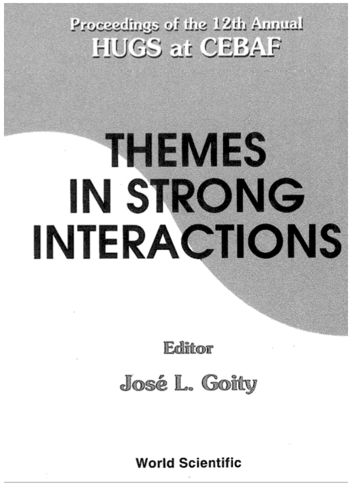
Spatial imaging of the nucleon

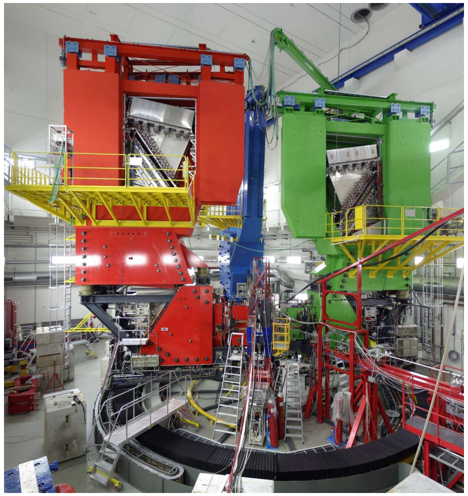
J. Roche (Ohio University)

- 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)



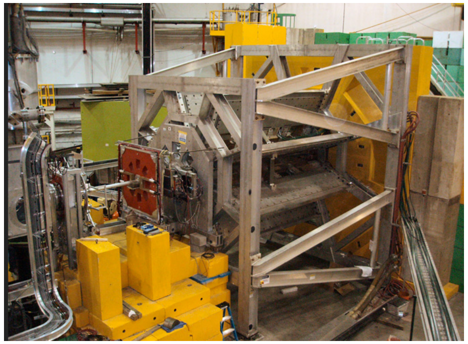


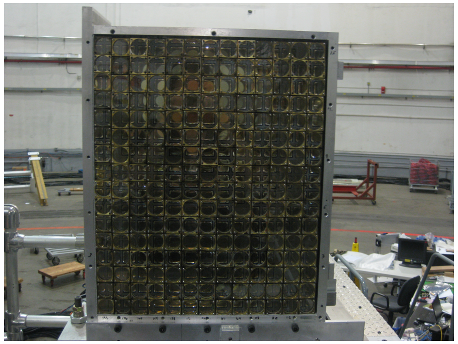
Polarizabilities of the nucleon: VCS@MAMI- Germany

Strange form factor the nucleon: GO@JLab

Physics beyond the Standard Model: QWEAK@Jlab

GPDs: DVCS-Hall A @Jlab





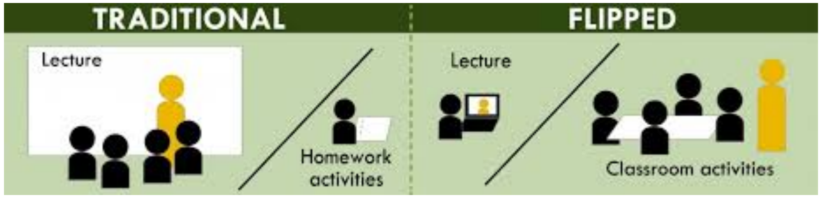
Absolute cross-sections measurements

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

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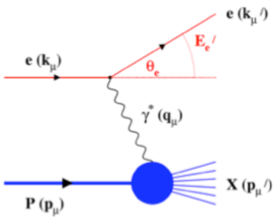
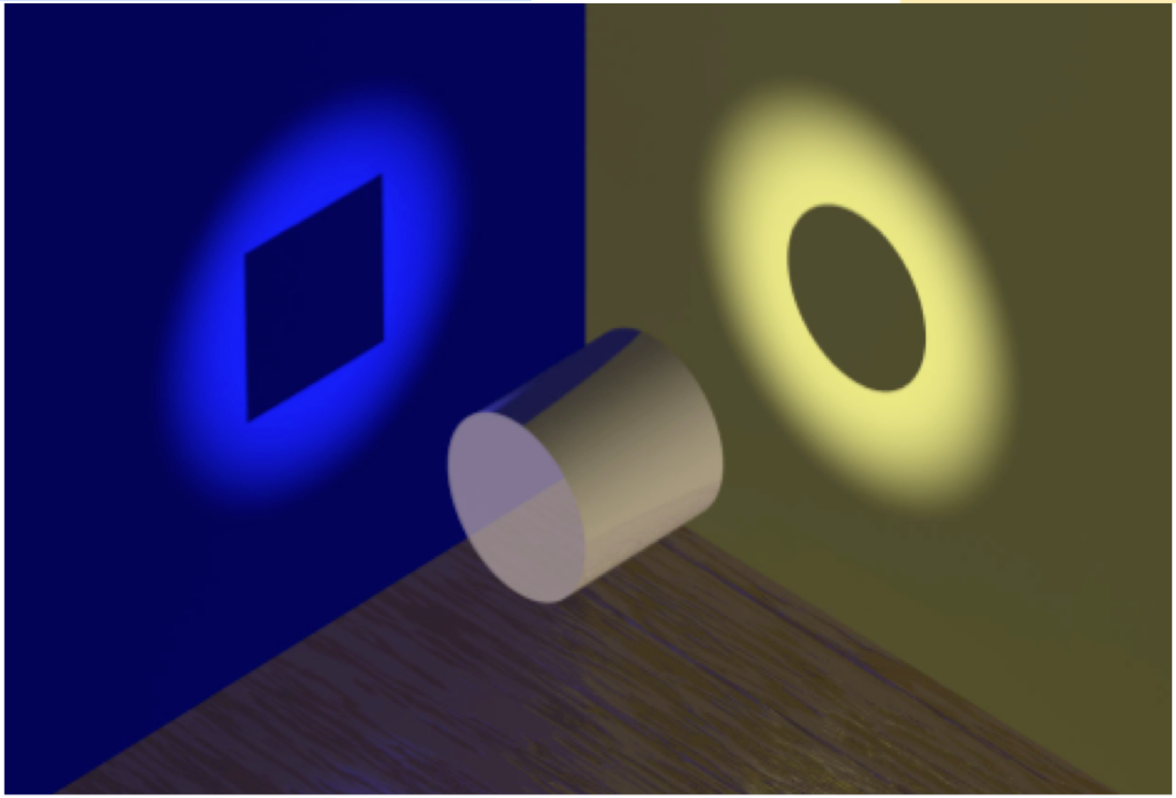
3D picture of the nucleon

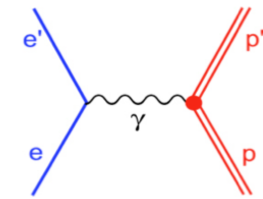
DIS Parton Distribution Functions



No information on the spatial location of the constituents



Elastic Form Factors



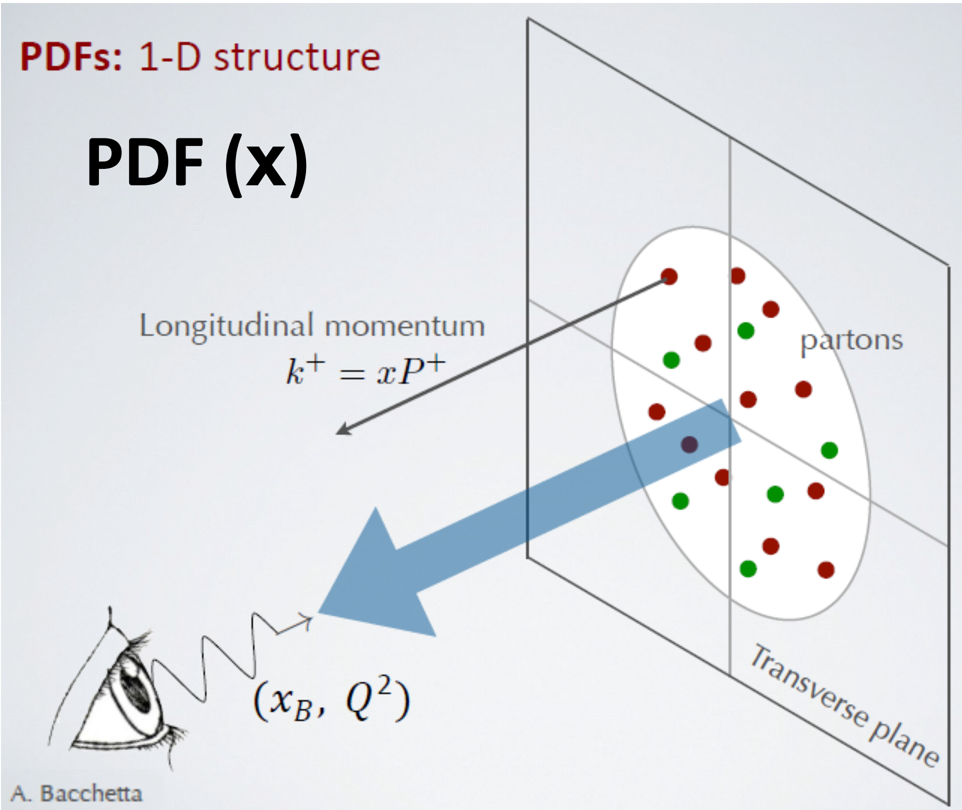
No information about the underlying dynamics of the system

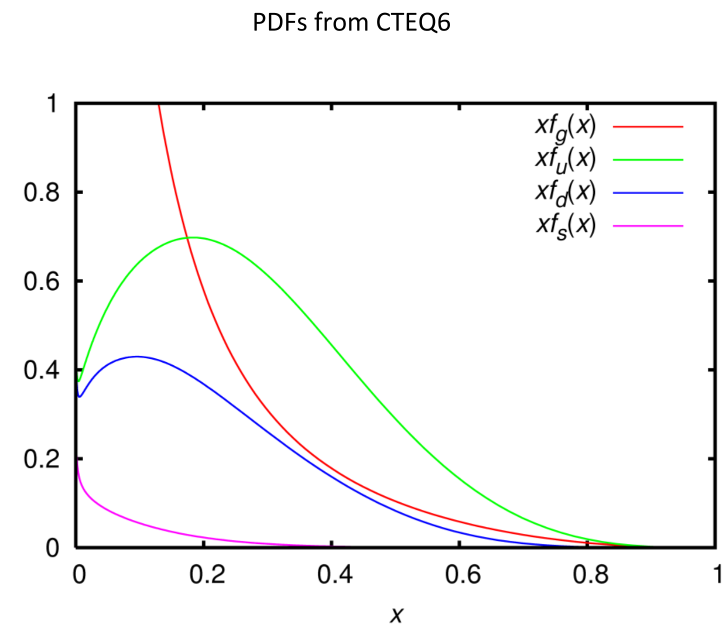
Generalized Parton Distribution Function :

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



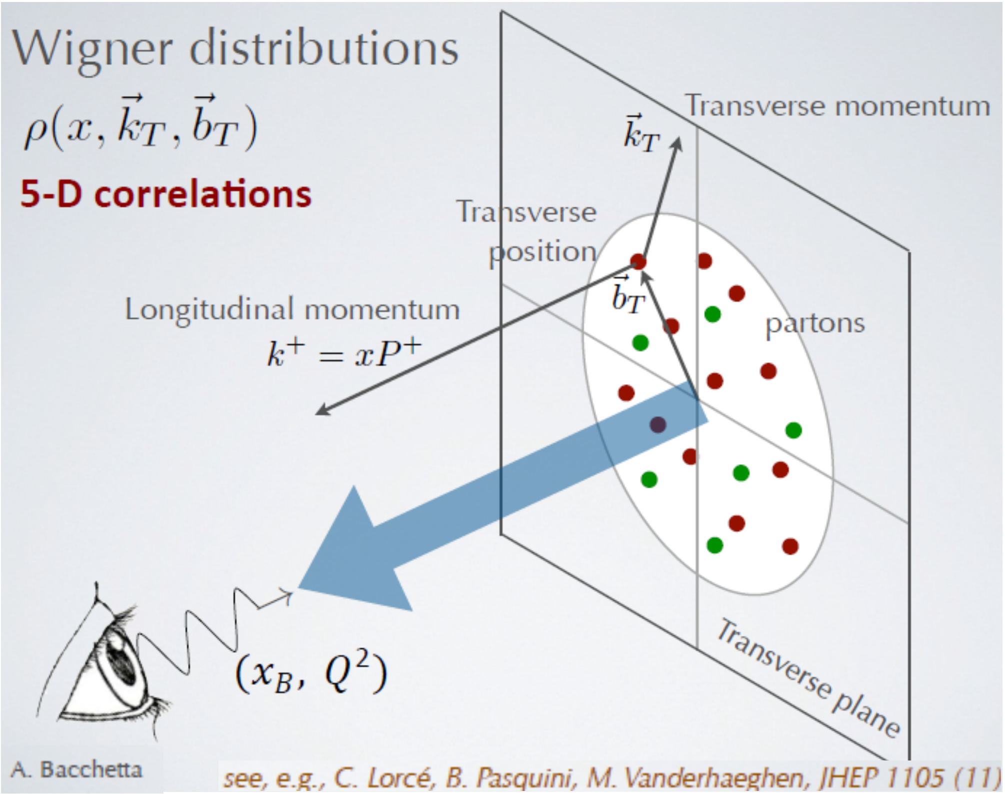


PDF measured in Deep Inelastic Scattering

$\ell p \rightarrow \ell' X$

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)

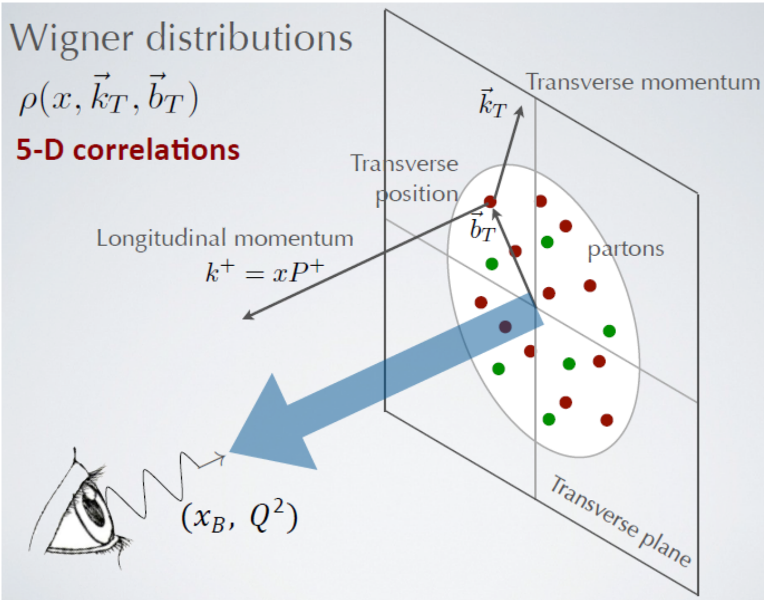
TMD (x, $k_\perp$) :
Transverse Momentum Distribution
(momentum in the transv. Plane)

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

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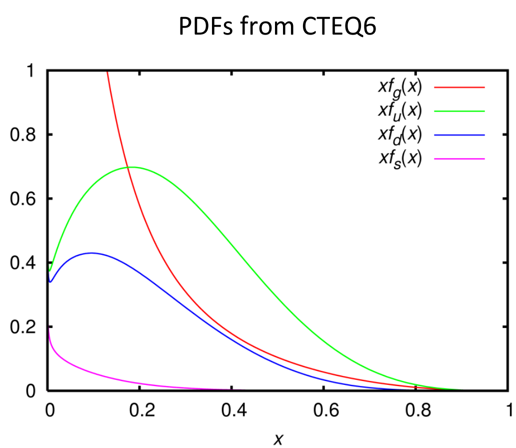
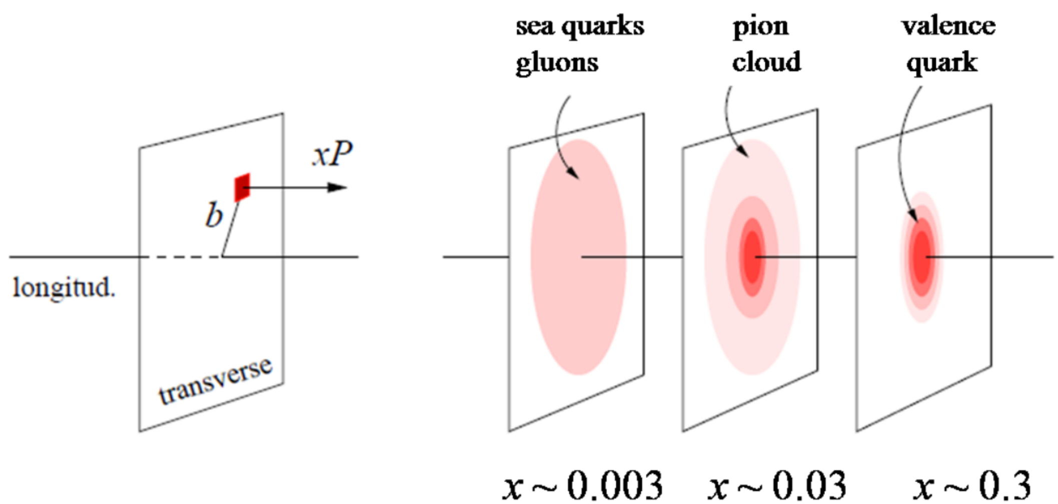
Generalised Parton Distribution

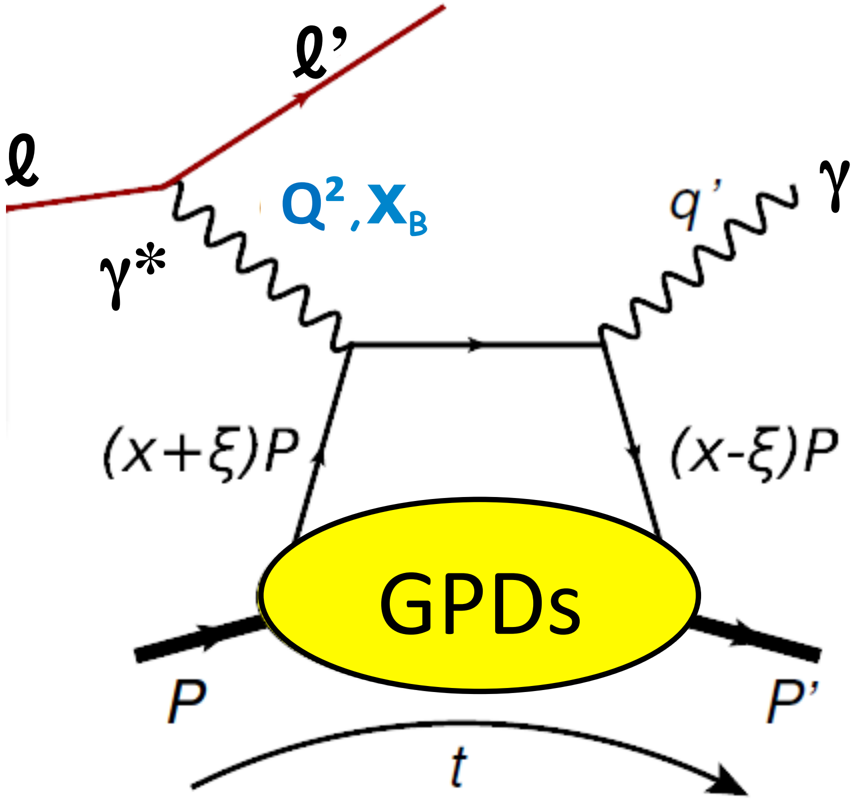
(position in the transverse plane)





M. Burkardt, Phys Rev D62

Exclusive reactions: handbag diagram



γ or ρ, ϕ, J/ψ,…

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

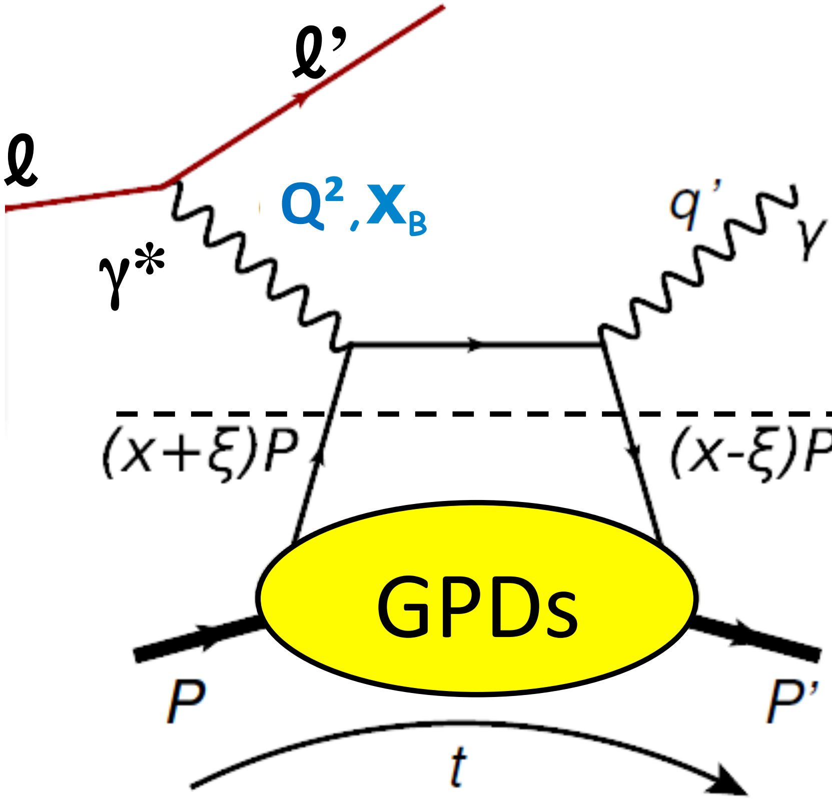
ξ: long. mom. difference $\simeq x_B/(2 - x_B)$

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
LO: QED
NLO: QCD perturbative

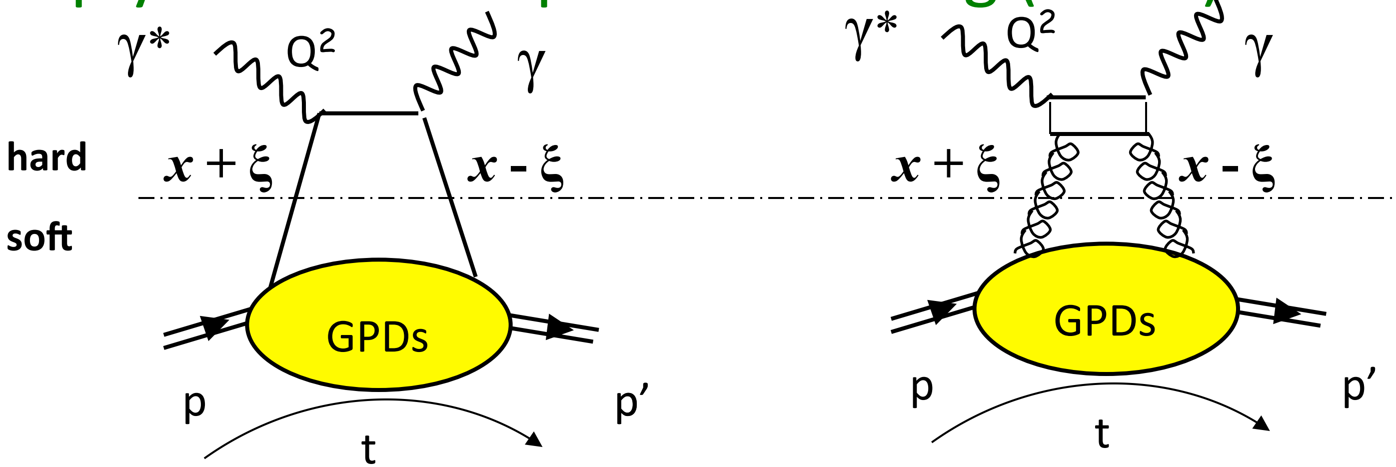
Soft process
Non perturbative QCD
described by GPDs

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

Exclusive reactions

Deeply Virtual Compton Scattering (DVCS):

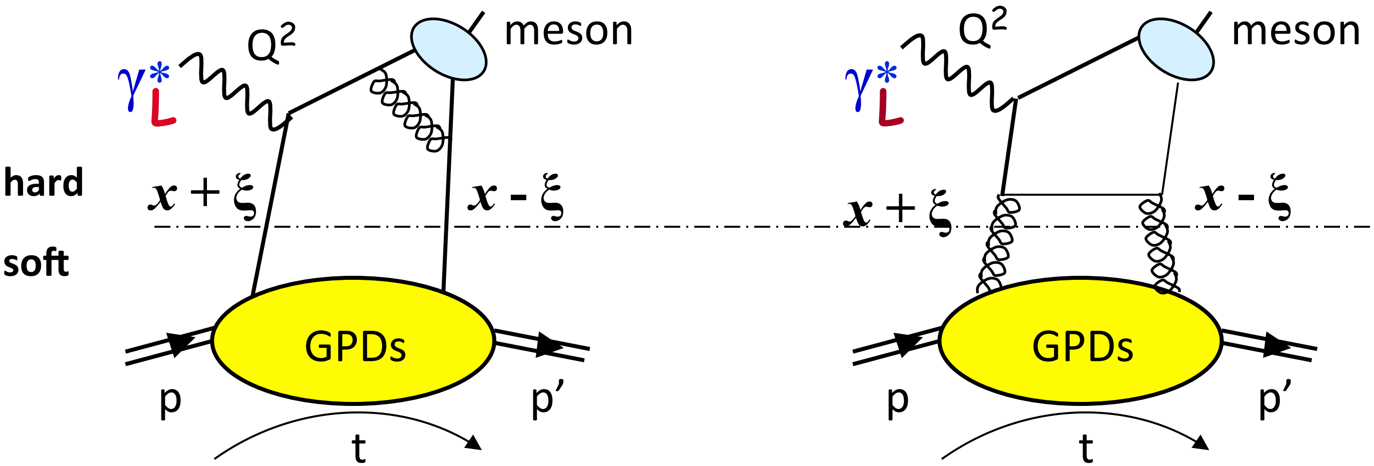
Factorisation:
Collins *et al.*



Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):



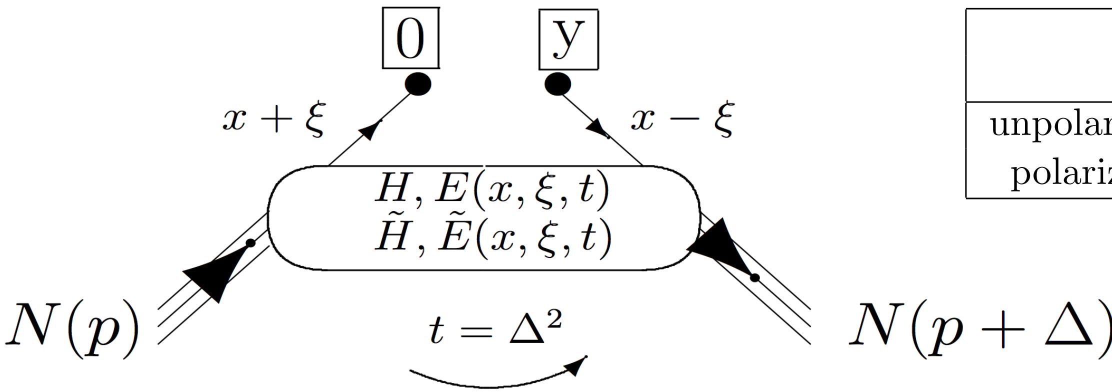
Quark contribution **Gluon contribution**

$+ \gamma^*_L$

Meson w.f.
Very slow scaling

Slide from N d'Hose, Tranversity 2014

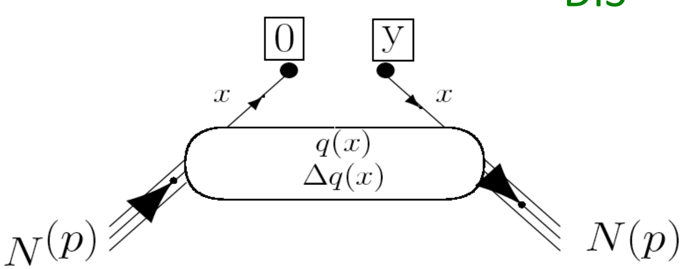
Generalized Parton Distributions



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

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

DIS

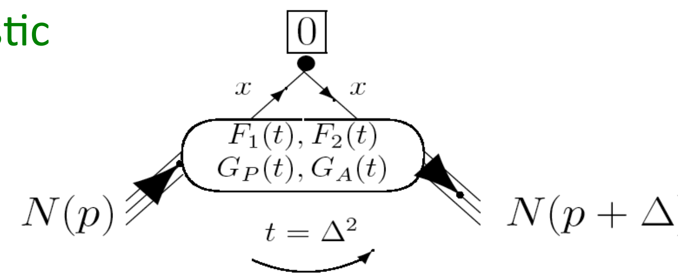


$$\boldsymbol{H^q(x,0,0) = q(x), -\bar{q}(-x)}$$

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

$$GPD \text{ first moments} \to \text{Form Factors}$$

Elastic



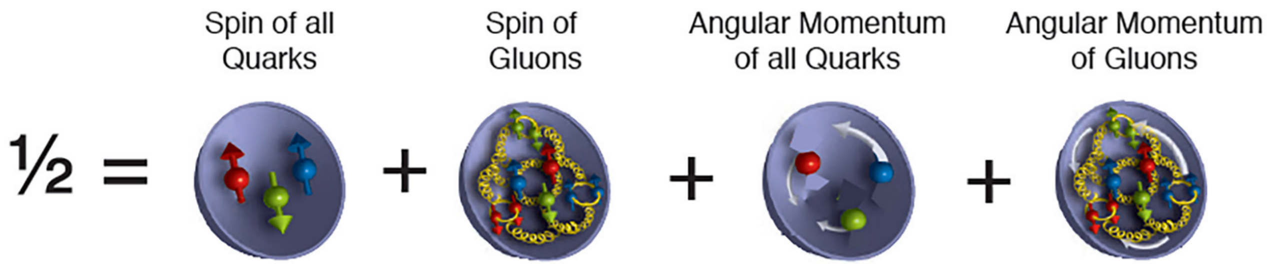
$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

