Timelike Compton Scattering

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3-D Structure of the Nucleon

Form Factors

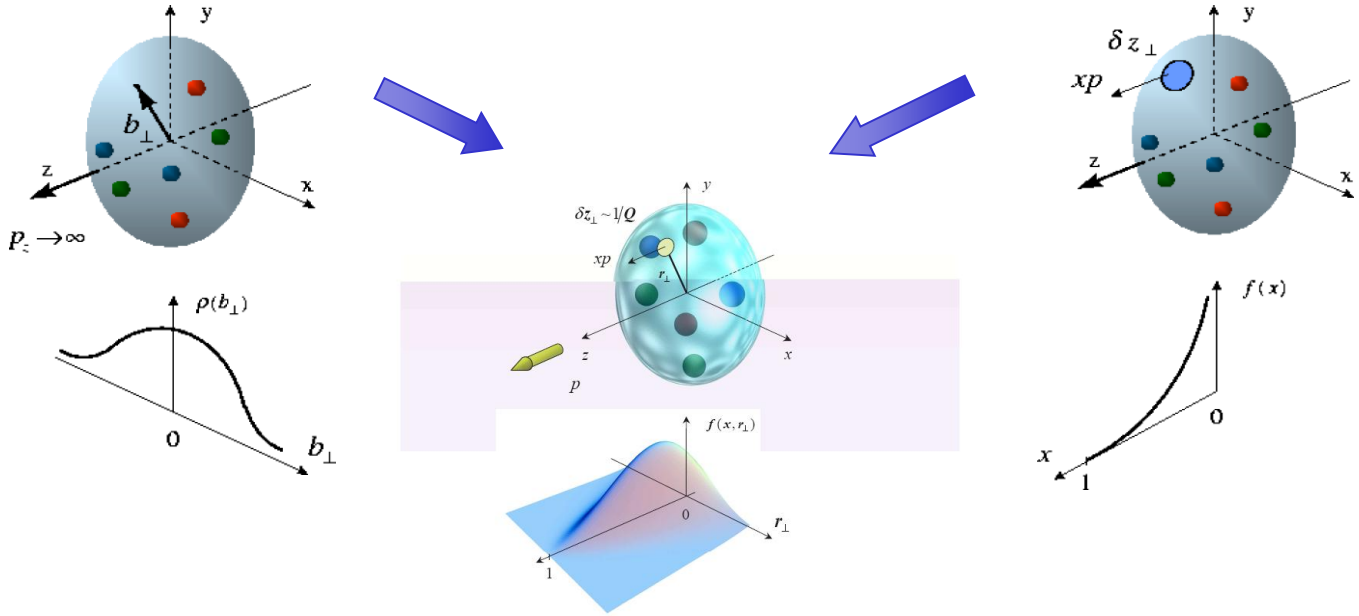
transverse charge and magnetization distributions

[GPD integrated over x]

Parton Distributions (PDFs)

longitudinal momentum (DIS)

[GPD forward limit]



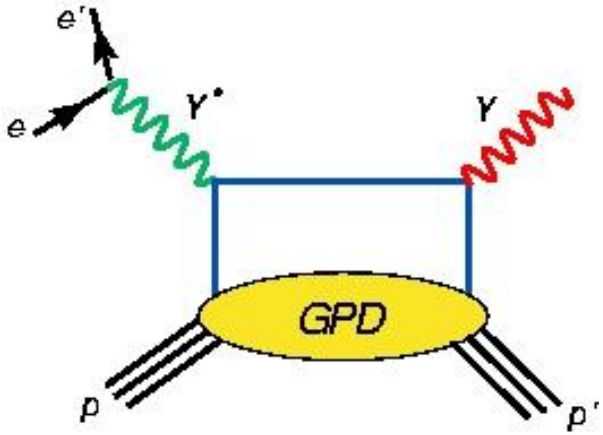
Generalized Parton Distributions (GPDs) [exclusive reactions]

Transverse spatial distribution of quarks with longitudinal momentum fraction x

GPDs "unify" form factors and parton distributions

Compton Scattering

- Real Compton Scattering
- Deeply Virtual Compton Scattering (DVCS)
  - Outgoing photon is real
  - Simplest probe of GPDs
- Timelike Compton Scattering (TCS)
  - Incoming photon is real
  - Complementary to DVCS
- Double DVCS
  - Both photons are virtual
  - Can provide most information
  - Experimentally challenging



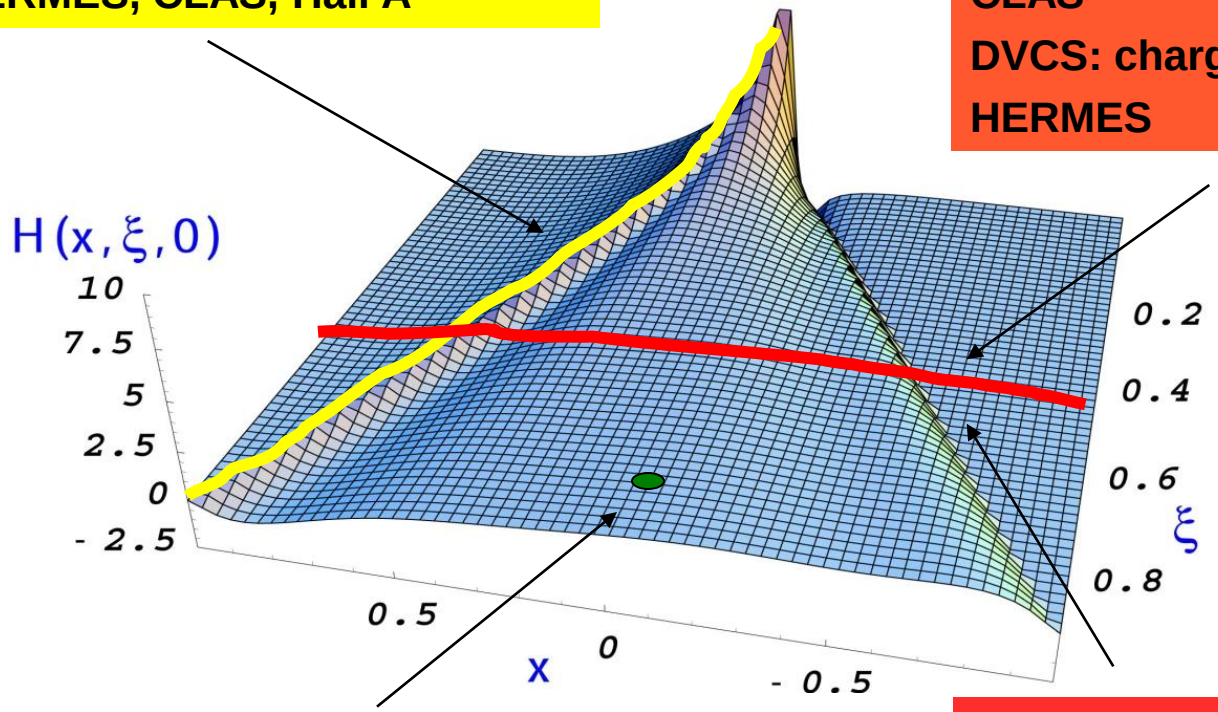
$$\gamma^* + p \rightarrow \gamma^* + p$$

