Associated-quarkonium production

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thanks to W. den Dunnen, C. Lorcé, C. Pisano, M. Schlegel, H.S. Shao
Part I

Quarkonium hadroproduction: where do we stand?
Reminder: QCD corrections for $\Upsilon$ at the Tevatron
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$\frac{d\sigma}{dP_T}|_{|y|<0.4} \times \text{Br (pb/GeV)}$

$P_T$ (GeV)

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

$\psi$ or $\Upsilon$

$\alpha_3^SP_{-8}$

$\alpha_5^SP_{-4}$

$g$ double $t$-channel gluon exchange at $\alpha_5^S$

Attention: the NNLO $\star$ is not a complete NNLO
Reminder: QCD corrections for $\Upsilon$ at the Tevatron


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

LO
NLO

$\alpha_3^3 P_T^{-8}$
$\alpha_4^4 P_T^{-6}$

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$\psi$ or $\Upsilon$

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$P_T$ (GeV)

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LO
NLO
NNLO

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$\alpha_3^3 P_T^{-8}$

$\alpha_4^4 P_T^{-6}$

$\alpha_5^5 P_T^{-4}$

+ double $t$-channel gluon exchange at $\alpha_5^5$

Attention: the NNLO* is not a complete NNLO
QCD corrections for $\Upsilon$ at the Tevatron & the LHC


$|b\rangle$ *(3S) (GeV/c) $\Upsilon$ of $T_p$

$[\text{nb/(GeV/c)}]$ $T_p/\sigma_3S \times B_3S$

$10^4 10^3 10^2 10^1 10^0$

$0 5 10 15$

LHCb data (2.0<y<4.5)
direct NNLO* CSM (2.0<y<4.5)
direct NLO CSM (2.0<y<4.5)
LHCb data (2.0<y<4.5)
direct NNLO* CSM (2.0<y<4.5)
direct NLO CSM (2.0<y<4.5)

$\sqrt{s} = 7$ TeV

$B^{3S} \times d\sigma_{3S}/dp_T$ [nb/(GeV/c)]

Attention: the NNLO* is not a complete NNLO

+ double $t$-channel gluon exchange at $\alpha^5_S$

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CSM predictions account for the $P_T$-integrated yield

$\rightarrow$ The yield vs. $\sqrt{s}$, $y$

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010; JPL, PoS(ICHEP 2010), 206 (2010); NPA 910-911 (2013) 470

(Here only LO curves*)

*NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$
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→ The yield vs. $\sqrt{s}$, $y$

- 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 $F^{direct}$)

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\[ \frac{d\sigma}{dy} |_{y=0} \times \text{Br} \]

\[ x \text{ Br (pb)} \]

\[ s^{1/2} \text{ (GeV)} \]

\[ F^{\text{direct}}_{\Upsilon(1S)} = 51 \pm 12 \% \]

\[ F^{\text{direct}}_{\Upsilon(1S+2S+3S)} = 42 \pm 10 \% \]

\[ \text{LO gg CSM} \]

\[ \text{STAR/CDF/CMS data} \]

\[ \text{CMS} \]

\[ \text{LHCb} \]

* NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$
The current situation in one slide ...

- Colour-Singlet Model (CSM) back in the game
  - large NLO and NNLO correction to the $P_T$ spectrum; but not perfect
  - CSM was always in the game for the $P_T$ integrated yield

- Colour-Octet Mechanism (COM) helps in describing the $P_T$ spectrum
  - Yet, the COM NLO fits differ a lot in their conclusions owing to their assumptions (data set, $P_T$ cut, polarisation fitted or not, etc.)

- All approaches have troubles in describing the polarisation, here or there

- New hope in double-parton fragmentation
  - Kang, Qiu, Sterman, PRL 108 (2012) 102002
  - Next-to-leading power in $P_T$; Not to be confused with Double-Parton Scattering

- All this motivates the study of new observables which can be more discriminant for specific effects
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- All this motivates the study of new observables which can be more discriminant for specific effects
Part II

Quarkonium + Quarkonium
$J/\psi + J/\psi \& J/\psi + \eta_c$

- LO to $J/\psi + J/\psi$ at $\alpha_S^4$
$J/\psi + J/\psi \ & \ J/\psi + \eta_c$

- **LO** to $J/\psi + J/\psi$ at $\alpha_S^4$
- At NLO, $t$ channel gluon exchange appear (harder $P_T$ spectrum)
**$J/\psi + J/\psi \& J/\psi + \eta_c$**

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[nicely confirmed by a full NLO]

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- $J/\psi + \eta_c$ suppressed by $C$ parity: LO at $\alpha_s^5$

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[First evaluation !]
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[Diagram showing the process of $J/\psi + J/\psi$ production]

- [Nicely confirmed by a full NLO]


[First evaluation !]
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**J/ψ + η_c** suppressed by $C$ parity: LO at $\alpha_S^5$

- [nicely confirmed by a full NLO]
- [First evaluation !]

