Heavy Flavour production at ATLAS and CMS
Outline

- Quarkonium S-waves production
  - The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states
  - $B_c^+$ and $B^+$ production cross sections

- Quarkonia production in (p+Pb and) pp
  - Production of $\psi(2S)$ and $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - Production of b-hadron pairs
Quarkonium production

Quarkonium production may occur through:

a) **Prompt** production: direct QCD process or **feed-down** from higher quarkonium states

b) **Non-prompt** production: from decays of long-lived b-hadrons (**charmonia only**)

The study of quarkonium (**prompt) producton** is suited to understand how quarks combine into a bound state (hadron) [non-perturbative QCD sector].

**NRQCD**: effective field theory that treats heavy quarkonia \((c\bar{c}, b\bar{b})\) as non-relativistic systems. Inclusive quarkonium production can be **factorized** in **two distinct** phases.

\[
\sigma(Q) = \sum_{n} S[Q\bar{Q}(n)] \cdot \mathcal{O}^{Q}(n)
\]

- **Short-distance coefficients (SDCs)**
- **Long-distance matrix elements (LDMEs)**

**Calculated** by perturbative QCD (expansions in \(\alpha_s\))

Relative relevance given by \(\nu = \nu/c \ll 1\) (**scaling rules**)

Determined from fits to experimental data

Theoretical predictions are organized as double expansions in \(\alpha_s\) and \(\nu\). Truncation of \(\nu\)-expansion for \(S\)-wave states in NRQCD includes 4 terms:

- 1 **Color Singlet (CS)** term
- 3 **Color Octet (CO)** terms

NRQCD predicts the existence of intermediate CO states in nature, that subsequently evolve into physical color-singlet quarkonia by non-perturbative emission of some gluons.
For both ATLAS and CMS experiments, dimuon decays provide a particularly clean signature to trigger on in order to reconstruct quarkonium states.
Also, to measure prompt and non-prompt yields simultaneously and disentangle the two contributions both CMS & ATLAS exploit a 2D mass and pseudo-proper time fit.

[1] PRL 114, 191802
Quarkonium S-waves prompt production

PLB 780 (2018) 251
Prompt quarkonium @ 13 TeV

- CMS performed a new analysis with Run II data (2.3 - 2.7 fb⁻¹) @13 TeV to extend the $p_T$-reach and thus testing the validity domain of NRQCD and if the scaling with energy works (w.r.t. Run I 7 TeV analysis [1]). The double differential cross sections are then calculated in several dimuon $p_T$ & $y$ bins as:

\[
\begin{align*}
\text{Fiducial region} & : \\
& \begin{cases} \\
& p_T(\mu^\pm) > 4.5 \text{ GeV} \\
& 0.3 < |\eta(\mu^\pm)| < 1.4 \\
& \text{or} \\
& p_T(\mu^\pm) > 4.0 \text{ GeV} \\
& |\eta(\mu^\pm)| < 0.3 \\
\end{cases}
\end{align*}
\]

\[
BR(q\bar{q} \rightarrow \mu^+\mu^-) \times \frac{d^2\sigma_{q\bar{q}}}{dp_T dy} = \frac{N_{q\bar{q}}(p_T, y)}{L\Delta y \Delta p_T} \cdot \frac{1}{e(p_T, y) A(p_T, y)}
\]

Fiducial region

\[
\begin{align*}
\sigma B(p_T, y) & = \frac{N_{q\bar{q}}(p_T, y)}{L\Delta y \Delta p_T} \cdot \frac{1}{e(p_T, y) A(p_T, y)}
\end{align*}
\]

Branching fraction to 2 $\mu$

- Cross sections @13 TeV are a factor 2-3 larger than the corresponding values @ 7 TeV and slowly increasing as a function of the dimuon $p_T$

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Branching fraction to 2 $\mu$

- Cross sections @13 TeV are a factor 2-3 larger than the corresponding values @ 7 TeV and slowly increasing as a function of the dimuon $p_T$

[1] PRL 114, 191802 SEE BACKUP
These results show similar scaling for both bottomonium and charmonium S-wave states and contribute to consolidate the underlying hypothesis of NRQCD and provide further input to constrain the theory parameters.
Quarkonia production (in p+Pb) and pp

