Lessons from LHC elastic & diffractive data

Valery Khoze, Alan Martin and Misha Ryskin

In the light of LHC data, we discuss the global description of all high-energy elastic and diffractive data, using a one-pomeron pole model, but including multi-pomeron interactions.

The LHC data indicate the need of a $k_T(s)$ behaviour, where $k_T$ is the parton transverse momentum along the partonic ladder structure of the pomeron.
Elastic amp. \( T_{\text{el}}(s,b) \)

\[
\text{Im} \ T_{\text{el}} = 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty} \Omega/2
\]

(s-ch unitarity)

Low-mass diffractive dissociation

introduce diff\(\text{ve}\) estates \(\phi_i, \phi_k\) (comb\(\text{ns}\) of \(p, p^*\)) which only undergo “elastic” scattering (Good-Walker)

\[
\text{Im} \ T_{ik} = 1 - e^{-\Omega_{ik}/2} = \sum \Omega_{ik}/2
\]

include high-mass diffractive dissociation

\[
\Omega_{ik} = \sum \{ M + \ldots + \}
\]
There exists only one Pomeron, which makes a smooth transition from the hard to the soft regime.

KMR model is a partonic approach which includes the $k_t$ dependence of the pomeron in the log(1/x) evolution/cascade, as well as eikonal and enhanced multi-pomeron absorptive effects.
Partonic structure of “bare” Pomeron

BFKL evolution in rapidity generates a ladder

\[ \frac{\partial \Omega(y, k_t)}{\partial y} = \bar{\alpha}_s \int d^2 k'_t \ K(k_t, k'_t) \ \Omega(y, k'_t) \]

- At each step, \( k_t \) and \( b \) of parton can be be changed – so, in principle, we have 3-variable integro-diff. eq. to solve

- Inclusion of \( k_t \) crucial to match soft and hard domains. Moreover, embodies less screening for larger \( k_t \) compared.

- We use a simplified form of the kernel \( K \) with the main features of BFKL – diffusion in \( \log k_t^2 \), \( \Delta = \alpha_p(0) - 1 \approx 0.3 \)

- \( b \) dependence during the evolution is prop’ to the Pomeron slope \( \alpha' \), which is v.small (\( \alpha'<0.05 \text{ GeV}^{-2} \)) -- so ignore. Only \( b \) dependence comes from the starting evol\( ^n \) distrib\( ^n \)

- Evolution gives

\[ \Omega = \Omega_{ik}(y, k_t, b) \]
How are Multi-Pomeron contributions included?

Now include rescatt of intermediate partons with the “beam” i and “target” k (KMR)

\[
\frac{\partial \Omega_k(y)}{\partial y} = \alpha_s \int d^2k'_t \exp(-\lambda(\Omega_k(y) + \Omega_i(y'))/2) K(k_t, k'_t) \Omega_k(y)
\]

\[
\frac{\partial \Omega_i(y')}{\partial y'} = \alpha_s \int d^2k'_t \exp(-\lambda(\Omega_i(y') + \Omega_k(y))/2) K(k_t, k'_t) \Omega_i(y')
\]

where \(\lambda \Omega_i,k\) reflects the different opacity of protons felt by intermediate parton, rather the proton-proton opacity \(\Omega_{i,k}\)

\(\lambda \sim 0.2\)

solve iteratively for \(\Omega_{ik}(y,k_t,b)\) inclusion of \(k_t\) crucial

Note: data prefer \(\exp(-\lambda \Omega) \rightarrow [1 - \exp(-\lambda \Omega)] / \lambda \Omega\)

Form is consistent with generalisation of AGK cutting rules
## Surprises from LHC diffractive data

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$(tot) (mb)</th>
<th>$B_{el}(0)$ (GeV$^{-2}$)</th>
<th>$\sigma^{SD}$(low M) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KMR (before LHC) predict at 7 TeV</td>
<td>88</td>
<td>18.5</td>
<td>6</td>
</tr>
<tr>
<td>Expt. at 7 TeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTEM</td>
<td>98.6 ±2.2</td>
<td>19.9 ±0.3</td>
<td>2.6 ±2.2</td>
</tr>
<tr>
<td>ATLAS (ALFA)</td>
<td>95.35 ±1.3</td>
<td>19.73 ±0.24</td>
<td></td>
</tr>
</tbody>
</table>

Also $\sigma^{SD}$(high M), $\sigma^{DD}$ predicted larger than TOTEM data

Something is missing in the KMR model
The strong interaction at high energies is one of the most difficult and unrewarding problems of HEP.

