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

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Accessing GPDs through exclusive reactions

Compton like reactions

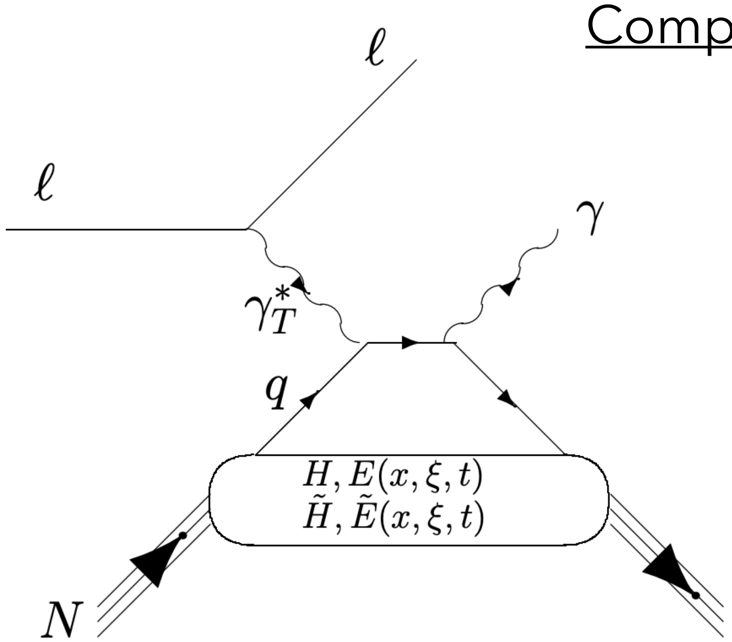


Fig : DVCS

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

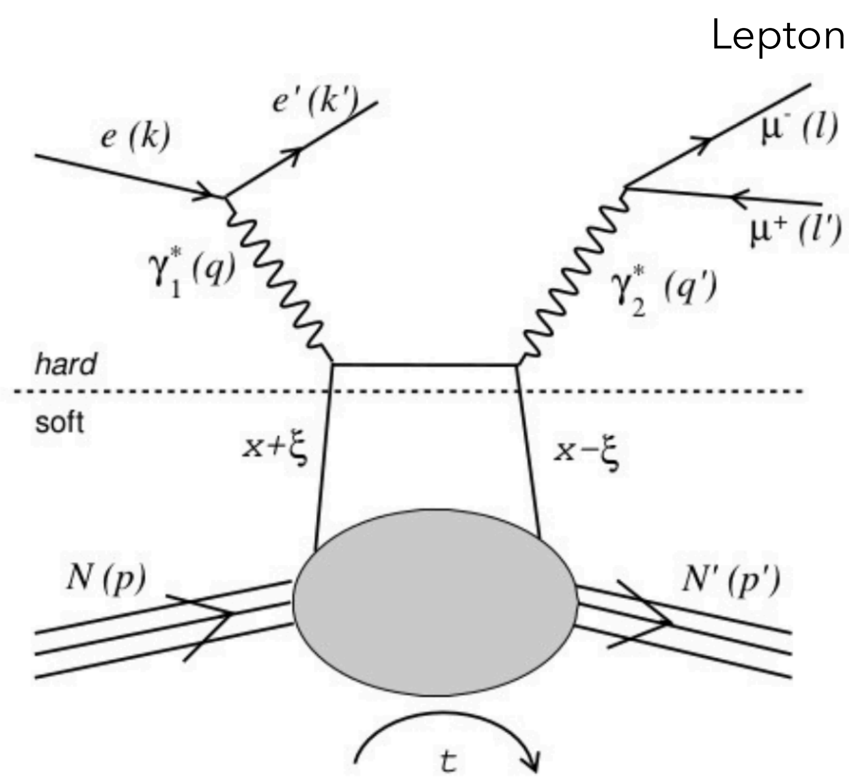


Fig : DDVCS

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

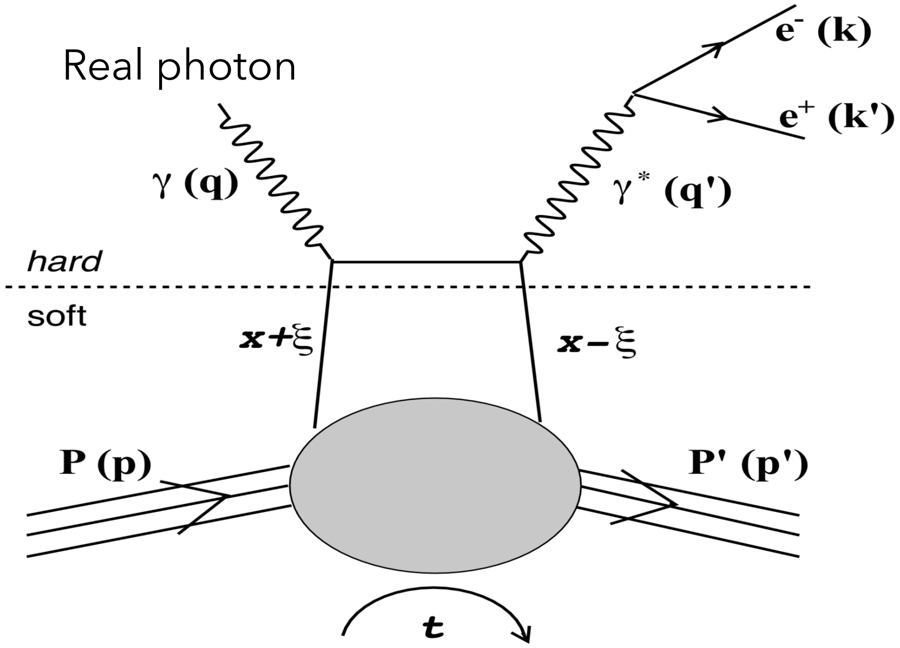


Fig : TCS

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

Meson production

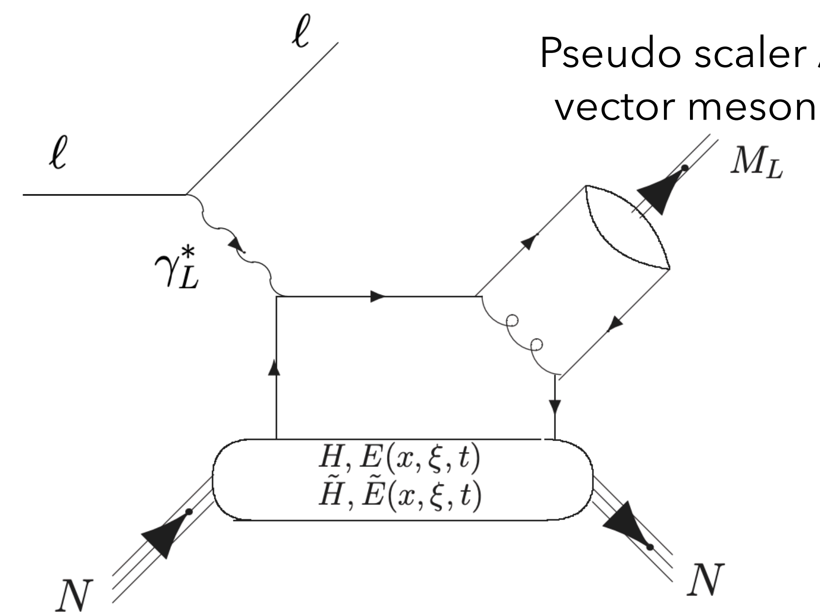


Fig : DVMP (quark Subprocess)

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

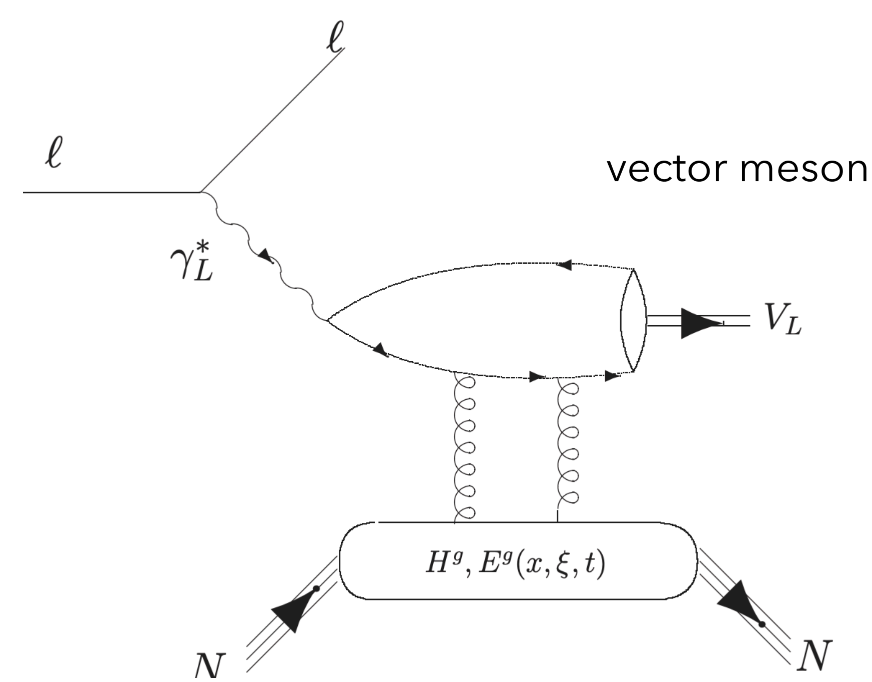


Fig : DVMP (gluon subprocess)

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

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

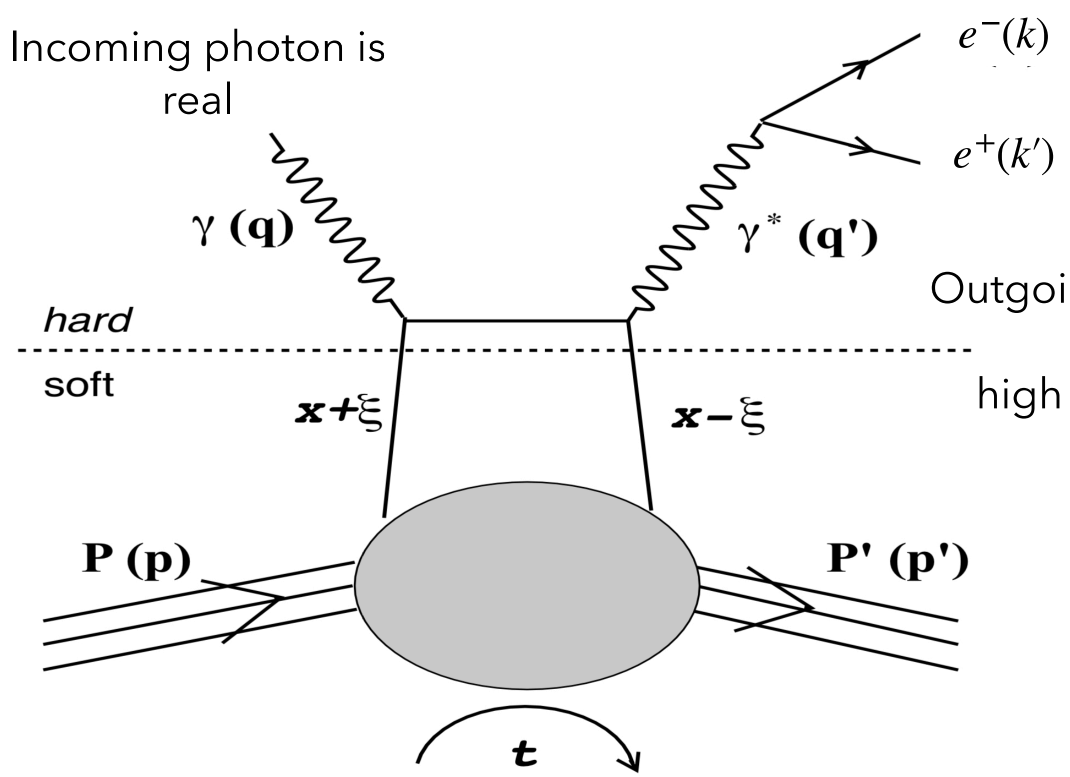


Fig : Time Like Compton Scattering

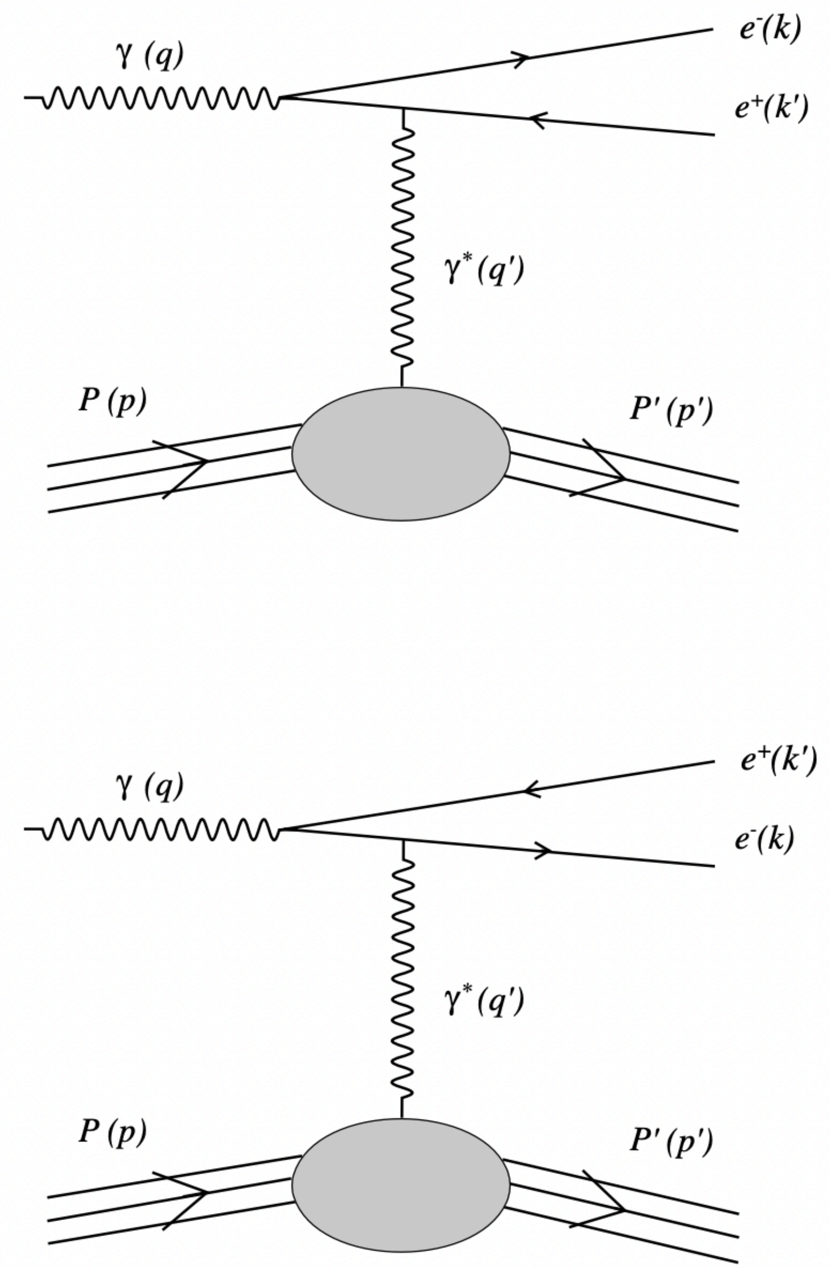
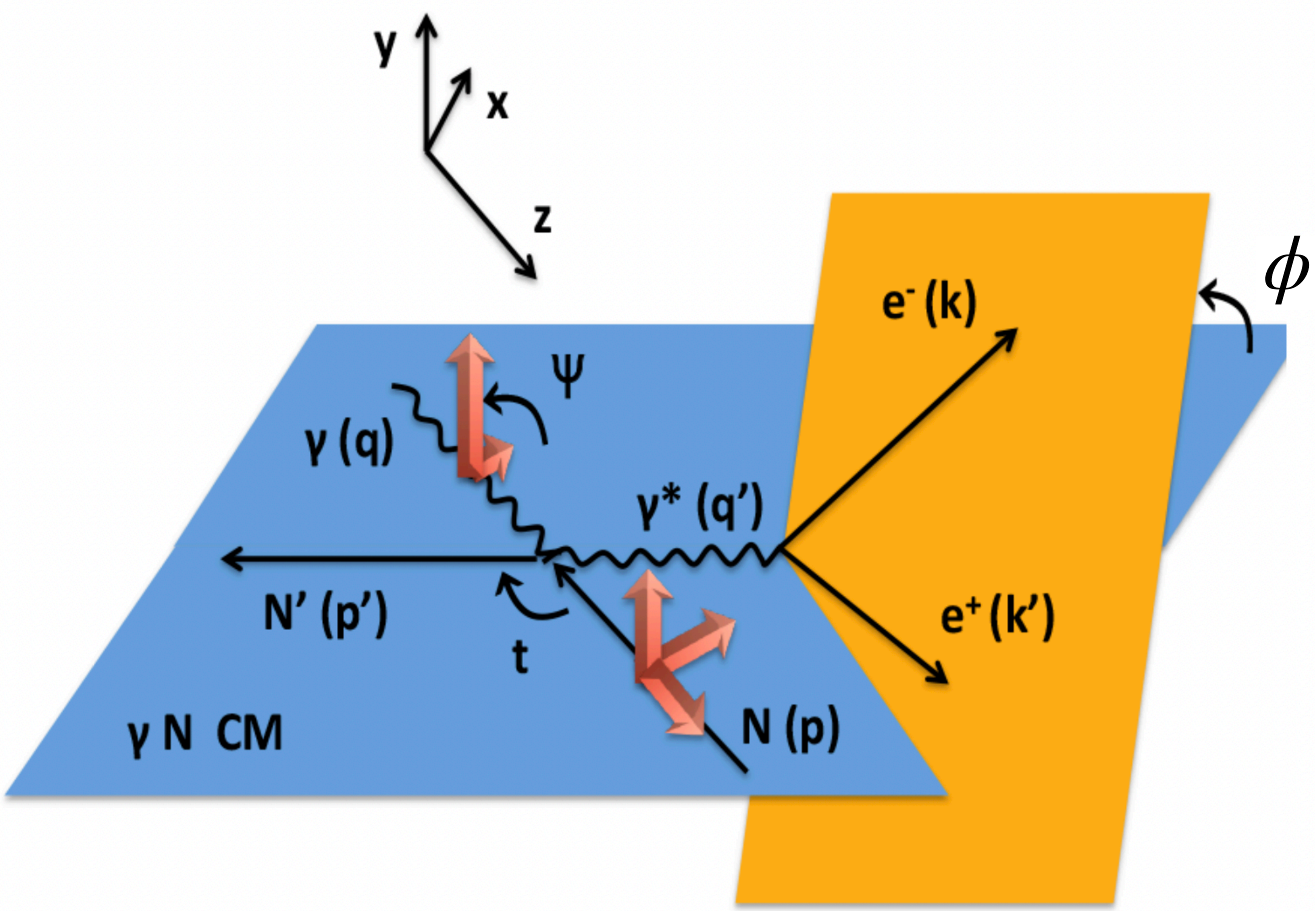


