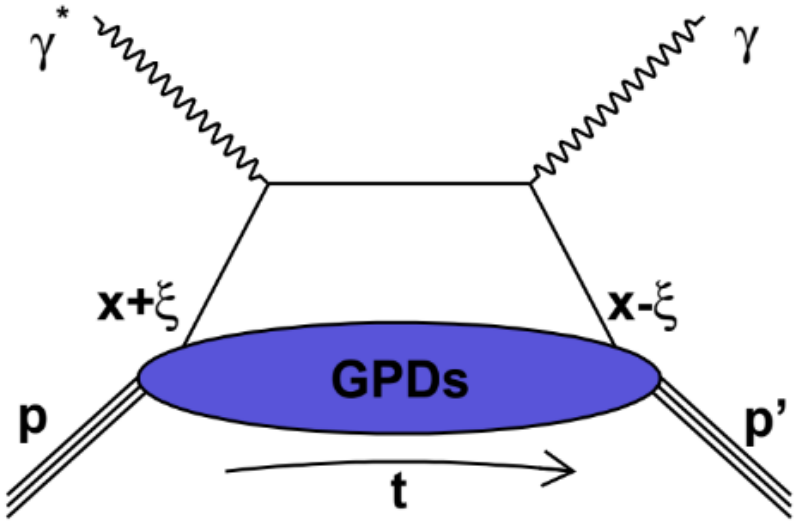
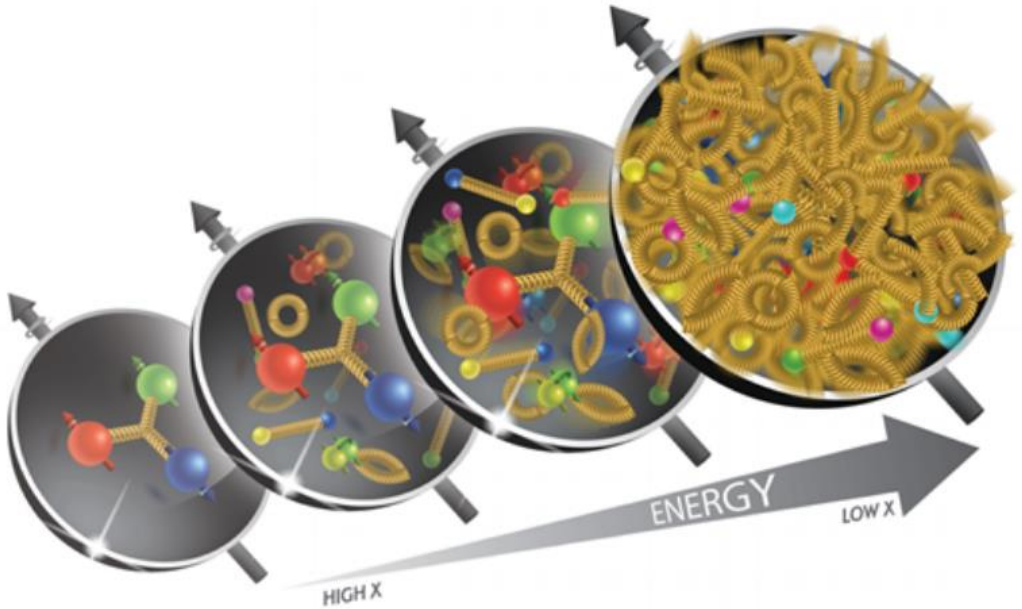
Deeply Virtual Compton Scattering and Spatial Imaging





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Outline

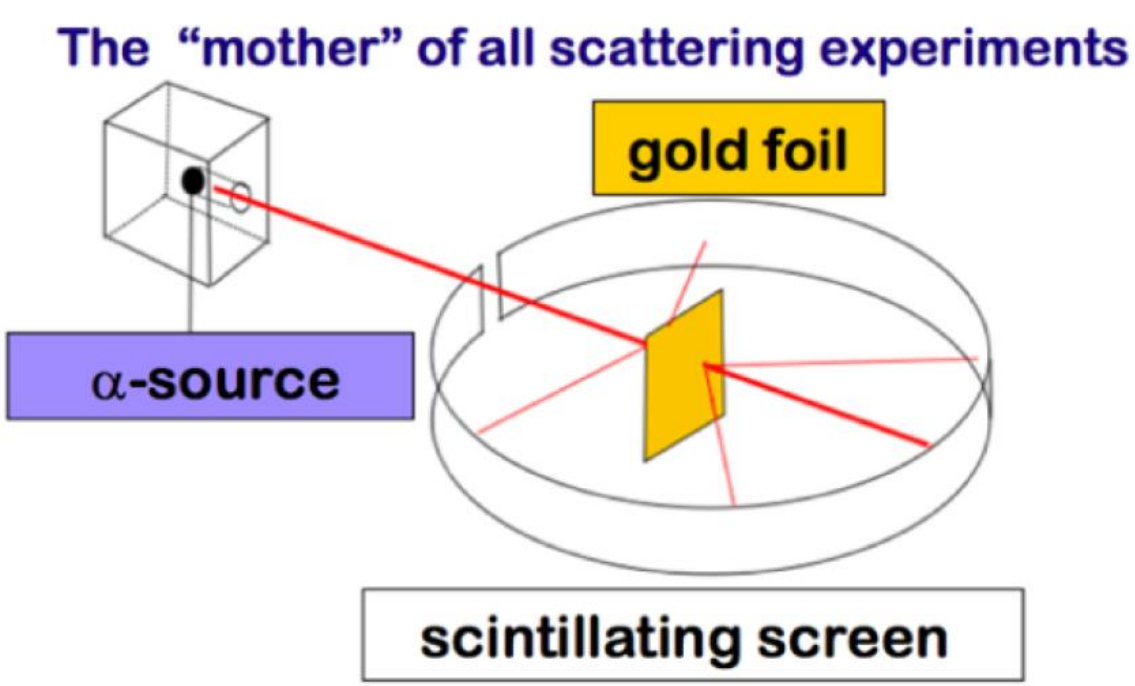
- Lecture 1: Introduction
  - Elastic scattering, form factors (FFs)
  - Deep Inelastic scattering, parton distribution functions (PDFs)
  - Exclusive reactions, Generalized Parton Distributions (GPDs)
- Lecture 2: Deeply Virtual Compton Scattering
  - Experimental results on proton targets
  - Flavor separation using quasi-free neutrons
- Lecture 3: Deeply Virtual Meson Production
  - Rosenbluth separation
  - Access to transversity GPDs
  - Flavor decomposition
- Lecture 4: Models and outlook
  - GPD models and parametrizations
  - 12 GeV experimental program on GPDs
- Lecture 5: Electron-Ion Collider
  - Imaging gluons inside the nucleon
  - The EIC project

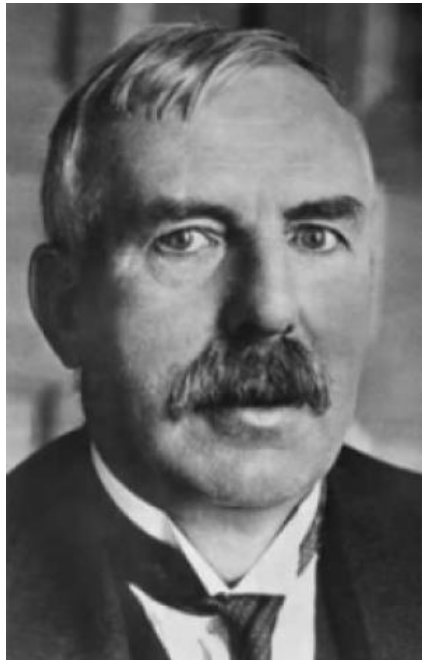
Lecture 1

- Introduction to scattering experiments
- Elastic scattering and form factors of the nucleon
- Deep Inelastic Scattering and parton distribution functions (PDFs)
  - Factorization at high Q^2
- Off-forward Compton Scattering
  - Generalized Parton Distributions (GPDs)
  - Deeply Virtual Compton Scattering (DVCS)
  - Interference with Bethe-Heitler (BH) process

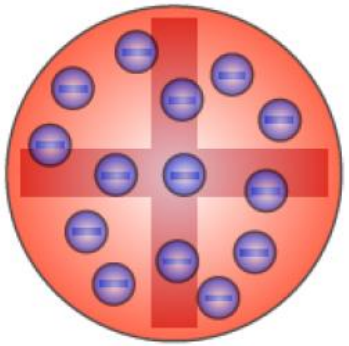
Introduction

The first exploration of subatomic structure was undertaken by Rutherford in Manchester using gold atoms as target and α particles as probes



