Time-like Compton Scattering
Revealing GPDs

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Electron-Ion Collider Workshop

Rutgers University/JLAB

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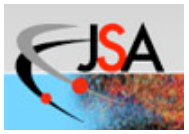
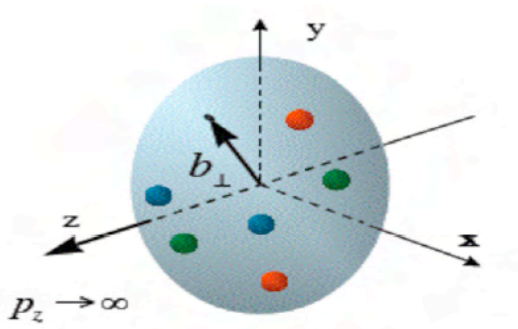
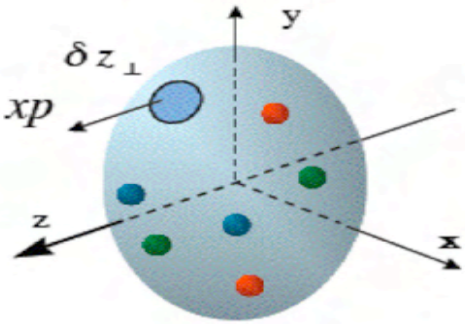
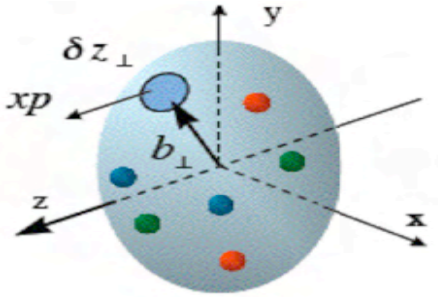


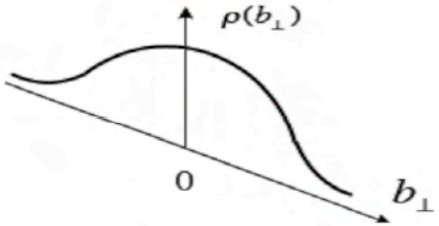
- GPDs and nucleon structure
- Extraction of GPDs from Experimental Data
- TCS phenomenology and observables
- Quasi-real Photoproduction of lepton pairs in CLAS
- Perspectives at 12 GeV (CLAS12)
- Perspectives for MEIC
- Summary

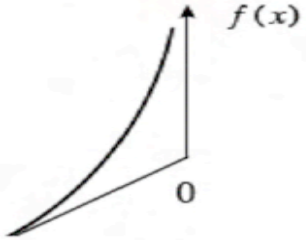
GPDs and Nucleon Structure

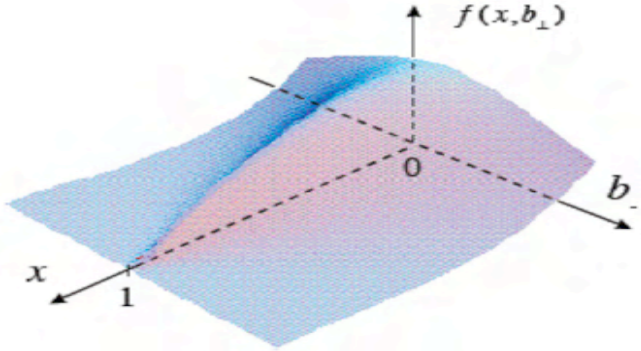












Elastic Form Factors – characterize charge and magnetization distrubutions in the impact parameter space

DIS Parton Distribution Functions - discovery of the quark and gluon substructure of the nucleon, with quarks carrying ½ of the nucleon‘s momentum and ~25% of its spin

Generalised Parton Distributions – 3-D imaging of the nucleon, the correlation of quark/antiquark transverse spatial and longitudinal momentum distributions, and on the quark angular momentum distribution

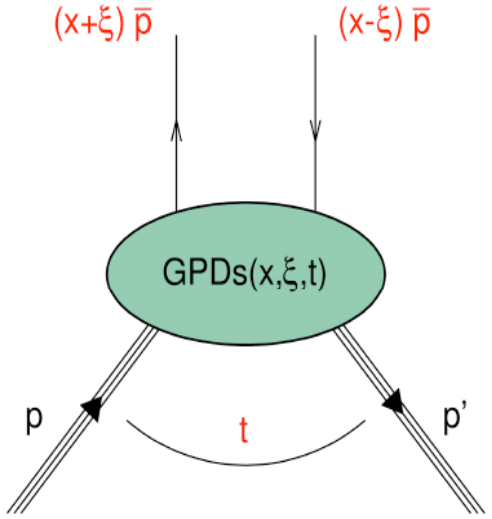
Determination of the GPDs

Boundary conditions

- GPDs $\rightarrow$ PDFs (in the limite t $\rightarrow$ 0)

$$H(x,0,0) = q(x), -\bar{q}(-x)$$

$$\tilde{H}(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)$$



- GPDs $\rightarrow$ FFs (first moments of GPDs)

$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

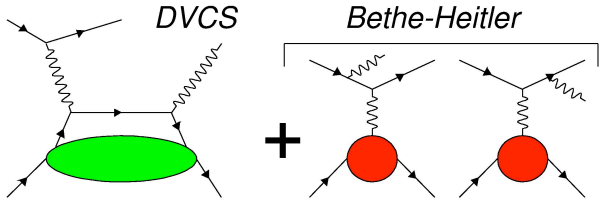
$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

Four chiral-even GPDs:

$$H_q, \tilde{H}_q, E_q, \tilde{E}_q$$

Accessing GPDs experimentally (DVCS)

ep' epγ =

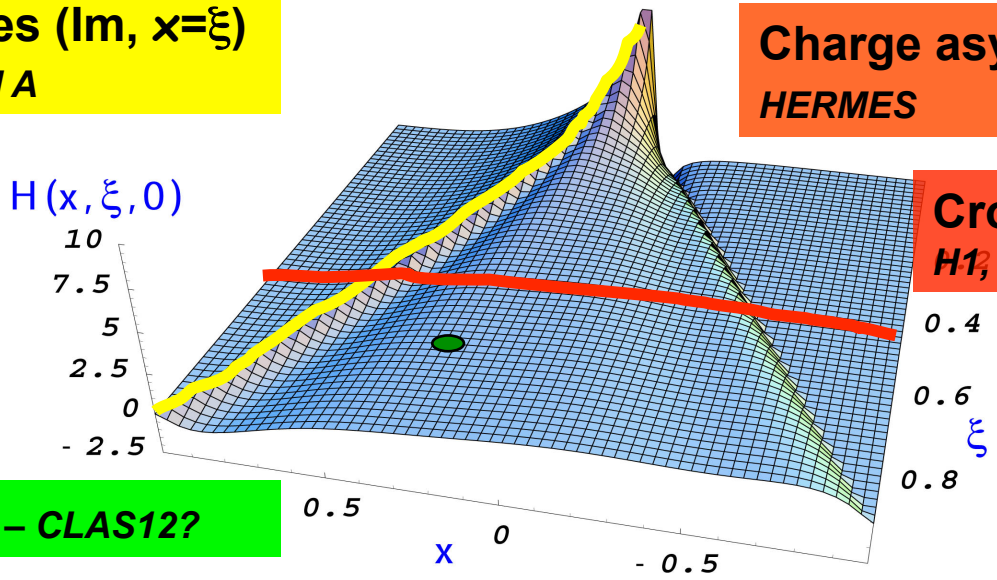


$$\mathcal{T} = \left|\mathcal{T}_{BH}\right|^2 + \left|\mathcal{T}_{DVCS}\right|^2 + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

$$\mathcal{H}(\xi,t) = \underbrace{i\pi\left[H(\xi,\xi,t) - H(-\xi,\xi,t)\right]}_{\text{Im}} + \underbrace{\mathrm{P}\int_{-1}^{+1} dx \left(\frac{1}{\xi - x} \pm \frac{1}{\xi + x}\right)\left[H(x,\xi,t) \mp H(-x,\xi,t)\right]}_{\text{Re}}$$

