Monte Carlo Studies

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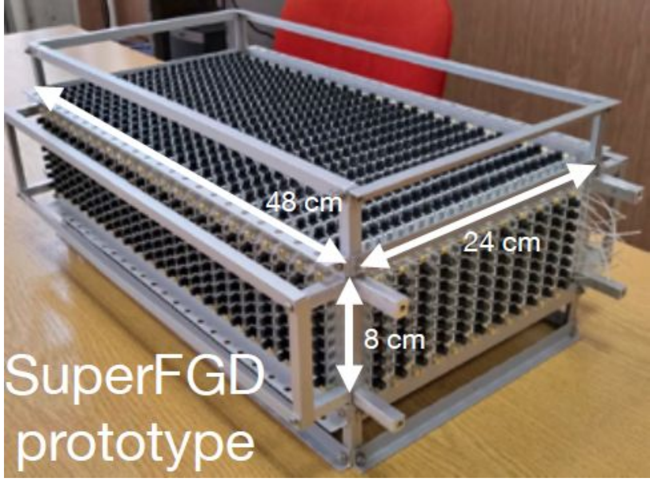
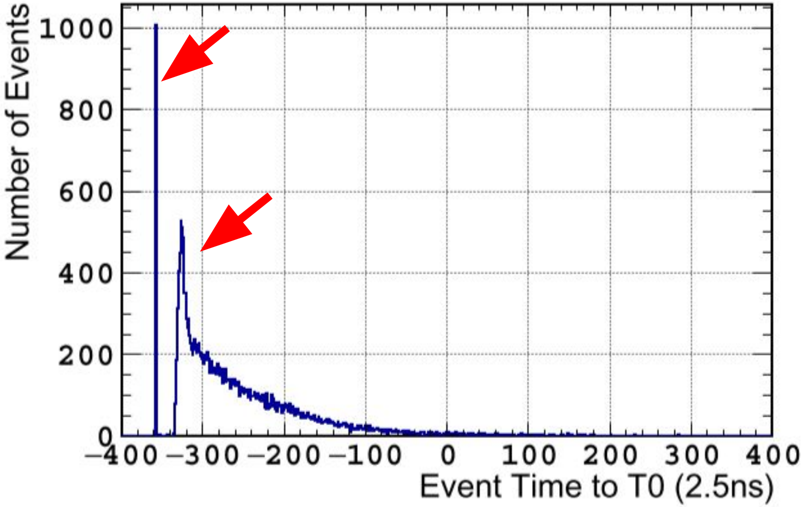
Stony Brook University

Los Alamos National Lab (LANL) Beam Test

Credit: Ciro Riccio



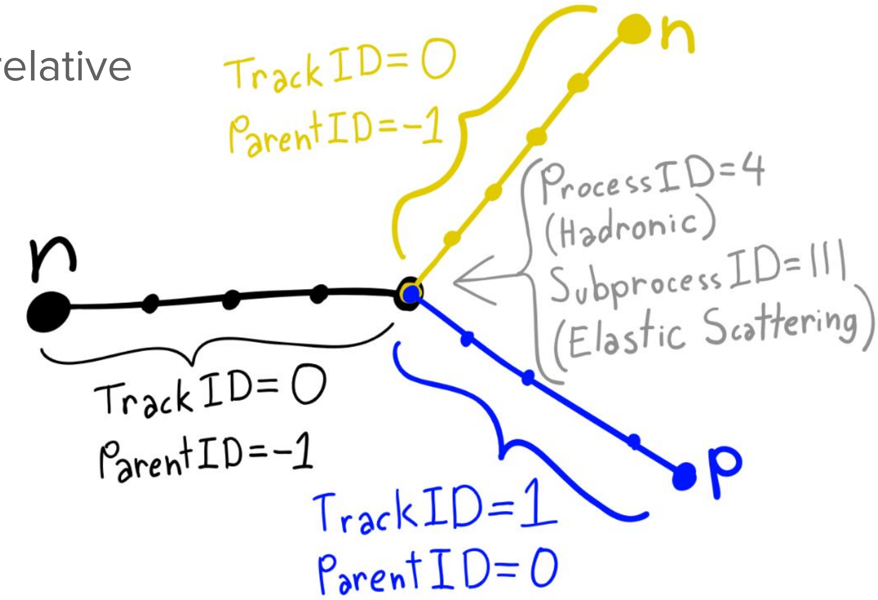
- SuperFGD Prototype constructed to prove SuperFGD technology & study detector performance
- Tested at LANL Weapons Neutron Research (WNR) facility
  - Data taken in 2019, 2020
- Exposure to Neutron & Gamma beam, 0-800 MeV Neutrons
- Neutron arrival time relative to gamma ➔ neutron (ToF)
- Measured total neutron cross section on CH
  - Published in Phys. Lett. B



A. Agarwal et al. Total neutron cross-section measurement on CH with a novel 3D-projection scintillator detector. Phys. Lett. B, 840:137843, 2023.

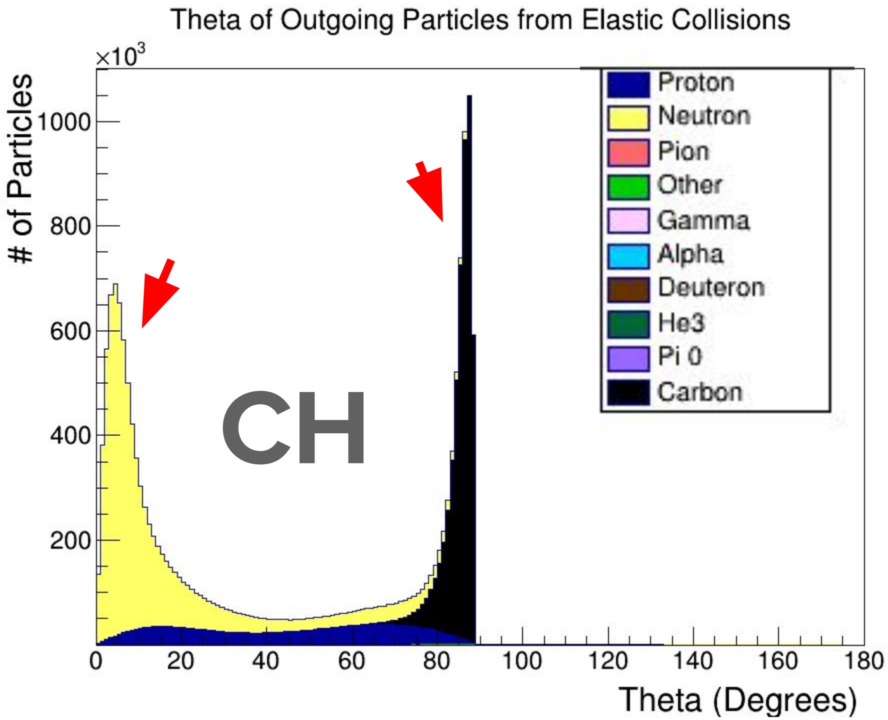
Monte Carlo (MC) Simulation Analysis

- Simulation of neutron interactions on a hydrocarbon (CH) target
  - Outgoing particle kinematics
    - Kinetic Energy, Momentum, θ (angle relative to beam)
  - Collision type (Elastic & Inelastic)
  - Particle Type (Proton, Neutron, etc.)
- First Hadronic interaction
- Vertex Cut
- Analyses on hydrogen & carbon target
- MC created using Geant4
- 1 Trajectory/tracked particle
  - Particle number in stack unique to trajectory
- Kinematics information stored per point
  - Process, SubProcess, total energy, momentum, position, etc.
- Notable results presented

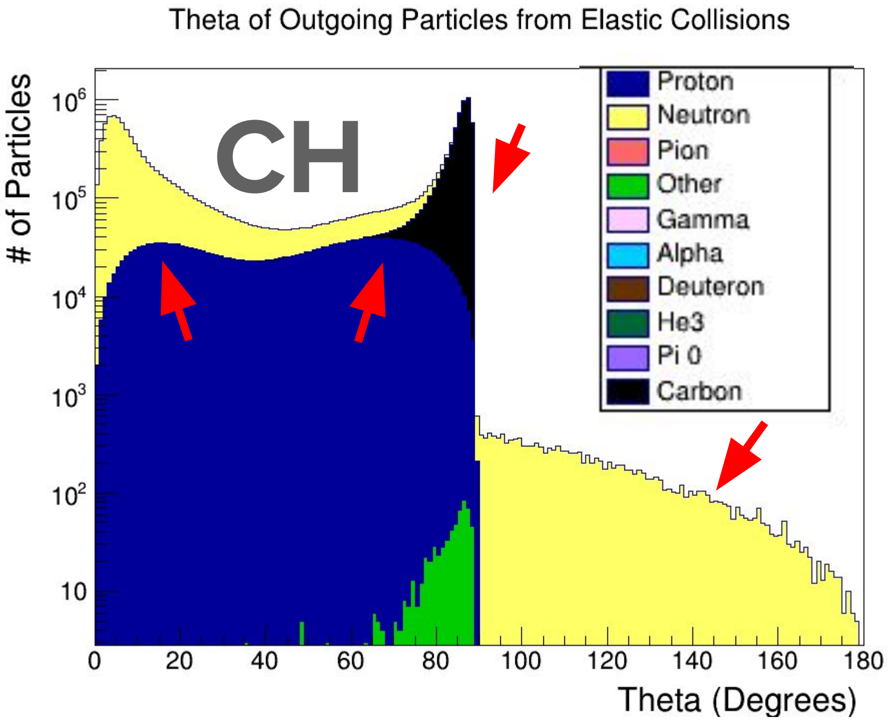


Elastic neutron interaction on Hydrogen, outgoing particles: proton and neutron

θ of Outgoing Particles from Elastic collisions on CH
(Stacked)

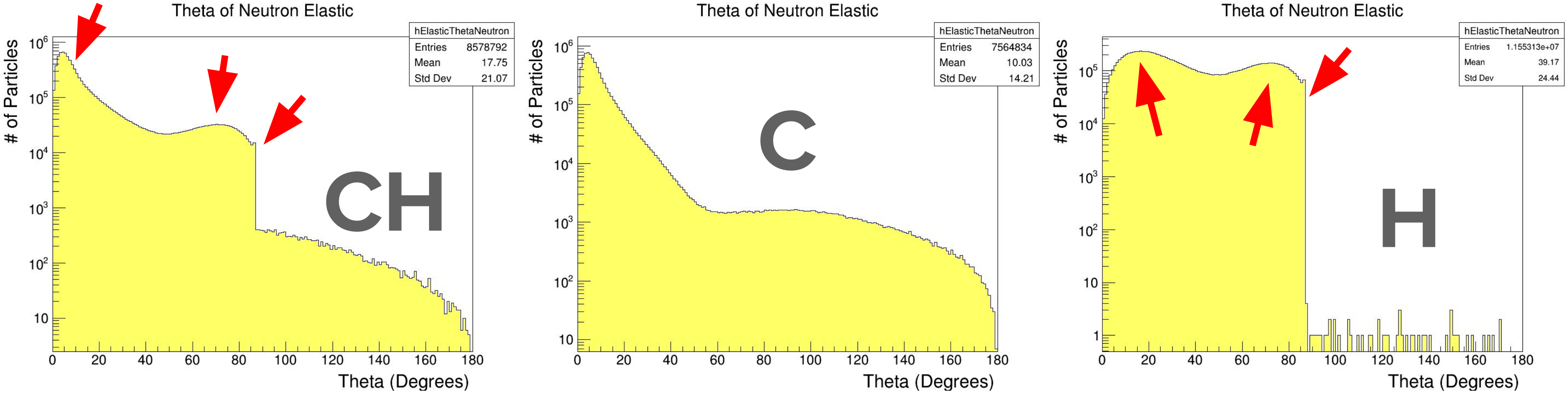


Linear Scale



Logarithmic Scale

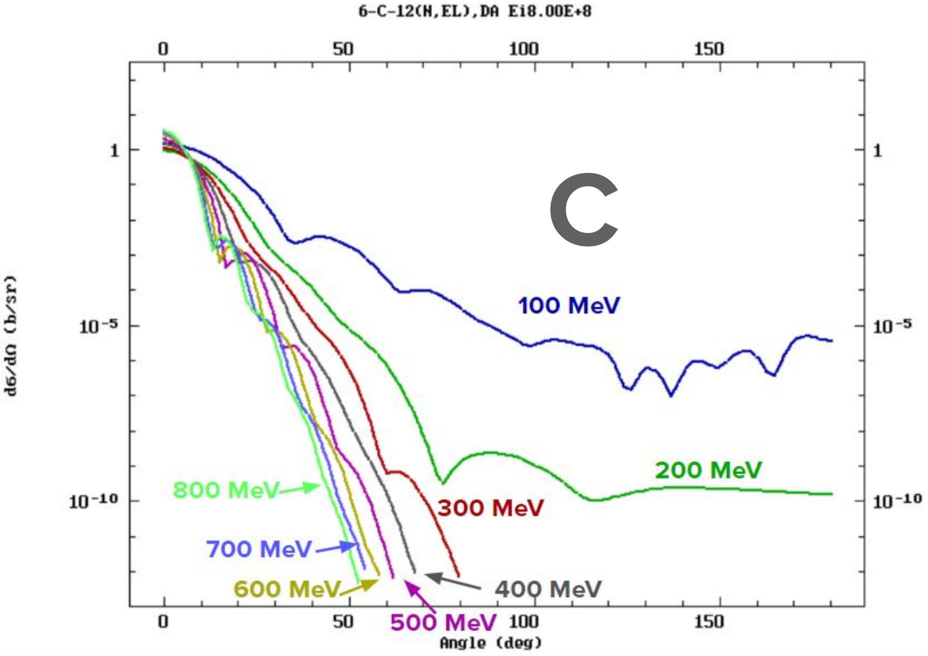
θ of Outgoing Neutrons from Elastic collisions (log scale)

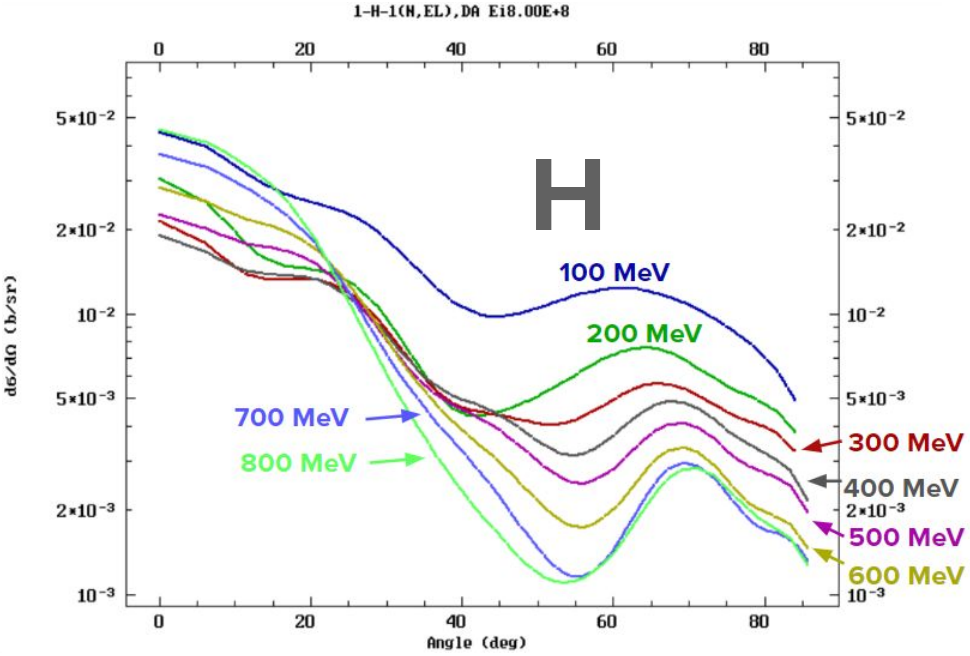


- Sharp drop at ~90°
  - Elastic scattering of neutron on Hydrogen
- Dip - Left peak higher than right peak

Cross Section as a function of θ

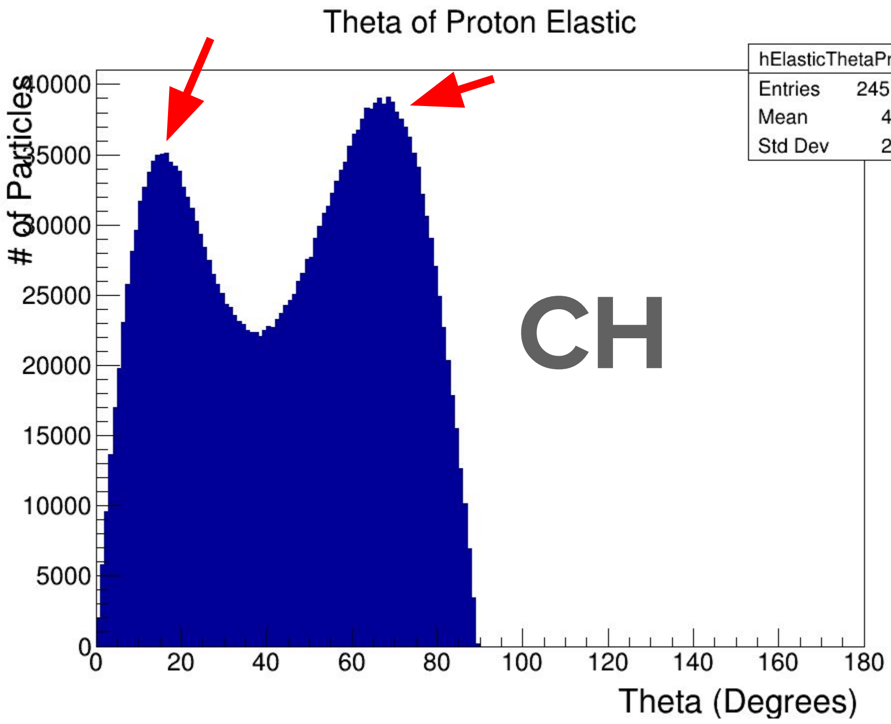
D. A. Brown et al. ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data. Nucl. Data Sheets, 148:1–142, 2018.