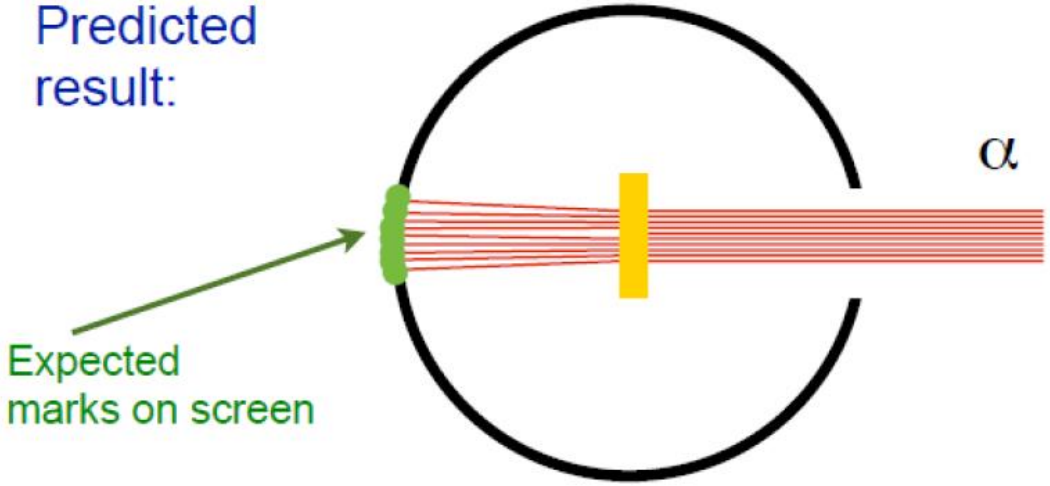


Rutherford experiment: expectation

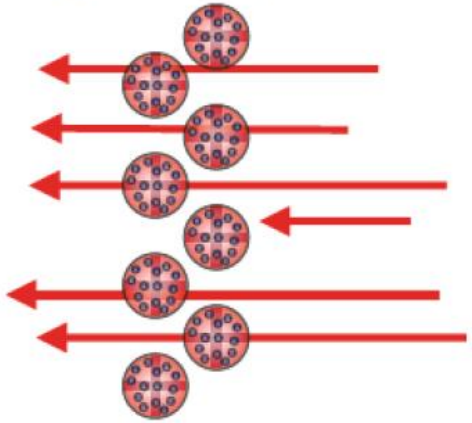


Thomson's
Plum Pudding Model

Predicted
result:

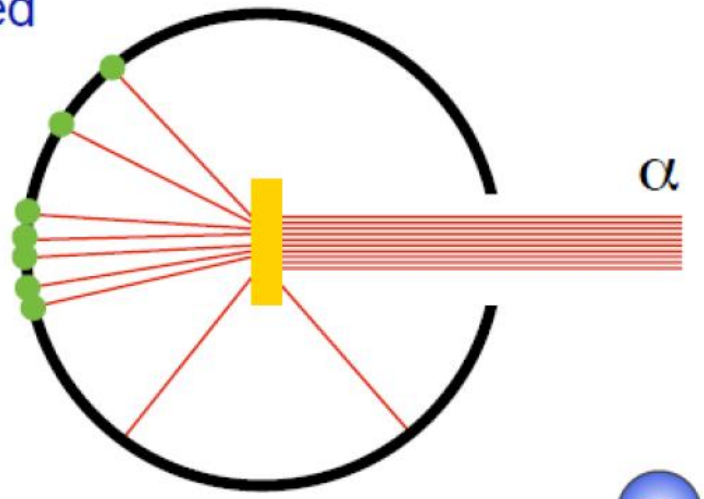


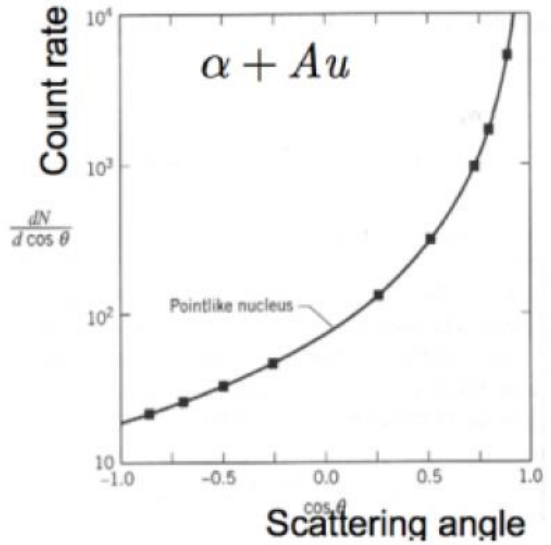
Detail of gold foil (Thomson):



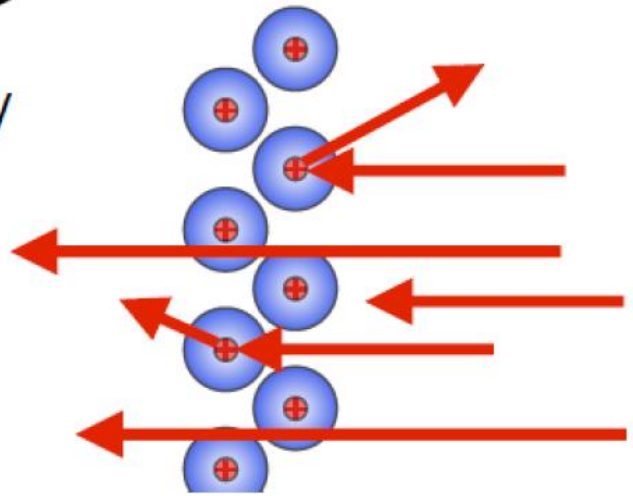
Rutherford experiment: result

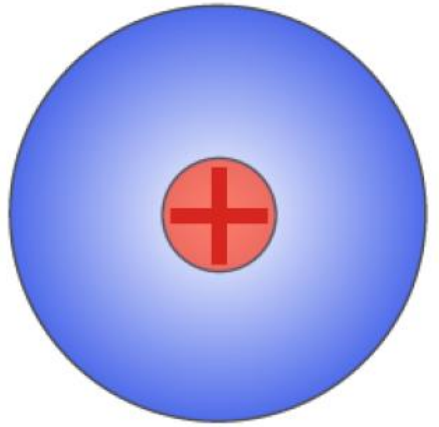
Observed result:





Positive Nucleus Theory explain α deflection:

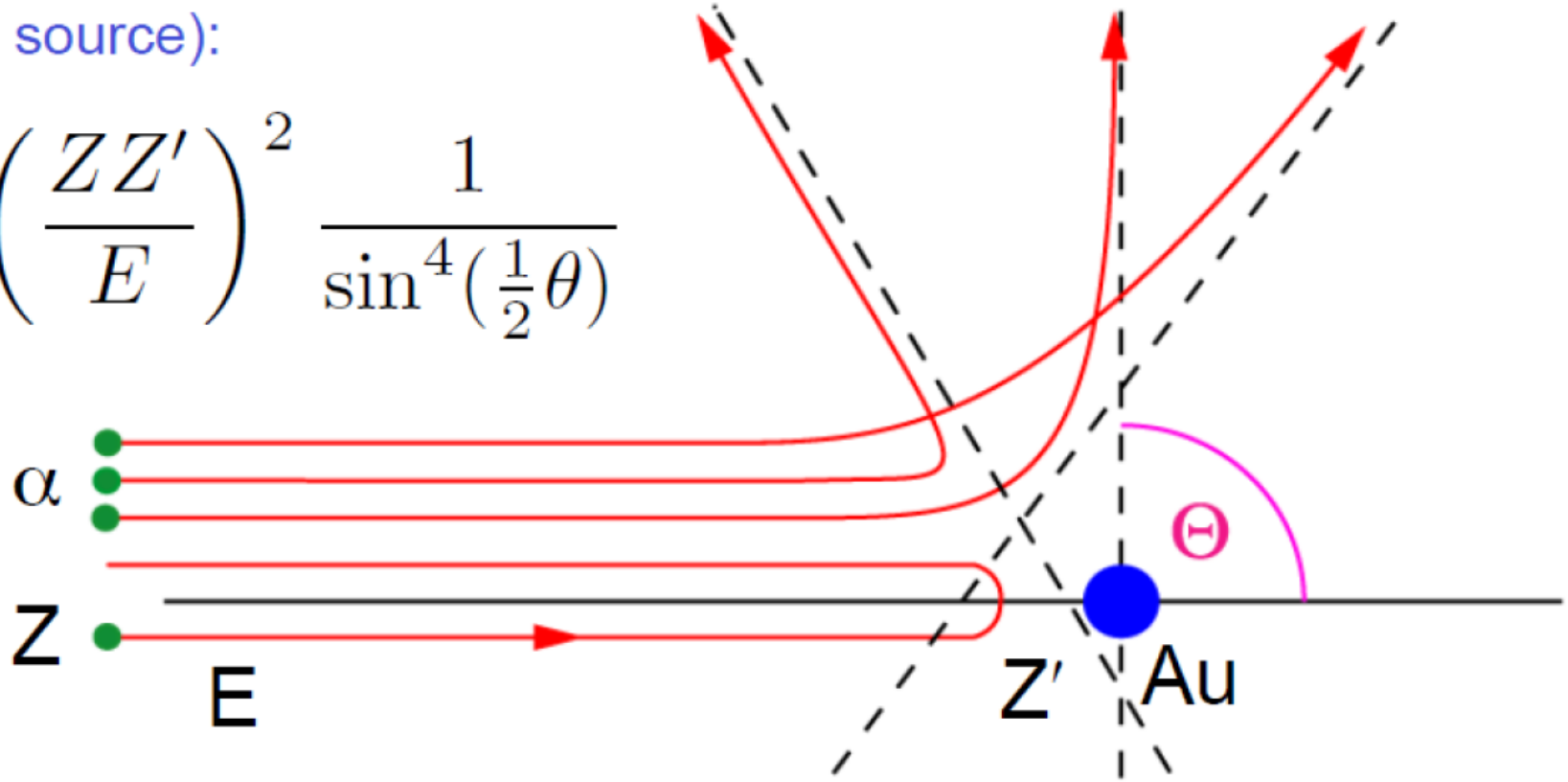




Rutherford experiment: result

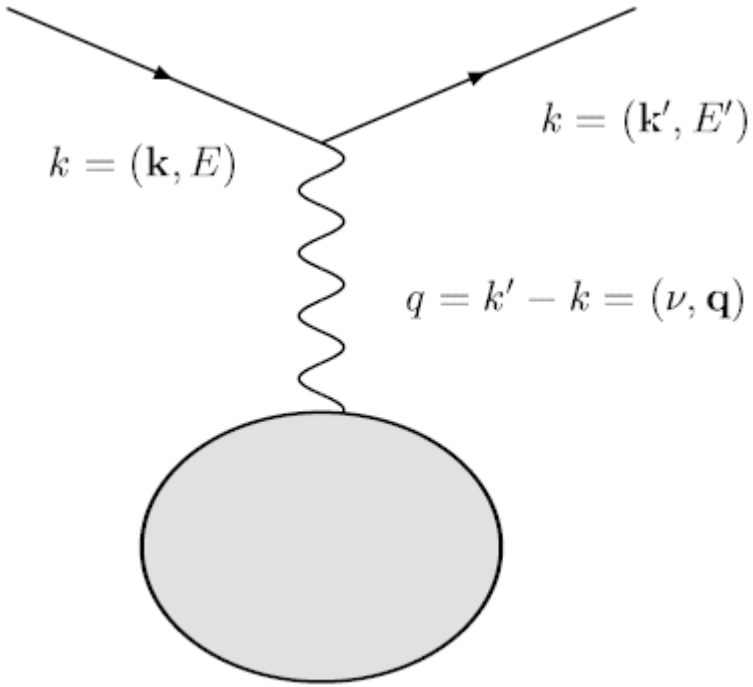
Elastic scattering of charged particles in Coulomb field (point-like source):

$$\frac{d\sigma}{d\Omega} = \left(\frac{ZZ'}{E}\right)^2 \frac{1}{\sin^4(\frac{1}{2}\theta)}$$



Probing the structure of the proton: elastic scattering

$ep \rightarrow ep$



Probing internal structure
through electron scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} |F(q)|^2$$

Form factor

For a spinless target with charge distribution $\rho(\mathbf{x})$

$$F(\mathbf{q}) = \int \rho(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} d^3x$$

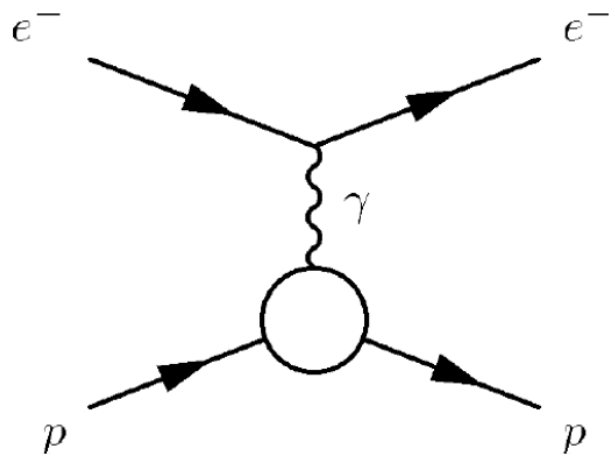
Elastic scattering: spin ½ particle

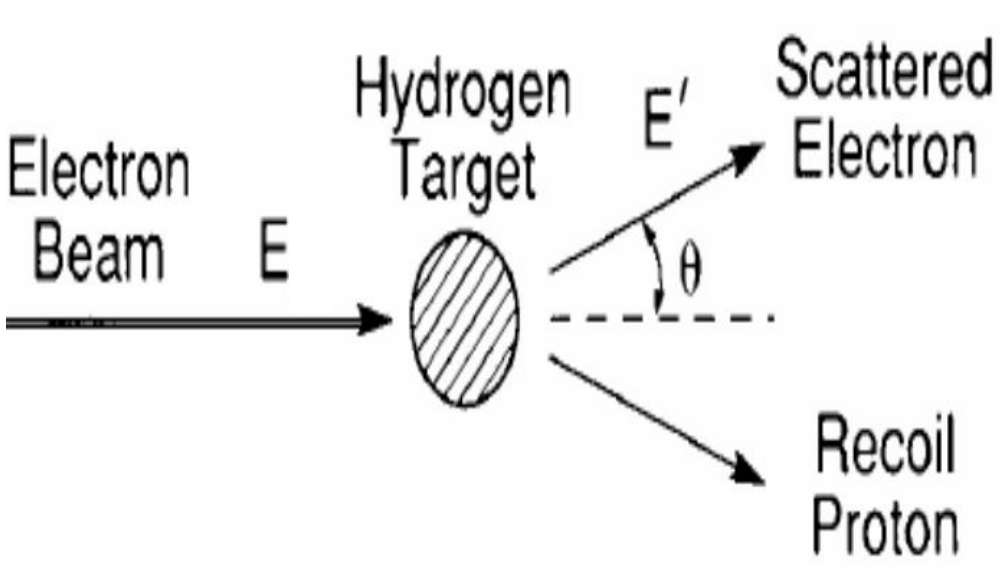
Rosenbluth (1950):

$$\frac{d\sigma}{d\Omega}(E) = \sigma_M(E)\left(\frac{E'}{E}\right)\left(\frac{G_{Ep}^2(q^2) + \tau G_{Mp}^2(q^2)}{1+\tau} + 2\tau G_{Mp}^2(q^2)\tan^2\frac{\theta}{2}\right)$$

