**Hard Diffraction – from Blois 1985 to 2005**

(or: Gaps — in my understanding after 20 years)

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- "Historical" mile stones
- **P**omeron problems
- Soft Colour Interaction model phenomenologically successful
- Towards proper QCD theory pert. and non-pert. QCD int’n with colour background field
- Conclusions

- **Before** Blois '85 – soft diffraction
  - quantum hadronic waves
  - **P**omeron-photon analogy
  - **P**omeron-hadron analogy
  - X system fireball or longitudinal?

- **At** Blois '85:
  - X is longitudinal (R608, UA4)
  - hard diffraction introduced!
JET STRUCTURE IN HIGH MASS DIFFRACTIVE SCATTERING

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We suggest that high-$p_T$ jets may emerge from diffractively produced high mass states. Experimental measurements of such high-$p_T$ structure would give new and valuable insight about the nature of the exchanged pomeron, or pomeron-like object. With the assumption of an effective gluon distribution for the pomeron structure, we estimate the cross section for the process $\bar{p} + p \rightarrow \bar{p} + X$, where $X$ contains two high-$p_T$ jets. Observable rates are found at SPS and Fermilab collider energies.

In hadronic interactions it is possible to produce quite massive systems via diffractive excitation. In the diffractive process

$$\bar{p} + p \rightarrow \bar{p} + X \quad \text{(1)}$$

the mass, $M_X$, of the system $X$ is related to Feynman $x_F$ of the recoil antiproton by $M_X^2 = (1 - x_F) s$. Bozzo et al. [1] have recently shown that the gross features of this process, namely scaling of the invariant cross section and $d\sigma/dM_X^2 \sim 1/M_X^2$ at fixed $t$, are valid up to $\sqrt{s} = 540$ GeV at the CERN SPS collider. However, very little is known about the structure of the system $X$.

For large $x_F$, the reaction (1) is believed to proceed via the exchange of a pomeron, as depicted in fig. 1a. Although this phenomenological description agrees rather well with existing data \footnote{Supported by US National Science Foundation Grant PHY79/24766.}, the true nature of the pomeron is still mysterious. It has been suggested \footnote{For recent reviews of diffractive interactions see, for example, refs. [2,3].} that the pomeron may be a system of two or more gluons, but there is no direct experimental evidence for a partonic structure. One might

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1985

The start . . .

Ingelman-Schlein
Physics Letters
B152 (1985) 256
First conference presentation was at Blois 1985 by GI

Jet structure in high mass
diffractive scattering

\[ P \] has a partonic substructure
may be possible to probe it in a
hard scattering process!

\[ \rightarrow \text{Characteristic event topology} \]

\[ \frac{d^2 \sigma_{P 	o X}}{dy dx} = \frac{d^2 \sigma_{P 	o X}}{dy dx} \frac{G_{P 	o X}}{G_{P 	o X}} \]

measured by WA95

total cross-section \( \sigma_{P \to X} \approx 1 \text{ mb} \) extracted
from data using Regge analysis (Tar-Martirosyan, Kaidalov,
Roy, Roberts).

Hard scattering from QCD:
\[ \sigma_{P 	o X} = \int dx dx' \frac{d^2 \sigma_{P 	o X}}{dy dx} \sum_{i,k} f_i(x, \alpha_s) G(x', \alpha_s) \]

\[ \rightarrow \text{a few thousand events/day} \]

What is pomeron structure function?
Assume gluons only
check sensitivity.

\[ xG(x) = 6x(1-x) \quad \text{two gluons} \]
\[ xG(x) = 6(1-x)^5 \quad \text{many gluons} \]
1988: Discovery of hard diffraction by UA8 at CERN $p\bar{p}$S