Fig : Bethe-Heitler diagrams

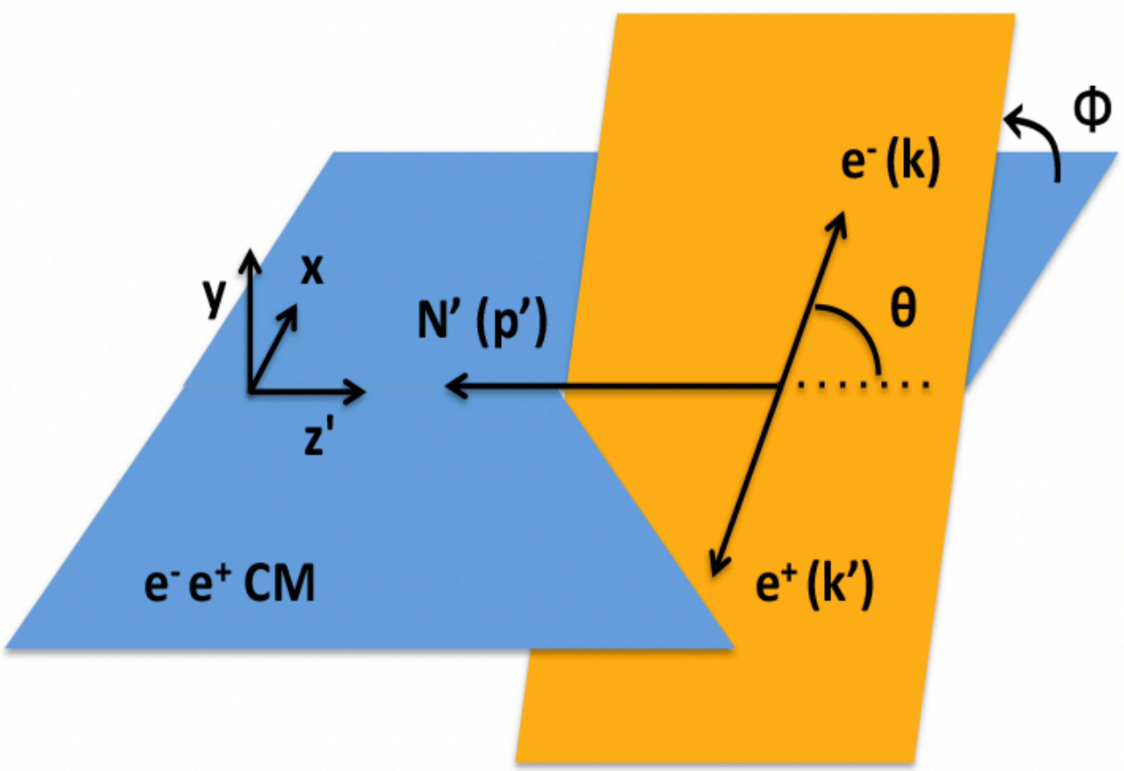
Source : M, Boer. et.al. Eur. Phys. J. A (2015) 51: 103

Timelike Compton Scattering

γN C.M. Frame



γ^* C.M. Frame



ψ : Angle between reaction plane and γ spin

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

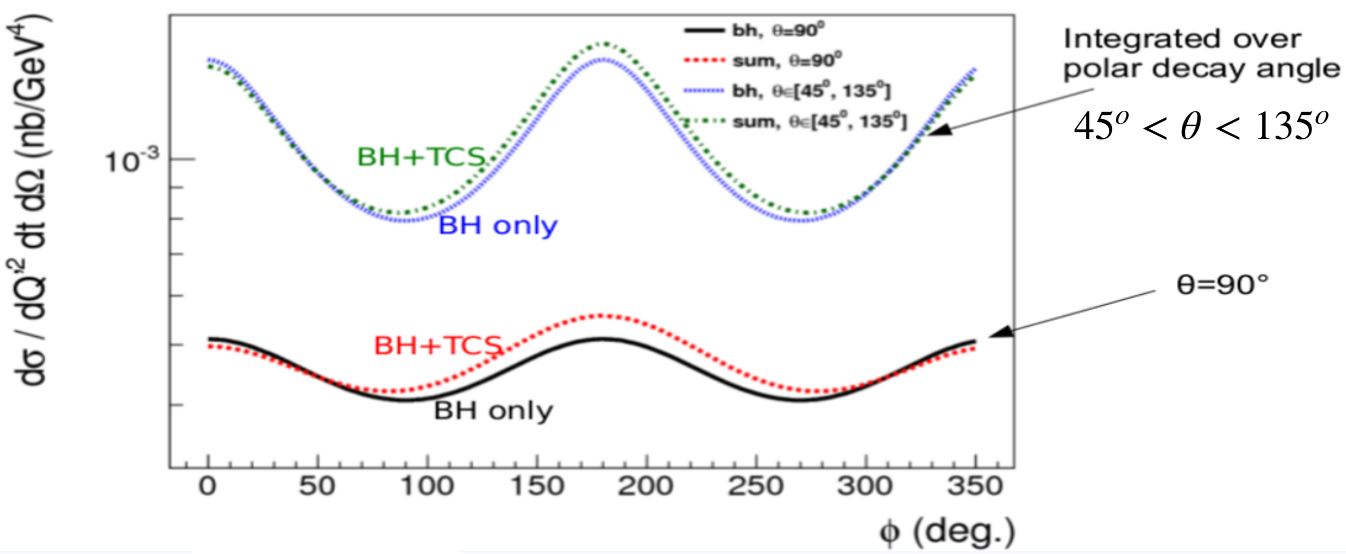
θ : Angle between γ^* and e^- (visible when boost to γ^* CM frame)

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

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

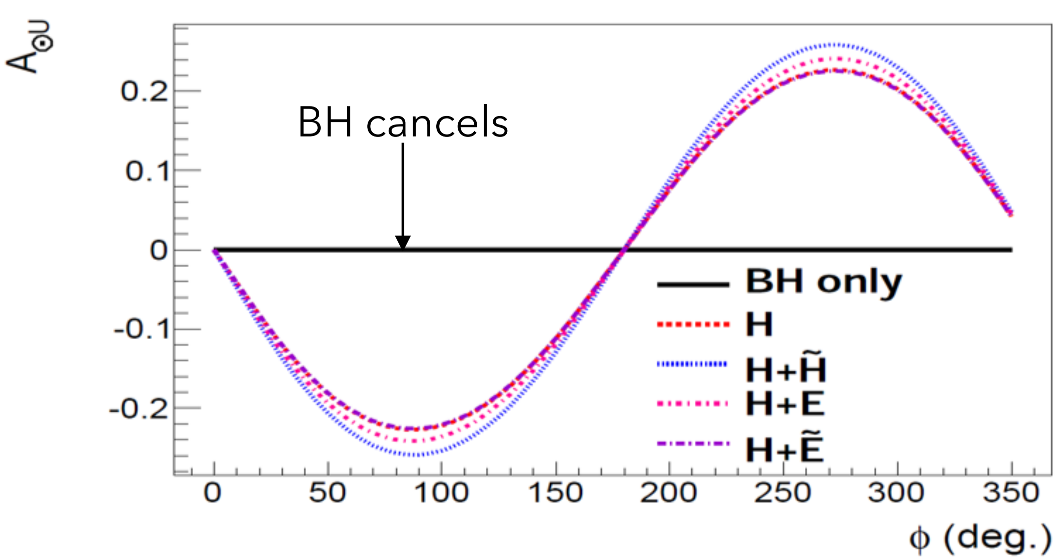
TCS observables and GPD sensitivity (Calculations)

Unpolarized Cross sections

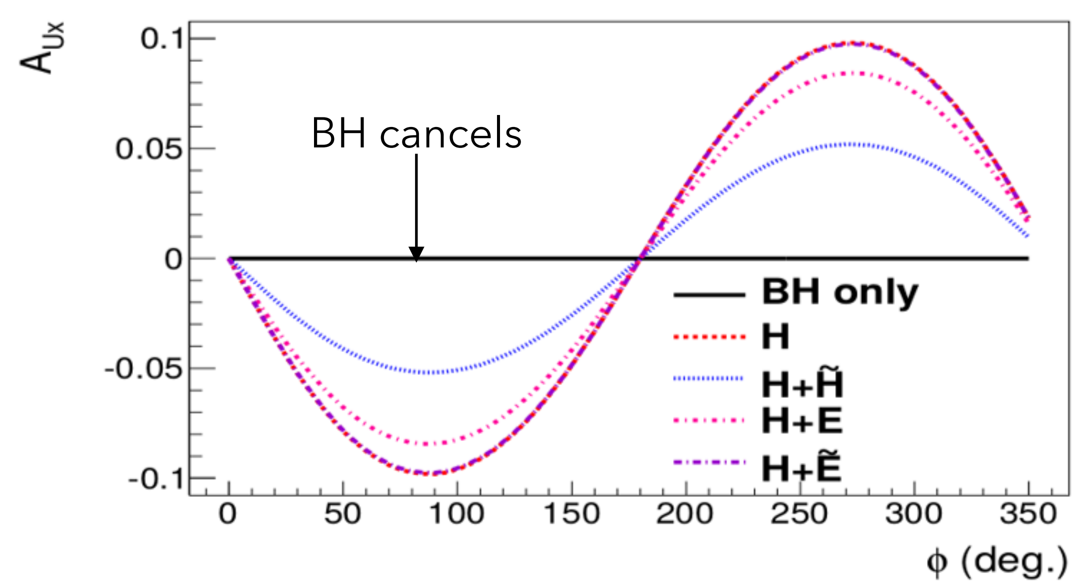


1. Unpolarized σ:
    1. sensitivity to both Im + Re part of amplitude
    2. difficult to measure as BH (only Real) dominant
2. Beam or target polarized Asymmetry :
    1. BH cancel, reflect interference (Im)
    2. easier to measure, quite large
    3. access Im(H), Im(H̃), Im(E)
3. Double spin asymmetry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

Circularly polarized beam asymmetry



Transversely polarized target asymmetry



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

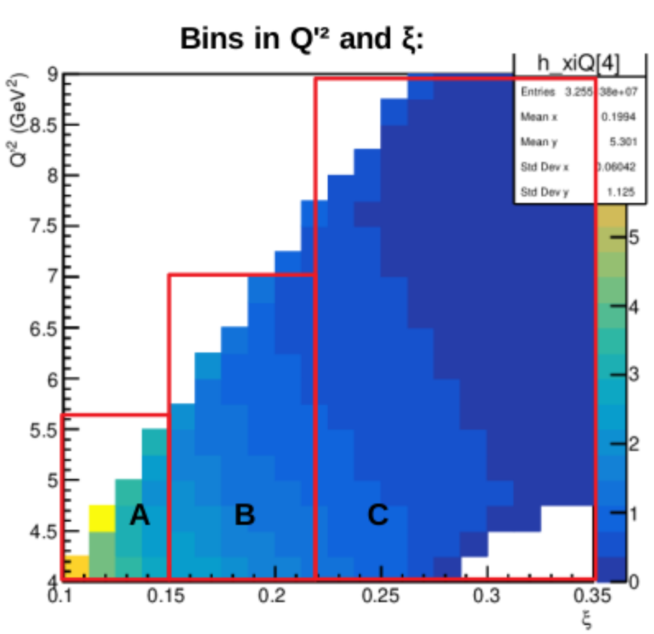
$$A_{UT} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \qquad \ldots (1)$$

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

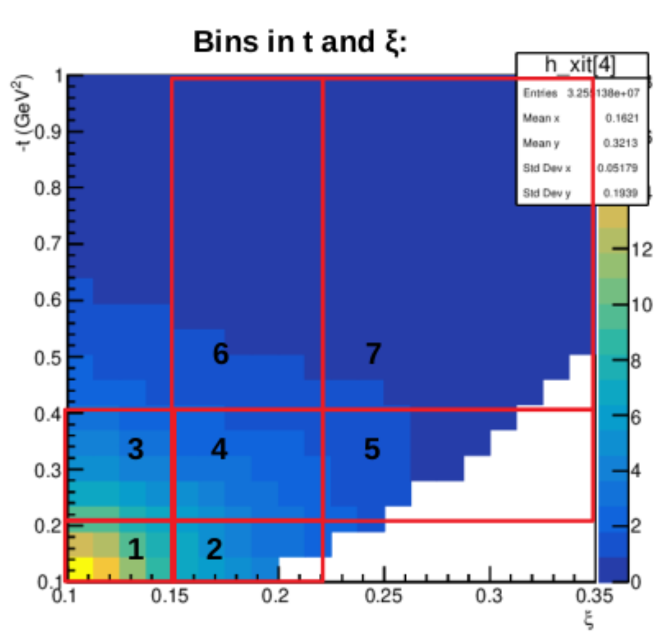
Polarized TCS: kinematic coverage & CFF accuracies

Kinematic coverage

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



A: $.10 < \xi < .15$; $4 < Q'^2 < 5.5$ GeV^2
B: $.15 < \xi < .22$; $4 < Q'^2 < 7$ GeV^2
C: $.22 < \xi < .35$; $4 < Q'^2 < 9$ GeV^2



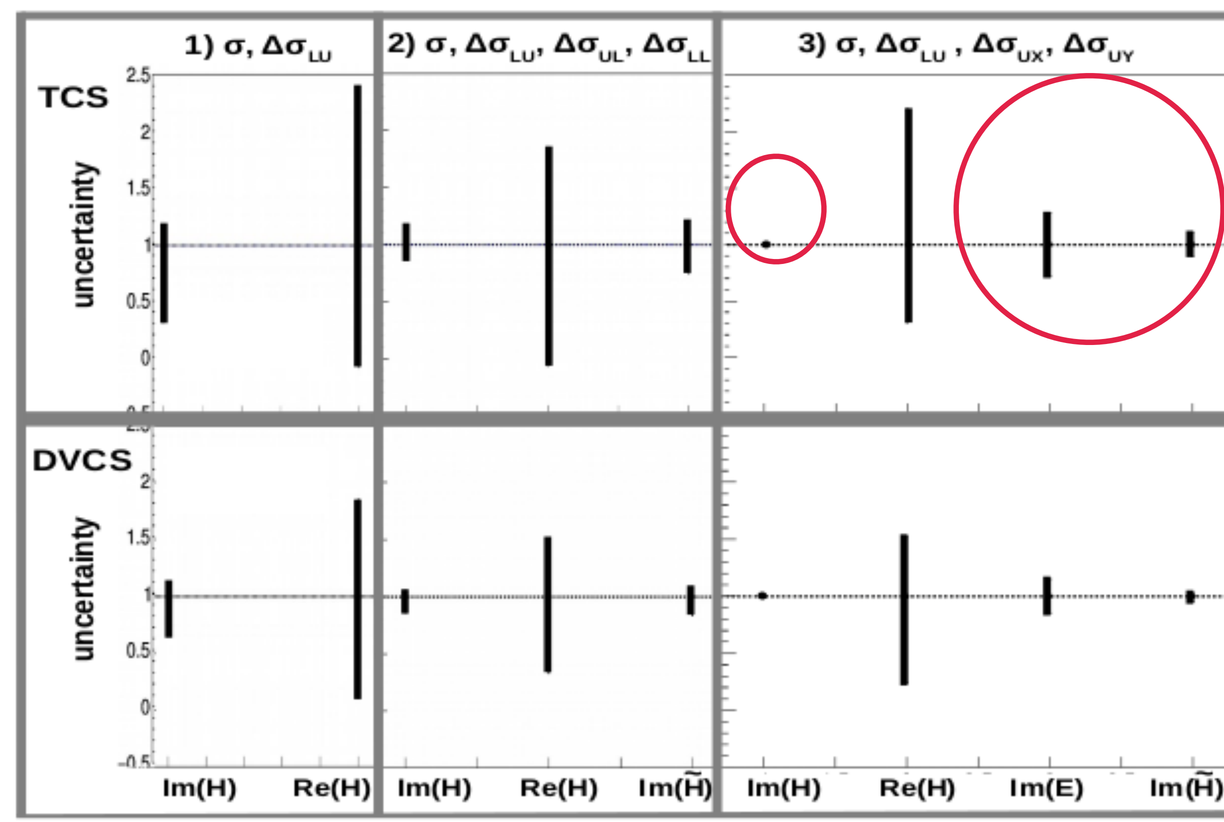
1, 2: $.1 < -t < .2$ GeV^2
3, 4, 5: $.2 < -t < .35$ GeV^2
6, 7: $.35 < -t < .7$ GeV^2

Kinematic region out of pion resonance production

Example estimates of accuracies on the model extraction of CFFs.

