Experimental Overview on DVCS Measurements (Past, Present and Future)

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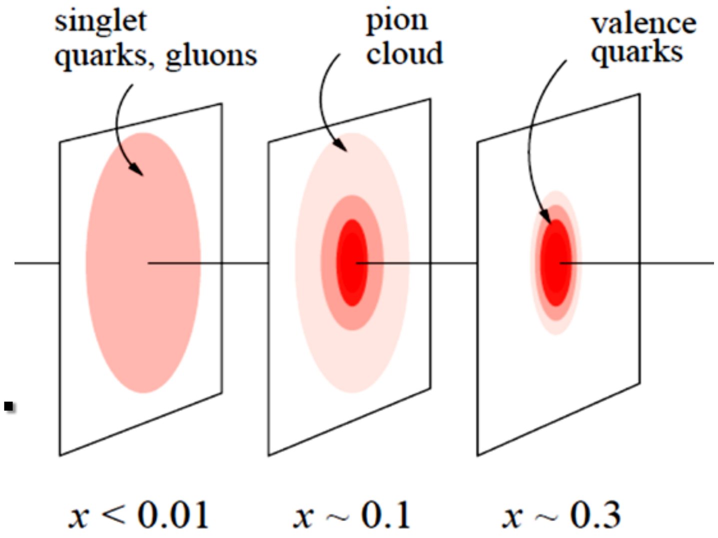
Outline of this talk:

- Introduction
- Experiments
- Selected results:
  - ➔ Cross section
  - ➔ Beam charge&spin difference
  - ➔ Interference Term
  - ➔ Measurements for GPD E

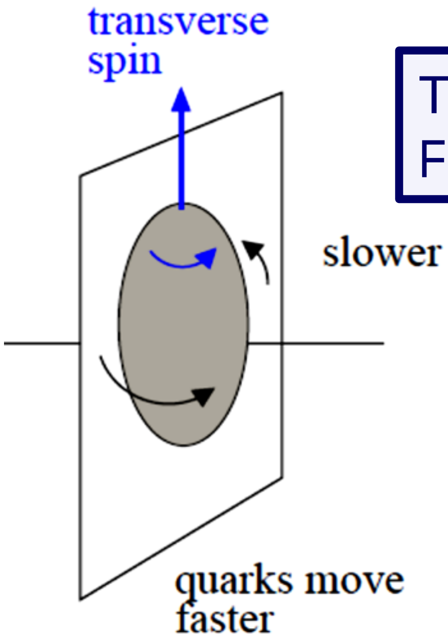
Nucleon Tomography

Holy grail:
Wigner Distributions
5 D picture of nucleon phase space $\rho(x,k_T,b_T)$



Experimentally from 3-D Pictures …

… in momentum space …



SIDIS

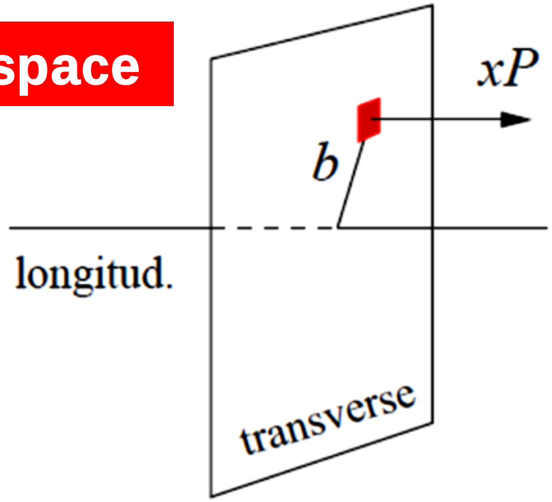
TMDs
$F(x,k_T)$

k_T-integrated

… in configuration space

GPDs
$H(x,b_\perp) \leftrightarrow H(x,\xi,t)$

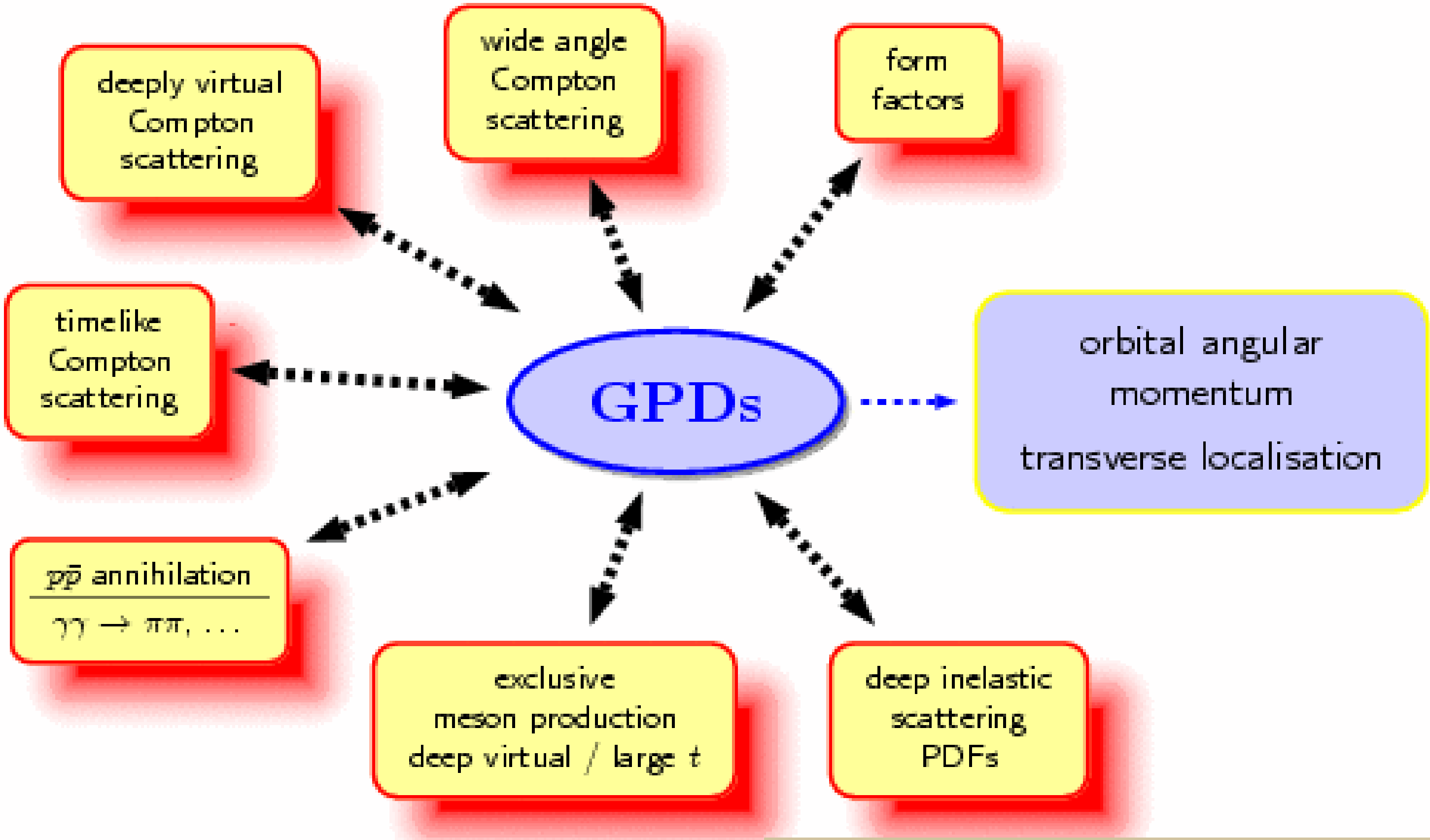
$\xi=0,\ t=0$



q(x)
1D Parton Distribution Functions

Exclusive reactions

Accessing GPDs

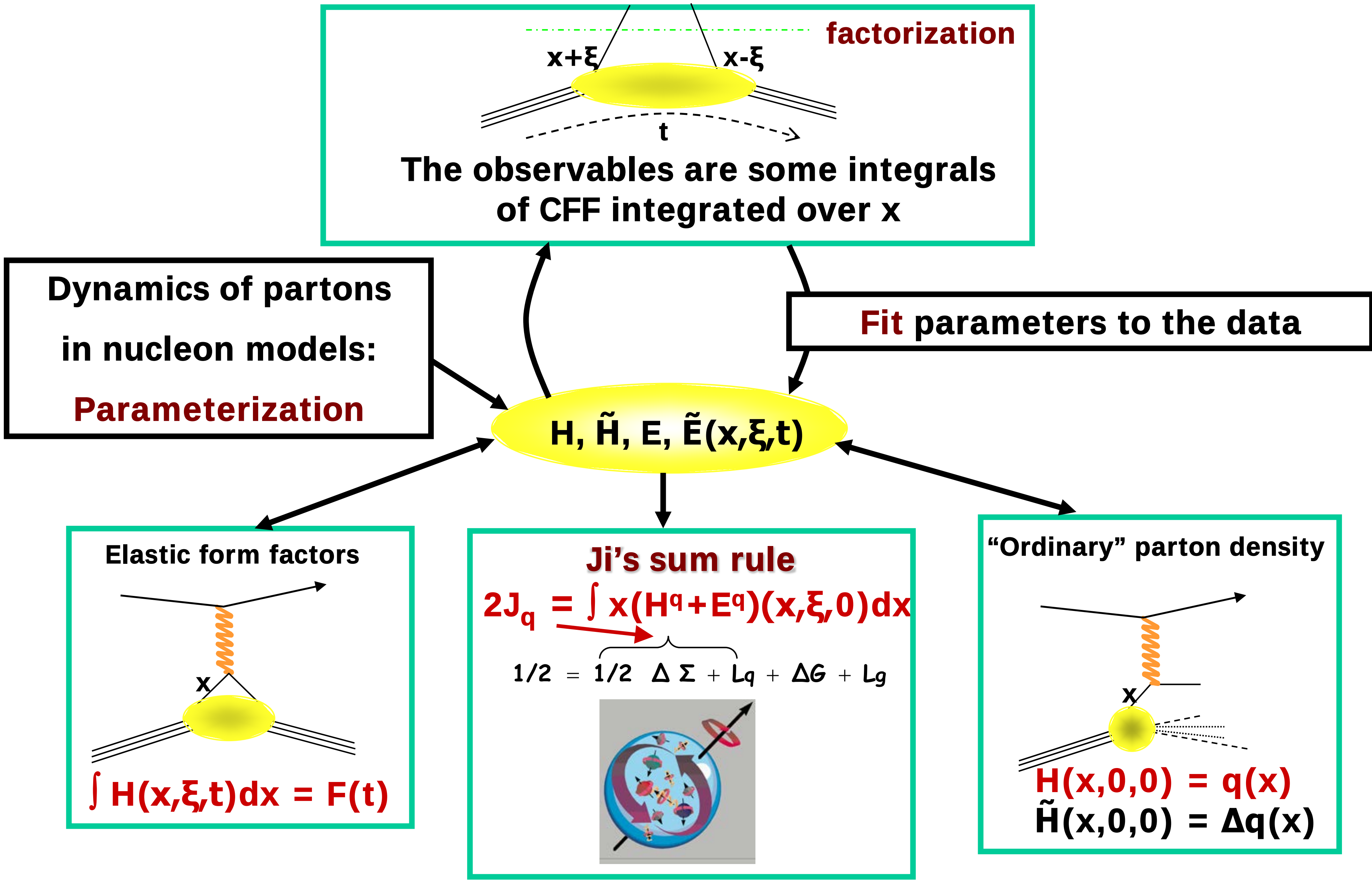


GPD filter by quantum numbers of final state:

- DVCS (γ): H, E, $\tilde{H}$, $\tilde{E}$
- VM (ρ,ω,ϕ): H, E
- different quark flavours (p,e): $\tilde{H}$, $\tilde{E}$

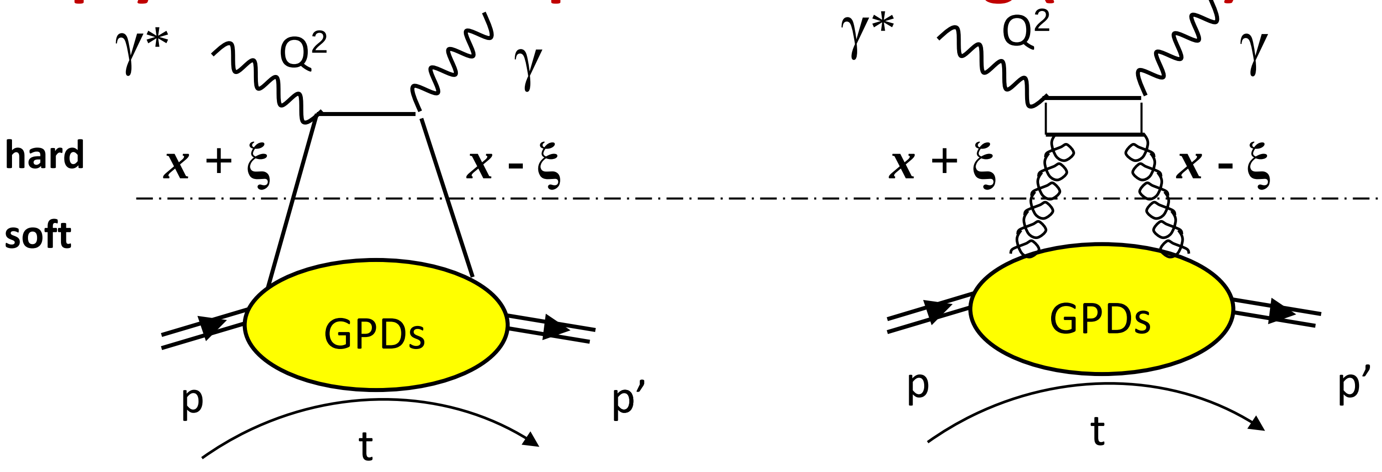
D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

GPDs and their Relation to Observables



Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):

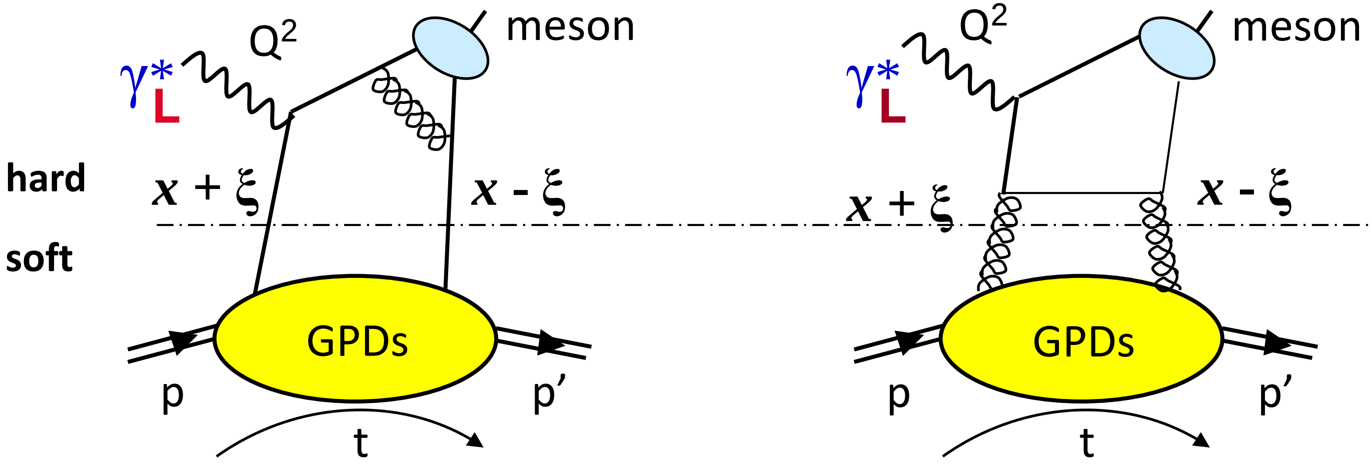


Factorisation:
Collins *et al.*

Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):



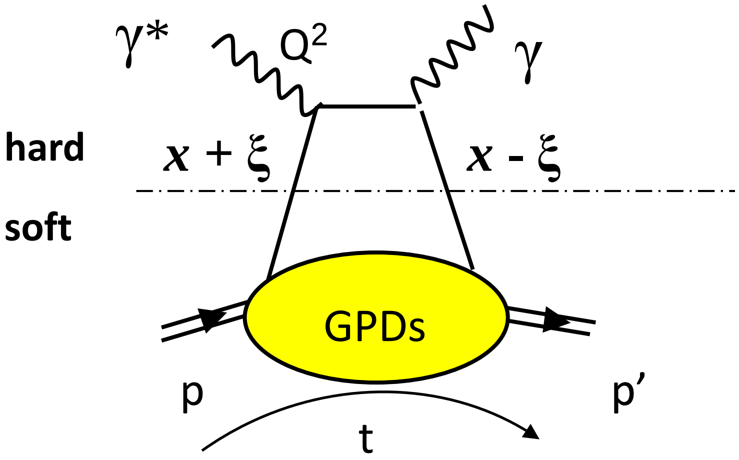
+ γ^*_L

Meson w.f.
Large power & NLO
Very slow scaling

Quark contribution **Gluon contribution**

Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):



Golden channel

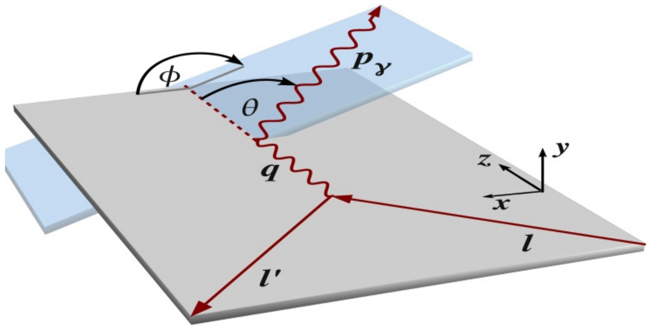
Definition of variables:

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

Cross Section & Angular Dependence



$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH}\,\mathcal{Re}\,T^{DVCS} + e_\mu P_\mu a^{BH}\,\mathcal{Im}\,T^{DVCS}$$

- $d\sigma^{BH} = \dfrac{\Gamma(x_B,Q^2,t)}{P_1(\phi)P_2(\phi)}(c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi)$ — **Known to 1 %**
- $d\sigma^{DVCS}_{unpol} = \dfrac{e^6}{y^2Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi)$
- $d\sigma^{DVCS}_{pol} = \dfrac{e^6}{y^2Q^2}(s_1^{DVCS}\sin\phi)$

