Double Deeply Virtual Compton Scattering at JLab (Hall C / Hall A)

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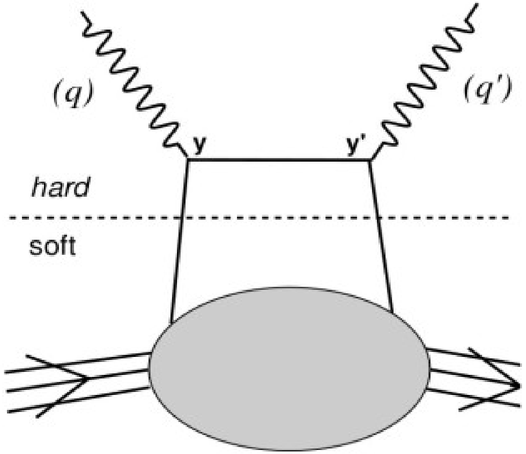
Virginia Tech

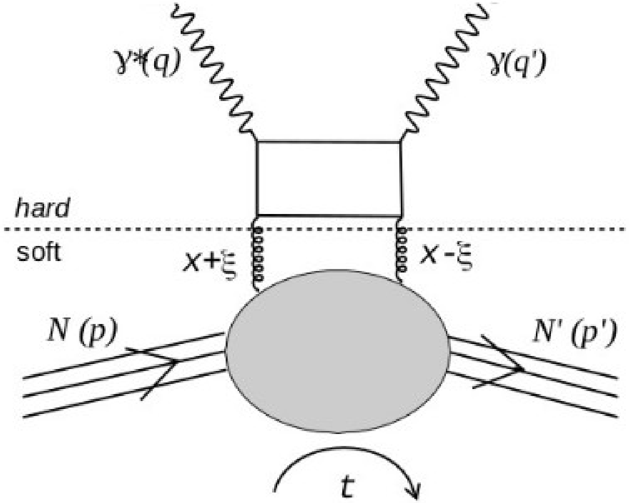
GHP, March 14th, 2025

PARTONIC STRUCTURE OF THE HADRONS

Work supported by DOE grant DE-SC0025657 and by Virginia Tech College of Science

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, ...

See Deb's talk for TCS

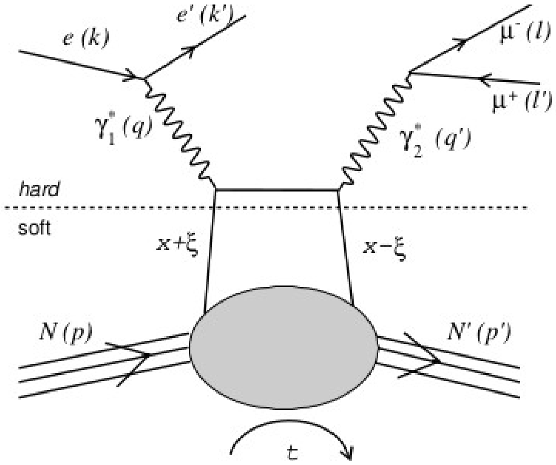
I will focus on DDVCS
in this presentation

Mahmoud's talk:
muon detector

Phenomenology of DDVCS

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

DDVCS



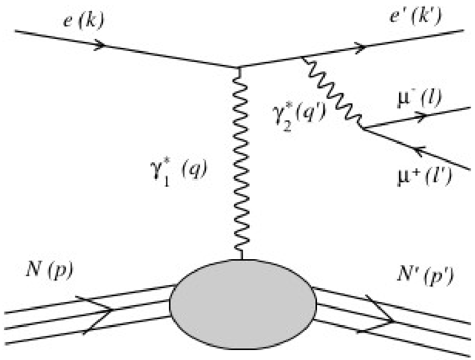
Variables definition/notations:

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

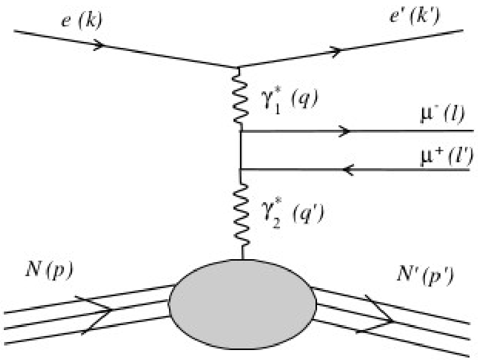
$$\Delta = p - p' = q - q' \text{ with } t = \Delta^2$$

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

"BH1"



"BH2"



"skewness":

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

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

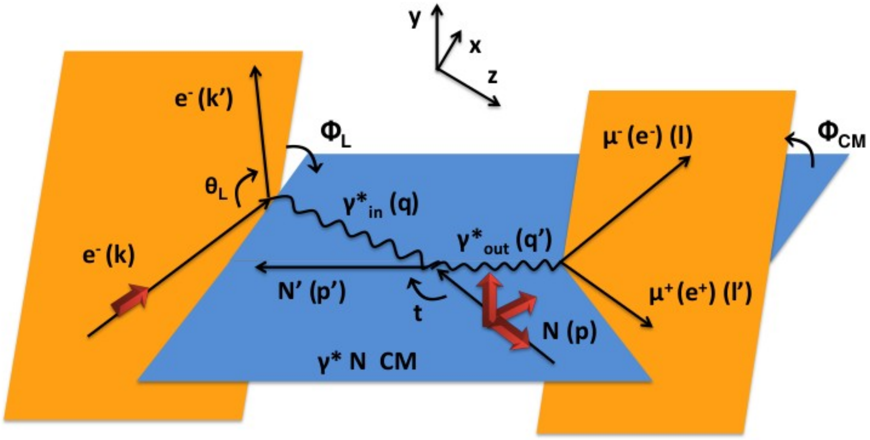
Phenomenology of DDVCS

7-independent variables for cross section.
Choice: E_e, ξ (or x_{bj}), t, Q^2, Q'^2, Φ_L, Φ_{CM}, θ_{CM}

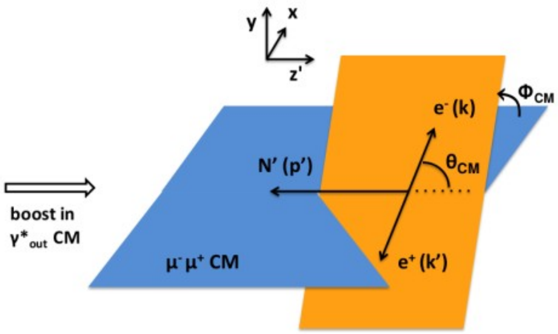
$$\frac{d^7\sigma}{dx_B\, dy\, dt\, d\phi_{LH}\, dQ'^2\, d\Omega_{CM}} = \frac{1}{(2\pi)^3}\frac{\alpha^4}{16}\frac{y x_{bj}}{Q^2\sqrt{1+\varepsilon^2}}\sqrt{1-\frac{4m_\mu^2}{Q'^2}}\,|\mathcal{T}|^2$$

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"

Observables to be mesured in DDVCS+BH

Unpolarized cross section and beam spin asymmetries:

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

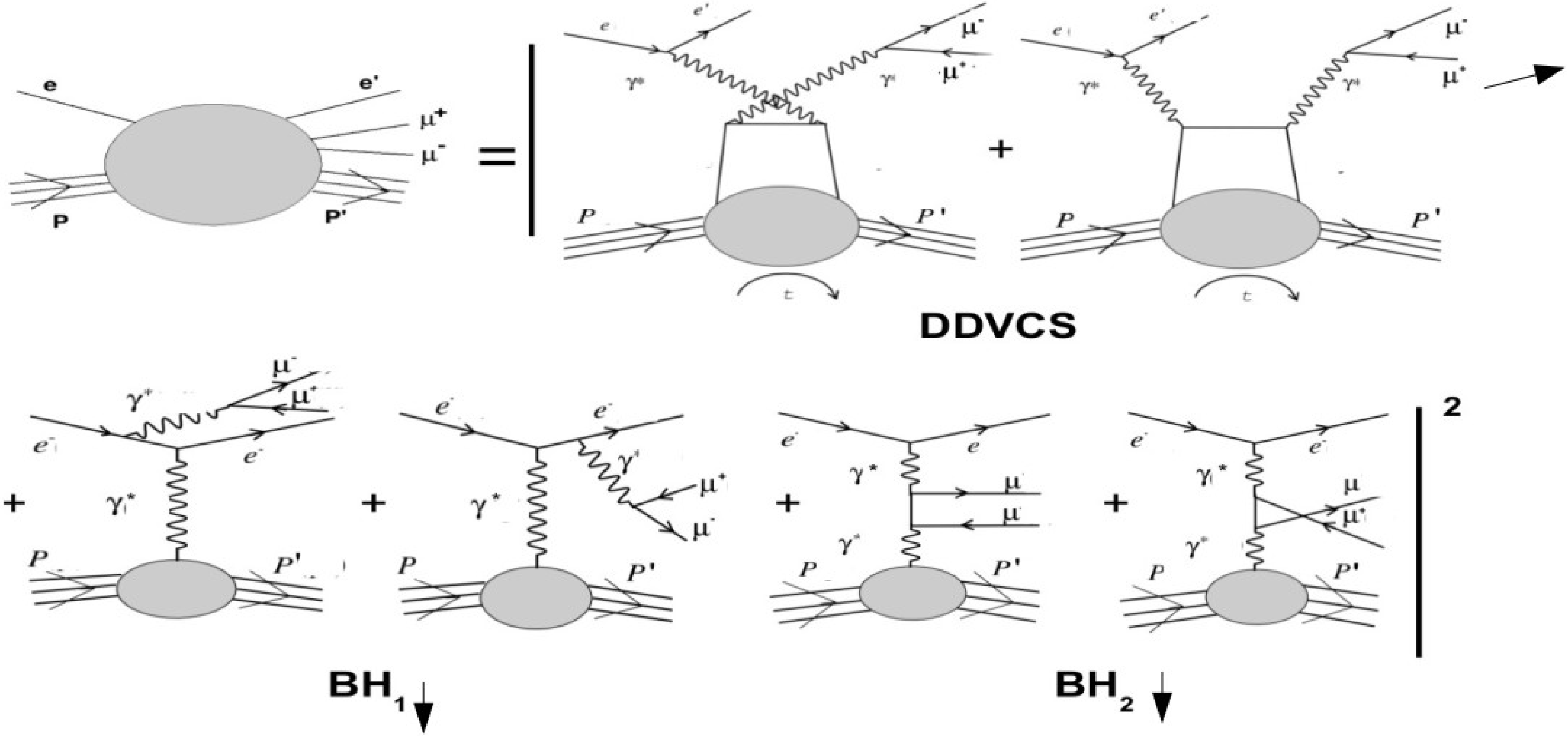
$$\propto \Im\mathrm{m} \left\{ F_1 \mathcal{H} - \frac{t}{4M_N^2} F_2 \mathcal{E} + \xi' (F_1 + F_2) \widetilde{\mathcal{H}} \right\} ,$$

- 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

- Charge asymmetry (left/right asymmetry): can access real part of the amplitude (suggested by theorists, work in progress)

Angular behavior and “effective” observables



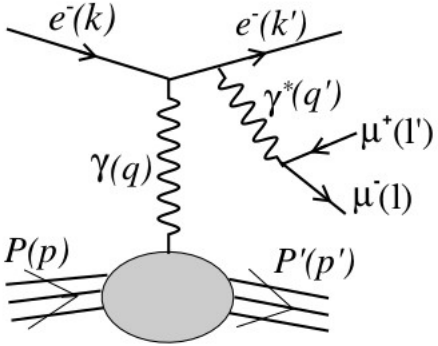
no favored direction for γ* emission or decay leptons

