DDVCS in with Hall C
Updates and LOI to PAC52

NPS collaboration meeting, July 17th 2024
Virginia Tech and Yerevan groups

presented by Keagan Bell, Ryan McLaughlin, and Marie Boër

Letter of Intent to PAC 52: Generalized Parton Distributions from Double Deeply Virtual Compton Scattering at Jefferson Lab Hall C

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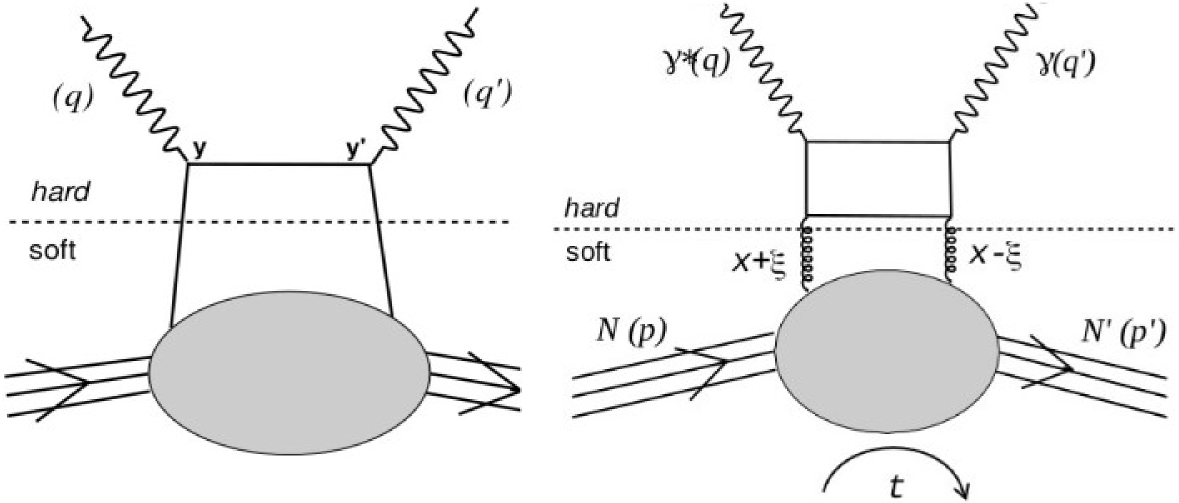
Abstract

This letter of intent presents our prospects for a first measurement of Double Deeply Virtual Compton Scattering (DDVCS) unpolarized cross sections and beam polarized spin asymmetries at Jefferson Lab Hall C, in the reaction $eP \to e'P'\mu^+\mu^-$, where two virtual photons are being exchanged between quarks and leptons. The scientific goal of this new experiment is to constrain the so-called Generalized Parton Distribution (GPDs) in the "ERBL" region, that is not accessed in any other Compton-like experiment, but is accessible in DDVCS thanks to a lever arm provided by the relative virtuality of the two photons. Constraining GPDs in this region is essential for tomographic interpretations, as it enables the deconvolution of momenta and extrapolation of the GPDs to "zero-skewness". A new muon detector, dedicated to this experiment, which could also open perspectives for other future measurements, will be developed and installed. The spectrometer and tracking for this experiment is derived from the setup we proposed in the past for a measurement of Timelike Compton Scattering (TCS), and intend to submit to the next PAC (in 2025) for both this target polarized measurement a complementary unpolarized TCS measurement.

Physics motivations and formalism

Hard Exclusive Compton-like reactions and Double Deeply Virtual Compton Scattering



Leading order / leading twist generic handbag diagram

γ (*) N → γ'(*) N'

DVCS: final photon is real, incoming is spacelike
(Spacelike Deeply Virtual Compton Scattering)

TCS: incoming is real, final is timelike
(Timelike Deeply Virtual Compton Scattering)

DDVCS: incoming is spacelike, outgoing is timelike
Double Deeply Virtual Compton Scattering

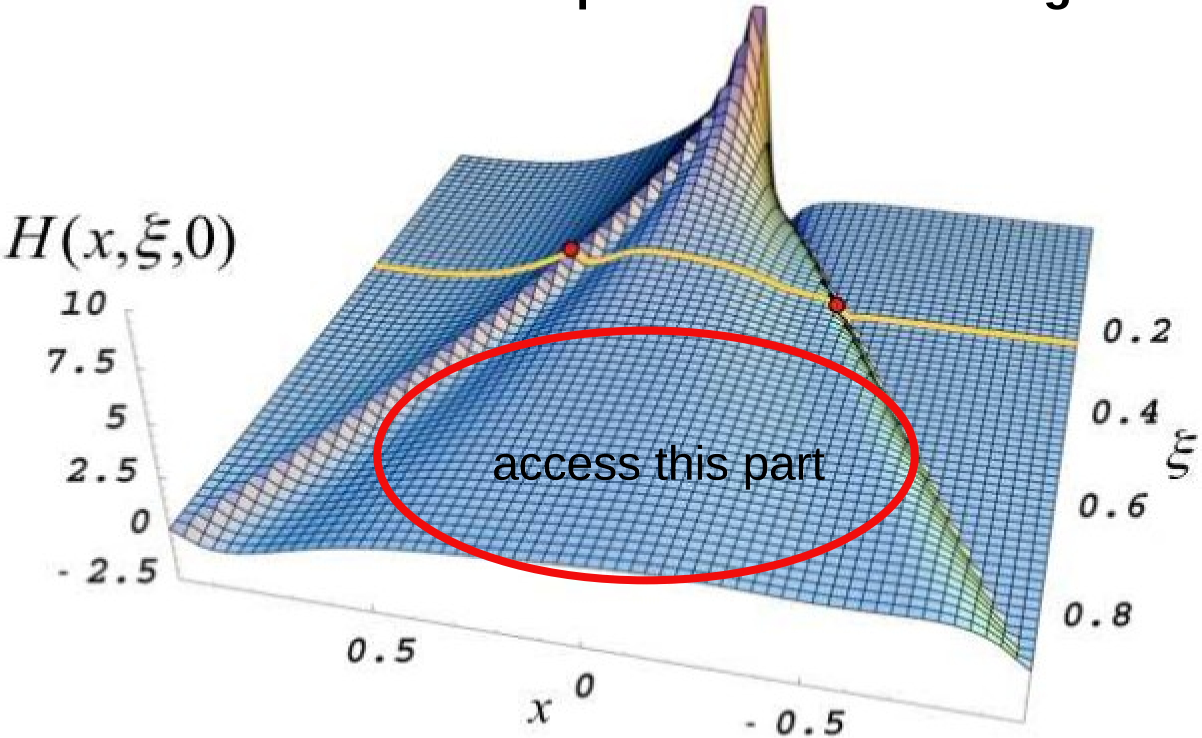
Other: multi-photons, photon+meson, ...

