Theory of Quarkonium production in hadron collisions

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Part I

History
Basic approach in $pp$: Common Sense Model (CSM)

Perturbative creation of 2 quarks $Q$ and $\bar{Q}$ BUT

$\alpha_3 s (2mQ)^4 P^8 T$

$\alpha_s \frac{(2mQ)^4}{P_T^8}$

Basic approach in \( pp \): Common Sense Model (CSM)

- Perturbative creation of 2 quarks \( Q \) and \( \bar{Q} \) BUT
  - on-shell (\( \times \))
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a \( ^3S_1 \) state (for \( J/\psi, \psi' \) and \( \Upsilon \))

\[ P_{T}^{8} \quad \sim \quad \frac{\alpha_{s}^{3}(2mQ)^{4}}{P_{T}^{8}} \]
Perturbative creation of 2 quarks $Q$ and $\bar{Q}$ BUT

- on-shell ($\times$)
- in a colour singlet state
- with a vanishing relative momentum
- in a $^3S_1$ state (for $J/\psi$, $\psi'$ and $\Upsilon$)

Non-perturbative binding of quarks

$\alpha_s^3 \frac{(2mQ)^4}{P_T^n}$

$\rightarrow$ Schrödinger wave function
Basic approach in \( pp \): Common Sense Model (CSM)

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Non-perturbative binding of quarks

Introduction of quark- and gluon- fragmentation processes:

\[ \alpha_s \frac{(2m_Q)^4}{P_T^2} \]
Basic approach in \( pp \): Common Sense Model (CSM)

- Perturbative creation of 2 quarks \( Q \) and \( \bar{Q} \) BUT
  - on-shell (×)
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a \( ^3S_1 \) state (for \( J/\psi, \psi' \) and \( \Upsilon \))
- Non-perturbative binding of quarks
- Introduction of quark- and gluon- fragmentation processes:
  - Effectively NLO (\( \alpha_s^4 \) instead of \( \alpha_s^3 \)):

\[
\alpha_s^3 \frac{(2m_Q)^4}{P_T^8}
\]

\[\rightarrow\] Schrödinger wave function

- Different \( p_T \) behaviour: \( P_T^{-4} \) vs. \( P_T^{-8} \)


\[\rightarrow\] Perturbative creation of 2 quarks \( Q \) and \( \bar{Q} \) BUT

Cacciari, Greco, Phys.Rev.Lett.73:1586,1994

Braaten et al., PLB333:548,1994
Basic approach in $pp$: Common Sense Model (CSM)

Failure of the CSM?

$\psi$ anomaly...

Results published in 1997

CDF, PRL 79:572, 1997

Along with $\chi_c$ feed-down extraction

CDF, PRL 79:578, 1997

1e-06
1e-05
1e-04
0.001
0.01
0.1
1
10
5
10
15
20
25
30

$d\sigma/dP_T |_{\eta<0.6}$ .Br (nb/GeV)

$\sqrt{s}=1.8$ TeV

$J/\psi$ production at the Tevatron

$\mu_0 = (4m_c^2 + P_T^2)^{1/2}$

unc. band: $\mu_0/2 < \mu_{f,r} < 2\mu_0$

$1.4$ GeV $< m_c < 1.6$ GeV

CDF data

$J/\psi + g$
May 1994: Seems to work for $J/\psi$ → “$\psi'$ anomaly” ...
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\( \frac{d\sigma}{dp_T} |_{\eta<0.6} \cdot \text{Br} \ (\text{nb/GeV}) \)

\( p_T \ (\text{GeV}) \)

\( \eta < 0.6 \)

\( \sqrt{s} = 1.8 \text{ TeV} \)

\( \mu_0 = (4m_c^2 + p_T^2)^{1/2} \)

unc. band:
\( \mu_0/2 < \mu_{f,r} < 2 \mu_0 \)
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CDF data

J/\psi +g

J/\psi + cc

J.P. Lansberg (SLAC – Stanford U.)

Theory of Quarkonium production

June 17, 2009
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**Failure of the CSM?**

→ Confirmation of the failure with $\Upsilon(nS)$ measurements. (Fragmentation suppressed)

\[
\frac{d\sigma}{dP_T} \mid |y|<0.4 \times Br \text{ (pb/GeV)}
\]

CDF, PRL 88:161802, 2002
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![Graphs showing $d\sigma/dP_T$ for $|y|<0.4$ and $\Upsilon(1S)$ prompt data $\times F_{\text{direct}}$ and $\Upsilon(3S)$ direct data $\times F_{\text{LO}}$]

$\Upsilon(1S)$ prompt data $\times F_{\text{direct}}$ LO

$\Upsilon(3S)$ direct data LO

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LHC: Ready to wait for the $\chi_c$ extraction, $\psi'$ or for $\Upsilon(3S)$?

