Studying parton correlations via double parton scatterings in associated quarkonium production at the LHC and the Tevatron

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Motivations for associated quarkonium production studies

The study of quarkonium production has been proposed to probe perturbative and nonperturbative properties of QCD.

J/ψ+W was proposed as a golden channel to probe the color octet contribution and thus to test NRQCD


J/ψ+J/ψ production could be the key process to study the double parton scattering (DPS)

Motivation for BSM search:

Y+W could be a decay channel of a charged Higgs boson


DPS becomes important in high √s collision :
\[ \Rightarrow \text{Important background in multi-particle final states} \]

Recent experimental progress:

ATLAS observed J/ψ+W and J/ψ+Z


CMS & ATLAS data of di-J/Ψ in conflict with NRQCD (color singlet model)

\[ \text{CMS Collaboration, JHEP 1409 (2014) 094.} \]
Quarkonium+vector boson production

Theoretical computations were carried out up to NLO in $\alpha_s$

- NLO NRQCD $J/\psi+W$: L. Gang et al., PRD 83 (2011) 014001;
- NLO NRQCD $J/\psi+Z$: L. Gang et al., JHEP 02 (2011) 071;

Based on these recent works, one expects the octet and singlet contributions to be on the same order of magnitude.

Let us note that, in addition, double parton scattering (DPS) could also contribute to such an associated production, just as $\gamma+\text{jet}$, $W+Z$, $W+W$ productions.
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Single Parton Scattering (SPS)  
Double Parton Scattering (DPS)
**ATLAS vs. “theory”**

Overall, the ATLAS data-theory comparison looks as follows:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>DPS</th>
<th>CSM</th>
<th>COM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\sigma_{\text{eff}} = 15,\text{mb}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z+J/\psi$</td>
<td>1.6$\pm$0.4 pb [1]</td>
<td>0.46 pb</td>
<td>0.025 - 0.125 pb [5]</td>
<td>&lt; 0.1 pb [4]</td>
</tr>
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<td>$W+J/\psi$</td>
<td>4.5$^{+1.9}_{-1.5}$ pb [2]</td>
<td>1.7 pb</td>
<td>(0.11$\pm$0.04) pb [6]</td>
<td>(0.16 - 0.22) pb [3]</td>
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**ATLAS data are significantly above** the SPS (CSM+COM), and the DPS can only account for a fraction of the data. ($> 3\,\sigma$ for $J/\psi+Z$, $> 2\,\sigma$ for $J/\psi+W$)

**A natural question arises:** Is SPS underestimated?
Building up an upper limit to the SPS with the color evaporation model

The CEM for single quarkonium production overshoots the data at high $p_T$ (see below). This is due to the dominance of the 1-gluon fragmentation ($\sim ^3S_1^8$).

The same is expected to occur for $J/\psi + W$ and $J/\psi + Z$.

$\Rightarrow$ CEM : conservative upper limit on the SPS yield

We will compute it in both cases at NLO with MadGraph5_AMC@NLO.

J. Alwall et al. , JHEP 07 (2014) 079
Results for the Color evaporation model at NLO

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<td>(0.16 - 0.22) pb</td>
<td>0.28$^\pm$0.07 pb $[2]$</td>
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$\Rightarrow$ Upper limit by CEM does not solve the problem.

$\Rightarrow$ Can it be solved by increasing the DPS?
**J/ψ + Z : tuning the DPS with ATLAS data**

We fit $\sigma_{\text{eff}}$ to the ATLAS data subtracted from the SPS and we obtain $\sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5})$ mb  

J.-P. Lansberg and H.-S. Shao, JHEP 1610 (2016) 153

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<td></td>
<td></td>
<td></td>
<td>$4.7$ mb</td>
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|                |            | $1.6\pm0.4$ pb | $1.47$ pb | $0.025 - 0.125$ pb | $< 0.1$ pb | $0.19^{+0.05}_{-0.04}$ pb [1] |

Prompt $J/\psi + Z$ production at 8 TeV LHC

- LO CEM SPS
- NLO CEM SPS
- DPS
- NLO CEM SPS+DPS
- ATLAS data

\[ \text{DPS: } \sigma_{\text{eff}} = 4.7 \text{ mb} \]

