Exclusive J/ψ and ψ(2S) vector meson production

Outline

• LHCb Experiment
• Central Exclusive Production (CEP)@LHCb
• Current Results
• Summary

On behalf of the LHCb Collaboration

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LHCb Experiment
LHCb is a dedicated flavour experiment with the main focus on CP-violation and New Physics in b- and c-mesons.

Performs indirect searches using quantum loops, complementary to energy frontier experiments ATLAS & CMS.)

Must provide: excellent position, vertex and momentum resolution & PID

A forward spectrometer is sufficient for the LHCb physics programme since produced b-bbar pairs are strongly correlated and forward peaked.
The LHCb detector at LHC (JINST 3 2008 S08005)
Two of the subsystems are especially vital for the CEP studying @ LHCb

- **VErtex LOcator (VELO)**
  - 84 micro-strip silicon sensors close to the IR
  - Precise track and vertex reconstruction
  - The best single hit spatial resolution at LHC
  - Allows for **backward track reconstruction**
  - No momentum information for backward tracks

- **Scintillator Pad Detector (SPD)**
  - Part of the LHCb calorimeter system
  - Tagging electric charge
  - Provides vital input to hardware trigger
  - Used primarily as **multiplicity** detector
Central exclusive production can be denoted qualitatively as follows

\[ h_1(p_1) + h_2(p_2) \rightarrow h_1(p'_1) \oplus X \oplus h_2(p'_2) \]

- Interacting hadrons do not undergo any "catastrophic process" (such dissociation) instead they interact via exchanging a colourless object and remain intact.

- However, they lose energy in order to produce only the final system \( X \) that can be observed in the detector.

- "\( \oplus \)" denotes symbolically the rapidity gaps.
  - Only the central system is produced, apart from that there should be no activity otherwise, thus, exclusive process.

- In principle four-momenta of the scattered hadrons (protons) can be measured by very forward detectors.

- In case of the LHCb both protons remain un-tagged.
CEP – physics motivation

- Exclusive processes are at the heart of QCD
- May help **improve understanding of soft scale** (non-perturbative) QCD
  - Actually almost all interesting things happen here (composite hadrons we observe)
- Studying **pomeron** (odderon) interactions
- Improve knowledge on low-\(x\) behavior of parton PDF
  - Sharp rise of gluon PDF for decreasing \(x\)
  - LHCb is sensitive to the gluon PDF down to \(x \sim 5 \cdot 10^{-6}\)
- Studying saturation (BFKL evolution)
- Help understand in general processes such \(gg \rightarrow X\) (\(gg \rightarrow H\))
CEP@LHCb

- Not a part of the „initial” core physics programme of the LHCb

- **Superb** tracking performance of the spectrometer and its **forward geometry** (rapidity reach up to $\eta \approx 5$) made the study feasible
  - VELO and SPD detectors essential for detecting **rapidity gap** (establishing exclusivity of a given event)

- **Flexible software trigger** allows to select events with **low pile-up**
  - Single interaction per crossing ($\sim 20\%$ of collected luminosity)
    - **Simpler** signal selection
    - High sensitivity to low $p/p_T$ particles

![Graph showing LHCb Average Mu at 4 TeV in 2012](image)
CEP@LHCb

- For now we study only **di-muon final states** (no hadronic)
  - analyses with hadronic final states ongoing
- Luminosity leveling with displaced p-p beams
  - Stable conditions throughout data taking runs

![Instantaneous Luminosity Graph](image)

![Beam Diagram](image)
CEP@LHCb

- Ah, and such events are very, very unusual for LHCb...

„Regular” LHCb event

... and a CEP one

- LHCb trigger system is amazing enough to select both types...

(Example copied from Paula Collins talk – thanks!)
CEP@LHCb

Ah, and such events are very, very unusual for the LHCb...

