Inclusive quarkonium production in pp (and pPb) at the LHC

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- on behalf of ALICE/ATLAS/CMS/LHCb collaboration

QCD@LHC 2022 @ Saclay (France)
<table>
<thead>
<tr>
<th>Title</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associated production of J/psi plus W or Z at NLO and implications on NRQCD factorization</td>
<td>Mathias Butenschoen [link]</td>
</tr>
<tr>
<td>S-wave quarkonium production and polarization in potential NRQCD</td>
<td>Xiangpeng Wang [link]</td>
</tr>
<tr>
<td>Quarkonium in the QGP from unquenched lattice QCD</td>
<td>Sajid Ali [link]</td>
</tr>
<tr>
<td>Challenges in quarkonium and exotic-state production in small systems</td>
<td>Elena Gonzalez Ferreiro [link]</td>
</tr>
<tr>
<td>Exclusive J/psi photoproduction in nucleus-nucleus UPCs at the LHC in NLO QCD</td>
<td>Vadim Guzey [link]</td>
</tr>
<tr>
<td>A simple model to include initial-state and hot-medium effects in the computation of quarkonium nuclear modification factor</td>
<td>Miguel Angel Escobedo Espinosa [link]</td>
</tr>
<tr>
<td>Heavy quarks and quarkonia in small systems</td>
<td>Zaida Conesa Del Valle [link]</td>
</tr>
<tr>
<td>Open heavy flavour/quarkonium associated production at the LHC</td>
<td>Achim Geiser [link]</td>
</tr>
<tr>
<td>Exclusive quarkonium production at the LHC</td>
<td>Adam Matyja [link]</td>
</tr>
<tr>
<td>Exotic Hadrons at LHC</td>
<td>Mindaugas Sarpis [link]</td>
</tr>
<tr>
<td>Joint TH EXP on quarkonia at the LHC</td>
<td>Maxim Nefedov [link]</td>
</tr>
<tr>
<td>Joint TH EXP on quarkonia at the LHC</td>
<td>Valerii Zhovkovska [link]</td>
</tr>
</tbody>
</table>

- Valuable Theory, Experiment, and Plenary talks for quarkonia!
  - and enjoy excursion in Paris!
Motivation

- Quarkonium production
  - Perturbative in heavy quark pair
  - Non-perturbative in the evolution to bound state

- Various hadronization models: QSM, QEM, (p)NRQCD, ...
  - Tension b/w models and data in low/high $p_T$
  - No clear sign of polarization observed (up to 60 GeV/c for $J/\psi$)

[JHEP 11 (2021) 181]

![Data vs. Theory](image1)

![Theory vs. Data](image2)

Data
- LHCb
  - $\sqrt{s} = 5$ TeV, 9.1 pb$^{-1}$
  - Prompt $J/\psi$
  - $2.0 < y < 4.5$

$\sigma(d\sigma/dp_T)$ [nb/(GeV/c)]

$p_T$ [GeV/c]

LHCb
- $\sqrt{s} = 7$ TeV
- $\psi$, $J/\psi$

$\lambda_0$

$\lambda_0$

$p_T$ [GeV/c]

[citation]

PRD 105 (2022) L111503

JHEP 11 (2021) 181

JHEP 03 (2022) 190

LHCb $\sqrt{s} = 7$ TeV

ALICE pp $\sqrt{s} = 13$ TeV
- Prompt $J/\psi$, $|y|<0.9$
  - $l_{NN} = 32.2 \text{ nb}^{-1} \pm 1.6\%$

[citation]

EPJC 74 (2014) 2872

PRD 105 (2022) L111503

JHEP 03 (2022) 190

JHEP 11 (2021) 181

[citation]

[citation]
Motivation

Quarkonium production

Perturbative

in heavy quark pair

Non-perturbative

in the evolution to bound state

Various hadronization models: QSM, QEM, (p)NRQCD, ...

