

Rare beauty and charm decays at LHCb

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on behalf of the LHCb collaboration

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Deep-Inelastic Scattering 2015

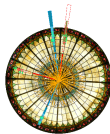


University of
Zurich ^{UZH}

DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Dallas, Texas
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April 28, 2015

1. Rare B decays:

- ▶ $B \rightarrow K\pi\pi\gamma$
- ▶ $B \rightarrow \mu\mu.$
- ▶ $b \rightarrow sll.$

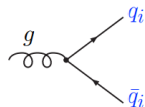
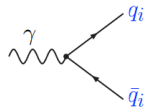
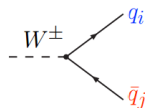
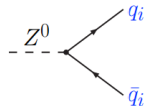
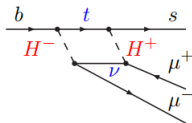
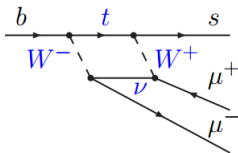
2. Charm decays:

- ▶ $D \rightarrow \mu\mu.$



Why rare decays?

- ▶ CKM structure in SM allows only the charged interactions to change flavour.
 - ▶ Other interactions are flavour conserving.
- ▶ One can escape the CKM structure and produce $b \rightarrow s$ and $b \rightarrow d$ only at loop level.
 - ▶ This kind of processes are suppressed in SM \rightarrow Rare decays.



► Operator Product Expansion and Effective Field Theory

$$H_{\text{eff}} = -\frac{4G_f}{\sqrt{2}} VV^* \sum_i \left[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\text{right-handed}} \right]$$

i=1,2 Tree

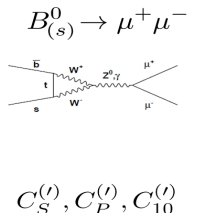
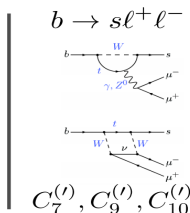
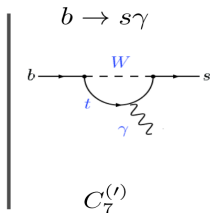
i=3-6,8 Gluon penguin

i=7 Photon penguin

i=9,10 EW penguin

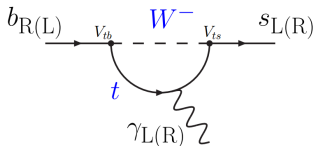
i=S Scalar penguin

i=P Pseudoscalar penguin



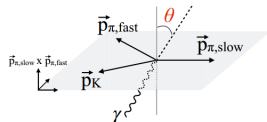
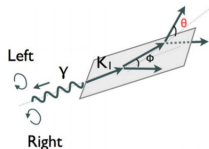
Radiative decays

- ▶ $B^0 \rightarrow K^* \gamma$ - first observed penguin!
 - ▶ CLEO, [[PRL, 71 \(1993\) 674](#)]
- ▶ B-factories probed NP measuring, inclusively/ semi-inclusively $\mathcal{B}(b \rightarrow s \gamma)$
- ▶ Is there anyway LHCb can contribute?
 - ▶ Measurements of $\mathcal{B}(b \rightarrow s \gamma)$ very difficult.
 - ▶ Can probe probe polarization!
- ▶ In SM, photons from $b \rightarrow s \gamma$ decays are left handed.
 - ▶ Charged current interactions: $C_7/C_7' \sim m_b/m_s$
- ▶ Can test C_7/C_7' using:
 - ▶ Mixing induced CP violation: [Atwood et. al. PRL 79 \(1997\) 185-188](#)
 - ▶ Λ_b baryons: [Hiller & Kagan PRD 65 \(2002\) 074038](#)



