Rare decays at LHCb

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on behalf of the LHCb collaboration

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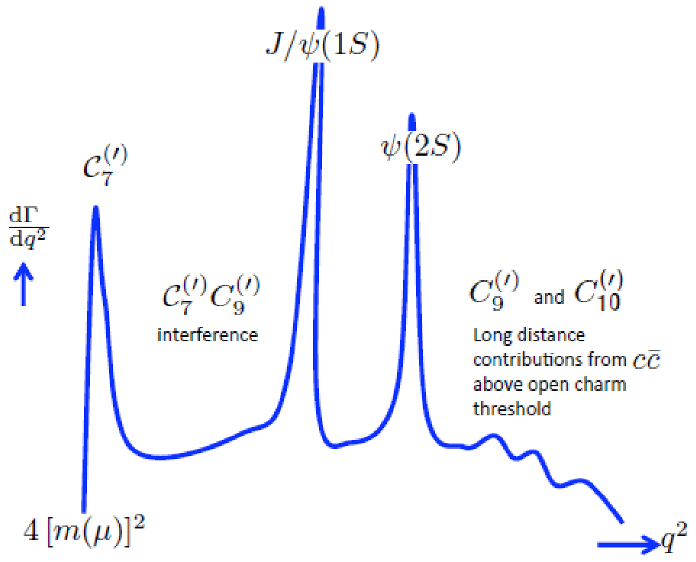
Outlook

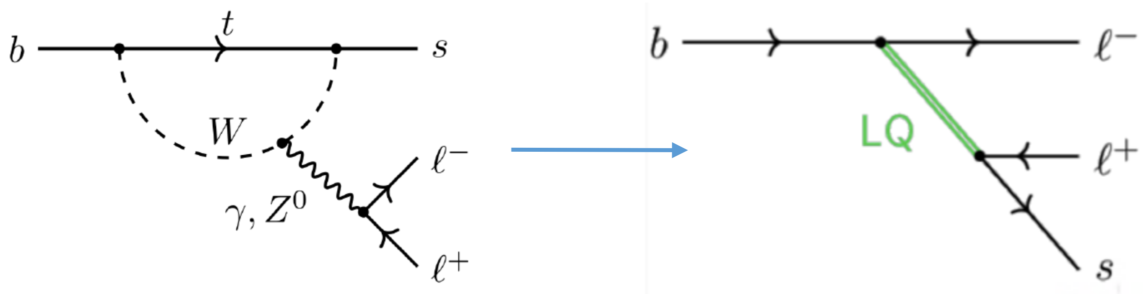
- Many interesting results, only list some of them…
- (Very) rare decays
  - $B_s^0 \to \mu^+\mu^-, B^0 \to \mu^+\mu^-$ & $B_s^0 \to \mu^+\mu^-\gamma$ [LHCb-PAPER-2021-007, in preparation]
  - $B_s^0 \to \phi\mu^+\mu^-$ & $B_s^0 \to f_2'\mu^+\mu^-$ [LHCb-PAPER-2021-014, in preparation]
- Angular analysis
  - $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]
  - $B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]
  - $B^0 \to K^{*0}e^+e^-$ [JHEP 12 (2020) 081]
- Lepton flavor universality (LFU)
  - R_K [arXiv:2103.11769]

Lepton Flavour Universality & rare decays

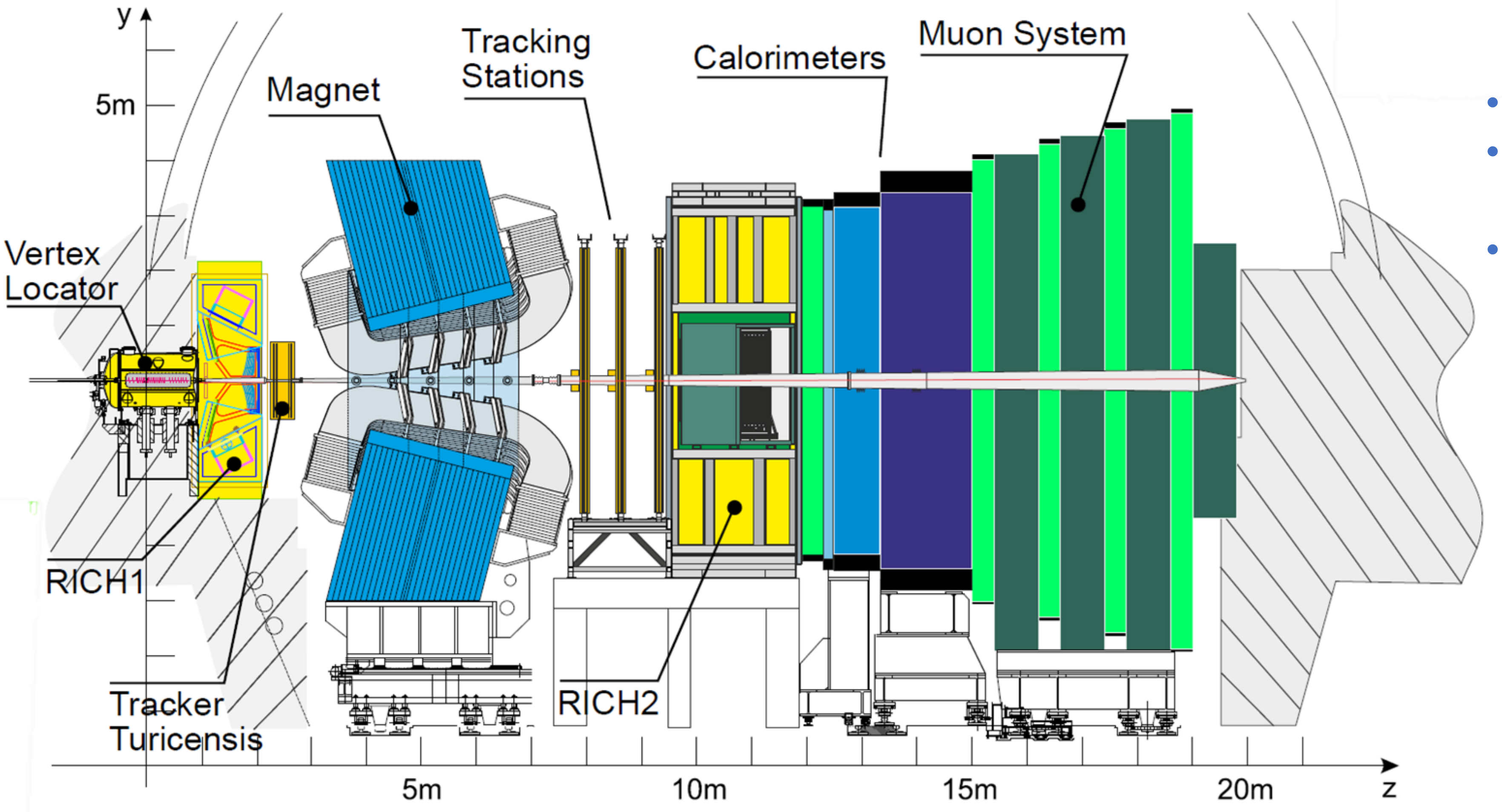
- Rare decays
  - Indirect search of New Physics (NP)
- Flavour Changing Neutral Currents (FCNC)
  - $b \to s l^+ l^-$ transitions
  - process exist only at loop level in the Standard Model (SM)
  - (very) low branching fractions, sensitive to NP contribution
  - described with effective field theory (EFT)
- Measurements as function of $q^2 = (m(ll))^2$, sensitive to different operator contributions (Wilson coefficients $C_7^{(\prime)}, C_9^{(\prime)}$ and $C_{10}^{(\prime)}$)



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



LHCb detector

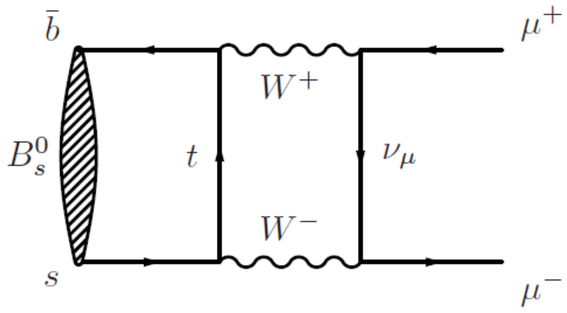


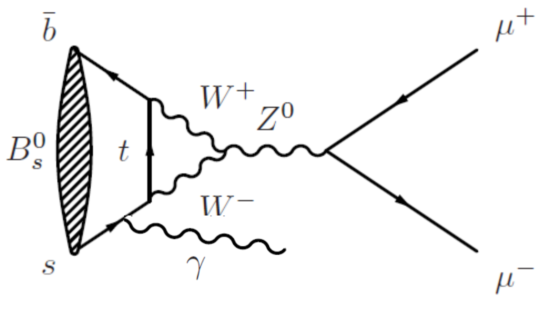
- Run 1 + 2: 9 fb^{-1}
- RICH: kaon and pion PID ~ 95%
- Muon System: Muon PID ~ 97%