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

No relation for the GPD E and $\tilde{E}$

RPP 76(2013) 066202

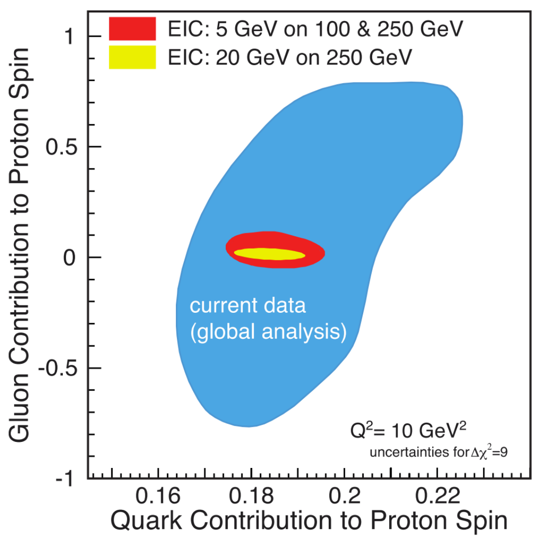
The "Holy grail" of GPDs (and TMDs) physics



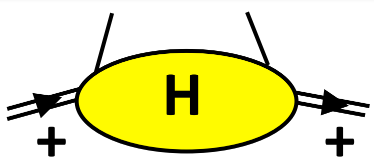
Contribution of the **angular momentum of quarks** to proton spin:

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

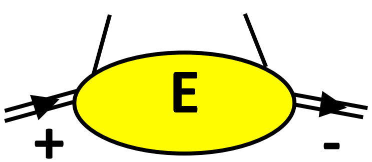
Ji's sum rule



RHIC spin physics results (LRP 2015)



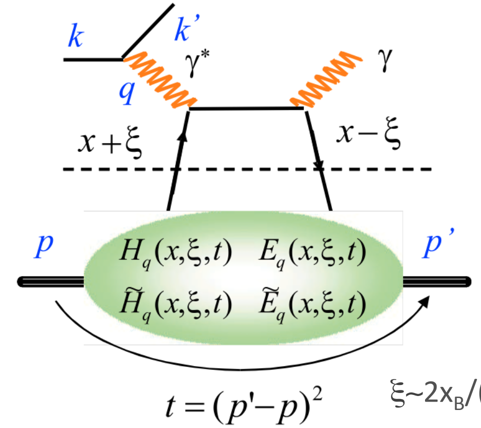
GPD H connects to the PDFs (symmetric initial-final states) Known from polarized DIS data



GPD E is the unknown

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

GPDs and Compton Form Factors

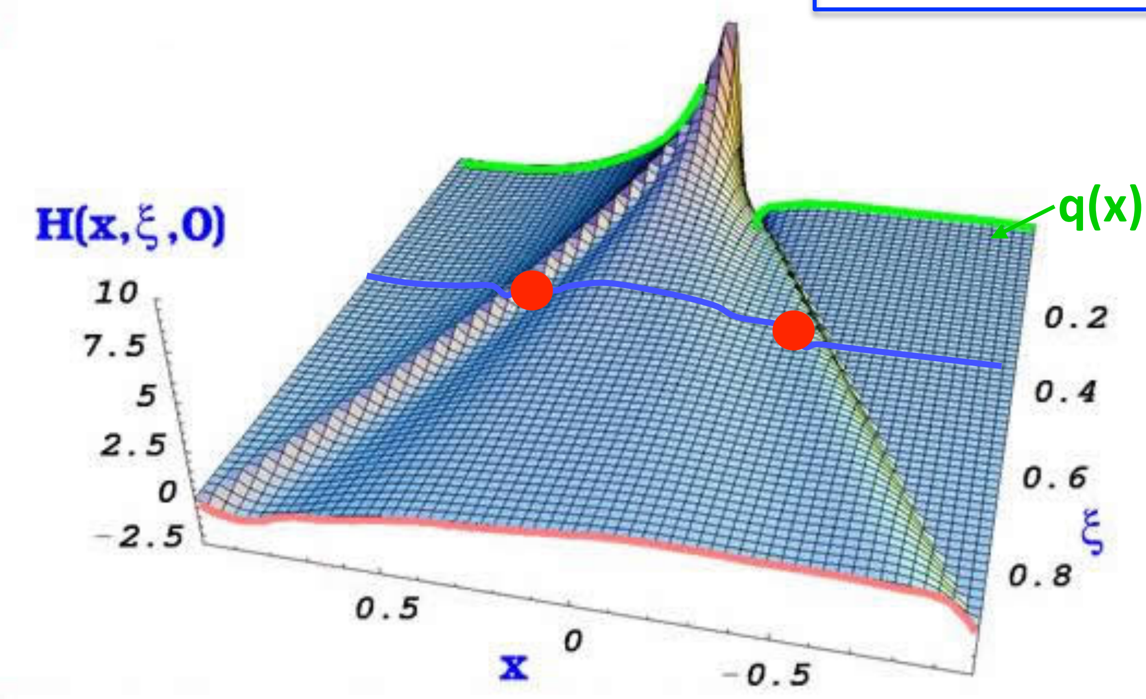


$\xi \sim 2x_B/(2-x_B)$

Cauchy theorem

CFF GPD

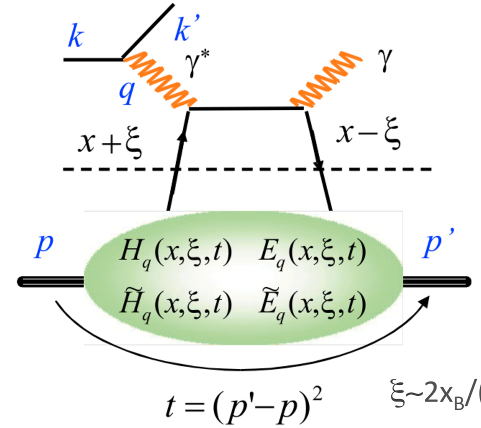
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$



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



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

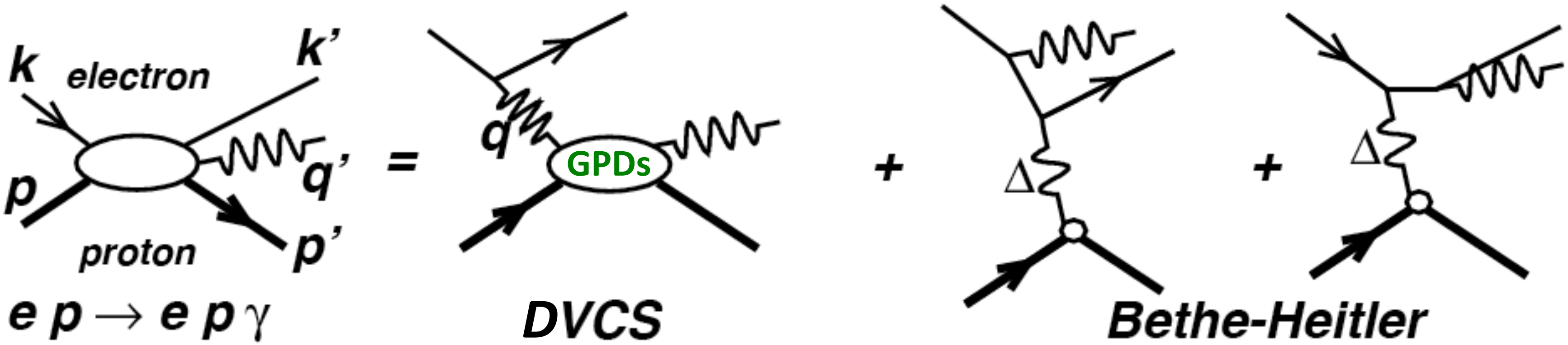
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \mathcal{D}(t)$$

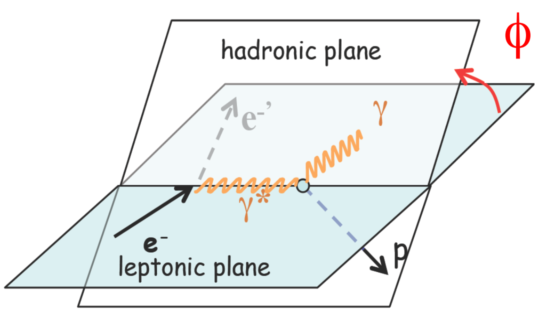
$\mathcal{D}$ term related to the Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

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

Measuring DVCS to access GPDs information



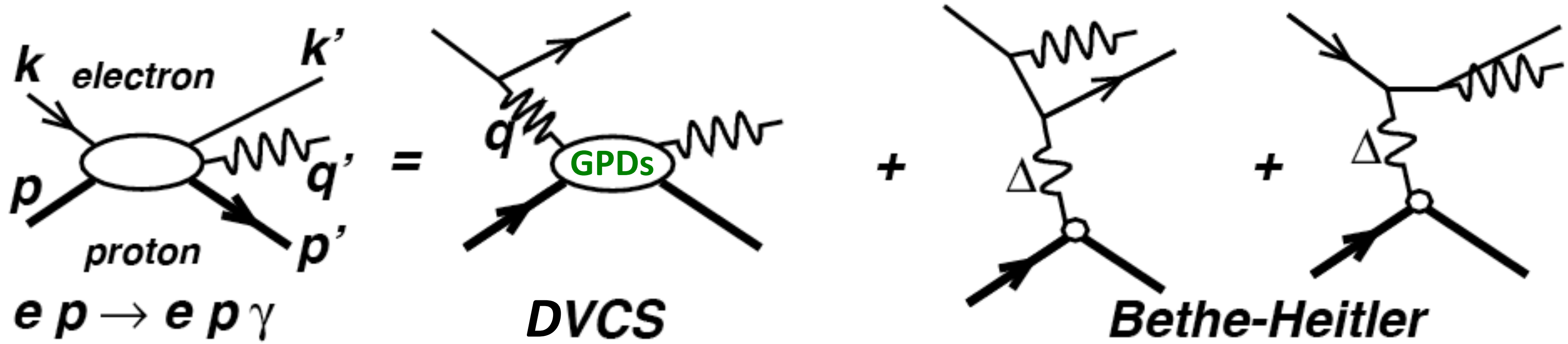
$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \quad d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$



P_l : polarization target or beam

e_l : charge of the lepton beam

Measuring DVCS to access GPDs information



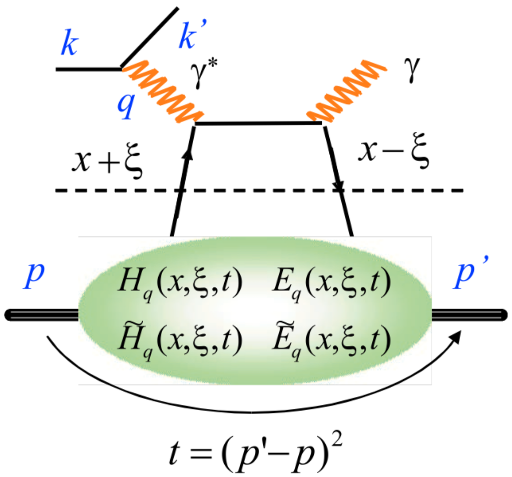
When only considering the handbag diagram (at leading twist)

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

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

- $|BH|^2$: Known to 1%
- $\Re e\,(T^{BH}\cdot T^{DVCS})$: Linear combinations of GPDs
- $|DVCS|^2$: Bilinear combinations of GPDS

Multipole expansion of the amplitude



The full DVCS amplitude (ep->epγ) is

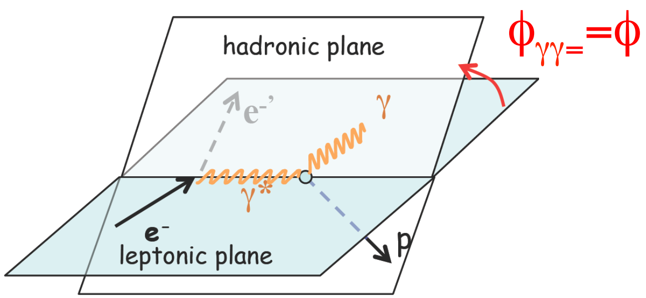
$$\mathcal{T}_{\rm VCS}(e^{\pm}) = \overline{u}(k',\lambda)\gamma_\mu u(k,\lambda)\frac{(\pm e)}{q^2}H^{\mu\nu}\epsilon^\dagger_\nu$$

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)



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

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

Harmonic coefficients

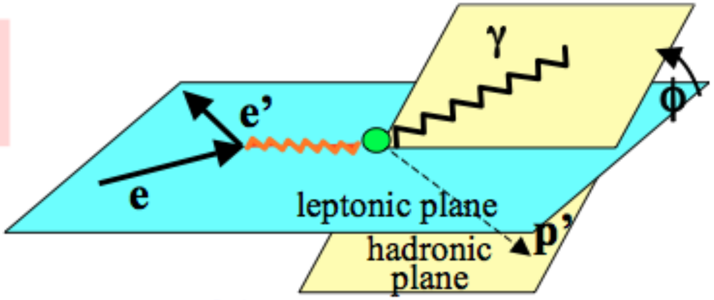
CFFs

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

DVCS sensitivities to CFFs

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

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



Polarized beam, unpolarized proton target:

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

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

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

Unpolarized beam, transverse proton target:

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

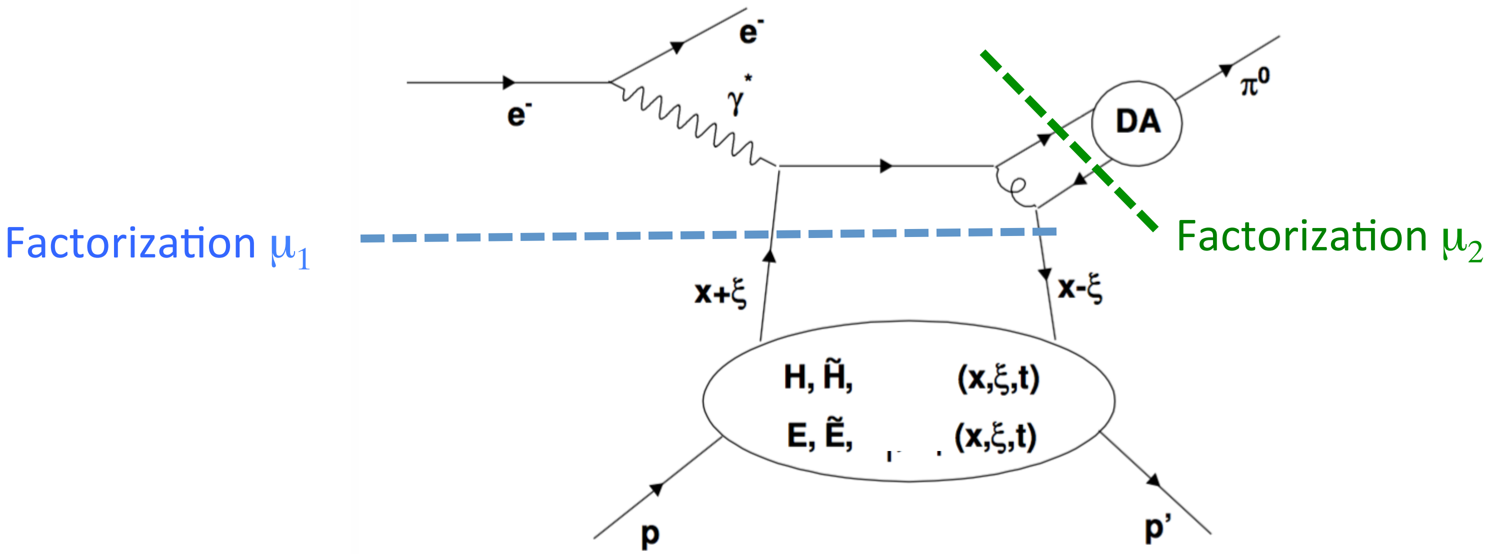
Polarized beam, unpolarized neutron target:

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

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.

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



Vector meson production $(\rho,\omega,\phi, J/\psi\ldots)$ ⇒ H & E

Pseudo-scalar production $(\pi,\eta\ldots)$ ⇒ $\tilde{H}$ & $\tilde{E}$

But also contribution from
- gluons and
- different quark flavor

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

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

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

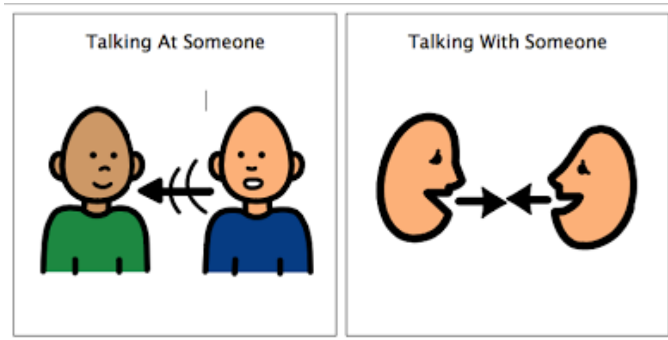
1 question: 30 m reading + 15 min discussions

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

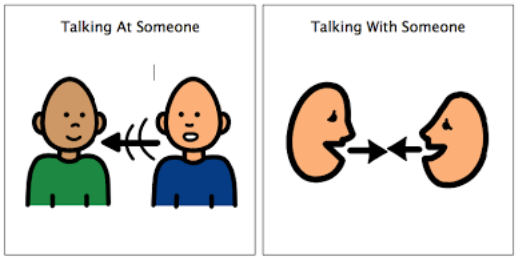
- How do the scaling violations observed in the DIS/PDF case express themselves in the DVCS/GPD case?
- How do they affect the parametrization of the DVCS cross-section in term of GPDs?

<u>Paper of reference</u>:

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

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

Section 1.2 and 1.4



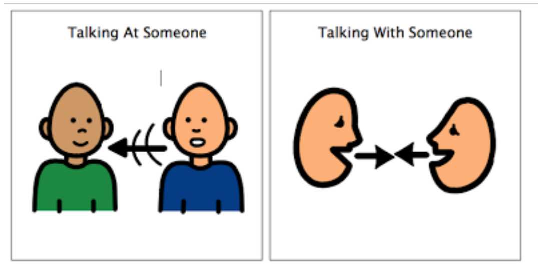
GPDs and Fitting procedures for DVCS

When trying to extract GPDs from DVCS data one often talks about the *curse of dimensionality*. What is this, why does it matter?

<u>Paper of reference</u>:

GPDs and Fitting Procedures for DVCS,

Kumericki and Mueller, 2016, DOI 10.1142/S2010019.



Spatial imaging of the nucleon

J. Roche (Ohio University)

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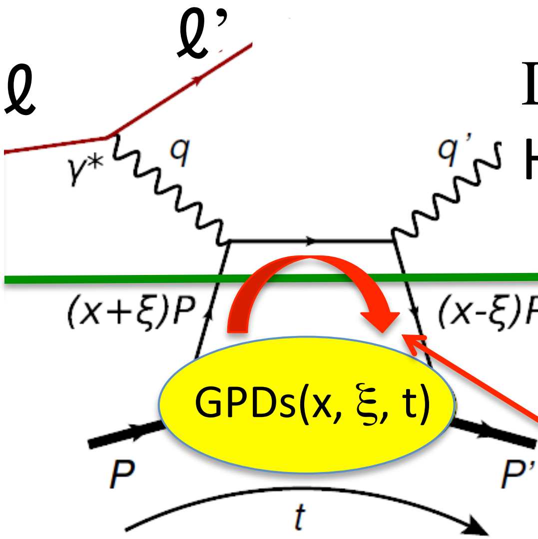
- Dedicated experiments are conducted world-wide.

- 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.

What we talked about during our last meeting



DVCS: ℓp→ ℓ' p' γ (golden channel)

HEMP: ℓp→ ℓ' p' ρ or ϕ or J/ψ,…

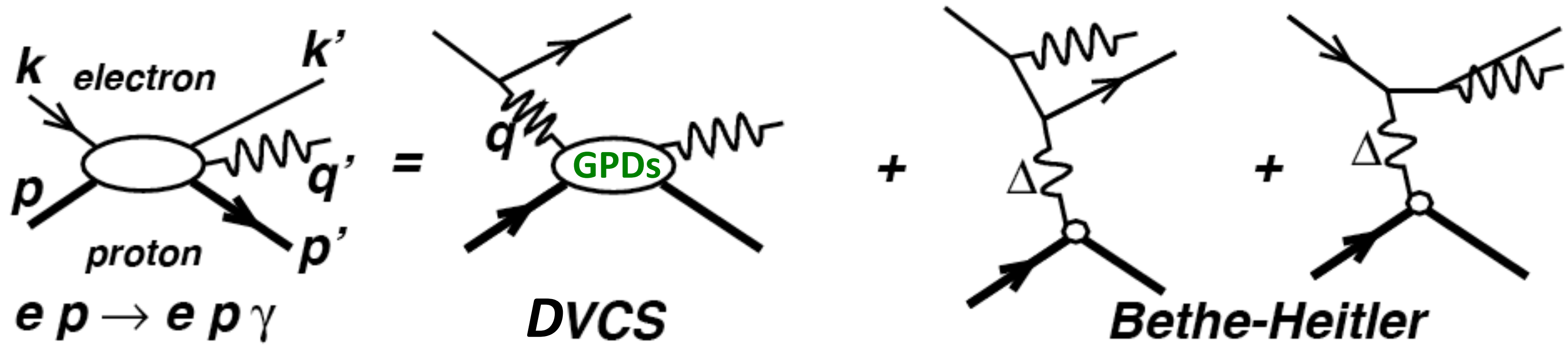
Factorization allow the introduction of the GPDs (need NLO and twist corrections)

Close loop makes the x variation of the GPDs inaccessible

Experimentally, instead on access CFFs (Re and Im parts)

⇒ 8 variable functions of ξ (~x_B) and t.

What we talked about during our last meeting

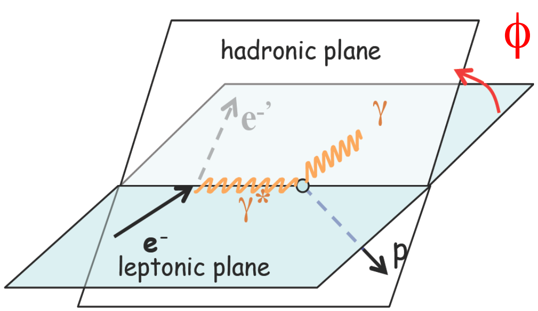


At leading twist:

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

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

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



The DVCS program worldwide

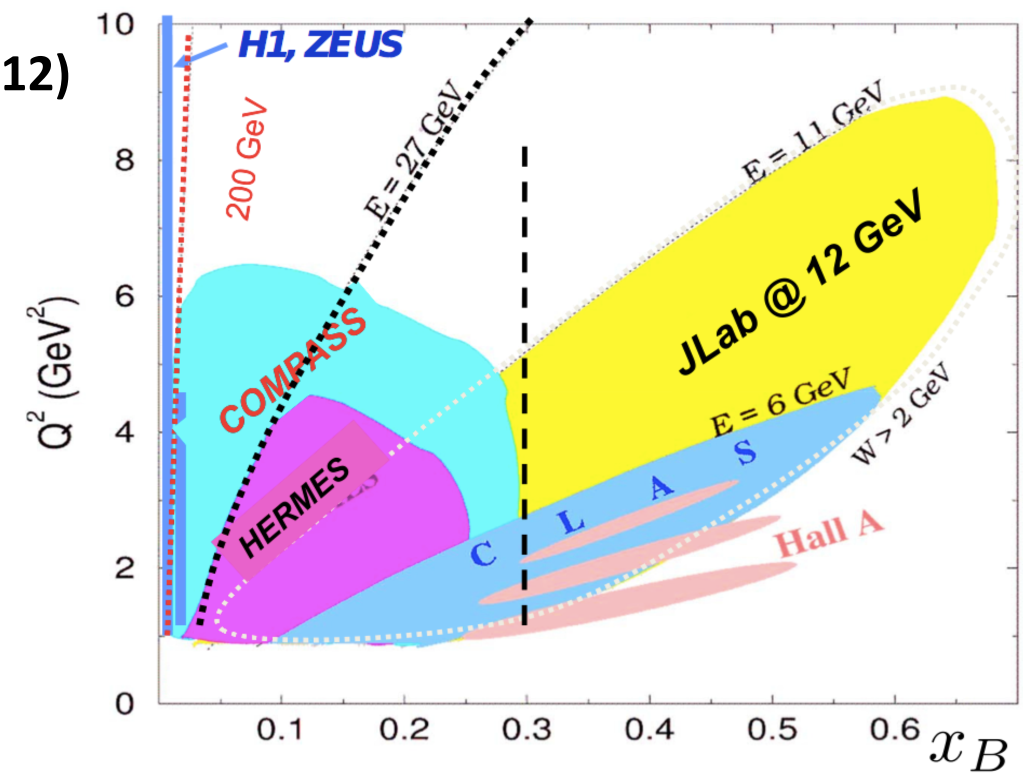
Experimental timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B, Hermes, H1&ZEUS): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2015 and later
- EIC program…

In the valence region (JLab 6 and JLab 12)

Partially complimentary, overlapping

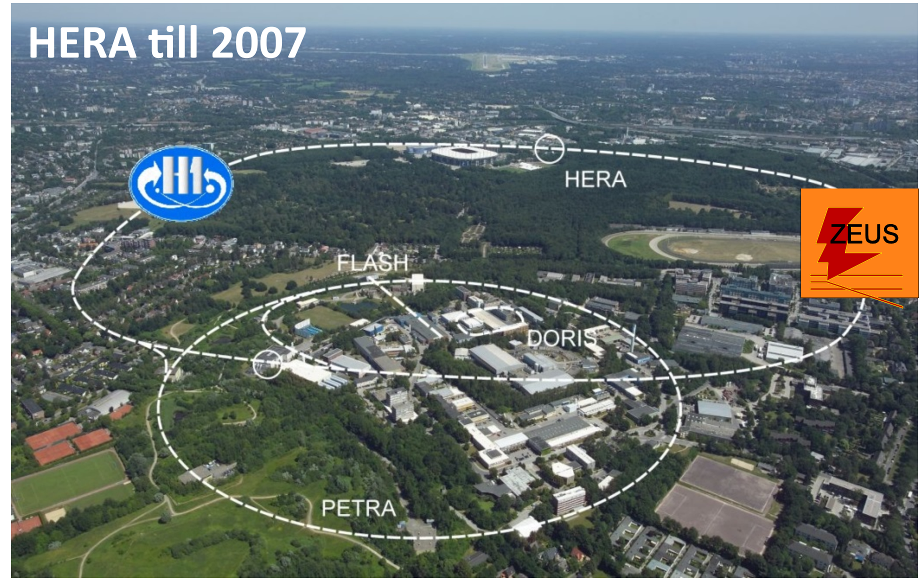
- Hall A/C
  - high accuracy (~5%)
  - limited kinematic
- Hall B:
  - wide kinematic range
  - limited accuracy (15+%)



The past and future experiments

Collider mode e-p forward fast proton

Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction



Slide from N d'Hose, Tranversity 2014

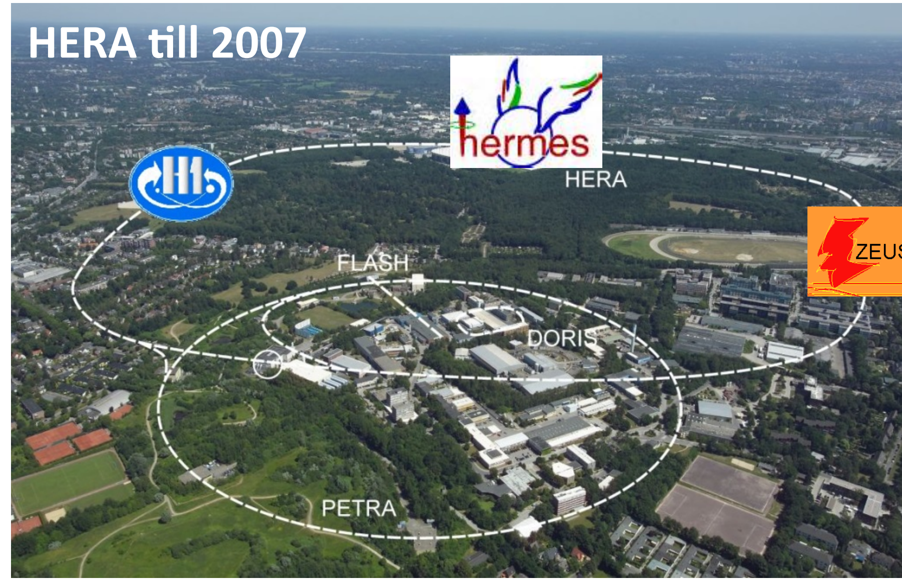
The past and future experiments

Collider mode e-p forward fast proton

Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

Fixed target mode slow recoil proton

Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



Slide from N d'Hose, Tranversity 2014

The past and future experiments

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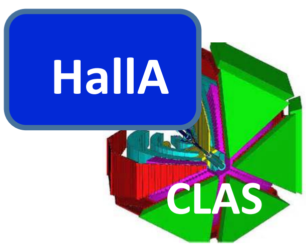


