Predictions of Diffraction at the LHC Compared to Experimental Results

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http://indico.cern.ch/event/icnfp2013
Total pp cross section: predicted in a unitarized parton model approach, which does not employ eikonalization and does not depend on the $\rho$-value.

Diffractive cross sections:
- SD - single dissociation: one of the protons dissociates.
- DD - double dissociation: both protons dissociate.
- CD – central diffraction: neither proton dissociates, but there is central diffractive production of particles.

Triple-Pomeron coupling: uniquely determined.

This is an updated version of a talk presented at EDS-2013.
DIFFRACTION IN QCD

Non-diffractive events

- color-exchange $\Rightarrow$ $\eta$-gaps exponentially suppressed

Diffractive events

- Colorless vacuum exchange $\Rightarrow$ $\eta$-gaps not suppressed

Goal: probe the QCD nature of the diffractive exchange
DEFINITIONS

SINGLE DIFFRACTION

\[ 1 - x_L \equiv \xi = \frac{M_X^2}{s} \]

Forward momentum loss

\[ \xi_{\text{CAL}} = \sum_{i=1}^{\text{all}} E_{i-tower} e^{-\eta_i} \]

since no radiation \( \rightarrow \) no price paid for increasing diffractive-gap width

\[ \left( \frac{d\sigma}{d\Delta \eta} \right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \Rightarrow \frac{d\sigma}{dM^2} \propto \frac{1}{M^2} \]
DIFFRACTION AT CDF

Elastic scattering

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

Total cross section

Optical Theorem

SD
Single Diffraction or Single Dissociation

DD
Double Diffraction or Double Dissociation

DPE/CD
Double Pom. Exchange or Central Dissociation

SDD
Single + Double Diffraction (SDD)

$\bar{p}$

$p$

$\bar{p} + p \rightarrow JJ, b, J/\psi, W$

exclusive $JJ...ee...\mu\mu...\gamma$

Predictions of Diffraction at the LHC

K. Goulianos
Basic and combined diffractive processes

<table>
<thead>
<tr>
<th>acronym</th>
<th>basic diffractive processes</th>
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<tbody>
<tr>
<td>SDp</td>
<td>$\bar{p}p \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p]$,</td>
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<tr>
<td>SDp</td>
<td>$\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p$,</td>
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<tr>
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<tr>
<td>DPE</td>
<td>$\bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + p$,</td>
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<td>2-gap combinations of SD and DD</td>
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<tr>
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Regge theory – values of $s_0$ & $g_{PPP}$?

\[ \alpha(t) = \alpha(0) + \alpha't \quad \alpha(0) = 1 + \varepsilon \]

\[ \sigma_T = \beta_1(0) \beta_2(0) \left( \frac{s}{s_0} \right)^{\alpha(0)-1} = \sigma_{0P}^{\tilde{p}} \left( \frac{s}{s_0} \right)^e \]  

\[ \frac{d\sigma_{el}}{dt} = \frac{\beta_1^2(t) \beta_2^2(t)}{16\pi} \left( \frac{s}{s_0} \right)^{2[\alpha(t)-1]} \]

\[ = \frac{\sigma_T^2}{16\pi} \left( \frac{s}{s_0} \right)^{2\alpha't} F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s)t} \]  

\[ F^4(t) \approx e^{b_{0,el}t} \Rightarrow b_{el}(s) = b_{0,el} + 2\alpha' \ln \left( \frac{s}{s_0} \right) \]

\[ \frac{d^2\sigma_{sd}}{dt d\xi} \]

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

\[ = f_{P/P}(\xi, t) \sigma_T^{\tilde{p}}(s', t) \]  

Parameters:

- $s_0$, $s_0'$ and $g(t)$
- set $s_0' = s_0$ (universal IP)
- determine $s_0$ and $g_{PPP} – how?$
A complication … ➔ Unitarity!

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

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

- the unitarity limit is already reached at \( \sqrt{s} \sim 2 \text{ TeV} \)!

- need unitarization
Factor of ~8 (~5) suppression at $\sqrt{s} = 1800$ (540) GeV

$\rightarrow$ diffractive $x$-section suppressed relative to Regge prediction as $\sqrt{s}$ increases

$\rightarrow$ Interpret flux as gap formation probability that saturates when it reaches unity

see KG, PLB 358, 379 (1995)
Single diffraction renormalized - 1


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 $\Rightarrow$ (re)normalize to unity

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

\[ \kappa = f_g \times \frac{1}{N_c^2 - 1} + f_q \times \frac{1}{N_c} \quad \frac{Q^2}{1} \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18 \]
\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} = \left[ \frac{\sigma_0}{16\pi} \sigma_{IP}^p \right] \frac{s^{2\epsilon}}{N(s, s_o)} \frac{e^{bt}}{(M^2)^{1+\epsilon}}
\]

\[b = b_0 + 2\alpha' \ln \frac{s}{M^2}\]

\[s_o^{CMG} = (3.7 \pm 1.5) \text{ GeV}^2\]

