Diffraction in ep and pp collisions

Anna Stasto

RIKEN BNL & Penn State U. & INP Krakow
Outline

- Diffraction in ep(A) (EIC)
  - Inclusive case
  - Exclusive processes (vector mesons)
- Diffraction in pp (RHIC)
  - elastic, single-diffractive, double diffractive
  - Central exclusive processes
Diffractive events

Characteristic feature is the existence of the rapidity gap.

- $s \gg -t, m_X^2, m_Y^2$
- vacuum quantum number exchange
- QCD: two gluons in color singlet state

- DIS: $s \gg Q^2 \gg \Lambda_{QCD}^2, -t, m_p^2$
- semihard processes: $x = Q^2 / s \ll 1$
- perturbative QCD applicable
Soft and hard diffraction

Two basic features of diffraction:

- rising cross sections with energy $s$
- large rapidity gaps: $\eta = -\log \tan(\theta/2)$ (color singlet exchange)

\[ \begin{align*}
X & \quad Y \quad 2\theta \\
\end{align*} \]

**Soft diffraction** (no hard scale): $\sigma \sim s^{\alpha_P(0)} \quad \alpha_P(t) = 1.08 + 0.25 \cdot t$

$pp \rightarrow p + p \quad \gamma p \rightarrow V(\rho,\omega,\phi) + p$

**Hard diffraction** (with hard scale): $1.1 < \alpha_P(0) < 1.4$

$pp \rightarrow jj + pp \quad \gamma^* p \rightarrow X + p \quad \gamma^* p \rightarrow V + p \quad \gamma p \rightarrow J/\psi + p$

In general, theoretical description very difficult:

**Soft diffraction**: phenomenology based on Regge models

**Hard diffraction**: difficulty of combining soft (gap) + hard(pQCD evolution)
Diffraction in ep

\[ e + p \rightarrow e' + p' + X \]

Proton stays intact and separated by a rapidity gap

- \( M^2 \) diffractive mass
- \( t = (p - p')^2 \) momentum transfer
- \( \Delta \eta = \ln 1/x_{IP} \) Rapidity gap

\[ x_{IP} = \frac{Q^2 + M^2 - t}{Q^2 + W^2} \]

momentum fraction of the Pomeron with respect to the hadron

\[ \beta = \frac{Q^2}{Q^2 + M^2 - t} \]

momentum fraction of the struck parton with respect to the Pomeron

\[ x = x_{IP} \beta \]

Bjorken x
**Diffraction in ep**

**Diffractive cross section**

\[
\frac{d^4 \sigma^D}{d\beta dQ^2 dx_{IP} dt} = \frac{2\pi \alpha^2_{em}}{\beta Q^4} \left(1 + (1 - y)^2\right) \left\{ F_2^D - \frac{y^2}{1 + (1 - y)^2} F_L^D \right\}
\]

**Diffractive structure functions**

\[
F_2^{D(4)} \quad F_L^{D(4)}
\]

**Dimensionless diffractive structure function**

\[
F^{D(3)}_{T,L}(x, Q^2, x_{IP}) = \int_{-\infty}^{0} dt \ F^{D(4)}_{T,L}(x, Q^2, x_{IP}, t)
\]

Collinear factorization works for diffractive processes.  

**Collinear approach (NLO):**

- twist 2

\[
C_{2,S,G}^{S,G}
\]

- coefficient function

\[
(C \otimes F)(\beta) = \int_{\beta}^{1} dz \ C(\beta/z) \ F(z).
\]

J.C. Collins
Collinear factorization, diffractive parton distributions

\[ S_D = \sum_{f=1}^{N_f} e_f^2 \beta \left\{ q_D^f(\beta, Q^2, x_{IP}, t) + \bar{q}_D^f(\beta, Q^2, x_{IP}, t) \right\} \]

\[ G_D = \beta g_D(\beta, Q^2, x_{IP}, t) \]

\[ \beta = x/x_{IP} \]

plays the role of the Bjorken variable in diffractive DIS

One can interpret the DDIS parton distributions as conditional probabilities for finding a parton with small fraction of momentum \( x \) in the proton, provided that the proton stays intact and it looses fraction of its momentum given by \( x_{IP} \).

DGLAP evolution with respect to the variable Q

\( (x_{IP}, t) \) are external parameters with respect to the DGLAP evolution

Regge factorization ansatz often used

\[ q_D^f(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) q_D^f(\beta, Q^2) \]

\[ g_D(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) g_D(\beta, Q^2) \].

