Spatial imaging of the nucleon

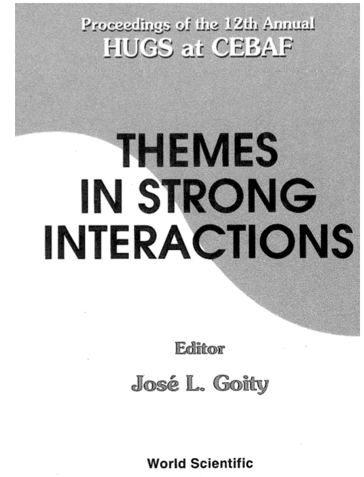
J. Roche (Ohio University)

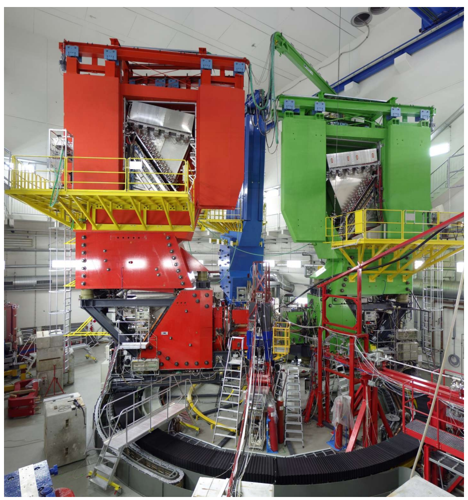
- Hard exclusive reactions allow the study of the 2+1 D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with elastic scattering.
- Dedicated experiments are conducted world-wide.
- The growing set of existing results is helping refine our approach to extracting the GPDs from the data and within limits some preliminary results.
- DVCS experiments are an essential part of the comprehensive GPD program with the 12 GeV CEBAF beam and the EIC.

Introduction

- '97 HUGS participant
- '98 PhD from France
- Postdoc at JLab ('99-06)

- Associate professor at Ohio U (NSF funded)



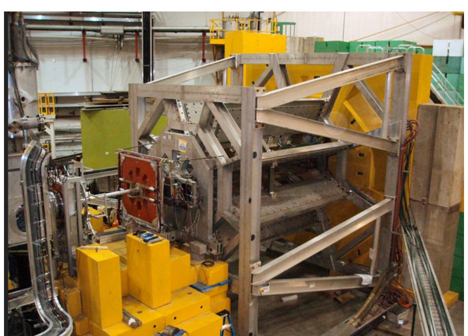


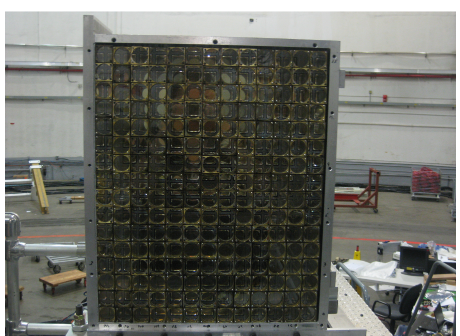
Polarizabilities of the nucleon: VCS@MAMI- Germany

Strange form factor the nucleon: GO@JLab

Physics beyond the Standard Model: QWEAK@Jlab

GPDs: DVCS-Hall A @Jlab





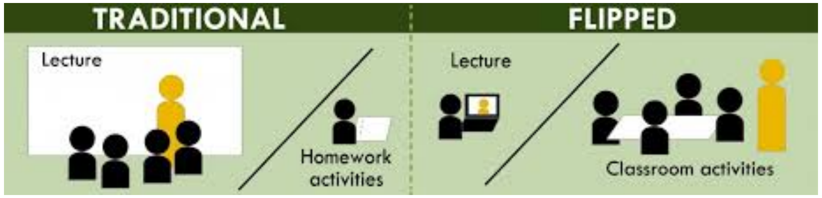
Absolute cross-sections measurements

Parity violation in Electron Scattering

Six hours together

Three 2-hours sessions:

- 30 minutes introduction by me
- Two rounds of questions I will ask you to think about
  - 30 minutes of your researching questions
  - 15 minutes of you presenting your finding to the class



The outline and some slides are inspired by a recent paper by N. d'Hose (CEA Saclay) 10.1051/epjconf/20158501004

Spatial imaging of the nucleon

J. Roche (Ohio University)

- Hard exclusive reactions allow the study of the 2+1 D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with elastic scattering.

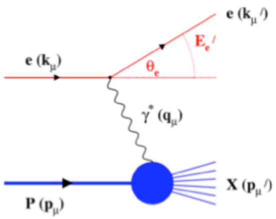
- Dedicated experiments are conducted world-wide.

- The growing set of existing results is helping refine our approach to extracting the GPDs from the data and within limits some preliminary results.

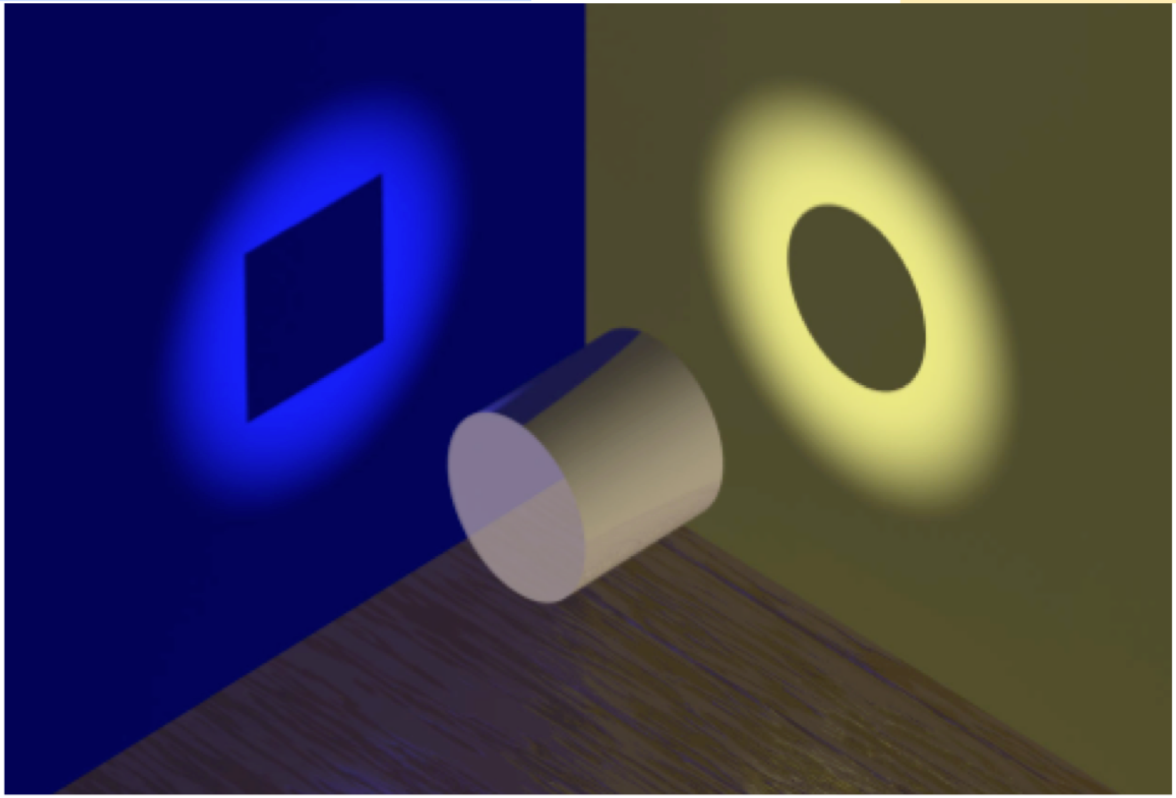
- DVCS experiments are an essential part of the comprehensive GPD program with the 12 GeV CEBAF beam and the EIC.