Increasing the DPS seems to solve the puzzle (the SPS yield favored by ATLAS acceptance is visible at $\Delta \phi = \pi$).
For \(J/\psi + W\), we obtain \(\sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{ mb}\)


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Prompt \(J/\psi + W^\pm\) production at 7 TeV LHC

\[\text{Br}(J/\psi + W^\pm) \frac{d^2\sigma(J/\psi + W^\pm)}{dp_T^2} \text{[GeV}^{-2}\text{]} \]

**p_T** distribution

**azimuthal distribution**

Like for the \(J/\psi + Z\) case, increasing the DPS seems to solve the puzzle.
Quarkonium pairs

Di-J/Ψ production studied by LHCb, CMS, ATLAS, D0

• Only D0 and ATLAS performed DPS extraction
  • D0 : \( \sigma_{\text{eff}} = 4.8 \pm 0.5(\text{stat}) \pm 2.5(\text{syst}) \text{ mb} \).
  • ATLAS : \( \sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst}) \text{ mb} \).
• SPS uncertainty too large to extract \( \sigma_{\text{eff}} \) from LHCb (low pT -> SPS also flat in \( \Delta\phi \))
• CMS did not try to extract \( \sigma_{\text{eff}} \)
  • DPS study by Lansberg and Shao \( \sigma_{\text{eff}} = (8.2 \pm 2.0 \pm 2.9) \text{ mb} \)
    J.-P. Lansberg and H.-S. Shao, PLB751, 479 (2015)
  • However on-going discussions about the actual size of SPS
    He and Kniehl, PRL 115, 022002 (2015)

The LO COM yield depends on \((\text{NRQCD LDME})^2\) and is thus affected by large uncertainties such that some colleagues wonder if the data could be described without the DPS.
To get the order of magnitude of the contribution from octet transition, we use again the CEM:

\[
\frac{d\sigma}{d|\Delta y|} \quad \text{[nb]} \\
\frac{d\sigma}{dM_{\psi\psi}} \quad \text{[nb/GeV]}
\]


Like for \(J/\Psi+Z/W\), CEM yield should give realistic estimation of the octet yield.

Since we found out that the LO NRQCD result of He & Kniehl overshoots our CEM result, we believe that their result is too optimistic (arguable choice of the LO LDMEs?)

We take this as the confirmation of the DPS extraction of Lansberg and Shao.
CEM result with ATLAS setup (fiducial)

$|\Delta y| :$

$M_{\psi\psi} :$

$\mathbf{p}_{T\psi\psi} :$

Experimental data:
ATLAS Collaboration, EPJC 76 (2017) 77.
CEM result with LHCb setup

$|\Delta y|$:

$M_{\Psi\Psi}$:

$p_{T\Psi\Psi}$:

$A_T$:

Experimental data:
D0 Collaboration, PRL 116, 082002 (2016).
Exp. data ($\sigma_{\text{exp}} = 68.8\pm12.7(\text{stat})\pm7.4(\text{syst})\pm2.8(\text{B})$ pb)


Our result of calculation of di-$\Upsilon$ (1S) production in CEM:

\[
\begin{align*}
0.050 \text{ pb} &< \sigma_{\text{fid}} < 0.172 \text{ pb} \quad \text{(NLO)} \\
0.027 \text{ pb} &< \sigma_{\text{fid}} < 0.125 \text{ pb} \quad \text{(LO)}
\end{align*}
\]

$\Rightarrow$ Deviation by more than $4\sigma$ !

Preliminary
Overall

⇒ All central rapidity quarkonium data point at a small $\sigma_{\text{eff}}$
Overall

All central rapidity quarkonium data point at a small $\sigma_{\text{eff}}$
Overall

$\sigma_{\text{eff}}$ [mb]

$\sqrt{s}$ [TeV]

$\Rightarrow$ All central rapidity quarkonium data point at a small $\sigma_{\text{eff}}$
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All central rapidity quarkonium data point at a small $\sigma_{\text{eff}}$
The associated production of $J/\psi+W/Z$ was measured by ATLAS: discrepancies with SPS+DPS ($\sigma_{\text{eff}}=15\text{mb}$) was seen.

In order to check whether the SPS was underestimated, we evaluated the NLO CEM yield for $J/\psi+W/Z$.

The conservative upper limit set by the CEM does not solve the discrepancy with the ATLAS data.

