DDVCS Experiment at JLab, Hall C

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NPS Collaboration Meeting :

Jefferson Lab

May 5-6, 2025

Accessing GPDs through exclusive reactions

Compton like reactions

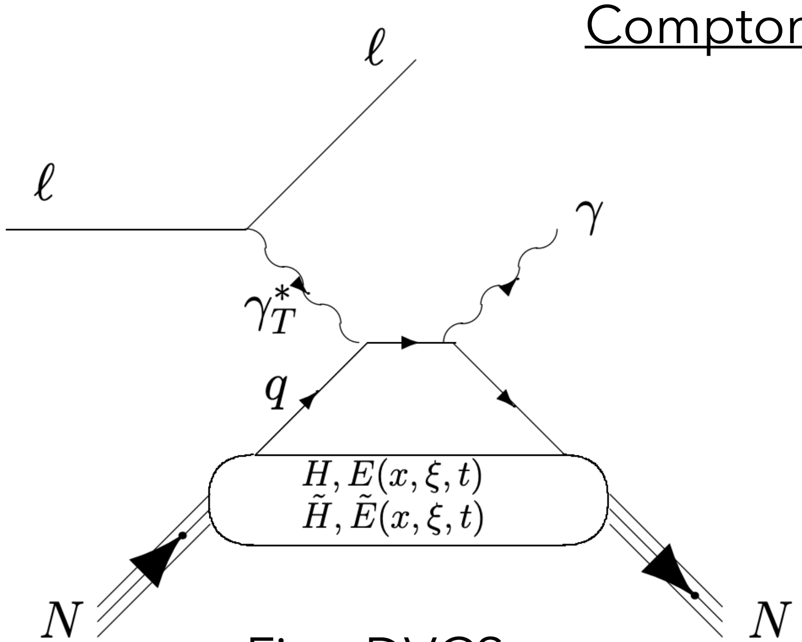


Fig : DVCS

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

(measure in multiple experiment)

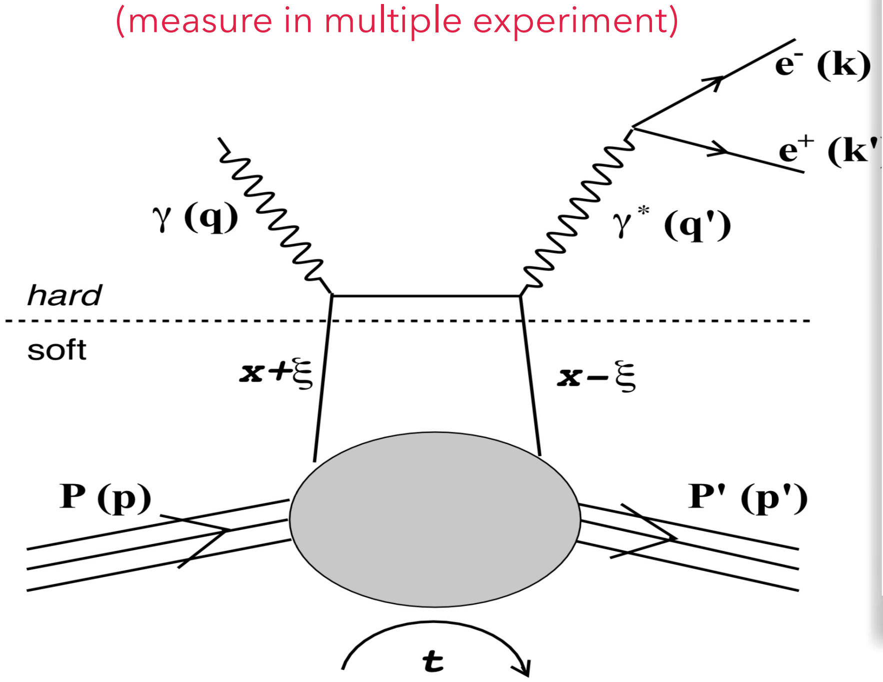


Fig : TCS

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

(measure for the first time at JLab)

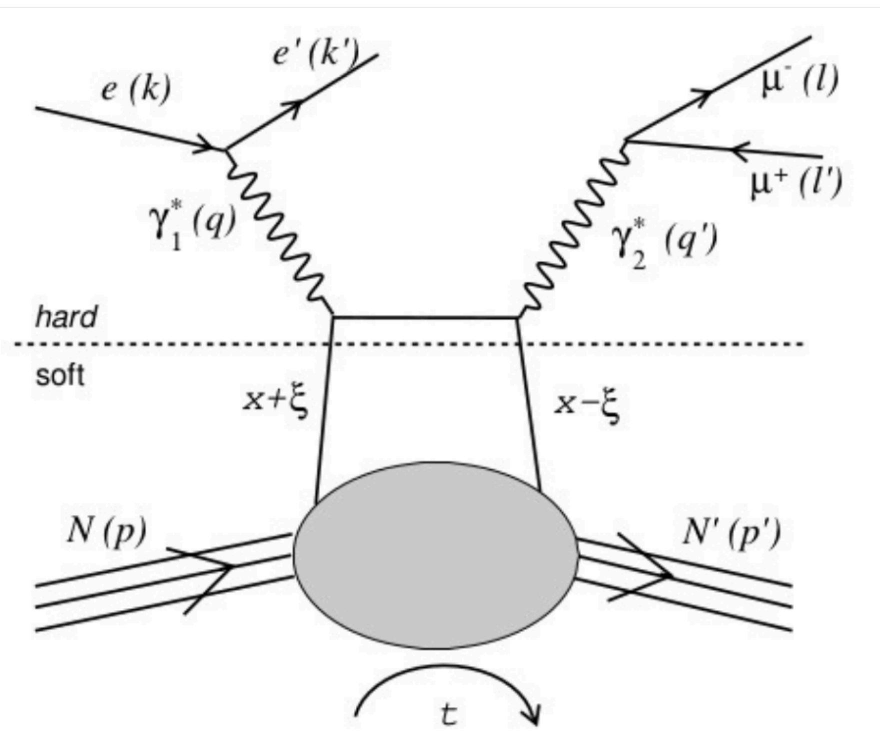


Fig : DDVCS

(no experiment yet)

Meson production

Pseudo scaler / vector meson

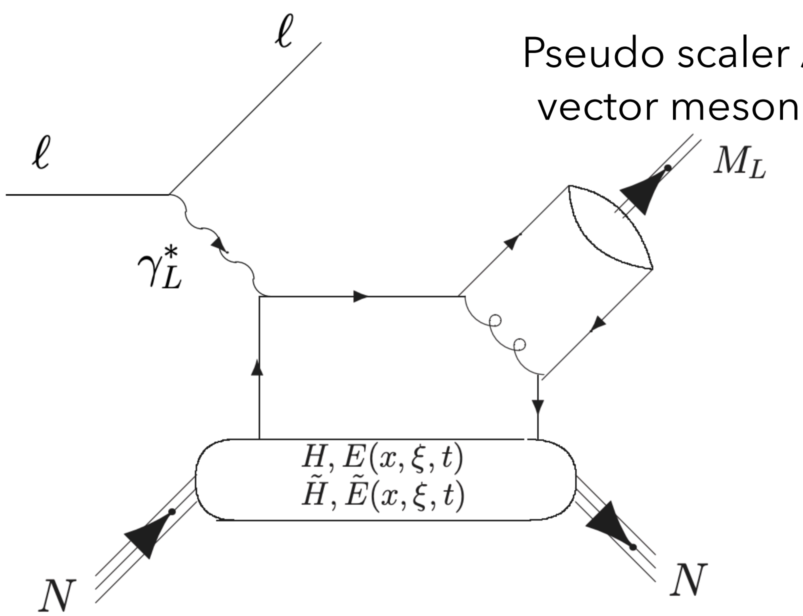


Fig : DVMP (quark Subprocess)

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

vector meson

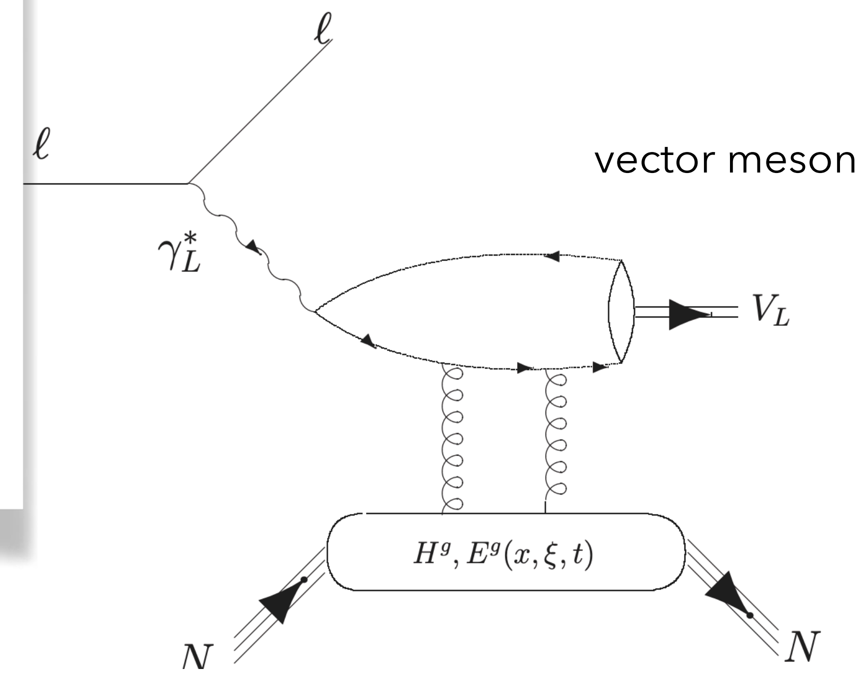


Fig : DVMP (gluon subprocess)

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

DDVCS

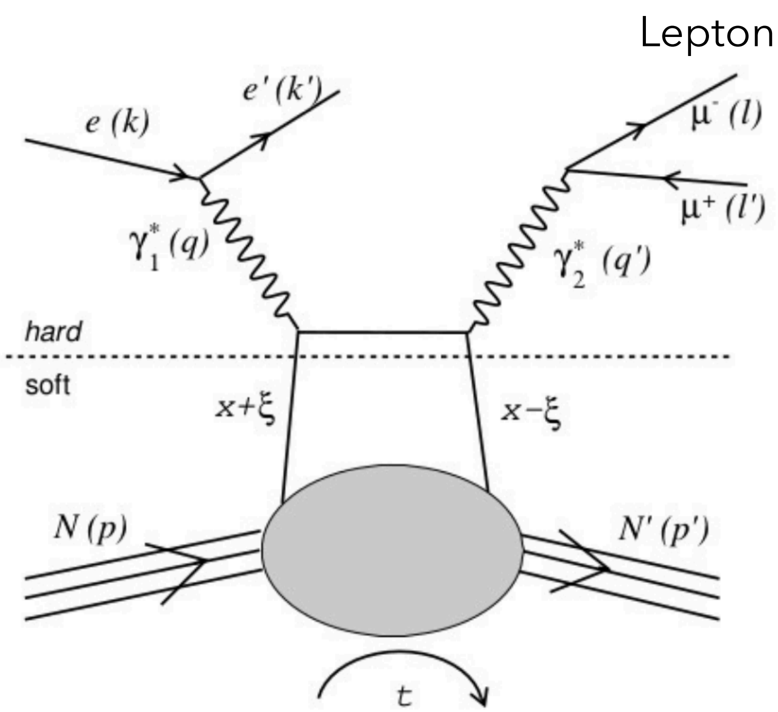


Fig1: DDVCS

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

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

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 ?

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

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

Experimental Setup : Di-Lepton Spectrometer

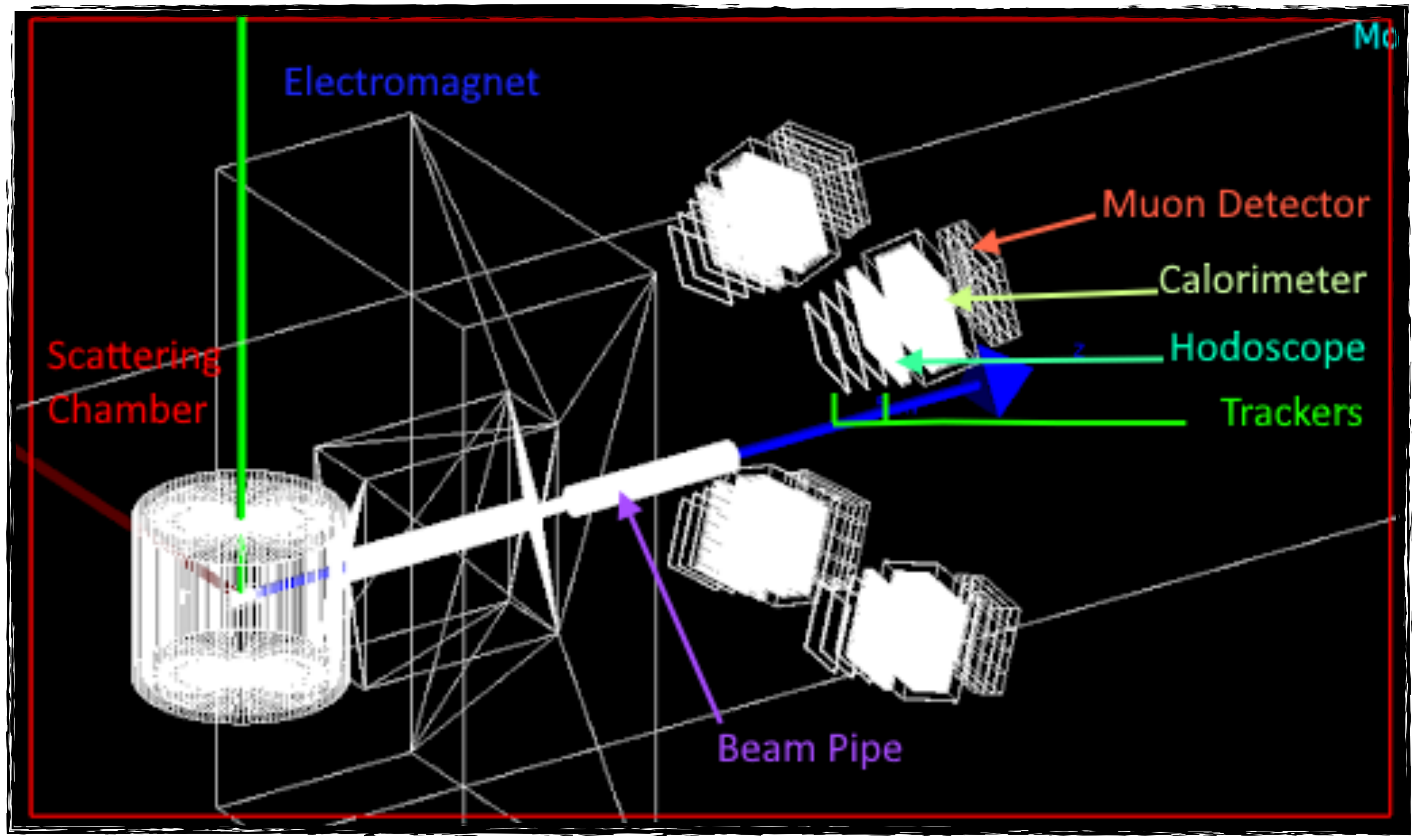
1. Current Hall C setup is not suitable for this kind of measurement

2. To do an exclusive measurement a new di-lepton spectrometer is needed

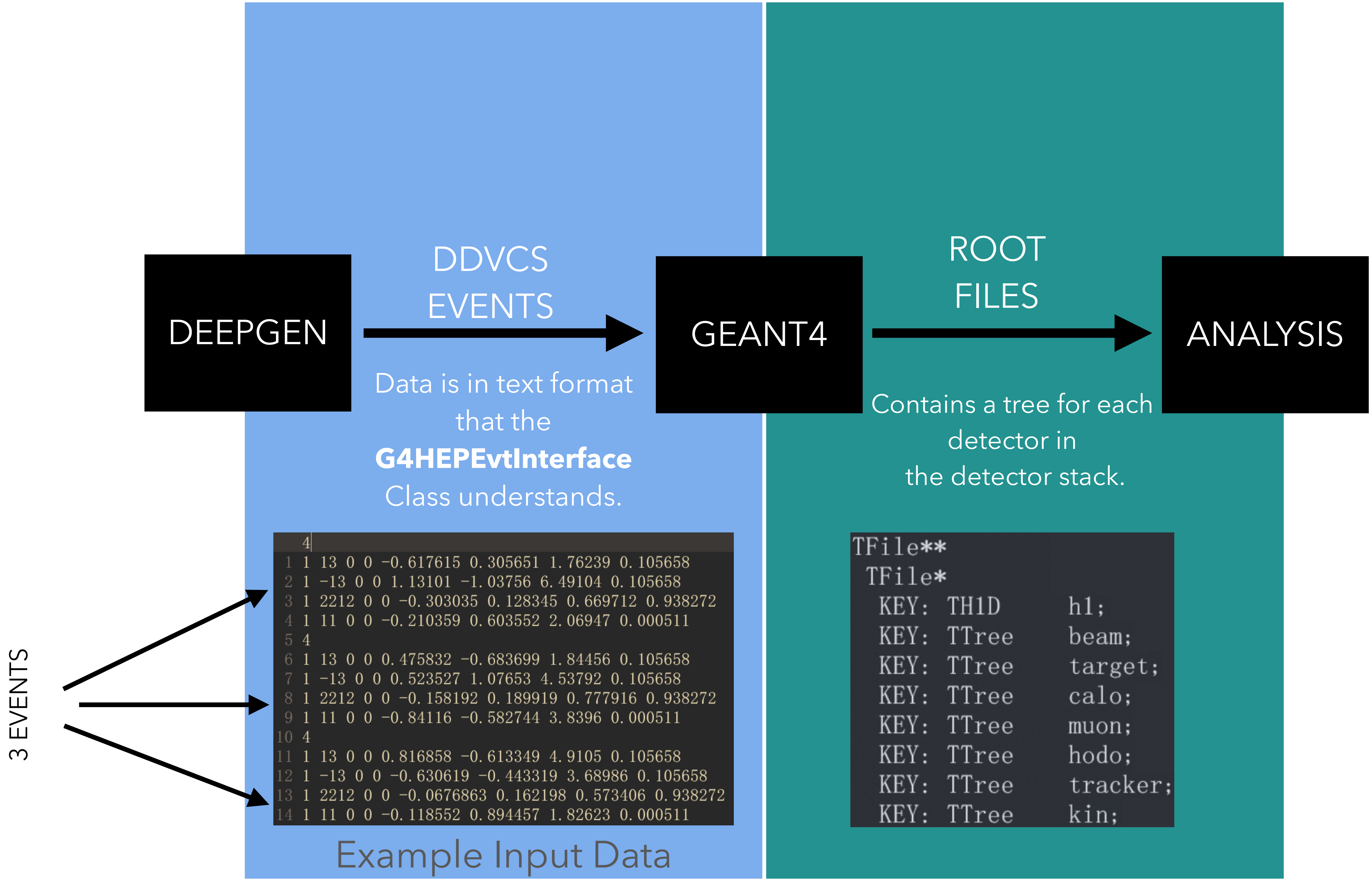
3. The same detector design can be adopted as for unpolarized TCS measurements if a muon detector is added to the setup