High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

Spectrometer

large acceptance det

Slide from N d'Hose, Tranversity 2014

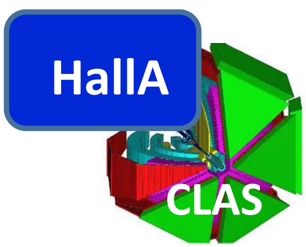
The past and future experiments

Collider mode e-p forward fast proton

Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

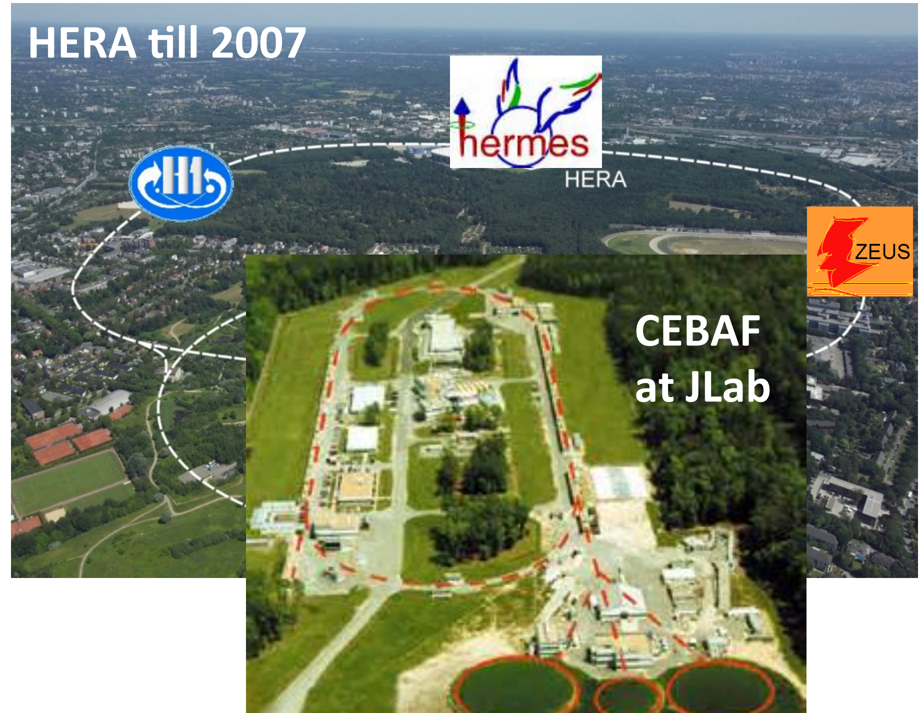
Fixed target mode slow recoil proton

Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



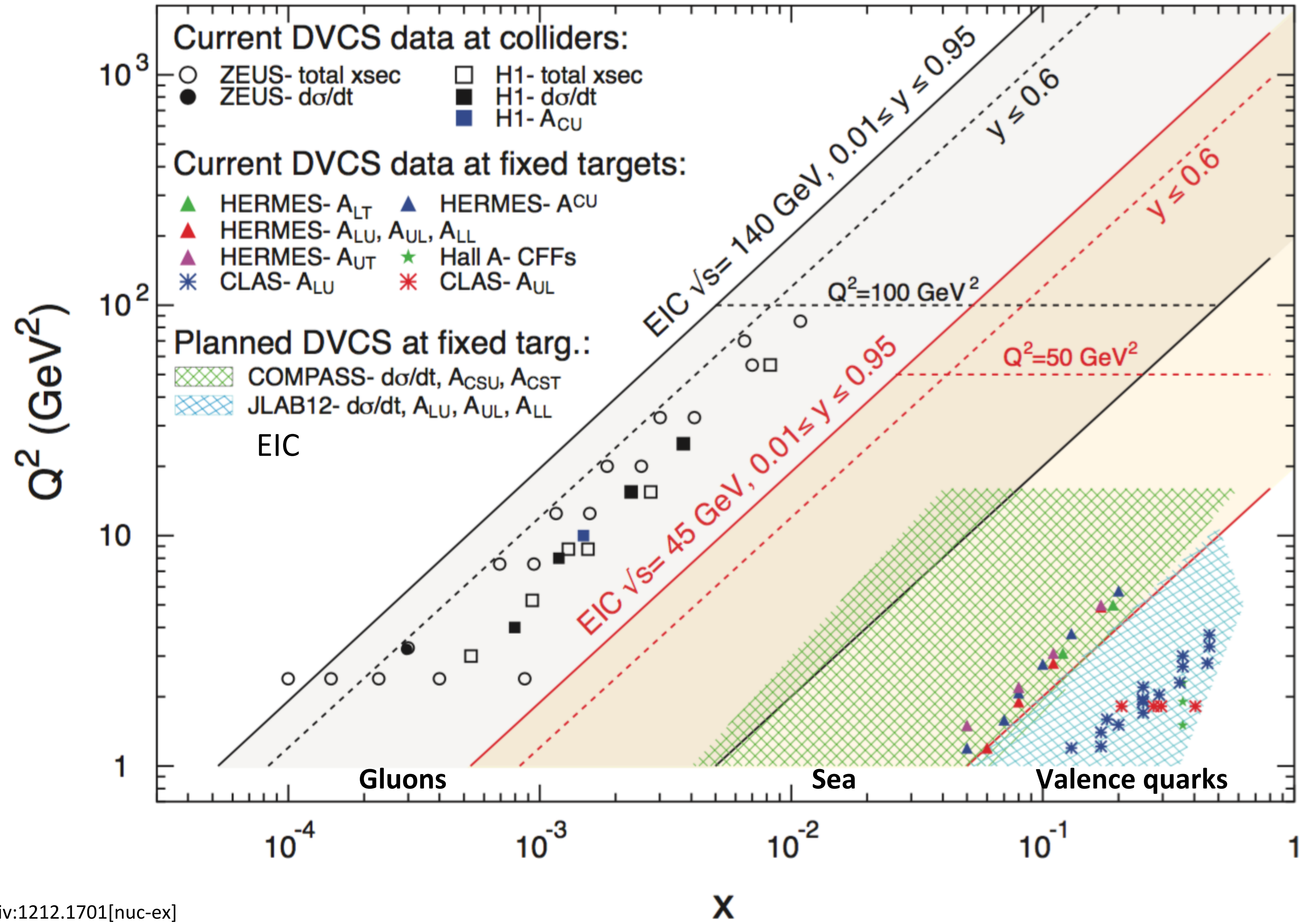
High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

Highly polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection



Slide from N d'Hose, Tranversity 2014

World wide DVCS measurements existing and planned



arXiv:1212.1701[nuc-ex]

The ideal experiment

High beam energy

ensure hard regime and large kinematic domain

polarized beam

availability of **positive** and **negative** leptons

variable energy for:

L/T separation for pseudo scalar production

ε separation for DVCS^2 and Interference (DVCS+BH)

H_2, D_2, Longitudinaly and Transversely Polarized Target

High luminosity

small cross section

fully differential analysis (x_B, Q^2, t, ϕ)

Hermetic detectors

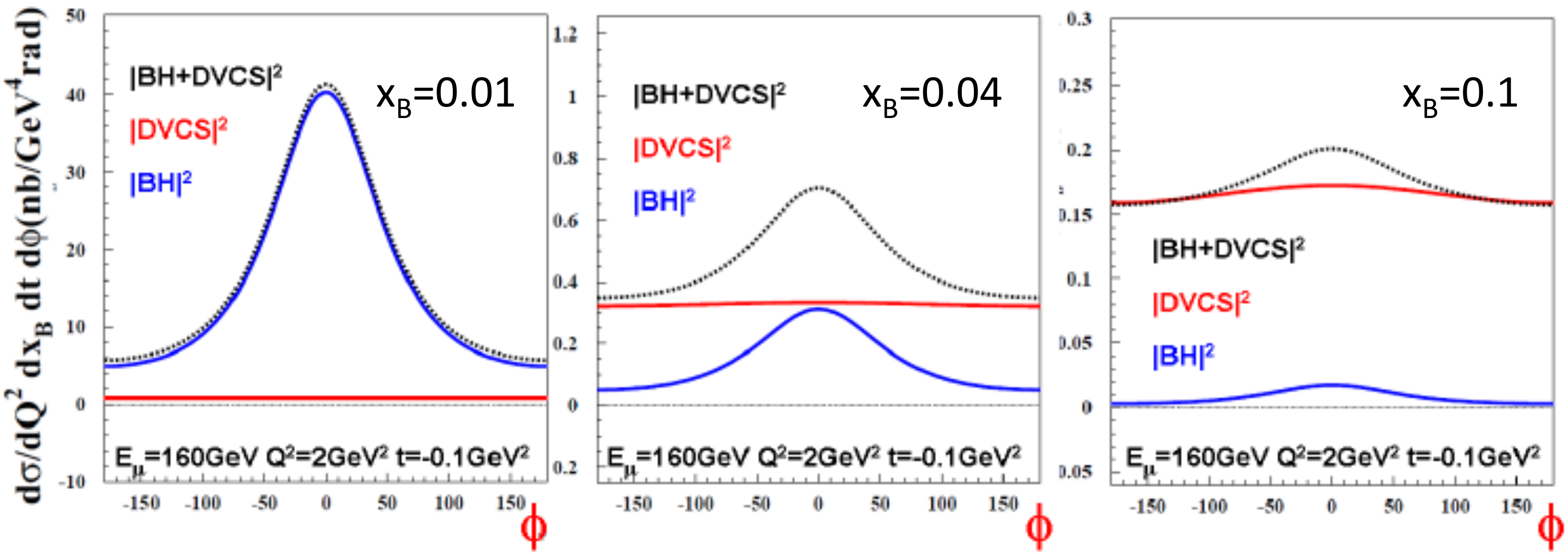
ensure exclusivity

but does not exist (yet)

Slide from N d'Hose, Tranversity 2014

High beam energy

Example at E_ℓ =160 GeV x_B ↗ **BH** ↘



BH dominates	Access to DVCS ampl.	DVCS dominates
Reference yield	Via interference	Study of $d\sigma/dt$
	⇩	⇩
	Jlab	**Only for high energy**
	HERMES, H1	**H1 & ZEUS**
	COMPASS	**COMPASS**

E_ℓ ↘ **BH** ↗

Slide from N d'Hose, Tranversity 2014

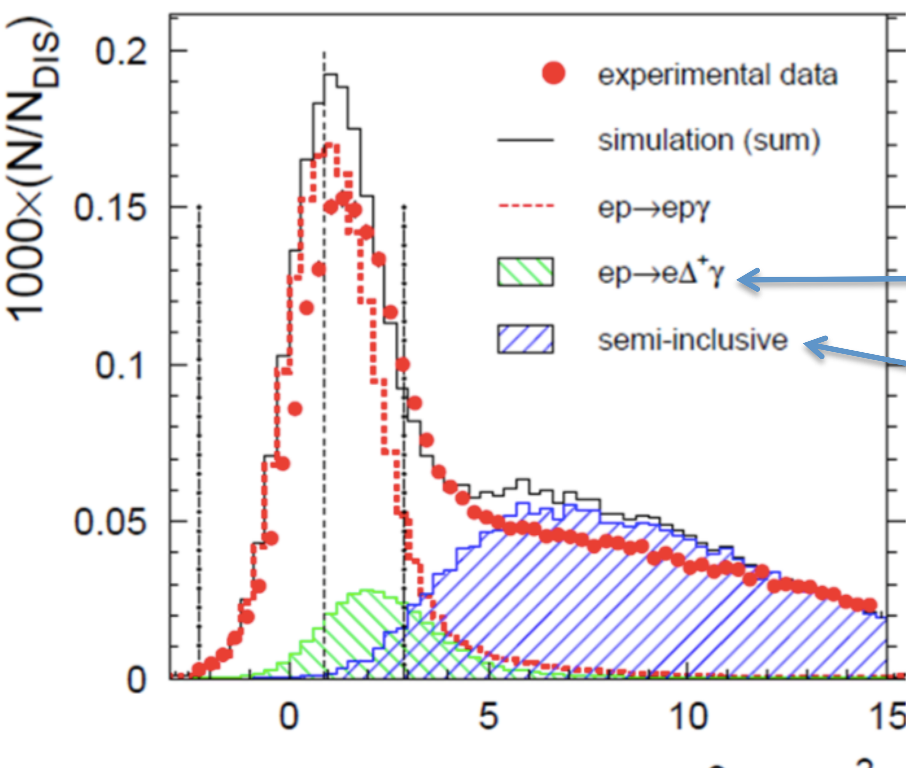
Exclusivity

Fixed target mode => slow recoil proton => **H(e,e'γ)X**

X can be
- p : ep -> epγ
- γp : ep -> epπ^0, π^0->γγ
- Nπ: ep -> eNγπ

…

without recoil detector



12% of the signal without recoil detector

ep⟶ e'+γ (+ γ + p'+…)

JHEP 1210, 042 (2012)

$$\bar{k} + \bar{p} = \bar{k}' + \bar{p}' + \bar{q}$$

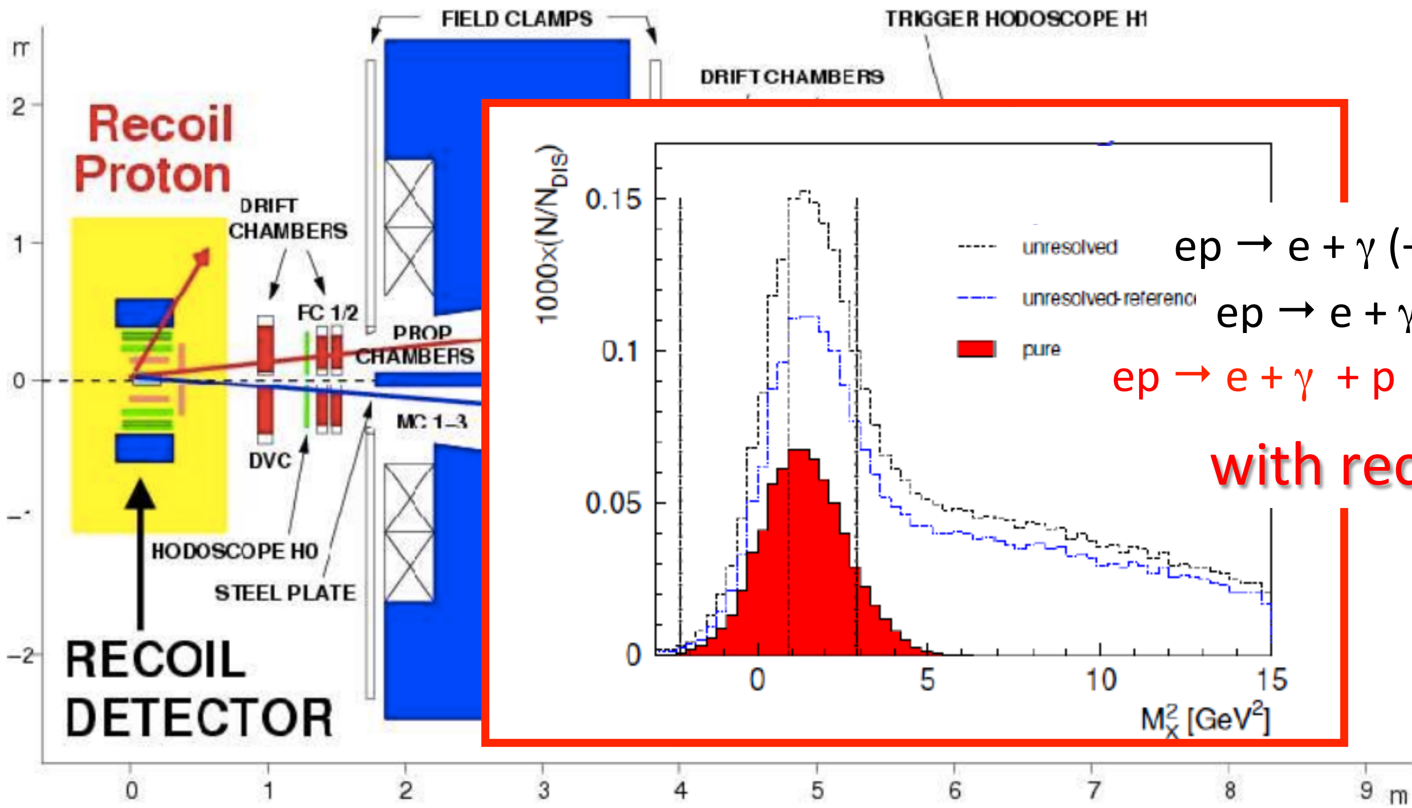
$$M_X^2 = \bar{p}'^2 = (\bar{k} + \bar{p} - \bar{k}' - \bar{q})^2$$

Exclusivity: Hermes recoil detector

Recoil detector installed in January 2006:

- Silicon strip detectors, scintillator fiber,
- 1T super conducting solenoid

e(p,e'p'γ) with 1% contamination



ep → e + γ (+ p +…)

ep → e + γ (+ p $_{\text{in acceptance}}$ +…)

ep → e + γ + p

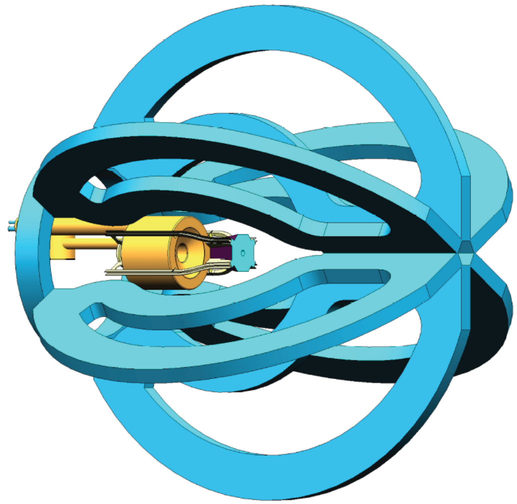
with recoil detector

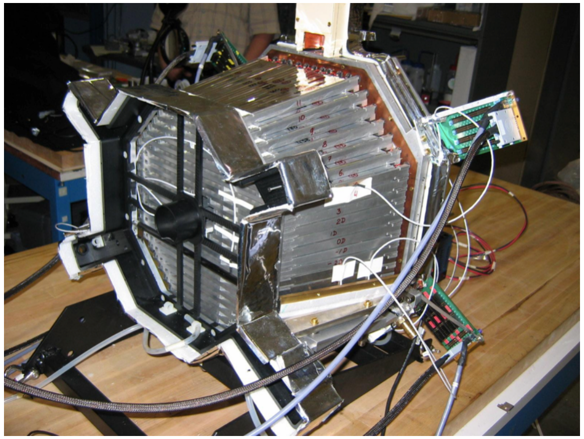
Hall B/JLab

Dedicated apparatus (added within Clas):

$PbWO_4$ calorimeter + 5 T super conducting solenoid

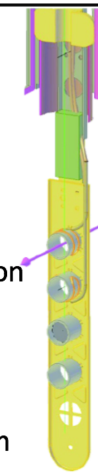
e(p,e'p'γ): ~5% contamination





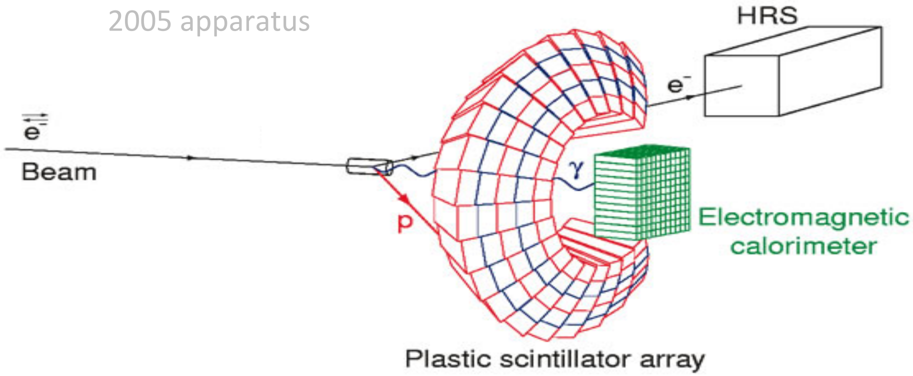
Longitudinally Polarized Target

- Frozen ammonia as a target material
- polarized by Dynamic Nuclear Polarization in a 5 Tesla homogeneous magnetic field
- monitored using a Nuclear Magnetic Resonance system



Beam spin and longitudinal target asymmetries published from dedicated or not dedicated experiments.

Exclusivity in Hall A/JLab

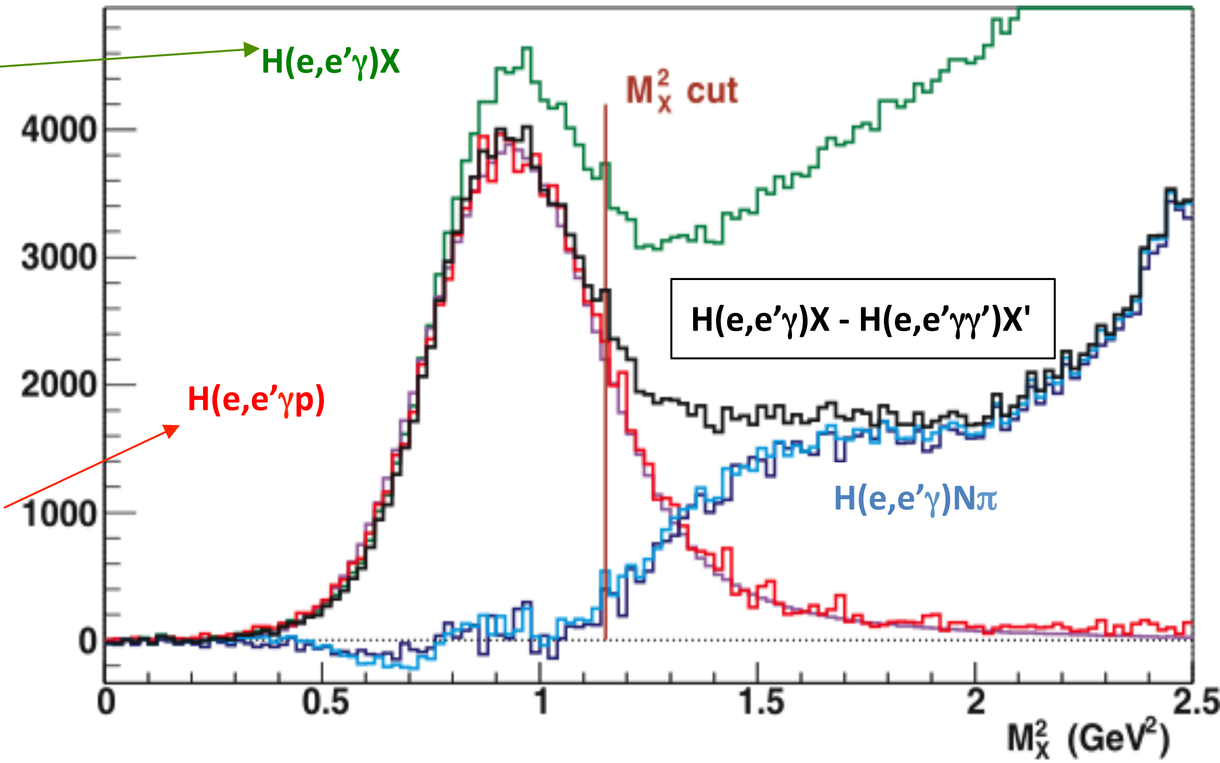


HRS+calorimeter
X can be
- p : ep -> epγ
- γp : ep -> epπ^0, π^0->γγ
- Nπ: ep -> eNγπ

…

HRS+calorimeter + proton array

(2005 data)



- Good resolution : no need for the proton array => solid angle easy to compute
- Remaining π contamination 1.7%

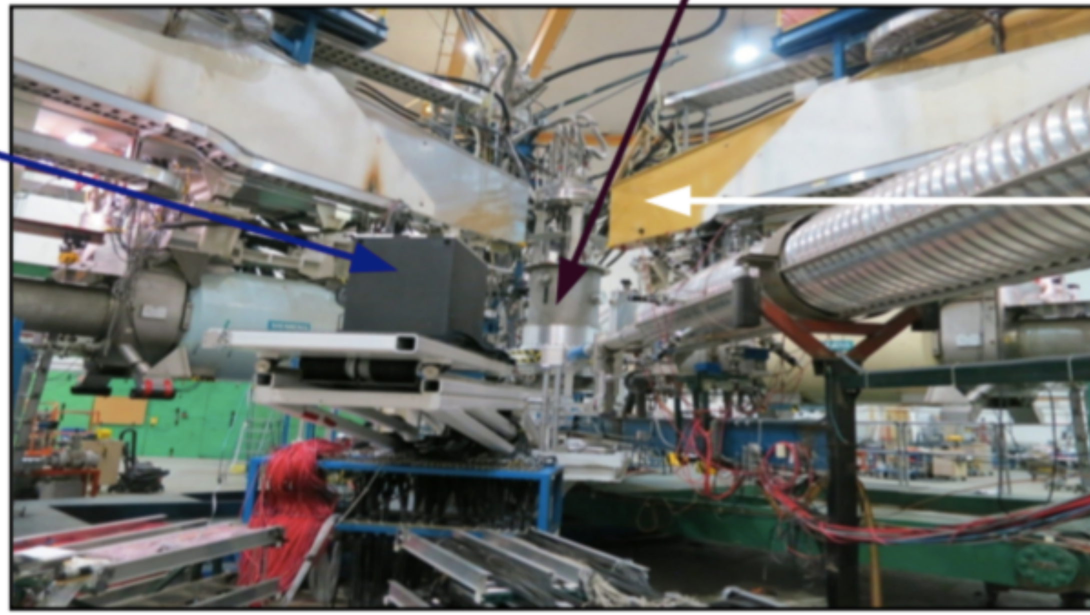
Hall A/JLab

p(e,e'γ)p'

TARGET

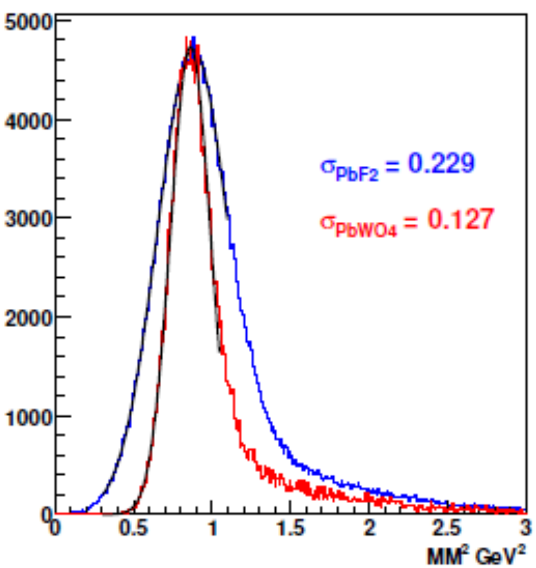
CALORIMETER
→ 208 PbF_2 blocks
→ Δq/q ~ 3%

→ Calorimeter energy resolution is our limiting factor in the missing mass reconstruction



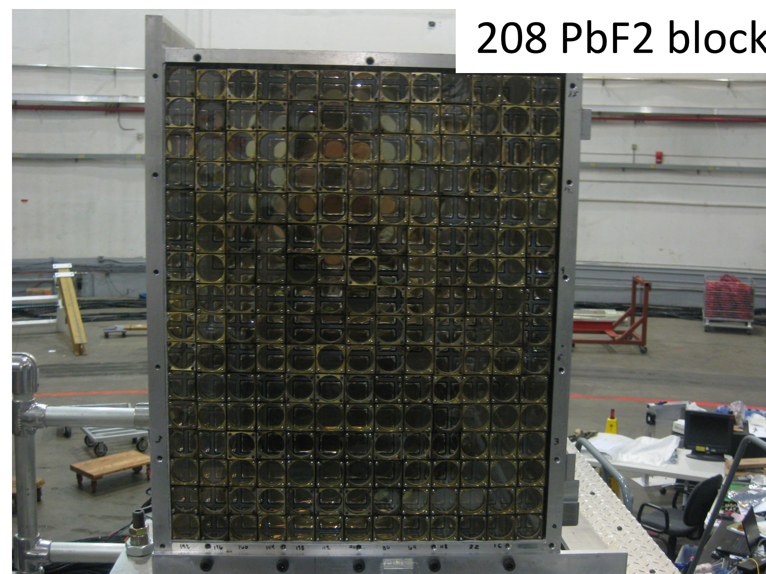
HRS
→ δp/P ~10^{-4}
Excellent!

