Diffraction, saturation and $pp$ cross sections at the LHC

Moriond QCD and High Energy Interactions
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(member of CDF and CMS)
CONTENTS

- Introduction
- Diffractive cross sections
- The total, elastic, and inelastic cross sections
- Monte Carlo strategy for the LHC
- Conclusions
Why study diffraction?

Two reasons: one fundamental / one practical.

- **fundamental**

  - measure $\sigma_T$ & $\rho$-value at LHC:
  - check for violation of dispersion relations
  - → sign for new physics
  - Bourrely, C., Khuri, N.N., Martin, A., Soffer, J., Wu, T.T
  - [http://en.scientificcommons.org/16731756](http://en.scientificcommons.org/16731756)

- **practical**: underlying event (UE), triggers, calibrations

  → the UE affects all physics studies at the LHC

NEED ROBUST MC SIMULATION OF SOFT PHYSICS
MC simulations:
Pandora’s box was unlocked at the LHC!

- Presently available MCs based on pre-LHC data were found to be inadequate for LHC
- MC tunes: the “evils of the world” were released from Pandora’s box at the LHC

... but fortunately, hope remained in the box
→ a good starting point for this talk

Pandora's box is an artifact in Greek mythology, taken from the myth of Pandora's creation around line 60 of Hesiod's *Works And Days*. The "box" was actually a large jar (πιθος *pithos*) given to Pandora (Πανδώρα) ("all-gifted"), which contained all the evils of the world. When Pandora opened the jar, the entire contents of the jar were released, but for one – hope. 

*Nikipedia*
Diffractive gaps

**definition:** gaps not exponentially suppressed

\[ \xi \approx \frac{M_x^2}{s} \]

\[ \frac{d\sigma}{d\Delta\eta} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi} \]
Diffractive p\bar p-p studies @ CDF

Elastic scattering

$\sigma_T = \text{Im } f_{el} (t=0)$

Total cross section

$\phi$ GAP $\eta$

OPTICAL THEOREM

$\phi$ $\eta$

SD

DD

DPE

SDD = SD + DD

Diffraction, saturation, and pp cross sections at the LHC

K. Goulianos
### Basic and combined diffractive processes

<table>
<thead>
<tr>
<th>acronym</th>
<th>basic diffractive processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SD}_{\bar{p}}$</td>
<td>$\bar{p}p \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p]$,</td>
</tr>
<tr>
<td>$\text{SD}_p$</td>
<td>$p\bar{p} \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p$,</td>
</tr>
<tr>
<td>DD</td>
<td>$p\bar{p} \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + [p \rightarrow X_p]$,</td>
</tr>
<tr>
<td>DPE</td>
<td>$\bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + p$,</td>
</tr>
<tr>
<td></td>
<td>2-gap combinations of SD and DD</td>
</tr>
<tr>
<td>$\text{SDD}_{\bar{p}}$</td>
<td>$p\bar{p} \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + [p \rightarrow X_p]$,</td>
</tr>
<tr>
<td>$\text{SDD}_p$</td>
<td>$p\bar{p} \rightarrow [\bar{p} \rightarrow X_{\bar{p}}]\text{gap} + X_c + \text{gap} + p$.</td>
</tr>
</tbody>
</table>

#### a 4-gap diffractive process

\[
\begin{align*}
\Delta\eta_1 & \quad \Delta\eta'_1 & \quad \Delta\eta_2 & \quad \Delta\eta'_2 & \quad \Delta\eta_3 & \quad \Delta\eta'_3 & \quad \Delta\eta_4 \\
\end{align*}
\]

\[
\begin{align*}
\eta'_1 & \quad \eta_2 & \quad \eta'_2 & \quad \eta_3 & \quad \eta'_3 \\
t_1 & \quad t_2 & \quad t_3 & \quad t_4 \\
\end{align*}
\]
Regge theory – values of $s_0$ & $g$?