1992 UA8: $P$'s quark/gluon structure with 'superhard' component
Event Topologies of Deep Inelastic Scattering

1. Diffractive scattering \((M_X = 5 \text{ GeV}, Q^2 = 19 \text{ GeV}^2, W = 123 \text{ GeV})\)

2. Non-diffractive scattering \((M_X = 45 \text{ GeV}, Q^2 = 13 \text{ GeV}^2, W = 93 \text{ GeV})\)
Diffractive DIS at HERA

$$\frac{d\sigma}{dx \, dQ^2 \, dx' \, dt} =$$

$$2\pi\alpha_s^2 \frac{x}{Q^4} (1 + (1 - y)^2) F_2^{D(4)}$$

$$F_2^{D(4)}(x, Q^2, x'_{IP}, t) =$$

$$f(x_{IP}, t) F_{IP}^{IP}(\beta, Q^2)$$

**IP** flux \( \text{IP} \) structure

Fits HERA rapidity gap data using both **IP** and **IR**eggeon

⇒ **IP** parton densities
\( H_0 \)

\[ x_F F_2^{D(3)}(x_F = 0.03, \beta, Q^2) \]

**QCD Altarelli-Parisi eq's fitted to \( F_2^{D(2)}(\beta, Q^2) \)**

\( \rightarrow \) parton densities

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\( H1 1994 + H1 Preliminary 1995 \)

\[ Q^2 = 4.5 \text{ GeV}^2 \]

\[ Q^2 = 12 \text{ GeV}^2 \]

\[ Q^2 = 75 \text{ GeV}^2 \]

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* scaling → scattering on point charges
* weak \( \beta (=z) \) dep
* \( \log Q^2 \) dep. → QCD
* hard partons

\( F_2^{D(2)} \sim F_2^P \) dominated by hard gluons

strong QCD evolution

\( \overline{P} \) model works (apparently)

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Pomeron problems:

- $\mathcal{P}$ model fitted to HERA data → fails for Tevatron data
  $\sigma$ (hard diffr) factor 6–100 too large → need ‘damping’ at high energies, e.g. $\mathcal{P}$ flux ‘renormalisation’

- $\mathcal{P}$ flux & structure not universal ill-defined for virtual $\mathcal{P}$

- Factorisation broken in diffractive $p\bar{p}$ → coherent interactions

- Improper with $\mathcal{P}$ ‘emitted’ from $p$
  soft, long space-time-scale interaction → $\mathcal{P}$–$p$ cross-talk

Alternative approach:

- no ’initial’ $\mathcal{P}$, not in proton wave fcn

- hard pQCD left unchanged
  – not affect by soft interactions

- non-pQCD below $Q_0^2 \sim 1$ GeV$^2$

- $\alpha_s$ large ⇒ large interaction probability e.g. unity for hadronisation!

- colour exchange modifies colour/string topology → different final state

- single model describing all final states
  – diffractive ↔ nondiffractive
Soft Colour Interaction model (SCI)

Soft interactions among partons & remnants (↔ proton colour field) below $Q_0^2 \sim 1 \text{ GeV}^2$

Add-on to Lund Monte Carlo’s LEPTO $(ep)$ and PYTHIA $(p\bar{p})$

$\text{ME} + \text{DGLAP PS} > Q_0^2 \rightarrow \text{SCI model} \rightarrow \text{String hadronisation} \sim \Lambda$

colour ordered parton state \hspace{1cm} rearranged colour order \hspace{1cm} modified final state

Single model describing all final states: diffractive ↔ nondiffractive

Proton remnant with $(1 - x_0)$ important for large gaps

Single parameter $P = const \approx 0.5$

gives probability for soft $(p \approx 0)$

colour-anticolour (gluon) exchange

between parton pairs,

determined from HERA rap-gap data

Gap-size is infrared sensitive observable!

