Double DVCS with CLAS12 in Hall-B

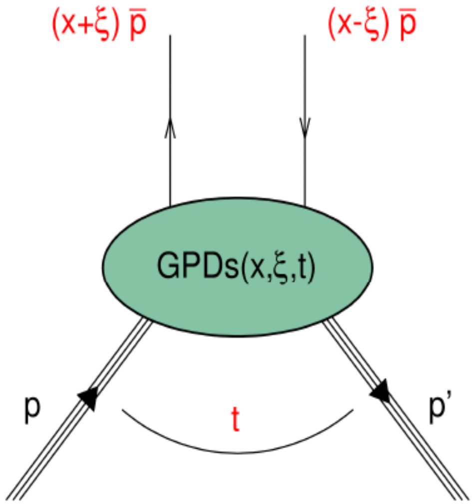
22 GeV upgrade physics discussions

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
  - μCLAS12 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, $M_{ll} > 2$ 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:

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

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

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

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

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

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

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

GPDs and the form factors of the QCD EMT

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

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

Mellin moments of GPDs linked to the EMT FF -

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

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

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:

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

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.

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

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

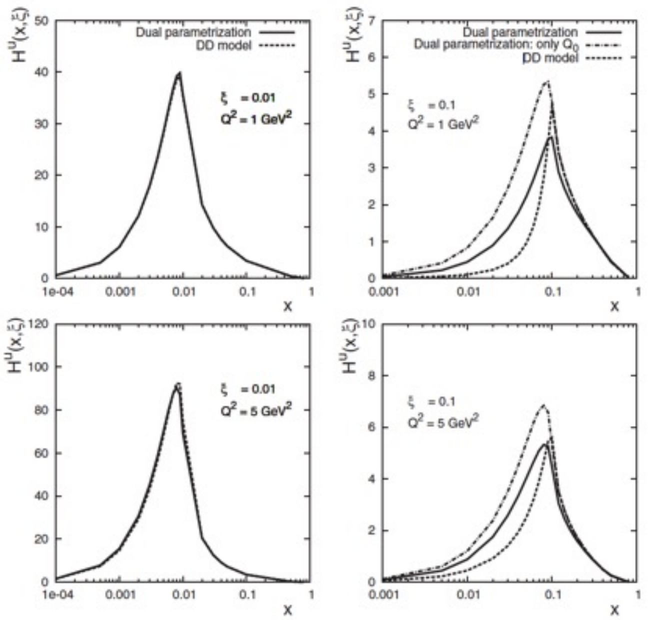
- Therefore, extracting information on GPDs from experimental observables is not straightforward and is a two-step process.
- And of course, the different flavor (gluon and quark) contributions must be separated – another topic of conversation.

GPDs from experimental data – two step process

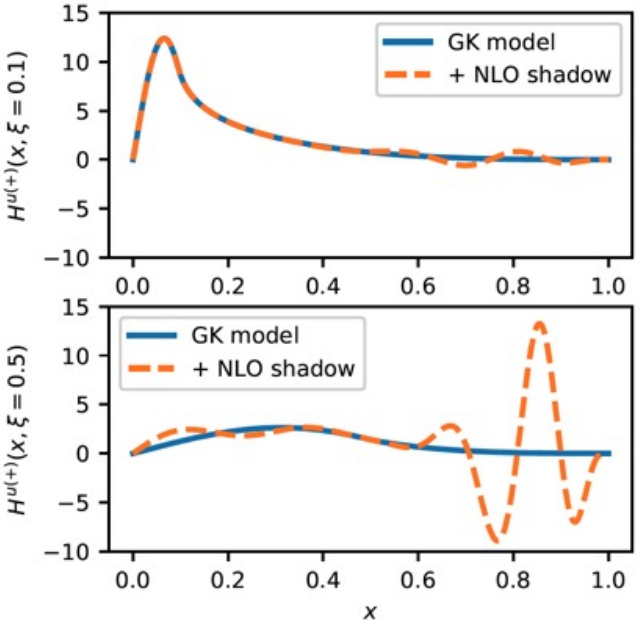
- Step one of accessing GPDs from experimental measurements is extracting CFFs from observables (asymmetries, cross sections). Several methods, at the leading twist, exist. *(See e.g. H. Moutarde, P. Sznajder, and J. Wagner, Eur. Phys. J. C 79, 614 (2019). M. Čuić, K. Kumerički, and A. Schäfer, Phys. 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. Dutrieux, 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.

