CPV, oscillations and rare B-decays in RUN 1

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Precise tracking is essential for B-physics.

With increasing pileup, the quality of tracking, vertexing was improved to achieve stability:
- $d_0$ resolution (the width of main peak) remained unchanged
- tails are potentially sensitive to fakes: no increase in the fake rate observed
Physics Motivation

- $B_s^0 \rightarrow J/\psi \phi$ expected to be sensitive to BSM physics
- CP-violation phase: $\phi_s$
  - CPV due to interference between:
    - Direct decay
    - Flavour oscillation
- SM Predictions:
  - $\phi_s = -0.0364 \pm 0.0016$ [rads]
  - Indirect determination via global fits
  - SM precision much smaller than experimental
  - Experimental measurement a viable BSM search
Methodology - fit

Time-Dependent Angular Analysis

- **Observables:**
  - Mass, lifetime, $p_T$, transversity angles, initial flavour
  - Per-candidate errors

- **UMLF $\rightarrow$ Physics parameters:**
  - $\phi_s$, $\Delta \Gamma_s$, $\Gamma_s$
  - Transversity amplitudes: $|A_0(0)|^2$, $|A_{\parallel}(0)|^2$, $|A_S(0)|^2$, $\delta_{\perp}$, $\delta_{\parallel}$, $\delta_{\perp} - \delta_S$
Methodology - tagging

OST Tagging

- Detect decay of pair-produced $b$
  - $p_T$ weighted sum of charges from decay
- Per-event tagger/probability:
  - Muon, electron (2012), jet-charge
- Calibrated with $B^{\pm} \rightarrow J/\psi K^{\pm}$
- Tagging applied probabilistically in fit

<table>
<thead>
<tr>
<th>Tagger</th>
<th>Efficiency [%]</th>
<th>Dilution [%]</th>
<th>Tagging Power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined muon</td>
<td>4.12 ± 0.02</td>
<td>47.4 ± 0.2</td>
<td>0.92 ± 0.02</td>
</tr>
<tr>
<td>Electrons</td>
<td>1.19 ± 0.01</td>
<td>49.2 ± 0.3</td>
<td>0.29 ± 0.01</td>
</tr>
<tr>
<td>Segment Tagged muon</td>
<td>1.20 ± 0.01</td>
<td>28.6 ± 0.2</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>Jet charge</td>
<td>13.15 ± 0.03</td>
<td>11.85 ± 0.03</td>
<td>0.19 ± 0.01</td>
</tr>
<tr>
<td>Total</td>
<td>19.7 ± 0.04</td>
<td>27.6 ± 0.06</td>
<td>1.49 ± 0.02</td>
</tr>
</tbody>
</table>
Mass/Lifetime Fits

![Graph showing mass distribution of $B_s^0$](image1)

**Figure:** $B_s^0$ mass distribution (2012)

![Graph showing lifetime distribution of $B_s^0$](image2)

**Figure:** $B_s^0$ lifetime distribution (2012)
Angular Projection Fits

Figure: $B_s^0$ angular fit projections
2D Scans - $\phi_s$ v's $\Delta \Gamma_s$

Figure: 2D scan (2011/2012)

Figure: 2D scan (Run 1)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Stat</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s \text{ rad}$</td>
<td>-0.098</td>
<td>0.084</td>
<td>0.040</td>
</tr>
<tr>
<td>$\Delta \Gamma_s \text{ [ps}^{-1}]$</td>
<td>0.083</td>
<td>0.011</td>
<td>0.007</td>
</tr>
<tr>
<td>$\Gamma_s \text{ [ps}^{-1}]$</td>
<td>0.677</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>0.514</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel(0)</td>
<td>^2$</td>
<td>0.227</td>
</tr>
<tr>
<td>$</td>
<td>A_S(0)</td>
<td>^2$</td>
<td>0.071</td>
</tr>
<tr>
<td>$\delta_{\perp} \text{ [rad]}$</td>
<td>4.13</td>
<td>0.33</td>
<td>0.16</td>
</tr>
<tr>
<td>$\delta_{\parallel} \text{ [rad]}$</td>
<td>3.15</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>$\delta_{\perp} - \delta_S \text{ [rad]}$</td>
<td>-0.08</td>
<td>0.04</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Table:** Run 1 result
All existing data consistent between each other and with the SM

- HFAG used Preliminary ATLAS version, May 2015, ATLAS ArXive numbers - presented here - slightly differ
- Room for NP in CPV $\phi_s$, need Run2 and LHC upgrade
Physics motivation

- $\Delta \Gamma_d$ is one of the parameters describing the time evolution of the $B^0_d$ system
- It is reliably predicted in the Standard Model
  \[
  \Delta \Gamma_d = (0.42 \pm 0.08) \cdot 10^{-2} (SM)
  \]
- Current experimental uncertainty still large to allow a comparison with the SM prediction
  \[
  \Delta \Gamma_d = (0.1 \pm 1.0) \cdot 10^{-2} (Experiment \ World \ Average)
  \]
- Additional measurements are required to constrain this quantity and verify the SM prediction
\[ \Delta\Gamma_d \text{ determined from ratio of proper decay time distributions of } B_d^0 \rightarrow J/\psi K_S^0 \text{ and } B_d^0 \rightarrow J/\psi K^* \]

- \( B_d^0 \rightarrow J/\psi K_S^0 \)

\[ \Gamma_d(t) \sim e^{-\Gamma t} \left( \cosh\frac{\Delta\Gamma_d}{2} t + \cos(2\beta) \sinh\frac{\Delta\Gamma_d}{2} t - A_p \sin(2\beta) \sin(\delta mt) \right) \]

- \( \beta \) CKM angle, \( A_p \) production asymmetry of \( B_d^0 \)

- \( B_d^0 \rightarrow J/\psi K^* \) almost insensitive to \( \Delta\Gamma_d \)

\[ \Gamma_d(t) \sim e^{-\Gamma t} \cosh\frac{\Delta\Gamma_d}{2} t \]
$B_d^0$ production asymmetry

- $B_d^0$ production asymmetry $A_p$ measured from a charge asymmetry $A_{obs}$, from a difference between $B_d^0 \rightarrow J/\psi K^*$ and $\overline{B}_d^0 \rightarrow J/\psi \overline{K}^*$ decays as a function proper decay lengths $L_{prop}$.
- $A_{obs}$ should oscillate if $A_p$ different from 0. Detector induced asymmetry included.

