Central exclusive production at LHCb

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Overview

– Motivations.
– Experimental signatures.
– Selecting exclusive events at LHCb.
– Results.
  – Exclusive $J/\psi$ and $\psi(2s)$. *J. Phys. G: Nucl. Part. Phys.* 41 (2014) 055002
  – Exclusive charmonium pairs. *J. Phys. G: Nucl. Part. Phys.* 41 (2014) 115002
  – Exclusive $\Upsilon$. LHCb-PAPER-2015-011
– Future work.
Motivations

- Test QCD at perturbative/non-perturbative frontier.
- Cross-section $\propto (\text{Gluon PDF})^2$
- Saturation effects.
- Search for odderon/tetraquarks/$X(3872)$.

At LHCb $x \sim 10^{-5}$

Large $xg(x, Q^2)$ uncertainty

Eur.Phys.J.C63:189-285,2009

Test QCD at perturbative/non-perturbative frontier.

Cross-section $\propto (\text{Gluon PDF})^2$
Elastic/diffractive physics

- Elastic scattering
- Single diffractive
- Double diffractive
- CEP (elastic)
- CEP (diffractive)

LHCb coverage

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CEP

**CEP signal:** $J/\psi$, $\psi(2s)$, $\gamma$

**CEP feed-down:** $\chi_c \rightarrow J\psi\gamma$

**CEP non-resonant:** $\gamma\gamma \rightarrow \mu\mu$
LHCb detector

Int. J. Mod. Phys. A 30, 1530022 (2015)

1.5<\eta<5

\mu_{\text{vis}} \sim 1.4

10\text{m}

Velo & Tracking

SPD (<10 hits)

Magnet

Muon (p_{T}>400 \text{ MeV}/c)

Calorimeters

RICH

Mu \text{on}
Advantages for CEP

- Pseudorapidity coverage
  - Forward tracks $1.5 < \eta < 5$
  - Backward tracks $-1.5 < \eta < -3$

- Low $p_T$ trigger for leptons, photons, hadrons
  - Muons $p_T > 400\text{MeV}/c$
  - Hadronic energy $E_T > 1\text{GeV}$
  - Particle ID with RICH: $\pi/K/p$

- Low pile-up conditions. $\sim 20\%$ of data between 2010-2012 has only single interaction.
Exclusive $J/\psi, \psi(2s)$ selection

- **Trigger:** One muon $p_T > 400\text{MeV}/c$, $SPD < 10$.

- **Selection:**
  - 2 reconstructed muons in forward region ($y$ gap 3.5 units). No other tracks with Velo hits.
  - No photons (reduce $\chi_c$ decays).
  - No tracks in backward region ($y$ gap 1.7 units).
  - Dimuon $p_T^2 < 0.8\text{GeV}^2/c^2$. $|M_{\mu\mu} - M_{J/\psi, \psi(2s)}| < 65\text{MeV}/c^2$.
  - 55,985 $J/\psi$ and 1565 $\psi(2s)$. 

No veto on backward tracks

Veto on backward tracks

CEP signal

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Non-resonant background

- Fit invariant mass distribution with Crystal Ball for signal and exponential for non-resonant background.
- In signal window $(0.8 \pm 0.1)\%$ and $(17.0 \pm 0.3)\%$ for $J/\psi$ and $\psi(2s)$. 

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Feed-down and inelastic background (Regge theory and HERA)

- **Feed-down:** $\chi_c \rightarrow J/\psi \gamma$ if photon outside acceptance or undetected.
- Scale exclusive $\chi_c$ data sample by fraction of exclusive $\chi_c$ identified as exclusive $J/\psi$ in simulation.