Theory: Ready to wait for a convincing model?
Further failure: $J/\psi$ production in $\gamma\gamma$ collisions at LEP II

\[e^+e^- \rightarrow e^+e^-J/\psi X \text{ at LEP2}\]

- DELPHI prelim.
- MRST98 fit
- CTEQ5 fit
- $\sqrt{S} = 197$ GeV
- $-2 < y_{J/\psi} < 2$

DELPHI, PLB 565 76, 2003
LO CSM also fails in photoproduction at HERA...
Basic approach in \( pp \): Common Sense Model (CSM)

\[ J/\psi \] photoproduction at HERA

e.g. H1, EPJC 25, 2, 2002; ZEUS, EPJC 27, 173, 2003

LO CSM also fails in photoproduction at HERA...

BUT NLO CSM is in agreement the data!

Why does the CSM fail?

Why does the CSM (basic pQCD approach) fail?

Specifically large QCD-corrections? Why so?

hints: NLO contributions for $\gamma p$, $P_T$ scaling of fragmentation channels
Why does the CSM fail?

Why does the CSM (basic pQCD approach) fail?

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- Hypotheses/constraints of the model too strong?
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→ Should the pair be perturbatively produced in a color singlet? Can’t it evolve?

  e.g. Colour Octet Mechanism, Colour Evaporation Model
Why does the CSM fail? Why does the CSM (basic pQCD approach) fail?

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- Hypotheses/constraints of the model too strong?

- Should the pair be perturbatively produced in a color singlet? Can’t it evolve?
  e.g. Colour Octet Mechanism, Colour Evaporation Model

- Can’t the quarks be produced off-shell? with relative momentum $\neq 0$?
  s-channel cut contribution
So far, the most fashionable solution: Colour Octet Dominance

Color Octet Mechanism: physical states can be produced by coloured pairs

NRQCD: Bodwin, Braaten, Lepage, 1995; Cho, Leibovich,...
So far, the most fashionable solution: Colour Octet Dominance

**Color Octet Mechanism**: physical states can be produced by *coloured pairs*

NRQCD: Bodwin, Braaten, Lepage, 1995; Cho, Leibovich, ...

→ $J/\psi$, $\psi'$ and $\Upsilon$ can be produced by a *single gluon*

✓ Gluon fragmentation then **LO in** $\alpha_S$: larger rates
So far, the most fashionable solution: Colour Octet Dominance

**Color Octet Mechanism:** Physical states can be produced by *coloured pairs*

- $J/\psi$, $\psi'$, and $\Upsilon$ can be produced by a single gluon
- Gluon fragmentation then LO in $\alpha_S$: larger rates
- When $P_{gluon} \gg$, the gluon is nearly on-shell and transversally pol.
- NRQCD spin symmetry: $Q$ has the same polarisation as the gluon
Why does the CSM fail?

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→ When $P_{\text{gluon}} \gg$, the gluon is nearly on-shell and transversally pol.

→ NRQCD spin symmetry: $Q$ has the same polarisation as the gluon

✗ Experimentally, this is clearly contradicted!

\[ \alpha = +1 \iff \text{Transverse} \quad \alpha = 0 \iff \text{Unpolarised} \quad \alpha = -1 \iff \text{Longitudinal} \]

CDF, PRL 99: 132001, 2007
Part II

Present
The s-channel cut contribution

So far, one considered only such configurations idem for NRQCD
The s-channel cut contribution

⇝ So far, one considered only such configurations idem for NRQCD

⇝ What about those? (i.e. the usual contributions to $\text{Im}(\mathcal{M})$)

JPL, J.R. Cudell, Yu.L. Kalinovsky, PLB633:301,2006
The s-channel cut contribution

So far, one considered only such configurations
idem for NRQCD

What about those?
(i.e. the usual contributions to $\text{Im}(\mathcal{M})$)

A bit challenging:
→ Quark relative momentum not fixed to zero; 2 more integrals
→ $c - \bar{c} - Q$ vertex has one leg off-shell

Introduction of a 4-point function – the $c - \bar{c} - Q - g$ coupling –
to preserve gauge-invariance
The s-channel cut contribution: first evaluation

If the $c - \bar{c} - Q - g$ coupling is constrained to satisfy:
→ gauge invariance,
→ low energy limit,
→ scaling limit,

it can be parametrised using two constants.
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If those are fixed to fit Tevatron data up to mid $P_T$:

RHIC data are very well described!
The $s$-channel cut contribution: first evaluation

H. Haberzettl, J.P.L, PRL 100,032006,2008

If the $c - \bar{c} - Q - g$ coupling is constrained to satisfy:

$\rightarrow$ gauge invariance,
$\rightarrow$ low energy limit,
$\rightarrow$ scaling limit,

it can be parametrised using two constants.

