



Rare decays in $b \rightarrow s/d$ sector

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on behalf of ATLAS, CMS, and LHCb collaboration

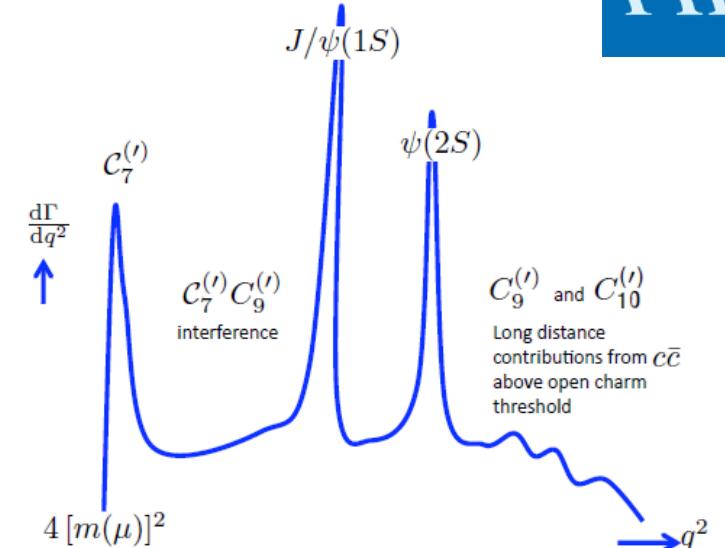


- Motivations
- Branching ratio
 - $B_s^0 \rightarrow \phi \mu^+ \mu^-$ & $B_s^0 \rightarrow f'_2 \mu^+ \mu^-$
 - $\Xi_b^- \rightarrow \Xi^- \gamma$
- Angular analysis
 - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - $B^+ \rightarrow K^{*+} \mu^+ \mu^-$
 - $B_s^0 \rightarrow \phi \mu^+ \mu^-$
- Lepton flavor universality (LFU)
 - R_K
- Summary

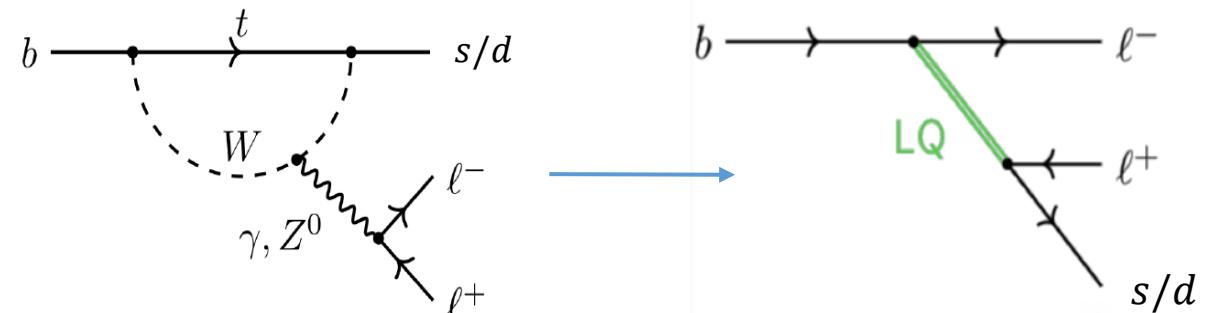
Motivations

- Rare decays
 - Indirect search of New Physics (NP)
 - FCNC process forbidden at tree-level in SM ($\mathcal{B} \sim \mathcal{O}(10^{-7})$)
 - $b \rightarrow s$ or $b \rightarrow d$ transitions
 - sensitive to NP contribution
 - described with effective field theory (EFT)
- Measurements as function of $q^2 = (m(l\bar{l}))^2$, sensitive to different operator contributions (Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$)
- BFs, angular observables, $R_X(*)$

see also [Jacco De Vries's talk](#) about $B_s^0 \rightarrow \mu^+ \mu^-$



$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i^{7,9,10,S,P} (C_i O_i + C'_i O'_i)$$

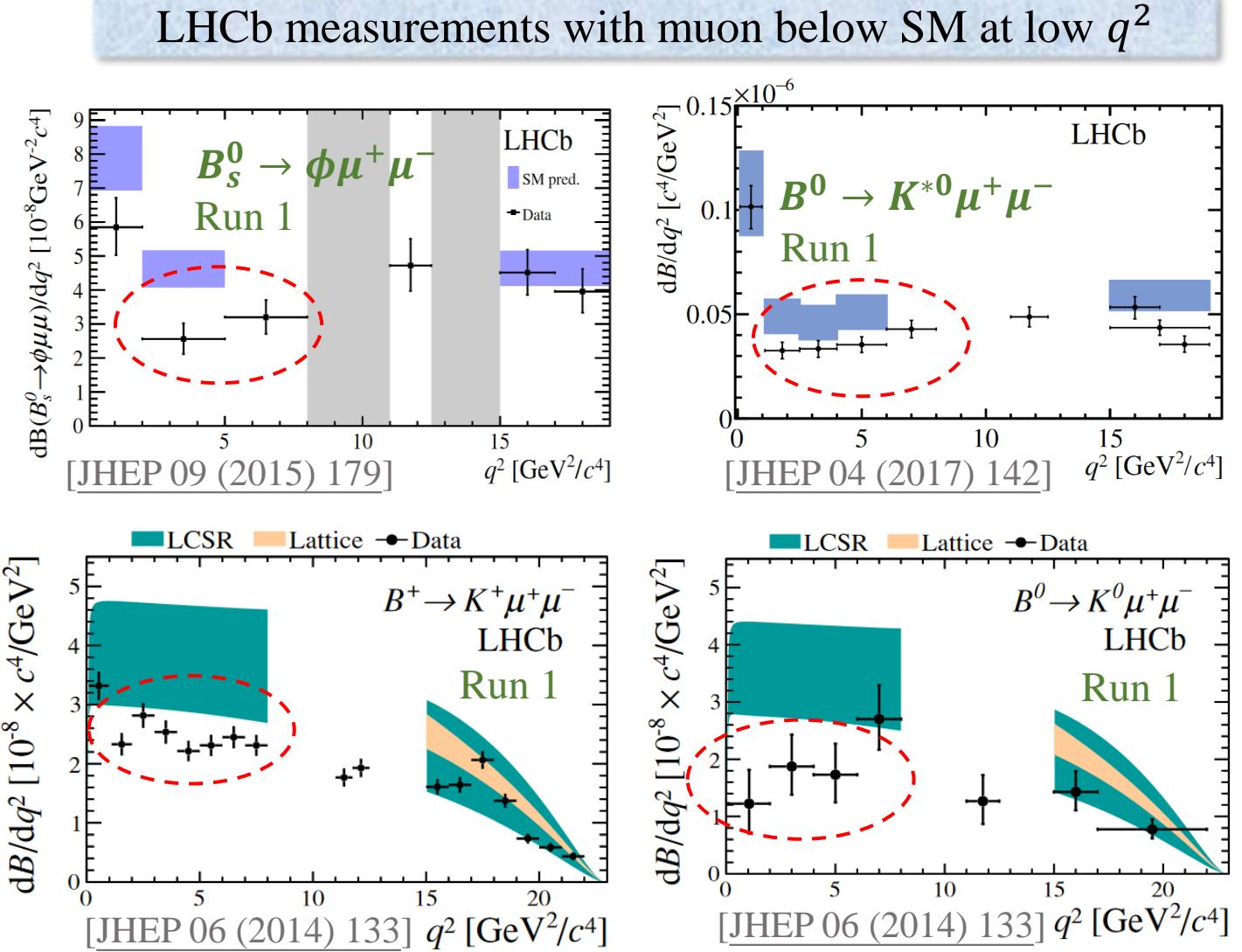
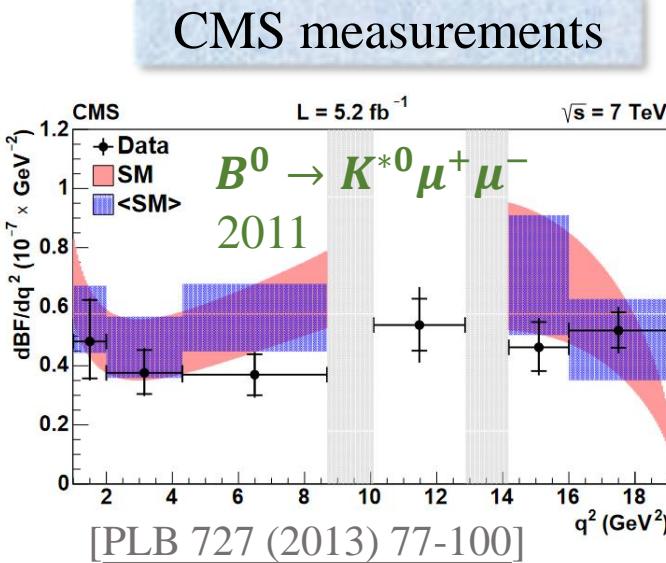


(*) X stands for K^+, K^{*0}, ϕ, pK , and etc.

