Rare decays at LHCb

Miguel Ramos Pernas
on behalf of the LHCb collaboration

Universidade de Santiago de Compostela

miguel.ramos.pernas@cern.ch

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Rare decays

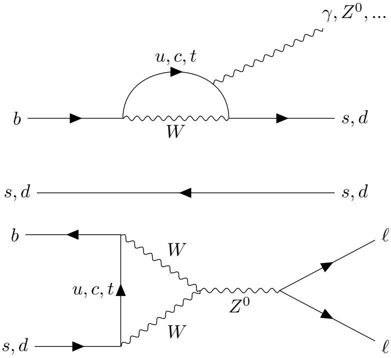
Flavour-Changing Neutral Currents (FCNC) forbidden at tree-level in the Standard Model (SM).

- Sensitivity to new particles increase (furthermore if they generate tree-level contributions).
- Allow to search for New Physics (NP) at higher scales than TeV.

For heavy hadrons, the description is done through effective field theory:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \frac{\kappa}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

Local operators ($\mathcal{O}_i$), Wilson coefficients (C_i), NP coupling (κ), NP scale (Λ_{NP}^2), NP operators ($\mathcal{O}_{\text{NP}}$)



The Wilson coefficients are determined from experimental results. Any deviation in a measurement is a sign of NP!

Probing New Physics in Wilson Coefficients

Dominant operators in the SM (primed operators are the chirality-flipped counterparts):

$$\mathcal{O}_7^{(\prime)} \propto \left(\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right) F^{\mu\nu}$$
$$\mathcal{O}_9^{(\prime)} \propto \left(\bar{s}\gamma_\mu P_{L(R)} b\right) \left(\bar{\ell}\gamma^\mu \ell\right)$$
$$\mathcal{O}_{10}^{(\prime)} \propto \left(\bar{s}\gamma_\mu P_{L(R)} b\right) \left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

$$\mathcal{O}_S^{(\prime)} \propto \left(\bar{s} P_{R(L)} b\right) \left(\bar{\ell}\ell\right)$$
$$\mathcal{O}_P^{(\prime)} \propto \left(\bar{s} P_{R(L)} b\right) \left(\bar{\ell}\gamma_5 \ell\right)$$

their associated coefficients can be probed in different RDs:

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	

Global fits to different decays allow to test the different SM observables.

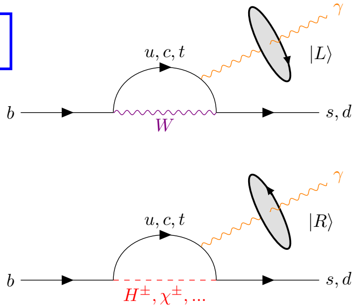
Radiative $b \to s\gamma$ decays

- Challenging at LHCb due to the photon reconstruction.
- Constraints to $|C_7|^2 + |C_7'|^2$ from CPV and $\mathcal{B}$ measurements.
- Room for NP in C_7', access through photon polarisation.
- Up to 50% right-handed polarisation in SM extensions [PRL 79:185].

In the SM γ_L predominates: $\frac{C_7'}{C_7} = \mathcal{O}\left(\frac{m_s}{m_b}\right)$

$$\alpha_\gamma^{\text{SM}} = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)} = 1 + \mathcal{O}\left(\frac{m_s}{m_b}\right)$$

- Competition with Belle-II which has a much more clean environment.
- Sensitivity on b-meson Decays will be carried by Belle-II, but radiative baryon decays will be territory of LHCb only!



Untagged analysis of $B_s^0 \to \phi\gamma$ [PRL 118:021801]

First experimental study of photon polarization in radiative B_s^0 decays.

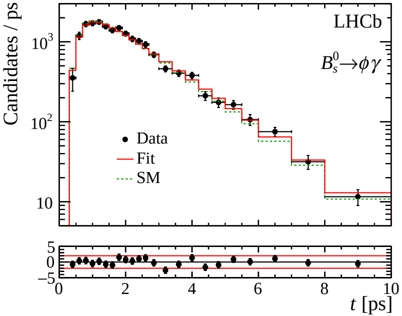
$$\Gamma(t) = e^{-\Gamma_s t}\left[\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2) \pm \mathcal{C}\cos(\Delta m_s t) \mp \mathcal{S}\sin(\Delta m_s t)\right]$$

Same production of B_s^0 and $\bar{B}_s^0 \Rightarrow \mathcal{C}$ and $\mathcal{S}$ cancel.

$$\mathcal{A}^{\Delta} = \sin(2\Psi) \quad \tan\Psi \equiv \frac{\left|A\left(\bar{B}_s^0 \to \phi\gamma_R\right)\right|}{\left|A\left(\bar{B}_s^0 \to \phi\gamma_L\right)\right|}.$$

SM prediction [PLB 664, 174 (2008)]:

$$\mathcal{A}^{\Delta}_{\text{SM}} = 0.047^{+0.029}_{-0.025}$$



Time-dependent efficiency calibrated with $B^0 \to K^{*0}\gamma$ decays.