If those are fixed to fit Tevatron data up to mid $P_T$:

RHIC data are very well described!

$\rightarrow$ $s$-channel cut contribution seems large, specifically at small $P_T$.

$\rightarrow$ This has to be tested: $ep$, $\gamma\gamma$.

$\rightarrow$ What about the real part? → Need for more observables!
The s-channel cut contribution: polarisation

$J/\psi$ polarisation in $pp$ at $\sqrt{s} = 200$ GeV measured by PHENIX
(note however that our computation does not include specific effects of $\chi_c$)
The s-channel cut contribution: polarisation

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$J/\psi$ polarisation in $pp$ at $\sqrt{s} = 200$ GeV measured by PHENIX

(note however that our computation does not include specific effects of $\chi_c$)

Yet, forward data seems to disagree with this evaluation ...
Describing the mid- and high-$P_T$ region: QCD corrections

Significant improvement, but we need something more...

Confirmed by B. Gong and J.X. Wang who computed the polarization as well.

What about for the $\Upsilon$?
Describing the mid- and high-$P_T$ region: QCD corrections

$J/\psi + c\bar{c}$: P. Artoisenet, J. P. L., F. Maltoni, PLB 653:60, 2007


CDF data for $J/\psi$ production at the Tevatron

$\sqrt{s} = 1.8$ TeV

$\text{Br: } 5.88\%$, $\langle 0\rangle < 1.16$ GeV

$\mu^2_0 = (4m_c^2 + P_T^2)^{1/2}$

Uncertainty band:

$\mu_0/2 < \mu_f, r < 2 \mu_0$

$1.4$ GeV $< m_c < 1.6$ GeV

$3\sigma$ significance improvement, but we need something more...

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CDF data

$J/\psi + g$

$J/\psi + cc$

unc. band: $\mu_0/2 < \mu_f,r < 2\mu_0$

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$J/\psi$ production at the Tevatron

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**J/\(\psi\) + c\(\bar{c}\):** P. Artoisenet, J.P.L, F. Maltoni, PLB 653:60, 2007

**NLO (e.g. \(J/\psi + gg\)):** J. Campbell, F. Maltoni, F. Tramontano, Phys. Rev. Lett. 98:252002, 2007

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**Figure:**

- **CDF data**
- **\(J/\psi + g\)**
- **\(J/\psi + cc\)**
- **\(J/\psi\) NLO**

**Graph:**

- \(d\sigma/dP_T\) at \(\eta < 0.6\), \(\text{Br} \ (\text{nb/GeV})\)
- **\(P_T\) (GeV)**
- NLO unc. band: \(\mu_0/2 < \mu_f < 2\mu_0\)
- \(1.4 \text{ GeV} < m_c < 1.6 \text{ GeV}\)

---

**Significant improvement, but we need something more...**

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**What about for the **\(\Upsilon\)**?**
Describing the mid- and high-$P_T$ region: QCD corrections

QCD corrections: $\alpha_S^4$ (NLO) for $\Upsilon$

$\Upsilon + c\bar{c}$: P. Artoisenet, J.P.L, F. Maltoni, PLB 653:60, 2007

NLO (e.g. $\Upsilon + gg$): J. Campbell, F. Maltoni, F. Tramontano, Phys. Rev. Lett. 98:252002, 2007

Close to an agreement with data

Can we do better?

J.P. Lansberg (SLAC – Stanford U.)
NLO QCD corrections to the Colour Octet Mechanism


- NLO corrections to COM channels have tiny effects on $d\sigma/dP_t$ at large $P_T$ and $\alpha$
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NLO QCD corrections to the Colour Octet Mechanism

- NLO corrections to COM channels have tiny effects on $d\sigma/dP_T$ at large $P_T$ and $\alpha$

- Confirmation that COM cannot describe the polarisation
- We definitely need something else!
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO

Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ contributions: NNLO


→ New $P_T^{-4}$ process at $\alpha_s^5$: $gg \rightarrow Qgmg$

→ Normally accounted by gluon fragmentation

→ What about the $t$-channel gluon exchange?

\[
\begin{align*}
\alpha_s^5 \quad \text{corrections} \\
\text{contributions: NNLO}\quad \ast
\end{align*}
\]
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*


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We propose to evaluate the $\alpha_s^5$ contributions by computing $jj \rightarrow Qjjj$
generated by MadOnia* and imposing cuts on the invariant mass of any light parton pair ($s_{ij}$)

*MadOnia: Automatic generation of tree-level quarkonium amplitudes
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*


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We propose to evaluate the $\alpha_s^5$ contributions by computing $jj \rightarrow Qjj j$ generated by MadOnia* and imposing cuts on the invariant mass of any light parton pair ($s_{ij}$)

→ Those cuts regulate the infrared and collinear divergences of the real emission processes $jj \rightarrow Qjj j$, present even at finite $P_T$

