WHY IS CENTRAL EXCLUSIVE PRODUCTION EXCITING?

Consider the elastic p-p differential cross-section

\[ \frac{d\sigma}{dt} \]

\[ |t| : \text{square of elastic scatter four-momentum transfer} \]
\[ : \text{inversely related to impact parameter, } b \]
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Large $b$ (small $t$): Coulomb scattering

TOTEM @ 7TeV
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\begin{itemize}
  \item Large $b$ (small $t$): Coulomb scattering \checkmark
  \item In between: diffractive minimum
  \item Small $b$ (high $t$): Perturbative QCD \checkmark
\end{itemize}

\textbf{TOTEM @ 7TeV}
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\[
\frac{d\sigma}{dt}
\]

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**In between: diffractive minimum**

**Large b (small t): Coulomb scattering**

**Small b (high t): Perturbative QCD**
WHY IS CENTRAL EXCLUSIVE PRODUCTION EXCITING?

Consider the elastic $p$-$p$ differential cross-section

$\frac{d\sigma}{dt}$

What is diffraction?

➤ **Soft:** low $p_T$ exchange between protons
➤ **Colourless:** does not force proton breakup

$|t|$ : square of elastic scatter four-momentum transfer

$|t|$ : inversely related to impact parameter, $b$
WHY IS CENTRAL EXCLUSIVE PRODUCTION EXCITING?

Consider the elastic $p$-$p$ differential cross-section

Why study diffraction:

- Models fail **disastrously**!
- Responsible for **40%** of total cross-section for high-energy $pp$ collisions
- Accompanies our hard processes (i.e. improve MC underlying event)

$|t|$: square of elastic scatter four-momentum transfer

$|t|$: inversely related to impact parameter, $b$
WHY IS CENTRAL EXCLUSIVE PRODUCTION EXCITING?

Consider the **gluon PDF,** \( g(x) \)

\[
\pm \frac{1}{10} \sqrt{\sum_{i=1}^{100} (\sigma(i) - \sigma(0))^2} \\
\text{NNPDF21 zmloz100}
\]

**Bjorken** \( x \): particle momentum fraction carried by the parton

\[
g(x) \quad g(x')
\]

Exploring complementary phasespace at low-\( x \)

\[
x = \frac{Q e^{\pm y}}{\sqrt{s}}
\]
WHAT DOES CEP LOOK LIKE?

To a theorist:

A diffractive, elastic scatter; production of a particle system dominantly populating the central rapidity region.
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To an LHCb experimentalist?
LHCB: A DETECTOR FOR CP

Tracking for CEP

- Silicon detector around pp interaction point
- Four downstream tracking stations:
  - silicon microstrips: TT + centre T1-3
  - straw tube drift chambers: outer T1-3

$$\eta = -\log(\tan(\theta/2))$$
LHCb: A Detector for \( \mathbb{C P} \)

**Calorimetry**
- Scintillating pad detector (charged multiplicity)
- \( N_{\text{hits}} \): 1 of the 3 LO trigger quantities!
- ECAL and HCAL

**SPD:** Event multiplicity limit

**ECAL:** Threshold for electron/photon CEP

**HCAL:** Threshold for hadron CEP
LHCB: A DETECTOR FOR \( \text{CP} \)

**Distinguishing hadrons**

- Two cherenkov detectors, before and after magnet
  - 1) \( C_4F_{10} \): track momentum 10 → 65 GeV/c
  - 2) \( CF_4 \): track momentum 15 → 100 GeV/c
- Better discrimination in ‘empty’ CEP events

**RICH: Principles**

Pattern recognition: easier for CEP!