- Motivations
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 - $B_s^0 \rightarrow \phi \mu^+ \mu^-$ & $B_s^0 \rightarrow f'_2 \mu^+ \mu^-$ [[arXiv:2105.14007](#)]
 - $\Xi_b^- \rightarrow \Xi^- \gamma$ [LHCb-PAPER-2021-017, in preparation]
- Angular analysis
 - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [[JHEP 10\(2018\) 047](#)] [[PLB 781 \(2018\) 517](#)] [[PRL 125 \(2020\) 011802](#)]
 - $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ [[JHEP 04 \(2021\) 124](#)] [[PRL 126 \(2021\) 161802](#)]
 - $B_s^0 \rightarrow \phi \mu^+ \mu^-$ [LHCb-PAPER-2021-022, in preparation]
- Lepton flavor universality (LFU)
 - R_K [[arXiv:2103.11769](#)]
- Summary

Differential BF rates

- Decay rates are consistently low
- Consistent with SM though large uncertainties



$B_s^0 \rightarrow \phi \mu^+ \mu^-$ and $B_s^0 \rightarrow f'_2 \mu^+ \mu^-$ @ LHCb

[arXiv:2105.14007]

LHCb
LHCf

- Updated with Run 1 + 2 dataset
- In the range of $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$
 - 3.6σ below SM prediction (LCSR+Lattice)
(1.8σ with LCSR alone)

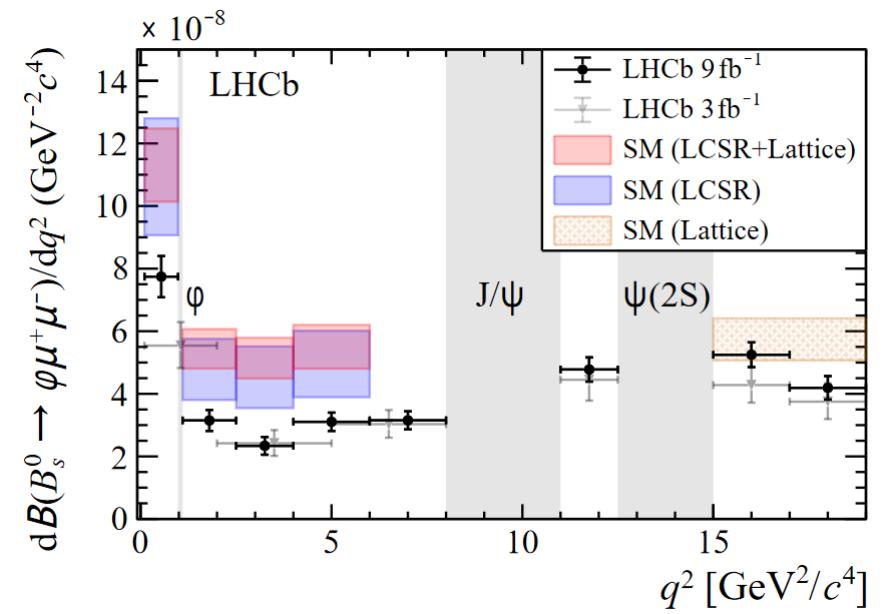
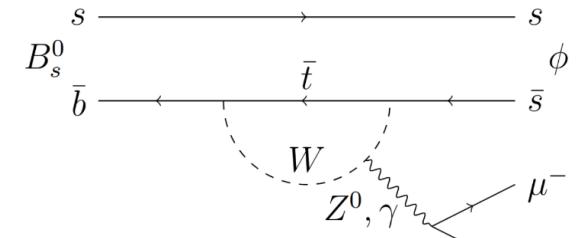
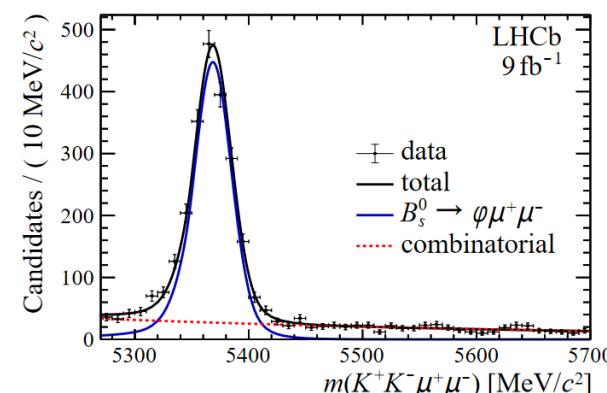
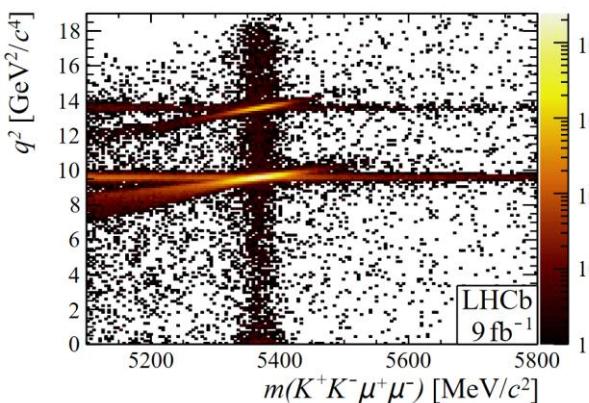
$$\frac{d\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}{q_{6.0}^2 - q_{1.1}^2} \times \frac{N_{\phi \mu^+ \mu^-}}{N_{J/\psi \phi}} \times \frac{\epsilon_{J/\psi \phi}}{\epsilon_{\phi \mu^+ \mu^-}} = (2.88 \pm 0.21) \times 10^{-8} \text{ GeV}^2/c^4$$

- Branching ratio integrated over q^2

$$\frac{\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = (8.00 \pm 0.21 \pm 0.16 \pm 0.03) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-) = (8.14 \pm 0.21 \pm 0.16 \pm 0.03 \pm 0.39) \times 10^{-7}$$

stat. syst. q^2 extrap. norm.



$B_s^0 \rightarrow \phi \mu^+ \mu^-$ and $B_s^0 \rightarrow f'_2(1525) \mu^+ \mu^-$ @ LHCb

[arXiv:2105.14007]

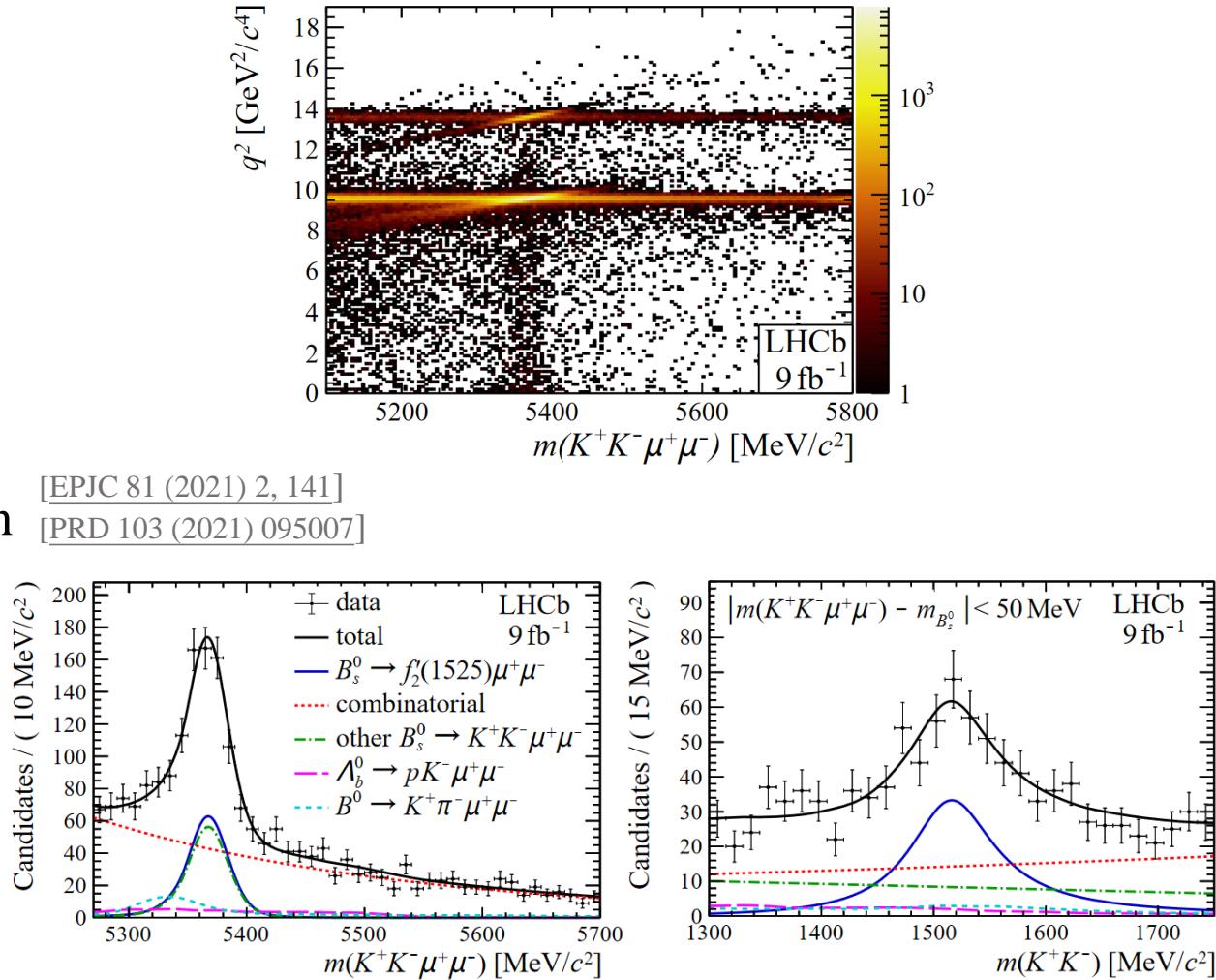
LHCb
LHCcp

- First measurement of $B_s^0 \rightarrow f'_2(1525) \mu^+ \mu^-$
- 2-dimentional fit to separate S-wave and P-wave contributions of $f'_2(1525)$ (distinguish signal)
- Observation with 9σ significance
- Branching Ratio in agreement with SM prediction

$$\frac{\mathcal{B}(B_s^0 \rightarrow f'_2 \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = (1.55 \pm 0.19 \pm 0.06 \pm 0.06) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \rightarrow f'_2 \mu^+ \mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$

stat. syst. q^2 extrap. norm.



