Electroweak penguin decays at LHCb

LHCP 2014, New York
2nd June 2014

Michel De Cian, University of Heidelberg
on behalf of the LHCb collaboration
Electroweak penguin decays at LHCb

- FCNCs only occur via penguin or box diagrams in the SM.
- New particles can enter in the loop, altering the branching fraction or the angular distribution.
- Will only talk about $b \rightarrow s \ell \ell$ transitions. See talk by Tom Blake on Thursday about other EW penguins.
- Allows constraints on Wilson coefficients $C_7^{(')}, C_9^{(')}, C_{10}^{(')}$.
- Quantities of interest depend on dimuon invariant mass (squared), $q^2$. 
Angular analysis of $B \to K \mu^+ \mu^-$ (I)

- Rare decay with $\mathcal{B} \approx 4.5 \cdot 10^{-7}$
- Sensitive to (pseudo)-scalar or tensor contributions.
- Angular distribution given by:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_\ell} = \frac{3}{4} (1 - F_H) \sin^2 \theta_\ell + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$$

- Two parameters, both zero or very small in SM.
  - $A_{FB}$: Forward-backward asymmetry
  - $F_H$: Fractional contribution to decay width from (pseudo)-scalar or tensor amplitudes (know as "flat term")
Angular analysis of $B \to K \mu^+ \mu^-$ (II)

- Use full 2011+2012 dataset ($3 \text{ fb}^{-1}$)
- $B^+ \to K^+ \mu^+ \mu^-$
  - Large sample, $4761 \pm 81$ candidates, can separate $B^+$ and $B^-$.  
- $B^0 \to K^0_S (\to \pi^- \pi^+) \mu^+ \mu^-$
  - Smaller sample, $176 \pm 17$ candidates: Only 50% decay to $K^0_S$, one additional particle to reconstruct, ...
  - Cannot distinguish $B^0$ and $\bar{B}^0$, measure $| \cos \theta_\ell |$, only access to $F_H$.  
- Correct for distortion of angular acceptance using simulation / exclude $B \to \psi(nS)K$ decays / veto MisID background
Angular analysis of $B \to K \mu^+ \mu^-$ (III)

- $B^+ \to K^+ \mu^+ \mu^-$

- $B^0 \to K_S^0 (\to \pi^- \pi^+) \mu^+ \mu^-$

Theoretical predictions from JHEP 01(2012) 107
Branching fractions of $B \to K^{(*)}\mu^+\mu^-$ decays (I)

- Measure branching fraction of $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ (all 3 fb$^{-1}$).
- Use the resonant channels $B \to J/\psi K^{(*)}$ as normalisation.

LCSR predictions from JHEP 01(2012) 107, JHEP 07(2011) 067
Lattice predictions from arXiv:1310.3207
Isospin asymmetry and $B \rightarrow K\mu^+\mu^-$ decays (I)

- Can also measure isospin asymmetry for $B \rightarrow K^*\mu^+\mu^-$ and $B \rightarrow K\mu^+\mu^-$ decays.

$$A_I = \frac{\mathcal{B}(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+} \mathcal{B}(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+} \mathcal{B}(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}$$

- Compatible with theoretical predictions (zero).
- With 1 fb$^{-1}$ a large discrepancy was observed...

Predictions from Phys. Rev. D 88 094004, JHEP 07(2011) 067
Isospin asymmetry of $B \rightarrow K\mu^+\mu^-$ decays (II)

What changed in the meantime?

- LHCb added another 2 fb$^{-1}$ of data.
- Previously assumption that equal amounts of $B^+$ and $B^0$ are produced at $\Upsilon(4S)$. Now assume isospin symmetry for $B \rightarrow J/\psi K^(*)$.
- All these effects reduce the discrepancy.
Lepton universality using \( B \to K\ell\ell \) decays (I)

• In the SM, coupling to all leptons is the same.

\[
R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}
\]

• Expect \( R_K^{SM} = 1 + O\left(\frac{m_\mu^2}{m_b^2}\right) \), small corrections due to phase space and Higgs penguin diagrams.

• New (pseudo)scalar operators might distinguish electrons and muons in models with an extended Higgs sector, deviation up to 10% wrt to SM.

• \( \frac{(R_K - 1)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} \sim 2 \cdot 10^{-5} \) for such models.

• \( R_K \) previously measured by BaBar and Belle with very limited statistics.

