ATLAS Results on Heavy Flavor Production and Decay

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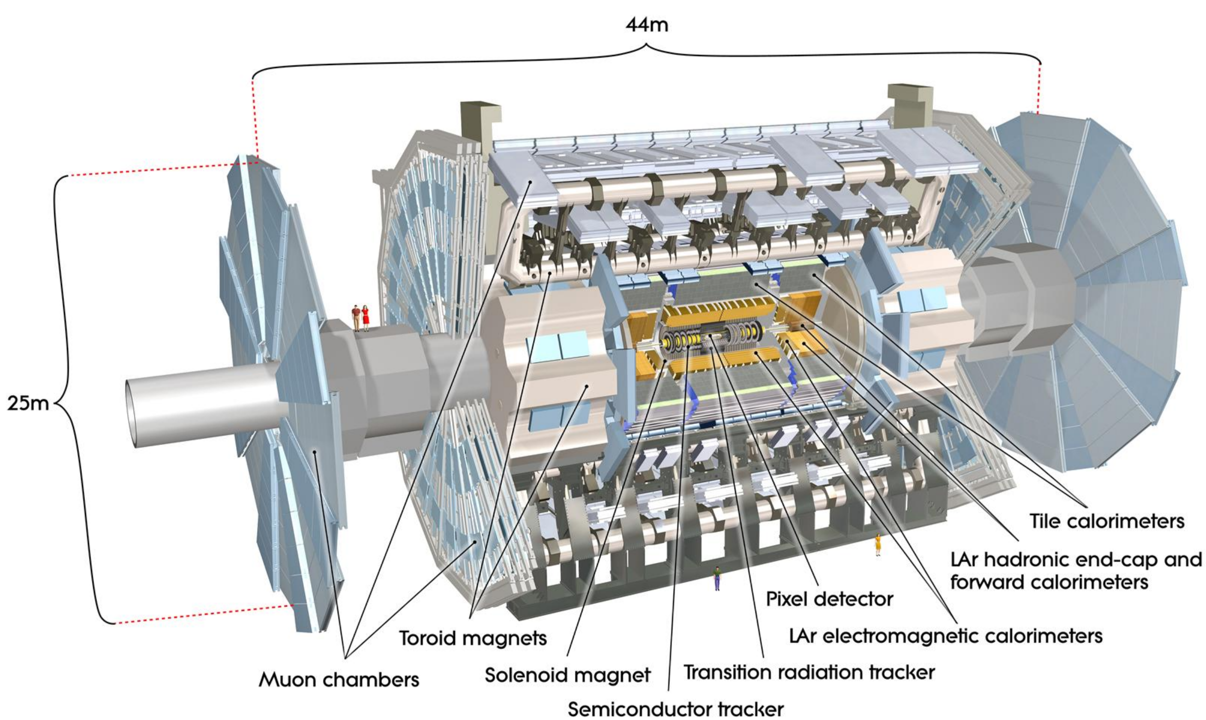
ICHEP2020
28 July – 6 August 2020

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 $B_{(s)} \to \mu^+\mu^-$ 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 ϕ_s through Time-dependent CP Violation in $B_s \to J/\psi\phi$ 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: $\frac{\sigma\left(B_c^{\pm}\right)\cdot B\left(B_c^{\pm}\to J/\psi\pi^{\pm}\right)}{\sigma\left(B^{\pm}\right)\cdot B\left(B^{\pm}\to J/\psi K^{\pm}\right)}$ is measured for bins:

- **2 p_T bins** for the rapidity range $|y(B)| < 2.3$:

$$13\text{ GeV} < p_T(B_c^{\pm}) < 22\text{ GeV and } p_T > 22\text{ GeV}$$

- **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 $B^{\pm}$ (B_c). Constrain the J/ψ mass to its world average value.