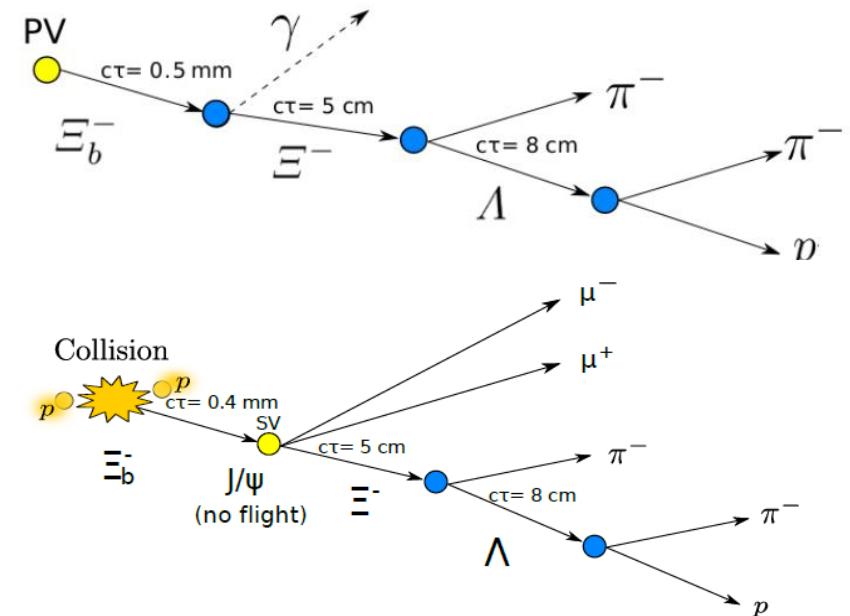
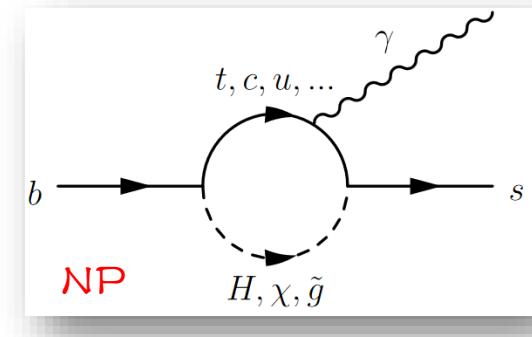
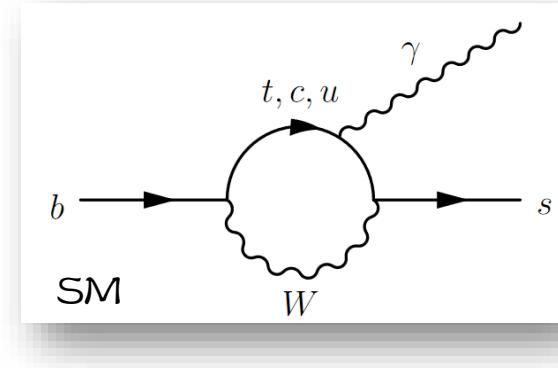


- $b \rightarrow s\gamma$ transition, known as radiative decays
- \mathcal{O}_7 (\mathcal{O}'_7) represents the left (right) operator, corresponding to emission of a left (right)-handed photon

$$\|r\| = \frac{c'_7}{c_7} \sim \mathcal{O}\left(\frac{m_s}{m_b}\right)$$

- Only b_L quark can couple with W^- boson, therefore γ_R comes from chirality flips in SM
- provide access to photon polarization
- Normalization mode: $E_b^- \rightarrow E^- J/\psi$

$$\mathcal{B}(E_b^- \rightarrow E^- J/\psi) = (\frac{3}{2} \pm 0.45) \frac{\tau_{E_b^-}}{\tau_{\Lambda_b^0}} \mathcal{B}(\Lambda_b^0 \rightarrow \Lambda J/\psi) = (5.3 \pm 2.4) \times 10^{-4}$$

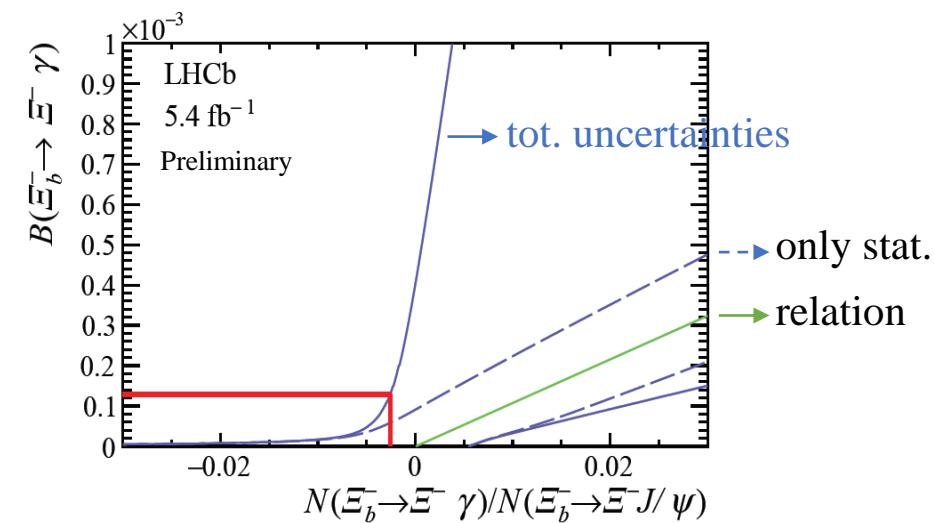
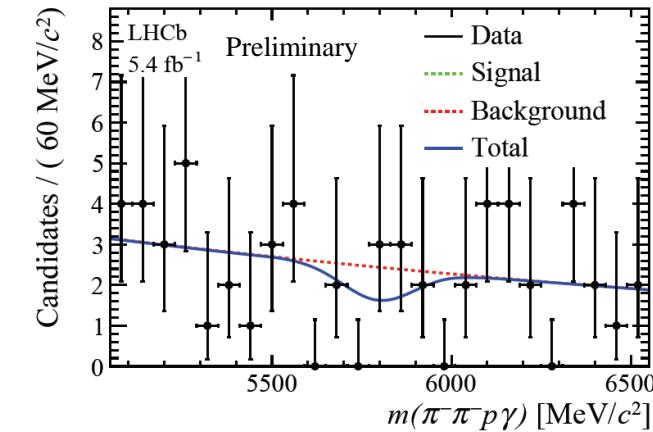




- Run 2 data
- First search for $\Xi_b^- \rightarrow \Xi^- \gamma$
- No signal observed, set with upper limit
- Systematic uncertainty mainly from normalization mode

$$\mathcal{B}(\Xi_b^- \rightarrow \Xi^- \gamma) = \mathcal{B}(\Xi_b^- \rightarrow \Xi^- J/\psi) \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) \times \frac{\epsilon(\Xi_b^- \rightarrow \Xi^- J/\psi)}{\epsilon(\Xi_b^- \rightarrow \Xi^- \gamma)} \frac{N(\Xi_b^- \rightarrow \Xi^- \gamma)}{N(\Xi_b^- \rightarrow \Xi^- J/\psi)} < 1.3 \times 10^{-4} \text{ at 95% CL}$$

- Reduce total systematics
- $$\frac{\mathcal{B}(\Xi_b^- \rightarrow \Xi^- \gamma)}{\mathcal{B}(\Xi_b^- \rightarrow \Xi^- J/\psi)} < 0.12 \text{ at 95% CL}$$
- **Exclude** LCSR predictions:
 $(3.03 \pm 0.10) \times 10^{-4}$ [PRD 83 (2011) 054007]
- **Consistent with** flavor-symmetry driven predictions:
 $(1.23 \pm 0.64) \times 10^{-5}$ [arXiv:2008.06624]



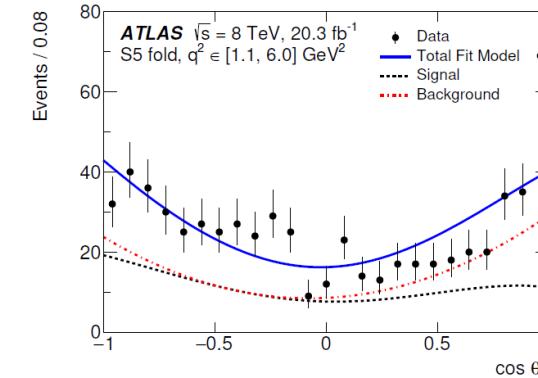
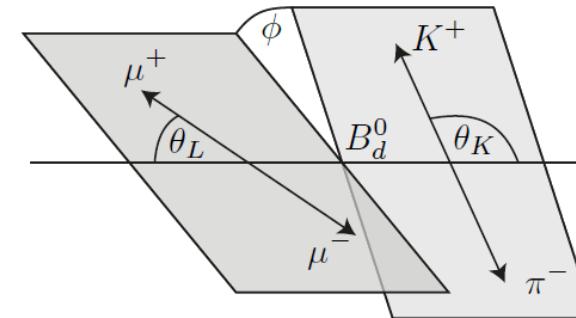
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Angular analysis

- Fully-described decays by 4 variables q^2 , angle $\vec{\Omega} = (\theta_l, \theta_K, \phi)$

$$\frac{d\Gamma[B \rightarrow K^* \mu\mu]}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

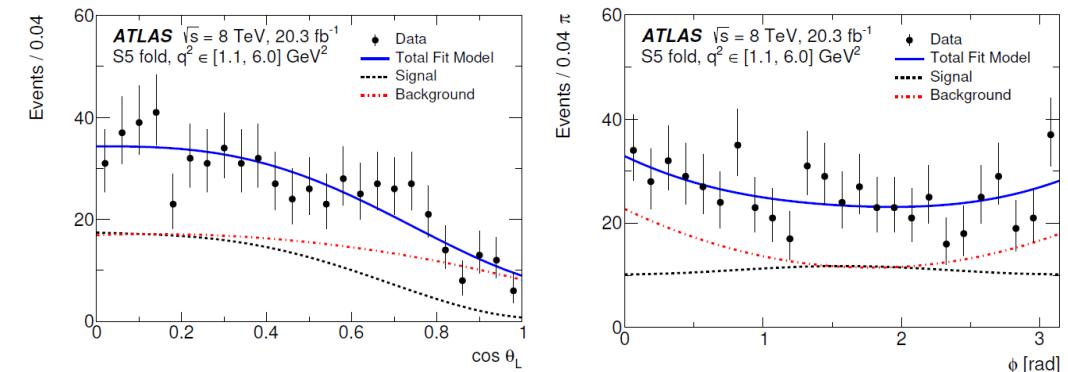
$I_i(q^2)$: angular coefficients, relates to amplitude $\mathcal{A}_{0,\parallel,\perp}^{L,R}$
 $f_i(\vec{\Omega})$: angular functions



