Diffraction at HERA

On behalf of H1 and ZEUS collaborations

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1st part:
Inclusive diffraction at HERA and the dynamical structure of the proton at low $x$...

2nd part:
The spatial structure of the nucleon from exclusive processes

Perspectives and Summary
Diffraction on nuclear waves

ELASTIC AND INELASTIC SCATTERING OF 1.37 GeV α-PARTICLES FROM $^{40,42,44,48}$Ca


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Received 6 October 1976
(Revised 9 December 1976)

$|t|^{1/2}$ dependence presents the standard diffractive pattern (optics)

Amplitude($q, k$) $\sim i k/2\pi \int db \ e^{ibq} D(b, k)$

Extract the structure in neutron for Calcium

Fig. 3. Differential cross sections of inelastic scattering of 1.37 GeV α-particles from the $3^-$ and $5^-$ states in $^{40}$Ca and the $2^+$ states in $^{43}$Ca and $^{44}$Ca.
Subnuclear waves

Probe the proton with a lepton beam
\[ \Rightarrow \text{Virtual photon (} \gamma^* \text{) of resolution } \sim 1/Q \]

Diffraction of subnuclear waves at HERA \([E_{\text{cm}}=320 \text{ GeV}]\)

\[ \gamma^* p \rightarrow X p \]

The proton is left intact (or quasi-intact)
** Color singlet exchange
** Presence of a GAP in rapidity (between X and p')

\[ \delta [\text{fm}] \simeq \frac{200 \text{ MeV}}{Q} \]
Total luminosity=1 fb⁻¹ for H1+ZEUS

350 collaborators per experiment (H1+ZEUS) +HERMES
Diffractive events are observed

Deep Inelastic Scattering (DIS) => $F_2$

Diffractive Deep Inelastic Scattering (DDIS) => $F^D_2$

This is the GAP with no particle
Experimental selection methods

Scattered proton in Leading Proton Spectrometers (LPS)

Limited by statistics and p-tagging systematics

`Large Rapidity Gap' (LRG) adjacent to outgoing (untagged) proton

Limited by p-diss systematics
Diff events are produced with a quite large rate

Lower $\eta_{\text{MAX}}$ means that the GAP with no particle is large
...illustration on all HERAII data (Lumi=330 pb$^{-1}$)
Why DIFF rate is large @ HERA (low x)?

...certain (Fock) states of the virtual photon $|\psi_k\rangle$ do not feel the strong interaction, while others are strongly affected...

$\Rightarrow$ Large fluctuations in the absorption coefficients of these states...

This is (obviously) linked to the dominance of the gluon density at small $x$.

It finds a natural extension in the dipole approach:

$T(b) \sim \alpha_s r^2 xG(x, 1/r^2)/(\pi R^2) \times \exp(-b^2/b_0^2)$
Kinematics and notations

Standard DIS variables ...

\[ x = \text{momentum fraction } q/p \]
\[ Q^2 = |\gamma^* 4\text{-momentum squared}| \]

Additional variables for diffraction ...

\[ t = \text{squared 4-momentum transfer at proton vertex} \]
\[ x_{IP} = \text{fractional momentum loss of proton} \]
\[ (\text{momentum fraction } IP/p) \]
\[ \beta = x / x_{IP} \]
\[ (\text{momentum fraction } q/IP) \]

Most generally \( ep \rightarrow eXY \) ...

In most cases here, \( Y=p \), (small admixture of low mass excitations)
Diffractive cross sections (definition)

Select diffractive events
Correct for detector effects
Derive cross sections (// F2)

\[ \frac{d^3 \sigma^D}{d x_P d\beta dQ^2} = \frac{2\pi \alpha^2_{\text{em}}}{\beta Q^4} \left[ 1 + (1 - y)^2 \right] \sigma_r^{D(3)}(x_P, \beta, Q^2) \]

\[ \sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1 + (1 - y)^2} F_L^{D(3)} \approx F_2^{D(3)}(x_P, \beta, Q^2) \]
Results \( (x_{IP} F_2^D)[Q^2] \): LRG selection
F2 versus F_{2D}^D

Each bin in $\beta$ is ONLY ~1-2% of the stat of a bin in $x$ in F2 plot
Scaling($Q^2$) of DIFF versus DIS

At large $\beta$ values: scaling violations still >0 for diffraction, <0 for standard DIS