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

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

\[\sigma_{sd} \xrightarrow{s \to \infty} \sim \frac{\ln s}{b \to \ln s} \Rightarrow \text{const}\]

set to unity \(\Rightarrow\) determines \(s_o\)
\[ \frac{d\sigma}{dM^2} \propto \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}} \rightarrow 1 \]

Independent of \( s \) over 6 orders of magnitude in \( M^2 \)

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

\[ d\sigma/dM^2 \bigg|_{t=0.05} \sim \text{ independent of } s \text{ over 6 orders of magnitude!} \]

KG&JM, PRD 59 (1999) 114017

\[ \Delta \equiv \epsilon \]

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

\[ d^2\sigma/dt dM^2 \bigg|_{t=-0.05} \sim \text{ independent of } s \text{ over 6 orders of magnitude!} \]

\[ \Delta = 0.05 \]

\[ \Delta = 0.15 \]

\[ \text{546 GeV std. flux prediction} \]

\[ \text{1800 GeV std. flux prediction} \]

\[ \text{renorm. flux prediction} \]
Scale $s_0$ and $PPP$ coupling

Pomeron flux: interpret as gap probability

$\Rightarrow$ set to unity: determines $g_{PPP}$ and $s_0$

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

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 $g_{PPP}$

KG, PLB 358 (1995) 379
Saturation at low $Q^2$ and small $x$

figure from a talk by Edmond Iancu
DD at CDF

\[ \frac{d^3 \sigma_{DD}}{dt dM_1^2 dM_2^2} \equiv \frac{d^2 \sigma_{SD}}{dt dM_1^2} \frac{d^2 \sigma_{SD}}{dt dM_2^2} \bigg/ \frac{d \sigma_{el}}{dt} \frac{s^{2\varepsilon} e^{b_{DD}t}}{(M_1^2 M_2^2)^{1+2\varepsilon}} \]

\[ \frac{d^3 \sigma_{DD}}{dt d\Delta \eta d \eta_c} = \left[ \frac{\kappa \beta^2(0)}{16 \pi} e^{2[\alpha(t)-1] \Delta \eta} \right] \left[ \kappa \beta^2(0) \left( \frac{s}{s_0} \right)^\varepsilon \right] \]

\[ \Delta \eta^0 = \eta_{\text{max}} - \eta_{\text{min}} \]

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

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

\[ \sigma_{DD} (\text{mb}) \text{ for } \Delta \eta > 3.0 \]
Rapidity Gaps in Fireworks
SDD at CDF

- Excellent agreement between data and MBR (MinBiasRockefeller) MC

\[
\frac{d^5 \sigma}{d t \bar{p} d t d \xi \bar{p} d \Delta \eta d \eta_c} = \left[ \frac{\beta(t)}{4\sqrt{\pi}} e^{[\alpha(t)-1] \ln(1/\xi)} \right]^2 \times \kappa \left[ \frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1] \Delta \eta} \right]^2 \kappa \left[ \beta^2(0) \left( \frac{s''}{s_0} \right) \epsilon \right]
\]
CD/DPE at CDF

- Excellent agreement between data and MBR
  ➔ low and high masses are correctly implemented
Diffractive cross sections

\[
\frac{d^2 \sigma_{SD}}{dtd\Delta y} = \frac{1}{N_{\text{gap}}(s)} \left[ \frac{\beta^2(t)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left( \frac{s'}{s_0} \right)^\varepsilon \right\},
\]

\[
\frac{d^3 \sigma_{DD}}{dtd\Delta y dy_0} = \frac{1}{N_{\text{gap}}(s)} \left[ \frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left( \frac{s'}{s_0} \right)^\varepsilon \right\},
\]

\[
\frac{d^4 \sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_c} = \frac{1}{N_{\text{gap}}(s)} \left[ \Pi_i \left[ \frac{\beta^2(t_i)}{16\pi} e^{2[\alpha(t_i)-1]\Delta y_i} \right] \right] \cdot \kappa \left\{ \kappa \beta^2(0) \left( \frac{s'}{s_0} \right)^\varepsilon \right\}
\]

\[
\beta^2(t) = \beta^2(0) F^2(t)
\]

\[
F^2(t) = \left[ \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \left( \frac{1}{1 - \frac{t}{0.71}} \right)^2 \right]^2 \approx a_1 e^{b_1 t} + a_2 e^{b_2 t}
\]

\[
\alpha_1 = 0.9, \quad \alpha_2 = 0.1, \quad b_1 = 4.6 \text{ GeV}^{-2}, \quad b_2 = 0.6 \text{ GeV}^{-2}, \quad s' = s e^{-\Delta y}, \quad \kappa = 0.17, \quad \kappa \beta^2(0) = \sigma_0, \quad s_0 = 1 \text{ GeV}^2, \quad \sigma_0 = 2.82 \text{ mb} \text{ or } 7.25 \text{ GeV}^{-2}
\]
Total, elastic & inelastic cross sections

\[ \sigma_{ND} = (\sigma_{\text{tot}} - \sigma_{\text{el}}) - (2\sigma_{SD} + \sigma_{DD} + \sigma_{CD}) \]