- CP-asymmetry observables: A_i
- CP-averaged observables: F_L , A_{FB} , S_{3-9}
- Optimized observables reduce form-factor uncertainties $P_i^{(')}$

$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

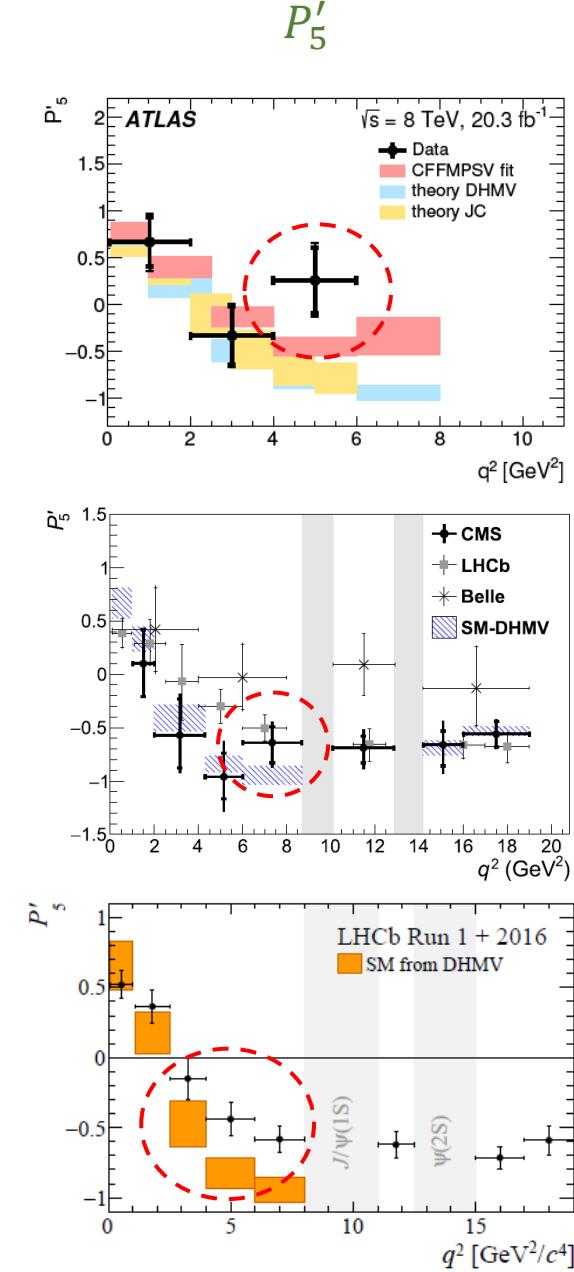
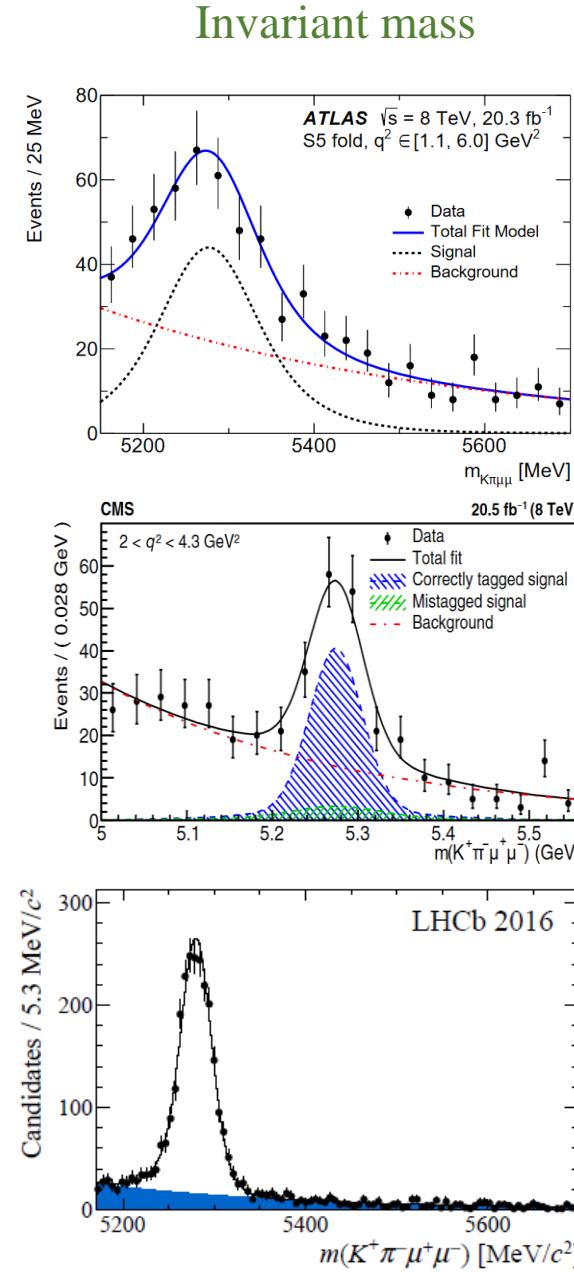
- Depend on Wilson coefficients and form factors



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

possible
discrepancies
at low q^2

- ATLAS measurements with 2012 data
[\[JHEP 10\(2018\) 047\]](#)
- CMS measurements with 2012 data
[\[PLB 781 \(2018\) 517\]](#)
- LHCb measurements with Run 1 + 2016 data
[\[PRL 125 \(2020\) 011802\]](#)



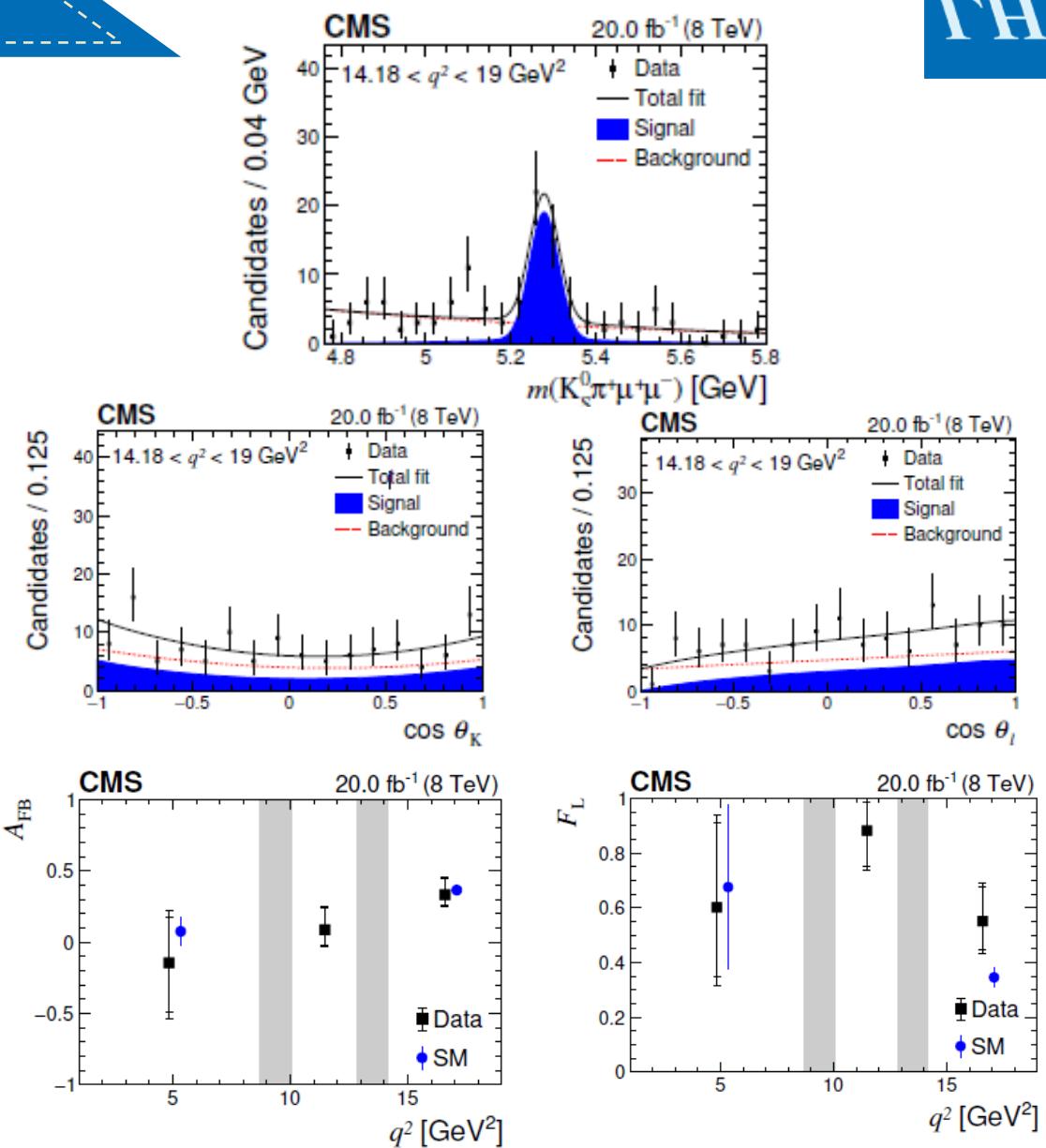
[JHEP 04 (2021) 124]

