Quarkonium production at the LHC: QCD corrections and new observables

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The CSM predictions account correctly for the yield

Difficulties in describing mid- and high-$P_T$ data?

Colour Octet Dominance is challenged at low/mid $P_T$ in pp

QCD corrections and polarisation

New Observables:

$Q + Q$

$Q + \gamma$
Part I

Context
the CSM predictions account for the yield

→ The yield vs. $\sqrt{s}$

- Unfortunately, very large th. uncertainties: masses, scales ($\mu_R$, $\mu_F$), gluon PDFs at low $x$ and $Q^2$, ... 
- Good agreement with RHIC, Tevatron and LHC data (multiplied by a constant $F^{\text{direct}}$)
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  - Good agreement with RHIC, Tevatron and LHC data (multiplied by a constant $F^{\text{direct}}$)
The CSM predictions account correctly for the yield $(\frac{d\sigma}{dy})$

$\rightarrow$ RHIC ($\sqrt{s} = 200$ GeV)

$\phi$ direct = 59 ± 10 %

PHENIX (PRL 09 232002)
PHENIX (2009; Prelim.)

NLO + NLO
LO

CMS
Prelim. ALICE
Prelim. ATLAS
Prelim. LHC-b

Quarkonium production at the LHC
The CSM predictions account correctly for the yield (\(\frac{d\sigma}{dy}\))

\[\rightarrow \text{RHIC (}\sqrt{s} = 200\ \text{GeV})\]

\[\rightarrow \text{LHC (}\sqrt{s} = 7\ \text{TeV})\]
Difficulties in describing mid- and high-$P_T$ data?

Impact of QCD corrections to CSM at mid and high $P_T$
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Impact of QCD corrections to CSM at mid and high \(P_T\)

\[
d\sigma/dP_T \mid_{|y|<0.4} \times Br \quad (pb/GeV)
\]

\[
\begin{array}{cccccccc}
0 & 1 & 10 & 100 & 0.001 & 0.1 & 1 & 10 \\
0 & 5 & 10 & 15 & 20 & 25 & 30 & 35 & 40 \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{LO} & \text{NLO} & \text{NNLO}\star \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{CDF data} & 1 \times 10^{-6} & 1 \times 10^{-5} & 0.0001 & 0.001 & 0.01 & 0.1 & 1 & 10 \\
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The NNLO\star is not a complete NNLO\rightarrow possibility of (large) uncanceled logs!

Two possibilities?

\[\downarrow \quad \downarrow\]

\[\text{NNLO} \approx \text{NLO} \quad \text{NNLO} \approx \text{NNLO}\star\]

\[\downarrow \quad \downarrow\]

\[\text{CO contributions likely significant} \quad \text{CS alone is enough}\]

\[\downarrow \quad \downarrow\]

\[\text{Issues with polarization unless} \quad \text{Ok with polarization}\]

\[\downarrow \quad \downarrow\]

\[e^+e^-\text{constraints on} \quad 1S [8]\]

\[\leftrightarrow \quad \text{NNLO Collinear fact.} ?\]
Difficulties in describing mid- and high-\(P_T\) data?

Impact of QCD corrections to CSM at mid and high \(P_T\)

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↓ ↓

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NNLO $\simeq$ NLO

NNLO $\simeq$ NNLO*
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\text{NNLO} & \approx \text{NLO} \\
\downarrow & \\
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\downarrow & \\
\text{Issues with polarization unless } ^3S_1^{[8]} \text{ small} & \\
\downarrow & \\
e^+e^- \text{ constraints on } ^1S_0^{[8]} & \text{ and } ^3P_J^{[8]} \\
\downarrow & \\
k_T \text{ fact.} & \leftrightarrow \text{NNLO Collinear fact. ?}
\end{align*}\]

J.P. Lansberg (IPNO)  Quarkonium production at the LHC  May 24, 2011  6 / 17
Models vs. LHCb data for the $J/\psi$ (Courtesy of J.He & P. Robbe)
Models vs. LHCb data for the $\Upsilon$ (borrowed from G. Manca, April’11)

Models vs. ATLAS data for the $J/\psi$ (borrowed from D. Price, April’11)

Difficulties in describing mid- and high-$P_T$ data?
the Colour Octet Dominance challenged at low/mid $P_T$ in pp?