„Regular“ LHCb event

... and a CEP one

LHCb trigger system is amazing enough to select both types...
CEP with di-muon final state

- Elastic scattering with intact and un-tagged protons
- Proceed via exchange of colourless objects ($\gamma$, pomeron)
- Studied in detail by theorists

- **LPAIR** (A.G Shamov and V.I Telnov, NIM A, 494 (2002), 51)
Current results

Exclusive $J/\psi$ and $\psi(2S)$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV

- **2010 data** ($\sim$ 37 pb$^{-1}$)

Updated measurements of exclusive $J/\psi$ and $\psi(2S)$ production cross-sections in $pp$ collisions at $\sqrt{s} = 7$ TeV

- **2011 data** ($\sim$ 930 pb$^{-1}$)
Signal selection (highlights)

- **Low level (hardware) trigger L0**
  - a muon candidate, $p_T > 400$ MeV
  - a di-muon candidate, $p_T > 80$ MeV (each track)
  - less than 20 (10 for 2011) SPD hits

- **Software HLT (High Level Trigger)**
  - a di-muon candidate $p_T < 800$ MeV
  - $M($di-muon$) > 2.7$ GeV

- **Offline selection**
  - both muons within LHCb acceptance ($2.0 < \eta < 4.5$)
  - no photons, no backward tracks (VELO veto)
  - mass window for a di-muon $\Delta M = 65$ MeV around expected $J/\psi$ or $\psi(2S)$ mass
Di-muon mass spectrum before (-) and after selection (-)

LHCb Preliminary

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

LHCb-CONF-2011-22
Selected signal (2010)

- Model of the mass spectra
  - Signal peak – Crystal-Ball
  - Background – exponential
- Observed events
  - 1492 exclusive J/ψ and 40 exclusive ψ(2S) – 2010
Selected signal (2011) - subsequent discussion related to this data sample

- Model of the mass spectra
  - Signal peak – Crystal-Ball function
  - Background – exponential
- Observed events
  - 55895 exclusive J/ψ and 1565 exclusive ψ(2S) – 2011

Cross-section measurement (2011)

- **Differential cross-section times branching fraction**
  to two muons with pseudorapidity defined by the LHCb angular acceptance

- Measured in bins of meson rapidity \( y \)

\[
\frac{d\sigma}{dy}_i = \frac{1}{\epsilon_{\text{single}} L \epsilon_i \Delta y} \cdot \frac{pN_i}{p}
\]

- \( p \) – Purity:
  - Non-resonant background
  - Feed-down background
  - Inelastic background

- \( N_i \) – Number of events in a given rapidity bin

- \( \epsilon_{\text{single}} \) – Selection of events with one p-p interaction per crossing
  - This follows very well the Poisson distribution (~ 21%)

- \( L \) – Sample integrated luminosity

- \( \epsilon_i \) – Efficiency:
  - Trigger (L0+HLT)
  - Tracking
  - Muon PID
  - Signal selection

Total efficiency varies from 0.66 to 0.89 depending on rapidity bin
**Purity estimation: non-resonant component**

- QED induced interactions that result in di-muon final state
- Estimated with signal events that passed all the cuts apart from mass window one
- Assume signal peak is modeled with CB curve and the continuum events with exponential
  - **Use sidebands to fit**
- Background estimated (within the mass window of respective states): 
  - \((0.8 \pm 0.1)\%\) for the J/ψ selection
  - \((17.0 \pm 0.3)\%\) for the ψ(2S) selection
Purity estimation: feed-down component

- The source of this background is exclusive production of other mesons

- Mainly problem for selecting J/ψ events

- Decays $\psi(2S) \rightarrow J/ψ \ X$, where $X$ is not detected
  - Can be significantly suppressed by hard 2 track only cut
  - Estimated using STARlight model
  - $(2.5 \pm 0.2)$ % of selected J/ψ events

- Radiative decays $χ_c \rightarrow J/ψ \ \gamma$, where $\gamma$ goes undetected
  - Suppressed by requiring no photons
  - Estimated using SuperChiC model
  - $(7.6 \pm 0.9)$ % of selected J/ψ events

- Feed-down to $ψ(2S)$ is expected to be small - coming from $X(3872)$
  - Results based on studies involving photon veto in selection algorithm gave $(2.0 \pm 0.2)$ % of selected $ψ(2S)$ events
Purity estimation: inelastic scattering

- This is the dominant background

- In general harder $p_T$ spectrum of produced $J/\psi$ is expected

- Was estimated using collision data (2011 sample)
  - $(34 \pm 6)\%$ for $J/\psi$ events
  - Similar estimate is assumed for $\psi(2S)$

- Overall purities:
  - $(59.2 \pm 1.2)\%$ for $J/\psi$ events
  - $(52.0 \pm 7.0)\%$ for $\psi(2S)$ events
  - $p_T < 0.8$ GeV$^2$
Cross section measurement

