Latest Results in Rare Decays at LHCb

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on behalf of the LHCb Collaboration

Moriond QCD and High Energy Interactions
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→ Photon polarisation in $b \to s\gamma$ transitions

→ Search for Majorana neutrinos in $B^- \to \pi^+ \mu^- \mu^-$

→ Search for the FCNC decay $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$

→ Angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$

→ Other $B \to K\mu\mu$ decays

→ Summary
Look for New Physics (NP) via direct and indirect searches

No evidence from direct searches so far

Indirect searches are complimentary and can probe higher energy scales

Flavour changing neutral currents (FCNC) are only allowed at the loop level in the SM

NP virtual particles can enter loops and alter branching fractions, angular distributions, CP observables and more
The LHCb Detector

A dedicated flavour physics experiment in the forward region at the LHC

3 fb$^{-1}$ of integrated luminosity from $pp$ collisions at 7 and 8 TeV

- Precise vertex reconstruction: $< 10\mu$m vertex resolution in $x$ and $y$
- Excellent charged particle separation: $\pi^\pm$ misID of 10% for 95% $K^\pm$ efficiency
- Clean identification of muons: misID of 1% for 98% $\mu^\pm$ efficiency
- Excellent mass resolution: typically 7–20 MeV
- Flexible low-$p_T$ trigger
Photon polarisation in $b \to s\gamma$ transitions

- Photons from $b \to s\gamma$ transitions are predominantly left-handed in the SM.

- NP contributions to loops may introduce a right-handed component.

- Up-down asymmetry, $A_{ud}$, proportional to photon polarisation.

- Fit $\cos \theta$ distribution from $B^+ \to K^+\pi^-\pi^+\gamma$ in bins of $K^+\pi^-\pi^+$ mass.
Photon polarisation in $b \rightarrow s\gamma$ transitions

$b \rightarrow s\gamma$ results

Four independent measurements of $A_{ud}$:

Non-zero up-down asymmetry at $5.2\sigma$ based on $3 \text{ fb}^{-1}$ of LHCb data

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

LHCb-PAPER-2014-001

However, limited knowledge of $K^+\pi^-\pi^+$ mass spectrum prevents calculation of a value for the photon polarisation
Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$

- Forbidden LNV decay probes Majorana neutrino masses between 250 and 5000 MeV
- Search valid for neutrino lifetimes between 0 and 1000 ps

Normalise to $B^- \rightarrow J/\psi K^-$

Combinatorial background from sideband fit, peaking backgrounds from MC

Previous LHCb measurement (LHCb-PAPER-2011-038) updated with full 3 fb$^{-1}$

LHCb-PAPER-2013-064
Majorana neutrinos results

- No signal observed
- Limits as a function of $m_{\nu}$ and $\tau_{\nu}$ using CL$_S$ method
- Signal efficiency is highest for short lifetimes
- $\text{BF}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9}$ at 95% CL for 1 ps lifetime

- Limits on fourth generation couplings, $|V_{\mu 4}|^2$, as a function of neutrino mass
Search for the FCNC decay $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$

- GIM suppression is more effective in charm than in $b$-decays
- Expected BF for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ of $\sim 10^{-9}$ in the SM
- Could be enhanced by NP

- Analyse 1 fb$^{-1}$ of $D^0$ from $D^{*+} \rightarrow D^0\pi^+$
- Normalise to $D^0 \rightarrow \pi^+\pi^-\phi(\mu^+\mu^-)$
- Fit signal yield in four bins of $\mu\mu$ mass:
Search for the FCNC decay $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$

**Rare $D^0$ decay results**

![Graphs showing decay distributions](image)

- **Low $m_{\mu\mu}$**
- **$\rho/\omega$ region**
- **$\phi$ region**
- **High $m_{\mu\mu}$**

Combined limit of

$$BF(D^0 \to \pi^+ \pi^- \mu^+ \mu^-) < 5.5 \times 10^{-7}$$

at 90% CL from the signal yields in the low $m_{\mu\mu} +$ high $m_{\mu\mu}$ bins

$\to 50 \times$ improvement on previous limit

LHCb-PAPER-2013-050
Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Angular distribution of FCNC decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ described by angles $\theta_\ell$, $\theta_K$ and $\phi$
- Depends on Wilson coefficients (short distance) and form factors (long distance)
- Study variables $P'_4$, $P'_5$, $P'_6$ and $P'_8$\footnote{S. Descotes-Genon, T. Hurth, J. Matias and J. Virto, JHEP, 05, 2013, 137} free from form factor uncertainties, using 1 fb$^{-1}$ of LHCb data

\[ \phi \] is the angle between decay planes in the $B^0$ rest frame
Angular observables results

→ Measure each observable in six \( q^2(\mu\mu) \) bins

→ 3.7\( \sigma \) discrepancy in \( P'_5 \) in \( 4.3 < q^2 < 8.68 \) GeV\(^2 \) bin
→ 0.5% probability of such a discrepancy in 24 independent measurements

→ 2.5\( \sigma \) discrepancy in \( P'_5 \) in \( 1 < q^2 < 6 \) GeV\(^2 \) bin

→ Possible interpretation as a NP contribution to Wilson coefficient \( C_9 \)

LHCb-PAPER-2013-037

Angular observables results

- Some disagreement about the handling of uncertainties
- New SM predictions from S. Jäger and J. Camalich\(^3\)
  → show reduced tension with the data
- Update to 3 fb\(^{-1}\) in progress!

