Timelike Compton Scattering (TCS) Measurements with Photoproduction in Hall D

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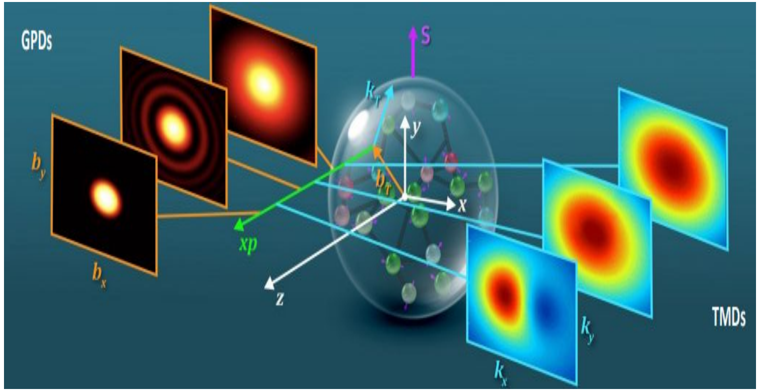
PARTONIC STRUCTURE OF THE HADRONS

Introduction: GPDs

Generalized Parton Distributions (GPDs) play a crucial role in advancing our understanding of the nucleon's internal structure.

They offer a unified framework to access a three-dimensional tomography of the nucleon. GPD($x,\xi=0,t$)

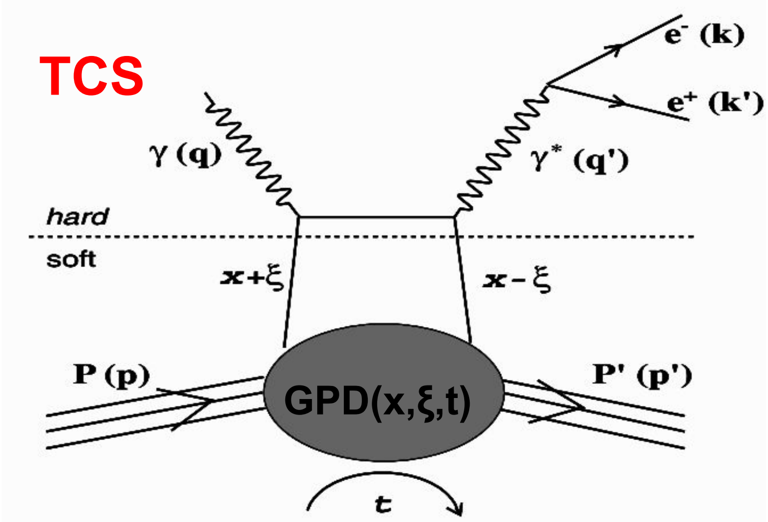


Timelike Compton Scattering (TCS) offers a valuable probe of GPDs.

We plan to measure the:

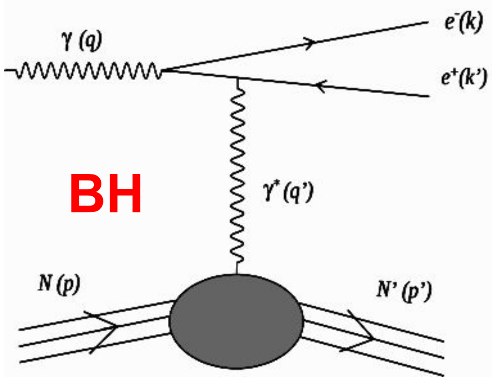
- ❖ Cross sections (1st: unpolarized, 2nd: polarized)
- ❖ The linearly polarized beam to unpolarised target asymmetry (A_lu)
- ❖ The observable C (moments of cross section) gives access to H_tilda

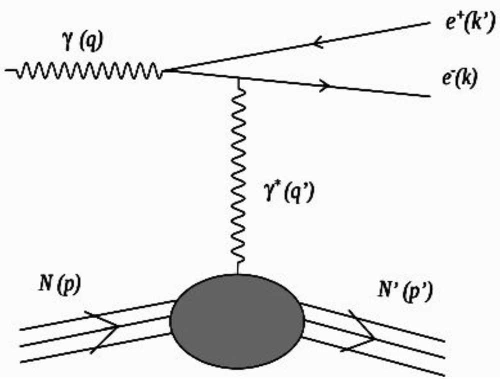
Globally: To produce the tomographic image of the nucleon !!!



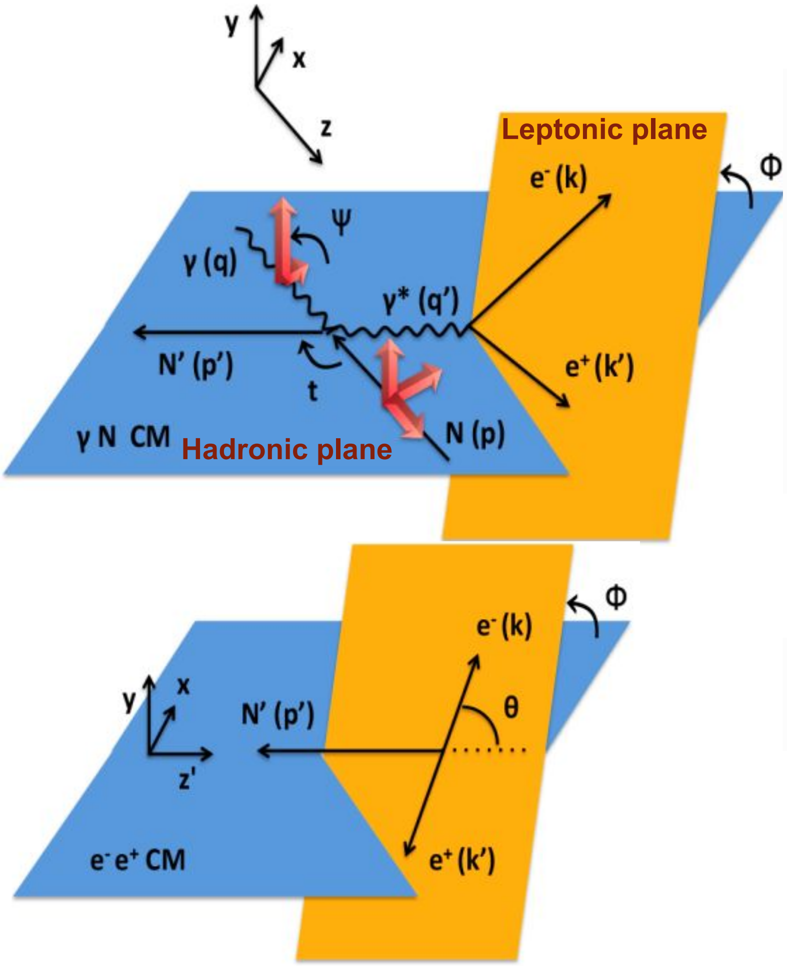
- $\mathrm{P} = \frac{1}{2}(\mathrm{p} + \mathrm{p}')$ — Average proton momentum
- $\Delta = \mathrm{p}' - \mathrm{p} = \mathrm{q} - \mathrm{q}'$ — Momentum transfer
- $\bar{\mathrm{q}} = \frac{1}{2}(\mathrm{q} + \mathrm{q}')$ — Average photon momentum
- $\xi = -\frac{\Delta\cdot\bar{q}}{2\mathrm{P}\cdot\bar{q}} = -\frac{\Delta^+}{2\mathrm{P}+} = \frac{\mathrm{Q}'^2}{2(s-m^2)+\Delta^2-\mathrm{Q}'^2}$ — Skewness:

  Fraction of longitudinal momentum transfer
- $x = \frac{k}{\mathrm{P}}$ — Momentum fraction carried by an active quark





Description of TCS in a frame (Showing kinematics)



- ψ — **Beam polarization angle**

  Angle between polarization vector of beam & hadronic plane.

  For spin asymmetry observables & polarization-dependent σ terms.

