Quarkonia as a tool to measure Double Parton Scatterings, gluon TMDs and (n)PDFs

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[Work done in collaboration with
M.G. Echevarria, T. Kasemets, C. Pisano, F. Scarpa, M. Schlegel, H.S. Shao, A. Signori]
Part I

Quick introduction
Production Models: 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/its differ 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
  - This motivates the study of new observables which can be more discriminant for specific effects

- Yet, quarkonium hadro production remains a very sensitive probe of the gluon content of the proton

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Part II

Quarkonia as probes of the glue
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*J.P. Lansberg (IPNO)  Quarkonia as a tool  April 5, 2017  5 / 22*
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- Conversely, one can test this hypothesis by comparing our curves with data → global agreement?
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- **Last but not least:** the automation of the evaluation allows one to study different nPDF sets AND the scale uncertainties: better control of the theory uncertainties
Some comparisons [top left by us; 3 other shown at QM2017]
Part III

New observables in quarkonium production
### New observables: what for?

<table>
<thead>
<tr>
<th>Observables</th>
<th>Experiments</th>
<th>CSM</th>
<th>CEM</th>
<th>NRQCD</th>
<th>Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi + J/\psi$</td>
<td>LHCb, CMS, ATLAS, D0 (+NA3)</td>
<td>NLO, NNLO*</td>
<td>LO ?</td>
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<td>$J/\psi + \text{hadron}$</td>
<td>STAR</td>
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<td>$J/\psi + Z$</td>
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<td>$J/\psi \text{ vs mult.}$</td>
<td>ALICE,CMS (+UA1)</td>
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$Z+$prompt $J/\psi$
Our re-analysis of $Z+\text{prompt } J/\psi$ at NLO and with DPS

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- This naturally points at a smaller $\sigma_{\text{eff}}$ (as other onium related data), but the $\Delta \phi$ distribution shows a peak at $\Delta \phi \simeq \pi \rightarrow$ SPS dominance ???
Issue with the azimuthal distribution?

It is important to note that what was shown by ATLAS is a raw yield distribution. Since their efficiency is larger at large $P_T$, large $P_T$ events have more chance to be recorded.

Our NLO CEM evaluation allows us to state that, in the ATLAS acceptance, DPS dominates at low $P_T$ and SPS at large $P_T$.

$\frac{Br(J/\psi \rightarrow \mu^+\mu^-)}{\sigma(Z)d\sigma(J/\psi+Z)/dp_T}$

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

DPS: $\sigma_{eff} = 4.7$ mb

Assumption: $B/S = 17/p_T(J/\psi)$

Events ($\pi/5$)

$\Delta \phi(Z,J/\psi)$

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![Prompt J/ψ+Z production at 8 TeV LHC](image)

- Br(J/ψ→$\mu^+\mu^-$) / $\sigma(Z)d\sigma(J/\psi+Z)/dp_T$ [GeV$^{-1}$]
- $p_T(J/\psi)$ [GeV]

**Prompt J/ψ+Z production at 8 TeV LHC**

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![Events (π/5)
∆φ(Z,J/ψ)]

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- We are waiting for an ATLAS update to confirm our explanation.
Part V

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Interesting check that nothing went wrong with the prompt analysis.
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- This gives an original handle on \(Z + b\) at lower \(P_T\) than \(b\)-jets.
- Interesting check that nothing went wrong with the prompt analysis.
- SPS predictions were absent at the time of the publication. We filled this gap using MadGraph5\_aMC@NLO and Pythia 8.1.

Differential cross section/distributions for non-prompt \(J/\psi + Z\) production: \(p_T\) distribution of \(J/\psi\) (left) and azimuthal angle distribution (right).