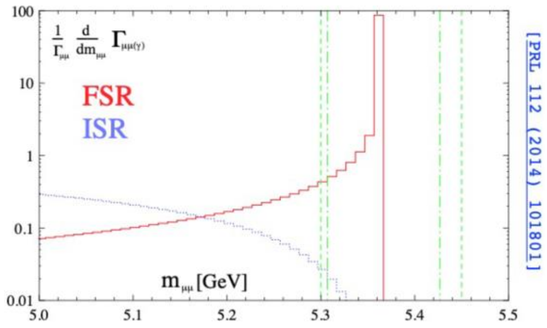
Measurement of $B^0_{(s)} \to \mu^+\mu^-(\gamma)$

[LHCb-PAPER-2021-007, in preparation]

- Measure with Run 1 and Run 2 datasets
- Search for $B^0_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$
- Very rare decay ($\mathcal{B}\sim\mathcal{O}(10^{-9})$), γ comes from radiative tail in ISR (large momentum) & FSR photon







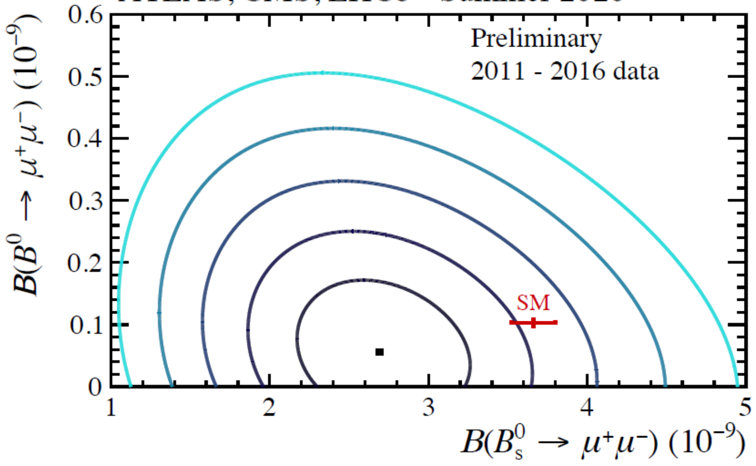
- First search for $B^0_s \to \mu^+\mu^-\gamma_{ISR}$ at high di-muon mass
- Theory predictions [JHEP 10 (2019) 232]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.66 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 1.027 \times 10^{-10}$$

- Recent status still compatible with SM predictions

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.69^{+0.37}_{-0.35} \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ @95\% CL}$$

ATLAS, CMS, LHCb - Summer 2020



[LHCb-CONF-2020-002, CMS PAS BPH-20-003, ATLAS-CONF-2020-049]

Measurement of $B^0_{(s)} \to \mu^+\mu^-(\gamma)$

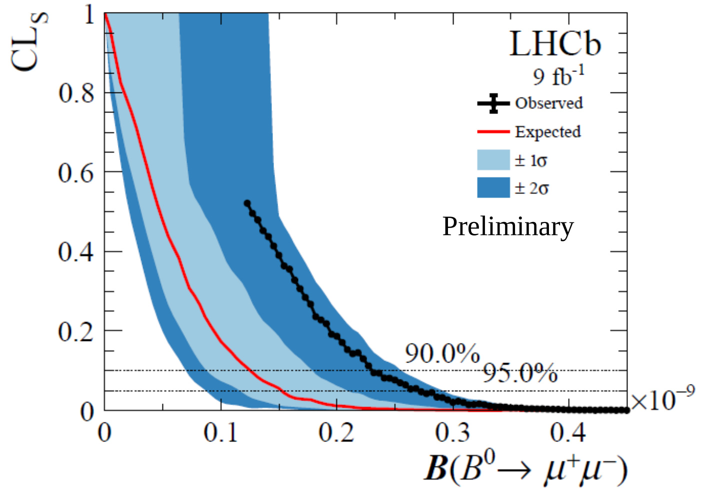
[LHCb-PAPER-2021-007, in preparation]

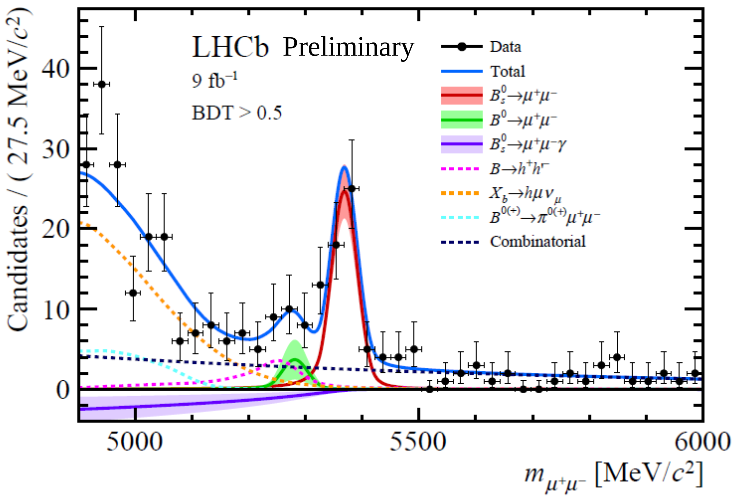
- Result agrees with SM prediction

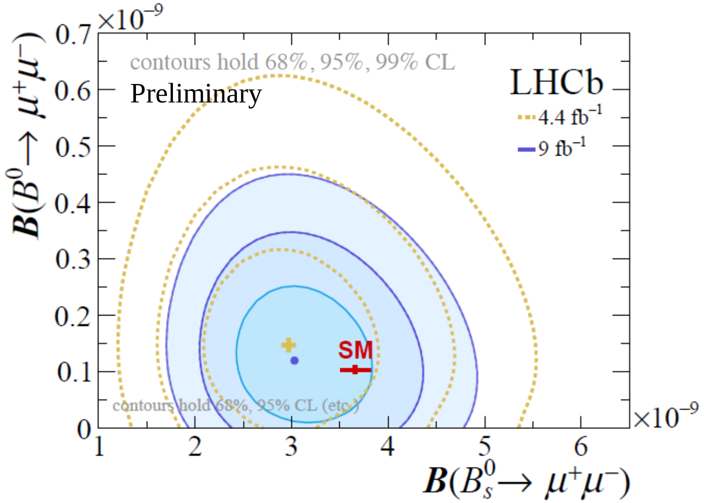
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

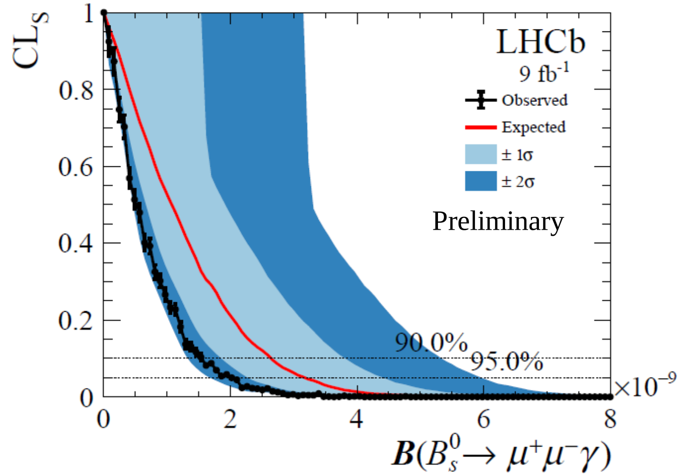
- $B_s^0 \to \mu^+\mu^- \sim 10\sigma$,
  no evidence of $B^0 \to \mu^+\mu^-$ ($\sim 1.7\sigma$) and $B_s^0 \to \mu^+\mu^-\gamma_{ISR}$
- Obtain upper limits

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma_{ISR})_{m_{\mu\mu} > 4.9\text{GeV}/c^2} < 2.0 \times 10^{-9} \text{ at } 95\% \text{ CL}$$





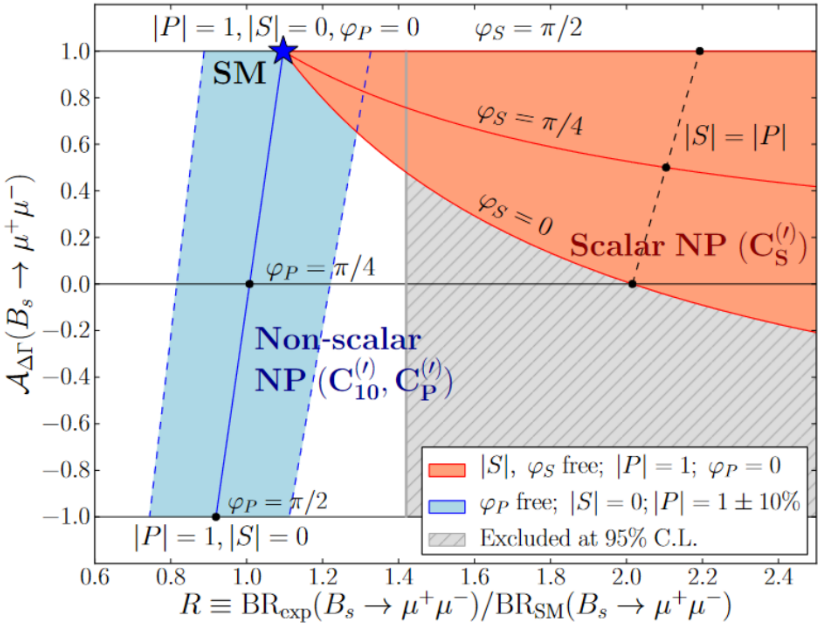




Measurement of $B^0_{(s)} \to \mu^+\mu^-(\gamma)$

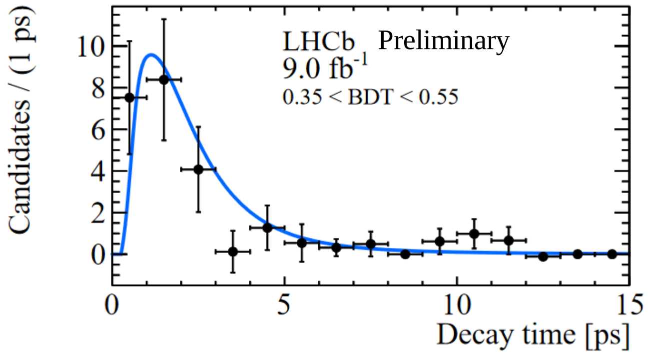
[LHCb-PAPER-2021-007, in preparation]

