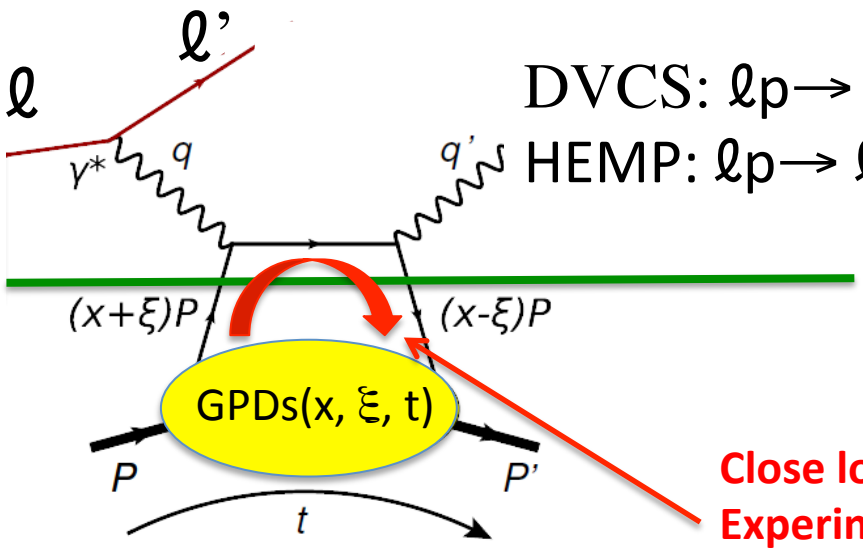
Spatial imaging of the nucleon

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.

What we talked about during our last meeting



DVCS: $\ell p \rightarrow \ell' p' \gamma$ (golden channel)

HEMP: $\ell p \rightarrow \ell' p' \rho$ or ϕ or J/ψ,…

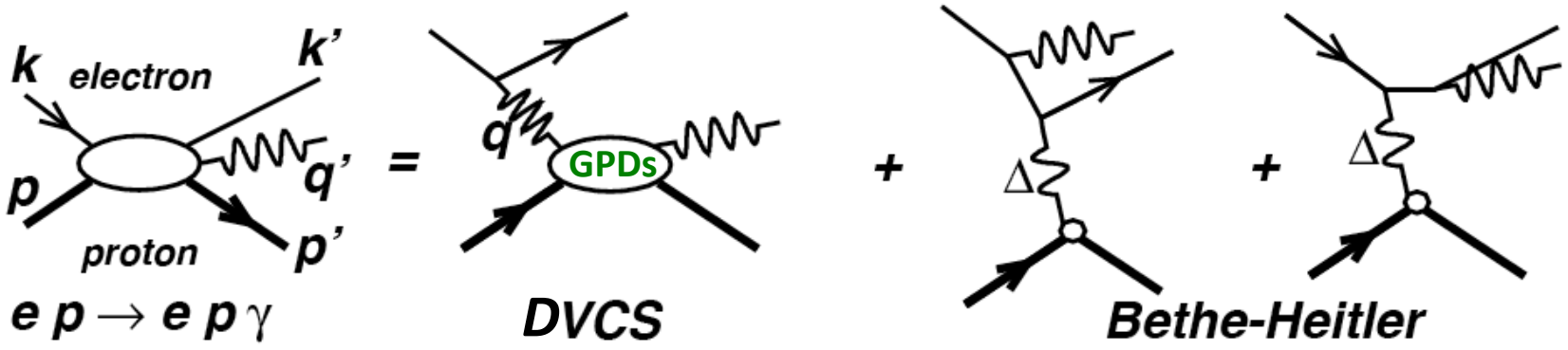
Factorization allow the introduction of the GPDs (need NLO and twist corrections)

Close loop makes the x variation of the GPDs inaccessible

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

$\Rightarrow$ 8 variable functions of ξ ($\sim x_B$) and t.

What we talked about during our last meeting



At leading twist:

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

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

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

The DVCS program worldwide

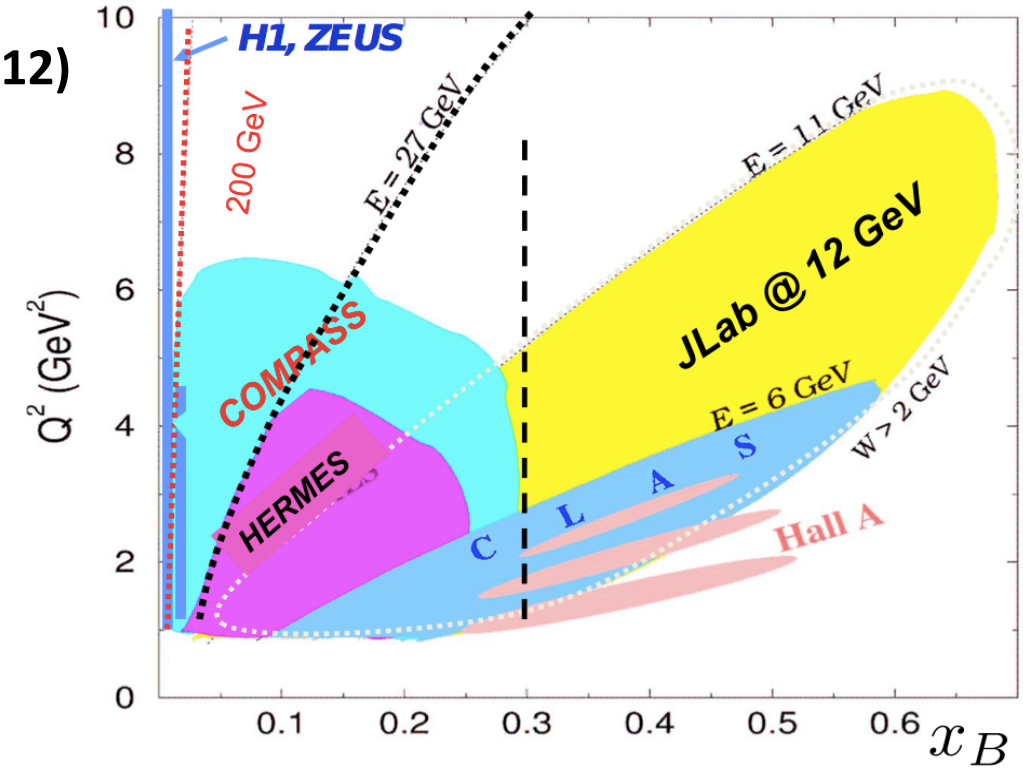
Experimental timeline

- 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

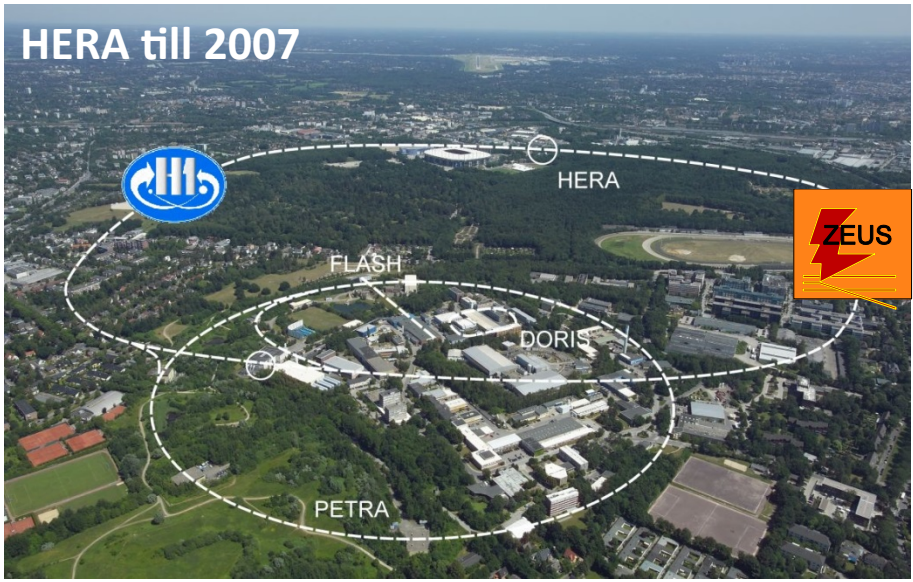
- Hall A/C
  - high accuracy (~5%)
  - limited kinematic
- Hall B:
  - wide kinematic range
  - limited accuracy (15+%)



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

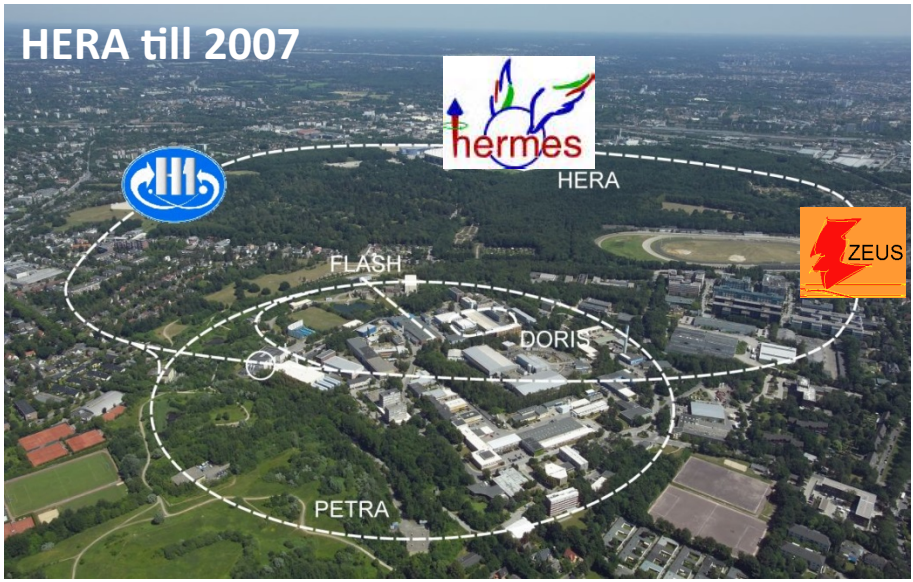
The past and future experiments

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



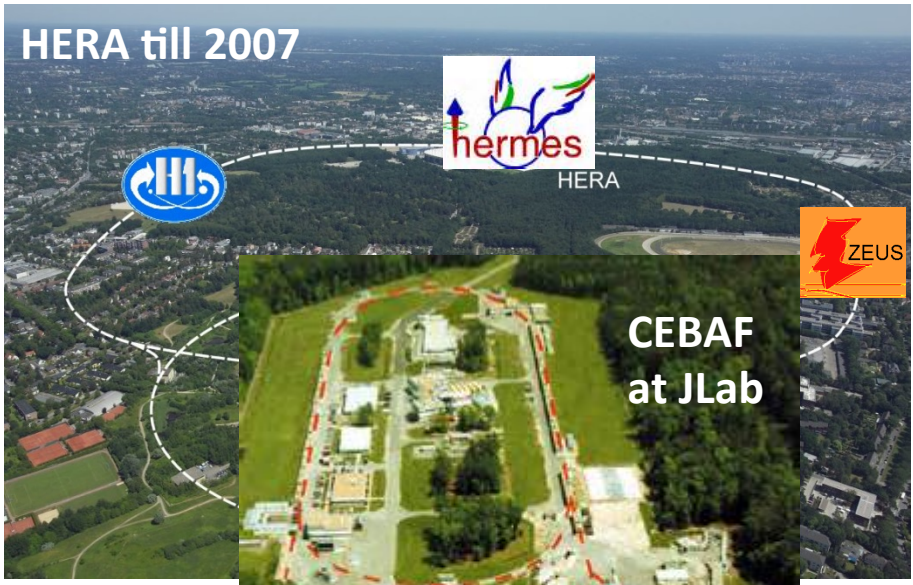
Slide from N d'Hose, Tranversity 2014

The past and future experiments

Collider mode e-p forward fast proton

ZEUS H1

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



Fixed target mode slow recoil proton

hermes

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

HallA CLAS

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

ZEUS H1

Polarised 27 GeV e-/e+
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~ Full event reconstruction

Fixed target mode slow recoil proton

hermes

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

HallA CLAS

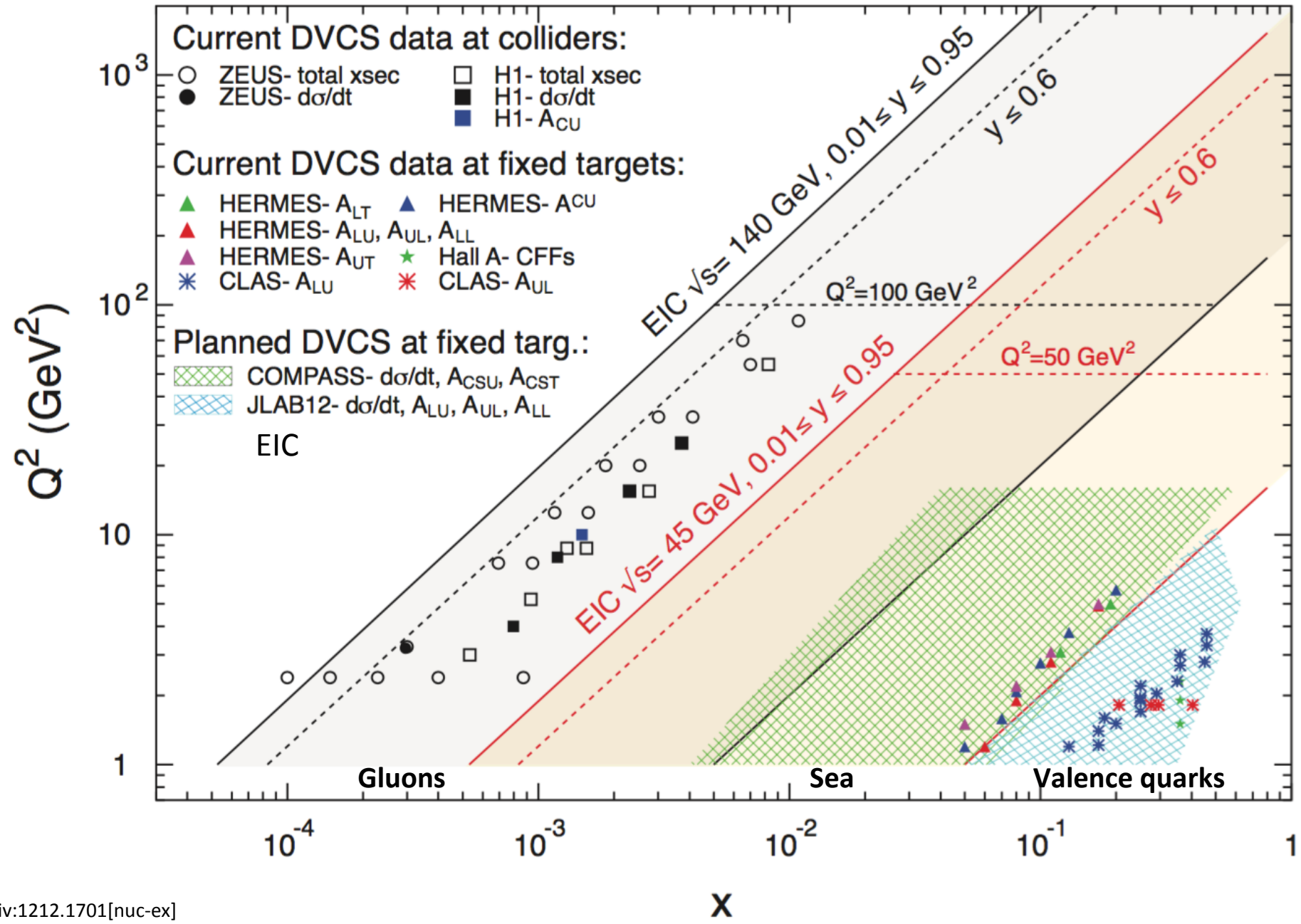
High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