EPJ C (2018) 78:171
Quarkonia production in \((p+Pb \text{ and } pp)\)

In EPJ C (2018) 78:171 ATLAS studied the modification of quarkonium S-wave states production in \(p+Pb\) collisions (2015 - 25 \(pb^{-1}\)) w.r.t. to \(pp\) collisions (2015 - 25 \(pb^{-1}\)), both at \(\sqrt{s} = 5.02\ \text{TeV per nucleon}\). The suppression in \(p+Pb\) collision (QGP medium not expected in \(p+A\)) is due \textit{COLD NUCLEAR MATTER} effects:

\[
R_{pPb} = \frac{1}{208} \frac{\sigma_{pPb}}{\sigma_{pp}}
\]

\[
\rho_{pPb}^{O(nS)/O(1S)} = \frac{R_{pPb}(O(nS))}{R_{pPb}(O(1S))}
\]

most of detector systematics & initial state cancel out

- Parton energy loss
- Nuclear pDF
- Final state interaction

The \textit{double differential cross sections} are then calculated in several dimuon \(p_T \& y\) bins as:

Fiducial region
\[p_T(\mu^+) > 4 \text{ GeV} \text{ and } |\eta(\mu)| < 2.4\]

\[
\frac{d^2\sigma_{O(nS)}}{dp_T dy^*} \times B(O(nS) \rightarrow \mu^+ \mu^-) = \frac{N_{O(nS)}}{\Delta p_T \times \Delta y \times L}
\]

each candidate is corrected with

\[
w_{\text{total}}^{-1} = A(O(nS)) \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{trig}}
\]

(enters in \(N_{O(nS)}\))

2D Mass – pseudoproper decay time PDF

\[
\text{PDF}(m_{\mu\mu}, \tau_{\mu\mu}) = \sum_{i=1}^{7} \kappa_i f_i(m_{\mu\mu}) \cdot h_i(\tau_{\mu\mu}) \otimes g(\tau_{\mu\mu})
\]

See backup

Mass resolution \(\sim 150\ \text{MeV}\), not able to totally separate different states

\(p_T(\mu) > 4 \text{ GeV}\) cause turn-on curve of bkg. at low \(p_T\), constrained by same charge / displaced control sample
Quarkonia production in (p+Pb and) pp

Prompt

The measured (25 pb$^{-1}$) prompt $J/\psi$ and $\psi$ (2S) $\sigma \cdot B$ in pp at $\sqrt{s} = 5.02$ TeV ($p_T$ and $y$ intervals), compared with NRQCD predictions (uncertainty bands from the choice of scale, $m_c$ and LDMEs) in range in $8 < p_T < 40$ GeV.

Results in good agreement

Non Prompt

The measured (25 pb$^{-1}$) non prompt $J/\psi$ and $\psi$ (2S) $\sigma \cdot B$ in pp at $\sqrt{s} = 5.02$ TeV ($p_T$ and $y$ intervals), compared with FONLL predictions (uncertainty bands from the choice of scale, $m_c$ and p.d.f.) in range in $8 < p_T < 40$ GeV.

Results in good agreement
The LDMEs for $\Upsilon$ s-waves production are only extracted from fitting experiment data at $p_T > 15$ GeV. At lower $p_T$, non-perturbative effects which break the NRQCD factorization and perturbation expansion.
The LDMEs for $\Upsilon$ s-waves production are only extracted from fitting experiment data at $p_T > 15$ GeV. At lower $p_T$ : non-perturbative effects which break the NRQCD factorization and perturbation expansion.

As a consequence of its construction, the bottomonium NRQCD model gives a relatively good description of the measured $\Upsilon(nS)$ production cross section at $p_T > 15$ GeV, while overestimates the production cross section at lower $p_T$.
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

arXiv:1805.11192 submitted to PRL
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

The bottomonium family ($b\bar{b}$) plays a special role in understanding how the strong force binds quarks because, due to the high quark mass, allows two important theoretical simplifications. The measurements of the masses of the $\chi_{b}(3P)$ triplet states ($J = 0, 1, \text{and} 2$), is especially interesting to probe details of the $bb$ interaction and test theoretical treatments of the influence of open-beauty states on the bottomonium spectrum.