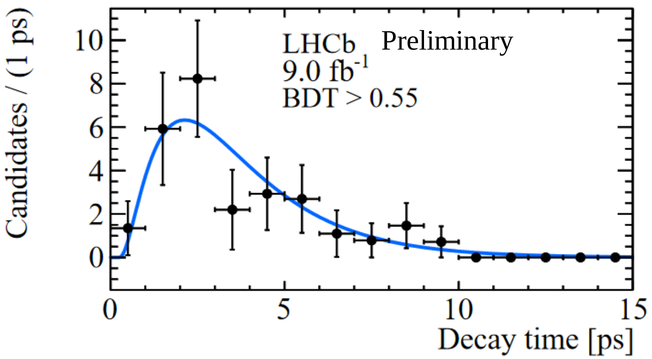
- Effective lifetime measurement of B^0_s
  - provide theoretically probe of NP close to SM prediction
  - only heavy B^0_s decays in SM
  - acts as eigenstates of light and heavy, related to short-lived (CP-even) and long-lived (CP-odd) components respectively
  - unknown mixture of CP-odd & CP-even states



[PRL 109 (2012) 041801]

- Effective lifetime $\tau(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03$ ps
- Result agrees with SM prediction [PTEP 2020 (2020) 8, 083C01]
  - comparable at $1.5\sigma(2.2\sigma)$ with CP-odd (CP-even) eigenstate

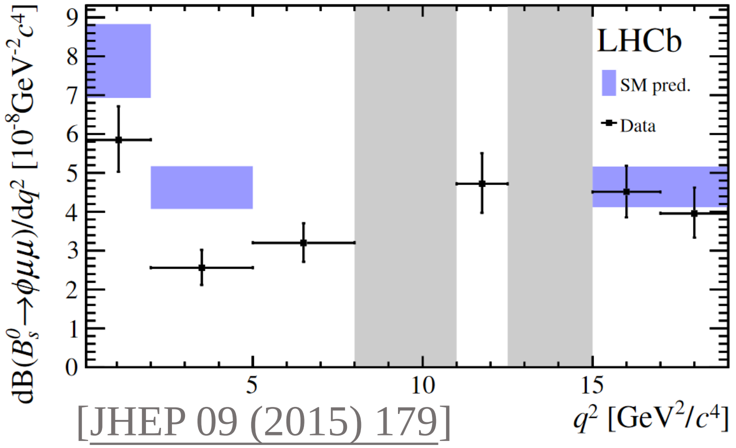




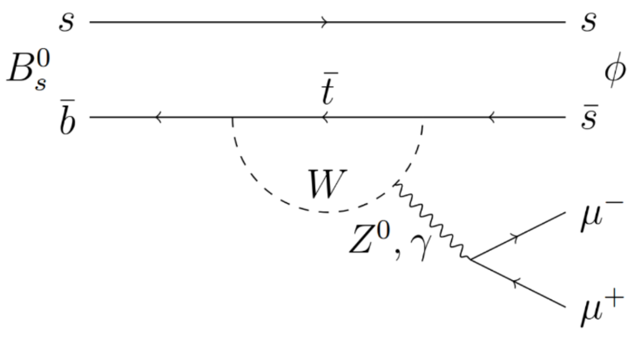
$B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'\mu^+\mu^-$

[LHCb-PAPER-2021-014, in preparation]

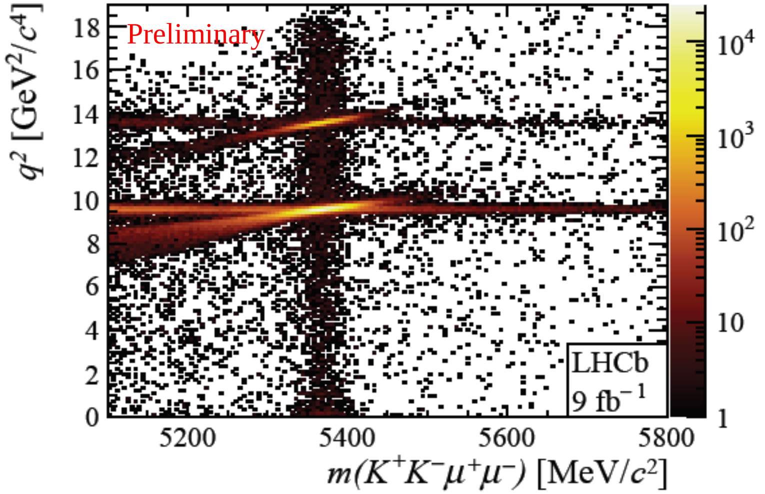
- Measure with Run 1 and Run 2 datasets
- previous result has $\sim 3\sigma$ below SM prediction at low q^2



[JHEP 09 (2015) 179]



clear signal after full selection



- Normalization mode: $B_s^0 \to J/\psi\phi$
- Measurement strategy

$$\frac{d\mathcal{B}(B_s^0\to\phi\mu^+\mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0\to J/\psi\phi)\times\mathcal{B}(J/\psi\to\mu^+\mu^-)}{q^2_{\rm max}-q^2_{\rm min}} \times \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}}$$

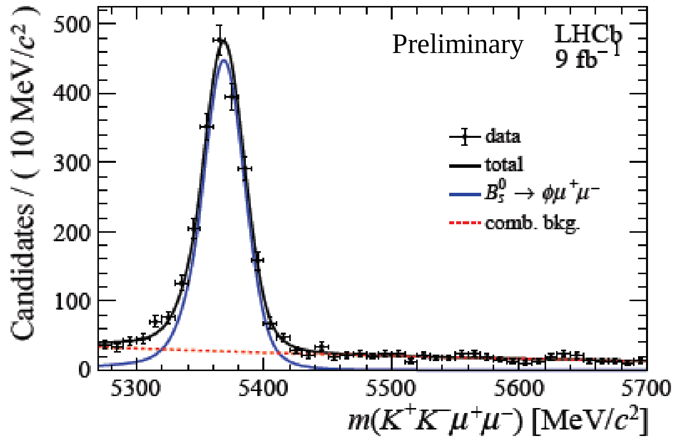
$$\frac{\mathcal{B}(B_s^0\to f_2'\mu^+\mu^-)}{\mathcal{B}(B_s^0\to J/\psi\phi)} = \mathcal{B}(J/\psi\to\mu^+\mu^-)\times\frac{\mathcal{B}(\phi\to K^+K^-)}{\mathcal{B}(f_2'\to K^+K^-)}\times\frac{N_{f_2'\mu^+\mu^-}}{N_{J/\psi\phi}}\times\frac{\epsilon_{J/\psi\phi}}{\epsilon_{f_2'\mu^+\mu^-}}$$

$B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'\mu^+\mu^-$

[LHCb-PAPER-2021-014, in preparation]

- In the range of $1.1<q^2<6.0\ \mathrm{GeV}^2/c^4$
  - 3.6σ below SM prediction (LCSR+Lattice) [PRL 112 (2014) 212003]
  - 1.8σ below SM prediction (LCSR) [PoS LATTICE2014 (2015) 372]

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = (2.88 \pm 0.21) \times 10^{-8}\ \mathrm{GeV}^2/c^4$$

