LHCb status and perspectives
Photoproduction and diffractive processes in pp, pA and AA collisions

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on behalf of the LHCb collaboration

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1. Forward physics at LHCb

2. The LHCb detector

3. Central Exclusive Production at LHCb
   - Single charmonium  
     (J Phys G41 055002)
   - Double charmonium  
     (J Phys G41 115002)

4. LHCb prospects
   - Continuing to exploit run 1 data set
   - Increased rapidity coverage for run 2
Forward physics at LHCb: studying QCD

Hard QCD:
- Perturbative and predictive
- Abundant experimental tests

Soft QCD:
- Difficult to calculate
- Crucially important: describes bound hadrons and the vacuum!
- Many opportunities for experimental input

Many open questions:
- Study of colourless objects: pomeron, Reggeon, odderon
- Existence of glueballs?
- Gluon PDF rise violates unitarity: new QCD phenomenology at low energy (saturation?)
**Diffraction:**

- Processes mediated by colour singlet exchange between colliding hadrons, with large rapidity gaps in the final state
  - Exchange involving pomeron: probe $g(x)$
  - ... in the low-$x$ region where poorly constrained
  - ... but region of great interest: e.g. describe underlying event
  - ... and where saturation effects could contribute
  - Cross sections modified by odderon etc

- Must either tag outgoing protons or detect proton remnants

- ... requires detector coverage at $\eta > 5$!

- **LHCb instruments:**
  - $2 < \eta < 5$
  - $(-3.5 < \eta < -1.5)$

- Can exploit $pp$ and $pA$ collisions

The LHCb detector

- Downstream: $2 < \eta < 5$
- Upstream: $(-3.5 < \eta < -1.5)$
- Maximum rapidity gap 3.5 units
- Can trigger on very low $p_T$ tracks

For diffractive physics need to detect outgoing proton or fragmentation or at least detect central system including presence of rapidity gap

- All diffractive events will have a large rapidity gap
- Most pp interactions distribute particles throughout $4\pi$

**Vertex Locator and tracking system:**
B and D vertex positions and track momenta

- IP resolution: 20µm
- $\Delta p/p$: 0.4-0.6 %

**RICH detectors:**
K/π separation

- LHCb trigger reduces 40MHz $\rightarrow$ (hardware) 1MHz $\rightarrow$ (software trigger) 3 kHz
LHCb explores an unusual portion of $x - Q^2$ down to $x = 10^{-6}$

Complementary to LHC GPDs

Effectively one colliding parton in a well-understood region, one unknown

LHCb run 1 data set: 3 fb$^{-1}$ pp collisions: 1.2% precision(!) [JINST 9 12005]

- LHCb average number of interactions per bunch crossing $\sim 1.5$: ideal
- Low multiplicity required (to establish rapidity gap) so single-interaction events only

![Graph of LHC 7 TeV Kinematics]
LHCb diffractive measurements
**Central Exclusive Production at LHC**

**Interactions of the form** \( pp \rightarrow pEp \)

- **QED background:** \( 2\gamma \) exchange
  - QED process with small proton form-factor corrections

- **Pomeron exchange:**
  - Pomeron is, at leading order, a pair of gluons in ++ state

- **Photoproduction:** Photon-pomeron fusion
  - Probes gluon density at small values of proton’s momentum fraction, \( x \)
  - Perturbative calculations accessible for higher mass of \( E \)

- **Double pomeron exchange:** Pomeron-pomeron fusion
  - \( E \) must be neutral \( PC = ++ \), no net flavour: \( f_{0,2}, \chi_{c,b}, \gamma\gamma, JJ, H \)
  - Low \( M(E) \): spectroscopy studies. High \( M(E) \): QCD and the pomeron
1) Exclusive $J/\psi$ and $\psi(2S)$ production

Measurement: differential production cross-section $\frac{d\sigma}{dy}$

Selection: $J/\psi$ or $\psi(2S) \rightarrow \mu^+\mu^-$ in 930 pb$^{-1}$ 7TeV data

- Hardware trigger:
  - 1 muon with $p_T > 400$ MeV, or dimuon with each $p_T > 80$ MeV
  - Number of SPD hits < 10

- Software trigger:
  - Dimuon with mass > 2.9 GeV, or with mass < 1 GeV and $p_T < 900$ MeV and distance of closest approach < 150 mm

- Offline:
  - Two identified muons in $2 < \eta(\mu) < 4.5$
  - No photons, no other forward tracks: $\Delta y = 3.5$
  - No backward tracks: $\Delta y = 1.7$
  - Dimuon mass in 65 MeV mass window of the $J/\psi$ and $\psi(2S)$ masses.
1) Exclusive $J/\psi$ and $\psi(2S)$ production

('Empty-detector' signal)

- Fit invariant mass: isolate QED background
  - **Signal**: Crystal ball function: 56,000 $J/\psi$, 1,600 $\psi(2S)$
  - **QED background**: Exponential (1% $J/\psi$ and 17% $\psi(2S)$ contamination)
1) Exclusive $J/\psi$ and $\psi(2S)$ production

A number of peaking backgrounds remain:

- ‘Feed-down’ decays: contamination can be estimated
  - $\psi(2S) \rightarrow J\psi \pi\pi$: 2.5 ± 0.2%
  - $\chi_c \rightarrow J\psi \gamma$: 7.6 ± 0.9%
  - $X(3872) \rightarrow \psi(2S) \gamma$: 2.0 ± 2.0%

- Inelastic CEP background

These backgrounds tend to produce a $J/\psi$ or $\psi(2S)$ spectrum with harder $p_T$ distribution than the exclusive signal.
1) Exclusive $J/\psi$ and $\psi(2S)$ production

