Experimental results on DVCS and HEMP for Generalized Parton Distributions

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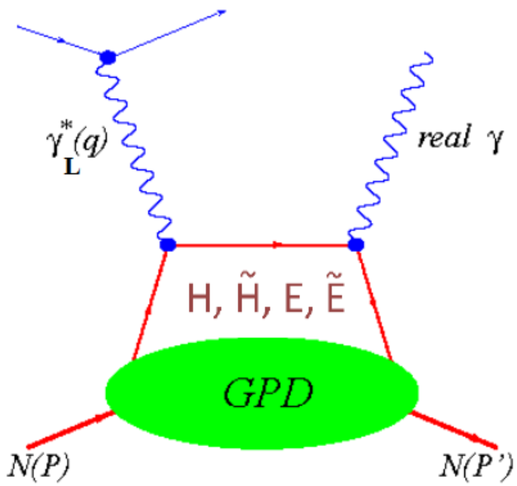
Diffraction and low x,Corigliano Calabro, Italy, Sept. 24-30, 2022

Accessing GPDs

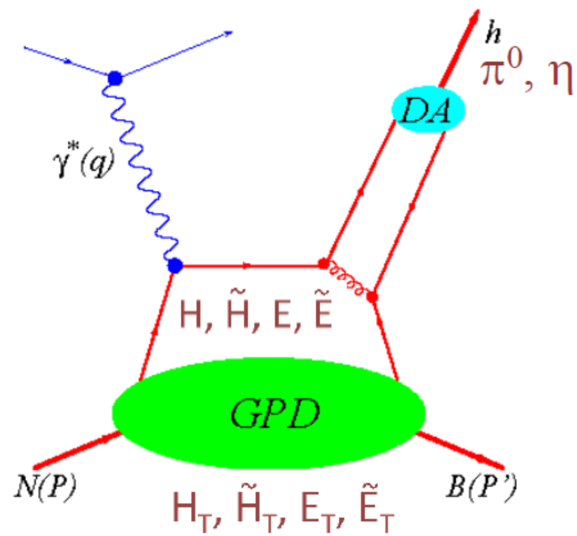
Physics goals: **- 3D mapping of Nucleon**
- sensitivity to Orbital Angular Momentum

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

Deeply Virtual Meson Production (DVMP)



+ 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

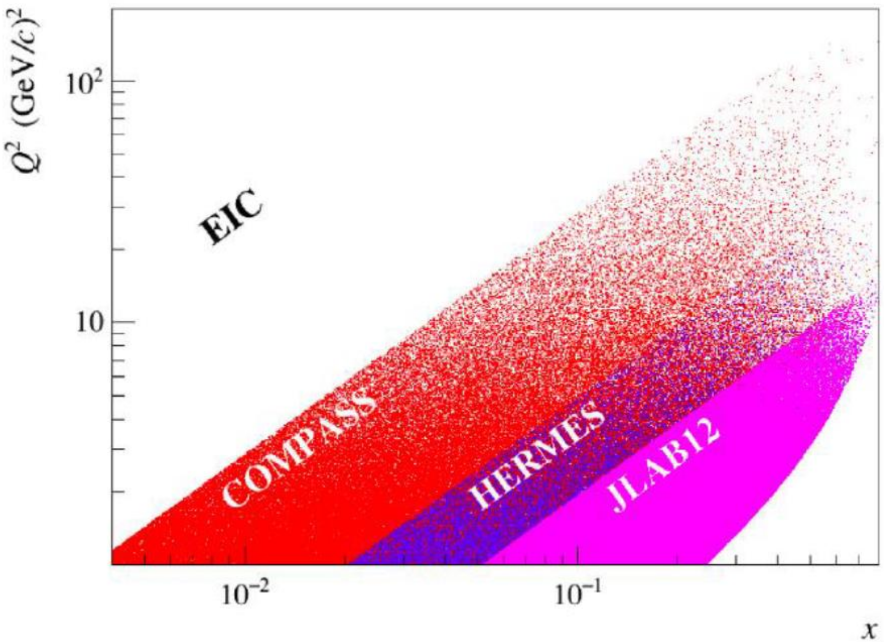
HERMES at DESY / COMPASS at CERN / JLab

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

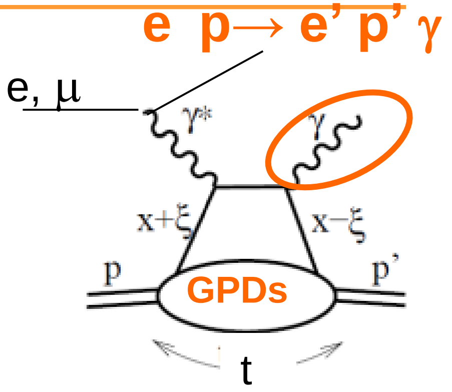
6 GeV → **12 GeV**
Polarized CW e^- beam
Pol=85%,
High luminosity

and pioneering work at
H1 and ZEUS.



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 (ρ, ω, ϕ)**

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**.

Rsults on
Deep Virtual Compton Scattering- DVCS

e p→ e' p' γ

DVCS mostly sensitive to:

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

Easiest

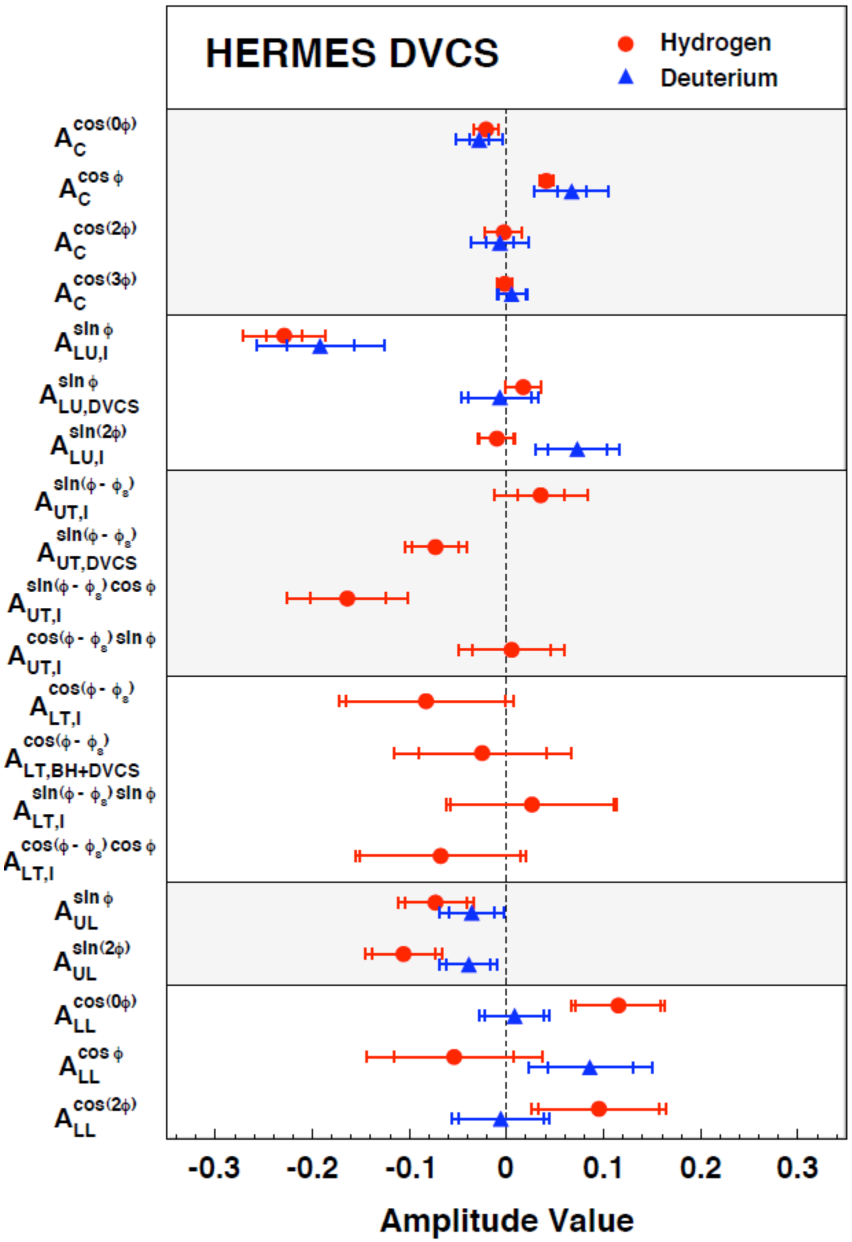
	Im **DVCS**	*Re* **DVCS**
$\mathcal{H}$	$A_{LU}, A_{\odot}$	σ, A_{UU}
$\widetilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
$\mathcal{E}$	A_{UT}	

$\mathcal{E}$ sensitive to OAM,
need transversely polarized target

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}

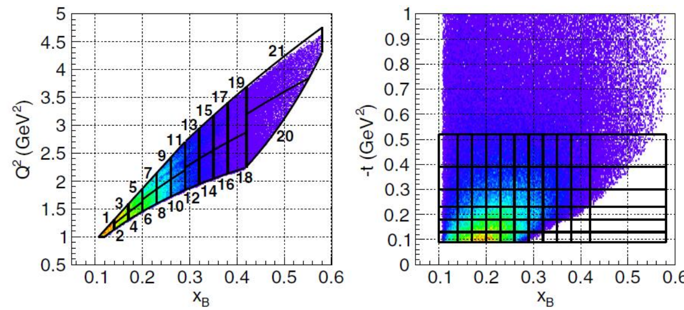
GPD $\tilde{H}$

DVCS – Jlab CLAS proton target, e H → e'p γ

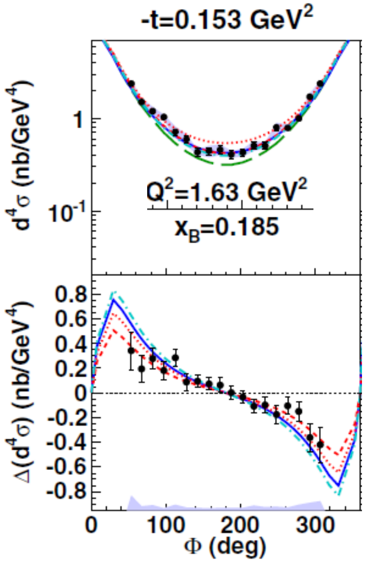
$d^4\sigma(x,Q^2,t,\phi)$ and **$\Delta(d^4\sigma)$ beam spin** difference, sensitive to *Im[H]* ~ $e^{-b(x)\,t}$

