Central exclusive production of $J/\psi$ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV

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Introduction

Central exclusive production: \( p + p \rightarrow p + X + p \)

- Clean final state with low event multiplicity
- \( X \) well isolated in rapidity
- Provides essential QCD information

\( J/\psi \) and \( \psi(2S) \) in CEP are produced through the fusion of a photon and a pomeron (a colorless strongly-coupled object), and can provide
  - A test of QCD
  - An investigation of the nature of the pomeron
  - A means for constraining the gluon parton distribution function
CEP at LHCb

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$
  - Rapidity range complementary to other experiments
  - Dedicated CEP trigger lines
  - Low pile-up environment
  - VELO has backward coverage
    $-3.5 < \eta < -1.5$

- HERSCHEL: new high rapidity shower counters in RunII;
  \eta coverage largely increased! Can reduce non-CEP backgrounds powerfully

VELO & Herschel: $-10 < \eta < -5, -3.5 < \eta < -1.5, 1.5 < \eta < 10$
Dataset and selections

- Measurement performed using 204 pb\(^{-1}\) data at \(\sqrt{s} = 13\) TeV

- Trigger requirements
  - **Hardware**: less than 30 deposits in the scintillating-pad (SPD); at least one muon with \(p_T > 200\) MeV/c
  - **Software**: < 10 reconstructed tracks; at least one muon

- Event selection
  - Two muons with \(2 < \eta < 4.5\)
  - \(M(\mu^+\mu^-) \in M(\psi) \pm 65\) MeV/c\(^2\)
  - \(p_T^2(\mu^+\mu^-) < 0.8\) (GeV/c)\(^2\)
  - Events with
    1) additional VELO tracks or
    2) neutral energy > 200 MeV or
    3) significant deposits in HERSCHEL (\(\Sigma_H\): sum of normalized signals in each channel) are removed

*Without \(M(\mu^+\mu^-)\) cut*
Cross-section calculation

- Differential cross-sections in bins of rapidity are measured.
- Master relation

\[ \frac{d\sigma_{\psi \rightarrow \mu^+\mu^-}}{dy} \left( 2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5 \right) = \frac{pN}{\varepsilon_{\text{rec}}\varepsilon_{\text{sel}}\Delta y\varepsilon_{\text{single}}L} \]

- \( p \): signal purity
- \( N \): number of selected events
- \( \varepsilon_{\text{rec}/\text{sel}} \): reconstruction/selection efficiency
- \( \Delta y \): width of the rapidity bin
- \( L \): integrated luminosity
- \( \varepsilon_{\text{single}} = \mu e^{-\mu} \): fraction of single interaction beam-crossings, assuming number of visible pp interactions follows Poisson distribution
  \[ P(n) = \frac{\mu^n e^{-\mu}}{n!} \]
Signal purity $p$

Remaining background sources

1) Non-resonant dimuon: fit to $M(\mu^+ \mu^-)$ distribution

2) Feed-down of CEP $\chi_c$ or $\psi(2S)$ to $J/\psi$
   - $\psi(2S)$: determined using simulated events normalized to $\psi(2S) \rightarrow \mu^+ \mu^-$ signal in data
   - $\chi_c$: determined using calibration sample reconstructed with $J/\psi + \gamma$, scaled by the ratio of $J/\psi$ to $J/\psi + \gamma$ in the simulated $\chi_c$ sample

3) Non-exclusive events where remnants are undetected

[CERN-LHCb-CONF-2016-007]
Utilization of HERSCHEL

- Good discrimination between CEP and non-CEP candidates

- Background level roughly halved compared to RunI analysis

[CERN-LHCb-CONF-2016-007]
Efficiencies $\varepsilon_{\text{rec}}$ and $\varepsilon_{\text{sel}}$

- **Reconstruction efficiency $\varepsilon_{\text{rec}}$**
  - Product of trigger, tracking and muon identification efficiency
  - Each determined from simulation and calibrated using data

- **Selection efficiency $\varepsilon_{\text{sel}}$**
  - $M(\mu^+ \mu^-)$ cut: fit to $M(\mu^+ \mu^-)$ distribution
  - $p_T^2(\mu^+ \mu^-)$ cut: fit to $p_T^2(\mu^+ \mu^-)$ distribution

- **Veto** on VELO, HERSCHEL or photon activity: fit to $p_T^2(\mu^+ \mu^-)$ distribution of non-resonant data sample with/without the cut