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

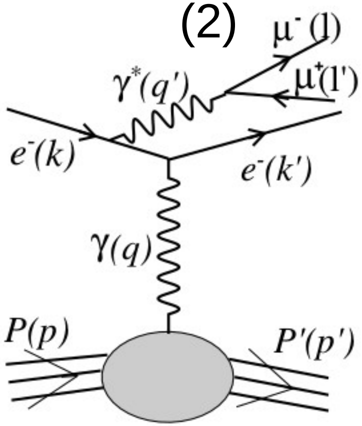
2 peaks when μ+ or μ- become collinear to γ
related to φ_{LH}=0 and 180°,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics) which position
the value of θ_{CM} for the peaks

Experimental and interpretation challenges

(1)

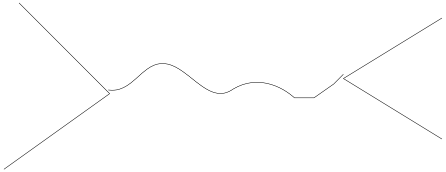


(2)



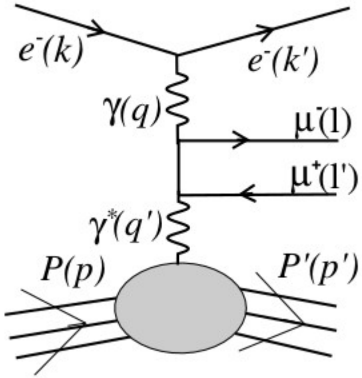
Interference with Bethe-Heitler

equivalent to pair production from e+e- annihilation

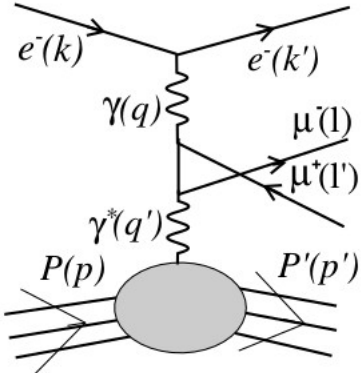


notations: γ1 connected to the beam and pair
and γ2 connected to the nucleon
see BH associated to DVCS when $Q'^2 \to 0$

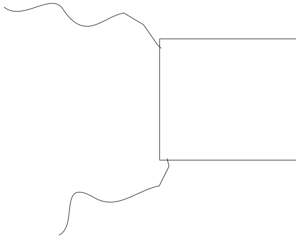
(3)



(4)



pair production from 2 virtual photons interaction



notations: γ1 connected to the beam
and γ2 connected to the nucleon
see "BH" associated to TCS when $Q^2 \to 0$

Studies of angular correlations with BH

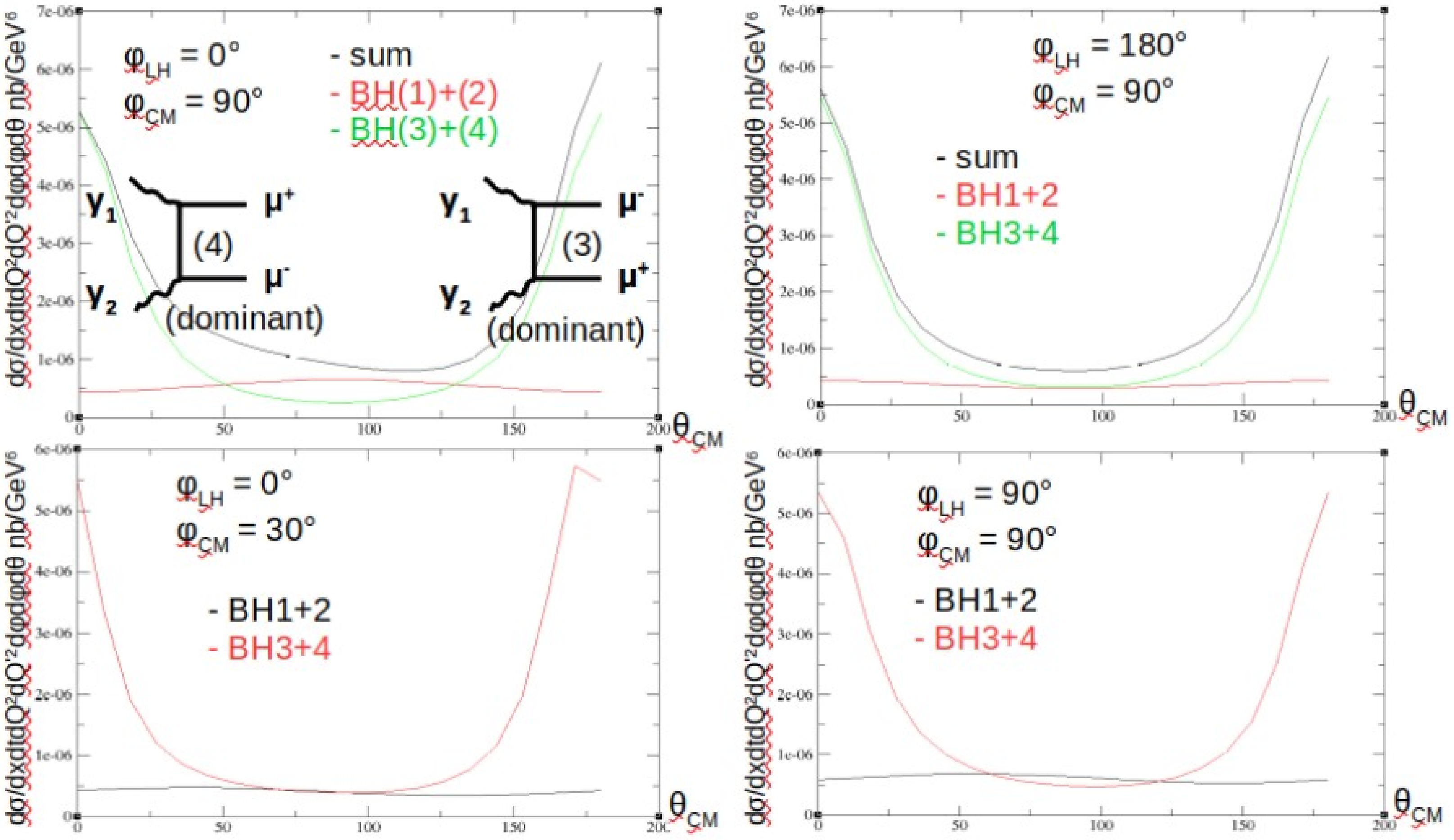
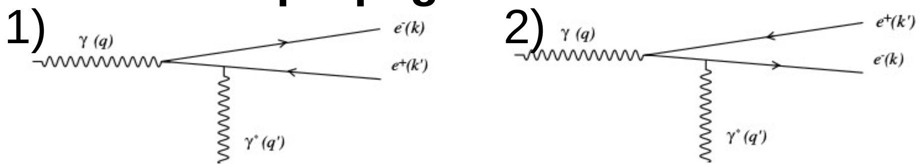


Figure 10: Angular distributions in θ_{CM} at fixed azimuthal angle values (indicated in each panel) computed with only some of the diagrams involved in the reaction.

Angular correlations ("as for TCS")

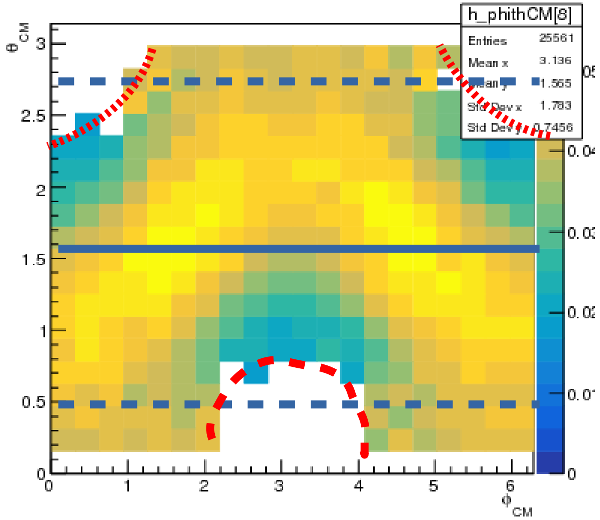
BH propagators



- BH peaks when e- or e+ collinear to incoming γ (from BH II)
- strong kinematic dependence at JLab energy
- one diagram becomes largely dominant / very asymmetric decays

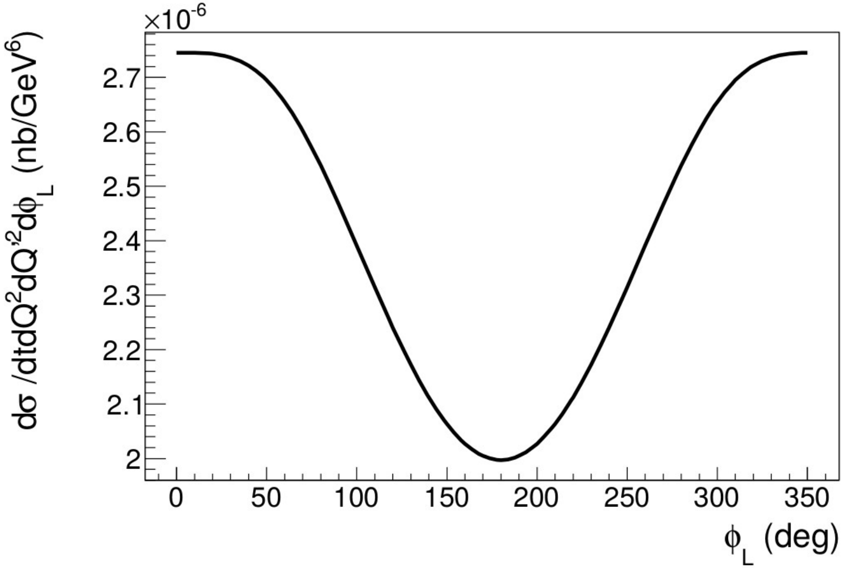
- Momentum and θ_{lab} cuts help already
- Q^2, Q'^2, xb, t dependent angular cut for "effective" observables

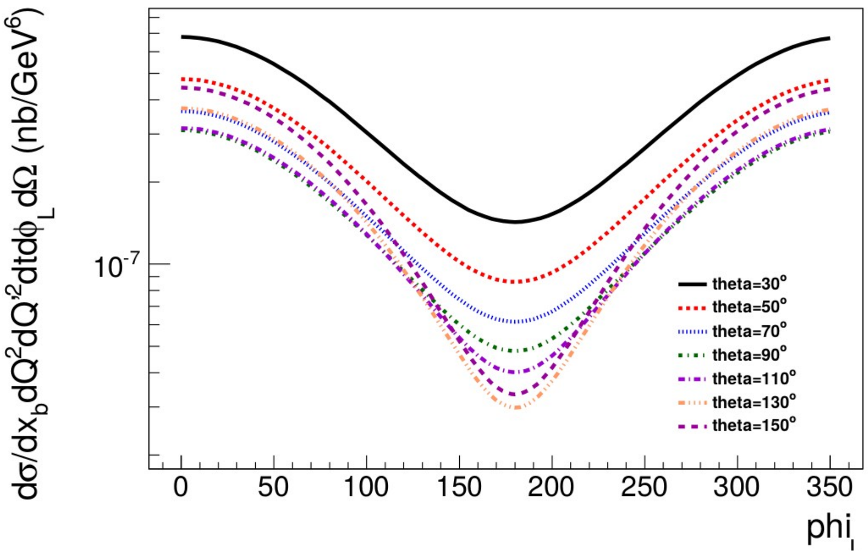
BH peaks: lepton 1 to beam direction, other almost "at rest" ⇒ momentum threshold and geometrical acceptance mostly prevent for too high rates and singularitie regions.
Angular + momentum acceptance is important



-- cut at 30°; 150°
-- acceptance cut
not included: cut of some bins next to singularities if not experimentaly "solvable" due to limited statistics (example 2 orders of magnitude increase of σ within a bin)

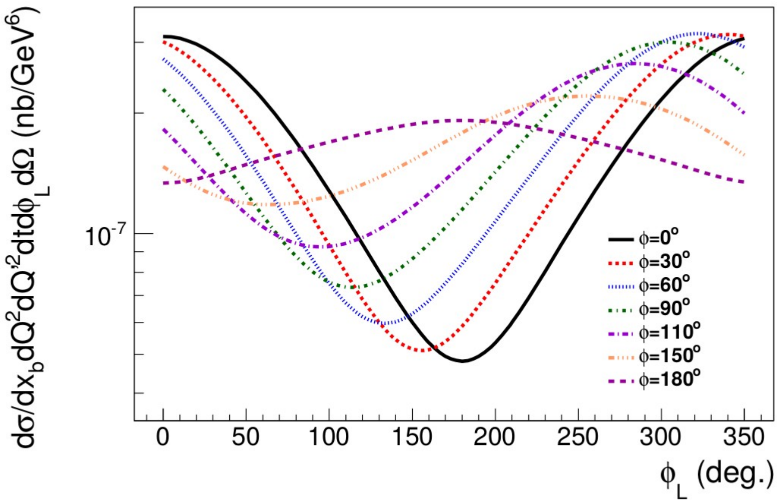
Cross sections versus angles





Due to strong angular dependence in 3 angles:

CFFs: 2D fits in φ_{CM}, φ_{LH}, as a function of ξ, ξ', t only Im($\mathcal{H}$) (ξ', ξ, t) will be possible to extract with unpolarized cross section and beam asym.