Spin asymmetries (Im, $x=\xi$)
HERMES, CLAS, Hall A

Charge asymmetry (|Re|)
HERMES



Cross sections ($|Re|^2$)
H1, Hall A

DDVCS (Im, $x \neq \xi$) – *CLAS12?*

Revealing GPDs

The extraction of GPDs from experimental data will require:

- extensive experimental program [with polarized beam/targets]

and

- the phenomenological parameterization of GPDs

Commonly used parameterization uses factorized ansatz for the t-dependence: e.g. the Regge parameterization $\sim x^{-\alpha' t}$

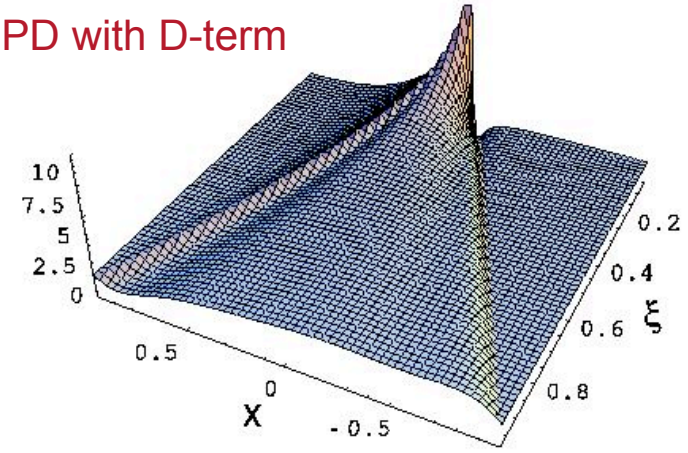
Parameterization of GPDs

DD-distributions

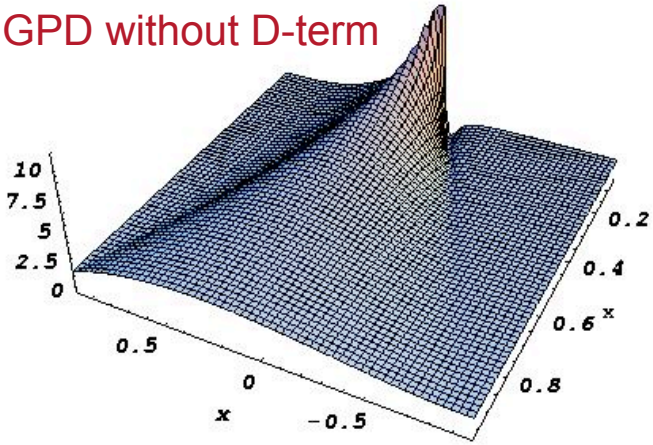
$$H^q(x,\xi) = H^q_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$

D-term – to satisfy polynomiality of Mellin moments of GPD

GPD with D-term

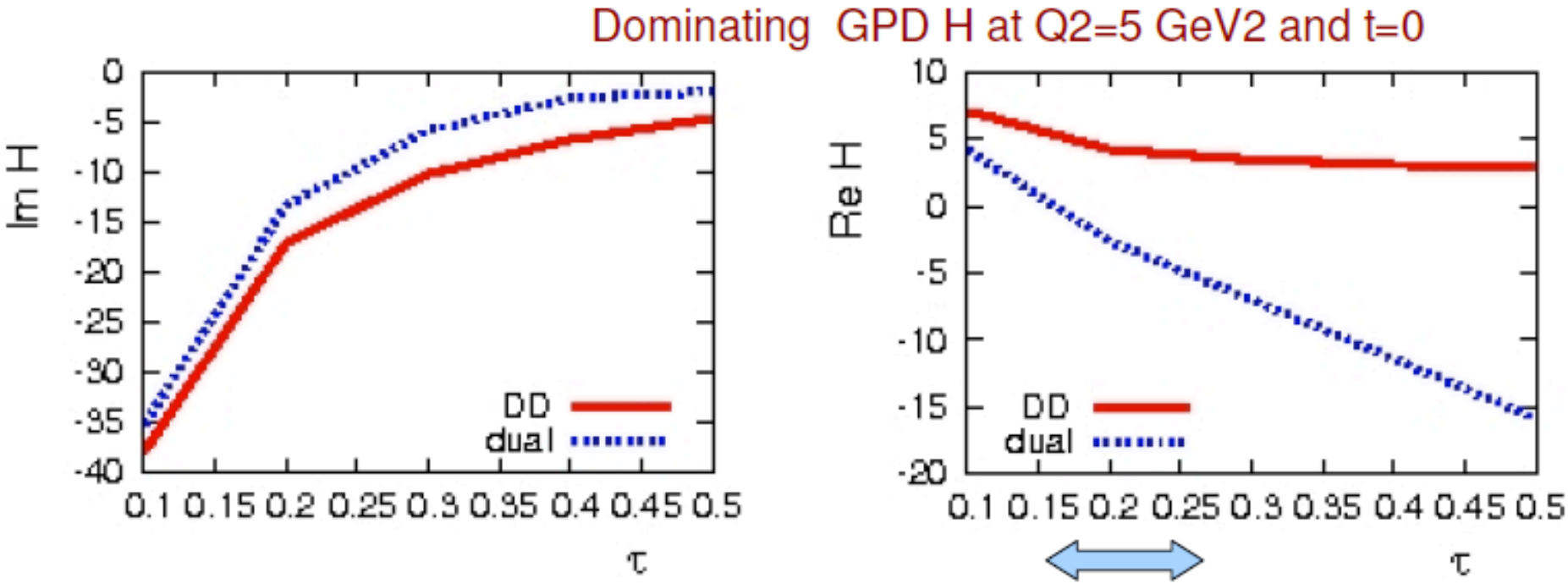


GPD without D-term



Real part of the Compton amplitude is sensitive to the D-term

Sensitivity to models of GPD



Calculations by V. Guzey

Extracting the GPDs

Global fit to the DVCS data, using models of GPDs - M. Guidal, Eur.Phys.J. **A37**, p319 (2008)

8 independent quantities to be fit -

$$\mathrm{Im}(\mathcal{H});\ \mathrm{Im}(\mathcal{E});\ \mathrm{Im}(\tilde{\mathcal{H}});\ \mathrm{Im}(\tilde{\mathcal{E}})$$

