Contents

- Introduction
- Elastic and total cross sections
- Soft diffraction
- Hard diffraction
- Exclusive Production
\( \bar{p}-p \) Interactions

**Non-diffractive:**
Color-exchange

**Diffractive:**
Colorless exchange with vacuum quantum numbers

Incident hadrons acquire color and break apart

\[ \text{CONFINEMENT} \]

Incident hadrons retain their quantum numbers remaining colorless

\[ \text{pseudo-DECONFINEMENT} \]

**Goal:** understand the QCD nature of the diffractive exchange
Diffractive $\bar{p}p$ Processes

Elastic scattering $\sigma_T=\text{Im } f_{el} (t=0)$ Total cross section

$\phi \quad \text{GAP}$

$\eta \quad \eta \quad \text{OPTICAL THEOREM}$

SD DD DPE SDD=SD+DD
CDF Run 1-0 (1988-89)

Elastic, diffractive, and total cross section
@ 546 and 1800 GeV

Roman Pot Spectrometers

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

Roman Pots with Trackers up to $|\eta| = 7$
CDF-I

Run-IC

**Dipoles**

- Recoll $\bar{P}$ Track
- Bellows

**Roman Pots**
- At 57 m

**Fiber Tracker Detail**
- 270 $\mu$m pitch, 2 m lever arm

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

---

CDF Detector

**Forward Detectors**
- **BBC** $3.2<\eta<5.9$
- **FCAL** $2.4<\eta<4.2$

---

HENALHC, 12-16 March 2007

**Diffraction from CDF to LHC**

K. Goulionos
ROMAN POT DETECTORS

BEAM SHOWER COUNTERS:
Used to reject ND events

MINIPLUG CALORIMETER
ELASTIC AND TOTAL CROSS SECTIONS

@ Tevatron: CDF and E710/811

⇒ use luminosity independent method

\[
\sigma_T^2 \sim \frac{1}{L} \left( 1 + \rho^2 \right) \frac{dN_{el}}{dt} \bigg|_{t=0} \quad \& \quad \sigma_T \sim \frac{1}{L} \left( N_{el} + N_{inel} \right)
\]

⇒ \[\sigma_T = \frac{16\pi}{1 + \rho^2} \left( \frac{dN_{el}}{dt} \bigg|_{t=0} \right) \frac{1}{N_{el} + N_{inel}}\]

Alert:

gatsby background \(N_{inel}\) yields small \(\sigma_T\)

gatsby undetected \(N_{inel}\) yields large \(\sigma_T\)
Total Cross Sections: Regge fit

CMG fit:
Covolan, Montagna, Goulianos
PLB 389 (1995) 176

Simultaneous Regge fit to pp, πp, and Kp x-sections using the eikonal approach to ensure unitarity

\[ \sigma \rightarrow s^\varepsilon \]
\[ \varepsilon = 1.104 \pm 0.002 \]

\[ \rightarrow \sigma_{LHC} = 115 \text{ mb} \]
@14 TeV
\( \sigma_T: \text{ other approaches} \)


\( \Rightarrow \) fit data using analyticity constraints
M. Block and F. Halzen, Phys. Rev. D 72, 036006

\[ \sigma_T^{(\text{LHC})} = 107.3 \pm 1.2 \text{ mb} \]

COMPETE Collaboration fits all available hadronic data and predicts:

\[ \sigma_{pp} = 111.5 \pm 1.2 \pm 4.1 \text{ mb} \]  

Recall CMG Regge fit: 115 mb
σ\text{T} and ρ-values from PDG

\[ ρ = \text{ratio of real/imaginary parts of elastic scattering amplitude at } t=0 \]

CDF and E710/811 disagree

N. Khuri and A. Martin: measuring ρ at the LHC tests discreteness of space-time
SOFT DIFFRACTION

Key words:
renormalization
scaling
QCD
multi-gap
Regge theory
σ_{SD} exceeds σ_T at \sqrt{s} \approx 2 \text{ TeV}.