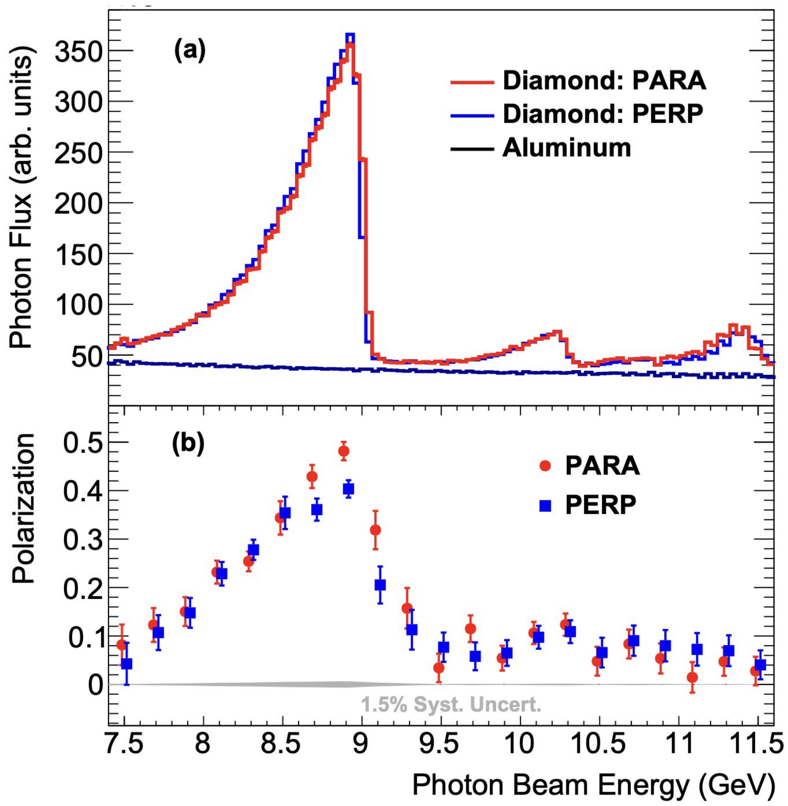
- $\mathbf{t = (p' - p)^2}$ — **Momentum transfer to the Nucleon**
- $\mathbf{Q'^2 = (k + k')^2}$ — **Virtuality of the outgoing Photon**
- ϕ — **Azimuthal angle between Hadronic & Leptonic Planes**

Is sensitive to the interference between TCS & BH

- $\boldsymbol{\theta}$ — **Lepton polar angle in the dilepton rest frame**

  Sensitive to the angular structure of the process.

Description of experiment



We use Linearly Polarized Photons at GlueX in Hall-D of Jefferson Lab.

Mean polarization in the peak range, after collimator: 35% with a 12-GeV incident electron beam.

We use GlueX-I + 30% of GlueX-II data

and

choose the reaction

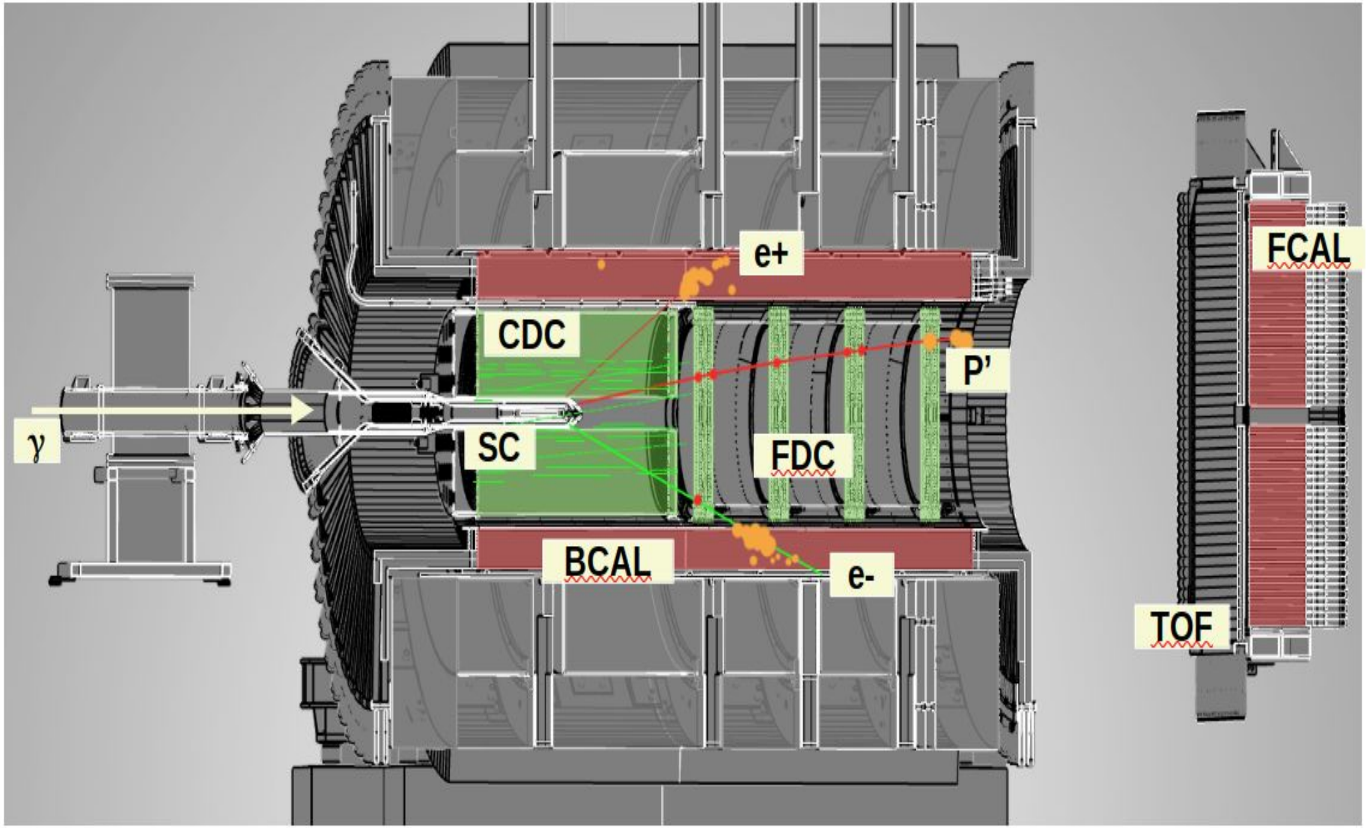
$\gamma p \rightarrow e^+e^-p'$.

The reaction contain contributions from both the dominant BH process and TCS.

The labels PARA and PERP refer to orientations of the diamond radiator that result in polarization planes that are parallel and perpendicular to the horizontal, respectively.

https://arxiv.org/pdf/2005.14272

Description of experiment



We use Linearly Polarized Photons at GlueX in Hall-D of Jefferson Lab.

for the studies.

We use GlueX-I + 30% of GlueX-II data

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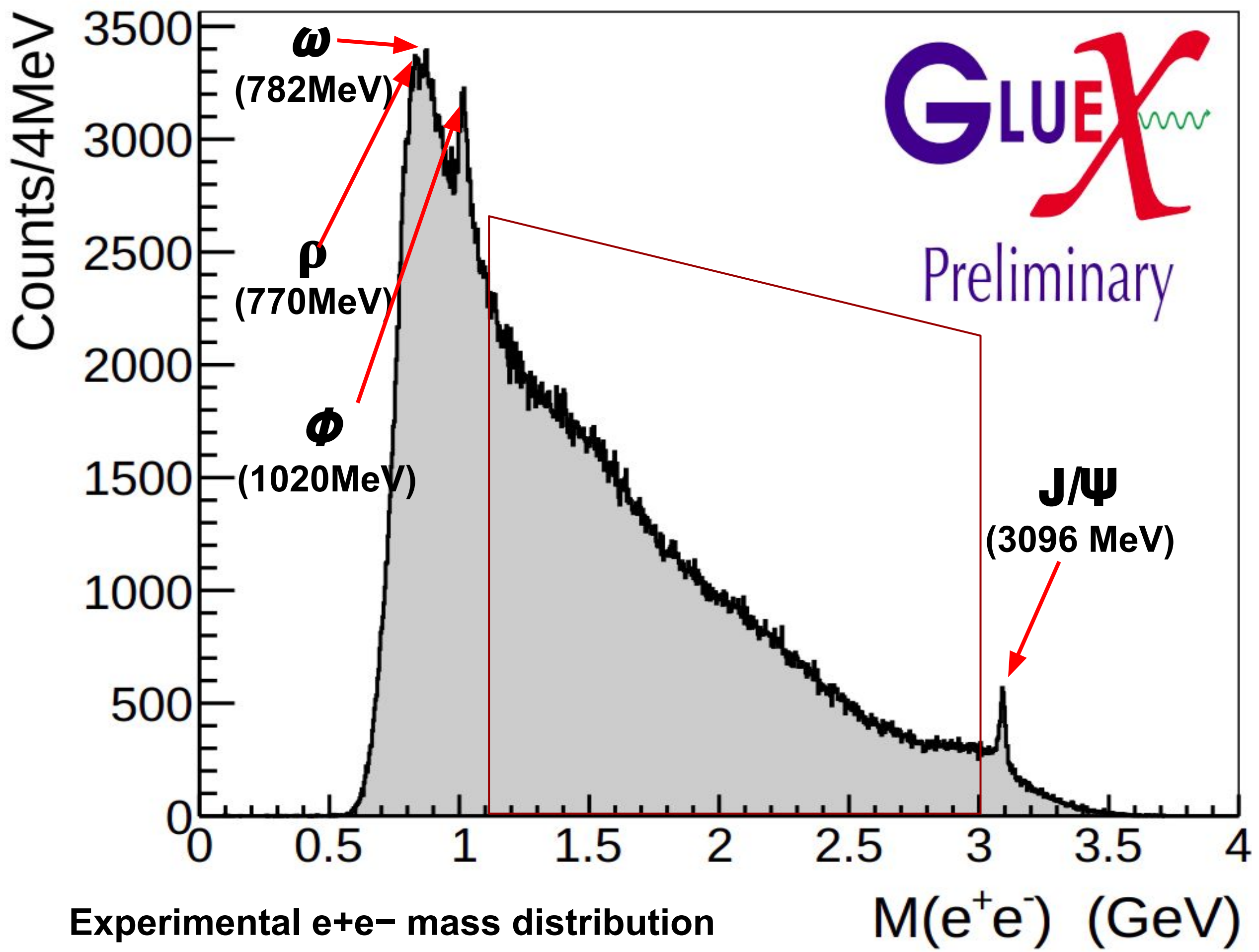
choose the reaction $\gamma p \to e^+e^-p'$.

