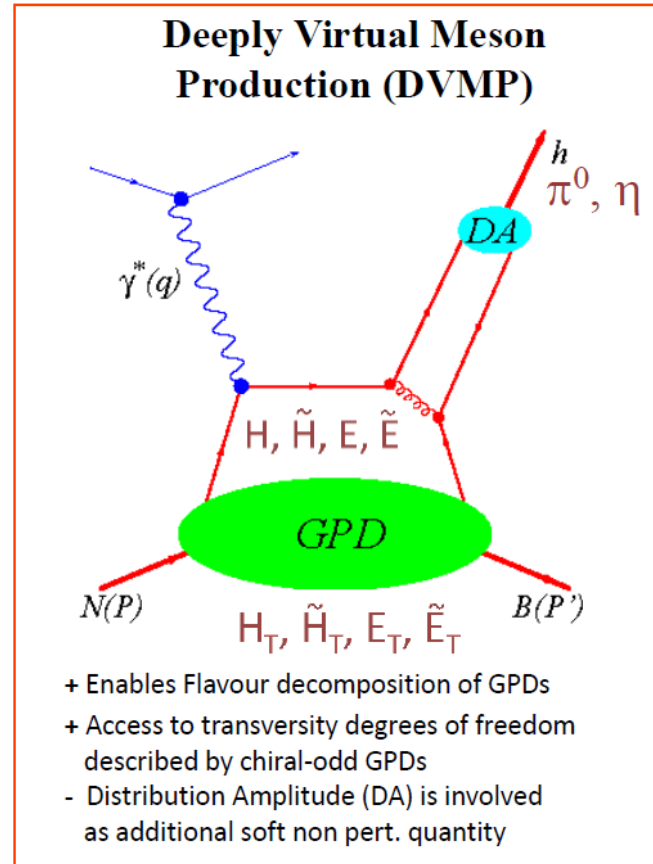
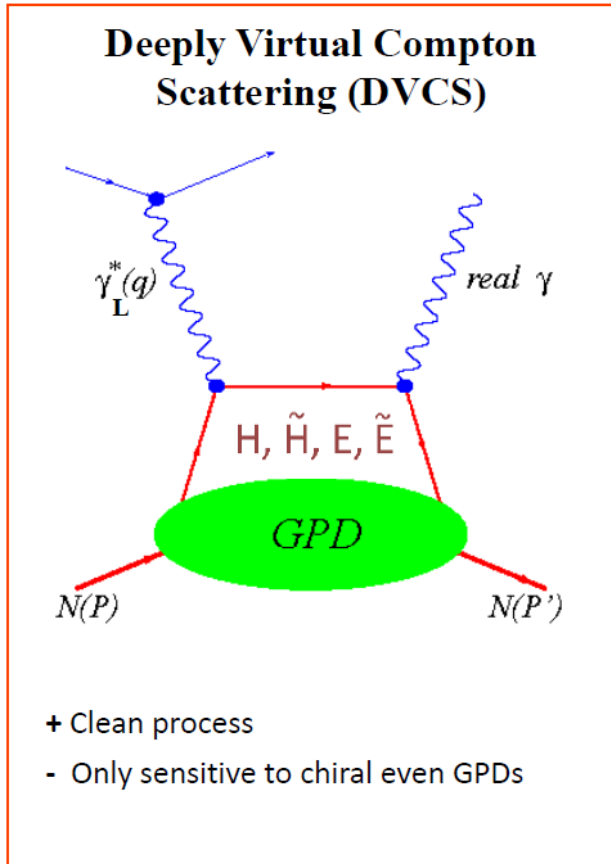


Experimental results on DVCS and HEMP for Generalized Parton Distributions

Fabienne KUNNE
CEA /IRFU Saclay, France

Accessing GPDs

- Physics goals: - **3D mapping of Nucleon**
 - **sensitivity to Orbital Angular Momentum**



27 GeV e⁺ & e⁻

Longit. polarized ~ 54%

Gaseous intern. polar target

1995 to 2007

160-200 GeV

Polarized muon beam DIS

Pion beam: Drell-Yan, J/ψ

Long solid polarized targets

6 GeV → 12 GeV

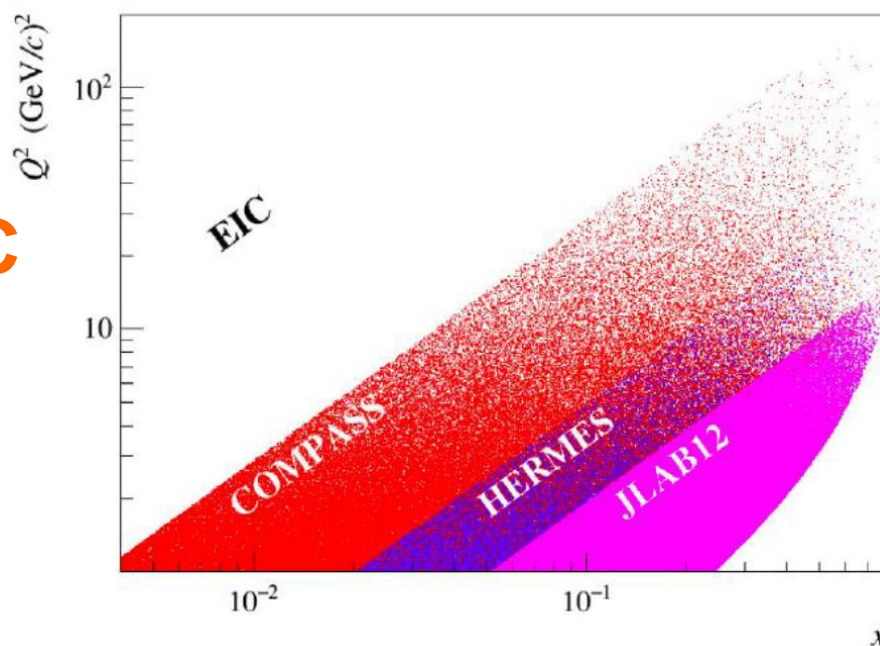
Polarized CW e⁻ beam

Pol=85%,

High luminosity

and pioneering work at
H1 and ZEUS.

... and future EIC



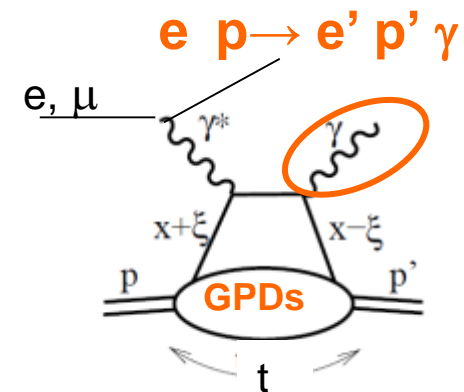
GPDs generalized Parton Distributions

See talk by J. Wagner

Want to determine Re and Im parts of 8 GPDs : $H, E, \tilde{H}, \tilde{E}$
and the 4 'transverse' ones
via 'exclusive' processes: **DVCS** (γ) and **HEMP** ($\rho, \omega, \phi...$)

DVCS interferes with Bethe-Heitler process

→ Can use interference terms (e.g. at Jlab)
or pure DVCS production (e.g. at COMPASS).



Method:

- Collect very large sample of data, numerous observables (cross sections and asymmetries) in 4 kinematic variables
- Global analyses to extract 8x2 (Re and Im) Compton Form Factors **CFFs**
- Deconvolutions to finally access **GPDs**.

Results on Deep Virtual Compton Scattering- DVCS

$e p \rightarrow e' p' \gamma$

DVCS mostly sensitive to:

U, L, T indexes refer to beam and target polarization

Easiest

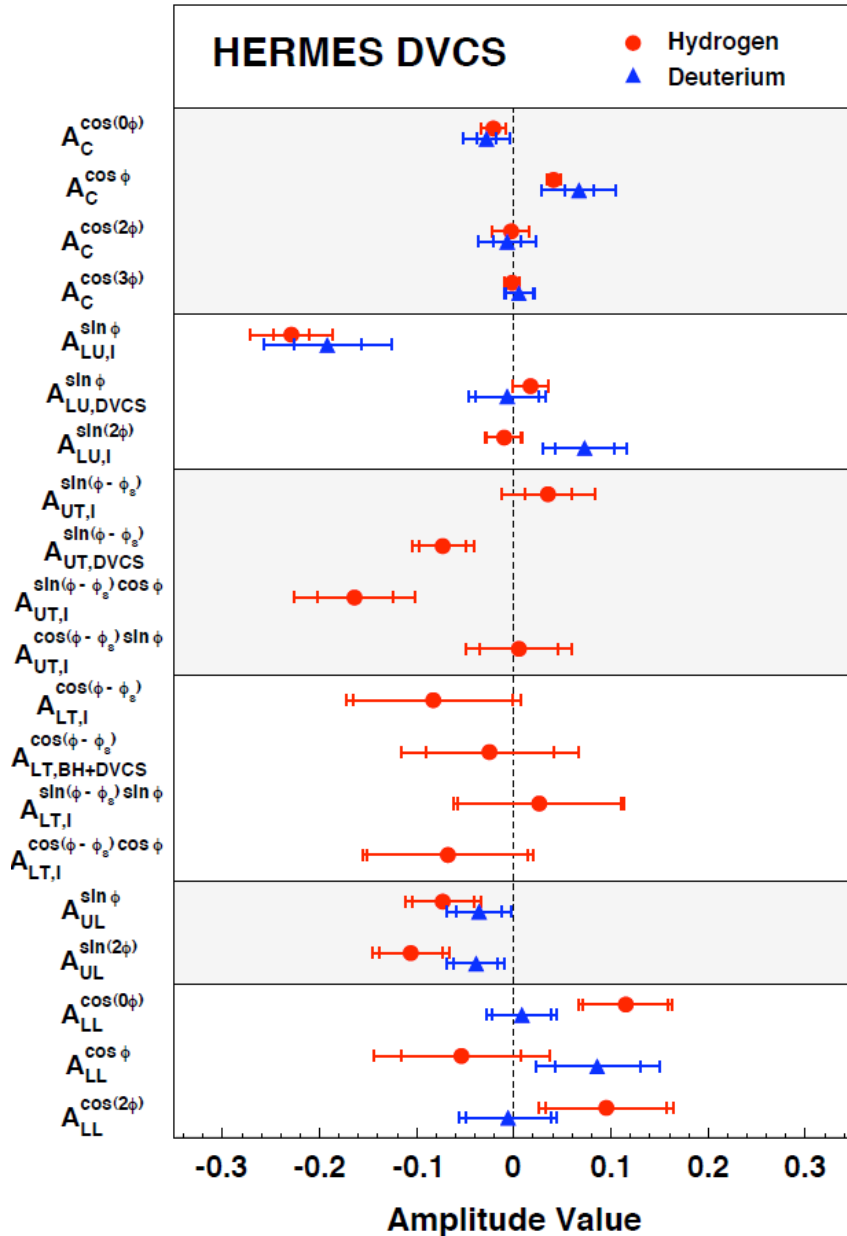
\mathcal{E} sensitive to OAM,
Can be measured with transversely polarized target

	<i>Im DVCS</i>	<i>Re DVCS</i>
\mathcal{H}	A_{LU}, A_{\odot}	σ, A_{UU}
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
\mathcal{E}	A_{UT}	

