# Report on n-$^3$He simulation using Geant4

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## Outline

1. Geometry factors
2. Simulation toolkit
3. Geometry and materials
4. Physics list
5. Primary particles : Neutron beam profile
6. Validation of the simulation
7. Outcome from the simulation

## Geometry factors

$$Y_i^h = \langle E_i(1 + hPA_p cos\theta) \rangle \tag{1}$$

$$A_m^i = \frac{Y_i^+ - Y_i^-}{Y_i^+ + Y_i^-} \tag{2}$$

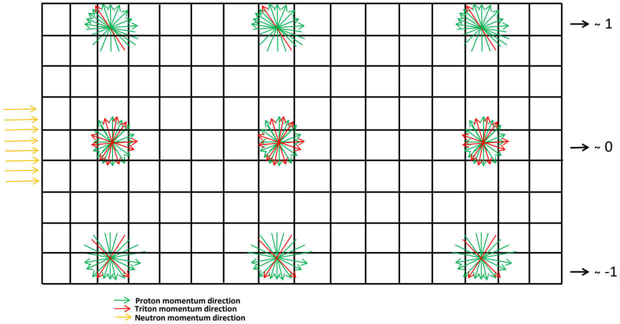
$$A_m^i = PA_p \frac{\langle E_i cos\theta \rangle}{\langle E_i \rangle} \tag{3}$$

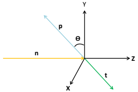
$$G_i = \frac{\langle E_i cos\theta \rangle}{\langle E_i \rangle} \tag{4}$$

$$A_p = \frac{1}{P} \frac{A_m^i}{G_i} \tag{5}$$

$$\langle E_i \rangle = \sum_{k=1}^{N} Q_i^k \tag{6}$$

$$G_i = \frac{\sum_{k=1}^{N} Q_i^k cos\theta_i^k}{\sum_{k=1}^{N} Q_i^k} \tag{7}$$



## Simulation toolkit : Geant4

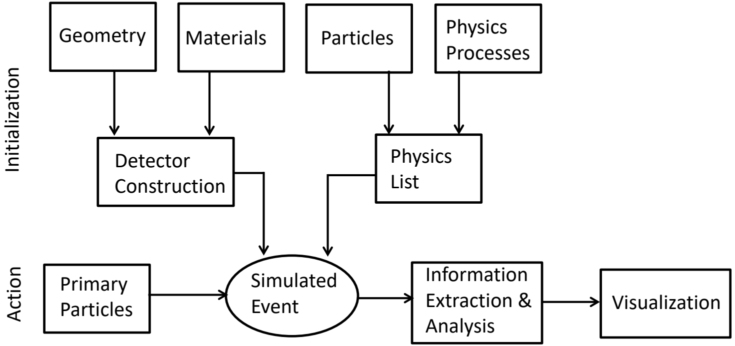
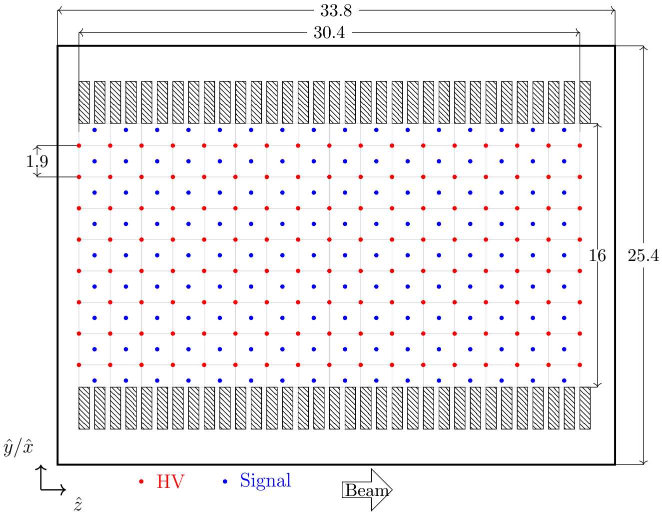