4. A dipole magnet is placed right after the scattering chamber to spatially separate μ^+ and μ^-

5. Detectors are placed in 4 quadrants
    1. Trackers (e.g. GEMs)
    2. Hodoscope (e.g. Scintillators)
    3. Calorimeter (e.g. NPS)
    4. Muon Detectors



Genat4 : Overview



Geant4 Summary

1. Instantiate a **G4RunManager**
2. Set the **User Initialization**
   1. Construct the geometry
      1. Mostly using **gdml** scripts
   2. Specify **physics list**
3. Set the **User Actions**
   1. Particle Generator Action
   2. Run Action
   3. Event Action
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   5. Stacking Action
   6. Stepping Action
4. Execute **G4UImanager** commands
   1. This begins a **run** in the simulation
   2. Or brings up the visualization

Collect the data in **Sensitive Detectors**

```cpp
G4bool MuonDetectorSD::ProcessHits(G4Step* step, G4TouchableHistory*) {
    G4TouchableHistory *touchable = (G4TouchableHistory *)step->GetPostStepPoint()->GetTouchable();
    G4int depth = touchable->GetHistoryDepth();

    if (depth == 3) {
        G4int         particle_id   = step->GetTrack()->GetParticleDefinition()->GetPDGEncoding();
        G4int         layer_index   = -1;
        G4int         detector_id   = -1;
        G4ThreeVector position      = step->GetPostStepPoint()->GetPosition();
        G4double      edep          = step->GetTotalEnergyDeposit();

        if (edep > 0.0) {
            // Scintillator
            G4VPhysicalVolume *Volume1 = touchable->GetHistory()->GetVolume(1);
            G4VPhysicalVolume *Volume2 = touchable->GetHistory()->GetVolume(2);
            G4VPhysicalVolume *Volume3 = touchable->GetHistory()->GetVolume(3);
            detector_id = Volume1->GetCopyNo(); // quarter
            layer_index = GetCopy(Volume2->GetName().c_str()); // layer
```

GDML : Geometry Description Markup Language

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no" ?>
<gdml xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:noNamespaceSchemaLocation="/work/hallc/nps/keagan/geant4/gdml/schema/gdml.xsd">

    <define>
        <constant name="DETECTOR_WIDTH"         value="75."/>
        <constant name="DETECTOR_HEIGHT"        value="75."/>
        <constant name="SCINTILLATOR_THICKNESS" value="2.5"/>
        <constant name="ABSORBER_THICKNESS"     value="25."/>
        <constant name="LAYER_SPACING"          value="0.5"/>
        <constant name="NUM_SCINTILLATORS"      value="4"/>

        <quantity name="detector_height" type="length" value="DETECTOR_HEIGHT" unit="cm"/>
        <quantity name="detector_width" type="length" value="DETECTOR_WIDTH" unit="cm"/>
        <quantity name="detector_thickness" type="length"
                  value="3*SCINTILLATOR_THICKNESS + 3*ABSORBER_THICKNESS + 5*LAYER_SPACING"
                  unit="cm"/>

        <quantity name="scintillator_width" type="length"
                  value="DETECTOR_WIDTH/NUM_SCINTILLATORS" unit="cm"/>
        <quantity name="scintillator_thickness" type="length" value="SCINTILLATOR_THICKNESS" unit="cm"/>

        <quantity name="absorber_thickness" type="length" value="ABSORBER_THICKNESS" unit="cm"/>
        <quantity name="spacing" type="length" value="LAYER_SPACING" unit="cm"/>
```

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Physics is specified using a **modular physics list**

```
G4VModularPhysicsList* physicsList = new FTFP_BERT;
physicsList->RegisterPhysics(new NPSAddOptics("Cerenkov & Scintillation") );
physicsList->RegisterPhysics(new G4StepLimiterPhysics());
runManager->SetUserInitialization(physicsList);
```

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```
ifstream file("beam_definition.txt");

string line;
istringstream iss;

getline(file, line);  iss.str(line);
iss >> fParticleName;
getline(file, line);  iss.str(line);
iss >> fPmin >> fPmax;
getline(file, line);  iss.str(line);
iss >> fX0 >> fY0 >> fZ0;
getline(file, line);  iss.str(line);
iss >> fDX >> fDY >> fDZ;
getline(file, line);  iss.str(line);
iss >> fThetaX >> fThetaY;
getline(file, line);  iss.str(line);
iss >> fdThetaX >> fdThetaY;
getline(file, line);  iss.str(line);
string mode_flag;
iss >> mode_flag;

file.close();
```

We specify the type of beam in a file called "beam_definition.txt"

We can choose to simulate the electron beam with a **particle gun.**

Or we can choose to feed in DEEPGen generated events for DDVCS.

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Bookkeeping is done at the end of every **Event Action**

```
if(CC) { // Calorimeter Collection
    int n_hit = CC->entries();

    for(int i=0;i<n_hit;i++) {
        G4int boundary_flag = (*CC)[i]->GetBoundaryFlag();
        //Fill Tree if track is within the calorimeter.
        if (boundary_flag == 0) {
            G4ThreeVector pos=(*CC)[i]->GetPos();
            //  G4int detpos = pos.getY() > 0.  ? 1 : -1;
            G4int detpos = (*CC)[i]->GetQuarter();
            G4int col = (*CC)[i]->GetCol();
            G4int row = (*CC)[i]->GetRow();
            G4int pid = (*CC)[i]->GetPID();
            G4double energy = (*CC)[i]->GetEnergy();
            fHistoManager->AddHit(detpos, col, row, energy, pid);
        }
    }
```

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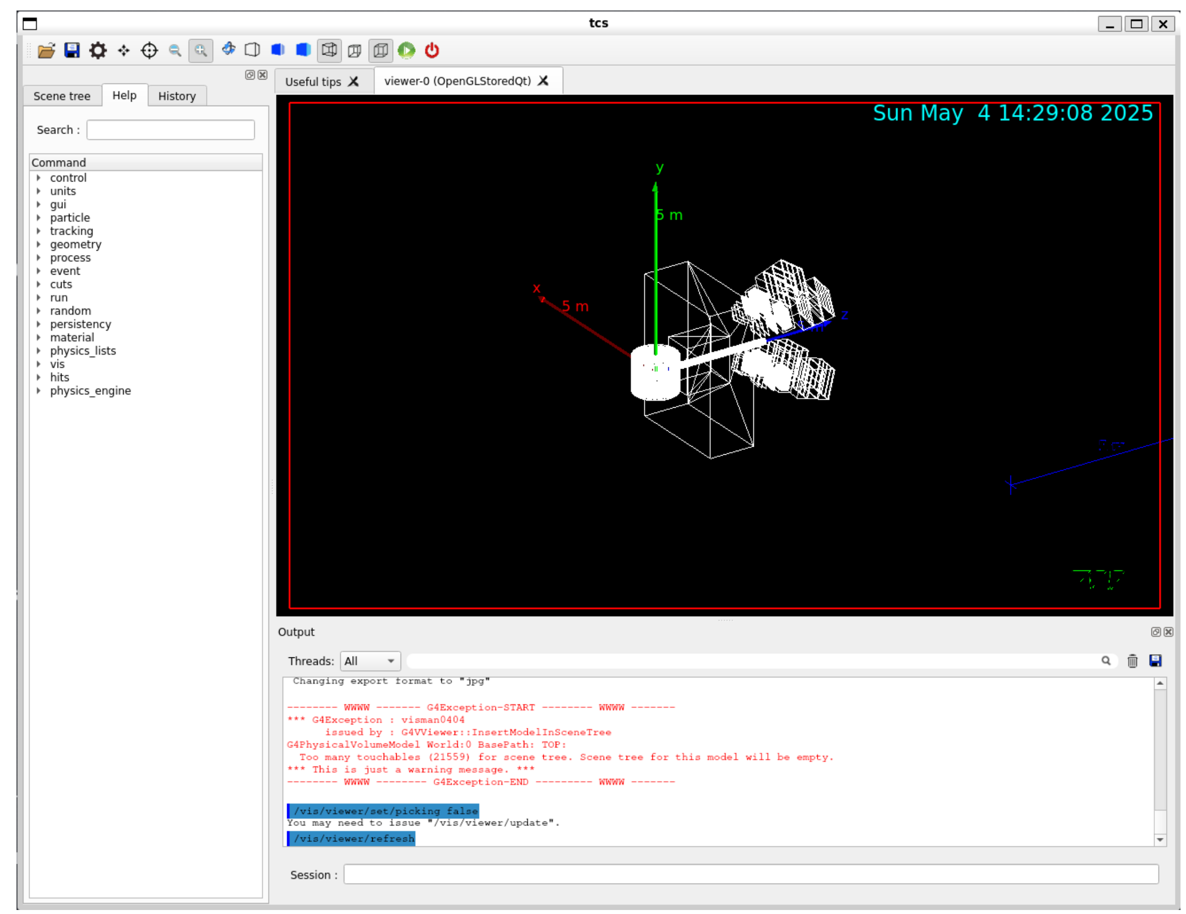
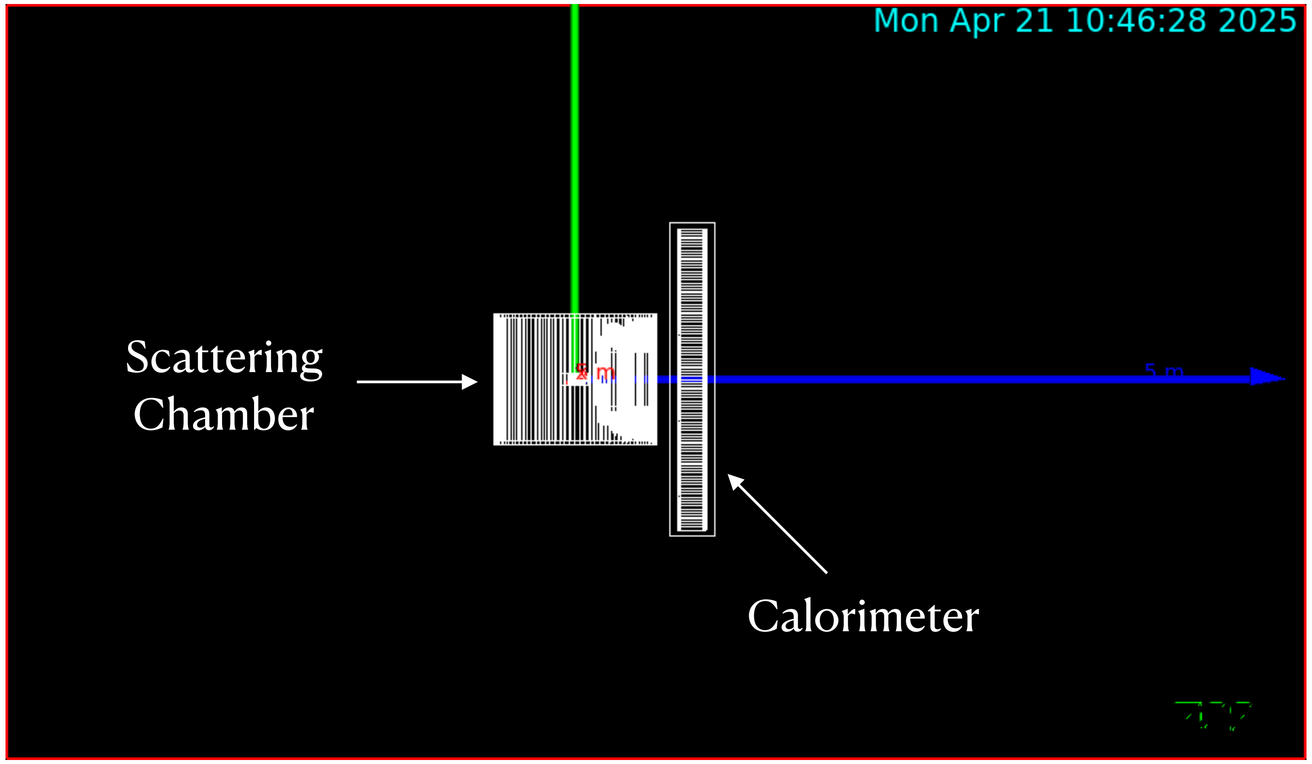
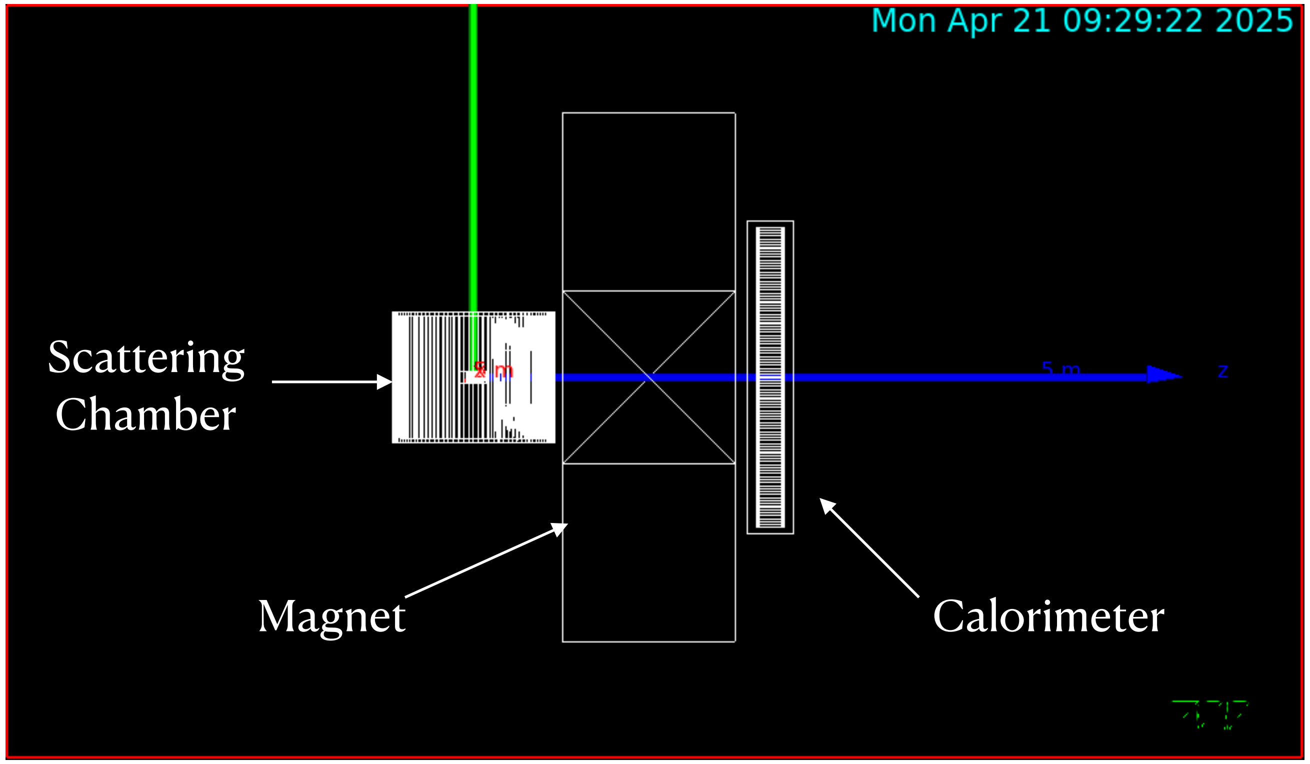
```
# Initialize kernel
/run/initialize
/control/verbose 0
/run/verbose 0
/event/verbose 0
/tracking/verbose 0
/material/g4/printMaterial
#
/run/beamOn 50000
```



The commands are specified in **macro** files.

Simple Setup





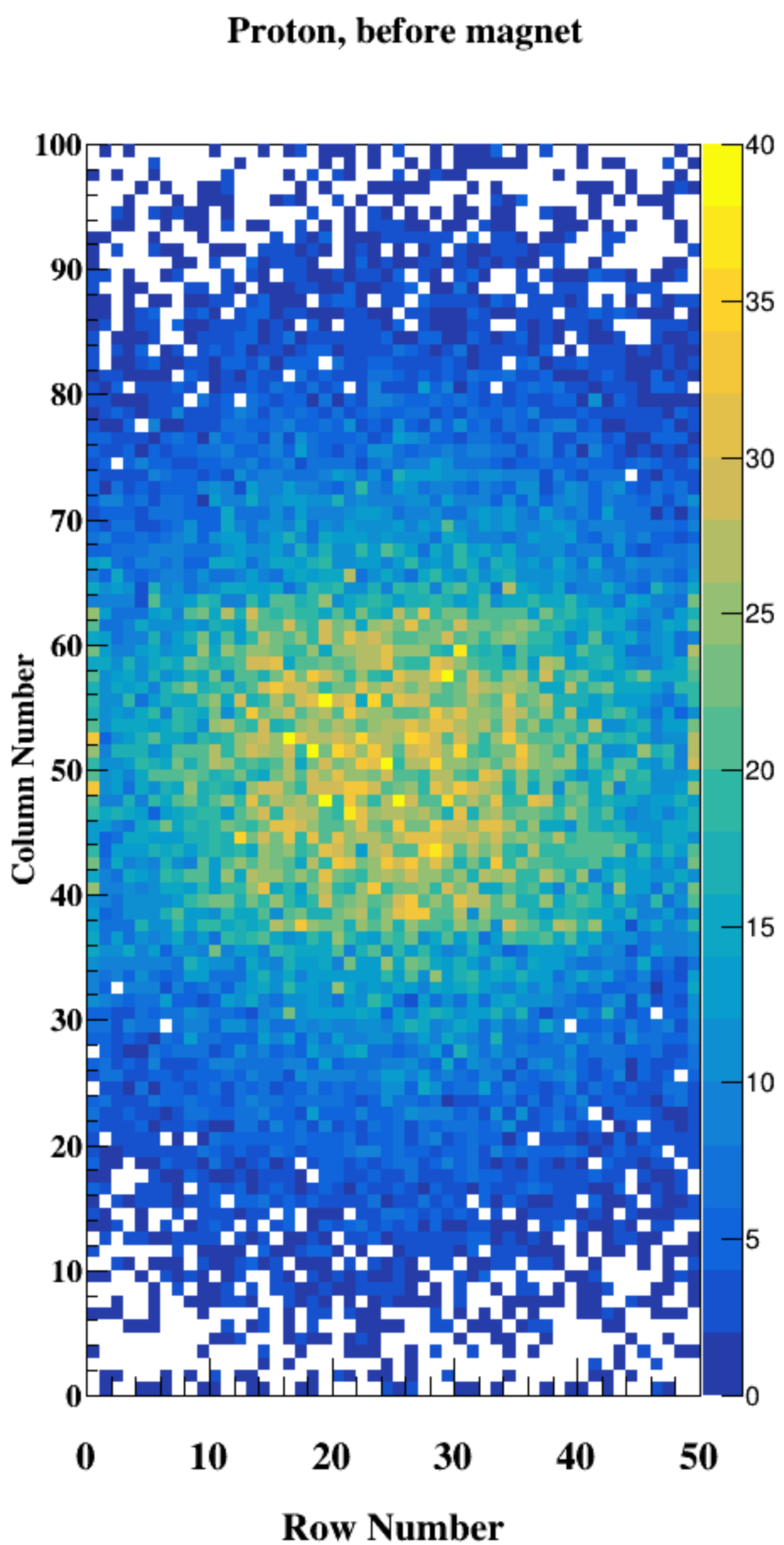
1. One calorimeter plane placed Before magnet
2. Face of the calorimeter is positioned at the location where the entrance to the magnet bore would typically be.