Untagged analysis to 3 fb^{-1} (2011 + 2012):

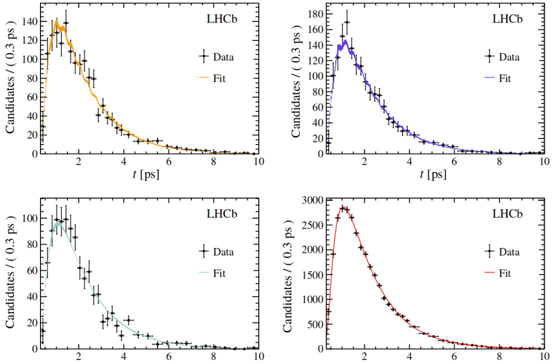
$$\mathcal{A}^{\Delta} = -0.98^{+0.46+0.23}_{-0.52-0.20}$$

Tagged analysis of $B_s^0 \to \phi\gamma$ [PRL 123:081802]

Use Same-Sign (SS) and Opposite Sign (OS) taggers:

- SS: identify the charge of the kaon in the fragmentation process; calibrated with $B_s^0 \to D_s^- \pi^+$ and $B_{s2}^*(5840)^0 \to B^+ K^-$.
- OS: find the associated $b\,(\bar{b})$ hadron from a $b\bar{b}$ production; calibrated with $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$.

Tagged $B_s^0 \to \phi\gamma$ | Tagged $\bar{B}_s^0 \to \phi\gamma$



Untagged $B_s^0 \to \phi\gamma$ | Untagged $B^0 \to K^{*0}\gamma$

With Run-I data only:

$\sim 5000\ B_s^0 \to \phi\gamma$

$\sim 33000\ B_s^0 \to K^{*0}\gamma$

$$S = 0.43 \pm 0.30 \pm 0.11$$

$$C = 0.11 \pm 0.29 \pm 0.11$$

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

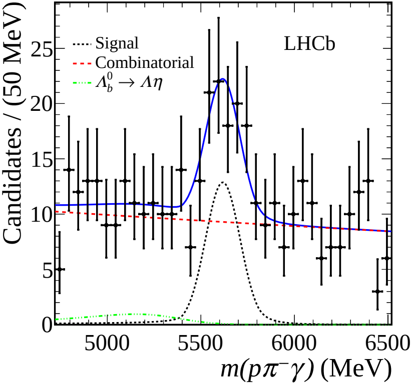
In agreement with the SM.

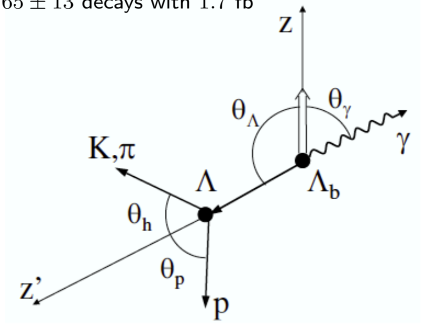
- Complementary to the $b \to s\gamma$ meson transitions, due to a different angular structure.
- Challenging due to the large lifetime of the Λ^0.
- 1.7 fb^{-1} studied (2016), much more on tape!
- First observation with 5.6σ.

Normalized to $B^0 \to K^{*0}\gamma$:

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

65 ± 13 decays with 1.7 fb^{-1}

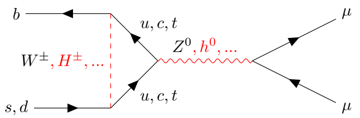




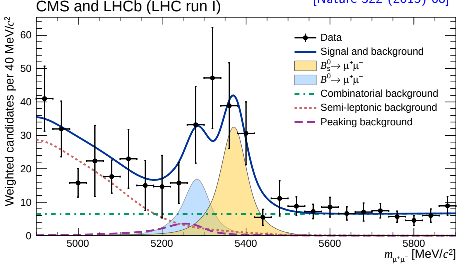
Leptonic $b \to \ell^+\ell^-$ decays

- Helicity suppressed in the SM due to mass difference between $B^0_{(s)}$ with respect to muons, electrons and taus.
- Theoretically clean due to a fully leptonic final state.
- $B^0_s \to \mu^+\mu^-$ has been one of the most important decays to study.
- Flavour anomalies encourage to study also decays with electrons and taus.
- Studies of $B^0_{(s)} \to \tau^+\tau^-$ and $B^0_{(s)} \to e^+e^-$ (new analysis under way), both experimentally challenging.

