Quarkonium production at LHCb

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Introduction

• Quarkonia production provides a test of QCD
• Quarkonia production mechanism is still not well understood

• Inclusive production ($J/\psi, \Upsilon, \chi_{b,c}, \eta_c$):
  – Test of Higher Order corrections
  – Relative importance of color singlet and color octet contributions
  – Tuning of MC
    $\Rightarrow$ understanding of the background for searches for new physics

• Exclusive production of charmonium
  – Pomeron exchange
  – Proble gluon PDF at low $x$
Outline

• The LHCb detector and quarkonia

• $J/\psi$ and $Y$ production

• Feeddown from $\chi_b$ to $Y$’s

• $\chi_b$ production

• $\eta_c$ production

• Exclusive production of charmonium
The LHCb detector and quarkonia

- Efficient muon trigger: $P_T(\mu_1) \times P_T(\mu_2) > 1.68 \text{ (GeV/c)}^2$
- Very good momentum resolution (0.5%): $\sigma = 13 \text{ MeV/c}^2$ on $J/\psi$
- Impact parameter resolution: $\sigma = 20 \mu\text{m} \Rightarrow$ prompt/secondary
- Very good muon identification: $\varepsilon \sim 97\%$ for ~1% $\pi \rightarrow \mu$ misid
- Backward coverage of the VELO: important for exclusive production
- Rapidity coverage: $2.0 < y < 4.5$

Results based on:
- 1fb$^{-1}$ at 7TeV (2011 data)
- 2fb$^{-1}$ at 8TeV (2012 data)
J/ψ production at 8 TeV

- J/ψ production measurement in LHCb:
  - Use J/ψ → µµ decay
  - Low pT muon trigger: 2 muons p_T > ~0.5 GeV/c
  - π→µ misid ~0.7%

  - prompt and from-b yields from 2D fit of m(µµ) and t_z
  - J/ψ is assumed to be produced unpolarized as supported by LHCb EPJ.C73(2013)2631, and ALICE PRL108(2012)082001 measurements
  - Efficiencies (trigger, µ id, reconstruction) validated using data-driven techniques

  - April 2012 (small) data sample used: 18.4±0.9 pb⁻¹
**J/ψ production at 8 TeV**

- Double differential cross-section for $p_T<15\text{GeV}/c$ and $2.0<y<4.5$

**Prompt J/ψ**

**J/ψ from-b**

In agreement with NLO NRQCD

In agreement with FONLL

PRL98(2007)252002
PRL106(2011)022003
EPJC61(2009)693

JHEP10(2012)137
JHEP05(1998)007
Y Production at 8 TeV

- Same analysis as for J/ψ (except no from-b)
- Assumption: Y not polarized as supported by CMS measurement ([PRL110(2013)081802])
- April 2012 (small) data sample used: 50.6±2.5 pb⁻¹
Y Production at 8 TeV

Y(1S)

\[
B_{1S} \times \frac{d\sigma_{1S}}{dp_T} [\text{nb/(GeV/c)}] \\
\]

\[
\begin{array}{c}
\text{CSM NLO} \quad \text{PRL98(2007)252002} \\
\end{array}
\]

\[
\begin{array}{c}
\text{CSM NNLO}^* \quad \text{PRL101(2008)152001} \\
\end{array}
\]

\[
\sum_{n=1}^{3} \text{(S)} \\
\]

\[
Y(2S) \\
\]

\[
B_{2S} \times \frac{d\sigma_{2S}}{dp_T} [\text{nb/(GeV/c)}] \\
\]

\[
\sum_{n=1}^{3} \text{(S)} \\
\]

\[
Y(3S) \\
\]

\[
B_{3S} \times \frac{d\sigma_{3S}}{dp_T} [\text{nb/(GeV/c)}] \\
\]

\[
\sum_{n=1}^{3} \text{(S)} \\
\]

• Comparison to theory:
  - CSM NLO PRL98(2007)252002 underestimates production
  - agreement with CSM NNLO* PRL101(2008)152001

