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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J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
CDF PRL 88 (2002) 161802;PRD 87, 052004 (2013)

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

$\psi$ or $\Upsilon$

$\alpha_s^3 P^{--8}$

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

$P_T$ (GeV)

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

LO
NLO

$\psi$ or $\Upsilon$

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

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

Attention: the NNLO $\star$ is not a complete NNLO
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NLO
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$\alpha_3^3 P_T^{-8}$

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$\psi$ or $\Upsilon$
$\alpha_5^5 P_T^{-4}$

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

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QCD corrections for $\Upsilon$ at the Tevatron & the LHC

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

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

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

Attention: the NNLO* is not a complete NNLO
CSM predictions account for the $P_T$-integrated yield

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

→ The yield vs. $\sqrt{s}$, $y$

(Here only LO curves*)

*NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$
CSM predictions account for the $P_T$-integrated yield

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 $F^{\text{direct}}$)

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The current situation in one slide ...

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- Colour-Singlet Model (CSM) back in the game
  [large NLO and NNLO correction to the $P_T$ spectrum; but not perfect]

- 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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Part II

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

- LO to $J/\psi + J/\psi$ at $\alpha_s^4$

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JPL, H.S. Shao PRL 111, 122001 (2013)

[nicely confirmed by a full NLO]

L.P. Sun et al. arXiv:1404.4042 [hep-ph]
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$J/\psi + \eta_c$ suppressed by $C$ parity: LO at $\alpha_S^5$

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- **LO** to \( J/\psi + J/\psi \) at \( \alpha_S^4 \)
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- Different $P_T$ spectrum & different $\Delta M$ distribution

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**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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P. Artoisenet, JPL, F. Maltoni, PLB 653:60, 2007
\( \Upsilon + b\)-tagged jet (or \( \Upsilon+ \) non-prompt \( J/\psi \))

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- \( \Upsilon + b \): discriminant for CSM vs. COM channels
- 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 + isolated $\gamma$

- At high energy, 2 gluons in the initial states: no quark
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**Q + isolated γ**

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- CS rate at NLO \(\simeq\) conservative (high) expectation\(^\dagger\) from CO

\(^\dagger\)In fact, the NLO CO yield can even be negative

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

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\(\dagger\)Possible at LHC: cf. \((c,b)\)−jet + γ studies by D0 up to \(P_{\gamma T} \simeq 150\) GeV:

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- CO rates may be clearly lower if \(^1S_0^8\) and \(^3P_J^8\) are indeed suppressed \(\text{at NLO}\)

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CO rates may be clearly lower if $^1S^0_0$ and $^3P^J_J$ are indeed suppressed
At NNLO*, CS rate clearly above (high) expectation from CO (at NLO)

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R.Li and J.X. Wang, arXiv:1401.6918

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May 1, 2014
\( Q + \text{isolated } \gamma \)

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

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

- Possible at LHC: cf. \((c, b) - jet + γ\) studies by D0 up to \(P_T^γ \sim 150\) GeV:

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$Q + \gamma$: **back-to-back** and both isolated

Representative diagrams contributing to the hadroproduction of $Q$ 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).
\( Q + \gamma: \text{back-to-back and both isolated} \)

Representative diagrams contributing to the hadroproduction of a \( Q \) in association with a photon at orders \( \alpha_s^2 \alpha_s \) (a), \( \alpha_s^3 \alpha_s \) (b, c), \( \alpha_s^4 \alpha_s \) (d, e, f).

- **Born (LO):** \( 2 \rightarrow 2 \) contributions (a)-(b) fall like \( P_T^{-8} \)
**Q + γ: back-to-back and both isolated**

![Representative diagrams](image)

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

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- **COM contributions similar to (d):**
  Instead of a 'hard' gluon, there would be multiple soft gluons.
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- (c)-(f): parton [\( \rightarrow \) some hadrons] in the central region;
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- **\( 2 \rightarrow 2 \) topologies contribute to** \( \Delta \phi_{Q-\gamma} = \pi \) (back-to-back) ;
  - smearing effect small for \( P_T \gg \langle k_T \rangle \)
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- **2 → 2 topologies contribute to** $\Delta \phi_{Q-\gamma} = \pi$ (back-to-back) ;
  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 $P_T$]
\( Q + \gamma \): 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 \( Q + \gamma \)
$Q + \gamma$: 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 $Q + \gamma$
- The “back-to-back” requirement also limits the DPS contributions
  [a priori evenly distributed in $\Delta \phi$]
**$Q + \gamma$: 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 $Q + \gamma$**
- 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)
$Q + \gamma$: 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 $Q + \gamma$
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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