- 2012 data
- Angular decay rate integrates out ϕ

$$\frac{1}{\Gamma} \frac{d^3\Gamma}{dcos\theta_K dcos\theta_\ell dq^2} = \frac{9}{16} \left\{ \frac{2}{3} [F_S + 2A_S \cos\theta_K] (1 - \cos^2\theta_\ell) \right. \\ + (1 - F_S) [2F_L \cos^2\theta_K (1 - \cos^2\theta_\ell)] \\ + \frac{1}{2} (1 - F_L) (1 - \cos^2\theta_K) (1 + \cos^2\theta_\ell) \\ \left. + \frac{4}{3} A_{FB} (1 - \cos^2\theta_K) \cos\theta_\ell \right\}.$$

- Observables: F_L , A_{FB}
- Dominated by statistical uncertainty
- Results consistent with SM

$$q^2 \in [1, 8.68] \cup [10.09, 12.86] \cup [14.18, 19] \text{ GeV}^2/c^4$$

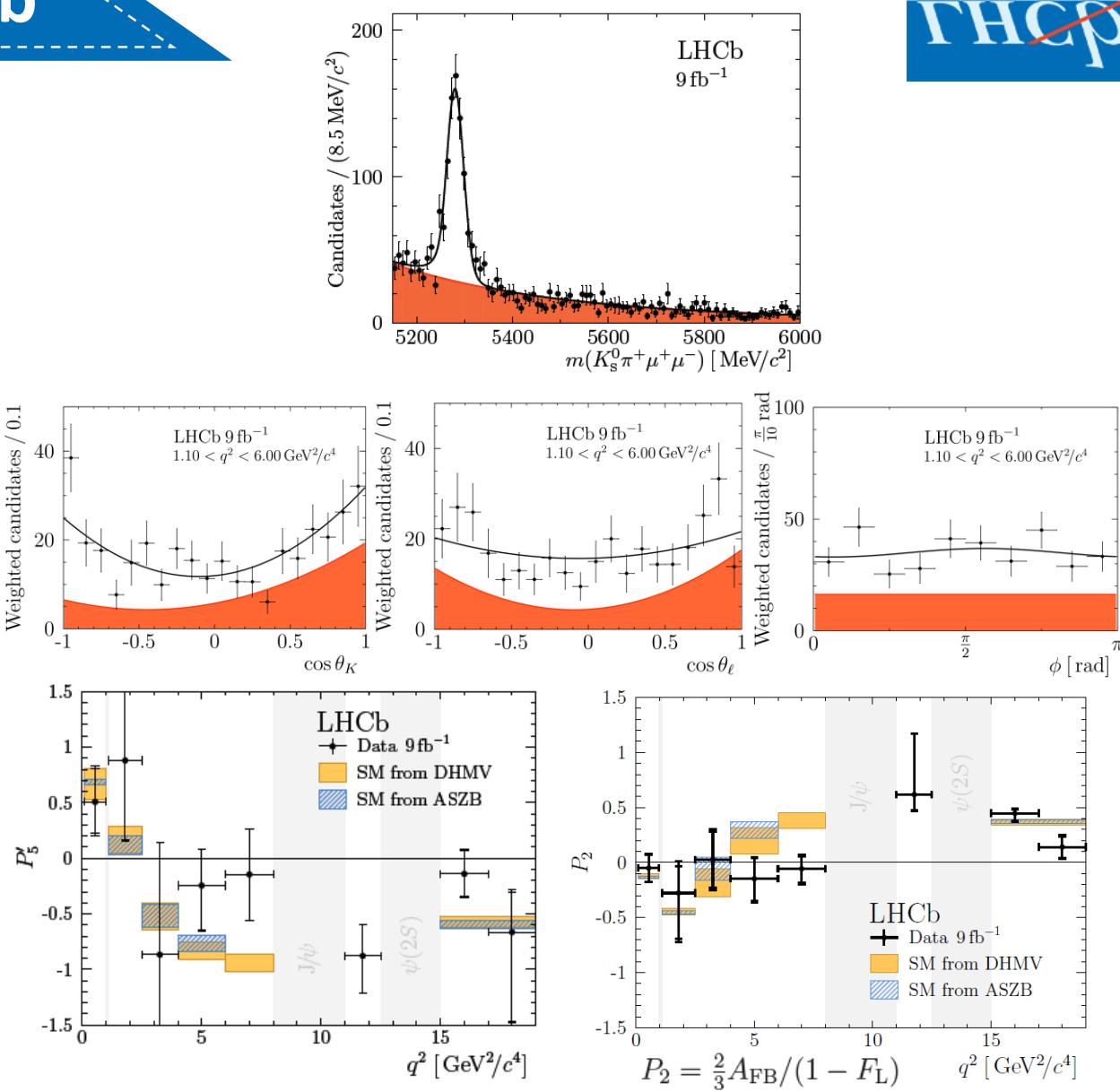


[PRL 126 (2021) 161802]

- Run 1 + 2 data
- Angular decay rate

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} \Big|_P = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \right. \\ \left. + \frac{4}{3}A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

- First time for full sets of CP-averaged observables
- $q^2 \in [0.1, 0.98] \cup [1.1, 8.0] \cup [11.0, 12.5] \cup [15.0, 19.0] \text{GeV}^2/c^4$
- Confirm the global tension with SM of 3.1σ (model dependent)

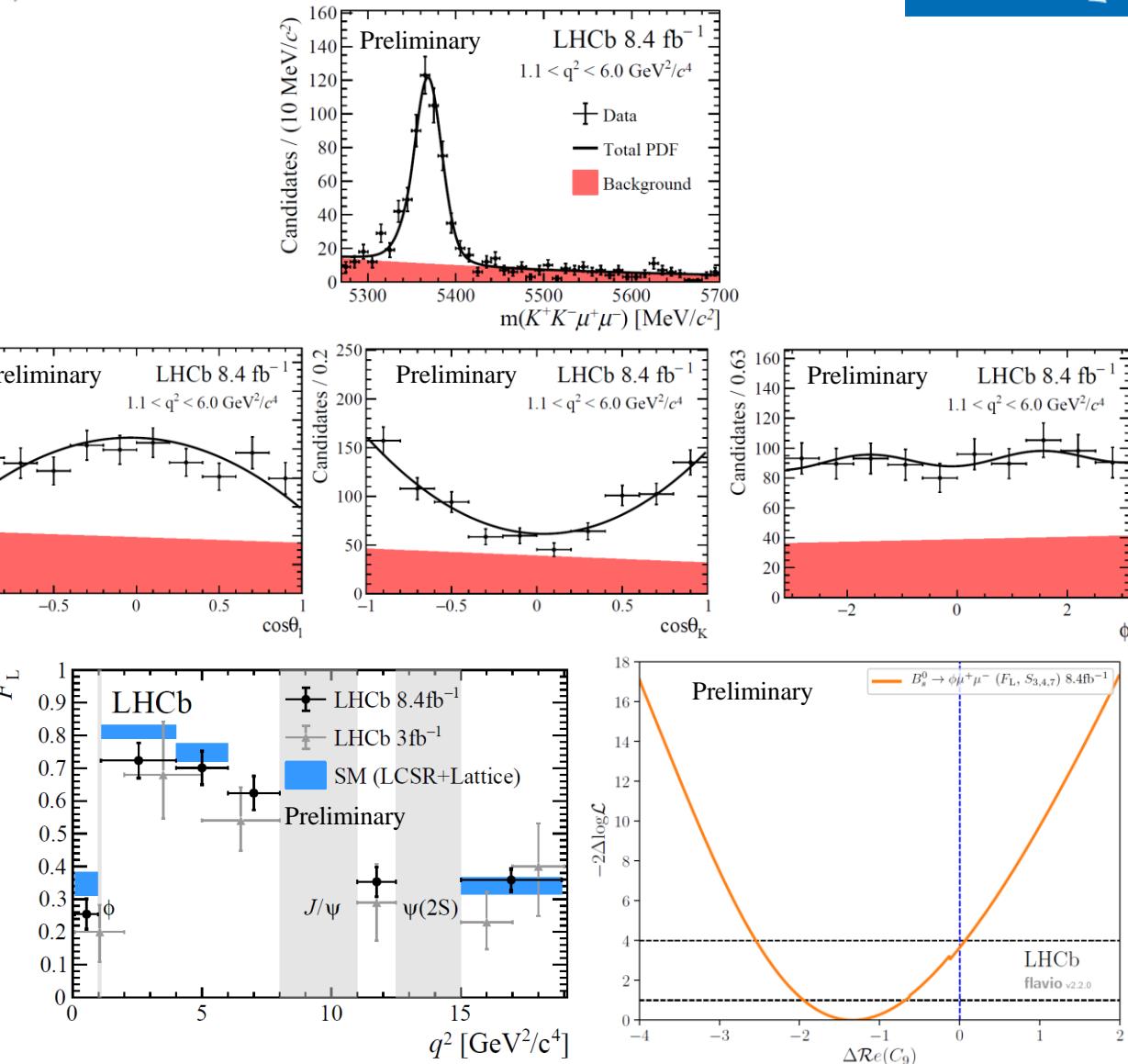




- Run 1 + 2 data
- Angular decay rate

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{dcos\theta_l \, dcos\theta_K \, d\phi} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K (1 + \frac{1}{3} \cos 2\theta_l) \right. \\ + F_L \cos^2 \theta_K (1 - \cos 2\theta_l) \\ + [S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi] \\ + [A_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB}^{CP} \sin^2 \theta_K \cos \theta_l] \\ + [S_7 \sin 2\theta_K \sin \theta_l \sin \phi + A_8 \sin 2\theta_K \sin 2\theta_l \sin \phi] \\ \left. + A_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

- Observables: $F_L, S_{3,4,7}, A_{FB}^{CP}, A_{5,8,9}$
- CP asymmetries and averages compatible with SM,
 F_L below SM at low q^2
- $q^2 \in [0.1, 0.98] \cup [1.1, 8.0] \cup [11.0, 12.5] \cup [15.0, 18.9] \text{ GeV}^2/c^4$
- $\Delta Re(C_9) = -1.3$ below SM hypothesis at 1.9σ