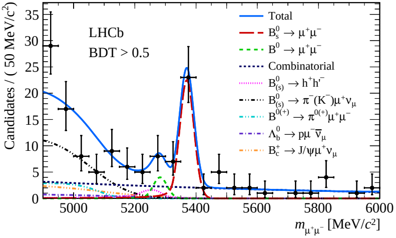
One of the main golden-channels to search for New-Physics in the past:

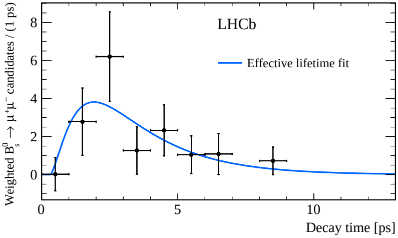


[Nature 522 (2015) 68]



Reported the first observation by a single experiment, using 4.4 fb^{-1} (2011-2016):





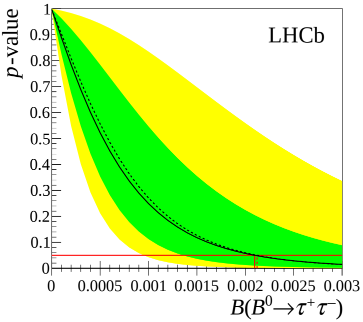
- $B^0_s \to \mu^+\mu^-$ observed with 7.8σ, no significant excess of $B^0 \to \mu^+\mu^-$.
- $B^0 \to \mu^+\mu^-$ limit set to 3.4×10^{-10} at 95% CL.
- ATLAS limit [JHEP 04 (2019) 098]: $\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 2.1 \times 10^{-10}$ at 95% CL
- First measurement of the $\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right)$ effective lifetime:

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

Distinguish between low- and high-mass states

- Reconstructing $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.
- Profit from the very good vertex resolution.
- Search with 3 fb^{-1} (2011 + 2012)

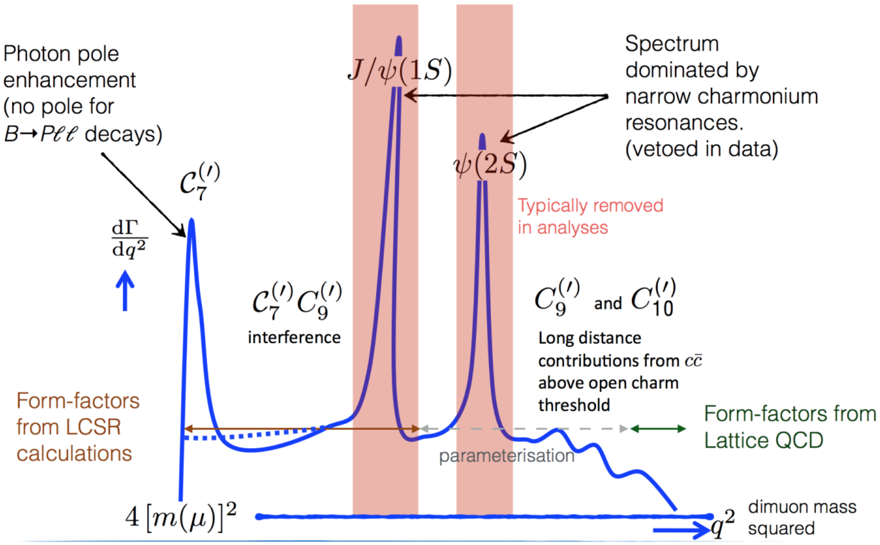
SM prediction [PRL 112:101801]:
$\mathcal{B}\left(B^0\right) = 2.22 \times 10^{-8}$
$\mathcal{B}\left(B^0_s\right) = 7.73 \times 10^{-7}$



$\mathcal{B}\left(B^0 \to \tau^+\tau^-\right) < 1.6 \times 10^{-3}$ at 90% CL
$\mathcal{B}\left(B^0_s \to \tau^+\tau^-\right) < 5.2 \times 10^{-3}$ at 90% CL

Best limit for $B^0 \to \tau^+\tau^-$
First limit for $B^0_s \to \tau^+\tau^-$

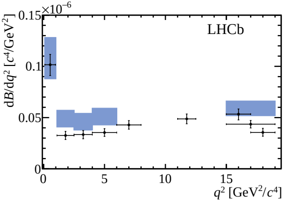
$b \to s\ell^+\ell^-$



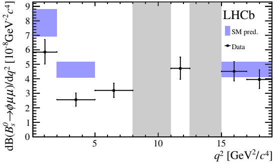
Photon pole enhancement (no pole for $B \to P\ell\ell$ decays)
$C_7^{(\prime)}$
$\frac{d\Gamma}{dq^2}$
$J/\psi(1S)$
$\psi(2S)$
Spectrum dominated by narrow charmonium resonances. (vetoed in data)
Typically removed in analyses
$C_7^{(\prime)} C_9^{(\prime)}$
interference
$C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
Long distance contributions from $c\bar{c}$ above open charm threshold
Form-factors from LCSR calculations
Form-factors from Lattice QCD
parameterisation
$4\,[m(\mu)]^2$
q^2
dimuon mass squared

Differential branching fractions in $b \to s\mu^+\mu^-$

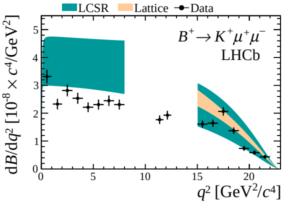
$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 04 (2017) 142]



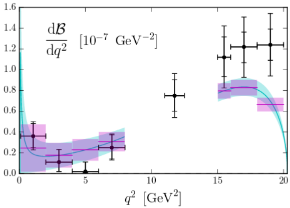
$B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