Cross sections
versus ϕ(LH) (initial) [left]
and ϕ(CM) (final) [right]

and 2 D calculation [bottom]

→we intend to develop 2D fits of Compton Form Factors to access GPDs from DDVCS (see later in this talk)

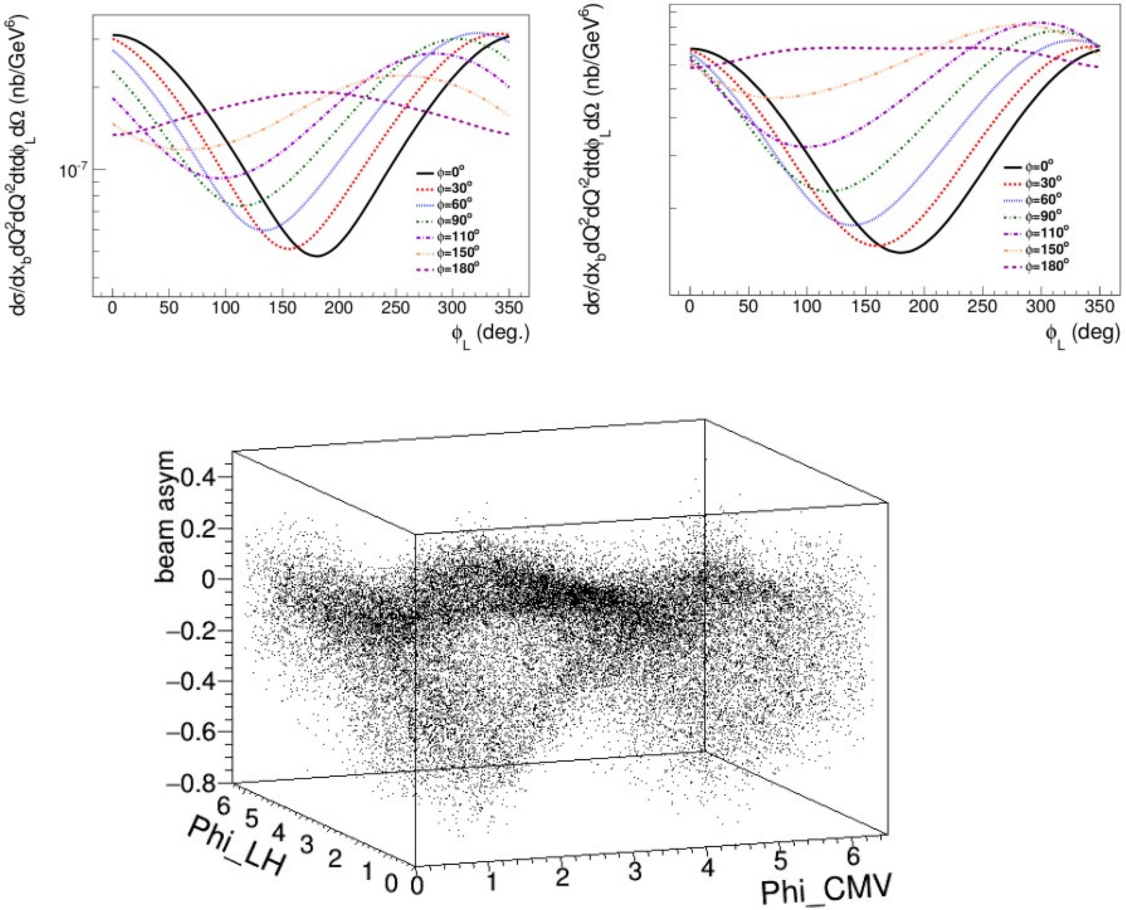
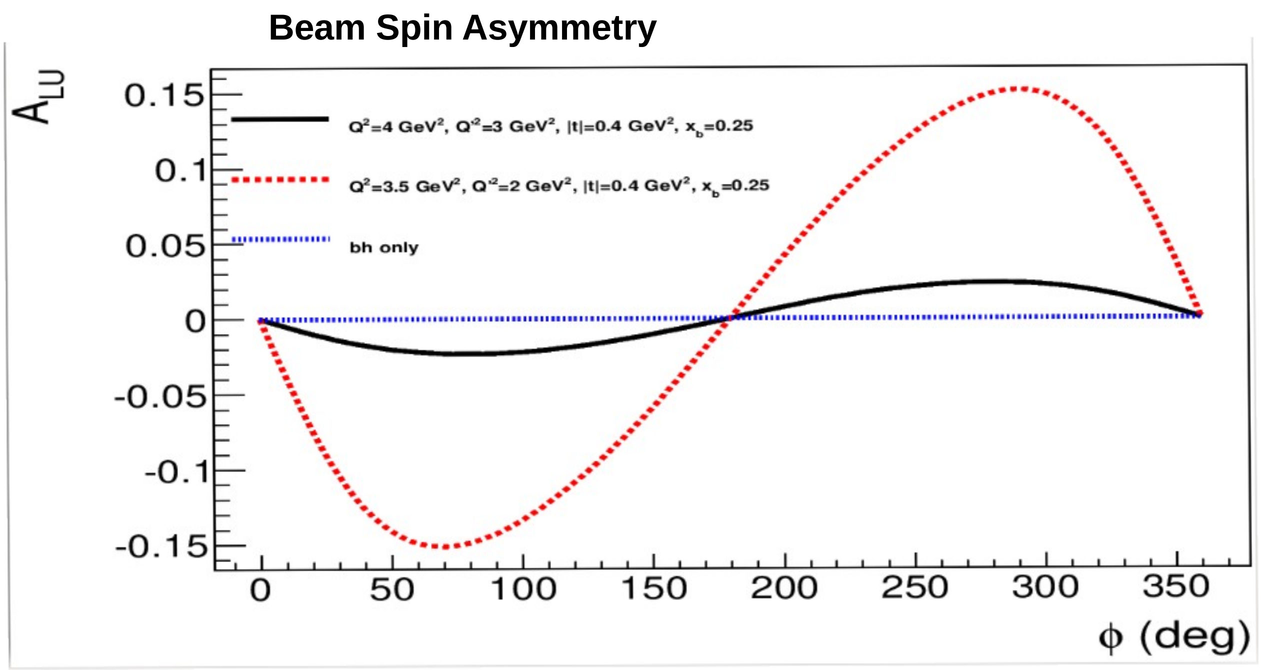


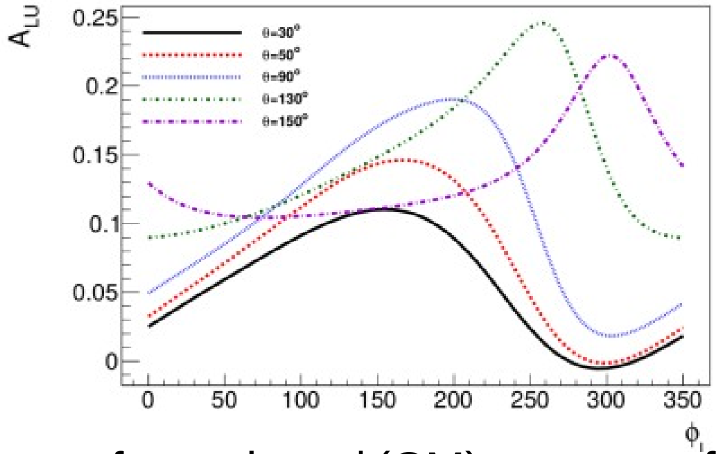
Figure 6: Top row: ϕ_{LH} dependencies of the unpolarized DDVCS+BH cross section for different fixed values of ϕ_{CM}. On the left, we selected a region ($\theta_{CM} = 90^o$) where the DDVCS/BH rate is the highest, and on the right, we selected a region where "BH2" largely dominates ($\theta_{CM} = 30^o$). 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.

DDVCS +BH Beam Spin Asymmetry



purely coming from interference between BH(1+2)*DDVCS asymmetries are sizeable.

Change of sign to be observed in different kinematic regions



for various ϕ(CM): same as for cross section, need to go 2D

Imaginary part of amplitude

BH cancels, comes from interference. Sizeable asymmetry and counts thanks to interference

Evolution of the beam spin asymmetry

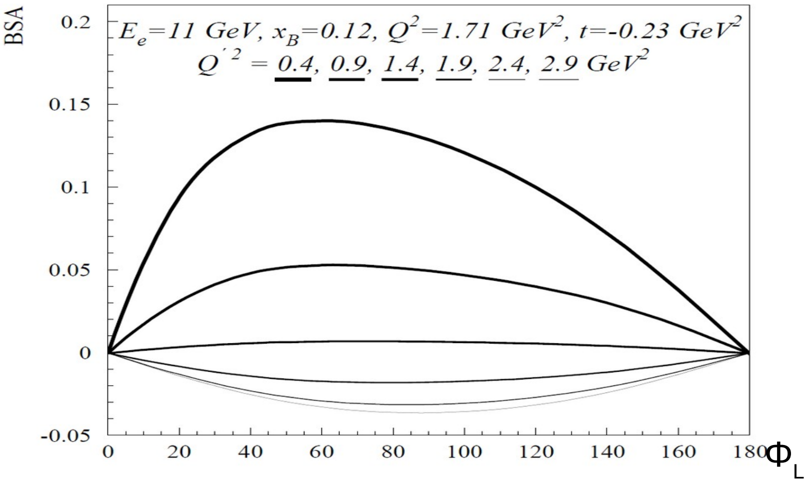
Sign change in BSA and interplay “spacelike” and “timelike” regions

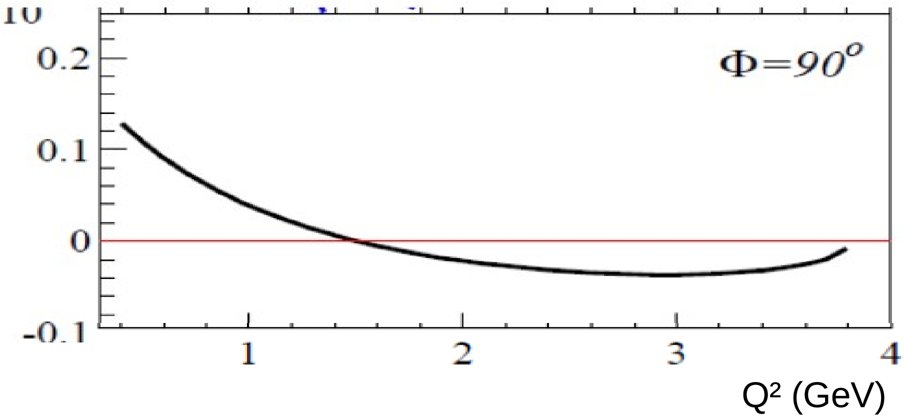
Calculations from M. Guidal (Trento, 2016)

→ scan of BSA in Q'² at fixed Q²

→ sign change in BSA vs Φ_L and vs φ_{CM} when Q'² ≈ Q²

asymmetry Q² scan





- Probing GPDs at x ≠ ξ → tomographic interpretations....
- Expectation of sign change for observables sensitive to Im (DDVCS) when moving from « spacelike » to « timelike » region

→ this reaction is unique for probing effects between these 2 regions.