All demanding in luminosity

HERMES- Summary of results

Gunnar Schnell at IWHSS-22, sept.2022



Beam-charge asymmetry: **e+ & e- beams**

GPD H

PRD 75 (2007) 011103

NPB 829 (2010) 1

JHEP 11 (2009) 083

Beam-helicity asymmetry: **A_{LU}**

GPD H

PRC 81 (2010) 035202

PRL 87 (2001) 182001

JHEP 07 (2012) 032

Transverse target spin asymmetries: **A_{UT}**

GPD E from proton target

A_{LT}

JHEP 06 (2008) 066

PLB 704 (2011) 15

Longitudinal target spin asymmetry: **A_{UL}**

GPD \tilde{H}

JHEP 06 (2010) 019

NPB 842 (2011) 265

Double-spin asymmetry: **A_{LL}**

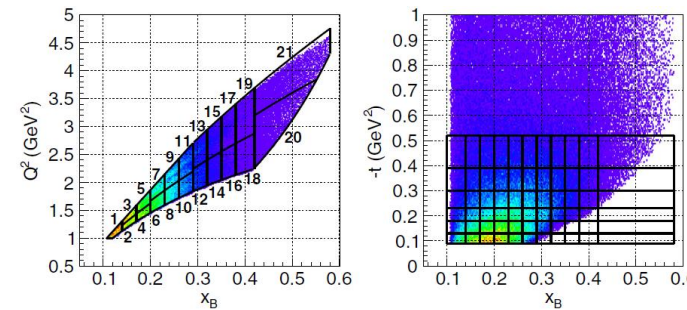
GPD \tilde{H}

DVCS – Jlab CLAS proton target, $e H \rightarrow e' p \gamma$

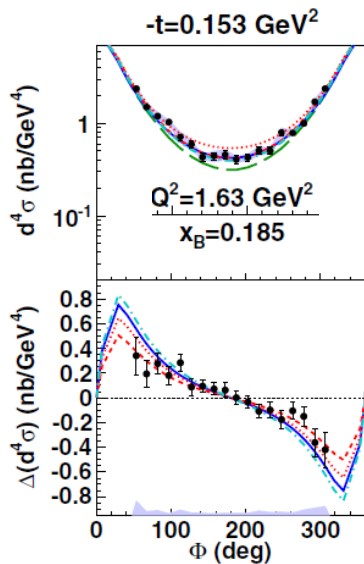
$d^4\sigma(x, Q^2, t, \phi)$ and $\Delta(d^4\sigma)$ beam spin difference,
sensitive to $Im[H] \sim e^{-b(x) t}$

b related to proton transverse size

K. Jo et al., CLAS, PRL 115 (2015)

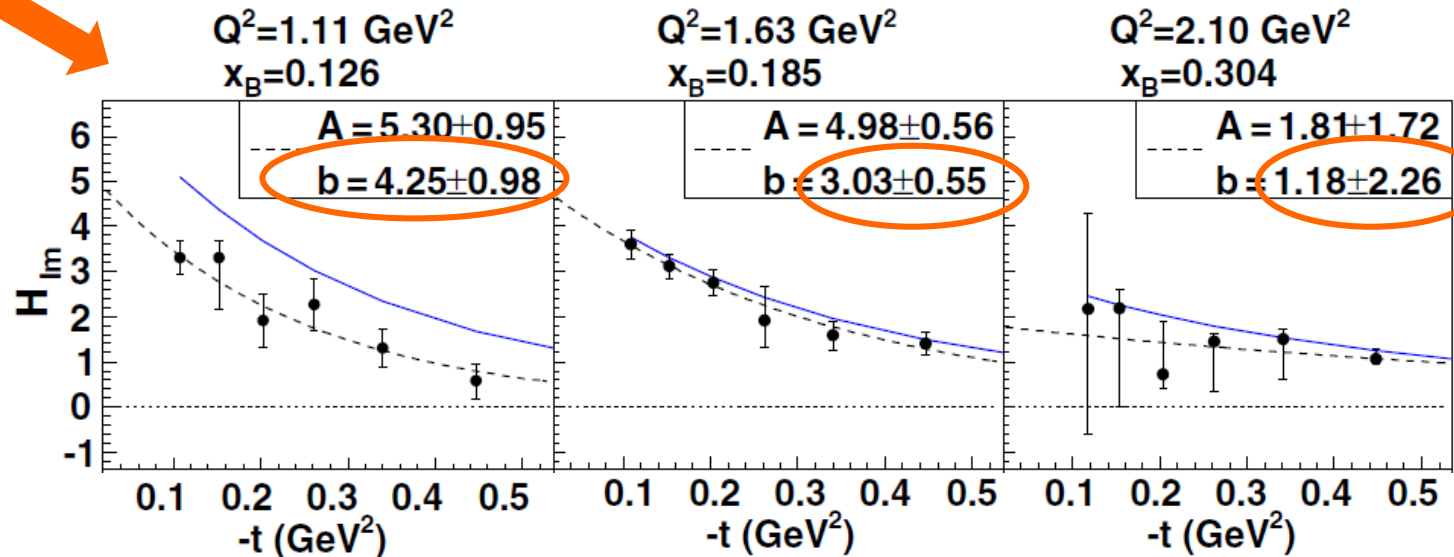


a sample:



— VGG
---- fit

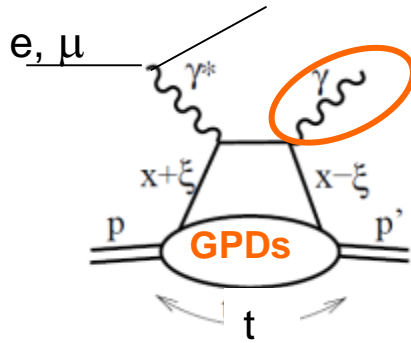
Assuming one GPD, fit to CFF at 3 x_B values:



b decreases as x_B increases
→ proton shrinking with x_B

DVCS- t-slope of Cross-section (COMPASS)

$$\mu^{+/-} p \rightarrow \mu p \gamma$$



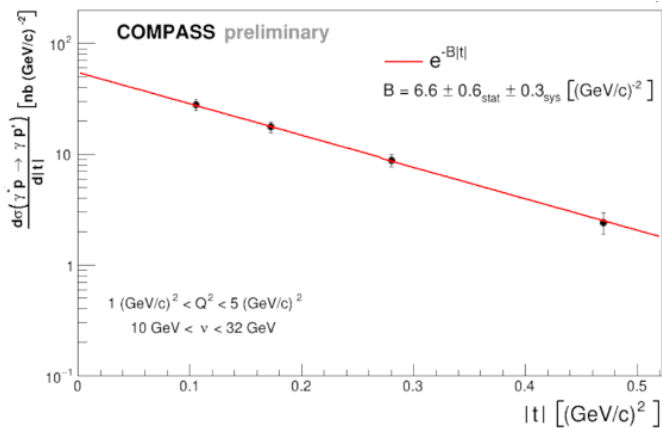
Combining data from $\vec{\mu}^+$ and $\overleftarrow{\mu}^-$ beams
(beam spin & charge sum),
measure t-slope of DVCS cross section

→ x dependence of transverse size of the nucleon

$$\sigma^{\text{DVCS}}/dt \sim \exp^{-B|t|}$$

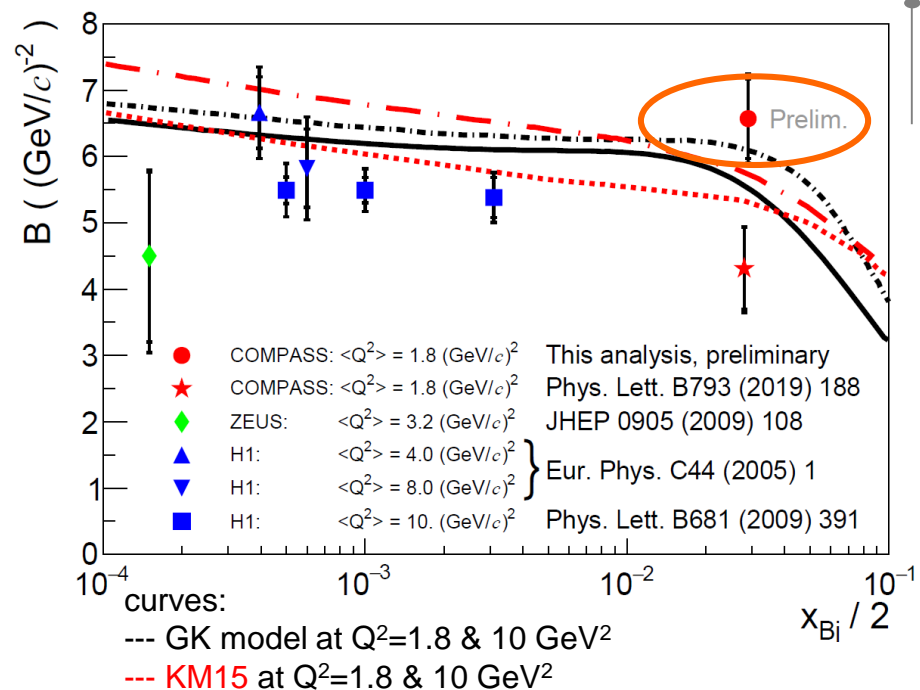
$$B(x_B) = \frac{1}{2} \langle r_{\perp}^2(x_B) \rangle$$

Measurement of proton transverse size vs x_B



2016 data :prelim. result
3 x more stat. expected from 2017 data

New prelim. COMPASS result:



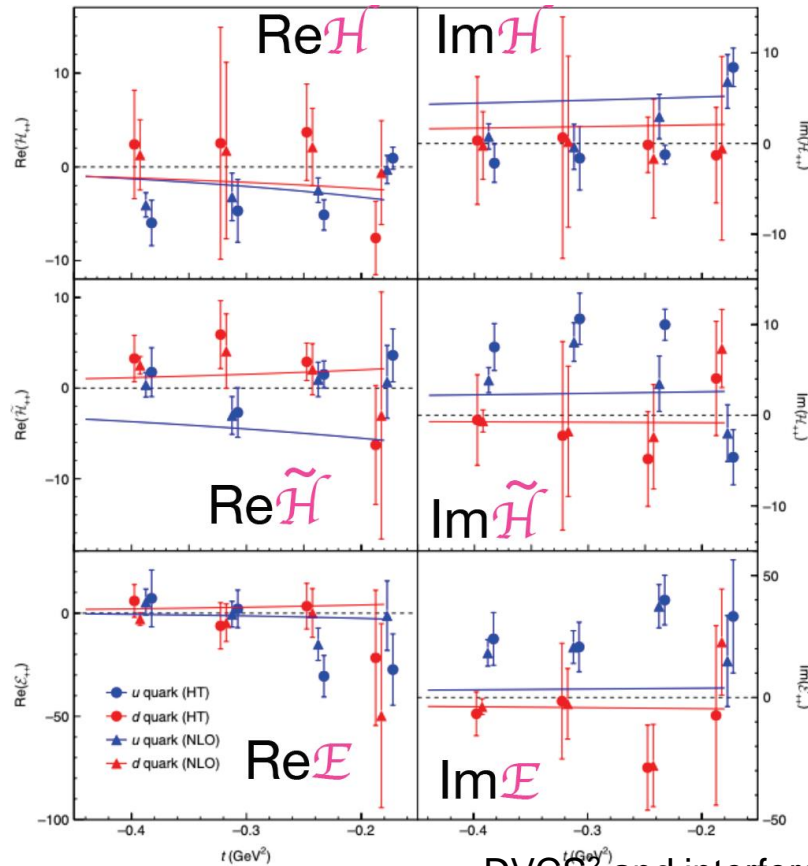
Flavour separation of CFFs

JLab Hall-A neutron and proton DVCS

Cross sections measured with LH₂ & LD₂ targets

t dependence of CFFs

u quark
d quark



Note larger scale for E

*Benali, Desnault, Mazouz et al.,
Nature Physics 16 (2020) 191-198*

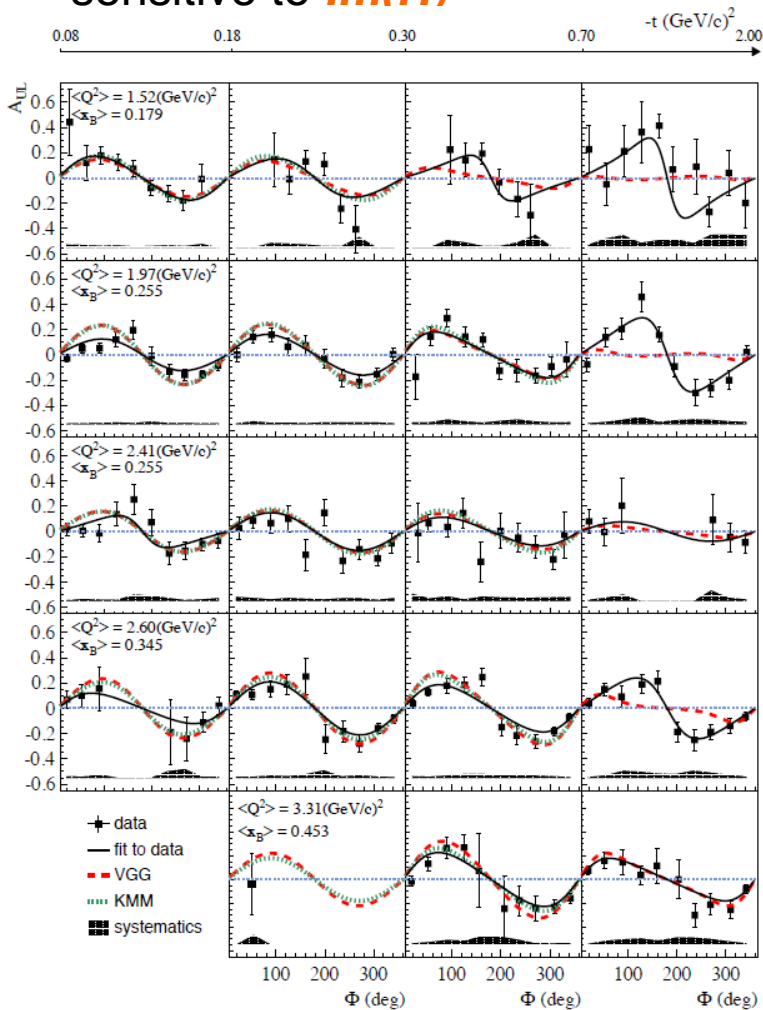
- DVCS² and interference extracted simultaneously
- curves: predictions of diquark model Goldstein et al.

u and d flavour separation for 3 CFFs

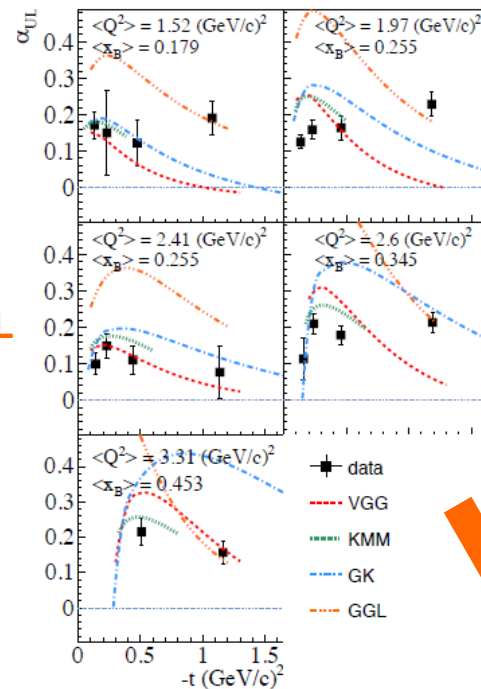
DVCS – Jlab CLAS \vec{p} target, $e \vec{p} \rightarrow e' (p) \gamma$

S. Pisano et al., CLAS, PRD 91 (2015) 5, 052014

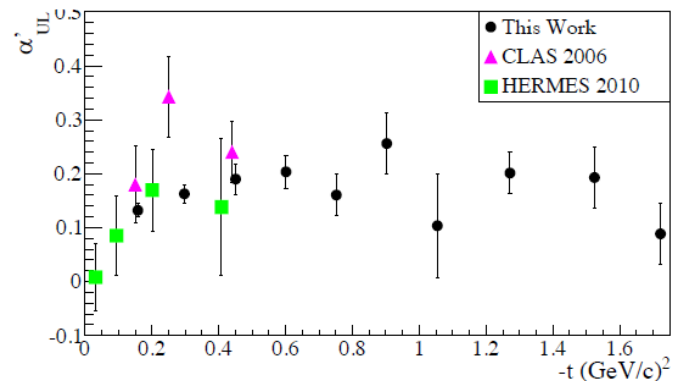
$A_{UL}(x, Q^2, t, \phi)$
sensitive to $Im(\tilde{H})$



ϕ modulation
amplitude α_{UL}



$\alpha'_{UL}(-t)$

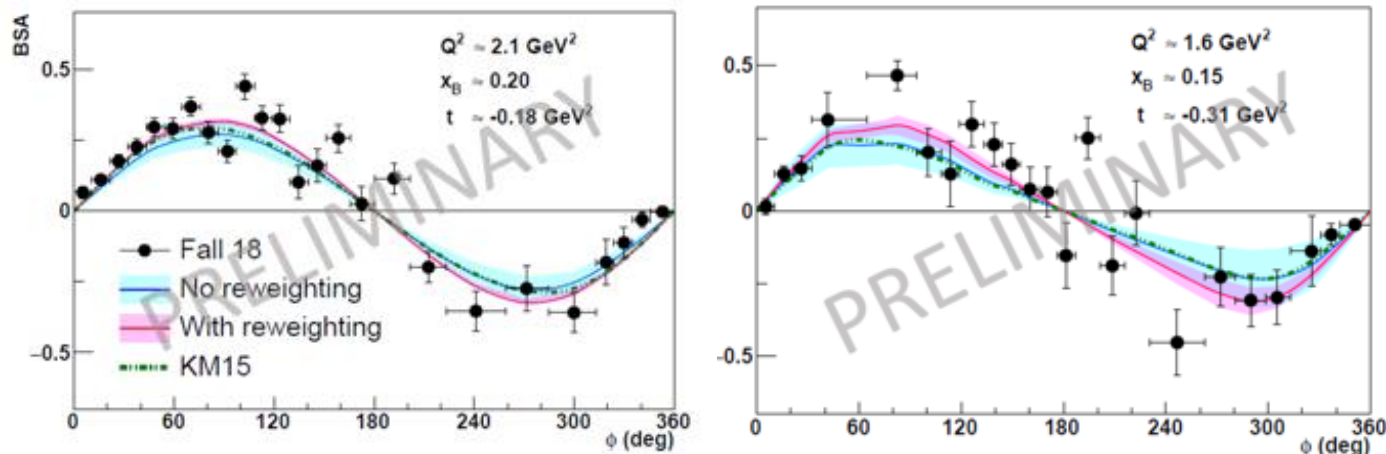


Possibility to access spatial distribution of quark helicity

DVCS – CLAS12 Beam Spin Asym (prelim.)

First results 12 GeV beam

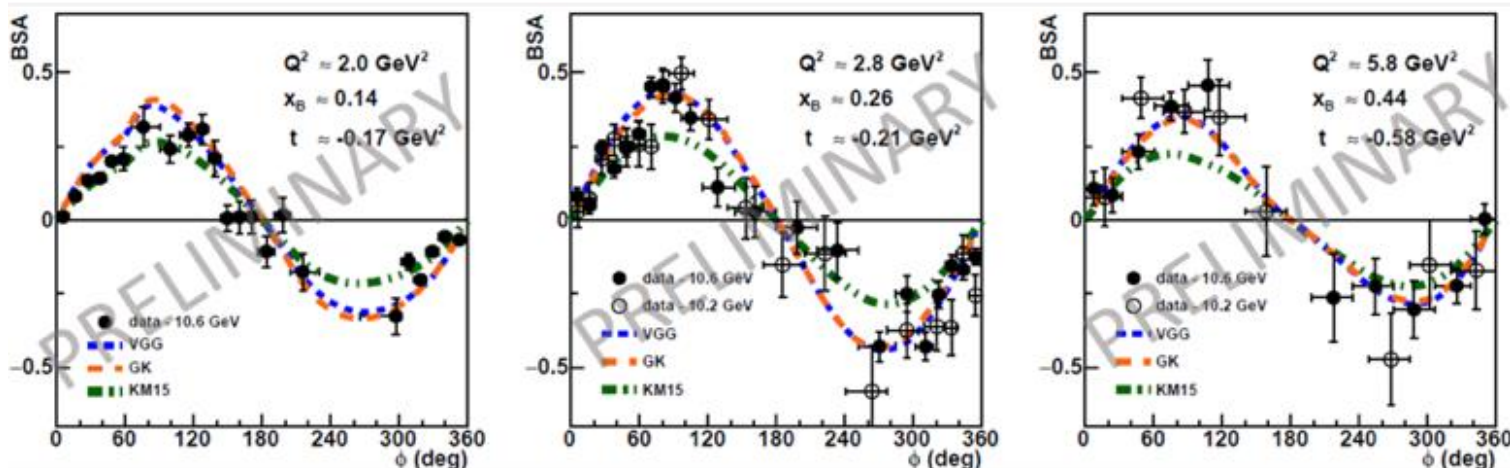
CLAS12 prelim., S.Stepanyan, IWHSS22, Sept.2022



Data 12 GeV, with curves based on earlier results obtained with 6 GeV beam data

	<i>Im</i> (DVCS, TCS)	<i>Re</i> (DVCS, TCS)
\mathcal{H}	$A_{LU}, A_{\odot U}$	σ, A_{UU}
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
\mathcal{E}	A_{UT}	

$$A_{LU} = \frac{a \sin \phi}{1 + c \cos \phi + d \cos 2\phi}$$



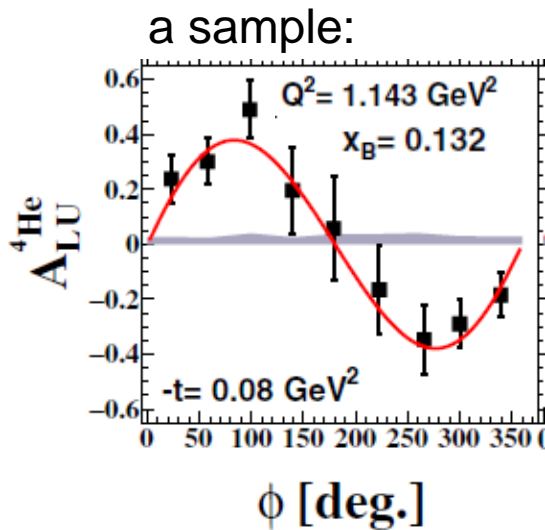
Towards higher Q^2 : very promising results – only 25% of stat used here