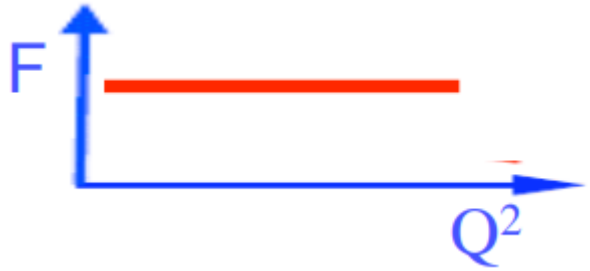
Point-like
Mott cross section

$$\tau = \frac{-q^2}{4M^2}$$



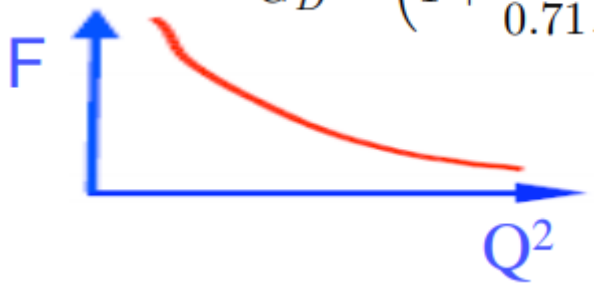


Charge density inside protons and neutrons



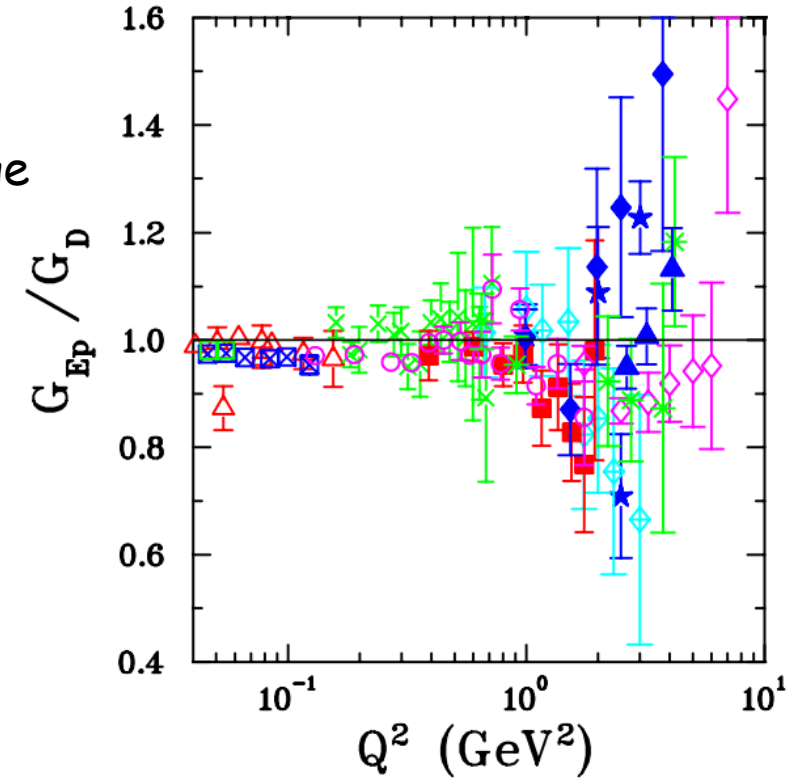
Point-charge: F(Q^2)=constant
photon always sees all of its charge

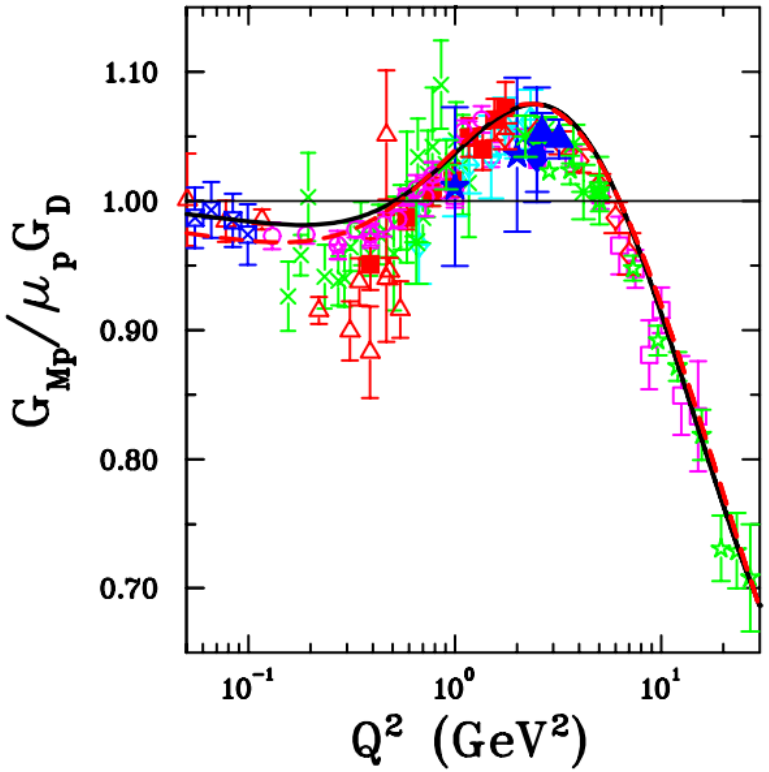
$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$



Elastic electron-proton scattering:
photon sees less charge as Q^2 increases

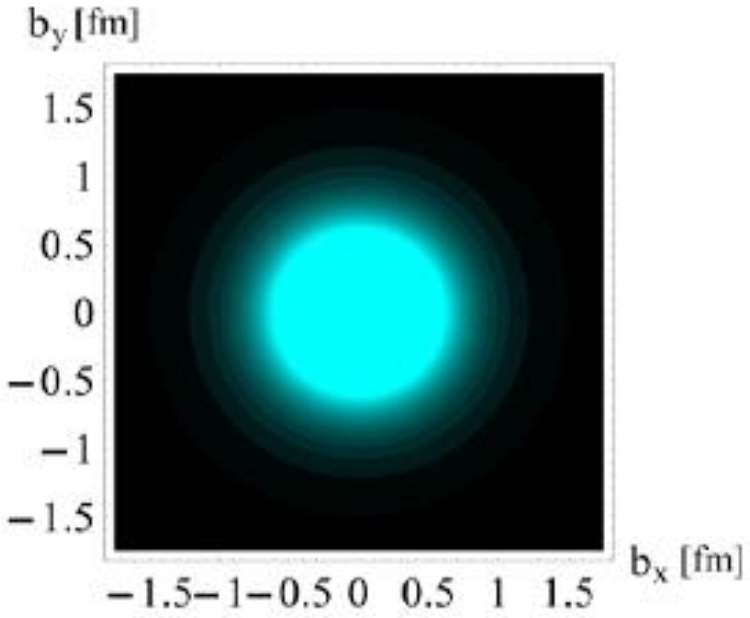
Experimental data as a function of the momentum transfer $Q^2=-q^2$:



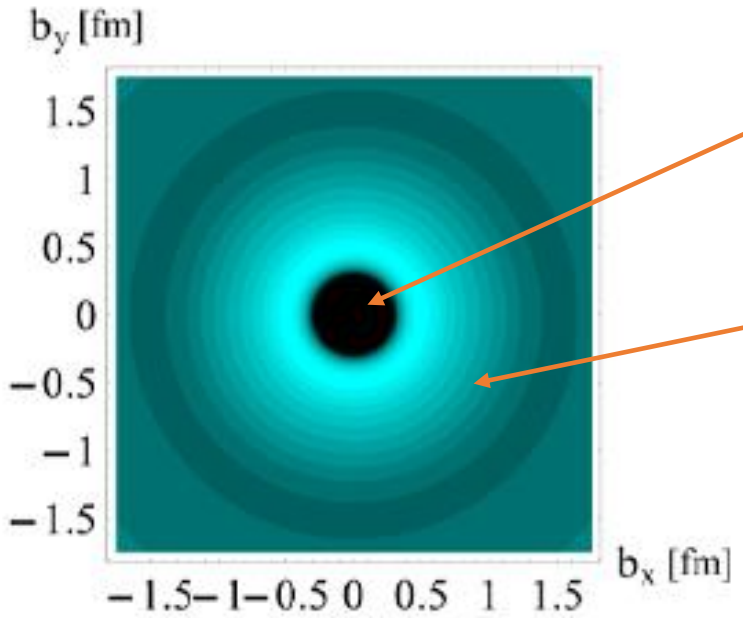


Punjabi *et al.* (2015)

