Electroweak and BSM Searches in B Physics with ATLAS

A. CERRI, FOR THE ATLAS COLLABORATION
Outline

• Introduction
• $\Delta \Gamma_d / \Gamma_d$
• $B^0 \rightarrow K^* \mu \mu$
• $B_s \rightarrow J/\psi \phi$, $B \rightarrow \mu \mu$ perspectives
• Conclusions
...I will not lecture you on detector performance, key detector elements, motivations, etc.

- General Purpose Experiments at the LHC are integrating large amounts of integrated luminosity
  - In 2016 alone, ATLAS integrated more than in all previous years combined

- GP Detectors are not fully tuned for flavour physics
  - No PID
  - High pile-up
  - Focus on central production
  - Other compromises (lepton ID threshold, momentum resolution etc.)

- There are however areas where advantage can be gained combining the strengths of the experiment
\[ \frac{\Delta \Gamma_d}{\Gamma_d} \]

Measurement of the relative width difference of the $B_0$-$\bar{B}_0$ system with the ATLAS detector

ATLAS Collaboration (Morad Aaboud (Oujda U.) et al.).
Published in JHEP 1606 (2016) 081
Experimental sensitivity still below SM predictions

\[
\frac{\Delta \Gamma_d}{\Gamma_d} (SM) = (0.42 \pm 0.08) \times 10^{-2}
\]

\[
\frac{\Delta \Gamma_d}{\Gamma_d} (World \ avg.) = (0.1 \pm 1.0) \times 10^{-2}
\]

○ New physics could still hide in \( \Delta \Gamma_d / \Gamma_d \)
○ Increased precision and complementing measurement methods important

• ATLAS measurement: \( \mathcal{L} = 25.2 \text{ fb}^{-1}, \sqrt{s} = 7, 8 \text{ TeV} \)
  ○ Decay rates difference for light/heavy eigenstates shows \( \Delta \Gamma_d / \Gamma_d \) dependency
  ○ Measured through relative ratio of \( B_d \) decays to \( J/\psi K_s \) vs \( J/\psi K^*(892) \)

---

Tuesday, August 15th, 2017

A. CERRI - FLAVOUR 2017 / QUY NHON
Method

• Time dependence of $B \to f$ decay rate:

$$
\Gamma[f, t] \propto e^{-\frac{\Delta \Gamma_q t}{2}} + A_P A_{CP}^{\text{dir}} \cos(\Delta m_q t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma_q t}{2} + A_P A_{CP}^{\text{mix}} \sin(\Delta m_q t)
$$

- $A_P$ is the particle/anti-particle production asymmetry
- $A_{CP}^{\text{dir}}$, $A_{\Delta \Gamma}$, and $A_{CP}^{\text{mix}}$ are well defined for CP/flavour eigenstates

• Base measurement on comparison of $B_d \to J/\psi K_s$ vs $B_d \to J/\psi K^*(892)$:
  - $J/\psi K_s$: $A_{CP}^{\text{dir}} = 0$, $A_{\Delta \Gamma} = \cos 2\beta$, $A_{CP}^{\text{mix}} = -\sin 2\beta$ (CP-specific)
  - $J/\psi K^*(892)$: $A_{CP}^{\text{dir}} = 1$, $A_{\Delta \Gamma} = 0$, $A_{CP}^{\text{mix}} = 0$ (flavour-specific)

• Fit the ratio of CP/flavour eigenstates to determine $\Delta \Gamma$:

$$
\frac{\Gamma[\psi K_s, t]}{\Gamma[\psi K^*, t]} = \frac{\cosh \frac{\Delta \Gamma_d t}{2} + \cos 2\beta \sinh \frac{\Delta \Gamma_d t}{2} - A_p \sin \Delta m_d t}{\cosh \frac{\Delta \Gamma_d t}{2} + A_p \cos \Delta m_d t}
$$

• Can determine $\Delta \Gamma_d$ and $A_p$ from data
Extracting Binned Signal Yields

- Signal counts are determined in bins of proper decay length
  - Use 10 bins between -0.3mm and 0.6mm
  - Yields determined through mass fits
  - Per-bin detector acceptance taken into account