***b* related to proton transverse size**

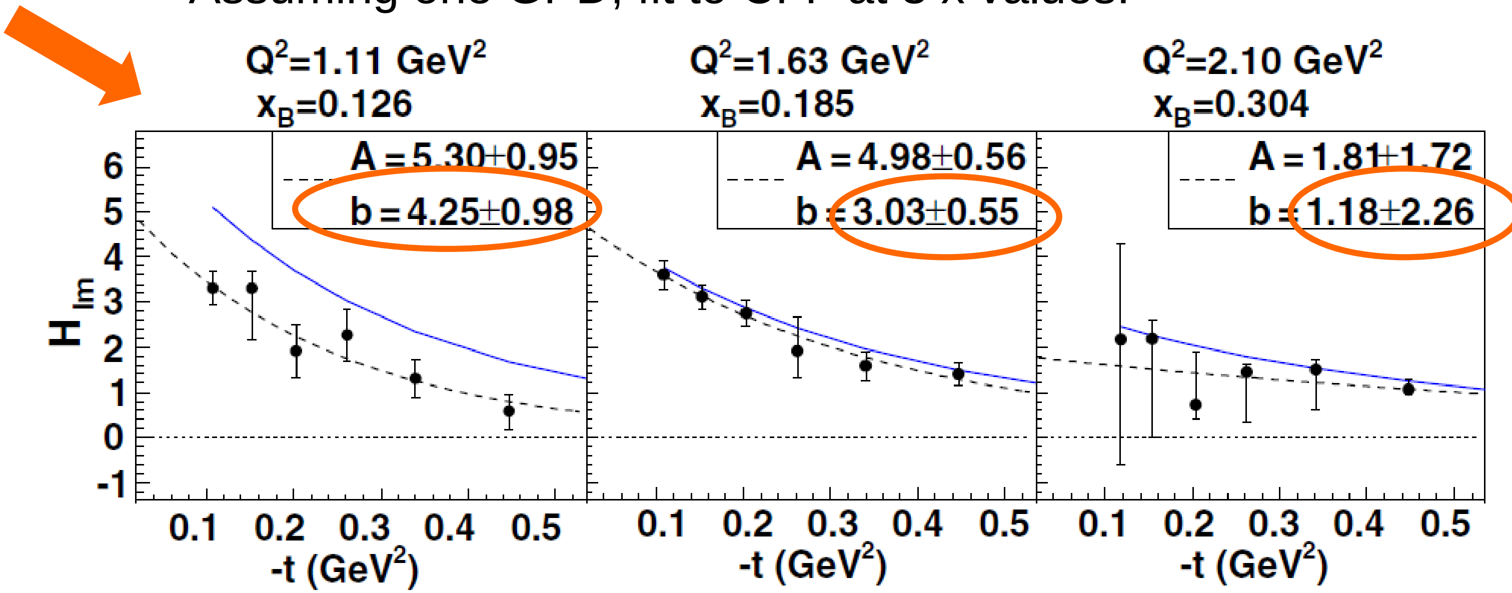
K. Jo et al., CLAS, PRL 115 (2015)



a sample:



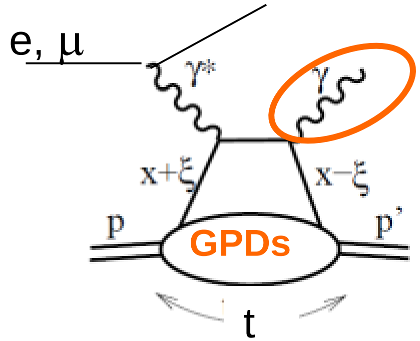
Assuming one GPD, fit to CFF at 3 x values:



***b* decreases as x_B increases**
→ proton shrinking with x_B

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

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

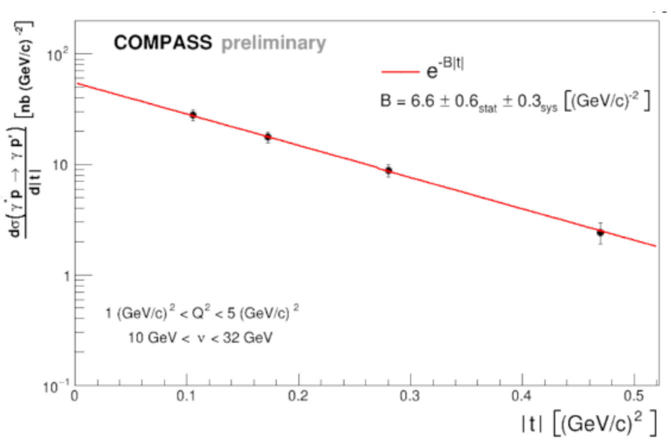


Combining data from $\overrightarrow{\mu+}$ and $\overleftarrow{\mu-}$ beams
(beam spin &charge sum),
measure t-slope of DVCS cross section
→ x dependence of transverse size of the nucleon

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

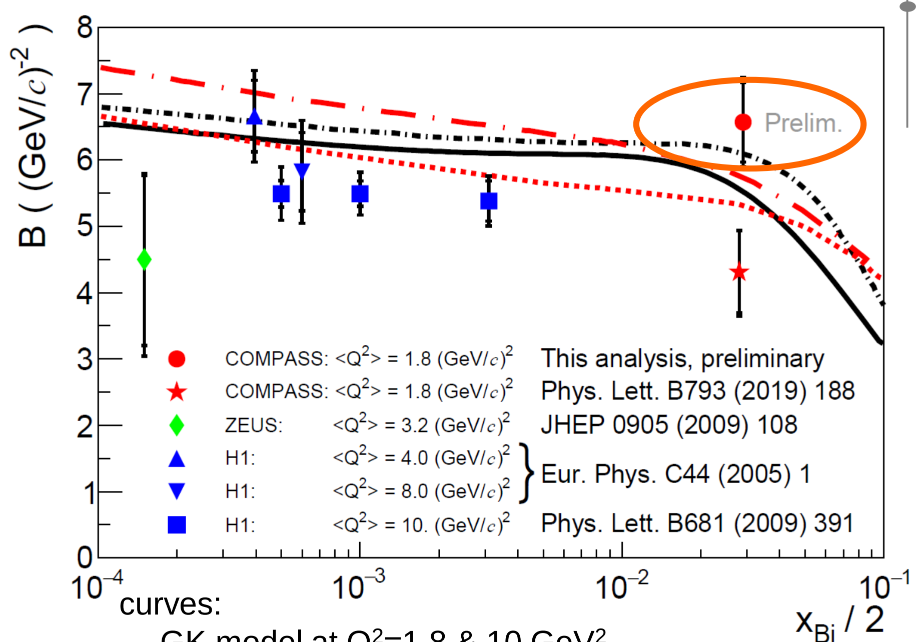
$$B(x_B) = ½ \langle r_\perp^2 (x_B) \rangle$$

Measurement of proton transverse size vs x_B



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

New prelim. COMPASS result:



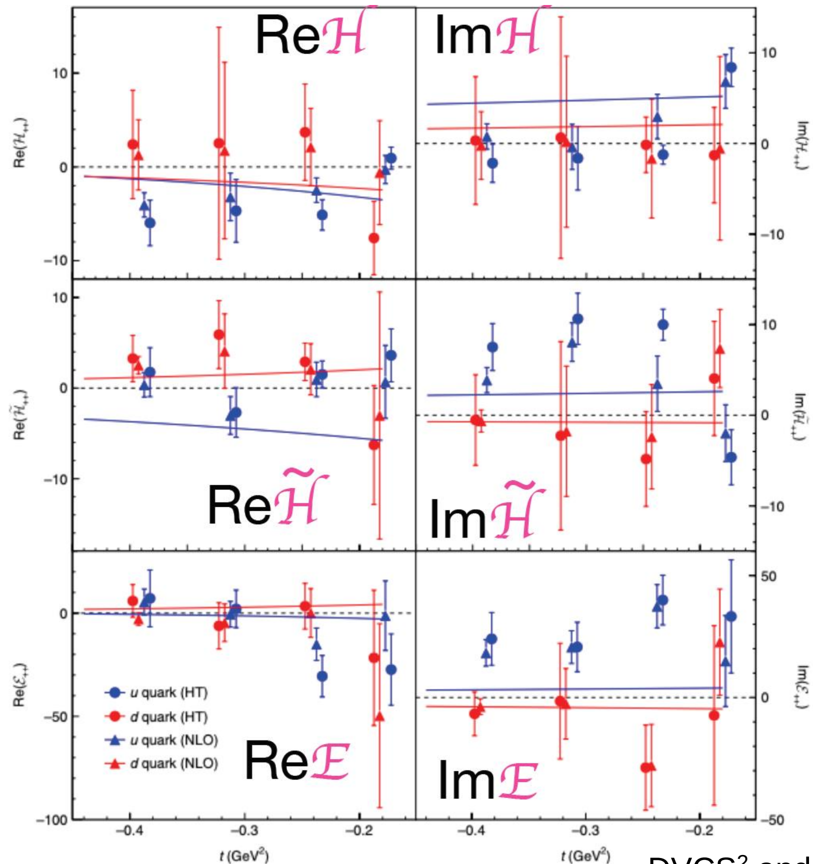
curves:
--- GK model at Q^2=1.8 & 10 GeV^2
--- KM15 at Q^2=1.8 & 10 GeV^2

Flavour separation of CFFs

JLab Hall-A neutron and proton DVCS

Cross sections measured with LH_2 & LD_2 targets

u quark
d quark



Note larger scale for E

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

- DVCS^2 and interference extracted simultaneously
- curves: predictions of diquark model Goldstein et al.