*Picture from*: V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - DOI 10.1007/978-3-319-49935-2_2
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

- The bottomonium family ($b\bar{b}$) plays a special role in understanding how the strong force binds quarks because, due to the high quark mass, allows two important theoretical simplifications. The measurements of the masses of the $\chi_{b}(3P)$ triplet states ($J = 0, 1, \text{and } 2$), is especially interesting to probe details of the $b\bar{b}$ interaction and test theoretical treatments of the influence of open-beauty states on the bottomonium spectrum.

- The $\chi_{b}(3P)$ was observed by ATLAS in 2011 as a new structure in the $Y(1S)\gamma$ and $Y(2S)\gamma$ decay modes.

- LHCb observed the $\chi_{b}(3P)\rightarrow Y(3S)\gamma$ decay channel.

- DØ saw the $\chi_{b}(3P)$ in the $\chi_{b}(3P) \rightarrow Y(1S)\gamma$ decay channel.

- CMS saw the $\chi_{b}(3P)$ in the $Y(1S), Y(2S), \text{and } Y(3S)$ radiative decays, in the 7 TeV data.
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states – $\Upsilon$ candidates

New result from CMS: the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states and their masses measurement through the decay channel

$\chi_{b}(3P) \rightarrow \Upsilon (3S) \gamma$

Based on pp data, at a center-of-mass energy of 13 TeV, in 2015, 2016, and 2017, corresponding to integrated luminosities of 2.7, 35.2, and 42.1 fb$^{-1}$ (80 fb$^{-1}$ total)

$\Upsilon(3S) \rightarrow \mu^+\mu^-$ decay triggering (@HLT) the event with a $\mu\mu$ pair with two opposite sign $\mu$ coming from a common vertex:

- $8.5\,\text{GeV} < M(\mu\mu) < 11.5\,\text{GeV}$
- $p_T(\mu\mu) > 7.9\,\text{GeV} \quad |y| < 1.25 \,(2015\text{-}2016)$
- $p_T(\mu\mu) > 11.9\,\text{GeV} \quad |y| < 1.5 \,(2017)$

The background level in the $\Upsilon(3S) \, \gamma$ mass distribution is reduced by selecting a high purity $\Upsilon(3S)$ sample:

- $M(\mu\mu) < M(\Upsilon(3S)) + 2.5 \, \sigma_m(y)$
  [assures S/B ratio > 0.5]
- $M(\mu\mu) > M(\Upsilon(3S)) - n_\sigma \sigma_m(y)$
  [reduces $\Upsilon(2S)$ contamination]

$n_\sigma = 2 \quad |y| < 0.9 \quad n_\sigma = 1.5 \quad 0.9 < |y| < 1.2$
The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states – $Y$ candidates

New result from CMS: the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states and their masses measurement through the decay channel

$$\chi_{b}(3P) \rightarrow Y(3S)\gamma$$

$\gamma \rightarrow e^+ e^-$ converted photon  \hspace{1cm} | \eta | < 1.2 \hspace{1cm} p_T > 500$ MeV

For an higher resolution, at the cost of a reduced yield (w.r.t. calorimetric energy measurements), only $e^+ e^-$ from a conversion in the beam pipe or in the tracker are considered [1].

For a more accurate measure the photon energy scale (PES) is calibrated through a $\chi_{c1} \rightarrow J/\psi \gamma \rightarrow \mu^+ \mu^- \gamma$ sample.

$$P.E.S. = \frac{m_{\mu\mu\gamma}^2 - m_{\mu\mu}^2}{M(\chi_{c1})^2 - M(J/\psi)^2}$$

The resulting function is then used for the event-by-event correction of the photon energy in the computation of the $Y\gamma$ invariant mass

The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ signal peaks are modeled with a double-sided Crystal Ball, and the total yield is $372 \pm 36$, with the two masses (in MeV):

$$M[\chi_{b2}(3P)] = 10524.02 \pm 0.57 \text{ (Stat)} \pm 0.18 \text{ (Sys)}$$
$$M[\chi_{b1}(3P)] = 10513.42 \pm 0.41 \text{ (Stat)} \pm 0.18 \text{ (Sys)}$$

N.B. the measured low mass peak resolution:
- $2.18 \pm 0.32$ MeV in $Y(3S)\gamma$ mass distribution
- $7$ MeV and $15$ MeV in $Y(1S)\gamma$ and $Y(2S)\gamma$