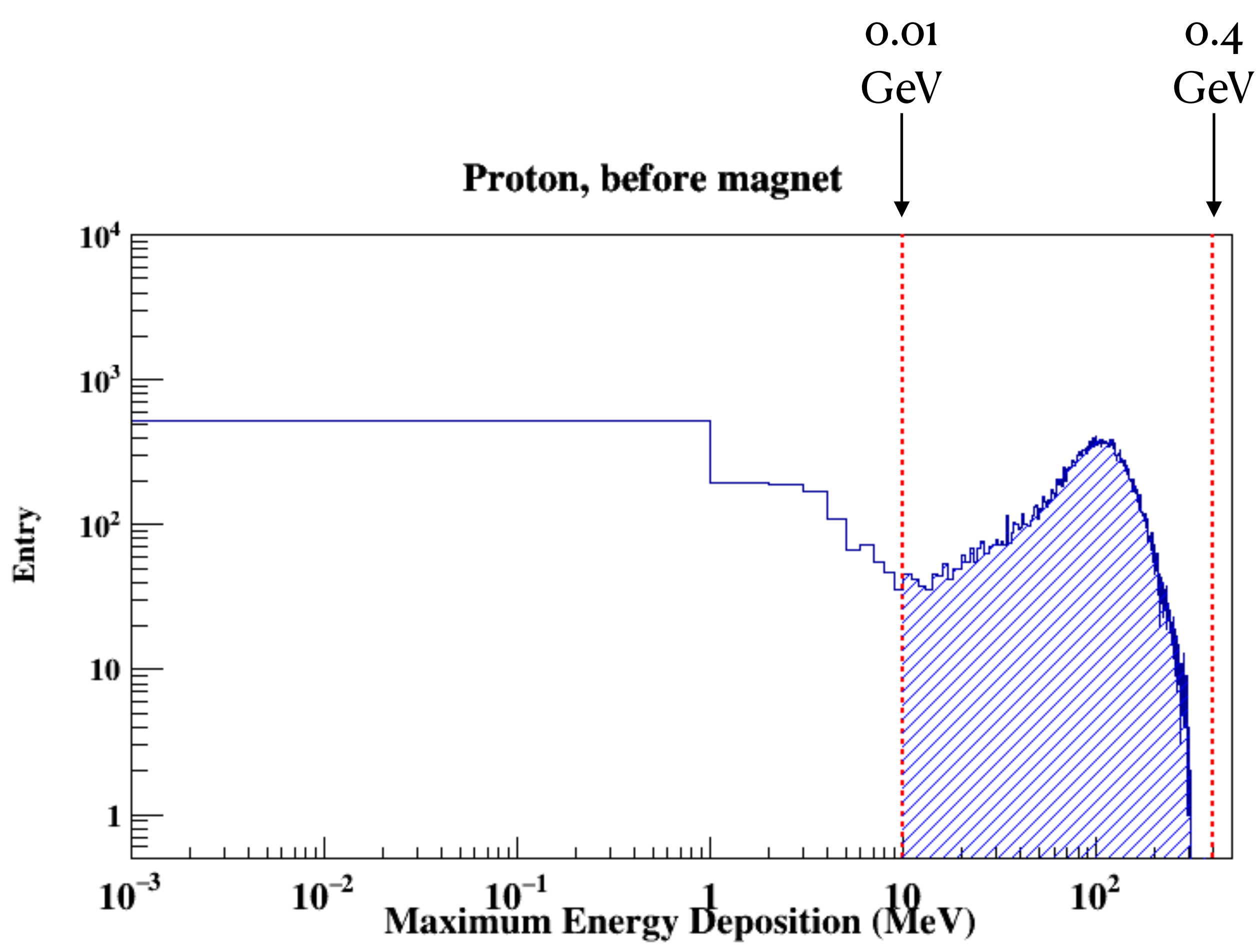
1. One calorimeter plane placed after magnet

Before Magnet

After Magnet

Proton - before magnet

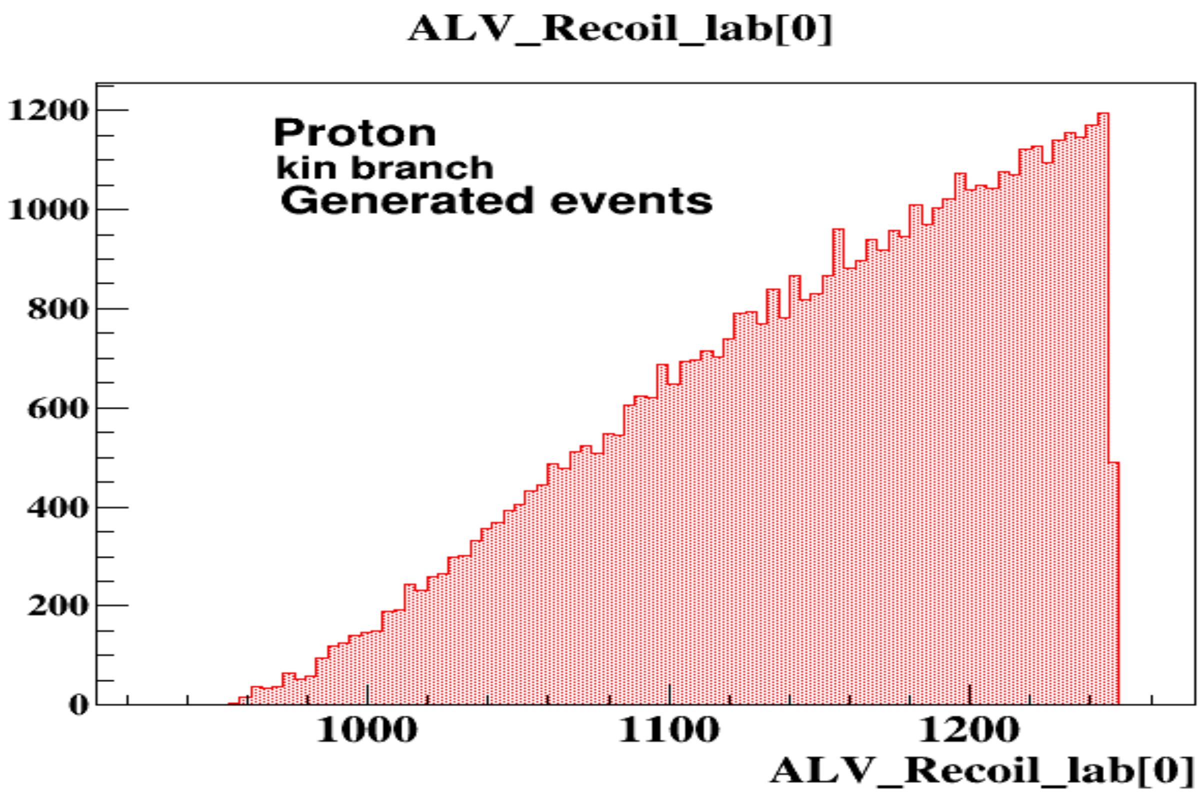




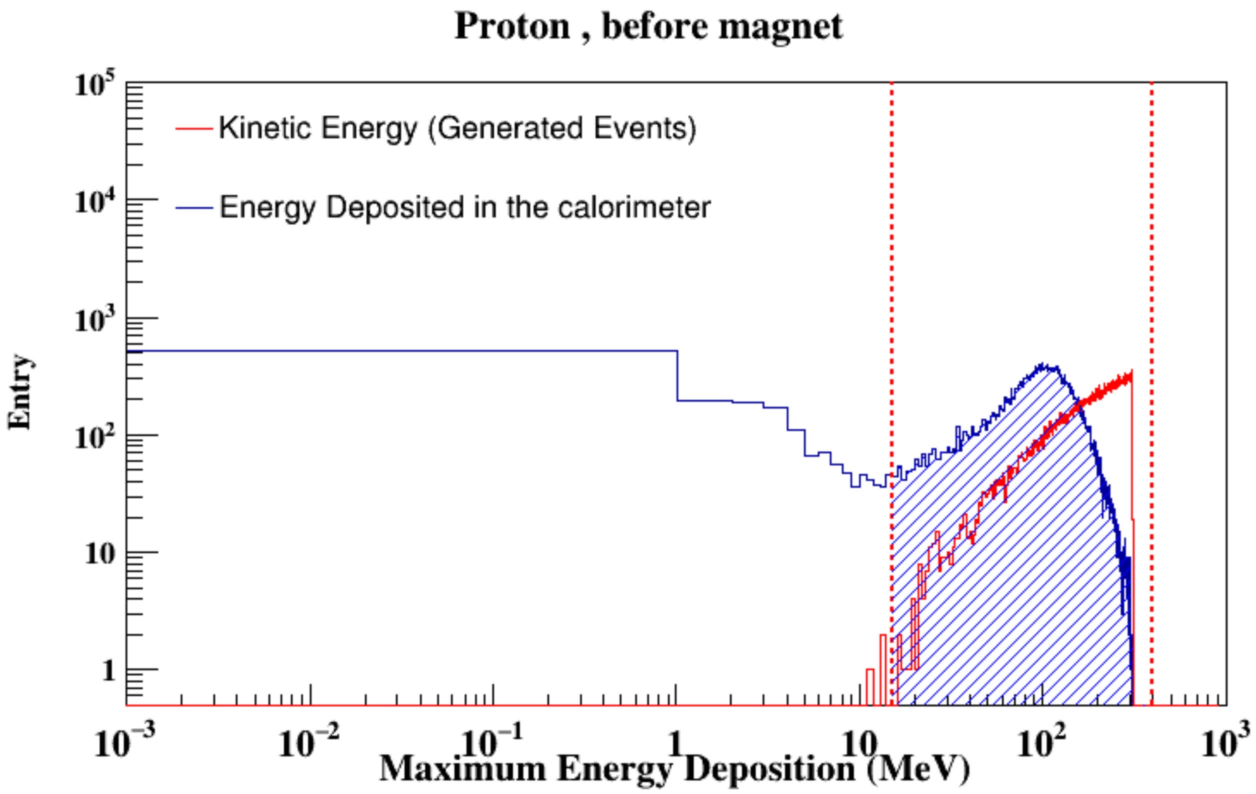
A1 = Area under the curve (blue shaded region)
= 39899

Kinetic Energy of proton

$$E_{K.E.} = E_{total} - m_0c^2$$

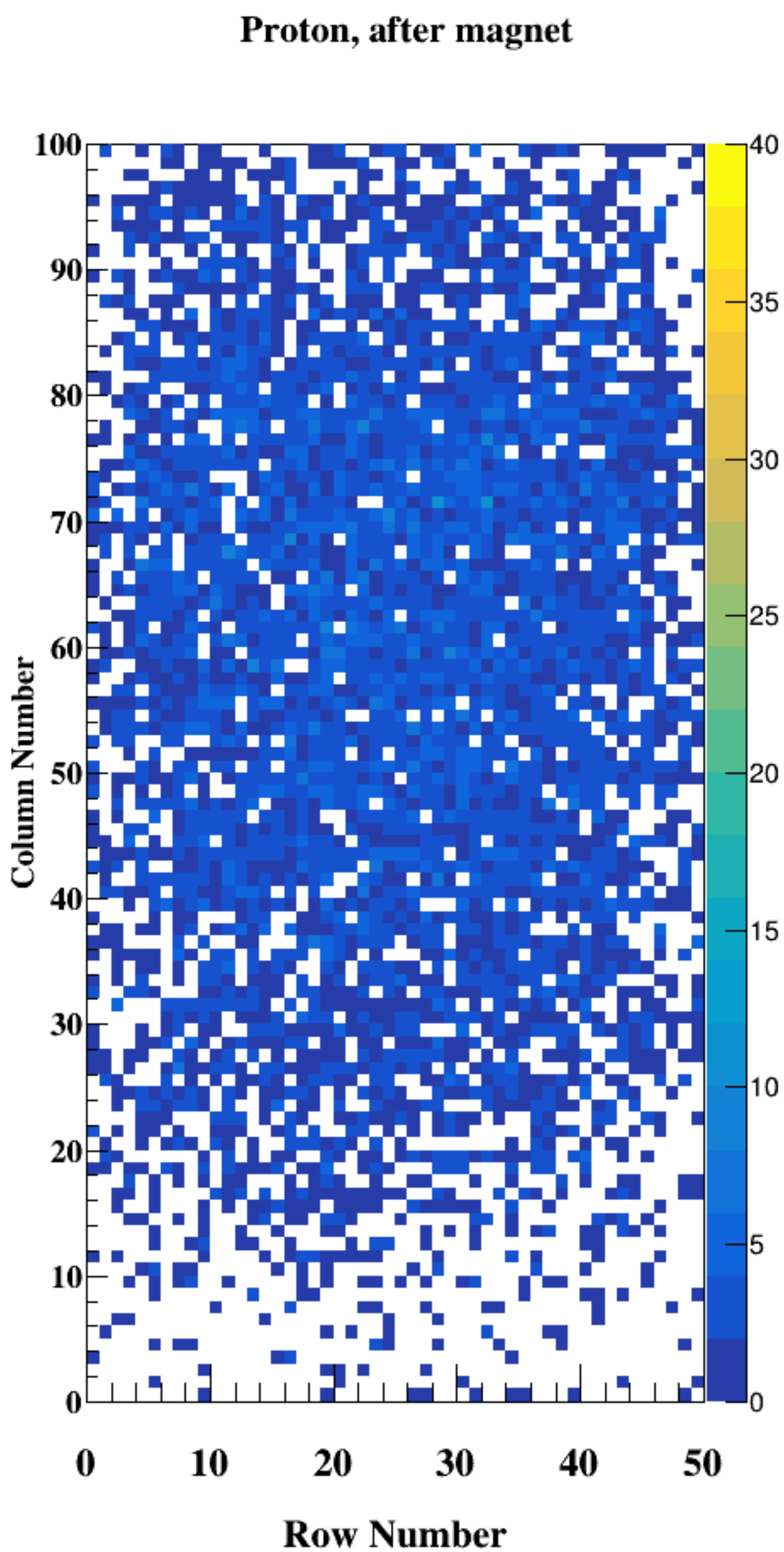


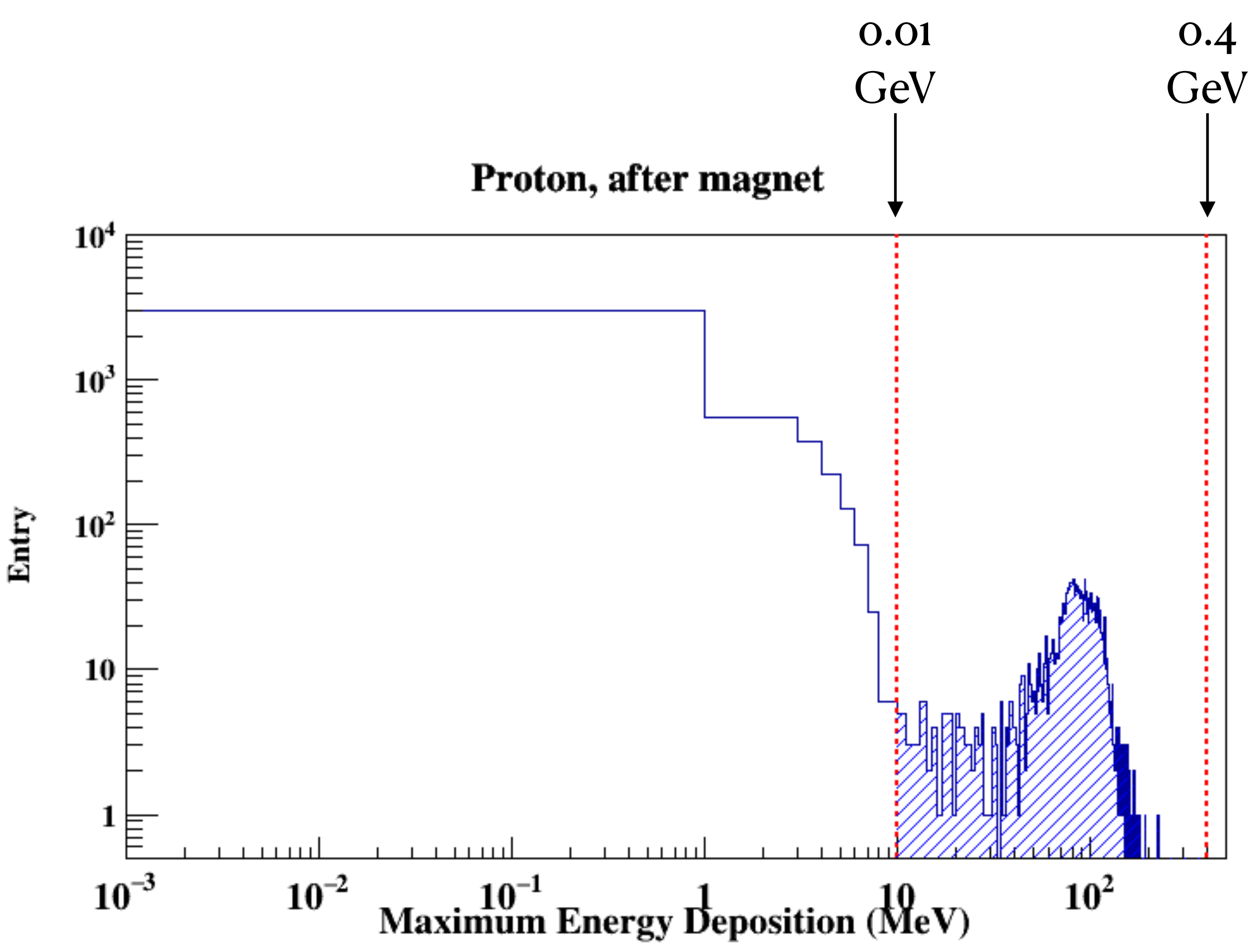
Total Energy of Protons From Generated Events



