QCD ASPECTS
OF HADRONIC DIFFRACTION

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High Energy Physics Seminar

University of Connecticut
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- CDF results
- Comparison with HERA
- QCD aspects
- Tev2LHC
What is Dark Energy?
Rapidity Gaps
Bj, PRD 47 (1993) 101: regions of (pseudo)rapidity devoid of particles

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

From Poisson statistics:

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

(\(\rho=\)particle density in rapidity space)

Gaps are exponentially suppressed

Diffractive interactions
Rapidity gaps at \(t=0\) grow with \(\Delta y\).

\[ \xi \equiv \frac{\Delta p}{p} \]

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

\[ \left( \frac{d\sigma}{d\Delta y} \right)_{t=0} \sim e^{2\varepsilon \Delta y} \]

\[ \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{(M^2)^{1+\varepsilon}} \]

2\(\varepsilon\): negative particle density!
Forty Years of Diffraction

http://physics.rockefeller.edu/dino/my.html

1960's  BNL: first observation of $pp \rightarrow pX$

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/ HERA:  QCD factorization breakdown

21st C  Multigap diffraction: restoration of factorization
         Ideal for diffractive studies @ LHC
The First 20 Years

\[ \frac{d^2 \sigma}{dt \, dM^2} \bigg|_{t=0.025} \]

\[ \xi = \frac{\Delta P_L}{P_L} \]

\[ \sigma \sim \frac{1}{\xi} \]

\[ M_X^2 \rightarrow (\text{GeV})^2 \]

\[ \ln s \]

\[ -\ln \xi \rightarrow \ln M^2 \]

\[ \Delta y \rightarrow \Delta y' \]

\[ \xi = \frac{\Delta p_L}{p_L} = \frac{M^2}{s} \]

\[ \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Leftrightarrow \frac{d\sigma}{d\Delta y} \propto \text{constant} \]

POMERON: color singlet w/vacuum quantum numbers

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The Last 20 Years

Diffraction@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)
- Double Diffractive (DD)
- Double Pomeron Exchange (DPE)
- Single + Double Diffractive (SDD)

PRL references
- (a) Gap J+Jet Jet
- (b) Jet Gap J+Jet
- (c) Gap Jet+Jet Gap

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
Diffraction in QCD

Derive diffractive from inclusive PDFs and color factors

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

\( Q^2 = 1 \text{ GeV}^2 \)

\( Q^2 = 75 \text{ GeV}^2 \)

\( \varepsilon_g = 0.20 \)

\( \varepsilon_q = 0.04 \)

\( \varepsilon_R = -0.5 \)

\( \lambda_g = 0.5 \)

\( \lambda_q = 0.3 \)
CDF in Run I-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

Additional Detectors
Trackers up to $|\eta| = 7$

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
Regge Theory

\[ T(s,t) = \frac{1}{s} \beta_1(t) \beta_2(t) S^{\alpha(t)} \phi_{a(t)} \]

\[ \sigma_T = \frac{2}{\beta(0)} S^{\alpha(0)-1} \]

Regge trajectories

Reggeon
\[ \alpha(t) = 0.5 + 0.9t \]

Pion
\[ \alpha(t) = 0 + 0.7t \]

Pomeron
\[ \alpha(t) = 1.1 + 0.25t \]
Unitarity problem:
With factorization and std pomeron flux $\sigma_{SD}$ exceeds $\sigma_T$ at $\sqrt{s} \approx 2$ TeV.

Renormalization:
normalize the pomeron flux to unity

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

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

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

KG, PLB 358 (1995) 379
A Scaling Law in Diffraction

Factorization breaks down in favor of $M^2$-scaling

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

renormalization

KG&JM, PRD 59 (1999) 114017

\[
\Delta \equiv \epsilon
\]

\[
\Delta = 0.05
\]

\[
\Delta = 0.15
\]

\[
\frac{1}{(M^2)^{1+\Delta}}
\]

renorm. flux prediction

std. and renorm. flux fits

\[
\frac{d^2\sigma}{dt dM^2} \mid_{t=0.05} (\text{mb GeV}^{-4})
\]
The QCD Connection

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

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

\[ \sim 1/\alpha_s \]

Elastic cross section forward scattering amplitude

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

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

\[
\int_{\Delta y = \ln s}^{\Delta y_{\min}} s^{2\varepsilon \Delta y} \approx s^{2\varepsilon}
\]

Renormalization removes the $s$-dependence $\rightarrow$ SCALING
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:

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

Pomeron intercept:

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

$\lambda$ HERA

$\lambda_{CTEQ5L}$

$Q^2 = 1 \text{GeV}^2$

$\lambda_g = 0.20$

$\lambda_q = 0.04$

$\lambda_R = 0.5$

$x \cdot f(x) = \frac{1}{\lambda}$

$f_g =$ gluon fraction

$f_q =$ quark fraction

$\int_{x=1/s}^{1} f(x) \, dx \sim s^{\lambda}$
Run-I A,B: Rapidity Gap Studies

Forward Detectors

BBC  3.2<\eta<5.9
FCAL  2.4<\eta<4.2
Central and Double Gaps

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

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

- **SDD: Single+Double Diffraction**
  - One forward + one central gap
Multigap Renormalization

