Selected measurements of rare decays at LHCb

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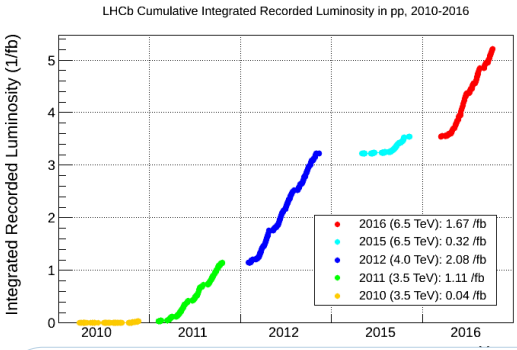
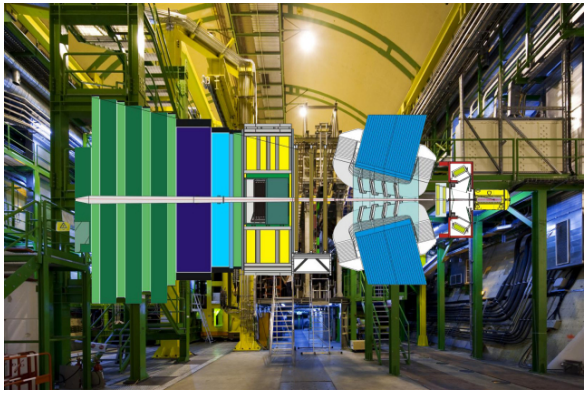
The LHCb experiment



- Single arm forward spectrometer
- Dedicated to heavy flavour physics
- Looks for indirect evidence of new physics in CP violation and rare decays

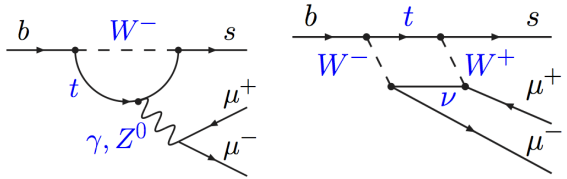


Momentum resolution:
$\delta p/p = 0.4$ % at 5 GeV to 0.6 % at 100 GeV
Impact parameter resolution:
$\sigma_{IP} \sim 20\ \mu$m
Primary vertex resolution:
13 μm in x and y, and 71 μm in z
Decay time resolution:
$\sigma_\tau \sim 50$ fs
Excellent particle identification

Int. J. Mod. Phys. A 30, 1530022 (2015), JINST 3 (2008) S08005

I. Suppressed modes

Mediated by electroweak Flavour Changing Neutral Current (FCNC) processes in the Standard Model (SM) :



Chosen $b \to sll$ measurements:

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

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

$\Lambda_b \to \Lambda\mu^+\mu^-$

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

II. Forbidden modes

E.g. Lepton Flavour Violating (LFV) processes - strictly forbidden in the SM, however, present in the nature PRL81 (1998) 1562 . Many extensions of the SM predict such processes.

Chosen analyses: $\tau \to \mu\mu\mu$, $B_{s,d} \to e\mu$, and many ongoing ...

Charged Lepton Flavour Violation (cLFV) has not been seen yet!

Rare Decays

Rare decays are a powerful probe of New Physics (NP):

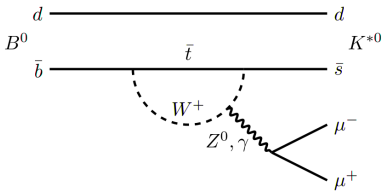
- they are suppressed in the SM, so more sensitive to NP
- there are many precise SM predictions

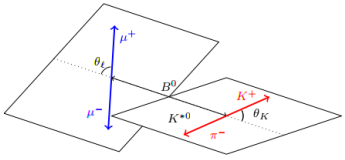
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[C_i(\mu) O_i(\mu) + C_i'(\mu) O_i'(\mu) \right]$$

$i = 1, 2$	Tree	Wilson coefficients C_i : perturbative short-distance effects
$i = 3 - 6, 8$	Gluon penguin	Operators O_i : non-perturbative long-distance effects
$i = 7$	Photon penguin	
$i = 9, 10$	Electroweak penguin	
$i = S$	Higgs (scalar) penguin	
$i = P$	Pseudoscalar penguin	