Tension b/w models and data in low/high p

No clear sign of polarization observed (up to 60 GeV/c for J/ψ)

Production mechanism still under investigation since the “November Revolution” in 1974 (48 years)

[PRl 33 (1974) 1404]

[PRD 105 (2022) L111503]

[EPJC 74 (2014) 2872]

[PRl 33 (1974) 1406]
First measurements of quarkonium production at the LHC!

Clear $J/\psi$ peak in dimuon mass spectra in all four experiments

The journey has just begun
Quarkonia @ LHC: “Firsts” measurements

Quite precision data already in Run1 with model comparisons (CS, CO, CE, NRQCD, …)
Quarkonia @ LHC: “Firsts” measurements

- Quite precision data already in Run1 with model comparisons (CS, CO, CE, NRQCD, ...)
- Also constraints to FONLL with prompt and nonprompt separation

[EPJC 71 (2011) 1575]

\[ B \times d\sigma/dp_T \ (\text{nb/GeV/c}) \]

[EPJC 71 (2011) 1645]

\[ B \times d\sigma/dp_T \ (\text{nb/GeV/c}) \]

[NPB 850 (2011) 387]

\[ B \times d\sigma/dp_T \ (\text{nb/GeV/c}) \]

\[ L = 314 \text{ nb} \]

\[ s = 7 \text{ TeV} \]

\[ |y_{J/\psi}| < 2.4 \]

\[ |y_{J/\psi}| < 1.2 \]

\[ |y_{J/\psi}| < 0.75 \]

\[ L = 2.2 \text{ pb}^{-1} \]

\[ B = J/\psi, \text{FONLL} \]

\[ B = J/\psi, \text{FONLL} \]

\[ ATLAS \int s dt = 2.2 \text{ pb}^{-1} \]

\[ s = 7 \text{ TeV} \]

\[ L = 314 \text{ nb}^{-1} \]

\[ p_T (\text{GeV/c}) \]

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\[ p_T (\text{GeV/c}) \]
Cutting edge cross section

- Precision measurements for $J/\psi$ mesons from low~high-$p_T$: 0~300 GeV/c
- Crucial constraints to theoretical developments (data uncertainty much smaller)

**[JHEP 03 (2022) 190]**

**[PLB 780 (2018) 251]**

**[ATLAS-CONF-2019-047]**
Measurements of S-wave charmonium states in various frames (CS, HX, ...)

No sign of nonzero polarization up to 60 (40) GeV/c for $\psi(2S)$ for $J/\psi$ and $\psi(2S)$
Polarization (2) : Bottomonia

- Measurements of S-wave charmonium states in various frames (CS, HX, ...)
- No sign of nonzero polarization up to 60 (40) GeV/c for J/\psi and \psi(2S)
- Similar results for Y(1S), Y(2S), Y(3S) up to p_T = 50 GeV/c
P-wave : Charmonia

\[ \chi_{c2}(1P)/\chi_{c1}(1P) \]

NRQCD LDME test using \( \chi_{c2}(1P)/\chi_{c1}(1P) \) ratio

Recent studies based on pNRQCD at high-\( p_T \) region

Polarization \( \lambda_\theta \)

Interesting studies for ‘relative’ polarization of \( \chi_{c1} \) vs \( \chi_{c2} \)

[JHEP 10 (2013) 115]

[JHEP 09 (2021) 032]

[JHEP 09 (2021) 032]

[PRl 124 (2020) 162002]
P-wave: Bottomonia

NRQCD LDME test using $\chi_{b2}(1P)/\chi_{b1}(1P)$ ratio — small overestimations compared to data

Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ with $\Delta M_{12} \approx 10$ MeV: Standard hierarchy of J=2 state heavier

CMS

$\sqrt{s} = 13$ TeV

L = 80.0 fb$^{-1}$
Significant amount of feed-down contribution observed in both charmonia and bottomonia

Lack of information for $\chi_b(mP) \rightarrow Y(nS)$ : limited on both data and theory
Only CS for $\eta_c(1S)$ production? $p_T$ shape could be sensitive to possible CO contribution...