Most of the theoretical predictions give a positive $\Delta M$: $9 < \Delta M < 18$ MeV (see backup). The only exception [1] give $\Delta M = -2$ MeV

CMS, with $80 fb^{-1} 13$ TeV pp data collected in 2015, 2016 and 2017, has been able to make the first observation of the doublet structure of the $\chi_{b}(3P)$ resonance. The mass difference between the $J = 1, 2$ states is measured to be:

$$M[\chi_{b2}(3P)] - M[\chi_{b1}(3P)] = 10.60 \pm 0.64 \text{ (stat)} \pm 0.17 \text{ (syst)} \text{ MeV}$$

The $\Delta M$ between the $J = 1$ and 2 states measured by CMS is significantly larger than 2 MeV: this supports the standard mass hierarchy.


Main systematic uncertainties:
- PES fit function (0.16 MeV)
- Bkg+CB fit functions (0.05 MeV)
- NO w.a. $Y(3S)$ mass uncertainty
Production of $\psi(2S)$ and $X(3872) \rightarrow J/\psi \pi^+\pi^-$

JHEP01 (2017) 117
Production of $\psi(2S)$ and $X(3872) \to J/\psi\pi^+\pi^-$

The $X(3872)$ is the first exotic state discovered in the decays $B^+ \to K^+ X(3872) \to K^+ (J/\psi\pi\pi)$ and confirmed by $\bar{p}p$ collisions - mainly prompt production: only $\sim 16\%$ from mesons. Largely confirmed also by LHC experiments (CMS, ATLAS, LHCb):

- $X(3872)$ now measured as $J_{PC}=1^{++}$, $M=3871.69 \pm 0.17$ MeV

Very close to $D^0 D^{0*}$ threshold; tetra-quark, molecule ($D^0 D^{0*}$ loose), mixed state? Still not clear (since 2003!)

8TeV 11fb$^{-1}$ pp data, ATLAS has studied the $J/\psi \pi\pi$ final state comparing $X$ and $\psi(2S)$ productions

- $|y| < 0.75$, $\Delta R(J/\psi, \pi^\pm) < 0.5$, $Q < 0.3$ GeV
- use $\tau = \frac{L_{xy} m}{c p_T}$ to select 4 pseudo-proper decay time bins
- $10 < p_T < 70$ GeV

12 < $p_T$ < 16 GeV $\quad$ lyl < 0.75

**ATLAS**

$\sqrt{s}=8$ TeV, 11.4 fb$^{-1}$

Data: -0.3 < $\tau$ < 0.025 ps ($w_0$)  
- Data: 0.025 < $\tau$ < 0.3 ps ($w_1$)  
- Data: 0.3 < $\tau$ < 1.5 ps ($w_2$)  
- Data: 1.5 < $\tau$ < 15 ps ($w_3$)
Production of $\psi(2S)$ and $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

In each $t$ bin the yield ($Y$) of $X$ and $\psi$ is determined:

$$f(m) = Y_\psi \left( f_1 G_1^\psi(m) + (1 - f_1) G_2^\psi(m) \right) + Y_X \left( f_1 G_1^X(m) + (1 - f_1) G_2^X(m) \right) + N(m - m_{th}) \epsilon p_2^{m - m_{th}} P(m - m_{th}),$$

The $p_T$-dependence of the $\sigma \cdot B$ ratio for prompt & non-prompt contributions:

Non-prompt split into:
- long lived
  - assumed to originate from the usual mix of $b$-mesons and $b$-baryons
- short lived
  - assumed to originate from $B_C$ mesons

Production of $B_c$ mesons in high-energy hadronic collisions - at low $p_T$ - is expected to be dominated by non-fragmentation processes. These processes are expected to have a $p_T$-dependence $\propto 1/p_T$ relative to the fragmentation contribution that instead dominates the production of long-lived $b$-hadrons.

$$\frac{\sigma(pp \rightarrow B_c) B(B_c \rightarrow X(3872))}{\sigma(pp \rightarrow non-prompt \ X(3872))} = (25 \pm 13(stat) \pm 2(sys) \pm 5(spin))\%$$  [for $p_T > 10$ GeV]

Since $B_c$ production is only a small fraction of the inclusive beauty production, this result could indicate that the production of $X(3872)$ in $B_c$ decays is enhanced compared to its production in the decays of other $b$-hadrons.
Production of $\psi(2S)$ and $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

Comparing results with theoretical predictions (with uncertainties):

- **ATLAS** data and NLO NRQCD predictions for $\psi(2S)$ decays.

