Rare B decays at LHCb

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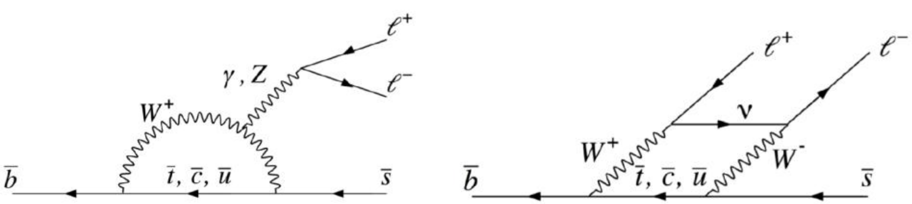
Content

- Why rare b decays?
- Rare b decays at LHCb:
  - Leptonic decays
  - Radiative decays
  - $b \to sll$
  - LFU tests
- Summary and prospects

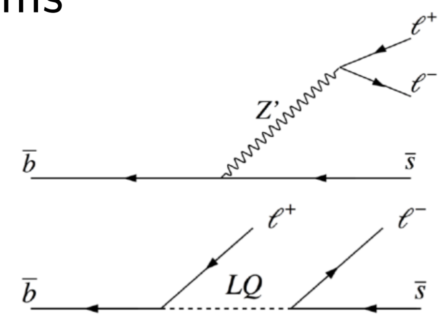
Why rare b decays?

- Flavour-Changing Neutral Currents (FCNC) highly suppressed in the SM
- $b \to s(d)$ decays: only via penguin or box diagrams

  => sensitive to new physics contributions



SM



NP?

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}_i'(\mu)\mathcal{O}_i'(\mu)}_{\text{right-handed part suppressed in SM}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

Wilson coefficients of interest:

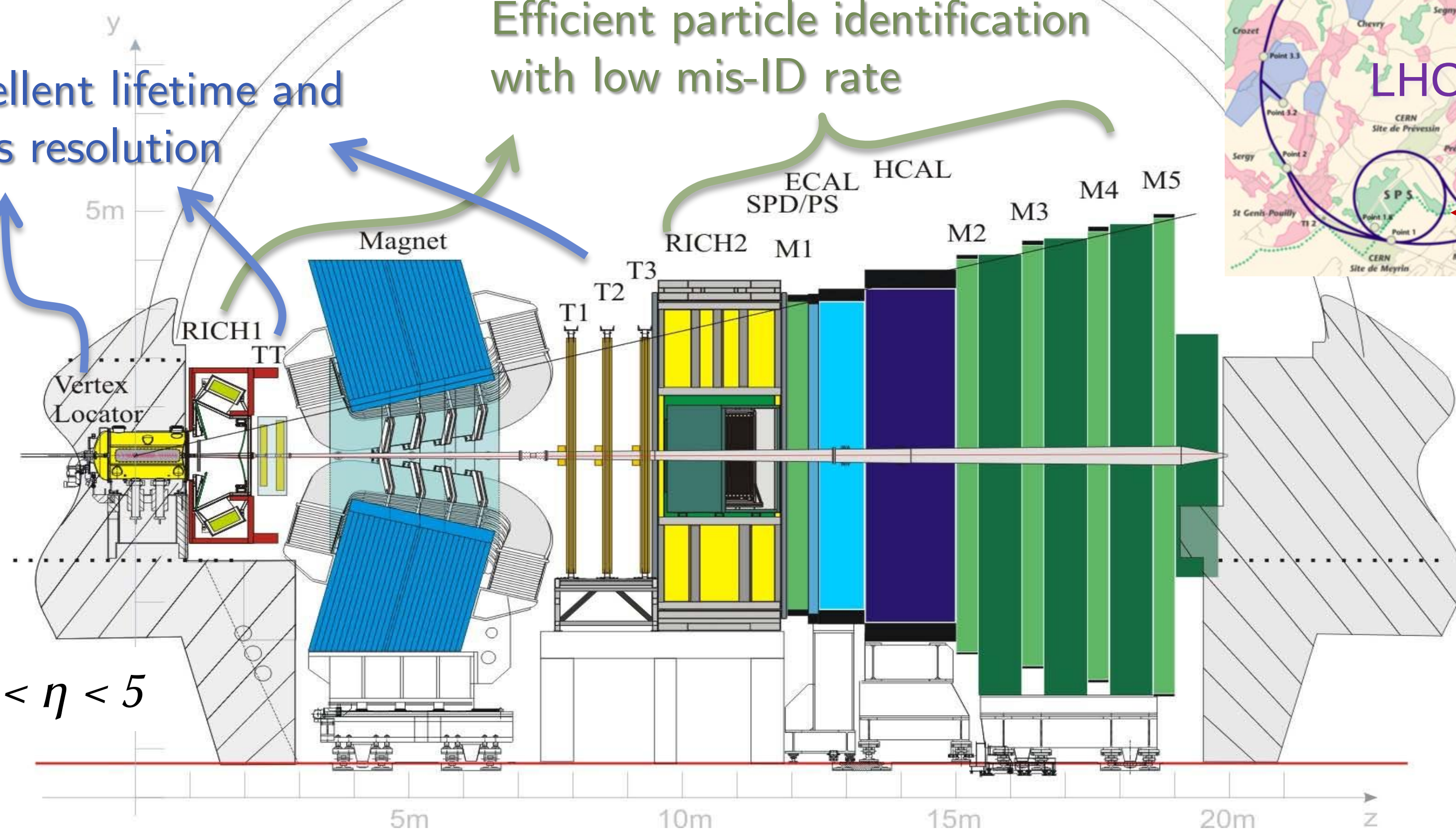
$C_7^{(\prime)}$ – couplings to photons

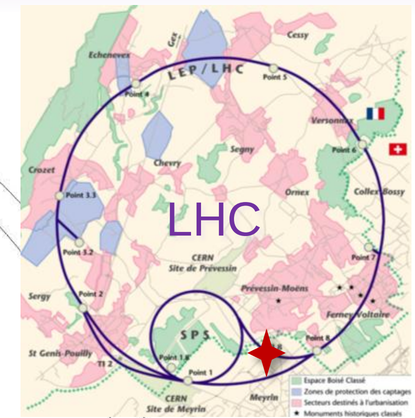
$C_9^{(\prime)}$, $C_{10}^{(\prime)}$ – couplings to leptons

LHCb detector

Excellent lifetime and mass resolution

Efficient particle identification with low mis-ID rate





$2 < \eta < 5$

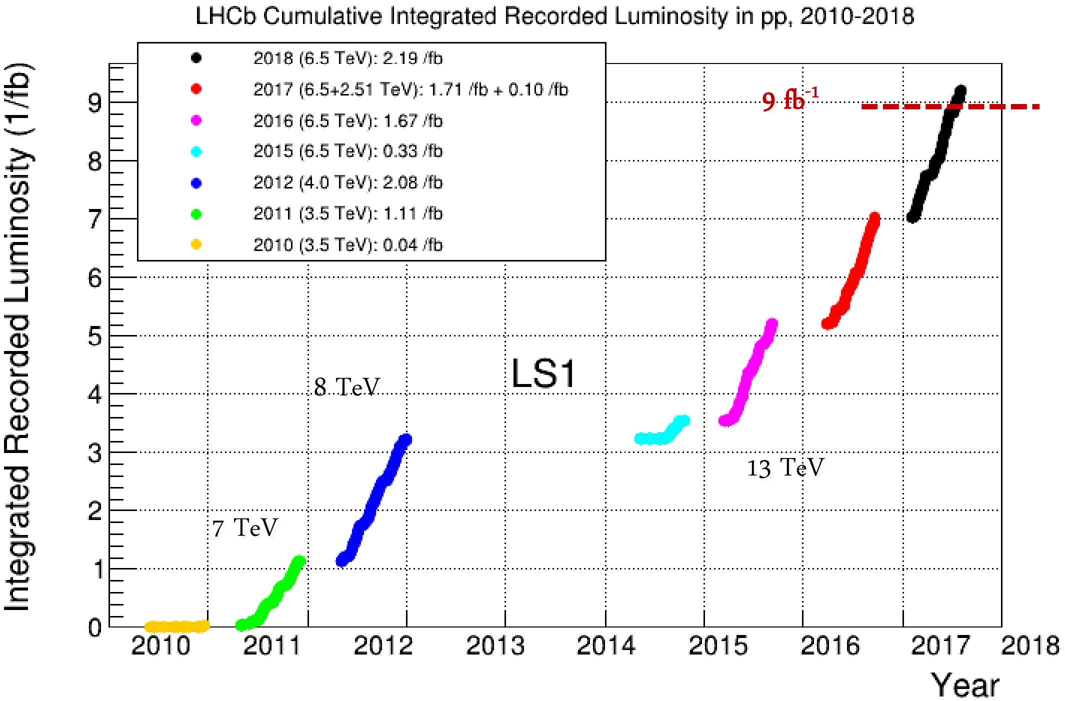
JINST 3 (2008) S08005
IJMPA 30 (2015) 153022

