Simulating an Active Target Time Projection Chamber

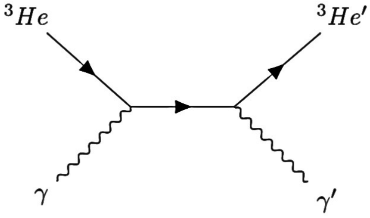
Alicia Postuma (she/her)

Mount Allison University

WNPPC 2022

Why we Need a Time Projection Chamber

- Experimental goal: study Compton scattering on helium-3 and helium-4 to measure electric and magnetic polarizabilities of the neutron [1]
- Active target determines energy, angle of recoil particle [2]



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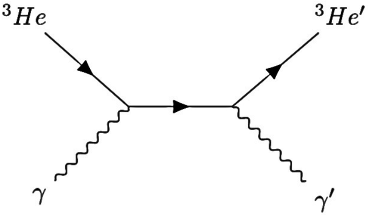

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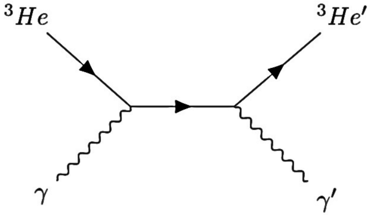

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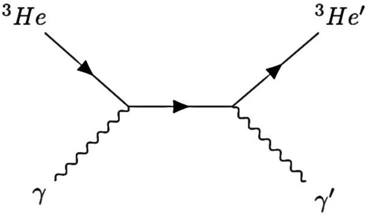

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γ': Measured in photon calorimeter

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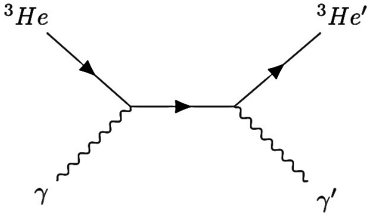

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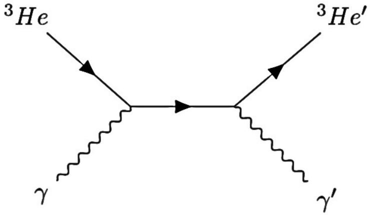

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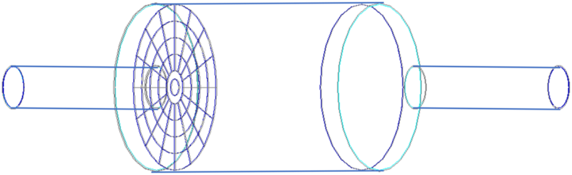
> Time Projection Chamber + photon calorimeters $\longrightarrow$ overdetermined kinematics!

Working Principle of a TPC



- Kinetic energy of target recoil ionizes gas
- Electrons drift through $\vec{E}$ field in active volume and are detected by anode
- Target recoil energy and track can be reconstructed from anode readout [3]

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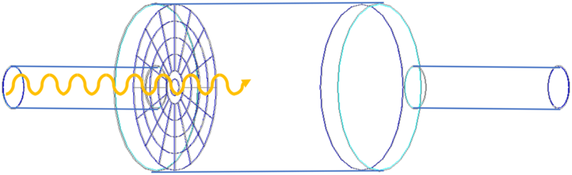

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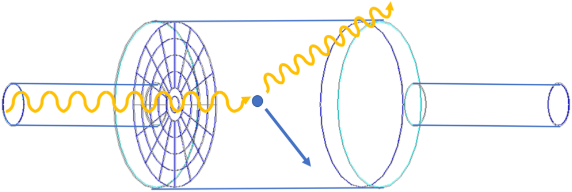

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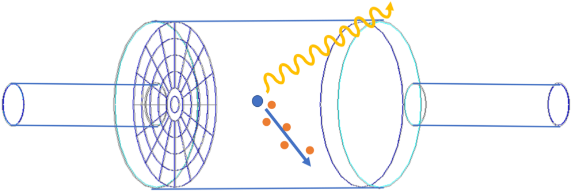

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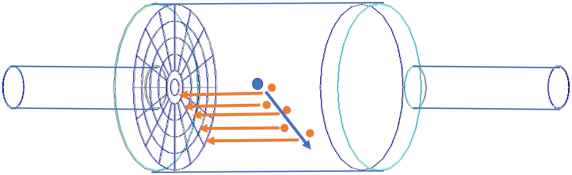

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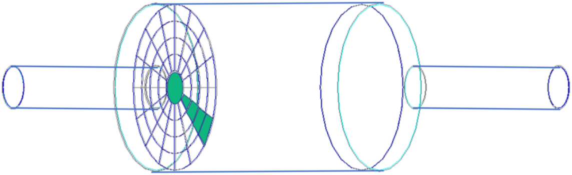

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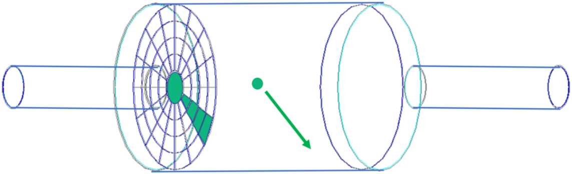

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Implementation in Geant4

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//main constructor function
G4VPhysicalVolume*
    A2TPC::Construct(G4LogicalVolume*
    MotherLogical, G4double Z0) {
    fMotherLogic=MotherLogical;
    G4cout<< "A2TPC::Construct() 
        Building the TPC." <<G4endl;