*MadOnia: Automatic generation of tree-level quarkonium amplitudes
Describing the mid- and high-\(P_T\) region: QCD corrections

\[ \alpha_5^5 \text{ corrections contributions: NNLO}^* \]


\[ \rightarrow \text{New } P_T^{-4} \text{ process at } \alpha_5^5: \quad gg \rightarrow Qggg \]

\[ \rightarrow \text{Normally accounted by gluon fragmentation} \]

\[ \rightarrow \text{What about the } t\text{-channel gluon exchange?} \]

We propose to evaluate the \(\alpha_5^5\) contributions by computing \(jj \rightarrow Qjjj\)

generated by MadOnia* and imposing cuts on the invariant mass of any light parton pair (\(s_{ij}\))

\[ \rightarrow \text{Those cuts regulate the infrared and collinear divergences of the real emission processes } jj \rightarrow Qjjj, \text{ present even at finite } P_T \]

\[ \rightarrow \text{Will not affect the leading } P_T \text{ topologies} \]

\[ \rightarrow \text{Will produce logs of } s_{ij}^{min} \text{ when acting on the sub-leading topologies in } P_T \]

*MadOnia: Automatic generation of tree-level quarkonium amplitudes

J.P. Lansberg (SLAC – Stanford U.)

Theory of Quarkonium production

June 17, 2009
Describing the mid- and high-\(P_T\) region: QCD corrections

\(\alpha_s^5\) corrections contributions: NNLO\(^\star\)


→ New \(P_T^{-4}\) process at \(\alpha_s^5\): \(gg \rightarrow Qggg\)
→ Normally accounted by gluon fragmentation
→ What about the \(t\)-channel gluon exchange?

We propose to evaluate the \(\alpha_s^5\) contributions by computing \(jj \rightarrow Qjjj\) generated by MadOnia\(^\star\) and imposing cuts on the invariant mass of any light parton pair \((s_{ij})\)

→ Those cuts regulate the infrared and collinear divergences of the real emission processes \(jj \rightarrow Qjjj\), present even at finite \(P_T\)
→ Will not affect the leading \(P_T\) topologies
→ Will produce logs of \(s_{ij}^{\text{min}}\) when acting on the sub-leading topologies in \(P_T\)
→ The sensitivity on those will vanish at large \(P_T\)
→ Can be checked at NLO since we have a complete calculation

\(^\star\) MadOnia: Automatic generation of tree-level quarkonium amplitudes

Describing the mid- and high-\(P_T\) region: QCD corrections

\[ \alpha_s^5 \text{corrections contributions: NNLO}^* \]
Describing the mid- and high-\(P_T\) region: QCD corrections

\(\alpha_s^5\) corrections contributions: NNLO* 

\[ \rightarrow \text{Validation at } \alpha_s^4: \text{the full NLO is amazingly well reproduced by } jj \rightarrow Qjj \]

\[ \begin{align*}
\text{d} \sigma/\text{d} P_T \mid y < 0.4 \times \text{Br (pb/GeV)} \\
\text{d} \sigma/\text{d} P_T \mid y < 0.6 \times \text{Br (nb/GeV)}
\end{align*} \]

Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*

$\rightarrow$ Validation at $\alpha_s^4$: the full NLO is amazingly well reproduced by $jj \rightarrow Qjj$

$\rightarrow$ Further validation with another process $Q + \gamma$: Full NLO vs $jj \rightarrow Q\gamma j$

$\gamma + jj: 0.5 < s_{ij}^{\text{min}} m_j^2 < 2$

$\psi' + jj: 1 < s_{ij}^{\text{min}} m_j^2 < 4$


Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO$^*$

→ Validation at $\alpha_s^4$: the full NLO is amazingly well reproduced by $jj \rightarrow Qjj$

$\frac{d\sigma}{dP_T} |_{y<0.4} \times Br (pb/GeV)$

$\frac{d\sigma}{dP_T} |_{y<0.6} \times Br (nb/GeV)$


→ Further validation with another process $Q + \gamma$: Full NLO vs $jj \rightarrow Qj\gamma$

$\frac{d\sigma}{dP_T} |_{y<0.6} \times Br (nb/GeV)$


→ $p\bar{p} \rightarrow Qjjj (j = g, u, d, s, c)$ with cuts:

first estimate of the impact of NNLO contributions ($\alpha_s^5$)
Describing the mid- and high-$p_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO


$\frac{d\sigma}{dp_T|_{|y|<0.4}} \times Br \ (pb/GeV)$

$\Upsilon(1S)$ prompt data $\times F^{\text{direct}}$

LO

$\Upsilon + bb$

NLO
Describing the mid- and high-\(P_T\) region: QCD corrections

\(\alpha_s^5\) corrections contributions: NNLO

\(\gamma(1S)\) prompt data \(\times F_{\text{direct}}\)

LO
\(\gamma + bb\)
NLO
NNLO

Exactly what is needed in normalisation and shape!
Describing the mid- and high-$P_T$ region: QCD corrections

$$\alpha_s^5$$ corrections contributions: NNLO*

see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

$\psi^{(2S)}$ prelim. CDF data at 1.96 TeV
$\psi' +cc$
NLO
NNLO

$\frac{d\sigma}{dP_T}|_{|y|<0.6} \times Br (nb/GeV)$

$P_T$ (GeV)
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*  

see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

PDF of the CDF data at 1.96 TeV for $\psi(2S)$ and $\psi'$ +cc.

