Quarkonia production in ATLAS and CMS experiments

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On behalf of the ATLAS and CMS Collaborations

Large Hadron Collider Physics Conference
29th May 2020
Introduction

• Heavy flavour production is very important for the understanding of QCD
• LHC’s remarkable performance provided ATLAS and CMS with over 150 fb⁻¹ of data during Run1 and Run2
  • using these large datasets new processes can be observed and more precise measurements can be made
• In this talk just a selection of topics


2) Measurement of the χc₁ and χc₂ polarisations in proton-proton collisions at √s=8 TeV (CMS) arXiv:1912.07706


4) Relative cross sections of the B_{c}⁺(2S) and B_{c}^{*+}(2S) states with respect to the B_{c}⁺ state in proton-proton collisions at √s=13 TeV CMS-PAS-BPH-19-001
Measurement of the production cross-section of J/ψ and ψ(2S) mesons at high transverse momentum in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

ATLAS-CONF-2019-047
Quarkonia production in ATLAS and CMS experiments
Measurement of the production cross-section of J/ψ and ψ(2S) mesons

- Quarkonia production provides a unique insight into QCD
  - produced either prompt or non-prompt
- Experimental data can be used to extract values of the Long-Distance Matrix Elements (LDMEs) to help the predictions of quarkonia cross-sections
- Although there are a lot of measurements, a universal library of LDMEs is still challenging to describe simultaneously the
  - quarkonia polarisations
  - quarkonia production in association with other particles
    - photo or electro quarkonia production
- So, it is important to widen the scope of results both in terms of quarkonia production mode and kinematic reach
Quarkonia production in **ATLAS** and CMS experiments

**Measurement of the production cross-section of J/ψ and ψ(2S) mesons**

- **Use of single muon triggers** and **full Run-2 dataset** allows to probe high-\(p_T\) range
  - previous analysis employed di-muon triggers, limiting the \(p_T\) range up to 100 GeV
  

- **Fit both di-muon invariant mass and pseudo-proper decay time to separate prompt and non-prompt components**

- **Measurement dominated by statistical uncertainty at high \(p_T\)**

- **At low \(p_T\) muon reconstruction and trigger contributed to the systematic uncertainty**
Quarkonia production in ATLAS and CMS experiments

Measurement of the production cross-section of J/ψ and ψ(2S) mesons

  - consistent results in overlap region
  - parameterisation \((b + p_T)^{-n}\) seems to be consistent with measurement
- Comparison of non-prompt production of quarkonia with FONLL
  - good agreement at low \(p_T\)
  - FONLL predicts higher cross-sections at high-\(p_T\)
Measurement of the $\chi_{c1}$ and $\chi_{c2}$ polarisations in proton-proton collisions at $\sqrt{s}=8$ TeV

Quarkonia production in ATLAS and CMS experiments

Measurement of the $\chi_{c1}$ and $\chi_{c2}$ polarisations

- $J/\psi$, $\psi(2S)$, $Y(1S)$, $Y(2S)$ and $Y(3S)$ **differential cross-sections** measured in ATLAS and CMS have **indistinguishable shapes** as a function of $p_T/M$
  - which is followed by the $\chi_{c1}$ and $\chi_{c2}$ states
- For **polarisations**, five S-wave states **compatible with unpolarised scenario**
  - do the $\chi_{c1}$ and $\chi_{c2}$ states follow?
- In NRQCD, $\chi_{c1}$ and $\chi_{c2}$ **polarisations** are determined by a single colour octet (CO) parameter
  - can be extracted **employing** $\chi_{c2}/\chi_{c1}$ **cross-section ratio**
- The polarisation of the two states should be opposite and almost maximal
  - in case they are similar, will pose a challenge to NRQCD
Measurement of the $\chi_{c1}$ and $\chi_{c2}$ polarisations

- First measurement of the polarisations of inclusively produced P-wave quarkonia using the 8 TeV dataset
- The $\chi_{c1}$ and $\chi_{c2}$ states are reconstructed via their radiative decays to $J/\psi \gamma$
  - di-muon trigger
  - photon being converted in the tracker
- Polarisation of $\chi_{cJ}$ equivalent to the polarisation of its daughter $J/\psi$
- 3 bins in $J/\psi$ $p_T$: 8-12, 12-18 and 18-30 GeV
- Angular decay parametrised as
  \[ 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi \]
Quarkonia production in ATLAS and CMS experiments

Measurement of the $\chi_{c1}$ and $\chi_{c2}$ polarisations

• $\chi_{c2}/\chi_{c1}$ yield ratios vs $\varphi$ and $\theta$ measured in data
  • solid and dashed curves indicate the NRQCD and unpolarised scenarios
• $\lambda_\theta$ for $\chi_{c2}$ according to the unpolarised and NRQCD scenarios
  • good agreement with the NQCD while the unpolarised scenario is strongly disfavoured