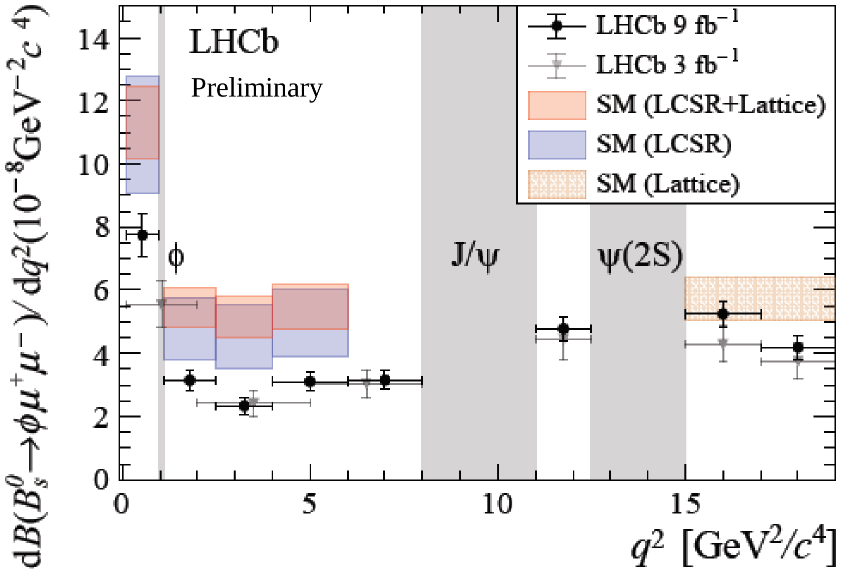


- Branching ratio integrated over q^2

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

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.00 \pm 0.21 \pm 0.16 \pm 0.03 \pm 0.39) \times 10^{-7}$$

stat. **syst.** **q^2 extrap.** **norm.**

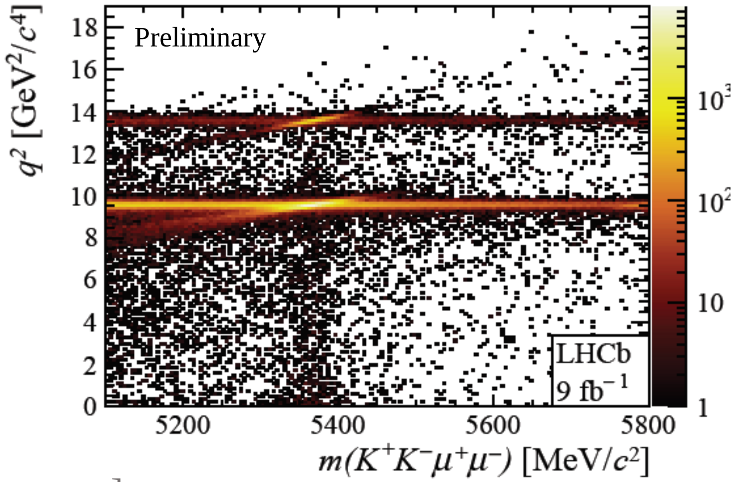


- Need more Theoretical inputs...

$B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'\mu^+\mu^-$

[LHCb-PAPER-2021-014, in preparation]

- First measurement of $B_s^0 \to f_2'(1525)\mu^+\mu^-$
- 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

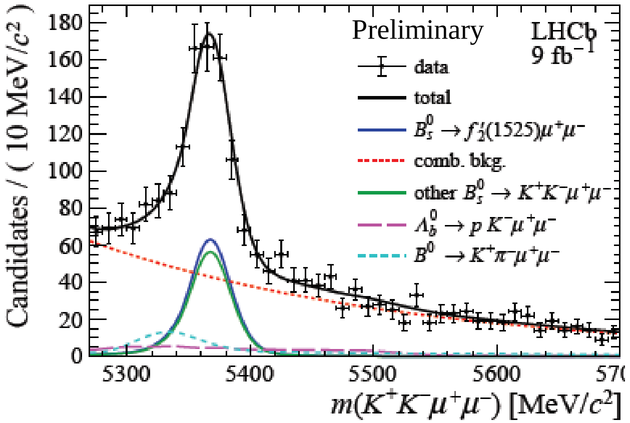


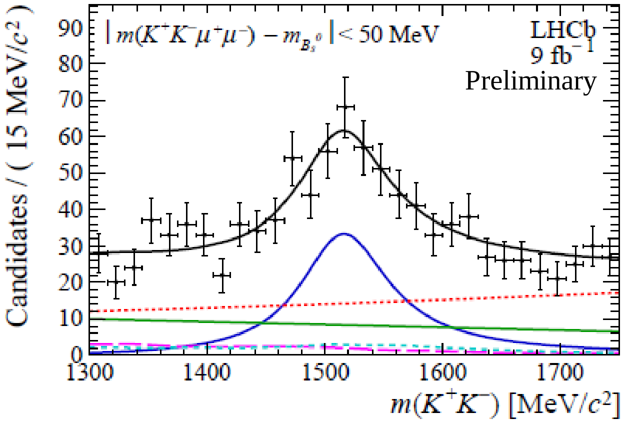
[EPJC 81 (2021) 2, 141]
[PRD 103 (2021) 095007]

$$\frac{\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = (1.55 \pm 0.19 \pm 0.06 \pm 0.06) \times 10^{-4}$$

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

stat. syst. q^2 extrap. norm.





Angular analysis of $B \to K^* l^+ l^-$

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

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

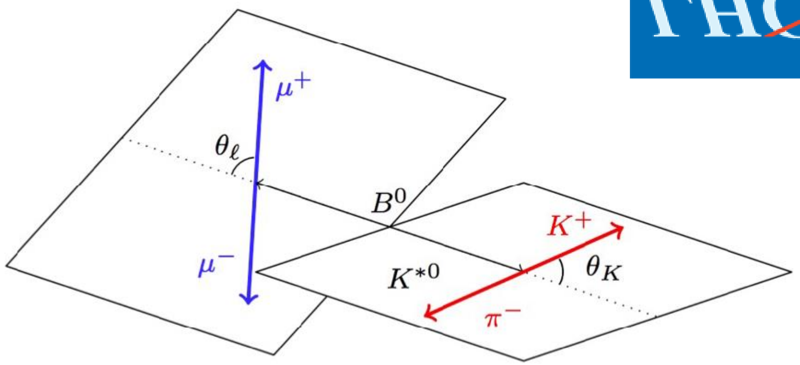
$I_i(q^2)$: angular coefficients, relates to amplitude $\mathcal{A}^{L,R}_{0,\parallel,\perp}$

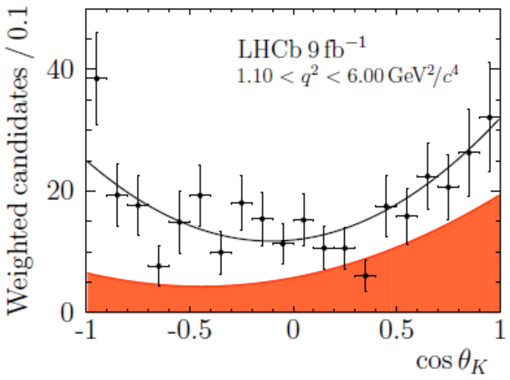
$f_i(\vec{\Omega})$: angular functions

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

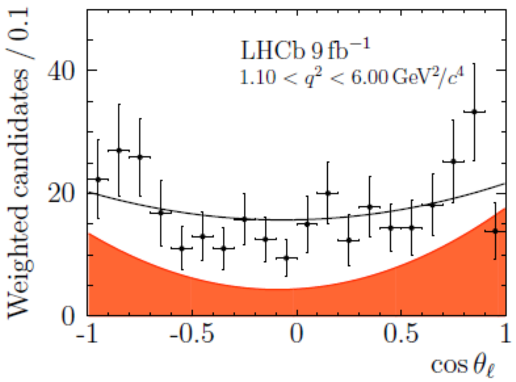
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

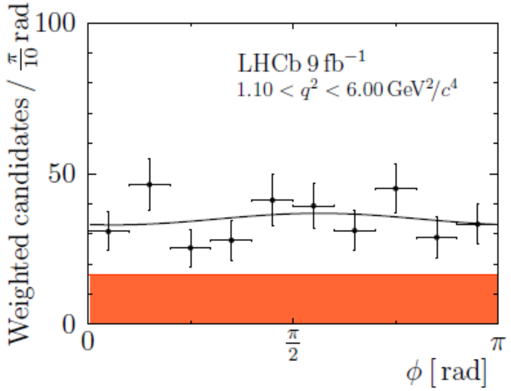
- Measurement CP-averaged observables from fit to data
  - exp. $B^+ \to K^{*+}\mu^+\mu^-$





[LHCb-PAPER-2020-041]



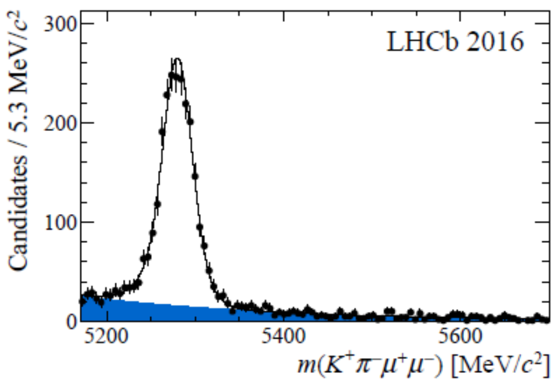


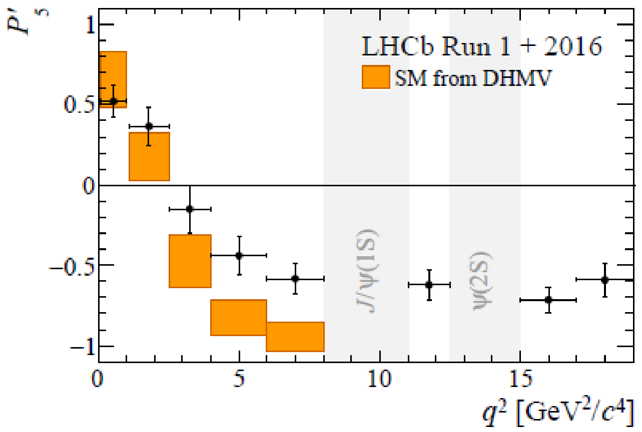
Angular analysis of $B \to K^* l^+ l^-$

$B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]

