Central Exclusive Production in $p\bar{p}$ Collisions at CDF II

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DIS 2012 Bonn, Germany
What is Central Exclusive Production?

- At hadron colliders reactions with vacuum quantum number (colorless) exchange are called diffractive.
- Characterized by rapidity gaps.

- Central produced system X with intact outgoing (anti-)proton.
- Large rapidity gaps on both sides.
- Can be exchange of strongly interactive objects or purely QED (Tevatron as photon collider) or a mixture of both.
Motivation

In case of QCD process:

- $p\bar{p} \rightarrow p + X + \bar{p}$,
  $+$ denote large rapidity gap.
- QCD factorization.
- Hard process: gluon-gluon fusion.
- Soft part difficult to calculate.
- Large uncertainties; strong PDF dependency; Sudakov suppression; gap survival factor $S^2$.

✓ Motivation: Measuring CEP processes certainly constrains theoretical calculations.

- Light exclusive standard model Higgs feasible at LHC.
- Many similar processes at Tevatron can test and calibrate predictions.
Fermilab, Tevatron and CDF
CDF Forward Coverage

- **BSC-1**: $5.4 < |\eta| < 5.9$
- **Miniplug**: $3.6 < |\eta| < 5.2$
- **BSC-2/3**: $6.4 < |\eta| < 7.4 (8.0)$
- **RPS**: $0.02 < \xi < 0.1$

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**Diagram Description**

- **CDF II**
  - **DIPOLEs**
  - **QUADs**
  - **PMTs**
  - **36 circular lead plates laminated with aluminum (1/4" thick)**

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**Additional Information**

- **Erik Brücken**
- **27.3.2012**
- **DIS 2012, Bonn**
- **5/20**
Key Method - Exclusivity (1)

Selection of rapidity gap events (plots from excl. $\gamma\gamma$ study).

- Using Calorimetry + BSC’s + CLC ($|\eta| < 7.4$).
- Calorimetry split into sections.

- Defining detector noise level using data triggered by bunch crossings (zero-bias).
- Reject events with signal above noise anywhere except signal showers.

Examples: Central EM CAL and BSC-1E (4 PMT’s)

Note: non interaction sample: no tracks, no CLC hits, no muon stubs.
Key Method - Exclusivity (2)

- Efficiency estimation using zero-bias data as well.
- Efficiency: Fraction of zero-bias events passing all cuts.

Exponential fit:
Intercept = 0.98 ± 0.2, Abs. value of slope ≈ 67 ± 6 mb (consistent with $\sigma_{\text{inel}}$)
Overview of CEP Analyses done at CDF

- **QED Production**
  - ★ Exclusive $e^+ e^-$ Production
  - ★ Exclusive $\mu^+ \mu^-$ Production

- **Photoproduction**
  - ★ Exclusive $J/\Psi$ Production
  - ★ Search for Exclusive Z Production

- **Double Pomeron Exchange**
  - ★ Exclusive Dijet Production
  - ★ Exclusive Charmonium and $\chi_c$ Production
  - ★ Exclusive $\gamma\gamma$ Production
Earlier: Exclusive Dijet Production

- $\bar{p} + p \to \mathbf{P} + \mathbf{P} \to \bar{p} + JJ + p$

\[ \sigma_{JJ}^{\text{excl}}(R_{ij} > 0.8) \text{(pb)} \]

\[ E_T^{\text{jet}, 2} > E_T^{\text{min}} \]
\[ |\eta^{\text{jet}, 2}| < 2.5 \]
\[ 3.6 < \text{gap} < 5.9 \]
\[ 0.03 < \frac{E_T}{p} < 0.08 \]

Data corrected to hadron level

- $\mathcal{L}_{\text{int}} = 310 \text{ pb}^{-1}$.
- $R_{JJ} = M_{JJ} / M_X \approx 1$.
- $J_Z = 0$ rule: jets should be gg, and qq suppressed.
- At high $R_{JJ}$ heavy flavor jets suppressed relative to inclusive.
- Good agreement with KMR.

\[ F_{bc/\text{incl}}(R_{ij} < 0.4) \]

\[ E_T^{\text{jet}}(\text{RAW}) > 10 \text{ GeV}, |\eta_{\text{jet}}| < 1.5 \]

\[ R_{ij} = M_{jj} / M_X \]

Exclusion Dijet
Exclusive Dilepton
Exclusive Z
New: Exclusive $\gamma \gamma$
Earlier: Exclusive $e^+e^-$ Production