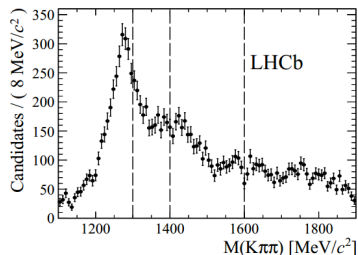
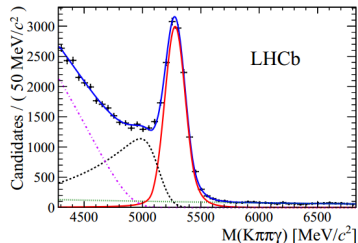
Photon polarization from $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- ▶ OR: Study $B \rightarrow K^{**} \gamma$ decays like $B^+ \rightarrow K_1(1270) \gamma$
 - ▶ Gronau & Pirjol PRD 66 (2002) 054008
- ▶ The trick is to get the photon polarization from the up-down asymmetry of photon direction in the $K\pi\pi$ rest frame.
 - ▶ No asymmetry \rightarrow Unpolarised photons.
- ▶ Conceptionally this measurement is similar to the Wu experiment, which first observed parity violation.



$B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ at LHCb

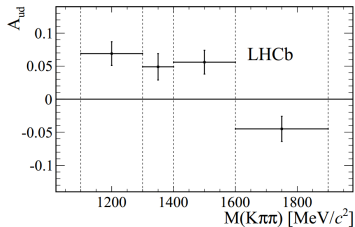
- ▶ LHCb looked at $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$, using un-converted photons.
- ▶ Got over 13.000 candidates in 3 fb^{-1} !
- ▶ [Phys. Rev. Lett. 112, 161801](#)
- ▶ $K^+ \pi^- \pi^+$ system has variety of resonances.
 - ▶ $K\pi\pi\pi$ system studied inclusively.
 - ▶ Bin the mass and look for polarization there.



Up-down asymmetry

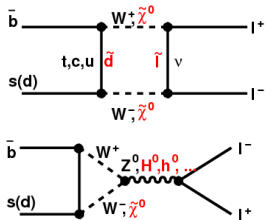
- ▶ Combining the 4 bins, gives 5.2σ significance from no photon polarization hypothesis.
- ▶ Unfortunately without understanding the hadron system it is impossible to tell if the photon is left or right-handed.

→ First observation of photon polarization in $b \rightarrow s\gamma$!



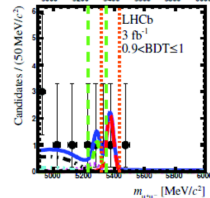
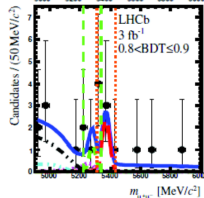
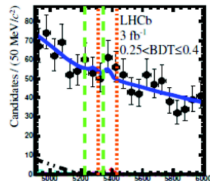
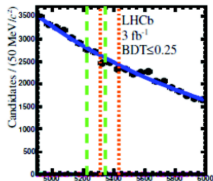
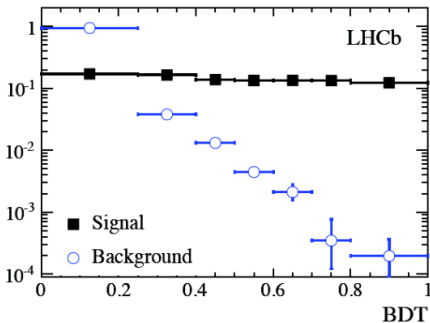
$B^0 \rightarrow \mu^+ \mu^-$

- ▶ Clean theoretical prediction, GIM and helicity suppressed in the SM:
 - ▶ $\mathcal{B}(B_s^0 \rightarrow \mu^- \mu^+) = (3.65 \pm 0.23) \times 10^{-9}$
 - ▶ $\mathcal{B}(B^0 \rightarrow \mu^- \mu^+) = (1.06 \pm 0.09) \times 10^{-10}$
- ▶ Sensitive to contributions from scalar and pseudoscalar couplings.
- ▶ Probing: MSSM, higgs sector, etc.
- ▶ In MSSM: $\mathcal{B}(B_s^0 \rightarrow \mu^- \mu^+) \sim \text{tg}^6 \beta / m_A^4$



$B^0 \rightarrow \mu^+ \mu^-$ searches

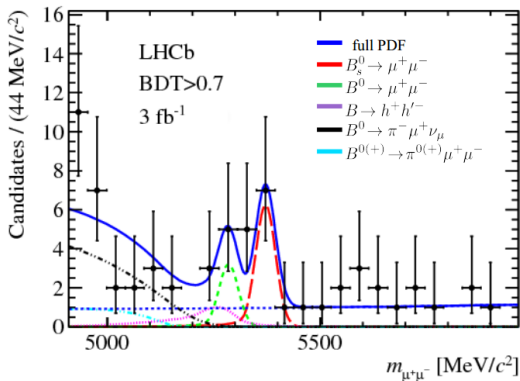
- ▶ Background rejection power is a key feature of rare decays \rightarrow use multivariate classifiers (BDT) and strong PID.