The reaction contain contributions from both the dominant BH process and TCS.

The basic Gluex detector responses from the selected events.

Exp. M(e+e-) distribution



Experimental e+e− mass distribution

Kinematics:
Energy = [8.2, 11.4] GeV
- Delta t = [0,1.4] GeV^2
< p/E> ± 3*sigma = 1.05,1.074

BH & TCS region:

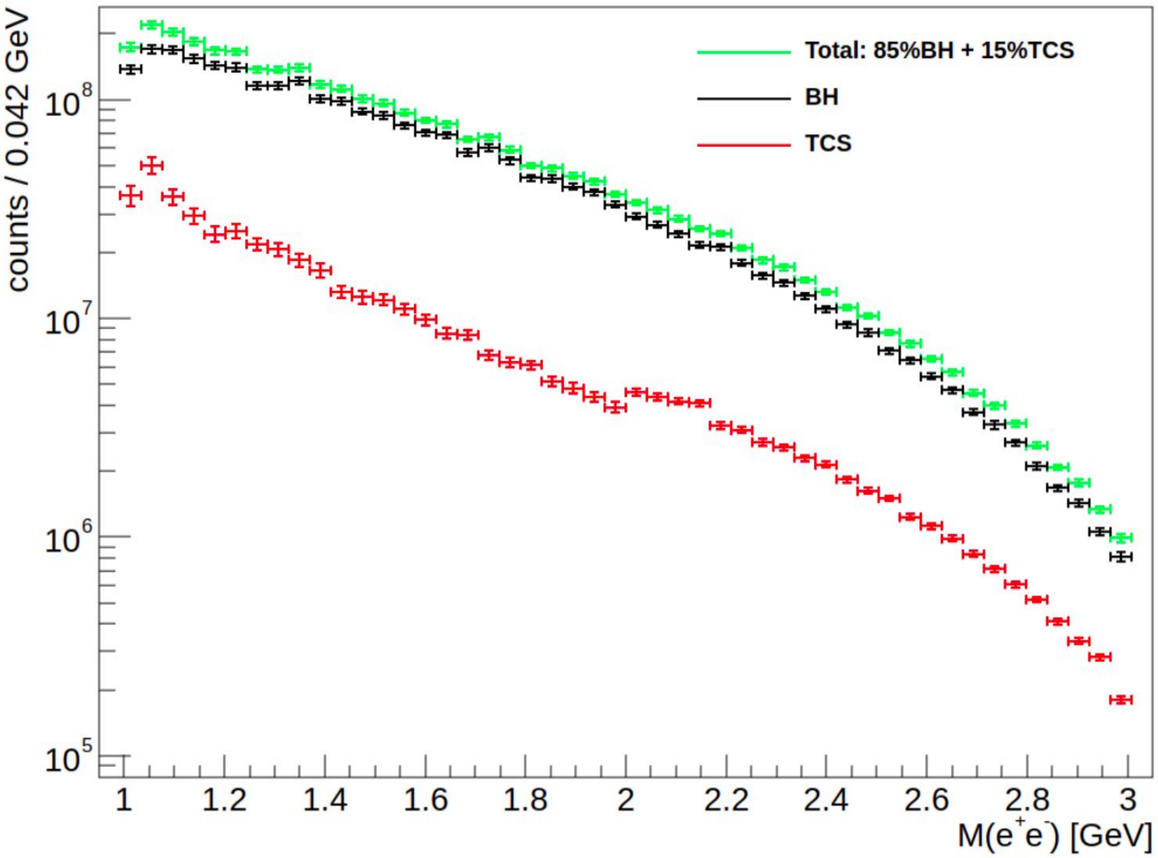
We choose the invariant mass M (e+e−) region of [1.1, 3.0]GeV

Lies away from many meson resonances. It's suitable for studies of GPDs.

Note: Some mesonic contributions still remain: $\rho(1450)$, $\rho(1700)$, & $\pi's$.

About 50% pi+pi- events in this mass distribution.

Simulated M(e+e-) distribution



Simulated e+e− mass distribution. Red, Black and Green points are TCS, BH and Total events respectively

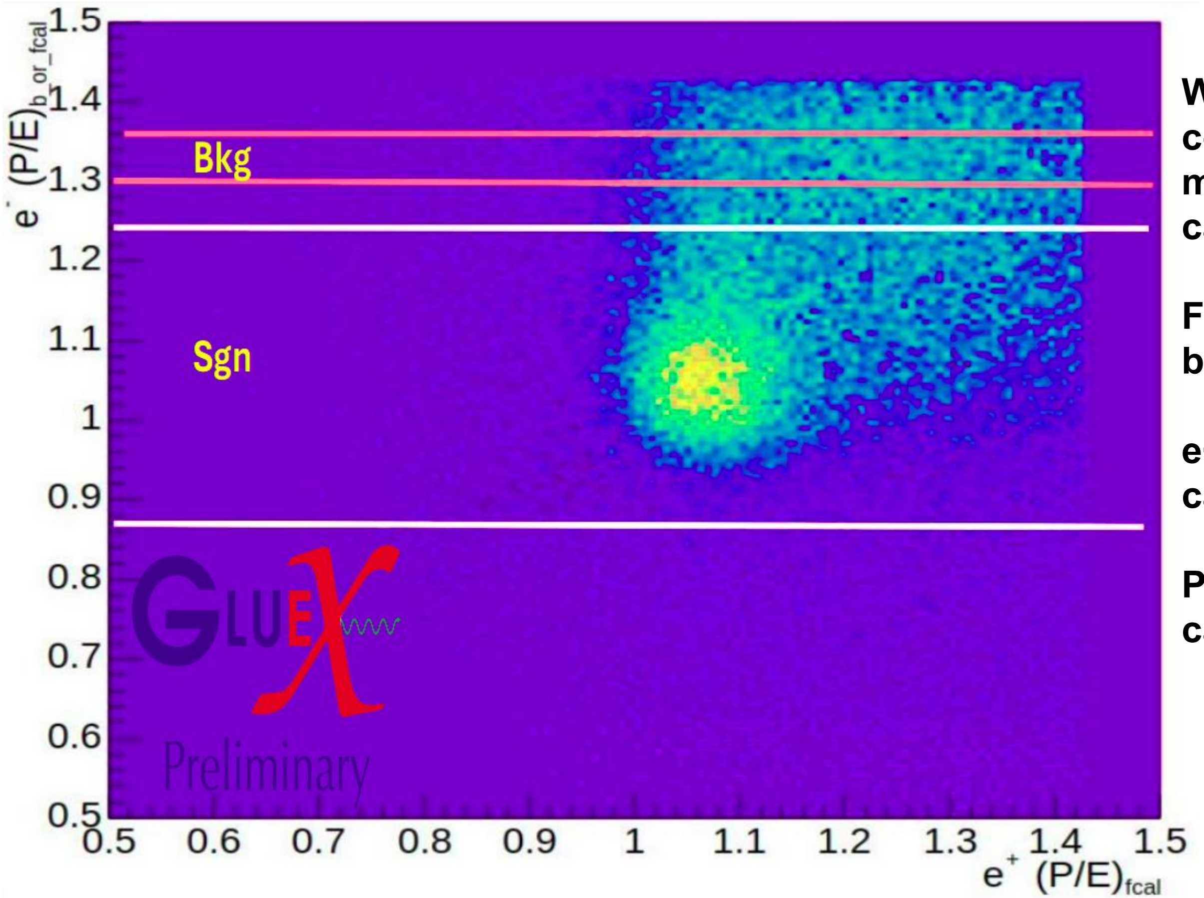
We incorporated a Monte Carlo event generator for generating TCS events in the GlueX simulation software.

