TCS and DDVCS with a dedicated setup in Hall C at JLab

Debaditya Biswas[1]
[1]Postdoctoral Research Associate, Virginia Tech

TOWARDS IMPROVED HADRON TOMOGRAPHY

WITH HARD EXCLUSIVE REACTIONS

27th July-1st August, 2025

Accessing GPDs through exclusive reactions

Compton like reactions

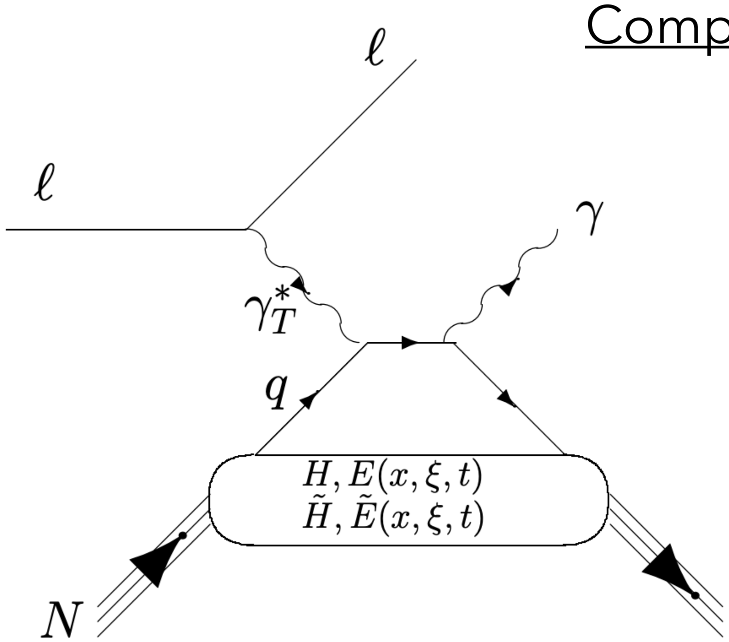


Fig : DVCS

https://arxiv.org/pdf/1511.04535.pdf

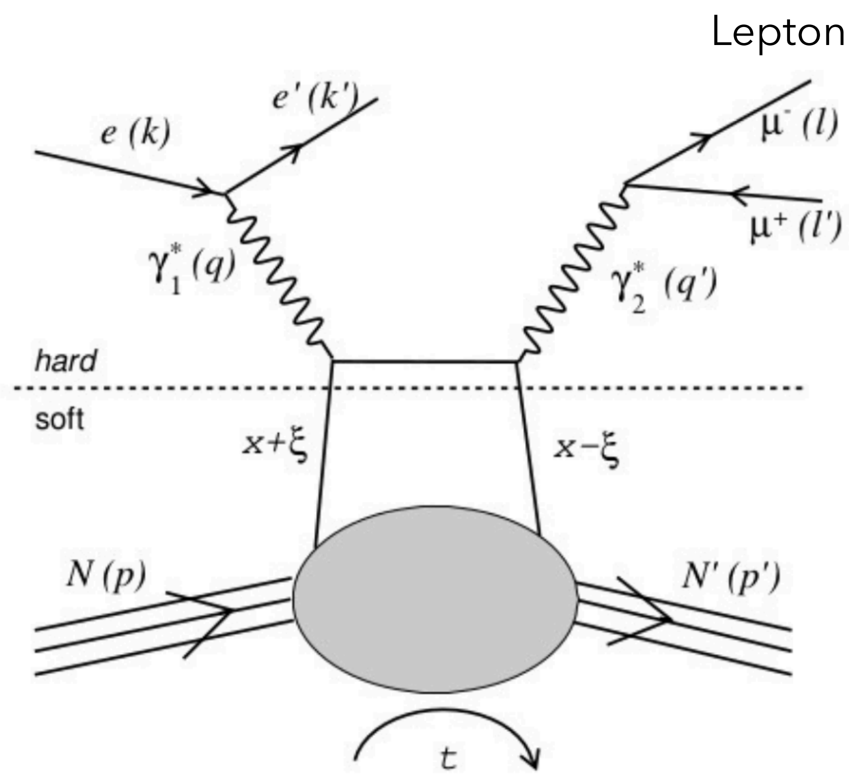


Fig : DDVCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

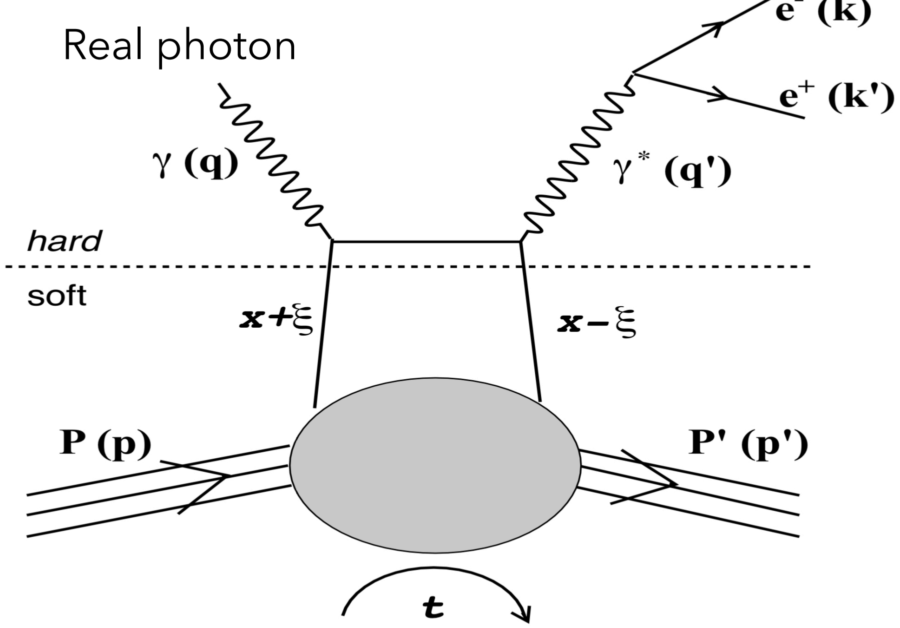


Fig : TCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

Meson production

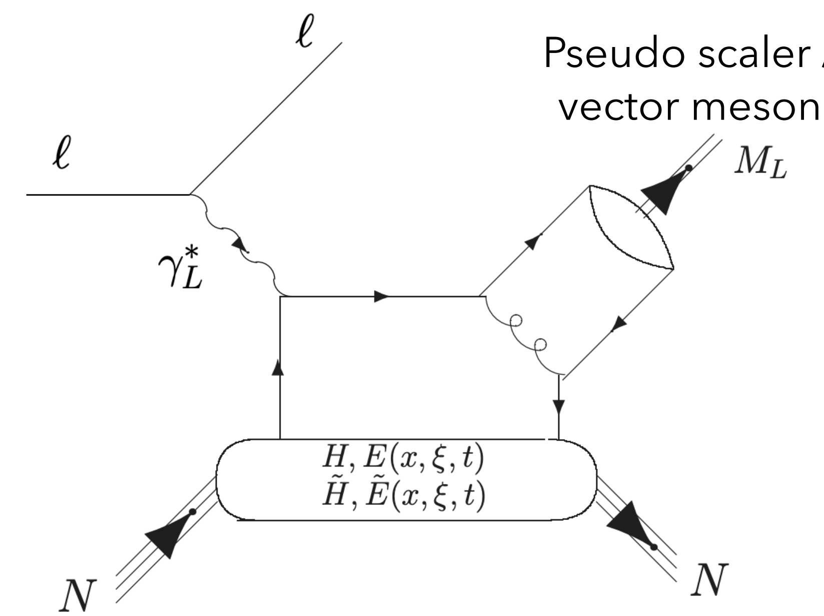


Fig : DVMP (quark Subprocess)

https://arxiv.org/pdf/1511.04535.pdf

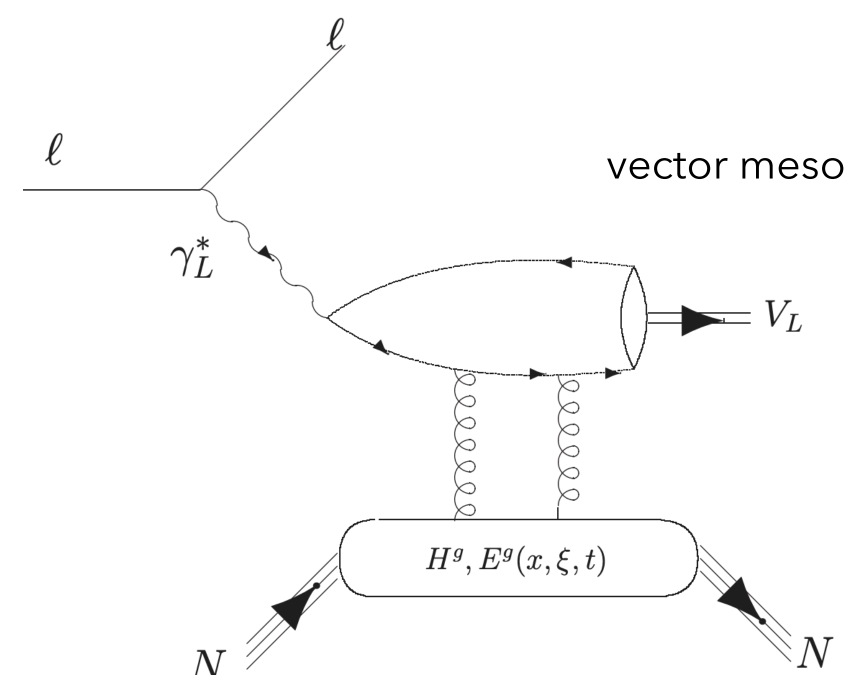


Fig : DVMP (gluon subprocess)

https://arxiv.org/pdf/1511.04535.pdf

Accessing GPDs through exclusive reactions

<u>Compton like reactions</u>

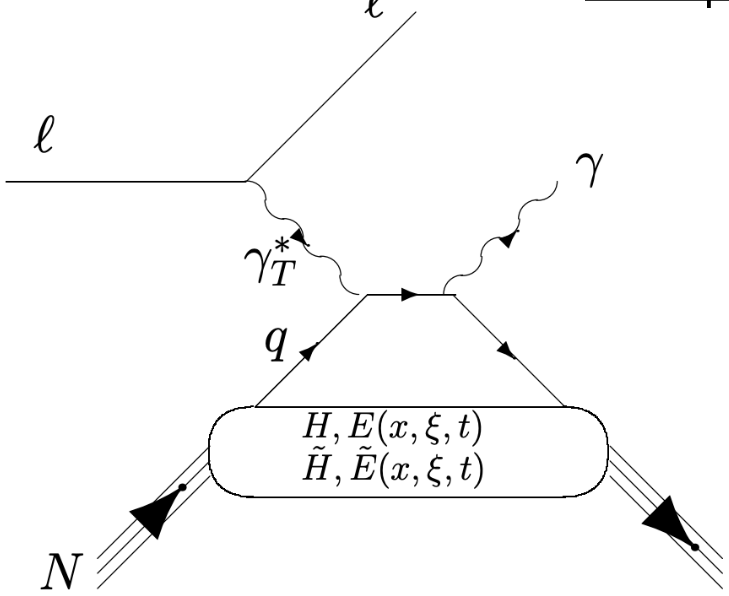


Fig : DVCS

https://arxiv.org/pdf/1511.04535.pdf

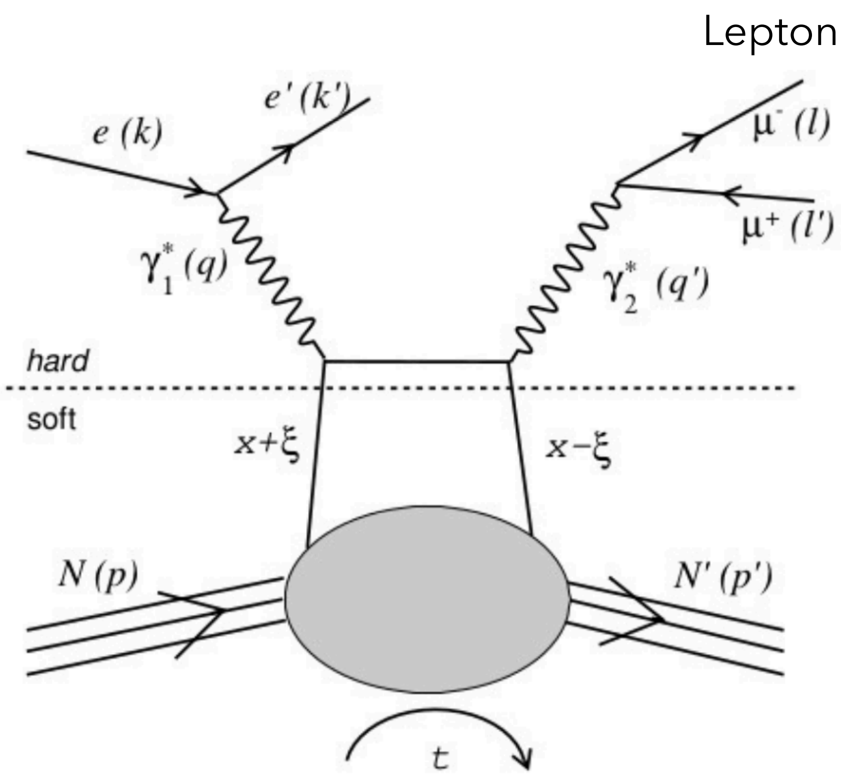


Fig : DDVCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

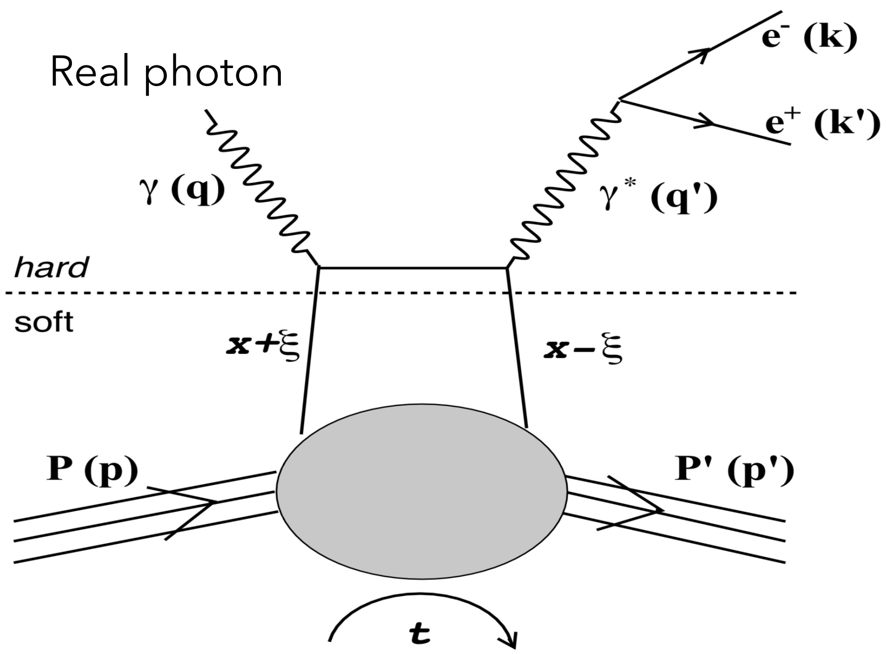


Fig : TCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

<u>Meson production</u>

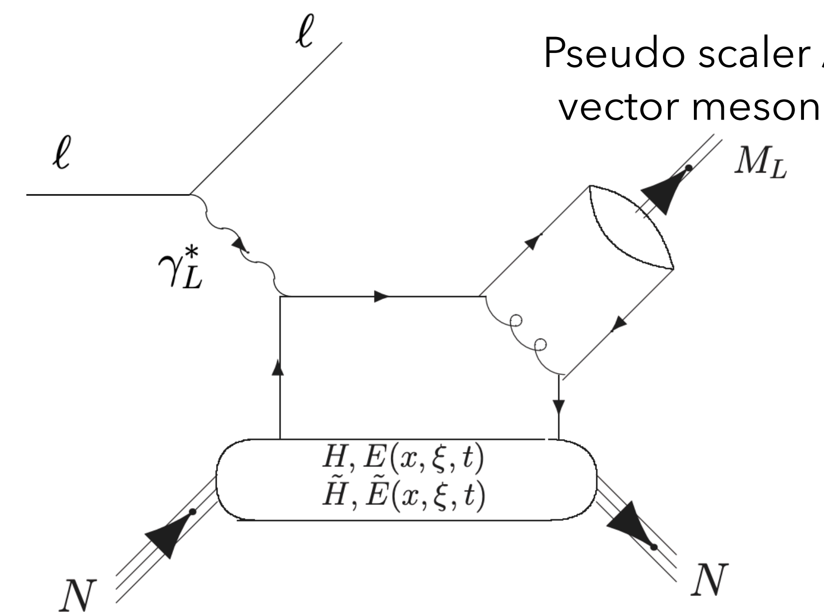


Fig : DVMP (quark Subprocess)

https://arxiv.org/pdf/1511.04535.pdf

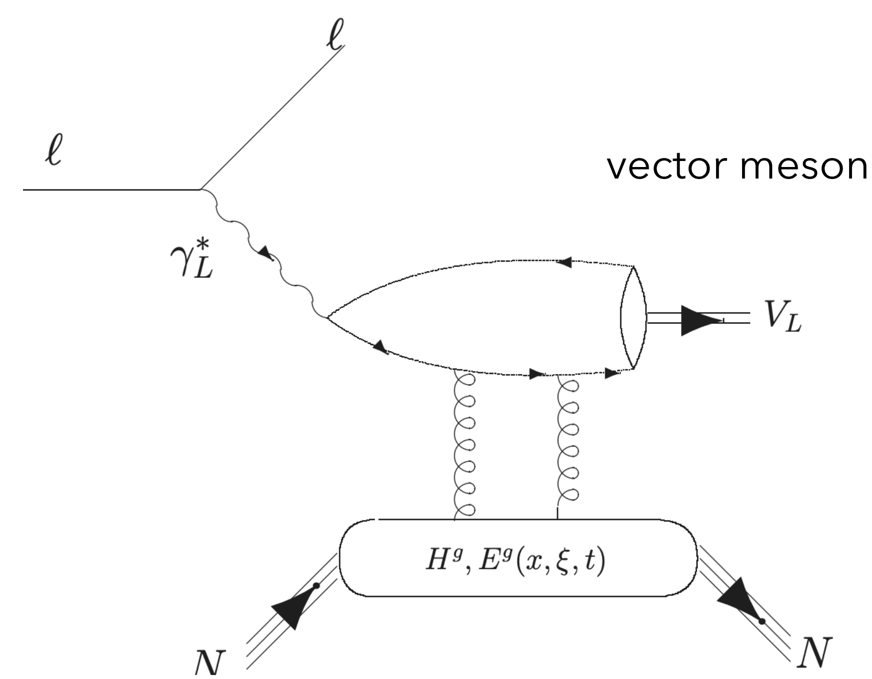


Fig : DVMP (gluon subprocess)

https://arxiv.org/pdf/1511.04535.pdf

Timelike Compton Scattering

$\gamma P \rightarrow e^{+}e^{-}P'$

1. TCS : scattering of a real photon off a quark of a nucleon which results in the emission of high virtuality photon and followed by the decay of the virtual photon into a lepton pair
2. TCS interfere with Bethe-Heitler like process
3. BH : splitting of a real photon in the nucleon electro magnetic field where high virtuality photon being exchanged

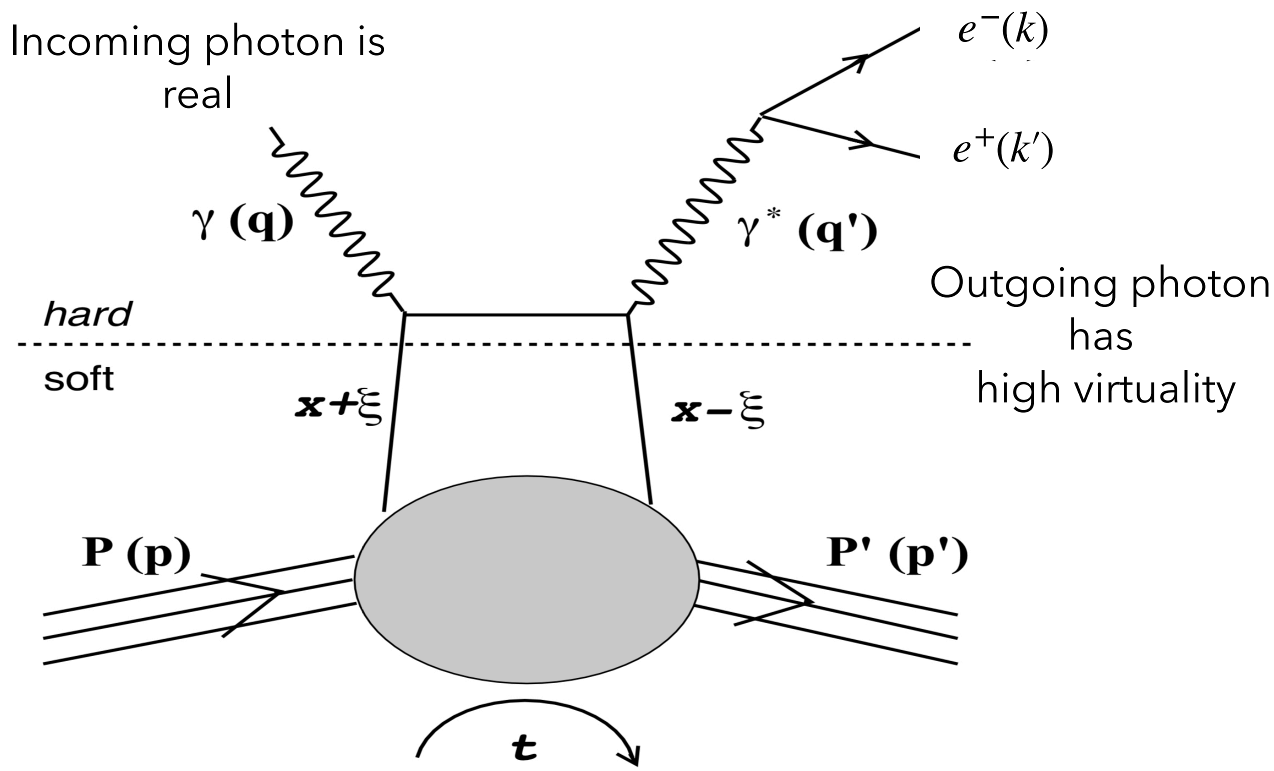


Fig : Time Like Compton Scattering

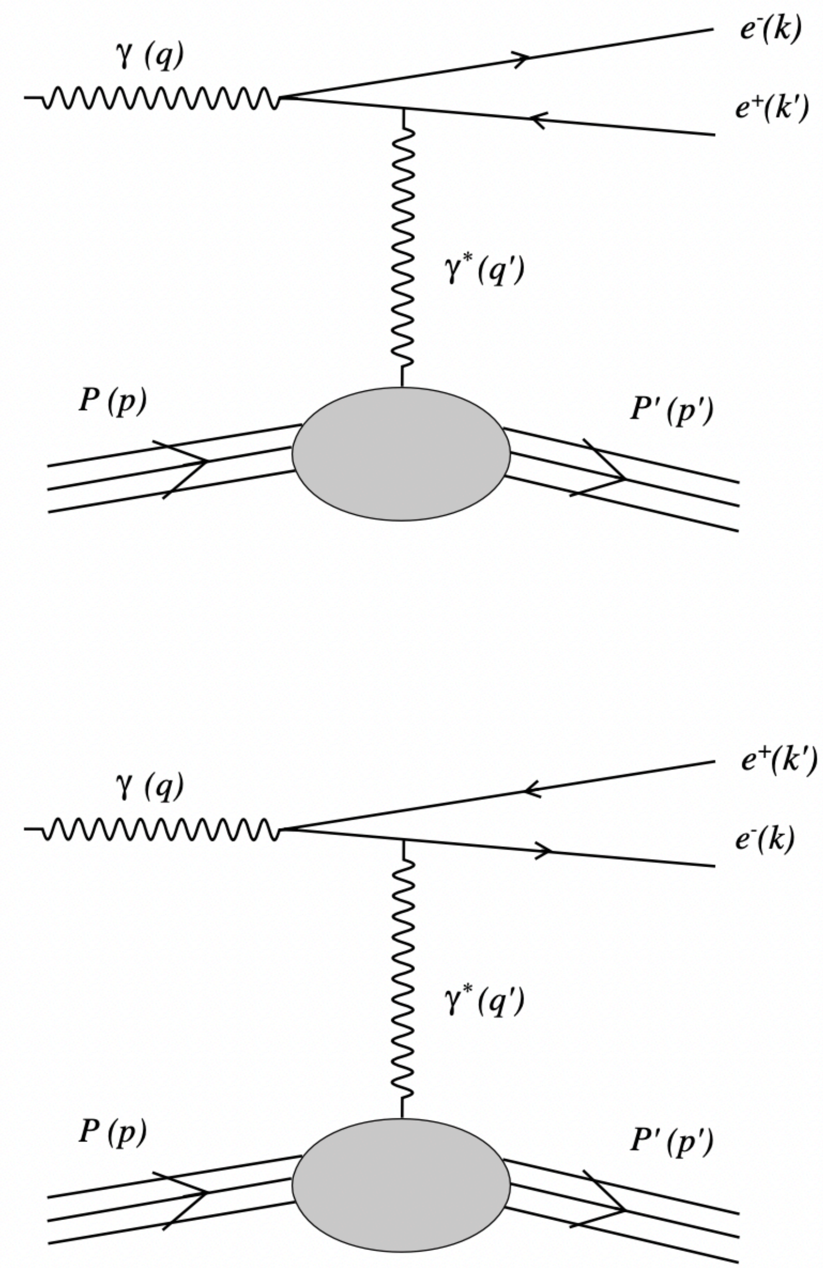


Fig : Bethe-Heitler diagrams

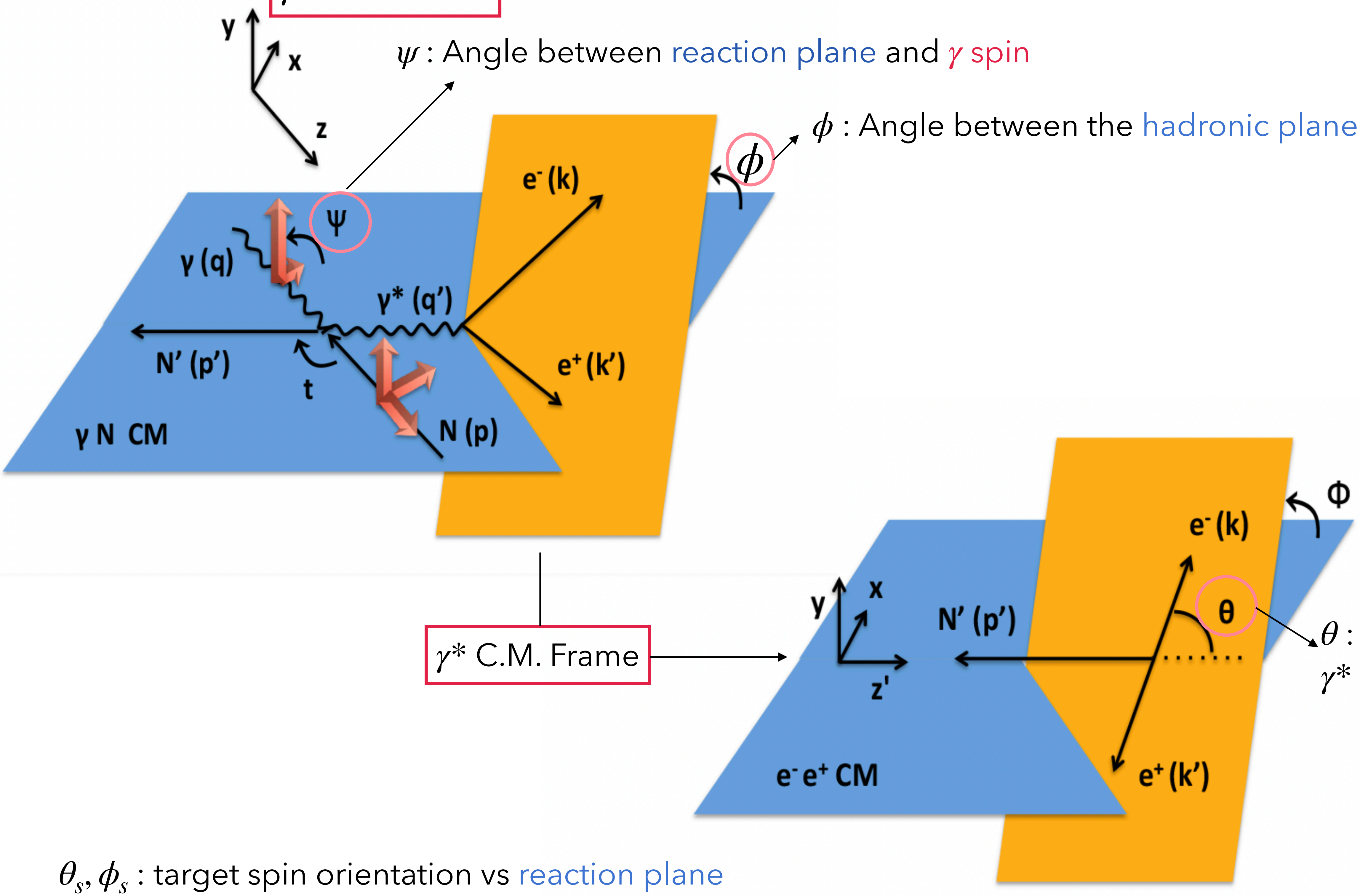
Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

Timelike Compton Scattering

γN C.M. Frame

ψ : Angle between reaction plane and γ spin

ϕ : Angle between the hadronic plane and e^+e^- plane



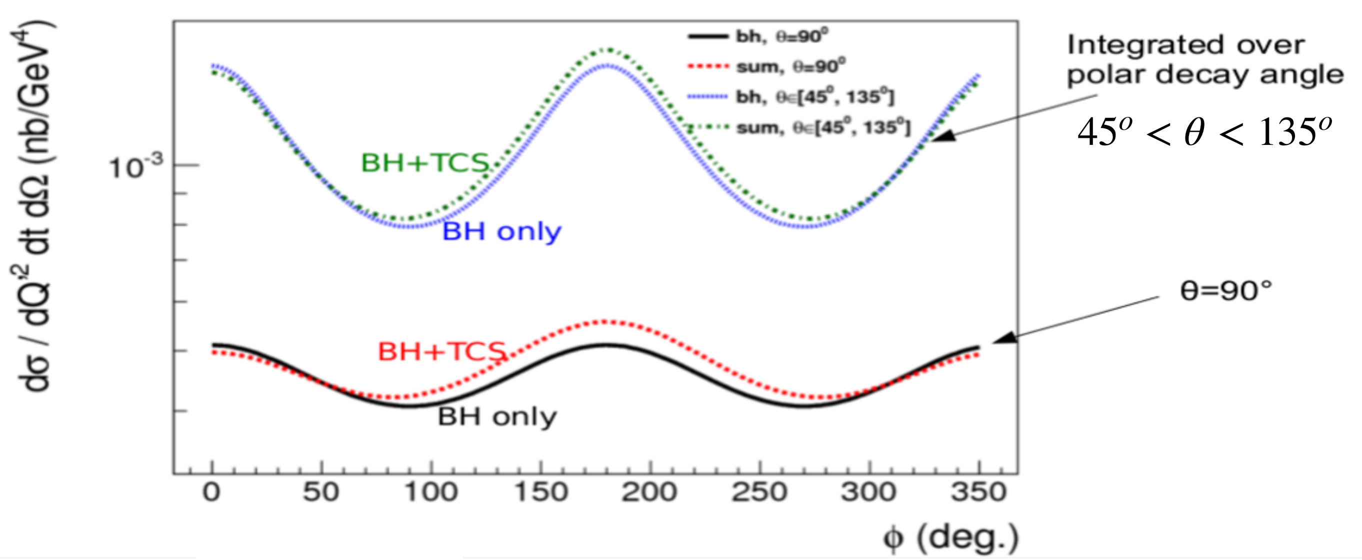
θ : Angle between γ^* and e^-

θ_s, ϕ_s : target spin orientation vs reaction plane

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

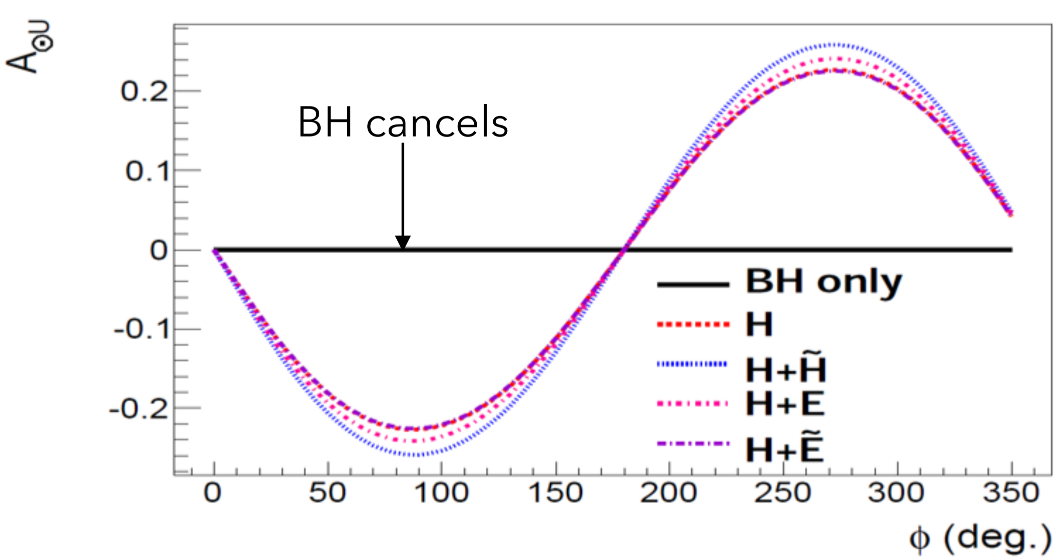
TCS observables and GPD sensitivity (Calculations)