- Updated with Run 1 + 2016 data
- Global tension of 3.3σ with SM $\mathcal{Re}(C_9)$

$q^2 \in [0.1,0.98] \cup [1.1,8.0] \cup [11.0,12.5] \cup [15.0,19.0]\mathrm{GeV}^2/c^4$

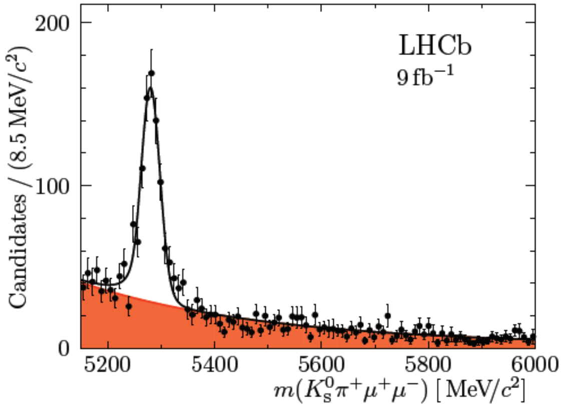


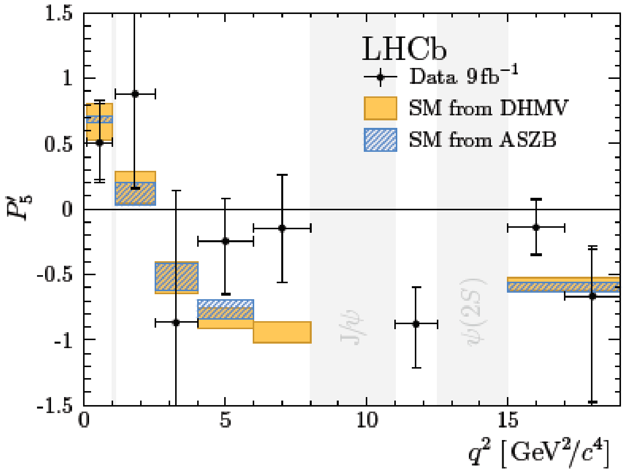


$B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]

- With full Run 1 + 2 data
- First time for full sets of CP-averaged observables
- Confirm the global tension with SM of 3.1σ

$q^2 \in [0.1,0.98] \cup [1.1,8.0] \cup [11.0,12.5] \cup [15.0,19.0]\mathrm{GeV}^2/c^4$

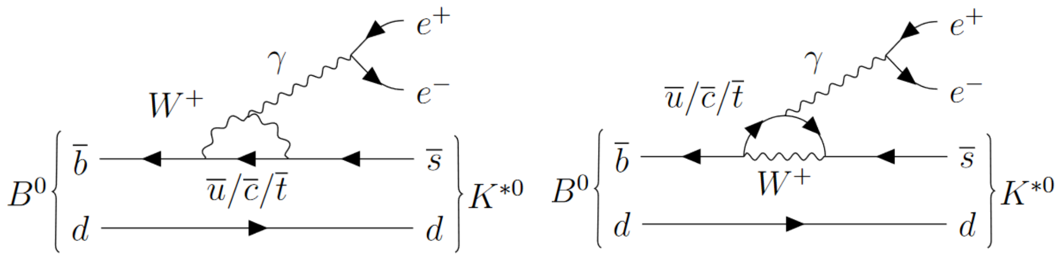




Angular analysis of $B \to K^* l^+ l^-$

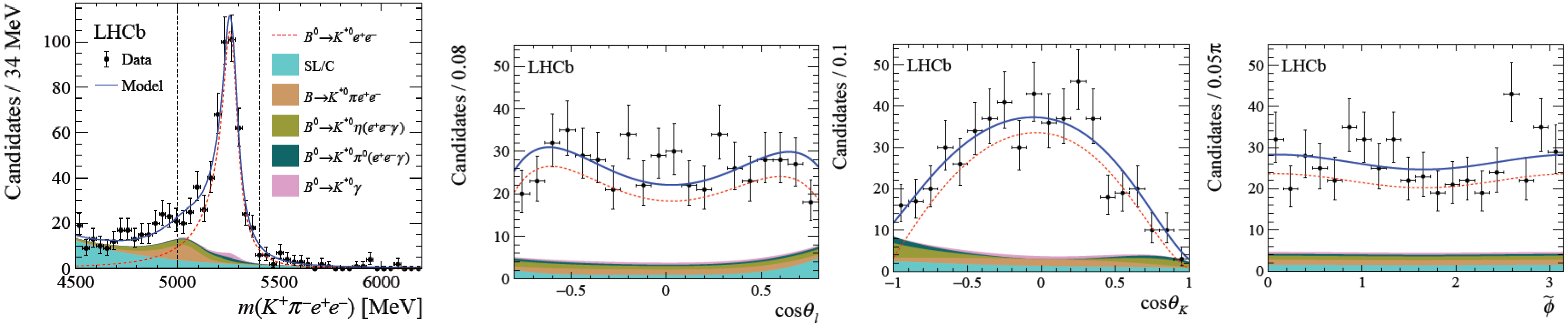
[JHEP 12 (2020) 081]

- Angular analysis of $B^0 \to K^{*0} e^+ e^-$
- Measure with Run 1 and Run 2 data
- 4 angular observables: $F_L, A_T^{(2)}, A_T^{Im}, and\ A_T^{Re}$



- First measure at very low q^2 region [0.0008, 0.257] GeV^2/c^4 to suppress $b \to s\gamma_{real}$ contribution
- Result consistent with SM [PRD 93 (2016) 1, 014028] [Nucl.Phys.B 854 (2012) 321-339]

$$F_L = 0.044 \pm 0.026 \pm 0.014, \qquad A_T^{Re} = -0.06 \pm 0.08 \pm 0.02$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02, \qquad A_T^{Im} = +0.02 \pm 0.10 \pm 0.01$$



Angular analysis of $B \to K^* l^+ l^-$

[JHEP 12 (2020) 081]

- $A_T^{(2)}, A_T^{Im}$ sensitive to photon polarization ($C_7^{(\prime)}$) at very low q^2

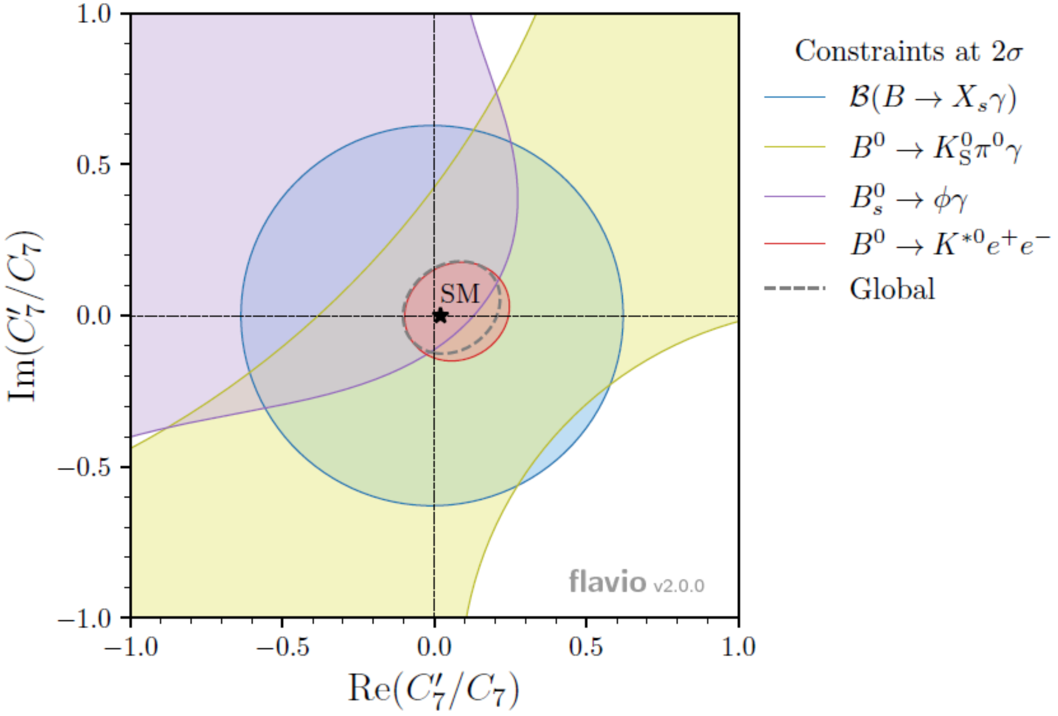
$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e\left(\mathcal{C}_7\mathcal{C}_7^{\prime *}\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7^{\prime}|^2}$$

$$A_T^{Im}(q^2 \to 0) = \frac{2\mathcal{I}m\left(\mathcal{C}_7\mathcal{C}_7^{\prime *}\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7^{\prime}|^2}$$

- Measure the polarization of $B^0 \to K^{*0}\gamma$ with both real and imaginary parts

- Provide the world's best constraint on $b \to s\gamma$ photon polarization, consistent with SM [JHEP 04 (2017) 027]

$$\begin{aligned} \mathrm{Re}\left(A_{\mathrm{R}}/A_{\mathrm{L}}\right) &= 0.05 \pm 0.05 \\ \mathrm{Im}\left(A_{\mathrm{R}}/A_{\mathrm{L}}\right) &= 0.01 \pm 0.05. \end{aligned}$$