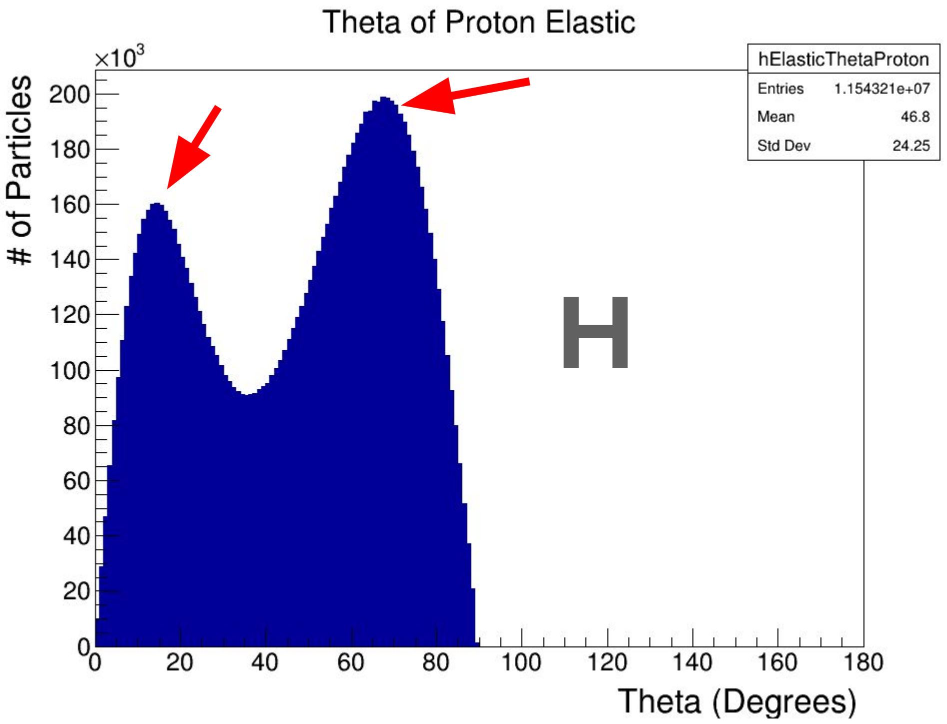




- Cross section changes as fxn of angle
- Dip in cross section as a function of angle
- Dip location changes as a function of energy

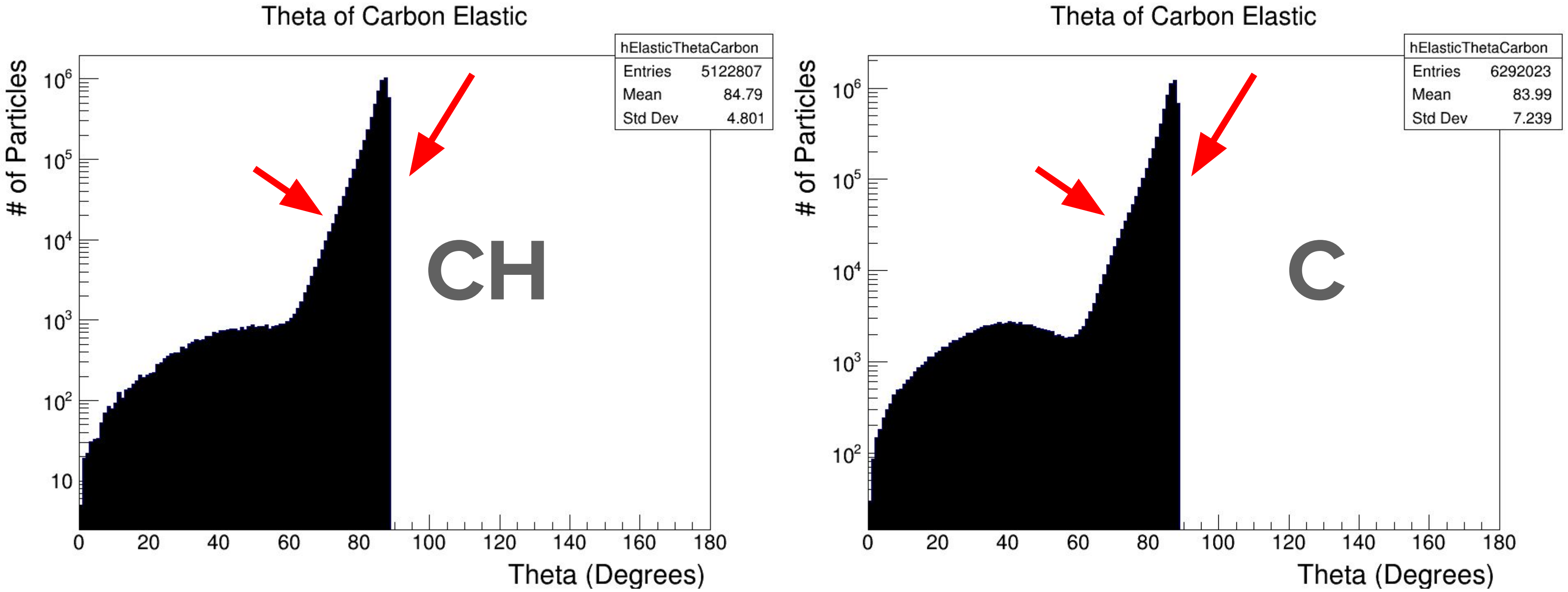
θ of Outgoing Protons from Elastic collisions (linear scale)





- Dip - Right peak higher than left peak
  - 90° angle between p & n

θ of Outgoing Carbons from Elastic collisions (log scale)

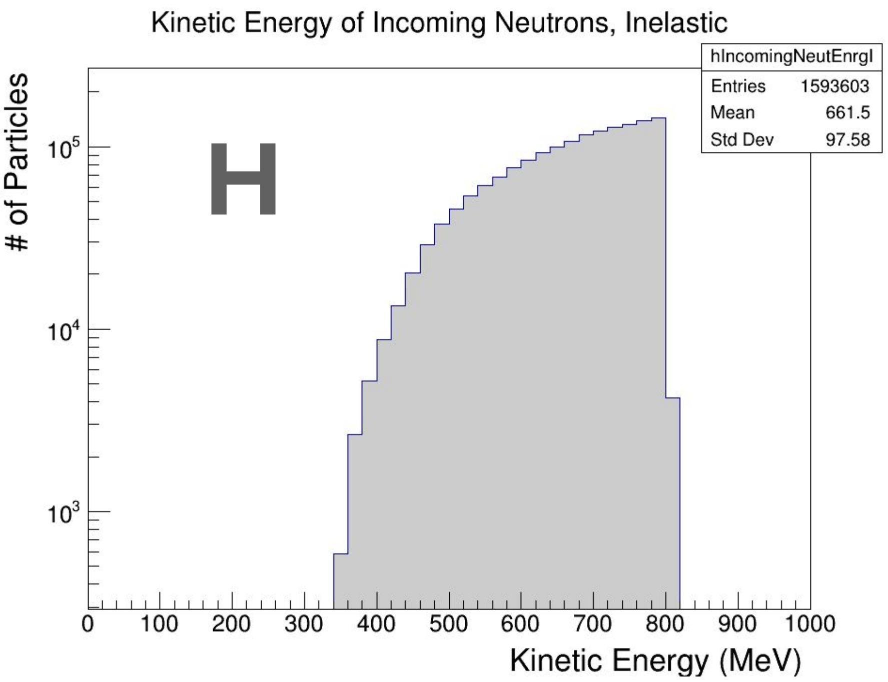


- Sharp drop at 90°
  - Classical Kinematics ➔ $m_{C12} >> m_n$

Kinetic Energy of Incoming Neutrons which interact Inelastically with Hydrogen

(Some) Neutron on Free Proton Possible Interaction Channels

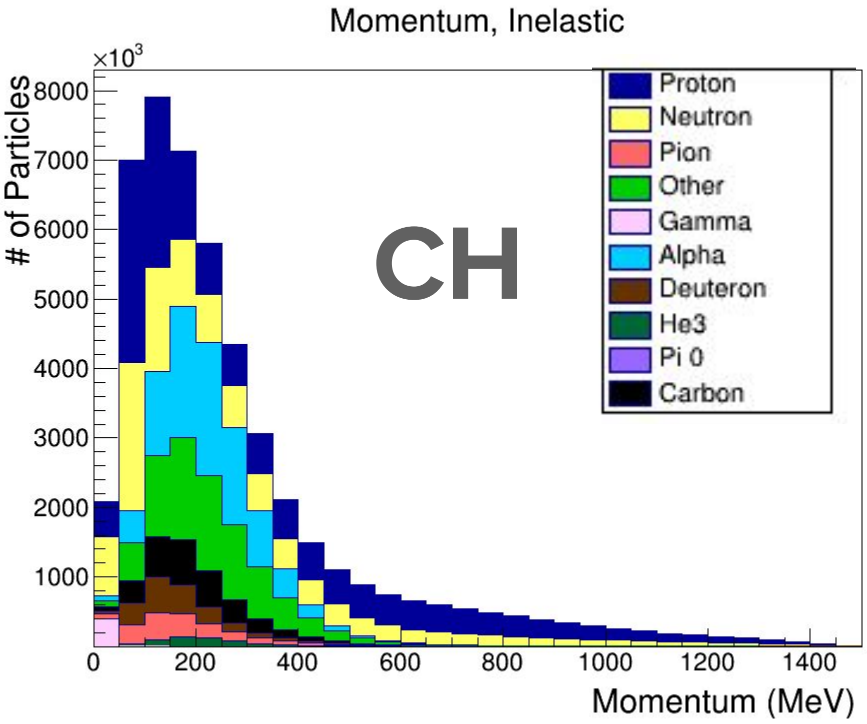
	E_{Thresh} (products at rest)
$1) n + p \rightarrow n + n + \pi^+$	~290MeV
$2) n + p \rightarrow p + p + \pi^-$	~286MeV
$3) n + p \rightarrow D + \pi^0$	~275MeV
$4) n + p \rightarrow n + p + \pi^0$	~279MeV

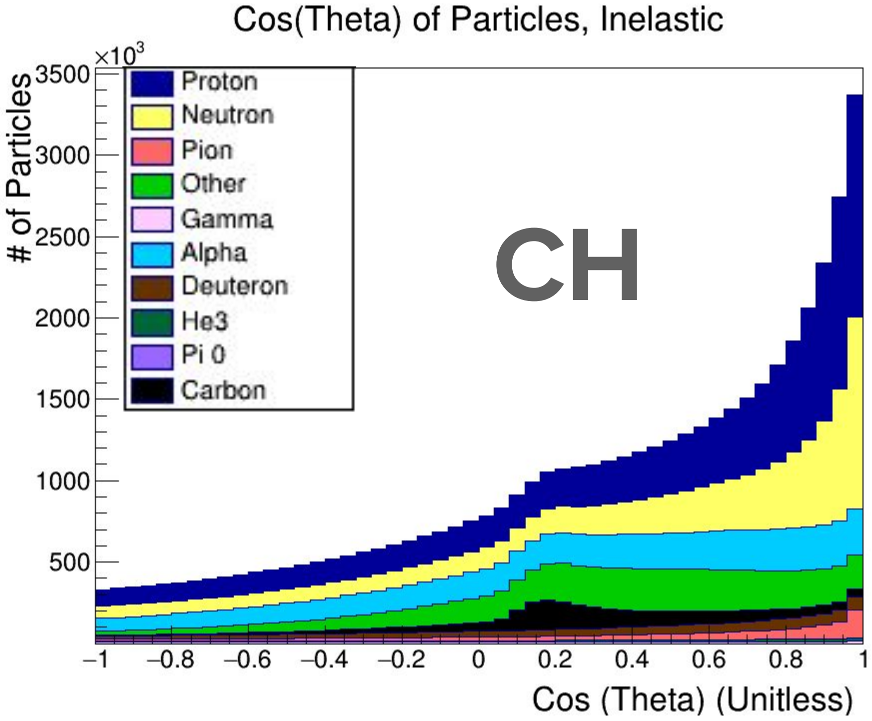


~75MeV Difference

- Future work

Momentum and Cos(θ) of Outgoing Particles from Inelastic Scattering on CH (stacked)





Linear Scale

Single Track Selection

- Recall: LANL Test Beam Paper Aims:
  - Measured total neutron cross section looking at depletion of # of events along detector
    - Selected neutron interactions with 1 outgoing charged particle - clear vertex identification
- Reduction & restructuring of MC simulations to resemble data
- Computed distances between reconstructed tracks and truth
  - Verify matching between reco & true
- Percentage of particle types contributing to single track events

Purity Analysis

- Largest distance between true and reconstructed tracks is 8.3mm, < half diagonal cube
- Purity analysis
  - Particle with maximum energy deposition per single track event
  - Particle type using MC information

Particle Type	Purity
p	84.7%
$\pi^{\pm}$	5.9%
α	2.7%
e^{-}	2.5%
$^{8}C -^{13}C$	1.3%
^{2}H	1.0%
e^{+}	0.3%
^{3}He	0.3%
μ^{+}	0.01%
μ^{-}	$< 0.01\%$
γ	$< 0.01\%$
n	$< 0.01\%$
Others	1.19%

First Interaction Process (ProcessID)	First Interaction Type (SubProcessID)	Purity
Hadronic	Inelastic Scattering	56.0%
	Elastic Scattering	41.2%
	Hadron at Rest	$< 0.01\%$
Electromagnetic	Compton Scattering	2.3%
	Gamma Conversion	0.3%
	Ionization	$< 0.01\%$
Decay	Decay	0.2%

Conclusions & Future Work

- Analyses on simulations of neutron interactions on CH show features consistent with ENDF data
    - Features of Geant4 version require further investigation
- Protons contribute most to single track events
- 56% of single track events from inelastic scattering, 41.2% from elastic
- MA Thesis successfully defended

- Comparisons of analysis on MC simulations to 2019, 2020 LANL beam test data
    - Particle multiplicity, outgoing particle angles, kinetic energies, etc.
- Investigations into different software versions to understand limitations of simulation analyses better
- Tech note in progress

Thank you very much for your attention!

References

Image Citations

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[16] Neutron geant4 simulation analysis. https://gitlab.com/neutron-lanltb-analysis/neutrong4simulationanalysis.

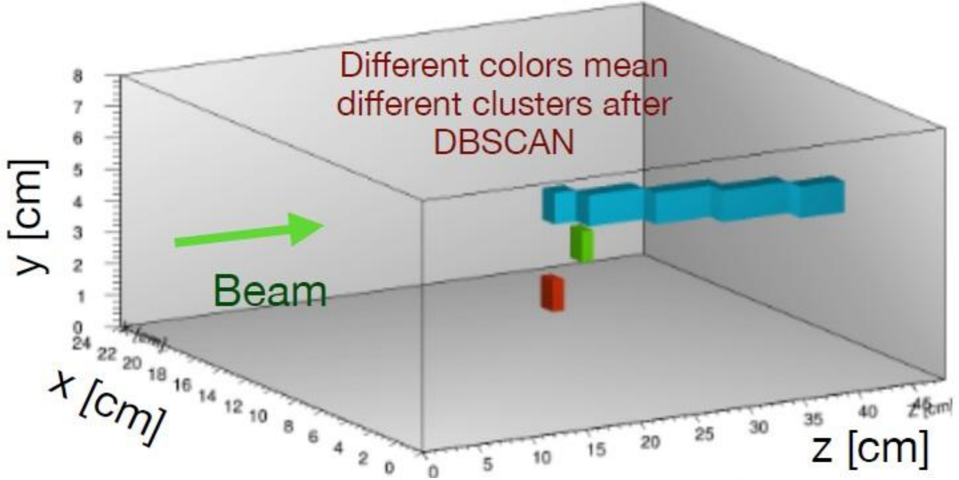
[17] Conversion & single track selection scripts. https://git.t2k.org/sfgd_tools/sfgd_framework.