**Different $P_T$ spectrum & different $\Delta M$ distribution**
The $k_T$ smearing completely flattens the $\Delta\phi$ distribution.

Implication for the DPS "extraction" ?????
\( \Upsilon + b \)-tagged jet (or \( \Upsilon + \) non-prompt \( J/\psi \))

- \( \Upsilon + b \): \( \sim 0.1 \) pb/GeV at the Tevatron, \( \sim 1 \) pb/GeV at the LHC (14 TeV)
- hard (flatter) \( P_T \) spectrum w.r.t. the inclusive LO CSM
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- Different topologies/correlation:
  - CSM: 1 $b$ away, 1 $b$ near(er)
  - COM: 2 $b$’s away (from a recoiling gluon)
Part III

Quarkonium + photon
$Q + \text{isolated } \gamma$

- At high energy, 2 gluons in the initial states: no quark
\( Q + \text{isolated } \gamma \)

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CS rate at NLO $\simeq$ **conservative** (high) expectation from CO

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In fact, the NLO CO yield can even be negative

R.Li and J.X. Wang, PLB 672,51,2009

R.Li and J.X. Wang, arXiv:1401.6918
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\[^\dagger\text{New info on CS vs CO w.r.t and strong constraints on CO fits}\]

\[^\dagger\text{Possible at LHC: cf. (c, b) - jet + γ studies by D0 up to Pγ ≃ 150 GeV : D0, PRL102 (2009) 192002.}\]
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\[\begin{array}{c}
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\[\text{Graphs showing the distribution of } \frac{d\sigma}{dP_T(y, \gamma, X)} \text{ at } P_T = 5 \text{ to } 45 \text{ GeV}\]

- New info on CS vs CO w.r.t and strong constraints on CO fits\(^\dagger\)

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\(J.P. \text{ Lansberg (IPNO)}\)
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New info on CS vs CO w.r.t and strong constraints on CO fits†

Possible at LHC: cf. $(c, b) - jet + \gamma$ studies by D0 up to $P_T^{\gamma} \simeq 150$ GeV:

†In fact, the NLO CO yield can even be negative

\[ \text{J.P. Lansberg (IPNO)} \]

\[ \text{Associated-quarkonium production} \]

\[ \text{May 1, 2014 11 / 27} \]
$Q + \gamma$: back-to-back and both isolated

Representative diagrams contributing to the hadroproduction of a $Q$ in association with a photon at orders $\alpha_s^2 \alpha$, $\alpha_s^3 \alpha$ (b, c), $\alpha_s^4 \alpha$ (d, e, f).
$Q + \gamma$: back-to-back and both isolated

- Born (LO): $2 \rightarrow 2$ contributions (a)-(b) fall like $P_T^{-8}$
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- **At NNLO:** topologies like (d) dominate at very large $P_T$

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  - Instead of a ’hard’ gluon, there would be multiple soft gluons.
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- **(c)-(f):** parton $\to$ some hadrons in the central region;
  - for (d), hadrons near the $Q$
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Representative diagrams contributing to the hadroproduction of a $Q$ in association with a photon at orders $\alpha_s^2\alpha_s$ (a), $\alpha_s^3\alpha_s$ (b, c), $\alpha_s^4\alpha_s$ (d, e, f).

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- **$2 \rightarrow 2$ topologies contribute to $\Delta \phi_{Q-\gamma} = \pi$ (back-to-back);**
  smearing effect small for $P_T \gg \langle k_T \rangle$
$Q + \gamma$: **back-to-back** and both isolated

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smearing effect small for $P_T \gg \langle k_T \rangle$

(c)-(f) populate $\Delta \phi_{Q-\gamma} < \pi$ [even $\Delta \phi \rightarrow 0$ for (c) and (d) at large $P_T$]
**Q + γ: back-to-back and both isolated**

- The studies is of an **isolated** quarkonium back-to-back with an (isolated) photon selects the **Born contributions to Q + γ**
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- The “back-to-back” requirement also limits the DPS contributions
  
  [a priori evenly distributed in \(Δφ\)]

