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2. Determination of (n)PDFs.
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Bibliography:
Diffraction:

- At HERA, ~10% of the events have a pseudorapidity gap in hadronic activity (or intact detected proton): **diffractive**.

- They measure the probability of the proton to remain intact in the scattering, while producing some activity far from the proton: exchange of a colourless object, called **Pomeron**.

*Diffraactive event in ZEUS at HERA*
Diffraction:

Standard DIS variables:
- electron-proton cms energy squared:
  \[ s = (k + p)^2 \]
- photon-proton cms energy squared:
  \[ W^2 = (q + p)^2 \]

Diffractive DIS variables:
- inelasticity
  \[ y = \frac{p \cdot q}{p \cdot k} \]
- Bjorken \( x \)
  \[ x = \frac{-q^2}{2p \cdot q} \]
- (minus) photon virtuality
  \[ Q^2 = -q^2 \]

- momentum fraction of the Pomeron w.r.t hadron
  \[ \xi \equiv x_{IP} = \frac{Q^2 + M_X^2}{Q^2 + W^2} - t \]
- momentum fraction of parton w.r.t Pomeron
  \[ \beta = \frac{Q^2}{Q^2 + M_X^2 - t} \]
- 4-momentum transfer squared
  \[ t = (p - p')^2 \]

\[ x_{Bj} = x_{IP} \beta \]
Diffractive SF and factorisation:

\[
\frac{d^3\sigma^D}{dx_{IP} \, dx \, dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} \, Y_+ \, \sigma_r^{D(3)}(x_{IP}, x, Q^2)
\]

\[
\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}
\]

\[
Y_+ = 1 + (1 - y)^2
\]

\[
F_{T,L}^{D(3)}(x, Q^2, x_{IP}) = \int_0^1 \, dt \, F_{T,L}^{D(4)}(x, Q^2, x_{IP}, t)
\]

\[
F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}
\]
For fixed $t$, $x_p$, collinear factorisation holds (Collins): diffractive PDFs expressing the conditional probability of finding a parton with momentum fraction $\beta$ with the proton remaining intact.

\[
\frac{d^3\sigma^D}{dx_{IP}\,dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} \, Y_+ \, \sigma_r^D(3)(x_{IP}, x, Q^2)
\]

\[
\sigma_r^D(3) = F_2^D(3) - \frac{y^2}{Y_+} \, F_L^D(3)
\]

\[
Y_+ = 1 + (1 - y)^2
\]

\[
F_{T,L}^D(3)(x, Q^2, x_{IP}) = \int_0^0 dt F_{T,L}^D(4)(x, Q^2, x_{IP}, t)
\]

\[
F_2^D(4) = F_T^D(4) + F_L^D(4)
\]

\[
d\sigma^{ep\rightarrow eXY}(x, Q^2, x_{IP}, t) = \sum_i f_i^D \otimes d\hat{\sigma}^{ei} + \mathcal{O}(\Lambda^2/Q^2)
\]
To extract DPDFs, an additional assumption is made: Regge factorisation that seems to work for not large too $x_P$.

\[
 f_i^D(x, Q^2, x_{IP}, t) = f_{IP/P}(x_{IP}, t) f_i(\beta = x/x_{IP}, Q^2)
\]

Pomeron flux

\[
 f_{IP/P}(x_{IP}, t) = A_{IP} \frac{e^{B_{IP} t}}{x^2 \alpha_{IP}(t) - 1}
\]

$f_i(\beta, Q^2)$ evolve with DGLAP evolution equations: fits to HERA data (additional contributions at large $x_P = \xi$ and small $\beta$).
Limitations at HERA (check of Regge factorisation, size and shape of the diffractive glue) can be overcome with EICs:

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

\[ x = \beta \xi < 0.4 \]

\[ 0.001 < y < 0.96 \]

\[ \beta < 1 \]

\[ 1.3 \text{ GeV}^2 \]

\[ 50 \text{ TeV} \]

\[ 60 \text{ GeV} \]

\[ 7 \text{ TeV} \]

\[ \text{HERA} \]

\[ \text{ZEUS-LRG} \]

\[ \text{H1-LRG} \]

\[ \text{HERA-FLPS} \]
Diffraction in ep and shadowing:

- Diffraction in ep is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.

nDPDFs at EICs:

- Diffractive PDFs have never been measured in nuclei, where incoherent diffraction becomes dominant at relatively small -t: interplay between shadowing and gap survival probability.