Parameterized by GPDs
Generalized Parton Distributions

Depend on x, xi, t

GPDs at xi=0 for tomographic interpretations: need deconvolution

Compton Form Factors decomposition and "off diagonal" access to GPDs



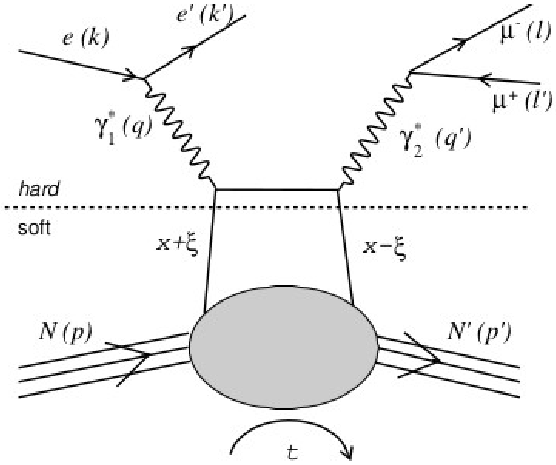
DVCS, TCS: $$\mathcal{H}(\xi,t)=\sum_q e_q^2\left\{\mathcal{P}\int_{-1}^{1}dx\,H^q(x,\xi,t)\left[\frac{1}{\xi-x}-\frac{1}{\xi+x}\right]+i\pi\left[H^q(\xi,\xi,t)-H^q(-\xi,\xi,t)\right]\right\}$$

DDVCS: $$\mathcal{H}(\xi',\xi,t)=\sum_q e_q^2\left\{\mathcal{P}\int_{-1}^{1}dx\,H^q(x,\xi,t)\left[\frac{1}{\xi'-x}-\frac{1}{\xi'+x}\right]+i\pi\left[H^q(\xi',\xi,t)-H^q(-\xi',\xi,t)\right]\right\}$$

Phenomenology of DDVCS

$$e(k) - e'(k') + p(p_1) \equiv \gamma^\star(q_1) + p(p_1) \to p'(p_2) + \gamma^\star(q_2) \to p'(p_2) + \mu^+(l^+) + \mu^-(l^-)$$

DDVCS



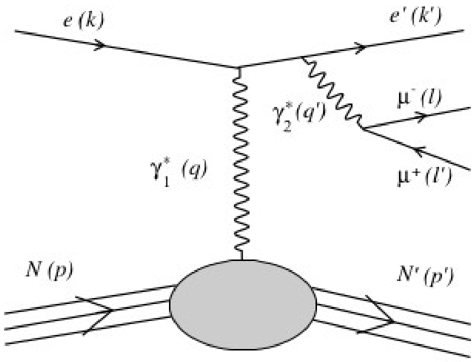
Variables definition/notations:

$$Q^2 = -q^2; \quad Q'^2 = q'^2 \quad q = \frac{1}{2}(q + q'); \quad p = p + p'$$

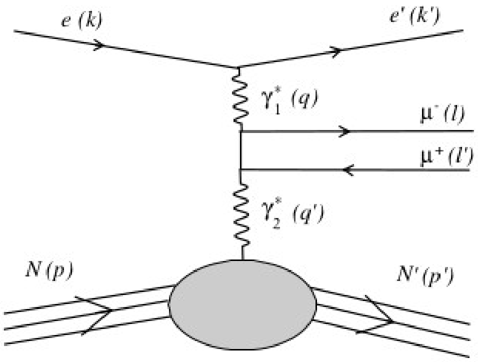
$$\Delta = p - p' = q - q' \text{ with } t = \Delta^2$$

$$x_B = -\frac{1}{2}\frac{q_1 \cdot q_1}{p_1 \cdot q_1}; \quad \xi' = -\frac{q \cdot q}{p \cdot q}; \quad \xi = \frac{\Delta \cdot q}{p \cdot q}$$

“BH1”



“BH2”



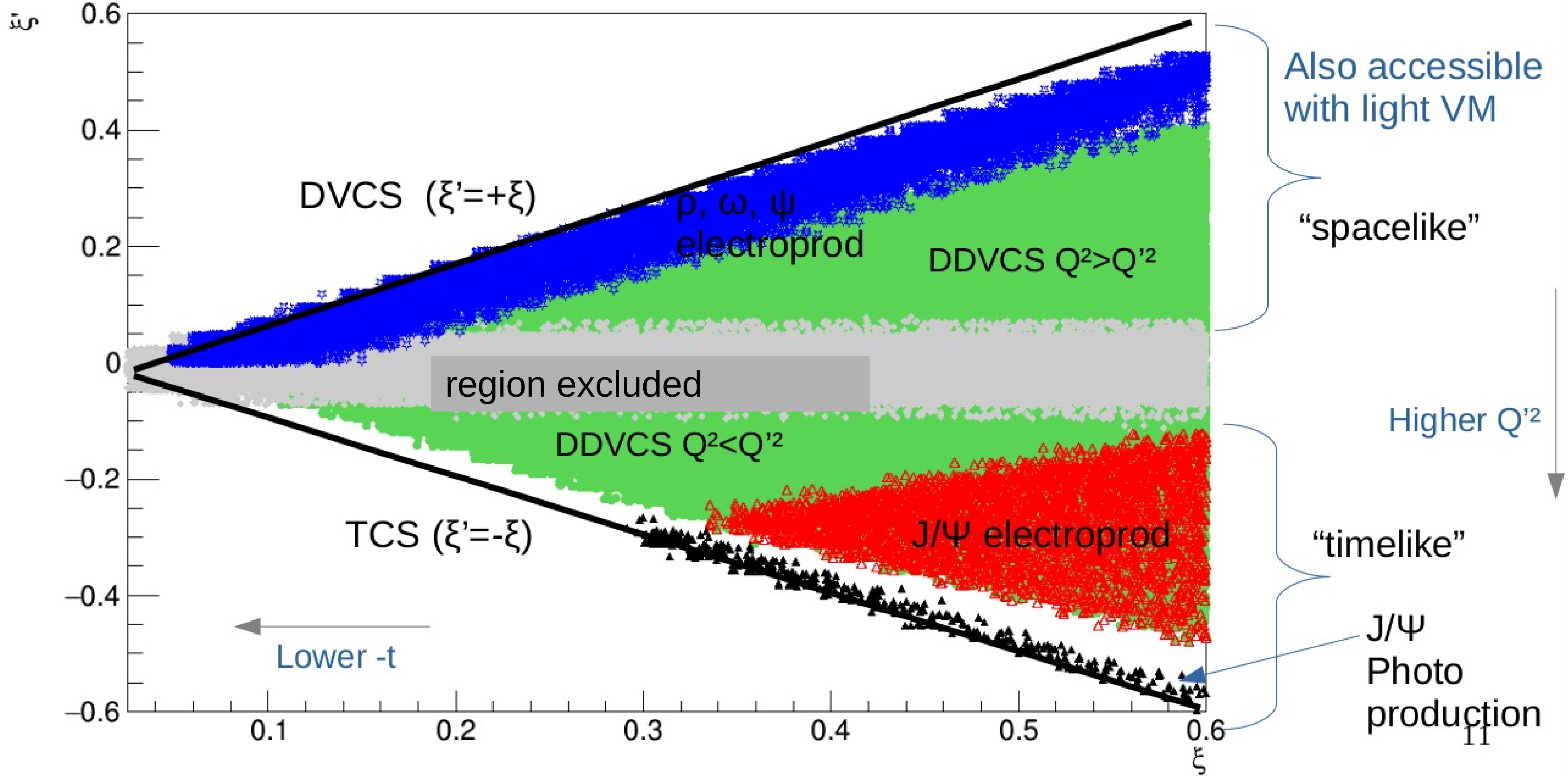
“skewness”:

$$\xi = \frac{Q^2 - Q'^2 + (\Delta^2/2)}{2(Q^2/x_B) - Q^2 - Q'^2 + \Delta^2}$$

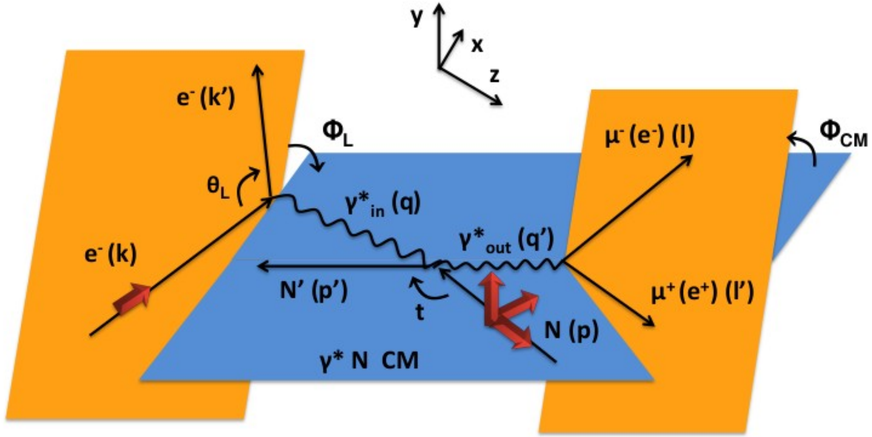
$$\xi' = -\frac{Q^2 + Q'^2}{2(Q^2/x_B) - Q^2 - Q'^2 + \Delta^2}$$

