Review of RENORM Diffractive Predictions for LHC up to 8 TeV and Extension to 13 TeV

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

DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
http://www.dis2015.org
Southern Methodist University
Dallas, TX, USA, April 27 - May 1, 2015
Basic and combined diffractive processes

CONTENTS

- Diffraction
  - SD1 \( p_1p_2 \rightarrow p_1 + \text{gap} + X_2 \) Single Diffraction / Dissociation –1
  - SD2 \( p_1p_2 \rightarrow X_1 + \text{gap} + p_2 \) Single Diffraction / Dissociation - 2
  - DD \( p_1p_2 \rightarrow X_1 + \text{gap} + X_2 \) Double Diffraction / Double Dissociation
  - CD/DPE \( p_1p_2 \rightarrow \text{gap} + X + \text{gap} \) Central Diffraction / Double Pomeron Exchange

- Renormalization → Unitarization
  - RENORM Model

- Triple-Pomeron Coupling
- Total Cross Section
- RENORM Predictions Confirmed
- RENORM Predictions Extended

References

- Previous talk (RENORM diffractive predictions extended to higher LHC and future accelerator energies) – similar to present talk
- Present talk (predictions compared to final CMS results)
RENORM: Basic and Combined Diffractive Processes

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

Cross sections analytically expressed in arXiv below:

Regge Theory: Values of $s_0$ & $g_{PPP}$?

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

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

\[ \sigma_T = \beta_1(0) \beta_2(0) \left( \frac{s}{s_0} \right)^{\alpha(0) - 1} = \sigma_T^{p\bar{p}} \left( \frac{s}{s_0} \right)^{\alpha(0) - 1} \quad (1) \]

\[
\frac{d\sigma_{el}}{dt} = \frac{\beta_1^2(t) \beta_2^2(t)}{16\pi} \left( \frac{s}{s_0} \right)^{2[\alpha(t) - 1]}
= \frac{\sigma_T^2}{16\pi} \left( \frac{s}{s_0} \right)^{2\alpha' t} \quad (2)
\]

\[ F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s)t} \quad (3) \]

\[ \frac{d^2\sigma_{sd}}{dt d\xi} = \frac{\beta_1^2(t)}{16\pi} \xi^{1-2\alpha(t)} \left[ \beta_2(0) g(t) \left( \frac{s'}{s_0'} \right)^{\alpha(0) - 1} \right] 
= f_{P/P}(\xi, t) \sigma_T^{p\bar{p}}(s', t) \quad (4) \]
Theoretical 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 $s$
  (also true for partial x-sections in impact parameter space)

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

- need unitarization

* similarly for $(d\sigma^{el}/dt)_{t=0}$ w.r.t. $\sigma_t$, but this is handled differently in RENORM
Factor of $\sim 8$ ($\sim 5$) suppression at $\sqrt{s} = 1800$ (540) GeV

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

$\xi$, $p$, $p'$

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

Renormalization

$\sqrt{s} = 22$ GeV

Regge

Regolarization

$\xi < 0.05$

Albrow et al.

Armitage et al.

UA4

CDF

E710

Cool et al.

Total Single Diffraction Cross Section (mb)

$540$ GeV

$1800$ GeV

$\sqrt{s} = 1800$ (540) GeV


DIS-2015 Dallas

RENORM Diffractive Predictions for LHC

K. Goulianos
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

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

Sub-energy x-section

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

**Single Diffraction Renormalized - 1**

Single Diffraction Renormalized - 2

Experimentally:

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

KG&JM, PRD 59 (114017) 1999

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

\[ \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18 \]
\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} = \left[ \frac{\sigma_\circ}{16\pi} \sigma_\circ^{IPp} \right] \frac{s^{2\epsilon}}{N(s, s_o)} \frac{e^{bt}}{(M^2)^{1+\epsilon}}
\]

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

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

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

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

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

set to unity \(\Rightarrow\) determines \(s_o\)
$M^2$ - Distribution: Data

$\frac{d\sigma}{dM^2}\bigg|_{t=-0.05} \sim$ independent of $s$ over 6 orders of magnitude!

$d\sigma/dM^2 \propto \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}} \rightarrow 1$

Regge data

$\Delta \equiv \epsilon$

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

$\Delta = 0.05$

$\Delta = 0.15$

$546$ GeV std. flux prediction

$1800$ GeV std. flux prediction

$\Rightarrow$ factorization breaks down to ensure $M^2$ scaling

http://physics.rockefeller.edu/publications.html
Scale $s_0$ and $PPP$ Coupling

- Pomerion flux: interpret it as gap probability
  - set to unity: determines $g_{PPP}$ and $s_0$

\[
\frac{d^2\sigma_{SD}}{dt d\xi} = f_{IP/p}(t, \xi) \sigma_{IP/p}(s\xi) \downarrow s_0^\varepsilon
\]

