Aspects of Diffraction at CDF

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The Rockefeller University & The CDF Collaboration
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• Introduction
• Run I review
• Run II results
• Conclusion
Introduction

What is hadronic diffraction?

\[ \xi = \frac{\Delta p_T}{p_L} = \frac{M_X^2}{S} \leq \frac{m_\pi}{m_p} \]

Diffraction dissociation

\[ \frac{d^2\sigma}{dt dM_X^2} \]

coherence

\[ \frac{1}{M_X^2} \sim \frac{1}{\xi} \]

Diffraction and Rapidity Gaps

- Rapidity gaps are regions of rapidity devoid of particles.

- Non-diffractive interactions: Rapidity gaps are formed by multiplicity fluctuations.

- Diffractive interactions: Rapidity gaps, like diamonds, 'live for ever'.

\[ \Delta y \approx -\ln \xi = \ln s - \ln M^2 \]

From Poisson statistics:

\[ P(\Delta \eta) = e^{-\rho \Delta y} \left( \rho = \frac{dn}{dy} \right) \]

(r = particle density in rapidity space)

Gaps are exponentially suppressed.

- Large rapidity gaps are signatures for diffraction.

\[ \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \rightarrow \frac{d\sigma}{d\Delta y} \sim \text{constant} \]
The Pomeron

- Quark/gluon exchange across a rapidity gap:

  POMERON

- No particles radiated in the gap:

  The exchange is COLOR-SINGLET with quantum numbers of vacuum

- Rapidity gap formation:

  NON-PERTURBATIVE

- Diffraction probes the large distance aspects of QCD:

  POMERON ⬅️ CONFINEMENT

- PARTONIC STRUCTURE
- FACTORIZATION
Diffraction at CDF in Run I

- **Elastic scattering**
  PRD 50 (1994) 5518

- **Total cross section**
  PRD 50 (1994) 5550

- **Diffraction**

  **SOFT diffraction**
  - Control sample
    - Non-Diffractive (ND)
    - Single-Diffractive (SD)
      - PRD 50 (1994) 5535
    - Double Diffractive (DD)
      - PRL 87 (2001) 141802
    - Double Pomeron Exchange (DPE)
      - PRL to be sub’d
    - Single + Double Diffractive (SDD)
      - PRL submitted

  **HARD diffraction**
  - PRL reference
    - with roman pots
      - W 78 (1997) 2698
      - JJ 74 (1995) 855
      - JJ 85 (2000) 4217
      - JJ 79 (1997) 2636
      - JJ 80 (1998) 1156
      - b-quark 84 (2000) 232
      - JJ 81 (1998) 5278
      - J/ψ 87 (2001) 241802

  | W    | 78 (1997) 2698 |
  | JJ   | 74 (1995) 855 |
  | JJ   | 85 (2000) 4217 |
  | JJ   | 79 (1997) 2636 |
  | JJ   | 80 (1998) 1156 |
  | b-quark | 84 (2000) 232 |
  | JJ   | 81 (1998) 5278 |
  | J/ψ  | 87 (2001) 241802 |

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\[ \sigma_T = \sigma_o s^\epsilon = \sigma_o e^{\epsilon \ln s} = \sigma_o s^{\alpha_{IP}(0)-1} \]
\[ \alpha_{IP}(t) = 1 + \epsilon + \alpha't \]

Pomeron trajectory

\[
\begin{align*}
\text{TOTAL CROSS SECTION} & \\
\text{ELASTIC SCATTERING} & \\
\text{SINGLE DIFFRACTION DISSOCIATION} & \end{align*}
\]

\[ \phi \Delta y \]
\[ \Delta y' \]
\[ y \]
\[ M_x \]

\[ \Delta y = \ln s - \Delta y' \]

\[ \frac{d^2\sigma}{d\Delta y' dt} = f_{IP/p}(\Delta y, t) \times \sigma_{IP-p}(\Delta y') \]

\[ C \cdot (e^{[\epsilon + \alpha't]t} F_p(t))^2 \]

\[ \kappa \times \sigma_o e^{\epsilon \Delta y'} \]

\[ \kappa = \frac{g_{IP-IP}(t)}{\beta_{IP-p}(0)} \]

\[ \text{COLOR FACTOR} \]

\[ \text{Gap probability} \]

