Experimental Overview of GPDs

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Transversity 2017, 11-15/12/2017, Frascati

DVCS on proton -> GPD *H*

Beam Spin Asym: HallA – CLAS - HERMES
Beam Charge Asym: HERMES – H1 – (COMPASS)
Cross section diff and sum: HallA – CLAS – COMPASS

Proton « tomography »

t-slope of DVCS x-section: H1 – ZEUS – COMPASS
Global fits of CFFs: HallA – CLAS

Exclusive p0 production: « transversity » GPDs

Cross section measurement: HallA – CLAS – COMPASS

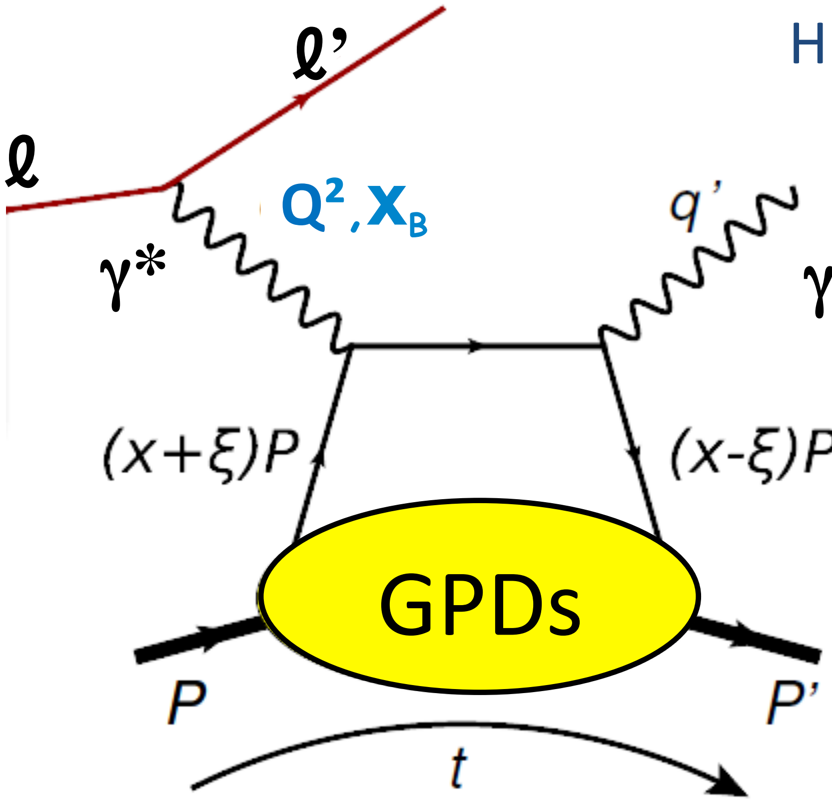
Hunting the GPD *E* → 'Holy grail' for OAM

Transv. Pol. Target Asym on the proton - HERMES - (JLab) – (COMPASS)
Beam Spin cross section on the neutron – HallA – (Jlab)

Exclusive reactions: DVCS and HEMP

DVCS: ℓp→ ℓ' p' γ (« golden » channel)

HEMP: **ℓp→ ℓ' p' ρ or φ or J/ψ,…**



Definition of variables:

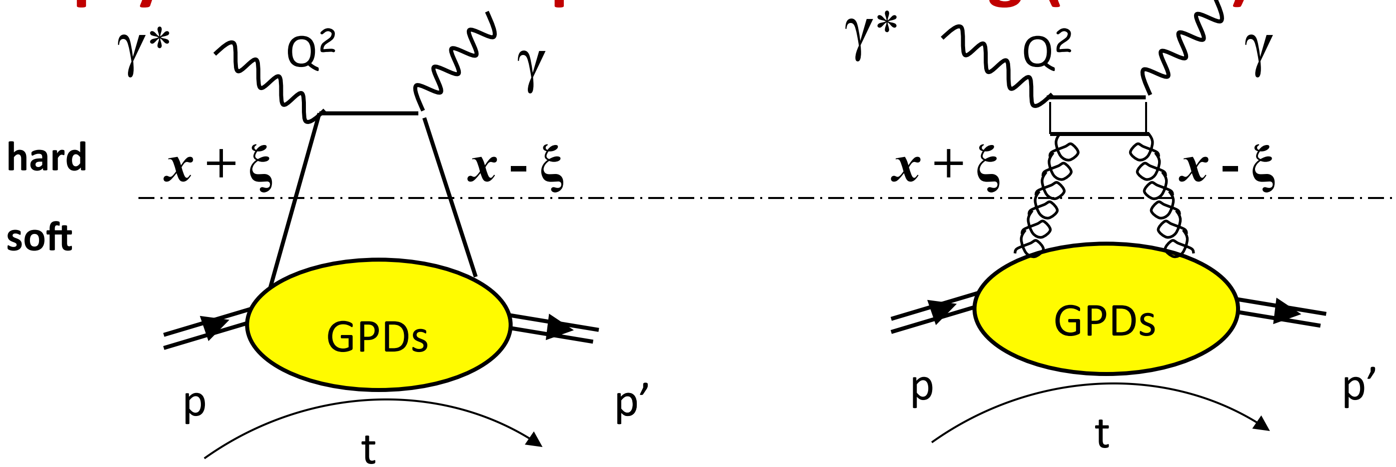
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

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)

Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):

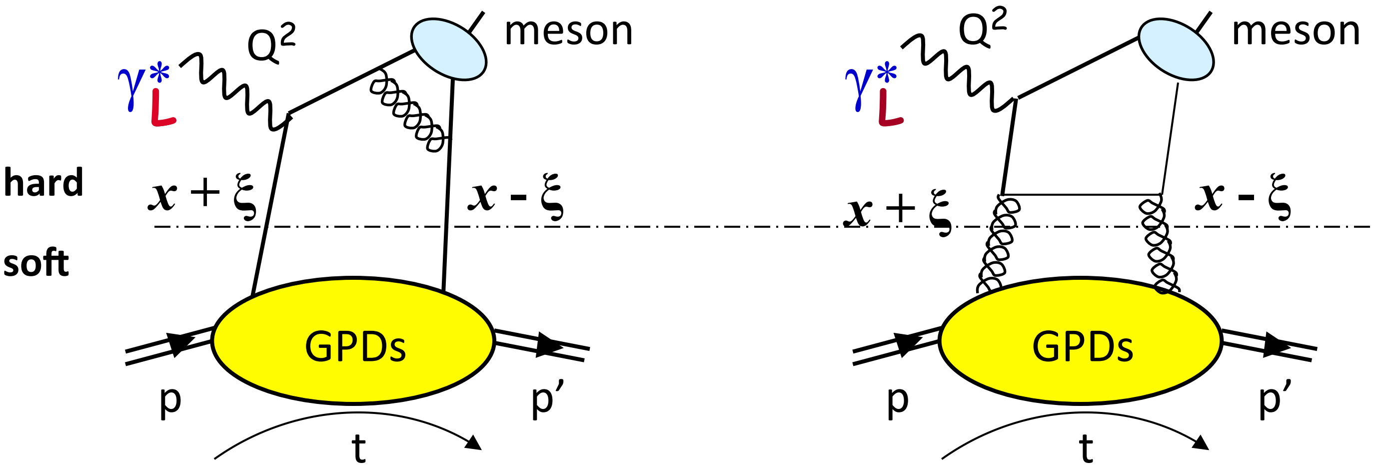
Factorisation:
Collins *et al.*



Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):



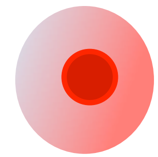
+ γ^*_L

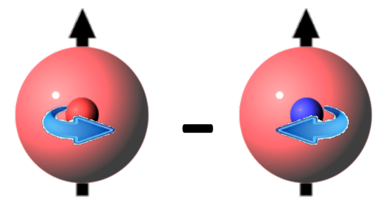
Meson w.f.
Large power & NLO
Very slow scaling

Quark contribution **Gluon contribution**

8 GPDs ←→ 8 TMDs

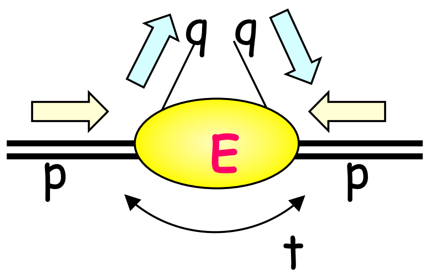
4 Chiral-even

$H \longleftrightarrow q$ or f_1 

"Elusive" $E \sim f_{1T}^{\perp}$ 

Sivers: quark k_T
& nucleon transv. Spin

Ji: $2J^q = \int x \, (H^q(x,\xi,0) + E^q(x,\xi,0)) \, dx$



Relation to OAM

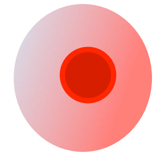
+ their partner for polarised quarks

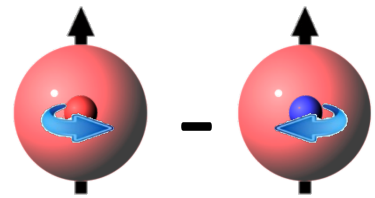
$\tilde{H} \longleftrightarrow \Delta q$ or g_{1L}

$\tilde{E} \sim g_{1T}$

8 GPDs ←→ 8 TMDs

2 of the 4 Chiral-even

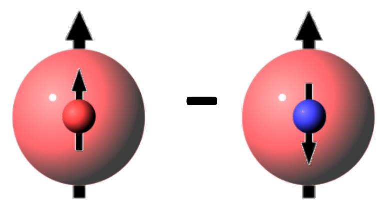
H ←→ q or f_1 

"Elusive" $E \sim f_{1T}^{\perp}$ 

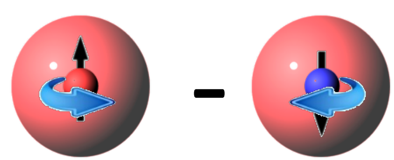
Sivers: quark k_T
& nucleon transv. Spin

Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

2 of the 4 Chiral-odd

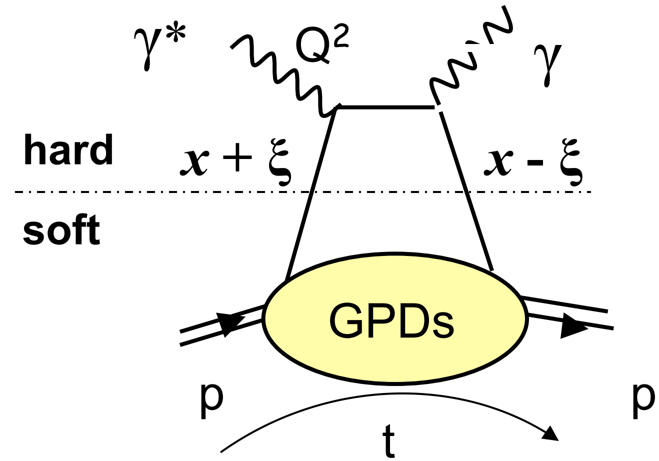
H_T ←→ h_1 

Transversity: quark spin
& nucleon transv. spin

$\bar{E}_T = 2\tilde{H}_T + E_T \sim h_1^{\perp}$ 

Boer-Mulders: quark k_T
& quark transverse spin

From DVCS to Compton Form Factors

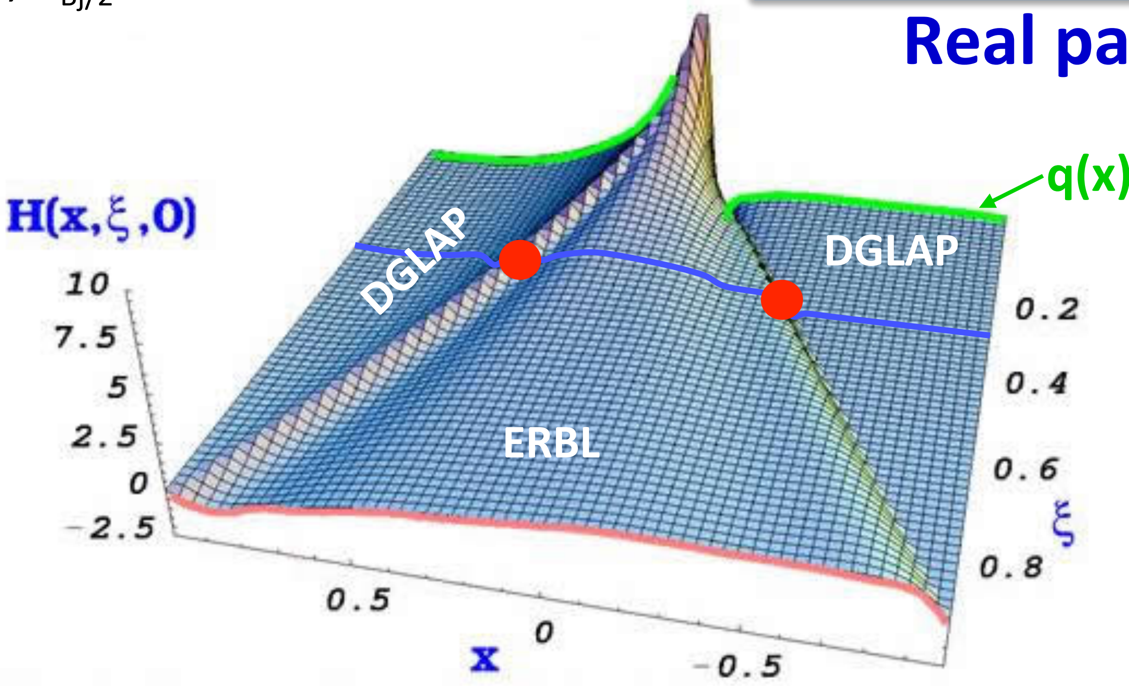


The DVCS amplitude at LT & LO in α_S:

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

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

Real part | **Imaginary part**

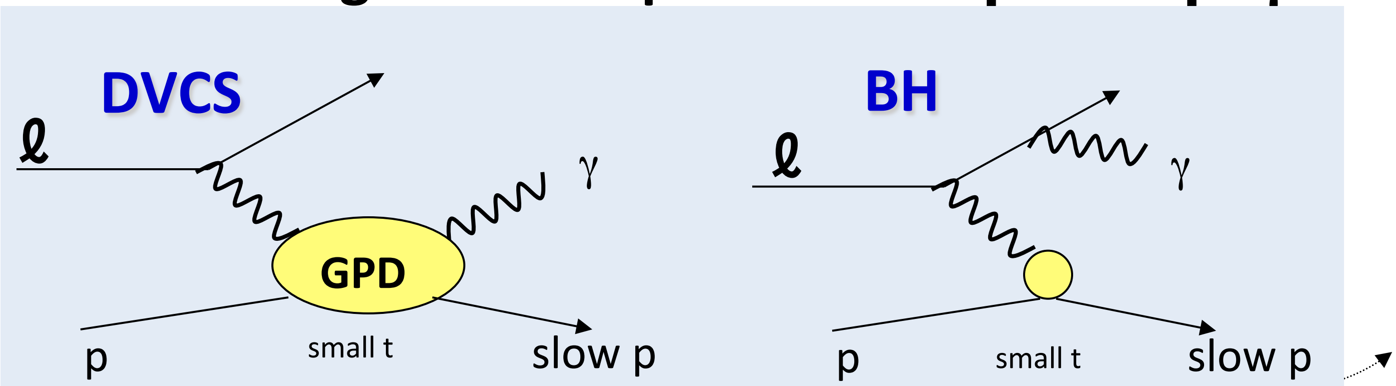


Im part measured in
Beam Spin
or **Target Spin** asymmetries

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

DVCS (golden channel) → CFF→ GPD H (E)

Exclusive Single Photon production ℓp→ ℓ' p' γ

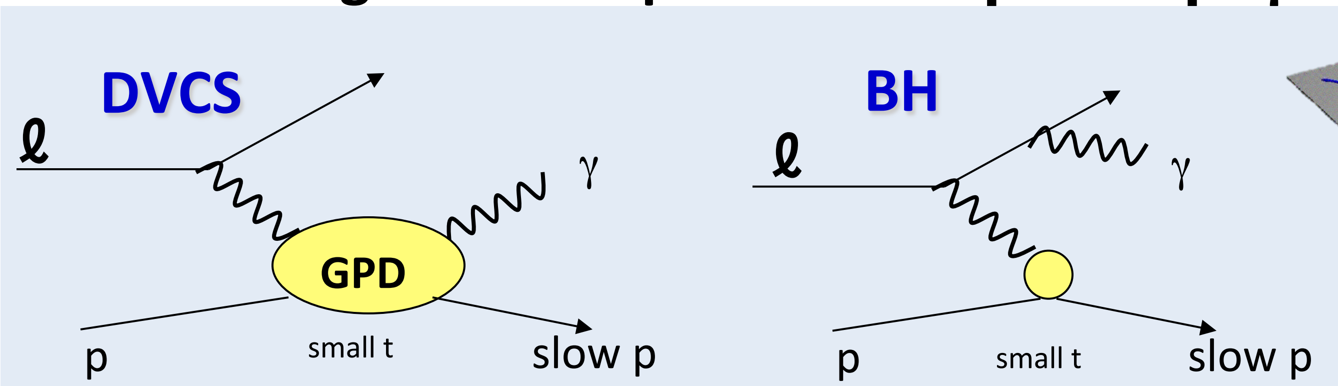


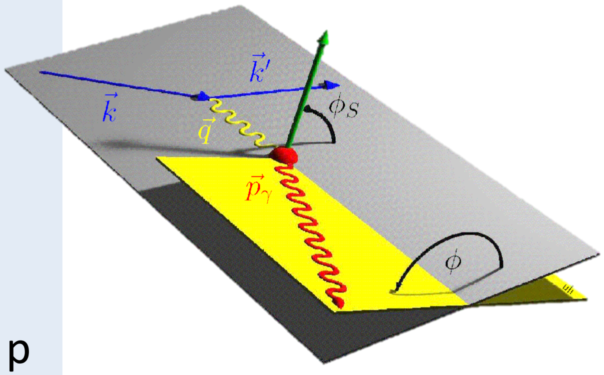
$d\sigma \propto |T^{BH}|^2 + Im(T^{DVCS}) \cdot T^{BH} + Re(T^{DVCS}) \cdot T^{BH} + |T^{DVCS}|^2$

Known to 1 %   Linear combination of GPDs   bilinear combination of GPDs

DVCS (golden channel) → CFF→ GPD H (E)

Exclusive Single Photon production $\ell p \rightarrow \ell' p' \gamma$





$$d\sigma \propto |T^{BH}|^2 + Im(T^{DVCS}) \cdot T^{BH} + Re(T^{DVCS}) \cdot T^{BH} + |T^{DVCS}|^2$$

Known to 1 % — Linear combination of GPDs — bilinear combination of GPDs

Beam Charge Difference on proton

small x_B

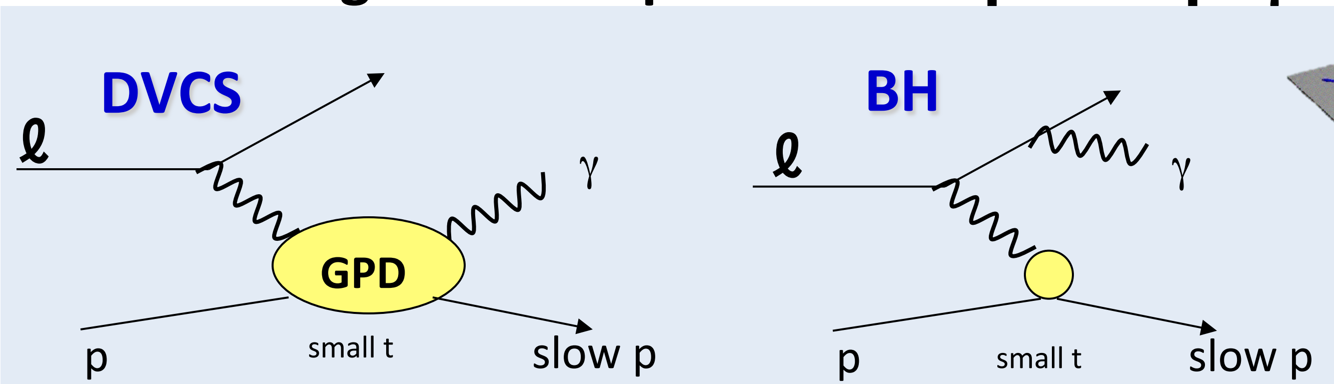
$$A_C^{\cos\phi} = Re\left(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - t/4m^2 F_2\mathcal{E}\right) \rightarrow Re\,(F_1\mathcal{H})$$

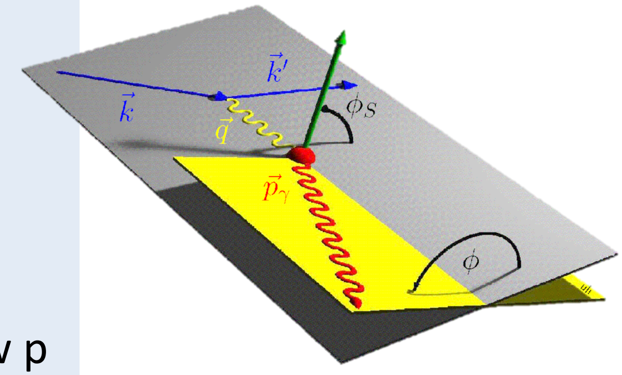
Beam Spin Difference on proton

$$A_{LU}^{\sin\phi} = Im\left(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - t/4m^2 F_2\mathcal{E}\right) \rightarrow Im\,(F_1\mathcal{H})$$

DVCS (golden channel) → CFF→ GPD H (E)