We show a sample containing 85% BH and 15% TCS events to demonstrate our event generator

The code is still in development.

The bump around 2.0 GeV is due to the combination of two different TCS regions in the generator (look table).

Subtraction of Pions Background Contribution



We subtract background(Bkg) contributions from Pions using the momentum to energy from calorimeters ratio (P/E) of the leptons.

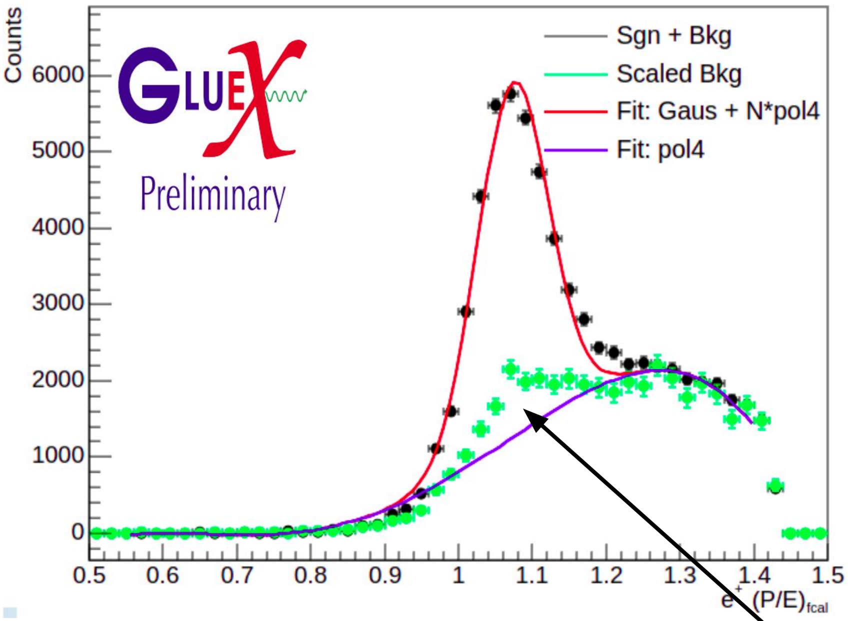
For e+ or e−, this ratio is expected to be ≈ 1 & above ≈ 1.25 are Bkg.

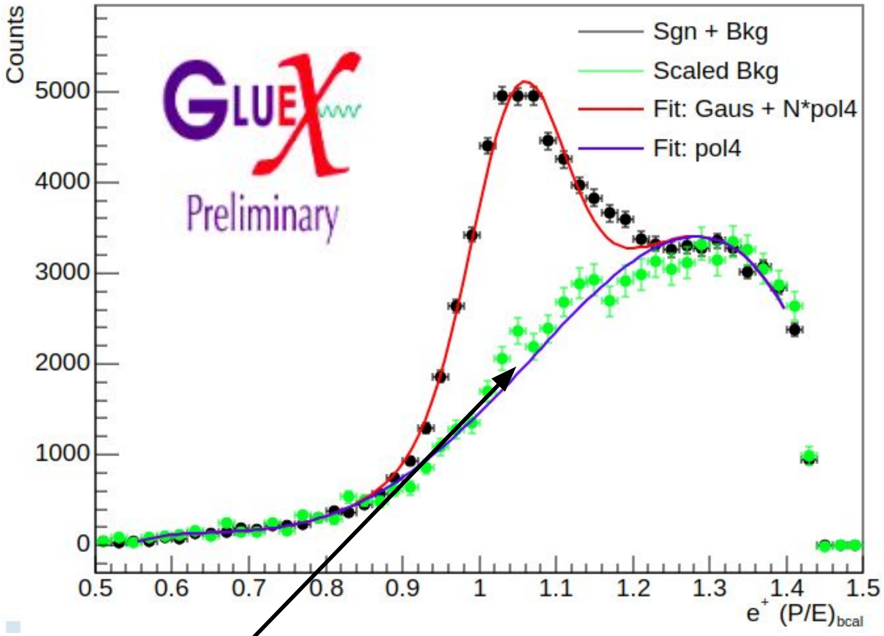
e+,e- deposit all energy in calorimeters.

Pions do not deposit all energy in calorimeters (hadronic shower)

e+ Momentum to Energy (P/E) deposited in FCAL vs e− P/E detected in either BCAL or FCAL

Signal Yield (in FCAL & BCAL) for e+e-





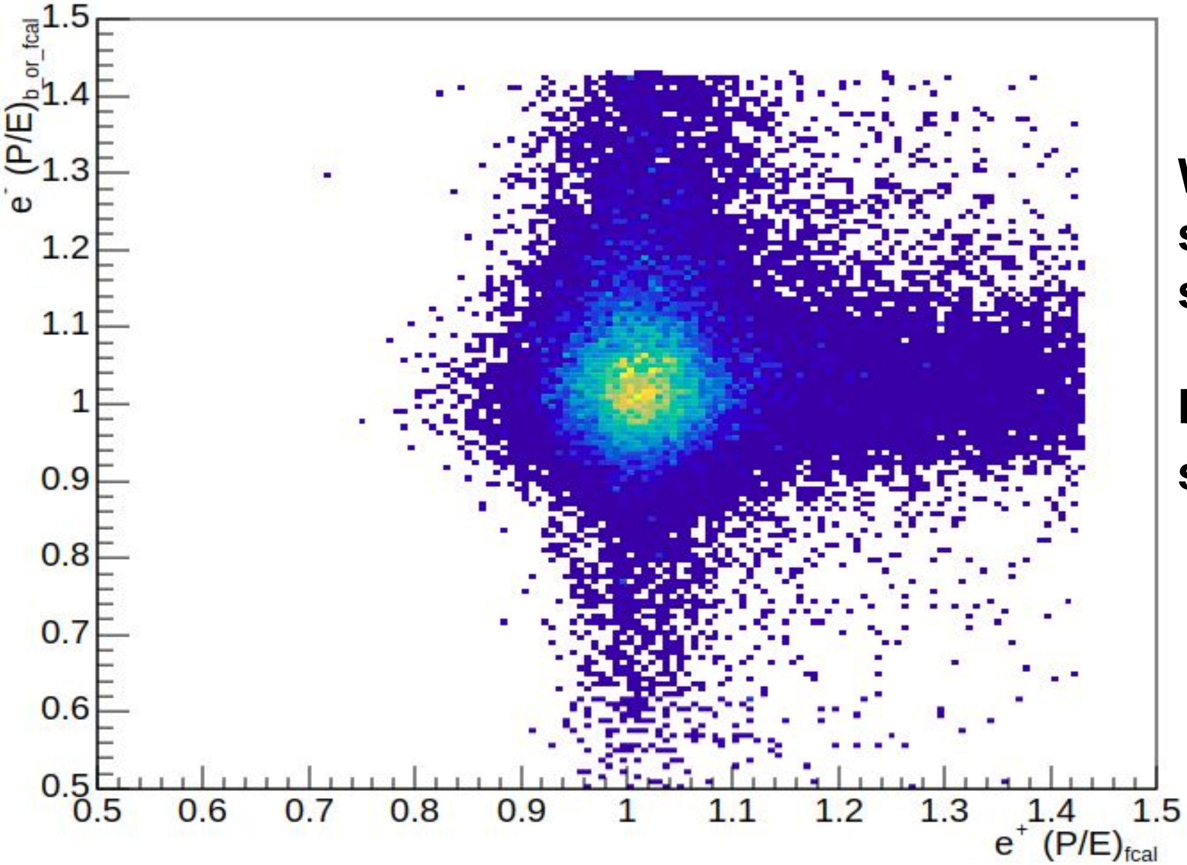
Black points are events within the signal region and green points are estimate of Pions background contribution.