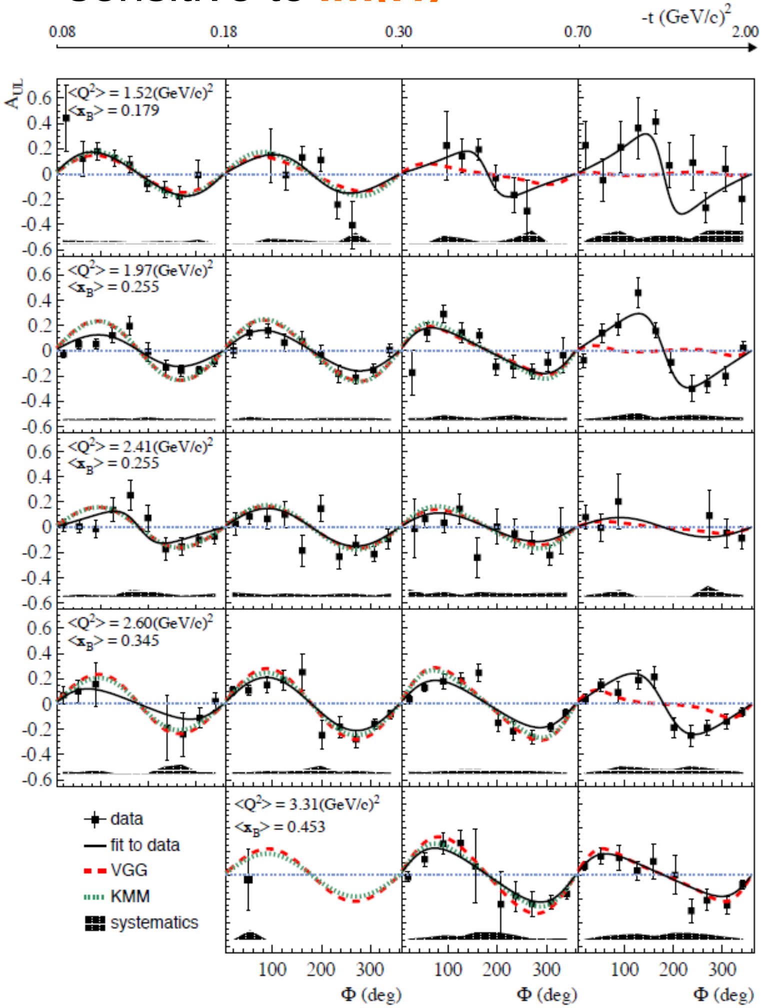
u and d flavour separation for 3 CFFs

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

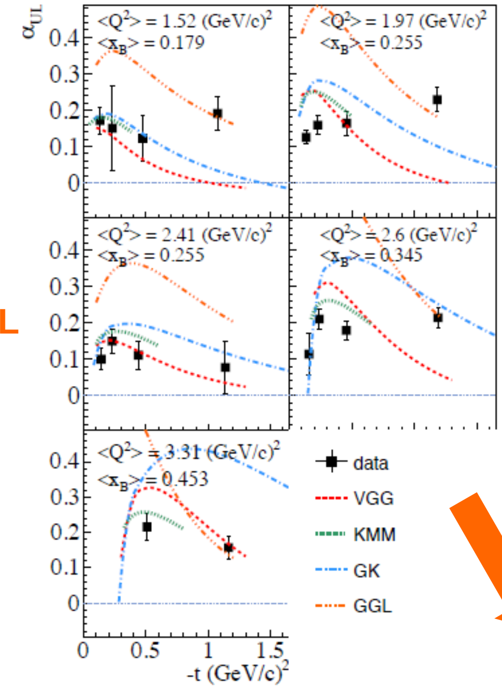
S.Pisano et al., CLAS, PRD 91 (2015) 5, 052014

A_{UL} (x, Q^2, t, ϕ)

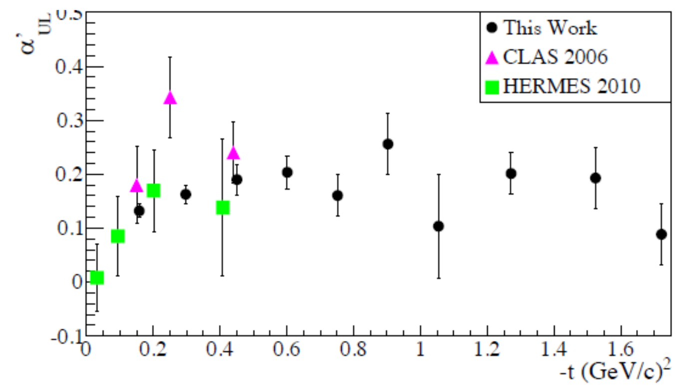
sensitive to $Im(\tilde{H})$



ϕ modulation amplitude α_{UL}



α'_{UL} (-t)



Possibility to access spatial distribution of quark helicity

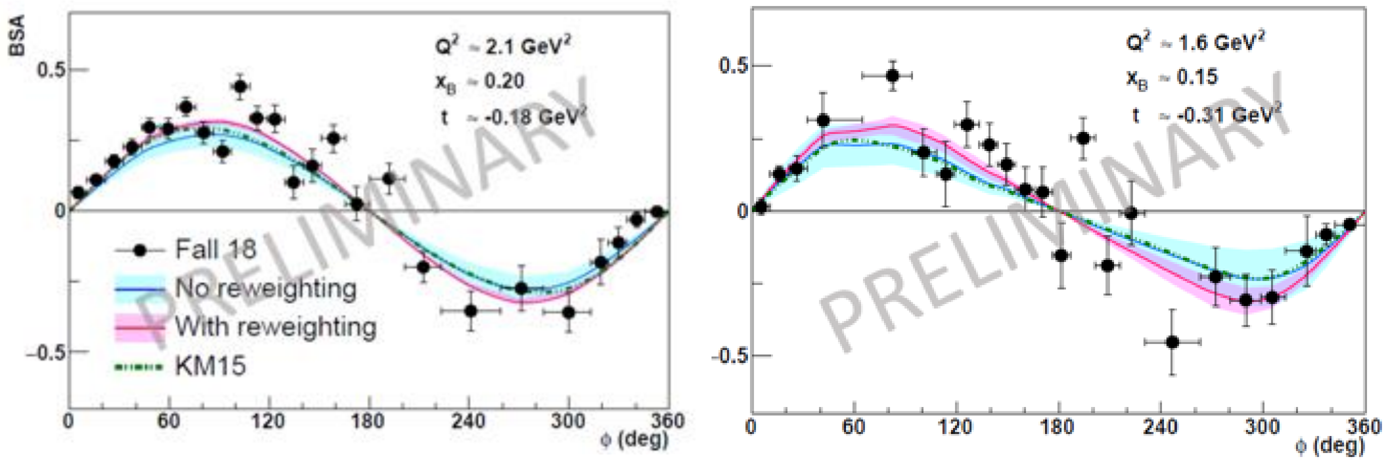
DVCS – CLAS12 Beam Spin Asym (prelim.)

First results 12 GeV beam

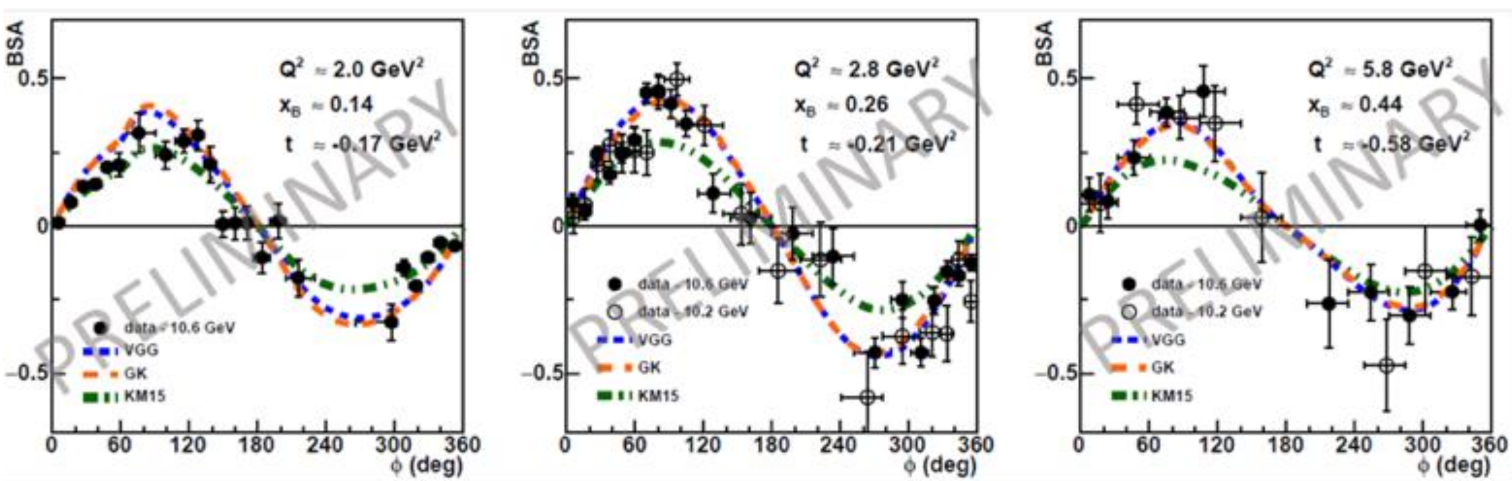
CLAS12 prelim., S.Stepanyan, IWHSS22, Sept.2022

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

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



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



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

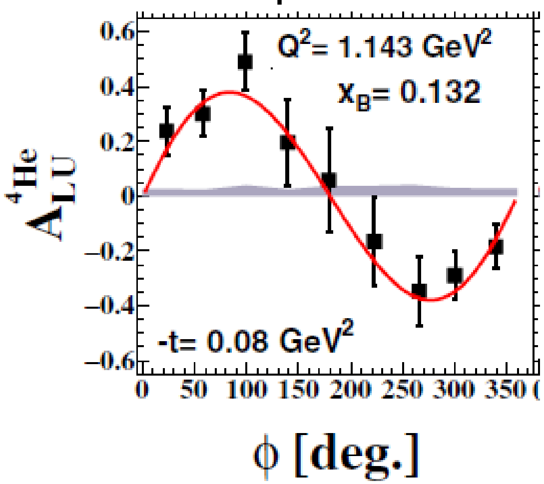
DVCS – Jlab CLAS ^{4}He target, e ^{4}He → e' γ α

