Rare decays at the LHC

Daniele Marangotto

INFN & Università degli Studi, Milano, Italy

on behalf of the LHCb collaboration,
including results from ATLAS, CMS and LHCb

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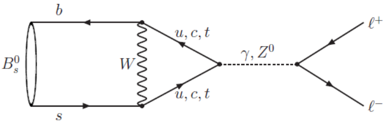
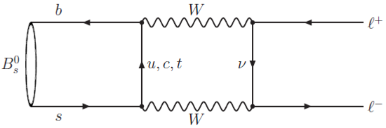
Outline

- Tests of lepton universality
  - $\mathcal{R}(K)$, $\mathcal{R}(K^*)$, $\mathcal{R}(D^*)$
- Angular analyses and differential branching fractions measurements
  - $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

Introduction

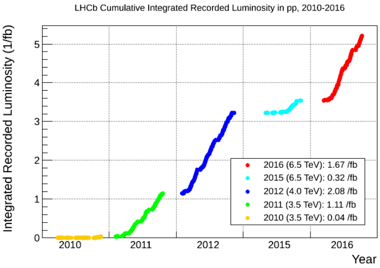
- Rare decays mediated by Flavour Changing Neutral Currents
- No tree-level diagrams in the SM, loop suppressed transitions
- Very sensitive to beyond the SM contributions

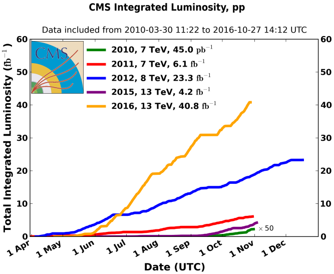




- Possible new physics effects on branching fractions (BF), angular observables, CPV, ...
- Powerful to constrain beyond the SM scenarios
- Different tensions with the SM already observed

LHC experiments data taking plan





- Run I: *pp* collisions at $\sqrt{s} = 7/8\,\mathrm{TeV}$
  - Recorded 3 fb^{-1} by LHCb and 29.4 fb^{-1} by ATLAS/CMS
- Run II: *pp* collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
  - Recorded 2 fb^{-1} by LHCb and 45 fb^{-1} by ATLAS/CMS
  - Expected 8 fb^{-1} by LHCb and 100 fb^{-1} by ATLAS/CMS by 2018 end
- Beauty cross-section doubled at Run II energy
  - Plenty of data are coming!

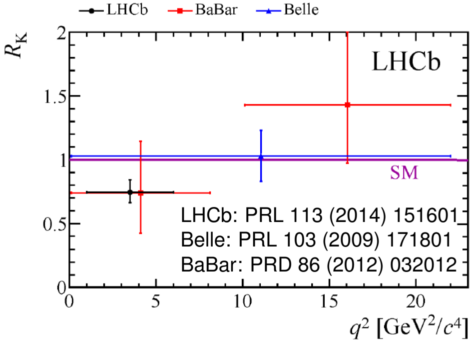
$\mathcal{R}(K)$

- Test of lepton universality in $B^+ \to K^+$ dileptonic decays, μ^- vs e^-
- The branching fraction ratio is close to one in the SM

$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

arXiv:1605.07633

- LHCb Run I measurement in $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ most precise to date

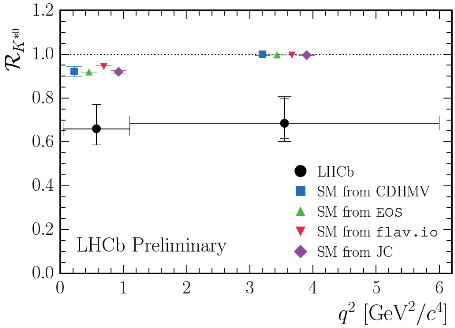


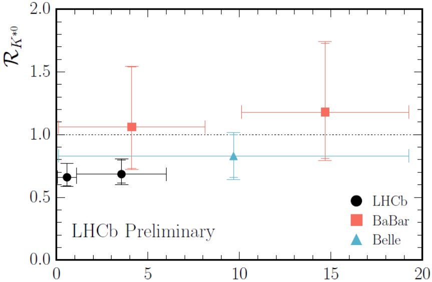
- Compatible with SM at 2.6σ
- Expected statistical uncertainty ≈ 0.03 after Run II, size of current systematic uncertainty
- Systematic uncertainty dominated by signal and background parametrization, to be reduced in the future