!! Measurement includes feedown – not theory !!
Y feed-down from $\chi_b$

- Add a photon to the Y candidates to study the transitions

$$\chi_b(mP) \rightarrow \gamma Y (nS) \quad (pT(\gamma) > 600 \text{ MeV}/c)$$

$$m(\chi_b) = m(\mu \mu \gamma) - m(\mu \mu) + m_{\text{PDG}}(Y): \text{cancellation of the detector resolution on Y invariant mass}$$

$$\Rightarrow \text{First observation of } \chi_b(3P) \rightarrow \gamma Y (3S)!$$
Y feed-down from $\chi_b$

- Feeddown derived from:

$$R^\chi_b = \frac{N_{\chi_b}}{N_Y} \times \frac{\mathcal{E}_Y}{\mathcal{E}_{\chi_b}}$$

- Systematic uncertainties:
  - photon efficiency: 3%
  - Unknown polarisation: 1-9%
  - Modeling of the 2 $\chi_b$ spin states (relative rate and mass splitting): up to 20%

$\Rightarrow$ Feeddown $\sim$ 30% for all Y’s!

In agreement with prediction from NLO NRQCD (arxiv:1410.8537)
Relative production of $\chi_{b,c}$ spin states

- Study the relative production of the 2 spin states $\chi_{b(c)2}(1P)$ and $\chi_{b(c)1}(1P)$
  ⇒ test color octet and color singlet relative contributions
- Use converted photons in order to separate the 2 states ($\sigma=1.2$ MeV for $\chi_b$)
  - Drawback: low efficiency

⇒ $\chi_b$ and $\chi_c$ results in agreement
⇒ Ratio of cross-section ~ flat with pT
⇒ Increase predicted by LO NRQCD at low pT seems softer

⇒ better agreement with prediction from NLO NRQCD (arxiv:1410:8537)
\( \chi_b(3P) \) mass

- Using all radiative transitions \( \chi_b(3P) \rightarrow \gamma \ Y(1,2,3S) \) with converted and non-converted photons

\[
\chi_b(3P) \rightarrow Y(1S) \ \gamma(\rightarrow ee)
\]

\[
\chi_b(3P) \rightarrow Y(2S) \ \gamma(\rightarrow ee)
\]

\[
\chi_b(3P) \rightarrow Y(3S) \ \gamma
\]

\[
\Rightarrow m(\chi_{b1}(3P)) = 10512.1 \pm 2.1_{\text{exp}} \pm 0.9_{\text{model}} \text{ MeV}/c^2
\]

In agreement with ATLAS measurement: \( m(\chi_b(3P)) = 10530 \pm 5 \pm 9 \text{ MeV}/c^2 \) PRL108(2012)152001

and theoretical prediction: \( m(\chi_{b1}(3P)) \sim 10516 \text{ MeV}/c^2 \) PRD38(1988)279
\( \eta_c \) production

- Theory: NRQCD predicts different pT dependance for \( \eta_c \) and J/\( \psi \) production (due to spin difference)

- LHCb analysis:
  - Use common decay of \( \eta_c \) and J/\( \psi \) to p\( \bar{p} \) and good LHCb particle ID for protons
  - \( pT(p\bar{p}) > 6.5 \text{GeV/c} \)
  - Clear signal in from-b sample \( (t_z > 80 \text{fs}) \) used for parametrizing the prompt signal shapes \( (t_z < 80 \text{fs}) \)
  + measurement of \( \eta_c \) natural width and \( \eta_c \)-J/\( \psi \) mass difference
$\eta_c$ production

- Normalize $\eta_c$ to $J/\psi$ using $J/\psi$ absolute cross-section measurement

$\Rightarrow$ $\eta_c$ production cross sections for $2<y<4.5$ and $p_T > 6.5$ GeV/c:

$\sigma_{\eta_c(1S)}^{\sqrt{s}=7\text{ TeV}} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06 \sigma_{J/\psi, B} \text{ \mu b}$,