Backup

Contents

Single Track Selection

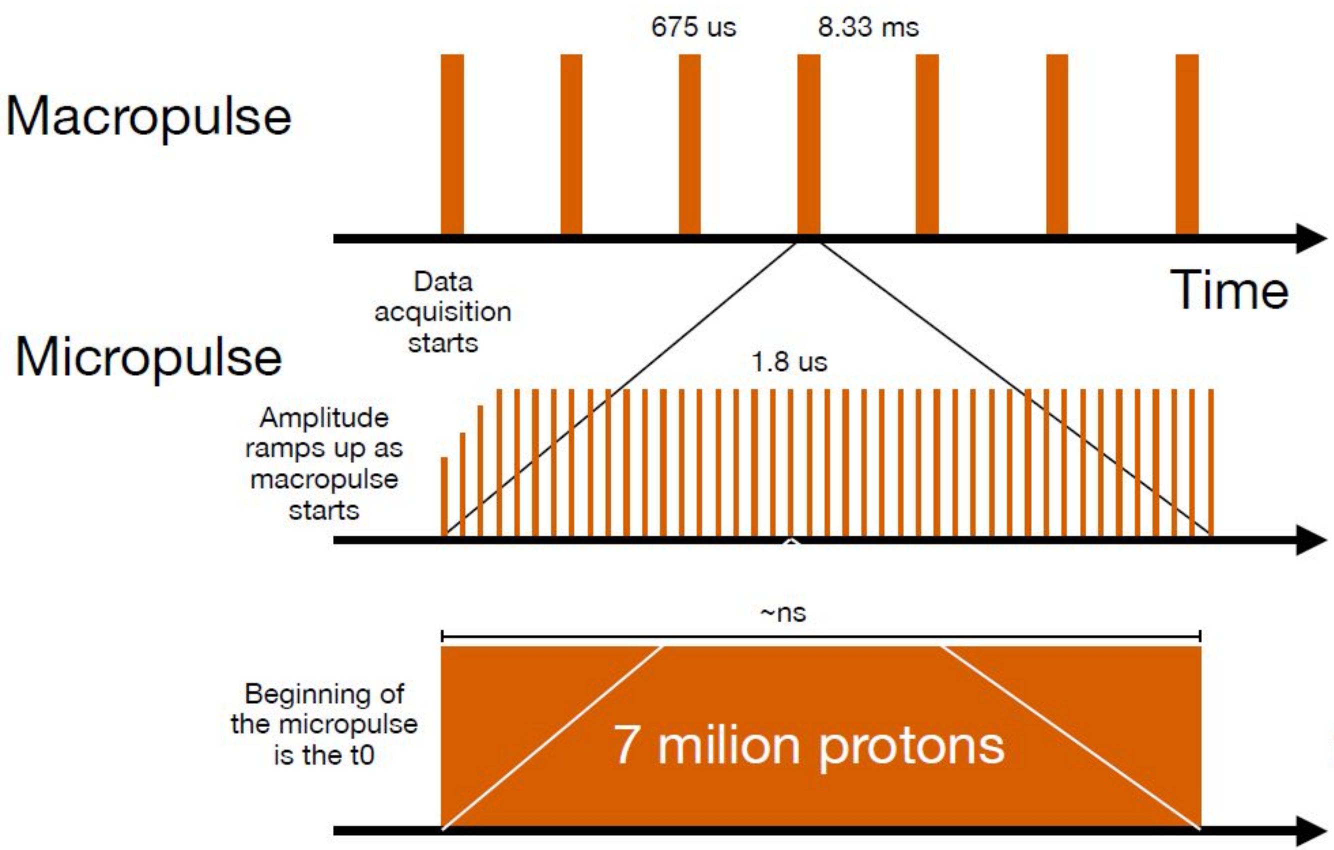
- Minimum energy deposit threshold
- >3 voxels (cubes), each with PE>20
- Within fiducial volume
- Clustering algorithm (DBSCAN)
- Cluster width within 1.7cm (cube diagonal)



Credit: Eric Zhong

Credit: Ciro Riccio

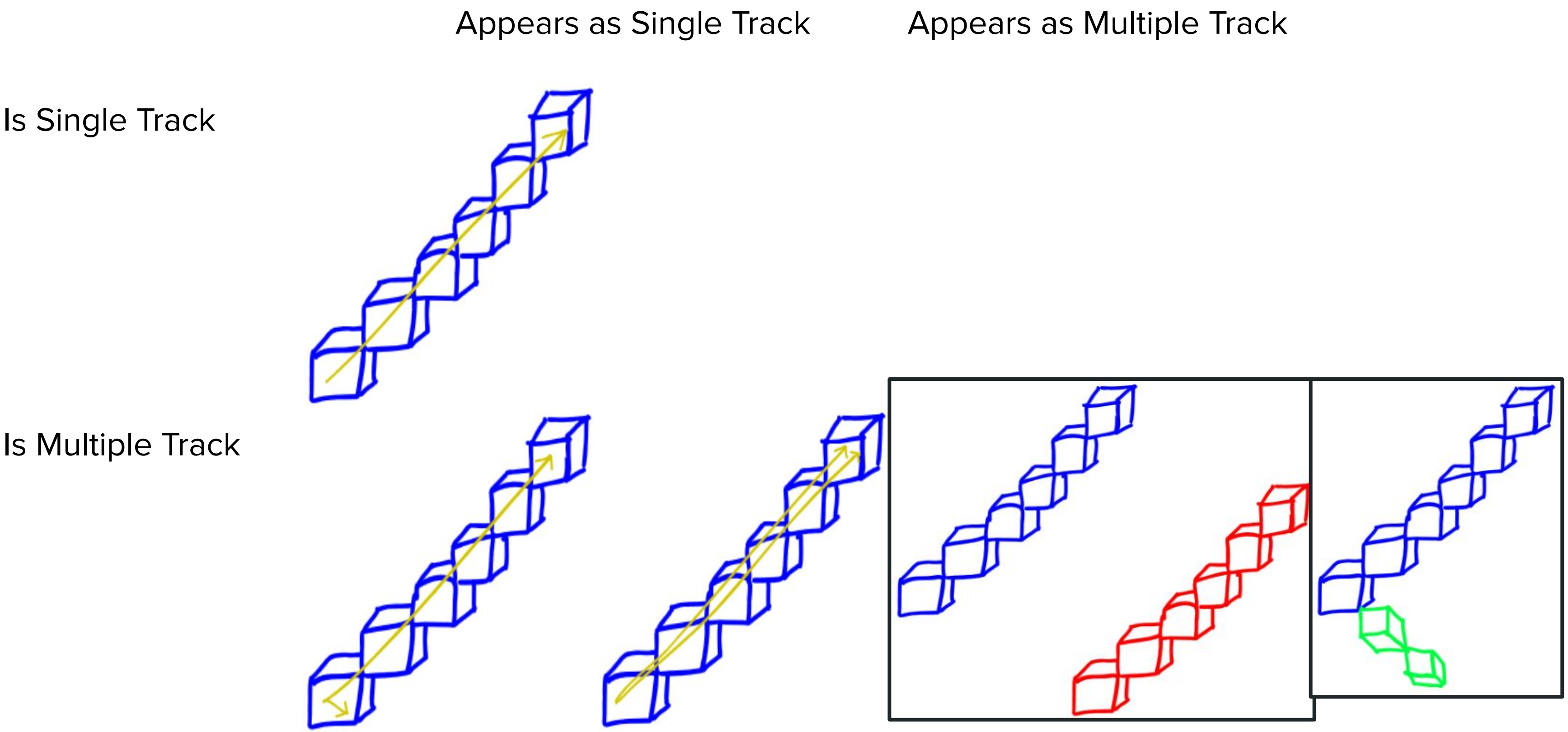
Beam Structure



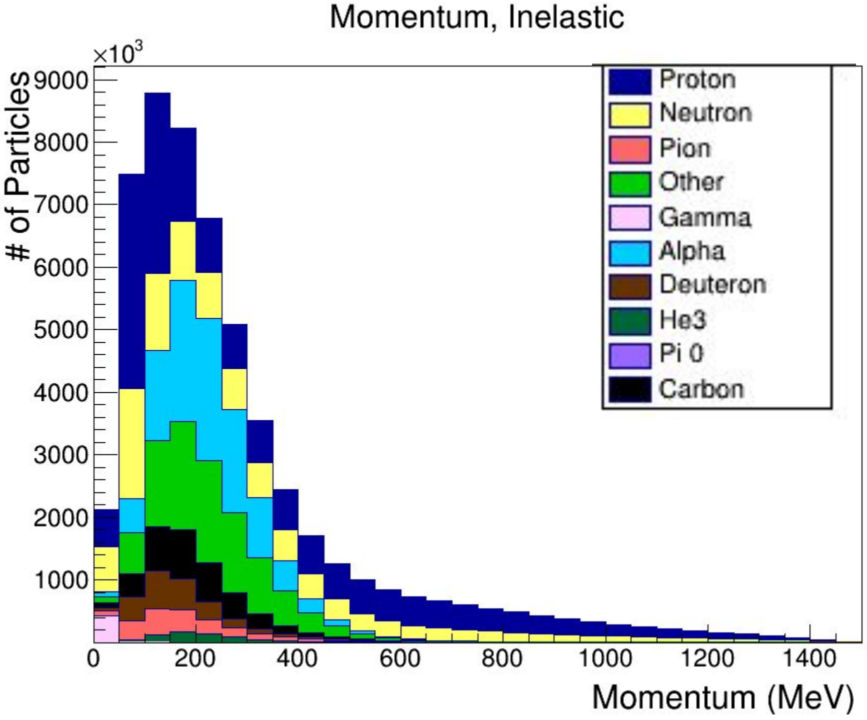
Protons impinge on the target and produce neutrons and gammas.

Credit: Ciro Riccio

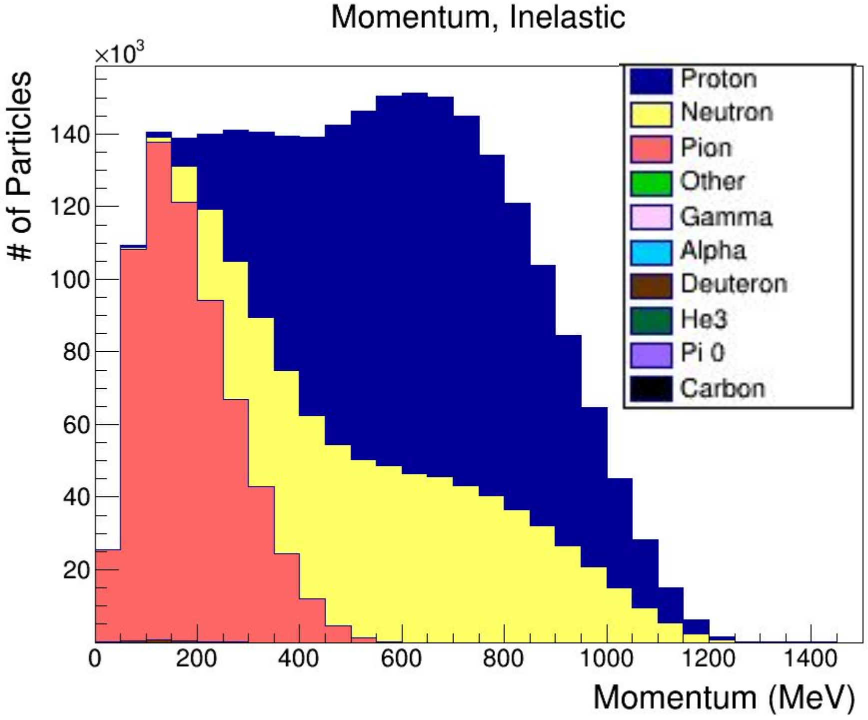
Single Track Selection: Physics Perspective



Momentum of Outgoing Particles from Inelastic Scattering on Carbon and Hydrogen Targets (stacked, log scale)



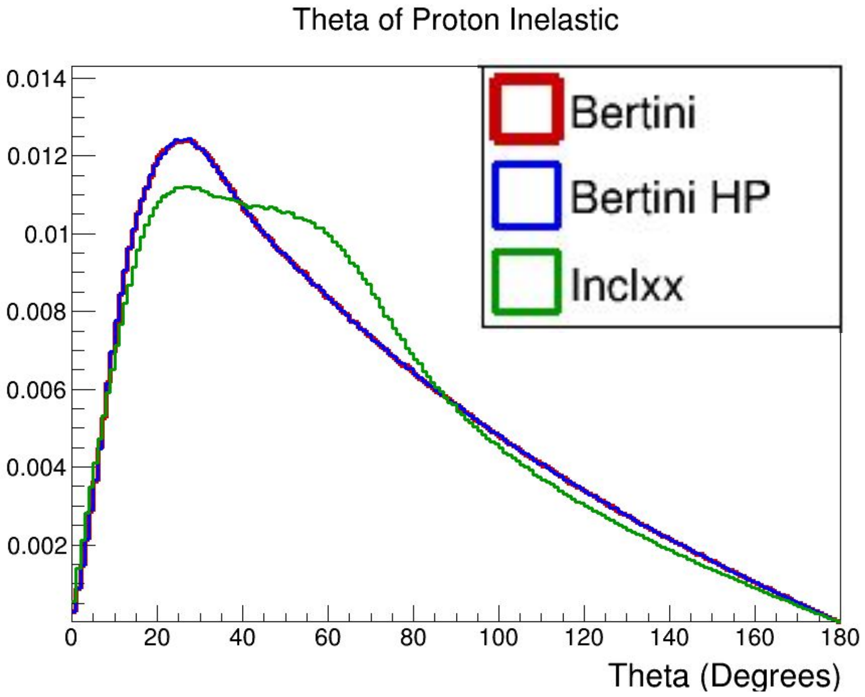
Carbon Target



Hydrogen Target

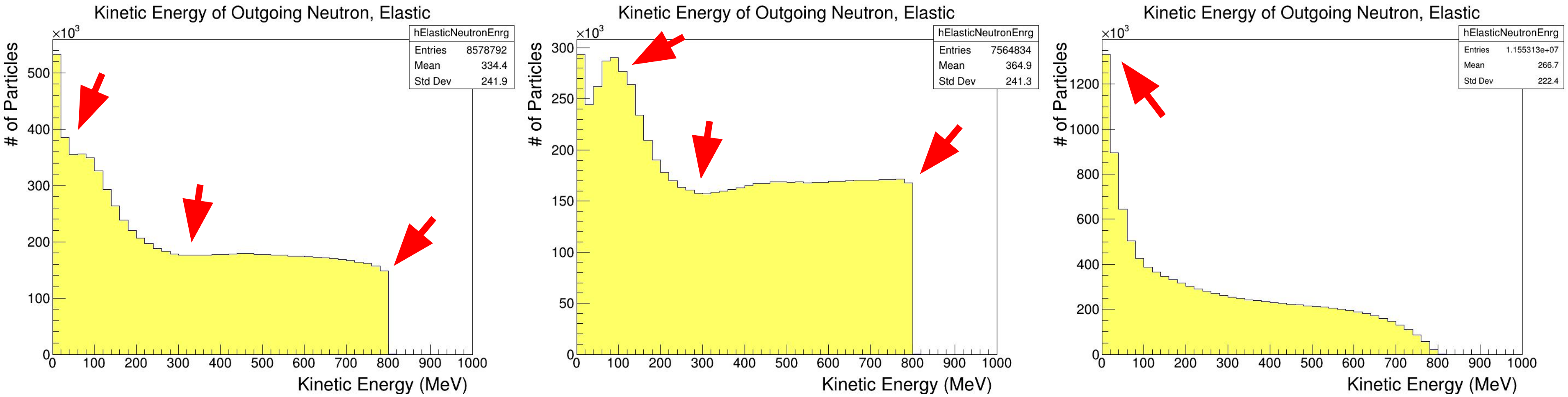
Physics List Comparisons

- Different models for particle-nuclei interactions
  - Expect: mostly effect neutron inelastic scattering on carbon
- Bertini
  - Uses Fermi Gas model
  - Small nucleon size relative to medium size
- Bertini High Precision (HP)
  - Extension of Bertini to 0-20 MeV
- Inclxx
  - Leige Intranuclear Cascade model
  - Reactions induced by light nuclei



Kinetic Energy of Outgoing Neutrons from Elastic collisions

(linear scale)



Hydrocarbon Target | Carbon Target | Hydrogen Target

- Sharp drop at 800MeV
    - Elastic scattering of neutron on Carbon
- Dip - ~350MeV
    - Cross Section

Neutron Interactions w/ Hydrogen (Inelastic)

$$E_{Threshold} = \frac{\left(\sum_{i=0} m_i c^2\right)^2 - \left(\sum_{j=0} m_j c^2\right)^2}{2 m_n c^2}$$

$i \in$ incident particle & target $\quad j \in$ products

(Some) Neutron on Free Proton Possible Interaction Mechanisms

Reaction	Threshold Energy for Incoming Neutrons for these interactions to take place (products at rest)
$1) n + p \rightarrow n + n + \pi^+$	~290MeV
$2) n + p \rightarrow p + p + \pi^-$	~286MeV
$3) n + p \rightarrow D + \pi^0$	~275MeV
$4) n + p \rightarrow n + p + \pi^0$	~279MeV

Cross Section as a function of Incoming Neutron K.E.