Kinetic Energy of the Protons

Proton - after magnet

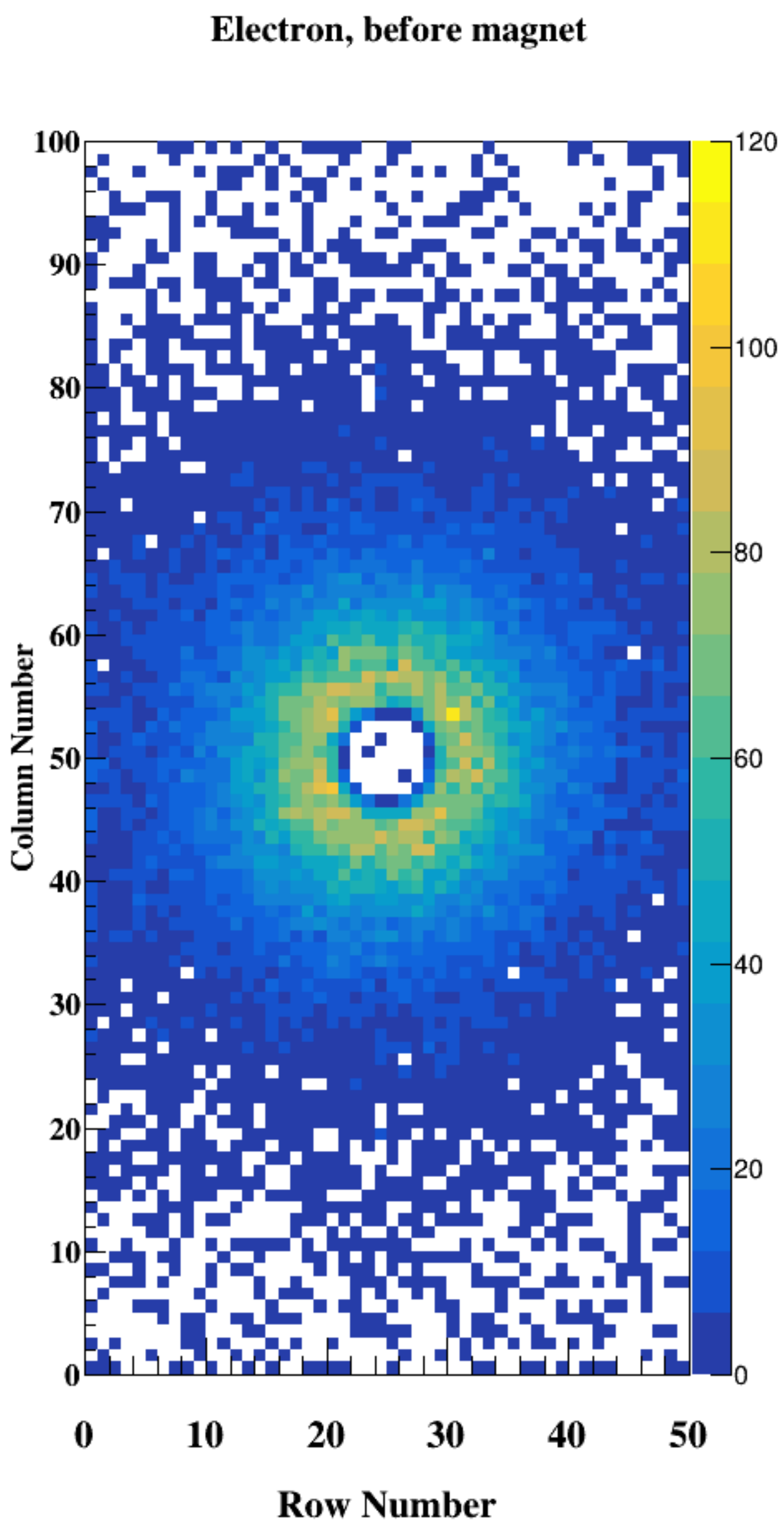


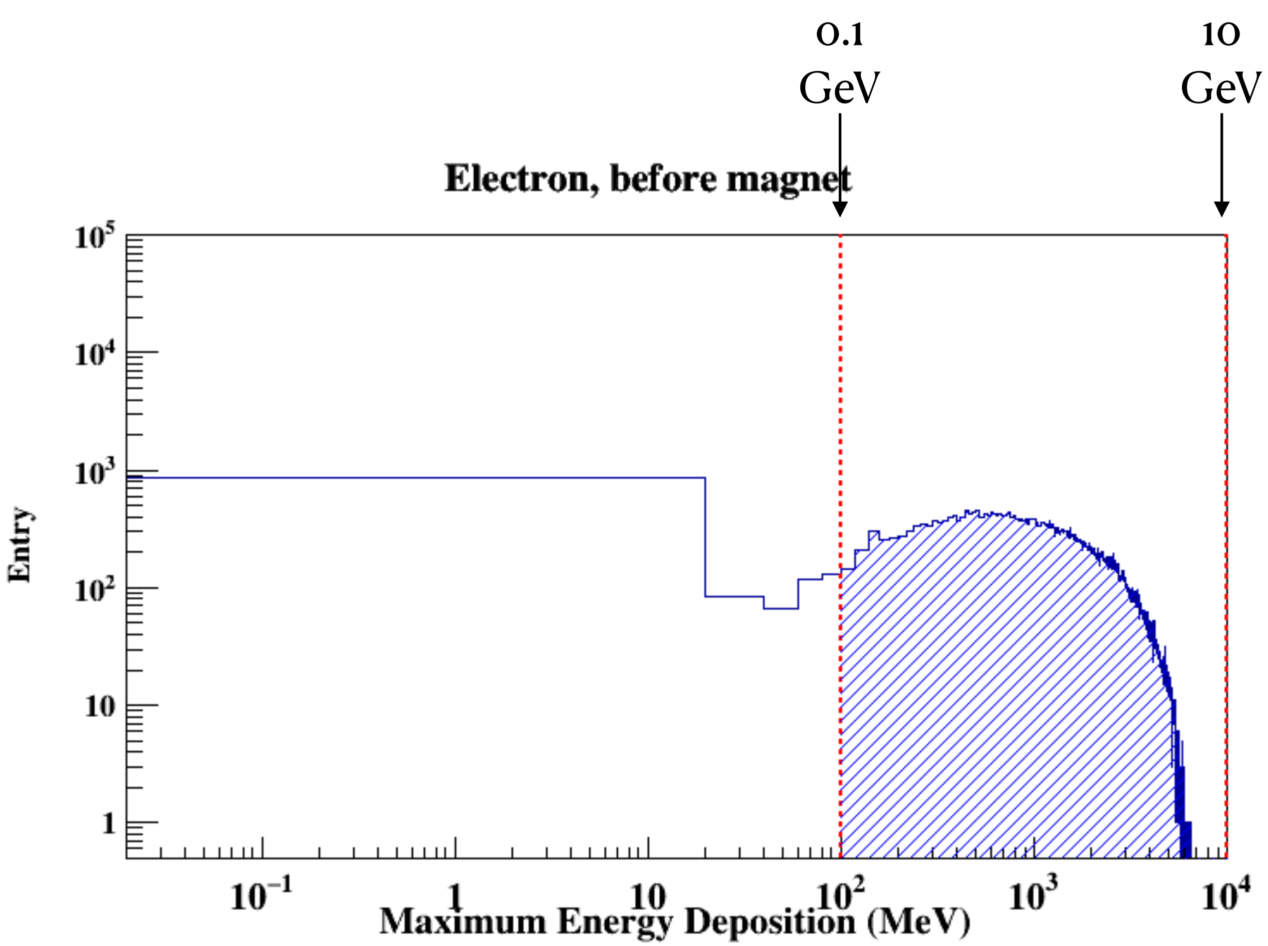


A2 = Area under the curve (blue shaded region) = 1958

Estimated protons passed the magnet :
(A2/A1)*100 = 4.91 %

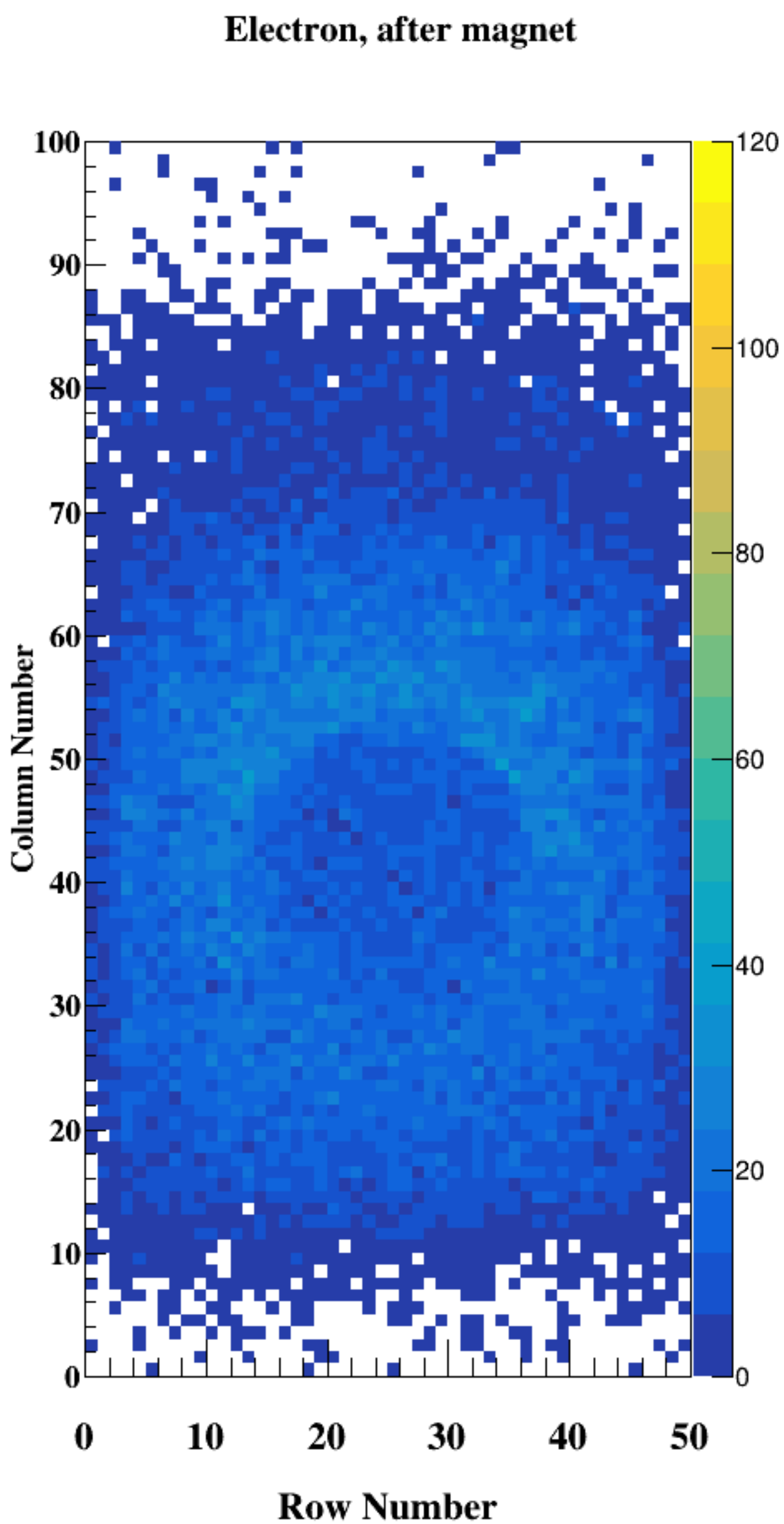
Electron - before magnet



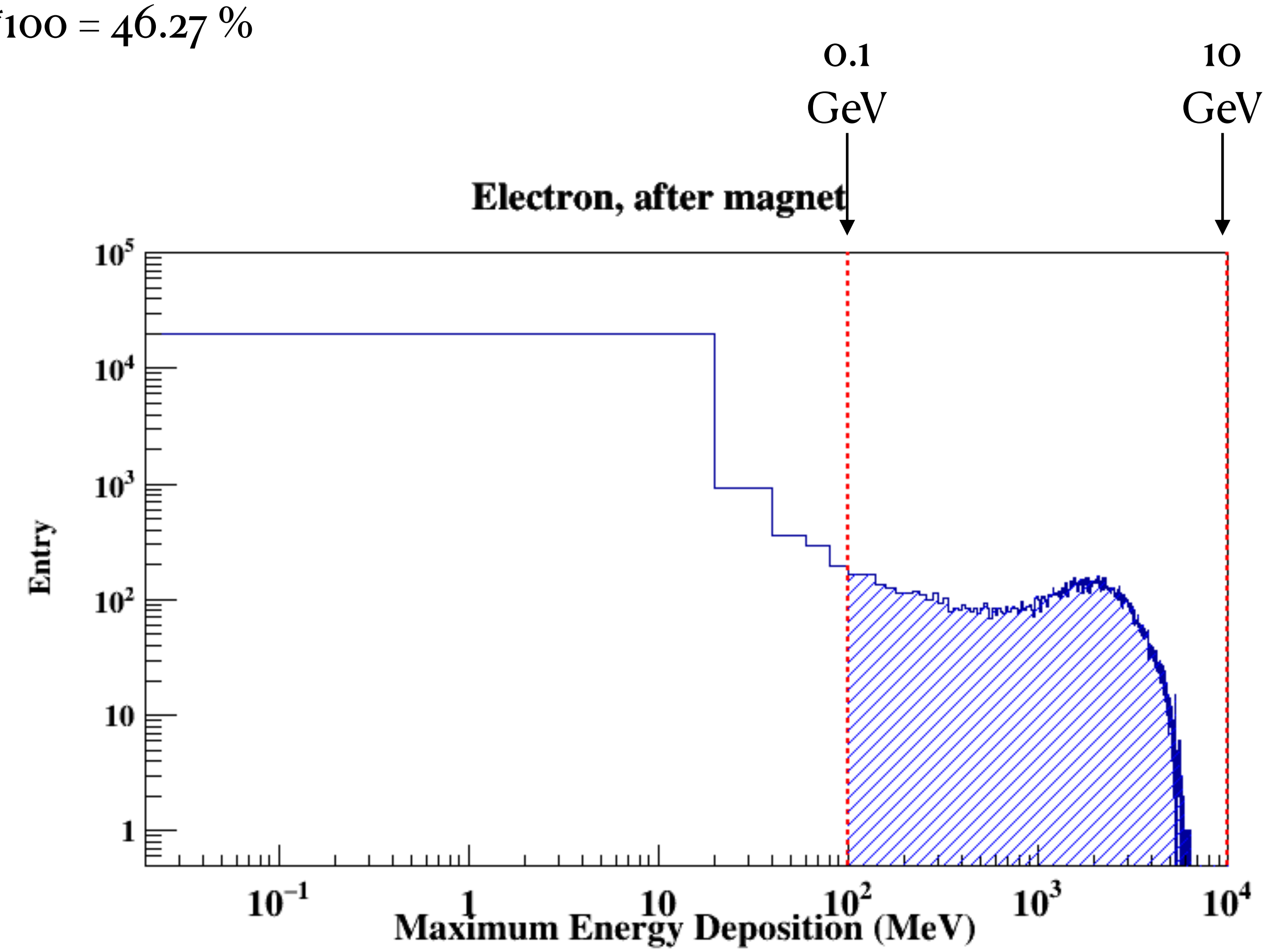


A1 = Area under the curve (blue shaded region)
= 44580

Electron - after magnet



(20627/44580)*100 = 46.27 %

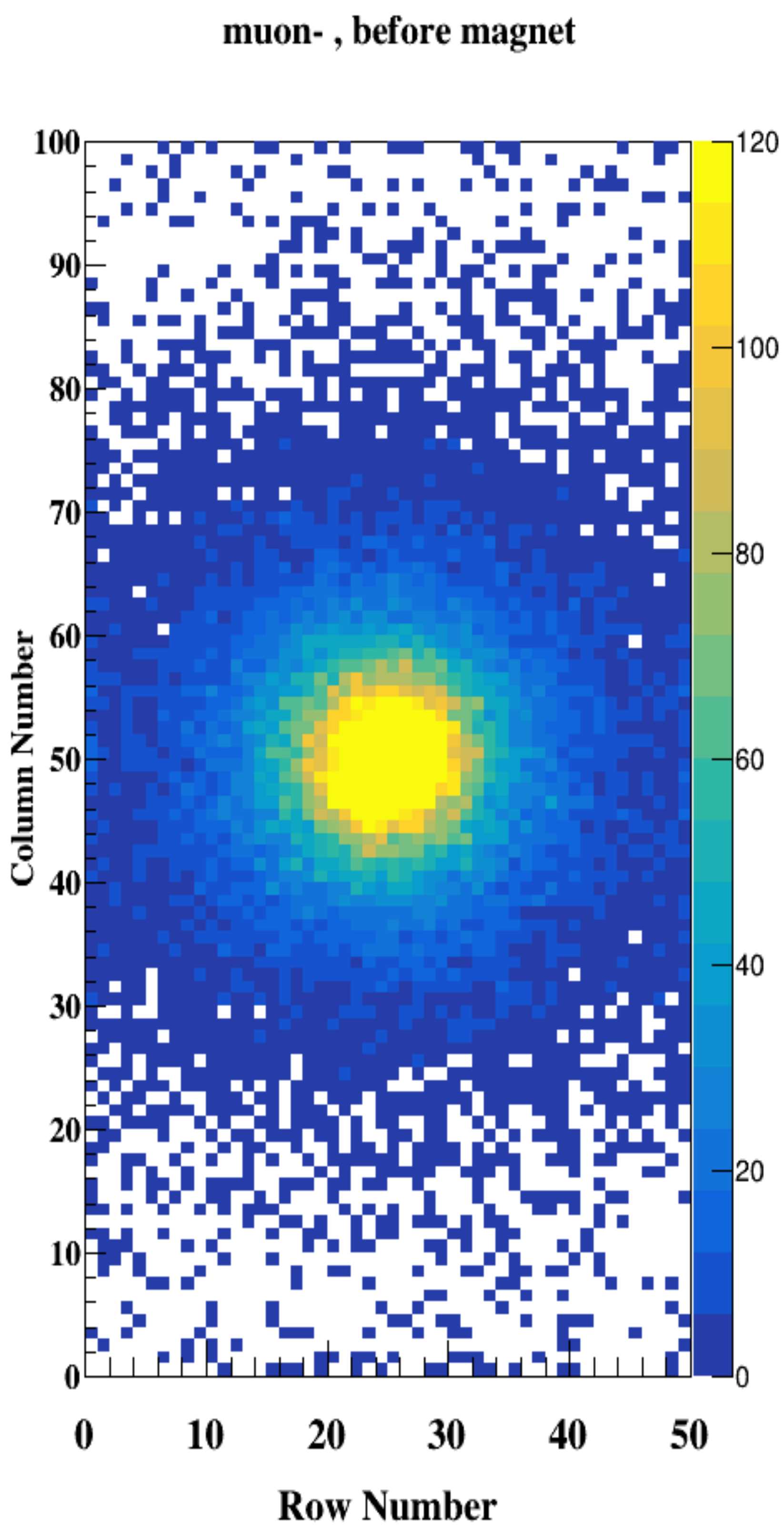