- ATLAS result $A_p = (0.25 \pm 0.48(stat) \pm 0.05(syst)) \cdot 10^{-2}$
Measurement of Width difference of $B_d^0$

$\Delta \Gamma_d$ result

\[ \Delta \Gamma_d \text{ result} \]

\[ \int L \, dt = 20.3 \text{ fb}^{-1} \]

**Figure:** Ratio of $L_{\text{prop}}^B$ distributions of $B_d^0 \to J/\psi K_S^0$ and $B_d^0 \to J/\psi K^*$, fitted to extract $\Delta \Gamma_d$

\[ \frac{\Delta \Gamma_d}{\Gamma_d} \quad \text{ATLAS Results} \]

\[ (-2.8 \pm 2.2(\text{stat}) \pm 1.7(\text{syst})) \cdot 10^{-2} \quad \text{(7 TeV data)} \]

\[ (0.8 \pm 1.3(\text{stat}) \pm 0.8(\text{syst})) \cdot 10^{-2} \quad \text{(8 TeV data)} \]

\[ (-0.1 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})) \cdot 10^{-2} \quad \text{(Combined)} \]
**Comparison**

\[ \frac{\Delta \Gamma_d}{\Gamma_d} \text{ Comparison} \]

\[ (-0.1 \pm 1.1(stat) \pm 0.9(syst)) \cdot 10^{-2} \text{ (ATLAS Run1)} \]
\[ (-4.4 \pm 2.5(stat) \pm 1.1(syst)) \cdot 10^{-2} \text{ (LHCb)} \]
\[ (1.7 \pm 1.8(stat) \pm 1.1(syst)) \cdot 10^{-2} \text{ (Belle)} \]
\[ (0.8 \pm 3.7(stat) \pm 1.8(syst)) \cdot 10^{-2} \text{ (Belle)} \]

- ATLAS result is consistent with other measurements
- It is consistent with the SM prediction

\[ (0.42 \pm 0.08) \cdot 10^{-2} \text{ (SM)} \]
$B_s^0/B_d^0 \rightarrow \mu^+\mu^-$ Physics motivation

**Theory**
- Flavour-changing neutral-current processes highly suppressed in SM
- $B_s^0/B_d^0 \rightarrow \mu^+\mu^-$ additional helicity suppression.
- SM prediction accurate:
  - $\text{Br} (B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\text{Br} (B_d^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

**Experiment**
- Experimental measurement a viable BSM search
- CMS and LHCb observation of $B_s^0 \rightarrow \mu^+\mu^-$ and evidence of $B_d^0 \rightarrow \mu^+\mu^-$:
  - $\text{Br} (B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
  - $\text{Br} (B_d^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$
Method

Signal

- Select signal di-muon events from data.
- Extract yield using an un-binned maximum-likelihood fit to the data.
- Use control samples to understand background suppression BDT and other cross checks.

Normalise signal to $B^0 \rightarrow J/\psi K^\pm$

- Requires knowledge of hadronisation probabilities $f_u/f_s$ and $f_u/f_d$
- Use the ATLAS result for $f_s/f_d = 0.240 \pm 0.020$. ATLAS Coll, PRL 11(2015) 262001(arXiv:1507.08925) and assuming isospin symmetry $f_u/f_d=1$. 
Backgrounds

- Combinatorial Background - muons from b, \( \bar{b} \) quarks
- Partially Reconstructed Decays:
  - Same Vertex (SV): \( b \rightarrow s\mu^+ qJ/\psi \)
  - Same Side (SS) cascades; e.g. \( b \rightarrow c\mu\nu_\mu \rightarrow s(d)\mu\mu\nu_\mu \)
- Fully reconstructed 2-body decays

Background suppression use a boosted decision tree (BDT) using signal and background variables. Figures showing background before BDT.
Using 25 fb$^{-1}$ of 7 TeV and 8 TeV proton–proton collision data ATLAS obtains:

\[
\begin{align*}
Br(B^0_d \rightarrow \mu^+\mu^-) &< 4.2 \times 10^{-10} \quad 95\% \ C.L. \\
Br(B^0_s \rightarrow \mu^+\mu^-) &< 3.0 \times 10^{-9} \quad 95\% \ C.L. \\
Br(B^0_s \rightarrow \mu^+\mu^-) &= (0.9^{+1.1}_{-0.8}) \times 10^{-9}
\end{align*}
\]

where the errors include both the statistical and systematic uncertainties.
Comparison, conclusion

- ATLAS is consistent with the SM, LHCb and CMS
- Room for NP destructively interfering with the SM
Using Run1 LHC data ATLAS made important contributions to CPV, mixing and rare decays of B-hadrons

Results are consistent with other experiments

Consistency with SM in all presented cases

Room for New Physics opened

Run2 data expected to increase precisions
Backup Slides