\( \pi/K \): excellent separation
LHCb: A DETECTOR FOR CP

Trigger
- **L0**: SPD hits < 10; PU hits < 3; min e/h/μ activity
  - Orthogonal to the rest of LHCb programme
- **HLT1**: Pass-through
- **HLT2**: Tracking ($p_T > 300$ MeV/c) & dedicated selections

Luminosity
- Average number of interactions per crossing $\sim 1.5$
- ‘Empty detector’ requirements reject events with >1 int.
- “Luminosity levelling”:
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To an LHCb experimentalist:

We infer **pomeron** exchange by searching for events with **large rapidity gaps**.
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but we have tunnel vision…
**CEP PROCESSES AT LHC**

Interactions of the form $pp \rightarrow p[^{\text{exclusive}}]p$

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

**Pomeron exchange:**
- **Photoproduction: Photon-pomeron fusion**
  - Probe $g(x)$ at small Bjorken $x$
  - More perturbative at higher $[^{\text{exclusive}}]$ mass
- **Double pomeron exchange: Pomeron-pomeron fusion**
  - $[^{\text{exclusive}}]$ preferred be neutral $J^{PC}=0^{++}$; no net flavour: $f_{0,2}$, $x_{c,b}$, $\gamma\gamma$, $JJ$, $H$
1) EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION

High energy charged particles as a source of Weizsacker-Williams photons
➤ study photon-hadron interactions at unprecedented energies w.r.t. HERA
➤ one proton interacting strongly; one by photon exchange

Assume factorisation of the soft and hard strong interactions
➤ Need probability for elastic p-p rescattering : mod. indep. using LHC measurements
  ➤ smaller impact parameter ⇒ reduced survival probability
➤ Ignore saturation effects (low saturation scale)
➤ Ambiguous source of photons!

Differential cross-section (J/ψ rapidity) probes photoproduction scale, W
Selection: $J/\psi$ or $\psi(2S) \rightarrow \mu^+\mu^-$ in 930 pb$^{-1}$ $p-p$ 7 TeV data

- **Hardware trigger:**
  - Single muon $p_T > 400$ MeV/c
  - Number of SPD hits < 10

- **Software trigger:**
  - Both muons $p_T > 400$ MeV/c

- **Offline:**
  - Two identified muons in $2<\eta<4.5$
  - No photons or other forward tracks
  - No backward tracks
  - 65 MeV/c$^2$ mass window for $J/\psi$ or $\psi(2S)$
1] **EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION**

`Empty-detector` signal

- **Fit invariant mass: isolate QED background**
  - **Signal:** Crystal ball: 56,000 J/ψ; 1,600 Ψ(2S)
  - **QED background:** Exponential: 1% J/ψ; 17% Ψ(2S)
A number of peaking backgrounds remain:

➤ ‘Feed-down’ decays: contamination can be estimated

➤ $\psi(2S) \rightarrow J/\psi\pi\pi$: $2.5 \pm 0.2\%$

➤ $\chi_c \rightarrow J/\psi\gamma$: $7.6 \pm 0.9\%$

➤ $X(3872) \rightarrow \psi(2S)\gamma$: $2.0 \pm 2.0\%$

➤ Inelastic CEP background

➤ These backgrounds tend to produce $J/\psi$ or $\psi(2S)$ with **harder $p_T$ than signal**
Determining exclusive contribution

- Fit the $p_T^2$ distribution of the exclusive 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 $5.7 \pm 0.1$ and $5.1 \pm 0.7$, consistent with HERA data via Regge theory extrapolation
  - 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
1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION

Interpretation

➤ L0 and NLO extrapolations from HERA data have been performed
➤ J/ψ (left) and ψ(2S) (right) data superimposed: good agreement at NLO
1) EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION

Implications for the gluon PDF, g(x)

- Sensitive in region $x \sim 10^{-6}$
- Not used in general PDF fits yet
  - skewing effects treated using Shuvaev transform
  - $\Rightarrow$ ‘Sudakov factor’ - no extra gluon emission
- Accurate to $O(x)$
- Cross-section depends on square of $g(x)$
- Sensitivity to $g(x)$ at low $x$ demonstrated:

```latex
hep-ph/9902410
```
Motivation similar to $J/\psi$ and $\psi(2S)$

- Occurs by photoproduction
- Perturbatively calculable hard process; depends on $g(x)^2$ to $x = 1.5 \times 10^{-5}$
- Photoproduction predictions exist at LO and NLO, differ greatly at this $W$
- Compare different models for $\Upsilon$ wave function and t-channel exchange
- LHCb probes a new kinematic region ($W_\pm = \sqrt{(M_\Upsilon \sqrt{s} e^{\pm y})}$)