Using DDVCS Q'² and meson masses to go "off-diagonal"

11 GeV beam, -t<1 GeV², W²<2 GeV², Q'² (TCS, DDVCS>2 GeV²), Q² (electroprod. > 1 GeV²)



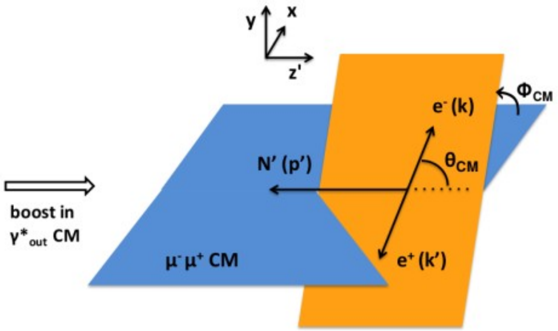
Angles and correlations



$$\frac{d^7\sigma}{dx_B\, dy\, dt\, d\phi_{LH}\, dQ'^2\, d\Omega_{CM}} = \frac{1}{(2\pi)^3}\frac{\alpha^4}{16}\frac{y x_{bj}}{Q^2\sqrt{1+\varepsilon^2}}\sqrt{1-\frac{4m_\mu^2}{Q'^2}}\,|\mathcal{T}|^2$$

with:

$$|\mathcal{T}|^2 = |\mathcal{T}_{DDVCS}|^2 + \mathcal{I}_1 + \mathcal{I}_2 + |\mathcal{T}_{BH_1}|^2 + |\mathcal{T}_{BH_2}|^2 + \mathcal{T}_{BH_{12}}$$



3 angles: azimuthal angle for incoming and outgoing lepton / polar for outgoing lepton

"BH1" influences strongly ϕ_L distribution
"BH2" influences strongly ϕ_{CM} distribution
θ: mostly rate of DDVCS/"BH2"

Study of angular correlations is essential to define obserbables, interpret projections, and design an experiment

Observables to be mesured in DDVCS+BH

Unpolarized cross section and beam spin asymmetries:

$$\left\{ \begin{array}{c} A_{\rm LU}^{\sin\phi_{LH}} \\ A_{\rm LU}^{\sin\phi_{CM}} \end{array} \right\} = \frac{1}{\mathcal{N}} \int_{\pi/4}^{3\pi/4} d\theta_{CM} \int_0^{2\pi} d\phi_{CM} \int_0^{2\pi} d\phi_{LH} \left\{ \begin{array}{c} 2\sin\phi_{LH} \\ 2\sin\phi_{CM} \end{array} \right\} \frac{d^7\overrightarrow{\sigma} - d^7\overleftarrow{\sigma}}{dx_{bj}\, dy\, dt\, d\phi_{LH}\, dQ'^2\, d\Omega_{CM}}$$

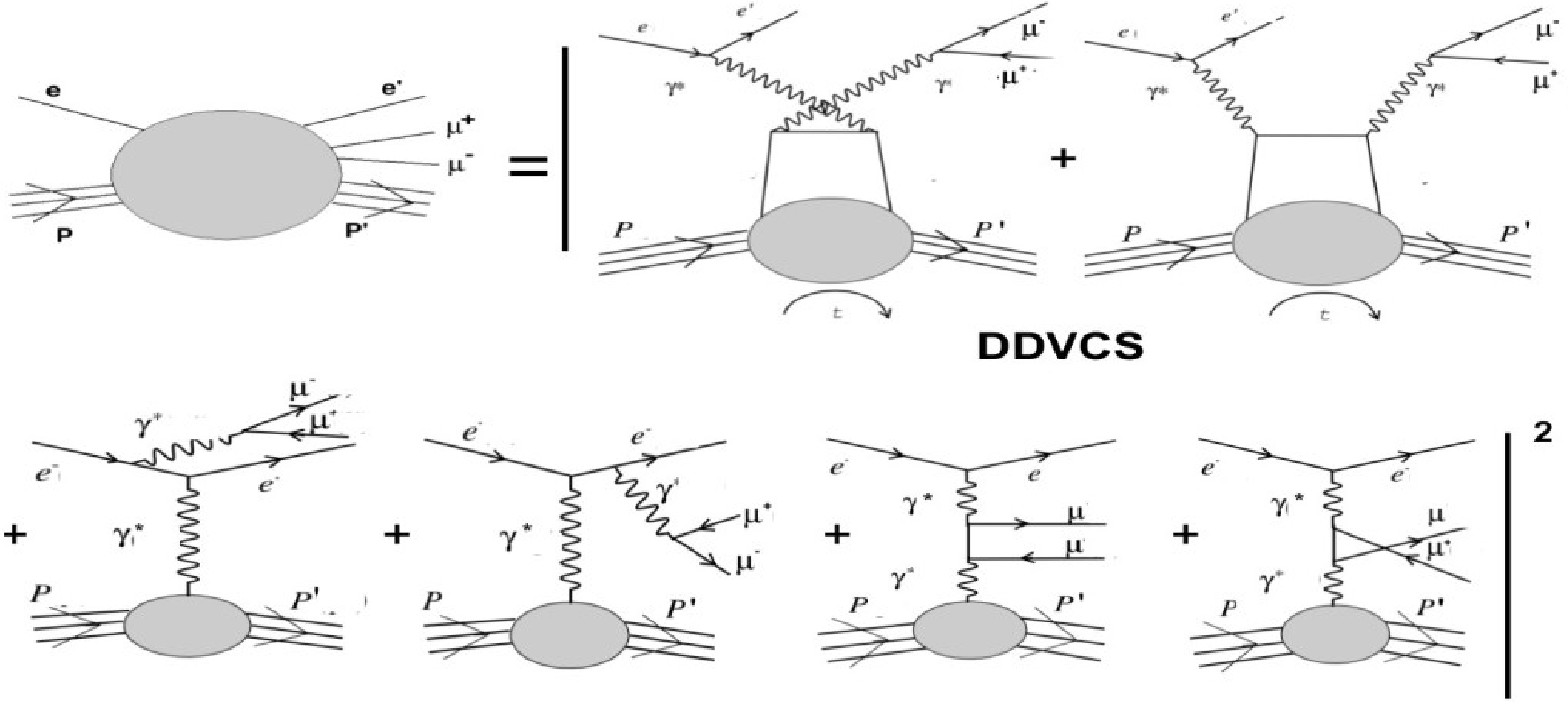
$$\propto \Im\mathrm{m} \left\{ F_1 \mathcal{H} - \frac{t}{4M_N^2} F_2 \mathcal{E} + \xi'(F_1 + F_2)\widetilde{\mathcal{H}} \right\} ,$$

- Unpolarized cross section gives access to Re and Im of amplitudes

- BSA gives access to Im(H)

We need to define “2D” ϕ_L versus ϕ_{CM} asymmetries. We can integrate over polar angle

