Measurements of Heavy Flavour Production at ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

Moriond QCD, 21-28 March 2015, La Thuile

New and updated results after previous Moriond QCD

Outline:

Introduction

Charmonium production

Bottomonium production

$J/\psi + J/\psi$ production
  CMS: HEP 09 (2014) 094

$Z + J/\psi$ production
  ATLAS: arXiv:1412.6428

Summary & Prospects

Back-up: additional plots

$W + J/\psi$ production
  ATLAS: JHEP 04 (2014) 172

triggers for heavy flavour physics
Quarkonium production

**Non-prompt** (from B decays) – probes open b quark production, fragmentation and B-decay kinematics
FONLL, matched NLO+NLL (“massive” NLO + resummation) 
GM-VFNS (“massless” NLO + mass-dependent terms)

**Prompt** (not from B decays) – probes specific mechanisms of Q̅Q system production and transformation to a meson

NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.

Color Singlet Model (CSM) – only CS diagrams.
Color Evaporation Model (CEM) – only one LDME.

To separate prompt and non-prompt (from B decays) production pseudo-proper time or length is used

\[
\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|p_T|}
\]

\[
L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{|p_T|}
\]
Charmonium production: $J/\psi$, $\psi(2S)$, $\chi_c$

ATLAS, $\psi(2S)$, JHEP 09 (2014) 079
ATLAS, $\chi_{c1/2}$, JHEP 07 (2014) 154

$\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

free from feed-downs of heavier charmonium states

$\psi(2S) \rightarrow \mu^+\mu^-$

CMS, $J/\psi$ and $\psi(2S)$, arXiv:1502.04155

$\chi_{c1/2} \rightarrow J/\psi \gamma$ $m_{J/\psi \pi^+\pi^-}$ [GeV]

$J/\psi \rightarrow \mu^+\mu^-$

CMS

$\psi(2S)$

25 $< p_T < 27.5$ GeV

$|y| < 1.2$

4.9 fb$^{-1}$ (7 TeV)

$J/\psi$

21 $< p_T < 22$ GeV

$|y| < 1.2$

4.55 fb$^{-1}$ (7 TeV)
\[ \psi(2S) \rightarrow J/\psi \rightarrow \mu^+ \mu^- \pi^+ \pi^-, \text{ non-prompt diff. } x\text{-sections} \]

- generally, reasonable description by FONLL and GM-VFNS predictions are harder than data

- NLO with “wrong” (FONLL) fragmentation is even harder
\( \chi_{c1/2} \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \gamma, \text{ non-prompt diff. } x\text{-sections} \)

ATLAS, \( \chi_{c1/2} \), JHEP 07 (2014) 154

Absolute \( \chi_{c1/2} \) cross sections are measured

ATLAS

\[ \int L \, dt = 4.5 \text{ fb}^{-1} \]

Isotropic Decay

\[ \chi_{c1} \]

Non-prompt \( |y^{J/\psi}| < 0.75 \)

\[ \chi_{c2} \]

FONLL describes reasonably (somewhat harder)
$\psi(2S)$, prompt diff. x-sections

NLO NRQCD (Faccioli et al.), fitted to low-$p_T$ data, is o.k.

- NLO NRQCD is generally o.k.
- CS is too low even at NNLO*
- CEM is somewhat too hard
$\chi_{c1/2} \to J/\psi \to (\mu^+\mu^-) \gamma$, ratios for prompt diff. $x$-sections

Y.-Q. Ma, K. Wang, and K.-T. Chao

L. A. Harland-Lang and W. J. Stirling

reasonable description by NLO NRQCD

LO CSM does not describe

good agreement between LHC experiments

fraction, $R_{\chi_c}$, of prompt $J/\psi$ produced in $\chi_c$ decays
ψ(2S) and χ_{c1/2}, prompt diff. x-sections

$k_T$ –factorization predictions (CS) (Baranov et al.) need to be re-tuned
Bottomonium production: $\Upsilon, \chi_b$