......

The LHC data showed that models [8-13] based on pomeron calculus failed to provide significant predictions and were not able to describe the data at high energy.
Very few measurements of $\sigma^{SD}(\text{low } M)$

\[
\begin{align*}
\sigma_{\text{low } M} & \quad = \quad 2-3 \quad = \quad 3 \quad = \quad ? \\
\sigma_{\text{elastic}} & \quad = \quad 7 \quad = \quad 12 \quad = \quad 25.4 \text{ mb}
\end{align*}
\]

Unexpectedly small
Before TOTEM, models predicted $\sigma_{\text{low } M} \sim 6-10 \text{ mb}$
Conventional Reggeon Field Theory assumes all $k_T$’s are limited, and that trajectories and couplings do not depend on energy, $\sqrt{s}$.

LHC data indicates problems --- recall the observed growth of the $\langle k_T \rangle$ of secondaries with energy.
pomeron–$\phi_i$ couplings, $\gamma_i$, are driven by $\langle r_{i,\text{parton}} \rangle$ in $\phi_i$ states

However, $\gamma_i$'s controlled by transverse size of pomeron ($\propto 1/k_{\text{pom}}$) when it becomes smaller than $\langle r_{i,\text{parton}} \rangle \propto 1/k_i$

$$\gamma_i \propto \frac{1}{(k_{\text{pom}}^2 + k_i^2)}$$

where $k_{\text{pom}}^2 = k_0^2 s^{0.28}$

As $s \to \infty$ all $\gamma_i$ become equal, $\gamma_i \propto 1/k_{\text{pom}}^2$ (all $\gamma_i \to 1$)

so dispersion decreases, $\sigma_{\text{SD}} \propto (\langle \gamma_i^2 \rangle - \langle \gamma_i \rangle^2) \to 0$

so dissociation is suppressed as collider energy increases

We call this the $k_T(s)$ effect
Decrease of $\gamma_i$ dispersion means screening brings 2-ch eikonal closer to 1-ch eik. and absorption smaller. As a result it speeds up the growth of $\sigma(tot)$ in the energy interval

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tevatron → LHC → 100 TeV (7 TeV)</th>
<th>TOTEM (7 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(tot)$ mb</td>
<td>77 → 98.7 → 166</td>
<td>98.6 ± 2.2</td>
</tr>
<tr>
<td>$B_{el}(0)$ GeV$^{-2}$</td>
<td>16.8 → 19.7 → 29.4</td>
<td>19.9 ± 0.3</td>
</tr>
<tr>
<td>$\sigma^{SD}(low \ M)$ mb</td>
<td>3.4 → 3.6 → 2.7</td>
<td>2.6 ± 2.2</td>
</tr>
</tbody>
</table>

The $k_T(s)$ effect brings model into agreement with the TOTEM data; also describes high-mass $\sigma^{SD}, \sigma^{DD}$ data.

The acceleration of the growth of $\sigma(tot)$ with $s$ only takes place in the interval where the $\gamma_i(s) \to 1$
Global fit with two-channel eikonal – needed for $\sigma^{SD}(\text{low } M)$

find form factors $F_i(t) \sim \exp(-b_i \sqrt{t})$ (coincidence—like Orear et al.)

Real part important, calculate from dispersion relation
Tension between high-mass $\sigma^{SD}$ data

Global fit exposes some tension between TOTEM and CDF (as well as ATLAS, CMS) single-diffractive data ---- see also Ostapchenko.

