Rare, radiative, and electroweak penguin decays of heavy flavour hadrons at LHCb

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on behalf the LHCb Collaboration

31th Rencontres de Blois

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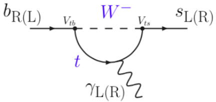
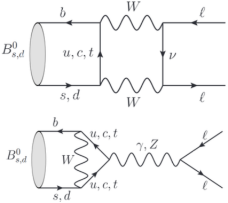
- Flavour Changing Neutral Currents (FCNC) :
  - forbidden at tree level in Standard Model (SM)
  - only occurs via loop diagrams in SM (penguin or box diagrams)

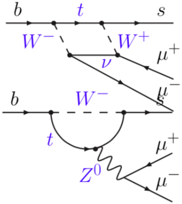
$b \to s\gamma$



$b \to \ell^+\ell^-$



$b \to s\ell^+\ell^-$



- New heavy particles may enter the game through loops
- Can alter observables such as branching ratios, angular distributions, ...

Indirect search can probe New Physics at **much larger scales**

Motivation for rare heavy flavour hadrons decays

- Parameterized in terms of an effective hamiltonian

Wilson Coefficient

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

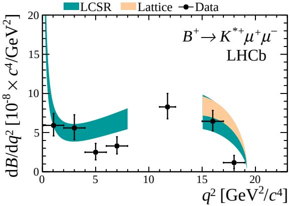
$i = 1, 2$	: Tree
$i = 3 - 6, 8$	: Gluon Penguin
$i = 7$	: Photon Penguin
$i = 9, 10$	: Electroweak Penguin
$i = S$	: Higgs (scalar) Penguin
$i = P$	: Pseudoscalar Penguin

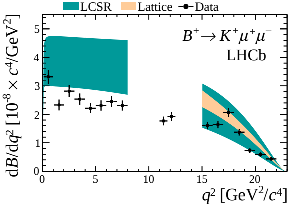
- Variables of interest :
  - $C_7^{(\prime)}$ Strength of the coupling to photons
  - $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$ Strength of the coupling to leptons
- Search for deviations of Wilson coefficient values with respect to SM predictions
- Also look for processes forbidden in SM : Lepton Flavour Violating Decays (see next talk by H. Cliff)

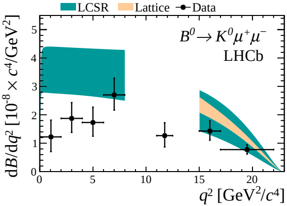
Experimental status

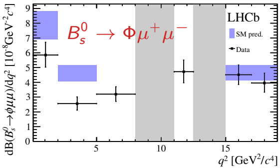
Several deviations with respect to Standard Model in $b \to s\ell^+\ell^-$ transitions in differential branching ratios and angular analysis

JHEP 06 (2014) 133

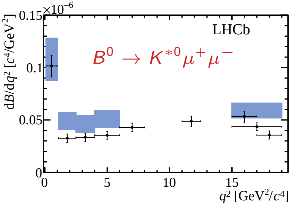




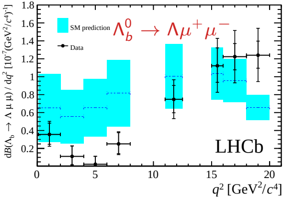




JHEP 09 (2015) 179



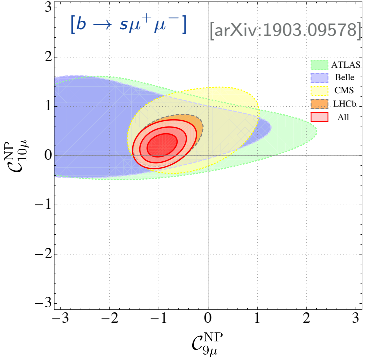
JHEP 11 (2016) 047



JHEP 06 (2015) 115

A hint for New Physics ?

Global fits emphasize scenarios where New Physics contributions arise from C_9 or both C_9 and C_{10}



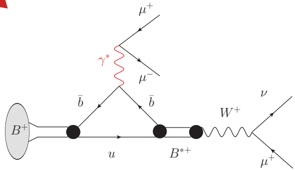
- See also [Phys. J. C (2015) 75: 382] , [Nucl Phys B 909 (2016) 737-777], [JHEP 06 (2016) 092], [Phys. Rev. D 96, 093006 (2017), [JHEP 1801 (2018) 093]
- Several NP model proposed to accomodate data :
  NP contribution from Z' [Phys.Rev.D93,074003] , lepto-quarks [Phys.Rev.D94,115005], etc

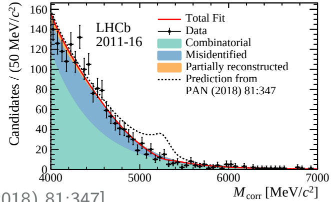
Crucial to improve measurements, and probe new modes

NEW

[arXiv:1812.06004]