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

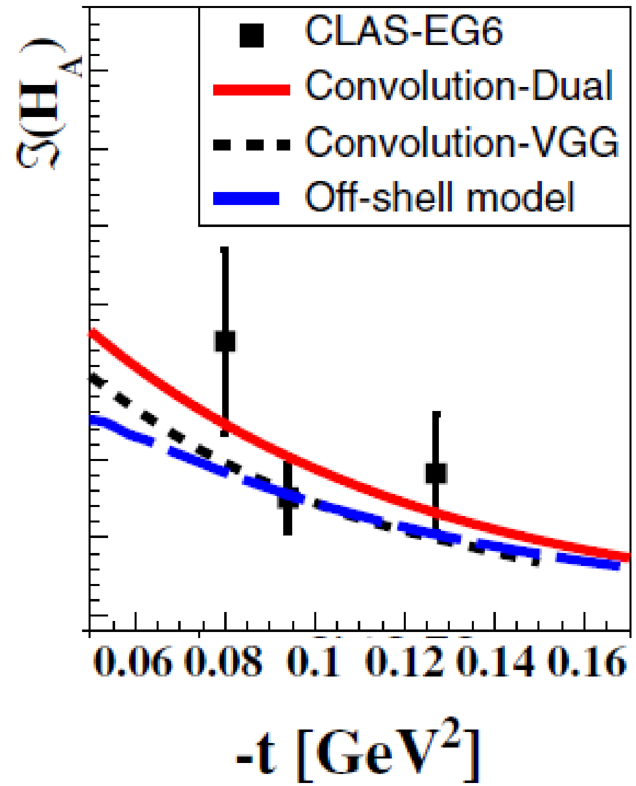
A_{LU} (x, Q^2, t, ϕ)
sensitive to ***Im(H)***

+ radial TPC for recoil α, ϕ=16cm

a sample:

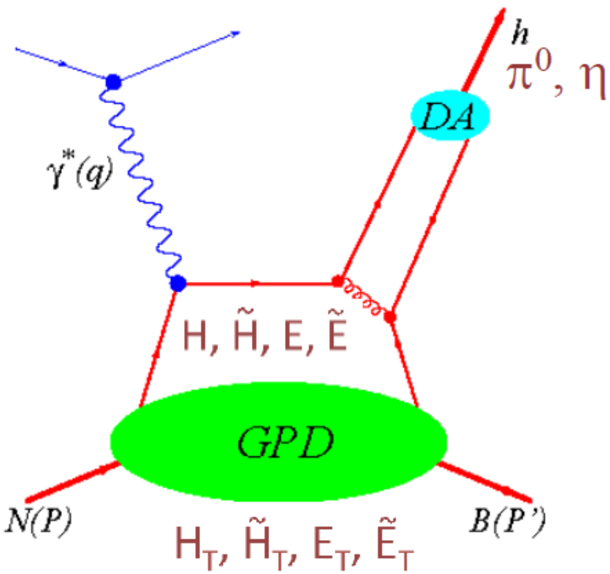


At LO- LT, only one GPD,
fit to *Re* and *Im [H(t)]*



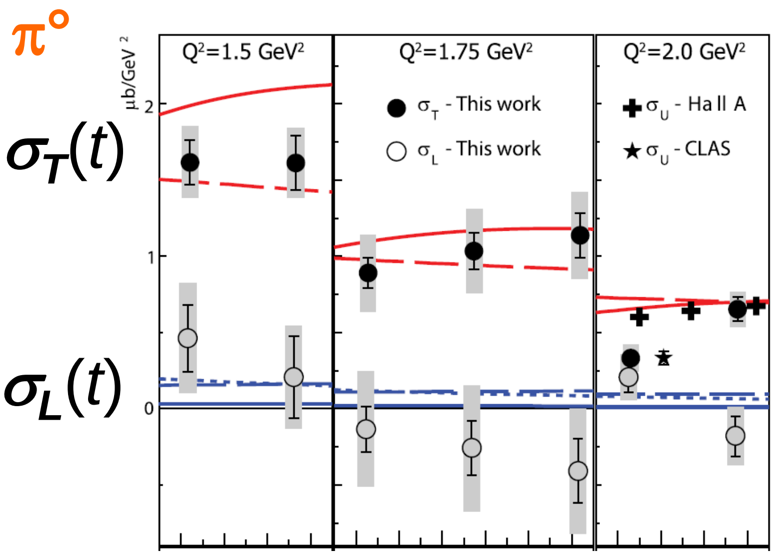
Promising ^{4}He study

Hard Exclusive Meson Production -HEMP



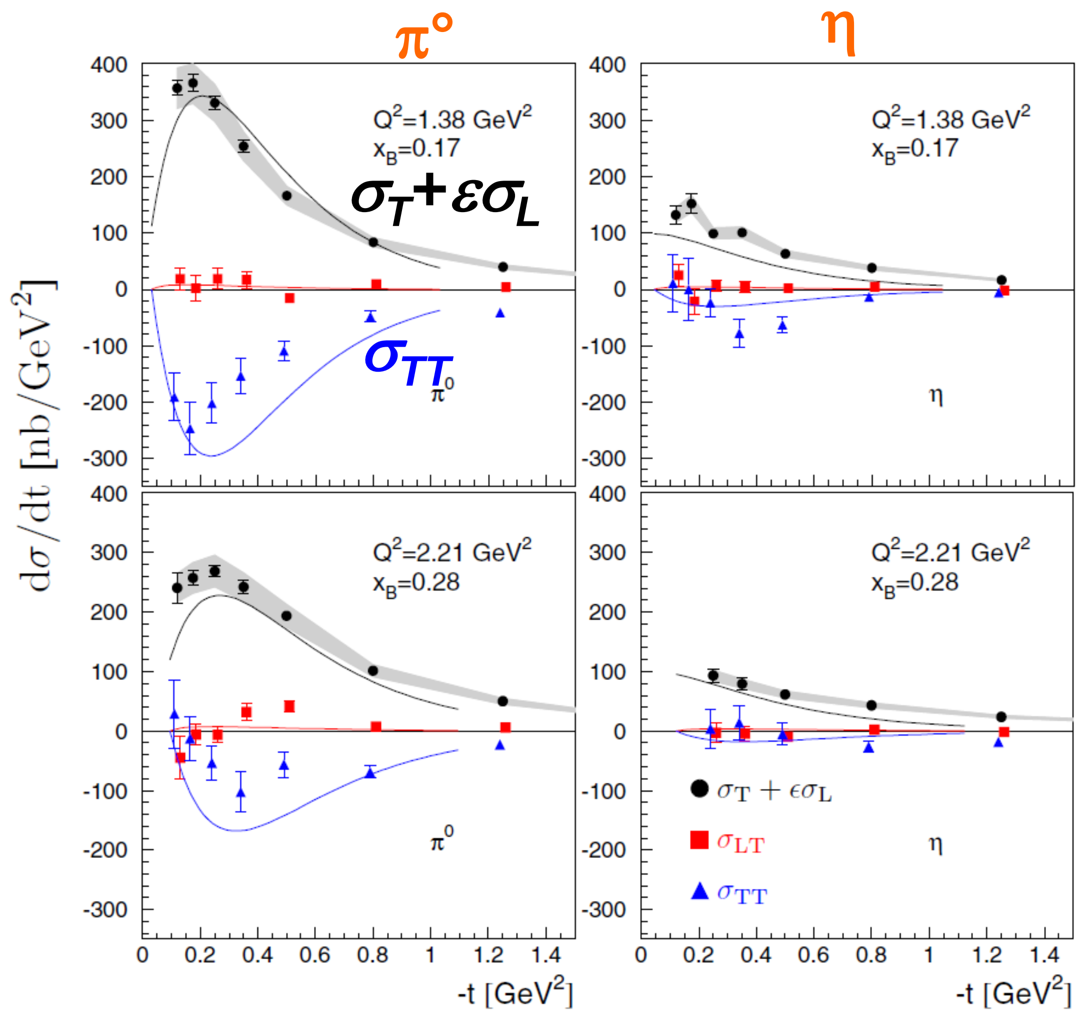
+ Enables Flavour decomposition of GPDs
+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