3D picture of the nucleon

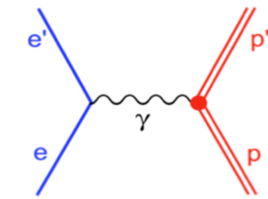
DIS Parton Distribution Functions



No information on the spatial location of the constituents



Elastic Form Factors



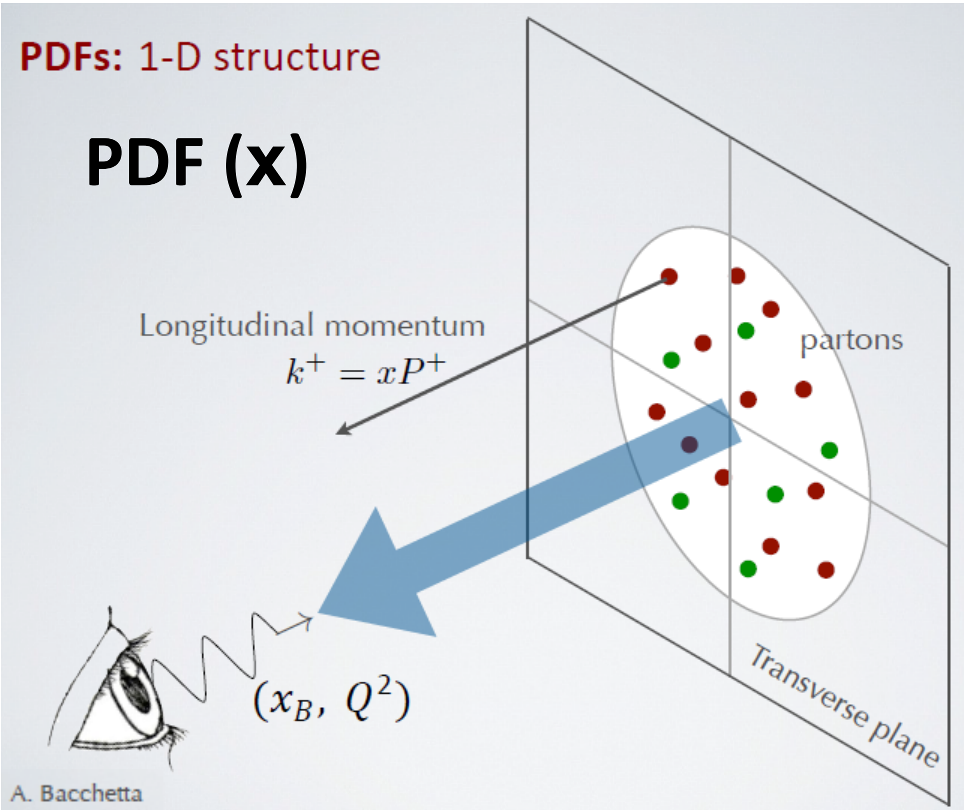
No information about the underlying dynamics of the system

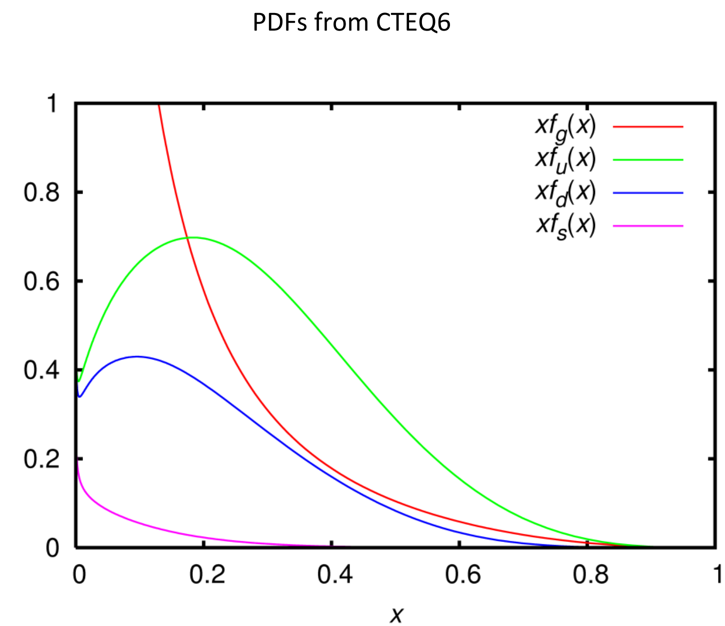
Generalized Parton Distribution Function :

3-D imaging of the nucleon with access to **correlations** between **transverse spatial distribution and longitudinal momentum distributions.**

Slide from S. Stepanyan, GHP April ‘15

From PDFs to TMDs and GPDs



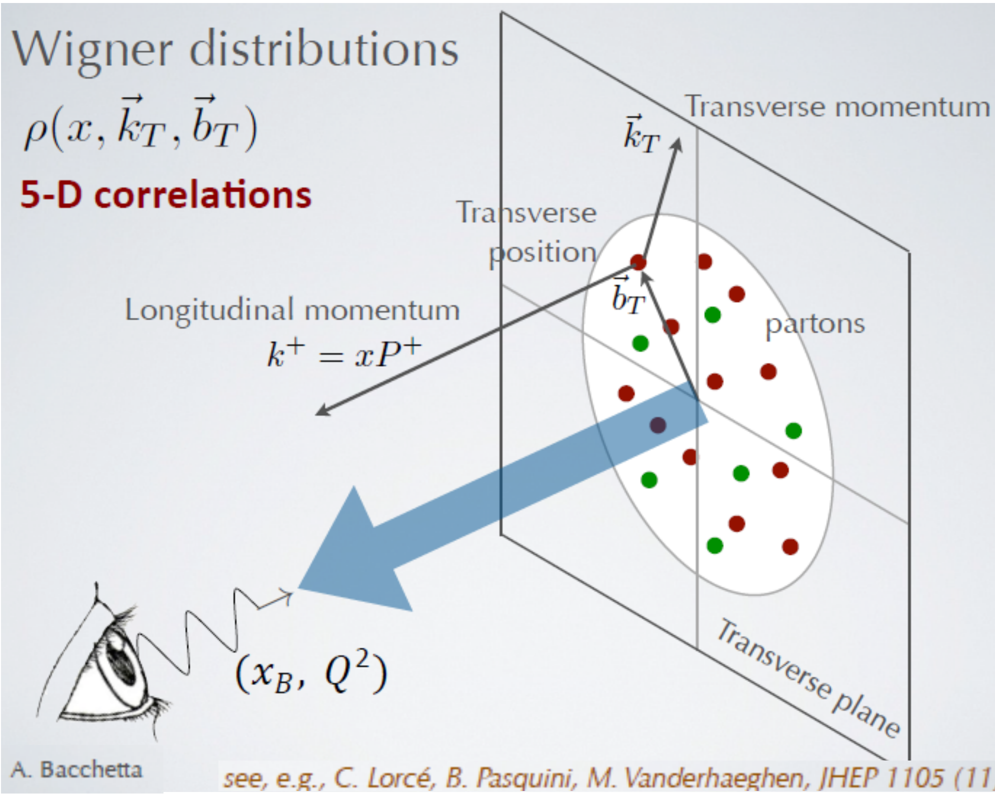


PDF measured in Deep Inelastic Scattering

$\ell p \rightarrow \ell' X$

Slide from N d'Hose, Tranversity 2014

From PDFs to TMDs and GPDs



3-dimensional nucleon structure
in momentum and configuration space:

GPD $(x, b_\perp)$:
Generalised Parton Distribution
(position in the transverse plane)

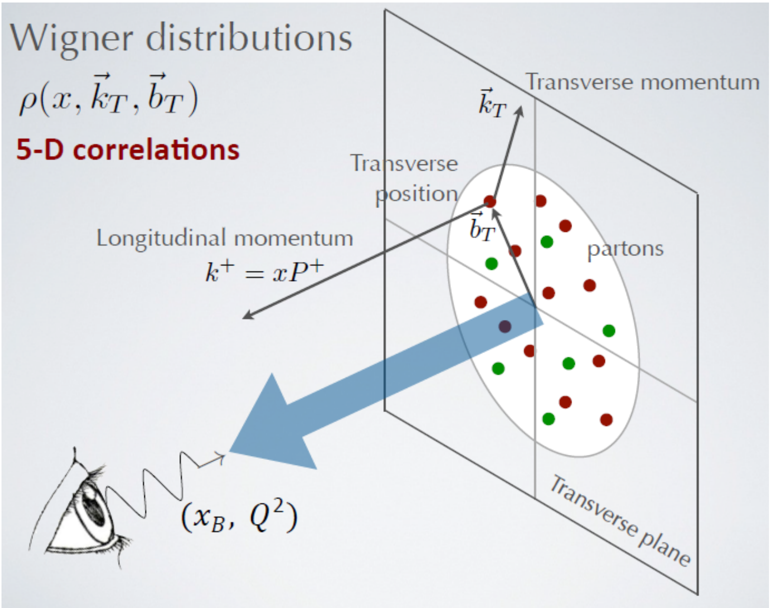
TMD $(x, k_\perp)$:
Transverse Momentum Distribution
(momentum in the transv. Plane)

TMD accessible in **SIDIS** and **DY**

GPD in **Exclusive reactions**
DVCS and **HEMP**

Slide from N d'Hose, Tranversity 2014

From PDFs to TMDs and GPDs



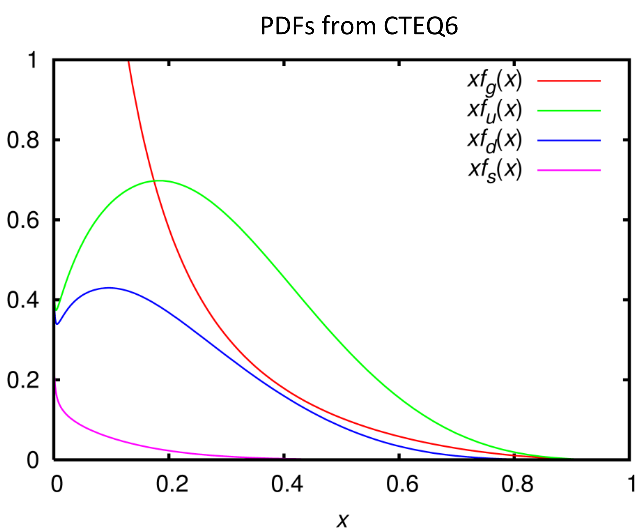
3-dimensional nucleon structure

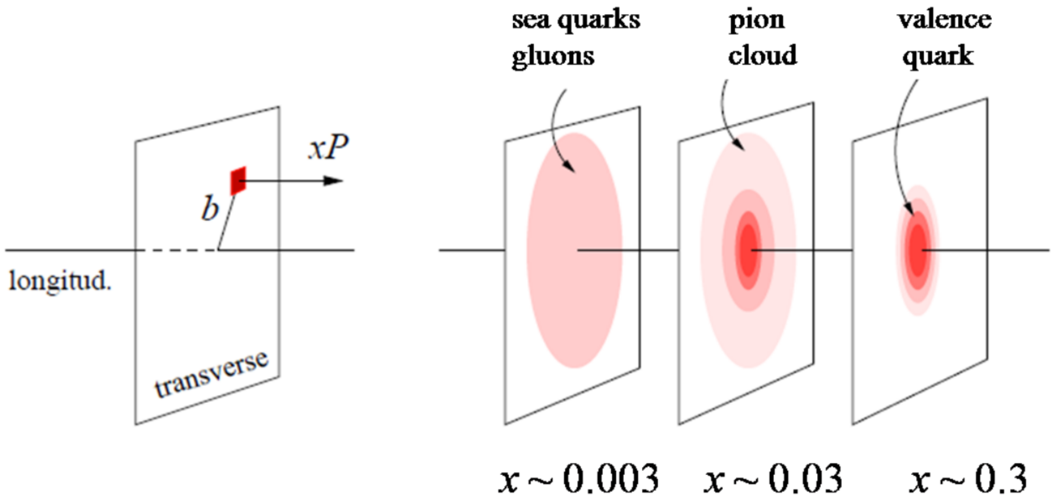
in momentum and configuration space:

GPD (x, $b_\perp$) :

Generalised Parton Distribution

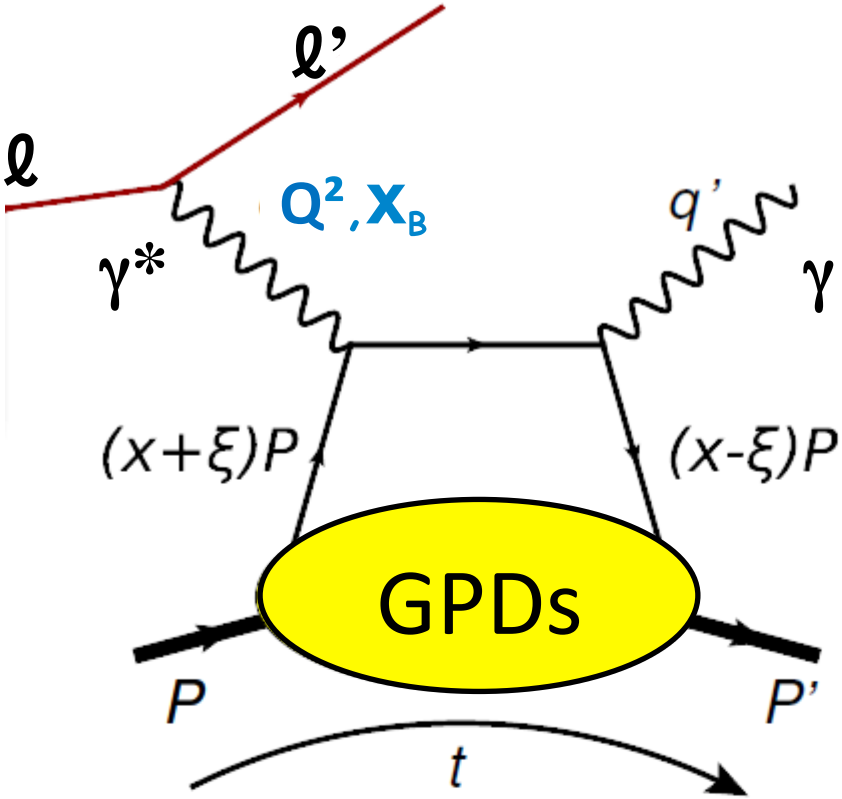
(position in the transverse plane)