Figure: A basic simulation process flow in Geant4

# Geometry and materials



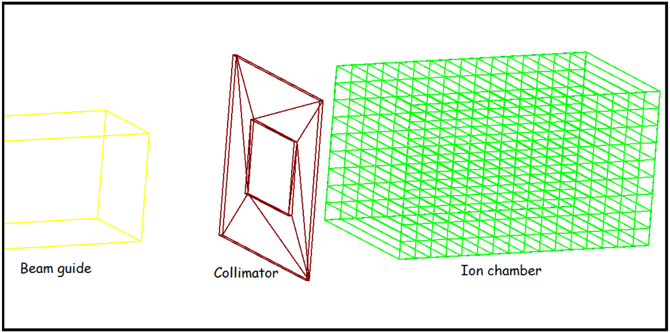



Figure: A simplified geometry of the setup

Using,

$$\rho = \frac{g}{V} = \frac{PM}{RT}$$

We get density of $^3$He, $\rho = 5.796952 \times 10^{-5}$ gm/cm$^3$

## Physics List

- Neutron absorption reaction :

$$n +^3 He \rightarrow p + t$$

  This is an inelastic hadronic process.
  **Process :** *G4NeutronInelasticProcess*
  **Model :** *G4ParticleHPInelastic* (High Precision model)
  **XS Data :** *G4ParticleHPInelasticData*, uses ENDF/B-VII (repackaged in G4NDL) data

- The energy loss of proton and triton through ionization.

$$p +^3 He \rightarrow p +^3 He^+ + e^-$$

$$t +^3 He \rightarrow t +^3 He^+ + e^-$$

  The relevant class is *G4hIonisation*

Alternative way is to use reference physics list QGSP_BERT_HP which is a collection of –
Quark Gluon String (QGS) model, Precomputed (P) model used for de-excitation, Bertini-style cascade (BERT) and High Precision (HP) neutron model.

## Primary particles : Neutron beam profile

Construction of the neutron beam profile was done in the following two steps :

- **Neutron energy distribution :** The monitor-1 (M1) signal was used to generate the neutron energy profile at detector position.
- **Neutron spatial profile :** The beam scan data was used to get the neutron's position distribution on the xy plane at the front edge of the detector.