COMPASS

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

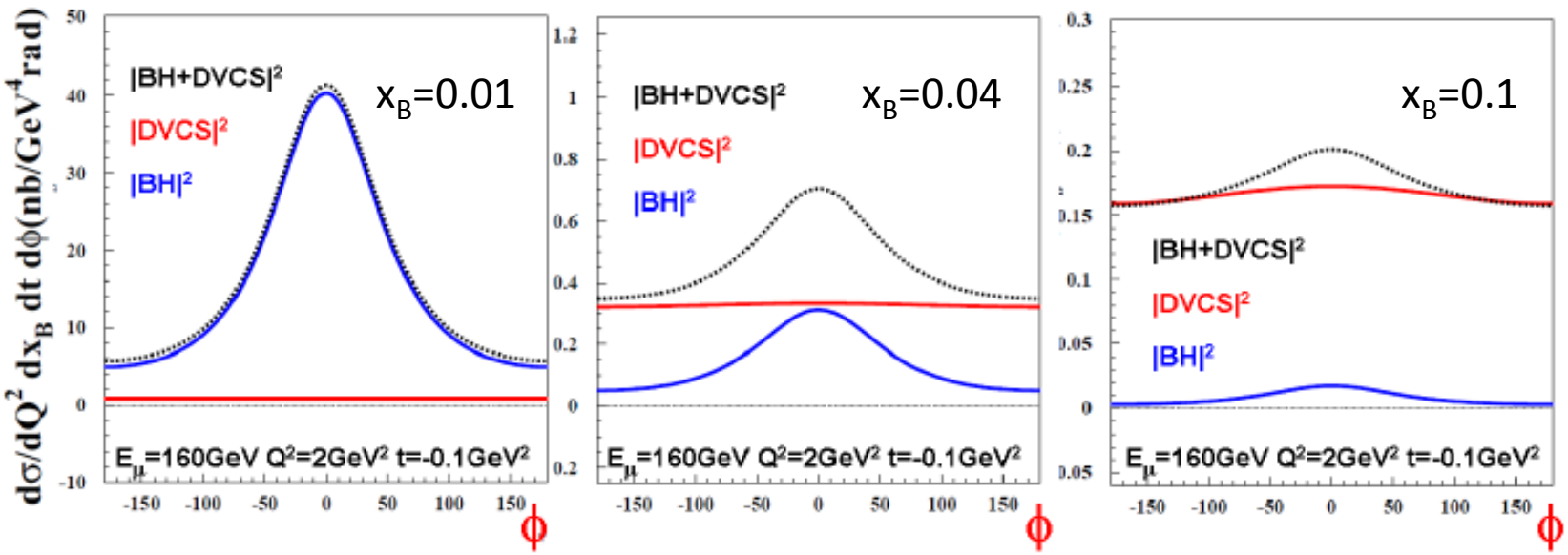
ensure exclusivity

but does not exist (yet)

Slide from N d'Hose, Tranversity 2014

High beam energy

Example at E_ℓ =160 GeV $x_B \nearrow$ **BH** $\searrow$



BH dominates
Reference yield

Access to DVCS ampl.
Via interference

DVCS dominates
Study of dσ/dt

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

Jlab
HERMES, H1
COMPASS

Only for high energy
H1 & ZEUS
COMPASS

Slide from N d'Hose, Tranversity 2014

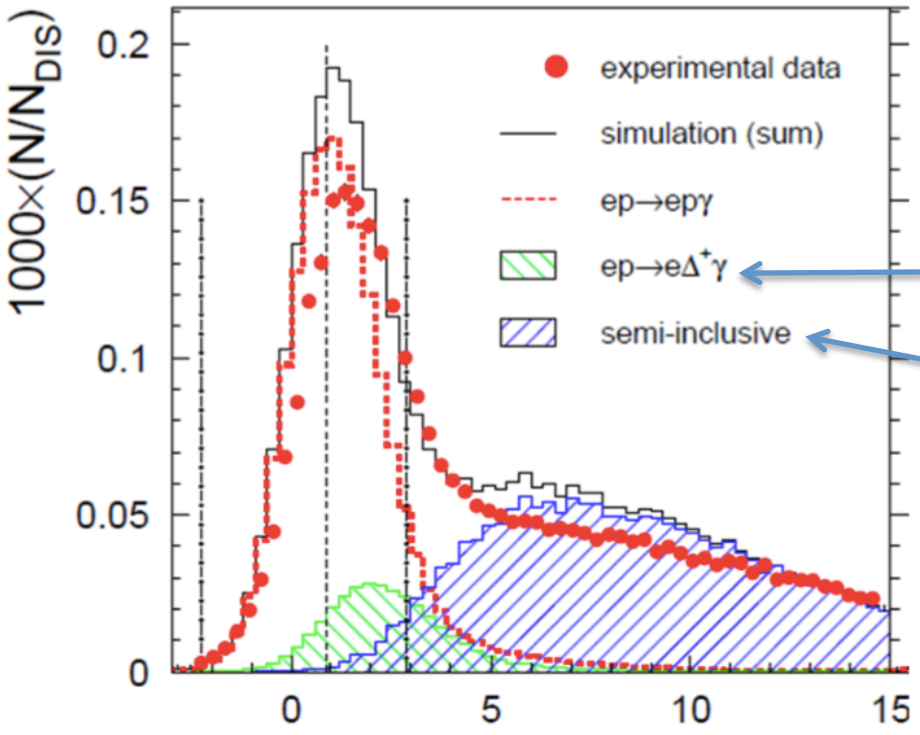
Exclusivity

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

without recoil detector

X can be

- p : ep -> epγ
- γp : ep -> epπ^0, π^0->γγ
- Nπ: ep -> eNγπ
- ...



