Probing soft QCD with exclusive reactions

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XIV Hadron Physics 2018, Florianopolis
Soft QCD: theory topics

✓ Low-x QCD phenomenology

**Measurements:** hard (inclusive/exclusive) QCD cross sections in the forward region

**Theory issues:** Parton saturation, non-linear QCD evolution, small-x (u)PDFs, quarkonia production mechanisms, $kt$-factorisation, multi-parton scattering, factorisation-breaking effects, testing ground for UHE CRs interactions in the atmosphere ...

✓ Hard/soft diffraction

**Measurements:** Total pp cross section, hard diffraction cross sections (heavy-Q, di-jets, Drell-Yan, vector bosons, quarkonia) and exclusive photoproduction (with forward p/n tagging)

**Theory issues:** Pomeron structure, gap survival, long-range fluctuations, diffractive factorisation breaking, color-screening effects, initial-state interactions, intrinsic heavy flavor, hadronisation, nucleon tomography, quarkonia production mechanisms, UE structure ...
**Diffraction: theory vs experiment**

✓ **The definition of diffraction is not unique**

**Theoretically:**

“The diffractive process is caused by t-channel Pomeron exchange i.e. by the exchange corresponding to the rightmost singularity in the complex angular momentum plane with vacuum quantum numbers.” A. Martin

**Experimentally:**

★ intact protons and/or rapidity gaps (no hadron activity)
★ gap definition

*mapping is not one to one!*

✓ **QCD modelling of diffraction is a major problem**

★ fluctuations during the hadronisation process (protons from recombination? gap size?)
★ low vs high mass diffractive dissociation
★ soft vs hard Pomeron
★ hard-soft factorisation breaking, etc

**Peripheral phenomenon!**

- elastic scattering
- single diffraction
- double IP exchange
- inelastic scattering

\[
\frac{dN}{dy} = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}
\approx - \ln \tan \frac{\theta}{2} = \eta \text{ pseudorapidity}
\]
Soft Pomeron

- interpreted in QCD as a >two gluon exchange
- not a simple pole but enigmatic non-local object

\[ \alpha_P(t) \approx \alpha_P(0) + \alpha'_P \ t \approx 1.08 + (0.25 \text{ GeV}^{-2}) \ t \]

Rise in total and elastic CS: “discovery” of Pomeron!

Pomeron “flux”

\[ \frac{d\sigma}{dt \ d\xi} = f_{IP/A}(\xi, t) \ \sigma_{BP}(M_X^2, t) \quad M_X^2 = \xi s \]

\[ \sigma_{BP}(M_X^2, t) \propto (M_X^2)^{\alpha_P(0) - 1} \quad \text{at large } M_X \]

Albrow, Coughlin, Forshaw, Prog.Part.Nucl.Phys 65 (2010) 149
Birth of hard diffraction: QCD modelling of Pomeron

**Introduce a hard scale to probe**
“parton skeleton” of the Pomeron!

**Access to gluon content of the Pomeron!**

**factorisation formula**

\[
\frac{d\sigma(ep \to e + 2 \text{ jets} + X' + Y)}{dt \cdot d(x_{IP} \cdot z_{IP})} = \sum_{i,j} \int dy f_{\gamma/e}(y) \int dx_\gamma f_{j/\gamma}(x_\gamma, \mu_F^2) \times \\
\times \int dt \int dx_{IP} \int dz_{IP} d\hat{\sigma}(ij \to 2 \text{ jets}) f_i^D(z_{IP}, \mu_F^2, x_{IP}, t).
\]

- Diffractive PDFs are non-universal
- They can not be exported to describe other hard diffractive processes (e.g. in pp)
- We need to calculate the survival probability of the LRG’s which is process-dependent
Regge factorisation scheme

One considers two different factorisations:

- **diffractive fact. n.**: proven by Collins for a hard diffractive scattering (hep-ph/9709499)
- **Regge fact. n.**: relates the power of $x_P$ in diffractive DIS to the power of $S$ in hadron-hadron elastic scattering and can be broken

\[ f_i^D(z_{IP}, \mu_F^2, x_{IP}, t) = f_{IP}(x_{IP}, t) f_{i,IP}(z_{IP}, \mu_F^2) \]

Berera, Soper PRD’96

**Pomeron PDFs**

- Universal (soft) Pomeron flux in the proton (Regge theory)
- DGLAP-evolved parton density in the Pomeron

**At larger $x$ subleading “Reggeon” is to be included**

$\ x_{IP} > 0.01$

\[ ... + f_{IR}(x_{IP}, t) f_{i,IR}(z, Q^2) \]