- Challenging experimental problem (LPS + ZDC?).

Coherent diffraction

Coherent p/A stays intact
Incoherent p/A breaks up

\[ \xi\sigma_{\text{red}} \] for e-Pb at \( E_{\text{Pb}/A} = 2.76 \text{ TeV} \) \( E_e = 60 \text{ GeV} \)

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ Q^2 = 100 \text{ GeV}^2 \]

\[ Q^2 = 10^2 \text{ GeV}^2 \]

\[ Q^2 = 10^3 \text{ GeV}^2 \]

\[ Q^2 = 10^4 \text{ GeV}^2 \]
Exclusive production:

- Exclusive production gives a 3D scan of the hadron/nucleus: gluon GPDs with vector mesons, quark GPDs with DVCS. It can be studied for $Q=0$ in UPCs, precision and $Q>0$ in EICs.

Off-diagonal matrix elements, appear in amplitudes.
Exclusive production:

- Exclusive production gives a 3D scan of the hadron/nucleus: gluon GPDs with vector mesons, quark GPDs with DVCS. It can be studied for Q=0 in UPCs, precision and Q>0 in EICs.

High acceptance essential!!!
It should not be the gluon PDF but the GPD:
- NLO estimated, not complete.
- Real part via dispersion relations:

\[ \frac{d\sigma}{dt}^{\text{LO}} (\gamma^* p \to J/\psi p) \bigg|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left( \frac{\alpha_s(\overline{Q}^2)}{\overline{Q}^4} xg(x, \overline{Q}^2) \right)^2 \left( 1 + \frac{Q^2}{M_{J/\psi}^2} \right) \]

NR WF

by hand (Regge)

\[ R_g = \frac{2^{2\lambda+3} \Gamma(\lambda + \frac{5}{2})}{\sqrt{\pi} \Gamma(\lambda + 4)} \]

\[ \lambda(Q^2) = \partial [\ln(xg)] / \partial \ln(1/x) \]

\[ \frac{\text{Re} A}{\text{Im} A} \approx \frac{\pi}{2} \lambda \]
The dipole picture:

- Long-lived (virtual) photon fluctuation, \( x < (2m_N R)^{-1} \sim 0.1 A^{1/3} \).

- Unified description of inclusive, diffractive and exclusive processes.

\[
\Delta^2 = -t
\]

\[
d\sigma^{\gamma^* p \to E p}_{T,L} = \frac{1}{16\pi} \left| A^{\gamma^* p \to E p}_{T,L} \right|^2 (1 + \beta^2) R_g^2 \beta = \tan \left( \frac{\pi \lambda}{2} \right), \lambda \equiv \frac{\partial \ln \left( A^{\gamma^* p \to E p}_{T,L} \right)}{\partial \ln(1/x)}
\]

\[
A^{\gamma^* p \to E p}_{T,L} = 2i \int d^2 r \int_0^1 dz \int d^2 b \ (\Psi_{\bar{E}}^{*} \Psi)_{T,L} e^{-i[b-(1-z)r]\cdot\Delta N(x,r,b)}
\]

- Correction to non-diagonal gluon PDF (skewedness) introduced.
- Boosted Gaussian VM WF fitted to leptonic decays.
- qqbarg component in diffraction, not yet in exclusive VM.
Elastic vector mesons (I):

\[ e + Au \rightarrow e + J/\psi + Au^{(*)} \]

\[ F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}} \]

\[ t = \Delta^2/(1-x) \approx \Delta^2 \]

Elastic vector mesons (II):

- Incoherent diffraction sensitive to fluctuations: hot spots? that determine the initial stage of HIC, the distribution of MPIs,

\[
\frac{d\sigma(\gamma p \rightarrow J/\psi p)}{dt} \bigg|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} \left| \left\langle A(x, Q^2, \tilde{A})_{T,L} \right\rangle \right|^2
\]

\[
\frac{d\sigma(\gamma p \rightarrow J/\psi Y)}{dt} \bigg|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} \left( \left| \left\langle A(x, Q^2, \tilde{A})_{T,L} \right\rangle \right|^2 - \left| \left\langle A(x, Q^2, \tilde{A})_{T,L} \right\rangle \right|^2 \right)
\]


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1703.09256
DVCS:

- Quark GPDs can be studied in DVCS.

- The evolution equations for TMDs and GPDs could be tested at the EICs.