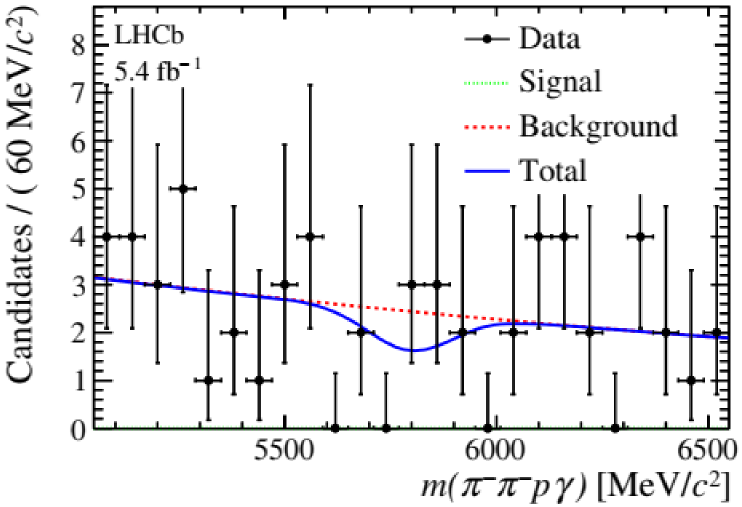
Compatible with SM prediction ($\alpha_\gamma = 1$)

# Search for $\Xi_b^- \to \Xi^-\gamma$

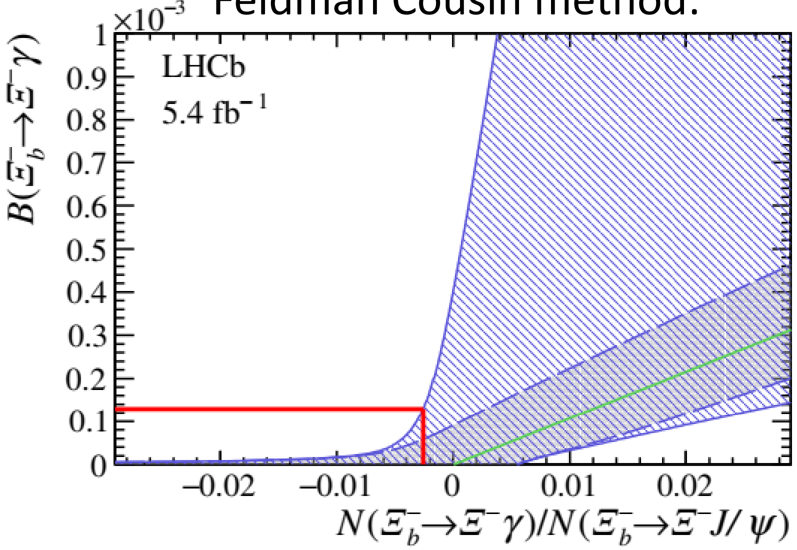



- First search
- Normalization channel: $\Xi_b^- \to \Xi^- J/\psi$

$\Xi_b^- \to \Xi^-\gamma$



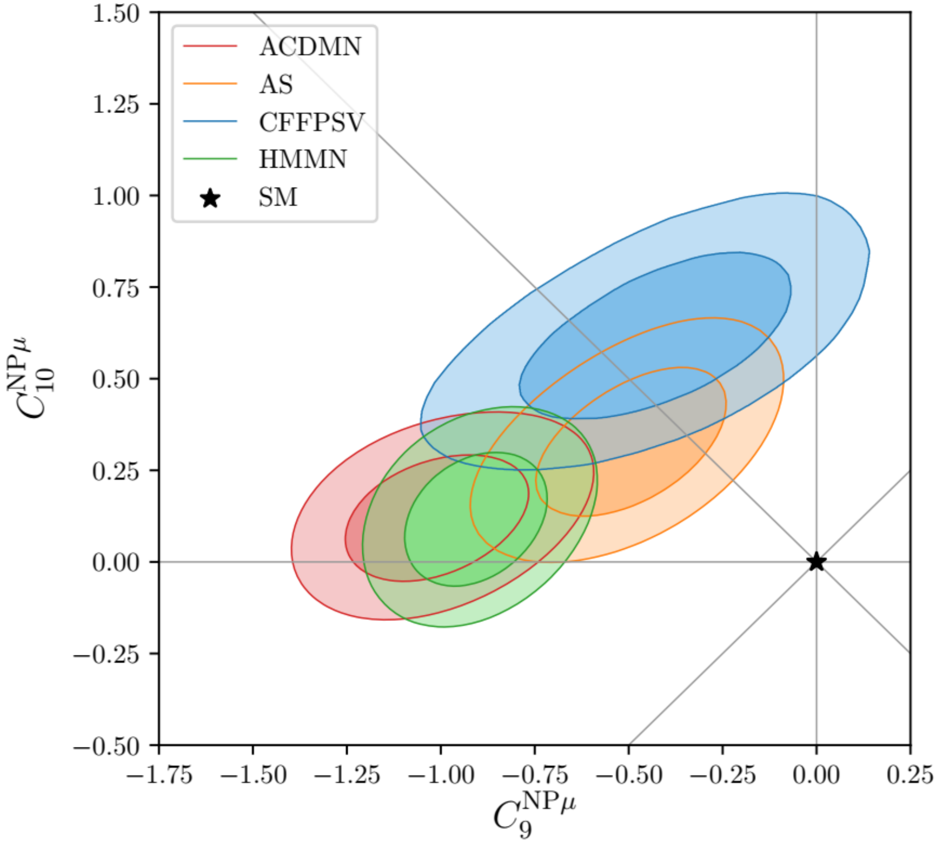

Feldman Cousin method:



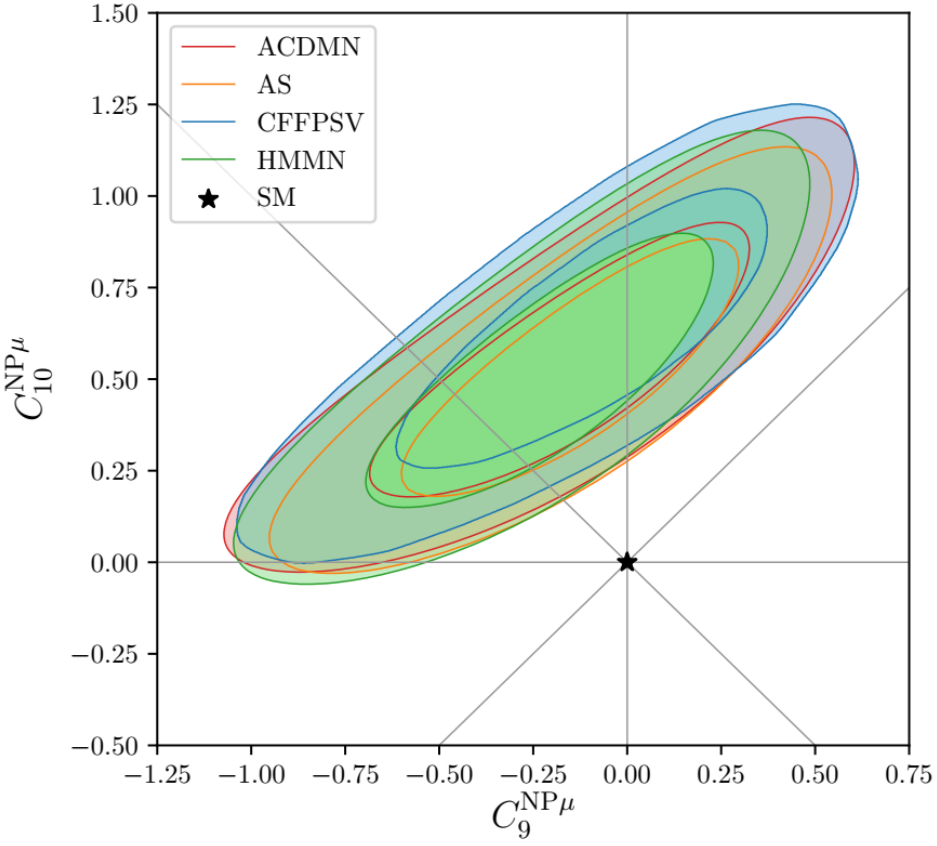

$\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) < 1.3(0.6) \times 10^{-4}$ at 95% (90%) CL

$\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)$ is the main source of uncertainty

# A coherent pattern?




Global fit based on experimental inputs from $b \to s\ell\ell$ and $b \to s\gamma$




fit to LFU observables + $B_s \to \mu\mu$

From B. Capdevila *et al.*'s talk @ Flavour Anomaly Workshop 2021

# Overview of rare charm decays @ LHCb

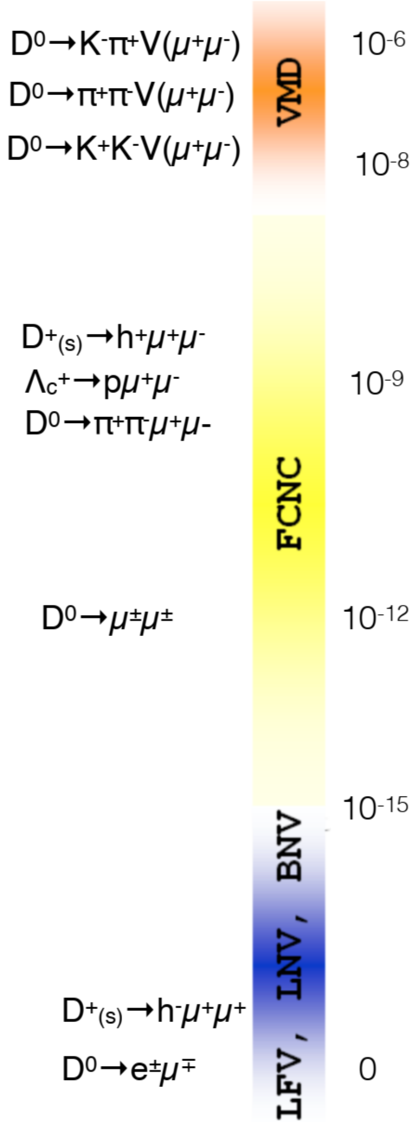
branching ratios, especially regions away from the resonances

- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
- search for $D^+_{(s)} \to h^+l^+l^-$ [PLB 724 203-212 (2013)] [JHEP 06 44 (2021)]
- search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
- search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
- observation of $D^0 \to h^-h^{(\prime)+} V(\mu^+\mu^-)$ [PLB 757 558-567 (2016)], [PRL 119, 181805 (2017)]

null tests based on (approximate) symmetries

- lepton-flavor/number-violation
  - search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - search for $D^+_{(s)} \to h^-l^+l^{(\prime)+}$, $D^+_{(s)} \to h^+\mu^\pm e^\mp$ [JHEP 06 44 (2021)]
- angular observables and CP asymmetries
  - angular analysis and search for CPV in $D^0 \to h^+h^-\mu^+\mu^-$

[PRL 121 091801 (2018)], [LHCb-PAPER-2021-035 ]