DVCS – Jlab CLAS ^4He target, $e\ ^4\text{He} \rightarrow e' \gamma \alpha$

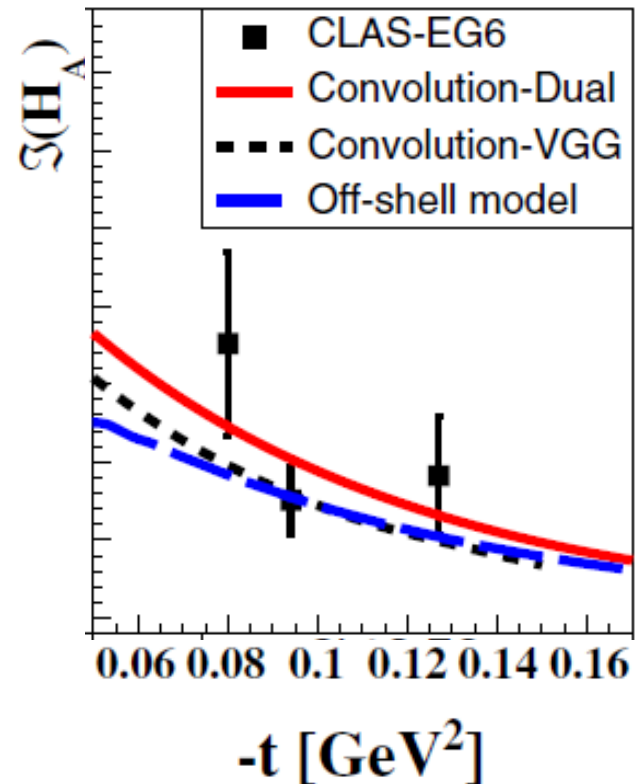
M. Hattawy et al., CLAS, PRL 119 (2017)

$A_{LU}^{4\text{He}}(x, Q^2, t, \phi)$
sensitive to $\text{Im}(H)$

+ radial TPC for recoil α , $\phi=16\text{cm}$

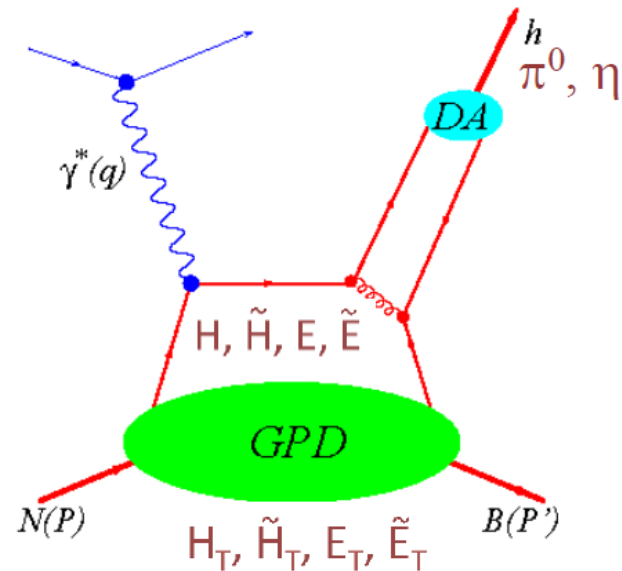


At LO- LT, only one GPD,
fit to Re and $\text{Im}[H(t)]$



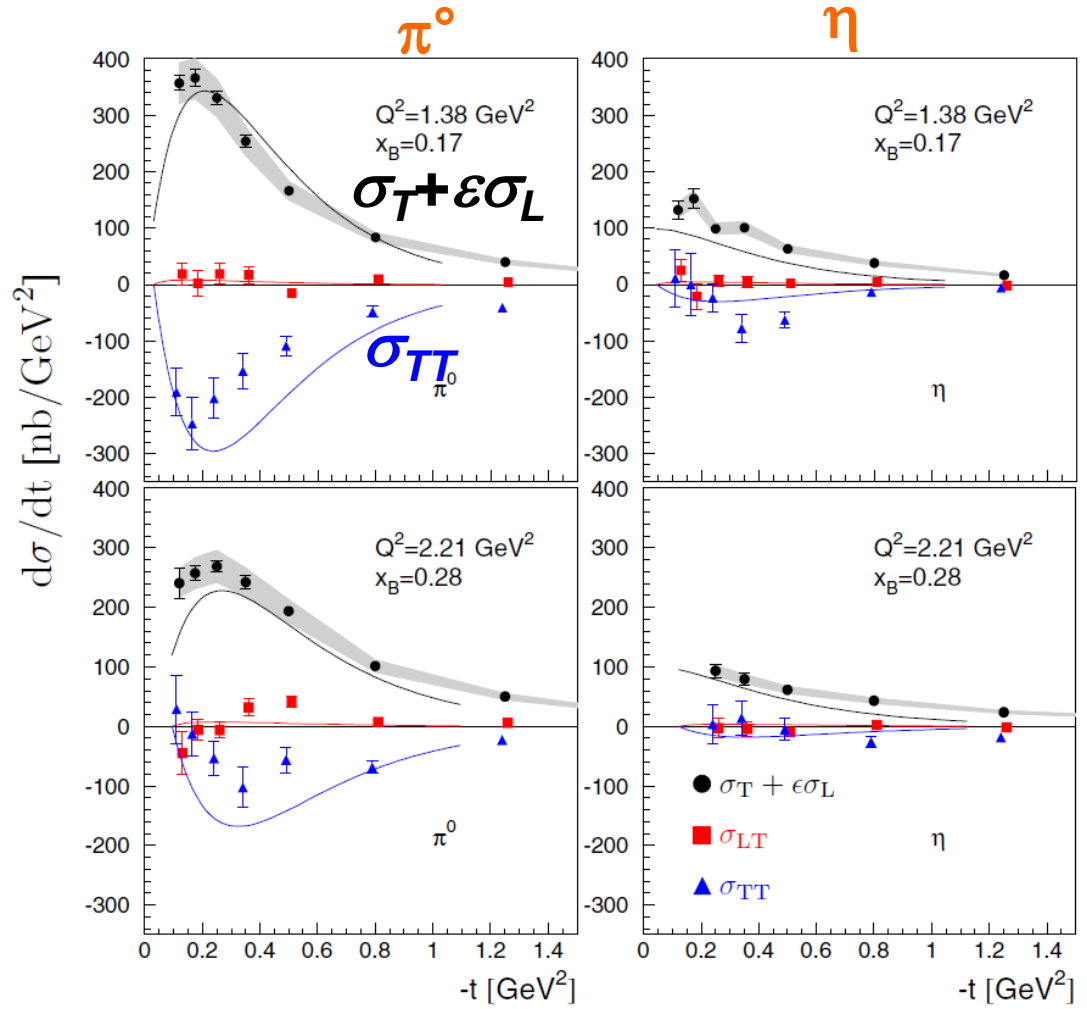
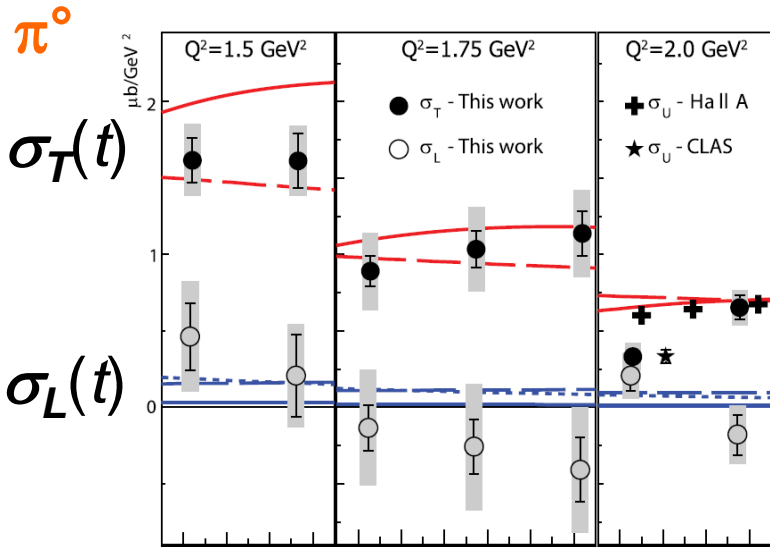
Promising ^4He study

Hard Exclusive Meson Production -HEMP



- + Enables Flavour decomposition of GPDs
- + Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

Mesons, DVMP – JLab, $e H \rightarrow e' (p) \pi^0 / \eta$



First clear separation
of σ_T and σ_L (Rosenbluth)
_____ GK
_____ GHLiuti

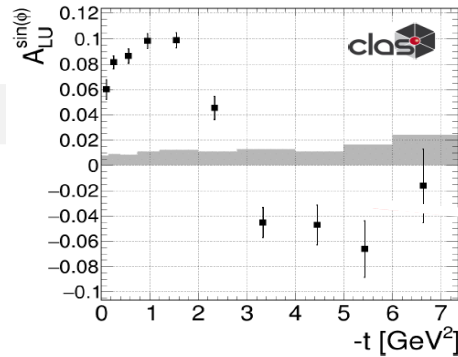
*M. Defurne et al., Hall A,
PRL 117 (2016) 262001*

I. Bedlinskiy et al., CLAS, PRC 95 (2017)

CLAS and CLAS12 excl. π^0 and π^+ production

Beam spin asymmetry π^+

S.Diehl et al., PRL125, 182001 (2020)

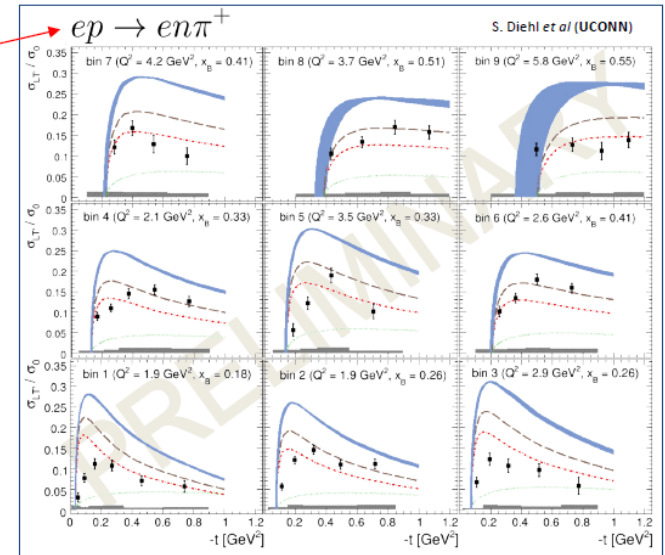
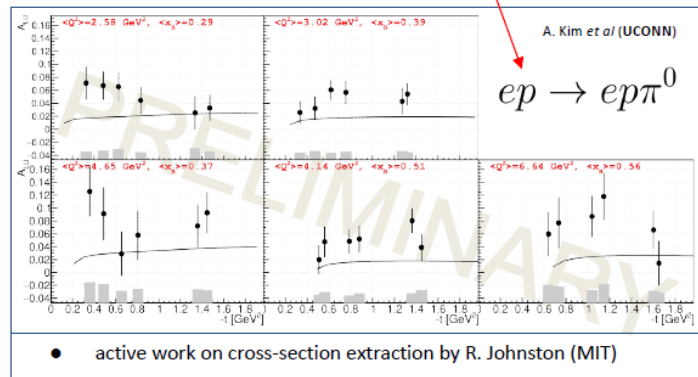