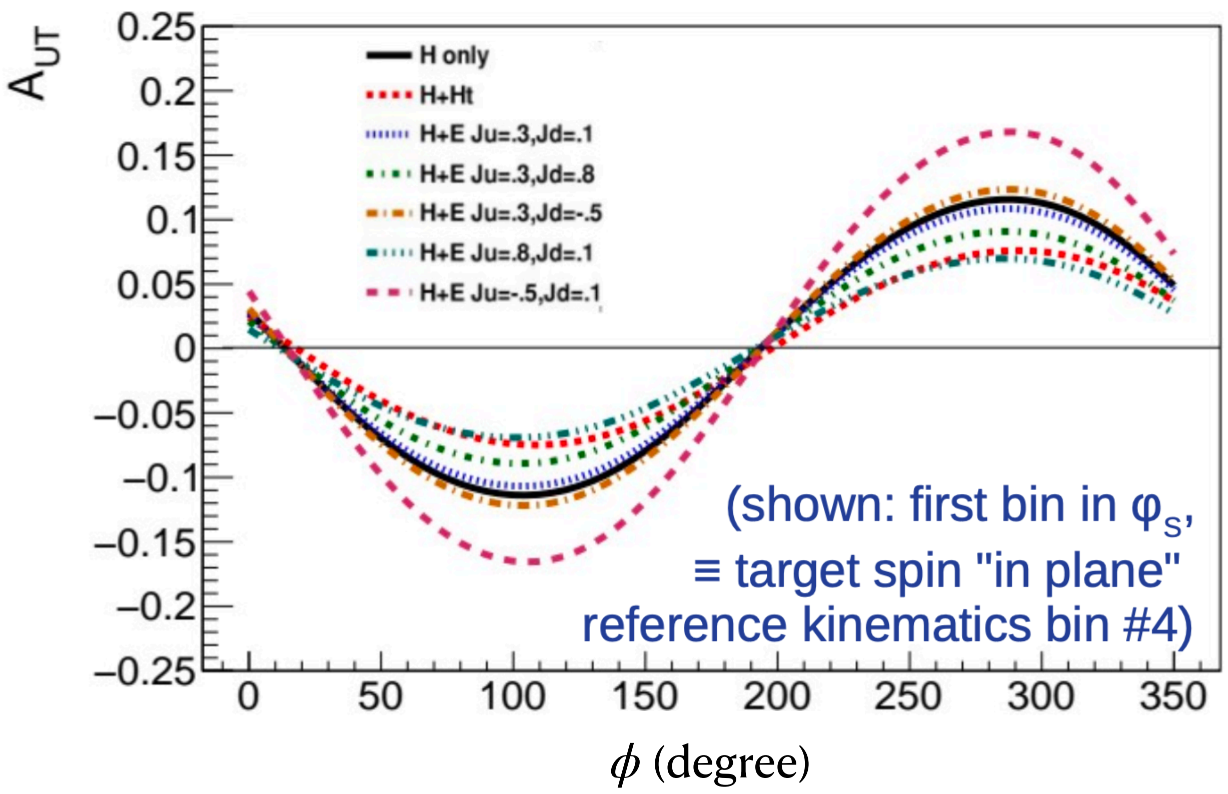
TCS with trans. pol. Target:

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

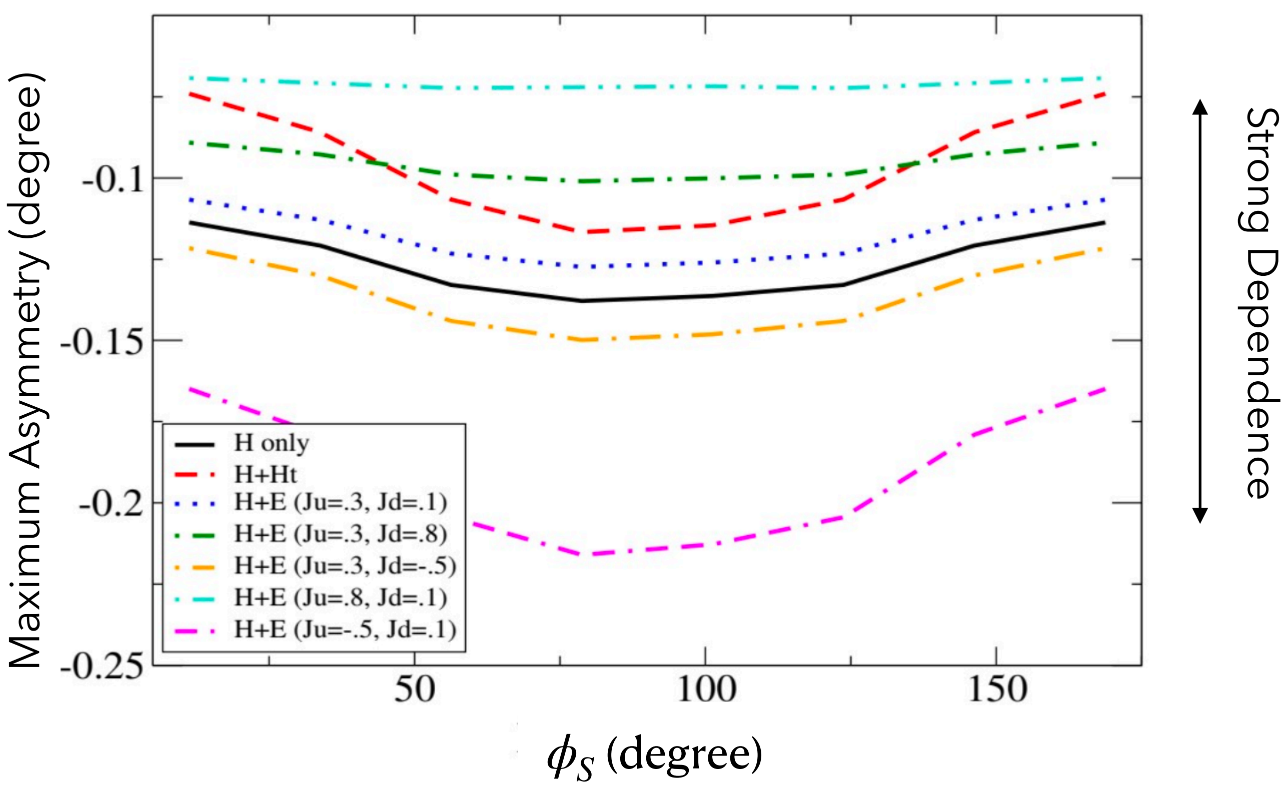


Polarized TCS: projected asymmetry

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

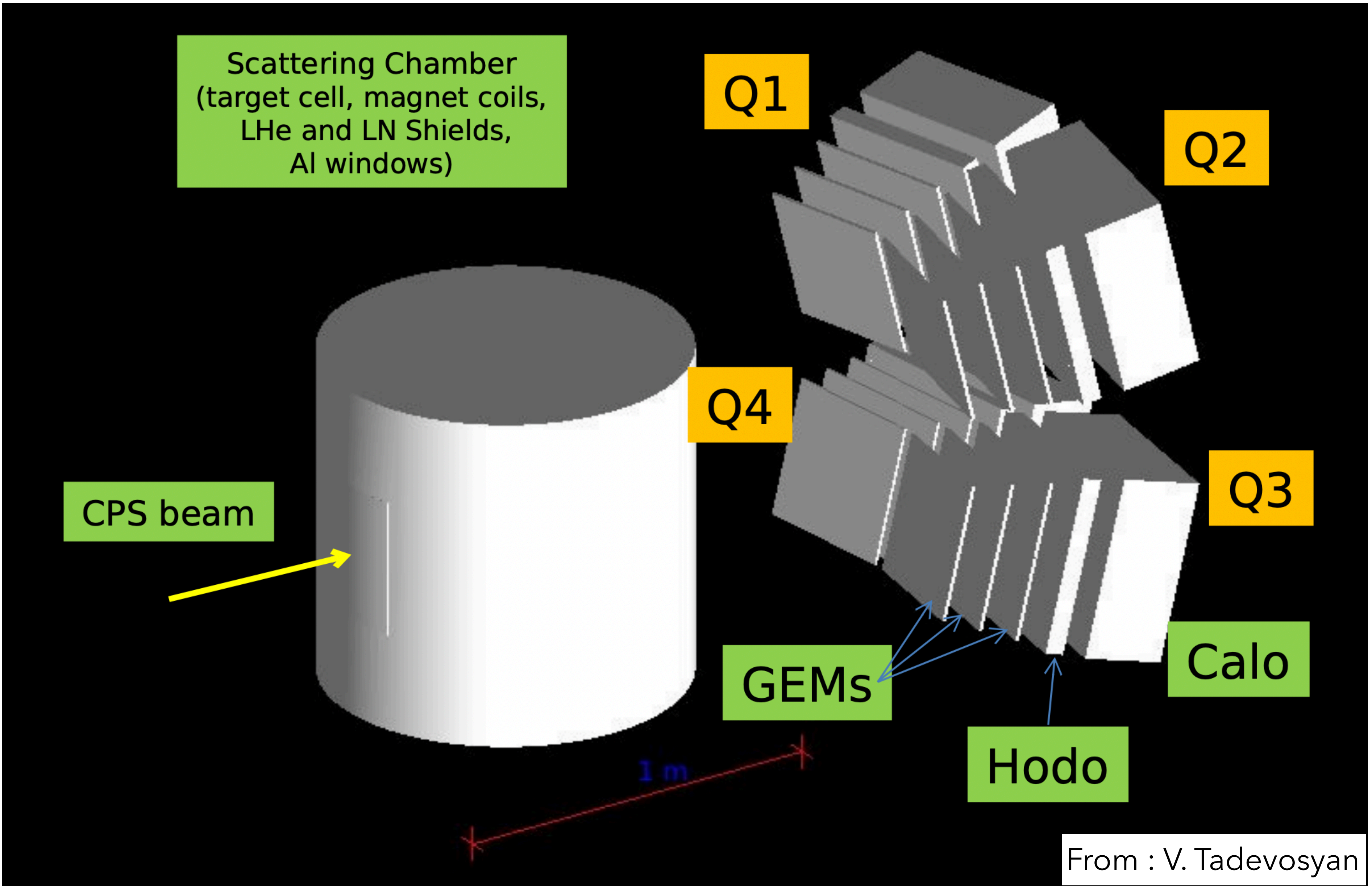


Fig : Geant4 simulation of detector setup at Hall C for proposed polarized TCS experiment

1. High intensity photon source 1.5 x 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 10^5 pb-1

Compact photon source

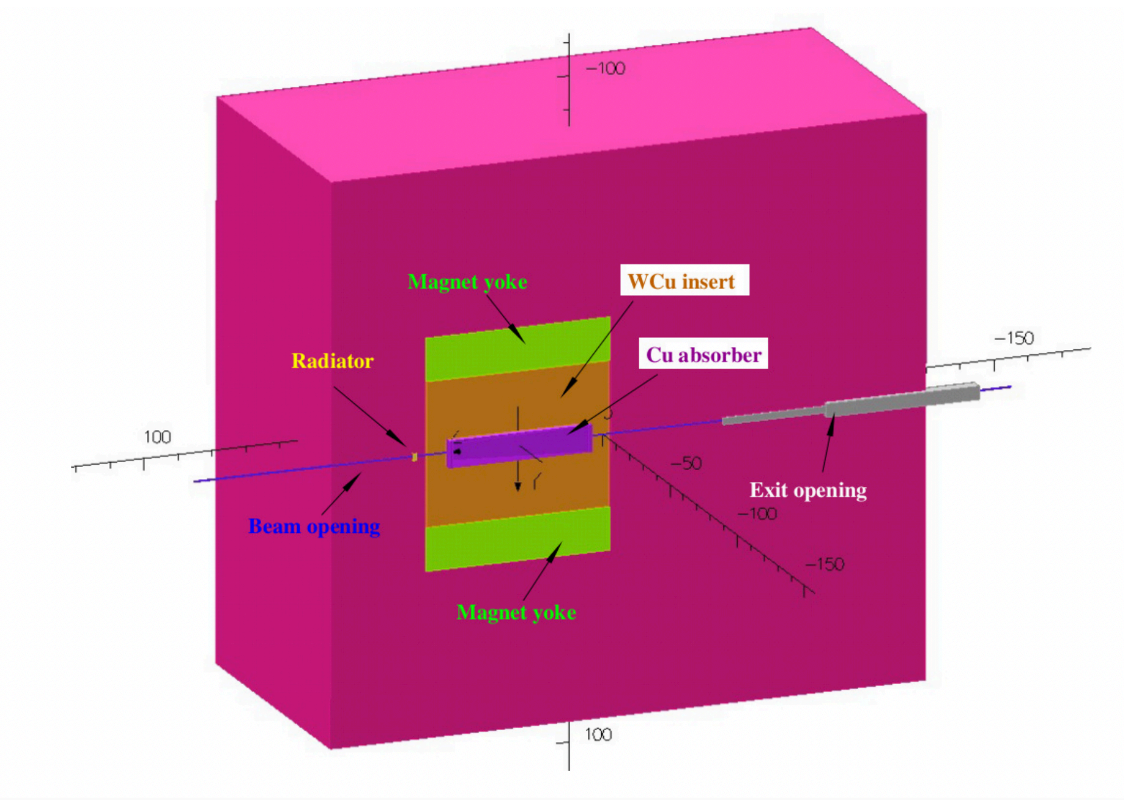
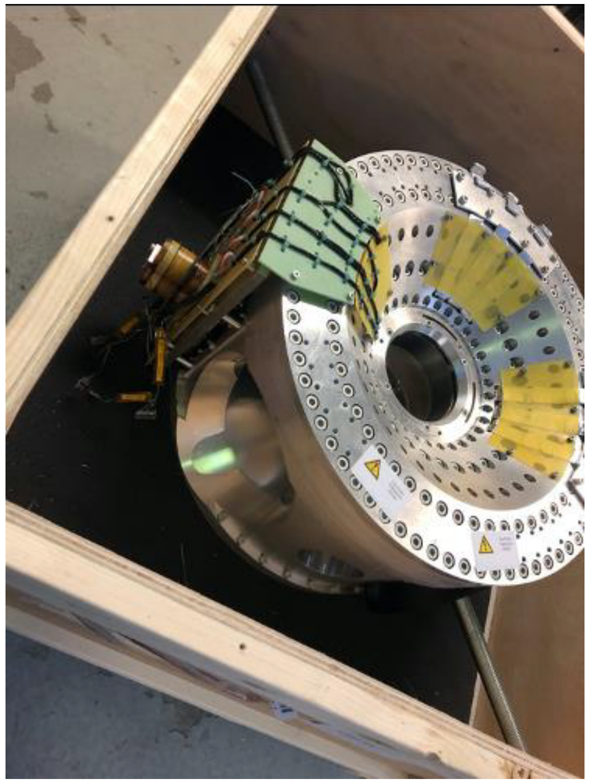


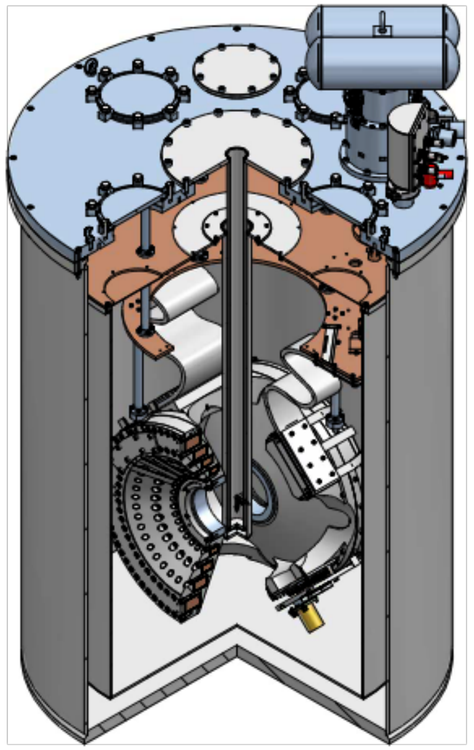
Fig : The CPS Cut off view

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





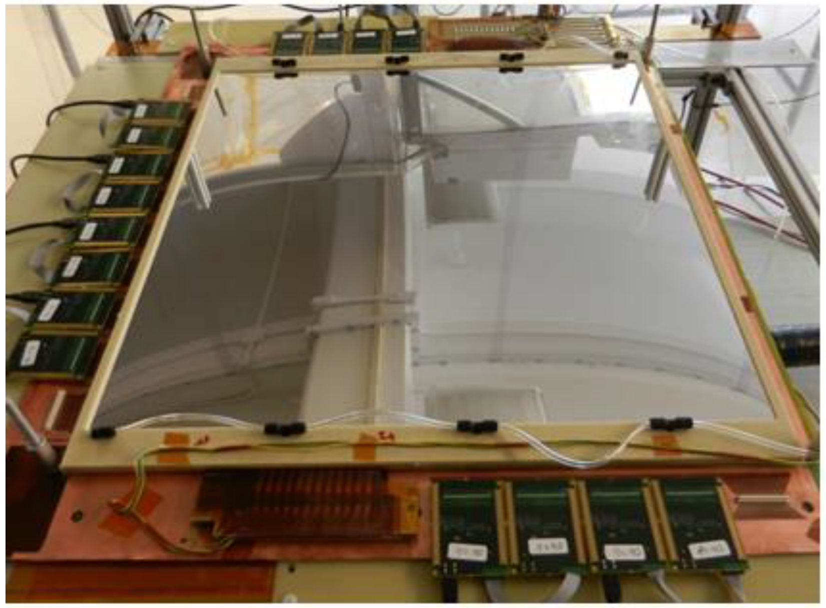
1. Target material: Liquid ammonia ($^{15}NH_3$), in LHe at 1°K.
2. Packing fraction 0.6.
3. Magnetic field generated by superconducting Helmhotz coils.
4. DNP polarization by 140 GHz, 20 W RF field.
5. Polarization monitored via NMR.
6. Depolarization mitigated by combined rotation (~1 Hz) around horizontal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

GEM Tracker , Hodoscope & Calorimeter

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



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

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 $2.5\%/\sqrt{E} + 1\%$
- 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)