- new particles in the loop level processes could significantly change observables
- the pattern of deviations can guide towards NP

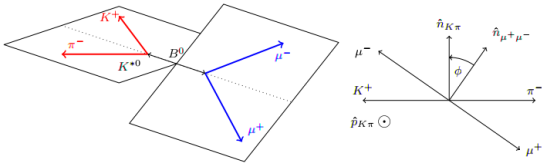
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular





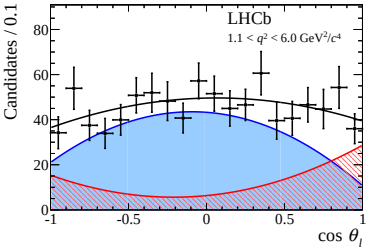
(a) θ_K and θ_ℓ definitions for the B^0 decay

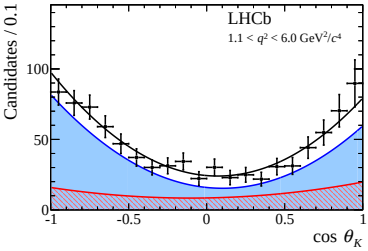
Four body decays such $B^0 \to K^{*0}\mu^+\mu^-$ are described by:
- three helicity angles (θ_l, θ_K, ϕ),
- the di-lepton invariant mass squared q^2.

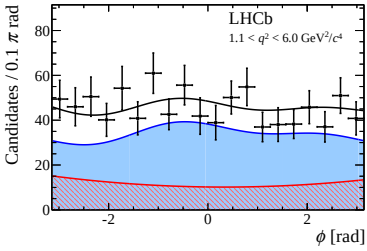


(b) ϕ definition for the B^0 decay

JHEP 1204 (2012) 104, JHEP 02 (2016) 104







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

The CP-averaged angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay:

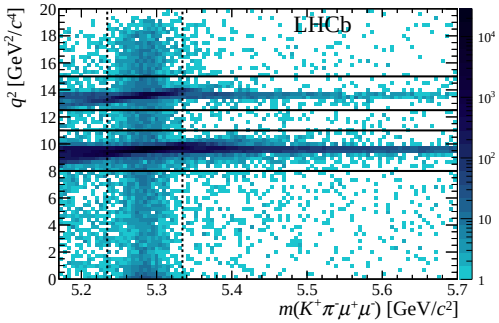
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l$$
$$-F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$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

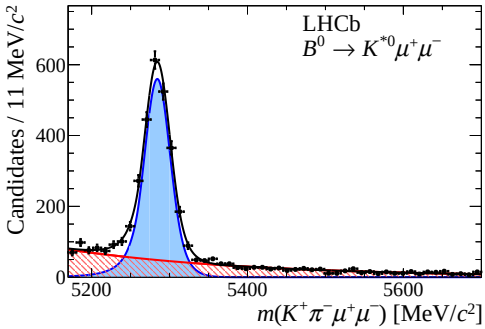
$A_{FB},\ F_L,\ S_j$ - are functions of Wilson coefficients

Additional sets of observables, for which the leading form-factor uncertainties cancel, e.g.: JHEP 1305(2013)137

$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

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





Signal yield: 2398 ± 57

Signal candidates:
$5170 < m(K^+\pi^-\mu^+\mu^-) < 5700$ MeV/c^2

K^{*0} candidates:
$796 < m(K^+\pi^-) < 996$ MeV/c^2

Combinatorial background is reduced using a boosted decision tree:

- trained fully on data
  - $B^0 \to J/\psi K^{*0}$ as a signal
  - $5350 < m(K^+\pi^-\mu^+\mu^-) < 7000$ as a background
- variables used for training
  - PID - kinematics and geometric quantities - isolations