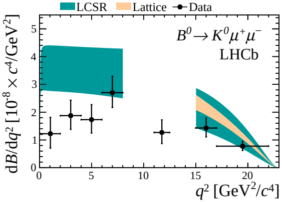
$B^+ \to K^+\mu^+\mu^-$ [JHEP 1406 (2014) 133]



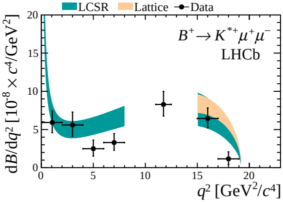
$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ [JHEP 06 (2015) 115] [PRD 93 (2016) 074501]



$B^0 \to K^0\mu^+\mu^-$ [JHEP 1406 (2014) 133]



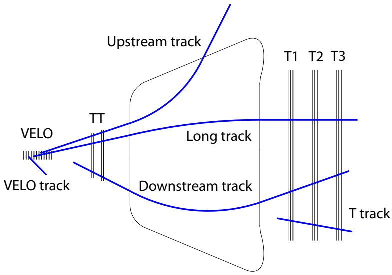
$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 1406 (2014) 133]



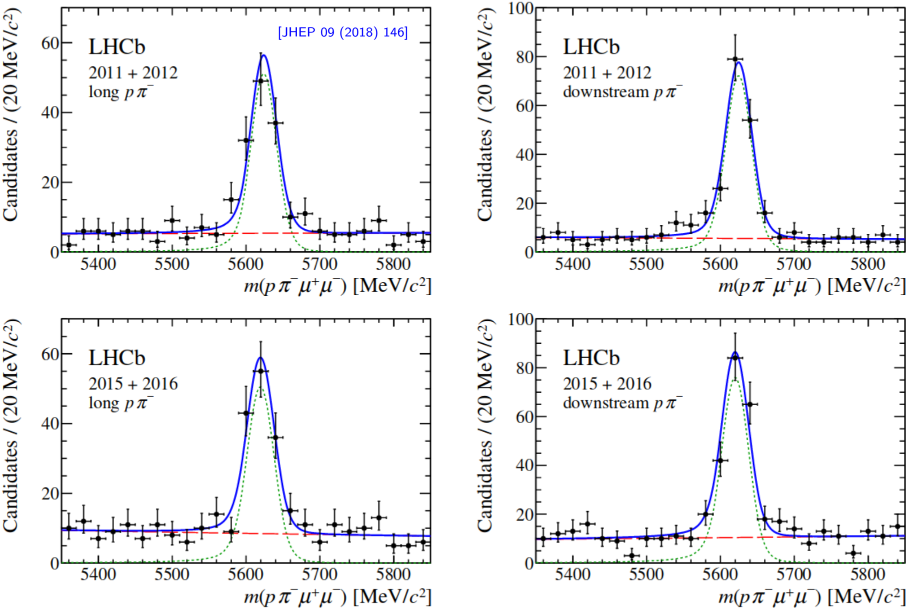
- Systematically below the standard model prediction.
- Tensions at $1 - 3\sigma$, but sizeable hadronic uncertainties.

Angular analyses in $b \to s\mu^+\mu^-$ baryon decays

- Complementary test to understand the nature of the anomalies.
- Spin-half particles can be produced polarized at the LHC.
- Di-quark system as an expectator.
- First study at LHCb with $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ decays [JHEP 09 (2018) 146].
- Use all the possible ways to reconstruct Λ^0 baryons (downstream + long tracks).
- Study in the region $15 < q^2 < 20\,(\text{GeV}/c^2)^2$, where most of the signal is present.
- Using 5 fb^{-1} of data (2011-2016), yielding $\sim 600\ \Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ decays.



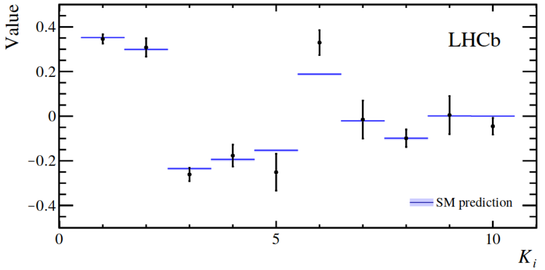
Angular analyses in $b \to s\mu^+\mu^-$ baryon decays



$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ [JHEP 09 (2018) 146]

- Angular analysis includes 5 angles.
- Use the method of moments due to the low statistics [PRD 91 (2015) 114012]:

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



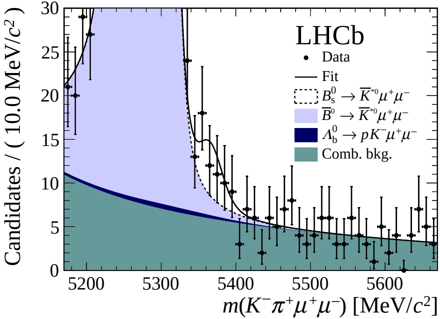
$A_{\rm FB}^{\ell} = -0.39 \pm 0.04$ (stat) ± 0.01 (syst)
$A_{\rm FB}^{h} = -0.30 \pm 0.05$ (stat) ± 0.02 (syst)
$A_{\rm FB}^{\ell h} = +0.25 \pm 0.04$ (stat) ± 0.01 (syst)

34 angular observables, 24 compatible with zero, as expected from the Λ_b^0 polarization at the LHC. Results compatible with the SM.