- Renormalized Pomeron flux determines $s_0$
- Get unique solution for $g_{PPP}$

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

KG, PLB 358 (1995) 379

\[
\frac{d^3\sigma_{\text{DD}}}{dtdM_1^2 dM_2^2} = \frac{d^2\sigma_{\text{SD}}}{dtdM_1^2} \frac{d^2\sigma_{\text{SD}}}{dtdM_2^2} \left/ \frac{d\sigma_{\text{el}}}{dt} \right. \\
\quad = \frac{[\kappa \beta_1(0) \beta_2(0)]^2}{16\pi s^2 e^{b_{\text{DD}}t}} (M_1^2 M_2^2)^{1+2\epsilon}
\]

\[
\frac{d^3\sigma_{\text{DD}}}{dtd\Delta\eta d\eta_c} = \left[ \frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t) - 1]\Delta\eta} \right] \left[ \kappa \beta^2(0) \left( \frac{s'}{s_0} \right)^\epsilon \right]
\]

gap probability  \quad x-section

\(\sqrt{s}=1800\) GeV

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

\(\Delta\eta = \eta_{\text{max}} - \eta_{\text{min}}\)

\(\sigma_{\text{DD}}\) (mb) for \(\Delta\eta > 3.0\)

- CDF
- UA5 (adjusted)
- Regge
- Renormalized gap

\(\sqrt{s}\) (GeV)

\(10^2\)

\(10^3\)

\(10^4\)

\(10^5\)
SDD at CDF

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

- Excellent agreement between data and MBR (MinBiasRockefeller) MC

\[
\frac{d^5 \sigma}{d t_P dt d \xi_P d \Delta \eta d \eta_c} = \left[ \frac{\beta(t)}{4 \sqrt{\pi}} e^{[\alpha(t_P)-1] \ln(1/\xi)} \right]^2 \times k \left[ \frac{\beta(0)}{4 \sqrt{\pi}} e^{[\alpha(t)-1] \Delta \eta} \right]^2 \kappa \left[ \beta^2(0) \left( \frac{s''}{s_0} \right)^{\epsilon} \right]
\]
Excellent agreement between data and MBR based MC

- Confirmation that both low and high mass x-sections are correctly implemented

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

\[ 0.035 \leq \xi_p \leq 0.095 \]

\[ |t_p| \leq 1.0 \text{ GeV}^2 \]
RENORM Diffractive Cross Sections

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

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

\[
\frac{d^4 \sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_0} = \frac{1}{N_{gap}(s)} \left[ \prod_i \left[ \frac{\beta^2(t_i)}{16\pi} e^{2[\alpha(t_i)-1]\Delta y_i} \right] \right] \cdot \kappa \left\{ \kappa \beta^2(0) \left( \frac{s'}{s_0} \right)^\epsilon \right\}
\]

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

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

\[\alpha_1=0.9, \, \alpha_2=0.1, \, b_1=4.6 \text{ GeV}^{-2}, \, b_2=0.6 \text{ GeV}^{-2}, \, s'=s e^{-\Delta y}, \, \kappa=0.17, \]

\[\kappa \beta^2(0)=\sigma_0, \, s_0=1 \text{ GeV}^2, \, \sigma_0=2.82 \text{ mb or 7.25 GeV}^{-2}\]
Total, Elastic, and Inelastic x-Sections

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

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


\[ \sqrt{s^{CDF}} = 1.8 \text{ TeV}, \sigma_{tot}^{CDF} = 80.03 \pm 2.24 \text{ mb} \]
\[ \sqrt{s_F} = 22 \text{ GeV} \quad s_0 = 3.7 \pm 1.5 \text{ GeV}^2 \]

\[ \sigma_{el}^{p\pm p} = \sigma_{tot}^{p\pm p} \times \left( \frac{\sigma_{el}}{\sigma_{tot}} \right)^{p\pm p}, \text{ with } \frac{\sigma_{el}}{\sigma_{tot}} \text{ from CMG small extrapol. from 1.8 to 7 and up to 50 TeV} \]
• 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:

\[ \sigma_t^{\text{LHC}} = \sigma_t^{\text{CDF}} + \frac{\pi}{s_0} \cdot \left( \ln^2 \frac{s_{\text{LHC}}}{s_F} - \ln^2 \frac{s_{\text{CDF}}}{s_F} \right) \]

\[ 98 \pm 8 \text{ mb at 7 TeV} \]
\[ 109 \pm 12 \text{ mb at 14 TeV} \]

Main error is due to \(s_0\).
How to Reduce Uncertainty in $s_0$

- glue-ball-like object → “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
  - 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 (2012) vs PYTHIA8-MBR

\[ \sigma_{\text{inel}}^{7 \text{ TeV}} = 72.9 \pm 1.5 \text{ mb} \]

\[ \sigma_{\text{inel}}^{8 \text{ TeV}} = 74.7 \pm 1.7 \text{ mb} \]