    ReadParameters("data/TPC.dat");
    DefineMaterials();
    MakeVessel();
    MakeAnodeCathode();
    MakeSensitiveDetector();
    MakeElectricField();
    PlaceParts();

    fMyPhysi = new G4PVPlacement(0,
        G4ThreeVector(0,0,Z0) ,
        fMyLogic, "TPC",
        fMotherLogic, false, 1,
        fIsOverlapVol);
    return fMyPhysi;
}
```

```
# Time Projection Chamber Parameters
# ACP 20 May 2021
#
# Vessel dimensions in mm
# length of main cell
# radius of main cell
# length of conical part of main cell
# wall thickness
# extension length
# extension inner radius
# Be window thickness:
TPC-Dim: 311.0 100.0 1.5 50.0 200.0 25.0 0.5
#
# Anode specifications in mm
# Thickness of G-10 layer
# Thickness of Cu layer
# Distance of anode from cell end
# Angular sections
Anode-Dim: 1.5 0.02 25 16
# # Cathode specifications in mm
# Thickness of steel layer
# Thickness of aluminum layer
# Distance to cathode from cell end
Cathode-Dim: 1.0 0.01 25
#
# Run Mode 0=no, 1=yes
# Check overlaps
Run-Mode: 0 1
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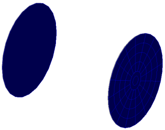

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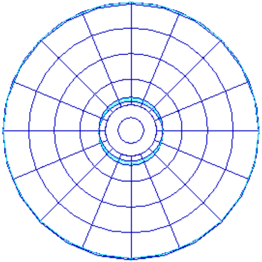

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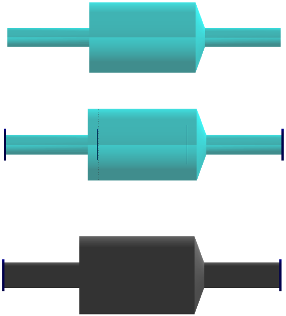

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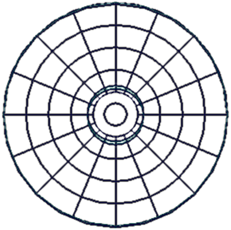
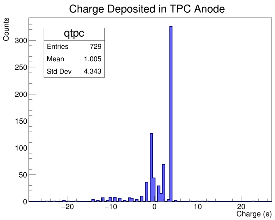
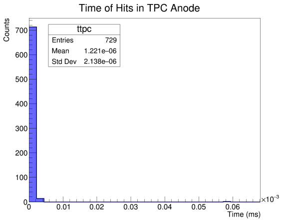
Simulation Output

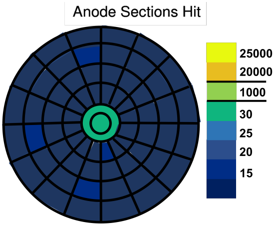


ntpc: Number of anode segments hit
itpc: ID of anode sections hit
qtpc: Charge deposited in hit
ttpc: Time of hit

Initial Simulated Data







Initial data were inconsistent with functionality of a TPC?!

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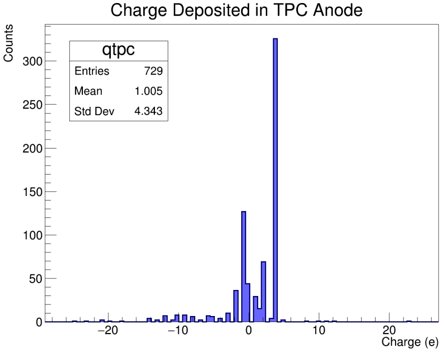

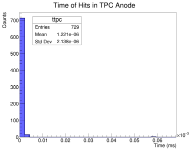

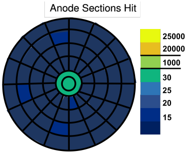

→ Most hits deposit positive charge?!

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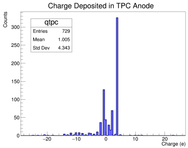

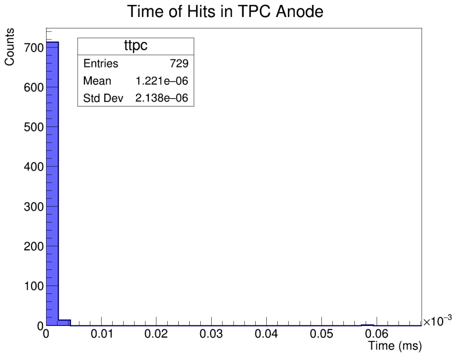

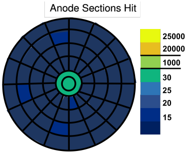

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→ Most hits are at exactly time zero?!

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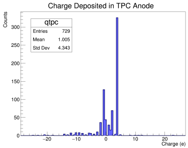
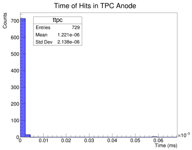
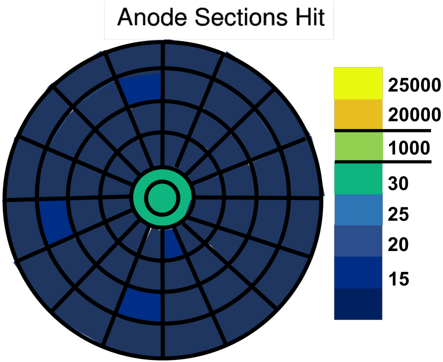






→ Most hits deposit positive charge?!