CMS, $\Upsilon(1/2/3S)$, arXiv:1501.07750

Probes specific mechanisms of $b\bar{b}$ system production and transformation to a meson (CS and CO)

$\chi_{b1/2} \rightarrow \Upsilon(1S) \gamma$

$\Upsilon(1/2/3S) \rightarrow \mu^+\mu^-$
**Bottomonium production: \( \Upsilon, \chi_b \)**

CMS, \( \Upsilon(1/2/3S) \), arXiv:1501.07750

CMS, \( \chi_{b1/2} \), arXiv:1409.5761

\[
\Upsilon(1/2/3S) \rightarrow \mu^+\mu^-
\]

\[
\chi_{b1/2} \rightarrow \Upsilon(1S) \gamma
\]

NLO NRQCD (Gong et al.) describes well including harder \( p_T \) spectra of \( \Upsilon(3S) \) (not expected in CEM)

NRQCD (Likhoded et al.) not fully consistent (used NRQCD scaling rules to scale from \( \chi_{c2}/\chi_{c1} \))
Prompt $J/\psi + J/\psi$ production

CMS, $J/\psi + J/\psi$, JHEP 09 (2014) 094

Probes specific mechanisms of $c\bar{c}c\bar{c}$ system production and transformation to 2 mesons; potentially sensitive to Double Parton Scattering (DPS)

446 ± 23 prompt $J/\psi + J/\psi$
no evidence for $\eta_b$
Prompt $J/\psi + J/\psi$ production

CMS, $J/\psi + J/\psi$, JHEP 09 (2014) 094

$$\sigma(pp \rightarrow J/\psi J/\psi + X) = 1.49 \pm 0.07 \pm 0.13 \text{ nb}.$$
**Z + J/ψ production (1st obs.)**


Prompt component probes mechanisms of cc̄ system production and transformation to a meson at high scale; potentially sensitive to Double Parton Scattering (DPS)
$Z + J/\psi (\rightarrow \mu^+\mu^-)$, $\Delta\phi$ distributions and DPS

**Prompt:** $56 \pm 10$

**Non prompt:** $95 \pm 12$

\[
\sigma_{\text{eff}} = 15 \pm 3 \text{ (stat.)}^{+5}_{-3} \text{ (sys.)} \text{ mb} \quad \text{ATLAS (W + 2 jets)}
\]

\[
\sigma_{\text{eff}} > 5.3 \text{ mb (3.7 mb) at 68\% (95\%)} \quad \text{ATLAS (Z + J/\psi)}
\]
Z + J/ψ (→μ⁺μ⁻), integrated and diff. cross sections

NRQCD: Mao et al.
CSM: Gong et al.

Predictions below data
Charmonium production, Non-Prompt: FONLL and GN-VFNS agree
Prompt: only NLO NRQCD generally agree

Bottomonium production: NRQCD generally agree, tensions with $\chi_{b2}/\chi_{b1}$ description

Prompt $J/\psi + J/\psi$ production: no $\eta_b$ signature, mostly from SPS, no relevant theoretical calculations

$Z + J/\psi$ production, Prompt: NRQCD too low, CSM even lower
Non-Prompt: no predictions

More results with available 25 fb$^{-1}$ in coming months
Waterfall of results at $\sqrt{s} = 13$ TeV in 1-2 years
Back-up Slides
ATLAS+CMS @ LHC

ATLAS: weight: ~7000 tons

Run 1
25 fb$^{-1}$
7-8 TeV

Run 2
100 fb$^{-1}$

Run 3
300 fb$^{-1}$

Run 4
HL-LHC
3000 fb$^{-1}$

Peak Lumi: $6.76 \times 10^{33}$ cm$^{-2}$
$\psi(2S) \rightarrow J/\psi (\rightarrow \mu^+\mu^-)\pi^+\pi^-$