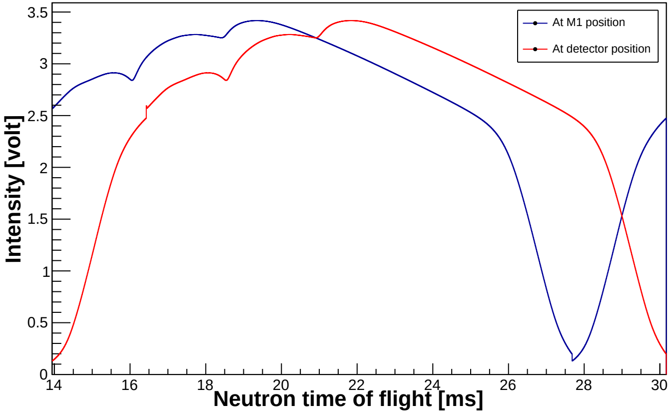



Figure: Propagating unconvoluted M1 signal at detector position

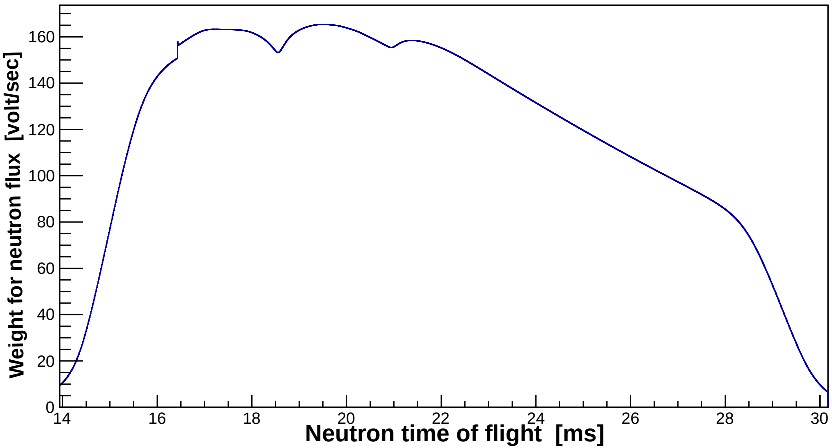



Figure: Corrected unconvoluted M1 signal at detector position

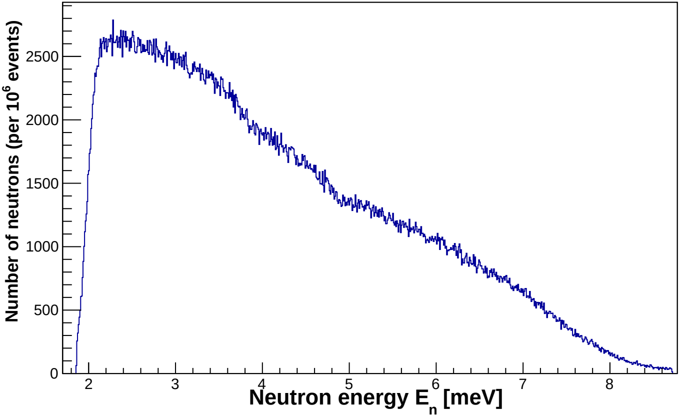



Figure: Generated neutron energy distribution

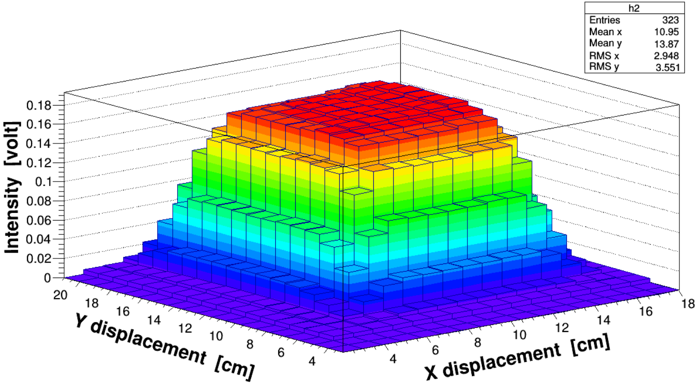



Figure: Neutron spacial beam profile at upstream position from the beam scan data

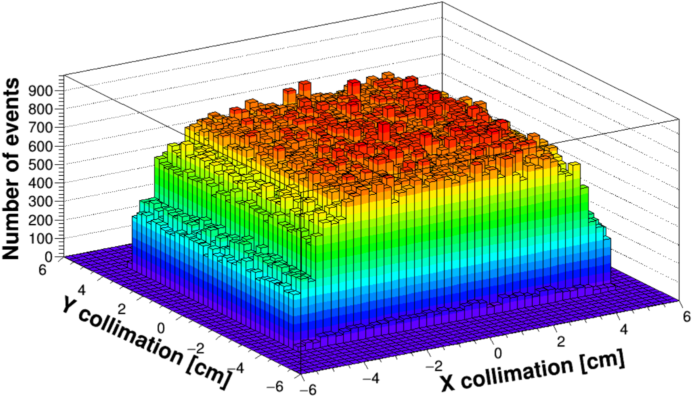



Figure: Neutron position distribution on the XY plane from simulation after collimation (default collimation). Total $10^6$ primary events considered.

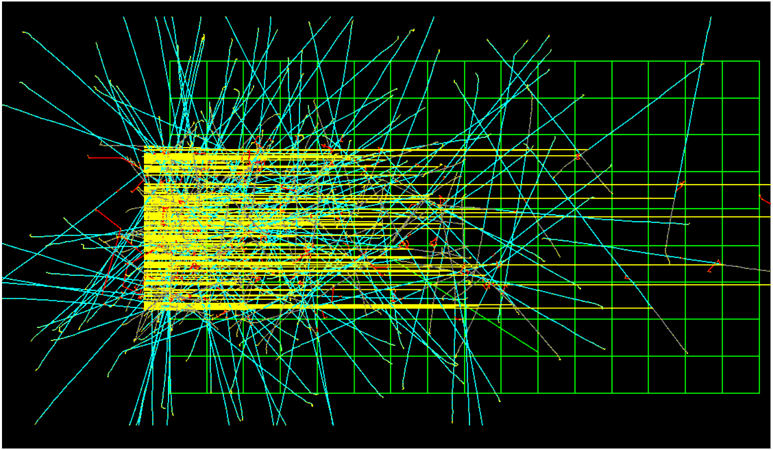


Figure: Example of simulated capture events (2D view) inside the chamber. Yellow tracks are neutrons, blue tracks are protons and gray tracks are tritons. Also visible, few red tracks which are electrons, and green tracks which are gammas.

## Validation of the simulation

1. The conservation of energy
2. The cross section comparison
3. The energy dependence of cross section
4. Comparison of stopping power with PSTAR and SRIM
4. The energy range relationship comparison with PSTAR and SRIM
6. The angular distribution of the outgoing particle's momentum
7. Comparison of yields with data
8. Comparison with collimation scan data

## The conservation of energy

$${}^{1}_{0}n + {}^{3}_{2}He \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$$