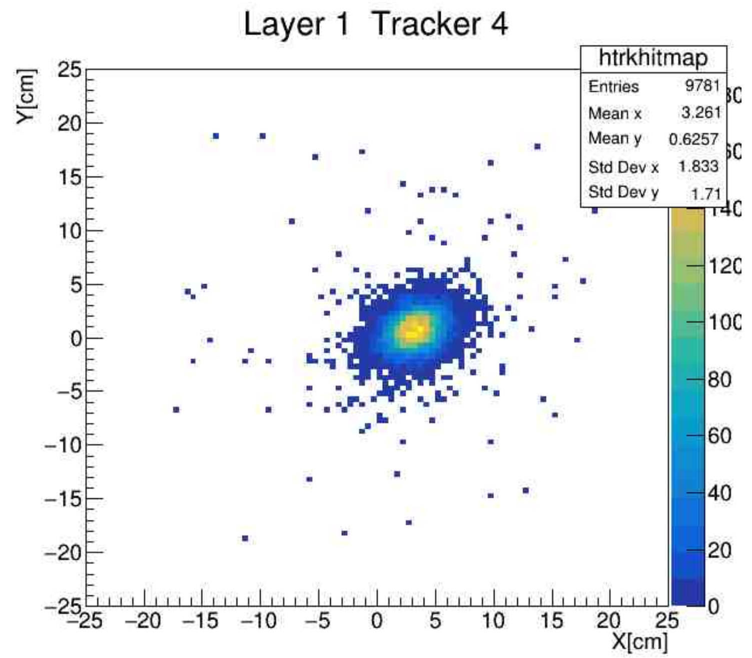
Polarized TCS : Recoil proton ID

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

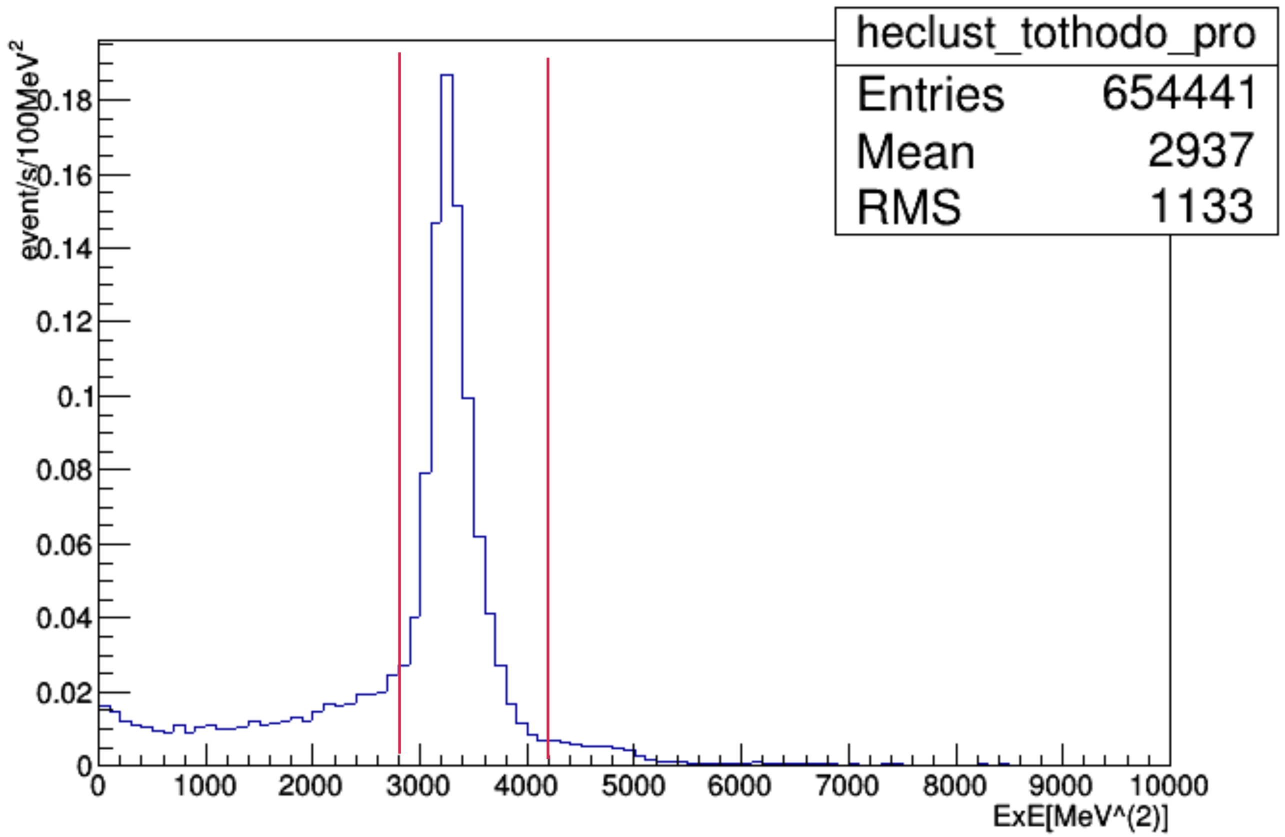
Cuts to select good protons :

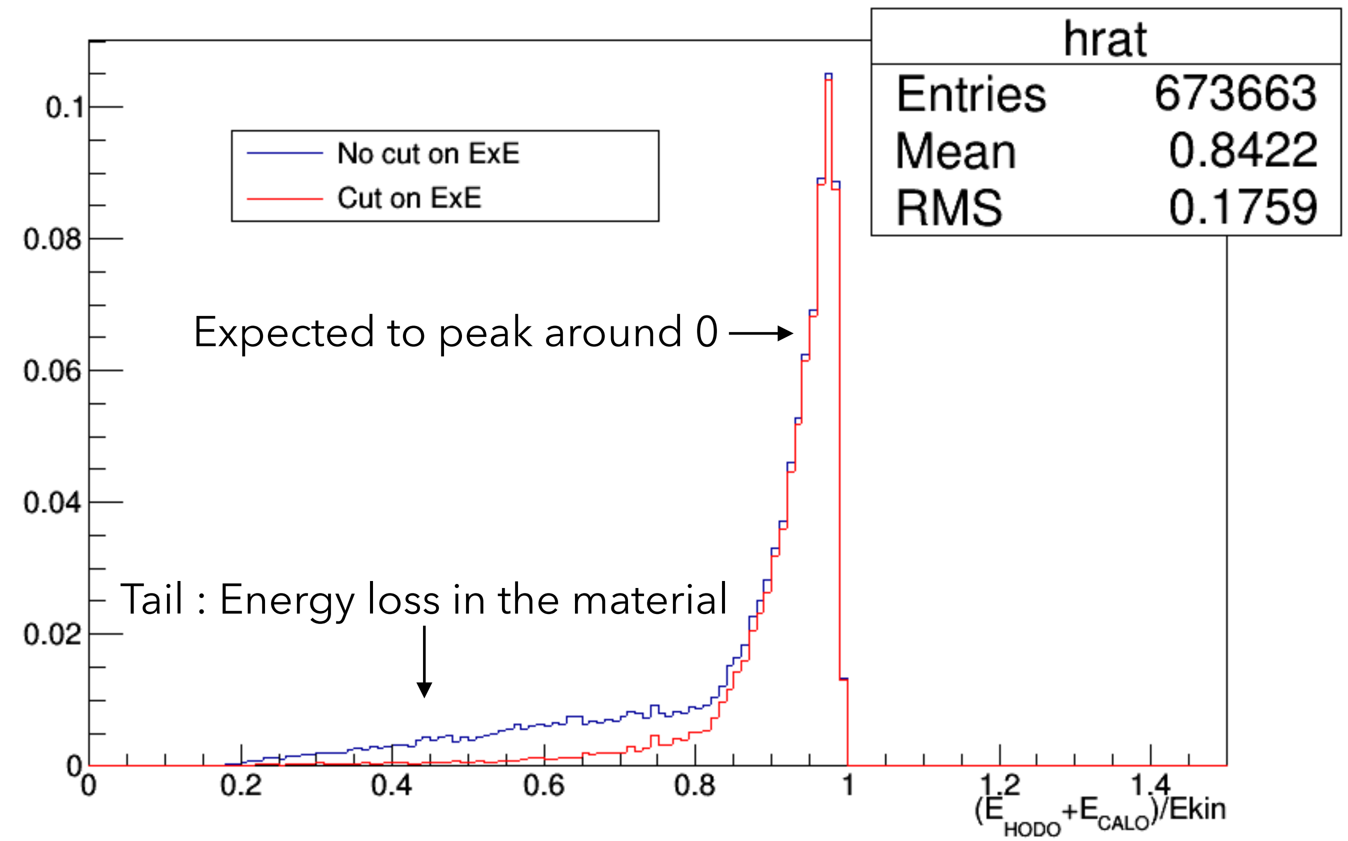
1. $E_{HODO} > 15$ MeV
2. 90 MeV $< E_{HODO} + E_{CALO} <$ 450 MeV
3. 2800 $MeV^2 <$ E.E $<$ 4200 MeV^2

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



GEM hit patter from 400 MeV/C protons





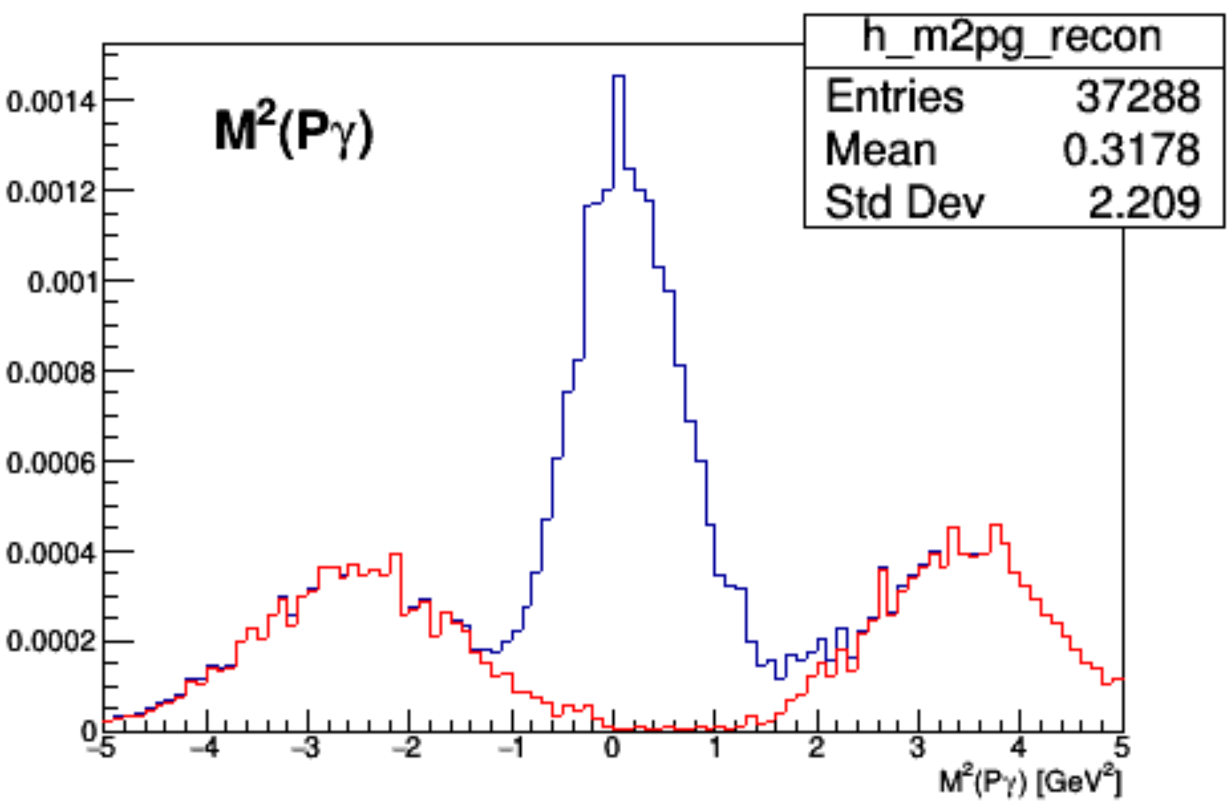
From : Vardan Tadevosyan

Polarized TCS : Lepton charge assignment

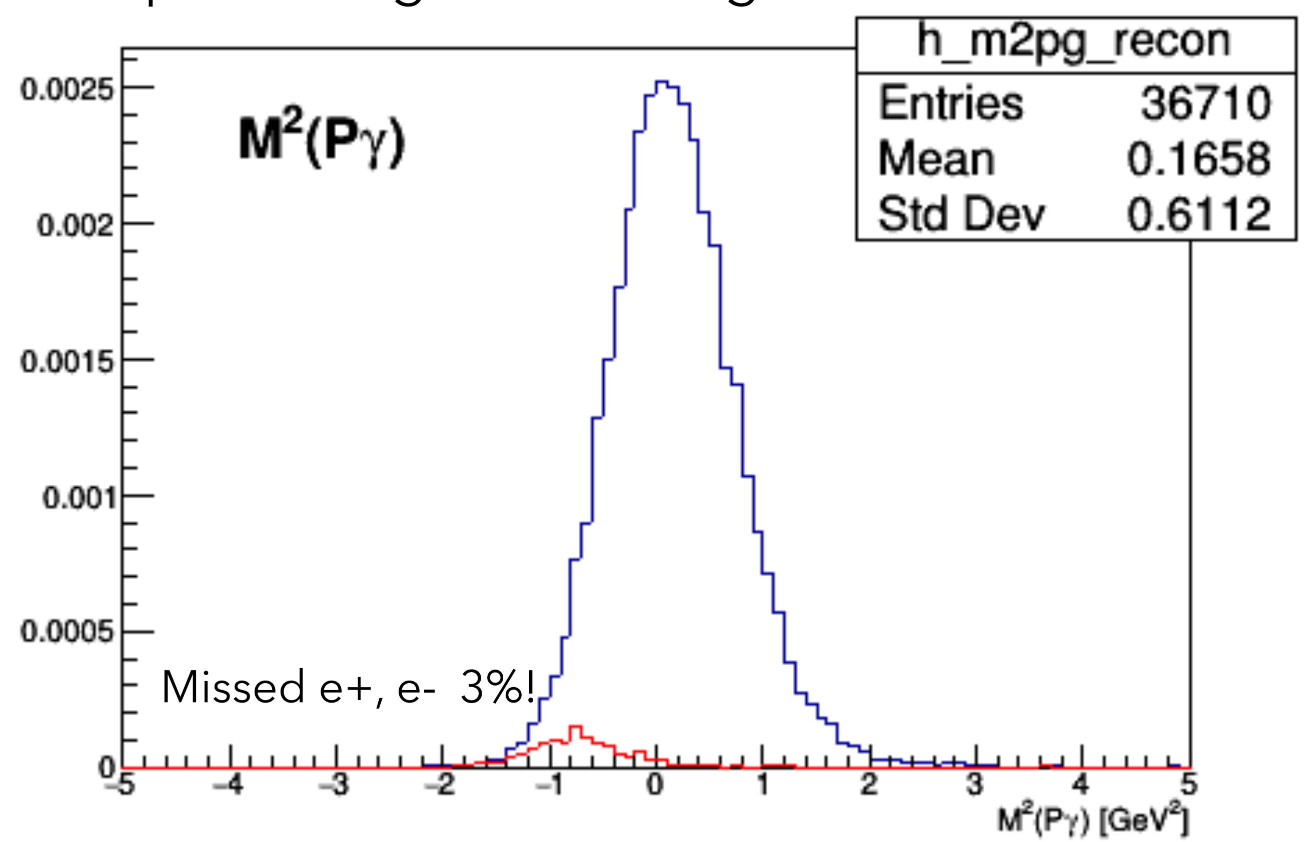
5T target field localized at target cell
Field behind scattering chamber too weak to distinguish pos. and neg. tracks.
Alternative: use reconstructed incident photon mass:

- 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

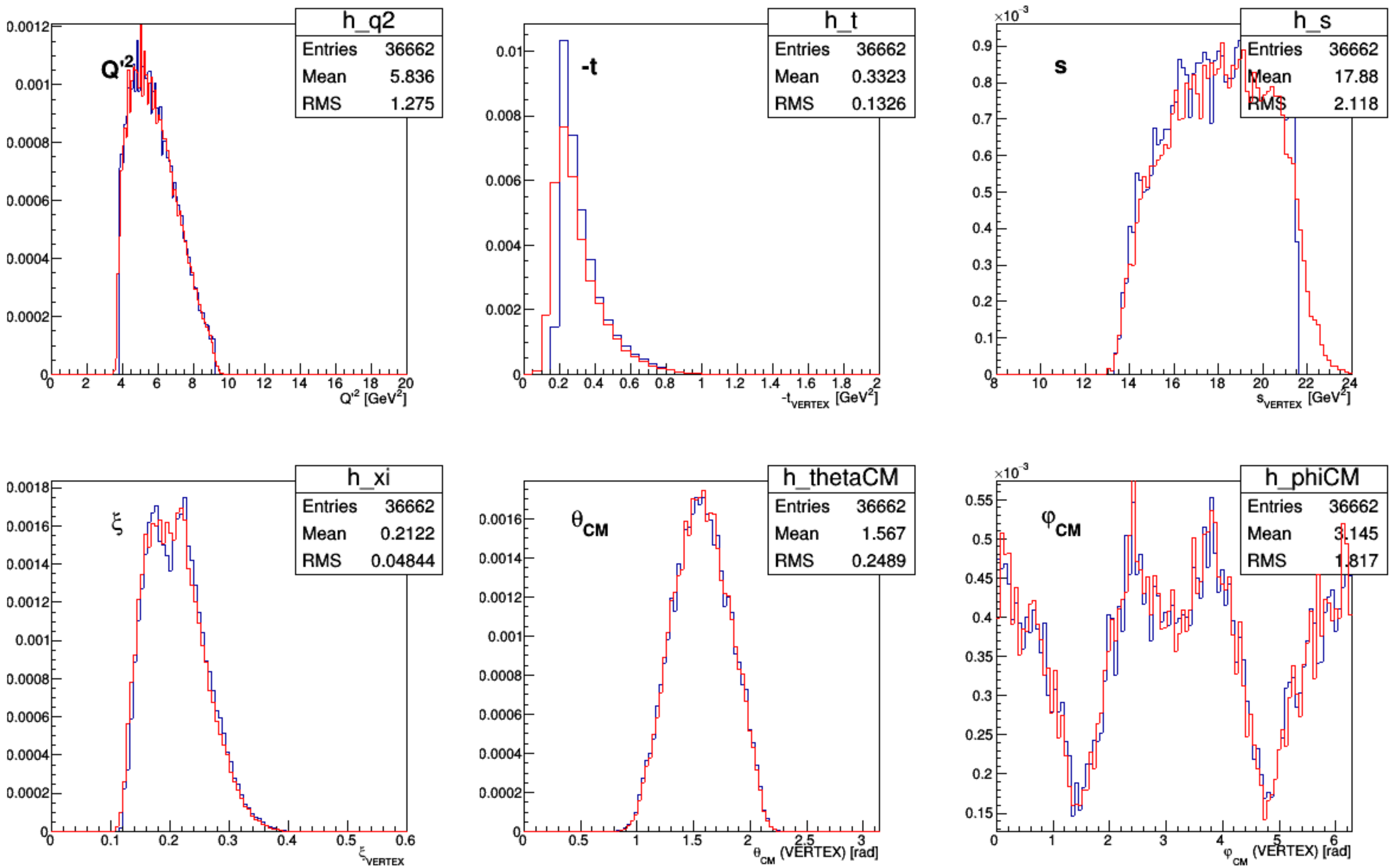


Lepton charges according to selection criteria



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. $\sigma^{\pm} \equiv \frac{d^5\sigma}{dQ'^2\ dt\ d\Omega\ dE_\gamma}$: 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 $\frac{d^5\sigma^{INT}}{dQ'^2\ dt\ d(cos\theta)\ d\phi\ dE_\gamma}$
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