Size $\Delta y_{max}$ of largest gap in DIS events

SCI $\Rightarrow$ plateau in $\Delta y_{max}$ characteristic for diffraction

Small parameter sensitivity

$P = 0.5$

$\cdots P = 0.1$

Large gaps at parton level
normally string across $\rightarrow$ hadrons fill up

SCI $\rightarrow$ new string topologies, some with gaps
Diffractive structure function in DIS

\[ x_{IP} F_2^{D(3)}(Q^2, \beta, x_{IP}) \]

SCI model describes main features of HERA rapidity gap data

Not bad for a one-parameter model!

GAL is an alternative formulation of the model, based on string interactions

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Single diffractive jets, $W$, $Z$, $b\bar{b}$, $J/\psi$ at the Tevatron

$$R_{\text{hard}} = \frac{1}{\sigma_{\text{tot}}^\text{hard}} \int_{x_F}^1 dx_F dF \frac{d\sigma_{\text{hard}}}{dx_F}$$

<table>
<thead>
<tr>
<th>$R_{\text{hard}}$ [%]</th>
<th>Exp. observed</th>
<th>SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>dijets</td>
<td>0.75 ± 0.10</td>
<td>0.7</td>
</tr>
<tr>
<td>$W$</td>
<td>1.15 ± 0.55</td>
<td>1.2</td>
</tr>
<tr>
<td>$W$ (DØ)</td>
<td>1.08 $^{+0.21}_{-0.19}$</td>
<td>1.2</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>0.62 ± 0.25</td>
<td>0.7</td>
</tr>
<tr>
<td>$Z$ (DØ)</td>
<td>1.44 $^{+0.62}_{-0.54}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$J/\psi$ (CDF)</td>
<td>1.45 ± 0.25</td>
<td>1.4</td>
</tr>
</tbody>
</table>

SCI → gap & $c\bar{c}$ colour octet → singlet → $J/\psi$

SCI model OK, Pomeron model too high, default PYTHIA too low
SCI also correctly describes two-gap events (Double Pomeron Exchange)

SCI model phenomenologically successful — Why?
Captures most essential QCD dynamics $\Rightarrow$ theory emerging . . .
QCD factorisation and rescattering

QCD factorization theorem \(\Rightarrow\) separation of hard and soft

Quark parton density function (PDF) is given by

\[
f_{q/N} \sim \int dx^- e^{-ix_B p^+ x^-/2} \langle N(p) | \bar{\psi}(x^-) \gamma^+ W[x^-; 0] \psi(0) | N(p) \rangle_{x^+ = 0}
\]

where \(W[x^-; 0] = \text{P} \exp \left[ig \int_0^{x^-} dw^- A^+_a(0, w^-, 0_\perp) t_a\right]\) is the Wilson line

Expanding the exponential we have

\[
W[x^-; 0] \sim 1 + g \int \frac{dk^+_1}{2\pi} \frac{\tilde{A}^+(k^+_1)}{k^+_1 - i\varepsilon} + g^2 \int \frac{dk^+_1 dk^+_2}{(2\pi)^2} \frac{\tilde{A}^+(k^+_1) \tilde{A}^+(k^+_2)}{(k^+_1 + k^+_2 - i\varepsilon)(k^+_2 - i\varepsilon)} + \ldots
\]

corresponding to the diagrams

\[
\begin{align*}
\begin{array}{c}
\times \quad p_i \\
\Rightarrow k_i
\end{array} & + \begin{array}{c}
\times \quad p_i - k_i \\
\Rightarrow k_i
\end{array} & + \begin{array}{c}
\times \quad p_i - k_i - k_2 \\
\Rightarrow k_i \\
\Rightarrow k_2
\end{array} & + \ldots
\end{align*}
\]

for rescattering of the struck quark via longitudinal \((A^+)\) instantaneous (in \(x^+)\) gluon exchange. No \(A^\perp\) within Ioffe coherence length \(x^- \sim 1/m_p x_B\)


QCD rescattering basis for SCI

1. A soft gluon with $k_1^+/p^+ \sim x_{IP}$ splits into large $q\bar{q}$ pair
   $g \rightarrow q\bar{q} \Rightarrow f(\beta) \sim \beta^2 + (1 - \beta)^2$