Description is a bit above TOTEM $\sigma^{SD}$ data and a bit below CDF, ATLAS, CMS data
Global KMR description below these SD data, yet above TOTEM $\sigma^{SD}$
Preliminary TOTEM results on single diffraction in three Mass bins

CMS integrated over $12 < M < 394$ GeV, just a bit smaller than $8 < M < 350$ GeV of TOTEM, in terms of log M.

<table>
<thead>
<tr>
<th>Mass interval (GeV)</th>
<th>(3.4, 8)</th>
<th>(8, 350)</th>
<th>(350, 1100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prelim. TOTEM data</td>
<td>1.8</td>
<td>3.3</td>
<td>1.4</td>
</tr>
<tr>
<td>CMS data</td>
<td>2.3</td>
<td>4.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Present model</td>
<td>2.3</td>
<td>4.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\( \sigma^{SD}(\text{high M}) \) mb

Uncertainty estimated on slope parameter $B \sim 15\%$ and on cross sections $\sim 20\%$.

Again above TOTEM below CMS.
t dependence of elastic slope shown by TOTEM as deviation from pure exponential \[ \frac{d\sigma(\text{el})}{dt} \sim \exp(19.38 t) \]

TOTEM data (preliminary)

KMR model preliminary

increase due absorptive corrections

decrease due
(i) pion-loop in pom.traj.
(ii) pomeron-proton ff

\[ \sqrt{s} = 8 \text{ TeV} \]
## KMR model values post-LHC

<table>
<thead>
<tr>
<th>(\sqrt{s}) (TeV)</th>
<th>(\sigma_{\text{tot}}) (mb)</th>
<th>(\sigma_{\text{el}}) (mb)</th>
<th>(B_{\text{el}}(0)) (GeV(^{-2}))</th>
<th>(\sigma_{\text{low}M_{SD}}) (mb)</th>
<th>(\sigma_{\text{low}M_{DD}}) (mb)</th>
<th>(\sigma_{\text{SD}}^{\Delta\eta}) (mb)</th>
<th>(\sigma_{\text{SD}}^{\Delta\eta_1}) (mb)</th>
<th>(\sigma_{\text{SD}}^{\Delta\eta_2}) (mb)</th>
<th>(\sigma_{\text{SD}}^{\Delta\eta_3}) (mb)</th>
<th>(\sigma_{DD}^{\Delta\eta}) ((\mu)b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>77.0</td>
<td>17.4</td>
<td>16.8</td>
<td>3.4</td>
<td>0.2</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>7.0</td>
<td>98.7</td>
<td>24.9</td>
<td>19.7</td>
<td>3.6</td>
<td>0.2</td>
<td>2.3</td>
<td>4.0</td>
<td>1.4</td>
<td>145</td>
<td>---</td>
</tr>
<tr>
<td>8.0</td>
<td>101.3</td>
<td>25.8</td>
<td>20.1</td>
<td>3.6</td>
<td>0.2</td>
<td>2.2</td>
<td>3.95</td>
<td>1.4</td>
<td>139</td>
<td>---</td>
</tr>
<tr>
<td>13.0</td>
<td>111.1</td>
<td>29.5</td>
<td>21.4</td>
<td>3.5</td>
<td>0.2</td>
<td>2.1</td>
<td>3.8</td>
<td>1.3</td>
<td>118</td>
<td>---</td>
</tr>
<tr>
<td>14.0</td>
<td>112.7</td>
<td>30.1</td>
<td>21.6</td>
<td>3.5</td>
<td>0.2</td>
<td>2.1</td>
<td>3.8</td>
<td>1.3</td>
<td>115</td>
<td>---</td>
</tr>
<tr>
<td>100.0</td>
<td>166.3</td>
<td>51.5</td>
<td>29.4</td>
<td>2.7</td>
<td>0.1</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

### TOTEM

- \(7\) TeV: \(98.6\) (2.2) mb, \(25.4\) (0.3) mb, \(19.9\) (2.2) mb, \(2.6\) (2.2) mb, \(1.8\) mb, \(3.3\) mb, \(1.4\) mb, \(116\) (25) \(\mu\)b
- \(\Delta\eta\) bins up to 20%
Main Conclusion