Renormalize to unity
KG, PLB 358(1995)379
Reggeons

\[ \sum_{i,x} \alpha_i(t) = \sum_{i,j,x} \alpha_i(t) \alpha_j(t) = \sum_{i,j,k} \alpha_i(t) \alpha_j(t) \alpha_k(t) \]

**Key players:**

- **\( IP-IP-IP \)**
  \[ \sim \frac{s^\varepsilon}{\xi^{1+\varepsilon}} \]
  \[ \sim \frac{s^{2\varepsilon}}{(M^2)^{1+\varepsilon}} \]
  \[ \sim s^{2\varepsilon} \]

- **\( IP-IP-R \)**
  \[ \sim \frac{1/\sqrt{s}}{\xi^{1+2\varepsilon+0.5}} \]
  \[ \sim \frac{s^{2\varepsilon}}{(M^2)^{1+2\varepsilon+0.5}} \]
  \[ \sim 2s^{2\varepsilon} \]

- **\( \pi-\pi-IP \)**
  \[ \sim s^\varepsilon \xi^{1+\varepsilon} \]
  \[ \sim \frac{1}{s^2} \left( M^2 \right)^{1+\varepsilon} \]
  \[ \sim s^\varepsilon \]

- **\( R-R-IP \)**
  \[ \sim s^\varepsilon \xi^\varepsilon \]
  \[ \sim \frac{1}{s} \left( M^2 \right)^{\varepsilon} \]
  \[ \sim s^\varepsilon \]

\[ \begin{align*}
\text{\( IP-IP-IP \)} & \quad \text{both rise at small} \ \xi \\
\text{but integral does not fit data;} & \\
\text{\( M^2 \)}-\text{dependence of} \ \text{IP-IP-R} & \quad \text{does not fit low-s data;}
\end{align*} \]

\[ \Rightarrow \text{KG: Renormalize} \ \text{IP-IP-IP} \]

- **\( \pi-\pi-IP \)**
  \[ \sim s^\varepsilon \xi^{1+\varepsilon} \]
  \[ \sim \frac{1}{s^2} \left( M^2 \right)^{1+\varepsilon} \]
  \[ \sim s^\varepsilon \]

- **\( R-R-IP \)**
  \[ \sim s^\varepsilon \xi^\varepsilon \]
  \[ \sim \frac{1}{s} \left( M^2 \right)^{\varepsilon} \]
  \[ \sim s^\varepsilon \]

\[ KG \ \& \ JM: \text{use renormalized} \ \text{IP-IP-IP plus} \ \pi-\pi-IP \ \text{with only} \ \xi_{IP-IP-IP} \ \text{as free parameter} \]
Soft Single Diffraction Data

\[ p(\bar{p}) + p \rightarrow p(\bar{p}) + X \]

**Total cross section**

*KG, PLB 358 (1995) 379*

\[ \sigma \sim s^{2\epsilon} \]

- Differential shape agrees with Regge
- Normalization is suppressed by factor \( \sim s^{2\epsilon} \)
- Renormalize Pomeron flux factor to unity

**Differential cross section**

*KG&JM, PRD 59 (114017) 1999*

\[ \frac{d\sigma}{dM^2} \propto \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}} \]

\[ \frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\epsilon}} \]

\( s \)-independent

**M² SCALING**
CDF Single Diffraction Data and Fits

Data versus MC
based on triple-Pomeron plus Reggeon
CDF PRD 50 (1994) 5535

Data at |t|=0.05 GeV^2
corrected for acceptance
KG&JM, PRD 59 (114017) 1999
Central and Double Gaps

- **Double diffraction**
  - Plot #Events versus $\Delta \eta$

- **Double Pomeron Exchange**
  - Measure
    $$\xi_p = \frac{1}{\sqrt{s}} \sum_{\text{all particles}} E_T^i \cdot e^{\eta_i}$$
  - Plot #Events versus $\log(\xi)$

