Measurement of the relative $B_c^{\pm}/B^{\pm}$ production cross section at ATLAS

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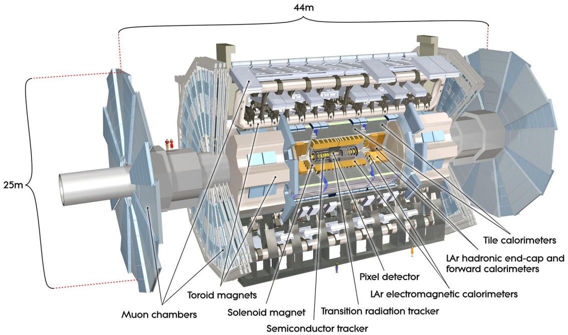
The ATLAS Detector @ LHC

- Subsystems essential for B-physics: Inner Detector and Muon Spectrometer.
- Inner Detector: tracking, momentum and vertexing, $|\eta|<2.5$, d^0 resolution $\sim$10 μm.
- Muon Spectrometer: trigger ($|\eta|<2.4$) and muon identification ($|\eta|<2.7$).
- J/ψ mass resolution: $\sim$60 MeV, $\Upsilon(1S)$: $\sim$119 MeV (resolutions depend on η).

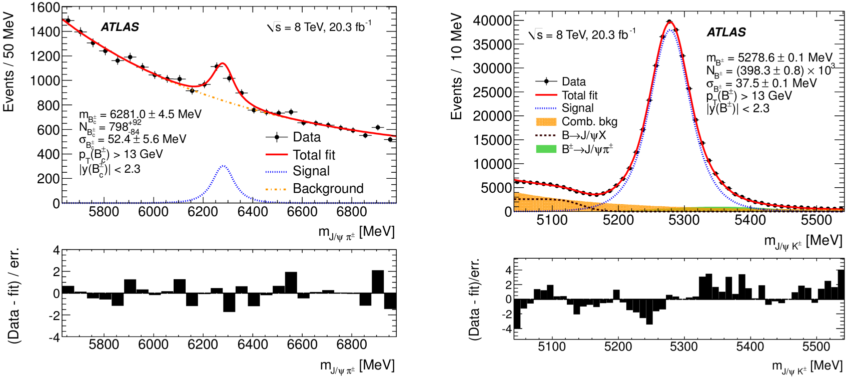


Relative $B_c/B^{\pm}$ production cross section

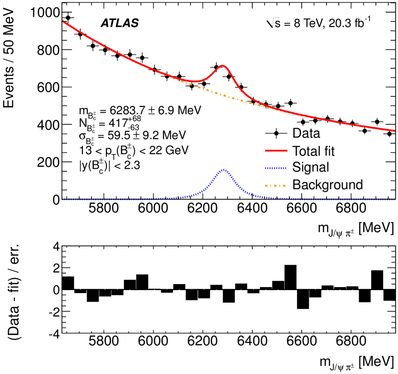
- 20.3 fb^{-1} of 8 TeV pp collision data.
- Submitted to Phys. Rev. D.
- https://arxiv.org/abs/1912.02672
- Motivation:
  - Test of QCD predictions.
  - Important input for heavy quark production models.
  - Performed differentially in p_{T} and y in the central rapidity region.
  - Complements CMS and LHCb measurements.

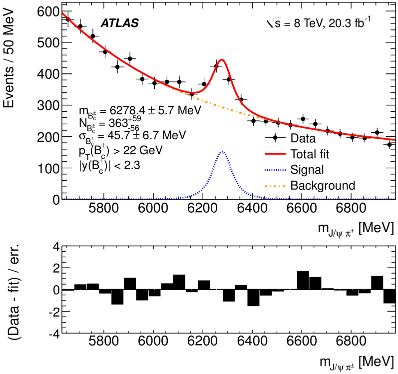
- $B_c^{\pm} \to J/\psi(\mu^+\mu^-)\pi^{\pm}$
- $B^{\pm} \to J/\psi(\mu^+\mu^-)K^{\pm}$
- Dimuon trigger, $p_{\mathrm{T}}(\mu_1, \mu_2) > 4$ GeV, 2.5 < m($\mu\mu$) < 4.3 GeV.
- J/ψ candidates are formed from oppositely charged muons, $p_{\mathrm{T}}(\mu) > 4$ GeV, $|\eta| < 2.3$, 2.6 < m(J/ψ) < 3.5 GeV. Three invariant mass windows, defined by the ATLAS detector resolution.
- Hadronic tracks: $p_{\mathrm{T}} > 2$ GeV.
- B candidates are formed from the 3 tracks: two muonic and one hadronic.
- The χ^2(B vertex)/NDoF < 1.8.
- Instead of a cut on B lifetime, a cut on d^0_{xy} hadron impact parameter significance is introduced, $d^0_{\mathrm{xy}}/\sigma(d^0_{\mathrm{xy}}) > 1.2$.
- Selections are optimised with MC signal and background data sideband studies.

- Extended unbinned maximum likelihood fits to the B meson invariant mass distributions yield $\sim$400k events for the $B^{\pm}$ and $\sim$800 events for the $B_c^{\pm}$.
- $p_{\mathrm{T}}(B) > 13$ GeV, $|y| < 2.3$.