The theoretical Q-value for this reaction is already known from the resulting mass change.
The masses of the reactants are
${}^{1}_{0}$n = 1.008665 amu
${}^{3}_{2}$He = 3.01603 amu
${}^{3}_{1}$H = 3.01605
${}^{1}_{1}$H = 1.007825 amu
So the resulting mass change is,
$\Delta m$ = 1.008665 + 3.01603 - 3.01605 - 1.007825 = 0.00082 amu
So, the Q-value = 0.00082 $\times$ 931.5 MeV = 763.83 keV

$$E_p = 573keV$$

$$E_t = 191keV$$

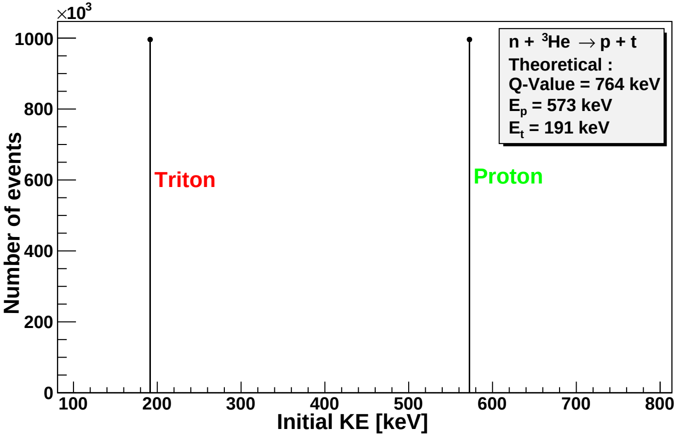



Figure: Initial kinetic energy of proton and triton in the simulation. Total $10^6$ events considered.

## Cross section comparison

To extract cross section value from this information, we note that the number of capture at position x inside the chamber is related to the capture cross section as –

$$I(x) = I_0 e^{-N\sigma x} N\sigma \tag{8}$$

where,
N = density of nuclei in the volume (nuclei/cm$^3$)
$\sigma$ = The capture cross section (barn, 1 barn =$10^{-28} m^2$)
$I_0$ = Initial beam intensity
I(x) = Number of neutrons captured per unit length at distance x
Linearizing the equation we can write,

$$lnI(x) = -N\sigma x + ln(I_0 N\sigma) \tag{9}$$

$$\frac{n}{V} = \frac{P}{RT} \tag{10}$$

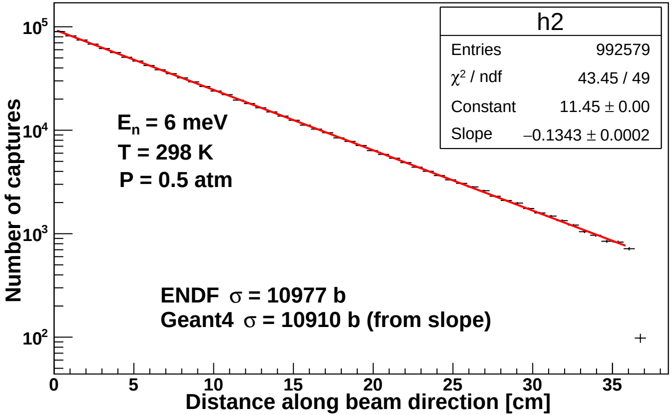



Figure: Capture cross section from the simulation with pencil beam. Target is at room temperature. The cross section from the simulation is compared with ENDF cross section value.

## The energy dependence of cross section

For thermal neutrons there is a region called “1/v region" where the absorption cross-section increases as the velocity (kinetic energy) of the neutron decreases according to the 1/v law.

