Diffraction Results at LHC: Solving a Puzzle using Precision RENORM-model predictions

Konstantin Goulianos
The Rockefeller University

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

Puzzle solved?
Basic and combined diffractive processes

CONTENTS

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

- Renormalization \(\rightarrow\) Unitarization
  - RENORM Model

- Triple-Pomeron Coupling: unambiguously determined

- Total Cross Section:
  - Unique prediction, based on a spin-2 tensor glue-ball model

References

- MBR MC Simulation in PYTHIA8, KG & R. Ciesielski, \url{http://arxiv.org/abs/1205.1446}
- EDS BLOIS 2015 Borgo, Corsica, France Jun 29-Jul 4, \url{https://indico.cern.ch/event/362991/}
- KG, Updated RENORM/MBR-model Predictions for Diffraction at the LHC, \url{http://dx.doi.org/10.5506/APhysPolBSupp.8.783}
- Moriond QCD 2016, La Thuile, Italy, March 19-26, \url{http://moriond.in2p3.fr/QCD/2016/}
- NPQCD16, Paris, June, \url{https://www.brown.edu/conference/14th-workshop-non-perturbative-quantum-chromodynamics/}
- DIFFRACTION 2016, Catania, Sep.2-8 2016 \url{https://agenda.infn.it/conferenceDisplay.py?confId=10935}

Similar talk

MIAMI 2018 Diffraction Results at LHC: Solving a Puzzle… K. Goulianos
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 \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p]),</td>
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<tr>
<td>SD(p)</td>
<td>(\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p),</td>
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<td>DD</td>
<td>(\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + [p \rightarrow X_p]),</td>
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<td>DPE</td>
<td>(\bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + p),</td>
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<tr>
<td>SDD(\bar{p})</td>
<td>(\bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + [p \rightarrow X_p]),</td>
</tr>
<tr>
<td>SDD(p)</td>
<td>(\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] \text{gap} + X_c + \text{gap} + p).</td>
</tr>
</tbody>
</table>

4-gap diffractive processes - Snowmass 2001

Cross sections analytically expressed in arXiv:

MIAMI 2018  Diffraction Results at LHC: Solving a Puzzle…  K. Goulianos
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?

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

\[
\sigma_T = \beta_1(0) \beta_2(0) \left( \frac{s}{s_0} \right)^{\alpha(0) - 1} = \sigma_0^{pp} \left( \frac{s}{s_0} \right)^{\alpha - 1}
\] (1)

\[
\frac{d\sigma_{el}}{dt} = \frac{\beta_1^2(t) \beta_2^2(t)}{16\pi} \left( \frac{s}{s_0} \right)^{2\alpha' t} F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s)t}
\] (2)

\[
F^4(t) \approx e^{b_{0,el} t} \Rightarrow b_{el}(s) = b_{0,el} + 2\alpha' \ln \left( \frac{s}{s_0} \right)
\] (3)

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

\[
= f_{P/P}(\xi, t) \sigma_T^{PP} (s', t)
\] (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 *
  \( \Rightarrow \) unitarity violation at high \( s \)
  (also true for partial x-sections in impact parameter space)

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

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

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

Renormalization

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

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 ➔ (re)normalize it 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 \( \Rightarrow \)

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

**QCD**: 

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

**Ref**: KG&JM, PRD 59 (114017) 1999

http://dx.doi.org/10.1103/PhysRevD.59.114017
\[
\frac{d^2 \sigma_{sd}(s, M^2, t)}{dM^2 dt} = \left[ \frac{\sigma^\infty}{16\pi} \sigma_{IPp} \right] \frac{s^{2\epsilon}}{N(s, s_o)} \frac{e^{bt}}{(M^2)^{1+\epsilon}}
\]

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

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

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

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

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

- affects only the \(s\)-dependence

- set \(N(s, s_o)\) to unity
- determines \(s_o\)
\[ \frac{d\sigma}{dM^2} \propto s^{2\varepsilon} \left( M^2 \right)^{1+\varepsilon} \]

\( \varepsilon = \Delta \)

\( \Rightarrow \) factorization breaks down to ensure \( M^2 \)-scaling

\( \text{Regge} \rightarrow \text{data} \)

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

KG&JM, PRD 59 (1999) 114017

http://dx.doi.org/10.1103/PhysRevD.59.114017

http://physics.rockefeller.edu/publications.html
Pomeron flux: interpreted as gap probability