1. Unpolarized Cross sections

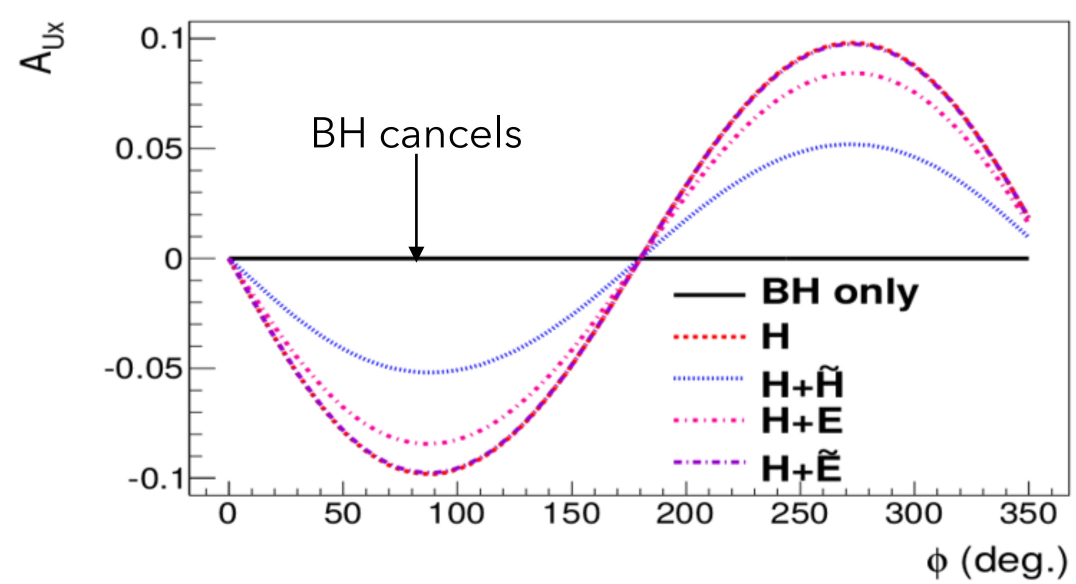


1. Unpolarized σ:
    1. sensitivity to both Im + Re part of amplitude
    2. difficult to measure as BH (only Real) dominant
2. Beam or target polarized Asymmetry :
    1. Cancels only for BH, reflect interference
    2. easier to measure, quite large
    3. access Im(H), Im(H̃), Im(E)
3. Double spin asymmetry or linear beam:
    1. strong constrains on Re
    2. very hard, dominated by BH

2A. Circularly polarized beam asymmetry



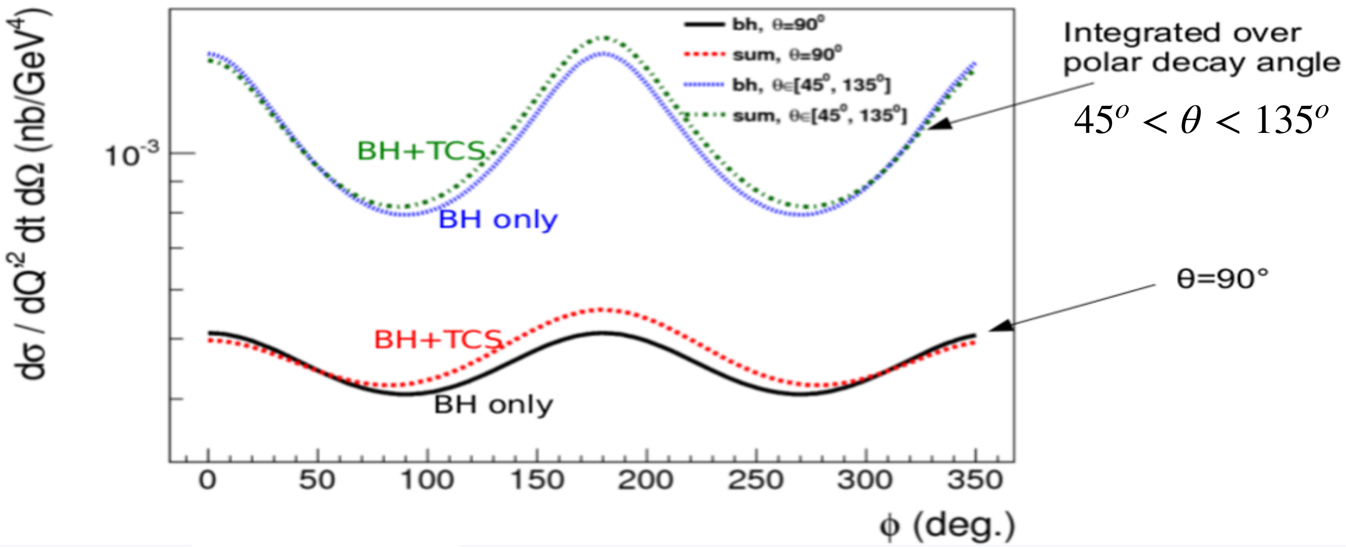
2B. Transversely polarized target asymmetry



from Boer, Guidal, Vanderhaeghen, Eur. Phys. J. A51 (2015) 8, 103

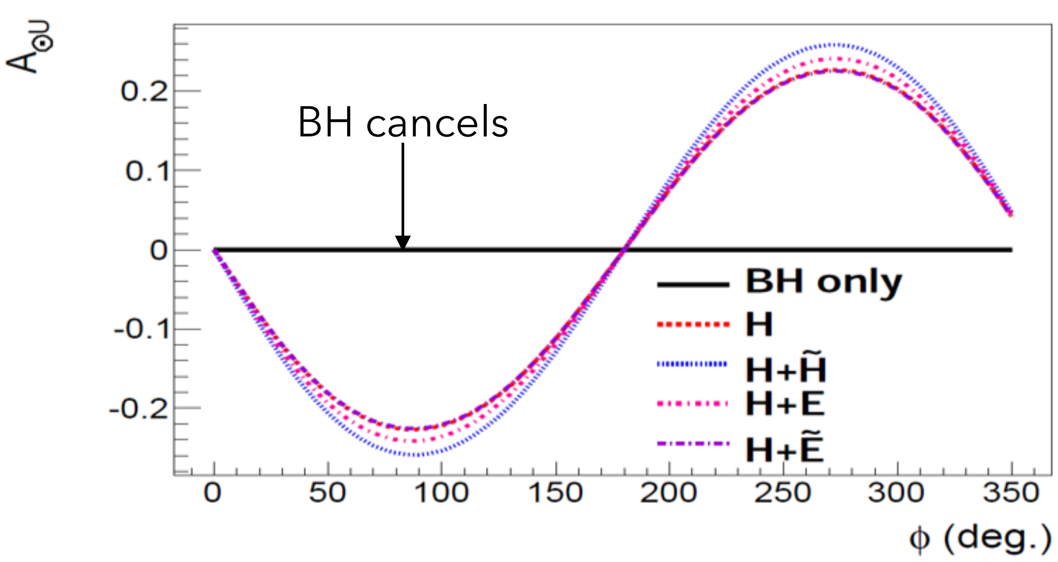
TCS observables and GPD sensitivity (Calculations)

1. Unpolarized Cross sections

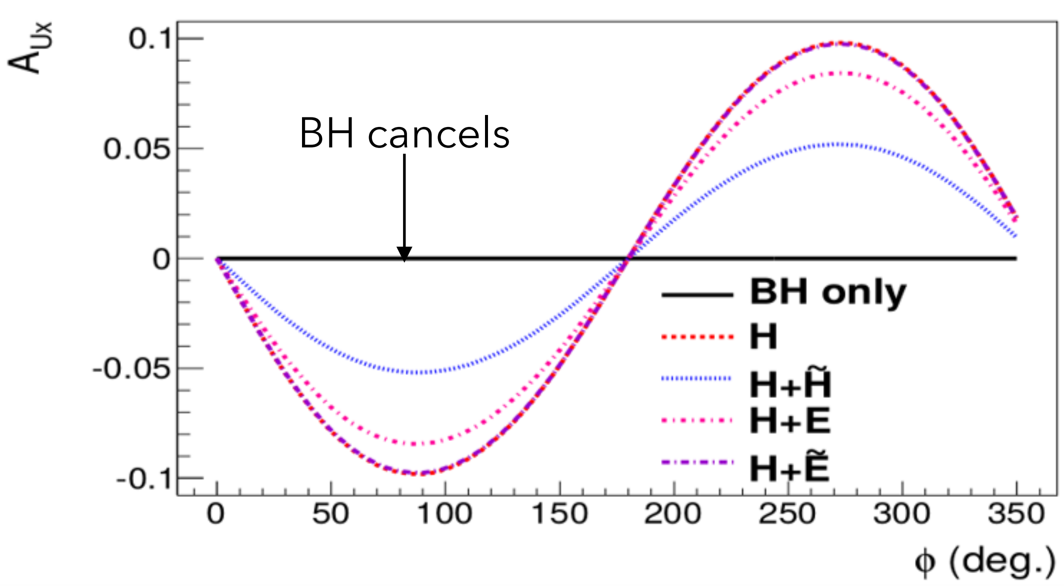


1. Unpolarized σ:
    1. sensitivity to both Im + Re part of amplitude
    2. difficult to measure as BH (only Real) dominant
2. Beam or target polarized Asymmetry :
    1. Cancels only for BH, reflect interference
    2. easier to measure, quite large
    3. access Im(H), Im(H̃), Im(E)
3. Double spin asymmetry or linear beam:
    1. strong constrains on Re
    2. very hard, dominated by BH

2A. Circularly polarized beam asymmetry



2B. Transversely polarized target asymmetry



from Boer, Guidal, Vanderhaeghen, Eur. Phys. J. A51 (2015) 8, 103

Physics Observables Polarized TCS:
cross section and transverse target spin asymmetry

Single Spin Asymmetry (A_{UT}) : unpolarized beam and transversely polarized target

$$A_{UT} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \qquad \ldots (1)$$

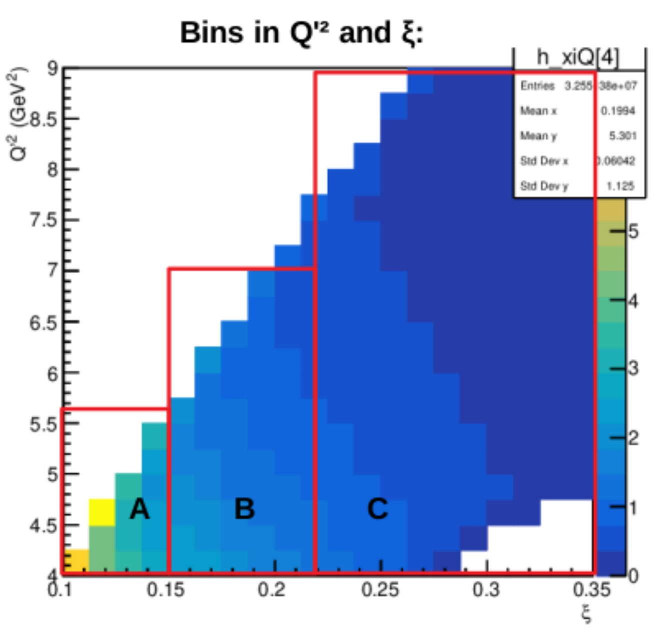
1. $\sigma^{\pm} \equiv \frac{d^6\sigma}{dQ'^2\ dt\ d\Omega\ d\phi_s\ dE_\gamma}$: 6 differential scattering cross-section TCS+BH
2. $\pm$: x direction (+) or y direction (-) of spin ϕ_s of the transversely polarized target
3. 6 differential cross section sensitive to Imaginary part of CFF
4. Asymmetry arises due to the interference between the TCS and BH processes
5. $A_{UT} \propto sin(\phi, \phi_s)$ moment of the $\frac{d^6\sigma^{INT}}{dQ'^2\ dt\ d(cos\theta)\ d\phi\ d\phi_s\ dE_\gamma}$
6. A_{UT} is sensible to the Imaginary part of the amplitude
7. As BH amplitude is purely Real, A_{UT} asymmetry is due to TCS process only

Pol. TCS experiment is Proposed in PAC-50 for Hall C

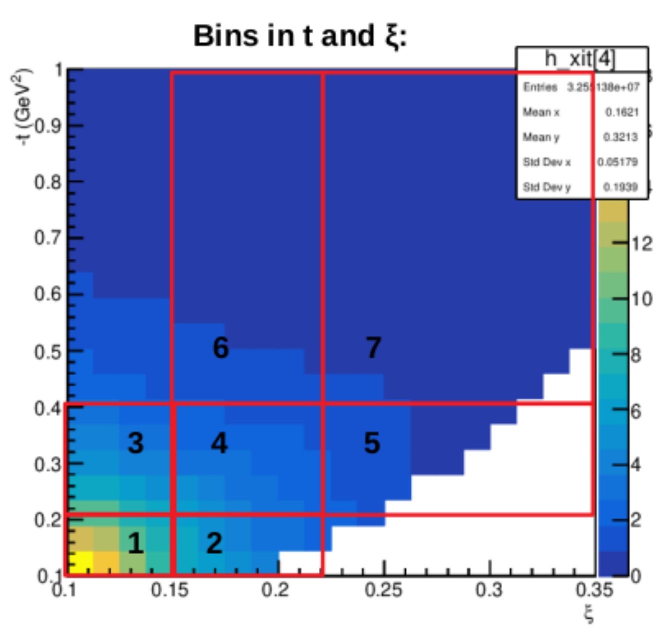
Polarized TCS: kinematic coverage & CFF accuracies

Kinematic coverage

1. 5.5< E_γ <11GeV : for most of the events E_γ>7.5 GeV
2. 0.1 < ξ < .35 : correlated with E_γ cut
3. 4< Q'^2 <9GeV2 : above the region of meson resonance and below J/ψ
4. 0.1 < $-t$ < 1 GeV2 : limited by statistics above 1 GeV^2, and proton tracking below 0.1 GeV^2
5. 30° < θ<150° : staying away from BH peaks



A: .10 < ξ < .15 ; 4 < Q'² < 5.5 GeV²
B: .15 < ξ < .22 ; 4 < Q'² < 7 GeV²
C: .22 < ξ < .35 ; 4 < Q'² < 9 GeV²



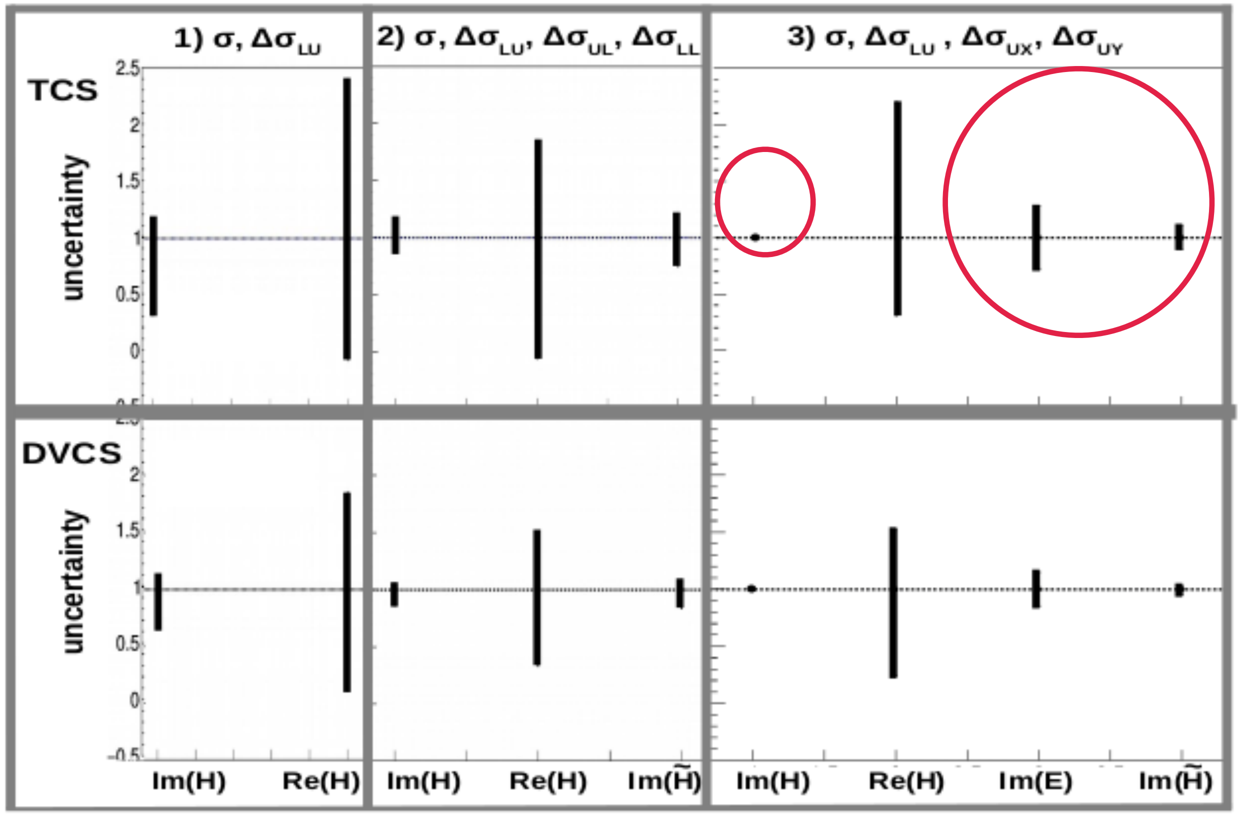
1, 2: .1 < -t < .2 GeV²
3, 4, 5: .2 < -t < .35 GeV²
6, 7: .35 < -t < .7 GeV²

Kinematic region out of pion resonance production

Example estimates of accuracies on the model extraction of CFFs.

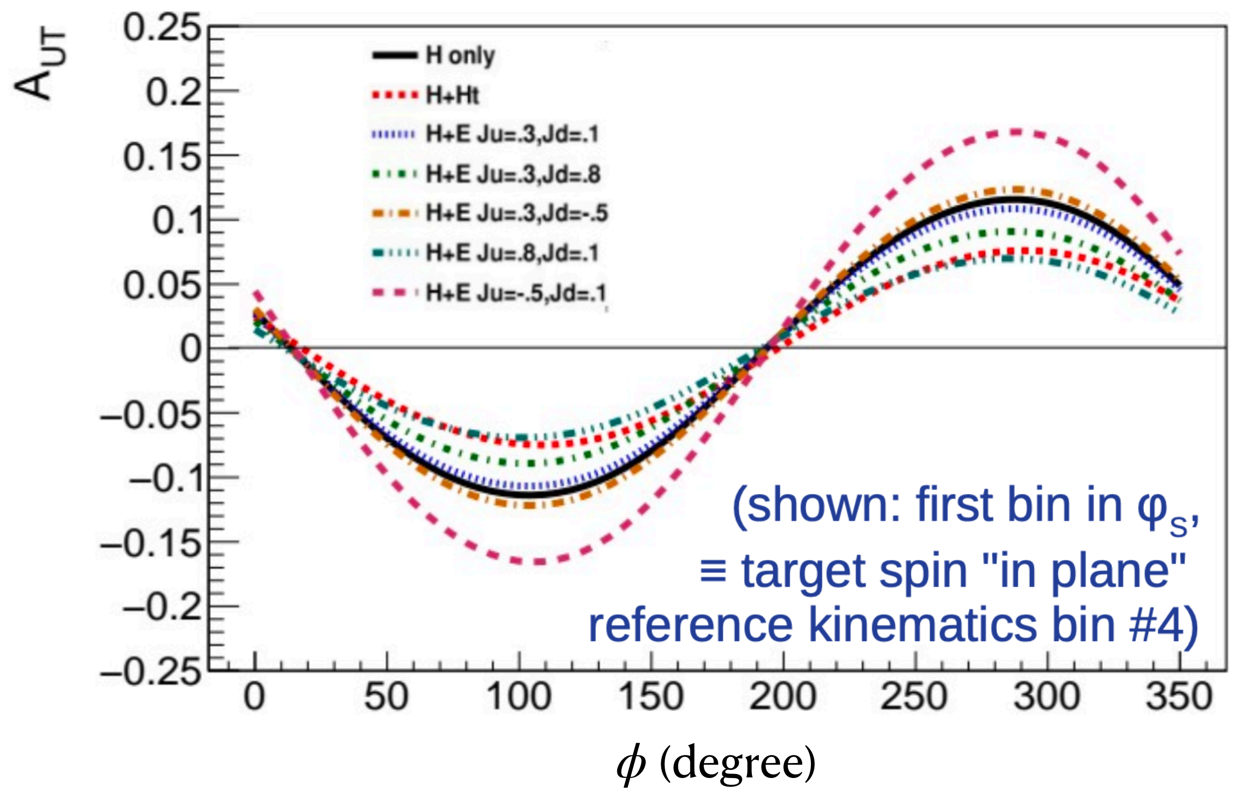
TCS with trans. pol. Target:

1. Allows for extraction of Im(E) (unique to this proposal)
2. Allows for extraction of Im(H) to good accuracy (universality tests)

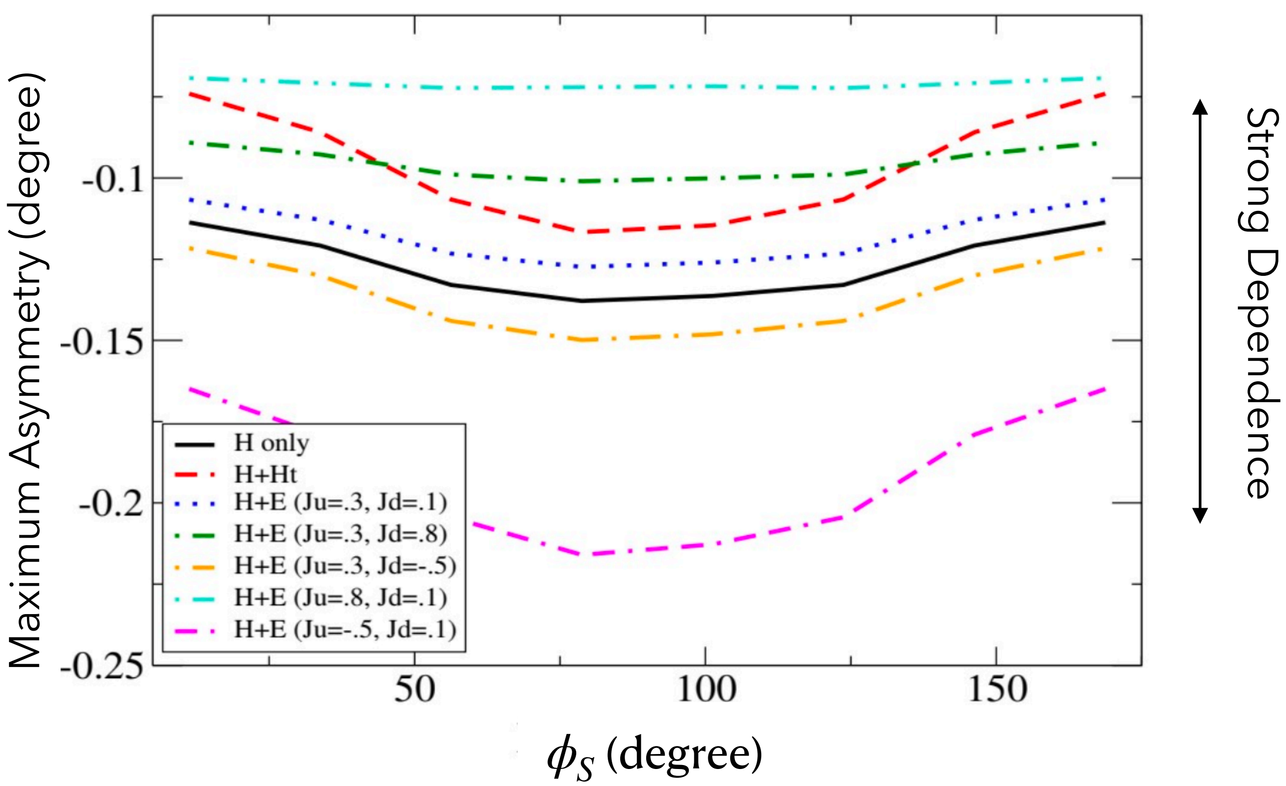


Polarized TCS: projected asymmetry

Dependence in GPD parametrization and J_u, J_d (VGG model) vs ϕ and $\phi_S = 0$



$sin(\phi)$ moment of transverse spin asymmetry vs ϕ_S, Dependence in GPD E and $J^{u,d}$ (VGG model)



High sensitivity with spin of different quarks ($J^{u,d}$)

Polarized TCS measurement setup for Hall C

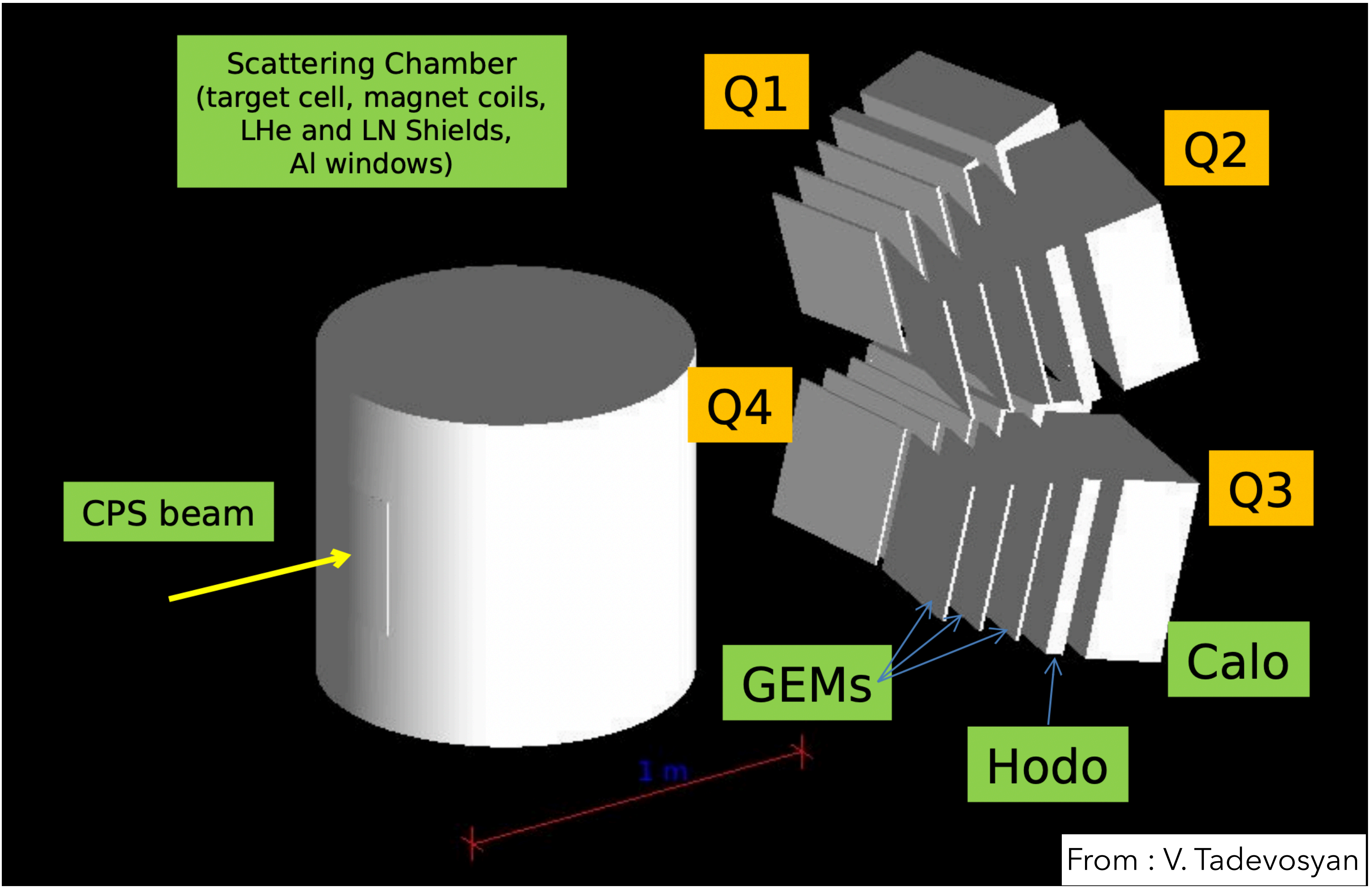


Fig : Geant4 simulation of detector setup at Hall C for proposed polarized TCS experiment

1. High intensity photon source 1.5 x 10^{12} γ/sec (CPS)

2. Target chamber: ammonia (NH_3) traget , 3cm Polarized via DNP

3. Tracking: GEM+hodoscopes, 4 symmetric quadrants

4. Calorimeters: 4 symmetric quadrants, equivalent of 2 NPS ~ 6° to 27° aperture

5.Lumi request: $5.85 \times 10^5\ pb^{-1}$

Compact photon source

NPS collaboration Meeting 2025
: "Discussions CPS Status and Plans" by Steven Lassiter

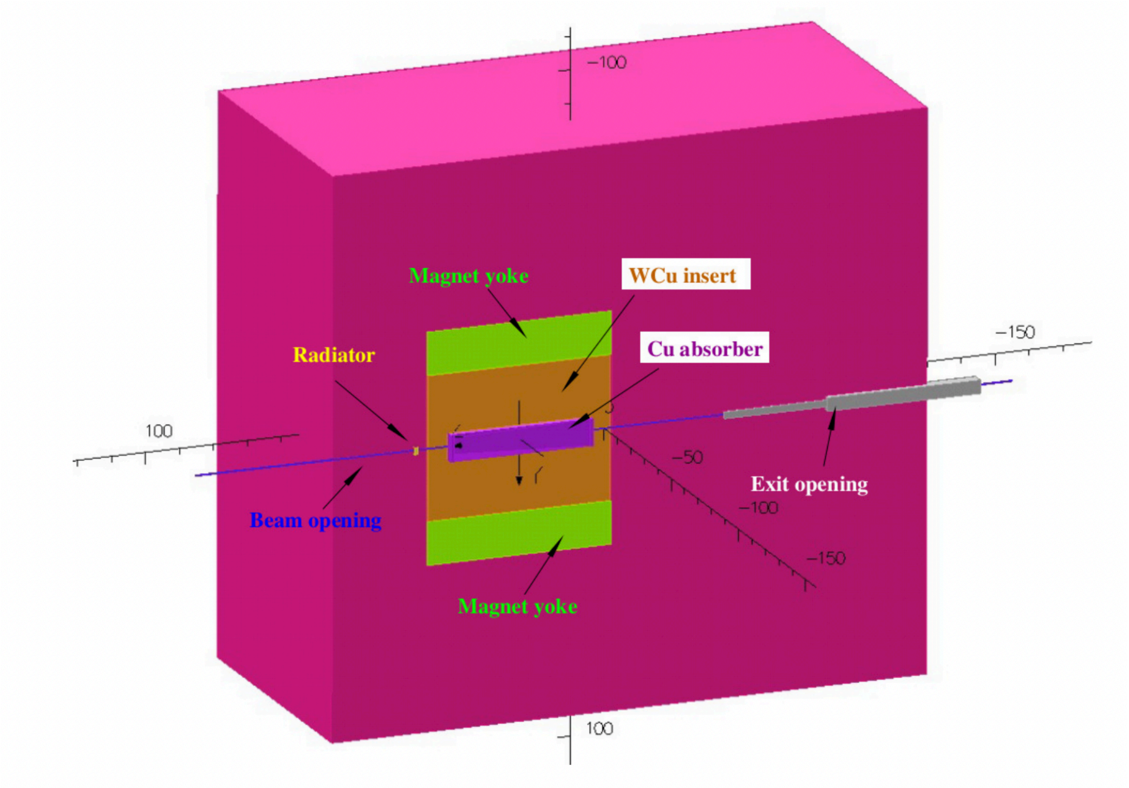
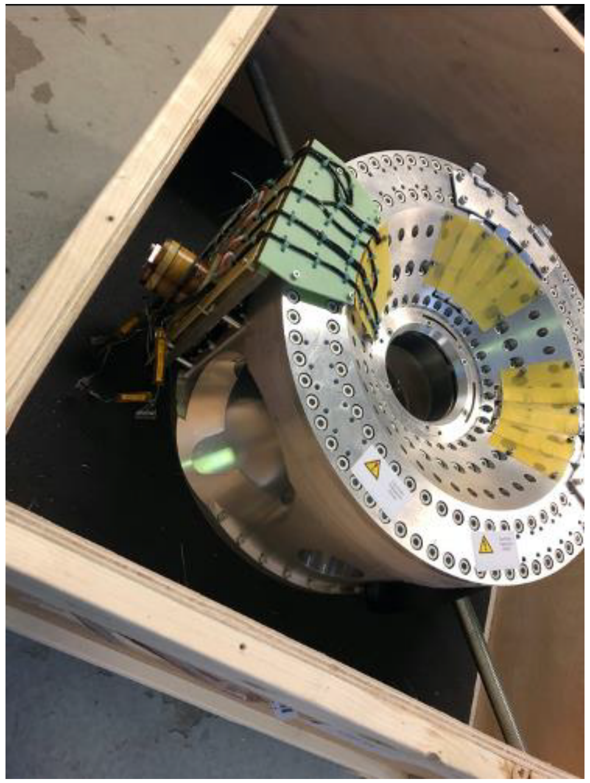


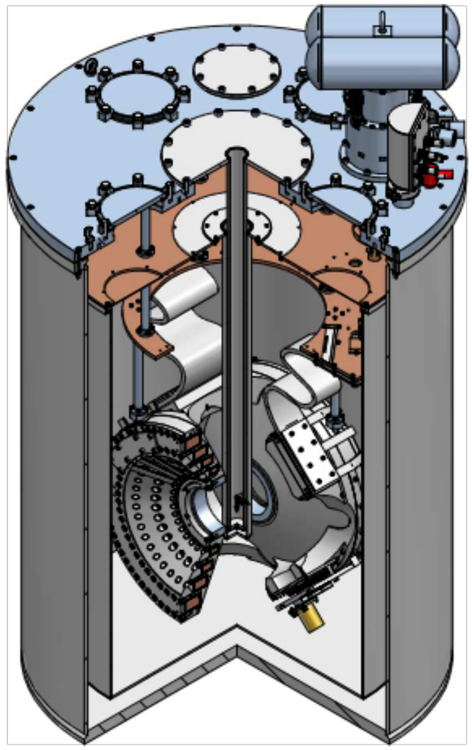
Fig : The CPS Cut off view

Source :A Conceptual Design Study of a Compact Photon Source (CPS) for Jefferson Lab

1. Spot size $\sim 0.9\ mm$ at a distance of 2m away from the radiator
2. Photon Flux $\sim 1.5 \times 10^{12}\ s^{-1}$ from electron beam current $2.5\ \mu A$ on 10% X_0 Cu radiator
3. Photon energy $> 0.5\ E_{beam}$
4. T warm magnet to bend incoming electrons to local beam dump
5. Source : D.Day et al., NIMA 957 (2020) 163429

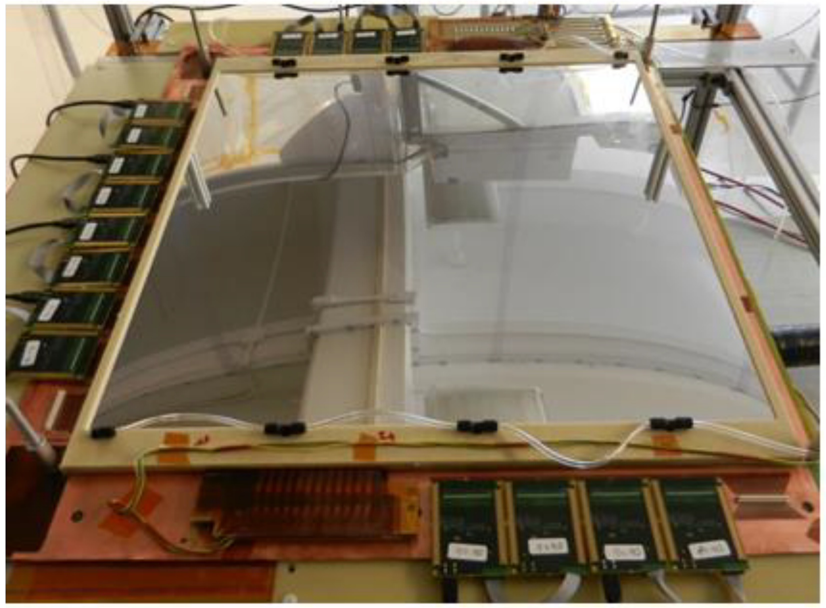
Polarized target





1. Target material: Ammonia ($^{15}NH_3$), in Liquid He at 1°K. Polarized by DNP (Dynamic Nuclear Polarization) method
2. Packing fraction 0.6.
3. Magnetic field generated by superconducting Helmhotz coils.
4. DNP polarization by 140 GHz, 20 W RF field.
5. Polarization monitored via NMR.
6. Depolarization mitigated by combined rotation (~1 Hz) around horizontal axis and vertical up/down movement (~10 mm).