Good agreement. Owing to the data uncertainties at low \(P_T\), we cannot constrain \(\sigma_{\text{eff}}\) more than with a lower limit, 5.0 mb, at 68 \% CL.
Part VI

Quarkonium-pair production
On the importance of QCD corrections: $P_T$ enhanced topologies

At Born (LO) order, the $P_{T\Psi\Psi}$ spectrum is $\delta(P_{T\Psi\Psi})$: 2 → 2 topologies
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- It can be affected by initial parton $k_T$ [↔ interest for TMD studies]
- By far insufficient (blue) to account for the CMS measured spectrum

![Graph showing $d\sigma/dP_T^{\psi\psi}$ vs $P_T^{\psi\psi}$]
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- It can be affected by initial parton $k_T$ [↔ interest for TMD studies]
- By far insufficient (blue) to account for the CMS measured spectrum

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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]
The so-called CMS puzzle

\[ \frac{d\sigma}{d|\Delta y|} \text{(nb)} \]

\[ \text{d}\sigma/\text{d}M_{\psi\psi} \text{(nb/GeV)} \]

7 TeV@LHC CMS Accep.

\[ M_{\psi\psi} \text{(GeV)} \]
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- At $P_T^{\psi\psi} \approx 0$, where the bulk of the yield lies, one has $M_{\psi\psi} \sim 2m_T^{\psi} \cosh \frac{\Delta y}{2}$
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- The most natural solution for this excess is the independent production of two $J/\psi$ $\rightarrow$ double parton scattering

- Predictions for LHCb, DPS $\gg$ SPS at large $\Delta y$
- He & Kniehl found at LO that CO $\gg$ CS at large $\Delta y$; yet still in disagreement with the data; NLO needed!

Z. He, B. Kniehl PRL 115, 022002 (2015)
On the importance of double parton scatterings at large $\Delta y$

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.
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D0 Coll. PRD 90 (2014) 111101
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- Fitting these MC templates, they splitted $129 \pm 46$ fb into $\sigma^{\text{DPS}} = 70 \pm 23$ fb and $\sigma^{\text{SPS}} = 59 \pm 23$ fb by comparing the histograms
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In turn, they obtained $\sigma_{eff} = 4.8 \pm 2.5$ mb.

A question arises: using $\sigma_{DPS} = \frac{1}{2} \frac{\sigma_{\psi} \sigma_{\psi}}{\sigma_{eff}}$ and $\sigma_{eff} = 4.8 \pm 2.5$ mb, can one account for the large $\Delta y$ CMS data?
On the importance of double parton scatterings at large $\Delta y$ II

Let us investigate the consistency between D/zero.fitted and CMS data.

For that we assume:

$$\sigma_{DPS}/one.fitted = \sigma_{five.fitted}$$

We take $\sigma_{eff}/four.fitted = \sigma_{eight.fitted}/two.fitted$.

$\sigma_{\psi\psi}$ are fitted from data with a Crystal Ball function parametrising $S_{AA}g\psi\psi$.

Gap between theory and CMS data is large and $M_{\psi\psi}$ by DPS+NLO

Agreement not altered elsewhere; improved even at low $P_T$ (see (a)).

Conversely, $\sigma_{eff}$ from our own CMS dataset yields $\sigma_{nine.fitted}$.

Fit done prior the ATLAS analysis good agreement!
On the importance of double parton scatterings at large $\Delta y$ II

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- For that we assume: $\sigma_{\text{DPS}} = \frac{1}{2} \frac{\sigma_{\psi} \sigma_{\psi}}{\sigma_{\text{eff}}}$
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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
On the importance of double parton scatterings at large $\Delta y$ II

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- For that we assume: $\sigma_{DPS} = \frac{1}{2} \sigma_\psi \sigma_\psi / \sigma_{eff}$
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- Fit done prior the ATLAS analysis → good agreement!
Predictions: excited states

Eventhoughwe inditanatural,accountingfor DPS introduces another parameter

How to check that one is not playing with a further d.o.f. on the theory side?

DPS vs SPS dominance are characterised by different feed-down patterns

We define $F_{\chi c}$ as the fraction of events containing at least one $\chi c | \psi \psi$.

Under DPS dominance (e.g., large $\Delta y$),

$$\frac{\sigma_{DPS, ab}}{\sigma a \sigma b} \approx \frac{\sigma_{eff}}{\sigma eff} \quad (m: symmetry factor)$$

$$F_{\chi c} \approx \frac{\sigma_{direct}}{\sigma_{direct}}$$

Under SPS dominance, $\psi \psi$ is slightly enhanced by symmetry factors, $F_{\chi c} \psi \psi$, unlike single quarkonium production, is not enhanced and is found to be small.

Overall:

$$(CSM)_{SPS} \quad \frac{\sigma_{DPS}}{\sigma_{SPS}}$$
Predictions: excited states

- Even though we find it a natural, accounting for DPS introduces another parameter.
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DPS vs SPS dominance are characterised by different feed-down patterns.

