Diffractive Physics

- Alternative s- and t-channel definitions of diffraction
- Why study diffraction?
- Partonic description of “soft” high-energy pp interactions, including diffraction
- Survival probability of large rapidity gaps
- “SHRiMPS” Monte Carlo

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1. Diffraction is elastic (or quasi-elastic) scattering caused, via s-channel unitarity, by the absorption of components of the wave functions of the incoming particles

\[ pp \rightarrow pp, \]
\[ pp \rightarrow pX \text{ (single proton dissociation, SD)}, \]
\[ pp \rightarrow XX \text{ (both protons dissociate, DD)} \]

Good for quasi-elastic proc. – but not high-mass dissociation.

2. A diffractive process is characterized by a large rapidity gap (LRG), which is caused by t-channel “Pomeron” exch.
(or, to be more precise, by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers).

Only good for very LRG events – otherwise
Reggeon/fluctuation contaminations.
s-channel unitarity

\[ S S^T = I \quad \text{with} \quad S = I + iT \quad \rightarrow \quad T - T^T = iT^TT \]

elastic unitarity

\[ 2 \text{Im} T_{el}(s,b) = \left| T_{el}(s,b) \right|^2 + G_{inel}(s,b) \]

\[
\begin{align*}
\frac{d^2 \sigma_{tot}}{d^2 b} &= 2 \text{Im} T_{el} = 2 \left( 1 - e^{-\Omega/2} \right) \\
\frac{d\sigma_{el}}{d^2 b} &= \left| T_{el} \right|^2 = \left( 1 - e^{-\Omega/2} \right)^2 \\
\frac{d\sigma_{inel}}{d^2 b} &= 2 \text{Im} T_{el} - \left| T_{el} \right|^2 = 1 - e^{-\Omega} \\
\end{align*}
\]

Opacity / Eikonal \( \Omega(s,b) \geq 0 \)

e.g. black disc

\[ \text{Im} T_{el} = 1, \quad b < R \quad \rightarrow \quad \sigma_{tot} = 2\pi R^2 \]

Prob. of no inelastic inter\( n \)
total absorption gives elastic scatt
Elastic amp. $T_{el}(s,b)$

$$\text{Im} \ T_{el} = \prod_{i} = 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty} \Omega/2$$

(s-ch unitarity)

proton dissociation?

Low-mass diffractive dissociation

introduce diffractive estates $\phi_i, \phi_k$ (combns of $p,p^*,..$) which only undergo "elastic" scattering (Good-Walker)

$$\text{Im} \ T_{ik} = \prod_{k}^{i} = 1 - e^{-\Omega_{ik}/2} = \sum \Omega_{ik}/2$$

what about high-mass diffractive dissociation?
Optical theorems

\[ \sigma_{\text{total}} = \sum_X \left| \mathcal{M} \right|^2 = \text{Im} \left( \frac{g_N}{\alpha_{IP}(0)} \right) \]

High-mass diffractive dissociation

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

\[ g_N^3 g_{3P} \left( \frac{M^2}{s_0} \right)^{\alpha_{IP}(0) - 1} \left( \frac{s}{M^2} \right)^{2\alpha_{IP}(t) - 2} \]
Optical theorems

\[ \sigma_{\text{total}} = \sum_X \left| X \right|^2 = \text{Im} \]

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

High-mass diffractive dissociation

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

but screening even more important
Elastic amp. $T_{el}(s,b)$

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

(s-ch unitarity)

bare amp. $\Omega/2$

(-20%)

Low-mass diffractive dissociation

introduce diffuse states $\phi_i, \phi_k$ (combinations of $p, p^* , ..$) which only undergo “elastic” scattering (Good-Walker)

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

(-40%)

include high-mass diffractive dissociation

$$\Omega_{ik} = \{ M \} + \cdots$$

(SD -80%)
Why study diffraction?

- Understand asymptotics, intrinsic interest
- Describe “min.bias/underlying events”
  40% of $\sigma_{\text{tot}}(\text{LHC})$ due to diffraction, (el. scatt., SD, DD).
  (LHC detectors do not have $4\pi$ geometry)
- $\text{Calc}^n$ of survival probabilities of LRG to soft rescatt.
  (e.g., $\text{pp} \rightarrow p + \text{Higgs} + p$)
- Needed for HE cosmic ray expts. (e.g. Auger).
- To construct an “all purpose” MC, incl. diffraction, and which merges “soft” and “hard” interactions

→ need partonic model of Pomeron
Shortly after the discovery of QCD it was proposed that (colourless) two-gluon exchange had properties of Pomeron exchange:

- vacuum quantum numbers, singularity at \( j=1 \)

Later, using the BFKL formalism, in which the t-ch gluons (rather than hadrons) become Reggeized, it was found possible (for sufficiently large \( k_T \)) to describe HE (low \( x \)) interactions in pQCD.