GPDs can be extracted from Helicity Amplitudes or Compton Form Factors

Probing GPDs through Compton Scattering

(Im, x=ξ)
DVCS: spin asymmetries
HERMES, CLAS, Hall A

(|Re|)
TCS: azimuthal asymmetry
CLAS
DVCS: charge asymmetry
HERMES



(Im, x ≠ ξ, x < |ξ|)
DDVCS

(|Re|^2)
DVCS: cross sections
H1, Hall A

TCS vs. DVCS

Pros

- Excellent tool for measuring the real part
- TCS and DVCS amplitudes are equivalent only to leading order
  - at finite Q^2, data on both reduces model dependence of GPD extraction
- TCS asymmetries are easy to compare directly with GPD models
  - Polyakov-Weiss D-term

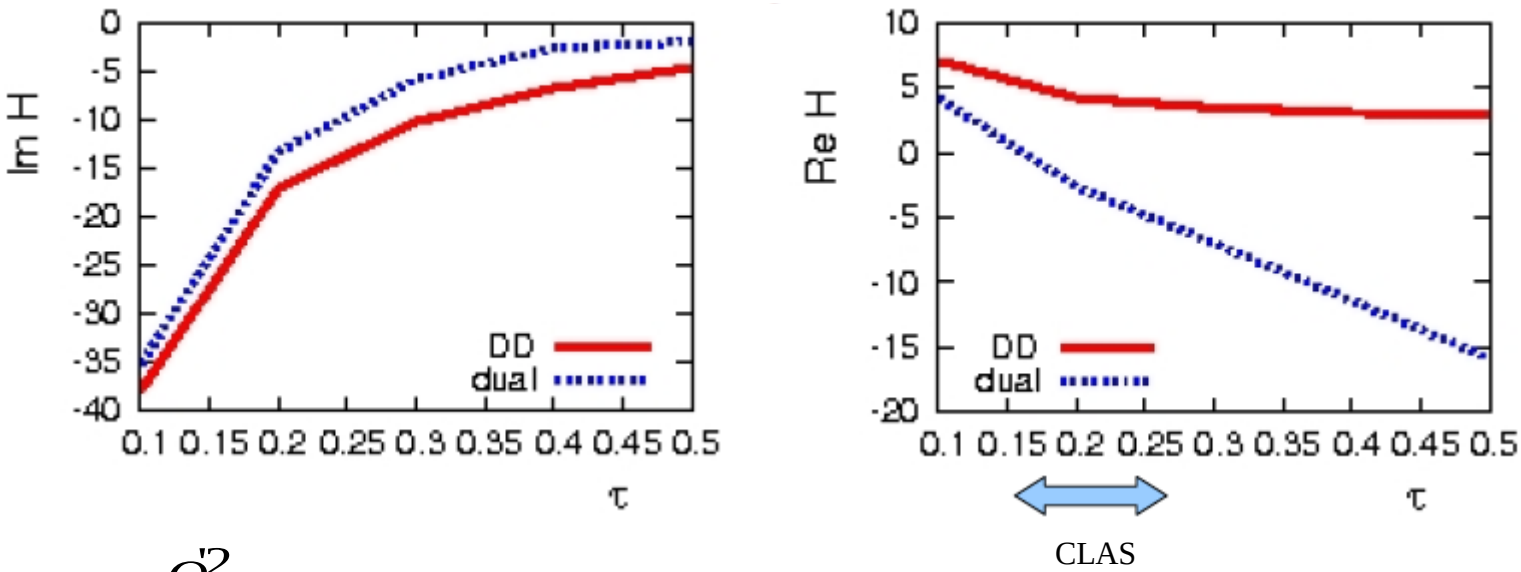
Cons

- Cross section smaller than for DVCS
  - enhancement through interference with Bethe-Heitler always needed
- Resonances in timelike final state limit Q'^2 coverage

GPD models sensitive to real part at large x

[Calculation by V. Guzey, 2010]