- Electron and positron each with $|\eta| < 2$ and $E_T > 5$ GeV.
- 16 events in data of 532 pb$^{-1}$
- $\sigma = 1.6^{+0.5}_{-0.3}$ (stat) $\pm 0.3$ (syst) pb.
- In good agreement with theory: $\sigma = 1.71 \pm 0.01$ pb (Lpair MC)
Earlier: Exclusive Dimuon Production

- Observation, Phys. Rev. Lett. 102, 242001 (2009)
- Many processes in the $p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p}$ study:

Figure: QED production of dimuon (left), photoproduction of $J/\Psi$ (middle), and DPE production of $\chi_c$ (right).

- Note: Additional $\gamma$ in charmonium production: $IPIP \rightarrow \chi_c \rightarrow J/\Psi + \gamma$
- $\mathcal{L}_{int} = 1.48 \text{ fb}^{-1}$. 
Exclusive $J/\Psi$ and $\Psi(2s)$ Production

$J/\Psi$ production: $243 \pm 21$ events.
- $d\sigma/dy|_{y=0} = 3.92 \pm 0.62$ nb.
- Theoretical Predictions:
  - 2.8 nb [Szczurek]
  - 2.7 nb [Klein & Nystrand]
  - 3.0 nb [Conclaves & Machado]
  - 3.4 nb [Motkya & Watt].

$\Psi(2s)$ production: $34 \pm 7$ events.
- $d\sigma/dy|_{y=0} = 0.54 \pm 0.15$ nb.
- $R = \frac{\Psi(2s)}{J/\Psi} = 0.14 \pm 0.05$
- HERA: $R = 0.166 \pm 0.012$ (similar kinematic region).
In exclusive cuts we allow additional EM tower with $E_T > 80$ MeV.

- Significant increase of events in $J/\Psi$ peak.
- Minor change in $\Psi(2s)$ peak.

$\Rightarrow$ Evidence for $\chi_c \rightarrow J/\Psi + \gamma$ production.

- $d\sigma/dy|_{y=0} = 75 \pm 14$ nb, compatible with theoretical predictions
  - 160 nb (Yuan 01)
  - 90 nb (KMR01)

- $J/\Psi$ production: +66 events.
- $\Psi(2s)$ production: +1 events.
Earlier: Search for Exclusive Z Production

- PRL 102, 222002 (2009).
- $\mathcal{L}_{int} = 2$ fb$^{-1}$.
- 0 candidates → upper limit on cross section.
- But high mass dileptons observed and cross section measured:
  $\sigma(\gamma\gamma \rightarrow l^+l^-, M_{l^+l^-} > 40$ GeV/c$^2) = 0.24^{+0.13}_{-0.10}$ pb.
- In good agreement with theory:
  $\sigma = 0.256$ pb.
New Exclusive $\gamma\gamma$: Trigger, Data and Selection

- Recorded data of 1.11fb$^{-1}$ integrated luminosity, triggered on 2 EM showers $> 2$ GeV and BSC-1 veto.
- Selection of EM object pairs plus nothing.
- EMO with $|\eta| < 1.0$ and $E_T > 2.5$ GeV.
- Filter for exclusivity (rapidity gap selection).
- Quality cuts and tracking cut.
- 2 samples:
  1. 2 EMO with good tracks $\Rightarrow 34$ $e^+e^-$ candidates.
  2. 2 EMO without any tracks $\Rightarrow 43$ $\gamma\gamma$ candidates.
**e^+e^-** Revisited - Control Study

- 1 quality track per EMO ($p_T > 1$ GeV/c).
- No bremsstrahlung
- Good check for analysis.

### Exclusive $e^+e^-$ (events) 34

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}_{\text{int}}$</td>
<td>$1.11 \pm 0.07 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>Electron pair eff.</td>
<td>$0.33 \pm 0.01 \text{(stat)} \pm 0.02 \text{(syst)}$</td>
</tr>
<tr>
<td>Exclusive eff.</td>
<td>$0.0680 \pm 0.004 \text{(syst)}$</td>
</tr>
<tr>
<td>Radiative acceptance</td>
<td>$0.42 \pm 0.08 \text{(syst)}$</td>
</tr>
<tr>
<td>Dissoc. background (events)</td>
<td>$3.8 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)}$</td>
</tr>
</tbody>
</table>

$$
\sigma_{e^+e^-,\text{exclusive}} \left|\eta(e)\right|<1, E_T(e)>2.5\text{GeV} = 2.88^{+0.57}_{-0.48} \text{(stat)} \pm 0.63 \text{(syst)} \text{ pb},
$$

compared to $3.25 \pm 0.07 \text{ pb (QED)}$.