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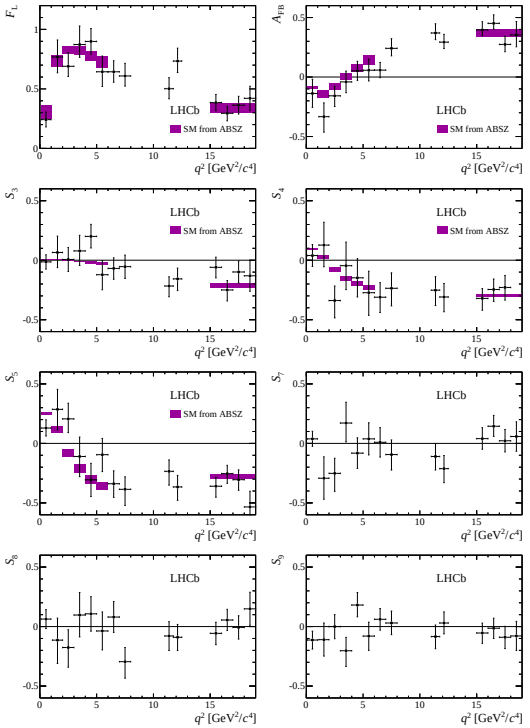
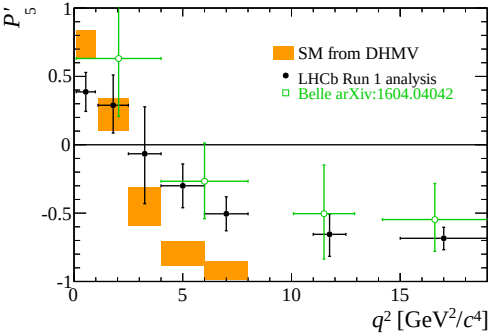
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular



The first full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decay (Run 1):

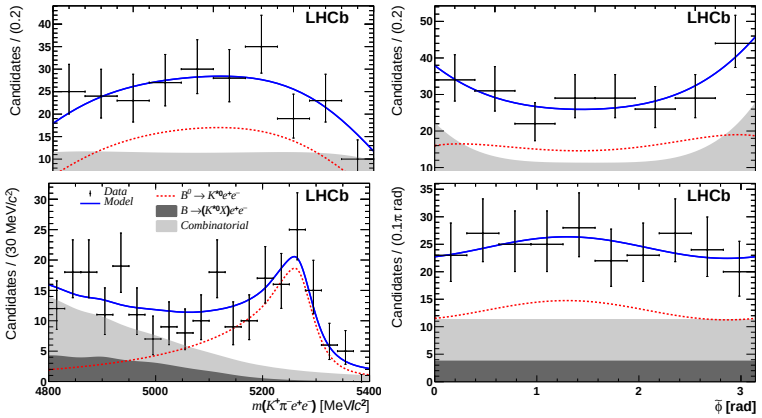
- tension in P_5'
- 3.4 σ global deviations from the SM
- the SM central value for $\mathrm{Re}(C_9)$ is 4.27, best fit-point corresponds to the $\Delta\mathrm{Re}(C_9) = -1.04 \pm 0.25$

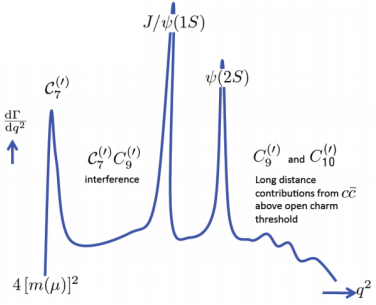


Phys. Rev. D 91, 114012 (2015), JHEP 1204 (2012) 104, JHEP 02 (2016) 104, Eur. Phys. J. C (2014) 74:2897

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

Experimentally challenging: bremsstrahlung, triggering.
Explore lower q^2 region, $0.002 < q^2 < 1.120\ \mathrm{GeV}^2/c^4$. Sensitive to C_7 Willson coefficient.
Lower yields than muon channel, 124 signal events in B^0 mass window $4800 - 5400\ \mathrm{MeV}/c^2$.
Results in a good agreement with SM predictions.