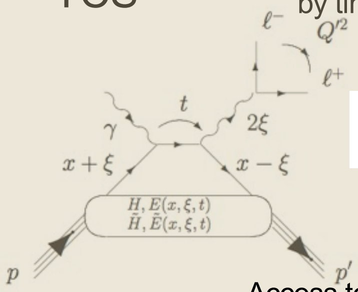
Closing the loop on virtual Compton scattering

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



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

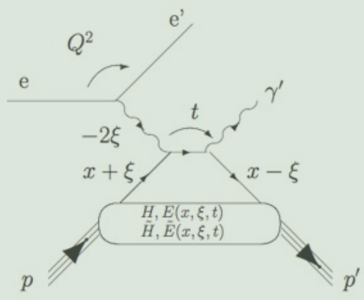
$$Im\ \mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t)$$

Access to the Re-part of the Compton amplitude

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

DVCS

Hard scale is defined by space-like photon

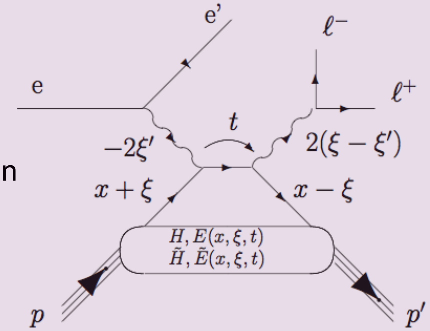


Jefferson Lab at the luminosity frontier is the only place in the world DDVCS can be measured!

µCLAS12 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



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

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

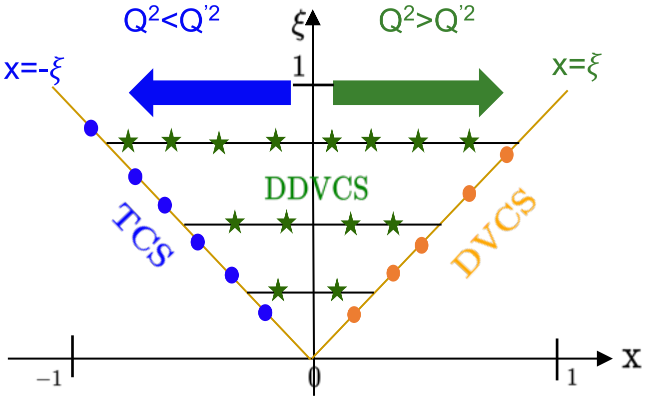
σ-DDVCS is three orders of magnitude smaller than σ-DVCS

CFFs and GPDs in Virtual Compton Scattering

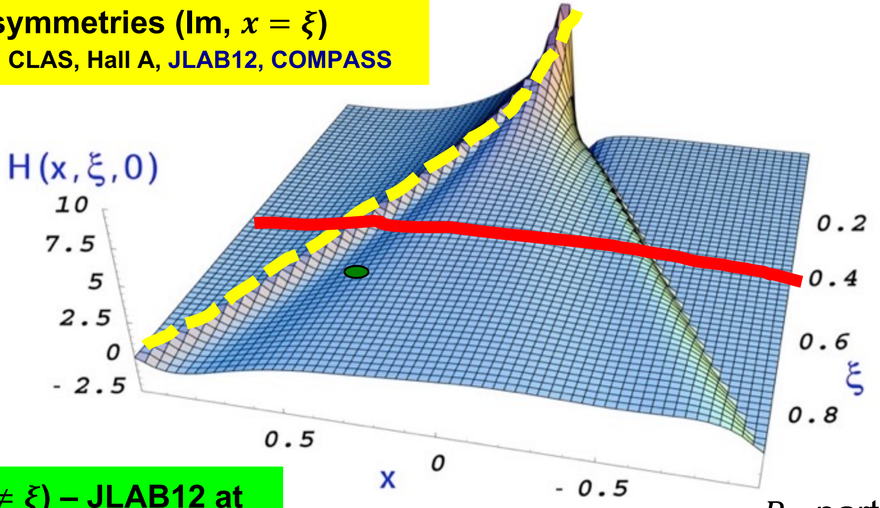
$$\mathcal{T}_{DVCS} \sim CFF\ \ \mathcal{H}(\xi,t) \propto i\pi[H(\xi,\xi,t) - H(\xi,\xi,t)] + P\int_{-1}^{+1} dx(\frac{1}{x-\xi} \pm \frac{1}{x+\xi})[H(x,\xi,t) \mp H(x,\xi,t)]$$

(the same for TCS)

$$\mathcal{T}_{DDVCS} \sim CFF\ \ \mathcal{H}(\xi,\xi',t) \propto i\pi[H(2\xi'-\xi,\xi,t) - H(-2\xi'+\xi,\xi,t)] + P\int_{-1}^{+1} dx(\frac{1}{x-(2\xi'-\xi)} \pm \frac{1}{x+(2\xi'-\xi)})[H(x,\xi,t) \mp H(x,\xi,t)]$$



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

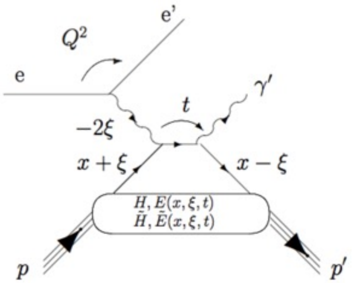
DDVCS (Im, $x \neq \xi$) – JLAB12 at *$L \geq 10^{37}$ cm^{-2} sec^{-1}*

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

a) The cross section is three orders of magnitude smaller than that of DVCS.