**Prompt:** compares well to NLO NRQCD

**Non-prompt:** FONLL, rescaled from $\psi(2S)$ prediction with kinematic template fit, overestimates data by factor 4 – 8.

For both states, di-pion decays through $\rho_0$ strongly favoured.

Mixture of $\chi_{c1}(2P)$ and $D^0D^{0*}$ molecular state.
$B_c^+$ and $B^+$ production cross sections

CMS PAS BPH-13-002
$B_c^+$ and $B^+$ production

$B^+(B^-)$ is the b-quark meson with the largest production rate composed of $u\bar{b}(\bar{u}b)$. $B_c^+(B_c^-)$ meson is a ground state of $\bar{b}c(b\bar{c})$ system and contains two heavy quarks of different flavours and its production is then much rarer $[\bar{b}b + \bar{c}c]$.

CMS has reported the inclusive and differential $(\gamma & p_T) \sigma \cdot B$

\[
B_c^\pm \rightarrow J/\psi (\rightarrow \mu\mu) \pi^\pm \quad B^\pm \rightarrow J/\psi (\rightarrow \mu\mu)K^\pm
\]

Theoretical prediction uncertainties up to 40%: renormalization, factorization scales and the $m_b$ dependencies.

Results from 4.77 fb$^{-1}$ Run I pp collisions @ 7 TeV: event selection based on displaced dimuon triggers.

\[\text{Kinematic region} \quad p_T > 10 \text{ GeV/c and } |y| < 1.5 \] to maximize $B_c^+$ significance $[S/\sqrt{(S+B)}]$.

\[S \text{ from Gaussian fit to MC} \quad [\text{BCVEGPY } gg \rightarrow B_c + b + c] \]

\[B \text{ from from } J/\psi \pi^+ \text{ sidebands in data} \]
**B_c^+ and B^+ production**

- **Inclusive** $\sigma \cdot B$ \[ p_T > 10 \text{ GeV/c} \quad |y| < 1.5 \]

  \[ B_c^\pm \rightarrow J/\psi \pi^\pm : 40.8 \pm 4.7 \text{ (stat)} \pm 2.8 \text{ (syst)} \text{ pb} \]

  \[ B^\pm \rightarrow J/\psi K^\pm : 5851.3 \pm 37.1 \text{ (stat)} \pm 446.4 \text{ (syst)} \text{ pb} \]

- **Differential** $\sigma \cdot B$ is measured in $p_T$ (and analogously $|y|$)

\[
\frac{d\sigma(pp \rightarrow B_c^+(B^+) X)}{dp_T(B_c^+, B^+)} \cdot B(B_c^+(B^+) \rightarrow J/\psi \pi^+(K^+)) = 2 \epsilon \cdot B(J/\psi \rightarrow \mu \mu) \cdot \Delta p_T(B_c^+, B^+) \cdot \mathcal{L}' \]

No. of candidates extracted by ML fit

The $\epsilon$ takes into account the **MC calculated** acceptance $A$ and the reconstruction efficiency $\epsilon_{\text{reco}}$ and the scale factors $(a_\mu, a_{\text{Disp}})$ to cover the discrepancy between corresponding efficiencies in data and MC [via Tag&Probe in both cases]

- **The experimental results for** $B_c^\pm$ compared to BCVEGPY with $B(B_c^\pm \rightarrow J/\psi \pi^\pm) = 3.3 \times 10^{-3}$

