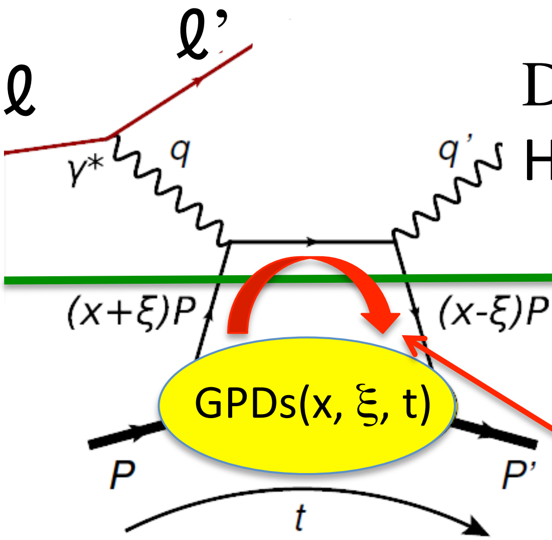
Spatial imaging of the nucleon-3

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

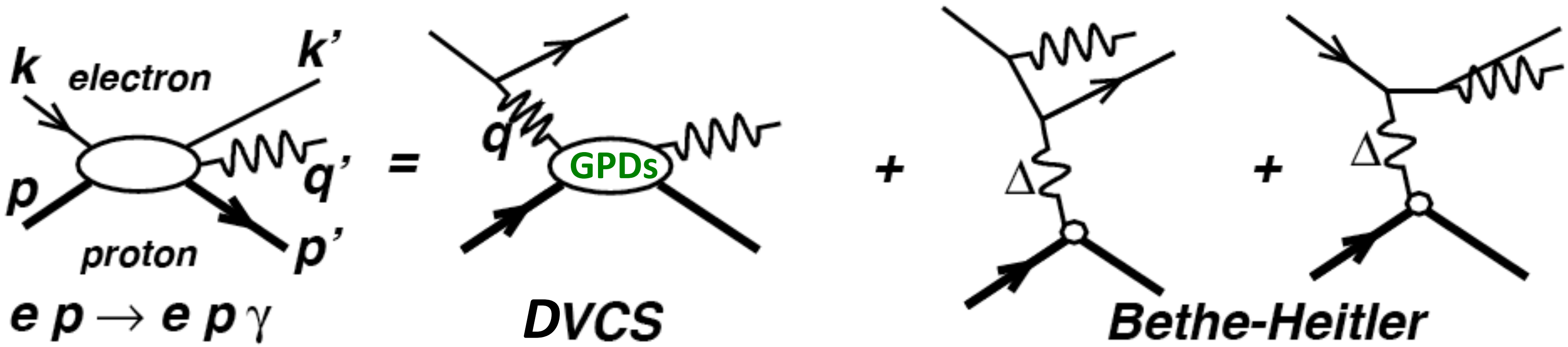
Experimentally, instead on access CFFs (Re and Im parts)

⇒ 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

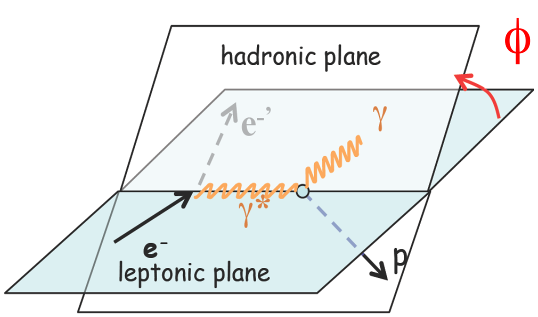


At leading twist:

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

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

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



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)

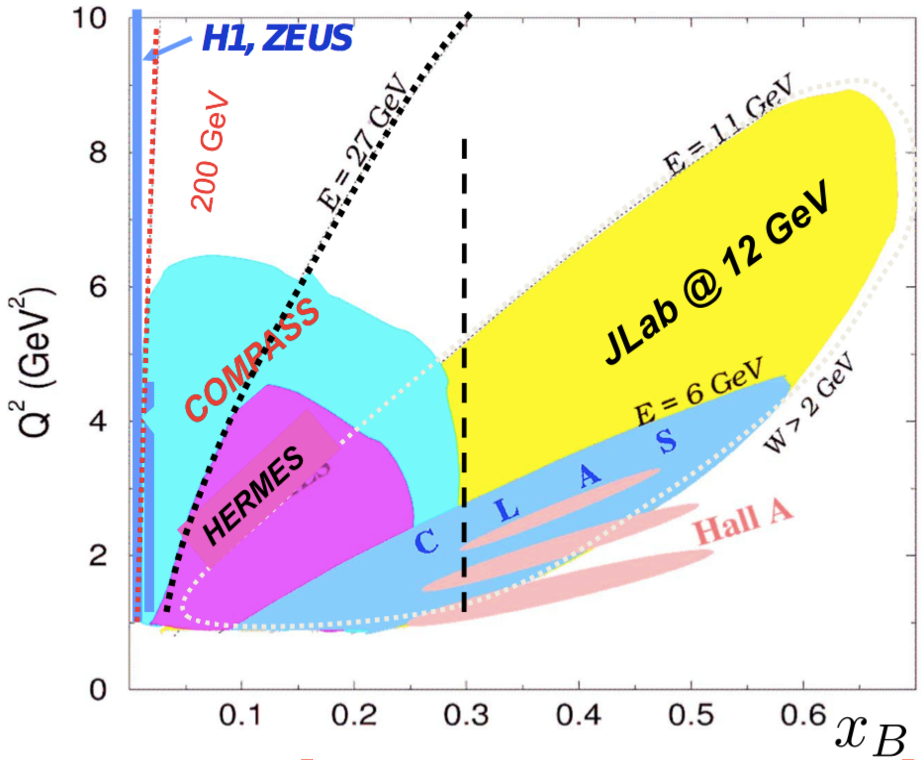
Hermetic detectors

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:

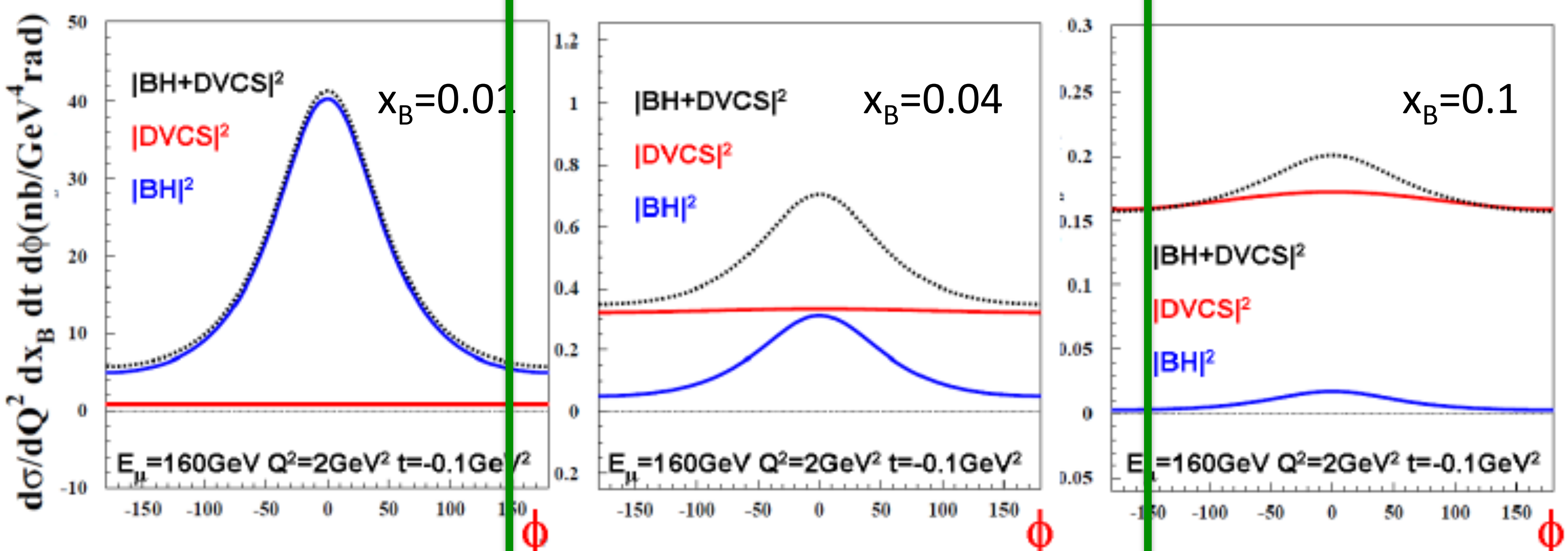
- Verify the formalism is applicable,
- Understand how to interpret the data.