12% of the signal without recoil detector

ep→ e'+γ (+ γ + p'+...)

JHEP 1210, 042 (2012)

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

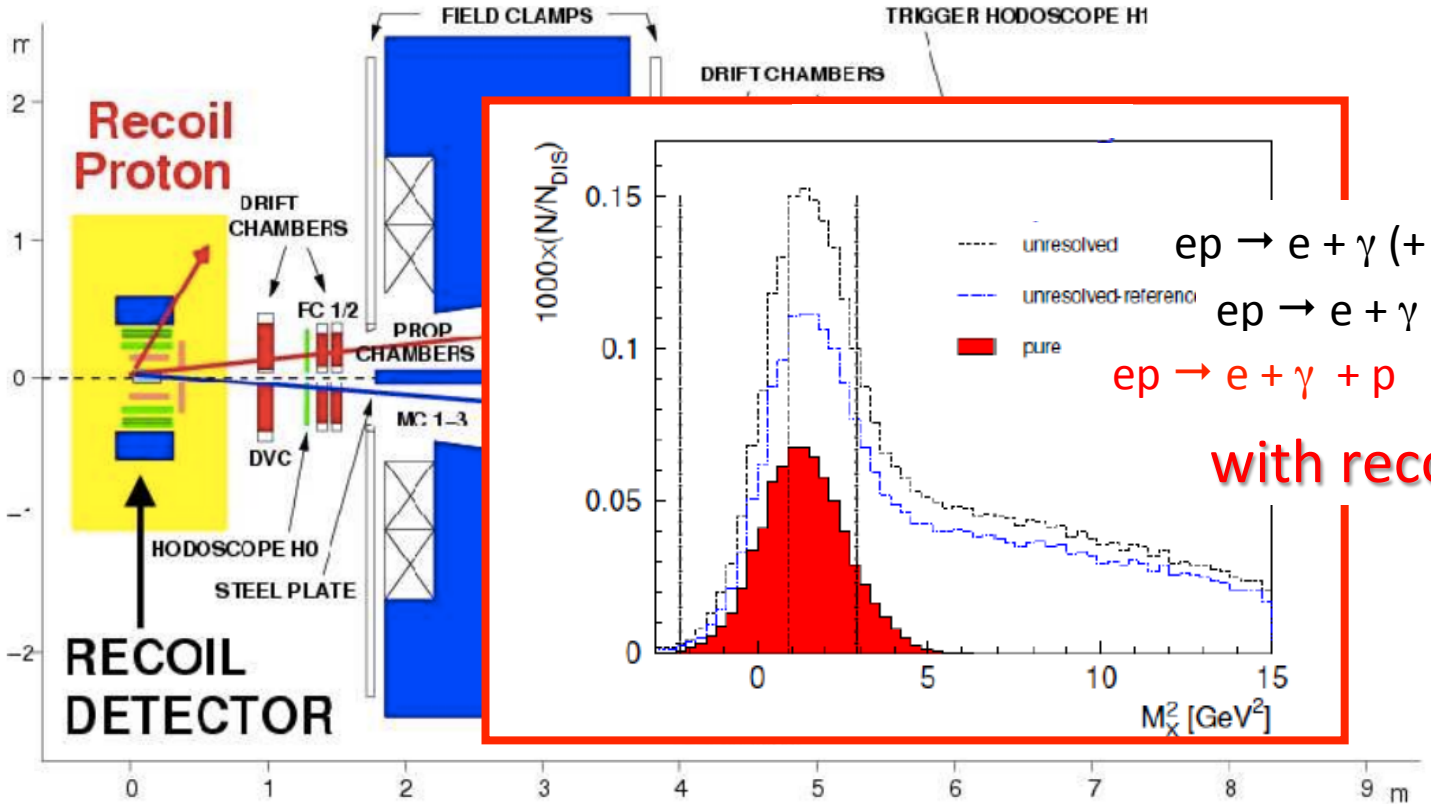
$$M_X^2 = \bar{p}'^2 = (\bar{k} + \bar{p} - \bar{k}' - \bar{q})^2$$

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

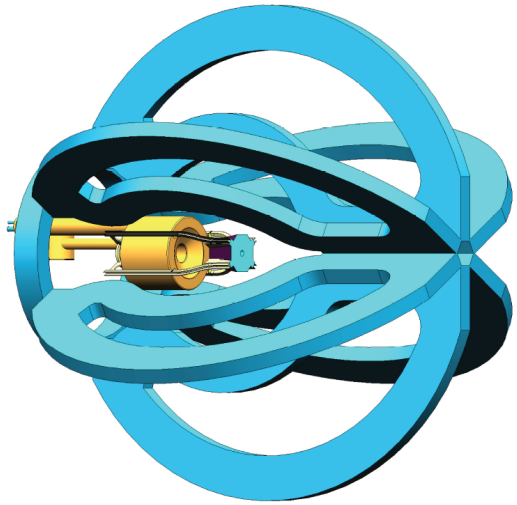
with recoil detector

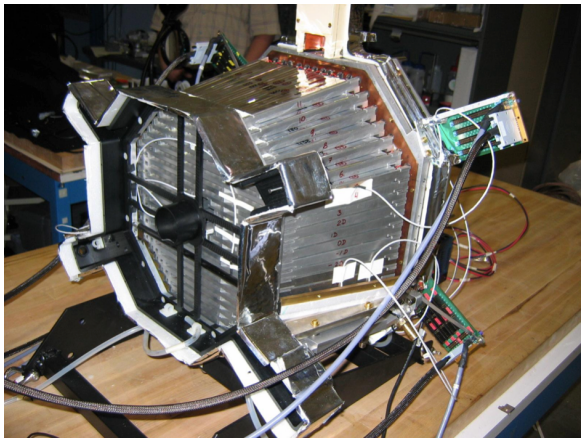
Hall B/JLab

Dedicated apparatus (added within Clas):

$PbWO_4$ calorimeter + 5 T super conducting solenoid

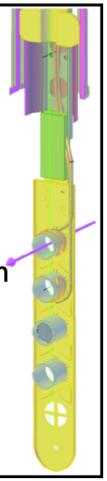
e(p,e'p'γ): ~5% contamination



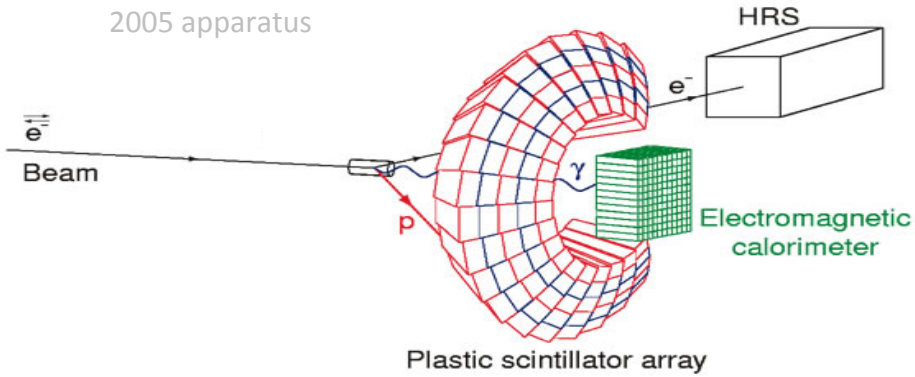


Longitudinally Polarized Target

- 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.