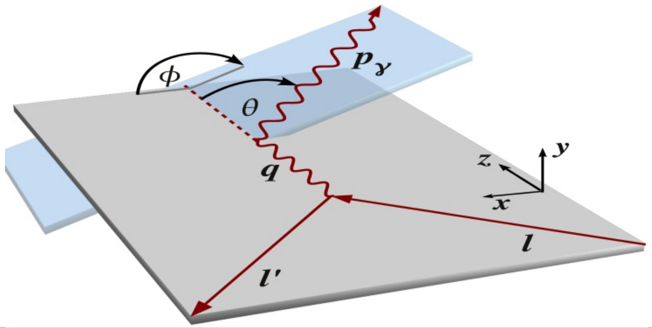
Bilinear combination of GPDs

- $a^{BH}\,\mathcal{Re}\,T^{DVCS} = \dfrac{e^6}{xy^3tP_1(\phi)P_2(\phi)}(c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi)$
- $a^{BH}\,\mathcal{Im}\,T^{DVCS} = \dfrac{e^6}{xy^3tP_1(\phi)P_2(\phi)}(s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi)$

linear combination of GPDs

Twist 2 | **Twist 3** | **Twist 2 gluon**

Example: Observables with unpolarized targets



$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathcal{R}e\, T^{DVCS} + e_\mu P_\mu a^{BH} \mathcal{I}m\, T^{DVCS}$$

- Beam Charge & Spin Sum:

$$\mathcal{S}_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH} \mathcal{I}m\, T^{DVCS}\right)$$

$$c_0^{DVCS+BH} + c_1^{DVCS+BH}\cos\phi + c_2^{DVCS+BH}\cos 2\phi)$$

$$\frac{d\sigma}{d|t|}$$

$$s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

$$\mathcal{I}m(F_1\mathcal{H})$$

- Beam Charge & Spin Difference:

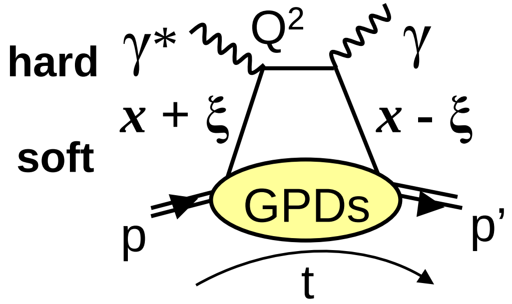
$$\mathcal{D}_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathcal{R}e\, T^{DVCS}\right)$$

$$s_1^{DVCS}\sin\phi$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$$\mathcal{R}e(F_1\mathcal{H})$$

Compton Form Factors are measured in DVCS

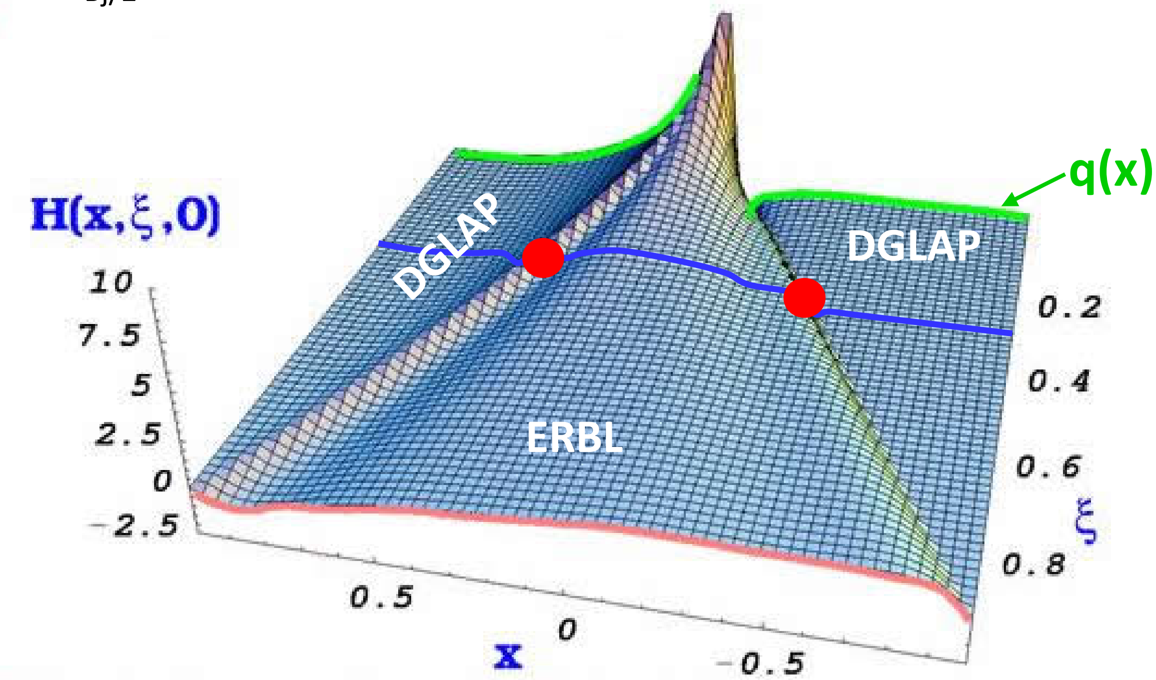


The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

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

t, $\xi \sim x_{Bj/2}$ fixed

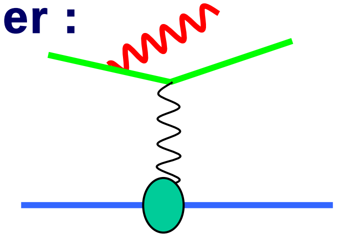


Im part measured in
Beam Spin
or **Target Spin** asymmetries

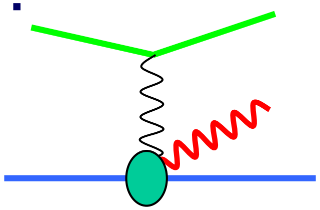
Real part measured in
Beam Charge asymmetry
or **cross section**

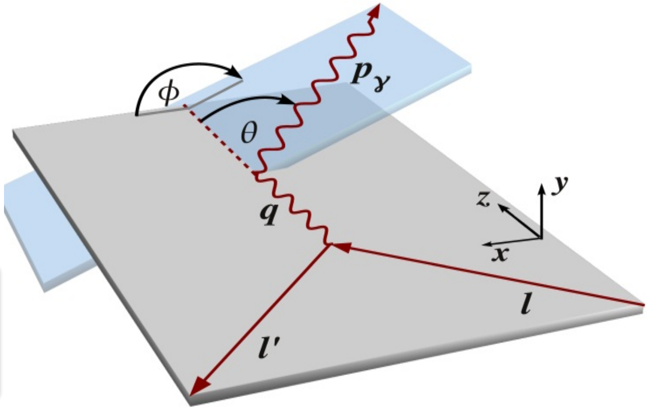
Bethe-Heitler & DVCS Cross Sections

Bethe-Heitler :



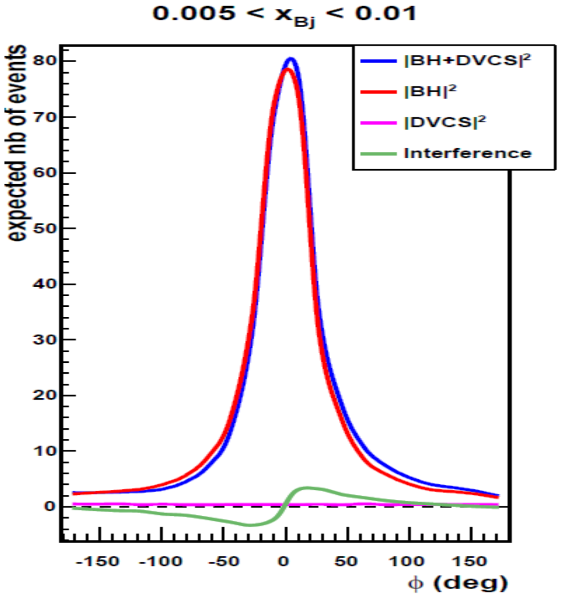
DVCS :



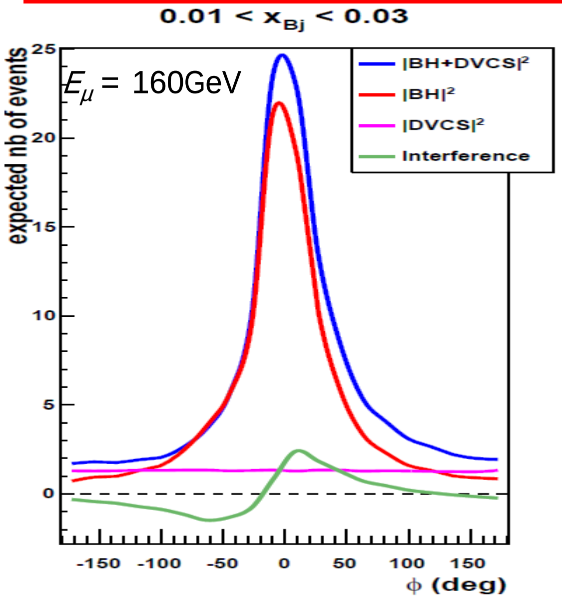


$$d\sigma \;\alpha\; |T_{BH}|^2 + \text{Interference Term} + |T_{DVCS}|^2$$

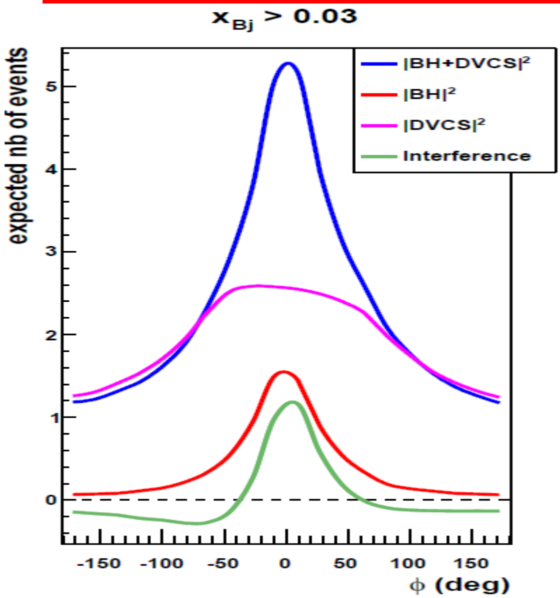
Low x_B: BH dominates



Large x_B: Int dominates



Large x_B: DVCS dominates



- **Reference yield from almost pure BH**
- **Study DVCS through interference term**
  - ➡ $\mathcal{R}e\, T^{DVCS}$ & $\mathcal{I}m\, T^{DVCS}$
- **Study $d\sigma^{DVCS}/dt$**
  - ➡ **Transverse Imaging**

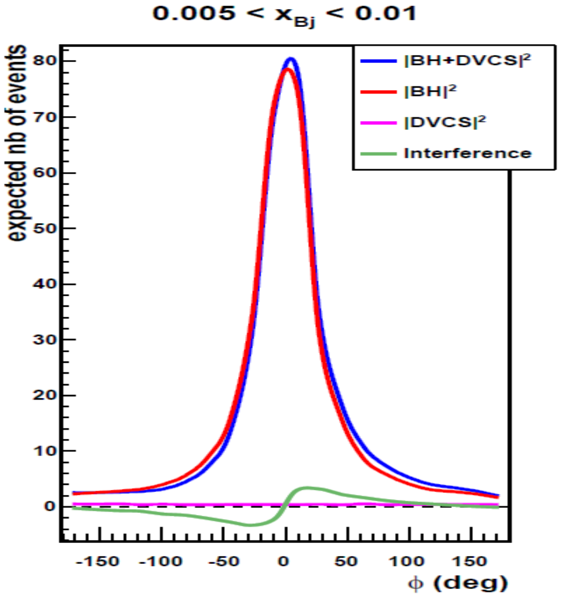
Focus on DVCS2^2 or Interference?

- Strong x_{Bj} - E_{beam} correlation in fixed target experiments

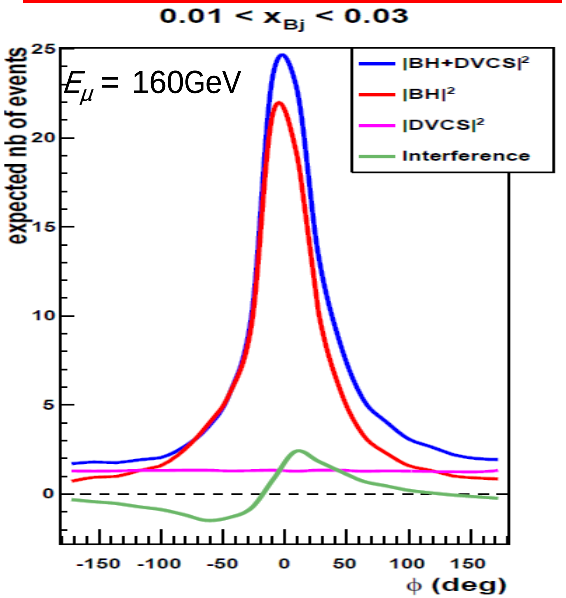
HERMES, JLAB, COMPASS

<u>Only</u>
H1, ZEUS, COMPASS

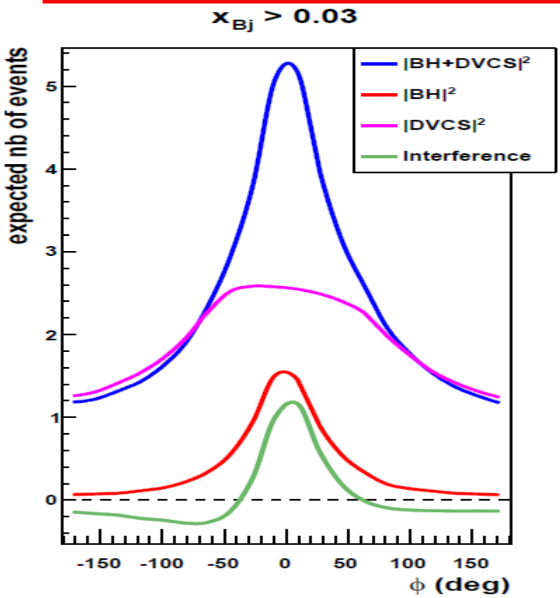
Low x_B: BH dominates



Large x_B: Int dominates



Large x_B: DVCS dominates



- **Reference yield from almost pure BH**
- **Study DVCS through interference term**
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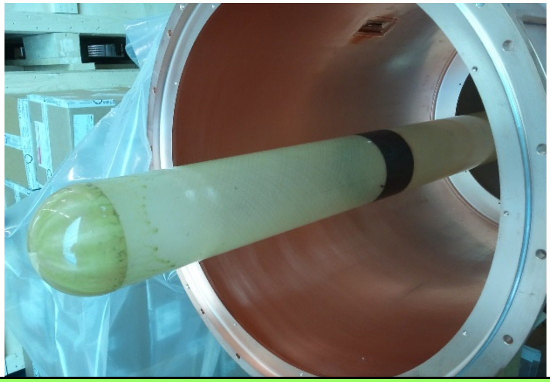
- **Study $d\sigma^{DVCS}/dt$**
  - ➡ **Transverse Imaging**

The ideal experiment

Beam:

- high beam energy to ensure hard regime
- longitudinally polarized beam
- positive and negative lepton beam
- variable energy for ε separation for DVCS² and interference term

High luminosity to allow fully differential analysis in x_{Bj} Q^2 t ϕ

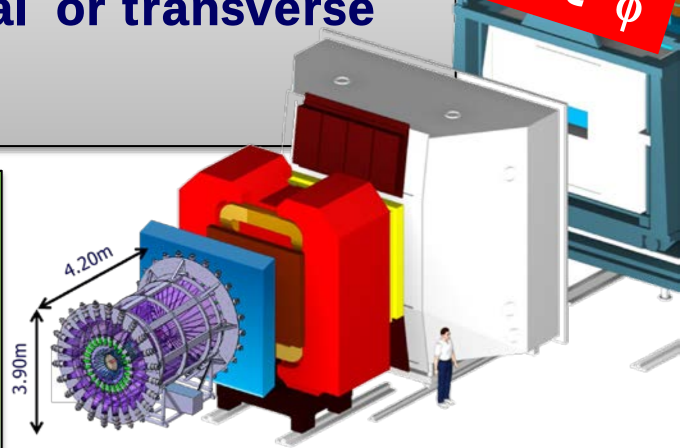


Target:

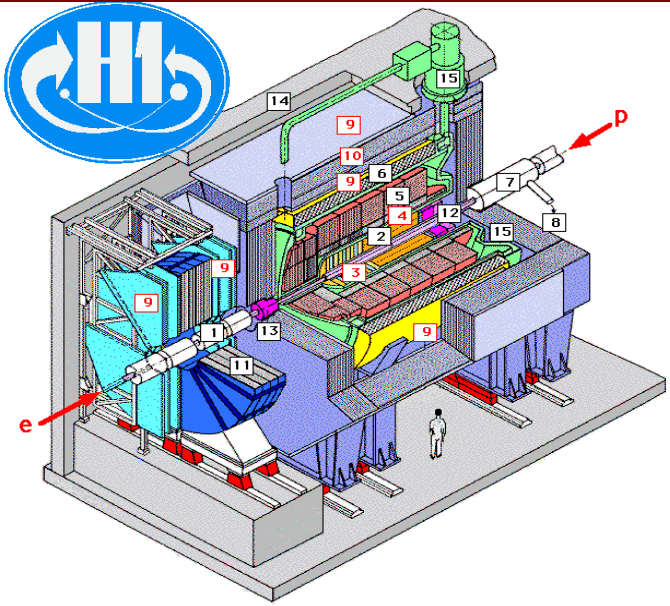
- H_2 and D_2
- unpolarized, longitudinal or transverse polarized target

Detector:

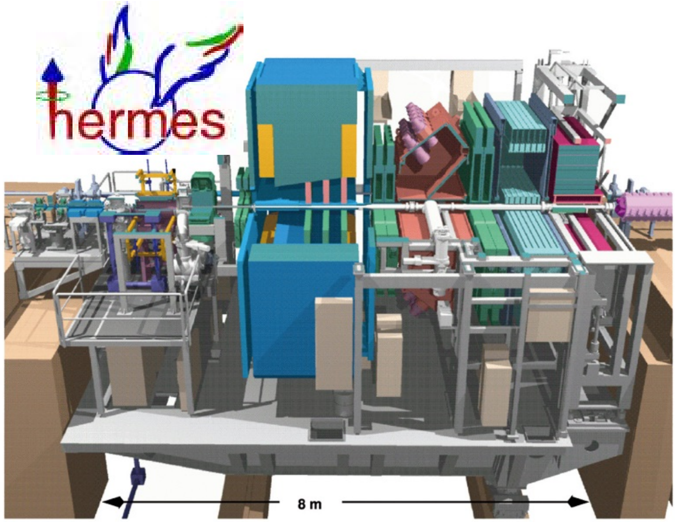
- hermetic to ensure exclusivity
- efficient calorimetry with good energy resolution



