Forty Years of Diffraction  
Twenty Years at the Tevatron

1960's  BNL: first observation of pp -> pX

1970's  Fermilab fixed target, ISR, SPS  
        → Regge theory & factorization


1980's  UA8: diffractive dijets  ⇒  hard diffraction

1990's  Tev Run-I:  Regge factorization breakdown
        Tev vs HERA:  QCD factorization breakdown

21st C  Multigap diffraction: restoration of factorization
        Ideal for diffractive studies @ LHC
CDF Run 1-0 (1988-89)  
Elastic, single diffractive, and total cross sections 
@ 546 and 1800 GeV  
Roman Pot Spectrometers

Roman Pot Detectors
- Scintillation trigger counters
- Wire chamber
- Double-sided silicon strip detector

Results
- Total cross section \( \sigma^{\text{tot}} \sim S^E \)
- Elastic cross section \( d\sigma/dt \sim \exp[2\alpha' \ln s] \) \( \rightarrow \) shrinking forward peak
- Single diffraction Breakdown of Regge factorization

Additional Detectors
Trackers up to \( |\eta| = 7 \)
Run 1-0 results in perspective

KG, PLB 358 (1995) 379
Total Single Diffractive x-Section

\[ \frac{d^2 \sigma_{SD}}{dt d\xi} = f_{IP/p}(t, \xi) \cdot \sigma_{IP-p}(s \xi) \]

- **Unitarity problem:**
  Using factorization and std pomeron flux \( \sigma_{SD} \) exceeds \( \sigma_T \) at \( \sqrt{s} \approx 2 \text{ TeV} \).

- **Renormalization:**
  Normalize the Pomeron flux to unity
  
  \[ \left( \int_{-\infty}^{\xi_{min}} \int f_{IP/p}(t, \xi) d\xi dt \right) = 1 \]

\[ \sigma_{SD} \sim s^{2\epsilon} \]

\[ KG, PLB 358 (1995) 379 \]

---

EDS 2005, 15-20 May 2005      Twenty Years of Diffraction at the Tevatron      K. Goulianos 5

Run-IC

Run-IA,B

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

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

CDF Detector

Forward Detectors
BBC  $3.2 < \eta < 5.9$
FCAL  $2.4 < \eta < 4.2$
Diffraction at CDF in Run I

- Elastic scattering: PRD 50 (1994) 5518
- Total cross section: PRD 50 (1994) 5550
- Diffraction

**SOFT diffraction**

- Non-Diffractive (ND): PRD 50 (1994) 5535
- Single-Diffractive (SD): PRL 87 (2001) 141802
- Double Diffractive (DD): PRL 93 (2004) 141601

**HARD diffraction**

- PRL references

**with roman pots**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ</td>
<td>87 (2001) 241802</td>
<td></td>
</tr>
</tbody>
</table>
Diffractive Fractions @ CDF

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

Fraction:
SD/ND ratio
at 1800 GeV

<table>
<thead>
<tr>
<th></th>
<th>Fraction(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hd</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>1.15 (0.55)</td>
</tr>
<tr>
<td>JJ</td>
<td>0.75 (0.10)</td>
</tr>
<tr>
<td>b</td>
<td>0.62 (0.25)</td>
</tr>
<tr>
<td>J/\psi</td>
<td>1.45 (0.25)</td>
</tr>
</tbody>
</table>

All ratios \( \sim 1\% \)
\( \rightarrow \) uniform suppression
\( \sim \) FACTORIZATION
Tevatron vs HERA: Breakdown of QCD Factorization

- **CDF**
- **H1**

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

- \[ H1 \text{ fit-2} \]
- \[ H1 \text{ fit-3} \]
- \[ CDF \text{ data} \]
- \[ E_T^{\text{jet}1,2} \geq 7 \text{ GeV} \]
- \[ 0.035 \leq \xi \leq 0.095 \]
- \[ |t| \leq 1.0 \text{ GeV}^2 \]

**H1**

**CDF**

**H1 2002 \( \sigma^D \) QCD Fit (prel.)**
Multigap Diffraction
(KG, hep-ph/0205141)
Elastic and Total Cross Sections

QCD expectations

The exponential rise of $\sigma_T(\Delta y')$ is due to the increase of wee partons with $\Delta y'$

(see E. Levin, An Introduction to Pomerons, Preprint DESY 98-120)