Charge density inside protons and neutrons



Proton

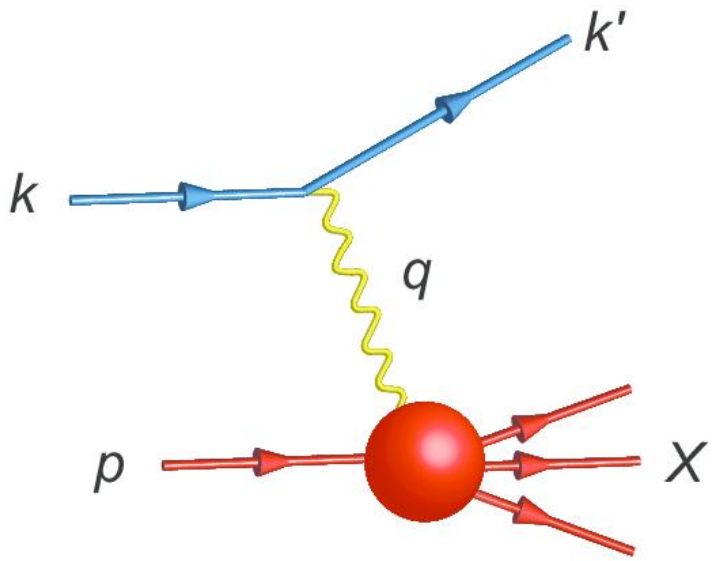


Neutron

Negative inner core

Positive outer surface

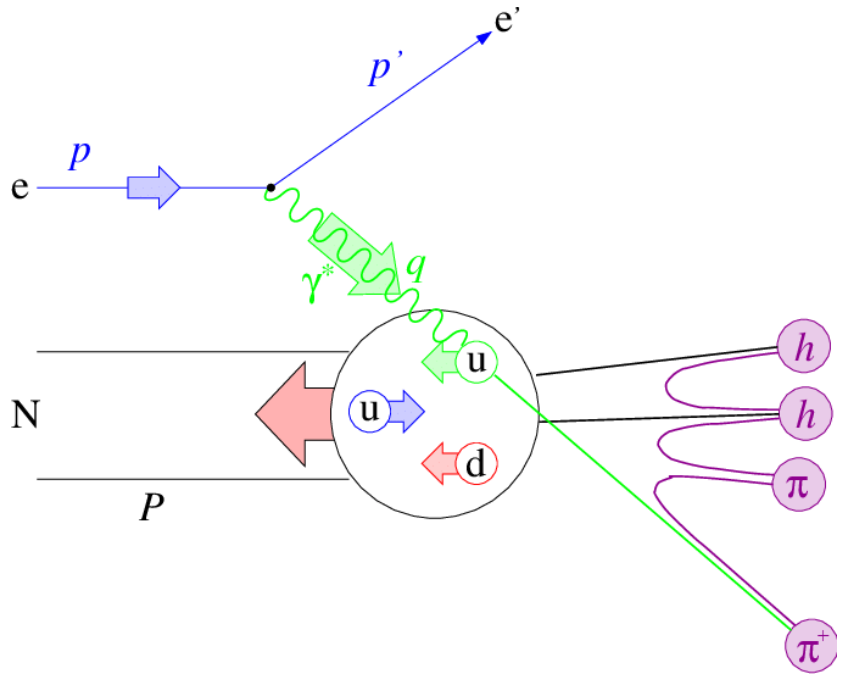
Deep inelastic scattering



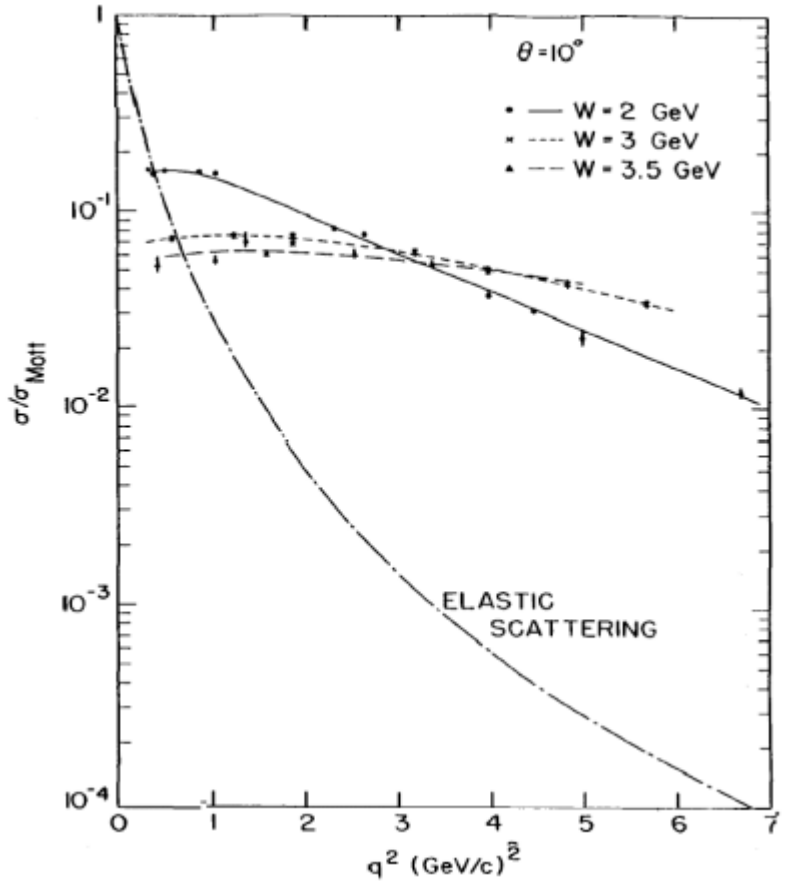
Invariant mass of the hadronic state:

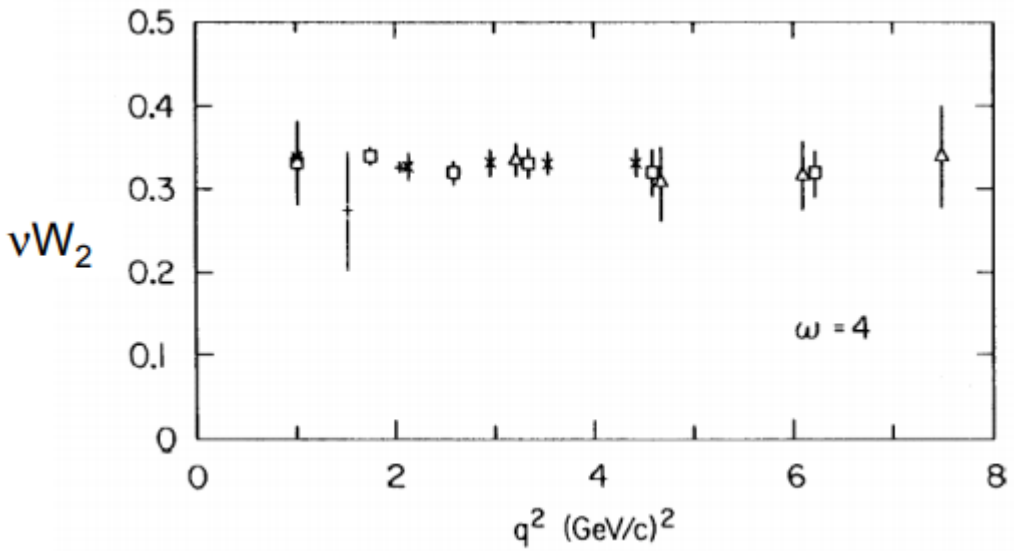
$$W^2 = (2M\nu + M^2 - Q^2) \qquad \nu = E - E'$$

$$\frac{d^2\sigma}{d\Omega dE'}(E, E', \theta) = \sigma_M \left(W_2(\nu, q^2) + 2W_1(\nu, q^2) \tan^2 \frac{\theta}{2} \right)$$



Unexpected results from SLAC e-P scattering





- The ratio σ/σ_{Mott}: no Q^2 dependence
- Structure function W_2 has no Q^2 dependence

Scattering against a point-like particle

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{point}} |F(q)|^2$$

$$2MW_1(\nu, q^2) = F_1(\omega)$$
$$\nu W_2(\nu, q^2) = F_2(\omega)$$

Bjorken Scaling

Parton model

Feynman (1969)

- Proton composed of point-like partons, from which the electrons scattered incoherently
- In an infinite momentum frame of reference: time dilation slowed down the motion of constituents
- Partons are assumed not to interact with one another while the virtual photon is exchanged (impulse approximation)

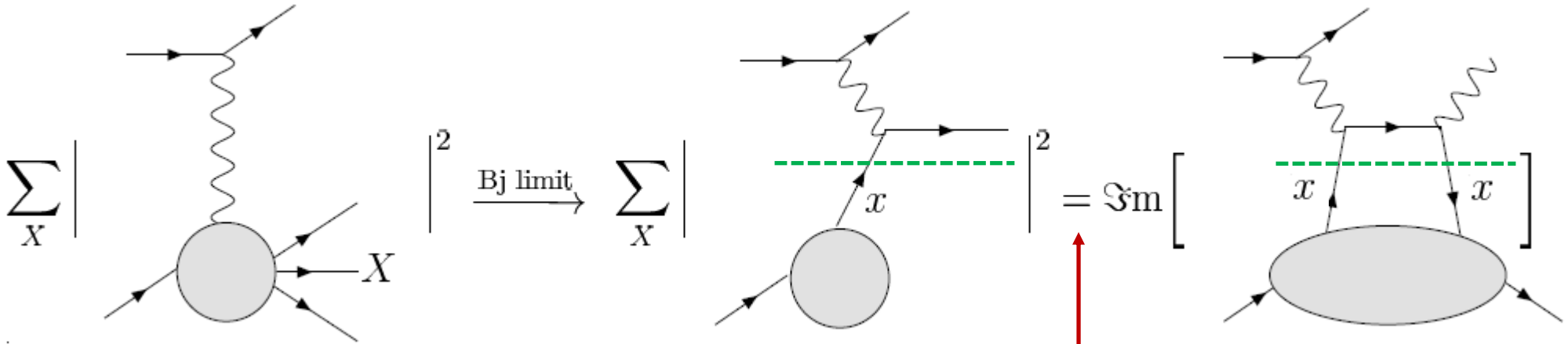
In this theory, electrons scatter from constituents that are "free" and the scattering reflects the properties and motion of the constituents