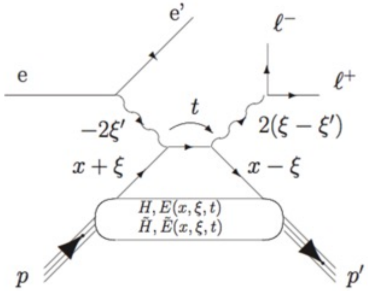
b) Ambiguities and anti-symmetrization issues with the decay leptons of the outgoing virtual photon and the incoming-scattered lepton.



$$Q^2 = -q^2 = (e-e')^2$$

$$x_B = \frac{Q^2}{2pq}$$

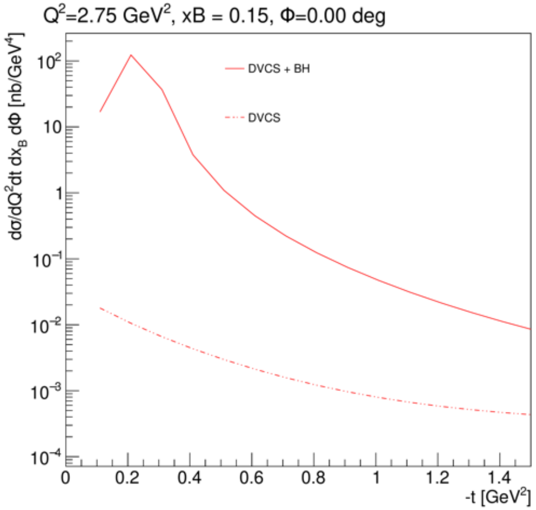
$$t = (p-p')^2$$

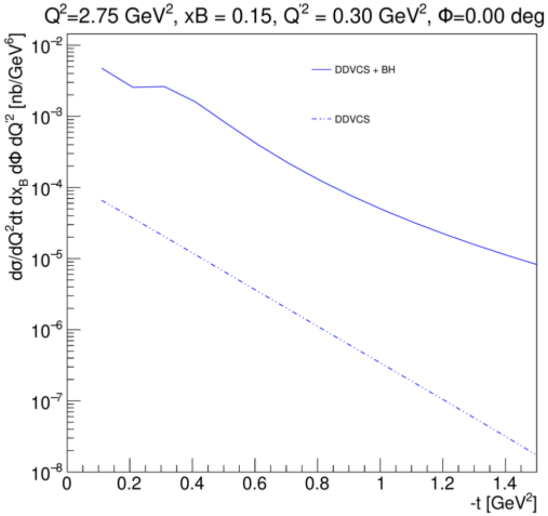


$$Q'^2 \equiv M^2 = (l^+ + l^-)^2$$

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

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





Cross sections from R. Paremuzyan, VGG code

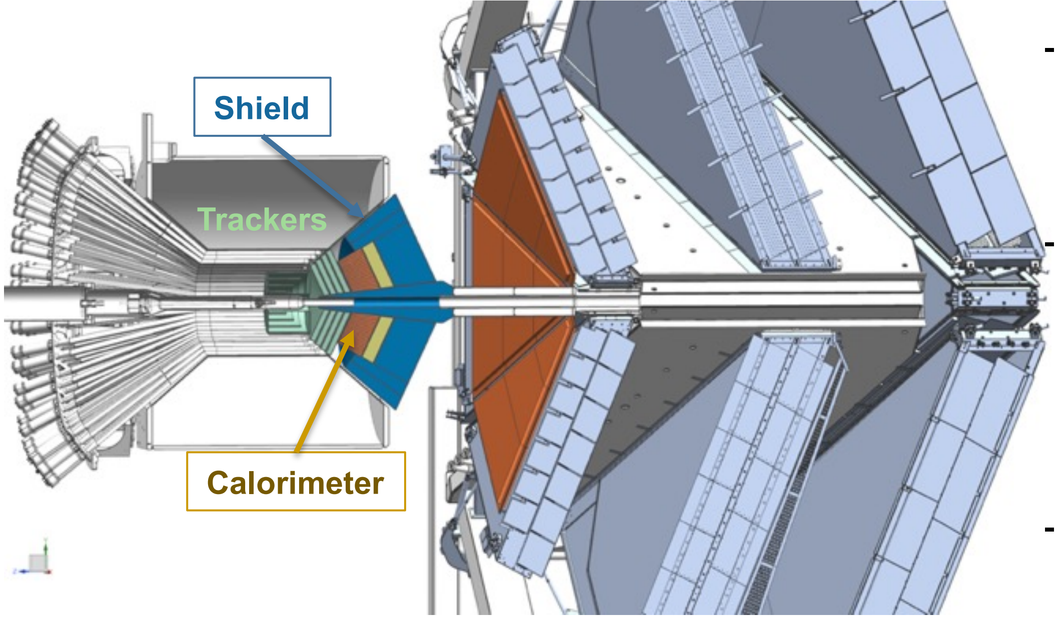
High luminosity CLAS12 for DDVCS

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

Detector capable of measuring

$$ep \rightarrow e'p'\mu^+\mu^- \ \ @\, L > 10^{37} cm^{-2} sec^{-1}$$

μCLAS12