- **SDD: single+double diffraction**
  - Central gaps in SD events

\[ \begin{align*}
\bar{p} & \quad \text{IP} \quad p \\
M_1 & \quad M_2 \\
\eta_{\min} & \quad \eta_{\max} \\
\text{ln } M_1 & \quad \text{ln } M_2
\end{align*} \]
Central and Double-Gap Results

Differential shapes agree with Regge predictions

One-gap cross sections require renormalization

Two-gap/one-gap ratios are $\approx \kappa \approx 0.17$
Soft Double Pomeron Exchange

CDF Preliminary

$$\sqrt{s} = 1800 \text{ GeV}$$

$$0.035 \leq \xi_p \leq 0.095$$

$$|t_p| \leq 1.0 \text{ GeV}^2$$

$$(1/\xi) \times \text{Number of Events per } \Delta \log \xi = 0.1$$

Data

DPE MC

SD MC

DPE+SD MC
Two-Gap Diffraction (hep-ph/0205141)

\[ \frac{d^7 \sigma}{\prod_{i=1}^{7} dV_i} = C \times \prod \left\{ e^{(\epsilon + \alpha' t_i) \Delta y_i} F_p(t_1) \right\}^2 \times \kappa^2 \left\{ \sigma_o e^{\epsilon (\Delta y'_1 + \Delta y'_2)} \right\} \]

Gap probability

Sub-energy cross section (for regions with particles)

Integral \( \sim s^{2\epsilon} \) \( \sim e^{2\epsilon \Delta y} \)

Renormalization removes the s-dependence \( \rightarrow \) SCALING

7 independent variables

\( \begin{align*}
\Delta y_1 & \quad \Delta y'_1 \\
\Delta y_2 & \quad \Delta y'_2 \\
y_1 & \quad y'_1 \\
y_2 & \quad y'_2 \\
t_1 & \quad \Delta y = \Delta y_1 + \Delta y_2 \\
t_2
\end{align*} \)
Multigap Diffraction (hep-ph/0205141)

Renormalize gap probability to calculate multigap cross sections

\[ f(\Delta y, t) \propto e^{(\epsilon + \alpha' t) \Delta y} \]

- \( f(\Delta y, t) \) Amplitude
- \( f(\Delta y, t) \) Amplitude
- \( f(\Delta y, t) \) Amplitude
- \( f(\Delta y, t) \) Amplitude
- \( f(\Delta y, t) \) Amplitude

\[ \Delta y_1 \quad \Delta y'_1 \quad \Delta y_2 \quad \Delta y'_2 \quad \Delta y_3 \quad \Delta y'_3 \quad \Delta y_4 \quad \Delta y'_4 \]

\[ y'_1 \quad y_2 \quad y'_2 \quad y_3 \quad y'_3 \quad y_4 \]

- 5 region-centers
- 1 sum of all gaps
- 4 t-values

- Use amplitude at \( t=0 \) for x-section

\[ \kappa = \frac{g(t)}{\beta(t)} \approx 0.17 \]

- Use amplitude squared for gaps

- Use amplitude squared for gaps

- Use amplitude squared for gaps

\[ P_{\text{gap}} = \frac{1}{N} \prod_{i=1}^{4} \left[ e^{(\epsilon + \alpha' t_i) \Delta y_i} \right]^2 \times [F_p(t_1) F_p(t_4)]^2 \]

- Use amplitude squared for gaps

- Use amplitude squared for gaps

- Use amplitude squared for gaps

- Use amplitude squared for gaps

\[ P_{\text{gap}} = \frac{1}{N} \times e^{2\epsilon \Delta y} \times f(V_i) |_{i=1}^{10} \]

- \( P_{\text{gap}} \) depends on sum of gaps

\[ N \propto s^{2\epsilon} \]

- Renormalization depends only on \( s \) — independent of the number of gaps!
Hard diffraction in Run I

