Beyond Standard Model searches in B decays with ATLAS

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The 17th International Conference on B-Physics at Frontier Machines
La Biodala – Isola d’Elba, Italy
6–11 May 2018
Introduction

- Studying heavy flavour decays provides an opportunity for indirect search for BSM physics
  - $b \to s(d)ll$ transitions occur via FCNC processes
  - Forbidden in SM at tree level and thus sensitive to New Physics contributions in the loop diagrams
- In this talk
  - Angular analysis of $B^0 \to \mu^+\mu^-K^*$ decay CERN-EP-2017-161, submitting to JHEP
    - Paper just released!
  - Measurement of the width difference in $B^0$-$\bar{B}^0$ system JHEP 06 (2016) 081, arXiv:1605.07485
  - (briefly) Studying rare decays $B^0(s) \to \mu^+\mu^-$ EPJC 76 (2016) 513, arXiv:1604.04263
$B^0 \rightarrow \mu^+ \mu^- K^{*0}$ angular analysis
Introduction

- The decay is forbidden in SM at tree level, occurs via suppressed loop diagrams
- BR(B^0 → μ^+μ^-K^0) = (1.03±0.06)×10^{-6} → allows differential decay rates measurement
  - **Measured parameters:** K^0 longitudinal polarization fraction F_L and angular parameters S_i, in bins of q^2 – dimuon mass squared
    - up to 3.4σ deviation in P_5′ was reported earlier by LHCb
    - Extracted from the fit to distributions of m_{Kπμμ}, cosθ_K, cosθ_L, φ
- **Data:** 20.3 fb^{-1} collected by ATLAS at √s=8 TeV in 2012
**Event selection**

- **Trigger:** inclusive set of selections
  - single, di-, and tri-muon requirements
- **Acceptance and mass cuts**
  - $|\eta(\pi, K, \mu)| < 2.5$
  - $p_T(\pi, K) > 0.5$ GeV, $p_T(\mu) > 3.5$ GeV
  - $m(K\pi) \in [846, 946]$ MeV
  - $m(K\pi\mu) \in [5150, 5700]$ MeV
- **$q^2$ ranges studied**
  - $q^2 \in [0.04, 6]\,[0.98, 1.1]$ GeV$^2$ – signal
  - $q^2 \in [8, 11]$ GeV$^2$ – control $J/\psi$
  - $q^2 \in [12, 15]$ GeV$^2$ – control $\psi(2S)$
- **Background suppression cuts**
  - $p_T(K^*) > 3$ GeV
  - $\tau/\sigma > 12.75$
  - $\cos\theta > 0.999$
  - $\chi^2/n.d.f(B^0) < 2$
- **Multiple candidate treatment**
  - choose best $\chi^2$ candidate
  - smallest $|m(K\pi)-m_{PDG}(K^0)|/\sigma(m(K\pi)) \rightarrow$ residual mis-tag rate ~11%

787 signal events passed
Angular fit model

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

- Use optimized $P_i^{(t)}$ instead of $S_i$ to reduce dependence on hadronic form factors

\[
P_1 = \frac{2S_3}{1 - F_L} \\
P_2 = \frac{2A_{FB}}{3(1 - F_L)} \\
P_3 = \frac{-S_9}{1 - F_L} \\
P_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}.
\]

- Statistics is not sufficient for fitting the full distribution (1)

- Use trigonometric "folding" to reduce the problem to 4 sets of fits for 3 parameters each: $F_L, S_3$ ($P_1$) and one of $S_{j=4,5,7,8} (P_{j=4,5,6,8}^{t})$

- E.g. for $F_L, S_3, S_4$:

\[
\begin{align*}
\phi & \rightarrow -\phi & \text{for } \phi < 0 \\
\phi & \rightarrow \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\
\theta_L & \rightarrow \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2},
\end{align*}
\]

- $F_L, S_3$ can be extracted from any of the fits \( \rightarrow \) use the one with the lowest systematics

- $S_6 (A_{FB})$ and $S_9$ cannot be extracted in this approach
Fitting procedure