\[
\sigma_T = \beta_1(0) \beta_2(0) \left( \frac{S}{s_0} \right)^{\alpha(0)-1} = \sigma_0^{p\bar{p}} \left( \frac{S}{s_0} \right)^{\epsilon} \\
\frac{d\sigma_{el}}{dt} = \frac{\beta_1^2(t) \beta_2^2(t)}{16\pi} \left( \frac{S}{s_0} \right)^{2(\alpha(t)-1)} = \frac{\sigma_T^2}{16\pi} \frac{s}{s_0} F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s) t} \\
F^4(t) \approx e^{b_{0,el} t} \Rightarrow b_{el}(s) = b_{0,el} + 2 \alpha' \ln \left( \frac{s}{s_0} \right)
\]

**Parameters:**
- $s_0$, $s_0'$, and $g(t)$
- set $s_0' = s_0$ (universal $IP$)
- determine $s_0$ and $g_{PPP}$ – how?

\[
\frac{d^2\sigma_{sd}}{dt d\xi} = \frac{\beta_1^2(t)}{16\pi} \xi^{1-2\alpha(t)} \left[ \beta_2(0) g(t) \left( \frac{s'}{s_0'} \right)^{\alpha(0)-1} \right]
\]

\[
= f_{P/p}(\xi, t) \sigma_T^{p\bar{p}}(s', t)
\]
A complication … \(\Rightarrow\) Unitarity!

\[
\left( \frac{d\sigma_{el}}{dt} \right)_{t=0} \sim \left( \frac{s}{s_0} \right)^{2\epsilon}, \quad \sigma_t \sim \left( \frac{s}{s_0} \right)\epsilon, \quad \sigma_{sd} \sim \left( \frac{s}{s_0} \right)^{2\epsilon}
\]

\(d\sigma/dt\) \(\sigma_{sd}\) grows faster than \(\sigma_t\) as \(s\) increases
\(\Rightarrow\) unitarity violation at high \(s\)
(similarly for partial x-sections in impact parameter space)

\(\Rightarrow\) the unitarity limit is already reached at \(\sqrt{s} \sim 2\) TeV
\( \sigma_{SD}^{T} \text{ vs } \sigma_{T} \text{ (pp & \bar{pp})} \)

\( \Rightarrow \) suppressed relative to Regge for \( \sqrt{s} > 22 \text{ GeV} \)

\( \sigma_{T} \) and \( \sigma_{SD}^{T} \) vs \( \sqrt{s} \) (GeV)

- \( \xi < 0.05 \)
- Albrow et al.
- Armitage et al.
- UA4
- CDF
- E710
- Cool et al.

Standard flux

Renormalized flux

**Factor of \( \sim 8 \text{ (~5) suppression at } \sqrt{s} = 1800 \text{ (540) GeV} \)**

**RENORMALIZATION MODEL**

KG, PLB 358, 379 (1995)

CDF Run I results

\( \sqrt{s} = 22 \text{ GeV} \)

\( 540 \text{ GeV} \)

\( 1800 \text{ GeV} \)
Single diffraction renormalized – (1)

\[ \kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17 \]

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

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

Gap probability \( \Rightarrow \) (re)normalize to unity

KG \( \Rightarrow \) CORFU-2001: hep-ph/0203141

Single diffraction renormalized – (2)

\[ \kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17 \]

**Experimentally:**

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

**QCD:**

\[ \kappa = f_g \times \frac{1}{N_c^2 - 1} + f_q \times \frac{1}{N_c} \]

\[\frac{Q^2}{1} = 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18\]
Single diffraction renormalized - (3)

\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} = \left[ \frac{\sigma_\circ}{16\pi} \sigma_{IPp}^{\circ} \right] \frac{s^{2\epsilon}}{N(s, s_0)} \frac{e^{bt}}{(M^2)^{1+\epsilon}}
\]

\[
b = b_0 + 2\alpha' \ln \frac{s}{M^2} \quad s_0^{\text{CMG}} = (3.7 \pm 1.5) \text{ GeV}^2
\]

\[
N(s, s_0) \equiv \int_{\xi_{\text{min}}}^{\xi_{\text{max}}} \int_{t=0}^{-\infty} d\xi \int_{0}^{\infty} dt f_{IP/p}(\xi, t) s \to \infty \sim s_0^\epsilon s^{2\epsilon} \frac{e^{bt}}{\ln s}
\]