$$\sigma_a \sim \frac{1}{v} \sim \frac{1}{\sqrt{E}} \tag{11}$$

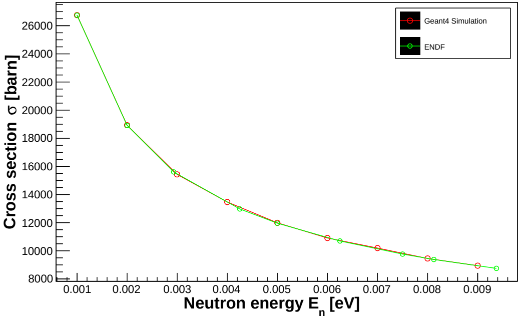



Figure: ENDF vs Geant4 cross section comparison for different thermal

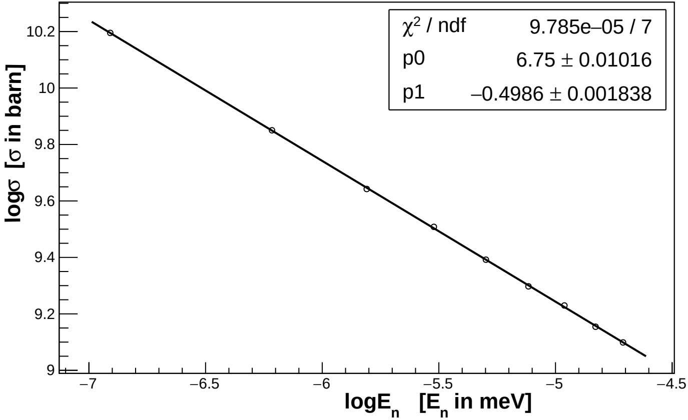



Figure: $\frac{1}{\sqrt{E}}$ depencence of crsoss section form simulation

## The stopping power and ionization curve

– Compare stopping power from simulation with that from PSTAR and SRIM.
– For PSTAR, the available medium is $^4He$.
– For PSTAR no triton data is available.
– However proton and triton stopping power in $^3$He can be estimated from PSTAR proton data in $^4$He.
To get triton data from PSTAR,

$$\left[\frac{dE_p}{dx}\right]_{E=E_0} = \left[\frac{dE_t}{dx}\right]_{E=3E_0} \tag{12}$$

$$R_t(E) = 3R_p(\frac{E}{3}) \tag{13}$$

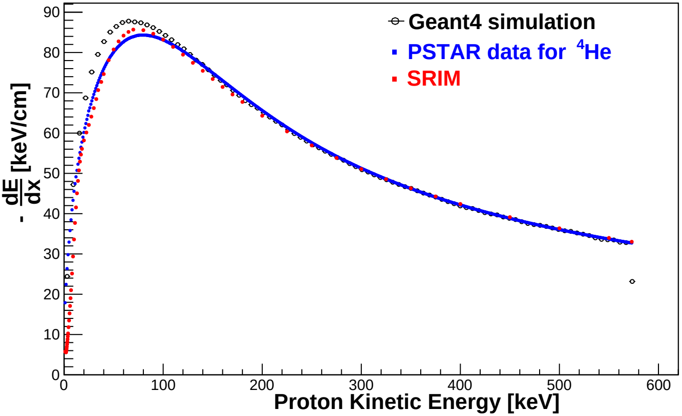



Figure: Proton stopping power as a function of kinetic energy from the Geant4 simulation, PSTAR data and SRIM. The target is at room temperature (298K) and 0.47 atm pressure.

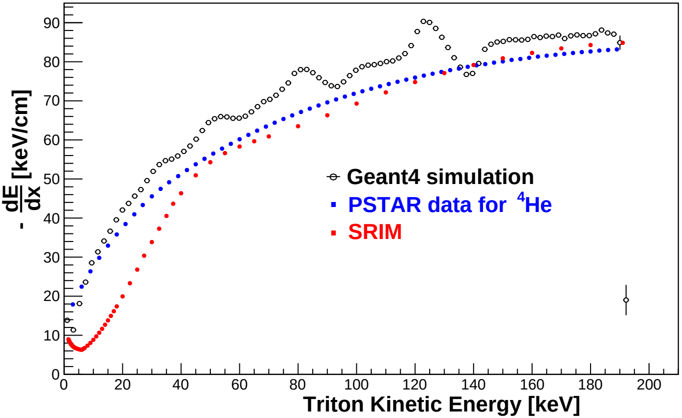
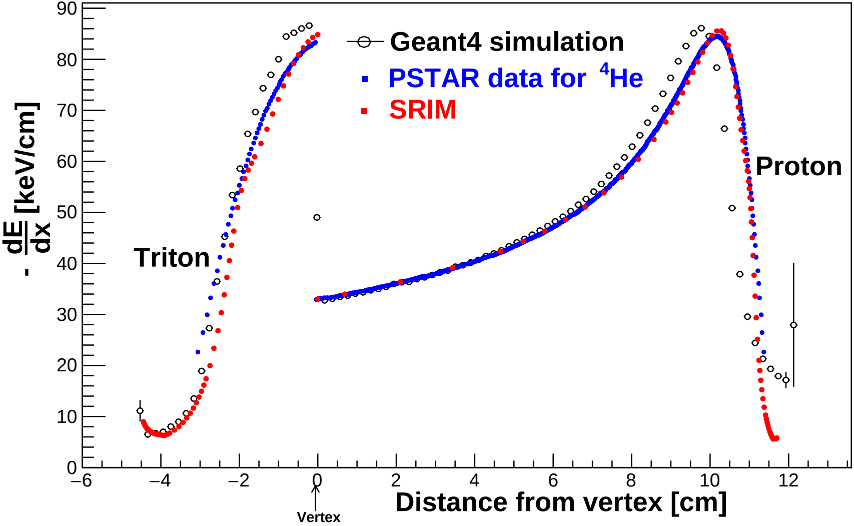



Figure: Triton stopping power as a function of kinetic energy from the simulation, PSTAR data and SRIM. The target is at room temperature (298K) and 0.47 atm pressure.