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

Pomeron-proton x-section

- Two free parameters: $s_0$ and $g_{PPP}$
- Obtain product $g_{PPP} s_0^{\varepsilon/2}$ from $\sigma_{SD}$
- Renormalize Pomeron flux: determines $s_0$
- Get unique solution for $g_{PPP}$
Regge factorization
\[
\frac{d^3\sigma_{DD}}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_{SD}}{dt dM_1^2} \frac{d^2\sigma_{SD}}{dt dM_2^2} / \frac{d\sigma_{el}}{dt} = \frac{[\kappa \beta_1(0) \beta_2(0)]^2}{16\pi} \frac{s^{2[\alpha(0)-1]}e^{b_{DD} t}}{(M_1^2 M_2^2)^{1+2[\alpha(0)-1]}}
\]

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

gap probability
x-section

\textbf{Regge}

\textbf{RENORM}

x-section divided by integrated gap prob.

http://physics.rockefeller.edu/publications.html
http://dx.doi.org/10.1103/PhysRevLett.87.141802

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**SDD at CDF**

- Excellent agreement between data and MBR (MinBiasRockefeller) MC

\[
\frac{d^5 \sigma}{d t_{\bar{p}} dt d\xi_{\bar{p}} d\Delta \eta d\eta_{c}} = \left[ \frac{\beta(t)}{4\sqrt{\pi}} e^{[\alpha(t_{\bar{p}})-1] \ln(1/\xi_{\bar{p}})} \right]^2 \times \kappa \left[ \frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1] \Delta \eta} \right]^2 \kappa \left[ \beta^2(0) \left( \frac{s''''}{s_o} \right)^{\epsilon} \right]
\]

http://physics.rockefeller.edu/publications.html
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.91.011802
Excellent agreement between data and MBR-based MC

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

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.91.011802
RENORM Diffractive Cross Sections

MBR Simulation in PYTHIA8 ➞ http://arxiv.org/abs/1205.1446

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

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

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

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

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

\[
\alpha_1 = 0.9, \quad \alpha_2 = 0.1, \quad b_1 = 4.6 \text{ GeV}^{-2}, \quad b_2 = 0.6 \text{ GeV}^{-2}, \quad s' = s e^{-\Delta y}, \quad \kappa = 0.17, \quad \kappa \beta^2(0) = \sigma_0, \quad s_0 (\text{units}) = 1 \text{ GeV}^2, \quad \sigma_0 = 2.82 \text{ mb or } 7.25 \text{ GeV}^{-2}
\]
Total, Elastic, and Total Inelastic x-Sections

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

R.J.M. Covolan 1, J. Montanha 2, K. Goulianos 3
The Rockefeller University, 1230 York Avenue, New York, NY 10021, USA

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

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

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

\[ \text{small extrapolation from 1.8 to 7 and up to 50 TeV} \]
The total 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 and therefore valid at \( \sqrt{s} = 1800 \) GeV.

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

- Use the Froissart formula as a saturated cross section

- Note that contributions from Reggeon exchanges at \( \sqrt{s} = 1800 \) GeV are negligible, as can be verified from the global fit of CMG.

- Obtain the total cross section at the LHC:

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

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

Uncertainty is due to \( s_o \)
Reduce Uncertainty in $s_0$

Review of CEP by Albrow, Coughlin, Forshaw [1006.1289](http://arxiv.org/abs/1006.1289)

Data: Peter C. Cesil, AFS thesis (courtesy Mike Albrow)

**Analysis:** S and D waves

**Conjecture:** tensor glue ball (spin 2)

**Fit:** Gaussian

20% increase in $s_0$ → x-sections decrease

2.10 GeV ± 0.68

2015

http://workshops.ift.uam-csic.es/LHCFWG2015/program

EDS 2015: http://dx.doi.org/10.5506/APhysPolBSupp.8.783

20% increase in $s_0$ → x-sections decrease

Data: Peter C. Cesil, AFS thesis (courtesy Mike Albrow)

