Exclusive and rare $B$ decays in ATLAS

Elisa Musto(*) on behalf of the ATLAS Collaboration

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Outline

**ATLAS @LHC:**
- detector
- 2010/2011 data taking
- **B-Physics measurements requirements:**
  - performance & trigger

**Exclusive B-decays overview**

**Rare B decays:**
- $B^0_s \rightarrow \mu^+ \mu^-$
The ATLAS detector

**AT**oroidal **LHC Ap**paratus

**Inner detector (|\(\eta| < 2.4\)):**
- *Silicon pixel and strip, Transition Radiator Tracker*
  \(\sigma_p/p \approx 3-5\%\)
  Impact parameter resolution ~ 10 \(\mu_m\)
- *2T Solenoidal field*

**Calorimeters (|\(\eta| < 5\)):**
- *EM: Pb-LAr*
  \(\sigma/E \approx 10%/\sqrt{E (GeV)} \oplus 0.7\%\)
- *HADRONIC: Iron/Scintillator Tiles*
  \(\sigma/E \approx 50%/\sqrt{E (GeV)} \oplus 3\%\)

**Muon Spectrometer (|\(\eta| < 2.7\)):**
- *Trigger chambers: RPC and TGC*
- *0.5 - 2 T Toroidal field*
- *Coordinate Measurements Chambers: MDT and CSC*
  \(\sigma/p \sim 5\%\) (for \(p_T = (10-100)\) GeV/c)
The ATLAS data-taking

Integrated luminosity:
- 2010: \( \sim 40 \text{ pb}^{-1} \)
- 2011: 5.6 fb\(^{-1} \)

Instantaneous luminosity:
- 2010: \( 2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- 2011: \( 3.65 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
The ATLAS data-taking

Integrated luminosity delivered to ATLAS:
- 2010: ~ 40 pb\(^{-1}\)
- 2011: 5.6 fb\(^{-1}\)

Pile-up is the challenge at high LHC luminosity!

Instantaneous luminosity:
- 2010: 2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}
- 2011: 3.65 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}

\begin{align*}
\text{data taking efficiency} & > 93\% \\
\mu & = \text{number of pile-up} \\
\nu_x & = \text{number of reconstructed vertices}
\end{align*}
Performance

B-Physics measurements rely on good muon reconstruction

- Good **Inner Detector** Vertexing/Tracking performance for precision measurements/muon momentum resolution

- Good **Muon Spectrometer** performance for muon trigger and identification

**Mass resolutions:** \( \sigma_m(J/\psi - \Upsilon) \sim (60 - 120) \text{ MeV} \) (ID dominated)
Trigger & B-Physics

ATLAS trigger:
- Output rate ~ 300 Hz
- three levels of event selection
- based on Region of Interests

Exclusive and rare B decays selections based on:
- Single muon triggers in 2010 (low luminosity)
- Di-muons triggers (+pre-scaled single muon) in 2011 (high luminosity)

B-Physics trigger thresholds kept un-prescaled during 2011 despite the increasing instantaneous luminosity

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \int L \, dt \approx 2.3 \text{ fb}^{-1} \]

\[ m_{\mu\mu} [\text{GeV}] \]

\[ \text{Entries / 50 MeV} \]
Exclusive B decays overview

ATLAS-CONF-2010-098

$B^\pm \rightarrow J/\psi (\mu^+\mu^-)K^\pm$

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

$\int L dt = 3.4$ pb$^{-1}$

$m_{J/\psi K} > 300 \mu$m

Calibration and reference

Entries / (30 MeV)

Events / (11.9 MeV)

$B^0_d \rightarrow J/\psi (\mu^+\mu^-) K^+$

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

$\int L dt = 40$ pb$^{-1}$

$\tau > 0.35$ ps

Reference and testing self-tagging

Events / (18 MeV)

$B^0_s \rightarrow J/\psi (\mu^+\mu^-) \phi(K^+K^-)$

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

$\int L dt = 40$ pb$^{-1}$

Current CP violation

Mixing and CP violation

Events / (18 MeV)