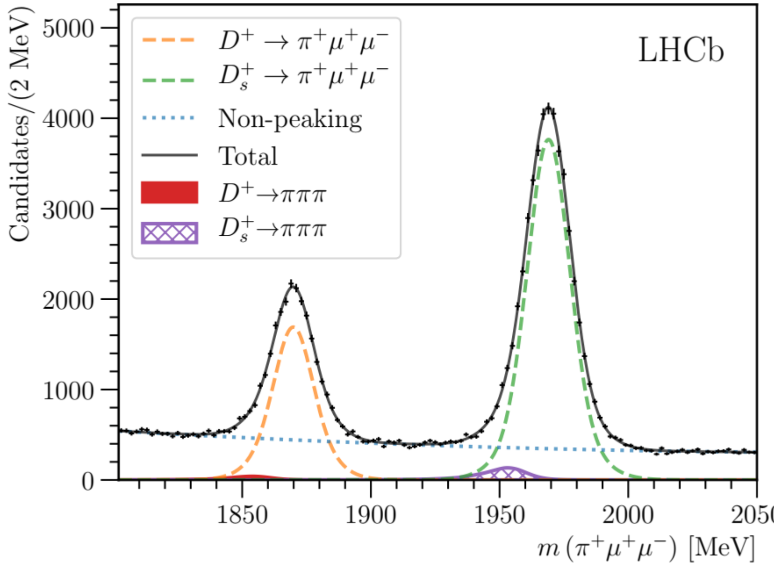


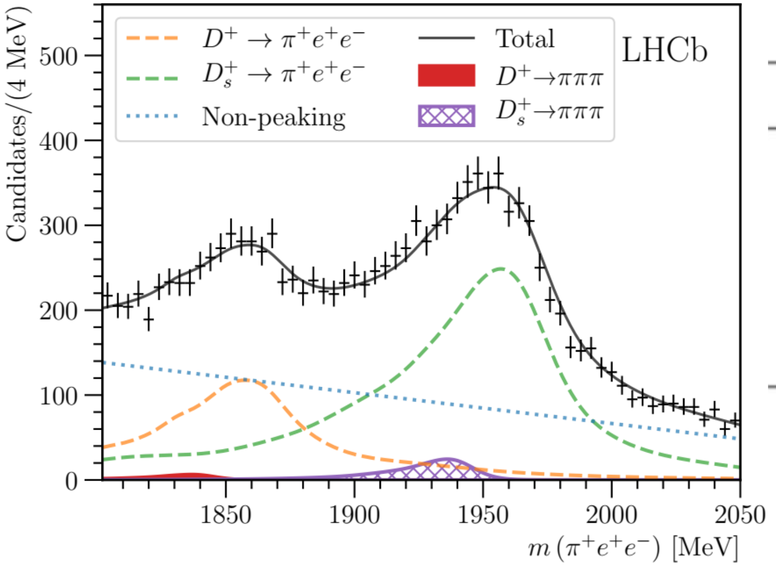
# Search for $D_{(s)}^{+} \to h^{\pm}\ell^{+}\ell^{(\prime)\mp}$ decays

- 25 decays
  LFV & LNV included
- Normalized with $D_{(s)}^{+} \to \phi(\ell\ell)\pi^{+}$
- Analysis based on 2016 dataset (1.7 fb$^{-1}$)

| | | | | |
|---|---|---|---|---|
| $D^+ \to \pi^+\mu^+\mu^-$ | $D^+ \to \pi^+e^+e^-$ | $D^+ \to K^+e^+e^-$ | $D_s^+ \to \pi^+e^+\mu^-$ | $D_s^+ \to K^+\mu^+e^-$ |
| $D^+ \to \pi^-\mu^+\mu^+$ | $D^+ \to \pi^-e^+e^+$ | $D_s^+ \to \pi^+\mu^+\mu^-$ | $D_s^+ \to \pi^+e^+e^-$ | $D_s^+ \to K^-\mu^+e^+$ |
| $D^+ \to \pi^+\mu^+e^-$ | $D^+ \to K^+\mu^+\mu^-$ | $D_s^+ \to \pi^-\mu^+\mu^+$ | $D_s^+ \to \pi^-e^+e^+$ | $D_s^+ \to K^+e^+\mu^-$ |
| $D^+ \to \pi^-\mu^+e^+$ | $D^+ \to K^+\mu^+e^-$ | $D_s^+ \to \pi^+\mu^+e^-$ | $D_s^+ \to K^+\mu^+\mu^-$ | $D_s^+ \to K^+e^+e^-$ |
| $D^+ \to \pi^+e^+\mu^-$ | $D^+ \to K^+e^+\mu^-$ | $D_s^+ \to \pi^-\mu^+e^+$ | $D_s^+ \to K^-\mu^+\mu^+$ | $D_s^+ \to K^-e^+e^+$ |

Allowed in the SM, Forbidden in the SM



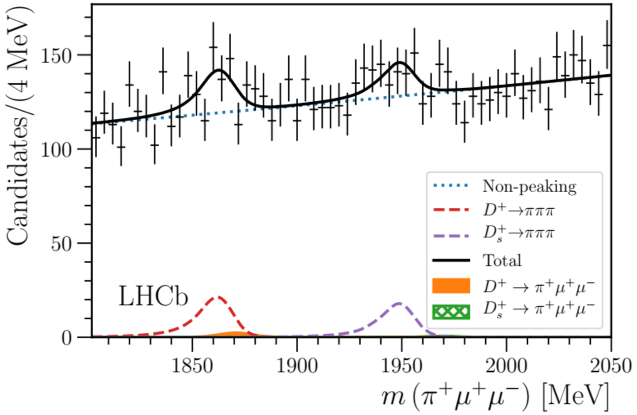



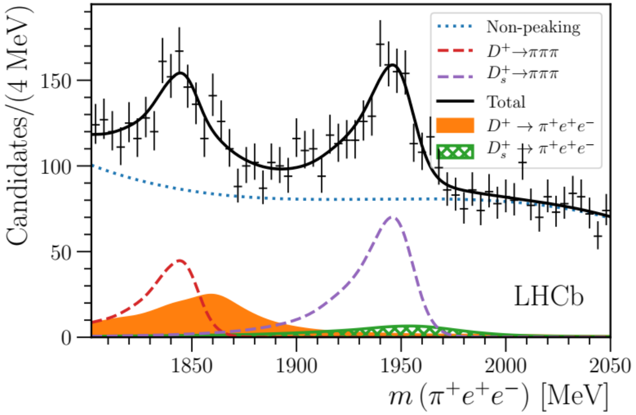

| Channel | Fitted yield |
|---|---|
| $D^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$ | 18 100±340 |
| $D^+ \to (\phi \to e^-e^+)\,\pi^+$ | 2160±180 |
| $D_s^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$ | 42 000±400 |
| $D_s^+ \to (\phi \to e^-e^+)\,\pi^+$ | 5320±180 |