$Q'^2 = 5\ \mathrm{GeV}^2$ and $t = 0$

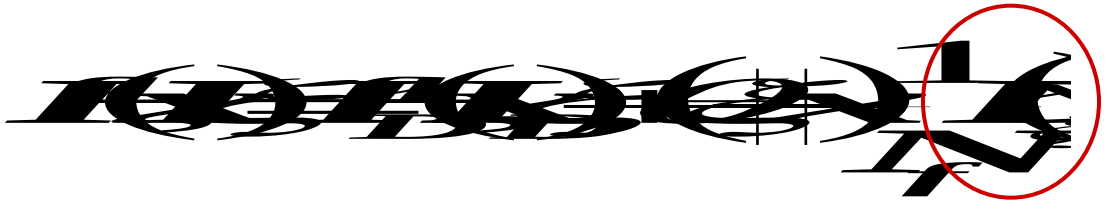


$$\tau = \frac{Q'^2}{s - M_p^2}$$

is the equivalent of Bjorken x, hard scale is given by $Q'^2 = M^2_{e+e-}$

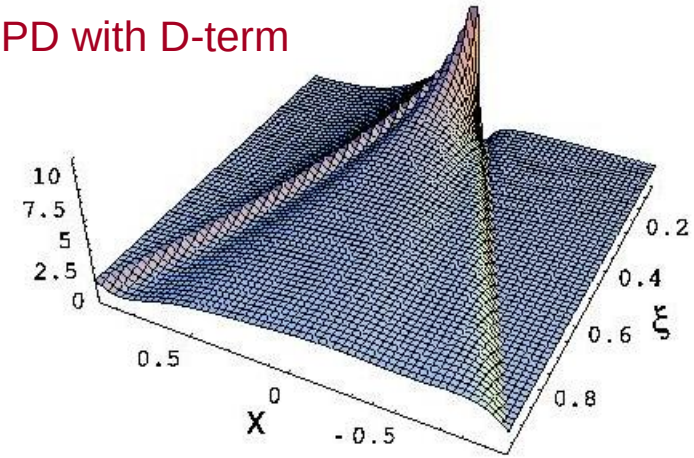
- Model predictions similar for Im H, but large differences for Re H
- Reliable measurements of real part are needed!

D-term in DD-parameterization of GPDs

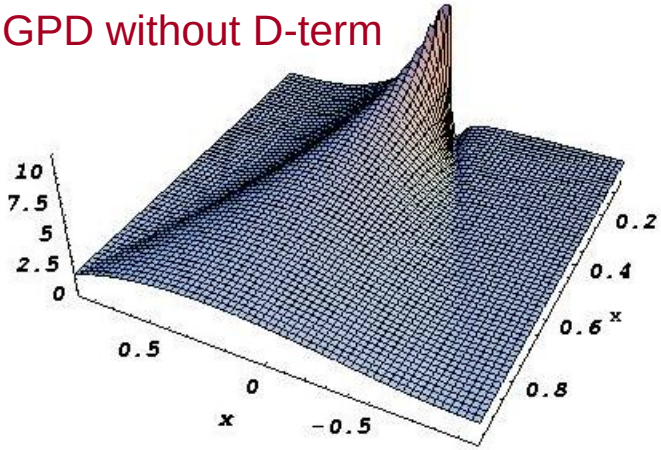


D-term – allows to satisfy polynomiality of Mellin moments of GPD

GPD with D-term

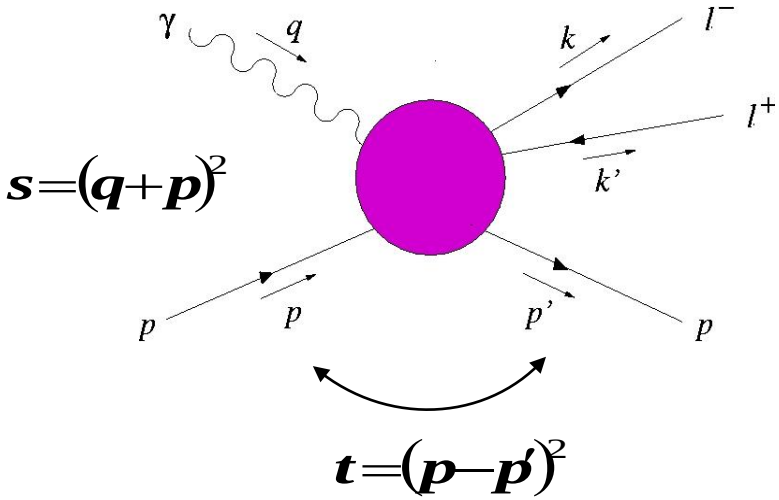


GPD without D-term

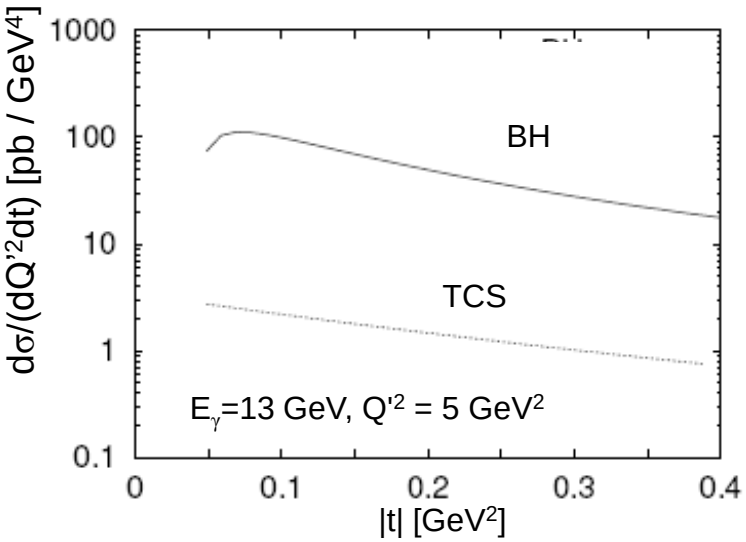


Real part of the Compton amplitude is very sensitive to the D-term

Photoproduction of Lepton Pairs



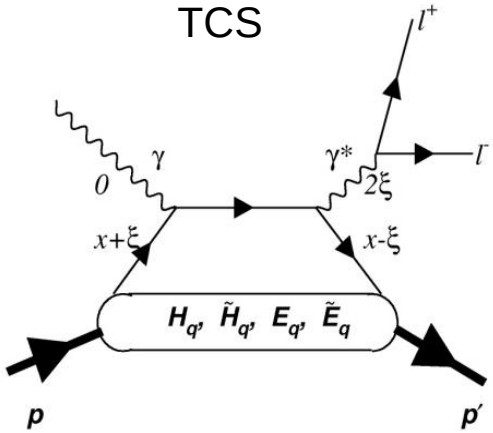
[E. Berger et al., Eur. Phys. J. C23, 675 (2002)]