GEM Tracker , Hodoscope & Calorimeter



SBS BT GEM prototype
(*K.Gnanvo et al., NIMA 782 (2015) 77-86*)

GEM trackers:
- Coordinate reconstruction accuracy $\sim 80\ \mu m$
- Background rate tolerance up to $10^6\ Hz/mm^2$
- Minimum material thickness along particle pass
- Big size manufacturing

Use at JLab: SBS, SoLID DDVCS, Prad

Hodoscopes:
- To provide dE/dX signal from low momentum recoil protons
- 2x2x5 cm^3 scintillators arranged in “Fly's eye” hodoscopic construction

Calorimeters, clones of the NPS calorimeter:
- 2x2x20 cm^2 $PBWO_4$ scintillator crystals, optically isolated
- Modules arranged in a mesh of carbon fiber/μ-metal
- Expected energy resolution 2.5%/√E + 1%
- Expected coordinate resolution ~3 mm at 1 GeV
- Modules arranged in 4 “fly's eye” assemblies of 23x23 matrix

Total number of modules needed 2116.

Assembling of NPS calorimeter (June 2022)

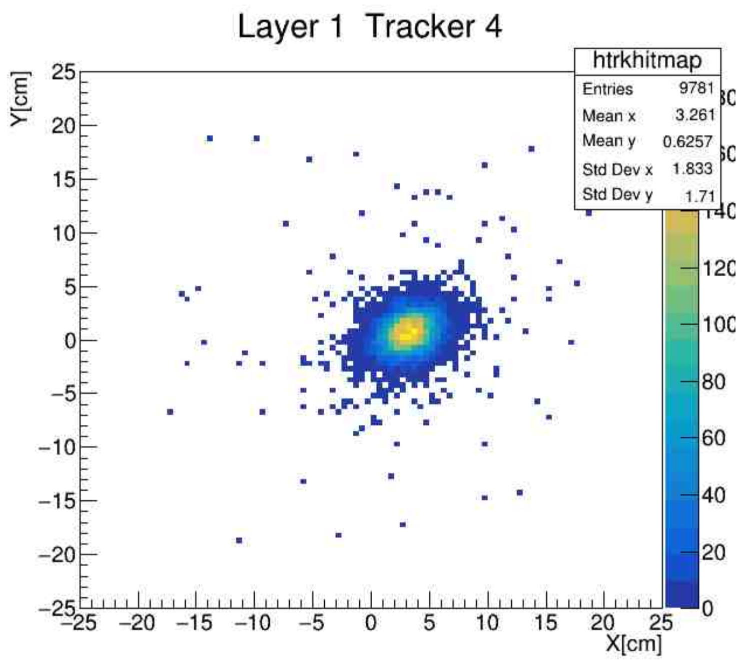
Polarized TCS : Recoil proton ID

Low energy protons : E_{kin} ~ 30 MeV - 450 MeV

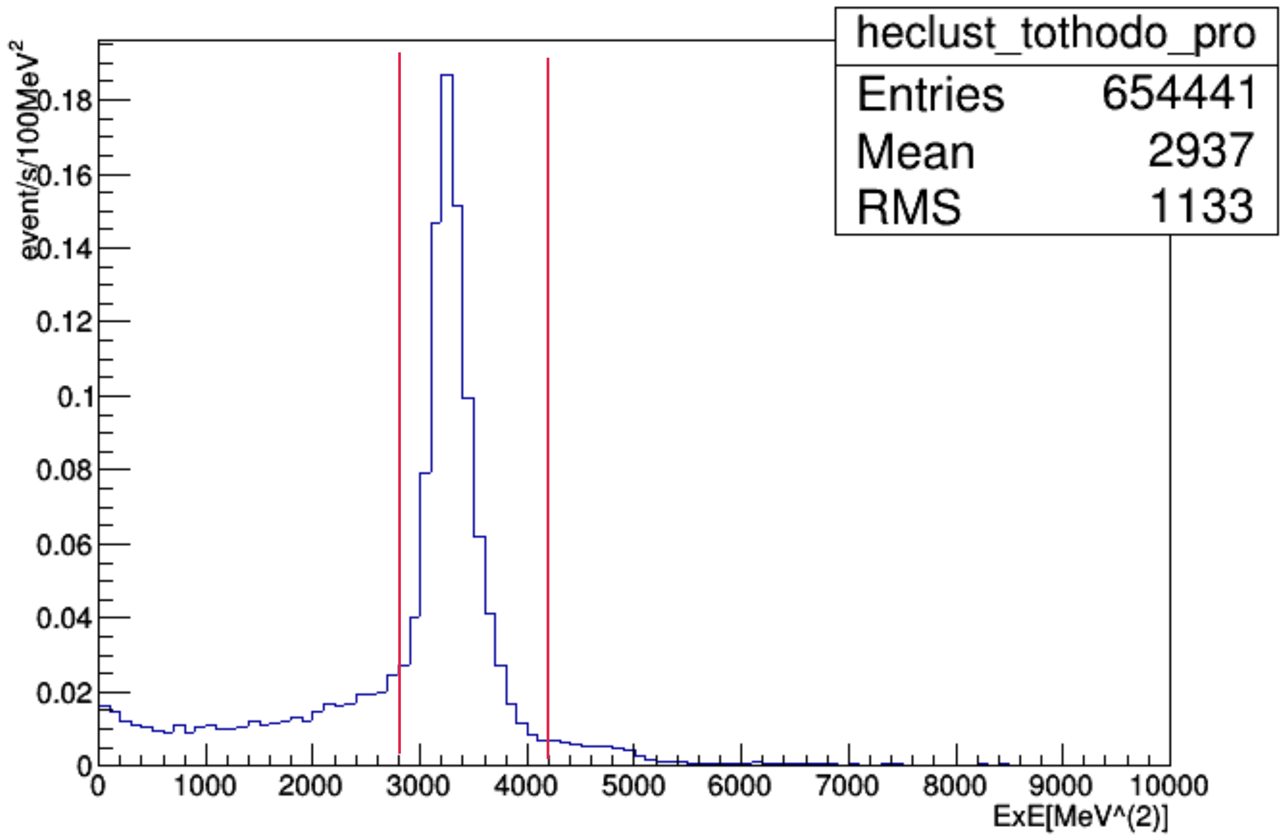
Cuts to select good protons :

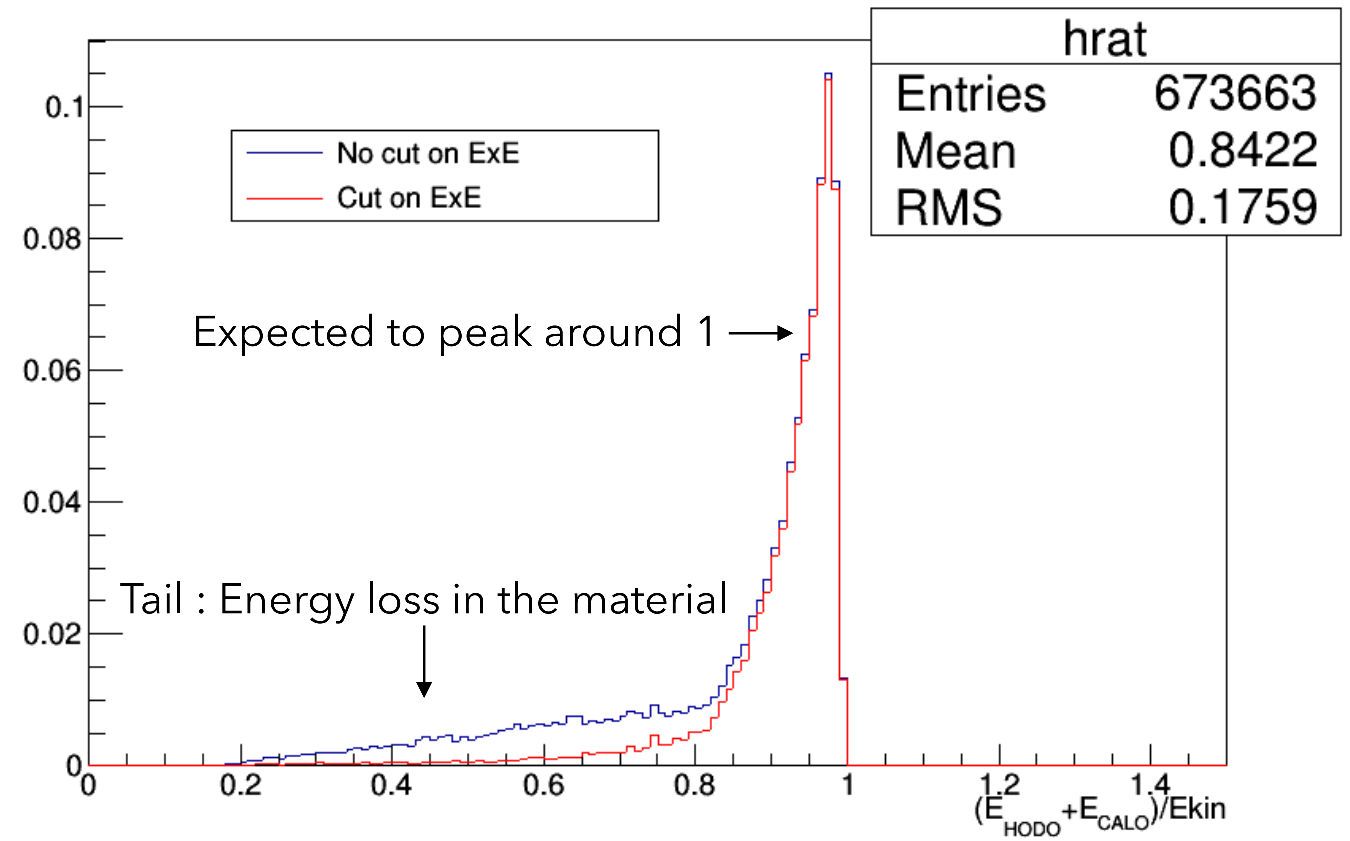
1. E_{HODO} > 15 MeV
2. 90 MeV < $E_{HODO} + E_{CALO}$ < 450 MeV
3. 2800 MeV^2 < E.E < 4200 MeV^2

Where $E.E = (E_{HODO} + E_{CALO} - 12).(E_{HODO} - 7)$



GEM hit patter from 400 MeV/C protons





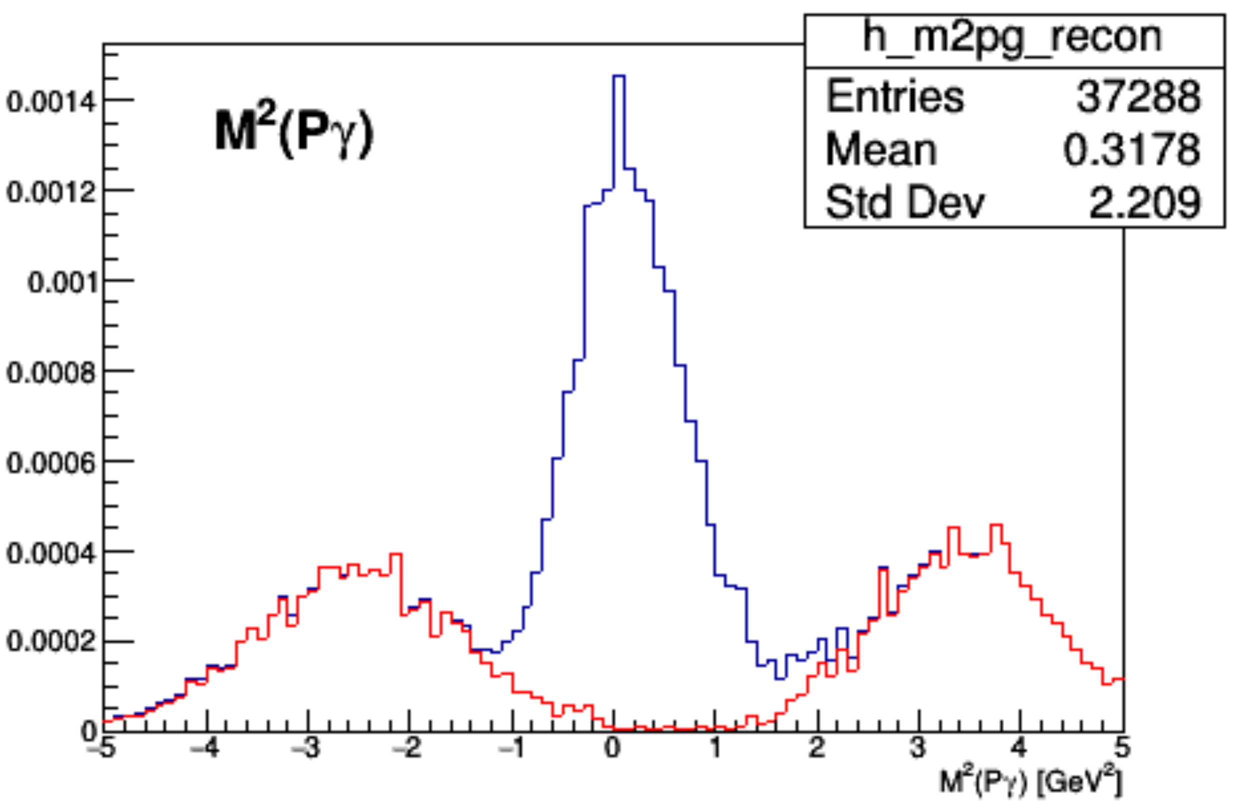
From : Vardan Tadevosyan

Polarized TCS : Lepton charge assignment

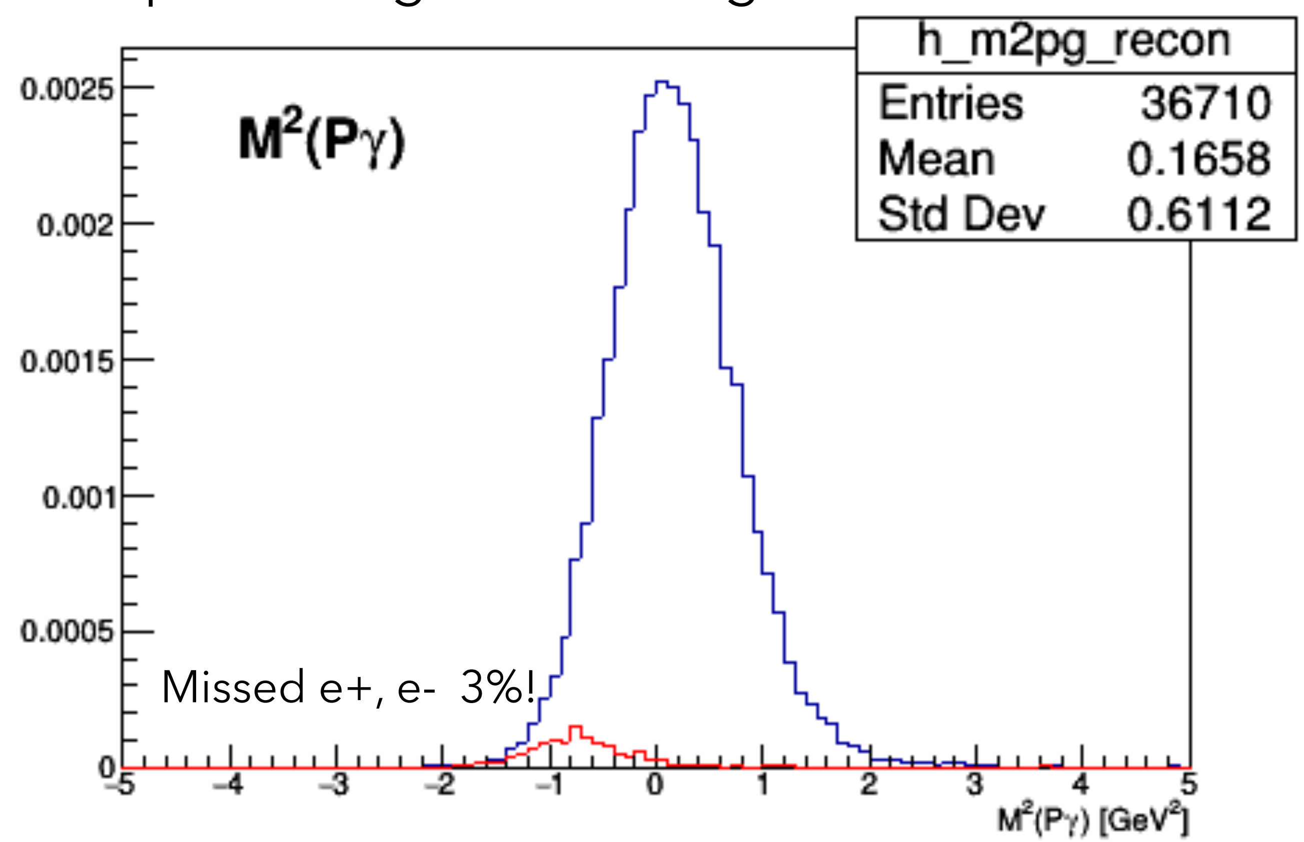
5T target field localized at target cell
Field behind scattering chamber too weak to distinguish pos. and neg. tracks.
Alternative: use reconstructed incident photon mass:

- Reconstruct recoil proton;
- Reconstruct leptons twice, by assigning (+,-) and (-,+) charges;
- Combine with reconstructed proton to get 2 masses, choose smaller one.

Random lepton charge assignment

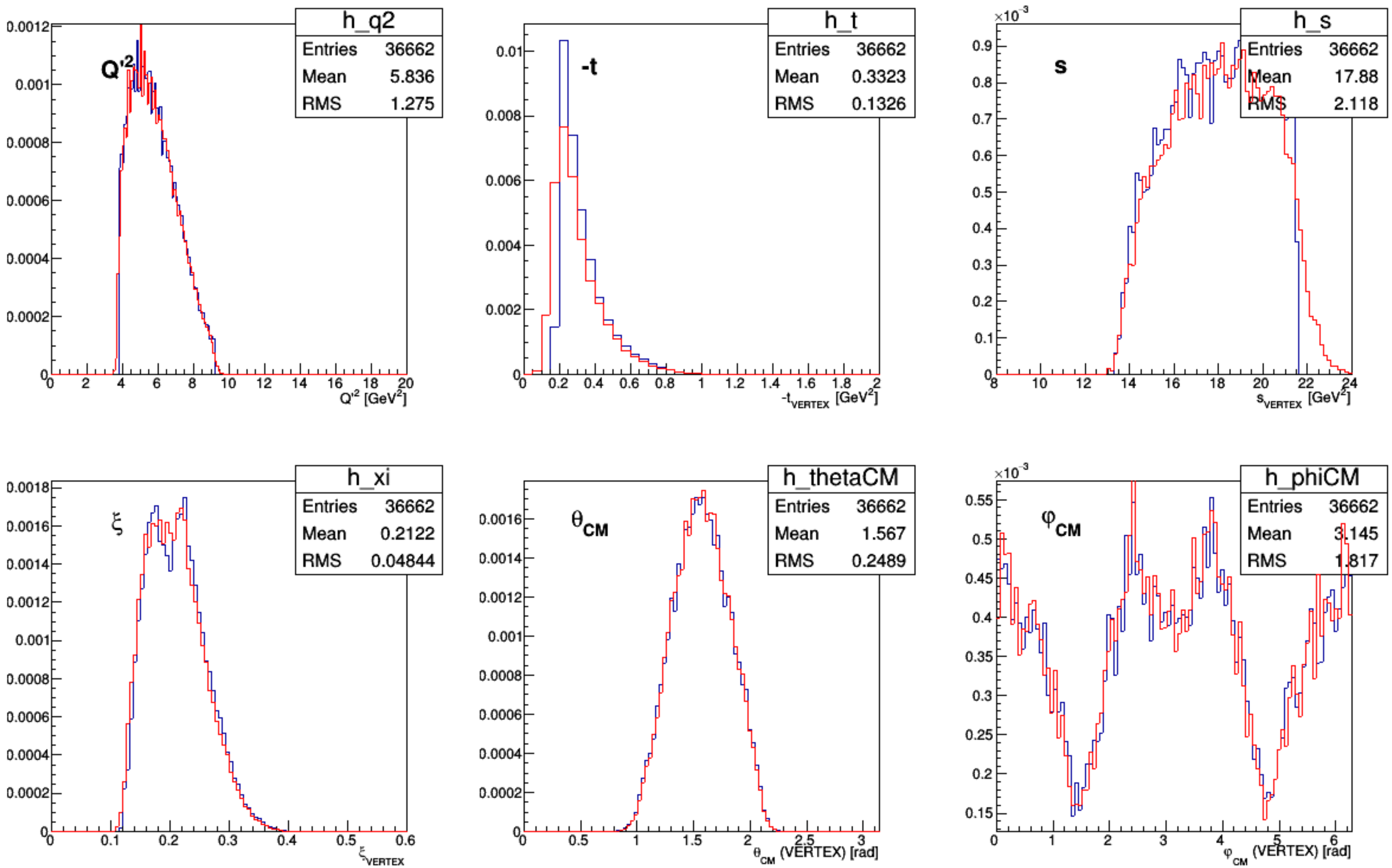


Lepton charges according to selection criteria



From : Vardan Tadevosyan

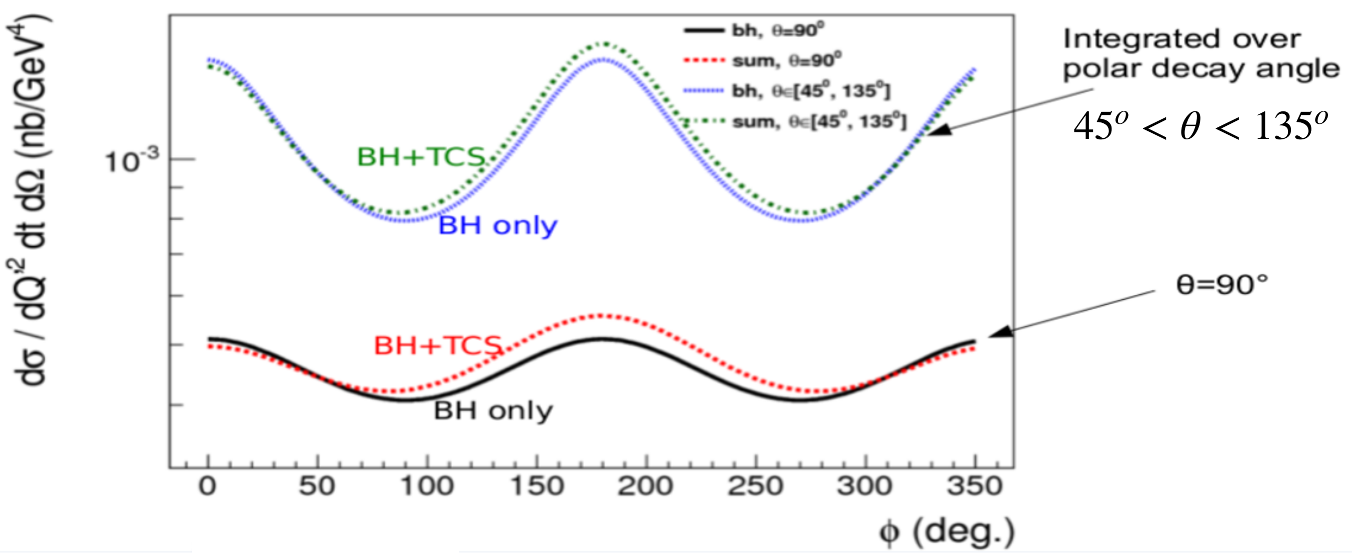
Polarized TCS : reconstructed vs true quantities



From : Vardan Tadevosyan

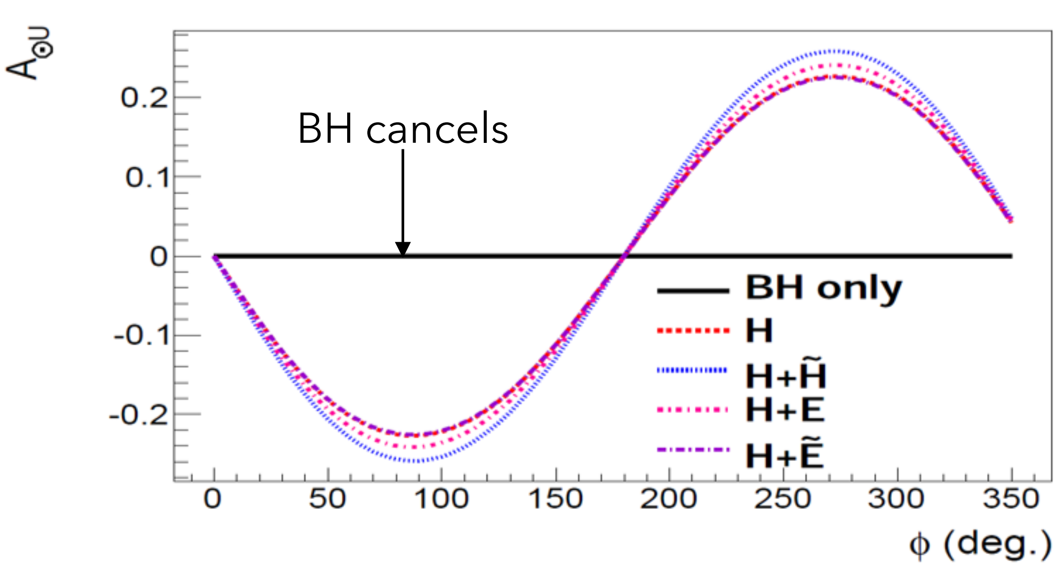
TCS observables and GPD sensitivity (Calculations)

1. Unpolarized Cross sections

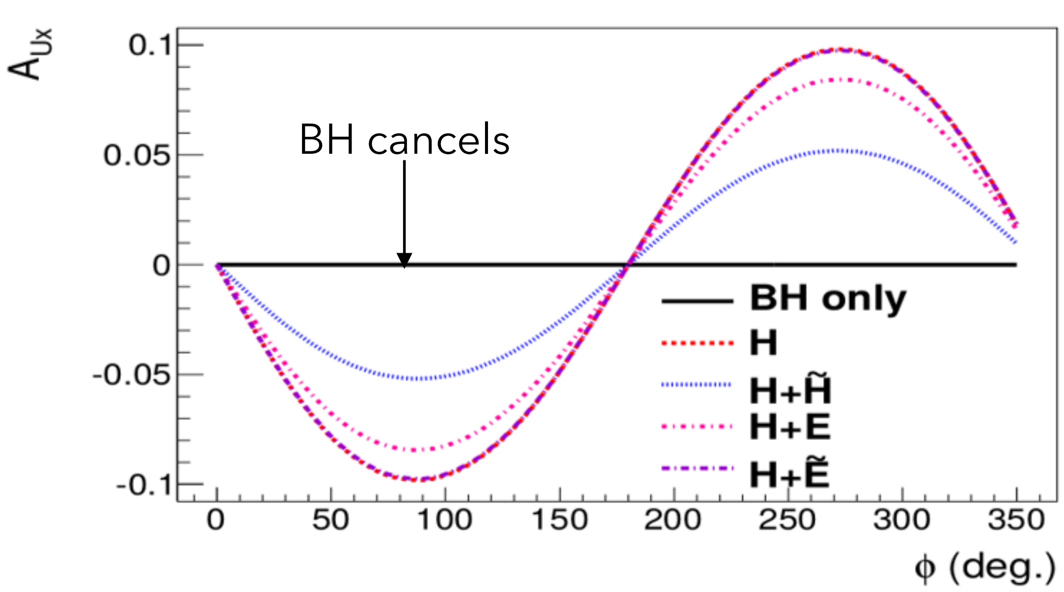


1. Unpolarized σ:
   1. sensitivity to both Im + Re part of amplitude
   2. difficult to measure as BH (only Real) dominant
2. Beam or target polarized Asymmetry :
   1. BH cancel, reflect interference
   2. easier to measure, quite large
   3. access Im(H), Im(H̃), Im(E)
3. Double spin asymmetry or linear beam:
   1. strong constrains on Re
   2. very hard, dominated by BH

2A. Circularly polarized beam asymmetry

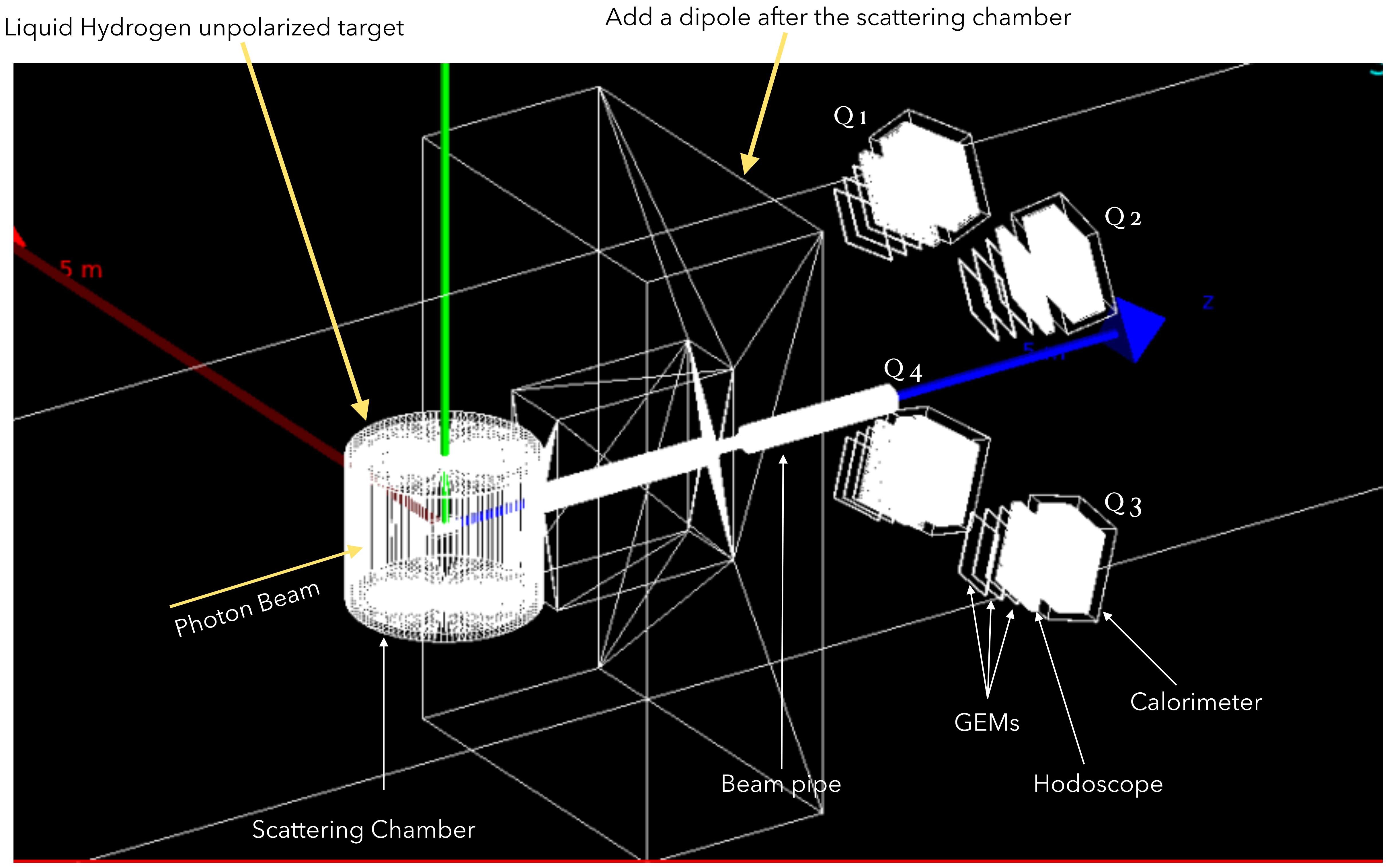


2B. Transversely polarized target asymmetry



from Boer, Guidal, Vanderhaeghen, Eur. Phys. J. A51 (2015) 8, 103

Unpolarized TCS measurement setup for Hall C



Physics Observables Unpolarized TCS :

unpolarized cross section and polarized beam spin asymmetry

Single Spin Asymmetry ($A_{\odot U}$) : circularly polarized beam and unpolarized target

$$A_{\odot U} = \frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}} \qquad \ldots (2)$$

