New observables in quarkonium production

J.P. Lansberg
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work done in collaboration with Hua-Sheng Shao (CERN)
Production Model: the current situation in one slide ...

Colour-Singlet Model (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/fitted differs a lot in their conclusions owing to their assumptions (dataset, $P_T$ cut, polarisation/fitted or not, etc.).

All approaches have troubles in describing the polarisation and/or the $\eta_c$ data (see Tuesday talks).

New hope in double-parton fragmentation (Kang, Qiu, Sterman, PRL). 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. Examples for which data exists: quarkonium-pair production, $J^\psi$, $Z$, ...
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Part I

Quarkonium-pair production
On the importance of $\alpha_s^5$ contributions to $J/\psi + J/\psi$ & $J/\psi + \eta_c$

- LO to $J/\psi + J/\psi$ at $\alpha_s^4$
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JPL, H.S. Shao PRL 111, 122001 (2013)

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The $P_T$ & $M_{\psi\psi}$ distributions depend very much on the topology (see later)

$\sigma_{\text{central \ LO \ SPS}} = 4.83$ nb; $\sigma_{\text{central \ NLO \ SPS}} = 5.34$ nb; $\sigma_{\text{LHCb \ measured}} = 5.1 \pm 1.0 \pm 1.1$ nb: is that all at low $P_T$?

L.P. Sun et al. arXiv:1404.4042 [hep-ph] [First evaluation! (green band)]

JPL, H.S. Shao PRL 111, 122001 (2013) [nicely confirmed by a full NLO]

L.P. Lansberg (IPNO) New observables in quarkonium production September 1, 2016 4 / 20
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- Large enhancement at high $P_T$

[picture of diagrams and plots]


New observables in quarkonium production

September 1, 2016 4 / 20
On the importance of QCD corrections: $P_T$ enhanced topologies

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![Graph showing $d\sigma/dP_T$ for $P_T^{\psi\psi}$ at 7 TeV@LHC, CMS Acceptance.](data: CMS Coll. JHEP 1409 (2014) 094)
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- Slight offset up to $P_T^{\psi\psi} \approx 20$ GeV [about a factor 2, but well within error bars]
- We do not expect NNLO ($\alpha_s^6$) contributions to matter where one currently has data
  [the orange histogram shows one class of leading $P_T \alpha_s^6$ contributions]
On the importance of QCD corrections (III)

- CMS sample affected by an acceptance $P_T$ cut (4-6 GeV)

CMS Coll. JHEP 1409 (2014) 094
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- As we will see, some kinematical distributions are also problematic → the so-called CMS puzzle
- As we will also see, this was foreseeable (this should not have been a puzzle at all)
The so-called CMS puzzle

Predictions for LHCb, DPS and QSPS at large $\Delta y$ C.H. Kom, A. Kulesza, W.J. Stirling PRL

He & Kniehl found at LO that CO QCS at large $\Delta y$; yet still in disagreement with the data; NLO needed!

J.P. Lansberg (IPNO) New observables in quarkonium production September 1, 2016
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Z. He, B. Kniehl PRL 115, 022002 (2015)
On the importance of double parton scatterings at large $\Delta y$ I

In fact, the argument of C.H. Kom, A. Kulesza, and W.J. Stirling was used by D0 to separate out DPS from SPS contributions.

![Graph showing data prompt, SP MC, DP MC, and Syst. uncertainty for $N_{\eta(J/\psi, J/\psi)}$ versus $\Delta \eta(J/\psi, J/\psi)$ at $L = 8.1 \text{ fb}^{-1}$](image)