- **The signal + Bkg histogram is subtracted from a scaled Bkg histogram.**

- **A fit of the resulting histogram (signal) is perform with a gaussian and integrated between 3σ to obtain the yield**

- **Signal in bkg shape for FCAL is higher than in BCAL: MC was used to estimate it**

Signal in background histogram (studied with MC)

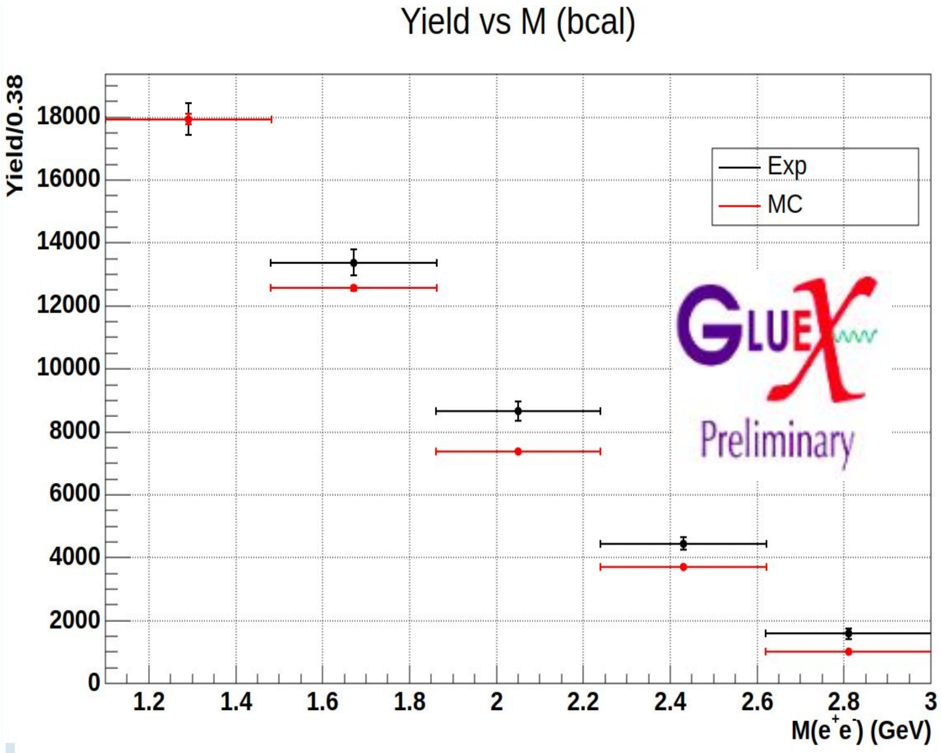


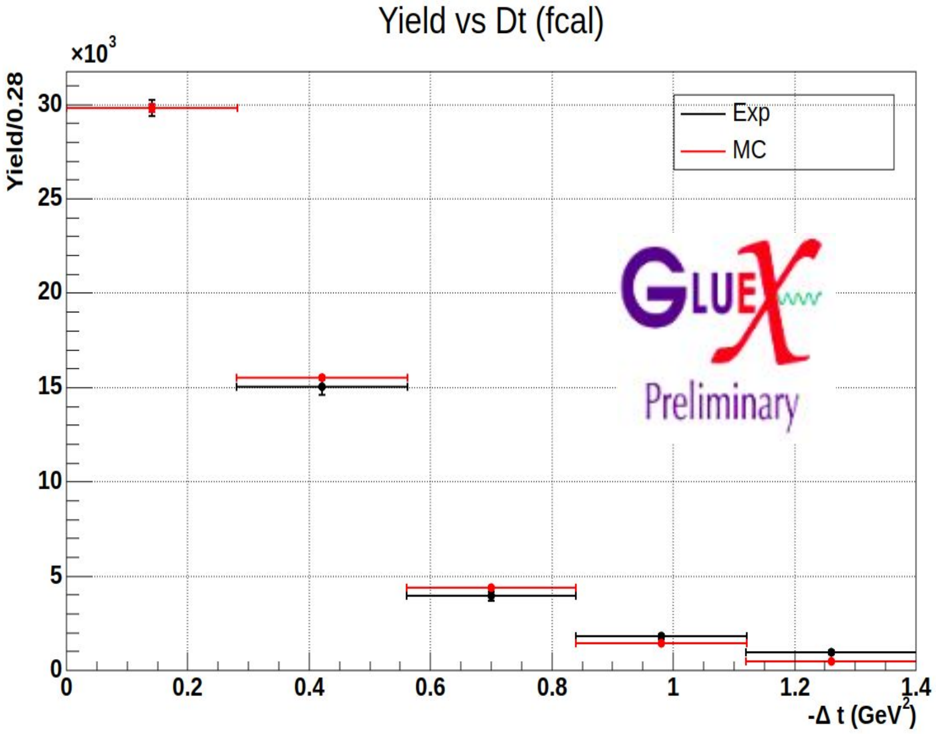
We can see the presence of the signal within the background selected region.

Effect is well-modeled with simulation and taken into account

e+ Momentum to Energy (P/E) deposited in FCAL vs e− P/E detected in either BCAL or FCAL

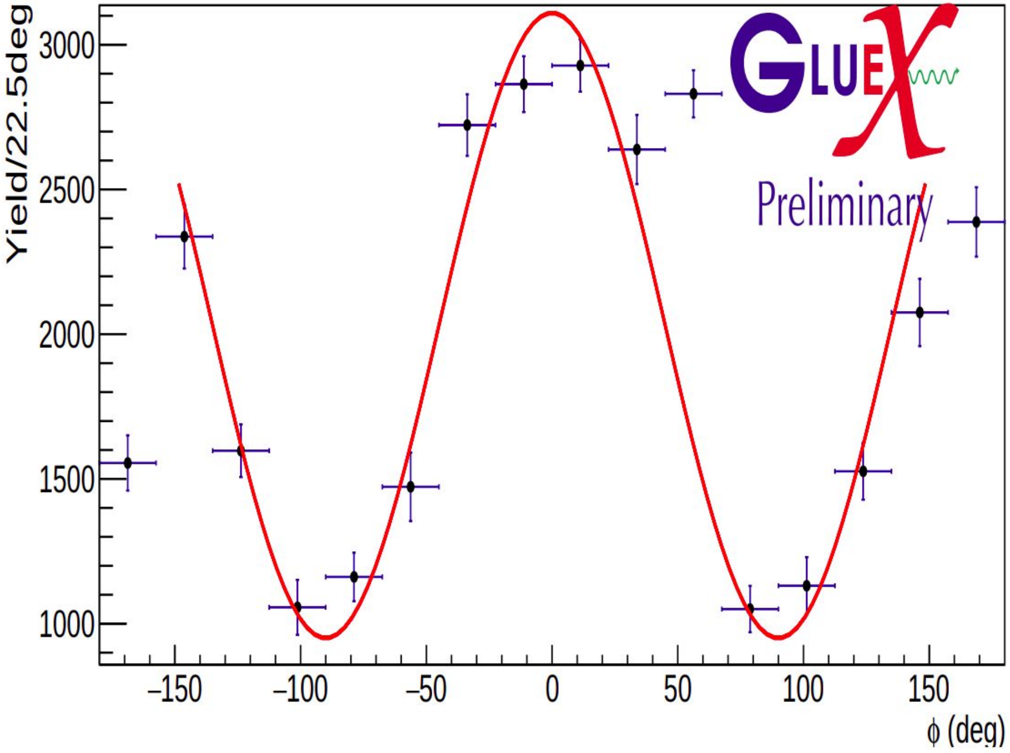
Exp & MC Yield: binned only in M(e+e-), -Dt





Extracted Yield binned in M(e+e-), -Dt : Shows a reasonable good agreement between Exp. data & Norm MC

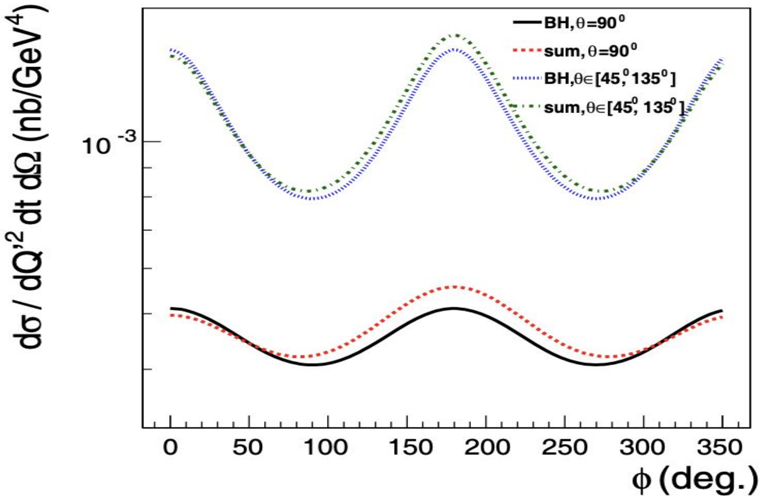
Step towards differential Cross Section



Yield in ϕ bin for obtaining unpolarised differential cross-section
The result shows the periodic behaviour of dσ/dQ′dtd(cosθ)dϕ

We obtained the yield in ϕ bin.
This will be use in obtaining the differential cross section in ϕ.