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**J.P. Lansberg (IPNO)**

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**May 1, 2014**

**13 / 27**
\( Q + \gamma \): back-to-back and both isolated

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- The “back-to-back” requirement also limits the DPS contributions [a priori evenly distributed in \( \Delta \phi \)]
- Unique candidate to pin down the gluon TMDs
  - gluon sensitive process
  - colorless final state (virtue of isolation): TMD factorisation applicable
  - small sensitivity to QCD corrections (most of them in the TMD evolution)
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- Unique candidate to pin down the gluon TMDs
  - gluon sensitive process
  - colorless final state (virtue of isolation): TMD factorisation applicable
  - small sensitivity to QCD corrections (most of them in the TMD evolution)
- Rates are not too small

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**Direct back-to-back Onium + \( \gamma \) at sqrt(s)=14 TeV**

**Color Singlet**

\[ \langle O^{1S}_{0}|(\Upsilon)\rangle \geq 0.02 \text{ GeV}^3 \]

**Color Octet**

\[ \langle O^{3S}_{1}|(J/\psi)\rangle \geq 0.002 \text{ GeV}^3 \]

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May 1, 2014 13 / 27
back-to-back $Q + \gamma$ and the gluon TMDs

The $q_T$-differential cross section involves $f_1^g(x, k_T, \mu_F)$ and $h_1^\perp g(x, k_T, \mu_F)$

$$\frac{d\sigma}{dQdY d^2 q_T d\Omega} = \frac{C_0(Q^2 - M_Q^2)}{s Q^3 D} \left\{ F_1 C \left[ f_1^g f_1^g \right] + F_3 \cos(2\phi_{CS}) C \left[ w_3 f_1^g h_1^\perp g + x_1 \leftrightarrow x_2 \right] + F_4 \cos(4\phi_{CS}) C \left[ w_4 h_1^\perp g h_1^\perp g \right] \right\} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$
back-to-back $Q + \gamma$ and the gluon TMDs

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We define: $S_{qT}^{(n)} = \left(\frac{d\sigma}{dQdYd\cos \theta_{CS}}\right)^{-1} \int d\phi_{CS} \pi \cos(n\phi_{CS}) \frac{d\sigma}{dQdYd^2q_Td\Omega}$
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- $S_{q_T}^{(0)} \leftrightarrow f_1^g(x, k_T, \mu_F)$: clean extraction is possible!
back-to-back $Q + \gamma$ and the gluon TMDs

The $q_T$-differential cross section involves $f^g_1(x, k_T, \mu_F)$ and $h^{\perp g}_1(x, k_T, \mu_F)$

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back-to-back $Q + \gamma$ and the gluon TMDs

The $q_T$-differential cross section involves $f_1^g(x, k_T, \mu_F)$ and $h_1^\perp g(x, k_T, \mu_F)$

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- $S_{q_T}^{(2)} \leftrightarrow f_1^g$ & $h_1^\perp g$
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Part IV

Quarkonium + W/Z boson
$Q + W/Z$ boson

- $Y + W/Z$ boson
$Q + W/Z$ boson

- $\Upsilon + W/Z$ boson
  - 95% C.L. upper limits obtained with $\mathcal{L} = 83\text{pb}^{-1}$ by CDF
**Q + W/Z boson**

- **Y + W/Z boson**
  - 95% C.L. upper limits obtained with $\mathcal{L} = 83\text{pb}^{-1}$ by CDF
    \[
    \sigma[p\bar{p} \rightarrow Y(1S) + W^\pm] \times Br(Y(1S) \rightarrow \mu\mu) < 2.3 \text{ pb}
    \]
    \[
    \sigma[p\bar{p} \rightarrow Y(1S) + Z^0] \times Br(Y(1S) \rightarrow \mu\mu) < 2.5 \text{ pb}
    \]  
  - NRQCD predictions (Signal dominated by CO into $\chi_b$)
    \[
    \sigma[p\bar{p} \rightarrow Y(1S) + W^\pm] \times Br(Y(1S) \rightarrow \mu\mu) \simeq 0.025 \text{ pb}
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    \[
    \sigma[p\bar{p} \rightarrow Y(1S) + Z^0] \times Br(Y(1S) \rightarrow \mu\mu) \simeq 0.0075 \text{ pb}
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CDF Collaboration, PRL. 90 (2003) 221803

\(Q + W/Z\) boson

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  - CSM yield expected to be 300 times smaller (??? ...)