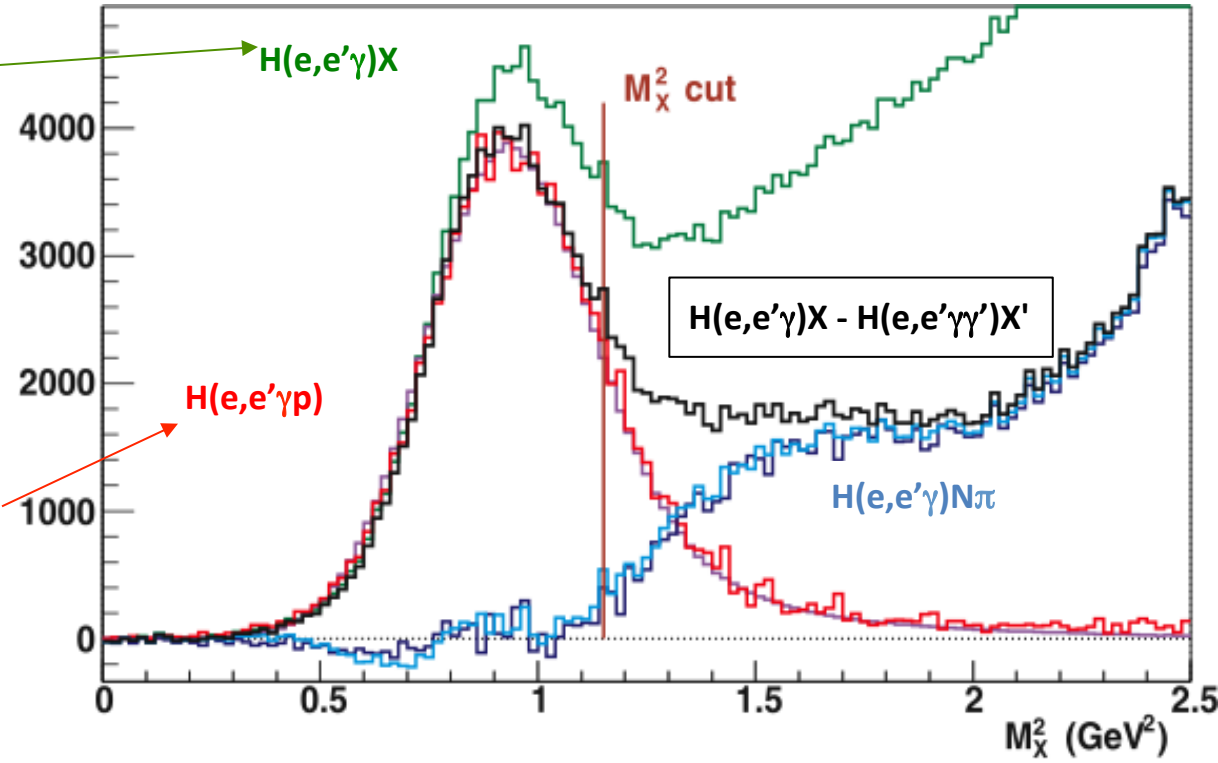
Exclusivity in Hall A/JLab

(2005 data)

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

…

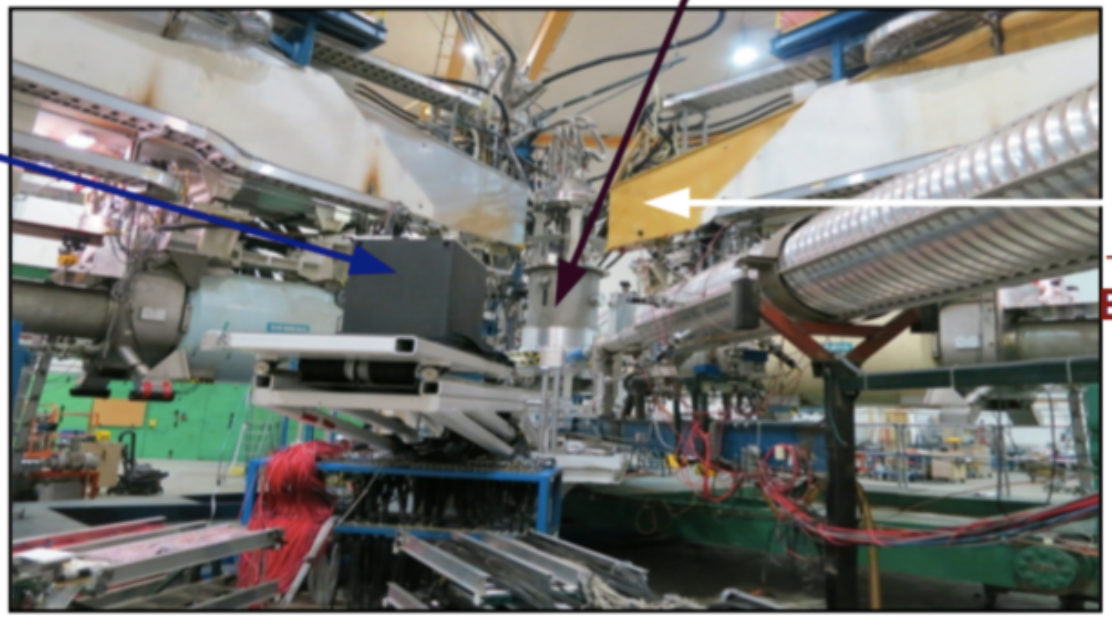
HRS+calorimeter + proton array



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

Hall A/JLab

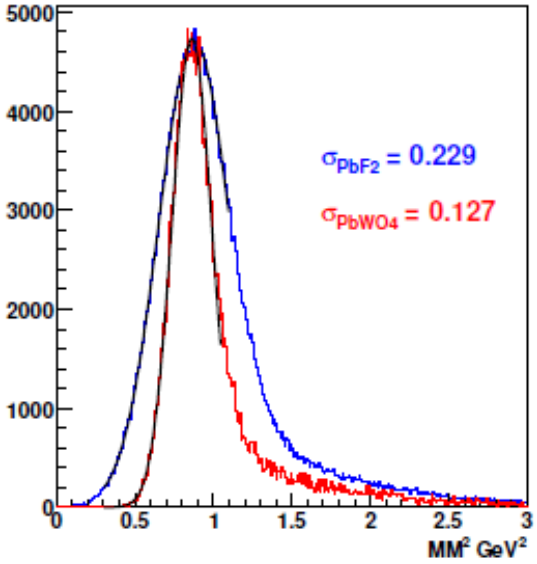
p(e,e'γ)p'