- Highly suppressed decay with $\mathcal{B} \propto |V_{ub}|^2$
  - Run 1 + 2016 ($4.7\,\text{fb}^{-1}$)
  - $M^{min}_{\mu^+\mu^-} < 980\,\text{MeV}/c^2$
  - Veto charmonium resonances
  - Exploit corrected mass variable:
    $$M_{corr} = \sqrt{M^2_{\mu\mu\mu} + {P'_T}^2} + P'_T$$
  - Normalize to $B \to J/\psi K^+$
- Only one theoretical estimate (vector-meson dominance): $\mathcal{B}(B^+ \to \mu^+\mu^-\mu+\nu_\mu) \sim 1.3 \times 10^{-7}$





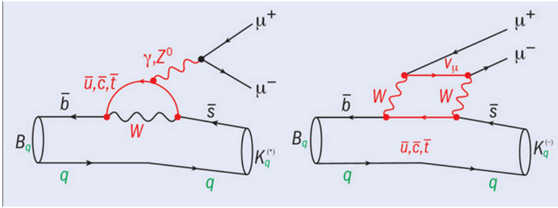
[PAN (2018) 81:347]

No signal observed. Best world limit set to :

$$\mathcal{B}(B^+ \to \mu^+\mu^-\mu+\nu_\mu) < 1.6 \times 10^{-8} \text{ at } 95\ \%\ \text{CL}.$$

Electroweak penguins

- Consider $b \to s(d)\ell\ell$
- Observables :
  - Branching ratios
  - Angular variables



Angular Analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

[JHEP 09 (2018) 146]

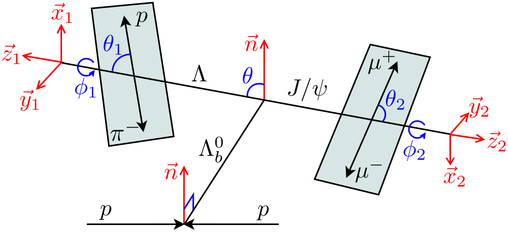
It is a $b \to s\ell^+\ell^-$ transition complementary to $B^0 \to K^{*0}\mu^+\mu^-$

- Richer angular distribution due to baryon spin and polarisation
- Analysis performed with data from 2011-2016 period ($5\,\mathrm{fb}^{-1}$)
- Focus on low recoil region : $15 < q^2 < 20\mathrm{GeV}^2/\mathrm{c}^4$
- Analysis exploits method of moments [JHEP 11 (2017) 138] :

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

f_i : angular functions

K_i : coefficients

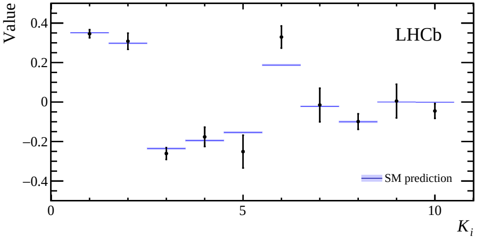


[Phys Lett. B724 (2013) 27]

Angular Analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

Full set of angular observables measured for the first time : [JHEP 09 (2018) 146]

- All parameters compatible with SM predictions
- K_{11} to K_{34} compatible with 0 : no initial Λ_b^0 polarization



Forward-backward asymmetries (combination of observables):

$$\text{lepton-side } (\propto K_3) : A_{FB}^{\ell} = -0.39 \pm 0.04(stat) \pm 0.01(syst)$$

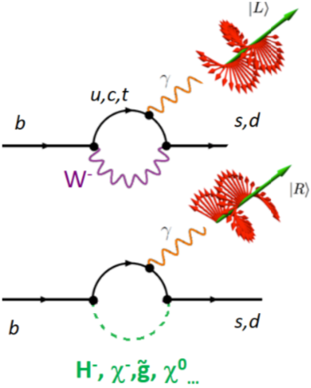
$$\text{hadron-side } (\propto K_4 \text{ and } K_5) : A_{FB}^{h} = -0.30 \pm 0.05(stat) \pm 0.02(syst)$$

$$\text{combined } (\propto K_6) : A_{FB}^{\ell h} = +0.25 \pm 0.04(stat) \pm 0.01(syst)$$

- Due to the chiral structure of W bosons, in the SM the photon polarization is predominantly left-handed , with a small right-handed component:

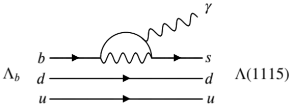
$$\frac{C_7'}{C_7} \equiv \mathcal{O}\left(\frac{m_s}{m_b}\right)$$

- In some models (like LRSM),$|A_R/A_L|$ up to $1/2$ [JHEP 12 (2013) 102]



First observation of the rare radiative decay $\Lambda_b^0 \to \Lambda\gamma$

- SM prediction for $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)$: 10^{-7} to 10^{-5}, with large uncertainties from form factors
- Best limit so far from CDF : $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) < 1.9 \times 10^{-3}$ at 90% CL.