Simulated M_X^2 resolution

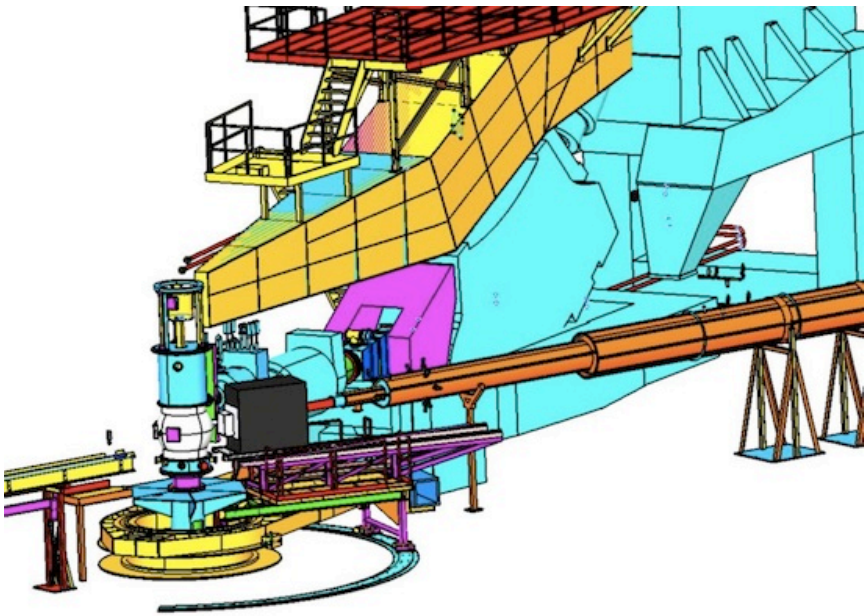


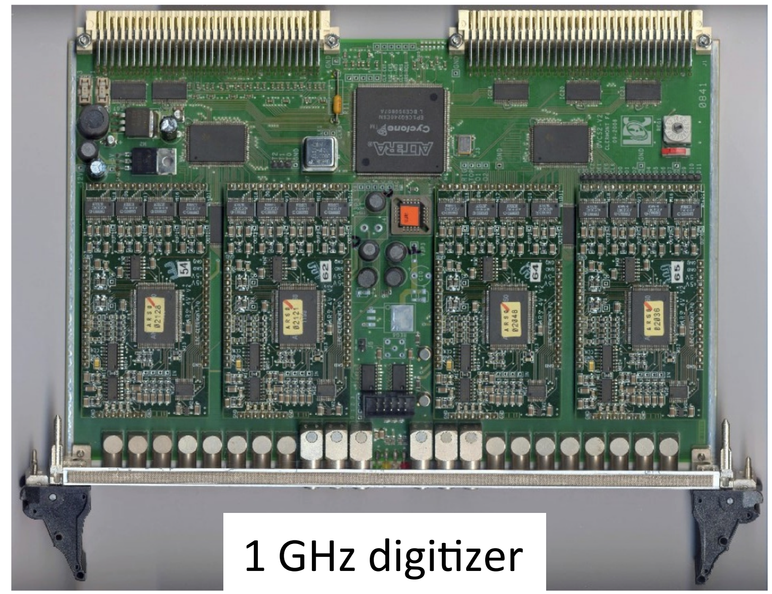
PbF2
3X3X18 cm block
~1000 pe
for 1 GeV outgoing
photon

208 PbF2 blocks

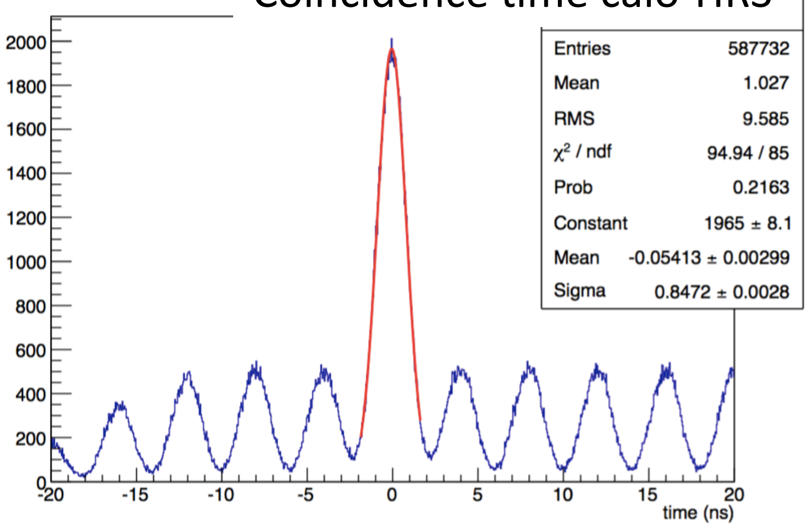


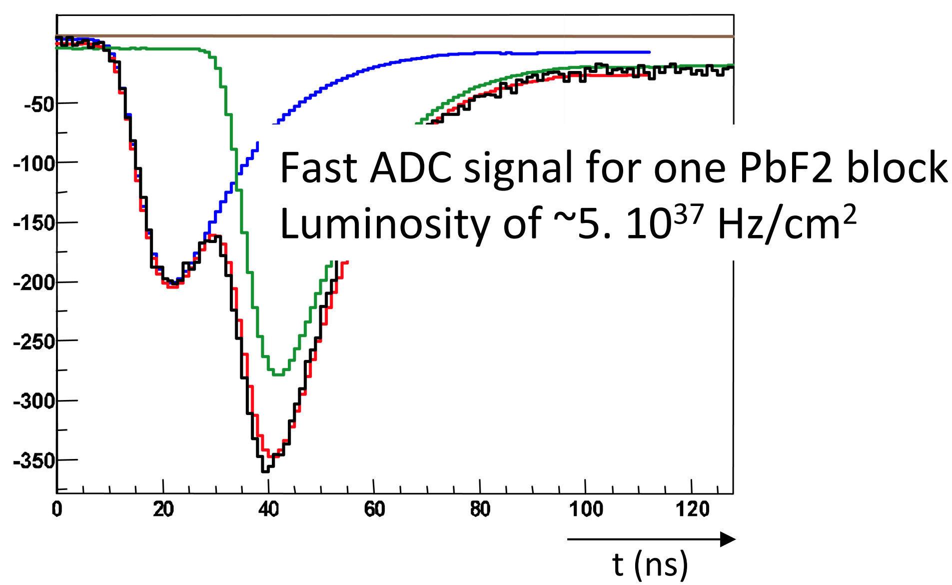
DVCS is a rare process: Pile-up and coincidence time





Coincidence time calo-HRS





Absolute cross-sections versus relative asymmetries

$$\sigma = \frac{d\sigma}{d\Omega} = \frac{N}{\mathcal{L}\, d\Omega}\epsilon$$

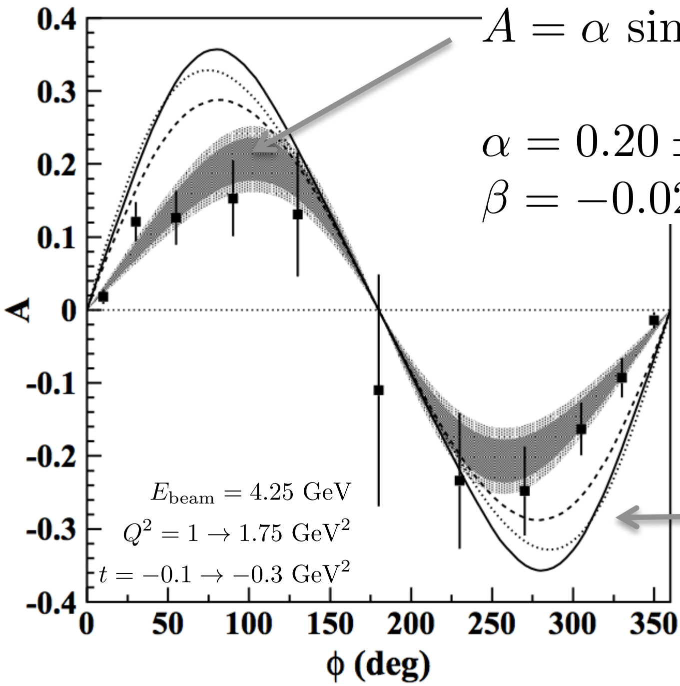
N : number of event detected
$\mathcal{L}$: luminosity
$d\Omega$: solid angle
ϵ : detector efficiency
P : polarization rate

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}} = \frac{1}{P}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

→ Experimentally "easy" to measure

The pioneering Hall B DVCS measurement of 2001: beam spin asymmetry

$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\sigma_{\text{total}}} = \frac{1}{P}\left(\frac{\overrightarrow{N} - \overleftarrow{N}}{\overrightarrow{N} + \overleftarrow{N}}\right)$$



$$A = \alpha \sin(\phi) + \beta \sin(2\phi)$$

$\alpha = 0.20 \pm 0.03$ $\leftarrow$ Twist 2 BH-DVCS interference

$\beta = -0.02 \pm 0.02$ $\leftarrow$ should vanish in the Bjorken regime

VGG model of GPDS

- - Center of the acceptance

.... With an assumed t variation

____ including twist 3 effects

S. Stepanyan et al. PRL, hep-ex:0107043

Also HERMES, PRL, hep-ex:0106068

Bjorken regime reached !! GPDs formalism applies !!

Absolute cross-sections versus relative asymmetries

$$\sigma = \frac{d\sigma}{d\Omega} = \frac{N}{\mathcal{L}\, d\Omega}\epsilon$$

N : number of event detected
$\mathcal{L}$: luminosity
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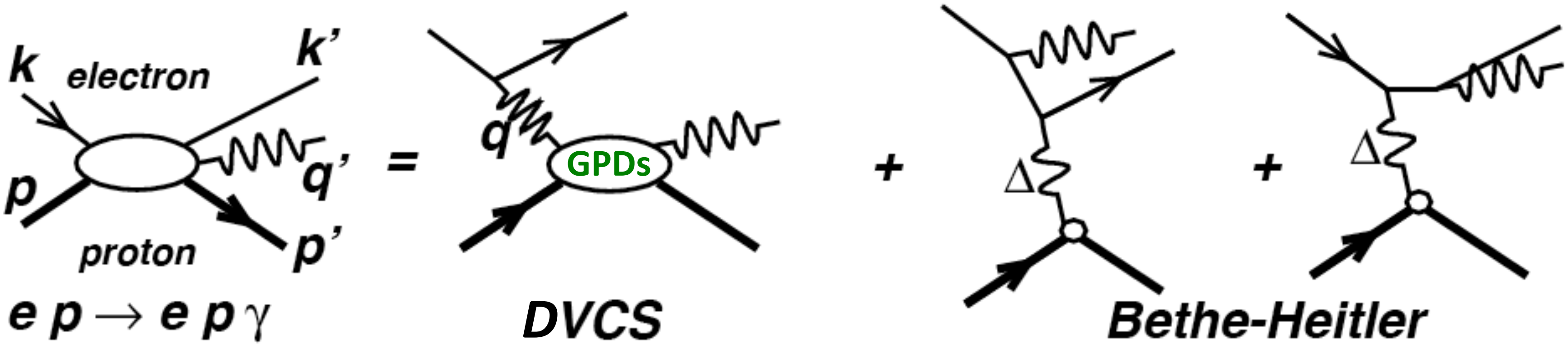
$$A = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}} = \frac{1}{P}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

Experimentally "easy" to measure

Needs to understand the total cross-section to reliably interpret the data

Measuring DVCS to access GPDs information



When only considering the handbag diagram (at leading twist)

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

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

$|BH|^2$: Known to 1%

$\Re e\,(T^{BH}\cdot T^{DVCS})$: Linear combinations of GPDs

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

Absolute cross-sections versus relative asymmetries

$$\sigma = \frac{d\sigma}{d\Omega} = \frac{N}{\mathcal{L}\, d\Omega}\epsilon$$

N : number of event detected
$\mathcal{L}$: luminosity
$d\Omega$: solid angle
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P : polarization rate

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}} = \frac{1}{P}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

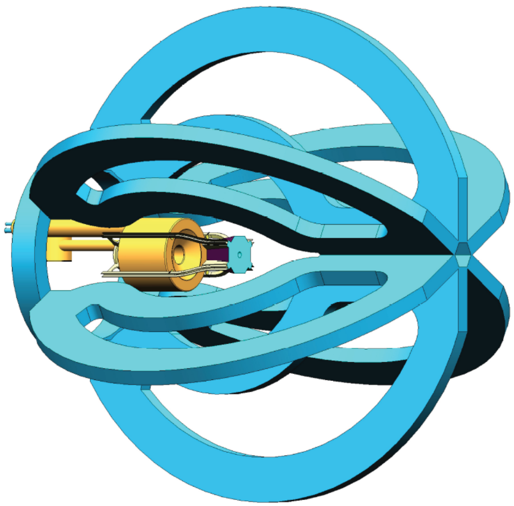
Experimentally "easy" to measure

Needs to understand the total cross-section to reliably interpret the data

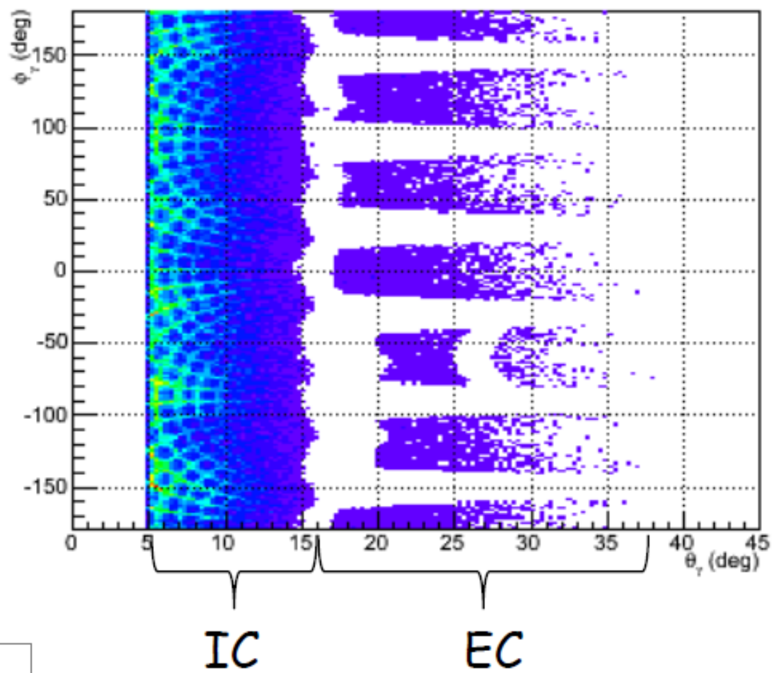
When possible, absolute cross-sections are better.

Absolute Cross-sections analysis in CLAS

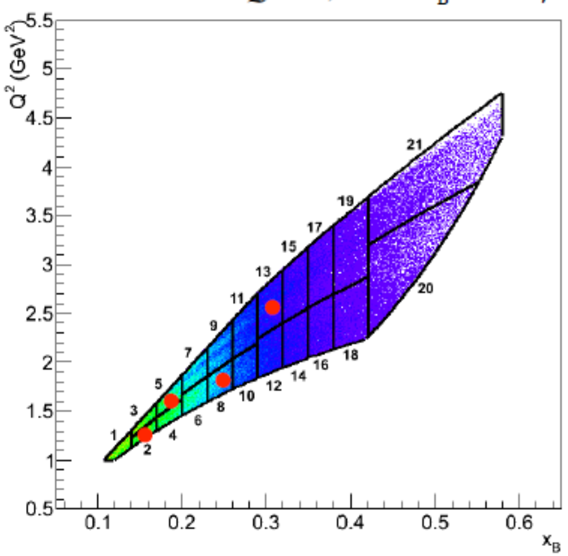
Difficulty of the task

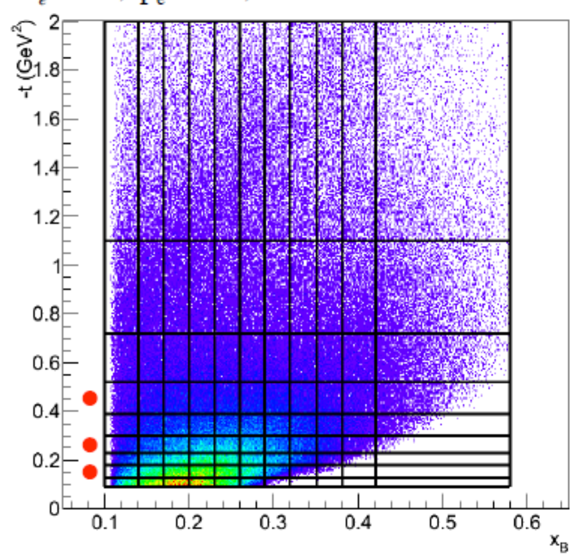


Photon : θ vs φ



$Q^2 > 1,\ 0.1 < x_B < 0.58,\ 21 < \theta_e < 45,\ p_e > 0.8,\ W > 2$





● 4 bins in $Q^2(x)$ vs 3 bins in t

Extracting cross-sections from the data: the Hall A scheme

$$\frac{d^4\sigma}{dx_b\,dt\,d\phi_\gamma\,dQ^2} = \Gamma^G|BH|^2 + \Gamma^1\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^2\Delta\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^3\mathcal{C}^{\mathcal{I}}(\mathcal{F}^{eff})$$

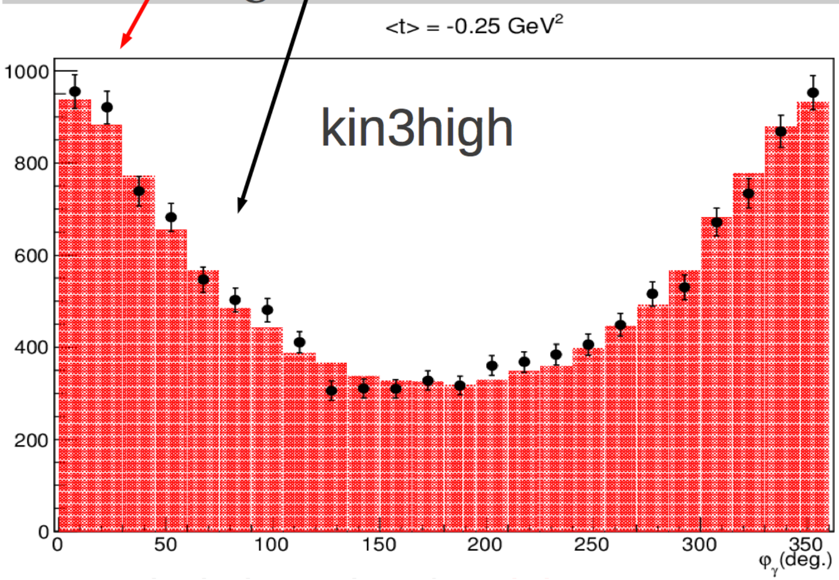
Guidance from NLO, twist 3 formalism: $\sin(n\phi)$, Q^2, x_{BJ},…

Γ^i : kinematic factors (calculable in experimental setup simulation)

C^i ($= C^I, \Delta C^I, C^I_{eff}$) : Compton Form Factors obtained by fit on the data

$$\chi^2 = \frac{\left(N^{MC} - N^{Exp}\right)^2}{\sigma^2} \longrightarrow N^{MC} = \int \frac{d\sigma}{d\Omega}\, d\Omega = \sum_{i=1}^{3} \left(\int \Gamma^i\, d\Omega\right) C^i$$

$$\frac{\delta\chi^2}{\delta C^i} = 0 \rightarrow \begin{Bmatrix} C^I \\ \Delta C^I \\ C^I_{eff} \end{Bmatrix}$$



Black dot: data / Red histogram: MC fit

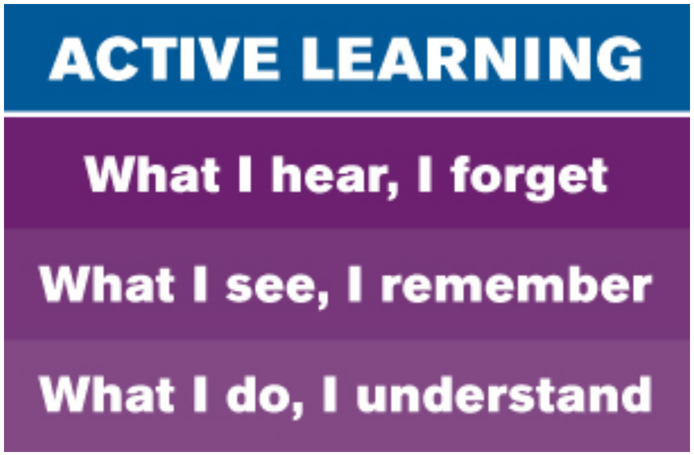
The extracted cross-section is parametrization independent.

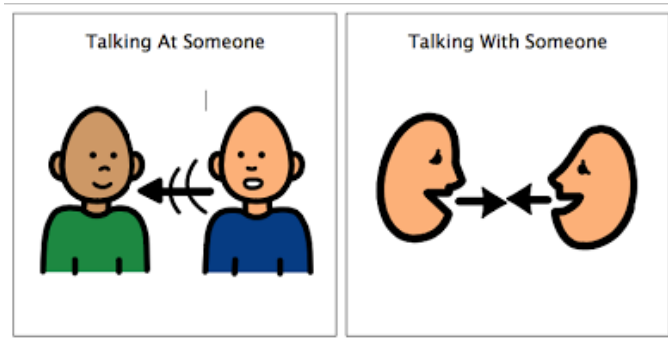
Interpreting the extracted CFFs needs to be done carefully:

- -8 GPDs (4 X 2),
- -twist 2-3 expansion…

Slide from C. Desnault

1 question: 30 m reading + 15 min discussions





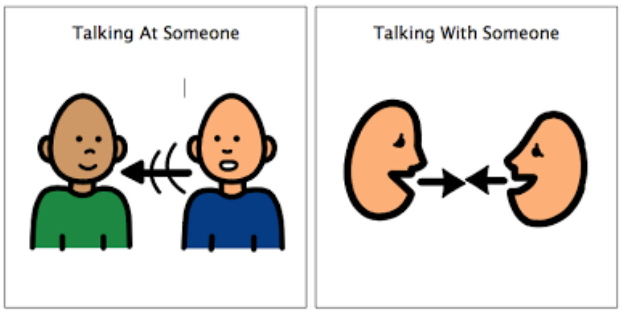
Group 1 Meriem*, Shokhna, Kieran, Carlos Y.	**Group 5** Nabil*, Brandon C., Fillipo, Manuel
Group 2 Frederic*, Shujie, Shivangi, Ryan	**Group 6** Brandon K.*, Alexa, Bailing, Gavin
Group 3 Waverly*, Sandra, Bijit, Arkadiusz	**Group 7** Holly, Larissa, David AQ, Giovanni
Group 4 Hamza, Scott, Marco, Dexu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

Hall B experimental analysis

Cross sections for the exclusive photon electroproduction on the proton and Generalized Parton Distributions

CLAS Collaboration (H.S. Jo (Orsay, IPN) et al.)

Published in Phys.Rev.Lett. 115 (2015) no.21, 212003
arXiv:1504.02009 [hep-ex]



Start reading at the * mark.

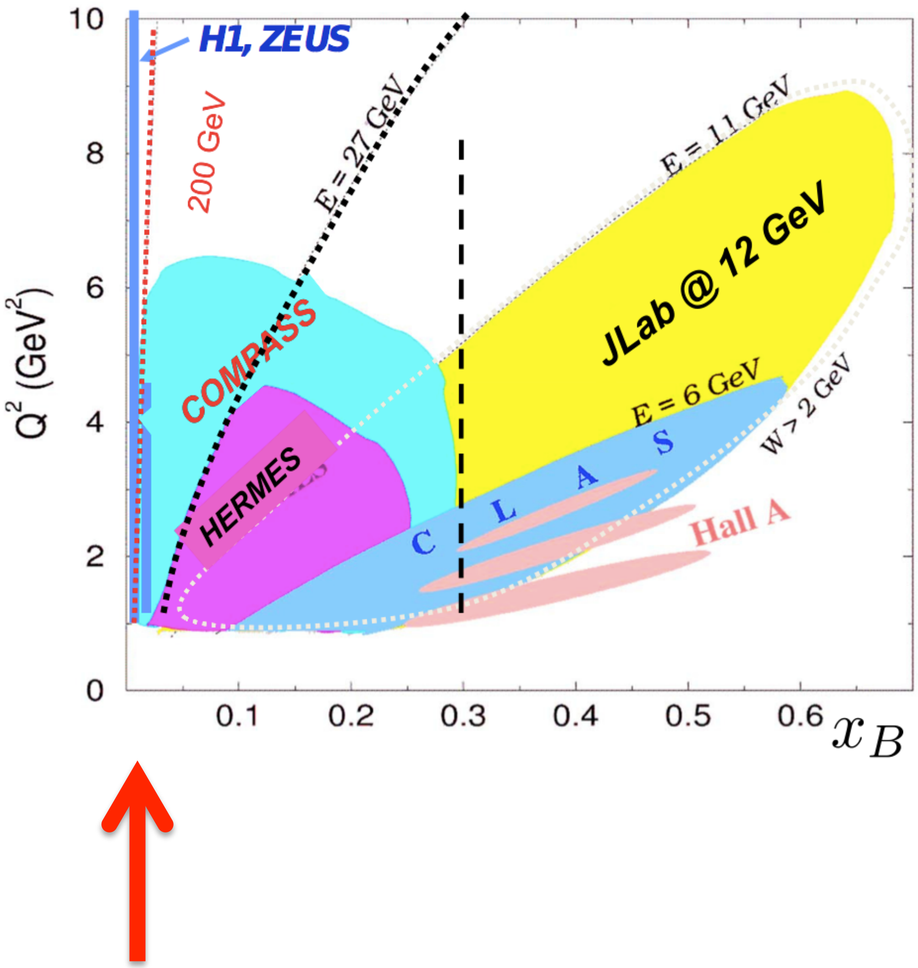
1. How are the events selected?
2. How is the cross-section calculated?
3. What is the precision of the extracted absolute cross-section?

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.

DVCS results (so far)



The gluon sector

Overall goal:

- Measure the transverse size of the nucleon versus x_B (2+1D imagining)
  - for the gluons, the sea and the valence quarks
  - For various quark flavor,
- Evaluate the orbital angular momentum of the quarks

In order to achieve this, one needs to:

- Verify the formalism is applicable,
- Understand how to interpret the data.

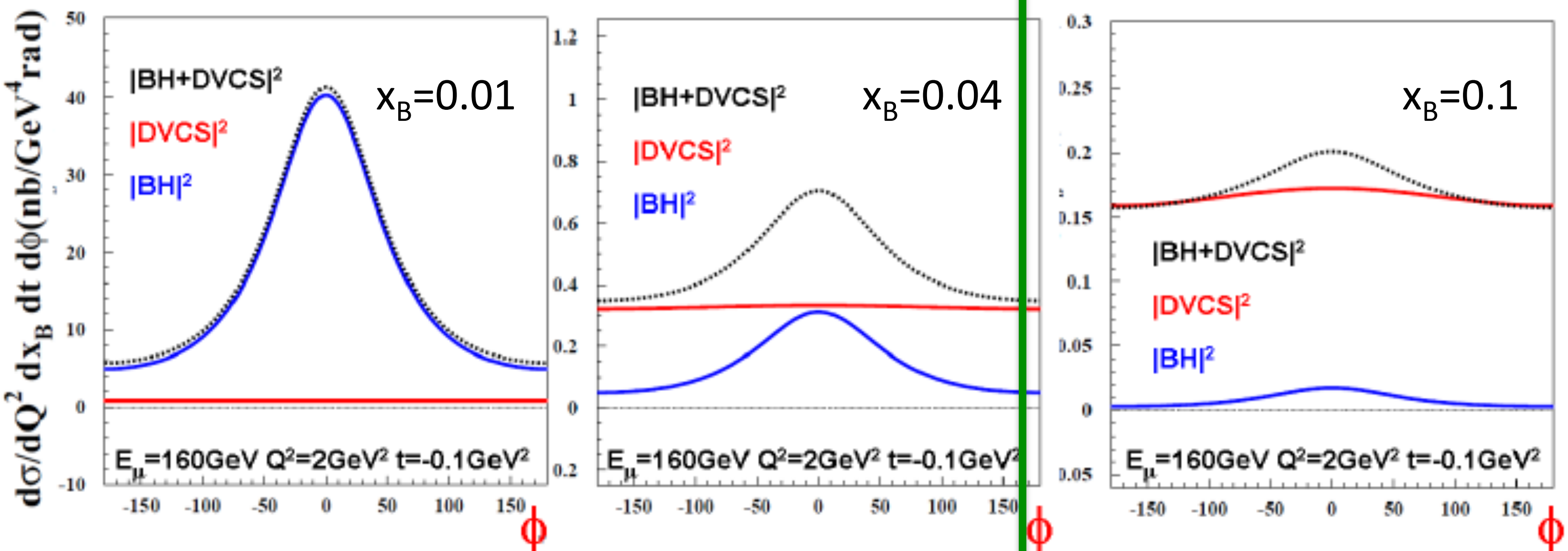
Asuming the formalism is applicable:

can one draw some conclusions (within reasonable approximations)?

- GPD H
- GPD E

High beam energy

Example at E_ℓ =160 GeV x_B ↗ **BH** ↘



BH dominates
Reference yield

Access to DVCS ampl.
Via interference

DVCS dominates
Study of dσ/dt

E_ℓ ↘ **BH** ↗

Jlab
HERMES, H1
COMPASS

Only for high energy
H1 & ZEUS
COMPASS

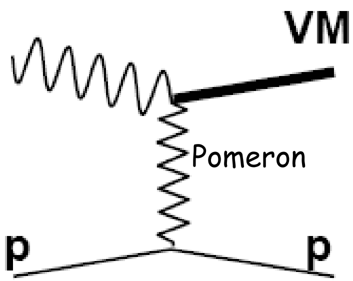
Slide from N d'Hose, Tranversity 2014

The gluon sector: are we in the hard regime?