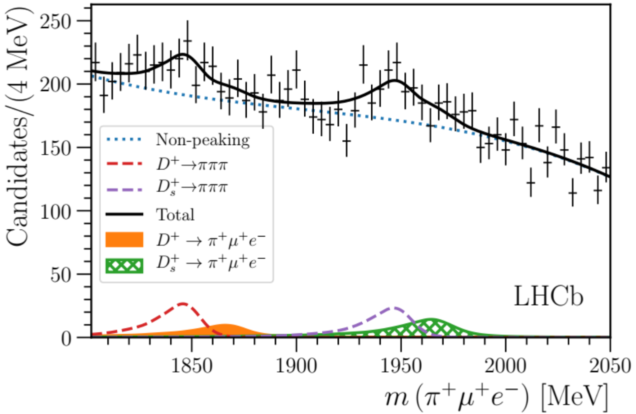
# Search for $D_{(s)}^{+} \to h^{\pm}\ell^{+}\ell^{(\prime)\mp}$ decays

JHEP 06 (2021) 44

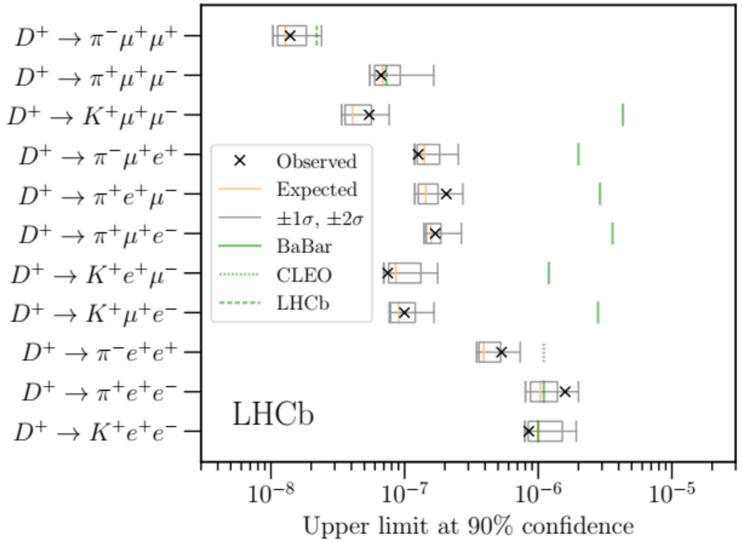
- No signal observed, BF limits are set down to $\mathcal{O}(10^{-8})$
- Results improve the prior world's best by up to a factor of 500