- A forward spectrometer for heavy flavour physics
  → A general purpose detector at forward region
- 1250 members, 79 institutes, 18 countries

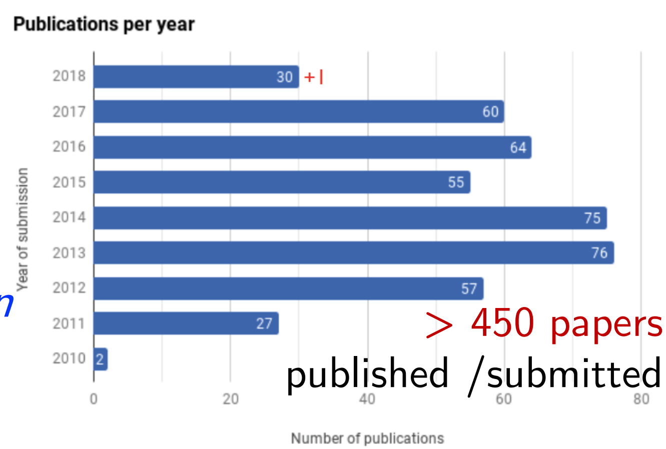
Operation

- Run I: 3 fb^{-1}
- End of Run II: > 9 fb^{-1}
- ~ 5 times more wrt Run I

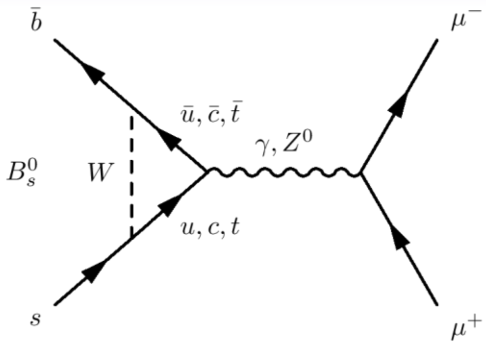
accounting for $\sigma_{\bar{b}b}$ increase

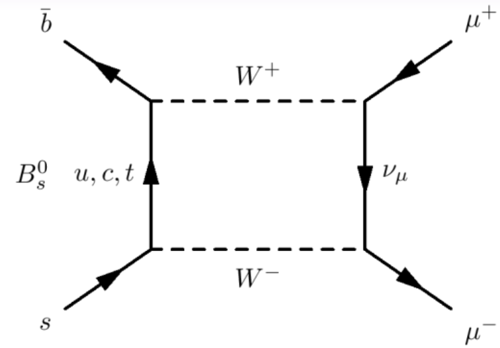


- A wealth of physics results produced with Run I already; new results emerging including Run II data



More to expect at HFCPV:
→ "CPV in B decays at LHCb", Yuehong Xie
→ "Charm CPV and rare decays at LHCb", Liang Sun
→ "Spectroscopy studies at LHCb", Jibo He

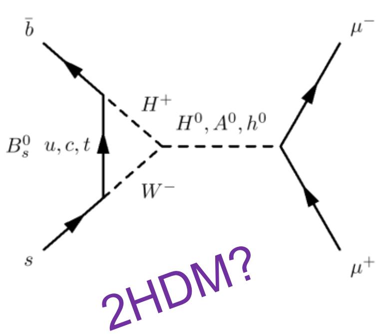


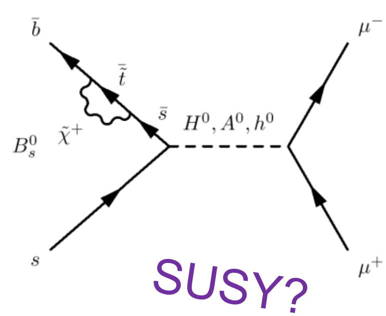


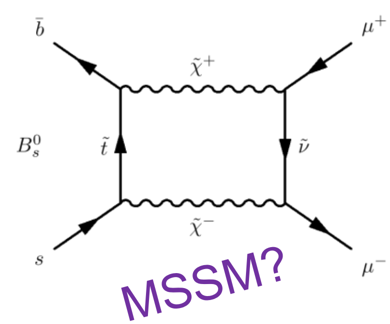
Leptonic $b \to ll$ decays

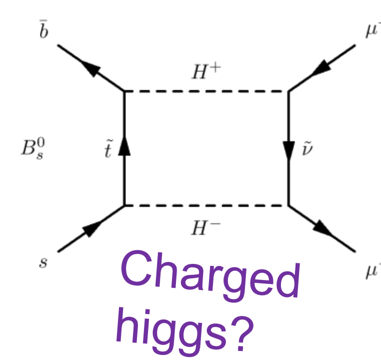
Highly suppressed in SM, theoretically clean final state

Very sensitive to new physics contribution





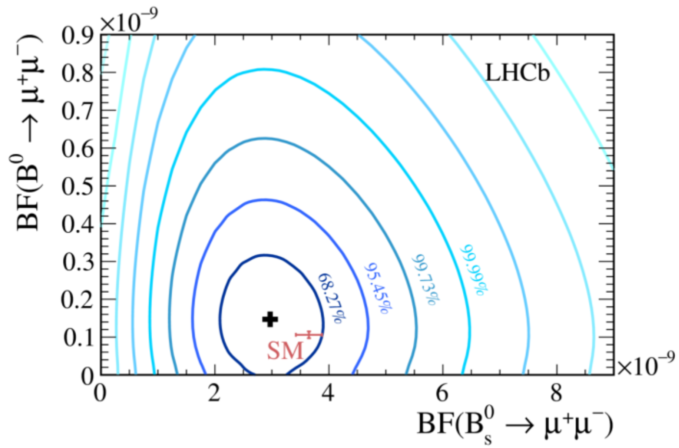




$B^0_{(s)} \to \mu^+\mu^-$

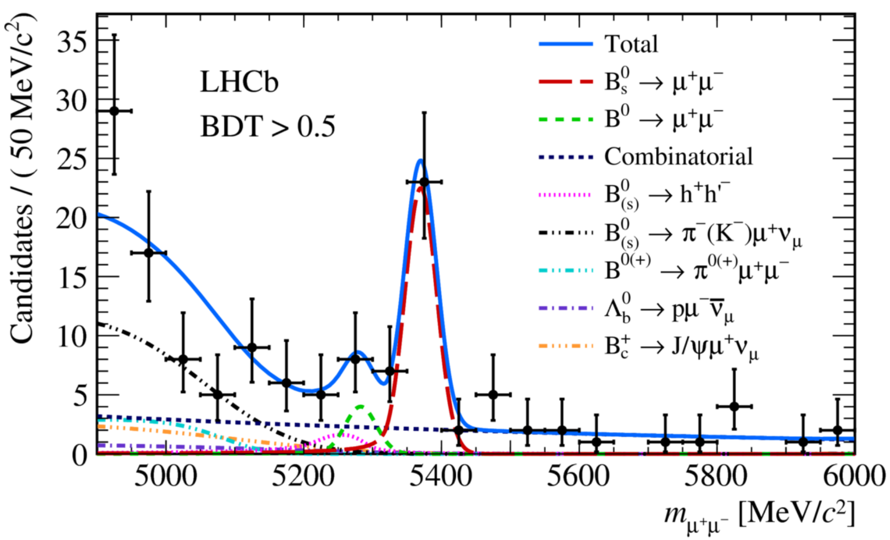
PRL 119 (2017) 191801

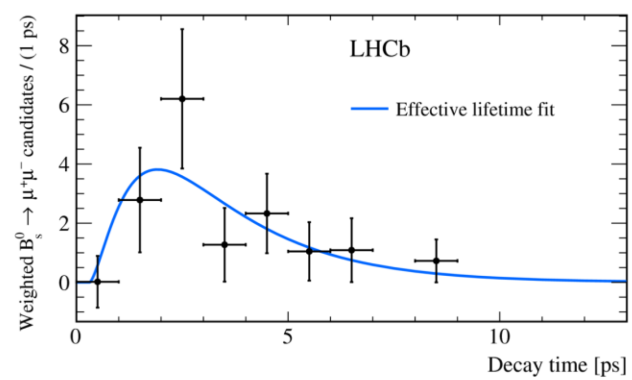
- First observation of $B^0_s \to \mu^+\mu^-$ by a single experiment using 4.4 fb^{-1} (2011~2016)
  - 7.6 σ significane
  - No evidence yet for $B^0 \to \mu^+\mu^-$