---

**ATLAS**

$\sqrt{s} = 8$ TeV

$\int L dt = 20.3\text{ fb}^{-1}$

$0.0 < l^B_{\text{prop}} < 0.3\text{ mm}$

**ATLAS**

$\sqrt{s} = 8$ TeV

$\int L dt = 20.3\text{ fb}^{-1}$

$0.0 < l^B_{\text{prop}} < 0.3\text{ mm}$

(Data - Fit)/\sigma

(Data - Fit)/\sigma
**Determination of $A_p$**

- Production asymmetry derived from observed time-dependent asymmetry of $J/\psi K^*(892)$ candidates (omitting CP violating mixing terms):
  \[
  \Gamma[t, \frac{B}{\bar{B}} \to J\psi K^*] = e^{-\Gamma a t} [\cosh \frac{\Delta \Gamma a t}{2} \pm A_p \cos \Delta mt]
  \]

- ct bins are fitted with predicted $A_{\text{exp}}$, accounting for **detector effects** (mostly tracking asymmetry for charged K):
  \[
  A_{\text{exp},i} = (A_{\text{det}} + A_{\text{osc},i})(1 - 2W)
  \]
  - $\chi^2 = 6.50$, d.o.f = 7
  - $A_{\text{det}} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$
    - Checked against MC
  - $A_p = (0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$

- Systematics driven by mis-tag fraction uncertainties and $|q/p|=1$ assumption

- Consistent with LHCb measurement

**First LHC measurement of production asymmetry in central region**
Determination of $\Delta \Gamma_d$

- Extract ct-dependent yields for $K^*$ and $K_s$ decays
- Fit ct-dependency leaving $\Delta \Gamma_d/\Gamma_d$ as the only free parameter

2011 Data, $\chi^2/NDF=4.34/7$

2012 Data, $\chi^2/NDF=2.81/7$

- Consistent result for the two datasets

\[
\Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.1\text{(stat.)} \pm 0.9\text{(syst.)}) \times 10^{-2}
\]

- Currently the most precise single measurement available on the market!

\[
[LHCb: \Delta \Gamma_d/\Gamma_d = (-4.4 \pm 2.5\text{(stat.)} \pm 1.1\text{(syst.)}) \times 10^{-2}]\]
NEW PRELIMINARY RESULT: ATLAS-CONF-2017-023

$B^0 \rightarrow K^* \mu \mu$
Motivation

• FCNC process, forbidden at LO
  ◦ Box and penguin contributions dominate
  ◦ NP processes may contribute to decay amplitudes

• Known tension between experiment and some theoretical models in P’5 (arXiv 1512.04442)

• New preliminary result from ATLAS
  ◦ Data from 2012 collisions @8 TeV $E_{CM}$, analysing 20.3 fb$^{-1}$ of 1,2,3-$\mu$ triggers
  ◦ Measured 6 overlapping bins of $q^2$: [0.04,6] GeV$^2$
  ◦ Differential decay amplitude analysis to extract coefficients sensitive to NP
  ◦ Fit performed in three angles: $\theta_L$, $\theta_K$, $\Phi$
Angular Analysis

• Differential decay amplitude:

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

• Si suffers from significant theory uncertainties, cancelled at leading order through:

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

• Exploiting symmetries of trigonometric functions we reduce the parameters extraction to: \( F_L, P_1, P'_{4,5,6,8} \)
Angular Analysis: fits

- Extended un-binned maximum likelihood fits to each of the fit variants and each $q^2$ bin
- Fit projections shown for
  - $m$, $\theta_L$, $\theta_K$, $\Phi$
  - $q^2=[0.04,2.0]$ GeV$^2$
  - $O(100)$ signal events each
Uncertainties

• Results are **statistics-limited**
  ◦ Control channels \([J/\psi K^* \text{ and } \psi(2s)K^*]\) used to extract nuisance parameters for signal PDF (mass, per-candidate mass resolution...)