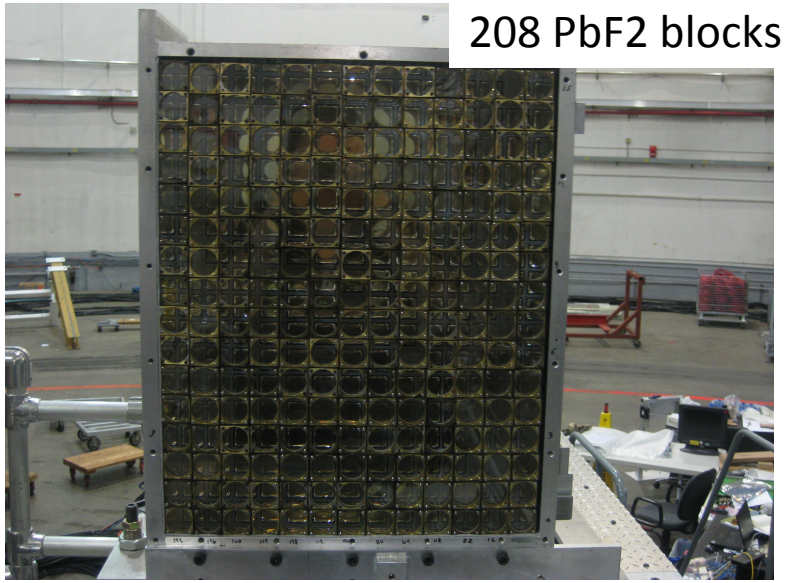
CALORIMETER
→ 208 PbF_2 blocks
→ Δq/q ~ 3%

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

Simulated M_X^2 resolution

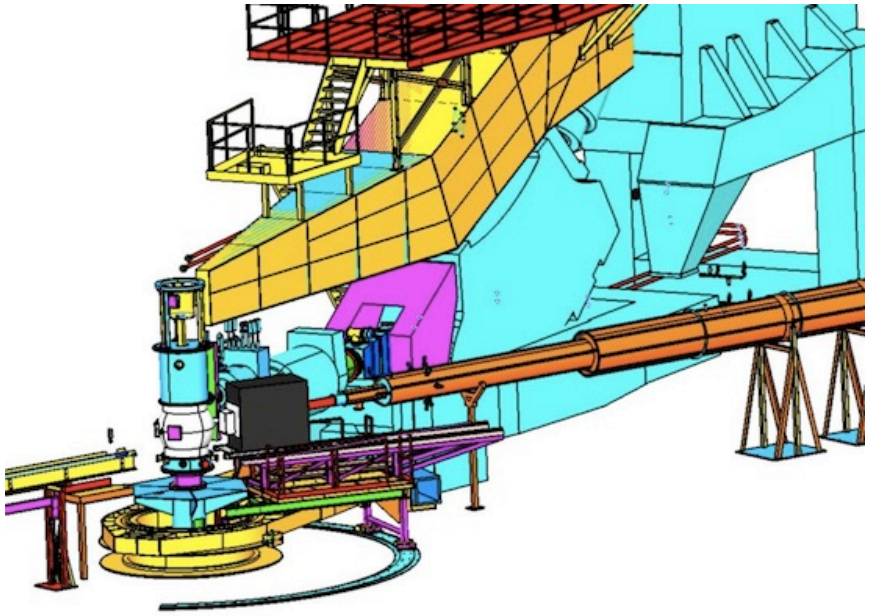


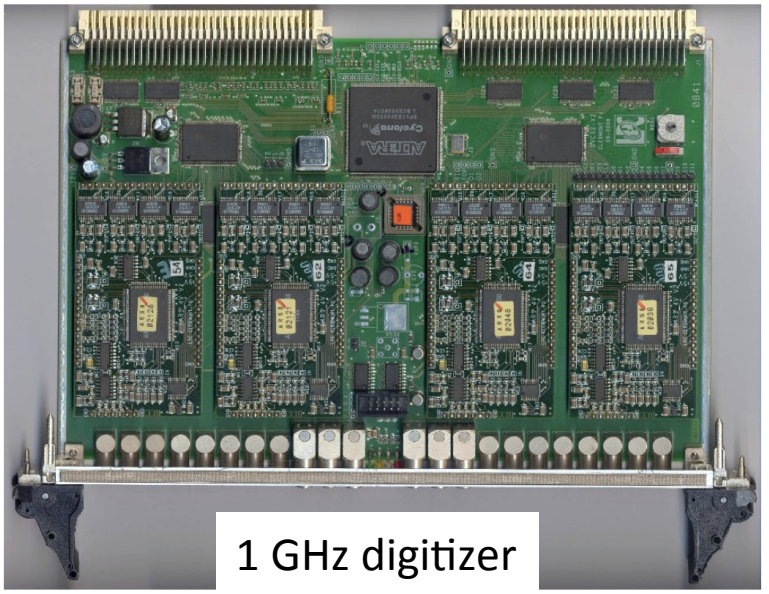
PbF2
3X3X18 cm block
~1000 pe
for 1 GeV outgoing photon



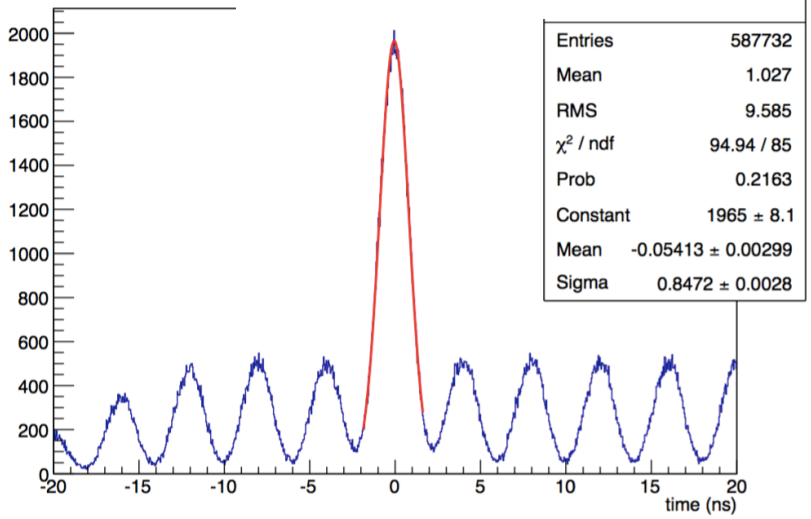
208 PbF2 blocks

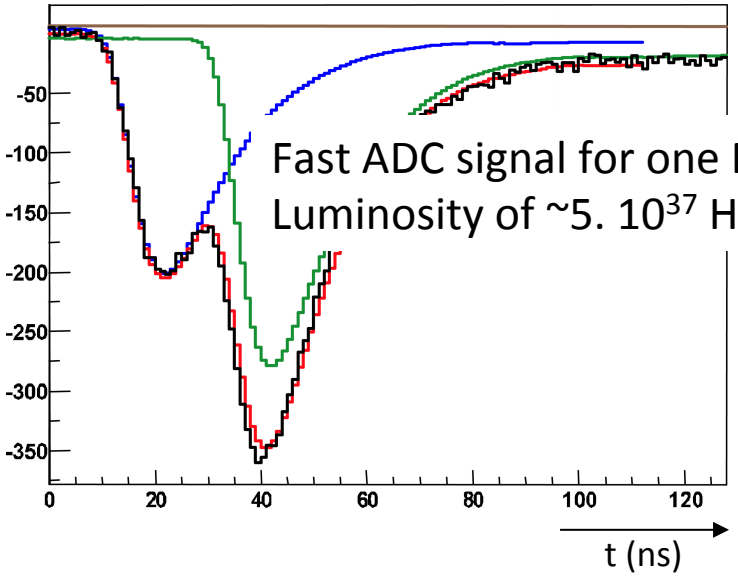
DVCS is a rare process: Pile-up and coincidence time