$B^\pm \rightarrow J/\psi (\mu^+\mu^-) \pi^\pm$

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

$\int L dt = 4.3$ fb$^{-1}$

Probes of heavy quark dynamics

All mass measurements agree with PDG values

E. Musto - DIS2012 - March 29, 2012
Exclusive B decays overview

A recent result: $\chi_b(3P) \rightarrow Y(1S,2S)\gamma$  

arxiv: 1112.5154

$M[\chi_b(3P)]=10.530\pm0.005\text{ (stat)}\pm0.009\text{ (syst)}\text{ GeV}$

compatible with computation based on potential model for quarkonia states
The $B^0_s \rightarrow \mu^+\mu^-$ decay
Motivations

Flavor Changing Neutral Current processes highly suppressed in the Standard Model (SM).
Deviations wrt SM predictions in several New Physics models.
Analysis strategy (1/2)

• Luminosity: 2.4 fb\(^{-1}\) of data, collected up to July 2011 (before a major change in the trigger)

• Reduced systematic uncertainties:
  ✦ high-yield reference channel with a similar final state:

\[
BR(B^0_s \rightarrow \mu^+\mu^-) = \frac{1}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \times BR(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s}
\]

- From data:
  - Yield of \(B^\pm \rightarrow J/\psi K^\pm\) used as reference channel
- From other measurements:
  - \(BR(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm) = (6.01 \pm 0.21) \times 10^{-5}\) [PDG]
  - \(f_u/f_s = 0.267 \pm 0.021\) [LHCb\(^{(1,2)}\)]

✦ Monte Carlo (MC) samples re-tuned using data-driven per event weights

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(1)"Averages of b-hadron, c-hadron, and \(\tau\)-lepton Properties" - 2011; 1010.1589.
(2)"Measurement of b hadron production fractions in 7 TeV collisions" - 2011;1111.2357
Analysis strategy (2/2)

- **Avoid possible sources of `a-priori' bias:**
  - blind the signal region \((5066 \text{ MeV} < m_{\mu\mu} < 5666 \text{ MeV})\): use MC to model signal
  - no optimization bias: data in sidebands
    \((4766 \text{ MeV} < m_{\mu\mu} < 5066 \text{ MeV} \cup 5666 \text{ MeV} < m_{\mu\mu} < 5966 \text{ MeV})\) split in:
      - odd numbered events, to optimize cuts
      - even numbered events channel, to estimate the yields after the cuts optimization

- **Improve signal/background separation:**
  - samples split in three mass resolution categories \((\sim 60 / 80 / 110 \text{ MeV})\)
    depending on muons pseudorapidity \((|\eta_{\max}| < 1.0/1.5/2.5)\)
  - multivariate analysis (MVA) used to combine the separation power of different variables
Signal/background discrimination

Background Composition:

- **continuum**: $b\bar{b} \to \mu^+\mu^- X$ modeled using data in sidebands, main contribution
- ‘resonant’: $B \to hh$ (KK, Kπ, ππ), “fake muons” from decays in flight, punch-throughs
  
  $\text{BR}(\text{fake rate}) \approx 10^{-9}$, close to SM branching ratio for signal, accounted in the upper limit extraction
- ‘mixed’: $b\bar{b} \to \mu^+ h^- X$, single muon +“fake muon”, negligible contribution

**Discriminating variables used in the multivariate classifier:**

- 14 selected:
  - for their discriminating power
  - avoiding using correlated variables
- exploit signal features, like:
  - PV-SV separation: $L_{xy}$, ct significance...
  - Symmetry of final state: pointing angle, $d_0$...
  - B hadronization features: Isolation, $P_T(B_s)$...