\[ \sigma_{\text{tot}}^p = \begin{cases} 
16.79s^{0.104} + 60.81s^{-0.32} \mp 31.68s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\
\sigma_{\text{tot}}^{\text{CDF}} + \frac{\pi}{s_0} \left[ \left( \ln \frac{s}{s_F} \right)^2 - \left( \ln \frac{s^{\text{CDF}}}{s_F} \right)^2 \right] & \text{for } \sqrt{s} \geq 1.8
\end{cases} \]

\[ \sqrt{s^{\text{CDF}}} = 1.8 \text{ TeV}, \ \sigma_{\text{tot}}^{\text{CDF}} = 80.03 \pm 2.24 \text{ mb} \]

\[ \sqrt{s_F} = 22 \text{ GeV}, \ s_0 = 3.7 \pm 1.5 \text{ GeV}^2 \]

\[ \sigma_{\text{el}}^{p\pm p} = \sigma_{\text{tot}} \times \left( \frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} \right), \ \text{with } \sigma_{\text{el}}/\sigma_{\text{tot}} \text{ from CMG} \]

\text{small extrapol. from 1.8 to 7 and up to 50 TeV} \]
• 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 $$\sqrt{s_F} = 22$$ GeV (Fig. 1) and therefore valid at $$\sqrt{s} = 1800$$ GeV.

• Use $$m^2 = s_0$$ in the Froissart formula multiplied by $$1/0.389$$ to convert it to mb$^{-1}$.

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

• Obtain the total cross section at the LHC:

$$\sigma_{t_{LHC}} = \sigma_{t_{CDF}} + \frac{\pi}{s_0} \cdot \left( \ln^2 \frac{s_{LHC}}{s_F} - \ln^2 \frac{s_{CDF}}{s_F} \right)$$

98 ± 8 mb at 7 TeV
109 ±12 mb at 14 TeV

Main error from $$s_0$$
Reducing the uncertainty in $s_0$

Saturation glueball?

- glue-ball-like object $\rightarrow$ “superball”
- mass $\rightarrow 1.9$ GeV $\rightarrow m_s^2 = 3.7$ GeV
  - agrees with RENORM $s_0 = 3.7$
- Error in $s_0$ can be reduced by factor $\sim 4$ from a fit to these data! $\rightarrow$ reduces error in $\sigma_t$. 

Figure 8: $M_{\pi^+\pi^-}$ spectrum in DIFE 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
TOTEM results vs PYTHIA8-MBR

σ_{inrl}^7\text{TeV} = 72.9 \pm 1.5 \text{ mb}

σ_{inrl}^8\text{TeV} = 74.7 \pm 1.7 \text{ mb}

TOTEM, G. Latino talk at MPI@LHC, CERN 2012

RENORM: 71.1 \pm 1.2 \text{ mb}

RENORM: 72.3 \pm 1.2 \text{ mb}
**SD and DD cross sections vs predictions**

- KG*: from CMS measurements after extrapolation into low $\xi$ using the MBR model.

*Includes ND background*
Inelastic cross sections at LHC vs predictions

CMS pp $\sqrt{s} = 7$ TeV

- CMS - HF based
- CMS - Vtx based
- ATLAS
- TOTEM
- ALICE
- PYTHIA 6
- PYTHIA 8
- PYTHIA 8 + MBR
- PHOJET
- EPOS 1.99
- QGSJET 01
- QGSJET II-03
- QGSJET II-04
- SIBYLL 2.1

TOTEM
PYTHIA8+MBR
Monte Carlo Strategy for the LHC …

MONTE CARLO STRATEGY

- $\sigma_{\text{tot}} \rightarrow$ from SUPERBALL model
- optical theorem $\rightarrow$ Im $f_{\text{el}}(t=0)$
- dispersion relations $\rightarrow$ Re $f_{\text{el}}(t=0)$
- $\sigma_{\text{el}} \leftarrow$ using global fit
- $\sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}}$
- differential $\sigma_{\text{sd}} \rightarrow$ from RENORM
- use *nesting* of final states for pp collisions at the $P$-$p$ sub-energy $\sqrt{s}$'

**Strategy similar to that of MBR used in CDF based on multiplicities from:**
“A new statistical description of hadronic and $e^+e^-$ multiplicity distributions“
Monte Carlo algorithm - nesting

Profile of a \textit{pp} inelastic collision

- Final state of MC w/no-gaps
  - Δ\(y'\) < Δ\(y'_{\text{min}}\)
  - Hadronize
- Δ\(y'\) > Δ\(y'_{\text{min}}\)
  - Generate central gap
  - Evolve every cluster similarly
- Repeat until Δ\(y'\) < Δ\(y'_{\text{min}}\)
SUMMARY

- Introduction
- Diffractive cross sections:
  - basic: SD1, SD2, DD, CD (DPE)
  - combined: multigap x-sections
  - ND → no diffractive gaps:
    - this is the only final state to be tuned
- Total, elastic, and total inelastic cross sections
- Monte Carlo strategy for the LHC – “nesting”

Thank you for your attention
Images
Fermilab 1971
First American-Soviet Collaboration
Elastic, diffractive and total cross sections
At the gorge of Samaria (1980)
Fermilab 1989
Opening night at Chez Leon
The End