$=>$ Large gluon content expected for DIFF
Diffraction at HERA is still a very active field: Below the abstracts for new results submitted to ICHEP 2010

419) The Longitudinal Diffractive Structure Function, $F^D_L$ [H1]
762) DIS with Leading Protons or Large Rapidity Gaps [ZEUS]
764) A QCD Analysis of ZEUS Diffractive Data [ZEUS]
421) Inclusive Measurement of Diffractive DIS [H1]
423) Measuring $F^D_2$ with a Very Forward Proton Spectrometer [H1]
418) Diffractive DIS Cross Sections with a Leading Proton [H1]
414) Leading Neutron Production in DIS [H1]
425) Diffractive Jet Production in DIS with a Leading Proton [H1]
416) Diffractive Dijet Photoproduction in ep Collisions [H1]
771) Leading Proton Production in DIS [ZEUS]
773) Dijet Photoproduction for Leading Neutron Events [ZEUS]
It took >10 years of analysis to reach this:

Sideway pb: time scale for these difficult analysis VS time scale of the appreciation of a research work...
Results ($x_{IP} F_L^D$)
Results \( (x_{IP} F_2^D) \): Proton Tag selection

Quadruple-differential cross sections! \( \sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t) \)

Integrated over \( t \) in this example H1-ZEUS comparison

- All available data used by both collaborations \( \rightarrow x_{IP} \sim 0.1 \)

- H1 HERA-II (157 pb\(^{-1}\)) yields higher \( Q^2 \) data

- Good H1-ZEUS agreement on kinematic dependences

- 15% difference in overall normalisation compatible with uncertainties
Comparison between F2D measurement methods

Proton Tag / LRG

• LRG selections contain typically 20% p diss
• No significant dependence on any variable
• ... well controlled, precise measurements
One major interest of F2D measurements

As already mentioned, inelastic inclusive diffraction is intimately linked to the structure of the proton at small $x$... with an better sensitivity to the gluon density (at small $x$) than standard F2

And at first order (in the development of dipole states) it can be written:

\[ \sigma_{\text{incl}} \sim |d^2r dz| \Psi(r,z,Q)|^2 T(x,r) \]
\[ d\sigma_{\text{diff}} /dt \sim 1/16\pi |d^2r dz| \Psi(r,z,Q)|^2 T^2(x_{IP},r) \]

\[ x \approx Q^2/W^2 << 1 \]
\[ x_{IP} \approx (Q^2 + Mx^2)/W^2 << 1 \]
One major interest of F2D measurements

This provides a direct sensitivity to possible saturation effects of the gluon density at small $x$ in the proton.

More precisely,

(a) diffractive scattering is dominated by dipoles of size $\sim 1/Q_s$

which gives at the experimental level

(b) $\sigma_{\text{diff}}/\sigma_{\text{incl}} \sim \text{constant}(x)$ at fixed $Q^2$ and $\beta$

(up to $\log[Q^2/Q_0^2]$ terms)
With no saturation effects (first approx)

As mentioned previously [with T $\sim xG$]

$\sigma_{\text{diff}} \sim \text{Coeff} \otimes [xG(x,Q^2)]^2$

$\sigma_{\text{DIS}} \sim \text{Coeff}' \otimes [xG(x,Q^2)]$

@ low $x$: $\sigma_{\text{DIS}} (F2) \sim 1/x^\lambda$ ($\lambda \sim 0.3$) $\Rightarrow \sigma_{\text{diff}} \sim 1/x^{2\lambda}$

And $\sigma_{\text{diff}}/\sigma_{\text{DIS}} \sim 1/x^\lambda$ function of $x$!
What happens (at first approx)

At sufficiently high scale @ high energy, gluon saturation cuts off the large dipole sizes at the semi-hard scale $1/Q_s$!

(see E.Iancu and many others)
Another view: QCD factorisation for diffractive events

QCD (Collins) factorisation at fixed $x_{IP}$ & $t$

Proton vertex factorisation of the $x_{IP}$ dependence (hypothesis not rooted in QCD)

\[ x_{IP} = 1 - \frac{p'^*}{p^*} \]
\[ t = (p' - p)^2 \]

\[ f_{i}^{D}(x, Q^2, x_{IP}, t) = f_{i}^{IP/p}(x_{IP}, t) \cdot f_{i}^{IP} \]
Before quants: experimental support of the Collins factorisation

Look at the ratio of the diffractive to inclusive cross section

Observation: $Q^2$ dependence approximately similar for diff and incl...