D0 Coll. PRD 90 (2014) 111101
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- Fitting these MC templates, they splitted $129 \pm 46$ fb into $\sigma^{DPS} = 70 \pm 23$ fb and $\sigma^{SPS} = 59 \pm 23$ fb by comparing the histograms.
- $\sigma^{SPS}_{\text{CSM}} = 170^{+340}_{-110}$ fb and $\sigma^{SPS}_{D0} = 59 \pm 23$ fb are still compatible at 1-$\sigma$ level.
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A natural question arises: using $\sigma^{\text{DPS}} = \frac{1}{2} \sigma_{\psi} \sigma_{\psi}$ and $\sigma_{\text{eff}} = 4.8 \pm 2.5$ mb, can one account for the large $\Delta y$ CMS data?
Let us investigate the consistency between DPS+NLO and CMS data. For that we assume:

\[ \sigma_{DPS} / one.fitted / two.fitted / \]

\[ \sigma_{ψ} \]

\[ \sigma_{ψ eff} \]

We take \( \sigma_{ψ eff} / four.fitted / eight.fitted \).

\[ / two.fitted / five.fitted \]

mb from DPS/zero.fitted.

\( σ_{ψ} \) are fit from data with a Crystal Ball function parametrising S^A gg ψ X.

Gap between theory and CMS data is filled at large \( Δy \) and \( M_{ψψ} \) by DPS+NLO CSMPSPS Agreement not altered elsewhere; improved even at low \( P_{ψψ} T \) (see (a)). Conversely, fitting our own \( σ_{ψ eff} \) from the CMS data should yield a value compatible with /four.fitted./eight.fitted mb.
On the importance of double parton scatterings at large $\Delta y$ II

- Let us investigate the consistency between D0 and CMS data
- For that we assume: $\sigma^{DPS} = \frac{1}{2} \frac{\sigma_\psi \sigma_\psi}{\sigma_{\text{eff}}}$
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Gap between theory and CMS data is filled at large $\Delta y$ and $M_{\psi\psi}$ by DPS + NLO* CSM SPS

---

**Figure (a)**: Graph showing the comparison between theory and CMS data for $P_T^{\psi\psi}$ distribution.

**Figure (b)**: Graph showing the acceptance cuts on $J/\Psi$.

**Figure (c)**: Graph showing the $d\sigma/dM_{\psi\psi}$ distribution.

---

On the importance of double parton scatterings at large $\Delta y$ II

- Let us investigate the consistency between D0 and CMS data
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- $\sigma_{\psi}$ are fit from data with a Crystal Ball function parametrising $|\mathcal{A}_{gg \to \psi \chi}|^2$


- Gap between theory and CMS data is filled at large $\Delta y$ and $M_{\psi \psi}$ by DPS + NLO* CSM SPS
- Agreement not altered elsewhere; improved even at low $P_T^{\psi \psi}$ (see (a))

[Graphs and plots showing the comparison between theory and CMS data are shown here.]
Let us investigate the consistency between D0 and CMS data.

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Agreement not altered elsewhere; improved even at low \( P_T^{\psi \psi} \) (see (a)).

Conversely, fitting our own \( \sigma_{\text{eff}} \) from the CMS data should yield a value compatible with 4.8 mb.
Our fit of the double parton scatterings

Table 2

Result of the fit of the DPS yield via $\sigma_{\text{eff}}$ on the 18 CMS values.

<table>
<thead>
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<th>$\sigma_{\text{eff}}$ (mb)</th>
<th>$\chi^2$</th>
<th>d.o.f.</th>
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<tbody>
<tr>
<td>$\sigma_1$</td>
<td>11.0</td>
<td>± 2.9</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>8.2</td>
<td>± 2.2</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>5.3</td>
<td>± 1.4</td>
</tr>
<tr>
<td>Only LO SPS</td>
<td>N/A</td>
<td>7.6</td>
</tr>
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Effect of the unknown $J_{\psi}$ polarization checked: $\sigma_2$ vs $\sigma_1$ five fitted% quoted by CMS

Sources of uncertainties:
- Template for $\sigma_\psi$ (see above)
- The CMS data uncertainties (incl. pol.)
- The theoretical uncertainties on the NLO† CSMSPS yield
Our fit of the double parton scatterings