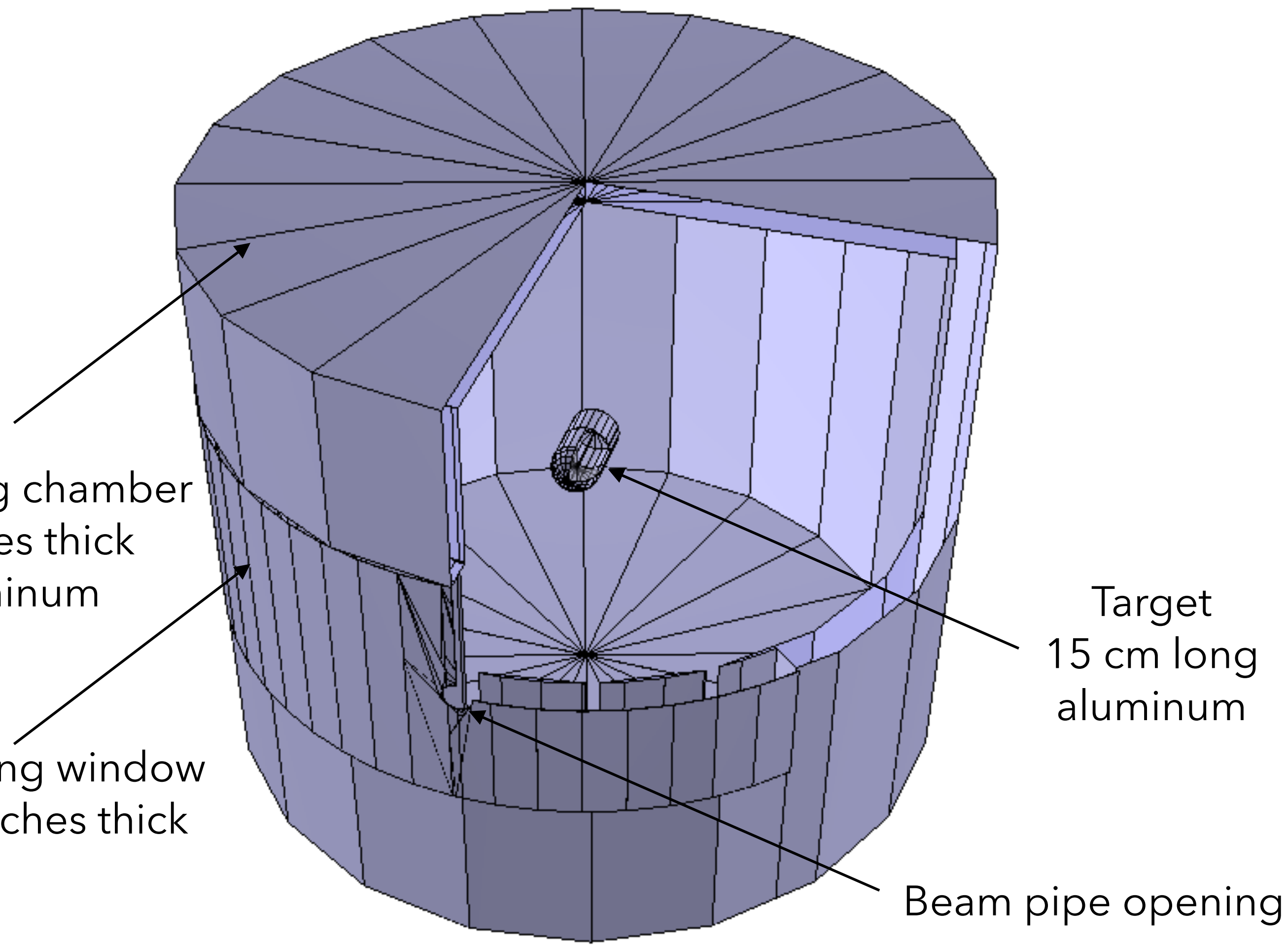


Fig : Geant4 simulation of scattering chamber and target

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

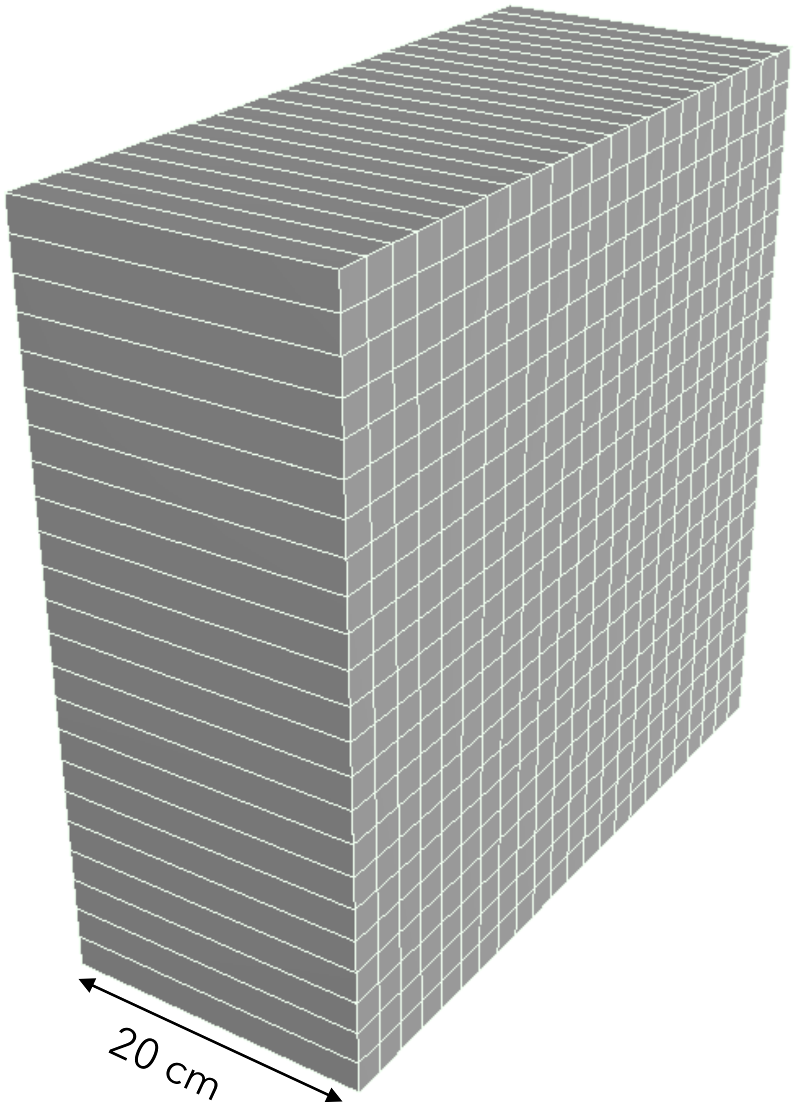


Fig : Geant4 simulation calorimeter

1. e^-, e^+, P detection and PID
2. Clones of the NPS calorimeter at Hall C
3. 2x2x20 cm² 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

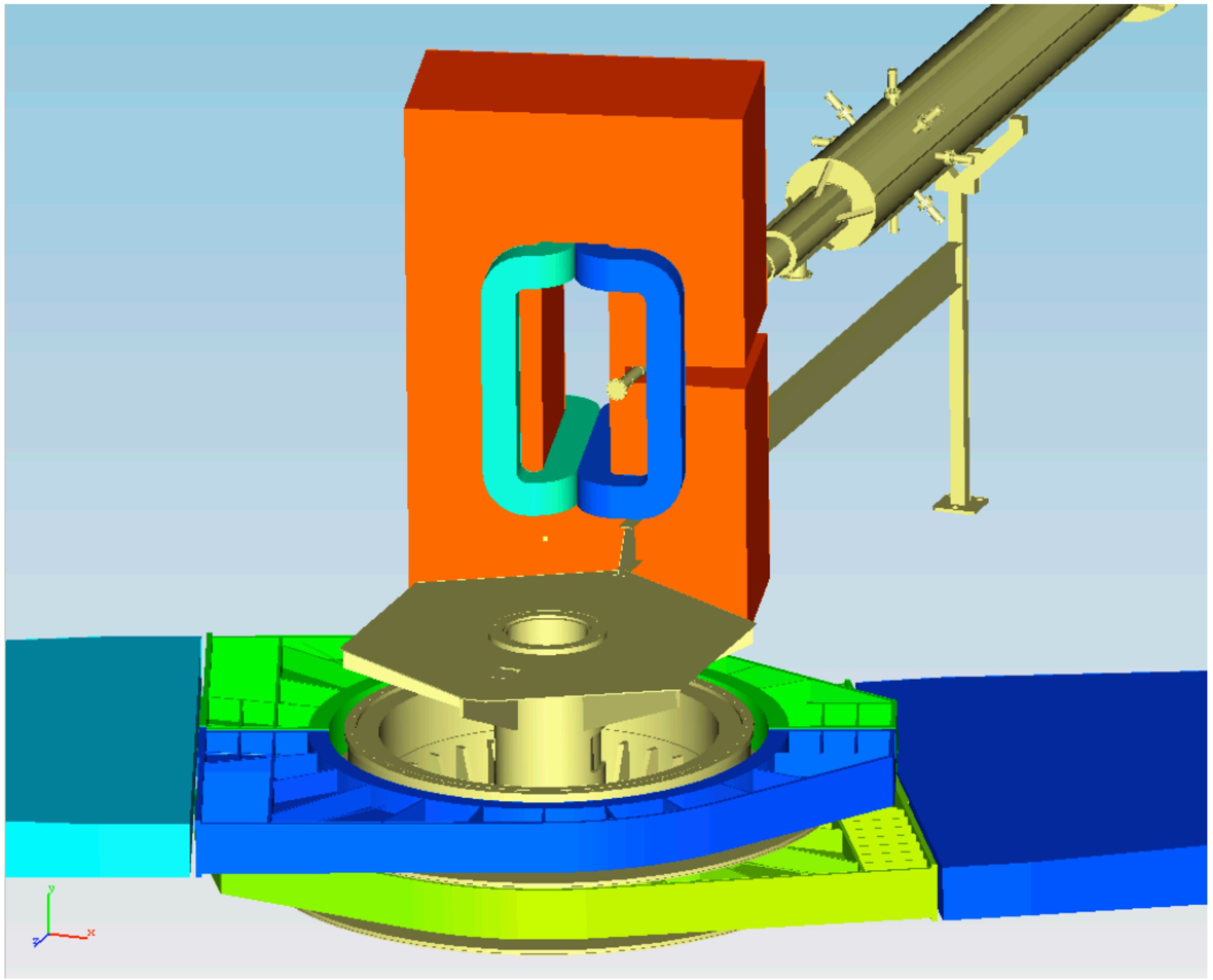


Fig : CAD Drawing for Super Bigbite Magnet
Source : https://userweb.jlab.org/~bogdanw/SBS-general.pdf

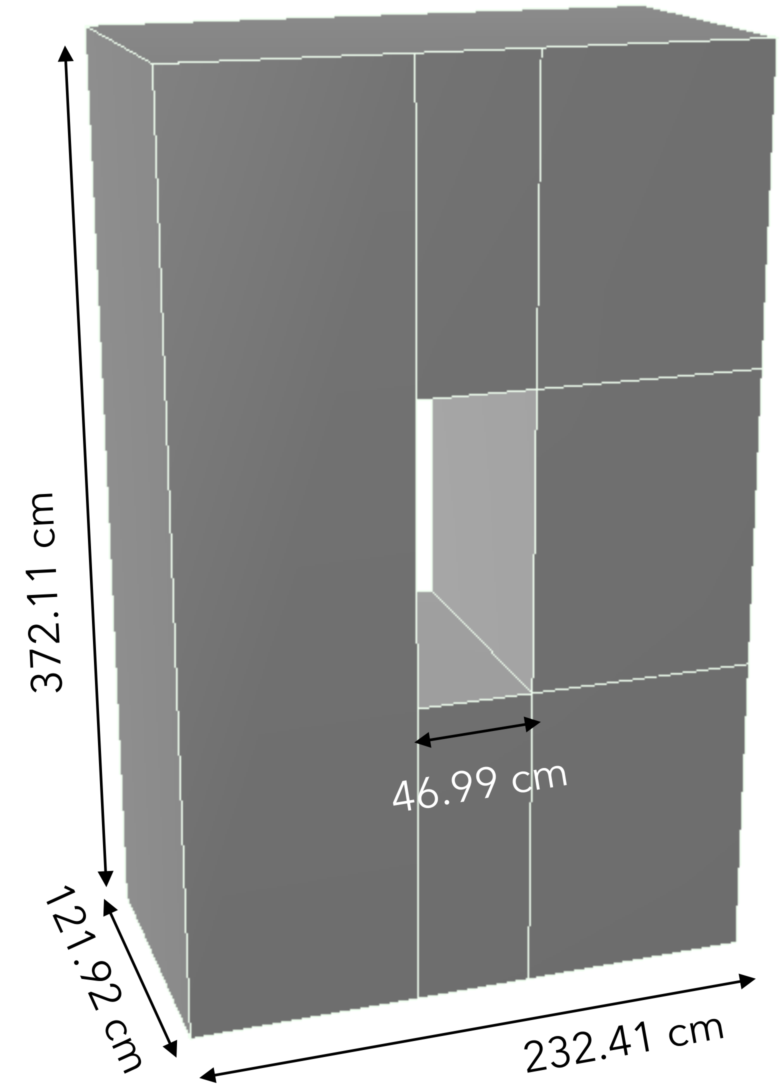
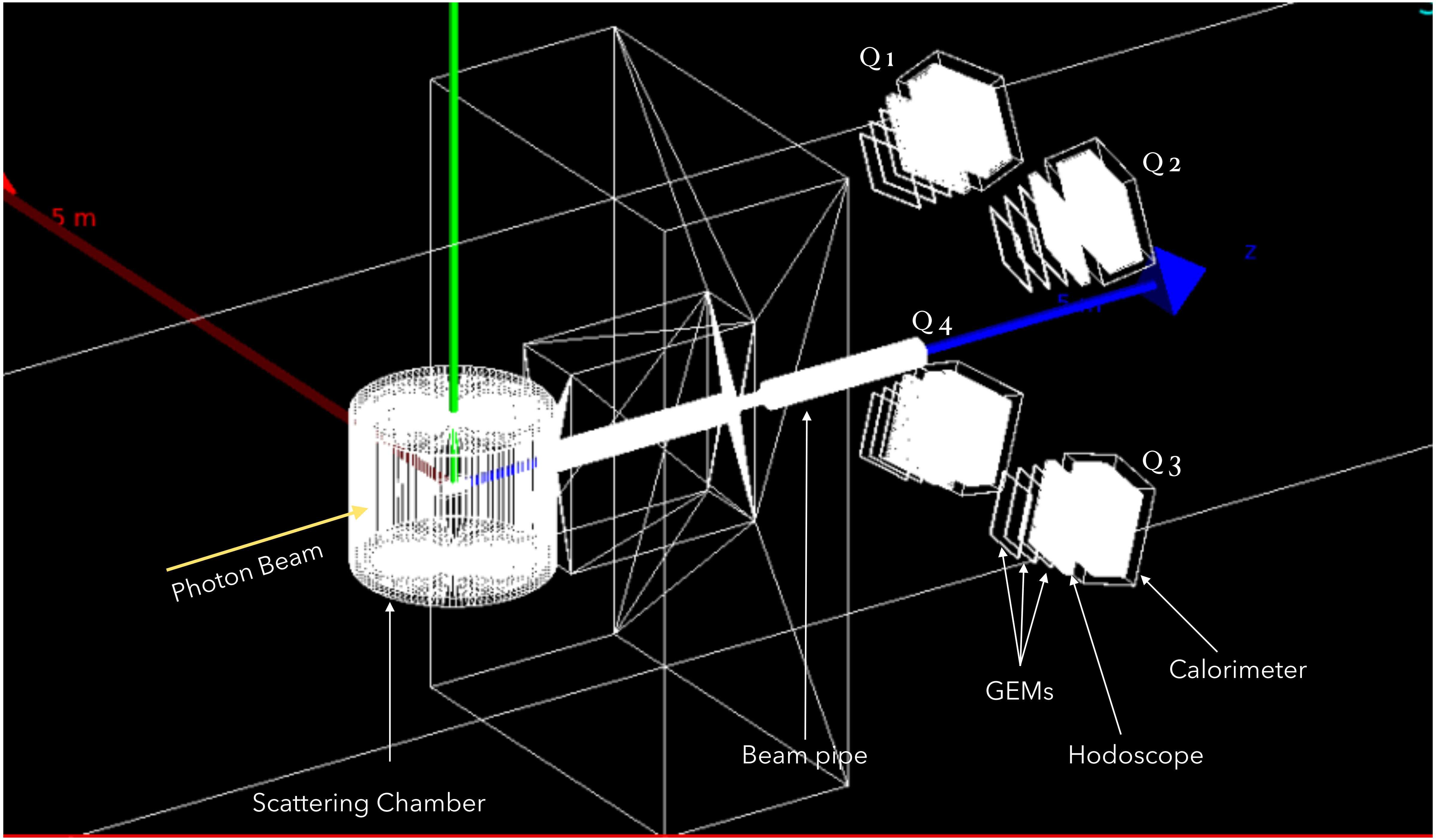


