Timelike Compton Scattering in Hall C at JLab : path forward in GPD studies

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HALL C Winter Collaboration Meeting,
18-19 January 2024

Accessing GPDs through exclusive reactions

Compton like reactions

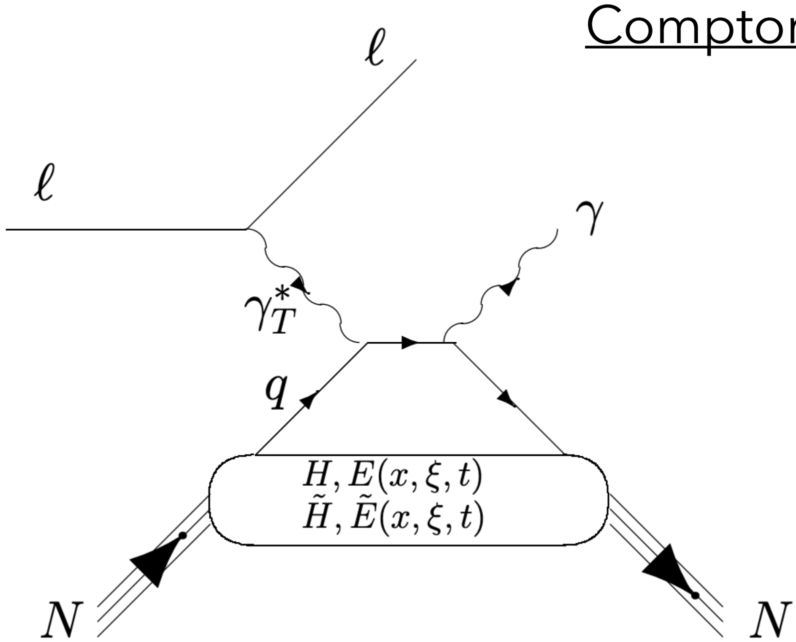


Fig : DVCS

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

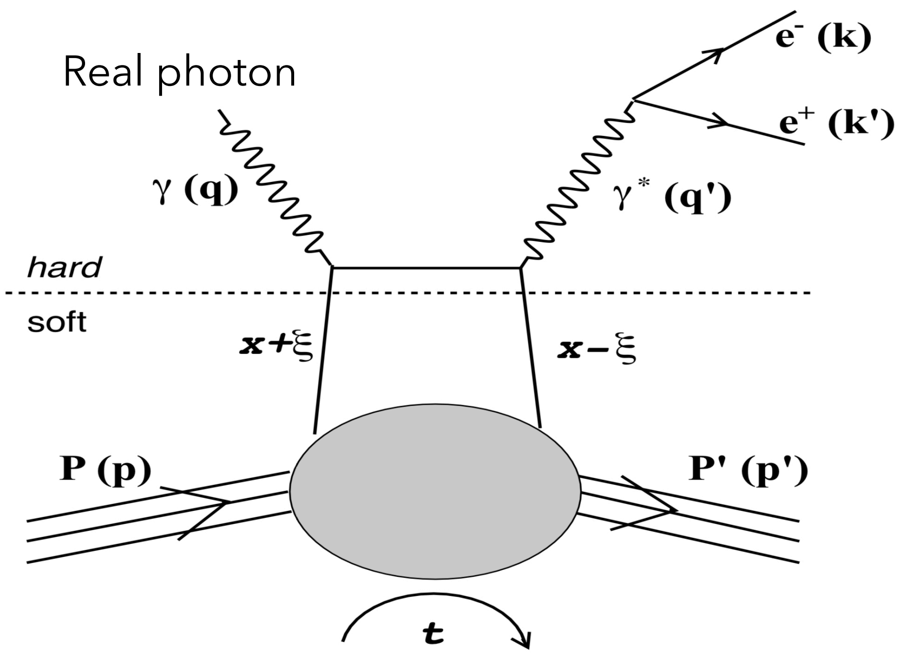


Fig : TCS

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

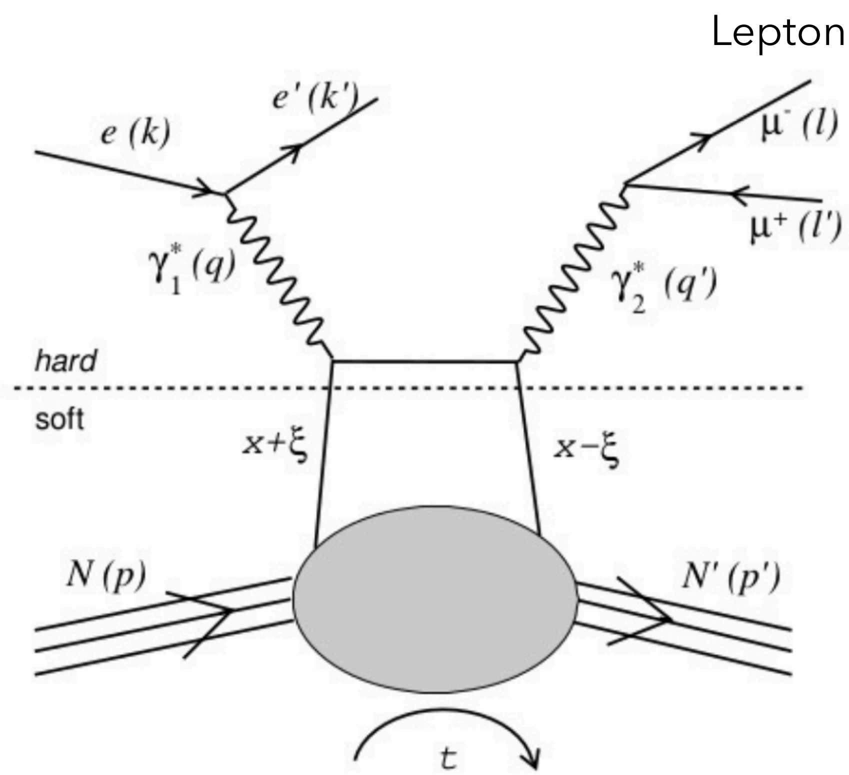


Fig : DDVCS

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

Meson production

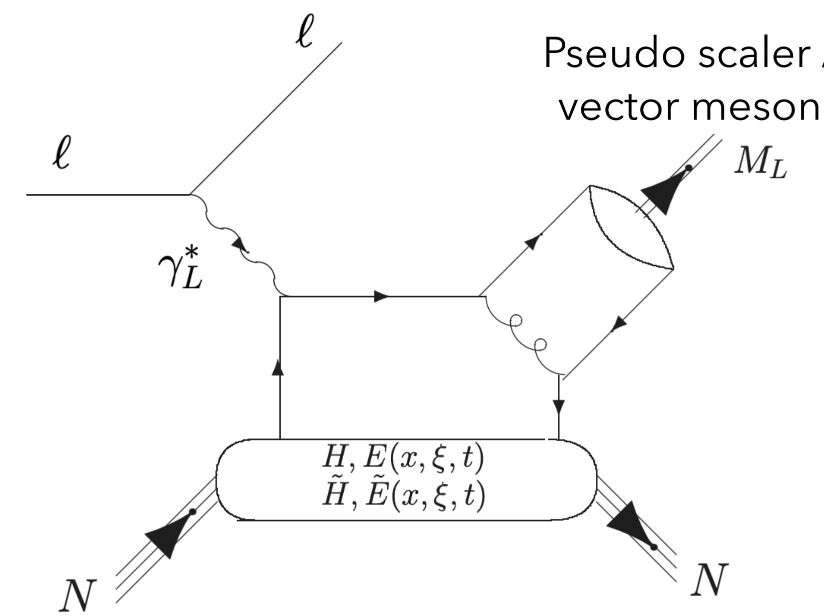


Fig : DVMP (quark Subprocess)

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

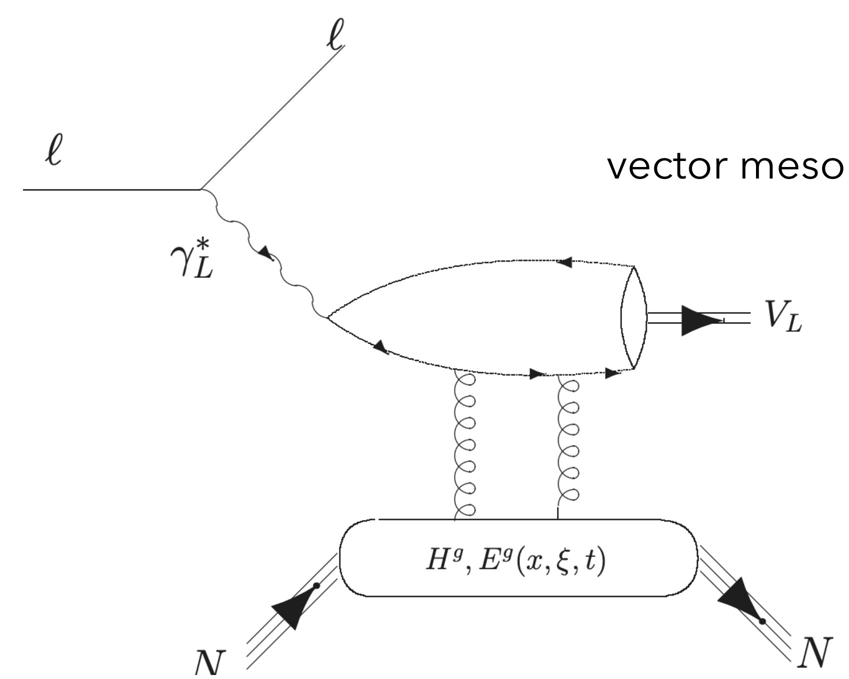


Fig : DVMP (gluon subprocess)