The NLO and NNLO predictions are shown.

- Nearly as good as for $\Upsilon$
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*

see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

ψ (2S) prelim. CDF data at 1.96 TeV
ψ ’ +cc
NLO
NNLO

✔ Nearly as good as for ϒ
✗ Still a gap opening at large $P_T$: CO ?
Describing the mid- and high-\(P_T\) region: QCD corrections

\[ \alpha_s^5 \text{corrections contributions: NNLO}^* \]

see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

\[
\frac{d\sigma}{dP_T} |_{|y|<0.6} x \text{Br (nb/GeV)}
\]

\(P_T\) (GeV)

\(\psi(2S)\) prelim. CDF data at 1.96 TeV

\(\psi' + cc\)

NLO

NNLO

\[1e^{-07} \quad 1e^{-06} \quad 1e^{-05} \quad 1e^{-04} \quad 1e^{-03} \quad 1e^{-02} \quad 1e^{-01}\]

\(\checkmark\) Nearly as good as for \(\Upsilon\)

\(\times\) Still a gap opening at large \(P_T\): CO ?

\(\times\) Very large uncertainty attached to the choice of \(\mu_r\)
Describing the mid- and high-$P_T$ region: QCD corrections

Γ and $J/\psi$ polarisation in hadroproduction at $\mathcal{O}(\alpha_S^5)$


see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

→ Cross sections seem OK (still not clear for $\psi$)

→ Polarisation?
Describing the mid- and high-\(P_T\) region: QCD corrections

\(\Upsilon\) and \(J/\psi\) polarisation in hadroproduction at \(\mathcal{O}(\alpha_s^5)\)

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Cross sections seem OK (still not clear for \(\psi\))
Polarisation?

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

\(P_T\) (GeV)

Direct \(\psi(2S)\) CDF data at \(s^{1/2} = 1.96\) TeV

\(\Upsilon\) + bb
NLO
NNLO

Comparison with prompt measurements from CDF and \(\Delta^0\)?
Feed-down from \(\chi_c\), \(\chi_b\) not known at NLO

Does it matter?
See P. Faccioli’s talk, next week.
Describing the mid- and high-$P_T$ region: QCD corrections

$\Upsilon$ and $J/\psi$ polarisation in hadroproduction at $\mathcal{O}(\alpha_S^5)$

see also JPL, arXiv:0811.4005 [hep-ph], EPJC in press

- Cross sections seem OK (still not clear for $\psi$)
- Polarisation?

\[ \alpha = \left( \sigma_T - 2 \sigma_L \right) / \left( \sigma_T + 2 \sigma_L \right) \]

Direct $\psi(2S)$ CDF data at $s^{1/2} = 1.96$ TeV

- Comparison with prompt measurements from CDF and $D\phi$ ??
- Feed-down from $\chi_c, \chi_b$ not known at NLO
Describing the mid- and high-$P_T$ region: QCD corrections

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$P_T$ (GeV)

$\rightarrow$ Comparison with prompt measurements from CDF and $D\phi$??

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Does it matter?

See P. Faccioli’s talk, next week.
Describing the mid- and high-$P_T$ region: QCD corrections

$\Upsilon$ cross section at the LHC


\[ \frac{d\sigma}{dP_T} \mid |y|<0.4 \times \text{Br (pb/GeV)} \]

$P_T$ (GeV)

$\Upsilon(1S)$ at $s^{1/2} = 14$ TeV

NLO

NNLO

J.P. Lansberg (SLAC – Stanford U.)

Theory of Quarkonium production

June 17, 2009 22 / 44
Colour Octet Dominance challenged at low/mid $P_T$ in pp?

- $e^+e^- \rightarrow J/\psi X$ CS at NLO: no space for CO ($^1S_0$ or $^3P_J$) in $B$-factory data

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  → a priori better agreement with $\gamma p$ where CO Dominance was excessive.

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Dealing with the mid- and high-$P_T$ region: QCD corrections

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But the $P_T$ dependence is badly reproduced and cannot be properly fit!
Part III

Perspectives for the future
New observable: $Q + Q\bar{Q}$

- **Double charm/beauty HADRO-production** should show large rates
  let us see how it can be a new valuable observable

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→ NRQCD factorisation? Colour transfer mechanism?