New: CLAS12
first results

$ep \rightarrow ep\pi^0$

$ep \rightarrow en\pi^+$

$$\sigma_{LT'} = \xi \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \times \text{Im} \left[\langle H_T \rangle^* \langle E \rangle + \langle \tilde{E}_T \rangle^* \langle H \rangle \right]$$

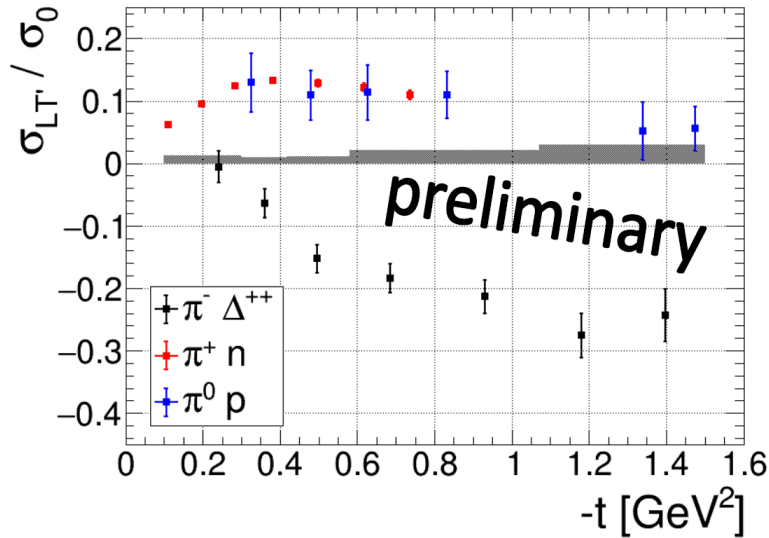


CLAS12 prelim, K.Joo, IWHSS 22, Sept.2022

CLAS12 exclusive π^+ , π^- and π^0 production

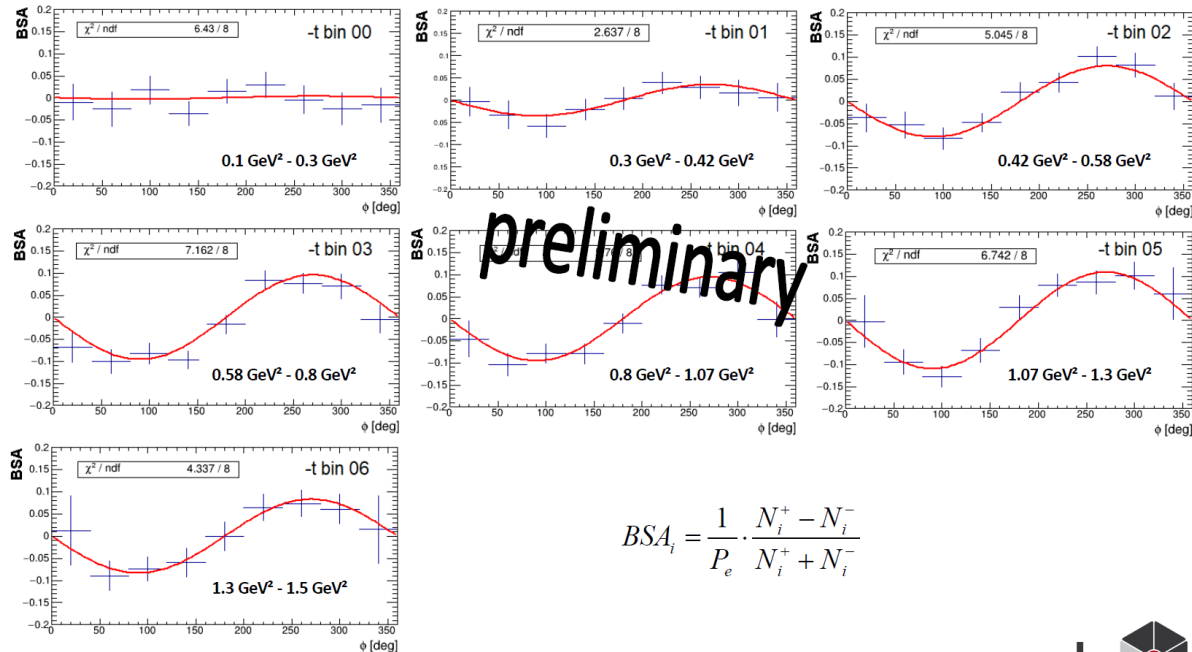
$\langle Q^2 \rangle = 2.48 \text{ GeV}^2$, $\langle x_B \rangle = 0.27$

CLAS12 prelim, K.Joo, IWHSS 22, Sept.2022



$ep \rightarrow ep \pi \Delta^{++}$

BSA (ϕ) in 7 t bins

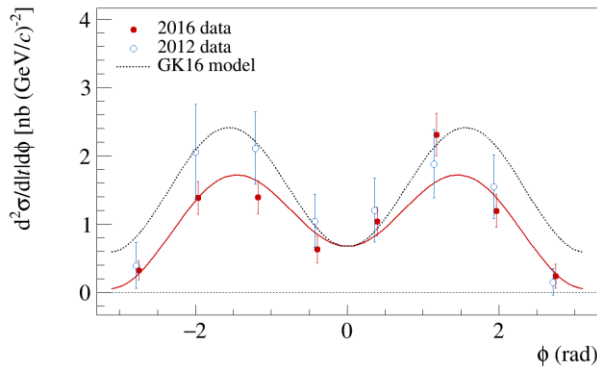


$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

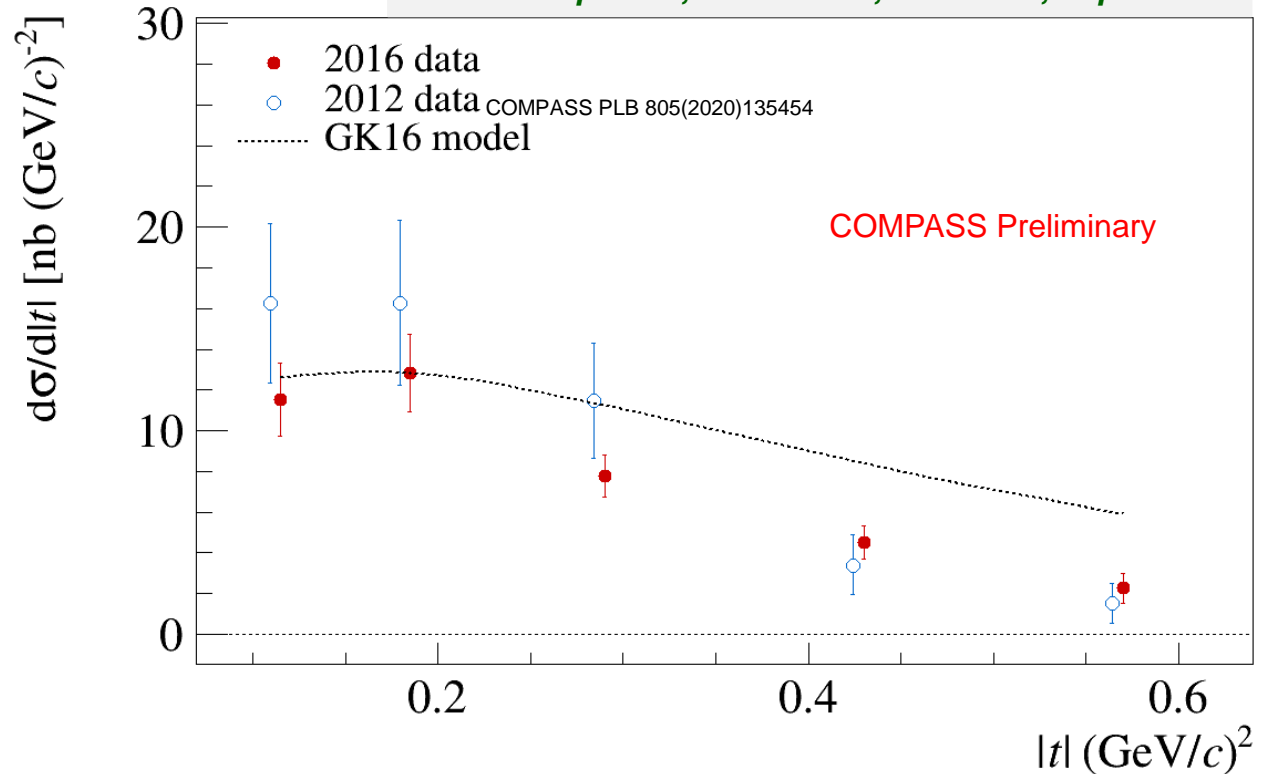
COMPASS exclusive π^0 production

$$\mu^{+/-} p \rightarrow \mu p \pi^0$$

25% of available statistics used



COMPASS prelim., M. Peskova, IWHSS 22, Sept.2022



Preliminary result on π^0 production at $x_B \sim 0.1$

→input for models as Goloskokov Kroll, Goldstein Liuti, etc.

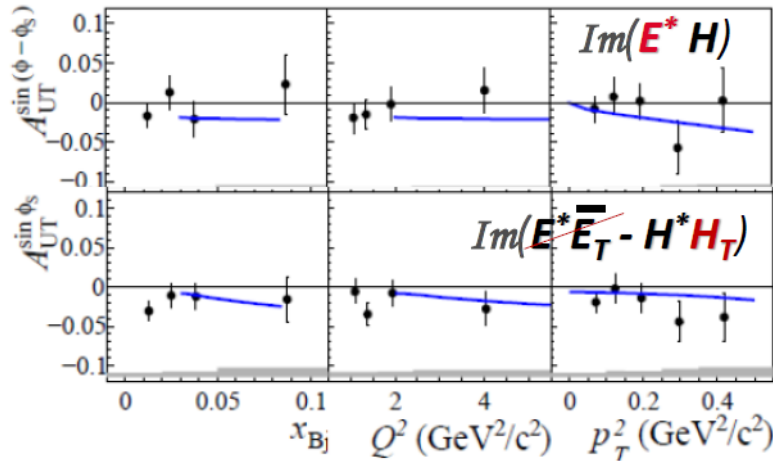
COMPASS HEMP of ρ^0 and ω

$\mu^{+/-} p \rightarrow \mu p \rho^0/\omega$ Transversely polarized target
 Sensitivity to GPD \mathbf{E}
 However, \mathbf{E}^u and \mathbf{E}^d of opposite sign

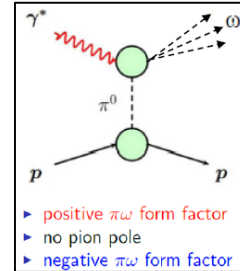
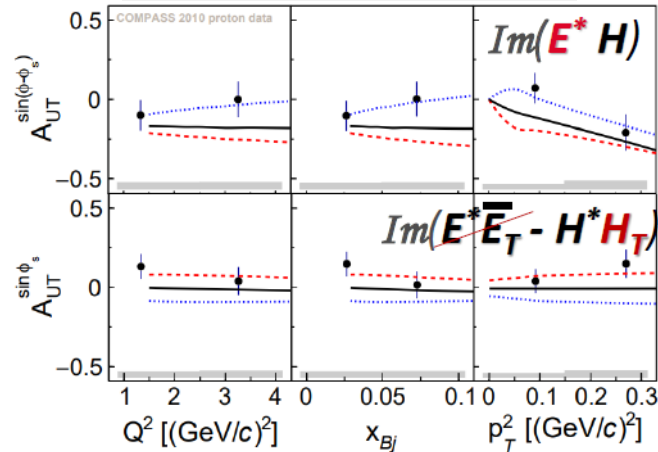
$$E_{\rho^0} = \frac{1}{\sqrt{2}} \left(\frac{2}{3} E^u \oplus \frac{1}{3} E^d + \frac{3}{4} \frac{E_g}{x} \right)$$

$$E_{\omega} = \frac{1}{\sqrt{2}} \left(\frac{2}{3} E^u \ominus \frac{1}{3} E^d + \frac{1}{4} \frac{E_g}{x} \right)$$