J.P. Lansberg (IPNO)  
Associated-quarkonium production  
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- **With 1 fb$^{-1}$ at $\sqrt{s} = 7\ \text{TeV}$ and a larger $(E \times A)(Y)$, one should see events if CO’s are at work**

CDF Collaboration, PRL. 90 (2003) 221803

$Q + W/Z$ boson

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- CSM yield expected to be 300 times smaller (??? ...)
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- $J/\psi + Z$ and $J/\psi + W$ recently computed at NLO in $\alpha_s$
  - L.Gang et al. PRD83,014001,2011; JHEP02(2011)071

- $J/\psi|Y + Z$ at NLO in $\alpha_s$ + Polarisation
  - B.Gong et al. JHEP 1303 (2013) 115
Rates similar for $\Upsilon + Z$ and $J/\psi + Z$  [Same for $Q + \gamma$ for $Q \gtrsim 20$ GeV]
Rates similar for \( \Upsilon + Z \) and \( J/\psi + Z \) [Same for \( Q + \gamma \) for \( Q \gtrsim 20 \text{ GeV} \)]
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- **Mass effects** ($m_c \leftrightarrow m_b$ less relevant because of $m_Z$)
- $|R(0)|^2$ is 10 times larger for $\Upsilon$ than for $J/\psi$
- Branching “only” 2.5 times smaller
**Y + Z cross sections**

- Rates similar for Y + Z and J/ψ + Z  [Same for Q + γ for Q ≳ 20 GeV]

![Graphs showing dσ/dP_T x Br (fb/GeV) vs. P_T (GeV) for Y and J/ψ](image)

- Mass effects (m_c ↔ m_b less relevant because of m_Z)
- |R(0)|^2 is 10 times larger for Y than for J/ψ
- Branching “only” 2.5 times smaller
- Potential probe of gluon TMDs as well
\( \Upsilon + Z : \Upsilon \) polarisation


\[ \alpha \left( P_{_{\Upsilon} T} \right) \]

\[ P_{_{\Upsilon} T} > 3 \text{ GeV} \]

\[ |y_{\Upsilon}| < 2.4 \]

\[ \sqrt{s} = 14 \text{ TeV} \]

LO: \( \mu_R = \mu_F = m_Z \)

NLO: \( \mu_R = \mu_F = m_Z \)

CSM predictions seem robust both for the yield and the polarisation.

Yield and polarisation at LO and NLO are similar, unlike the inclusive case.

It is not clear why the difference exists; further investigation is needed.
\( \Upsilon + Z : \Upsilon \) polarisation


\[ \alpha(P_{\Upsilon T}) \]

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$\Upsilon + Z$ polarisation

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**Y + Z : Y polarisation**

Y polarisation at LO and NLO are similar

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- not clear why: need for further investigation
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J/ψ + W

'ψ + W offers a clean test of the colour octet contributions'

In the CSM, the $W$ boson cannot be emitted by the charm quark loop replacing the gluon in $\psi + g$, the $\gamma$ in $\psi + \gamma$ or the $Z$ in $\psi + Z$. 

\( J/\psi + W \)

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- In the CSM, the \( W \) boson cannot be emitted by the charm quark loop replacing the gluon in \( \psi + g \), the \( \gamma \) in \( \psi + \gamma \) or the \( Z \) in \( \psi + Z \)
- One needs a light-quark line to emit the \( W \)
- In the COM, the light-quark line also radiates a gluon which produces a \( ^3S_i^{[8]} \) octet \( Q\bar{Q} \)
In the CSM, the $W$ boson cannot be emitted by the charm quark loop replacing the gluon in $\psi + g$, the $\gamma$ in $\psi + \gamma$ or the $Z$ in $\psi + Z$

One needs a light-quark line to emit the $W$

In the COM, the light-quark line also radiates a gluon which produces a $^3S^1_8$ octet $Q\bar{Q}$

The corresponding process suppressed in the CSM by $\alpha_s^2$
(similarly to the gluon fragmentation in the inclusive case)

Usual conclusion:
*the CSM contribution is strongly suppressed even at rather low $P_T$*
To check this, we have considered two kinds of "LO" CSM process At $\alpha_1$ (EW) and LO in $\alpha_s$ ($\alpha_3$ vs. $\alpha_2$ for COM), we have fusion involves gluon PDFs (enhanced w.r.t $q(x)$ at high $\sqrt{s}$) "LO" contains leading power in $P_T$ $\rightarrow$ no kinematical suppression At $\alpha_3$ and $\alpha_0$ $s$, we also have $q\bar{q}$ fusion $\rightarrow \gamma^* W \rightarrow J/\psi W^\pm$: negligible since $\alpha_3$? J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218
direct $J/\psi + W$

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- At $\alpha_{(EW)}^1$ and LO in $\alpha_s$ ($\alpha_S^3$ vs. $\alpha_S^2$ for COM),
- we have $s g$ fusion

\[ \text{direct } J/\psi + W \]
To check this, we have considered two kinds of “LO” CSM process:

- At $\alpha_{(EW)}^1$ and LO in $\alpha_s$ ($\alpha_s^3$ vs. $\alpha_s^2$ for COM), we have *sg fusion*
- involves gluon PDFs (enhanced w.r.t $q(x)$ at high $\sqrt{s}$)

\[ J/\psi + W \]
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pure EW process.
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At $\alpha^1_{(EW)}$ and LO in $\alpha_s$ ($\alpha^3_s$ vs. $\alpha^2_s$ for COM), we have $sg$ fusion
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pure EW process

$q\bar{q}' \rightarrow \gamma^* W \rightarrow J/\psi W$ : negligible since $\alpha^3$ ?
Results

J.P. Lansberg, C. Lorè, PLB 726 (2013) 218

- Associated-quarkonium production
- May 1, 2014 21 / 27
**Results**

- **sg fusion small at Tevatron energies; q\bar{q}' enhanced in p\bar{p} collisions**
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- **CSM q̅q′** competes with **COM q̅q′** if \( \langle O_{J/\psi}(^3S_1^{[8]}) \rangle \leq 3 \times 10^{-3} \text{ GeV}^3 \)!

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**J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218**
Results

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- **sg** fusion small at Tevatron energies; **q̄q′** enhanced in **p̄p** collisions
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- **q̄q′** **COM and CSM** have the same **\( P_T \)** dependence


- **sg** fusion small at Tevatron energies; **q̅q’** enhanced in **p̅p** collisions
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Results

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- **sg** fusion small at Tevatron energies; \( q\bar{q}' \) enhanced in \( pp \) collisions
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- **sg** fusion becomes large at LHC energies
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sg fusion small at Tevatron energies; $q\bar{q}'$ enhanced in $p\bar{p}$ collisions

CSM $q\bar{q}'$ competes with COM $q\bar{q}'$ if $\langle O_{J/\psi}^{3S_1^{[8]}} \rangle \leq 3 \times 10^{-3}$ GeV$^3$ !

$q\bar{q}'$ COM and CSM have the same $P_T$ dependence

sg fusion becomes large at LHC energies

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CSM contributions larger than COM at the LHC
**Results**

- *sg* fusion small at Tevatron energies; *q̅q′* enhanced in *p̅p* collisions
- **CSM** *q̅q′* competes with **COM** *q̅q′* if \[ \langle O_{J/\psi} (3 S_1^{[8]}) \rangle \leq 3 \times 10^{-3} \text{ GeV}^3 \]
- *q̅q′* **COM** and **CSM** have the same \( P_T \) dependence
- *sg* fusion becomes large at LHC energies
- *sg* fusion competes with *q̅q′* annihilation in *pp* collisions
- **CSM** contributions larger than **COM** at the LHC
- Unfortunately, *J/ψ + W* not a clean test of colour octets

but measured by ATLAS!
Rapidity distribution – Comparison with ATLAS

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Cross sections are not very large

Comparison with ATLAS

arXiv:1401.2831 [hep-ex]

LO CSM total
LO CSM g+s fusion
LO CSM via γ*

no cut on W decay products; for W+ and W-
μ_R=μ_F=m_W x (0.75,2;1,1;2,0.75) and
m_c=1.5+/-0.1 GeV for CSM

direct-J/ψ+W at sqrt(s)=8 TeV

Feed-down from ψ(2S): 0.15±0.04 fb
Feed-down from χ_c: 3.7±2.1 fb
Sum: 4.5±2.3 fb

ATLAS data

total prompt: 25±10 fb
DPS subtracted: 15±10 fb [marginal agreement]
Cross sections are not very large
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CSM

$$\sigma = \sigma (P_T^\psi > 8.5 \text{GeV}, |y^\psi| < 2.4)$$
Rapidity distribution – Comparison with ATLAS

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ATLAS data
- total prompt: $25 \pm 10$ fb

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  - Sum: $4.5 \pm 2.3$ fb
ATLAS data
  - total prompt: $25 \pm 10$ fb
  - DPS subtracted: $15 \pm 10$ fb

\[ \sigma = \sigma(P_T^\psi > 8.5\text{GeV}, |y^\psi| < 2.4) \]
Part V

Quarkonium + hadron
\( Q + \) hadron azimuthal correlations

\( \rightarrow J/\psi + \) hadron azimuthal correlations


PYTHIA might not be reliable (Color Singlet at LO: \( gg \rightarrow J/\psi g \))

Need for updates with NLO and NNLO

\( gg \rightarrow J/\psi gg \): peak at \( \Delta \phi = \pi \) (activity from the recoiling jet)

\( gg \rightarrow J/\psi g g \): peak at \( \Delta \phi = \pi \) + activity between 0 and \( \pi \)

\( gg \rightarrow J/\psi g g g \): peak at \( \Delta \phi = \pi \) + activity between 0 and \( \pi \)+ near jet?
$Q + \text{hadron}$ azimuthal correlations

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The aim of STAR was to extract the $B$ feed-down to $J/\psi$:

more activity near the $J/\psi$ than for prompt production

Could that be used to discriminate octet vs. singlet hadronisation?