The assumption of near-vanishing parton-parton interaction during electron scattering (at high Q^2) was later shown to be a consequence of QCD known as *asymptotic freedom*

Factorization

$$\sigma_{\mathrm{DIS}}(x,Q^2) = \sum_i q_i(x)\,\sigma_{eq\to eq}(x,Q^2)$$

Parton Distribution Function (PDF)

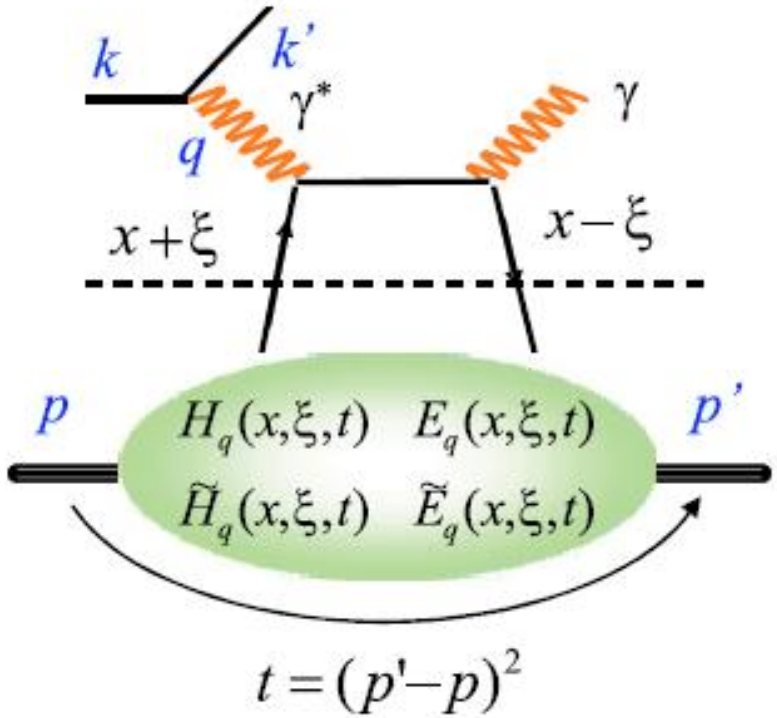


Optical theorem

$$x = \frac{Q^2}{2P\cdot q} = x_B$$

Off-forward Compton scattering

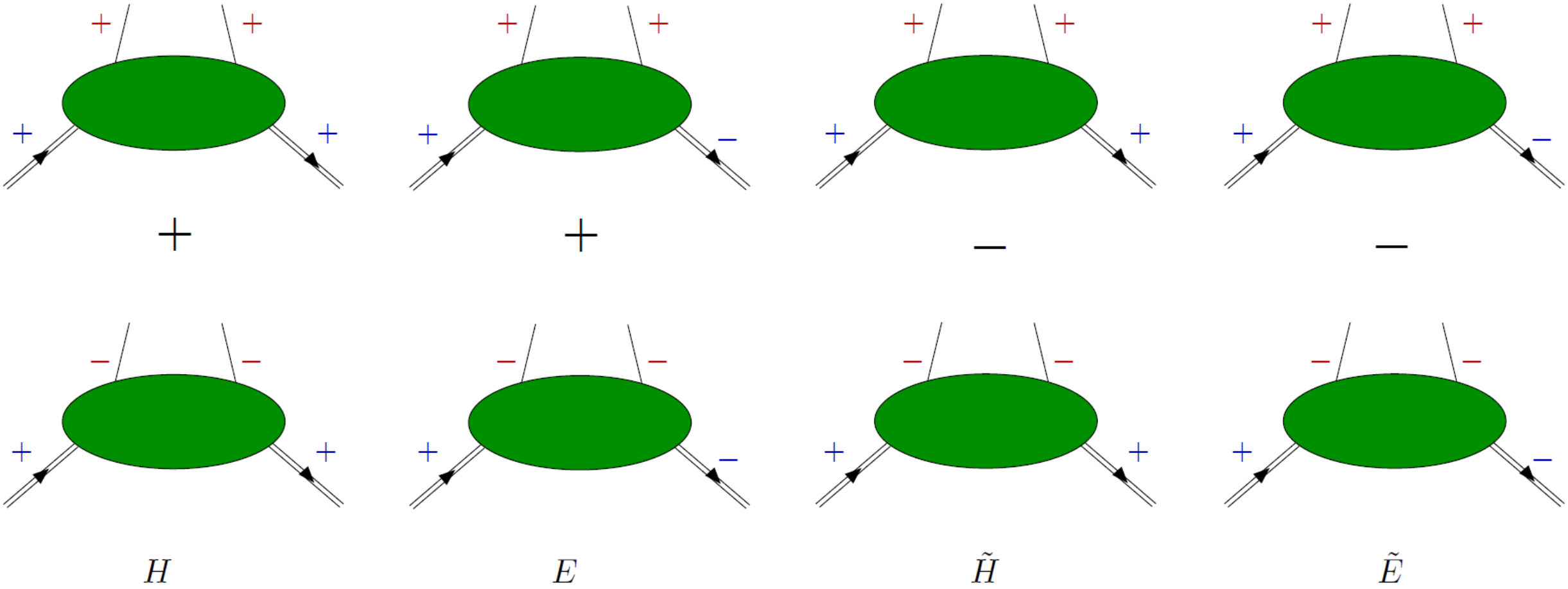
$$e\ p \to e'\ p'\ \gamma$$



$$\gamma^*\ p \to p'\ \gamma$$

Deeply Virtual Compton Scattering (DVCS)

Generalized Parton Distribution (GPDs)



Properties of GPDs

Forward limit:

$$H^f(x,0,0) = q_f(x)\,,$$
$$\tilde{H}^f(x,0,0) = \Delta q_f(x)$$

Polynomiality:

$$\int_{-1}^{1} dx\, x^n\, H(x,\xi,t) = a_0 + a_2\xi^2 + a_4\xi^4 + \cdots + a_n\xi^n$$

1st moments:

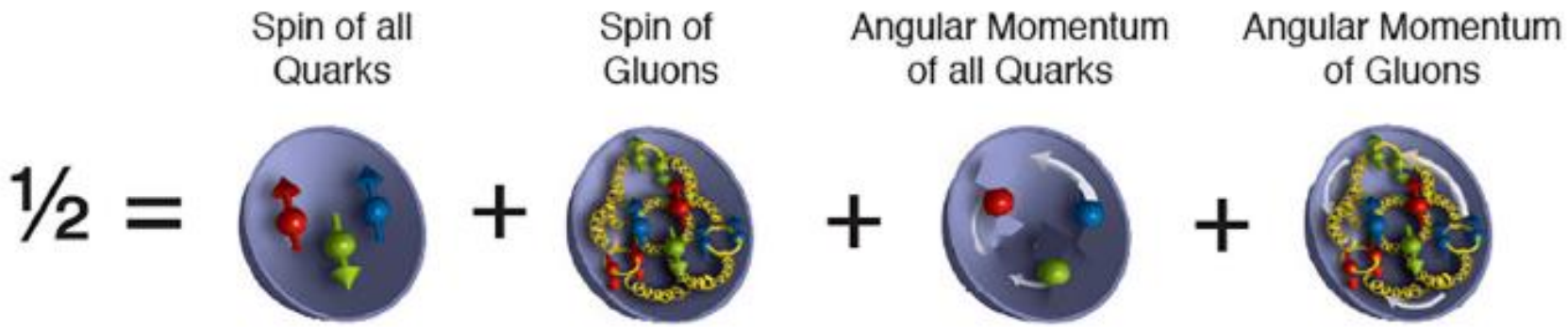
$$\int_{-1}^{1} dx\, H^f(x,\xi,t) = F_1^f(t) \qquad \forall\xi$$
$$\int_{-1}^{1} dx\, E^f(x,\xi,t) = F_2^f(t) \qquad \forall\xi$$
$$\int_{-1}^{1} dx\, \tilde{H}^f(x,\xi,t) = G_A^f(t) \qquad \forall\xi$$
$$\int_{-1}^{1} dx\, \tilde{E}^f(x,\xi,t) = G_p^f(t) \qquad \forall\xi$$

Ji's sum rule

X. Ji (1996)

Second moment of GPDs H+E:

$$\frac{1}{2}\int_{-1}^{1} dx\, x[H^f(x,\xi,0) + E^f(x,\xi,0)] = J^f \qquad \forall\xi$$