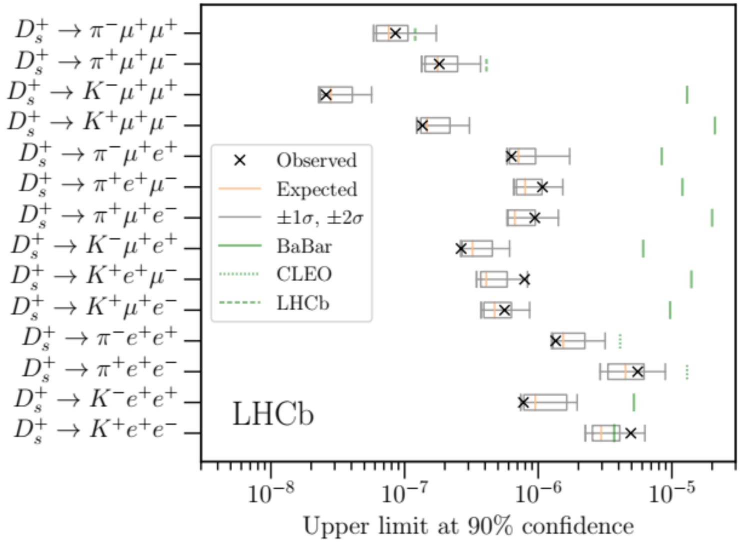



Regions dominated by resonances in dilepton mass spectrum are vetoed



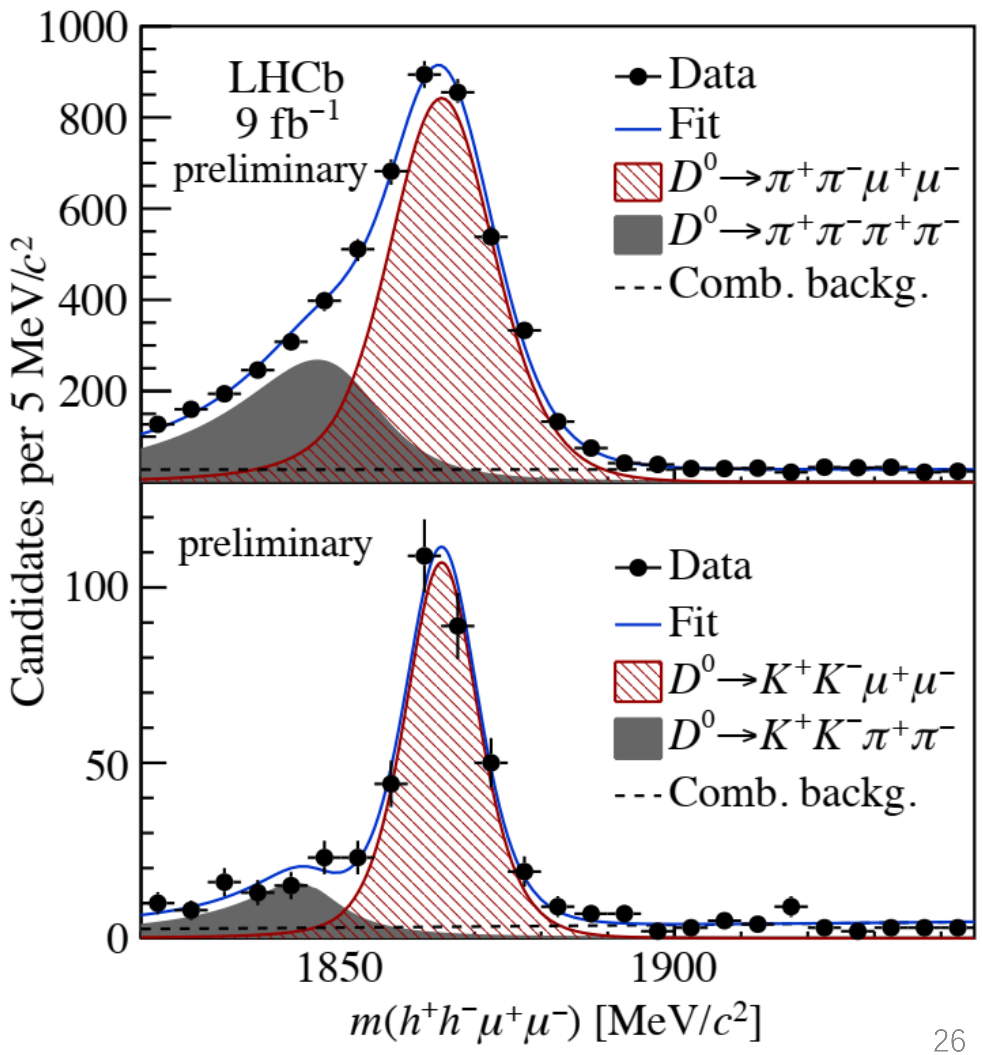
# CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$

- Rarest charm meson decays observed, dominated by resonant contributions

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

- First full angular analysis with 9 fb$^{-1}$ data
- $D^0$ selected from flavor specific $D^{*+} \to D^0\pi^+$

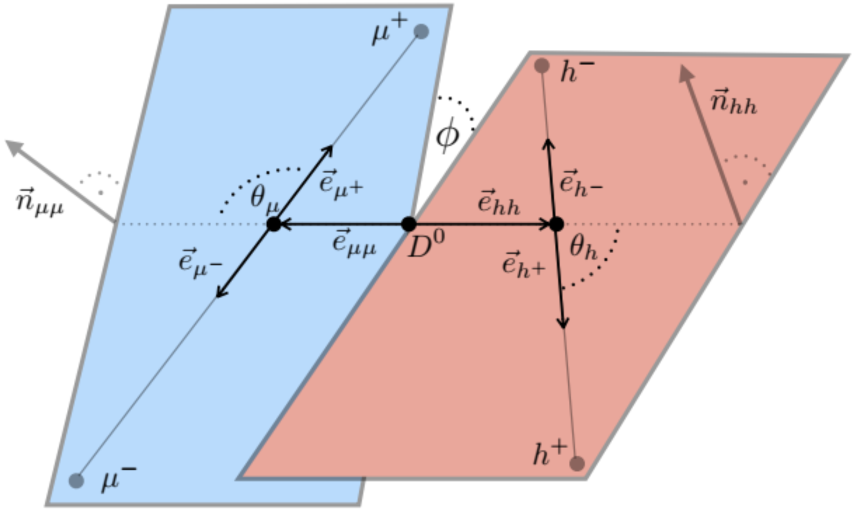
N($D^0 \to \pi^+\pi^-\mu^+\mu^-$) ~3500
N($D^0 \to K^+K^-\mu^+\mu^-$) ~ 300



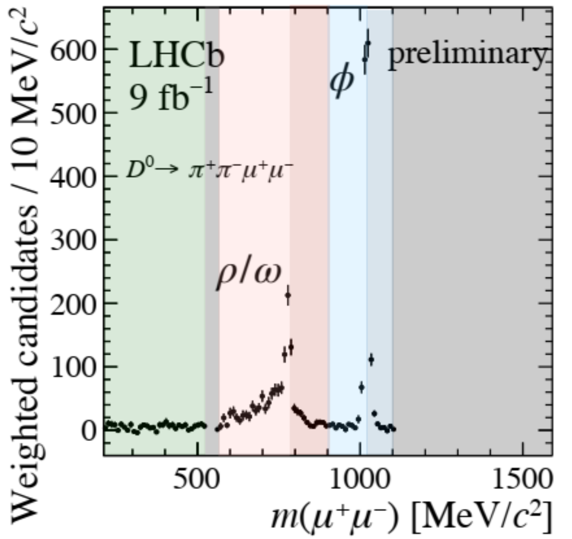
# Differential decay rate in $D^0 \to hh\mu^+\mu^-$