• **Dominant sources of systematic uncertainties:**
  ◦ Fake \((K\pi)\) backgrounds (e.g. at high \(\cos \theta_K \sim 1\) contributions from \(B^+ \rightarrow K/\pi \mu \mu X\) and fake \(K^*\))
  ◦ Partially reconstructed \(B \rightarrow D \rightarrow X\) decays around \(|\cos \theta_L| \sim 0.7\)
  ◦ Other combinatorial and peaking background sources (e.g. \(\Lambda_b\) decays model added/removed in fit)
  ◦ Alignment and B-field calibrations
  ◦ Possible S-wave contributions (\(\sim 5\%\), included as systematics)
  ◦ Examples:
    ◦ \(F_L\) larges systematics from \(\cos \theta_K\) and \(\cos \theta_L\) backgrounds: 0.11
    ◦ \(S_i\) systematics also from background uncertainties: 0.01-0.13
Comparison With Theory

- OPE fits to LHCb data (CFFMPSV) (separate plots in back-up)
- Factorisation QCD computation (DHMV)
- Jäger-Camalich
- ...more in back-up
- Bottomline: compatible with theoretical calculations
Comparison With Other Experiments

All P’ are in general compatible with theory and other experimental determinations
$B_s \rightarrow J/\psi \phi$, $B \rightarrow \mu \mu$

status & perspectives
• Time-dependent angular analysis
  ◦ BLUE method used to combine 2011/2012 results
  ◦ Combination is statistically limited
  ◦ Precision determined by ct resolution

• No new result approved yet

• Run 2 dataset collection continues with comparable efficiency

• Expect extrapolation to scale essentially with luminosity

• Ct resolution improvement from IBL in run 2 will improve effective tagging dilution by x4
• Latest result available based on full Run 1 statistics

• Projected uncertainties comparable to CMS
  ◦ “under-fluctuation” on signal yield negatively affects contours/limits
  ◦ Breakdown of differences in terms of mass resolution vs statistical methods well understood
  ◦ Working in improved statistical extraction

• Analysis group plan:
  ◦ First iteration of the analysis based on 2015 dataset
  ◦ Second result will be based on full Run 2 dataset

• Result is statistically limited: expect sensitivity to essentially scale with statistics

• Topological triggers exploited in Run II to maintain signal data taking efficiency
Conclusions

- Wide ranging programme of NP investigations with Beauty ATLAS
- Precision measurements of decay rate parameters $\Delta\Gamma_d$
  - Most precise single-experiment measurement available on the market
  - Further constraining possibilities for NP
- Recently published results by ATLAS on the angular analysis of the $B_d \rightarrow K^*\mu\mu$
  - All $P'$ parameters compatible with the theoretical predictions and the other experiments
  - Measurements are all statistically limited
- Most analyses now engaged with Run 2 datasets
- All results discussed are statistics-limited: very encouraging perspectives with Run 2 datasets
  - Crucial use of topological triggers and partial event building to maintain low trigger thresholds in the high pile-up regime
Backup
Comparison With Theory for $K^*\mu\mu$

- $S_i$ coefficients compared to:
  - Operator Product Expansion (OPE) (fits to LHCb data) (CFFMPSV)
  - Factorisation QCD computation (DHMV)
Comparison With exp. for $K^{*}\mu\mu$

- Comparable to other experiments and theory, with $\sim 3\sigma$ largest deviation in single bin.
- w.r.t. DHMV; $P_5'$ shows similar trend to LHCb in [4,6] GeV$^2$, at $\sim 2.7\sigma$.  


# $K^*\mu\mu$ Event Yields

<table>
<thead>
<tr>
<th>$q^2$ [GeV$^2$]</th>
<th>$n_{\text{signal}}$</th>
<th>$n_{\text{background}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.04, 2.0]</td>
<td>128 ± 22</td>
<td>122 ± 22</td>
</tr>
<tr>
<td>[2.0, 4.0]</td>
<td>106 ± 23</td>
<td>113 ± 23</td>
</tr>
<tr>
<td>[4.0, 6.0]</td>
<td>114 ± 24</td>
<td>204 ± 26</td>
</tr>
<tr>
<td>[0.04, 4.0]</td>
<td>236 ± 31</td>
<td>233 ± 32</td>
</tr>
<tr>
<td>[1.1, 6.0]</td>
<td>275 ± 35</td>
<td>363 ± 36</td>
</tr>
<tr>
<td>[0.04, 6.0]</td>
<td>342 ± 39</td>
<td>445 ± 40</td>
</tr>
</tbody>
</table>