- To assess the systematics, we used 3 fits of $\sigma_\psi$
  - Fit 1: CDF and LHC data as done by Kom et al
  - Fit 2: CDF and LHC data (including new larger-$P_T$ data)
  - Fit 3: only CDF data (supposedly close to the D0 template)

\[
\begin{array}{cccc}
\sigma_e f [\text{mb}] & \chi^2 & \text{d.o.f.} & \text{d.o.f.} \\
\sigma_\psi \text{Fit 1} & 25 & 11 & \pm 2.9 & 1.9 & 16 \\
\sigma_\psi \text{Fit 2} & 8.2 & \pm 2.2 & 1.8 & 16 \\
\sigma_\psi \text{Fit 3} & 5.3 & \pm 1.4 & 1.9 & 16 \\
\text{Only LO SPS} & \text{N/A} & 7.6 & 17 \\
\text{Only NLO} \ast & \text{SPS} & \text{N/A} & 2.6 & 17 \\
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### Table 2

<table>
<thead>
<tr>
<th>$\sigma_{\text{DPS}}$ [mb]</th>
<th>$\chi^2$/d.o.f.</th>
<th>d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit 1</td>
<td>11.2 ± 2.9</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
</tr>
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New observables in quarkonium production
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Result of the fit of the DPS yield via $\sigma_{\text{eff}}$ on the 18 CMS values.

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$\sigma_{\text{DPS}}$ computed for D0 & LHCb; agreement checked: $\chi^2_{\text{d.o.f.}}$ : 0.5-1.2 (LHCb) & 0.06-0.5 (D0)
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- $\sigma^\text{DPS}$ computed for D0 & LHCb; agreement checked:
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- Best agreement with Fit 3 confirming the consistency:
  $\sigma_{\text{eff}} = 4.8 \pm 2.5$ mb vs $\sigma_{\text{eff}} = 5.3 \pm 1.4$ mb
Our fit value for $\sigma_{\text{eff}}$: $8.2 \pm 2.0 \pm 2.9 \text{ mb}$
Predictions: excited states

JPL, H.-S. Shao PLB 751 (2015) 479
Predictions: excited states

- Even though we find it a natural, accounting for DPS introduces another parameter.
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- Under DPS dominance (e.g. large $\Delta y$), $\sigma^{\text{DPS}}_{ab} = \frac{m}{2} \frac{\sigma_a \sigma_b}{\sigma_{\text{eff}}} (m: \text{symmetry factor})$

$$F^{\chi_c}_{\psi\psi} = F^{\chi_c}_\psi \times \left( F^{\chi_c}_\psi + 2F^{\text{direct}}_\psi + 2F^{\psi'}_\psi \right),$$

$$F^{\psi'}_{\psi\psi} = F^{\psi'}_\psi \times \left( F^{\psi'}_\psi + 2F^{\text{direct}}_\psi + 2F^{\chi_c}_\psi \right),$$

$$F^{\text{direct}}_{\psi\psi} = \left( F^{\text{direct}}_\psi \right)^2$$
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- Under SPS CSM dominance,
  - $F_{\psi\psi}^{\psi'}$ is slightly enhanced by symmetry factors,
  - $F_{\psi\psi}^{\chi_c}$, unlike single quarkonium production, is not enhanced and is found to be small
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<tr>
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<th>(CSM) SPS</th>
<th>DPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\psi'\psi}^{\psi'}$</td>
<td>45%</td>
<td>20%</td>
</tr>
<tr>
<td>$F_{\psi'\psi}^{\chi_c}$</td>
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</tr>
</tbody>
</table>
Part II

$J/\psi + Z$ production
ATLAS analyses

Following the pioneering searches by CDF, for the first time ATLAS recently observed associated production of $J^{+\psi}W$ and $J^{+\psi}Z$.
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L. Gang et al. PRD 83 (2011) 014001; JHEP02(2011)071
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For both, these SPS predictions seem too small to reproduce the data, even when some DPS contributions are considered