Coincidence time calo-HRS





Fast ADC signal for one PbF2 block
Luminosity of ~5. 10^{37} Hz/cm^2

Absolute cross-sections versus relative asymmetries

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

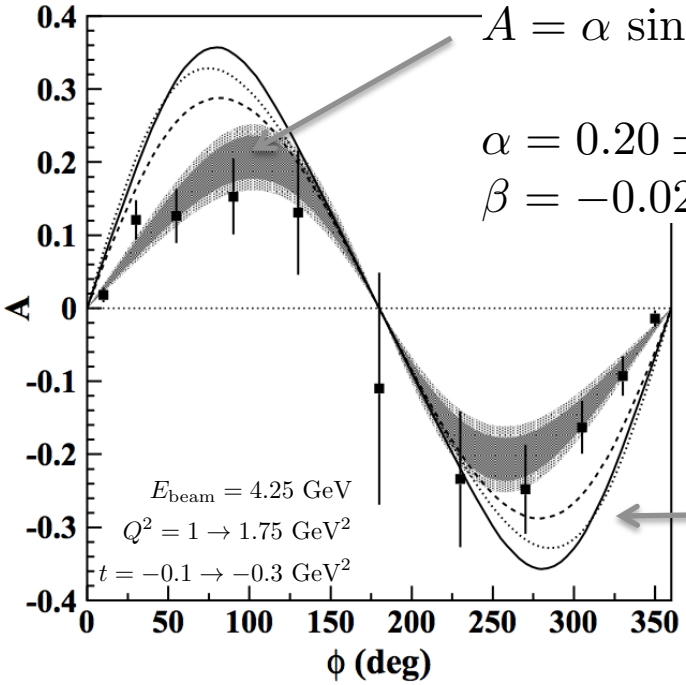
N : number of event detected
$\mathcal{L}$: luminosity
$d\Omega$: solid angle
ϵ : detector efficiency
P : polarization rate

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

Experimentally “easy” to measure

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

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



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

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

$\beta = -0.02 \pm 0.02$ ← 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

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

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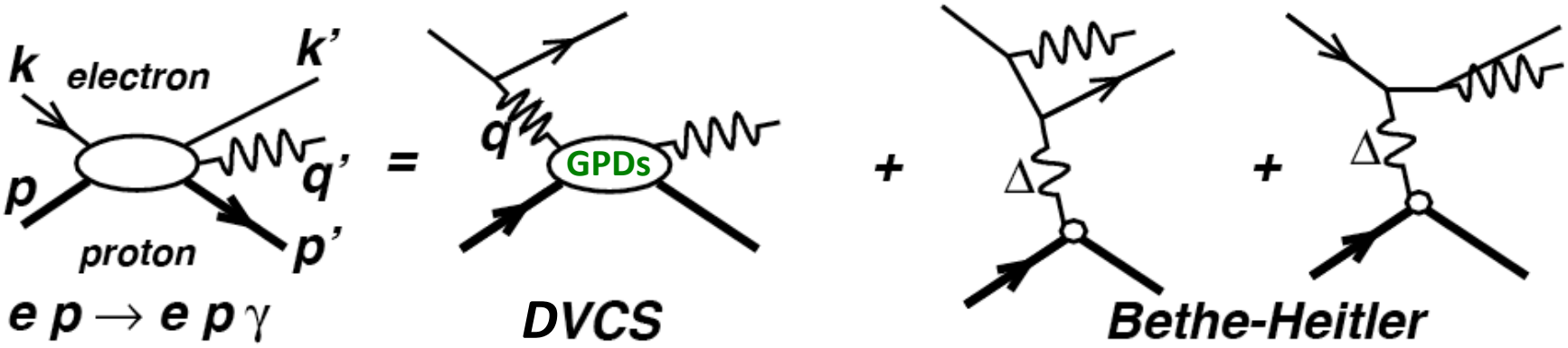
Experimentally “easy” to measure

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)

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

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

Known to 1%

Linear combinations of GPDs

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
ϵ : detector efficiency
P : polarization rate

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

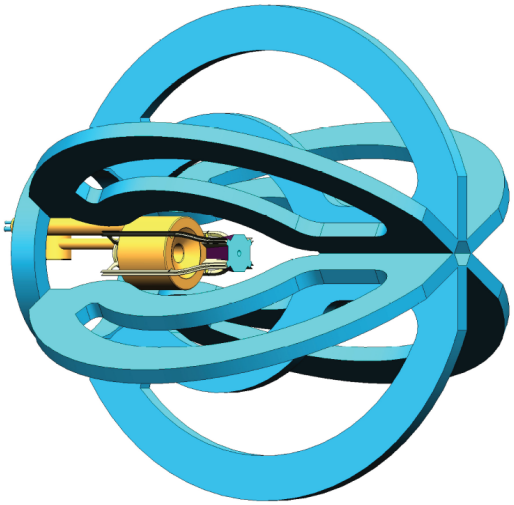
Experimentally "easy" to measure

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

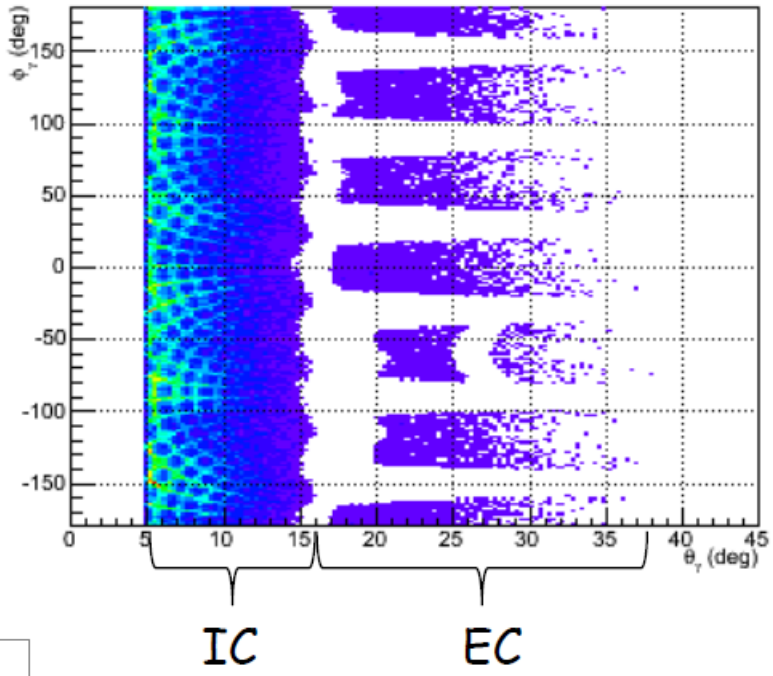
When possible, absolute cross-sections are better.