A concept first introduced in LOI12-16-004

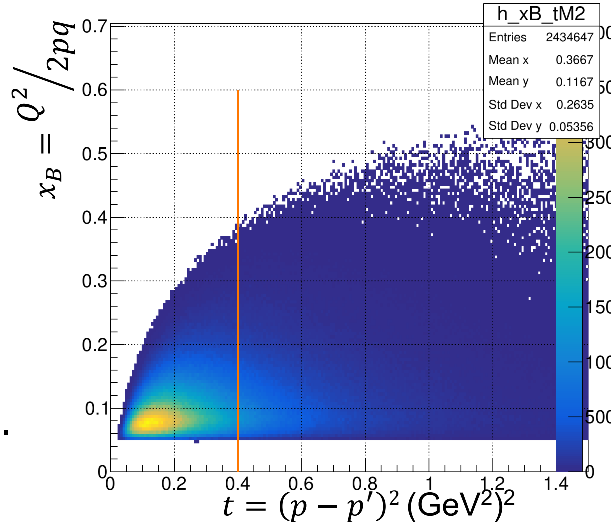
A simple concept:

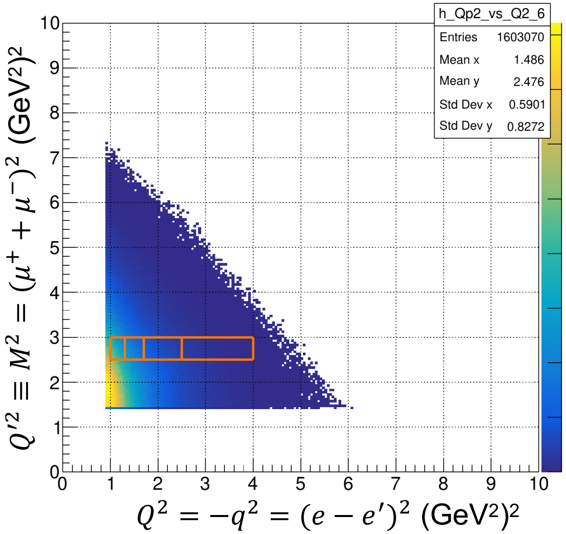
- Remove HTCC and block the CLAS12 forward with a W-shield and $PbWO_4$ calorimeter to prevent flooding of DC by EM background;
- Scattered electrons will be detected in the calorimeter, while the shield will work as a pion filter, as most charged pions will shower and will not reach the forward tracking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

Kinematical coverage at 11 GeV

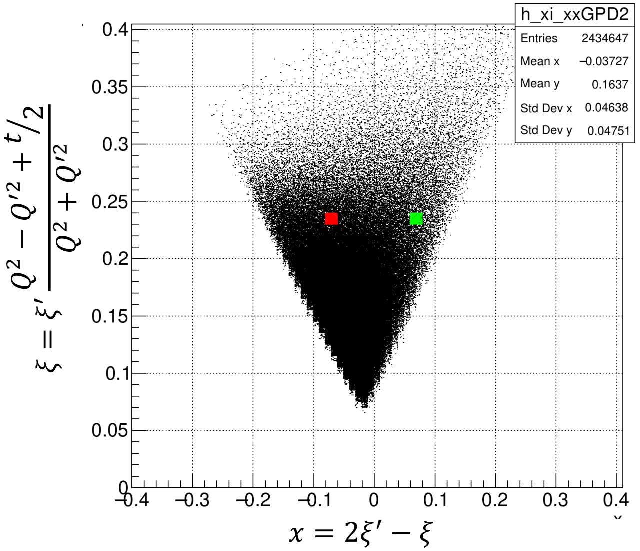
$$ep \rightarrow e'p'\mu^+\mu^-$$

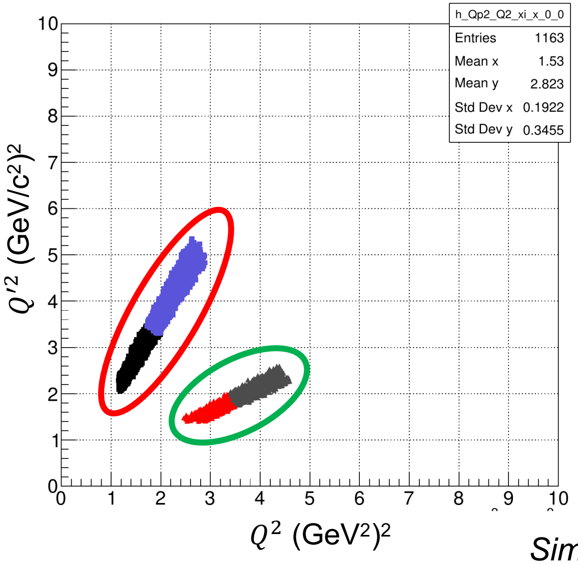
- GRAPE event generator, BH only.
- The whole region is measured simultaneously.
- At 11 GeV, the interesting region is $Q'^2 > 2$ (GeV/c²)².