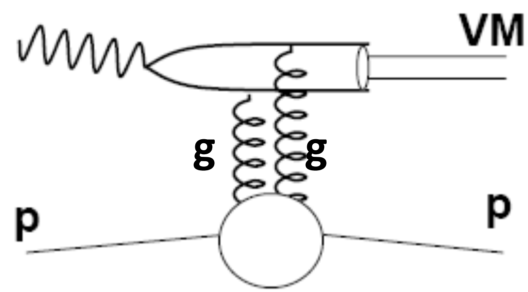
Total energy in the γ*p system

$$\sigma(W) \propto W^{\delta}$$

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



'soft'



'hard'

✓ **δ increases from soft (~0.2) to hard (~0.8)**

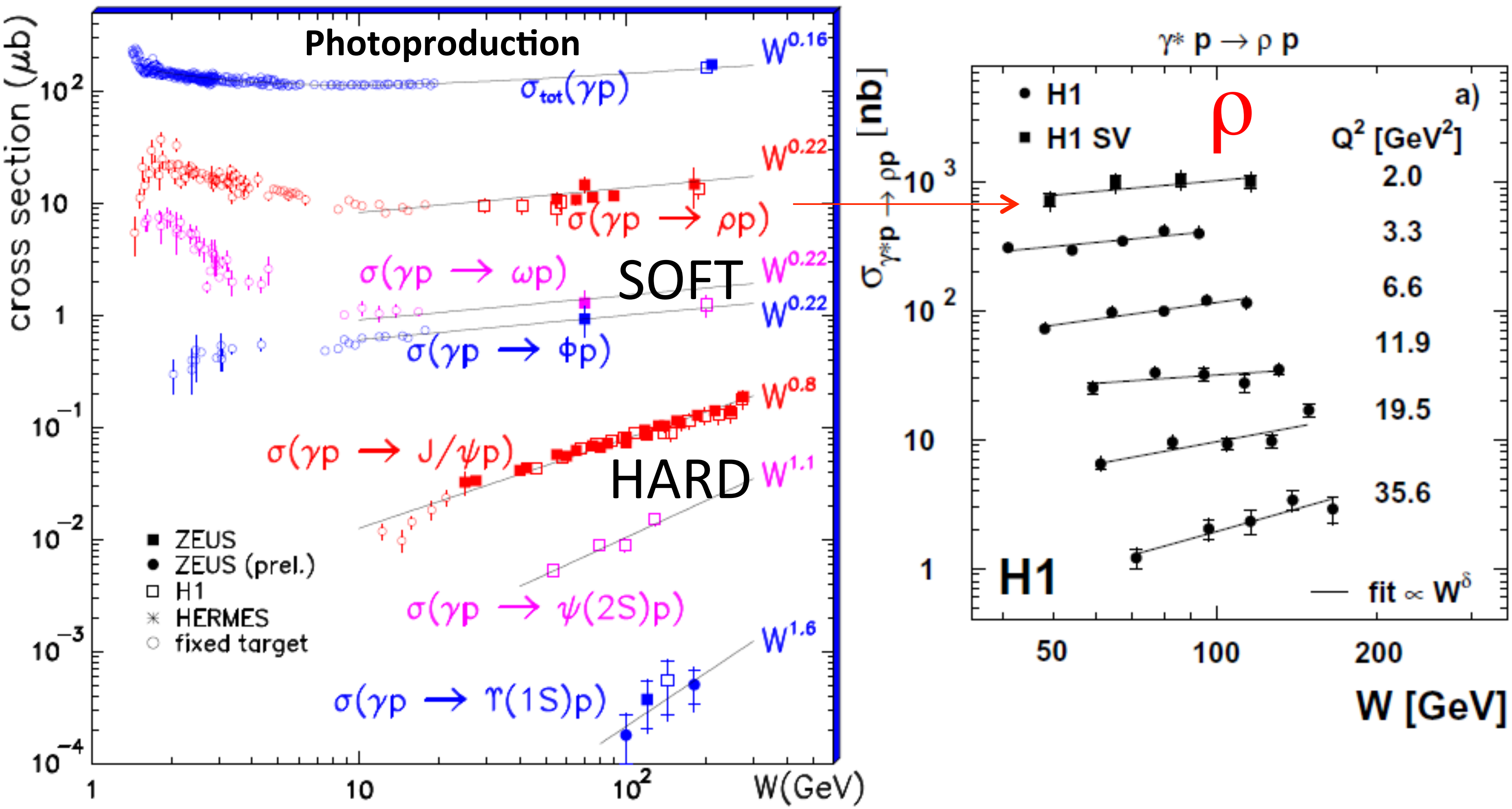
↓ **'soft Pomeron'** ↓ **$xg(x,Q^2)^2$: increased gluon density**

✓ **b decreases from soft (~10 GeV^{-2}) to hard (~5 GeV^{-2})**

Slide from N d'Hose, Tranversity 2014

Cross-section and W dependence

$$\sigma(W) \propto W^{\delta}$$



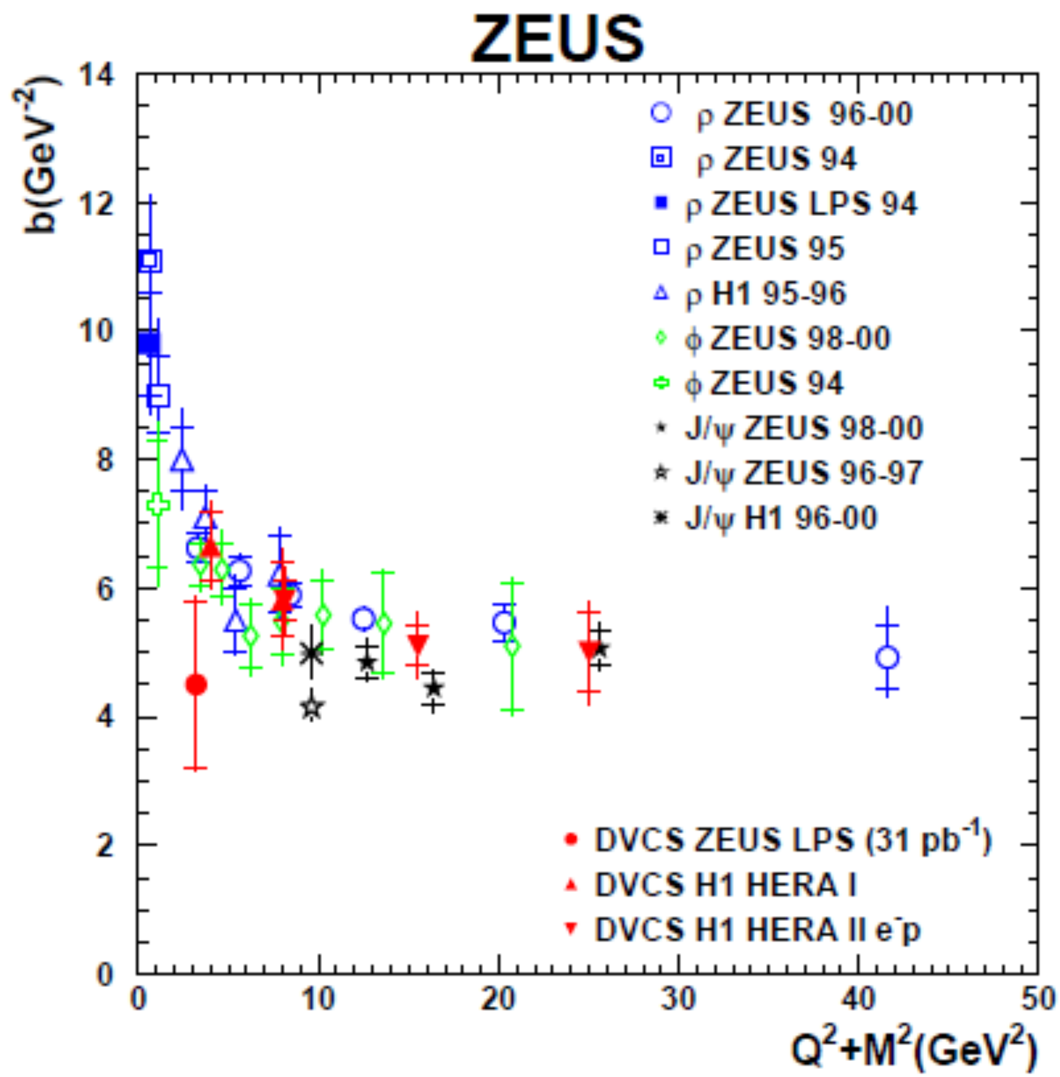
Slide from N d'Hose, Tranversity 2014

Cross-section and t dependence

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

sensitivity
to the nucleon transverse size
+ to the meson transverse size

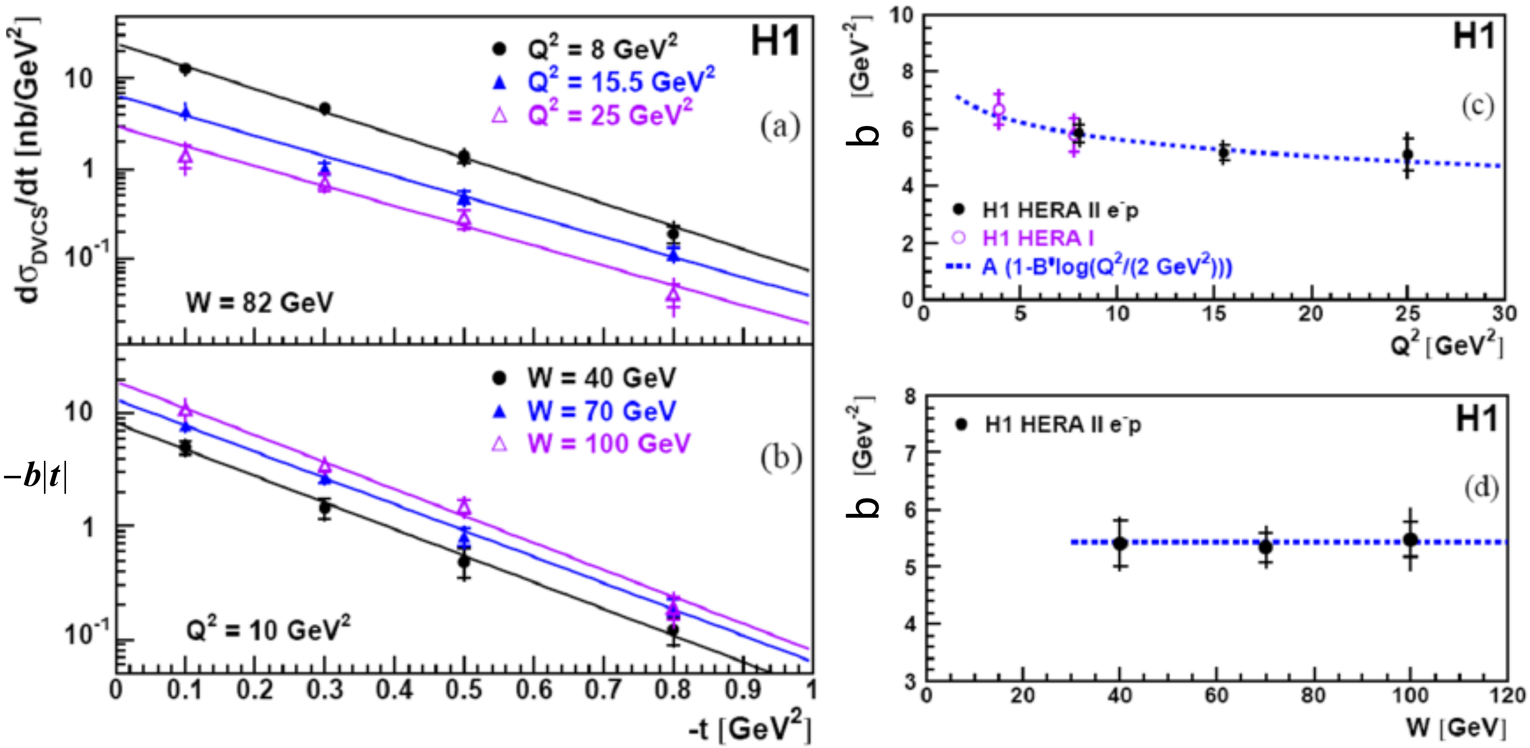
J/ψ and DVCS
in the hard regime
at small Q^2



Slide from N d'Hose, Tranversity 2014

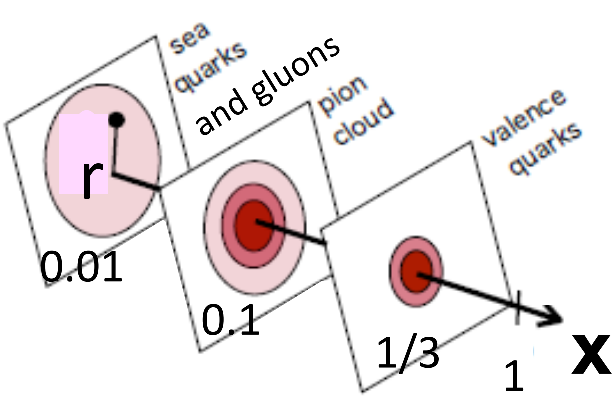
DVCS Cross-section and t dependence

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



Almost no evolution as a function of W

b= 5.45 ± 0.19 ± 0.34 GeV^2 at <Q^2> = 8 GeV^2 and <x> = 1.2 10^{-3}



$$< r_\perp^2(x_B) > \approx 2\, b(x_B)$$

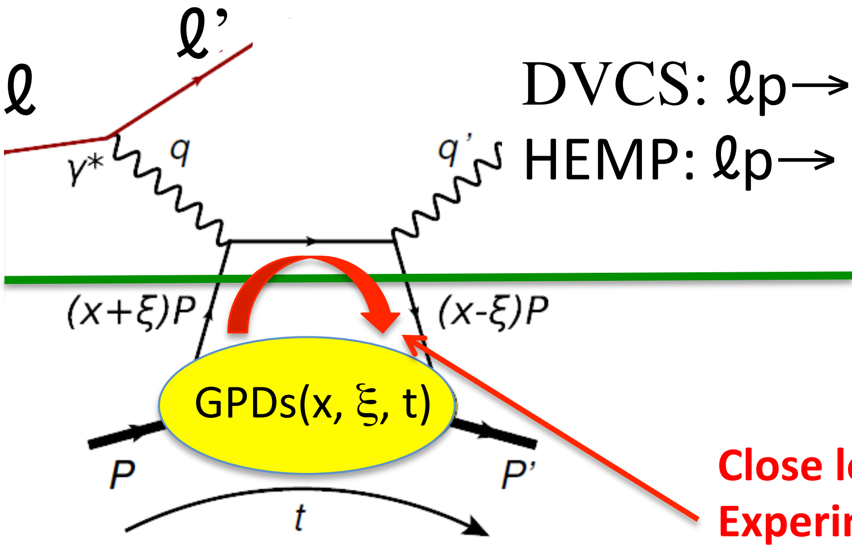
$$\sqrt{< r_\perp^2 >} = 0.65 \pm 0.02 \text{ fm}$$

Spatial imaging of the nucleon-3

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.

What we talked about during previous meetings



DVCS: ℓp→ ℓ' p' γ (golden channel)

HEMP: ℓp→ ℓ' p' ρ or ϕ or J/ψ,…

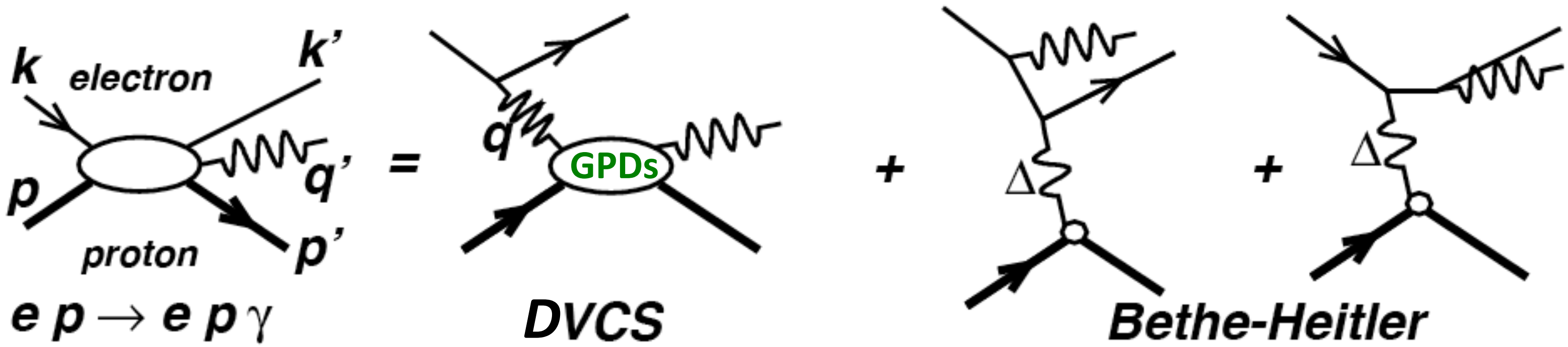
Factorization allow the introduction of the GPDs (need NLO and twist corrections)

Close loop makes the x variation of the GPDs inaccessible
Experimentally, instead on access CFFs (Re and Im parts)
⇒ 8 variable functions of ξ (~x_B) and t.

CFF ↓ GPD ↓

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

What we talked about during previous meetings

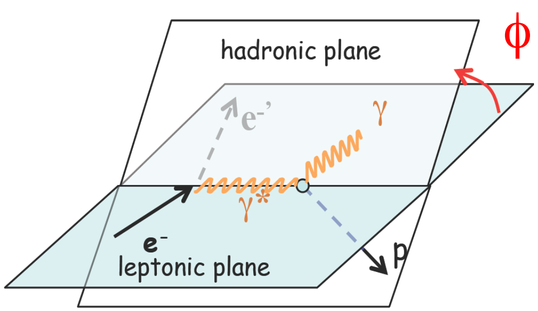


At leading twist:

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

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

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



The ideal experiment

High beam energy

ensure hard regime and large kinematic domain

polarized beam

availability of **positive** and **negative** leptons

variable energy for:

L/T separation for pseudo scalar production

ε separation for DVCS^2 and Interference (DVCS+BH)

H_2, D_2, Longitudinaly and Transversely Polarized Target

High luminosity

small cross section

fully differential analysis (x_B, Q^2, t, ϕ)

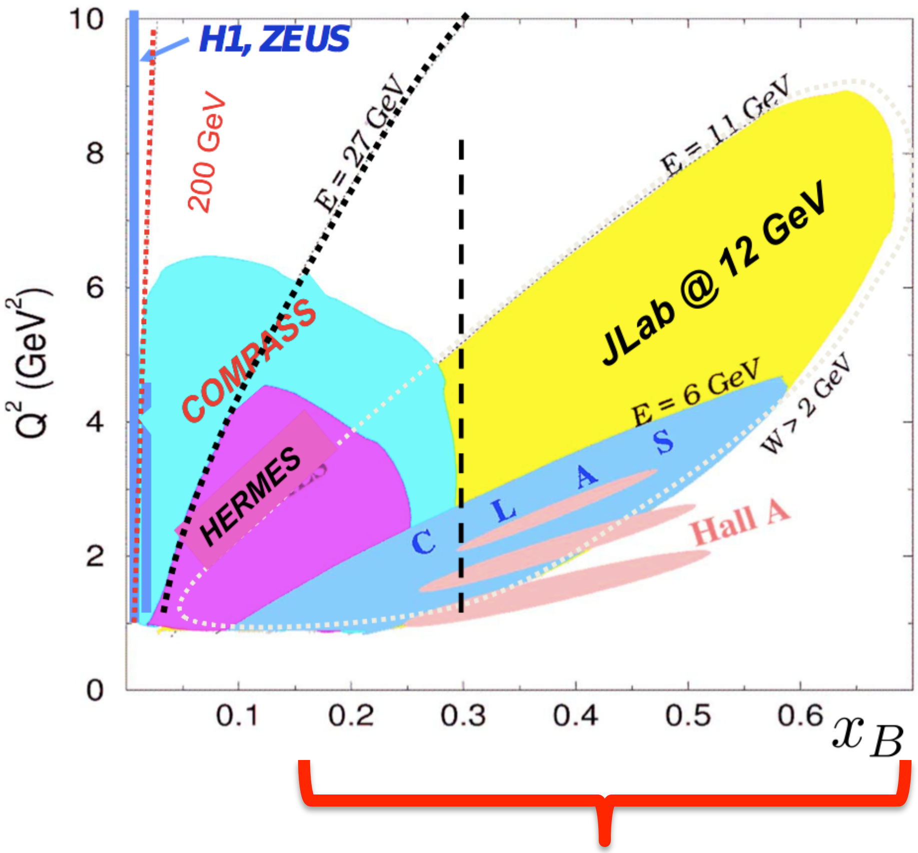
Hermetic detectors

ensure exclusivity

but does not exist (yet)

Slide from N d'Hose, Tranversity 2014

DVCS results (so far)



The valence + sea sector

Overall goal:

- Measure the transverse size of the nucleon versus x_B (2+1D imagining)
  - for the gluons, the sea and the valence quarks
  - For various quark flavor,
- Evaluate the orbital angular momentum of the quarks

In order to achieve this, one needs to:

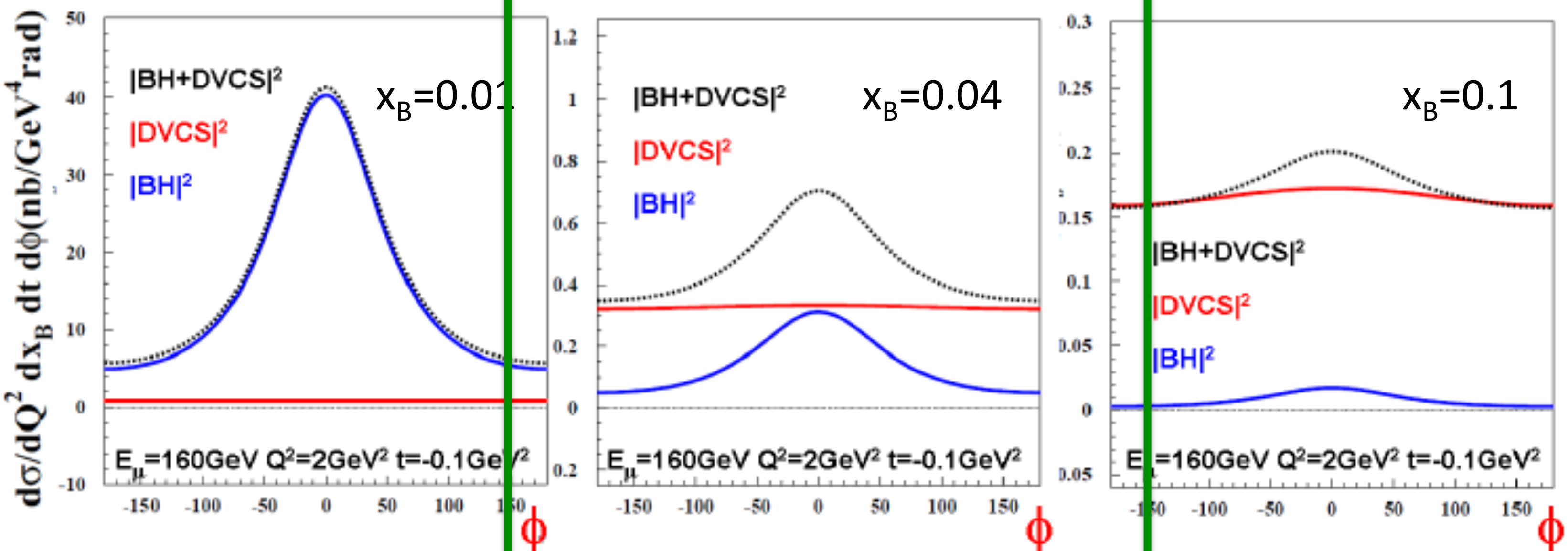
- Verify the formalism is applicable,
- Understand how to interpret the data.

Assuming the formalism is applicable:
can one draw some conclusions (within reasonable approximations)?

- GPD H
- GPD E

High beam energy

Example at E_ℓ =160 GeV x_B ↗ **BH** ↘



BH dominates
Reference yield

Access to DVCS ampl.
Via interference

Jlab
HERMES, H1
COMPASS

DVCS dominates
Study of $d\sigma/dt$

Only for high energy
H1 & ZEUS
COMPASS

E_ℓ ↘ **BH** ↗

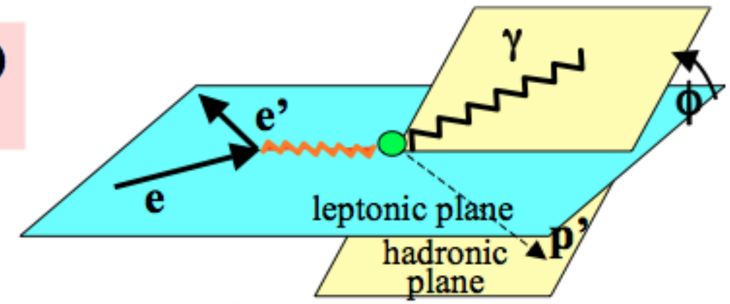
Slide from N d'Hose, Tranversity 2014

DVCS sensitivities to CFFs
(at leading order and leading twist)

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

Sensitive to $\mathscr{Im}$(BH-DVCS) ie $\mathscr{Im}$(CFF)

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



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:

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

Polarized beam, unpolarized neutron target:

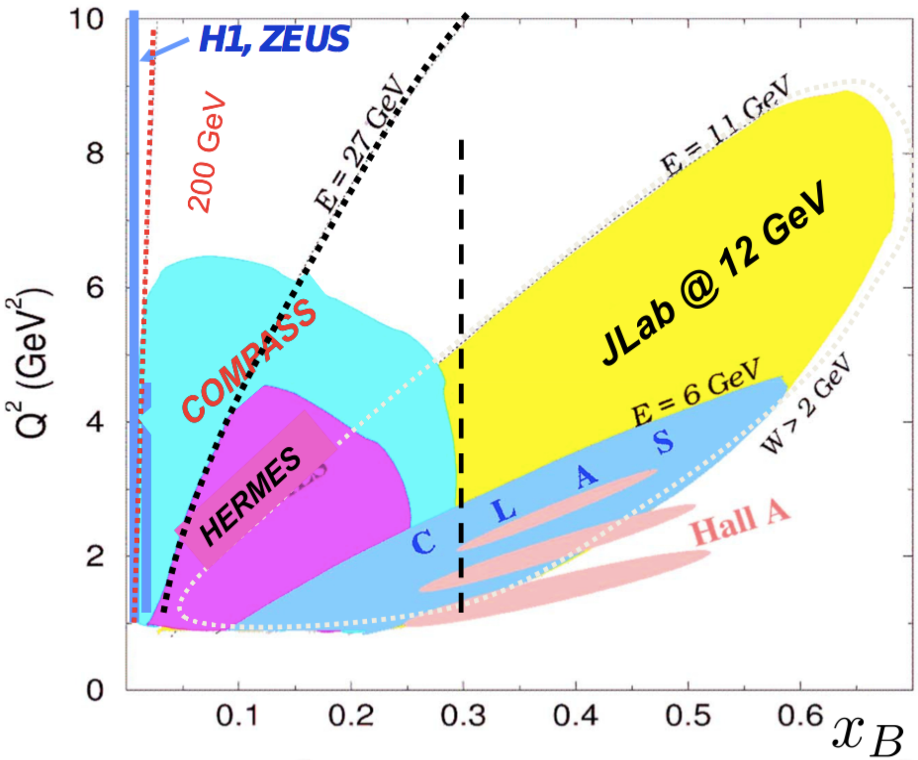
$$\Delta\sigma_{LU} \sim \sin\phi \; \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\} d\phi \;\Rightarrow\; H_n, \tilde{H}_n, E_n$$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(x, \xi, t) = 4/9\, H_u(x, \xi, t) + 1/9\, H_d(x, \xi, t)$$
$$H_n(x, \xi, t) = 1/9\, H_u(x, \xi, t) + 4/9\, H_d(x, \xi, t)$$

DVCS results (so far)



The valence + sea sector

Overall goal:

- Measure the transverse size of the nucleon versus x_B (2+1D imagining)
    - for the gluons, the sea and the valence quarks
    - For various quark flavor,
- Evaluate the orbital angular momentum of the quarks

In order to achieve this, one needs to:

- Verify the formalism is applicable,
- Understand how to interpret the data.