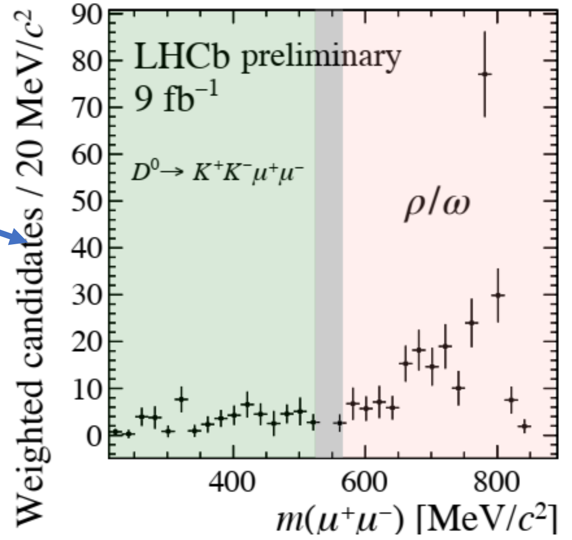
$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = \begin{aligned} & I_1 + \\ & I_2 \cdot \cos 2\theta_\mu + \\ & I_3 \cdot \sin^2 2\theta_\mu \cos 2\phi + \\ & I_4 \cdot \sin 2\theta_\mu \cos\phi + \\ & I_5 \cdot \sin\theta_\mu \cos\phi + \\ & I_6 \cdot \cos\theta_\mu + \\ & I_7 \cdot \sin\theta_\mu \sin\phi + \\ & I_8 \cdot \sin 2\theta_\mu \sin\phi + \\ & I_9 \cdot \sin^2\theta_\mu \sin 2\phi \end{aligned}$$

$I_5, I_6, I_7$ clean null tests!




$p^2 = m^2(h^+h^-)$
$q^2 = m^2(\mu^+\mu^-)$




- Measure $p^2$, $\cos\theta_h$ integrated $\langle I_i \rangle$ separately for $D^0/\overline{D}^0$ in $q^2$ bins

$$\langle I_{2,3,6,9}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \int_{-1}^{1} d\cos\theta_h \; I_{2,3,6,9}$$

$$\langle I_{4,5,7,8}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \left[\int_{-1}^{0} d\cos\theta_h - \int_{0}^{1} d\cos\theta_h\right] I_{4,5,7,8}$$

$$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-) \langle \overline{I}_i \rangle\right] \qquad \langle S_{5,6,7}\rangle \overset{SM}{=} 0$$

$$\langle A_i \rangle = \frac{1}{2}\left[\langle I_i \rangle - (+) \langle \overline{I}_i \rangle\right] \qquad \langle A_i\rangle \overset{SM}{=} 0$$

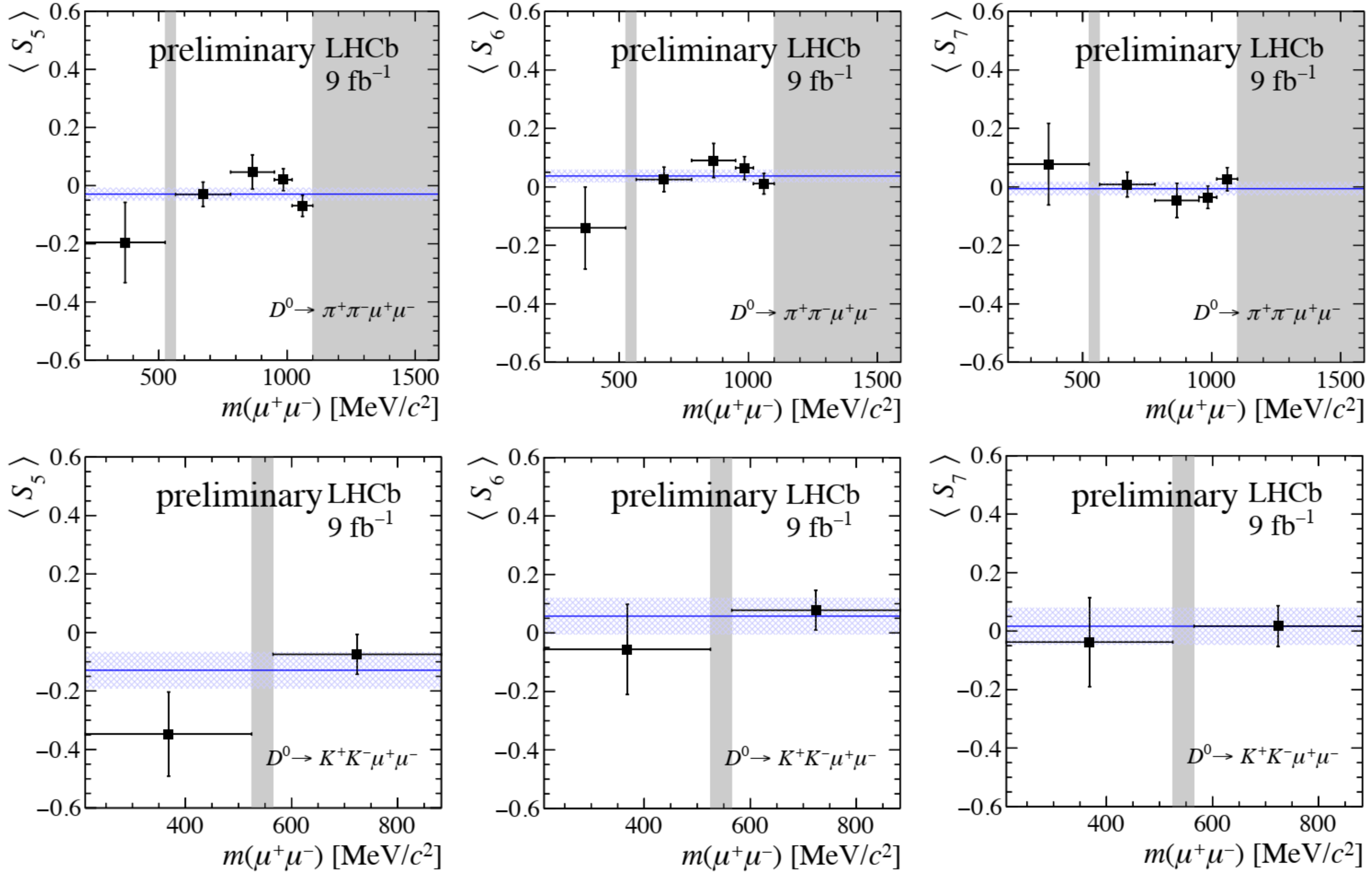
i=2,..,9

for CP even (CP odd) coefficients

# Flavor-averaged observables $\langle S_i \rangle$

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"