If we ignore changes in the fits of COM matrix elements due to QCD corrections:

- CSM contributions dominate at low $P_T$
- COM contributions (may) dominate from $P_T \geq 15$ GeV
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- CSM contributions dominate at low $P_T$
- COM contributions (may) dominate from $P_T \geq 15$ GeV
- Integrated cross section largely dominated by CSM contributions
- Can rely on CSM predictions for $\alpha$ for $P_T \leq 15$ GeV
$\bar{Q} + Q\bar{Q}$: polarisation


$J/\psi + c\bar{c}$

$\Upsilon + b\bar{b}$
Q + Q̅Q: polarisation

J/ψ + c̅c: polarisation with COM ("old" CO matrix elements)

P. Artoisenet, private communication
New observable: $J/\psi + \gamma$ (at the LHC)

- $B$ feed-down expected to be proportionally less important
- idem for the $\chi_c$ feed-down

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R.Li and J.X. Wang, PLB 672:51, 2009
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- Color-singlet rate at NLO similar to a conservative (high) expectation from Colour-octets

- But...

NNLO* one order of magnitude than NLO

↓

The yield will be dominated by the Color singlet transitions!

Once more, no kinematical enhancements for CO
Part IV

Bridging the gap with $pA$ and $AA$ studies
A first study

Investigate on:

the possible impact of the specific $J/\psi$-production kinematics on the [gluon] shadowing effects
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previous studies considered Drell–Yan-like kinematics, as a $2 \rightarrow 1$ process
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- Easy to handle:
  - $y^{J/\psi}$ and $p_T^{J/\psi}$ (if one takes $M_T$) directly give $x_{1,2}$
Bridging the gap with $pA$ and $AA$ studies: one example

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  - Straightforward evaluation of the gluon PDF shadowed in the nucleus at $x_2$ (and $x_1$ in $AA$)
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- but is this approximation justified?
  - A priori, no: the LO QCD process for $J/\psi$ production is $2 \rightarrow 2$

 **C-parity conservation**
On the kinematics of $J/\psi$ production

If $F^A_g(x, \vec{r}, z, \mu_f)$ gives the distribution of a gluon of mom. fract. $x$ at a position $\vec{r}, z$ in a nucleus $A$, the differential cross-section reads:

$$\frac{d\sigma_{AB}}{dy dP_T dB} = \int d\vec{r}_A dz_A dz_B \int dx_1 dx_2 \int d\vec{r}_A dz_A dz_B \times F^A_g(x_0^1, \vec{r}_A, z_A, \mu_f) \times F^B_g(x_0^2, \vec{r}_B, z_B, \mu_f) \times \sigma_{Intr.} \gg(O(x_0^1, x_0^2)) \times 2\hat{s}P_T d\sigma_{gg \rightarrow J/\psi+g} \delta(\hat{s} - \hat{t} - \hat{u} - M^2) \times S_A(\vec{r}_A, z_A) S_B(\vec{r}_B, z_B) \times S_A(\vec{r}, z_A) S_B(\vec{r}, z_B) \times x_1, 2 = m_T \sqrt{s_{NN}} \exp(\pm y) \equiv x_2 = x_1 m_T \sqrt{s_{NN}} e^{-y - M^2} \sqrt{s_{NN}} (\sqrt{s_{NN}} x_1 - m_T e^y) $$
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If $\mathcal{F}_g^A(x, \vec{r}, z, \mu_f)$ gives the distribution of a gluon of mom. fract. $x$ at a position $\vec{r}, z$ in a nucleus $A$, the differential cross-section reads:

$$
\frac{d\sigma_{AB}}{dy \, dP_T \, db} = \int d\vec{r}_A \, dz_A \, dz_B \times \mathcal{F}_g^A(x_1^0, \vec{r}_A, z_A, \mu_f) \mathcal{F}_g^B(x_2^0, \vec{r}_B, z_B, \mu_f) \times \sigma_{gg}^{\text{Intr.}}(x_1^0, x_2^0) \times S_A(\vec{r}_A, z_A) S_B(\vec{r}_B, z_B)
$$

2 → 1 kinematics with intrinsic $p_T$

$$
\int dx_1 dx_2 \int d\vec{r}_A \, dz_A \, dz_B \times \mathcal{F}_g^A(x_1, \vec{r}_A, z_A, \mu_f) \mathcal{F}_g^B(x_2, \vec{r}_B, z_B, \mu_f) \times 2\hat{s} P_T \frac{d\sigma_{gg \to J/\psi + g}}{d\hat{t}} \delta(\hat{s} - \hat{t} - \hat{u} - M^2) \times S_A(\vec{r}, z_A) S_B(\vec{r}_B, z_B)
$$