Observables proposed (for Hall C measurement)

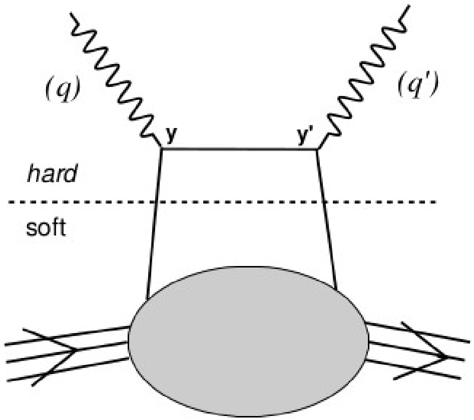
- truncated integral over θ and ϕ(CM) versus ϕ(LH) dependence of the unpolarized cross section and single beam spin asymmetry

- similar method as for TCS to limit the integrals, staying away from “BH peaks”

- we still need to study the correlation between the 2 types of BH
(some work has been done for SoLID by a collaborator, work in progress)

- limited number of bins, with as much statistics as possible on each to get a first measurement of DDVCS at JLab

Extraction of GPDs from Compton Form Factors (CFFs)



In DVCS and TCS: pole at x=±ξ

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx}_{\mathrm{Re}(\mathcal{H})} - \underbrace{i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}(\mathcal{H})} + \ldots$$

Difference between TCS and DVCS at asymptotic limit:
ξ'=ξ for DVCS and ξ'=-ξ for TCS → complex conjugate structure

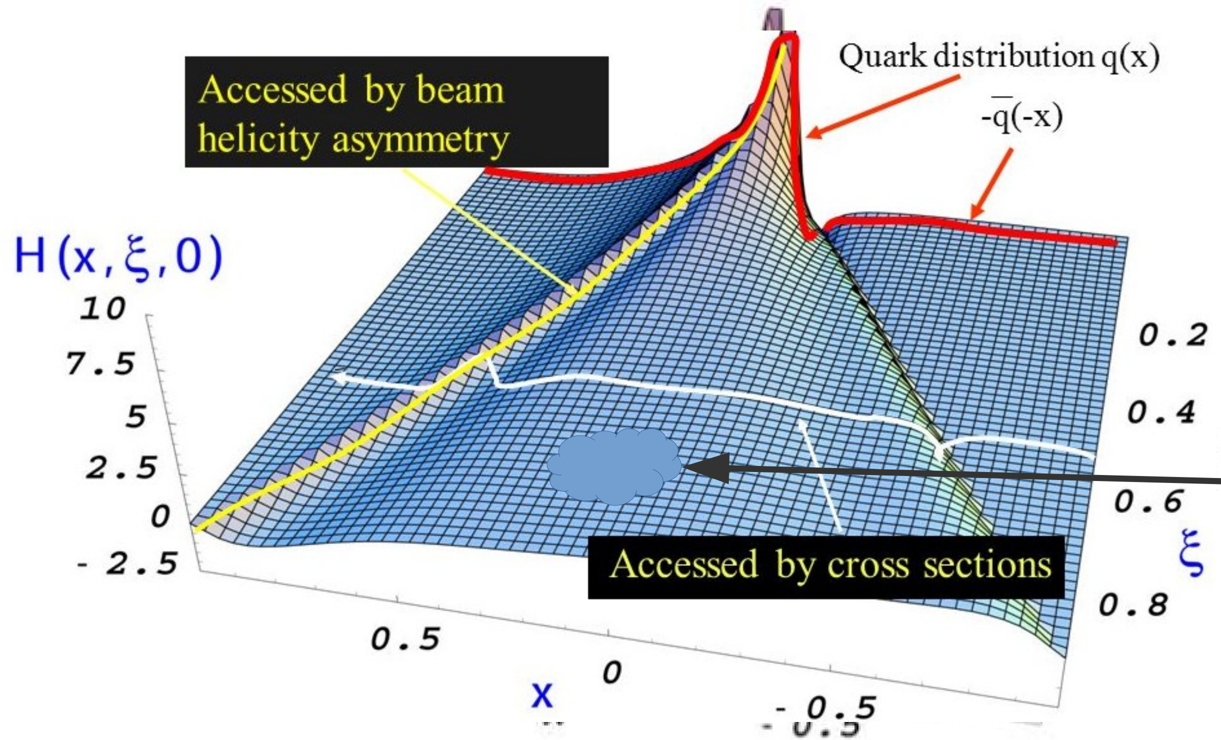
In DDVCS: ξ' dependence, due to 2 photons being virtual

$$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi) + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi)} dx - i\pi H(2\xi' - \xi,\xi,t) + \ldots$$

$$\xi = \xi' \cdot \frac{Q^2 + Q'^2}{Q^2}$$

We can express it as a function of Q^2/Q'^2, getting a "lever arm" in the propagator to disentangle x and ξ

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



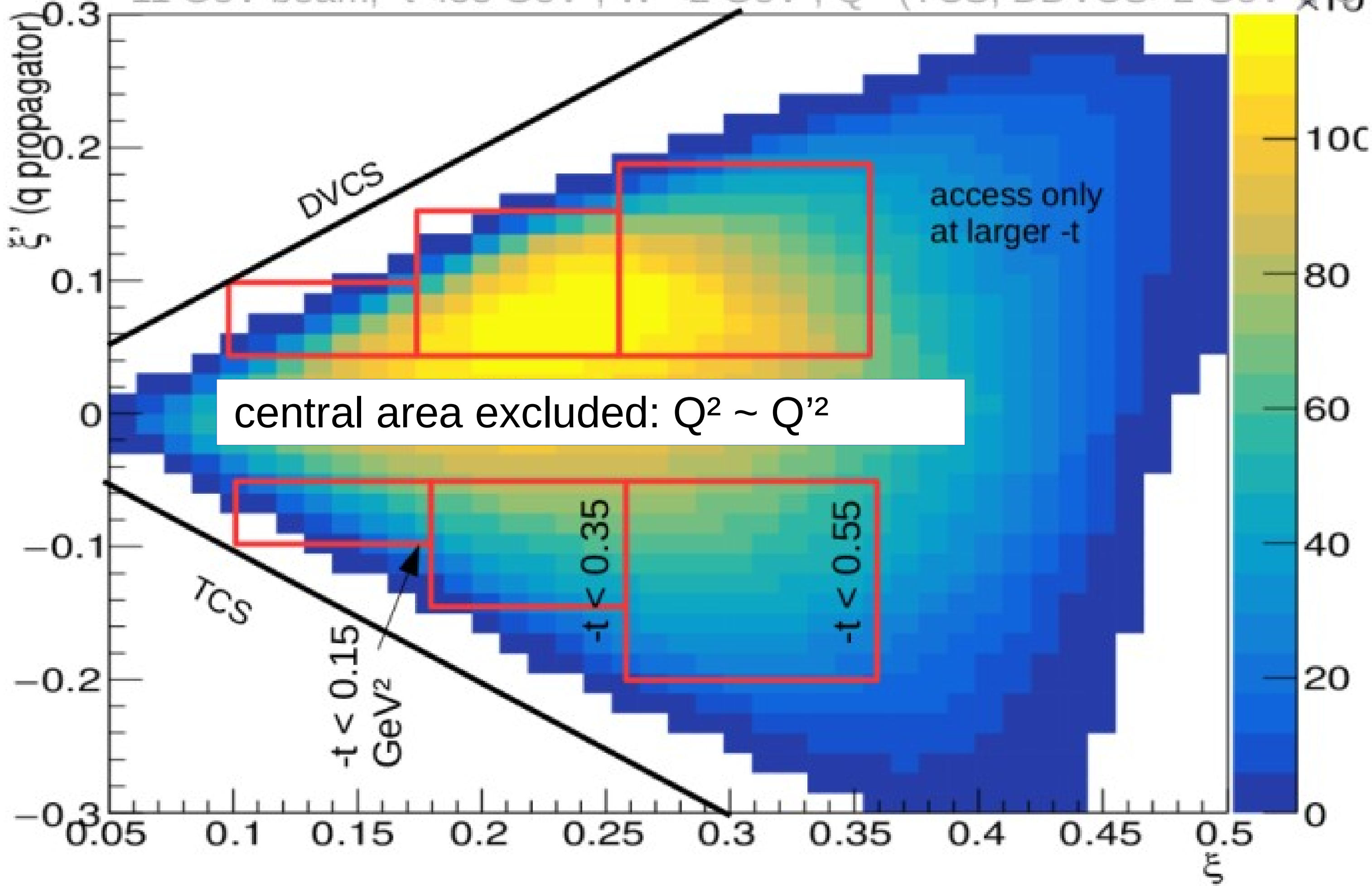
GPDs in the ERBL region

with DDVCS

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

Off diagonal "lever arm": phase space for JLab, 11 GeV electron



Q'² < Q² : spacelike"

Bins in ξ, ξ', -t

$-.2 < \xi' < .2$
$.05 < \xi < .36$
[correlated to t bin]
$0.05 < -t < .55$

Q² < Q'² : "timelike"

(binning proposed for Hall C)

We can in principle access the red bins, wider area at larger -t. Central region excluded: $Q^2 \sim Q'^2$

Proposed experiment (LOI) for JLab Hall C

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

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David Gaskell[§],
David Hamilton[¶],
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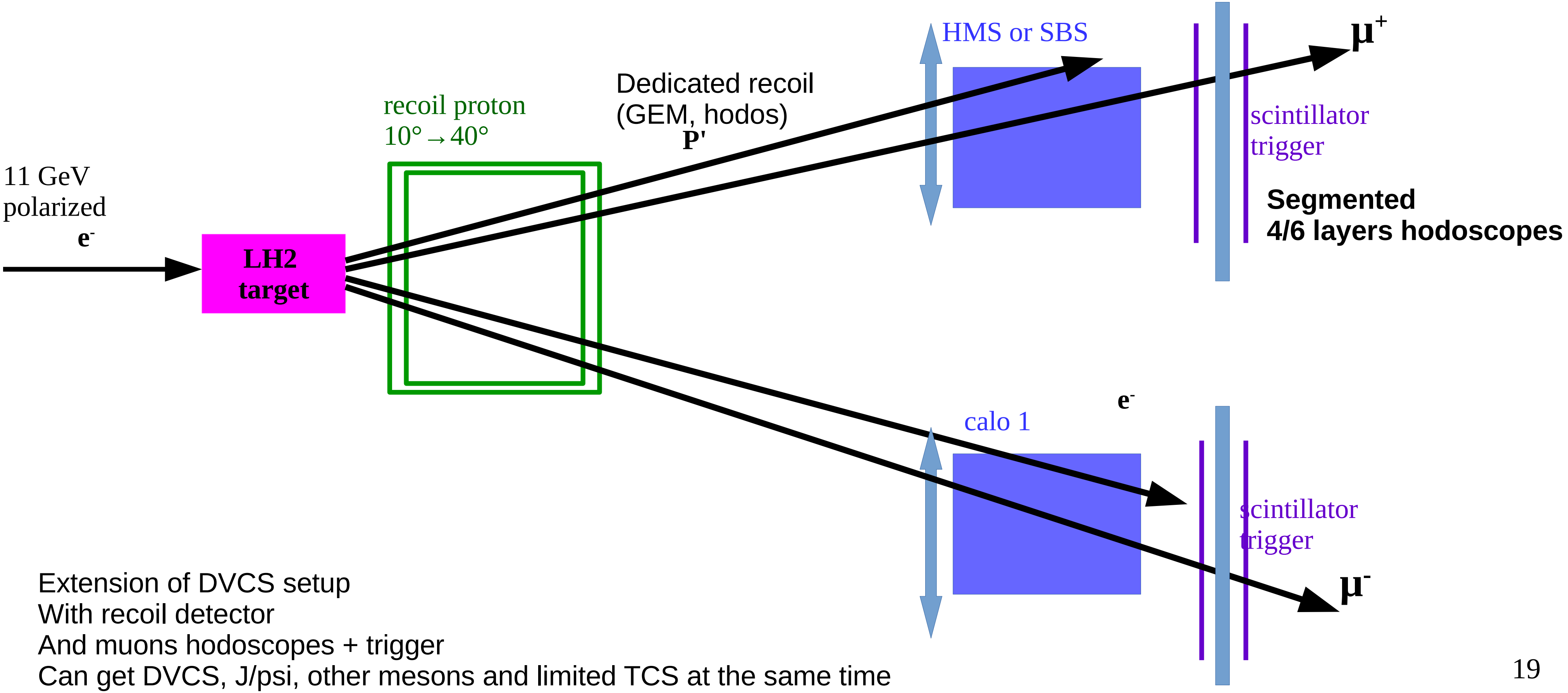
May 1^{st}, 2024