2. The $\gamma^*$ scatters and a large size $q - \bar{q}$ ‘dipole’ is formed

3. Instantaneous gluon exchanges may make dipole color singlet
   • At large $M_X$, $q\bar{q} - g$ dipole dominates
     – soft gluon splits into $gg$ pair
       $g \rightarrow gg \Rightarrow f(\beta) \sim 1/\beta$
     – compact $q\bar{q}$ pair not resolved
   • Higher order emissions do not destroy the rapidity gap!
     $k_\perp \gg p_2\perp$ and $k^+ \ll p_2^+$
     $\Rightarrow$ rapidity of $k$ larger than that of $p_2$

The ‘pomeron remnant’ is soft — first splitting is in the sea
Consequences for diffractive DIS

- Same hard sub-process in diffractive and non-diffractive events
- Same $Q^2$ dependence in diffractive and inclusive DIS
- Same energy ($W$ or $x_B$) dependence in diffractive and inclusive DIS

$\Rightarrow \sigma_{\text{diff}}/\sigma_{\text{tot}}$ independent of $x_B$ and $Q^2$, as observed in data

- Amplitudes from rescattering dominantly imaginary, as expected for diffraction
- Rescattering gluons have small momenta $\Rightarrow \beta$ dependence of diffractive PDF's from underlying (non-perturbative) $g \rightarrow q\bar{q}$ and $g \rightarrow gg$ processes

- Effective IP flux:
  $$f_{IP/p}(x_{IP}) \sim g(x_{IP}, Q^2_0)$$

Effective IP structure function:
  $$f_{q/IP}(\beta, Q^2_0) \sim \beta^2 + (1 - \beta)^2$$
  $$f_{g/IP}(\beta, Q^2_0) \sim 1/\beta$$
Hard diffraction in hadron–hadron collisions

- Diffractive factorization theorem does not hold
- Data shows $\sim 1\%$ diffraction instead of $\sim 10\%$ in DIS
- Both target and projectile coloured $\rightarrow$ different rescattering $\rightarrow$ lower probability for colour neutralization
- DPE possible
- SCI model reproduces data
Summary

SCI model OK with data:

- gap events in DIS
- leading protons/neutrons in DIS
- diffractive jets, $W, Z, b\bar{b}, J/\psi$
  at Tevatron
- high-$p_\perp J/\psi, \psi', \Upsilon$ at Tevatron
- $J/\psi, \psi'$ in fixed target $\pi A$ and $p A$

Not bad for simple (one-parameter) model!

∃ alternative/related models

Parton rescattering theory in QCD:

- Hard sub-process universal
  not affected by soft interaction
- PDF $\sim$ LF wave fcn $\otimes$ soft rescattering
- Rescattering via soft gluons,
  instantaneous in LF time
  May shield colour $\rightarrow$ rapidity gap
- Soft rescattering does not resolve
  hard emissions
- Different colour environments
  (particles/collisions)
  $\Rightarrow$ diffraction/gaps process dependent
Semiclassical approach

Buchmüller, Hebecker et al.

\[ \xi F_2^{D(3)} = 0.04 \]

\[ Q_2^2 = 4.5 \text{ GeV}^2 \]

\[ \beta = 0.1 \]

\[ Q_2^2 = 7.5 \text{ GeV}^2 \]

\[ \beta = 0.2 \]

\[ Q_2^2 = 9 \text{ GeV}^2 \]

\[ \beta = 0.4 \]

\[ Q_2^2 = 12 \text{ GeV}^2 \]

\[ \beta = 0.65 \]

\[ Q_2^2 = 18 \text{ GeV}^2 \]

\[ \beta = 0.9 \]

\[ Q_2^2 = 28 \text{ GeV}^2 \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ \xi \]

\[ P \]

proton rest frame Breit frame

\[ p \text{ rest frame: } \gamma \rightarrow q\bar{q} \text{ or } q\bar{q}g \text{ dipole} \]

soft interaction with proton colour field estimated by Wilson loop over colour field