- Shown examples: SM null tests $\langle S_{5,6,7} \rangle$ [$\langle S_6 \rangle \sim A_{FB}$]



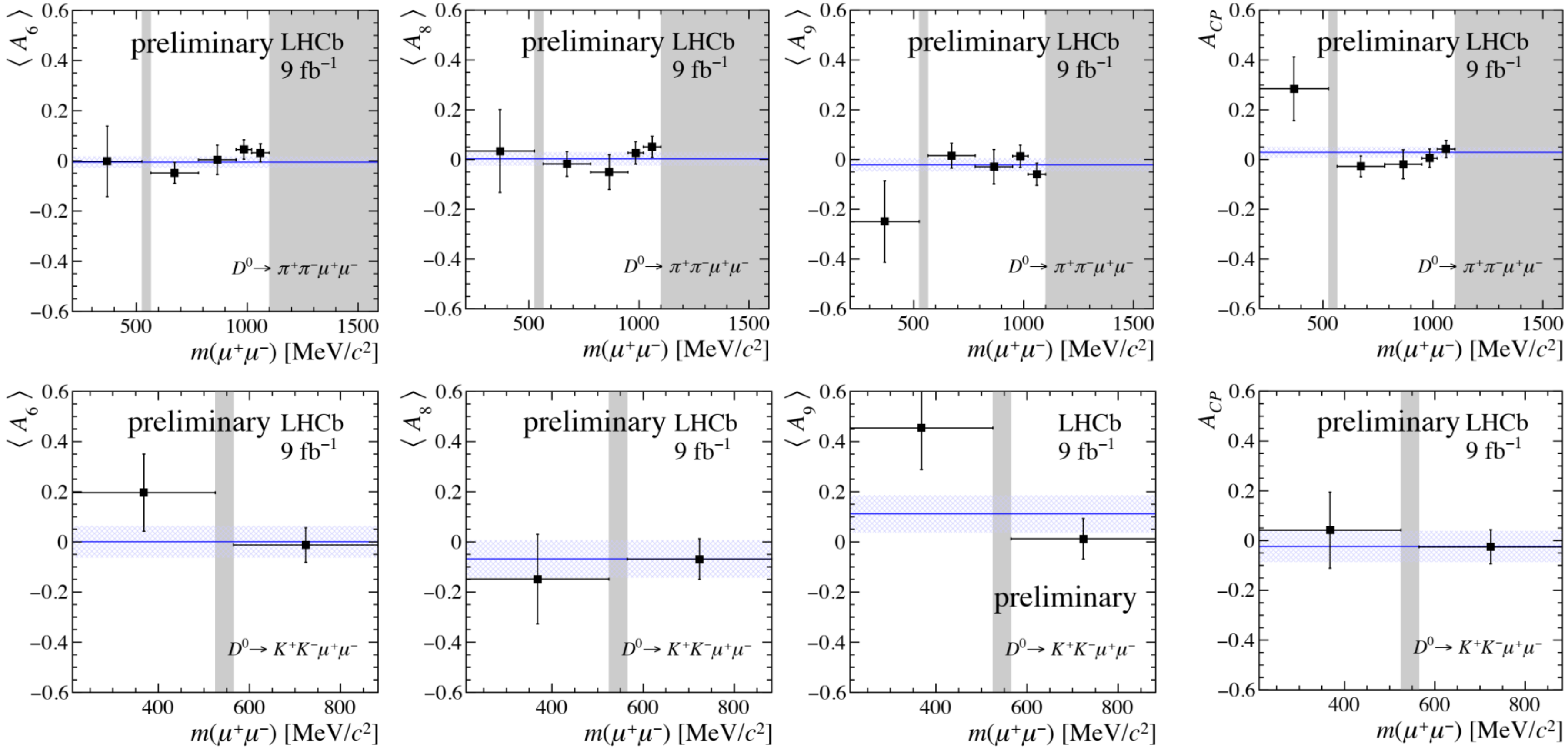

**agreement with SM predictions**
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

# $CP$ asymmetries $\langle A_i \rangle$

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"

- Shown: $\langle A_6 \rangle$ [$\langle A_6 \rangle \sim A_{FB}^{CP}$], $\langle A_{8,9} \rangle$ [triple-product-asym.] & $A_{CP}$




- overall agreement wrt. to SM hypothesis considering $A_{CP}$, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