Abstract

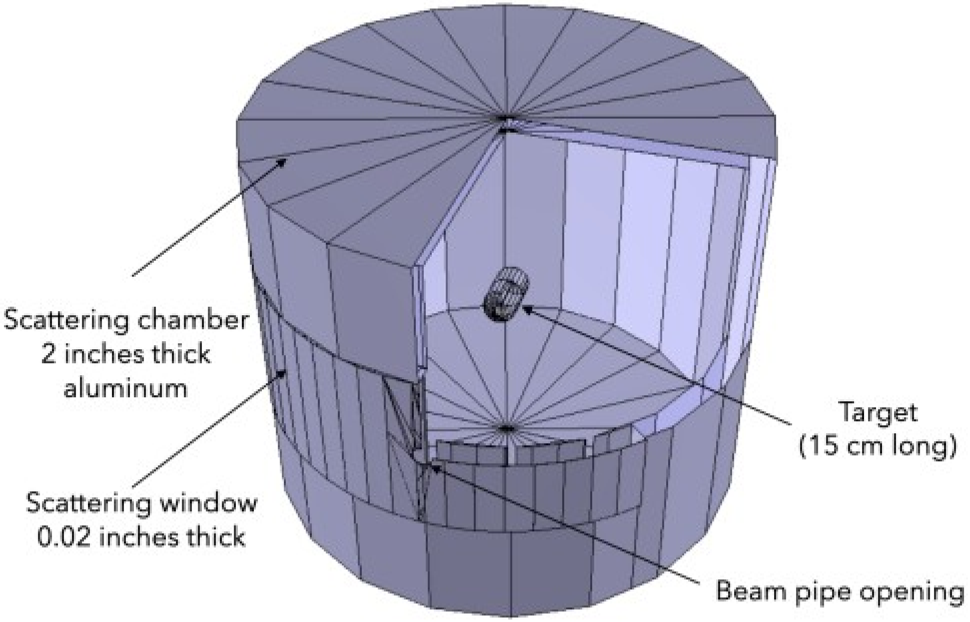
This letter of intent presents our prospects for a first measurement of Double Deeply Virtual Compton Scattering (DDVCS) unpolarized cross sections and beam polarized spin asymmetries at Jefferson Lab Hall C, in the reaction $eP \rightarrow e'P'\mu^+\mu^-$, where two virtual photons are being exchanged 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.

Dedicated setup proposed for Hall C

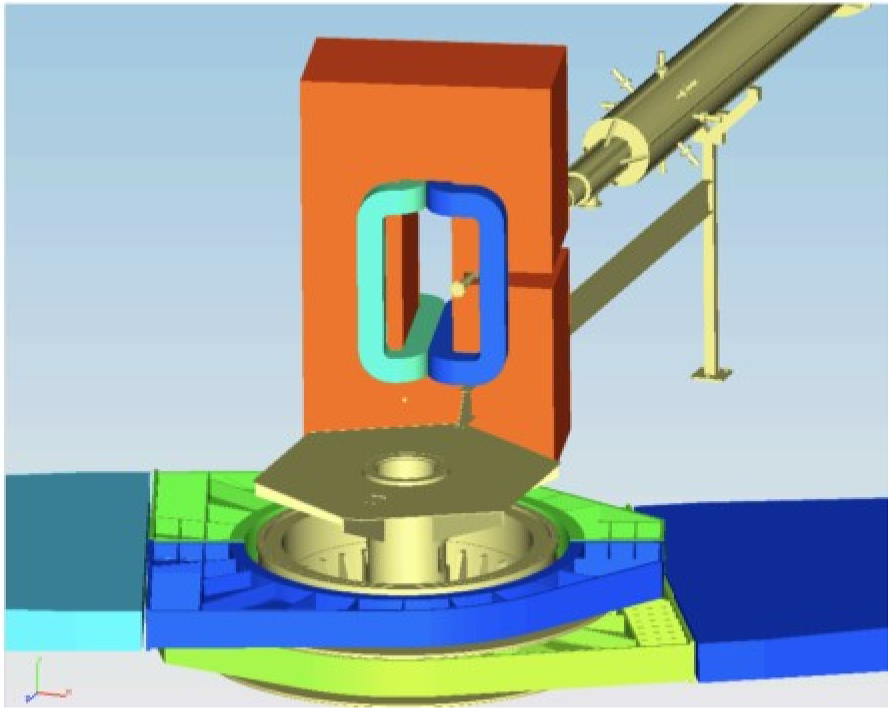


Extension of DVCS setup
With recoil detector
And muons hodoscopes + trigger
Can get DVCS, J/psi, other mesons and limited TCS at the same time

Most things need to be developed or re-used



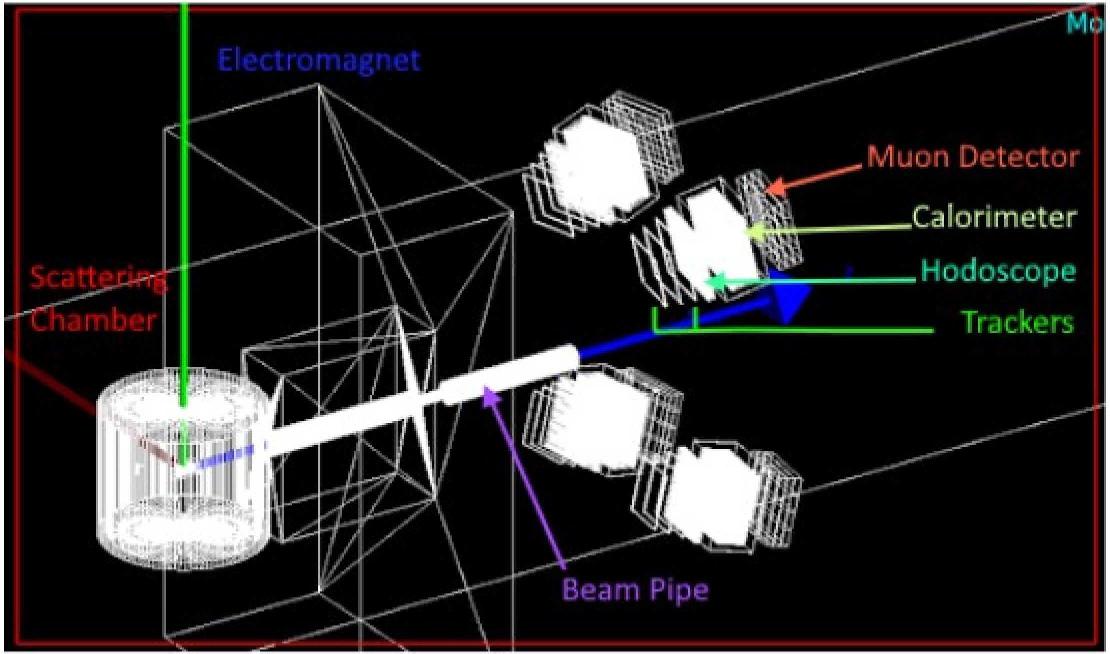
target and scattering chamber



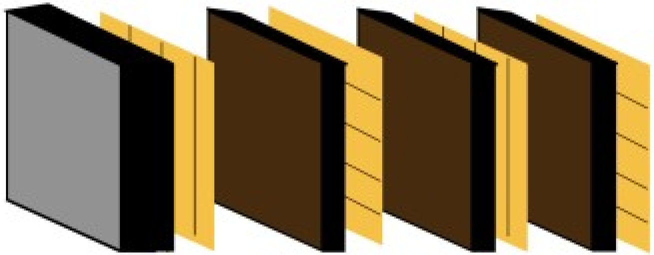
SBS magnet (in Hall A now)

Plan to use for unpolarized TCS (see Deb's talk) – then similarly for DDVCS

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.



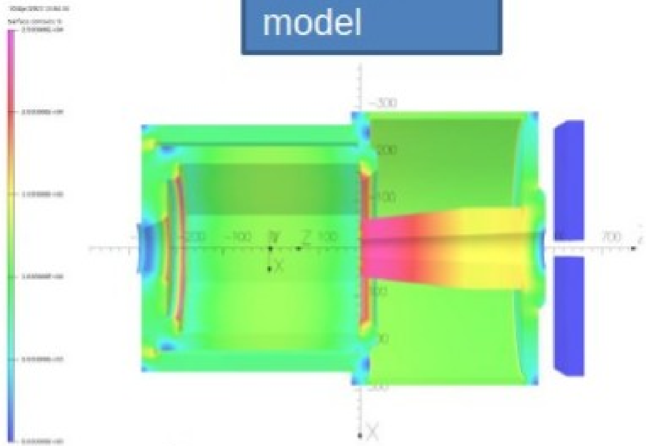
(b) Conceptual design of the muon detector. Two segmented scintillator planes are sandwiched between three absorber planes. The segmentation of the first and second scintillator planes offers spatial information along the x and y axes, respectively.

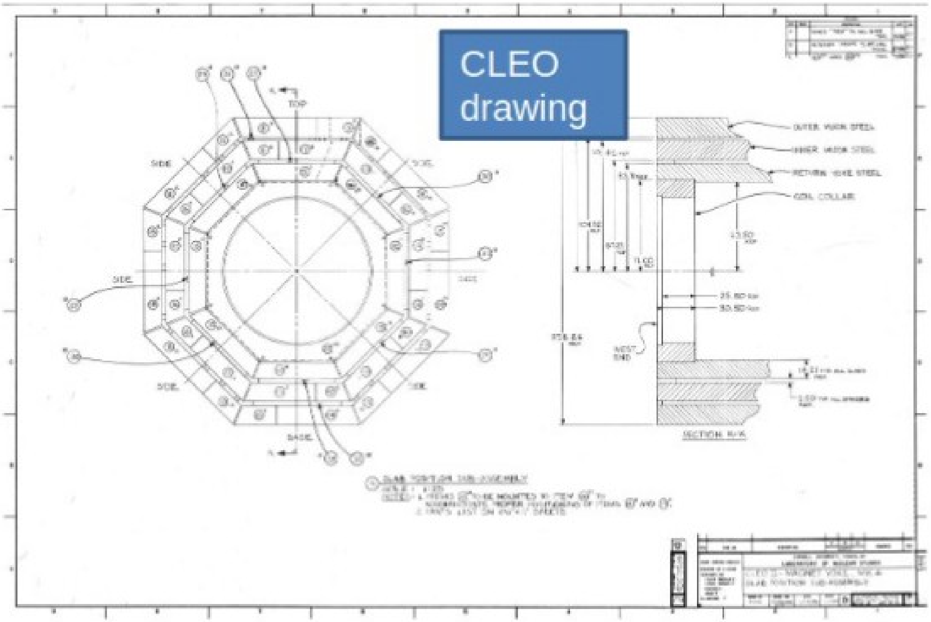
See Mahmoud's talk

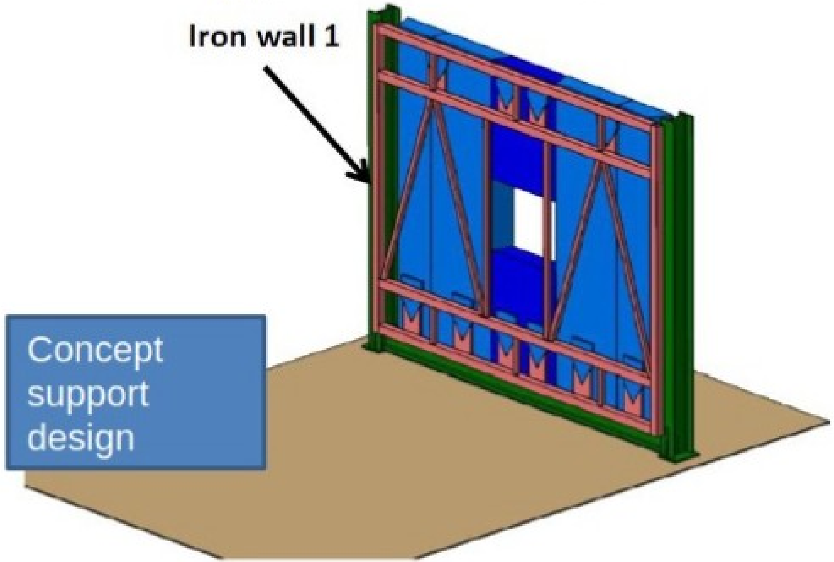
Iron Shielding: from CLEO

Reuse 6 of 8 CLEO octagon outer layer iron
Each one is about 36x254x533cm
No problem with space
Field (<10G),force(<1N),torque(<2Nm) are small