- TCS cross section is small compared with Bethe-Heitler for all kinematics
  - cannot be accessed directly
- The interference term is, however, larger and easy to isolate

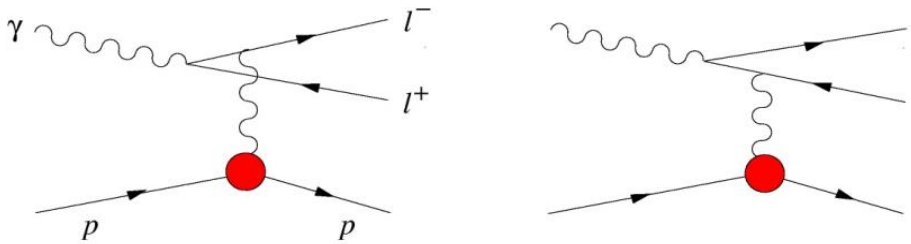
Observables

TCS



+

Bethe-Heitler (BH)



- Under reversal of the lepton charge:
  - Compton and BH amplitudes are *even*
  - Interference term is *odd*
  - Observables that change sign project out *only the interference term*

- Example of observable: azimuthal angular distribution of the lepton pair

The interference term

To leading order, in terms of helicity amplitudes:

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

$$-\cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\,\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\,\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big],$$

$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--}$$

$$-\sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big]$$

ν: circular polarization of incoming photon also gives access to imaginary part

$$\frac{1}{2}\sum_{\lambda,\lambda'}|M^{\lambda'-,\lambda-}|^2 = (1-\eta^2)\Big(|\mathcal{H}_1|^2 + |\tilde{\mathcal{H}}_1|^2\Big) - 2\eta^2\,\mathrm{Re}\Big(\mathcal{H}_1^*\,\mathcal{E}_1 + \tilde{\mathcal{H}}_1^*\,\tilde{\mathcal{E}}_1\Big)$$

$$-\Big(\eta^2 + \frac{t}{4M^2}\Big)|\mathcal{E}_1|^2 - \eta^2\frac{t}{4M^2}|\tilde{\mathcal{E}}_1|^2,$$

Azimuthal e^+e^- asymmetries in TCS

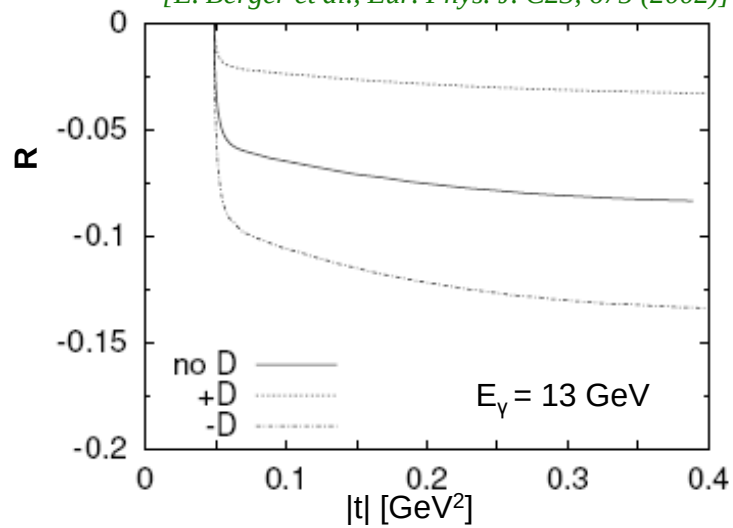
- Example: ratio of weighted cross sections

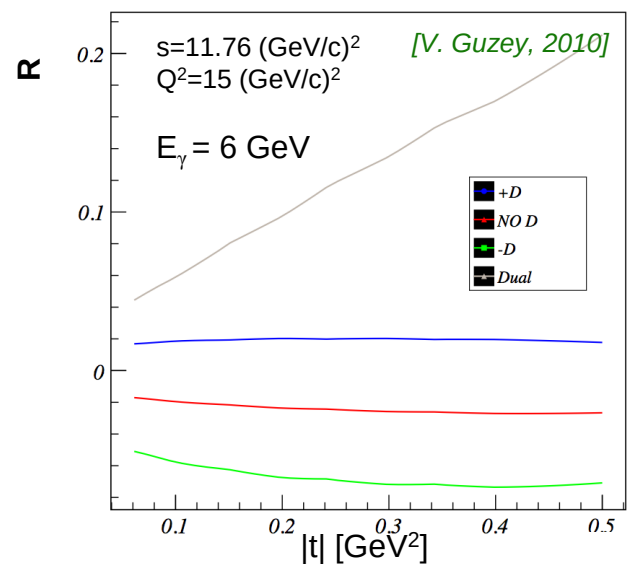
$$\frac{dS(\varphi)}{d\varphi dQ^2 dt}$$

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

- Numerator is proportional to Re M^{--}
  - cos φ part of interference term
- R can be compared directly with GPD models even in experiments with limited statistics
- Sensitive to Polyakov-Weiss D-term

[E. Berger et al., Eur. Phys. J. C23, 675 (2002)]





TCS at JLab 6 and 12 GeV

6 GeV

- New CLAS data collected with tagged real photons (g12)
  - Data ready for analysis (will start in the fall)

- Several CLAS data sets with quasi-real photons (e1-6, e1f)
  - Analysis in final stages (1 PhD completed)