Exclusive Single Photon production ℓp→ ℓ' p' γ





$d\sigma \; \alpha \; |T^{BH}|^2 \; + \; Im(T^{DVCS}) \cdot T^{BH} + Re(T^{DVCS}) \cdot T^{BH} \; + \; |T^{DVCS}|^2$

Known to 1 % — Linear combination of GPDs — bilinear combination of GPDs

Beam Spin Asym on **neutron**

$A_{LU}^{\sin\phi} \rightarrow Im\,(F_{1n}\mathcal{H} - F_{2n}\mathcal{E})$

$\mathcal{H}$ and $\mathcal{E}$

On the same footing

Transv. Target Spin Asym on proton

$A_{UT}^{\sin(\phi-\phi s)\cos\phi} \rightarrow Im\,(F_2\,\mathcal{H} - F_1\mathcal{E})$

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

Hard Exclusive Meson Production (HEMP):

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

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

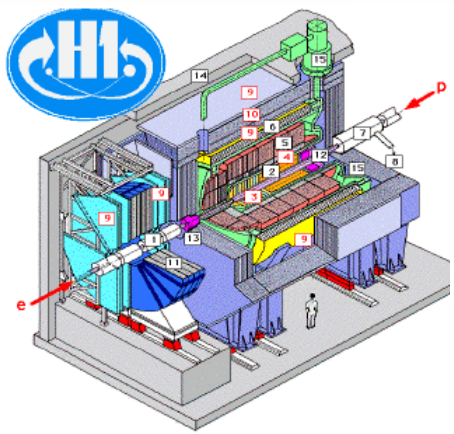
$$H\rho^0 = 1/\sqrt{2}\,(2/3\, H^u + 1/3\, H^d + 3/8\, H^g)$$

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

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

See talk by **C. Van Hulse**
On Monday

The past and future experiments



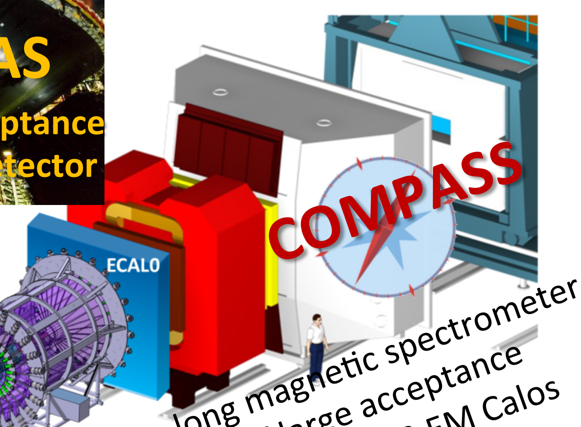
Collider mode e-p forward fast proton

HERA: **H1** and **ZEUS**
Polarised 27 GeV e-/e+
Unpolarized 920 GeV proton
~ Full event reconstruction

Fixed target mode slow recoil proton

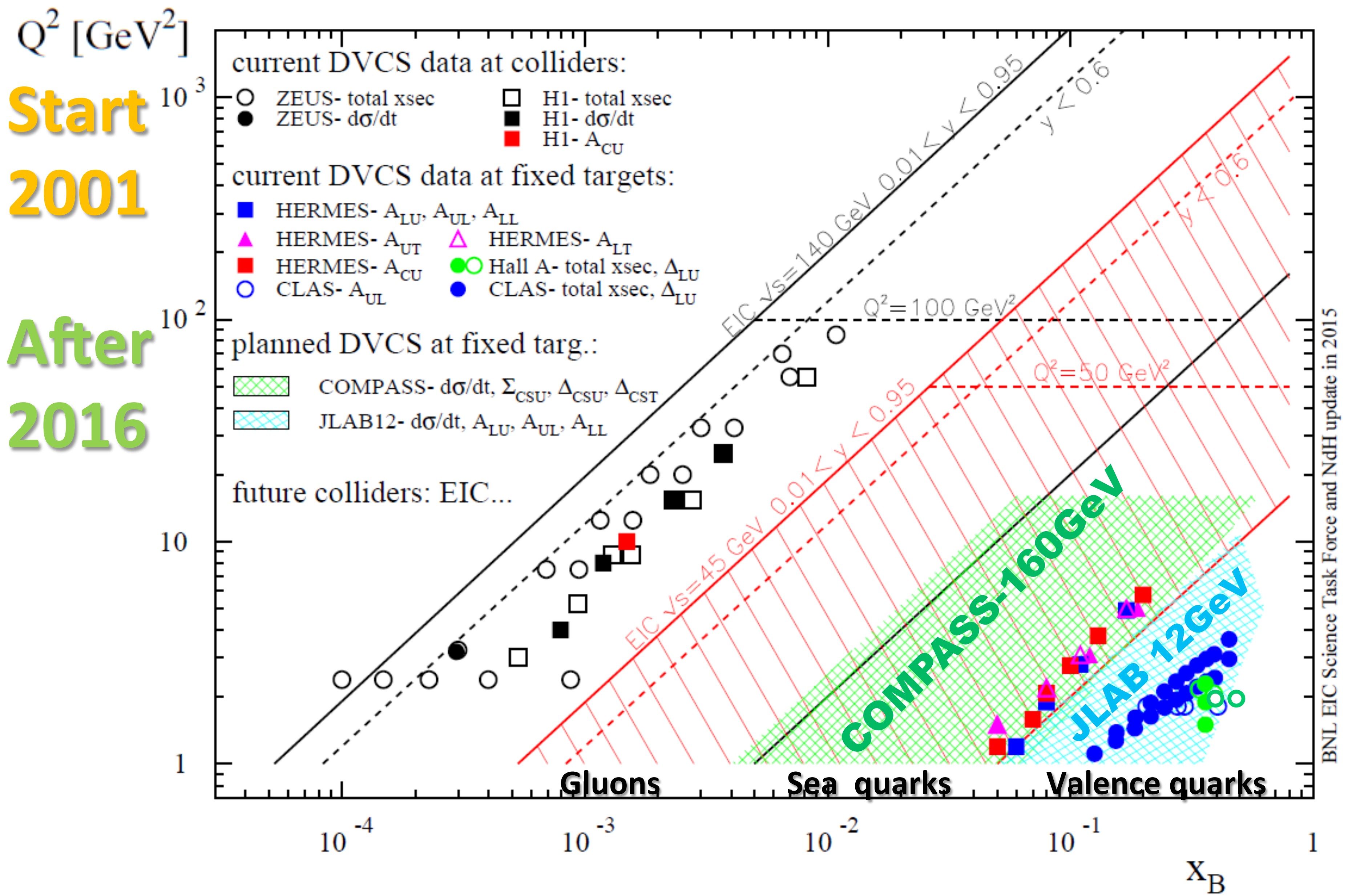
HERMES: Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector

Jlab: Hall A, C, CLAS High lumi, polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique



COMPASS @ CERN: Polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
2012-17 with recoil detection

The past and future DVCS experiments



DVCS-BH interference on the proton

→ *Im* DVCS with Beam Helicity Dependent X-sect.

→ *Re* DVCS with Beam Charge Difference and Unpolarized X-section

→ mainly constrains on the GPD H

Beam Charge or Spin **Asymmetries**

→ easier to measure, harder to interpret

Beam Charge or Spin **x-section diff./sum**

→ harder to measure, more direct to interpret

Azimuthal dependence of BH+DVCS

$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell \, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell \, \mathrm{Im}\, I)$$

Well known

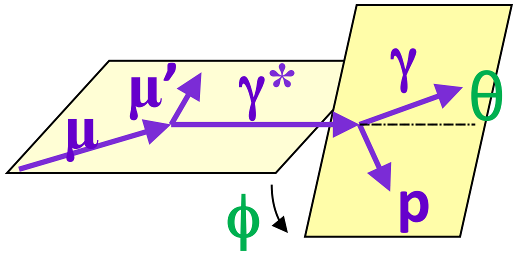
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



Twist-2 >>

- Twist-3,
- Twist-2 double helicity flip for gluons

$s_1^I = Im\ \mathcal{F}$ $\quad$ $c_1^I = Re\ \mathcal{F}$

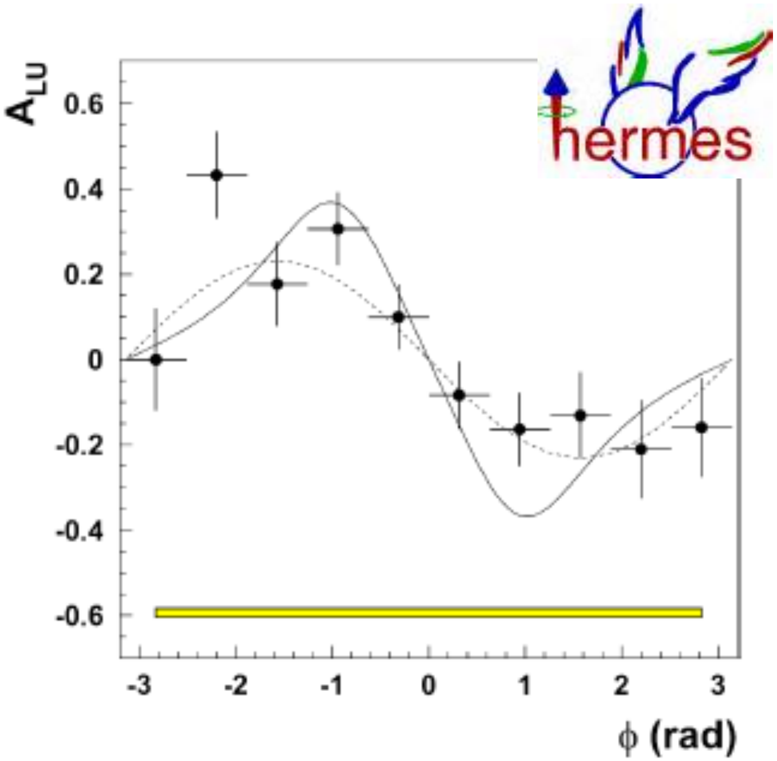
$$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - t/4m^2 F_2\mathcal{E} \xrightarrow{\text{at small } x_B} F_1\mathcal{H} \quad \text{for proton}$$

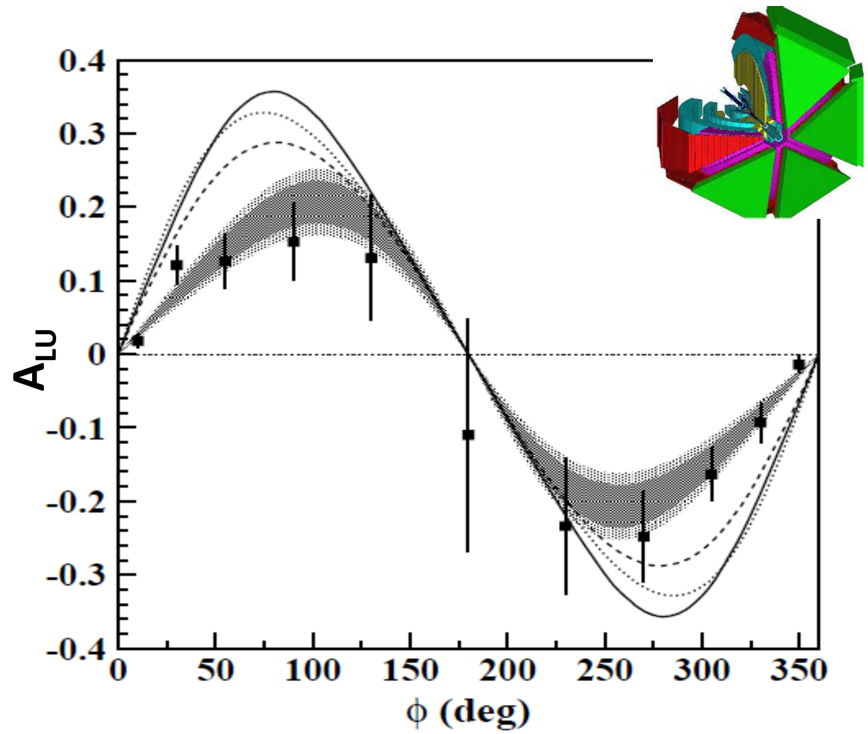
NB: to extract $\mathcal{E}$ use a neutron (deuteron) target or a transversely pol. target

to extract $\tilde{\mathcal{H}}$ use a longitudinally polarized target

First DVCS interference signals

BSA asymmetries – PRL87 (2001)





Validate the dominance of the handag contribution (Fit and VGG model)

BSA and BCA with HERMES

Last analyses with the complete set of data including 2006-07

Combined analysis of charge and polarisation observables
to separate interference term and DVCS^2 contributions

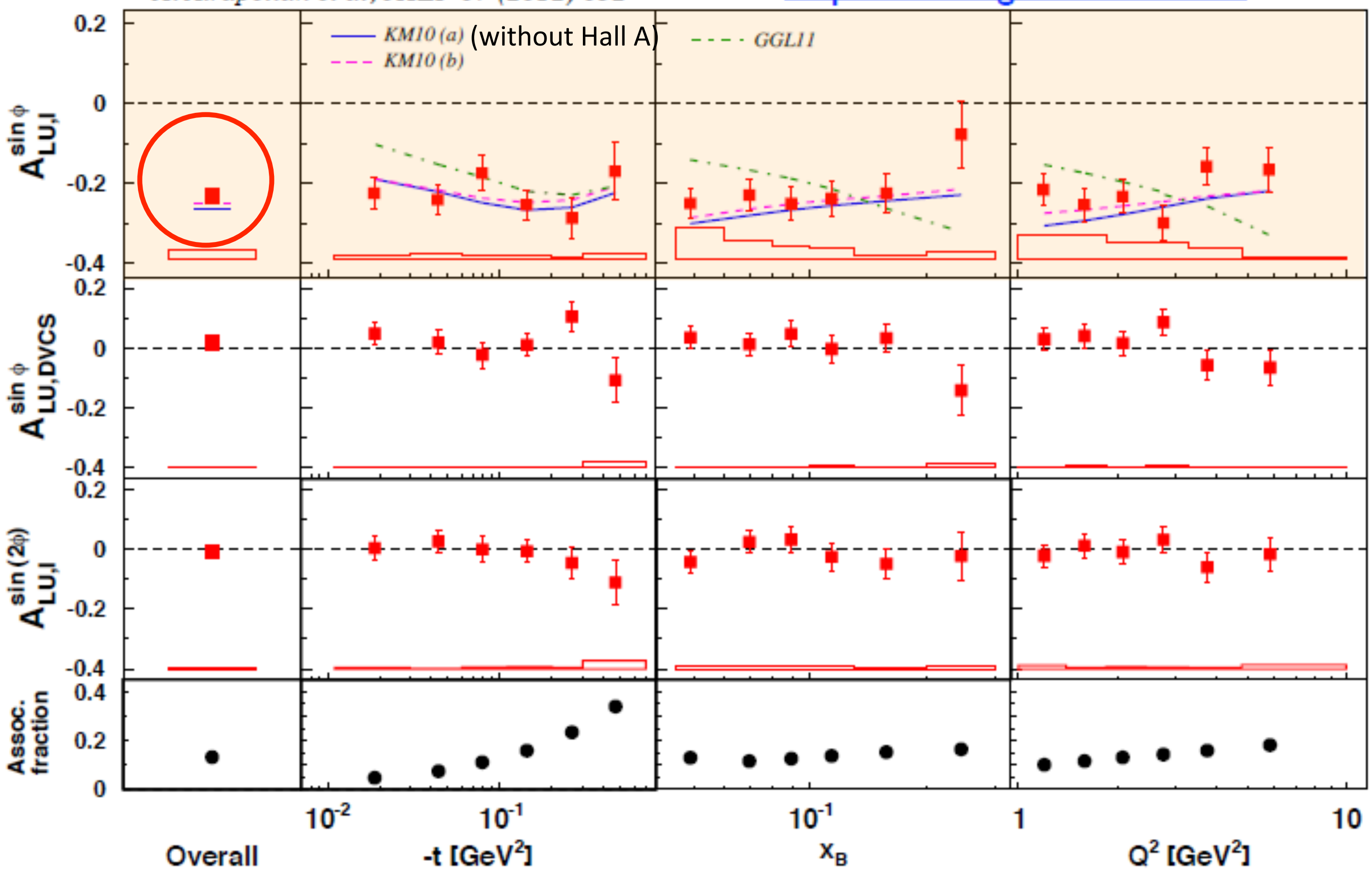
$$\sigma_{\mathrm{LU}}(\phi; P_l, e_l) = \sigma_{\mathrm{UU}}(\phi) \cdot \{1 + P_l A_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + e_l P_l A_{\mathrm{LU}}^{\mathcal{I}}(\phi) + e_l A_{\mathrm{C}}(\phi)\}$$

$$s_1^{\mathrm{DVCS}} sin(\phi) \qquad \sum_{n=1}^{2} s_n^{\mathrm{I}} sin(n\phi) \qquad \sum_{n=0}^{3} c_n^{I} cos(n\phi)$$

Beam Spin Asymmetry - HERMES

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 DVCS²

sin 2ϕ term higher twist

resonant fraction $ep \to e\gamma\Delta^+$

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

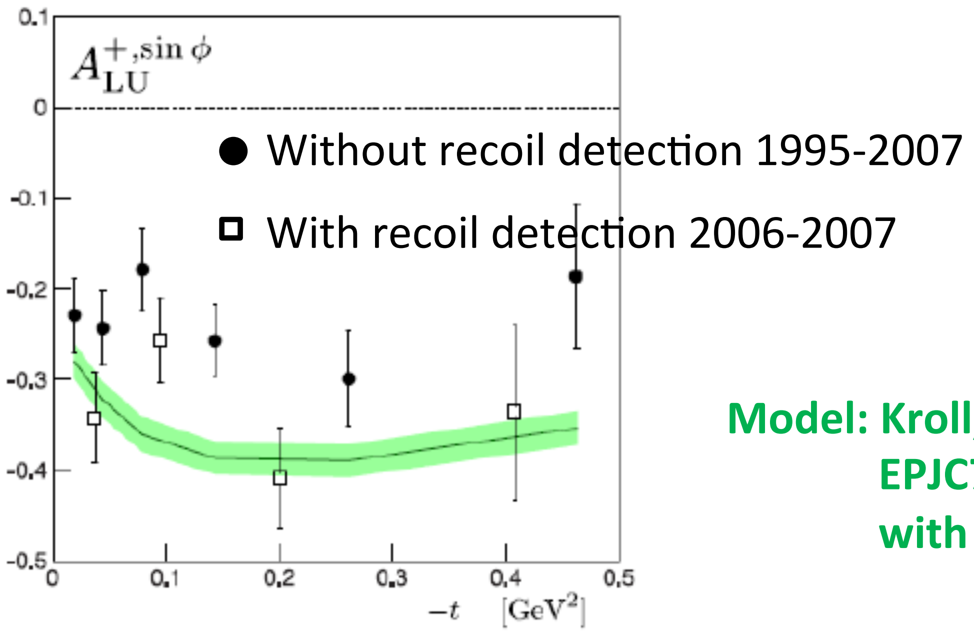
Kumerički and Müller, Nucl. Phys. **B841** (2010)

GHL11: flexible parameterization

http://arxiv.org/abs/1012.3776

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

BSA with recoil detector - HERMES



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

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

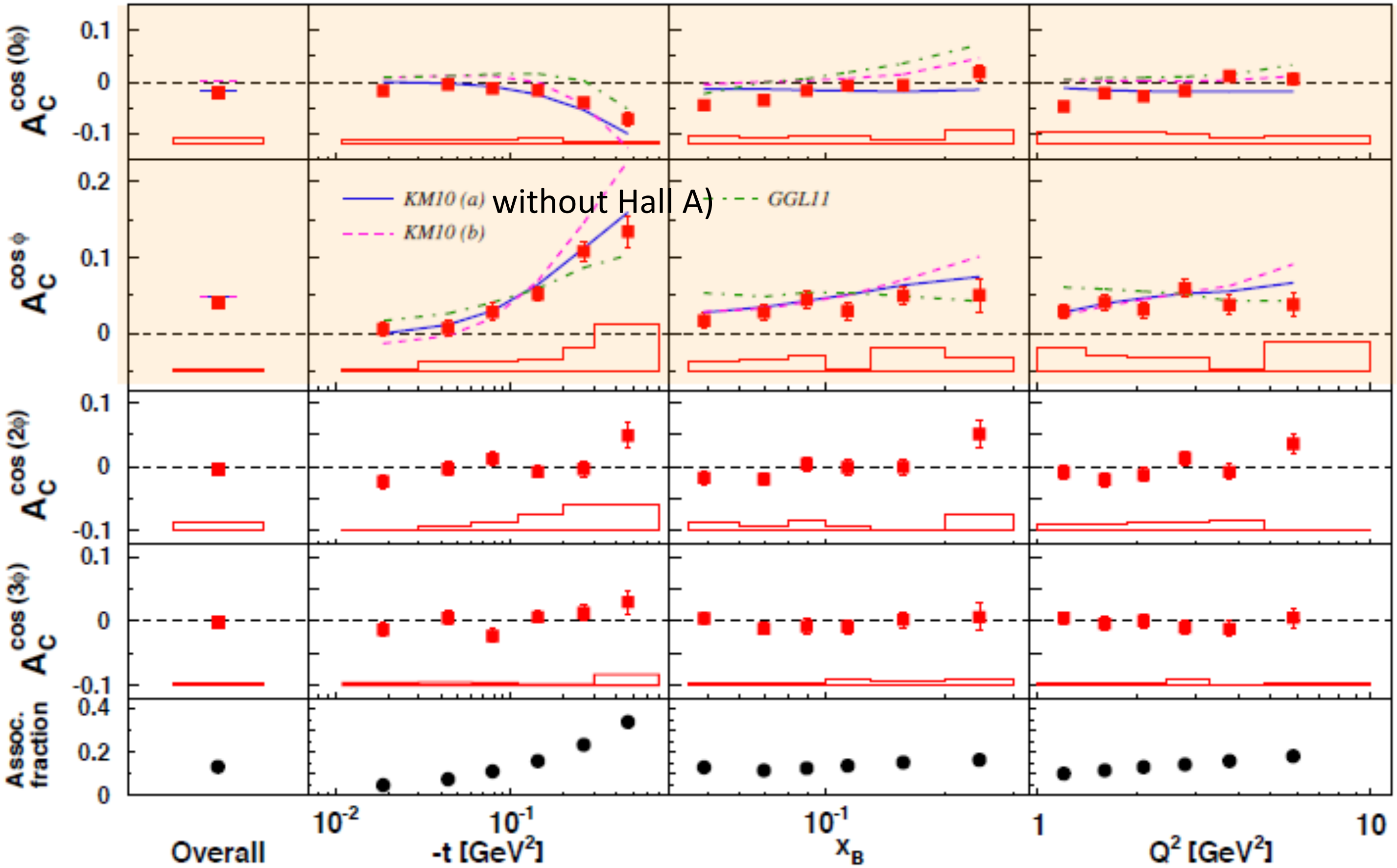
The leading asymmetry has increased by 0.054 ± 0.016