M. Burkardt, Phys Rev D62

Exclusive reactions



DVCS: ℓp→ ℓ' p' γ (golden channel)

HEMP: **ℓp→ ℓ' p' ρ or ϕ or J/ψ,…**

Definition of variables:

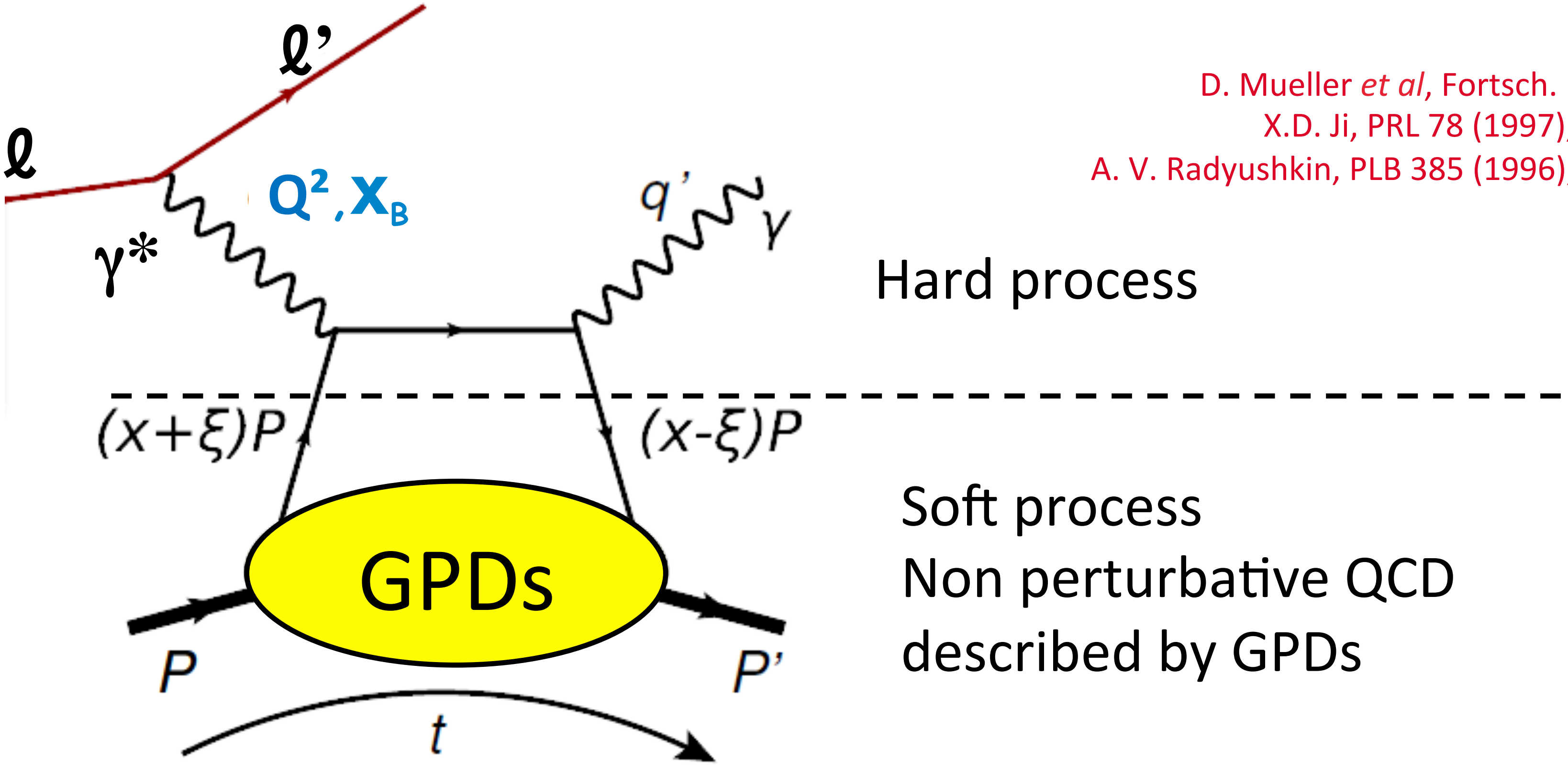
x: average long. momentum - NOT ACCESSIBLE

ξ: long. mom. difference $\simeq x_B/(2 - x_B)$

t: four-momentum transfer
related to $b_\perp$ via Fourier transform

Slide from N d'Hose, Tranversity 2014

GPDs and factorization



D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

Hard process

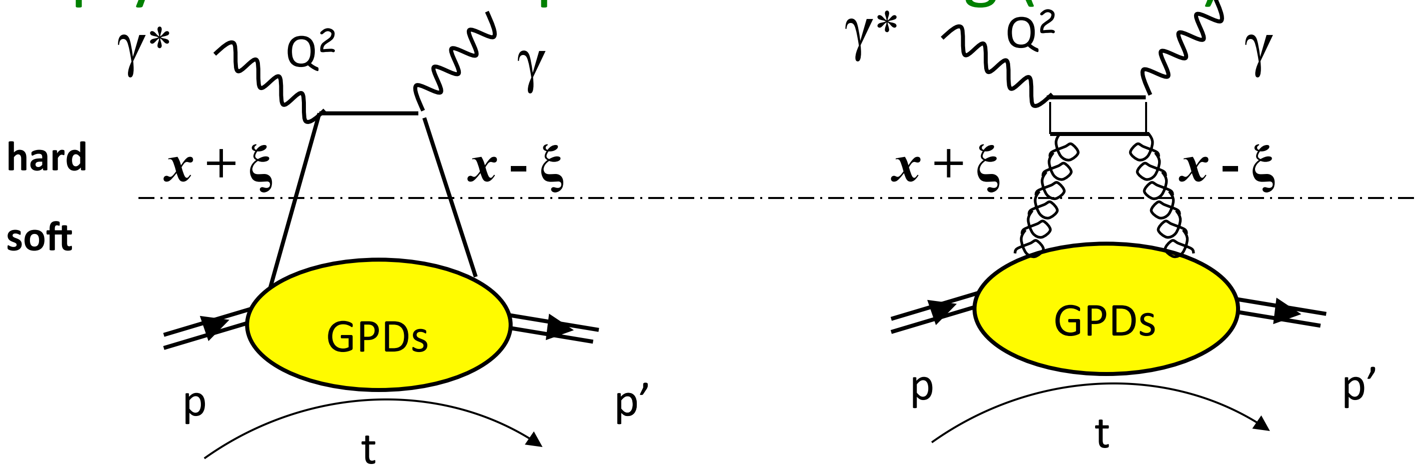
Soft process
Non perturbative QCD
described by GPDs

The minimal Q^2 at which the factorization holds **must be tested** and established by **experiments**

Exclusive reactions

Deeply Virtual Compton Scattering (DVCS):