[PRL 109 (2012) 191801]
[PRD 91 (2015) 052004]
[PRL 123 (2019) 081802]

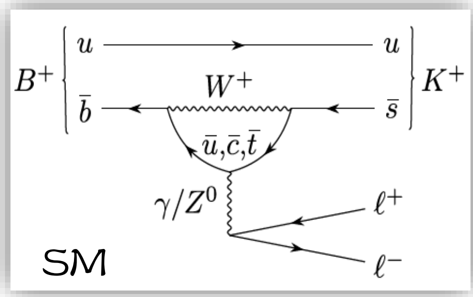
R_K measurement at LHCb

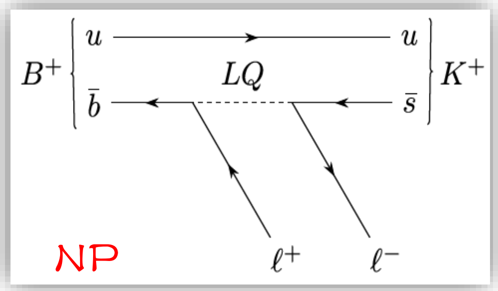
[arXiv:2103.11769]

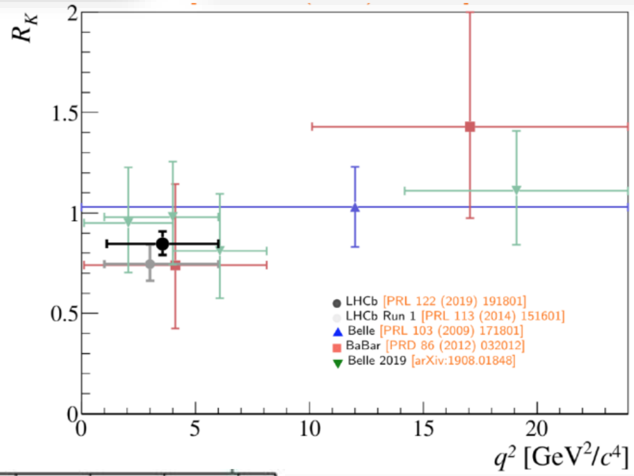
- Test of lepton flavor universality (LFU)

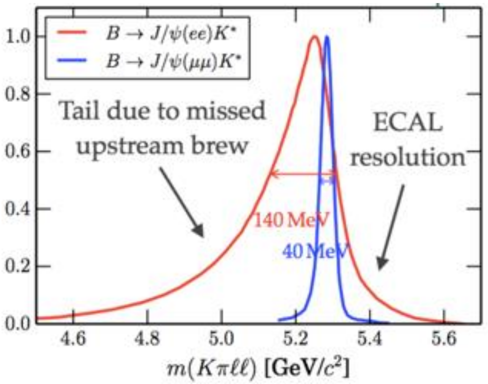
$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2} \overset{SM}{=} 1 \pm \mathcal{O}(1\%)$$

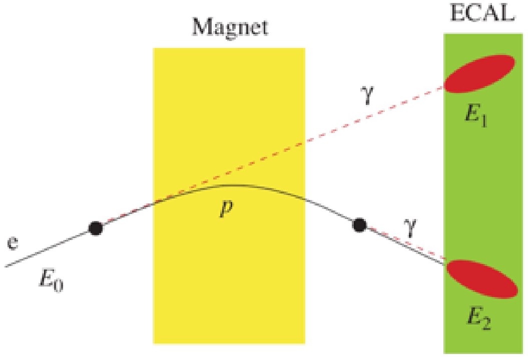
  - $q^2 \in [1.1, 6.0]\mathrm{GeV}^2/c^4$
- Updated measurement using a full Run 1 + 2 dataset
  - following essentially identical procedure
  - previous result in tension with SM prediction at level of $\mathbf{2.5\sigma}$ [PRL 122 (2019) 191801]
- Challenging due to bremsstrahlung radiation
  - significant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











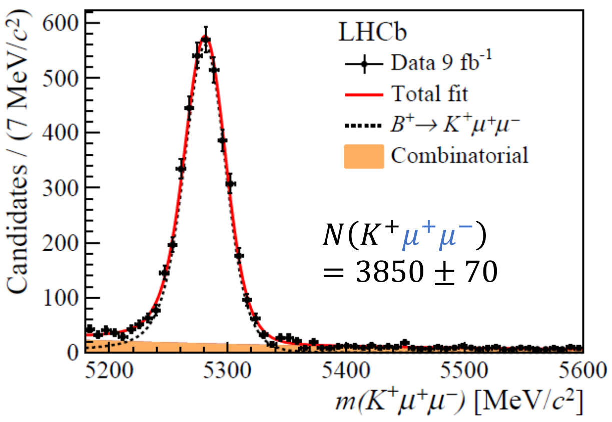
R_K measurement at LHCb

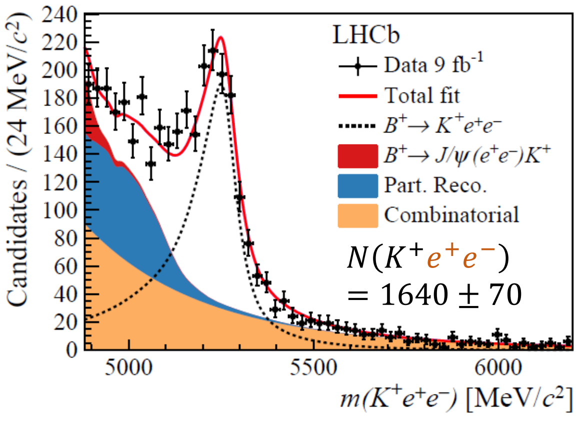
[arXiv:2103.11769]

- Measuring R_K with

$$R_K = \frac{N_{rare}^{\mu^+\mu^-}}{N_{rare}^{e^+e^-}} \cdot \frac{\varepsilon_{rare}^{e^+e^-}}{\varepsilon_{rare}^{\mu^+\mu^-}} \cdot \frac{N_{control}^{e^+e^-}}{N_{control}^{\mu^+\mu^-}} \cdot \frac{\varepsilon_{control}^{\mu^+\mu^-}}{\varepsilon_{control}^{e^+e^-}}$$

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





R_K measurement at LHCb

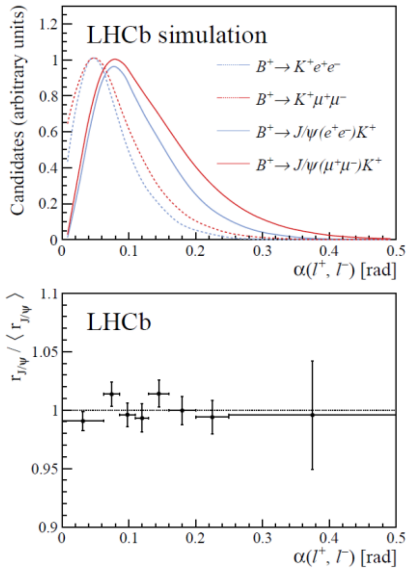
[arXiv:2103.11769]

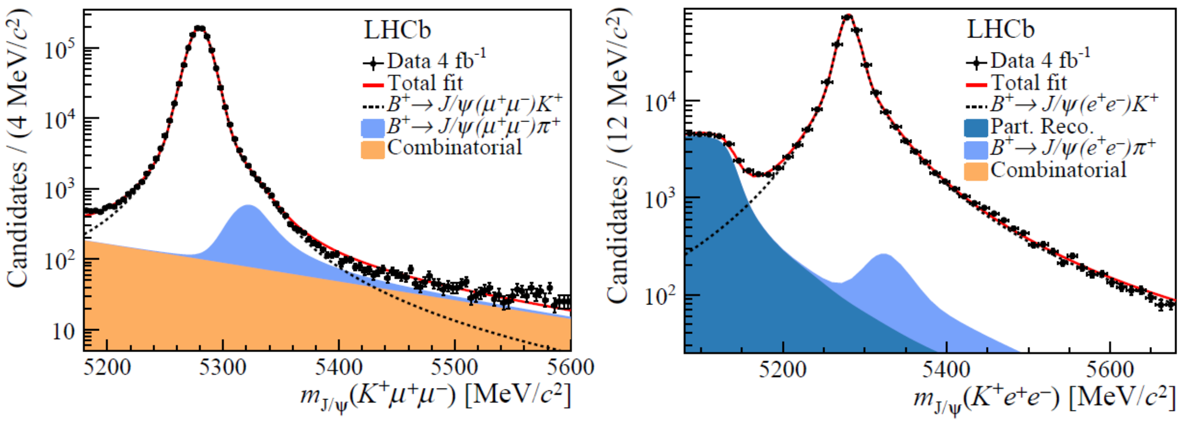
- Measuring R_K with

$$R_K = \frac{N_{rare}^{\mu^+\mu^-}}{N_{rare}^{e^+e^-}} \cdot \frac{\varepsilon_{rare}^{e^+e^-}}{\varepsilon_{rare}^{\mu^+\mu^-}} \cdot \frac{N_{control}^{e^+e^-}}{N_{control}^{\mu^+\mu^-}} \cdot \frac{\varepsilon_{control}^{\mu^+\mu^-}}{\varepsilon_{control}^{e^+e^-}}$$