\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} \xrightarrow{s \to \infty} \sim \ln s \frac{e^{bt}}{(M^2)^{1+\epsilon}}
\]

\[
\sigma_{sd} \xrightarrow{s \to \infty} \sim \frac{\ln s}{b \to \ln s} \Rightarrow \text{const}
\]
Single diffraction renormalized – (4)

\[ \frac{d^2 \sigma}{dt \, d\Delta y} = N_{\text{gap}} \cdot C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon + \alpha' \tau) \Delta y} \right\}^2 \cdot \kappa \cdot \left\{ \sigma_0 \, e^{\varepsilon \Delta y'} \right\} \]

\[ N_{\text{gap}}^{-1}(s) = \int_{\Delta y, t} \text{P}_{\text{gap}}(\Delta y, t) \, d\Delta y \, dt \xrightarrow{s \to \infty} C' \cdot \frac{s^{2 \varepsilon}}{\ln s} \]

\[ \frac{d^2 \sigma}{dt \, d\Delta y} = C'' \left[ e^{\varepsilon(\Delta y - \ln s)} \cdot \ln s \right] e^{(b_0 + 2\alpha' \Delta y) t} \]

- grows slower than \( s^\varepsilon \)

→ Pumplin bound obeyed at all impact parameters
$M^2$ distribution: data

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

Independent of $S$ over 6 orders of magnitude in $M^2$

\[ \rightarrow M^2 \text{ scaling} \]

Regge data

\[ \Delta \equiv \varepsilon \]

\[ \Delta = 0.05 \]

\[ \Delta = 0.15 \]

\[ s \sim \text{ independent of } s \text{ over 6 orders of magnitude!} \]

\[ \implies \text{ factorization breaks down to ensure } M^2 \text{ scaling} \]
Scale $s_0$ and triple-pom coupling

Pomeron flux: interpret as gap probability
$\rightarrow$ set to unity: determines $g_{PPP}$ and $s_0$

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

Pomeron-proton x-section

- Two free parameters: $s_0$ and $g_{PPP}$
- Obtain product $g_{PPP} \cdot s_0^{\varepsilon/2}$ from $\sigma_{SD}$
- Renormalized Pomeron flux determines $s_0$
- Get unique solution for $g_{PPP}$

$$
g_{PPP} = 0.69 \text{ mb}^{-1/2} = 1.1 \text{ GeV}^{-1} \\
s_0 = 3.7 \pm 1.5 \text{ GeV}^2
$$

KG, PLB 358 (1995) 379
Saturation “glueball” at ISR?

Giant glueball with \( f_0(980) \) and \( f_0(1500) \) superimposed, interfering destructively and manifesting as dips (???)

Figure 8: \( M_{\pi^+\pi^-} \) spectrum in DIPE at the ISR (Axial Field Spectrometer, R807 [97, 98]). Figure from Ref. [98]. See M.G.Albrow, T.D. Goughlin, J.R. Forshaw, hep-ph>arXiv:1006.1289
Multigap cross sections, e.g. SDD

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

5 independent variables

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

\[ t_1 \quad \Delta y = \Delta y_1 + \Delta y_2 \quad t_2 \]

Gap probability

\[ \int_{\Delta y, t} \sim s^{2\varepsilon} / \ln s \]

Sub-energy cross section (for regions with particles)

Same suppression as for single gap!

KG, hep-ph/0203141

Moriond QCD 2011

Diffraction, saturation, and pp cross sections at the LHC

K. Goulianos
SDD in CDF: data vs NBR MC

http://physics.rockefeller.edu/publications.html

- Excellent agreement between data and NBR (MinBiasRockefeller) MC

\[
\frac{d^5\sigma}{dt_{\bar{p}}dt_{t}d\xi_{\bar{p}}d\Delta\eta_{0}d\eta_{c}} = \left[ \beta(t) \frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1] \ln(1/\xi)} \right]^2 \times \kappa \left[ \frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1] \Delta\eta} \right]^2 \kappa \left[ \beta^2(0) \left( \frac{s_{II}}{s_{o}} \right)^{\epsilon} \right]
\]

Moriond QCD 2011  Diffraction, saturation, and pp cross sections at the LHC  K. Goulianos  19
Multigaps: a 4-gap x-section

Presented at DIS-2005, XIII\textsuperscript{th} International Workshop on Deep Inelastic Scattering,
April 27 - May 1 2005, Madison, WI, U.S.A.