$\mathcal{R}(K^*)$ preliminary

- Test of lepton universality analogous to $\mathcal{R}(K)$ in $B^0 \to K^{*0} l^+ l^-$
- LHCb Run I preliminary measurement in low- and central-q^2 regions, $0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4$ and $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$, recently presented at CERN
- Very challenging analysis due to the different ways muons and electrons interact with the detector
- $\mathcal{R}(K^*)$ measured relative to $B^0 \to K^{*0} J/\psi(\to l^+ l^-)$, to reduce systematic uncertainties
- K^{*0} reconstructed as $K^+\pi^-$ within $100\,\mathrm{MeV}$ from $K^*(892)^0$ resonance
- Blind analysis to avoid experimental biases

$\mathcal{R}(K^*)$ preliminary



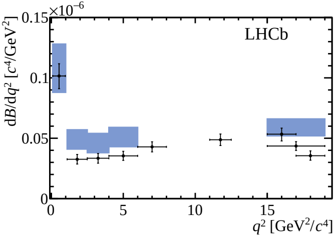


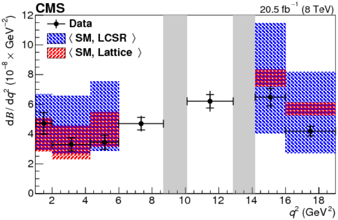
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Low (central)-q^2 result compatible with SM at $2.2 - 2.4(2.4 - 2.5)\sigma$
- Similar behaviour shown by $\mathcal{R}(K)$ measurement
- Statistically dominated measurement, with slightly larger uncertainties than $\mathcal{R}(K)$ one, expected at $\approx^{+0.040}_{-0.027}$ level after Run II

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

- Measured differential branching fractions in q^2 for $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ and $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ found lower than SM predictions with tensions at $2-3\sigma$.
- Latest Run I LHCb (*JHEP 11 (2016) 047*) and CMS (*PLB 753 (2016) 424-448*) $B^0 \to K^{*0}\mu^+\mu^-$ BF measurements in agreement with SM predictions arXiv:1503.05534 (LCSR) & PRD 89 (2014) 094501 (Lattice)



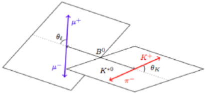


- Main systematic uncertainty from knowledge of normalization channel, i.e. $\mathcal{B}(B^0 \to J/\psi K^{*0})$

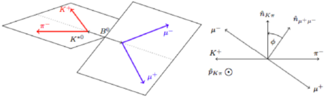
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- Study of the full angular distribution of the final state particles (θ_l,θ_K,ϕ)
- Described by eight observables $A_{\rm FB}$, $F_{\rm L}$, S_i, function of Wilson coefficients

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



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



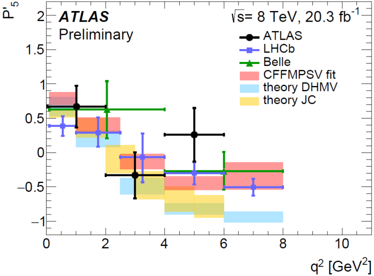
(b) ϕ definition for the B^0 decay

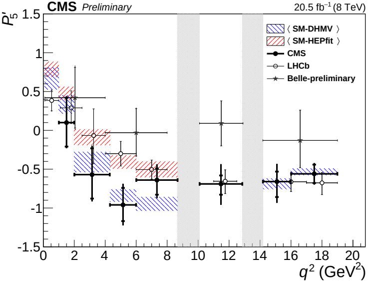
- Observables in which hadronic form factors uncertainties cancels at leading order can be defined like

$$P_5' \equiv \frac{S_5}{\sqrt{F_{\rm L}(1-F_{\rm L})}}$$

JHEP 05 (2013)137

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





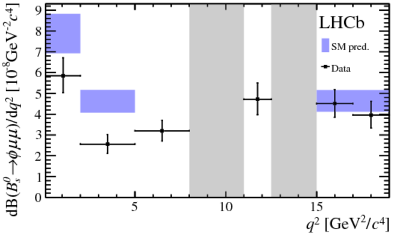
- P_5' LHCb local deviation from SM DHMV:
  - 2.8σ in $4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$; 3.0σ in $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
- Statistically dominated measurement