J.P. Lansberg (IPNO)
Associated-quarkonium production
May 1, 2014 24/27
**Q + hadron azimuthal correlations**

→ $J/\psi$ + hadron azimuthal correlations

![Graph showing azimuthal correlations](graph.png)

- PYTHIA might not be reliable (Color Singlet at LO: $gg \rightarrow J/\psi g$)

**Talk by M. Cervantes (STAR) at WWND 2011**
**Q + hadron azimuthal correlations**

→ $J/\psi +$ hadron azimuthal correlations


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$\Upsilon +$ hadron azimuthal correlations

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→ $\Upsilon$ + hadron azimuthal correlations

The aim of STAR was to extract the $B$ feed-down to $J/\psi$:
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**Q + hadron azimuthal correlations**

\[ \rightarrow J/\psi + \text{hadron azimuthal correlations} \]

![Graph showing azimuthal correlations](image)

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**Y + hadron azimuthal correlations**

- The aim of STAR was to extract the \( B \) feed-down to \( J/\psi \):
  - more activity near the \( J/\psi \) than for prompt production

Could that be used to discriminate octet vs. singlet hadronisation?
Part VI

$J/\psi + \text{charm}$
Double charm: $J/\psi + D$

$\rightarrow J/\psi + D$ or $J/\psi$+lepton in the yield integrated over $P_T$

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010
Double charm: $J/\psi + D$

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plot for RHIC kinematics
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- Near $D$ or lepton: signal of $c \rightarrow J/\psi + c$ “fragmentation”
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\[ \frac{N(J/\psi + c)}{N(J/\psi + X)} (\%) \]

plot for RHIC kinematics

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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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![Graph](image)

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→ First measurement by LHCb ($p_T^D \geq 3$ GeV $\Rightarrow p_T^{\text{charm quark}}$ not small)

![Graph](image)

LHCb, JHEP 1206 (2012) 141
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First measurement by LHCb ($p_T^D \geq 3$ GeV $\Rightarrow p_T^{\text{charm quark}}$ not small)

At low $P_T$, we should be careful about the $k_T$ smearing effect on $\Delta \phi$
Conclusions and Outlooks

- LO pQCD (CSM) reproduces the yield: relevant for heavy-ion studies: LO CSM is $gg \rightarrow Qg$
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  Dominant contributions are known only at Born order ($gg \rightarrow J/\psi g g$)

J.P. Lansberg (IPNO)
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  the opportunity of extracting $g(x)$ with quarkonium
- and by extension the gluon TMDs (gluon transverse motion)
  for the first time
Part VII

Backup
Despite th. uncertainties, CSM predictions are parameter free!
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At LO in $v^2$, one *de facto* predicts direct cross-section ratios

$$
\sigma^{\text{direct}}(\Upsilon(3S)) / \sigma^{\text{direct}}(\Upsilon(1S)) = \frac{|\psi_{3S}(0)|^2}{|\psi_{1S}(0)|^2} \sim 0.34
$$

$$
\sigma^{\text{direct}}(\Upsilon(2S)) / \sigma^{\text{direct}}(\Upsilon(1S)) = \frac{|\psi_{2S}(0)|^2}{|\psi_{1S}(0)|^2} \sim 0.45
$$

$$
\sigma^{\Upsilon(1S)}(|y| < 2) \rightarrow \ell\ell \simeq 7.4 \text{ nb}
$$

$$
\sigma^{\Upsilon(3S)}(|y| < 2) \rightarrow \ell\ell \simeq 1.0 \text{ nb}
$$

CMS, PRD 83, 112004 (2011)

Extrapolated $3S$ direct yield: $0.34 \times 150 \text{ nb} \sim 50 \text{ nb}$

$$
\sigma^{\Upsilon(3S)}(|y| < 2) \rightarrow \ell\ell \simeq 1 \text{ nb}
$$

$100\%$ direct $\rightarrow \sigma^{\Upsilon(3S)} \sim 45 \text{ nb}$

CMS, PRD 83, 112004 (2011)

NEW: the $3S$ yield likely not $100\%$ direct

*cf.* $\chi_b(3P)$ observation by ATLAS

Despite the uncertainties, CSM predictions are parameter free! At LO in $v^2$, one 	extit{de facto} predicts direct cross-section ratios.

