Overview on heavy flavour and quarkonium production in $pp$ collisions

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on behalf of the collaborations of ALICE, ATLAS, CMS, and LHCb
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Outline

- Introduction
- Heavy quarkonium production
- Associated heavy quark and quarkonium production
- $B_c$ studies at the LHC
- Open charm and $b$ hadron productions
- Results from RHIC $pp$ collisions
- Summary

Disclaimer:
This is not a full review for all results. I focus on the LHC results.
Introduction

- Study of heavy flavour and quarkonium in \( pp \) collisions can help to understand QCD
  - Hadronic production mechanism of heavy quarkonium is a long standing problem

- Reference of QGP and cold nuclear matter effects studies

- Large cross-sections of heavy flavor production at high energy \( pp \) collisions
  - \( \sigma_{b\bar{b}} \approx 300 - 500 \ \mu\text{b} \) @ 7 – 14 TeV
  - \( \sigma_{c\bar{c}} \approx 15 \ \sigma_{b\bar{b}} \)
LHC detectors and coverage
Heavy quarkonium production

- $\eta_c (1S)$
- $J/\psi, \psi (2S), \Upsilon (nS)$
- $\chi_c, \chi_b$
Prompt and non-prompt separation

- A fraction of charmonium states comes from $b$-hadron decays
  - **prompt**: direct and feed-down
  - **non-prompt**: from $b$-hadron decays

- Prompt and non-prompt separated by pseudo proper time in longitudinal or transverse direction

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LHCb, EPJC 71 (2011) 1645
**$\eta_c(1S)$ production**

- Different $p_T$ dependence for $\eta_c$ and $J/\psi$ expected by NRQCD
- LHCb reconstructed $\eta_c(1S)$ using $\eta_c \rightarrow p\bar{p}$ decay
  - thanks to excellent LHCb PID for hadrons
  - $J/\psi \rightarrow p\bar{p}$ used as reference channel
- Clear signal peaks in “from-$b$” sample
  - Used to fix prompt signal shapes
- Natural width and $\Delta m = m(J/\psi) - m(\eta_c)$ measured
  - $\Gamma = 25.8 \pm 5.2 \pm 1.9$ MeV/$c^2$; $\Delta m = 114.7 \pm 1.5 \pm 0.1$ MeV/$c^2$
**$J/\psi$ cross-sections**

- Measured at 2.76, 7 and 8 TeV, up to $p_T < 120$ GeV/c
- NLO NRQCD gives good description on data
- Energy dependence for non-prompt $J/\psi$ agrees with FONNL (Fixed Order plus Next-to-Leading Logarithms)

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**Graphs and Tables**

1. **CMS, JHEP 02 (2012) 011**
   - CMS, PAS BPH-14-001

2. **LHCb, JHEP 06 (2013) 064**
   - Energy dependence

3. **ATLAS, NPB 850 (2011) 387**

4. **ALICE, EPJC 74 (2014) 2974**
   - Multiplicity dependence

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**References**

- ATLAS, NPB 850 (2011) 387
- CMS, PAS BPH-14-001
- LHCb, JHEP 06 (2013) 064
- ALICE, EPJC 74 (2014) 2974
ψ(2S) production

- Feed-down negligible: good to compare with theory
- $\psi(2S) \rightarrow \mu^+\mu^-$ and/or $J/\psi \pi^+\pi^-$ used

Fraction of $J/\psi$ from $\psi(2S)$
$\Upsilon(nS)$ production

- Similar analyses using $\Upsilon(nS) \rightarrow \mu^+ \mu^-$ decay channels
- Same theoretical models, but with different feed-down contributions

ATLAS, PRD 87 (2013) 052004

 CMS, PAS BPH-12-006

LHCb, JHEP 06 (2013) 064
\[ \Upsilon(nS) \] production: differential cross-sections

- CMS: shape transitions from exponential to power-law at \( p_T = 20 \text{ GeV/c} \)
- Shapes similar across all \( \Upsilon(nS) \) states

\[ \begin{aligned}
&\text{CMS Preliminary} \\
&pp, \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.9 \text{ fb}^{-1} \\
&\Upsilon(1S), \gamma(\mu\mu) = 0.6 \\
&\text{Exponential fit: } 10 < p_T < 20 \text{ GeV} \\
&\text{Power-law fit: } 20 < p_T < 100 \text{ GeV} \\
\end{aligned} \]
Consistency between LHC experiments

Graph showing the distribution of $d\sigma / dy$ [nb] for ALICE, CMS, ATLAS, and LHCb. The plot represents data at $\sqrt{s} = 7$ TeV with $8 < p_T < 15$ GeV.