Mainly dilution due to the associated DVCS

Beam Charge Asymmetry - HERMES

Complete data set including 2006-07 witjour recoil detection

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



constant term

cos ϕ term

$\mathcal{R}e$ **F1** $\mathcal{H} < 0$

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)*

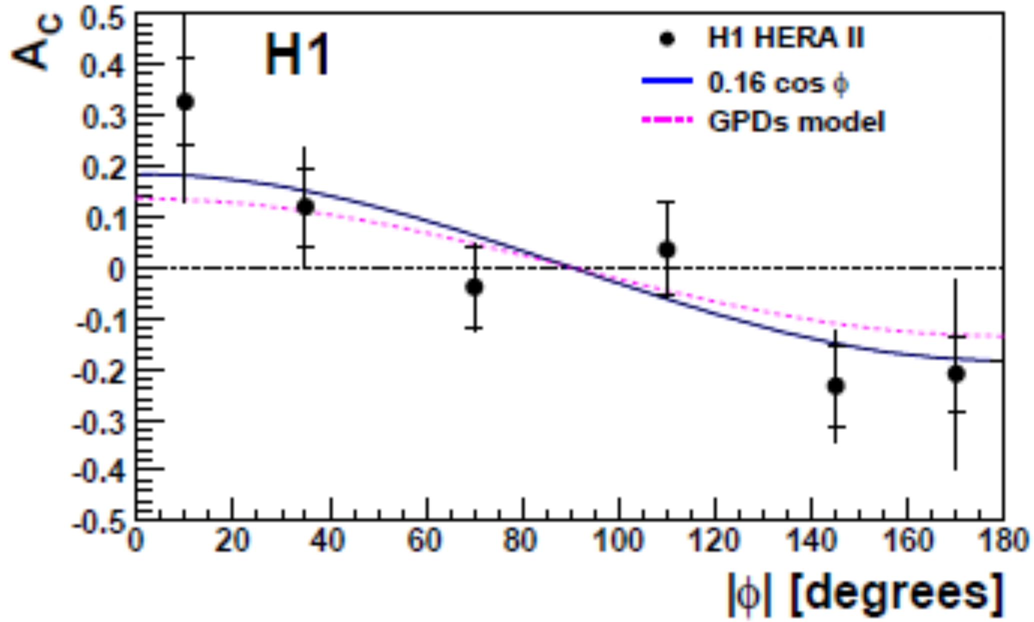
GHL11:
http://arxiv.org/abs/1012.3776

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

Beam Charge Asymmetry - H1

First measuremeent at a collider

- Low $x_B = 10^{-4} – 10^{-2}$
- $65 < Q^2 < 80$ GeV^2
- $30 < W < 140$ GeV
- $|t| < 1$ GeV^2



Positive cosϕ amplitude
Sign change compared to HERMES

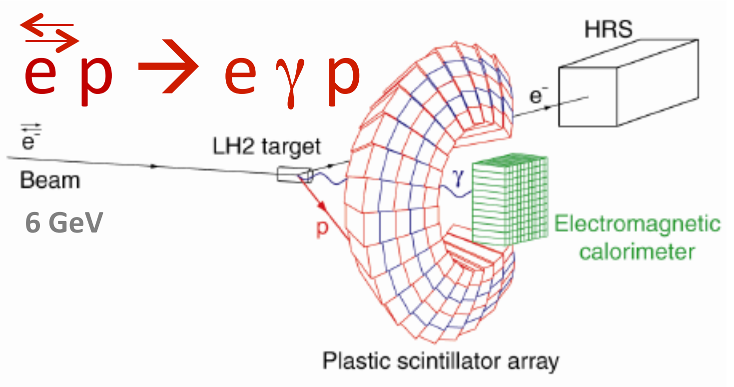
$\mathcal{R}e\,\mathcal{H}$ **> 0 at H1**

Beam Spin Sum and Diff of DVCS - HallA

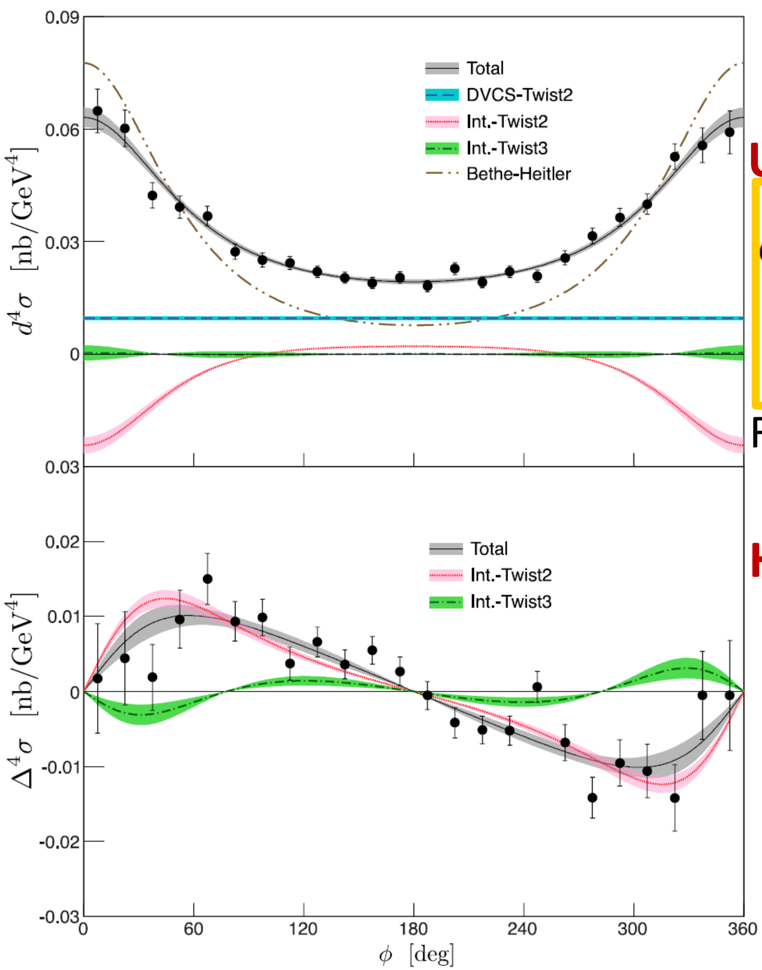
E00-110 pioneer experiment with magnetic spectrometer

x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2 Defurne et al. PRC92, 055202 (2015)

x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2



x_B=0.36, Q^2= 2.3 GeV^2, -t= 0.32 GeV^2



Unpolarized cross section

$$d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$

$$\longrightarrow d\sigma^{BH} + c_0^{DVCS} + c_0^I + c_1^I \cos\phi + c_2^I \cos 2\phi$$

Further separation ➔ need of different beam energies

Helicity Dependent cross section

$$d\sigma^{\leftarrow} - d\sigma^{\rightarrow} \propto d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I$$

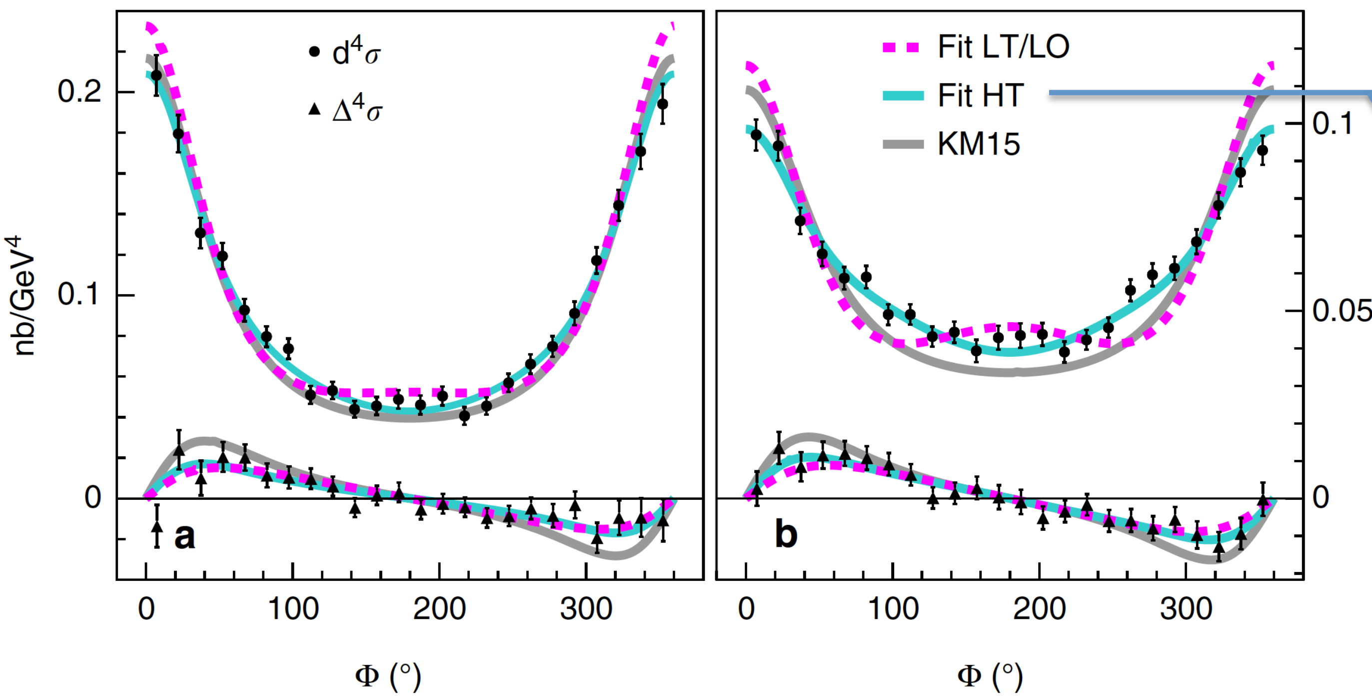
$$\longrightarrow s_1^I \sin\phi + s_2^I \sin 2\phi$$

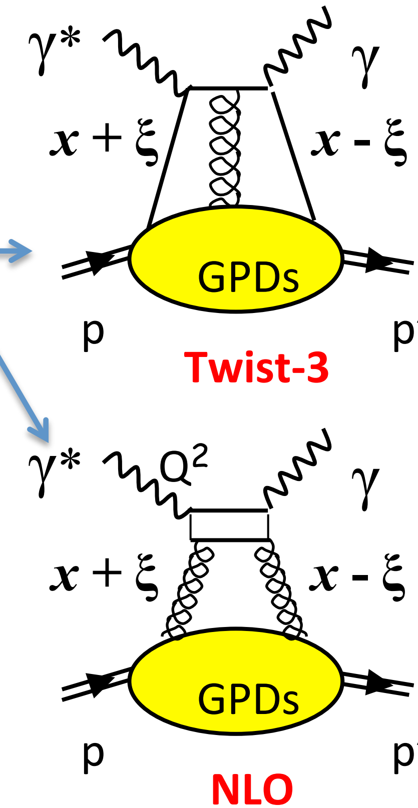
New high-precision Hall-A data

Hall-A experiment **E07-007** (2010) M. Defurne et al., Nat. Comm. 8 (2017) 1408

Fixed $x_B = 0.36$, Q2 = 1.5, 1.75, 2.0

Two different beam energies -> BH-DVCS separation



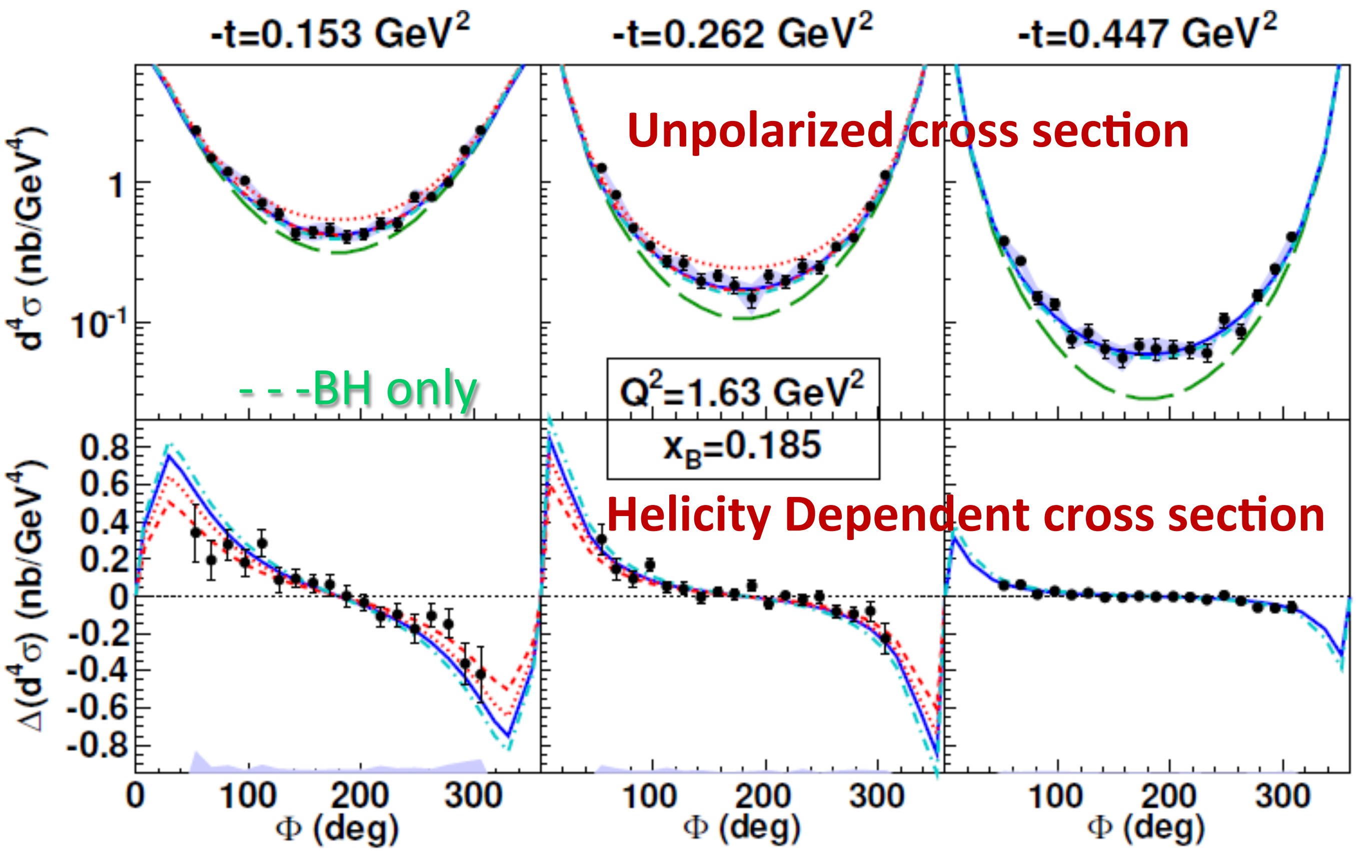


Either **NLO** or **twist-3** terms are needed to properly fit the Beam-helicity independent & dependent cross-sections

Beam Spin Sum and Diff of DVCS - CLAS

21 bins in (x_B, Q^2) or 110 bins (x_B, Q^2 t)
- Jo et al. PRL115, 212003 (2015)

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



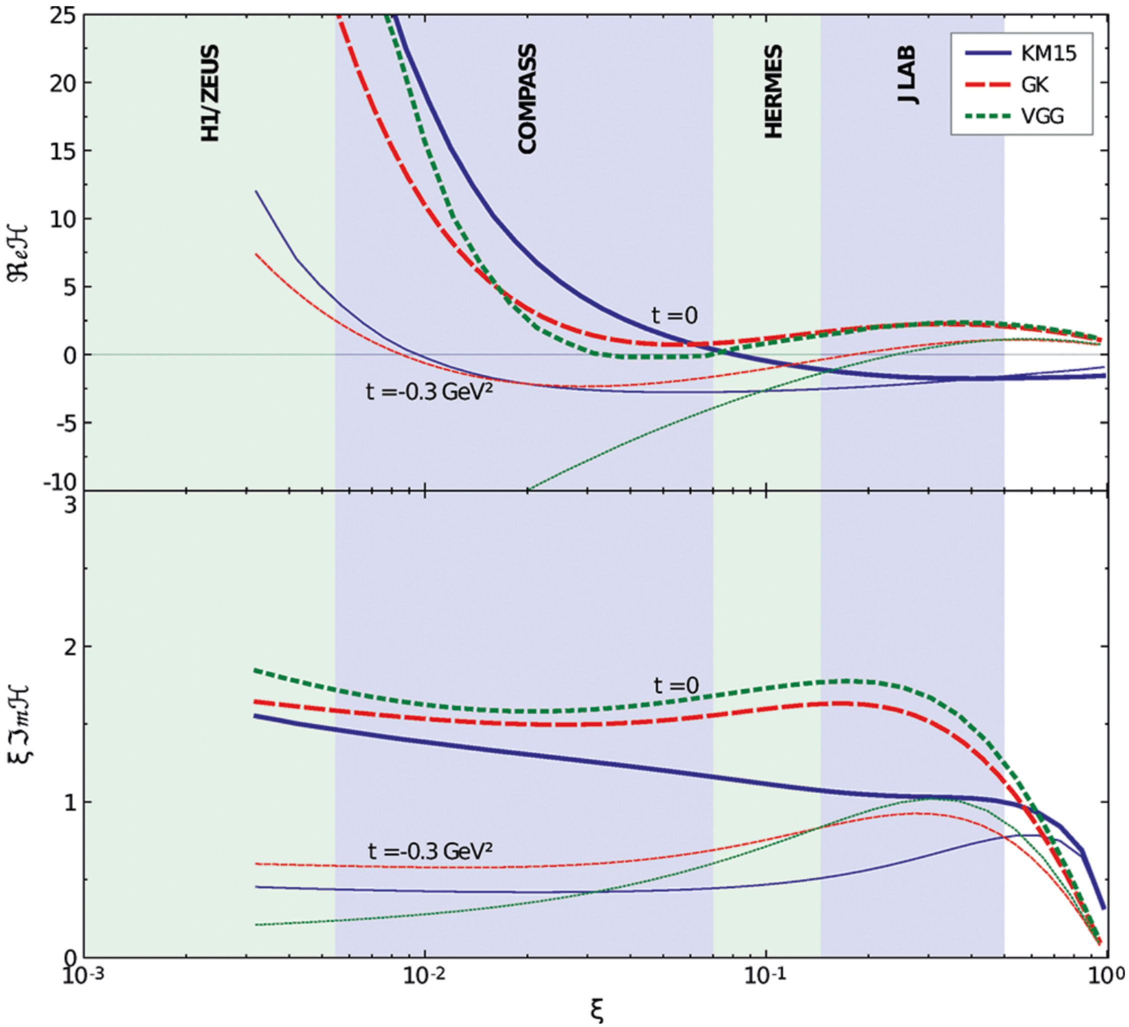
models:

VGG Vanderhaeghen, Guichon, Guidal
PRL80(1998),PRD60(1999), PPNP47(2001), PRD72(2005)
1rst model of GPDs
constant evolution

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model
Goloskokov, Kroll, EPJC42,50,53,59,65,74
for GPD adjusted on the hard exclusive meson production at small x_B
"universality" of GPDs

KM10a - - - **KM10 ....** Kumericki, Mueller, NPB (2010) 841
Flexible parametrization of the GPDs based on both a Mellin-Barnes representation and dispersion integral which entangle skewness and t dependences
Global fit on the world data ranging from H1, ZEUS to HERMES, JLab

Summary of *ReH* and *ImH* from global analyses



ReH
Still poorly constrained

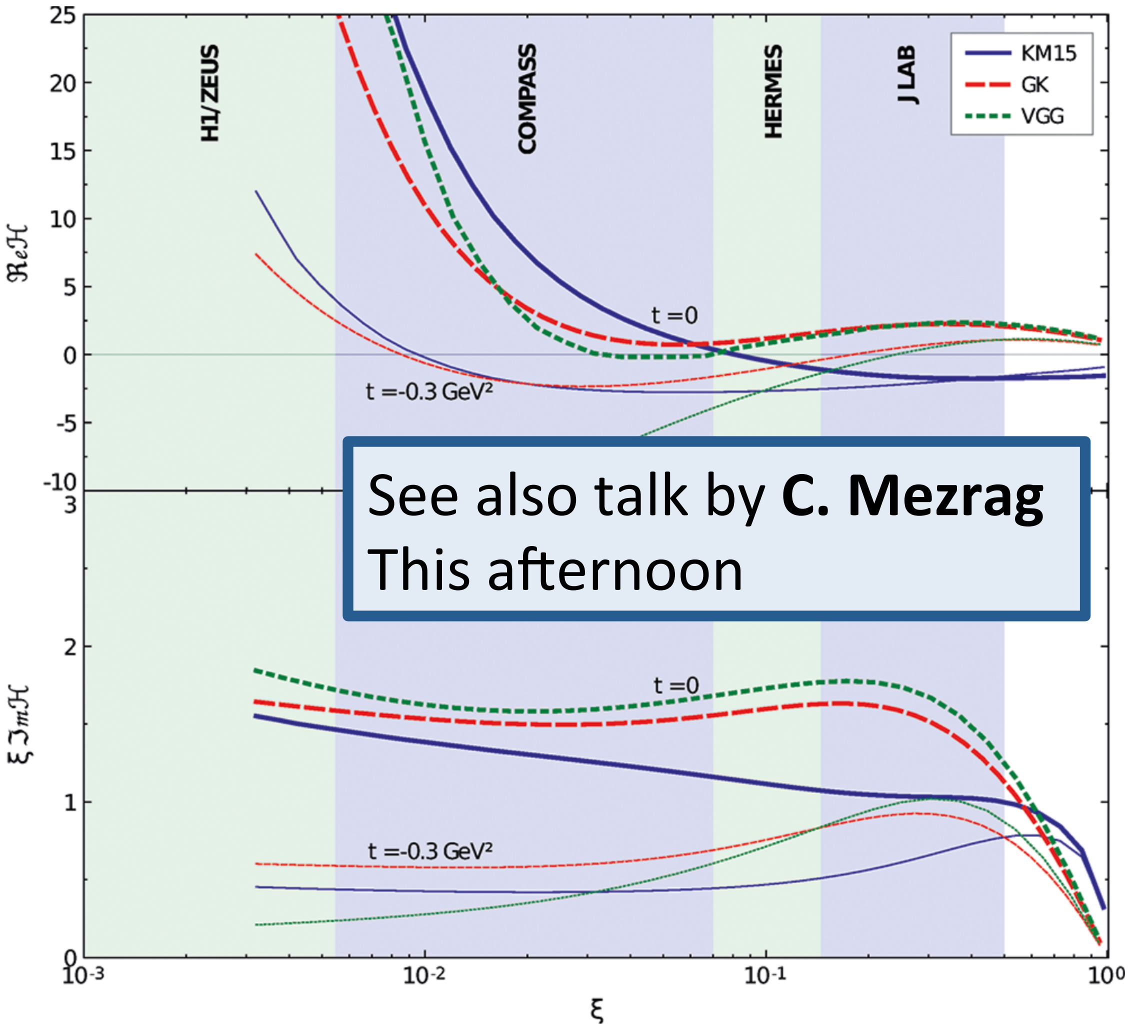
ImH Better known?