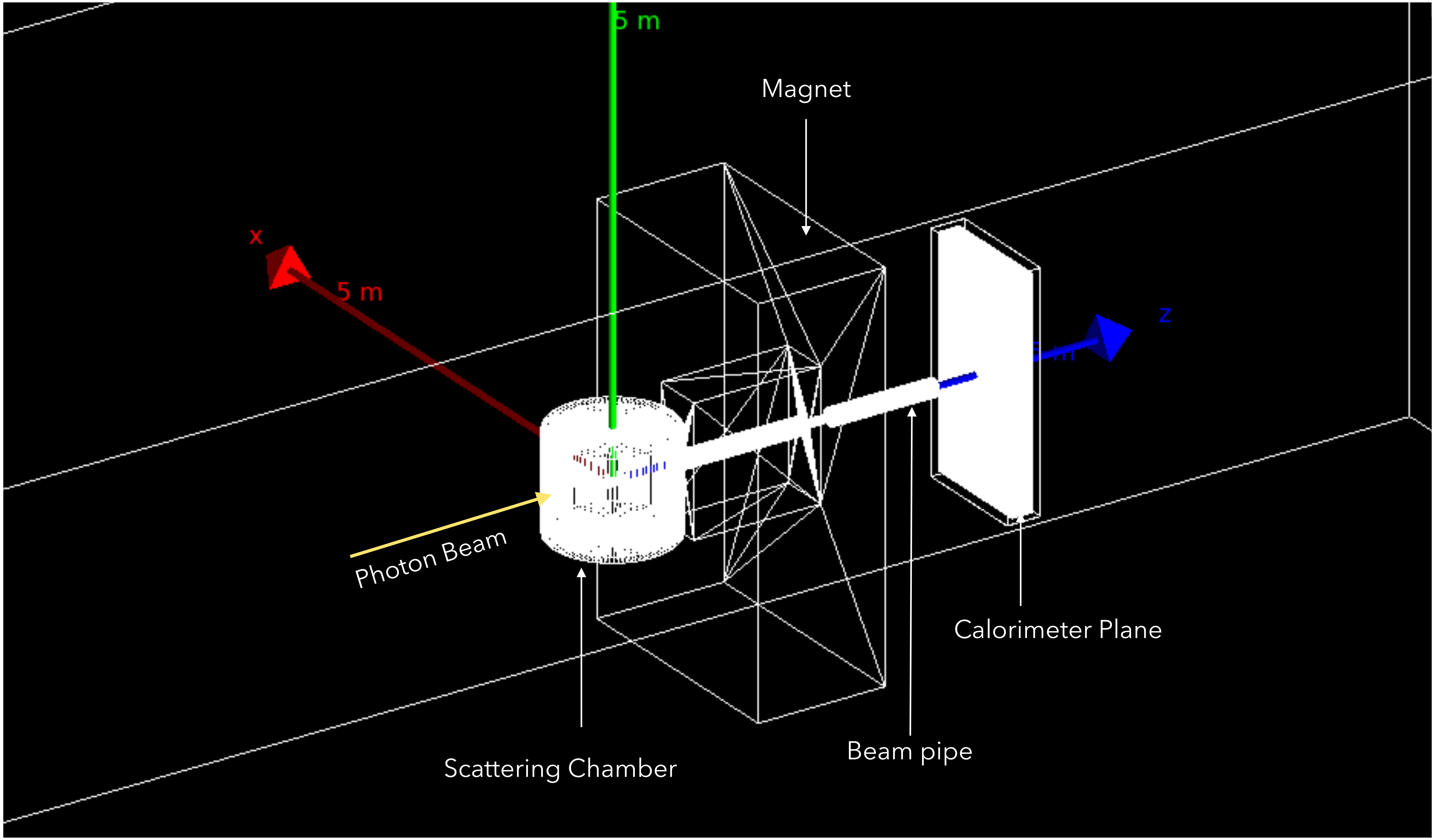
Fig : Geant4 simulation of simple magnet geometry