2 → 2 kinematics with extrinsic $p_T$
On the kinematics of $J/\psi$ production

If $\mathcal{F}_g^A(x, \vec{r}, z, \mu_f)$ gives the distribution of a gluon of mom. fract. $x$ at a position $\vec{r}, z$ in a nucleus $A$, the differential cross-section reads:

$$\frac{d\sigma_{AB}}{dy \ dP_T \ db} =$$

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\[ \times \ \mathcal{F}_g^A(x_1^0, \vec{r}_A, z_A, \mu_f) \mathcal{F}_g^B(x_2^0, \vec{r}_B, z_B, \mu_f) \]
\[ \times \ \sigma_{gg}^{\text{Intr.}}(x_1^0, x_2^0) \]
\[ \times \ S_A(\vec{r}_A, z_A) S_B(\vec{r}_B, z_B) \]

\[ x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(\pm y) \equiv x_{1,2}(y, P_T) \]

$2 \rightarrow 1$ kinematics with intrinsic $p_T$

$2 \rightarrow 2$ kinematics with extrinsic $p_T$

\[ \int dx_1 dx_2 \int d\vec{r}_A \ dz_A \ dz_B \]
\[ \times \ \mathcal{F}_g^A(x_1, \vec{r}_A, z_A, \mu_f) \mathcal{F}_g^B(x_2, \vec{r}_B, z_B, \mu_f) \]
\[ \times \ 2\hat{s} P_T \frac{d\sigma_{gg \rightarrow J/\psi + g}}{d\hat{t}} \delta(\hat{s} - \hat{t} - \hat{u} - M^2) \]
\[ \times \ S_A(\vec{r}, z_A) S_B(\vec{r}_B, z_B) \]

\[ \delta(\ldots) \rightarrow x_2 = \frac{x_1 m_T \sqrt{s_{NN} e^{-y} - M^2}}{\sqrt{s_{NN}}(\sqrt{s_{NN} x_1 - m_T e^y})} \]
For a given couple $(y, p_T)$, $x_2$ is larger in the extrinsic scheme.
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Antishadowing peak at \(\sim 10^{-1}\)
On the kinematics of $J/\psi$ production II

For a given couple $(y, p_T)$, $x_2$ is larger in the extrinsic scheme.

Antishadowing peak at $\sim 10^{-1}$

We expect different shadowing effects in both cases.
Antishadowing peak shifted to less negative $y$
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Let us add a break-up cross section
Following PHENIX [PRC 77, 024912 (2008)], we expect a good match for the **intrisinc** scheme with $\sigma_{\text{abs}}$ close to 2.8 mb (dashed purple curve).
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Larger value needed in the extrinsic scheme.
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Larger value needed in the extrinsic scheme.

A real (preliminary) fit gives $\sigma_{\text{abs}}^{\text{intr}} = 3.2$ mb and $\sigma_{\text{abs}}^{\text{extr}} = 3.9$ mb.
In fact, the PHENIX fit needs different $\sigma_{abs}$

* $\sigma_{breakup} = 5.2^{+1.6}_{-1.8}$ mb
* $\sigma_{breakup} = 2.4^{+1.9}_{-1.6}$ mb
* $\sigma_{breakup} = 3.2^{+1.6}_{-1.5}$ mb

Results for d+Au collisions

d+Au centrality dependence


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Indeed the intrinsic scheme can’t reproduce the bckwd data with $\sigma_{abs} = 2.8$.
In fact, the PHENIX fit needs different $\sigma_{abs}$

- Indeed the intrinsic scheme can’t reproduce the bckwd data with $\sigma_{abs} = 2.8$.
- The extrinsic scheme fits well the data in the 3 regions with one single $\sigma_{abs}$.
Results for d+Au collisions

d+Au transverse-momentum dependence


|y|<0.35
|y|<1.2
1.2<y<2.2

NDSg

EKS98

EPS08


Shadowings effects on polarisation in d+Au collisions

First predictions ever of shadowing effects on polarisation!

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe. in progress
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\[ \alpha \approx 0.35 - 0.4. \]


A priori no longer valid in view of the (N)NLO results. . .

needs to be reconsidered!
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with:

$T_{\text{extrinsic } p} = 0 \text{ mb abs } \sigma_{\text{EKS}}$

Prelim. PHENIX d+Au data, talk by A. Lebedev, for the PHENIX collaboration
DNP/JPS Joint Fall Meeting, 2005.

J.P. Lansberg (SLAC – Stanford U.)
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No CNM effects on polarisation? Watch out for feed-down effects!
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"Q polarization in HI collisions as a possible signature of the QGP"

"The QGP is expected to screen away the nonperturbative physics; therefore those quarkonia which escape from the plasma should possess polarization as predicted by perturbative QCD. We estimate the expected $J/\psi$ polarization at small $P_T$, and find that [...] $\alpha \simeq 0.35 - 0.4$.”