CDF Forward Detectors

Acceptance: $0 < |t| < 1$, $0.03 < \xi < 0.1$

CDF Detector

- BBC 3.2<\eta<5.9
- FCAL 2.4<\eta<4.2

Diffractive dijets

Scintillator fiber xy-tracker
270 \mu m pitch, 2 m lever arm

DIPOLE MAGNETS

x<0.97

x=1

Rapidity gaps

Antiproton tag

CDF

\bar{p}

\eta = 0

\eta = 0.9

\eta = 2.4

\eta = 4.2

0

5

10

15

20

25

30

35

TOWERS

NUMBER OF EVENTS

FCAL

BBC

Acceptance: 0 < |t| < 1, 0.03 < \xi < 0.1
Hard Diffraction Using Rapidity Gaps

- **SINGLE DIFFRACTION**
  \[ \overline{p}p \rightarrow X + \text{gap} \]
  SD/ND gap fraction (%) at 1800 GeV

<table>
<thead>
<tr>
<th>( X )</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W )</td>
<td>1.15 (0.55)</td>
<td></td>
</tr>
<tr>
<td>( JJ )</td>
<td>0.75 (0.10)</td>
<td>0.65 (0.04)</td>
</tr>
<tr>
<td>( b )</td>
<td>0.62 (0.25)</td>
<td></td>
</tr>
<tr>
<td>( J/\psi )</td>
<td>1.45 (0.25)</td>
<td></td>
</tr>
</tbody>
</table>

- **DOUBLE DIFFRACTION**
  \[ \overline{p}p \rightarrow \text{Jet} - \text{gap} - \text{Jet} \]
  DD/ND gap fraction at 1800 GeV

- All SD/ND fractions ~1%
- Gluon fraction \( f_g = 0.54 \pm 0.15 \)
- Suppression by ~5 relative to HERA

Just like in ND except for the suppression due to gap formation
**Diffractive Dijets with Leading Antiproton**

**ISSUES:**
1) QCD factorization > \( F^{SD}(\xi, t, x, Q^2) \) is \( F^{SD} \) universal?
2) Regge factorization > \( F^{SD}(\xi, t, \beta, Q^2) = f_{IP-flux}(\xi, t) \times f_{IP}(\beta, Q^2) \)

\( \beta \equiv x / \xi \) momentum fraction of parton in IP

**METHOD** of measuring \( F^{SD} \):
- measure ratio \( R(\xi, t) \) of SD/ND rates for given \( \xi, t \)
- set \( R(\xi, t) = F^{SD} / F^{ND} \)
- evaluate \( F^{SD} = R \times F^{ND} \)

\( X_{Bj} \) Bjorken-x of antiproton

\[
x_{Bj} = \frac{1}{\sqrt{s}} \sum_{\# \text{jets}} E_T^i e^{-\eta^i}
\]

\( F^{ND}(x, Q^2) \) Nucleon structure function

\( F^{SD}(\xi, t, x, Q^2) \) Diffractive structure function
### Dijets in Single Diffraction

**Test QCD factorization**

\[ F_{JJ}^D (\beta) \]

Suppressed at the Tevatron relative to predictions based on HERA parton densities

**Test Regge factorization**

\[ F_{JJ}^D (\xi, \beta) = C \beta^{-n} \xi^{-m} \]

Regge factorization holds

\[ m \approx 1 \Rightarrow \text{Pomeron exchange} \]

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18
Dijets in Double Pomeron Exchange

Test of factorization

\begin{align*}
R_{SD/ND} & \\
R_{DPE/SD} & \end{align*}

\textbf{(not detected)}

\[ R^{DPE}_{SD} \approx 5 \times R^{SD}_{ND} \]

Factorization breaks down

The second gap is un-suppressed!!!
Run II Diffraction at the Tevatron

CDF Forward Detectors

 ✓ MiniPlug calorimeters \(3.5<\eta<5.5\)
 ✓ Beam Shower Counters \(5.5<\eta<7.5\)
 ✓ Antiproton Roman Pot Spectrometer
Run II Forward Detector Layout
MiniPlug Run II Data

- ADC counts in MiniPlug towers in a pbar-p event at 1960 GeV.
  - “jet” indicates an energy cluster and may be just a hadron.
  - Approximately 1000 counts = 1 GeV