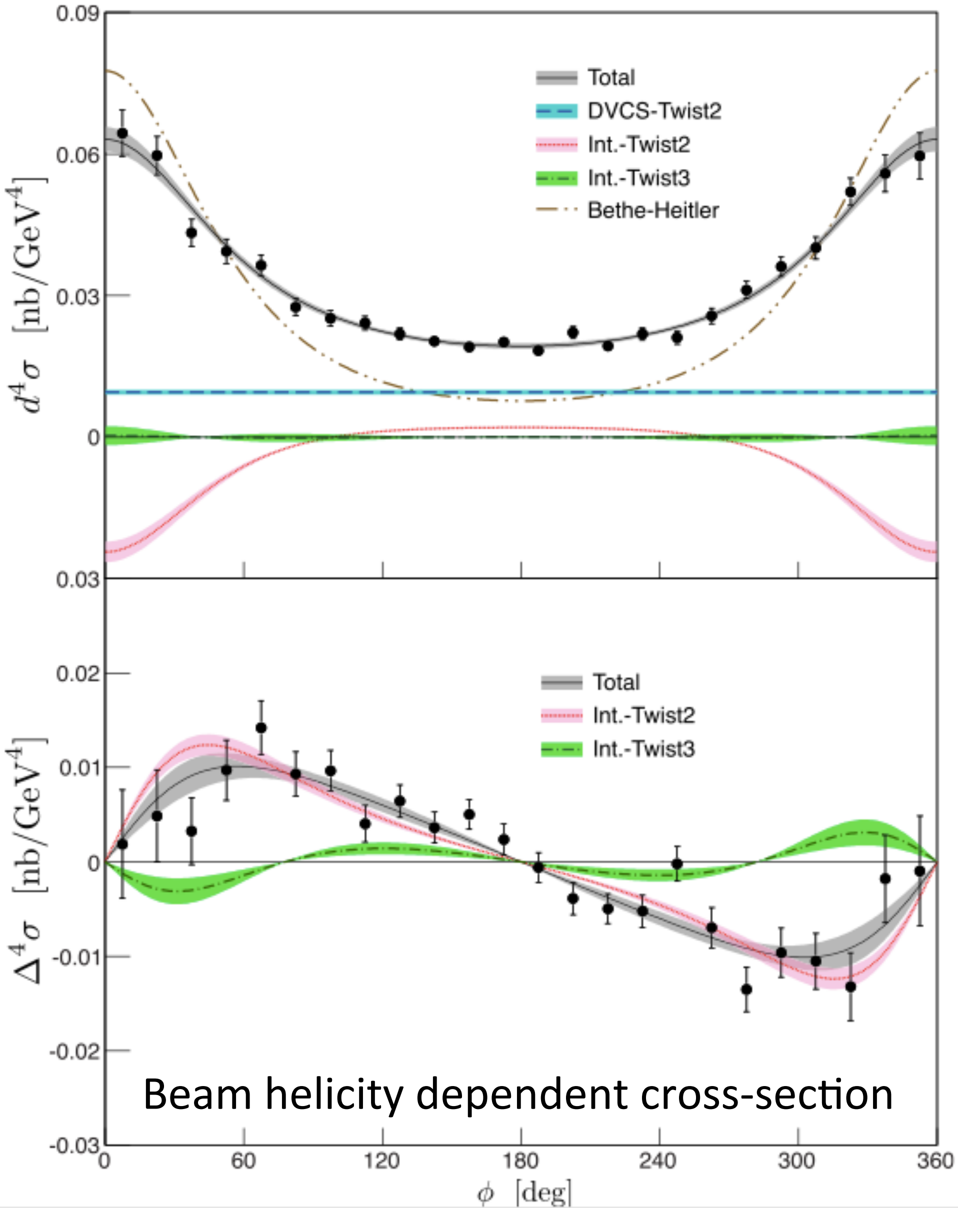
Short of these completely under control:

can one draw some conclusions (within reasonable approximations)?

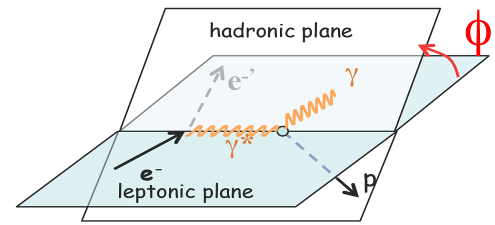
- GPD H
- GPD E

Hall A E00-110: cross section **azimuthal analysis**

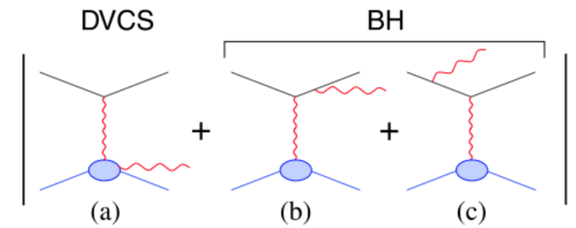
$x_B = 0.37, \quad Q^2 = 2.36\ \mathrm{GeV}^2, \quad -t = 0.32\ \mathrm{GeV}^2$



From Phys.Rev.Lett. 97 (2006) 262002
to : **arXiv:1504.05453 April '15**



ep ⟶ epγ =



$$d^4\sigma = \mathcal{T}^2_{\mathrm{BH}} + \mathcal{T}_{\mathrm{BH}}\mathcal{R}e(\mathcal{T}_{\mathrm{DVCS}}) + \mathcal{T}^2_{\mathrm{DVCS}}$$

$$\mathcal{R}e(\mathcal{T}_{\mathrm{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}}\cos\phi + c_2^{\mathcal{I}}\cos 2\phi$$

$$\mathcal{T}^2_{\mathrm{DVCS}} \sim c_0^{\mathrm{DVCS}} + c_1^{\mathrm{DVCS}}\cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\mathrm{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\mathrm{DVCS}}) \sim s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

Extracting cross-sections from the data: the Hall A scheme

$$\frac{d^4\sigma}{dx_b dt d\phi_\gamma dQ^2} = \Gamma^G |BH|^2 + \Gamma^1 \mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^2 \Delta\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^3 \mathcal{C}^{\mathcal{I}}(\mathcal{F}^{eff})$$

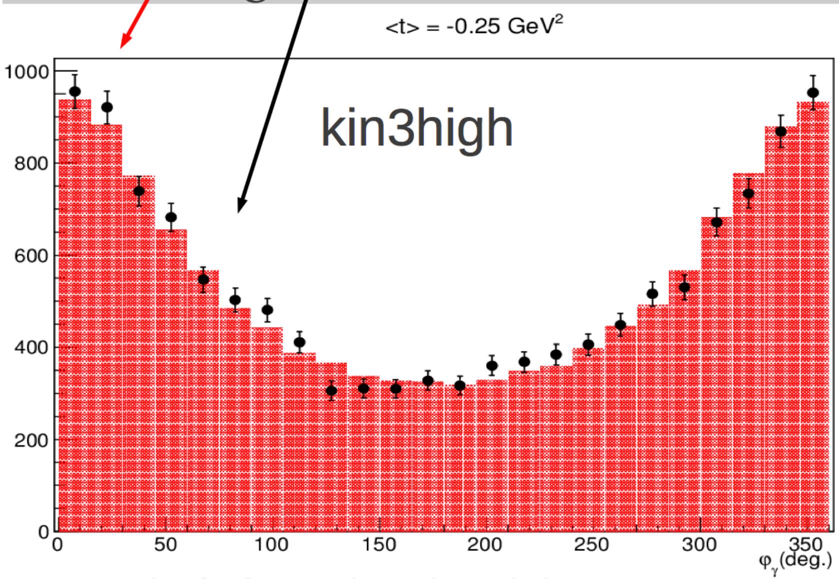
Guidance from NLO, twist 3 formalism: $\sin(n\phi)$, Q^2, x_{BJ},…

Γ^i : kinematic factors (calculable in experimental setup simulation)

C^i (= C^I, ΔC^I, C^I_{eff}) : Compton Form Factors obtained by fit on the data

$$\chi^2 = \frac{(N^{MC} - N^{Exp})^2}{\sigma^2} \longrightarrow N^{MC} = \int \frac{d\sigma}{d\Omega} d\Omega = \sum_{i=1}^{3} \left(\int \Gamma^i d\Omega\right) C^i$$

$$\frac{\delta\chi^2}{\delta C^i} = 0 \rightarrow \begin{Bmatrix} C^I \\ \Delta C^I \\ C^I_{eff} \end{Bmatrix}$$



Black dot: data / Red histogram: MC fit

The extracted cross-section is parametrization independent.

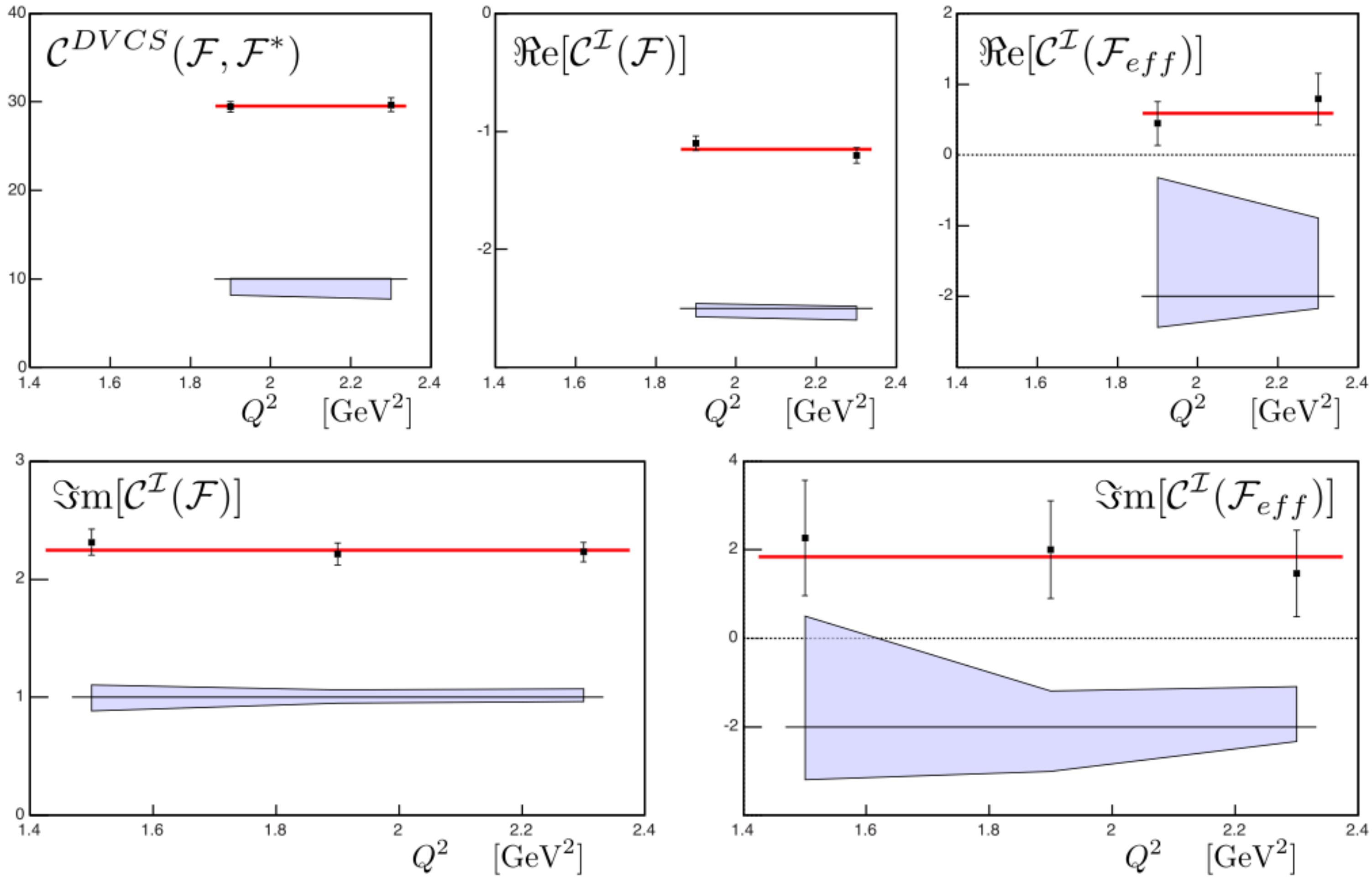
Interpreting the extracted CFFs needs to be done carefully:

- -8 GPDs (4 X 2),
- -twist 2-3 expansion…

Slide from C. Desnault

Hall A E00-110: cross section **Q^2 dependence**

arXiv:1504.05453 April '15



No Q^2 dependence within this limited range => leading twist dominance
Need to be checked over a larger Q^2 bite

Future precision measurement of the DVCS at JLab

Medium term 12GeV era JLab data

E12-13-007: apparatus to be built

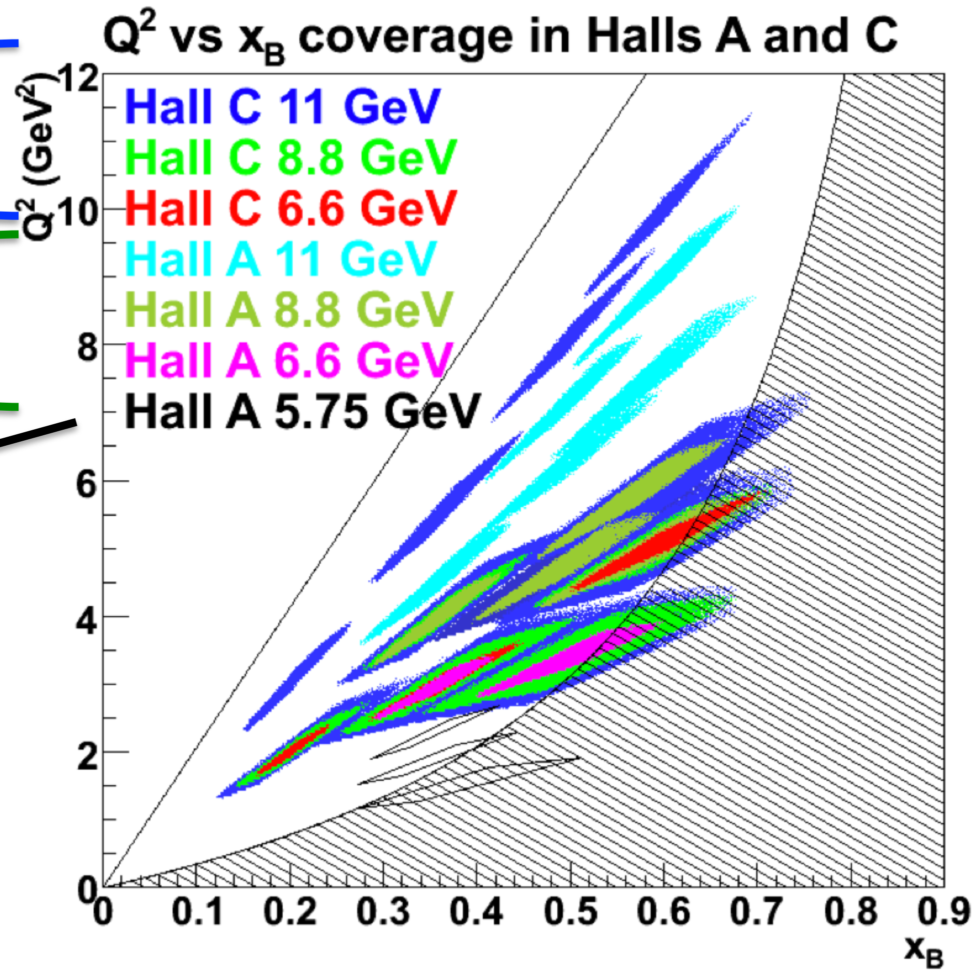
Upcoming 12GeV era JLab data

E12-06-114: data to be taken in 2014-16

Existing 6GeV era Jlab data

E00-110: PRL 97: 262002 (2006)

E07-007: analysis in progress



F. Georges will present his thesis work
On these data later this week.

The program features:

- Q^2 scans at fixed x_B → Scaling test
- Identical kinematic points measured at different beam energies → $DVCS^2$ test

Hall A E07-007: analysis in progress (data taken in 2010)

Goal:

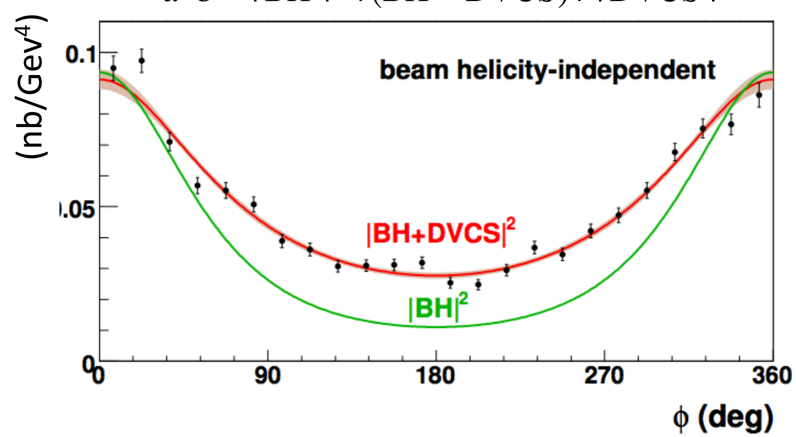
To separate the BH.DVCS interference contribution from the $DVCS^2$ contribution,

And L/T separation of the deeply virtual π^0 production,

Also $DVCS^2$ on the neutron.

Motivated by the first generation result

$$d^5\sigma = |BH|^2 + (BH \bullet DVCS) + |DVCS|^2$$



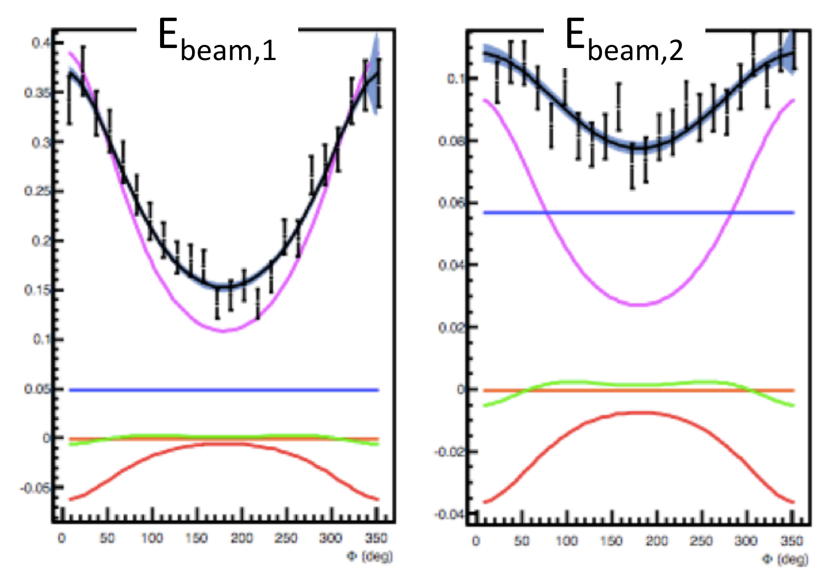
	Kin 1		Kin 2		Kin3	
Q^2 (GeV^2)	1.5		1.75		2.0	
X_b	0.36		0.36		0.36	
E_{beam} (GeV)	3.36	5.55	4.45	5.55	4.45	5.55

Rosenbluth type separation

$$\sigma_1 = |BH|^2 + \Gamma_1 |DVCS|^2 + \Gamma_1' Re(I)$$

$$\sigma_2 = |BH|^2 + \Gamma_2 |DVCS|^2 + \Gamma_2' Re(I)$$

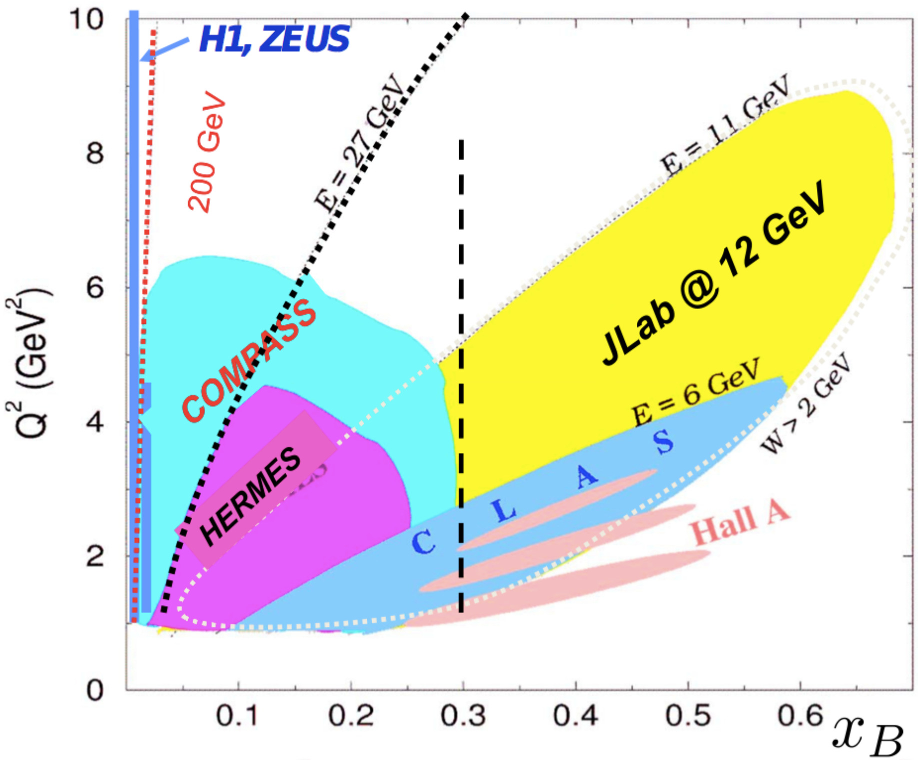
E^3_{beam} E^2_{beam}



BH Twist 3 interference

Twist 2 Interference Twist 2 DVCS

DVCS results (so far)



The valence + sea sector

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- Measure the transverse size of the nucleon versus x_B (2+1D imagining)
  - for the gluons, the sea and the valence quarks
  - For various quark flavor,
- Evaluate the orbital angular momentum of the quarks

In order to achieve this, one needs to:

- Verify the formalism is applicable,
- Understand how to interpret the data.

Assuming the formalism is applicable:
can one draw some conclusions (within reasonable approximations)?
- GPD H
- GPD E

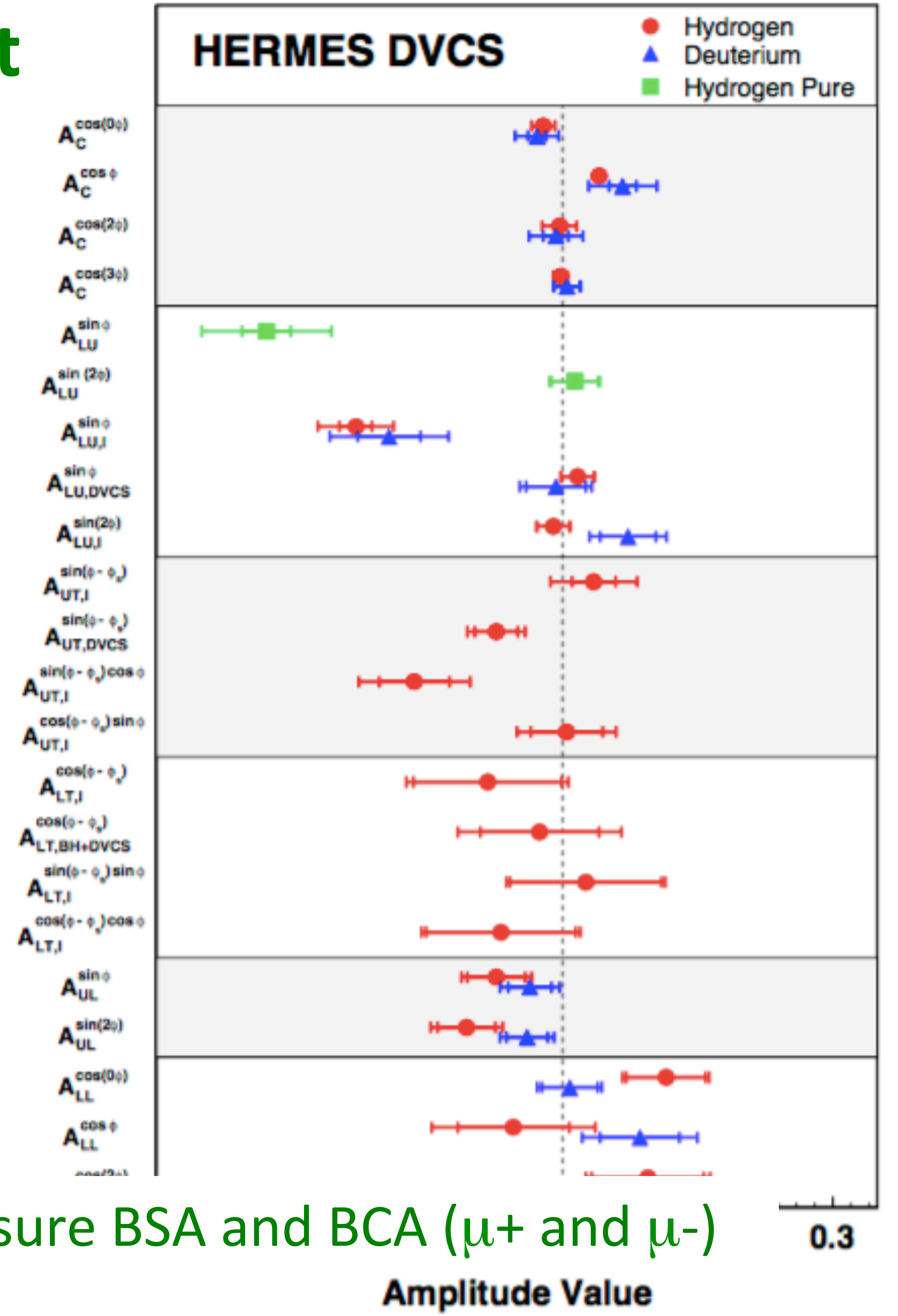
The very complete data set from Hermes

Longitudinal polarized electron/positron beam
Scattering off a transversely or longitudinally
polarized hydrogen target

Example of Longitudinally polarized beam off a

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l A_{LU}^{DV}$$

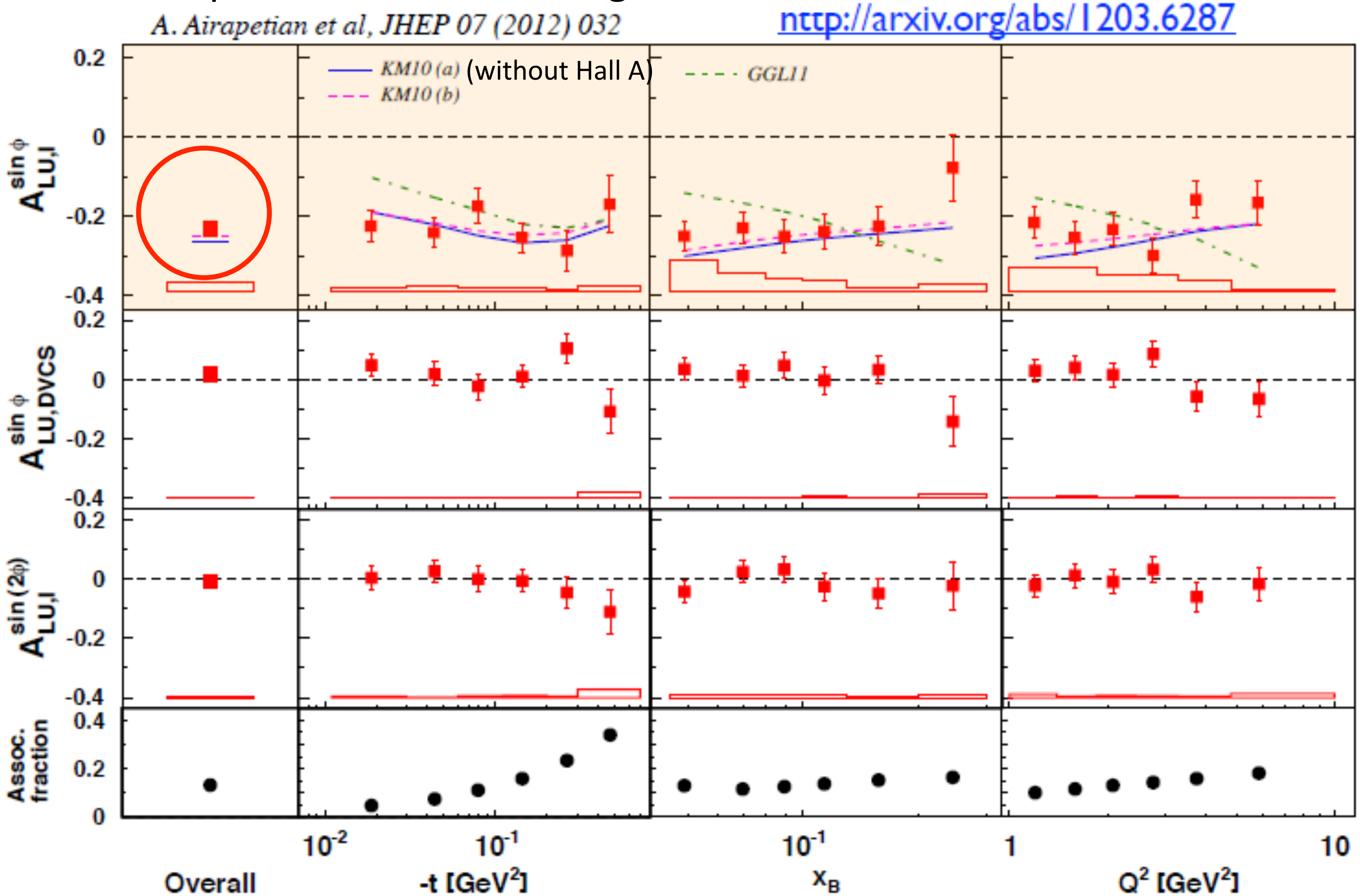
$$s_1^{DVCS} sin(\phi) \qquad \sum_{n=}^{2}$$



Compass will also be able to measure BSA and BCA (μ+ and μ-)

BSA with Hermes ($\vec{e}$, $\overleftarrow{e}$)