<table>
<thead>
<tr>
<th>Number of primary vertices</th>
<th>Isolation cut efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>0.85</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>0.75</td>
</tr>
<tr>
<td>12</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

$\sqrt{s} = 7 \text{ TeV}$

$\int L dt = 2.4 \text{ fb}^{-1}$
Selection optimization

Optimize the estimator\(^{(\ast)}\) \( \mathcal{P} = \frac{\epsilon_{\text{sig}}}{a^2 + \sqrt{N_{\text{bkg}}}} \) (\(a=2\) for 95\% CL limit)

- for the three mass resolution categories
- as a function of the width of search window in mass and the lower cut on BDT output

\(^{(\ast)}G.\) Punzi,


\( \int \) Ldt = 2.4 fb\(^{-1}\) \( \sqrt{s} = 7 \) TeV

- Ranked as best classifier
- Correlation with the mass checked with a test signal at 6.5 GeV
**Inputs to Single Event Sensitivity**

\[ SES = \frac{1}{N} \times \frac{\mathcal{A}_{J/\psi K^\pm} \mathcal{E}_{J/\psi K^\pm}}{\mathcal{A}_{\mu^+ \mu^-}} \times BR(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm) \times \frac{f_u}{f_s} \]

**Reference channel yield**

\[ \text{ATLAS Preliminary} \]
\[ N = 7 \text{ TeV} \]
\[ \int L \, dt = 2.4 \, \text{fb}^{-1} \]

\[ m_{J/\psi K^\pm} \text{ [MeV]} \]

**Output:**

<table>
<thead>
<tr>
<th>Resolution category</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\eta_{\text{max}}</td>
<td>&lt;1.0</td>
<td></td>
</tr>
<tr>
<td>B^\pm \rightarrow J/\psi K^\pm</td>
<td>yield</td>
<td>4298</td>
<td>1407</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>±1.6%</td>
<td>±2.8%</td>
<td>±3.0%</td>
</tr>
<tr>
<td>Syst. uncertainty</td>
<td>±2.9%</td>
<td>±7.4%</td>
<td>±14.1%</td>
</tr>
</tbody>
</table>

**Resolution category**

| SES \,[x \, 10^{-8}] | \(|\eta_{\text{max}}|<1.0| | \(|\eta_{\text{max}}|<1.5| | \(|\eta_{\text{max}}|<2.5| |
|---------------------|---|---|---|
| 0.71 | 1.6 | 1.4 |

\[ 1/(4.45\pm0.38)\times10^3 \text{ [PDG + LHCb]} \]
Unblinding

Resolution category

| Resolution category | $|\eta_{\text{max}}| < 1.0$ | $|\eta_{\text{max}}| < 1.5$ | $|\eta_{\text{max}}| < 2.5$ |
|---------------------|-----------------------------|-----------------------------|-----------------------------|
| Background Events   | 5                           | 0                           | 2                           |
| Even                |                             |                             |                             |
| Odd (biased)        | 1                           | 1                           | 1                           |

Continuous background interpolation: 6.1 ev.

Note: expected ‘resonant’ background: 0.24 events (η bins merged)
Upper Limit

Before the unblinding......

<table>
<thead>
<tr>
<th>95% CLs limit expectations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Even sidebands</td>
<td>2.3×10⁻⁸</td>
</tr>
<tr>
<td>Odd sidebands</td>
<td>1.7×10⁻⁸</td>
</tr>
<tr>
<td>All bins merged</td>
<td>2.8×10⁻⁸</td>
</tr>
</tbody>
</table>

.....after the unblinding

Observed limit: \(2.2 \times 10^{-8}\) @ 95% CL

Next steps:

• Use of spectrometer information to improve mass resolution for forward muons

• MC-based continuous background model - remove statistical uncertainty on event count in sidebands

• Use Full 2011 (and 2012) statistics

Expect improvements better than \(\sqrt{\text{Lumi}}\)!
Summary & plans

ATLAS made several interesting measurements on B decays channels:

✓ Observation of B-hadrons and lifetimes
✓ First observation of a new state at LHC: $\chi_b(3P)$
✓ Upper Limit on $\text{BR}(B^0_s \rightarrow \mu^+\mu^-)$

On the horizon:

› B-hadrons decays:
  › CP violation and mixing with $B^0_s \rightarrow J/\psi \phi$
  › $\Lambda_b, B^+_c, B^0_s$ physics

› Rare Decays:
  › $\text{BR}(B^0_s \rightarrow \mu^+\mu^-)$ upper limit update with full statistics
  › $B^0_s \rightarrow \mu^+\mu^-\phi$, $B^0_d \rightarrow \mu^+\mu^-K^*$
Back-up
All subsystems maintain high performance!