FUTURE:

- **COMPASS**:
  fill gap at intermediate x
- **JLab12**:
  extended kin. coverage
  increased precision
- **EIC**:
  "ultimate machine"?

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)
VGG M. Vanderhaeghen, P. A. M. Guichon, and M. Guidal, PRD60 (1999), PRD72(2005)

Summary of $Re\mathcal{H}$ and $Im\mathcal{H}$ from global analyses



See also talk by **C. Mezrag**
This afternoon

$Re\mathcal{H}$
Still poorly constrained

$Im\mathcal{H}$ Better known?

FUTURE:
- **COMPASS**: fill gap at intermediate x
- **JLab12**: extended kin. coverage increased precision
- **EIC**: “ultimate machine”?

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
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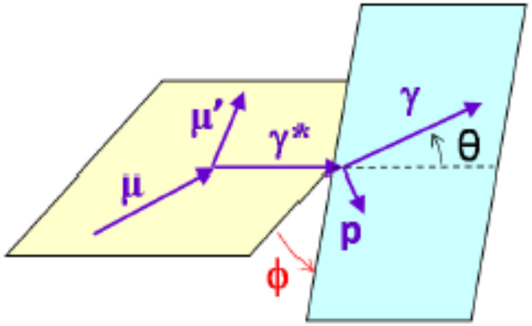
COMPASS @ CERN – Data Taking in 2016/17

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}\, A^{DVCS} + e_\mu P_\mu a^{BH} \mathrm{Im}\, A^{DVCS}$$

$$\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVSC}_{pol} &\propto s_1^{DVCS}\sin\phi \\
a^{BH}\mathrm{Re}\, A^{DVCS} &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
a^{BH}\mathrm{Im}\, A^{DVCS} &\propto s_1^I\sin\phi + s_2^I\sin 2\phi
\end{aligned}$$

Twist-2 >> (Twist-3, Twist-2 gluon)



$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \rightarrow \mathcal{R}e\ \mathbf{F1}\ \mathcal{H}$

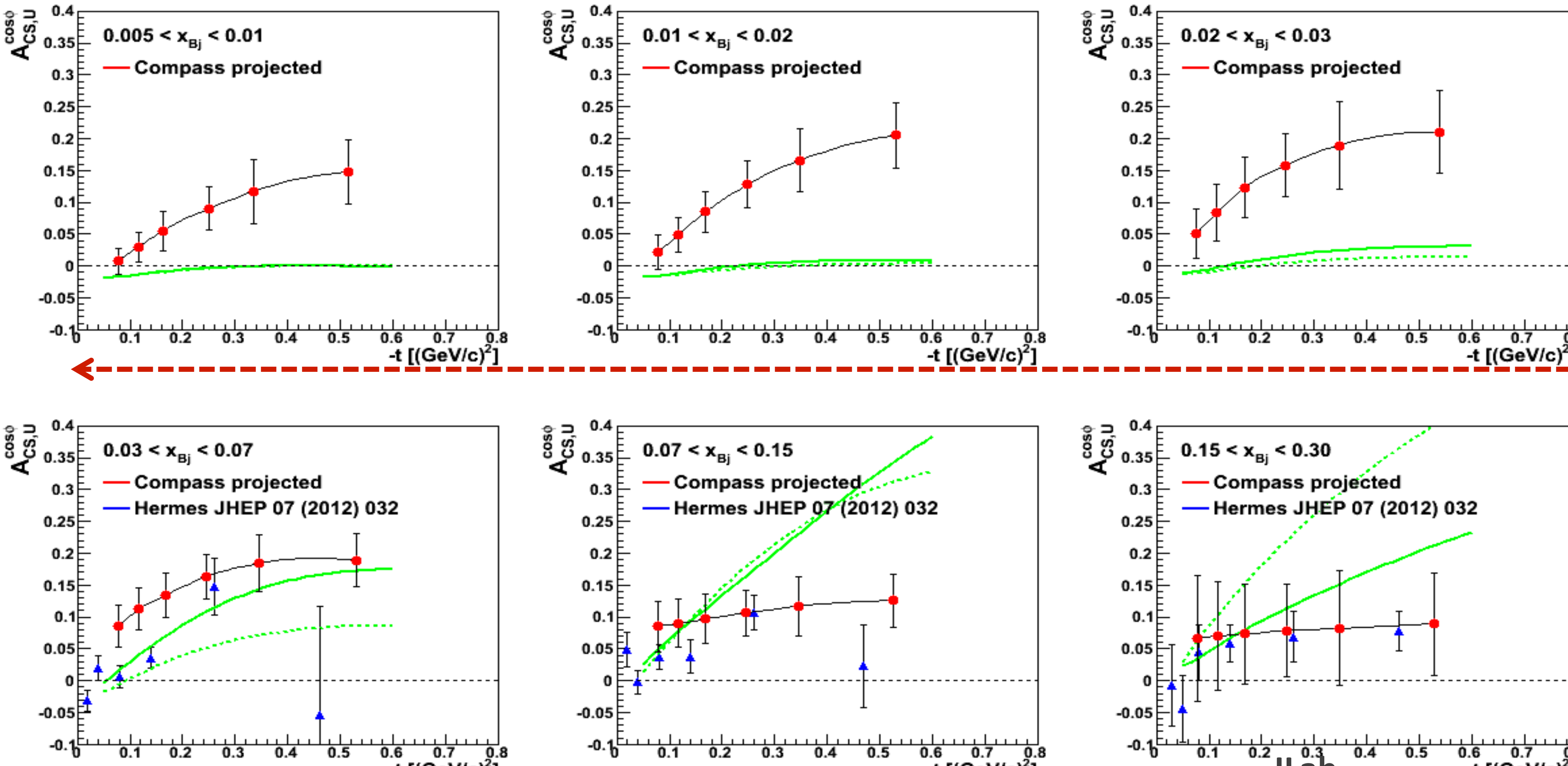
$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \rightarrow \mathcal{I}m\ \mathbf{F1}\ \mathcal{H}$

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\varphi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1\, \mathcal{R}e\, \mathcal{H}$$

$A_{CS,U}^{\cos\phi}$ related to c_1^{Int}

Predictions with
VGG and **D.Mueller**

$\mathcal{R}e\,\mathcal{H}$ > 0 at H1
< 0 at HERMES/JLab
Value of x_B for the node?



HERMES

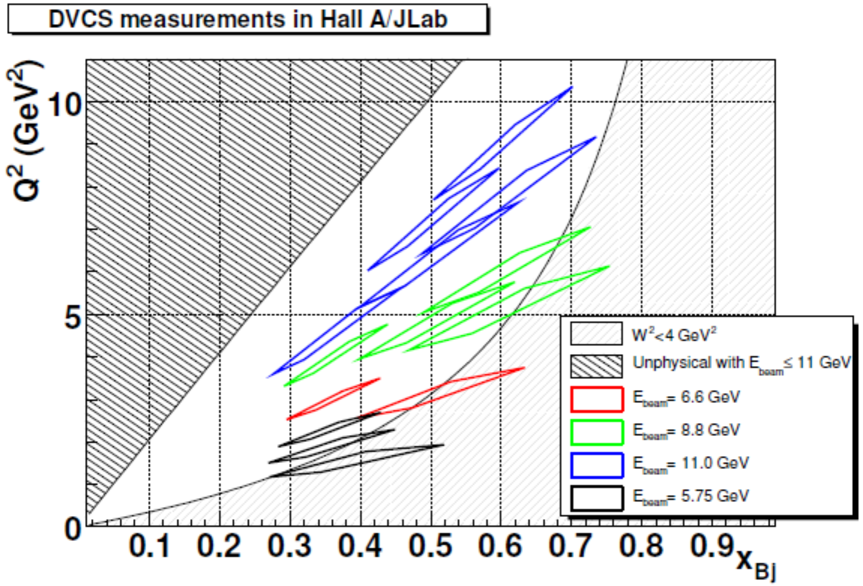
JLab

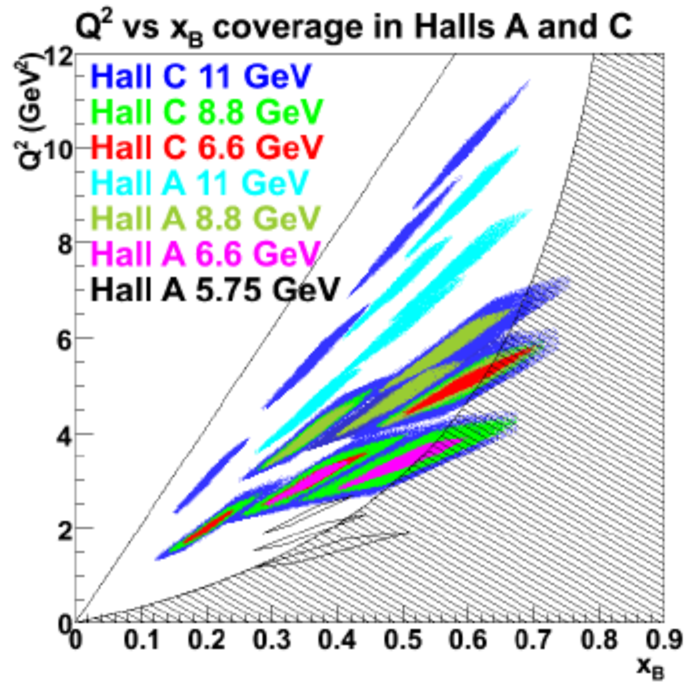
COMPASS 2 years of data E_μ= 160 GeV 1 < Q^2 < 8 GeV^2 with ECAL2 + ECAL1 + ECAL0

FUTURE: HALL-A & HALL-C @ Jlab12

with magnetic spectrometer + Calorimeter

JLab12 with 3, 4, 5 pass beam
(6.6, 8.8, 11.0 GeV beam energy)





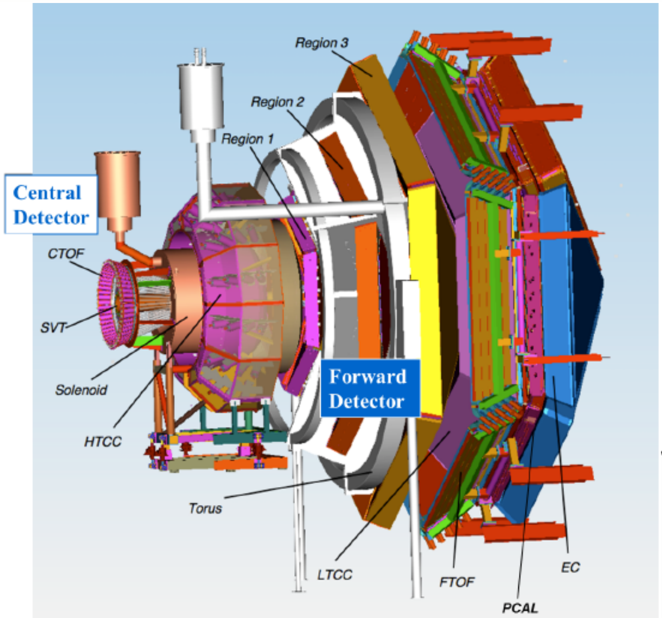
- Absolute cross-section measurements
- Test of scaling: Q^2 dependence of $d\sigma$ at fixed x_{Bj}
- Increased kinematical coverage

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

First run after the 12GeV upgrade
Now 2014

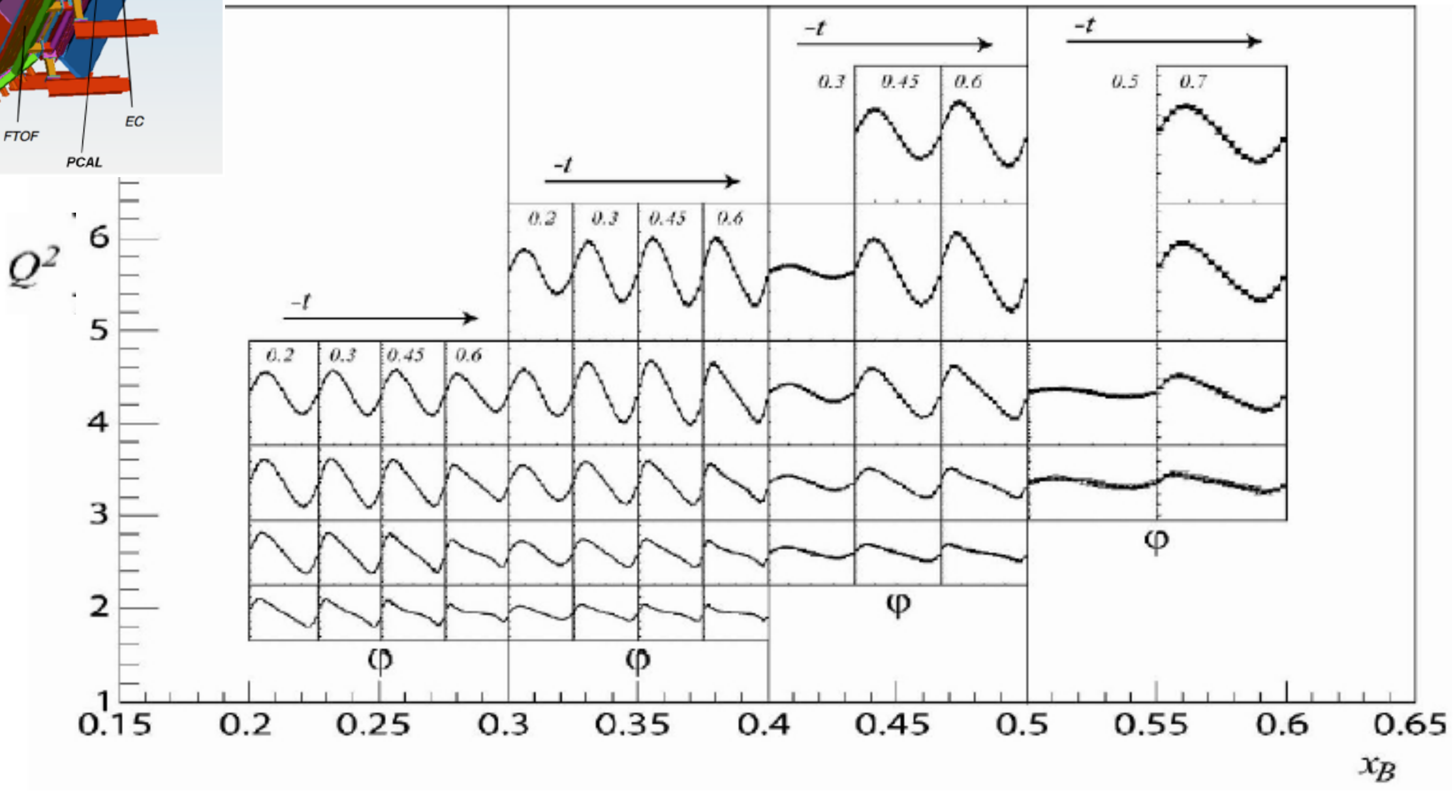
Need a new challenging Calo
~ 2018

FUTURE: CLAS12 @ Jlab



Approved experiment E12-06-119

LH_2 Target and Long. Pol. Target
Extended (Q^2,x_B) coverage
Planned for 201?

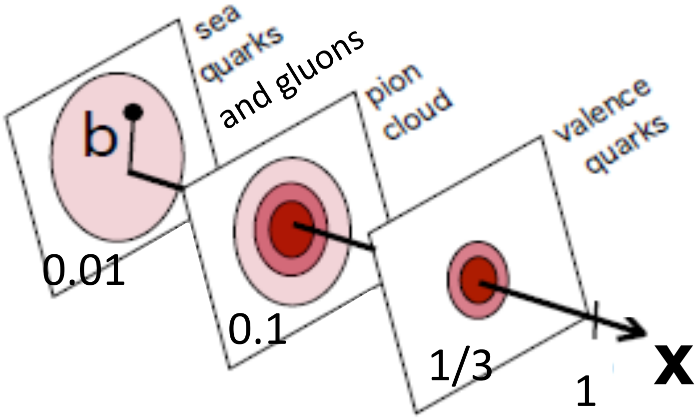


Nucleon « tomography »

→ t-slope of DVCS x-section

→ Global fits of DVCS **CFFs**

Nucleon « tomography »



x-dependent spatial distribution of partons in the transverse plane

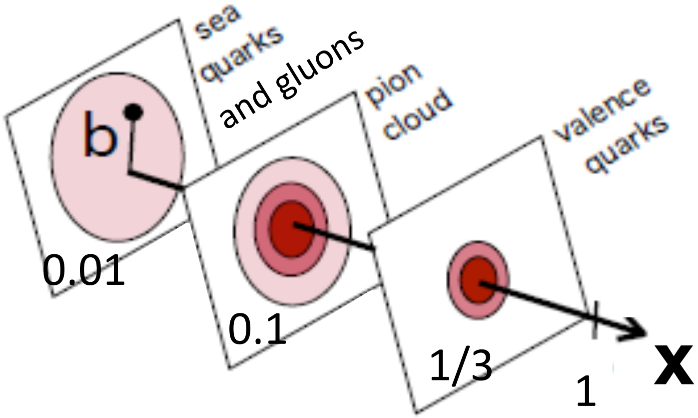
$$\langle b_\perp^2(x)\rangle^f = -4\frac{\partial}{\partial t}\ln H^f(x,0,t)\Big|_{t=0}$$

$H(x,0,t) \propto e^{-B_0(x)/t}$

⬇

$< b_\perp{}^2 (x)> = 4B_0(x)$

Nucleon « tomography »



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$H(x,0,t) \propto e^{-B_0(x)/t}$

$\Downarrow$

$< b_\perp^2 (x)> = 4B_0(x)$

Unpol. DVCS x-section mostly sensitive to

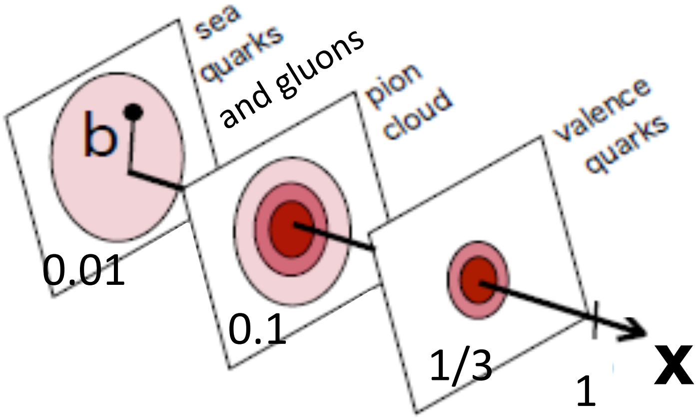
$Im\,\mathcal{H}(\xi,t) \propto H\,(x=\xi,\xi,t)$