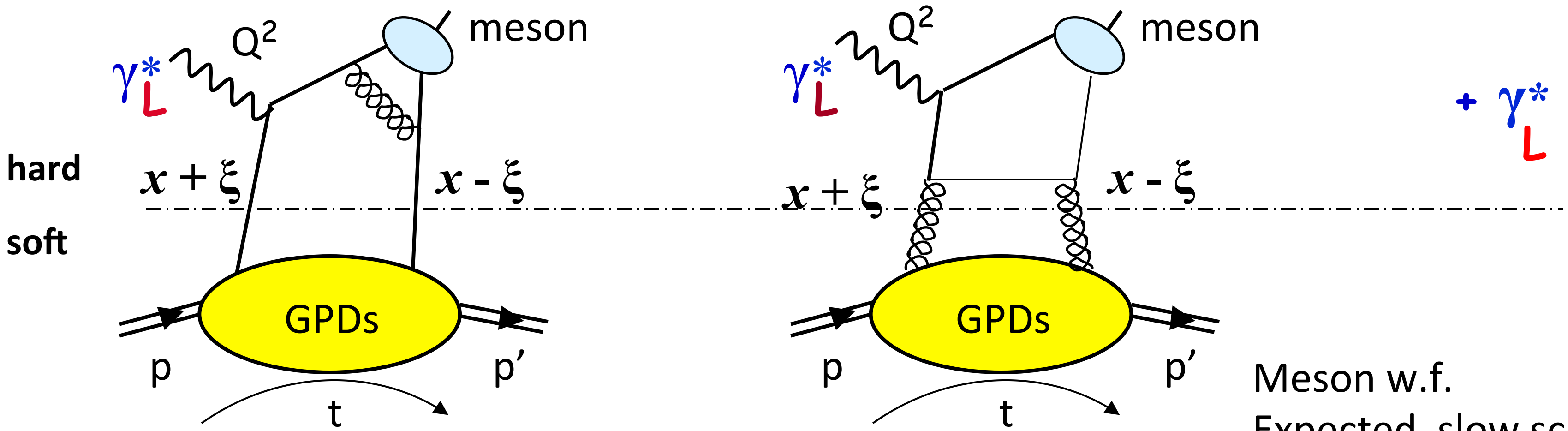
Factorisation:
Collins *et al.*



Q^2 large

$t \ll Q^2$

Hard Exclusive Meson Production (HEMP):



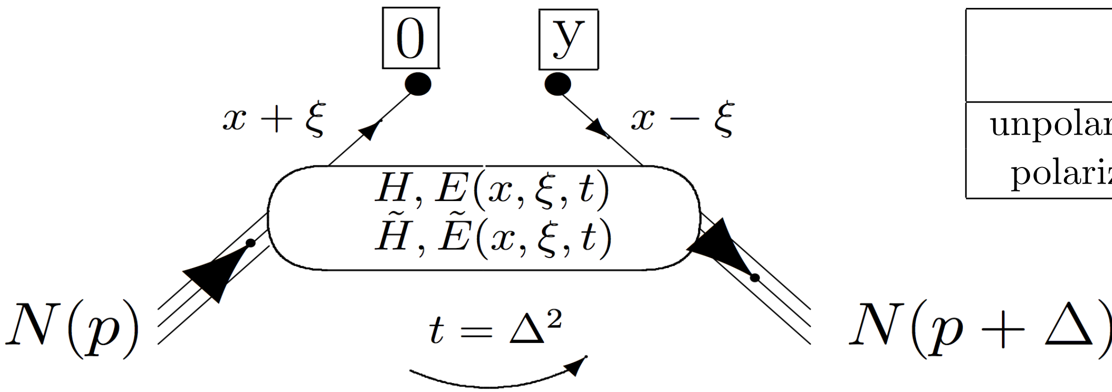
Quark contribution **Gluon contribution**

+ γ^*_L

Meson w.f.
Expected slow scaling

Slide from N d'Hose, Tranversity 2014

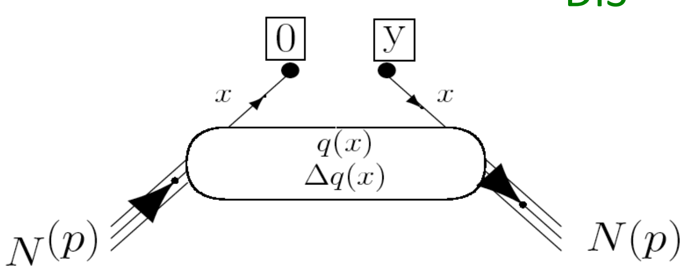
Generalized Parton Distributions



	Nucleon Helicity	
	conserving	non-conserving
unpolarized GPD	H	E
polarized GPD	$\tilde{\mathrm{H}}$	$\tilde{\mathrm{E}}$

$$\lim_{t\to 0}(GPD) \to PDF$$

DIS



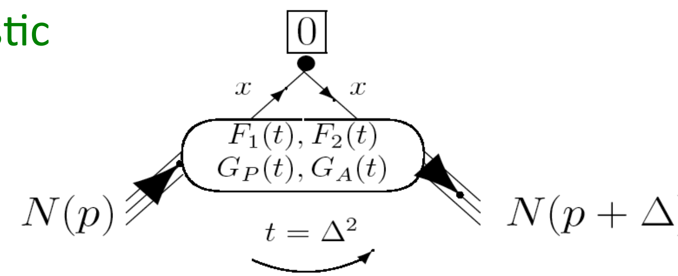
$$\boldsymbol{H^q(x,0,0) = q(x), -\bar{q}(-x)}$$

$$\boldsymbol{\tilde{H}^q(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)}$$

No relation for E(x,0,0)

GPD first moments $\to$ Form Factors

Elastic

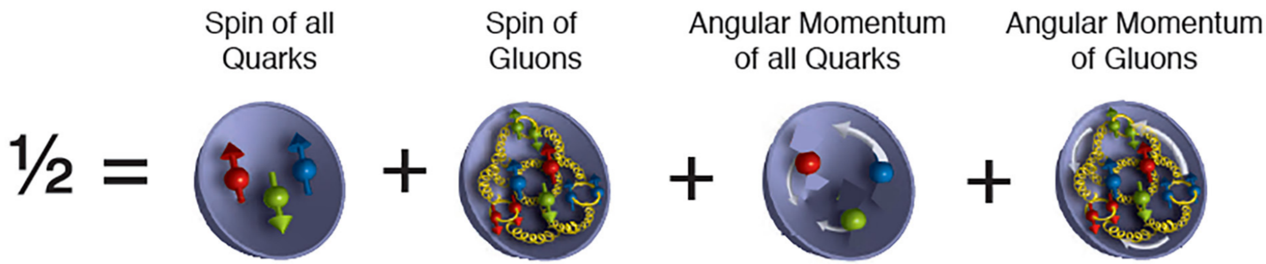


$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \qquad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \qquad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

RPP 76(2013) 066202

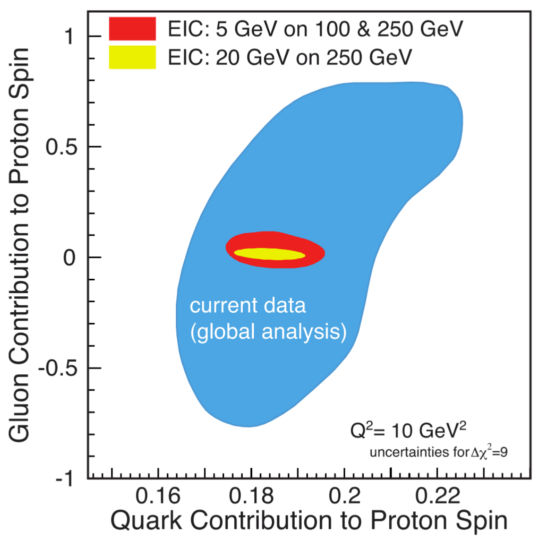
The "Holy grail" of GPDs (and TMDs) physics