Luminosity uncertainties:
- ALICE: $\pm 3.5\%$
- CMS: $\pm 4.0\%$
- ATLAS: $\pm 3.4\% (J/\psi), \pm 3.9\% (Y)$
- LHCb: $\pm 10\% (J/\psi), \pm 3.5\%$ (others)

Plot from H. Woehri @ Quarkonium 2014
χc production

- Reconstructed in the χc → J/ψγ decay mode, with a converted photon or a photon detected in calorimeters
- Good agreement of dσ/dp_T with NLO NRQCD
- Large fraction of J/ψ comes from χc decays: 20 – 30%
  - Good agreements with NLO NRQCD and between experiments
\( \chi_b \) production

- Similar analyses using \( \chi_b \rightarrow \Upsilon(nS)\gamma \) decays
- Photons reconstructed by \( e^+e^- \) or detected in calorimeters
- \( \chi_b(3P) \) first observed by ATLAS
- \( \chi_{b2}/\chi_{b1} \) production ratio measured
  - Nice agreement between CMS and LHCb

ATLAS, PRL 108 (2012) 152001
CMS, arXiv:1409.5761
LHCb, JHEP 10 (2014) 088
**$\chi_b$ production: feed-down**

- Production ratio of $\chi_b(mP)$ relative to $\Upsilon(nS)$ by LHCb
- Large fraction of $\Upsilon(nS)$ from feed-down: $\sim 30\%$

LHCb, EPJC 74 (2014) 3092
**$X_b$ search**

- Hidden-beauty counterpart of $X(3872)$
- Searched in $\Upsilon(1S)\pi^+\pi^-$: no evidence, upper limits are set
- No evidence for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$

**ATLAS, PLB 740 (2015) 199**
**CMS, PLB 727 (2013) 57**
Associated production

- Study of single parton scattering (SPS) and double parton scattering (DPS)
  - $J/\psi$ (open charm) + $J/\psi$ (open charm)
  - $J/\psi$ (open charm) + $W(Z)$
Associated production

ATLAS, JHEP 04 (2014) 172
CMS, JHEP 02 (2014) 013
LHCb, PLB707 (2012) 052
LHCb, JHEP 06 (2012) 141

CMS: $W + c$

$\sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}$
(theory: $\sigma = 4 \text{ nb}$)

PRD84 (2011) 094023
$B_c$ studies at the LHC

- Unique meson with two open heavy flavours
  - Rich spectrum and decay modes
- Mass, lifetime and production measured more precisely
- Many new $B_c$ decay channels observed, e.g.,
  - $B_c^+ \rightarrow B_s^0\pi^+$  first $B$ to $B$ weak decay
  - $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$ first $B_c$ baryonic decay
- Excited S-wave state observed by ATLAS
$B_c$ differential production

- Double differential production ratio
  \[ R(p_T, y) = \frac{d\sigma_{B^+_c}(p_T, y)B(B^+_c \rightarrow J/\psi\pi^+)}{d\sigma_{B^+}(p_T, y)B(B^+ \rightarrow J/\psi K^+)} \]

- Dependence on $p_T$ and $y$ observed
  - Agree with BCVEGPy

- $R = (0.683 \pm 0.018 \pm 0.009)\%$
  ($p_T < 20 \text{ GeV}/c; 2.0 < y < 4.5$)

LHCb, arXiv:1411.2943
Observation of excited $B_c$ states

- ATLAS observed excited $S$-wave state in $B_c^{\pm} \pi^+ \pi^-$ final state
- $m = 6842 \pm 4 \pm 5 \text{ MeV}/c^2$

ATLAS, PRL113 (2014) 212004
Open charm and beauty at the LHC

- Open charm productions
- $B$-meson productions
- Electrons from heavy flavor
Open charm production

- Differential cross-sections of $D^0$, $D^+$, $D^{*+}$, $D_s^+$ and $\Lambda_c^+$
- Agree with FONLL (JHEP 10 (2012) 137) and GMVFNS (EPJC 72 (2012) 2082)
- Yield increases with multiplicity, similar trend for both $D$ and $J/\psi$
- Compatible azimuthal correlation distributions in $pp$ and $p\text{Pb}$
$B$ mesons production