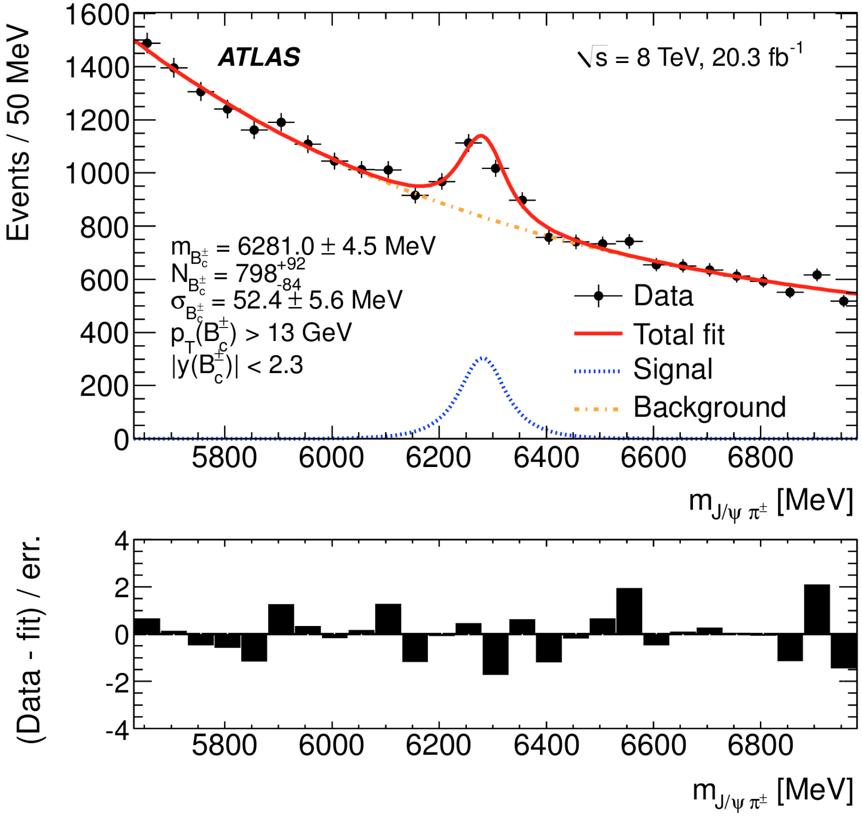
- **Remove combinatorial background** in which J/ψ is combined with unrelated light hadron: select on significance of impact parameter of hadron track relative to PV in transverse plane.

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

- Find $$\frac{\sigma\left(B_c^{\pm}\right)\cdot B\left(B_c^{\pm}\rightarrow J/\psi\pi^{\pm}\right)\cdot B\left(J/\psi\rightarrow\mu^{+}\mu^{-}\right)}{\sigma\left(B^{\pm}\right)\cdot B\left(B^{\pm}\rightarrow J/\psi K^{\pm}\right)\cdot B\left(J/\psi\rightarrow\mu^{+}\mu^{-}\right)}=\frac{N^{reco}\left(B_c^{\pm}\right)}{N^{reco}\left(B^{\pm}\right)}\cdot\frac{\varepsilon\left(B^{\pm}\right)}{\varepsilon\left(B_c^{\pm}\right)}$$

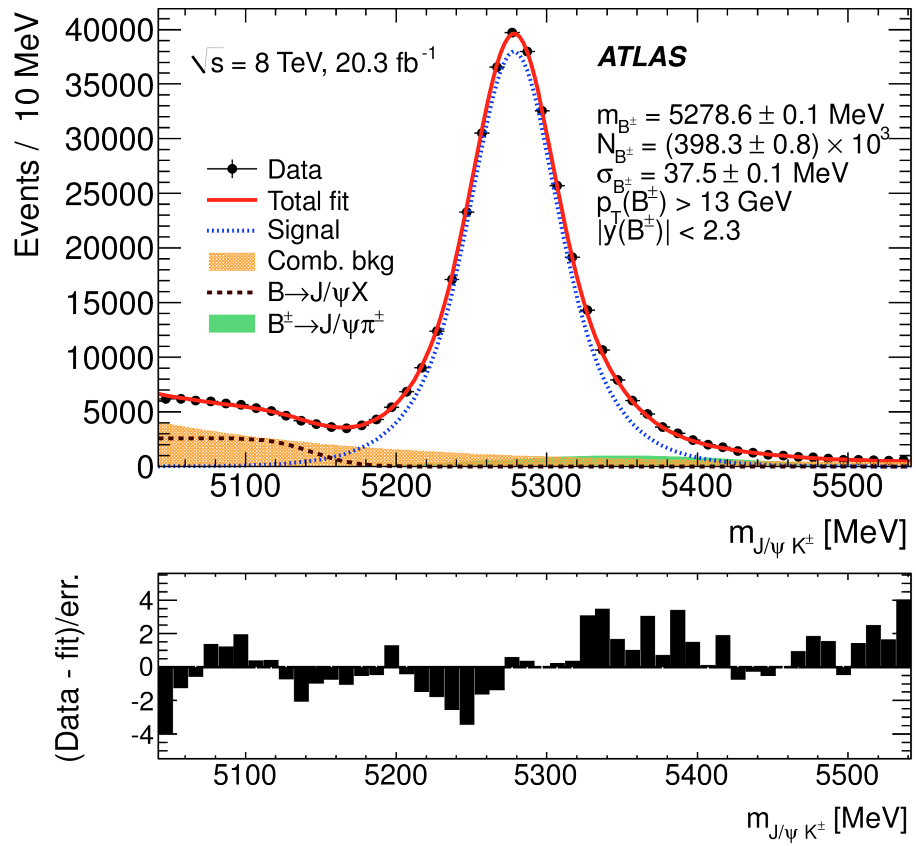
where ε's are efficiencies and N^{reco} is extracted from mass distributions by unbinned maximum-likelihood fits.