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- **Lepton flavor universality (LFU)**
 - R_K [[arXiv:2103.11769](#)]
- Summary

R_K measurement @ LHCb

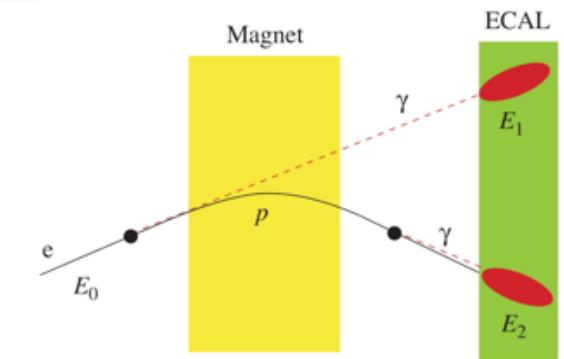
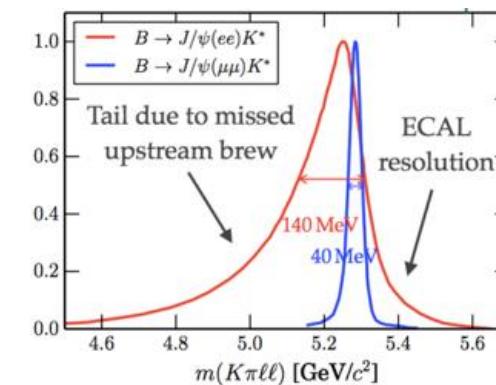
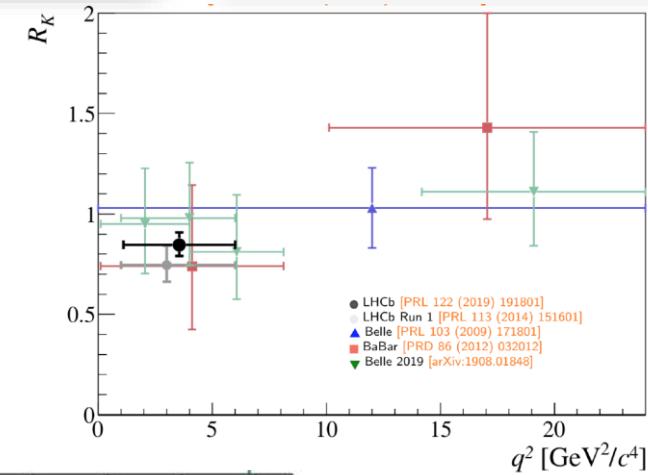
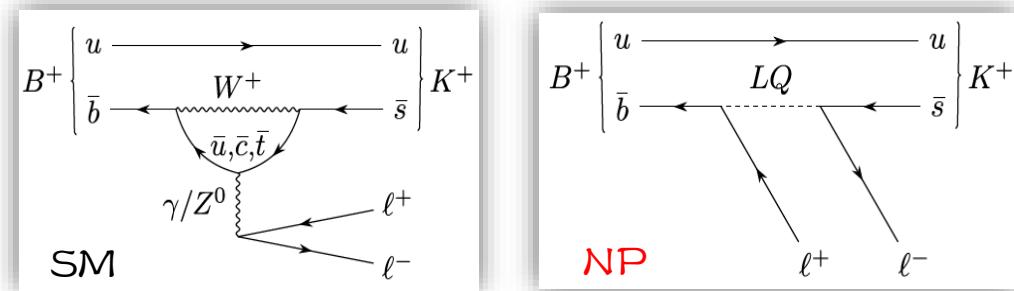
LHCb
LHCcp

[arXiv:2103.11769]

- Test of lepton flavor universality (LFU)

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} dq^2} \stackrel{SM}{=} 1 \pm \mathcal{O}(1\%)$$

- $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$
- Updated measurement using a full Run 1 + 2 dataset
 - following essentially identical procedure
 - previous result in tension with SM prediction at level of **2.5 σ** [PRL 122 (2019) 191801]
- Challenging due to bremsstrahlung radiation
 - significant portions of energy loss for electron
 - different trigger strategy for muon and electron
 - recovery algorithm in calorimeter



R_K measurement @ LHCb

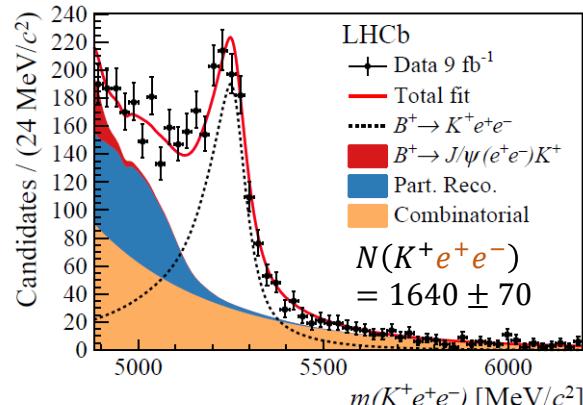
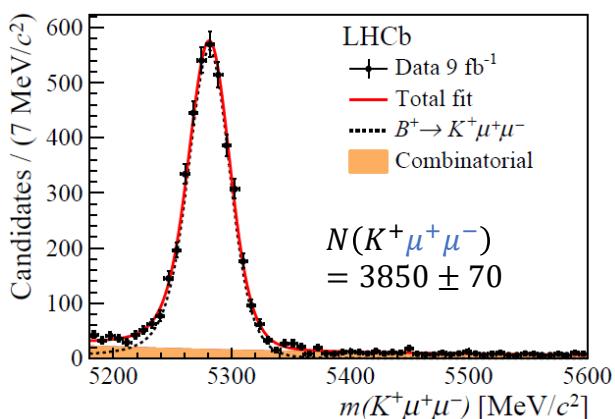
[arXiv:2103.11769]

LHCb
LHCcp

- Measuring R_K with

$$R_K = \frac{N_{rare}^{\mu^+\mu^-}}{N_{rare}^{e^+e^-}} \cdot \frac{\varepsilon_{rare}^{e^+e^-}}{\varepsilon_{rare}^{\mu^+\mu^-}} \cdot \frac{N_{control}^{J/\psi(e^+e^-)}}{N_{control}^{J/\psi(\mu^+\mu^-)}} \cdot \frac{\varepsilon_{control}^{J/\psi(\mu^+\mu^-)}}{\varepsilon_{control}^{J/\psi(e^+e^-)}}$$

- extracted as a parameter of a simultaneous fit of muon & electron modes



R_K measurement @ LHCb

[arXiv:2103.11769]

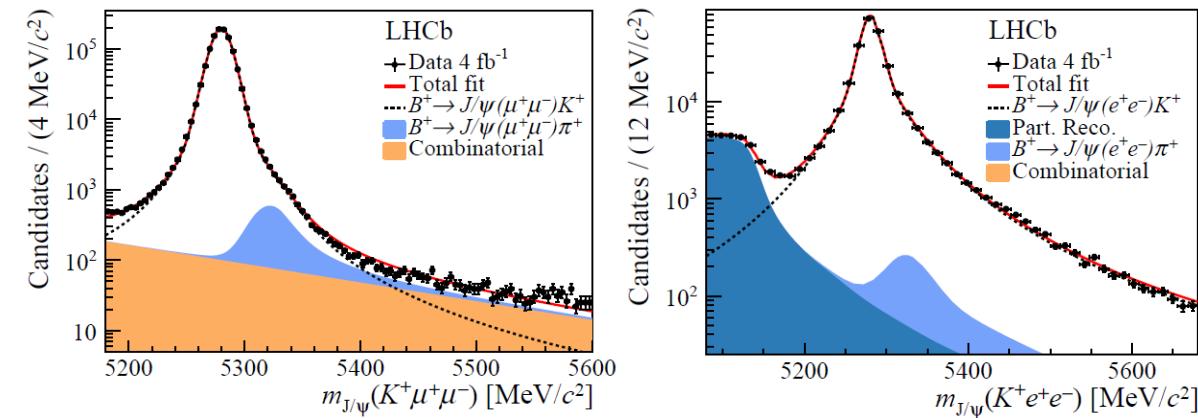
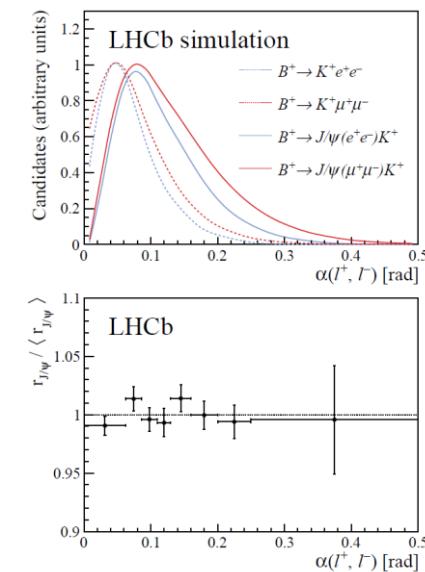
LHCb
LHCf

- Measuring R_K with

$$R_K = \frac{N_{rare}^{\mu^+\mu^-}}{N_{rare}^{e^+e^-}} \cdot \frac{\varepsilon_{rare}^{e^+e^-}}{\varepsilon_{rare}^{\mu^+\mu^-}} \cdot \frac{N_{control}^{J/\psi(e^+e^-)}}{N_{control}^{J/\psi(\mu^+\mu^-)}} \cdot \frac{\varepsilon_{control}^{J/\psi(\mu^+\mu^-)}}{\varepsilon_{control}^{J/\psi(e^+e^-)}}$$