The LHC elastic and diffractive data expose deficiencies of the KMR model predictions based on global fits of pre-LHC data:

--- $\sigma(\text{tot})$ is larger than expected
--- $B_{el}(0)$ is larger than expected
--- TOTEM diffractive rates are smaller than predicted

These discrepancies may all be removed by noting that the “pomeron – proton (diffractive estate)” couplings should tend to a common limit as $s \to \infty$, when the decreasing pomeron size starts to control the couplings --- the $k_T(s)$ effect.

Possible experimental check: measure the $p_T$ of B or D mesons as a function of $s$, and see the growth of $p_T$ coming from the larger $p_T$ of the incoming gluons in $gg \to QQ(\bar{\text{bar}})$.
BACK UP SLIDES
Double Dissociation

\[ \frac{B_{SD}^2}{B_{el}B_{DD}} \]

\[ \frac{\sigma_{DD} \sigma_{el}}{(\sigma_{SD})^2} \approx \frac{1.36}{6.8} \frac{0.16}{(0.08)^2} \approx 5.0 \]

Discrepancy reconciled by \( k_T(s) \) effect

TOTEM data

\[ \frac{\sigma_{DD} \sigma_{el}}{(\sigma_{SD})^2} \approx \frac{0.116 \times 25}{(0.9)^2} \approx 3.6 \]
DGLAP $\ln k_t^2$ evolution interval overestimates $\langle k_t \rangle$ and underestimates growth $dN/d\eta$

BFKL $\ln(1/x)$ evolution interval not strongly-ordered in $k_t$
$dN/d\eta = n_p \left(dN_{1-Pom}/d\eta\right)$
$n_p = \text{no. of Poms. grows}$

(a) single BFKL Pom.
(b) DGLAP-based MC
(c) BFKL (inc. enhanced)

$\frac{d\sigma_{subp}}{dk_t^2} \sim \frac{1}{k_t^4}$
$\rightarrow$ tune cutoff to data
$k_{\min} \sim s^a$, $a=0.12$

Enh: $\sigma_{abs} \sim \frac{1}{k_t^2}$
$\rightarrow$ dynamic cutoff $k_{sat}$
$\rightarrow$ besides SD, DD
the same central rapidity interval as that selected by TOTEM, which corresponds to $M_{\text{diss}} = (8, 350)$ GeV at $\sqrt{s} = 7$ TeV. $\sigma_{SD}$ is calculated for the dissociation of one proton.
High-energy pp interactions

Reggeon Field Theory with phenomenological soft Pomeron

smooth transition using QCD / “BFKL” / hard Pomeron

There exists only one Pomeron, which makes a smooth transition from the hard to the soft regime

Can this be the basis of a unified partonic model for both soft and hard interactions ??
A vacuum-exchange object drives soft HE interactions. Not a simple pole, but an enigmatic non-local object. Rising $\sigma_{\text{tot}}$ means multi-Pom diags (with Regge cuts) are necessary to restore unitarity. $\sigma_{\text{tot}}$, $d\sigma_{\text{el}}/dt$ data, described, in a limited energy range, by eff. pole $\alpha_{\text{P}}^{\text{eff}} = 1.08 + 0.25t$

Sum of ladders of Reggeized gluons with, in LLx BFKL, a singularity which is a cut and not a pole. When HO are included the intercept of the BFKL/hard Pomeron is $\alpha_{\text{P}}^{\text{bare}}(0) \sim 1.3 - 1.4$

$\Delta = \alpha_{\text{P}}(0) - 1 \sim 0.35$

$\alpha_{\text{P}}^{\text{eff}} \sim 1.08 + 0.25 t$

up to Tevatron energies

$(\sigma_{\text{tot}} \sim S^\Delta)$

$\alpha_{\text{P}}^{\text{bare}} \sim 1.35 + 0 t$

with absorptive (multi-Pomeron) effects
BFKL stabilized

\[ \Delta = \alpha_p(0) - 1 \]