First significant indication of kinematic differences between the various quarkonia states
Measurement of $J/\psi$ production in association with a $W^{\pm}$ boson with pp data at 8 TeV

Quarkonia production in ATLAS and CMS experiments

Measurement of J/ψ production in association with a W± boson

• **J/ψ production in association with a W boson** could be used to study **Colour Singlet** and **Colour Octet** contributions
  • W boson requirement in final state selects dedicated CS/CO diagrams
  • Two contributions in the final state, where the J/ψ meson and the W boson are potentially produced via either
    • Single Parton Scattering (**SPS**)  
    • Double Parton Scattering (**DPS**)  
  • indistinguishable on an event-by-event basis
    • use of discriminating variables - azimuthal angle between the two particles
      •flat contribution from DPS - peak at Δφ = π from SPS
    • DPS governed by “universal” effective cross-section - \( \sigma_{\text{eff}} \)
Quarkonia production in **ATLAS** and CMS experiments

Measurement of $J/\psi$ production in association with a $W^{\pm}$ boson

- **Measurement of** $R_{J/\psi} = \sigma_{W+J/\psi}/\sigma_W$ using the 8 TeV dataset
- Single high-$p_T$ trigger
- Fit both di-muon invariant mass and pseudo-proper decay time to separate prompt and non-prompt components
- Double parton scattering component estimation
  - probability that a $J/\psi$ meson is produced by a second hard process
  - $P_{W+J/\psi} = \sigma_{J/\psi}/\sigma_{\text{eff}}$
  - exact value of $\sigma_{\text{eff}}$ is unknown
    - $\sigma_{\text{eff}} = 15 \pm 3 \, \text{(stat.)} \, ^{+3}_{-3} \, \text{(sys.)} \, \text{mb}$ from $W+2$ jet events
    - $\sigma_{\text{eff}} = 6.3 \pm 1.6 \, \text{(stat.)} \, \pm 1.0 \, \text{(sys.)} \, \text{mb}$ from prompt $J/\psi$ pair production
  - both values consistent at low $\Delta \varphi$

\[ R_{J/\psi} = \frac{\sigma_{W+J/\psi}}{\sigma_W} \]

\[ P_{W+J/\psi} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}} \]

\[ \sigma_{\text{eff}} = 15 \pm 3 \, \text{(stat.)} \, ^{+3}_{-3} \, \text{(sys.)} \, \text{mb} \]

\[ \sigma_{\text{eff}} = 6.3 \pm 1.6 \, \text{(stat.)} \, \pm 1.0 \, \text{(sys.)} \, \text{mb} \]
Quarkonia production in ATLAS and CMS experiments

Measurement of J/ψ production in association with a W± boson

- Systematic uncertainty dominated by the vertex separation between the J/ψ meson and the W boson
- **Fiducial, inclusive** (corrected for the J/ψ spin-alignment) and **DPS-subtracted measurements**
  - DPS-subtracted measured ratio give the opportunity to be compared with theoretical predictions (CO only) - which is found to be in agreement
  - lower $\sigma_{\text{eff}}$ brings the calculated cross-ratio in agreement with measurement
  - **neither $\sigma_{\text{eff}}$ makes the calculations agree with the J/ψ $p_T$ spectrum**
    - probably due to the lack of CS contributions
Relative cross sections of the $B_c^+(2S)$ and $B_c^{*-}(2S)$ states with respect to the $B_c^+$ state in proton-proton collisions at $\sqrt{s}=13$ TeV

CMS-PAS-BPH-19-001
Quarkonia production in ATLAS and CMS experiments

Relative cross sections of the $B_{c}^{+}(2S)$ and $B_{c}^{*+}(2S)$ states with respect to the $B_{c}^{+}$

- Although the **charmonia** and **bottomonia** spectra is **well explored**
  - $B_{c}^{+}$ **meson** knowledge is limited
    - different heavy quark flavours allow only transitions through photons or pion pairs
  - First discovery of the $B_{c}^{+}$ meson in 1998 by CDF [PRL 81 (1998) 2432]
    - lowest in mass bound state, of the bc family of mesons
  - ATLAS observed the $B_{c}^{+}(2S)$ state [PRL 113 (2014) 212004]
  - CMS observed the $B_{c}^{*+}(2S)$ state [PRL 122 (2019) 132001]
    - decaying to $B_{c}^{*+}\pi^{+}\pi^{-} \rightarrow B_{c}^{+}\gamma\pi^{+}\pi^{-}$ - where the soft photon is not detected
    - same final state as $B_{c}^{+}(2S) \rightarrow B_{c}^{+}\pi^{+}\pi^{-}$