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**ATLAS Detector Status**

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>95.9%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.3%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.5%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>99.9%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>99.5%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>97.7%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.0%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>99.7%</td>
</tr>
</tbody>
</table>
Muon trigger ad pile-up

ATLAS Trigger Operations (Oct. 22 & 25, 2011)

12 trains, 50ns, 1332 bunches

no trains, 10 bunches

Cross section (µb)

<µ> interactions per bunch crossing

L1 rate (kHz) at L = 10^{-34} cm^2 s^{-1}

12 trains, 50ns, 1332 bunches

no trains, 10 bunches

EM16VH
MU11
TAU30
J75

2TAU8 _EM10VH
2TAU11
2MU4
2EM12
4J10 (+2)

high \( p_T \)
stable wrt pile-up

low \( p_T \)
affected by fake rate;
tighter selections used
Discriminating variables (1/2)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>a_{2D}</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>Angle $(\Delta \phi^2 + \Delta \eta^2)^{1/2}$ between $\Delta \vec{x}$ and $\vec{p}_T$</td>
</tr>
<tr>
<td>$L_{xy}$</td>
<td>Scalar product in the transverse plane of $(\Delta \vec{x} \cdot \vec{p}_T)/</td>
</tr>
<tr>
<td>$ct$ significance</td>
<td>Proper decay length $ct = L_{xy} \times m_B/</td>
</tr>
<tr>
<td>$\chi^2_{xy}, \chi^2_z$</td>
<td>$\chi^2$ computed between the measured PV and SV positions in ($x,y$) and $z$, respectively</td>
</tr>
</tbody>
</table>
Figure 1: Signal-filled histogram (and sidebands-empty histogram) distributions for the selection variables.

Distributions from MC and data are compared for all discriminating variables listed above.

Table 1 provides the list of the discriminating variables used in this analysis to separate backgrounds: These variables exploit these features to discriminate against potential backgrounds: pairs of prompt charged tracks 2e: g: 

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{0.7}$</td>
<td>Ratio of $</td>
</tr>
<tr>
<td>$</td>
<td>d_0^{\text{max}}</td>
</tr>
<tr>
<td>$</td>
<td>D_{xy}^{\text{min}},</td>
</tr>
<tr>
<td>$P_T^B$</td>
<td>$B$ transverse momentum</td>
</tr>
<tr>
<td>$P_{L}^{\text{max}}, P_{L}^{\text{min}}$</td>
<td>Maximum and minimum momentum of the two muon candidates along the $B$ direction</td>
</tr>
</tbody>
</table>
Data/MC comparison

Derived MC corrections weights to account for:
- Final-state selections on MC, different between $B^+$ and $B_s$: residual differences due to different b-quark hadronization have been assessed by using $B^0_s \rightarrow J/\psi \phi$ control sample
- Differences between MC and data, primarily in B kinematics ($p_T, \eta$)

After corrections still differences observed on some discriminating variables: taken as systematic uncertainties in the $\varepsilon A$ ratio
BDT independence test

Fake signal at 6.5 GeV

No mass dependence of the TMVA selection
$B^{\pm} \rightarrow K^{\pm} J/\psi$ mass ranges

\[ \int L \, dt = 2.4 \text{ fb}^{-1} \]

$\sqrt{s} = 7 \text{ TeV}$

*ATLAS Preliminary*

Even events only

Signal region

Sidebands

Energy (Entries/10 MeV): 0, 100, 200, 300, 400, 500, 600, 700, 800, 900

mass ranges: 5000, 5100, 5200, 5300, 5400, 5500, 5600