Support the fact that evolution equations ($Q^2$) can be applied for diff... (// standard inclusive F2)
\[ \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha' t \]

\[ \alpha_{IP}(0) = 1.11 \pm 0.02 \pm 0.02 \]

// « soft Pomeron »
(consistent between H1/ZEUS)

\[
\text{B (low } x_{IP} \text{)} \sim 6-7 \text{ GeV}^{-2} \text{ for H1 and ZEUS}
\]
Why the «Regge» factorisation is reasonable?

\[ a_D^{P}(x_P, z, Q^2) = f_P(x_P) a_P^P(z, Q^2) \]

This means that if we divide \( F_2^D \) by \( f_{IP}(x_{IP}) \) the dependence in \((z=\beta, Q^2)\) must be the same for all \( x_{IP} \) values (small \( x_{IP}<10^{-2} \))...
Diffractive PDFs

Large gluon content (in the IP) carrying the main part of the momentum

Again (with another view) => Enhanced sensitivity to ‘saturation effects’ of the gluon density at small $x$ in the proton

As anticipated with the $>0$ scaling violations till large $\beta$

Large uncertainty @ large $\beta$
1st part:
Inclusive diffraction at HERA and the dynamical structure of the proton at low $x$... Few words on Tevatron

2nd part:
The spatial structure of the nucleon from exclusive processes

Summary
Processes under study

Exclusive production of Vector Mesons or real photon (DVCS)

$DVCS := \text{Deeply Virtual Compton Scattering}$

$t$ is the momentum exchange (squared) at the proton vertex
Nucleon structure from the Basic principle

The Fourier transform of the square root of the cross section (VM) is directly related to the S matrix

\[ S(x, r_Q, b) = 1 - \frac{1}{2\pi^{3/2} N(Q)} \int d^2 \Delta e^{-i\Delta b} \sqrt{\frac{d\sigma}{dt}} \]

\( b := b_\perp \) is the impact parameter in the proton

\( N(Q) \) is a flux factor (coming from the overlap of \( \gamma^* \) and VM wave function)

\( S \) tells us how dense the nucleon looks like!

\( S=0 \) means blackness (unitarity limit)

and \( 1-S^2 \) is the interaction probability of the \( \gamma^* \) (or dipole) that hits the nucleon at impact parameter \( b \)

Program: Measure \( d\sigma/dt \), extract \( S \) and then conclude on the proton structure
Analysis done for $x < 10^{-2}$ with HERA data on $\rho$ exclusive production

Large error at small $b$ due to the lack of data for $|t| > 0.6$ GeV$^2$

Interaction probability $> 50\% (75\%)$ in the center of the proton $b < 0.3$ fm (« black disk »)

And then, proton is more transparent when $b$ is increasing ('grey area') (more transparent also at larger $Q^2$ - smaller dipole (probe) size - similar to optics)

Similar results for $J/\psi$
Imaging the quark/gluon structure of the proton

Historical measurement:

In 1955, R. Hosftadter measures the elastic cross section ep -> ep
\[ \frac{d\sigma}{dt} \sim |F.F.[-\Delta^2]|^2 \]  \hspace{1cm} (F.F.:=Form Factor) \hspace{1cm} \Delta=p'-p

Then \[ \rho(r) = \int d^3\Delta/(2\pi)^3 \exp(i\Delta r) F.F.(-\Delta^2) \]

=> Charge Radius of the proton ~ 0.8 fm
Imaging the quark/gluon structure of the proton

**Historical measurement:**
In 1955, R. Hosftadter measures the elastic cross section $ep \rightarrow ep$

$$\frac{d\sigma}{dt} \sim |F.F.[-\Delta^2]|^2$$

(F.F. := Form Factor) $\Delta = p' - p$

Then $\rho(r) = \int d^3\Delta/(2\pi)^3 \exp(i\Delta r) F.F.(-\Delta^2)$

$\Rightarrow$ Charge Radius of the proton $\sim 0.8$ fm

**DVCS (Deeply Virtual Compton Scattering):** $\gamma^* p \rightarrow \gamma p$

is extending this seminal work:

$$\frac{d\sigma}{dt} \sim |H(x,-\Delta_T^2)|^2$$

with $x \sim x_{\text{Bjorken}}$

where $H(x,t)$ generalises the concept of FF for given $x$
**Imaging the quark/gluon structure of the proton**