$H(x=\xi,\xi,t) \propto e^{-B(\xi)/t}$

$\Downarrow$

$< r_\perp^2 (\xi)> = 4B(\xi)$

Nucleon « tomography »



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↓

$< b_\perp^2 (x)> = 4B_0(x)$

model dependent

$H(x=\xi,\xi,t)$ α $e^{-B(\xi)/t}$

↓

$< r_\perp^2 (\xi)> = 4B(\xi)$

Unpol. DVCS x-section mostly sensitive to

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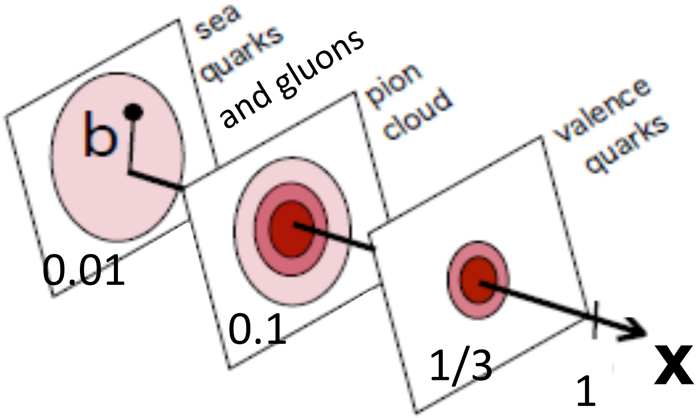
Nucleon « tomography »



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⬇

$< r_\perp{}^2 (\xi)> = 4B(\xi)$

Unpol. DVCS x-section mostly sensitive to

$Im\,\mathcal{H}(\xi,t)\ \alpha\ H\,(x=\xi,\xi,t)$

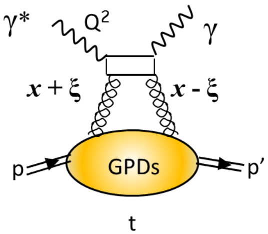
$d\sigma_{DVCS}/dt\ \ \alpha\ \ e^{-B'(x_B)}/t$ ➔ $< r_\perp{}^2 (x_B)> \approx 2B'(x_B)$

$\xi \approx x_B/2$

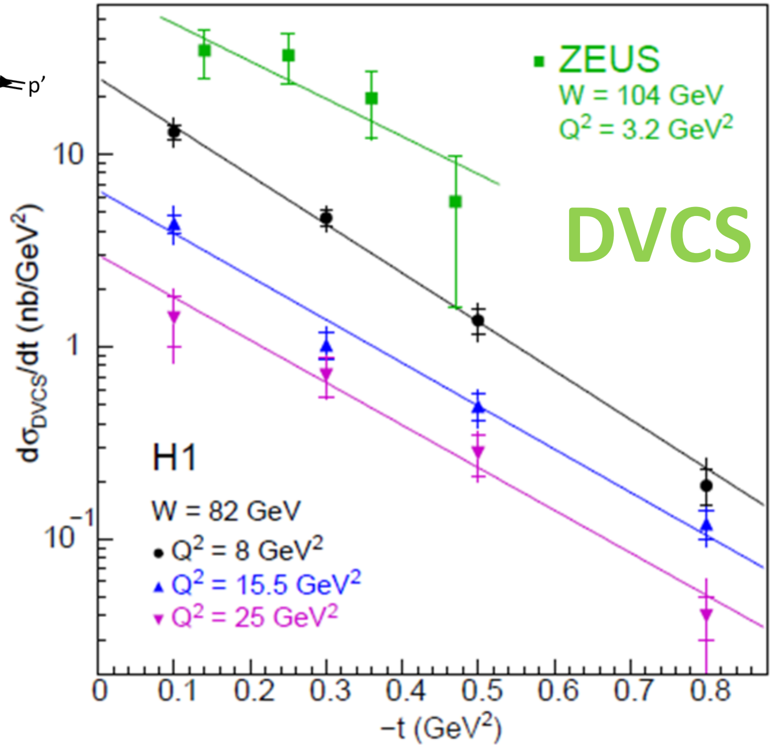
Gluon imaging @ HERA

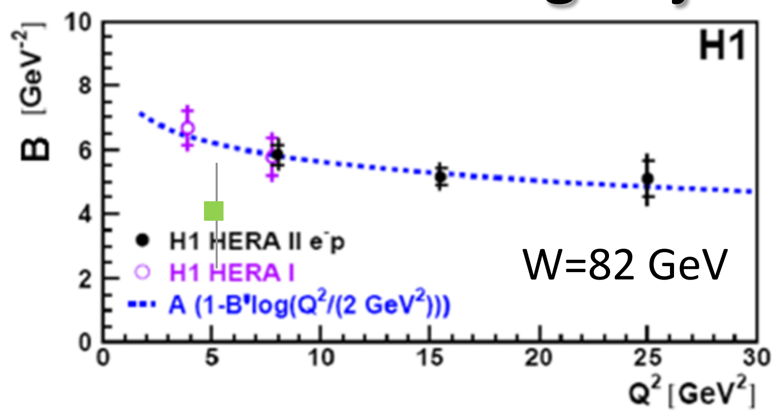
$$d\sigma^{DVCS}/dt = e^{-B|t|}$$

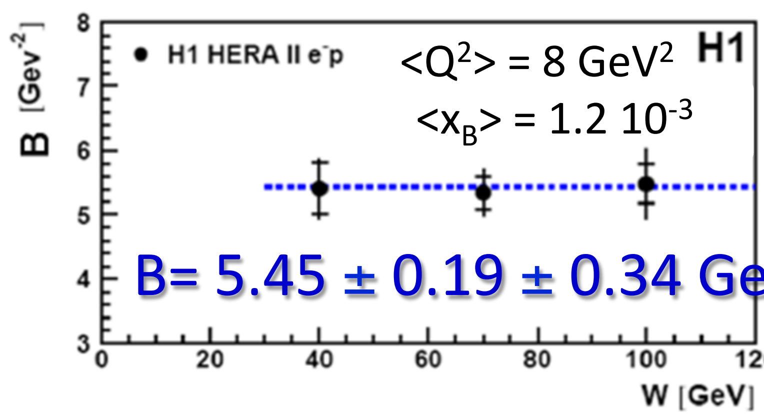
B is related to the transversed size of the scattering objects



Aaron et al., H1 Coll, PLB659 (2008)



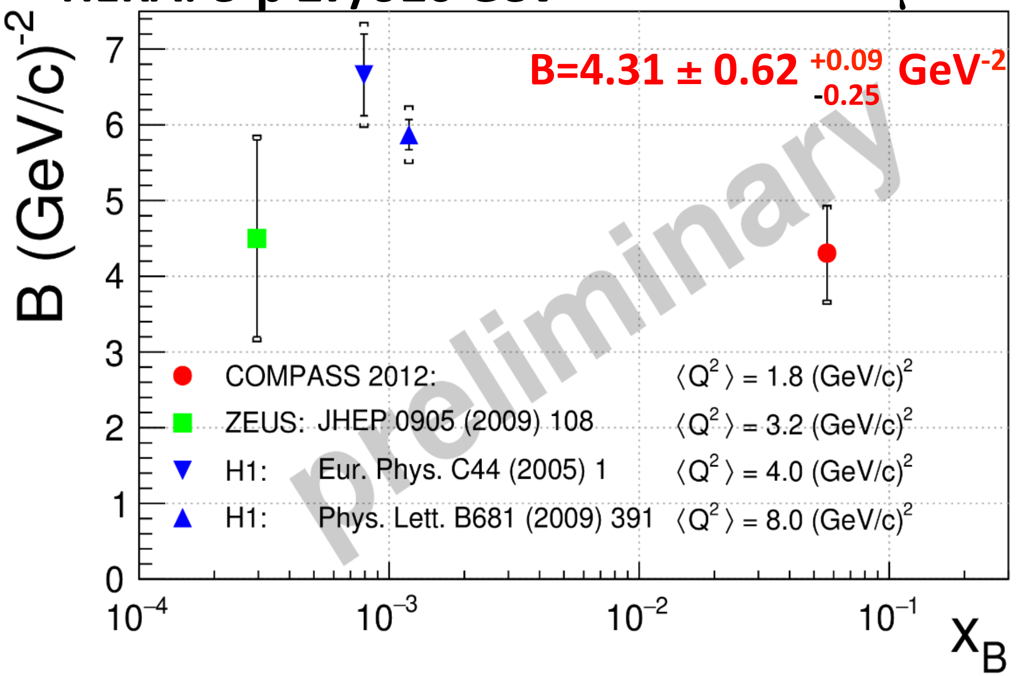


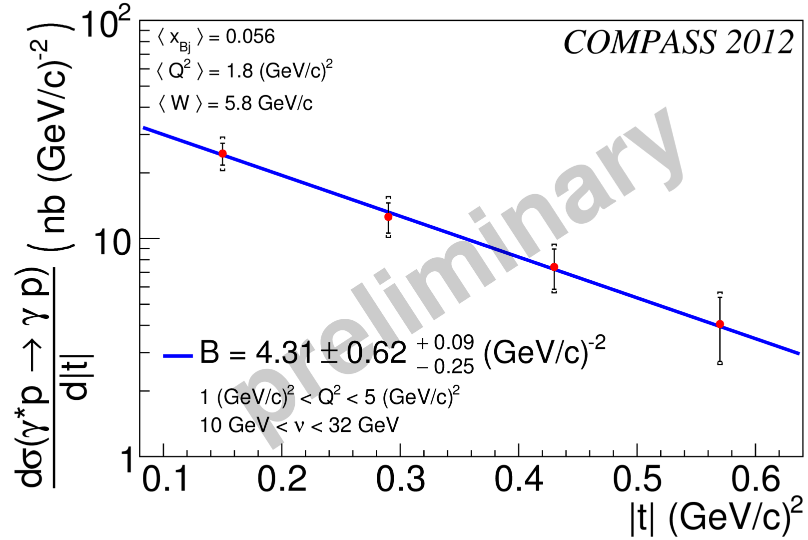


$B = 5.45 \pm 0.19 \pm 0.34$ GeV^{-2}

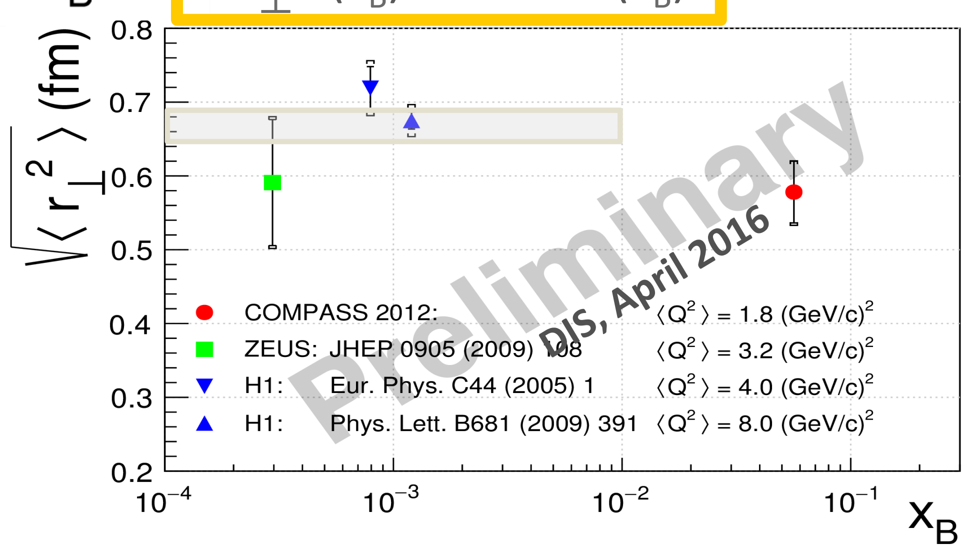
Sea quark imaging @ COMPASS

HERA: $e^{\pm}p$ 27/920 GeV **COMPASS: $\mu^{\pm}$ 200 GeV**





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

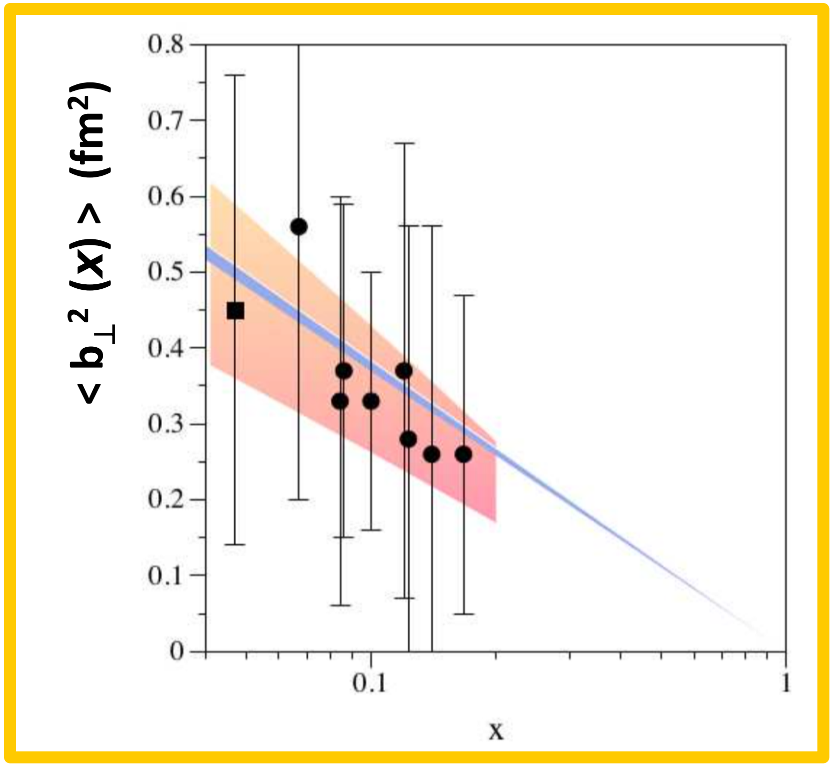


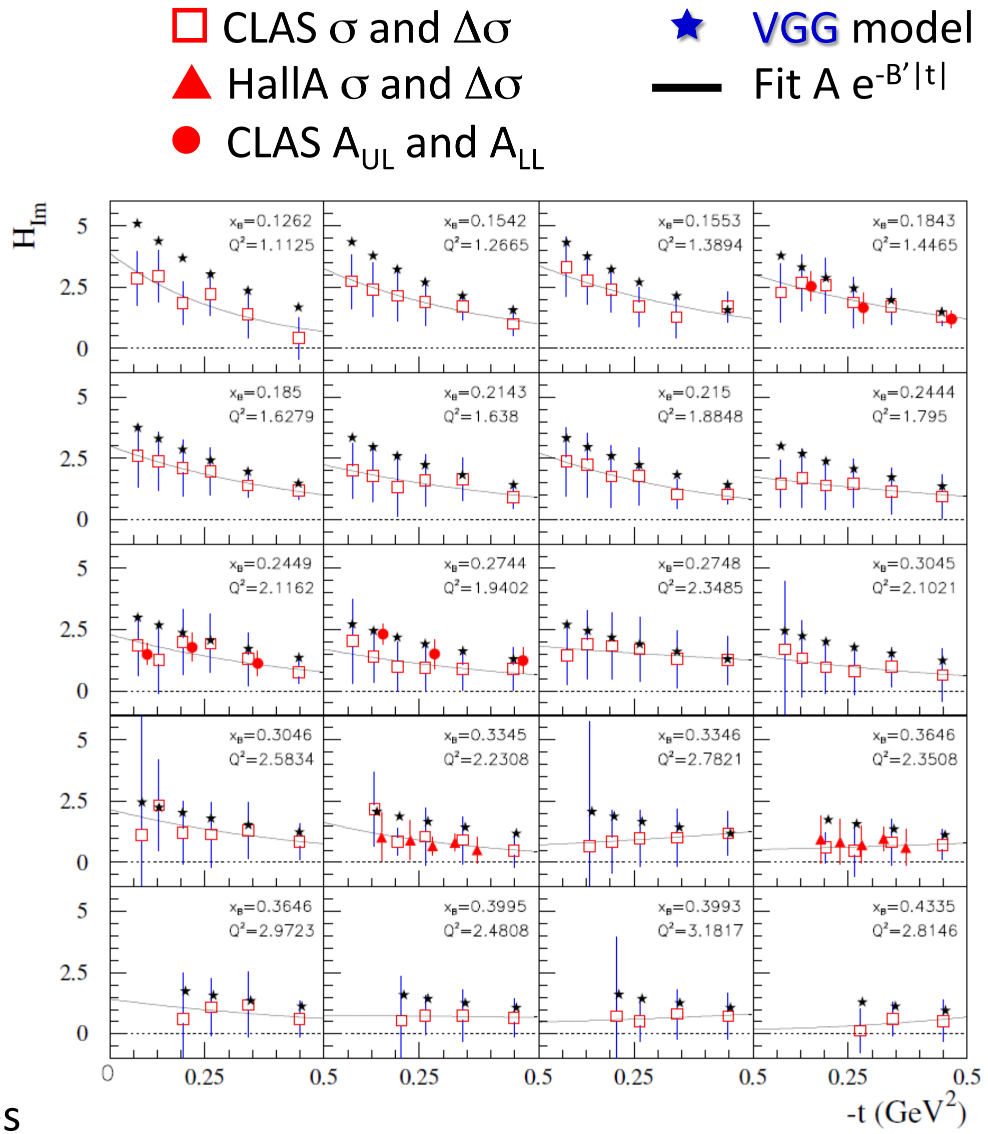
Dedicated data taking @ COMPASS in 2016/17. Expected ≈10x statistics

Valence quark imaging at Jlab

Fit of 8 CFFs at L.O and L.T.

Dupré, Guidal, Niccolai, Vanderhaeghen
Eur.Phys.J. A53 (2017) no.8, 171





Error bars dominated by model uncertainties
In the fitting procedure

Exclusive π^0 production and chiral-odd GPDs

→ π^0 cross-sections – CLASS & COMPASS

→ Rosembluth separation – HALL A

Excl. π^0 and the chiral-odd H_T and E_T – Jlab CLAS

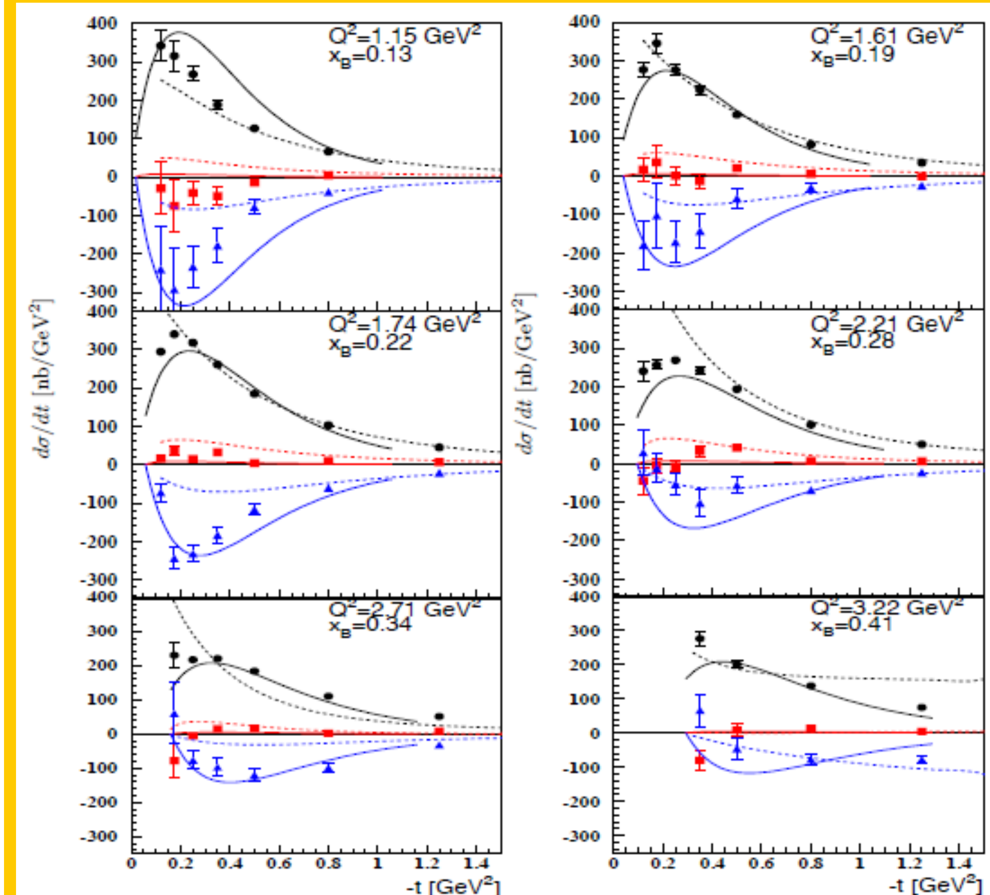
e p → e π^0 p $$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

- $$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$ ≈ only a few % of $\frac{d\sigma_T}{dt}$

  $$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

- $$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

- $$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$



Large impact of $\bar{E}_T$ clearly visible in σ_{TT} and in the dip at small t of σ_T

solid lines : **GK** EPJA47 (2011)
Dotted lines: **GHL** JPG:NPP39 (2012)