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Results for Au+Au and Cu+Cu collisions

AA rapidity dependence


\[ R_{AA} = \frac{N_{part}}{syst_{global} = \pm 10\%} \]

- intrinsic $p_T \sigma_{abs} = 2.8 \text{ mb}$
- extrinsic $p_T \sigma_{abs} = 4.2 \text{ mb}$

\[ R_{AA} = \frac{N_{part}}{280 \pm 4} \]

- $N_{part} = 280 \pm 4$

\[ R_{AA} = \frac{N_{part}}{140 \pm 5} \]

- $N_{part} = 140 \pm 5$

\[ R_{AA} = \frac{N_{part}}{60 \pm 4} \]

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\[ R_{AA} = \frac{N_{part}}{14 \pm 2} \]

- $N_{part} = 14 \pm 2$

\[ R_{AA} = \frac{N_{part}}{86 \pm 2} \]

- $N_{part} = 86 \pm 2$

\[ R_{AA} = \frac{N_{part}}{45 \pm 2} \]

- $N_{part} = 45 \pm 2$

\[ R_{AA} = \frac{N_{part}}{21 \pm 1} \]

- $N_{part} = 21 \pm 1$

\[ R_{AA} = \frac{N_{part}}{6 \pm 0} \]

- $N_{part} = 6 \pm 0$

Behaviour rather flat in the intrinsic scheme (blue curve)

Maximum at $y = 0$ for the extrinsic scheme (red curve)

This effect may reduce the need for recombination of $c \bar{c}$ pairs (maximum at $y = 0$)
Behaviour rather flat in the intrinsic scheme (blue curve)
AA rapidity dependence


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Results for Au+Au and Cu+Cu collisions

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Part V

Conclusions and Outlooks
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- Off-shell effects via $s$-channel cut contributions matter at small $P_T$
- ... but **QCD-corrections bring agreements in**
  - $\gamma p$ for $J/\psi$  
  - $e^+e^-$ for $J/\psi + \eta_c$  
  - $pp$ for $\Upsilon$  


Time has come for another look? new observables?
- on the one hand, avoiding the presence of Colour Octets
- on the other hand, testing the presence of Colour Octets
- and for which LO contributions in $\alpha_s$ show a leading $P_T$ scaling
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(first) new observables: $Q + Q\bar{Q}$ ($Q + \gamma$), $Q+$hadron correlations
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- (first) new observables: \( Q + Q\bar{Q} \) (\( Q + \gamma \)), \( Q \) + hadron correlations
- Other proposals are welcome!
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Other proposals are welcome!

Time has come for a critical look at studies in heavy-ion collisions

- Shadowing effects and kinematics

Conclusions and Outlooks II

- Time has come for another look? new observables?
  - on the one hand, avoiding the presence of Colour Octets
  - on the other hand, testing the presence of Colour Octets
  - and for which LO contributions in $\alpha_s$ show a leading $P_T$ scaling
  - (first) new observables: $Q + Q\bar{Q}$ ($Q + \gamma$), $Q+$hadron correlations
  - Other proposals are welcome!

- Time has come for a critical look at studies in heavy-ion collisions
  - Shadowing effects and kinematics

- or to extract info on prod. mechanisms in $pp$ from heavy-ion studies
Part VI

Backup slides
Inclusive cross section at NNLO* compared to STAR data

\[ \frac{1}{2 \pi P_T} \frac{d\sigma}{dP_T dy} |_{|y|<1.0} Br \ (\text{nb}/\text{GeV}) \]

Prelim. STAR (incl. B and \( \chi_c \) feed-down)

high NNLO*: \( \mu = 0.5 \ (4m_c^2 + P_{T}^2)^{1/2} \), \( m_c = 1.4 \ \text{GeV}, s_{ij}^{\text{min}} = 2.25 \ \text{GeV}^2 \)

low NNLO*: \( \mu = 2.0 \ (4m_c^2 + P_{T}^2)^{1/2} \), \( m_c = 1.6 \ \text{GeV}, s_{ij}^{\text{min}} = 9.00 \ \text{GeV}^2 \)

\( s^{1/2} = 200 \ \text{GeV} \)
New observable: $J/\psi + cc$ (with STAR)

$\frac{d\sigma}{dP_T} |_{|y|<1.0} \times Br(J/\psi \rightarrow l^+ l^-)$ (nb/GeV)

$|s|^{1/2} = 200$ GeV

No theoretical uncertainty shown

Only with color singlet transitions

$gg \rightarrow J/\psi + cc$

$qq \rightarrow J/\psi + cc$

Total

JPL, arXiv:0811.4005 [hep-ph], EPJC in press