Rare beauty and charm decays at LHCb

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on behalf of the LHCb collaboration

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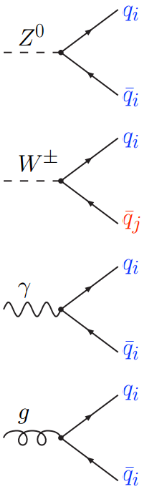
QCD 2015

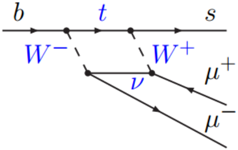
July 3, 2015

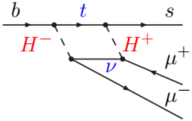
1. Rare B decays:
    - $\mathrm{B} \to \mathrm{K}\pi\pi\gamma$
    - $\mathrm{B} \to \mu\mu$.
    - $\mathrm{b} \to \mathrm{s}\ell\ell$.
2. Charm decays:
    - $\mathrm{D} \to \mu\mu$.

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.







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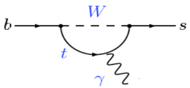
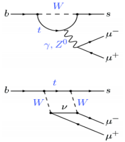
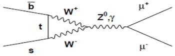
Tools

- **Operator Product Expansion and Effective Field Theory**

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

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

$b \to s\gamma$	$b \to s\ell^+\ell^-$	$B^0_{(s)} \to \mu^+\mu^-$
		
$C_7^{(\prime)}$	$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$	$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

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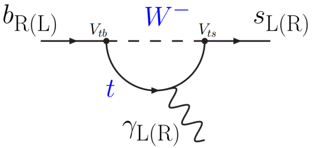
Radiative decays

- $B^0 \to K^*\gamma$ - first observed penguin!
  - CLEO, [PRL, 71 (1993) 674]
- B-factories probed NP measuring, inclusively/ semi-inclusively $\mathcal{B}(b \to s\gamma)$
- Is there anyway LHCb can contribute?
  - Measurements of $\mathcal{B}(b \to s\gamma)$ very difficult.
  - Can probe probe polarization!



- In SM, photons form $b \to s\gamma$ 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

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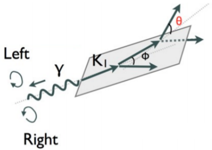
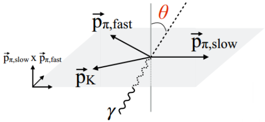
Photon polarization from $B^+ \to K^+\pi^-\pi^+\gamma$

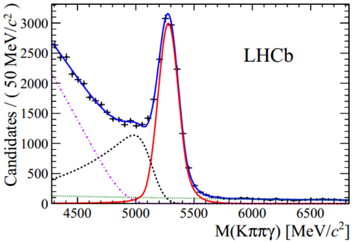
- OR: Study $B \to K^{**}\gamma$ decays like $B^+ \to K_1(1270)\gamma$
  - Gronau & Pirjol PRD 66 (2002) 054008
- The trick is to get the photon polarization from the up-down asymmetry of photon direction in the $K\pi\pi$ rest frame.
  - No asymmetry $\to$ Unpolarised photons.
- Conceptionally this measurement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

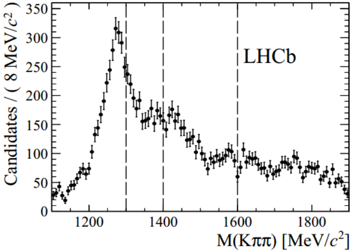




$B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb

- LHCb looked at $B^+ \to K^+\pi^-\pi^+\gamma$, 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.





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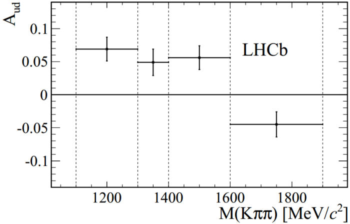
Up-down asymmetry

- 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.



$\longrightarrow$ First observation of photon polarization in b $\rightarrow$ sγ!