We define $F^{\chi_c}_{\psi\psi}$ ($F^{\psi'}_{\psi\psi}$) as the fraction of events containing at least one $\chi_c$ ($\psi'$).
Even though we find it a natural, accounting for DPS introduces another parameter.

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Under DPS dominance (e.g. large $\Delta y$), $\sigma_{ab}^{\text{DPS}} = \frac{m}{2} \frac{\sigma_a \sigma_b}{\sigma_{\text{eff}}} \ (m: \text{symmetry factor})$

$$F_{\Psi\psi}^{\chi_c} = F_{\Psi\psi}^{\chi_c} \times \left( F_{\Psi\psi}^{\chi_c} + 2 F_{\Psi}^{\text{direct}} + 2 F_{\Psi}^{\psi'} \right), \quad F_{\Psi\psi}^{\psi'} = F_{\Psi\psi}^{\Psi} \times \left( F_{\Psi}^{\psi'} + 2 F_{\Psi}^{\text{direct}} + 2 F_{\Psi}^{\chi_c} \right), \quad F_{\Psi\psi}^{\text{direct}} = (F_{\Psi}^{\text{direct}})^2$$
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- Under SPS CSM dominance,
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<table>
<thead>
<tr>
<th></th>
<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>
<td>small</td>
<td>50%</td>
</tr>
</tbody>
</table>
Harvesting new quarkonium data
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4 quarkonium extractions using theory ingredients!

- ATLAS (np J/ψ+Z, Lansberg-Shao)
- ATLAS (J/ψ+Z, Lansberg-Shao)
- CMS (J/ψ+J/ψ, Lansberg-Shao)
- D0 (J/ψ+Y, Shao-Zhang)
- D0 (J/ψ+J/ψ)
- ATLAS preliminary (J/ψ+J/ψ)
- CDF (4 jets)
- CDF (γ+3 jets)
- D0 (γ+3 jets)
- ATLAS (W+2 jets)
- CMS (W+2 jets)
Part VII

Conclusion
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Confirmation by the recent ATLAS study using our predictions (see ATLAS, EPJC (2017) 77:76)
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- Still for di-$J/\psi$, this provide evidence for
  1. the dominance of $\alpha_s^4$ (LO) CS contributions for the **total cross section**, 
  2. the dominance of $\alpha_s^5$ (NLO) CS contributions at mid and large $P_{T\psi\psi}$, 
  3. the dominance of DPS contributions at large $\Delta y$ and at large $M_{\psi\psi}$.
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A small $\sigma_{\text{eff}}$, i.e. large DPS, is also required to describe $J/\psi + Z$, but also $\Upsilon + J/\psi$

D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001
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- Lower limit on $\sigma_{\text{eff}}$ from $Z + (b \rightarrow J/\psi)$

  JPL, H.S. Shao NPB 916 (2017) 132
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- Lower limit on $\sigma_{\text{eff}}$ from $Z + (b \rightarrow J/\psi)$

- Hint at a flavour dependence of $\sigma_{\text{eff}}$?

- As outlooks, TMD-oriented studies using associated quarkonium production should now become possible for $\Upsilon + \gamma$, later for $Q + \ell^+ \ell^-$

Part VIII

Back-up slides
CEM results for single $J/\psi$

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

![Graph showing differential cross section $d\sigma/dP_T$ for di-$J/\psi$ at 7 TeV LHC with CMS acceptance and SPS only. The graph includes contributions from LO CO+sm, LO NRQCD+sm, NLO* CS+LO CO, and LO CO+sm+NLO CS+LO CO. The results are compared with the Single $J/\psi$ LDME fit by M. Butenschoen, B. Kniehl, arXiv:1105.0820, PRD 84 (2011) 051502.]

