Physics with EW penguins at LHCb
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on behalf of the LHCb collaboration
- LHCb covers a pseudorapidity $\eta = 2 - 5$.
- Excellent momentum resolution: $\Delta p/p = 0.4\% - 0.6\%$ in $5 - 140$ GeV/$c$.
- $K - \pi$ separation up to 100 GeV/$c$.
- All presented analyses with $\approx 1$ fb$^{-1}$ collected in 2011.
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Rare decay with $\mathcal{B} = (1.05^{+0.16}_{-0.13}) \times 10^{-6}$ [PDG]
- Decay only possible via penguin- or box diagrams, "new physics" can enter at the same level as SM physics.
- Four-particle final state: Plenty of observables in angular distributions.
$B^0 \to K^{*0} \mu^+ \mu^-$: Angular distribution (I)

- Decay can be fully described by three angles ($\cos \theta_\ell$, $\cos \theta_K$, $\phi$) and the dimuon invariant mass (square) $q^2$. 
**B^0 \rightarrow K^{*0} \mu^+ \mu^-**: Angular distribution (II)

- Apply "folding": $\phi \rightarrow \phi + \pi$ for $\phi < 0$: Cancels four terms.
- And leaves...

$$\frac{d^4(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell \, d \cos \theta_K \, d\phi \, dq^2} \propto \begin{aligned}
F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) + \\
F_L \cos^2 \theta_K(2 \cos^2 \theta_\ell) + \\
\frac{1}{4} (1 - F_L)(1 - \cos^2 \theta_K)(2 \cos^2 \theta_\ell - 1) + \\
S_3 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \cos 2\phi + \\
\frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_\ell + \\
S_9 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \sin 2\phi
\end{aligned}$$

- This expression was simultaneously fitted to the angles and the invariant mass in 2011 dataset.
- The $S_i$ expressions are the $CP$ averaged $I_i$ expressions.
- Neglect lepton masses and S-wave contribution ($\rightarrow$ systematics).
$B^0 \to K^{*0} \mu^+\mu^-$: EXPERIMENTAL ASPECTS

- Some experimental details:
  - Cut out $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S) K^{*0}$, veto peaking background, e.g. $B_s^0 \to \phi \mu^+\mu^-$.  
  - Select signal events with a BDT.
  - Correct for acceptance effects with event-by-event correction using simulation.
  - Correct for simulation ↔ data differences with control channels (e.g. $J/\psi \to \mu^+\mu^-$ for particle identification)
$B^0 \to K^{*0} \mu^+ \mu^-$: Angular observables

Theory predictions from [C. Bobeth et al., JHEP 07 (2011) 067] and references therein
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: Differential branching fraction

- Differential branching fraction determined with normalisation to $B^0 \rightarrow J/\psi K^{*0}$.

Theory prediction from [C. Bobeth et al., JHEP 07 (2011) 067] and references therein
Measuring the zero-crossing point in $A_{FB}$ of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (I)

- Zero-crossing point of $A_{FB}$ has a very clean prediction, as the form factors cancel (to first order).
- Zero-crossing point was extracted using "unbinned counting" technique:
  - Split dataset in "forward" and "backward" events (with respect to $\cos \theta_\ell$).
  - Perform a 2D unbinned extended maximum likelihood fit to ($q^2$, mass) for forward and backward.
- Extract $A_{FB} = \frac{N_F \cdot PDF_F (q^2) - N_B \cdot PDF_B (q^2)}{N_F \cdot PDF_F (q^2) + N_B \cdot PDF_B (q^2)}$
Measuring the zero-crossing point in $A_{FB}$ of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (II)

- Standard Model theory predicts zero-crossing in $4.0 - 4.3 \text{ GeV}^2/c^4$ (central values)
  
- LHCb preliminary result: $4.9^{+1.1}_{-1.3} \text{ GeV}^2/c^4$
**C.P.-ASYMMETRY IN $B^0 \to K^{*0} \mu^+ \mu^-$ (I)**

- Form $A_{C.P.} = \frac{\Gamma(B^0 \to \bar{K}^{*0} \mu^+ \mu^-) - \Gamma(B^0 \to K^{*0} \mu^+ \mu^-)}{\Gamma(B^0 \to \bar{K}^{*0} \mu^+ \mu^-) + \Gamma(B^0 \to K^{*0} \mu^+ \mu^-)}$

- Predicted to be $\mathcal{O}(10^{-3})$ in SM, very clean prediction due to form factor suppression.