Mesons, DVMP – JLab, e H → e' (p) π° / η



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

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

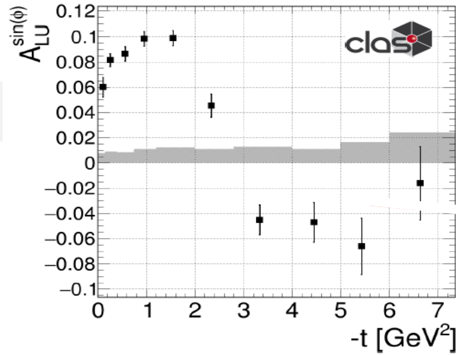


I. Bedlinskiy et al., CLAS, PRC 95 (2017)

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

Beam spin asymmetry π+

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

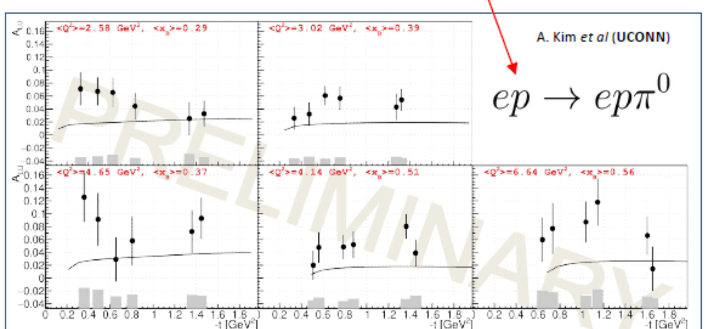


New: CLAS12 first results

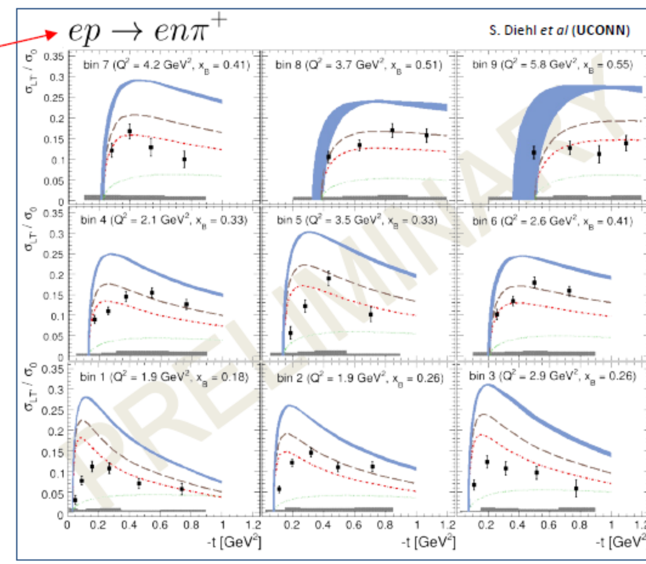
ep → epπ^0

ep → enπ^+

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



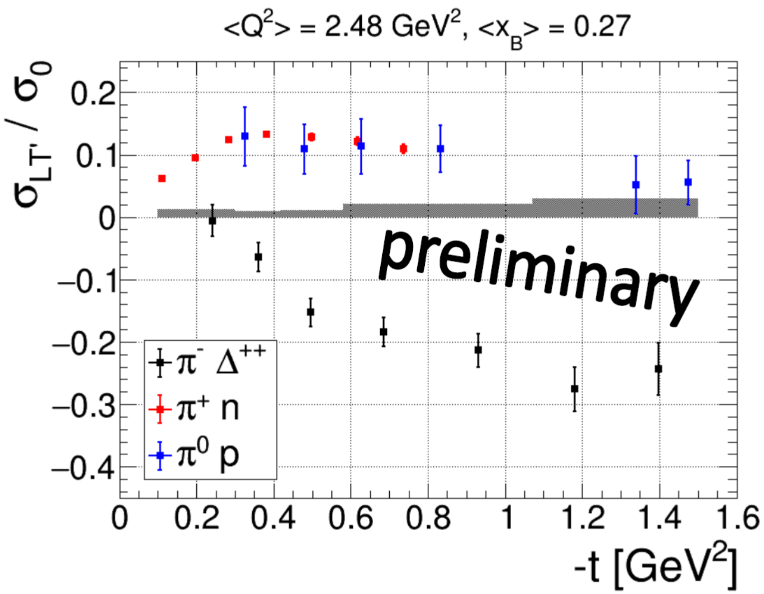
• active work on cross-section extraction by R. Johnston (MIT)



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

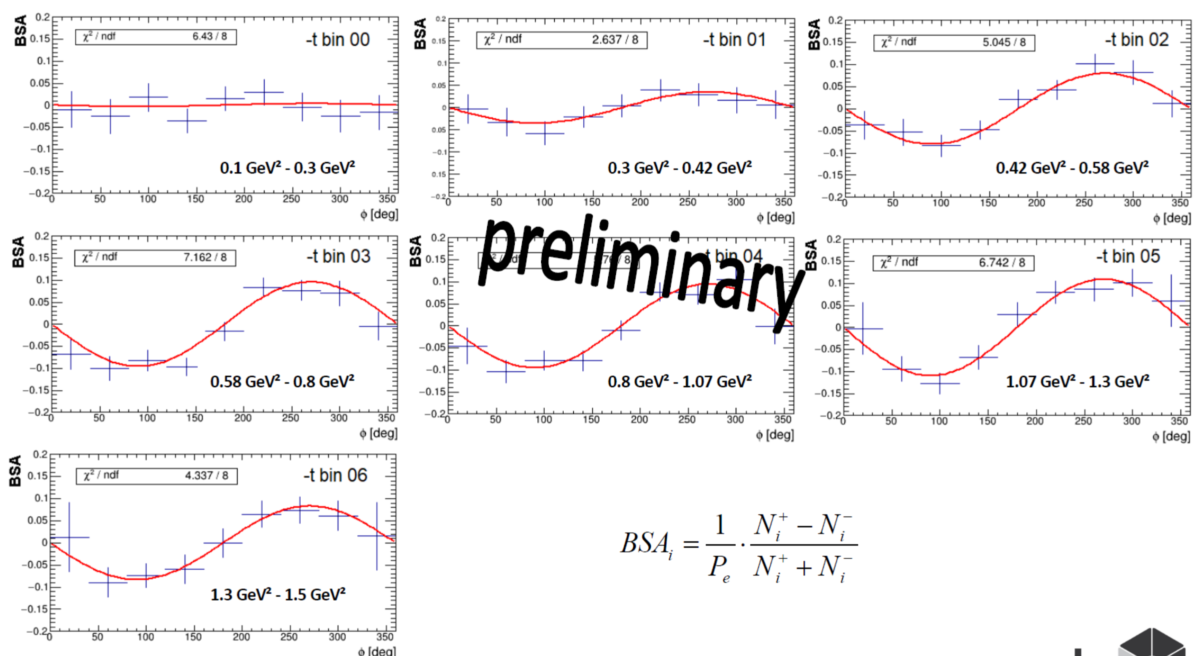
CLAS12 exclusive π^+, π^- and π^0 production

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



ep → ep $\pi^-\Delta^{++}$

BSA (ϕ) in 7 t bins



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

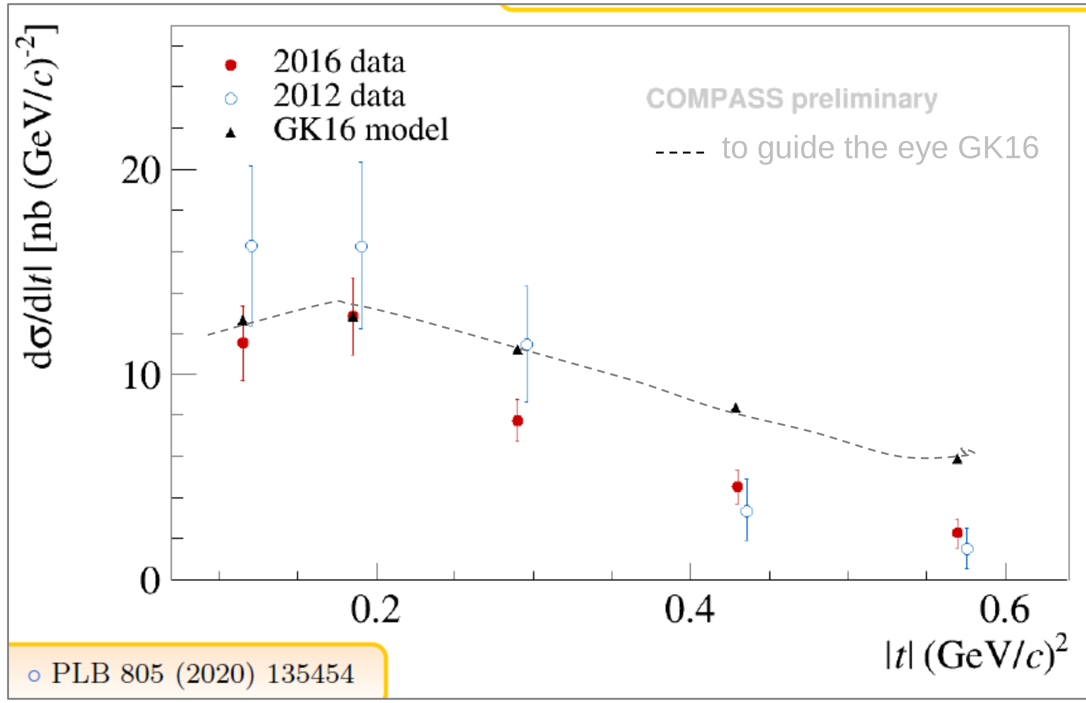
COMPASS exclusive π^0 production

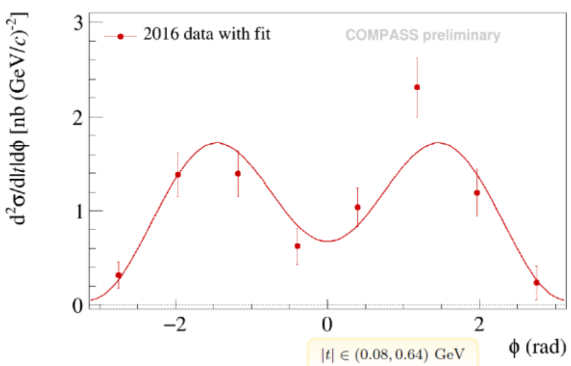
COMPASS prelim., M. Peskova, IWHSS 22, Sept.2022

$\mu^{+/-}$ p→ μ p π^0

- recoil proton detection + ECALs

Only 25% of available stat. used





Preliminary result on π^0 production at x_B~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 **E**
However, E^u and E^d of opposite sign

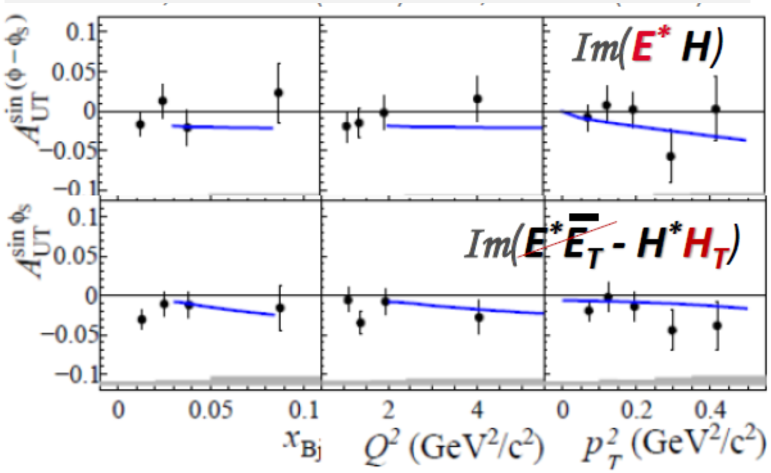
$\rho^0 \rightarrow \pi^+\pi^-$

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

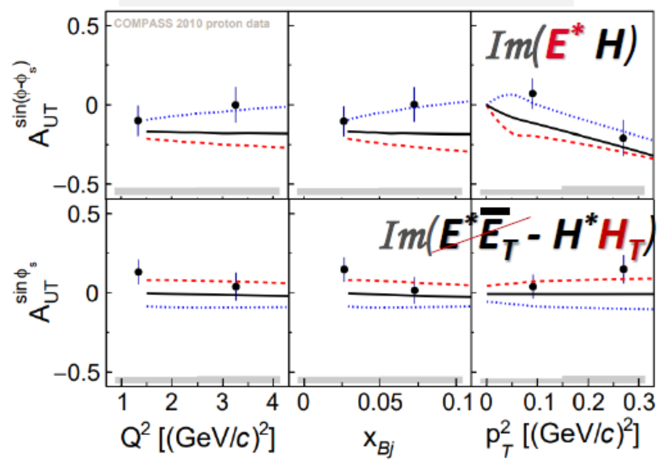
$\omega \rightarrow \pi^+\pi^-\pi^0$

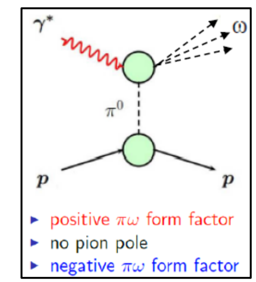
$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}\frac{E_g}{x}\right)$$