Complete data set including 2006-07



sin φ term
Im **F1** $\mathcal{H}$

sinφ term from DVCS²

sin 2φ term higher twist

resonant fraction ep → eγΔ⁺

KM: http://arxiv.org/abs/0904.0458

Kumerički and Müller, Nucl. Phys. ***B841*** *(2010)*

GHL11: flexible parameterization

http://arxiv.org/abs/1012.3776

G. Goldstein, J. Hernandez and S. Liuti, ***Phys. Rev. D84*** *(2011)*

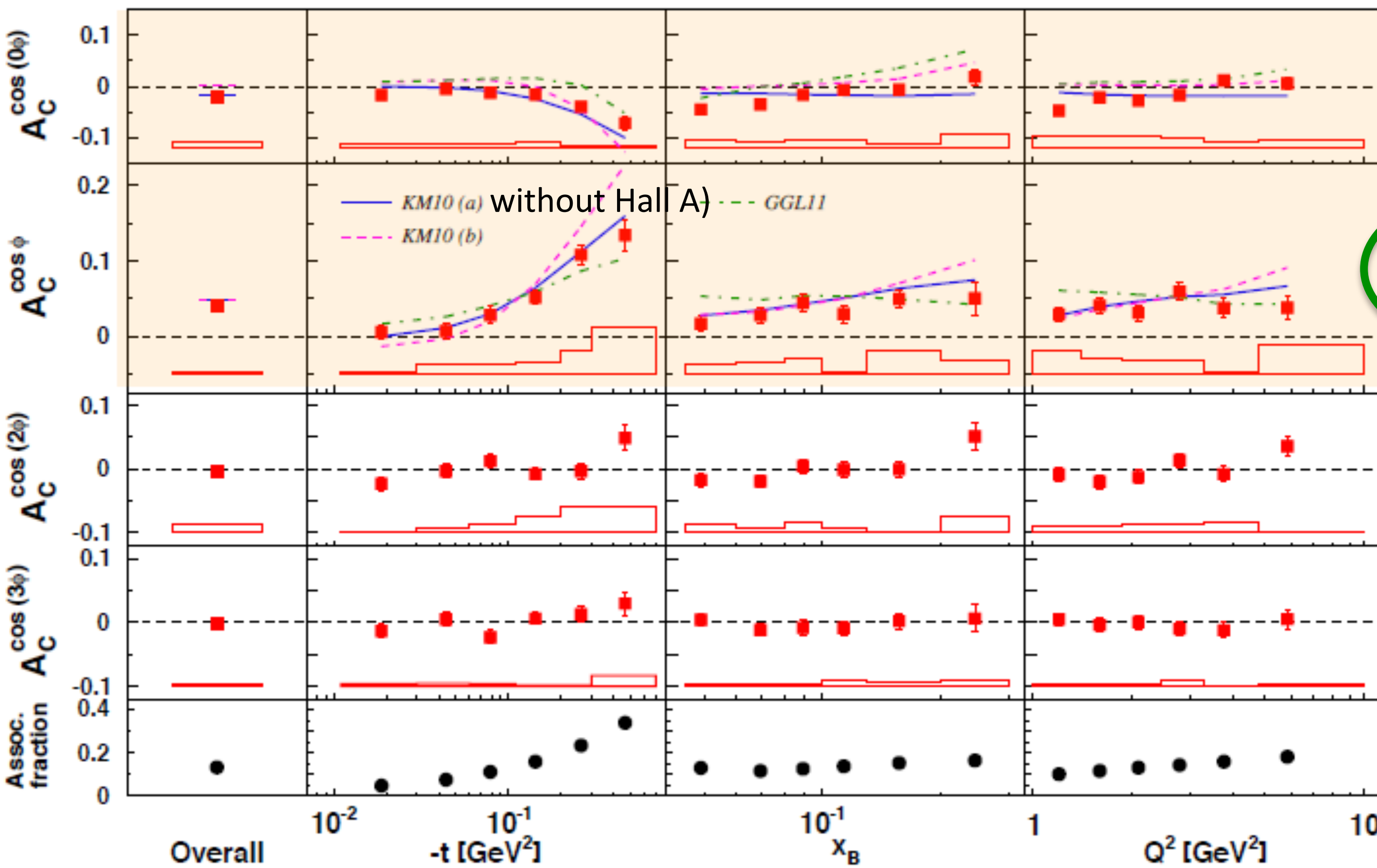
Slide from N d'Hose, Tranversity 2014

BCA with Hermes (e^+, e^-)

So far unique access to Re$\mathcal{H}$

Complete data set including 2006-07 with recoil detection

A. Airapetian et al, JHEP 07 (2012) 032 http://arxiv.org/abs/1203.6287



constant term

cos ϕ term
Re F1 $\mathcal{H}$

cos 2ϕ term
higher twist

cos 3ϕ term
gluon twist

resonant fraction
ep → eγΔ⁺

KM: http://arxiv.org/abs/0904.0458

Kumerički and Müller, Nucl. Phys. ***B841*** *(2010)*

GHL11:
http://arxiv.org/abs/1012.3776

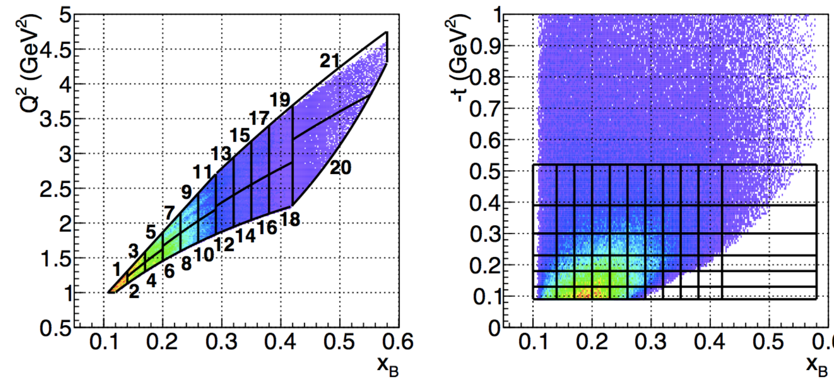
G. Goldstein, J. Hernandez and S. Liuti, ***Phys. Rev. D84*** *(2011)*

Slide from N d'Hose, Tranversity 2014

Hall B E01-113 cross sections

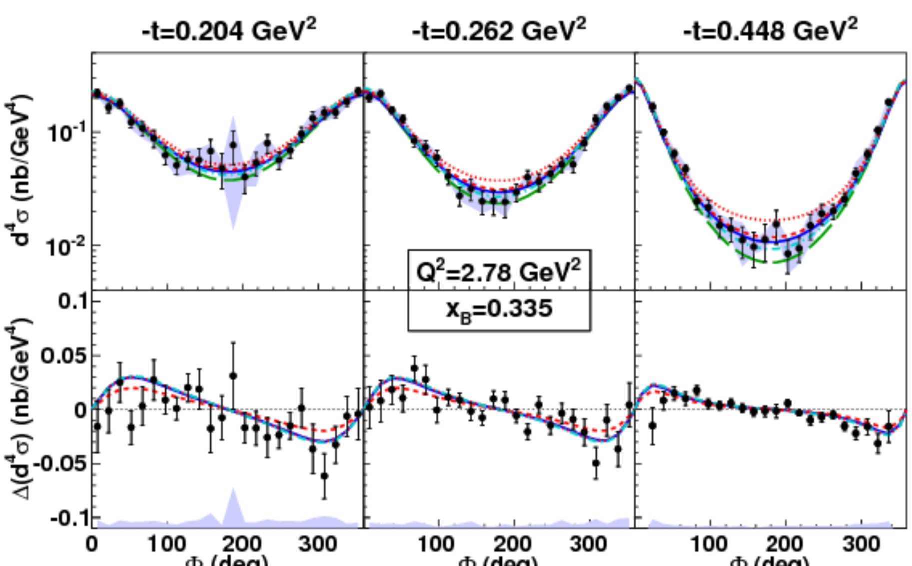
$$\text{BSA} = \frac{\Delta^4\sigma}{d^4\sigma}\ \text{(PRL 2006)} \quad \Rightarrow \quad \Delta^4\sigma \quad \text{and} \quad d^4\sigma\ \text{(arXiv:1504.02009, Apr '15)}$$

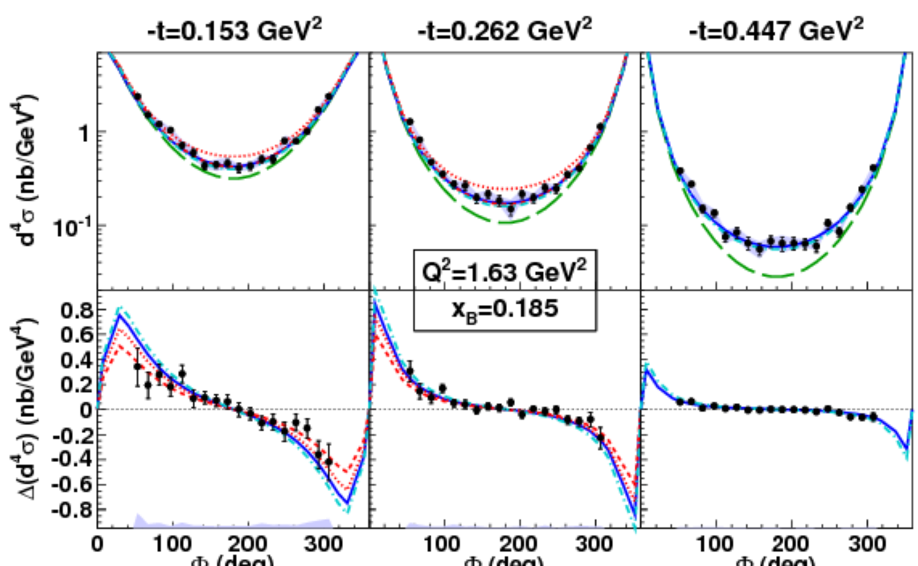
★ 110 bins in (x_B, Q^2 and t)



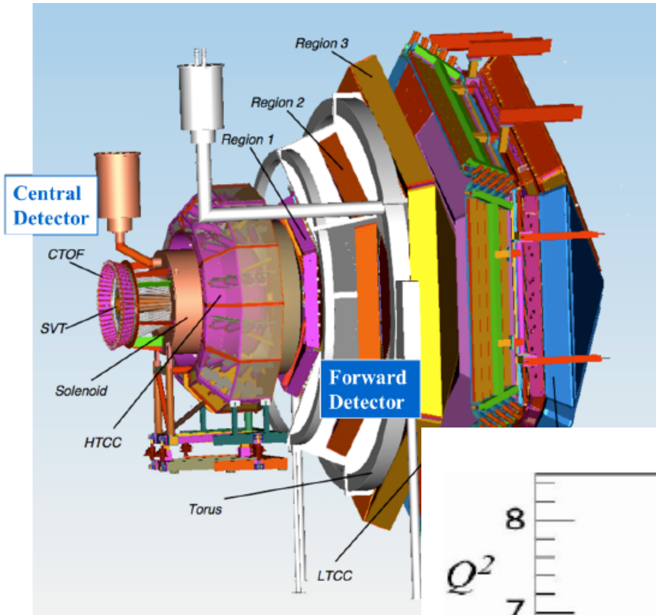
- Compatible with Hall A results in overlapping regions

- Leading twist models describe the data within uncertainties (more than 15%)





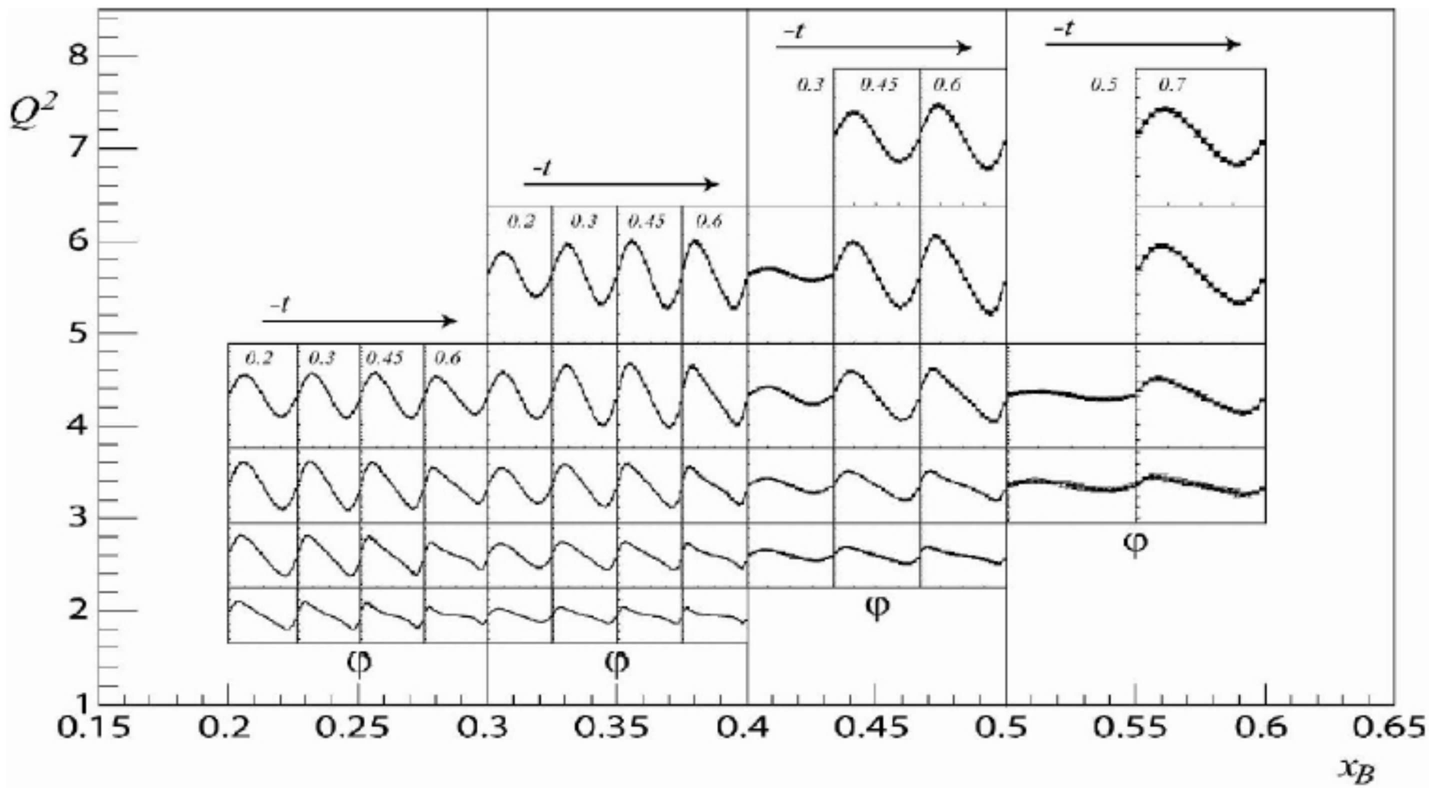
E12-06-119: Future DVCS experiment with CLAS12



Beam spin asymmetry

LH_2 Target and Long. Pol. Target

Mostly sensitive to **Im($\mathcal{H}$)**



CLAS data local fits

Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\ \}d\phi$$

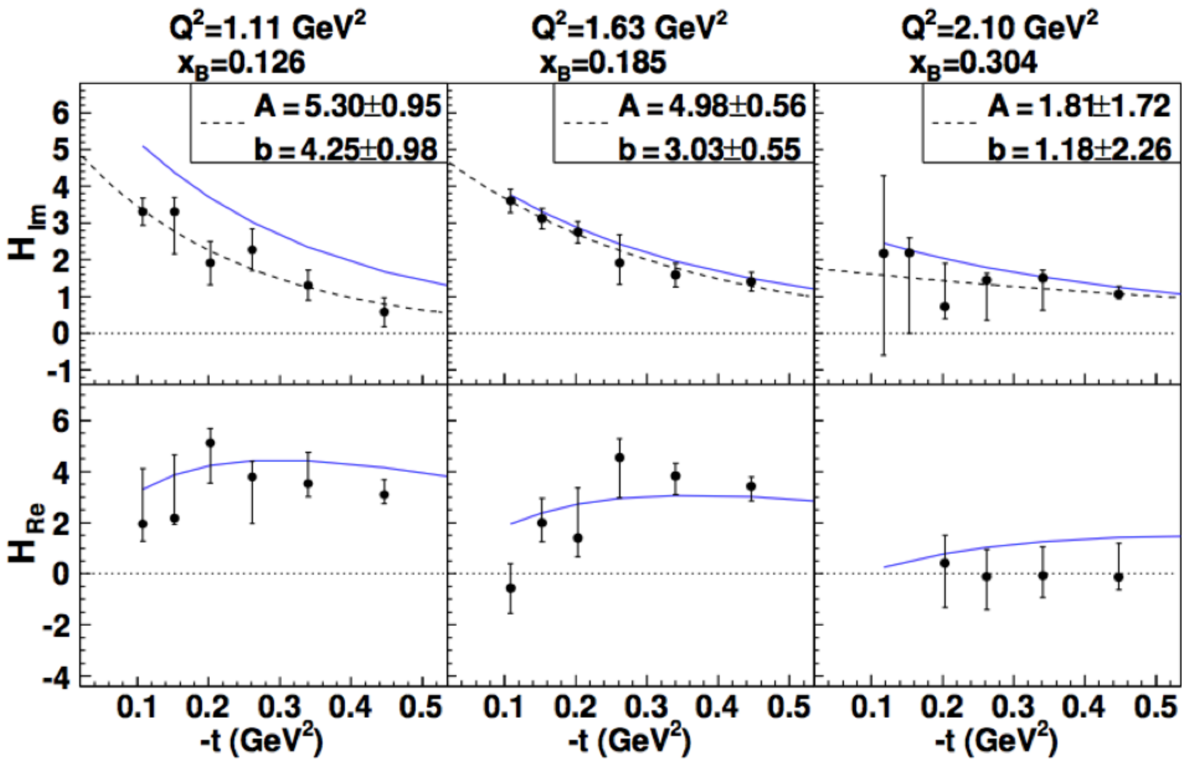


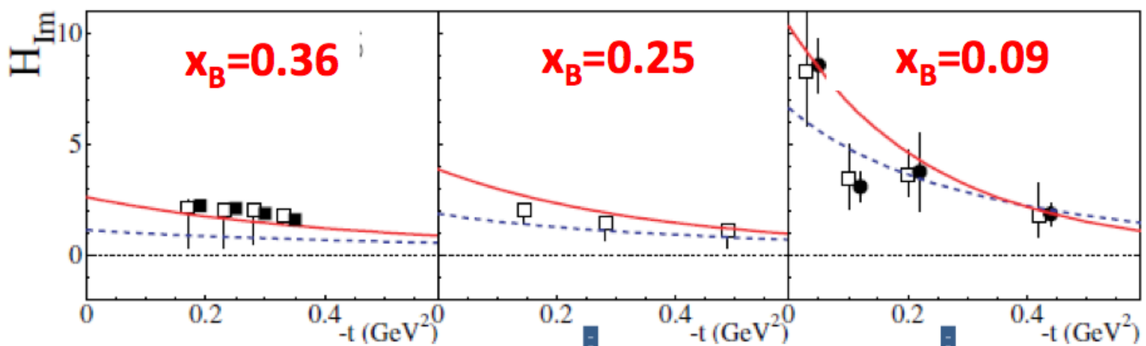
Fig. 8. (Color online) Results of the CFF fit of the CLAS unpolarized and beam-polarized cross-sections for H_{Im} (upper panel) and H_{Re} (lower panel), with only the GPDs H and $\tilde{H}$, for three (Q^2, x_B) bins, as a function of t. The blue solid curves are the predictions of the VGG model. The black dashed curves show the fit of the results by the function Ae^{bt}.

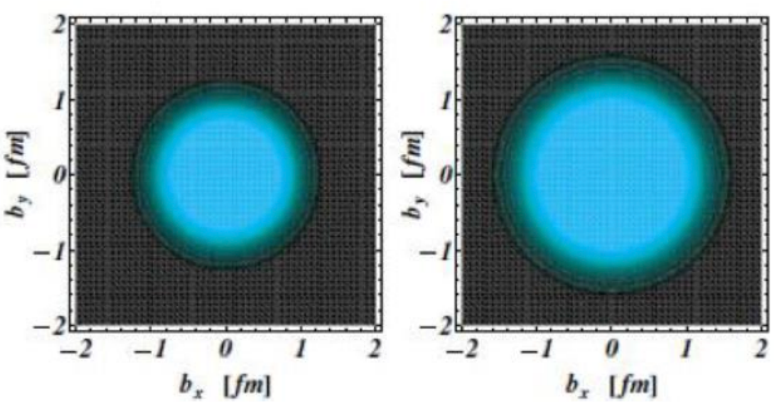
Towards the 3D Structure of the Proton (past 10 years)

the CFF H in *Im* DVCS

e⁻ 6 GeV		e± 27 GeV
Jlab Hall A	**Jlab CLAS**	**HERMES**
Beam Spin Diff	Beam Spin Asym	Beam Spin Asym
Beam Spin Sum	Long Pol targ Asym	Beam Charge Asym

●○■□ Different local fits
VGG model (red line)
KM10 global fit on the world data ranging from H1,ZEUS to HERMES, JLab (blue dashed line)





To “extract the GPDs”, one can:

- Compare data to models of the GPDs
- Extract 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 CFFs.

Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

An encouraging proof of concept: one is looking forward to much refined data and analysis.

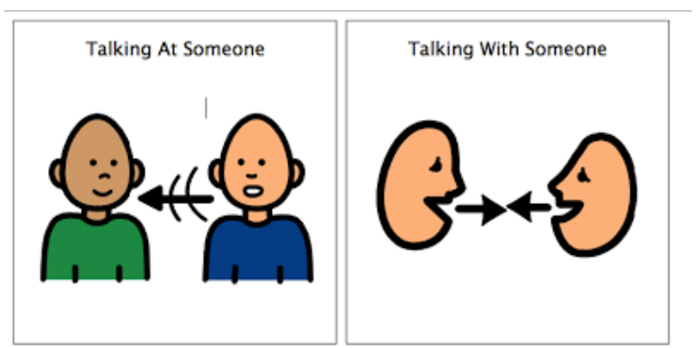
1 question: 30 m reading + 15 min discussions

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, Manuel
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	*: familiar with GPDs/DVCS

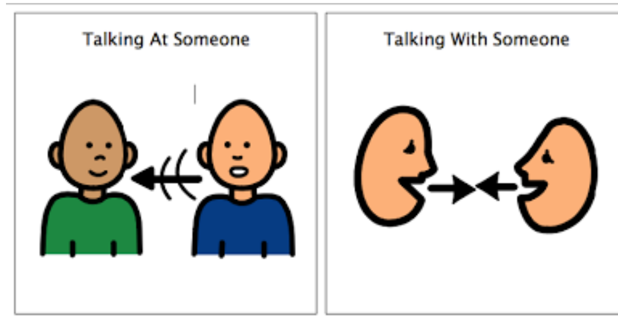
Model of GPDs

What have we learnt about GPD experiment so far?

C. Munoz-Camacho (IPN Orsay, France)
HRD thesis, July 2014

Spatial imaging is catchy but the real physics is in the models of GPDs that are trying to reproduce data.

What are the three types of models considered when trying to reproduce DVCS data?

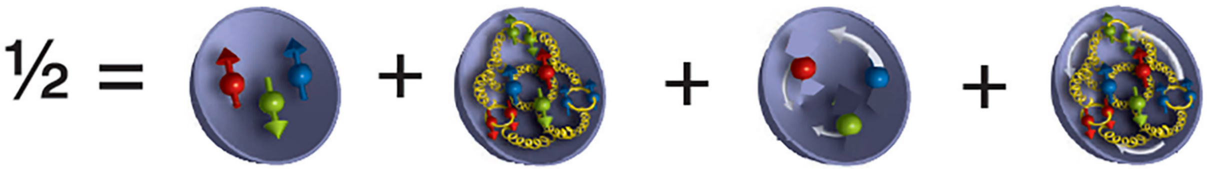


Hunting the GPD E

→ Transv. Target Spin asymmetry of DVCS –HERMES
→ Beam Spin Diff of DVCS on a neutron - JLab
→ Also Compass results from ρ production (not discussed here)

Slide from N d'Hose, Tranversity 2014

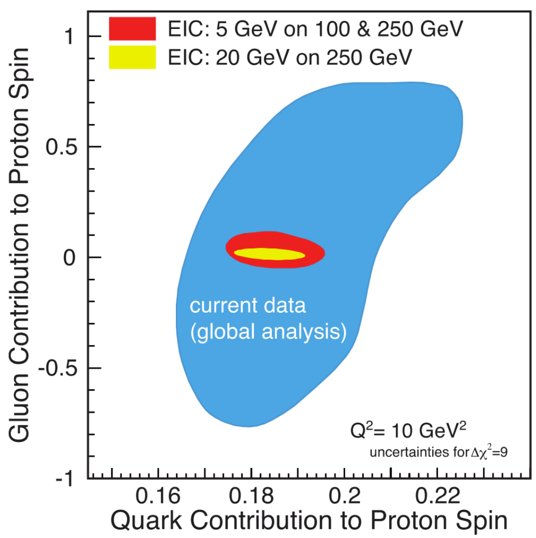
The "Holy grail" of GPDs (and TMDs) physics



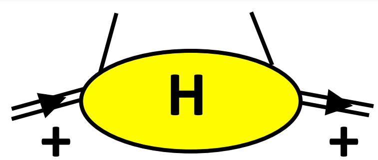
Contribution of the **angular momentum of quarks** to proton spin:

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

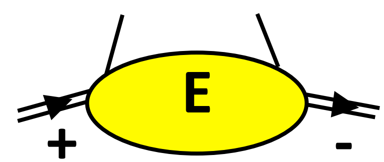
Ji's sum rule



RHIC spin physics results (LRP 2015)



GPD H connects to the PDFs (symmetric initial-final states) Known from polarized DIS data

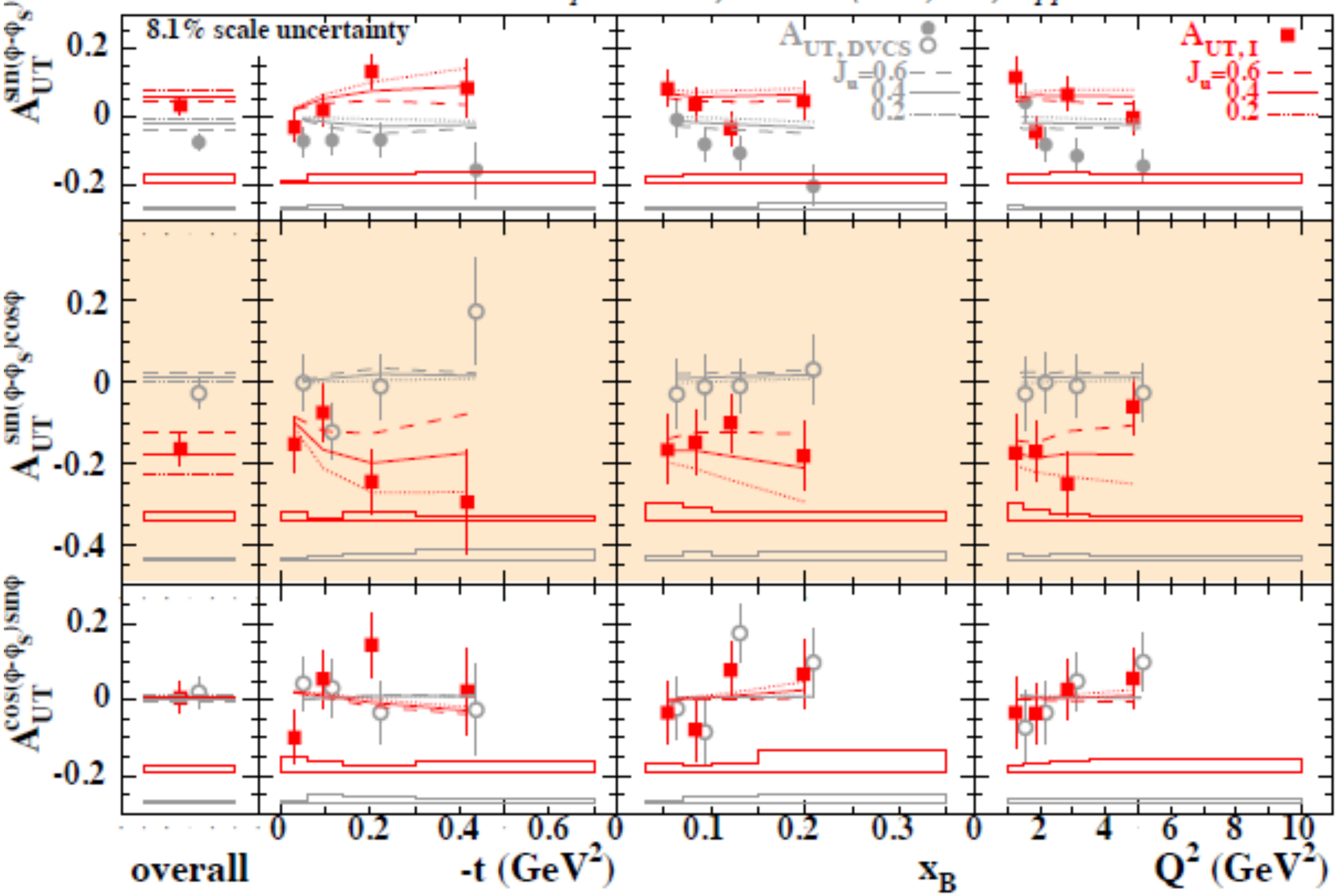


GPD E is the unknown

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

Transverse spin target asymmetry on proton Hermes

A. Airapetian et al, JHEP 06 (2008) 066, 24pp



But also Large $A_{UT,DVCS}$ $\sin(\phi-\phi_S)$ with strong x_{Bj} depend.