- Data set: 2.9 $fb^{-1}$ $pp$ collisions at $pp \sqrt{s} = 7, 8$ TeV
Selection very similar to that for J/ψ analysis

- Two well-reconstructed muons with mass 9 - 20 GeV/c^2
- No other forward or backward charged tracks

Candidate: 06:57, July 29th 2011. \( m_\Upsilon = 9457 \text{ MeV/c}^2 \) and \( p_T^2 = 0.2 \text{ GeV}^2/c^2 \)
Two-stage fitting procedure:

- Invariant mass distribution: isolate continuum dimuon production
- Determine background contamination from $\chi_b \rightarrow \Upsilon \gamma$ feed-down in data
- $p_T^2$ distribution: inelastic b.g. has harder spectrum
  - Exclusive signal and $\chi_b$ background modelled using SuperChiC

Efficiencies

- Correct using simulated samples: trigger and reconstruction: $\sim 80\%$ efficient
- Event-level requirements imply single-interaction events only: $20\%$ of data
2) EXCLUSIVE $\Upsilon(1S,2S,3S)$ PRODUCTION

Systematic uncertainties
➤ Largest uncertainties due to description of $\chi_b$ background $p_T^2$ behaviour
➤ Subdominant contribution from description of exclusive signal

Results
➤ Compare rapidity distribution with predictions at LO and NLO
➤ Extract underlying photon-proton cross-section and compare to different models
➤ NLO predictions agree well; slight preference for BG $\Upsilon$ w.f. model
Motivation

➤ Proceeds by double-pomeron fusion. Born-level prediction \(\sim 2-7\text{pb}\)

➤ Test selection rule for CEP within ‘Durham model’ \(J_z^{PC}=0^{++}\)
  ➤ 1% suppression!

➤ Shape of \(J/\psi J/\psi\) mass distribution has lower theory uncertainty
3] DOUBLE CHARMONIUM PRODUCTION

Selection:
- 3 fb\(^{-1}\) pp collisions at 7 and 8 TeV
- Trigger identical to previous analyses
- No additional VELO tracks
- No additional photon activity
- Reconstruct \(\chi_c \rightarrow J/\psi \gamma\)

One t-channel gluon participates in hard interaction, other shields colour charge
3] DOUBLE CHARMONIUM PRODUCTION

`Empty-detector’ signal

- Cross-section calculated for a range of double-charmonium states
- Largest systematic uncertainty related to final state geometrical acceptance

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

➤ First evidence for double-charmonium CEP
➤ Estimate of exclusive component is $42 \pm 13\%$
➤ Total cross-section and relative size of $J/\psi \psi(2S)$ signal agree with theory
  ➤ errors are large and theory only Born-level
➤ Observed double charmonium mass spectrum agrees with prediction
WE NEED WIDER VISION (THE ‘HERSCHEL’ PROJECT)

We infer pomeron exchange by searching for events with large rapidity gaps

...but proton dissociation or gluon emission with activity outside LHCb contaminates our samples

Run 1 solution: fit $p_T^2$ distribution e.g.

~50% not CEP

- Fit can be model dependent
- Large biases for small samples
- Background level depends on final state

Must tag the protons or extend LHCb coverage!
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WHAT IS HERSCHEL (1/2)

Five sets of scintillators, in the tunnel either side of LHCb

Detect showers from high rapidity particles interacting with the beam-pipe elements
WHAT IS HERSCHEL (2/2)

Greatly increased rapidity coverage

Single Diffraction
Double Diffraction
Central Exclusive (elastic)
Central Exclusive (inelastic)
Elastic Scattering

LHCb

Pseudorapidity of parent particles

B0, B1, F1, B2, F2
**HISTORY**

- **March 2014:** Engineering Change Request
- **Spring 2014:** Fabricate scintillator panels
- **July 2014:** PMT & divider assembly
- **Summer 2014:** Hydraulic frame
- **Autumn 2014:** Scintillator calibration
- **November 2014:** Tunnel installation
- **Winter 2014:** Crate positioning
- **Jan/Feb 2015:** New read-out electronics, Grounding
- **Summer 2015:** Data-taking begins
- **September 2015:** Herschel stable & available offline!
BUILDING HERSCHEL