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



COMPASS NPB915 (2017)





$\rightarrow$ **ω promising** despite π^0 pole contribution

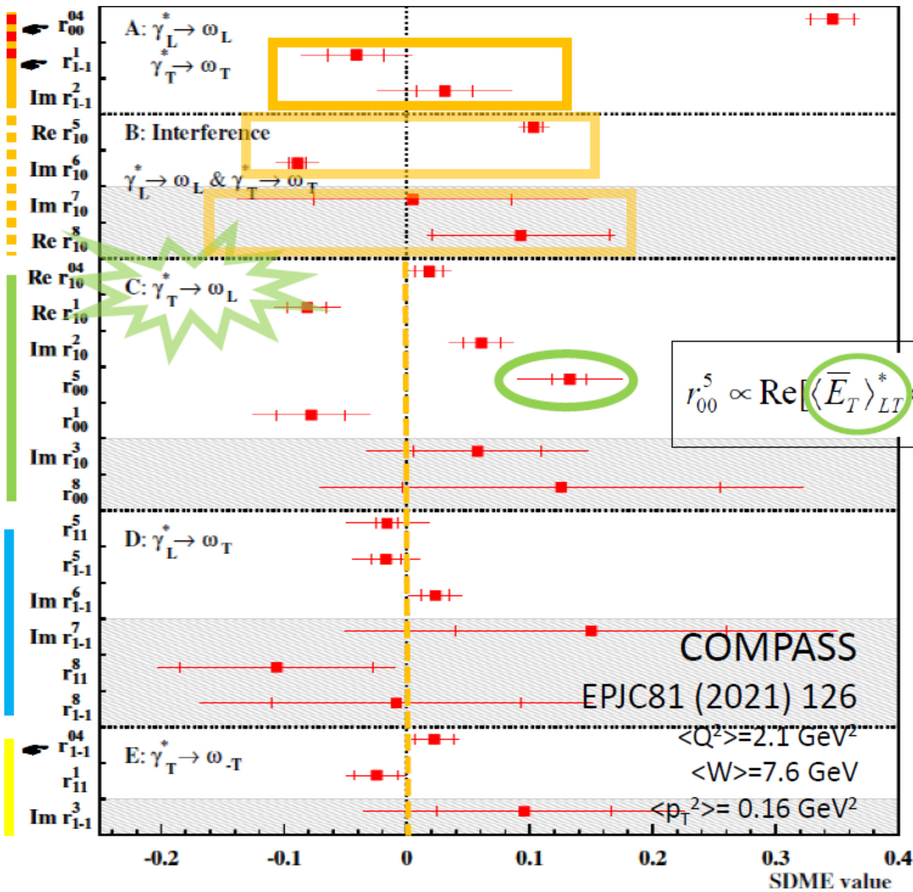
Acces to GPDs E_T, H_T …

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

COMPASS ω SDME

Spin Density Matrix Elements

COMPASS EPJC81 (2021) 126



If SCHC (s channel helicity conservation):

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0$$
$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0$$
$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0$$

measurements:

$$= -0.010 \pm 0.032 \pm 0.047$$
$$= 0.014 \pm 0.011 \pm 0.013$$
$$= -0.088 \pm 0.110 \pm 0.196$$

All the other SDME in classes C,D, E should be 0

not observed for class C

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

From Goloskokov and Kroll, EPJC74 (2014) 2725

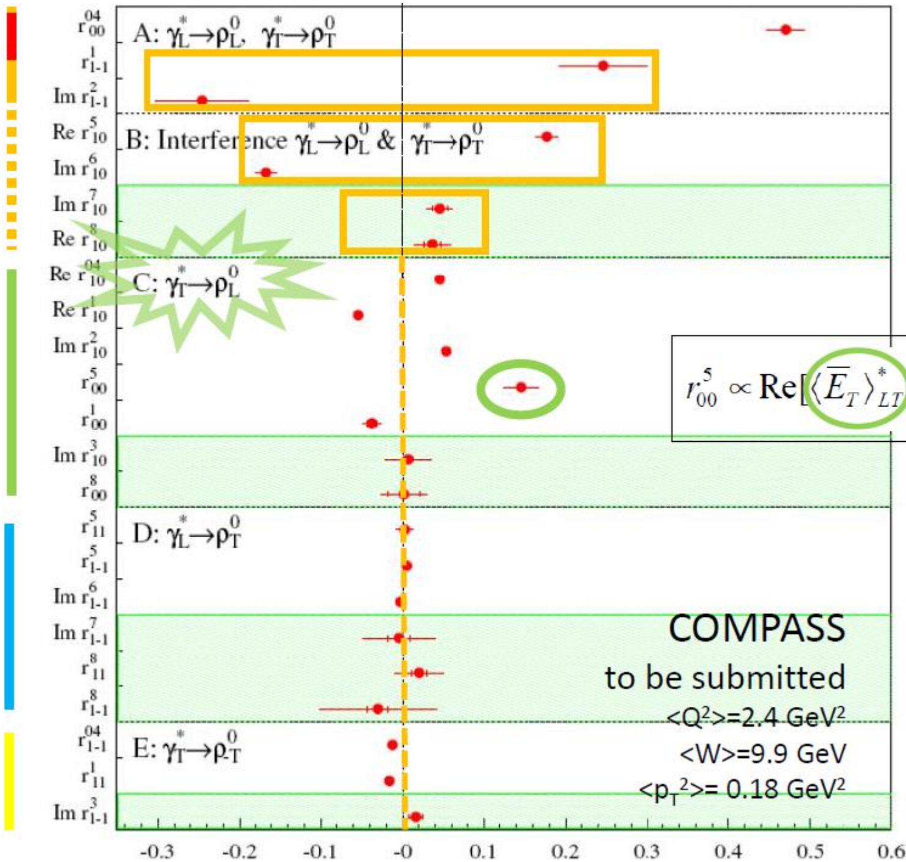
$F\omega$=2/3F^u - 1/3 F^d

➔ Both 2 terms are important

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

COMPASS ρ^0 SDME (prelim.)

COMPASS prelim, N. d'Hose, IWHSS22 Sept 2022



If SCHC ($\lambda_\gamma = \lambda_V$) | measurements:

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0 \quad = 0.000 \pm 0.005 \pm 0.003,$$

$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0 \quad = 0.011 \pm 0.002 \pm 0.002,$$

$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0 \quad = 0.009 \pm 0.014 \pm 0.028.$$

All the other SDME in classes C,D, E should be 0

not observed for class C

$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

From Goloskokov and Kroll, EPJC74 (2014) 2725

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

➔ The first term dominates and r^5_{00} probes $\overline{E}_T$

(H^u, H^d) of same sign
($\overline{E}^u_T$, $\overline{E}^d_T$) of same sign
(H^u_T, H^d_T) of opposite sign
(E^u, E^d) of opposite sign

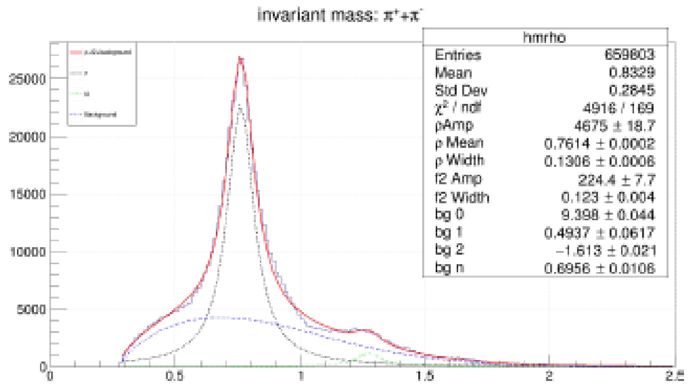
CLAS12 ρ^0 exclusif prelim.

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

$$r^1_{00}\sigma_0 \sim \left|\bar{E}_T\right|^2$$

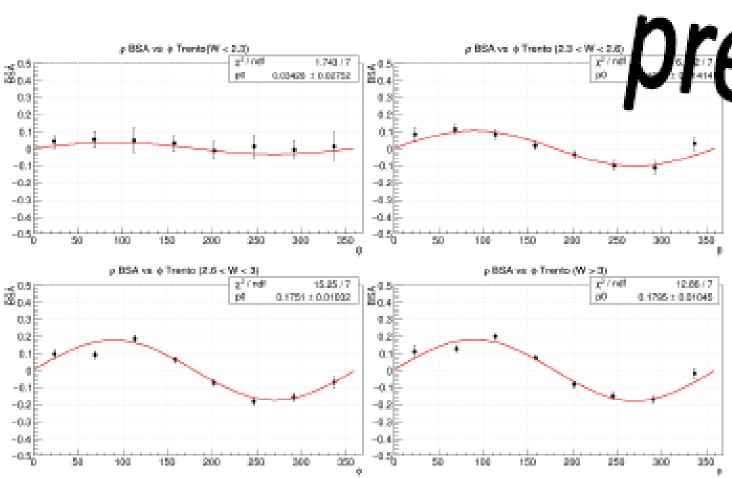
$$r^5_{00}\sigma_0 \sim \mathrm{Re}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$

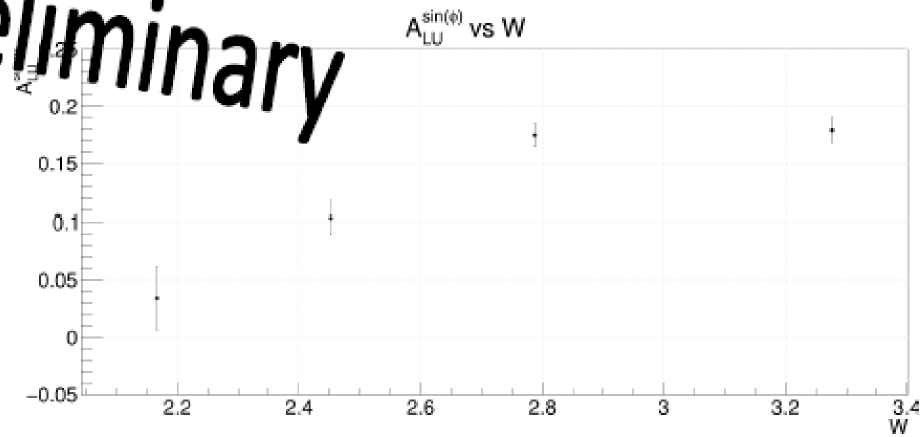
$$r^8_{00}\sigma_0 \sim \mathrm{Im}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$



$$\sigma_{LT'} \sim r^8_{00} \sim \mathrm{Im}\left[\langle H_T\rangle^*\langle E\rangle + \langle\bar{E}_T\rangle^*\langle H\rangle\right]$$