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

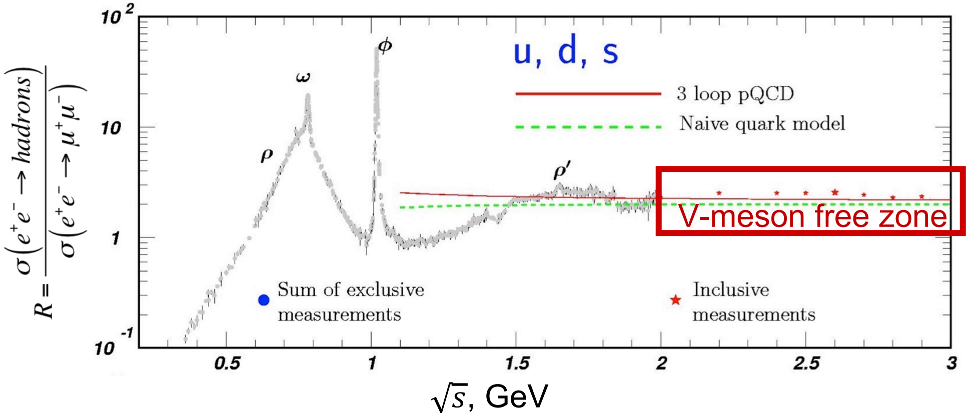




- ξ - x bin fixes the ratio Q'^2/Q^2 while their values are unconstrained.
- For each ξ - x bin asymmetry can be measured at different Q'^2 and Q^2, can be a scaling test for GPDs.

Simulations from R. Paremuzyan

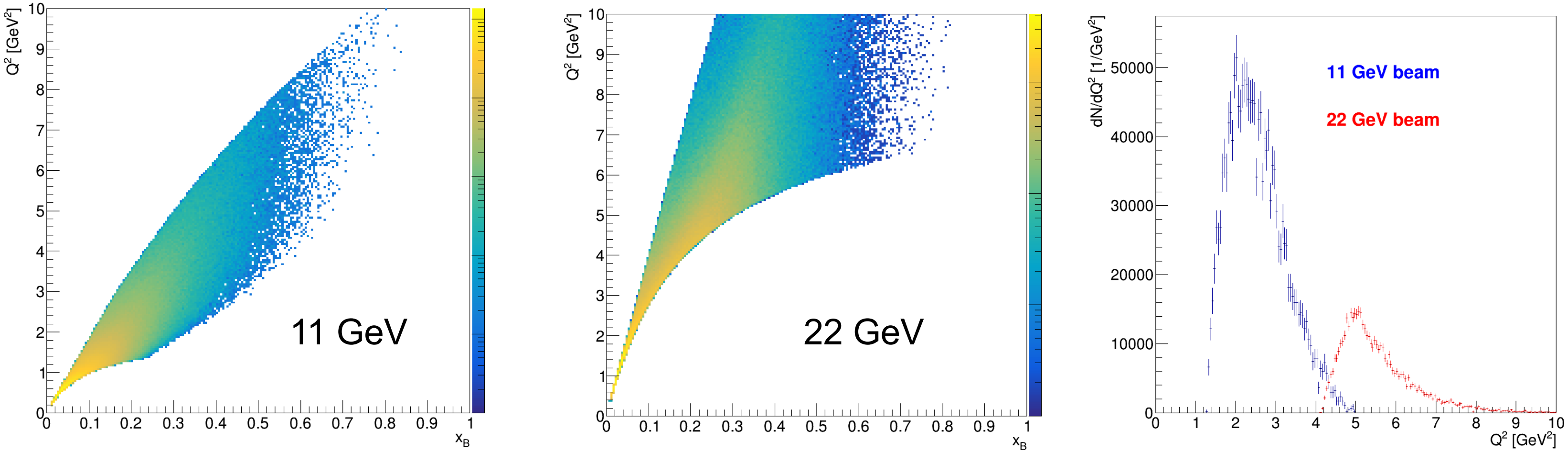
DDVCS at 20+ GeV



Expand measurements in spacelike, $Q^2 > Q'^2$, and timelike, $Q^2 < Q'^2$, regimes to the resonance free region $Q'^2 > 4$ (GeV/c²)²