**Analysis:** S and D waves

**Conjecture:** tensor glue ball (spin 2)

**Fit:** Gaussian

- $<M_{tgb}> = \sqrt{s_0} = 2.10\pm0.68$ GeV
- $s_0 = 4.42\pm0.34$ GeV

MIAMI 2018

Diffraction Results at LHC: Solving a Puzzle… K. Goulianos
Predictions vs Measurements with/reduced Uncertainty in $s_0$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>MBR/Exp</th>
<th>$\sigma_{\text{tot}}$</th>
<th>$\sigma_{\text{el}}$</th>
<th>$\sigma_{\text{inel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>MBR</td>
<td>95.4±1.2</td>
<td>26.4±0.3</td>
<td>69.0±1.0</td>
</tr>
<tr>
<td></td>
<td>TOTEM totem-lumInd</td>
<td>98.3±0.2±2.8</td>
<td>24.8±0.2±1.2</td>
<td>73.7±3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98.0±2.5</td>
<td>25.2±1.1</td>
<td>72.9±1.5</td>
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<tr>
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<td>ATLAS</td>
<td>95.35±1.36</td>
<td>24.00±0.60</td>
<td>71.34±0.90</td>
</tr>
<tr>
<td>8 TeV</td>
<td>MBR</td>
<td>97.1±1.4</td>
<td>27.2±0.4</td>
<td>69.9±1.0</td>
</tr>
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<td></td>
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<td>74.7±1.7</td>
</tr>
<tr>
<td>13 TeV</td>
<td>MBR</td>
<td>103.7±1.9</td>
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<td>73.5±1.3</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td></td>
<td>$\sigma_{\text{inel}}=73.1±0.9(\text{exp})±6.6(\text{lumi})±3.8(\text{extra.}\text{mb})$</td>
<td></td>
</tr>
</tbody>
</table>

- **RENNORM/MBR with a tensor-Pomeron model** predicts measured cross sections to the $\sim1\%$ level
- **Test of RENNORM/MBR**: ATLAS results using the ALFA and RP detectors to measure the cross sections

Stay tuned!

**From my Moriond-2016 Talk**

| Totem 7 TeV  | http://arxiv.org/abs/1204.5689 |
| Totem 8 TeV: | http://dx.doi.org/10.1103/PhysRevLett.111.012001 |
| Atlas/Totem 13TeV DIS15 | https://indico.desy.de/contributionDisplay.py?contribId=330&conflId=12482 |

**MIAMI 2018**

Diffraction Results at LHC: Solving a Puzzle… K. Goulianos
### Predictions vs Measurements w/reduced Uncertainty in $s_o$ #1

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>MBR/Exp</th>
<th>Reference (next slide)</th>
<th>$S_{tot}$</th>
<th>$S_{el}$</th>
<th>$S_{inel}$</th>
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<td>ATLAS</td>
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<tr>
<td>TOTEM</td>
<td>2</td>
<td></td>
<td>101.7±2.9</td>
<td>27.1±1.4</td>
<td>74.7±1.7</td>
</tr>
<tr>
<td>TOTEM_Lum_Ind</td>
<td>3</td>
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<td>98.0±2.5</td>
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<td>101.7±2.9</td>
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<td>CMS</td>
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</tbody>
</table>

| 73.1±0.9 (exp) ±6.6 (lumi) ±3.8 (extr) |
| 71.3±0.5 (exp) ±2.1 (lumi) ±2.7 (extr) |
Caveat (slide from my ICNFP-2016 talk)

The MBR $\sigma_{el}$ is larger than the ATLAS and the TOTEM_lum_Ind measurements by ~2 mb at $\sqrt{s}=7$ TeV, which might imply a higher MBR prediction at $\sqrt{s}=13$ TeV by 2-3 mb. Lowering the MBR $\sigma_{el}$ prediction would lead to a larger $\sigma_{inel}$. This interplay between $\sigma_{el}$ and $\sigma_{inel}$ should be kept in mind as more results of $\sigma_{el}$ and $\sigma_{tot}$ at $\sqrt{s}=13$ TeV become available.

- RENORM/MBR with a tensor-Pomeron model predicts measured cross sections to the ~1% level.
- Test of RENORM/MBR: ATLAS results using the ALFA and RP detectors to measure the cross sections.

Stay tuned!

2) Totem 7 TeV http://arxiv.org/abs/1204.5689
4) Totem 8 TeV http://dx.doi.org/10.1103/PhysRevLett.111.012001
### MBR vs. ICHEP 2016 cross-section results

<table>
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</table>
| 8 TeV    | MBR    |                   | 97.1±1.4          | 27.2±0.4  | 69.9±1.0  | **ATLAS vs. MBR in excellent agreement at 8 TeV**
|          | TOTEM  | 4                 | 101.7±2.9         | 27.1±1.4  | 74.7±1.7  |
|          | ATLAS-ALFA fit | 5 & 6 ICHEP16 | **96.1±0.9** | 24.3±0.4  | 73.5±1.3  |
| 13 TeV   | MBR    |                   | 103.7±1.9         | 30.2±0.8  |           |
|          | ATLAS  | 5 & 6 ICHEP16     |                   |           |           |
|          | ALFA-fit-result | 7+ICHEP16 |                    |           |           |