• First analysis by LHCb, uses 3 fb\(^{-1}\).
Lepton universality in $B \to K\ell\ell$ decays (II)

- Relative branching fraction measurement, using $B^+ \to J/\psi K^+$, with $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$ as normalisation channels.
- $B^+ \to K^+ e^+e^-$ challenging:
  - Recover loss by Bremsstrahlung by adding ECAL cluster energy (> 75 MeV).
  - Signal shape strongly depends on number of Bremsstrahlung photons, $p_T$ and occupancy of the event \(\to\) split analysis in 3 trigger categories.
  - $B^0 \to K^* e^+e^-$ largest contribution to part. background.
  - About 5\times less signal than in $B \to K\mu^+\mu^-$, mainly due to low trigger and reconstruction efficiency.
Lepton universality in $B \to K \ell \ell$ decays (III)

- Form double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- Largest remaining systematics are fit model and trigger efficiency.
- Only consider $1 \text{ GeV}^2/c^4 < q^2 < 6 \text{ GeV}^2/c^4$. Theoretically well predicted: No charm loop contributions, not charm resonances.
- Most precise measurement to date:

$$R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(sys)}$$

- Compatible with SM prediction within $2.5\sigma$. 
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

\[
\frac{d^4(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell \ d \cos \theta_K \ d\phi \ dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \right. \\
\left. \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell + \right. \\
S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \\
S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell + \\
S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + \\
S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- Neglect lepton masses, average $B^0$ and $\bar{B}^0$.
- Can measure all coefficients of the angular terms in bins of $q^2$.
- Use different foldings to reduce number of coefficients.
- Only analysed $1 \text{ fb}^{-1}$ so far.
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ (II)

- All results compatible with the SM predictions.

Predictions from JHEP 07(2011) 067 and references therein
Angular analysis of $B^0 \rightarrow K^{*-0} \mu^+\mu^-$ (III)

- Measure coefficients with reduced form-factor uncertainties:
  $$P_{4,5}' = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

- $P_5'$ deviates from SM prediction by $\approx 4\sigma$, probability is 0.5% to have one bin (out of 24) fluctuating by at least that much.

- Uncertainties on theoretical predictions are a much discussed topic.

- Analysis on 3 fb$^{-1}$ needed to confirm experimental result.

Predictions from JHEP 05 (2013) 137
Deviation in $C_9$?

- All branching fractions presented in this talk are below the theoretical predictions.
- The $P_5'$ discrepancy can be reduced when allowing for a lower value of $C_9$.
- As a consequence the diff. BRs for high $q^2$ are more compatible with the predictions.
- → See Tom Blake's talk for a more detailed discussion, different views and possible interpretations on Thursday.

$C_9^{NP} = -1.0, \ C_9' = 1.2$
Summary

- Electroweak penguin decays are an ideal laboratory to look for physics effects beyond the Standard Model.
- LHCb has analysed a great variety of $b \rightarrow s \ell \ell$ transitions.
  - Measured for the first time $R_K$, testing lepton universality.
- All measured differential branching fractions tend to have a lower value than theoretically predicted.
- $P_5'$ anomaly still waits an explanation - does the Wilson coefficient $C_9$ deviate from the SM prediction?
  - Will the future reveal the truth?
Backup
Angular fits for $B \to K \mu^+ \mu^-$

$B^0 \to J/\psi K^+$

(a) $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$  LHCb

$B^0 \to J/\psi K^+$

(b) $15.0 < q^2 < 22.0$ GeV$^2$/c$^4$  LHCb

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

(c) $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$  LHCb

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

(d) $15.0 < q^2 < 22.0$ GeV$^2$/c$^4$  LHCb
Acceptance correction for $B \rightarrow K \mu^+ \mu^-$

![Graphs showing acceptance correction for $B \rightarrow K \mu^+ \mu^-$ with various $q^2$ ranges.](image)

(a) LHCb simulation
$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

(b) LHCb simulation
$15.0 < q^2 < 22.0 \text{ GeV}^2/c^4$
Mass distribution for $B^0 \rightarrow K^+ e^+ e^-$ (I)

- Individual yields:
  - $e$ triggered: $172^{+20}_{-19}$
  - $K$ triggered: $20^{+16}_{-14}$
  - neither: $62 \pm 13$

triggered = triggered in the hardware trigger
Mass distribution for $B^0 \to K^+ e^+ e^-$ (II)

![Mass distribution for $B^0 \to K^+ e^+ e^-$ (II)](image-url)
Branching fraction of $B^0 \to K^{*0} \mu^+ \mu^-$

- Use $B^0 \to J/\psi K^*$ to normalise the branching fraction.

Predictions from JHEP 07(2011) 067 and references therein
Angular definitions in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay

(b) $\phi$ definition for the $B^0$ decay

(c) $\phi$ definition for the $\bar{B}^0$ decay
The LHCb detector

- LHCb covers a pseudorapidity $\eta = 2 - 5$.
- Excellent momentum resolution: $\Delta p/p = 0.4\% - 0.6\%$ in $5 - 140 \text{ GeV}/c$.
- $K - \pi$ separation up to 100 GeV/$c$. 