Experiments in the past

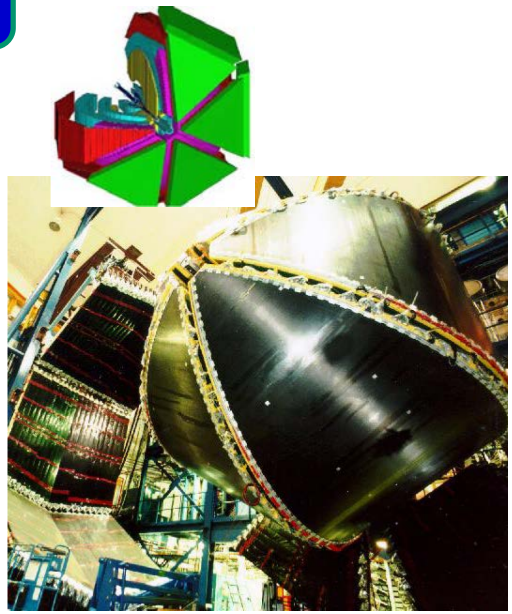


Polarised 27 GeV e^-/e^+
Unpolarised 920 GeV p
~ Full event reconstruction

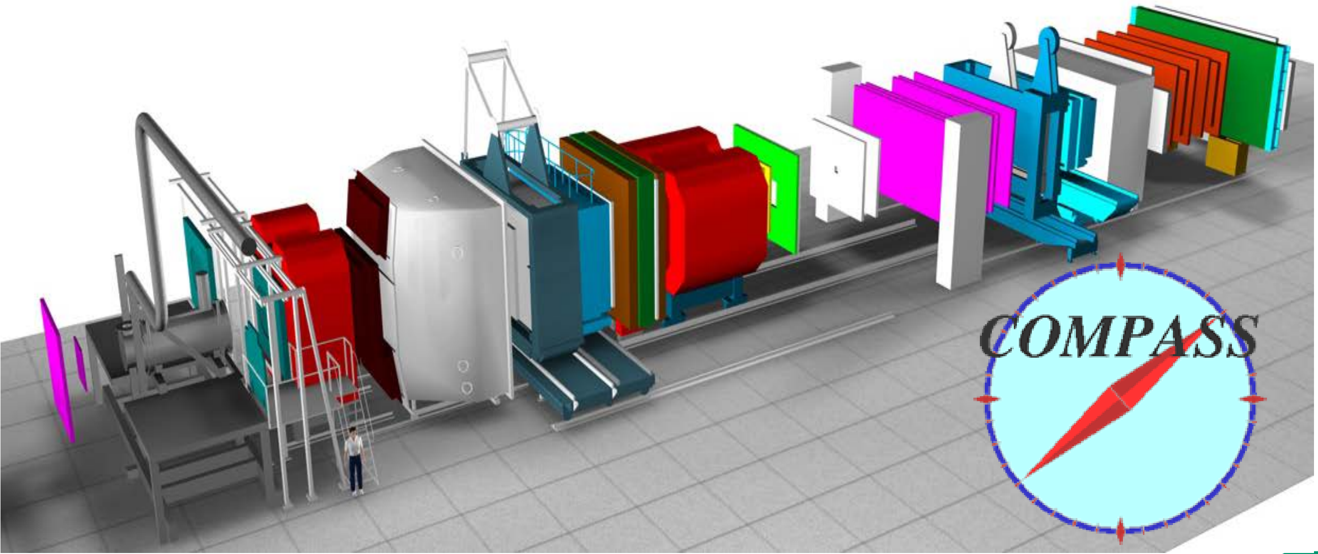


Polarised 27 GeV e^-/e^+
Long, trans polarized p, d
Missing mass technique,
2006-07 recoil detector

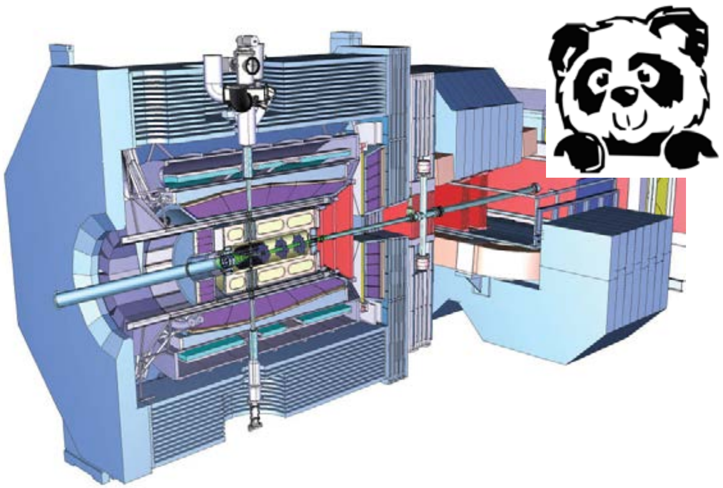
Highly polarization 6 GeV e^-
Highest luminosity
Long, trans. polarized p, d
Missing mass technique



Present & Future Experiments (limited to this decade ... maybe ...)

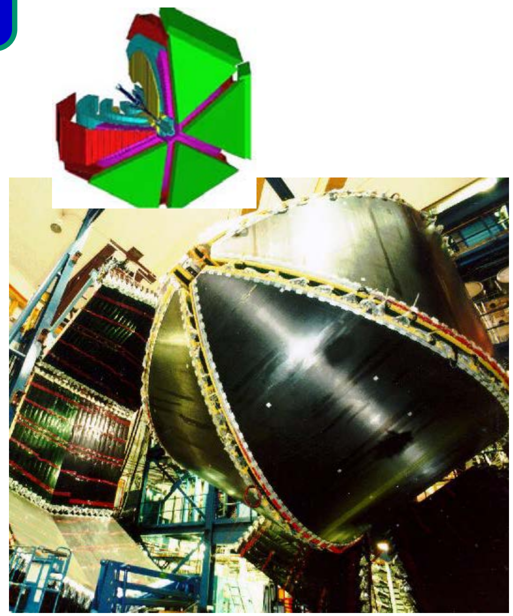


Highly polarised **160 GeV μ^+/μ^-**
Unpolarized p
(Long, trans. polarized p, d)
Recoil detection

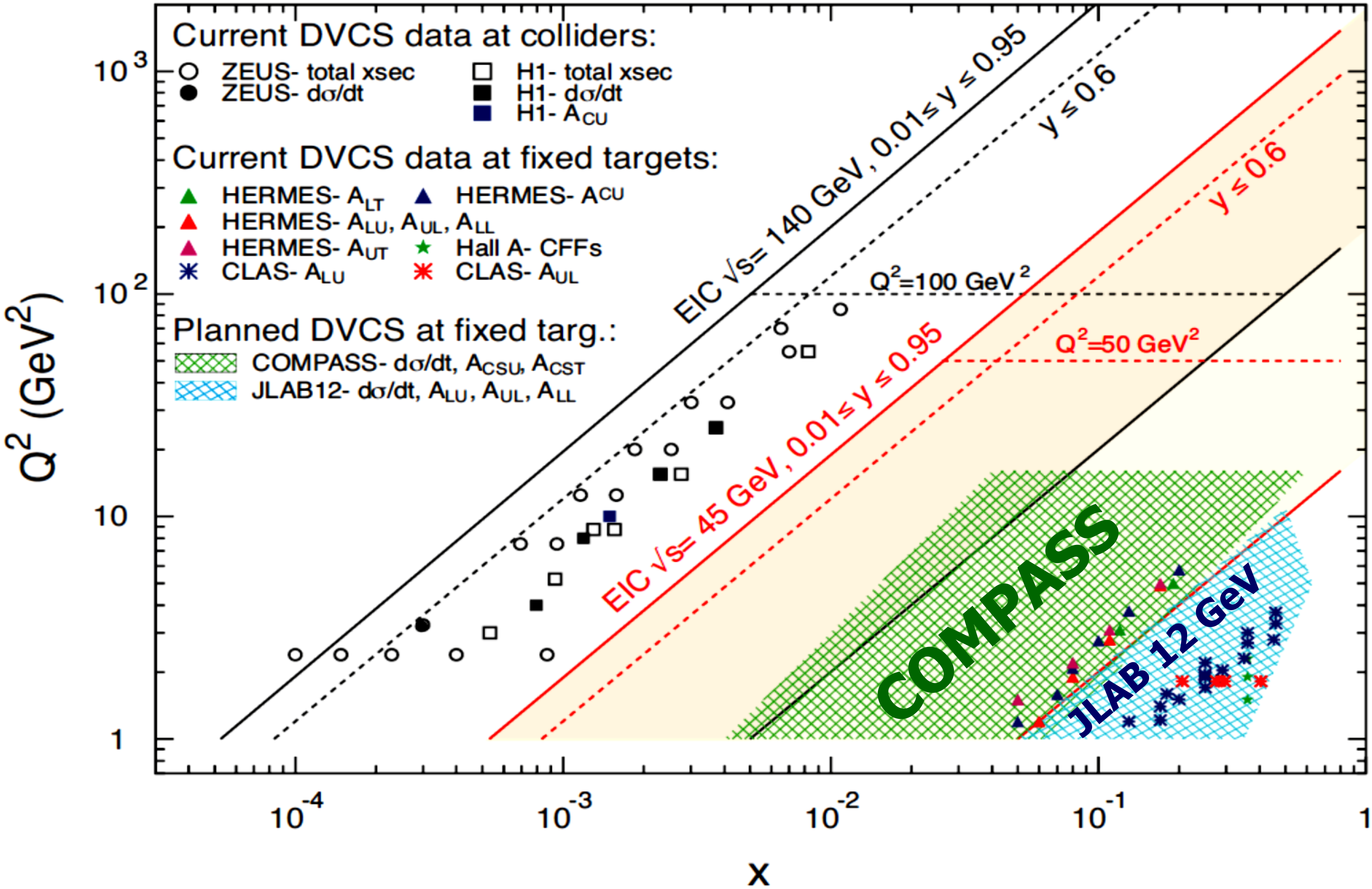


Antiproton beam, fixed target p
time-like form factors

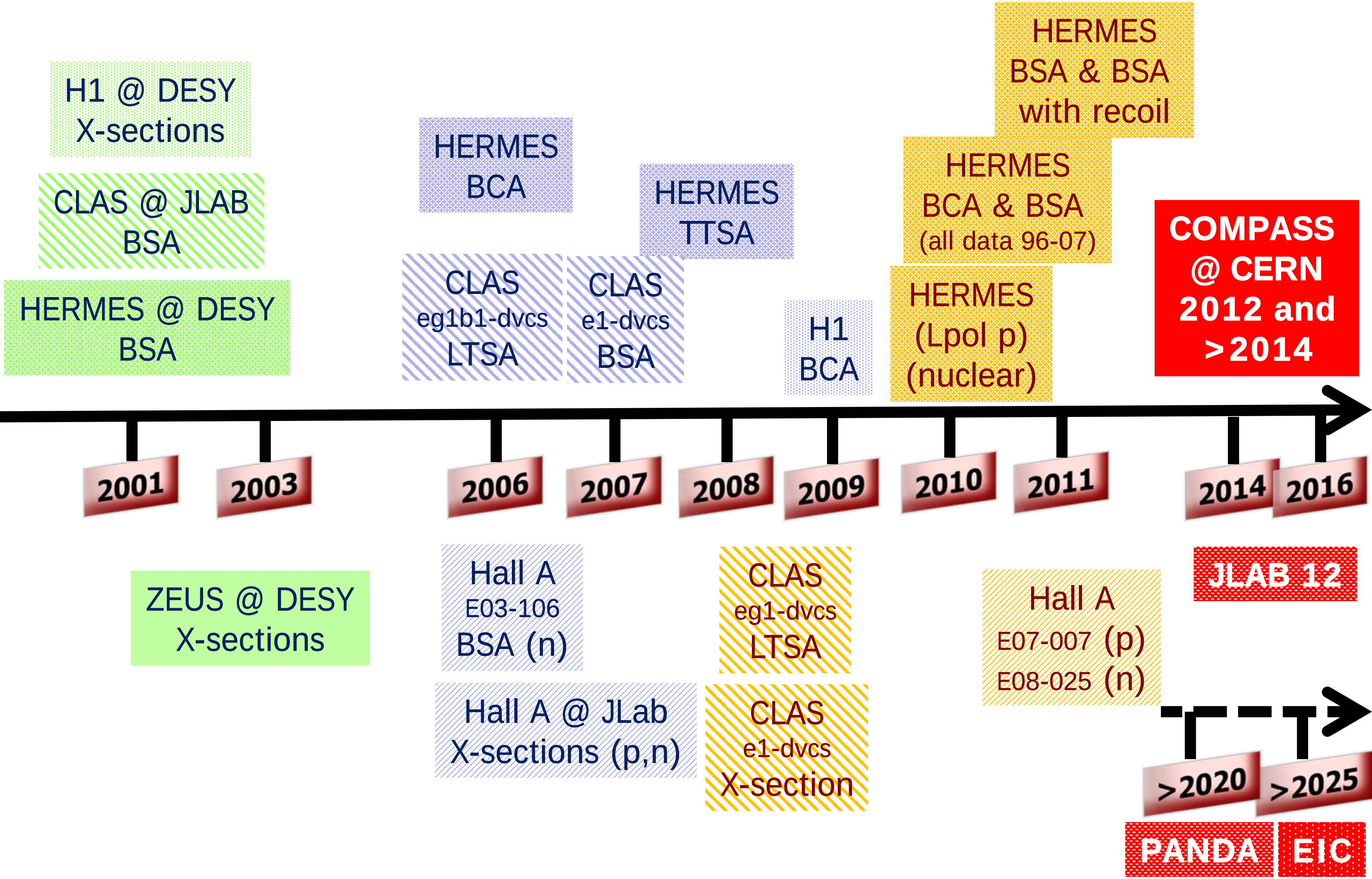
Highly polarization 12 GeV e^-
Highest luminosity
Long, trans. polarized p, d
Missing mass technique