- At 13 TeV MBR is happy between the ATLAS and CMS ICHEP results
  - awaiting settlement between the two experiments – keep tuned!
### MBR vs. ICHEP 2016 cross-sections

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>Input source</th>
<th>Reference*</th>
<th>σ_{tot} (mb)</th>
<th>σ_{el} (mb)</th>
<th>σ_{inel} (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>MBR</td>
<td>a</td>
<td>95.4 ± 1.2</td>
<td>26.4 ± 0.3</td>
<td>69.0 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td>b</td>
<td>95.35 ± 1.36</td>
<td>24.00 ± 0.60</td>
<td>71.34 ± 0.90</td>
</tr>
<tr>
<td></td>
<td>TOTEM</td>
<td>c</td>
<td>101.7 ± 1.36</td>
<td>27.1 ± 1.4</td>
<td>74.7 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>TOTEM_Lum_ind</td>
<td>d</td>
<td>98.0 ± 2.5</td>
<td>24.00 ± 0.60</td>
<td>72.9 ± 1.5</td>
</tr>
<tr>
<td>8</td>
<td>MBR</td>
<td>a</td>
<td>97.1 ± 1.4</td>
<td>27.2 ± 0.4</td>
<td>69.9 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>TOTEM</td>
<td>e</td>
<td>101.7 ± 2.9</td>
<td>27.1 ± 1.4</td>
<td>74.8 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>ATLAS_ALFA_fit</td>
<td>(h) ICHEP16</td>
<td>96.1 ± 0.9</td>
<td>24.3 ± 0.4</td>
<td>xxx</td>
</tr>
<tr>
<td>13</td>
<td>MBR</td>
<td>a</td>
<td>103.7 ± 1.9</td>
<td>30.2 ± 0.8</td>
<td>73.5 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td>f &amp; g</td>
<td>xxx</td>
<td>xxx</td>
<td>73.1 ± 0.9(exp)±3.8(extr)±6.6(lumi)</td>
</tr>
<tr>
<td></td>
<td>ATLAS_ALFA_fit</td>
<td>(h) ICHEP16</td>
<td>xxx</td>
<td>xxx</td>
<td>79.3 ± 0.6(exp)±2.5(extr)±1.3(lumi)</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>(h) ICHEP16</td>
<td>xxx</td>
<td>xxx</td>
<td>71.3 ± 0.6(exp)±2.7(extr)±0.1(lumi)</td>
</tr>
</tbody>
</table>

*Reference:
(a) http://arxiv.org/abs/1205.1446
(b) http://arxiv.org/abs/1408.5778
(c) http://arxiv.org/abs/1204.5689
(d) http://iopscience.iop.org/article/10.1209/0295-5075/101/21004
(e) http://dx.doi.org/10.1103/PhysRevLett.111.012001
(f) M. Trzebinski (ATLAS), DIS-2016 [7]-(a)
(g) H. Van Haevermaet (CMS), DIS-2016 [7]-(b)
(h) T. Sykora, Cross sections summary, ICHEP16 [8]
Excellent agreement between TOTEM and MBR at 2.76 TeV

Awaiting forthcoming results at 13 TeV from ATLAS, CMS, TOTEM
Reasonable agreement between TOTEM and MBR predictions

Possible Odderon effects not included in MBR
10.4 Discussion

This section concludes with an example of how theoretical considerations may be examined using these results. A. Martin has pointed out [10.6] that by taking $E = \frac{1}{2}(F(pp) - F(pp))$ at $t = 0$ and defining the quantity $\rho = \Re F / \Im F$, one can demonstrate from the optical theorem the following identity:

$$\rho = \Delta \rho = \Delta \rho_0 + \rho(pp).$$

Additionally, it is possible to prove using dispersion relations that if $\Delta \sigma = E^{-Q}$ then $\rho = \cot(\pi Q/2)$. If one uses the value $\alpha = 0.56 \pm 0.01$ which Amos et al. found in applying the Amaldi-type parametrization of Eq. 3.15, then $\rho = 0.827 \pm 0.026$. Using $\Delta \sigma = 1.94 \text{ mb}$, the UA6 measurements inserted into Eq. 10.4 give $\rho = 0.84 \pm 0.34$, consistent with the assumption that $\Delta \sigma \to 0$ asymptotically as $E^{-Q}$. On the other hand, the fit assuming a significant odd-under-crossing amplitude of Ref. 3.7 predicts for the UA6 energy $\rho_{odd}(pp) = -0.007$ and $\rho_{odd}(pp) = 0.054$, yielding $\Delta \rho = 0.061$. This demonstrates a difference between the UA6 result and the odderon prediction of $0.022 \pm 0.014$ which, while not suggestive, does not rule out the possibility of an odd-under-crossing amplitude dominating at high energies.