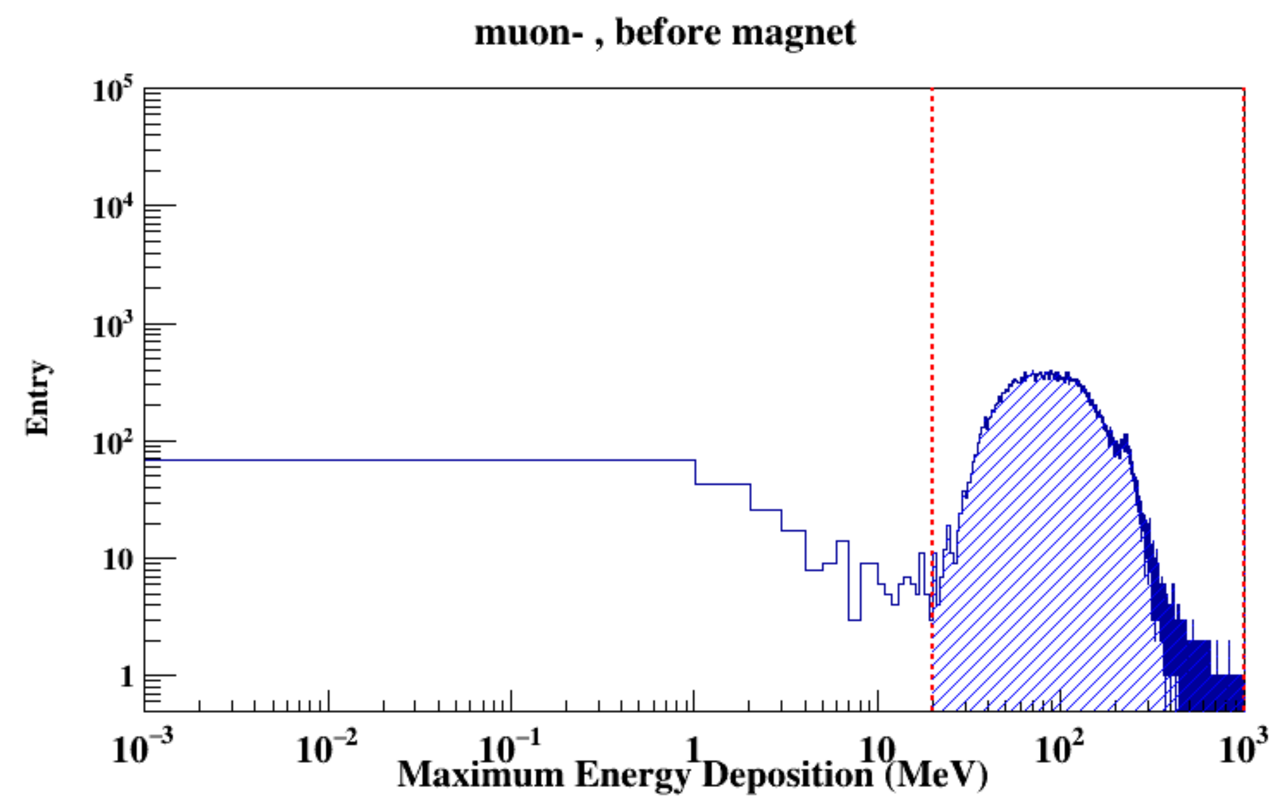
20627

A2 = Area under the curve (blue shaded region) = 20627

Estimated protons passed the magnet :
(A2/A1)*100 = (20627/44580)*100 = 46.27 %

Muon - before magnet

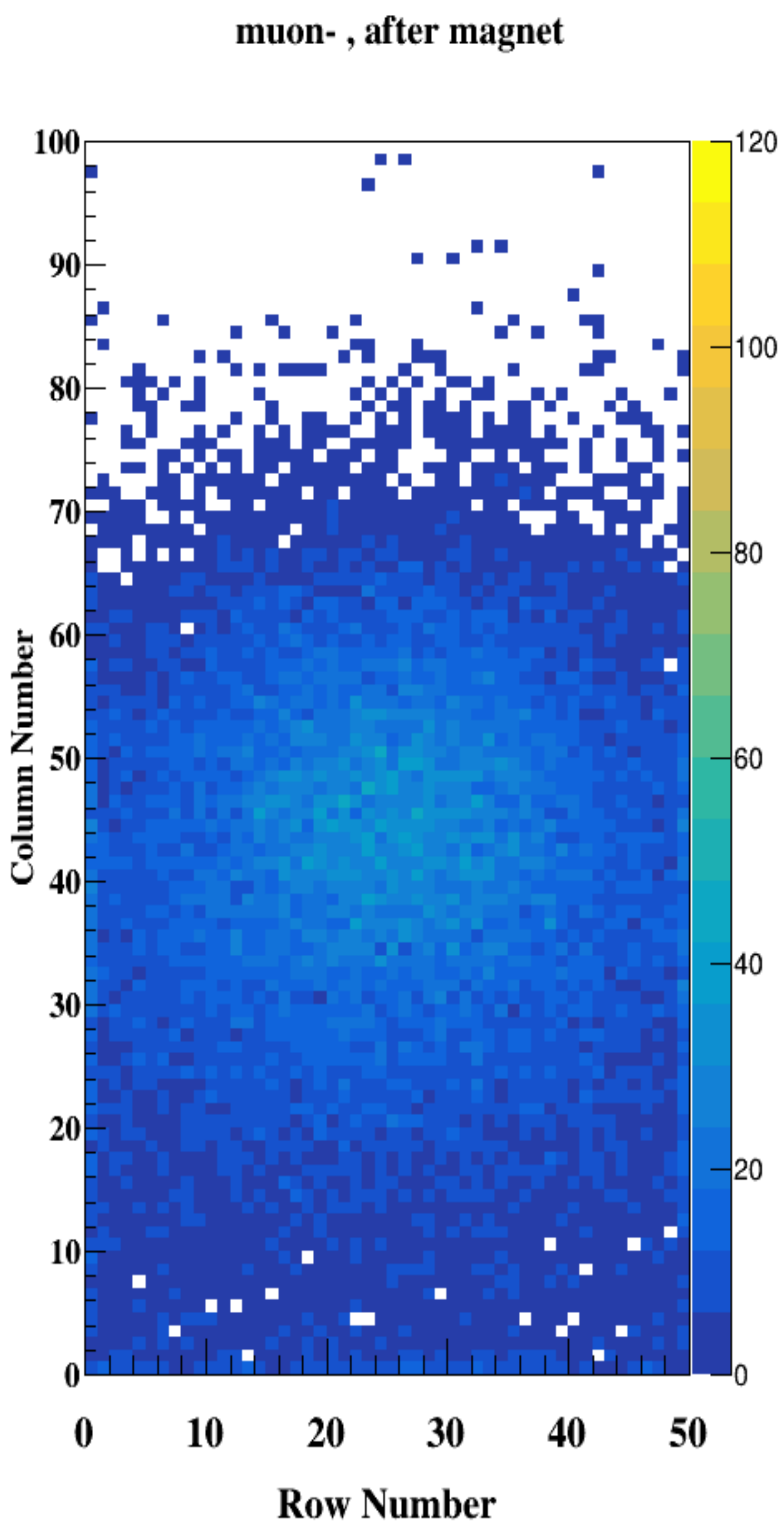


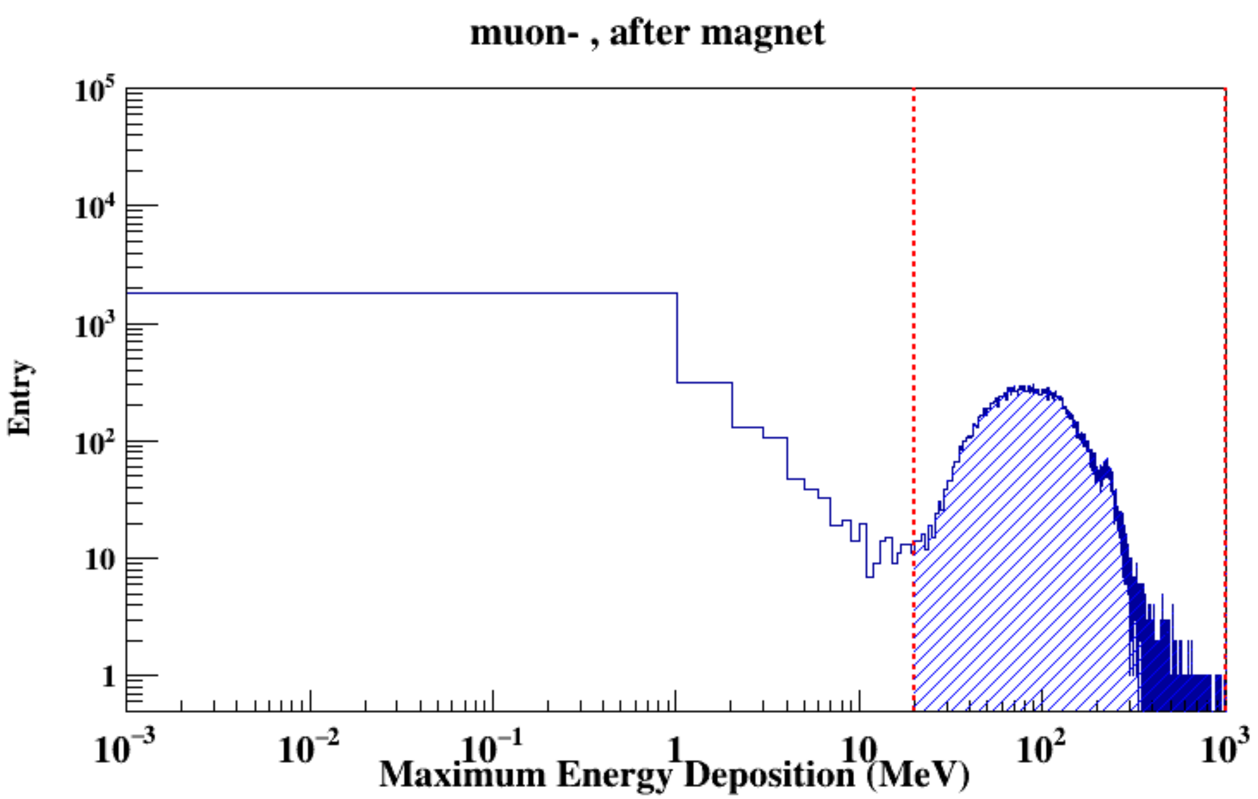


A1 = Area under the curve (blue shaded region)

= 48350

Muon - after magnet

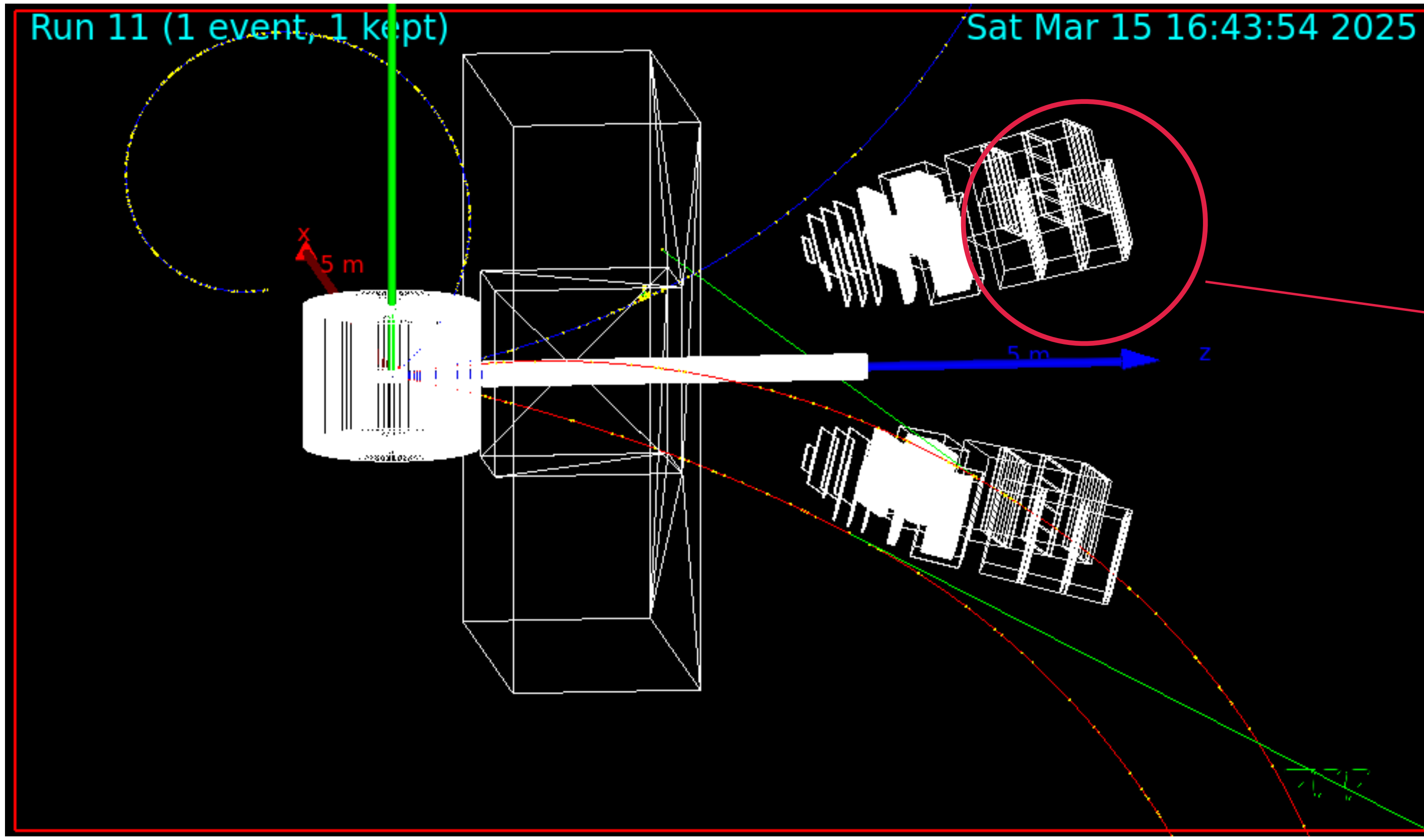


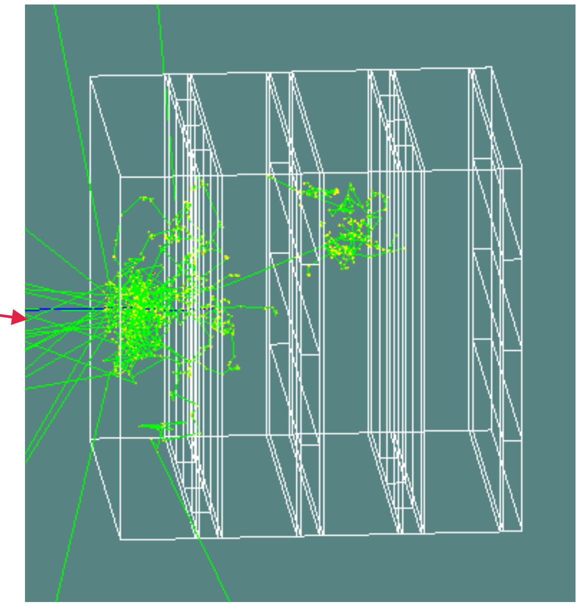


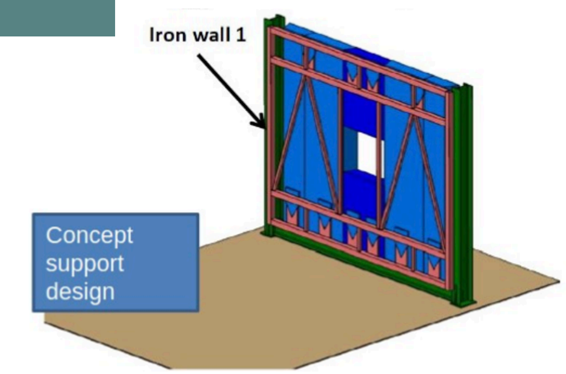
A2 = Area under the curve (blue shaded region) = 34302

