Exclusive hadron and multiple hadron production in the forward acceptance

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

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Collaboration

- ≈900 physicists
- 64 universities/laboratories
- 16 countries
- >100 papers published

Physics Programme

- CP violation
- rare decays
- electroweak physics
- lepton flavour violation
- charm physics
- production and spectroscopy
- **LHCb** is dedicated for studying heavy quark flavour physics
- It is a **single arm** forward spectrometer with pseudorapidity coverage $2 < \eta < 5$
- Precise tracking system (VELO, upstream and downstream tracking stations and warm 4 Tm magnet)
- Particle identification system (RICH detectors, calorimeters and muon stations)
- Partial information from calorimeters and muon system contribute to L0 trigger (hardware) that works at LHC clock – **40 MHz**
- Full detector readout at **1 MHz**
CEP – definition

- 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 dissociation instead they interact via exchanging a colourless object and **remain intact**

- However, they **lose energy** in order to produce 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 very important probes for testing QCD
- Studying *pomeron*-γ (photo-production) interactions
  - At leading order it can be interpreted as a pair of gluons
  - Probes gluon P.D.F. at small fraction, x, of proton momentum
  - For kinematical reach of the LHCb $x \approx 5 \cdot 10^{-6}$
  - For higher mass final state X perturbative calculations viable
- Double *pomeron exchange* (pomeron-pomeron fusion)
  - Final state must be neutral – no open flavour
  - Help understand in general processes such $gg \rightarrow X$ ($gg \rightarrow H$)
  - For low mass final state mainly spectroscopy studies
  - For higher masses testing QCD and pomeron structure
- Recently also great deal of interest from theory related to QED induced processes (two photon exchange) – A. Szczurek et al. [arXiv:1409.1541]
CEP@LHCb 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)
Two of the subsystems are especially vital for the CEP studying @ LHCb (establishing the rapidity gap)

- **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
Current results on exclusive $J/\psi$ and $\psi(2S)$ production

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

- **2011 data** (~ 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
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**

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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 $y$

\[
\left( \frac{d\sigma}{dy} \right)_i = \frac{1}{\varepsilon_{single} \mathcal{L} \varepsilon_i \Delta y} \frac{pN_i}{\varepsilon_i}
\]

$p$ – Purity:
- Non-resonant background
- Feed-down background
- Inelastic background

$N_i$ – Number of events in a given rapidity bin

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

$\mathcal{L}$ – Sample integrated luminosity

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

Total efficiency varies from 0.66 to 0.89 depending on rapidity bin
Purity estimation: 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$^2$
Proposed improvement for detecting CEP events

HeRSChel – High Rapidity Shower Counters for LHCb

- System of scintillator planes
- Instrumented with photomultiplier tubes
- Dedicated to detect particle showers induced in the beam pipe
- Significant enhancement of the efficiency to identifying rapidity gaps
- A huge step forward for CEP studies in LHCb
- Ready for Run II
Cross section measurement

- Integrated cross-sections

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

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

- Differential cross-sections

![Graph of J/ψ](a)  

![Graph of ψ(2S)](b)
Integrated cross section measurement

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

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**J/ψ**

- Goncalves and Machado
- Jones, Martin, Ryskin, Teubner
- Motyka and Watt
- Schaefer and Szczurek
- STARLIGHT (Klein,Nystrom)
- SUPERCHIC (Hartland-Lang, Khoze, Ryskin, Stirling)
- LHCb

**ψ(2S)**

- Jones, Martin, Ryskin, Teubner
- STARLIGHT
- SUPERCHIC
- LHCb

Charmonium pairs production

- Production via exchange of two pomerons
- Comparison of exclusive and inclusive J/ψ mass spectra
  - Helps to understand J/ψ pairs production
- Sensitive to exotics
- Comparison with various theoretical predictions
- Cross-sections for J/ψ J/ψ and J/ψ ψ(2S) pairs measured by LHCb
- Upper limits established for ψ(2S) ψ(2S) and X_{c(0,1,2)} X_{c(0,1,2)}
Integrated cross section measurement

\[ \sigma_{J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-} = 58 \pm 10 \pm 6 \text{ pb} \]

\[ \sigma_{J/\psi \psi(2S) \rightarrow \mu^+ \mu^- \mu^+ \mu^-} = 63^{+27}_{-18} \pm 10 \text{ pb} \]

- First observation of CEP with pairs of charmed mesons at LHCb
- Measured cross sections in reasonable agreement with theoretical predictions
Summary

- **Exclusive J/ψ and ψ(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 **3 papers**.

- Still more statistics waiting in 2012 data.

- Plans for extending analyses concerning exclusive production:
  - new particles (e.g., χc)
  - include also hadronic modes.

- **First observation** of CEP with pairs of charmed mesons at LHCb.

- Measured **integrated cross sections** for production of J/ψ J/ψ and J/ψ ψ(2S) pairs.
Back-up
- 300(H)/250(V) mrad
- Muon system
- Calorimeters
- OT – Outer Tracker
- IT – Inner Tracker
- TT – Trigger Tracker
- TT+IT (Silicon Tracker)
- Dipole magnet
- Vertex Locator
- Interaction Point
- RICH detectors

- Single arm spectrometer geometry
- Fully instrumented in rapidity range 2 < η < 5
- Capable of reconstructing backward tracks (-4 < η < -1.5)