Geant4 simulation
PSTAR data for $^4$He
SRIM
Triton
Proton
$-\frac{dE}{dx}$ [keV/cm]
Distance from vertex [cm]
Vertex
0
10
20
30
40
50
60
70
80
90
−6
−4
−2
0
2
4
6
8
10
12

# The energy range relationship

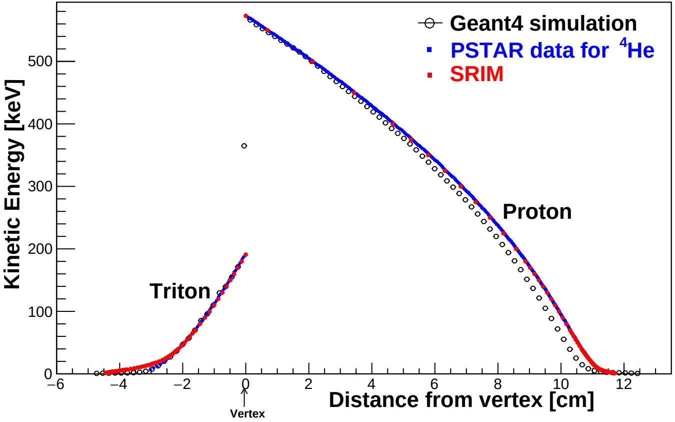
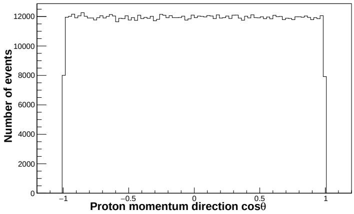
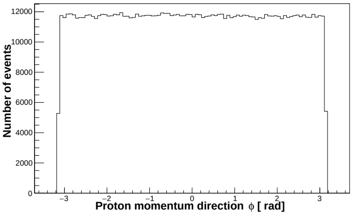



Figure: Comparison of proton and triton energy vs distance in $^3$He after the reaction from the simulation with PSTAR data and SRIM.

# The angular distribution of tracks

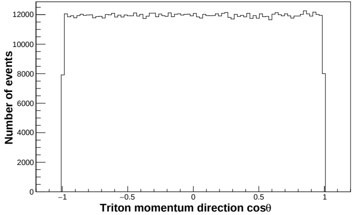



(a) Distribution of proton momentum direction cos$\theta$

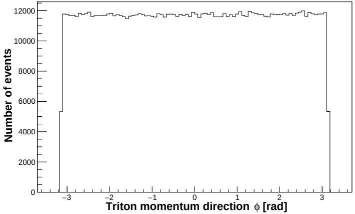



(b) Distribution of proton momentum direction $\phi$

Figure: Proton momentum angular distribution in the simulation. Total primary events considered $10^6$.



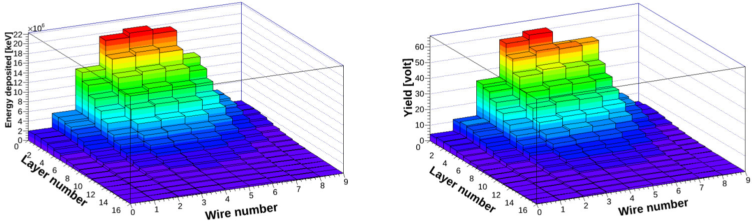

(a) Distribution of triton momentum direction cos$\theta$




(b) Distribution of triton momentum direction $\phi$

Figure: Triton momentum angular distribution in the simulation. Total primary events considered $10^6$.

# Comparison of yield




(a) Yield distribution from simulation

(b) Yield distribution form typical n-$^{3}$He data

Figure: Yield distribution in the ion chamber from simulation and typical n-$^{3}$He run data.