$b \to d\mu^+\mu^-$ decays

- If NP particles behave on a similar way for d quarks, we must see deviations in $b \to d\ell^+\ell^-$ transitions too.
- Cabibbo suppressed mode, ~ 25 times smaller $\mathcal{B}$ than $b \to s\ell^+\ell^-$ transitions.
- Allows for measuring V_{td}/V_{ts}, to constrain the Minimal Flavour Violation hypothesis.
- $b \to d\ell^+\ell^-$ transitions already observed in the past [JHEP 10 (2015) 034] [JHEP 04 (2017) 029].

$B^0 \to \bar{K}^{*0}\mu^+\mu^-$ [JHEP 07 (2018) 020]



- Equivalent to $B^0 \to K^{*0}\mu^+\mu^-$.
- Many interesting cross-checks between K^{*0} and $\bar{K}^{*0}$ modes.
- First evidence 3.4σ with 5 fb^{-1}.
- $\mathcal{B}_{\text{SM}} \in [3, 4] \times 10^{-8}$ [PRD 98 (2018) 094012] [EPJC 73 (2013) 2593] [IJMP A21 (2006) 6125]
- $\mathcal{B} = (2.9 \pm 1.0 \pm 0.2 \pm 0.3) \times 10^{-8}$

LFU: R_K and R_{K^*}

Motivation:

- Universal coupling of the gauge bosons to leptons in the SM.
- In the SM, branching fractions in $b \to q\ell^+\ell^-$ transitions differ depending on the lepton mass (affecting phase-space and helicity).
- Any sign of lepton flavour non-universality would be a direct sign of NP.

Aim to study the double ratios:

$$R_{K^{*0}} \equiv \frac{\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0\to K^{*0}e^+e^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to e^+e^-))}$$

$$R_{K} \equiv \frac{\mathcal{B}(B^+\to K^{+}\mu^+\mu^-)}{\mathcal{B}(B^+\to K^{+}J/\psi(\to\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+\to K^{+}e^+e^-)}{\mathcal{B}(B^+\to K^{+}J/\psi(\to e^+e^-))}$$

$$\left|\frac{\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)}{\mathcal{B}\left(J/\psi \to e^+e^-\right)}\right|_{\text{SM}} = 1$$

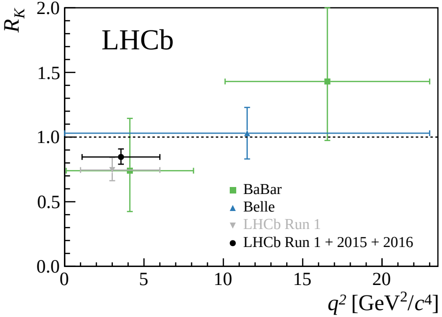
The $R_{K^{*0}/K}$ measurements profit from:

1. Double ratio μ/e allows to get rid of QCD uncertainties and some experimental systematics.
2. Sensitivity to high masses of NP particles (indirect search).
3. $B^0 \to K^{*0}J/\psi$ and $B^+ \to K^+J/\psi$ serve as normalization and control modes.
4. Measure $r_{J/\psi}$ from ratios of $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$, as a cross-check!

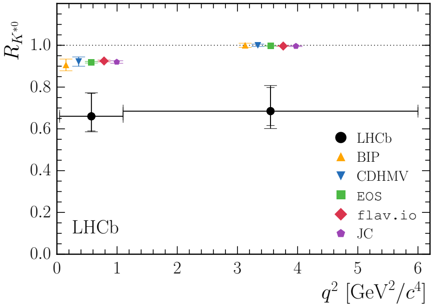
LFU: R_K and R_{K^*}

Results are $\sim 2.4\sigma$ away from the SM:

5 fb^{-1} (2011-2016) [PRL 112:191801]



3 fb^{-1} (2011-2012) [JHEP 08 (2017) 055]

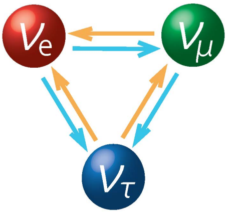


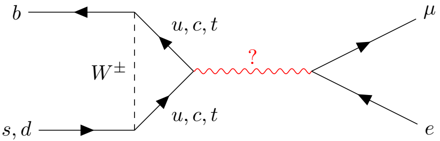
Effort now put on:

- Increase statistics and reduce systematics.
- Tests for LFU in other modes: $B_s^0 \to \phi\ell^+\ell^-$, $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$, $\Lambda_b^0 \to pK^-\ell^+\ell^-$, ...
- Run-II data will tell...

Lepton Flavour Violation (LFV)

- Neutrino oscillations is an evidence of LFV in the neutral lepton sector.
- Not explained by the SM.
- No LFV has been observed so far in the charged sector, e.g. $\ell \to \ell' \gamma$.
- Many models link LFU violation and LFV: SUSY, GUTs, ...
- Anomalies observed in $b \to s \ell^+ \ell^-$ might be accompanied by LFU violation.
- Worth having a look to $b \to \ell \ell'$ and $b \to s \ell \ell'$ transitions.