Example invariant mass distributions:



B_c

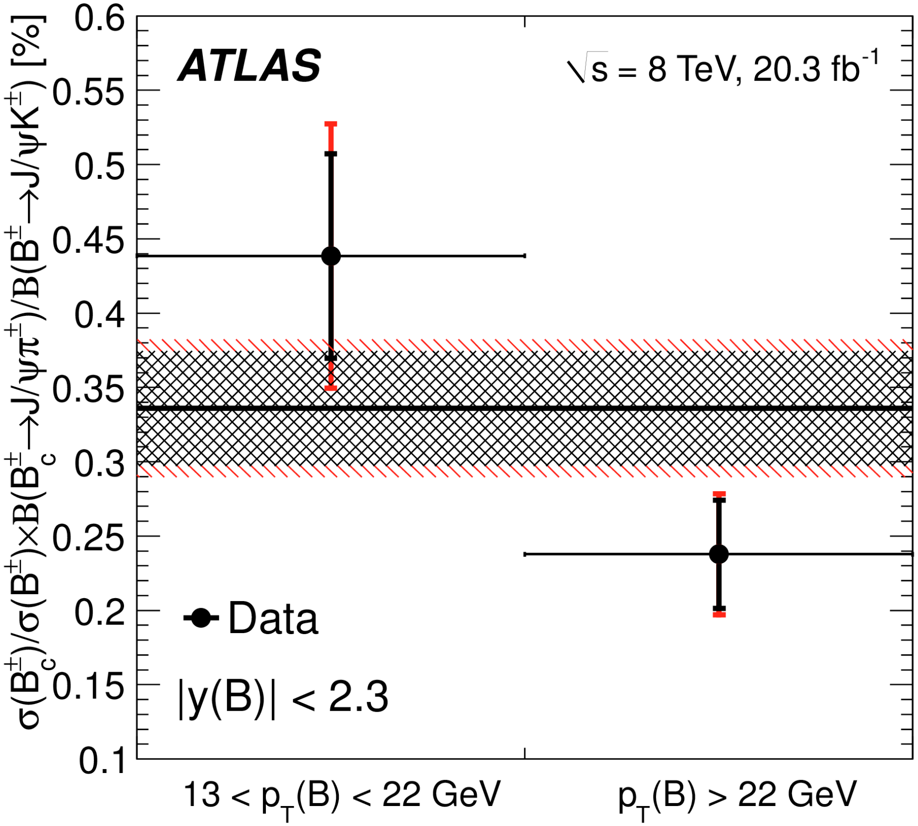
$B^\pm$



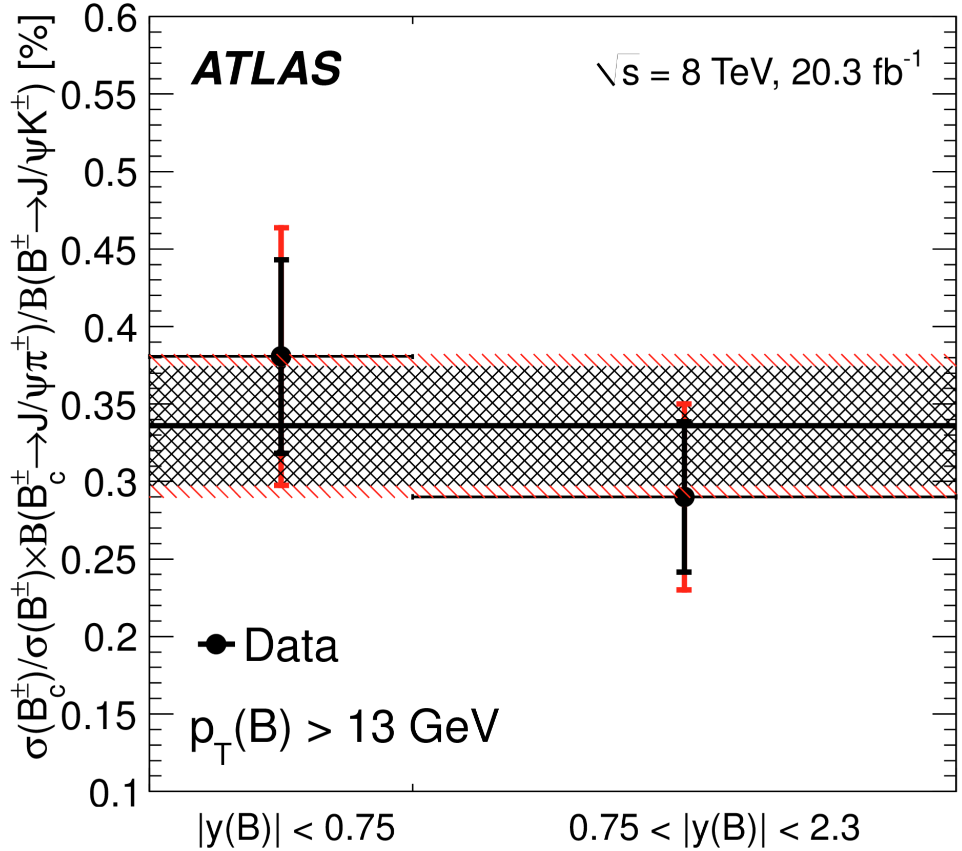
Inclusive result: For full range $p_T > 13$ GeV and $|y| < 2.3$, the production cross section ratio is $0.34 \pm 0.04_{(st)} \pm 0.02_{(sy)} \pm 0.01_{(lifetime)}$.

Differential (points) and inclusive (lines) results:

Error bars: inner – stat; outer – stat+syst+lifetime
Error bands: double hatch – stat; single hatch – stat+syst+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:

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

and

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

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:

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

and

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

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

*JHEP 04 (2019) 098. **M. Beneke et al., JHEP 10 (2019) 232. ‡Eur. Phys. J. C 76 (2016) 513.

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 fb^{-1}** collected by ATLAS at 13 TeV

- **ATLAS in Run 1** measured***:

$$\mathbf{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

and

$$\mathbf{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ @95\% CL}$$

- **Measurements of these channels by CMS and LHCb are also available**ʒ separately and in combination.

* C.S. Huang et al., PRD 59 (19990 011701; C. Hamzaoui et al., PRD 59 (1999) 095005; S.R. Choudhury and N. Gaur, Phys. Lett. B 451 (1999) 86; K.S. Babu and C.F. Kolda, PRL 84 (2000) 228.
† G. D'Ambrosio et al., Nucl. Phys. B 645 (2002) 155; A.J. Buras, Phys. Lett. B 566 (2003) 115.
** S. R. Choudhury et al., Int. J. Mod. Phys. A 21 (2006) 2617.
‡ S. Davidson and S. Descotes-Genon, JHEP 11 (2010) 073; D. Guadagnoli and G. Isidori, Phys. Lett. B 724 (2013) 63.
*** Eur. Phys. J. C 76 (2016) 513.
ʒ CMS, PRL 111 (2013) 101804; LHCb, PRL 111 (2013) 101805; CMS and LHCb, Nature 522 (2015) 68; LHCb, PRL 118 (2017) 191801.