\textbf{Multigap Diffraction at LHC}

\[ \Delta \eta_1 \quad \Delta \eta'_1 \quad \Delta \eta_2 \quad \Delta \eta'_2 \quad \Delta \eta_3 \quad \Delta \eta'_3 \quad \Delta \eta_4 \]

\begin{align*}
\Delta \eta_i & = \Delta \eta'_i \\
t_1 & = \eta'_1 \\
t_2 & = \eta_2 \\
t_3 & = \eta'_3 \\
t_4 & = \eta_3
\end{align*}

10 independent variables \( t_i, \eta_i, \eta'_i, \) and \( \Delta \eta \equiv \sum_{i=1}^{4} \Delta \eta_i \)

\[ \frac{d^{10} \sigma^D}{\prod_{i=1}^{10} dV_i} = N_{gap}^{-1} F_p^2(t_1) F_p^2(t_4) \prod_{i=1}^{4} \left\{ e^{[\epsilon + \alpha' t_i] \Delta \eta_i} \right\}^2 \times \kappa^4 \left[ \sigma_0 e^\epsilon \sum_{i=1}^{3} \Delta \eta'_i \right] \]

\text{gap probability}
• Use the Froissart formula as a saturated cross section

\[ \sigma_t(s > s_F) = \sigma_t(s_F) + \frac{\pi}{m^2} \cdot \ln^2 \frac{s}{s_F} \]

• This formula should be valid above the knee in \( \sigma_{sd} \) vs. \( \sqrt{s} \) at \( \sqrt{s_F} = 22 \text{ GeV} \) (Fig. 1) and therefore valid at \( \sqrt{s} = 1800 \text{ GeV} \).

• Use \( m^2 = s_o \) in the Froissart formula multiplied by \( 1/0.389 \) to convert it to \( \text{mb}^{-1} \).

• Note that contributions from Reggeon exchanges at \( \sqrt{s} = 1800 \text{ GeV} \) are negligible, as can be verified from the global fit of Ref. [7].

• Obtain the total cross section at the LHC:

\[ \sigma_t^{\text{LHC}} = \sigma_t^{\text{CDF}} + \frac{\pi}{s_o} \cdot \left( \ln^2 \frac{s^{\text{LHC}}}{s_F} - \ln^2 \frac{s^{\text{CDF}}}{s_F} \right) \]

\[ \sqrt{s_F} = 22 \text{ GeV} \]

SUPERBALL MODEL

98 ± 8 mb at 7 TeV
109 ±12 mb at 14 TeV
Total inelastic cross section

ATLAS measurement of the total inelastic x-section

Renormalization model

<table>
<thead>
<tr>
<th>√s [TeV]</th>
<th>σ_t</th>
<th>σ_{el}</th>
<th>σ_{inel}</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>98 ± 8</td>
<td>27 ± 2</td>
<td>71 ± 6</td>
</tr>
<tr>
<td>8</td>
<td>100 ± 8</td>
<td>28 ± 2</td>
<td>72 ± 6</td>
</tr>
<tr>
<td>14</td>
<td>109 ± 12</td>
<td>32 ± 4</td>
<td>76 ± 8</td>
</tr>
</tbody>
</table>

The σ_{el} is obtained from σ_t and the ratio of el/tot

**σ^{SD} and ratio of \( \alpha'/\varepsilon \)**

PHYSICAL REVIEW D 80, 111901(R) (2009)

**Pomeron intercept and slope: A QCD connection**

Konstantin Goulianos

\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} = \left[ \frac{\sigma_\circ}{16 \pi} \sigma^{pp}_\circ \right] \frac{s^{2\varepsilon}}{N(s)} \frac{1}{(M^2)^{1+\varepsilon}} e^{bt}
\]

\[
\Rightarrow \left[ 2\alpha' e^{(\epsilon b_0)/\alpha'} \sigma^{pp}_\circ \right] \frac{\ln s^{2\varepsilon}}{(M^2)^{1+\varepsilon}} e^{bt}
\]

\[
\sigma_{pp/\bar{p}p}^{tot} = \sigma_\circ \cdot e^{\varepsilon \Delta \eta}.
\]

\[
\sigma_{sd}^\infty = 2\sigma_\circ^{pp} \exp \left[ \frac{\epsilon b_\circ}{2\alpha'} \right] = \sigma_\circ^{pp}
\]