(KG, hep-ph/0205141)

\[
\frac{d^5 \sigma}{\prod_{i=1}^{5} dV_i} = C \times \left( F_p^2 (t_1) \prod_{i=1}^{2} \left\{ e^{(\varepsilon + \alpha' t_i) \Delta y_i} \right\}^2 \right) \times \kappa^2 \left\{ \sigma_0 \ e^{\varepsilon (\Delta y'_1 + \Delta y'_2)} \right\}
\]

5 independent variables

Gap probability
\[ \sim e^{2 \varepsilon \Delta y} \]

Sub-energy cross section
(for regions with particles)

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

Same suppression as for single gap!
Central & Double-Gap Results

Differential shapes agree with Regge predictions

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

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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
Soft Diffraction Summary

Experiment:

- $M^2$ - scaling
- Non-suppressed double-gap to single-gap ratios

Phenomenology:

- Generalized renormalization
- Obtain Pomeron intercept and tripe-Pomeron coupling from inclusive PDF’s and color factors
Hard Diffraction @ CDF

- **SOFT DIFFRACTION**
  \[ \xi = \Delta P_L / P_L \]
  \[ \xi = \text{fractional momentum loss of scattered (anti)proton} \]

- **HARD DIFFRACTION**
  \[ \Delta \eta = -\ln \xi \]
  \[ \ln M_X^2 \]

Variables: \((\xi, t)\) or \((\Delta \eta, t)\)

Additional variables: \((x, Q^2)\)

\[ x_{Bj} = \sum E_T^{\text{jet}} e^{-\eta^{\text{jet}}} / \sqrt{s} \]

\[ x = \beta \xi, \quad Q^2 = (E_T^{\text{jet}})^2 \]
Diffractive Fractions @ CDF

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

SD/ND fraction at 1800 GeV

<table>
<thead>
<tr>
<th>X</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>

All fractions \(\sim 1\%\)

⇒ Factorization \(\sim\) OK @ Tevatron at fixed c.m.s. energy.
Pomeron exchange \hspace{1cm} \text{Color reorganization}

\[ F_2^{D(3)}(\xi, x, Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F_2(x, Q^2) \]
Inclusive vs Diffractive DIS


\[ F_2 \sim x^{-\lambda} \]

\[ \alpha_p(0) - 1 \]

\[ (\varepsilon_q + \lambda)/2 \]

\[ F_2^{D(3)}(\xi, \beta, Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(Q^2)}{(\beta \xi)^{\lambda(Q^2)}} \propto \frac{1}{\xi^{1+\varepsilon+\lambda}} \cdot \frac{C}{\beta^{\lambda}} \]
At fixed $x$: flat $Q^2$-dependence

At fixed $Q^2$: flat $x$-dependence
Diffractive Dijets @ Tevatron

\[ F^D(\xi, x, Q^2) \propto \frac{1}{\xi^{1+2\varepsilon}} \cdot F(x/\xi, Q^2) \]
Run-IC  

CDF-IC

Diagrams of the CDF detector setup, including components such as diode magnets, scrapers, and a 270µm pitch fiber tracker. Key acceptance parameters are noted:

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

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Roman Pot tracking

FIBER TRACKER

Reconstructed track
A bunch of fibers
True Track

Pot 3
Pot 2
Pot 1

• : measured hit position

0.255mm, (≈30µm)

0.3mm

• : Scintillating fiber
(KURARAY SCSF81 single clad)

Expected position resolution 80 µm
Expected angle resolution 60 µrad

Run 175066, Event 517876
POT-X Fiber
POT-1 POT-2 POT-3

ξ = 0.059

POT-Y Fiber
POT-1 POT-2 POT-3
Diffractive Structure F'n @CDF

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

- **Measure ratio of SD/ND dijet rates as a function of** \( x_{\bar{p}} \)
  
  \[ x_{\bar{p}} \equiv \frac{p_{g,q}/p_{\bar{p}}}{\sqrt{s}} \]

  \[ R_{SD/ND}(x_{\bar{p}}) \approx R_0 \cdot x_{\bar{p}}^{-0.45} \]

- **In LO-QCD ratio of rates equals ratio of structure fn's**

  \[ F_{jj}(x_{\bar{p}}) = x_{\bar{p}} \left[ g(x_{\bar{p}}) + \frac{C_F}{C_A} \sum (q_i(x_{\bar{p}}) + \bar{q}_i(x_{\bar{p}})) \right] \]

SD/ND Rates vs \( x_{\bar{p}} \)

- \( \langle \xi \rangle = 0.04 \ 0.05 \ 0.06 \ 0.07 \ 0.08 \ 0.09 \)
- \( \Delta \xi = 0.01 \)
- \( E_T^{jet1,2} \geq 7 \text{ GeV} \)
- \( |t| \leq 1.0 \text{ GeV}^2 \)
- stat errors only

\( x = 0.5 \times \xi_{\text{min}} \)