Total cross section:
power law rise with energy

$\sigma_T(s) = \sigma_o s^\epsilon = \sigma_o e^{\epsilon \Delta y'}$

Elastic cross section:
forward scattering amplitude

$\text{Im} f_{el}(s,t) \propto e^{(\epsilon + \alpha' t) \Delta y}$

$\Delta y' = \ln s$
Single Diffraction

2 independent variables: \( t, \Delta y \)

\[
\frac{d^2\sigma}{dt\,d\Delta y} = C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon + \alpha' t)\Delta y} \right\}^2 \cdot \kappa \cdot \left\{ \sigma_o \, e^{\varepsilon \Delta y'} \right\}
\]

gap probability

sub-energy x-section

Gap probability MUST be normalized to unity!

\[
k = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17
\]
The Factors $\kappa$ and $\varepsilon$

Experimentally:

$$\kappa = \frac{g_{IP-IP}}{\beta_{IP-p}} = 0.17 \pm 0.02, \quad \varepsilon = 0.104$$

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

Color factor:

$$\kappa = f_g \times \frac{1}{N_c^2 - 1} + f_q \times \frac{1}{N_c} \frac{Q^2 = 1}{4} \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18$$

Pomeron intercept:

$$\varepsilon = \lambda_g \cdot w_g + \lambda_q \cdot w_q = 0.12$$

\[\lambda_{HERA}\]

\[\lambda_{CTEQ5L}\]

\[\int_{x=1/s} f(x) dx \sim s^{\lambda}\]

$f_g$=gluon fraction  
$f_q$=quark fraction

Q$^2$ = 1 GeV$^2$
Multigap Cross Sections

\[ \frac{d^5 \sigma}{\prod dV_i} = C \times F_p^2(t_1) \prod_{i=1-2} \left\{ e^{(\varepsilon+\alpha't_i)\Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o e^{\varepsilon(\Delta y'_1+\Delta y'_2)} \right\} \]

Gap probability
\[ \int_{\Delta y,t} \sim s^{2\varepsilon} \]

Same suppression as for single gap!

Sub-energy cross section (for regions with particles)

5 independent variables

\[ \Delta y_1 \quad \Delta y'_1 \quad \Delta y_2 \quad \Delta y'_2 \]

color factors
Central and Two-Gap CDF Results

Agreement with renormalized Regge predictions

➢ One-gap cross sections are suppressed
➢ Two-gap/one-gap ratios are \( \approx \kappa = 0.17 \)
Gap Survival Probability

\[ S = \frac{S_{2\text{-gap}/1\text{-gap}}}{S_{1\text{-gap}/0\text{-gap}}} \]

\[ S_{2\text{-gap}/1\text{-gap}} (1800 \text{ GeV}) \approx 0.23 \]

\[ S_{2\text{-gap}/1\text{-gap}} (630 \text{ GeV}) \approx 0.29 \]

Results similar to predictions by:
Gotsman-Levin-Maor
Kaidalov-Khoze-Martin-Ryskin
Soft color interactions
**Diffractive DIS @ HERA**

Factorization holds: J. Collins

**Pomeron exchange**

\[ p \xrightarrow{\gamma^*} e \quad \text{IP} \xrightarrow{\xi, t} \]

**Color reorganization**

\[ p \xrightarrow{\gamma^*} e \quad \text{reorganize} \]

\[ F_2^{D(3)}(\xi, x, Q^2) \propto f_q(\xi, Q^2 = m_{\text{hadron}}^2) \cdot F_2(x, Q^2) \]

Brodsky et al. rescattering?
Inclusive vs Diffractive DIS

\[
F_2^{D(3)}(\xi, \beta, Q^2) \begin{array}{l}
\xi \leq 0.05 \\
\sum_{q,R} \frac{1}{\xi^{1+\epsilon_{q,R}}} \cdot C_{Q^2} \cdot \frac{1}{\lambda \cdot Q^2} \cdot \sum_{q,R} \frac{1}{\xi^{1+\epsilon_{q,R}+\lambda \cdot Q^2}} \cdot C_{Q^2} \\
\end{array}
\]

\[\sim x^{-\lambda}\]

\[\alpha_p(0)-1 \quad (\epsilon_q+\lambda)/2\]