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

Timelike Compton Scattering

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

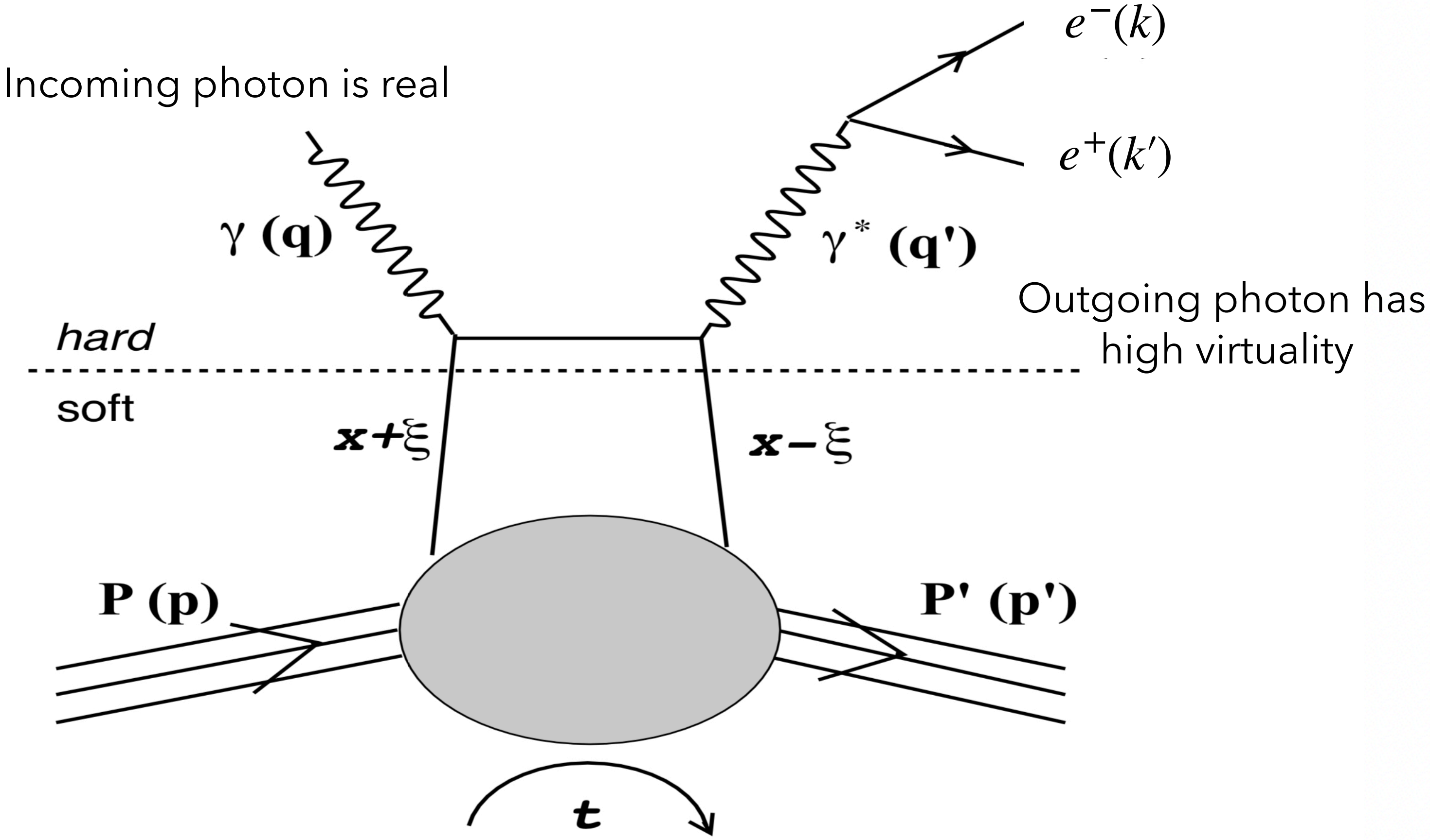


Fig : Time Like Compton Scattering

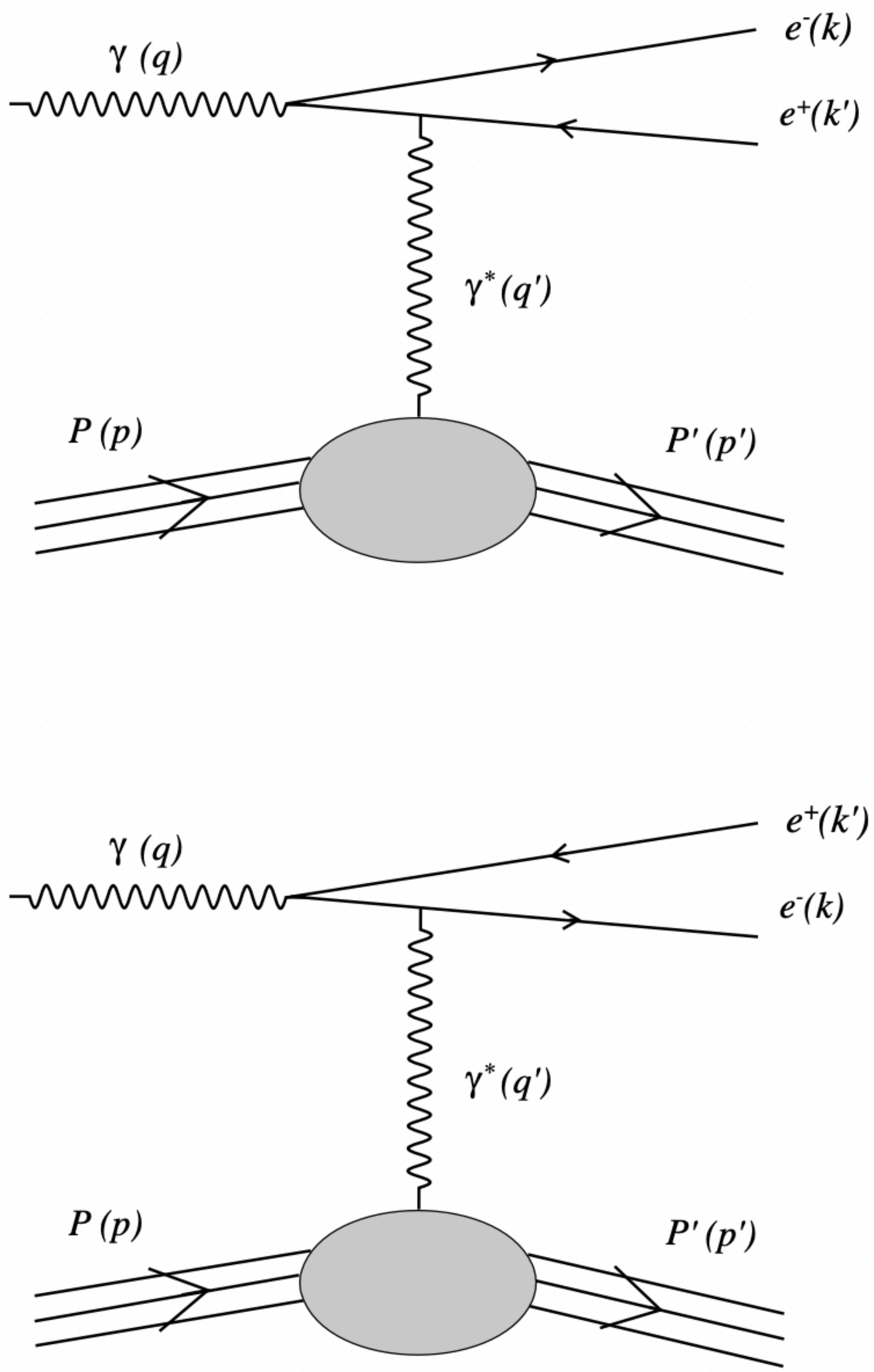
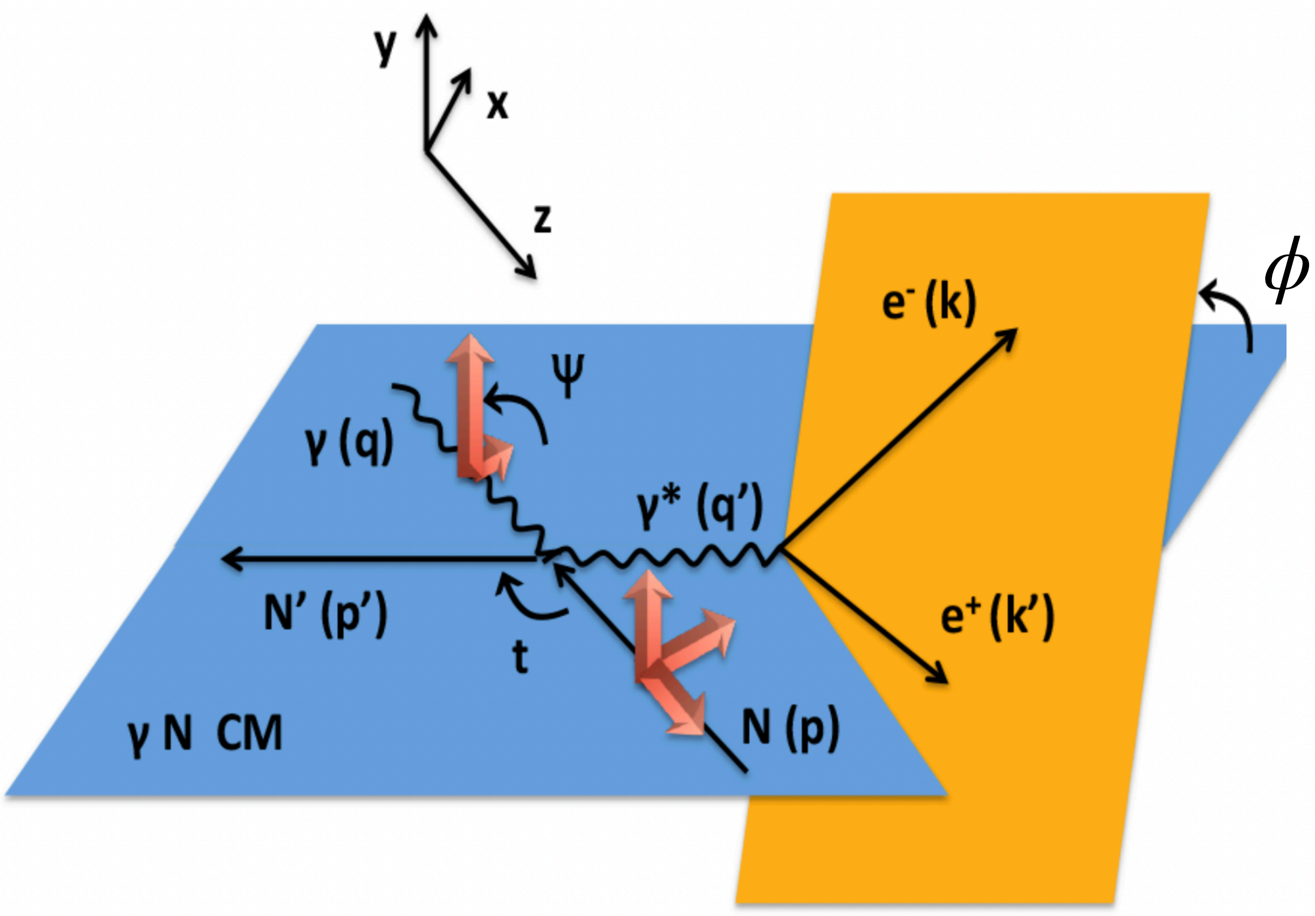


Fig : Bethe-Heitler diagrams

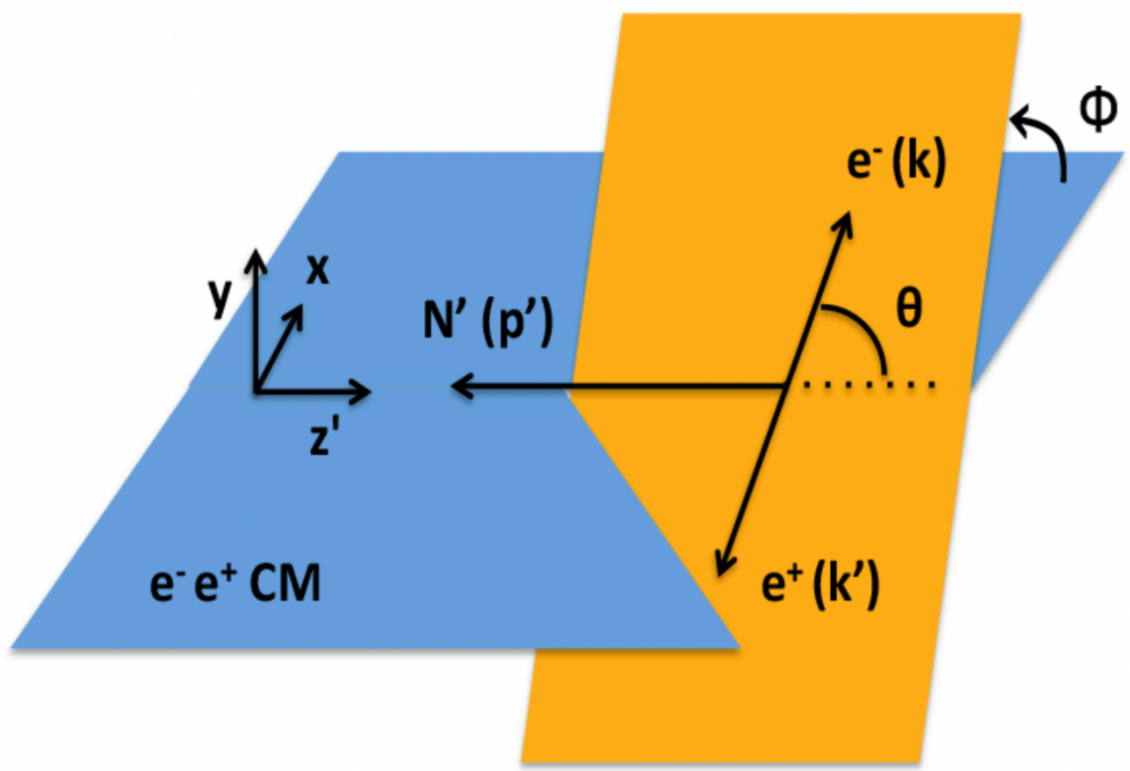
Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

Timelike Compton Scattering

γP C.M. Frame



γ^* C.M. Frame



ψ : Angle between reaction plane and γ spin

ϕ : Angle between the hadronic plane (blue) and e^+e^- plane (yellow)

θ : Angle between γ^* and e^-

θ_s, ϕ_s : target spin orientation vs reaction plane (blue)

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

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

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

Polarized TCS: kinematic coverage & CFF accuracies

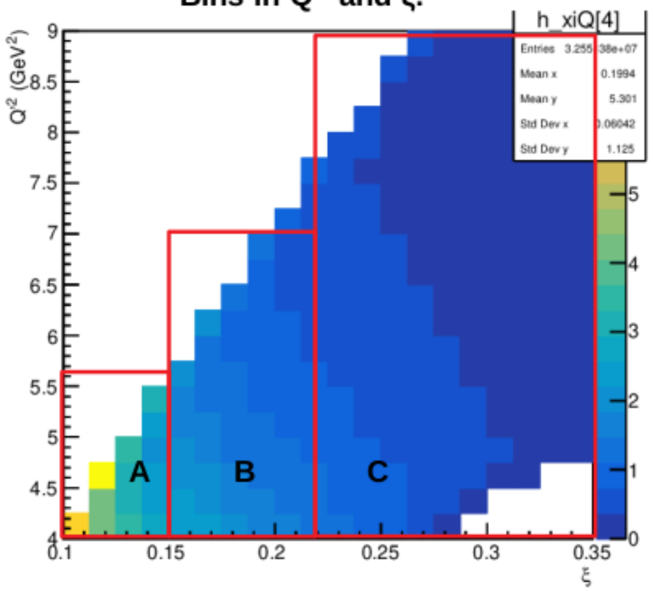
Example estimates of accuracies on the model extraction of CFFs.

TCS with trans. pol. Target:

- Allows for extraction of **Im(E)** (**unique to this proposal**)
- Allows for extraction of **Im(H) to good accuracy** (**universality tests**)
-

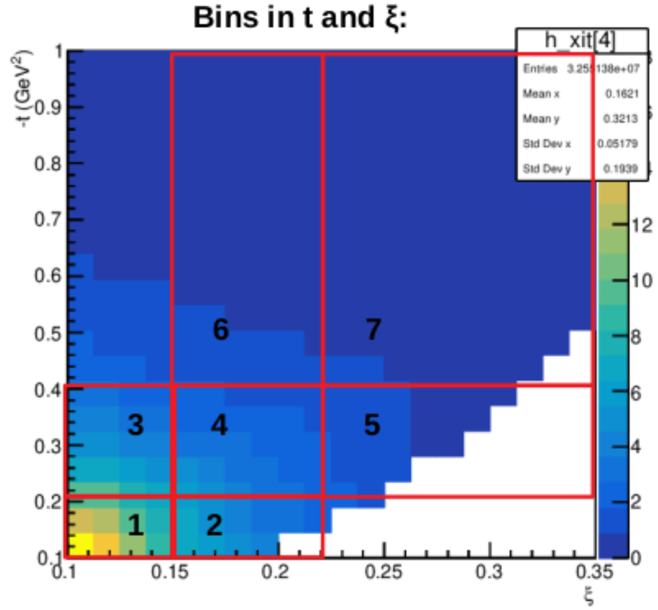
Kinematic coverage

Bins in Q'² and ξ:

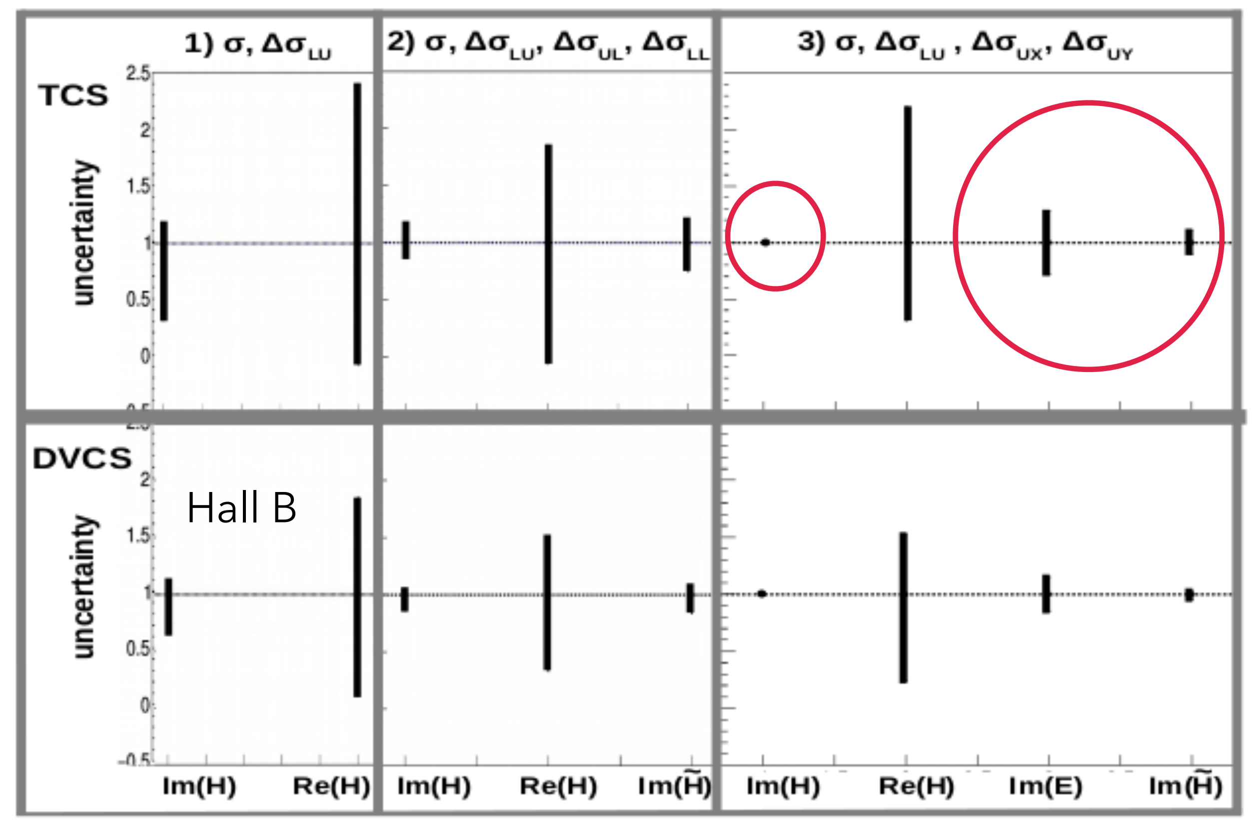


A: .10 < ξ < .15 ; 4 < Q'² < 5.5 GeV²
B: .15 < ξ < .22 ; 4 < Q'² < 7 GeV²
C: .22 < ξ < .35 ; 4 < Q'² < 9 GeV²

Bins in t and ξ:



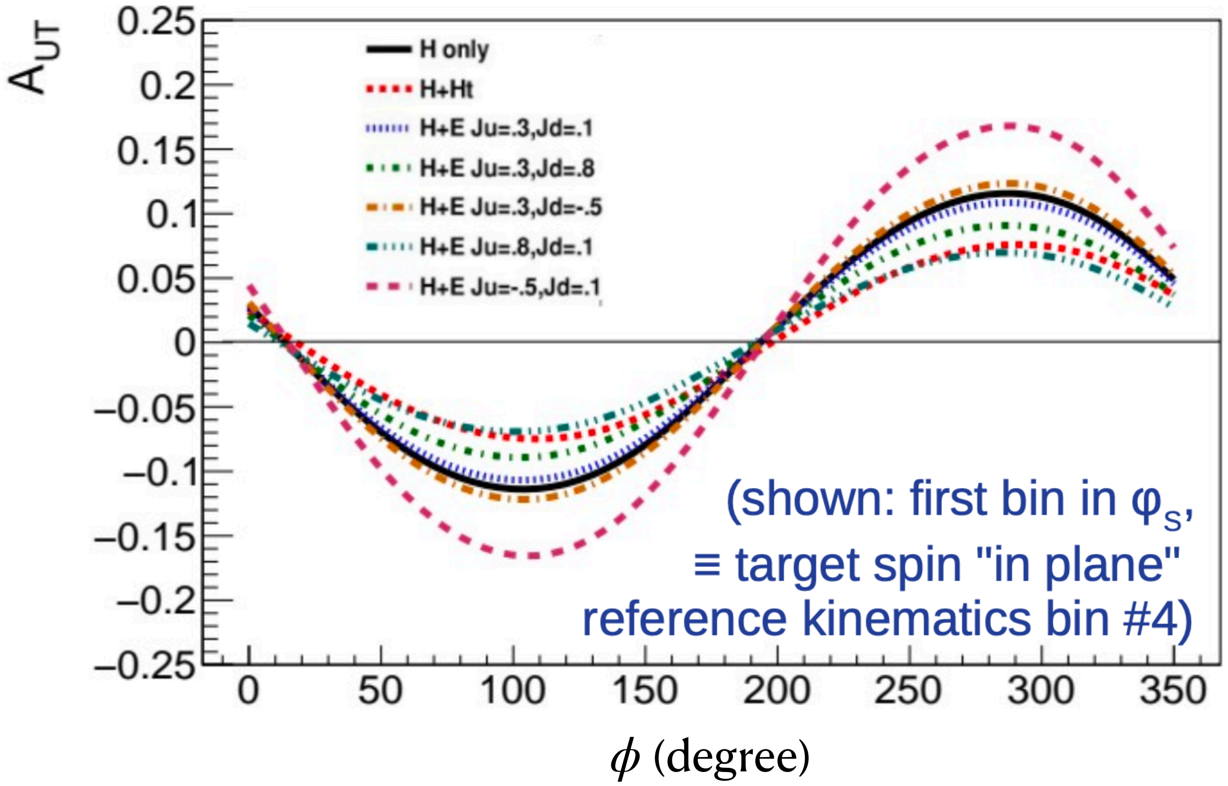
1, 2: .1 < -t < .2 GeV²
3, 4, 5: .2 < -t < .35 GeV²
6, 7: .35 < -t < .7 GeV²



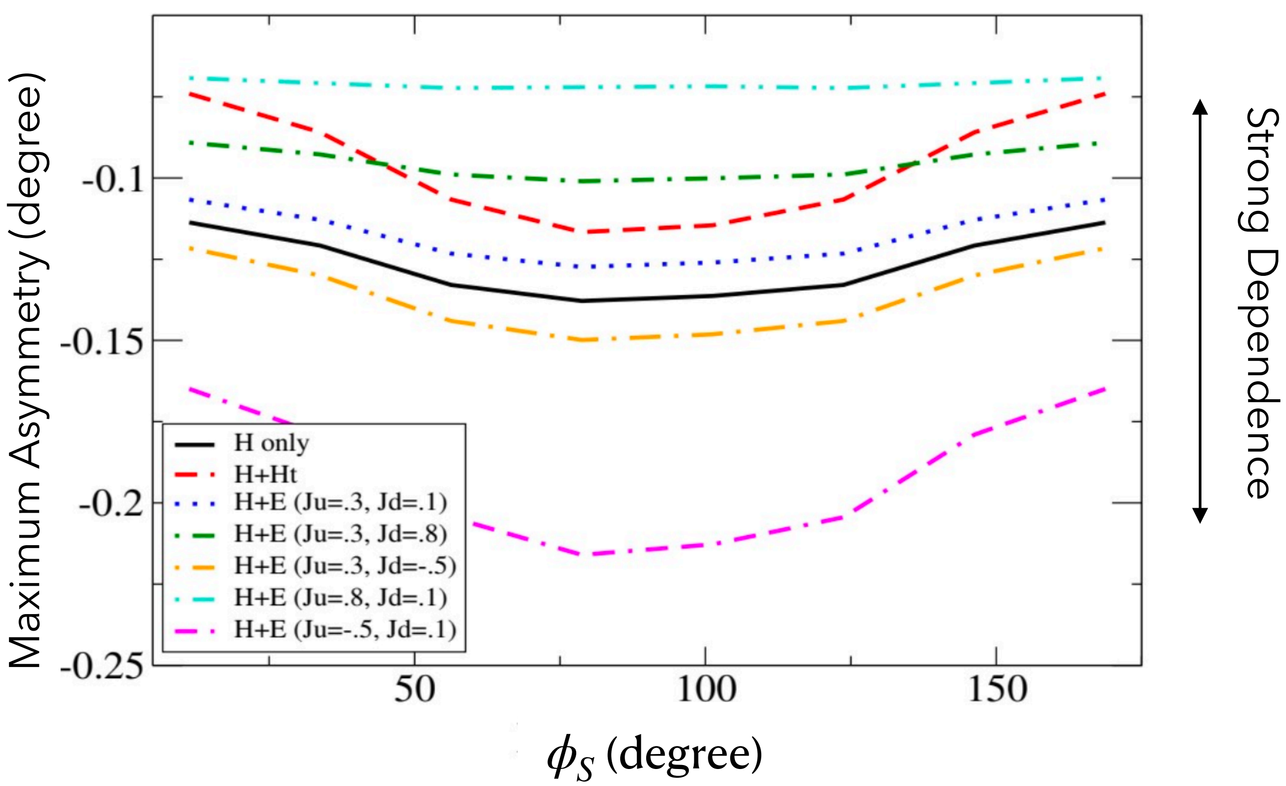
Kinematic region out of pion resonance production

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

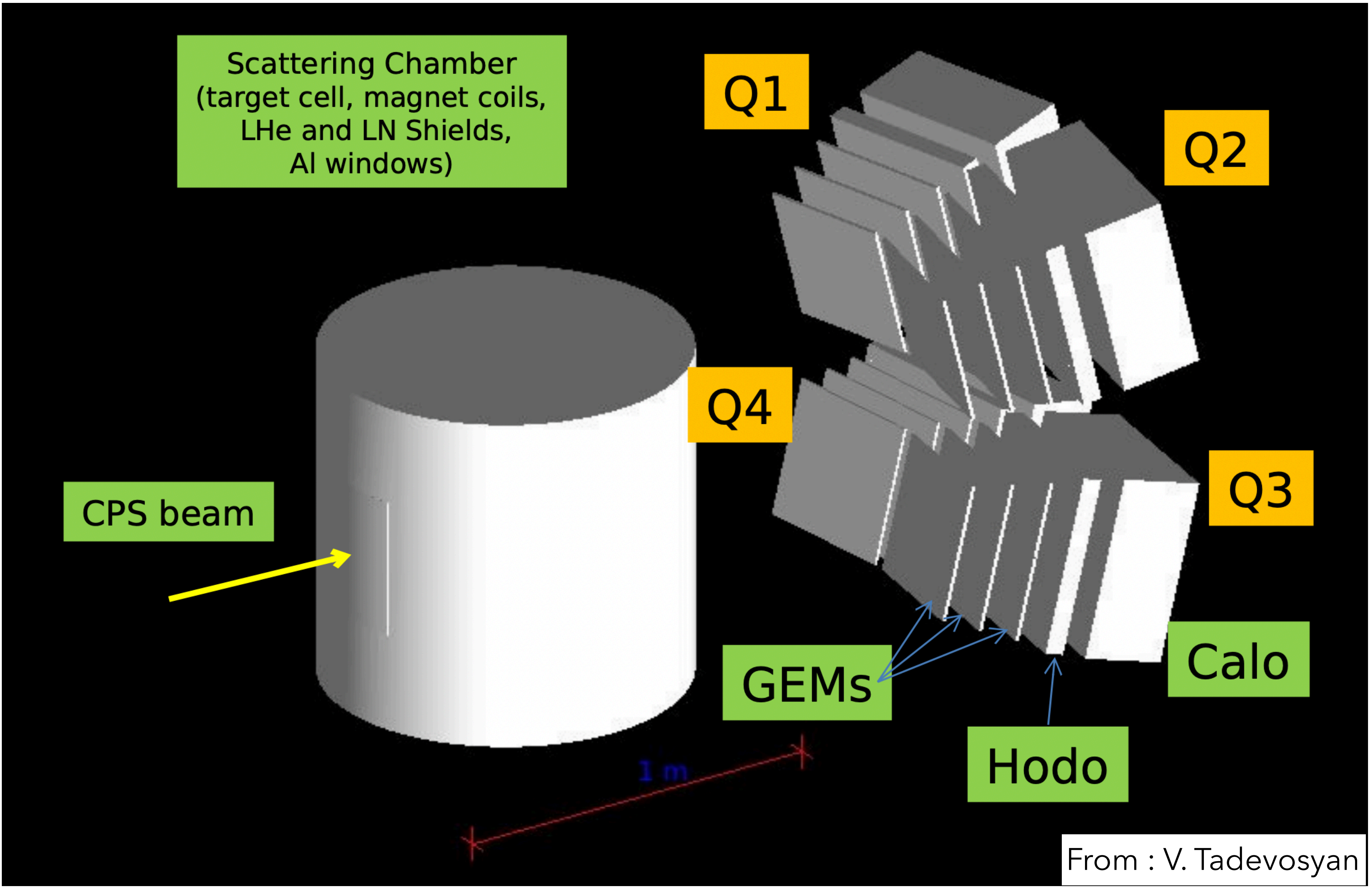


Fig : Geant4 simulation of detector setup at Hall C for proposed polarized TCS experiment