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

- First measurement of $B^0_s \to \mu^+\mu^-$ lifetime
  - $\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05$ ps





$$\tau_{\mu^+\mu^-} = \frac{\tau_{B^0_s}}{1 - y_s^2}\left(\frac{1 + 2A^{\mu^+\mu^-}_{\Delta\Gamma} y_s + y_s^2}{1 + A^{\mu^+\mu^-}_{\Delta\Gamma} y_s}\right)$$

1 in SM; [-1, 1] in NP

$B^0_{(s)} \to \tau^+\tau^-$

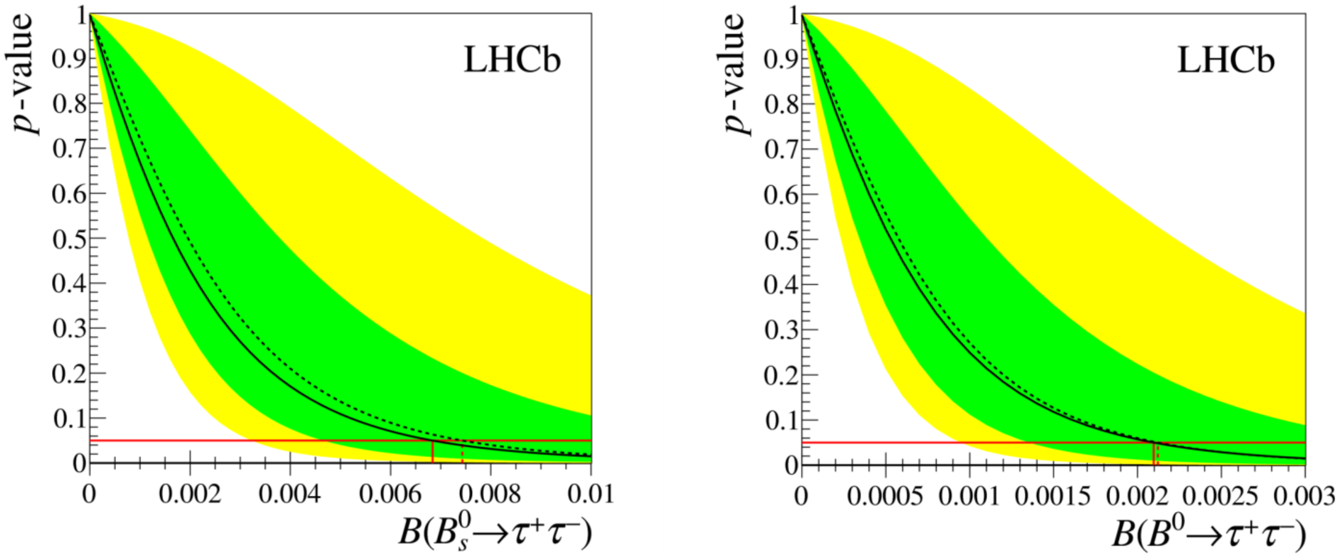
PRL 118 (2017) 251802

- τ decay very challenging due to missing neutrinos
- First direct limit on $B^0_s \to \tau^+\tau^-$ and world best limit on $B^0 \to \tau^+\tau^-$
  - Exploiting excellent vertex resolution in hadronic final state $\pi\pi\pi\nu$
  - Search with 3 fb^{-1} (Run I)

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$

SM:

$$\mathcal{B}(B^0_s \to \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$$

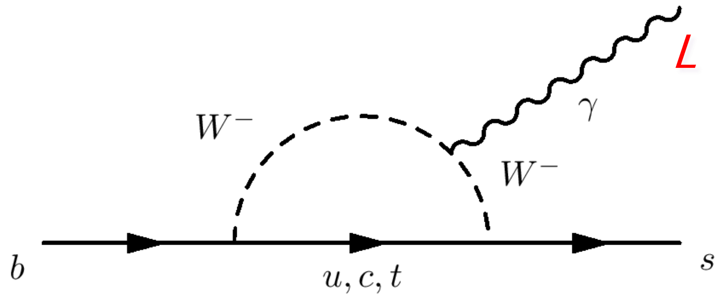


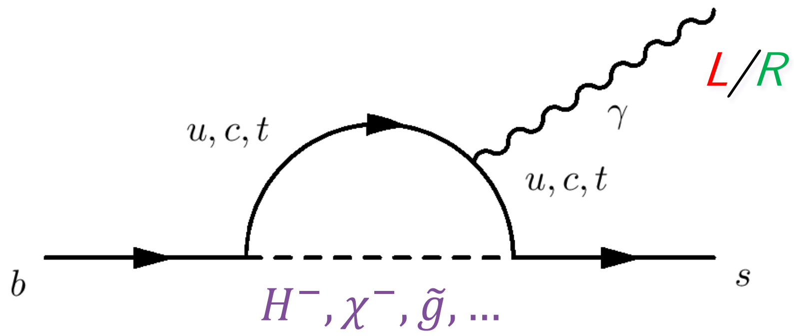
Radiative $b \to s\gamma$ decays

Studied in detail in B factories

Most sensitive to $C_7^{(\prime)}$

Photon polarization dominantly left-handed in SM;
 up to 50% right-handed in SM extension!