- Extended ML fit with each of the fit variants in bins of $q^2$
  \[
  \mathcal{L} = \frac{e^{-N}}{n!} \prod_{i=1}^{n} \sum_{j} n_j \mathcal{P}_{ij}(m_{K\pi\mu\mu}, \cos \theta_K, \cos \theta_L, \phi; \hat{\rho}, \hat{\theta}),
  \]

- $j = 1, 2$ for signal and combinatorial background PDFs
  - other exclusive sources of background are accounted for only for systematics

- Sequential fitting procedure
  0) Extract the mass and width parameters of $B^0$ from $J/\psi$ control region $\rightarrow$ fix them
  1) Fit only the $m_{K\pi\mu\mu}$ to extract the nuisance parameters: signal and background yields, background mass shape $\rightarrow$ fix them
    2) Add the angular distributions and extract the parameters of interest $F_L$ and $S (P^{(*)})$

- The procedure extensively validated using toy MC

- Bins of $q^2$: [0.04, 2.0], [2.0, 4.0], [4.0, 6.0] GeV$^2$
  - Also fit in [0.04, 4.0], [1.1, 6.0], [0.04, 6.0] GeV$^2$ to facilitate comparisons to various predictions and experiments
Fit projection

- **Signal model:**
  \[ P = \varepsilon(\cos \theta_K)\varepsilon(\cos \theta_L)\varepsilon(\varphi) \times g(\cos \theta_K, \cos \theta_L, \varphi) \times G(m_{\text{pp}}) \]
  
  - **Angular acceptance:** polynomials extracted from MC
  
  - **Differential decay rate**
  
  - **Mass shape:** Gaussian with per-candidate errors, fixed from $c\bar{c}$ control region

- **Background model**
  
  - **Mass shape:** exponential
  
  - **Angular shapes:** factorized into 1D terms – 2nd order Chebyshev polynomials

Fit in $q^2 \in [0.04, 2.0]$ GeV$^2$ for $S_5$ folding scheme is shown
Results

- Deviations for $P_4'$ and $P_5'$ in $q^2 \in [4, 6] \text{ GeV}^2$ bin from DHMV calculation are $2.7\sigma$
- Consistent with those reported by LHCb (comparison with experiments on backup)
- All measurements are within 3σ range covered by the predictions

Statistical uncertainty dominates
$B^0 - \bar{B}^0$ system width difference
Introduction

- Standard model prediction for the width difference $\Delta \Gamma_d = \Gamma^L_d - \Gamma^H_d$:
  - $\Delta \Gamma_d = (0.45 \pm 0.08) \times 10^{-2}$
- World average before (BaBar, Belle, LHCb):
  - $\Delta \Gamma_d = (0.1 \pm 1.0) \times 10^{-2}$
- Other independent measurements do not constrain $\Delta \Gamma_d$
  - It was shown that relatively large variations due to NP contributions would not break other SM tests
- Good independent test complementary to other measurements

- **Data:** 25.2 fb$^{-1}$ of $\sqrt{s} = 7$ and 8 TeV collected by ATLAS in 2011-2012
- **Method:** measuring the lifetime-dependent ratio of $B^0_d$ decays rates to $J/\psi K^*$ and $J/\psi K^0_S$
Analysis strategy

- Time-dependent $B\rightarrow f$ decay rate
  \[
  \Gamma(t, f) \equiv \sigma(B^0_q)\Gamma(B^0_q(t) \rightarrow f) + \sigma(\bar{B}^0_q)\Gamma(\bar{B}^0_q(t) \rightarrow f)
  \]
  \[
  \propto e^{-\Gamma_q t} \left[ \cosh \frac{\Delta\Gamma_q t}{2} + A_P A^\text{dir}_{CP} \cos(\Delta m_q t) + A_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_q t}{2} + A_P A^\text{mix}_{CP} \sin(\Delta m_q t) \right]
  \]

- $A_p$ is $B/\bar{B}$ production asymmetry (due to presence of valence light quark)

