

Double DVCS with CLAS12 in Hall-B

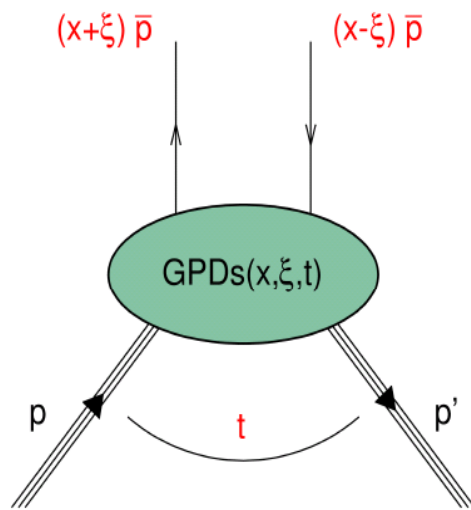
22 GeV upgrade physics discussions

Questions to address

- What fundamental property of nature are we exploring? What hypothesis are we testing?
 - Nucleon tomography using GPD framework
 - Issues with the extraction of GPDs from DVCS and TCS observables
- What is being measured, and how precisely can it be measured?
 - Accessing GPD variable x with DDVCS
 - μ CLAS12 for operations @ $L > 10^{37} cm^{-2} sec^{-1}$
 - Experimental projections
- Why are 22 GeV electrons necessary to make the measurement?
 - Accessing space-like regime for time-like virtualities in pQCD region, above meson resonances, $M_U > 2$ GeV

GPD framework

- GPDs, accessible in hard exclusive reactions (DVCS, TCS, DVMP), describe the correlation of quark/antiquark transverse spatial and longitudinal momentum, the quark angular momentum distributions.
- They exhibit interesting properties, such as *polynomiality*, and are subject to several constraints:



At leading-twist, there are four chiral-even (parton helicity-conserving) GPDs:

$$H^q; E^q; \tilde{H}^q; \tilde{E}^q$$

- in the forward limit ($\xi \rightarrow 0, t \rightarrow 0$) H and \tilde{H} GPD reduce to quark, anti-quark, and gluon PDFs

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

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

- and the first moments of quark GPDs are related to the Dirac, Pauli, axial, and pseudoscalar form factors

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t) \quad \int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$

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

GPDs and the form factors of the QCD EMT



The QCD energy-momentum tensor (EMT) of the nucleon:

$$\langle p', s' | \hat{T}_{\mu\nu}^a(x) | p, s \rangle = \bar{u}' \left[A^a(t) \frac{\gamma_{\{\mu} P_{\nu\}}}{2} + B^a(t) \frac{i P_{\{\mu} \sigma_{\nu\}} \rho \Delta^\rho}{4m} + D^a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m} + m \bar{c}^a(t) g_{\mu\nu} \right] u$$

Mellin moments of GPDs linked to the EMT FF -

$$\int_{-1}^1 dx \, x \mathbf{H}^a(\mathbf{x}, \xi, t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^1 dx \, x \mathbf{E}^a(\mathbf{x}, \xi, t) = B^a(t) - \xi^2 D^a(t)$$

and the nucleon spin -

$$\mathbf{J}_q = \frac{1}{2} \sum_q [A^a(0) + B^a(0)]$$

$$= \frac{1}{2} \sum_a \int_{-1}^1 dx \, x (H^a(x, \xi, 0) + E^a(x, \xi, 0))$$

Ji, Phys. Rev. Lett 77 / Phys. Rev. D 55, 1997.

The $D^a(t)$, or D -term (*M. Polyakov, C. Weiss, Phys. Rev. D 60, 114017*), characterizes the distribution of the shear forces, $s(r)$, and the pressure, $p(r)$, inside the nucleon:

$$\text{Re}\mathcal{H}(\xi, t) = D(t) + \mathcal{P} \int_{-1}^1 dx \left(\frac{1}{\xi - 1} - \frac{1}{\xi + 1} \right) \text{Im}\mathcal{H}(\xi, t)$$

V. Burkert et al. REVIEWS OF MODERN PHYSICS, VOLUME 95, OCTOBER–DECEMBER 2023.

From experimental observables to GPDs

- The experimental observables, for example, asymmetries and cross sections in DVCS/TCS, are parametrized by complex-valued CFF.

$$\mathcal{T}_{DVCS/TCS} \sim \mathcal{F}(\xi, t)$$

- The CFFs are expressed as convolutions of complex-valued hard-scattering coefficient functions with the real-valued GPDs.

$$\text{Im}\mathcal{F}(\xi, t) = i\pi \sum_a [F^a(\xi, \xi, t) - F^a(-\xi, \xi, t)]$$

$$\text{Re}\mathcal{F}(\xi, t) = P \int_{-1}^1 dx \left(\frac{1}{\xi - x} \pm \frac{1}{\xi + x} \right) \sum_a [F^a(x, \xi, t) \mp F^a(-x, \xi, t)]$$

- Therefore, extracting information on GPDs from experimental observables is not straightforward and is a two-step process.
- And of course, the different flavor (gluon and quark) contributions must be separated – another topic of conversation.

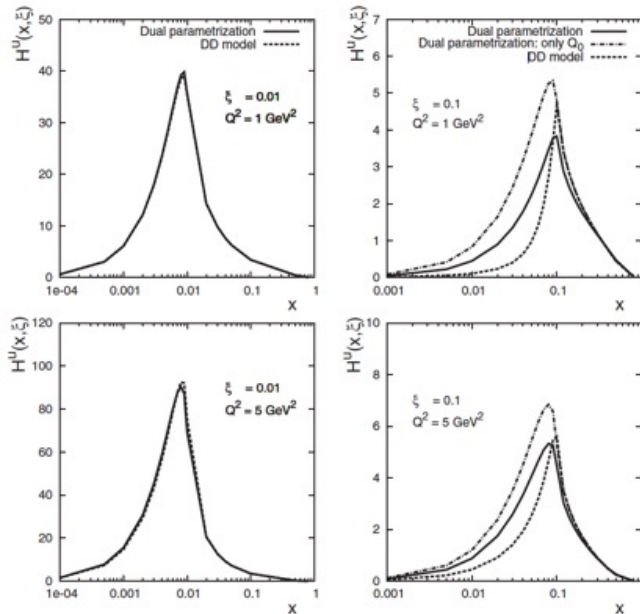
GPDs from experimental data – two step process