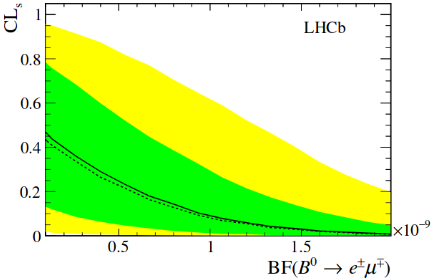


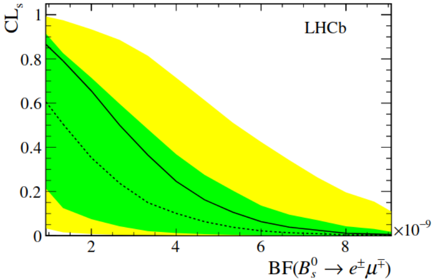


$B^0_{(s)} \to e^\pm \mu^\mp$ [JHEP 03 (2018) 078]

Results using $3\ \mathrm{fb}^{-1}$ (2011-2012) and improved selection:

- Enhanced in NP models up to $\mathcal{O}\left(10^{-11}\right)$.
- Results compatible with background-only hypothesis.
- World best limits in both decays by LHCb.





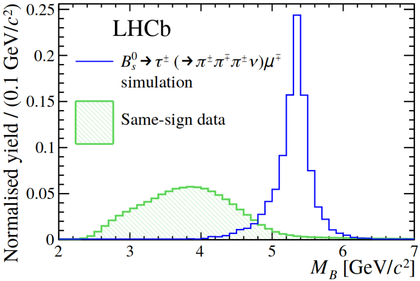
$\mathcal{B}\left(B^0 \to e^\pm \mu^\mp\right) < 1.0 \times 10^{-9}$ at 90% CL
$\mathcal{B}\left(B^0_s \to e^\pm \mu^\mp\right) < 5.4 \times 10^{-9}$ at 90% CL

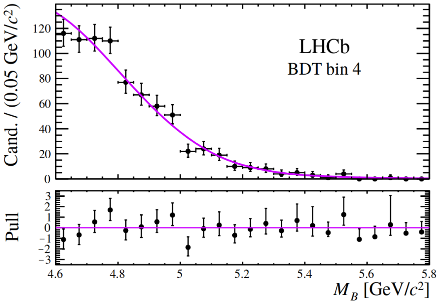
→ **Best limits up to date!**

$B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$ [arXiv:1905.06614 submitted to PRL]

More challenging than $B^0_{(s)} \to e^{\pm}\mu^{\mp}$:

- τ reconstructed as $\tau^- \to \pi^+\pi^-\pi^- \left(\pi^0\right) \nu_\tau$.
- Lifetime resolution crucial to remove $B^0_{(s)} \to D^-_{(s)} \left(\to \mu^- \bar{\nu}_\mu\right) \pi^+\pi^-\pi^+$.
- $B^0 \to a_1(1260)^- \mu^+\nu_\mu$ rejected by requirements in the lifetime too $\mathcal{B} \sim 10^{-4}$.

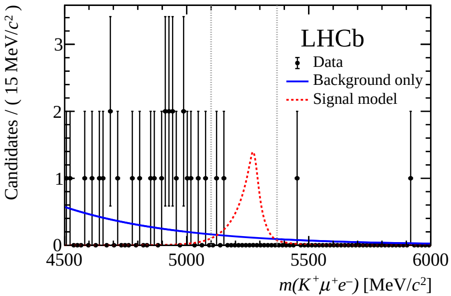


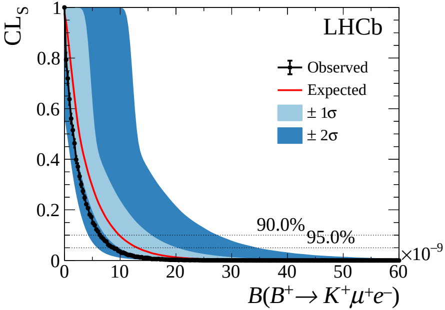


$\mathcal{B}\left(B^0 \to \tau^{\pm}\mu^{\mp}\right) < 1.2 \times 10^{-5}$ at 90% CL
$\mathcal{B}\left(B^0_s \to \tau^{\pm}\mu^{\mp}\right) < 3.4 \times 10^{-5}$ at 90% CL

Best limit for $B^0 \to \tau^{\pm}\mu^{\mp}$
First limit for $B^0_s \to \tau^{\pm}\mu^{\mp}$

- More closely related to the $b \to s\ell^+\ell^-$ transitions.
- In leptoquark models, branching fractions can be around $[10^{-8}, 10^{-10}]$ [JHEP 12 (2016) 027] [JHEP 06 (2015) 072].
- Very clean, normalized to $B^+ \to J/\psi\,(\to \mu^+\mu^-)\,K^+$ and $B^+ \to J/\psi\,(\to e^+e^-)\,K^+$.