Diffractive scattering occurs through the exchange of the Pomeron, parametrized by the flux, and the hard scattering of the photon on the quark which is in the Pomeron, and carries a fraction of its momentum \( \beta = x/x_{IP} \).
Universal description in the leading order in $\log(s)$ \( (N. N. Nikolaev, B. G. Zakharov) \)

- Scattering amplitude \( (A = \gamma^*, \gamma, V) \)

\[
\mathcal{A}(\gamma^* + p \rightarrow A + p) = \int d^2r dz \, \Psi_A^{*} N_{q\bar{q}} \Psi_{\gamma}
\]

- \( N_{q\bar{q}}(r, b, Y = \ln(1/x)) \) is the dipole scattering amplitude

- Find \( N_{q\bar{q}} \) from

\[
\sigma_{tot} \sim \text{Im} \, \mathcal{A}(\gamma^* + p \rightarrow \gamma^* + p)
\]

and test in DDIS processes.

Factorization at small $x$
Universality of dipole amplitude

**Inclusive**

\[ \sigma_{\text{tot}} = \int_{r,z} |\Psi(r, z, Q)|^2 \hat{\sigma}_{\bar{q}q}(x, r) \]

\[ x \simeq \frac{Q^2}{W^2} \ll 1 \]

**Diffractive**

\[ \frac{d\sigma_{\text{dif}}}{dt} |_{t=0} = \frac{1}{16\pi} \int_{r,z} |\Psi(r, z, Q)|^2 \hat{\sigma}_{\bar{q}q}^2(x_{\text{IP}}, r) \]

\[ x_{\text{IP}} \simeq \frac{Q^2 + M^2}{W^2} \ll 1 \]

Dipole cross section:

\[ \hat{\sigma}_{\bar{q}q}(x, r) = 2 \int d^2b \left( 1 - S(x, r, b) \right) \]
Diffraction and saturation

Golec-Biernat, Wusthoff

Dipole cross section

\[ \sigma_T \sim \frac{\sigma_0}{Q^2 R_0^2} + \frac{\sigma_0}{Q^2 R_0^2} \log(Q^2 R_0^2) + \frac{\sigma_0}{Q^2 R_0^2} \]

\[ \sigma_T^D \sim \frac{\sigma_0^2}{Q^4 R_0^4} + \frac{\sigma_0^2}{Q^4 R_0^4} + \frac{\sigma_0^2}{Q^4 R_0^4} \]

\[ R_0 = \frac{1}{Q_s} \]

Overlap function in the dipole model

Inclusive: dominated by relatively hard component

Diffractive: dominated by the semi-hard momenta

Contribution of different dipole sizes
**Diffraction and saturation**

Golec-Biernat, Wuesthoff

Diffraction is a collective phenomenon. Explore relation with saturation.

\[
s_{T} \sim \frac{\sigma_0}{Q^2 R_0^2} \begin{cases} 
& r < 2/Q \\
& 2/Q < r < 2R_0 \\
& r > 2R_0 
\end{cases}
\]

\[
\sigma_T^D \sim \frac{\sigma_0^2}{Q^4 R_0^4} + \frac{\sigma_0^2}{Q^2 R_0^2} + \frac{\sigma_0^2}{Q^2 R_0^2} \quad R_0 = \frac{1}{Q_s}
\]

\[
\sigma_L^D \sim \frac{\sigma_0^2}{Q^4 R_0^4} + \frac{\sigma_0^2}{Q^4 R_0^4} \log(Q^2 R_0^2) + \frac{\sigma_0^2}{Q^4 R_0^4} \cdot
\]

Inclusive: dominated by relatively hard component

Diffractive: dominated by the semi-hard momenta

overlap function in the dipole model:
Diffractive to inclusive ratio in ep

Constant ratio naturally explained in the saturation model.

Golec-Biernat, Wuesthoff
Diffraction in eA

Two possibilities for the diffractive events in nuclei:

Coherent
No-breakup

Incoherent
With breakup into nucleons
The gap is still there

Challenge for the experiment: measure the breakup, forward neutrons.
Diffractive to inclusive ratio in eA

Predictions give 20%-40% for $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ in the regime down to $10^{-6}$

Cazaroto, Carvalho, Goncalves, Navarra

Kowalski, Lappi, Venugopalan
Exclusive diffraction of VM

- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude.
- Suitable process for estimating the ‘blackness’ of the interaction.
- $t$-dependence provides an information about the impact parameter profile of the amplitude.