COMPASS NPB 865 (2012)1, PLB731 (2014) 19



COMPASS NPB915 (2017)



→ ω promising despite π^0 pole contribution

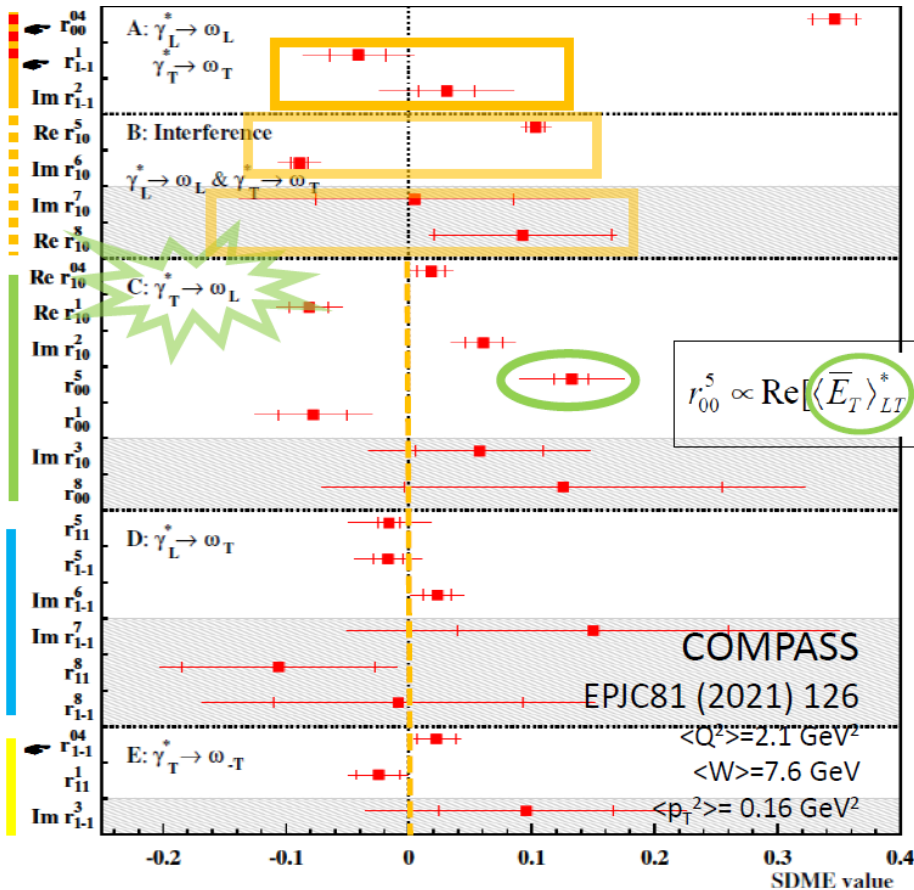
Access to GPDs $\mathbf{E}_T, \mathbf{H}_T \dots$

GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x , longitudinal $\gamma_L^* p \rightarrow M p$ and transv. polar. $\gamma_T^* p \rightarrow M p$ quark and gluon contributions (GPDs $\mathbf{H}, \mathbf{E}, \mathbf{H}_T, \mathbf{E}_T$) and beyond leading twist

COMPASS ω SDME

Spin Density Matrix Elements

COMPASS EPJC81 (2021) 126



If SCHC (s channel helicity conservation):

$$r_{1-1}^1 + \text{Im}\{r_{1-1}^2\} = 0 \quad = -0.010 \pm 0.032 \pm 0.047.$$

$$\text{Re}\{r_{10}^5\} + \text{Im}\{r_{10}^6\} = 0 \quad = 0.014 \pm 0.011 \pm 0.013.$$

$$\text{Im}\{r_{10}^7\} - \text{Re}\{r_{10}^8\} = 0 \quad = -0.088 \pm 0.110 \pm 0.196.$$

All the other SDME in classes C,D, E should be 0 not observed for class C

$$r_{00}^5 \propto \text{Re}\left[\langle \bar{E}_T \rangle_{LT}^* \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle_{LT}^* \langle E \rangle_{LL}\right]$$

From Goloskokov and Kroll, EPJC74 (2014) 2725

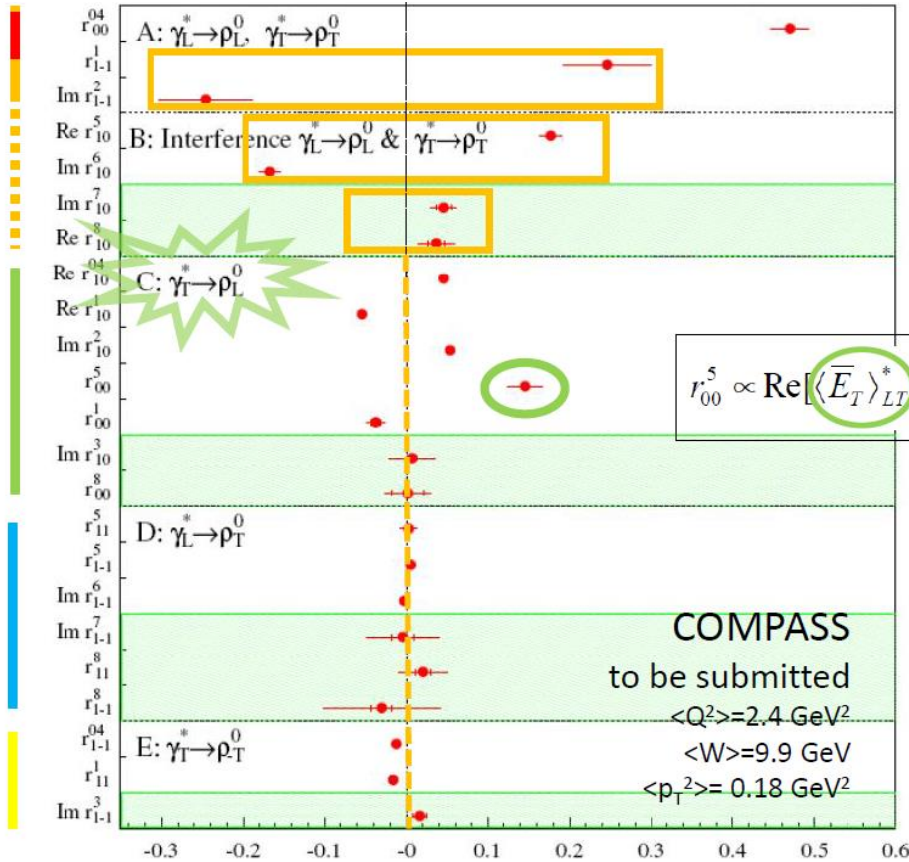
$$F_{\omega} = 2/3 F^u - 1/3 F^d$$

→ Both 2 terms are important

- (H^u, H^d) of same sign
- $(\bar{E}_T^u, \bar{E}_T^d)$ of same sign
- (H_T^u, H_T^d) of opposite sign
- (E^u, E^d) of opposite sign

COMPASS ρ^0 SDME (prelim.)

COMPASS, *subm. EPJC, hep-ex/2210.16932*



If SCHC ($\lambda_\gamma = \lambda_\nu$)

$$r_{1-1}^1 + \text{Im}\{r_{1-1}^2\} = 0 \quad = 0.000 \pm 0.005 \pm 0.003,$$

$$\text{Re}\{r_{10}^5\} + \text{Im}\{r_{10}^6\} = 0 \quad = 0.011 \pm 0.002 \pm 0.002,$$

$$\text{Im}\{r_{10}^7\} - \text{Re}\{r_{10}^8\} = 0 \quad = 0.009 \pm 0.014 \pm 0.028.$$

All the other SDME in classes C,D, E should be 0
not observed for class C

$$r_{00}^5 \propto \text{Re}[\langle \bar{E}_T \rangle_{LT}^* \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle_{LT}^* \langle E \rangle_{LL}]$$

From Goloskokov and Kroll, EPJC74 (2014) 2725

$$F_{\rho^0} = 2/3 F^u + 1/3 F^d$$

→ The first term dominates and r_{00}^5 probes \bar{E}_T

(H^u, H^d) of same sign
 $(\bar{E}_T^u, \bar{E}_T^d)$ of same sign
 (H_T^u, H_T^d) of opposite sign
 (E^u, E^d) of opposite sign

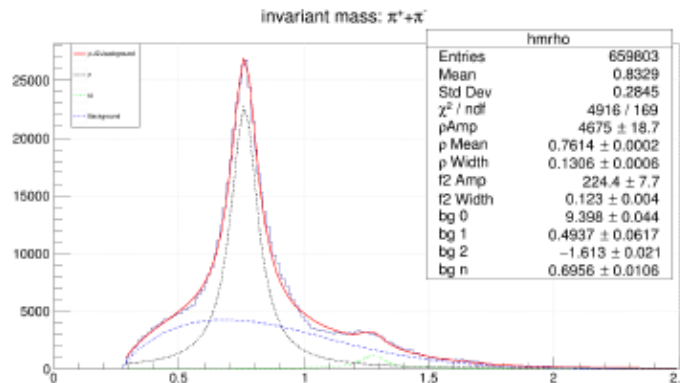
CLAS12 ρ^0 exclusif **prelim.**

CLAS12 *prelim, K.Joo, IWHSS 22, Sept.2022*

$$r_{00}^1 \sigma_0 \sim |\bar{E}_T|^2$$

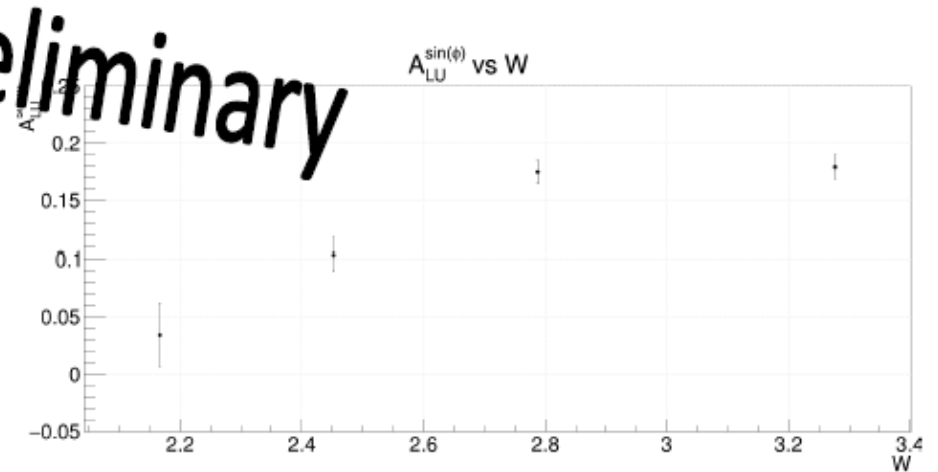
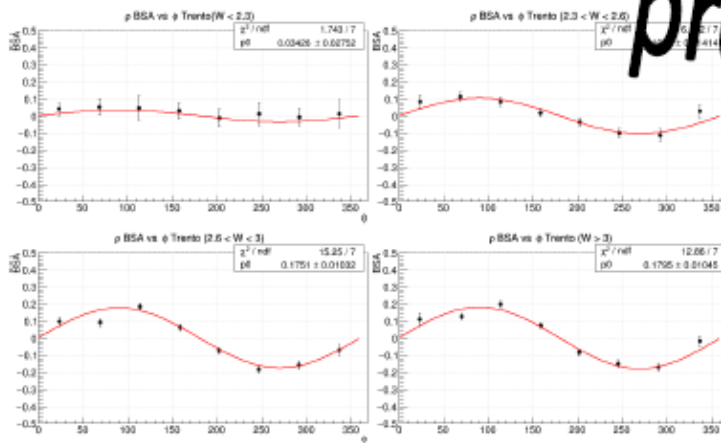
$$r_{00}^5 \sigma_0 \sim \text{Re} [\langle \bar{E}_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle]$$