$P_T^{\psi\psi}$ (GeV)

$d\sigma/dP_T^{\psi\psi}$ (nb/GeV)

7 TeV @ LHC
CMS Accep.
SPS only
arXiv:1105.0820

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

- **Adding CO** using NLO LDMEs of the Hamburg group has **no impact**
On the (non-)importance of CO channels for di-$J/\psi$

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We disagree “that their inclusion nearly fills the large gap”

---

J.P. Lansberg (IPNO)  
Quarkonia as a tool

April 5, 2017  25 / 22

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**Figure 1:**
- **Left panel:** $d\sigma/dM_{\psi\psi}$ (nb/GeV) as a function of $M_{\psi\psi}$ (GeV) for LO CSM, NLO$^*$ CSM, and $\psi c\bar{c}\psi$ CSM.
- **Right panel:** $d\sigma/dM_{\psi\psi}$ (nb/GeV) as a function of $M_{\psi\psi}$ (GeV) with LO NRQCD, NLO$^*$ CS+LO CO.

**Graphs:**
- 7 TeV@LHC CMS Accep.

**Table:**
- Z. He, B. Kniehl PRL 115, 022002 (2015)
**On the (non-)importance of CO channels for di-J/ψ**

- **Adding CO** using NLO LDMEs of the Hamburg group has **no impact**
- Same with other NLO LDMEs, by the PKU group (incl. my co-author), by the IHEP group as well as by Bodwin et al.
- We disagree “that their inclusion nearly fills the large gap”
- 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>
</tbody>
</table>

**Single J/ψ LDME fit:** M. Butenschoen, B. Kniehl arXiv:1105.0820, PRD 84 (2011) 051505

**Z. He, B. Kniehl** PRL 115, 022002 (2015)
Another way to see this with 2 CO channels

Using for the upper bound:

\[ O_J \sim \hat{\psi}^{/one.fitted/zero.fitted} \hat{\psi}^{/three.fitted} (S_{/eight.fitted/one.fitted} \hat{\psi}^{/one.fitted/zero.fitted} \hat{\psi}^{/two.fitted}). \]

\[ O_J \sim \hat{\psi}^{/three.fitted/zero.fitted} \hat{\psi}^{/one.fitted/zero.fitted} \hat{\psi}^{/two.fitted/zero.fitted} \hat{\psi}^{/one.fitted/zero.fitted} \hat{\psi}^{/two.fitted/zero.fitted} \hat{\psi}^{/two.fitted/zero.fitted}. \]
Using for the upper bound: \[ \langle O^{J/\psi} (^3S^8_1) \rangle < 2.8 \times 10^{-3} \text{ GeV}^3 \] & \[ \langle O^{J/\psi} (^1S^8_0) \rangle < 5.4 \times 10^{-2} \text{ GeV}^3 \]

[see the solid and dashed black lines]
Another way to see this with 2 CO channels

Using for the upper bound: \( \langle \mathcal{O}^{I/\psi}(3S_1^{[8]}) \rangle < 2.8 \times 10^{-3} \text{ GeV}^3 \) & \( \langle \mathcal{O}^{I/\psi}(1S_0^{[8]}) \rangle < 5.4 \times 10^{-2} \text{ GeV}^3 \)  
[see the solid and dashed black lines]

Nota: \( \eta_c \) data : \( \langle I/\psi(1S_0^{[8]}) \rangle = \langle \eta_c(3S_1^{[8]}) \rangle < 1.46 \times 10^{-2} \text{ GeV}^3 \)

\[ \text{JPL, H.-S. Shao PLB 751 (2015) 479} \]

\[ \text{H. Han et al. PRL 114 (2015) 092005} \]
Another way to see this with 2 CO channels

- Using for the upper bound: \( \langle O^J/\psi (3 S_1^{[8]}) \rangle < 2.8 \times 10^{-3} \text{ GeV}^3 \) & \( \langle O^J/\psi (1 S_0^{[8]}) \rangle < 5.4 \times 10^{-2} \text{ GeV}^3 \)
  [see the solid and dashed black lines]

- Nota: \( \eta_c \) data: \( \langle J/\psi (1 S_0^{[8]}) \rangle = \langle \eta_c (3 S_1^{[8]}) \rangle < 1.46 \times 10^{-2} \text{ GeV}^3 \)

- Ignoring all previous constraints and fitting (one channel at a time) the LDME on the CMS data one gets irrealistically large values:
  \( \langle O^J/\psi (3 S_1^{[8]}) \rangle = 0.42 \pm 0.12 \text{ GeV}^3 \) & \( \langle O^J/\psi (1 S_0^{[8]}) \rangle = 0.91 \pm 0.22 \text{ GeV}^3 \) !!!

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H. Han et al. PRL 114 (2015) 092005