1. $\sigma^{\pm} \equiv \dfrac{d^5\sigma}{dQ'^2 \; dt \; d\Omega \; dE_{\gamma}}$: 5 differential scattering cross-section TCS+BH
2. $\pm$: right (+) or left (-) handed circular polarization of the real photon
3. 5 differential cross section sensitive to both Real and Imaginary part of CFF
4. Asymmetry arises due to the interference between the TCS and BH processes
5. $A_{\odot U} \propto sin(\phi)$ moment of the $\dfrac{d^5\sigma^{INT}}{dQ'^2 \; dt \; d(cos\theta) \; d\phi \; dE_{\gamma}}$
6. $A_{\odot U}$ is sensible to the Imaginary part of the amplitude
7. As BH amplitude is purely Real, $A_{\odot U}$ asymmetry is due to TCS process only

Scattering Chamber & Target

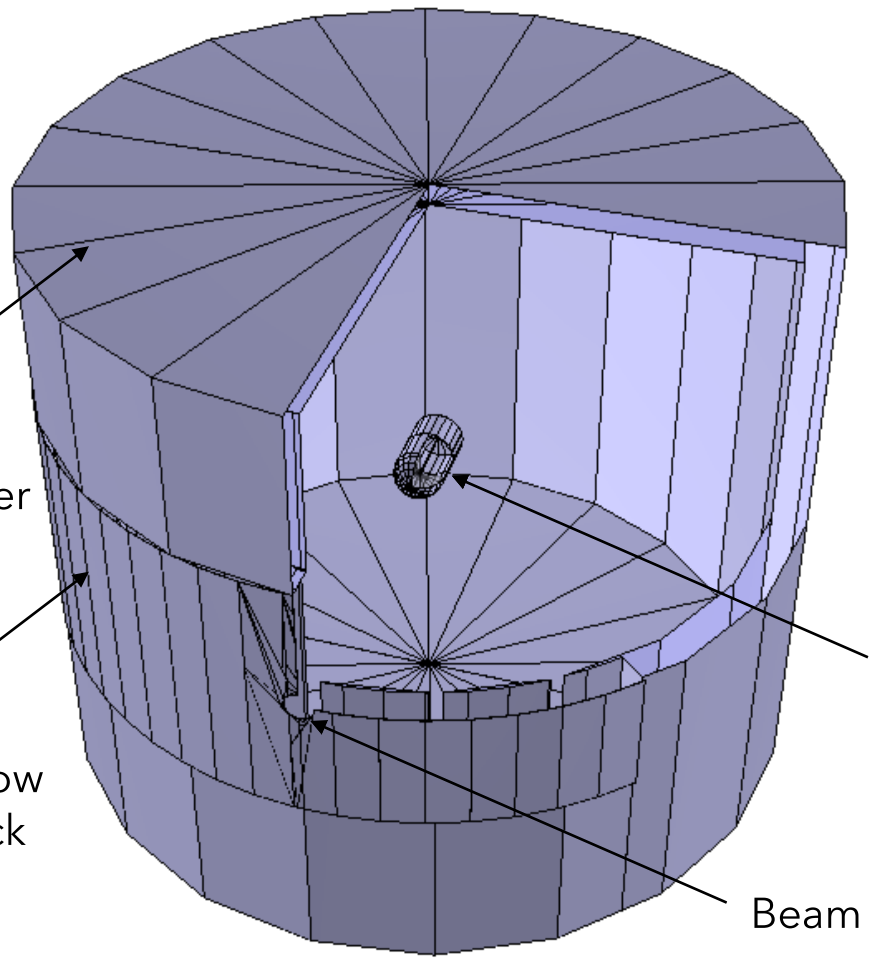


Fig : Geant4 simulation of scattering chamber and target

1. Scattering chamber inner diameter = 41 inches
2. Scattering chamber outer diameter = 45 inches
3. Angular range : horizontal HMS : 3.2 to 77.0 degrees
4. Angular range : SHMS : 3.2 to 47.0 degrees
5. Vertical angular range : ±17.3 degrees
6. Target thickness of Entrance and exit cap = 0.1778 cm
7. Target cell wall thickness = 0.0254 cm

Calorimeter

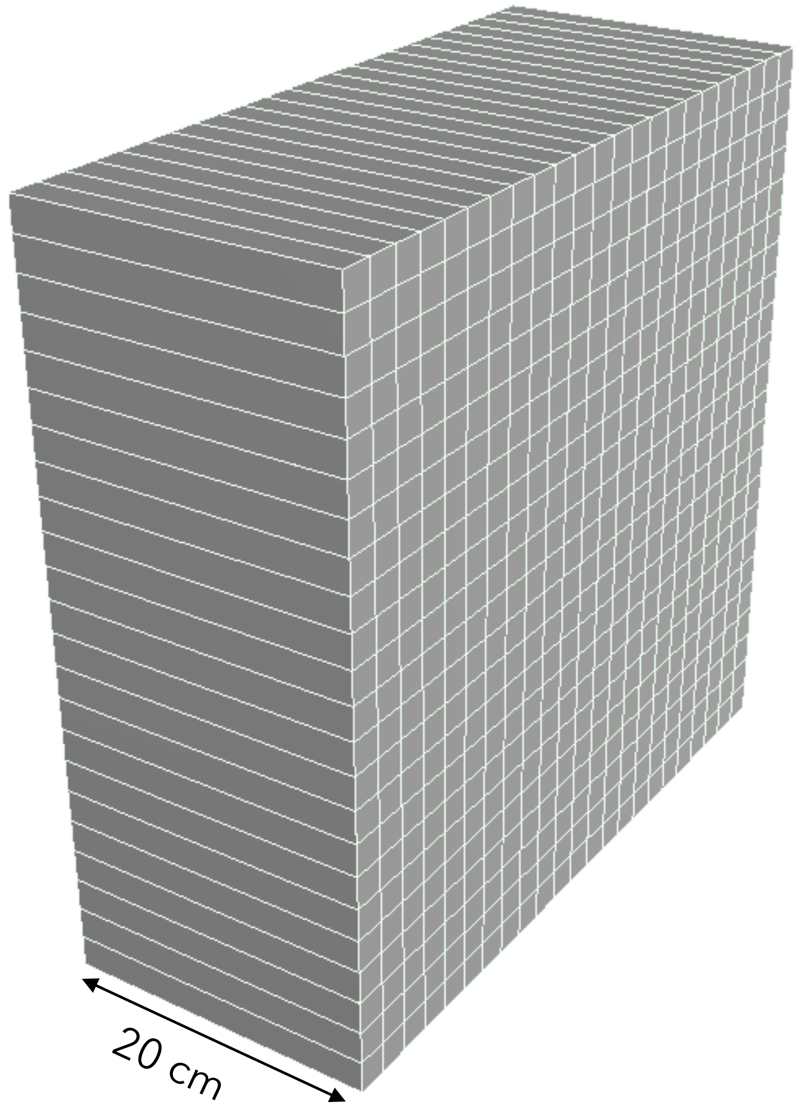


Fig : Geant4 simulation calorimeter

1. e^-, e^+, P detection and PID
2. Clones of the NPS calorimeter at Hall C
3. 2x2x20 cm^2 PBWO4 scintillator crystal
4. Expected energy resolution $\frac{2.5\,\%}{\sqrt{E}} + 1\,\%$
5. Coordinate resolution ~3 mm at 1 GeV
6. Fly's eye assembly of 23x23 matrix of total 2116 modules

Magnet : Separate the outgoing particles

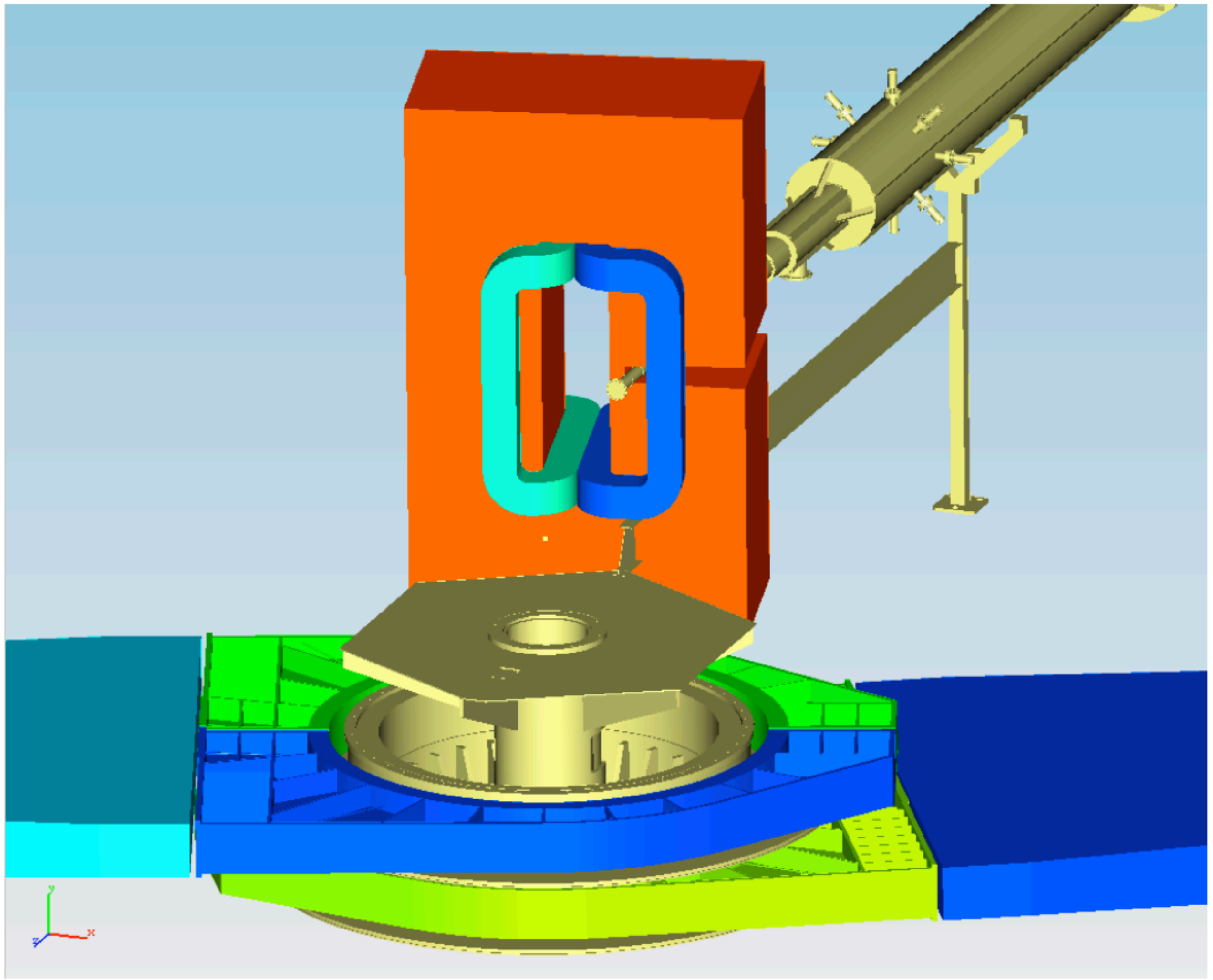


Fig : CAD Drawing for Super Bigbite Magnet
Source : https://userweb.jlab.org/~bogdanw/SBS-general.pdf

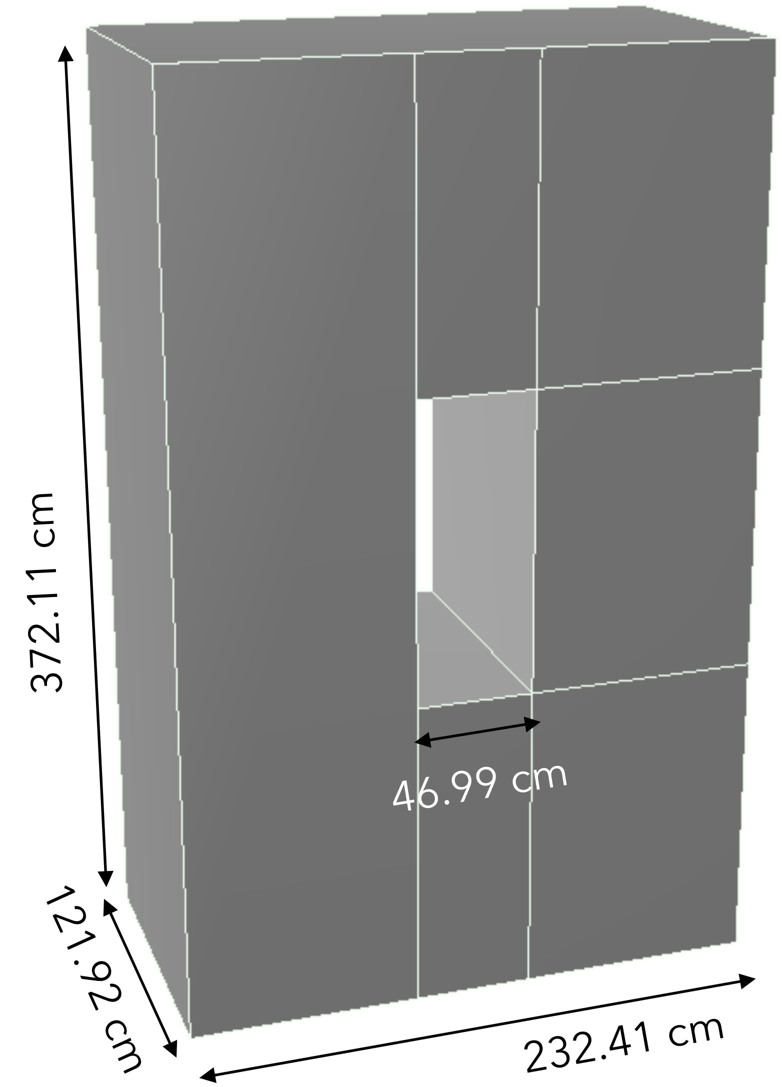
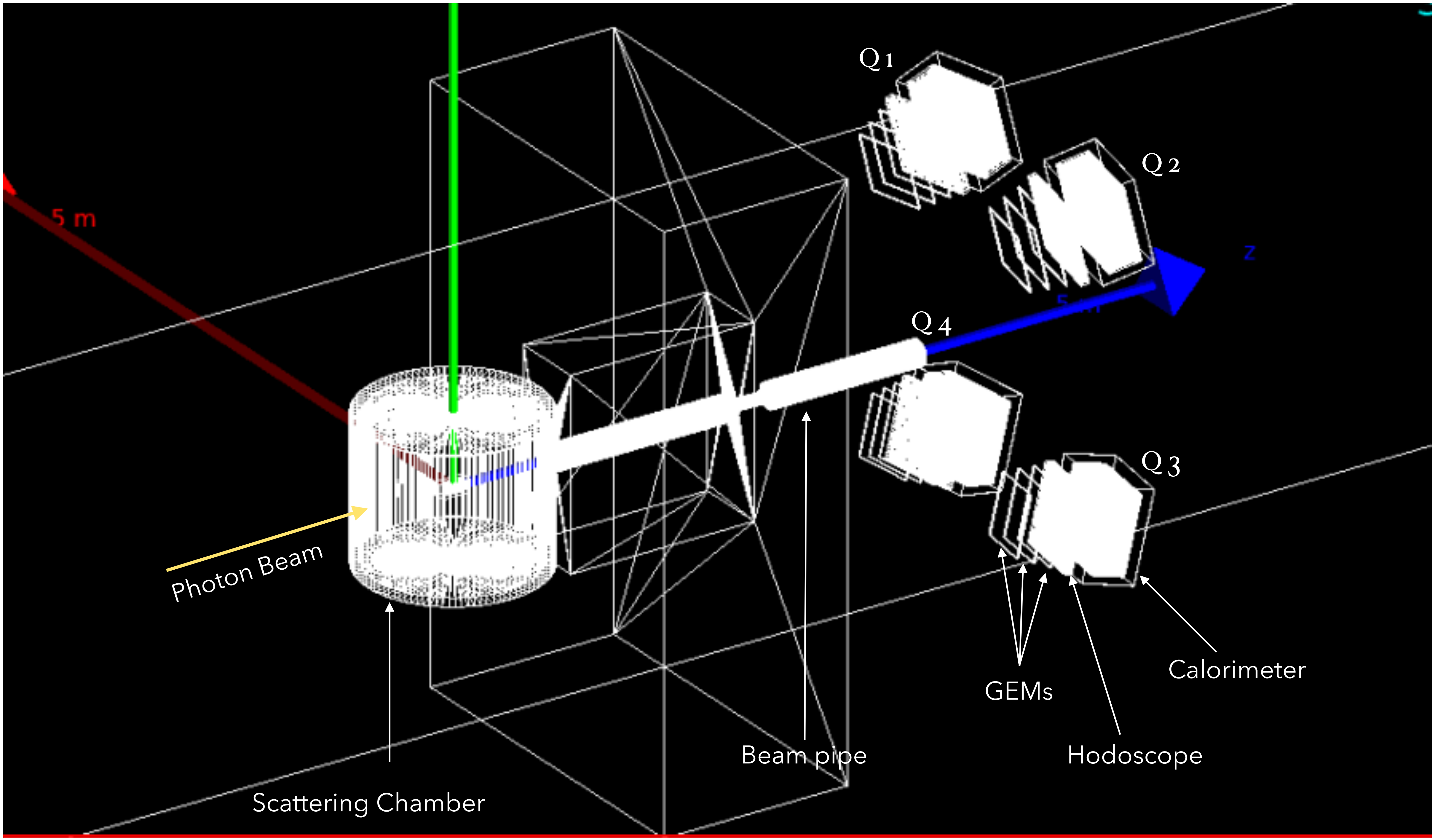


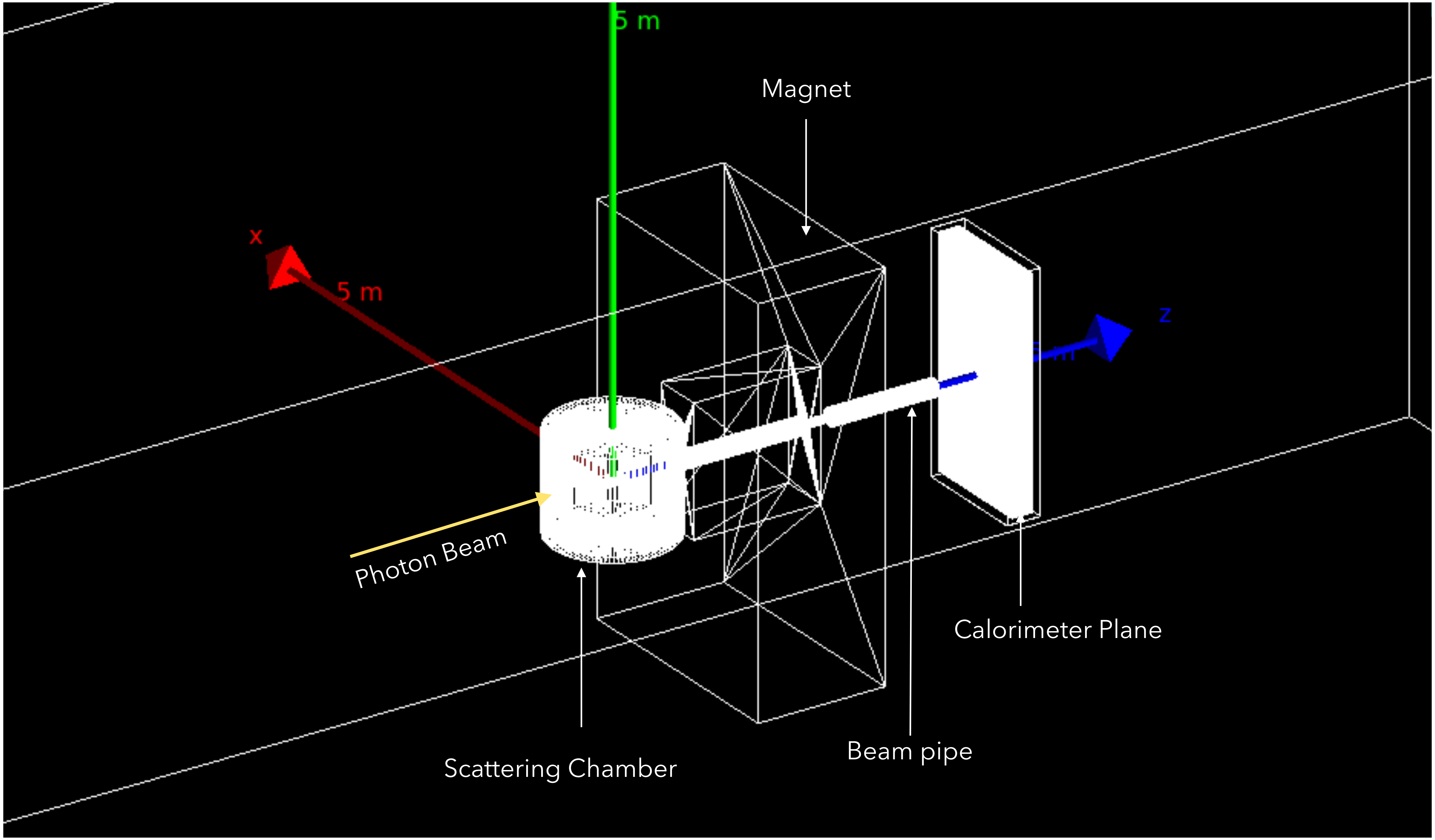
Fig : Geant4 simulation of simple magnet geometry

1. The field integral is 2.4 Tesla-meter with 1.2 m long pole

Unpolarized TCS measurement setup for Hall C

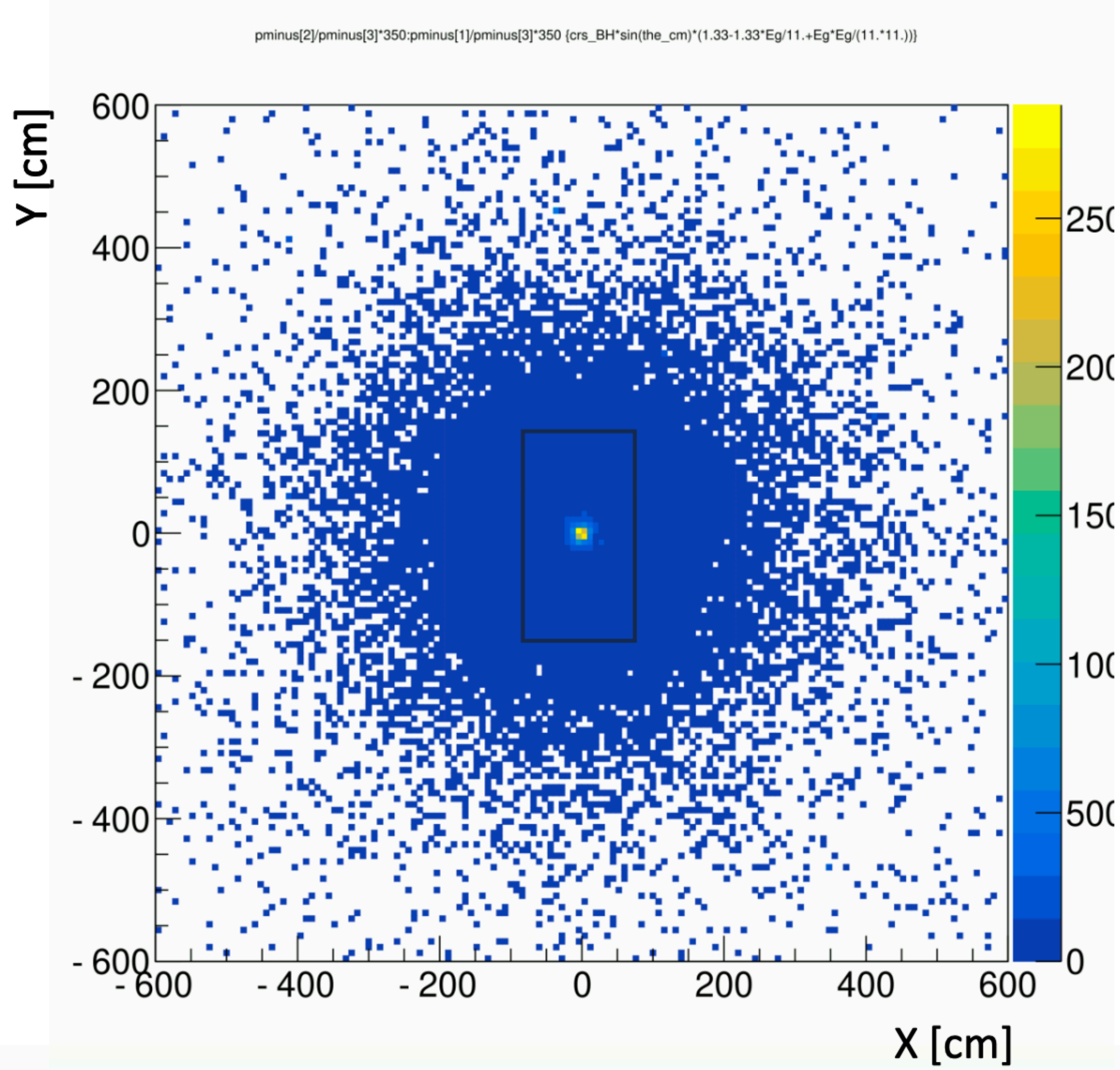


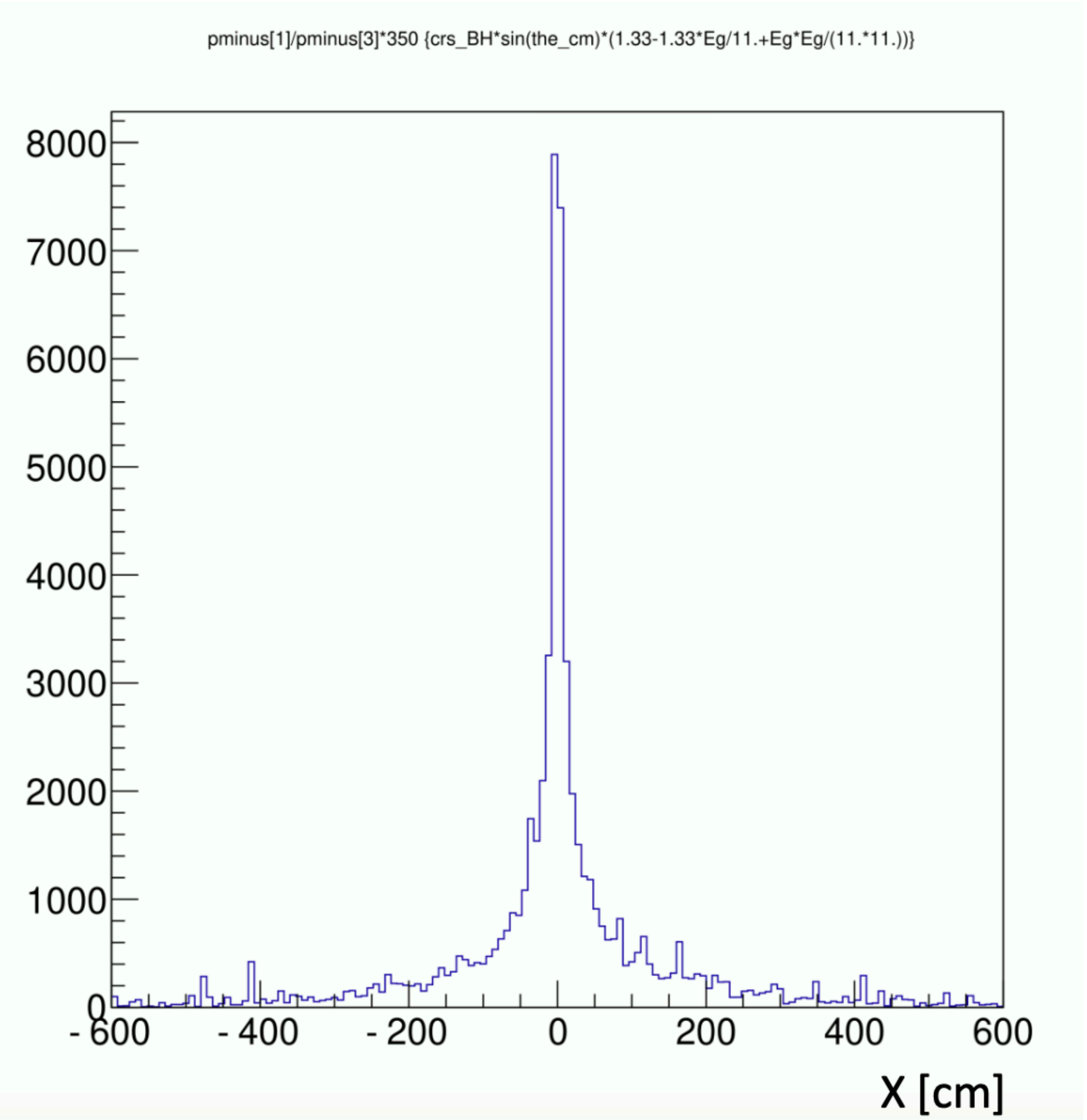
Geant4 Simulation :Simple One Calorimeter Plane Setup



Geant4 Simulation : projection of electrons w/o magnetic field

1. TCS weighted events (from DEEPGen event generator) for electrons
2. Projected to Z = 350 cm plane (face of the calorimeter)
3. No magnetic Field
4. Rectangle at the center of the 2D plot encompasses the events passing through the magnetic bore
5. Expect Similar for positrons

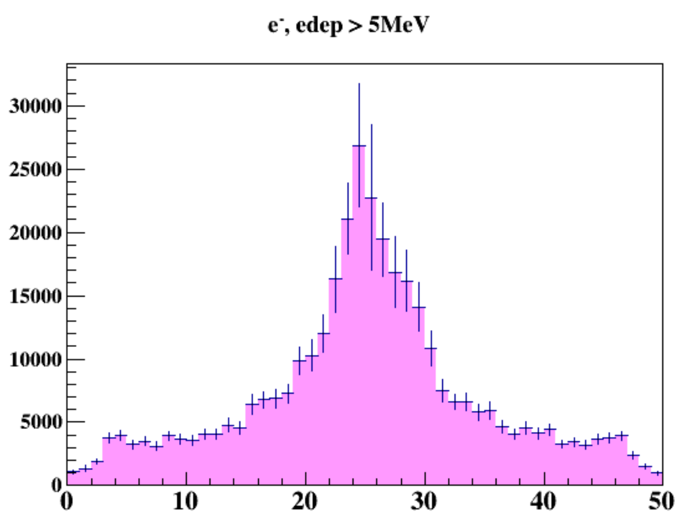




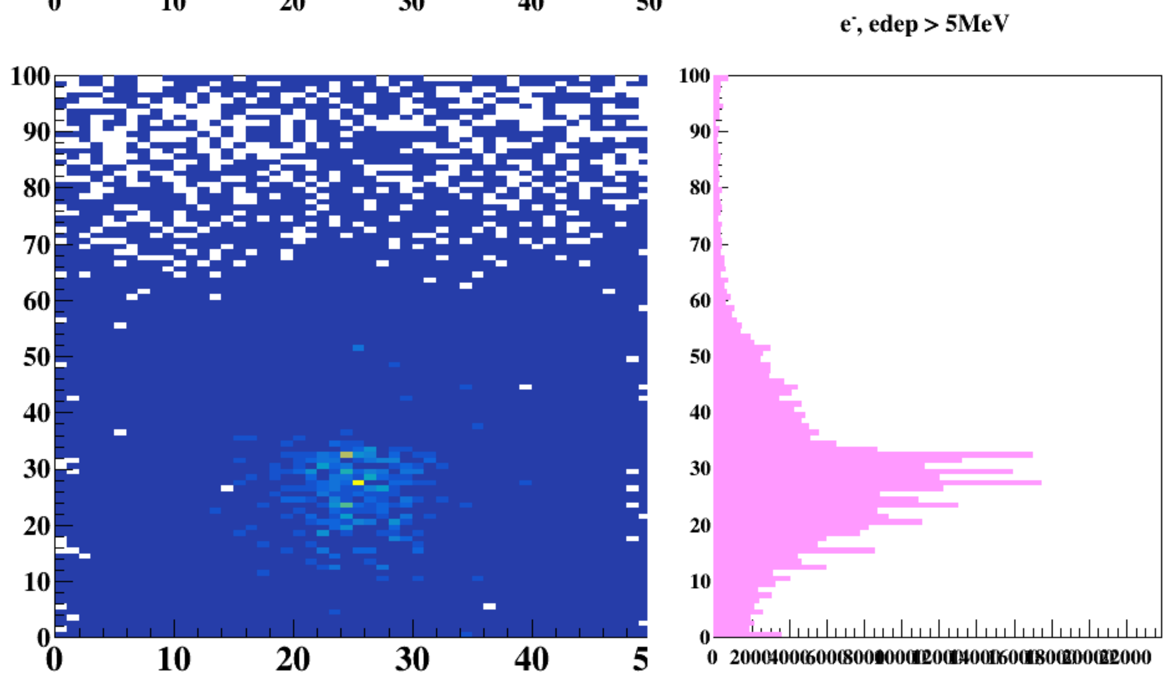
From : Vardan Tadevosyan

Geant4 Simulation : charge assignment to leptons

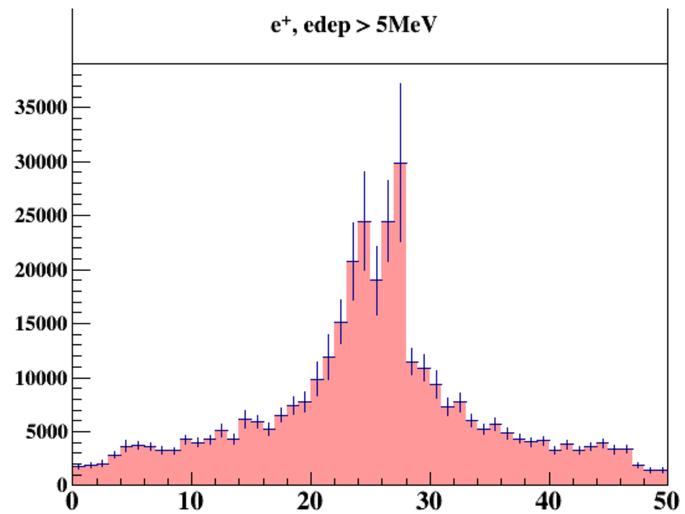
Projection of electron on calorimeter plane