Multiplicity distribution in SD and ND events
Run II Data Samples

Triggers

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>J5</td>
<td>At least one cal tower with ET &gt; 5 GeV</td>
</tr>
<tr>
<td>RP inclusive</td>
<td>Three-fold coincidence in RP trigger counters</td>
</tr>
<tr>
<td>RP+J5</td>
<td>Single Diffractive dijet candidates</td>
</tr>
<tr>
<td>RP+J5+BSC-GAP_p</td>
<td>Double Pomeron Exchange dijet candidates</td>
</tr>
</tbody>
</table>

- Results presented are from ~26 pb\(^{-1}\) of data
- The Roman Pot tracking system was not operational for these data samples
- The $\xi$ of the (anti)proton was determined from calorimeter information:

$$\xi^X = \frac{1}{\sqrt{s}} \sum_{\text{cal towers}} E_T^{i} e^{(-)+\eta^{i}}$$

(-)+ is for (anti)proton
Diffractive Dijet Sample

$\xi^X_{\frac{X}{p}}$ - distribution

CDF Run II Preliminary

- ND+SD & SD+MB overlap events

SD events

$0.03 < \xi < 0.1$

Flat region

$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \Rightarrow \frac{d\sigma}{d\log\xi} = \text{constant}$

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Diffractive Dijet Structure Function

Ratio of SD to ND dijet event rates as a function of $x_{Bj}$ compared with Run I data

No $\xi$ dependence observed within $0.03 < \xi < 0.1$ (confirms Run I result)

Ratio of SD to ND dijet event rates as a function of $x_{Bj}$ for different values of $Q^2=ET^2$

No appreciable $Q^2$ dependence observed within $100 < Q^2 < 1600$ GeV
In SD data with RP+J5 trigger select events with rapidity gap in both the BSC_p and MP_p (3.5 < \eta < 7.5)
## Data Selection

<table>
<thead>
<tr>
<th>DPE: RP+J5+BSC_GAP_p</th>
<th>DPE dijet candidates</th>
<th>Prescale=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD: RP+J5</td>
<td>Single Diffractive dijet candidates</td>
<td>Prescale=280</td>
</tr>
<tr>
<td>ND: J5</td>
<td>Tower with ET &gt; 5 GeV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cuts</th>
<th>DPE</th>
<th>SD</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triggered Events</td>
<td>397K</td>
<td>356K</td>
<td>278K</td>
</tr>
<tr>
<td>N_{\text{vertex}}(Q12) \leq 1</td>
<td>365K</td>
<td>205K</td>
<td>196K</td>
</tr>
<tr>
<td></td>
<td>347K</td>
<td>195K</td>
<td>186K</td>
</tr>
<tr>
<td>MET significance \leq 6</td>
<td>347K</td>
<td>195K</td>
<td>186K</td>
</tr>
<tr>
<td>BSC offline cut (GAP)</td>
<td>317K</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>RP offline cut (RP-Hit)</td>
<td>309K</td>
<td>193K</td>
<td>N/A</td>
</tr>
<tr>
<td>N_{\text{jets}}(R=0.7) \geq 2</td>
<td>204K</td>
<td>158K</td>
<td>160K</td>
</tr>
<tr>
<td></td>
<td>163K</td>
<td>122K</td>
<td>123K</td>
</tr>
<tr>
<td>E^{\text{jet2}}_{\text{corr}} &gt; 10 GeV</td>
<td>116,473</td>
<td>93,567</td>
<td>85,038</td>
</tr>
<tr>
<td>0.01 &lt; \xi_{\frac{X}{p}} &lt; 0.1</td>
<td>54,552</td>
<td>14,956</td>
<td>N/A</td>
</tr>
<tr>
<td>MP-East Nhite = 0</td>
<td>17,101</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
DPE Dijet Kinematics

CDF Run II Preliminary

Transverse Energy of Leading Jet

\[ \frac{1}{N_{\text{TOT}}} \frac{dN}{dE_{T}} \]