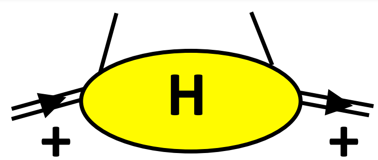
Contribution of the **angular momentum of quarks** to proton spin:

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

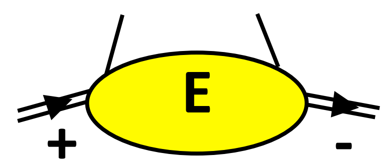
Ji's sum rule



RHIC spin physics results (LRP 2015)



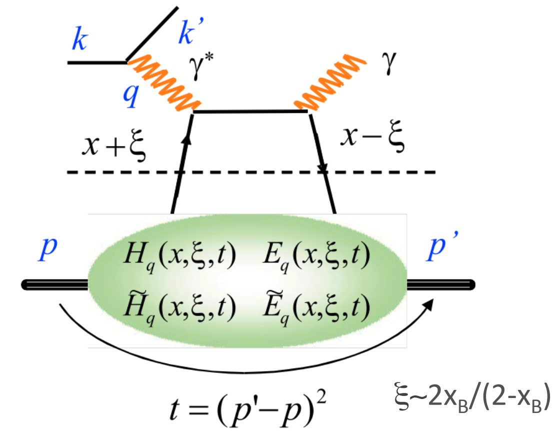
GPD H connects to the PDFs (symmetric initial-final states)



GPD E is the most unknown

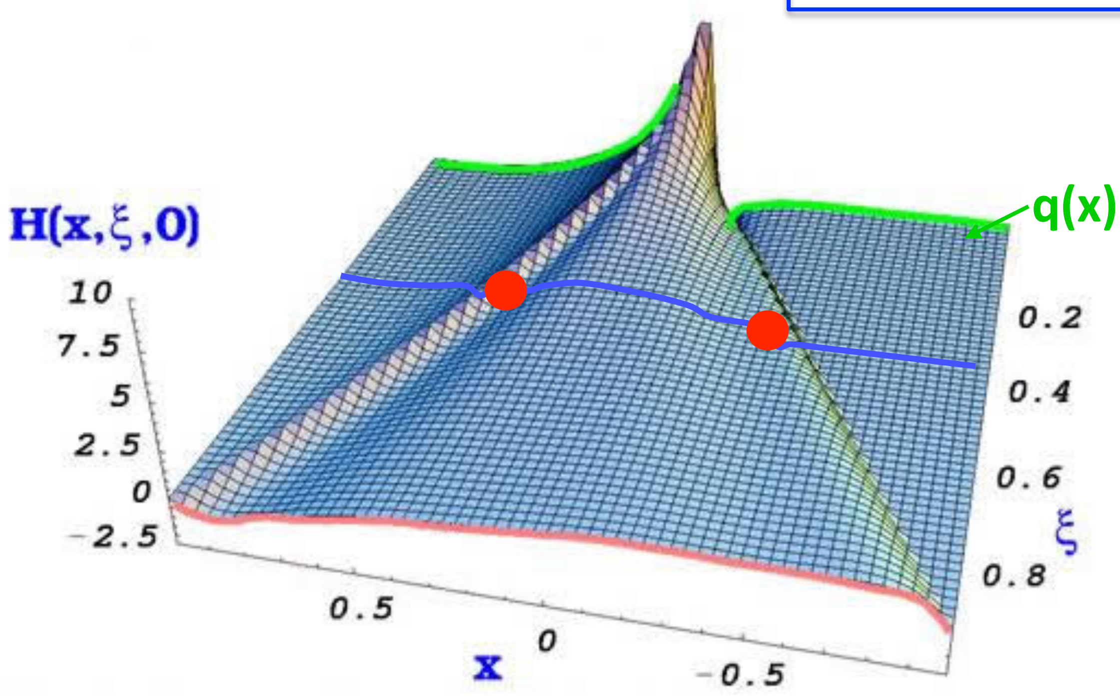
Experimentally, producing enough data to support the integration over the whole x range is a challenge.

GPDs and Compton Form Factors



CFF ↓ GPD ↓

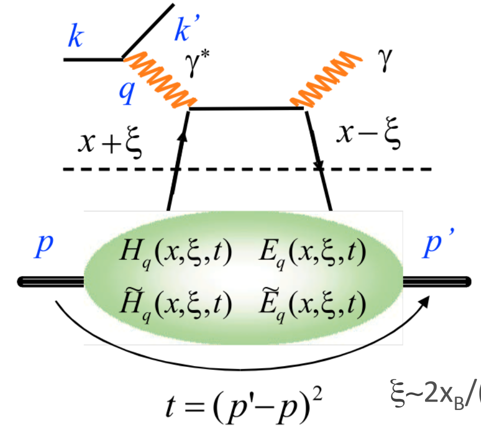
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$



Im part measured in
Beam Spin
or **Target Spin**
cross section difference

Real part measured in
Beam Charge
cross section difference or
Total cross section

GPDs and Compton Form Factors



$\xi \sim 2x_B/(2-x_B)$

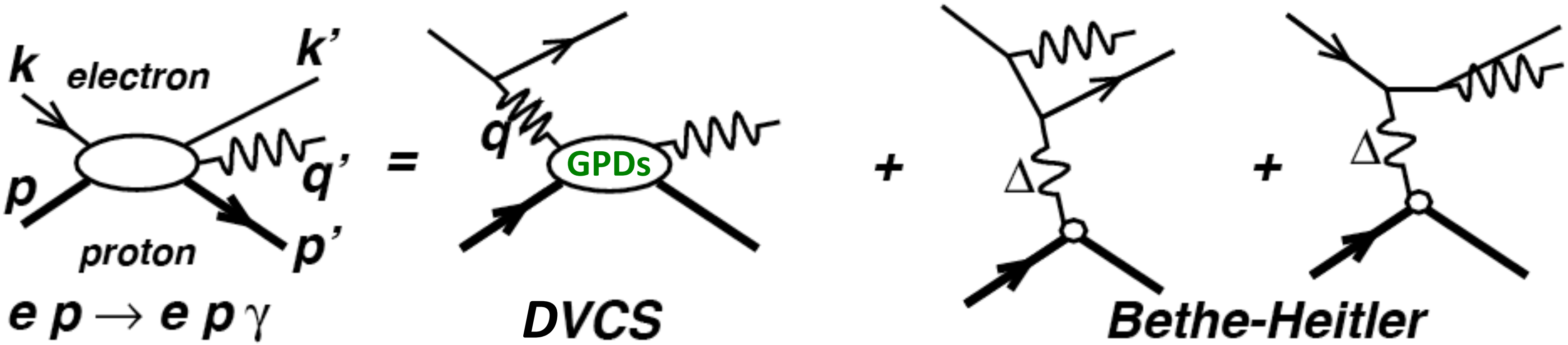
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$

$$\mathcal{Re}\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{Im}\,\mathcal{H}(x,t)}{x-\xi} + \mathcal{D}(t)$$

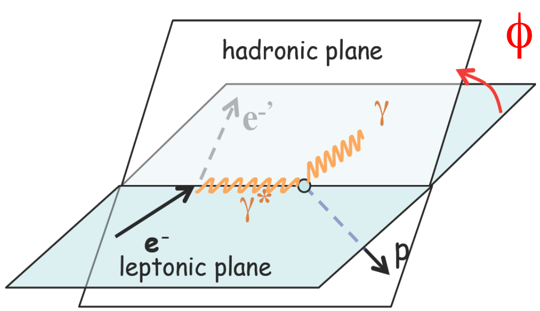
$\mathcal{D}$ term related to the Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

The Imaginary part and the Real part are not trivially related: both need to be measured.