<table>
<thead>
<tr>
<th>Particle</th>
<th>Predicted Mass [MeV]</th>
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<tbody>
<tr>
<td>$B_{c}$</td>
<td>6247 - 6286</td>
</tr>
<tr>
<td>$B_{c}^{*}$</td>
<td>6308 - 6341</td>
</tr>
<tr>
<td>$B_{c}(2S)$</td>
<td>6835 - 6882</td>
</tr>
<tr>
<td>$B_{c}^{*}(2S)$</td>
<td>6881 - 6914</td>
</tr>
</tbody>
</table>
Quarkonia production in ATLAS and CMS experiments

Relative cross sections of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states with respect to the $B_c^+$

- Measurement of cross section ratios using the 13 TeV dataset
  - di-muon trigger
  - $B_c^+$ reconstructed through its $J/\psi\pi^+$ decay mode
    - $R^+ \equiv \frac{\sigma(B_c^+(2S))}{\sigma(B_c^+)} = 3.57 \pm 0.69\text{ (stat)} \pm 0.32\text{ (syst)}\%$
    - $R^{*+} \equiv \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+)} = 4.91 \pm 0.69\text{ (stat)} \pm 0.57\text{ (syst)}\%$
    - $\frac{R^{*+}}{R^+} \equiv \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^{*+}(2S))} = 1.39 \pm 0.35\text{ (stat)} \pm 0.09\text{ (syst)}$
  - no significant variation with the $p_T$ or $|y|$ of the $B_c^+$ meson is observed
  - shape of di-pion invariant mass is also examined

![Graphs showing measurements](image)
Summary

• Using Run1 and Run2 datasets ATLAS and CMS Collaborations increase the number of measurements and contribute towards the understanding of the quarkonia production
  • increasing the precision and
  • increasing the kinematic reach of past measurements
  • probing rarer processes
• Many interesting results not covered here are presented in other flavour physics talks

• Only a fraction of available data analysed so far...
  • road ahead includes the exploration of the available data from the collaborations - including the parked CMS data
  • ... and the preparations for the restart and Run3!!

Stay tuned!

ATLAS results

CMS results
backup
Quarkonia production in ATLAS and CMS experiments

ATLAS detector

**ATLAS Preliminary**

Data 2018

$\sqrt{s} = 13$ TeV

58.45 fb$^{-1}$

Entries / 10 MeV

$m(\mu^+\mu^-)$ [GeV]

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Quarkonia production in ATLAS and CMS experiments

CMS detector

CMS DETECTOR
Total weight: 14,000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

STEEL RETURN YOKE
12,000 tonnes

SILICON TRACKERS
Fast (100x134 μm²) - 168 M channels
Micromegas (10x14 μm²) - 20 M channels

SUPERCONDUCTING SOLENOID
Nabium titanium coil carrying ~ 9,000 A

MUON CHAMBERS
Barrel: 290 DIP Tube, 880 Resistive Plate Chambers
End-caps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~ 1m² - 137,000 channels

FORWARD CALORIMETER
Steel + Quartz Fibre ~ 2,800 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~7,800 scintillating PV0, crystals

HADRON CALORIMETER (HCAL)
Steel + Plastic scintillator ~ 7,800 channels

Events/GeV x Prescale

CMS
Preliminary

Online Reconstructed Dimuon Events
p_{T}(μ) > 3 GeV, η(μ) < 2.4, opposite sign

L1-Trigger Selection Requirements

μ+ μ- invariant mass [GeV]
**Systematics**

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty [%]</th>
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<tbody>
<tr>
<td></td>
<td>$</td>
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<tr>
<td>$J/\psi$ mass fit</td>
<td>8.7</td>
</tr>
<tr>
<td>Vertex separation</td>
<td>12</td>
</tr>
<tr>
<td>$\mu_{J/\psi}$ efficiency</td>
<td>2.0</td>
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<tr>
<td>Pile-up</td>
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<tr>
<td>$J/\psi + Z$ and $J/\psi + W^{\pm}(\rightarrow \tau^{\pm}\nu)$</td>
<td>3.5</td>
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<tr>
<td>Efficiency correction</td>
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Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>(R^+)</th>
<th>(R^{++})</th>
<th>(R^{++}/R^+)</th>
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<tbody>
<tr>
<td>J/(\psi) (\pi^+) fit model</td>
<td>4.4</td>
<td>4.4</td>
<td>-</td>
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<tr>
<td>(B_c^+) (\pi^+\pi^-) fit model</td>
<td>5.9</td>
<td>2.9</td>
<td>2.9</td>
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<tr>
<td>Efficiencies: statistical uncertainty</td>
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<td>1.4</td>
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<td>Efficiencies: dispersion among years</td>
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<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Efficiencies: dipion tracking</td>
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<td>4.2</td>
<td>-</td>
</tr>
<tr>
<td>Decay kinematics</td>
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<tr>
<td>Helicity angle</td>
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<tr>
<td>Total systematic uncertainty</td>
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<td>11.5</td>
<td>6.4</td>
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