$R_{J/\psi}$

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





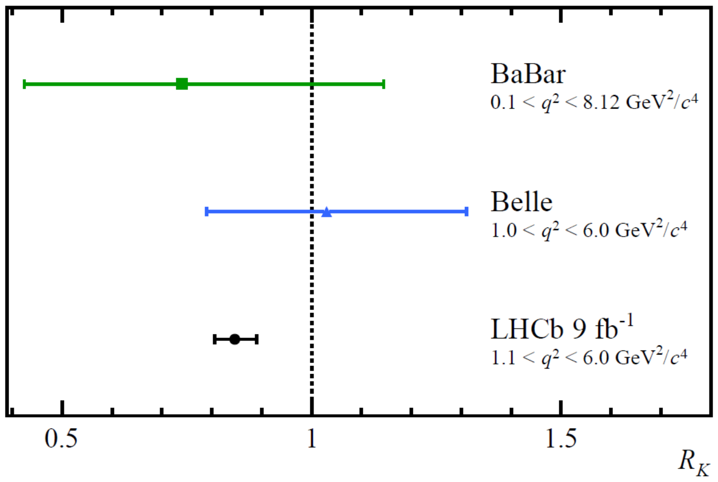
R_K measurement at LHCb

[arXiv:2103.11769]

- Measuring R_K with

$$R_K = \frac{N^{\mu^+\mu^-}_{rare}}{N^{e^+e^-}_{rare}} \cdot \frac{\varepsilon^{e^+e^-}_{rare}}{\varepsilon^{\mu^+\mu^-}_{rare}} \cdot \frac{N^{e^+e^-}_{control}}{N^{\mu^+\mu^-}_{control}} \cdot \frac{\varepsilon^{\mu^+\mu^-}_{control}}{\varepsilon^{e^+e^-}_{control}}$$

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



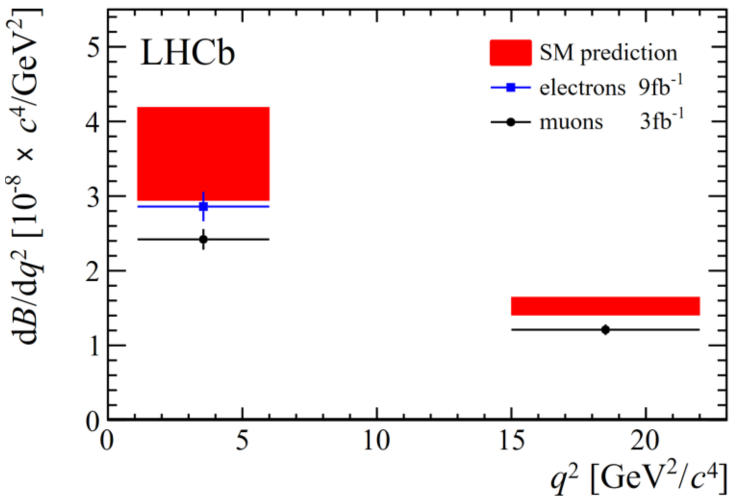
- Supersede the previous LHCb analysis
- Below SM prediction with a tension of 3.1σ

[Eur. Phys. J. C76 (2016) 440, JHEP 06 (2016) 092]

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

- Branching ratio for electron mode measured as well

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



Summary

- Presented results from LHCb $b \to s l^+ l^-$ measurements
  - Search for $B^0_{(s)} \to \mu^+\mu^-(\gamma)$ and $B^0_s \to \phi(f_2')\mu^+\mu^-$ (very) rare decays
  - Angular analysis of $B \to K^*\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$
  - Test of Lepton Flavor Universality R_K

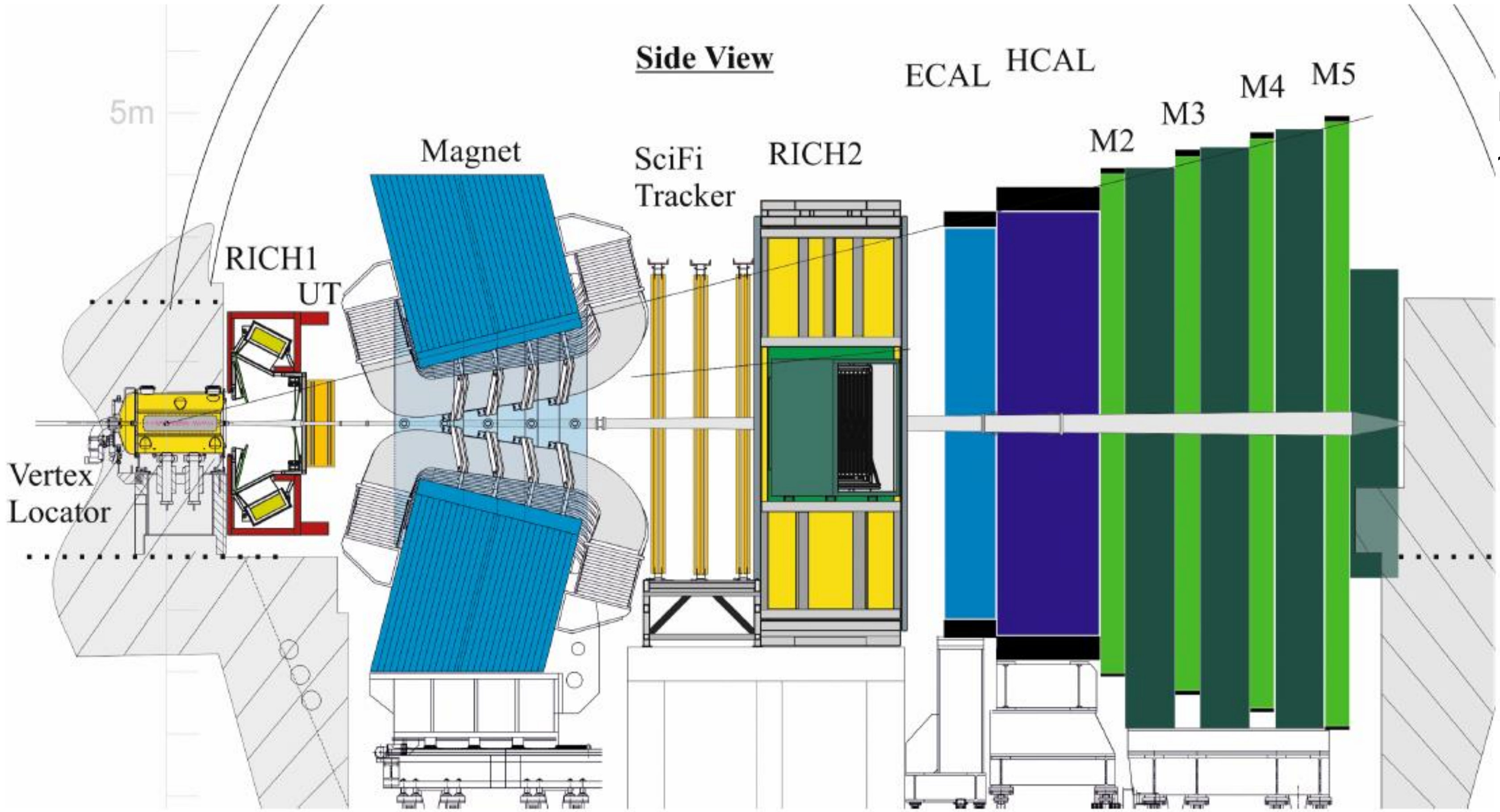
- Well in agreement with the SM prediction, $\sim 3\sigma$ tension remains for NP
- More data needed to confirm the trend, we expect nice development in the future
- LHCb will continue to study rare decays to discover hints of new physics

- Other updates coming soon
  - search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$
  - updated angular analysis of $B^0_s \to \phi\mu^+\mu^-, B^+ \to K^+e^+e^-$
  - $R_{K^*}, R_{K^0_S}, R_\phi$
  - …

Thank you for your attention!