**LL1/x:** $\Delta_0 = \bar{\alpha}_s \cdot 4 \ln 2$

**NLL1/x:** \[ \Delta = \Delta_0 \left( 1 - 6.5 \bar{\alpha}_s \right) \]

Intercept $\Delta = \alpha_p(0) - 1 \sim 0.35$

$\Delta$ depends weakly on $k_t$ for low $k_t$

Small-size “BFKL” Pomeron is natural object to continue from “hard” to “soft” domain

see, for example, Salam, Zakopane school 1999
Vector meson production at HERA
~ bare QCD Pomeron at high $Q^2$
~ no absorption

$Q^2$

$\alpha'_P(0) \sim 0.25$
after absorption

$\alpha'_P(0) \sim 0$

$\alpha'_P(0) \sim 1.1$
after absorption

$\alpha_P(0) \sim 1.35$

$\alpha_P(0) \sim 1.1$

$\alpha_P(0) \sim 1.35$

$\alpha_P^\text{bare}(0) \sim 0$

$\alpha_P^\text{bare}(0) \sim 1.35$
Phenomenological hints that $R_{\text{bare Pom}} \ll R_{\text{proton}}$

small slope $\alpha'_{\text{bare}} \sim 0$

success of Additive QM

small size of triple-Pomeron vertex

small size of BEC at low $N_{\text{ch}}$

Pomeran is a parton cascade which develops in $\ln(1/x)$ space, and which is not strongly ordered in $k_t$.

However, above evidence indicates the cascade is compact in $b$ space and so the parton $k_t$’s are not too low. We may regard the cascade as a **hot spot** inside the two colliding protons.
Optical theorems

\[ \sigma_{\text{total}} = \sum_X \left| \left( \begin{array}{c} p \\ t \\ p \end{array} \right) \right|^2 = \text{Im} \left( \begin{array}{c} g_N \\ \alpha_{IP}(0) \\ g_N \end{array} \right) \]

High-mass diffractive dissociation

\[ \left( \begin{array}{c} p \\ t \\ p \end{array} \right)^2 = \left( \begin{array}{c} \alpha_{IP}(t) \\ \alpha_{IP}(t) \\ \alpha_{IP}(t) \end{array} \right) = \left( \begin{array}{c} g_N \\ g_N^3 \alpha_{IP}(0) \\ g_N \end{array} \right) \]

at high energy use Regge

\[ g_N^2 \left( \frac{s}{s_0} \right)^{\alpha_{IP}(0)-1} \]

\[ g_N^3 \frac{\alpha_{IP}(0)-1}{\frac{s}{M^2}}^2 \alpha_{IP}(t)-2 \]
Optical theorems

\[ \sigma_{\text{total}} = \sum_X \left| \alpha_{IP}(t) \right|^2 \]

At high energy use Regge triple-Pomeron diag

but screening/s-c unitarity important so \( \sigma_{\text{total}} \) suppressed

High-mass diffractive dissociation

\[ \left| \alpha_{IP}(t) \right|^2 \]

but screening important

\[ g_N^3 g_{3P} \left( \frac{M^2}{s_0} \right)^{\alpha_{IP}(0)-1} \left( \frac{s}{M^2} \right)^{2\alpha_{IP}(t)-2} \]
\[ \exp(-B_{\text{exp}}t) \frac{d\sigma_{\text{el}}}{dt} \text{ (mb/GeV}^2) \]

\[ B_{\text{exp}} = 16.3 \text{ GeV}^{-2} \]

\[ \text{EF710 (filled) + CDF (open)} \]

\[ \text{FNAL (Tevatron)} \]
Schegelsky, Ryskin 1112.3243

\[ B_{el} = B_0 + 2\alpha'_{\text{eff}} \ln\left(\frac{s}{s_0}\right) \]

\[ B_{el} = B_0 + b_2 \ln^2\left(\frac{s}{s_0}\right) \]