- **Inelastic:** Largest background due to diffractive $J/\psi$ and $\psi(2s)$ with gluon radiation or proton dissociation. Characteristic $p_T$ of these processes is larger.
- Regge theory: Exclusive production $\frac{d\sigma_{\text{excl.}}}{dt} \propto e^{b_st}$ where $t \approx -p_T^2 c^2$ is 4-momentum transfer at proton pomeron vertex.
- For $|t| < 1.2$ GeV$^2$ proton dissociative production $\frac{d\sigma_{\text{diss.}}}{dt} \propto e^{b_{pd}t}$.
- Extrapolate HERA values to LHC energies $b(W) = b_0 + 4\alpha' \log(W/W_0)$ and get $b_s \approx 6\text{GeV}^{-2}$ and $b_{pd} \approx 1\text{GeV}^{-2}$.

| $\text{GeV}^{-2}$ | $b_s$          | $b_{pd}$          |
|------------------|----------------|-------------------|
| $J/\psi$ (ZEUS)  | $4.15 \pm 0.05^{+0.30}_{-0.18}$ | $-$               |
| $J/\psi$ (H1)    | $4.88 \pm 0.15$               | $1.07 \pm 0.11$   |
| $\psi(2s)$ (H1)  | $4.3 \pm 0.6$                  | $0.59 \pm 0.17$   |

Eur.Phys.J.C24(2002)345; Eur.Phys.J.C73(2013)2466; Phys.Lett.B541(2002)251; Phys.Lett.B568(2003)205
Inelastic background: LHCb fit

\[ \frac{F_s}{N_1} e^{-b_s p_T^2 c^2} + \frac{F_{pd}}{N_2} e^{-b_{pd} p_T^2 c^2} + \frac{F_{fd}}{N_3} F_{fd}(p_T^2) \]

| GeV^{-2} | b_s \quad b_{pd} |
|----------|----------------|
| J/ψ      | 5.70 ± 0.11    | 0.97 ± 0.04  |
| ψ(2s)    | 5.1 ± 0.7      | 0.8 ± 0.2    |

J/ψ, χ^2/ndf = 115/96

Purity 0.592 ± 0.012

ψ(2s), χ^2/ndf = 11/16

Purity 0.52 ± 0.07

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Exclusive pairs of $J/\psi$, $\psi(2S)$, $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$

- Double pomeron exchange (DPE), two different production mechanisms.
- Double parton scattering (DPS) in inclusive measurement?
- Compare mass spectrum of exclusive production where DPS is low.
Exclusive pairs of $J/\psi, \psi(2S), \chi_{c0}, \chi_{c1}, \chi_{c2}$
Exclusive $\Upsilon(nS)$ production

LHCb-PAPER-2015-011

- Higher mass perturbative QCD?
- Similar to $J/\psi$. Mass window now 9-20 GeV/$c^2$. Feed-down from $\chi_b$. 
Cross-section measurement

- Standard cross-section formula.

- $\varepsilon_{sel} = 87\%$. No extra tracks, $p_T^2$, $\gamma$ veto, mass window, SPD hits.

- Trigger and muon identification efficiencies using tag-and-probe methods on $J/\psi$ resonance. Product $\varepsilon_{trg}\varepsilon_{id}$ about 80%.

- $\varepsilon_{single}$ about 24%.

- Dominant uncertainties due to:
  - Shape of inelastic background for $J/\psi$
  - Purity determination for $\psi(2S)$
  - Feed-down background model for $\Upsilon$
**J/ψ and ψ(2S) cross-sections**

J. Phys. G 41 (2014) 055002; JHEP 11 (2013) 085

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- Error bars denote uncorrelated uncertainty. Bands denote total uncertainty.
- Data described by pQCD. NLO in better agreement.
- Data also described by saturation models.
Y cross-sections

- Error bars denote uncorrelated uncertainty. Boxes denote total uncertainty.
- Data cannot be described by LO.
Total cross-section comparison

\[ J/\psi \]

\[ \psi(2S) \]

Goncalves and Machado
Jones, Martin, Ryskin, Teubner
Motyka and Watt
Schaefer and Szczurek

STARLIGHT
(Schaefer, Szczurek, Stirling)
SUPERCHIC
(Harland-Lang, Ryskin, Stirling)

LHCb

1. Phys. Rev. C84 (2011) 011902; 2. JHEP 11 (2013) 085; 3. Phys. Rev. D78 (2008) 014023;
4. Phys. Rev. D76 (2007) 094014; 5. Phys. Rev. Lett. 92 (2004) 142003; 6. Eur. Phys. J C65 (2010) 433;
Comparing LHCb results with HERA