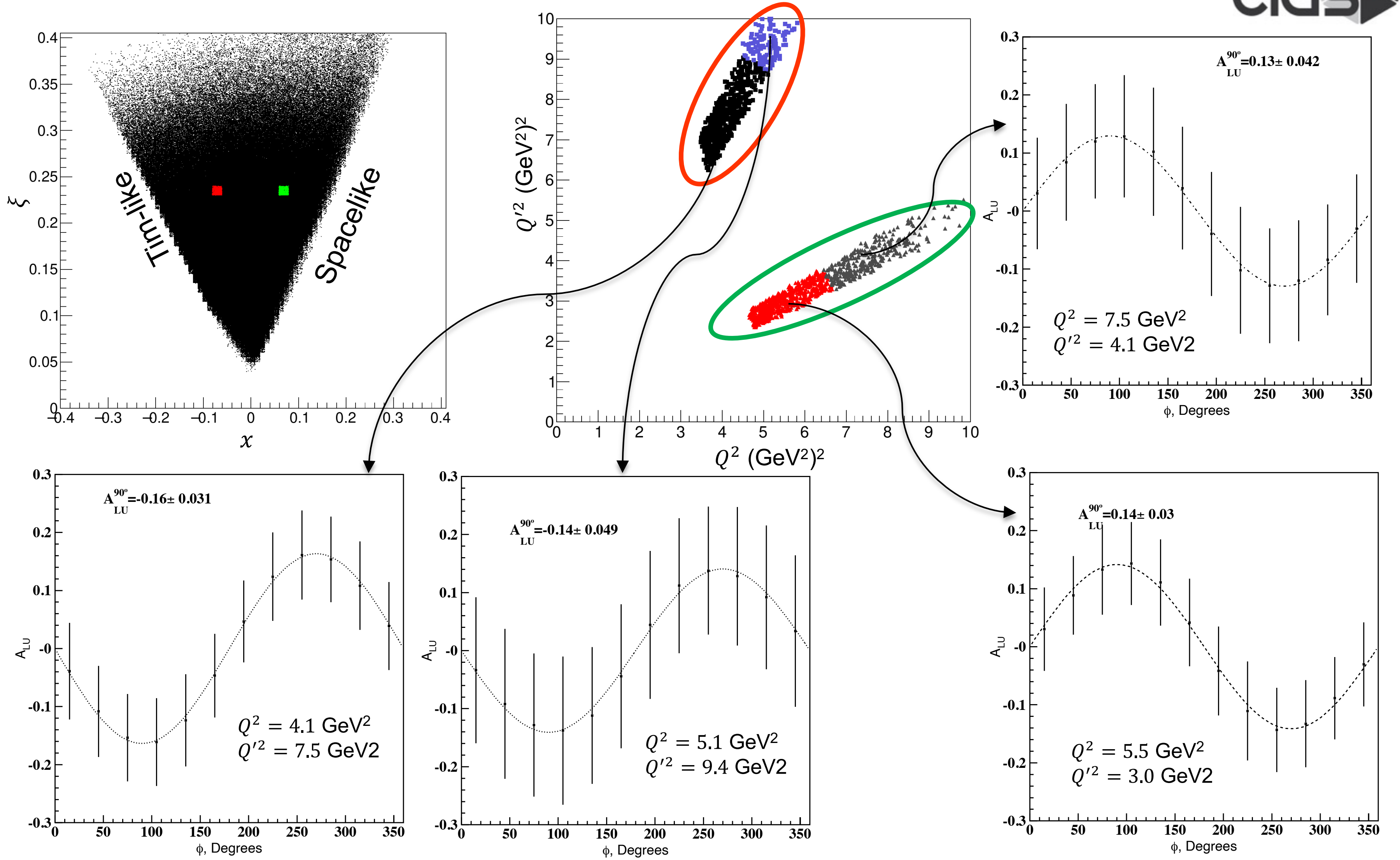
$\mu CLAS12$ will perform with higher energy beams.