$r_{J/\psi}$

- extracted as a parameter of a simultaneous fit of muon & electron modes



- Measuring R_K with

$$R_K = \frac{N_{rare}^{\mu^+\mu^-}}{N_{rare}^{e^+e^-}} \cdot \frac{\varepsilon_{rare}^{e^+e^-}}{\varepsilon_{rare}^{\mu^+\mu^-}} \cdot \frac{N_{control}^{J/\psi(e^+e^-)}}{N_{control}^{J/\psi(\mu^+\mu^-)}} \cdot \frac{\varepsilon_{control}^{J/\psi(\mu^+\mu^-)}}{\varepsilon_{control}^{J/\psi(e^+e^-)}}$$

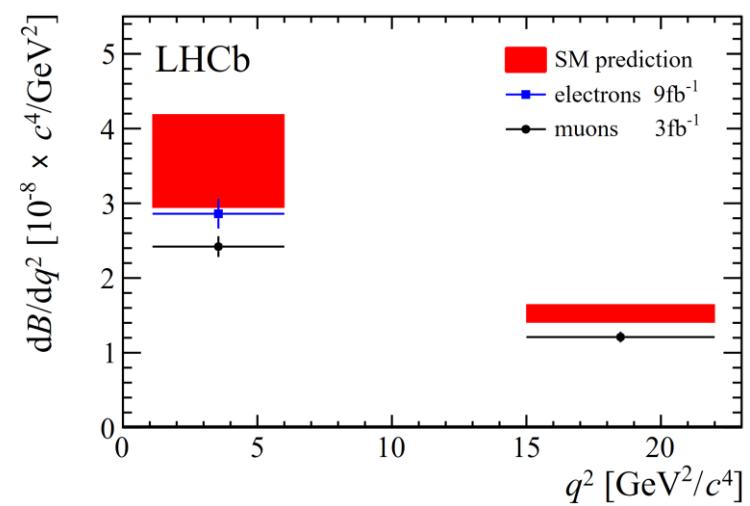
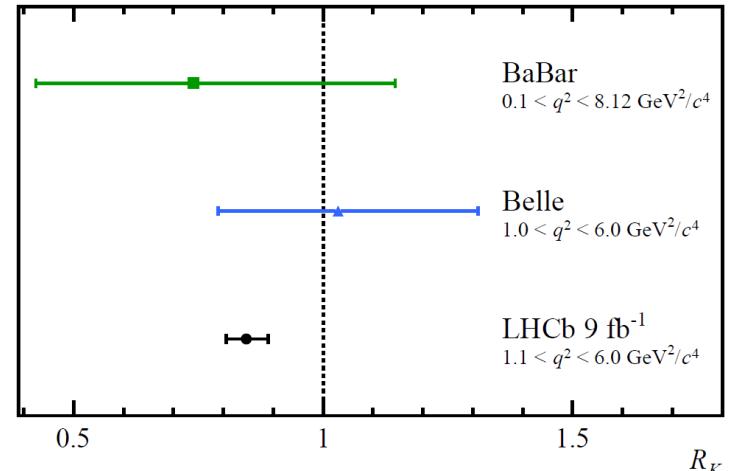
- extracted as a parameter of a simultaneous fit of muon & electron modes

- Supersede the previous LHCb analysis
- Below SM prediction with a tension of 3.1σ

$$R_K(1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = 0.846^{+0.042}_{-0.039} {}^{+0.013}_{-0.012}$$

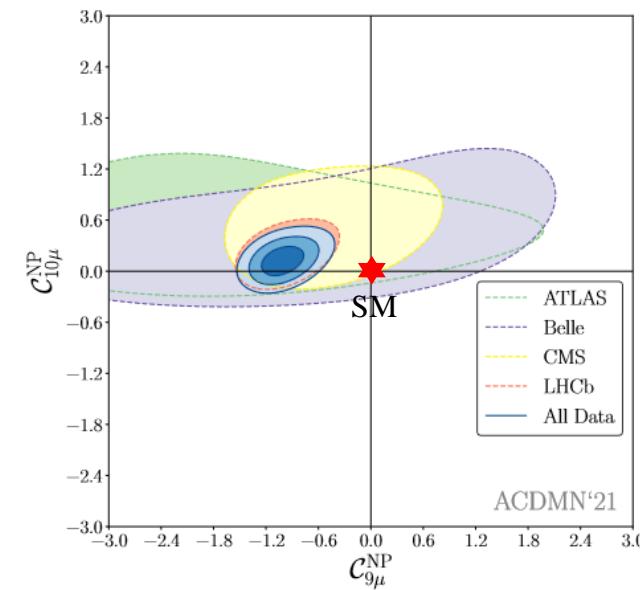
- Branching ratio for electron mode measured as well

$$\frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2}(1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = (28.6^{+1.5}_{-1.4} \pm 1.3) \times 10^{-9} c^4/\text{GeV}^2$$

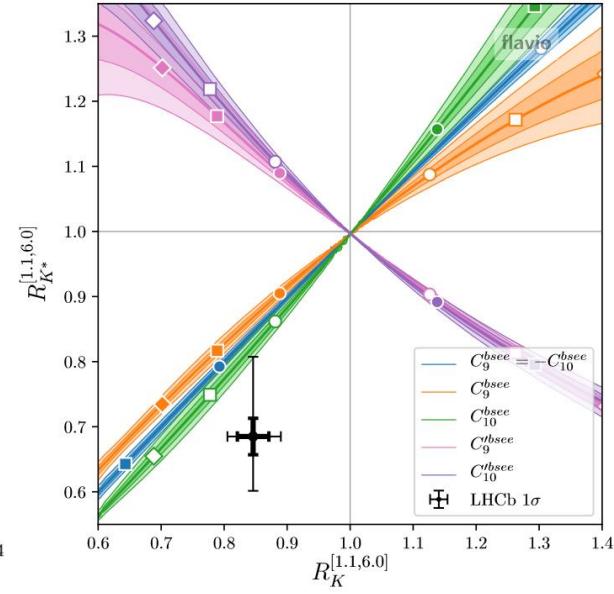
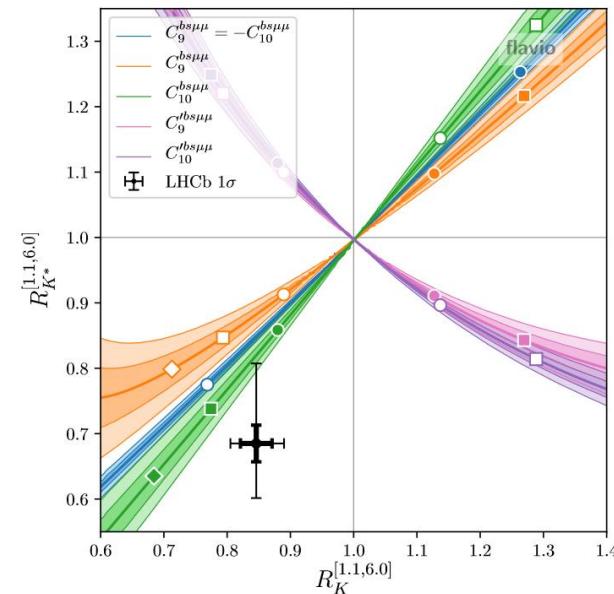
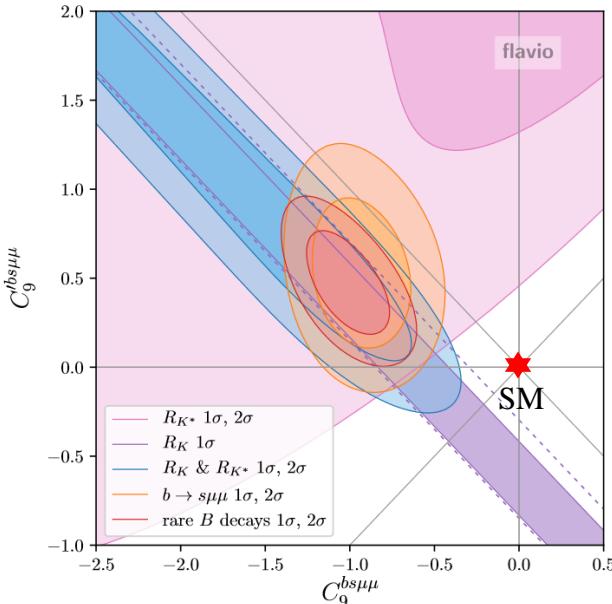
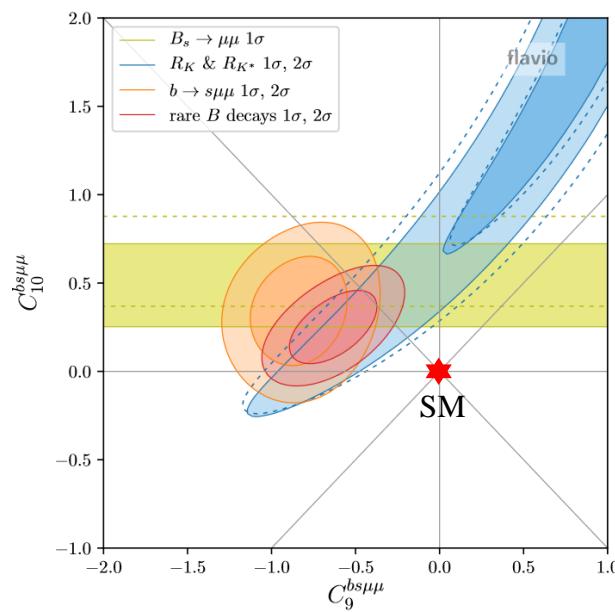


Global fit

- Far away from SM after considering combinations
- Tension with interesting discrepancy for C_9 far from 0
- Many model-independent fits seem to favor $C_9^{NP} < 0$
- NP: vector leptoquarks Z' ?