→ Most hits are at exactly time zero?!

→ Few hits recorded anywhere in the anode?!

The Problem

Following tracking information for electrons shows that they are not being drifted through the electric field.

****

G4Track Information: Particle = e-, Track ID = 18, Parent ID = 1

****

Step	X	Y	Z	KineE	dEStep	TrakLeng
0	0 nm	0 nm	544 nm	57.3 eV	0 eV	0 fm
1	-3.69 nm	4.13 nm	545 nm	0 eV	57.3 eV	7.52 nm
2	-3.69 nm	4.13 nm	545 nm	0 eV	0 eV	**7.52 nm**

****

Electron Drift

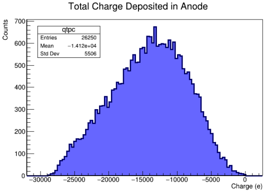
Geant4 "low energy" range [4]	**Drift electron energies**
100 eV - 1GeV	$<$1 eV

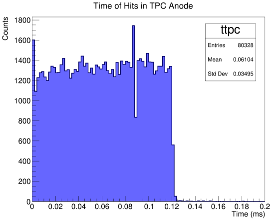
- Custom definition of electron drift in *G4FastSimulation* [5] A2DriftModel
- Interface this with the rest of the A2Geant4 program

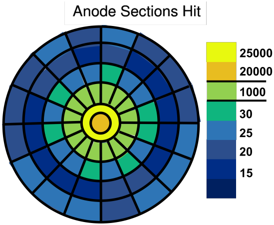
Simulate in Magboltz [6]:		Implement in Geant4 [7]:
Drift velocity	$\longrightarrow$	Travel time of e^-
Diffusion coeffients	$\longrightarrow$	Final position of e^-

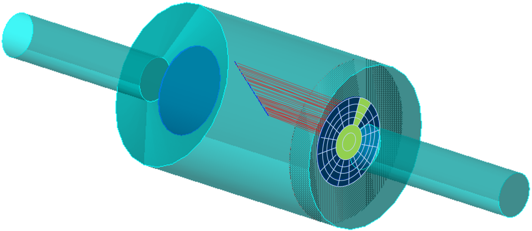
```
class A2DriftModel : public G4VFastSimulationModel {
public:
        A2DriftModel(G4String, G4Region*, A2Target*,A2SD*);
        ~A2DriftModel();
        virtual G4bool IsApplicable(const
            G4ParticleDefinition&); //return true for e-
        virtual G4bool ModelTrigger(const G4FastTrack&);
            //trigger if particle energy is below 1 keV
        virtual void DoIt(const G4FastTrack&,
            G4FastStep&); //pass control of particle to
            the model
        //I did NOT name this function, the name comes
            from the base class
protected:
        virtual void Transport(...); //drift electron in
            field
        void ProcessHit(...); //create hit in sensitive
            detector
};
```

Improved Simulated Data









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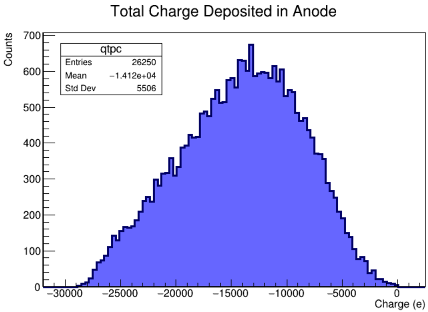

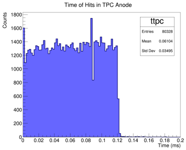

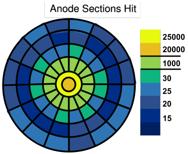

→ Large amount of negative charge deposited in TPC

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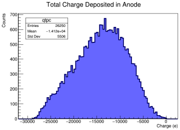

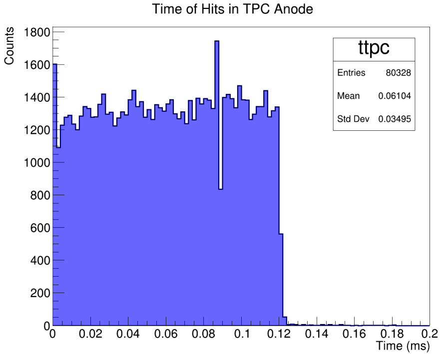

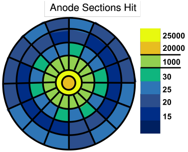

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→ Realistic time distribution

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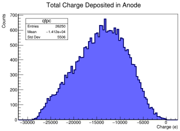
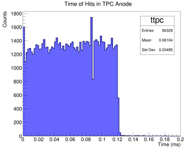
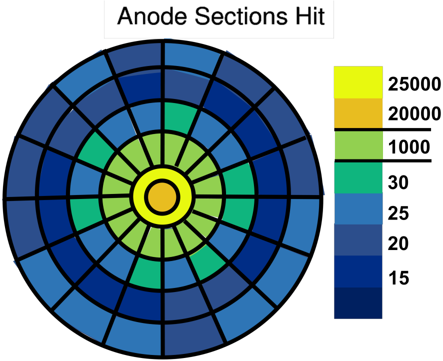