Simple ratios of Schrödinger wave function at the origin:

$$\frac{\sigma(\text{direct } Y(3S))}{\sigma(\text{direct } Y(1S))} = \frac{\psi_{3S}(0)^2}{\psi_{1S}(0)^2} \sim 0.34$$

$$\frac{\sigma(\text{direct } Y(2S))}{\sigma(\text{direct } Y(1S))} = \frac{\psi_{2S}(0)^2}{\psi_{1S}(0)^2} \sim 0.45$$
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\[
\sigma(Y(1S)(|y| < 2)) Br_{\ell\ell} \sim 7.4 \text{ nb} \quad \text{50\% direct} \quad \sigma(\text{direct } Y(1S)) \sim 150 \text{ nb}
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\sigma(Y(3S)(|y| < 2)) Br_{\ell\ell} \sim 1.0 \text{ nb} \xrightarrow{100\% \text{ direct}} \sigma(\text{direct } Y(3S)) \sim 45 \text{ nb}
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CMS, PRD 83, 112004 (2011)
Cross section ratio I

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- $\sigma(Y(1S)(|y| < 2)) Br_{\ell\ell} \simeq 7.4 \text{ nb}$ \[50\%]direct $\rightarrow \sigma(\text{direct } Y(1S)) \sim 150 \text{ nb}$

- Extrapolated 3S direct yield: $0.34 \times 150 \text{ nb} \sim 50 \text{ nb}$

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- NEW: the 3S yield likely not 100% direct
  cf. $\chi_b(3P)$ observation by ATLAS \[PRL, 108, 152001 (2012)]
Cross section ratio II

- CSM extrapolation
- LHCb $2.0 < y < 4.5$
- CMS $|y| < 2.0$

- Mass effects at low $P_T$: not included in the results:
  - $\Upsilon(nS)$
  - NRQCD

- Feed-down: simple kinematical effect:
  - $P_{\text{daughter}} T \sim M_{\text{daughter}} M_{\text{mother}} P_{\text{mother}}$

- Harmless if $d\sigma/dP_T \propto P^{-n}$ with $n$ fixed,
  - harmful if $n$ changes, especially true at low $P_T$ where $d\sigma/dP_T$ can be flat.
\textbf{Cross section ratio II}

- \textbf{\( P_T \) dependence of cross section ratios:}
Cross section ratio II

- $P_T$ dependence of cross section ratios:
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**$P_T$ dependence of cross section ratios:**

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Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

$q\bar{q}' \rightarrow \gamma^* W \rightarrow J/\psi W$ and $q\bar{q}' \rightarrow g^* W \rightarrow J/\psi W$ are very similar

why?
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why?

Let us simplify and look at

$q\bar{q}' \rightarrow \gamma^* \rightarrow J/\psi$ vs. $q\bar{q}' \rightarrow g^* \rightarrow J/\psi$
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The cross sections are well-known:
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The cross sections are well-known:

- CSM: $\hat{\sigma}^{[1]}_{\gamma^*} = \frac{(4\pi\alpha)^2 e_q^2 e_{\bar{q}}^2}{M_Q^3 s} \delta \left( x_1 x_2 - \frac{M_Q^2}{s} \right) |R(0)|^2$
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- **COM:** $\hat{\sigma}^{[8]}_{g^*} = \frac{(4\pi\alpha_s)^2 \pi}{27M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) \langle O_Q(3S_1^1) \rangle$
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- **COM:** $\hat{\sigma}[8]_{g^*} = \frac{(4\pi\alpha s)^2 \pi}{27 M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) \langle O_Q(3S_1^{[1]}) \rangle$

The ratio gives:

$$\frac{\hat{\sigma}[1]_{\gamma^*}}{\hat{\sigma}[8]_{g^*}} = \frac{6\alpha^2 e_q^2 e_{\bar{q}}^2 \langle O_Q(3S_1^{[1]}) \rangle}{\alpha_s^2 \langle O_Q(3S_1^{[8]}) \rangle} \langle O_Q(3S_1^{[1]}) \rangle = 2N_c (2J + 1) \frac{|R(0)|^2}{4\pi}$$
Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

$q\bar{q}' \to \gamma^* W \to J/\psi W$ and $q\bar{q}' \to g^* W \to J/\psi W$ are very similar. Why?