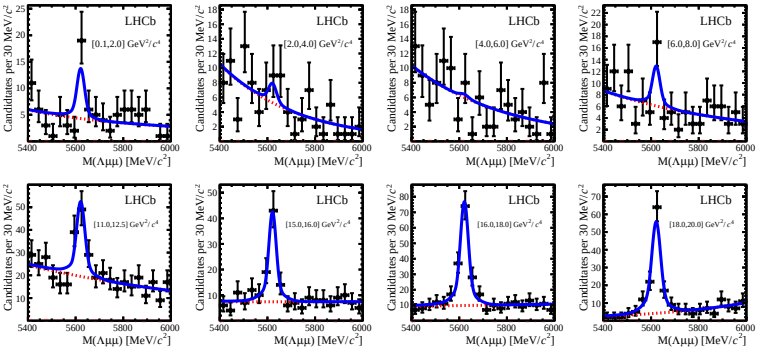




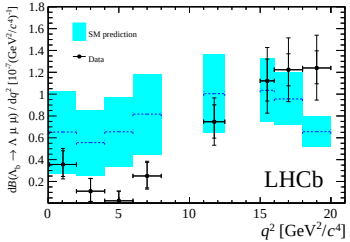
JHEP04(2015)064

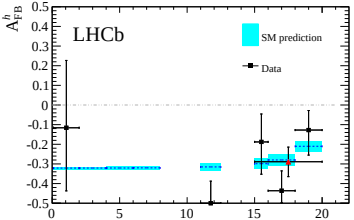
$\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$

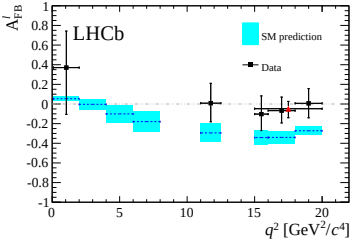
Normalized to $\Lambda_b \to \Lambda J/\psi$.
No evidence for signal in low q^2 $(2 - 8\ \mathrm{GeV}^2/c^4)$ region.
More statistics needed.



JHEP06(2015)115

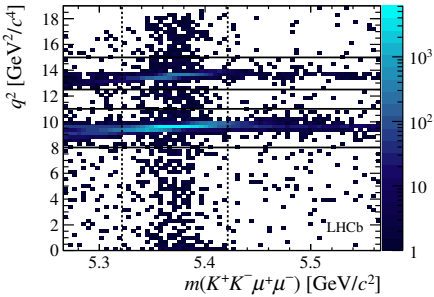


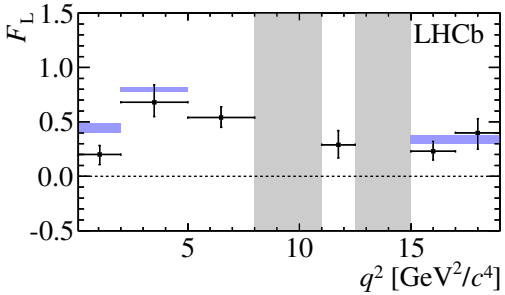


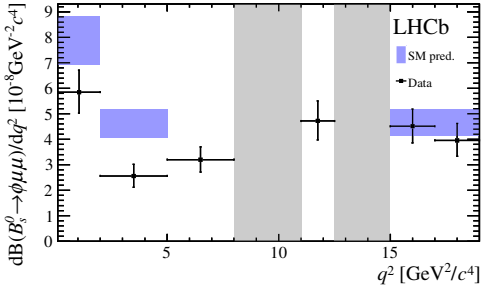


$B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$

Similar to $B^0 \to K^{*0}\mu^+\mu^-$, experimentally very clean (narrow ϕ resonance.).
Final state not self-tagging - less observables is accessible.
Angular distributions - good agreement with SM.
Branching fraction - differs from SM by $3.3\ \sigma$



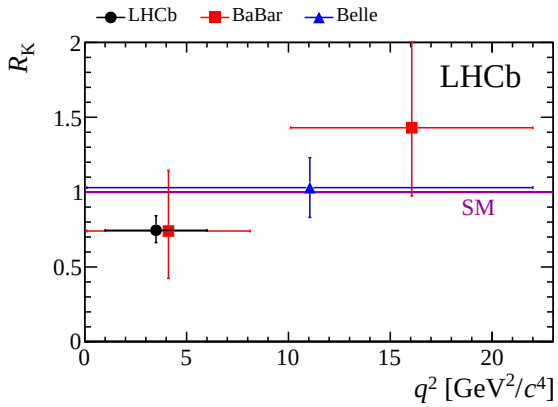




JHEP09(2015)179

Lepton universality test R_K

Testing lepton universality with $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$:



$$R_K = \frac{\mathcal{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{BR}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

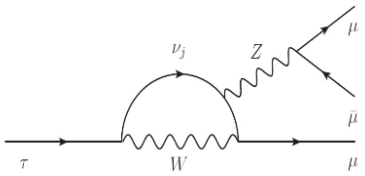
Analysis of the $3fb^{-1}$ data.