The method:

- The channels are measured relative the abundant and well measured channel

$$B^+ \to J/\psi\left(\mu^+\mu^-\right)K^+$$

- Extract the desired branching fractions **B** as:

$$\mathbf{B}\left(B^0_{(s)} \to \mu^+\mu^-\right) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \left[\mathbf{B}\left(B^+ \to J/\psi K^+\right) \times \mathbf{B}\left(J/\psi \to \mu^+\mu^-\right)\right] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

$N_{d(s)}$ is the $B^0_{(s)} \to \mu^+\mu^-$ signal yield

ε's are (acceptance $\times$ efficiency) in fiducial regions, including integrated lumi and trigger selections

$N_{J/\psi K^+}$ is the $B^+ \to J/\psi K^+$ yield

$\frac{f_u}{f_{d(s)}}$ is the ratio of hadronization probabilities of a b-quark into B^+ and into $B^0_{(s)}$

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**.

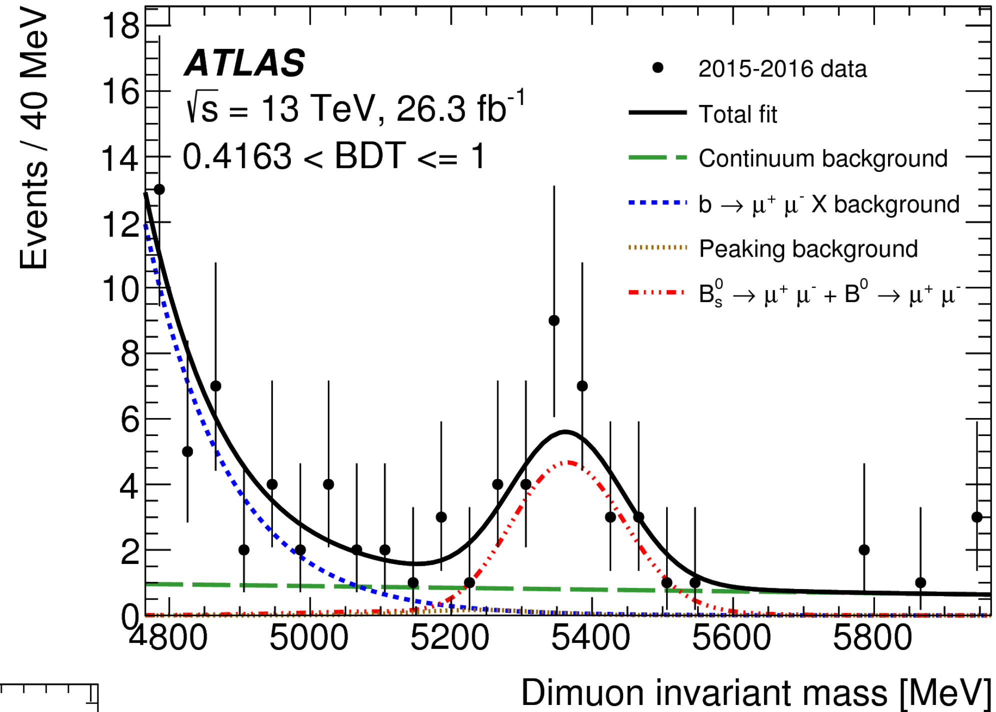
- **Background** composition:

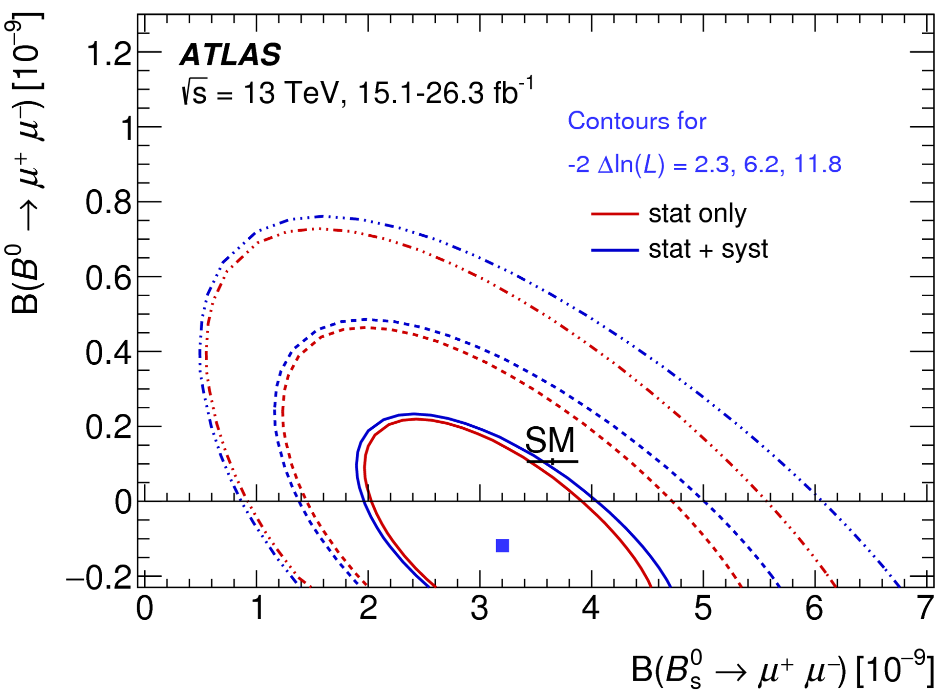
    - **Continuum – dominates**: Muons originating from uncorrelated hadron decays. Weakly dependent on $m_{\mu\mu}$.
    - **Partially reconstructed decays**
    - **Peaking background** $B^0_{(s)} \rightarrow hh'$ with both hadrons misidentified as muons.