CLAS Coll, Bedlinskiy et al., PRC90(2014)2-025205

Excl. π^0 and the chiral-odd H_T and E_T – Jlab CLAS

e p → e π^0 p $$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

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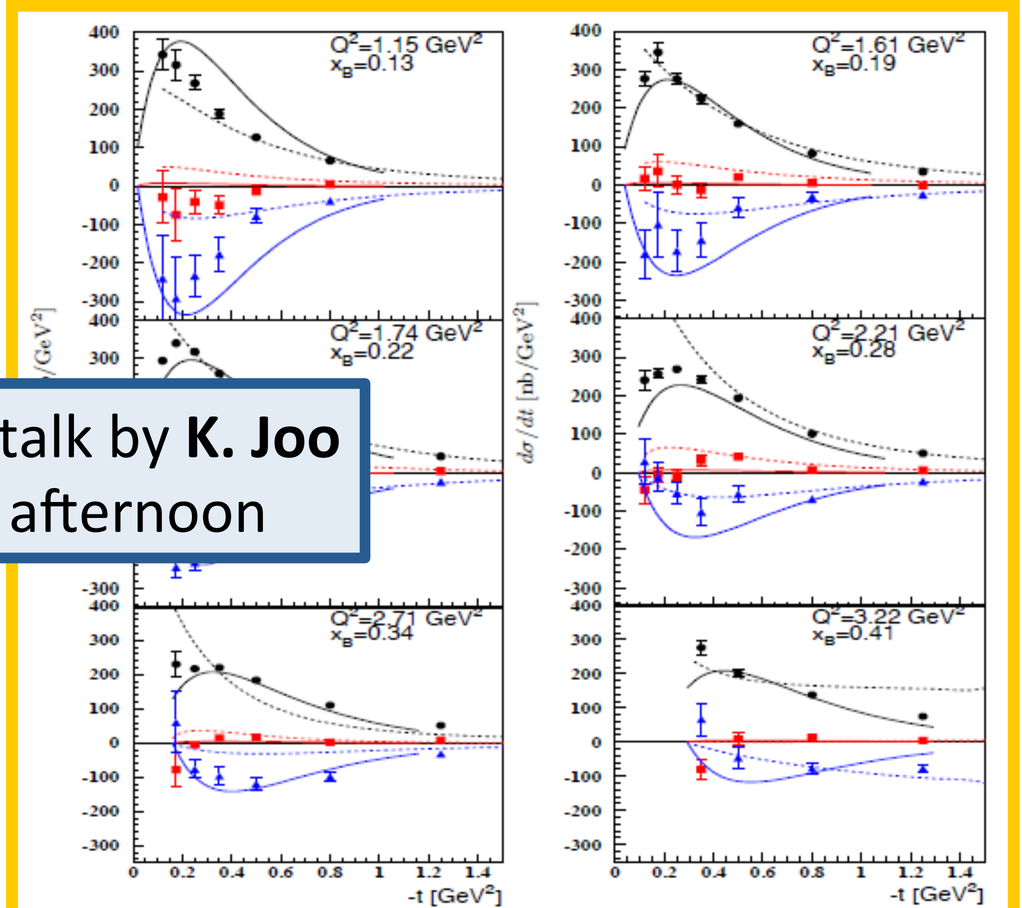
- $$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

- $$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

- $$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$



See talk by **K. Joo**
This afternoon

Large impact of $\bar{E}_T$ clearly visible in σ_{TT} and in the dip at small t of σ_T

solid lines : **GK** EPJA47 (2011)
Dotted lines: **GHL** JPG:NPP39 (2012)

CLAS Coll, Bedlinskiy et al., PRC90(2014)2-025205

Excl. π^0 and the chiral-odd H_T and E_T – Jlab HALL-A

$e\, p \rightarrow e\, \pi^0\, p$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

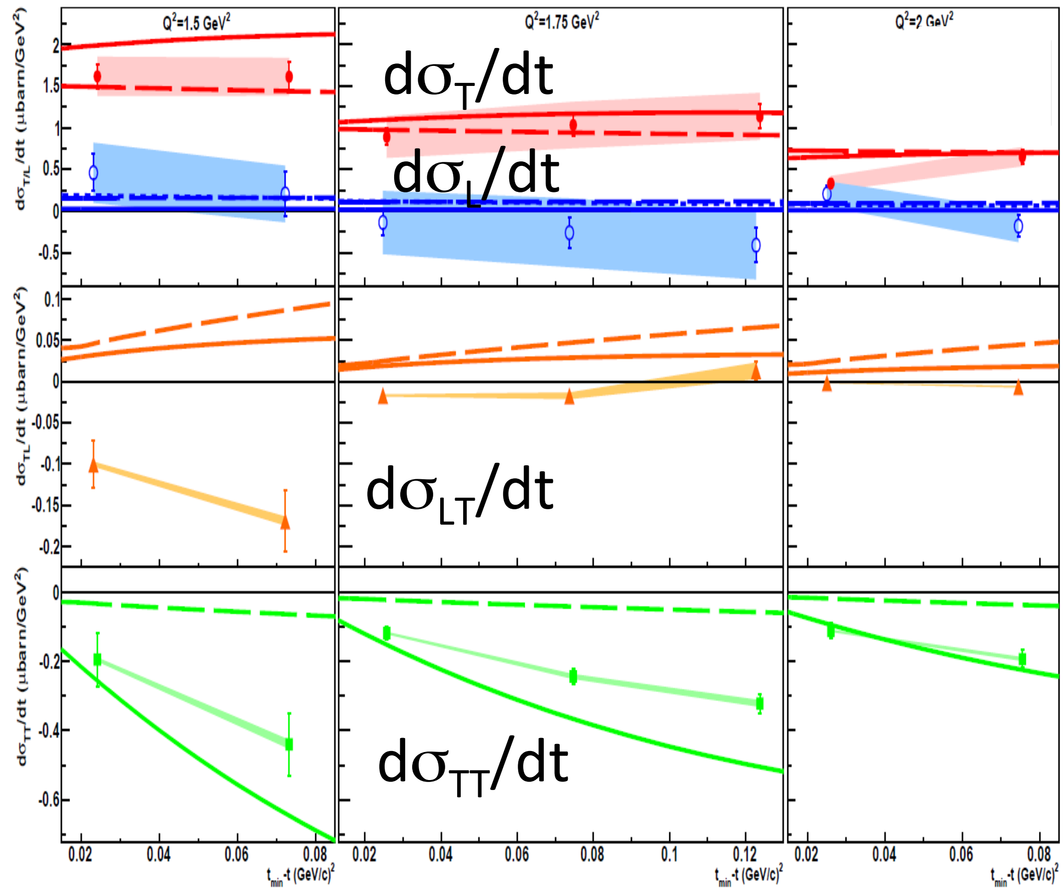
$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\} << \frac{d\sigma_T}{dt}$$

Confirmation -HallA

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$



Hall A: σL and σT separation

Defurne et al. ArXiv:1608.01003

solid lines : **GK** EPJA47 (2011)

Dashed lines: **GHL** JPG:NPP39 (2012)

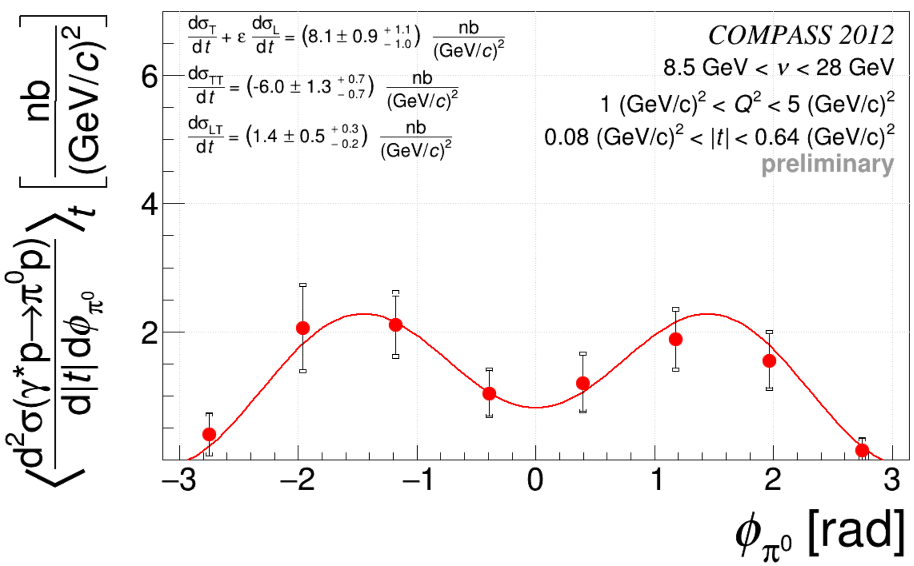
Excl. π^0 and the chiral-odd H_T and E_T - COMPASS

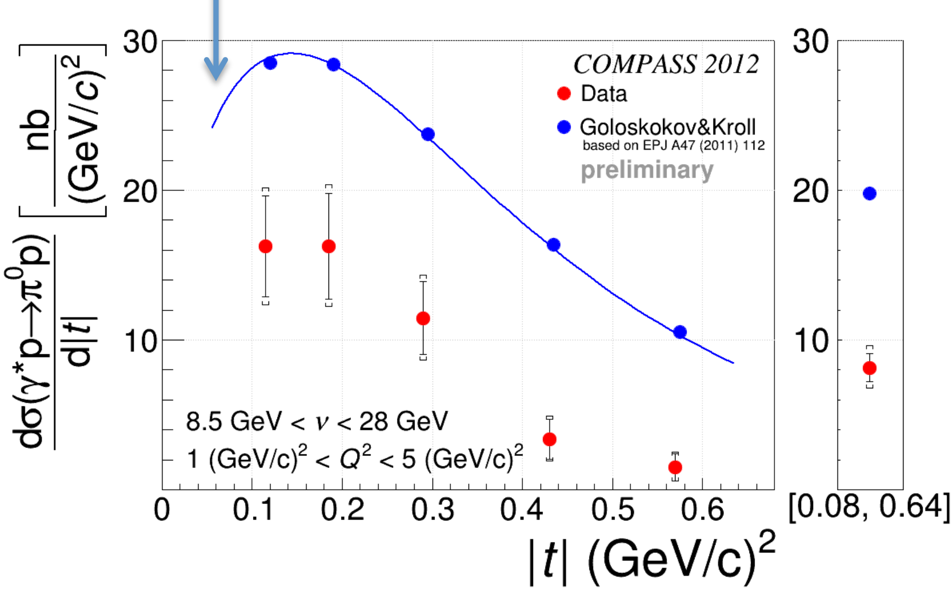
e p → e π^0 p $\quad \frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi\frac{d\sigma_{LT}}{dt}\right]$

$\frac{\sigma_{TT}}{dt}$ = -6.0 ± 1.3 -> sizeable and negative, same trend as JLab

$\frac{\sigma_{LT}}{dt}$ = 1.4 ± 0.5 -> small but positive

Dip at small *t* linked to large contribution of $\overline{E}_T$





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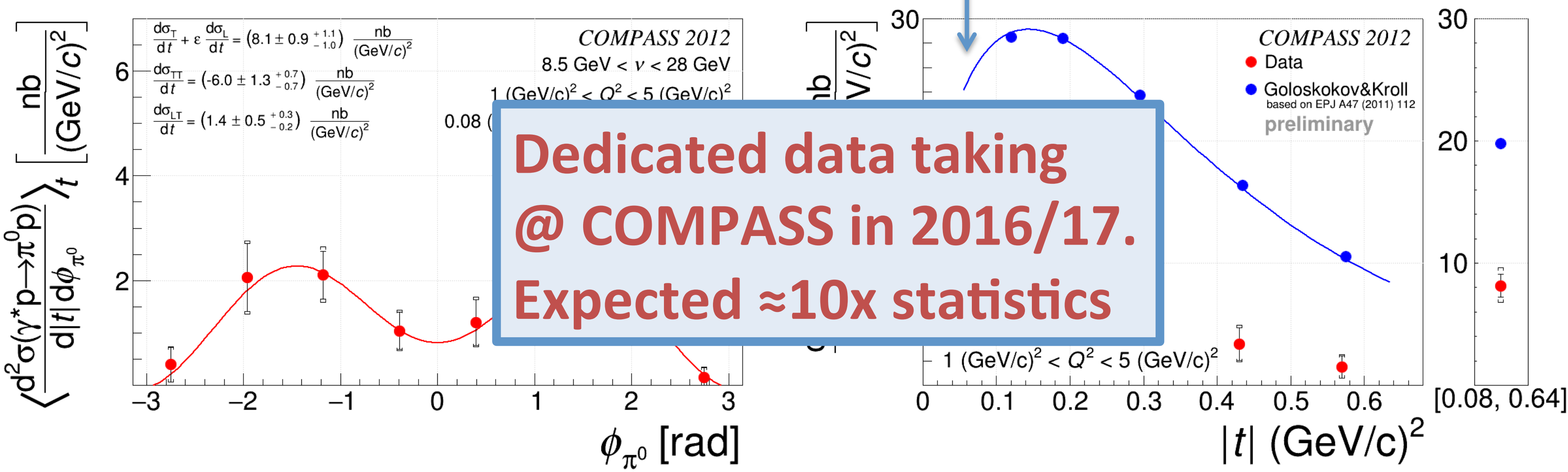


Dedicated data taking @ COMPASS in 2016/17. Expected ≈10x statistics

solid lines : **GK** EPJA47 (2011)

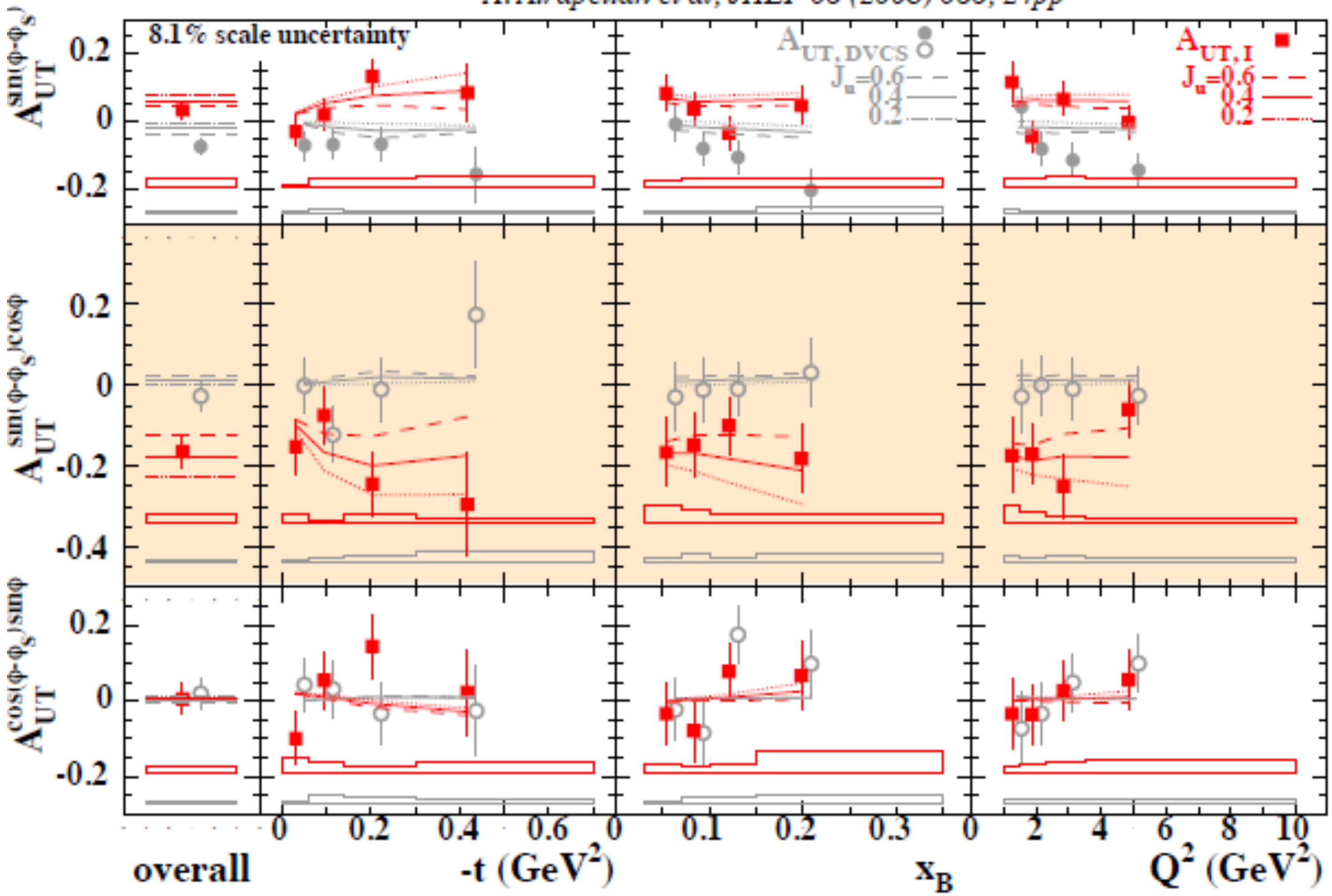
The Quest for the GPD E

→ Transv. Target Spin Asymm. of DVCS – HERMES

→ Future: CLAS12, COMPASS

Trans. Target Spin Asymm. on a proton – HERMES

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



But also Large $A_{UT,DVCS}$ sin(ϕ-ϕ_S)
With strong xB depend.

Large
$A_{UT,I}$ sin(ϕ-ϕ_S) cos ϕ
Sensitive to Ju, Jd
(VGG model)

The Future Quest for the GPD E

CLAS12 at Jlab

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

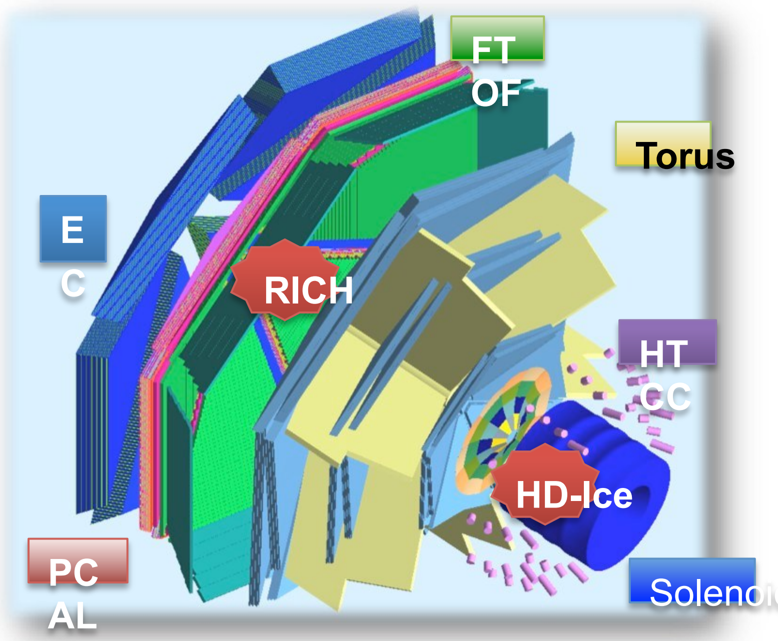
$$\Delta\sigma_{LU} \sim Im\,(F_{1n}\,\mathcal{H} - F_{2n}\,\mathcal{E})$$

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

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



The Quest for the GPD E

CLAS12 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

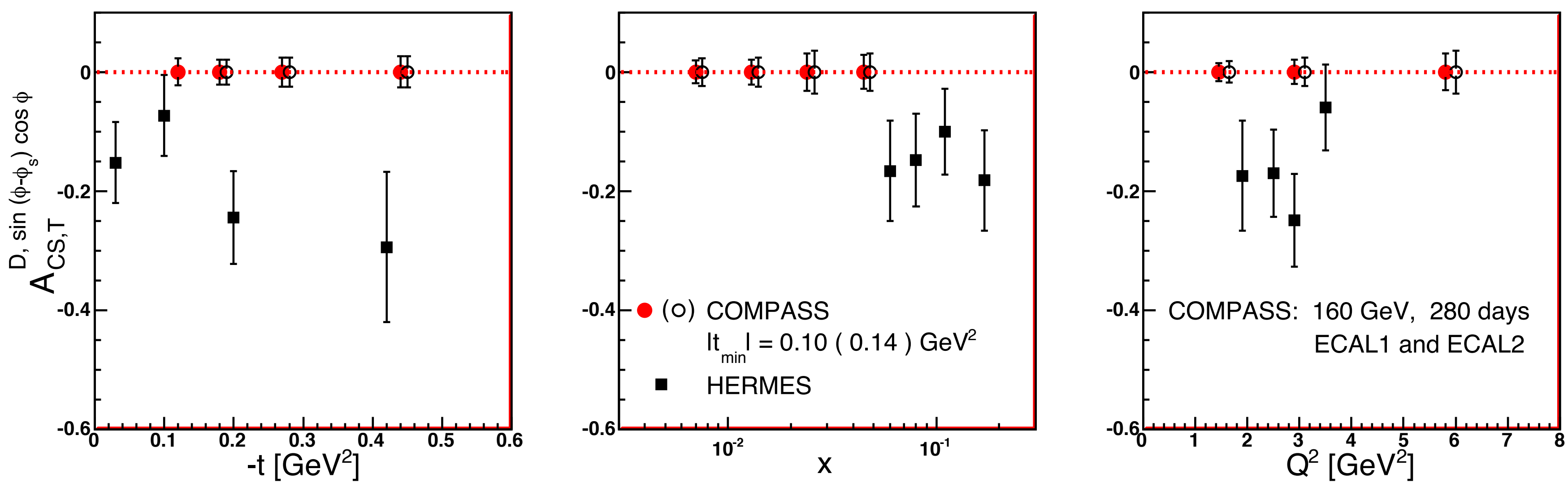
$\vec{e}\, p^{\uparrow} \to e\, p\, \gamma$ E12-12-010