1. High intensity photon source 1.5 x 1012 γ/sec (CPS)

2. Target chamber: NH3, 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 x 105 pb-1

Compact photon source

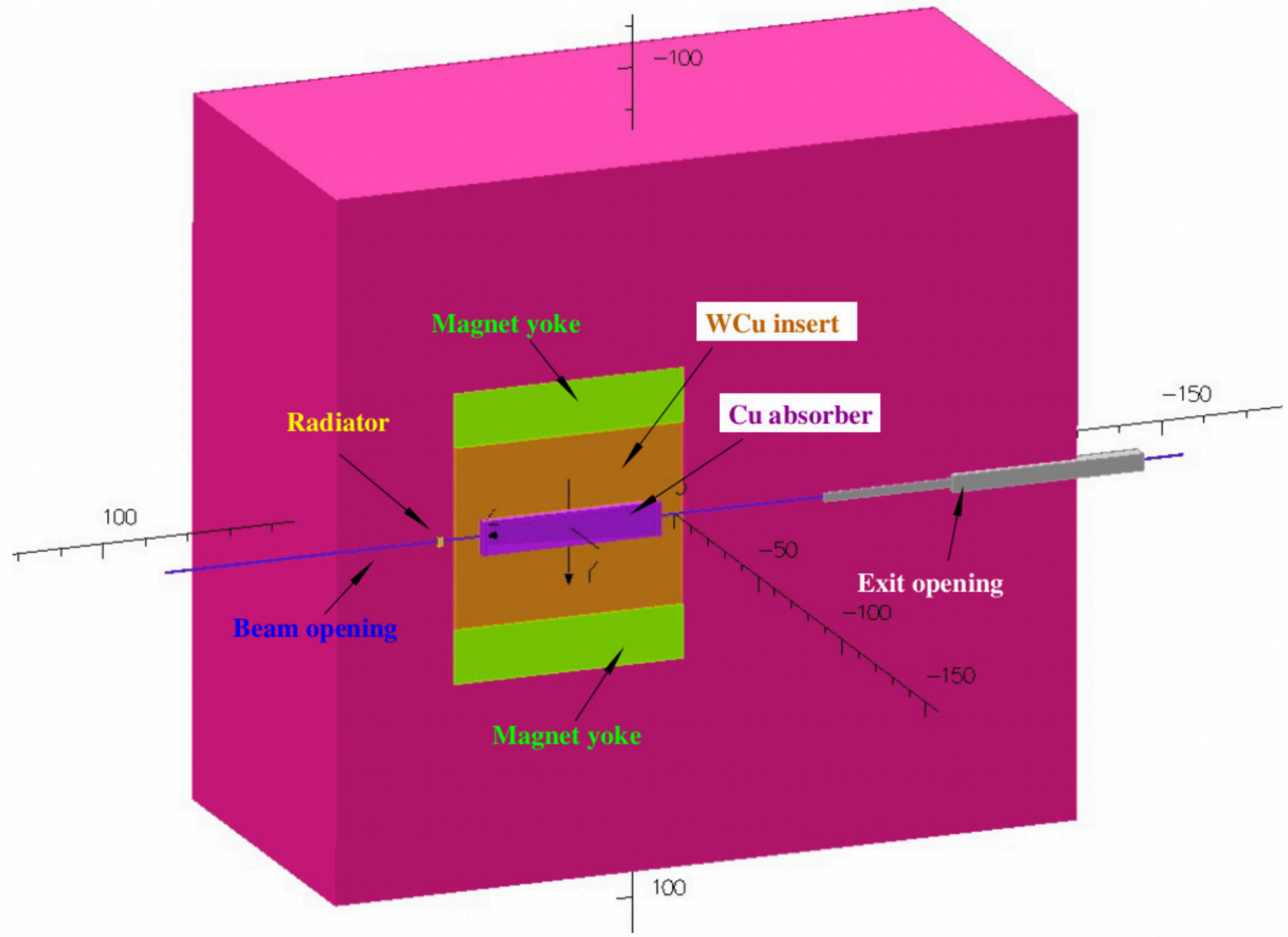


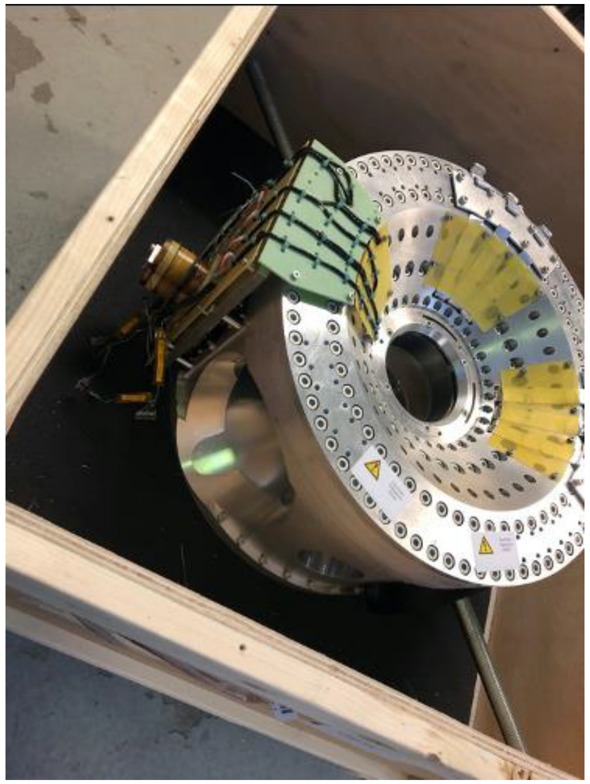
Fig : The CPS Cut off view

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

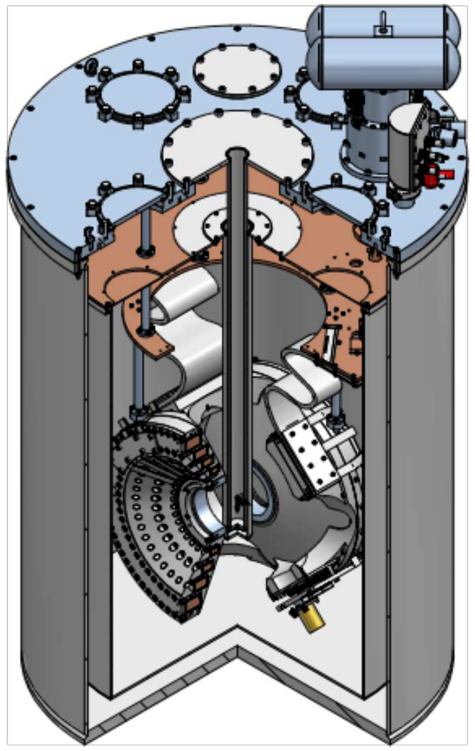
Polarized target

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



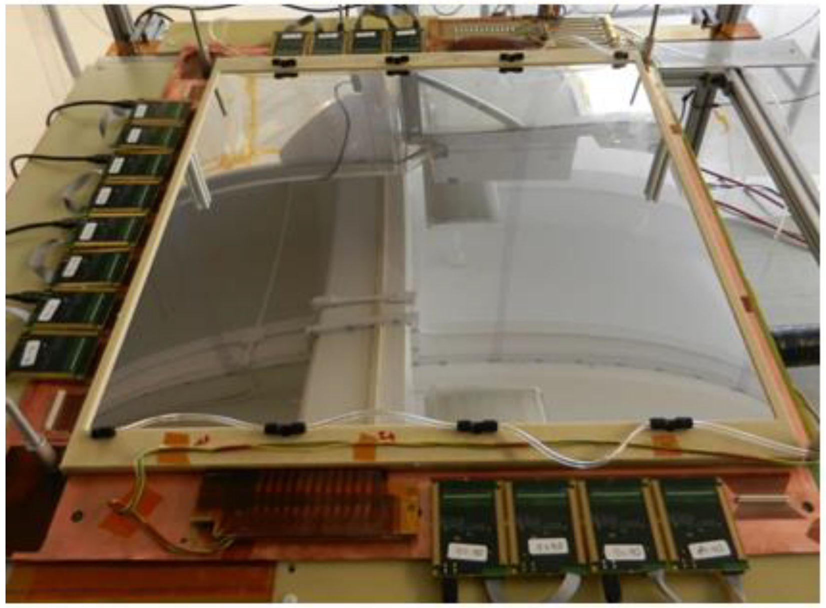
<u>New polarizing magnet arrived in September 2021!</u>

- Drop-in replacement for old Jlab-UVA target
- 5 T magnetic field, 100 ppm uniformity
- ±25° horizontal opening angle in transverse field configuration (increase from ±18° --> increase of TCS acceptance, help with background rates.)
-



Horizontal field orientation

GEM Tracker , Hodoscope & Calorimeter



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

<u>GEM trackers:</u>
- 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

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

<u>Calorimeters, clones of the NPS calorimeter:</u>
- 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)

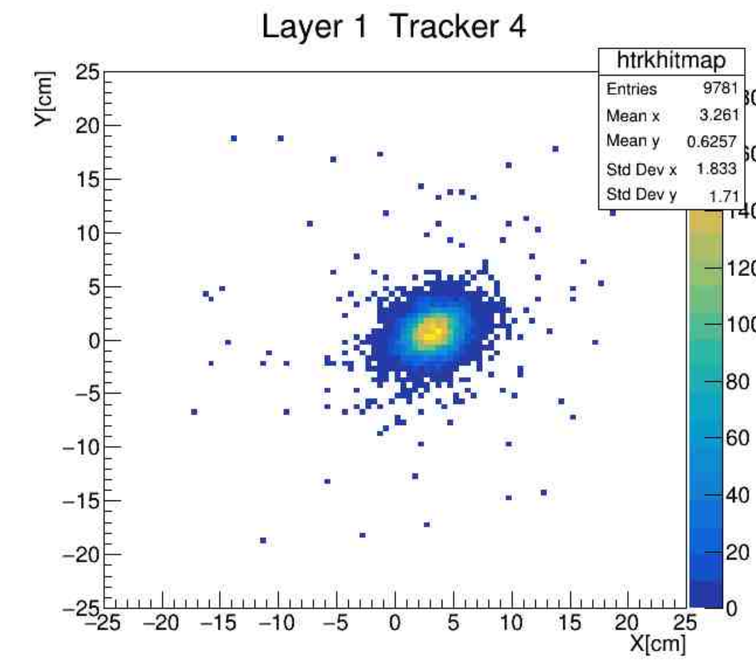
Polarized TCS : Recoil proton ID

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

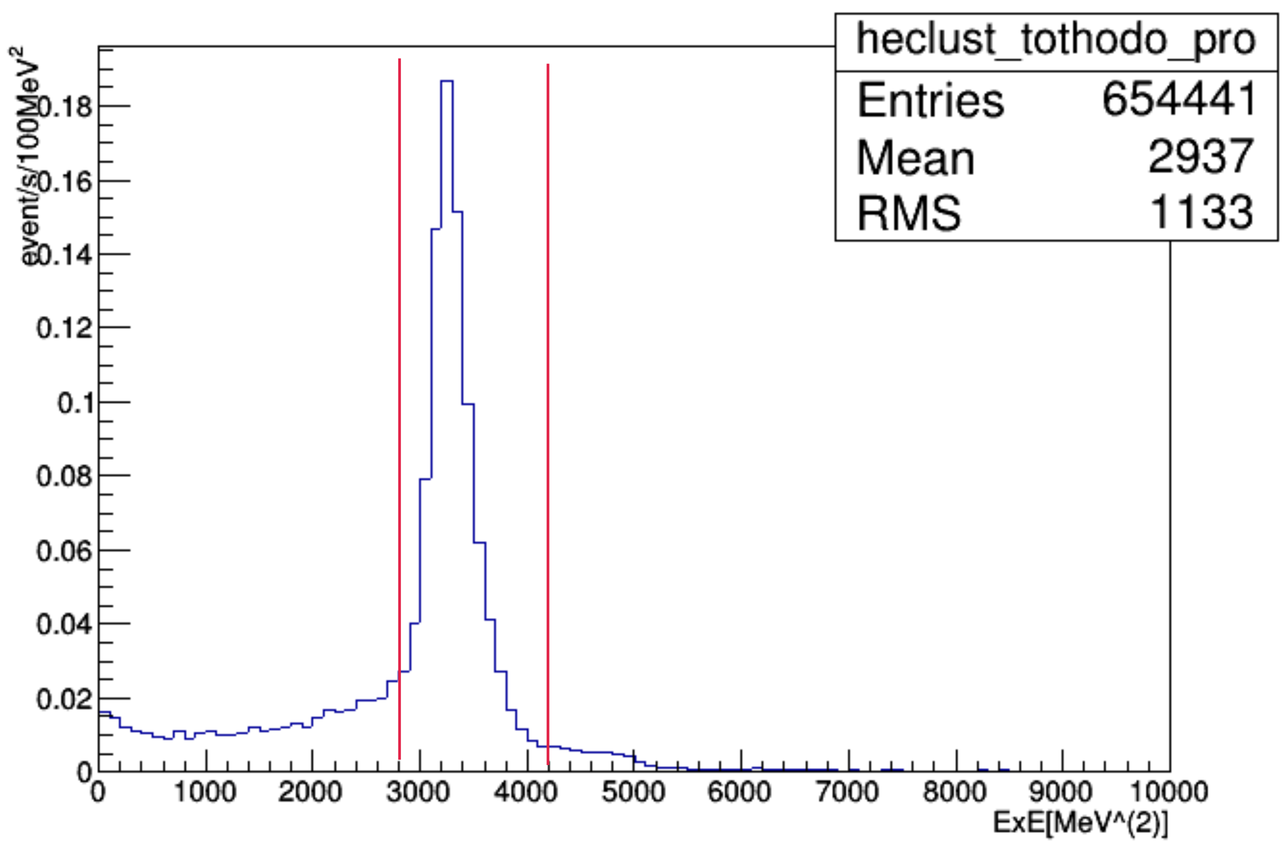
Cuts to select good protons :

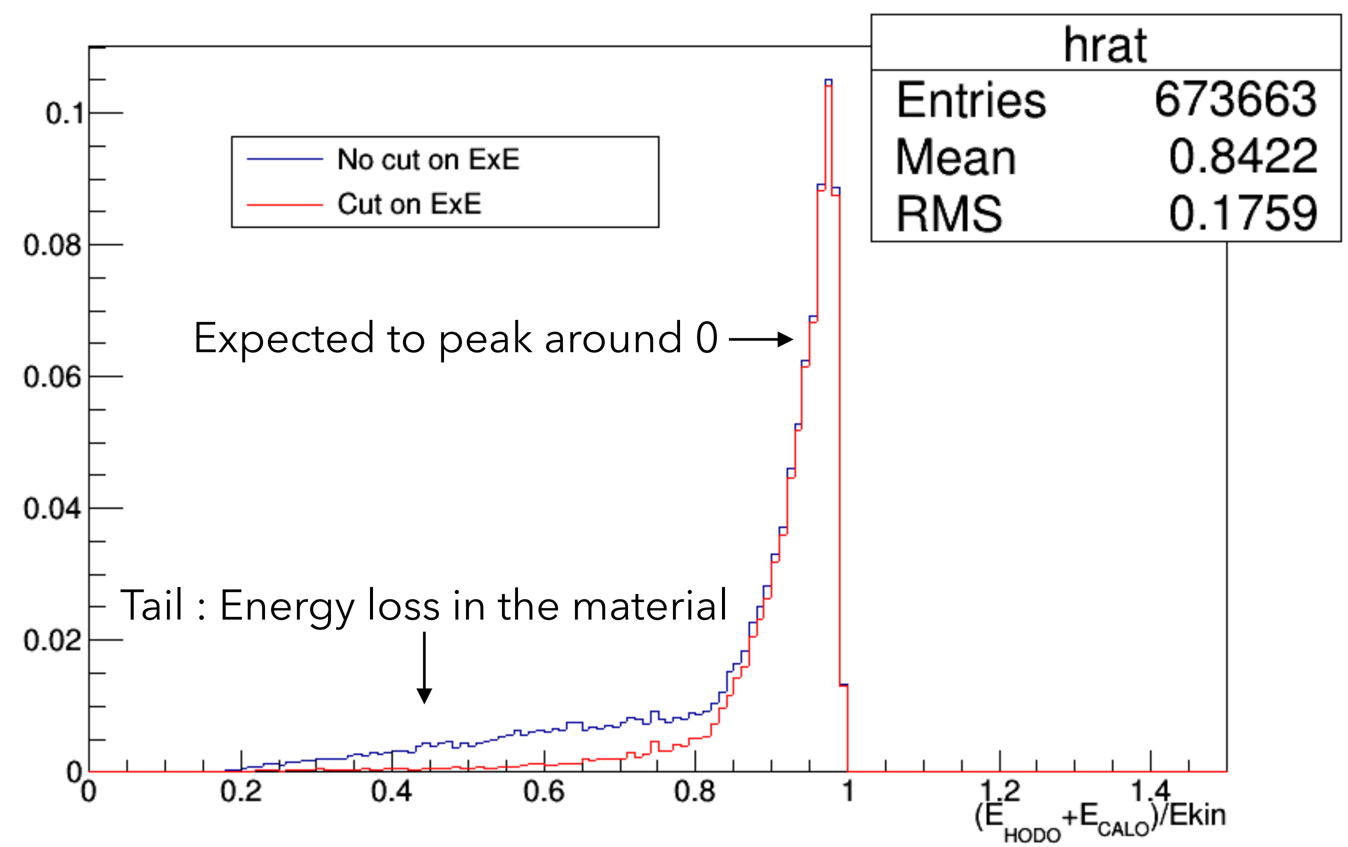
1. E_{HODO} > 15 MeV
2. 90 MeV < $E_{HODO} + E_{CALO}$ < 450 MeV
3. 2800 MeV^2 < E.E < 4200 MeV^2