**Diagram:**

- Direct back-to-back Onium + $\gamma$ at $\sqrt{s} = 14$ TeV

**Graphs:**

- $d\sigma/dQ/dY/d\cos\theta_{CS} \times \text{Br}(\text{Onium} \rightarrow \mu \mu)$ (fb/GeV)
- $Q_{\Upsilon} + \gamma$ (GeV)
- $Q_{J/\psi} + \gamma$ (GeV)

- Color Singlet
- Color Octet

- Associated-quarkonium production

- J.P. Lansberg (IPNO)
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 $h_1^\perp g(x, k_T, \mu_F)$

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

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\[
\frac{d\sigma}{dQdYd^2q_Td\Omega} = \frac{C_0(Q^2 - M_Q^2)}{sQ^3D}\left\{F_1 C[f_1^g f_1^g] + F_3 \cos(2\phi_{CS}) C[w_3 f_1^g h_1^\perp g + x_1 \leftrightarrow x_2] + F_4 \cos(4\phi_{CS}) C[w_4 h_1^\perp g h_1^\perp g]\right\} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)
\]

- We define: $S_{qT}^{(n)} = \left(\frac{d\sigma}{dQdYd\cos\theta_{CS}}\right)^{-1}\int d\phi_{CS}\pi \cos(n\phi_{CS}) \frac{d\sigma}{dQdYd^2q_Td\Omega}$
The $q_T$-differential cross section involves $f_{1}^{g}(x, k_T, \mu_F)$ and $h_{1}^{\perp g}(x, k_T, \mu_F)$.

\[
\frac{d\sigma}{dQ dY d^2q_T d\Omega} = \frac{C_0(Q^2 - M_Q^2)}{s Q^3 D} \left\{ F_1 \left[ f_{1}^{g} f_{1}^{g} \right] + F_3 \cos(2\phi_{CS}) C \left[ w_3 f_{1}^{g} h_{1}^{\perp g} + x_1 \leftrightarrow x_2 \right] + F_4 \cos(4\phi_{CS}) C \left[ w_4 h_{1}^{\perp g} h_{1}^{\perp g} \right] \right\} + \mathcal{O} \left( \frac{q_T^2}{Q^2} \right)
\]

We define: $S_{q_T}^{(n)} = \left( \frac{d\sigma}{dQ dY d\cos \theta_{CS}} \right)^{-1} \int d\phi_{CS} \pi \cos(n\phi_{CS}) \frac{d\sigma}{dQ dY d^2q_T d\Omega}$

$S_{q_T}^{(0)} \leftrightarrow f_{1}^{g}(x, k_T, \mu_F)$: clean extraction is possible!
back-to-back $Q + \gamma$ and the gluon TMDs

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- $S_{q_T}^{(0)} \leftrightarrow f_1^g(x, k_T, \mu_F)$: clean extraction is possible!
- $S_{q_T}^{(4)} \leftrightarrow h_1^\perp g(x, k_T, \mu_F)$: a nonzero $S_{q_T}^{(4)}$ (or $\int dq_T S_{q_T}^{(4)}$) would indicate a nonzero gluon linear polarisation in unpolarised gluon
back-to-back $Q + \gamma$ and the gluon TMDs

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Part IV

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

- Υ + W/Z boson

CDF Collaboration, PRL. 90 (2003) 221803

NRQCD predictions (Signal dominated by CO into χb):

σ[p¯p → Υ(1S) + W⁺] × Br(Υ(1S) → µµ) ≃ 0.025 pb

σ[p¯p → Υ(1S) + Z0] × Br(Υ(1S) → µµ) ≃ 0.0075 pb

E. Braaten, J. Lee, and S. Fleming, PRD 60, 91501 (1999)

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

With 1 fb⁻¹ at √s = 7 TeV and a larger (E×A)(Υ), one should see events if CO's are at work