**Historical measurement:**
In 1955, R. Hosftadter measures the elastic cross section $ep \rightarrow ep$
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Then
\[ \rho(r) = \int d^3\Delta (2\pi)^3 \exp(i\Delta r) F.F.(-\Delta^2) \]

\[ \Rightarrow \text{Charge Radius of the proton} \sim 0.8 \text{ fm} \]

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is extending this seminal work:
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where $H(x,t)$ generalises the concept of FF for given $x$

\[ q(x,r_T) = \int d^2\Delta_T/(2\pi)^2 \exp(i\Delta_T r_T) H(x,-\Delta_T^2) \]

$H$ is called a GPD
Generalised PDF

With DVCS, we probe the spatial extend (Tansverse) of parton$[x]$ in the nucleon
**GPDs as a generalisation of PDFs and F.F.**

**Form factors**
- Location of partons in nucleon

**Parton distributions**
- Longitudinal momentum fraction $x$

**Generalised parton distributions (GPDs)**
- Longitudinal momentum fraction $x$ at transverse location $b$

*Only known framework to gain information on 3D picture of hadrons*
First, we need to prove experimentally that DVCS measured (at HERA) is a hard process: $e^+ p \rightarrow e^- \gamma p$

In average:

$\sigma_{DVCS} \sim W^\delta$ with $\delta \sim 0.6$

** Hard (QCD) process

** Factorisation makes sense

Note: $\delta \sim 0.2 - 0.3$ for soft reactions
Experimental results

Very efficient parameterisation of the $t$ dependence at low $x \sim 10^{-3}$
\[ d\sigma_{\text{DVCS}}/dt \sim \exp(bt) \]

In average $Q^2 > 5 \text{ GeV}^2$
\[ b = 5.41 \pm 0.14 \pm 0.31 \text{ GeV}^{-2} \]
which gives $\Rightarrow$
\[ [\langle r_T^2 \rangle]^{1/2} = 0.64 \pm 0.02 \text{ fm} \]
Comments on $b$ and $[<r_T^2>]^{1/2}$

For $<Q^2> = 10 \text{ GeV}^2$ and $<x> = 1.2 \times 10^{-3}$

$$b = 5.41 \pm 0.14 \pm 0.31 \text{ GeV}^{-2}$$

$$[<r_T^2>]^{1/2} = 0.64 \pm 0.02 \text{ fm}$$

The statistical limit is reached

Transverse width of the parton distribution (probed in the reaction)

The spatial structure of the proton (in slices of $x$):
cloud of slow (low $x$) gluons/sea-quarks and a core of fast (large $x$) quarks...

Sea quarks and gluons
More refined theoretical analysis of $[<r_T^2>]^{1/2}$

From Mueller et al. ('09), global fits of low $x$ DVCS data (H1/ZEUS)+F2
With different hypothesis on $t$ dependences (and initial param of $H$)...

Profile distributions for sea-quarks and gluons in the proton @ $x=10^{-3}$

$Q^2=4 \text{ GeV}^2$

$[<r_T^2>_{q \text{ or } g}]^{1/2} \sim 0.64 \text{ fm} : \text{OK}$
**Reminder:**
Diffraction on Calcium gives the internal structure of the Calcium...

Similarly for exclusive processes

\[ f(t) \Rightarrow \text{impact parameter distributions} \]

Resolve the spatial structure of the nucleon

\[ F_g(x, t) = \int d^2\rho \, e^{-i\vec{\Delta} \cdot \vec{\rho}} \, F_g(x, \rho) \]

Illustration of \( u_{\text{valence}} \) quark images (impact parameter in the proton)
Remark 1: The interplay between $x$ and $t$

We can examine the dependence of $B(x)$

Let’s write $B(x) = B_0 + \alpha' \log(1/x)$

From previous slide, we know that $\alpha'$ is small

for all VM + DVCS at HERA we observe a small value of $\alpha'$ and even smaller values when $Q^2$ is increased.