- In addition to the full bin we define two bins in p_{T}: [13—22 GeV] and [>22 GeV] and two bins in rapidity: $|y|<0.75$ and $0.75<|y|<2.3$.
- Bin sizes are selected to equalize the $B_c^{\pm}$ yields.
- Example: fits for two bins in p_{T} for the $B_c^{\pm}$.





Analysis overview (4/4)

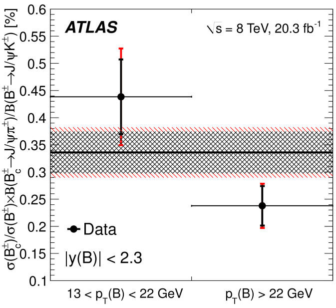
- The relative cross section times branching fraction is given by:

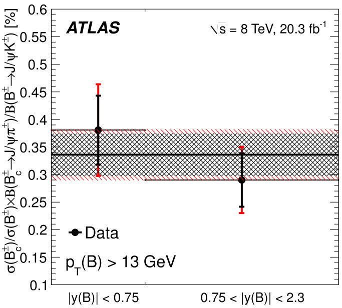
$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm\to J/\psi K^\pm)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)} = \frac{N^{\text{reco}}(B_c^\pm)}{N^{\text{reco}}(B^\pm)}\cdot\frac{\epsilon(B^\pm)}{\epsilon(B_c^\pm)}$$

- $N^{reco}(B)$ are obtained from the fits. Overall analysis efficiencies $\epsilon(B_c^\pm)$ and $\epsilon(B^\pm)$ are obtained from the MC.
- MC is corrected in several ways:
  - sPlot reweighting of the $p_{\mathrm{T}}(B)$ and $y(B)$ distributions;
  - trigger acceptance;
  - distributions of variables used for minimal selections.

The measurement of the relative cross section times branching fraction is performed in five bins:

Analysis bin	$\sigma(B_c^\pm)/\sigma(B^\pm) \times \mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)/\mathcal{B}(B^\pm \to J/\psi K^\pm)$
$p_T(B) > 13$, $\lvert y(B)\rvert < 2.3$	$(0.34 \pm 0.04_{stat} \pm 0.02_{syst} \pm 0.01_{lifetime})\%$
$13 < p_T(B) < 22$, $\lvert y(B)\rvert < 2.3$	$(0.44 \pm 0.07_{stat} \pm 0.04_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 22$, $\lvert y(B)\rvert < 2.3$	$(0.24 \pm 0.04_{stat} \pm 0.01_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 13$, $\lvert y(B)\rvert < 0.75$	$(0.38 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 13$, $0.75 < \lvert y(B)\rvert < 2.3$	$(0.29 \pm 0.05_{stat} \pm 0.02_{syst} \pm 0.01_{lifetime})\%$





- The measurement precision is limited by the statistical uncertainty on the number of $B_c^{\pm}$ candidates.
- The following systematic uncertainties are considered:
  - fitting procedure (including Cabibbo-suppressed decays contribution);
  - trigger, reconstruction and tracking effects;
  - $B_c^{\pm}$ lifetime uncertainty;
  - MC-related uncertainties (sample size, minimal selection criteria).
- The measurement suggest a dependence on the p_{T}: the production cross section of the $B_c^{\pm}$ meson decreases faster with p_{T} than the production cross section of the B meson. No significant dependence on rapidity has been observed.

Remarks on phenomenology (1/2)

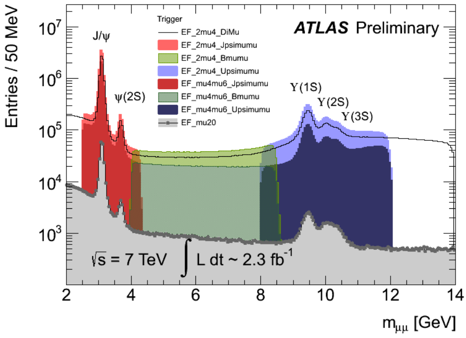
- The production mechanism of the $B_c^{\pm}$ differs from the one of the $B^{\pm}$: in the latter case heavy b-quark catches light u-quark from the sea.
- For the $B_c^{\pm}$ case a collinear production of two distinct heavy quarks is required.
- The complete perturbative calculation for $gg \to B^{+} b\bar{c}$ was performed by several authors (e.g. hep-ph/9408242, hen-ph/9408284, hep-ph/94042346), with results in some disagreement with each other.
- Results depend on different choices of the gluon distribution functions and on the scale of the α_s.