Estimated protons passed the magnet :
(A2/A1)*100 = (34302/48350)*100 = 70.95 %

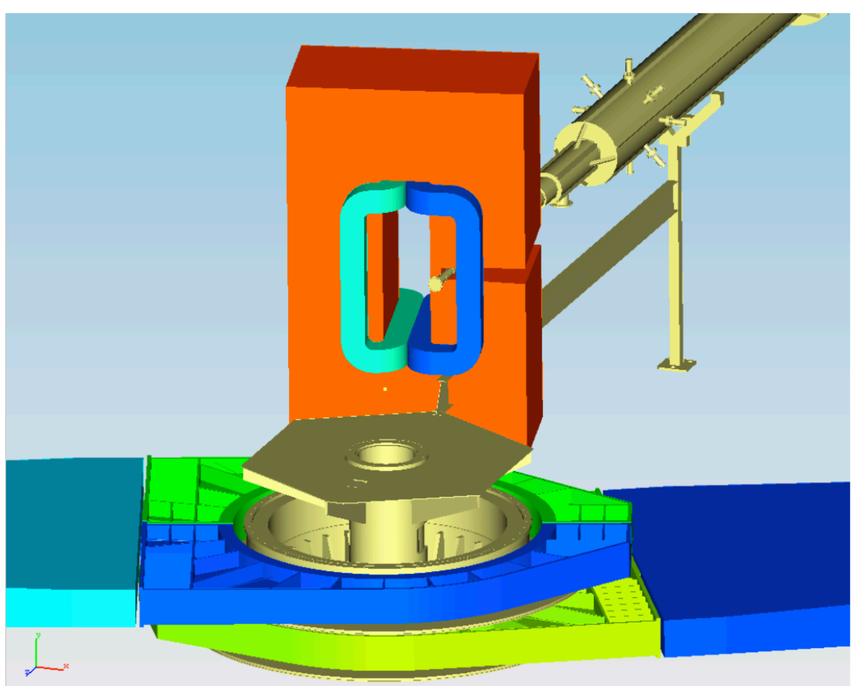
Optimization of the design in progress



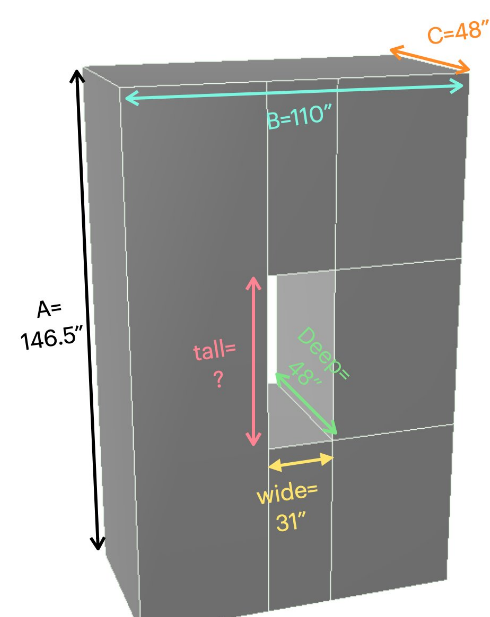




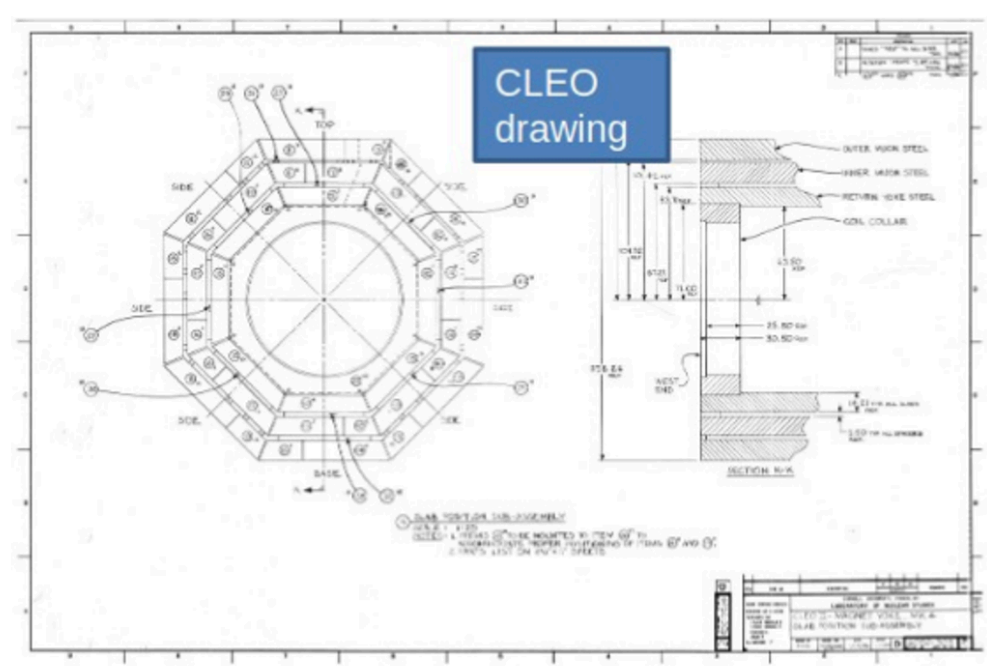
CAD Drawing for Super Bigbite Magnet
Source : https://userweb.jlab.org/~bogdanw/SBS-general.pdf



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

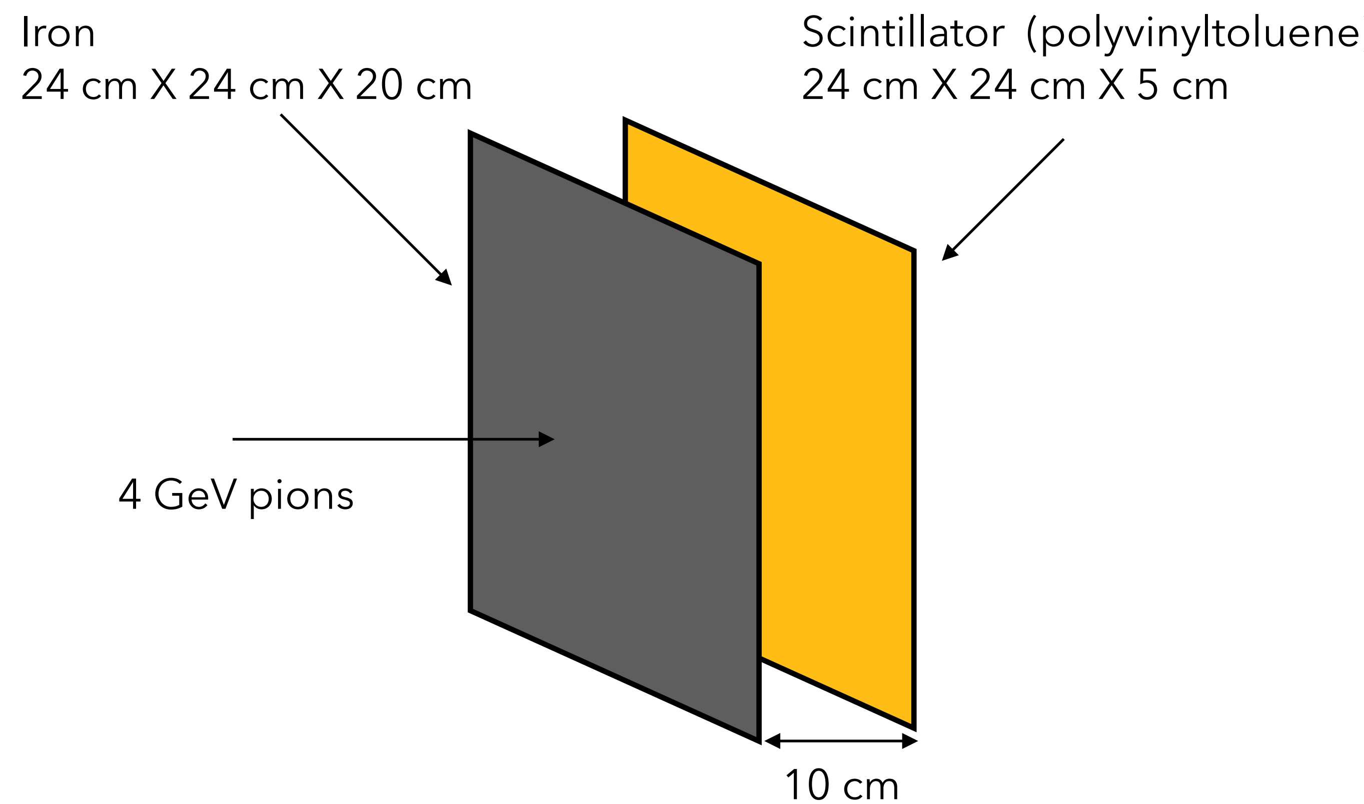


Geant4 simulation of simple magnet geometry

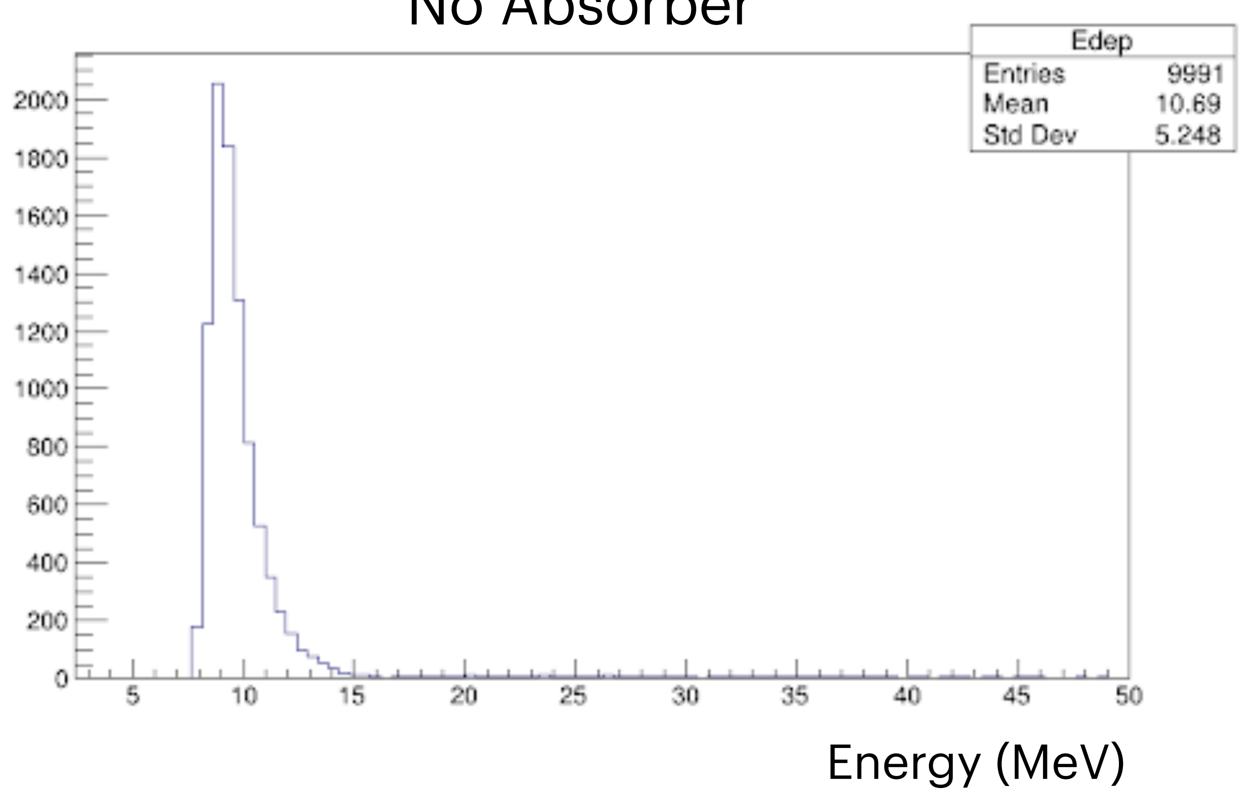


Pion signal w and w/o an absorber in front of scintillator

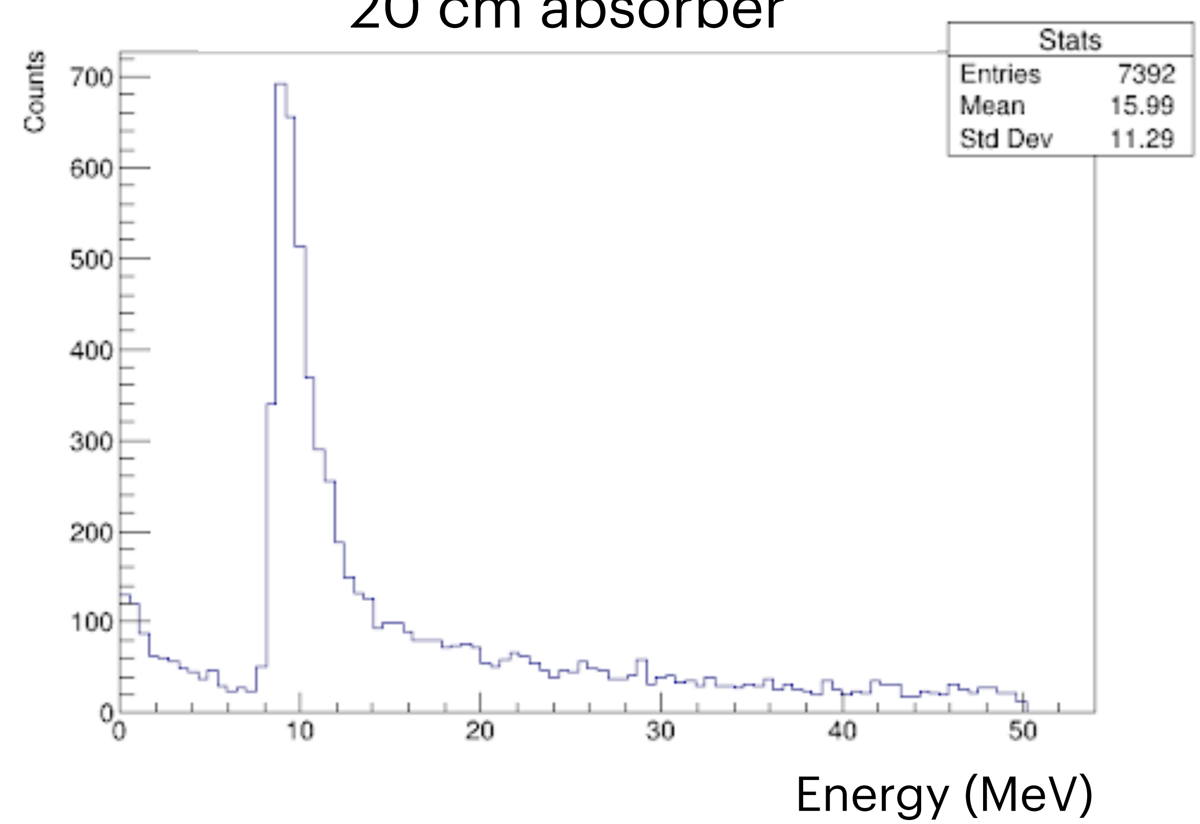
1. 1 absorber - 1 scintillator
2. 4 GeV pions were fired from a particle gun
3. Energy deposited by pions and all other particles generated in the interaction is histogrammed (w and w/o absorber)
4. Distinctive low energy secondary peak (from hadronic interaction of pions with the absorber) emerges in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



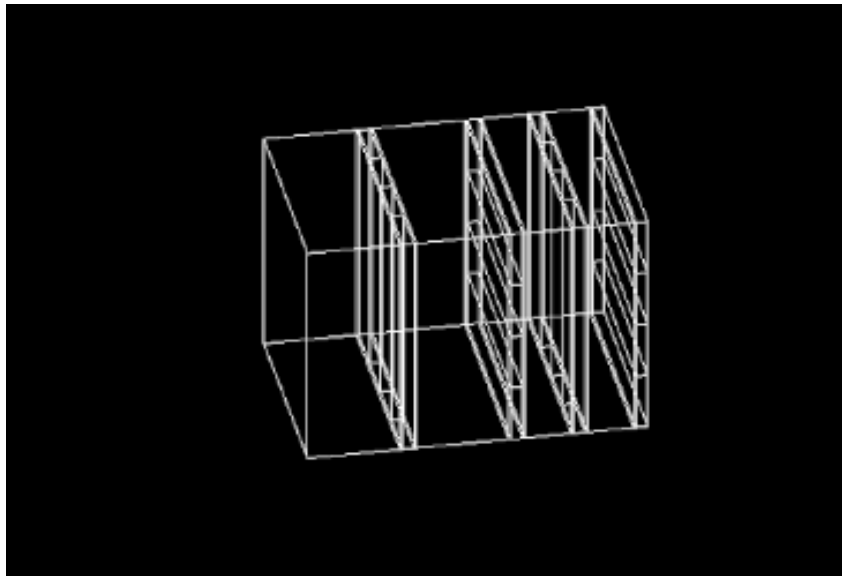
No Absorber



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

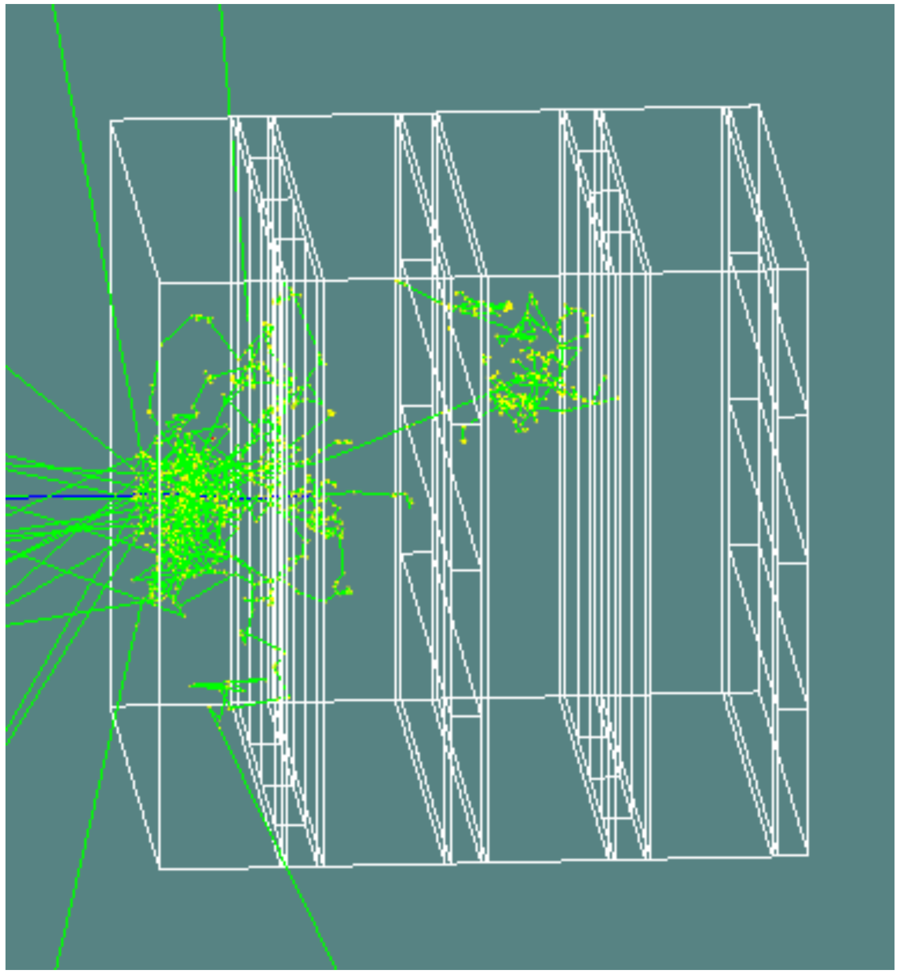
hits in each layer of scintillator				6 GeV
particle	scint 1	scint 2	scint 3	scint 4
mu-	10000	9997	9996	9994
pi+	3001	417	146	50