→ Large amount of negative charge deposited in TPC

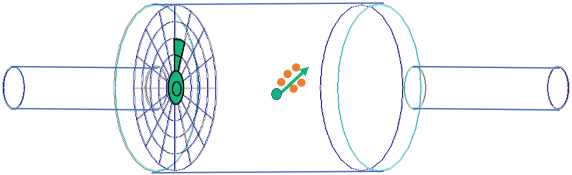
→ Realistic time distribution

→ Many different anode sections hit

Event Reconstruction

1. **Recoil energy**
2. Recoil polar angle

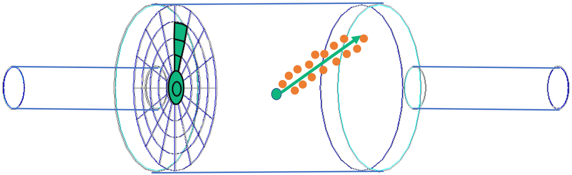
→ Apply to Compton scattering



Event Reconstruction

1. **Recoil energy**
2. Recoil polar angle

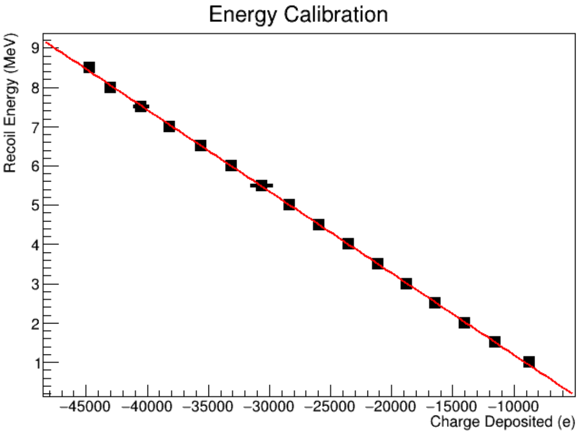
→ Apply to Compton scattering



Event Reconstruction

1. **Recoil energy**
2. Recoil polar angle

→ Apply to Compton scattering

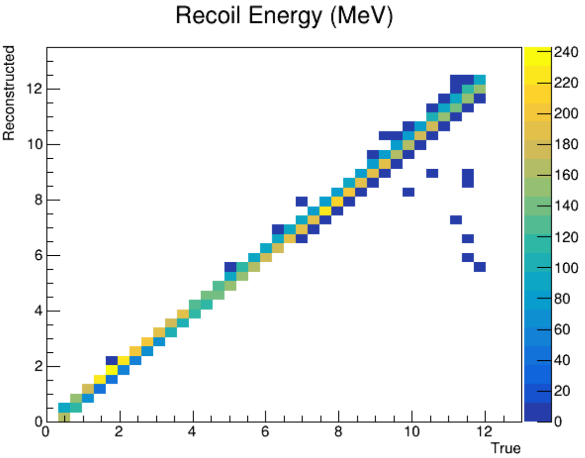


$$T = A + BQ$$

Event Reconstruction

1. **Recoil energy**
2. Recoil polar angle

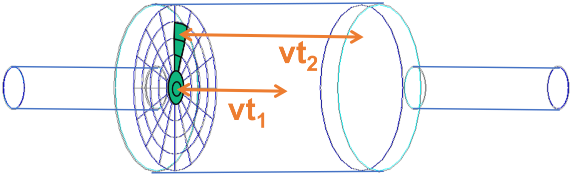
→ Apply to Compton scattering



Event Reconstruction

1. Recoil energy
2. **Recoil polar angle**

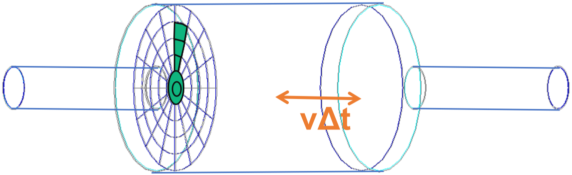
→ Apply to Compton scattering



Event Reconstruction

1. Recoil energy
2. **Recoil polar angle**

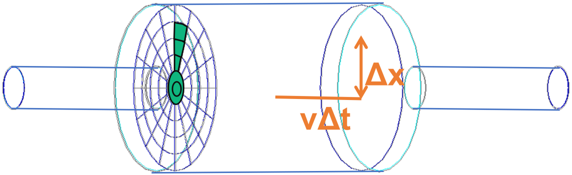
→ Apply to Compton scattering



Event Reconstruction

1. Recoil energy
2. **Recoil polar angle**

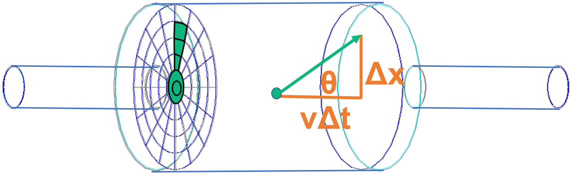
→ Apply to Compton scattering



Event Reconstruction

1. Recoil energy
2. **Recoil polar angle**

→ Apply to Compton scattering

