ATLAS Results on Heavy Flavor Production and Decay

Sally Seidel, for the ATLAS Collaboration
ICHEP2020
28 July – 6 August 2020
Two recent results in heavy flavors from ATLAS, using LHC pp data.

ATLAS from inside to out:

- Inner detector (pixel, silicon microstrips, straw-tube TRT) $|\eta| < 2.5$, surrounded by a 2T axial B field from the solenoid
- Sampling calorimeters (LAr EM $|\eta| < 3.2$; Scint tile HAD $|\eta| < 3.2$; LAr HAD $1.5 < |\eta| < 4.9$)
- Air core toroids provide B field for Muon drift tubes + cathode strip chambers (muon tracking to $|\eta| < 2.7$) and resistive plate + thin gap chambers (triggering to $|\eta| < 2.4$)
I. Relative $B_c^{\pm}/B^\pm$ Production Cross Section at 8 TeV
II. The Process $B_{(s)} \rightarrow \mu^+\mu^-$ at 13 TeV, using 2015-16 Data

Please take note of these other interesting ATLAS B-Physics talks at this conference:

- ATLAS Results on Quarkonia and Associated Production (B. Abbott, Tuesday, 19:59 CEST)
- Measurement of the Weak Mixing Phase $\phi_s$ through Time-dependent CP Violation in $B_s \rightarrow J/\psi\phi$ Decay in ATLAS (T. Jakoubek, Wednesday, 19:38 CEST)
- ATLAS Studies of Spectroscopy and Exotics (S. Turchikhin, Thursday, 09:15 CEST)
Measurement of the Relative $B_c^\pm/B^\pm$ Production Cross Section at 8 TeV

**Message and motivation:** No published calculation of the relative cross section at 8 TeV is available. Evidence of dependence of this ratio upon $p_T(B)$ is shown. This is the first measurement of this relative cross section for this combination of fiducial volume and energy.

**The outcome:**

\[
\frac{\sigma(B_c^\pm) \cdot B(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm) \cdot B(B^\pm \to J/\psi K^\pm)}
\]

is measured for bins:

- **2 p_T bins** for the rapidity range $|y(B)| < 2.3$:
  
  \[13 \text{ GeV} < p_T(B_c^\pm) < 22 \text{ GeV} \text{ and } p_T > 22 \text{ GeV}\]

- **2 rapidity bins** for the p_T range $p_T(B) > 13$ GeV:
  
  \[|y| < 0.75 \text{ and } 0.75 < |y| < 2.3\]

- **and for the full range:** $p_T > 13$ GeV and $|y| < 2.3$

* arXiv:1912.02672 [hep-ex].
The method:

- **Find the J/ψ**: combine every oppositely-signed pair of muons, constrain to a common vertex.

- **Find the B candidates**: fit the tracks of the 2 muons to a charged-hadron track, constrain to a common vertex. Charged hadron takes kaon (pion) mass for B± (Bc). Constrain the J/ψ mass to its world average value.

- **Remove combinatorial background** in which J/ψ is combined with unrelated light hadron: select on significance of impact parameter of hadron track relative to PV in transverse plane.

- **Remove partially-reconstructed Bc** semileptonic decays in which a muon fakes a hadron.

- **Find**
  \[
  \frac{\sigma(B_c^\pm) \cdot B(B_c^\pm \rightarrow J/\psi\pi^\pm) \cdot B(J/\psi \rightarrow \mu^+\mu^-)}{\sigma(B^\pm) \cdot B(B^\pm \rightarrow J/\psi K^\pm) \cdot B(J/\psi \rightarrow \mu^+\mu^-)} = \frac{N_{reco}(B_c^\pm) \cdot \epsilon(B^\pm)}{N_{reco}(B^\pm) \cdot \epsilon(B_c^\pm)}
  \]

  where ε’s are efficiencies and \(N_{reco}\) is extracted from mass distributions by unbinned maximum-likelihood fits.
Example invariant mass distributions:

Inclusive result: For full range $p_T > 13$ GeV and $|y| < 2.3$, the production cross section ratio is $0.34 \pm 0.04_{(st)} \pm 0.02_{(sy)} \pm 0.01_{(lifetime)}$. 
The differential measurement suggests a possible dependence on $p_T$: the production cross section of the $B_c$ decreases faster with $p_T$ than the production cross section of the $B^\pm$.