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\[ F_{JJ}^{D}(\xi, \beta, Q^2) @ Tevatron \]

\[ F^{D}(\xi, \beta, Q^2) \propto \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C(Q^2)}{(x/\xi)^{\lambda(Q^2)}} \propto \frac{1}{(\beta s)^{2\varepsilon}} \cdot \frac{1}{\xi^{1+2\varepsilon}} \cdot \frac{C}{\beta \lambda} \]

\[ N_{\text{renorm}}^{-1} = \int_{\xi_{\text{min}}}^{1} \frac{d\xi}{\xi^{1+2\varepsilon}} \quad \xi_{\text{min}} = \frac{x_{\text{min}}}{\beta s} \sim \frac{1}{\beta s} \rightarrow (\beta s)^{2\varepsilon} \]

\[ R_{ND}^{SD}(x) \sim \frac{1}{S^{2\varepsilon}} \cdot \frac{1}{\xi^{1 - \lambda(Q^2)}} \cdot x^{-(2\varepsilon)} \]

\[ \varepsilon_g = 0.2 \rightarrow x^{-0.4} \]
Tevatron vs HERA: Factorization Breakdown

Predicted in KG, PLB 358 (1995) 379
Restoring Factorization

R(SD/ND)

R(DPE/SD)

DSF from two/one gap: factorization restored!

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CDF-II

Tag leading $p$-bar @ $0.02 < \xi < 0.1$

Reject (retain) 95% of ND (SD) events

detect forward particles
MiniPlug Calorimeter

About 1500 wavelength shifting fibers of 1 mm dia. are 'strung' through holes drilled in 36 x 1/4” lead plates sandwiched between reflective Al sheets and guided into bunches to be viewed individually by multi-channel photomultipliers.
Artist's View of MiniPlug

84 towers

25 in → 5.5 in
Diffractive dijets

$\xi$ : momentum loss fraction of pbar

$$\xi = \frac{\sum_{\text{all towers}} E_T e^{-\eta}}{\sqrt{s}}$$

Approx. flat at $\xi < 0.1$

MP energy scale: $\pm 25\% \rightarrow \Delta \log \xi = \pm 0.1$

RP acceptance (0.03 < $\xi$ < 0.1) ~ 80% (Run I)

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ξ: RP vs calorimeter

ξ\text{cal} = (0.94 ± 0.03) ξ_{RP}

σ/mean ~ 30%

Overlap events

Signal region

ξ_{RP} distribution for slice of ξ_{RP}
Q$^2$-dependence of SD/ND ratio

- No appreciable Q$^2$ dependence within 100 < Q$^2$ < 10,000 GeV$^2$
- Pomeron evolves similarly to proton
Exclusive Dijets in DPE

Interest in diffractive Higgs production

Calibrate on exclusive dijets

Dijet mass fraction

$$R_{jj} = \frac{M_{jj}^{cone}}{M_X}$$

<table>
<thead>
<tr>
<th>$E_T^{jet}$</th>
<th>$\sigma_{DPE}^{excl , jj} (R_{jj} &gt; 0.8)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>$970 \pm 65 \pm 272 \text{ pb}$</td>
</tr>
<tr>
<td>25 GeV</td>
<td>$34 \pm 5 \pm 10 \text{ pb}$</td>
</tr>
</tbody>
</table>

Upper limit for excl DPE-jj consistent with theory: KMR $\rightarrow$ 60 pb @ $25 < E_T^{jet} < 35$ GeV

CDF Run II Preliminary

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Gap Between Jets

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

Question

\[ \Delta y_{\text{gap}} \rightarrow ??? \rightarrow \Delta y_{\text{jet}} \]

\[ R_{\text{LHC}}^{J-G-J}(s') = R_{\text{TEV}}^{J-G-J}/S \approx 1\%/0.2 \approx 5\% \]
## CDF2LHC

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q^2, t) dependence of DSF</td>
<td>close to ready</td>
</tr>
<tr>
<td>Exclusive $\chi_c$ production</td>
<td>close to ready</td>
</tr>
<tr>
<td>Low mass states in DPE</td>
<td>need good trigger</td>
</tr>
<tr>
<td>Exclusive b-bbar production in DPE</td>
<td>need b-trigger</td>
</tr>
<tr>
<td>$\xi$-dependence of DSF</td>
<td>need low lum run</td>
</tr>
<tr>
<td>Jet-gap-Jet w/jets in miniplugs</td>
<td>need low lum run</td>
</tr>
</tbody>
</table>

$$\Delta y^{\text{gap}} = \Delta y^{\text{jet}} \Rightarrow \text{BFKL}$$

$$\Delta y^{\text{gap}} \neq \Delta y^{\text{jet}} \Rightarrow \text{composite}$$
Summary

**SOFT DIFFRACTION**
- $M^2$-scaling
- Non-suppressed double-gap to single-gap ratios

**HARD DIFFRACTION**
- Flavor-independent SD/ND ratio
- Little or no $Q^2$-dependence in SD/ND ratio

✓ Universality of gap prob. across soft and hard diffraction
✓ Pomeron evolves similarly to proton

Diffraction appears to be a low-$x$ partonic exchange subject to color constraints