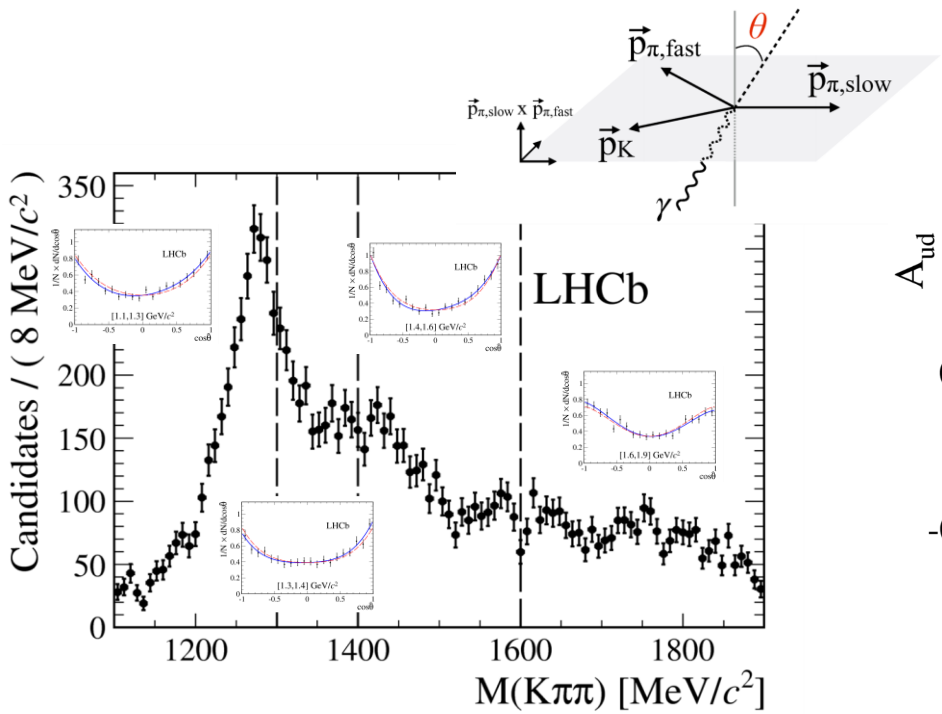


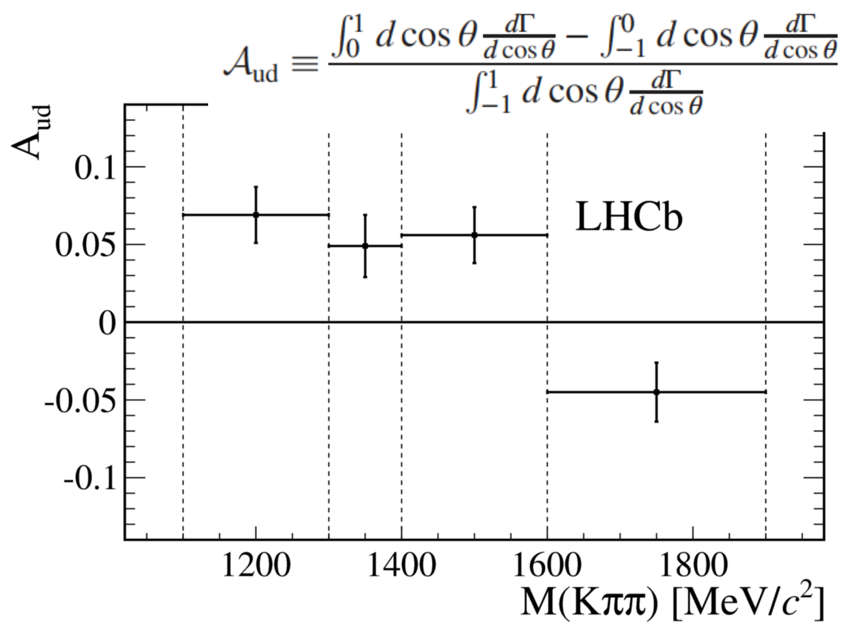


$B^+ \to K^+\pi^+\pi^-\gamma$

PRL 112 (2014) 161801

- Photon polarization in $B^+ \to K^+\pi^+\pi^-\gamma$
  - First direct observation (5.1σ) of photon polarization using 3 fb^{-1} Run I data





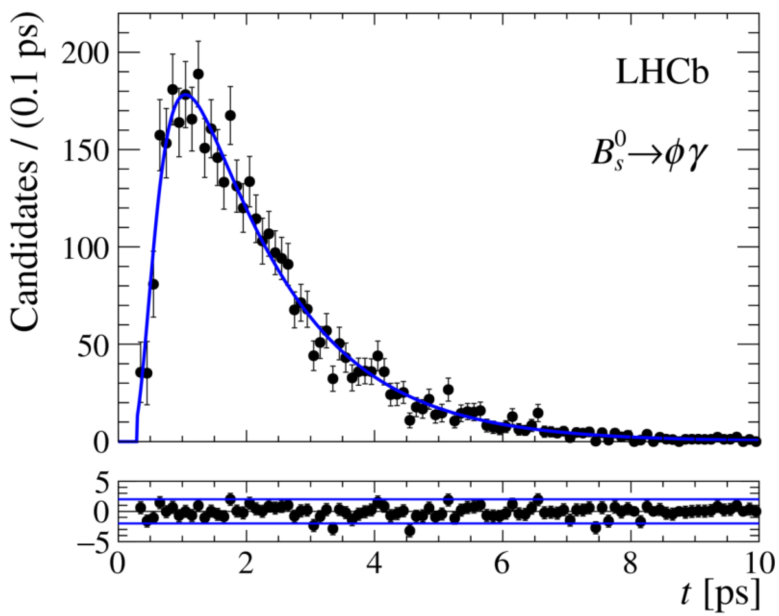
$B_s^0 \to \phi\,\gamma$

PRL 118 (2017) 021801

- Photon polarization in B_s studied for the first time
  - Time-dependent decay rate sensitive to right- over left-handed γ polarization

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[cosh(\frac{\Delta\Gamma_s t}{2}) - \mathcal{A}^{\Delta} sinh(\frac{\Delta\Gamma_s t}{2}) \pm \mathcal{C} cos(\Delta m_s t) \mp \mathcal{S} sin(\Delta m_s t)\right]$$

$$\frac{2\,\mathrm{Re}[\frac{q}{p}(\bar{\mathcal{A}}_L \mathcal{A}_L^* + \bar{\mathcal{A}}_R \mathcal{A}_R^*)]}{|\mathcal{A}_L|^2 + |\bar{\mathcal{A}}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_R|^2}$$



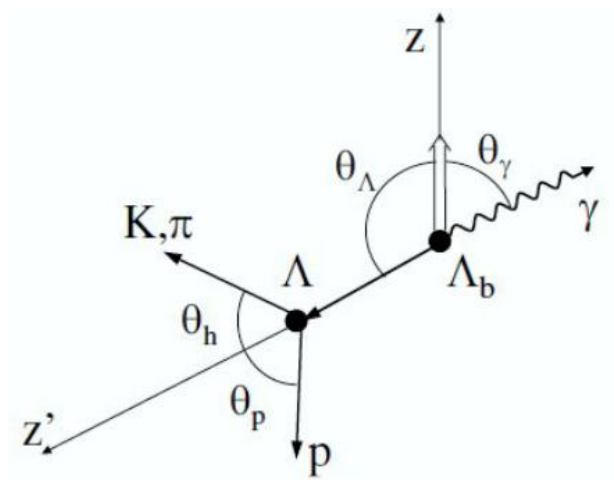
$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

SM prediction: $0.047^{+0.029}_{-0.025}$

PLB 664 (2008) 174

$b \to s\gamma$ in baryonic decays

- Opportunity in baryonic decays

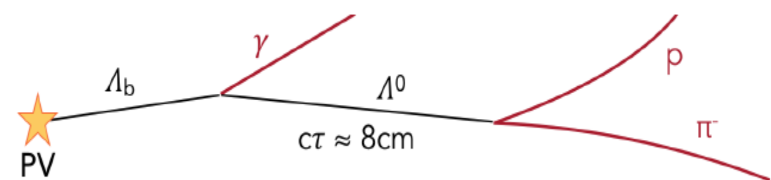


- $\Lambda_b^0 \to \Lambda^0 \gamma$
  - SM predicting BR ~ (0.06 – 1) × 10^{-5}.
  - Polarization of γ accessible in angular analysis

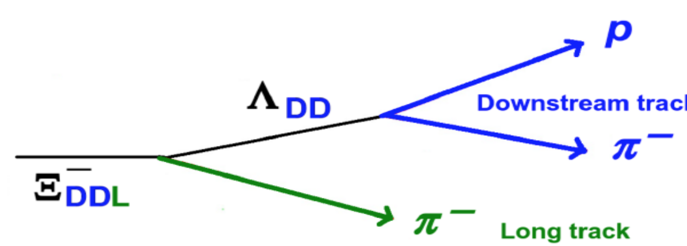
$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$
$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$

$$\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}$$

- $\Xi_b^- \to \Xi^- \gamma$, $\Omega_b^- \to \Omega^- \gamma$



- Difficulty: no secondary vertex, many downstream tracks
- Results expected soon

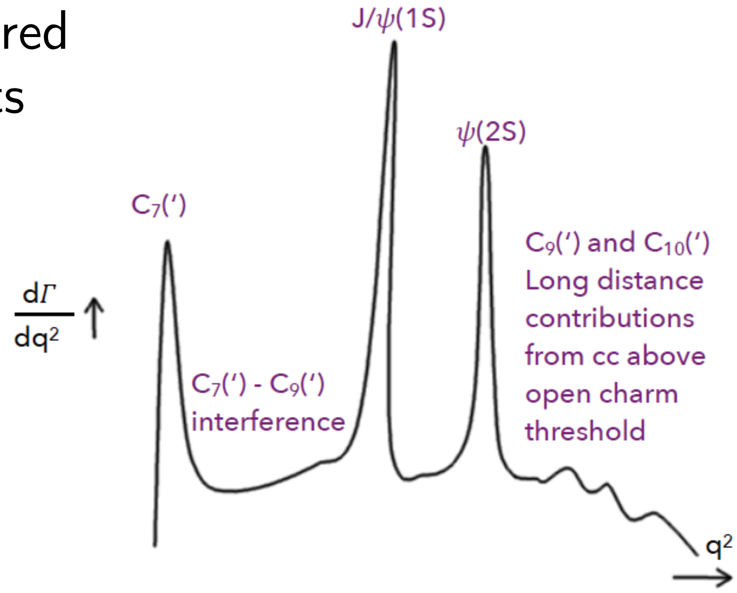


Semileptonic decays $b \to sll$

Different regions of dimuon mass squared sensitive to different Wilson coefficients