Events at the edge of acceptance: systematics or fiducial cuts may help to understand what happens. Or it may need to be excluded.

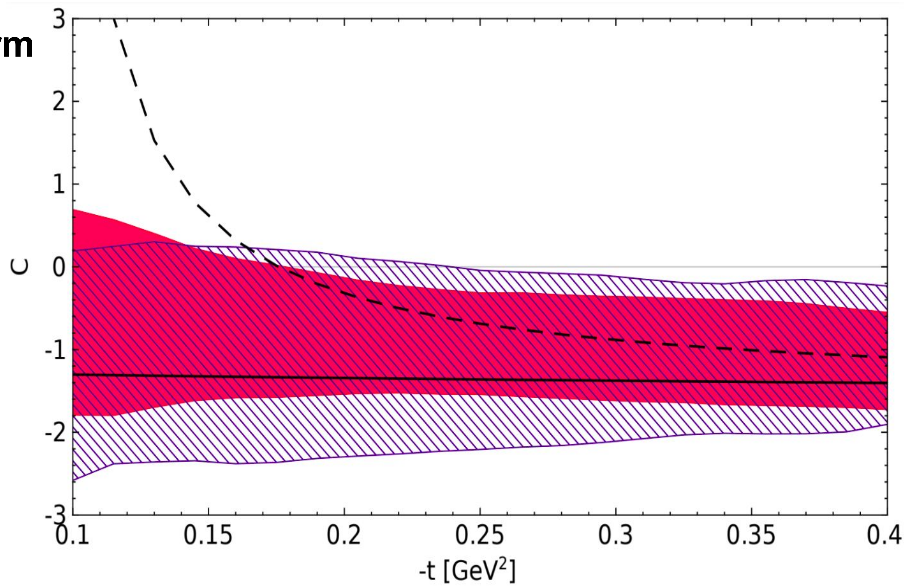


[1] M. Bo¨er, M. Guidal, and M. Vanderhaeghen. Timelike compton scattering off the proton and generalized parton distributions. The European Physical Journal A, 51:103, 2015.

Outlook: TCS Observable sensitive to CFF H-tilda

The observable C is sensitive only to the interference term and provides information on the Compton form factor H-tilda

$$C = \frac{\int_0^{2\pi} d\Phi_h 2\int_0^{2\pi} d\phi \cos(\phi) \int_{\pi/4}^{3\pi/4} \sin\theta d\theta d^5\sigma}{2\int_0^{2\pi} d\Phi_h \cos(2\Phi_h) 2\int_0^{2\pi} d\phi \cos(3\phi) \int_{\pi/4}^{3\pi/4} \sin\theta d\theta d^5\sigma}$$
$$= \frac{2-3\pi}{2+\pi} \frac{\mathrm{Re}\left[\mathscr{H} F_1 - \frac{t}{4M^2}\mathscr{E} F_2 - \xi\widetilde{\mathscr{H}}(F_1+F_2)\right]}{\mathrm{Re}\left[\mathscr{H} F_1 - \frac{t}{4M^2}\mathscr{E} F_2 + \xi\widetilde{\mathscr{H}}(F_1+F_2)\right]}.$$



TCS observable C vs −t. The shaded red (dashed blue) bands correspond to predictions from the global fit of DVCS data presented and are evaluated using LO (NLO) spacelike-to-timelike relations. **The dashed (solid) lines correspond predictions from the GK GPD model evaluated with LO (NLO) TCS coefficient functions.**

The plot shows possible values of C for for TCS with linearly polarized beam [2]. This is a future goal for this analysis.

[2] O. Grocholski, H. Moutarde, B. Pire, P. Sznajder, and J. Wagner. Data-driven study of timelike compton scattering. The European Physical Journal C, 80(2), February 2020.

Summary

We want to measure TCS using e+e- pairs in GlueX.

We have:

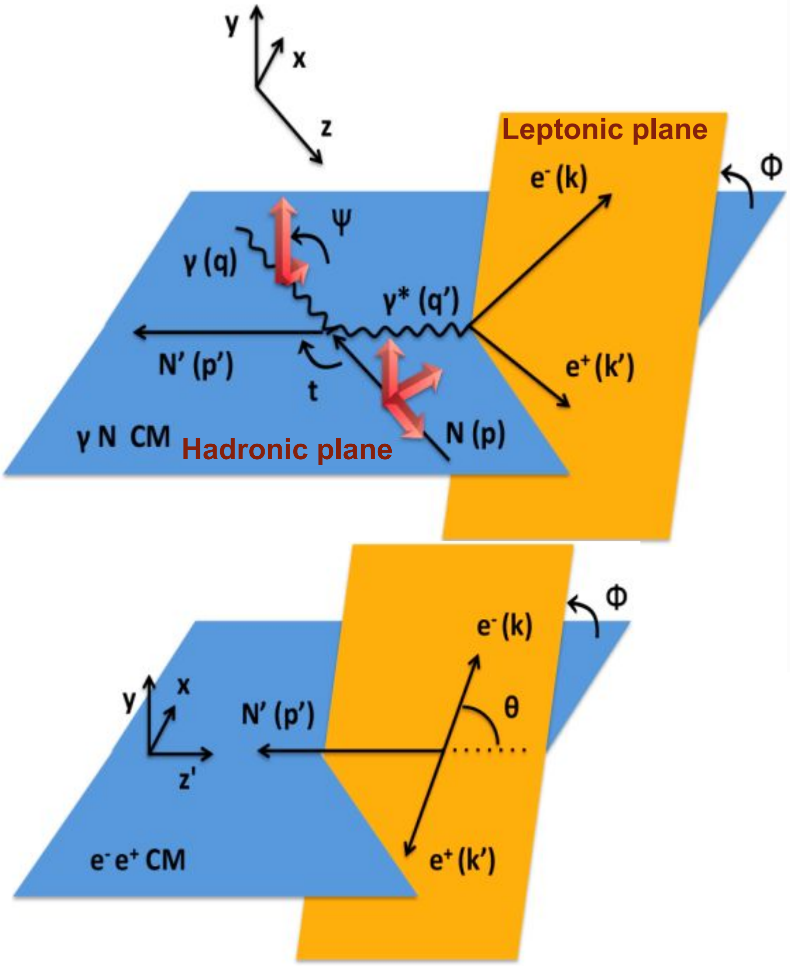
- ❖ Incorporated TCS MC in GlueX Simulation software (with plan to have a single table for the MC)
- ❖ Obtained yields. The Exp. and MC yields were in reasonable good agreement
- ❖ Additional methods (ML) for subtracting the pion background is being look into. This will probably reduce but may not completely eliminate the background

The future plan is to:

- ❖ 1st obtain the unpolarized cross section to identify TCS
- ❖ Then obtain the polarized cross section (more Challenging)
- ❖ Then obtain the observable C

Thanks for your attention!!!
https://gluex.org/thanks/

Description of TCS in a frame (Showing kinematics)



- ψ — **Beam polarization angle**

  Angle between polarization vector of beam & hadronic plane.

  For spin asymmetry observables & polarization-dependent σ terms.