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 $x_B \nearrow$ **BH** $\searrow$



BH dominates
Reference yield

Access to DVCS ampl.
Via interference

DVCS dominates
Study of dσ/dt

Jlab
HERMES, H1
COMPASS

Only for high energy
H1 & ZEUS
COMPASS

$E_\ell \searrow$ **BH** $\nearrow$

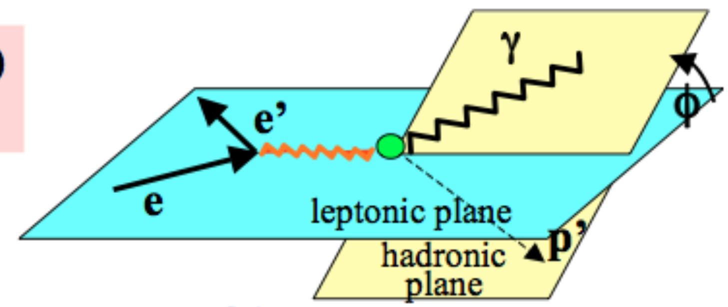
Slide from N d'Hose, Tranversity 2014

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-DVS)

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



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:

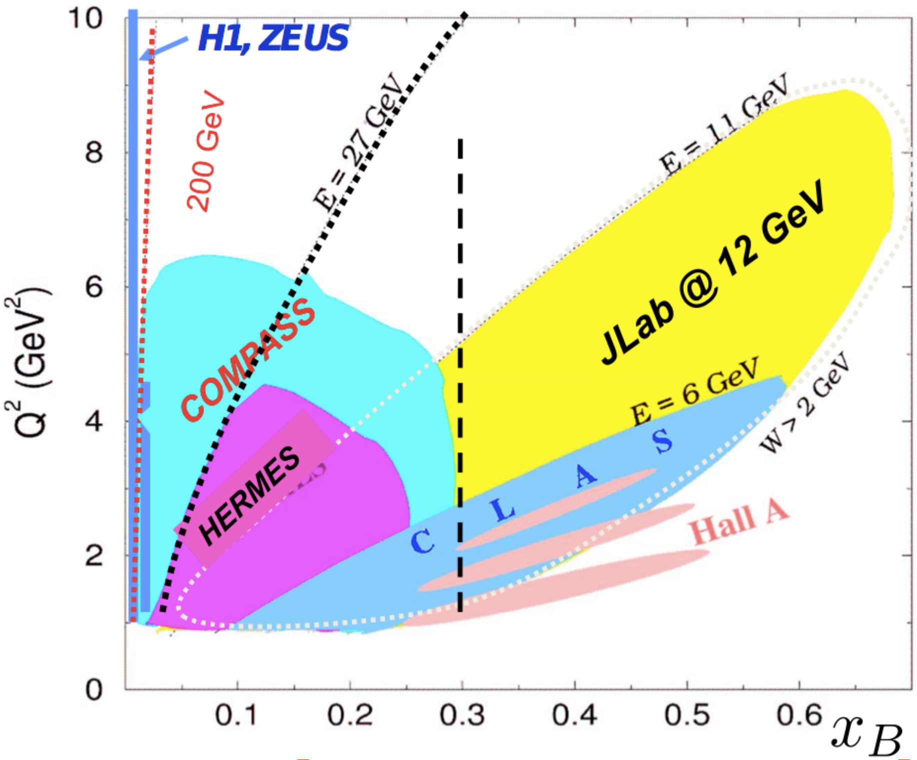
$$\Delta\sigma_{LU} \sim \sin\phi \, \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \;\Rightarrow\; H_n, \tilde{H}_n, E_n$$

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.

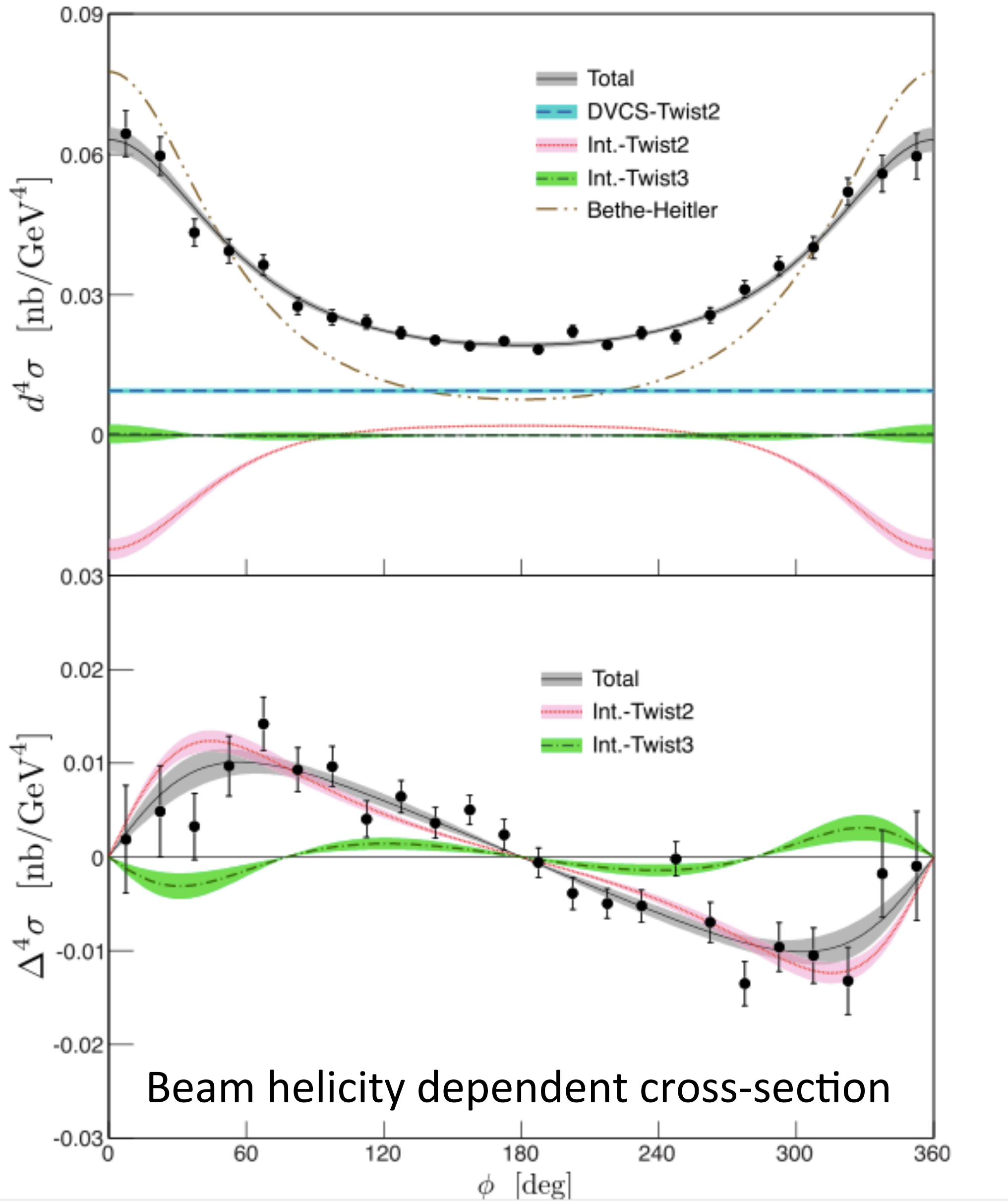
Short of these completely under control:
can one draw some conclusions (within reasonable approximations)?

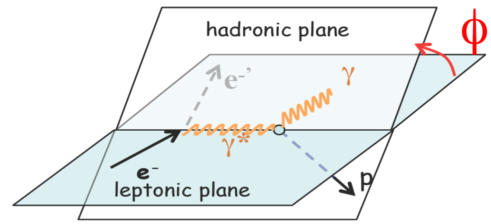
- GPD H
- GPD E

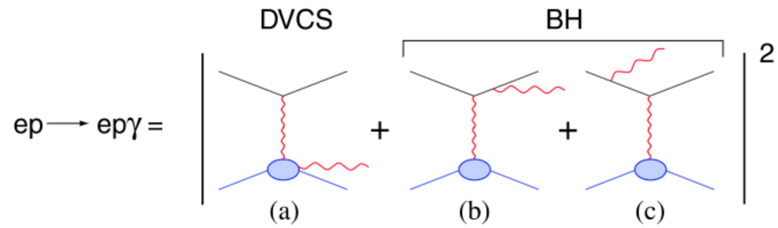
Hall A E00-110: cross section **azimuthal analysis**

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

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







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

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

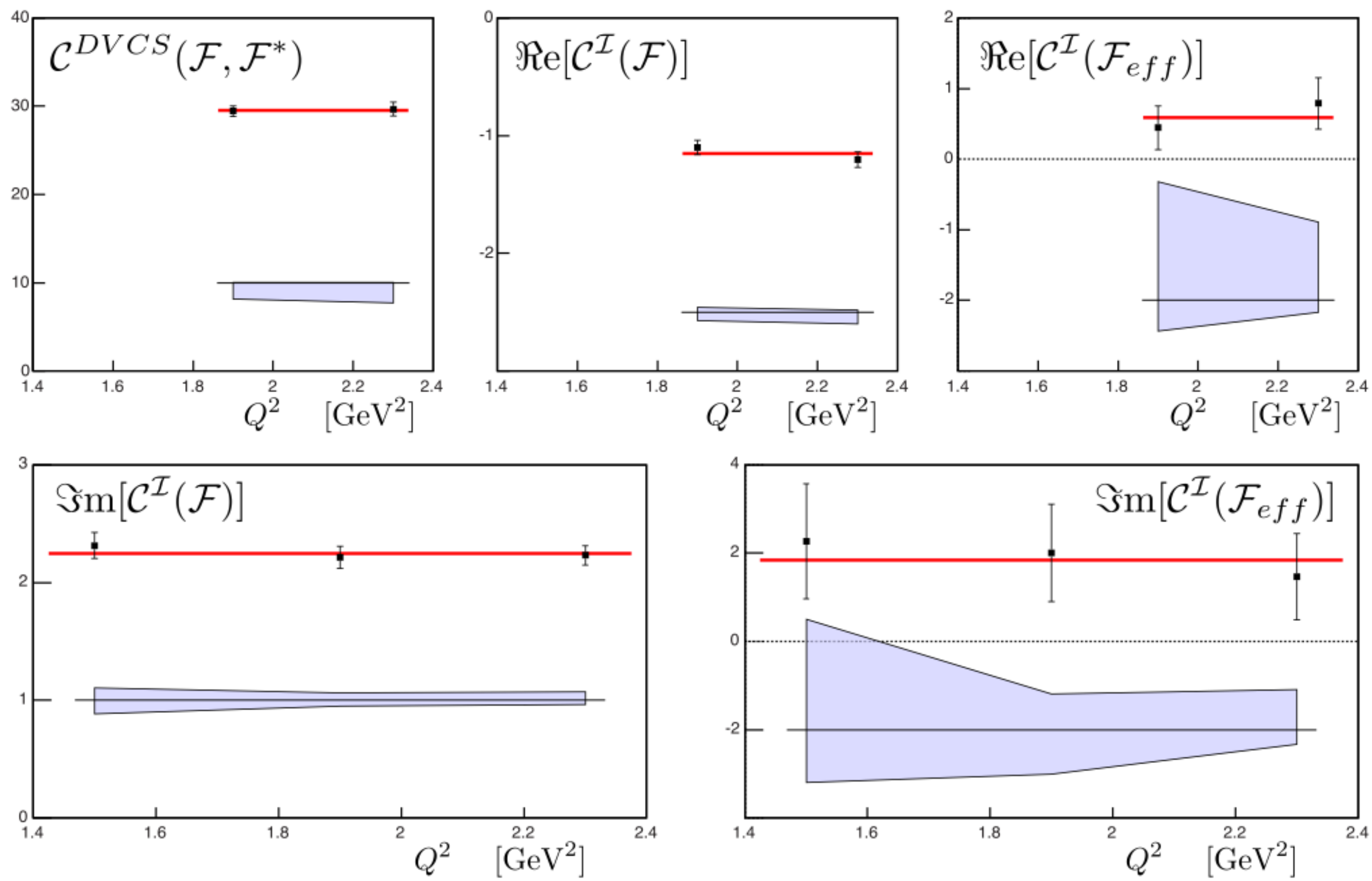
$$\mathcal{T}_{\mathrm{DVCS}}^2 \sim c_0^{\mathrm{DVCS}} + c_1^{\mathrm{DVCS}}\cos\phi$$