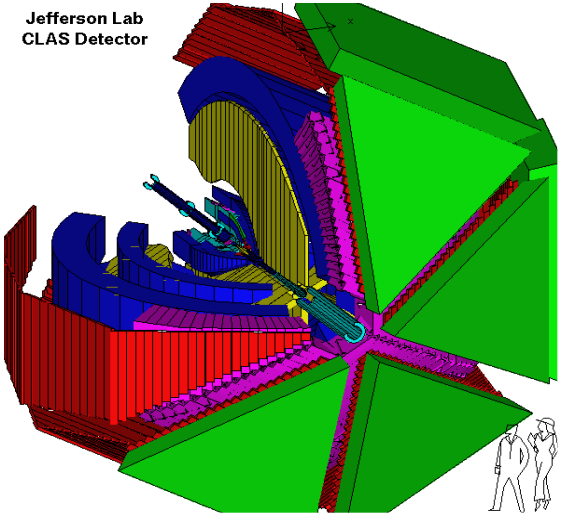
12 GeV

- Experiments with quasireal photons planned at CLAS12
  - Very good electron identification and momentum resolution

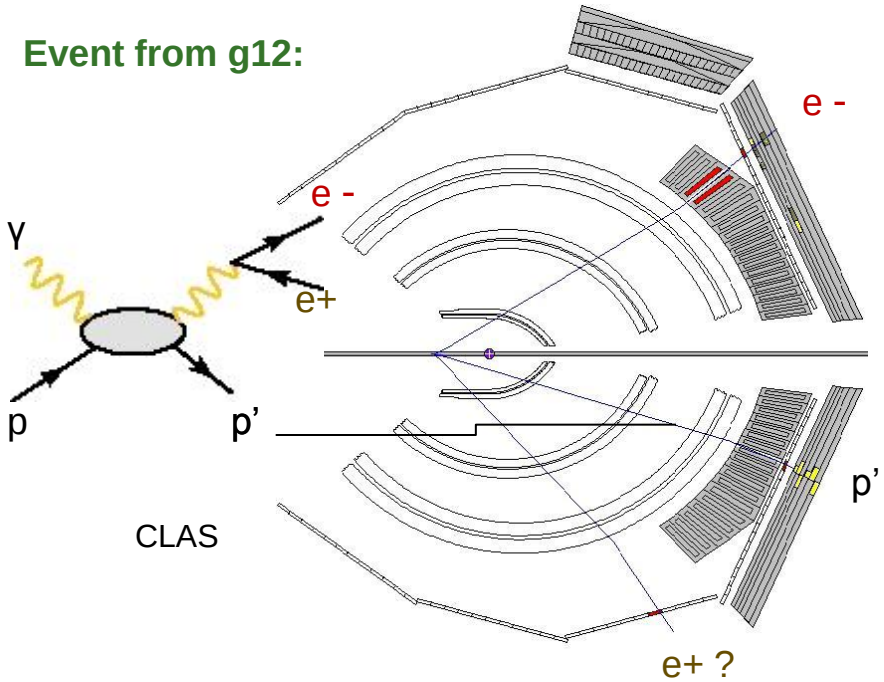
- Experiments with real photons in Hall D natural next step
  - Linear polarization at 9 GeV, circular at 12 GeV
  - Good forward and backward acceptance

The CLAS g12 experiment

Cebaf Large Acceptance Spectrometer (CLAS)



Event from g12:

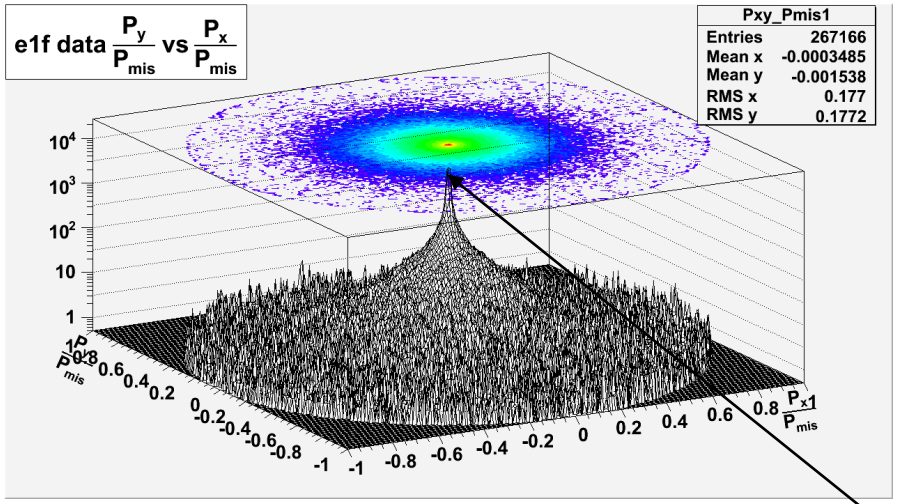


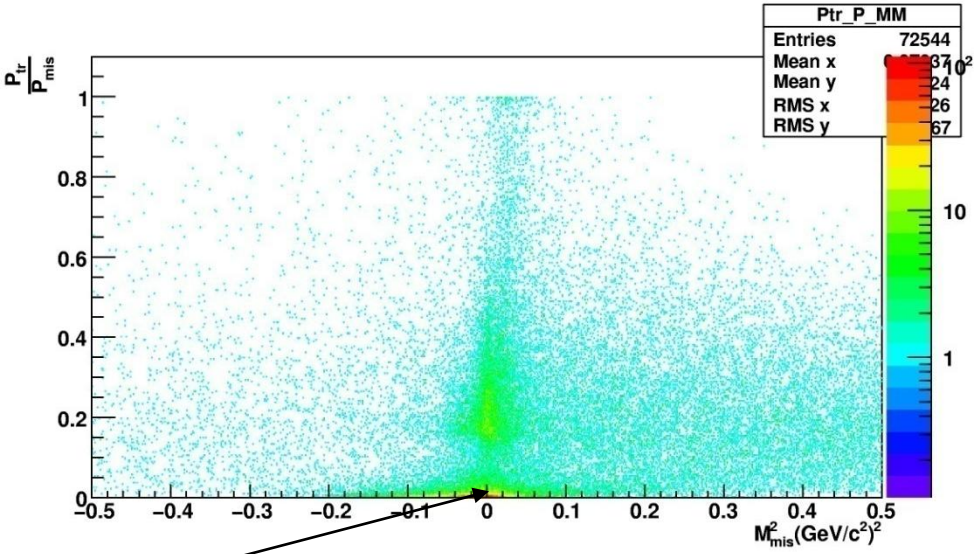
- The g12 experiment carried out between March 29 and June 8, 2008.
- Tagged real photons with energies of 3.6 – 5.4 GeV on LH2 target.
- CLAS Cerenkovs and calorimeter allow good pion rejection
  - 10^{-7} with two leptons detected, 10^{-4} with one lepton detected
- 25 billion two- and three-track events collected (mostly hadron triggers)