J/ψ + Z and J/ψ + W recently computed at NLO in αs

L.Gang et al. PRD 83, 014001, 2011; JHEP 02(2011)071

J/ψ | Υ + Z at NLO in αs + Polarisation

B.Gong et al. JHEP 1303 (2013) 115

J.P. Lansberg (IPNO)
$Q + W/Z$ 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
    \[
    \sigma(p\bar{p} \to \Upsilon(1S) + W^\pm) \times Br(\Upsilon(1S) \to \mu\mu) < 2.3 \text{ pb}
    \]
    \[
    \sigma(p\bar{p} \to \Upsilon(1S) + Z^0) \times Br(\Upsilon(1S) \to \mu\mu) < 2.5 \text{ pb}
    \] (1)
  - NRQCD predictions (Signal dominated by CO into $\chi_b$)
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    \]
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    \] (2)

CDF Collaboration, PRL. 90 (2003) 221803

E. Braaten, J. Lee, and S. Fleming, PRD 60, 91501 (1999)
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- $J/\psi + Z$ and $J/\psi + W$ recently computed at NLO in $\alpha_s$

- $J/\psi|Y + Z$ at NLO in $\alpha_s + \text{Polarisation}$
Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $Q + \gamma$ for $Q \gtrsim 20$ GeV]

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

Potential probe of gluon TMDs as well
Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $Q + \gamma$ for $Q \gtrsim 20$ GeV]

Mass effects ($m_c \leftrightarrow m_b$ less relevant because of $m_Z$) $|y_{J/\psi}| < 2.4$ is 10 times larger for $\Upsilon$ than for $J/\psi$

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Potential probe of gluon TMDs as well
\( \Upsilon + Z: \Upsilon \) polarisation

\[ \text{B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115} \]

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

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

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

\( |y_{\Upsilon}| < 2.4 \)

\( P_T^{\Upsilon} > 3 \text{ GeV} \)

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

Unlike the inclusive case, it is not clear why this is the case. Further investigation is needed.
\( Y + Z : Y \) polarisation

- \( Y \) polarisation at LO and NLO are similar

\( P_{T}^{Y} > 3 \text{ GeV} \)

\( |y^{\gamma}| < 2.4 \)

\( \sqrt{s} = 14 \text{ TeV} \)

LO: \( \mu_{R} = \mu_{F} = m_{Z} \)

NLO: \( \mu_{R} = \mu_{F} = m_{Z} \)
$\Upsilon + Z : \Upsilon$ polarisation

- $\Upsilon$ polarisation at LO and NLO are similar
- unlike the inclusive case
- not clear why: need for further investigation

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B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115
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$J/\psi + W$

"'\psi + W offers a clean test of the colour octet contributions'"

V. D. Barger, S. Fleming and R. J. N. Phillips, PLB 371, 111 (1996)
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 $\psi + Z$
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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 $Q\bar{Q}$

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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 $P_T$.
direct $J/\psi + W$

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

To check this, we have considered two kinds of "LO" CSM process at $\alpha_1$ (EW) and LO in $\alpha_s$ ($\alpha_3^s$ vs. $\alpha_2^s$ for COM), we have

sg 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 $\alpha_0$, we also have $q\bar{q}$ fusion, $J/\psi W^{\pm}$, $q\bar{q}' \gamma^\ast \rightarrow J/\psi W^{\pm}$: negligible since $\alpha_3$?
To check this, we have considered two kinds of “LO” CSM process.
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- At $\alpha_{(EW)}^{-1}$ and LO in $\alpha_s$ ($\alpha_s^3$ vs. $\alpha_s^2$ for COM), we have $sg$ fusion.
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- It involves gluon PDFs (enhanced w.r.t $q(x)$ at high $\sqrt{s}$).

The process involves $s(\bar{s})$, $c(\bar{c})$, and $W^\pm$ interaction, leading to $J/\psi$ production.
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.
- This involves gluon PDFs (enhanced w.r.t $q(x)$ at high $\sqrt{s}$).
- “LO” contains leading power in $P_T$.
- $\rightarrow$ no kinematical suppression.
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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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At $\alpha_s^3$ and $\alpha_s^0$, we also have $q\bar{q}$ fusion.