In fact, $J/\psi+W/Z$ show evidence for DPS.

$J/\psi+Z : \sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5}) \text{ mb}$

$J/\psi+W : \sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{ mb}$

$J/\Psi+J/\Psi$ production also requires DPS contributions in some part of the phase space.

$\sigma_{\text{eff}}$ seems to be smaller for quarkonia than for jets: hint for flavor dependence?

**Summary:**

- The associated production of $J/\psi+W/Z$ was measured by ATLAS: discrepancies with SPS+DPS ($\sigma_{\text{eff}}=15\text{mb}$) was seen.
- In order to check whether the SPS was underestimated, we evaluated the NLO CEM yield for $J/\psi+W/Z$.
- The conservative upper limit set by the CEM does not solve the discrepancy with the ATLAS data.
- In fact, $J/\psi+W/Z$ show evidence for DPS.
  - $J/\psi+Z : \sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5}) \text{ mb}$
  - $J/\psi+W : \sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{ mb}$
- $J/\Psi+J/\Psi$ production also requires DPS contributions in some part of the phase space.
- $\sigma_{\text{eff}}$ seems to be smaller for quarkonia than for jets: hint for flavor dependence?
End
Digression on DPS

At high energies, multiple parton interactions can become relevant, despite of being formally of higher twist.

They are in fact necessary to restore the unitarity of the cross section and are related to the strong increase of the parton densities at high energy.

Similarly, this can also happen for Double hard Parton Scatterings (DPS) which then occur independently.

As such it makes sense to parametrize the DPS cross sections by the so-called pocket-formula:

\[ \sigma^{\text{DPS}}(A + B) = \frac{\sigma(A)\sigma(B)}{\sigma_{\text{eff}}} \]

In the case of J/\(\psi\)+W and J/\(\psi\)+Z, ATLAS used their measured cross sections for \(\sigma(J/\psi)\), \(\sigma(W)\) and \(\sigma(Z)\), and \(\sigma_{\text{eff}}\) determined by their W+2jets data (see below).

\[ 15 \text{ mb} \]
CM energy = 7 TeV

Cuts:

\[ p_T > 4.5 \text{ GeV} \]

\[ 1.43 < |y_\Psi| < 2.2 \] \hspace{1cm} (\( p_T > 4.5 \text{ GeV} \))

Linear in \( p_T \) from boundaries \hspace{1cm} (4.5 \text{ GeV} < p_T < 6.5 \text{ GeV})

\[ |y_\Psi| < 1.2 \] \hspace{1cm} (\( p_T > 6.5 \text{ GeV} \))

(Rapidity depends on the \( p_T \) region)

$|\Delta y|:$

$M_{\psi\psi}:$

$|p_{T\psi\psi}|:$
CM energy = 8 TeV

Cuts:

\[ p_T > 8.5 \text{ GeV} \quad \quad |y_\Psi| < 2.1 \quad \quad \text{(Inclusive)} \]

Fiducial cuts (cuts on muons from J/\Psi decay):

Trigger muons from J/\Psi: \[ p_T(\mu) > 4 \text{ GeV} \]

\[ |\eta(\mu)| > 2.3 \]

ATLAS Collaboration, EPJC 76 (2017) 77.
CM energy = 13 TeV

Cuts (inclusive):

\[ p_T < 10 \text{ GeV} \quad 2.0 < y_\psi < 4.5 \]  
(asymmetric)

CM energy = 1.96 TeV

p$\bar{p}$ collision

Measure final states with Y(1S), Y(2S) or Y(3S) associated with a J/$\psi$

Fiducial cuts (cuts on muons from J/$\Psi$ and Y decays):

$p_T(\mu) > 2$ GeV

$|\eta(\mu)| > 2.0$

D0 Collaboration, PRL 116, 082002 (2016).
Y+Y production (CMS, 8TeV)

CM energy = 8 TeV

Cut (inclusive):

\[ |y| < 2.0 \]

**J/ψ+Υ production (D0, p\bar{p}, 1.96TeV)**

| Δφ |  
|---|---|

![Graph showing distribution of Δφ](image1)

| Δy |  
|---|---|

![Graph showing distribution of Δy](image2)

**Experimental data:**
D0 Collaboration, PRL 116, 082002 (2016).

**Comparison with Shao and Zhang PRL 117, 062001 (2016)**