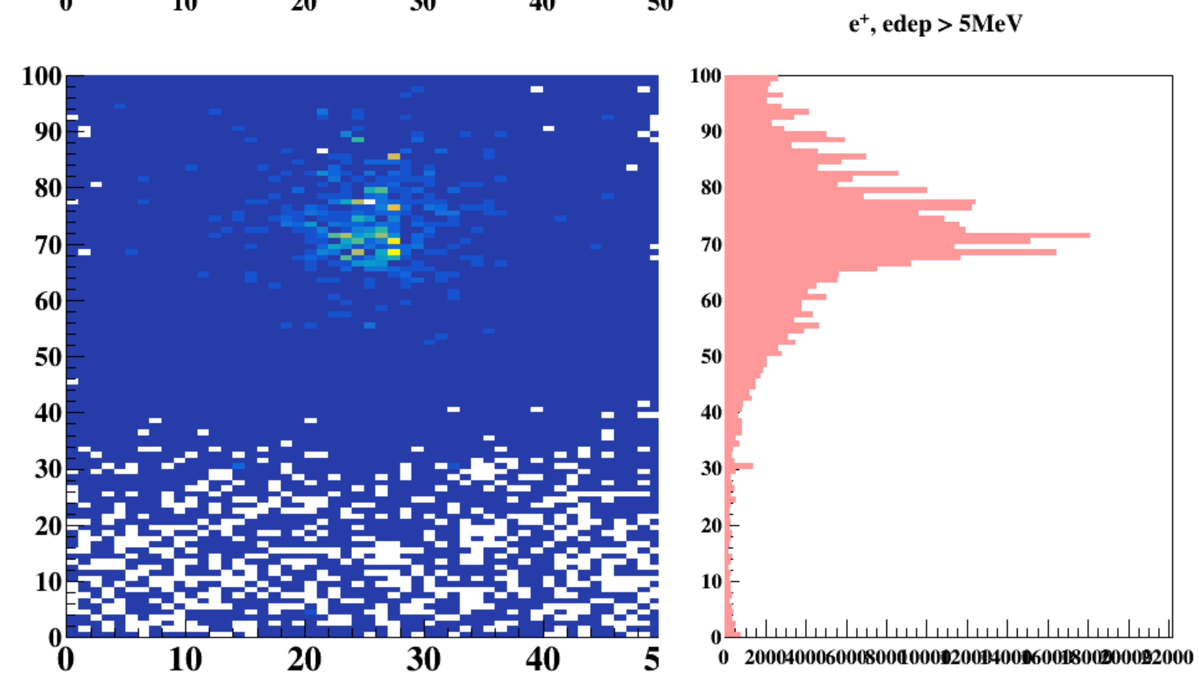
1. Magneti fiels : 2.4 T-m
2. For each event only the hit with maximum energy deposition is considered



Projection of positron on calorimeter plane

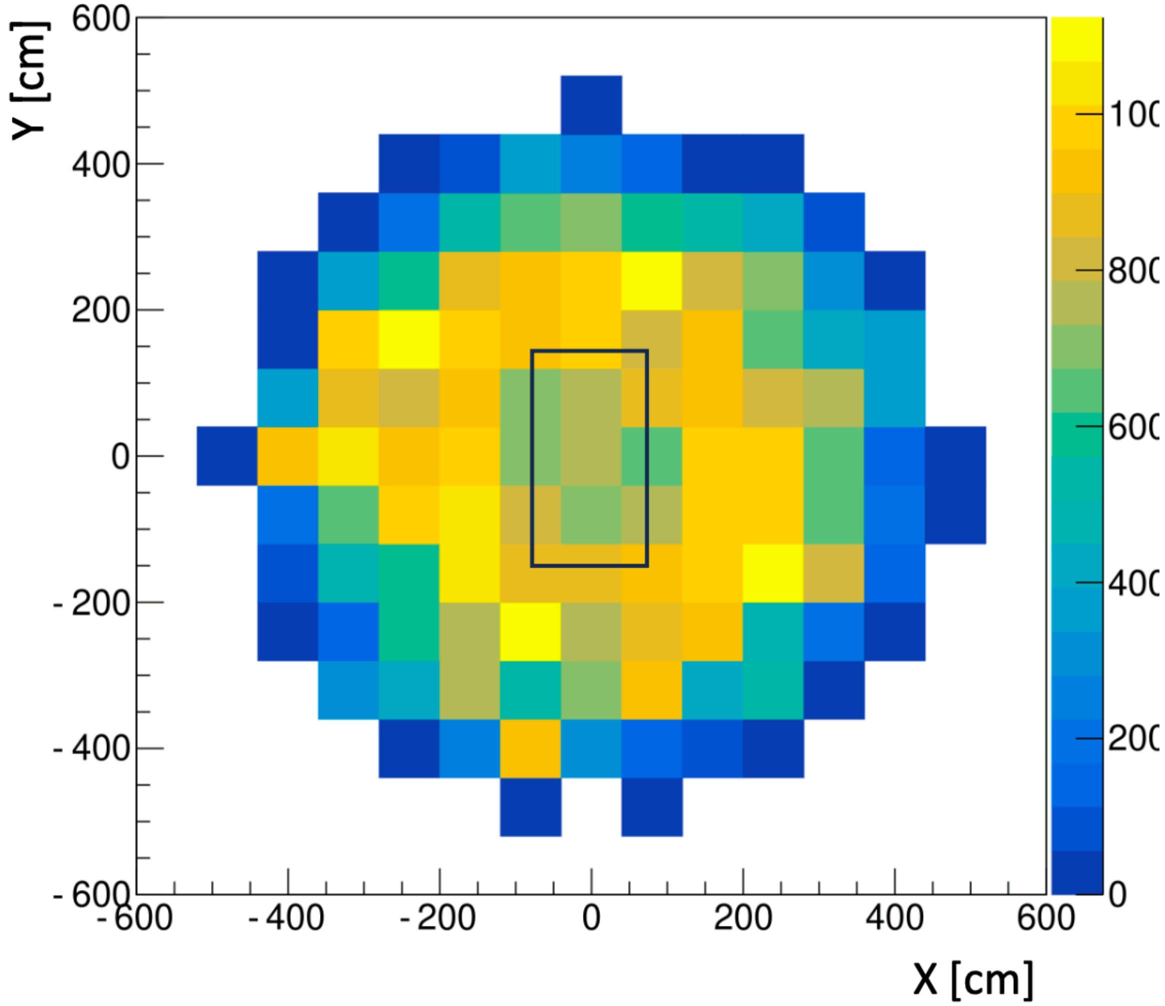


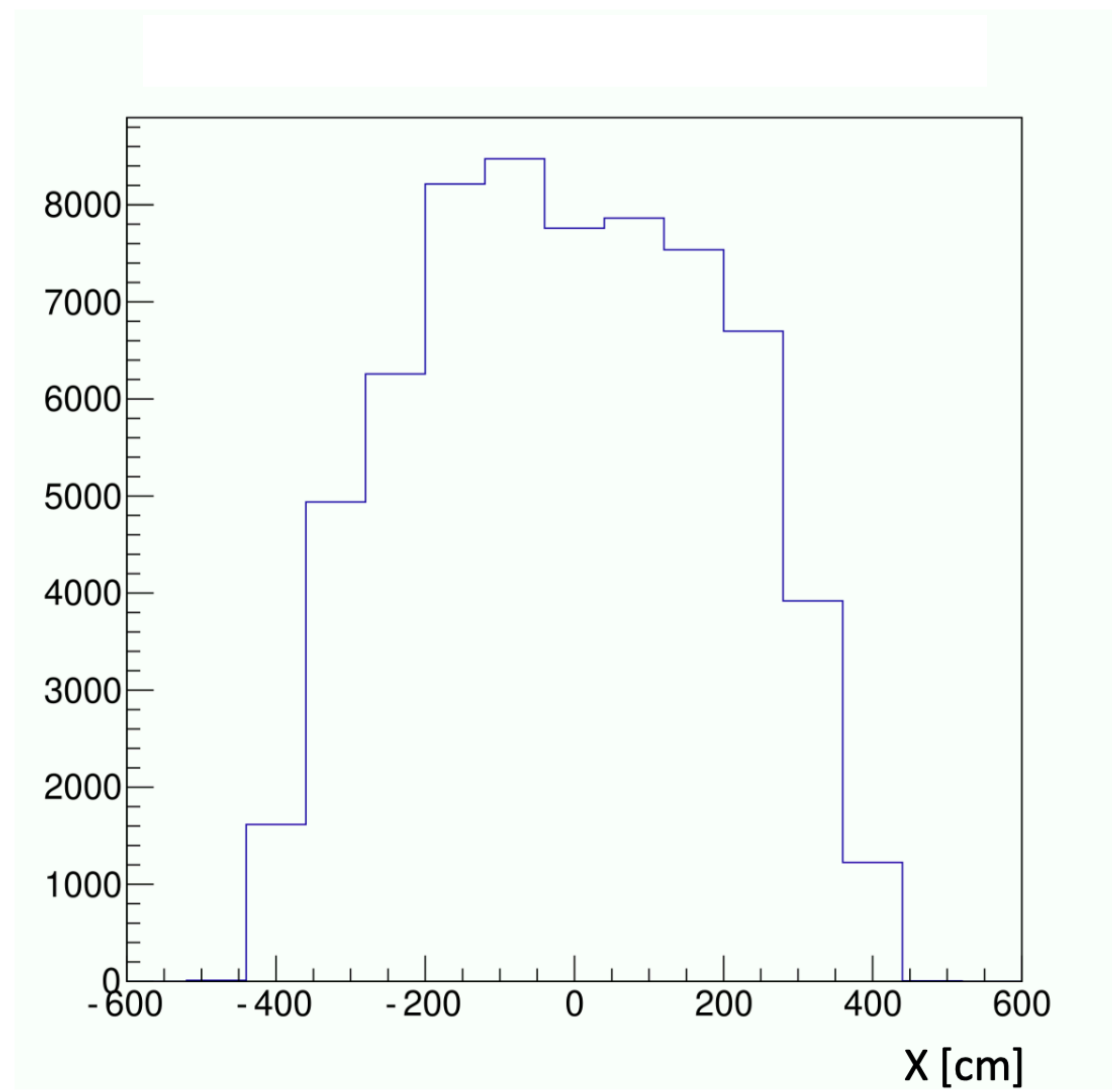
1. Magneti fiels : 2.4 T-m
2. For each event only the hit with maximum energy deposition is considered



Geant4 Simulation : projection of protons w/o magnetic field

1. TCS weighted events (from DEEPGen event generator) for recoil protons
2. Projected to Z = 350 cm plane (face of the calorimeter)
3. No magnetic Field
4. Rectangle at the center of the 2D plot encompasses the events passing through the magnetic bore

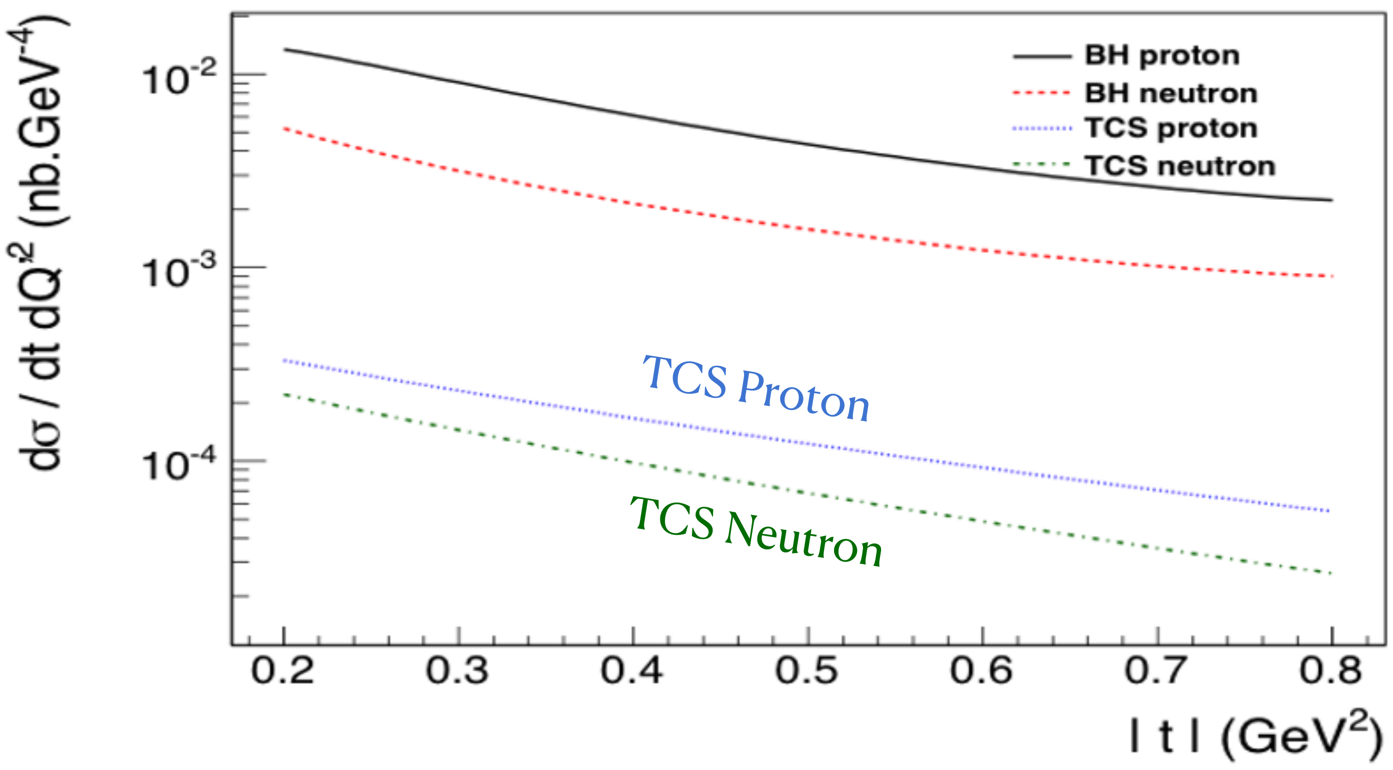




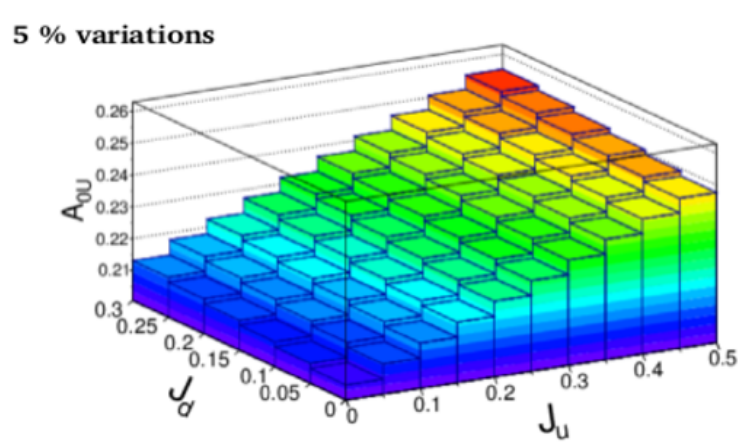
From :

Possible extension to measure TCS for neutron

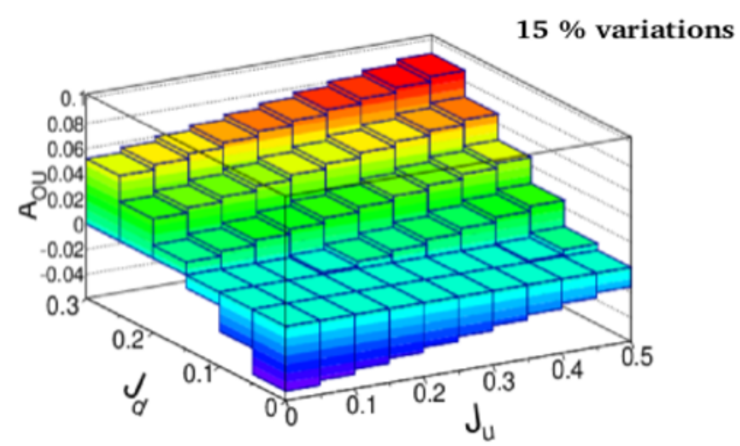
Comparison of Proton and Neutron
Unpolarized cross sections vs -t



BSA : Proton



BSA : neutron

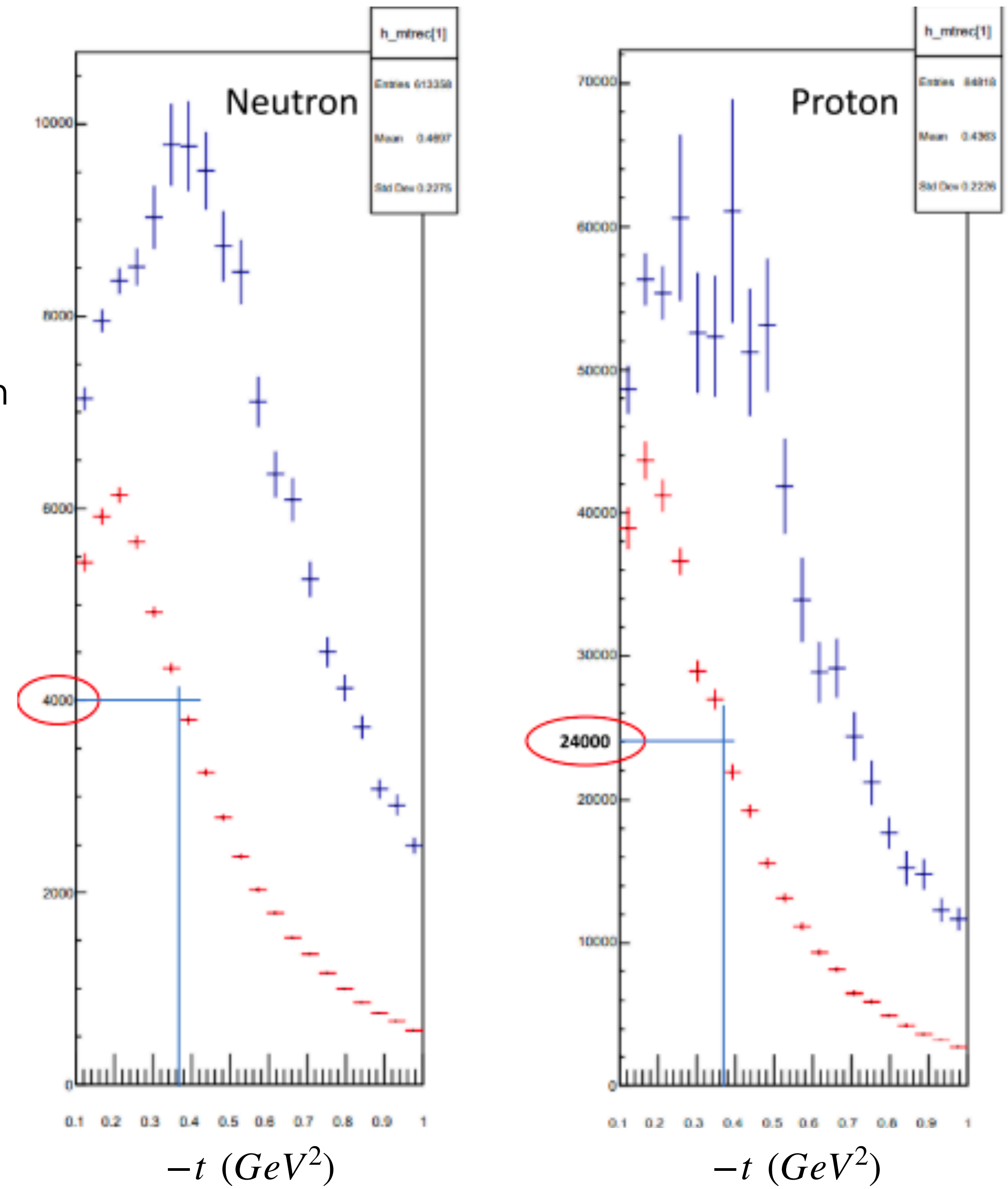


From Boer, Guidal, Vanderhaeghen, EPJA 52 (2016) 33

1. Neutron unpolarized cross section is small compared to proton cross section but still not suppressed
2. Sizable Asymmetry
3. But BSA of neutron is very much sensitive to J_u and J_d
4. Similar sensitivity to GPD
5. With Longitudinally polarized target single and double spin asymmetry measurement is possible
6. With linearly polarized beam experiment will be sensitive to Re(H)

Possible extension to measure TCS for neutron

1. Preliminary study to show the feasibility of the measuring TCS for neutron
2. Number of reconstructed TCS events (weighted by cross-section) plotted against -t
3. Study before having the full Geant4 simulation
4. In principle it is possible to do the measurement on neutron, provided we have an neutron detector



From : Camille Zindy & M. Boer, 2021

Accessing GPDs through exclusive reactions

Compton like reactions

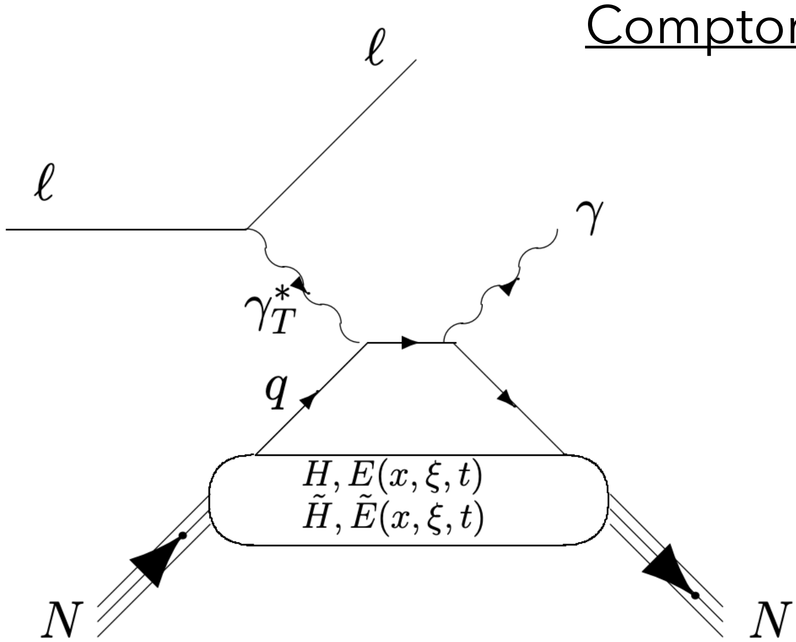


Fig : DVCS

https://arxiv.org/pdf/1511.04535.pdf

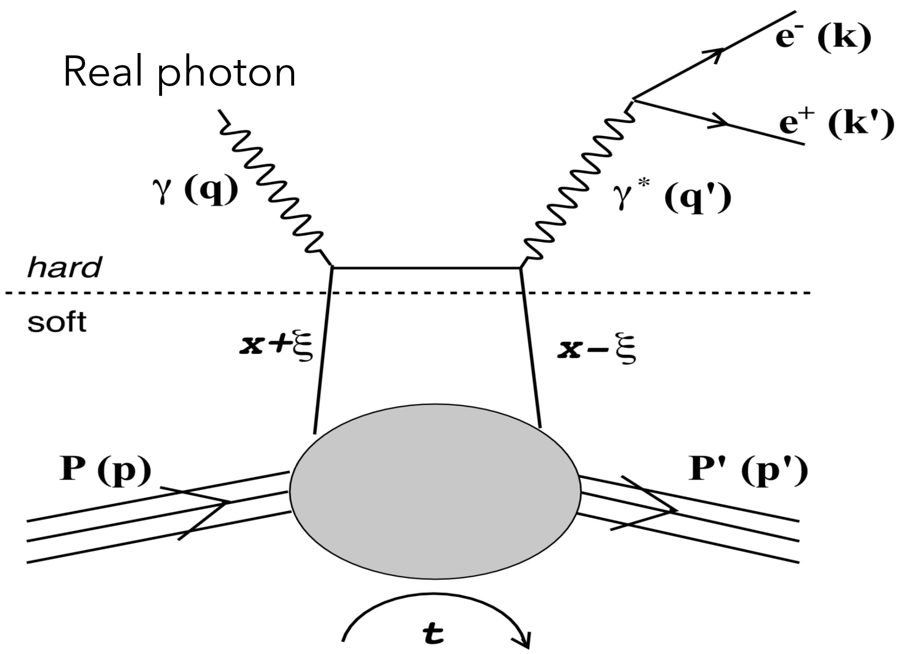


Fig : TCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

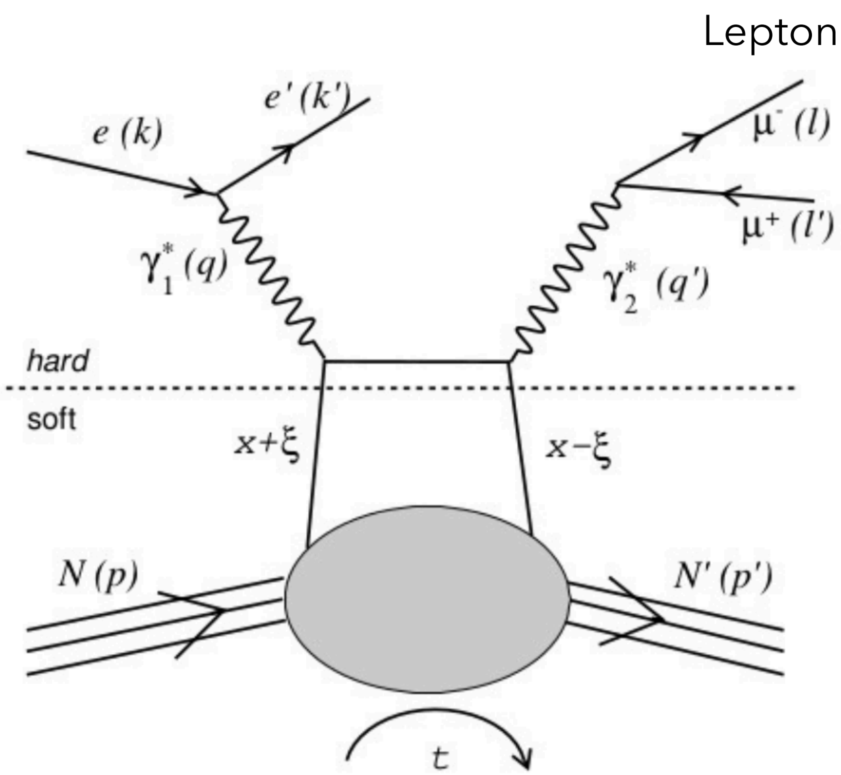


Fig : DDVCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

Meson production

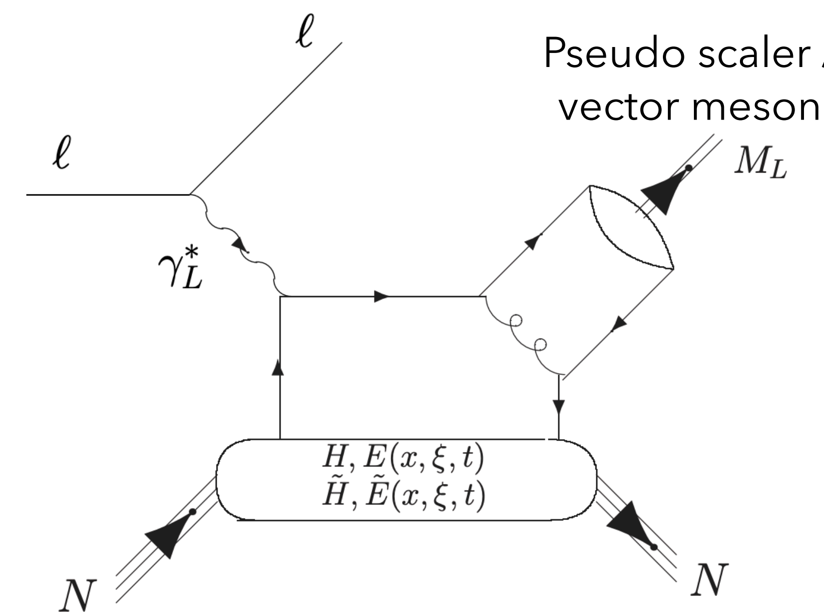


Fig : DVMP (quark Subprocess)

https://arxiv.org/pdf/1511.04535.pdf

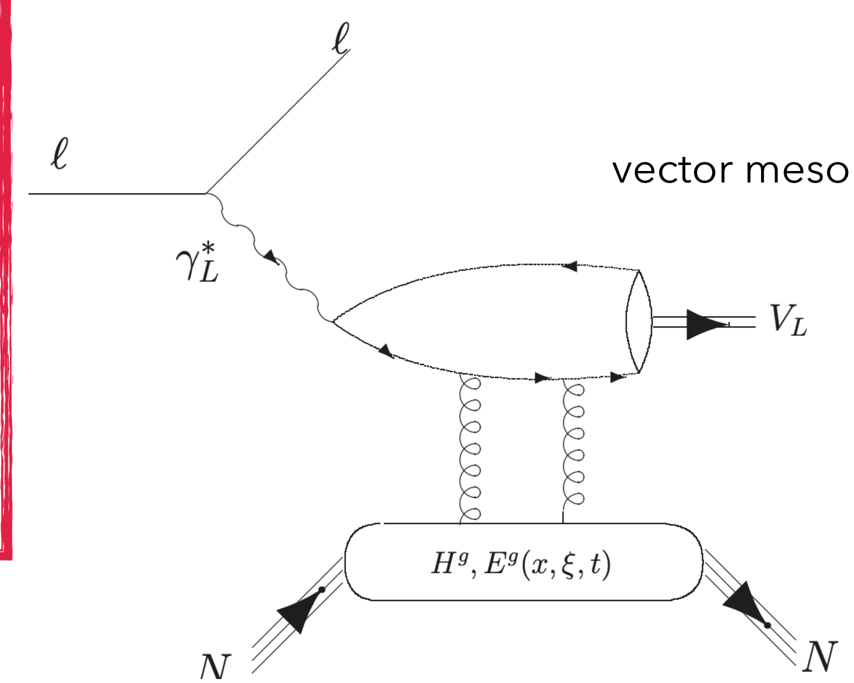


Fig : DVMP (gluon subprocess)

https://arxiv.org/pdf/1511.04535.pdf

DDVCS

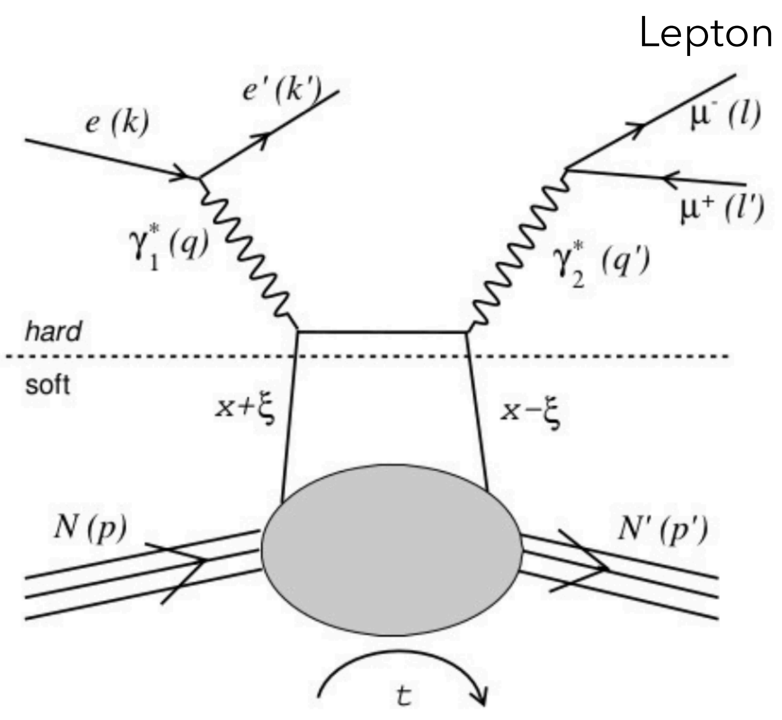


Fig1: DDVCS

Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51:

WHY DDVCS ?

1. The incoming and outgoing photon virtualities : $Q^2 = -q^2, Q'^2 = -q'2$
2. The four momentum transfer to nucleon : $\Delta = q - q'$
3. $t = \Delta^2$
4. Decomposition of the skewness variables in terms of virtualities and Δ

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

5. Q'^2 dependence of the numerators enables us to access the off diagonal Phase space , in the contrary for TCS and DVCS $\xi = \xi'$

WHY $\mu^+ + \mu^-$ final state ?