- ▶ Normalize the BF to $B^+ \rightarrow J/\psi(\mu\mu)K^+$ and $B^0 \rightarrow K\pi$.

$B^0 \rightarrow \mu^+ \mu^-$ Results

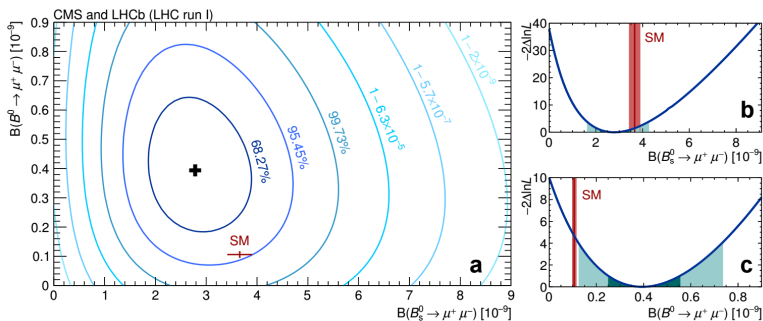
- ▶ Nov. 2012:
 - ▶ First evidence 3.5σ for $B^0 \rightarrow \mu^+ \mu^-$ with 2.1 fb^{-1} .
- ▶ Summer 2013:
 - ▶ Full data sample: 3 fb^{-1} .



- ▶ Measured BF:
 $\mathcal{B}(B_s^0 \rightarrow \mu^- \mu^+) = (2.9_{-1.0}^{+1.1}(\text{stat.})_{-0.1}^{+0.3}(\text{syst.})) \times 10^{-9}$
- ▶ 4.0σ significance!
- ▶ $\mathcal{B}(B^0 \rightarrow \mu^- \mu^+) < 7 \times 10^{-10}$ at 95% CL
- ▶ PRL 110 (2013) 021801
- ▶ CMS result: PRL 111 (2013) 101805

$$\mathcal{B}(B_s^0 \rightarrow \mu^- \mu^+) = (2.8_{-0.6}^{+0.7}) \times 10^{-9}$$

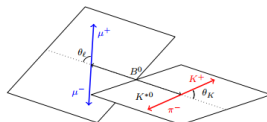
$$\mathcal{B}(B^0 \rightarrow \mu^- \mu^+) = (3.9_{-1.4}^{+1.6}) \times 10^{-10}$$



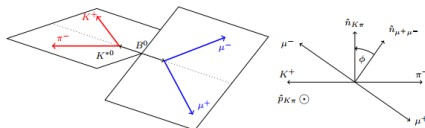
► [arXiv:1411.4413](https://arxiv.org/abs/1411.4413)

$B^0 \rightarrow K^* \mu \mu$ angular distributions

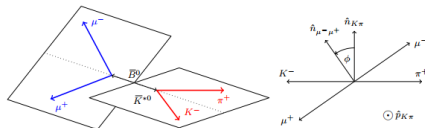
- ▶ Can probe photon polarization using virtual photons in $b \rightarrow s \ell \ell$.
- ▶ LHCb favourite: $B^0 \rightarrow K^* \mu \mu$.
- ▶ Sensitive to lot of new physics models.
- ▶ Decay described by three angles θ_1, θ_K, ϕ and dimuon invariant mass q^2 .
- ▶ Analysis is performed in bins of q^2 .



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



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the \bar{B}^0 decay

$B^0 \rightarrow K^* \mu \mu$ angular distributions

- ▶ Angular distributions depends on 11 angular terms:

$$\frac{d^4\Gamma[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{d \cos \theta_\ell d \cos \theta_K d\phi dq^2} = \frac{9}{32\pi} \left[J_1^S \sin^2 \theta_K + J_1^C \cos^2 \theta_K + J_2^S \sin^2 \theta_K \cos 2\theta_\ell + J_2^C \cos^2 \theta_K \cos 2\theta_\ell + \right. \\ J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \\ J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + \\ \left. J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

where the J_i are bilinear combinations of helicity amplitudes.