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



GEM hit patter from 400 MeV/C protons





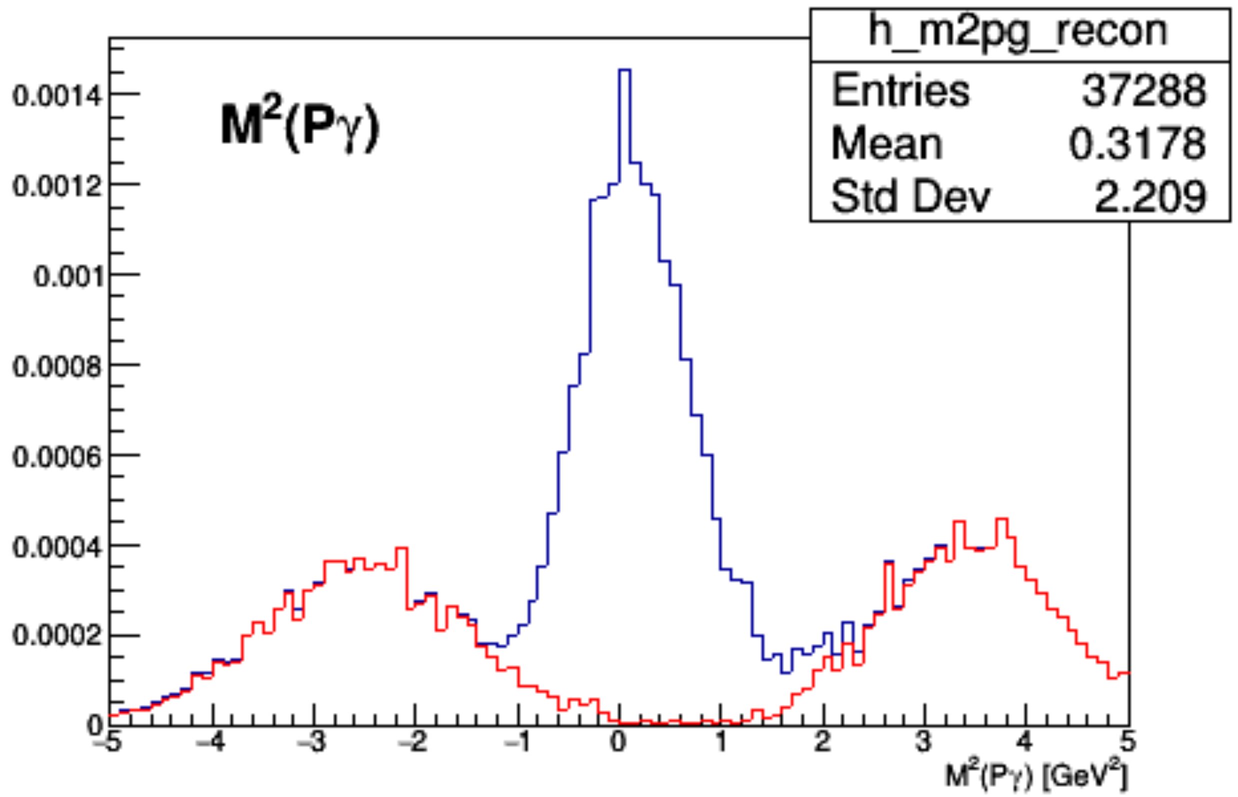
From : Vardan Tadevosyan

Polarized TCS : Lepton charge assignment

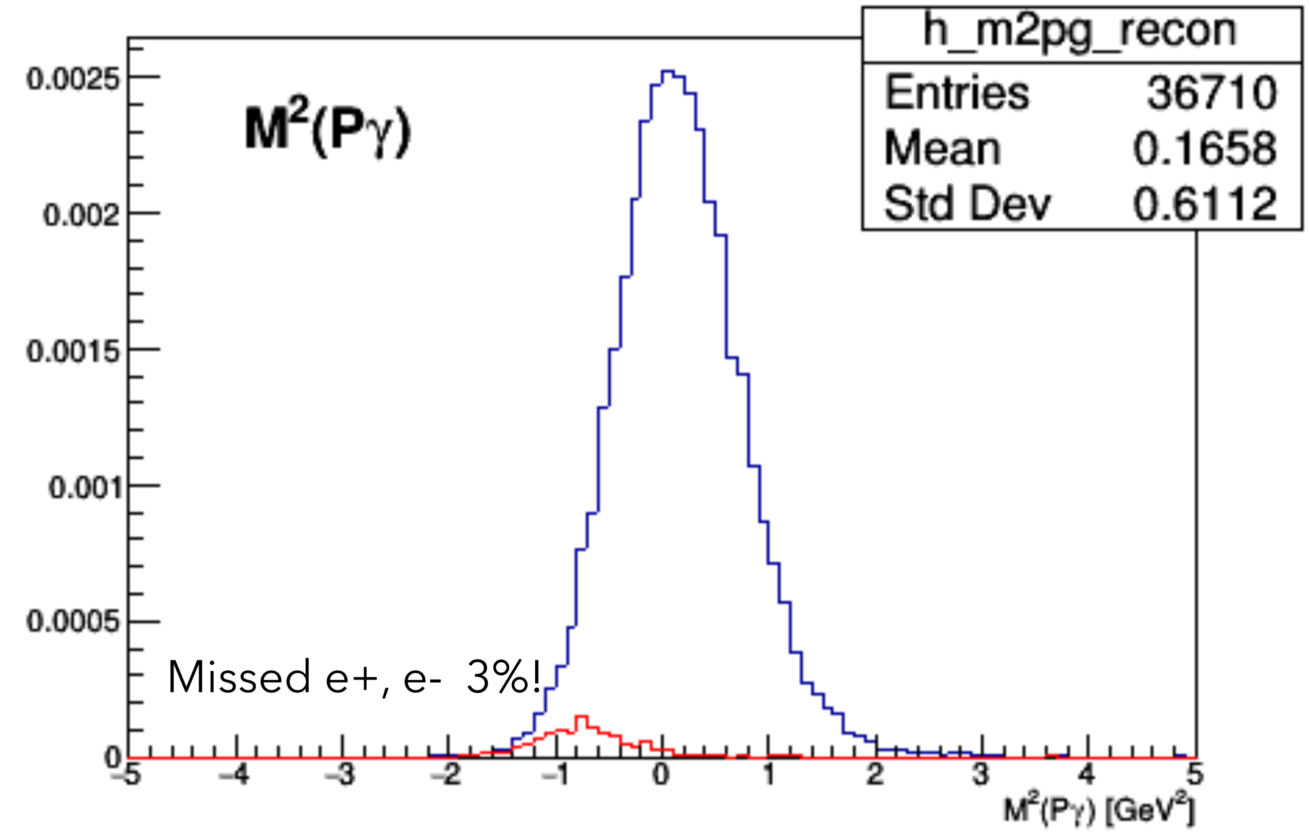
5T target field localized at target cell
Field behind scattering chamber too weak to distinguish pos. and neg. tracks.
Alternative: use reconstructed incident photon mass:

- 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

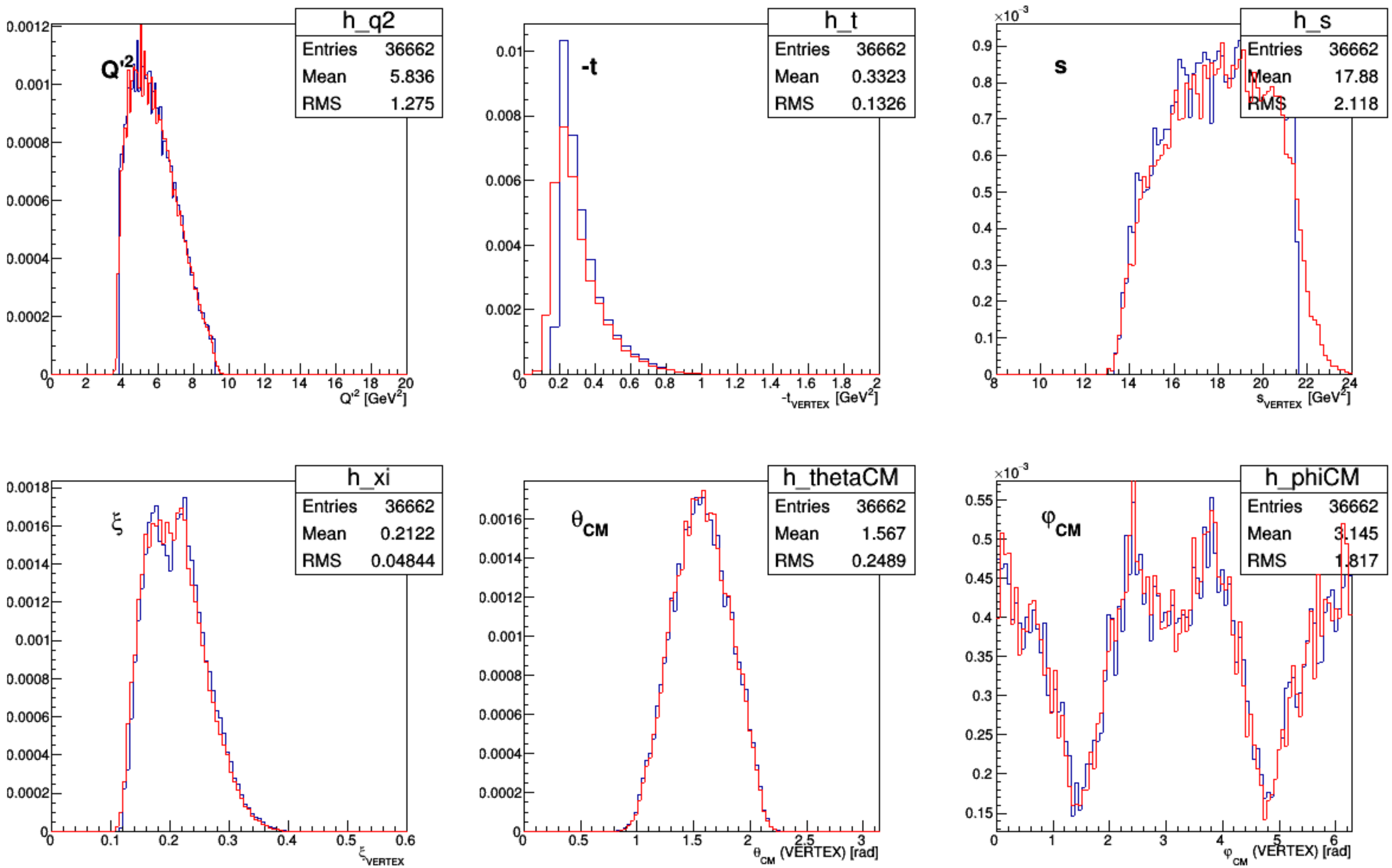


Lepton charges according to selection criteria



From : Vardan Tadevosyan

Polarized TCS : reconstructed vs true quantities



From : Vardan Tadevosyan

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

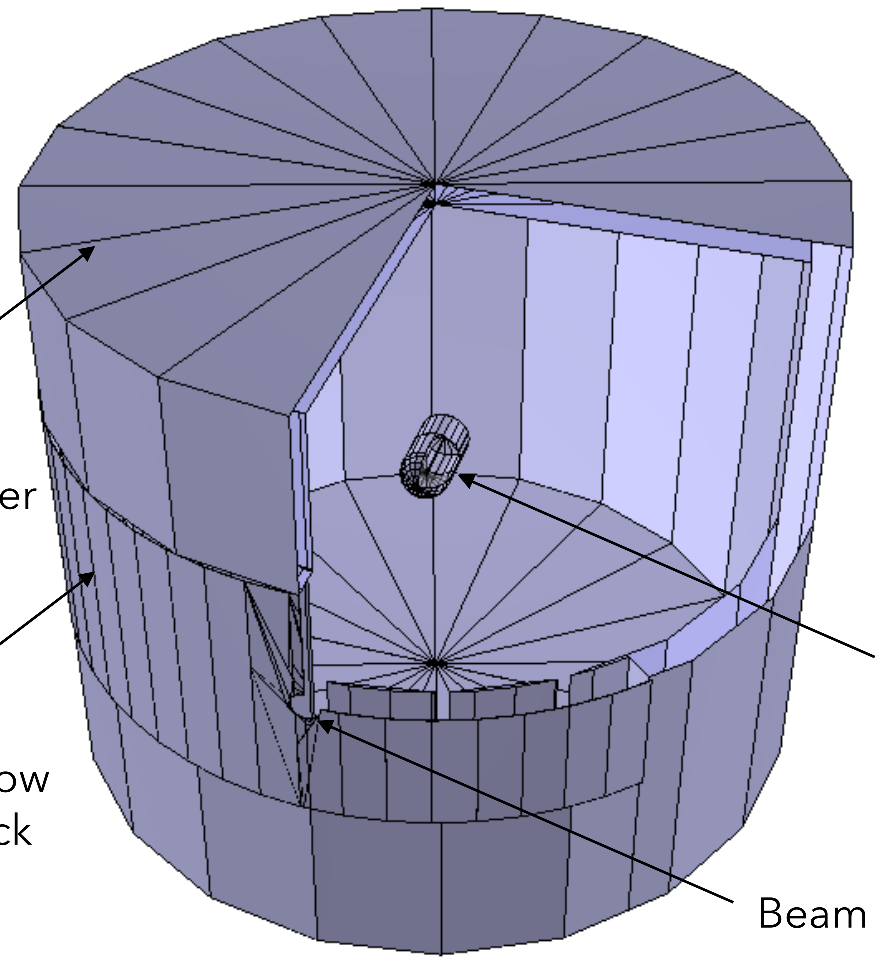


Fig : Geant4 simulation of scattering chamber and target

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

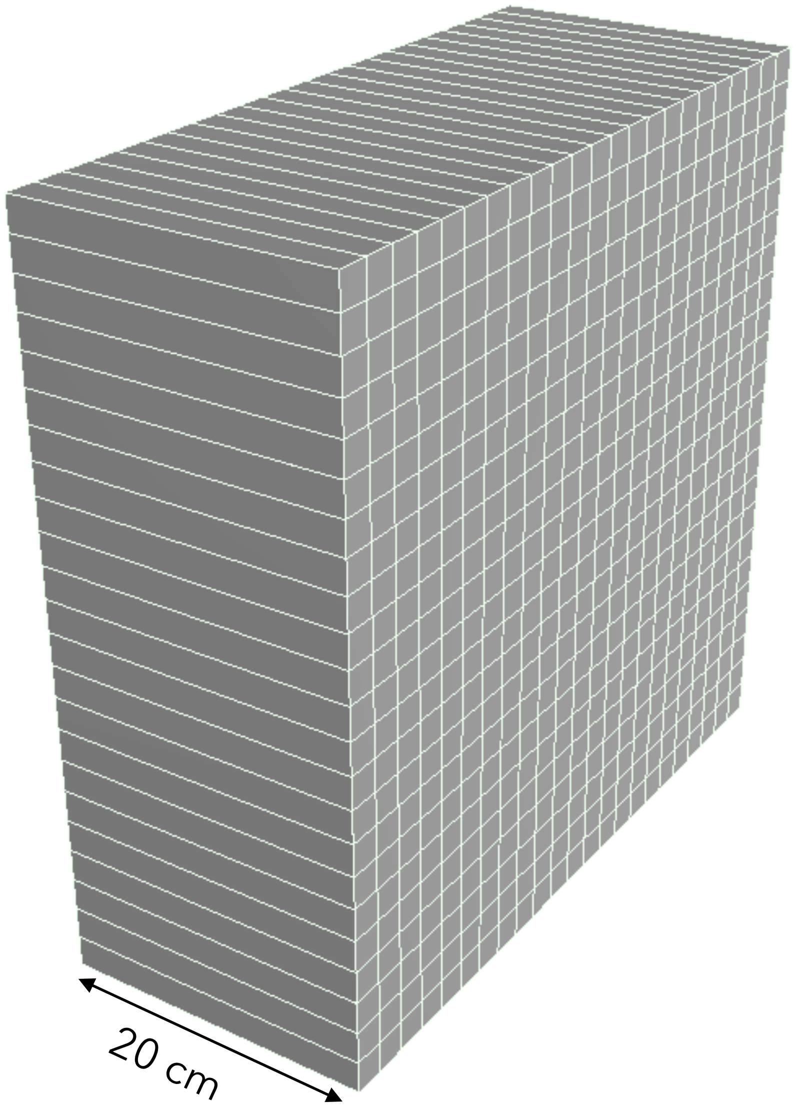


Fig : Geant4 simulation calorimeter

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

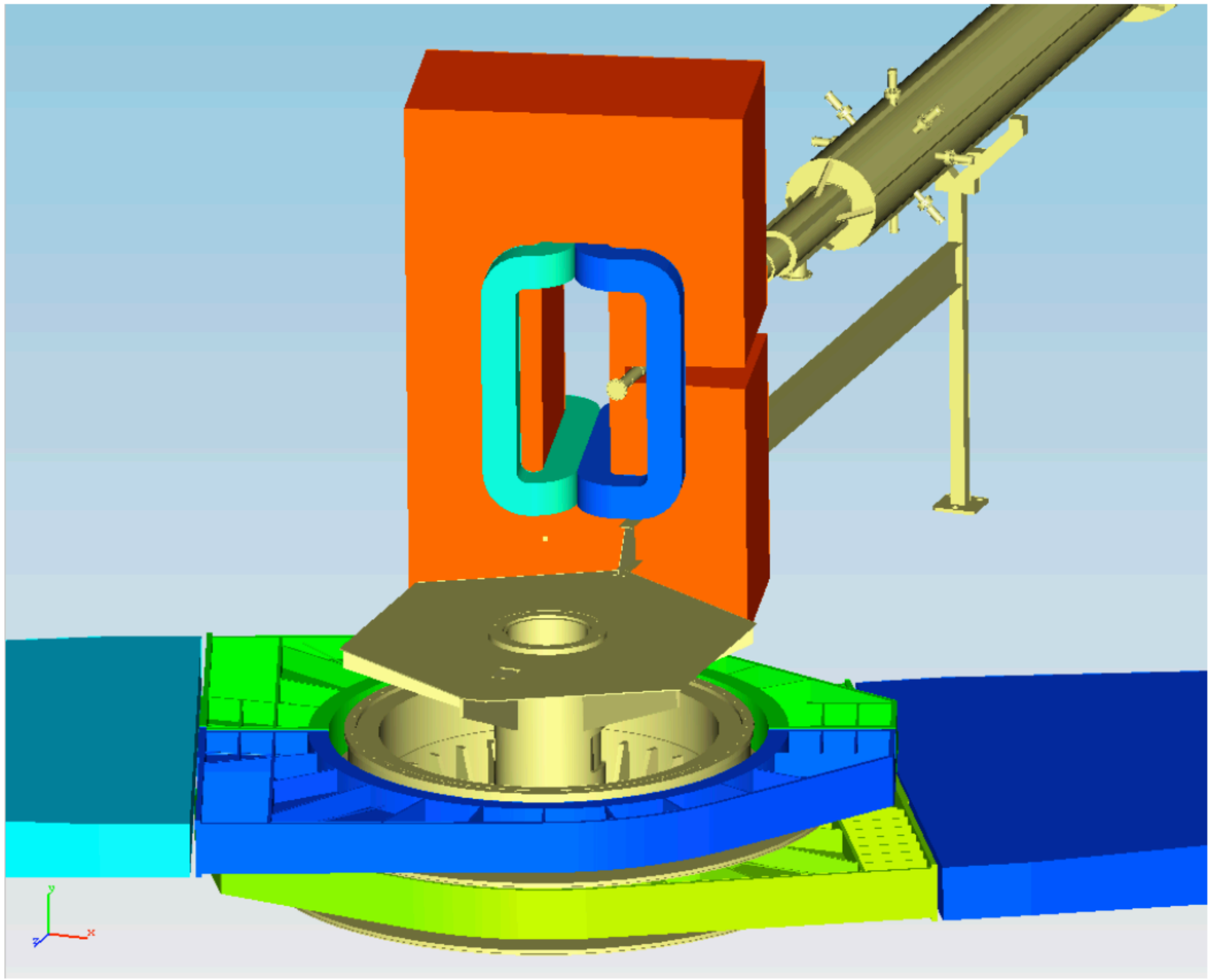


Fig : CAD Drawing for Super Bigbite Magnet
Source : https://userweb.jlab.org/~bogdanw/SBS-general.pdf

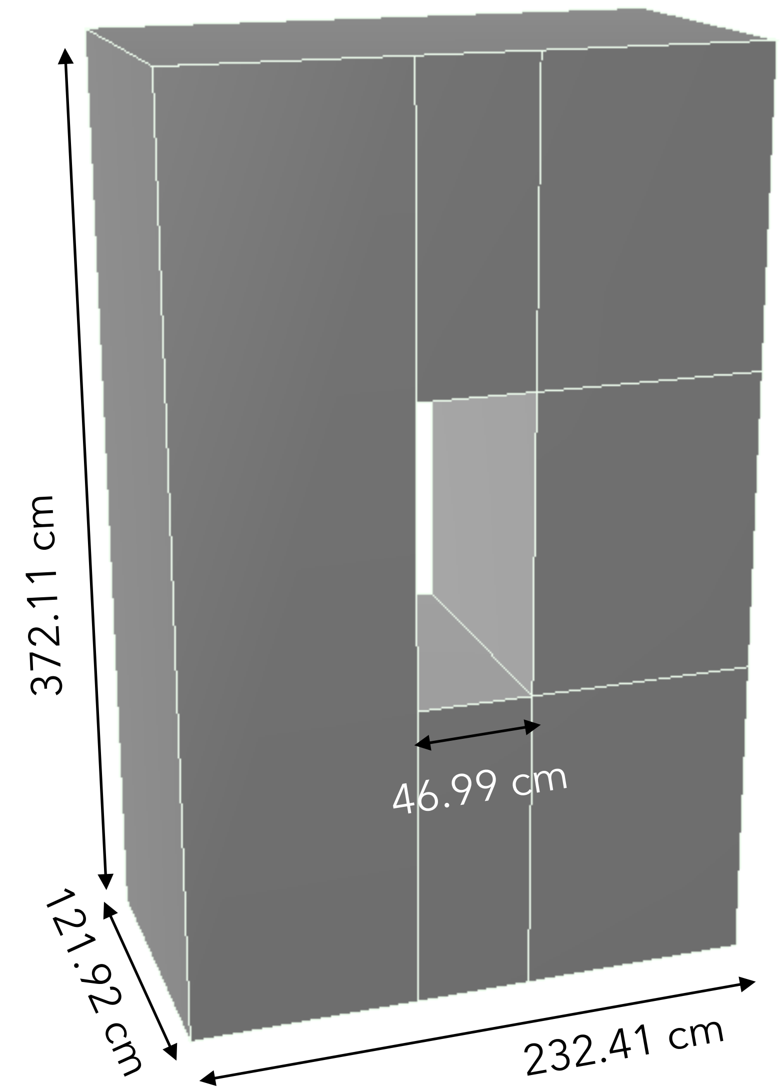
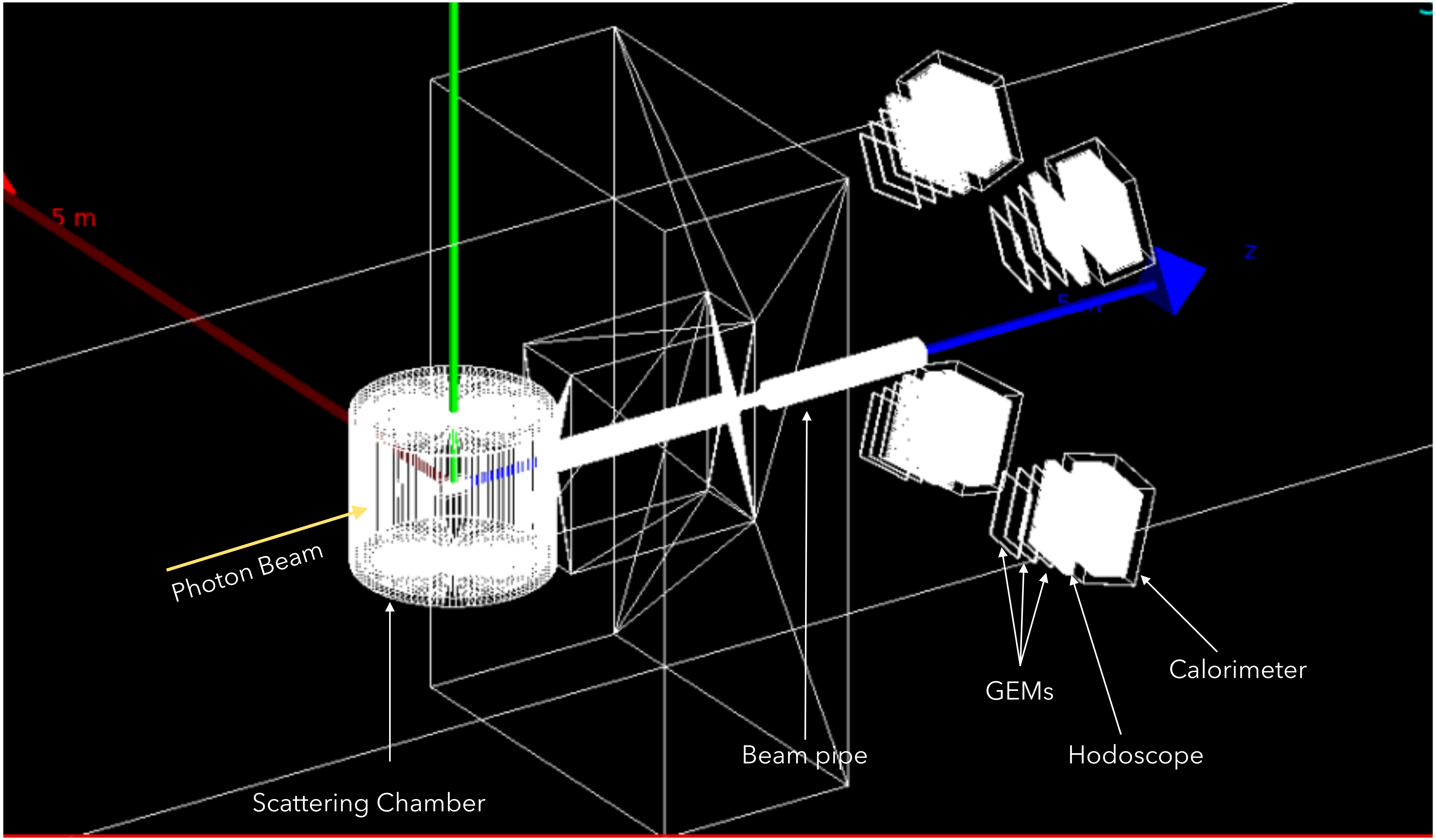


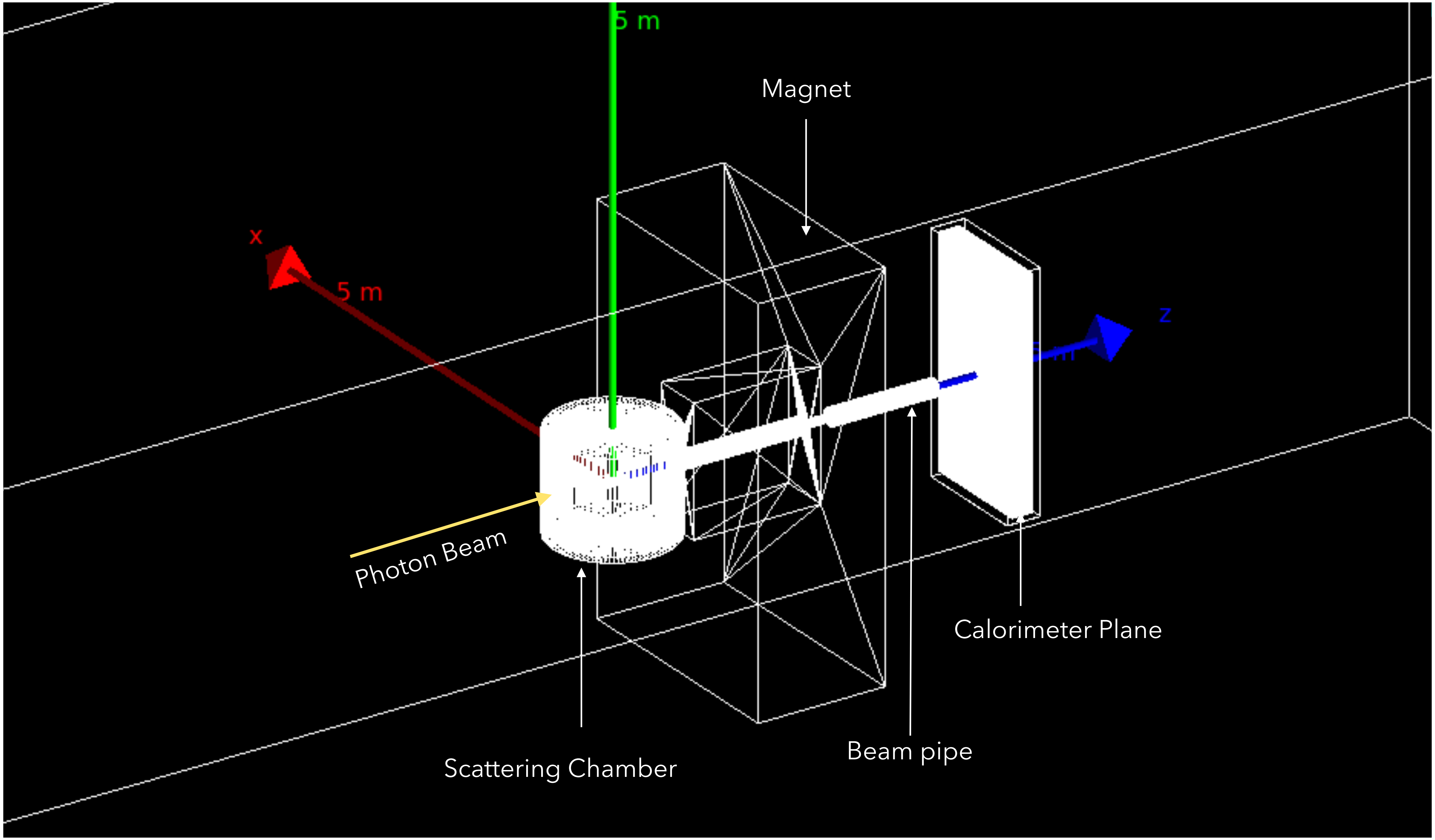
Fig : Geant4 simulation of simple magnet geometry