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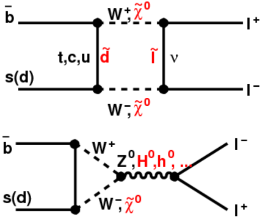
- Clean theoretical prediction, GIM and helicity suppressed in the SM:
  - $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^-\mu^+) = (1.06 \pm 0.09) \times 10^{-10}$
- Sensitive to contributions from scalar and pesudoscalar couplings.
- Probing: MSSM,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



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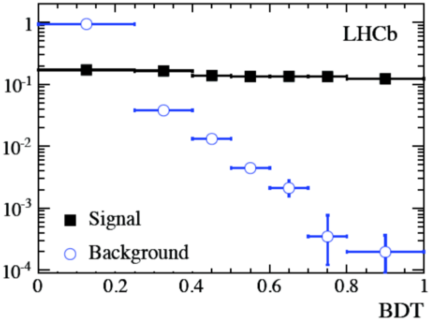
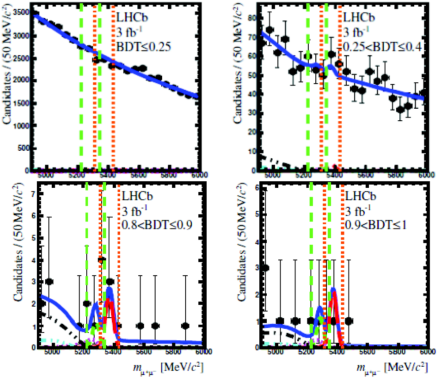
$B^0 \to \mu^+\mu^-$ searches

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





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

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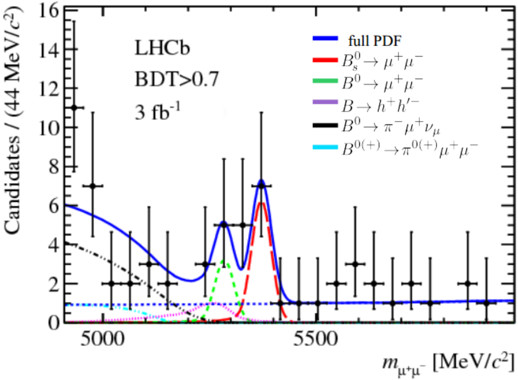
$B^0 \to \mu^+\mu^-$ Results

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



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

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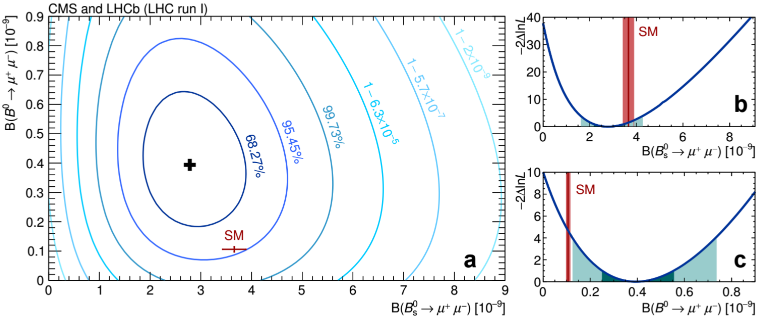
LHCb+CMS Combination

$$\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^-\mu^+) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$



- Nature 522, 7554
- See Daniele Fasanella talk for CMS side.

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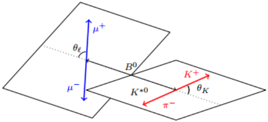
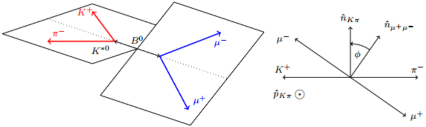
$B^0 \rightarrow K^{*}\mu\mu$ angular distributions

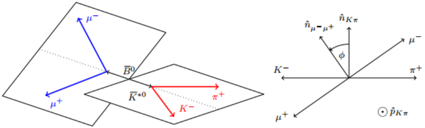
- Can probe photon polarization using virtual photons in $b \rightarrow s\ell\ell$.
- LHCb favourite: $B^0 \rightarrow K^{*}\mu\mu$.
- Sensitive to lot of new physics models.
- Decay described by three angles θ_l, θ_K, ϕ and dimuon invariant mass q^2.
- Analysis is performed in bins of q^2.



(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 $\overline{B}^0$ decay

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

- Angular distributions depends on 11 angular terms:

$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

where the J_i are bilinear combinations of helicity amplitudes.