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

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

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

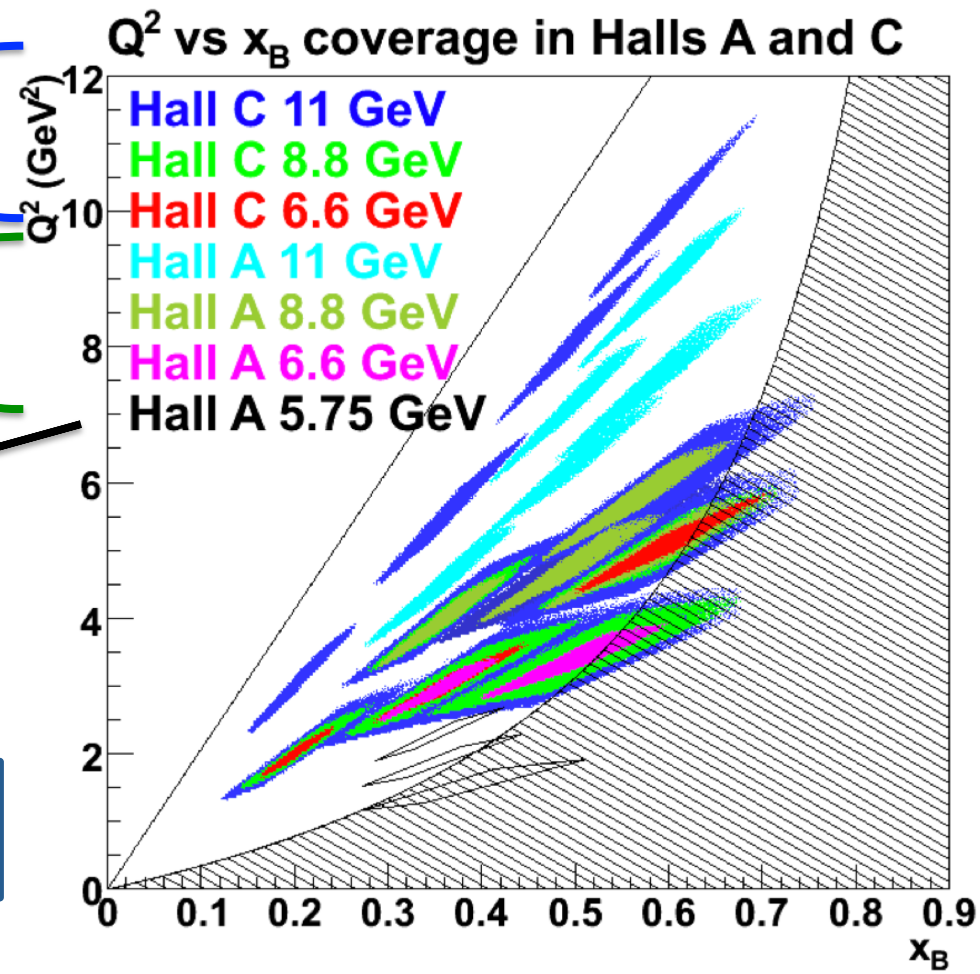
Future precision measurement of the DVCS at JLab

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)

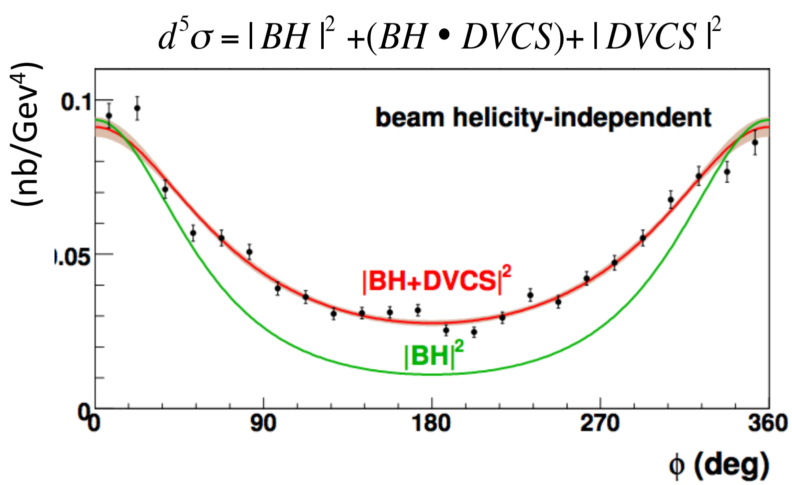
Goal:

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



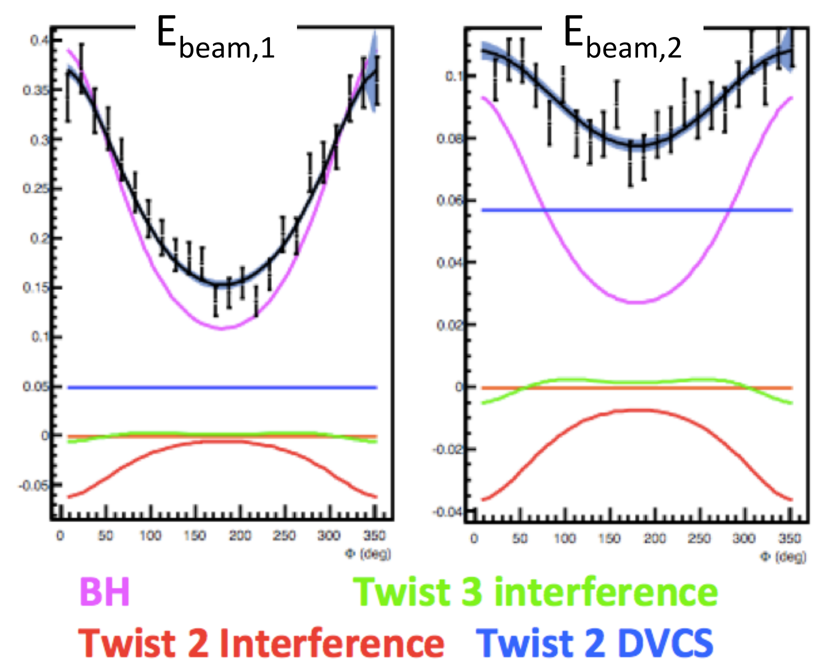
	Kin 1		Kin 2		Kin3	
Q^2 (GeV^2)	1.5		1.75		2.0	
X_b	0.36		0.36		0.36	
E_{beam} (GeV)	3.36	5.55	4.45	5.55	4.45	5.55

Rosenbluth type separation

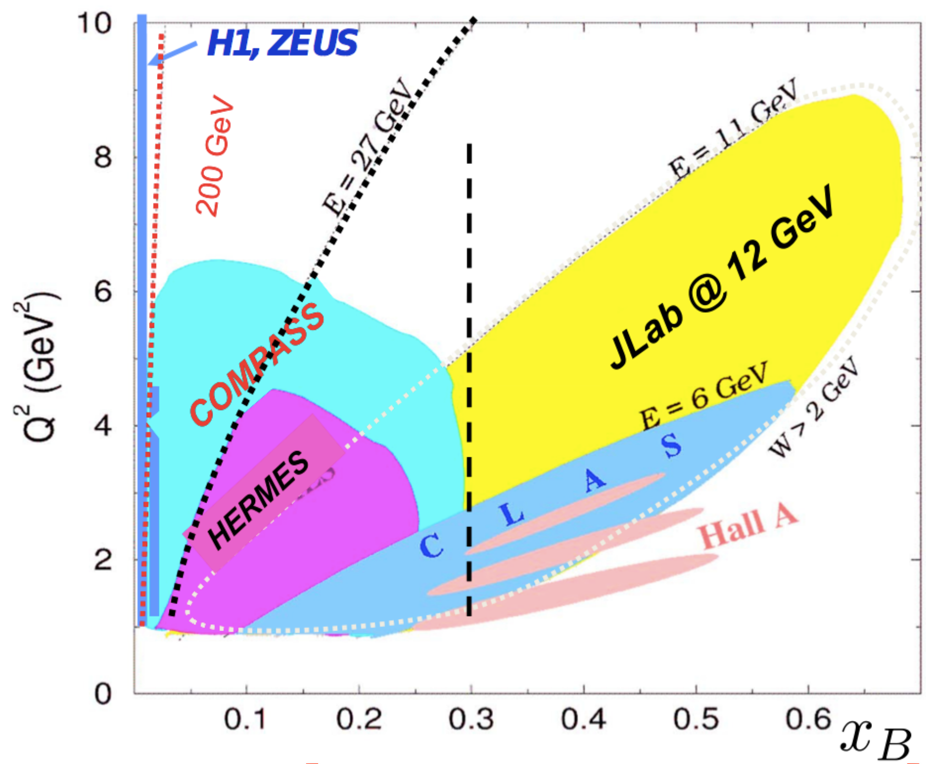
$$\sigma_1 = |BH|^2 + \Gamma_1 |DVCS|^2 + \Gamma_1' Re(I)$$