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

Unpolarized TCS measurement setup for Hall C

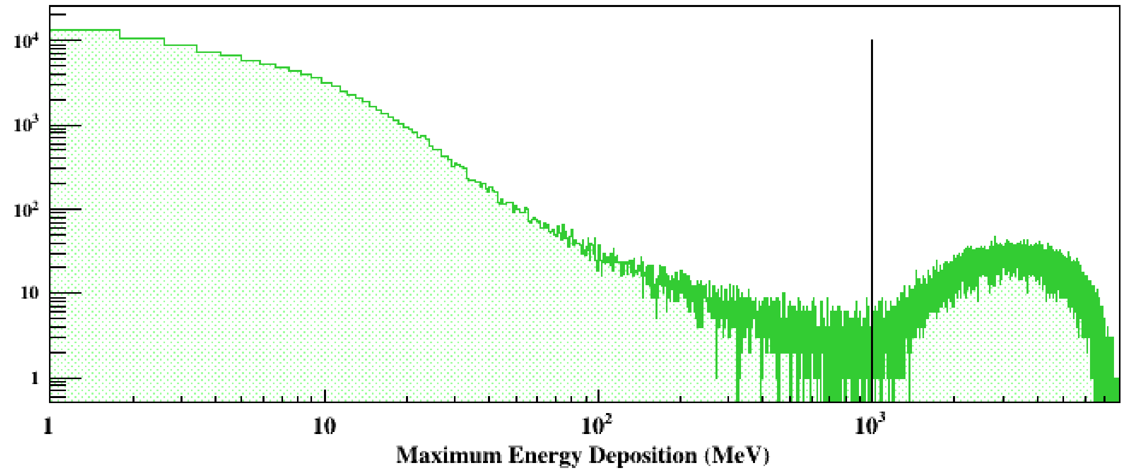


Geant4 Simulation :Simple One Calorimeter Plane Setup

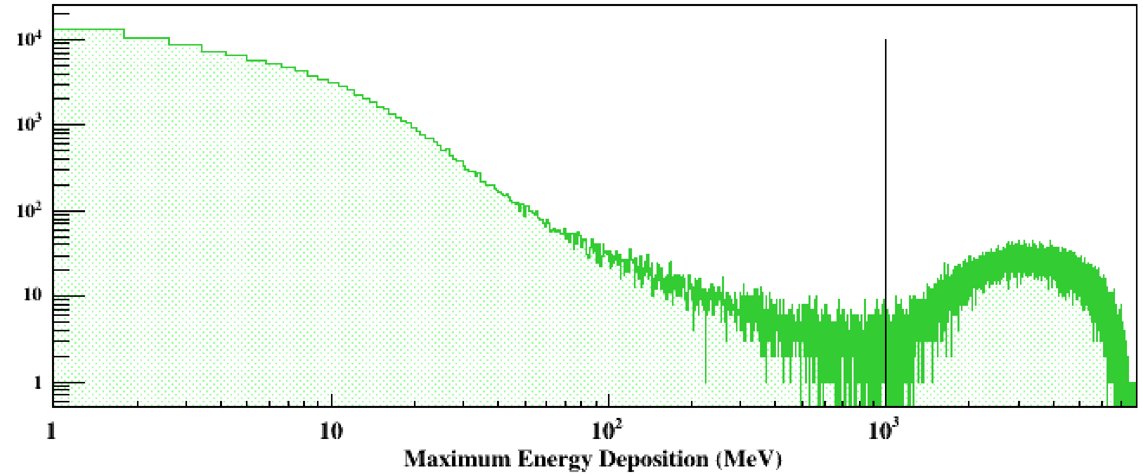


Geant4 Simulation : maximum energy distribution

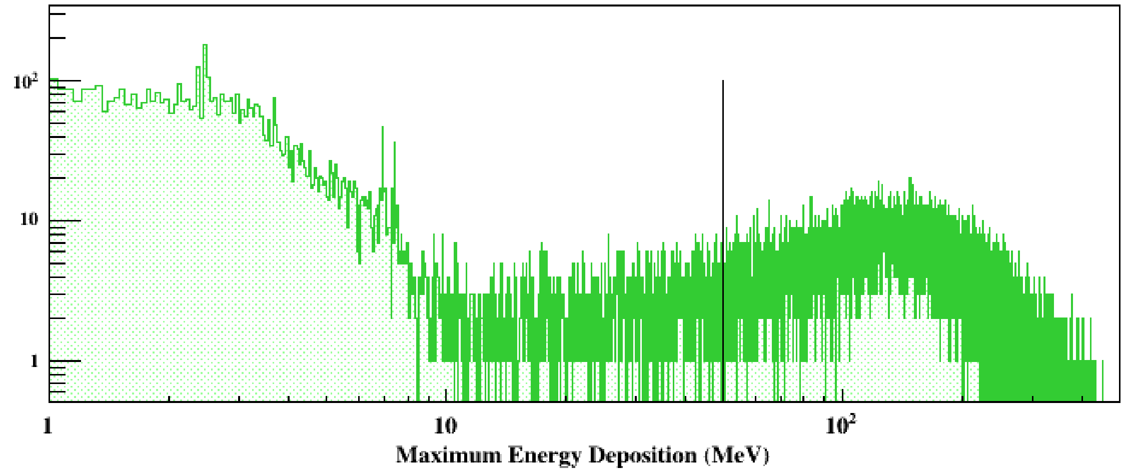
Electron



Positron

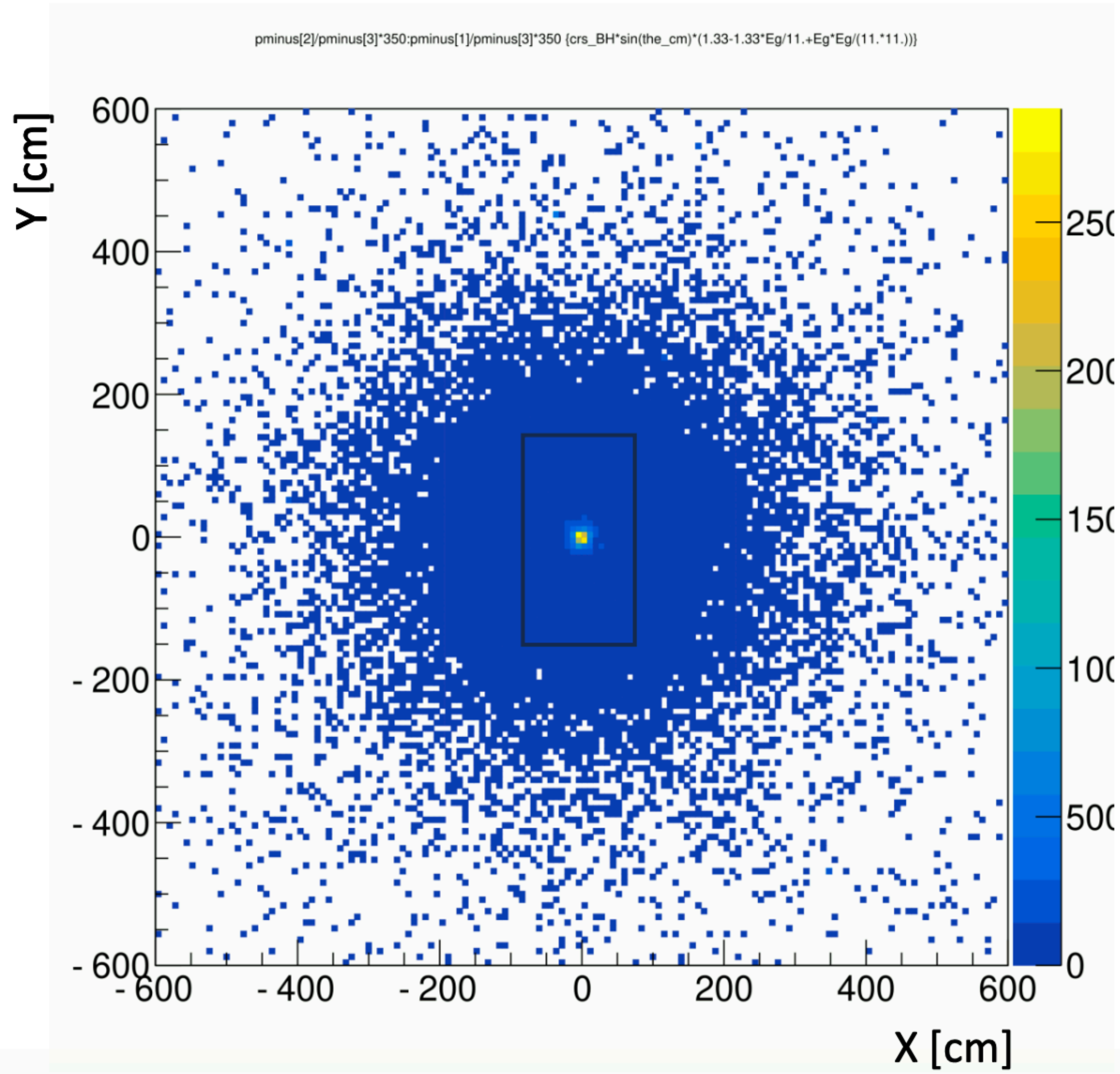


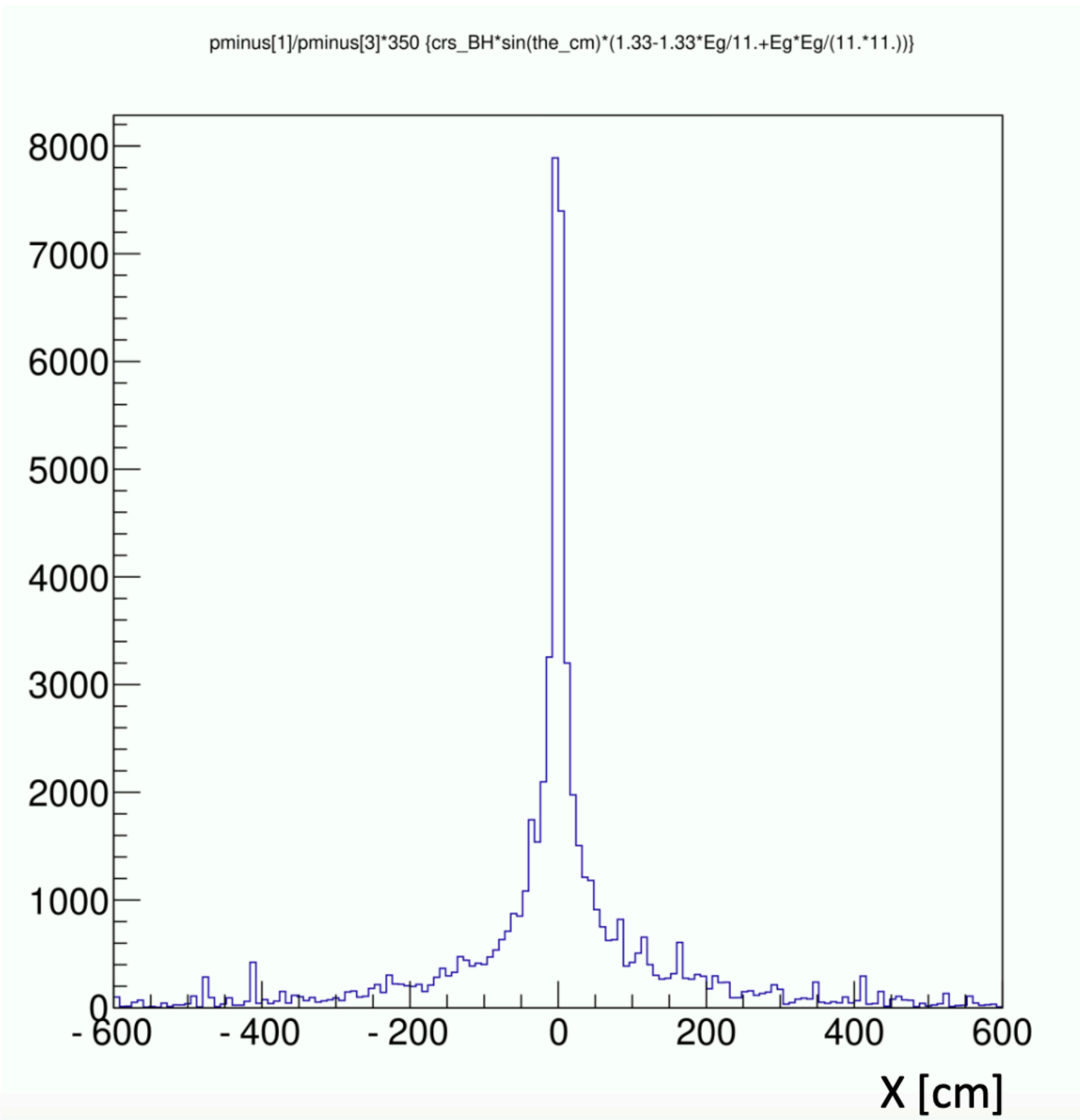
Proton



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

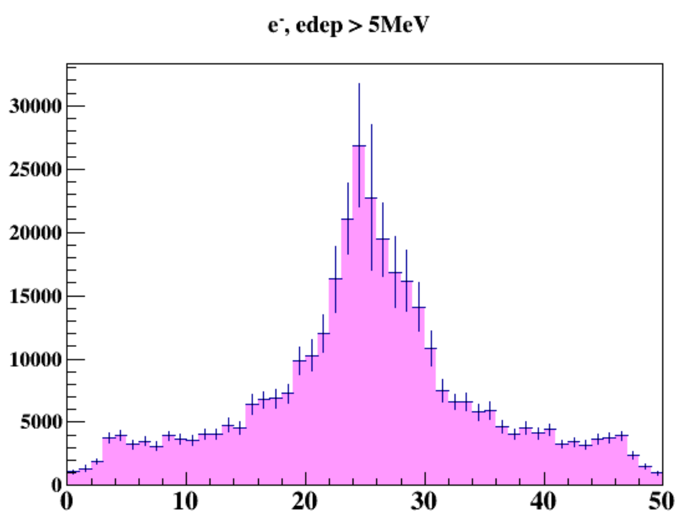




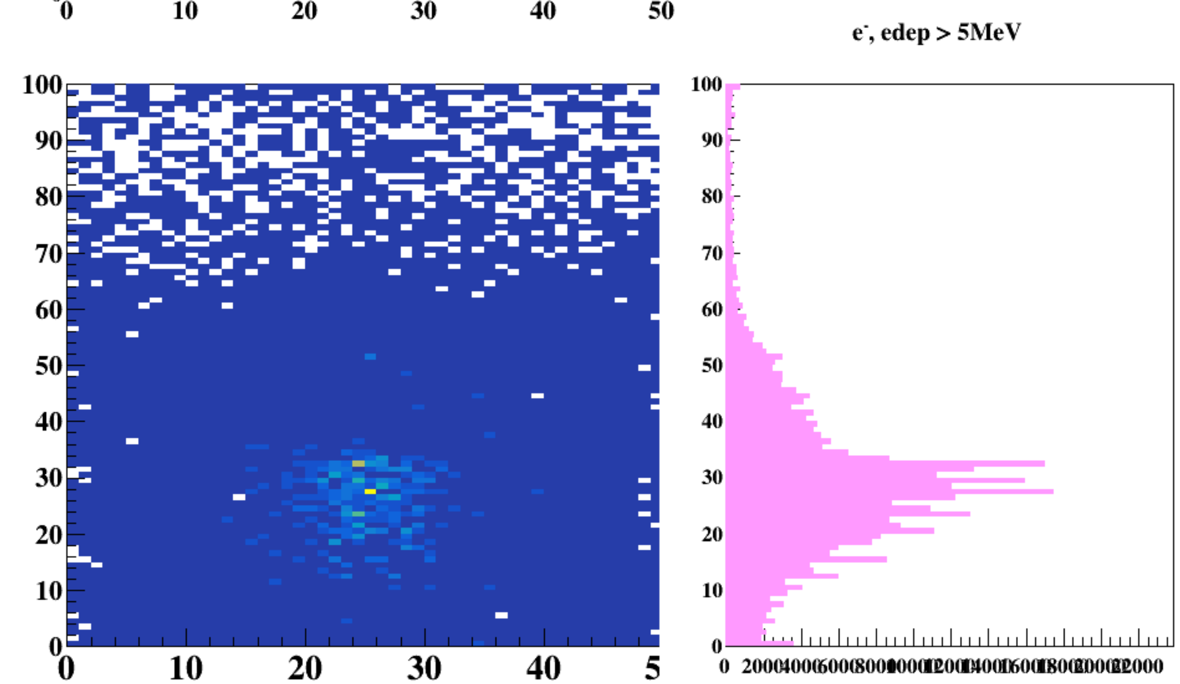
From : Vardan Tadevosyan

Geant4 Simulation : charge assignment to leptons

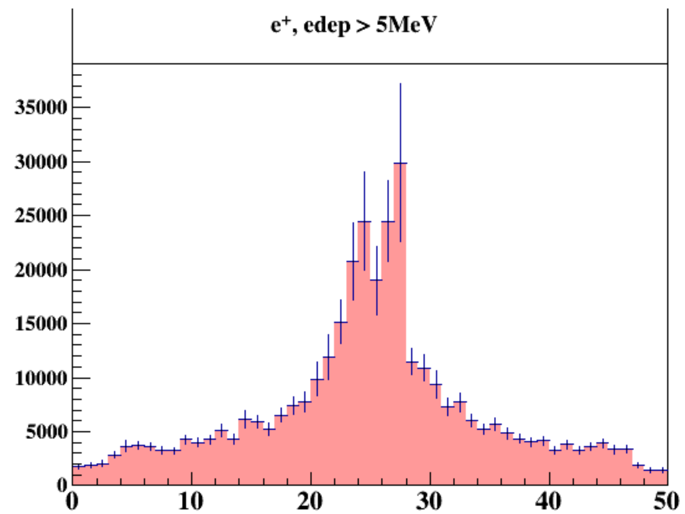
Projection of electron on calorimeter plane