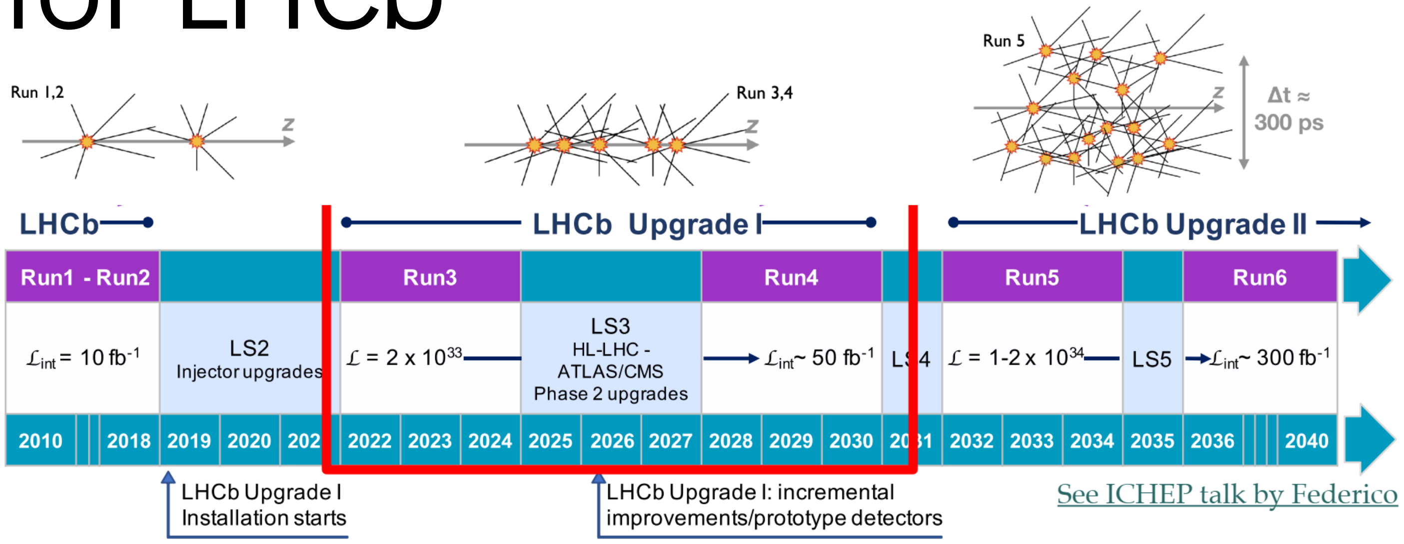
| | |
|---|---|
| $D^0 \to \pi^+\pi^-\mu^+\mu^-$ | p = 79% (0.3$\sigma$) |
| $D^0 \to K^+K^-\mu^+\mu^-$ | p = 0.8% (2.7$\sigma$) |

preliminary

consistent with SM

# Run3 and beyond for LHCb

- A new LHCb detector for Run3 with 5x higher luminosity
- Real time trigger with GPUs
- Goals for Runs 3-4: collect 5x more data in dimuon channels, 10x in hadronic channels




See ICHEP talk by Federico

Ready for HL-LHC

| Observable | Current LHCb (up to 9 fb$^{-1}$) | | Upgrade I (23 fb$^{-1}$) | (50 fb$^{-1}$) | Upgrade II (300 fb$^{-1}$) |
|---|---|---|---|---|---|
| **Rare Decays** | | | | | |
| $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$ | 71% | [40, 41] | 34% | — | 10% |
| $S_{\mu\mu}$ $(B^0_s \to \mu^+\mu^-)$ | — | | — | — | 0.2 |
| $A_T^{(2)}$ $(B^0 \to K^{*0}e^+e^-)$ | 0.10 | [52] | 0.060 | 0.043 | 0.016 |
| $A_T^{\rm Im}$ $(B^0 \to K^{*0}e^+e^-)$ | 0.10 | [52] | 0.060 | 0.043 | 0.016 |
| $\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$ | $^{+0.41}_{-0.44}$ | [51] | 0.124 | 0.083 | 0.033 |
| $S_{\phi\gamma}(B^0_s \to \phi\gamma)$ | 0.32 | [51] | 0.093 | 0.062 | 0.025 |
| $\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$ | $^{+0.17}_{-0.29}$ | [53] | 0.148 | 0.097 | 0.038 |
| **Lepton Universality Tests** | | | | | |
| $R_K$ $(B^+ \to K^+\ell^+\ell^-)$ | 0.044 | [12] | 0.025 | 0.017 | 0.007 |
| $R_{K^*}$ $(B^0 \to K^{*0}\ell^+\ell^-)$ | 0.10 | [61] | 0.031 | 0.021 | 0.008 |
| $R(D^*)$ $(B^0 \to D^{*-}\ell^+\nu_\ell)$ | 0.026 | [62, 64] | 0.007 | — | 0.002 |

# Summary

- LHCb has been extremely successful in searching for NP in rare decays of heavy flavor hadrons
- Flavor anomalies in $b \to s\ell^+\ell^-$ reinforced by recent measurements
  - A coherent pattern?
  - LU related to muon g-2 anomaly?
- Continuing efforts in analyzing Runs 1-2 data
  - Stay tuned for more exciting results!
- Run 3 is upcoming, more data may be able to solve the puzzle
- Synergies from BESIII important in the quest

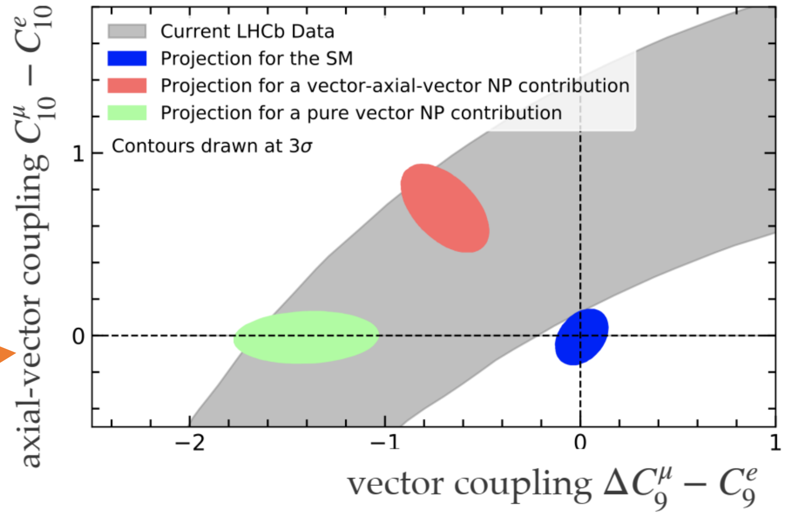


Image credit Patrick Koppenburg