\(^3\)http://uk.arxiv.org/abs/1212.2263
Isospin asymmetry in $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ discrepancy motivates searches for other $B \rightarrow K \mu \mu$ decays using 3 fb$^{-1}$
- Update of previous result, which found a 4.4σ discrepancy in $A_I$ from SM in 1 fb$^{-1}$ data
- Latest results consistent with SM
- Shape of differential branching fractions consistent with SM, but systematically below lattice predictions
- To appear in LHCb-PAPER-2014-006
Angular analysis of $B \to K \mu^+ \mu^-$ decays

- Angular analysis to determine the forward-backward asymmetry, $A_{FB}$, and the flat parameter $F_H$, which together define the differential angular decay rate for $B^+ \to K^+ \mu^+ \mu^-$ and $B^0 \to K_s^0 \mu^+ \mu^-$ decays
- All results consistent with SM
- To appear in LHCb-PAPER-2014-007
Summary

A wealth of new results on rare decay searches from LHCb

- First observation of photon polarisation in $b \to s \gamma$ transitions
- World’s best limits on $B^- \to \pi^+ \mu^- \mu^-$ and $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$ decays
- Form-factor independent observables in $B^0 \to K^*0 \mu^+ \mu^-$ with a hint of a discrepancy from the SM
- Upcoming publications on additional $B \to K \mu \mu$ decays

Expect further results as the 3 fb$^{-1}$ dataset is fully exploited!
Backup
LHCb integrated luminosity

- **2012: 4 + 4 TeV**
  - Delivered Luminosity: 2.21 fb⁻¹
  - Recorded Luminosity: 2.08 fb⁻¹

- **2011: 3.5 + 3.5 TeV**
  - Delivered Luminosity: 1.21 fb⁻¹
  - Recorded Luminosity: 1.10 fb⁻¹

- **2010: 3.5 + 3.5 TeV**
  - Delivered Luminosity: 0.04 fb⁻¹
  - Recorded Luminosity: 0.04 fb⁻¹
The trigger reduces the event rate via:

1. L0: Hardware selection using calo clusters and muon system hits
2. HLT1: Loose software selection using VELO and tracking station tracks
3. HLT2: Full software reconstruction creates composite particles
The LHCb trigger: 2012

- Introduction of partial deferred triggering in 2012
- 20% of events passing L0 saved to disk and processed inter-fill
- Effective 20% increase in CPU power
- Used to reduce track $p_T$ thresholds from 500 to 300 MeV → significant trigger efficiency improvements for decays with low $p_T$ tracks
- Further improvements for Run II
$b \rightarrow s\gamma : \cos \theta$ fits

all Legendre components up to the fourth power
only even Legendre components up to the fourth power
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- : \text{new observables} \]

\[ \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos \theta_I d\cos \theta_K d\phi dq^2} = \]

\[ \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_I \right. \]

\[ - F_L \cos^2 \theta_K \cos 2\theta_I + S_3 \sin^2 \theta_K \sin^2 \theta_I \cos 2\phi \]

\[ + S_4 \sin 2\theta_K \sin 2\theta_I \cos \phi + S_5 \sin 2\theta_K \sin \theta_I \cos \phi \]

\[ + S_6 \sin^2 \theta_K \cos \theta_I + S_7 \sin 2\theta_K \sin \theta_I \sin \phi \]

\[ + S_8 \sin 2\theta_K \sin 2\theta_I \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_I \sin 2\phi ] \]
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- : \text{differential angular distribution} \]

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos \theta_I d\cos \theta_K d\phi dq^2} = \frac{9}{16\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_I 
- F_L \cos^2 \theta_K \cos 2\theta_I + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_I \cos 2\phi 
+ \frac{1}{2} (1 - F_L) A_T^{Re} \sin^2 \theta_K \cos \theta_I + (S/A)_9 \sin^2 \theta_K \sin^2 \theta_I \sin 2\phi \right] \]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: angular observables

![Graphs showing $F_L$, $A_T$, $A_T^{Re}$, and $A_6$ as functions of $q^2$ for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ with data from LHCb.]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: differential BF

Zero crossing point: $q_0^2 = 4.9 \pm 0.9 \text{ GeV}^2/c^4$

c.f. SM: $4.36^{+0.33}_{-0.31} \text{ GeV}^2/c^4$

LHCb-PAPER-2013-019