Let us simplify and look at $q\bar{q}' \to \gamma^* \to J/\psi$ vs. $q\bar{q}' \to g^* \to J/\psi$

The cross sections are well-known:

- **CSM:**
  \[
  \hat{\sigma}^{[1]}_{\gamma^*} = \frac{(4\pi\alpha)^2 e_Q^2 e_{\bar{Q}}^2}{M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) |R(0)|^2
  \]

- **COM:**
  \[
  \hat{\sigma}^{[8]}_{g^*} = \frac{(4\pi\alpha s)^2 \pi}{27 M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) \langle \mathcal{O}_Q(3S^1_1) \rangle
  \]

The ratio gives:

\[
\frac{\hat{\sigma}^{[1]}_{\gamma^*}}{\hat{\sigma}^{[8]}_{g^*}} = \frac{6\alpha^2 e_Q^2 e_{\bar{Q}}^2 \langle \mathcal{O}_Q(3S^1_1) \rangle}{\alpha_s^2 \langle \mathcal{O}_Q(3S^1_8) \rangle} \quad \langle \mathcal{O}_Q(3S^1_1) \rangle = 2N_c(2J + 1) |R(0)|^2
\]

Colour factor: $2N_c$
Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

\[
\frac{\hat{\sigma}^{[1]}_{\text{via } \gamma^*}}{\hat{\sigma}^{[8]}_{\text{via } g^*}} = \frac{6e_q^2e_Q^2\langle O_Q( {^3S_1}^{[1]} ) \rangle}{\alpha_s^2\langle O_Q( {^3S_1}^{[8]} ) \rangle}
\]

The ratio depends on the initial quark, $q$, on $\alpha_s$ at $\mu_R \approx m_Q$ and on the ratio of the non-perturbative coefficients. For $J/\psi$ production in $u\bar{u}$ fusion and for $\langle O_{J/\psi}( {^3S_1}^{[8]} ) \rangle = 2.2 \times 10^{-3}$ GeV$^3$, the ratio CSM vs. COM is $2/3$.

For $\Upsilon$ production, it is about the same (smaller but $\alpha_s$ also smaller and $|R(0)|$ larger).

If we add the $W$ emission, the charge factor changes and $\mu_R$: $O(m_Q) \rightarrow O(m_W) \rightarrow$.

This explains our results for $J/\psi + W$.

General conclusion: For production processes involving light quarks, the CSM via off-shell photon competes with the COM via off-shell gluon.
Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

$$\frac{\hat{\sigma}_{\text{via } \gamma^*}^{[1]}}{\hat{\sigma}_{\text{via } g^*}^{[8]}} = \frac{6\alpha_s^2 e_q^2 e_Q^2 \langle O_Q(3S^1_1) \rangle}{\alpha_s^2 \langle O_Q(3S^8_1) \rangle}$$

- The ratio depends on the initial quark, $q$, on $\alpha_s$ at $\mu_R \simeq m_Q$ and on the ratio of the non-perturbative coefficients.
Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

\[
\frac{\hat{\sigma}^{[1]}_{\text{via } \gamma^*}}{\hat{\sigma}^{[8]}_{\text{via } g^*}} = \frac{6\alpha_s^2 e_q^2 e_Q^2 \langle O_Q(\,^3S_1^{[1]}\,\rangle}{\alpha_s^2 \langle O_Q(\,^3S_1^{[8]}\,\rangle}
\]

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Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

\[
\frac{\hat{\sigma}_{\text{via } \gamma^*}^{[1]}}{\hat{\sigma}_{\text{via } g^*}^{[8]}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle O_Q(\frac{3}{2}S_1^{[1]}) \rangle}{\alpha_s^2 \langle O_Q(\frac{3}{2}S_1^{[8]}) \rangle}
\]

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  \]
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Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

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\frac{\hat{\sigma}^{[1]}_{\text{via } \gamma^*}}{\hat{\sigma}^{[8]}_{\text{via } g^*}} = \frac{6\alpha^2 e_q e_Q^2 \langle O_Q(3S_1^{[1]}) \rangle}{\alpha_s^2 \langle O_Q(3S_1^{[8]}) \rangle}
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Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

$$\frac{\hat{\sigma}_{\text{via } \gamma^*}^{[1]}}{\hat{\sigma}_{\text{via } g^*}^{[8]}} = \frac{6\alpha_s^2 e_q^2 e_Q^2 \langle O_Q(\ 3S_1^{[1]}\rangle}{\alpha_s^2 \langle O_Q(\ 3S_1^{[8]}\rangle}$$

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General conclusion:

For production processes involving light quarks, the CSM via off-shell photon competes with the COM via off-shell gluon.