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

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



DVCS results (so far)



The valence + sea sector

Overall goal:

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- GPD E

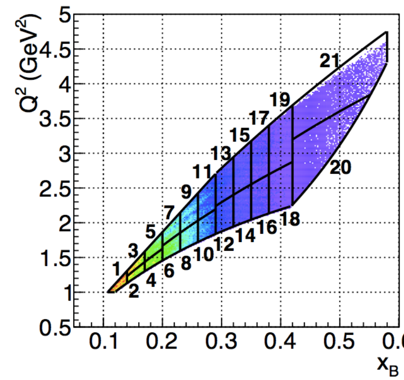
Hall B E01-113 cross sections

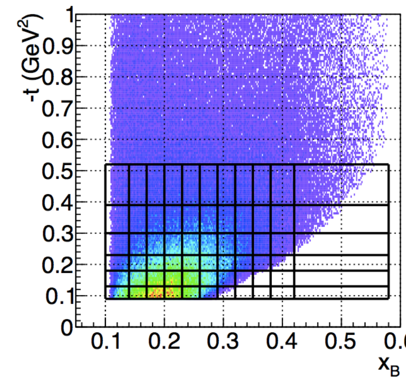
$$\mathrm{BSA} = \frac{\Delta^4\sigma}{d^4\sigma}\ (\mathrm{PRL\ 2006}) \quad \Rightarrow \quad \Delta^4\sigma \quad \mathrm{and} \quad d^4\sigma\ (\mathrm{arXiv{:}1504.02009,\ Apr\ '15})$$

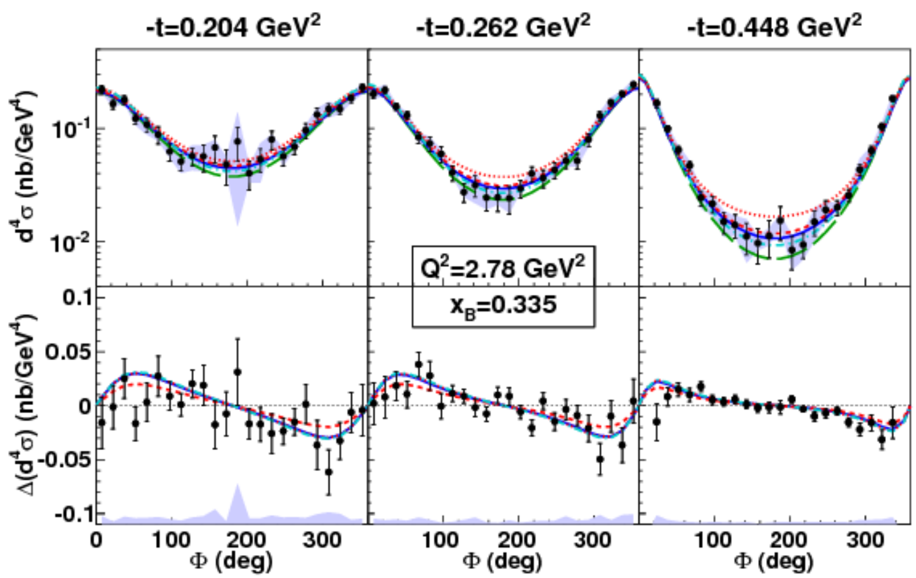
★ 110 bins in (x_B, Q^2 and t)

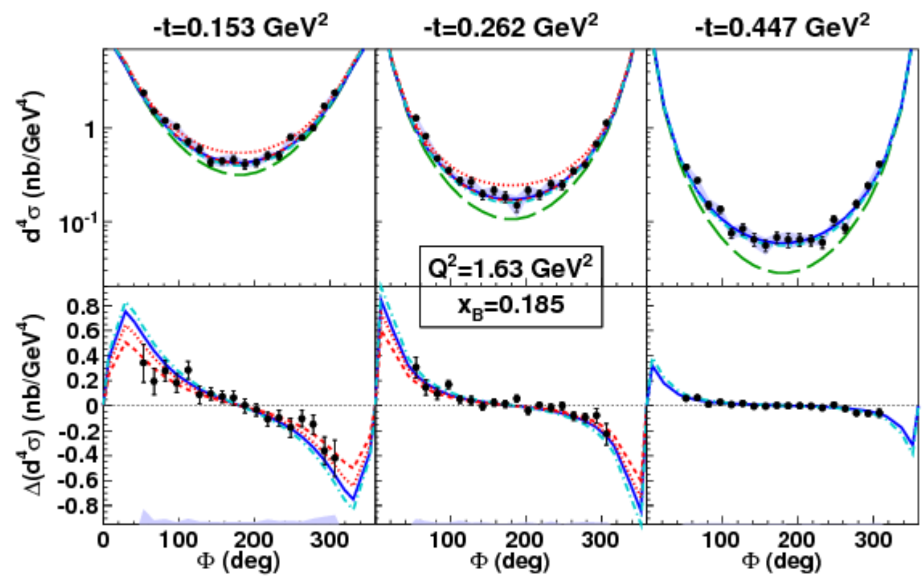
- Compatible with Hall A results in overlapping regions