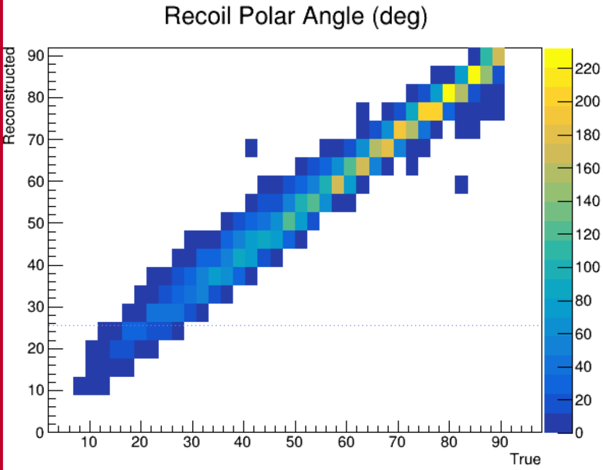


$$tan\theta = \frac{\Delta x}{v_{drift}\Delta t}$$

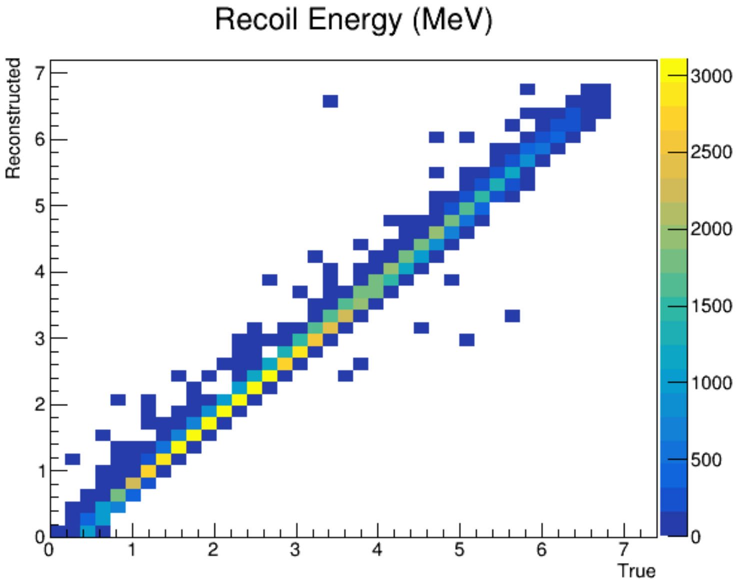
Event Reconstruction

1. Recoil energy
2. **Recoil polar angle**

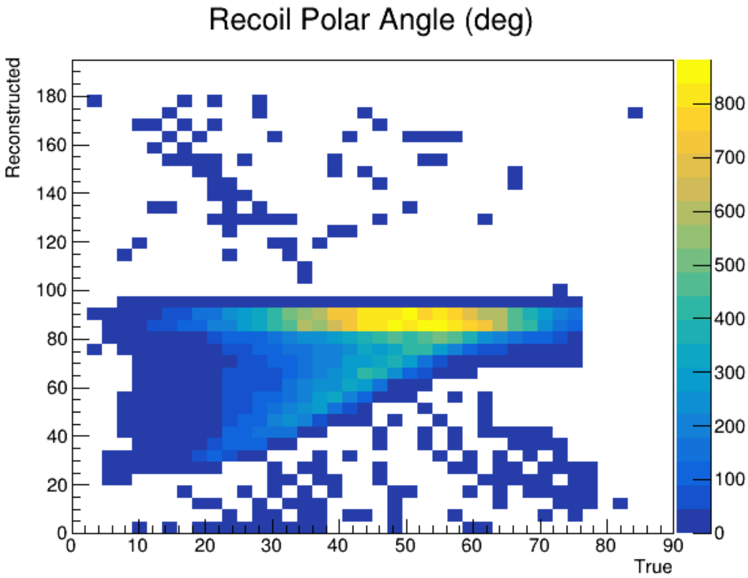
→ Apply to Compton scattering



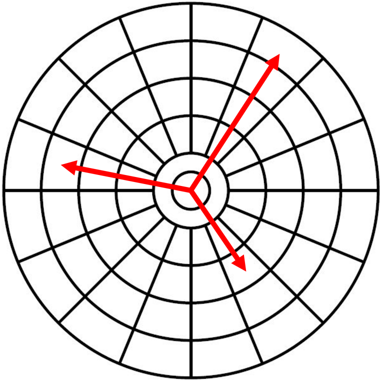
Energy: Compton Scattering 100 MeV



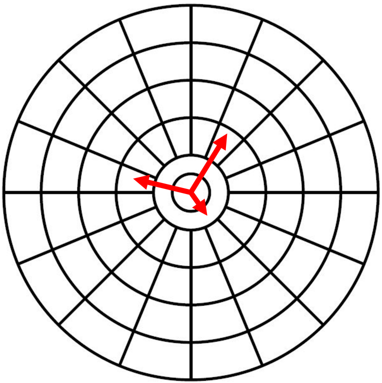
Angle: Compton Scattering 100 MeV



A Kinematic Challenge

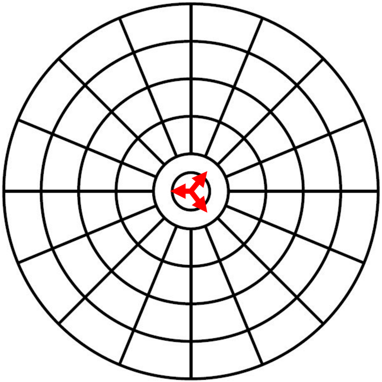


A Kinematic Challenge



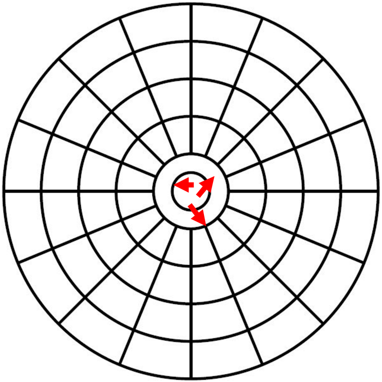
- Low energy + high pressure → short tracks

A Kinematic Challenge



- Low energy + high pressure → short tracks
- Energy-angle relation → anode projection even shorter

A Kinematic Challenge



- Low energy + high pressure → short tracks
- Energy-angle relation → anode projection even shorter
- Beam width ≈ projection length → $\sigma(x) = x$

A Kinematic Challenge

- Low energy + high pressure $\rightarrow$ short tracks
- Energy-angle relation $\rightarrow$ anode projection even shorter
- Beam width $\approx$ projection length $\rightarrow$ $\sigma(x) = x$

Possible solutions:

Lower pressure: longer tracks $\Longleftrightarrow$ lower event rate
New anode design?