Large $A_{UT,I}$ $\sin(\phi-\phi_S)\cos\phi$ Sensitive to Ju, Jd (VGG model)

$$A_{UT,DVCS}^{\sin(\phi-\phi_S)} \sim \mathrm{Im}[\mathcal{E}^*\mathcal{H}]$$

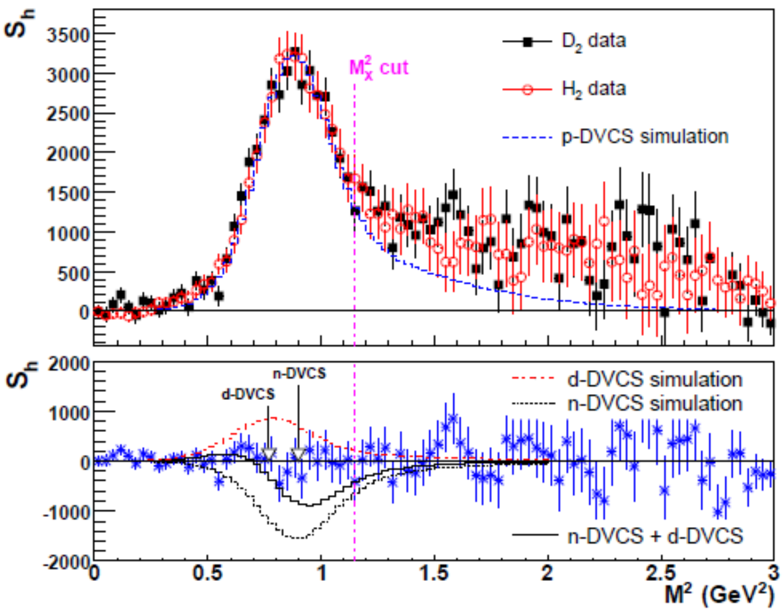
$$A_{UT,DVCS}^{\sin(\phi-\phi_S)} \neq 0 \implies \mathcal{E} \neq 0$$

Slide from N d'Hose, Tranversity 2014

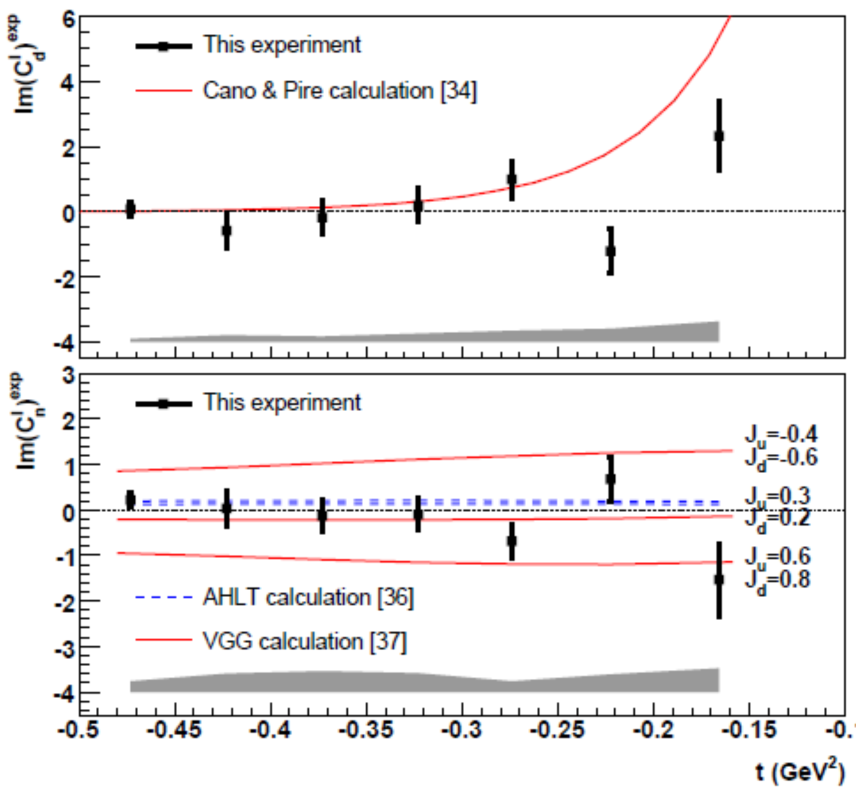
DVCS on the neutron in Hall A/JLab

M. Mazouz et al., PRL 2007, arXiv:0709.0450 [nucl-ex]

$$D(\vec{e}, e'\gamma)X = d(\vec{e}, e'\gamma)d + n(\vec{e}, e'\gamma)n + p(\vec{e}, e'\gamma)p + \ldots$$



$M_X^2 = (q + m_p - q')^2$



M. Benali will present the results of her analysis later this week.

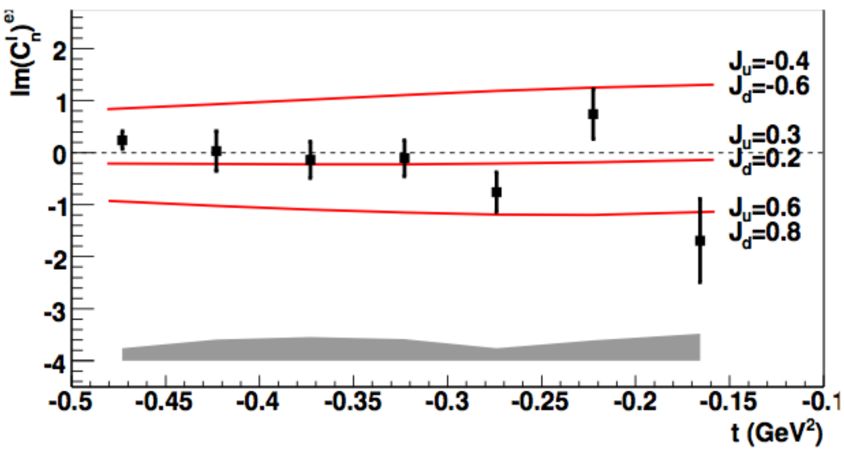
Next:

- 2010: run E08-025 with LD2 target (two beam energies at a given Q^2)
- 2016: CLAS12 with 11 GeV with LD2 target + neutron detector (ToF)

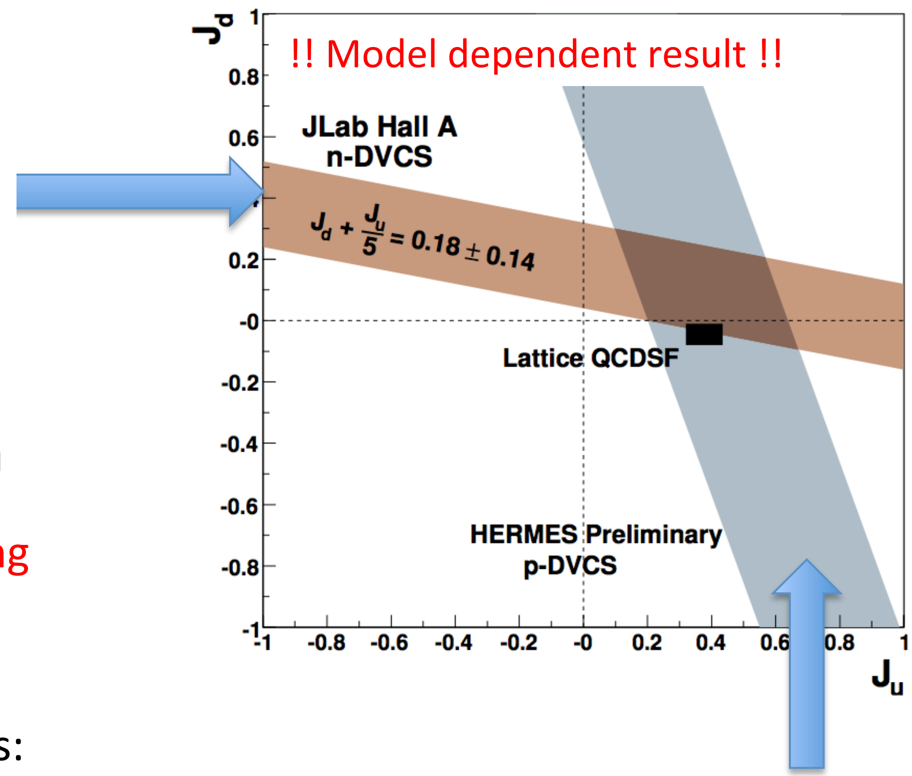
Ji's sum rule on the fraction of the proton spin carried by quarks:

M. Mazouz et al., PRL 2007, arXiv:0709.0450 [nucl-ex]

$$\frac{1}{2} = J_q + J_g \quad \text{and} \quad J_q = \lim_{t \to 0} \int_{-1}^{+1} dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$$



VGG model with various parameters defining the GPD E (-> different values of J_u and J_d)



Hermes:
Unpolarized beam, transversely polarized proton target

Ji, PRL 78:610 (97) VGG, Phys Rev D 60: 094017 (99) Lattice, PRL 92:042002 (04) Hermes, Eur Phys J C46:729 (06)

Hunting for the GPD E with CLAS 12 at JLab

$\vec{e}\, d \rightarrow e\, n\, \gamma\, (p)$ E12-11-003

$$\Delta\sigma_{LU} \sim Im\,(F_{1n}\, \mathcal{H} - F_{2n}\, \mathcal{E})$$

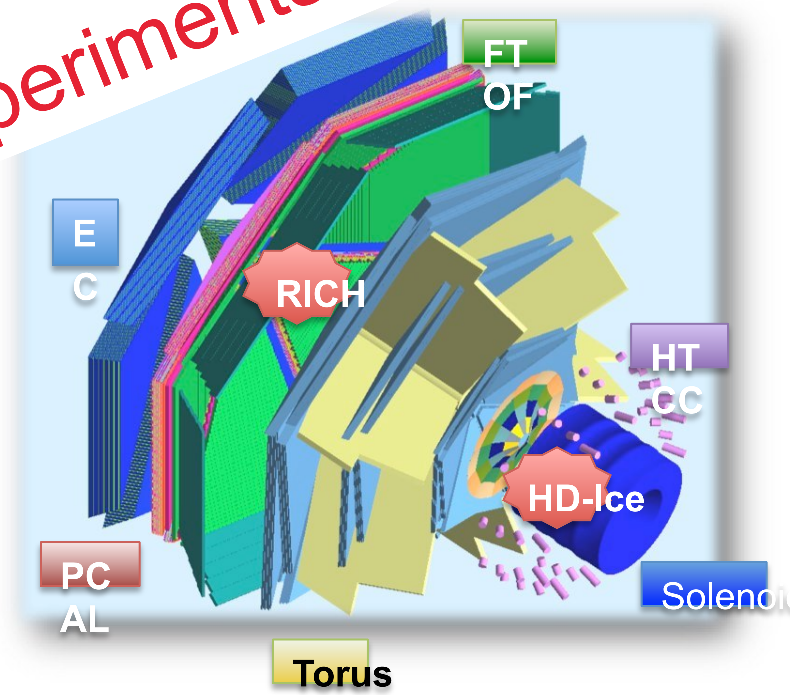
With LD2 target + CLAS12
+ Forward Calorimeter
+ Neutron Detector ToF

$\vec{e}\, p^{\uparrow} \rightarrow e\, p\, \gamma$ E12-12-010

$$\Delta\sigma_{UT}^{\sin(\phi-\phi s)\cos\phi} = Im\,(F_2\, \mathcal{H} - F_1 \mathcal{E})$$
$$\Delta\sigma_{LT}^{\sin(\phi-\phi s)\cos\phi} = Re\,(F_2\, \mathcal{H} - F_1 \mathcal{E})$$

With th target
H)

Selected in the «High Impact » experiments



Slide from N d'Hose, Tranversity 2014

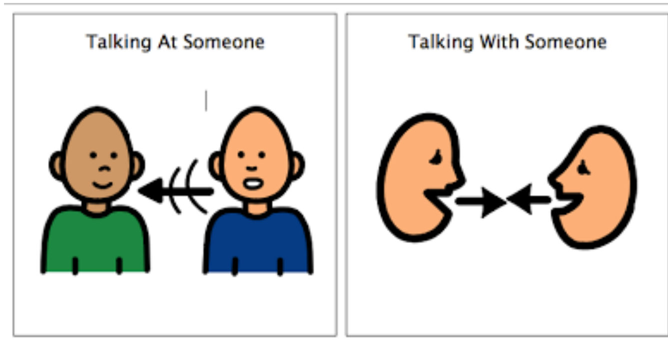
1 question: 30 m reading + 15 min discussions

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, Manuel
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	*: familiar with GPDs/DVCS

GPDs studies at JLab 12 GeV

The Multi-Hall Deep Exclusive Scattering Program at 12 GeV

A. Biselli et al. (2014?)

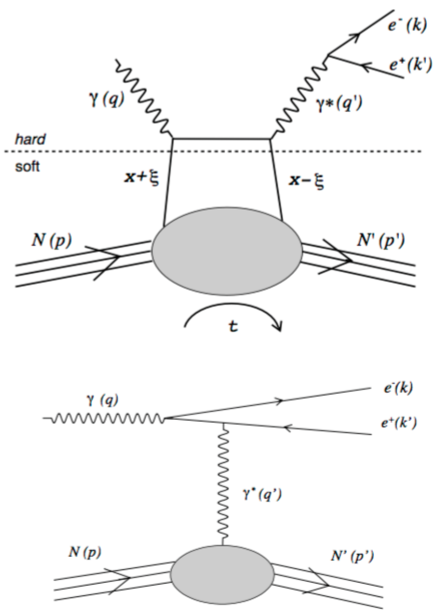


Figure 1: Top: The direct TCS diagram (at QCD leading-twist); there is also a crossed diagram. Bottom: The BH diagram; there is also a diagram where the spacelike virtual photon couples to the electron instead of the positron.

Explain how the different hall are complementary?

Which experiments aim at measuring the GPD E?

What is the overall goals of HEMP program with JLab12?

Overall JLab 12 GeV DVCS proposals

- E12-06-114: Hall A unpolarized protons
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons
- E12-13-010: Hall C unpolarized protons

Unique access to the GPD E
and from there
to the orbital angular momentum of the quarks.

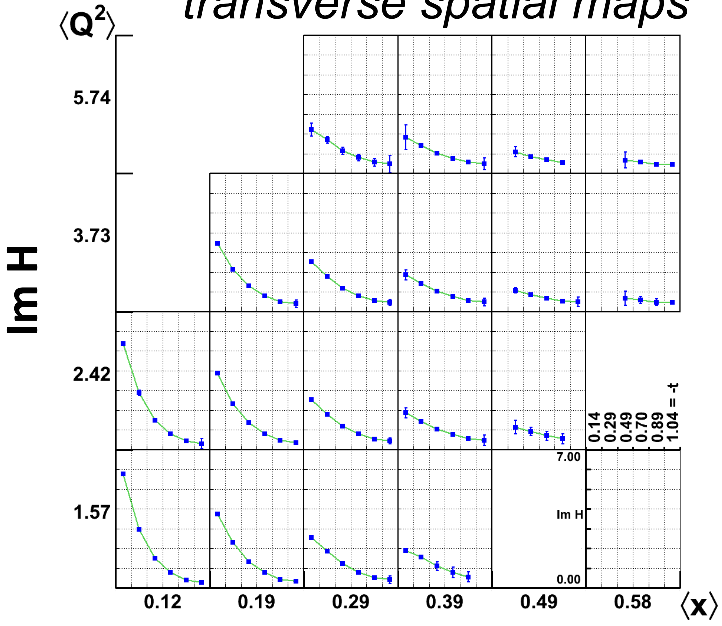
The polarized HDICE target is challenging.

Towards the 3D Structure of the Proton (next 7 years?)

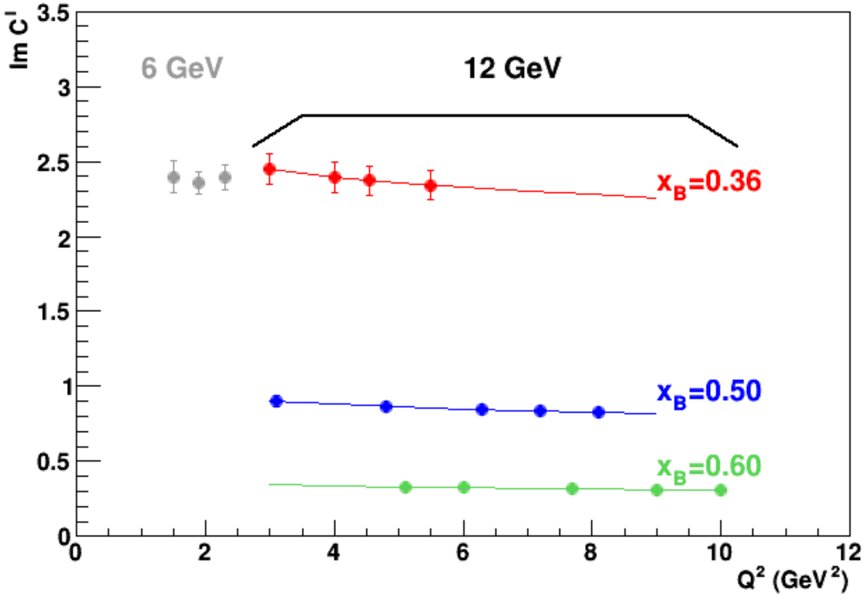
6 GeV data:
Hall B beam-spin asymmetries and cross sections data show potential for imaging studies from analysis in x, Q^2 and t.

6 GeV data:
Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

***12 GeV projections for Hall B**:*
(beam-spin and target-spin asymmetries)
transverse spatial maps



***12 GeV projections for Hall A/C**:*
confirm formalism



Conclusion and perspectives

Since more than 10 years large experimental efforts for DVCS and HEMP

Validity of GPD analysis of DVCS data, Dominance of twist-2

Dominance of the GPD H: **Im$\mathcal{H}$** rather well known,

Re$\mathcal{H}$ poorly constrained ⇨ Beam Charge Diff. and cross section measurements

The GPD **E** poorly constrained ⇨ Transversely Pol. Target measurements on proton

or measurements on neutron

Progress in theory and phenomenolgy

Beyond Leading Order, Leading Twist

Extraction of the GPDs:

- local fits of the CFF for each kinematic bin independently
- global fits using paramaterisation of the GPDs
- neural network: same technique as for PDFs (with error estimate)

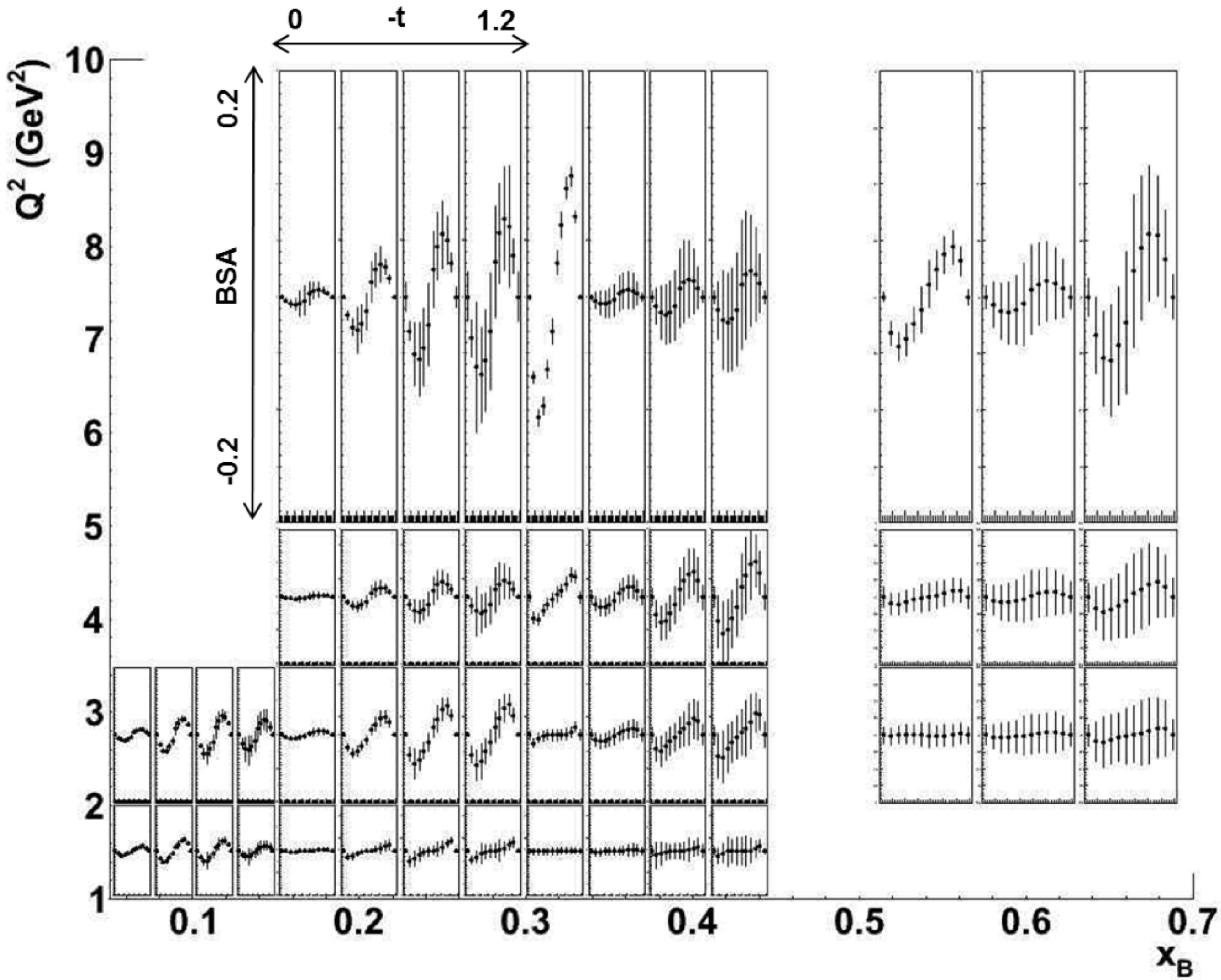
a lot of work for challenging experiments and theory

Slide from N d'Hose, Tranversity 2014

Thank you.

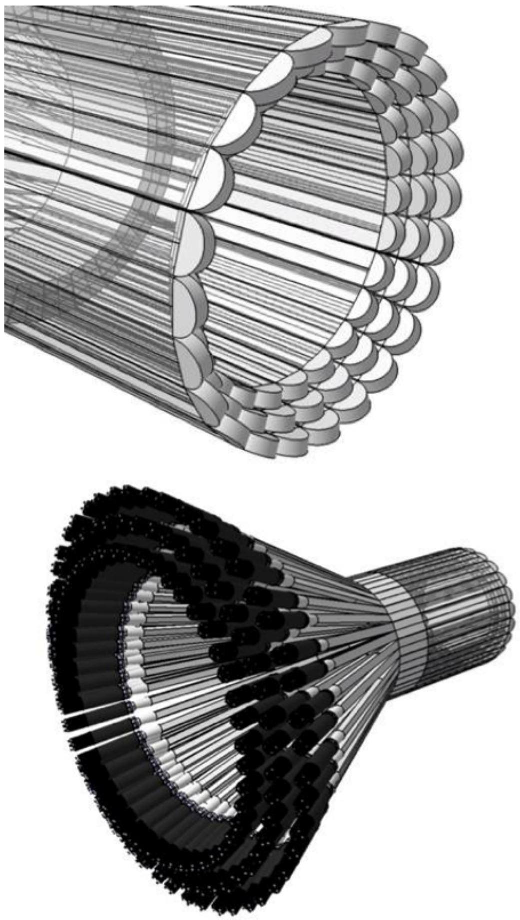
Hall B E12-11-003: DVCS on the neutron with CLAS12 (projections)

90 days of beam

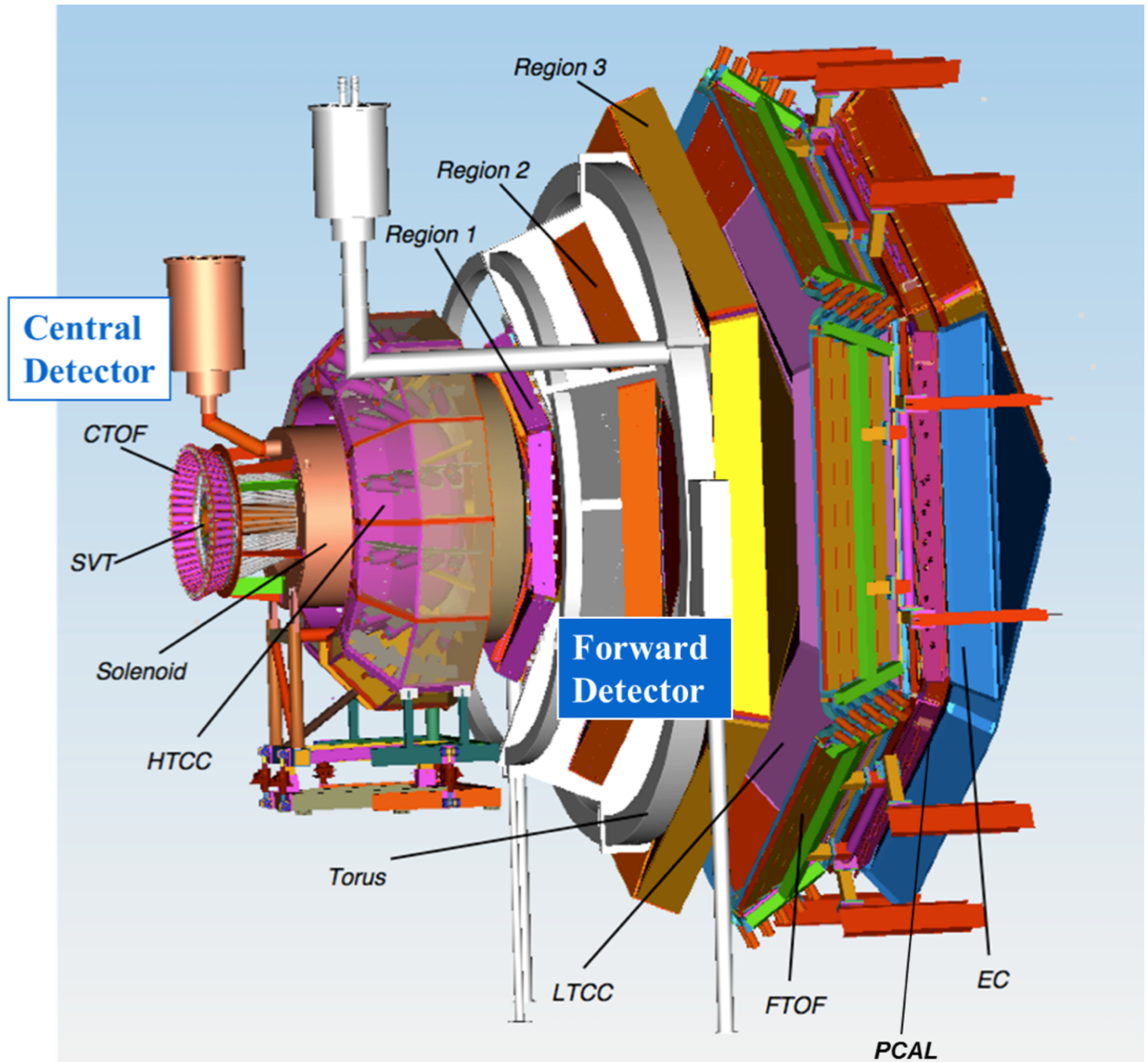


Hall B E12-11-003: DVCS on the neutron with CLAS12

$$\vec{e}d \rightarrow e'n\gamma(p)$$

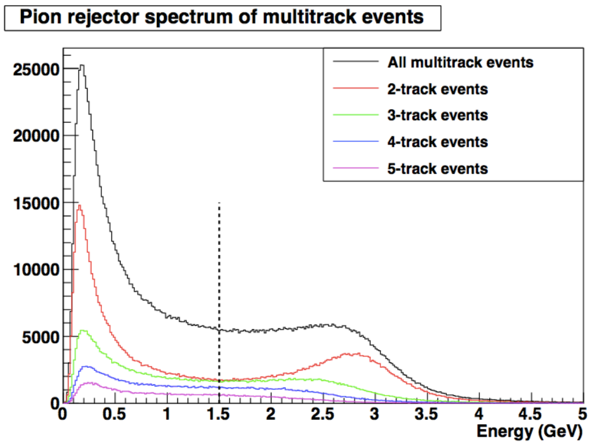


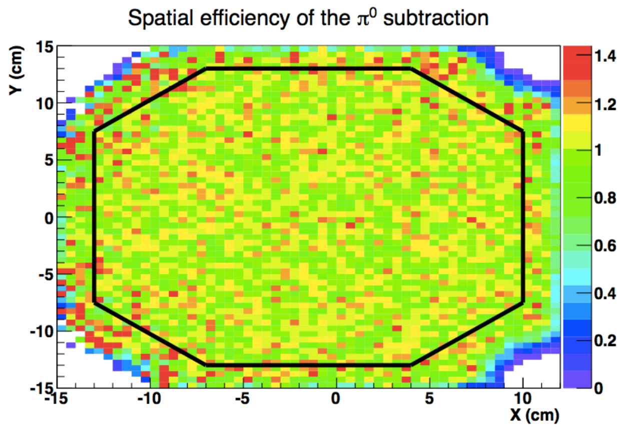
Central Neutron detector

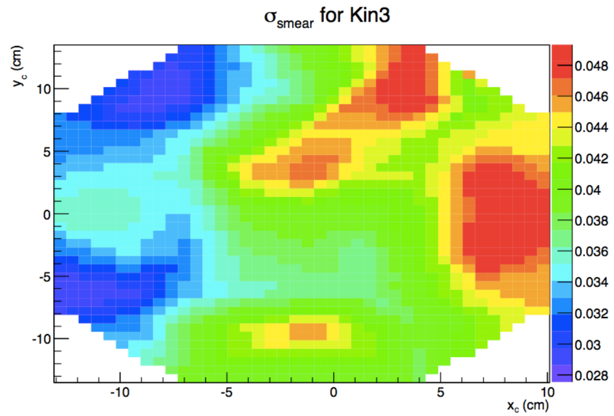


R-analysis of 2005 data

(by grad student M. Defurne – CEA Saclay)







Better correction for events lost in reconstruction algorithm for VDC

Fiducial cuts on calorimeter to take into account π^0 subtraction efficiency

Better description of the energy resolution of the calorimeter.

Cross-sections have changed some, but the conclusions from the first article hold:

- No contribution from the twist 3 part of the interference.
- Large contribution from the $DVCS^2$