RENORM: 71.1±1.2 mb

TOTEM, G. Latino talk at MPI@LHC, CERN 2012
ATLAS - in Diffraction 2014
(Talk by Marek Taševský, slide#19

Comparison with previous measurements

\[ \sigma_{\text{tot}} \]

\[ \sigma_{\text{el}} \]

\[ \sigma_{\text{inel}} \]

The same run in 2011, Lumi-dependent method:

ATLAS: \( \sigma_{\text{tot}} = 95.4 \pm 1.4 \text{ mb} \) (Lumi unc=2.3%)  
TOTEM: \( \sigma_{\text{tot}} = 98.6 \pm 2.2 \text{ mb} \) (Lumi unc=4%)  
\( \text{Difference} = 1.3 \sigma \)

ATLAS value \( \sim 2\sigma \) below COMPETE fit, but closer to predictions by Block & Halzen, KMR, Soffer.

ALFA significantly improves precision of the previous ATLAS \( \sigma_{\text{inel}} \) measurement:

ATLAS: \( \sigma_{\text{el}} = 24.0 \pm 0.6 \text{ mb} \) (Lumi unc=2.3%)  
TOTEM: \( \sigma_{\text{el}} = 25.4 \pm 1.1 \text{ mb} \) (Lumi unc=4%)  
\( \text{Difference} = 1.1 \sigma \)
The CMS Detector

CASTOR forward calorimeter important for separating SD from DD contributions
CMS Data vs MC Models (2015)-1

SD dominated data

DD dominated data

- Error bars are dominated by systematics
- DD data scaled downward by 15% (within MBR and CDF data errors)
Central \( \eta \)-gap x-sections (DD dominated)

- P8-MBR provides the best fit to data

- All above models too low at small \( \Delta \eta \)
SD/DD Extrapolations to $\xi_x \leq 0.05$ vs MC Models
**COLUMNS**

**Mass Regions**
- Low  $5.5<M_X<10$ GeV
- Med.  $32<M_X<56$ GeV
- High $176<M_X<316$ GeV

**ROWS**

**MC Models**
- PYTHIA8-MBR
- PYTHIA8-4C
- PYTHIA6-Z2*
- PHOJET
- QGSJET-II-03
- QGSJET-04
- EPOS-LHC

**CONCLUSION**

PYTHIA8-MBR agrees best with the reference model and is used by CMS in extrapolating to the unmeasured regions.

---

**DIS-2015 Dallas**

**RENorm Diffractive Predictions for LHC**

K. Goulianos
Charged Mult’s vs MC Model – 3 Mass Regions


Mass Regions
- Low 5.5<MX<10 GeV
- Med. 32<MX<56 GeV
- High 176<MX<316 GeV

CERN ISR & SppS 540 GeV

Diffractive data vs MGD

DIS-2015 Dallas  RENORM Diffractive Predictions for LHC  K. Goulianos
Pythia8-MBR Hadronization Tune

Diffraction: tune SigmaPomP

\[ n_{ave} = \frac{\sigma_{QCD}}{\sigma_{IPp}} \]

\( \sigma_{pp}(s) \) expected from Regge phenomenology for \( s_0 = 1 \text{ GeV}^2 \) and DL t-dependence.

**Red line:** best fit to multiplicity distributions.

(in bins of \( M_x \), fits to higher tails only, default pT spectra)

Diffraction: QuarkNorm/Power parameter

\[ P(q) = \frac{\text{probPickQuark}}{\text{probPickQuark} + 1} \]

- 5./\( M_x \) (Norm=5, Power=1, 4C default)
- 0.65*\( M_x^{0.15} \) (Norm=0.65, Power=-0.15)

\( P(q) = \frac{1}{\text{probPickQuark} + 1} \)

SD and DD x-Sections vs Models

Single Diffraction

Double Diffraction

Includes ND background
Uncorrected $\Delta \eta^F$ distribution vs MCs

Stable-particle x-sections for $pT>200$ MeV and $|\eta|<4.7$ compared to the ATLAS 2012 result similar result
**Monte Carlo Algorithm - Nesting**

**Profile of a pp Inelastic Collision**

- **no gap**
  - **final state of MC w/no-gaps**

- **gap**
  - $\Delta y' < \Delta y'_{\text{min}}$
  - hadronize
  - $\Delta y' > \Delta y'_{\text{min}}$
  - generate central gap

- **gap**
  - evolve every cluster similarly

- **gap**
  - repeat until $\Delta y' < \Delta y'_{\text{min}}$
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
- Monte Carlo strategy for the LHC – “nesting”

Warm thanks to my CDF and CMS colleagues, and to Office of Science of DOE
Special thanks to Robert A. Ciesielski, my collaborator in the PYTHIA8-MBR project

Thank you for your attention!

DIS-2015 Dallas  RENORM Diffractive Predictions for LHC  K. Goulianos