Summary and Outlook

- TPC as active target gives **good reconstruction of energy**
  → Still the best option for the experiment
- Experimental kinematics **limit feasibility of angular reconstruction**
- Use Geant4 simulation and reconstruction framework to find solutions
  → Optimize pressure, anode design

Compton scattering on helium-3 in the Time Projection Chamber
= measurement of neutron polarizabilties!

Acknowledgements

My thanks to...

- Dr. David Hornidge
- Dr. Vahe Sokhoyan - TPC project guidance
- Dr. Philippe Martel - general computing questions
- Dr. Evgeny Maev - PNPI liaison
- Mount Allison University, A2, PNPI, NSERC

We recognize and acknowledge that this research was carried out on the unceded lands of the Mi'kmaw people.

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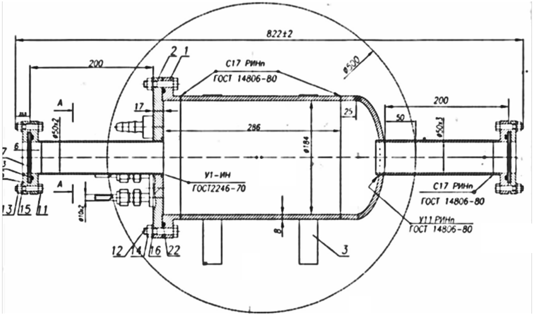
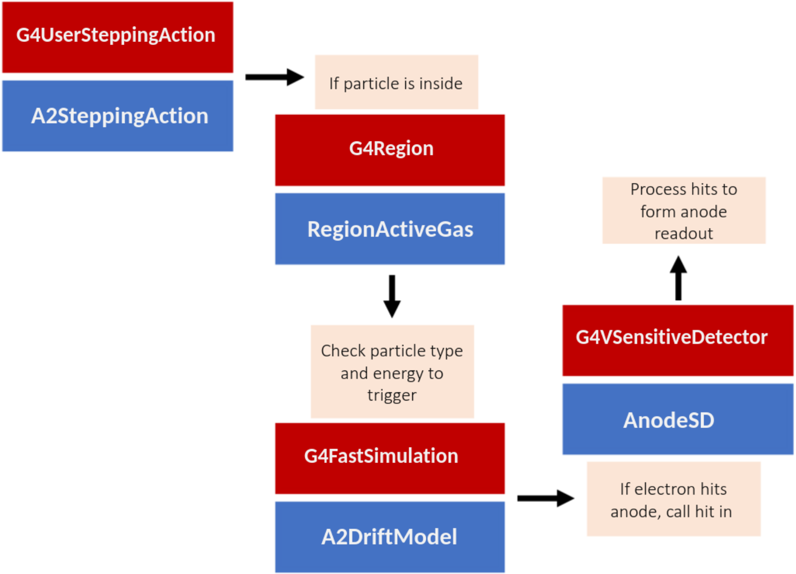
- A2-Collaboration, Proposal for the experiment: Compton scattering on the He isotopes with an active target, MAMI PAC, 2013.
- R3B Collaboration, Technical report for the design, construction and commissioning of the Active Target for FAIR (ACTAF) for the R3B experiment, Technical report, 2016, FAIR/NUSTAR/R3B/ACTAF.
- Y. Ayyad, D.Bazin, S. Beceiro-Novo, M. Cortesi, and W. Mittig, **EPJ** A54(2018).
- Geant4 Collaboration, Book for Application Developers, Release 10.3, 2017.
- A. Zaborowska, Fast simulation, Geant4 Advanced Course at CERN, 2020.
- D. Pfeiffer et al., **NIM** A935, 121 (2019).
- F. Metzger, TPC-Signal Simulation, presentation slides, 2020.

EXTRA SLIDES

Parameters Used



- Dimensions from schematics by Evgeny Maev (PNPI)
- Helium-3 or Helium-4
- Customizable gas pressure (20-25 bar)
- Uniform 2 kV/cm electric field
- Walls 8 mm aluminum


G4UserSteppingAction
A2SteppingAction
If particle is inside
G4Region
RegionActiveGas
Check particle type
and energy to
trigger
G4FastSimulation
A2DriftModel
If electron hits
anode, call hit in
G4VSensitiveDetector
AnodeSD
Process hits to
form anode
readout

Definition of Electron Drift

Gaussians based on work by Fabian Metzger.