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



Simulations from R. Paremuzyan

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



Simulations from R. Paremuzyan

Statistics is from GRAPE, asymmetries is from VGG

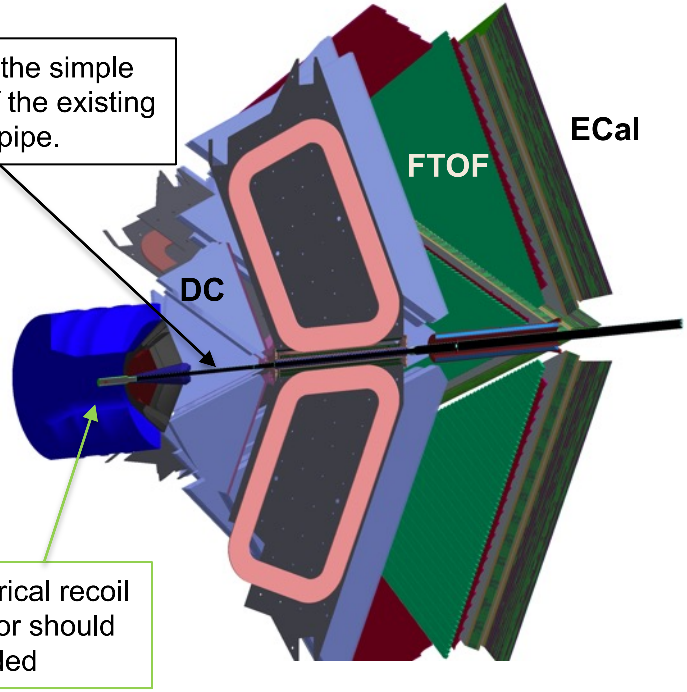
Summary

- 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

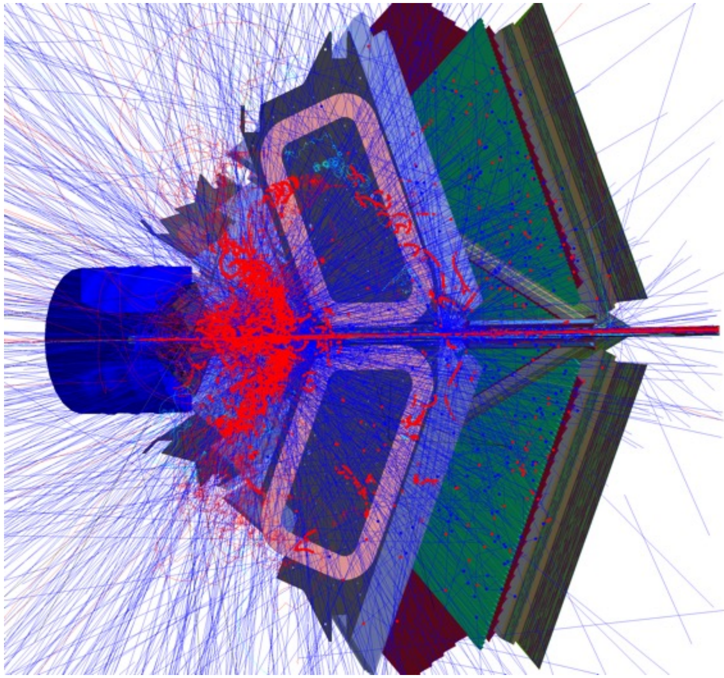
GEANT4 model

- 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 LOI12-16-004 validated the concept for* $L = 10^{37} cm^{-2} sec^{-1}$)



Shielding is the simple extension of the existing CLAS12 W-pipe.

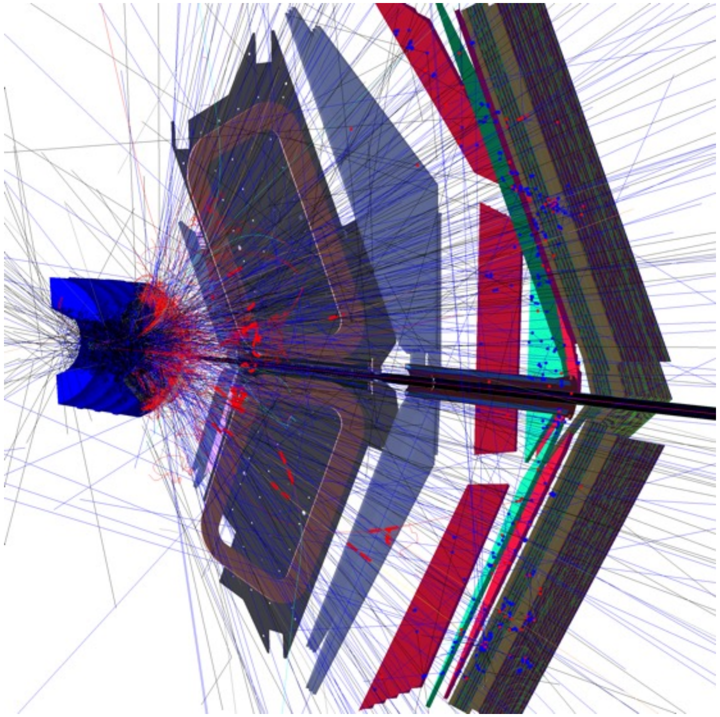
Cylindrical recoil detector should be added



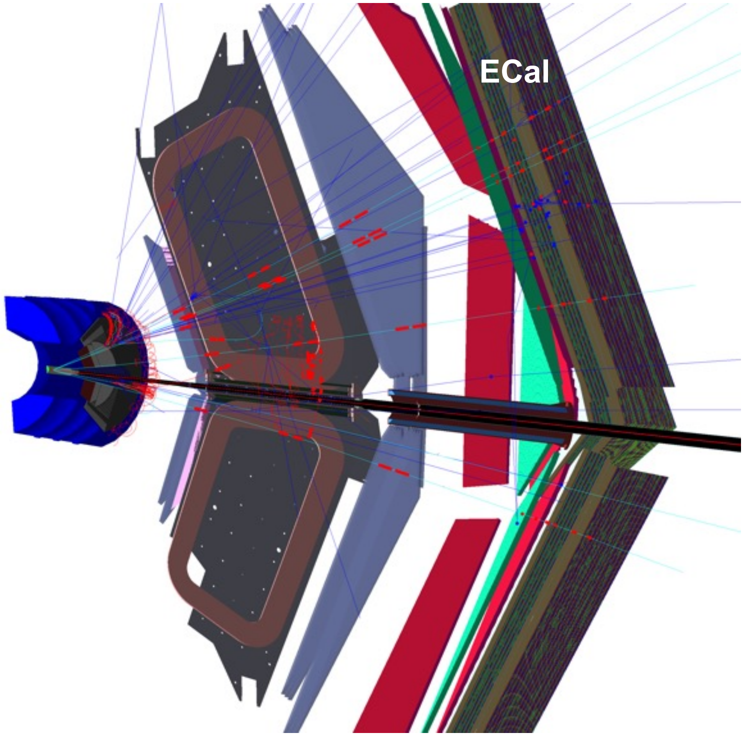
100k 11 GeV electrons in 250 ns

μ/π – separation

6 GeV π^+



6 GeV μ^+

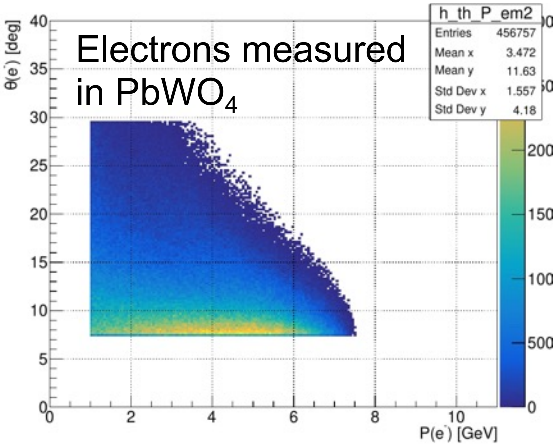


Most pions will shower in the calorimeter/shielding and will not reach drift chambers, much less the ECal.