$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g$$

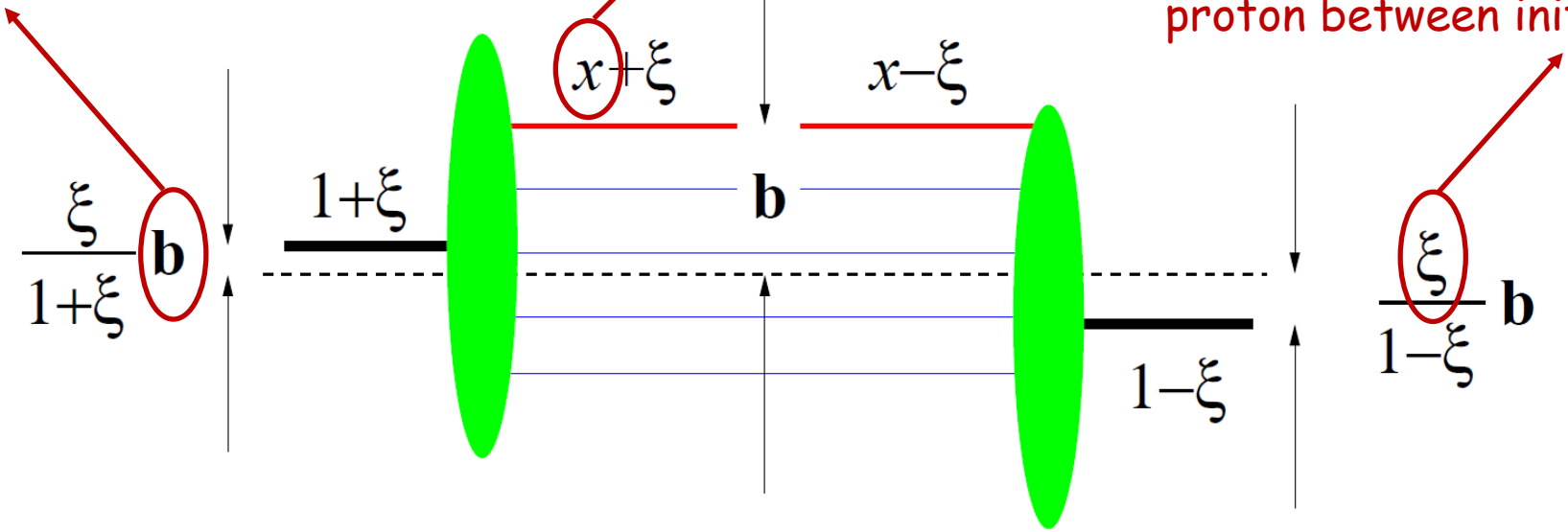
Physical interpretation of GPDs

Burkardt (2000), Diehl (2002)

Average momentum of the parton

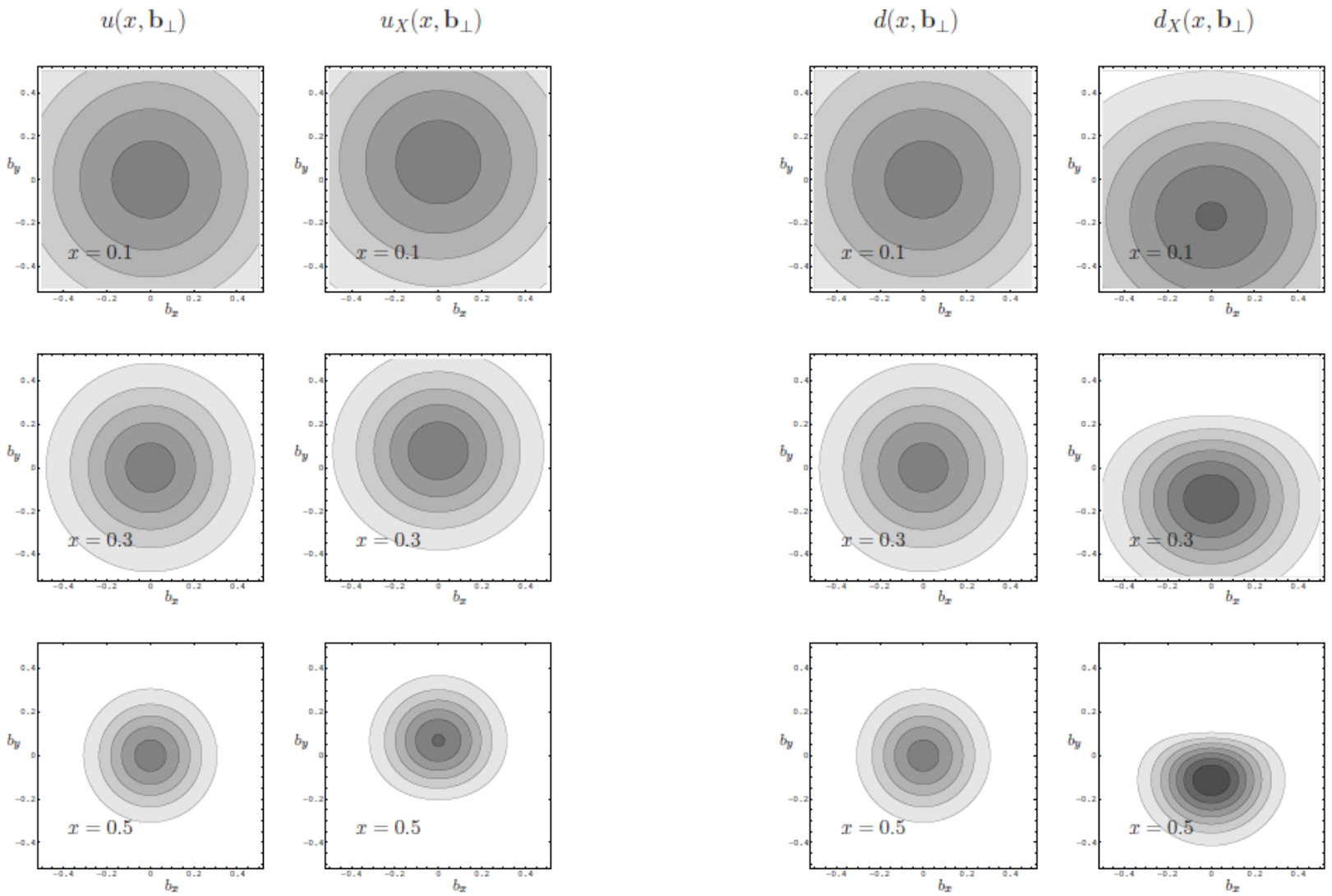
Impact parameter:
Fourier-conjugate of GPD variable t

Determines the transverse shift of the proton between initial and final state

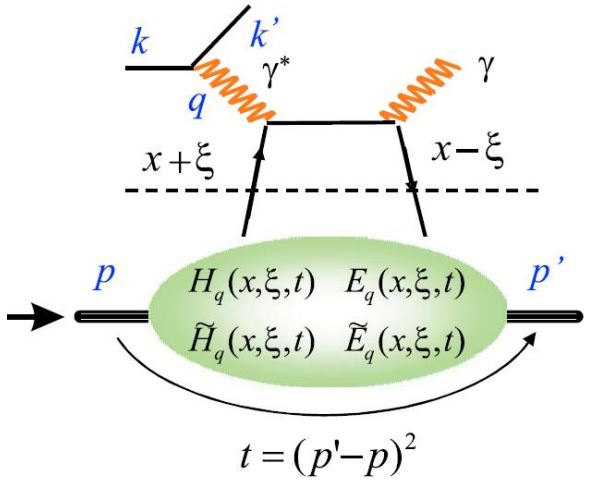


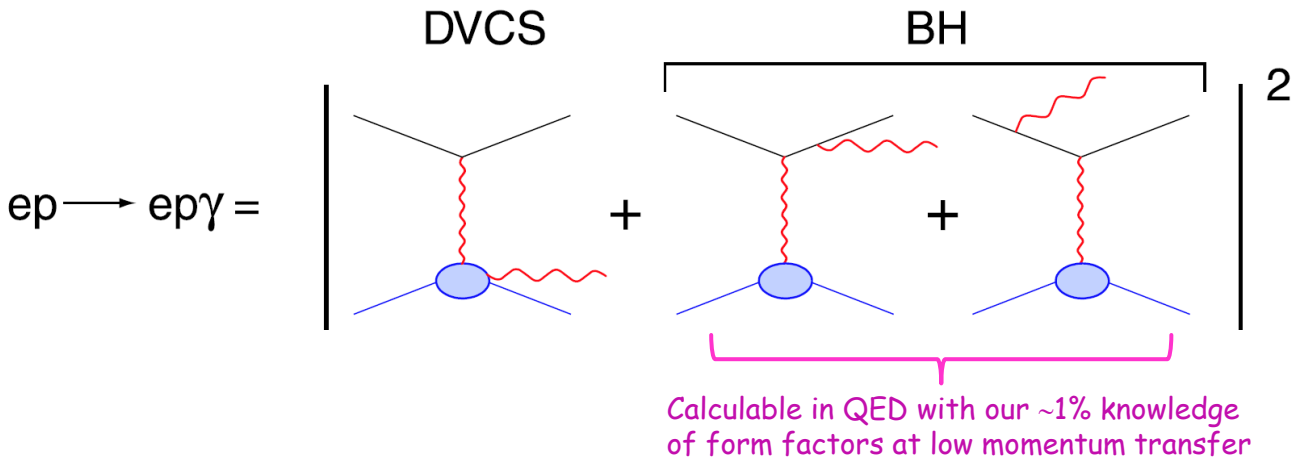
Transverse position of partons and longitudinal momentum