Ratio of $\eta_c(2S)/\psi(2S)$ suggested to be a cleaner probe: free from feed-down corrections
**J/ψ in jets**

- PYTHIA show discrepancy for the amount of jet-fragmentation of J/ψ production
- Improvement possible with inclusion of improved of jet & gluon fragmentation functions
Production of $J/\psi$ in jets compared with NRQCD LDME parameter sets based on FJF

BCKL set in agreement in all three $z$ ranges \(\rightarrow\) predicts also small polarization at high-$p_T$

: Caveat of deviation with other results ($\eta_c$, measurements in B factories, ...)
**J/ψ in jets**

- **J/ψ with one jet.**
- **J/ψ with two jets.**

**Production of J/ψ in jets compared with NRQCD LDME parameter sets based on FJF**

- BCKL set in agreement in all three z ranges — predicts also small polarization at high-\(p_T\):
  - Caveat of deviation with other results (\(\eta_c\), measurements in B factories, …)

**Worth looking at jet multiplicity and the relative angle?**

- Already ongoing attempts in pp 200 GeV
Fixed target J/$\psi$ results

Results compared to HELAC-Onia (+CT14NLO & nCTEQ15 PDF) and ICEM model
→ caveat of HELAC-Onia computation ingredients?

J/$\psi$-to-D$^0$ ratio: $\alpha'$ compatible with expectations from atomic mass number scaling
→ no evidence of QGP-like effect in PbNe @ 68.5 GeV
Quarkonia in pA

**J/ψ & ψ(2S)**

- Stronger suppression for ψ(2S) than J/ψ — also for Y(1S), Y(2S), Y(3S)
- Origin of additional suppression for excited quarkonium states still under investigation
  - comover breakup? possible CGC? hot nuclear matter effect?

**Y(nS)**
Prompt $J/\psi$ vs $b \rightarrow J/\psi$ in pA

- Indication of different in-medium effects for charm vs bottom at forward-$y$
- Not seen at mid-$y$? $\rightarrow$ Need better precision to resolve flavour dependent nuclear effects
Y in pp w UE study

Different excited-to-ground state ratio for DRR vs SRR?

- Need improved precision + exact multiplicity & p_T matching
- Related to MPI/UE/correlation/...?

CMS [JHEP 11 (2020) 001]

Y(2S)/Y(1S)
Y(3S)/Y(1S)
No dependence of $N_{\text{track}}$ within cone $\Delta R<0.5$

- Different from comover model expectation (n.b. $p_T>7\text{ GeV}/c$ / $N_{\text{track}}$ cutoff values)

- Decrease disappears in low-sphericity

- Connection with UE for jetty events?

$\Sigma$ in pp w UE study

\[ S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad S_T^y = \frac{1}{\Sigma_i p_{T_i}^2} \sum_i \frac{1}{p_{T_i}^2} \left( \frac{p_{x_i}^2}{p_{y_i}^2} + p_{x_i}^2p_{y_i} \right) \]
Summary

- Successful achievement of quarkonium measurements in the past ~10 years @ LHC
- Precision cross section results in inclusive quarkonium production for S-wave quarkonium
  : uncertainty smaller than theory calculations
- No significant polarization observed for S-wave quarkonium states from low- to high-\(p_T\)
- \(J/\psi\) in jets or associated with jet(s) as new probes to understand quarkonium production
- Puzzle of quarkonium modification in pA collisions still not resolved
- Mystery of yield ratios w.r.t UE in pp collisions
  — rapidity gap study to be done sophisticatedly
Back-up
Charmonia in pPb

- Agreement with nPDF modification for J/ψ
- Additional suppression for ψ(2S): hint for comover breakup
Quarkonium production in pPb