Differential cross section for exclusive VM production

$$\frac{d\sigma}{dt} = \frac{1}{16\pi} |A_{el}(x, \Delta, Q)|^2$$

Amplitude for elastic scattering

$$A_{el}(x, \Delta, Q) = \sum_{\hat{h}, \hat{h}^*} \int d^2r \, dz \, \psi_{\gamma^*}^{\hat{h}, \hat{h}^*}(z, r; Q) A_{el}^{q\bar{q}-p}(x, r, \Delta) \psi_{\gamma}^{\hat{h}, \hat{h}}(z, r)$$

Elementary amplitude for elastic scattering

$$A_{el}^{q\bar{q}-p}(x, r, \Delta) = \int d^2b \, \tilde{A}_{el}^{q\bar{q}-p}(x, r, b)e^{ib\Delta} = 2 \int d^2b \, [1 - S(x, r, b)] e^{ib\Delta}$$

Optical theorem

$$\sigma_{tot}^{q\bar{q}-p}(x, r) = Im \, iA_{el}^{q\bar{q}-p}(x, r, \Delta = 0).$$
Impact parameter profile

Munier, Stasto, Mueller

Profile extracted from the HERA data

Kowalski, Teaney

Extrapolations of the S matrix towards lower values of $x$

$t$-dependence vs impact parameter dependence.

What is the characteristic size of the proton in strong interactions?

$1 - S^2$ probability that a dipole passing the proton will induce an inelastic reaction at the given impact parameter

Models indicate significant ‘blackness’ for central impact parameter

$Q^2 \sim 5 \text{ GeV}^2$

$x = 10^{-5} - 10^{-6}$
Diffraction in pp

General (soft) processes with rapidity gaps at hadron-hadron colliders

- Elastic scattering
- Single diffractive scattering
- Double diffractive scattering

Difficulty: no hard scale...

Gribov Regge-Pomeron theory: multiple exchanges and interactions of Pomerons

<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>single Pomeron exchange</td>
<td>multiple Pomeron exchange. unitarization</td>
<td>proton excitations in the intermediate states</td>
<td>High mass diffraction. Single diffraction dissociation</td>
<td>Double diffractive dissociation</td>
</tr>
</tbody>
</table>

\[
\frac{\sigma_{el} + 2\sigma_{SD} + \sigma_{DD}}{\sigma_{tot}} \sim
\]

For Tevatron and LHC
Diffraction in pp

Unfortunately, no complete solution to the Gribov Pomeron calculus so far...

What we know up to now:

- Partonic description of hard Pomeron at small coupling (BFKL Pomeron)
- Triple Pomeron vertex
- Resummation of certain classes of fan diagrams (fan diagrams, BK equation)
- Gribov- Pomeron calculus does indeed emerge from QCD (Kovner-Lublinsky)

Difficulties:

- Hard Pomeron valid for pQCD regime, unknown how to continue to strong coupling
- Large higher order corrections, need of resummation beyond leading log1/x
- Needs to resum a complete set of diagrams (loops)
- Couplings to target and projectile particles
- ...

One needs to rely on many model assumptions
Diffraction in pp: phenomenology

(E. Avsar, G. Gustafson, L. Lönnblad, 0709.1368 [hep-ph])

- Dipole evolution at small x
- Include Pomeron loops
- Include constraints from kinematics
- Model confinement
- Monte-Carlo framework
- Simultaneous description of deep inelastic data and hadron-hadron cross sections (total, elastic, diffractive)

Also: Khoze, Martin, Ryskin; Levin et al; Kaidalov et al; Ostapchenko;...

DIS

Hadron-hadron
Diffraction and the shape of proton

- Diffractive/elastic scattering gives important information about the shape of the proton and its change with the increasing energy
- Need precise measurement of the elastic slope \( B(t) = \frac{d(\ln d\sigma_{el}/dt)}{dt} \)
- Small \( t \) region is responsible for periphery of the proton. Opacity (density) is small hence large contribution to the survival probability of gaps.
- Determination of ratio of real/imaginary part of the scattering amplitude
- Large \( t \) region is crucial for understanding what happens in the centre of the interaction region: how dense the system is, how close to the unitarity is the amplitude.
- RHIC could give us information about the B slope in the energy between low energy measurements and Tevatron/LHC range.
- pp vs ppbar differences? Should in principle vanish at higher energies. RHIC can help us answer these questions.
Central exclusive production in diffraction

Khoze, Martin, Ryskin
Harland-Lang, Khoze, Ryskin, Stirling
Pasechnik, Szczurek, Terayev

\[ pp(\bar{p}) \rightarrow p + X + p(\bar{p}) , \]

- At higher energies, LHC, one can study new states (Higgs, SUSY) produced exclusively via such mechanism
- At lower energies, Tevatron and RHIC, crucial test of theoretical framework of QCD
- Tevatron measured central exclusive production with various states (talk by Christina Mesropian)
- Test of energy dependence, RHIC-Tevatron-LHC

Particularly interesting is production of heavy quarkonia

\( \chi_c \) \( \chi_b \)

Valuable tool for analysing NRQCD, physics of bound states etc...
General framework

Harland-Lang, Khoze, Ryskin, Stirling

\[ T = \pi^2 \int \frac{d^2 Q_\perp \mathcal{M}}{Q_\perp (Q_\perp - p_{1\perp})^2 (Q_\perp + p_{2\perp})^2} f_g(x_1, x_1', Q_1^2, \mu^2; t_1) f_g(x_2, x_2', Q_2^2, \mu^2; t_2), \]