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

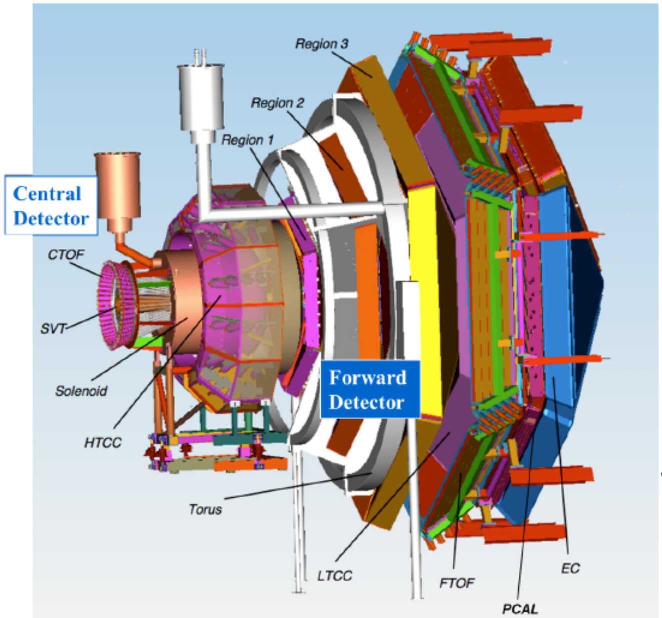






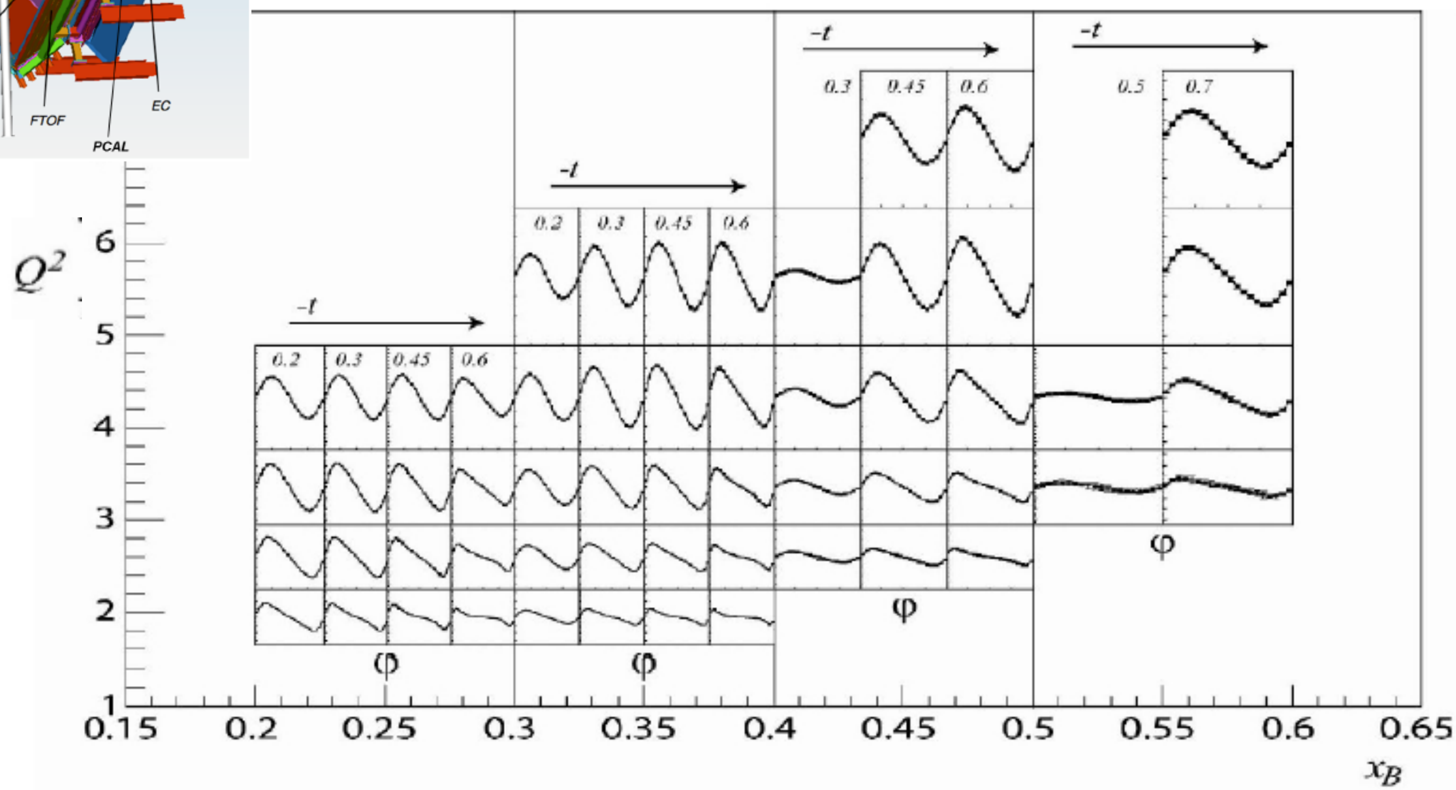


E12-06-119: Future DVCS experiment with CLAS12



Beam spin asymmetry
LH_2 Target and Long. Pol. Target

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



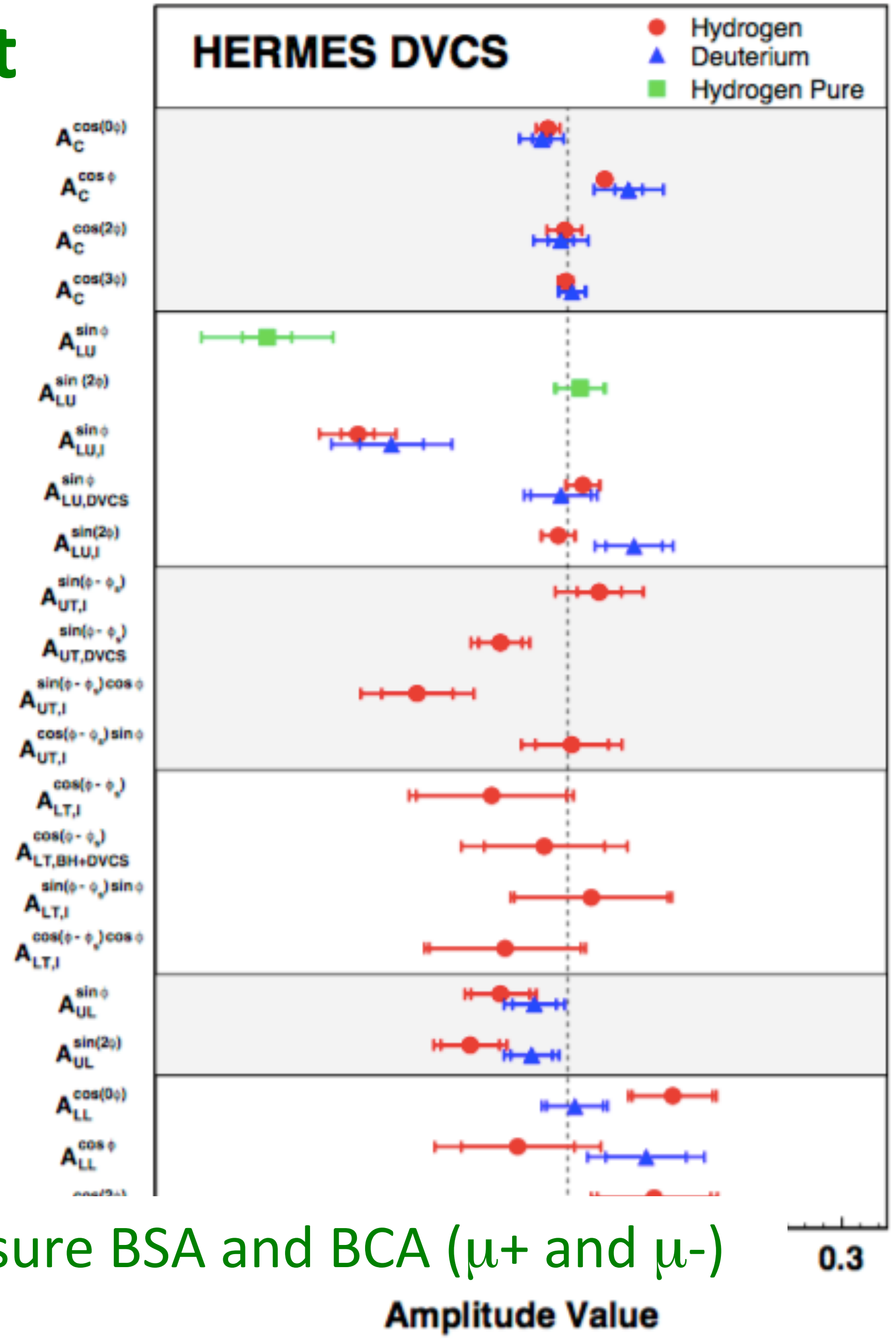
The very complete data set from Hermes

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

Example of Longitudinally polarized beam off a

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

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

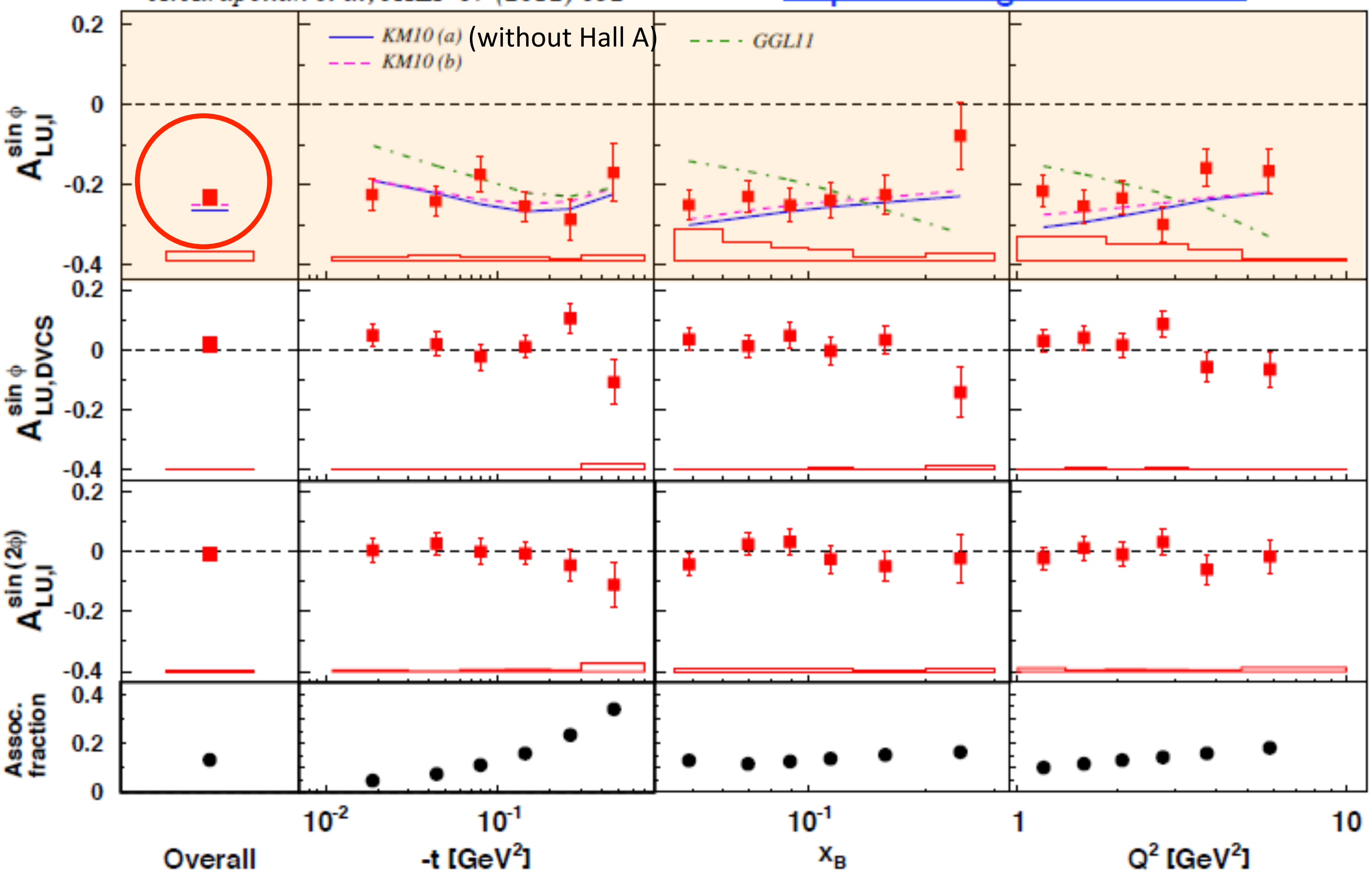


Compass will also be able to measure BSA and BCA (μ+ and μ-)