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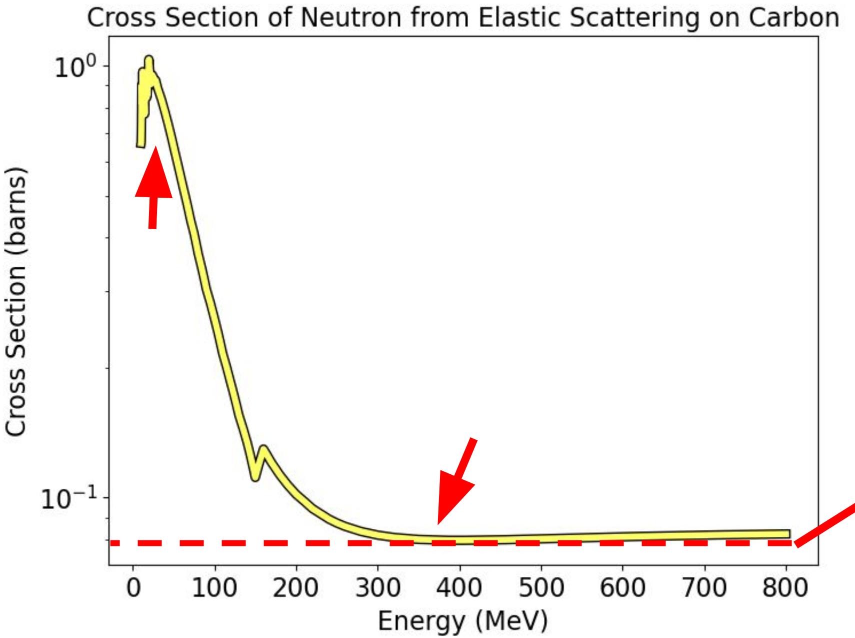
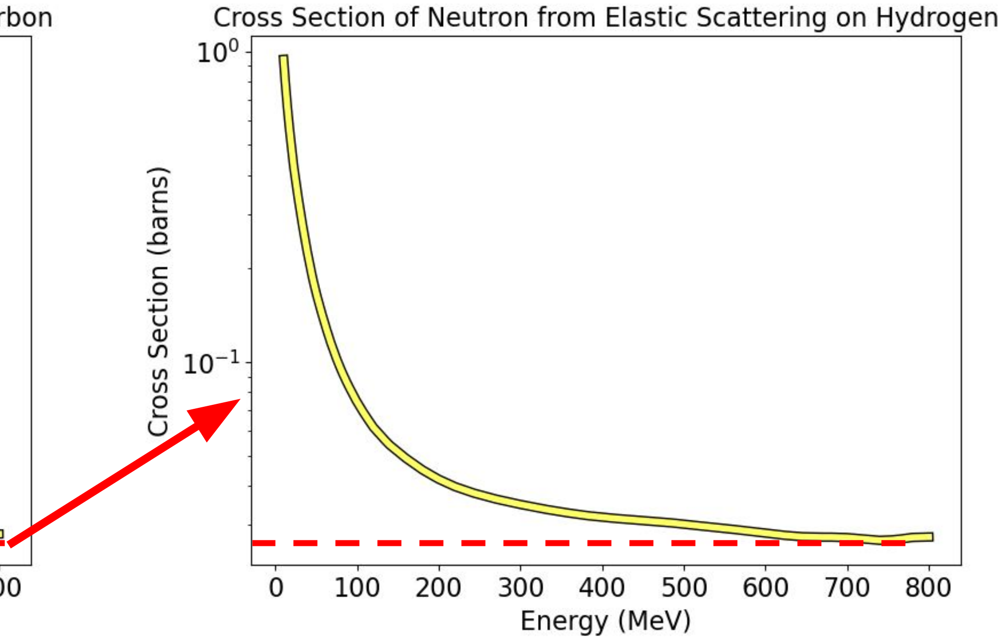
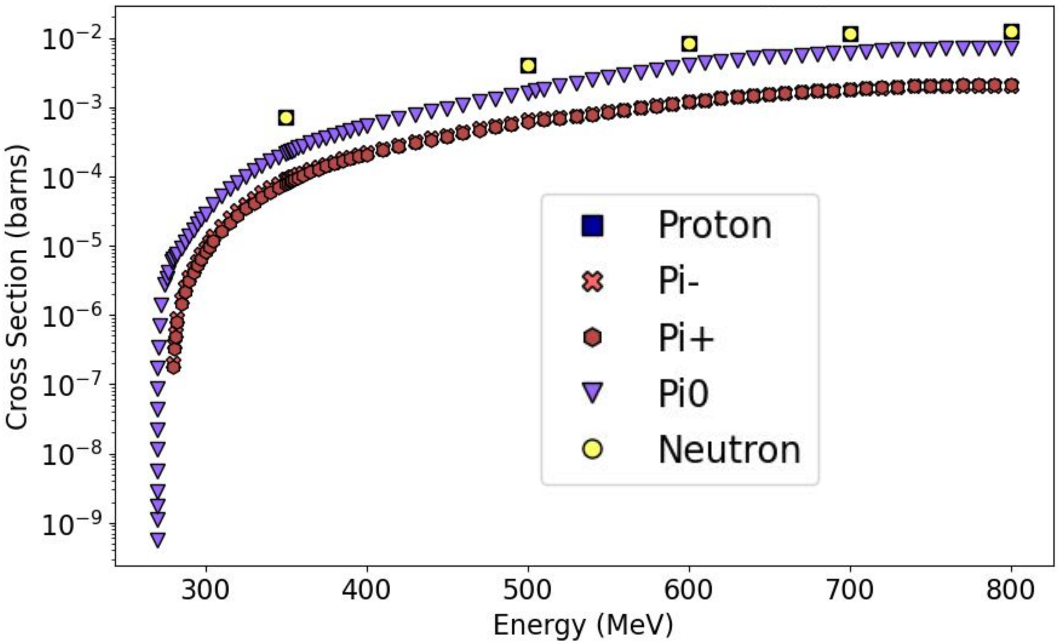


Carbon Target



Hydrogen Target

Cross Section as a function of Energy for Outgoing Particles from Inelastic Scattering on Hydrogen



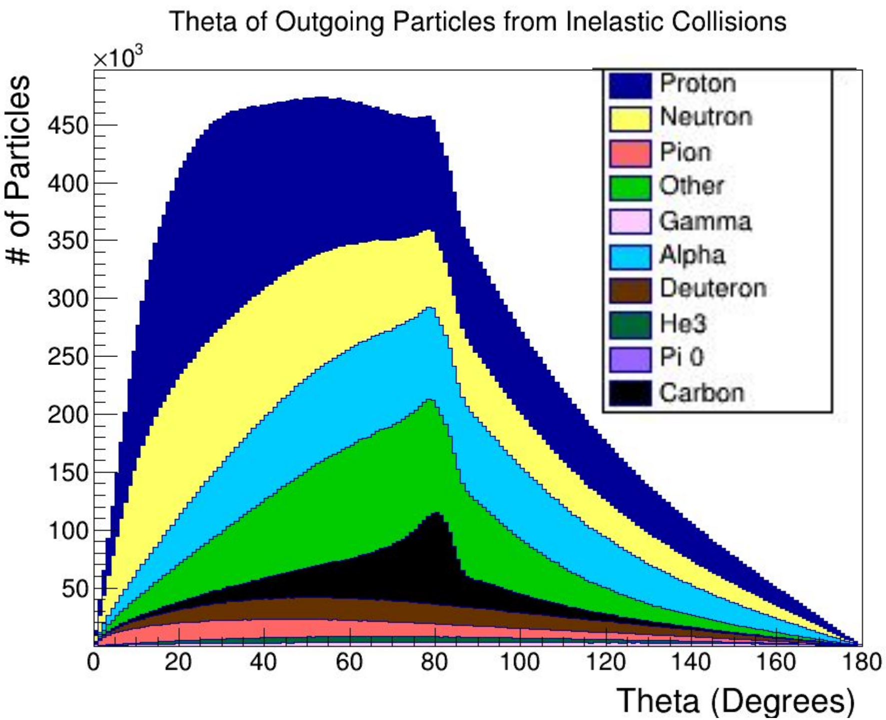
Particle Type Production	Integrated Cross Section for 0-800 MeV using ENDF Data	
π^+	~0.511 barns	~2.702 barns
π^-	~0.515 barns	
π^0	~1.676 barns	
Total	~2.709 barns	

D. A. Brown et al. ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data. Nucl. Data Sheets, 148:1–142, 2018.

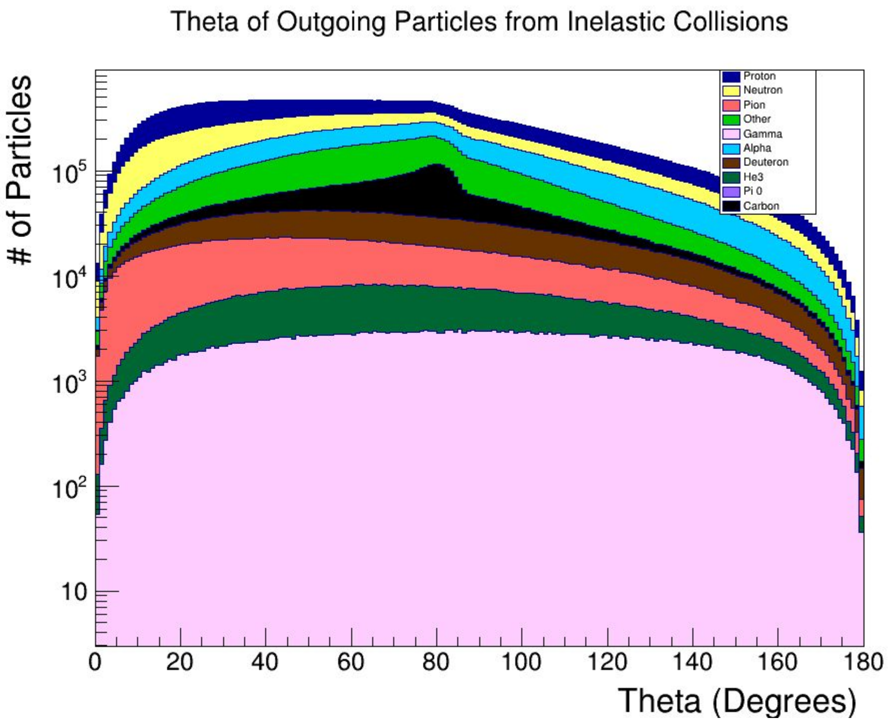
➡ This version of software doesn't track π^0's?

- Future work

θ of Outgoing Particles from Inelastic Scattering on CH (stacked)

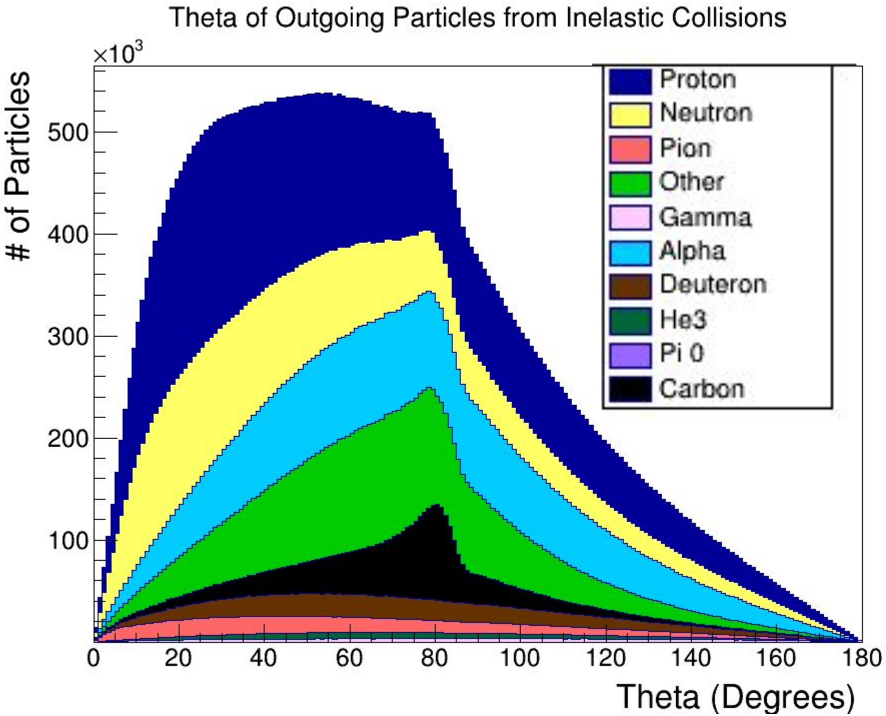


Linear Scale

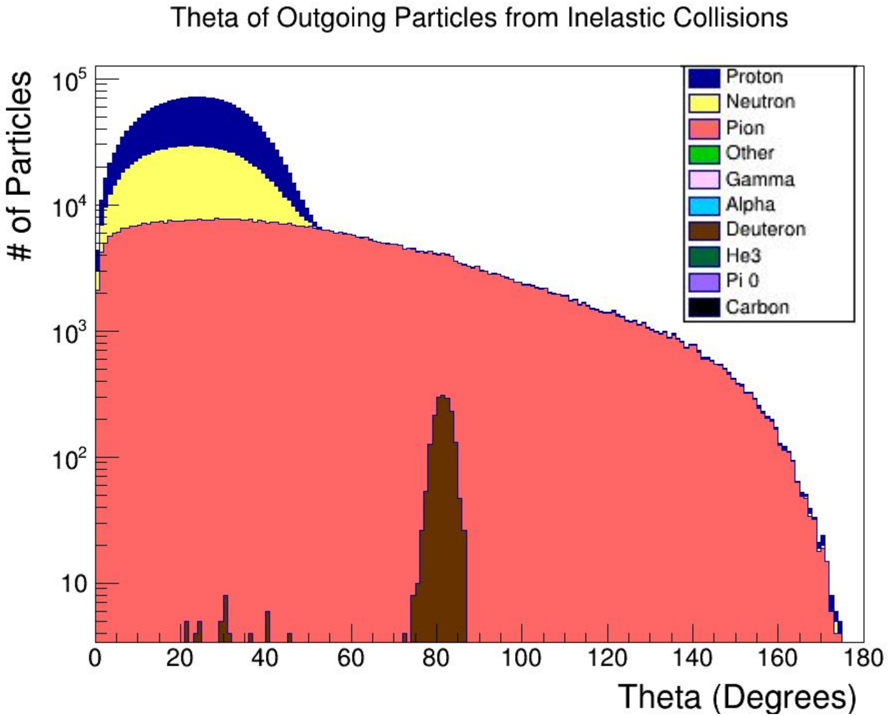


Logarithmic Scale

θ of Outgoing Particles from Inelastic Scattering on Carbon and Hydrogen Targets (stacked, log scale)

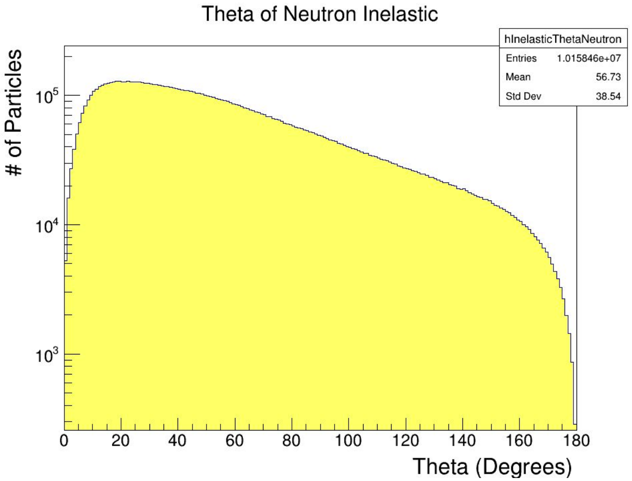


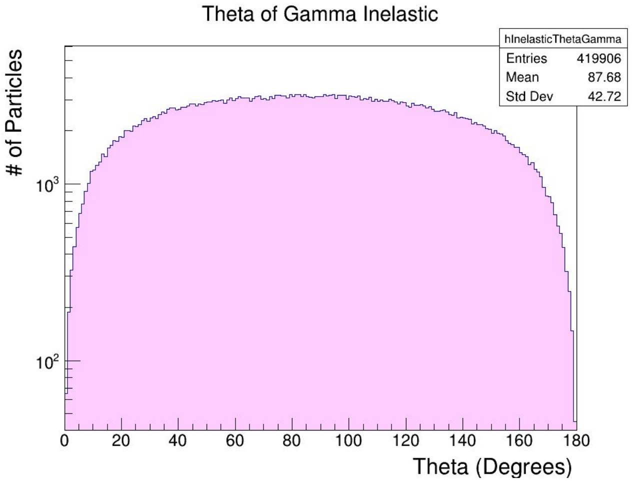
Carbon Target

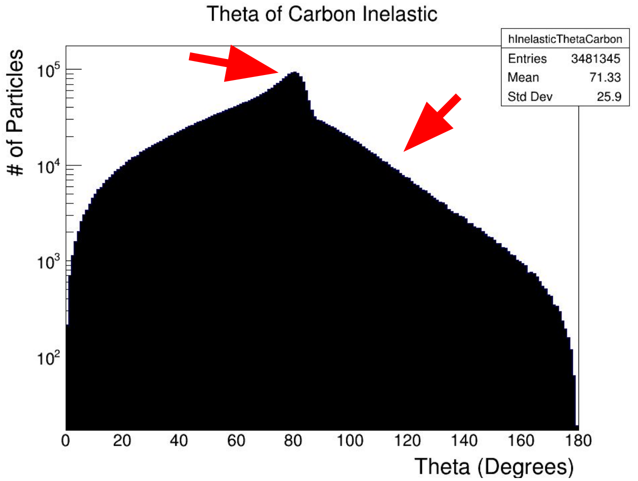


Hydrogen Target

Notable Features for θ of Outgoing Particles from Inelastic Collisions on Carbon (log scale)





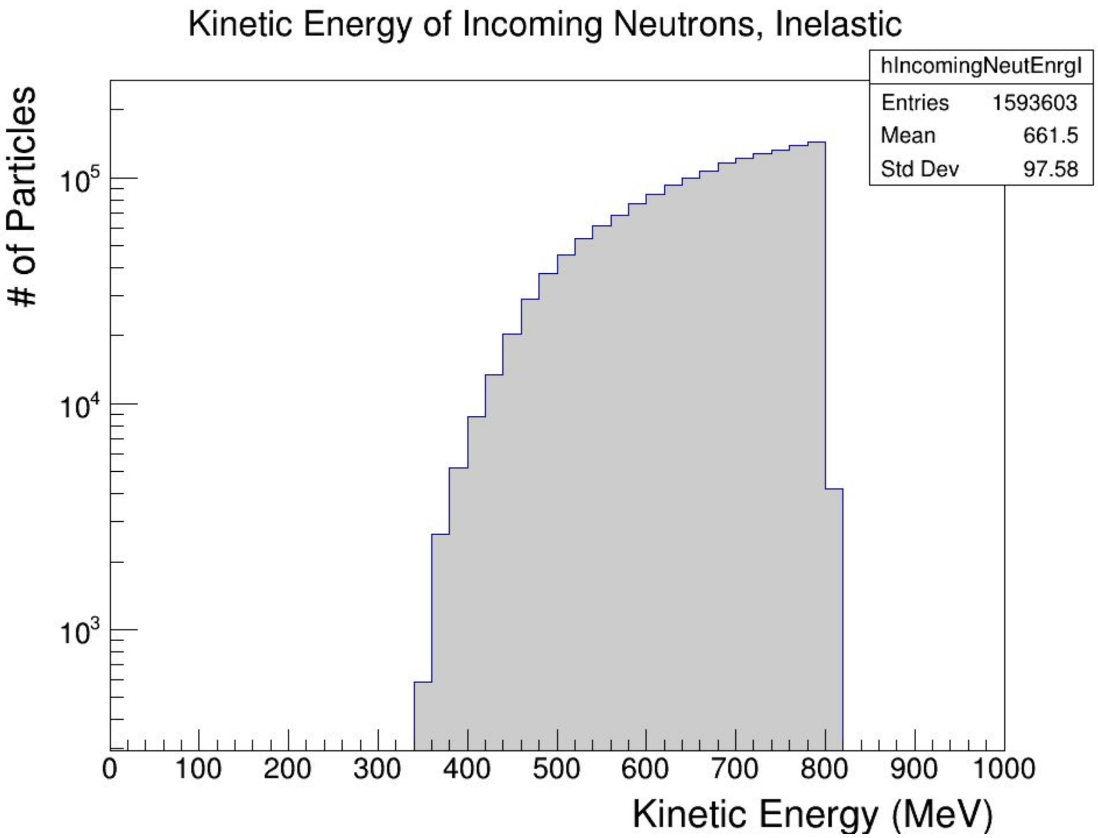


- θ_γ isotropic distribution
  - $m_\gamma = 0$

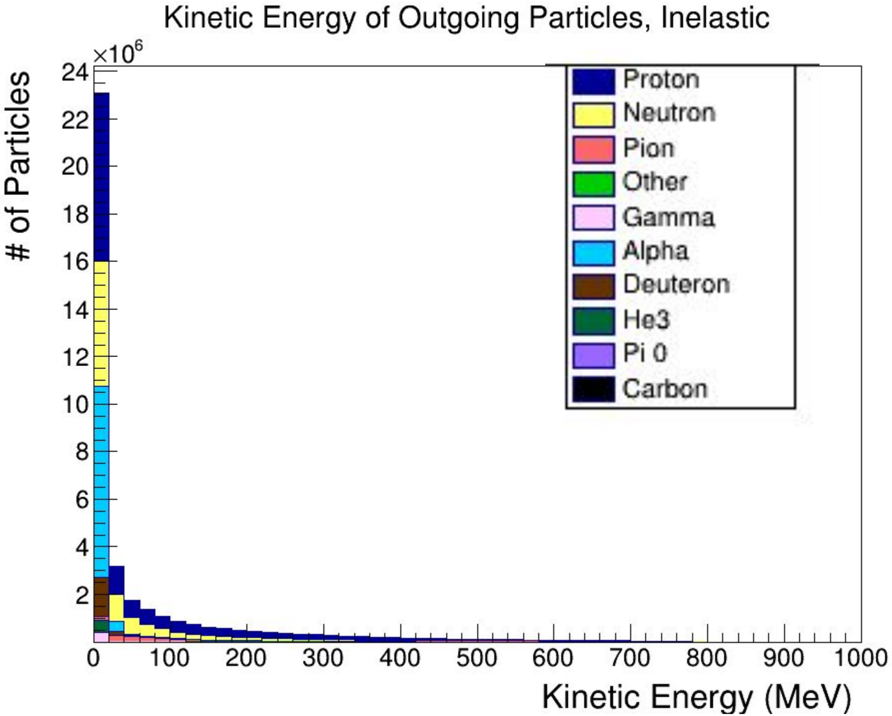
- Peak at $\theta_{12C} \cong 85°$
  - Feature of elastic scattering
- Gradual decline for $\theta_{12C} > 90°$
  - Inelastic → CoM Energy not conserved