Renormalization
Pomeron flux integral (re)normalized to unity

\[ \int_{t=-\infty}^{0.1} \int_{\xi_{\text{min}}}^{0} f_{\text{IP/\bar{p}}}(t, \xi) \, d\xi \, dt = 1 \]

\[ \sigma_{SD} \sim s^{2\varepsilon} \]
A Scaling Law in Diffraction

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

\( \varepsilon \equiv \Delta \)

\( \sigma \propto \frac{1}{(M^2)^{1+\Delta}} \)

\( \Delta \) Independent of \( S \) over 6 orders of magnitude in \( M^2 \)!

Factorization breaks down so as to ensure \( M^2 \)-scaling!
The QCD Connection

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

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

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

Total cross section: power law increase versus \( S \)

\[ \sim 1/\alpha_s \]

Elastic cross section: forward scattering amplitude

\[ \text{Im } f_{el}(s,t) \propto e^{(\epsilon + \alpha't)\Delta y} \]
Single Diffraction in QCD

(KG, hep-ph/0205141)

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

$\sim e^{2\varepsilon \Delta y}$

$\int_{\Delta y = \ln s}^{\Delta y_{\text{min}}} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon}$

Renormalization removes the s-dependence \(\rightarrow\)-scaling
Multi-gap Renormalization

(KG, hep-ph/0205141)

\[
\begin{align*}
\frac{d^5\sigma}{\prod_{i=1}^{5} dV_i} &= C \times F_p^2(t_1) \prod_{i=1}^{2} \left\{ e^{(\epsilon+\alpha't_i)\Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o e^{\epsilon(\Delta y'_1+\Delta y'_2)} \right\} \\
\Delta y &= \Delta y_1 + \Delta y_2
\end{align*}
\]

5 independent variables

\[\left\{ \begin{array}{c}
y'_1 \\
t_1 \\
\Delta y \\
t_2 \\
y'_2 \\
\end{array} \right.\]

Gap probability

\[\sim e^{2\epsilon \Delta y} \]

Sub-energy cross section

(for regions with particles)

\[\int_{\Delta y_{\text{min}}}^{\Delta y_{\text{max}}} \frac{2\epsilon \Delta y}{s} \approx s^{2\epsilon} \]

Same suppression as for single gap!

color factors

\[C\times F_p^2(t_1)\prod_{i=1}^{2} \left\{ e^{(\epsilon+\alpha't_i)\Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o e^{\epsilon(\Delta y'_1+\Delta y'_2)} \right\} \]
Central and Double Gaps @ CDF

- **Double Diffraction Dissociation**
  - One central gap

- **Double Pomeron Exchange**
  - Two forward gaps

- **SDD: Single+Double Diffraction**
  - One forward + one central gap
Central & Double-Gap CDF Results

Differential shapes agree with Regge predictions

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

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

\( S^{1\text{-gap}/0\text{-gap}} (1800 \text{ GeV}) \approx 0.23 \)

\( S^{2\text{-gap}/1\text{-gap}} (630 \text{ GeV}) \approx 0.29 \)

Results similar to predictions by:
Gotsman-Levin-Maor
Kaidalov-Khoze-Martin-Ryskin
Soft color interactions

\[ \sqrt{s} \] sub-energy

CDF: one-gap/no-gap
CDF: two-gap/one-gap
Regge prediction
Renorm-gap prediction
HARD DIFFRACTION

- Diffractive fractions
- Diffractive structure function → factorization breakdown
- Restoring factorization
- $Q^2$ dependence
- $t$ dependence
- Hard diffraction in QCD

$dN/d\eta$

$\eta$ →

$JJ, W, b, J/\psi$
Diffractive Fractions @ CDF

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

<table>
<thead>
<tr>
<th></th>
<th>Fraction(%)</th>
</tr>
</thead>
<tbody>
<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>

Fraction: SD/ND ratio at 1800 GeV

All ratios \( \sim 1\% \)

\( \Rightarrow \) uniform suppression

\( \sim \) FACTORIZATION!
Diffractive Structure Function: Breakdown of QCD Factorization

The diffractive structure function at the Tevatron is suppressed by a factor of ~10 relative to expectation from pdf’s measured by H1 at HERA.

Using preliminary pdf’s from H1 2002 $\sigma^D_t$ QCD Fit (prel.)