[CERN-LHCb-CONF-2016-007]

LHCb Preliminary

Signal
Background

$J/\psi$
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$J/\psi$ analysis uncertainty (%)</th>
<th>$\psi(2S)$ analysis uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton dissociation</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Non-resonant background</td>
<td>0.1</td>
<td>1.4</td>
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<tr>
<td>Feed-down background</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Mass-window</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>HERSCHEL Veto</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Total excluding luminosity</td>
<td>5.9</td>
<td>6.1</td>
</tr>
</tbody>
</table>

- **Proton dissociation:**
  Uncertainty due to imperfect modelling in the fit to $p_T^2 (\mu^+ \mu^-)$; determined using alternative models

- **Tracking efficiency:**
  Uncertainty due to variation of efficiencies determined from the calibration data sample

[CERN-LHCB-CONF-2016-007]
Cross-sections

- Total cross-sections
  $\sigma_{J/\psi \rightarrow \mu^+ \mu^-} \left(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5\right) = 407 \pm 8{\text{(stat)}} \pm 24{\text{(syst)}} \pm 16{\text{(lumi)}} \text{ pb}$
  $\sigma_{\psi(2S) \rightarrow \mu^+ \mu^-} \left(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5\right) = 9.4 \pm 0.9{\text{(stat)}} \pm 0.6{\text{(syst)}} \pm 0.4{\text{(lumi)}} \text{ pb}$

- Differential cross-sections with respect to rapidity
  ✓ Better agreement with JMRT NLO predictions

[CERN-LHCb-CONF-2016-007]

[JHEP 11 (2013) 085]

Relation with the photo-production cross-section $\sigma_{\gamma p \rightarrow \psi p}$

$$\sigma_{pp \rightarrow pXp} = r(W_+)k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow \psi p}(W^+) + r(W_-)k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow \psi p}(W^-)$$

- $r(W_{\pm})$: gap survival factor; taken from previous studies
- $k_{\pm}$: photon energy, $= m_\psi / 2 \times e^{\pm |\gamma|}$
- $\frac{dn}{dk_{\pm}}$: photon flux; taken from previous studies
- $W_{\pm}$: center-of-mass energy of the photon-proton system;

$$W_{\pm} = \sqrt{m_\psi \times e^{\pm |\gamma|} \times \sqrt{s}}$$

can explore $W = 2$ TeV with $\sqrt{s} = 13$ TeV data collected by LHCb; the highest energy so far!
**Photo-production cross-section (cont.)**

**$J/\psi$ production:**
- In agreement with 7 TeV results where they overlap
- Reach extended to $W \sim 2$ TeV
- Deviation from the power-law fit to H1 data at highest energies
- Good agreement with JMRT NLO prediction

**$\psi(2S)$ production:**
- Good agreement with H1 data extrapolation, which is scaled from the $J/\psi$ power-law fit
- Larger statistics needed

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**References:**
- [JHEP 11 (2013) 085]
- [CERN-LHCb-CONF-2016-007]
Summary

- Central exclusive $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 13$ TeV measured using data collected by LHCb
  - Low background level shows good performance of HERSCHEL
  - Both $J/\psi$ and $\psi(2S)$ show better agreement with JMRT NLO prediction
  - The photo-production cross-section of $J/\psi$ shows deviation from power-law extrapolation of HERA data
  - More data is needed to make a critical comparison for $\psi(2S)$

Thank you!
Backup
The LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$

- **Vertex Locator:** $\sigma_{PV,x/y} \sim 10 \mu m, \sigma_{PV,z} \sim 60 \mu m$
- **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100 \text{ GeV}/c$
- **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- **ECAL:** $\sigma_E/E \sim 10\% / \sqrt{E} \otimes 1\%$ (E in GeV)
- **HCAL:** $\sigma_E/E \sim 70\% / \sqrt{E} \otimes 10\%$ (E in GeV)

[JINST 3 (2008) S08005]
VELO&Herschel: $-10 < \eta < -5$, $-3.5 < \eta < -1.5$, $1.5 < \eta < 10$
HepData record

- Record of $J/\psi$ and $\psi(2S)$ in CEP at $\sqrt{s} = 7$ TeV:  
  http://dx.doi.org/10.17182/hepdata.66883

- Record of $J/\psi$ and $\psi(2S)$ in CEP at $\sqrt{s} = 13$ TeV will be available when the paper is published