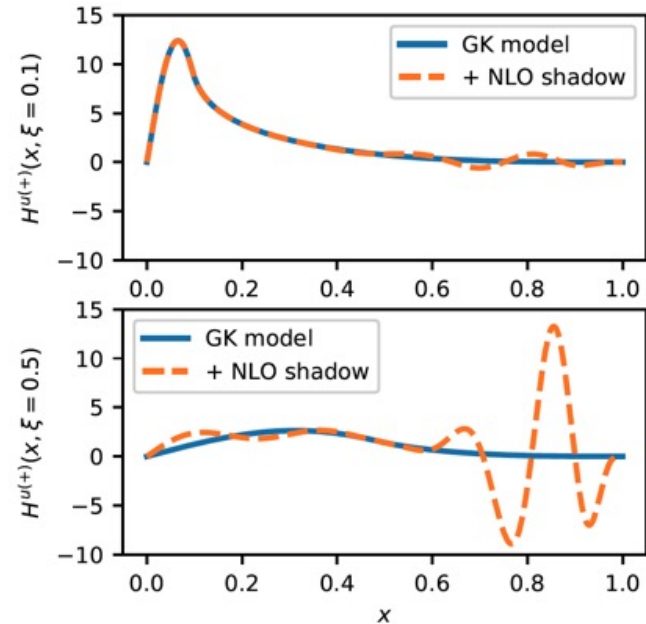
- Step one of accessing GPDs from experimental measurements is extracting CFFs from observables (asymmetries, cross sections). Several methods, at the leading twist, exist. (See e.g. *H. Moutarde, P. Sznajder, and J. Wagner, Eur. Phys. J. C 79, 614 (2019)*. *M. Čuić, K. Kumerički, and A. Schäfer, Phys. Rev. Lett. 125, 232005 (2020)*.)
- The second step, inferring information on GPDs from CFFs, is challenging. One of the GPD variables, the average longitudinal light-front momentum fraction of the active parton x , is integrated out of the CFFs.
- There is no unique solution in going from CFFs to GPDs. Various GPD functions can explain experimental data at different scales, adding to the field's complexity.
- Filtering through various GPD models and parameters will also be limited by experimental uncertainties.

Models of GPDs and SGPDs

- Moreover, recent studies of deconvolution have revealed the existence of a class of functions, shadow GPDs (SGPD) with a null CFF and a null forward limit at a given scale μ^2 , that will contribute to solutions in the GPD extraction.



V. Guzey and T. Teckentrup, *Phys. Rev. D* 74, 054027 (2006)



V. Bertone, H. Dutriex, C. Mezrag, H. Moutarde, and P. Sznajder, *Phys. Rev. D* 103, 114019 (2021)

- While the QCD evolution of GPDs in ξ and Q^2 can be used to exclude a large class of SGPDs, processes directly sensitive to the x dependence of GPDs is the only direct way to challenge the problem experimentally.

Closing the loop on virtual Compton scattering

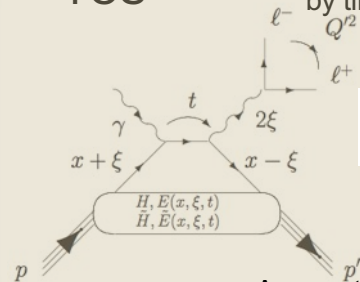


JLAB Flagship program – accessing GPDs through measurements of beam/target asymmetries and the cross sections of Compton processes (TCS and DVCS)

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

TCS

Hard scale is defined by time-like photons



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

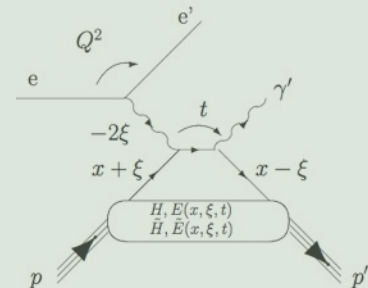
$$\text{Im } \mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t)$$

Access to the Re-part of the Compton amplitude

Started in 2001, PRL 87, 182002. Now is the flagship physics program

Hard scale is defined by space-like photon

DVCS

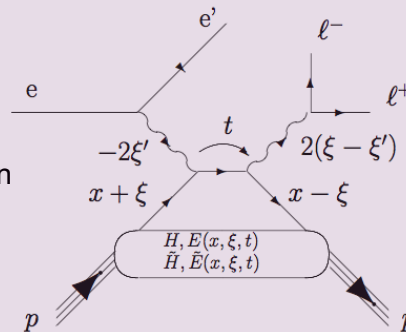


Jefferson Lab at the luminosity frontier is the only place in the world DDVCS can be measured!

μ CLAS12 in Hall B and SoLID in Hall A are the two proposed facilities capable of carrying out such measurements.

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

CFFs and GPDs in Virtual Compton Scattering

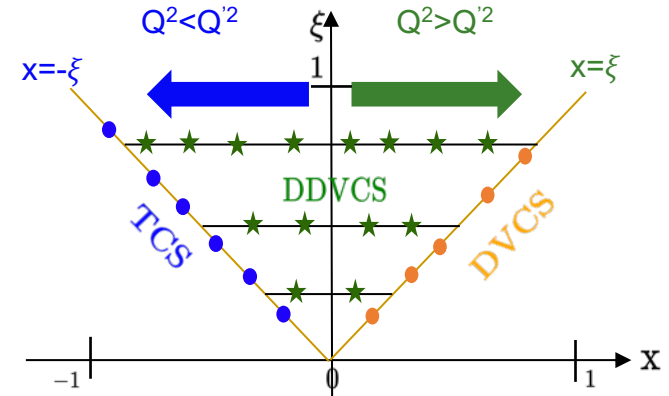


$$\mathcal{T}_{DVCS} \sim \text{CFF} \mathcal{H}(\xi, t) \propto i\pi [H(\xi, \xi, t) - H(\xi, \xi, t)] + \quad (\text{the same for TCS})$$

$$P \int_{-1}^{+1} dx \left(\frac{1}{x-\xi} \pm \frac{1}{x+\xi} \right) [H(x, \xi, t) \mp H(x, \xi, t)]$$