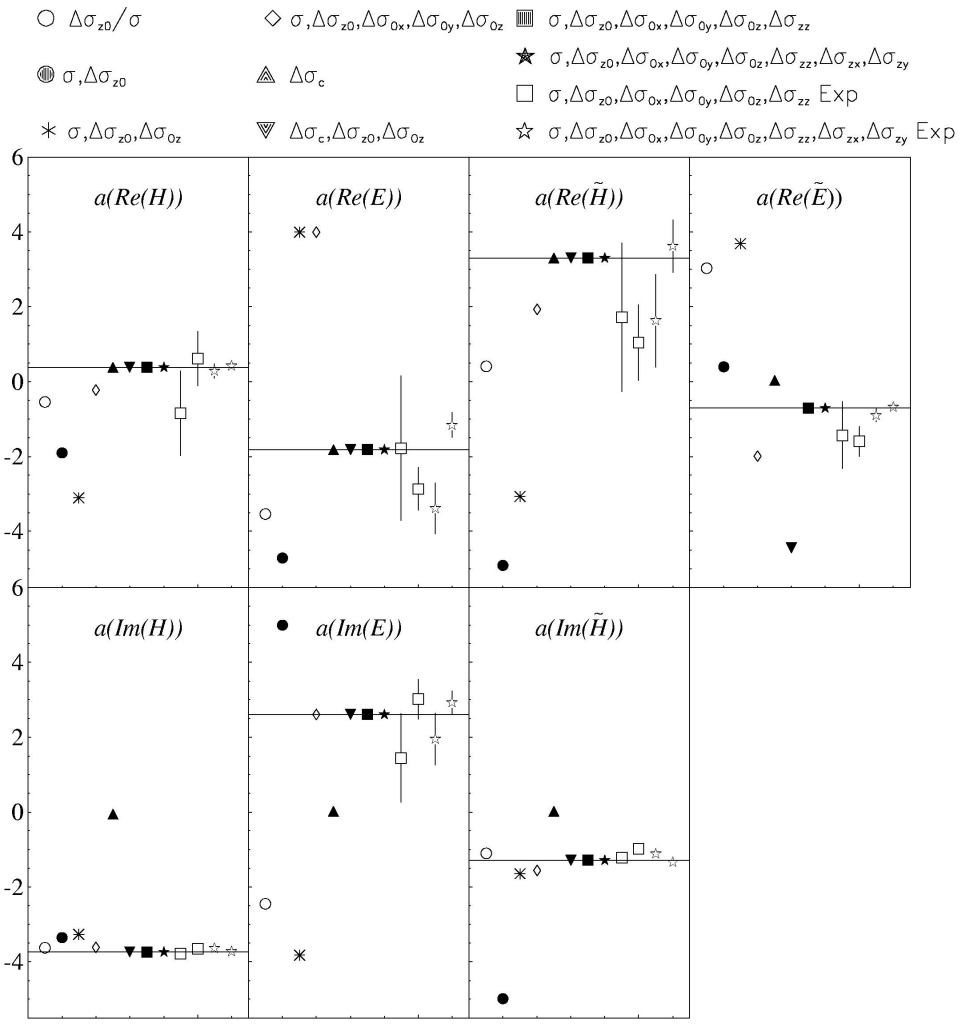
$$\mathrm{Re}(\mathcal{H});\ \mathrm{Re}(\mathcal{E});\ \mathrm{Re}(\tilde{\mathcal{H}});\ \mathrm{Re}(\tilde{\mathcal{E}})$$

Using 9 independent observables -

$$\sigma;\ \Delta\sigma_{z0};\ \Delta\sigma_{0x};\ \Delta\sigma_{0y};\ \Delta\sigma_{0z};$$

$$\Delta\sigma_{zx};\ \Delta\sigma_{zy};\ \Delta\sigma_{zz};\ \Delta\sigma_{c};$$

Assumption - $\mathrm{Im}(\tilde{\mathcal{E}}) = 0$



Conclusions from the fits

- In general, with enough observables fit constrains all seven CFFs

There might be possibilities to reduce the number of independent parameters – dispersion relations or model motivated ansatzes

- Imaginary parts of CFFs $\mathcal{H}$ and $\tilde{\mathcal{H}}$ can be reliably extracted from σ, $\Delta\sigma_{z0}$ and $\Delta\sigma_{0z}$ – ongoing and planned experiments at JLAB
- Real parts of the CFFs can be reliably reconstructed
  - from BCA measurements – requires lepton beams of both charges

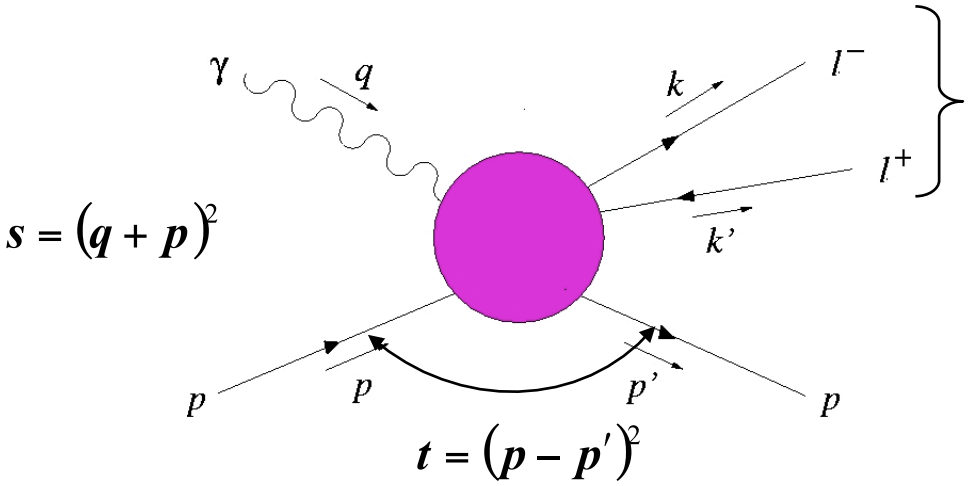
and/or

  - in the combined analysis of several (at least 6) beam and/or target spin asymmetry measurements – will potentially have large systematic uncertainties and requires huge amount of data

Time-like Compton Scattering (TCS)

Information on the real (imaginary) part of the Compton amplitude can be obtained from photoproduction (circularly polarized) of lepton pairs

$$\gamma\ p \rightarrow p\ l^+\ l^-\ ;\quad l = e, \mu$$



Hard scale

$$Q'^2 = M^2_{l^+l^-} = (k + k')^2$$

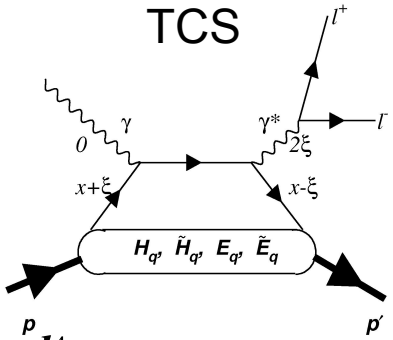
$$\eta = \frac{Q'^2}{2s - Q'^2}$$

TCS is the inverse process to DVCS. Contributions of higher twists are different for DVCS and TCS processes and hence measuring both will help to obtain stronger constraints on GPDs

Lepton pair photo-production

- BH contributes at the amplitude level and always dominates in the cross section

TCS



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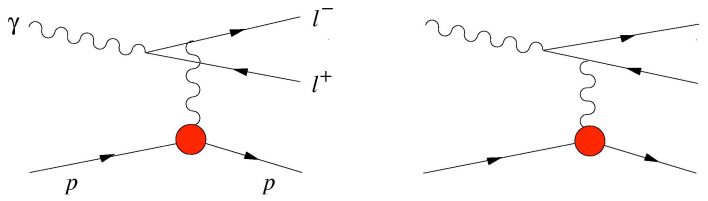
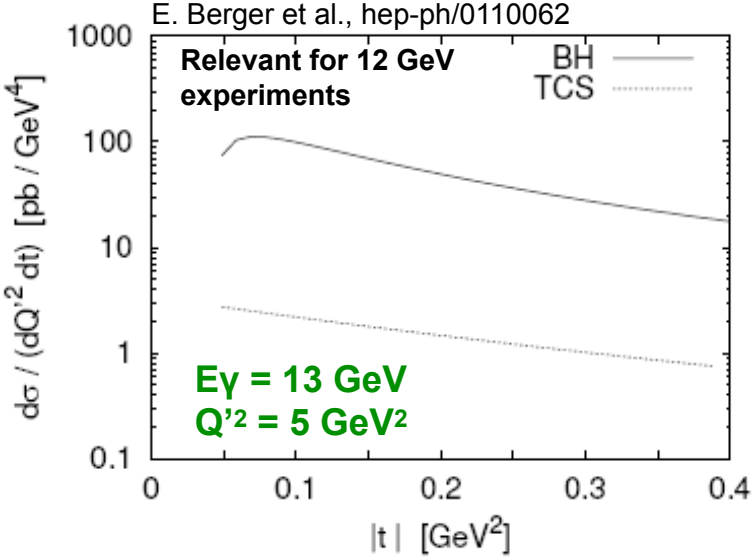
Bethe-Heitler (BH)