Kinetic Energy of Incoming Neutrons which interact Hadronically on Hydrogen Target (stacked)

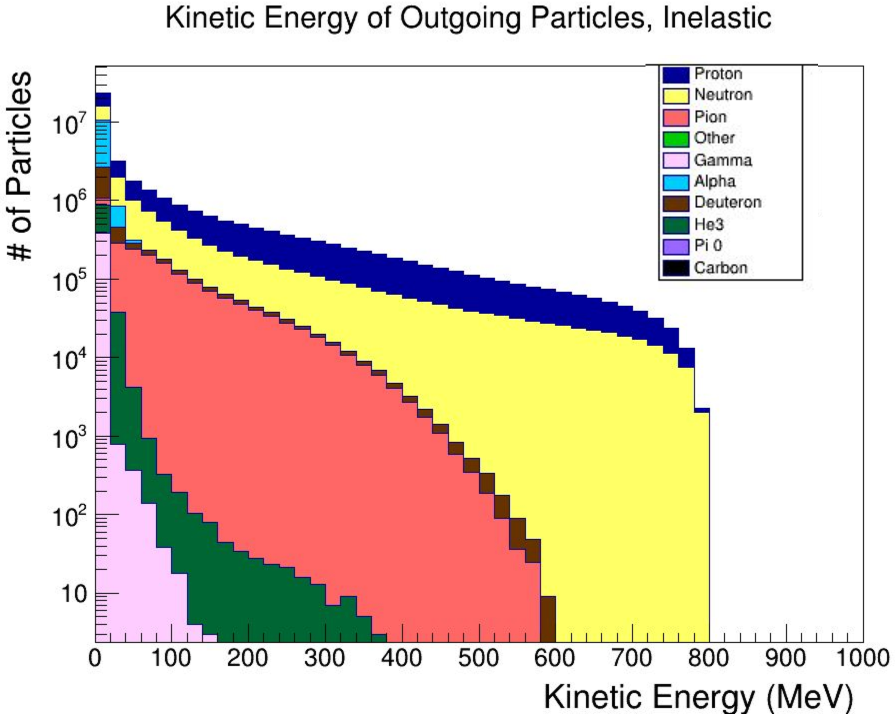
- Start seeing inelastic processes occur at ~350 MeV
- Recall: Minimum threshold energy for incoming neutrons ~275 MeV
- ~75MeV Difference
  - Future work



Kinetic Energy of Outgoing Particles from Inelastic Scattering on Carbon Target (stacked)

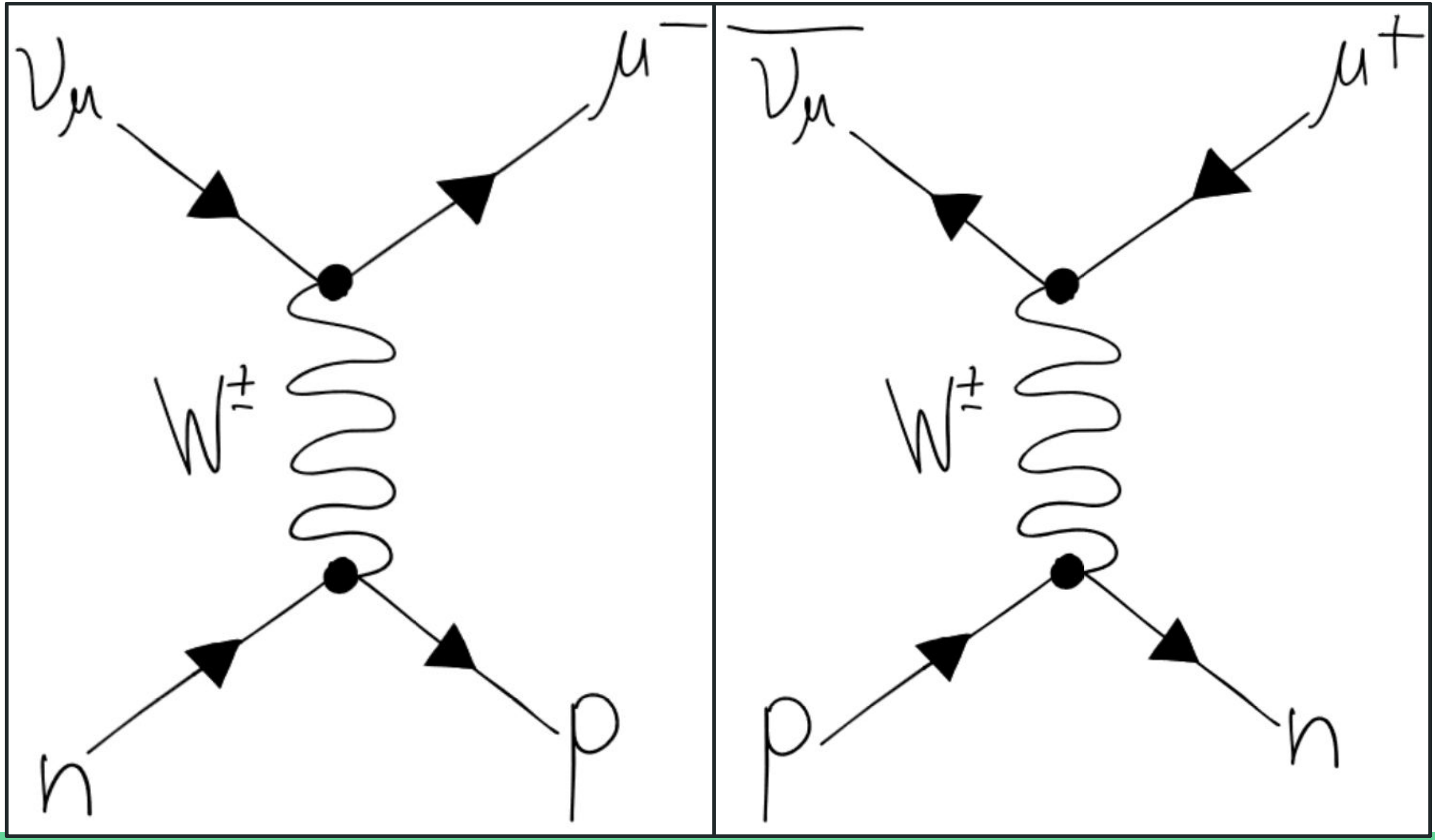


Linear Scale

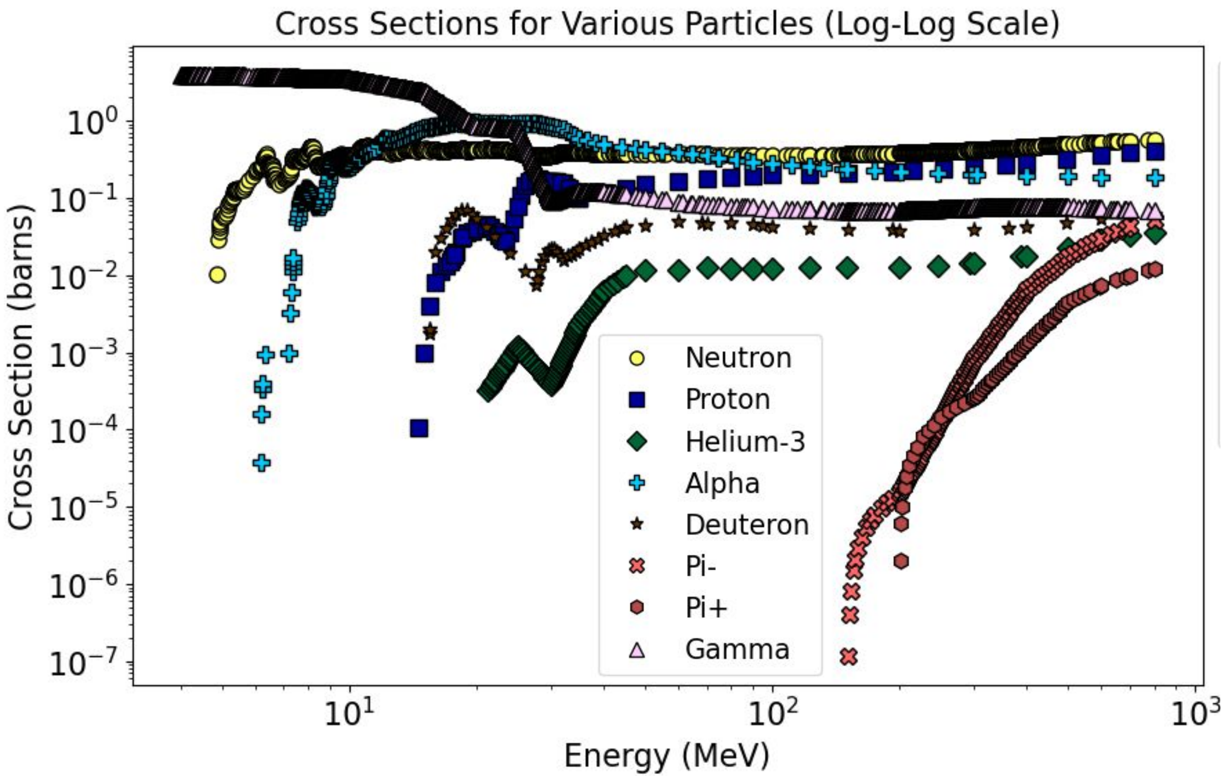


Logarithmic Scale

Examples of CCQE interactions



Cross Section as a function of Energy for Outgoing Particles from Inelastic Scattering on Carbon



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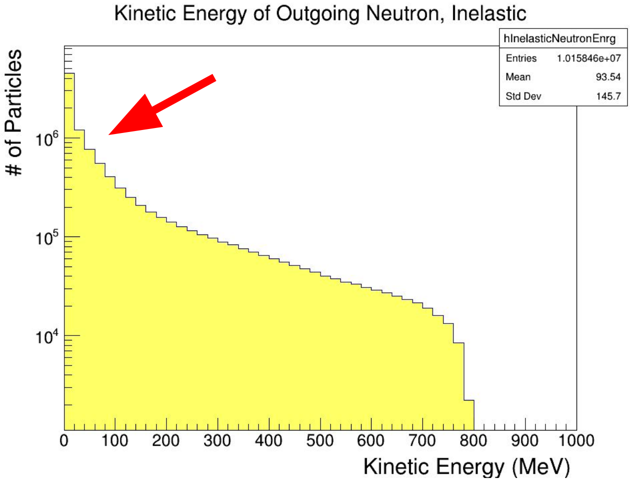
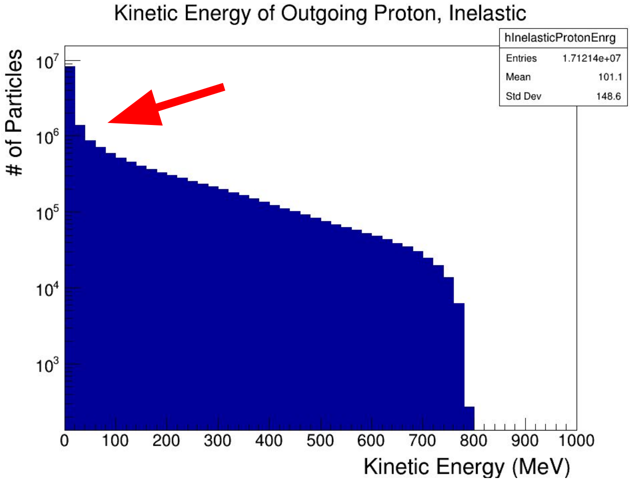
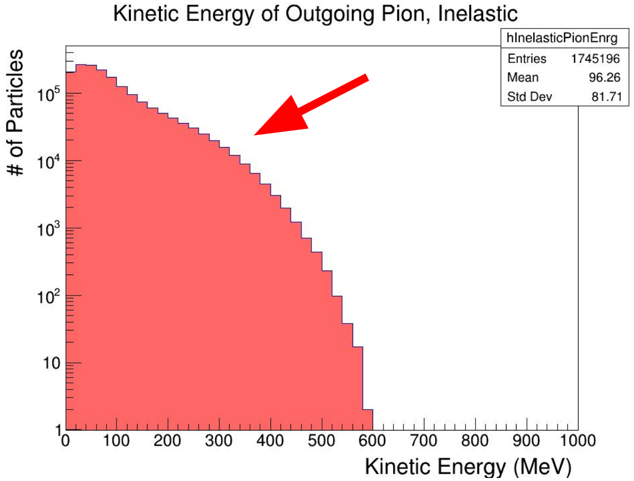
Kinetic Energy of Outgoing Particles from Inelastic Collisions on Hydrogen (logarithmic scale)

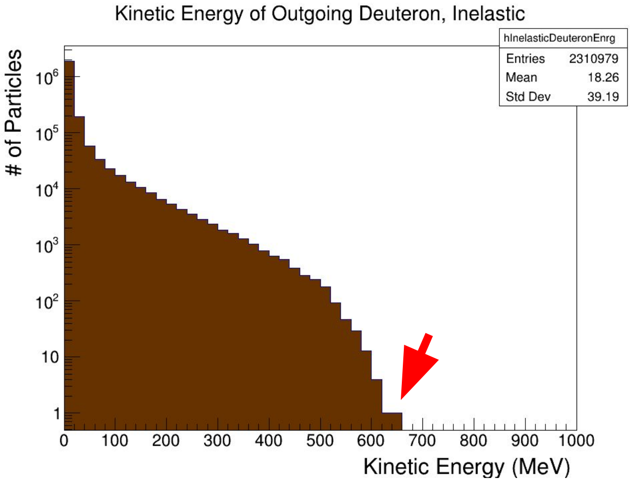


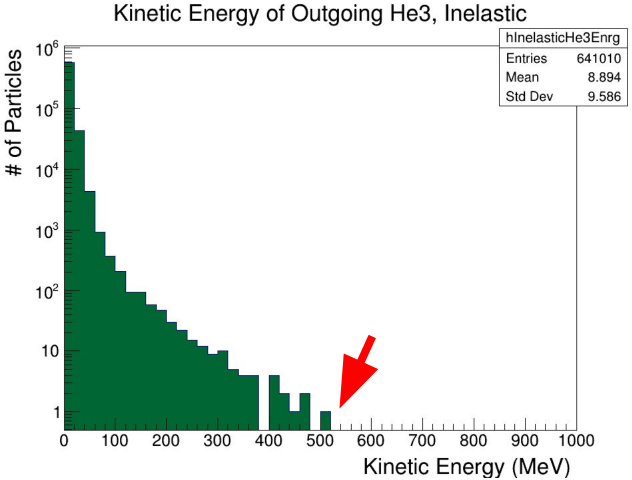


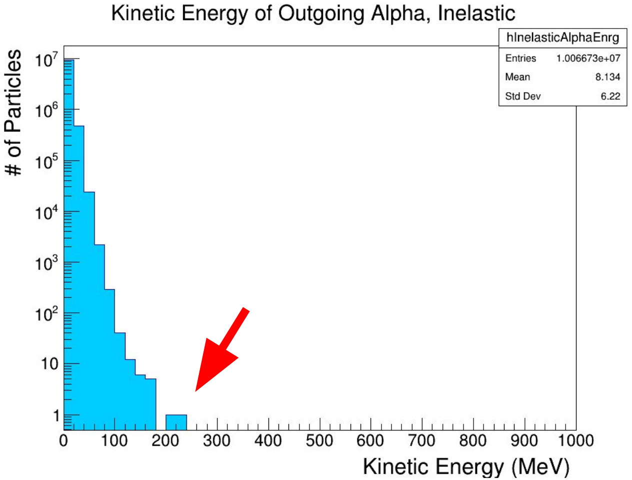


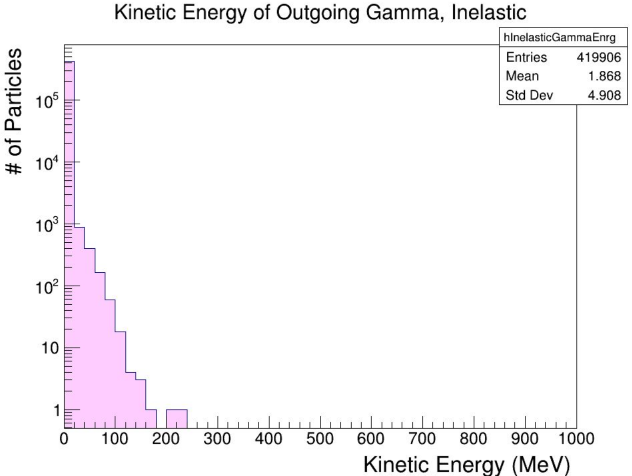
Kinetic Energy of Outgoing Particles from Inelastic Collisions on Hydrogen