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

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

With the **HD ice target**
(transv pol =60% H)

$\vec{e}\, p^{\uparrow} \to e\, p\, \gamma$ @ COMPASS (part of LOI in preparation)



Conclusions and perspectives

Large worldwide experimental effort for DVCS and HEMP

- 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

Precise data on the widest possible kinematic range are needed
➔ High priority for Jlab12, COMPASS and future EIC

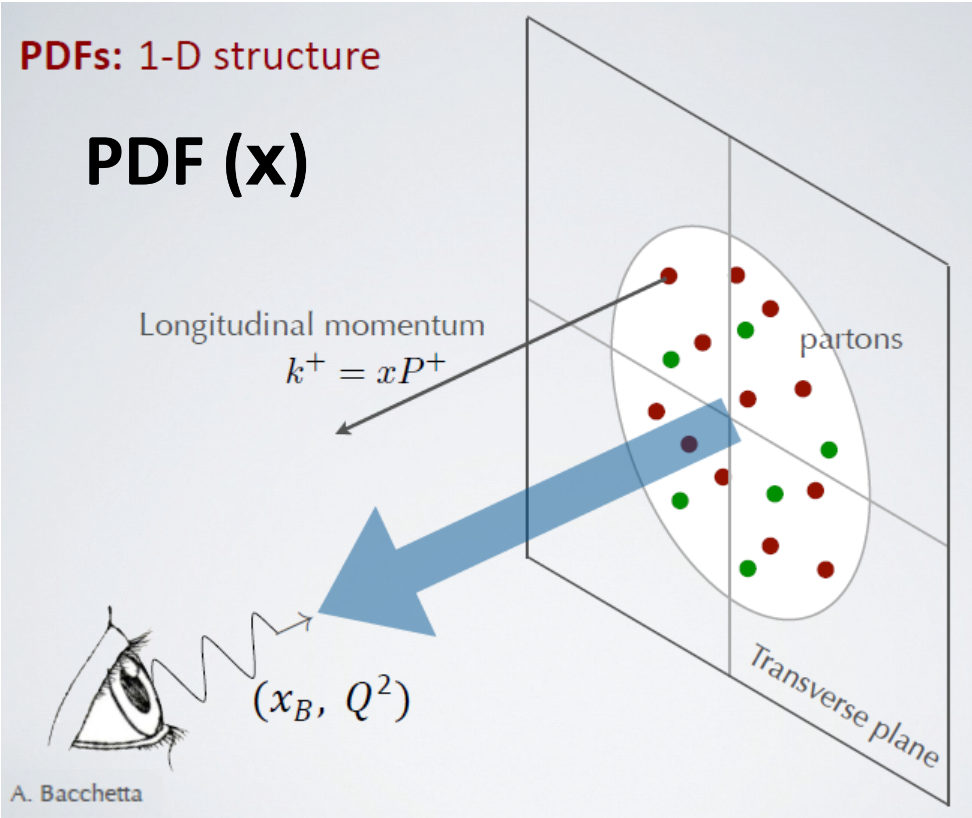
Global fits needed to interpret
the existing and forthcoming mesurements

Important complementary information
from excl. Meson production (only briefly touched in my talk)

A lot of work is ahead of us…

BACKUP

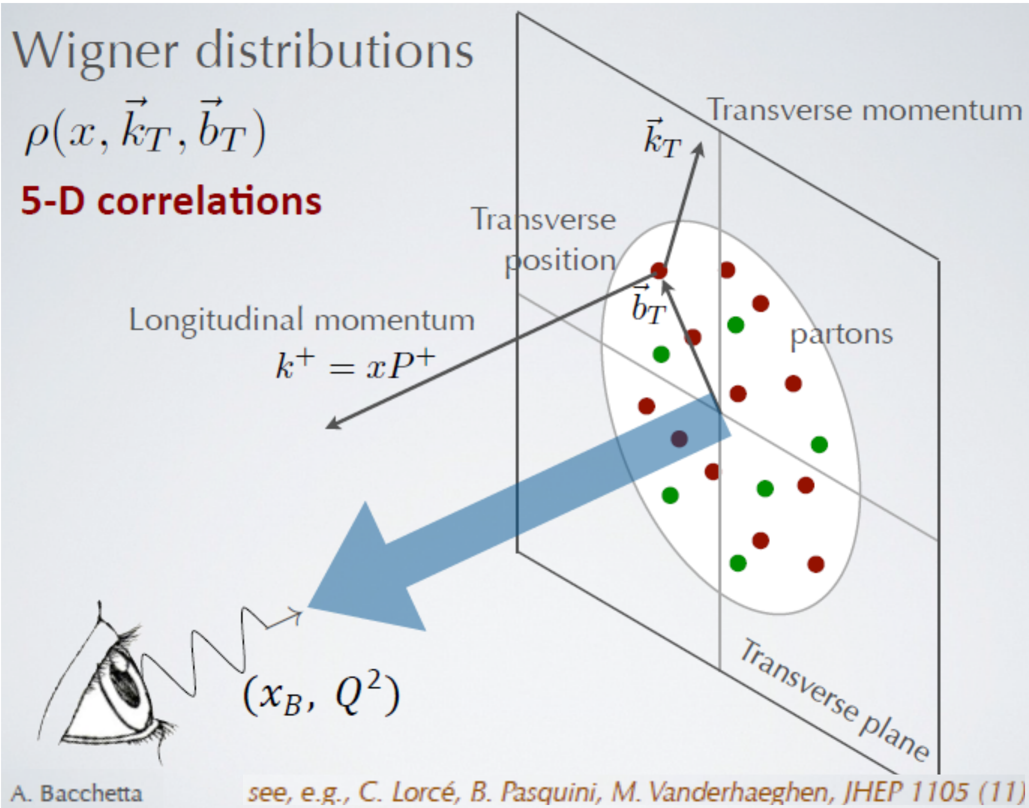
From PDFs to TMDs and GPDs



PDF measured in Deep Inelastic Scattering

$$\ell p \rightarrow \ell' X$$

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)

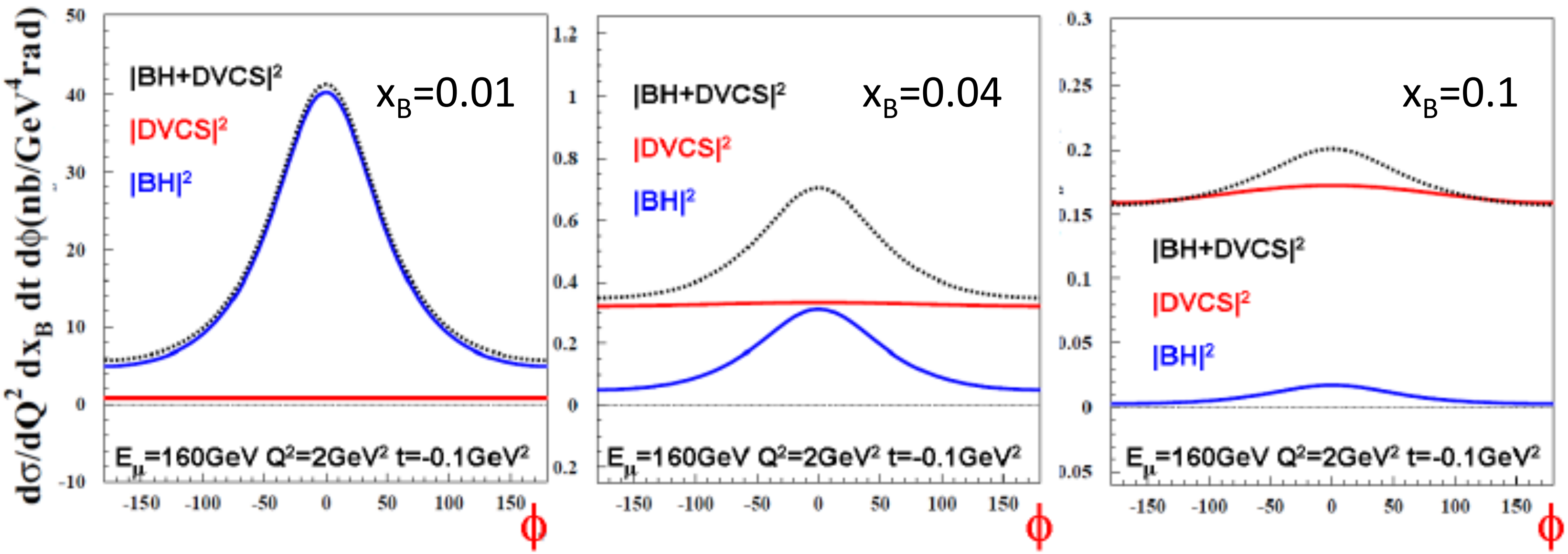
TMD accessible in **SIDIS** and **DY**

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

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 $d\sigma/dt$

E_ℓ ↘ BH ↗

Jlab
HERMES, H1
COMPASS

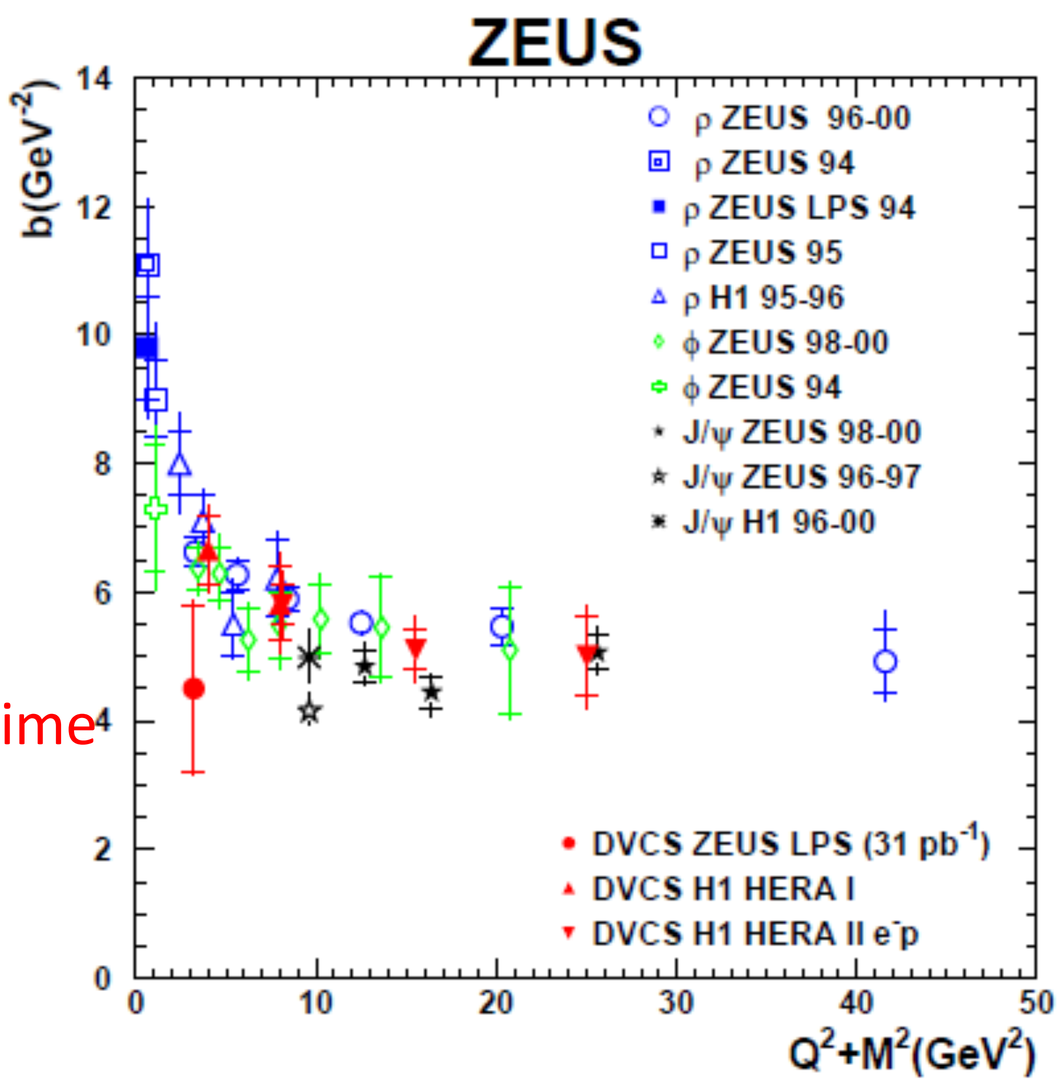
Only for high energy
H1 & ZEUS
COMPASS

Cross sections and t dependence

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

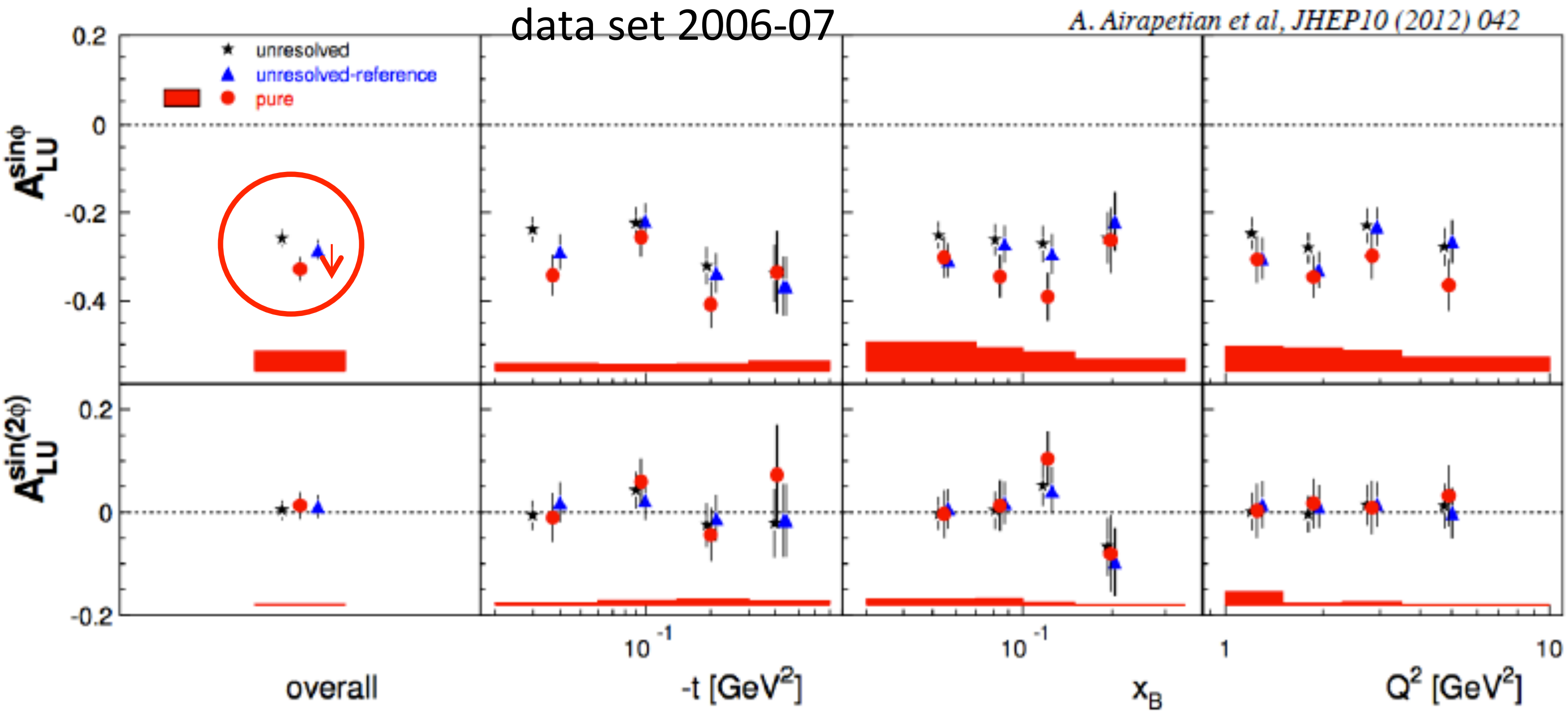
sensitivity
to the nucleon transverse size
+ to the meson transverse size

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



BSA with recoil detector with HERMES

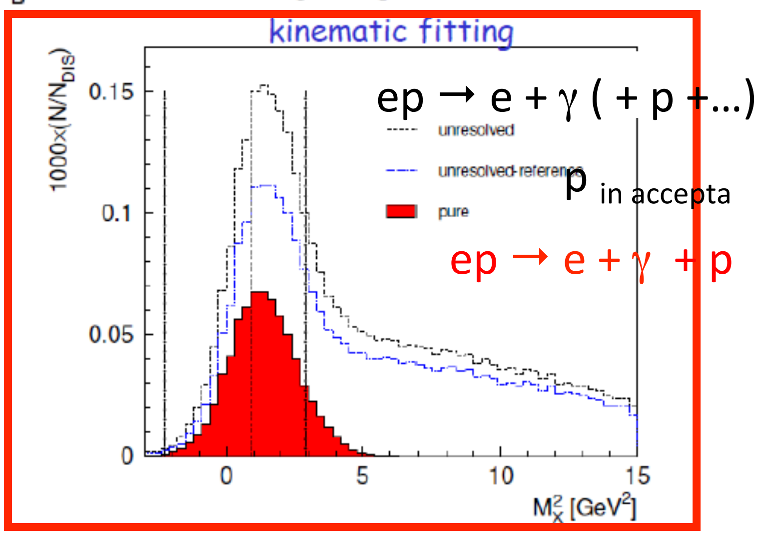
data set 2006-07



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 the associated DVCS

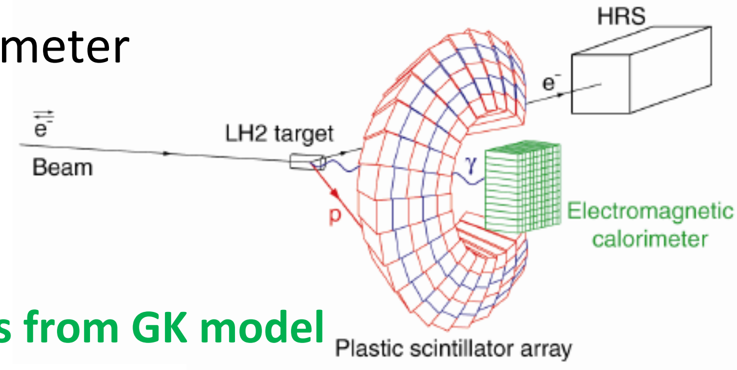


Beam Spin Sum and Diff of DVCS - HallA

E00-110 pioneer experiment with magnetic spectrometer

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

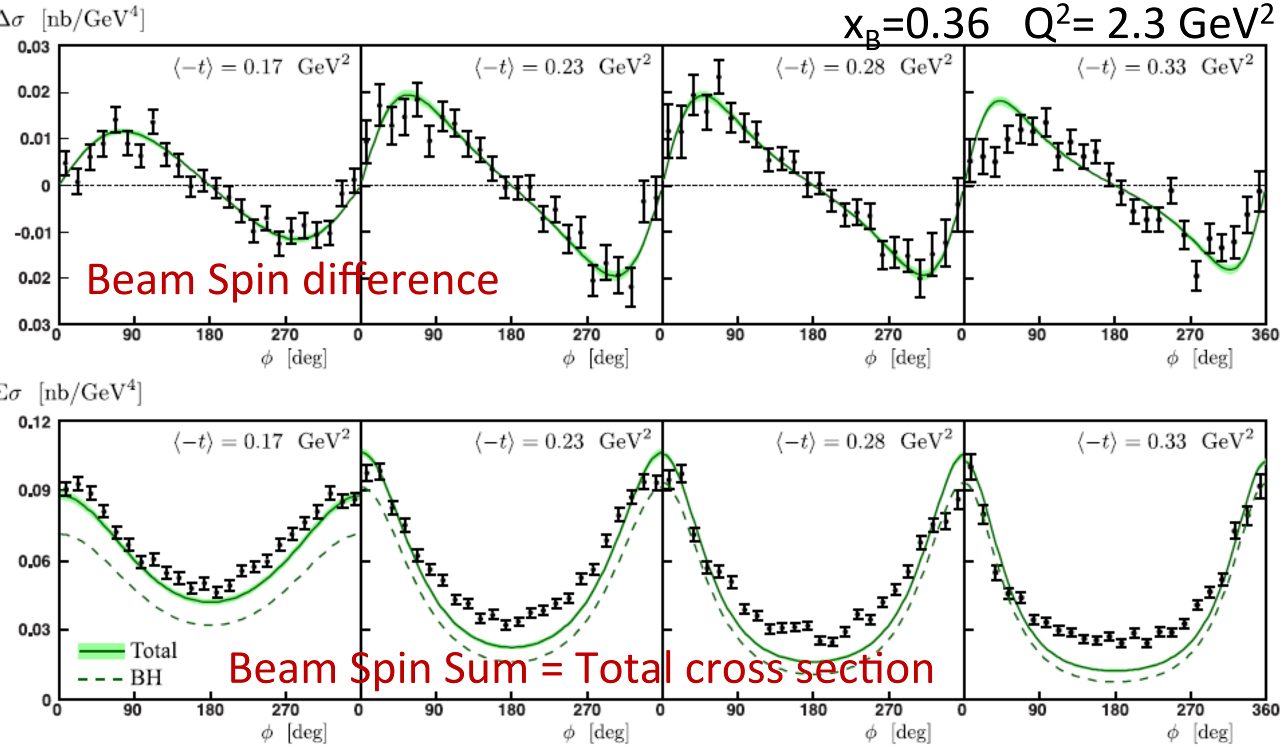
$\vec{e}\,p \rightarrow e\,\gamma\,p$



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

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

x_B=0.36 Q^2= 2.3 GeV^2



Do we understand Hall A data?