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

Missing momentum analysis of final state

$$ep \to e^+e^-p X$$

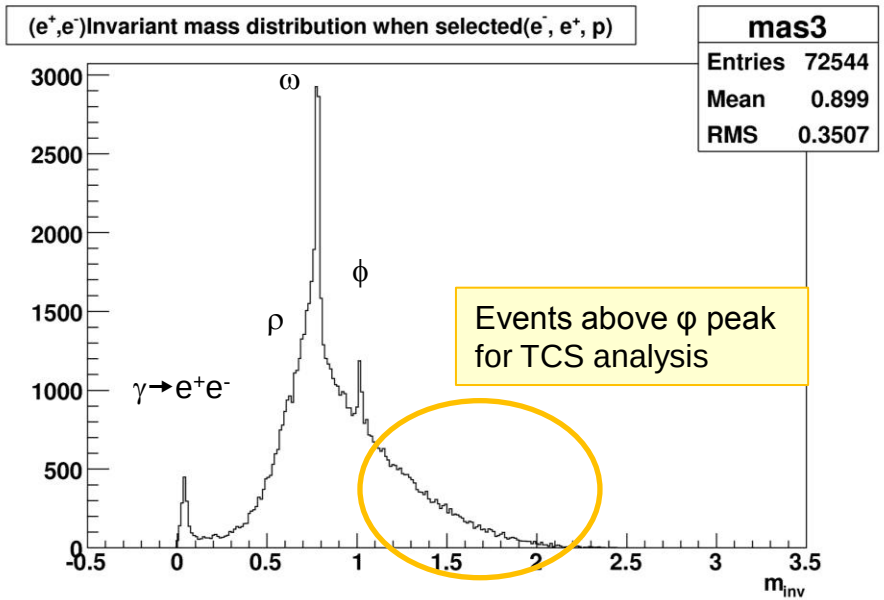


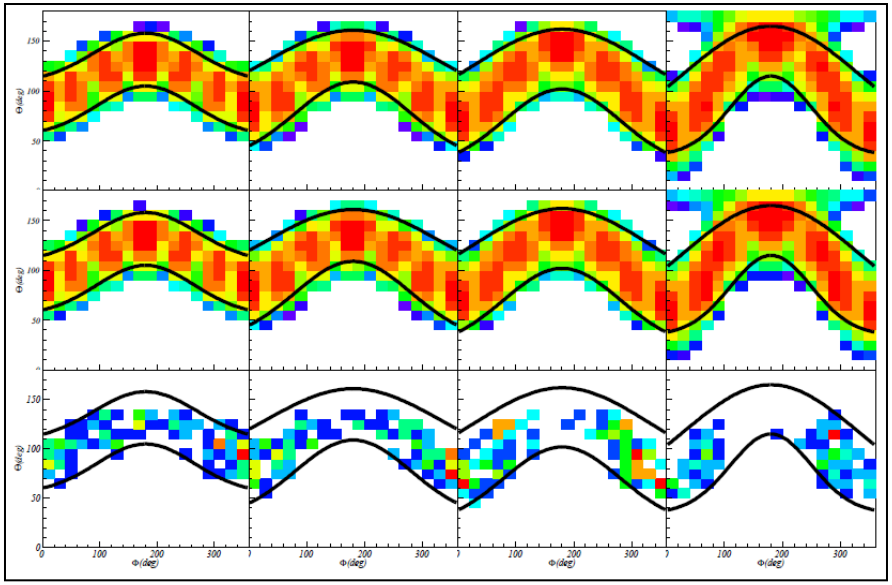


X – is identified as an electron scattered at 0 degrees, $Q^2<0.01$ $(GeV/c)^2$ and $|M_X^2|<0.1$ $(GeV)^2$

CLAS e1-6 and e1f experiments

CLAS/e1-6



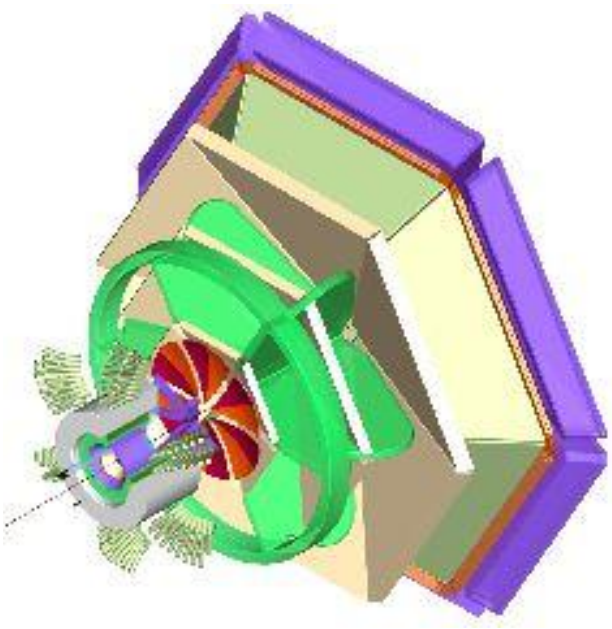


- Several CLAS data sets with 6 GeV electron beams available

- CLAS has good particle identification and resolution, but complicated acceptance
- Comparison with hermetic detector (GLUEX) would be interesting