Observables:

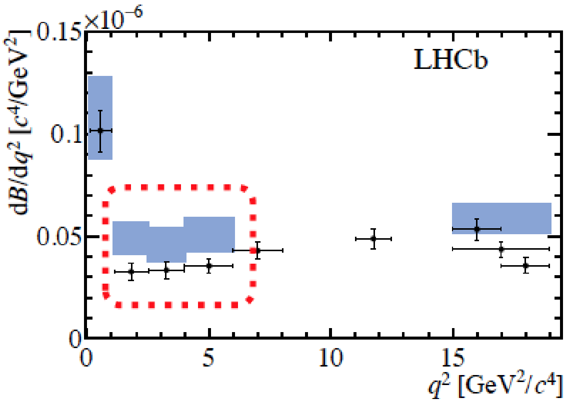
- Branching ratios
- Angular variables
- Lepton universality



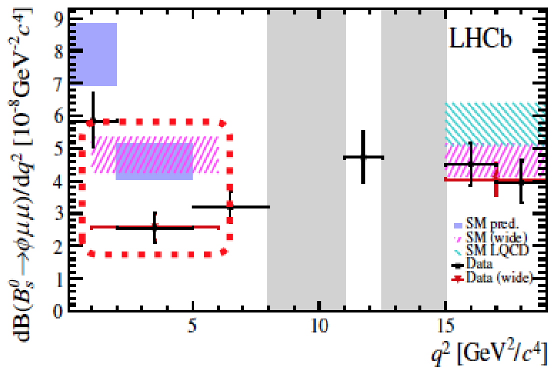
Branching ratios of $b \to s\mu^+\mu^-$ decays

- Data consistently below SM predictions; tension at $1{\sim}3\sigma$ level

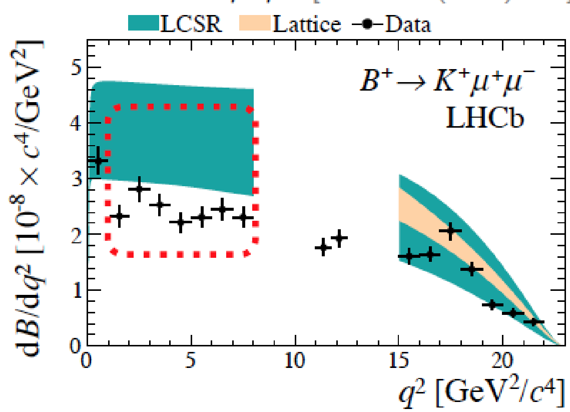
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



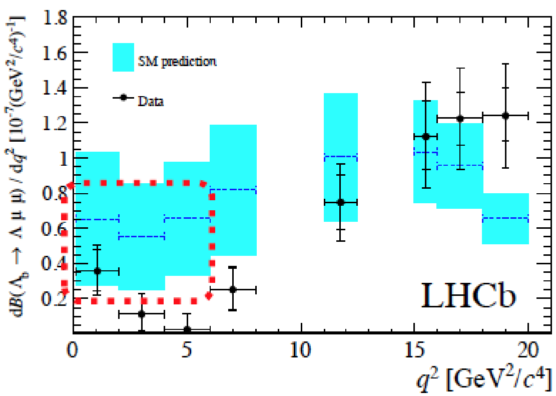
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



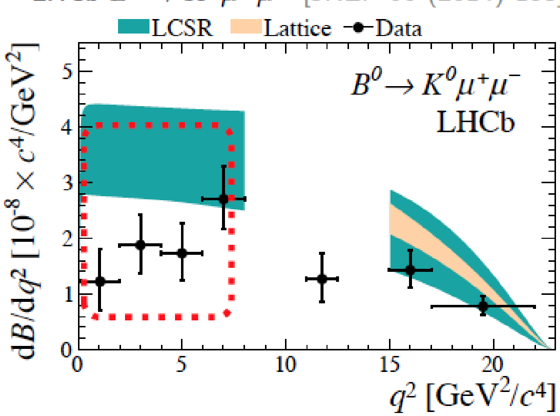
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



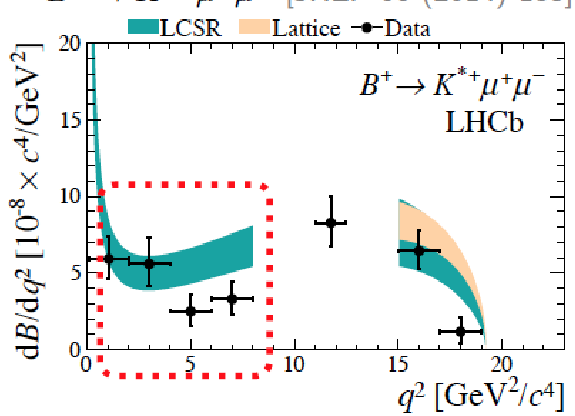
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



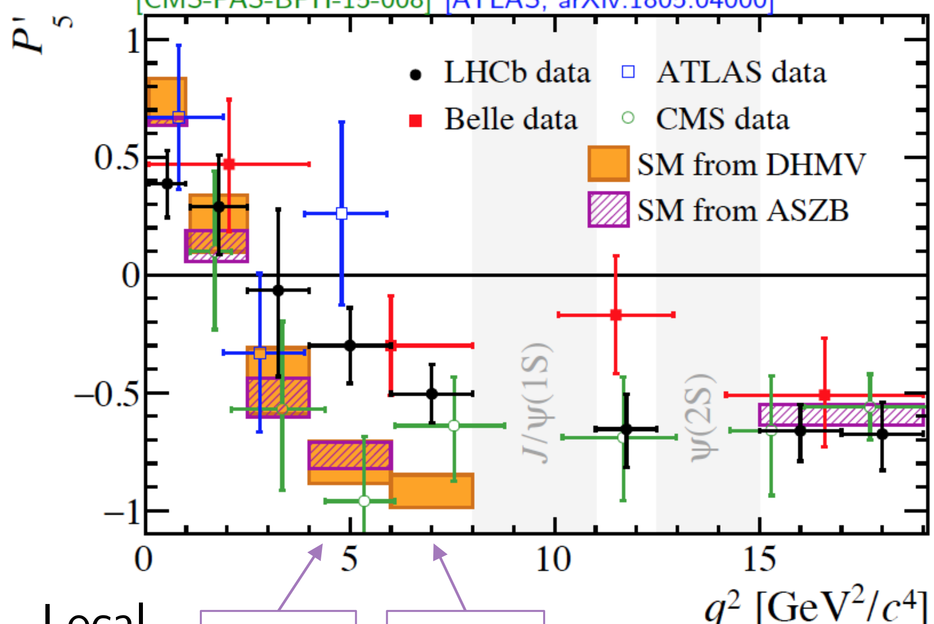
$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]



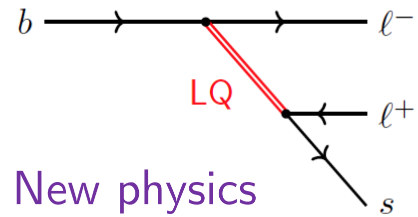
Angular analyses in $B^0 \to K^{*0}\mu^+\mu^-$

- Rich angular structure in $b \to sll$, where P_5' is less dependent on form-factor
- LHCb only global analysis: 3.4σ deviation from SM
- Update with Run II ongoing

[LHCb, JHEP 02 (2016) 104] [Belle, PRL 118 (2017) 111801] [CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]



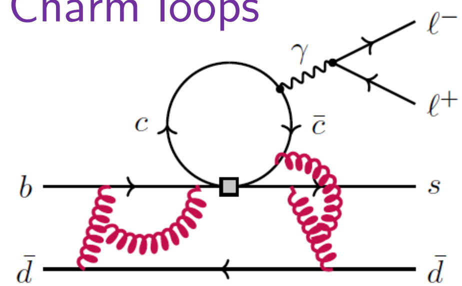
Local deviation: 2.8σ 3.0σ



New physics

vs.