Angular behavior and “effective” observables



no favored direction for γ* emission or decay leptons

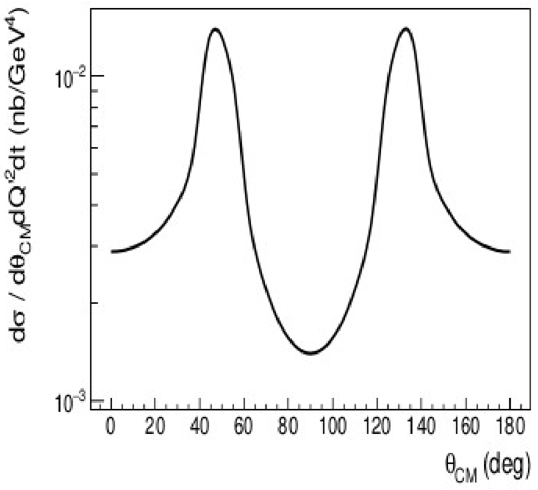
BH_1

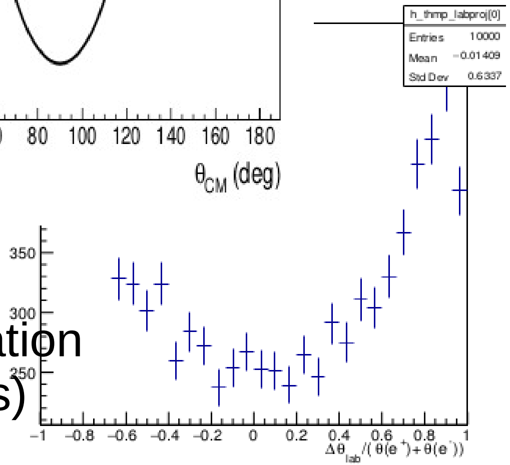
peak when γ' becomes collinear to e
related to φ_{LH}=0,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics)
and "y"→e' angle

BH_2

2 peaks when μ+ or μ- become collinear to γ
related to φ_{LH}=0 and 180°,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics) which position
the value of θ_{CM} for the peaks

Method developed for TCS+BH angles





(direct calculation
vs simulations)

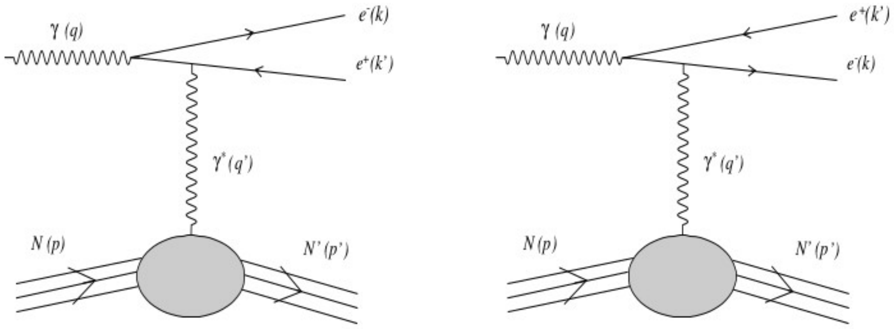


Figure 1: Bethe-Heitler leading order and leading twist diagrams.

(similar to "BH2")

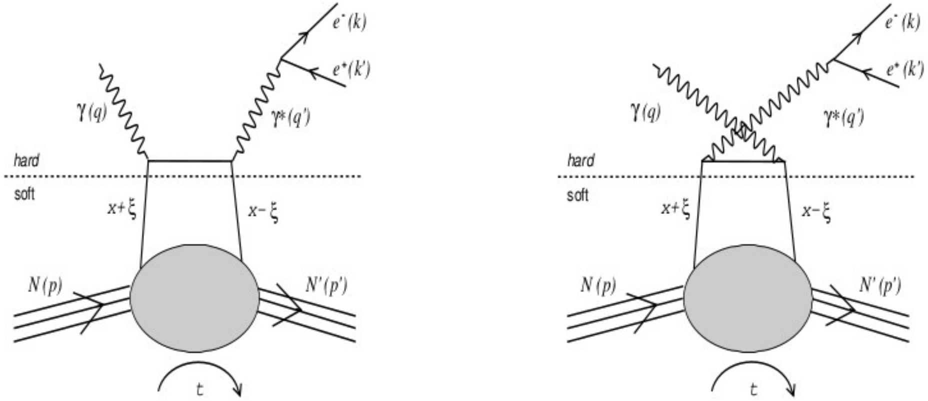


Figure 2: TCS leading order and leading twist handbag diagrams.

First peak = positron diagram
Second peak = electron diagram

when e' becomes collinear to incoming photon. Depends on E, t, Q'²

Some studies (just an example to understand)

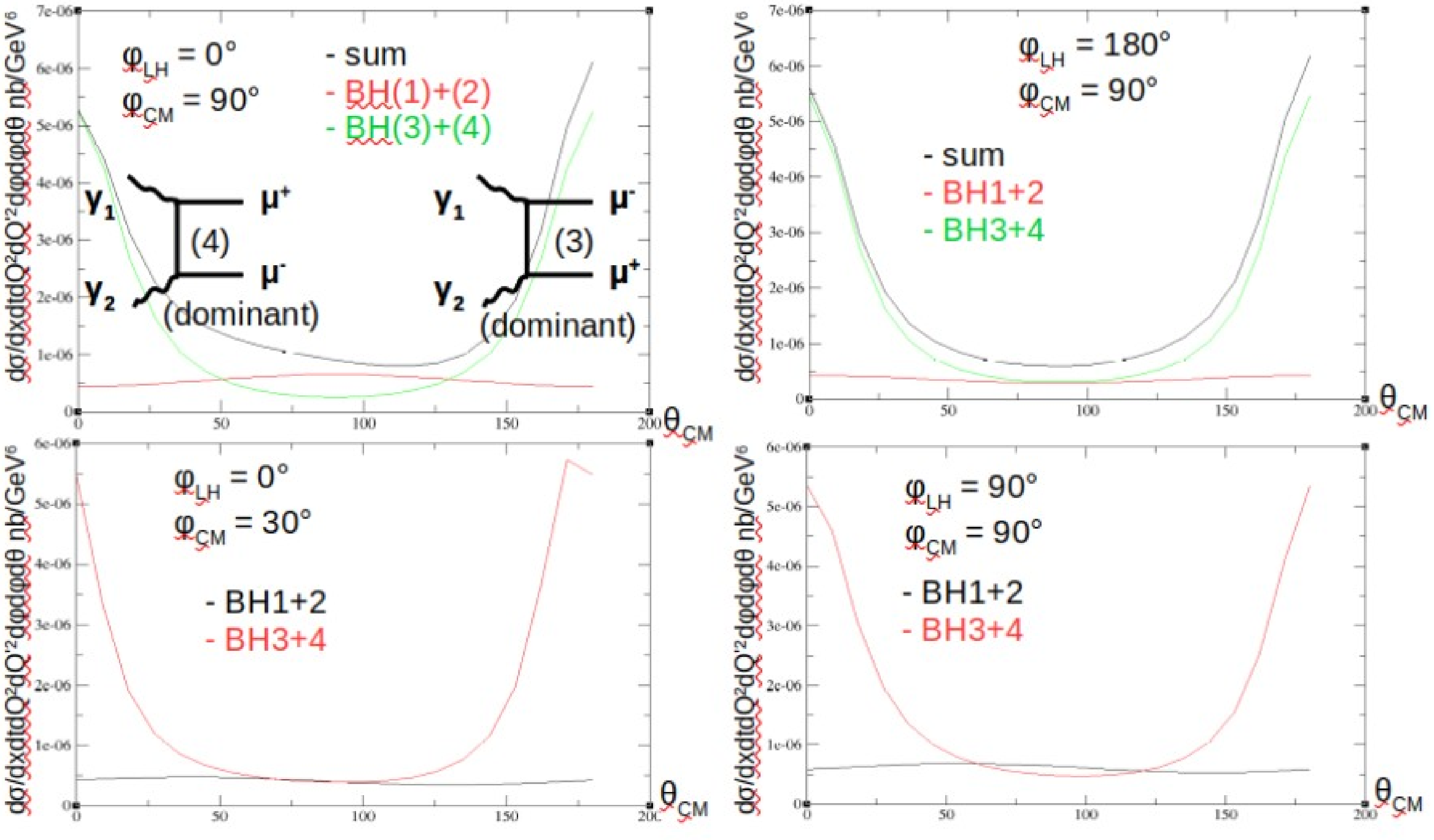


Figure 10: Angular distributions in θ_{CM} at fixed azimuthal angle values (indicated in each panel) computed with only some of the diagrams involved in the reaction.