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

Complete data set including 2006-07

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



sin ϕ term

Im **F1** $\mathcal{H}$

sinϕ term from DVCS^2

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)*

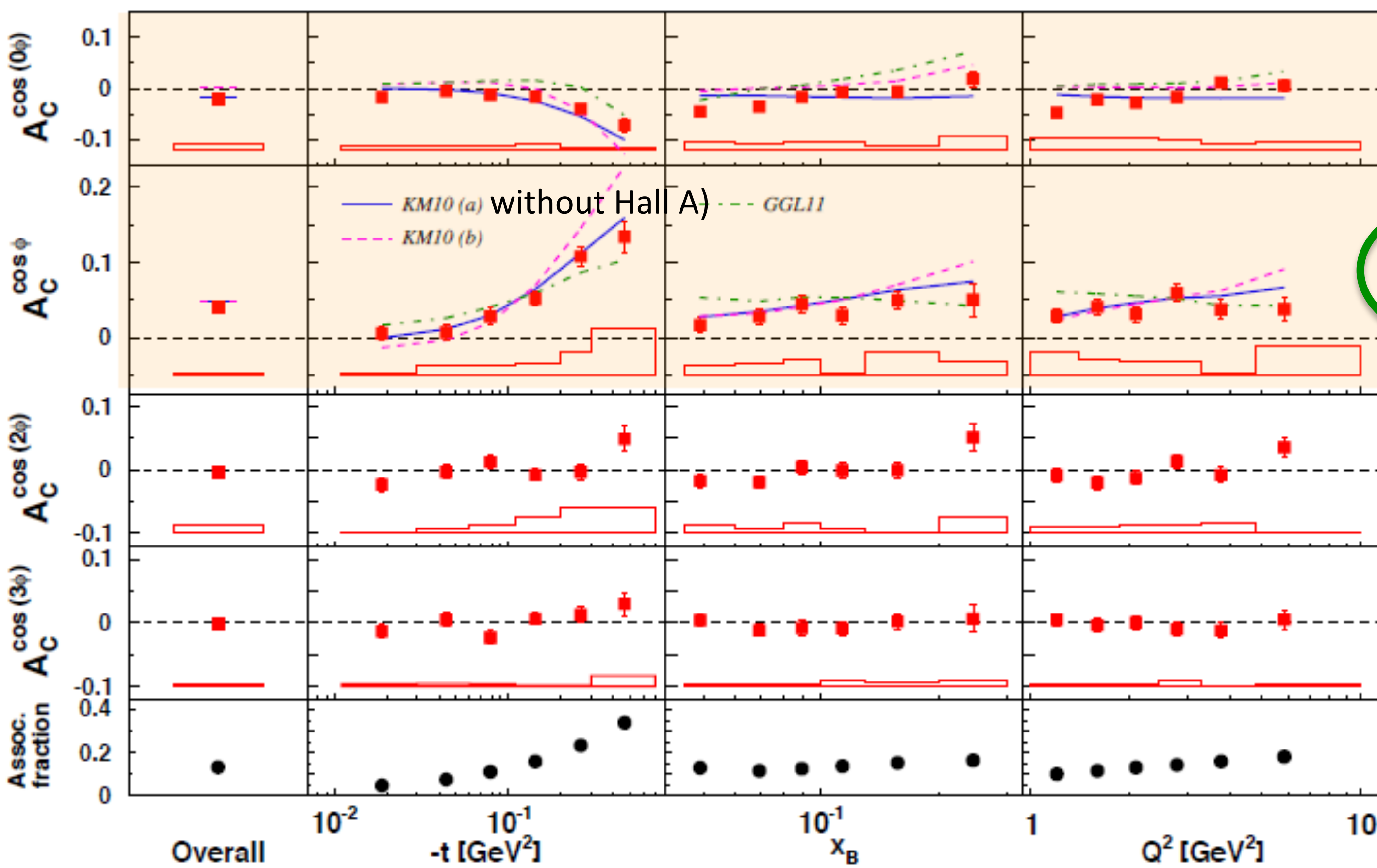
Slide from N d'Hose, Tranversity 2014

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 → e$\gamma\Delta^+$

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)*

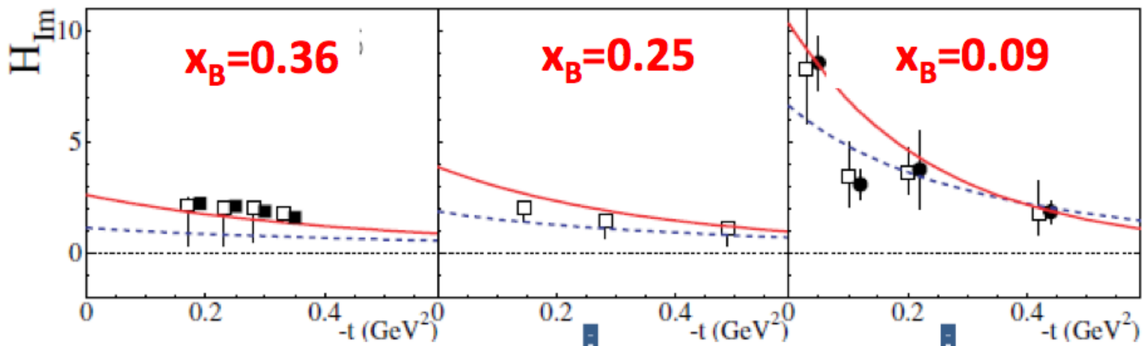
Slide from N d'Hose, Tranversity 2014

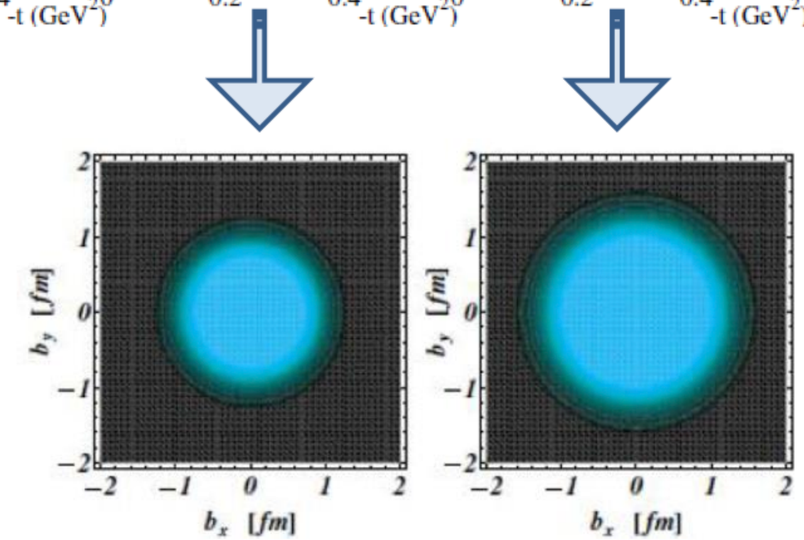
Towards the 3D Structure of the Proton (past 10 years)

the CFF H in *Im* DVCS

e⁻ 6 GeV		$e^{\pm}$ 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 solid 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.

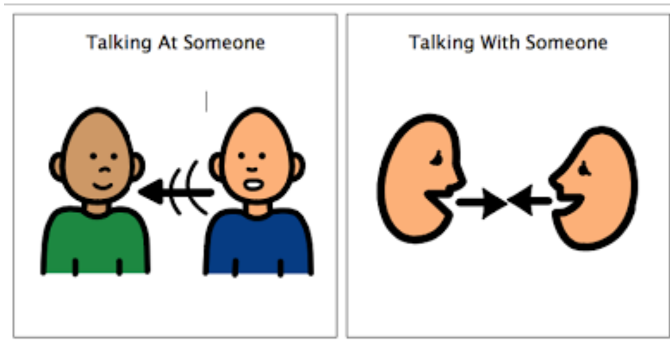
1 question: 30 m reading + 15 min discussions

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

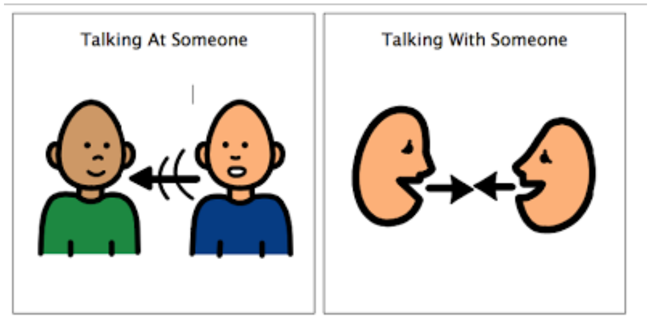
Model of GPDs

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?

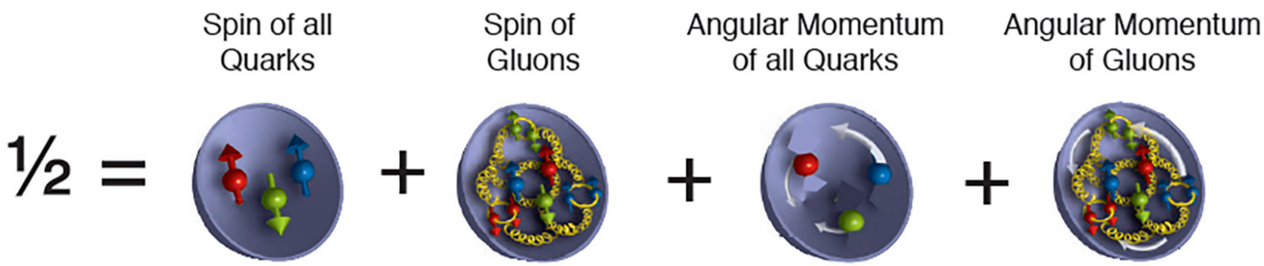


Hunting the GPD E

- → 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

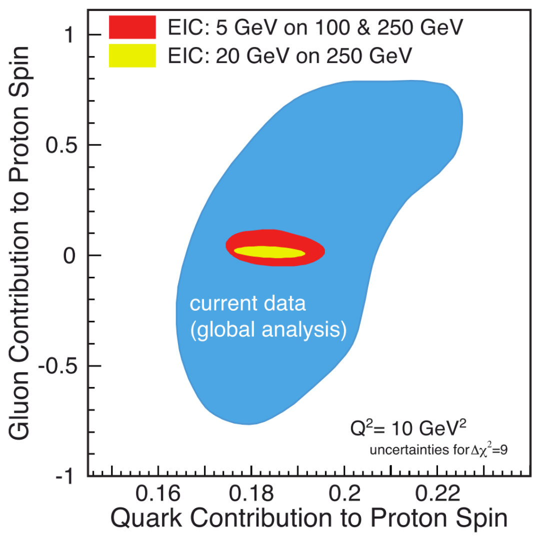
The "Holy grail" of GPDs (and TMDs) physics