- Naively, the higher the p_{T} the higher the chance for the $c\bar{c}$-pair to be created.
- The data show the opposite behaviour, and this is also consistent in fact with what seen for the $B_s^0/B^\pm$ ratio.
- Michelangelo Mangano in private discussion suggests the following two possible explanations:
  - at low p_{T}, the $B_c^\pm$ is mostly formed by the b-quark finding nearby a $\bar{c}$, created independently as part of the hard process ($gg \to bbcc$). When p_{T} becomes larger, it is more rare to find the b and $\bar{c}$ close enough in phase-space so that they bind together;
  - at low p_{T}, the $c\bar{c}$ comes mostly from the first and only gluon emission of the produced b-quark: $b \to b + g[\to \bar{c}]$. The $b - \bar{c}$ pair is automatically in a color-singlet state and if they are close enough in phase space they bind. When we go to higher p_{T}, there is enough acceleration for more gluons being radiated, e.g. there could be a second gluon radiated after the primary $g \to \bar{c}$ splitting, and therefore the $b + \bar{c}$ system is not in a color singlet state. It is a bit like a Sudakov suppression effect, the larger the p_{T}, the less likely it is to have the b and $\bar{c}$ nearby.

Conclusions

- ATLAS has studied the $B_c^{\pm}/B^{\pm}$ production cross section at 8 TeV.
- Differential (p_{T}, y) study in the central rapidity region.
- The measurement suggests some p_{T} dependence.

- B-physics starts with single or di-muon triggers with various thresholds:
  - $p_{\mathrm{T}}(\mu) > 6$ GeV
  - $p_{\mathrm{T}}(\mu) > 18$ GeV
  - $p_{\mathrm{T}}(\mu_1) > 4$ GeV and $p_{\mathrm{T}}(\mu_2) > 4$ GeV
  - $p_{\mathrm{T}}(\mu_1) > 6$ GeV and $p_{\mathrm{T}}(\mu_2) > 4$ GeV
  - $p_{\mathrm{T}}(\mu_1) > 6$ GeV and $p_{\mathrm{T}}(\mu_2) > 6$ GeV



Di-muon mass range:

$m(\mu\mu) \in [2.5; 4.3]$ GeV for final states containing J/ψ;

$m(\mu\mu) \in [4.0; 8.5]$ GeV for $B \to \mu$ transitions.

Table 1: Summary of corrections due to the minimal selection criteria in the MC simulation. The first uncertainty is statistical, the second one is systematic.

Analysis bin	Correction to the $B_c^{\pm}$	Correction to the $B^{\pm}$
$p_{\mathrm{T}}(B) > 13$, $\lvert y(B)\rvert < 2.3$	$0.0969 \pm 0.0004 \pm 0.0024$	$0.0929 \pm 0.0004 \pm 0.0022$
$13 < p_{\mathrm{T}}(B) < 22$, $\lvert y(B)\rvert < 2.3$	$0.0829 \pm 0.0004 \pm 0.0031$	$0.0826 \pm 0.0004 \pm 0.0029$
$p_{\mathrm{T}}(B) > 22$, $\lvert y(B)\rvert < 2.3$	$0.2164 \pm 0.0014 \pm 0.0018$	$0.2213 \pm 0.0013 \pm 0.0017$
$p_{\mathrm{T}}(B) > 13$, $\lvert y(B)\rvert < 0.75$	$0.0984 \pm 0.0007 \pm 0.0033$	$0.0996 \pm 0.0007 \pm 0.0035$
$p_{\mathrm{T}}(B) > 13$, $0.75 < \lvert y(B)\rvert < 2.3$	$0.0952 \pm 0.0005 \pm 0.0014$	$0.0859 \pm 0.0005 \pm 0.0016$

The efficiency of the analysis selection criteria, $\epsilon^{\text{selection}}$, derived from MC simulation, is incorporated into the final efficiency ratios.
The efficiency ratios $\epsilon(B^{\pm})/\epsilon(B_c^{\pm})$, excluding the Minimal Selection Criteria corrections, are found to be:

- 2.19 ± 0.05 for $13 < p_{\mathrm{T}} < 22$,
- 1.22 ± 0.03 for $p_{\mathrm{T}} > 22$,
- 1.75 ± 0.03 for $p_{\mathrm{T}} > 13$,
- 1.74 ± 0.05 for $|y| < 0.75$,
- 1.76 ± 0.04 for $0.75 < |y| < 2.3$.

Table 2: Summary of the absolute values of systematic uncertainties for the analysis efficiency ratios.

Source of uncertainty	Absolute value of the uncertainty in the efficiency ratio				
	$p_{\mathrm{T}} > 13$	$13 < p_{\mathrm{T}} < 22$	$p_{\mathrm{T}} > 22$	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$
Size of the MC samples and the event counting	0.03	0.05	0.03	0.05	0.04
sPlot-based MC reweighting procedure	0.04	0.03	0.03	0.05	0.06
Minimal selection criteria	0.04	0.09	0.02	0.06	0.03
Tracking uncertainty	0.01	0.01	0.01	0.01	0.01

Table 3: Summary of all systematic uncertainties for the number of signal events in the combined bin ($p_{\mathrm{T}} > 13$, $|y| < 2.3$).

Source of uncertainty	Uncertainty value	
	$B_c^{\pm}$	$B^{\pm}$
Signal model of the fit	2.4%	0.1%
Cabibbo-suppressed decay modeling	2.4%	0.5%
Background model of the fit	2.9%	0.1%
Trigger effects and reconstruction effects	0.9%	0.9%
B-meson lifetime uncertainty	0.7%	$<$ 0.1%