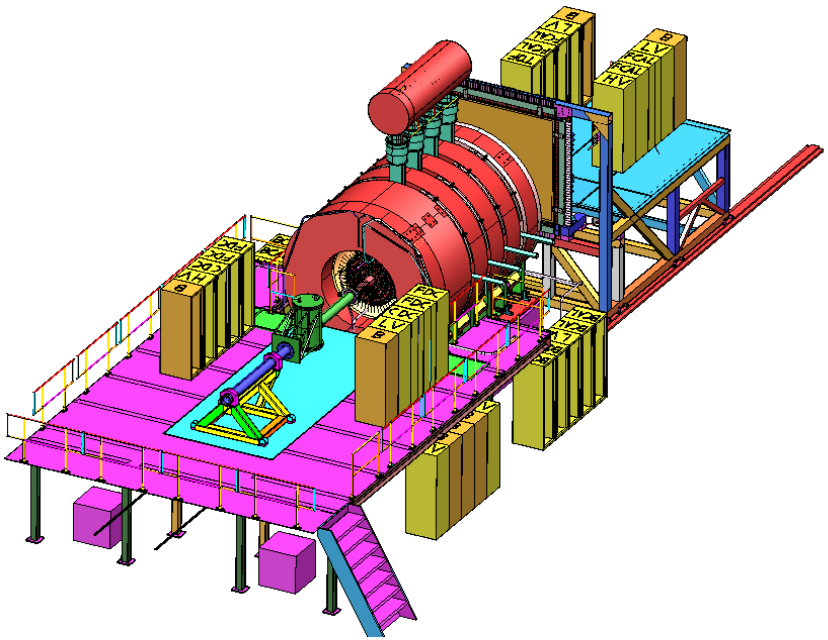
TCS at 12 GeV

CLAS12 in Hall B



- TCS with quasi-real photons
- Circular photon polarization

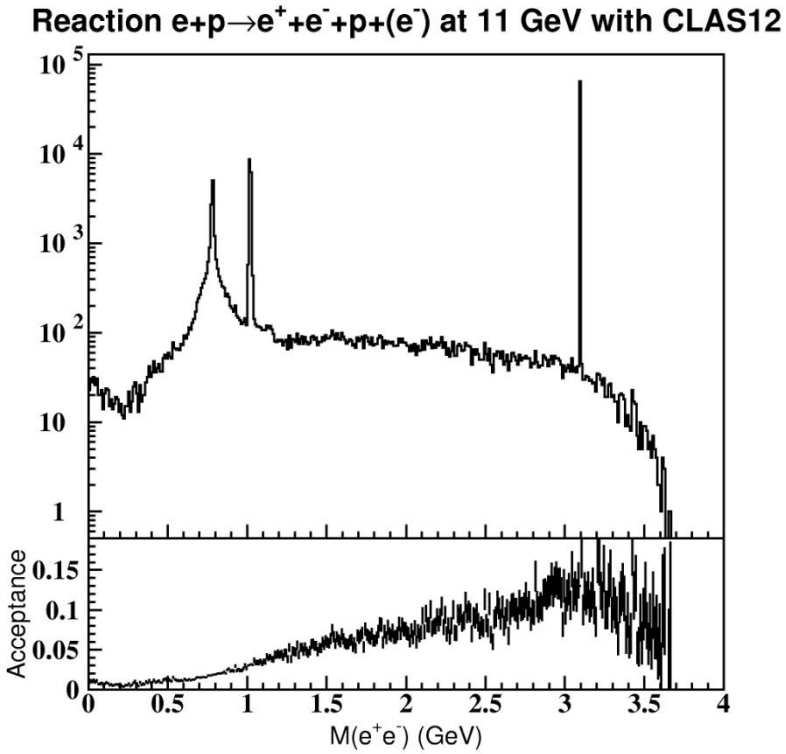
GlueX in Hall D

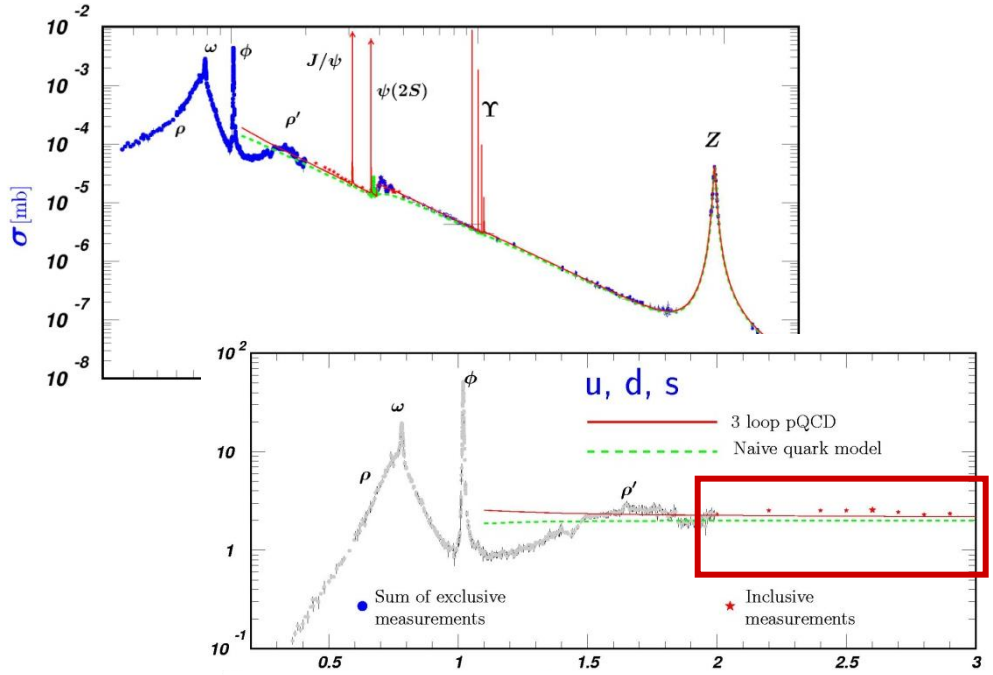


- TCS with tagged real photons
- Linear photon polarization

- Can be run in parallel with other experiments
- Several years of beam time potentially available