Kinematic Coverage



Some DVCS related measurements

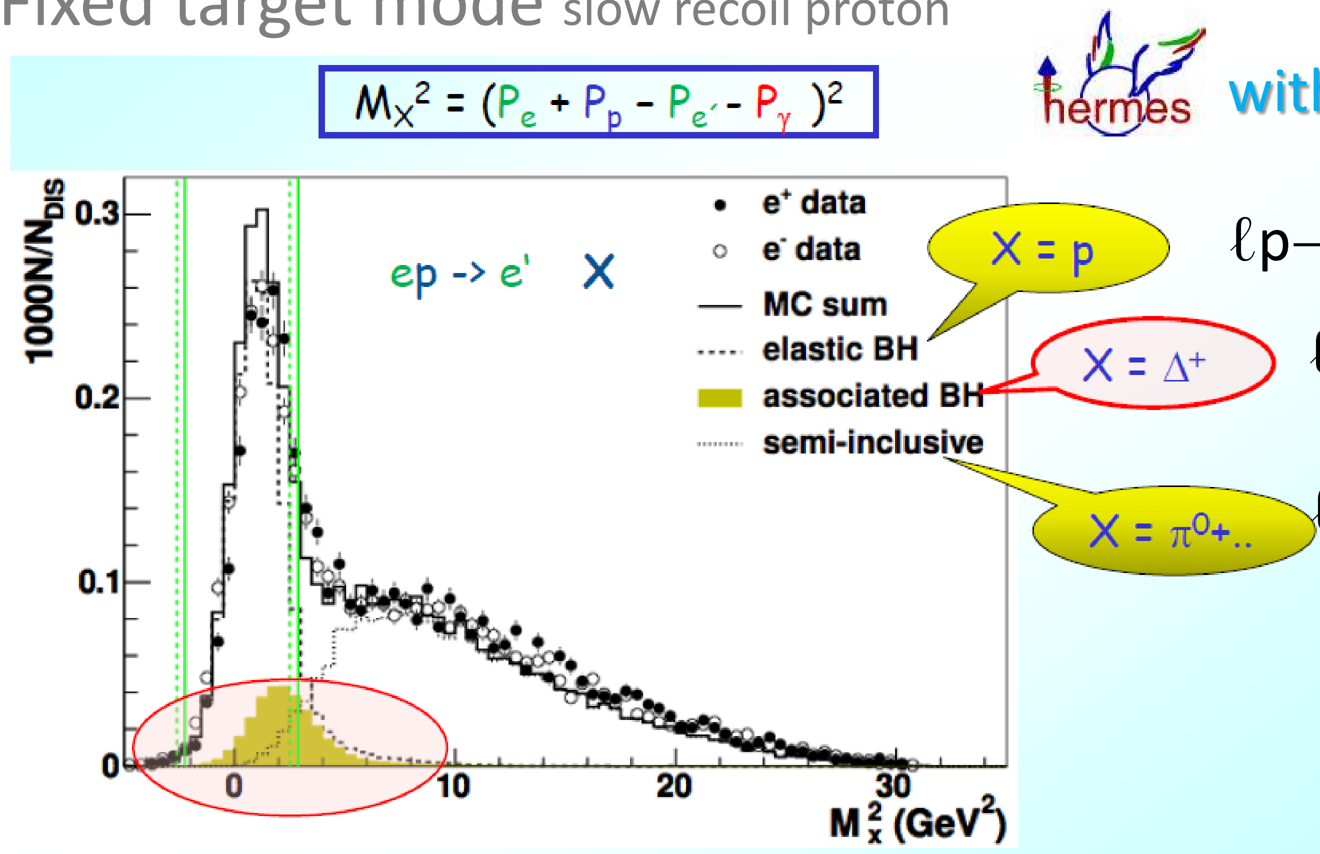


Exclusivity: ep → e + γ + p

Fixed target mode slow recoil proton

$M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2$

without recoil detector



$\ell p \rightarrow \ell' + \gamma\ (+p')$

$\ell p \rightarrow \ell' + \gamma\ (+\Delta^+)$

$\ell p \rightarrow \ell' + \gamma\ (+\gamma + p' + \ldots)$

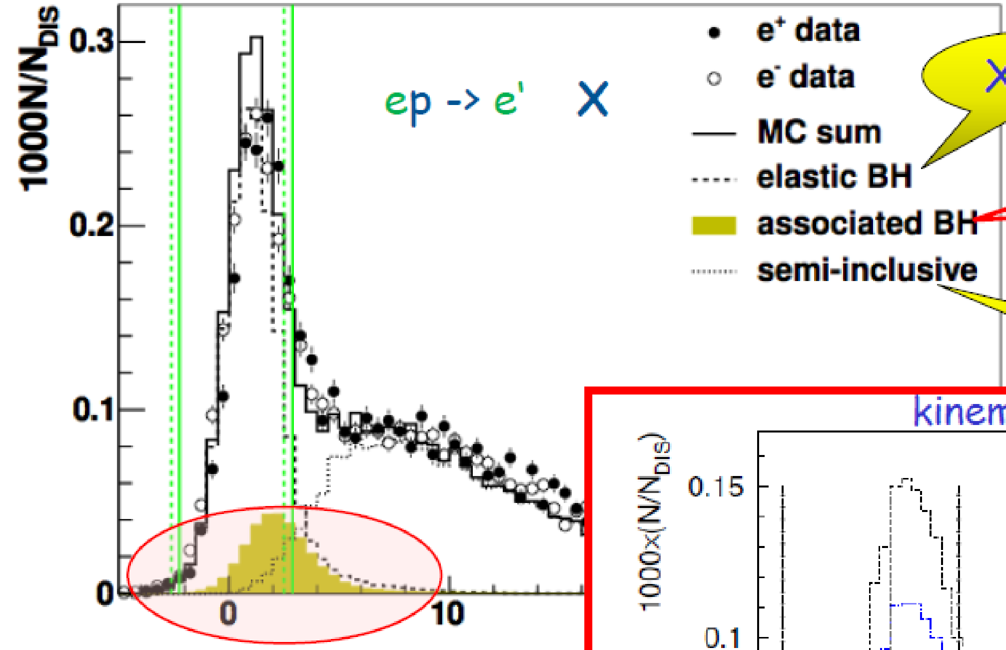
from π^0 decay…

Exclusivity: $ep \to e + \gamma + p$

Fixed target mode slow recoil proton

$$M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2$$

without recoil detector

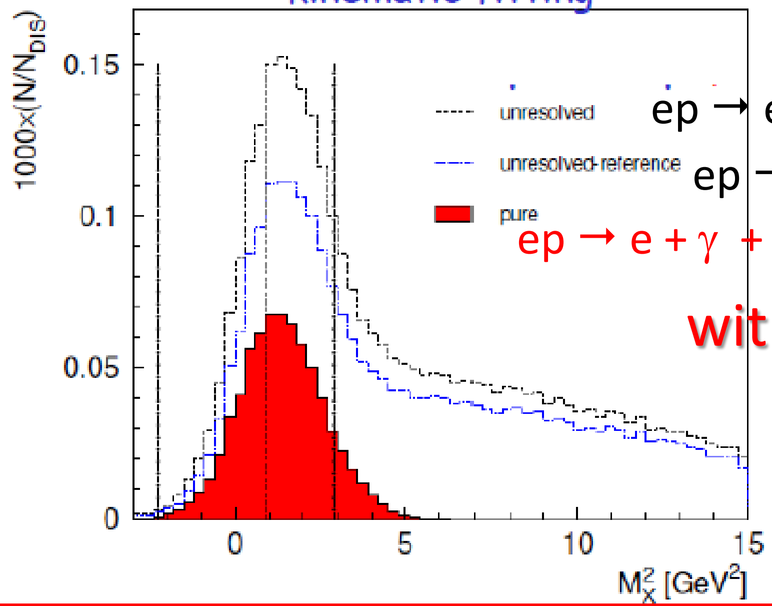


X = p — $\ell p \to \ell' + \gamma\ (+p')$

X = Δ^+ — $\ell p \to \ell' + \gamma\ (+\Delta^+)$

X = π^0+.. — $\ell p \to \ell' + \gamma\ (+ \gamma + p' + \ldots)$ from π^0 decay…

kinematic fitting



$ep \to e + \gamma\ (+ p + \ldots)$

$ep \to e + \gamma\ (+ p_{\text{in acceptance}} + \ldots)$

$ep \to e + \gamma + p$

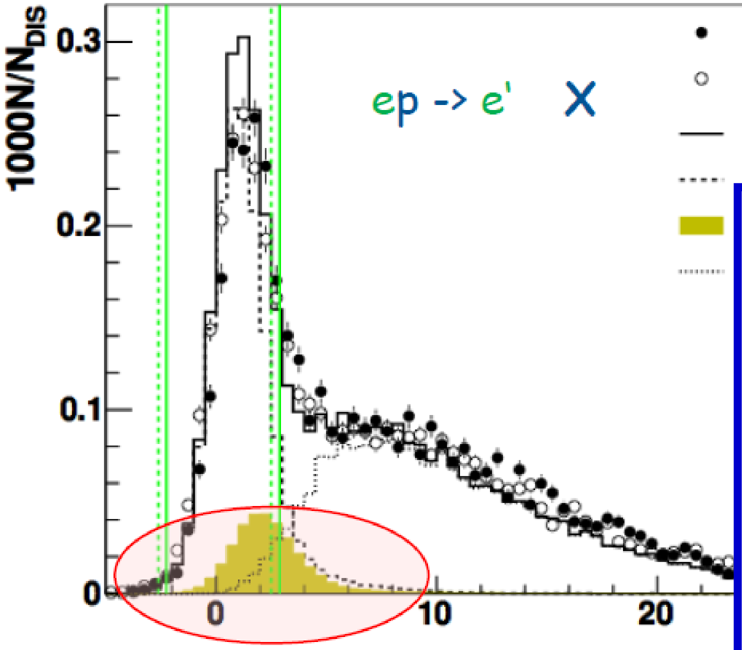
with recoil detector

Exclusivity: ep → e + γ + p

Fixed target mode slow recoil proton

$$M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2$$

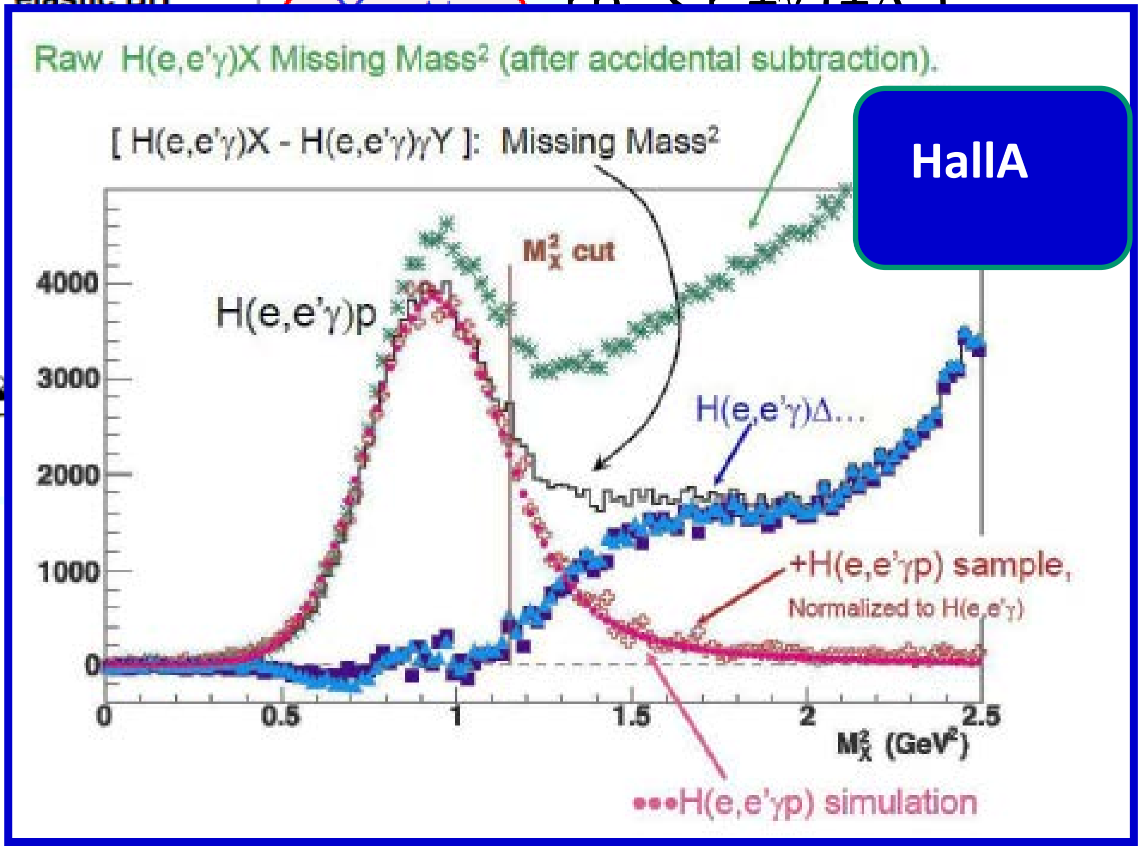
without recoil dtector



X = p

ℓp→ ℓ'+γ (+p')

ℓp → ℓ'+γ (+Δ+)

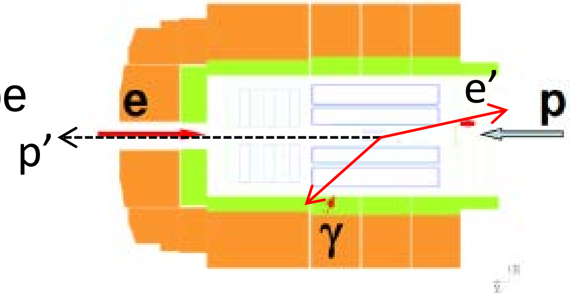


Background suppression
~ syst. error

Exclusivity: ep → e + γ + p

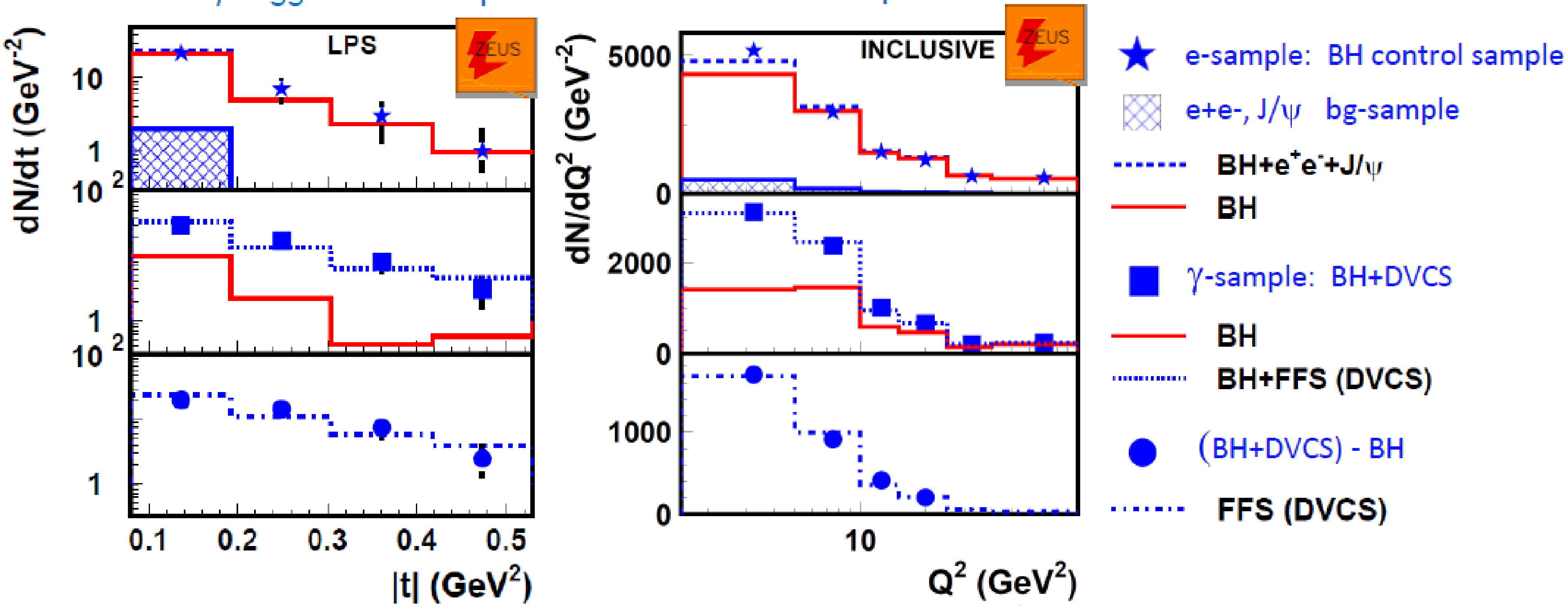
Collider mode e-p forward fast proton

Outgoing proton escapes through the beam pipe
Tagged in forward proton spectrometer



LPS: *p* tagged data sample

full data sample



Interference term integrated over ϕ → pure DVCS cross section

Selected results and perspectives

Cross sections measurements: DVCS and mesons

Study of the GPD H with DVCS on proton:

Beam Spin Asymmetry:	HallA – CLAS - HERMES
Beam Charge Asymmetry:	HERMES – H1 – COMPASS
Cross section difference and sum:	HallA – CLAS – COMPASS

Hunting GPD E:

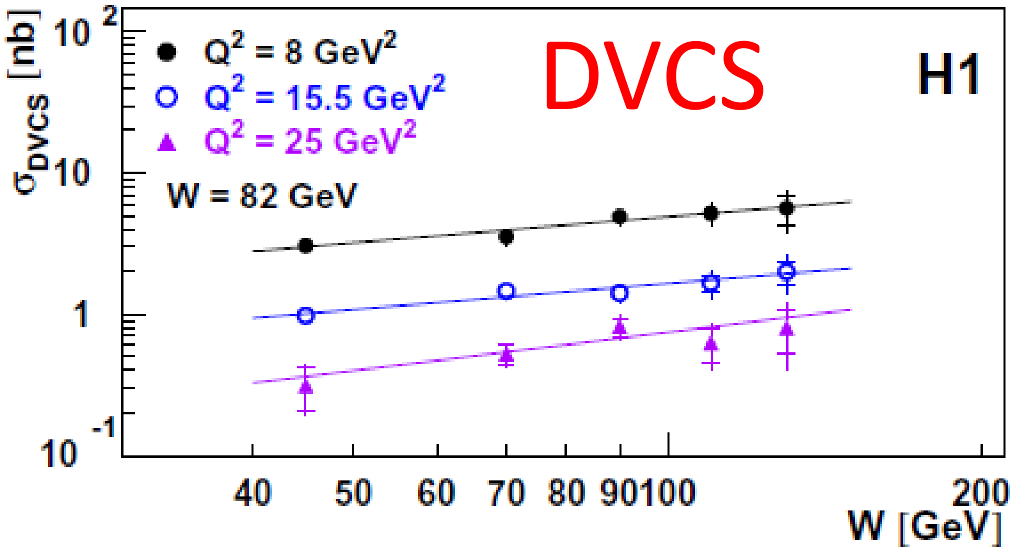
Beam Spin cross section on the neutron:	HallA
Transverse pol. Target Asymmetry on proton:	HERMES

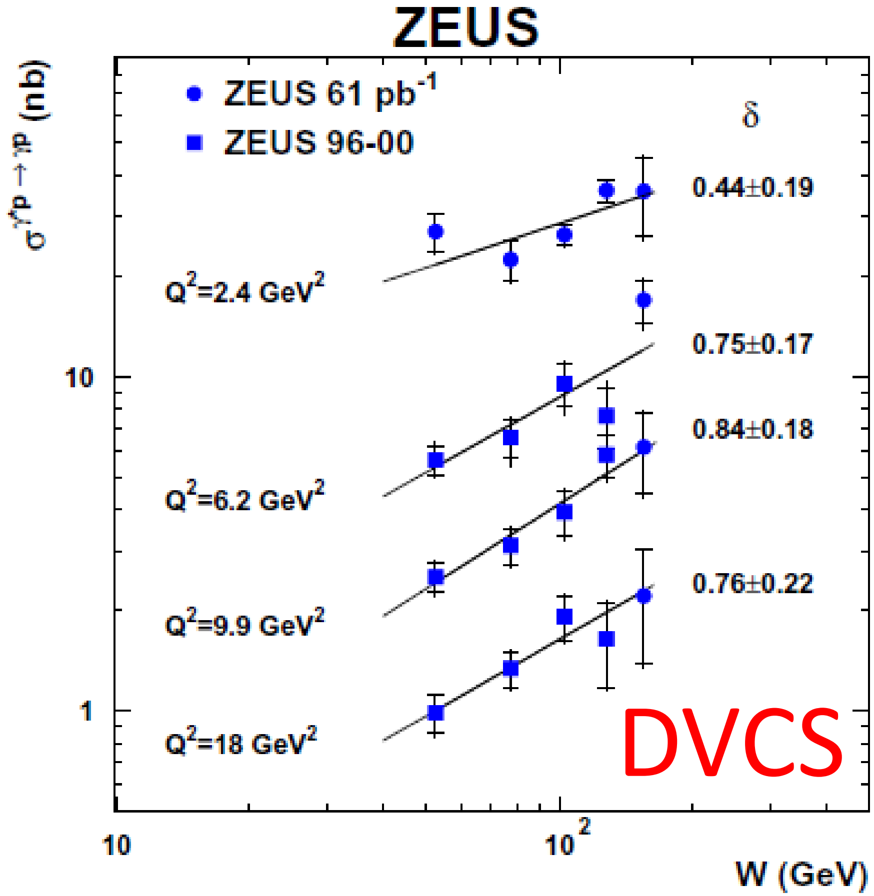
→ 'Holy grail' for OAM

Cross sections and W dependence

Are we in the hard regime ?

