Central Exclusive Production and Soft QCD at LHCb

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LHCb is one of the four main experiments on the LHC ring.

Its aim is to investigate the decays of hadrons that contain b&c quarks and so provide insight into the phenomenon of matter-antimatter asymmetries.

The collaboration comprises of 1355 physicists and engineers from 79 institutes in 18 Countries.
LHCb detector

- The tracking system: VERTex LOcator (VELO) + T stations
- Two Ring Imaging Cherenkov detectors (RICH1 and RICH2): charged hadron identification in the momentum range from 2 to 100 GeV/c
- The calorimeter system:
  - Scintillating Pad Detector (SPD)
  - PreShower (PS)
  - Electromagnetic Cal (ECAL)
  - Hadronic Cal (HCAL)
- Muon detection system: M1-M5
- IP (impact parameter) resolution: 20 µm @ high-pT
- Momentum resolution: Δp/p = 0.5 % at low momentum to 1.0% at 200 GeV/c
- Track reconstruction eff: ~96% for long tracks
- LHCb trigger: hardware -> reduces 40 MHz of data to 1 MHz
  software trigger → 4 kHz

Unique pseudorapidity range:
- forward range: 2<η<5
- backward range: -3.5<η<-1.5
After LS2 (2021):

- Proton–proton collision rate at LHCb will be increased by a factor of five
- The whole detector will read at the full rate of 40 MHz to allow event selection to be done more precisely and flexibly by the software
- RICH detectors will be equipped with a new mirror system.
- New silicon-microstrip sensors and SciFi tracking

~ 10 fb⁻¹ data recorded in RUN1+RUN2 after LS2: 50 fb⁻¹

More statistics -> reduced uncertainties
Latest LHCb public results:

13 July 2019: Observation of two new beauty baryon particles.

28 June 2019: Updated measurement of the CP-violating phase $\phi_s$.

26 March 2019: Observation of new pentaquarks.

21 March 2019: Discovery of CP violation in charm particle decays.

To be covered:

- **CEP results at LHCb @ 7 TeV:** Updated measurements of exclusive $J/\psi$ and $\psi(2S)$ production cross-sections in pp collisions at $\sqrt{s}=7$ TeV [J. Phys. G 41 (2014) 055002]

- **Ion collisions:** Study of coherent $J/\psi$ production in lead-lead collisions at $\sqrt{s}=5$ TeV with the LHCb experiment [LHCb-CONF-2018-003] → Preliminary results

- **CEP with HeRSCHeL @LHCb:** Central exclusive production of $J/\psi$ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV [JHEP 10 (2018) 167]

- **SoftQCD@LHCb:** Measurement of the inelastic pp cross-section at centre-of-mass energy of $\sqrt{s} = 13$ TeV [JHEP 06 (2018) 100]

**HepData record:**

- record for $J/\psi$ and $\psi(2S)$ in CEP at 7 TeV: https://doi.org/10.17182/hepdata.66883
- record for inelastic cross-section measurement at 13 TeV: https://doi.org/10.17182/hepdata.89782
**Introduction**

- CEP is the process in which particles are produced by colourless propagators via the reaction $pp \rightarrow p + X + p$

**Signal signature**
- central system
- large rapidity gaps between central system and outgoing protons

**Background**
- diffractive processes involving proton dissociation

**Possibilities**
- transition between soft and hard pomeron $\rightarrow$ Soft QCD
- very clean final state $\rightarrow$ high benefit
The LHCb experiment is rapidly becoming a major actor in CEP searches, the HeRSCheL subdetector is now allowing to reduce the non-CEP background to a minimum.

- 5 stations of scintillating planes located along the beampipe
- sensitive to activity (no tracking)

Detecting a CEP event requires the detection of rapidity gaps in the distribution of the final state particles

➤ HeRSCheL largely extends the ability to veto diffractive final states
CEP published results at LHCb

**J/ψ and ψ(2S) production @ 7 TeV**

- 930 pb$^{-1}$ of 2011 data at 7 TeV
- exactly two muons in the acceptance
- $p_T(\mu) > 400$ MeV/c

\[ \sigma_{pp \rightarrow J/\psi \rightarrow \mu^+\mu^-} (2.0 < \eta_{\mu^\pm} < 4.5) = 291 \pm 7 \pm 19 \text{pb} \]

\[ \sigma_{pp \rightarrow \psi(2S) \rightarrow \mu^+\mu^-} (2.0 < \eta_{\mu^\pm} < 4.5) = 6.5 \pm 0.9 \pm 0.4 \text{pb} \]

without HeRSCHeL

Transverse momentum squared distributions for (a) $J/\psi$ and (b) $\psi(2S)$

Differential cross-section for (a) $J/\psi$ and (b) $\psi(2S)$ production compared to LO and NLO predictions