Measuring DVCS to access GPDs information



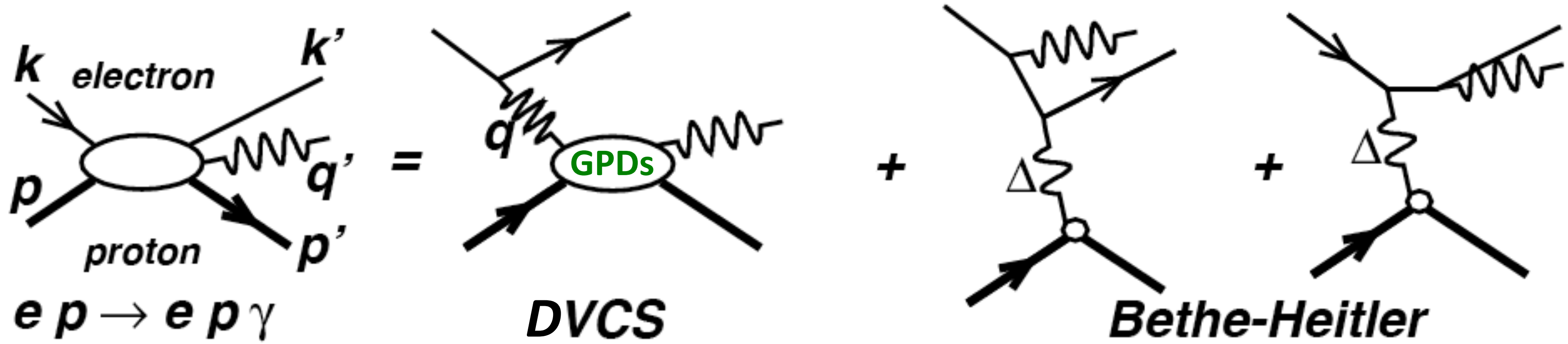
$$\frac{\mathbf{d^4\sigma(lp \to lp\gamma)}}{\mathbf{dx_B dQ^2 d|t| d\phi}} = \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{P_l} \quad \mathbf{d\sigma^{DVCS}_{pol}} + \mathbf{e_l}\,(\mathbf{Re(I)} + \mathbf{P_l Im(I)})$$



P_l : polarization target or beam

e_l : charge of the lepton beam

Measuring DVCS to access GPDs information



When only considering the handbag diagram (at leading twist)

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

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

$|BH|^2$ → Known to 1%

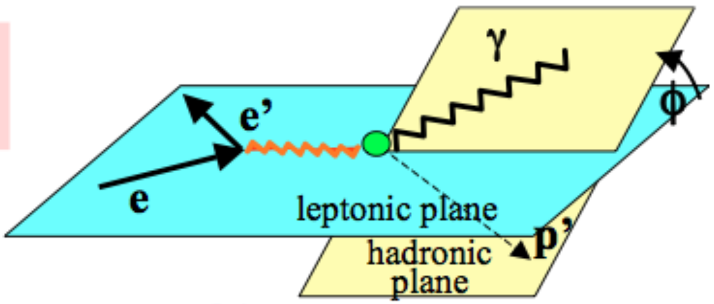
$\Re e \left(T^{BH} \cdot T^{DVCS}\right)$ → Linear combinations of GPDs

$|DVCS|^2$ → Bilinear combinations of GPDS

DVCS sensitivities to GPDs

$$\Delta\sigma = d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma}$$

$\xi = x_B/(2-x_B)$
$k = -t/4M^2$



Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi \;\Rightarrow\; H_p, \tilde{H}_p, E_p$$

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \mathbf{Im}\{F_1 \tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi \;\Rightarrow\; H_p, \tilde{H}_p$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi \, \mathbf{Im}\{k(F_2 H - F_1 E) + \ldots\}d\phi \;\Rightarrow\; H_p, E_p$$

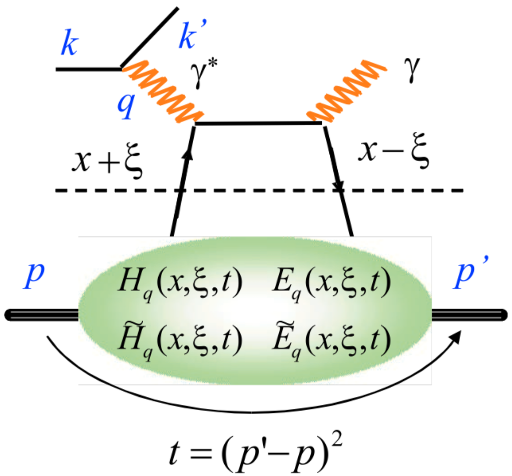
Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \;\Rightarrow\; H_n, \tilde{H}_n, E_n$$

To “extract the GPDs”, one can:

- Compare data to models of the GPDs (Double-distribution models, dual models, Mellin-Barnes models)
- Fit the CFFs from data:
    - world-wide data fitted at once (8 quantities varying with x_B and t),
    - fit data points versus ϕ at one kinematic point choosing a limited set of GPDs.

Multipole expansion of the amplitude



The full DVCS amplitude (ep->epγ) is

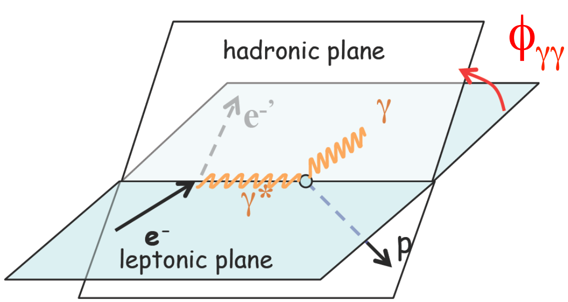
$$\mathcal{T}_{\rm VCS}(e^{\pm}) = \overline{u}(k',\lambda)\gamma_\mu u(k,\lambda)\frac{(\pm e)}{q^2}H^{\mu\nu}\epsilon^{\dagger}_{\nu}$$

The hadronic tensor is

$$H^{\mu\nu}_{\rm LO,twist\,2} = \frac{1}{2}(-g^{\mu\nu})_{\perp}\overline{U}(p')\left[(n\cdot\gamma)\mathcal{H}(\xi,t)+\frac{i}{2M}n_\kappa\sigma^{\kappa\lambda}\Delta_\lambda\mathcal{E}(\xi,t)\right]U(p)$$
$$-(\epsilon^{\mu\nu})_{\perp}\overline{U}(p')\left[(n\cdot\gamma\gamma_5)\widetilde{\mathcal{H}}(\xi,t)+(\gamma_5 n\cdot\Delta)\widetilde{\mathcal{E}}(\xi,t)\right]U(p)\;,$$

CFFs

In practice, one exploits the azimuthal modulation of the DVCS(and its interference)