The discrepancy is largest for $J/\psi + Z$, which I discuss now

based on JPL, H.S. Shao arXiv:1608.03198 [hep-ph]
The ATLAS puzzle
The ATLAS puzzle

- **Assuming a DPS yield with** $\sigma_{\text{eff}} = 15 \text{ mb}$ *(because of their 4 jet analysis)*

  - Prompt DPS subtracted
  
  $$ R_{J/\psi+Z}^{\text{DPS}} = \frac{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) \sigma(pp \rightarrow Z + J/\psi)}{\sigma(pp \rightarrow Z)} $$

  $$ = \left( 45 \pm 13_{\text{stat}} \pm 6_{\text{syst}} \pm 10_{\text{DPSsub}} \right) \times 10^{-7} $$
The ATLAS puzzle

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- **whereas**
  
  - the CS based predictions are around $(1 - 5) \times 10^{-7}$
Assuming a DPS yield with $\sigma_{\text{eff}} = 15 \text{ mb}$ (because of their 4 jet analysis),

$$R_{J/\psi+Z}^{\text{DPS subtracted}} = \mathcal{B}(J/\psi \to \mu^+\mu^-) \frac{\sigma(pp \to Z + J/\psi)}{\sigma(pp \to Z)}$$

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whereas

- the CS based predictions are around $(1 - 5) \times 10^{-7}$
- the most optimistic NRQCD-based predictions (CS+CO) reaches $9 \times 10^{-7}$
The ATLAS puzzle

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- A priori, the $\Delta \phi$ distribution hints at a significant SPS yield (peak at $\pi$)
Assuming a DPS yield with $\sigma_{\text{eff}} = 15 \text{ mb}$ (because of their 4 jet analysis) and prompt $R_{J}/2$ subtracted:

$$R_{J}/2 = \frac{B(J/\psi \rightarrow \mu^+ \mu^-) \sigma(pp \rightarrow Z + J/\psi)}{\sigma(pp \rightarrow Z)}$$

$$= \frac{45 \pm 13_{\text{stat}} \pm 6_{\text{syst}} \pm 10_{\text{DPS sub}}}{10^{-7}}$$

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- Gap opening at large $P_T^{J/\psi}$
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- A priori, the $\Delta \phi$ distribution hints at a significant SPS yield (peak at $\pi$)
- Gap opening at large $P_T^\psi$
- We have thus decided to re-analyse the SPS theory with the Colour-Evaporation Model (CEM) which usually overshoots data at large $P_T^\psi$ (↔ upper SPS limit)
Our re-analysis
Our re-analysis

- We use a NLO CEM computation of $J/\psi + Z$ with the single non-perturbative CEM parameter $P_\psi^{\text{prompt}}$ fit to the latest single-$J/\psi$ ATLAS data at 8 TeV.
Our re-analysis

- We use a NLO CEM computation of $J/\psi + Z$ with the single non-perturbative CEM parameter $\mathcal{P}_\psi^{\text{prompt}}$ fit to the latest single-$J/\psi$ ATLAS data at 8 TeV.
- Just as the CEM tends to produce too many $J/\psi$ at large $P_T$, we expect it to be the same for $J/\psi + Z$ and to provide us with an upper SPS limit.

[NRQCD predictions would be very disparate; some give $\sigma < 0$]
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The theoretical uncertainty for the (N)LO SPS is from the renormalisation and factorisation scales. All quantities are in units of $10^{-7}$.
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- This gives a $2-\sigma$ discrepancy with a DPS contribution set by $\sigma_{\text{eff}} = 15 \text{ mb}$
Boosting the DPS yield

Some quarkonium studies point at a $\sigma_{\text{eff}}$ lower than zero fitted mb. By fitting the first two fitted points ($\Delta /{\text{uni03D5}} /\text{zero.fitted}$), ATLAS got an upper DPS limit where $\sigma_{\text{DPS}} /\text{three.fitted}$.