[S. Jones, A. Martin, et. al]
Coherent J/ψ production in lead-lead collisions at 5 TeV
Ultraperipheral collisions (UPC)

Introduction

- reactions in which two ions interact via their *cloud* of virtual photons
- intensity of the electromagnetic field proportional with $Z^2$

UPC interactions

Characteristics:
- low momentum transfer
- low transverse momentum
- the nucleus that emits the photon remains intact after the collision, no additional particles

a) photon-photon collisions  
b) photonuclear collisions

UPC photonuclear collisions

a) the photon interacts with the whole nucleus

b) the photon interacts with a single nucleon inside the nucleus

Coherent $J/\psi$ production in PbPb $\rightarrow$ Pb+$J/\psi$+Pb: $\gamma$ “pomeron” $\rightarrow J/\psi$

- Data set: lead-lead collisions at $\sqrt{s}=5$ TeV in 2015

- Event selection:
  - Hardware level: $J/\psi \rightarrow \mu^+\mu^-$
  - $p_T(\mu)>900$ MeV

- Software level: $M_{\mu^+\mu^-}>2.7$ GeV

- Offline selection:
  - Muon selection: $p_T>500$ MeV in $2<\eta<5$
  - $J/\psi$ selection: $p_T<1$ GeV

$J/\psi$ and $\psi(2s)$: double sided Crystal-Ball function
non-resonant: exponential multiplied by a first-order polynomial
Signal determination

- **1st step:**
  fit on the invariant mass to determine all the \( J/\psi \) candidates (coherent and incoherent \( J/\psi \), feed-down coming from \( \psi(2s) \))

- **2nd step:**
  fit on the \( \log(p_T^2) \) of \( J/\psi \) to determine the signal yield in the presence of bkg. (incoherent \( J/\psi \) and feed-down \( \psi(2S) \))

background and signal are modelled by templates taken from the STARlight event generator

![Distribution of \( \log(p_T^2) \) of dimuon candidates.](image)
Coherent cross-section:

**LHCb preliminary**

\[ \sigma = 5.3 \pm 0.2 \text{(stat.)} \pm 0.5 \text{(syst)} \pm 0.7 \text{(lumi)} \text{ mb} \]

The analysis is repeated in bins of half unit rapidity \( y_{J/\psi} \)

<table>
<thead>
<tr>
<th>( J/\psi ) rapidity</th>
<th>( d\sigma / dy ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00-2.50</td>
<td>3.0 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>2.50-3.00</td>
<td>2.60 ± 0.19 ± 0.25</td>
</tr>
<tr>
<td>3.00-3.50</td>
<td>2.28 ± 0.15 ± 0.21</td>
</tr>
<tr>
<td>3.50-4.00</td>
<td>1.73 ± 0.15 ± 0.17</td>
</tr>
<tr>
<td>4.00-4.50</td>
<td>1.10 ± 0.22 ± 0.13</td>
</tr>
</tbody>
</table>
Measurement performed with 204 pb⁻¹ data at 13 TeV

- μ=1.1 → half of the visible interactions there is a single pp collision

Trigger requirements:

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

- 2 reconstructed muons in $2<\eta<4.5$
- mass within 65 MeV/c² from $J/\psi$ or $\psi(2S)$ mass
- $p_T^2 < 0.8$ GeV²
Non-resonant background
continuum lepton pair production

Feed-down background:
ψ(2S)/χ_c - undetected remaining particles produced in association with J/ψ or outside the detector

Proton dissociation contamination
Inelastic production of mesons: one or both protons dissociate or gluon radion

Ways to extract the proton dissociation background:
- fit data with 2 exponentials (one for the signal and one for the pr. diss. bkg)
- use the two independent samples below and above HeRSChE veto to constrain the background
Cross section results

- Total cross-section

\[ \sigma_{J/\psi \rightarrow \mu^+\mu^-} \quad (2 < \eta_\mu < 4.5) = 399 \pm 16 \text{(stat.)} \pm 10 \text{ (syst.)} \pm 16 \text{ (lumi)} \text{ pb} \]

\[ \sigma_{\psi(2S) \rightarrow \mu^+\mu^-} \quad (2 < \eta_\mu < 4.5) = 10.2 \pm 1.0 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

- Differential cross-sections with respect to rapidity: better agreement with JMRT NLO prediction
# Systematic uncertainties

pp→p+ J/ψ or ψ(2S)+p

<table>
<thead>
<tr>
<th>Source</th>
<th>J/ψ analysis (%)</th>
<th>ψ(2S) analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HeRSCheL veto</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>2 VELO track</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0 photon veto</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Mass window</td>
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<tr>
<td>p^{2T}_T veto</td>
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</tr>
<tr>
<td>Proton dissociation</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Feed-down</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.7</td>
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<tr>
<td>Muon ID efficiency</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Trigger efficiency</td>
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<td>0.2</td>
</tr>
<tr>
<td>Total excluding luminosity</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