- Asymmetry up to 15% in certain models.

- Use the same corrections / selection / binning-scheme as for the $B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis.

- Additional difficulty: Measured is

  $A_{raw} = A_{C.P.} + A_{Detector} + \kappa A_{Production}$

  $\kappa = \frac{\int_0^\infty \epsilon(t)e^{-\Gamma t} \cos \Delta mt \, dt}{\int_0^\infty \epsilon(t)e^{-\Gamma t} \cosh \frac{\Delta mt}{2} \, dt}$

[Graph showing asymmetry $A_{C.P.}$ vs. $q^2$ (GeV$^2$) with $R_{V,A}$ and $R_{V,A}'$ present]
**CP-ASYMMETRY IN $B^0 \to K^{*0} \mu^+ \mu^-$ (II)**

- $A_{\text{Detector}}$: Detector asymmetries cancel when taking the average between the two magnet polarities.
- $A_{\text{Detector}}/A_{\text{Production}}$: Use $B^0 \to J/\psi K^{*0}$ as a control channel.
- $A_{CP} \approx A_{\text{raw}}(B^0 \to K^{*0} \mu^+ \mu^-) - A_{\text{raw}}(B^0 \to J/\psi K^{*0})$
- Residual differences due to kinematical differences are accounted for in the systematic uncertainty.
- $A_{CP} = -0.072 \pm 0.040 \text{ (stat)} \pm 0.005 \text{ (sys)}$
**Measurement of** $B^+ \rightarrow K^+ \mu^+ \mu^-$

- Rare decay, $\mathcal{B} = (4.36 \pm 0.15 \pm 0.18) \times 10^{-7}$ [arXiv:1209.4284]
- Use a loose preselection and a BDT for the final selection. Training on $B^+ \rightarrow J/\psi K^+$ (signal) and $B^+ \rightarrow K^+ \mu^+ \mu^-$ sidebands (background).
- Cut out resonant regions of $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \psi(2S) K^+$.
- Remaining peaking background accounted for in the fit.
Measurement of $B^+ \rightarrow K^+ \mu^+ \mu^-$:
Branching fraction

- Determine branching fraction in 7 bins of $q^2$, using $B^+ \rightarrow J/\psi K^+$ as a normalisation channel and accounting for differences in the efficiencies.
- $\mathcal{B} = (4.36 \pm 0.15 \pm 0.18) \times 10^{-7}$, taking excluded charmonium resonance regions into account.
- World's best measurement of $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$.
**Measurement of** $B^+ \rightarrow K^+ \mu^+ \mu^-$: **Angular Analysis**

- Theory predictions from [C. Bobeth et al., JHEP 07 (2011) 067] and [C. Bobeth et al., JHEP 01 (2012) 107]

- \[
\frac{1}{\Gamma} \frac{d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{d \cos \theta_{\ell}} = \frac{3}{4} (1 - F_H) (1 - \cos^2 \theta_{\ell}) + \frac{1}{2} F_H + A_{FB} \cos \theta_{\ell}
\]
- Acceptance correction using simulation in $q^2$ and $\cos \theta_{\ell}$.
- Simultaneous fit to mass and $\cos \theta_{\ell}$. Background modeled with second-order polynomial in angles.
Isospin asymmetry (I)

- Measure "Isospin asymmetry": \[ \frac{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^{*+} \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^{*+} \mu^+ \mu^-)} \]
- Predicted to be very small.
- Use \( B \rightarrow J/\psi K^* \) as a normalisation channel.
- \( B^+ \rightarrow K^{*+} \mu^+ \mu^- \) is challenging due to \( K_s^0 \) reconstruction from \( K^{*+} \rightarrow K_s^0 \pi^+ \).
- Results for \( B \rightarrow K^* \mu^+ \mu^- \) agree well with prediction.