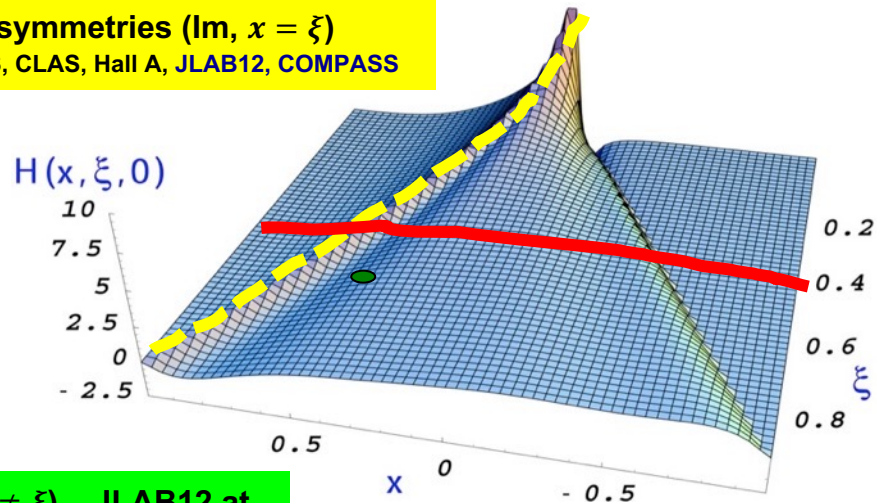
$$\mathcal{T}_{DDVCS} \sim \text{CFF} \mathcal{H}(\xi, \xi', t) \propto i\pi [H(2\xi' - \xi, \xi, t) - H(-2\xi' + \xi, \xi, t)] +$$

$$P \int_{-1}^{+1} dx \left(\frac{1}{x-(2\xi'-\xi)} \pm \frac{1}{x+(2\xi'-\xi)} \right) [H(x, \xi, t) \mp H(x, \xi, t)]$$



Spin asymmetries (Im, $x = \xi$)

HERMES, CLAS, Hall A, JLAB12, COMPASS



Angular asymmetry in TCS (|Re|)
JLAB12

Charge asymmetry in DVCS (|Re|)
HERMES, COMPASS, JLAB12

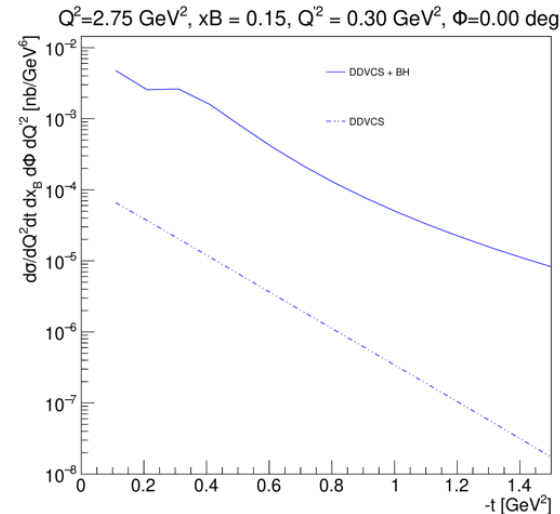
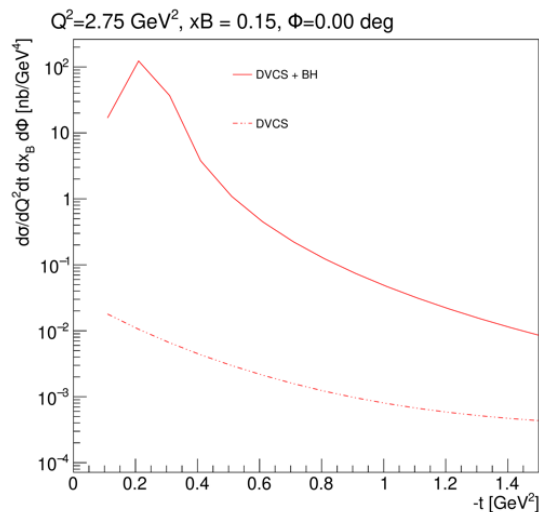
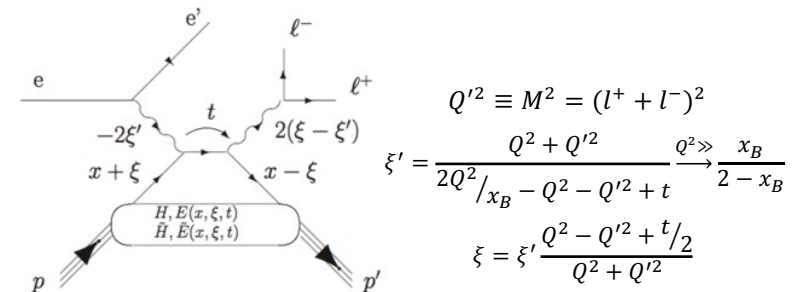
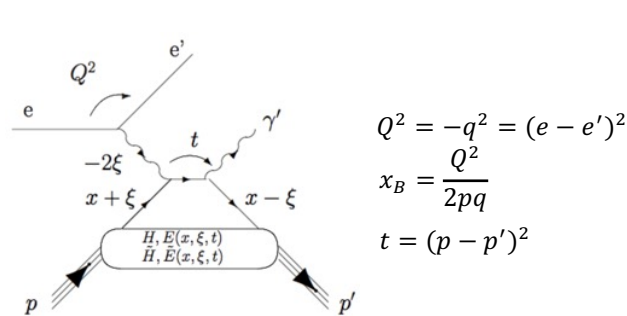
DVCS Cross sections (|Re|²)
H1, Hall A, JLAB12, COMPASS

DDVCS (Im, $x \neq \xi$) – JLAB12 at
 $L \geq 10^{37} \text{ cm}^{-2} \text{ sec}^{-1}$

Re part of CFFs provides a direct measurement of the D-term and access to the mechanical properties of the proton

Challenges to measure DDVCS

- The cross section is three orders of magnitude smaller than that of DVCS.
- Ambiguities and anti-symmetrization issues with the decay leptons of the outgoing virtual photon and the incoming-scattered lepton.