Color singlet exchange \( \Rightarrow \) diffraction

Leading twist diffraction from large dipoles, with one soft parton (mostly gluon) \( (\text{cf. aligned jet model}) \)

which tests the large distances in the proton field

Model fits HERA \( F_2^{D(3)} \) data

**Perturbative QCD approach for two-gluon exchange**

*Comparison with the BEKW model*  

(Bartels, Ellis, Kowalski and Wüsthoff, 1998)

\[
\begin{align*}
\text{(qq)}_T & = c_T \cdot F_{qq}^T + c_L \cdot F_{qq}^L + c_g \cdot F_{qqg}^T \\
F_{qq}^T & = (x_{IP}/x_{IP}) n_T(Q^2) \cdot \beta(1-\beta), \quad \beta \text{ from theory} \\
F_{qq}^L & = (x_{IP}/x_{IP}) n_L(Q^2) \cdot \frac{Q_0^2}{Q^2 + Q_0^2} \cdot \ln(\frac{7}{4 + \frac{Q^2}{4\beta Q_0^2}})^2 \cdot \beta^3(1-2\beta)^2, \\
F_{qqg}^T & = (x_{IP}/x_{IP}) n_g(Q^2) \cdot \ln(1 + \frac{Q^2}{Q_0^2}) \cdot (1-\beta)^\gamma
\end{align*}
\]

From data, \( n_L(Q^2) \approx 0 \) and

\( n_T(Q^2) \approx n_g(Q^2) \approx n_1 \ln(1 + \frac{Q^2}{Q_0^2}) \)

\( \therefore c_T = 0.117 \pm 0.003, c_L = 0.171 \pm 0.012 \)

\( c_g = 0.0093 \pm 0.0003, n_1 = 0.066 \pm 0.003 \)

\( \gamma = 8.32 \pm 0.51, \chi^2/ndf = 132/198 \)

• (qq)\_L only substantial at very large \( \beta \)

(\(qq\))\_T dominates at \( \beta > 0.15 \)

(\(qq\))\_T dominates at small \( \beta \)
Gap between jets ⇒ hard QCD exchange

Rapidity gap between a pair of jets
→ $|t|$ across gap is large
→ different from “normal” diffraction

Elastic parton-parton scattering by hard colour singlet exchange (hard pomeron)

High energy limit $s/|t| \gg 1 \Rightarrow$ amplitude dominated by terms $\sim [\alpha_s \ln(s/|t|)]^n$

BFKL equation resums these terms, with
- virtual corrections
- reggeization of exchanged gluons

Evidence for BFKL dynamics ⇐

Enberg, GI, Motyka, PL B524 (2002) 273
Numerical solution of BFKL eqn.
with non-leading corrections
consistency constraint & running coupling
in Pythia reproduces Tevatron data

$E_T$ and $\Delta \eta$ dependences OK
asymptotic Mueller-Tang ⇒ wrong $E_T$-dep.
Absolute normalisation OK
correct gap survival probability with SCI that destroy gaps
Conclusions after 20 years of hard diffraction

• Good progress:
  Discovery of hard diffraction in $p\bar{p}$ and $ep \Rightarrow$ lots of good data
  Developments of theory/models $\Rightarrow$ working phenomenologies
  $\Rightarrow$ New and major part of our research field

• My view:
  $IP$ not in proton wave fcn, but effect of scattering
  Interaction with colour field interesting approach
  $\leftrightarrow$ avoids $IP$ problems (conceptual, flux)
  $\leftrightarrow$ one model for gap and no-gap final states

• But, still gaps in my (our) understanding

• Future with interesting problems
  New ideas/approaches
  New collaborations
  Lots of fun . . . $\Rightarrow$ Blois 2007 will also be interesting