Timelike window at 12 GeV



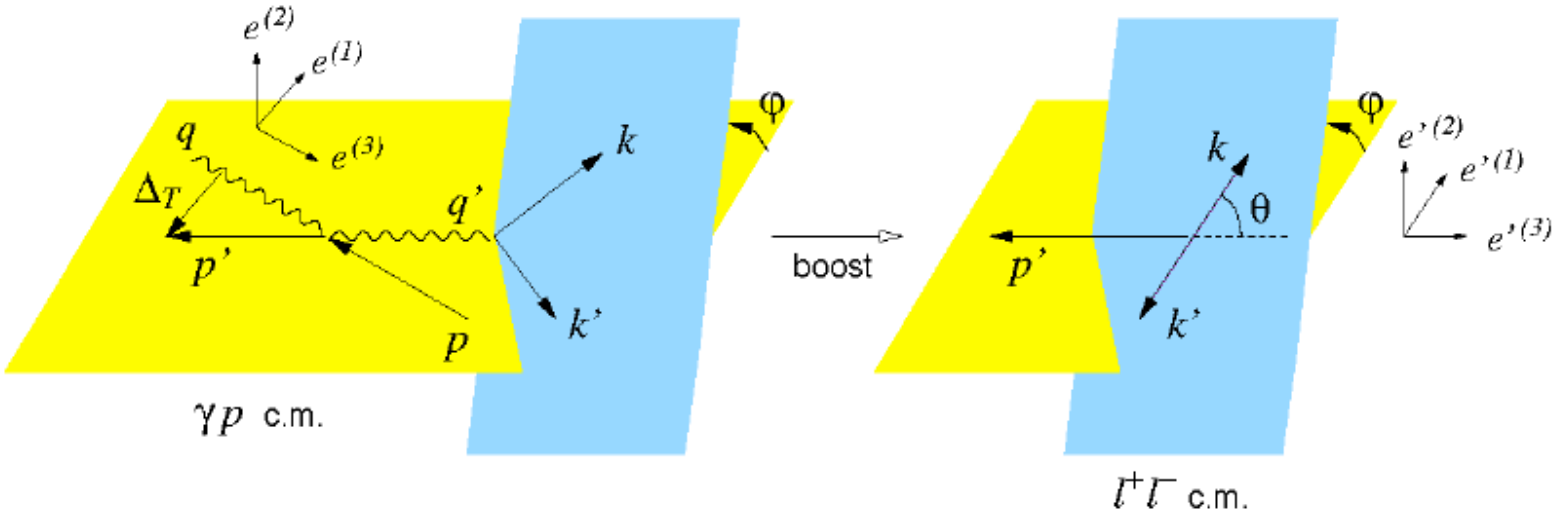


- JLab 12 GeV kinematics are ideally suited for TCS
- Data can be taken in the resonance-free region between ρ' and J/Ψ

Summary

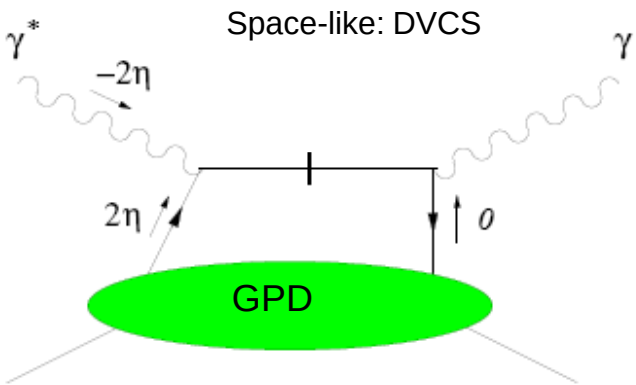
- TCS can be an important part of the JLab DVCS program, providing
  - Real part of amplitude
  - Corrections at finite Q^2
  - Direct comparison with GPD models
- First experiments completed in Hall B at Jefferson Lab
  - g12 with tagged real photons – analysis to begin soon
  - several data sets using electron beams – analysis in progress
- Natural extension to 12 GeV (in two Halls?)
  - Can share several years of beam time with approved experiments

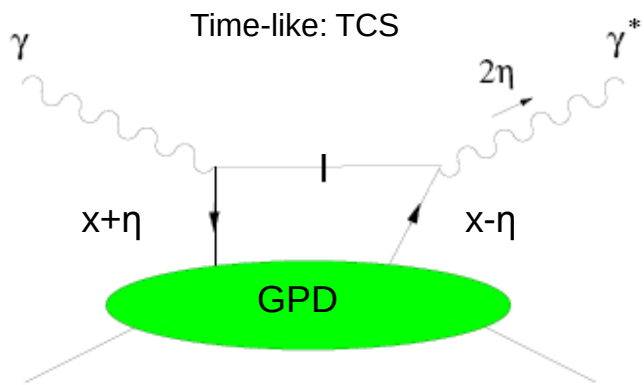
TCS kinematics



- p,p' = momentum of the incoming and scattered proton
- q,q'=momentum of the incoming and scattered photon
- k,k'=momentum of e^-, e^+
- θ = angle between the scattered proton and the electron
- φ = angle between lepton scattering and reaction plane

Factorization Scale in Compton Scattering





$$x_B = \frac{Q^2}{2M_p(E_\gamma - M_p)} \qquad \xi = x_B/(2-x_B)$$

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

$$\gamma^* p \to \gamma p$$

- γ^* has a large spacelike virtuality
- -t is small

$$\gamma p \to \gamma^* p$$

- γ^* has a large timelike virtuality
- -t is small

- Accessing physics contained in GPDs requires hard-soft factorization to apply
- In TCS, the hard scale is given by the mass of the final state photon (Q'^2)
  - experimentally accessed as the invariant mass of the produced lepton pair