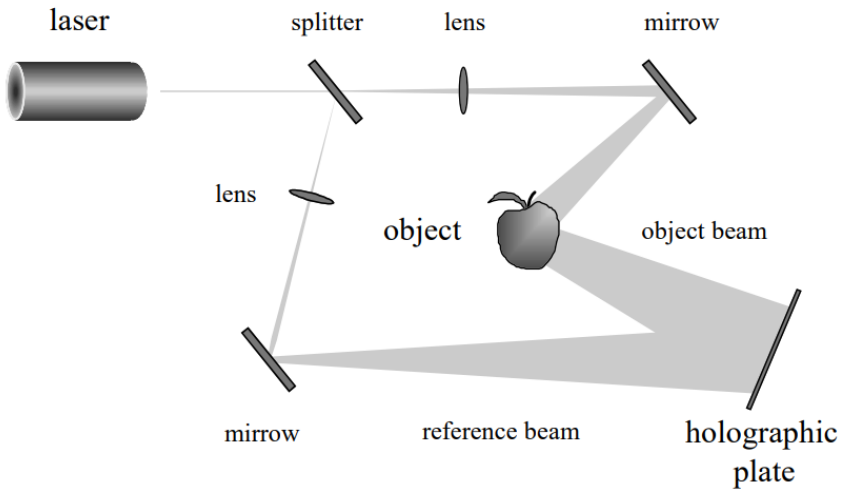
3D imaging of the proton with DVCS

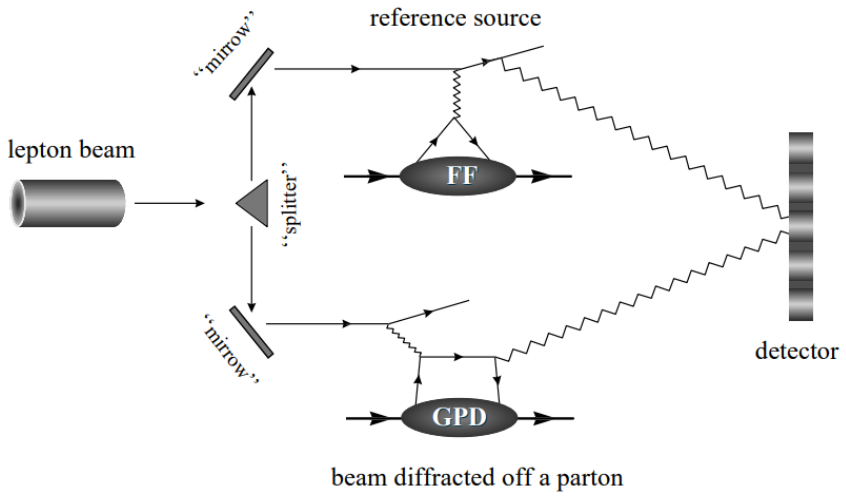


DVCS and Bethe-Heitler









DVCS and BH interference

$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

When only 1 quark of the proton is involved in the reaction:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\left(T^{BH}\cdot T^{DVCS}\right)$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\left(T^{BH}\cdot T^{DVCS}\right) + |DVCS|^2$$

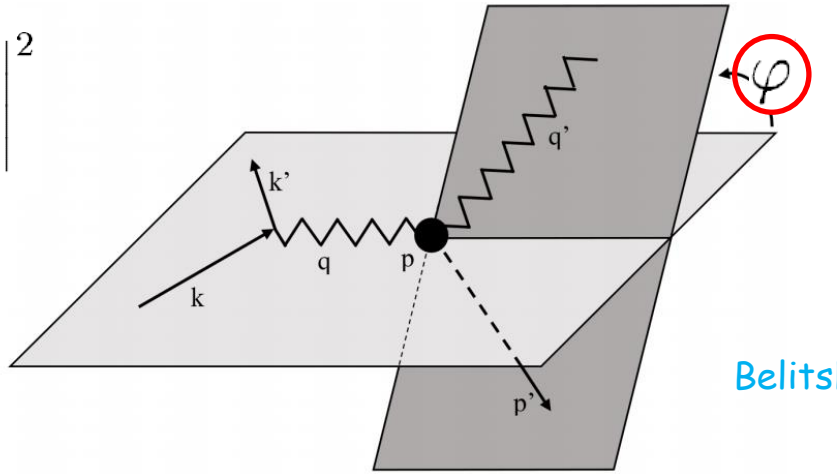
Using a polarized electron beam

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH\cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

Azimuthal dependence of the DVCS cross section

$$\frac{d^5\sigma}{dQ^2 dx_B d\varphi_e dt d\varphi} = \frac{\alpha^3 x_B y}{16\pi^2 Q^2 \sqrt{1+4x_B^2 M^2/Q^2}} \left|\frac{\mathcal{T}}{e^3}\right|^2$$

$$|\mathcal{T}|^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I}$$



Belitsky, Müller, Kirchner (2000)

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_B^2 y^2 [1+4x_B^2 M^2/Q^2]^2 t \mathcal{P}_1(\varphi)\mathcal{P}_2(\varphi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\varphi) + s_1^{\rm BH} \sin\varphi \right\},$$

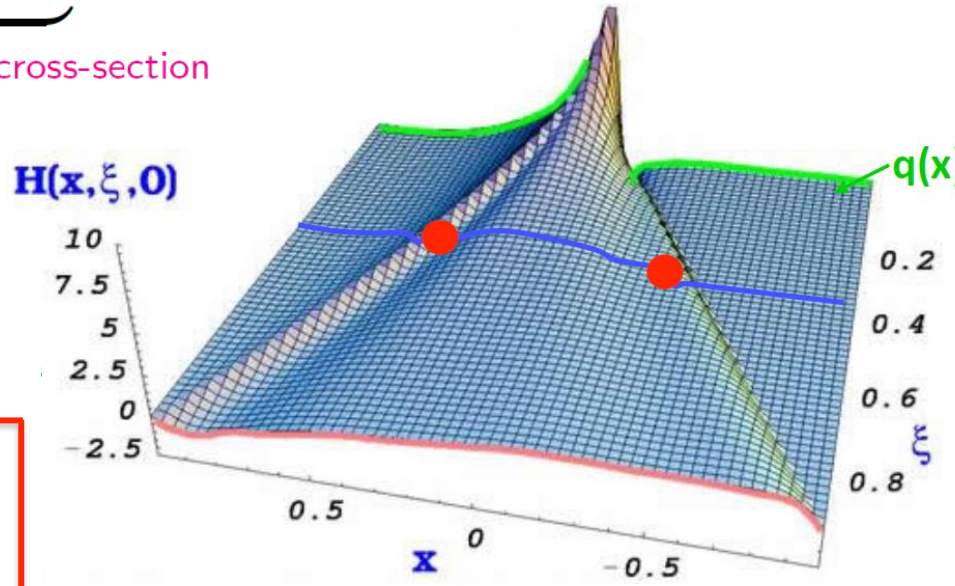
$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2} \left[c_n^{\rm DVCS} \cos(n\varphi) + s_n^{\rm DVCS} \sin(n\varphi) \right] \right\},$$

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 t \mathcal{P}_1(\varphi)\mathcal{P}_2(\varphi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\varphi) + s_n^{\mathcal{I}} \sin(n\varphi) \right] \right\},$$

GPDs and Compton Form Factors (CFFs)

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$



CFF $\mathcal{H}$ = GPD $\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon}$ = $\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}$ $- i\,\pi\, H(x=\xi,\xi,t)$

Accessing GDPs from DVCS

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (lTSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B k F_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BlTSA)

$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

Summary

- Elastic form factors provide a spatial imaging of charge and magnetization inside proton and neutrons in the transverse plane
- DIS and parton distribution functions provide a 1D imaging of the longitudinal momentum of partons inside nucleons
- GPDs provide a combination of both, and allow a 2+1D imaging of quarks (and gluons) in the transverse plane as a function of their longitudinal momentum.
- GPDs can be accessed experimentally through DVCS (lecture 2), but also through electroproduction of mesons at high momentum transfer Q^2 (lecture 3).