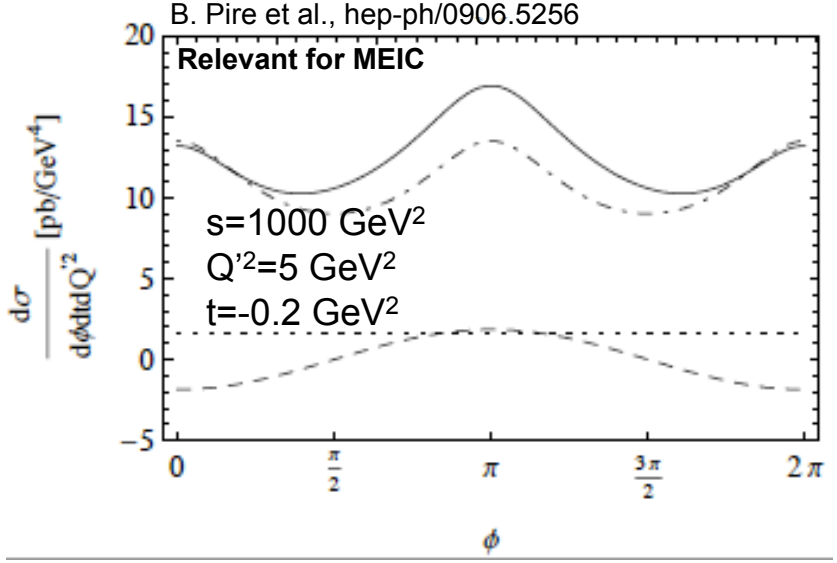


$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \propto |T^{BH}|^2 + T^{BH} \bullet \mathrm{Re}(T^{VCS}) + h_{\oplus} T^{BH} \bullet \mathrm{Im}(T^{VCS}) + |T^{VCS}|^2$$

E. Berger et al., hep-ph/0110062

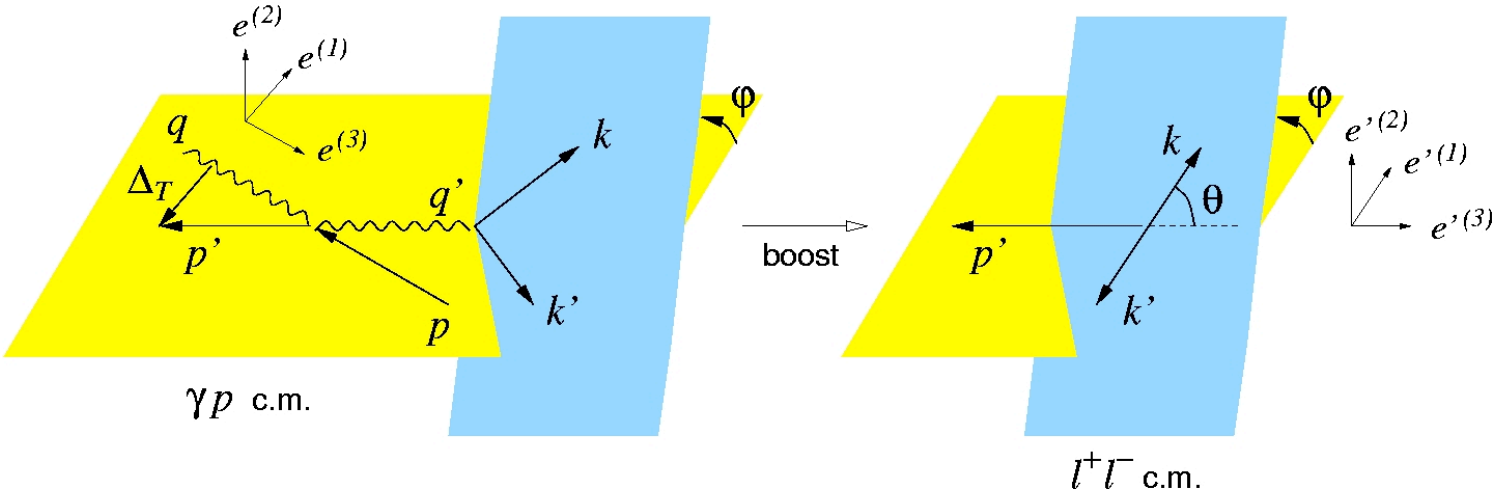


B. Pire et al., hep-ph/0906.5256



Interference term and angular harmonics

lepton pair is produced in C-odd state by TCS and in a C-even state by BH, azimuthal angular dependence will project out the interference – analogous to BCA in DVCS



$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\,\tilde{M}^{--}\right.$$
$$\left. -\cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\,\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\,\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right],$$
$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--}\right.$$
$$\left. -\sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right]$$

Observables

$$\frac{dS}{dQ'^2\,dtd\varphi} = \int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ'^2\,dtd\varphi d\theta} d\theta$$

Lepton propagators:

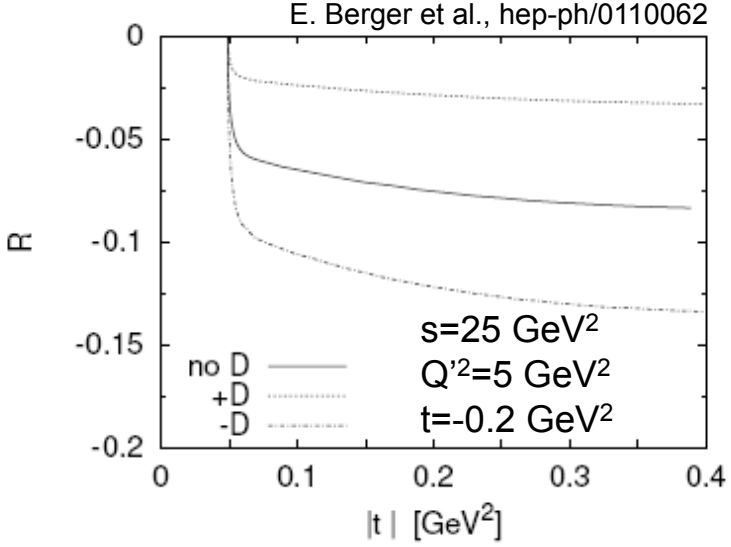
$$L_0 = \frac{Q'^4 \sin^2\theta}{4};$$

$$L = \frac{(Q'^4 - t)^2 - 4\left[(k-k')(p-p')\right]^2}{4}$$

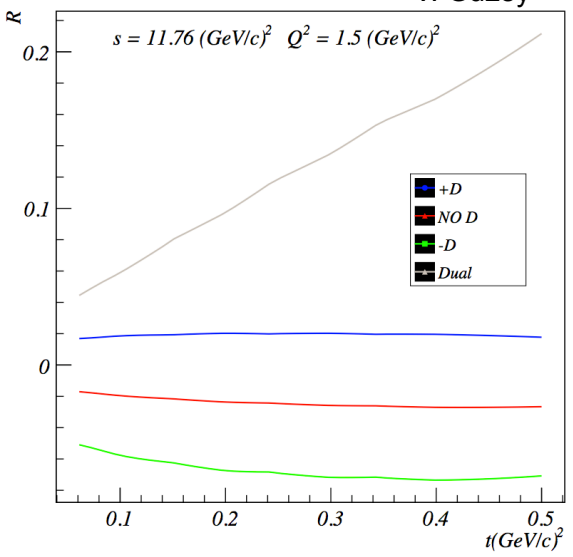
Observable:

$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ'^2 dtd\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2 dtd\varphi}}$$