\[
\sigma_\circ^{pp} = \beta^{pp}(0) \cdot g(t) = \kappa \sigma_\circ^{pp}
\]

\[
\kappa = \frac{f_g^{\infty}}{N_c^2 - 1} + \frac{f_q^{\infty}}{N_c}
\]

\[b_\circ = R_p^2/2 = 1/(2m_\pi^2).
\]

\[
r = \frac{\alpha'}{\varepsilon} = -\left[ 16m_\pi^2 \ln(2\kappa) \right]^{-1}
\]

\[
r_{pheno} = 3.2 \pm 0.4 \text{ (GeV/c)}^{-2}
\]

\[
r_{exp} = 0.25 \text{ (GeV/c)}^{-2}/0.08 = 3.13 \text{ (GeV/c)}^{-2}
\]
\( \sigma^{AB}(s) = X^{AB} s^\epsilon + Y^{AB} s^{-\eta} \quad \epsilon = 0.0808 \)

\[
\sigma_{\text{tot}}^{AB}(s) = \sigma_{\text{el}}^{AB}(s) + \sigma_{\text{sd}(XB)}^{AB}(s) + \sigma_{\text{sd}(AX)}^{AB}(s) + \sigma_{\text{dd}}^{AB}(s) + \sigma_{\text{nd}}^{AB}(s)
\]

\[
\frac{d\sigma_{\text{sd}(XB)}^{AB}(s)}{dt \, dM^2} = \frac{g_{3\text{IP}}}{16\pi} \beta_{A\text{IP}} \beta_{B\text{IP}}^2 \frac{1}{M^2} \exp(B_{s\text{d}(XB)t}) F_{s\text{d}}
\]

\[
\frac{d\sigma_{\text{sd}(AX)}^{AB}(s)}{dt \, dM^2} = \frac{g_{3\text{IP}}}{16\pi} \beta_{A\text{IP}}^2 \beta_{B\text{IP}} \frac{1}{M^2} \exp(B_{s\text{d}(AX)t}) F_{s\text{d}}
\]

\[
\frac{d\sigma_{\text{dd}}(s)}{dt \, dM^1_2 \, dM^2_2} = \frac{g_{3\text{IP}}^2}{16\pi} \beta_{A\text{IP}} \beta_{B\text{IP}} \frac{1}{M^1_2} \frac{1}{M^2_2} \exp(B_{dd}t) F_{dd}
\]

**some comments:**
- \( 1/M^2 \) dependence instead of \((1/M^2)^{1+\epsilon}\)
- F-factors put “by hand” – next slide
- \( B_{dd} \) contains a term added by hand - next slide
Diffraction in PYTHIA -2

\[ B_{sd(XB)}(s) = 2b_B + 2\alpha' \ln \left( \frac{s}{M^2} \right), \]
\[ B_{sd(AX)}(s) = 2b_A + 2\alpha' \ln \left( \frac{s}{M^2} \right), \]
\[ B_{dd}(s) = 2\alpha' \ln \left( e^4 + \frac{ss_0}{M_1^2 M_2^2} \right) \]

note:
- $1/M^2$ dependence
- $e^4$ factor

Fudge factors:
- suppression at kinematic limit
- kill overlapping diffractive systems in dd
- enhance low mass region

\[ F_{sd} = \left( 1 - \frac{M^2}{s} \right) \left( 1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M^2} \right), \]
\[ F_{dd} = \left( 1 - \frac{(M_1 + M_2)^2}{s} \right) \left( \frac{s m_p^2}{s m_p^2 + M_1^2 M_2^2} \right) \times \left( 1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M_1^2} \right) \left( 1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M_2^2} \right) \]
CMS: observation of Diffraction at 7 TeV

An example of a beautiful data analysis and of MC inadequacies

CMS Preliminary 2010

13: CMS inclusive single diffraction observation: data vs. MC.