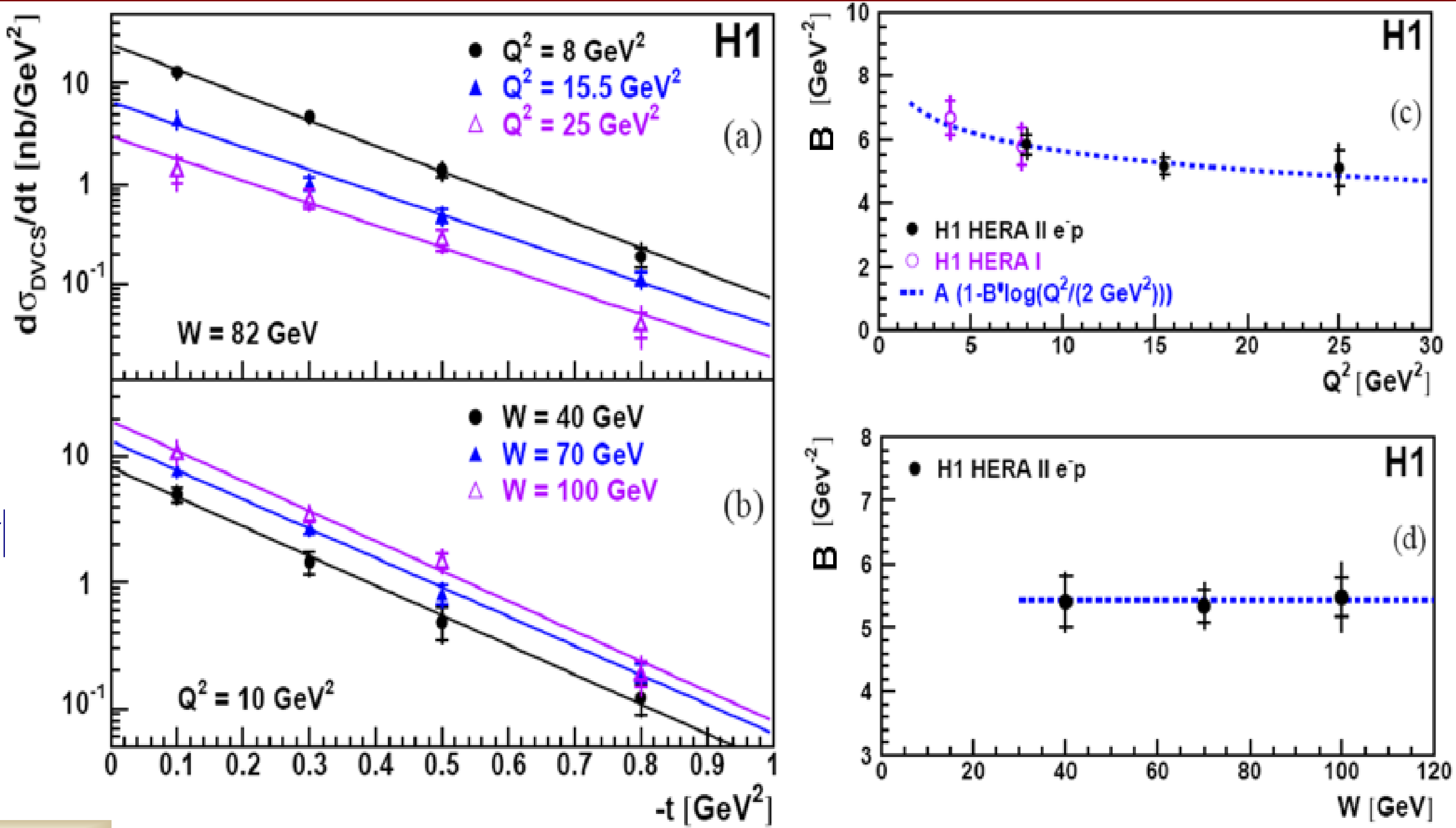
$$\sigma(W) \propto W^{\delta}$$





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

Cross sections and t dependence



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

$$\left\langle r_{\perp}^{2}(x_B)\right\rangle \sim 2B(x_B)$$

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

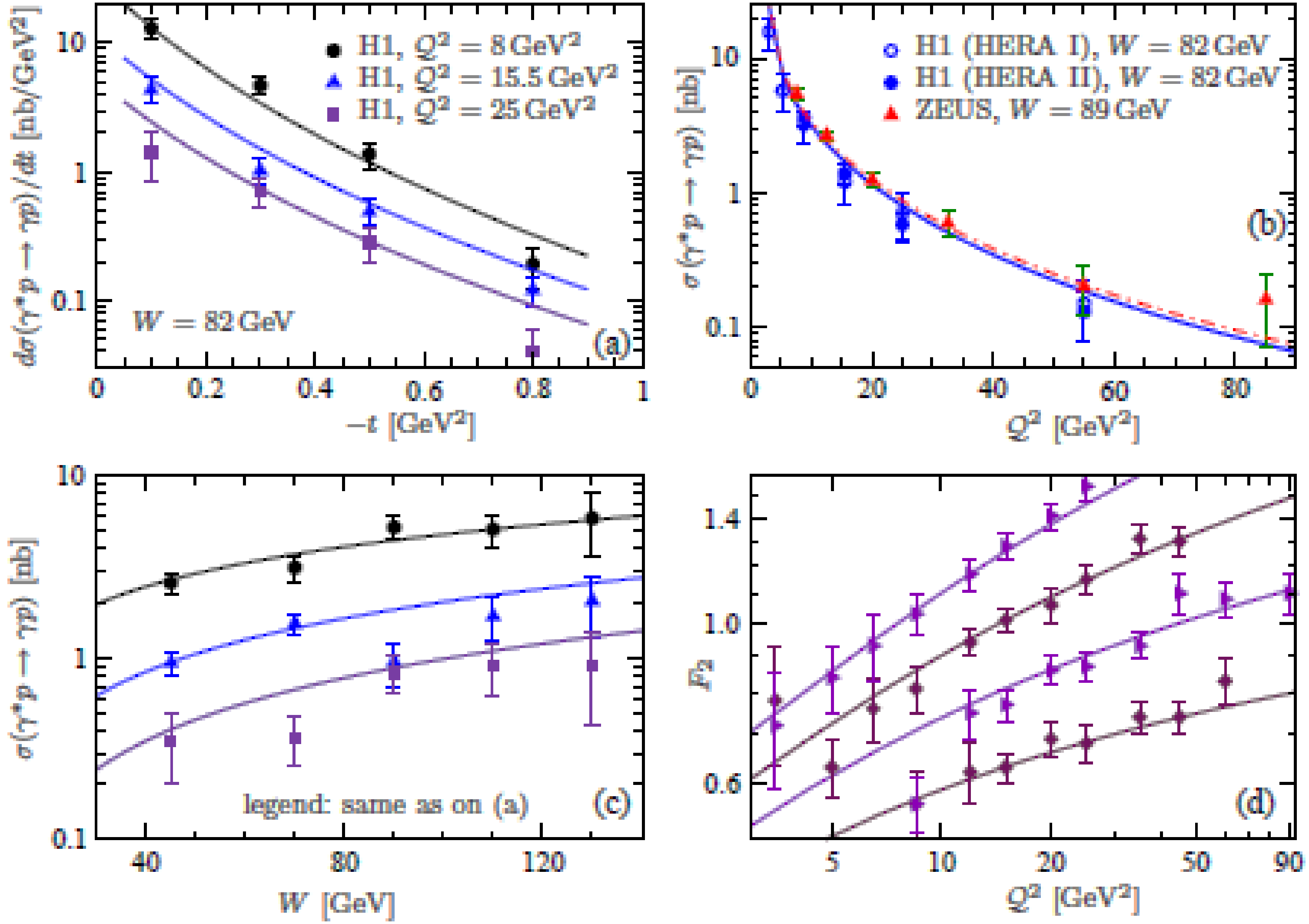
Almost no evolution as a function of W

B= 5.45 ± 0.19 ± 0.34 GeV^2

at <Q^2> = 8 GeV^2 and <x> = 1.2 10^{-3}

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

Predictions for DVCS from KM model



KM10: Kumericki and Mueller NPB (2010) 841; arXiv:0904.0458
one of the most general parameterization of GPDs based on their mathematic
Properties fit to the DVCS data and DIS

COMPASS: Beam Charge & Spin Difference $\mathcal{S}_{CS,U}$ - Transverse imaging

$$S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\, Im\, T^{DVCS}\right)$$

- Using $\mathcal{S}_{CS,U}$
- Integrating over ϕ
- Subtracting BH

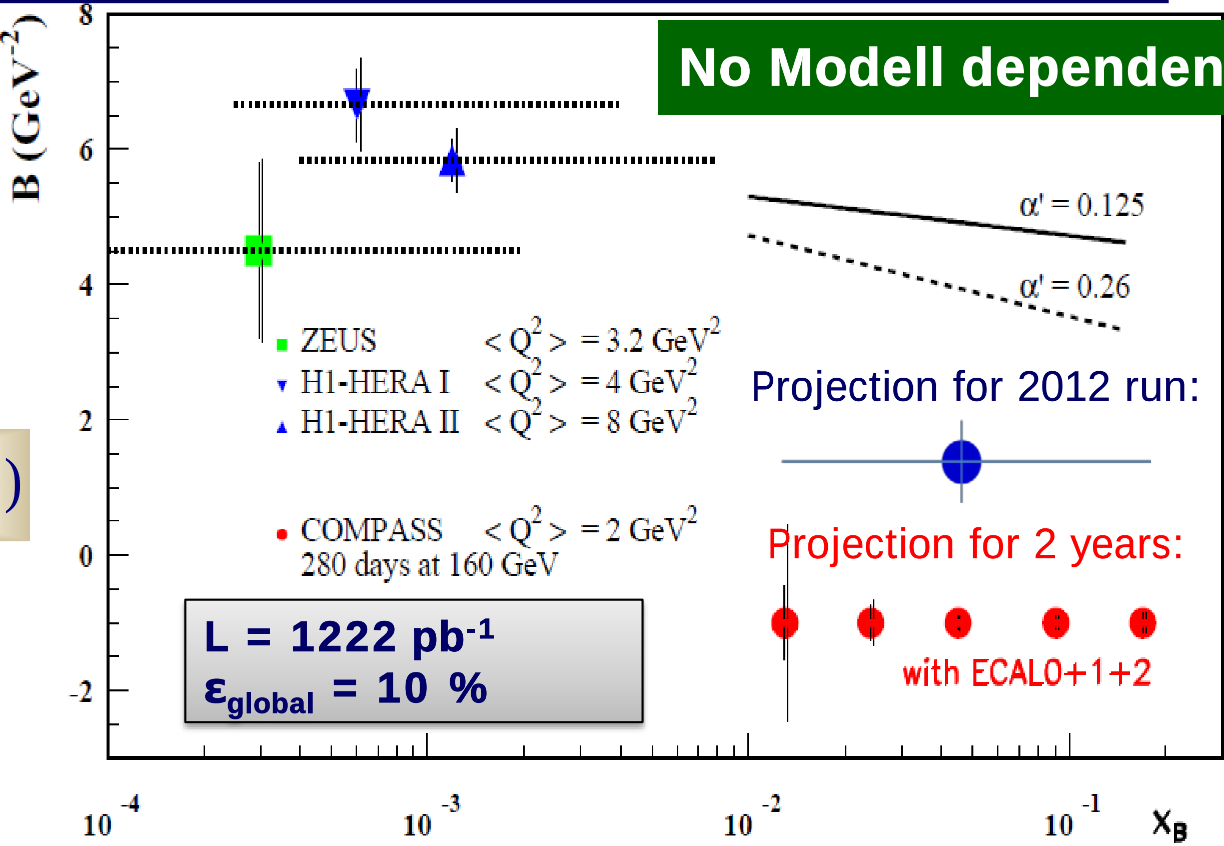
$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}$$

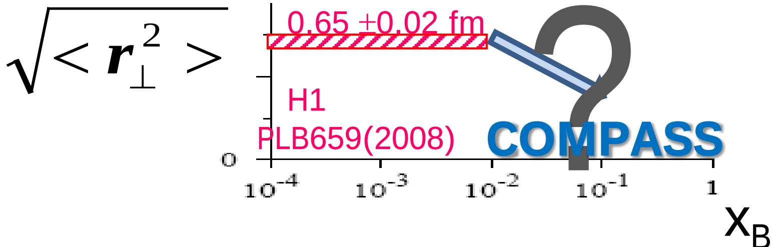
$$\langle r_\perp^2(x_B)\rangle \sim 2B(x_B)$$

- Ansatz at small x_B: ($x \sim x_B$)

$$B(x_B) = b_0 + 2\alpha' \ln \frac{x_0}{x_B}$$

No Modell dependence

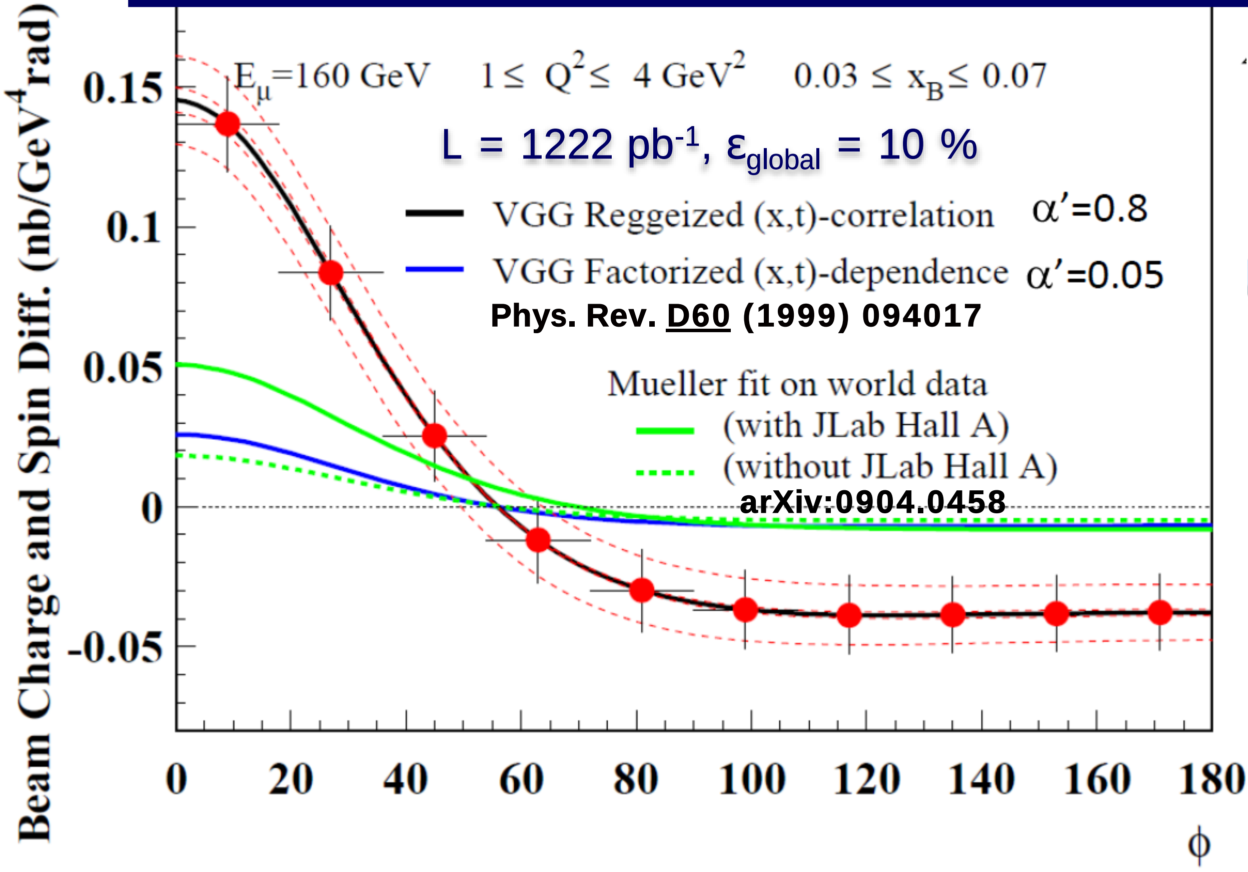


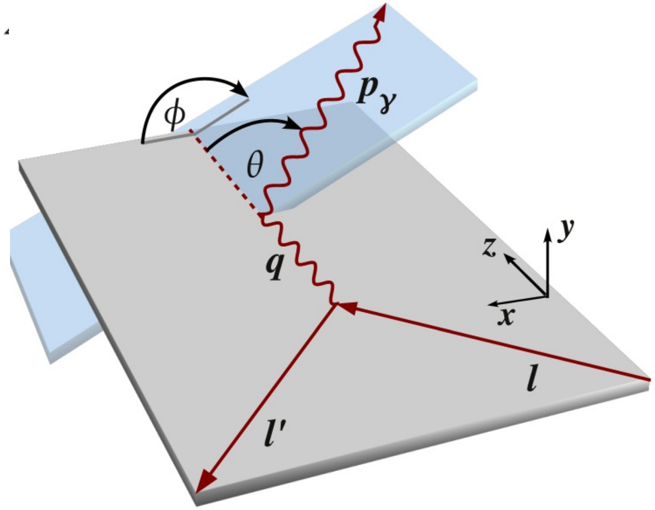


measure α' with accuracy > 2.5 σ for any α' > 0.125

Beam Charge & Spin Difference $\mathcal{D}_{CS,U}$

$$\mathcal{D}_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathcal{R}e\, T^{DVCS}\right)$$





Gives access to:
$\mathcal{R}e$ **F1** $\mathcal{H}$

- **Need to control detector acceptance and beam flux with high precision**
- **Error band includes a 3 % systematic uncertainty between μ^+ and μ^-**
- **Use inclusive events and BH for check**

Beam Charge & Spin Asymmetry $\mathcal{D}_{CS,U} / \mathcal{S}_{CS,U}$

BCSA $= \mathcal{D}_{CS,U} / \mathcal{S}_{CS,U}$

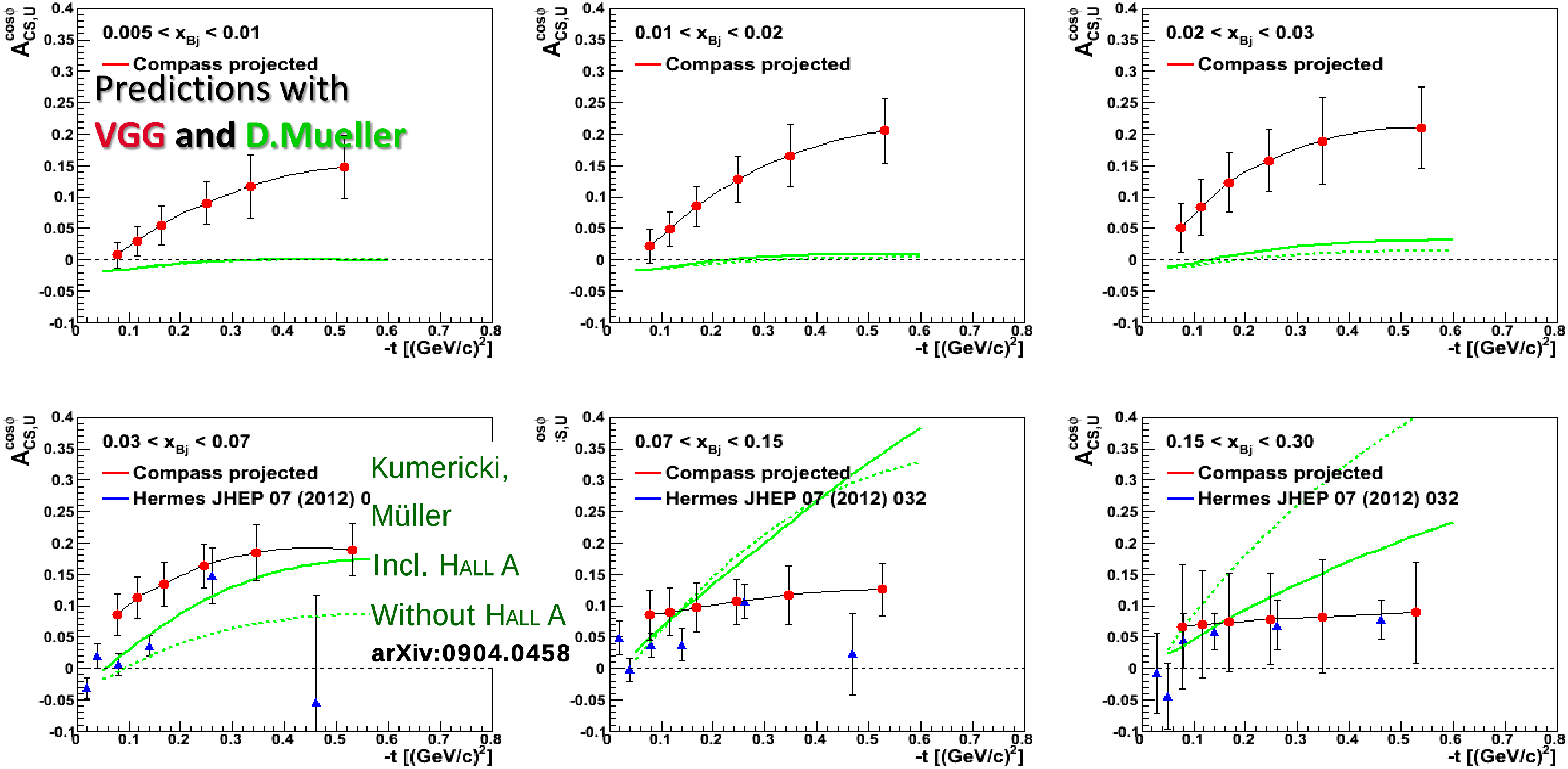
$= A_0 + A_{CS,U} \cos\phi + A_2 \cos 2\phi$