- Differential cross-sections of $B^+$, $B^0$, and $B_s^0$
- Well agree with FONLL (JHEP 03 (2001) 006)
- $\sigma(pp \to B^\pm X) = 41.4 \pm 1.5_{\text{stat}} \pm 3.1_{\text{syst}} \mu b \ (p_T < 40 \text{ GeV}/c, \ 2.0 < y < 4.5)$
- $f_{\bar{b} \to B^+} = (40.1 \pm 1.3)\%$

ATLAS, JHEP 10 (2013) 042
CMS, PRL 106 (2011) 112001
CMS, PRL 106 (2011) 252001
CMS, PRD 84 (2011) 052008
LHCb, JHEP 04 (2012) 039
Electrons from heavy flavour

- Electrons from semileptonic decays of heavy-flavour hadrons measured at 2.76 TeV
- Agree with theory

**Beauty-decay electrons**

**dσ_{b\bar{b}}/dy vs \sqrt{s}**

ALICE arXiv:1405.4117
ALICE PLB738 (2014) 97
Heavy flavour at RHIC

- $J/\psi$ and $\psi(2S)$
- Open charm
$J/\psi$ and $\psi(2S)$ at RHIC

- $J/\psi$ production at $\sqrt{s} = 200$ (500)GeV
  - Agree with NLO NRQCD
  - Follows $x_T$ scaling with $n = 5.6$ for $p_T > 5$ GeV/c
    \[
    x_T \equiv \frac{2p_T}{\sqrt{s}} ; \frac{d^2\sigma}{2\pi p_T dp_T dy} \equiv g(x_T)/(\sqrt{s})^n
    \]

- $\psi(2S)$ production relative to $J/\psi$
  - First measurement at $\sqrt{s} = 500$ GeV
  - Consistent with other results
  - Constrain feed-down from $\psi(2S)$

New Forward Silicon Vertex Tracker in PHENIX helps improve mass resolution and bkg rejection

First result of forward $\psi(2S)$ to $J/\psi$ ratio at RHIC
Open charm at RHIC

- Open charm cross-sections down to very low $p_T$ ($\sim 0.4$ GeV/$c$)
- Consistent with FONLL
Summary

Many measurements of heavy quark and quarkonium in $pp$ collisions have been made at the LHC

- $\eta_c(1S)$ production using $\eta_c \rightarrow p\bar{p}$
- Cross-sections of $J/\psi, \psi(2S), \Upsilon(nS)$ in a wide range of rapidity and transverse momentum
- $\chi_c$ and $\chi_b$ productions, and the ratios of $\chi_{c2}/\chi_{c1}$ and $\chi_{b2}/\chi_{b1}$
- Associated productions: double $J/\psi, J/\psi$ (open charm) + $W(Z)$, $J/\psi$ + open charm, and open charm+open charm
- $B_c$ studies: differential production, excited states, new decays
- open charm and $b$-hadron productions
- Electrons from heavy flavour decays

Results from RHIC at $\sqrt{s} = 500$ GeV or lower

More results using the LHC RUN I and RUNN II data expected

Thank you!
Backup slides
Polarisation of $J/\psi$, $\psi(2S)$ and $\Upsilon(nS)$

- ALICE first measured $\lambda_\theta$ of $J/\psi$ in $pp$ at 7 TeV
- LHCb measured polarisation of $J/\psi$ and $\psi(2S)$
- CMS additionally measured polarisation of $\Upsilon(nS)$
- ALICE, CMS and LHCb results agree well
Data taking of LHC experiments

LHC 2011 RUN (3.5 TeV/beam)

- ATLAS 5.626 fb$^{-1}$
- CMS 6.136 fb$^{-1}$
- LHCb 1.217 fb$^{-1}$
- ALICE 4.877 pb$^{-1}$

PRELIMINARY

LHC 2012 RUN (4 TeV/beam)

- ATLAS 23.269 fb$^{-1}$
- CMS 23.269 fb$^{-1}$
- LHCb 2.192 fb$^{-1}$
- ALICE 9.678 pb$^{-1}$

PRELIMINARY

(generated 2012-06-21 00:39 including fill 2267)