Then, negligible interplay between $x/t$ at small $x$ ($x < 0.01$) [within errors]

Essential measure for GPD parameterization!
Remark 2: Another result from t-slopes measurements

We can measure inelastic DVCS: \( ep \rightarrow e \gamma Y \) (for \( M_Y > 1.4 \text{ GeV} \))

Which gives =>
\[
\omega := \left[ \frac{d\sigma_{\text{inel}}}{dt} / \frac{d\sigma_{\text{el}}}{dt} \right]_{t=0} \sim 0.25
\]
This ratio is quite universal among Vector Meson production and independent of \( Q^2 \)!
Clearly related to fluctuations of the Gluon field in the proton
\( \omega \sim \langle G^2 \rangle - \langle G \rangle^2 / \langle G \rangle^2 \)
Must be measured at different energies and compare with predictions
=> Important result for pp scattering
Remark 3: Dipole sizes DIS versus DVCS

\[ W(x, Q^2, r) = d^2r \ W() \]

Where \( r \) is the size of the dipoles contributing to the DVCS process (size of the \( \gamma^* := q-qbar \) pair).

With increasing \( Q^2 \), the contribution of large size configurations decreases rapidly... (QCD)

If we compare the profile function for DVCS & DIS @ same kinematics

\[ \Rightarrow \ \sigma(\text{DVCS}) = \int d^2r \ W() \]

\( \Rightarrow \) The contributions of large size configs is larger in DVCS!

(// diffractive reactions: DIS dominated by dipoles of \( b \sim 1/Q \) and DIFF by \( b \sim 1/Qs \))
Sensitivity to GPD H: Beam Charge Asymmetry (BCA)

Interference between QCD & QED at HERA

Principles:
- DVCS and Bethe-Heitler (QED graphs) have the same final state
- Both processes interfere
- The BCA is sensitive to this interference
- At HERA II, we have almost 150pb\(^{-1}\) for each set \(e^+p\) and \(e^-p\) with ~0 average polarisation per set...

We measure:
\[
A_C(\phi) = \frac{[d\sigma^+/d\phi - d\sigma^-/d\phi]}{[d\sigma^+/d\phi + d\sigma^-/d\phi]}
\]

\[
A_C(\phi) = p_1 \cos \phi = 2A_{BH} \frac{\text{Re} A_{DVCS}}{|A_{DVCS}|^2 + |A_{BH}|^2} \cos \phi
\]

Proportional to a GPD (modulo a convolution with a known function)
Beam Charge Asymmetry (BCA)

Kin bin (H1):
\( x = 1.2 \times 10^{-3} \)
\( Q^2 = 10 \text{ GeV}^2 \)

=>
Extract one value for \( A_c(\cos\phi) \) for this bin...

We obtain \( A_c(\phi) = (0.16 \pm 0.04 \pm 0.06) \cos(|\phi|) \)
which gives:
\[
\text{Re} A_{DVCS} / \text{Im} A_{DVCS} = 0.2 \pm 0.05 \pm 0.08
\]

+ test of the dispersion relations

Then, \( \text{Re} A_{DVCS} \) is an essential variable to constraint GPDs

*Good description obtained by present GPD models*
From BCA & DVCS cross section, we can determine a key observable: \( \eta = \frac{\text{Re}(a_{\text{DVCS}})}{\text{Im}(a_{\text{DVCS}})} \)

\[ \Rightarrow \eta = 0.23 \pm 0.10 \quad (1) \]

We have another way to extract this ratio from dispersion relations:
\[ \eta = \frac{\text{Re}(a_{\text{DVCS}})}{\text{Im}(a_{\text{DVCS}})} = \tan\left(\frac{\pi}{2} \frac{\delta}{4}\right) \]

@ low \( x \) with \( \sigma_{\text{DVCS}} \sim W^{\delta} \) with \( \delta \sim 0.75 \) (similar value for H1 & ZEUS)

\[ \Rightarrow \eta = 0.28 \pm 0.07 \quad (2) \]

Both values (1) & (2) are in good agreement => Good confidence in the difficult BCA measurement...
All experiments are useful in determination (fits) of GPDs: with the goal of a better understanding of how the proton is built up by partons.
What GPDs($x, t$) look like?

From Diehl et al.

Small $t$: close to PDFs

As $|t|$ is increasing

(i) Presence of a maximum
(ii) Shift of the maximum to higher $x$

$\Rightarrow$ high $|t|$ means high $x$ for the struck parton

// Feynman mechanism...

In the future, the aim is to improve this knowledge and also the general $(x_1, x_2, t)$ dependence...
Summary (on F2D)

As an experimentalist, I want to remind that it took 10Y to get all the points on this plot of F2D! ... consequences on saturation effects in QCD are still under study...