- ▶ Not enough events in our data sample to fit for 11 parameters
→ need to simplify!
- ▶ Can use symmetries, to reduced the the parameters
to 9 → still a bit large!

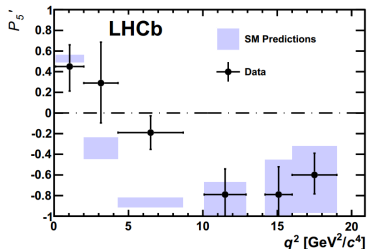
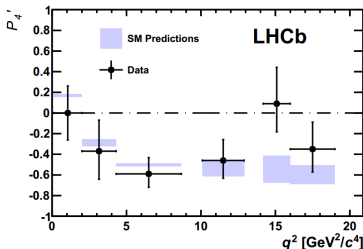
$B^0 \rightarrow K^* \mu\mu$ Folding

- ▶ One can simplify the angular distribution by folding: eg. $\phi \rightarrow \phi + \pi$ for ($\phi < 0$).
- ▶ Cancels terms with $\cos \phi$ and $\sin \phi$.

$$\frac{d^4\Gamma[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{d \cos \theta_\ell d \cos \theta_K d\phi dq^2} = \frac{9}{32\pi} \left[J_1^S \sin^2 \theta_K + J_1^C \cos^2 \theta_K + J_2^S \sin^2 \theta_K \cos 2\theta_\ell + J_2^C \cos^2 \theta_K \cos 2\theta_\ell + \right. \\ J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi} + \\ \cancel{J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi} + J_6 \cos^2 \theta_K \cos \theta_\ell + \cancel{J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi} + \\ \left. \cancel{J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi} + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

$B^0 \rightarrow K^* \mu\mu$ angular distributions

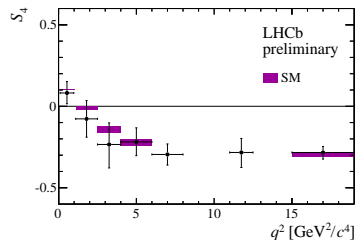
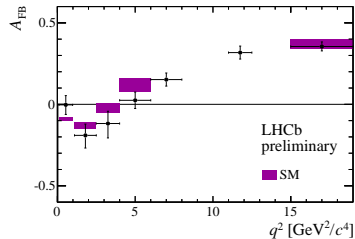
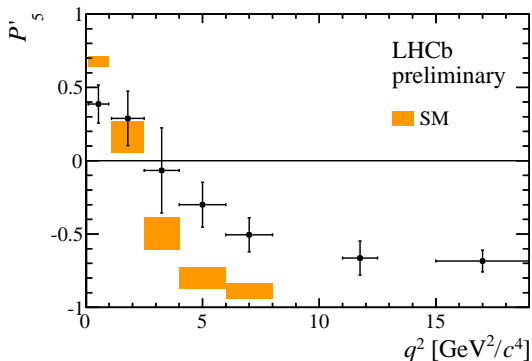
- ▶ Different foldings cancel different angular observables. [PRL 111 191801 (2013)]



- ▶ Observables $P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$
- ▶ Leading form-factor uncertainties cancel.
- ▶ In 1 fb^{-1} , LHCb observes a local discrepancy of 3.7σ in P'_5 .
- ▶ Probability that at least one bin varies by this much is 0.5%.
- ▶ SM prediction form: JHEP 05 (2013) 137

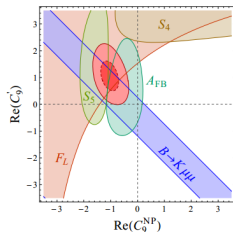
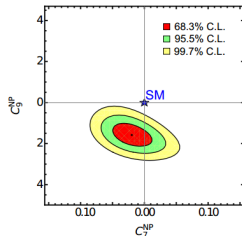
$B^0 \rightarrow K^* \mu\mu$ update with 3 fb^{-1}

- ▶ Recently we release a preliminary result with 3 fb^{-1} [LHCb-CONF-2015-002]
- ▶ Anomaly stays at 3.7σ .
- ▶ Soon a full result with finer bins!