→ Measurement of $\mathcal{R}e(F_1 \mathcal{H})$

$\mathcal{R}e(F_1\mathcal{H}) > 0$ @ H1

< 0 @ HERMES

Node? Where in x_{Bj}?→ COMPASS



DVCS interference on the proton

→ $\mathcal{I}m$ DVCS with BSA or Beam Spin difference

→ $\mathcal{R}e$ DVCS with BCA or Beam Charge difference

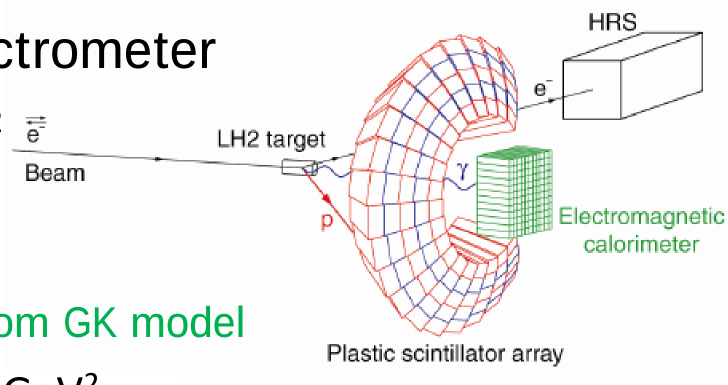
→ mainly constrains on the GPD H

Beam Spin Sum and Difference - HallA

E00-110 pioneer experiment with magnetic spectrometer

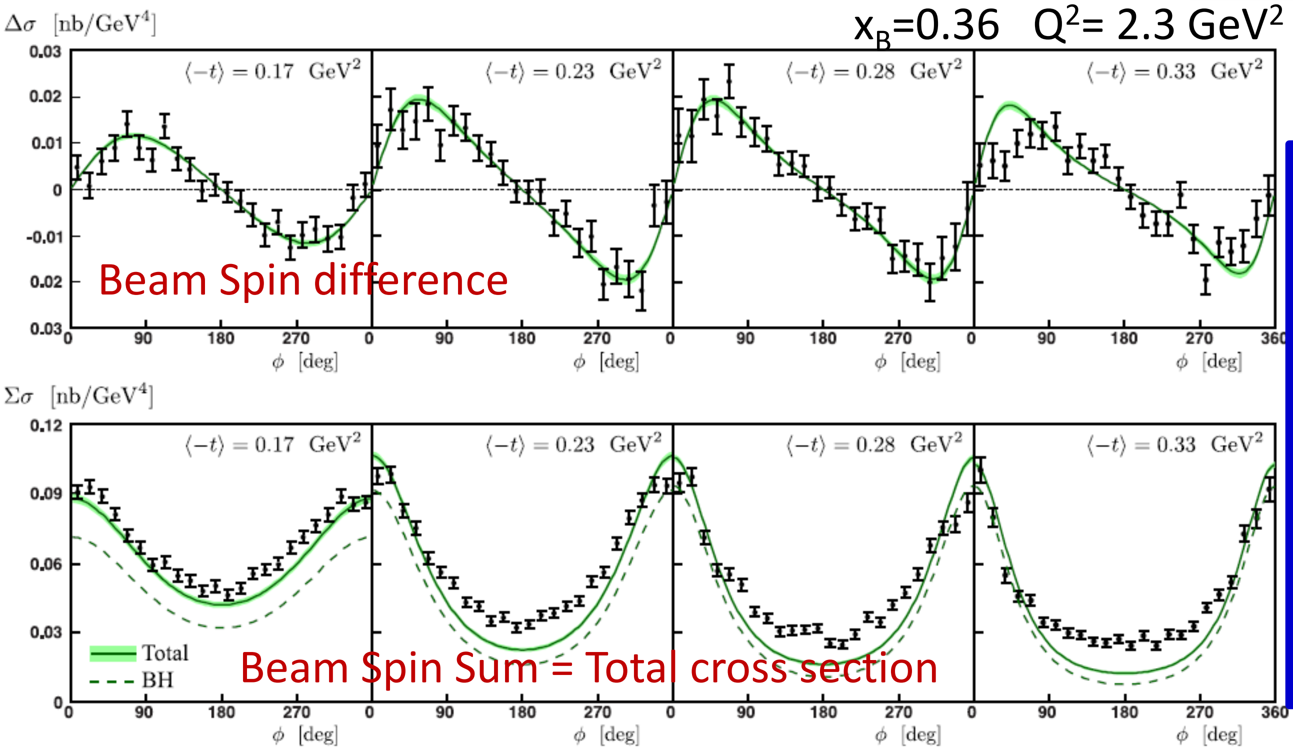
3 measurements: x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2

$\vec{e}\,p \rightarrow e\,\gamma\,p$



Data: Munoz et al. PRL97, 262002 (2006)

Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model



News:

- Re-analysis of the data (MC, RC, normalisation/DIS)
- 2010: run E07-007 Rosenbluth-like DVCS^2/Int sparation
- 2014: HallA with 11 GeV
- 2018: HallC with 11 GeV

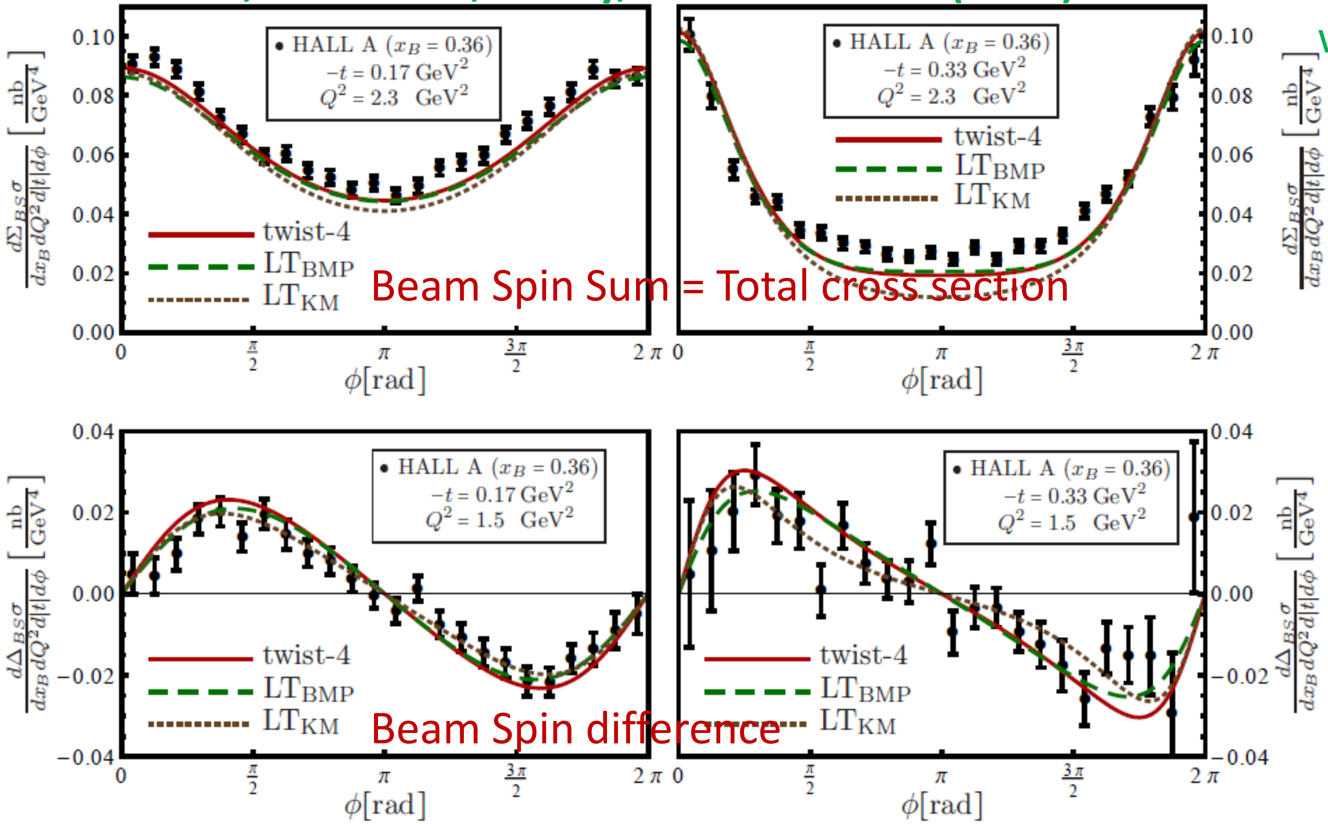
Beam Spin Sum and Difference - HallA

Data: Munoz et al. PRL97, 262002 (2006)

Model: Braun, Manashov, Pirnay, Mueller PRD79 (2014)

GK12 model evaluated with KM and BMP prescription

including kinematic corrections (finite-t, target mass corr.)



Beam Spin Sum = Total cross section

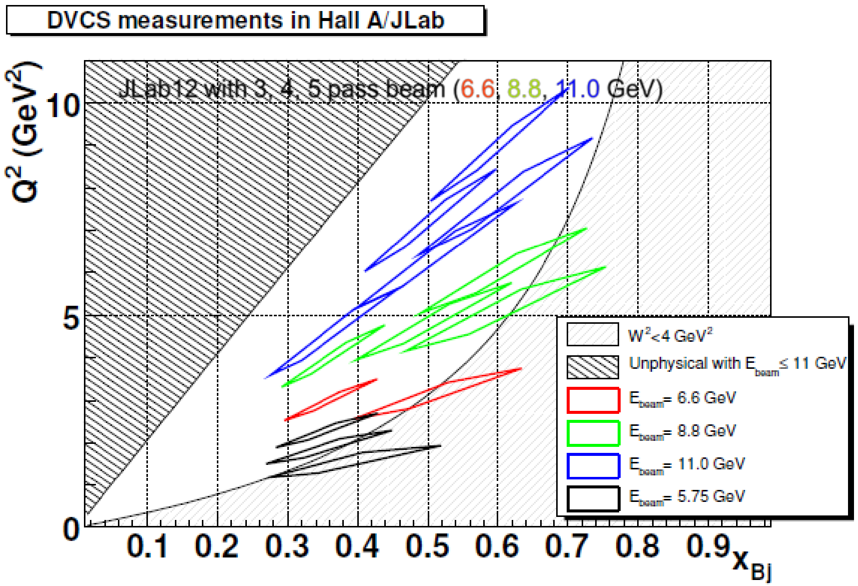
Beam Spin difference

Do we understand Hall A data?

JLAB Hall A & Hall C - future

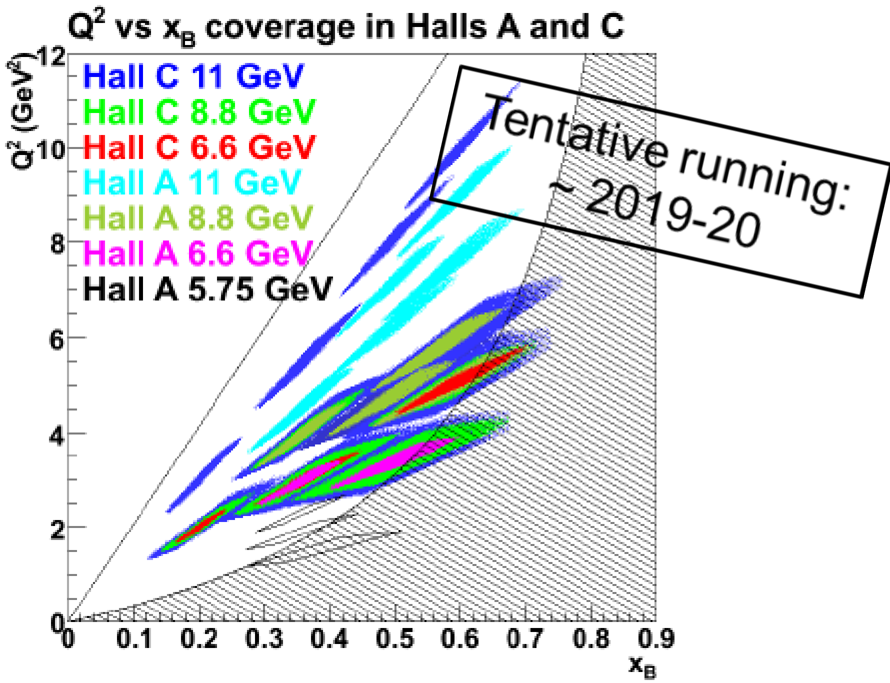
with magnetic spectrometer + Calorimeter

E12-06-114: DVCS at 11 GeV in Hall A



- Absolute cross-section measurements
- Test of scaling: Q^2 dependence of dσ at fixed x_{Bj}
- Increased kinematical coverage

Start on Feb 2014,
for 1 year of data taking



E12-13-010: DVCS at 11 GeV in Hall C

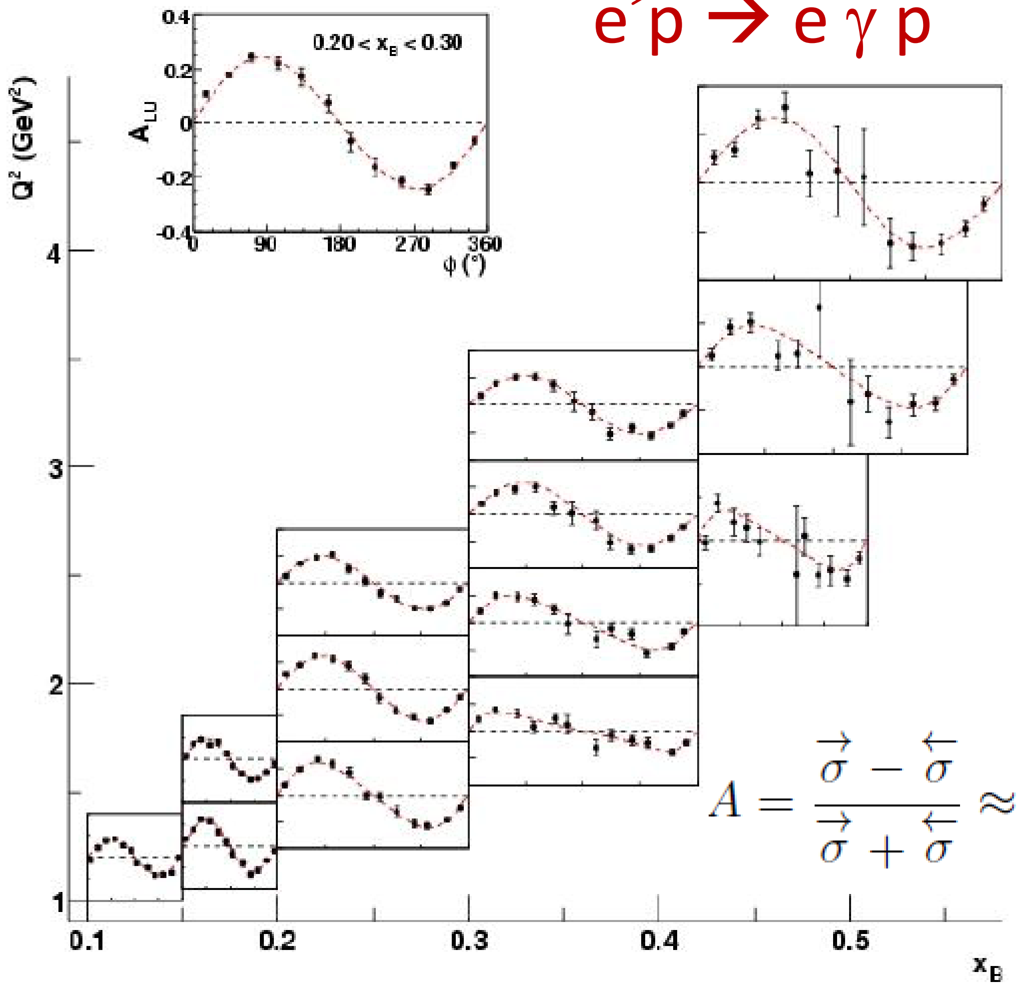
- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low-x_B extension (thanks to sweeping magnet)

Need a new challenging Calorimeter

CLAS: BSA in a large kinematic domain

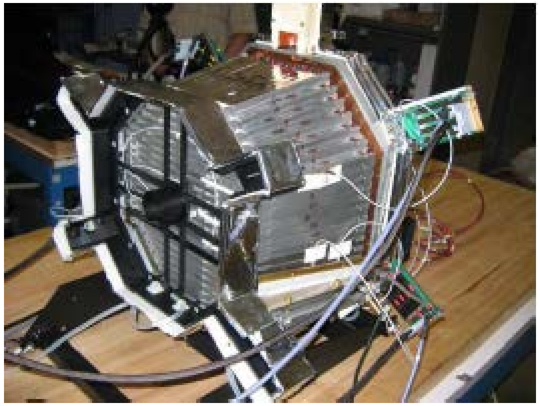
Part 1 of the E01-113 or e1-DVCS exp

$\vec{e}p \rightarrow e\gamma p$



Data: Girod et al. PRL100, 162002 (2008)