Diffractive Dijets @ Tevatron

\[ F^D(\xi, x, Q^2) \propto \frac{1}{\xi^{1+2\varepsilon_{soft}}} \cdot F(x/\xi, Q^2) \]
$F^D_{JJ}(\xi, \beta, Q^2) @ Tevatron$

$$F^D(\xi, \beta, Q^2) = N_{\text{renorm}} \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C(Q^2)}{(x/\xi)^{2\lambda(Q^2)}} = \left(\frac{2\varepsilon}{(\beta s)^2} \right) \cdot \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C(Q^2)}{\beta^{2\lambda(Q^2)}}$$

$$N_{\text{renorm}}^{-1} = \int_{\xi_{\text{min}}}^{1} \frac{d\xi}{\xi^{1+2\varepsilon}} \xrightarrow{\xi_{\text{min}}=\frac{x_{\text{min}}}{\beta s}} \approx \frac{1}{\beta s} \cdot \left(\frac{\beta s}{2\varepsilon}\right)$$

RENORM \Rightarrow R^{SD\ SD}_{\text{ND}}(x) = \frac{2\varepsilon}{s^{2\varepsilon}} \cdot \frac{1}{\xi^{1-\lambda(Q^2)}} \cdot x - (2\varepsilon)

$\varepsilon_g = 0.2 \rightarrow x^{-0.4}$
SD/ND Dijet Ratio vs $x_{Bj}$ @ CDF

$R(x) = \frac{F_{jj}^{SD}(x)}{F_{jj}^{ND}(x)}$

$\langle \xi \rangle = 0.04, 0.05, 0.06, 0.07, 0.08, 0.09$

$\Delta \xi = 0.01$

$E_{T_{jet1,2}} > 7 \text{ GeV}$

$|t| < 1.0 \text{ GeV}^2$

Stat. errors only

$\beta = 0.5$

Flat $\xi$ dependence

$0.035 < \xi < 0.095$

$R(x) = x^{-0.45}$
Restoring Factorization @ Tevatron

DSF from two/one gap: factorization restored!
Gap Between Jets

\( \bar{p} + p \rightarrow \text{Jet} + \text{Gap} + \text{Jet} \)

\[ R^{J-G-J}_{\text{TEV}}(s') \approx 1\% \]

\[ R^{J-G-J}_{\text{LHC}}(s') = \frac{R^{J-G-J}_{\text{TEV}}}{S} \approx \frac{1\%}{0.2} \approx 5\% \]
Gap Between Jets

Is the diffractive exchange BFKL-like or simply a color rearrangement?

\[ \bar{p} + p \rightarrow \text{Jet + Gap + Jet} \]

\[ \Delta y_{\text{gap}} \]

\[ \Delta y_{\text{jet}} \]

Question

\[ \Delta y_{\text{gap}} \leftrightarrow ??? \rightarrow \Delta y_{\text{jet}} \]
Low-x and Diffraction

Derive diffractive from inclusive PDFs and color factors

\[ x \cdot f(x) = \frac{1}{x^\varepsilon(\text{or } \lambda)} \]

SOFT \( Q^2 = 1 \text{ GeV}^2 \)
- \( \varepsilon_g = 0.20 \)
- \( \varepsilon_q = 0.04 \)
- \( \varepsilon_R = -0.5 \)

HARD \( Q^2 = 75 \text{ GeV}^2 \)
- \( \lambda_g = 0.5 \)
- \( \lambda_q = 0.3 \)
Run 2 CDF Diffractive Program

- **Single Diffraction**
  - $\xi$ and $Q^2$ dependence of $F_{jj}^D$
  - Process dependence of $F^D(W, J/\psi)$

- **Double Diffraction**
  - Jet-Gap-Jet: $\Delta\eta^{\text{gap}}$ for fixed large $\Delta\eta^{\text{jet}}$

- **Double Pomeron Exchange**
  - $F_{jj}^D$ on p-side vs $\xi$-pbar

Also:

**Exclusive central production**
- Dijets, $\chi_c$

**Other**
- Tev4LHC issues
Summary

- Diffraction is a low-x QCD phenomenon subject to color constraints.
- Multigap processes offer the opportunity to study diffraction without complications arising from rapidity gap survival issues.
- Regularities observed in Run 1 at the Tevatron and in results obtained at HERA paint a picture of the Pomeron as a composite object constructed from the underlying inclusive pdf's of the (anti)proton. This picture could be further clarified and advanced to a theory by studies at the LHC.