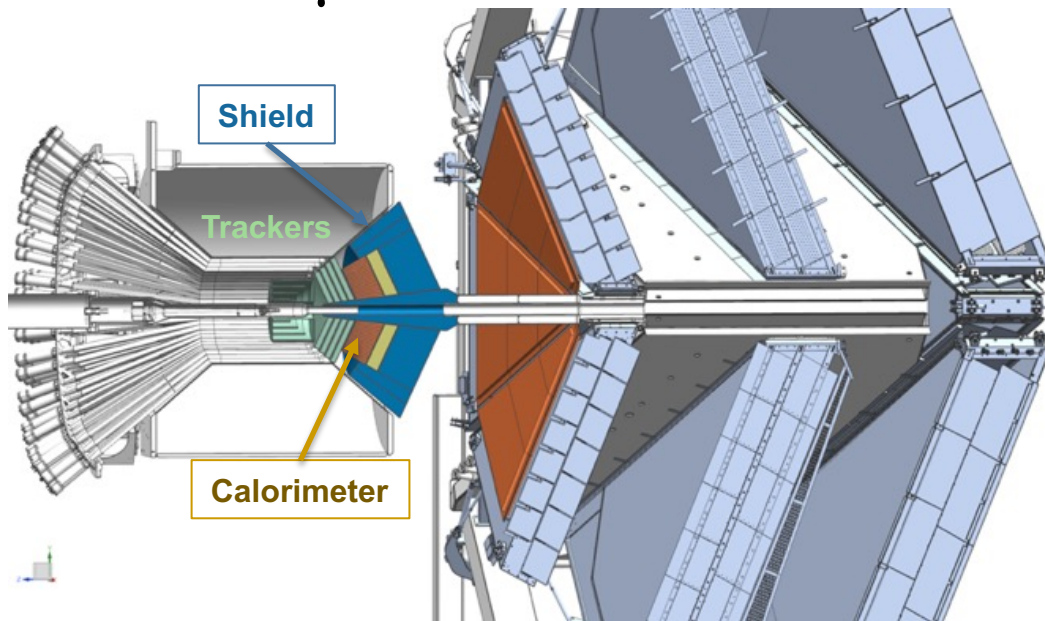
Cross sections from R. Parenduzyan, VGG code

High luminosity CLAS12 for DDVCS

Di-muon electroproduction, using upgraded CLAS12, will overcome these challenges.

Detector capable of measuring
 $ep \rightarrow e'p'\mu^+\mu^- @ L > 10^{37} \text{ cm}^{-2} \text{ sec}^{-1}$

μ CLAS12



A simple concept:

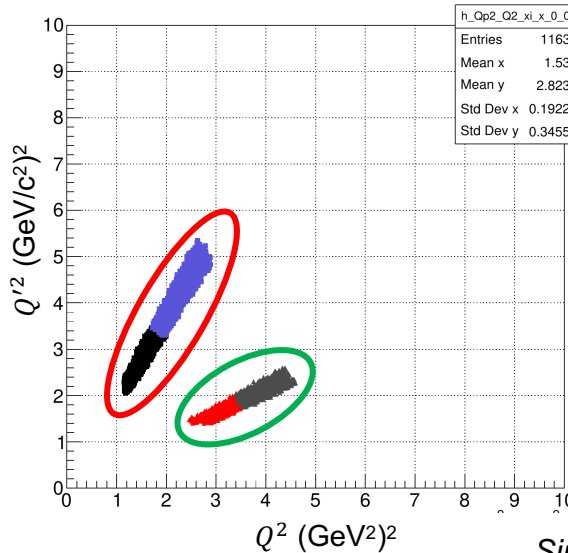
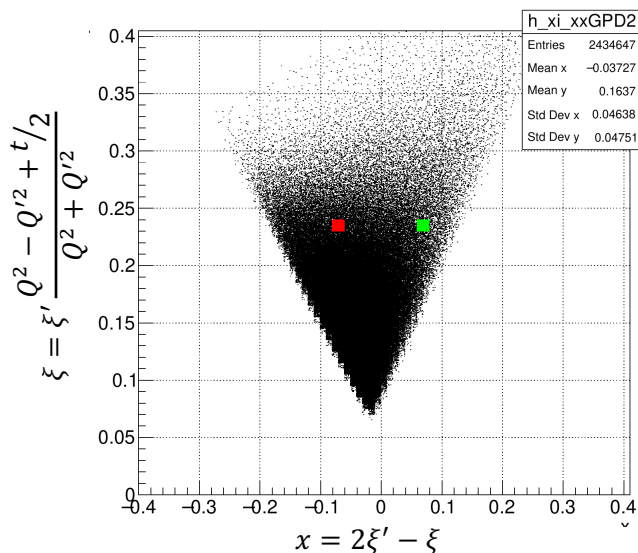
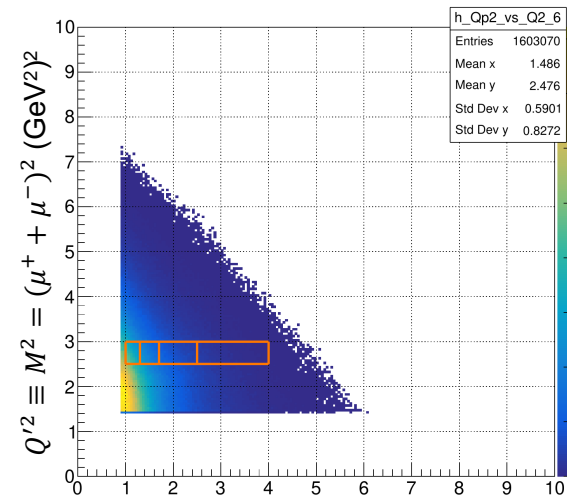
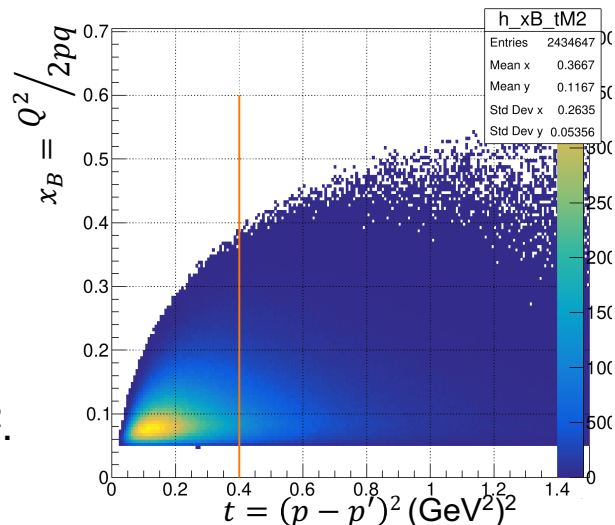
- Remove HTCC and block the CLAS12 forward with a W-shield and PbWO_4 calorimeter to prevent flooding of DC by EM background;
- Scattered electrons will be detected in the calorimeter, while the shield will work as a pion filter, as most charged pions will shower and will not reach the forward tracking system;
- Remove CVT, instead use a high rate MPGDs for the central and forward (in front of the calorimeter) tracking.