- $\mathbf{t = (p' - p)^2}$ — **Momentum transfer to the Nucleon**

- $\mathbf{Q'^2 = (k + k')^2}$ — **Virtuality of the outgoing Photon**

- ϕ — **Azimuthal angle between Hadronic & Leptonic Planes**

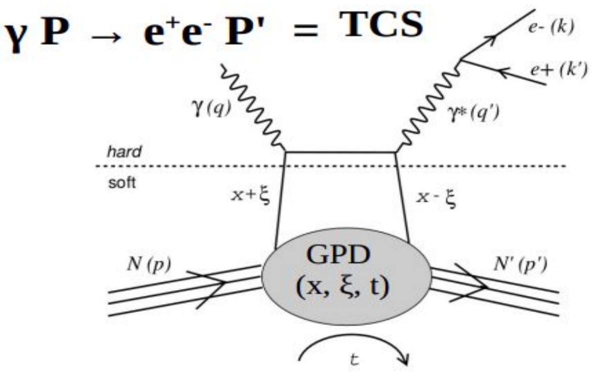
  Governs the interference between the TCS & BH processes.

  Angular modulations of the cross section.

- θ — **Lepton polar angle in the dilepton rest frame**

  Sensitive to the angular structure of the process.

$$A_{lU}(\Psi) = \frac{\sigma(\Psi) - \sigma(\Psi + \pi/2)}{\sigma(\Psi) + \sigma(\Psi + \pi/2)}$$



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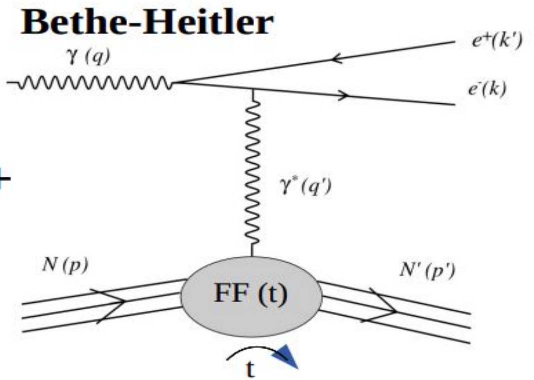
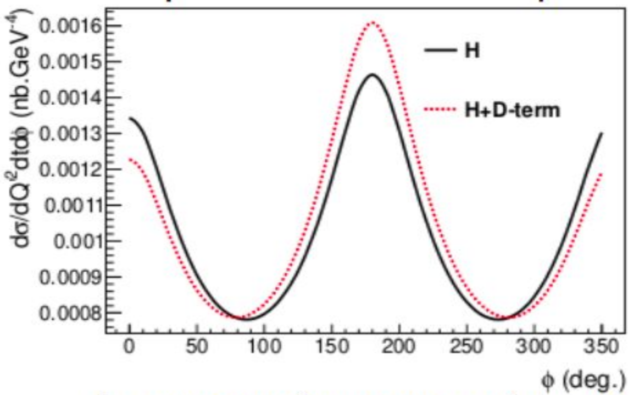
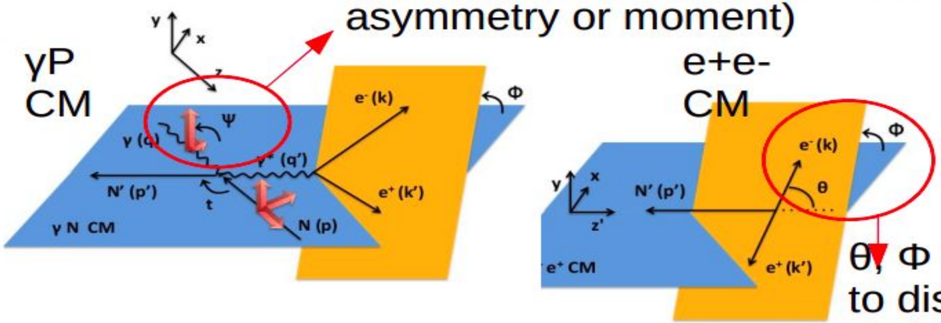


unpolarized x-sec vs φ

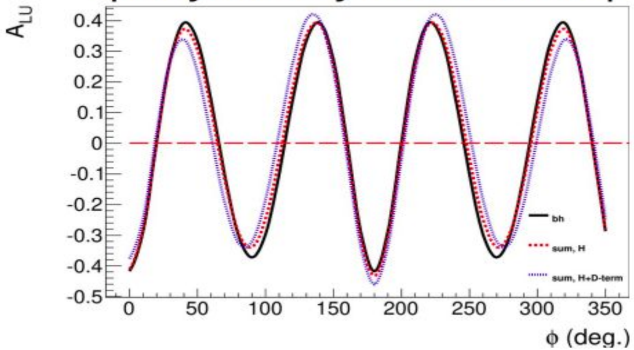


ψ angle photon polarization (taking asymmetry or moment)



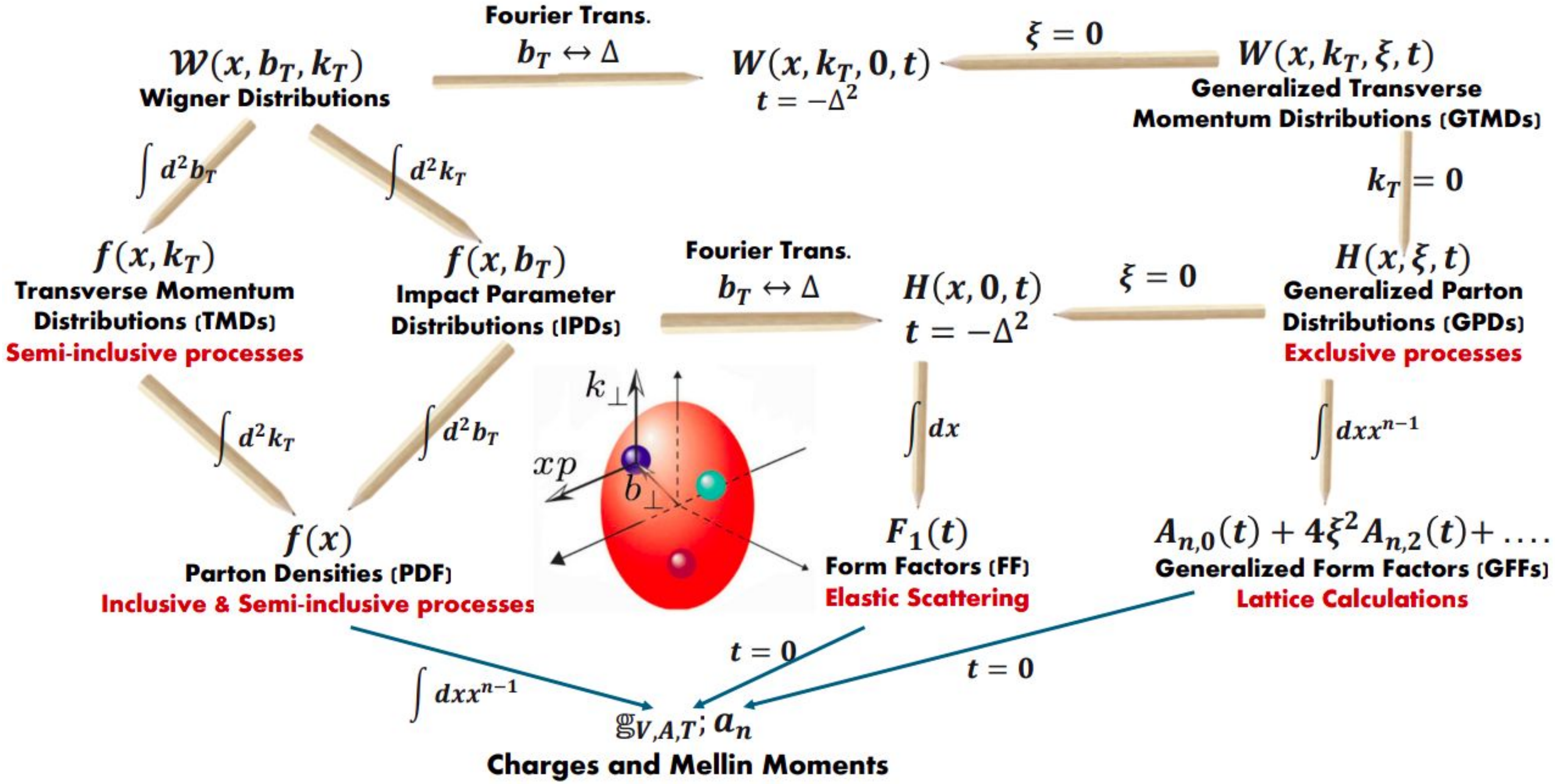
θ, Φ decay used to disentagle BH and TCS

ψ asymmetry moment vs φ



Goal: photon's polarization asymmetries, sensitive to real part of amplitude (CFFs) and D-term