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

Unpolarized TCS measurement setup for Hall C

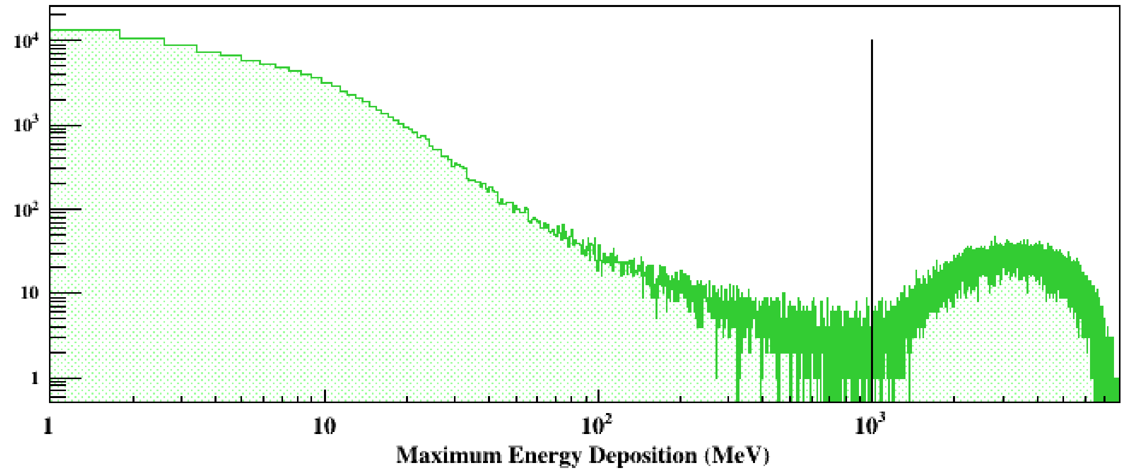


Geant4 Simulation :Simple One Calorimeter Plane Setup

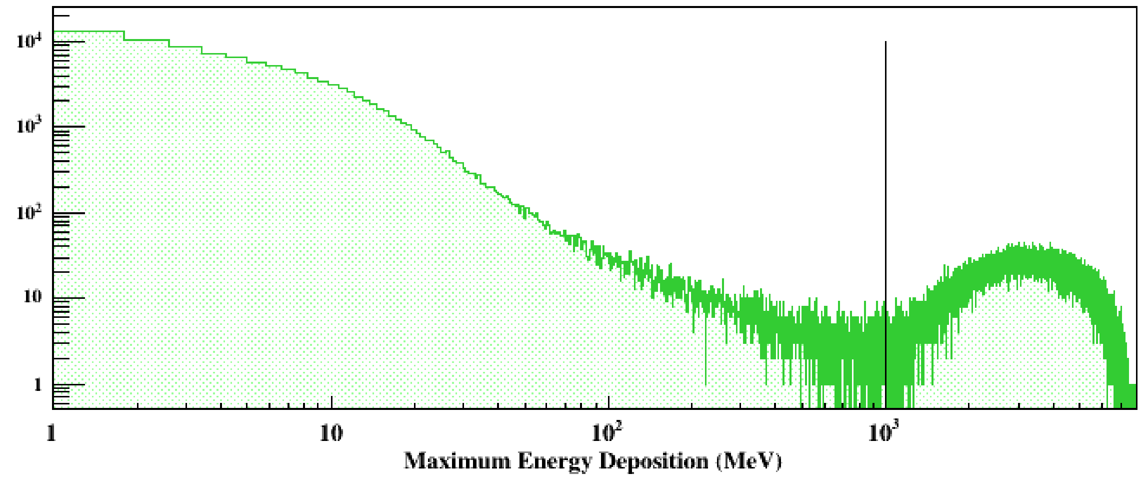


Geant4 Simulation : maximum energy distribution

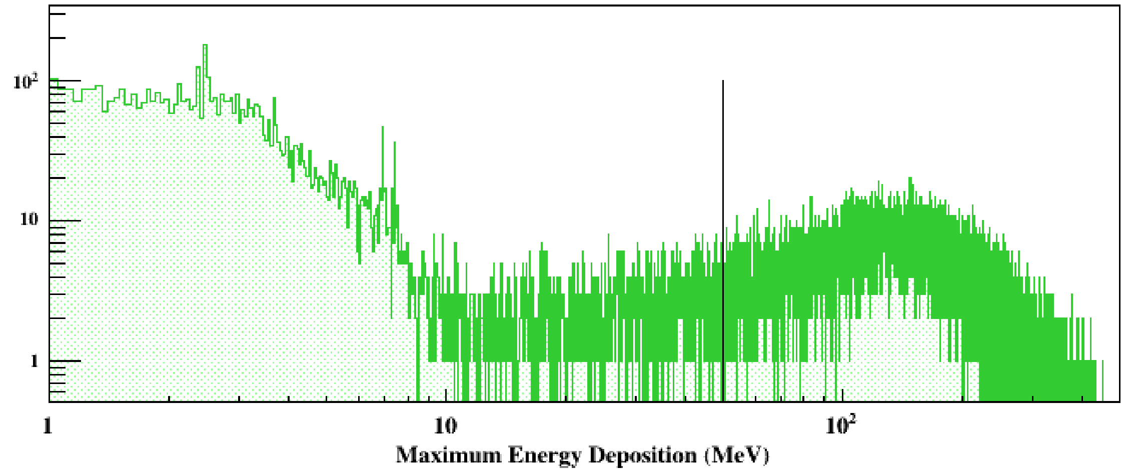
Electron



Positron

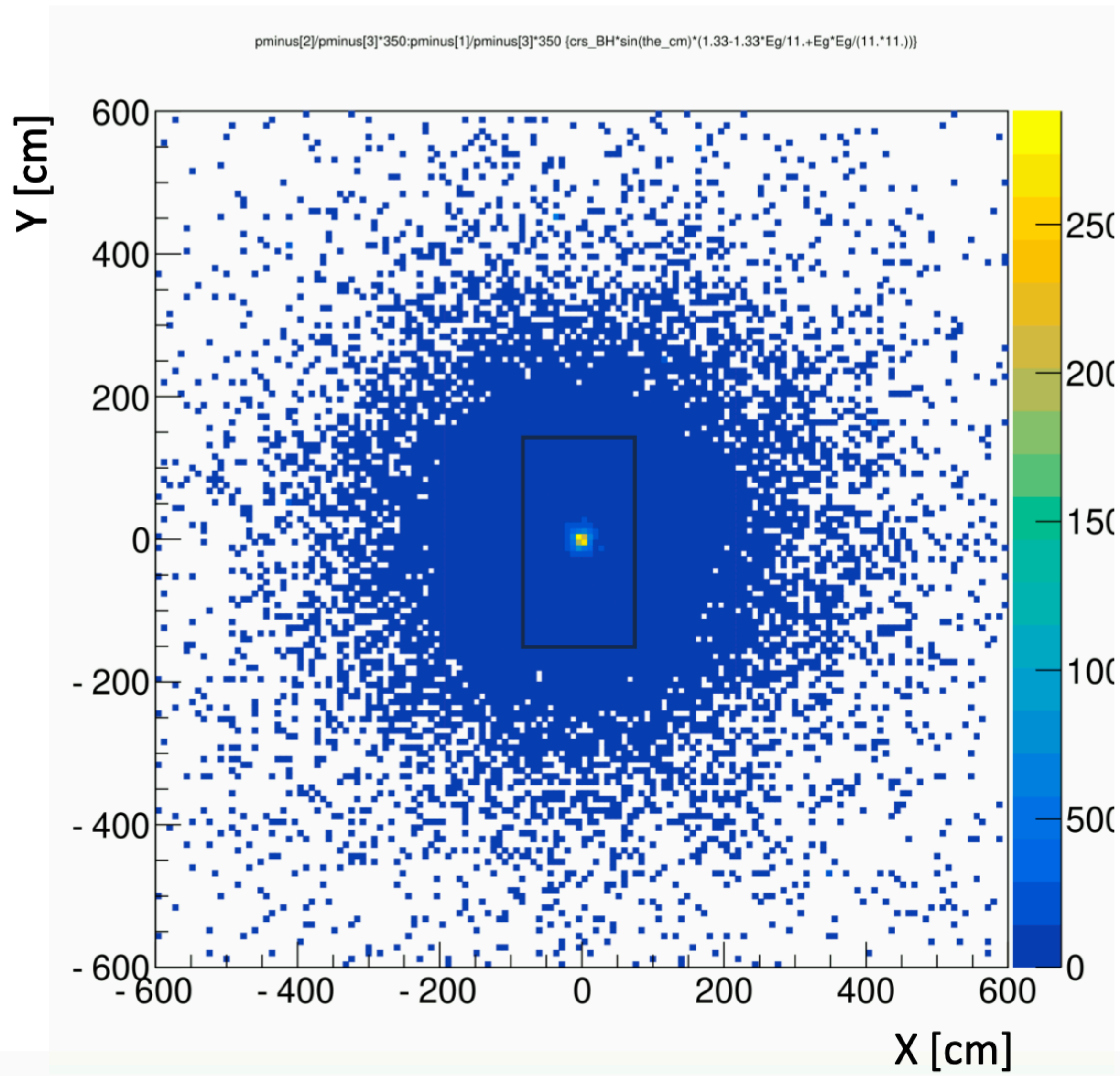


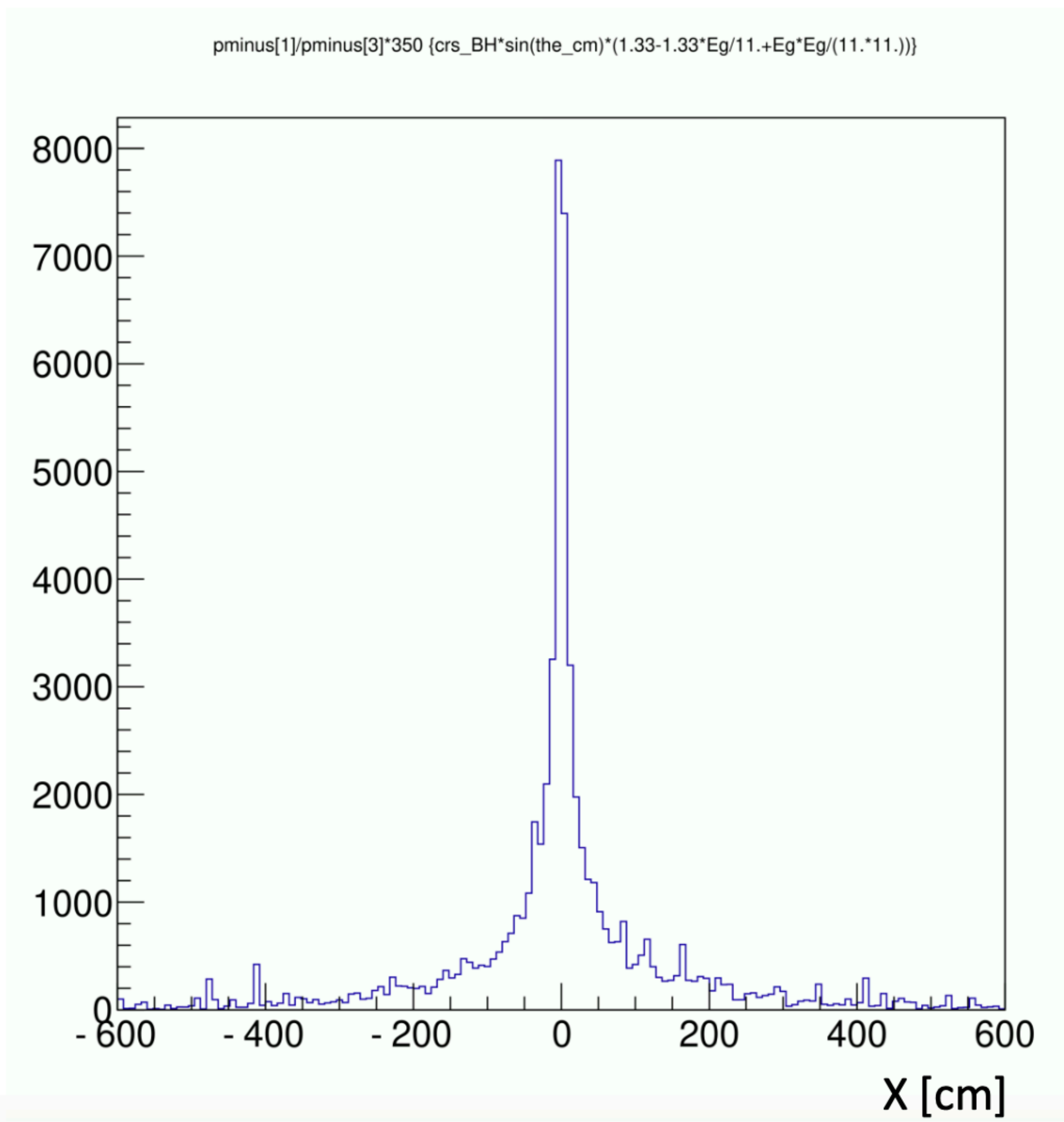
Proton



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

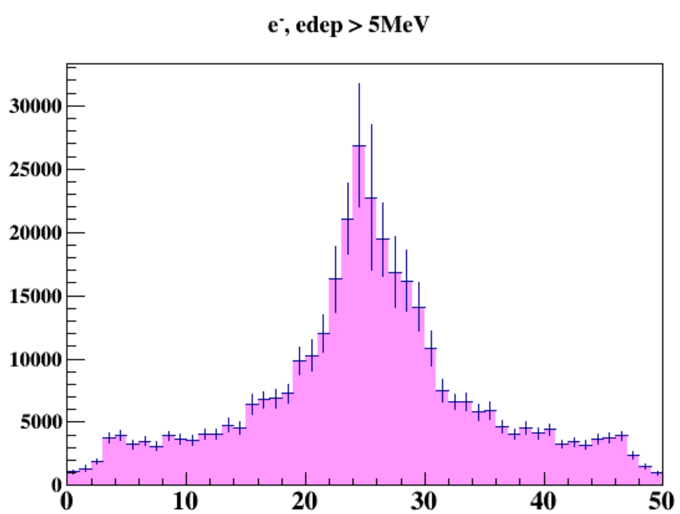




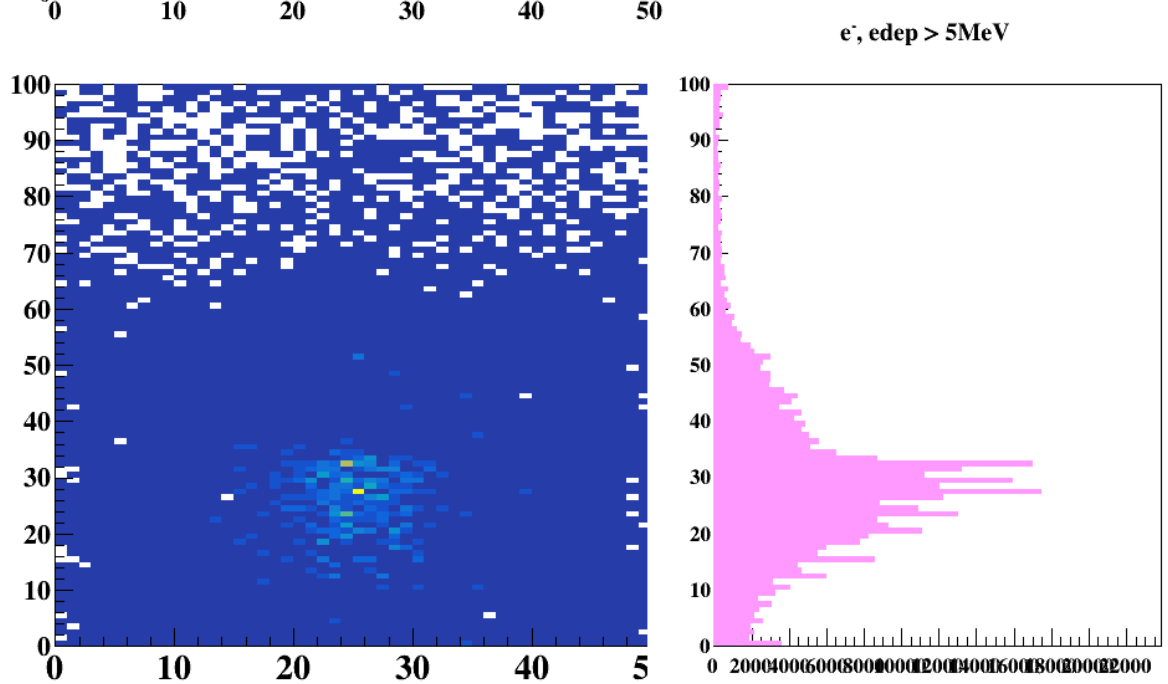
From : Vardan Tadevosyan

Geant4 Simulation : charge assignment to leptons

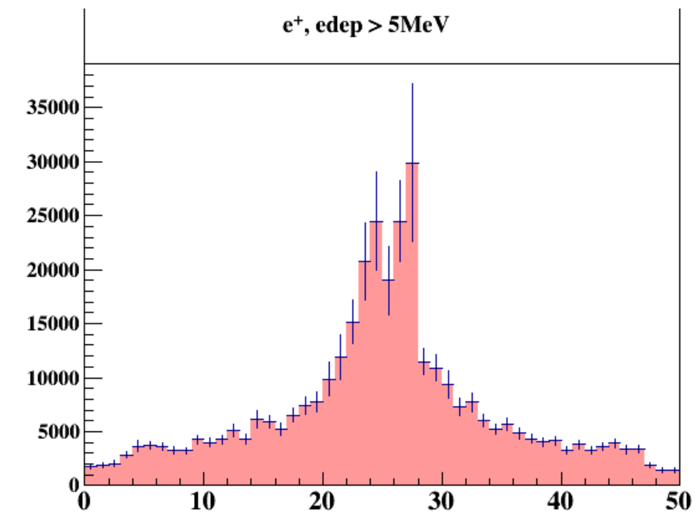
Projection of electron on calorimeter plane



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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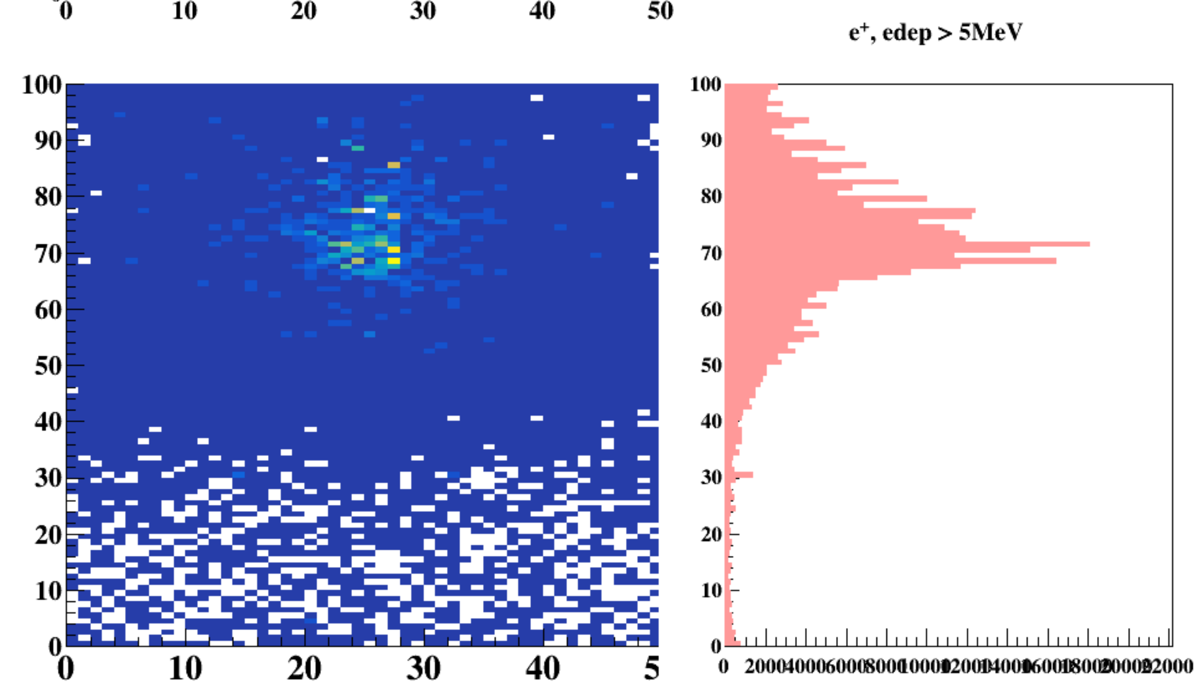
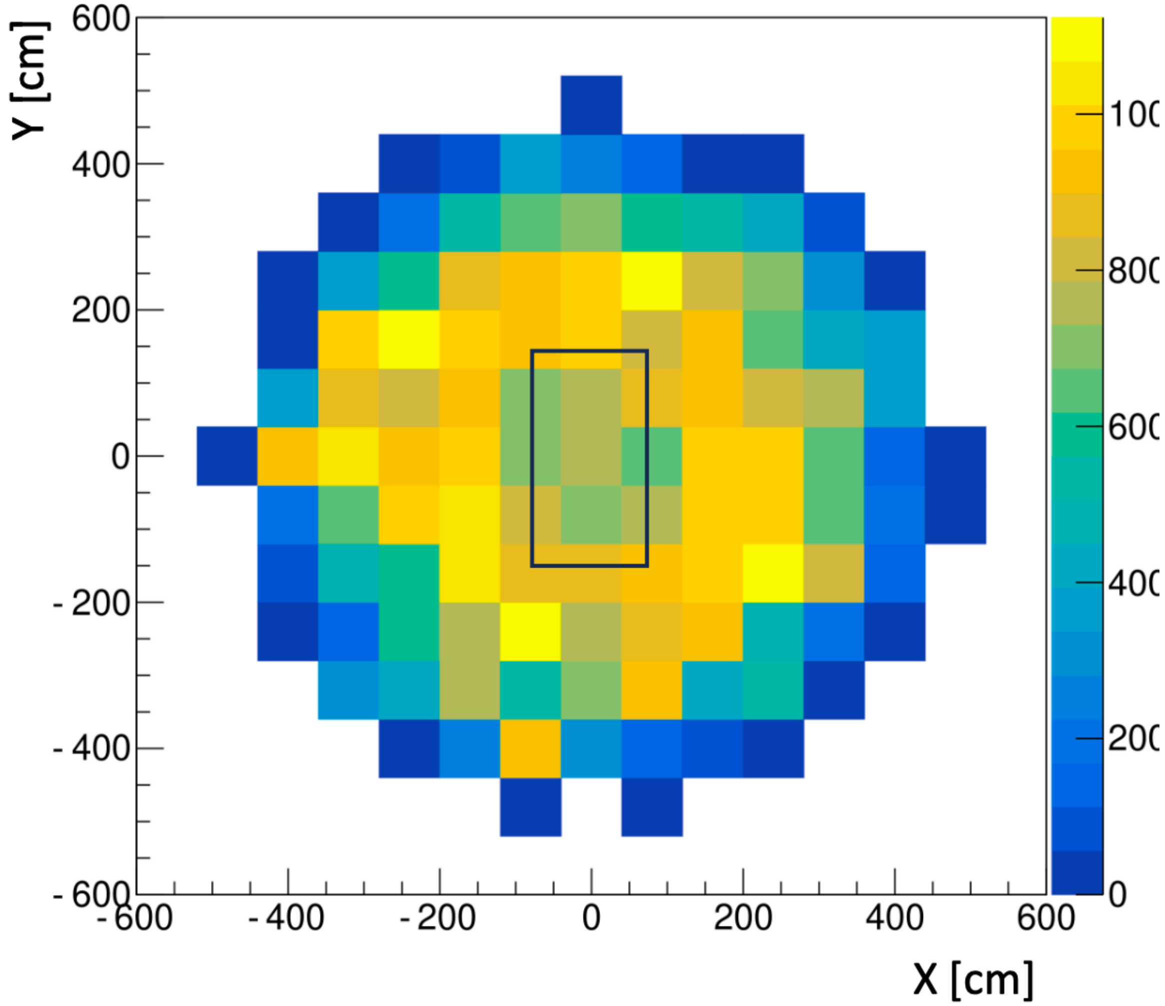
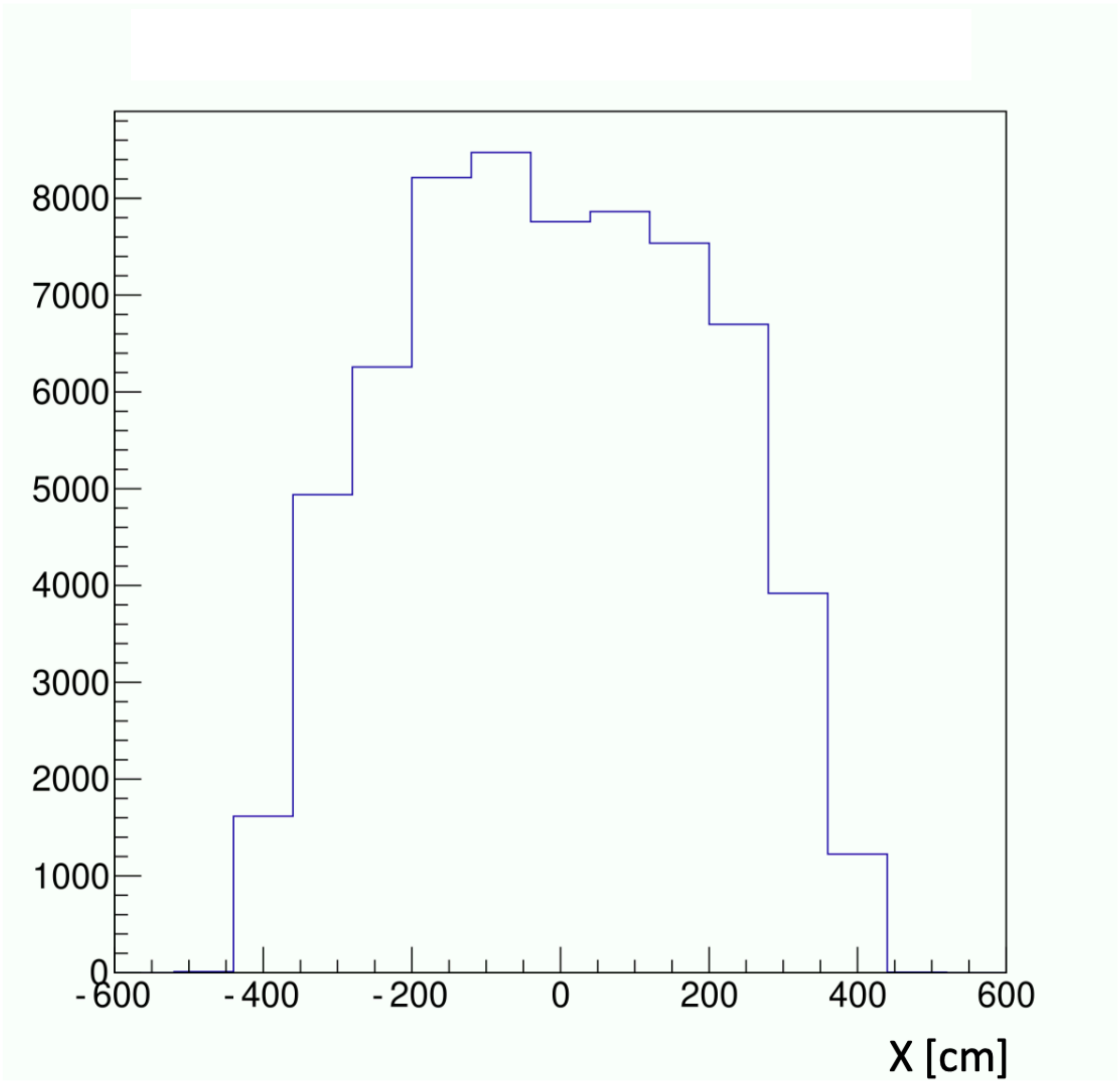


Geant4 Simulation : projection of protons w/o magnetic field

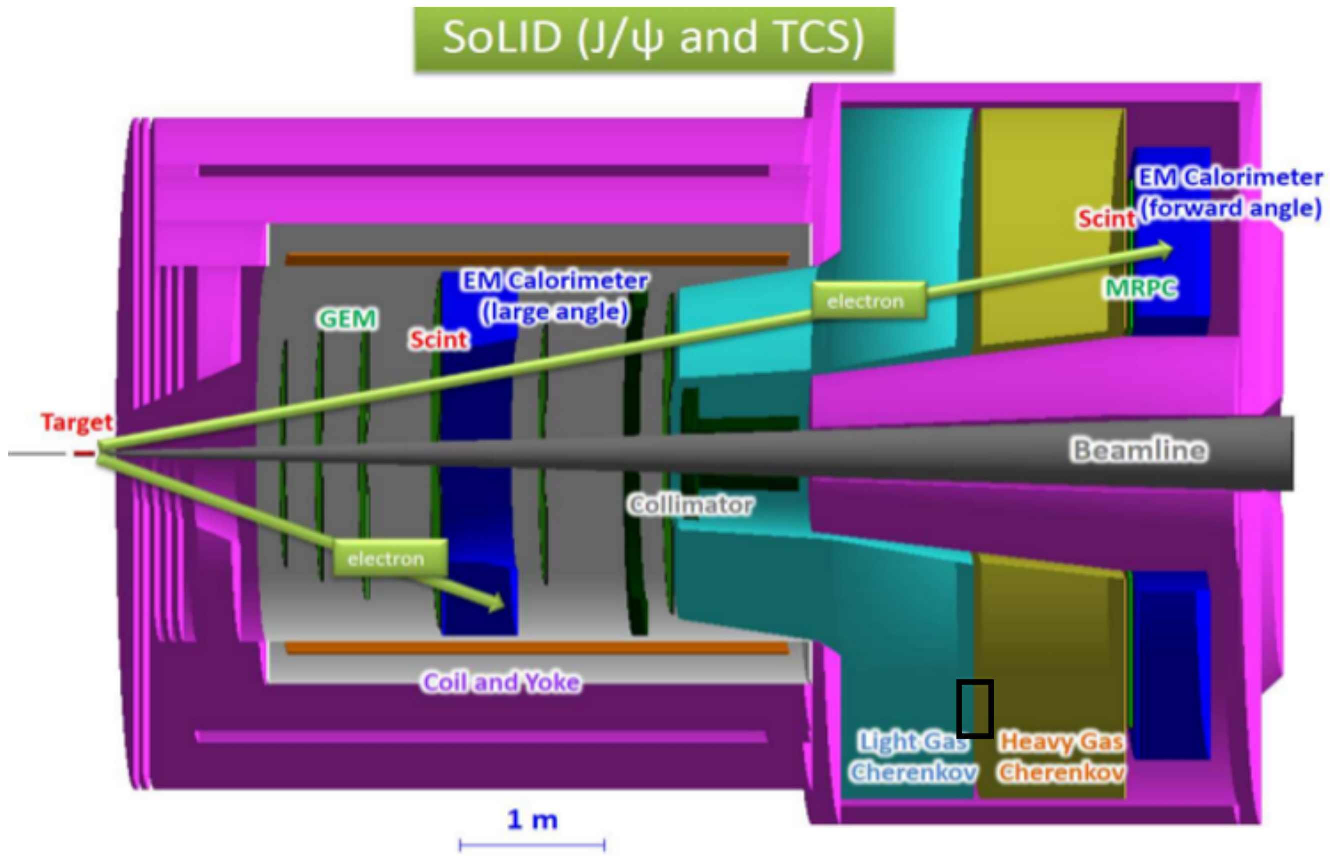
1. TCS weighted events (from DEEPGen event generator) for recoil protons
2. Projected to Z = 350 cm plane (face of the calorimeter)
3. No magnetic Field
4. Rectangle at the center of the 2D plot encompasses the events passing through the magnetic bore