### Table:

<table>
<thead>
<tr>
<th>$p_T(B_c^\pm)$ (GeV)</th>
<th>$n_{\text{sig}}$</th>
<th>$\epsilon$</th>
<th>$d\sigma/dp_T(B_c^\pm) \times \mathcal{B}$ (pb/GeV)</th>
<th>BCVEGPY (pb/GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-16</td>
<td>101.0 ± 23.0</td>
<td>0.0050 ± 0.0001</td>
<td>5.48 ± 1.25 ± 0.42</td>
<td>2.02</td>
</tr>
<tr>
<td>16-22</td>
<td>101.3 ± 18.1</td>
<td>0.0380 ± 0.0005</td>
<td>0.77 ± 0.14 ± 0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>22-50</td>
<td>107.0 ± 18.1</td>
<td>0.1030 ± 0.0014</td>
<td>0.06 ± 0.01 ± 0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>$</td>
<td>y</td>
<td>(B_c^\pm)$</td>
<td>$n_{\text{sig}}$</td>
<td>$\epsilon$</td>
</tr>
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<td></td>
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<tr>
<td>0-0.5</td>
<td>99.6 ± 16.3</td>
<td>0.0122 ± 0.0001</td>
<td>28.23 ± 4.62 ± 2.07</td>
<td>10.20</td>
</tr>
<tr>
<td>0.5-0.9</td>
<td>101.6 ± 18.8</td>
<td>0.0139 ± 0.0002</td>
<td>31.77 ± 5.87 ± 2.48</td>
<td>9.91</td>
</tr>
<tr>
<td>0.9-1.5</td>
<td>99.3 ± 20.9</td>
<td>0.0137 ± 0.0002</td>
<td>21.07 ± 4.44 ± 1.51</td>
<td>9.03</td>
</tr>
<tr>
<td>inclusive</td>
<td></td>
<td>$n_{\text{sig}}$</td>
<td>$\sigma \times \mathcal{B}$ (pb)</td>
<td>BCVEGPY (pb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>309.68 ± 35.78</td>
<td>40.78 ± 4.71 ± 2.84</td>
<td>14.48</td>
</tr>
</tbody>
</table>

A scale factor $\sim 2.75$ holds
A scale factor of 2.75 holds between the experimental results and to BCVEGPY theoretical predictions. Theory has large uncertainties for a number of reasons (e.g. non-perturbative $B_c^\pm \rightarrow J/\psi X$ transition; only the color-singlet $1S$-wave and $1P$-wave $B_c^\pm$ are considered).

The shape of the measurement shows consistency with the predictions from BCVEGPY (the normalization is not consistent with the theory predictions).
**B⁺ production**

**Differential \( \sigma \cdot B \)** compared to theoretical approaches (PYTHIA, FONLL, NLO) with theoretical uncertainty of 35%.

\[ FONLL \quad f_{bb \rightarrow B^+} = 0.337 \quad m_b = 4.75 \pm 0.25 \text{ GeV}/c^2 \quad \mu_F = \mu_C = \mu_0 \]

The **theoretical predictions** are in good agreement with the measurements. Also the inclusive **\( \sigma \)**

\[
\sigma_{\text{FONLL}} = 4896.8^{+1667.6}_{-1086.7} \text{(scale)} \pm 249.3 \text{ (mass)}
\]

Good agreement with previous experimental results:

\[
\left( \sigma(B^±_c \rightarrow J/\psi \pi^±) / \sigma(B^± \rightarrow J/\psi K^±) \right) = 0.49 \pm 0.06 \%
\]

\[ = [0.48 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.05 \text{ (} \tau_{B_c} \text{)}] \% \quad [1]
\]

\( \sigma \) for [13 < \( p_T \) < 120 \text{ GeV}/c, |y| < 1.5] common ph.sp.

\[ = 163.1 \pm 2.27 \text{ (stat)} \pm 9.13 \text{ (sys)} \quad [2]
\]

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Production of $b$-hadron pairs

JHEP11 (2017) 062
Production of b-hadron pairs

- Small angle ($\Delta R$) production of $bb$ pairs in $pp$ collisions, within the context of $b$- and $c$- quarks production, provides a particularly useful mean of investigation:
  - high sensitivity to the details of QCD predictions
  - main background for $VH$ ($\rightarrow bb$) processes

1) b-hadron from $b \rightarrow J/\psi (\rightarrow \mu \mu) + X$ (feed down included)
2) b-hadron from $b \rightarrow \mu + Y$ (semileptonic cascade included)

Three $\mu$ final state
- $p_T(\mu_{1,2,3}) > 6$ GeV
- $|\eta (\mu_{1,2})| < 2.3$
- $|\eta(\mu_3)| < 2.5$