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



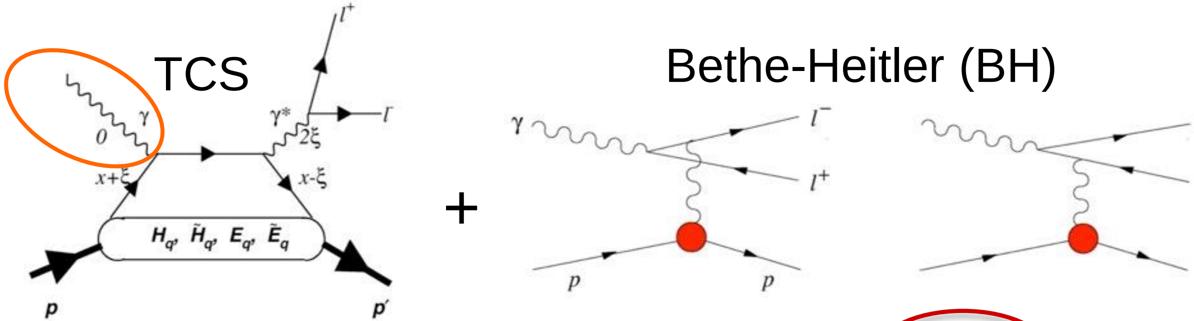


Impressive statistics on ρ^0
+ ongoing work on ω, ϕ, Δ^{++}

TCS - CLAS12 first measurements

TCS= 'mirror' of DVCS

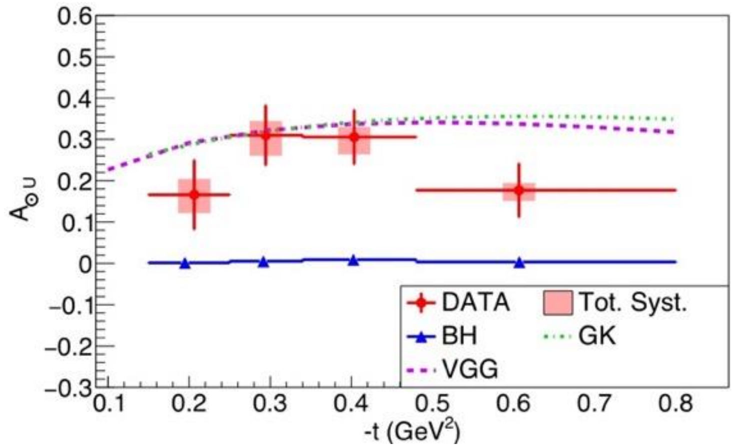
CLAS12, P. Chatagnon et al., PRL127, 262501 (2021)



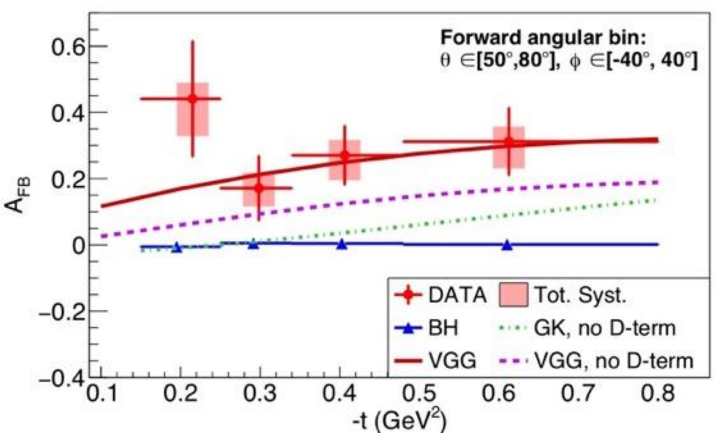
$$\sigma(\gamma \mathbf{p} \to \mathbf{p}'\mathbf{e}^+\mathbf{e}^-) = \sigma_{\mathbf{BH}} + \sigma_{\mathbf{TCS}} + \sigma_{\mathbf{INT}}$$

- BHA, $A_{\odot U} \sim \sin\varphi ImM^{--}$, universality of GPDs
- FB asymmetry, $A_{FB} \sim \cos\varphi ReM^{--}$, access to the EM FF $D^Q(t)$ (D-term).

Beam helicity asymmetry ~ ***Im CFF***



Forward backward asymmetry ~***Re CFF***



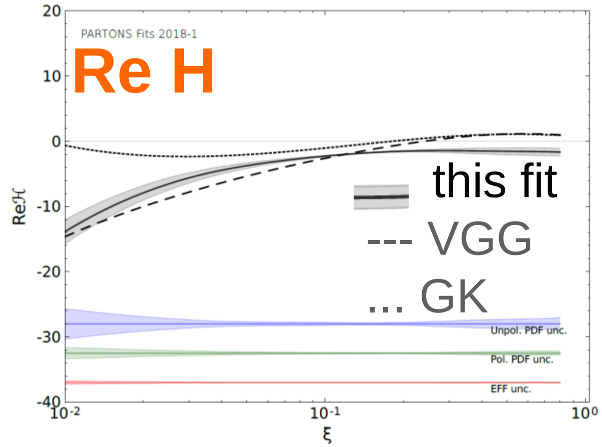
CFFs from globat fits of DVCS data

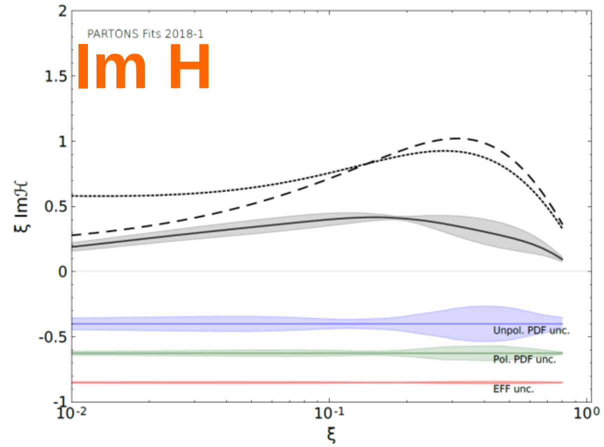
Example: 'PARTON' fit at LO/LT DVCS proton,
Including **Jlab, HERMES and COMPASS data**
2600 / 3970 points
with constraints on GPDs (PDFs, elastic Form Factors, limits at x→1...)

See talk by J. Wagner

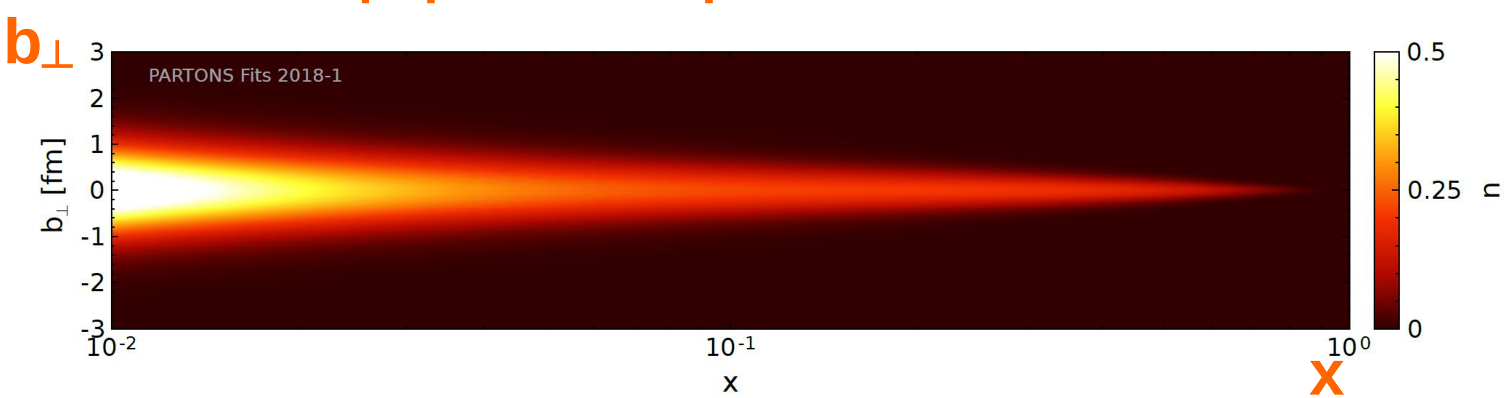
H. Moutarde, P.Sznajder, J. Wagner, Eur. Phys. J. C78 (2018)11, 890

CFFs:

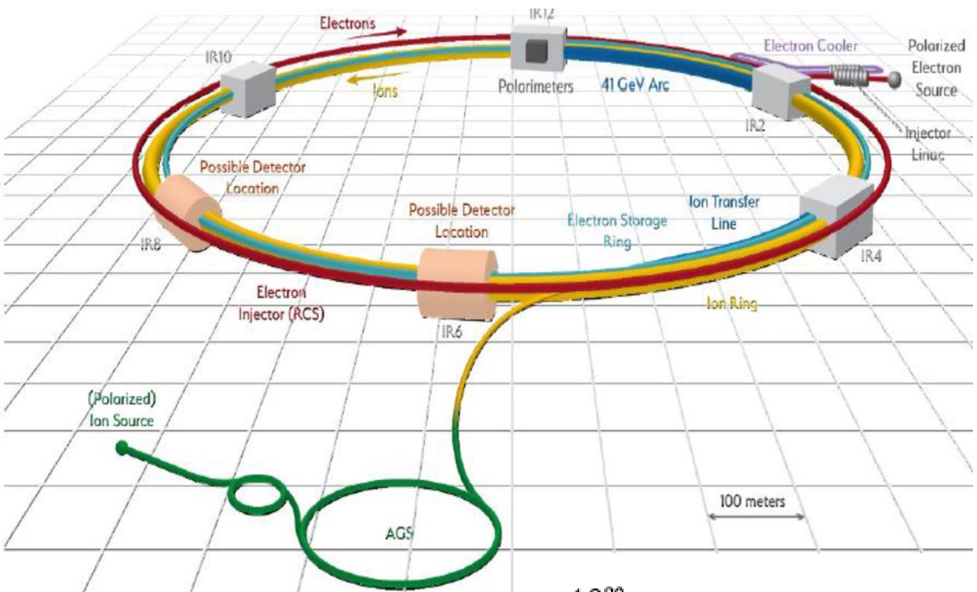




Position of up quarks in a proton:

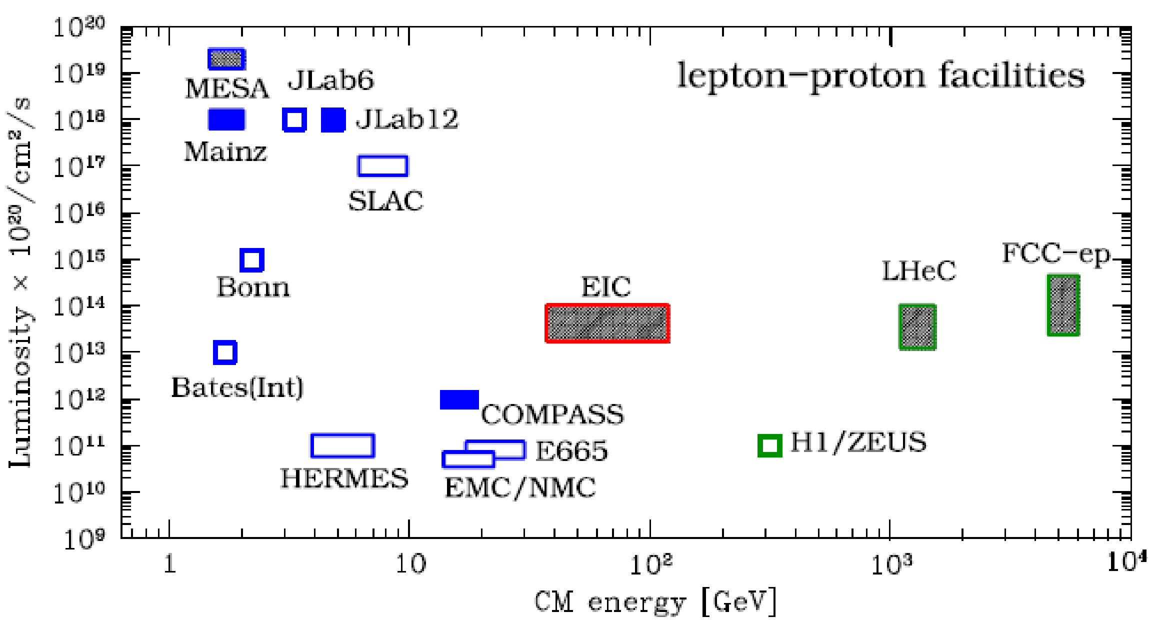


Future US Electron Ion Collider



- 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 **10^{34} cm^{-2}sec^{-1}**

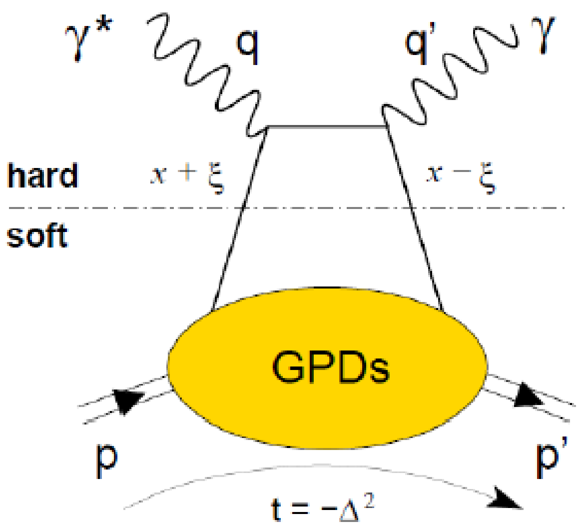


Conclusion

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

Backup slides

GPDs - Definitions



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

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

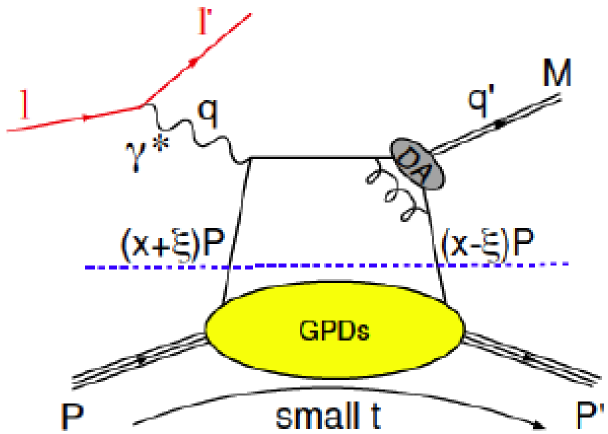
Nucleon Polarisation	Quark Polarisation: Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

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

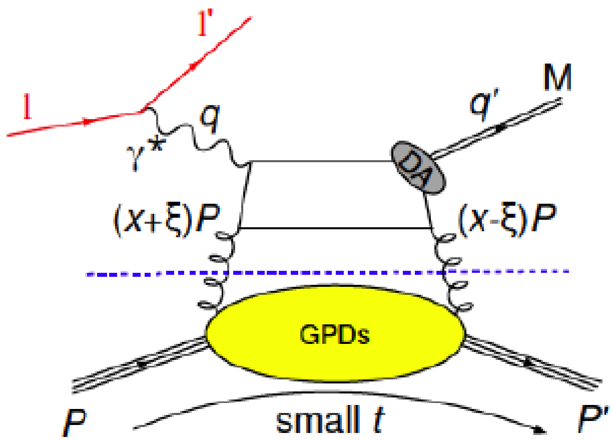
$$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \frac{H(x,\xi,t)}{x-\xi} + i\pi H$$

HEMP – sensitivity to CFFs and q/g contrib.

Quark contribution



Gluon contribution



Hard Exclusive Meson Production:

- 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 $\bar{E}^f_T = 2\tilde{H}^f_T + E^f_T$, and H^f_T

HEMP cross section

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

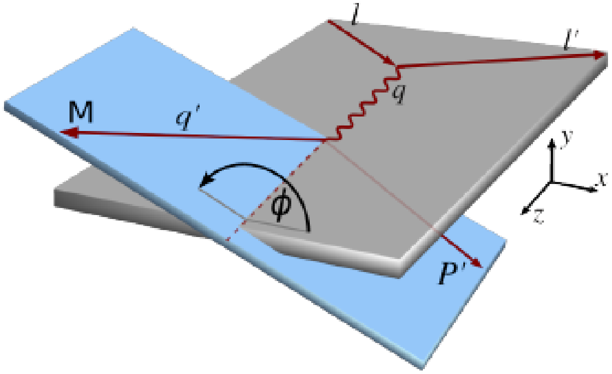
GPDs in exclusive π^0 production

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

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

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

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



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} is the minimum value of $|t|$

S. Stepanyan, IWHSS2022

Compton Scattering and GPDs

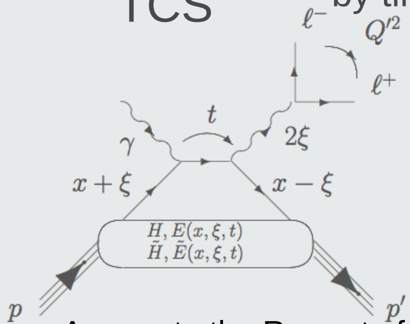
CLAS12 GPD studies

First experimental measurement with CALS12
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



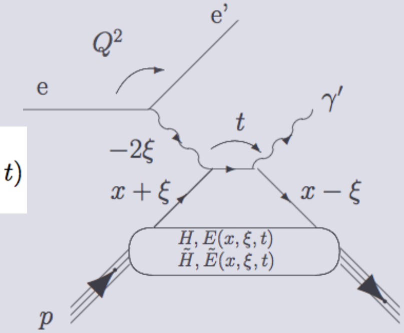
$$Re\ \mathcal{H}(\xi,t) = PV \int_{-1}^{1} dx\, C^{-}(\xi,x) H(x,\xi,t)$$

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

Access to the Re-part of the Compton amplitude

DVCS

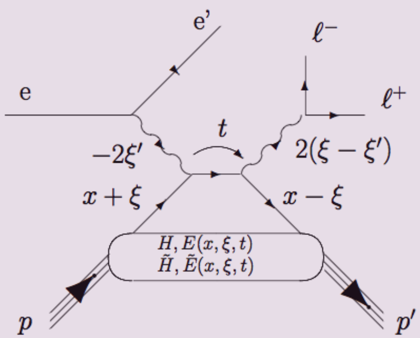
Hard scale is defined by space-like photon



μCLAS12, one of two proposed facilities capable of measuring

DDVCS

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



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

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

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

TCS

BHA Beam Helicity Asymmetry

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

FB Forward Backward Asymmetry

$$\mathbf{A_{FB}}(\theta_{\mathbf{0}},\phi_{\mathbf{0}}) = \frac{\mathbf{d}\sigma(\theta_{\mathbf{0}},\phi_{\mathbf{0}}) - \mathbf{d}\sigma(\pi-\theta_{\mathbf{0}},\pi+\phi_{\mathbf{0}})}{\mathbf{d}\sigma(\theta_{\mathbf{0}},\phi_{\mathbf{0}}) + \mathbf{d}\sigma(\pi-\theta_{\mathbf{0}},\pi+\phi_{\mathbf{0}})} = \frac{-\frac{\alpha_{\mathbf{em}}^{\mathbf{3}}}{\mathbf{4}\pi\mathbf{s^2}}\frac{\mathbf{1}}{-\mathbf{t}}\frac{\mathbf{m_p}}{\mathbf{Q'}}\frac{\mathbf{1}}{\tau\sqrt{\mathbf{1}-\tau}}\frac{\mathbf{L_0}}{\mathbf{L}}\cos\phi_{\mathbf{0}}\frac{(\mathbf{1}+\cos^{\mathbf{2}}\theta_{\mathbf{0}})}{\sin(\theta_{\mathbf{0}})}\mathrm{Re}\tilde{\mathbf{M}}^{--}}{\mathbf{d}\sigma_{\mathbf{BH}}(\theta_{\mathbf{0}},\phi_{\mathbf{0}}) + \mathbf{d}\sigma_{\mathbf{BH}}(\pi-\theta_{\mathbf{0}},\pi+\phi_{\mathbf{0}})}$$