• decrease of the main uncertainties compared to previous analysis (J. Phys. G 41 (2014) 055002)
• proton dissociation background uncertainty ↓ thanks to HeRSCheL detector
• better tracking understanding
Photoproduction cross section

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

From [JHEP 11 (2013) 085]:

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

- $r(W_\pm)$-gap survival factor, from HERA (Table 2 from [JHEP 11 (2013) 085])
- $k_\pm$-photon energy
- $dm/dk_\pm$-photon flux
- $W^2_\pm=2k_\pm\sqrt{s}$-invariant mass of the photon-proton system
✓ J/ψ 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

✓ ψ(2S) production
• Good agreement with H1 data extrapolation, which is scaled from the J/ψ power-law fit
From exclusive two particle final states to normal inelastic interactions

Two muons and no other activity

Typical event in LHCb
SoftQCD@LHCb
Measurement of the inelastic pp cross-section at centre-of-mass energy of $\sqrt{s} = 13$ TeV

**Aim of the analysis**: calculate the $\sigma_{\text{inel}}$ using prompt and long-lived particles inside the LHCb acceptance and extrapolate it to the full phase space

- **Primary measurement**: fiducial cross section at $\sqrt{s} = 13$ TeV
- **Delivered result**: total inelastic cross-section

\[ \sigma_{\text{inel}} = \sum \sigma_x \quad \text{where} \quad x \in \{\text{ND, SD, DD}\} \]

**Data used:**
- pp collisions at centre-of-mass energy $\sqrt{s} = 13$ TeV
- both polarities of the LHCb dipole magnet
- 691 million events in 49 runs from 8 LHC fills

- ND: non-diffractive contribution
- SD: single diffractive contribution
- DD: double-diffractive contribution
Fiducial cross-section

Selection
- at least one long-lived prompt charged particle
- $p>2$ GeV/c
- $\Delta t>30$ ps
- pseudorapidity: $2<\eta<5$

$\sigma_{acc} \equiv \frac{(\mu - \mu_{bkg})N_{evt}}{L_{tot}}$

- $\mu - \mu_{bkg}$ - average no. of int per event obtained from fraction of empty events and correcting for detector inefficiency and wrongly reconstructed tracks; the number of inelastic interactions per event described through a Poisson distribution.
- $N_{evt}$ - number of collected events
- $L_{tot}$ - integrated luminosity

$\sigma_{acc}=62.2 \pm 0.2 \pm 2.5$ (lumi) mb
Extrapolation to full phase-space

\[ \sigma_{inel} = F_T \sigma_{acc} = \sum_x \sigma_x \quad \text{where } x \in \{ \text{ND, SDA, SDB, DD} \} \]

\[ F_T - \text{extrapolation factor determined from generator-level simulations} \]

\[ F_T = \frac{\sum_x \sigma_x}{\sum_x \sigma_x \nu_x} = \frac{1}{\sum_x f_x \nu_x} = 1.211 \pm 0.072 \]

fraction of inelastic cross section obtained with MC and data constraint

fraction of visible interactions with at least one prompt long-lived particle within the acc.

neglected: CEP and interference effects between different contributions
Total inelastic cross section

\[ \sigma_{\text{inel}}(\sqrt{s} = 13\text{TeV}) = 75.4 \pm 3.0(\text{exp}) \pm 4.5(\text{extr})\text{mb} \]

due to exp. unc. of the fiducial cross-section

due to the cross-section extrapolation

improved calibration of the luminosity scale:
- lumi unc. reduced from 3.5% to 1.7%
- exp. unc. reduced from 4.3% to 3.0%
- central value shifted up by 2.7%.
• Central exclusive production results with Run 1 data shows a good agreement with the theory

• The coherent differential J/ψ production cross-section, measured in bins of J/ψ rapidity in lead-lead collisions at 5 TeV and compared with theoretical predictions → more data to be studied (2018 dataset) using HeRSCHeL → reduction of the incoherent background is expected after vetoing significant energy detected in HeRSCHeL

• J/ψ and ψ(2S) central exclusive production cross-sections with 2015 dataset have been calculated in pp data with $\sqrt{s}$=13 TeV

✓ reduced level of background shows a good performance of HeRSCHeL
✓ both vector mesons agree with JMRT NLO prediction
✓ photo-production of J/ψ->deviation from power law extrapolation of HERA data

• Inelastic pp cross-section
✓ a new measurement of the inelastic pp cross-section was performed at 13 TeV and is in good agreement with the measurements by the ATLAS and TOTEM collaborations
Thanks for your attention!