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

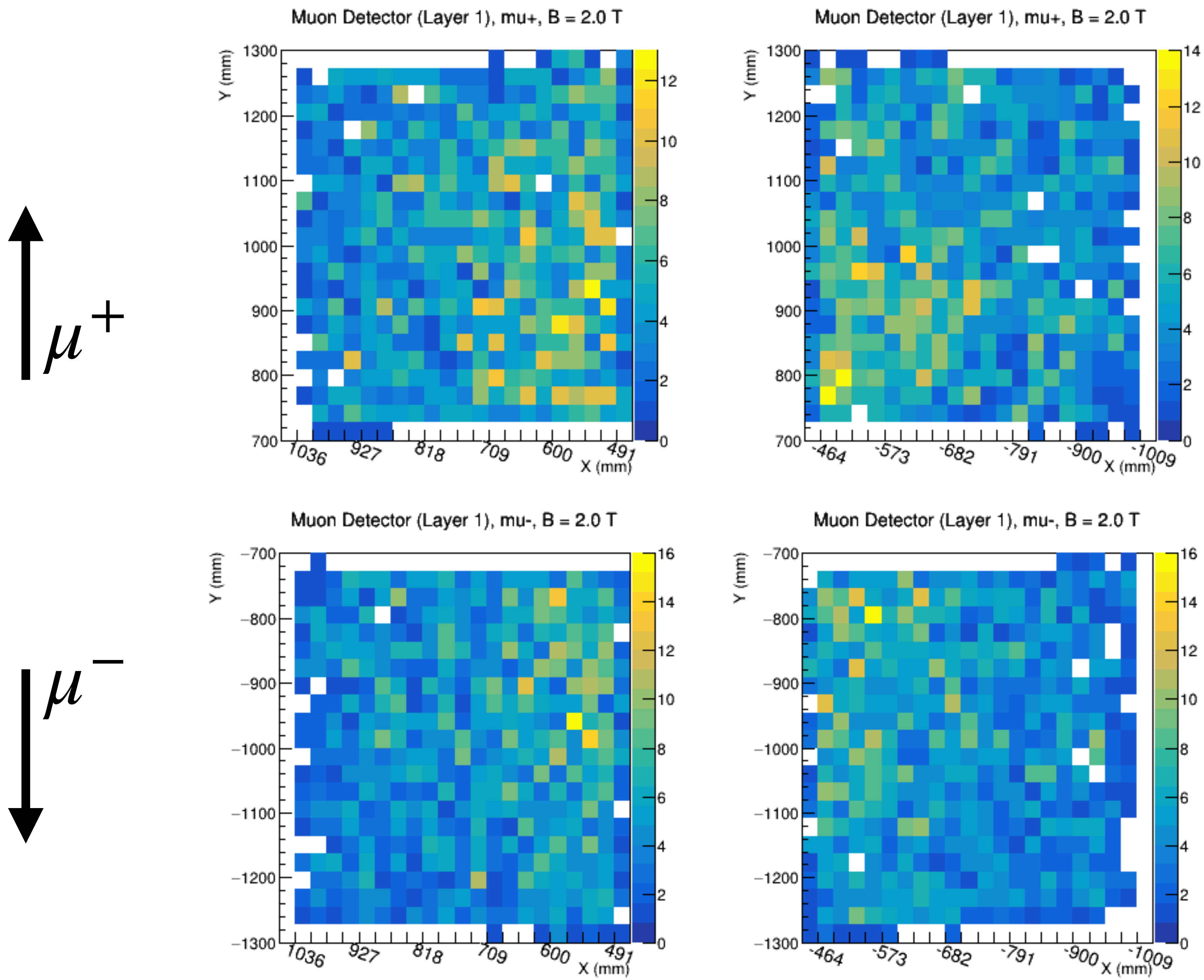
Muon Detector Design

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:

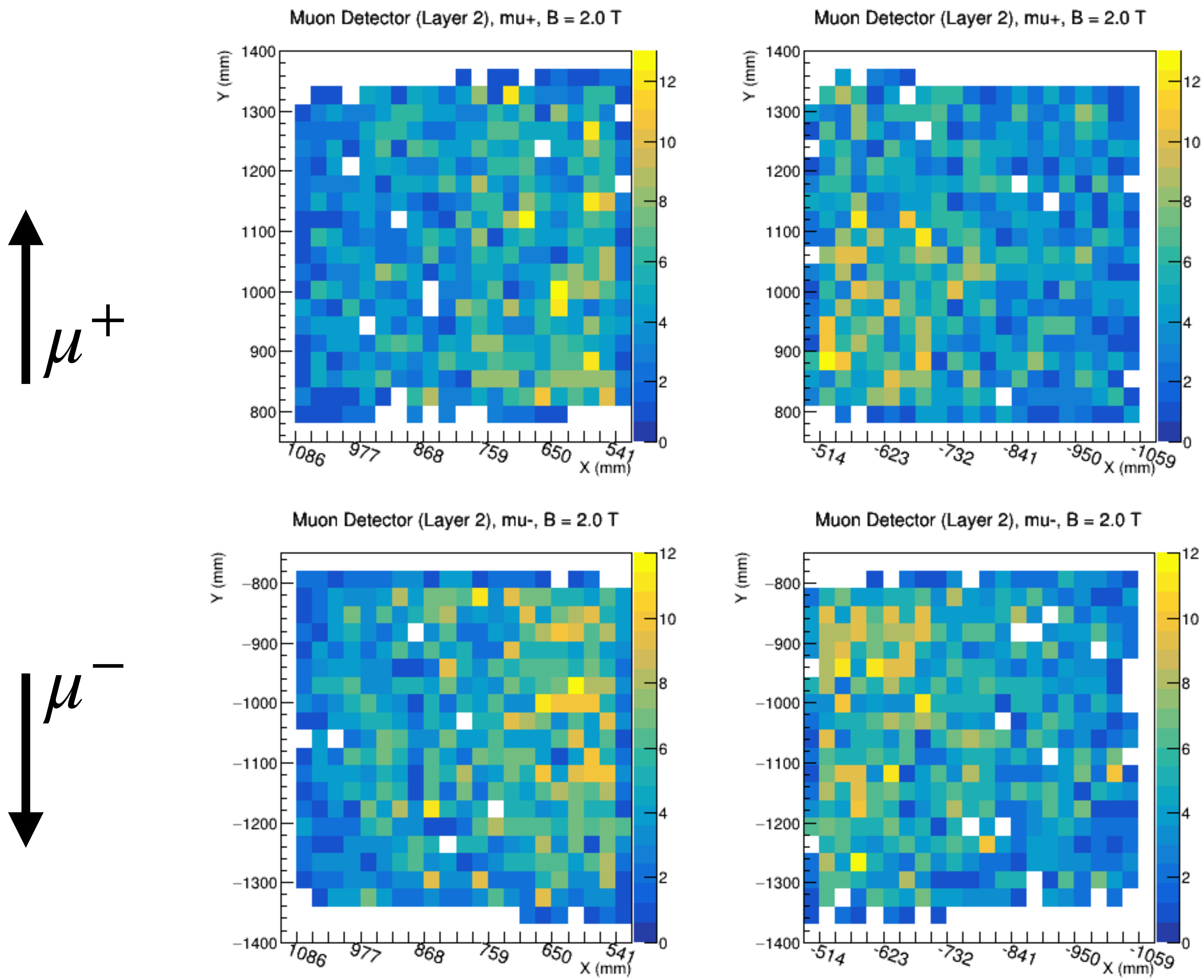
- Distance from target: **~370 cm**
- Dimensions: **56 cm by 56 cm**
- Scintillator:
    - Material: **Polystyrene**
    - Thickness: **2.5 cm** per layer
- Pion Absorber:
    - Material: **Iron**
    - Thickness: **25 cm** per layer