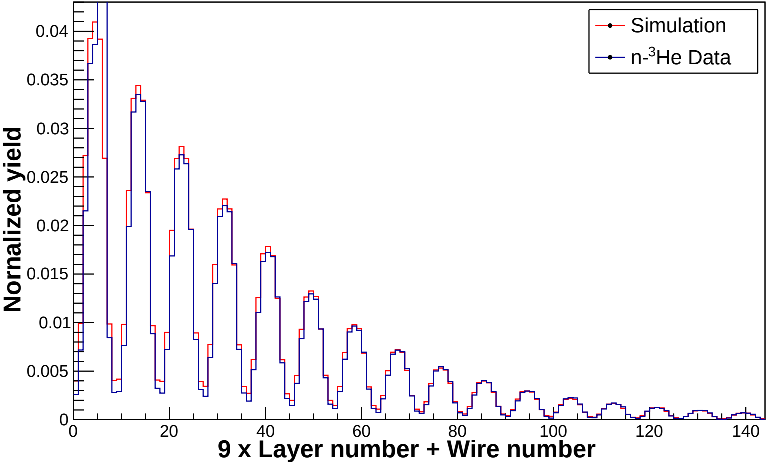
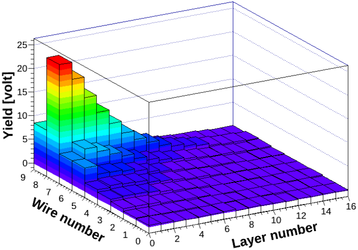
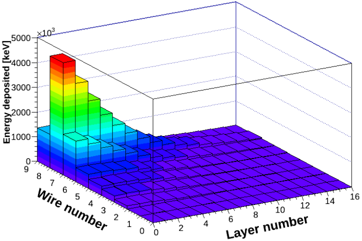



Figure: Yield distribution in the ion chamber from simulation and typical n-$^{3}$He data

# Comparison with beam scan data




(a) Yield distribution from data for collimation scan : run# 37990




(b) Yield distribution from simulation for collimation scan : run# 37990

Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 37990

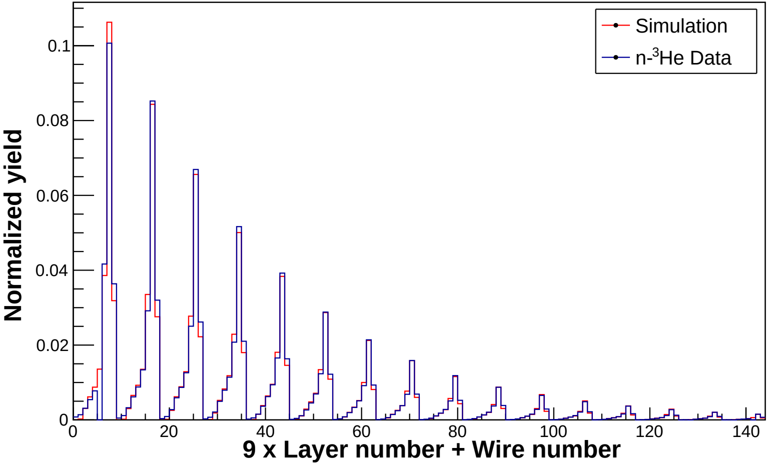
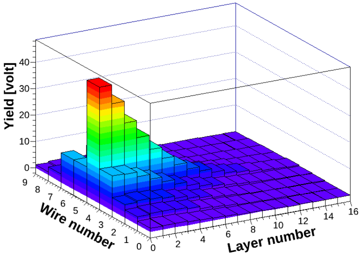
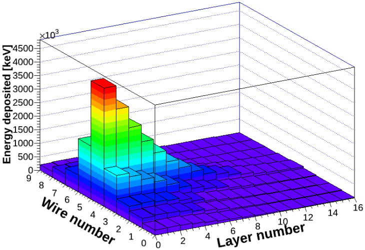



Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 37990




(a) Yield distribution from data for collimation scan : run# 38000




(b) Yield distribution from simulation for collimation scan : run# 38000

Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 38000

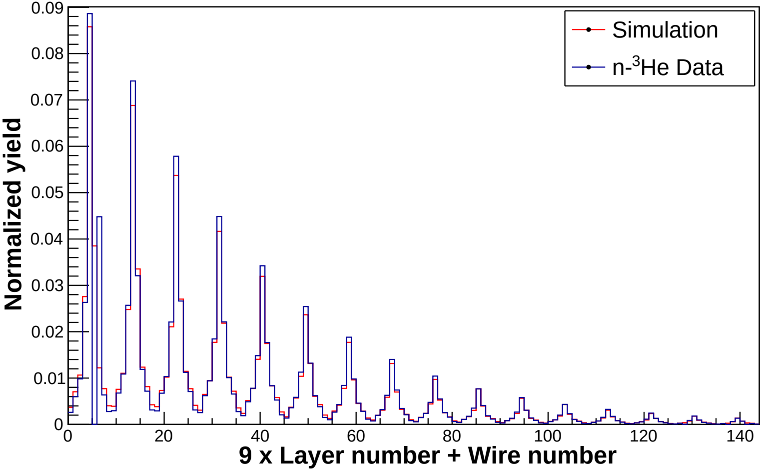
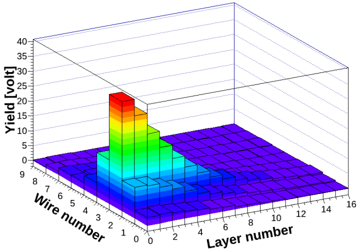
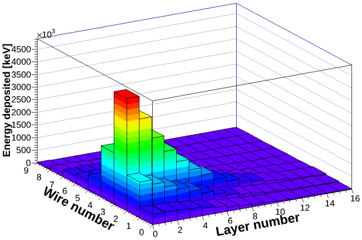



Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 38000




(a) Yield distribution from data for collimation scan : run# 38006




(b) Yield distribution from simulation for collimation scan : run# 38006

Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 38006

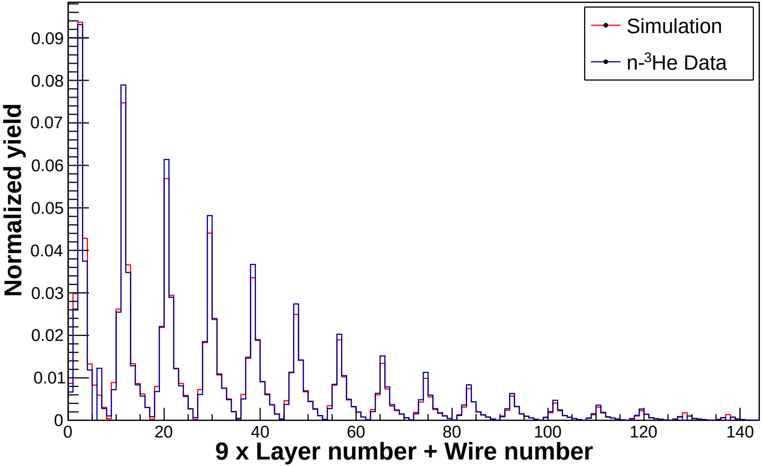



Figure: Yield distribution in the ion chamber from simulation and data for collimation scan : run# 38006

# Outcome from the simulation

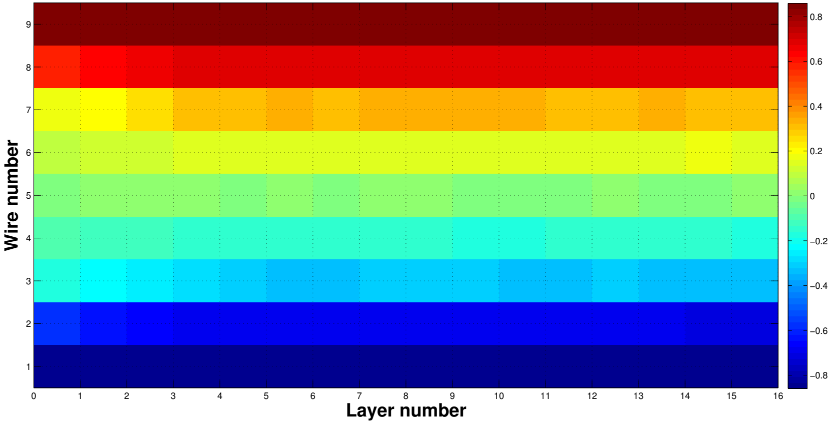



Figure: The distribution of geometry factors for all the signal wires

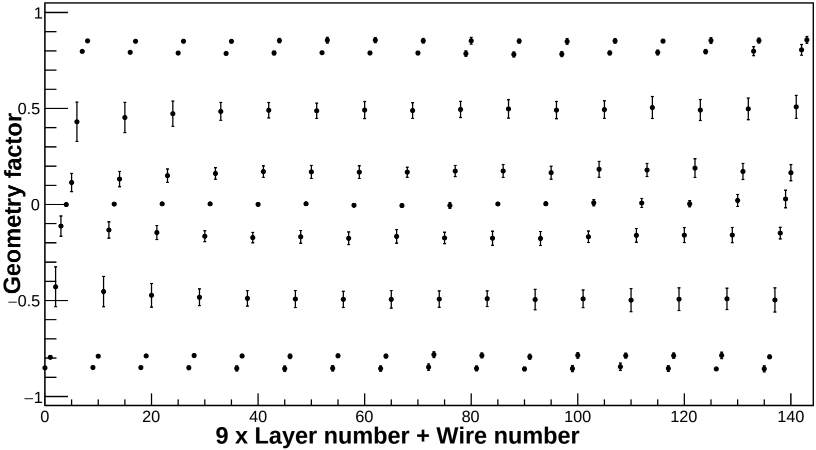



Figure: The geometry factors with errors