TOSCA model







Studies with different material and thicknesses.
Retained for now: 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

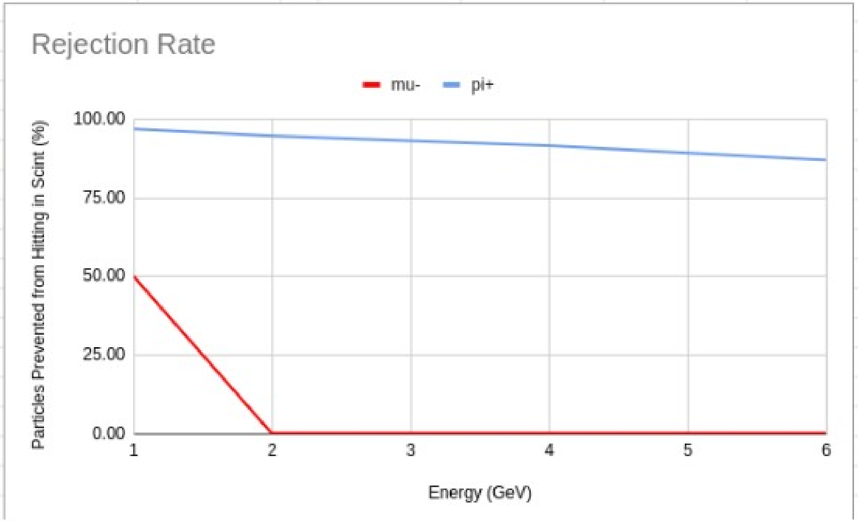
hits in each layer of scintillator				1 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9998	9993	1	0
pi+	1080	279	0	0

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

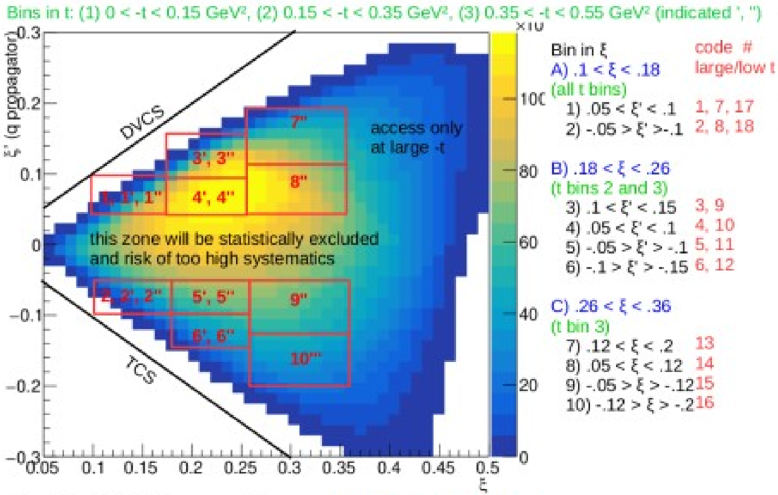
hits in each layer of scintillator				6 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	9997	9997	9997	9994
pi+	3011	1428	631	244

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

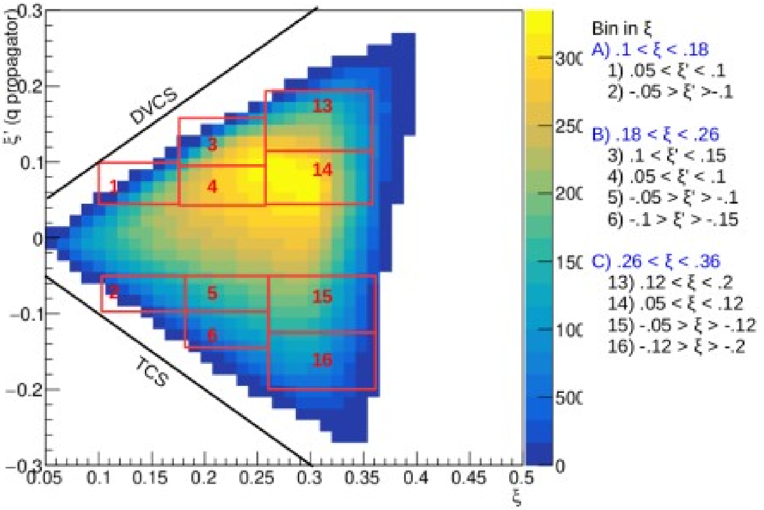


See Mahmoud's talk

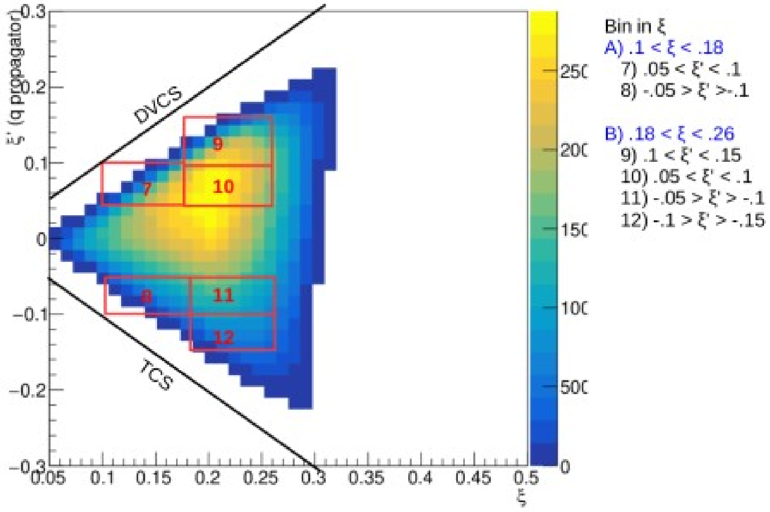
Projections: bins to be measured in Hall C



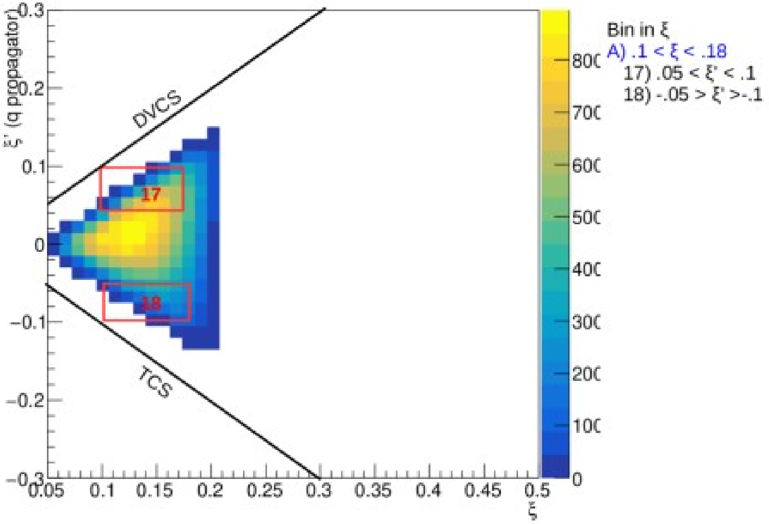
Binning in ξ, ξ', at large -t (3) 0.35 < -t < 0.55 GeV²



Binning in ξ, ξ', at medium -t (2) 0.15 < -t < 0.35 GeV²



Binning in ξ, ξ', at low -t (1) tmin < -t < 0.15 GeV²



Hall A with SOLID

Double Deeply Virtual Compton Scattering in the di-muon channel with the SoLID spectrometer

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LOI 2023

Camsonne, Boër, Voutier, Zhao et al.