- BFKL sums up the leading \( (\alpha_s \log 1/x)^n \) contributions and builds up the hard/pQCD/BFKL Pomeron.

- The Pomeron, is not a pole, but a branch cut in the complex angular momentum plane, plus more complicated cuts at HO

- The partonic ladder structure of the Pomeron is generated by the BFKL-like evolution in rapidity

Low, Nussinov
High-energy pp interactions

**soft**

Reggeon Field Theory with phenomenological soft Pomeron

**hard**

pQCD partonic approach

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

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 $\alpha_{P\text{ bare}}(0) \sim 1.35$

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

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

up to Tevatron energies

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

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

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: \[ \Delta = \Delta_0 (1 - 6.5 \bar{\alpha}_s) \]

DGLAP: \[ \alpha_s \ln Q^2 \]

BFKL: \[ \alpha_s \ln 1/x \]

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

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

$\alpha_{P}^{\text{eff}} \sim 1.08 + 0.25t$ up to Tevatron energies

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

$\alpha_{P}^{\text{bare}} \sim 1.35 + 0 t$ with absorptive (multi-Pomeron) effects
Vector meson production at HERA
~ bare QCD Pom. at high $Q^2$
~ no absorption

$\alpha_P(0) \sim 1.1$ after absorption
$\alpha_P^{\text{bare}}(0) \sim 1.35$

$\alpha_P'(0) \sim 0.25$ after absorption
$\alpha_P'^{\text{bare}}(0) \sim 0$
BFKL evolution in rapidity generates 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 changed – so, in principle, we have 3-variable integro-diff. eq. to solve

KMR model uses simplified form of the kernel \( K \) with the main features of BFKL – diffusion in \( \log k_t^2 \), \( \Delta = \alpha_p(0) - 1 \sim 0.35 \)

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

- \( b \) 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

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

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

\[
\frac{\partial \Omega_k(y)}{\partial y} = \bar{\alpha}_s \int d^2 k_t' \exp\left(-\lambda(\Omega_k(y) + \Omega_i(y'))/2\right) K(k_t, k_t') \Omega_k(y)
\]

\[
\frac{\partial \Omega_i(y')}{\partial y'} = \bar{\alpha}_s \int d^2 k_t' \exp\left(-\lambda(\Omega_i(y') + \Omega_k(y))/2\right) K(k_t, k_t') \Omega_i(y')
\]

where \(\lambda \Omega_{i,k}\) reflects the different opacity of protons felt by intermediate parton, rather the proton-proton opacity \(\Omega_{i,k}\) \(\lambda \approx 0.3\)

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

Note: data prefer \(\exp(-\lambda \Omega) \rightarrow \frac{[1 - \exp(-\lambda \Omega)]}{\lambda \Omega}\)

Form is consistent with generalisation of AGK cutting rules
In principle, knowledge of $\Omega_{ik}(y,k_t,b)$ allows the description of all soft, semi-hard pp high-energy data:

$\sigma_{\text{tot}}, \ d\sigma_{\text{el}}/dt, \ d\sigma_{\text{SD}}/dtdM^2, \ \text{DD, DPE...}$

LRG survival factors $S^2$

PDFs and diffractive PDFs at low x and low scales

Indeed, such a model can describe the main features of all the data, in a semi-quantitative way, with just a few physically motivated parameters:

Examples:

(i) $d\sigma/dy \sim s^{0.2}$ like the LHC data for 0.9 to 7 TeV

(ii) gap survival, $S^2$, for $pp \rightarrow p + H + p$
(iii) \( d\sigma_{\text{inel}}/d(\Delta\eta) \) for particles with \( p_T > 200 \text{ MeV} \)

ATLAS data 7 TeV

fluctuations in hadronization

\[ \Delta\eta \sim \ln(s/M^2) \]