$$r_{00}^8 \sigma_0 \sim \text{Im} [\langle \bar{E}_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle]$$



$$\sigma_{LT'} \sim r_{00}^8 \sim \text{Im} [\langle H_T \rangle^* \langle E \rangle + \langle \bar{E}_T \rangle^* \langle H \rangle]$$

$$BSA = \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$

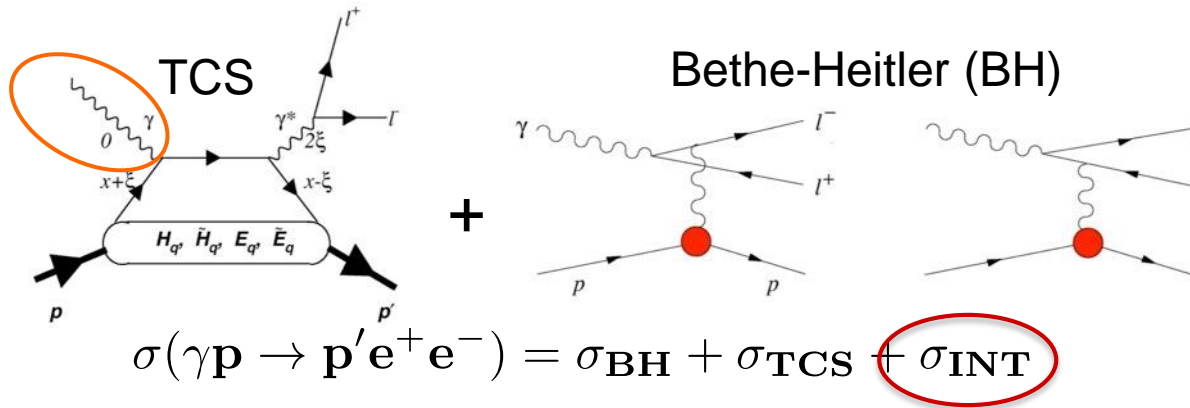


Impressive statistics on ρ^0
+ ongoing work on $\omega, \phi, \Delta^{++}$

TCS - CLAS12 first measurements

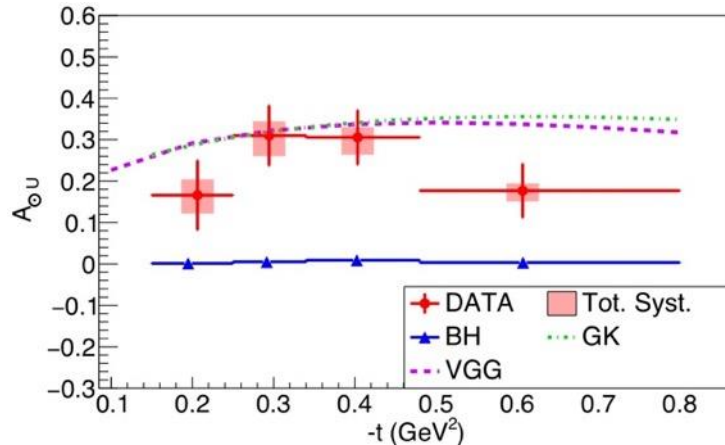
TCS= 'mirror' of DVCS

CLAS12, P. Chatagnon et al., PRL127, 262501 (2021)

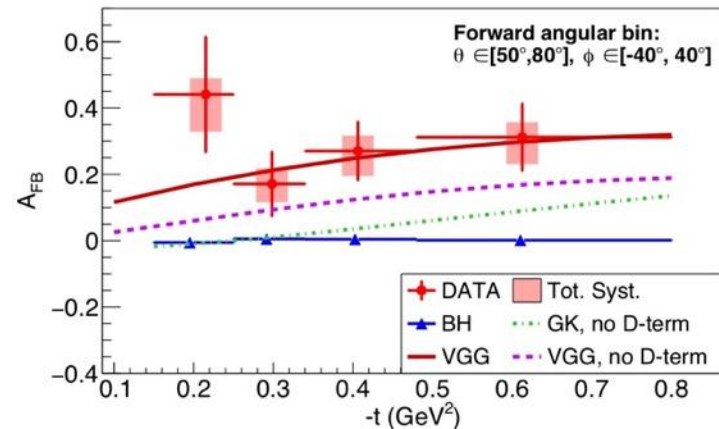


- BHA, $A_{\odot U} \sim \sin \varphi \text{Im} M^{--}$, universality of GPDs
- FB asymmetry, $A_{\text{FB}} \sim \cos \varphi \text{Re} M^{--}$, access to the EM FF $D^q(t)$ (D-term).

BHA - Beam helicity asymmetry $\sim \text{Im } CFF$



FB - Forward backward asymmetry $\sim \text{Re } CFF$



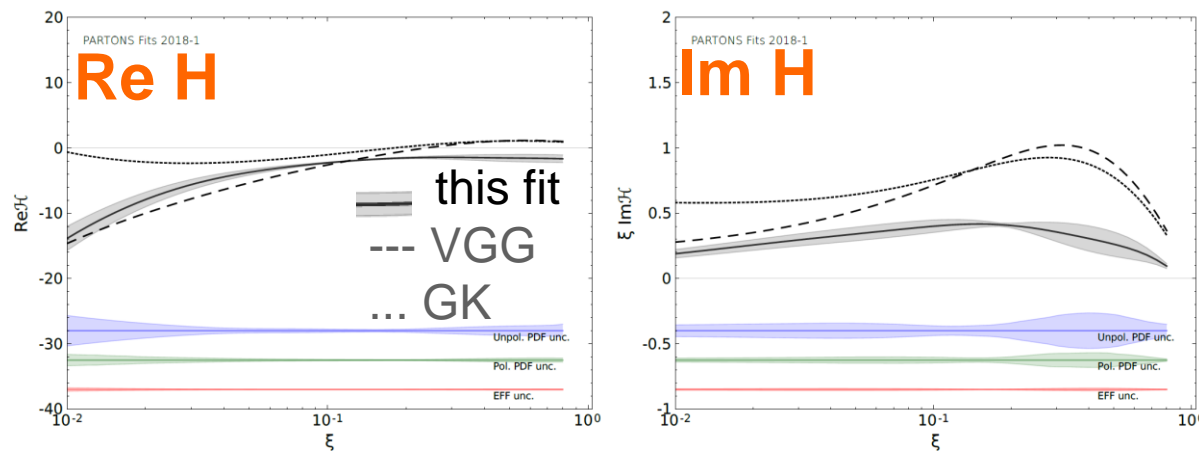
CFFs from global fits of DVCS data

Example: 'PARTON' fit at LO/LT DVCS proton,
Including **Jlab, HERMES and COMPASS data**
2600 / 3970 points
with constraints on GPDs (PDFs, elastic Form Factors, limits at $x \rightarrow 1$...)

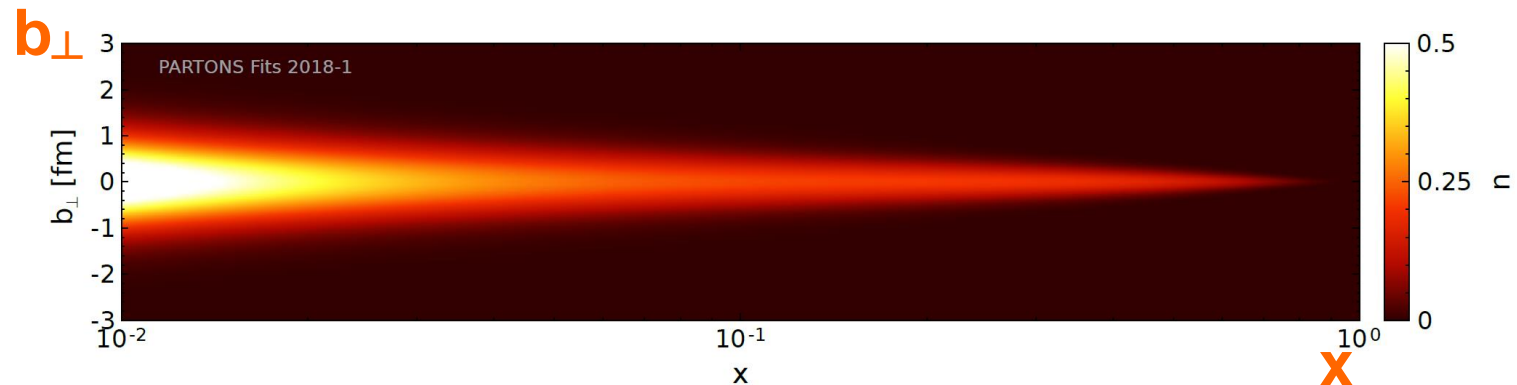
See talk by J. Wagner

CFFs:

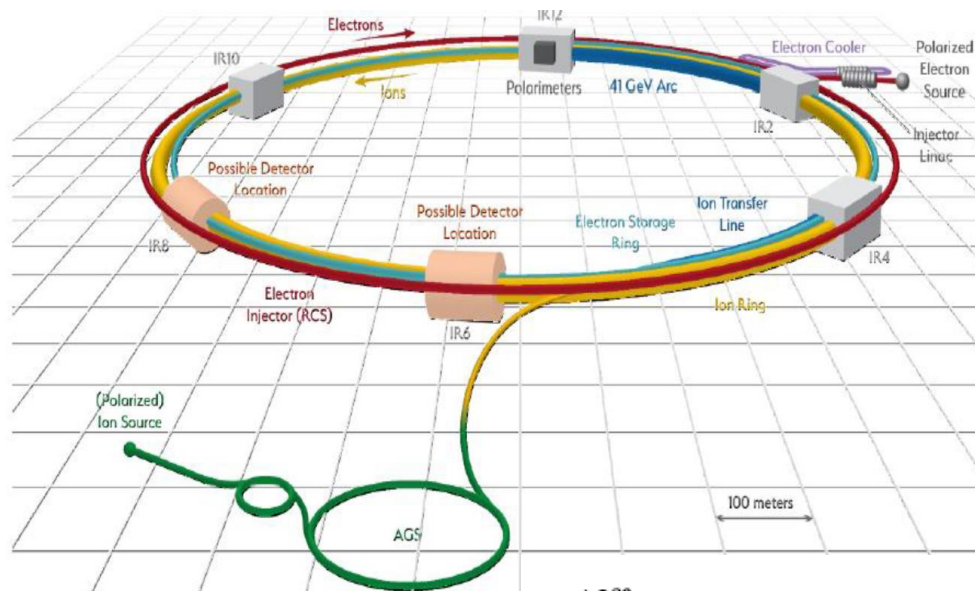
H. Moutarde, P.Sznajder, J. Wagner, *Eur. Phys. J. C78 (2018)11, 890*