E. Berger et al., hep-ph/0110062



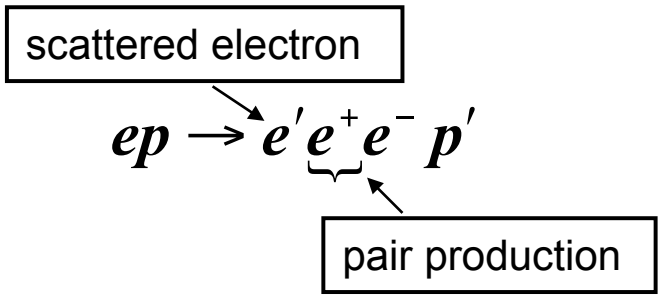
V. Guzey



First TCS analysis from CLAS data

Analysis of electroproduction data to select events in the quasi-real photoproduction region, when incoming electron scatters at ~0 degrees

In the production of e^+e^- pair, there are two electrons in final state



Final state to analyze

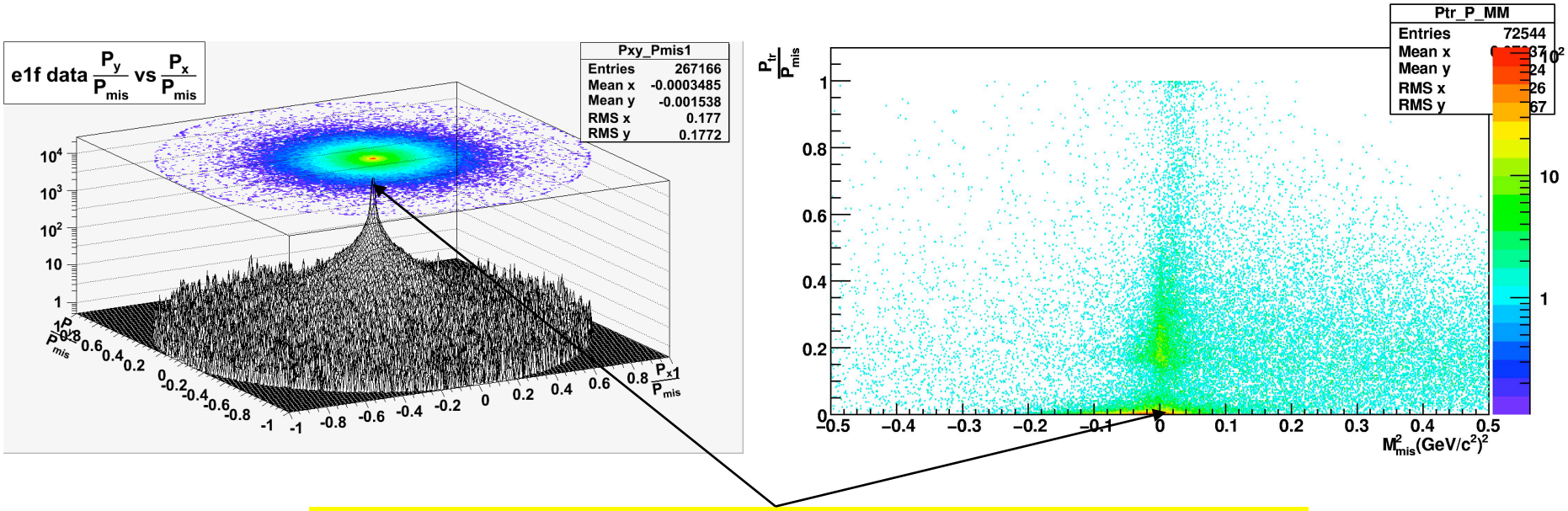
$$ep \rightarrow e^+ e^- pX$$

Scattered electron kinematics is deduced from missing momentum analysis

Quasi-real photoproduction of e^+e^- in

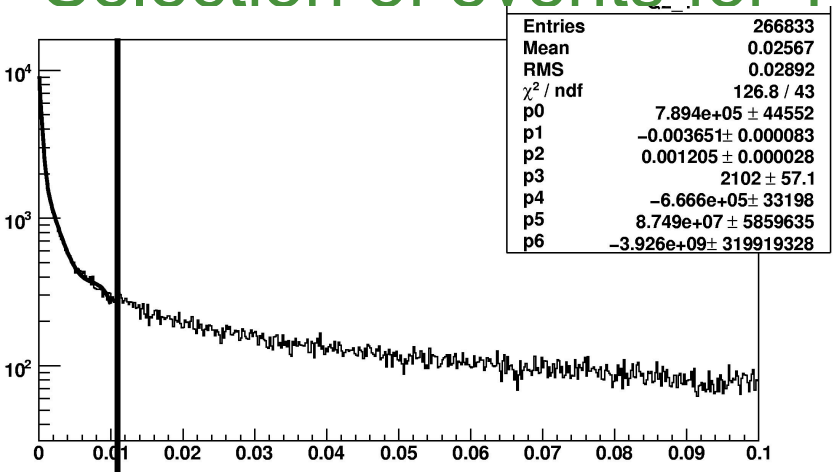
Missing momentum analysis for final state -

$$ep \rightarrow e^+e^- pX$$



X – is identified as an electron scattered at 0 degrees, $Q^2<0.01$ (GeV/c)^2 and $|M_X^2|<0.1$ (GeV)^2