A concept first introduced in LOI12-16-004

Kinematical coverage at 11 GeV

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

- GRAPE event generator, BH only.
- The whole region is measured simultaneously.
- At 11 GeV, the interesting region is $Q'^2 > 2$ (GeV/c²)².

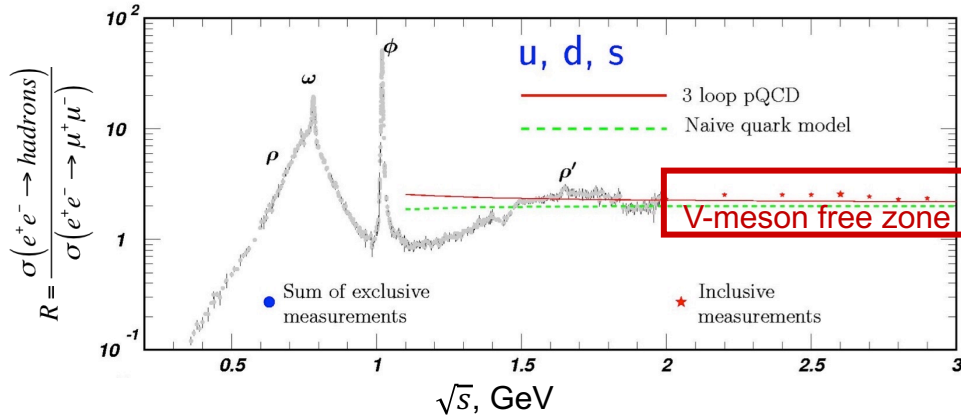


$$x_B = \frac{Q^2}{2pq} \quad \xi' = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

- ξ - x bin fixes the ratio Q'^2/Q^2 while their values are unconstrained.
- For each ξ - x bin asymmetry can be measured at different Q'^2 and Q^2 , can be a scaling test for GPDs.

Simulations from R. Paremuzyan

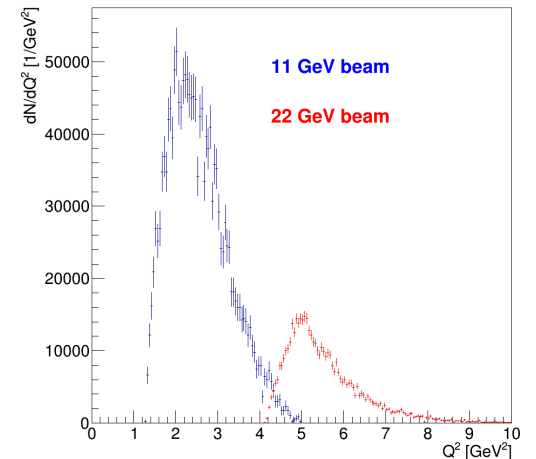
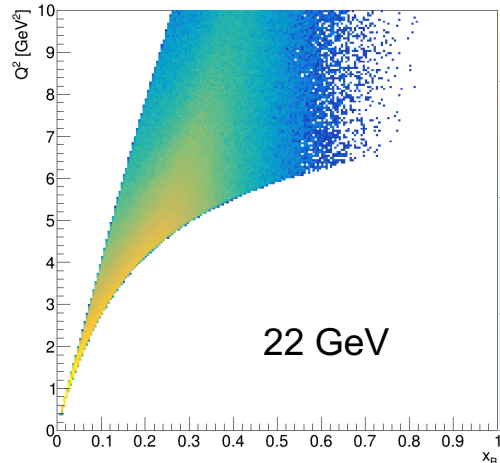
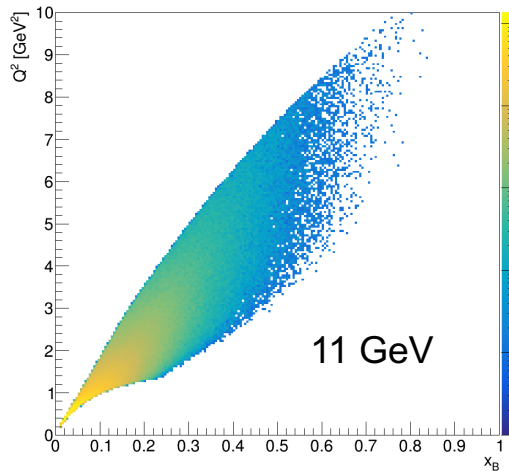
DDVCS at 20+ GeV



Expand measurements in spacelike, $Q^2 > Q'^2$, and timelike, $Q^2 < Q'^2$, regimes to the resonance free region $Q'^2 > 4 \text{ (GeV}/c^2)^2$

μ CLAS12 will perform with higher energy beams.