$\mathcal{B}\left(B^+ \to K^+\mu^-e^+\right) < 7.0 \times 10^{-9}$ at 90% CL
$\mathcal{B}\left(B^+ \to K^+\mu^+e^-\right) < 6.4 \times 10^{-9}$ at 90% CL

→ **New world best limits!**

Prospects [LHCb-PUB-2018-009]

Very promising future ahead:

- LHCb is currently having its major Upgrade for Run-III/IV.
- Most of the analyses are statistically limited.
- Systematic uncertainties will also decrease.
- Increase of the luminosity maintaining the current detector performance.

Observables	Current LHCb	Upgrade-I	Belle II	Upgrade-II	ATLAS/CMS
LFU					
R_K	0.1	0.025	0.036	0.007	
R_{K^*}	0.1	0.031	0.032	0.008	
$\boldsymbol{b \to \ell^+\ell^-}$					
$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)}$	90%	34%		10%	21%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%		2%	

Conclusions

Decays through FCNC provide clean observables to test the SM and look for NP:

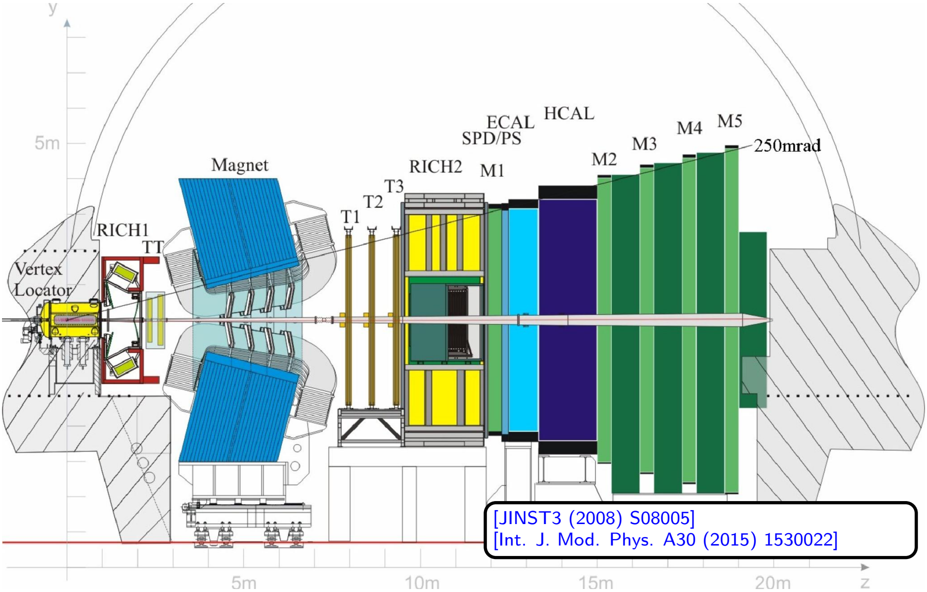
- C_7 is well constrained, but there is room for NP in C_7'.
- Stringent constraints to New Physics from $B_s^0 \to \mu^+\mu^-$.
- Tensions in $b \to s\ell^+\ell^-$ transitions in both differential BR and angular observables, pointing towards NP in C_9 or C_9 and C_{10}.
- Deviations simultaneously in R_K and R_{K^*}, free of hadronic uncertainties.
- Searches for LFV in several b-decays in order to look for a relation with LFU

For the near future...

- Explore new $b \to s\mu^+\mu^-$ decay modes, in order to confirm anomalies.
- Look for anomalies in other type of decays: baryons, $b \to d\ell^+\ell^-$, ...
- Currently exploiting the information collected so far, with a promising future for the upgrades.

BACKUP

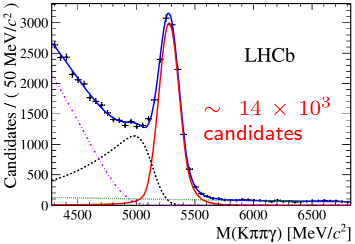
The LHCb detector



[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

Old measurements of photon polarisation

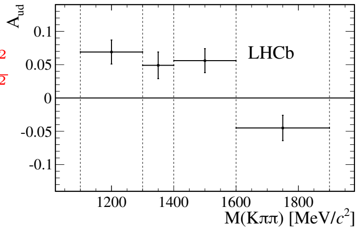
First observation in $B^+ \to K^+\pi^+\pi^-\gamma$ with 3 fb^{-1} (2011 + 2012) [PRL 112:161801]



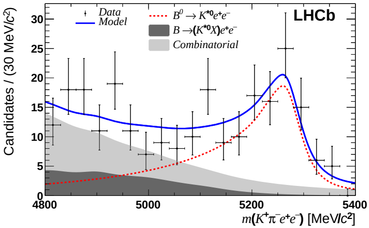
$A_{\rm ud} \propto \frac{|C_7|^2 - |C_7'|^2}{|C_7|^2 + |C_7'|^2}$

5.2σ deviation!