- **Integrated cross-sections**

  \[ \sigma_{J/\psi \rightarrow \mu^+ \mu^-}(2 < \eta_{\mu^+} + \eta_{\mu^-} < 4.5) = 291 \pm 7 \text{(stat.)} \pm 19 \text{(sys.) pb} \]

  \[ \sigma_{\psi(2S) \rightarrow \mu^+ \mu^-}(2 < \eta_{\mu^+} + \eta_{\mu^-} < 4.5) = 6.7 \pm 0.9 \text{(stat.)} \pm 0.4 \text{(sys.) pb} \]

- **Differential cross-sections**

  ![J/ψ](a)

  ![ψ(2S)](b)
Cross section measurement

- Comparison with theoretical predictions – **good agreement!**
  - NLO describes data better than LO based predictions
  - better description for J/psi than for psi(2S)
  - uncertainties are highly correlated between the bins

![Graph showing comparison between J/psi and psi(2S)]

Comparison with HERA results (differential cross-section)

- The LHCb measurement can be related to photoproduction using:

\[
\frac{d\sigma_{pp\rightarrow pJ/\psi p}}{dy} = r_+ k_+ \frac{dn}{dk_+} \sigma_{p\rightarrow pJ/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{p\rightarrow pJ/\psi p}(W_-)
\]

Measured \hspace{1cm} Extracted

\[\frac{dn}{dk_{\pm}}\] photon flux: Weizsacker-Williams approximation

\[k_{\pm} \approx (M_{J/\psi}/2)\exp(|y|)\] photon energy

\[(W_{\pm})^2 = 2k_{\pm}\sqrt{s}\] mass of the photon-proton system

- Twofold ambiguity for LHCb – for each rapidity bin we have two solutions (see next slide) for photon-proton c.m. energy
Comparison with HERA results (differential cross-section)

- The LHCb measurement can be related to photoproduction using:

\[
\frac{d\sigma_{pp\to pJ/\psi}}{dy} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p\to pJ/\psi}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p\to pJ/\psi}(W_-)
\]

- Obtained results are compatible with the HERA data!
- Some deviation from simple power law prediction (Regge theory) seen
  - this may be explained either by saturation or higher order diagrams
Exclusive $J/\psi$ and $\psi(2s)$ cross-sections have been successfully measured at LHCb using 2010 and 2011 data samples. Obtained results are consistent with photo-production results from HERA. Published 2 papers. Still more statistics waiting in 2012 data. Plans for extending analyses concerning exclusive production:

- new particles (e.g., $\chi_c$)
- include also hadronic modes

Detector improvements in order to increase rapidity gap (installation of scintillator counters to reject inelastic background)

This study may contribute to better understanding of pomeron and measurement of gluon PDF for very small $x$.

Sensitivity to models including saturation effect.
Back-up
Correlated uncertainties expressed as a percentage of the final result

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$\epsilon_{\text{sel}}$</td>
<td>1.4%</td>
</tr>
<tr>
<td>Purity determination (J/$\psi$)</td>
<td>2.0%</td>
</tr>
<tr>
<td>Purity determination ($\psi$ (2S))</td>
<td>13.0%</td>
</tr>
<tr>
<td>$^*\epsilon_{\text{single}}$</td>
<td>1.0%</td>
</tr>
<tr>
<td>$^*\text{Acceptance}$</td>
<td>2.0%</td>
</tr>
<tr>
<td>$^*\text{Shape of the inelastic background}$</td>
<td>5.0%</td>
</tr>
<tr>
<td>$^*\text{Luminosity}$</td>
<td>3.5%</td>
</tr>
<tr>
<td>Total correlated statistical uncertainty (J/$\psi$)</td>
<td>2.4%</td>
</tr>
<tr>
<td>Total correlated statistical uncertainty ($\psi$ (2S))</td>
<td>13.0%</td>
</tr>
<tr>
<td>Total correlated systematic uncertainty</td>
<td>6.5%</td>
</tr>
</tbody>
</table>
\[ f(x; \alpha, n, \bar{x}, \sigma) = N \cdot \begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leq -\alpha \end{cases} \]

where

\[ A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right), \]
\[ B = \frac{n}{|\alpha|} - |\alpha|, \]
\[ N = \frac{1}{\sigma(C + D)} \]
\[ C' = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) \]
\[ D = \sqrt{\frac{\pi}{2}} \left(1 + \text{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right) \]