Objects in Hadron structure & reactions to access

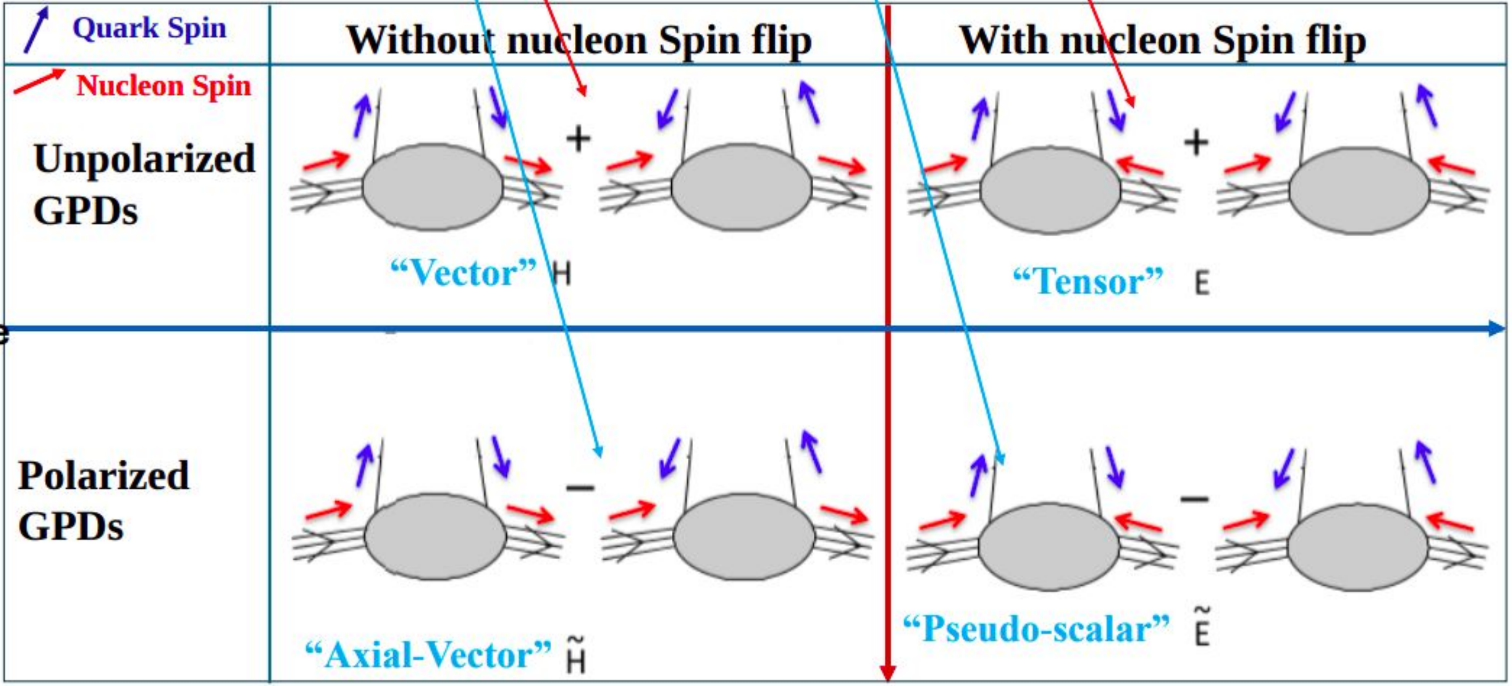


Backup: Ji decomposition of GPDs

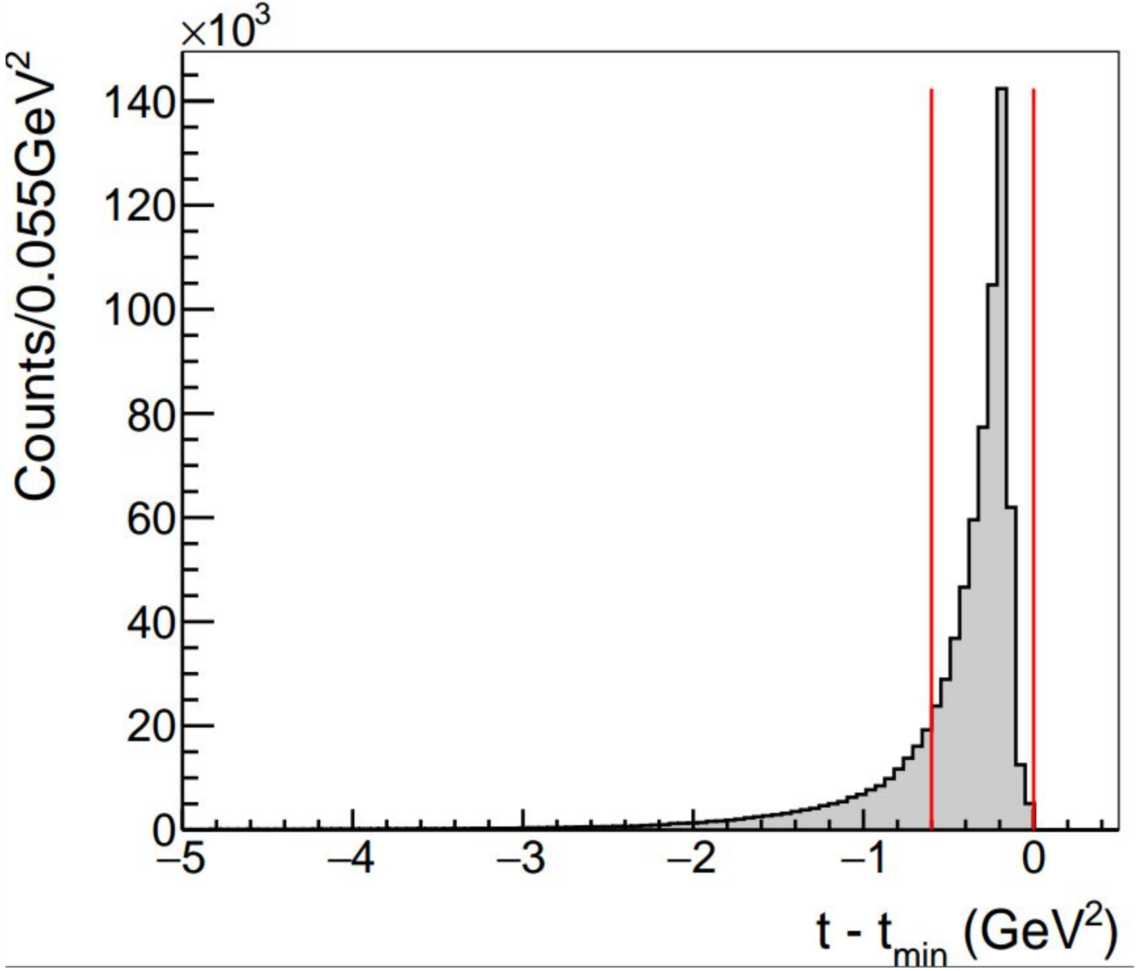
$$H^{\mu\nu} = \frac{1}{2}\left(-g_{\mu\nu}\right)_{\perp} \int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} + \frac{1}{x+\xi+i\epsilon}\right)\left(H(x,\xi,t)\bar{u}(p')\gamma^{\alpha} n_{\alpha} u(p) + E(x,\xi,t)\bar{u}(p') i\sigma^{\alpha\beta} n_{\alpha} \frac{\Delta_{\beta}}{2m} u(p)\right)$$

$$-\frac{i}{2}\left(\epsilon_{\nu\mu}\right)_{\perp} \int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right)\left(\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^{\alpha} n_{\alpha}\gamma_{5} u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\gamma_{5} \frac{\Delta.n}{2m} u(p)\right)$$

Note:
The blue part of the equation is the
Quark loop part
&
The black part is the
Nucleon structure



Forward Scattering Selection (Hard Scale)



The limit $-t \to 0$ corresponds to **forward scattering**:
Virtual & incident photon proceeds in thesame direction.

Hard scale of TCS must satisfy the conditions:
$Q'^2 \gg m_p$ and $Q'^2 \gg -t$
for the GPD factorization to hold.

As $-t$ increases, the **validity of the factorization** & **leading-twist approximations** diminishes.

$$t - t_{\min} = 2 \cdot |\vec{p}| \cdot |\vec{p}'| \cdot (\cos\theta - 1)$$

t_{min} occurs at $\theta = 0$.

$\vec{p}, \vec{p}'$: target & detected protons' momentum 3-vectors

$$-0.6\ GeV^2 \leq t - t_{\min} \leq 0$$