SM predictions
DHMV: JHEP 12 (2014) 125
JC: JHEP 05 (2013) 043 & PRD 93 (2016) 014028
CFFMPSV/SM-HEPfit: JHEP 06 (2016) 116 & arXiv:1611.04338 (employs LHCb data)

Data
LHCb: JHEP 02(2016)104
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008
Belle: arXiv:1604.04042

$B_s^0 \to \phi\mu^+\mu^-$ BF & angular analysis

- LHCb measured the differential branching fraction in q^2 and performed a full angular analysis of $B_s^0 \to \phi\mu^+\mu^-$ with Run I data (*JHEP 1509 (2015) 179*)
- The measured BF is below SM predictions (EPJC 75 (2015) 382 & arXiv:1503.05534), as seen in other $b \to s\mu^+\mu^-$ processes



- BF in $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ interval more than 3σ lower than SM

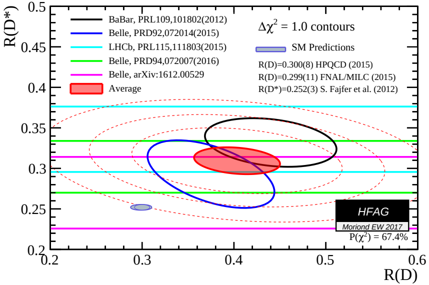
- Angular observables compatible with SM predictions
- Differential BF dominated by statistical uncertainty

$\mathcal{R}(D^*)$

- Test of lepton universality in $B^0 \to D^*$ semileptonic decays, τ^- vs μ^- (not a rare decay but interesting in the context of LFU tests)
- The branching fraction ratio is theoretically clean

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B^0 \to D^* \tau \nu_\tau)}{\mathcal{B}(B^0 \to D^* \mu \nu_\mu)} = 0.252 \pm 0.003 \qquad \text{PRD 85 (2012) 094025}$$

- LHCb Run I measurement, with τ measured in $\mu\nu_\mu\nu_\tau$, consistent with SM prediction at 2.1σ



- $\mathcal{R}(D^*)$ world average exceed the SM predictions by 3.4σ
- Including the $\mathcal{R}(D^*)$-$\mathcal{R}(D)$ correlation, the SM tension is at about 3.9σ

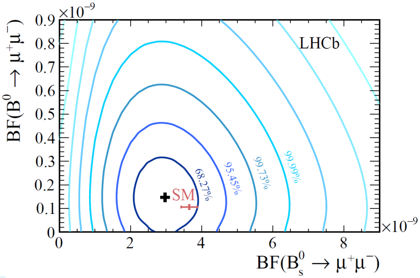
$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

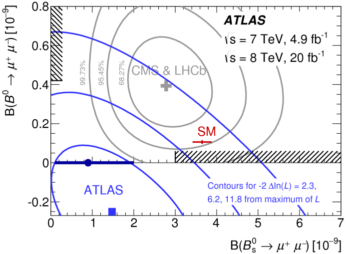
- Very small branching fractions precisely predicted in the SM, very useful to constrain new physics scenarios
- Combined analysis of CMS and LHCb Run I data: observation of the B_s^0 mode (6.2σ) and evidence for $B^0 \to \mu^+\mu^-$ (3.0σ) (*Nature 522 (2015) 68-72*)
- Latest LHCb analysis including 1.4 fb^{-1} of Run II data (arXiv:1703.05747)
  - $B_s^0 \to \mu^+\mu^-$ observed at 7.8σ and most precise BF determination to date
  - No evidence (1.6σ) of $B^0 \to \mu^+\mu^-$
  - First measurement of $B_s^0 \to \mu^+\mu^-$ effective lifetime

$$\tau_{\mu^+\mu^-} = \frac{\int t\,\Gamma(B_s^0(t) \to \mu^+\mu^-)dt}{\int \Gamma(B_s^0(t) \to \mu^+\mu^-)dt}$$