Absolute Cross-sections analysis in CLAS

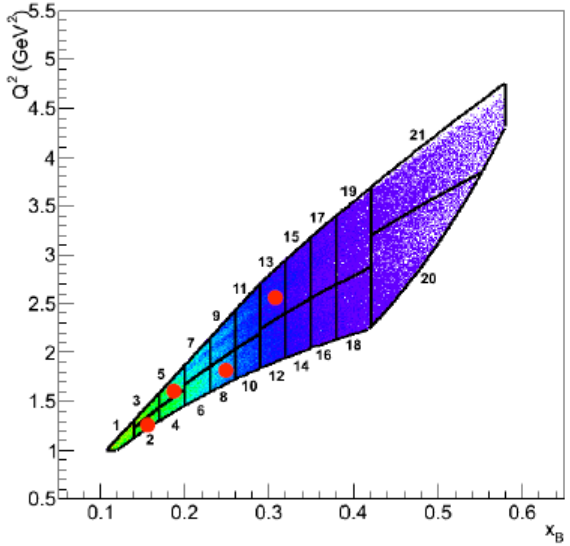
Difficulty of the task

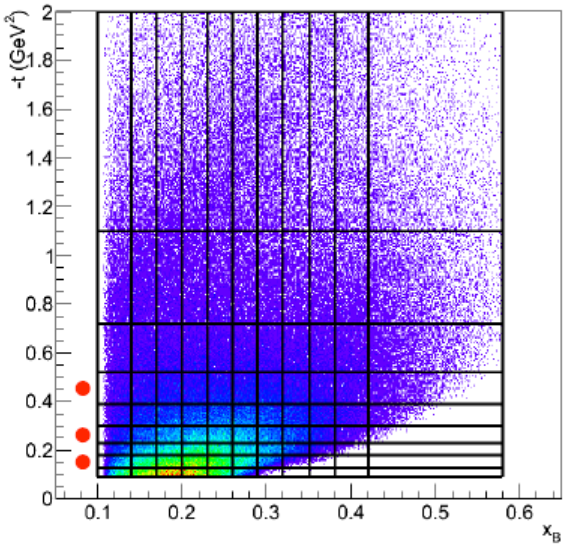


Photon : θ vs ϕ



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





- 4 bins in Q^2(x) vs 3 bins in t

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

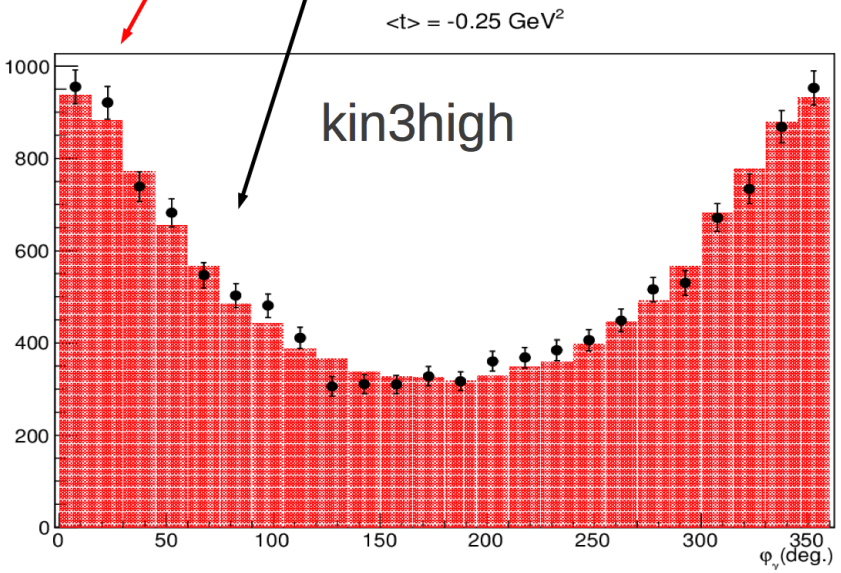
$$\frac{d^4\sigma}{dx_b dt d\phi_\gamma dQ^2} = \Gamma^G |BH|^2 + \Gamma^1 \mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^2 \Delta\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^3 \mathcal{C}^{\mathcal{I}}(\mathcal{F}^{eff})$$

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

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

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



Black dot: data / Red histogram: MC fit

The extracted cross-section is model independent.

Interpreting the extracted CFFs needs to be done carefully: 8 GPDs (4 X 2), twist 2-3 expansion…

Slide from C. Desnault

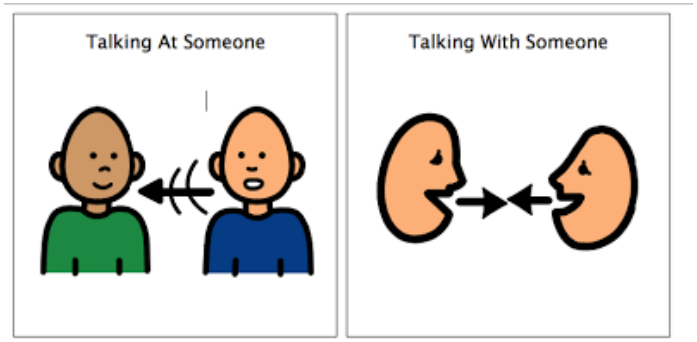
1 question: 30 m reading + 15 min discussions

ACTIVE LEARNING

What I hear, I forget

What I see, I remember

What I do, I understand



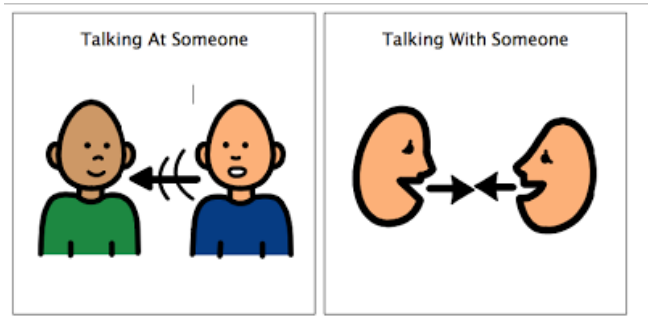
Group 1 Meriem*, Shokhna, Kieran, Carlos Y.	**Group 5** Nabil*, Brandon C., Fillipo, Manuel
Group 2 Frederic*, Shujie, Shivangi, Ryan	**Group 6** Brandon K.*, Alexa, Bailing, Gavin
Group 3 Waverly*, Sandra, Bijit, Arkadiusz	**Group 7** Holly, Larissa, David AQ, Giovanni
Group 4 Hamza, Scott, Marco, Dexu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

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?