• No single MC describes the data in their entirety
**Monte Carlo Strategy for the LHC**

**MONTE CARLO STRATEGY**

- $\sigma^T \to$ from SUPERBALL model
- optical theorem $\to$ $\text{Im } f_{el}(t=0)$
- dispersion relations $\to$ $\text{Re } f_{el}(t=0)$
- $\sigma_{el}$
- $\sigma_{inel}$
- differential $\sigma^{SD} \to$ from RENORM
- use *nesting* of final states (FSs) for $pp$ collisions at the $IP-p$ sub-energy $\sqrt{s'}$

---


“A new statistical description of hardonic and $e^+e^-$ multiplicity distributions“
Monte Carlo algorithm - nesting

Profile of a $pp$ inelastic collision

- no gap
- gap
- gap

$\Delta y' < \Delta y'_{\text{min}}$

$\Delta y' > \Delta y'_{\text{min}}$

generate central gap

repeat until $\Delta y' < \Delta y'_{\text{min}}$

$\ln s'$

$\eta'_c$

$\Delta y'_{\text{min}}$

final state from MC w/no-gaps

evolve every cluster similarly

EXIT

$t$
SUMMARY

- Introduction
- Diffractive cross sections
  - basic: $SD_p$, $SD_\bar{p}$, DD, DPE
  - combined: multigap x-sections
  - ND → no-gaps: final state from MC with no gaps
    - this is the only final state to be tuned
- The total, elastic, and inelastic cross sections
- Monte Carlo strategy for the LHC – use “nesting”
BACKUP
**RISING X-SECTION IN PARTON MODEL**

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

Emission spacing controlled by \( \alpha \)-strong

\( \Rightarrow \sigma_T \): power law rise with energy

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

\( \alpha' \) reflects the size of the emitted cluster,

which is controlled by \( 1/\alpha_s \) and thereby is related to \( \epsilon \)

\[ \text{Forward elastic scattering amplitude} \]

\[ \text{assume linear } t \text{-dependence} \]

\[ \text{Im } f_{el}(s, t) \propto e^{(\epsilon + \alpha' t) \Delta y} \]
Gap survival probability

\[ S = \frac{S_{1 \text{-gap}/0 \text{-gap}} (1800 \text{ GeV}) \approx 0.23}{S_{2 \text{-gap}/1 \text{-gap}} (630 \text{ GeV}) \approx 0.29} \]
Diffraction in MBR: dd in CDF

\[ \frac{d^3 \sigma_{\text{DD}}}{d \eta d M_1^2 d M_2^2} = \left[ \frac{k \beta_1^2(0)}{16 \pi} e^{2(\alpha_i - 1) \Delta \eta} \right] \left[ \kappa \beta_2^2(0) \left( \frac{s'}{s_0} \right)^\epsilon \right] \]

\[ \frac{d^2 \sigma_{\text{SD}}}{d \eta d M_1^2} \]

\[ \frac{d^2 \sigma_{\text{SD}}}{d \eta d M_2^2} \]

\[ \frac{d \sigma_{\text{el}}}{d \tau} \]

\[ s^{2\epsilon} e^{b \Delta \eta} \]

\[ (M_1^2 M_2^2)^{1+2\epsilon} \]

\[ \ln M_1^2 \]

\[ \ln M_2^2 \]

\[ \ln s \]

\[ \eta_{\text{min}} \]

\[ \eta_{\text{max}} \]

\[ \eta \]

\[ \sqrt{s} = 1800 \text{ GeV} \]

- DATA
- DD + non-DD MC
- non-DD MC

\[ \Delta \eta = \eta_{\text{max}} - \eta_{\text{min}} \]

\[ \text{events} \]

\[ \text{mb} \text{ (mb) for } \Delta \eta > 3.0 \]

\[ \sqrt{s} (\text{GeV}) \]

\[ \text{CDF} \]

\[ \text{UA5 (adjusted)} \]

\[ \text{Regge} \]

\[ \text{Renormalized gap} \]

\[ \text{renormalized} \]

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Diffraction in MBR: DPE in CDF

http://physics.rockefeller.edu/publications.html

- Excellent agreement between data and MBR
  ➔ low and high masses are correctly implemented
Dijets in $\gamma p$ at HERA from RENORM

K. Goulianos, POS (DIFF2006) 055 (p. 8)

Factor of $\sim 3$ suppression expected at $W \sim 200$ GeV (just as in pp collisions) for both direct and resolved components.
Saturation at low $Q^2$ and small-$x$

figure from a talk by Edmond Iancu
The end