- SD\(_{p}\) : \(0.03 < \xi_{p} < 0.1\)
- GAP\(_{p}\) : \(3.6 < \eta_{\text{gap}} < 7.5\)
- \(E_{T}^{\text{jet}} > 10 \text{ GeV}\)

CDF Run II Preliminary

Mean RMS

\[ \eta^{*} = \left( \eta_{\text{jet1}} + \eta_{\text{jet2}} \right) / 2 \]

CDF Run II Preliminary

Transverse Energy of Second Leading Jet

- SD\(_{p}\) : \(0.03 < \xi_{p} < 0.1\)
- GAP\(_{p}\) : \(3.6 < \eta_{\text{gap}} < 7.5\)
- \(E_{T}^{\text{jet}} > 10 \text{ GeV}\)

CDF Run II Preliminary

\[ \frac{1}{N_{\text{TOT}}} \frac{dN}{dE_{T}} \]

- SD\(_{p}\) : \(0.03 < \xi_{p} < 0.1\)
- GAP\(_{p}\) : \(3.6 < \eta_{\text{gap}} < 7.5\)
- \(E_{T}^{\text{jet}} > 10 \text{ GeV}\)

\[ \Delta \phi = |\phi_{\text{jet1}} - \phi_{\text{jet2}}| \text{ (radian)} \]
Inclusive/Exclusive DPE Dijet Predictions

Khoze, Martin, Ryskin

Enberg, Ingelman, Timneanu

Exclusive dijets in Run I CDF kinematics
~ 1nb (factor 2 uncertainty)

Recent Calculation: ~ 60pb
(25 < E_T^jet < 35 GeV, |η_1 - η_2| < 2)

Used to normalize calculations to predict e.g., diffractive Higgs production

Boonekamp, Peschanski, Royon

Appleby, Forshaw
Limit on Exclusive DPE Dijets (Run I)

Dijet mass fraction

\[ R_{jj} = \frac{M_{jj}}{M_X} \]

\( M_{JJ} \) based on energy within cone of 0.7

\( \Rightarrow \) look for exclusive dijets in window

\( 0.7 < R_{jj} < 0.9 \)

\( \sigma(\text{inclusive}) = 44.6 \pm 4.4(\text{stat}) \pm 21.6(\text{syst}) \) nb

\( \sigma(\text{exclusive}) < 3.7 \) nb (95% CL)

Observed \( \sim 100 \) DPE dijet events

© 0.035 \( < \xi < 0.095 \)

© Jet \( E_T > 7 \) GeV

© Rapidity gap in \( 2.4 < \eta < 5.9 \)
Run II: Exclusive DPE Dijets?

CDF Run II Preliminary

\[ \text{Dijet Mass Fraction} \]
\[ SD_p : 0.03 < \xi_p < 0.1 \]
\[ E_{T}^{jet} > 10 \text{ GeV} \]

\[ R_{jj} = M_{jj} / M_x \]

No exclusive dijet bump observed

\[ |\eta_{jet1,2}| < 2.5, \ 0.03 < \xi_{p} < 0.1, \ 3.6 < \eta_{gap} < 7.5, \ R = 0.7 \]

Minimum \[ E_{T}^{jet1} \]

Cross Section: \[ \sigma_{DPE}^{excl, jj} (R_{jj} > 0.8) \]

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>$970 \pm 65$ (stat) $\pm 272$ (syst) pb</td>
</tr>
<tr>
<td>25 GeV</td>
<td>$34 \pm 5$ (stat) $\pm 10$ (syst) pb</td>
</tr>
</tbody>
</table>
Double Pomeron Exchange Dijet Events

Rjj=0.81, Jet1(2)=33.4(31.5) GeV

Rjj=0.36, Jet1(2)=36.2(33.3) GeV
SUMMARY

Soft and hard conclusions

**Soft Diffraction**

- Use the reduced energy cross section
- Pay a color factor $\kappa$ for each gap

**Hard Diffraction**

- Get gap size from renormalized $P_{\text{gap}}$

Diffraction is an interaction between low-$x$ partons subject to color constraints