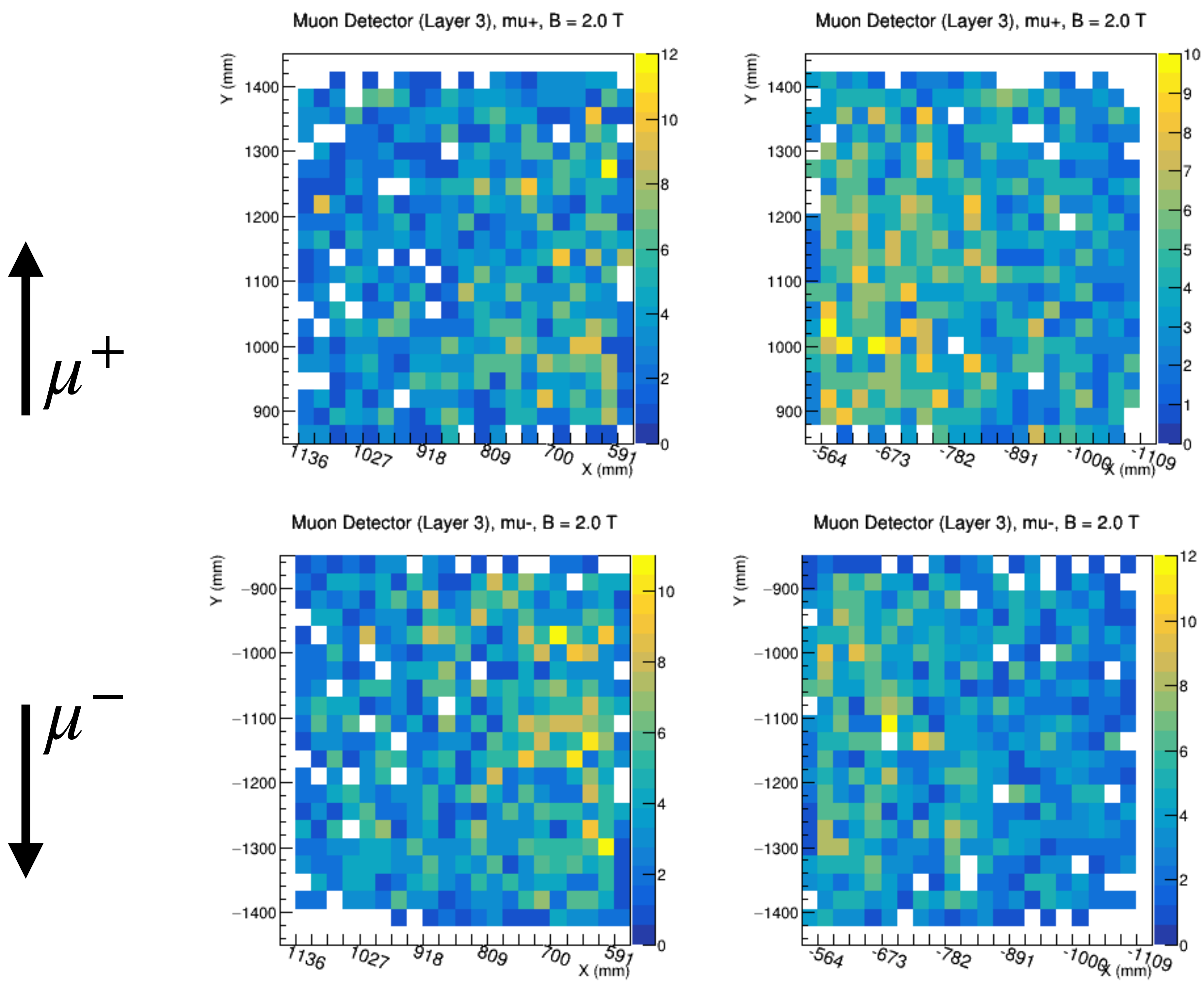
Muon Occupancy - 1st scintillator layer



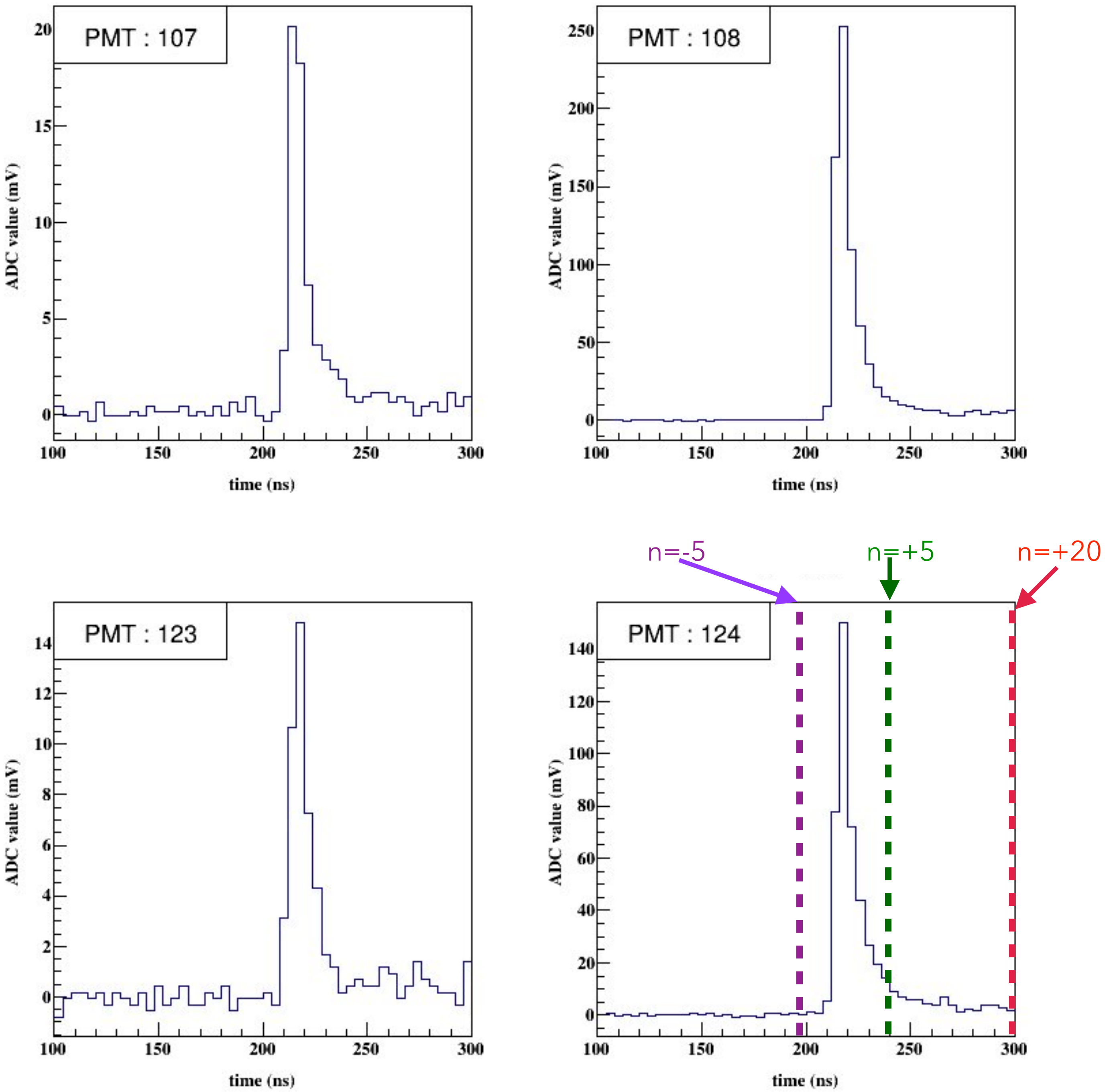
Muon Occupancy - 2nd scintillator layer



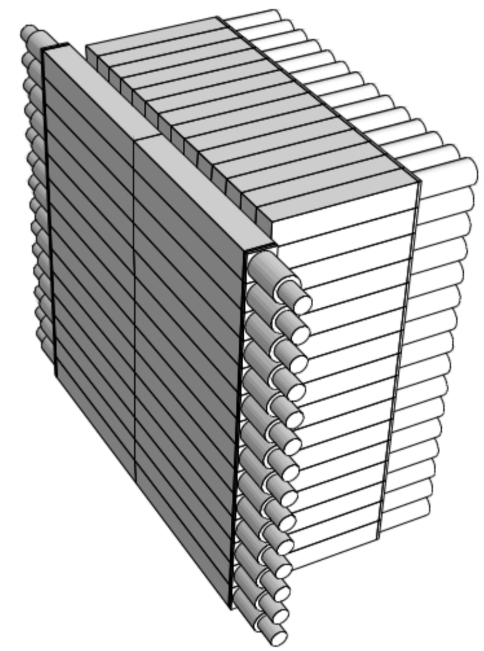
Muon Occupancy - 3rd scintillator layer



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



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



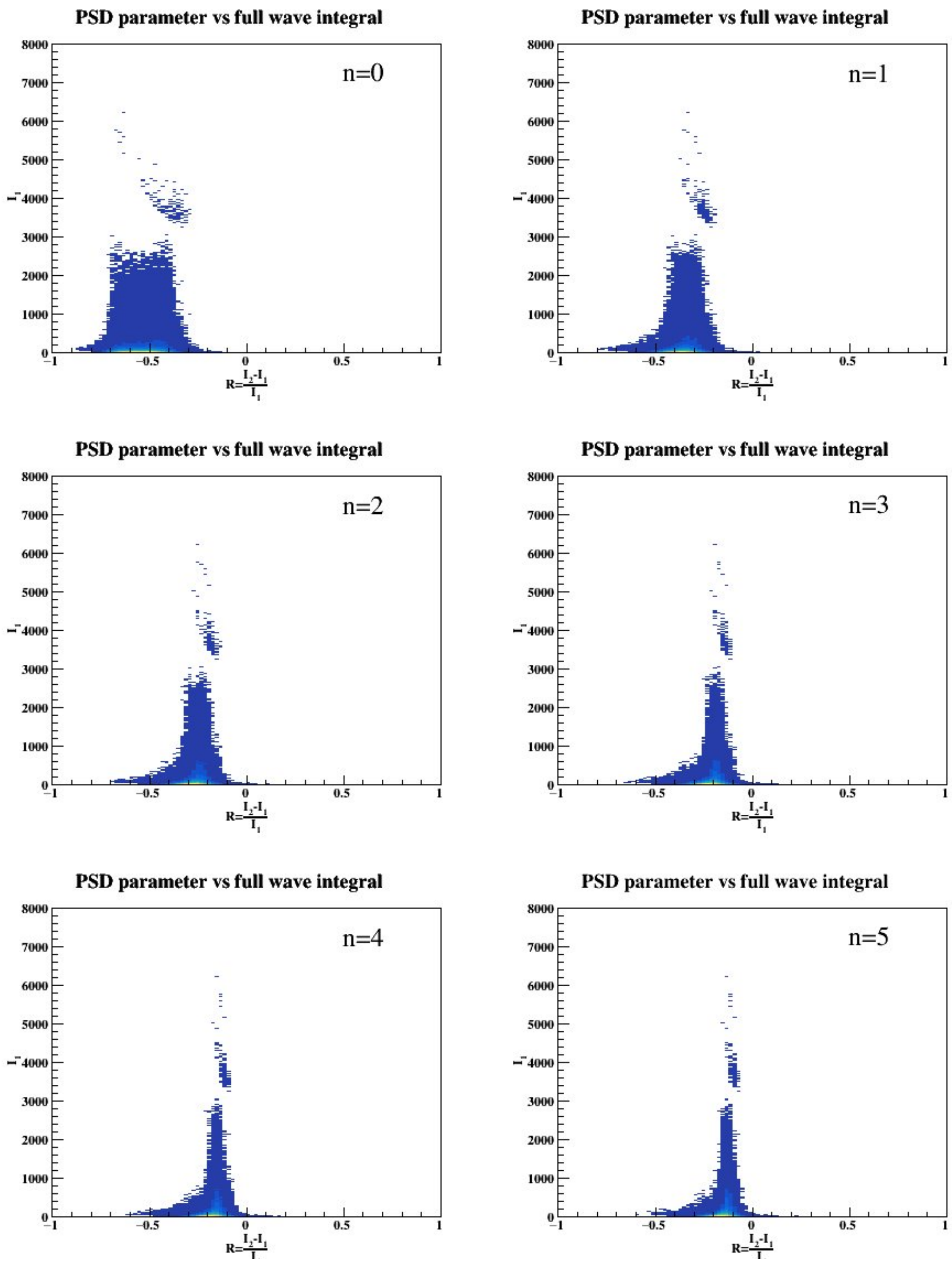
SHMS Calorimeter : shower counter

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 : $R = (I_2 - I_1)/I_1$

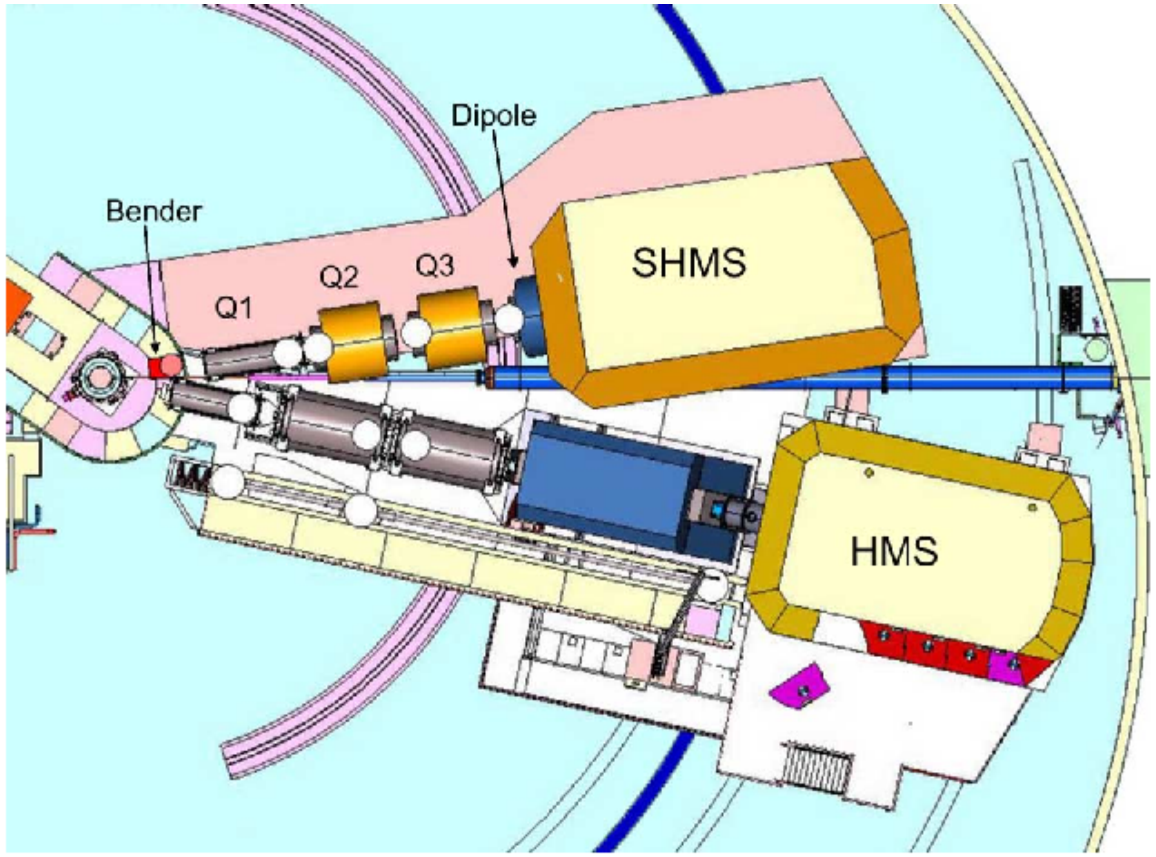
Pulse Shape Discrimination : e^{-}/π PID



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

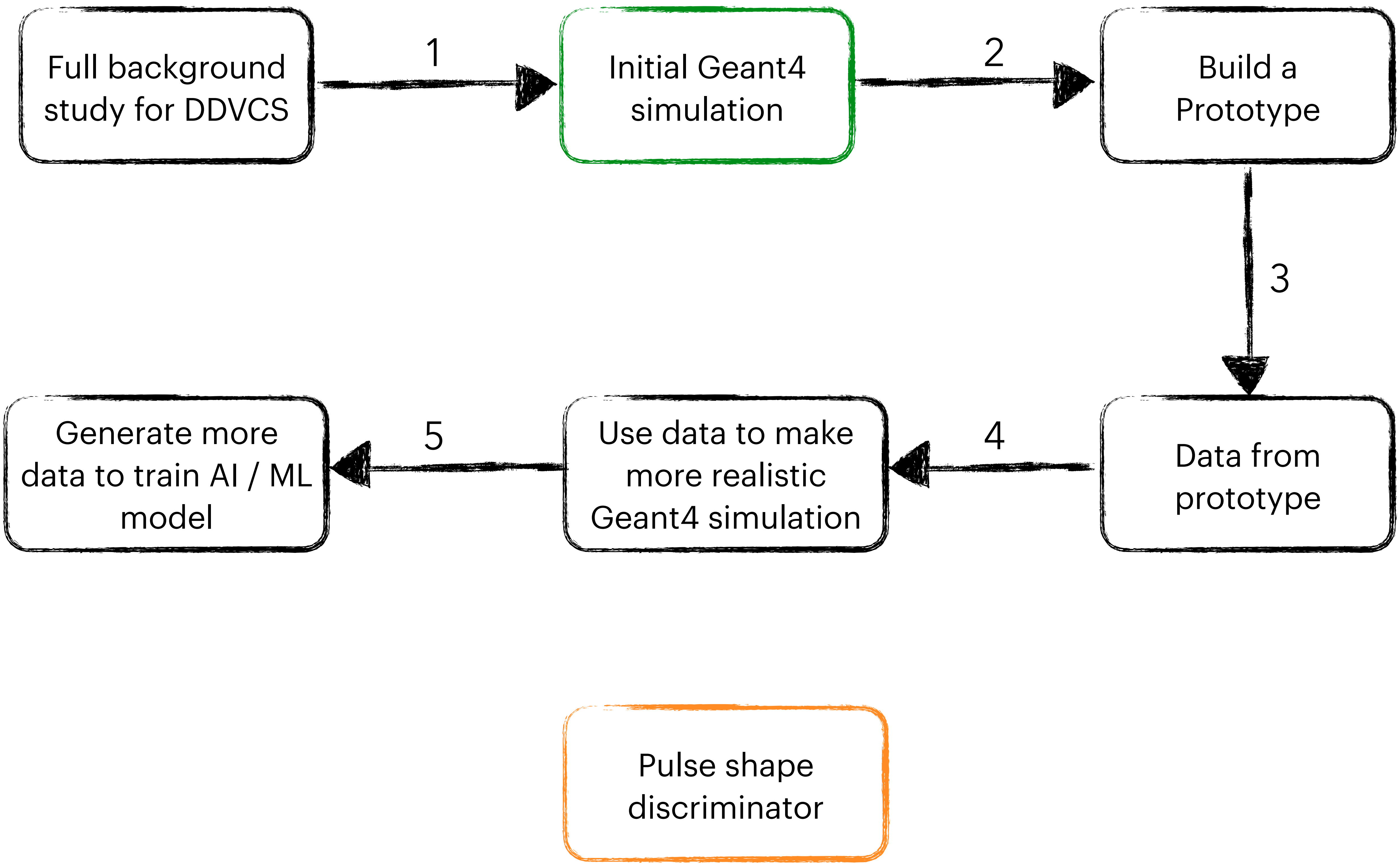
Prototype

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 for moving forward



LOI : PAC 52

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

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.

Summary

1. LOI is already submitted in PAC 52
2. The physics case in well accepted by PAC
3. Geant 4 simulation for the experimental setup is complete
4. 5% of the generated protons are passing through the di-pole magnet
5. Muon are very forward moving
6. Rate calculation and vertex reconstruction study are in progress
7. PSD process is being studied for a potential mu-pi separation for the muon detector
8. Progress in DAQ for prototype
9. To do: Full background study

Acknowledgement:
Keagan Bell
Marie Boer
Brad Sawatzky
Dave Gaskell
Vardan Tadevosyan
And other collaborators

Workshop this summer

Towards improved hadron femtography with hard exclusive reactions, edition IV, Jefferson Lab, 2025

Jul 28 – 31, 2025
America/New_York timezone

Enter your search term

- Overview
- Timetable
- Sessions
- Participant List
- Registration
- Registration fee
- Abstracts
- Social activities
- Code of Conduct
- Past editions

This workshop is the fourth edition of the series, for which previous editions took place at Virginia Tech (2022), JLab (2023) and ECT* Trento (2024). **We are welcoming you for this fourth edition at Jefferson Lab from July 28th-31st, 2025**.

Our goal is to bring together theorists and experimentalists in hadronic physics to discuss recent progress and directions to improve our knowledge of hard exclusive reactions and interpretations such as hadron imaging. Each year emphasizes a "special topic" to which we are dedicating a full day and extra discussions. This year, we are particularly interested in fits and global simulations. We will discuss how to extract objects such as generalized parton distributions (GPDs) and gravitational form factors (GFFs).

Besides fits sensitve to GPDs and simulations, we will also discuss, among physics topics, Compton-like reactions (DVCS, TCS...), hard exclusive meson production, exclusive associated meson production, and exclusive studies in ultra-peripheral collisions.

The workshop will take place in person at Jefferson Lab. Remote attendance is possible as an audience but we ask for all presentations to be in-person.

We will have a round table on a dedicated topic at the end of each day.

We encourage all those interested in this workshop to submit an abstract (deadline July 3d, 2025). Note that we are introducing this year a poster session for junior participants. Please encourage your students to attend!

Sessions:

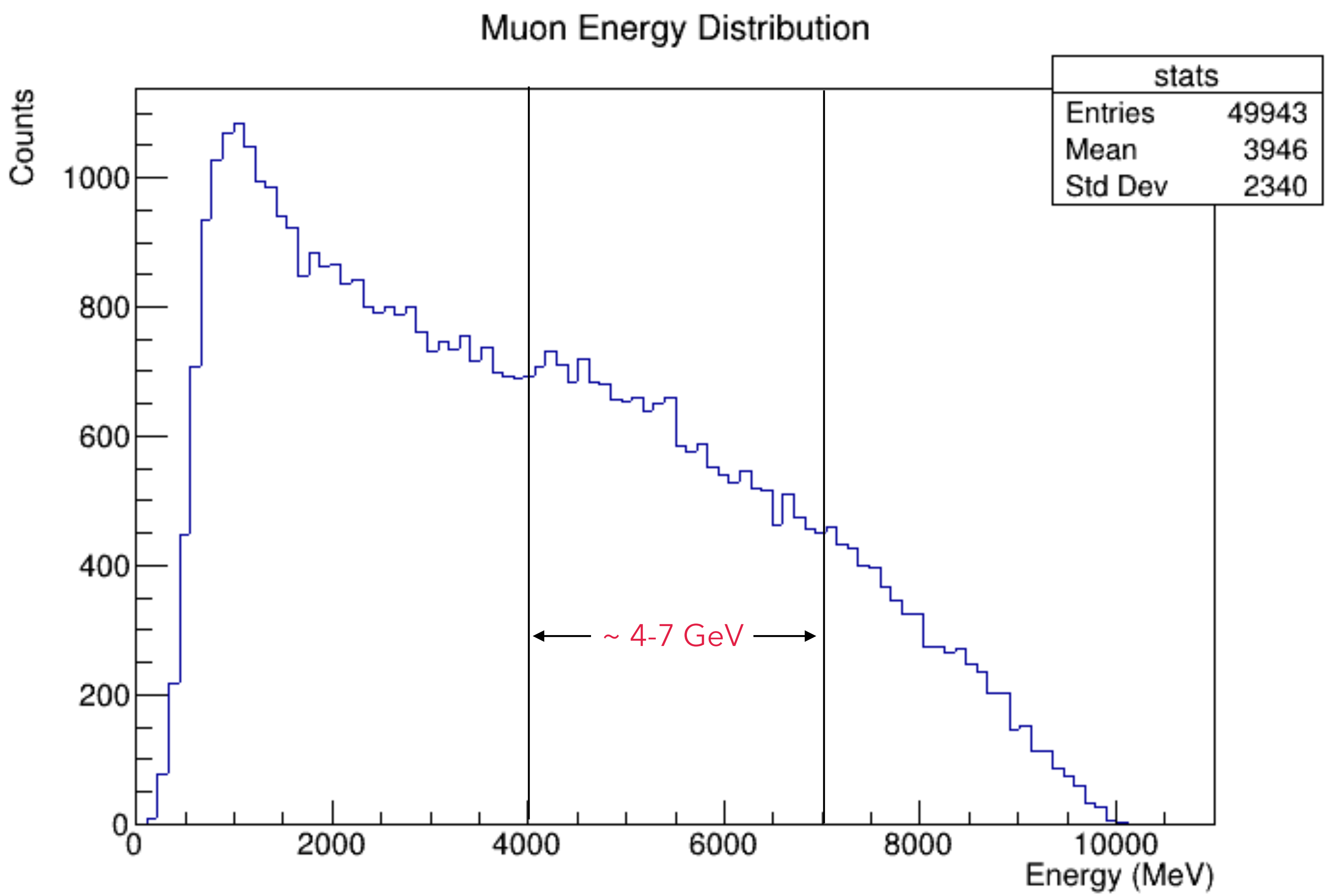
1. QCD fits
2. Software and simulations
3. Hard exclusive meson production
4. Compton-like reactions
5. Hard exclusive reactions with multiple particles
6. GFFs, proton mass and pressure
7. Exclusive physics at high-energy colliders

Organization: scientific sessions, round tables, poster session.

Muon Energy - from generated events

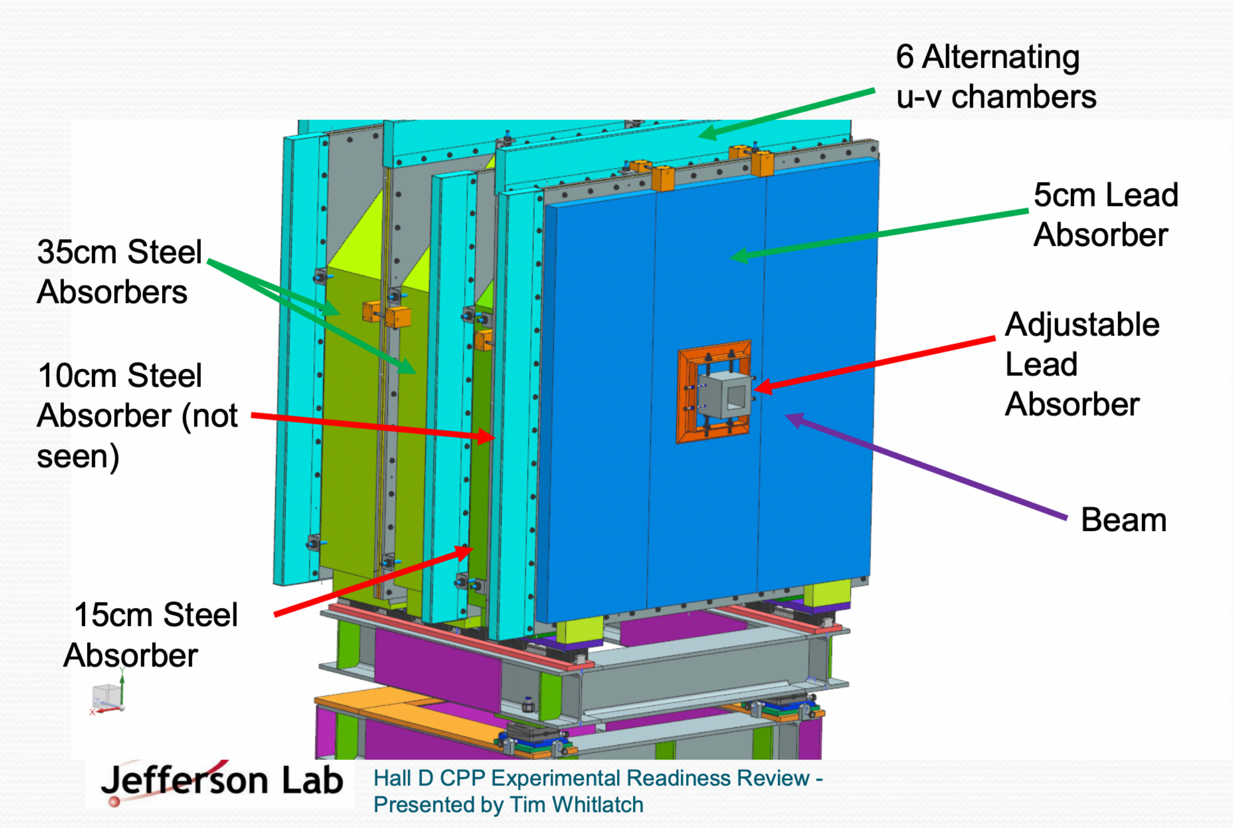
1. DEEPGEN (by M. Boer) event generator is used to simulate the DDVCS events

2. To consider more symmetric muon pairs above 2 GeV invariant mass, more natural cut for maximum number of muons becomes ~4-7 GeV



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