Backup

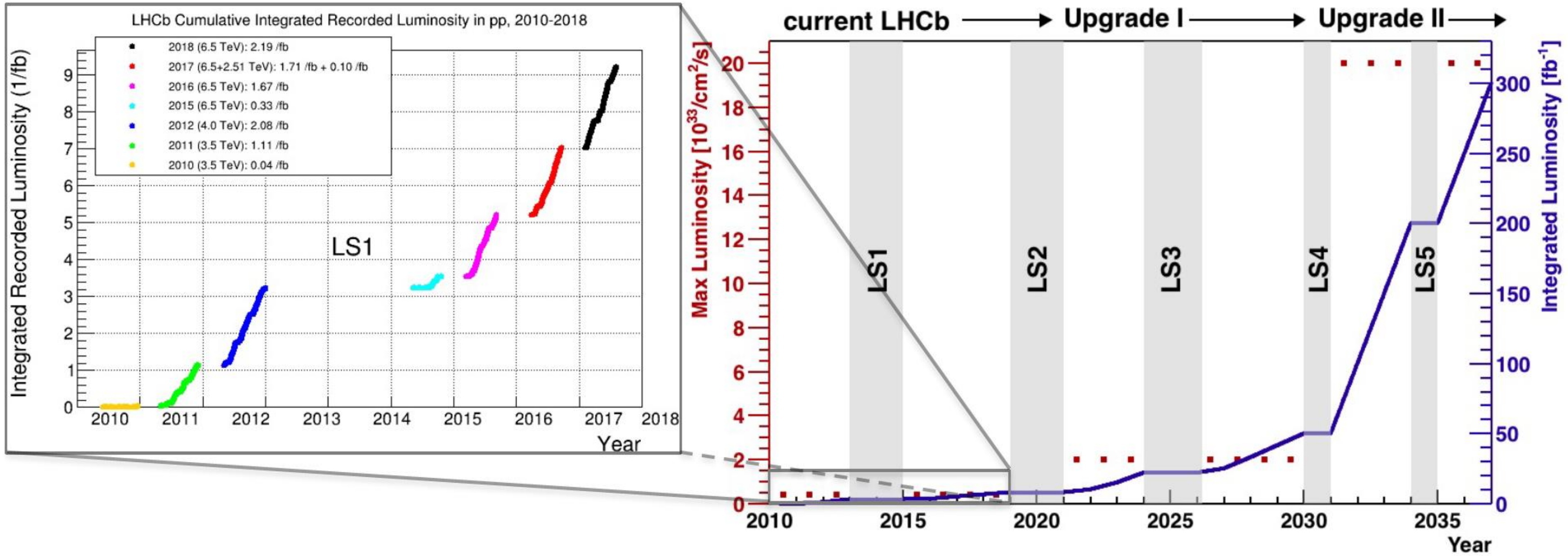
LHCb detector (upgrade)



Run-III
~23 fb^{-1} for data-taking

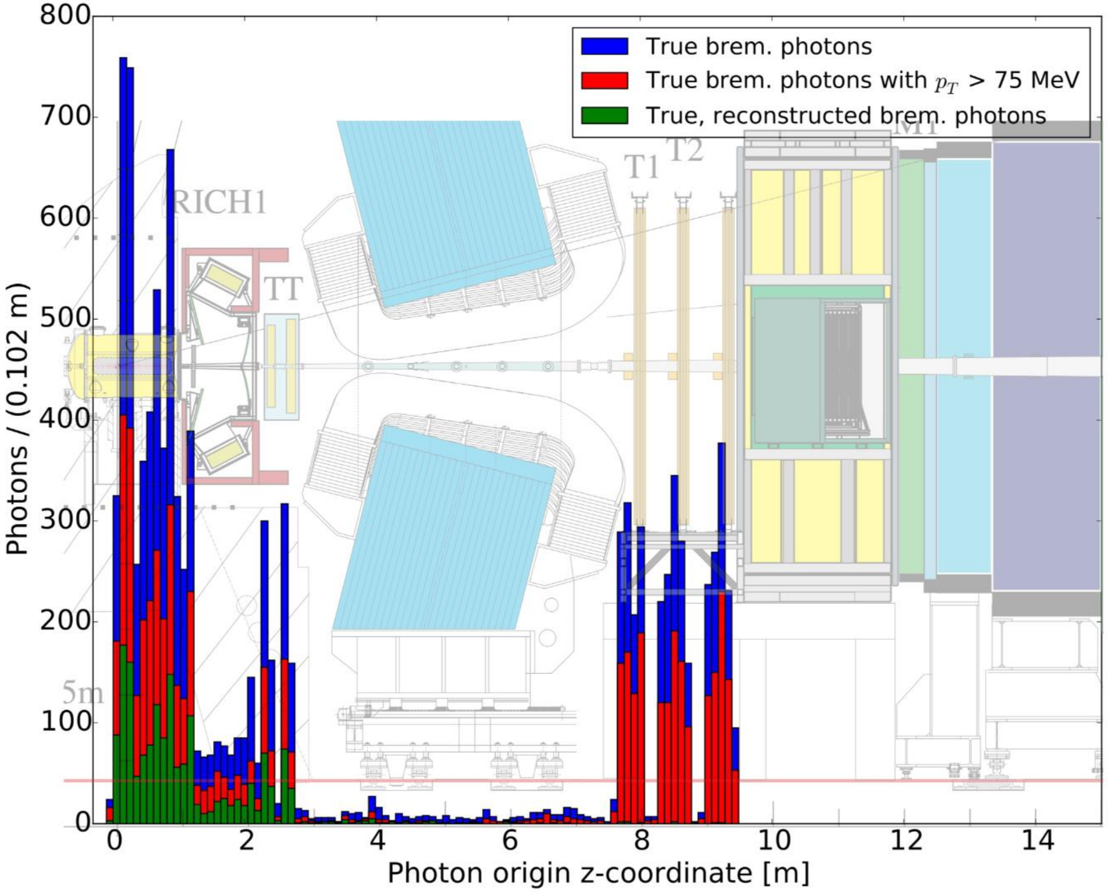
CERN-LHCC-2018-014, LHCB-TDR-018

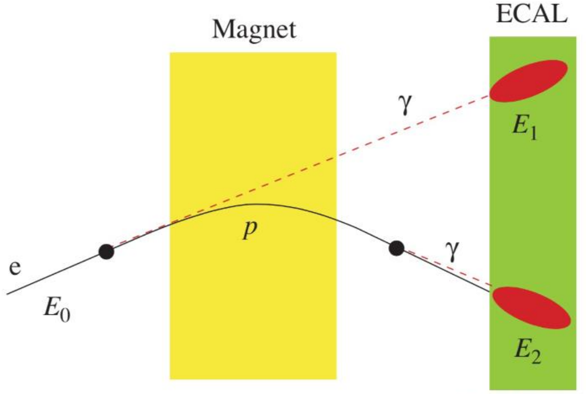
LHCb luminosity prospects

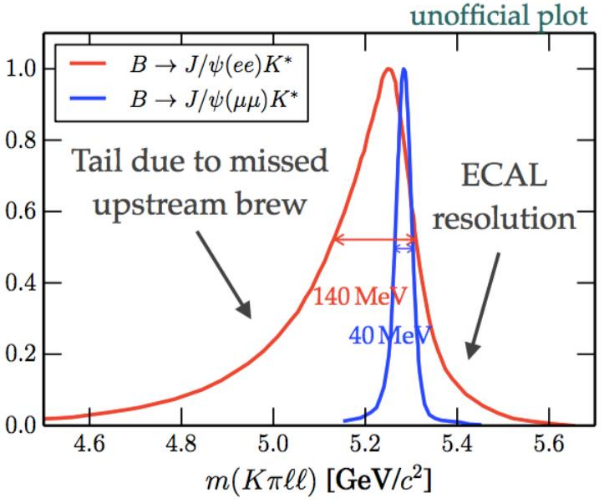


LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

Bremsstrahlung corrections



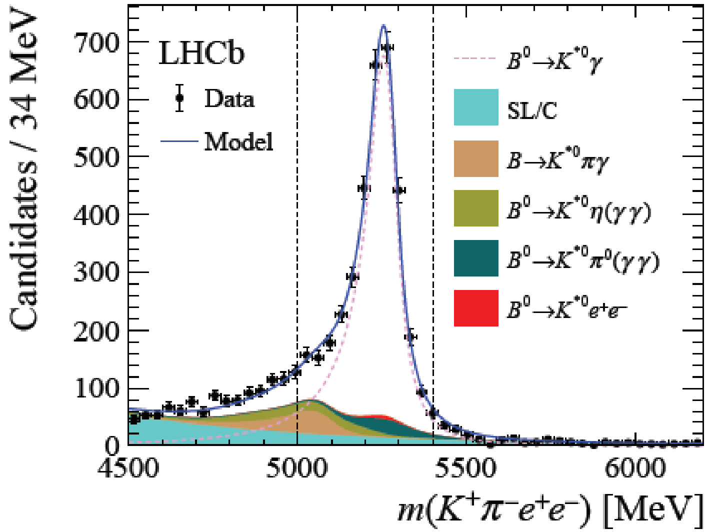




Angular analysis of $B \to K^* l^+ l^-$

[JHEP 12 (2020) 081]

- $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$
- redefinition of ϕ: $\tilde{\phi} = \begin{cases} \phi + \pi \text{ if } \phi < 0 \\ \phi \text{ if } \phi \geq 0 \end{cases}$
- S-wave contribution is <1%, negligible
- Polarization of $b \to s\,\gamma$ transition can be expressed as the ratio of C_7 $(left - handed)$ and $C_7'(right - handed)$
- photons are almost on-shell
- q^2 selection<0.25 minimize sensitivity to vector and axial-vector currents($C_{9,10}^{(\prime)}$)



control mode $b \to s\,\gamma$

Backup

- Status of $B \to K\tau\tau$
- upper limit, at the 90% confidence level, is $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$
- branching fraction $\mathcal{B}(B_s^0 \to \tau^+\tau^-)) < 6.8 \times 10^{-3}$ at the 95% CL
- $\mathcal{B}(B^0 \to \tau^+\tau^-)) < 2.1 \times 10^{-3}$ at the 95% CL [PRL 118 (2017) 251802]

- Different regions in $q^2 = m^2(ll)$ are sensitive to different operator contributions
- C_i, O_i: wilson coefficients that for SM contributions
- C_i', O_i': wilson coefficients that for NP contributions

$$O_7^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu} \qquad O_7'^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$$

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_S'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,,$$

$$O_P^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$