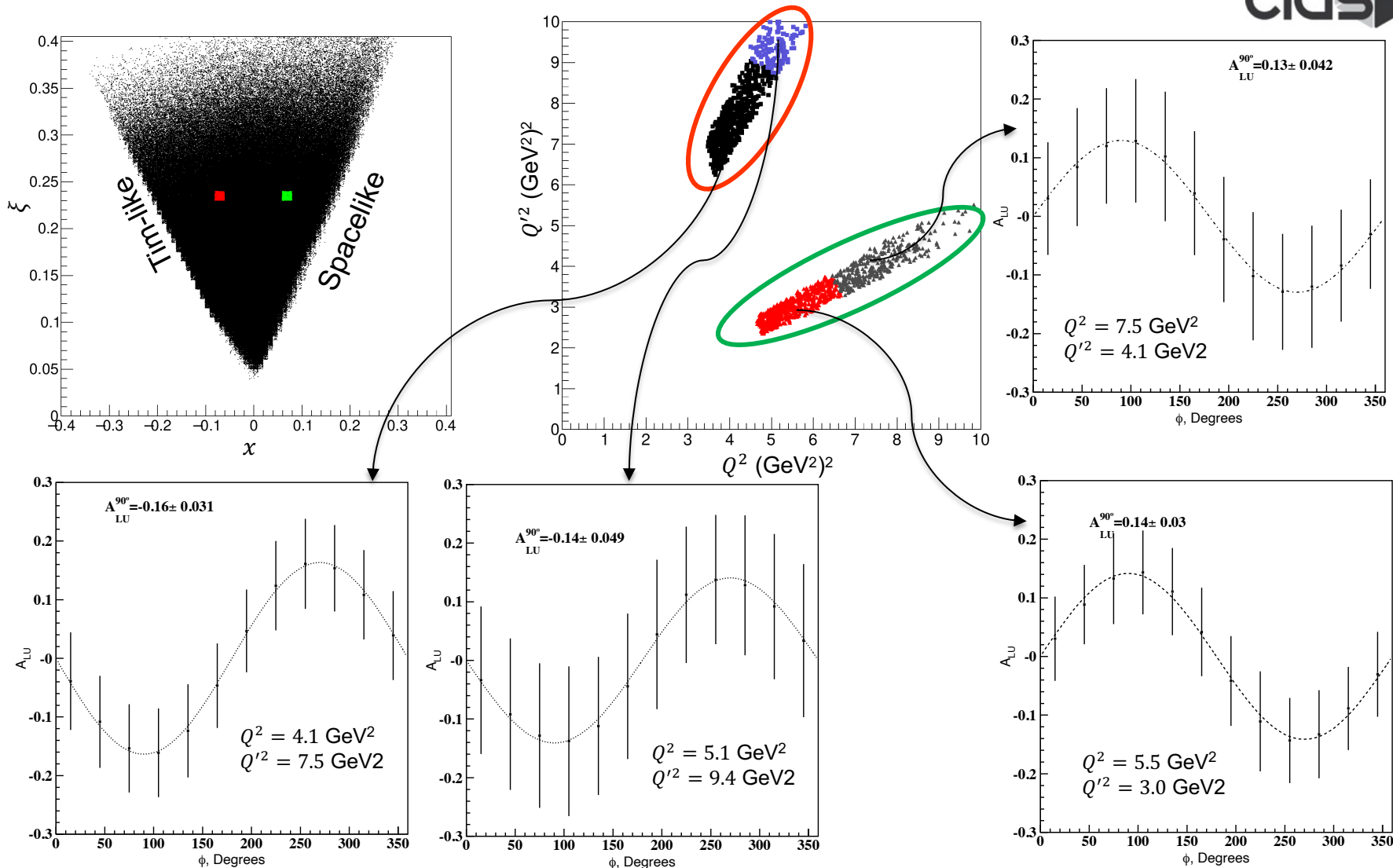
$$ep \rightarrow e'p'\mu^+\mu^-$$



Simulations from R. Paremuzyan



Projections: BSA 200 days @ $10^{37} \text{ cm}^{-2} \text{ sec}^{-1}$



Simulations from R. Paremuzyan

Statistics is from GRAPE, asymmetries is from VGG



22 GeV upgrade physics discussion - HighLumi CLAS12



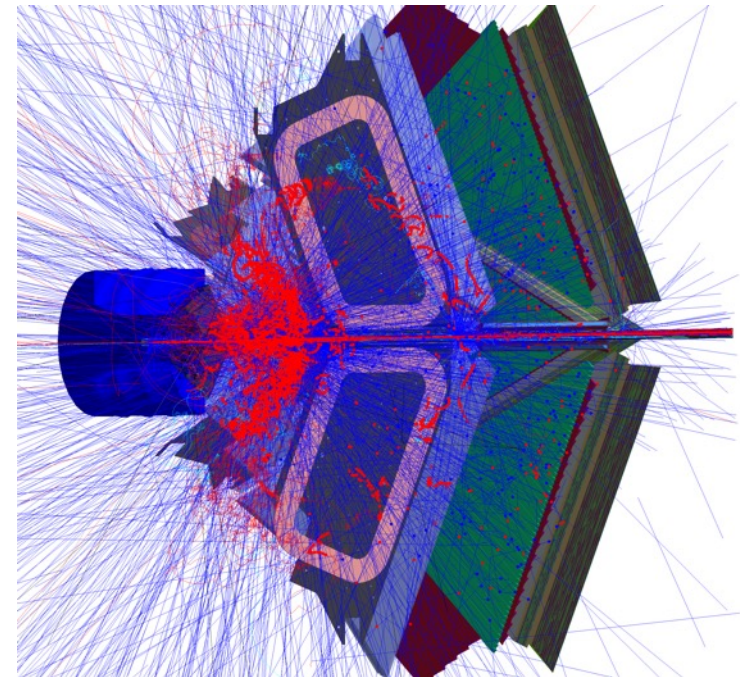
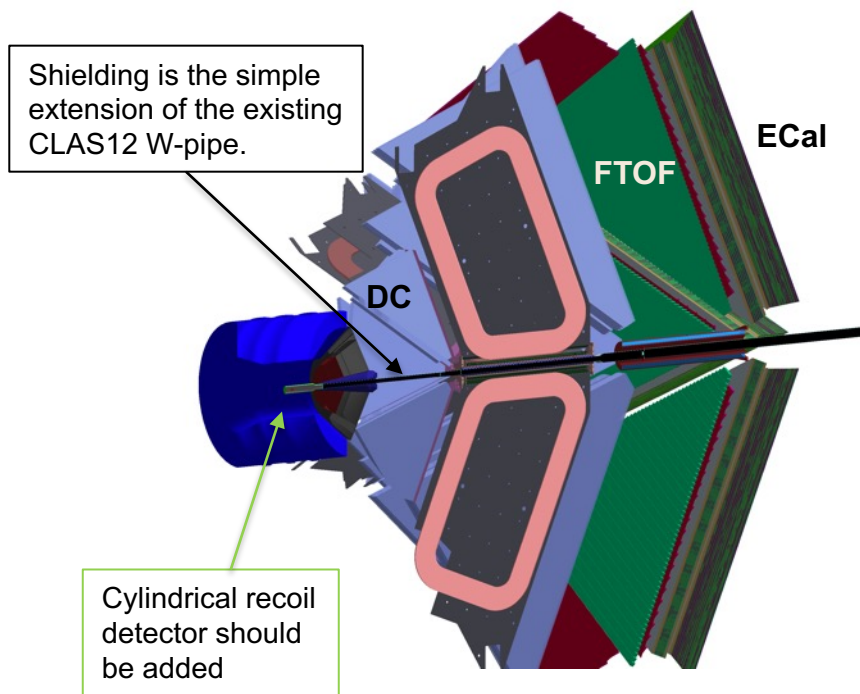
Summary