- $A^\text{dir}_{CP}$, $A_{\Delta\Gamma}$, and $A^\text{mix}_{CP}$ are well defined for either CP- or flavour-specific states:
  - $J/\psi K^0_S$ – CP state: $A^\text{dir}_{CP} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A^\text{mix}_{CP} = -\sin 2\beta$
  - $J/\psi K^{*0}$ – flavour state: $A^\text{dir}_{CP} = 1$, $A_{\Delta\Gamma} = 0$, $A^\text{mix}_{CP} = 0$

For $J/\psi K^0_S$:

- used to extract the $\Delta\Gamma_d$

- $A_p$ can be also extracted from data

For $J/\psi K^{*0} + J/\psi \bar{K}^{*0}$:

- provides normalization of the above to reduce the systematics uncertainties

- terms corresponding to production asymmetry and CPV in mixing are $\sim 10^{-3}$–$10^{-4}$ and neglected
Extraction of signal yields

- Both decay channel signal yields are extracted in bins of proper decay length (in transverse plane)

<table>
<thead>
<tr>
<th>Bin number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower edge [mm]</td>
<td>−0.3</td>
<td>0.0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
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<td>6.0</td>
</tr>
</tbody>
</table>

- Using fits to mass of reconstructed \( J/\psi K^{*0} \) and \( J/\psi K^0_s \) candidates
- Per-bin detector acceptances are further accounted for in the measurement
Production asymmetry determination

- Production asymmetry is derived from time-dependent asymmetry between $J/\psi K^0 + J/\psi \bar{K}^0$:
  
  $$
  \Gamma[t, B^0(\bar{B}^0) \rightarrow J/\psi K^0/\bar{K}^0] = e^{-\Gamma dt} \left[ \cosh \frac{\Delta \Gamma dt}{2} + (-)A_p \cos \Delta m dt \right]
  $$

- Neglect CPV in mixing term
- Observed charge asymmetry $A_{i,obs}$ is fitted with $A_{i,exp} = (A_{det} + A_{i,osc})(1-2W)$
- $W = 0.12 \pm 0.02$ – $K/\pi$ mis-tag fraction  
  - from simulation
- $A_{det}$ - detector asymmetry for $K^*/K^-$ reconstruction
- Fit results
  - $A_{det} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$  
    - agrees with simulation
  - $A_p = (0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$
  - $\chi^2/\text{n.d.f.} = 6.50/7$
  - Systematics dominated by the $W$ uncertainty and deviation of $|q/p|$ from unity
- The $A_p$ value consistent with LHCb  
  - the first measurement at LHC in central region
Extraction of $\Delta \Gamma_d$

- Extract yields of $J/\psi K^0$ and $J/\psi K^0_S$ in bins of proper decay length
- Fit the efficiency-corrected ratio $R_{i,\text{cor}} = \frac{N_i(J/\psi K^0_S) \epsilon_i(B^0 \rightarrow J/\psi K^0)}{N_i(J/\psi K^0) \epsilon_i(B^0 \rightarrow J/\psi K^0_S)}$ leaving $\Delta \Gamma_d/\Gamma_d$ the only free parameter

- Consistent between 7 and 8 TeV datasets; combined result: $\Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.0 \text{(stat.)} \pm 0.9 \text{(syst.)}) \times 10^{-2}$
  - Statistically dominated measurement; largest systematics comes from the signal yield fits and MC statistics
- Most precise single measurement to date
  - PDG 2016 including this result: $\Delta \Gamma_d/\Gamma_d = (-0.2 \pm 1.0) \times 10^{-2}$
$B^0_{(s)} \rightarrow \mu^+ \mu^- \text{ rare decays}$
**B^0_{(s)} \to \mu^+\mu^-** results

- No significant signals observed:
  - Observed: \( N_s = 11, N_d = 0 \)
    \((N_s = 16 \pm 12, N_d = -11 \pm 9\) if not positively constrained\)
  - Expected: \( N_s = 41, N_d = 5 \)

- Measured BR:
  - \( \text{BR}(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} \)