(logarithmic scale)



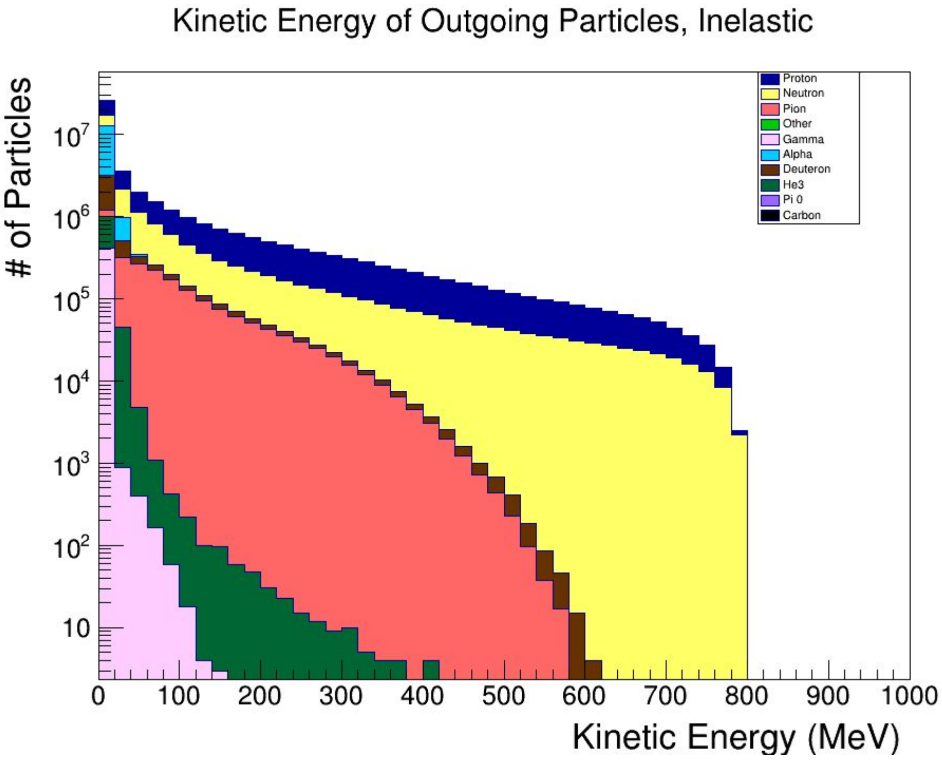


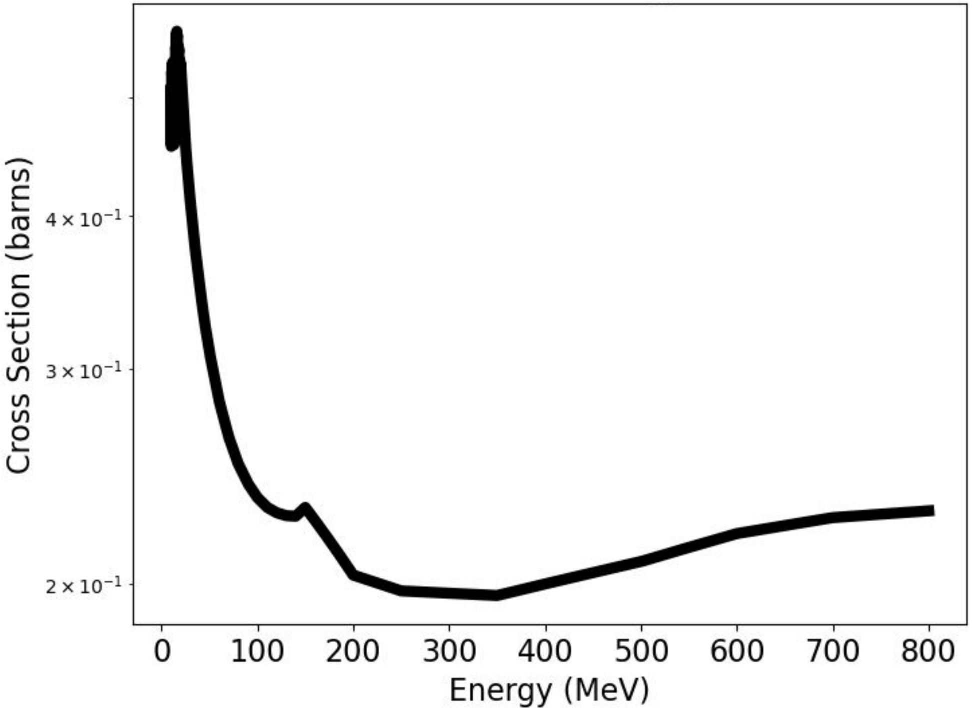




- Higher mass ➔ lower E_{Max}
  - Conservation of Momentum

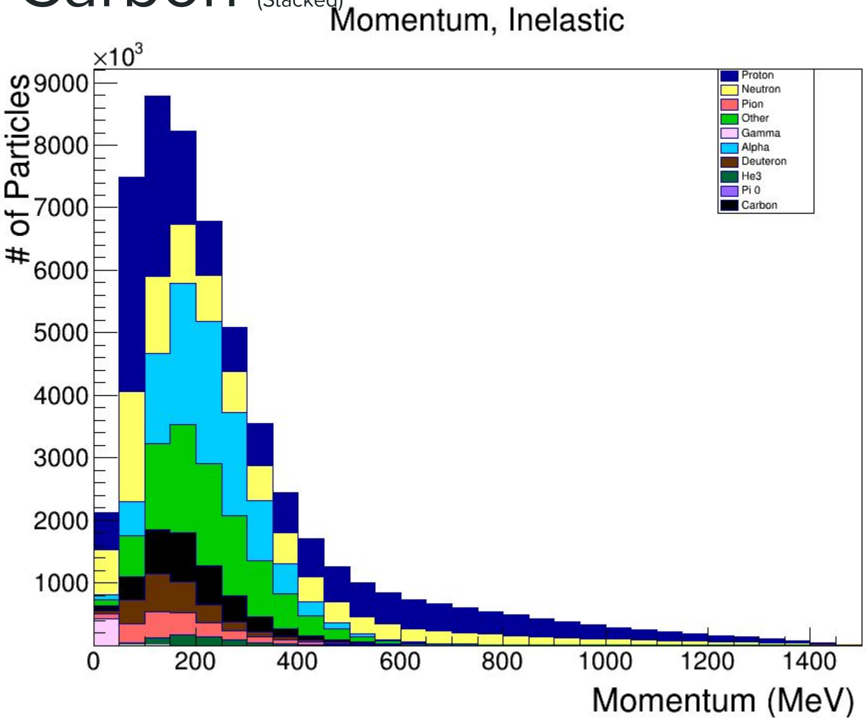
Kinetic Energy of Outgoing Particles from Inelastic Collisions on Carbon (Stacked)

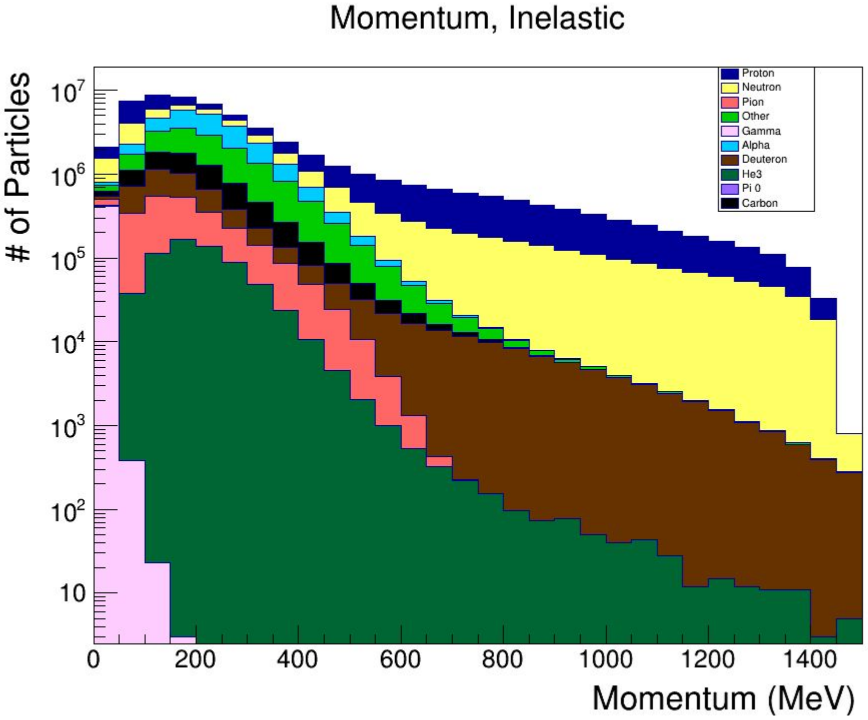


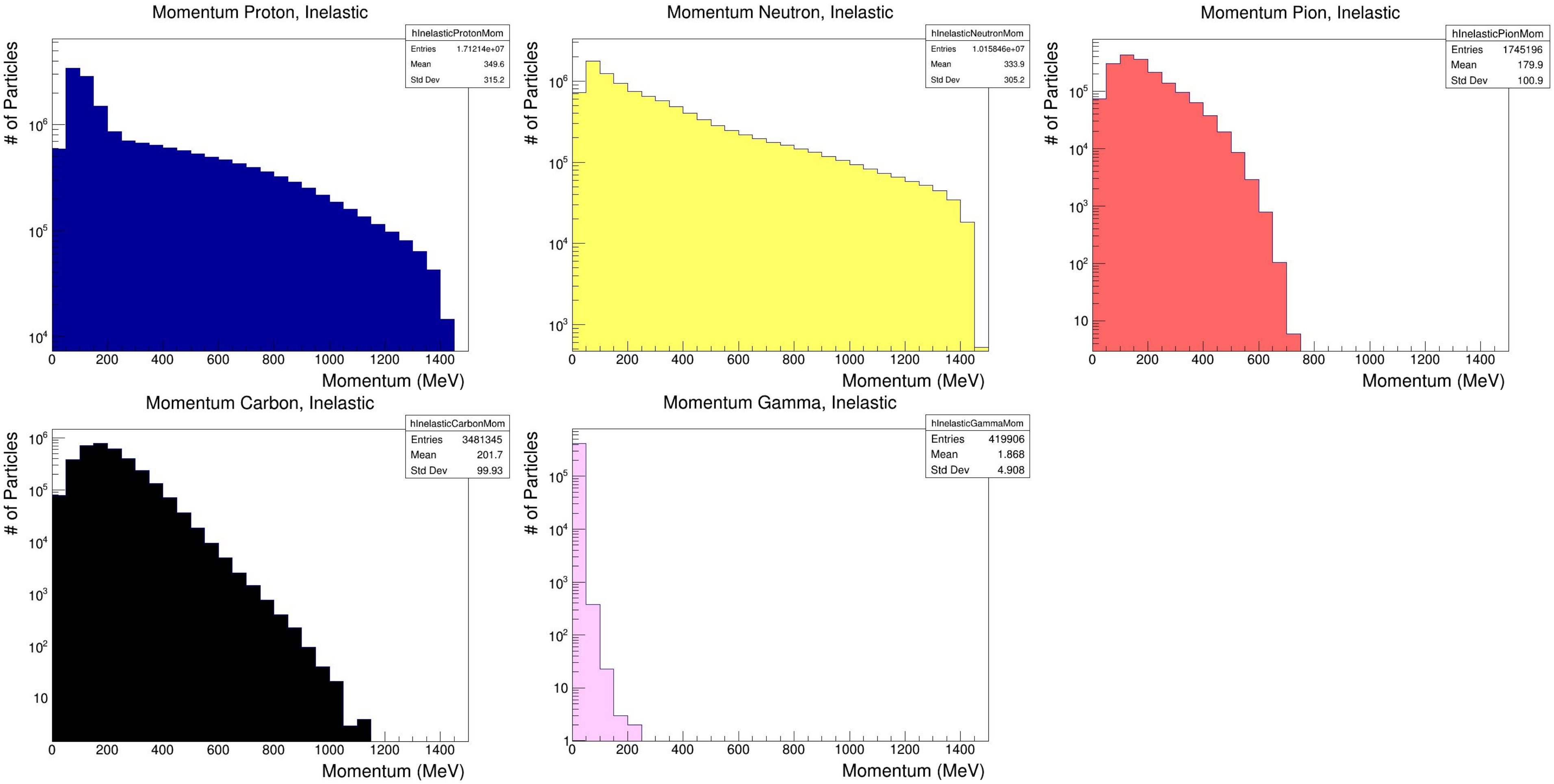


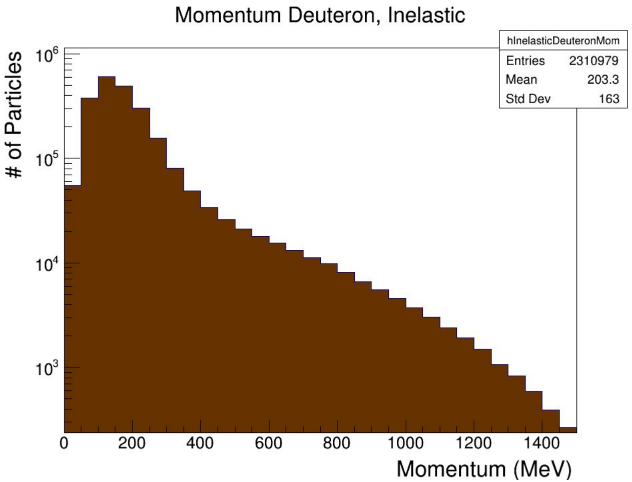
D. A. Brown et al. ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data. Nucl. Data Sheets, 148:1–142, 2018.

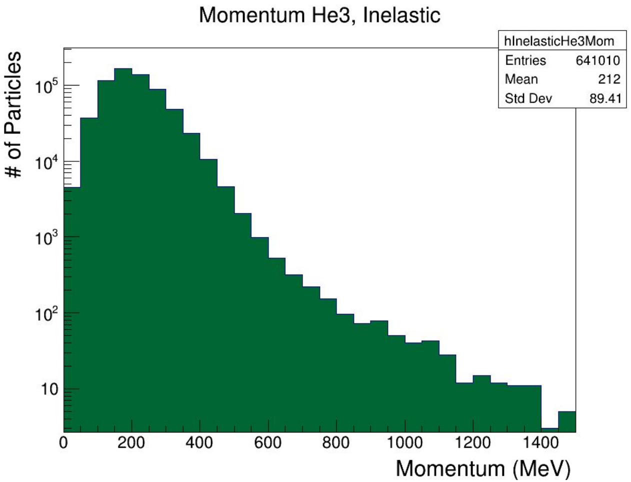
Momentum of Outgoing Particles from Inelastic Collisions on Carbon (Stacked)

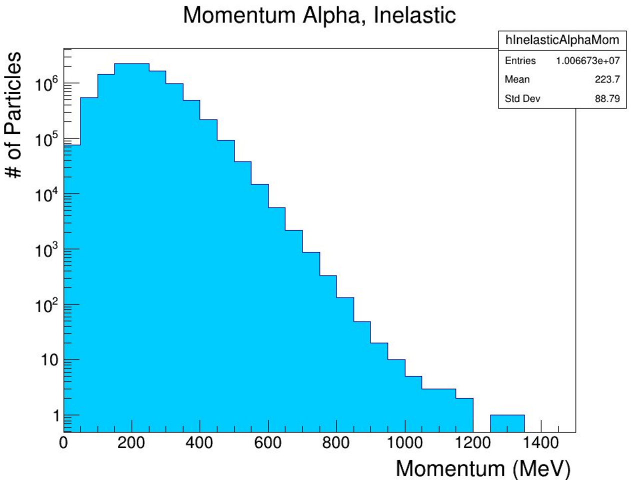


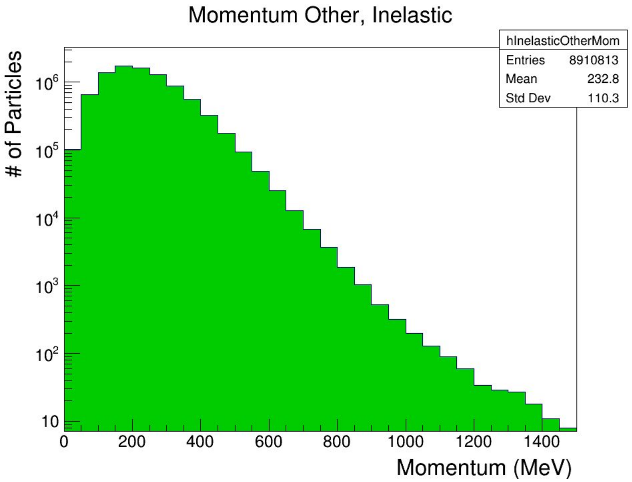



Momentum Proton, Inelastic
hInelasticProtonMom
Entries 1.71214e+07
Mean 349.6
Std Dev 315.2
# of Particles
Momentum (MeV)
Momentum Neutron, Inelastic
hInelasticNeutronMom
Entries 1.015846e+07
Mean 333.9
Std Dev 305.2
# of Particles
Momentum (MeV)
Momentum Pion, Inelastic
hInelasticPionMom
Entries 1745196
Mean 179.9
Std Dev 100.9
# of Particles
Momentum (MeV)
Momentum Carbon, Inelastic
hInelasticCarbonMom
Entries 3481345
Mean 201.7
Std Dev 99.93
# of Particles
Momentum (MeV)
Momentum Gamma, Inelastic
hInelasticGammaMom
Entries 419906
Mean 1.868
Std Dev 4.908
# of Particles
Momentum (MeV)