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- Pure EW process.
To check this, we have considered two kinds of “LO” CSM process

At $\alpha_3^{(EW)}$ and LO in $\alpha_s$ ($\alpha_3^3$ vs. $\alpha_s^2$ 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. Lorcé, PLB 726 (2013) 218

Associated-quarkonium production

May 1, 2014 21 / 27
**Results**

- **sg fusion small at Tevatron energies;** *q̅q′* enhanced in *p̅p* collisions
\begin{itemize}
  \item \textit{sg} fusion small at Tevatron energies; \textit{q\bar{q}'} enhanced in \textit{p\bar{p}} collisions
  \item CSM \textit{q\bar{q}'} competes with COM \textit{q\bar{q}'} if $\langle O_{J/\psi}(^{3}S_{1}^{[8]}) \rangle \leq 3 \times 10^{-3}$ GeV$^3$!
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**Results**

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

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

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- $sg$ fusion becomes large at LHC energies
- *sg* fusion small at Tevatron energies; *q̅q′* enhanced in *p̅p* collisions
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- *q̅q′* COM and CSM have the same $P_T$ dependence
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- *sg* fusion competes with *q̅q′* annihilation in *pp* collisions
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- **CSM** **q̅q′** competes with **COM** **q̅q′** if $\langle O_{J/\psi}(^3S_1^{[8]}) \rangle \leq 3 \times 10^{-3}$ GeV$^3$!
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**Results**

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

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- Unfortunately, **J/\psi + W** not a clean test of colour octets

but measured by ATLAS!
Rapidity distribution – Comparison with ATLAS

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

Cross sections are not very large

Comparison with ATLAS

arXiv:1401.2831 [hep-ex]

CSM

\[ \sigma = \sigma (\psi(T > 8.5 \text{GeV}), |y_{\psi}| < 2.4) \]

direct: 0.6 ± 0.2 fb

Feed-down from \( \psi(2S) \): 0.15 ± 0.04 fb

Feed-down from \( \chi_c \): 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]

no cut on W decay products; for W\(^+\) and W\(^-\)

\( \mu_R = \mu_F = m_W \times (0.75, 2; 1, 1; 2, 0.75) \) and

\( m_c = 1.5/0.1 \text{ GeV for CSM} \)
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Comparison with ATLAS

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- total prompt: $25 \pm 10$ fb
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$\sigma = \sigma(P_T^{\psi} > 8.5\text{GeV}, |y^{\psi}| < 2.4)$
Rapidity distribution – Comparison with ATLAS

Cross sections are not very large

Comparison with ATLAS

CSM

- direct: $0.6 \pm 0.2$ fb
- Feed-down from $\psi(2S)$: $0.15 \pm 0.04$ fb
- Feed-down from $\chi_c$: $3.7 \pm 2.1$ fb
- 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

→ $J/\psi$ + hadron azimuthal correlations

STAR Collab., Phys.Rev.C80:041902 (R), 2009.

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

Need for updates with NLO and NNLO.

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

$gg \rightarrow J/\psi gg$: peak at $\Delta \phi = \pi +$ activity between 0 and $\pi$.

$gg \rightarrow J/\psi ggg$: peak at $\Delta \phi = \pi +$ near jet?
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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

$\rightarrow J/\psi +$ hadron azimuthal correlations

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Talk by M. Cervantes (STAR) at WWND 2011

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

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010
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plot for RHIC kinematics

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- 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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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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- QCD corrections open leading $P_T$ channel: they are needed!
  - $2 \rightarrow 3, 2 \rightarrow 4$ channels

Drawback: large theoretical uncertainties. . .
Dominant contributions are known only at Born order ($gg \rightarrow J/\psi, gg g$)
(N)NLO corrections alter the polarisation: transverse $\rightarrow$ longitudinal (in HX)
CO fits of x-section disagree in their prediction of polarisation
Need for new observables, need for NLO evaluations at the LHC or elsewhere!
Given the precision of the data at low $P_T$, one should re-think the opportunity of extracting $g(x)$ with quarkonium and by extension the gluon TMDs (gluon transverse motion) for the first time.
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J.P. Lansberg (IPNO)
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Part VII

Backup
Cross section ratio I

- Despite th. uncertainties, CSM predictions are parameter free!
Cross section ratio I

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- At LO in $v^2$, one *de facto* predicts direct cross-section ratios.

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

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

\[
\text{Br}_{\ell\ell} \simeq 7.4 \text{ nb}
\]

\[
\text{Br}_{\ell\ell} \simeq 1.0 \text{ nb}
\]

CMS, PRD 83, 112004 (2011)

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

$3S$ direct yield likely not 100% direct. cf. $\chi_{b}(3P)$ observation by ATLAS.