JHEP 09 (2014) 079

~ 200 000 $\psi(2S)$ mesons
- contributes to inclusive $J/\psi$ x-sections
- free from feed-downs of heavier charmonium states

To separate prompt and non-prompt (from B decays) production pseudo-proper lifetime is used

$$\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|p_T^*|} \quad L_{xy} = \frac{\vec{L} \cdot \vec{p}_T^*}{|p_T^*|}$$
\( \chi_{c1/2} \to J/\psi (\to \mu^+\mu^-) \gamma \)

**JHEP 07 (2014) 154**

To separate prompt and non-prompt (from B decays) production pseudo-proper lifetime is used

\[
\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|\vec{p}_T|} \quad \quad L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{|\vec{p}_T|}
\]
\[ \psi(2S) \rightarrow J/\psi \rightarrow \mu^+ \mu^- \pi^+ \pi^- \text{, prompt diff. x-sections} \]

- NLO NRQCD is generally o.k.
- CS is too low even at NNLO*
- CEM is somewhat too hard
$W + J/\psi \rightarrow \mu^+\mu^-$

**ATLAS, W + J/ψ, JHEP 04 (2014), 172**
**W + J/ψ (→μ⁺μ⁻), Δφ distr. and rates w.r.t. inclusive W**

DPS:

\[ \sigma_{\text{eff}} = 15 \pm 3 \text{(stat.)}^{+5}_{-3} \text{(sys.)} \text{mb} \]

10.8 ± 4.2

LO CS: Lansberg et al.  
NLO CO: Mao et al.
X(3872) Production via decays to $J/\psi \pi^+\pi^-$

Assuming $J^{PC} = 1^{++}$ unpolaredised

Ratio to $\psi(2S)$ times BR

NRQCD: significantly exceeds measured value

pT shape ok
Differential cross sections vs GM-VFNS

[Graphs showing differential cross sections with various models and data points]

ATLAS Preliminary \( \sqrt{s} = 7 \text{ TeV} \) \( L_{\text{int}} = 1.1 \text{ nb}^{-1} \)

- Data 2010, \( |\eta(D^{*\pm})|<2.1 \)
- GM-VFNS, charm only
- FONLL
- MC@NLO
- POWHEG-PYTHIA

[Graphs showing differential cross sections with various models and data points for different \( p_T(D^{*\pm}) \) values]

ATLAS Preliminary \( \sqrt{s} = 7 \text{ TeV} \) \( L_{\text{int}} = 1.1 \text{ nb}^{-1} \)

- Data 2010, \( p_T(D^{*\pm}) > 3.5 \text{ GeV} \)
- GM-VFNS, only charm
- MC@NLO
- FONLL
- POWHEG-PYTHIA
Total charm cross section

ATLAS-CONF-2011-017:

Extrapolation with NLO QCD:

\[
\sigma_{cc}^{\text{tot}} = 7.13 \pm 0.28\text{(stat.)}^{+0.90}_{-0.66}\text{(syst.)} \pm 0.78\text{(lum.)}^{+3.82}_{-1.90}\text{(extr.)}\text{mb}
\]

ALICE Coll., JHEP 07 (2012) 191:

LHC measurements of the total charm production cross section agree.
B+ Meson Production - ATLAS

\[ \frac{d\sigma(pp \rightarrow B^+X)}{dp_T} \] [\mu b/GeV]

\[ \sqrt{s}=7 \text{ TeV} \]

\[ \int L dt=2.4 \text{ fb}^{-1} \]

\[ 9 \text{ GeV} < p_T < 120 \text{ GeV} \]

\[ F_{b \rightarrow B^+}=(40.1 \pm 1.3) \% \]

CMS: \[ |y(B^+)|<2.4 \quad p_T(B^+)<30 \text{ GeV} \]
**Trigger for the Flavour Physics**

- In 2011 single muon triggers became prescaled or moved towards high $p_T$ threshold. Di-muon triggers dominated in the B-trigger menu.