- 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

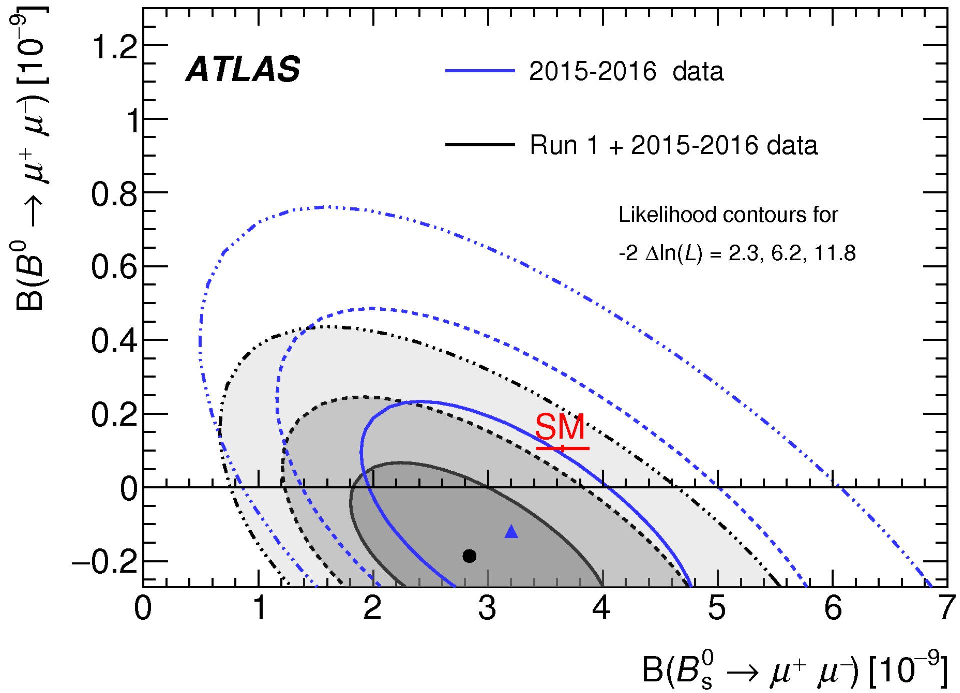
Example dimuon invariant mass distribution in the unblinded data, for one interval of the BDT classifier





Likelihood contours for the simultaneous fit to **B**($B^0_s \to \mu^+\mu^-$) and **B**($B^0 \to \mu^+\mu^-$), in 2015-16 data

Likelihood contours of the combination of Run 1 and 2015-16 Run 2 results



For the 2015-16 data alone,

$\mathbf{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$

$\mathbf{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$ @ 95% CL

For the 2015-16 Run 2 data combined with the ATLAS Run 1 measurement,

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

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

In the Standard Model hypothesis, the expected values would be,

$\mathbf{B}(B_s^0 \to \mu^+\mu^-) = (3.6^{+1.1}_{-1.0}) \times 10^{-9}$

$\mathbf{B}(B^0 \to \mu^+\mu^-) < 7.1 \times 10^{-10}$ @ 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.*