No significant dependence on rapidity is observed.
Study of the Rare Decays of $B_s^0$ and $B^0$ into Muon Pairs, using 2015-16 data*  

**Message and motivation:** Branching fractions for $B^0(s) \rightarrow \mu^+\mu^-$ are highly suppressed both due to the associated flavor changing neutral current and to helicity. Predicted** branching ratios are:

$$B(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

and

$$B(B^0 \rightarrow \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

The smallness and precision of the predictions provide a favorable environment for observing deviations that could indicate contributions from new physics.

**The outcome:**

- A single fit determines the signal yields for both modes. Using 2015-2016 data combined with the Run 1 result‡, finds:

$$B(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$

and

$$B(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10} \quad @95\% \text{ CL}$$

- This combined result differs from the Standard Model prediction by 2.4 standard deviations.

Foundational information:

- Deviations from the Standard Model (SM) prediction arise in Minimal SUSY*, Minimal Flavor Violation†, Two-Higgs Doublet**, and other models‡.

- This measurement uses $26.3 \text{ fb}^{-1}$ collected by ATLAS at 13 TeV

- ATLAS in Run 1 measured***:
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} \]
  and
  \[ B(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} \text{ @95\% CL} \]

- Measurements of these channels by CMS and LHCb are also available³ separately and in combination.

---

**The method:**

- The channels are measured relative the abundant and well measured channel
  \[ B^+ \to J/\psi (\mu^+ \mu^-) K^+ \]

- Extract the desired branching fractions \( B \) as:
  \[
  B \left( B^0 \to \mu^+ \mu^- \right) = \frac{N_{d(s)}}{\varepsilon_{\mu^+ \mu^-}} \times \left[ \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}} \right]
  \]
  - \( N_{d(s)} \) is the \( B^0 \to \mu^+ \mu^- \) signal yield
  - \( \varepsilon \)'s are (acceptance \( \times \) efficiency) in fiducial regions, including integrated lumi and trigger selections
  - \( N_{J/\psi K^+} \) is the \( \mu^+ \mu^- \) yield
  - \( \frac{f_u}{f_{d(s)}} \) is the ratio of hadronization probabilities of a \( b \)-quark into \( B^+ \) and into \( B^0 \)
the method, continued:

- A **blind analysis** is used, with data of $m_{\mu^+\mu^-} \in [5166,5526]$ MeV excluded until selections are finalized.

- Selections use a **multivariate (boosted decision tree, BDT) classifier** with reference $B^+ \rightarrow J/\psi (\mu^+\mu^-)K^+$ and control $B^0_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$.

- Events are separated into **classifier intervals for maximum fit sensitivity**.

- **Background** composition:
  - **Continuum – dominates**: Muons originating from uncorrelated hadron decays. Weakly dependent on $m_{\mu^+\mu^-}$.
  - **Partially reconstructed decays**
  - **Peaking background** $B^0_{(s)} \rightarrow hh'$ with both hadrons misidentified as muons.

- Signal yield extracted by **unbinned maximum likelihood fit** to dimuon distribution.

- The product of **this analysis of 2015-2016 data is combined with ATLAS Run 1 results** to produce the latest public result
Example dimuon invariant mass distribution in the unblinded data, for one interval of the BDT classifier.
Likelihood contours of the combination of Run 1 and 2015-16 Run 2 results

For the 2015-16 data alone,
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2^{+1.1}_{-1.0}) \times 10^{-9} \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-10} \text{ @ 95\% CL} \]

For the 2015-16 Run 2 data combined with the ATLAS Run 1 measurement,
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \text{ @ 95\% CL} \]

In the Standard Model hypothesis, the expected values would be,
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.1}_{-1.0}) \times 10^{-9} \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) < 7.1 \times 10^{-10} \text{ @ 95\% CL} \]

The measurement is consistent, within 2.4 standard deviations, with the Standard Model hypothesis.
Summary

ATLAS presents 2 recent results on heavy flavor production and decay:

- Measurement of the production cross section of $B_c$ mesons relative to $B^\pm$ mesons – new data in an energy and fiducial volume regime for which no prediction exists, and some indication of $p_T$ dependence in the ratio.

- Study of the rare decays of $B_s^0$ and $B^0$ into muon pairs – Simultaneous measurements of the two channels, combining Run 1 and 2015-16 Run 2 data, are consistent with expectations from the Standard Model, differing from the expected central value by 2.4 standard deviations.