Beam Spin Sum and Diff of DVCS - HallA

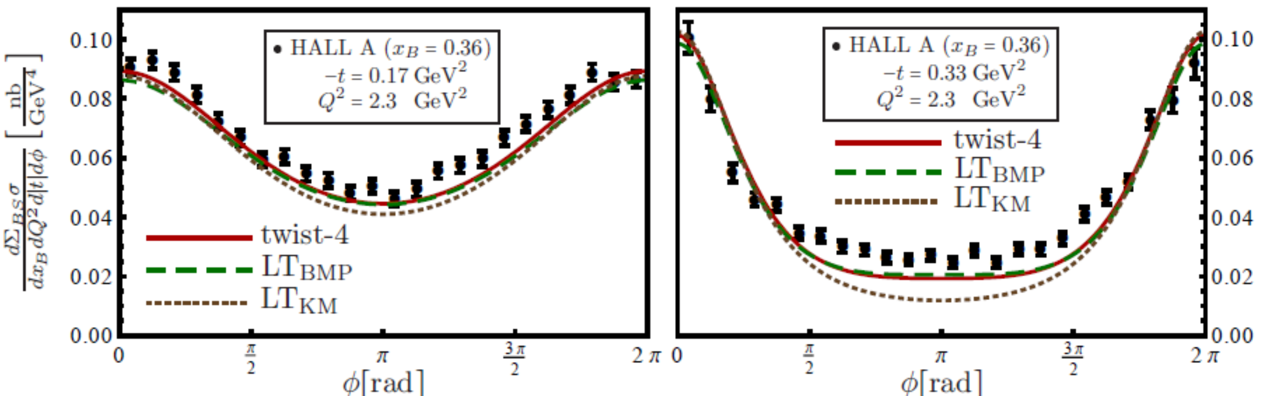
Data: Munoz et al. PRL97, 262002 (2006)

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

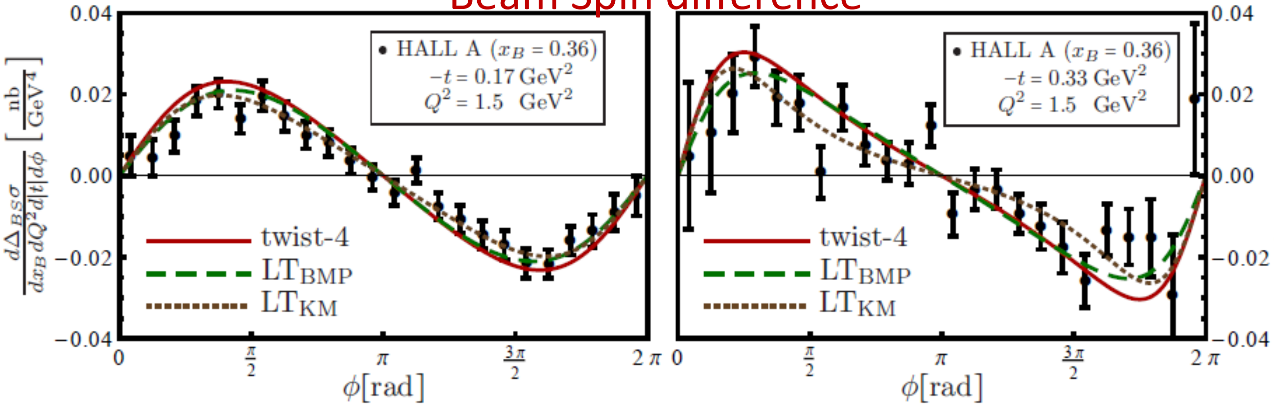
GK12 model evaluated with KM and BMP prescription

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

Beam Spin Sum = Total cross section



Beam Spin difference

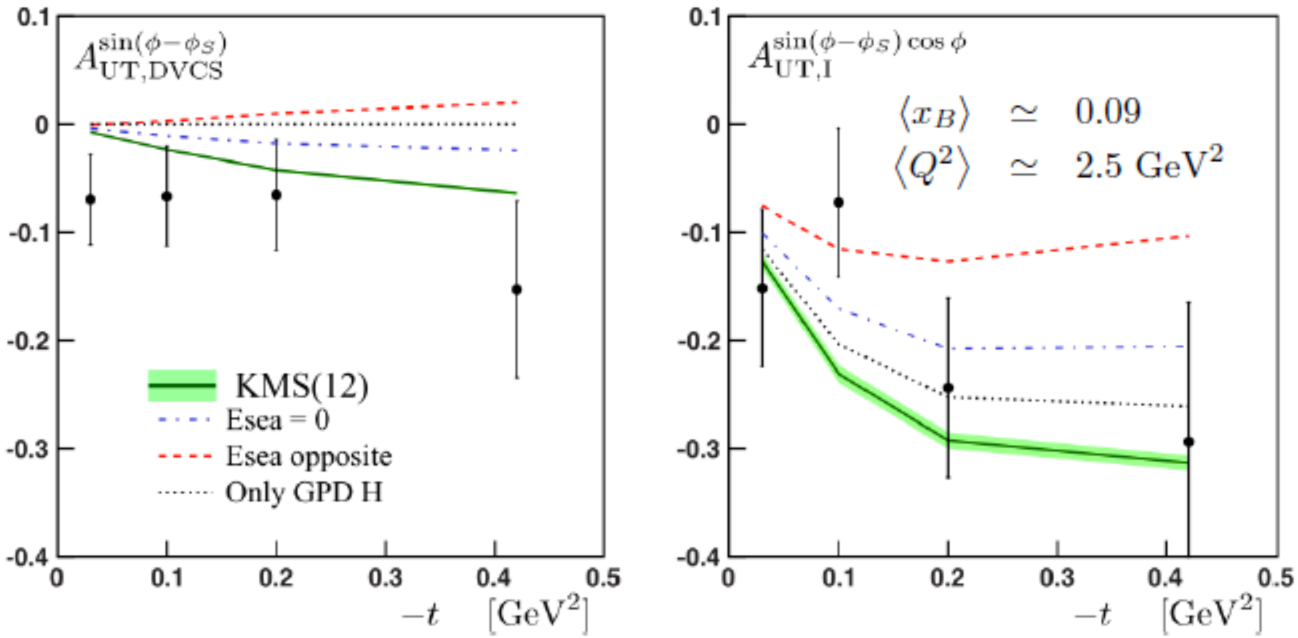


Do we understand Hall A data?

News:
- 2010: run E07-007 Rosenbluth-like DVCS^2/Int sparation
- 2014: HallA with 11 GeV
- 2018: HallC with 11 GeV

Trans. Target Spin Asymmetry on a proton – HERMES

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



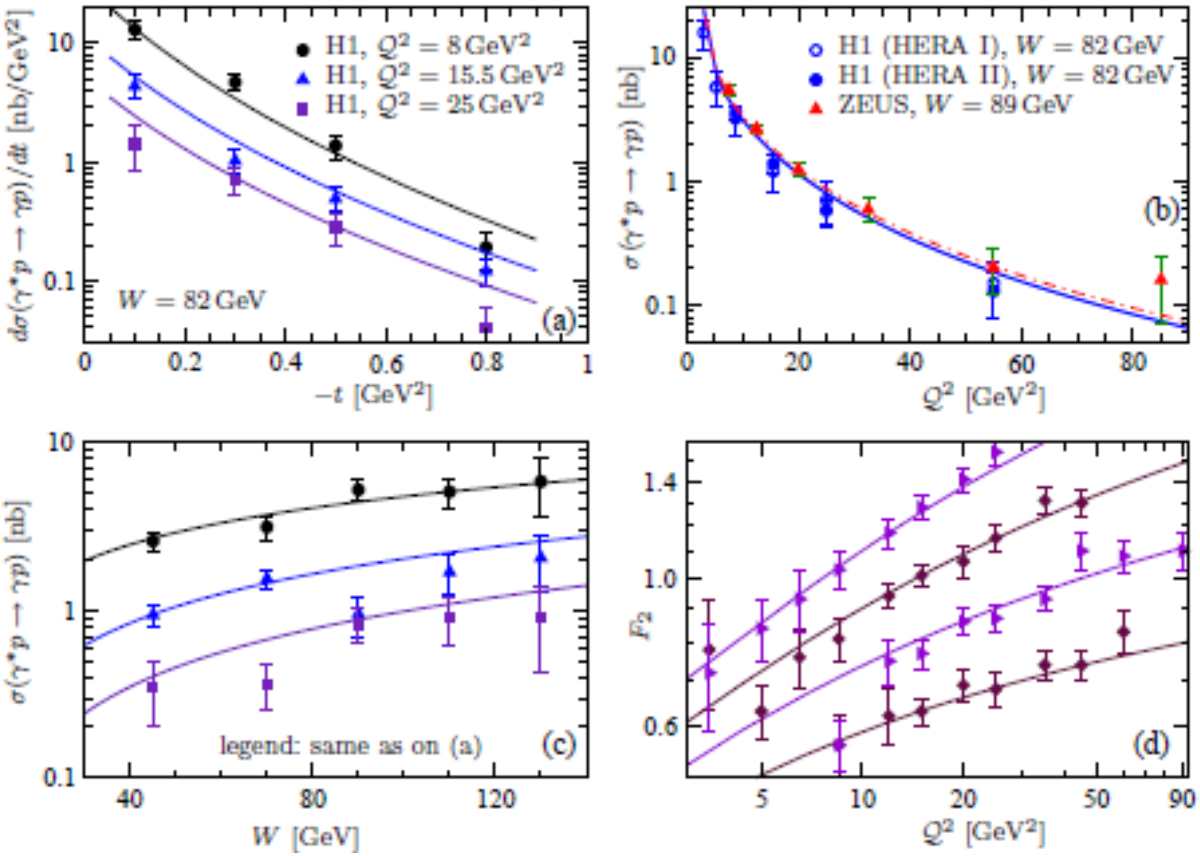
$$A_{\mathrm{UT,DVCS}}^{\sin(\phi-\phi_S)} \sim \mathrm{Im}[\mathcal{E}^* \mathcal{H}]$$

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

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}

E sea < 0 is favored by HERMES data

Predictions for DVCS from KM model



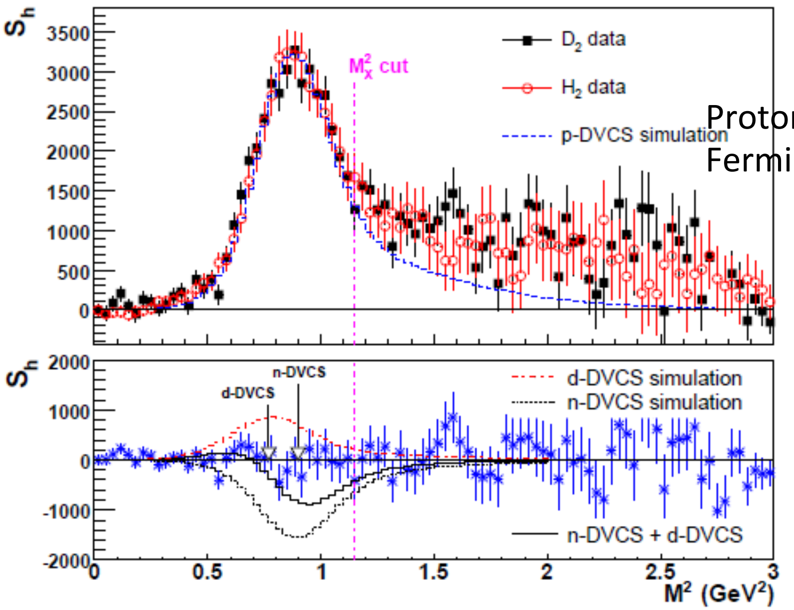
KM10: Kumericki and Mueller NPB (2010) 841; arXiv:0904.0458

one of the most general parameterization of GPDs based on their mathematic properties

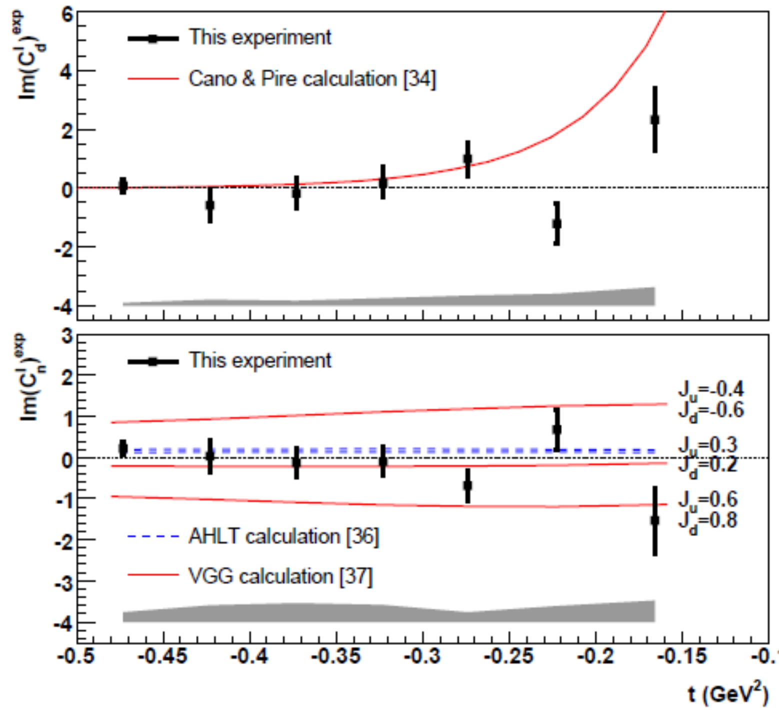
fit to the DVCS data and DIS

DVCS on a neutron – HALL A

DVCS on LD2 target= DVCS on quasi- free proton + quasi-free neuton + coherent DVCS on D



Proton Including Fermi motion



Next:

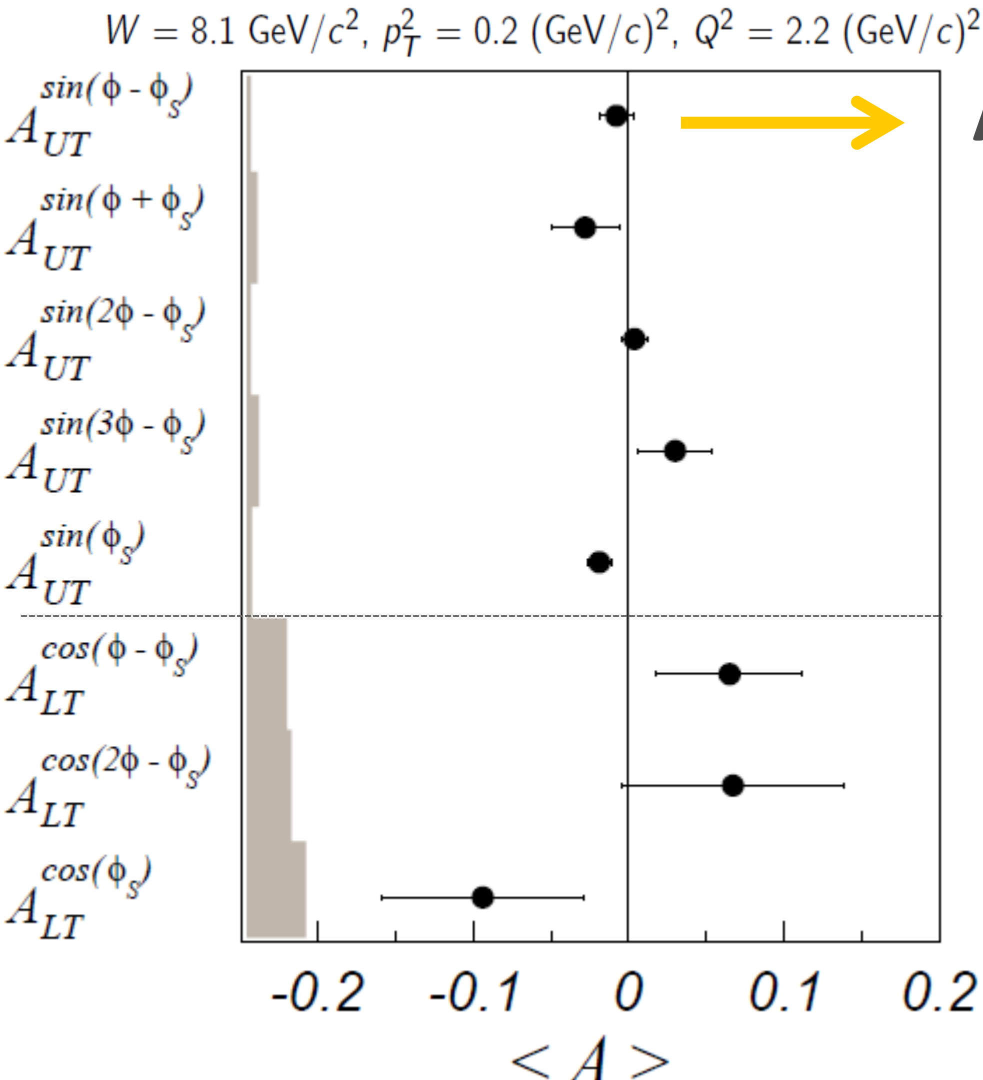
- 2010: run E08-025 with LD2 target
  Rosenbluth-like DVCS^2/Int separation

- 2018: CLAS12 with 11 GeV with LD2 target + neutron detector (ToF)

exclusive ρ^0 production with Transv. Polar. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non détecté}}$, $\rho^0 \hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,with transv. polar. NH3 target, without recoil detector



$A_{UT}^{\sin(\phi - \phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/8\ E^g$
Cancellation between gluon and sea contributions and **$E^{u\ val} \sim -E^{d\ val}$**

COMPASS, NPB865 (2012) 1-20
(similar res HERMES PLB679(2000) 100)

ω production very interesting

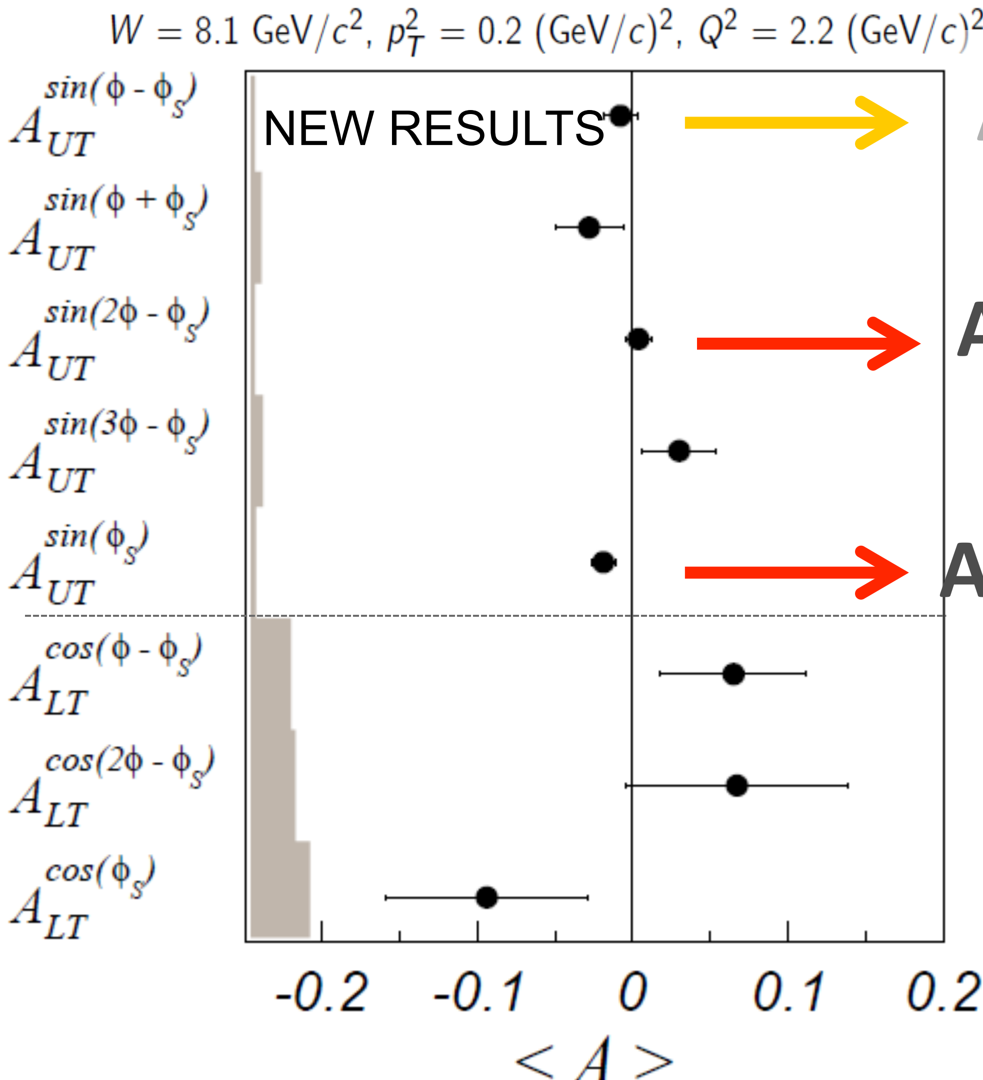
analysis on going

exclusive ρ^0 production with Transv. Polar. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non détecté}}$

$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

$A_{UT}^{\sin(2\phi-\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$

$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

➔ **H_T should not be small**

COMPASS, PLB 731 (2014) 96