Full amplitude analysis ongoing



First measurement in $B^0 \to K^{*0} e^+e^-$ with 3 fb^{-1} (2011 + 2012) [JHEP 04 (2015) 064]



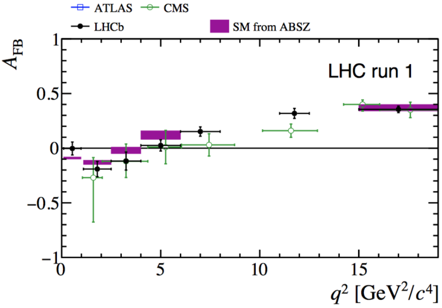
When $q^2 \to 0$:

$$A_T^{(2)} \to \frac{2\mathcal{R}e\left(C_7 C_7'^*\right)}{|C_7|^2 + |C_7'|^2} \qquad A_T^{\rm Im} \to \frac{2\mathcal{I}m\left(C_7 C_7'^*\right)}{|C_7|^2 + |C_7'|^2}$$

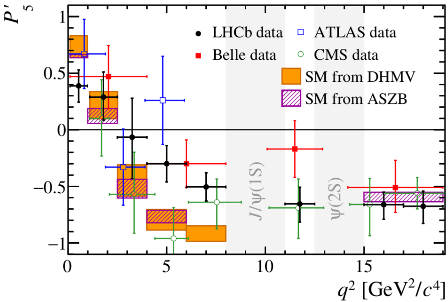
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{\rm Im} = +0.14 \pm 0.22 \pm 0.05$$

Update with full dataset ongoing

$B^0 \to K^{*0}\mu^+\mu^-$ and P_5'



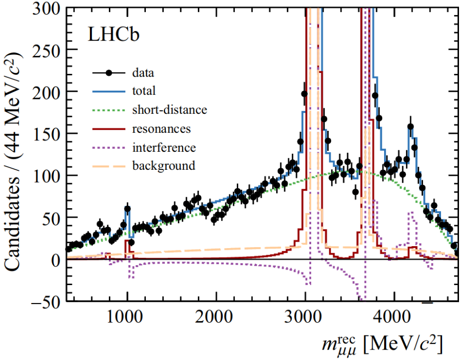
Belle measurement also includes $B^0 \to K^{*0}e^+e^-$.

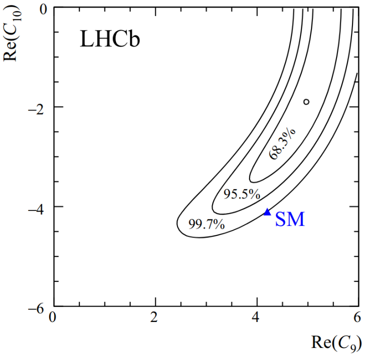


- Good agreement in many angular observables.
- P_5' less dependent on the form-factors.
- Deviations in P_5' (3.4σ LHCb only), sensitivity dominated by LHCb.
- Measurements by LHCb [JHEP 02 (2016) 104], Belle [arXiv:1612.05014 (submitted to PRL)], CMS [PLB 781 (2018) 04:030] and ATLAS [JHEP 10 (2018) 047], affected by different systematics.
- Update with Run-II ongoing, including also $B^0 \to K^{*0}e^+e^-$.

Phase difference in $B^+ \to K^+\mu^+\mu^-$ [EPJC (2017) 77: 161]

- Fit to the full di-muon invariant mass spectrum: ρ, ω, ϕ, J/ψ, $\psi(2S)$, $\Psi(3770)$, $\Psi(4040)$, $\Psi(4160)$, $\Psi(4415)$.
- Study of the phase difference of long- and short-distance contributions, important to understand the long-distance effects in the SM.
- Interference is small, 3σ deviation in C_{10}/C_9 plane.

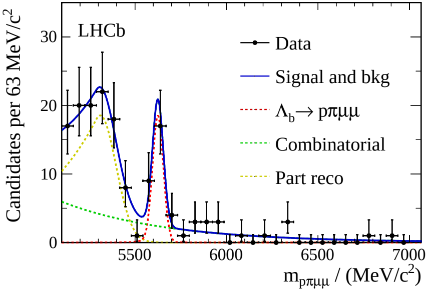




$$\mathcal{B}_{\text{short}}\left(B^+ \to K^+\mu^+\mu^-\right) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

Other $b \to d\ell^+\ell^-$ transitions

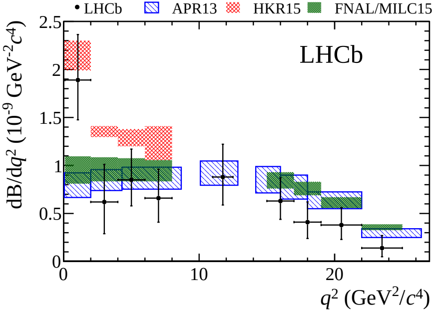
$\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ [JHEP 04 (2017) 029]



$\mathcal{B} = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$

First observation of a $b \to d$ transition in a baryon decay.

$B^+ \to \pi^+\mu^+\mu^-$ [JHEP 10 (2015) 034]



$\mathcal{B} = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$

$A_{\text{CP}} = -0.11 \pm 0.12 \pm 0.01$

Most precise up to date.