$eN \to e'N'l^+l^-$

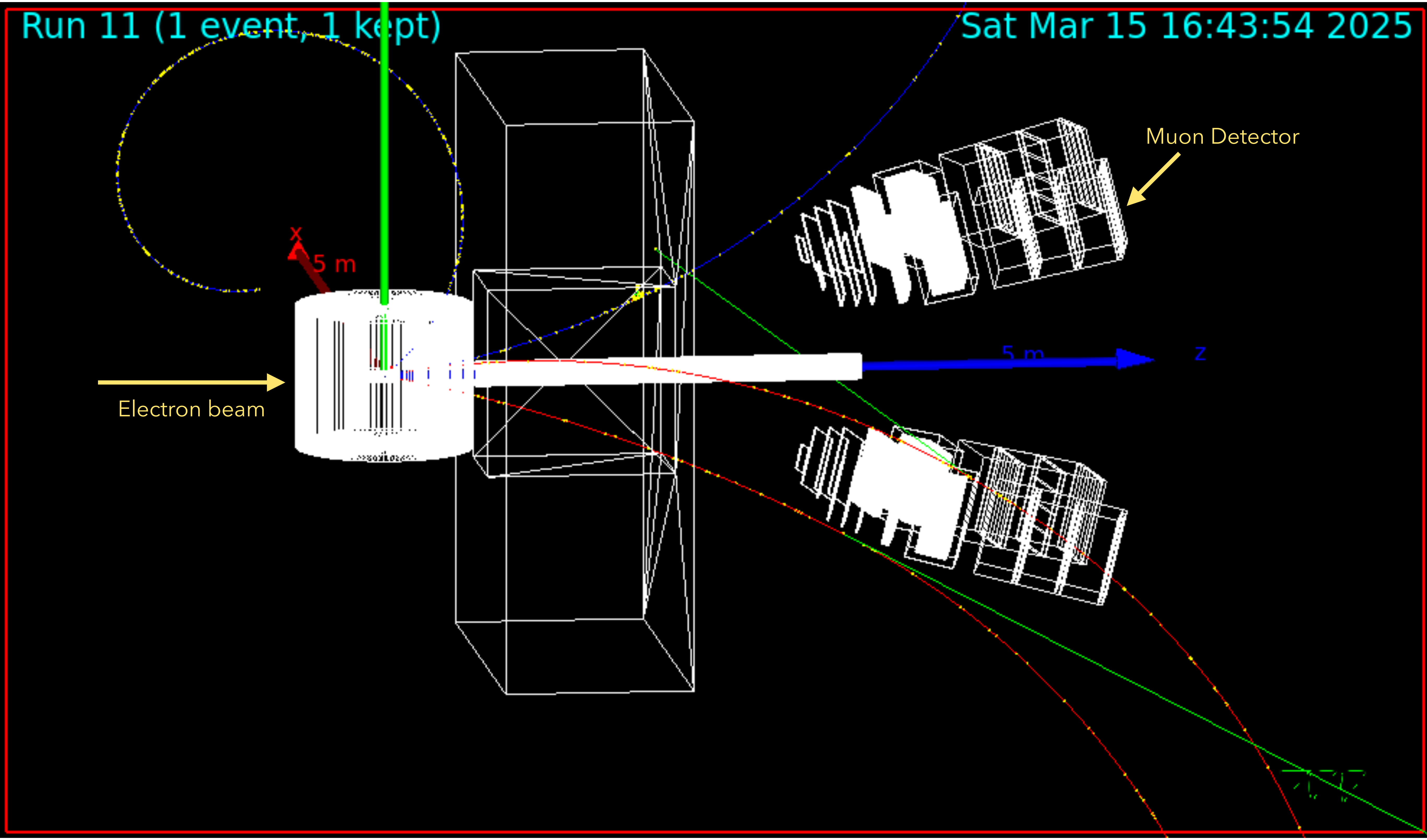
Due to anti-symmetrization and beam electrons : final state electrons are indistinguishable from the beam electrons

So, we rely on the muons at the final state

WHY JLab HALL C (compared to other halls) ?

1. High luminosity helps in obtaining precise DDVCS measurement
2. Cross sections can be measure (not only asymmetry) with sufficient resolution ->helps to examine the GPD evolution
3. All these together help to deconvolute the kinematic variables ->essential for the proton's tomographic picture

Di-lepton spectrometer with muon detector



Analysis Framework and Simple Setup

DEEPGEN → DDVCS EVENTS → GEANT4 → ROOT FILES → ANALYSIS

Data is in text format that the **G4HEPEvtInterface** Class understands.

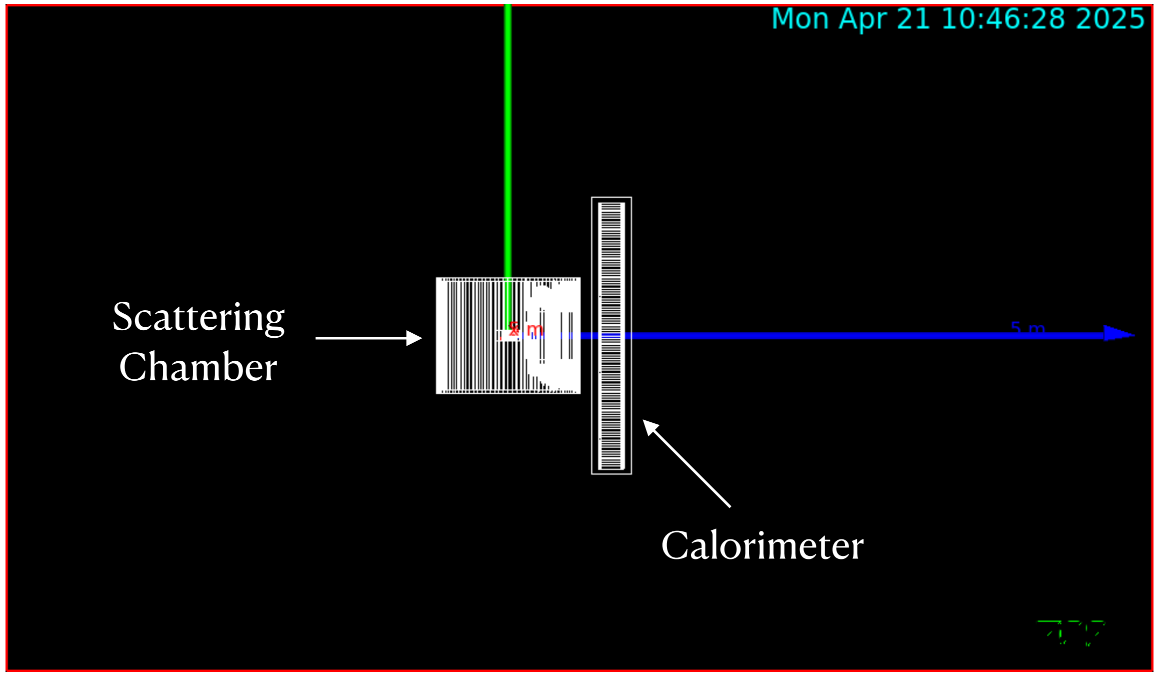
```
4
1 13 0 0 -0.617615 0.305651 1.76239 0.105658
1 -13 0 0 1.13101 -1.03756 6.49104 0.105658
1 2212 0 0 -0.303035 0.128345 0.669712 0.938272
1 11 0 0 -0.210359 0.603552 2.06947 0.000511
4
1 13 0 0 0.475832 -0.683699 1.84456 0.105658
1 -13 0 0 0.523527 1.07653 4.53792 0.105658
1 2212 0 0 -0.158192 0.189919 0.777916 0.938272
1 11 0 0 -0.84116 -0.582744 3.8396 0.000511
4
1 13 0 0 0.816858 -0.613349 4.9105 0.105658
1 -13 0 0 -0.630619 -0.443319 3.68986 0.105658
1 2212 0 0 -0.0676863 0.162198 0.573406 0.938272
1 11 0 0 -0.118552 0.894457 1.82623 0.000511
```

Example Input Data

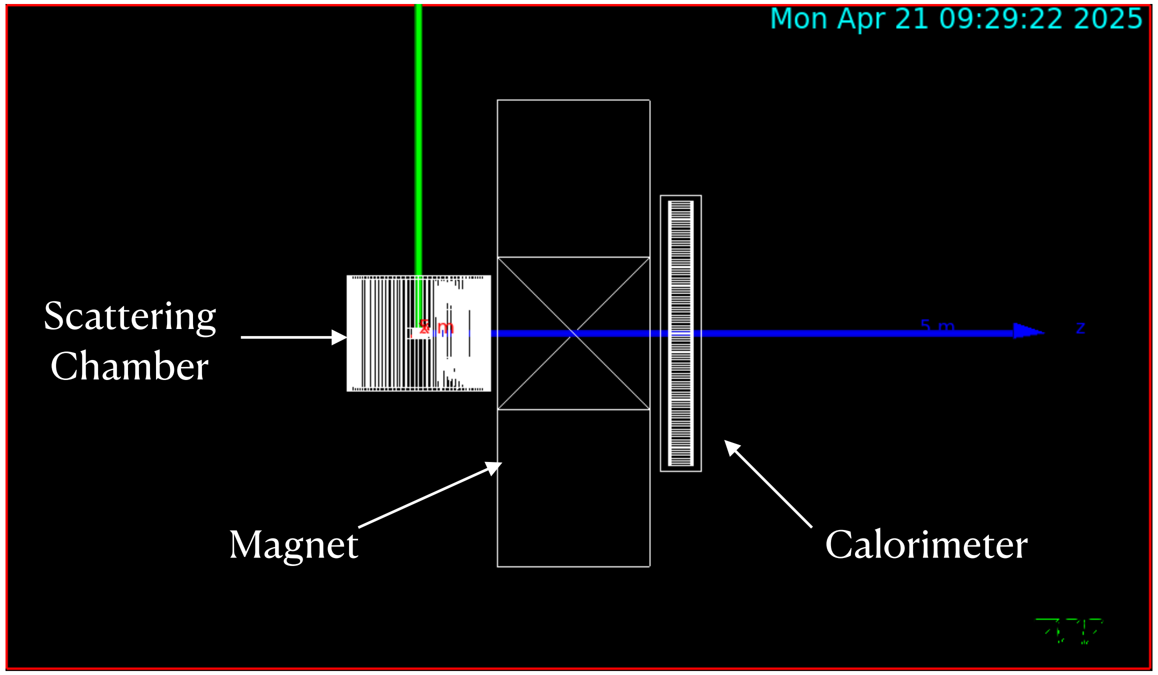
Contains a tree for each detector in the detector stack.

```
TFile**
 TFile*
  KEY: TH1D     h1;
  KEY: TTree    beam;
  KEY: TTree    target;
  KEY: TTree    calo;
  KEY: TTree    muon;
  KEY: TTree    hodo;
  KEY: TTree    tracker;
  KEY: TTree    kin;
```

✓ Full Geant4 simulation
Analysis framework

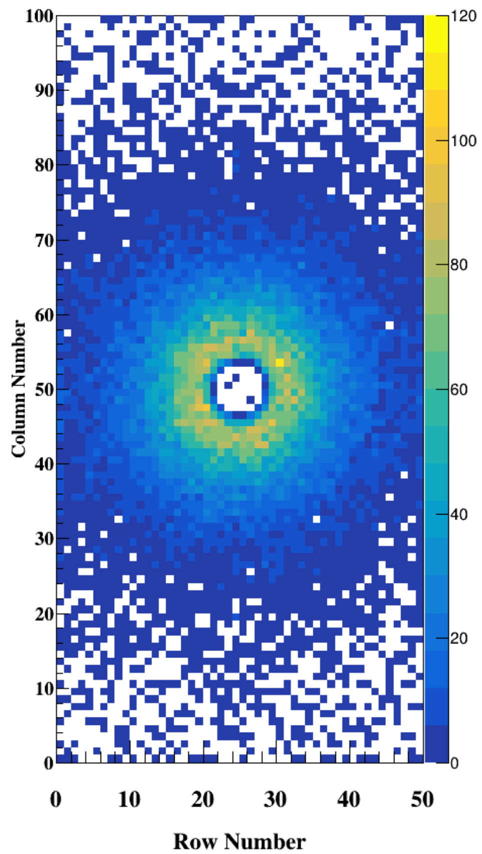


Before Magnet

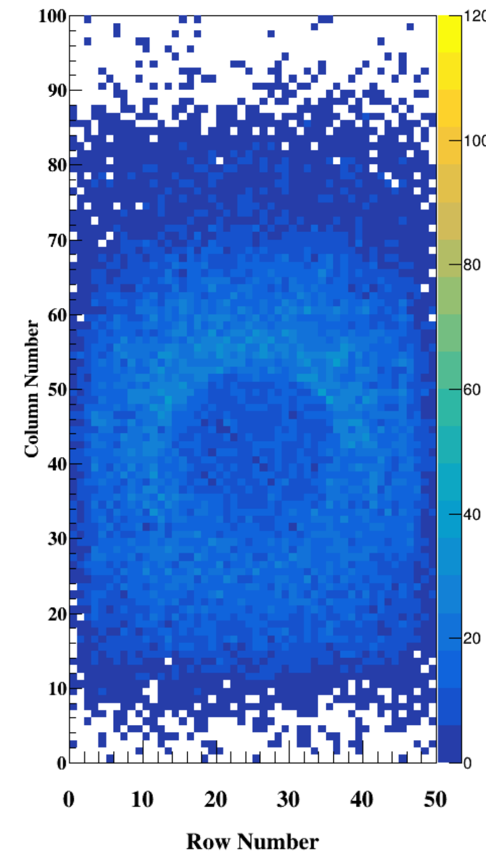


After Magnet

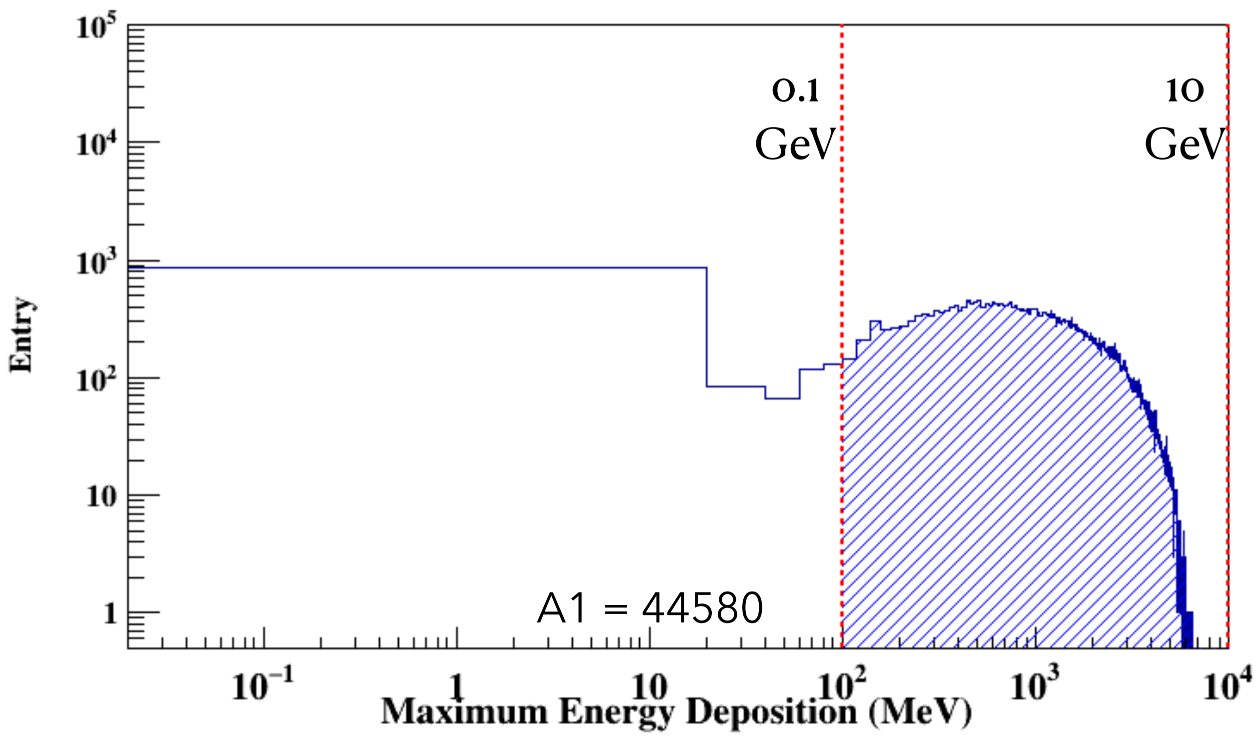
Electron

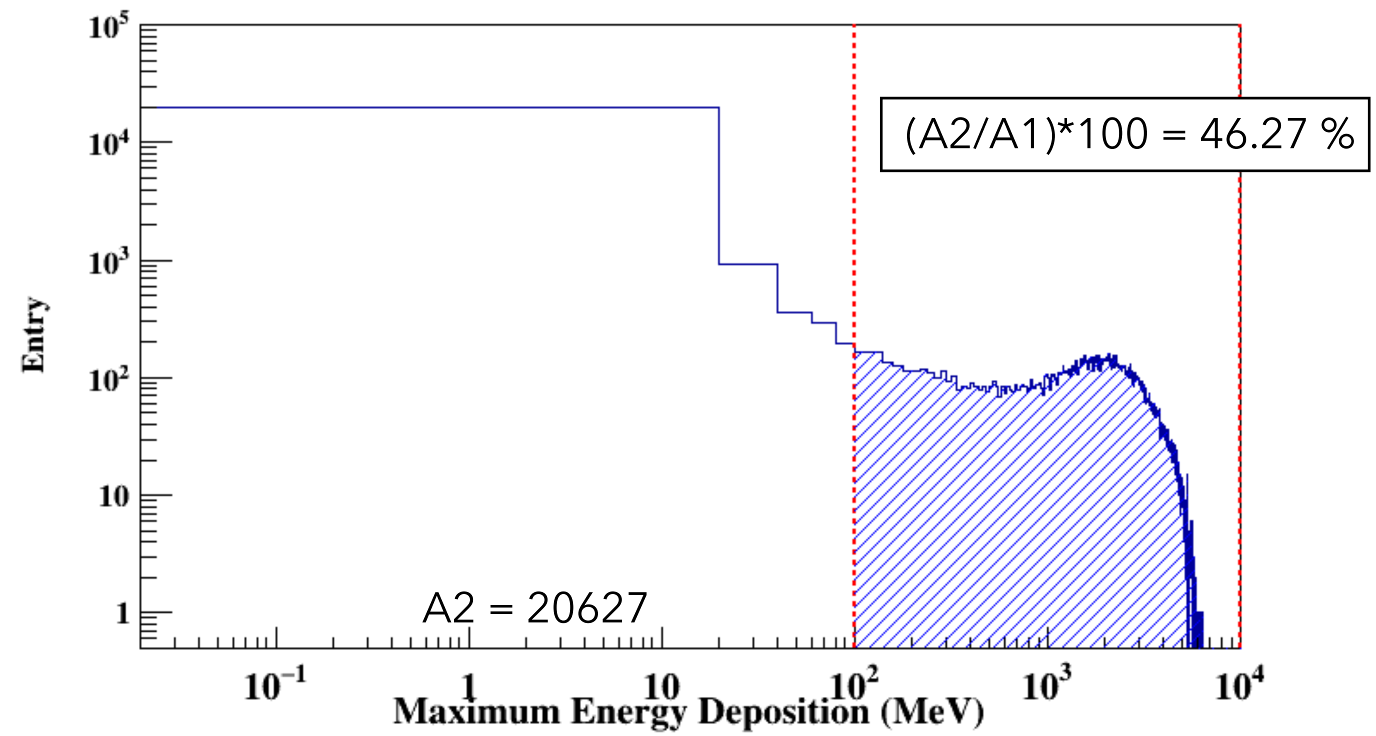


Electron, before magnet

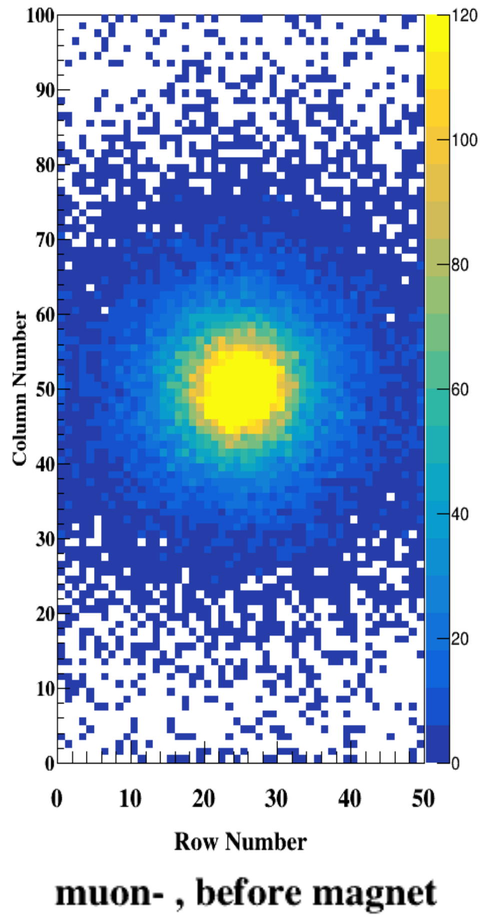


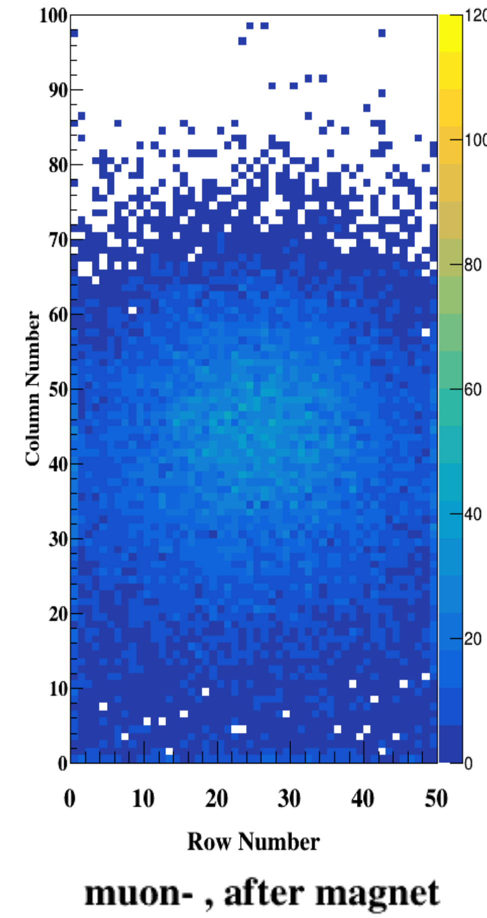
Electron, after magnet

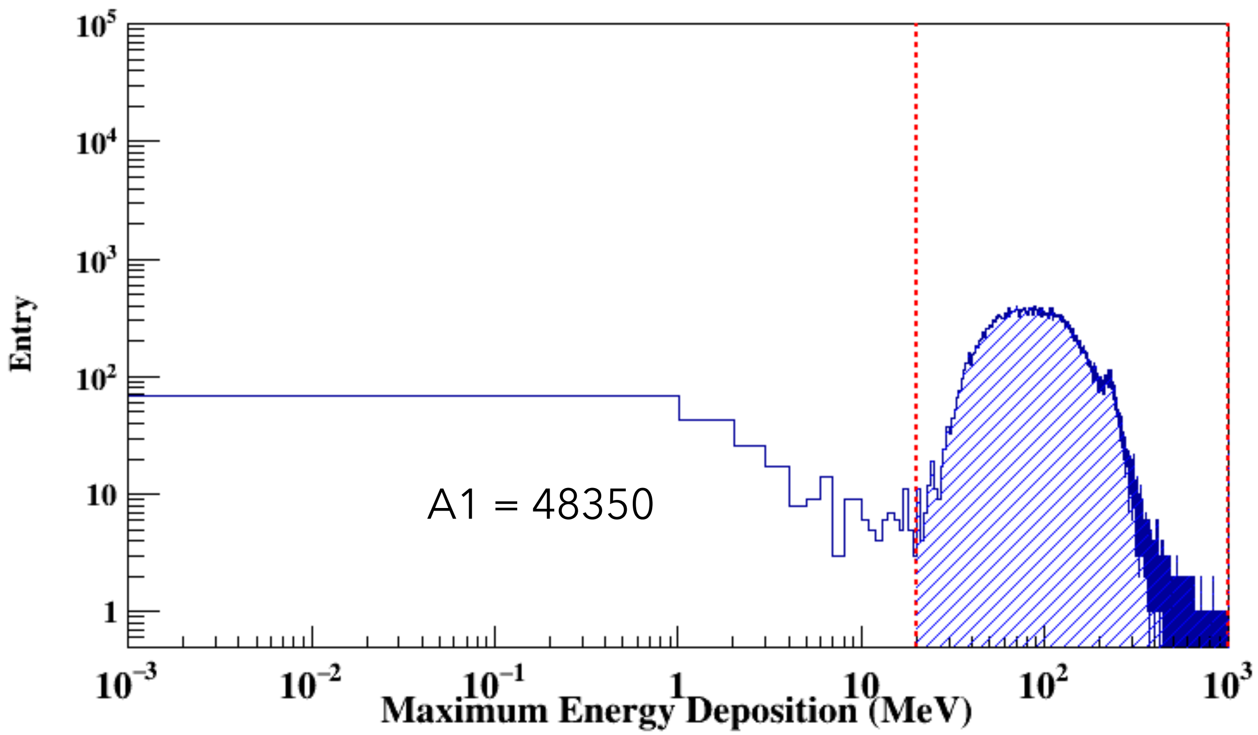


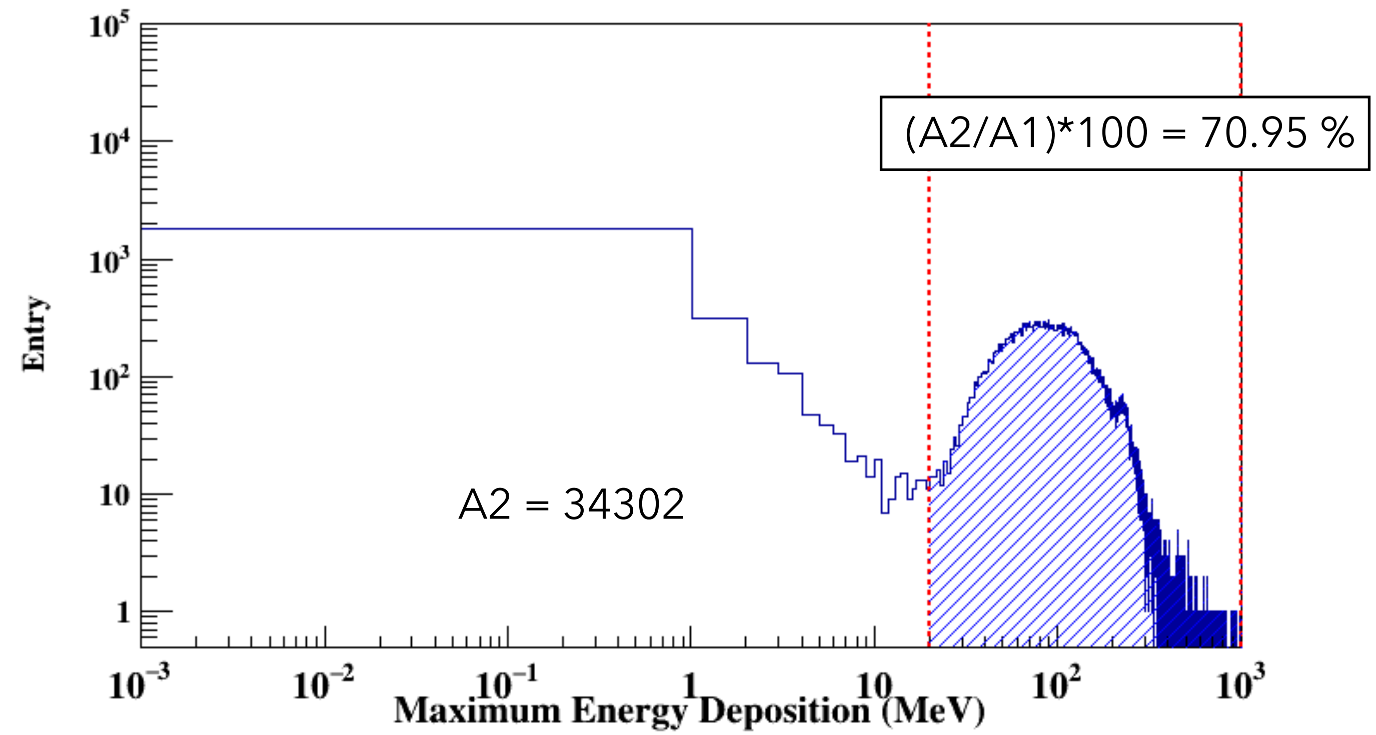


Muon

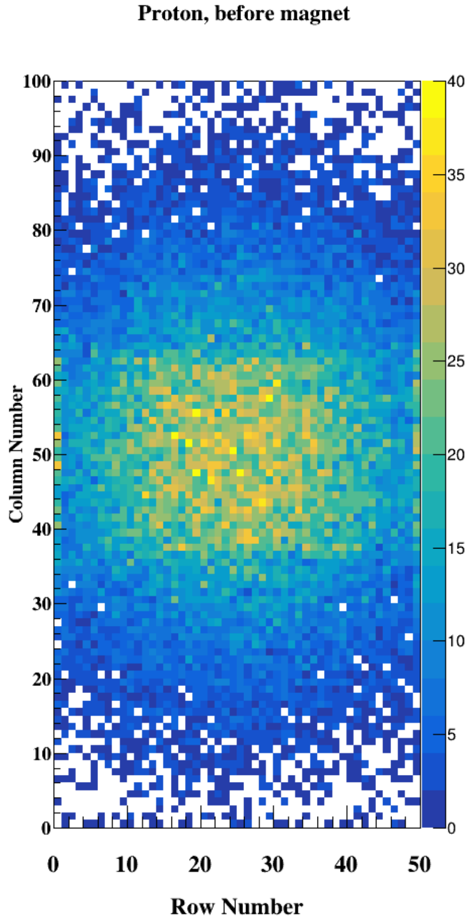

Column Number
Row Number
muon- , before magnet

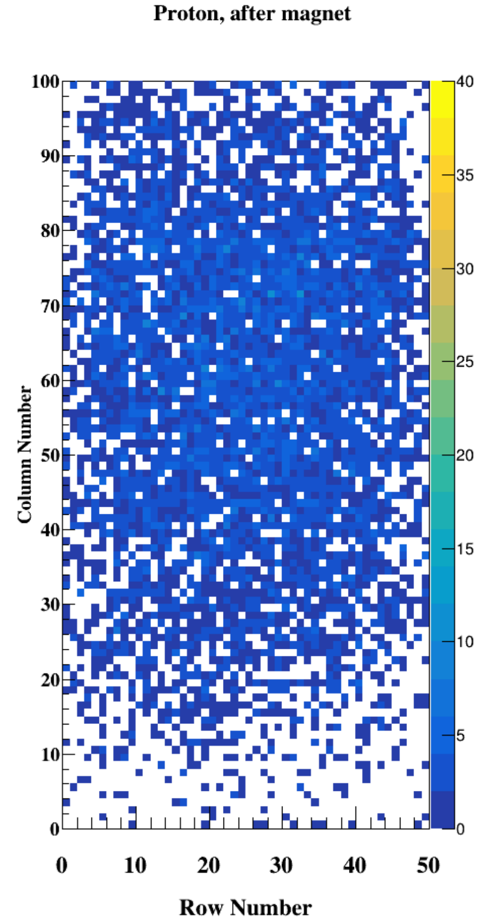

Column Number
Row Number
muon- , after magnet

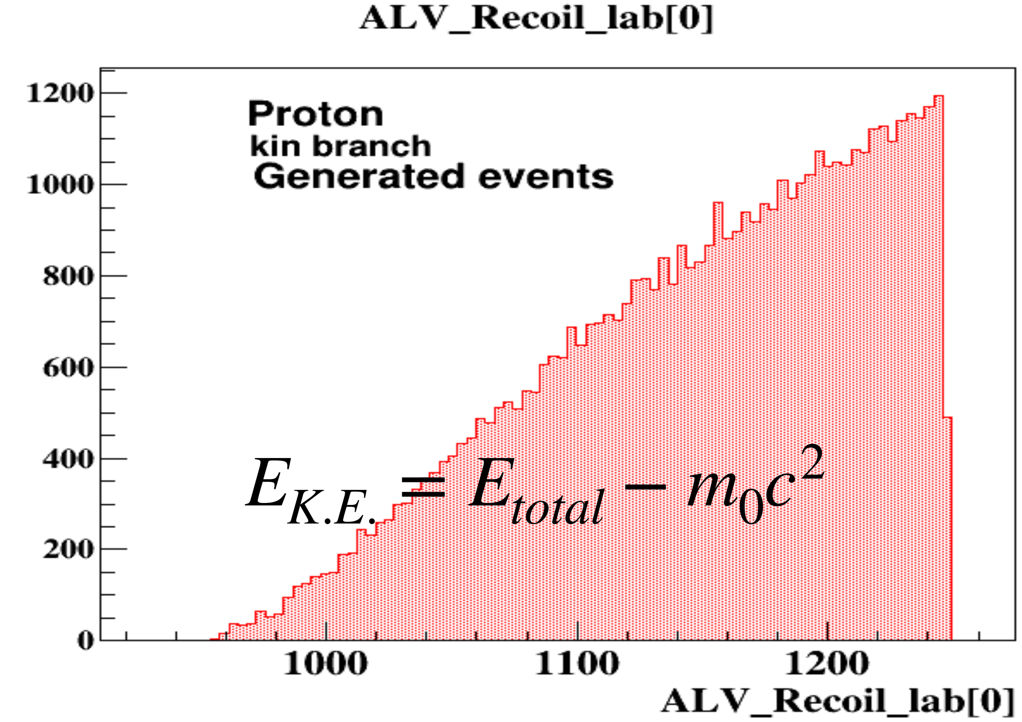

Entry
A1 = 48350
Maximum Energy Deposition (MeV)


Entry
(A2/A1)*100 = 70.95 %
A2 = 34302
Maximum Energy Deposition (MeV)