Position of up quarks in a proton:



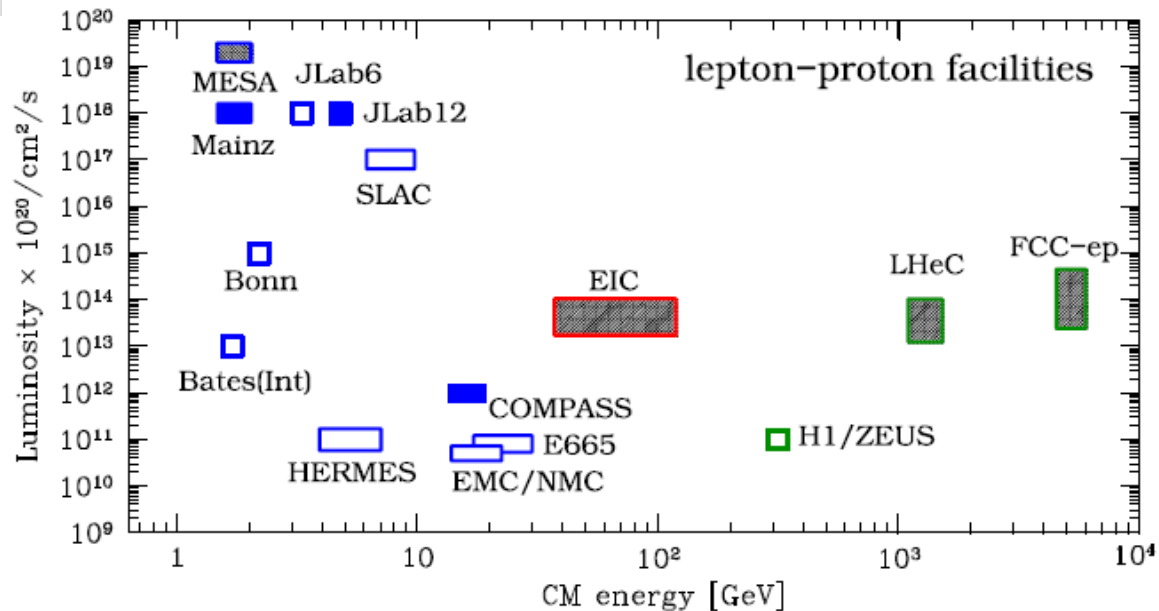
Future US Electron Ion Collider



- Hadrons up to 275 GeV existing RHIC complex, incl. polarized p
- Electrons up to 18 GeV Storage ring, polarized e⁻

→ sqrt(s)=**20 -140 GeV**
 → Design to reach **10³⁴ cm⁻²sec⁻¹**

For exclusive measurements DVCS & HEMP, see talk by S. Fazio

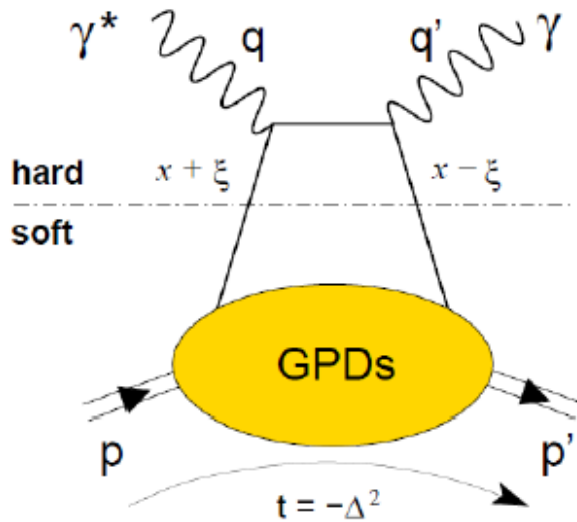


Conclusion

- Plenty of results on DVCS & HEMP (Jlab 6 GeV, COMPASS, HERMES)
Measurements are difficult, demanding in precision and luminosity.
- Data from Jlab 12 GeV coming
- Global analyses preparing for CFF extractions
- EIC measurements much awaited for...

Backup slides

GPDs - Definitions



Definition of variables:
 $q \dots \gamma^*$ four-momentum
 $x \dots$ average longitudinal momentum fraction of initial and final parton (NOT accessible)
 $\xi \dots$ difference of longitudinal-momentum fraction between initial and final parton $\approx x_B / (2 - x_B)$
 $t \dots$ four-momentum transfer

- 4 chiral-even GPDs (parton helicity conserved)
- 4 chiral-odd (or transversity) GPDs (parton helicity flipped)

		Quark Polarisation		
		Unpolarised (U)	Longitudinally polarised (L)	Transversely polarised (T)
Nucleon Polarisation	U	H		\bar{E}_T
	L		\tilde{H}	\tilde{E}_T
	T	E	\tilde{E}	H_T, \tilde{H}_T

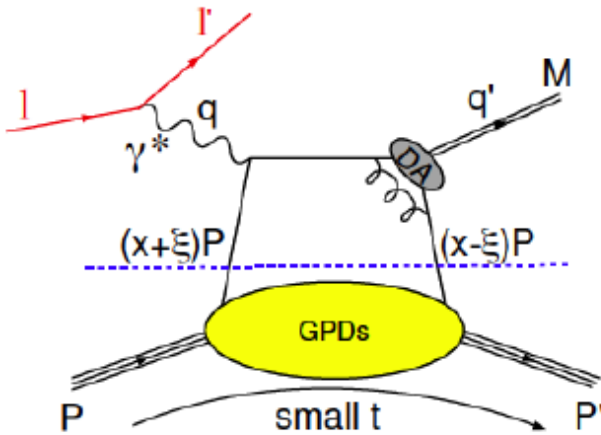
GPDs enter the exclusive processes through **Compton Form Factors (CFF)**

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

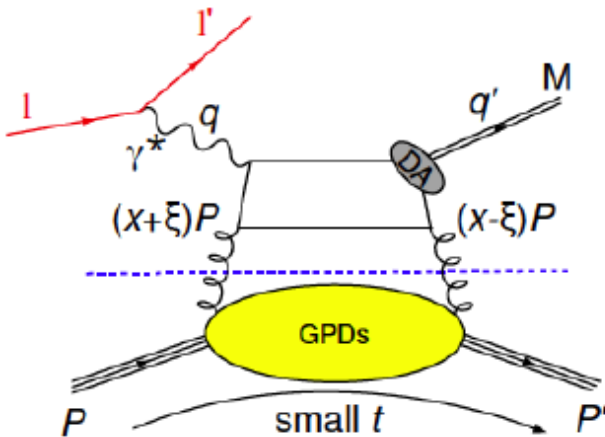
HEMP – sensitivity to CFFs and q/g contrib.

Hard Exclusive Meson Production:

Quark contribution



Gluon contribution



- Flavour separation for specific GPDs due to different partonic content of mesons
- Gluon and quark contributions at the same order in α_s for vector mesons
- DVCS sensitive to H^f , E^f , \tilde{H}^f , and \tilde{E}^f
- At the leading twist:
 - Vector meson production sensitive to H^f , and E^f
 - Pseudoscalar mesons production is described by GPDs \tilde{H}^f , and \tilde{E}^f
- Both vector meson and pseudoscalar mesons (as the π_0 presented in this talk) are also sensitive to $\bar{E}_T^f = 2\tilde{H}_T^f + E_T^f$, and H_T^f

HEMP cross section

$$\frac{d^2\sigma_{\gamma^*p}}{dt d\phi} = \frac{1}{2\pi} \left[\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)} \cos\phi \frac{d\sigma_{LT}}{dt} \right]$$

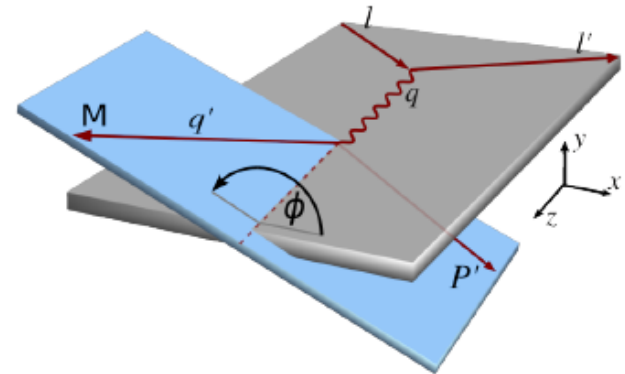
GPDs in exclusive π^0 production

$$\frac{d\sigma_L}{dt} \propto \left[(1 - \xi^2) |\langle \tilde{\mathcal{H}} \rangle|^2 - 2\xi^2 \text{Re}(\langle \tilde{\mathcal{H}} \rangle^* \langle \tilde{\mathcal{E}} \rangle) - \frac{t'}{4M^2} \xi^2 |\langle \tilde{\mathcal{E}} \rangle|^2 \right]$$

$$\frac{d\sigma_T}{dt} \propto \left[(1 - \xi^2) |\langle \mathcal{H}_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{\mathcal{E}}_T \rangle|^2 \right]$$

$$\frac{d\sigma_{TT}}{dt} \propto t' |\langle \bar{\mathcal{E}}_T \rangle|^2$$

$$\frac{d\sigma_{LT}}{dt} \propto \xi \sqrt{1 - \xi^2} \sqrt{-t'} \text{Re}(\langle \mathcal{H}_T \rangle^* \langle \tilde{\mathcal{E}} \rangle)$$



Impact of \bar{E}_T should be visible in $\frac{d\sigma_{TT}}{dt}$, and also a dip at small t of $\frac{d\sigma_T}{dt}$

$$t' = t - t_{min}, t_{min} \text{ is the minimum value of } |t|$$

Compton Scattering and GPDs

CLAS12 GPD studies

μ CLAS12, one of two proposed facilities capable of measuring

First experimental measurement with CLAS12
PRL 127, 262501 (2021)

Started in 2001, PRL 87, 182002
Is the large part of the CLAS12 physics program

TCS Hard scale is defined by time-like photons

Access to the Re-part of the Compton amplitude

$$Re \mathcal{H}(\xi, t) = PV \int_{-1}^1 dx C^-(\xi, x) H(x, \xi, t)$$

$$Im \mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t)$$

DVCS Hard scale is defined by space-like photon

DDVCS Both space-like and time-like photons can set the hard scale

$$\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - (2\xi' - \xi) + i\epsilon} + \dots$$

$$H(2\xi' - \xi, \xi, t) + H(-(2\xi' - \xi), \xi, t)$$

σ -DDVCS is three orders of magnitude smaller than σ -DVCS
The main driver of the high luminosity upgrade

BHA Beam Helicity Asymmetry

$$A_{\odot U} = \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} \sin\phi \frac{(1+\cos^2\theta)}{\sin(\theta)} \text{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

FB Forward Backward Asymmetry

$$A_{\text{FB}}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(\pi - \theta_0, \pi + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(\pi - \theta_0, \pi + \phi_0)} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} \cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)} \text{Re}\tilde{M}^{--}}{d\sigma_{\text{BH}}(\theta_0, \phi_0) + d\sigma_{\text{BH}}(\pi - \theta_0, \pi + \phi_0)}$$