Charm loops



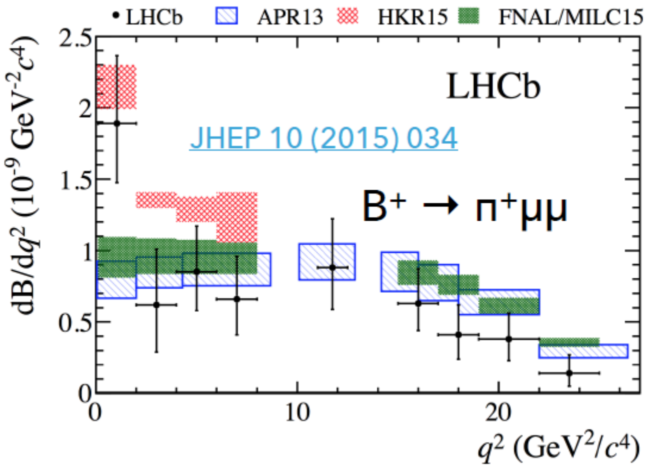
Significance depending on hadronic charm-loop uncertainties

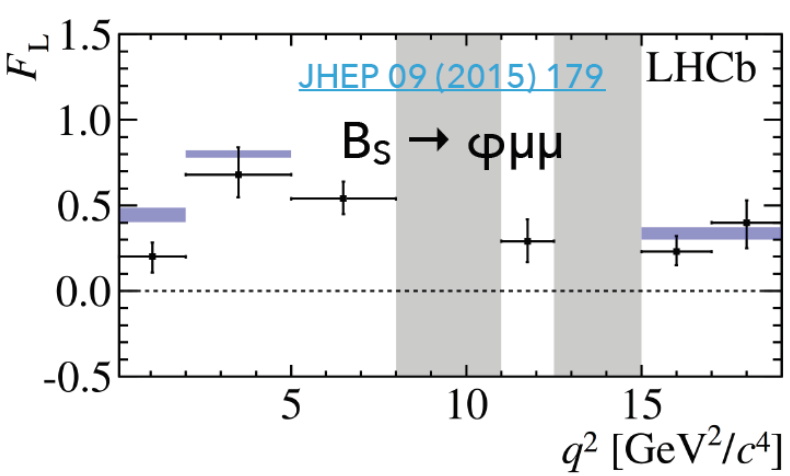
arXiv: 1406.0566

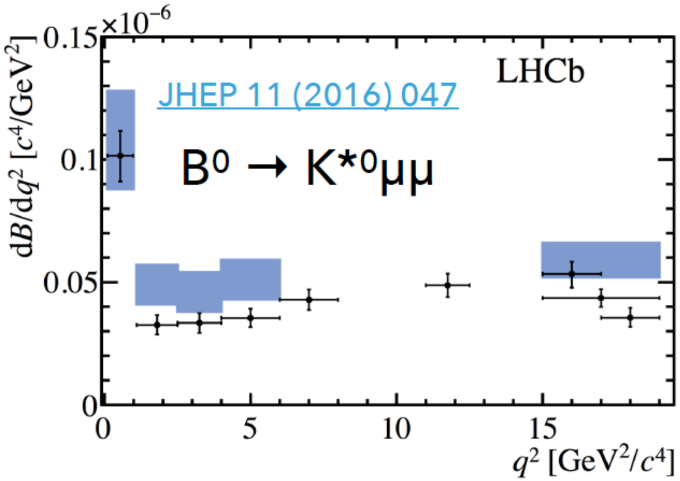
More angular analyses

- Many analyses of $B_{(s)} \to X\mu\mu$ have been produced with Run I data only, and limited by statistics

- Updates including Run II ongoing



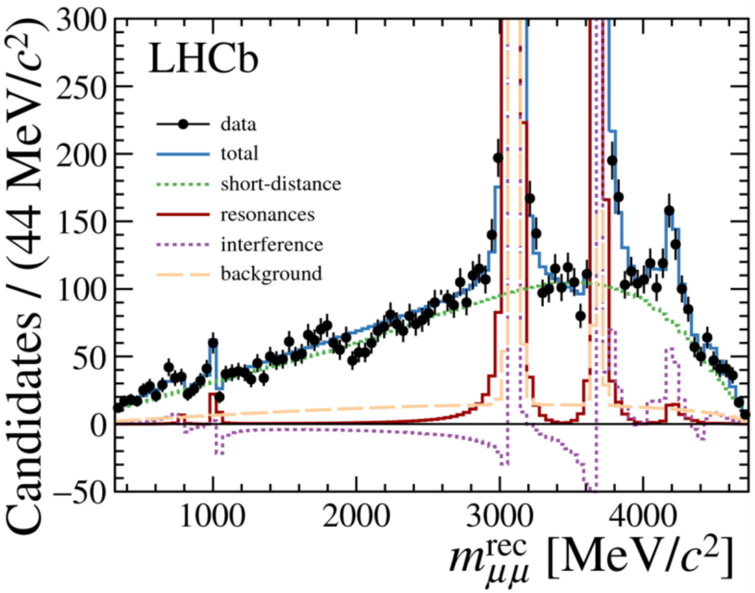


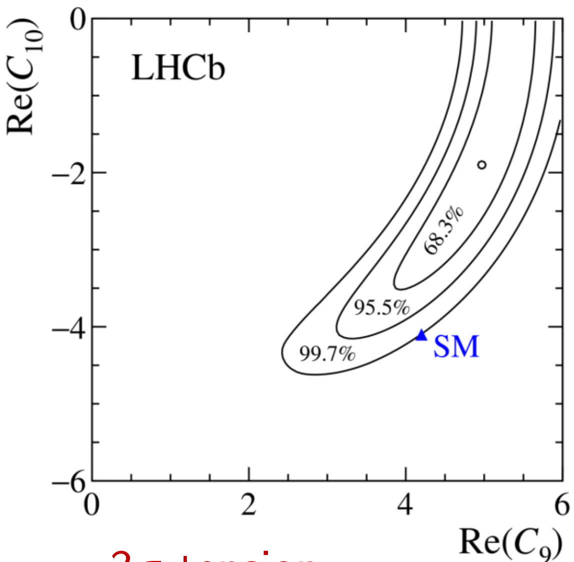


Phase difference in $B^+ \to K^+\mu^+\mu^-$

EPJC (2017) 77:161

- Tension in P_5':
  - NP in short distance? Or sizable long-distance effects away from resonances?
- Phase difference between the short- and long-distance amplitudes measured by fitting the full dimuon mass spectrum
- Including resonances: $\rho, \omega, \phi, J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)$





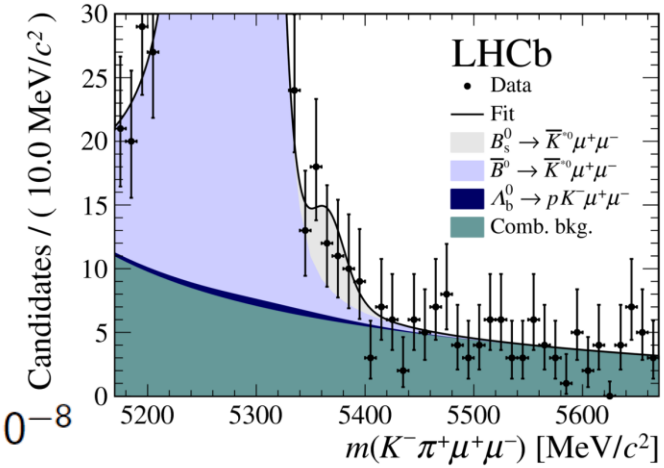
3σ tension

Exploring new modes: $b \to dll$

JHEP 07 (2018) 020

- First evidence found in $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$
  - 3.4σ using 4.6 fb^{-1} data (up to 2016)
  - Extremely challenging due to contamination from $\bar{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-)$$
$$= (2.9 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.3(\mathrm{norm})) \times 10^{-8}$$