A definitive answer awaits precise comparisons of $pp$ and $pp$ at higher energies.
Odderon first motivated in 1973 (Lukaszuk, Nicolescu) by Regge exchange for high-energy cross sections; for example \( pp \) and \( p\bar{p} \)

\[
A_{\pm} = A(pp) \pm A(p\bar{p})
\]

simple poles \( \alpha_{p,0}(0) \sim 1 \)

\[
A_+(pp) = A_+(p\bar{p}) \quad C = +1 \\
A_-(pp) = A_-(p\bar{p}) \quad C = -1
\]

Pomeron --- dominately imag

Odderon --- dominately real

Maximal Odderon: odd-sig term as strong as allowed by asymptotic theorems

1. Pomeranchuk theorem \( \Delta \sigma \equiv \sigma(p\bar{p}) - \sigma(pp) \sim \text{Im} A_- \to 0 \) as \( s \to \infty \)

2. Generalized Pomeranchuk th: \( \frac{\sigma(p\bar{p})}{\sigma(pp)} \to 1 \) as \( s \to \infty \)

Conclusion (from slide # 16)
The Odderon remains elusive
But with experimental ingenuity and precision it stands a good chance of being cornered
Total inelastic cross section @13 TeV

Require an activity in HF or CASTOR calorimeters

\[
\xi_x = \frac{M_X^2}{s} \quad \xi_Y = \frac{M_Y^2}{s}
\]

CASTOR calorimeter \((-6.6<\eta<-5.2))

HF calorimeter \((3.2<|\eta|<5.2))

\[\xi_x > 10^{-7} \quad \xi_Y > 10^{-6}\]

HF only: \[\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8 \text{ (syst)} \pm 1.6 \text{ (lumi)} \text{ mb}\]

HF and CASTOR: \[\sigma(\xi_x > 10^{-7} \text{ or } \xi_Y > 10^{-6}) = 68.6 \pm 0.5 \text{ (syst)} \pm 1.6 \text{ (lumi)} \text{ mb}\]

Good agreement with ATLAS measurement
MinBias models for hadron-hadron scattering predict higher cross section than measured
Pythia8-MBR Hadronization Tune

An example of the diffractive tuning of PYTHIA-8 to the RENORM-NBR model

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

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

**Red line:** best fit to multiplicity distributions.
(in bins of Mx, fits to higher tails only, default pT spectra)

R. Ciesielski, “Status of diffractive models”, CTEQ Workshop 2013

https://indico.cern.ch/event/262192/contributions/1594778/attachments/463480/642352/CTEQ13diffraction.pdf
SD and DD x-Sections vs Models


Diffraction Results at LHC: Solving a Puzzle… K. Goulianos

MIAMI 2018
Monte Carlo Algorithm - Nesting

Profile of a pp Inelastic Collision

- no gap
- gap

Finally state of MC w/no-gaps

\[ \Delta y' < \Delta y'_{\text{min}} \]

\[ \Delta y' > \Delta y'_{\text{min}} \]

hadronize

generate central gap

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

\[ \ln s' = \Delta y' \]

evolve every cluster similarly

Diffraction Results at LHC: Solving a Puzzle… K. Goulianos
SUMMARY

- Review of RENORM predictions of diffractive physics
  - basic processes: SD1, SD2, DD, CD (DPE)
  - combined processes: multigap x-sections
  - ND ➔ no diffractive gaps: the only final state to be tuned
- Monte Carlo strategy for the LHC – “nesting”
- Precision RENORM $\sigma_{\text{tot}}$ prediction with tensor glue-ball model
- ICHEP 2016
  - At 8 TeV ATLAS and MBR in excellent agreement
  - Disagreement between TOTEM and MBR persists
  - At 13 TeV MBR lies comfortably (!) between the ATLAS and CMS
  - Agreement at 8 TeV, compatibility at 13 TeV
- LHCC-2017: NEW TOTEM RESULTS at 8 and 13 TeV vs. MBR
- Krakow-2018: CMS and ATLAS total-inelastic converge towards MBR!
- NESTING in MC simulation

Thank you for your attention!