- The description of the partonic structure of hadronic matter is a major thrust of the JLab 12 GeV.
- The Compton scattering is the golden reaction for mapping GPDs, and a large set of data from DVCS and TCS measurements are already available for phenomenological analysis.
- These data (DVCS & TCS) are crucially important yet limited for inferring information on GPDs from experimental observables, as one of the GPD variables (x) is completely integrated out.
- Double DVCS, on the other hand, allows mapping of GPDs in the x -space, and Jefferson lab, home to high luminosity experiments, is the only place DDVCS can be studied.
- CLAS12 in Hall B, with modest upgrades, and SoLiD in Hall-A, can provide a wealth of data on DDVCS in a wide kinematic range.
- Opportunities for DDVCS exist with high energy machine, >20 GeV, where measurements will cover meson resonance free time-like region.

Backups

GEANT4 model

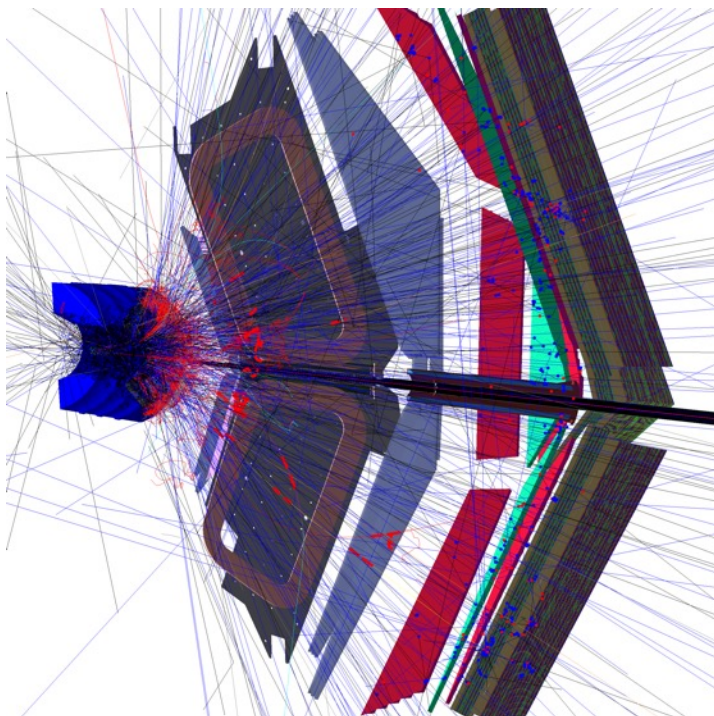
- The forward part of the proposed upgrade (calorimeter and the shielding) is in the CLAS12 MC, GEMC (M. Ungaro).
- Simulations are underway to understand backgrounds in detectors, optimize shielding and determine luminosity limitations. (*Earlier studies for LO12-16-004 validated the concept for $L = 10^{37} \text{ cm}^{-2} \text{ sec}^{-1}$*)



100k 11 GeV electrons in 250 ns

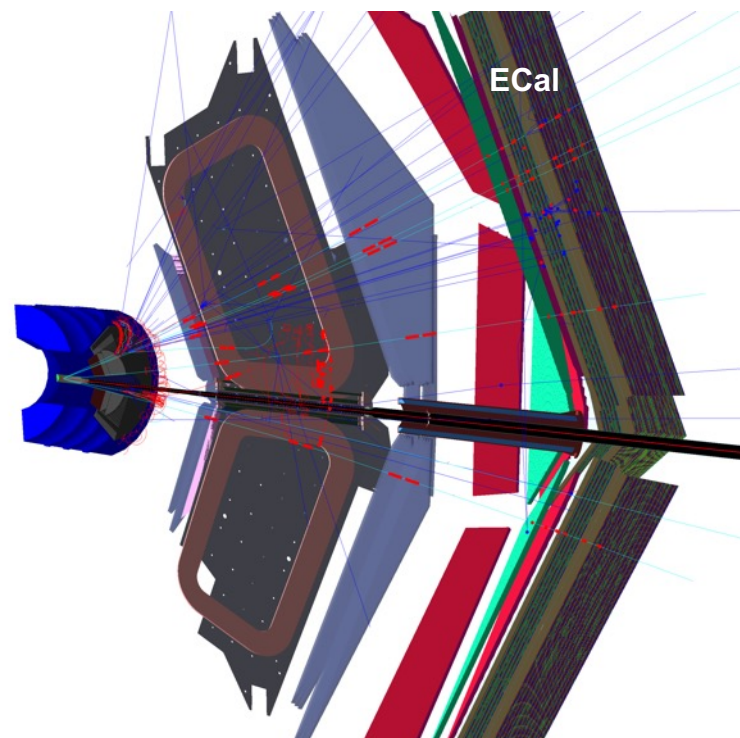
μ/π – separation

6 GeV π^+



Most pions will shower in the calorimeter/shielding and will not reach drift chambers, much less the ECal.