Position:

$$\mu_x = x_0, \mu_y = y_0$$
$$\sigma_x = \sigma_y = \tilde{D}_T \sqrt{|z_0 - z_{anode}|}$$

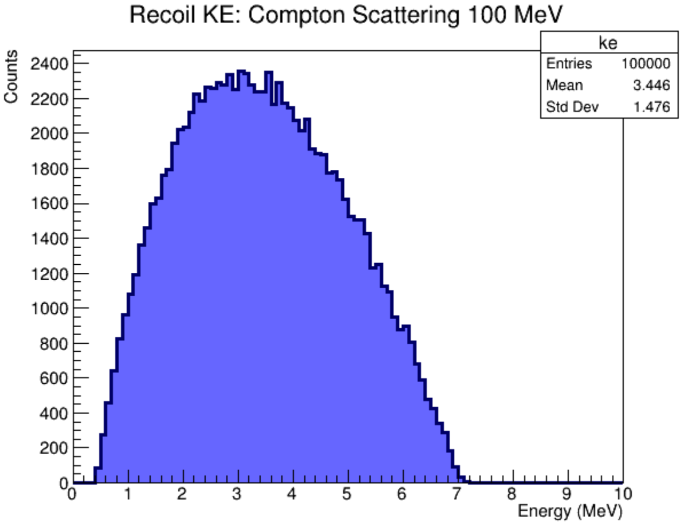
- Mean is initial (x,y) position of simulated electron
- Standard deviation depends on transverse diffusion coefficient and distance to anode

Time:

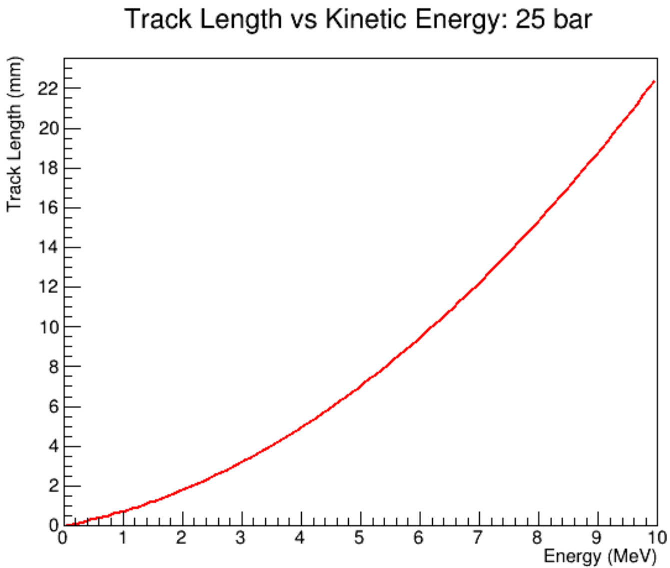
$$\mu_t = \frac{|z_0 - z_{anode}|}{v_{drift}}$$
$$\sigma_t = \frac{\tilde{D}_L}{v_{drift}} \sqrt{|z_0 - z_{anode}|}$$

- Mean is distance to anode divided by drift velocity
- Standard deviation depends on lateral diffusion coefficient, drift velocity, and distance to anode

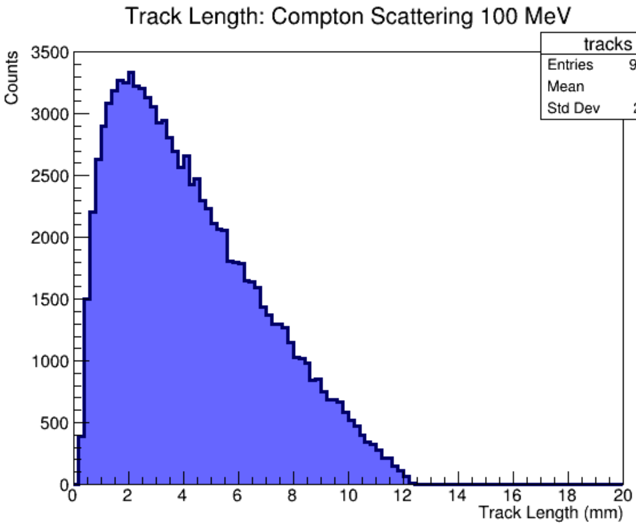
Kinematics


Recoil KE: Compton Scattering 100 MeV
ke
Entries 100000
Mean 3.446
Std Dev 1.476
Counts
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10
Energy (MeV)

Kinematics

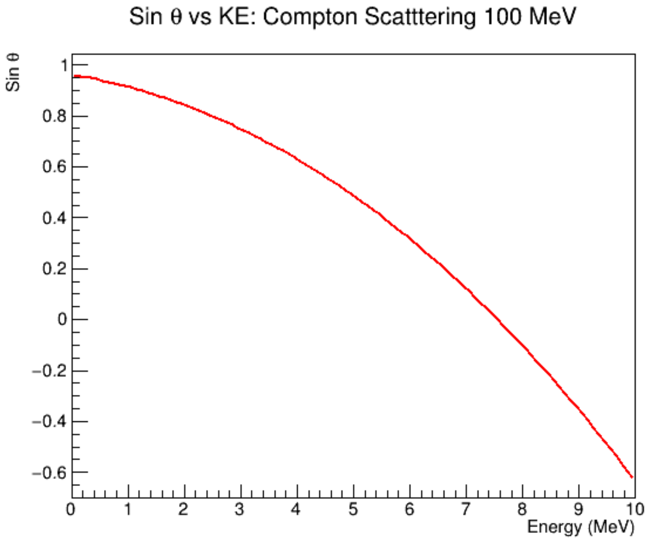

Track Length vs Kinetic Energy: 25 bar
Track Length (mm)
0
2
4
6
8
10
12
14
16
18
20
22
0
1
2
3
4
5
6
7
8
9
10
Energy (MeV)