$\sigma_{\eta_c(1S)}^{\sqrt{s}=8\text{ TeV}} = 0.59 \pm 0.11 \pm 0.09 \pm 0.08 \sigma_{J/\psi, B} \text{ \mu b}$,

$\Rightarrow$ Input to theory for estimate of CS/CO contributions (arXiv: 1411.1247)

$\Rightarrow$ Inclusive branching fraction of b-hadrons to $\eta_c$

$\mathcal{B}(b \rightarrow \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.25 \pm 0.67_B) \times 10^{-3}$

Uncertainty from $\text{Br}(\eta \rightarrow p\bar{p})$, $\text{Br}(J/\psi \rightarrow p\bar{p})$ and $\text{Br}(b \rightarrow J/\psi X)$

$\Rightarrow$ Similar $p_T$ dependance
Exclusive charmonium production

- **Exclusive $J/\psi$, $\psi(2S)$ and $\chi_c$ production:**
  - test of QCD and pomeron exchange
  - sensitive to gluon-saturation effects
  - provides constraints on gluon PDF at small $x$ ($5 \times 10^{-6}$)

- **LHCb analysis:**
  - single $J/\psi$, $\psi(2S)$ exclusive production
  - double charmonium exclusive production: $J/\psi$, $\psi(2S)$ and $\chi_c$

⇒ **select events with**
  - exclusively 2 or 4 tracks identified as $\mu$ (no other activity)
    - Use backward extension of the vertex detector
  - no photons or 1 for $\chi_c \rightarrow J/\psi \gamma$
  - low $p_T$ ($>400\text{MeV/c}$)
Exclusive $J/\psi$ and $\psi(2S)$ production

- **Backgrounds:**
  - Non resonant (QED)
  - Feeddown ($\chi_c$)
  - Inelastic

- **Signal and inelastic background shapes:**
  - Regge theory: $\exp(-bp_T^2)$
  - $b$ parameters fitted to data in agreement with extrapolation from HERA’s data

Shapes from Regge theory
In agreement with extrapolation of HERA’s measurement
Exclusive $J/\psi$ and $\psi(2S)$ production

- Differential cross section in agreement with NLO prediction and with saturation models

LO and NLO
JHEP1311(2013)085
Double charmonium exclusive production

- Similar analysis for double exclusive production of $J/\psi$, $\psi(2S)$ and $\chi_c$

Cross sections in $2.0 < y < 4.5$ (elastic + inelastic):

$\sigma^{J/\psi J/\psi} = 58 \pm 10{\text{(stat)}} \pm 6{\text{(syst)}} \text{ pb}$,
$\sigma^{J/\psi \psi(2S)} = 63^{+27}_{-18}{\text{(stat)}} \pm 10{\text{(syst)}} \text{ pb}$,
$\sigma^{\psi(2S)\psi(2S)} < 237 \text{ pb}$,
$\sigma^{\chi_c0\chi_c0} < 69 \text{ nb}$,
$\sigma^{\chi_c1\chi_c1} < 45 \text{ pb}$,
$\sigma^{\chi_c2\chi_c2} < 141 \text{ pb}$,

2 $J/\psi$ production cross section in agreement with theory prediction but large errors on both sides.

Shapes in agreement with expectations from single production

Exclusive fraction: $42 \pm 13 \%$
Summary and Prospects

• LHCb is contributing to the progress in understanding quarkonium production:
  Inclusive
  – Differential production cross section (J/ψ, ψ(2S), Y’s, η_c)
  – Including production from b
  – Feeddown of χ_b to Y’s
  Exclusive charmonium
  – Single and double charmonium

⇒ Constraints on QCD models, PDFs, MC tuning

• Prospects
  – Bottomonium measurements are mostly statistically limited ⇒ more to come
  – Y polarisation
  – Production measurements of J/ψ, Y (ψ(2S)) will be repeated at 13 TeV with early 2015 data