Projected observables for experiment at JLab and studies of angular correlations

Still need to work on:
2D fits of CFFs on
the 2 azimuthal angle with all GPDs included

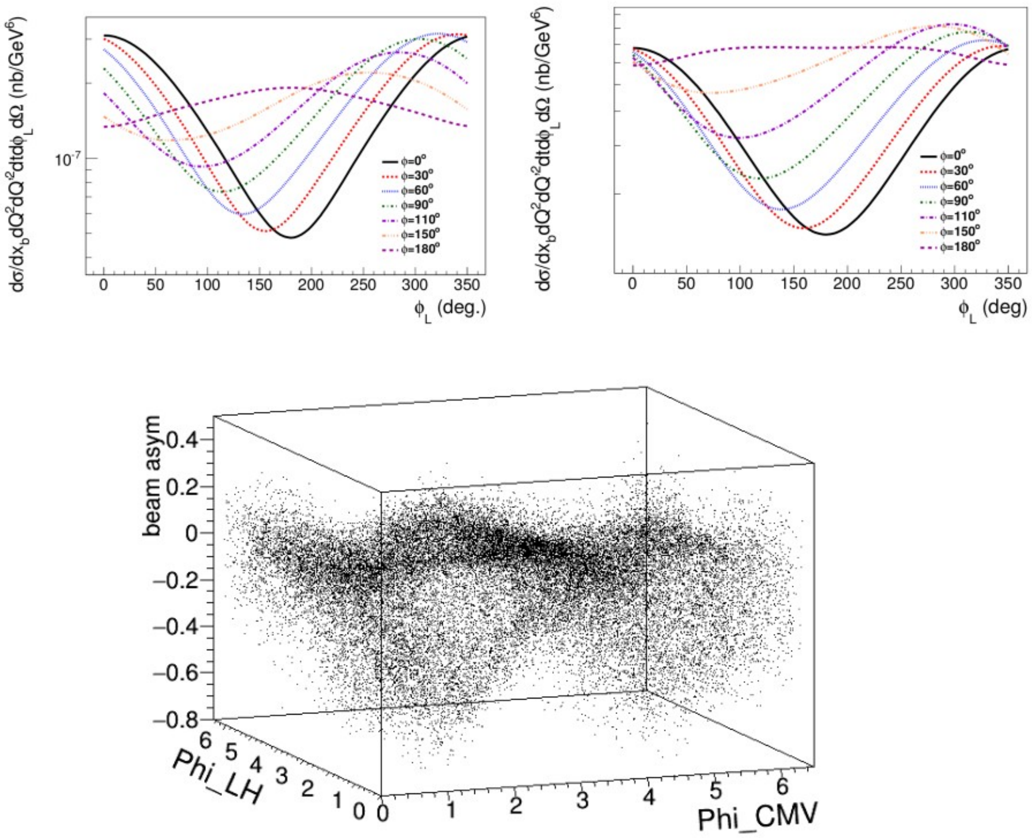


Figure 6: Top row: ϕ_{LH} dependencies of the unpolarized DDVCS+BH cross section for different fixed values of ϕ_{CM}. On the left, we selected a region ($\theta_{CM} = 90^o$) where the DDVCS/BH rate is the highest, and on the right, we selected a region where "BH2" largely dominates ($\theta_{CM} = 30^o$). Bottom: 2-D ϕ_{LH} versus ϕ_{CM} dependencies of the beam spin asymmetries. This is showing that the 2 angles must be measured independently and was can't integrate over one of them.

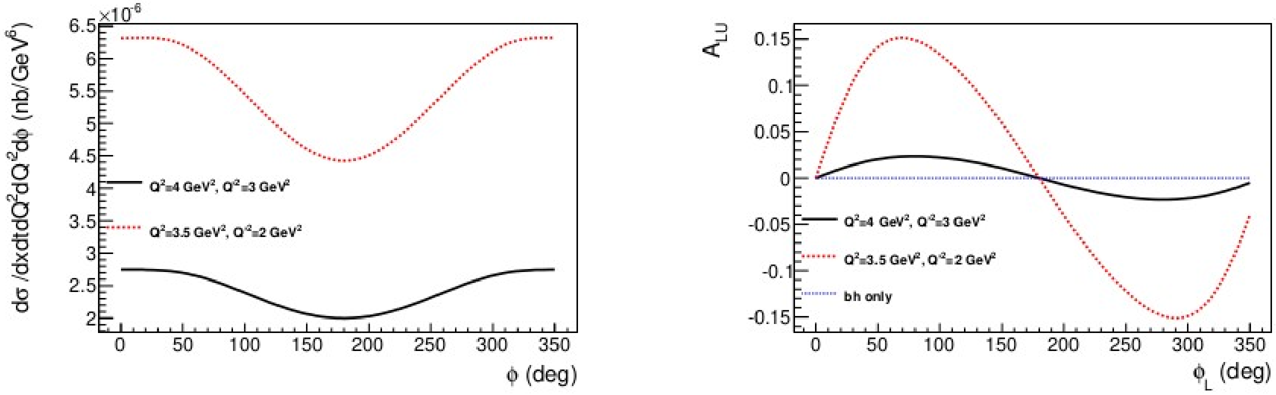


Figure 7: Out-of-plane ϕ_{LH} angular dependence of the differential cross section (left) and the beam spin asymmetry (right) for the $eP \to e'p\mu^+\mu^-$ process at E=11 GeV, x_{bj}=0.25, t=-0.4 GeV^2, and different virtual photon masses.