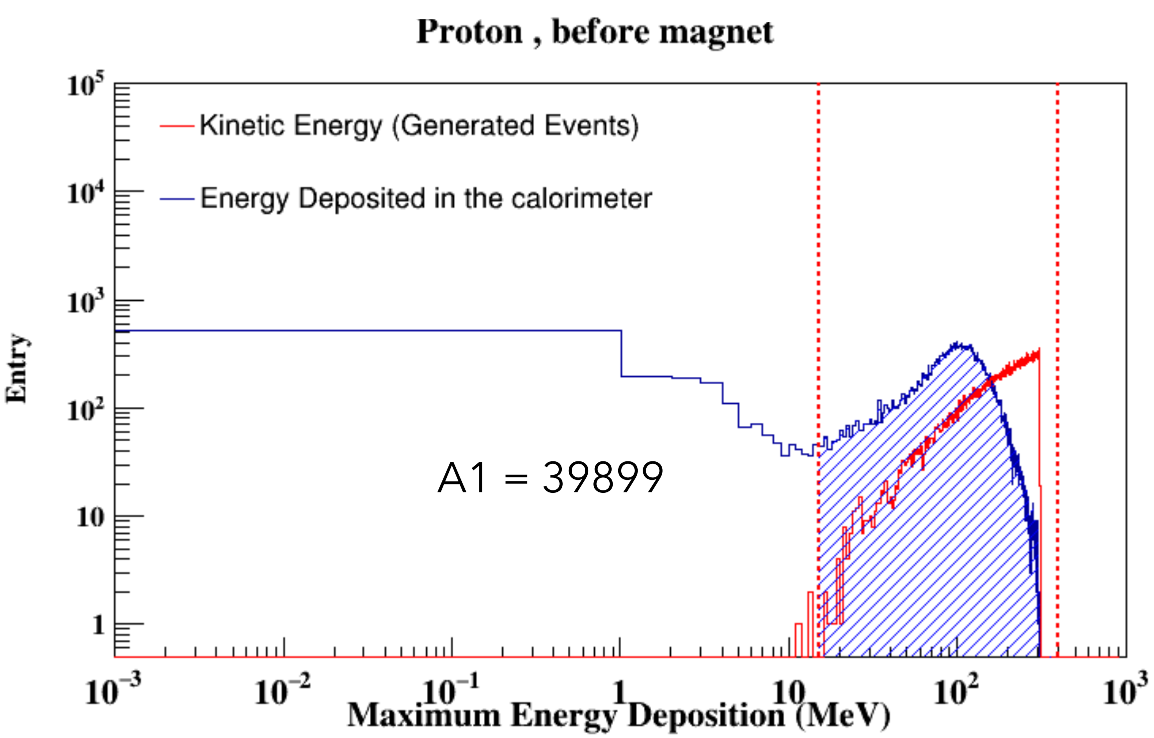
Proton

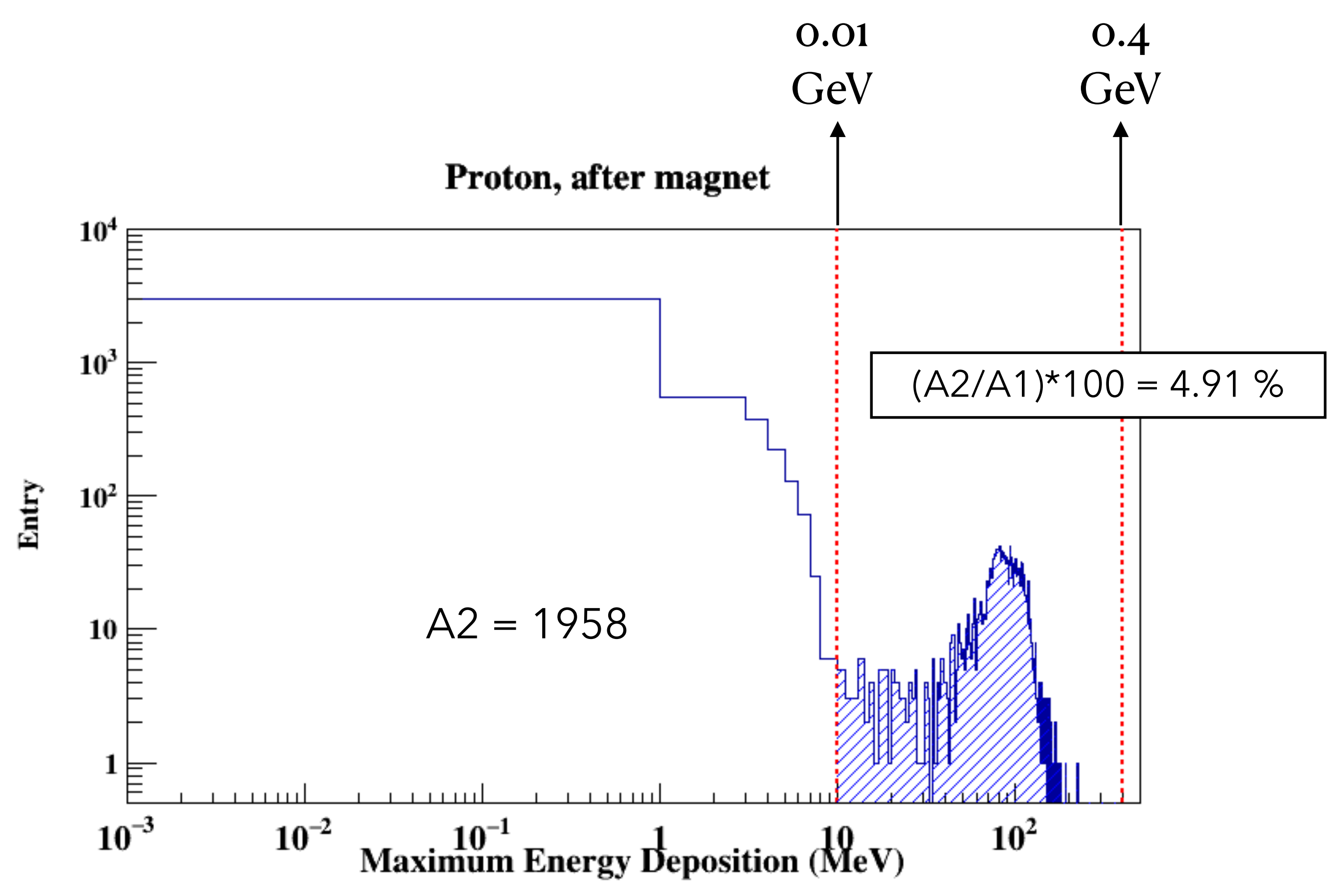




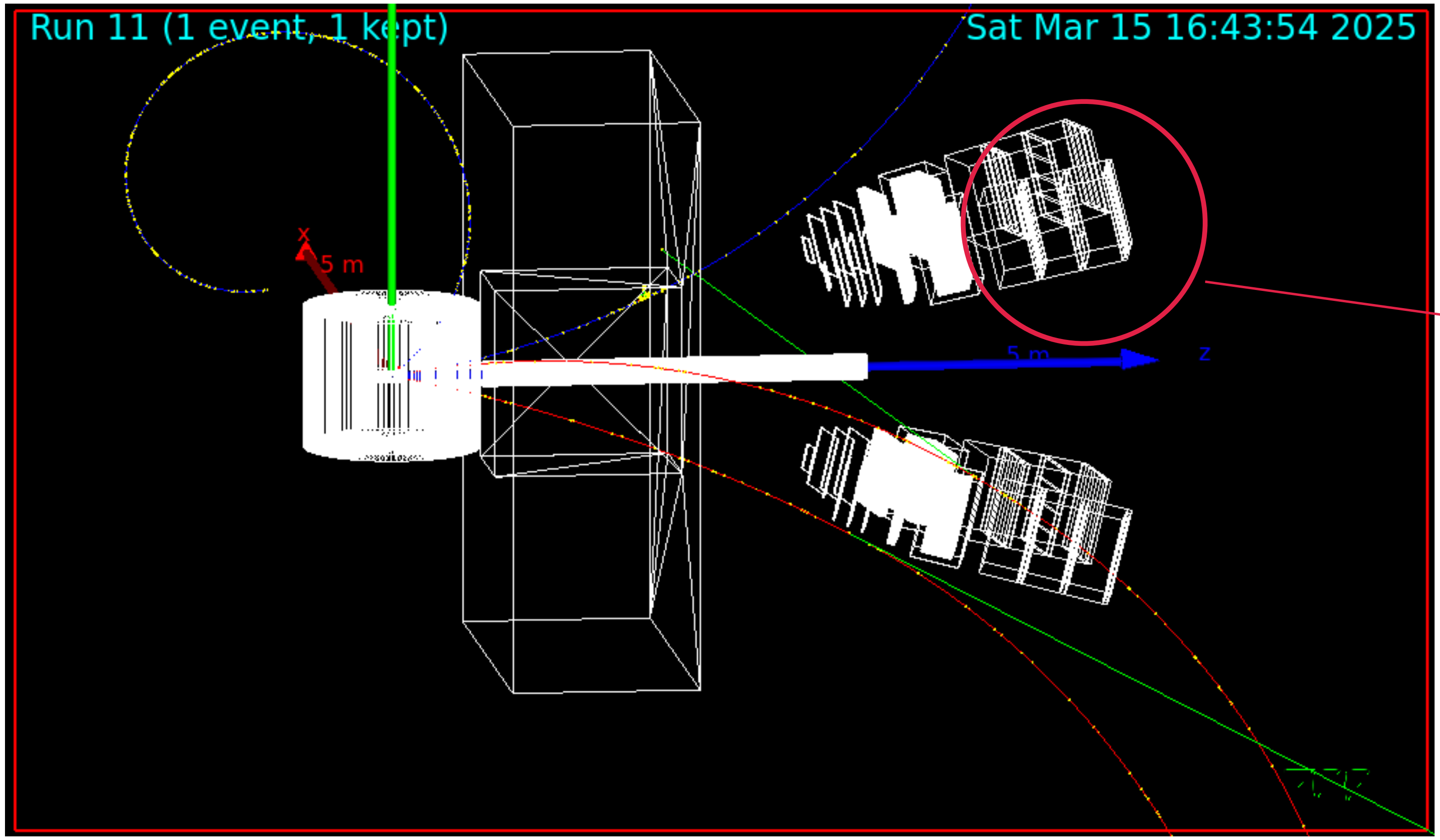


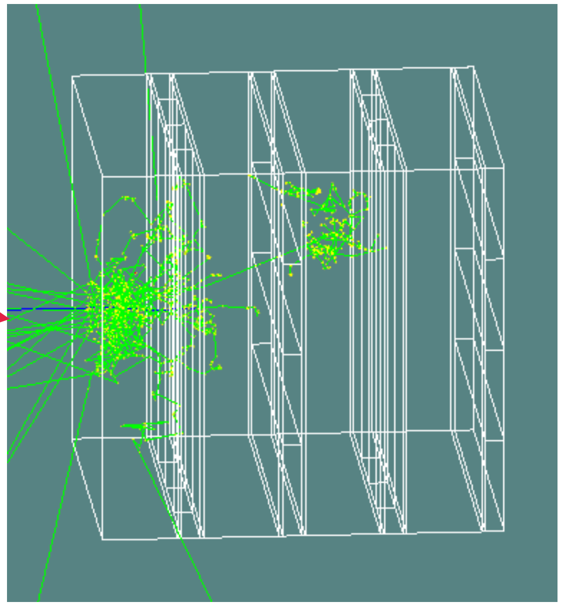
Total Energy of Protons From Generated Events

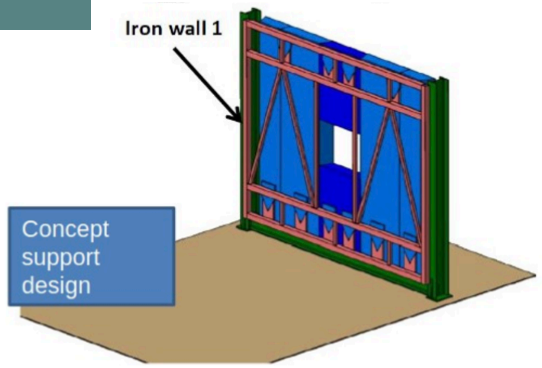




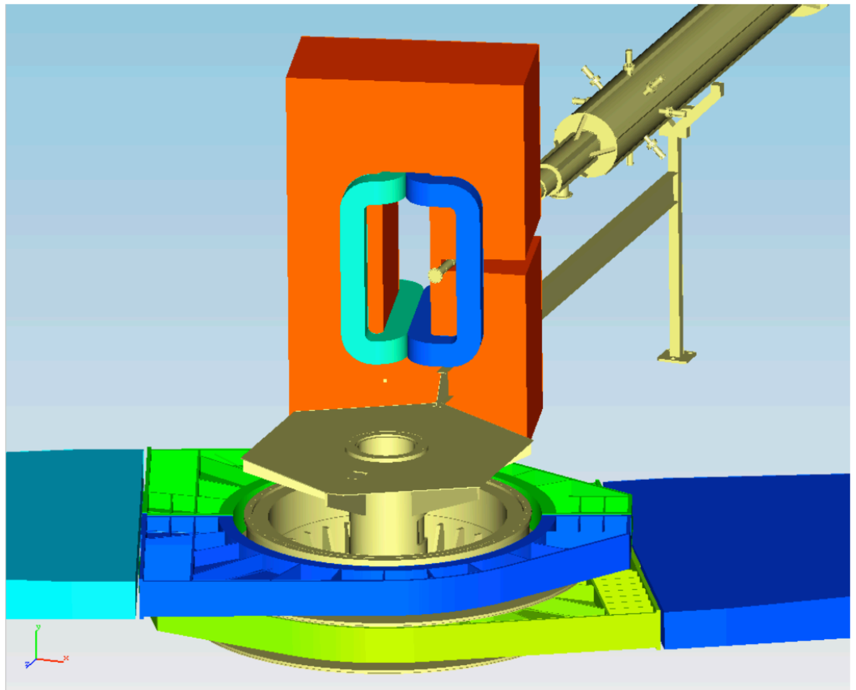
Optimization of the design in progress

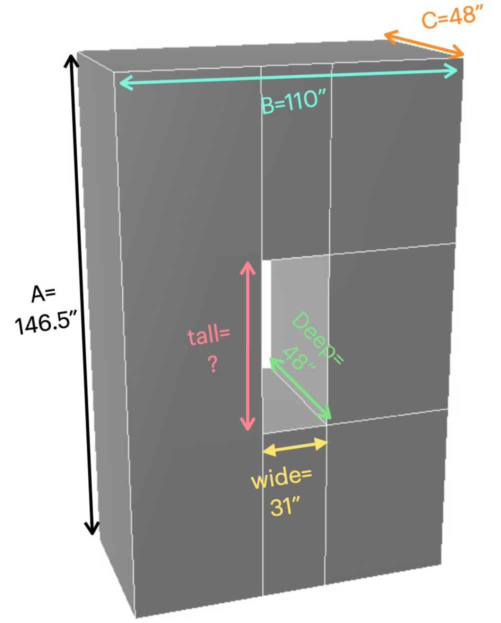


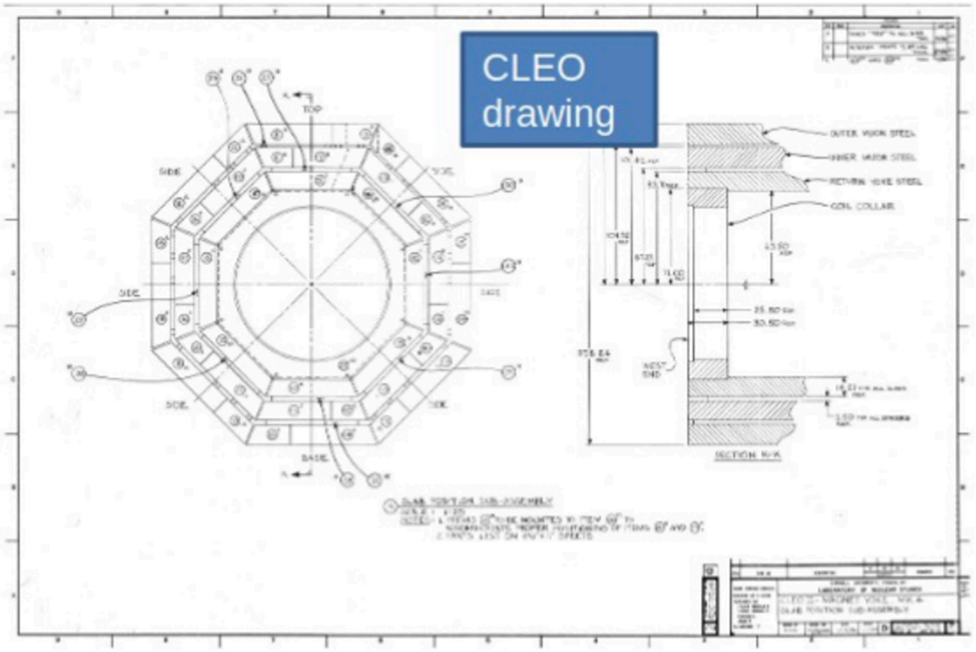




CAD Drawing for Super Bigbite Magnet
Source : https://userweb.jlab.org/~bogdanw/SBS-general.pdf





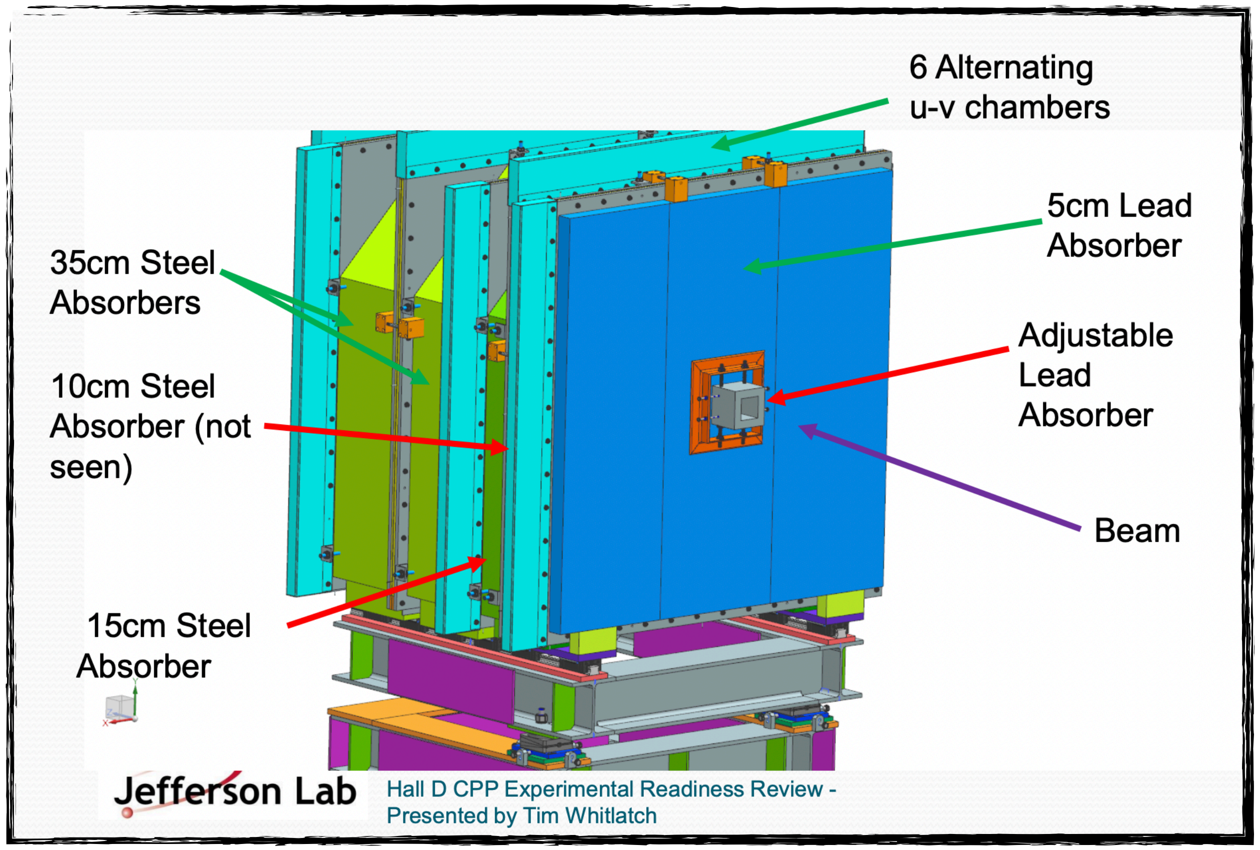


1. The field integral is 2.0 Tesla-meter with 1.2 m long pole

Geant4 simulation of simple magnet geometry

How to Detect Muons ?

1. World Wide Experiments
   1. Belle Experiment K_L^0 and Muon Subsystem
   2. CLEOII
   3. EIC KLM Proposal
   4. CPP experiment at Hall D etc…
2. Main theme of any muon detector : multiple layers of background absorber and active material (to pick up signal) placed alternatively
3. For example : The Hall D muon detector is composed of six layers of MWPC (U-V layers) and five layer of absorbers arranged in this order : 5 cm Pb , U-V layer, 10 cm steel, U-V layer, 15 cm steel, U-V layer, 35 cm steel, U-V layer, 35 cm steel, U-V layer, U-V layer.
4. Hall C :
   1. Large pion background, di-lepton spectrometer is a open geometry model, no shielding around
   2. Comparable mass of muon (105.7 MeV) and pion (139.570 MeV) makes it harder for traditional SHMS/HMS PID (e.g. cannot tune Cherenkov to one particle and not for the other)
   3. Space constraint : No space for large detector array
   4. Engineering constraint : How to hold bulky detectors in four quadrants
   5. Money constraint : Can't be too expensive

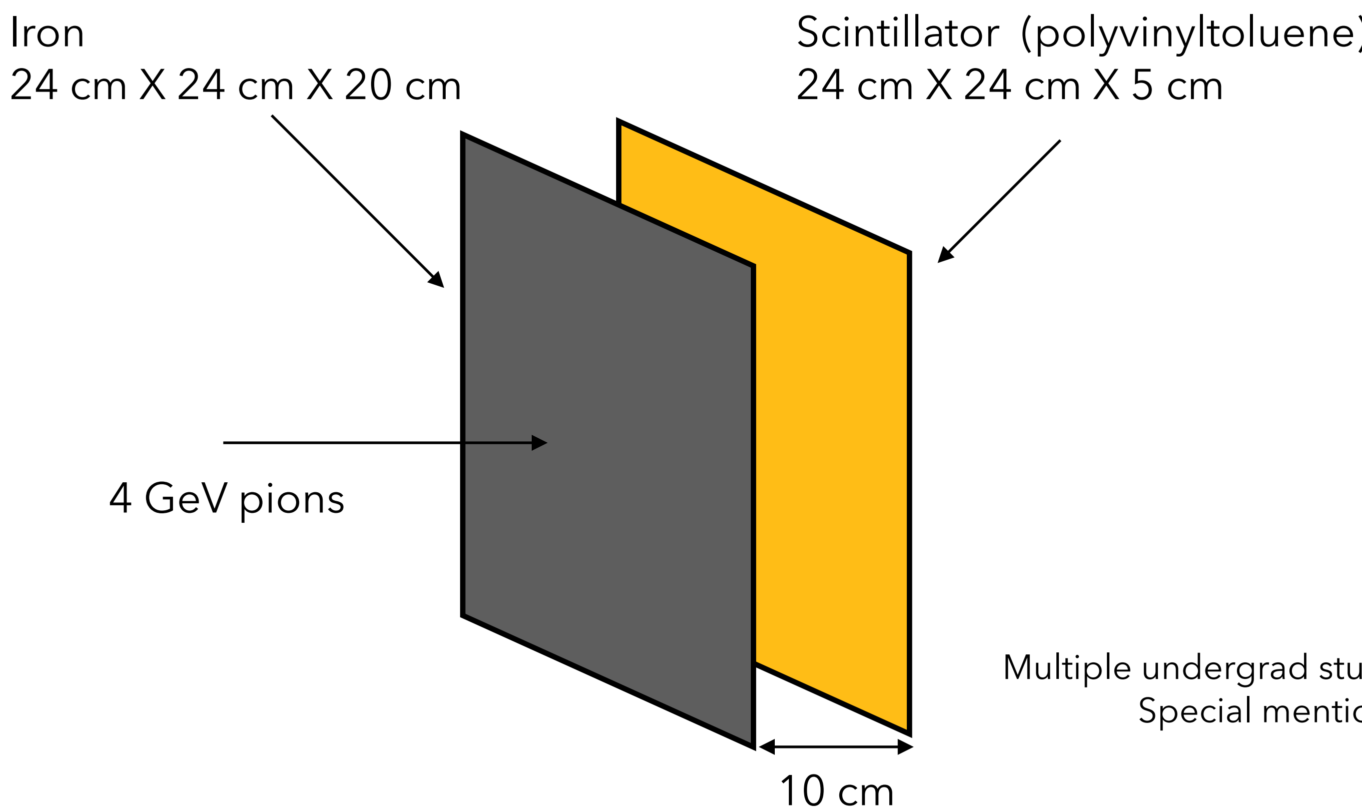


Source : https://halldweb.jlab.org/DocDB/0049/004903/002/CPP_ERR_Eng_Feb_2021_v4.pdf

GlueX Experiment Document 4903-v2, by Timothy Whittch

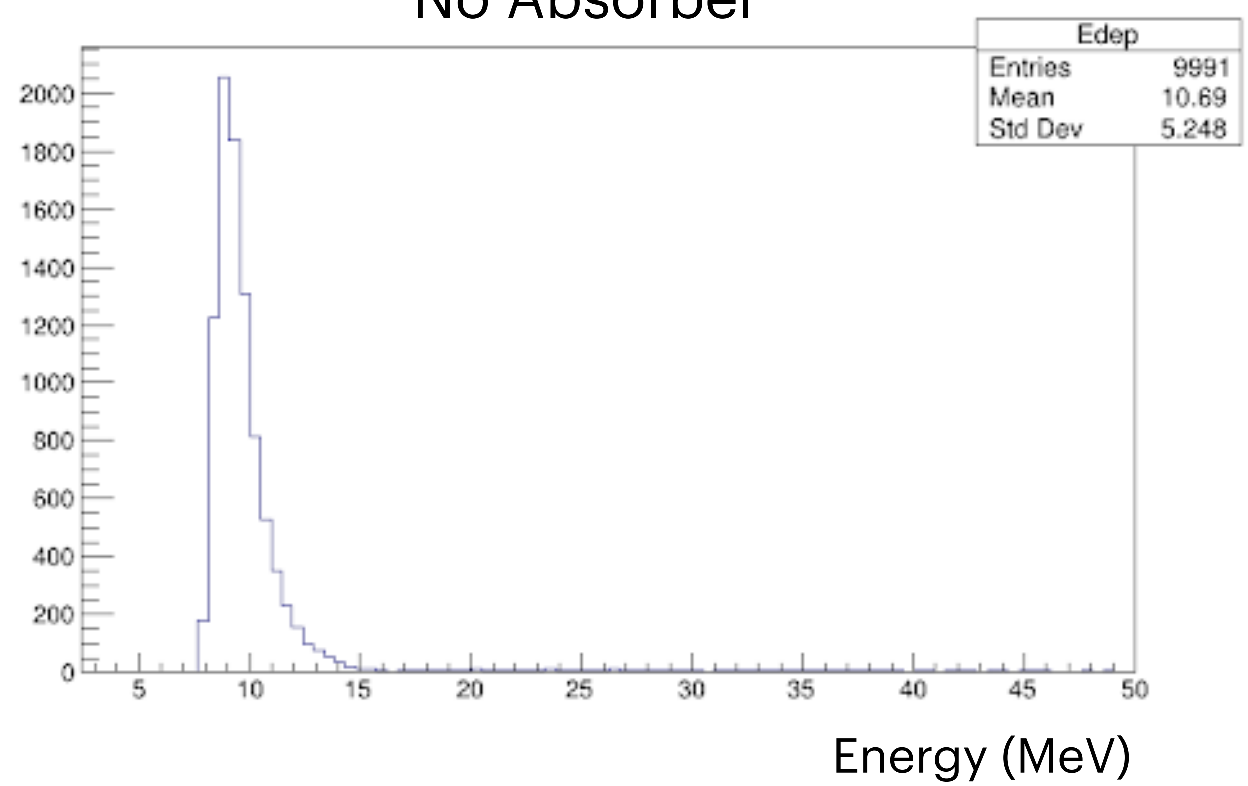
Pion signal w and w/o an absorber in front of scintillator

1. 1 absorber - 1 scintillator
2. 4 GeV pions were fired from a particle gun
3. Energy deposited by pions and all other particles generated in the interaction is histogrammed (w and w/o absorber)
4. Distinctive low energy secondary peak (from hadronic interaction of pions with the absorber) emerges in presence of the absorber

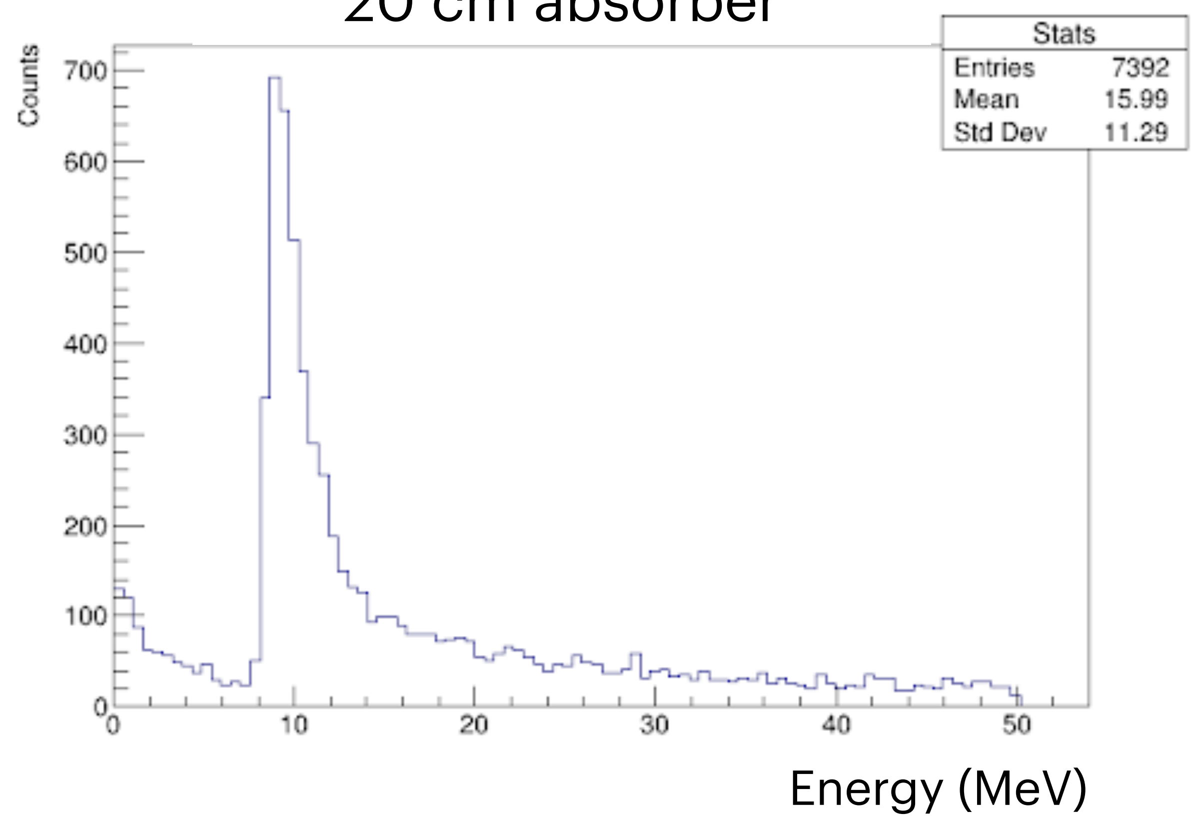


Multiple undergrad students work in this project..
Special mention to **Keagan Bell**

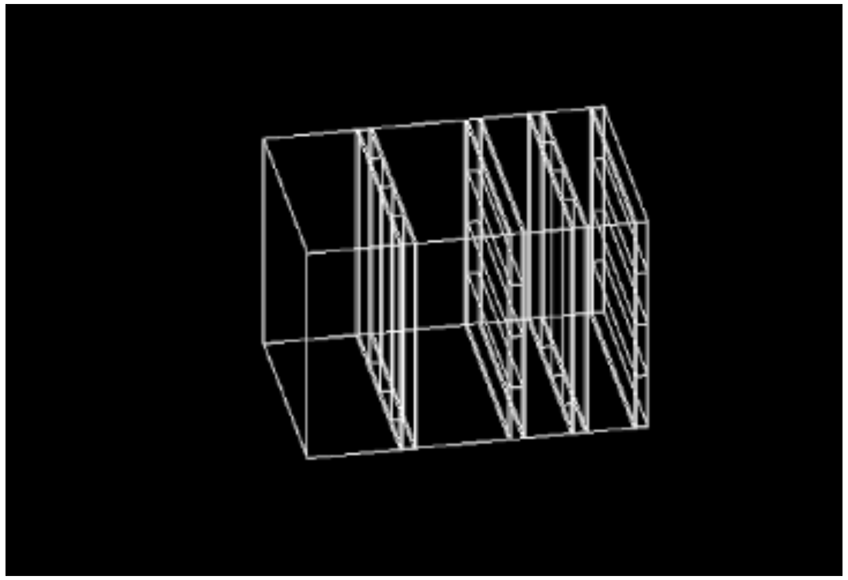
No Absorber



20 cm absorber



Multiple absorber-scintillator



1. Next step : From simple 1 absorber and 1 scintillator model to 4 absorber (iron / lead) - 4 scintillator model
2. Different combinations of absorber widths were tried, e.g. 20 cm-20cm-20cm-20cm; 40cm-20cm-20cm-20cm; 40cm-40cm-20cm-20cm
3. 10,000 Pions and muons were shot from a particle gun
4. Total number of interactions from only pions / muons were counted in each of the scintillator
5. 40cm-40cm-20cm-20cm turns out to be the most effective in blocking pions

40 cm iron -scint 1 - 40 cm iron - scint 2 -
20 cm iron - scint 3 - 20 cm iron - Scint 4

hits in each layer of scintillator				**4 GeV**
particle	**scint 1**	**scint 2**	**scint 3**	**scint 4**
mu-	9998	9998	9998	9998
pi+	3088	452	132	48

hits in each layer of scintillator				**6 GeV**
particle	**scint 1**	**scint 2**	**scint 3**	**scint 4**
mu-	9997	9996	9996	9996
pi+	4618	797	281	103