\( Q_T \) factorization assumed

\( \mathcal{M} \) is the amplitude for \( gg \rightarrow X \) sub-process

\( f_g \) unintegrated skewed parton (here gluon) distributions in the proton

Factorized t-dependence

\[ f_g(x, x', Q^2, \mu^2; t) = f_g(x, x', Q^2, \mu^2) F_N(t), \]

Proton form factor, phenomenological parametrization

\[ F_N(t) = \exp(bt/2), \text{ with } b = 4 \text{ GeV}^{-2} \]
\[
\frac{d\sigma}{dy_X} = \int d^2p_{1\perp} d^2p_{2\perp} \frac{|T(p_{1\perp}, p_{2\perp})|^2}{16^2\pi^5} S_{\text{eik}}^2(p_{1\perp}, p_{2\perp}),
\]

\(p_{1T}, p_{2T}\) transverse momenta of the protons

Survival factor in impact parameter space

\[
S_{\text{eik}}^2(b_t) = \exp(-\Omega(s, b_t)).
\]

Slow variation with the energy

<table>
<thead>
<tr>
<th></th>
<th>(\chi_0)</th>
<th>(\chi_1)</th>
<th>(\chi_2)</th>
<th>(\eta_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>0.058</td>
<td>0.15</td>
<td>0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>LHC (7 TeV)</td>
<td>0.037</td>
<td>0.11</td>
<td>0.084</td>
<td>0.13</td>
</tr>
<tr>
<td>LHC (10 TeV)</td>
<td>0.033</td>
<td>0.10</td>
<td>0.078</td>
<td>0.11</td>
</tr>
<tr>
<td>LHC (14 TeV)</td>
<td>0.029</td>
<td>0.091</td>
<td>0.072</td>
<td>0.10</td>
</tr>
<tr>
<td>RHIC</td>
<td>0.092</td>
<td>0.23</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

Need to include survival factor due to the enhanced graphs
Cross section estimates for central exclusive production

Harland-Lang, Khoze, Ryskin, Stirling

\[ c \bar{c} \]

\begin{tabular}{|c|c|c|c|c|}
\hline
\( \sqrt{s} \) (TeV) & 0.5 & 1.96 & 7 & 10 & 14 \\
\hline \( \frac{d\sigma}{d\chi_c}(pp \to pp(J/\psi + \gamma)) \) & 0.57 & 0.73 & 0.89 & 0.94 & 1.0 \\
\hline \( \frac{d\sigma(1^+)}{d\sigma(0^+)} \) & 0.59 & 0.61 & 0.69 & 0.69 & 0.71 \\
\hline \( \frac{d\sigma(2^+)}{d\sigma(0^+)} \) & 0.21 & 0.22 & 0.23 & 0.23 & 0.23 \\
\hline
\end{tabular}

Table 3: Differential cross section (in nb) at rapidity \( y_\chi = 0 \) for central exclusive \( \chi_{cJ} \) production via the \( \chi_{cJ} \to J/\psi\gamma \) decay chain, summed over the \( J = 0, 1, 2 \) contributions, at RHIC, Tevatron and LHC energies, and calculated using GRV94HO partons, as explained in the text.

Interesting prediction: the energy increase by factor 10 only gives a moderate increase in the cross section.

Compensating effects:

- Higher energy: increase of the gluon density at small \( x \)
- This comes at a price: survival factors drop down
- Larger rapidity gap, larger enhanced absorption

RHIC can pin down the magnitude of these effects at lower energies. Comparison with Tevatron can constrain the models for the absorption.
Summary

- **Diffraction is a very intriguing phenomenon in QCD collisions.**
- Theoretical description very difficult: diffraction involves soft physics. Collective phenomenon: proton stays intact; large distance scales involved; factorization breaking when going from ep to pp.
- **Interplay between saturation physics and diffraction.**
- **Possibilities for EIC:**
  - Inclusive diffraction on nuclei. Diffractive to total ratios.
  - Exclusive vector meson production. Is the energy dependence (x dependence) for VM in eA the same/different as in ep?
  - Measurement of t dependence in exclusive vector meson production provides an insight into the impact parameter profile of the target.
- **Possibilities for RHIC:**
  - Standard questions: t- slope of elastic cross section. What about t=0? Extraction of rho parameter.
  - Central exclusive production. Especially heavy quarkonia. Pin down the theoretical uncertainties on the survival probabilities.
  - Other: search for the Odderon? Importance of the spin in diffraction: not much is known here, anything that will be measured will provide valuable information about the nature of diffraction (for example: are asymmetries vanishing?).