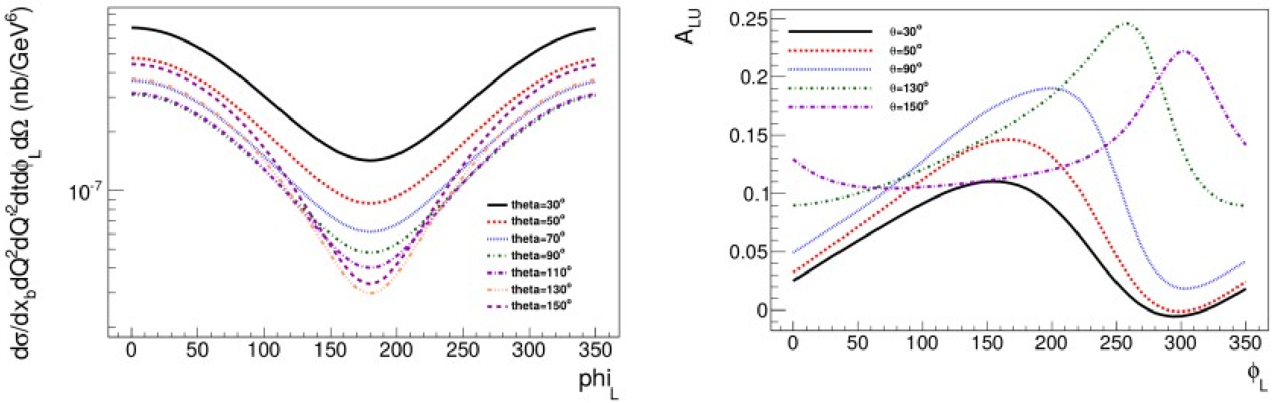
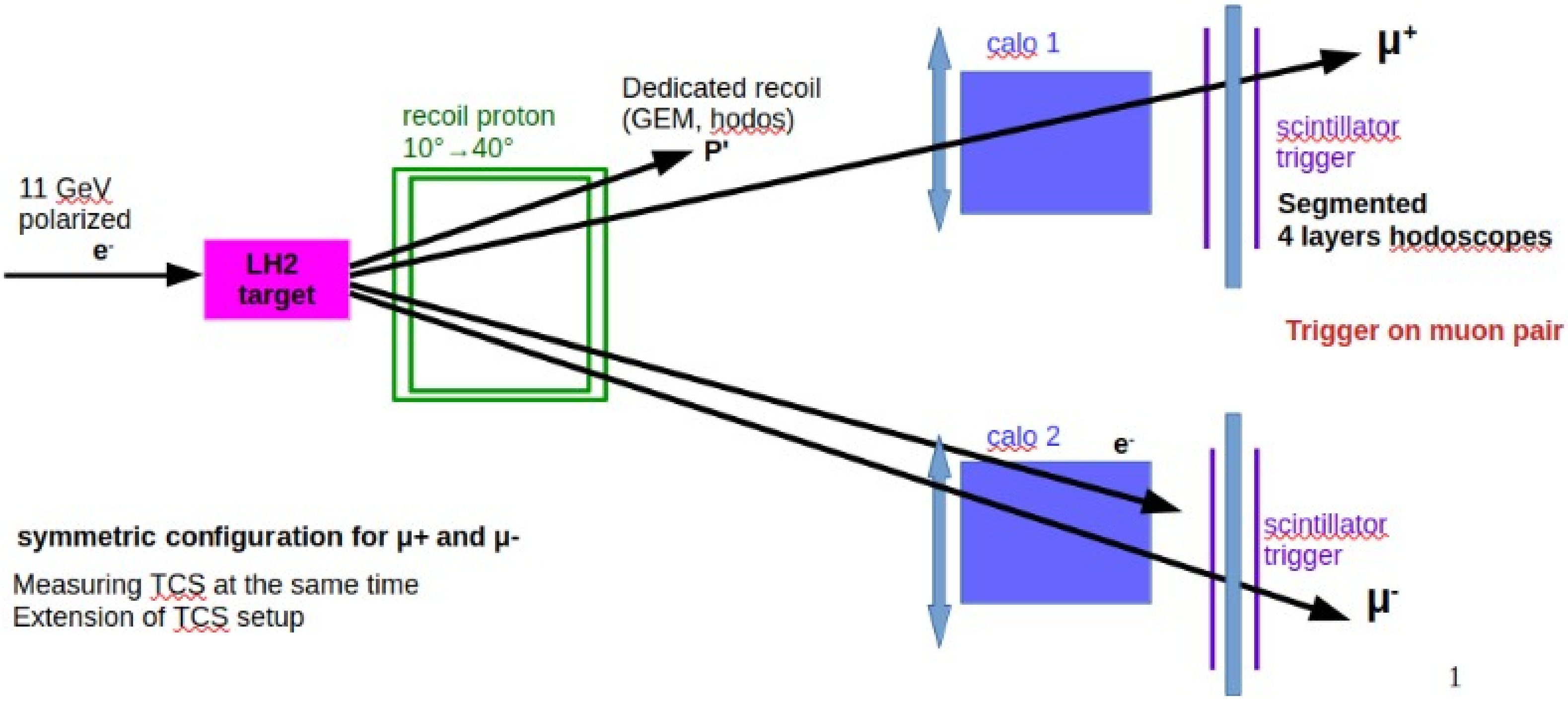


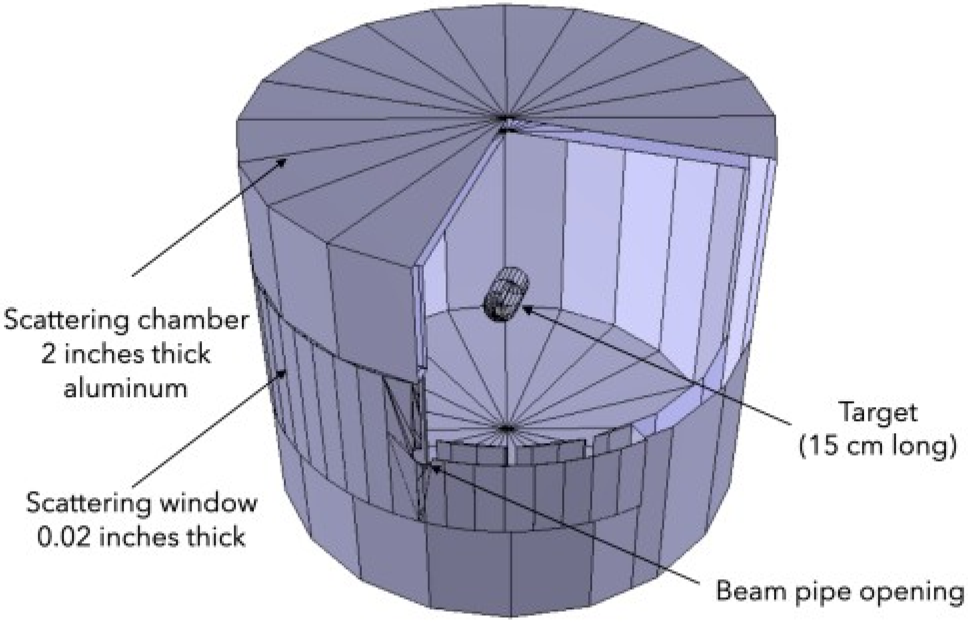
Figure 8: Out-of-plane angular dependence of the differential cross section for various polar angles of the muon (left) and for the differential beam spin asymmetry (right)