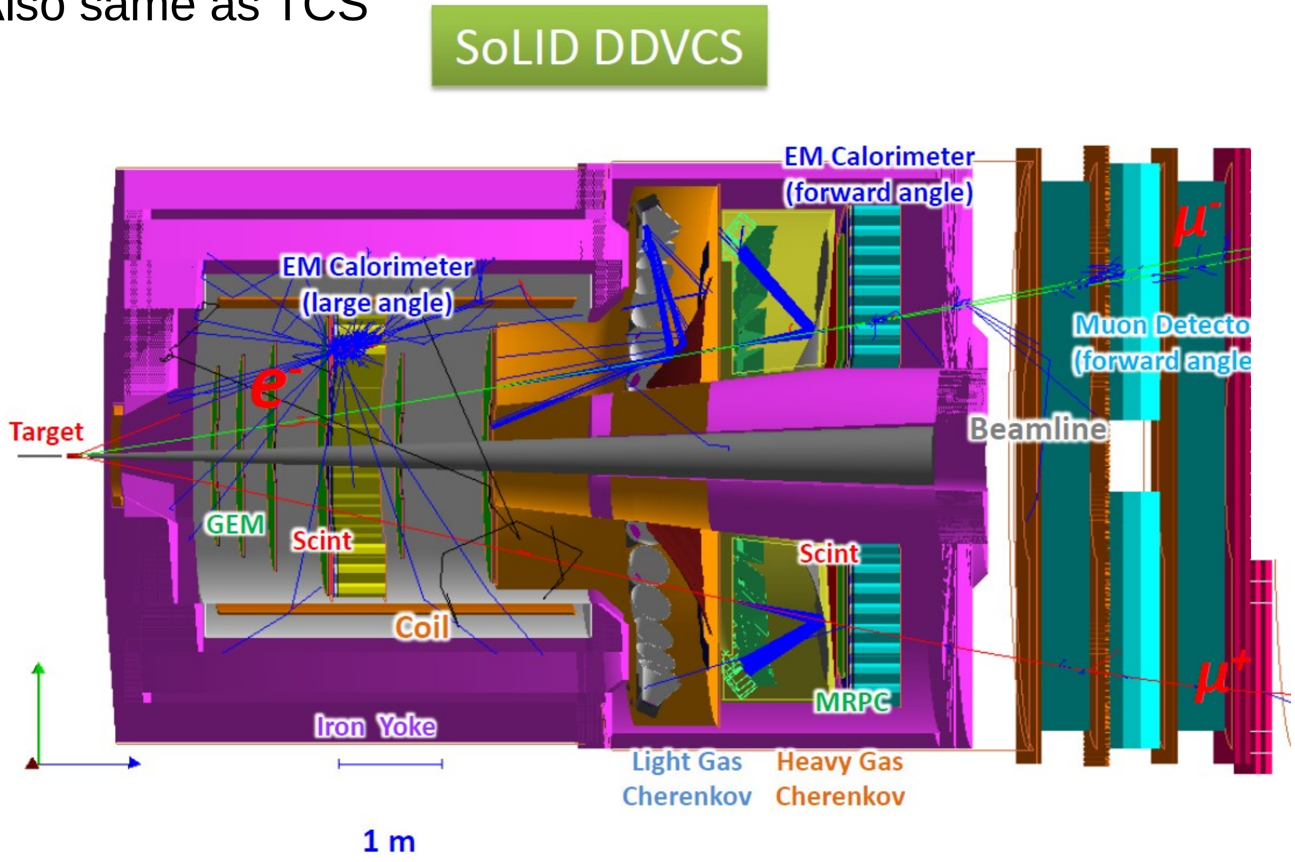
Endorsed by SoLID collaboration

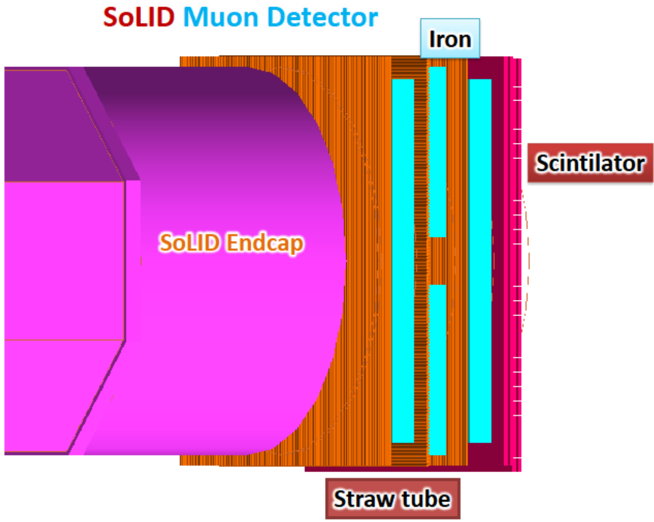
Collaboration with theorists for physics case: B. Pire, J. Wagner, P. Snajdzer, V. Martinez

Some simulations here: Sebastian Alvarado (student in Orsay), Previous student: Shenying Zhao

Proposed experiment (LOI) for JLab Hall A

Using similar setup as J/psi experiment E12-12-006, with additional muon detector
Also same as TCS



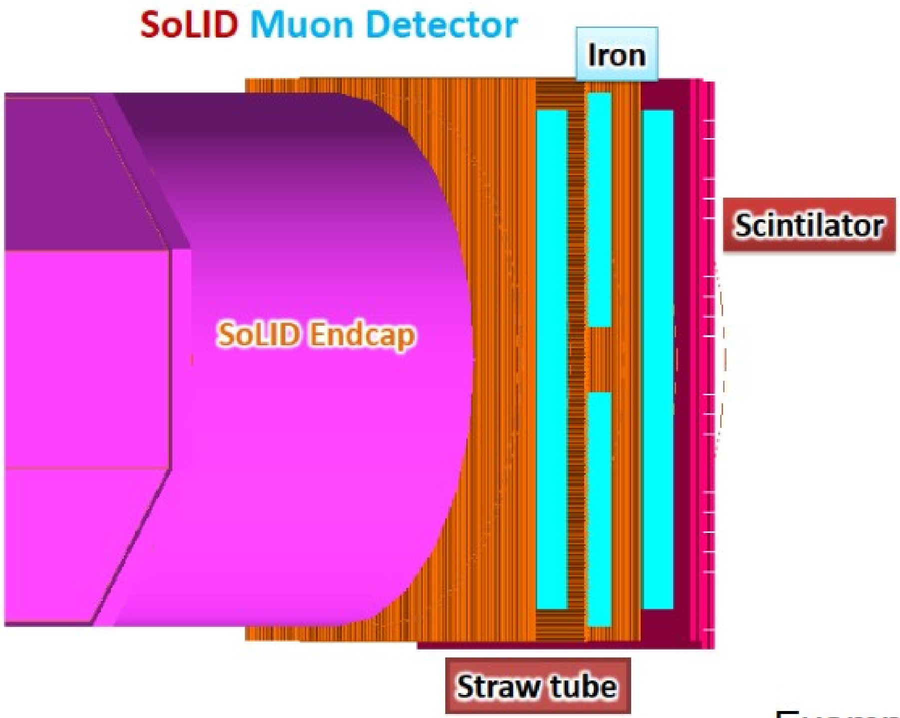


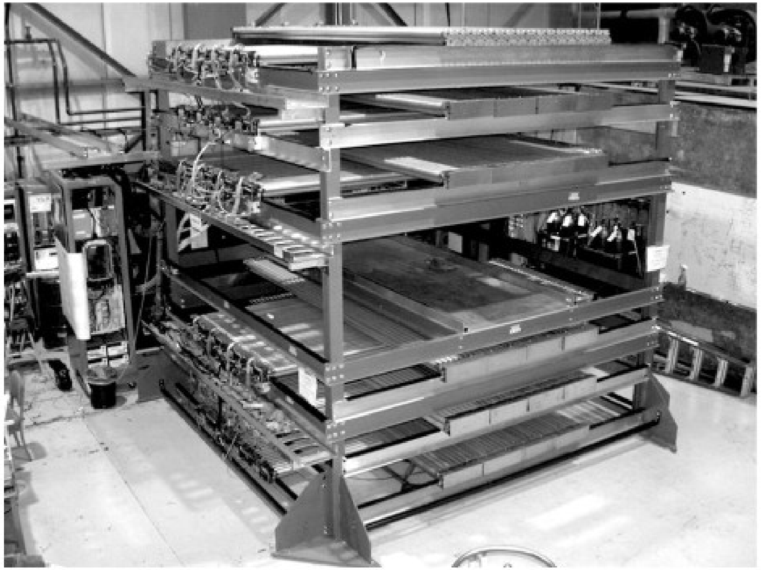
3 layers iron (shielding)
3 layers straw tubes (tracking)
2 layers scintillators (trigger)

Boër, Camsonne, Voutier, Zhao, et al. LOI submitted 2023

Forward muon detector (proposed addition)

3 layer iron to block charged pions, 3 layer straw tubes for tracking, 2 layer scintillators for trigger





Example of straw tube chambers similar to Seaquest experiment

Forward muon detector (proposed addition)

Other options under consideration:

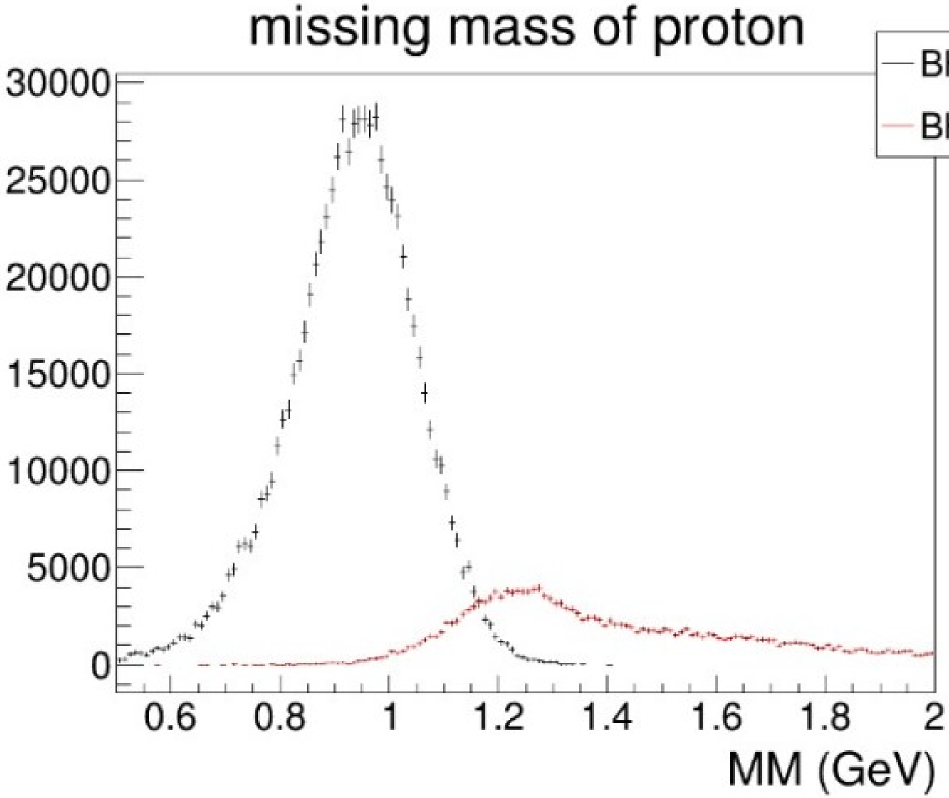
- using the same detector as Hall C (but larger, more panels?)

- option with extra straw tubes (cheaper) or GEM (more tracking)

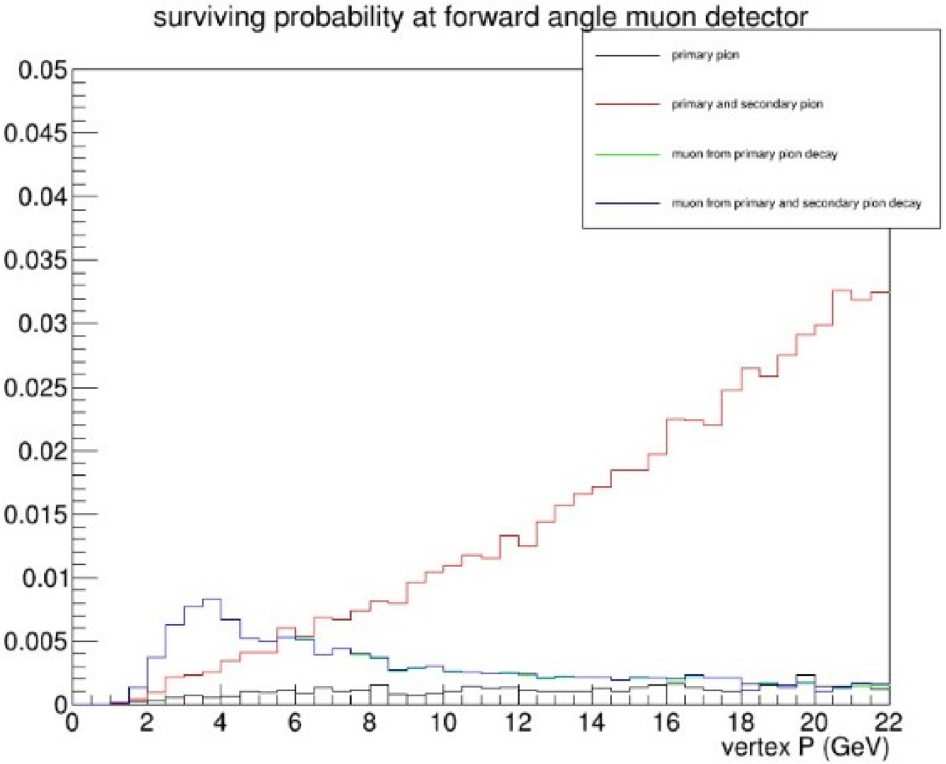
- scintillating fibers inside of scintillating bars (cheaper option used in Hall B, suggested to us by LHCb colleagues)

We are currently re-doing simulations for submission of a proposal next PAC in May