Fitting the whole yield within uncertainties with SPS set to zero fitted gives a lower limit for $\sigma_{\text{eff}} /\text{four.fitted}$ / seven.fitted mb. With the NLOCEM and its uncertainties (upper SPS limit), we can obtain an upper limit of seven.fitted /one.fitted mb.

Both approaches yield compatible results, but what about the azimuthal spectrum if the SPS yield is six.fitted of the ATLAS yield?
Boosting the DPS yield

- Some quarkonium studies point at a $\sigma_{\text{eff}}$ lower than 10 mb

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Fitting the whole yield within uncertainties with SPS set to 0 gives a lower limit for $\sigma_{\text{eff}} = 4.7$ mb. With the NLO CEM and its uncertainties (upper SPS limit), we can obtain an upper limit of 7.1 mb.

Both approaches yield compatible results, but

What about the azimuthal spectrum if the SPS yield is 1/6 of the ATLAS yield?
Issue with the azimuthal distribution?
It is important to note that what is shown is a raw yield distribution and that ATLAS efficiency is larger at large $P_T$: large $P_T$ events have more chance to be recorded.
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Can the peak size (with only $1/6$ of SPS events overall) be due to that? **YES!**
- The last plot has been made by folding our DPS and SPS cross sections by an estimation of the ATLAS efficiency, and it works.
Part III

Conclusion
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For the first time, our study shows that both DPSs and the NLO QCD corrections to SPSs are crucial to account for the existing $J/\psi$ data. ICHEP News: Confirmation by the recent ATLAS study using our predictions: ATLAS-CONF-

two.fitted/zero.fitted/one.fitted/six.fitted-

zero.fitted/four.fitted/seven.fitted.

Still for $J/\psi$, this provides evidence for

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We have also derived generic formulae predicting feed-down contributions or, equally speaking, charmonium-pair-production rates involving excited states, in case DPSs dominate. These do not depend on $\sigma_{\text{eff}}$.

CHECK

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D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001
Part IV

Back-up slides
Comparison between the ATLAS data (EPJC 76 (2016) 283) and the CEM results for $d\sigma/dy/dp_T$ of $J/\psi +$ a recoiling parton at (left) LO and (right) NLO at $\sqrt{s} = 8$ TeV. [The theoretical uncertainty band is from the scale variation.]
On the (non-)importance of CO channels for di-$J/\psi$
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![Graph showing differential cross section $d\sigma/dP_T^{\psi\psi}$ for di-$J/\psi$ production at 7 TeV LHC. The graph compares different theoretical calculations including LO CO+sm, LO NRQCD+sm, and NLO* CS+LO CO. The CMS acceptance threshold is indicated as 7 TeV@LHC SPS only, and the arXiv reference is arXiv:1105.0820.]

On the (non-)importance of CO channels for di-$J/\psi$

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Z. He, B. Kniehl PRL 115, 022002 (2015)
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- In terms of \(\chi^2_{d.o.f}\):

<table>
<thead>
<tr>
<th></th>
<th>LO CO + NLO* CSM w/o DPS</th>
<th>NLO* CSM w DPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\chi^2_{d.o.f})</td>
<td>3.0</td>
<td>1.9</td>
</tr>
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</table>


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J.P. Lansberg (IPNO)  
New observables in quarkonium production  
September 1, 2016  
23 / 20
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- Ignoring all previous constraints and fitting (one channel at a time) the LDME on the CMS data one gets irrealistically large values:
  $\langle O^{J/\psi}(3S_1^{[8]}) \rangle = 0.42 \pm 0.12$ GeV$^3$ & $\langle O^{J/\psi}(1S_0^{[8]}) \rangle = 0.91 \pm 0.22$ GeV$^3$ !!!