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**CDF Run II Preliminary**

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)
New Exclusive $\gamma\gamma$: Numbers and Kinematics

- No tracks in event.
- No conversion allowed.

<table>
<thead>
<tr>
<th>Exclusive $\gamma\gamma$ (events)</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{int}}$</td>
<td>$1.11 \pm 0.07 \text{ fb}^{-1}$</td>
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<tr>
<td>Photon pair eff.</td>
<td>$0.40 \pm 0.02 \text{ (stat)} \pm 0.03 \text{ (syst)}$</td>
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<tr>
<td>Exclusive eff.</td>
<td>$0.0680 \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>Conversion acceptance</td>
<td>$0.57 \pm 0.06 \text{ (syst)}$</td>
</tr>
<tr>
<td>$\pi^0\pi^0$ background (events)</td>
<td>$0.0, &lt; 15 \text{ (95% C.L.)}$</td>
</tr>
<tr>
<td>Dissoc. backg. (events)</td>
<td>$0.14 \pm 0.14 \text{ (syst)}$</td>
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</tbody>
</table>

Note: Normalized to data. No overflow! Could be $\gamma\gamma$ or $\pi^0\pi^0$ ($\gamma\pi^0$ forbidden by C-parity).
New Exclusive $\gamma\gamma$: Background

Main background: inelastic $\gamma\gamma$ ($p$-dissociation) and possibly exclusive $\pi^0\pi^0$

- $\pi^0 \rightarrow \gamma\gamma$; $\Delta \phi_{\text{min}} = 3.1^\circ$ for $p(\pi^0) = 5$ GeV
- Reconstructing of showers in wire chambers at shower max.
- Signal to hypothesis test with composition of signal and b/g MC.
- Scaled $\gamma\gamma$ and $\pi^0\pi^0$ MC.
- Using Pearson’s $\chi^2$ methods.
- Most likely b/g fraction $= 0$; $< 34\%$ (95% CL) (15 events).
- Durham: $\pi^0\pi^0$ b/g $< 1\%$ ((KMR, Harland-Lang, arXiv:1105.1626 [hep-ph].)

![Graph](CDF Run II Preliminary)

- CDF Run II Preliminary

<table>
<thead>
<tr>
<th>Sum of CES showers</th>
<th>Data</th>
<th>$\gamma\gamma$ MC (scaled)</th>
<th>$\pi^0\pi^0$ MC (scaled)</th>
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</thead>
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$\chi^2 = 2.67$

$F_{\pi^0\pi^0} = 0.00$

$F_{\pi^0\pi^0}(95\%\text{CL}) < 0.34$

Erik Brücken 27.3.2012

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New Exclusive $\gamma\gamma$: Conclusions

<table>
<thead>
<tr>
<th>Theoretical</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{SuperCHIC}}^{</td>
<td>\eta</td>
</tr>
<tr>
<td>$\sigma_{\text{SuperCHIC}}^{</td>
<td>\eta</td>
</tr>
</tbody>
</table>

- First observation of exclusive $\gamma\gamma$ in hadron-hadron collisions.
- Measurement of the cross section of the exclusive production of two high-$E_T$ photons in hadron-hadron collisions.
- This corresponds to 1 in 25 billion inelastic collisions.
- Constraint on central exclusive Higgs if existing (produced by same mechanism).
Summary and What’s Next?

CDF II results on CEP

✓ Observation of Exclusive Dijet events → PRD 77, 052004 (2008).
✓ Observation of Exclusive $e^+ e^- → PRL 98, 112011$ (2007).
✓ Observation of Exclusive Charmonium and Dimuon → PRL 102, 242001 (2009).
✓ Search for Exclusive Z & High Mass Dilepton → PRL 102, 222002 (2009).

What next?

• Gap-X-Gap study: X being $\geq 2$hadrons, and $\chi_c \rightarrow \pi^+ \pi^-, K^+ K^-$.  
• More on exclusive $\gamma \gamma$ and $\pi^0 \pi^0$ (limit?).
• Analysis of low s scan data (300 and 900 GeV).