PRL, 108, 152001 (2012)
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At LO in $v^2$, one *de facto* predicts direct cross-section ratios

Simple ratios of Schrödinger wave function at the origin:

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$$\sigma(Y(1S)(|y| < 2)) Br_{\ell\ell} \sim 7.4 \text{ nb} \quad \text{50%direct} \quad \Rightarrow \quad \sigma(\text{direct } Y(1S)) \sim 150 \text{ nb}$$

CMS, PRD 83, 112004 (2011)
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\sigma(\text{direct } Y(1S)(|y| < 2)) Br_{\ell\ell} \sim 7.4 \text{ nb} \quad \rightarrow \quad \sigma(\text{direct } Y(1S)) \sim 150 \text{ nb}
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Extrapolated 3S direct yield: $0.34 \times 150 \text{ nb} \sim 50 \text{ nb}$

\[
\sigma(\text{direct } Y(3S)(|y| < 2)) Br_{\ell\ell} \sim 1.0 \text{ nb} \quad \rightarrow \quad \sigma(\text{direct } Y(3S)) \sim 45 \text{ nb}
\]
Cross section ratio I

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- At LO in $v^2$, one *de facto* predicts direct cross-section ratios
- Simple ratios of Schrödinger wave function at the origin:

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\sigma(Y(3S)(|y| < 2)) Br_{\ell\ell} \sim 1.0 \text{ nb} \quad \xrightarrow{100\% \text{ direct}} \quad \sigma(\text{direct } Y(3S)) \sim 45 \text{ nb}
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CMS, PRD 83, 112004 (2011)

- NEW: the $3S$ yield likely not 100% direct
  cf. $\chi_b(3P)$ observation by ATLAS

PRL, 108, 152001 (2012)
Cross section ratio II

Mass effects at low $P_T$: not encoded in the $v_2$ results: $M_\Upsilon(nS)$

NRQCD $= 2m_b$

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

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

- $P_T$ dependence of cross section ratios:
**Cross section ratio II**

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

$q\bar{q}' \rightarrow \gamma^* W^3 S_{[1]} \rightarrow J/\psi W$ and $q\bar{q}' \rightarrow g^* W^3 S_{[8]} \rightarrow J/\psi W$ are very similar why?
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\[
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The cross sections are well-known:

\[
\hat{\sigma}[^1]_{\gamma^*} = \frac{4\pi\alpha^2 e^2 q e Q M^2 Q}{s} \frac{\delta (x_1 x_2 - M_Q^2)}{|R(0)|^2}
\]

\[
\hat{\sigma}[^8]_{g^*} = \frac{4\pi\alpha^2 S}{27} \frac{\langle O_Q(3S[^8]_1) \rangle}{\langle O_Q(3S[^1]_1) \rangle} \alpha^2 S \frac{\langle O_Q(3S[^8]_1) \rangle}{\langle O_Q(3S[^1]_1) \rangle} = \frac{2N_c}{4\pi} (2J + 1) \frac{|R(0)|^2}{4\pi}
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- **COM:** $\hat{\sigma}^{[8]}_{g^*} = \frac{(4\pi\alpha S)^2 \pi}{27M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) \langle \mathcal{O}_Q \left( \frac{3 S_1^3}{8} \right) \rangle$

Colour factor: $2 N_c (2J + 1)$
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?

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

The cross sections are well-known:

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

- **COM**: $\hat{\sigma}^{[8]}_{g^*} = \frac{(4\pi\alpha S)^2 2\pi}{27M_Q^3 s} \delta \left( x_1 x_2 - M_Q^2 / s \right) \langle O_Q(3S_1^{[8]}) \rangle$

The ratio gives:

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

$$\langle O_Q(3S_1^{[1]}) \rangle = 2N_c(2J + 1) \frac{|R(0)|^2}{4\pi}$$
Discussion: CSM via $\gamma^*$ vs. COM via $g^*$

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

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

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 $\langle O_{J/\psi}(3S_1^{[8]}) \rangle = 2/3 \times 10^{-3}$ 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 $|R(0)|_2$ larger).

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

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.
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.
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- 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 $2/3$
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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.