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

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

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

$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi} + \cancel{J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi} + J_6 \cos^2\theta_K \cos\theta_\ell + \cancel{J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi} + \cancel{J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi} + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

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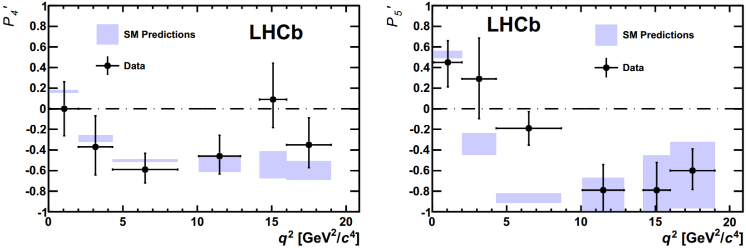
$B^0 \to K^*\mu\mu$ angular distributions

- 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 discreapncy 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

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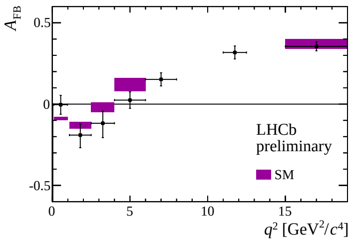
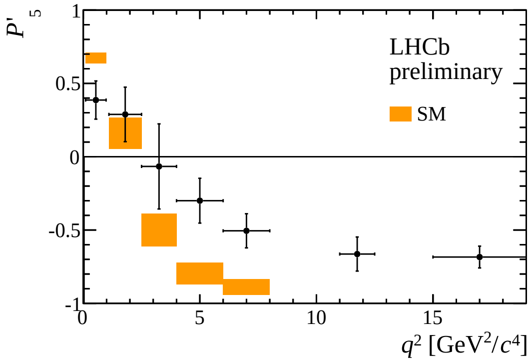
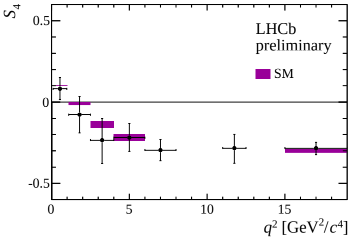
$B^0 \to K^*\mu\mu$ update with 3 fb^{-1}

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







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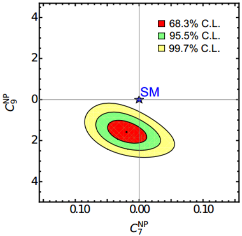
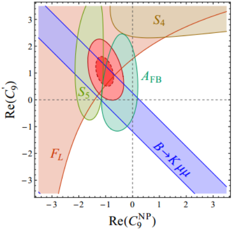
Understanding the $B^0 \to K^* \mu\mu$ anomaly

- Matias, Decotes-Genon & Virto performed a global fit to the avaible $b \to s\gamma$ abd $b \to s\ell\ell$.
- 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 $\mathcal{O}(10\ TeV)$
- EPJC 73 2646 (2013)



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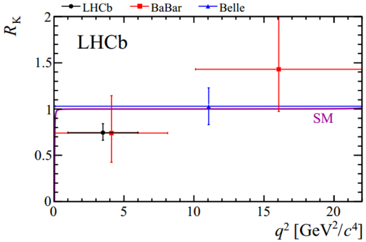
Lepton universality

- If Z' is responsible for the P_5' anomaly, does it couple equally to all flavours?

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

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



LHCb-PAPER-2014-024 [Preliminary],

Belle [PRL 103 (2009) 171801] ,

BaBar [PRD 86 (2012) 032012]

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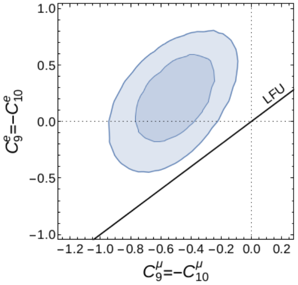
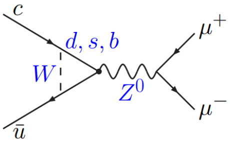
Lepton universality with $B^0 \to K^* \mu\mu$ anomaly

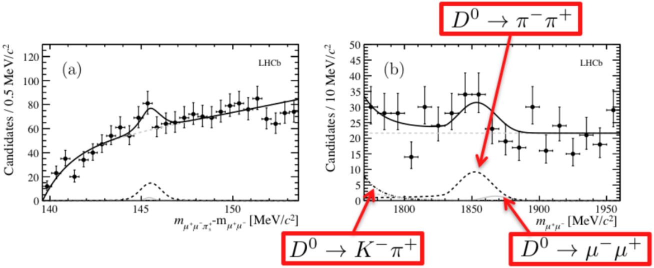
- Lepton flavour universality cannot be explained by any QCD effect!
- This effect is consistent with anomaly (non universal Z')
- Global fit to $b \to s\mu^-\mu^+$ and $b \to se^-e^+$ seems to favour Z' with non lepton universal couplings.

  Ghosh et al. 1408.4097



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





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

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Conclusions

- Rare decays play important role in hutting NP.
- Can access NP scales beyond reach of GPD.
- Tension in b $\rightarrow$ s$\ell\ell$, 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.