**Determining exclusive contribution**

- Fit the $p_T^2$ distribution of the $J/\psi/\psi(2S)$ candidates

**Feed-down background:** Yield and shape determined using data

**Inelastic background:** Yield and shape vary
  - $J/\psi$ slope $0.97 \pm 0.04$ and $\psi(2S)$ slope $0.8 \pm 0.2$ consistent with HERA

**Exclusive signal:** Yield and shape vary
  - Signal slope $5.7 \pm 1.1$ and $5.1 \pm 0.7$ consistent with Regge theory extrapolation of HERA data
  - Signal purity: $59 \pm 1\%$ ($J/\psi$) and $52 \pm 7\%$ ($\psi(2S)$)

**Largest systematic uncertainties arise through the description of the $p_T^2$ fit**
Interpretation

- LO and NLO\textsuperscript{1} extrapolations from HERA data have been performed
- $J/\psi$ (left) and $\psi(2S)$ (right) data are superimposed: good agreement with NLO

\textsuperscript{1}JHEP 1311 (2013) 085
2) Double charmonium production

Measurement: production cross-section

\[ pp \rightarrow p(X)p, \quad X = \{ J/\psi J/\psi, J/\psi \psi(2S), \psi(2S)\psi(2S), \chi_{ci}\chi_{ci} \} \]

Motivation

- Exchange of two pomerons
- Cross-section and mass spectrum sensitive to exotics: e.g. glueballs or tetraquarks
- Relate cross section to calculated \( \sigma(gg \rightarrow J/\psi J/\psi) \) using Durham model\(^2\)

Selection: in 3 fb\(^{-1}\) \( pp \) collisions

- Very similar to exclusive \( J/\psi / \psi(2S) \) analysis
- No additional tracks reconstructed in the VELO
- No additional photon activity
- Reconstruct \( \chi_c \rightarrow J/\psi \gamma \)

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\(^2\) Int.J.Mod.Phys. A29 (2014) 1430031
2) Double charmonium production

‘Empty-detector’ signal

(b) Dimuon mass fit

(c) Example: \( J/\psi J/\psi \) \( p_T^2 \) fit

- Cross section calculated for a range of double-charmonium states
- Largest systematic uncertainty relates to the final state geometrical acceptance (estimated for a range of values of dimeson mass, \( p_T \) and rapidity)

\[
\begin{align*}
\sigma^{J/\psi J/\psi} & = 65 \pm 11 \text{ (stat)}^{+6}_{-13} \text{ (syst)} \text{ pb}, \\
\sigma^{J/\psi \psi(2S)} & = 72^{+30}_{-20} \text{ (stat)}^{+10}_{-16} \text{ (syst)} \text{ pb}, \\
\sigma^{\psi(2S) \psi(2S)} & < 255 \text{ pb at } 90\% \text{ c.l.}, \\
\sigma^{X_{c0}X_{c0}} & < 75 \text{ nb at } 90\% \text{ c.l.}, \\
\sigma^{X_{c1}X_{c1}} & < 49 \text{ pb at } 90\% \text{ c.l.}, \\
\sigma^{X_{c2}X_{c2}} & < 150 \text{ pb at } 90\% \text{ c.l.}.
\end{align*}
\]
2) Double charmonium production

Interpretation

- First observation of CEP for pairs of charmonium mesons
- Estimate of exclusive component in ‘empty-detector’ signal is $42 \pm 13\%$
- Measurement of $\sigma(J/\psi J/\psi) = 24 \pm 9\,pb$ and $\frac{\sigma(J/\psi J/\psi(2S))}{\sigma(J/\psi J/\psi)} = 1.1^{+0.5}_{-0.4}$ in reasonably good agreement with subsequent theoretical calculation\(^3\)
- Observed $J/\psi J/\psi$ mass spectrum in good agreement with shape (independent of renormalisation/factorisation scales) from MSTW08LO

\(^3\)arXiv:1409.4785
LHCb measurement prospects
Extending LHCb rapidity coverage: Concept

- Biggest challenge currently is to establish the rapidity gap
- High proportion (50% for $J_\psi J_\psi$ CEP) of ‘empty-detector’ signal where proton dissociation escapes down the beampipe
- Expecting large run 2 data set at low pile-up

Install scintillators either side of LHCb
  - Detect showers from high rapidity particles interacting with the beam-pipe elements
Simulated energy densities in first scintillator station (LHCb simulation)

- **(a) Min-bias**
- **(b) Single-diffractive**
- **(c) CEP-like**

- Each station must be sensitive to \( \sim 100 \) hits to effectively veto single diffractive events, while tolerating \( \sim 2500 \) hits/event in minimum bias operating conditions.
- Efficiency is good even for low energy particles, beyond geometric acceptance due to showering.
Extending LHCb rapidity coverage: Installation

- The stations installed and cabled
- Commissioning tests underway
- Read-out chain maturing
Summary

Exciting opportunities for CEP studies at LHCb

- LHCb’s forward acceptance provides unique window on CEP and other diffractive physics
- Spectroscopy in a very clean environment
- QCD studies
  - very low-x gluon PDF
    - increased $\sqrt{s}$ allows probing of even lower $x$ (CEP $J/\psi \rightarrow x = 2 \times 10^{-6}$)
  - nature of pomeron
  - sensitivity to glueballs, odderons, tetraquarks
- Run 1:
  - published analyses: $J\psi/\psi(2S)$ and double-charmonium CEP
  - many more analyses would be interesting in future: $\Upsilon(1S, 2S, 3S), X(3872)$, light resonances, double open-charm, $\chi_c, \chi_b$...
  - exploit $pA$ data
- Introduction of FSCs for 2015 will greatly enhance LHCb’s CEP programme