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- $e^+e^- \rightarrow J/\psi gg$ CO at NLO: 0.9-1.0 pb using universality with Tevatron

IF one ignores the CSM: upper bound on CO

$$\langle 0|\mathcal{O}_{J/\psi}^{[1S_0^{(8)}]}|0\rangle + 4.0 \langle 0|\mathcal{O}_{J/\psi}^{[3P_0^{(8)}]}|0\rangle / m_c^2 \leq (2.0 \pm 0.6) \times 10^{-2} \text{ GeV}^3$$

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    \[
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ISR resummations would smear the divergence at $P_T \rightarrow 0$ out.
Would this further enhance the CO yield at low $P_T$?
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  \[ \langle 0 | \mathcal{O}^{J/\psi [^1S_0^{(8)}]} | 0 \rangle + 4.0 \langle 0 | \mathcal{O}^{J/\psi [^3P_0^{(8)}]} | 0 \rangle / m_c^2 \leq (2.0 \pm 0.6) \times 10^{-2} \text{ GeV}^3 \]

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Would this further enhance the CO yield at low $P_T$?
Y & ψ polarisation within CSM and COM


Complete modification of the CSM polarisation at NLO (also at NNLO)

α = (σ T - 2σ L) / (σ T + 2σ L)  
P_T (GeV)

LO
ϒ + bb
NLO
NNLO

COM polarisation basically unchanged at NLO

Polarisation from χ_Q Feed-down unknown at NLO:
α_{total} = F_{direct} . α_{direct} + (1 - F_{direct}) . α_{feed-down}
if α_{feed-down} ≃ 0 → F_{feed-down} α_{direct} (far from -1 and +1)

Without assumptions: If χ_Q → 3S_1 γ is E1: α_{max} from χ_Q = +1 and α_{min} from χ_Q = -0.45.

PHENIX data (|y| < 0.35)
**QCD corrections and polarisation**

**Y & ψ polarisation within CSM and COM**


→ **Complete modification** of the CSM polarisation at NLO (also at NNLO*)

\[ \alpha = \frac{\sigma_T - 2 \sigma_L}{\sigma_T + 2 \sigma_L} \]

**α** = (σ\(_T\) - 2σ\(_L\))/(σ\(_T\) + 2σ\(_L\))

**P\(_T\)** (GeV)

**LO**

**ϒ + bb**

**NLO**

**NNLO**

PHENIX data (|y|<0.35)

**direct NLO**

+ approx. Feed-down

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Quarkonium production at the LHC

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Y & ψ polarisation within CSM and COM

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→ Polarisation from $\chi_Q$ Feed-down unknown at NLO:

\[
\alpha_{tot} = F_{dir.} \alpha_{dir.} + \left(1 - F_{dir.}\right) \alpha_{FD} \quad \text{if } \alpha_{FD} \approx 0 \quad \Rightarrow \quad F_{direct} \alpha_{direct} \quad \text{(far from -1 and +1)}
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  - Without assumptions:
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![Graph showing polarisation](image-url)
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- \[ \alpha_{tot} = F_{dir} \alpha_{dir} + (1 - F_{dir}) \alpha_{FD} \]

  if \[ \alpha_{FD} \approx 0 \] then \[ F_{direct} \alpha_{direct} \] (far from -1 and +1)

- Without assumptions:

  - If \[ \chi_Q \rightarrow ^3 S_1 \gamma \] is E1: \[ \alpha_{max}^{from \chi_Q} = +1.00 \] and \[ \alpha_{min}^{from \chi_Q} = -0.45 \]
**Y & ψ polarisation within CSM and COM**

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Part II

what we expect from the LHC:
Part II

what we expect from the LHC: new measurements
New observables

→ $J/\psi + D$ or $J/\psi + \text{lepton}$ in the yield integrated over $P_T$

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010
New observables

\[ J/\psi + D \text{ or } J/\psi + \text{lepton} \text{ in the yield integrated over } P_T \]

- peak at $\Delta \phi = \pi$

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S. J. Brodsky and JPL, PRD 81 051502 (R), 2010

plot for RHIC kinematics
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  - Near $D$ or lepton: signal of $c \rightarrow J/\psi + c$ “fragmentation”
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- Near \( D \) or lepton: signal of \( c \rightarrow J/\psi + c \) “fragmentation”
- No near \( D \) in \( gg \rightarrow gg \rightarrow ^3S_1^{[8]} g \rightarrow J/\psi c\bar{c} \) (If any \( c \), both are away)
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  → $\Upsilon + b\bar{b}$: $\Upsilon + \text{one } b$ tagged jet

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$\to J/\psi + \gamma$

- At high energy, 2 gluons in the initial states: no quark
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D0, PRL102 (2009) 192002.

J.P. Lansberg (IPNO)
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- Need for a better understanding of shadowing (at small and not so small $x$)
Part IV

Backup
Describing the mid- and high-$P_T$'s: QCD corrections
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P. Artoisenet, J. P. L, F. Maltoni, PLB 653:60, 2007


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$P_T$ (GeV)

$\Upsilon (1S)$ prompt data $x$ F direct

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$\psi$ or $\Upsilon$

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Talk by M. Cervantes (STAR) at WWND 2011

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Gluon shadowing at different scales for Pb ions

http://lapth.in2p3.fr/generators

$Q^2 = 10\text{ GeV}^2$

http://lapth.in2p3.fr/generators

$Q^2 = 25\text{ GeV}^2$

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$Q^2 = 50\text{ GeV}^2$