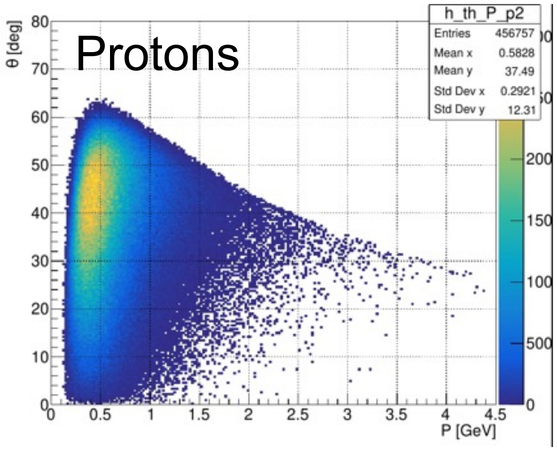
Conversely, muons will lose some energy in the calorimeter/shielding but will reach drift chambers and Ecal. Ecal is where muons are IDed.

Final state particles

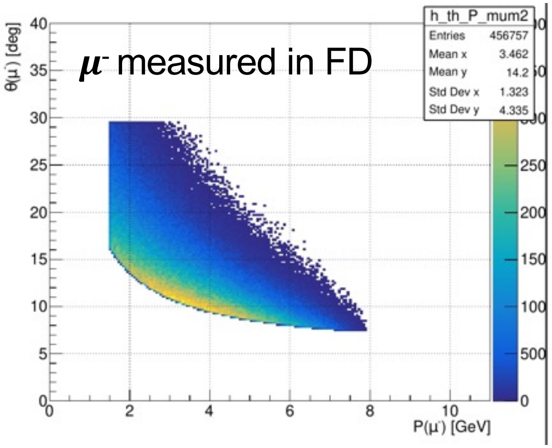
- Electrons and muons are confined within the calorimeter and FD.
- Recoil proton detection will be limited to $\vartheta > 40^o$, not crucial for DDVCS.



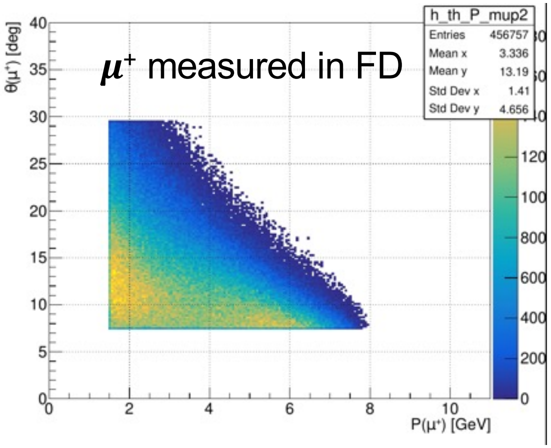
Electrons measured in PbWO$_4$



Protons



μ^- measured in FD

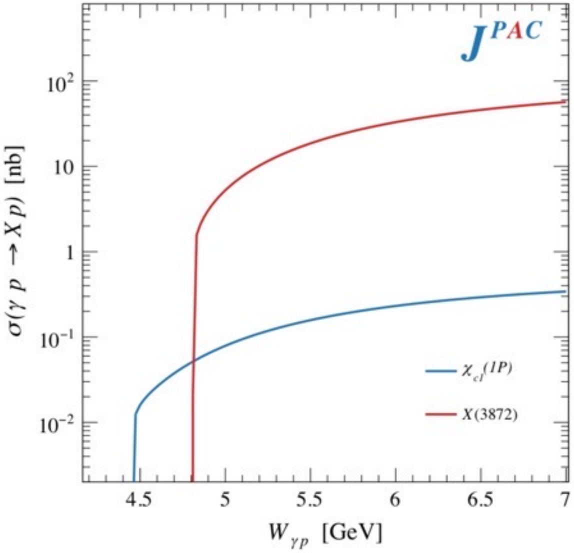


μ^+ measured in FD

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.
- $\boldsymbol{\mu}$CLAS12 at 10^{37} cm^{-2} sec^{-1} will contribute to the studies of the lowest mass states.
- An example, well know exotic χ_{c1}(3872), aka X(3872), first discovered by Belle in 2003.

$$\gamma p \rightarrow \chi_{c1}(3872)p'$$



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 $\boldsymbol{\chi_{c1}}$(3872) per hour** in each decay mode

χ_{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%
  $\chi_{c1} \rightarrow \gamma\gamma\gamma\mu^+\mu^-$ BR≥ 2x10^{-4}

- $\chi_{c1} \rightarrow \gamma\, \psi(2S)$ BR= 4%
  $\psi(2S) \rightarrow \mu^+\mu^-$ BR=0.8%
  $\chi_{c1} \rightarrow \gamma\mu^+\mu^-$ BR≥ 2.3x10^{-4}