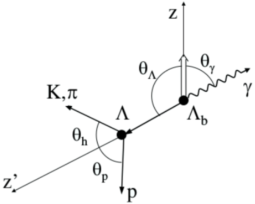
⇒ **Room for improvement**

- If observed, offers access to photon polarization measurements in b-baryon decays through angular analysis

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b^0} \cos\theta_\gamma$$

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

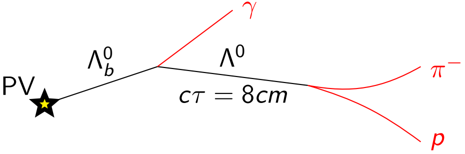
Depend on C_7 and C_7'



First observation of the rare radiative decay $\Lambda_b^0 \to \Lambda\gamma$

[arXiv:1904.06697]

- Using LHCb 2016 data ($1.7\,\mathrm{fb}^{-1}$)



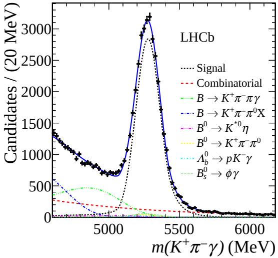
- Very challenging mode : no secondary vertex
  - long Λ lifetime
  - no direction from γ cluster
- Use well known $B^0 \to K^{*0}\gamma$ a a normalisation mode :

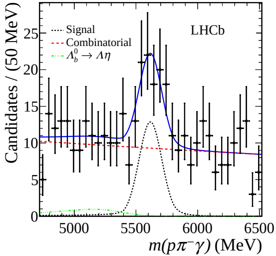
$$\frac{N(\Lambda_b^0 \to \Lambda\gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda^0 \to p\pi^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda\gamma)}{\epsilon(B^0 \to K^{*0}\gamma)}$$

- $\frac{f_{\Lambda_b^0}}{f_{B^0}}$ from recent LHCb measurements at 13 TeV [arXiv:1902.06794]
- Input branching fractions from PDG
- Efficiencies from simulation and calibration samples

First observation of the rare radiative decay $\Lambda_b^0 \to \Lambda\gamma$

[arXiv:1904.06697]





Signal excess with 5.6 σ significance

Branching fraction measurement within range of SM predictions

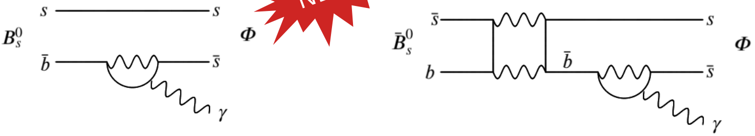
$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm \underset{(stat)}{1.5} \pm \underset{(syst)}{0.6} \pm 0.7\ ) \times 10^{-6}$$

systematic from external measurement dominated by the ratio $f_{\Lambda_b^0}/f_{B^0}$

Photon Polarisation in $B_S^0 \to \Phi\gamma$

[arXiv:1905.06284]

NEW



Time-dependent decay rates for $B_s^0 \to \Phi\gamma$ and $\bar{B}_s^0 \to \Phi\gamma$ grant access to the photon polarization :

$$\Gamma_{B_S^0\to\Phi\gamma}(t) \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right]$$

$$\Gamma_{\bar{B}_S^0\to\Phi\gamma}(t) \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C\cos(\Delta m_s t) + S\sin(\Delta m_s t)\right]$$

Depend on C_7 and C_7'

$\Delta\Gamma_s$ and Δm_s: decay width and mass differences between the B_s^0 mass eigenstates

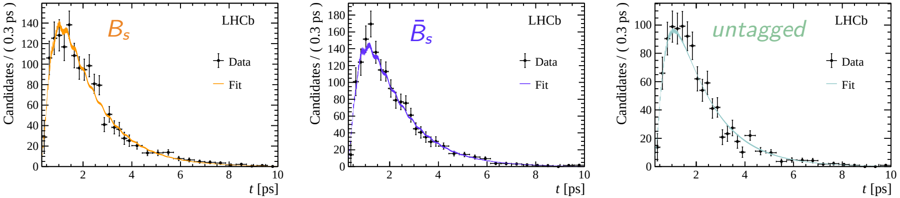
C: measure of the direct CP violation

S: measure of the $B_s^0 - \bar{B}_s^0$ mixing

Photon Polarisation in $B_S^0 \to \Phi\gamma$

Strategy for the analysis : [arXiv:1905.06284]

- $B^0 \to K^*\gamma$ used as control channel for decay time efficiency
- Fit of B_s mass used to obtain a background substracted time-dependent decay rate
- simultaneous proper time fit of both signal + control channel, with per event mistag probability and decay time uncertainty



$S = 0.43 \pm 0.30 \pm 0.11$ — 1.3σ

$C = 0.11 \pm 0.29 \pm 0.11$ — 0.3σ

$\mathcal{A} = -0.67^{+0.37}_{0.41} \pm 0.17$ — 1.7σ

compatible with SM @

Summary

Rare b-hadrons decays allow to probe larger energy scales through indirect measurements

- Tension wrt SM in both differential BR and angular observables
- Analyses are currently exploiting full potential of Run 2 to confirm them
- Lepton Flavour Universality observables provide complementary tests (see next talk)

Latest Results from LHCb

- Best world limit on $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$
- Full angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ compatible with SM
- First observation of $\Lambda_b^0 \to \Lambda\gamma$
- First measurement of C and S in $B_s^0 \to \Phi\gamma$ decay : compatible with SM

Run 2 analyses still ongoing... exciting times ahead