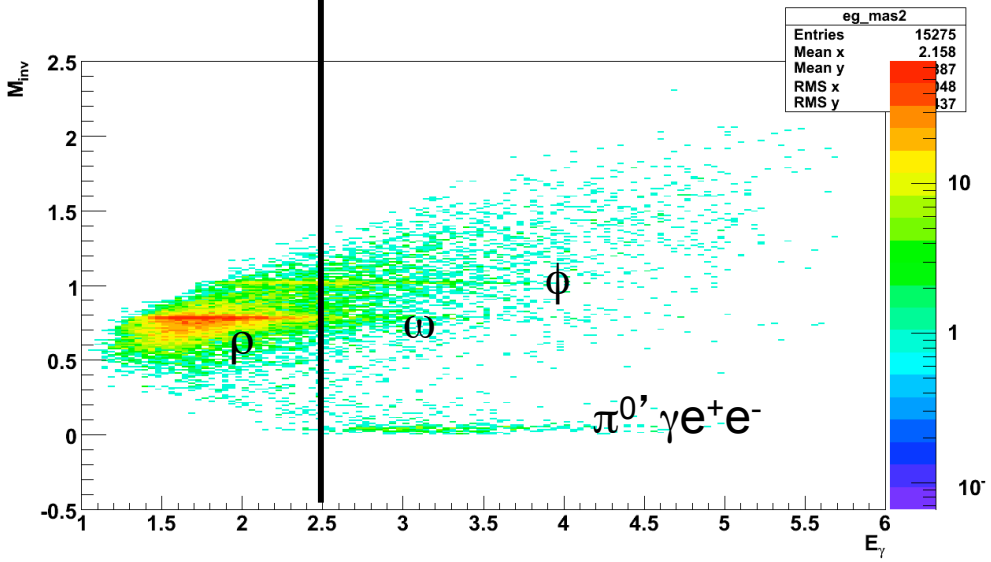
Selection of events for TCS



Quasi-real photoproduction

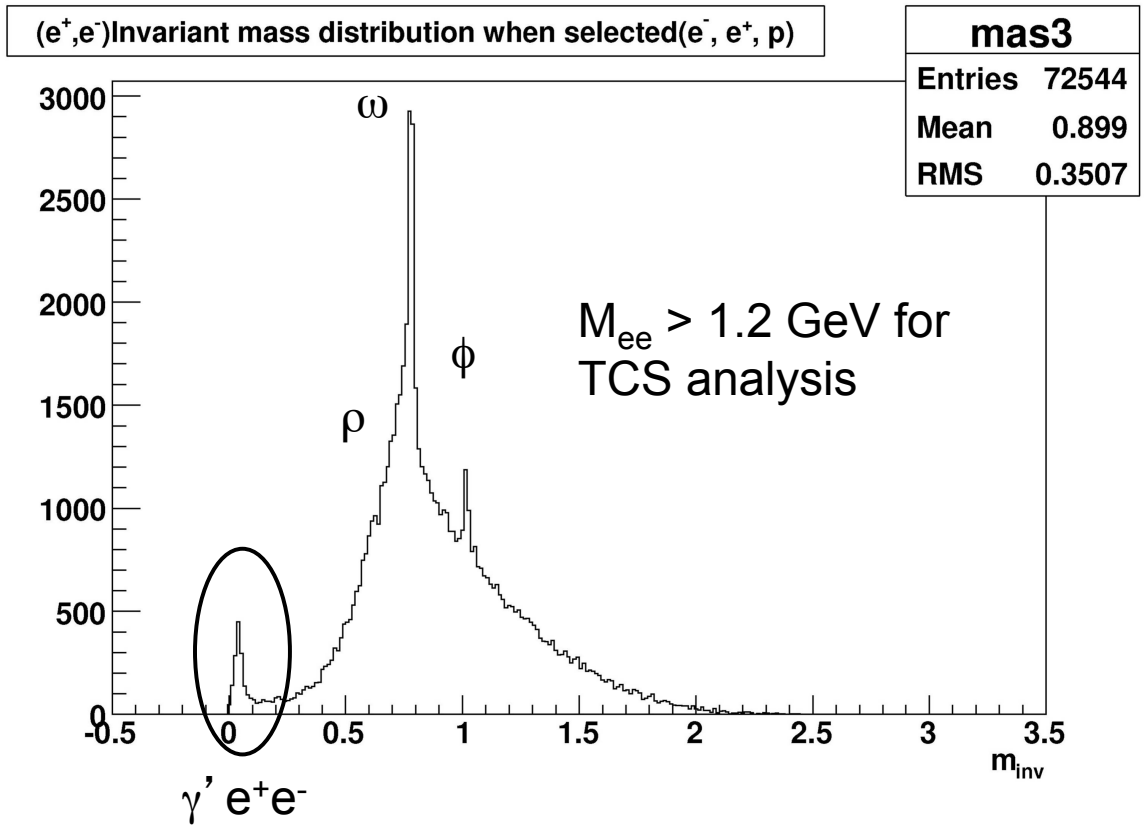
Q^2~0, consistent with detector resolution