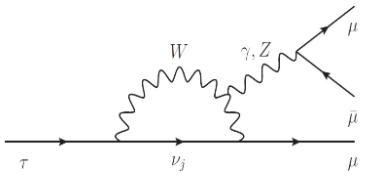
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{sys})$$ - 2.6 σ with the SM

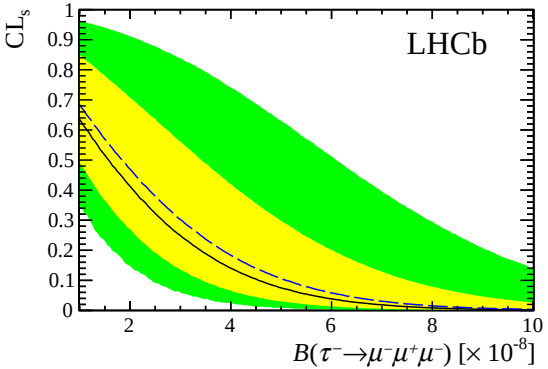
Phys. Rev. Lett. 113, 151601 (2014)

cLFV: $\tau^- \to \mu^+\mu^-\mu-$

Lepton flavour violating $\tau^- \to \mu^+\mu^-\mu-$ decay forbidden in SM.
Penguin level with neutrino oscillation: $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^+) < 10^{-40}$ - beyond experimental reach. Eur. Phys. J. C57 (2008) 13







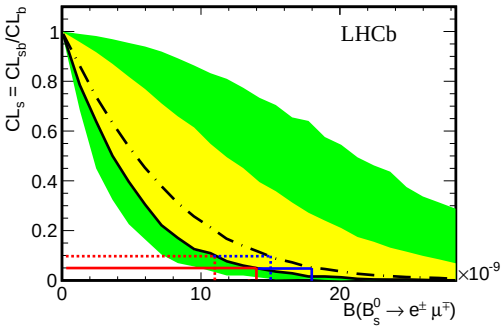
Normalized to $D_s^- \to \phi(\to \mu^-\mu^+)\pi^-$.
No evidence is found for a signal.
The limit is set at 90% confidence level on the branching fraction $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^+) < 4.6 \times 10^{-8}$.
JHEP 02 (2015) 121

cLFV: $B_{s/d} \to e^{\pm}\mu^{\mp}$

Data sample, corresponding to an integrated luminosity of $1\ \mathrm{fb}^{-1}$ of $\sqrt{s} = 7\ \mathrm{TeV}$ collisions. Upper limits on the branching fractions at 90% (95%) confidence level:

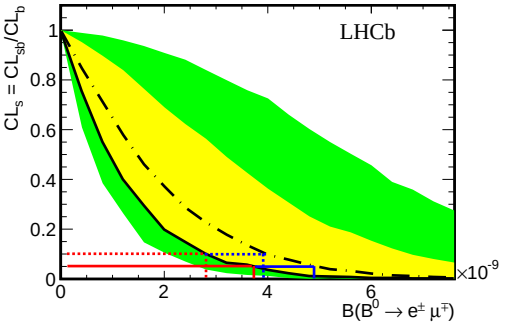
$$\mathcal{B}(B_s \to e^{\pm}\mu^{\mp}) < 1.1\,(1.4) \times 10^{-8}$$
$$\mathcal{B}(B_d \to e^{\pm}\mu^{\mp}) < 2.8\,(3.7) \times 10^{-9}$$

Phys.Rev.Lett. 111 (2013) 141801



Other (ongoing) LFV analyses:

$B^+ \to K^+ e\mu$
$B^+ \to K^+ \tau\mu$
$B^0 \to \phi e\mu$
$B^0 \to K^{*0} e\mu$
$B^0 \to K^{*0} \tau\mu$
...



Summary

- Rare decays are powerful tool for searching for BSM effects.
- Full angular analysis of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ - clear tension with SM.
- We've seen differences with SM in measurements of differential branching fraction vs q^2.
- Measurements go to the same direction.
- Many more analysis in the pipe line.
- We still need improvement both on theory and experimental side.

Thank you for your attention :)