(generated 2013-01-29 18:28 including fill 3453)
$J/\psi$ polarisation

Polarisation measured at $\sqrt{s} = 200$ GeV
LHCb in a nutshell

Impact parameter: \( \sigma_{IP} = 20 \, \mu m \)
Proper time: \( \sigma_\tau = 45 \, \text{fs} \) for \( B_s^0 \to J/\psi \phi \) or \( D_s^+ \pi^- \)
Momentum: \( \Delta p/p = 0.4 \sim 0.6\% \) (5 – 100 GeV/c)
Mass: \( \sigma_m = 8 \, \text{MeV}/c^2 \) for \( B \to J/\psi X \) (constrained \( m_{J/\psi} \))
RICH \( K - \pi \) separation: \( \epsilon(K \to K) \sim 95\% \) mis-ID \( \epsilon(\pi \to K) \sim 5\% \)
Muon ID: \( \epsilon(\mu \to \mu) \sim 97\% \) mis-ID \( \epsilon(\pi \to \mu) \sim 1 \sim 3\% \)
ECAL: \( \Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})} \)

Candidates/(25 MeV/c^2)

υ(1S) JHEP 06 (2013) 064
υ(2S)
υ(3S)
Quarkonium analyses at the LHC

- Most analyses use dimuon final states
  - Low background, good mass resolution

\[
\begin{align*}
\sigma &= 14 \text{ MeV} \\
2.5 < \eta(\mu) < 5.0
\end{align*}
\]

\[
\begin{align*}
\sigma &= 46 \text{ MeV} \\
|\eta(\mu)| < 2.7
\end{align*}
\]

\[
\begin{align*}
\sigma &= 72 \text{ MeV} \\
2.5 < \eta(\mu) < 4.0
\end{align*}
\]

\[
\begin{align*}
\sigma &= 21 \text{ MeV} \\
|\eta(\mu)| < 2.4
\end{align*}
\]
$W$+open charm production

CMS, JHEP 02 (2014) 013
$J/\psi + W$ production

Naively, one expects DPS to be flat in azimuthal opening angle if the two processes are entirely uncorrelated... so is this an indication of DPS and SPS $J/\psi + W$ production?

No acceptance corrections

Looks as though the estimated SPS contribution isn’t fully accounted for by theory... note this erratum to the CS prediction: PL B 738 (2014) 529-529 - reduces CS component

Slide from James Catmore @ QWG2014
\( J/\psi + Z \) production

\[ \text{Lowest pT bin } \sim \text{mostly DPS} \]

\[ \text{SPS drops off less steeply with } p_T \text{ than DPS so highest bins are SPS dominated} \]

\[ \text{Theory discrepancy gets more pronounced with increasing } p_T \text{ c.f. inclusive spectra, where NRQCD now does a reasonable job} \]

Slide from James Catmore @ QWG2014
Ratio of $\chi_{c2}/\chi_{c1}$

- Ratio of $\chi_{c2}/\chi_{c1}$ is also interesting
- Nice agreement between experiments
- Nice agreement with NLO NRQCD at high $p_T$

ATLAS, JHEP 07 (2014) 154
CMS, EPJC 72 (2012) 2251
LHCb, JHEP 10 (2014) 115
$D_s^+ - D_s^-$ PRODUCTION ASYMMETRY

Measured with decays $D_s^{\pm} \rightarrow \phi\pi^{\pm}$
- $\sim 0.8$ million signal decays in $1 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$.

Production asymmetry in bins of $D_s^{\pm} (p_T, y)$

$$A_P = \frac{\sigma D_s^+ - \sigma D_s^-}{\sigma D_s^+ + \sigma D_s^-}$$

Includes a precise measurement of the $\pi^{\pm}$ detection asymmetry
- With $D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^- \pi^+\pi^-\pi^+$ decays,
- Incorporated into $A_P$ determination.

3 bins in $p_T$ range [2, 25] GeV,
3 bins in $y$ range [2.0, 4.5].

Average asymmetry integrated over full range

$$A_P = (-0.33 \pm 0.22 \pm 0.10)\%$$
ALICE prompt $J/\psi$
ALICE $J/\psi$ @ 2.76 TeV
Λ^0_b production

- Λ^0_b production measured at 7 TeV
  - Using Λ^0_b → J/ψΛ
  - \( p_T > 13 \text{ GeV}/c, \ 2.2 < \eta < 4.5 \)

- \( \sigma(Λ^0_b) B(Λ^0_b → J/ψΛ) = 4.19 \pm 0.61_{\text{stat}} \pm 0.37_{\text{syst}} \text{ nb} \)
- \( \sigma(\bar{Λ}^0_b) B(\bar{Λ}^0_b → J/ψ\bar{Λ}) = 2.63 \pm 0.48_{\text{stat}} \pm 0.27_{\text{syst}} \text{ nb} \)
$\Upsilon$ in p+p from STAR

Upsilon signal upto 10 GeV

L. Kosarzewski
Hot Quarks 2014