Proposed setup and R&D for muon detector

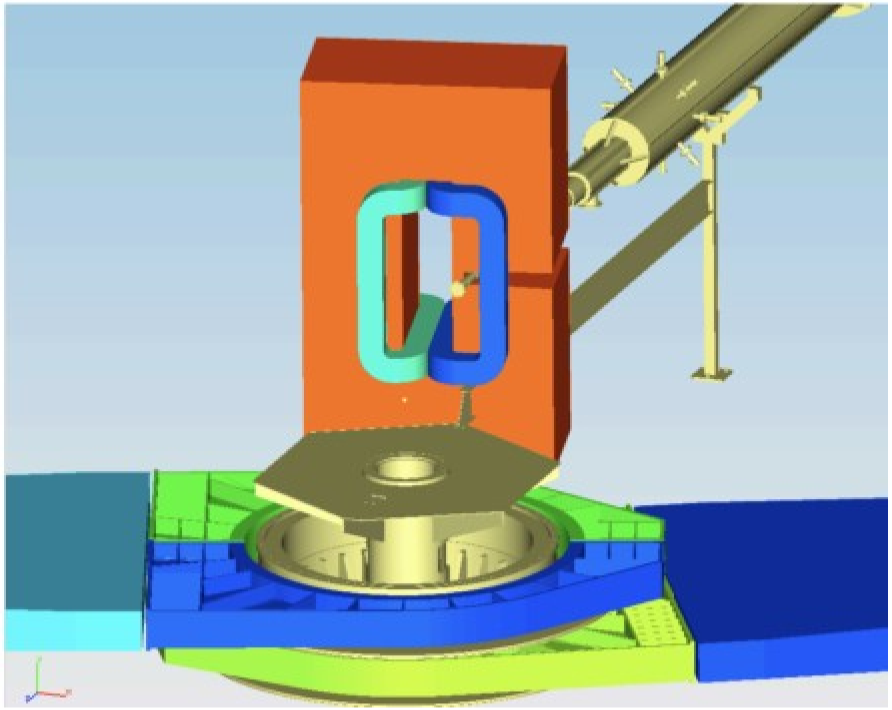
Dedicated setup proposed for Hall C



Most things need to be developed or re-used



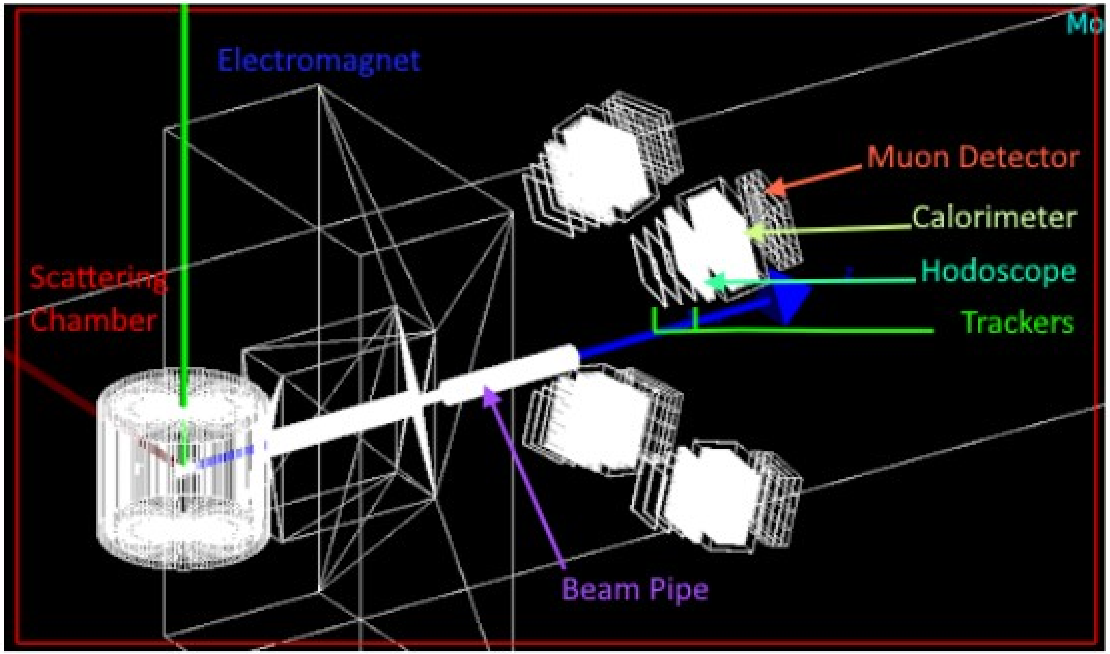
target and scattering chamber



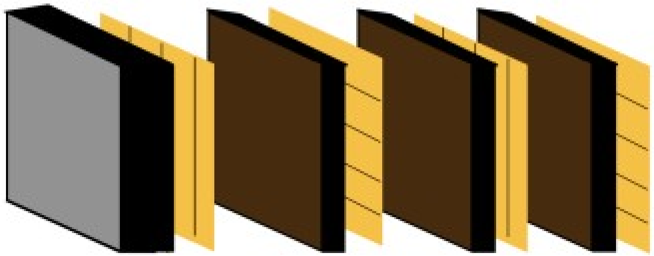
SBS magnet (in Hall A now)

this is what we are proposing in parallel for unpolarized TCS (see Vardan's talk)

GEANT4 simulations: new muon detector



(a) Geant4 simulation of the full di-lepton spectrometer for DDVCS experiment in Hall C. Each of the four quadrants of detectors consists of trackers, hodoscopes, calorimeter and muon detector.



(b) Conceptual design of the muon detector. Two segmented scintillator planes are sandwiched between three absorber planes. The segmentation of the first and second scintillator planes offers spatial information along the x and y axes, respectively.

Studying different material and thicknesses.
Retained for LOI: 20 cm lead, then 20+20+20cm iron absorber and 15 cm plastic scintillators

combined total hits in all four scintillators				
particle	1 GeV	2 GeV	4 GeV	6 GeV
mu-	19992	39987	39983	39985
pi+	1359	2237	3476	5314

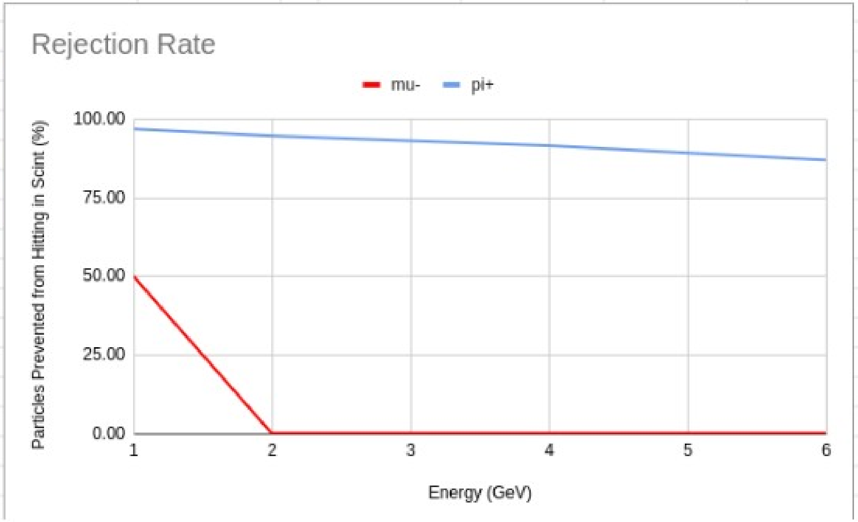
hits in each layer of scintillator				1 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9998	9993	1	0
pi+	1080	279	0	0

hits in each layer of scintillator				2 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9998	9998	9998	9993
pi+	1485	536	186	40

hits in each layer of scintillator				4 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9997	9996	9996	9994
pi+	2100	919	349	108

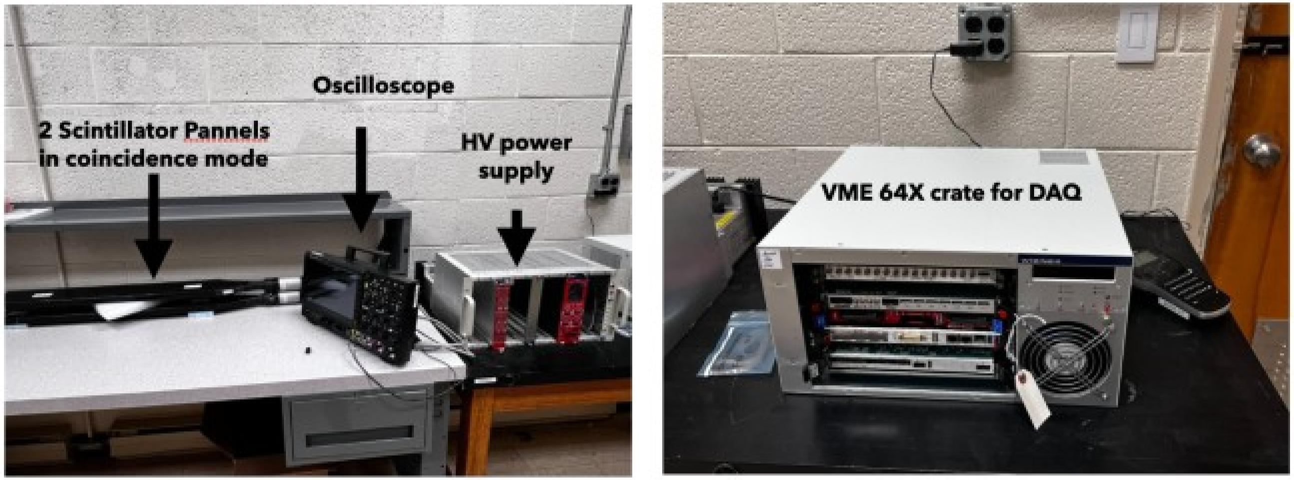
hits in each layer of scintillator				6 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9997	9997	9997	9994
pi+	3011	1428	631	244

rejection rate		
energy (GeV)	mu-	pi+
1	50.02	96.60
2	0.03	94.41
4	0.04	91.31
6	0.04	86.72