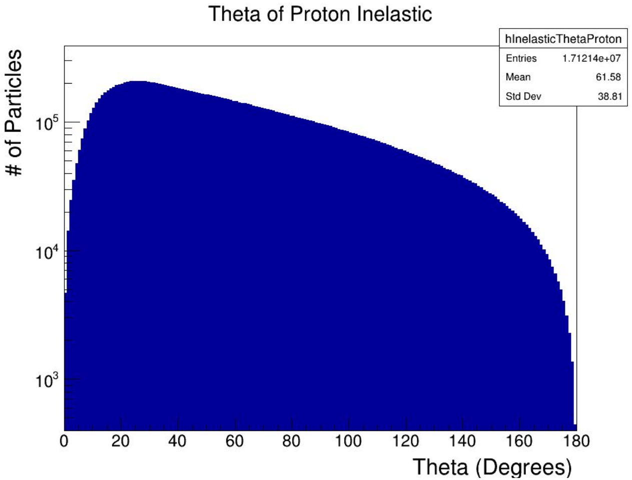

Momentum Deuteron, Inelastic
hInelasticDeuteronMom
Entries 2310979
Mean 203.3
Std Dev 163
# of Particles
Momentum (MeV)

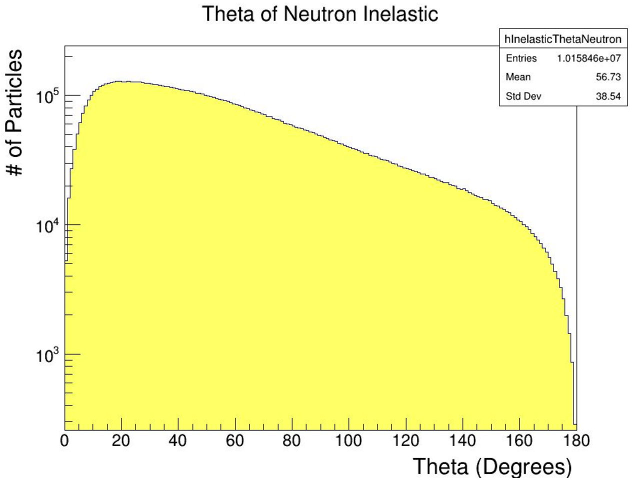

Momentum He3, Inelastic
hInelasticHe3Mom
Entries 641010
Mean 212
Std Dev 89.41
# of Particles
Momentum (MeV)

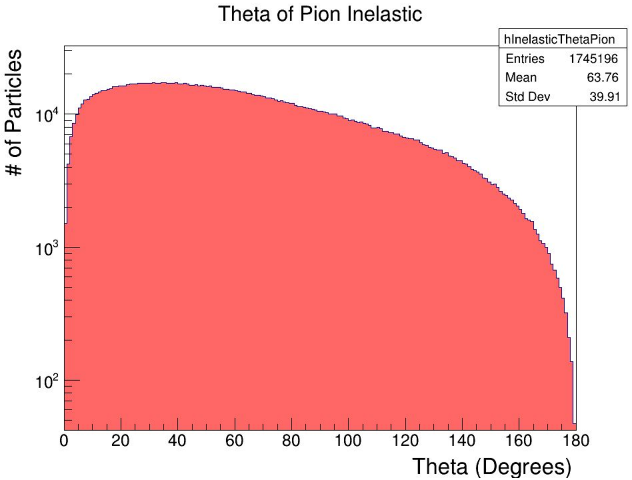

Momentum Alpha, Inelastic
hInelasticAlphaMom
Entries 1.006673e+07
Mean 223.7
Std Dev 88.79
# of Particles
Momentum (MeV)

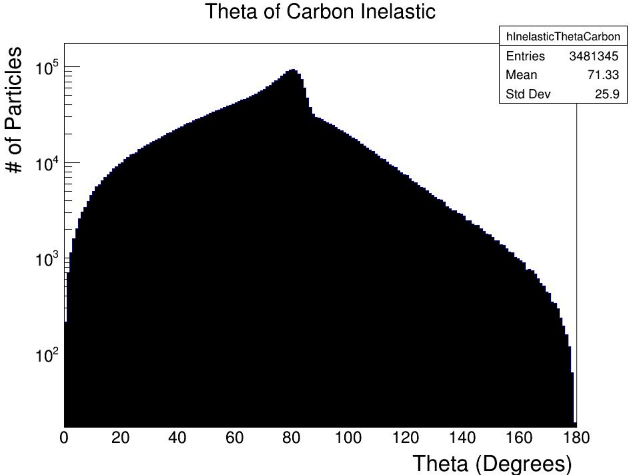

Momentum Other, Inelastic
hInelasticOtherMom
Entries 8910813
Mean 232.8
Std Dev 110.3
# of Particles
Momentum (MeV)

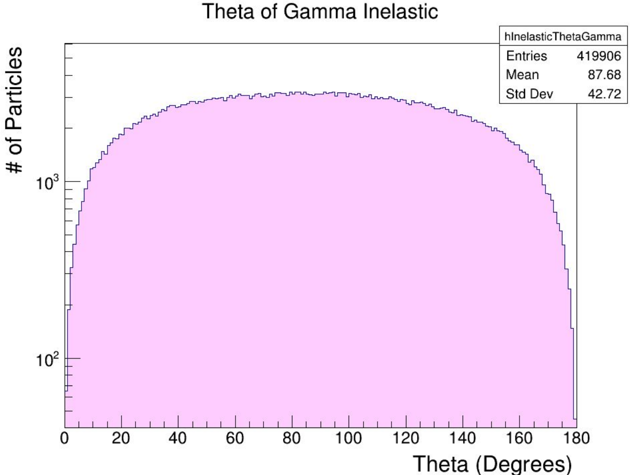
θ of Outgoing Particles from Inelastic collisions on Carbon (log scale)



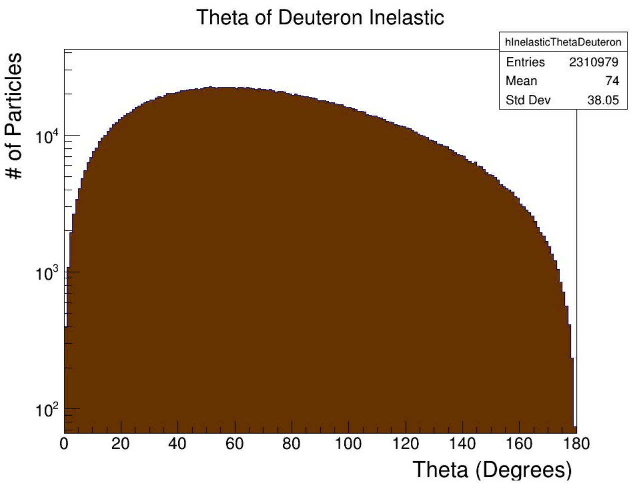


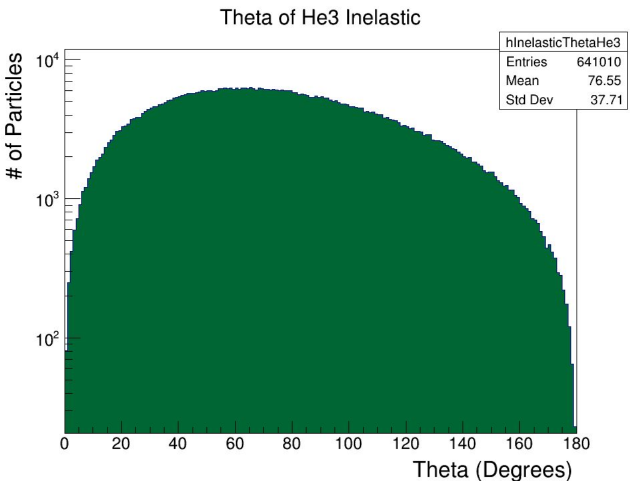


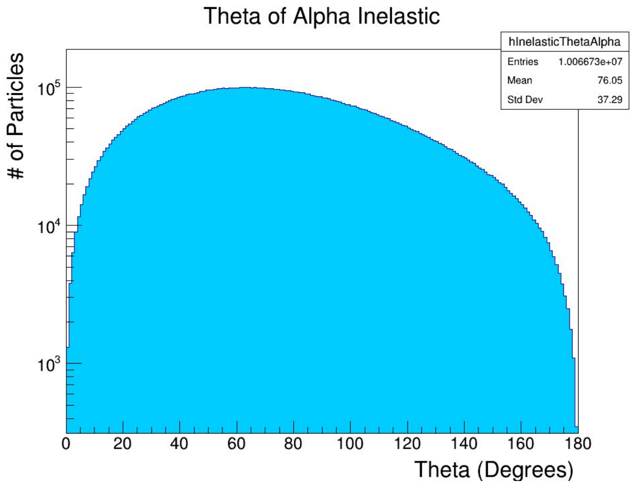


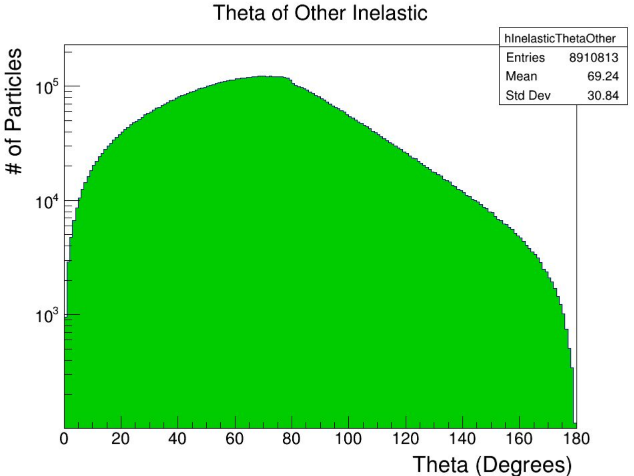


θ of Outgoing Particles from Inelastic collisions on Carbon (log scale)

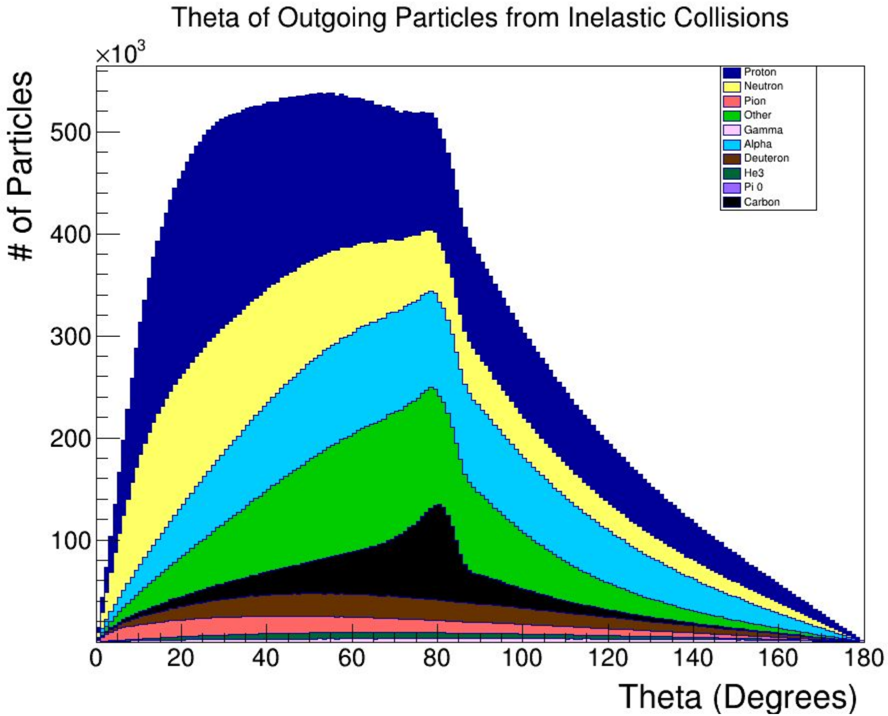




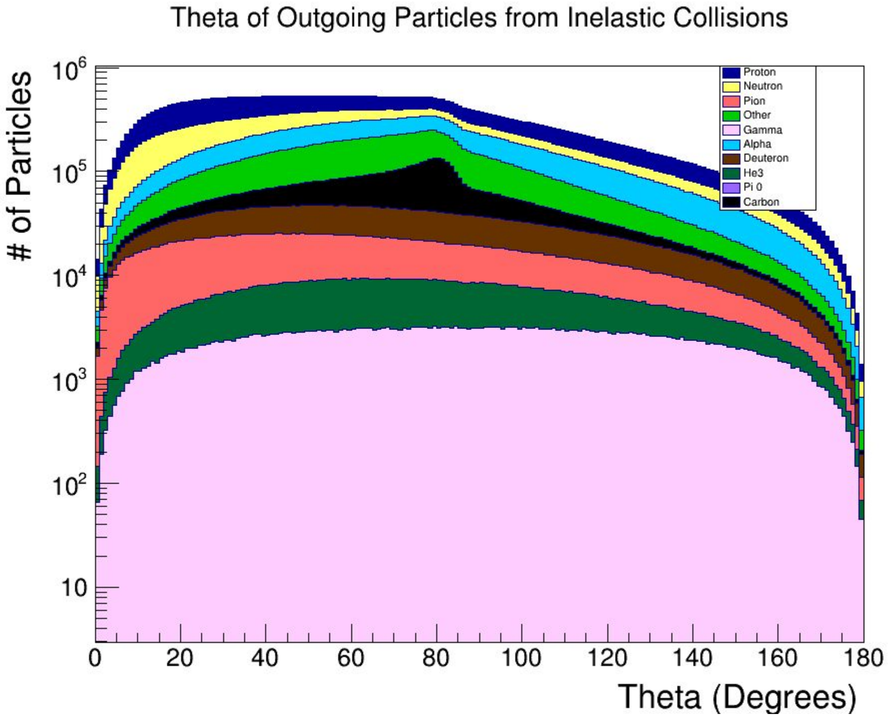




θ of Outgoing Particles from Inelastic Scattering on Carbon Target (stacked, log scale)

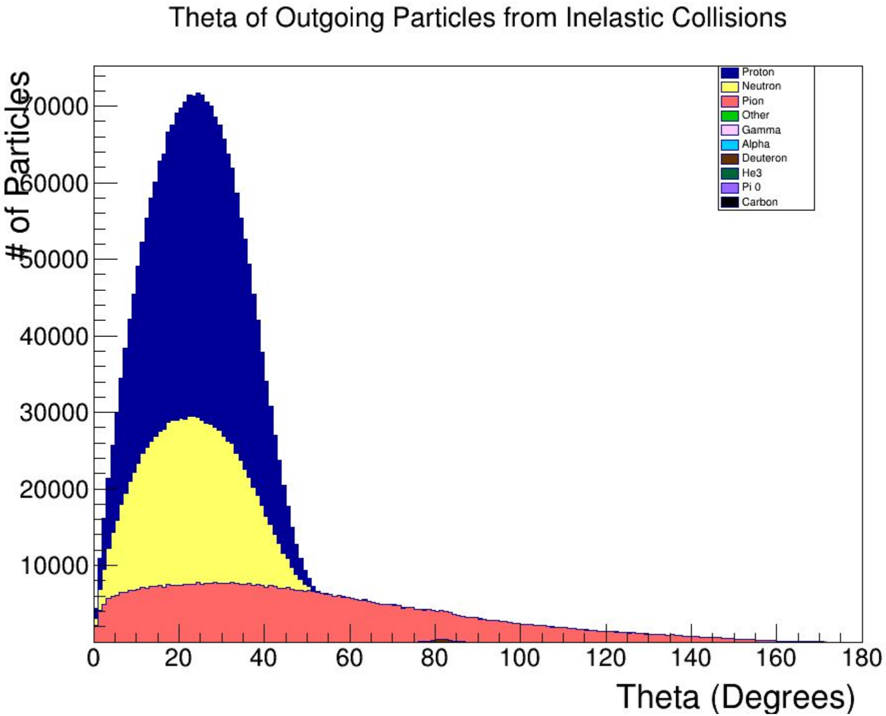


Carbon Target

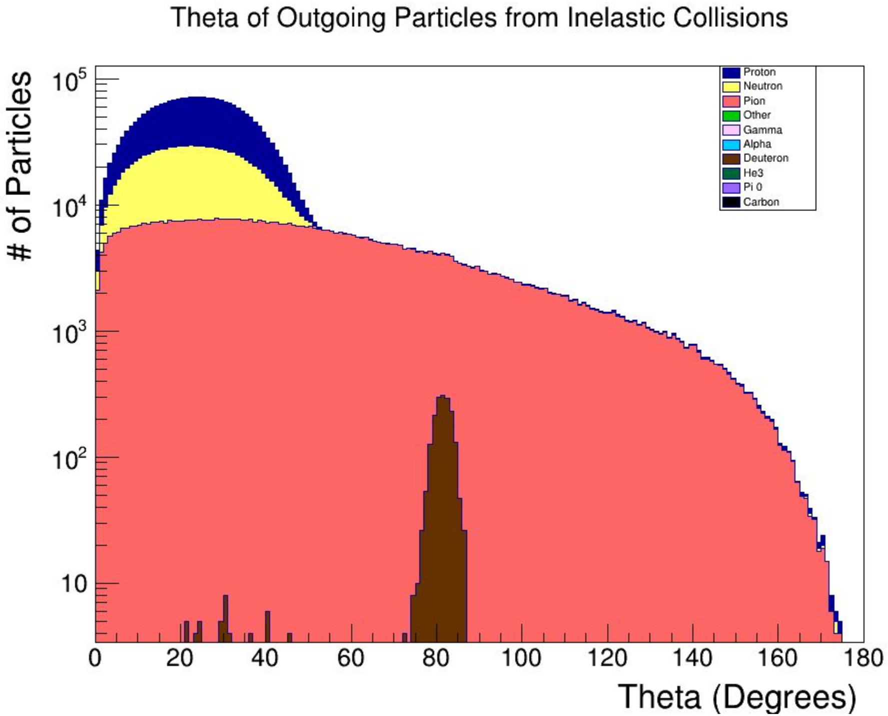


Hydrogen Target

θ of Outgoing Particles from Inelastic Scattering on Hydrogen Targets (stacked, log scale)