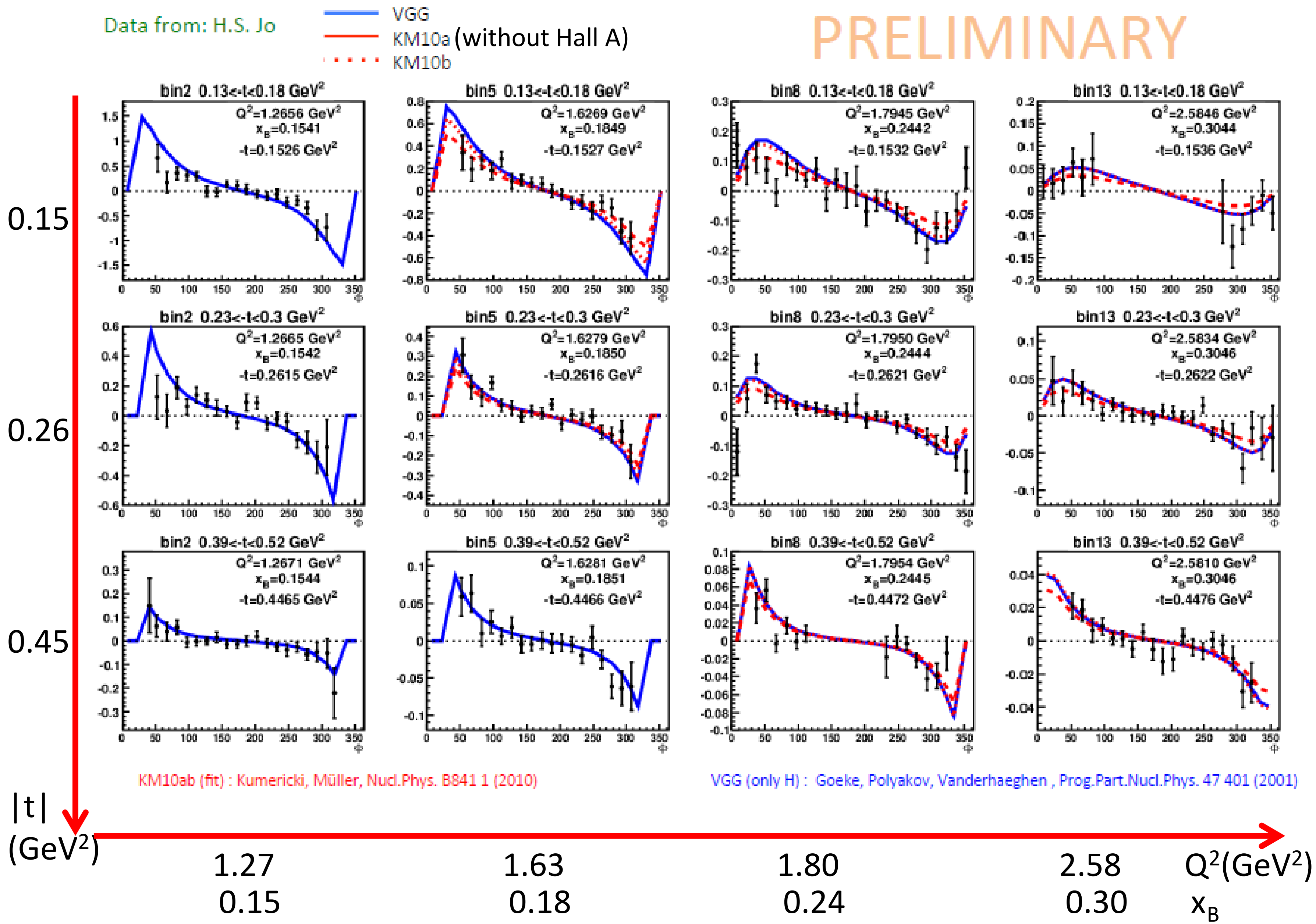
CLAS + Inner Calorimter
Solenoid magnet



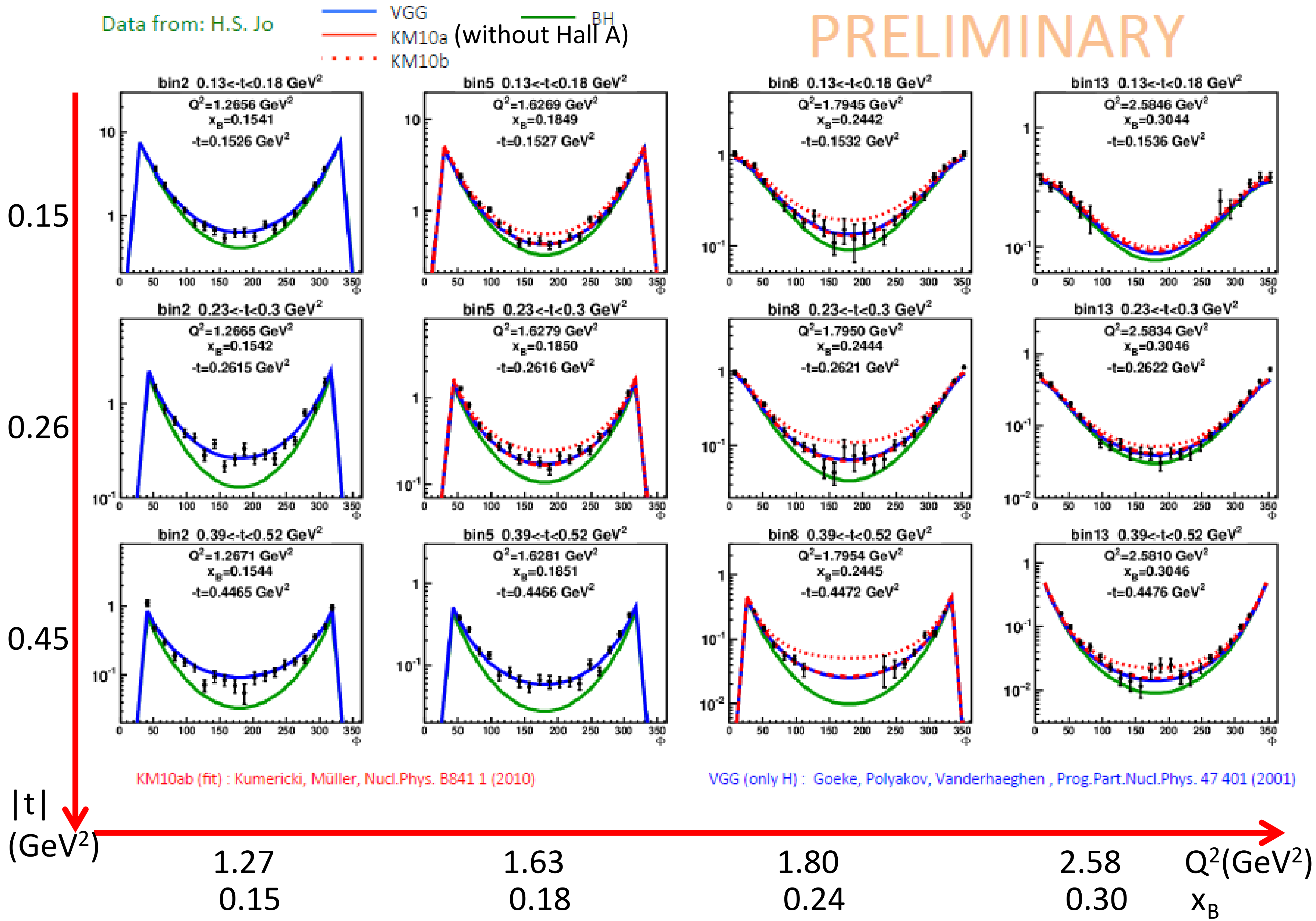
$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \approx \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

No simple interpretation of α

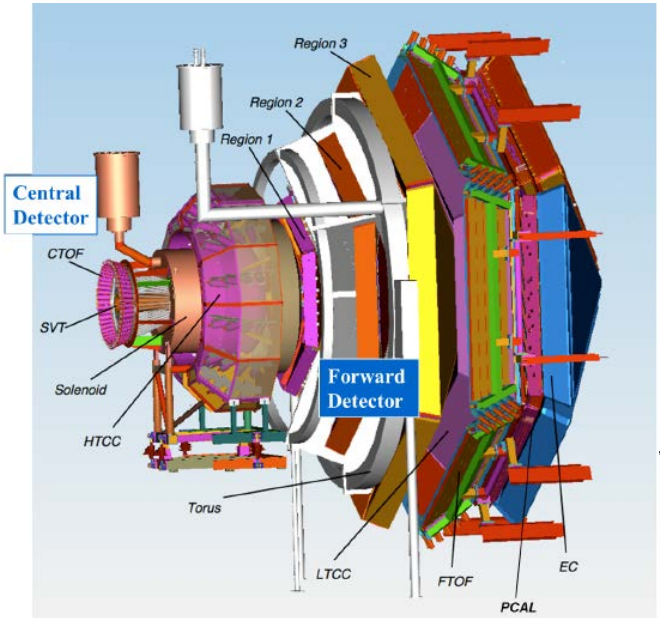
Beam Spin Difference - CLAS



Beam Spin Sum - CLAS



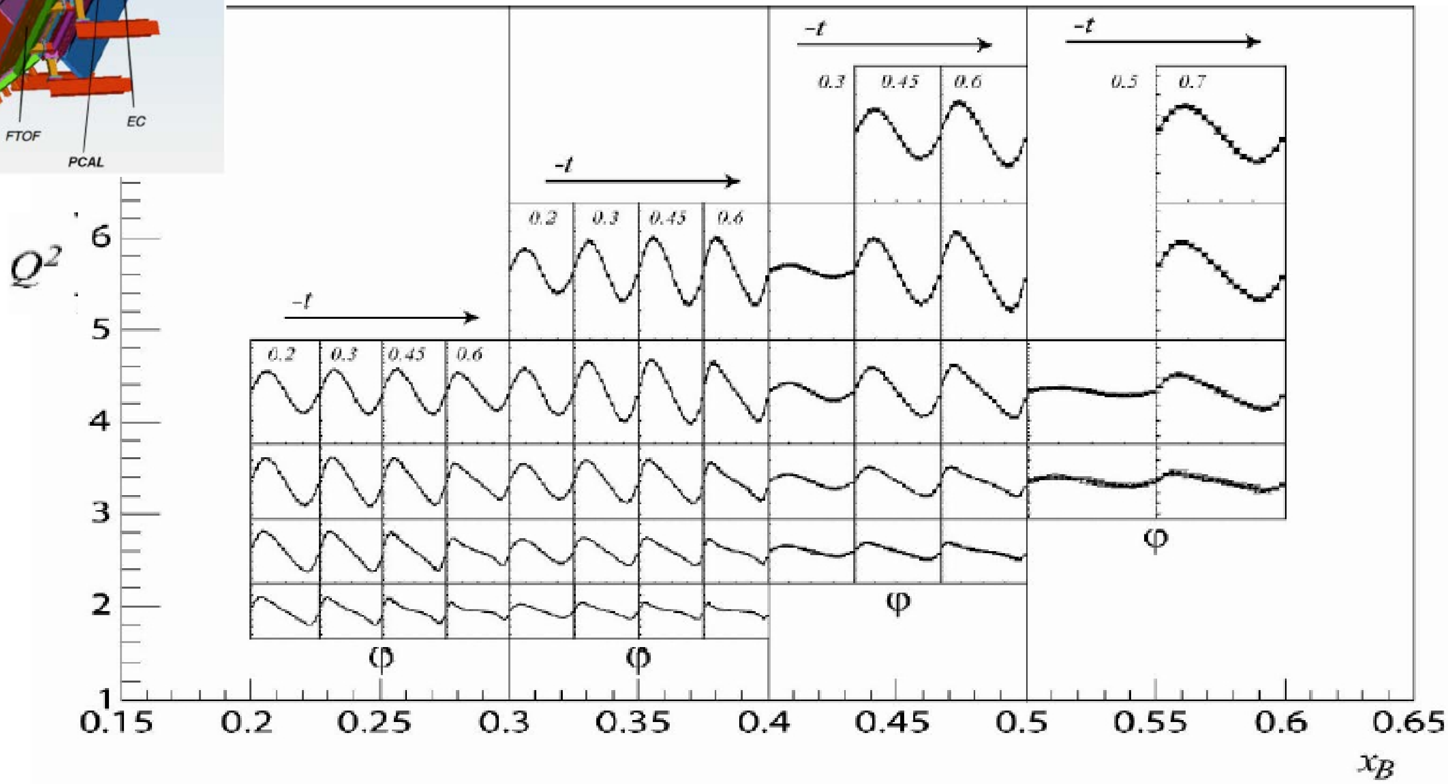
Future - CLAS12



E12-06-119

Strong effort in Detector upgrades

LH_2 Target and Long. Pol. Target in 2016

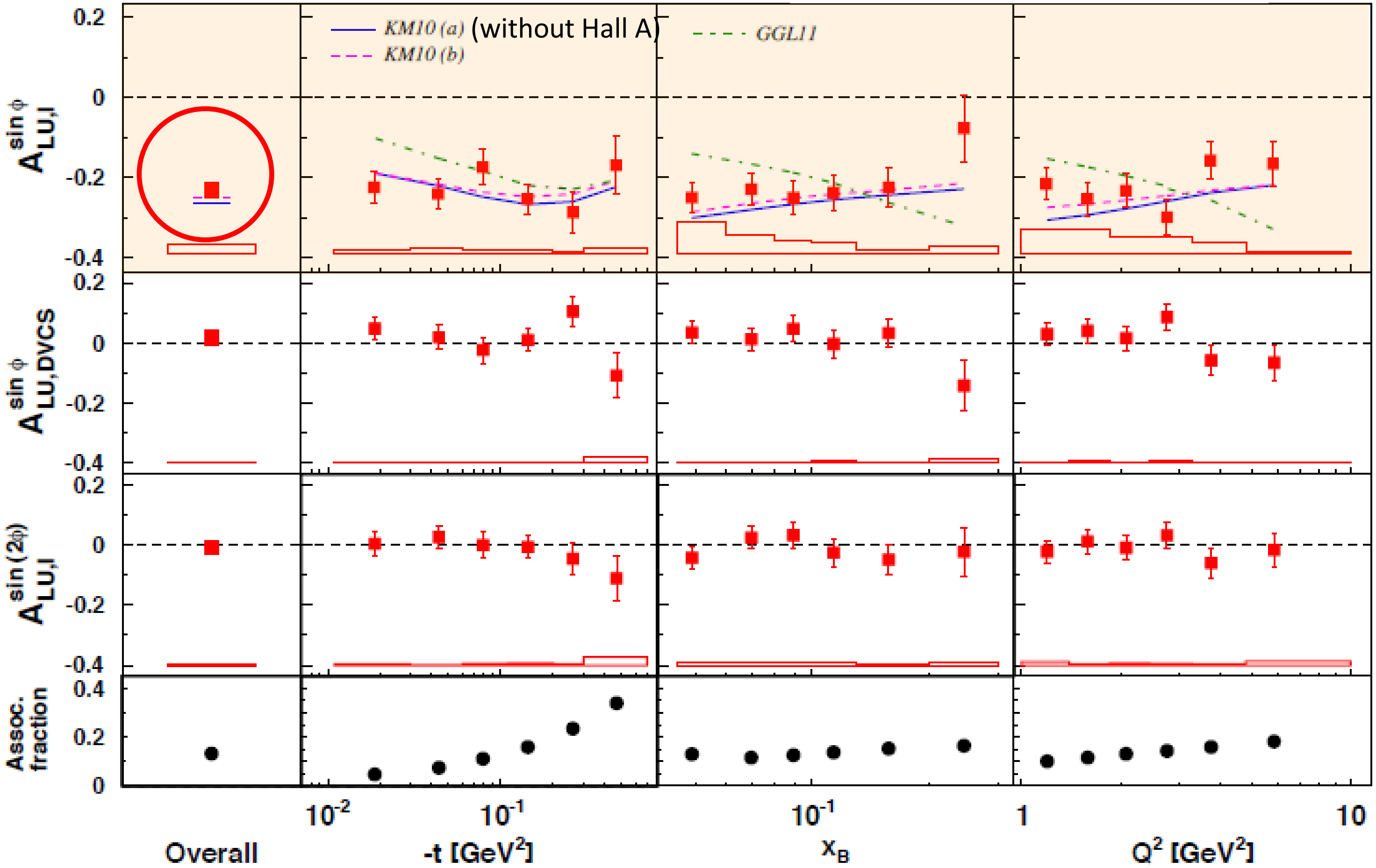


BSA - HERMES

Complete data set including 2006-07

A. Airapetian et al, JHEP 07 (2012) 032

GHL11 - flexible parameterization



sin ϕ term

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

sinϕ term
from DVCS^2

sin 2ϕ term
higher twist

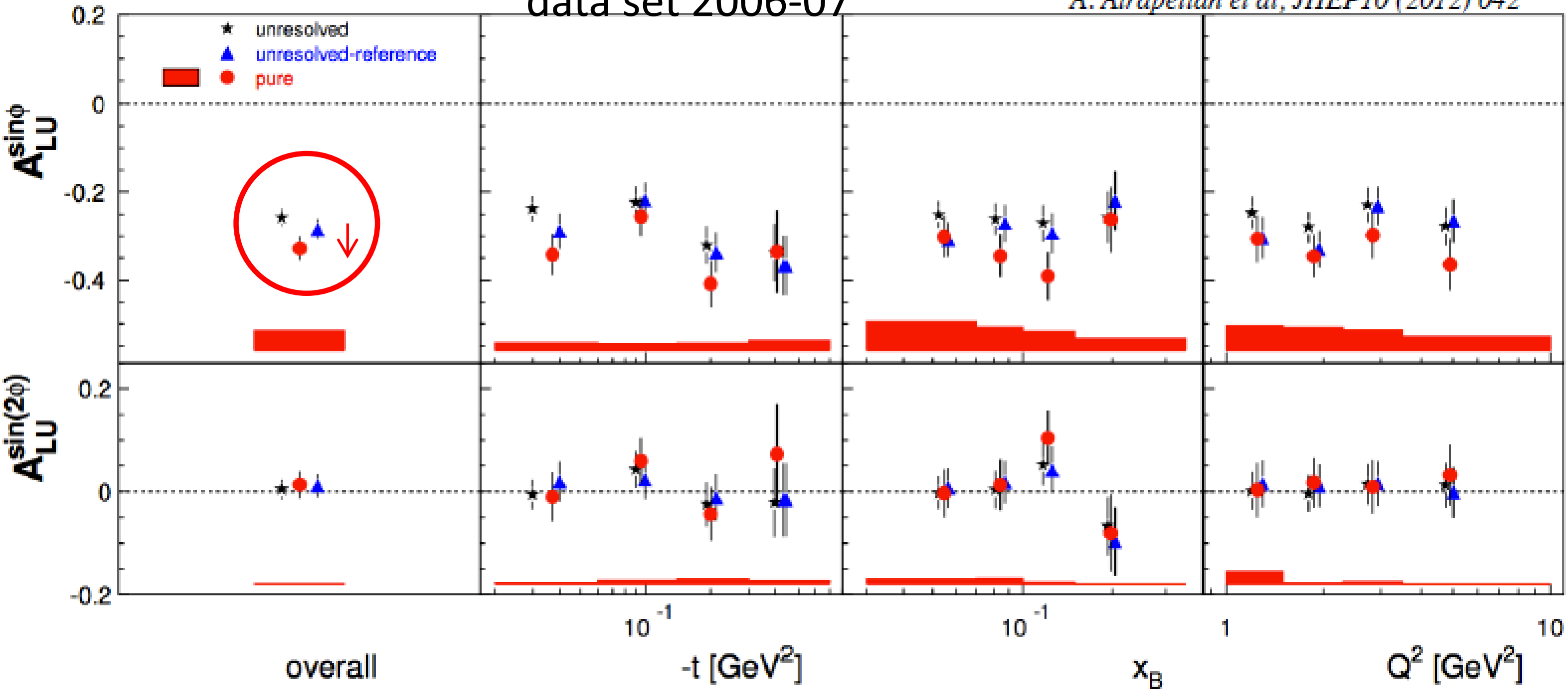
resonant fraction
ep → eγΔ$^+$

Kumericki,Müller Nucl. Phys. B841 (2010)
Goldstein, Hernandez, Liuti Phys. Rev. D84 (20101)