Disentangle prompt, non-prompt, fake yields:
- $J/\psi$ from 2D mass-lifetime fit;
- Selection of $J/\psi$ with $|\tau| > 0.25$ mm/c and tighter mass cut $2.95 < m(J/\psi) < 3.25$ GeV
- $\mu_3$ from 2D $d_0$ significance x BDT output fit;

8TeV 11fb$^{-1}$ pp data
Production of b-hadron pairs

- Small angle ($\Delta R$) production of bb pairs in pp collisions, within the context of b- and c- quarks production, provides a particularly useful mean of investigation:
  
  - high sensitivity to the details of QCD predictions
  - main background for VH ($\rightarrow$ bb) processes

1) b-hadron from $b \rightarrow J/\psi (\rightarrow \mu\mu) + X$ (feed down included)
2) b-hadron from $b \rightarrow \mu + Y$ (semileptonic cascade included)

Irreducible backgrounds (e.g. sail-through, c-hadrons semileptonic, $B_c \rightarrow J/\psi + \mu + X$) are subtracted.

Most of the systematics come from $\mu$ trigger, reco efficiencies, $J/\psi$ model fit and background components.
Production of b-hadron pairs

Total measured cross section in the fiducial region

\[ \sigma(B(\rightarrow J/\psi[\rightarrow \mu^+\mu^-] + X)B(\rightarrow \mu + X)) = 17.7 \pm 0.1\text{(stat)} \pm 2.0\text{(syst)} \text{ nb.} \]

Differential cross-sections compared to: PYTHIA8 with different $g \rightarrow bb$ splitting kernel options

\[ \Delta R(J/\psi, \mu) \]

\[ m(J/\psi, \mu) \]
Production of b-hadron pairs

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Differential cross-sections compared to: different generators (Herwig, Sherpa …)

PYTHIA 8: pt splitting closest agreement
Production of $b$-hadron pairs

- Total measured cross section in the fiducial region

\[
\sigma(B(\rightarrow J/\psi[\rightarrow \mu^+\mu^-] + X)B(\rightarrow \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}) \text{ nb.}
\]

- $|\eta(\mu)| < 2.5$
- $|\eta(\mu_2)| < 2.3$
- $p_T(\mu_1, 2, 3) > 6 \text{ GeV}$

- $g \rightarrow bb$ splitting kernel tested for PYTHIA8 and comparison of multiple generators (PYTHIA 8 $p_T$ splitting & Herwig++ best agreement)

- Normalised differential cross sections were measured for **several kinematic observables** (see back-up for further plots).

\[
\Delta R(J/\psi, \mu) \quad y_{\text{boost}} \quad p_T(J/\psi, \mu) \quad p_T/m \quad \Delta y(J/\psi, \mu) \quad m(J/\psi, \mu) \quad \Delta \phi(J/\psi, \mu)
\]

In particular, the measurement of the production of **nearby $b$-hadron** pair down to $\Delta R \to 0$ provides new inputs for constraining further measurements.
"I am putting myself to the fullest possible use, which is all I think that any conscious entity can ever hope to do"

HAL9000
BACKUP
**Prompt production @ 7TeV**

**Charmonium S-wave States** [uncertainties from int. luminosity and branching fractions not included]

![Graph showing data for charmonium S-wave states](Image)

**Bottomonium S-wave States** [uncertainties from int. luminosity not included]

![Graph showing data for bottomonium S-wave states](Image)

---

\[ B \cdot \frac{d\sigma^2}{dydp_T} \]

significant improvement in terms of precision and \( p_T \) reach (\( p_T \approx 100 \text{GeV} \)) w.r.t. previous CMS results CMS, e.g. [1]

**Blue curve** shows a power-law fit to \( J/\psi \) cross sections

**FKLSW**: calculation of the \( \psi(2S) \) cross sec. using LDMEs determined in a global fit of cross secs. and polarizations: \( \psi(2S) \) predominantly unpolarized

---

\[ B \cdot \frac{d\sigma}{dp_T} \]

All 3 \( Y(nS) \) states show similar trends

Transition from exponential to power-law behaviour at \( p_T \approx 20 \text{ GeV} \) (fit holds for all the 3 states)

**NLO calculations** from [PRL 112, 032001] have been extended to cover the range \( p_T < 100 \text{ GeV} \) and describe data trend for all 3 \( Y(nS) \) states.