[arXiv:2104.08921]



[arXiv:2103.13370]

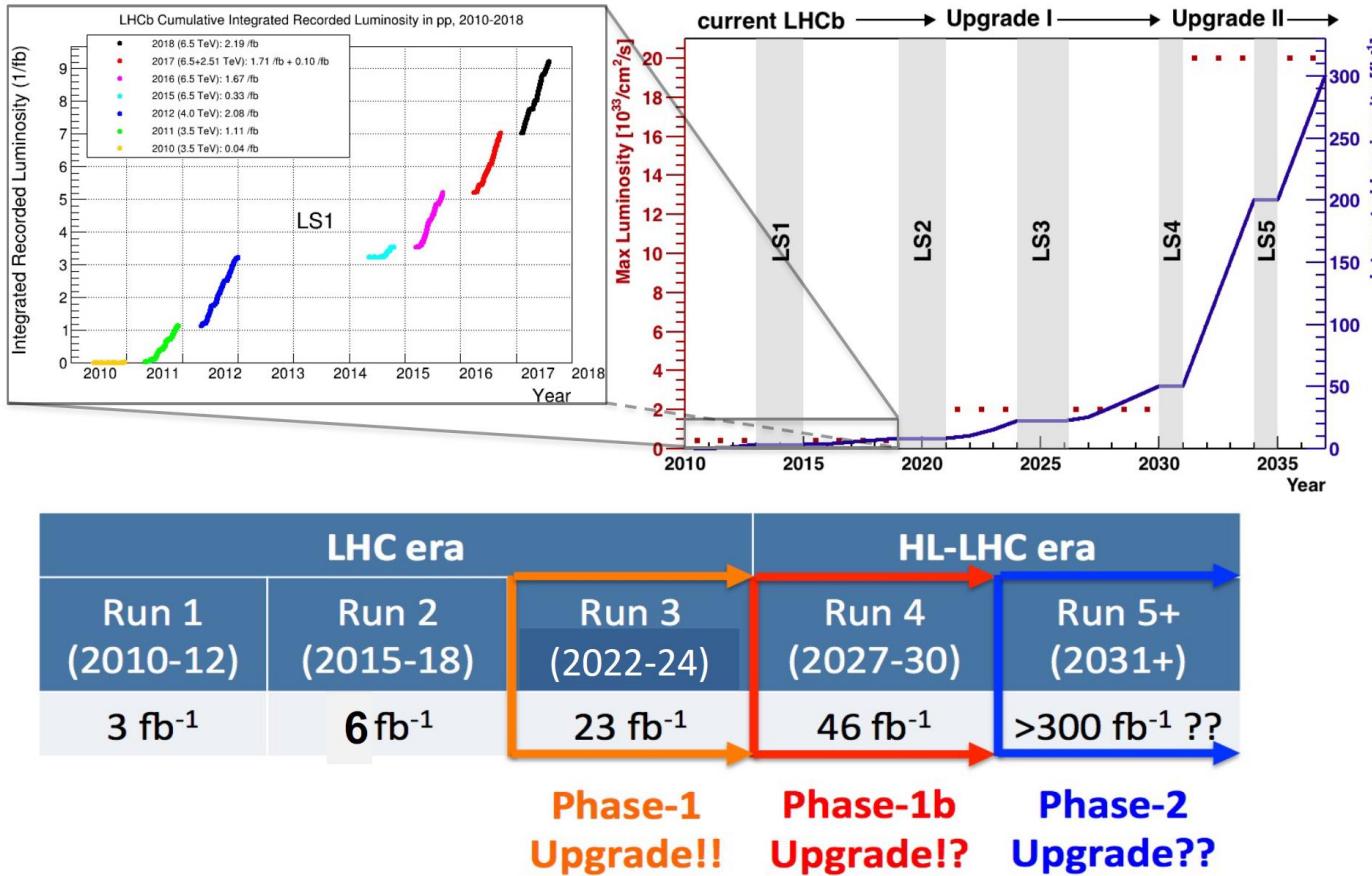
- Most of the results are well in agreement with the SM prediction
- Global fit to clean observables over larger significance deviation
- More data needed to confirm the trend, expect nice development in the future
- Run 3 to start next year with 5 times inst. lumi. at LHCb
- HL-LHC will increase current dataset by 100 times
- Interest on rare decays to discover hints of new physics will persist

Thank you for your attention!

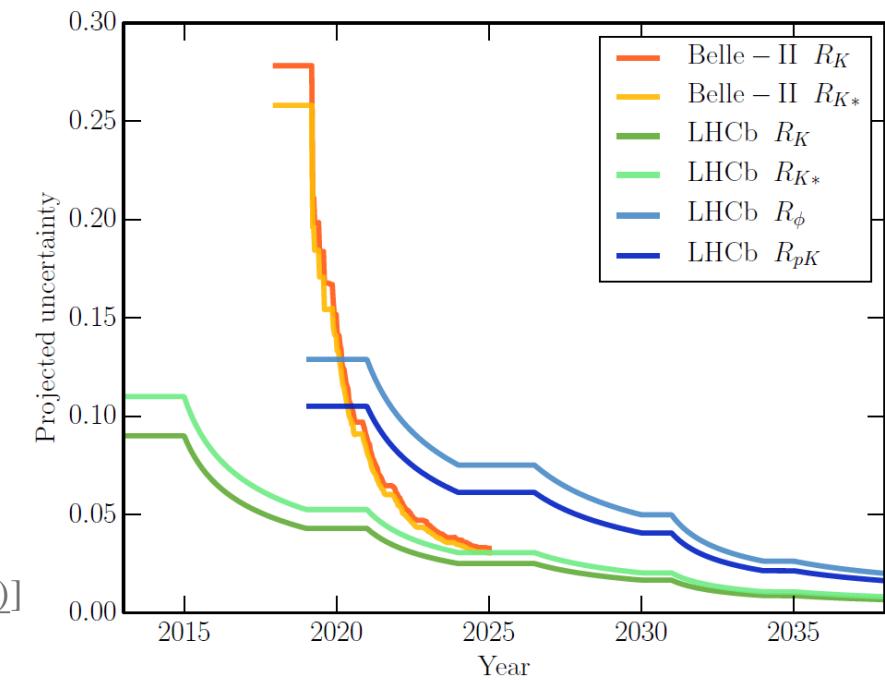


Backup

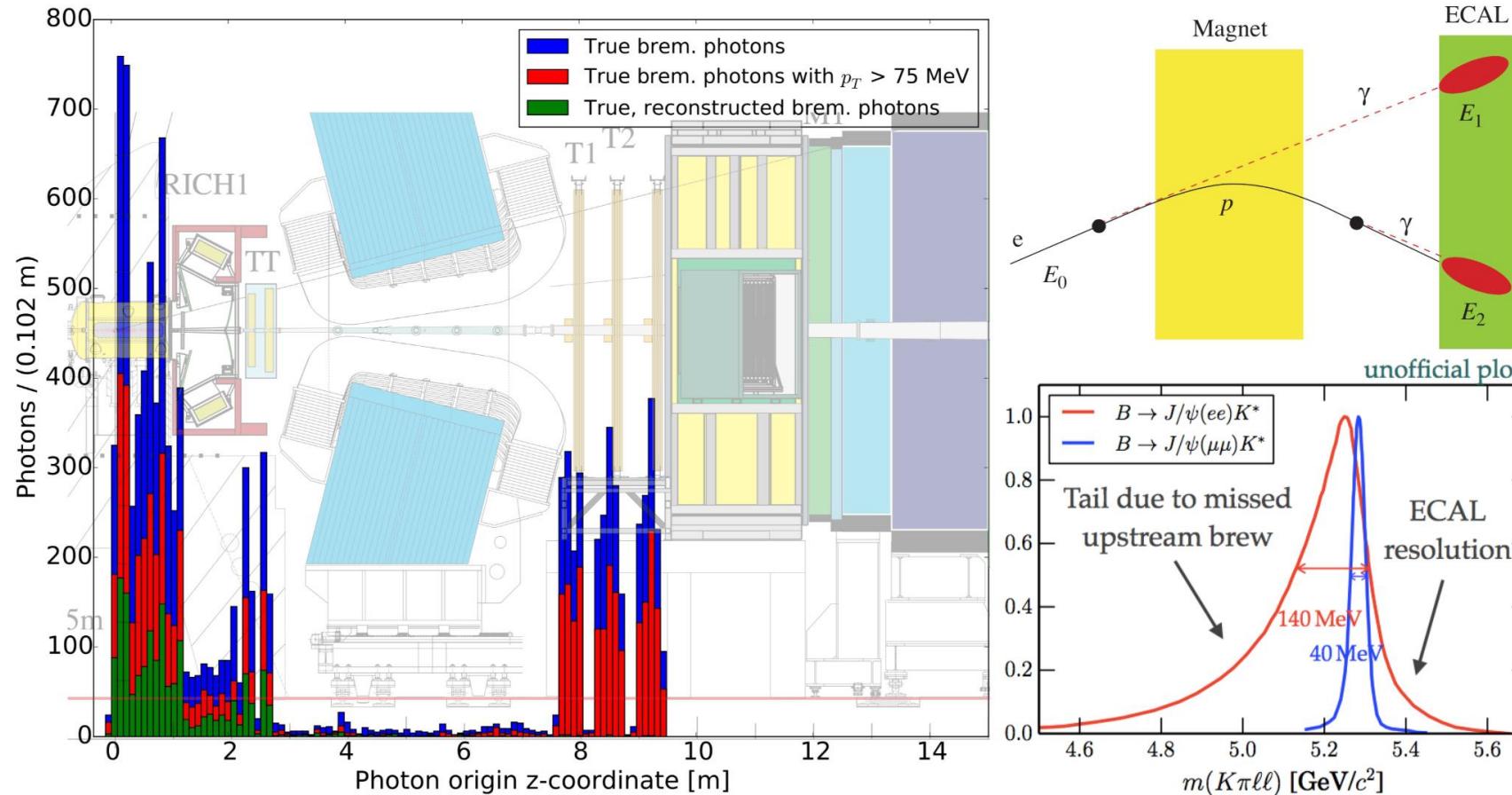
LHCb luminosity prospects



[Journal of Physics G: Nuclear and Particle Physics, Volume 46, Number 2 (2018)]



Bremsstrahlung corrections





Most precise measurement of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ angular observables to date