BSA with recoil detector - HERMES

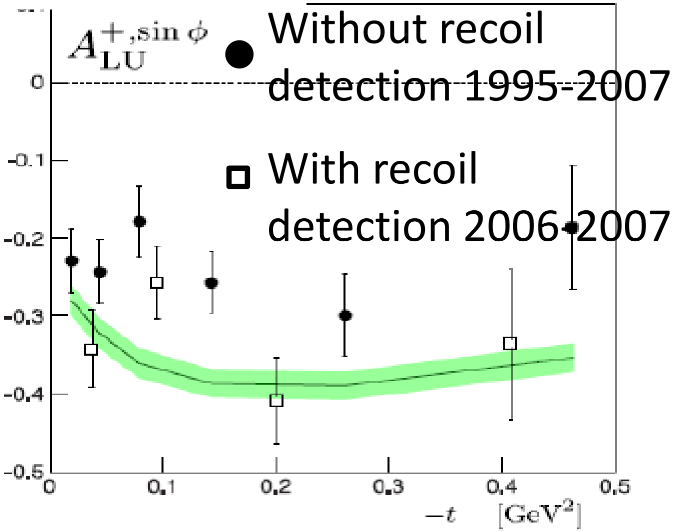
data set 2006-07

A. Airapetian et al, JHEP10 (2012) 042



High-purity event selection shows that there is only a small influence on the extracted BSA amplitude from events involving a Δ particle (associated DVCS)

The leading asymmetry has increased by 0.054 ± 0.016
Mainly dilution due to associated DVCS

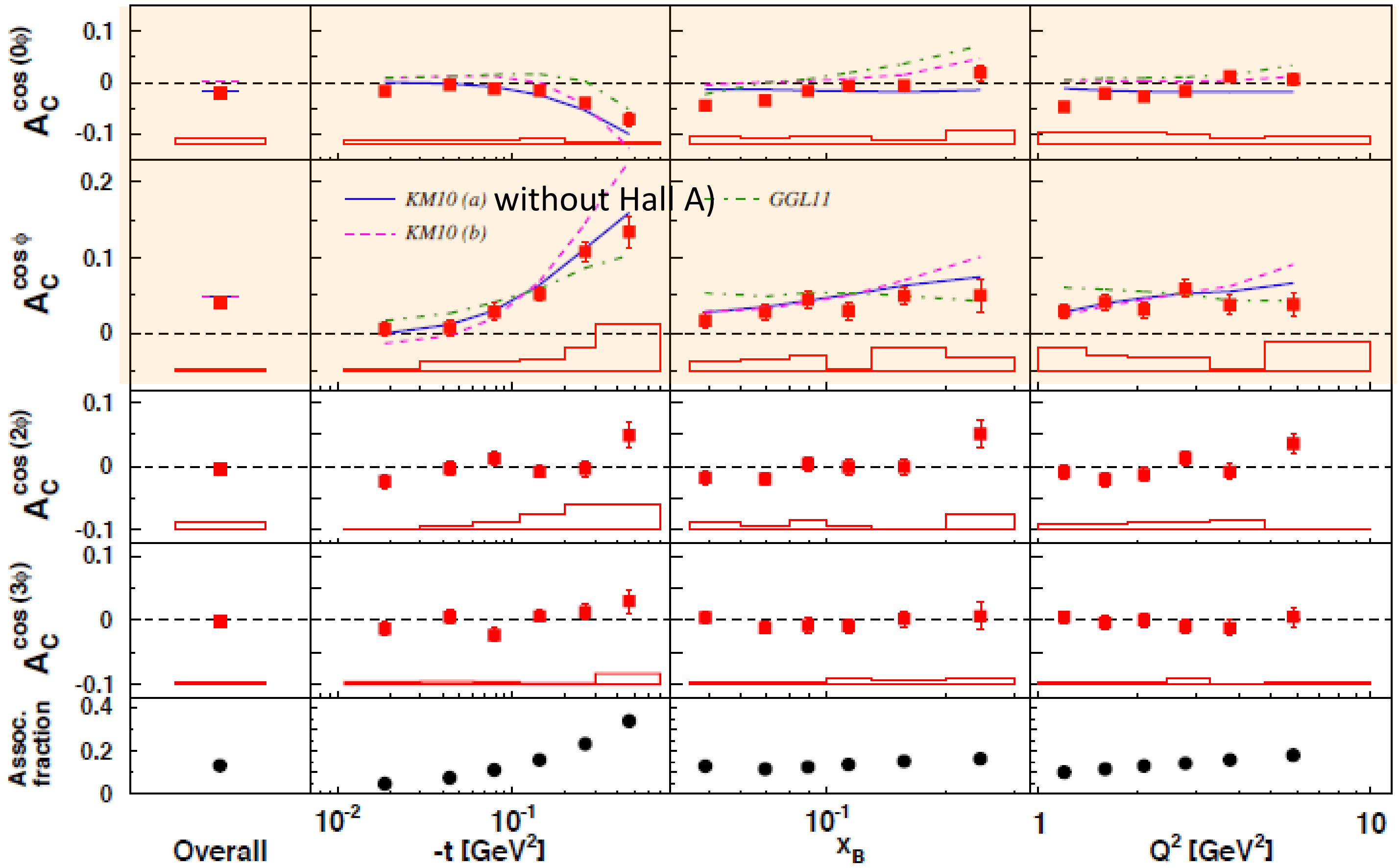


Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model

BCA - HERMES

Complete data set including 2006-07 without recoil detection

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



constant term

cos ϕ term

Re **F1** *H*

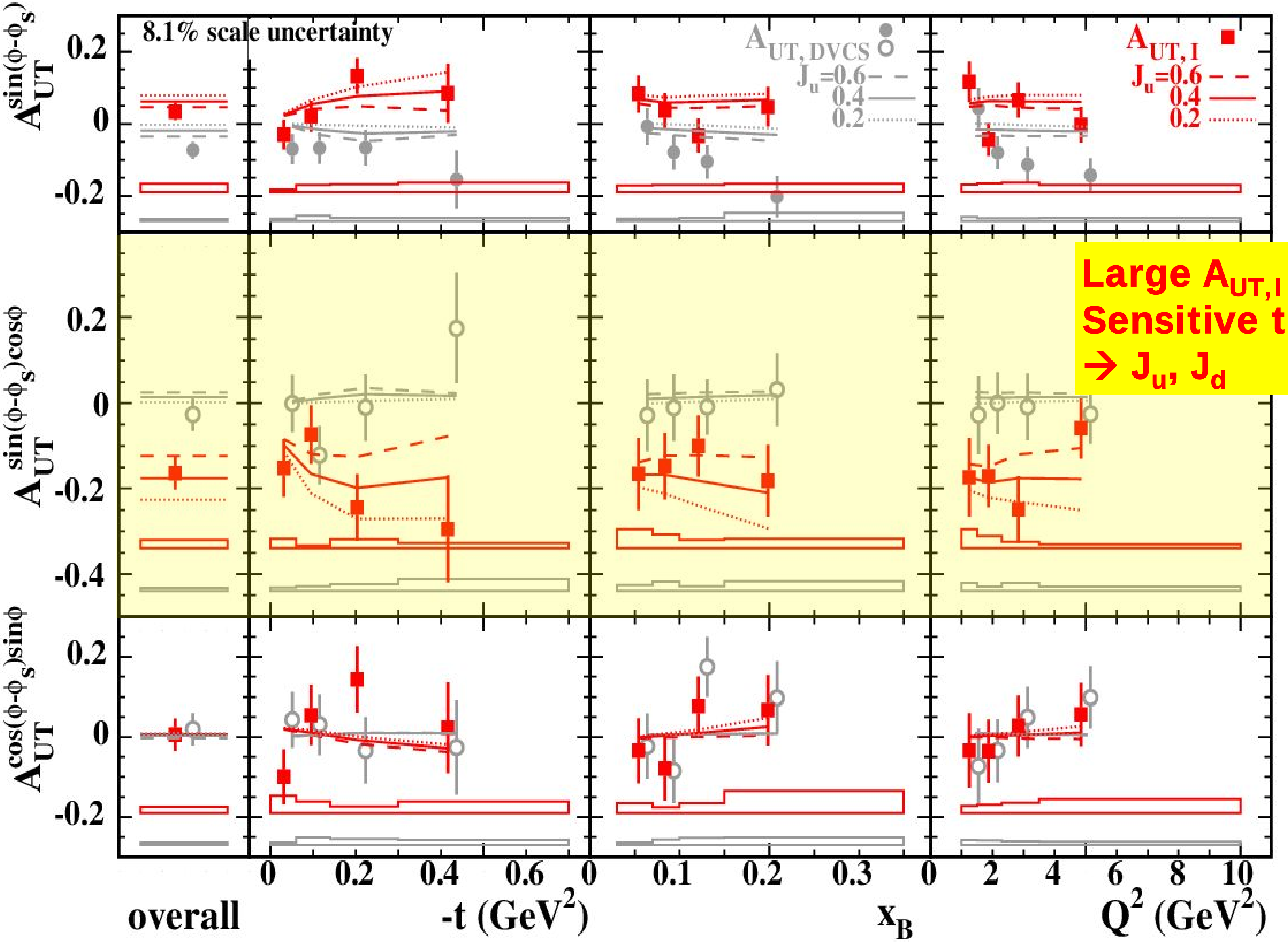
cos 2ϕ term
higher twist

cos 3ϕ term
gluon twist

resonant fraction
ep → eγΔ$^+$

Kumericki,Müller Nucl. Phys. B841 (2010)
Goldstein, Hernandez, Liuti Phys. Rev. D84 (20101)

GPD E Trans. Target Spin Asymmetry (Proton) HERMES



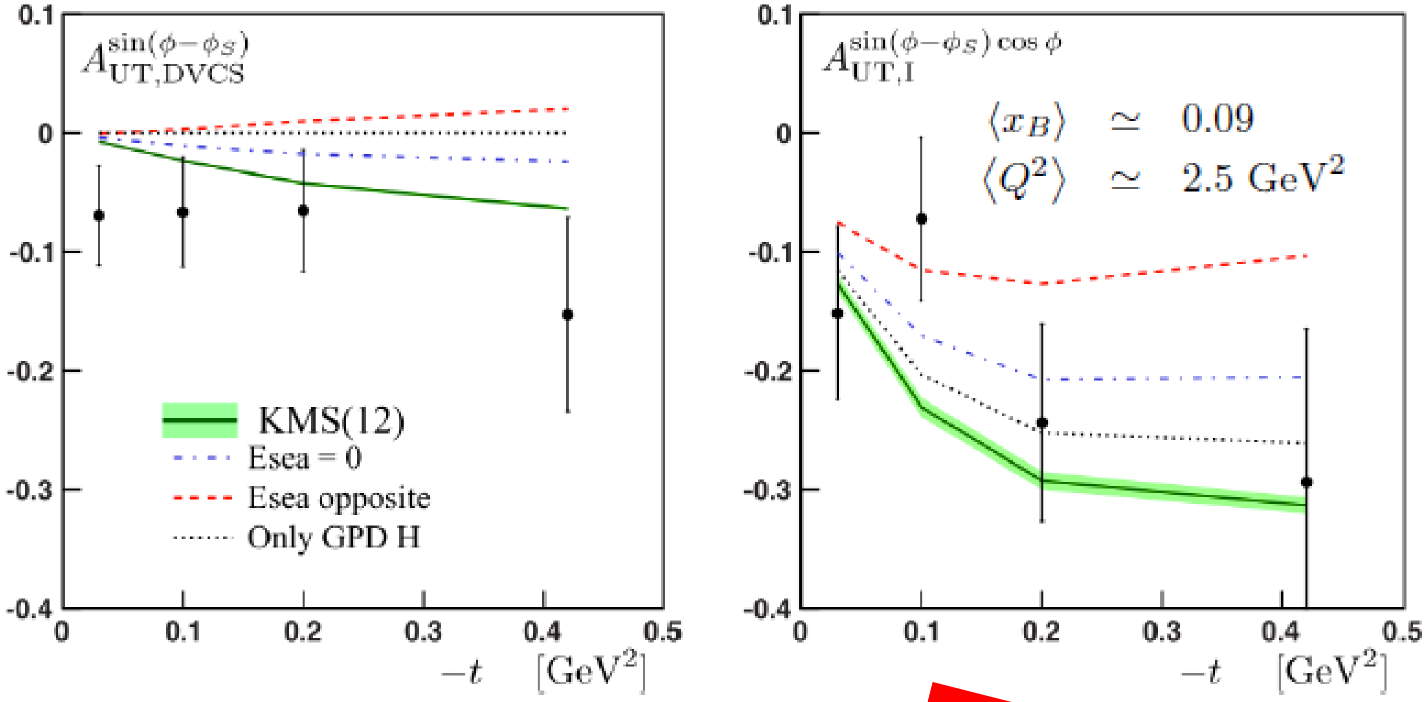
Also large $A_{UT,DVCS}$ $\sin(\phi-\phi_S)$ With strong x_{Bj} dependence

Large $A_{UT,I}$ $\sin(\phi-\phi_S)\cos\phi$ Sensitive to GPD E → J_u, J_d (VGG model)

Airapetian et al., HERMES, JHEP06 (2008) 066

Trans. Target Spin Asymmetry (Proton) - HERMES

Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model



E^{sea} < 0 is favored by HERMES data

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

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

cancellation between $\mathcal{E}^s$ and $\mathcal{E}^g$ does not occur as for ρ^0 asymmetry, DVCS observables are very sensitive to E_{sea}

Hunting the GPD E with CLAS12 at Jlab

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

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

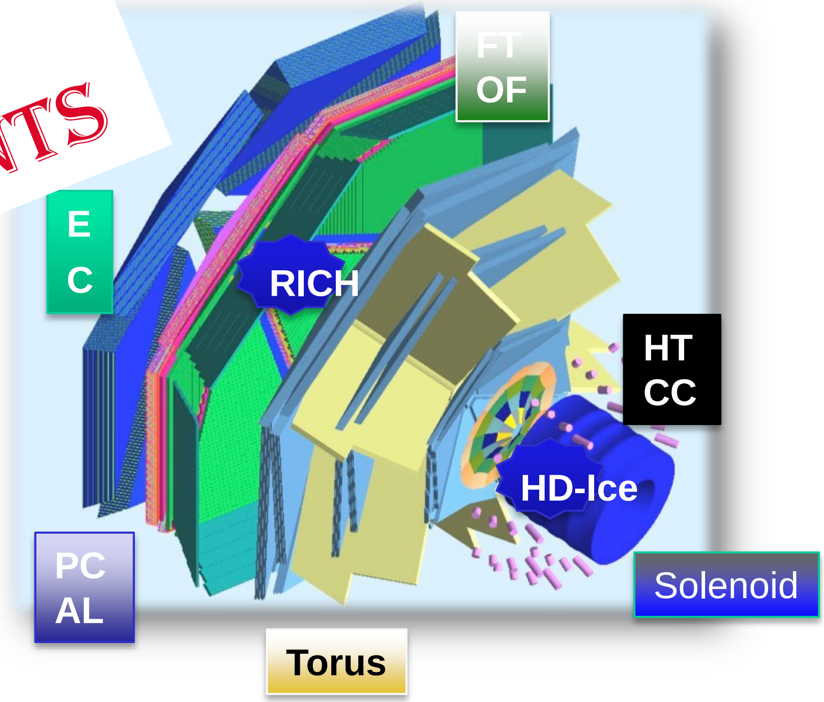
With LD2 target + CLAS12
+ Forward Calorimeter
+ Neutron Detector ToF

$\vec{e}\, \vec{p} \rightarrow e\, p\, \gamma$ 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 the **HD ice target**
(transv pol =60% H)
+ CLAS12

SELECTED IN THE «HIGH IMPACT» EXPERIMENTS

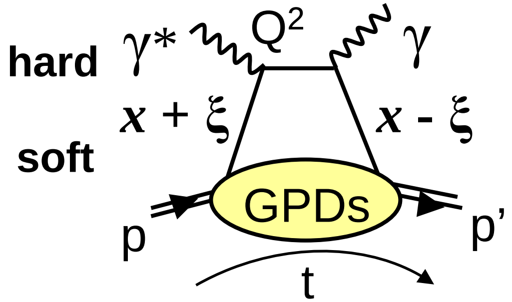


The End

Thank you for your attention

Dragon: among many others it is a symbol for fortune and glory ... like the measurements of GPDs

Compton Form Factors are measured in DVCS



The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

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

t, $\xi \sim x_{Bj/2}$ fixed

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

Im part measured in **Beam Spin** or **Target Spin** asymmetries

Real part measured in **Beam Charge** asymmetry or **cross section**

$\mathcal{D}$ *term* related to the Energy-Momentum Tensor :

Polyakov, PLB 555 (2003) 57-62