J/ψ Production in Jets

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on behalf of the LHCb Collaboration

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Overview

• 21 published quarkonia results!

Measurement of forward $J/\psi$ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV

Forward production of $\Upsilon$ mesons in $pp$ collisions at $\sqrt{s} = 7$ TeV and 8 TeV

Production of associated $\Upsilon$ and open charm hadrons in $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering

Study of $\psi(2S)$ production and cold nuclear matter effects in $pPb$ collisions at $\sqrt{s}_{NN} = 5$ TeV

Measurement of the $J/\psi$ pair production cross-section in $pp$ collisions at $\sqrt{s} = 13$ TeV

• detector and datasets

• $J/\psi$ production in jets
• fully instrumented between $2 < \eta < 5$
• momentum resolution between 0.5% at 5 GeV to 1% at 200 GeV
• secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$
Data Acquisition

- real-time calibration and full event reconstruction in Run 2
- full detector readout in Run 3
Inclusive Dimuon Trigger

Candidates

\begin{align*}
\text{LHCb preliminary} & \\
\eta \rightarrow \mu \mu (\gamma) & \\
\eta & \\
\omega / \rho & \\
\phi & \\
\psi (2S) & \\
\psi (1S) & \\
\Upsilon (2S) & \\
\Upsilon (3S) & \\
Z & \\
V & \\
\chi^2 & \\
T_p & \\
\text{–} & \\
\mu^+ \mu^- & \\
\mu^\pm \mu^\pm & \\
\end{align*}

\begin{align*}
\text{Prompt Trigger Output} & \\
p_T (\mu) > 1 \text{ GeV}, \chi^2_{IP} (\mu) < 6, \chi^2_V (\mu \mu) < 9 & \\
\mu \text{-ID neural network} > 0.95 & \\
\end{align*}
$J/\psi$ Production in Jets
NRQCD

- non-relativistic QCD (NRQCD) factorizes quarkonia production

\[
\frac{d\sigma(pp \to H + X)}{d^3p} = \sum_{s,L,J} \frac{d\sigma(pp \to Q\bar{Q}[^{2s+1}L_J] + X)}{d^3p} \langle \mathcal{O}^H [^{2s+1}L_J] \rangle
\]

- physical state expanded into Fock states

\[
\begin{align*}
  gg &\to c\bar{c}[^3S_1^{(1)} g] \\
  gg &\to c\bar{c}[^3S_1^{(8)} g] \\
  gg &\to c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}] g
\end{align*}
\]
1. NRQCD hard process, octet states showered with QCD splittings
2. Shower with NRQCD splittings, match with hard process

- $J/\psi$ trigger writes out full events
- Select jets with $J/\psi$s
- Measure $z \equiv p_T(J/\psi)/p_T(\text{jet})$
Signal Determination

- determine $J/\psi$ signal yield with mass fits
- separate prompt (direct) from displaced ($b \rightarrow J/\psi$) yields with pseudo-lifetime fits

\[ \tilde{\tau} \equiv (x_z - x_z(PV))m/p_z \]
Unfolding

- correct for $z$ resolution and $p_T(j)$ resolution, $\approx 20 - 25\%$
- perform 2D unfolding in $z$ and $p_T(j)$ (iterative Bayesian)
Displaced Results

LHCb, arXiv:1701.05116

Data (syst) vs. Pythia 8 for $b \rightarrow J/\psi$

LHCb

$\sqrt{s} = 13$ TeV

$J/\psi$ Production in Jets

$z(J/\psi)$
Displaced Results

LHCb, arXiv:1701.05116

The plot shows the differential cross section $d\sigma/\sigma$ as a function of $z(J/\psi)$ from LHCb simulation. The simulation was performed at $\sqrt{s} = 13$ TeV with $b \to J/\psi$. The plot compares different configurations:

- **Pythia 8**
- **no g-split**
- **no MPI**

The $z(J/\psi)$ range is from 0 to 1.
Prompt Results

LHCb, arXiv:1701.05116

$J/\psi$ Production in Jets

$\psi/J(z)$

- Data (syst)
- DPS
- LO NRQCD
- SPS

$\sigma_{eff} = 31 \text{ mb (PYTHIA default)}$

$\sqrt{s} = 13$ TeV

LHCb Prompt
Prompt Results

LHCb, arXiv:1701.05116

\[
\frac{d\sigma}{\sigma} (z) = \begin{cases} 
\text{LO } 3S_1^{(1)} + \text{MPI} & \text{LO } 3S_1^{(8)} + \text{MPI} \\
\text{LO } 3S_1^{(1)} & \text{LO } 3S_1^{(8)} \\
\text{NLO}^* \text{ } 3S_1^{(1)} & \text{NLO}^* \text{ } 3S_1^{(8)} 
\end{cases}
\]

LHCb simulation
\[ \sqrt{s} = 13 \text{ TeV} \]

Prompt

\[
\frac{d\sigma}{\sigma} (z(J/\psi))
\]

\[
z(J/\psi)
\]
Outlook
LHCb: $p_T > 20$ GeV, $z_{\text{tag}} > 0.1$, $\eta \in [3, 4]$
Conclusions

- exciting new quarkonia physics underway
- measurements need to be expanded
  - $\psi(2S)$, $\Upsilon$,
  - absolute distributions
  - polarization
  - ...
- new methods to test quarkonia splittings

Thank you!
Backup
Datasets

V. Vagnoni (2015) HL-LHC

- projected luminosity per run

<table>
<thead>
<tr>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
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<tbody>
<tr>
<td>Run 1(a) 2011</td>
<td>Run 4 2027 - 2029</td>
</tr>
<tr>
<td>Run 1(b) 2012</td>
<td>Run 5 2031 - ?</td>
</tr>
<tr>
<td>Run 2 2015 - 2019</td>
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<tr>
<td>Run 3 2021 - 2023</td>
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<tr>
<td>1 fb$^{-1}$</td>
<td>23 fb$^{-1}$</td>
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<tr>
<td>5 fb$^{-1}$</td>
<td>?</td>
</tr>
<tr>
<td>15 fb$^{-1}$</td>
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</tbody>
</table>

- $p$Pb and PbPb heavy ion and fixed target $p$He datasets

- LHCb upgrade during LS 2
  - LHCb-PUB-2014-040
  - replacement of readouts and photo-detectors for the RICHs
  - replacement of tracking detectors
  - full software trigger, see LHCb-TDR-016
    - currently limited by hardware readout at 1 MHz
    - upgrade will read out entire detector at 40 MHz
Comparison

LHCb, arXiv:1701.05116

ψ / J

z

0.2 0.4 0.6 0.8 1

σ / σ d 0

0.1 0.2

Prompt (syst)

b→J/ψ (syst)

LHCb

√s = 13 TeV

Ilten

J/ψ in Jets

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Uncorrected Signal Yields

LHCb, arXiv:1701.05116

\[ \psi / J(z_{0} \text{ } 0.2 \text{ } 0.4 \text{ } 0.6 \text{ } 0.8 \text{ } 1) \text{ Yield} / 0.1 \]

Reconstructed

LHCb = 13 TeV

\[ \sqrt{s} < 20 \text{ GeV} \]

\[ p_{T} \text{ (jet)} < 30 \text{ GeV} \]

Prompt

\[ b \rightarrow J/\psi \]