Understanding the $B^0 \rightarrow K^* \mu \mu$ anomaly

- ▶ Matias, Decotes-Genon & Virto performed a global fit to the available $b \rightarrow s \gamma$ and $b \rightarrow s l l$.
- ▶ Found 4.5σ discrepancy from SM.
- ▶ Fit favours $C_9^{NP} = 1.5$
- ▶ [PRD 88 074002 \(2013\)](#)
- ▶ Straub & Altmannshofer performed a global analysis and found discrepancies at the level of 3σ . Data again best describes a modified C_9 .
- ▶ Data can be explained by introducing a flavour changing Z' boson, with mass $\mathcal{O}(10 \text{ TeV})$
- ▶ [EPJC 73 2646 \(2013\)](#)

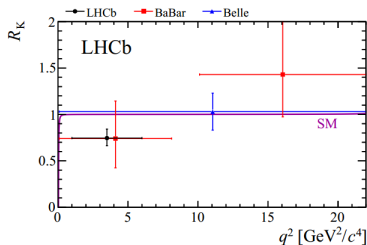


Lepton universality

- ▶ If Z' is responsible for the P'_5 anomaly, does it couple equally to all flavours?

$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}).$$

- ▶ Challenging analysis.
- ▶ Migration of events modeled by MC.
- ▶ Correct bremsstrahlung.
- ▶ Take double ratio with $B^+ \rightarrow J/\psi K^+$ to cancel systematics.
- ▶ In 3fb^{-1} , LHCb measures $R_K = 0.745^{+0.090}_{-0.074}(\text{stat.})^{+0.036}_{-0.036}(\text{syst.})$
- ▶ Consistent with SM at 2.6σ .



LHCb-PAPER-2014-024 [Preliminary].

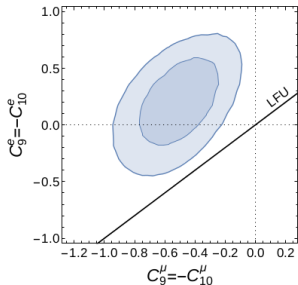
Belle [PRL 103 (2009) 171801],

BaBar [PRD 86 (2012) 032012]

Lepton universality with $B^0 \rightarrow K^* \mu\mu$ anomaly

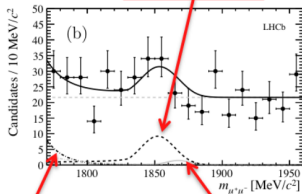
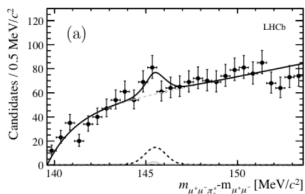
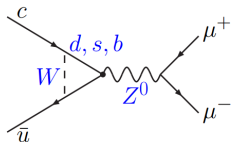
- ▶ Lepton flavour universality cannot be explained by any QCD effect!
- ▶ This effect is consistent with anomaly (non universal Z')
- ▶ Global fit to $b \rightarrow s\mu^-\mu^+$ and $b \rightarrow se^-e^+$ seems to favour Z' with non lepton universal couplings.

Ghosh et al. 1408.4097



FCNC in charm decays

- ▶ GIM cancelation effective in $c \rightarrow u$ transitions due to small size of m_b .
- ▶ SM prediction: $\mathcal{B}(D^0 \rightarrow \mu\mu) \sim 6 \times 10^{-11}$



- ▶ Use $D^{*\pm}$ and exploit small Δm for background suppression.
- ▶ Limitation is $\pi \rightarrow \mu$ mis-id.
- ▶ Limit: $\mathcal{B}(D^0 \rightarrow \mu\mu) < 6.2 \times 10^{-9}$ at 90% CL
- ▶ [PLB 725 \(2013\) 15-24](#)

Conclusions

- ▶ Rare decays play important role in putting NP.
- ▶ Can access NP scales beyond reach of GPD.
- ▶ Tension in $b \rightarrow sll$, theory correct?
- ▶ List of decays presented in this talk is just a tip of iceberg:
 - ▶ Please look at ours: isospin, A_{CP} .
 - ▶ More are on their way.