**Reggeon PDFs** taken from pion (GRV)

Fit $z$ and $Q^2$ dependence at fixed $x_{IP}$ and $t$

- Flux parametrisation
  \[ f(x_{IP}, t) = \frac{A e^{B t}}{x_{IP}^{2 \alpha(t) - 1}} \]
  with $\alpha(t) = \alpha(0) + \alpha'$

✓ DPDFs are extracted from global NLO fits of inclusive diffraction data at HERA
✓ Predictions based upon extracted DPDFs are fairly consistent with theoretical models
✓ Important tool for diffractive factorisation breaking studies (especially in had-had coll.)
**Single diffractive pp cross section at high energies**

**Tevatron**

\[
\frac{\sigma(\text{hard diffraction})}{\sigma(\text{hard})} \sim 1\% \ll 10\% \sim \frac{\sigma(\text{diffractive DIS})}{\sigma(\text{DIS})}
\]

**HERA**

\[
q_{IP}(x, Q^2) \text{ and } g_{IP}(x, Q^2) \text{ fitted to DIS } F_2^D
\]

Non-universality!

Factor 10 too large diffractive cross section at Tevatron!

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

factorisation is broken by gap survival effects!

Factor of \(\sim 8 \, (~5)\) suppression at \(\sqrt{s} = 1800 \, (540) \, \text{GeV}\)

Rockefeller Model (by K Coulianos)

\[
f_{IP/p}(\xi, t) \Rightarrow N_s^{-1} \cdot f_{IP/p}(\xi, t)
\]

\[
N_s \equiv \int_{\xi(\text{min})}^{\xi(\text{max})} d\xi \int_{t=0}^{-\infty} dt f_{IP/p}(\xi, t) \sim s^{2\epsilon}
\]

Pythia 8-MBR implementation
Soft vs hard Pomeron

**Soft diffraction**

only soft scales  \( R \sim 1 \text{ fm} \)
elastic scattering, low mass diffraction etc

**Hard diffraction**

at least, one hard scale  \( \mu^{-1} \ll R \)

Regge Field Theory with phenomenological DL Pomeron
\[
\alpha_p^{\text{eff}} \sim 1.08 + 0.25 t
\]

perturbative QCD (BFKL) “bare”Pomeron
\[
\alpha_p^{\text{bare}} \sim 1.35 + 0 t
\]
Beyond factorisation: hadronic diffraction via dipoles

Incoming hadrons are not elementary — experience soft interactions dissolving them leaving much fewer rapidity gap events than in ep scattering

interplay between hard and soft fluctuations is pronounced!

Diffractive Drell Yan (semi-hard)

superposition has a Good-Walker structure

\[ \propto \sigma(\vec{R}) - \sigma(\vec{R} - \alpha \vec{r}) = \frac{2\alpha \sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} (\vec{r} \cdot \vec{R}) + O(r^2) \]

Diffractive DIS \( \propto r^4 \propto 1/M^4 \) vs diffractive DY \( \propto r^2 \propto 1/M^2 \)

★ diffractive factorisation is automatically broken

★ any SD reaction is a superposition of dipole amplitudes

★ gap survival is automatically included at the amplitude level on the same footing as dip. CS

★ works for a variety of data in terms of universal dip. CS

Sophisticated dipole cascades are being put into MC: Lund Dipole Chain model (DIPSY) Ref. G. Gustafson, and L. Lönnblad

SD DY/gauge bosons

SD heavy quarks

RP et al 2011,12

Kopeliovich et al 2006
Sensitivity to the color string topology fluctuations

Edin, Ingelman, Rathsman

\[ ME + DGLAP \ PS > Q_0^2 \]

colour ordered parton state

\[ \rightarrow \]

SCI model

rearranged colour order

\[ \rightarrow \]

String hadronisation \( \sim \Lambda \)

modified final state

Single model describing all final states: diffractive \( \leftrightarrow \) nondiffractive

Gap events not 'special', but fluctuation in colour/hadronisation

Soft gluons can only change phase of propagating quark and it's color — should be resumed!

\[
M(\delta) = \int d^2b \exp(-ib) \hat{M}^{\text{hard}}(b)\hat{M}^{\text{soft}}(b)
\]

reconnection probability becomes dynamical

\[
\hat{M}^{\text{soft}}(b, r) \propto (1 - e^A \ln \frac{|b-r|}{|b|})
\]

Edin, GI, Rathsman

Single parameter model

diffractive events from fluctuations in color string topology!
Diffractive W production in high-energy pp collisions

Features:

✓ clean environment (color singlet)
✓ well-defined hard scale (tests of QCD factorisation)
✓ high sensitivity to the production mechanism
✓ large enough cross section to be experimentally observed and tested

\[ z = \frac{|p_z|/p_{\text{beam}}}{pp \rightarrow p[W^\pm X]} \]

6.425 Perugia 0
- proton no CR
- proton GAL
- proton SCI
- cluster ×0.1
- \( m_{cl} < 1.5 \text{ GeV} \)

\( \sqrt{s} = 14 \text{ TeV} \)

6.425 Perugia 11
- proton no CR
- proton GAL
- proton SCI
- cluster ×0.1
- \( m_{cl} < 1.5 \text{ GeV} \)

\( \sqrt{s} = 14 \text{ TeV} \)

- background for anomalous couplings studies with forward detectors
  see C. Royon

SD/ND ~ 1\% for SCI/GAL close to Tevatron data!

Mainly gluon-initiated diffraction at large Z!
Saturation studies via coherent diffraction

Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case ($e_A^* > e_{VA}$).

Experimental separation of incoherent diffraction based mainly on ZDC.

Unusual features can arise from deviations from Gaussian matter distribution, e.g., characteristic dips in model by Rezaeian et al. within LHeC sensitive $t$ range.

Saturation effects

$\gamma^* p \rightarrow J/\psi + p$

$\gamma^* A \rightarrow J/\psi A$

$t = 0$, $Q^2 = 0$

$\gamma^* A \rightarrow J/\psi A$

$Q^2 = 0$

With breakup
More exclusive/diffractive reactions...

Examples of typical exclusive reactions studied so far...

many covered in SuperChic and FPMC Monte Carlo generators

Example: Diffractive di-jets at Tevatron

![Graph showing Dijet cross sections at Tevatron](image)

Example: Diffractive di-jet at the LHC

![Graph showing Dijet cross sections at LHC](image)
Nucleon tomography: phase space distributions

What do we know about the nucleon?

It is a complicated object!

\[ H(k, P, \Delta) = (2\pi)^{-4} \int d^4z \, e^{izk} \times \langle p(P + \frac{1}{2}\Delta)|\bar{q}(-\frac{1}{2}z)\Gamma q(\frac{1}{2}z)|p(P - \frac{1}{2}\Delta)\rangle \]

Partons also experience a transverse motion at a given impact parameter!

\[ f(k, P) \quad \text{parton correlation function} \]

\[ \int dk^- \quad \text{TMD} \]

\[ W(x, k, b) \quad \text{Wigner distribution} \]

\[ \int d^2k \quad \xi = 0 \]

\[ \int d^2b \]

\[ f(x, b) \quad \text{impact parameter distribution} \]

\[ \int d^2k \quad \xi = 0 \]

\[ \int dx x^{n-1} \quad \xi = 0 \]

\[ \sum_{k=0}^{n} A_{nk}(\Delta^2) (2\xi)^k \quad \text{GFFs} \]

Figure from Ref. M. Diehl, arXiv: 1512.01328
Accessing the gluon Wigner from exclusive dijets in UPC


Photon-target cross section:

\[
\frac{d\sigma^{p\gamma}}{dy_1 dy_2 d^2k_1 \cdot d^2k_2} = N_c \alpha_{em} (2\pi)^2 q^+ \delta(k_1^+ + k_2^+ - q^+) \sum_f e_f^2 2z(1-z)(z^2 + (1-z)^2) |\vec{M}|^2
\]

Nucleus-target cross section:

\[
\frac{d\sigma^{pA}}{dy_1 dy_2 d^2k_1 \cdot d^2k_2} \approx \omega \frac{dN}{d\omega} \frac{2(2\pi)^4 N_c \alpha_{em}}{P^2} \sum_f e_f^2 z(1-z)(z^2 + (1-z)^2) (A^2 + 2 \cos 2(\phi - \phi_\Delta) AB)
\]

Separate measurements of A and B

full information about the gluon Wigner!
✓ Definition of diffraction is not unique but understood
✓ We have seen the Pomeron at work both in soft and hard regimes, as well as in the transition region — marginal agreement with data is achieved despite large uncertainties
✓ Matching between “soft” DL and “hard” BFKL Pomerons is a big challenge, but there is a progress
✓ Many theoretical developments in QCD-ish modelling of soft/hard Pomeron
✓ Diffraction is highly sensitive to small-x/long distance and multiple exchange physics
✓ Such effects as Regge/diffractive factorisation breaking, fluctuations in hadronisation, color screening need a proper universal treatment
✓ Further MC development/improvements and measurements are required