"parameter-free" predn \( \sim 1 \text{ mb/unit rap.} \)
(ii) Calculation of $S^2$

average over diff. estates $i,k$ over $b$

$$S^2 = \frac{\sum_{i,k} \int d^2b \left| a_{pi} \right|^2 \left| a_{p'k} \right|^2 |\mathcal{M}_{ik}|^2 \exp(-\Omega_{ik}(s,b))}{\sum_{i,k} \int d^2b \left| a_{pi} \right|^2 \left| a_{p'k} \right|^2 |\mathcal{M}_{ik}|^2}$$

hard m.e. $i.k \rightarrow H$

prob. of proton to be in diffractive estate $i$

survival factor w.r.t. soft $i$-$k$ interaction. Recall that $e^{-\Omega}$ is the prob. of no inelastic scatt. (which would otherwise fill the gap)

<table>
<thead>
<tr>
<th>Values of $S^2$</th>
<th>SD</th>
<th>CD</th>
<th>DD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>LHC</td>
<td>0.06</td>
<td><strong>0.02</strong></td>
<td>0.10</td>
</tr>
</tbody>
</table>

$pp \rightarrow p+H+p$
Double diffractive (exclusive) Higgs production

Advantages of $pp \rightarrow p + H + p$ if $M_H < 140$ GeV

- If outgoing protons are tagged far from IP then $\sigma(M) \sim 1$ GeV (mass also from H decay products)

- **Unique** chance to study $H \rightarrow b\bar{b}$:  
  QCD $b\bar{b}$ background suppressed by $J_z=0$ selection rule  
  $S/B\sim 1$ for SM Higgs $M < 140$ GeV

- Very **clean** environment, even with pile-up---10 ps timing

- **SUSY Higgs**: parameter regions with larger signal $S/B\sim 10$,  
  even regions where conv. signal is challenging and diffractive signal enhanced----$h, H$ both observable

- Azimuth angular distribution of tagged p’s $\rightarrow$ spin-parity $0^{++}$

  but $\sigma \sim 2$ fb
Present data from the LHC

The $<p_T>$ of hadrons measured by ATLAS, CMS, ALICE is smaller than that expected from the **DGLAP-based** MC’s (which have strong-ordering in $k_T$ going from the protons to the central region).

Even after tuning the MC’s, the data have smaller $<p_T>$ and give a larger particle density $dN/dy$.

This indicates the need for a **BFKL-based** MC (with multi-Pomeron absorptive corrections), where we have diffusion in $\log k_T$ and a growth of particle density as we go to large initial energy, that is smaller $x$.

Ostapchenko (based on Kaidalov and co-workers)
Lund dipole cascade model (Flemsburg,Gustafson,Lonnblad)
SHRiMPS (SHERPA) based on KMR model
Existing “all purpose” (DGLAP) Monte Carlos split eikonal

\[ \Omega(s,b) = \Omega_{\text{soft}} + \Omega_{\text{hard(pQCD)}} \]

Seek MC that describes all aspects of minimum bias -- total, differential elastic Xsections, diffraction, jet prod...— in a unified framework; capable of modelling exclusive final states.

SHERPA Monte Carlo based on KMR framework

“SHRiMPS” MC

= Soft-Hard Reactions involving Multi-Pomeron Scatt.

Krauss, Hoeth, Zapp et al
Total, inelastic and elastic cross section at various energies

\[ \sigma_{\text{tot}}, \sigma_{\text{inel}}, \sigma_{\text{el}} \]

SHRiMPS $\Delta = 0.35, \lambda = 0.3, \Lambda^2 = 1.5$
Charged particle $p_{\perp}$ at 7 TeV, track $p_{\perp} > 100$ MeV, for $N_{ch} \geq 2$
Toward $\Sigma p_T$

Away $\Sigma p_T$

Transverse $\Sigma p_T$
Conclusions

• **s-ch unitarity** is important for quasi-elastic scattering or LRG events

• **Multi-Pomeron** exchange diagrams restore unitarity:

• Altho’ \( g_{3P} \approx 0.3 g_N \), high-mass proton dissociation is **enhanced** at the LHC

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

• Unitarity is restored for LRG by small survival prob. \( S^2 \) of gaps e.g. \( S^2 \approx 0.015 \) for \( pp \rightarrow p + H + p \) (\( M_H = 120 \) GeV at 14 TeV)

• LRG also from **fluctuations** in hadrons: ATLAS study different \( p_T \) cuts and \( \Delta \eta \)

• QCD/BFKL Pomeron **can lead to framework** for “soft” physics

• Partonic structure of Pomeron, with multi-Pomeron contributions can describe all soft (\( \sigma_{\text{tot,el,SD}} \)) and semihard (PDFs, minijets..) physics - KMR

• Forms the basis of “all purpose” **MC** - Krauss, Hoeth, Zapp et al
3-ch eikonal description of elastic pp data