- All results in agreement with SM expectations

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$



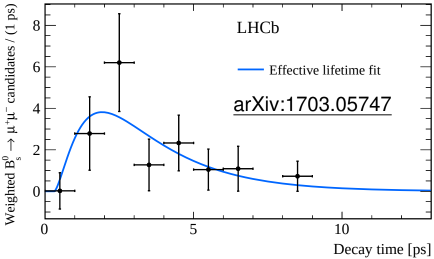


	SM	LHCb	CMS+LHCb	ATLAS
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)(10^{-9})$	3.66 ± 0.23	$3.0 \pm 0.6^{+0.3}_{-0.2}$	$2.8^{+0.7}_{-0.6}$	$0.9^{+1.1}_{-0.8}$
$\mathcal{B}(B^0 \to \mu^+\mu^-)(10^{-10})$	1.06 ± 0.09	< 3.4	$3.9^{+1.6}_{-1.4}$	< 4.2

SM: PRL 112 (2014) 101801, arXiv:hep-ph/1311.0903
LHCb: arXiv:1703.05747, submitted to PRL
CMS+LHCb: Nature 522 (2015) 68-72 arXiv:hep-ex/1411.4413
ATLAS: EPJ C76 (2016) 513 arXiv:1604.04263

Upper limits at 95% C.L.

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$



- Decay time distribution from mass fit (sPlot)
- Strategy validated on $B^0 \to K^+\pi^-$

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

- CMS prospects for Run II: $\delta\mathcal{B}(B_s^0 \to \mu^+\mu^-) \approx 14\%$ (CMS-PAS-FTR-14-015)
- LHCb: expected statistical uncertainty on $B_s^0 \to \mu^+\mu^- \approx 0.33 \times 10^{-9}$ at Run II end, level of current systematic uncertainties. Main systematic source given by the knowledge of f_s/f_d
- No limiting systematic uncertainties foreseen for $B^0 \to \mu^+\mu^-$ study

Summary

- LFU tests showed deviations with respect to SM predictions between $2-4\sigma$, consistent among each other
- Differential BF in $b \to s\mu^+\mu^-$ processes consistently lower than SM predictions at $2-3\sigma$ level, compatible with LFU results
- Anomaly at 3σ level for P_5' angular observable in $B^0 \to K^{*0}\mu^+\mu^-$
- $B^0/B_s^0 \to \mu^+\mu^-$ BF probed down to $10^{-9}/10^{-10}$ level, very useful to constrain new physics scenarios
- Latest global fits in tension with SM at $4-5\sigma$ level, e.g. arXiv:1704.05340, arXiv:1704.05435, arXiv:1704.05444, arXiv:1704.05438

Prospects

- Increasing precisions by a factor $2.6 - 2.8$ with LHC Run II, no limiting systematic uncertainties foreseen
- New measurements coming soon (LHCb side)
  - $\mathcal{R}(K)$ including 2015-16 data
  - $\mathcal{R}(\phi)$ including 2015-16 data
  - $\mathcal{R}(D^{*})$ with τ measured in $\pi^{+}\pi^{-}\pi^{-}\nu_{\tau}$
  - LFU test with $B_s^0 \to D_s^{(*)}\tau\nu_{\tau}$
  - LFU test with $\Lambda_b^0 \to \Lambda_c^{+(*)}\tau\nu_{\tau}$
- $+$ updates with Run II data
- Are we approaching new physics? Let's see...

Backup Slides

LHCb status and prospects

- Run I: recorded 1 and 2 fb^{-1} at $\sqrt{s} = 7$ and 8 TeV, respectively
- Run II: recorded 2 fb^{-1} at $\sqrt{s} = 13\,\mathrm{TeV}$ by 2016 end
  expected 8 fb^{-1} by 2018 end
- Beauty cross-section in LHCb acceptance doubled at Run II energy

$$\frac{\sigma(pp \to b\bar{b}X, 13\,\mathrm{TeV})}{\sigma(pp \to b\bar{b}X, 7\,\mathrm{TeV})} = 2.14 \pm 0.02 \pm 0.13$$

PRL 118 (2017) 052002

- Beauty events recorded by 2016 end

$$\frac{N_b(\text{Run I + 2015-16})}{N_b(\text{Run I})} \approx 2.4$$

→ Statistical uncertainties $\div 1.5$

- Beauty events expected after Run II completion

$$\frac{N_b(\text{Run I+Run II})}{N_b(\text{Run I})} \approx 6.7$$

→ Statistical uncertainties $\div 2.6$