For TCS analysis, $\sqrt{s} > 1.8\,GeV$

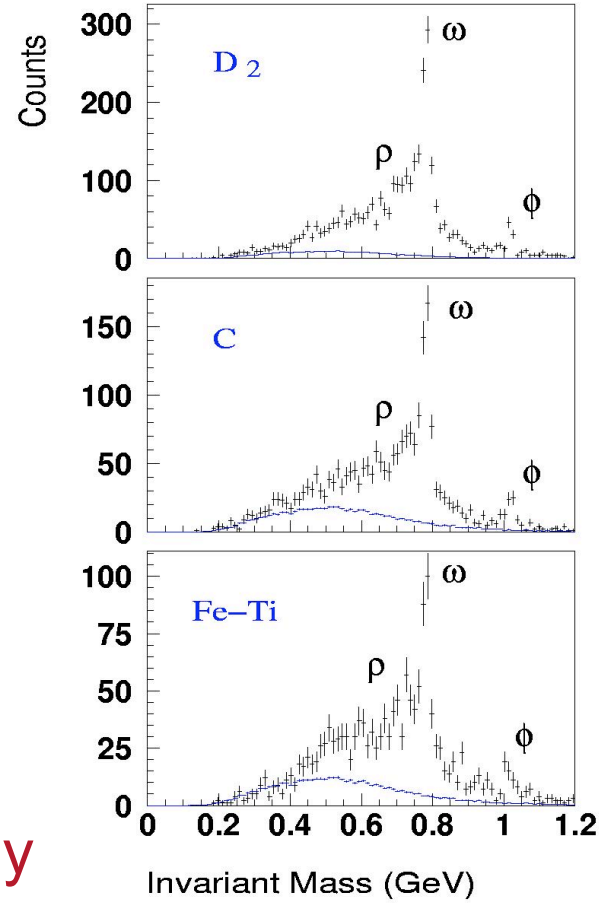


Photoproduction of lepton pairs

CLAS/E1-6

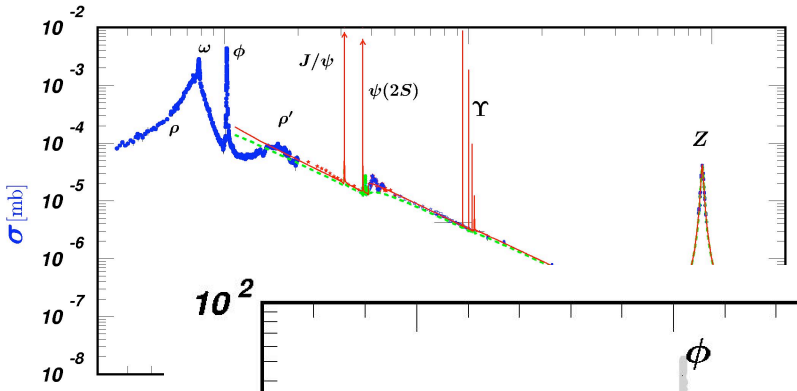


CLAS/G7



Analysis of e1-6 and e1f data are underway

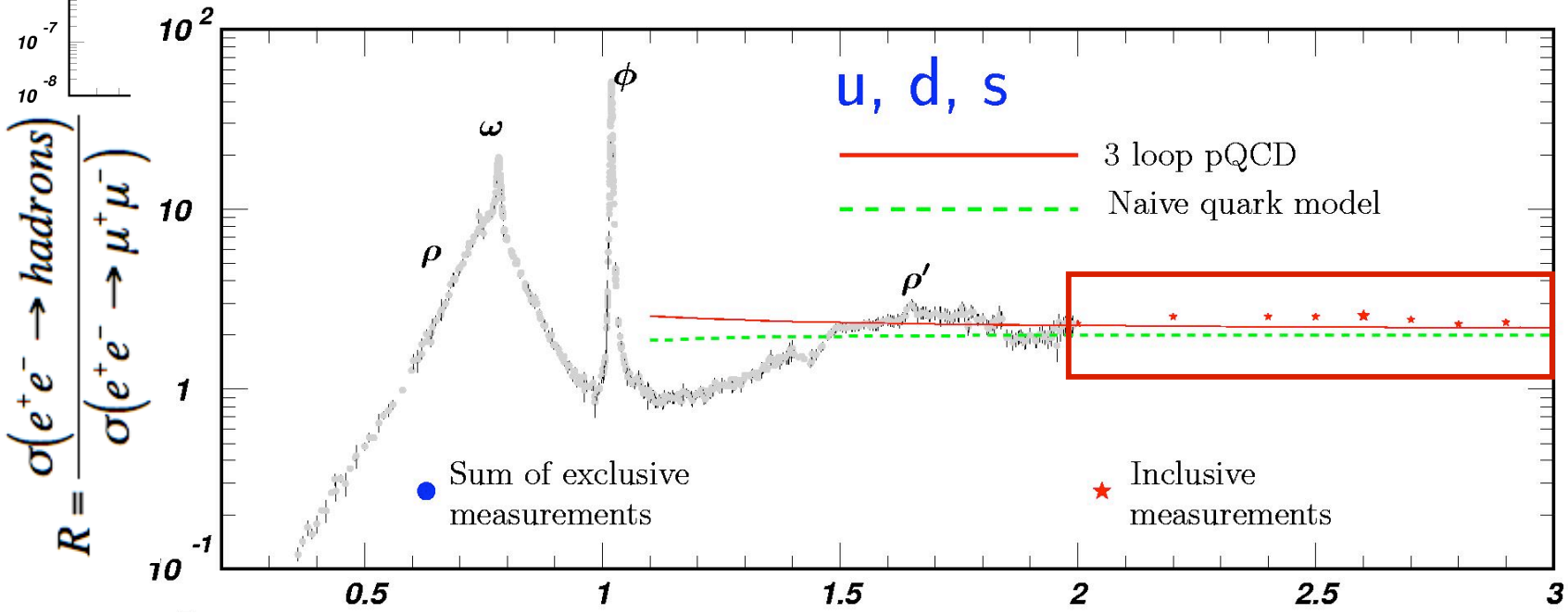
TCS at high energies



The most suitable region of masses for TCS studies at high energies

$$\sqrt{s} > 5\,GeV$$

2 GeV < M_{ee} < 3 GeV



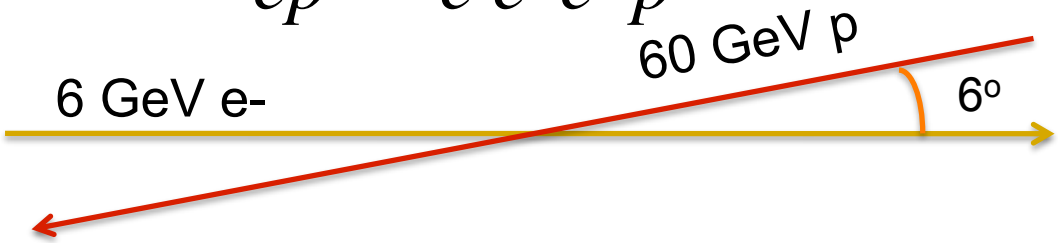
TCS with CLAS12

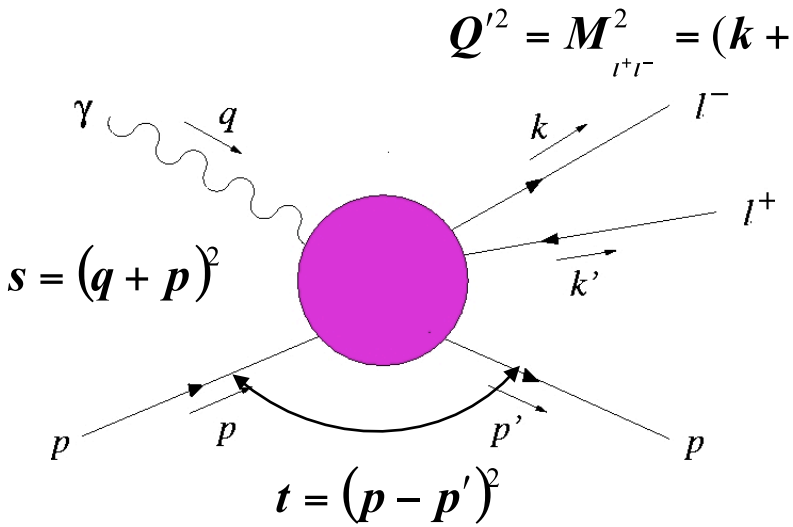
- No real photon beams will be available with E_γ>~6 GeV
- The same technique can be used - electroproduction of lepton pairs in the quasi-real photoproduction region
- Significant amount of beam time for electroproduction at 11 GeV with CLAS12 is already aproved

Proposal	Contact Person	Physics	Energy (GeV)	PAC days	Parallel Running	Run Group
PR-09-103	Gothe, Mokeev	N* at high Q^2	11	60	80	120
E12-06-119a	Sabatie	DVCS pol. beam	11	80		
E12-06-112	Avakian	$ep \rightarrow e\pi^{+/-/0} X$	11	60		
E12-06-108	Stoler	DVMP in π^0,η prod	11	80		
		L/T separation	8.8	20	20	
			6.6	20	20	

TCS at MEIC

$$ep \rightarrow e'e^+e^-p'$$





$$\eta = \frac{Q'^2}{2s - Q'^2}$$

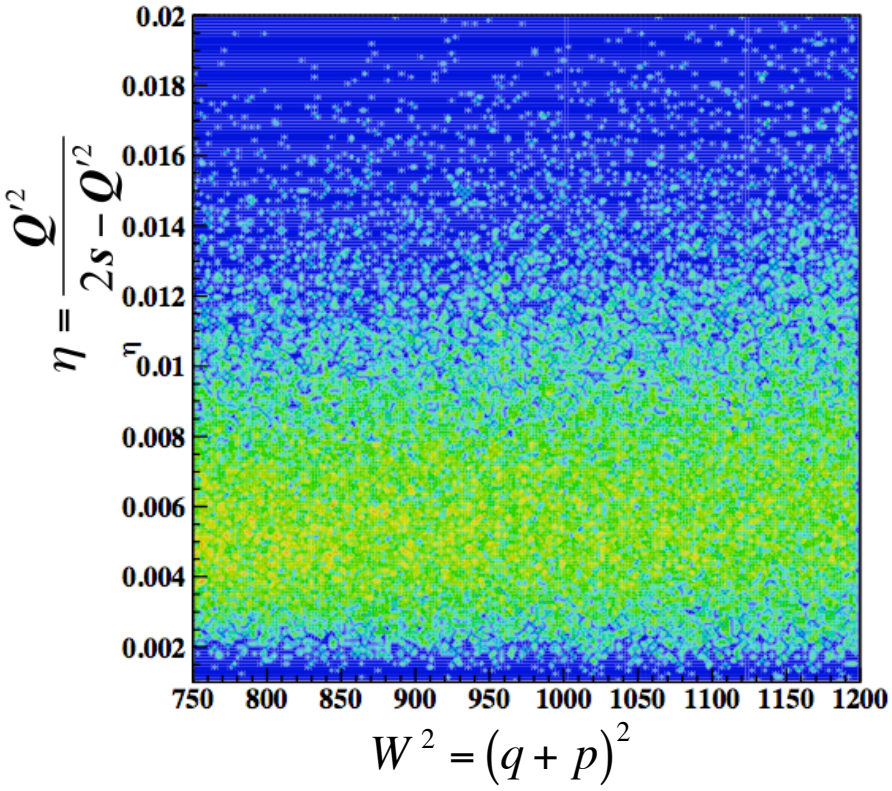
Final state to be detected

$$ep \rightarrow e'e^+e^-X$$

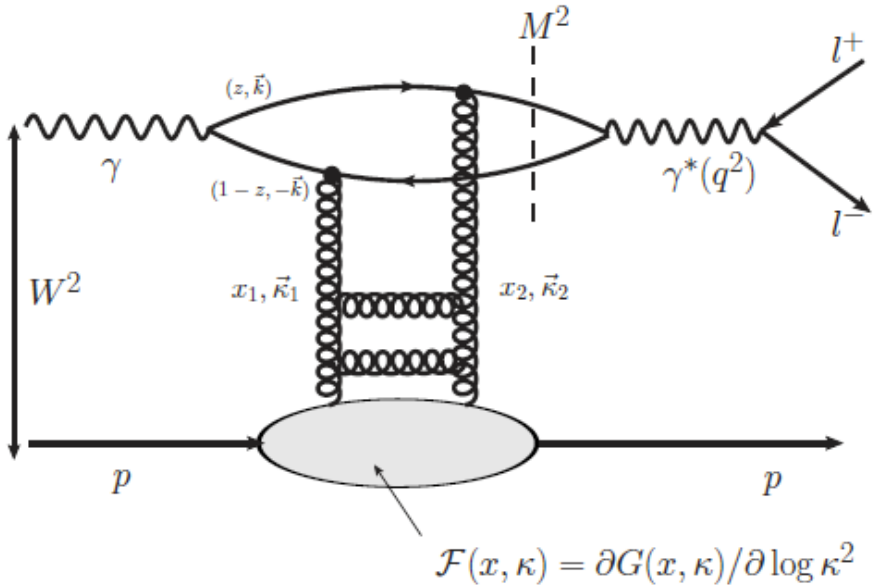
Simpler to identify than DVCS
Cross section is ~ few to 10 pb
(B. Pire et al.)