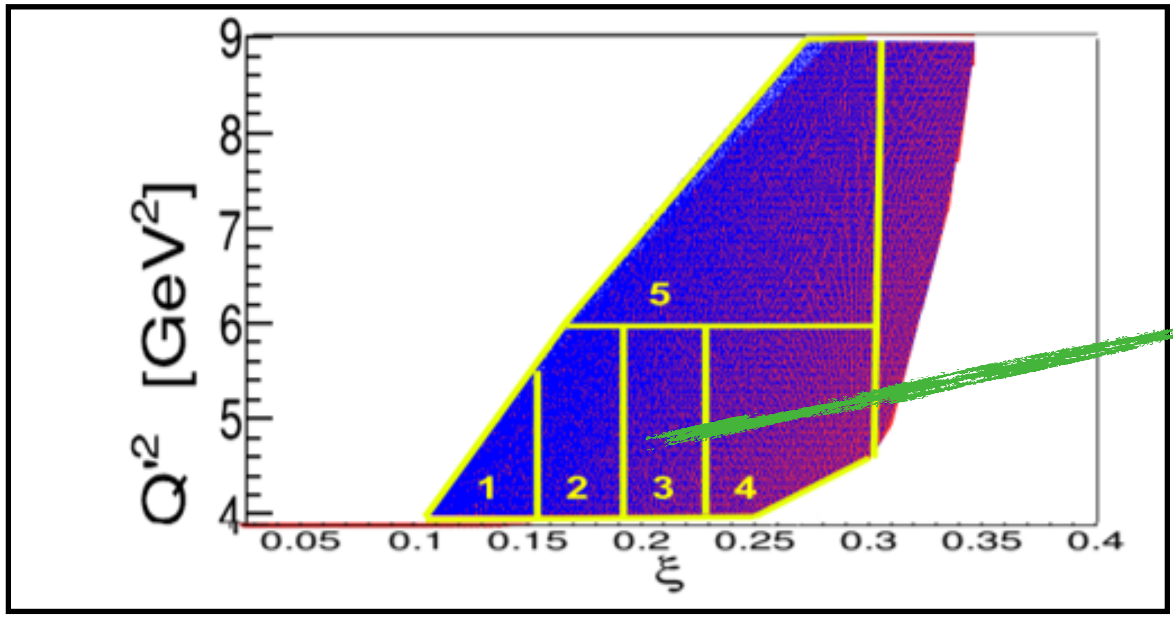


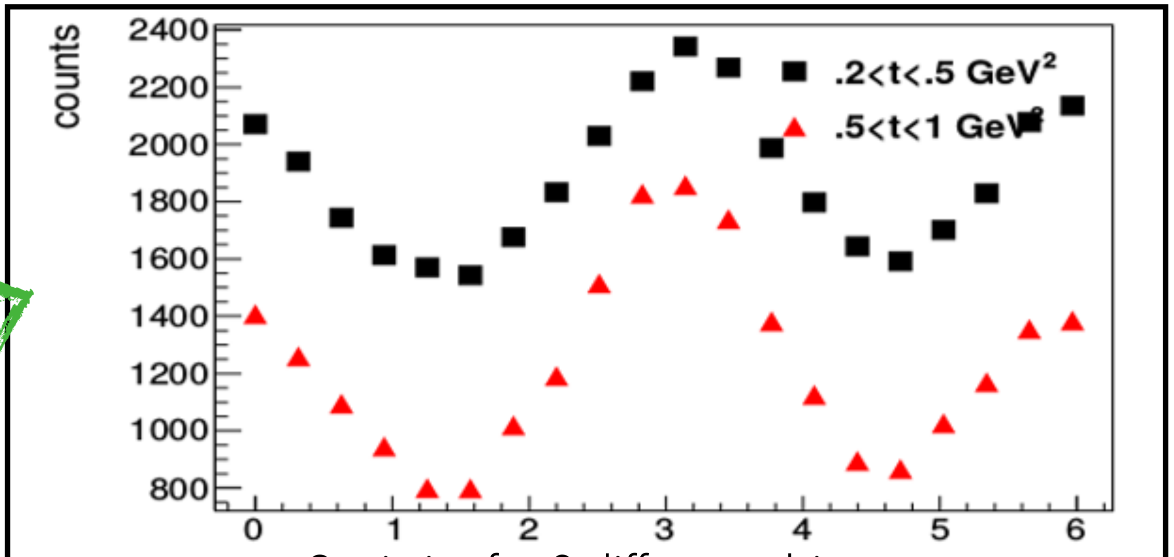
From :

TCS measurement in Hall A (SoLID)



1. Approved unpolarized TCS experiment (unpolarized LH2 target & circularly polarized beam) measurement as a run group proposal (E12-12-006A) along with J/Ψ experiment
2. Quasi real photon beam (real photon beam in hall C)
3. Similar to CLAS12 measurement but with larger statistics and narrower acceptance
    1. Large acceptance compared to hall C and binning in Q'^2 enables us to look into GPD evolution
    2. Possible GPD universality study by comparing Extracted from TCS and DVCS
4. This setup has the potential to be used for the polarized (polarized target) measurement also

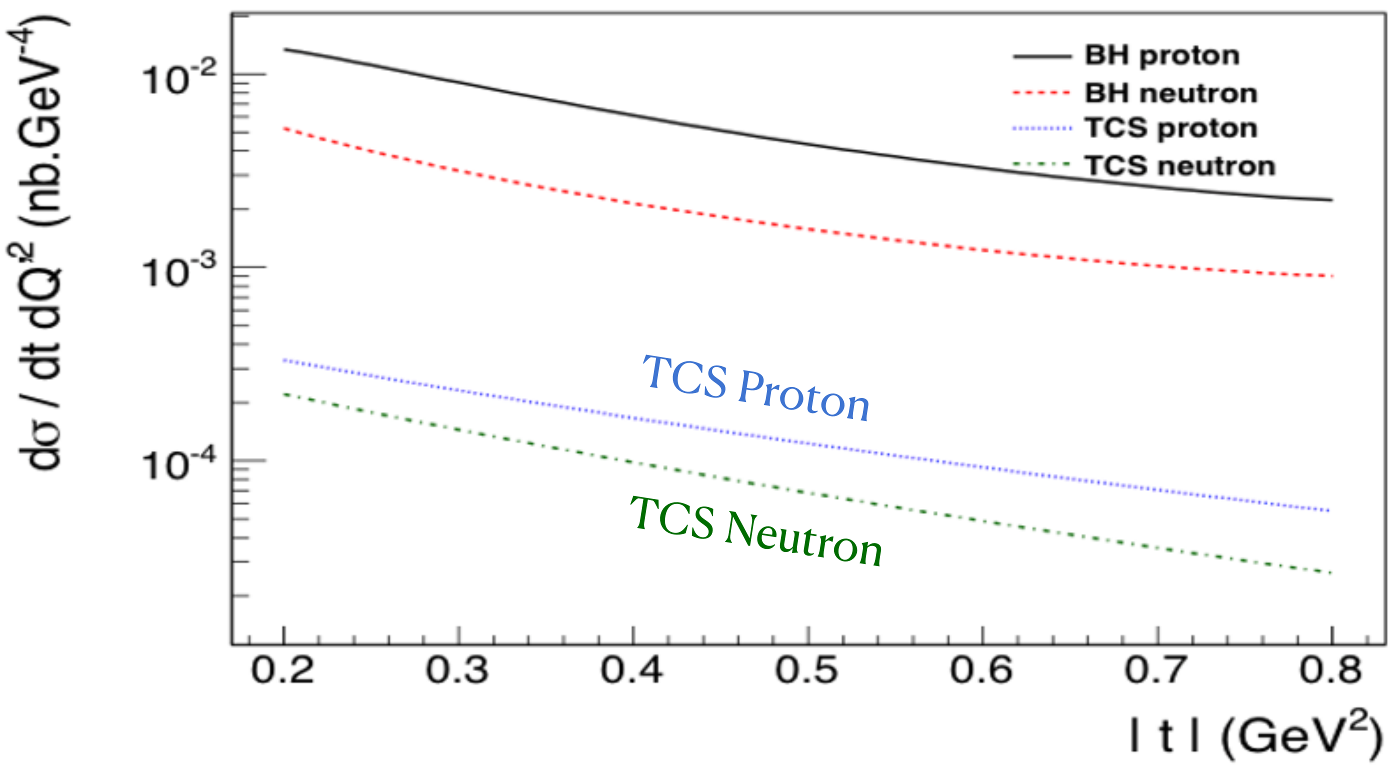




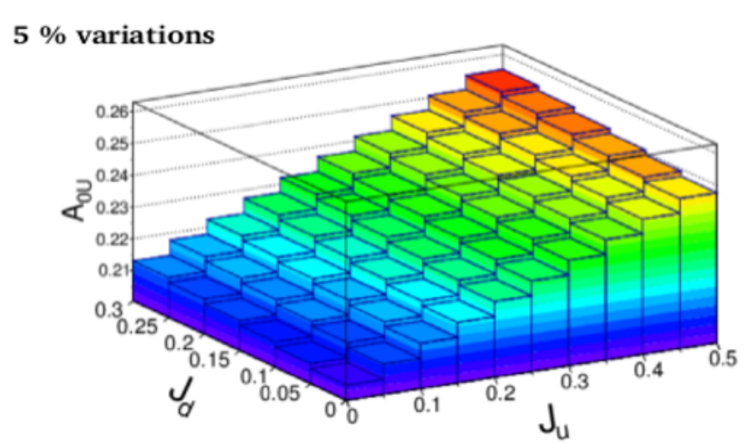
Statistics for 2 different t bins

Possible extension to measure TCS for neutron

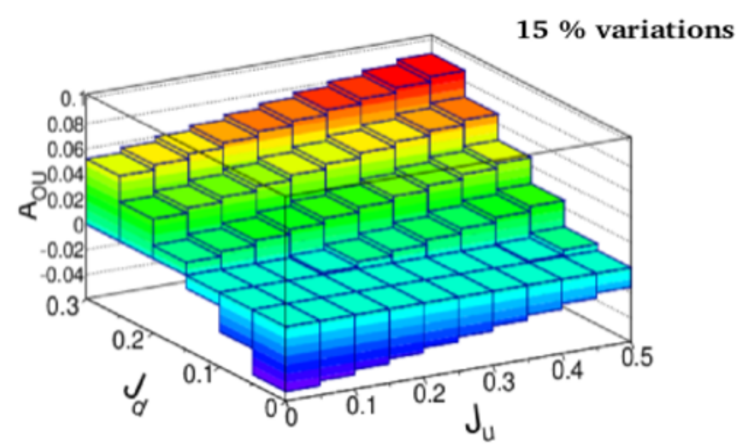
Comparison of Proton and Neutron
Unpolarized cross sections vs -t



BSA : Proton



BSA : neutron

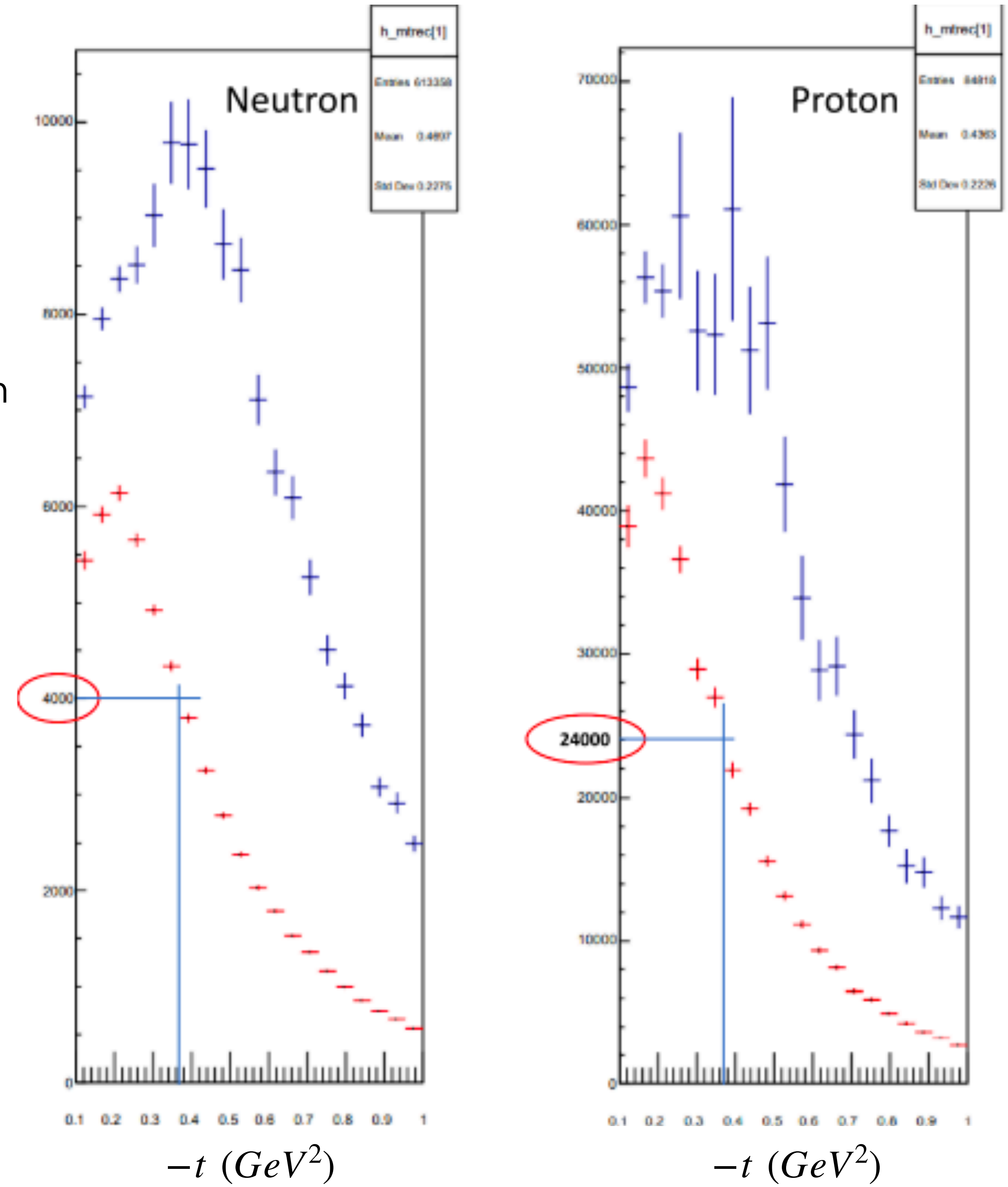


From Boer, Guidal, Vanderhaeghen, EPJA 52 (2016) 33

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

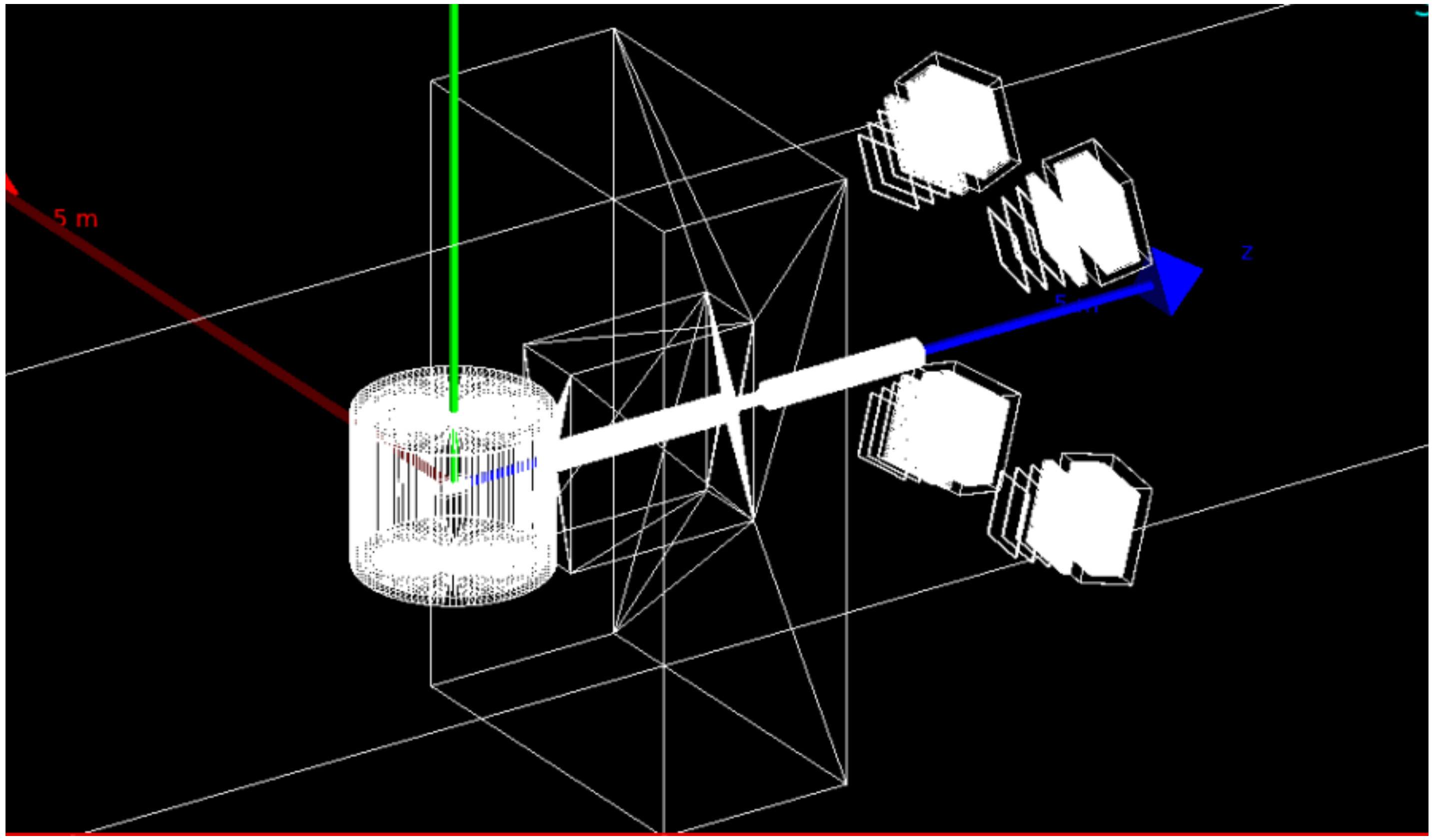
1. Preliminary study to show the feasibility of the measuring TCS for neutron
2. Number of reconstructed TCS events (weighted by cross-section) plotted against -t
3. Study before having the full Geant4 simulation
4. In principle it is possible to do the measurement on neutron, provided we have an neutron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



From : Camille Zindy & M. Boer, 2021

Summary

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



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