**Isospin asymmetry (II)**

- Measure "Isospin asymmetry": \[
  \frac{\Gamma(B^0 \to K^0 \mu^+ \mu^-) - \Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^0 \to K^0 \mu^+ \mu^-) + \Gamma(B^+ \to K^+ \mu^+ \mu^-)}
\]
- Predicted to be very small.
- Use \( B \to J/\psi K \) as a normalisation channel.
- \( B^0 \to K^0 \mu^+ \mu^- \) is challenging due to \( K_s^0 \) reconstruction.
- \( A_I \) shows a 4.4\( \sigma \) deviation from 0, driven by low \( B(B^0 \to K^0 \mu^+ \mu^-) \).

Branching Fraction Measurement of $B^+ \to \pi^+ \mu^+ \mu^-$

- Fit four distributions simultaneously: $B^+ \to J/\psi K^+$, misidentified $B^+ \to J/\psi K^+$, $B^+ \to K^+ \mu^+ \mu^-$, $B^+ \to \pi^+ \mu^+ \mu^-$
- Measured branching fraction: $\mathcal{B} = (2.3 \pm 0.6\text{ (stat)} \pm 0.1\text{ (sys)}) \times 10^{-8}$
- In good agreement with SM expectation: $(1.96 \pm 0.21) \times 10^{-8}$.


- Also determine: $R = \frac{\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)} = f^2 \frac{|V_{td}|^2}{|V_{ts}|^2}$
- Which leads to: $\left| \frac{V_{td}}{V_{ts}} \right| = 0.266 \pm 0.035\text{ (stat)} \pm 0.007\text{ (sys)}$
Summary

- EW penguins are a very active area in LHCb.
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ is a “golden-channel” and allows measurement of many observables: angular analysis, zero-crossing point of $A_{FB}$, differential branching fraction, Isospin asymmetry, $CP$ asymmetry.
- $B^+ \rightarrow K^+ \mu^+ \mu^-$: Angular analysis, differential branching fraction and Isospin asymmetry.
- Discovery of $B^+ \rightarrow \pi^+ \mu^+ \mu^-$, rarest B decay ever observed.
- 2011+2012 ($\approx 3.2 \; fb^{-1}$) data will allow more precision, more observables and (hopefully) conclusions on discrepancies.
Backup
$B^0 \to K^{*0} \mu^+ \mu^-$: Full Angular Distribution

- If we neglect lepton masses and S-wave component, the angular distribution of $B^0 \to K^{*0} \mu^+ \mu^-$ is:

$$
\frac{d^4 \Gamma}{d \cos \theta_\ell \ d \cos \Theta_K \ d \phi \ dq^2} \propto I_1^s \sin^2 \Theta_K + I_1^c \cos^2 \Theta_K \\
+ (I_2^s \sin^2 \Theta_K + I_2^c \cos^2 \Theta_K) \cos 2\Theta_\ell \\
+ I_3 \sin^2 \Theta_K \sin^2 \theta_\ell \cos 2\phi \\
+ I_4 \sin 2\Theta_K \sin 2\theta_\ell \cos \phi \\
+ I_5 \sin 2\Theta_K \sin \theta_\ell \cos \phi \\
+ (I_6^s \sin^2 \Theta_K + I_6^c \cos^2 \Theta_K) \cos \theta_\ell \\
+ I_7 \sin 2\Theta_K \sin \theta_\ell \sin \phi \\
+ I_8 \sin 2\Theta_K \sin 2\theta_\ell \sin \phi + \\
+ I_9 \sin^2 \Theta_K \sin^2 \theta_\ell \sin 2\phi
$$

- The $I_i$ depend on $q^2$ and contain the (transversity) amplitudes of the $K^{*0}$.
- All $I_i$ are observables, 8 of them are independent.