Manufacturing the scintillating counters

- Light-guides attached
- 2 LEDs per counter to aid calibration and to monitor ageing
- PMT calibration over range of HV and counter calibration using a cosmic stand
BUILDING HERSCHEL

Signal calibration

- Signal, after clipping, fits within 25ns
- Ample light yield: ~170 photo-electrons per MIP
- Read-out electronics changed to fix pedestal drift
BUILDING HERSCHEL

Tunnel installation

➤ Hardware fully installed and operational
➤ DAQ complete
➤ In stable state for offline analysis! $L^{-1} \sim 300 \text{ pb}^{-1}$
➤ Work to integration in the Level-0 trigger ongoing
What does our exclusive signal look like in Herschel?

Correlations between B and F sides

Correlations with the rest of LHCb
A BRIGHT FUTURE WITH HERSCHEL

We infer pomeron exchange by searching for events with large rapidity gaps

Consider exclusive process: $pp \rightarrow p + \mu \mu + p$

- LHCb rapidity gap: 2 long and no other velo tracks
- LHCb + Herschel adds $N(ADC_{HRC}) < 3\sigma_{Pedestal}$ veto

- Top priority: integrate with L0; factor $\sim 8$ reduction in CEP L0 rate
- Exclusive $J/\psi$ at 13 TeV (bg reduced by factor $\sim 3 - 4$) paper in preparation
- Herschel performance paper in preparation
CONTINUING EXPLOITATION OF RUN 1 DATA

Analyses of interest using Run 1 data

1) **Exclusive quarkonium production in p-Pb data:**
   - Weizsacker-Williams photon flux enhanced by $Z^2$
   - Photon emission ambiguity resolved

2) **Exclusive exotica production in p-p data:**
   - Pomeron exchange constrains quantum numbers of the CEP system
CONTINUING EXPLOITATION OF RUN 1 DATA

Analyses of interest using Run 1 data

3) **Double open-charm production in p-p data:**
   - Many exotic candidates in inclusive $D^{(*)}D^{(*)}$ spectroscopy
   - DD molecule, tetraquarks, ccg hybrids, conventional charmonium
     - Would not expect $X(3872) \rightarrow D^*D$ since hadronisation of the short-distance $c$ anti-$c$ pair to form loosely bound $D^*D$ state accompanied by other emission
     - If $X(3872)$ is conventional $\chi_{c1}$ then should be produced in CEP
(URGENT!) CHALLENGES

1. It is essential to include CEP in PDF fits
   ➤ CEP probes extremely low $x$; $g(x)$ poorly known
   ➤ Methods to include CEP with small systematic uncertainties are available
   ➤ PDF fitting groups are cautious!

2. Models of double open-charm production needed!
   ➤ Measurement of prompt, correlated $D^0D^0$ production absent at LHC
   ➤ No predictions or simulations exist

3. Enormous samples of exclusive continuum dimuon production are available
   ➤ Simple, calculable QED process
   ➤ Should be used to test predictions for soft-QCD survival factors & photon flux
EARLY RUN 2 DATA

Early data shows promising signals:

➤ **Di-pion candidate** in empty event

➤ **Trigger tracking thresholds reduced to** $p_T > 100$ MeV/c

➤ **Can probe low-mass glueball candidates**
EARLY RUN 2 DATA

Early data shows promising signals:

➤ **J/ψ and ψ(2S) candidates** in empty event

➤ Much greater handle on inelastic backgrounds
  ➤ main source of Run 1 background and, often, systematic uncertainty

➤ Continue to probe gluon PDF at very low $x$
An exciting two years!

➤ **Diffractive physics demands greater study!**

➤ **CEP now a well-established field for LHCb**
  ➤ demonstrated via three Run 1 publications…
  ➤ … and a number of exciting topics for Run 2

➤ **The Herschel project is a game-changer for diffractive physics at LHC(b)**