SoLID exclusivity and background projections



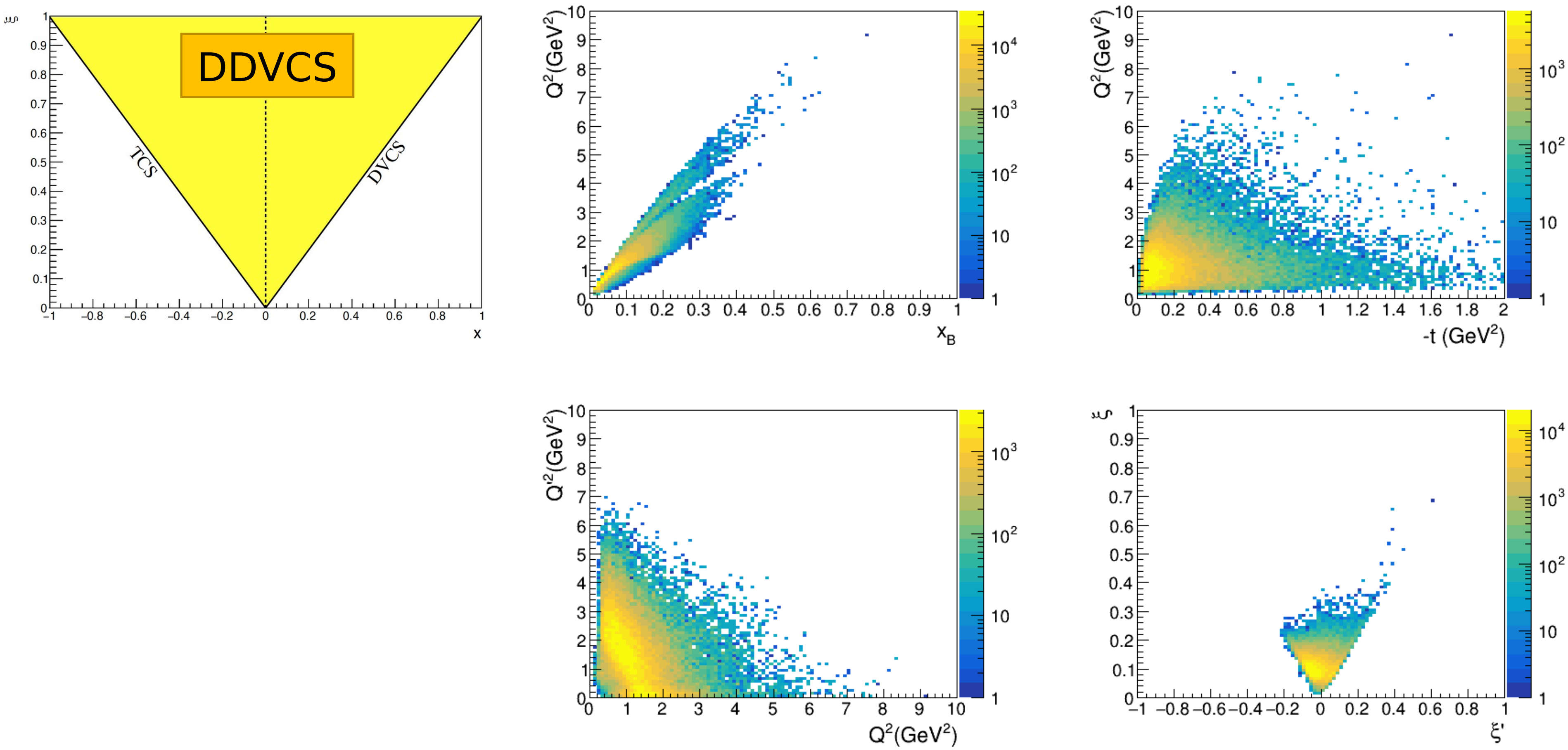
fine enough resolution to select DDVCS+BH



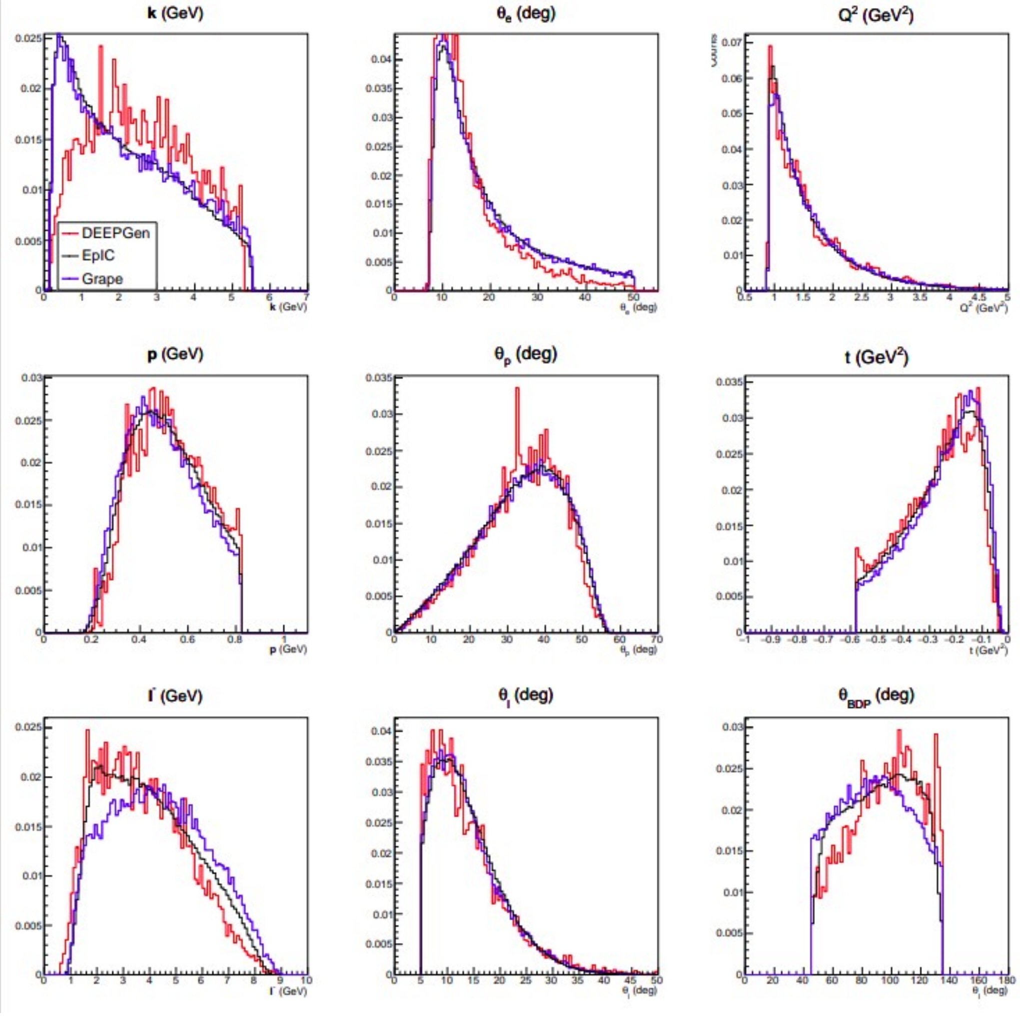
high rate of pion rejection after muon detector

Simulations: acceptance

coverage

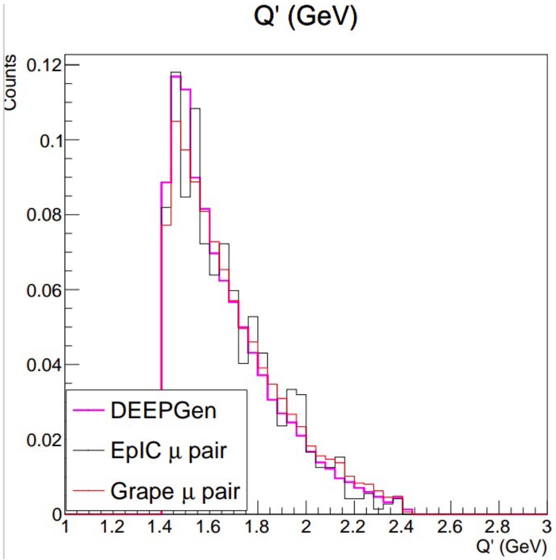


Simulations: event generators comparisons



Version 1 (2015): first version of DEEPGen
Version 2 (2023): Grape
Version 3 (2025): ePIC (?) - may use others too

Here comparison of kinematic projections with different generators / models. All in agreement, observed difference at low momentum from narrower generation phase space with DEEPGen



ePIC: Wagner, Snazjder, Martinez et al

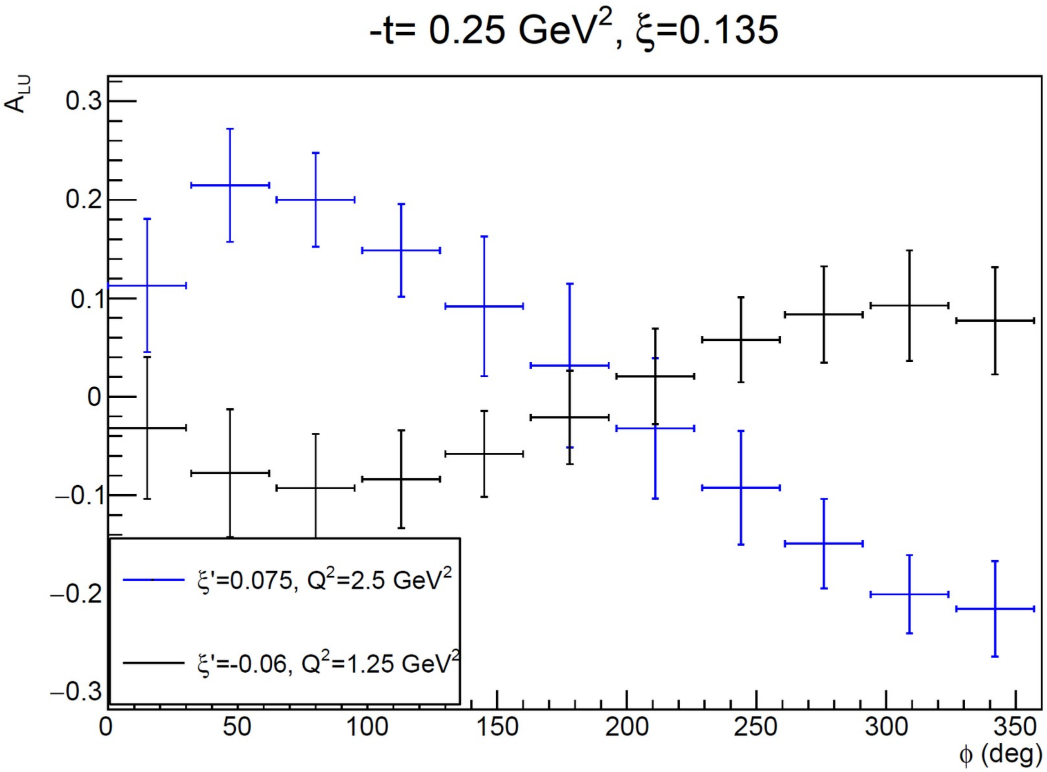
DEEPGen: Boër based on VGG

Grape: used in HERA, BH only

study done by Sebastian Alvarado (Orsay)

Beam Spin Asymmetry projection

projection



$$A_{LU}^{\pm}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma_+^{\pm} - d^5\sigma_-^{\pm}}{d^5\sigma_+^{\pm} + d^5\sigma_-^{\pm}} \tag{15}$$
$$= \frac{d^5\widetilde{\sigma}_{DDVCS} \mp d^5\widetilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}}$$

One bin as example,
out of 40 4D kinematic bins

Summary

- DDVCS is a golden channel for GPD studies, especially deconvolution of x and ξ for tomographic interpretations, relying on extrapolation to $\xi = 0$ and $t = \Delta^{\perp}$

- We are proposing a first high intensity measurement with a dedicated setup for Hall C, based on proposed setup for TCS (unpolarized and polarized extensions) [Deb's talk]
This could be a very first measurement of DDVCS in a few kinematic bins
LOI submitted in 2024 received positive feedback from PAC, going for proposal in 2025

- We are proposing a next measurement using SoLID in Hall A with muon detector extension
It was first submitted as LOI in 2015, then in 2023. Going for proposal in 2025.
Advantage is wider acceptance and high intensity. Possible future extensions for higher intensity
May enable more observables (real part with charge asymmetry…) and/or study of evolution

- This program is complementary to TCS and DVCS studies, also mesons in Hall A, C, also B, D
Note: Hall B also works on a complementary dedicated design with muon detectors.