Kinematics

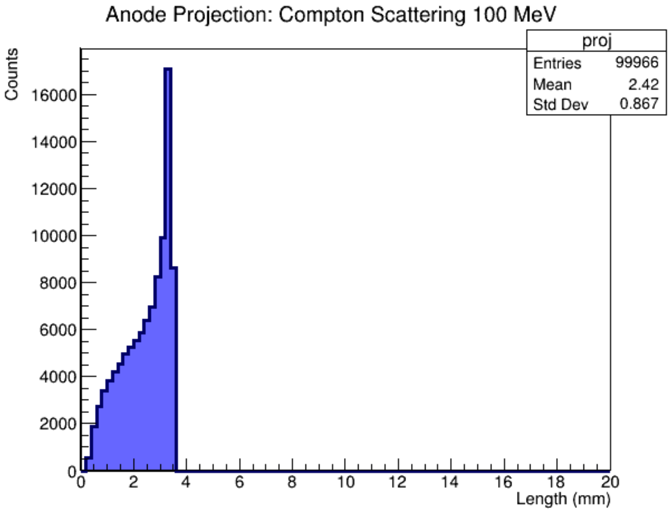


Track Length: Compton Scattering 100 MeV
Counts
Track Length (mm)
tracks
Entries 99966
Mean 4.31
Std Dev 2.644
0
500
1000
1500
2000
2500
3000
3500
0
2
4
6
8
10
12
14
16
18
20

Kinematics

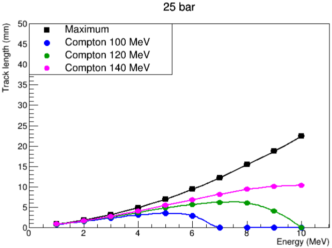

Sin θ vs KE: Compton Scatttering 100 MeV
Sin θ
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
0
1
2
3
4
5
6
7
8
9
10
Energy (MeV)

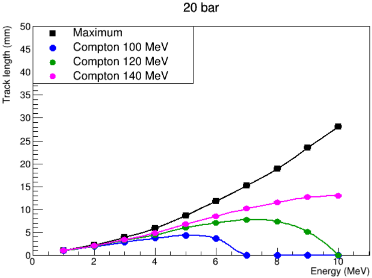
Kinematics

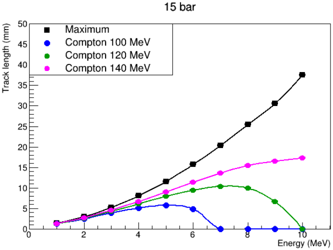


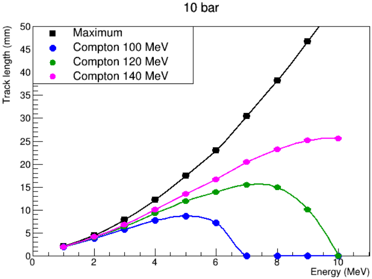
Anode Projection: Compton Scattering 100 MeV
proj
Entries 99966
Mean 2.42
Std Dev 0.867
Counts
0
2000
4000
6000
8000
10000
12000
14000
16000
0 2 4 6 8 10 12 14 16 18 20
Length (mm)

Tracks and Anode Projections

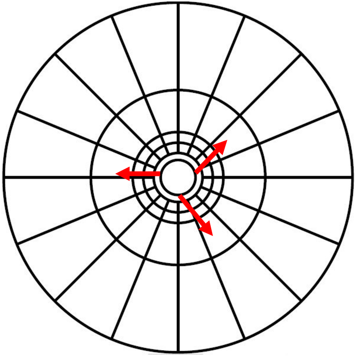






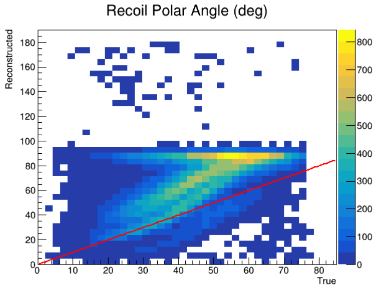


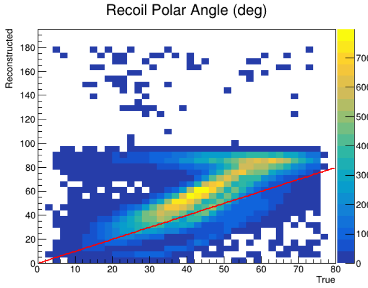
Suggested Anode Design

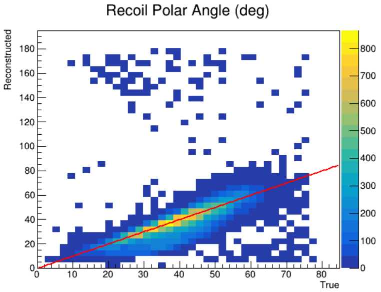


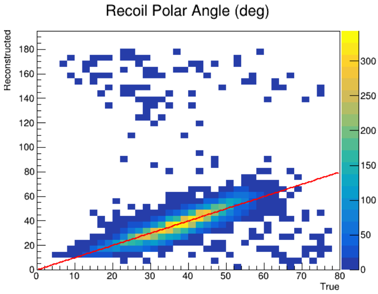
- Inner circle entirely encompasses the beam
- No particle track extends beyond the outer radius
- The majority of Compton scattering events cause hits in the ring and at least one outer section

Experimenting with Angular Reconstruction









Optimizing Pressure