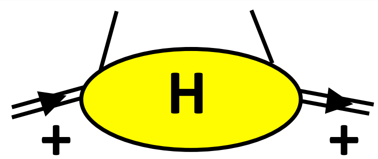
Contribution of the **angular momentum of quarks** to proton spin:

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

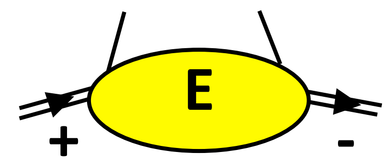
Ji's sum rule



RHIC spin physics results (LRP 2015)



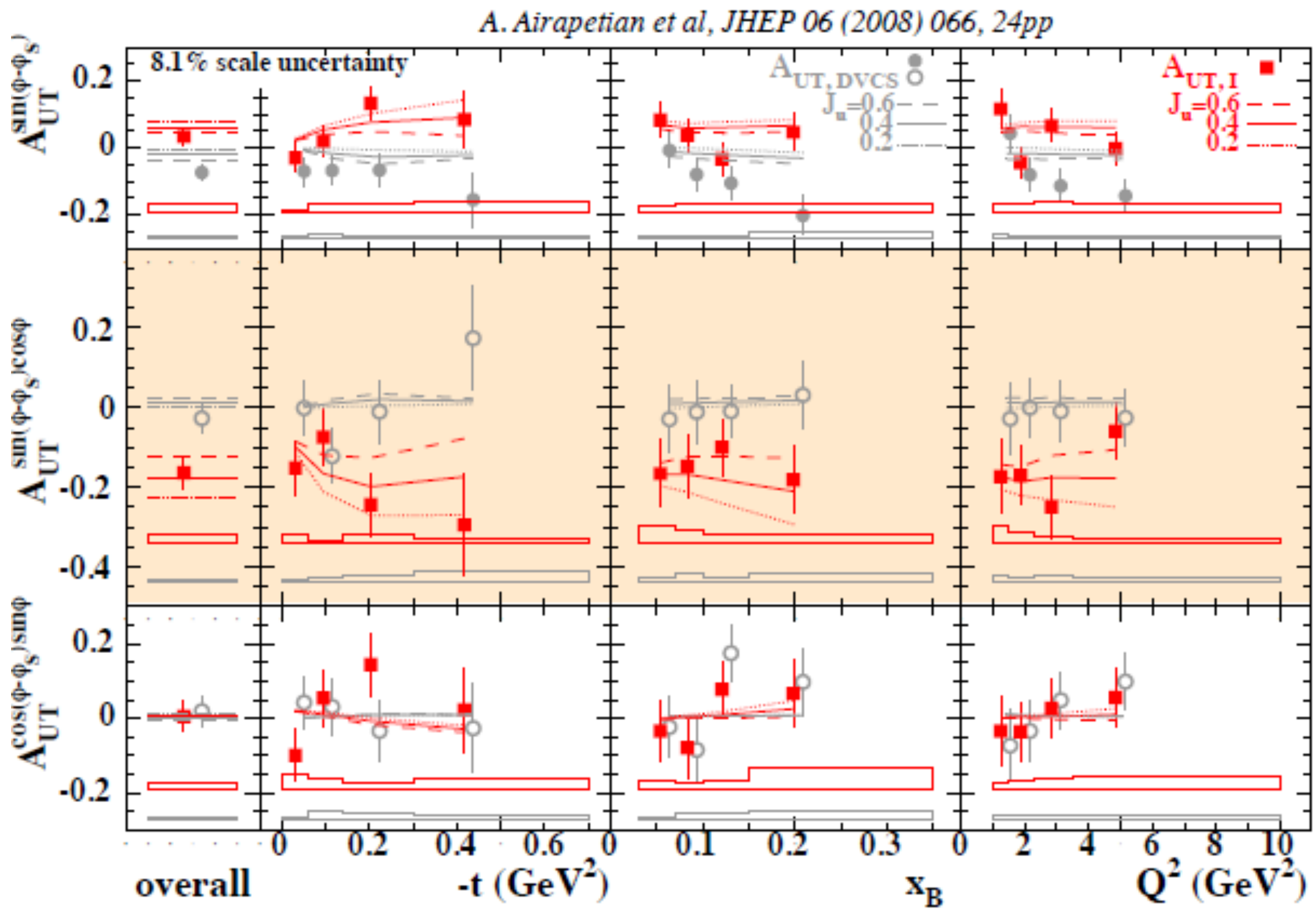
GPD H connects to the PDFs (symmetric initial-final states)
Known from polarized DIS data



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



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)

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

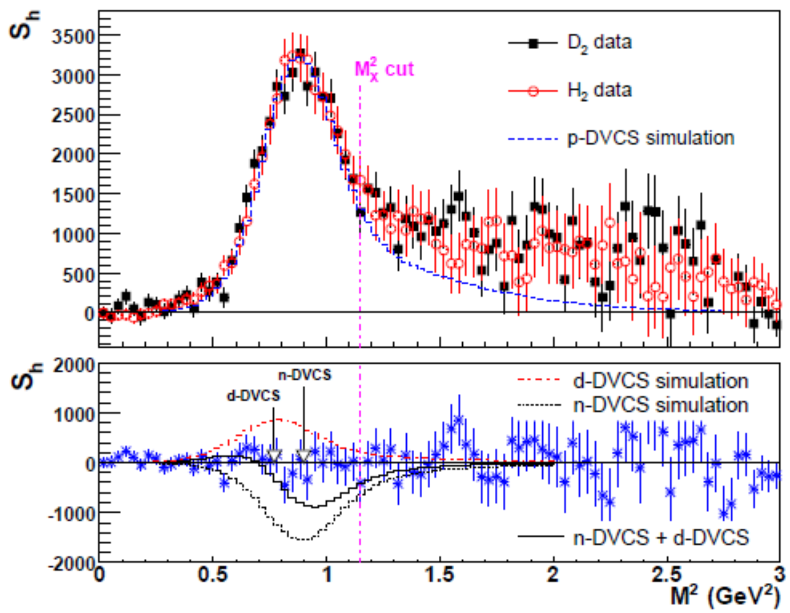
$$A_{UT,DVCS}^{\sin(\phi-\phi_S)} \neq 0 \implies \mathcal{E} \neq 0$$

Slide from N d'Hose, Tranversity 2014

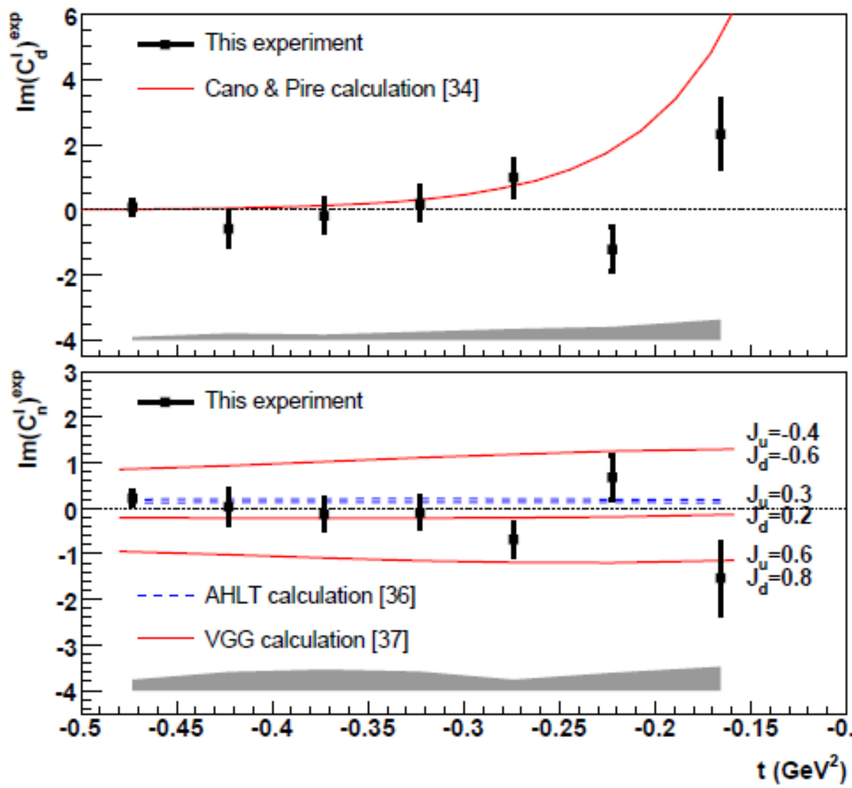
DVCS on the neutron in Hall A/JLab

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

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



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



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

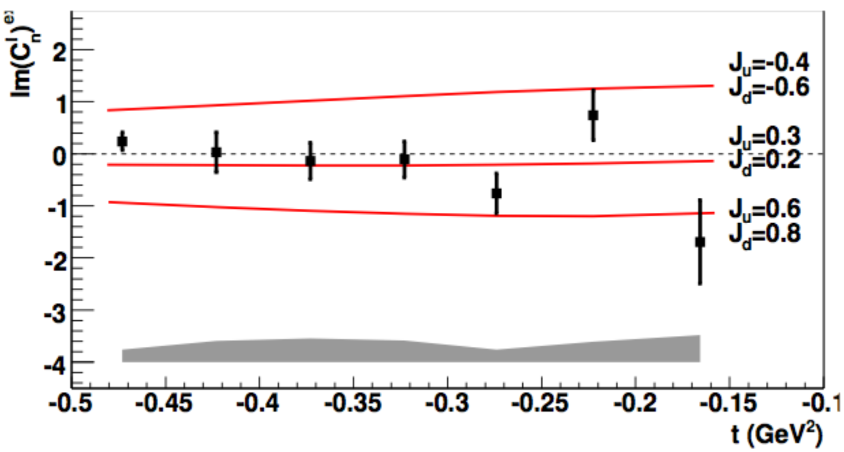
Next:

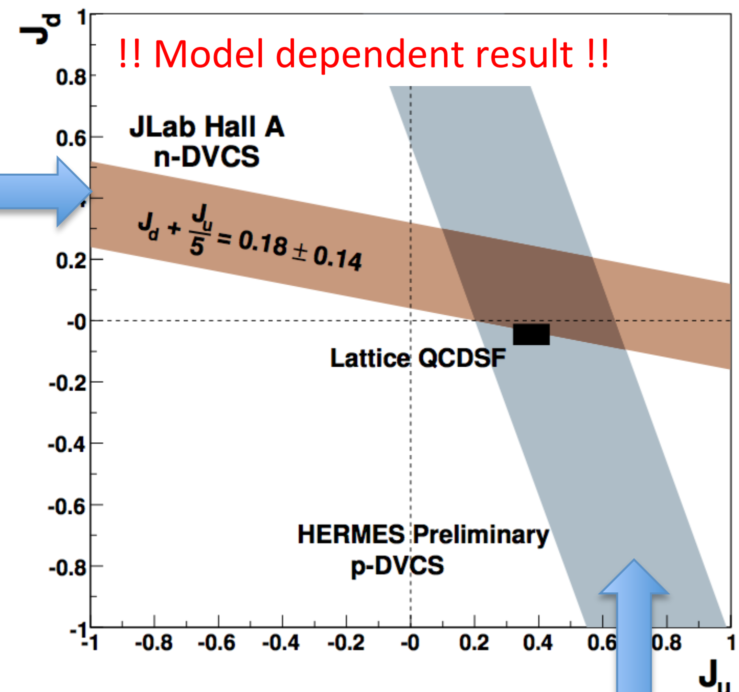
- 2010: run E08-025 with LD2 target (two beam energies at a given Q^2)
- 2016: CLAS12 with 11 GeV with LD2 target + neutron detector (ToF)

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]

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





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

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

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

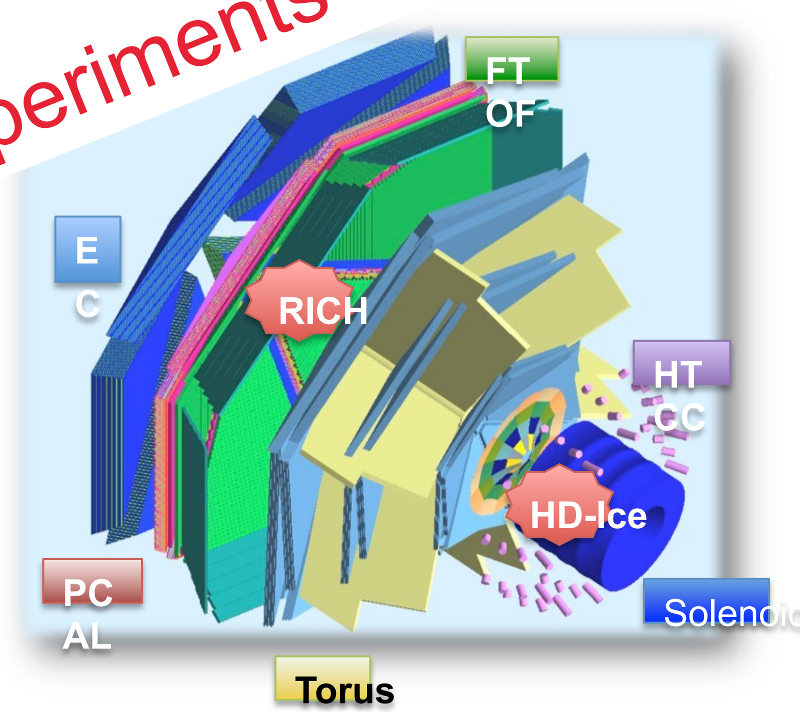
With LD2 target + CLAS12
+ Forward Calorimeter
+ Neutron Detector ToF

$\vec{e}\, p^{\uparrow} \to e\, p\, \gamma$ 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

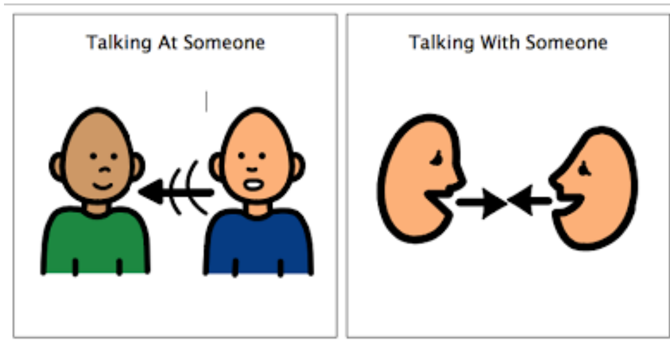
1 question: 30 m reading + 15 min discussions

ACTIVE LEARNING

What I hear, I forget

What I see, I remember

What I do, I understand

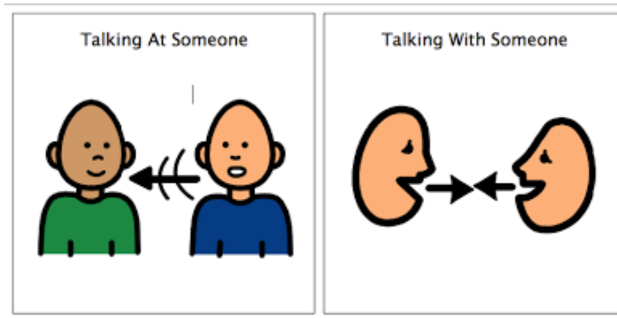


Group 1 Meriem*, Shokhna, Kieran, Carlos Y.	**Group 5** Nabil*, Brandon C., Fillipo, Manuel
Group 2 Frederic*, Shujie, Shivangi, Ryan	**Group 6** Brandon K.*, Alexa, Bailing, Gavin
Group 3 Waverly*, Sandra, Bijit, Arkadiusz	**Group 7** Holly, Larissa, David AQ, Giovanni
Group 4 Hamza, Scott, Marco, Dexu	**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?)



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.

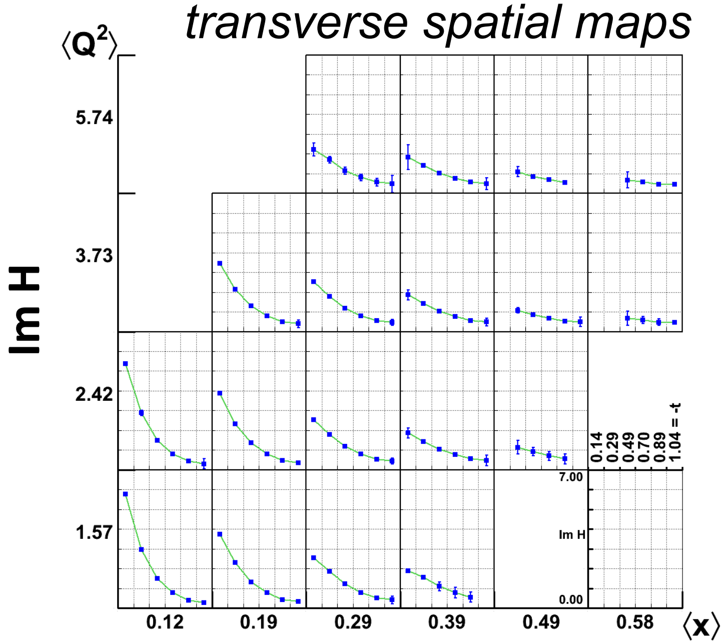
The polarized HDICE target is challenging.

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

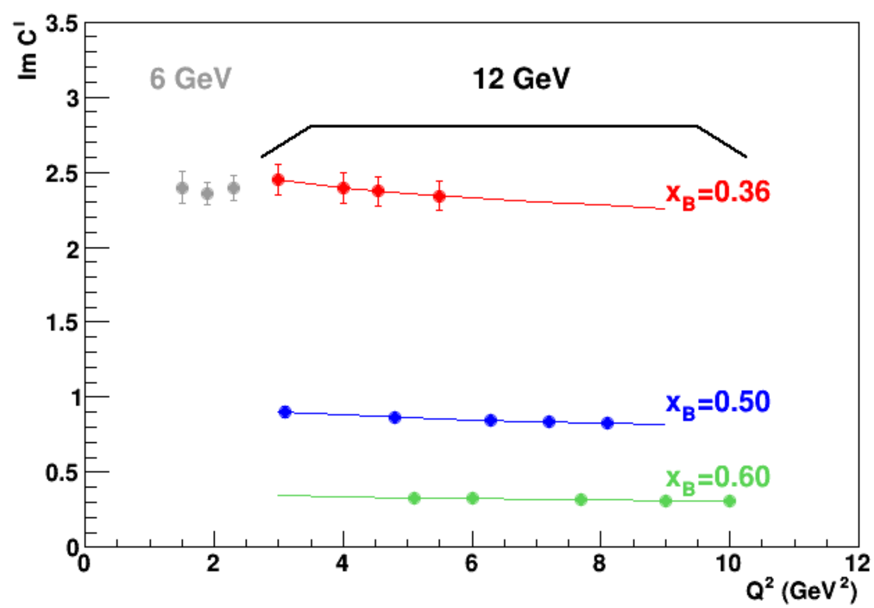
6 GeV data:
Hall B beam-spin asymmetries and cross sections data show potential for imaging studies from analysis in x, Q^2 and t.

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