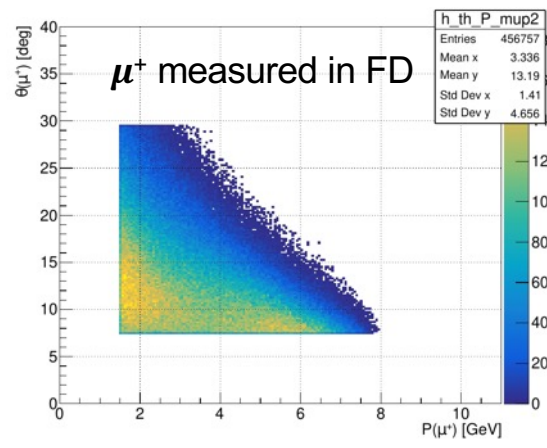
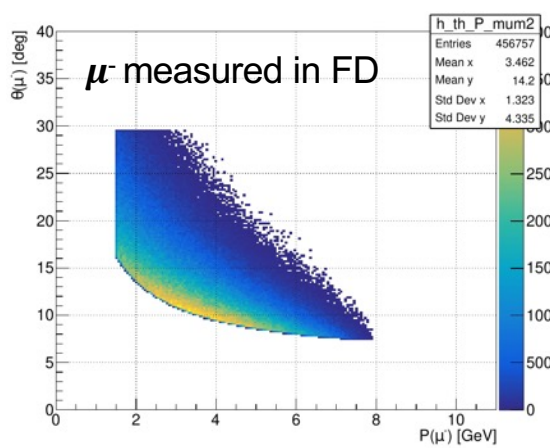
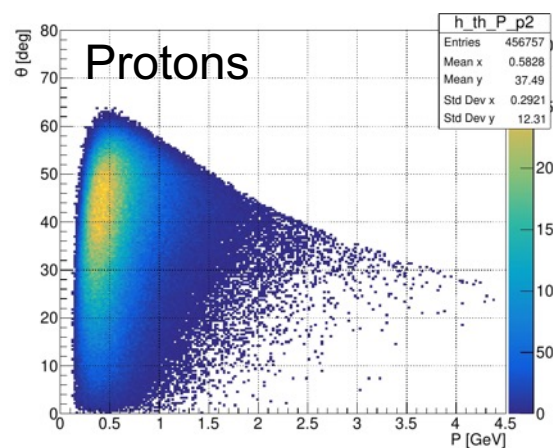
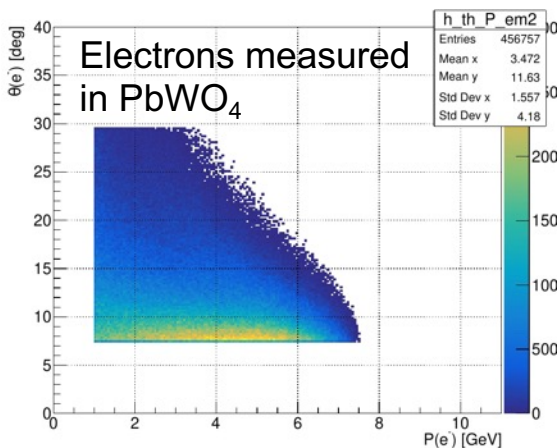
6 GeV μ^+



Conversely, muons will lose some energy in the calorimeter/shielding but will reach drift chambers and Ecal. Ecal is where muons are IDed.

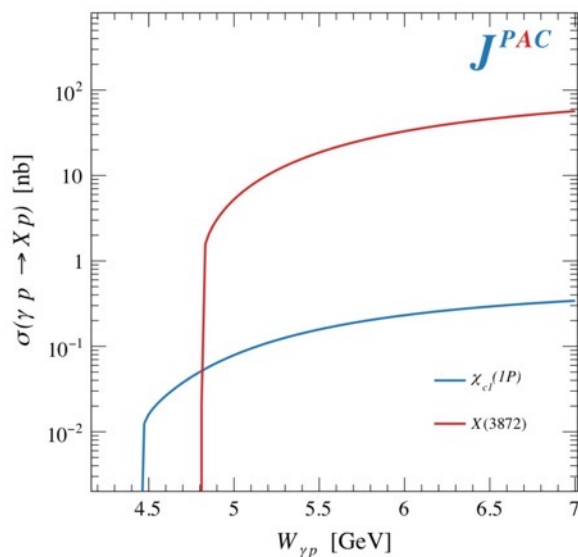
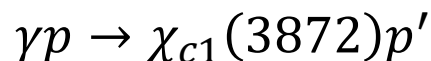
Final state particles

- Electrons and muons are confined within the calorimeter and FD.
- Recoil proton detection will be limited to $\vartheta > 40^\circ$, not crucial for DDVCS.



A topic for another conversation: XYZ spectroscopy

- Several states in the charmonium region have been discovered that do not fit into a simple $q\bar{q}$ model.
- JLAB energy upgrade (20+ GeV) will open a phase space for the photoproduction of some of these states.
- μ CLAS12 at 10^{37} cm⁻² sec⁻¹ will contribute to the studies of the lowest mass states.
- An example, well know exotic $\chi_{c1}(3872)$, aka X(3872), first discovered by [Belle in 2003](#).



The luminosity in the energy range 13 GeV to 22 GeV is 100 nb^{-1} , even with a modest efficiency of 2%, one expects **>50 detected $\chi_{c1}(3872)$ per hour** in each decay mode

$\chi_{c1}(3872)$ decay modes:

- $\chi_{c1} \rightarrow \omega J/\psi$ BR= 4.3%
 $\omega \rightarrow \gamma\pi^0$ BR=8.28%
 $J/\psi \rightarrow \mu^+\mu^-$ BR=6%
 $\chi_{c1} \rightarrow \gamma\gamma\mu^+\mu^-$ BR $\geq 2 \times 10^{-4}$
- $\chi_{c1} \rightarrow \gamma \psi(2S)$ BR= 4%
 $\psi(2S) \rightarrow \mu^+\mu^-$ BR=0.8%
 $\chi_{c1} \rightarrow \gamma\mu^+\mu^-$ BR $\geq 2.3 \times 10^{-4}$