- 95\% C.L. limits are set:
  - \( \text{BR}(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9} \)
  - \( \text{BR}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \)

- Compatibility of the simultaneous fit with the SM:
  - \( p = 4.8\% \ (2.0\sigma) \)

- ATLAS result is compatible with CMS and LHCb Run-1 measurements and the Run-2 LHCb measurement (PRL 118 (2017) 191801, arXiv:1703.05747)

- ATLAS analysis on Run-2 data is on-going
Summary

- Three NP-sensitive B-physics analyses were presented:
- Angular analysis of $B^0 \rightarrow \mu^+ \mu^- K^0$ decay
  - Uses Run-1 $\sqrt{s} = 8$ TeV data, 20.3 fb$^{-1}$
  - Results are compatible with theoretical predictions and other experiments
- Measurement the $B^0 - \bar{B}^0$ width difference
  - Full Run-1 data statistics, 25.2 fb$^{-1}$
  - First measurement of the central production asymmetry, consistent with LHCb (and with 0)
  - Most precise single measurement of $\Delta \Gamma_d / \Gamma_d$
  - Still far from the SM precision
- Both measurements statistically limited $\rightarrow$ repeating them on Run-2 data
- $B^0_{(s)} \rightarrow \mu^+ \mu^-$ rare decays study was done only on full Run-1 so far
  - Expected precision comparable to that of CMS or LHCb, but suffer from “under-fluctuation” of signal yield
  - Run-2 (2015+2016) analysis results to come soon
- Keep in touch for new results!
Backup slides
Results – comparison to other experiments

- Deviations for $P'_4$ and $P'_5$ in $q^2 \in [4, 6] \text{ GeV}^2$ bin from DHMV calculation are $2.7\sigma$
- Consistent with those reported by LHCb
- All measurements are within $3\sigma$ range covered by the predictions
$B^0_{(s)} \rightarrow \mu^+ \mu^-$ rare decays
Analysis strategy

- FCNC process, CKM and helicity suppressed
- SM predictions:
  - $\text{Br}(B_0^s \to \mu^+\mu^-) = (3.65\pm0.23)\times10^{-9}$
  - $\text{Br}(B^0 \to \mu^+\mu^-) = (1.06\pm0.09)\times10^{-10}$
- Experimentally very clear signature sensitive to NP
- ATLAS analysis uses full Run-1 data of 25 fb$^{-1}$ at $\sqrt{s} = 7$ and 8 TeV
- Signal decay Br measured w.r.t. reference mode $B^+ \to J/\psi(\mu^+\mu^-)K^*$
  \[
  \mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-) = \frac{N_{d(s)}}{\epsilon_{\mu^+\mu^-}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \frac{\epsilon_{J/\psi K^+} \times f_{d(s)}}{N_{J/\psi K^+}}
  \]
- Many uncertainties reduced
- Complicated multi-variate event selection
  - "Continuum-BDT" to suppress combinatorial muon pairs
  - "Fake-BDT" for mis-identified muons suppression (e.g. from $B^0 \to \pi K$ decays)
Signal fits

- ML fit in 3 bins of \textit{continuum-BDT} with equal 18% signal efficiency
- If yields positively constrained
  - $N_s = 11, N_d = 0$
- No constraints:
  - $N_s = 16 \pm 12, N_d = -11 \pm 9$
- SM expectation:
  - $N_s = 41, N_d = 5$
Results

- Measured BR:
  - $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) = (0.9_{-0.8}^{+1.1}) \times 10^{-9}$
- 95% C.L. limits are set:
  - $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 3.0 \times 10^{-9}$
  - $\text{BR}(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10}$
- Compatibility of the simultaneous fit with the SM:
  - $p = 4.8\% (2.0\sigma)$

- ATLAS result is compatible with CMS and LHCb Run-1 measurements
- Tension in $B^0$ is reduced with the Run-2 LHCb measurement (PRL 118 (2017) 191801, arXiv:1703.05747)
  - LHCb Run-2: $\text{BR}(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95% C.L.
  - ATLAS analysis on Run-2 data is on-going