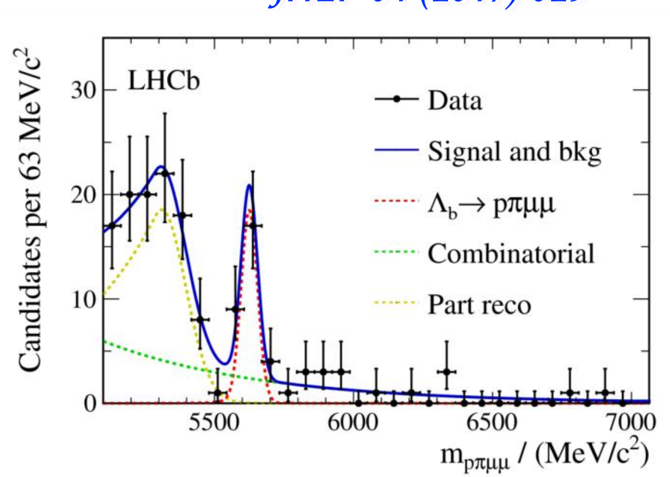


Exploring new modes: baryonic decay

JHEP 04 (2017) 029

- First observation of $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$.
  - First b to d transition in baryons

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-)$$
$$= (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$$

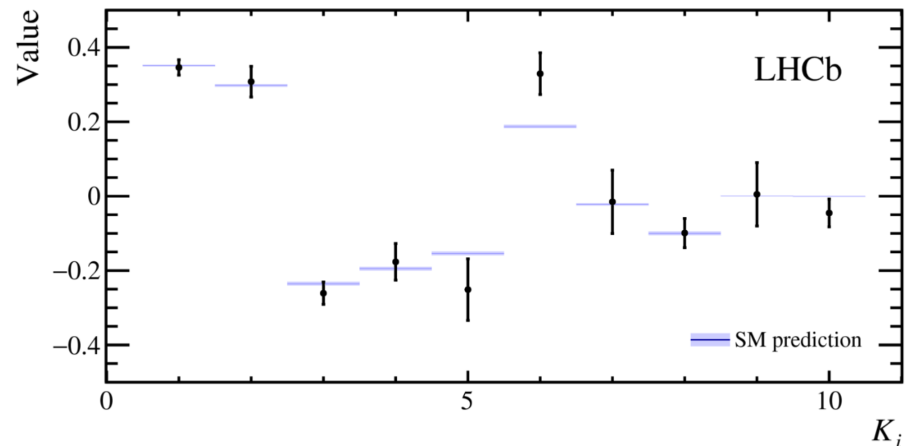


New modes (cont.): $\Lambda_b^0 \to \Lambda\,\mu^+\mu^-$

JHEP 09 (2018) 146

- Angular moments measured for $\Lambda_b^0 \to \Lambda\,\mu^+\mu^-$
  - Focus on high q^2 region (15, 20) $(\mathrm{GeV}/c^2)^2$
  - Full bases of observables measured with limited statistics, compatible with SM predictions

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega})$$



Forward-backward symmetry in lepton-/hadron-side /combined:

$$A_{FB}^{l} = -0.39 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$
$$A_{FB}^{h} = -0.30 \pm 0.05(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$
$$A_{FB}^{lh} = +0.25 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

Lepton Flavour Universality tests

$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$ accurately predicted in SM $\sim \mathcal{O}(1\%)$

Different interaction of e/μ in matter

$\rightarrow$ experimentally challenging!

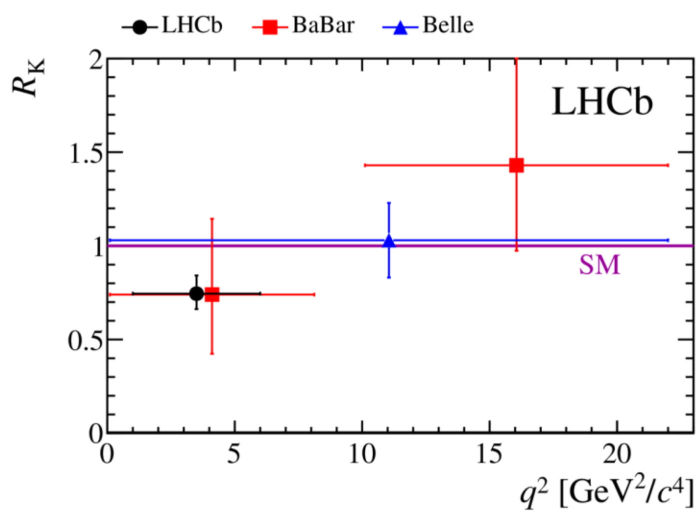
Significant Bremsstrahlung from e

Large threshold in ECAL due to pileup

$R(K), R(K^*)$

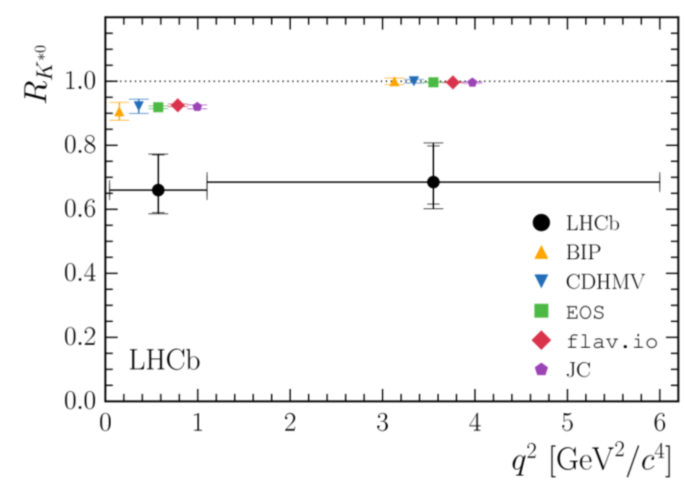
- Double ratios measured for systematic cancellation and cross-checks
  - $R(X) = \frac{\mathcal{B}(B\to X\mu\mu)}{\mathcal{B}(B\to Xee)} = \frac{\mathcal{B}(B\to X\mu\mu)}{\mathcal{B}(B\to XJ/\psi(\mu\mu))} \times \frac{\mathcal{B}(B\to XJ/\psi(ee))}{\mathcal{B}(B\to Xee)}$

PRL 113 (2014) 151601



2.6 σ

JHEP 08 (2017) 055



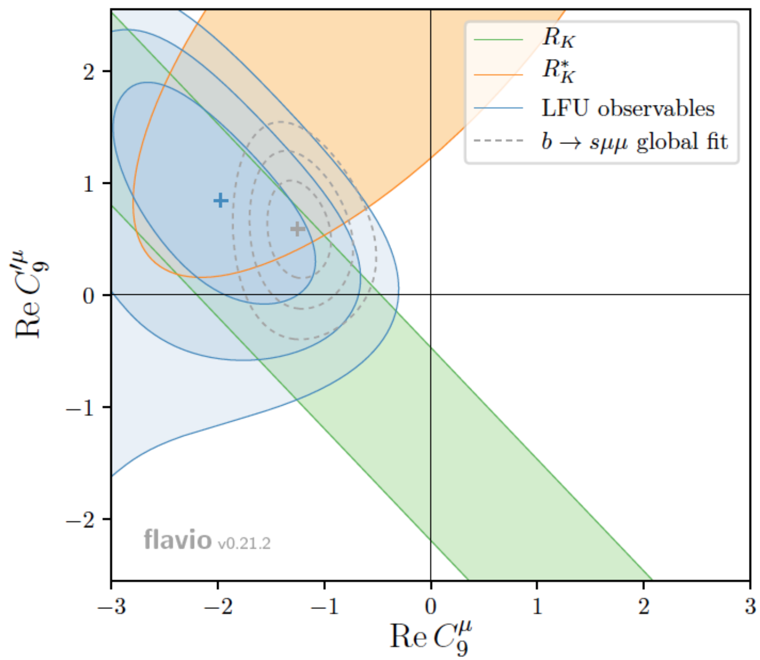
2.1 ~ 2.5 σ

- LFU tests in other modes: $B_s^0 \to \phi\, l^+l^-, B^+ \to K^+\pi^+\pi^-l^+l^-, \Lambda_b^0 \to pK^-l^+l^-$, …

Global fits of all $b \to sll$ decays

- LFU observables consistent with Branching Ratio and angular measurements

PRD 96 (2017) 055008



Proposed models to explain the anomalies:

- *Lepto-quarks*
- *Pati-Salam models*
- *Massive vector bosons*
- *…*

Lepton Flavour Violation in $B^0_{(s)} \to e^\pm\mu^\mp$

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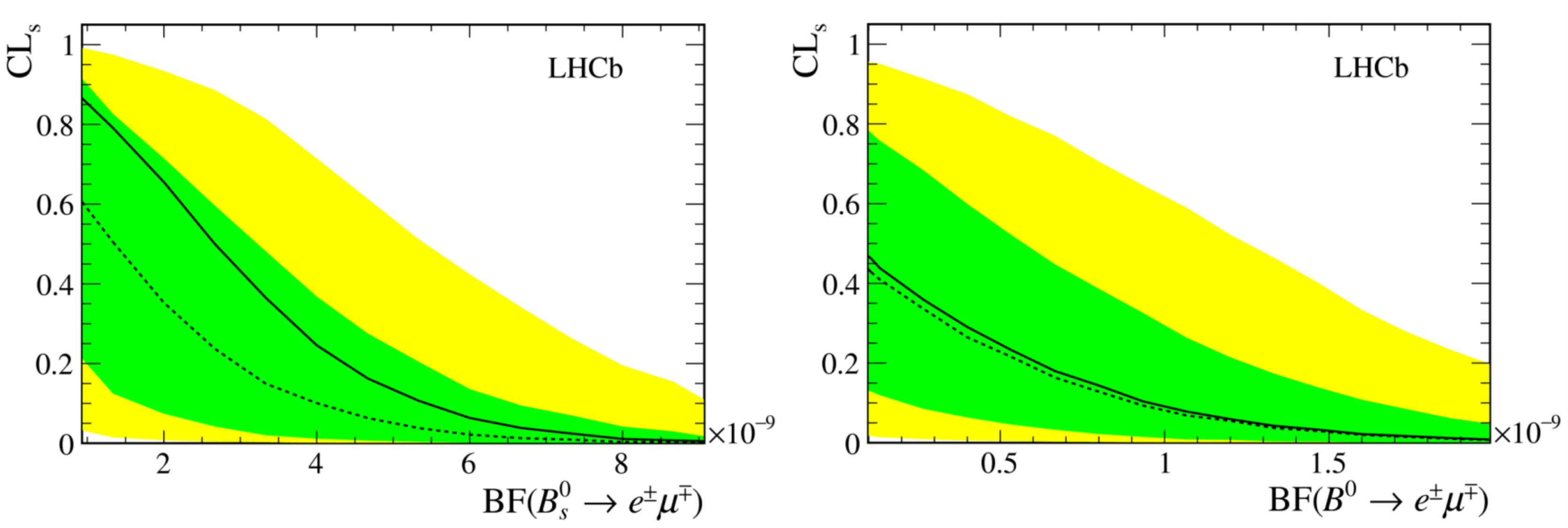
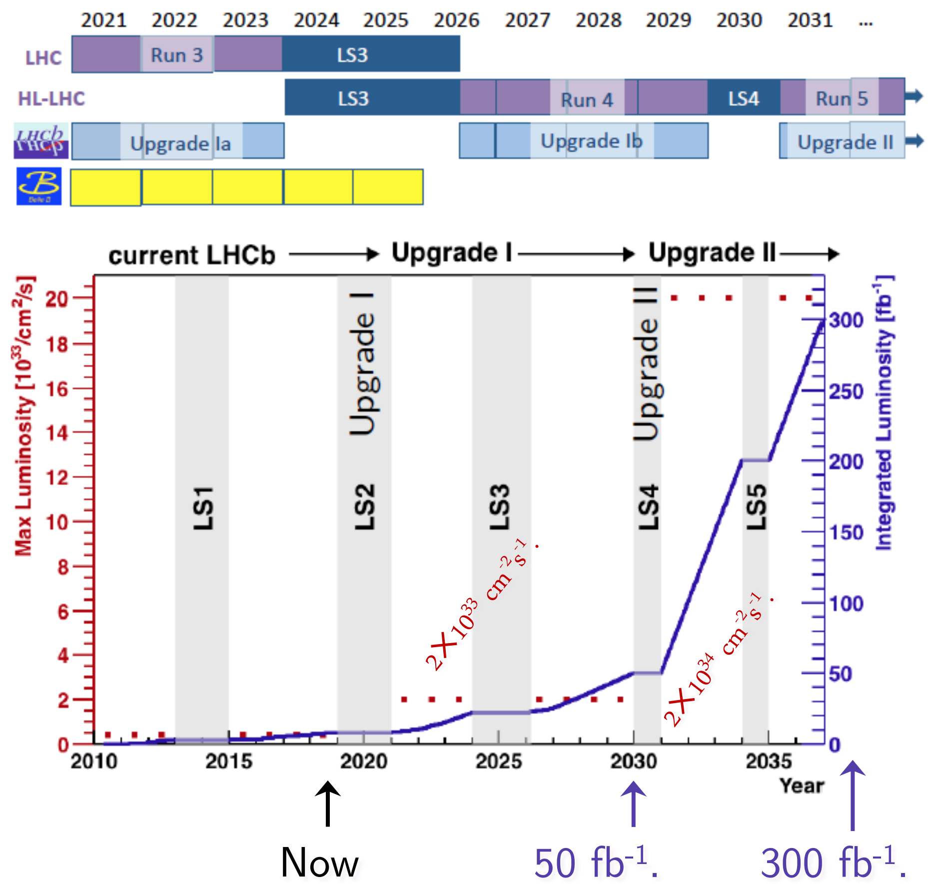
- LFV forbidden in the SM, can be enhanced by NP
- Search using Run I data compatible with background-only hypothesis



$$\mathcal{B}(B_s^0 \to e^+\mu^-) < 5.4 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$
$$\mathcal{B}(B^0 \to e^+\mu^-) < 1.0 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$

Looking into the future

- Upgrade I:
  - Removal of L0 → full software trigger enhancing efficiencies (esp. hadronic FS)
  - Readout at inelastic 30 MHz rate
  - Sub-detector replacement for higher occupancy & radiation hardness
- Upgrade II (+Ib):
  - Fully exploiting the potential at HL-LHC era
  - Coping with pileup ~50



More details:
→ "LHCb upgrade and prospects", Zhenwei Yang

Prospects of rare decays

arXiv: 1808.08865
Physics case for an LHCb Upgrade II

With 300 fb^{-1} in HL-LHC:

$B_s \to \mu\mu$

- $\Delta\mathcal{B} \sim 0.16 \times 10^{-9}$
- $\Delta\left(\frac{\mathcal{B}(B_s \to \mu\mu)}{\mathcal{B}(B \to \mu\mu)}\right) \sim 10\%$
- $\Delta\tau_{\mu\mu}^{eff} \sim 2\%$, time-dep. CP

$b \to s\gamma$

- Systematics dominated in $K\pi\pi\gamma, \phi\gamma$
- $\Delta\alpha_\gamma \sim$ 4%(10%) in $\Lambda_b^0 \to \Lambda\gamma$ $(\Xi_b^- \to \Xi^-\gamma)$

$b \to s(d)ll$ & LFU

Yield	1 result	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29 [254]	970	3300	46000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [255]	430	1400	20000
$B_s^0 \to \phi e^+e^-$	–	80	260	3700
$\Lambda_b^0 \to pKe^+e^-$	–	210	700	9800
$B^+ \to \pi^+e^+e^-$	–	20	75	1000
R_X precision	Run 1 result	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [254]	0.046	0.025	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [255]	0.070	0.038	0.010
R_ϕ	–	0.163	0.089	0.024
R_{pK}	–	0.100	0.054	0.014
R_π	–	0.304	0.165	0.044

Summary

- LHCb searched for rare b decays in many final states with high precision
  - Quite a few 2/3-sigma level tension with SM:
    - *$b \rightarrow sll$ BR, P_5', R(K), R(K*), ...*
  - Most results fully exploiting Run I data, intensive work with Run II ongoing (4 times more b yield expected!)
- End of Run II *pp* collision but not end of the story...
  - A busy schedule for upgrade will provide ever higher luminosity
  - Hence higher precision and more possibilities
- New ideas / interpretations welcome!