$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6(s_e-M^2)^2}{x^2_{\rm Bj}Q^6}\left\{\sum_{n=0}^{2}c_n^{\rm DVCS}\cos(n\phi_{\gamma\gamma})+\sum_{n=1}^{2}s_n^{\rm DVCS}\sin(n\phi_{\gamma\gamma})\right\}$$

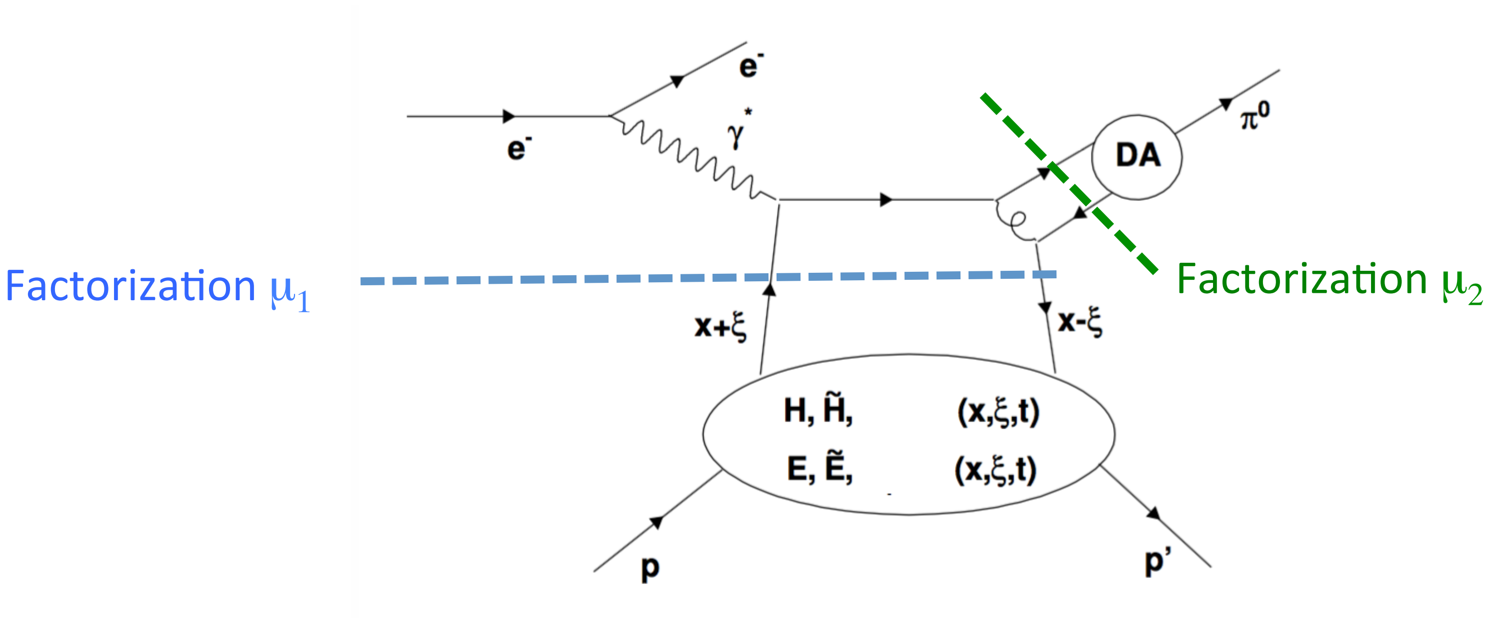
$$c_0^{DVCS} = f(kine)\left\{4(1-x_{Bj})\mathcal{H}\mathcal{H}^* + 4\left(1-x_{Bj}+\frac{2Q^2+t}{Q^2+x_{Bj}t}\,\frac{\epsilon^2}{4}\right)\tilde{\mathcal{H}}\tilde{\mathcal{H}}^*+...\right\}$$

Harmonic coefficients

CFFs

$$c^I_{unp} = g(kine)\left\{F_1\mathcal{H}-\frac{t}{4M^2}F_2\mathcal{E}+\frac{x_{Bj}}{2-x_{Bj}+x_{Bj}\frac{t}{Q^2}}(F_1+F_2)\tilde{\mathcal{H}}+...\right\}$$

HEMP → (MFF)^2 → filter of GPDs and flavors



Vector meson production (ρ,ω,ϕ, J/ψ…) ⇒ H & E

Pseudo-scalar production (π,η…) ⇒ $\tilde{H}$ & $\tilde{E}$

But also contribution from
- gluons and
- different quark flavor

$$H\rho^0 = 1/\sqrt{2}\ (2/3\ H^u + 1/3\ H^d + 3/8\ H^g)$$

$$H\omega = 1/\sqrt{2}\ (2/3\ H^u - 1/3\ H^d + 1/8\ H^g)$$

$$H\phi = -1/3\ H^s - 1/8\ H^g$$

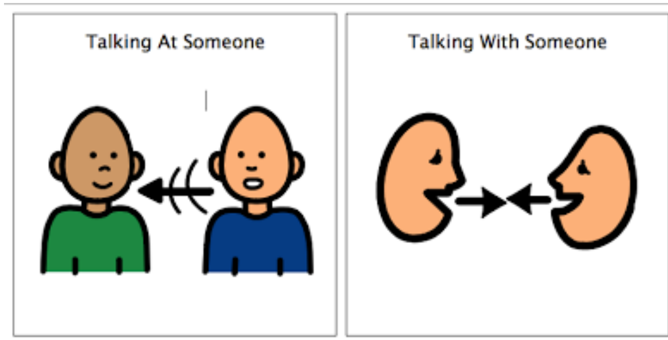
1 question: 30 m reading + 15 min discussions

ACTIVE LEARNING

What I hear, I forget

What I see, I remember

What I do, I understand



Group 1 Meriem*, Shokhna, Kieran, Carlos Y.	**Group 5** Nabil*, Brandon C., Fillipo
Group 2 Frederic*, Shujie, Shivangi, Ryan	**Group 6** Brandon K.*, Alexa, Bailing, Gavin
Group 3 Waverly*, Sandra, Bijit, Arkadiusz	**Group 7** Holly, Larissa, David AQ, Giovanni
Group 4 Hamza, Scott, Marco, Dexu	**Group 8** Luca*, Elias, David R.
Group 9 Abel, Tao, Rajesh, Manuel	*: familiar with GPDs/DVCS

Factorization, scaling and twist

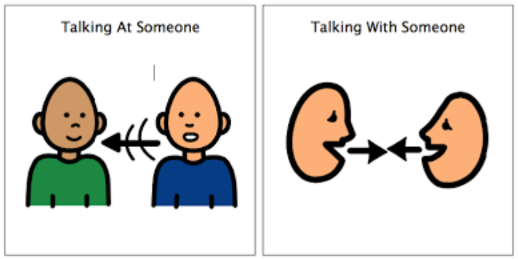
- How do the scaling violations observed in the DIS/PDF case express themselves in the DVCS/GPD case?
- How do they affect the parametrization of the DVCS cross-section in term of GPDs?

Paper of reference:

M. Defurne, 2016, Thesis document, Université Paris-Sud.

Photon and π^0 electroproduction at Jefferson Laboratory- Hall A

Section 1.2 and 1.4



GPDs and Fitting procedures for DVCS

When trying to extract GPDs from DVCS data one often talks about the *curse of dimensionality*. What is this? What are the ways the authors list to deal with it?

Paper of reference:

GPDs and Fitting Procedures for DVCS,

Kumericki and Mueller, 2016, DOI 10.1142/S2010019.