CMS

[PLB 835 (2022) 137397]

pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

CMS

[PLB 790 (2019) 509]

pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

CMS

Similar trend observed for bottomonia and charmonia
Y pPb at LHC

1. Sequential suppression: $R_{pPb}(Y(1S)) > R_{pPb}(Y(2S)) > R_{pPb}(Y(3S))$

2. Possible description with comover interaction model

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**Figure:**

- CMS Preliminary
- PbPb 368 μb⁻¹, pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)
- $|y_{CM}| < 1.93$
- $|y_{pPb}| < 2.4$
- $|y_{AA}| < 30$ GeV/c
- 95% CL
- PbPb 368 μb⁻¹, pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

**References:**

- [PLB 835 (2022) 137397]
- [EPJC 78 (2018) 171]
- [PLB 806 (2020) 135486]
- [JHEP 11 (2018) 194]
- [PLB 835 (2022) 137397]
Flow in pPb

CMS

pPb 186 nb\(^{-1}\) (8.16 TeV)

- Still not clear the feature of finite \(J/\psi\) \(v_2\)
- Compatible with prompt \(D^0\)

[PLB 813 (2020) 136036]
Y in pp w UE study

If Y-particle correlation only
→ Only affect forward region

Decreasing trend for all regions: **Linked with UE!**
- No clear ordering
- Note: \( Y_p^T > 7 \text{ GeV/c} \)

CMS

\[ \frac{Y(nS)}{Y(1S)} \]

Forward:
- \( Y(2S) / Y(1S) \)
- \( Y(3S) / Y(1S) \)

Transverse:
- \( Y(2S) / Y(1S) \)
- \( Y(3S) / Y(1S) \)

Backward:
- \( Y(2S) / Y(1S) \)
- \( Y(3S) / Y(1S) \)

\[ N^\Delta\phi_{\text{track}} \]

\[ p_T^{\mu\mu} > 7 \text{ GeV}, \ |\Delta y^{\mu\mu}| < 1.2 \]

\[ 4.8 \text{ fb}^{-1} (7 \text{ TeV}) \]

[JHEP 11 (2020) 001]
P-wave state in pPb

First measurement of $\chi_c$ states in pPb

Agreement with pp measurements
Y(nS)/Y(1S) vs E_T & N_{trk}

[JHEP 04 (2014) 103]

CMS

E_T^{h_{T}>4} [GeV] vs \frac{Y(2S)}{Y(1S)}

CMS

N_{trk}^{h_{T}<2.4} vs \frac{Y(2S)}{Y(1S)}

CMS

CMS

CMS

CMS
Prompt vs nonprompt $J/\psi$ in pA

[EPJC 77 (2017) 269]

$34.6 \text{ nb}^{-1} (\text{pPb } 5.02 \text{ TeV})$

CMS

Prompt $J/\psi$

$6.5 < p_T < 30 \text{ GeV/c}$

$0 < |y| < 0.9$

$0.9 < |y| < 1.5$

$5 < p_T < 6.5 \text{ GeV/c}$

$1.5 < |y| < 1.93$

CMS

Nonprompt $J/\psi$

$6.5 < p_T < 30 \text{ GeV/c}$

$0 < |y| < 0.9$

$0.9 < |y| < 1.5$

$5 < p_T < 6.5 \text{ GeV/c}$

$1.5 < |y| < 1.93$
$\Xi(E_{c}; z_1) \equiv \frac{N(E_{c}; z_1)}{\int_{0.3}^{0.8} N(E_{c}; z) \, dz}$

$\sim 85\%$ of $J/\psi$ are produced within a jet
($E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1$, $E_{\text{jet}} > 19$ GeV, $|\eta_{\text{jet}}| < 1$)
Rapidity gap measurement

- Rapidity gap study for excited-to-ground state ratio vs event multiplicity
- $\psi(2S)/J/\psi$ or $Y(nS)/Y(1S)$ vs $N_{\text{trk}}$ for ①, ②, ③ in fixed $N_{\text{trk}}$ region
- Take advantage of wide rapidity range from all LHC experiments: possible for both pp and pPb

ATLAS: $|y| < 1.6-2.0$
CMS: $|y| < 2.4$
ALICE: $2.5 < y < 4.0$
LHCb: $2.0 < y < 4.5$