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



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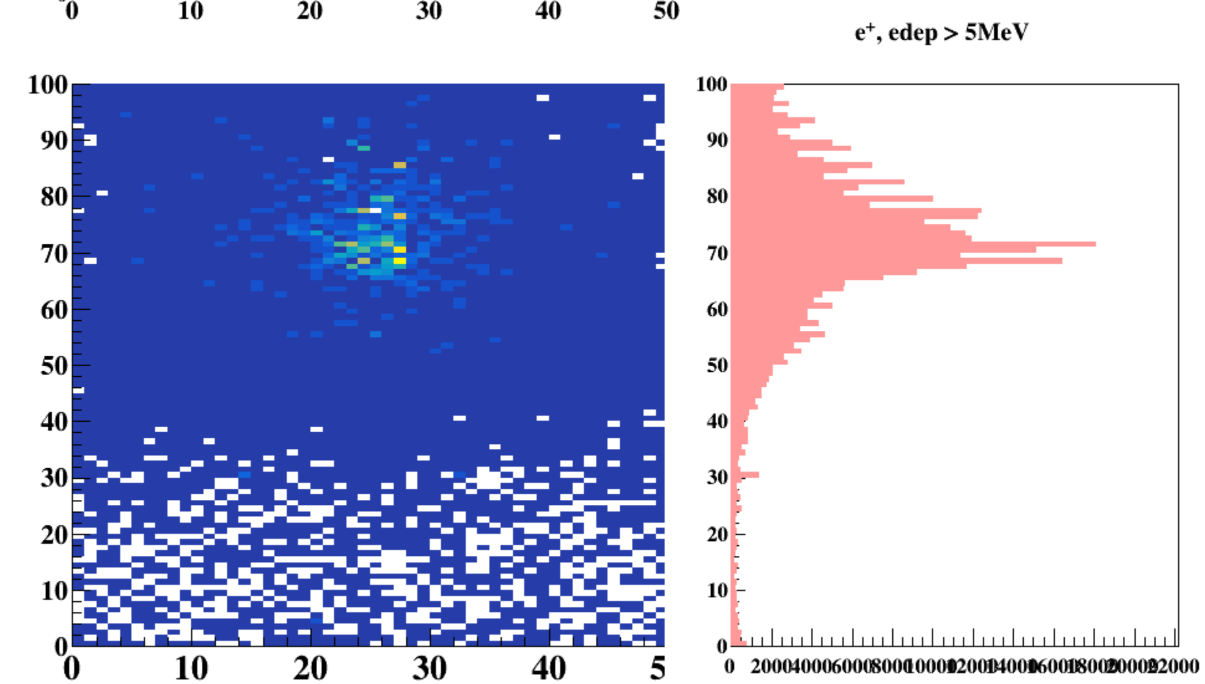
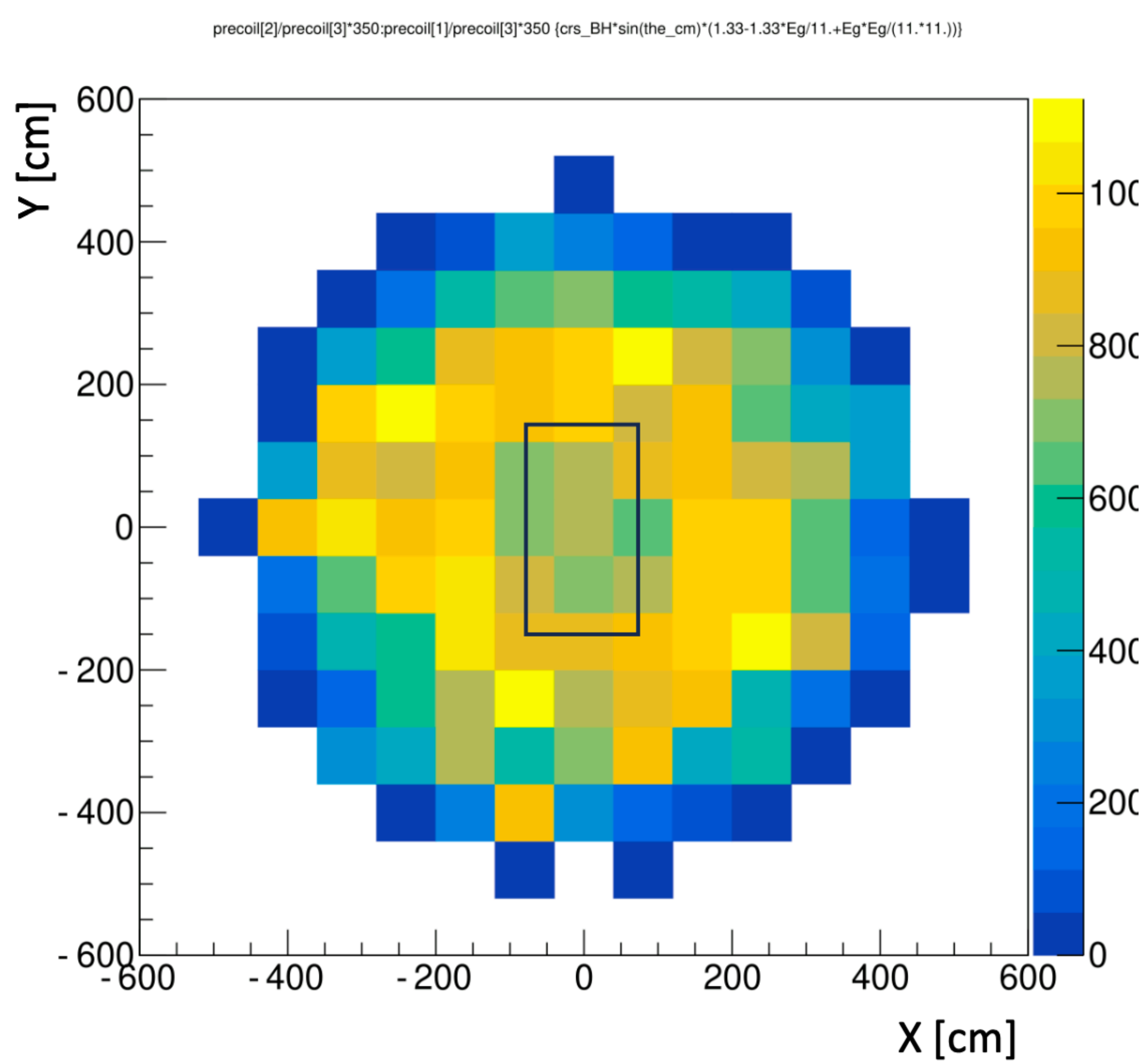
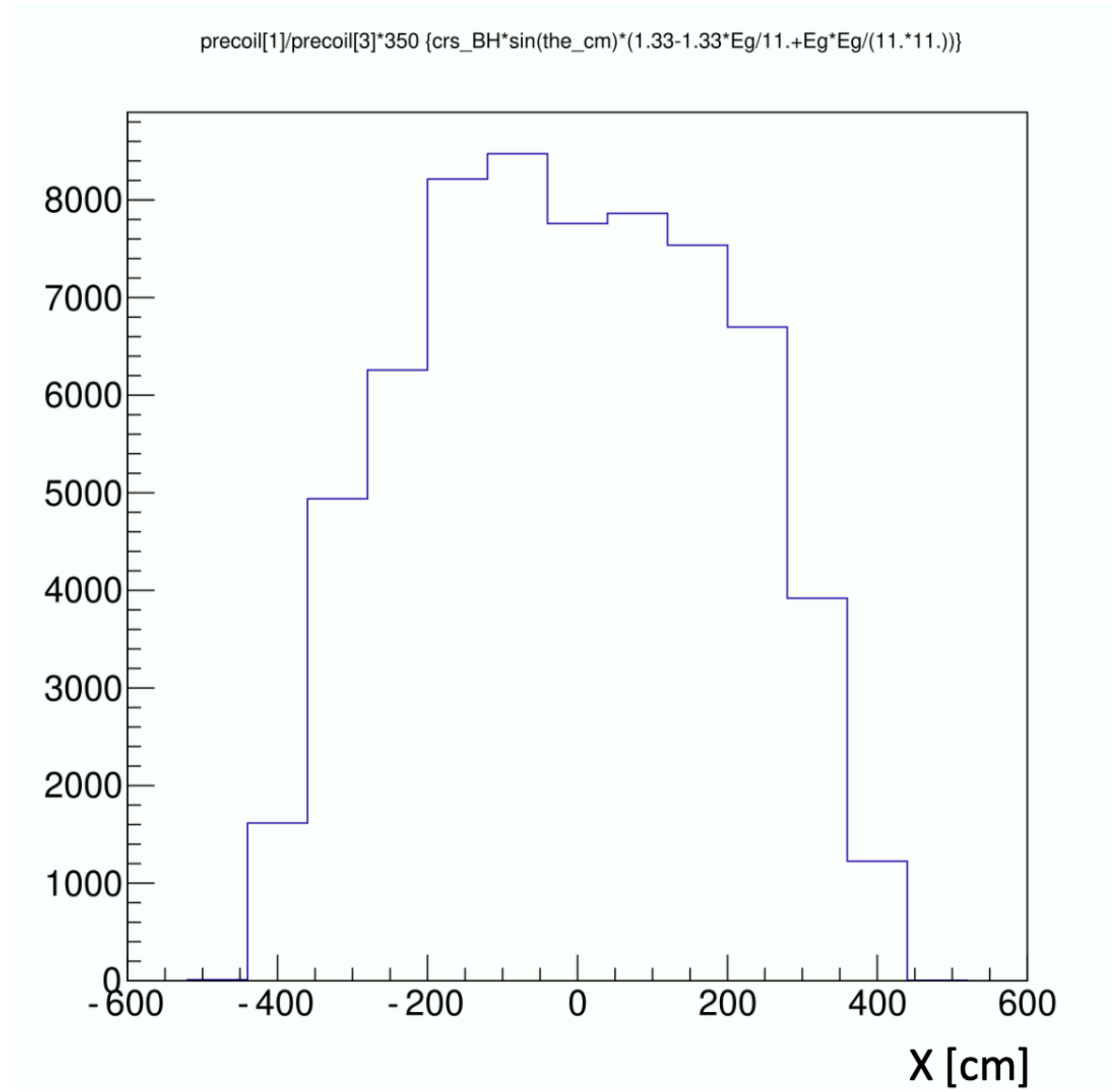


Geant4 Simulation : projection of protons w/o magnetic field

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

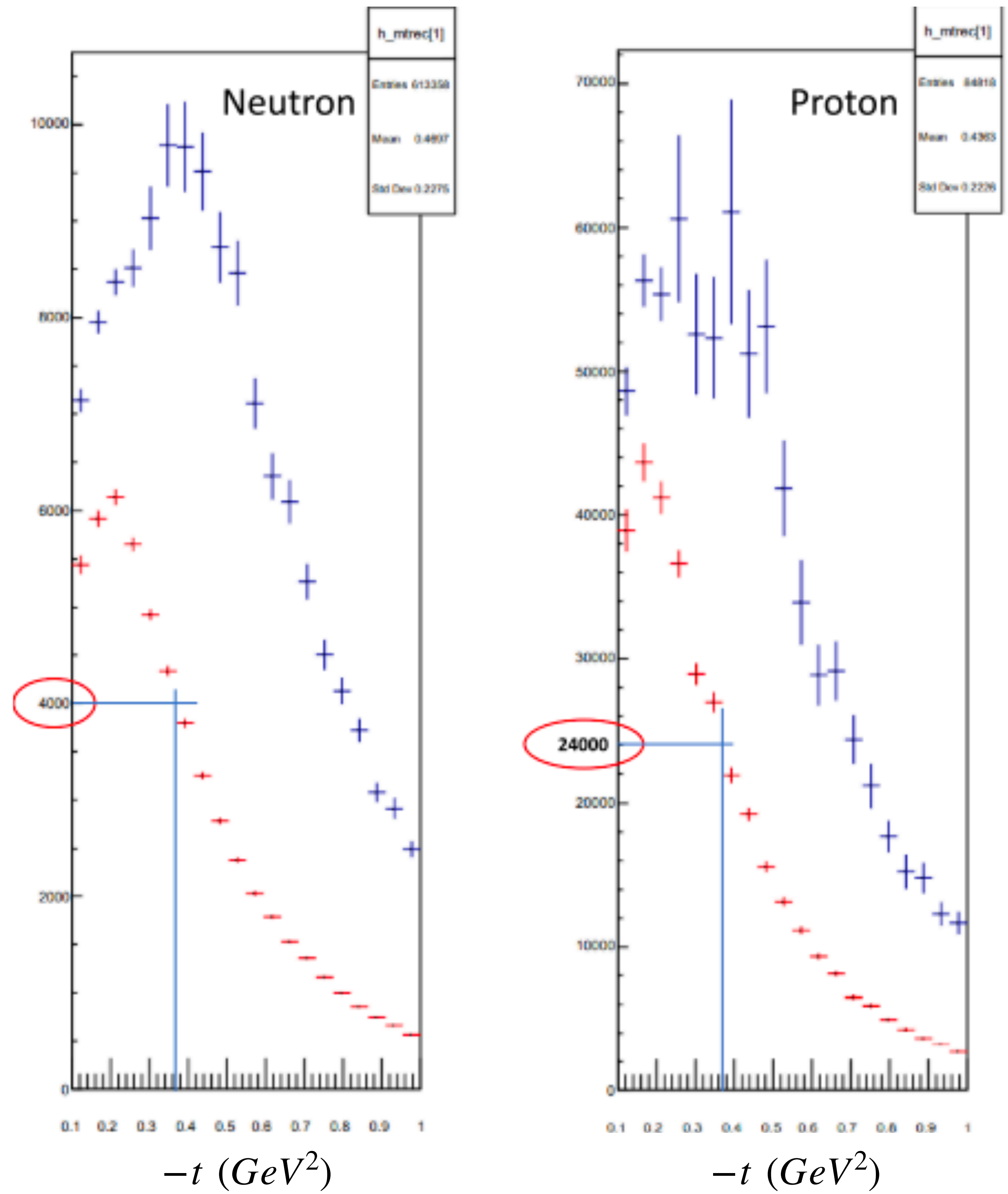




From : Vardan Tadevosyan

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 plotted against -t weighted by cross-section
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

Summary

1. DEEPGen simulator (written by M.Boer) is used to generated polarized / Unpolarized TCS events

2. Unpolarized TCS : Geant4 Simulation for the detector setup is ready

3. Unpolarized TCS : propose to measure both asymmetry and cross-sections

4. Unpolarized / polarized TCS : This measurement will be dedicated TCS measurement at Hall C

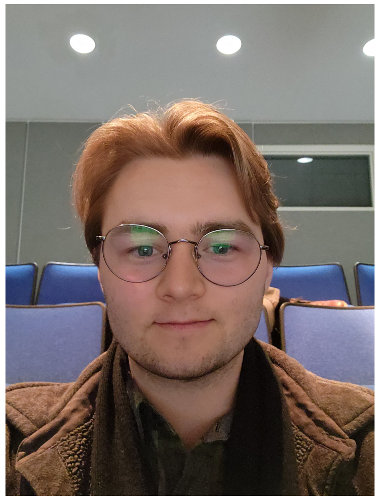
5. Unpolarized / polarized TCS : Also, can run sooner than SoLID unpolarized TCS proposed experiment

6. Unpolarized TCS : Higher statistics compared to SoLID, and with a real photon beam

7. Unpolarized TCS : Working on full background simulations for a new PAC proposal

8. In principle it is possible to measure both proton and neutron TCS

Polarized TCS : Full background studies and PID : most important



Next talk : Keagan Bell, undergrad at VT