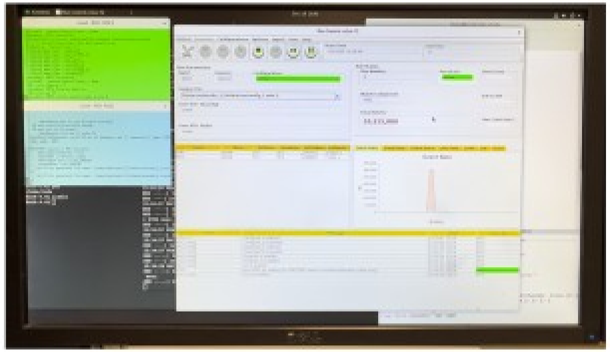


Harware R&D in parallel

Here is the basic setup we started with in our lab at VT.
DAQ/CODA based on JLab software – plan to test at JLab during another run.



(a)



(b)

We are setting up DAQ, then we plan to move towards building a simple prototype.
We are making funding requests for a larger scale prototype that can be tested at JLab

Summary and PAC/TAC comments

- LOI was submitted this year to PAC – waiting for the PAC report

- Theory review positive, not many comments. Just need to rearrange some notations

- Still need full background studies and actual rates (in progress, using Pythia and others)

- Muon detector setup: GEANT4 studies in progress, complemented by some tests in the lab

- Deb got JSA postdoc prize for his work and proposed R&D for the muon detector

- Can repurpose detectors/magnet/ shielding from other experiments, but need to develop the “2 lepton arms” concept with GEMs, hodoscopes, ECAL, then muon detector – based on “TCS”

- Suggestion from reviewers: see next few slides

PAC comments summary (Kresimir Kumericki)

- likes the work on angular correlations. Just few comments on plots / clarify conventions

- need actual counting rates

- need to include magnet effects (in GEANT4)

- discuss complementarity with other proposals at JLab (SoLID submitted as LOI in 2023, CLAS12 didn’t submit this year but are working on it too)

- beam dump comment (see TAC)

To do from us:

- Fits of CFFs from DDVCS
- compare different models (if available) – maybe work from Warsaw group
- physics background
- finalize angular studies (not fully included in generator, just in projections)
- We have a theorist (Kemal Tezgin) who just join our group and is working related things

Theory review (A. Radyushkin, R. Edwards)

This letter of intent proposes to study generalized parton distributions using the Double Deeply Virtual Compton Scattering (DDVCS) in the di-muon channel, i.e. the reaction $ep \to ep\gamma^* \to ep\mu^+\mu^-$ at 11 GeV incident beam energy. Unlike the usual Deeply Virtual Compton Scattering process $ep \to ep\gamma$, in which the final photon is real, the DDVS involves a timelike virtual photon γ^*, and the the nonzero virtuality of the final photon allows to investigate separately the x- and ξ-dependences of the GPDs, such as $H(x, \xi; t)$, while DVCS can give information about GPD on the diagonal $x = \xi$. In particular, DDVCS can access the GPDs in the so-called ERBL evolution region where $|x| \leq \xi$. The ability to decouple the experimental x- and ξ-dependences opens off-diagonal investigation of GPDs. More importantly, it enables to put constraints on the deconvolution of these two variables and the extrapolation of the skewness variable ξ to $\xi = 0$ value, which enters in the Ji's sum rule relating (an integral of) GPDs with the total angular momentum of the nucleon

no comments we have to work on here.

TAC comments

1. The DDVCS yield is proportional to α^4, so the cross sections are small. For a first DDVCS measurement, this LOI's scheme of employing an unpolarized target and a high luminosity facility such as Hall C seems very reasonable.

2. The setup in this LOI is an attempt to extend a so-far-unreviewed "unpolarized TCS" concept to the DDVCS reaction where a scattered e- and a μ+μ- pair need to be detected. The plan is to make fairly low resolution measurements of all 4 final state particles, which not only helps establish exclusivity, but helps determine the two azimuthal angles. It is a very complicated setup, with unusually complicated kinematics, so there may have some significant misunderstandings of the collaboration's intent. (seems we need to make some points more clear – submit TCS unpolarized next year in parallel, which was our intent this year but we got delayed)

3. The SBS dipole magnet would be located just downstream of the scattering chamber, centered on zero degrees, and bending vertically. The advantage of using a dipole magnet in that, with suitable tracking detectors, it allows the measurement of momenta, and distinguishes between positively and negatively charged particles. This dipole might be fine for the unpolarized TCS setup which has not been reviewed. However, there are 2 possibly fatal concerns if this dipole is used with an electron beam:

i. The dipole magnet will bend the primary beam almost 4 degrees, so a complementary dipole at least as powerful as the SBS would be needed to steer the 1 MWatt beam safely to the dump.

ii. After radiation and Moller scattering in the 15cm LH2 target, the 11 GeV exhaust beam will have acquired a significant low energy e- component at small angles. (The acquired e+ component is higher order.) The dipole magnet will deflect these low energy electrons into a vertical stripe. In principle, this stripe could miss the calorimeters which will be located on beam left and beam right. But in practice these electrons will dump on the downstream beam pipe and shower into the calorimeters. Dumping kilowatts of electrons at this location seems incompatible with high resolution calorimeter operation (and with staying beneath JLab's annual site boundary dose limits).

= we need to work on addressing these comments

4. We suggest exploring a less symmetric setup for DDVCS:

i. Use the SHMS to detect and identify the scattered e-. The SHMS has higher resolution than a PbWO4 calorimeter, has excellent e- PID, and is designed for high luminosity operation. This will accurately determine the electron scattering plane and the properties of the initial space-like photon.

ii. Appropriate kinematics (Q2 ~ 1 and W ~ 3) can be achieved with the SHMS at 7.3 degrees. The corresponding q-vector is at 8.9 degrees on the opposite side of the beamline. (The LOI mentions the constraint W > 2. But the final state has to decay into a proton and timelike virtual photon with physical mass Q' = 2, so we assume W ~3 for now.)

iii. The question is then whether an appropriate magnet and detectors could be laid out, centered on the q-vector. Since the scattered electron would be detected in the SHMS, the complex PbWO4 calorimeters would not be needed, only appropriate detectors for protons and di-muons. The di-muon spectrometer might make an attractive NSF MRI proposal.

our comments: 1. already explored, acceptance too small. 2. not sure. 3. calorimeter have higher coverage but this is a fair comments, we agree with that.

5. A full proposal should include:
i. How is PID established for every particle?
ii. How is the energy or momentum of each particle determined, and with what resolution?
iii. Rates: signal rates, accidental coincidence rates, singles rates for all detectors.

our responses
I. muon detector / pions will be stopped. same problem as TCS for e and P
ii. we need more work to get accurate resolutions
iii. same.