---

The $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

Theoretical predictions refs


Production of b-hadron pairs

**PYTHIA8 with different $g \rightarrow bb$ splitting kernel options**

<table>
<thead>
<tr>
<th>Option label</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. 1</td>
<td>The same splitting kernel, $(1/2)(z^2 + (1-z)^2)$, for massive as massless quarks, only with an extra $\beta$ phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method.</td>
</tr>
<tr>
<td>Opt. 4</td>
<td>A splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, normalised so that the $z$-integrated rate is $(\beta/3)(1+r/2)$, and with an additional suppression factor $(1-m_{qq}^2/m_{dipole}^2)^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2.</td>
</tr>
<tr>
<td>Opt. 5</td>
<td>Same as Option 1, but reweighted to an $\alpha_s(k m_{qq}^2)$ rather than the normal $\alpha_s(p_T^2)$, with $k = 1$.</td>
</tr>
<tr>
<td>Opt. 5b</td>
<td>Same as Option 5, but setting $k = 0.25$.</td>
</tr>
<tr>
<td>Opt. 8</td>
<td>Same as Option 4, but reweighted to an $\alpha_s(k m_{qq}^2)$ rather than the normal $\alpha_s(p_T^2)$, with $k = 1$.</td>
</tr>
<tr>
<td>Opt. 8b</td>
<td>Same as Option 8, but setting $k = 0.25$.</td>
</tr>
</tbody>
</table>
Production of b-hadron pairs

Differential cross-sections compared to: PYTHIA8 with different $g \rightarrow bb$ splitting kernel options

![Graphs showing differential cross-sections compared to PYTHIA8 with different $g \rightarrow bb$ splitting kernel options.](image-url)
Production of b-hadron pairs

Differential cross-sections compared to: different generators (Herwig, Sherpa . . .)
Quarkonia production in (p+Pb and) pp

Probability density functions for individual components in the central fit model used to extract the prompt and non-prompt contributions for charmonium signals and backgrounds:

$$PDF(m_{\mu\mu}, \tau_{\mu\mu}) = \sum_{i=1}^{7} \kappa_i f_i(m_{\mu\mu}) \cdot h_i(\tau_{\mu\mu}) \otimes g(\tau_{\mu\mu})$$

<table>
<thead>
<tr>
<th>i</th>
<th>Type</th>
<th>Source</th>
<th>$f_i(m_{\mu\mu})$</th>
<th>$h_i(\tau_{\mu\mu})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$J/\psi$</td>
<td>Prompt</td>
<td>$\omega_1 C B_1(m_{\mu\mu}) + (1 - \omega_1) G_1(m_{\mu\mu})$</td>
<td>$\delta(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>2</td>
<td>$J/\psi$</td>
<td>Non-prompt</td>
<td>$\omega_1 C B_1(m_{\mu\mu}) + (1 - \omega_1) G_1(m_{\mu\mu})$</td>
<td>$E_1(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>3</td>
<td>$\psi(2S)$</td>
<td>Prompt</td>
<td>$\omega_2 C B_2(m_{\mu\mu}) + (1 - \omega_2) G_2(m_{\mu\mu})$</td>
<td>$\delta(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>4</td>
<td>$\psi(2S)$</td>
<td>Non-prompt</td>
<td>$\omega_2 C B_2(m_{\mu\mu}) + (1 - \omega_2) G_2(m_{\mu\mu})$</td>
<td>$E_2(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>5</td>
<td>Background</td>
<td>Prompt</td>
<td>$F$</td>
<td>$\delta(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>6</td>
<td>Background</td>
<td>Non-prompt</td>
<td>$E_3(m_{\mu\mu})$</td>
<td>$E_4(\tau_{\mu\mu})$</td>
</tr>
<tr>
<td>7</td>
<td>Background</td>
<td>Non-prompt</td>
<td>$E_5(m_{\mu\mu})$</td>
<td>$E_6(\tau_{\mu\mu})$</td>
</tr>
</tbody>
</table>

CB Crystal Ball - G Gaussian - E Exponential - F constant distribution - $\delta$ delta function.

The parameter $\omega_i$ is the fraction of CB component in signal.