Rare beauty and charm decays at LHCb

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1. Rare B decays:
   ▶ $B \rightarrow K\pi\pi\gamma$
   ▶ $B \rightarrow \mu\mu$
   ▶ $b \rightarrow s\ell\ell$

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**

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

- \(i = 1,2\) Tree
- \(i = 3-6,8\) Gluon penguin
- \(i = 7\) Photon penguin
- \(i = 9.10\) EW penguin
- \(i = S\) Scalar penguin
- \(i = P\) Pseudoscalar penguin

**Diagrams:**

- **b → s\(\gamma\)**
  - \(C_7^{(t)}\)

- **b → s\(\ell^+\ell^-\)**
  - \(C_7^{(t)}, C_9^{(t)}, C_{10}^{(t)}\)

- **\(B^0_{(s)} \rightarrow \mu^+\mu^-\)**
  - \(C_S^{(t)}, C_P^{(t)}, C_{10}^{(t)}\)
Radiative decays

- $B^0 \rightarrow K^*\gamma$ - first observed penguin!
  - CLEO, [PRL, 71 (1993) 674]
- B-factories probed NP measuring, inclusively/semi-inclusively $B(b \rightarrow s\gamma)$
- Is there anyway LHCb can contribute?
  - Measurements of $B(b \rightarrow s\gamma)$ very difficult.
  - Can probe probe polarization!
- In SM, photons form $b \rightarrow s\gamma$ 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
  - $\Lambda_b$ baryons: Hiller & kagan PRD 65 (2002) 074038
Photon polarization from $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- OR: Study $B \rightarrow K^{**} \gamma$ decays like $B^+ \rightarrow K_1(1270) \gamma$
- 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.
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.
Combining the 4 bins, gives $5.2\sigma$ 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:
  - $\mathcal{B}(B^0_s \rightarrow \mu^- \mu^+) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \rightarrow \mu^- \mu^+) = (1.06 \pm 0.09) \times 10^{-10}$

- Sensitive to contributions from scalar and pseudoscalar couplings.

- Probing: MSSM, higgs sector, etc.

- In MSSM: $\mathcal{B}(B^0_s \rightarrow \mu^- \mu^+) \sim \tan^6 \beta / m_A^4$
Background rejection power is a key feature of rare decays → use multivariate classifiers (BDT) and strong PID.

Normalize the BF to \(B^+ \rightarrow J/\psi(\mu\mu)K^+\) and \(B^0 \rightarrow K\pi\).
\[ B^0 \rightarrow \mu^+ \mu^- \] \hspace{1cm} \text{Results}

- **Nov. 2012:**
  - First evidence $3.5\sigma$ for $B^0 \rightarrow \mu^+ \mu^-$. with $2.1 \text{ fb}^{-1}$.

- **Summer 2013:**
  - Full data sample: $3 \text{ fb}^{-1}$.

- Measured BF:
  \[ \mathcal{B}(B^0_s \rightarrow \mu^- \mu^+) = (2.9^{+1.1}_{-1.0} \text{(stat.)}^{+0.3}_{-0.1} \text{(syst.)}) \times 10^{-9} \]
  - $4.0\sigma$ 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
LHCb+CMS Combination

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

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

▶ arXiv:1411.4413
\[ B^0 \rightarrow K^* \mu \mu \text{ angular distributions} \]

- 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 \( \theta_\ell, \theta_K, \phi \) and dimuon invariant mass \( q^2 \).
- Analysis is performed in bins of \( q^2 \).
$B^0 \rightarrow K^* \mu \mu$ angular distributions

- Angular distributions depends on 11 angular terms:

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

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!
One can simplify the angular distribution by folding: eg. $\phi \rightarrow \phi + \pi$ for ($\phi < 0$).

Cancels terms with $\cos \phi$ and $\sin \phi$.

\[
\frac{d^4\Gamma[B^0 \rightarrow K^{*0}_{\mu\mu}]}{d \cos \theta_\ell \ d \cos \theta_K \ d\phi \ dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]
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
Recently we release a preliminary result with $3 \text{ fb}^{-1}$ [LHCb-CONF-2015-002].

Anomaly stays at $3.7 \sigma$.

Soon a full result with finer bins!
Matias, Decotes-Genon & Virto performed a global fit to the available $b \rightarrow s\gamma$ abd $b \rightarrow s\ell\ell$.

- Found $4.5\sigma$ 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 $3\sigma$. Data again best describes a modified $C_9$.

- Data can be explained by introducing a flavour changing $Z'$ boson, with mass $O(10 \text{ TeV})$
- EPJC 73 2646 (2013)
If $Z'$ is responsible for the $P'_5$ anomaly, does it couple equally to all flavours?

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

Challenging analysis.

Migration of events modeled by MC.

Correct bremsstrahlung.

Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.

In $3fb^{-1}$, LHCb measures

\[
R_K = 0.745^{+0.090}_{-0.074} \text{(stat.)}^{+0.036}_{-0.036} \text{(syst.)}
\]

Consistent with SM at 2.6$\sigma$. 

Belle [PRL 103 (2009) 171801],
BaBar [PRD 86 (2012) 032012]
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 $b \to s e^- e^+$ 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 $\Delta m$ 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 hunting NP.
- Can access NP scales beyond reach of GPD.
- Tension in $b \to s\ell\ell$, 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.