- HERA ep collider. Photon from electron. 
  \( \sigma_{\gamma p \rightarrow \nu p} \) as function of \( \gamma p \) CM energy \( W \).
- \( W^2 = M \sqrt{s} e^{\pm|y|} \)
- At LHC photon radiates from proton.
- Model the exclusive \( pp \) cross-section using HERA.

\[
\frac{d\sigma}{dy}_{pp \rightarrow p J/\psi p} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\psi p}(W^+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\psi p}(W^-)
\]

- Account for relative photon flux \( \frac{dn}{dk_{\pm}} \) with \( k_{\pm} \sim (m_V/2) \exp(\pm|y|) \).
- Gap survival factors \( r_{\pm} \) account for other hadron-hadron interactions that spoil exclusivity.
- Sum of two cross-sections corresponding to situations where photon is either target or emitter.
Comparing LHCb results with HERA: \( J/\psi \)

Assume power law \( \sigma_{\gamma p \rightarrow J/\psi p}(W) = 81(W/90\text{GeV})^{0.67} \text{nb} \) for \( \sigma_{\gamma p \rightarrow J/\psi p}(W^-) \).

\[ \frac{d\sigma}{dy}_{pp \rightarrow pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\psi p}(W^+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\psi p}(W^-) \]
Comparing LHCb results with HERA: $\Upsilon$

- Cross-section vs. $\gamma p$ CM energy $W$ again shows superiority of NLO over LO.
- $\Upsilon$ probing a new regime in $W$. 

![Graph showing LHCb results](image)
Future prospects

- HERSCHEL: High Rapidity Shower Counter
- Increase size of rapidity gap (to $\pm 9$). Reduce inelastic backgrounds.
- Trigger for hadrons, photons, electrons as well as muons.
- Exclusive $\Lambda$, $D$, low mass resonances in analysis of continuum, glueballs, .....
Take home

- LHCb well suited to study of exclusive vector meson production with decays to muon final-states.
- In particular this is due to low $p_T$ trigger and low pileup running conditions.
- Theoretical predictions on the market describe the data well - NLO pQCD and saturation models.
- Run-2 to include wider range of final-states and improved selection with HERSCHEL.
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Pileup \((\varepsilon_{single})\)

- *pp* interaction defined as interaction with 1 or more tracks having VELO information.
- The number of these, \(n\), follows poisson distribution.

\[
P(n) = \frac{\mu^n e^{-\mu}}{n!}
\]

- \(\mu \sim 1.4\) in 2011 data taking.
- Scale luminosity by \(\varepsilon_{single} = P(0) = 0.241 \pm 0.003\).
$J/\psi$ and $\psi(2S)$ cross-sections

J. Phys. G 41 (2014) 055002; Phys. Rev. D78 (2008) 014023; Phys.Rev. D88 (2013) 017504

Data described by saturation models.
### Total cross-section comparison

All predictions in agreement with data.

| [pb]                      | $J/\psi$ | $\psi(2S)$ | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|--------------------------|----------|------------|----------------|----------------|----------------|
| Goncalves and Machado$^1$| 275      | -          | -              | -              | -              |
| JMRT$^2$                 | 282      | 8.3        | -              | -              | -              |
| Motyka and Watt$^3$      | 334      | -          | -              | -              | -              |
| Shafer and Szczurek$^4$  | 317      | -          | -              | -              | -              |
| Starlight$^5$            | 292      | 6.1        | -              | -              | -              |
| SuperChic$^6$            | 317      | 7.0        | -              | -              | -              |
| LHCb                     | 291 ± 20 | 6.5 ± 1.0  | 8.97 ± 2.43    | 1.27 ± 0.89    | < 3.2 (95% C.L.) |

$^1$Phys. Rev. C84 (2011) 011902; $^2$JHEP 11 (2013) 085; $^3$Phys. Rev. D78 (2008) 014023;

$^4$Phys. Rev. D76 (2007) 094014; $^5$Phys. Rev. Lett. 92 (2004) 142003; $^6$Eur. Phys. J C65 (2010) 433;