TCS kinematics

Kinematical reach

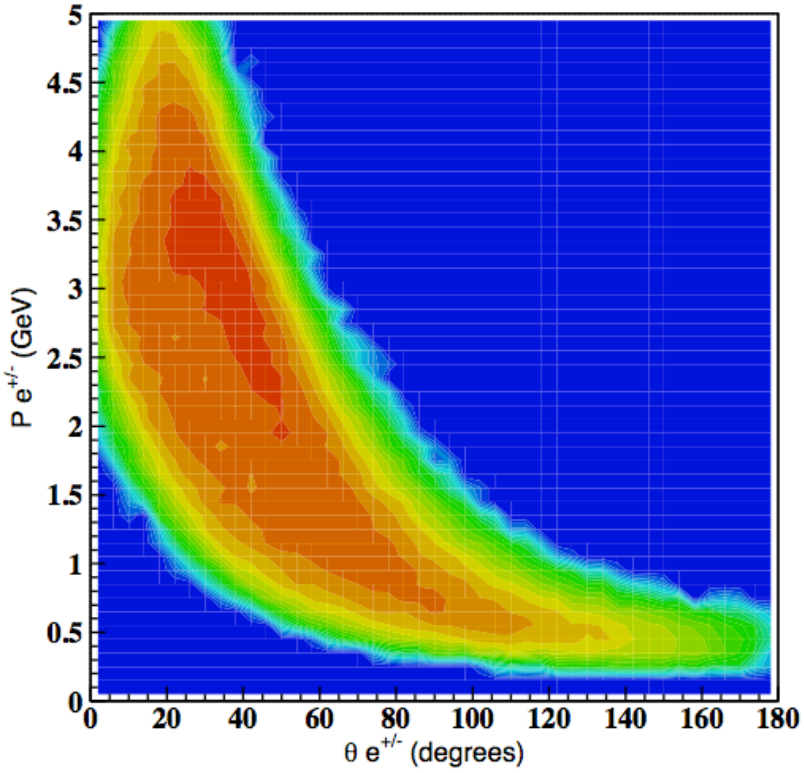


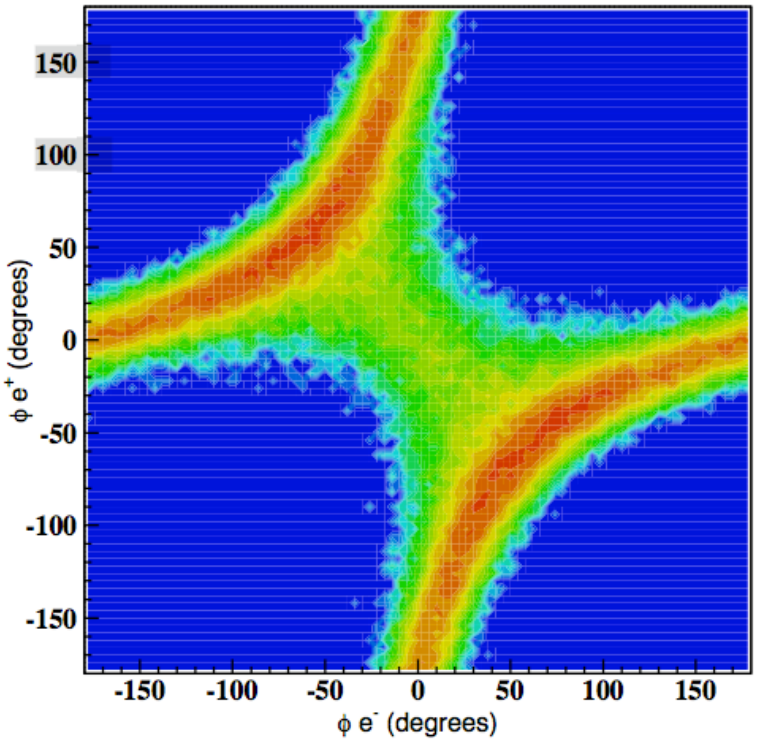
Accessing see quark and gluonic GPDs in the small skwedeness egion



Quasi-real photoproduction $ep \to e'e^+e^-(p')$

- 1 to 3 GeV scattered electron gets detected in very forward angles, ~0°
- Recoil proton escapes detection
- Two leptons can be detected in the main detector





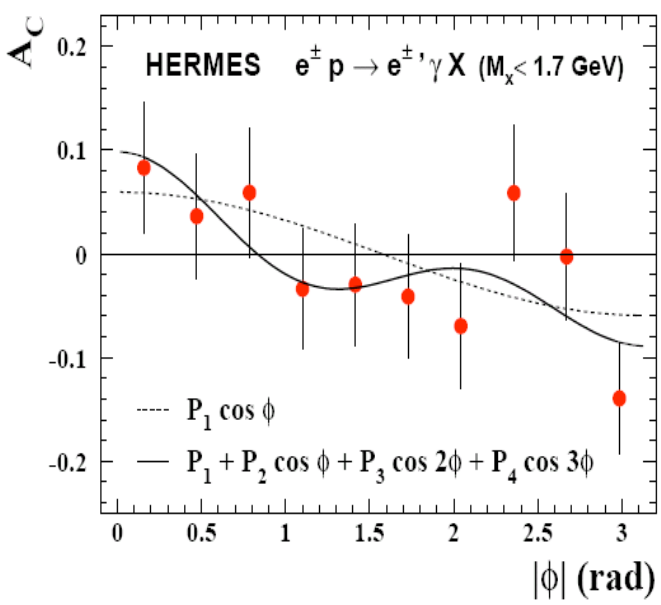
Summary

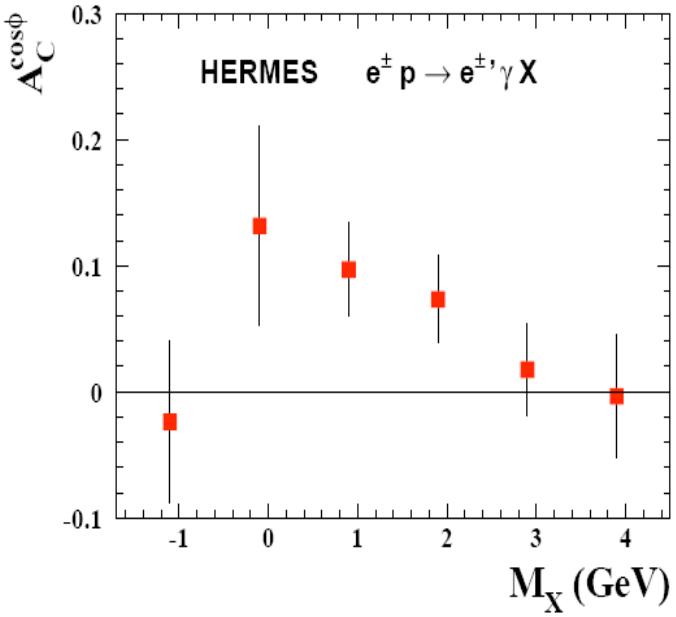
- Extraction of GPDs require combined analysis of large set of experimental data using models of GPDs. Field is rapidly growing, construction of complex analysis framework is in progress
- DVCS data alone will not be sufficient to fully constrain the GPDs.
- Time-like Compton Scattering will provide important information on the real part of the Compton amplitude and complementary information on the imaginary part – advantage, e.g., different contributions for higher twist effects
- At 12 GeV, exploring GPDs will be limited to valence quark GPDs
- Extending DVCS and TCS studies to higher energies (mEIC) will open a new possibilities to study see quark and gluonic GPDs

Backups

Beam charge asymmetry

$$A_C(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \propto \frac{Re\mathcal{H}}{F_1} \cdot cos\phi$$





A. Airapetian et al., HERMES coll., Phys. Rev. D **75,** 011103(R) (2007)

BCA requires lepton beams of both charges, not available in any of existing facilities