Similar suppression factor as in soft diffraction relative to Regge expectations!
Restoring QCD Factorization

The diffractive structure function measured on the proton side in events with a leading antiproton is NOT suppressed relative to predictions based on DDIS.
Diffractive Structure Function: \( Q^2 \) dependence

\[ E_T^{\text{jet}} \sim 100 \text{ GeV}! \]

Small \( Q^2 \) dependence in region \( 100 < Q^2 < 10,000 \text{ GeV}^2 \)

\( \Rightarrow \) Pomeron evolves as the proton!
Diffractive Structure Function: \( t \)-dependence

Fit \( \frac{d\sigma}{dt} \) to a double exponential:

\[
F = 0.9 \cdot e^{b_1 \cdot t} + 0.1 \cdot e^{b_2 \cdot t}
\]

- No diffraction dips
- No \( Q^2 \) dependence in slope from inclusive to \( Q^2 \sim 10^4 \text{ GeV}^2 \)
- Same slope over entire region of \( 0 < Q^2 < 4,500 \text{ GeV}^2 \) across soft and hard diffraction!
Hard Diffraction in QCD

Derive diffractive from inclusive PDFs and color factors

Deep sea
Valence quarks
Antiproton
Proton
EXCLUSIVE PRODUCTION

Measure exclusive $jj$ & $\gamma\gamma$ → → → Calibrate predictions for $H$ production rates @ LHC

C. Royon, hep-ph/0308283
B. Cox, A. Pilkington, PRD 72, 094024 (2005)

Clean discovery channel

Search for exclusive dijets:
Measure dijet mass fraction

$$R_{jj} = \frac{M_{jj}}{M_x (\text{all calorimeters})}$$

Look for signal as $M_{jj} \rightarrow 1$

Search for exclusive $\gamma\gamma$

✓ 3 candidate events found
✓ 1 (+2/-1) predicted from ExHuME MC*
✓ background under study

* See talk by V. Khoze

KMR: $\sigma_H (\text{LHC}) \sim 3$ fb
S/B \sim 1 if $\Delta M \sim 1$ GeV
Exclusive Dijet Signal

Dijet fraction - all jets

CDF Run II Preliminary

Dijet fraction – all jets

CDF+H1

Excess over MC predictions at large dijet mass fraction

b-tagged dijet fraction

CDF Run II Preliminary

DPE data (stat. only)
POMWIG : CDF+H1
- Background
- POMWIG + Background

DPE data (SVT)
Systematic Uncertainty

Exclusive b-jets are suppressed by $J_Z = 0$ selection rule

HERA&LHC, 12-16 March 2007

Diffraction from CDF to LHC

K. Goulianos
$R_{JJ}(\text{excl})$: Data vs MC

CDF Run II Preliminary

\[ F_{\text{excl}} = 15.0 \pm 1.2 \% \text{ (stat. only)} \]

- DPE data (stat. only)
- POMWIG: CDF+H1
- ExHuME
- Best Fit to Data

3.6 < |$\eta_{gap}$| < 5.9
$E_{T2} > 10 \text{ GeV}$
$E_{T3} < 5 \text{ GeV}$

ExHuME (KMR): $gg \rightarrow gg$ process

$\Rightarrow$ uses LO pQCD

Exclusive DPE (DPEMC)

$\Rightarrow$ non-pQCD based on Regge theory

Shape of excess of events at high $R_{jj}$ is well described by both models
\( jj_{\text{excl}} \): Exclusive Dijet Signal

**COMPARISON**

Inclusive data vs MC @ b/c-jet data vs inclusive
Comparison with hadron level predictions
**$J J_{\text{excl}}$: cross section predictions**

ExHuME Hadron-Level Differential Exclusive Dijet Cross Section vs Dijet Mass

(dotted/red): Default ExHuME prediction

(points): Derived from CDF Run II Preliminary excl. dijet cross sections

Statistical and systematic errors are propagated from measured cross section uncertainties using ExHuME $M_{jj}$ distribution shapes.
Summary

TEVATRON - what we have learnt

- $M^2$ - scaling
- Non-suppressed double-gap to single-gap ratios
- Pomeron: composite object made up from underlying pdf's subject to color constraints

LHC - what to do

- Elastic and total cross sections & $\rho$-value
- High mass (≥4 TeV) and multi-gap diffraction
- Exclusive production (FP420 project)
  - Reduced bgnd for std Higgs to study properties
  - Discovery channel for certain Higgs scenarios