40 cm lead -scint 1 - 40 cm lead - scint 2 -
20 cm lead - scint 3 - 20 cm lead - Scint 4

hits in each layer of scintillator				**4 GeV**
particle	**scint 1**	**scint 2**	**scint 3**	**scint 4**
mu-	10000	10000	9999	9997
pi+	2028	245	66	18

hits in each layer of scintillator				**6 GeV**
particle	**scint 1**	**scint 2**	**scint 3**	**scint 4**
mu-	10000	9997	9996	9994
pi+	3001	417	146	50

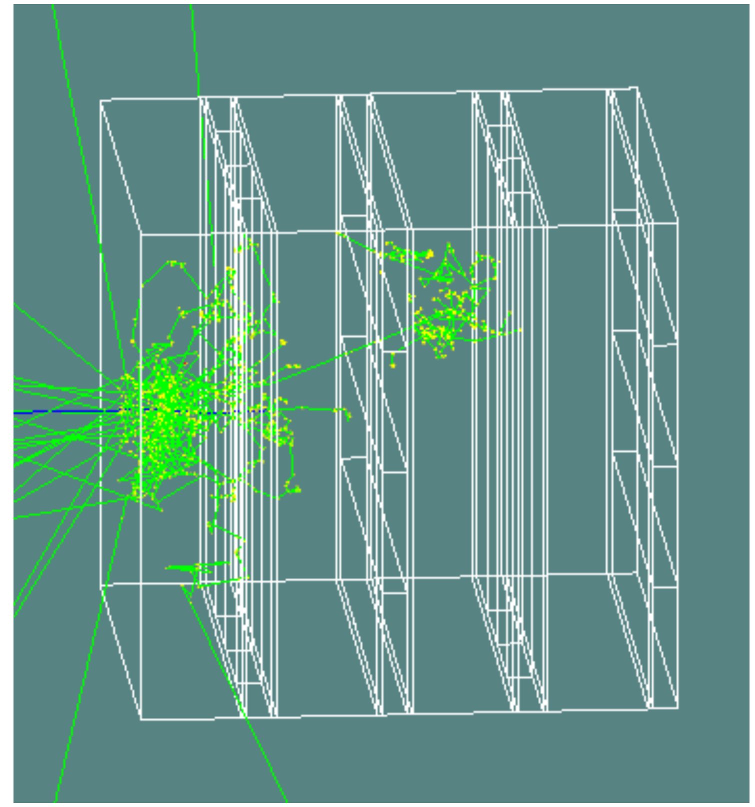
1. Of course this is 1st (or even 0th) order of study
2. Interactions below some threshold will not be detected
3. Multiple scattering of same particle within a time interval of O(10 ns) cannot be resolved
4. Comprehensive study of the DDVCS background is needed with more realistic Geant4 simulation

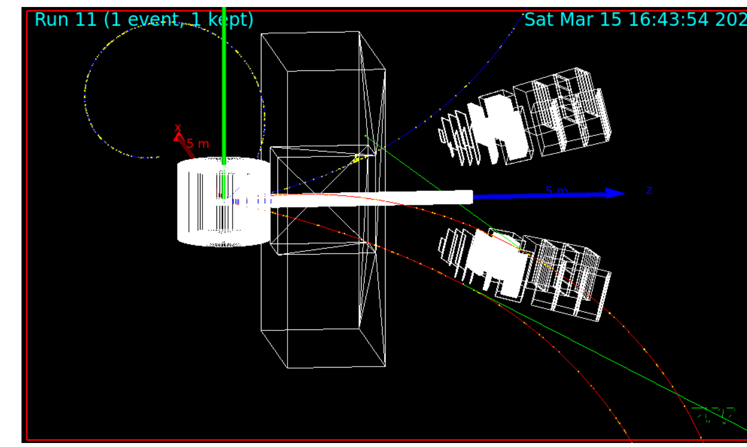
Muon Detector

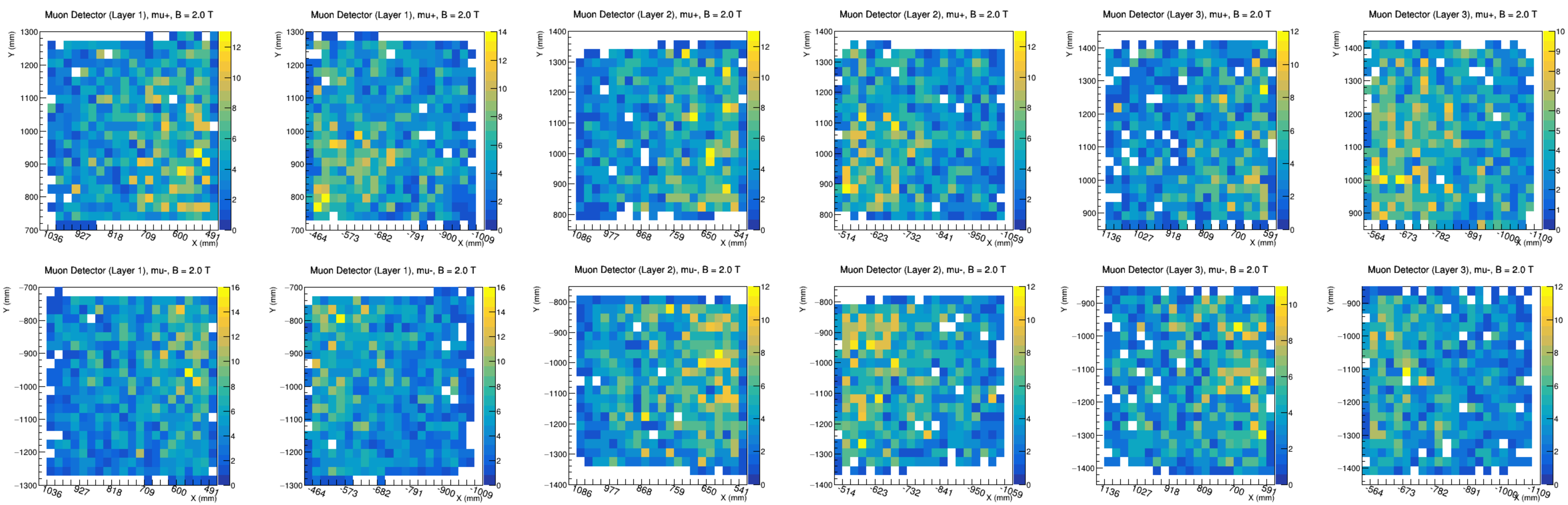
The Muon Detector is placed at the back of the detector stack.

The Muon Detector consists of a layered design of "pion absorbers" and scintillators:

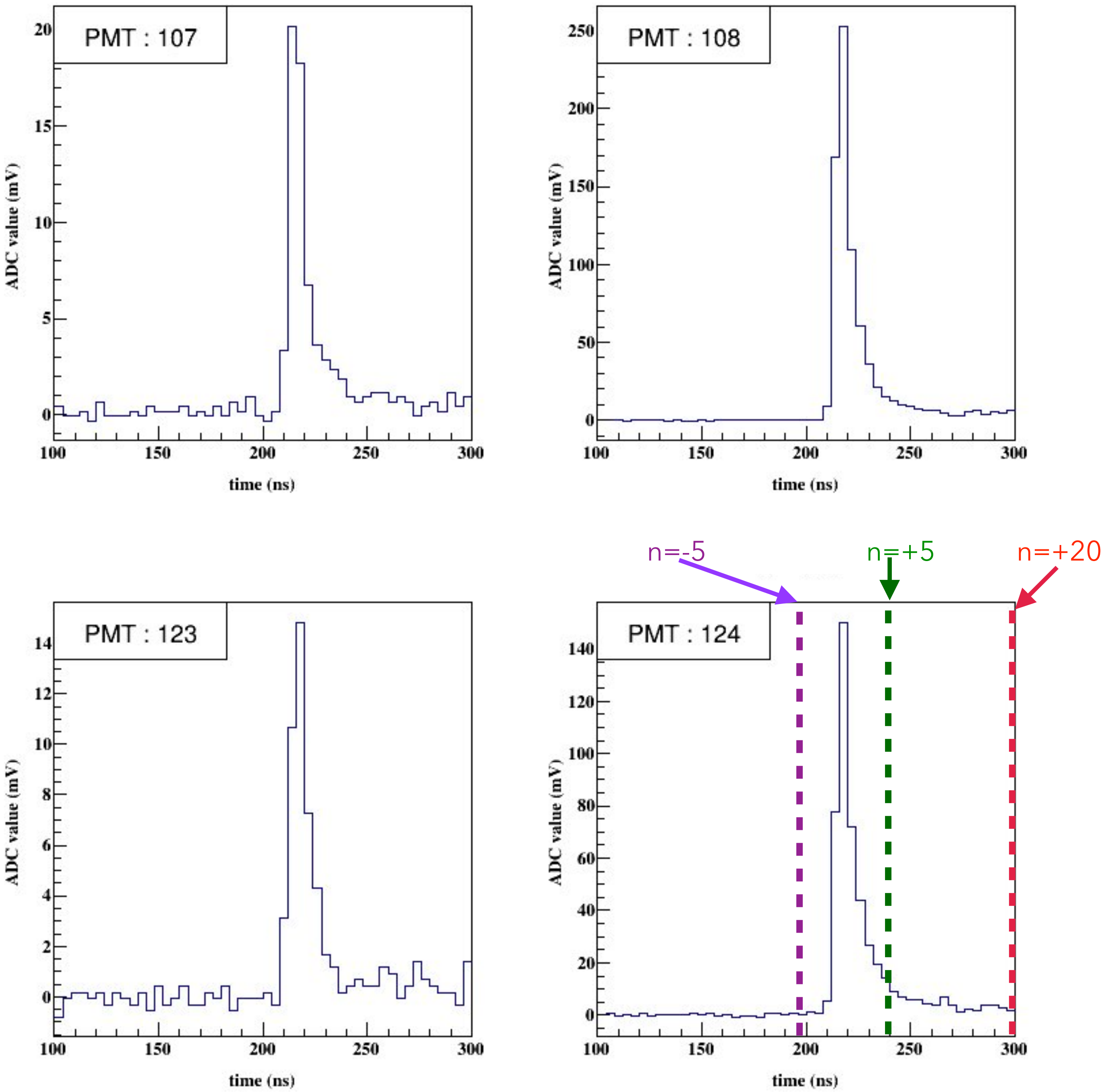
- Distance from target: **~370 cm**
- Dimensions: **56 cm by 56 cm**
- Scintillator:
  - Material: **Polystyrene**
  - Thickness: **2.5 cm** per layer
- Pion Absorber:
  - Material: **Iron**
  - Thickness: **25 cm** per layer



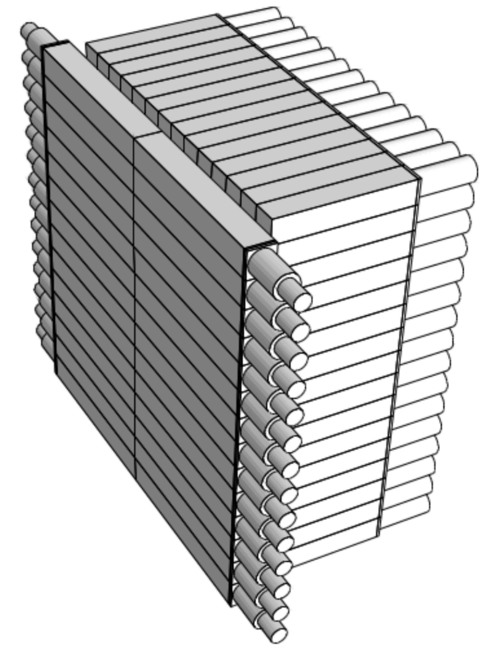




Pulse Shape Discrimination : e^{-}/π PID



ADC values (mV) [pedestal subtracted] vs time (ns)



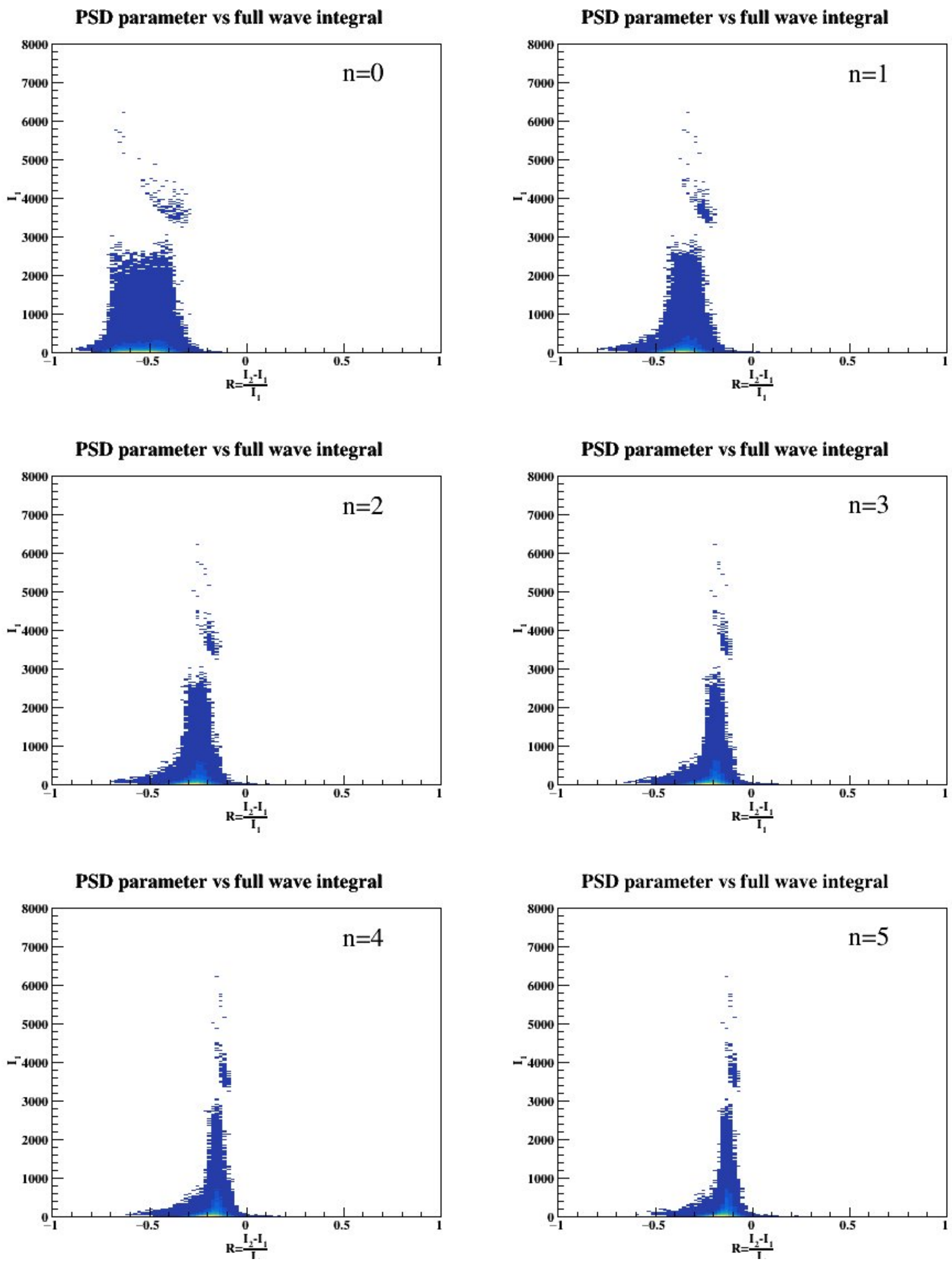
SHMS Calorimeter : shower counter

F-101 type lead glass blocks

1. FADC250 mode 10 full waveform data
2. Records the ADC value in every 4 nS

I_1 = Full wave integral (bin_{max} - 5 : bin_{max} + 20)
I_2 = Prompt wave integral (bin_{max} - 5 : bin_{max} + n)
N = 0, 1, 2, 3, 4, 5
PSD Parameter : $R = (I_2 - I_1)/I_1$

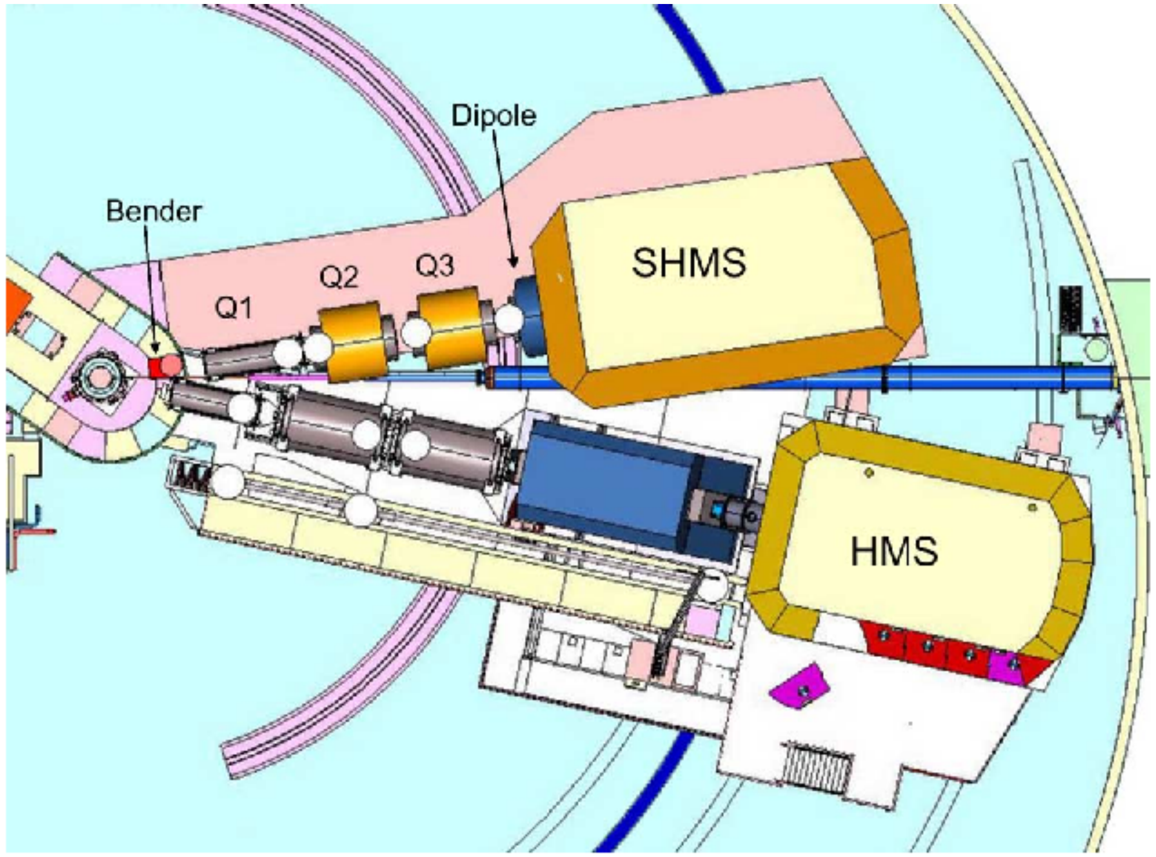
Pulse Shape Discrimination : e^{-}/π PID



1. No separation is seen along R direction
2. So, PSD is not very useful for SHMS calorimeter data
3. Does not produce much scintillation light component
4. Other detectors :
    1. BigByte ?
    2. Gluex ?
    3. Class12 ?
    4. NPS Lead Tungstate ($PbWO_4$) : RG1 data not useful for e^{-}/π separation, as only neutral particles reach the spectrometer. Probably γ/π^0 separation can be checked.
    5. LAD Scintillator detector : If some data were taken in FADC250 mode 10 , it will be useful for PSD analysis

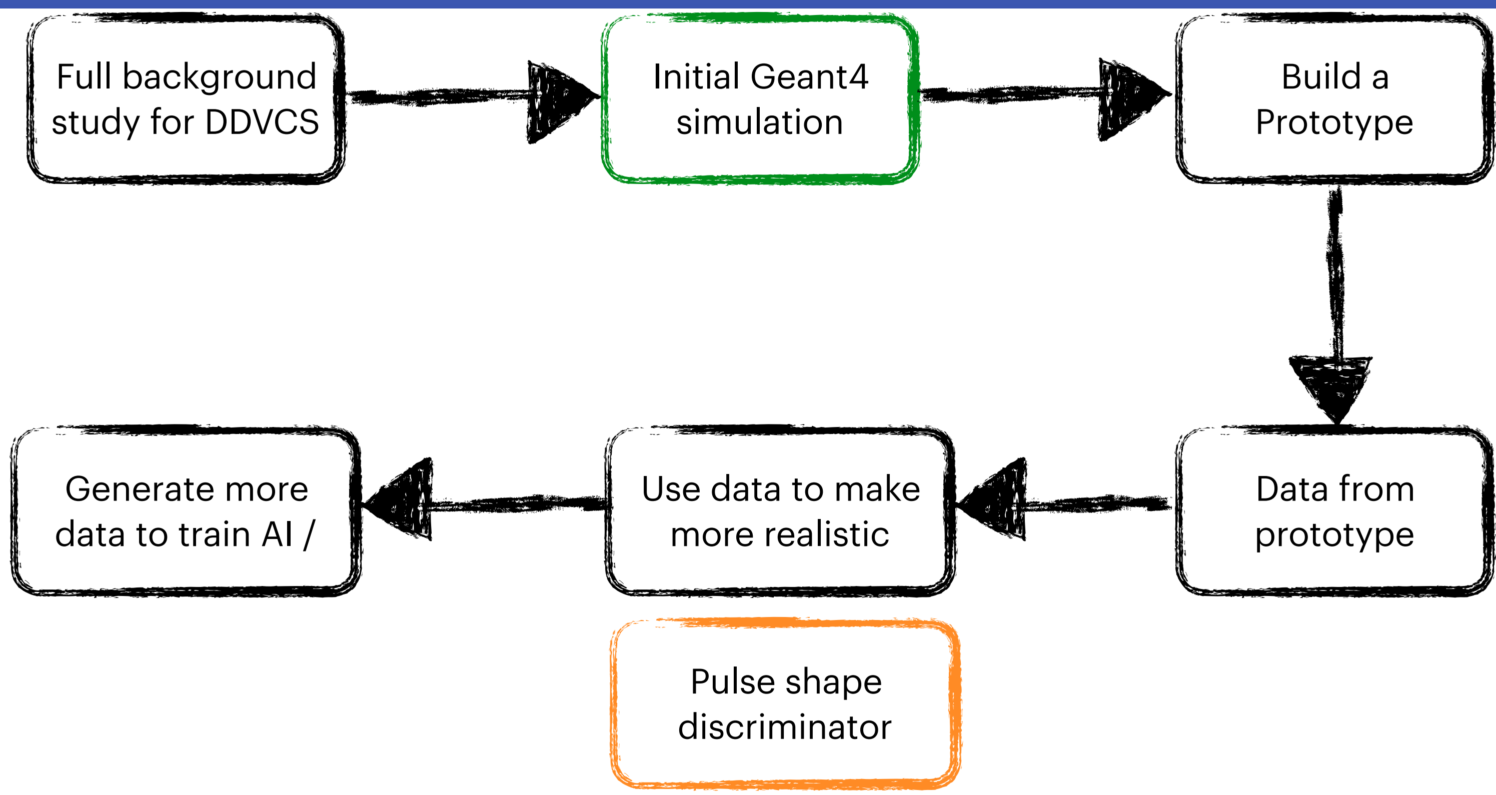
Prototype

1. No Geant4 simulation can100% mimic the experimental reality
2. So, at some point we should think of making and testing a prototype in real hall environment
3. Making a prototype is comparatively easy , testing is not !
4. Data taking with the prototype need to be non invasive to current Hall setup
5. The test run should be parasitic to other approved experiments
6. Placing the prototype anywhere on the hall floor is not an option :
    1. Then no control over the particles going into the detector
    2. Cannot determine the momentum / energy of the particle
    3. Will flood the detector with huge background
7. Can we think of any platform behind the SHMS (or another existing spectrometer in Hall A or C) to place the prototype ?
    1. In that case most of the backgrounds will be shielded by the spectrometer
    2. Particle momentum will be known using the SHMS magnet , data will be interpretable
    3. Then we can think of optimizing the Geant4 simulation for this conditions



DAQ for prototype at Virginia Tech

Plan moving forward Muon Detector



Detection of Muons for studying Double Deeply Virtual Compton Scattering (DDVCS) in Hall C, JLab

Debaditya Biswas

March 8, 2024

Abstract

This proposal is centered around the development of a Geant4 simulation for a muon detector, with the aim of facilitating DDVCS experiments in Hall C, JLab. The objective is to create a cost-effective and efficient muon detector capable of operating effectively in environments with high pion backgrounds. This document outlines the setup for the DDVCS experiment in Hall C, emphasizes the significance of a muon detector, and presents a plan for muon detection using both traditional PID methods and AI/ML algorithms.

DOE Early Career Grant : Marie Boer :DE-SC0025657 (early career program)

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

Debaditya Biswas,* Marie Boër,†
Dipangkar Dutta,‡
David Gaskell,§
David Hamilton,¶
Hamlet Mkrtchyan,‖ Vardan Tadevosyan**

May 1^{st}, 2024

LOI : PAC 52

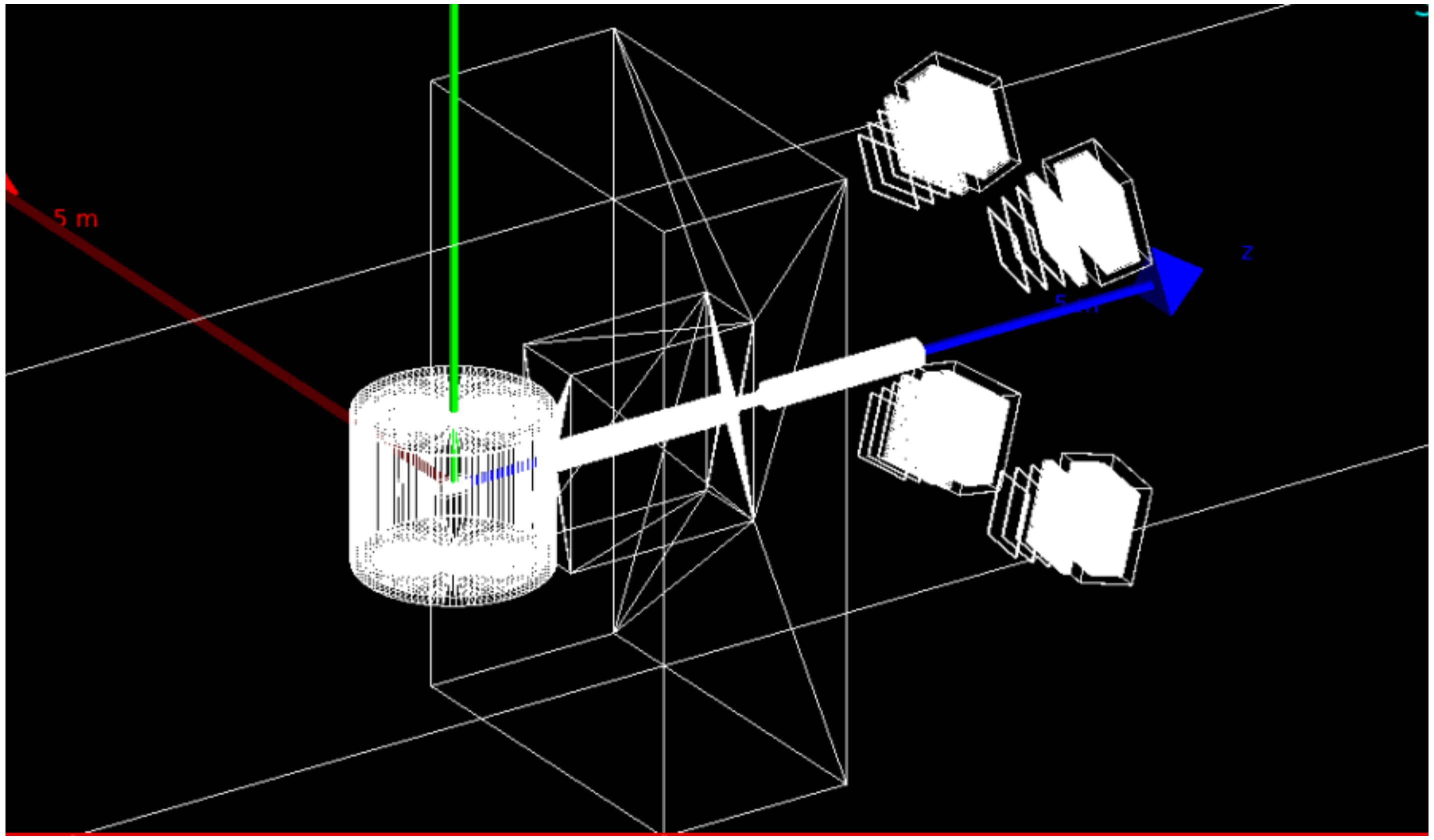
Abstract

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.

JSA Postdoctoral Prize Grant - 10 K

Summary

A newly proposed di-lepton spectrometer at Hall C will enable us to measure :
polarized TCS (di-lepton spectrometer)
unpolarized TCS (di-lepton spectrometer + magnet)
DDVCS (di-lepton spectrometer + magnet + muon detector)



This work is supported by the
The DOE Office of Science, Nuclear Physics :
DE-SC0025657 (early career program)
DE-SC0024618 (AI/ML for NP, EXCLAIM collaboration)

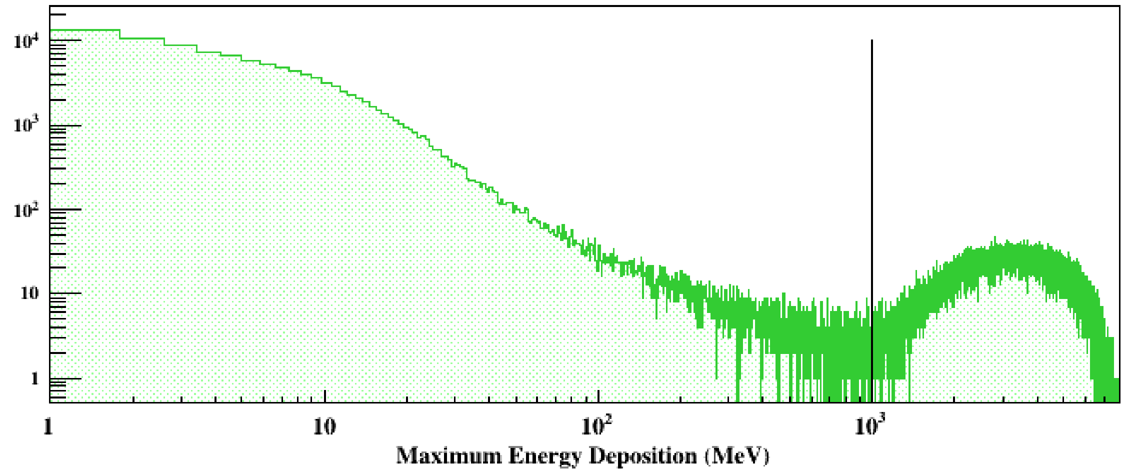
Back Up

TCS Program

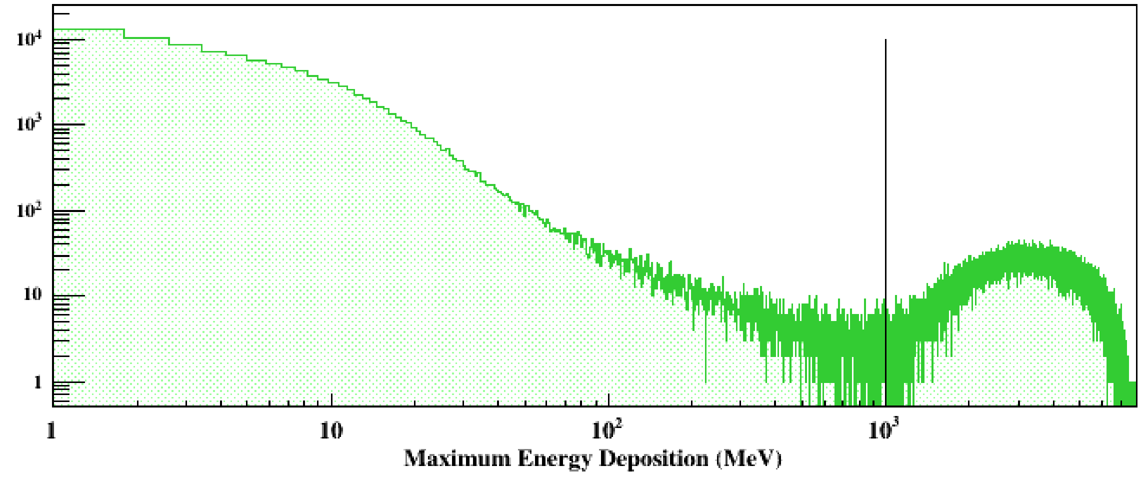
Observables	GPD	Target	Beam	Experiments
Unpol. cross sections vs ϕ	$\Re(H), \Im(H)$	Unpolarized (Lh2)	unpolarized	ClAS12 , SoLID (future), Unpol. TCS in Hall C
Cross sections vs ϕ	$\Im(H), \Im(\tilde{H})$	Unpolarized (Lh2)	Circularly polarized	ClAS12 , SoLID (future), Unpol. TCS in Hall C
Cross sections vs ϕ & ψ	$\Re(H), D - term$	Unpolarized (Lh2)	Linearly polarized	Possible with GlueX
Cross sections vs ϕ	$\Im(\tilde{H})$	Longitudinally polarized target	unpolarized	Possible with CLAS12
Cross section vs ϕ & ϕ_S	$\Im(E), \Im(\tilde{H})$	Transversely polarized target	unpolarized	Pol. TCS in Hall C Work in progress
Double spin asym. vs ϕ	$\Re(CFF)$	log. Polarized	Circularly polarized	Extremely interesting but very difficult
Double spin asym. vs ϕ & ϕ_S	$\Re(CFF)$	trans. Polarized	Circularly polarized	Extremely interesting but very difficult
Double spin asym. vs ϕ & ψ	$\Im(CFFs)$	log. Polarized	Longitudinally polarized	Not useful too complex and not enough info
Double spin asym. vs ϕ_S & ψ	$\Im(CFFs)$	trans. Polarized	Longitudinally polarized	Not useful too complex and not enough info

Geant4 Simulation : maximum energy distribution

Electron



Positron



Proton