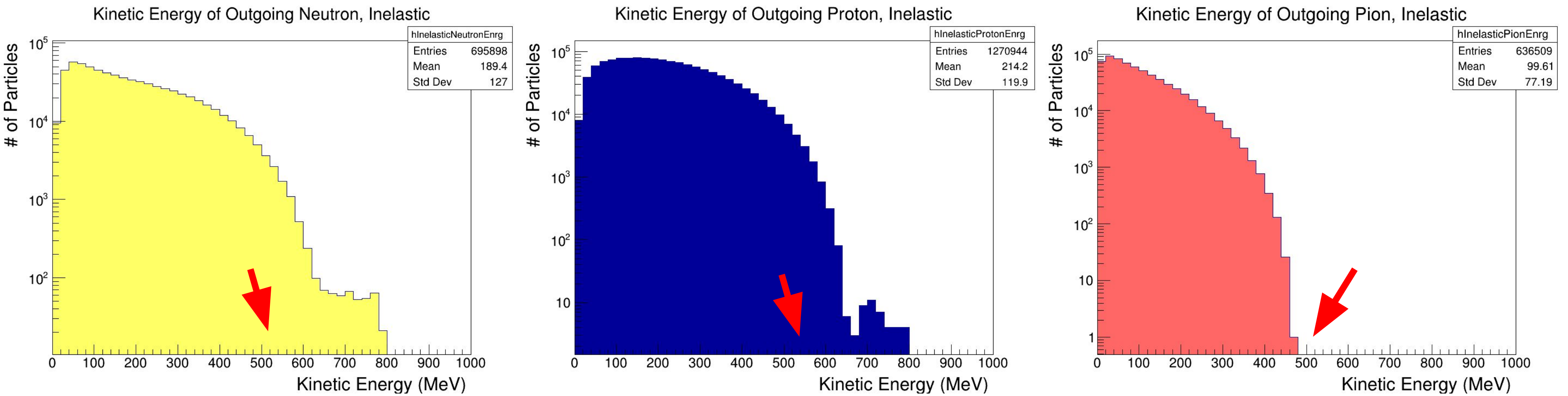


Carbon Target



Hydrogen Target

Kinetic Energy of Outgoing Particles from Inelastic Collisions on Hydrogen (logarithmic scale)

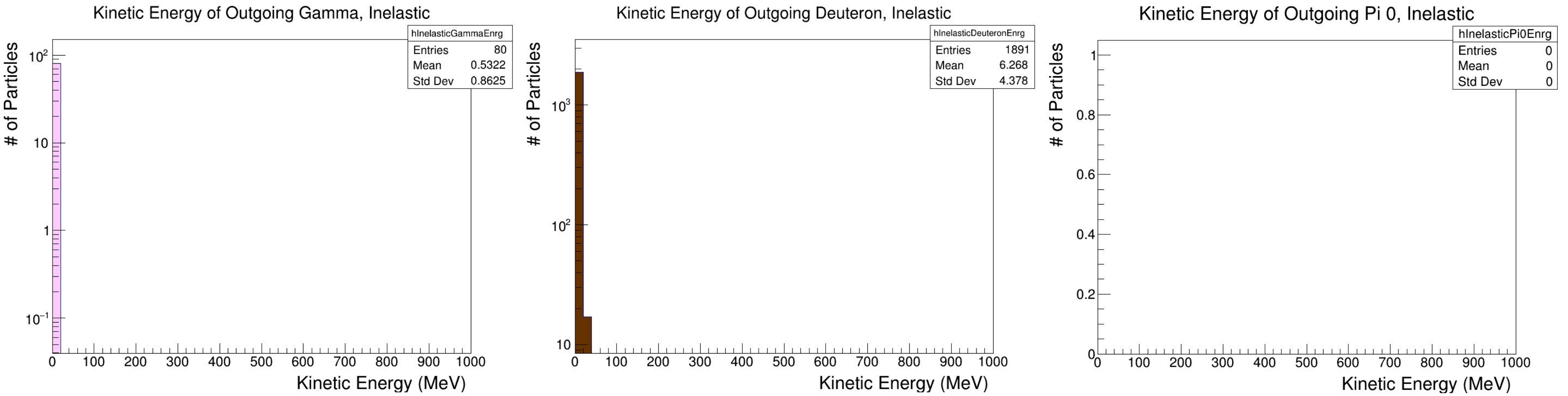


- Recall: $E_{Thresh} \cong 275$ MeV
  - ~521 MeV E_{Max} Pion (800 MeV neutron, max energy transfer)

$$n + p \rightarrow n + p + \gamma$$

Outgoing Particles from Elastic collisions on CH

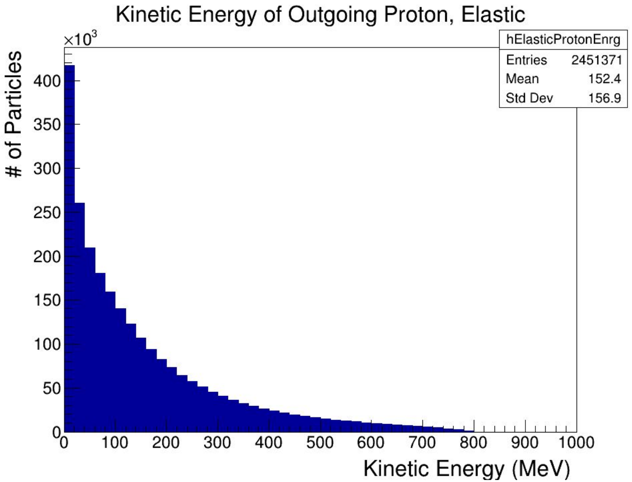
(Stacked)



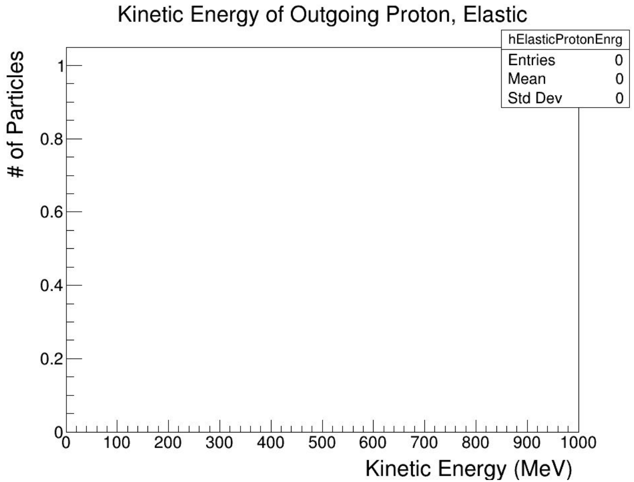
- $E_{Deuteron} < 20$ MeV ➔ $E_{\pi 0} < 485$ MeV
  - No π^0 production whatsoever

Kinetic Energy of Outgoing Protons from Elastic collisions

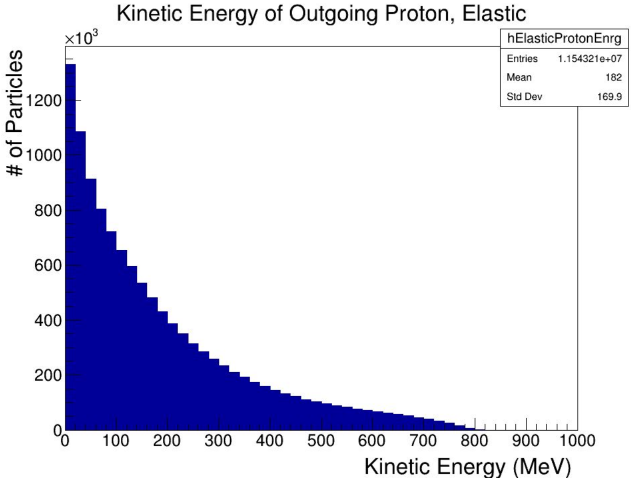
(linear scale)



Hydrocarbon Target



Carbon Target

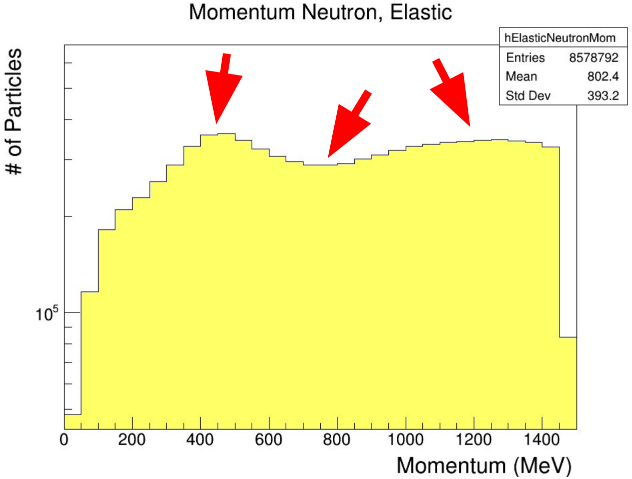


Hydrogen Target

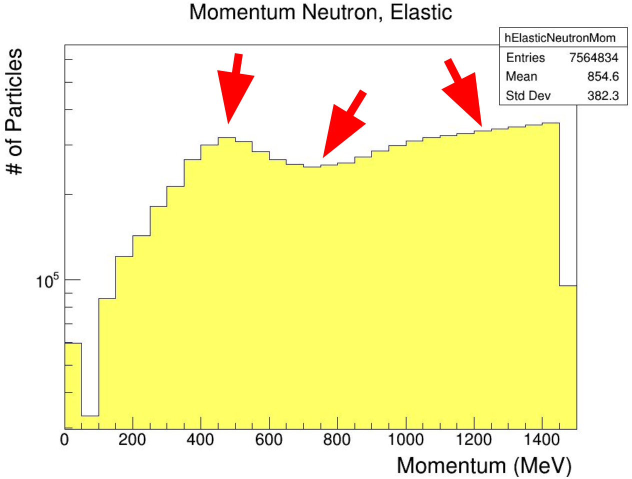
- Gradual decline
  - Matches cross section

Momentum of Outgoing Neutrons from Elastic collisions

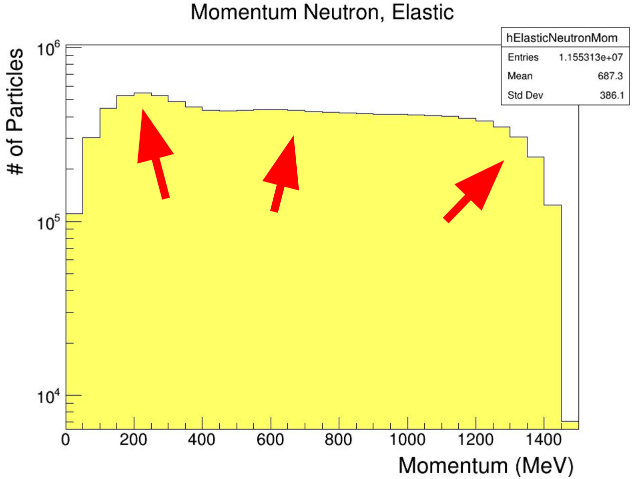
(log scale)



Hydrocarbon Target



Carbon Target

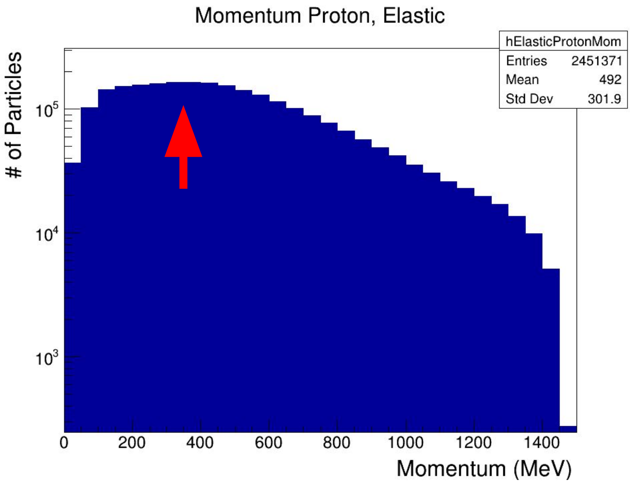


Hydrogen Target

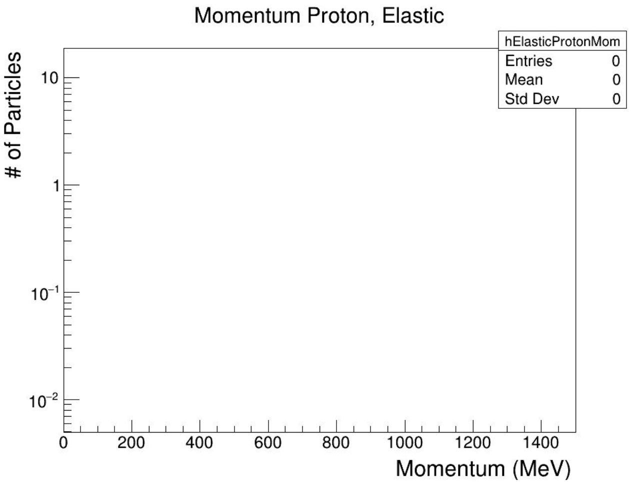
- Dip at ~600MeV

Momentum of Outgoing Protons from Elastic collisions

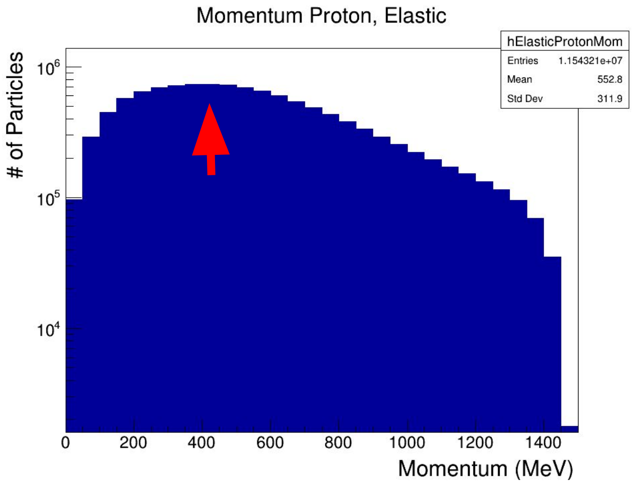
(log scale)



Hydrocarbon Target



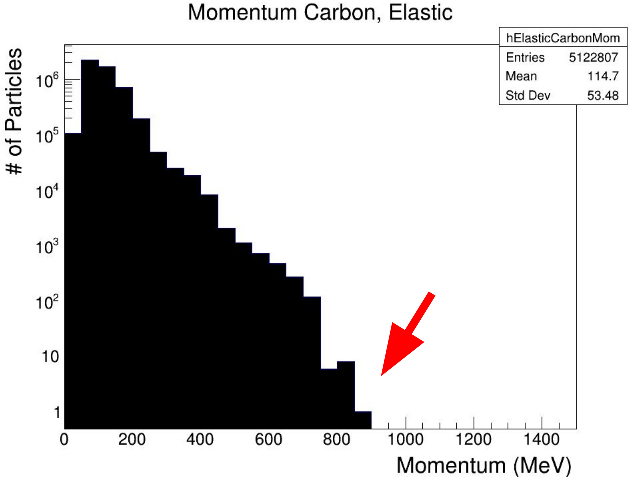
Carbon Target



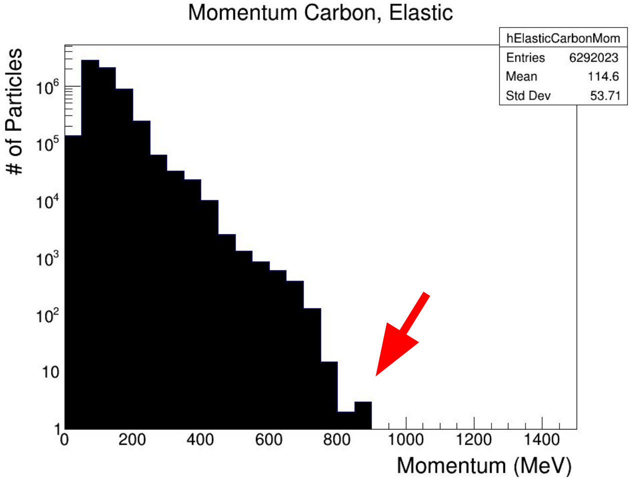
Hydrogen Target

Momentum of Outgoing Carbons from Elastic collisions

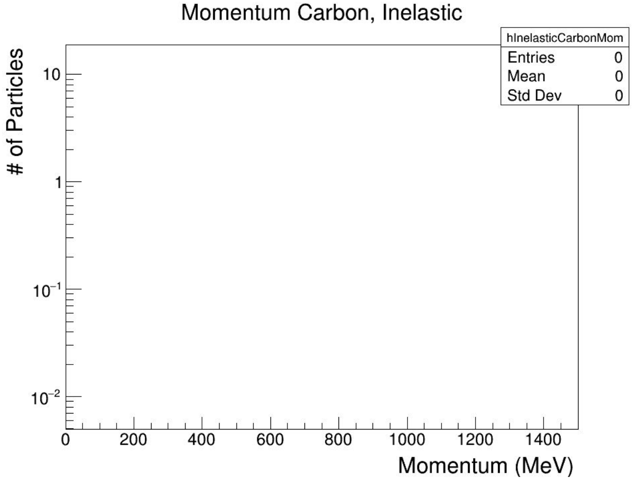
(log scale)



Hydrocarbon Target



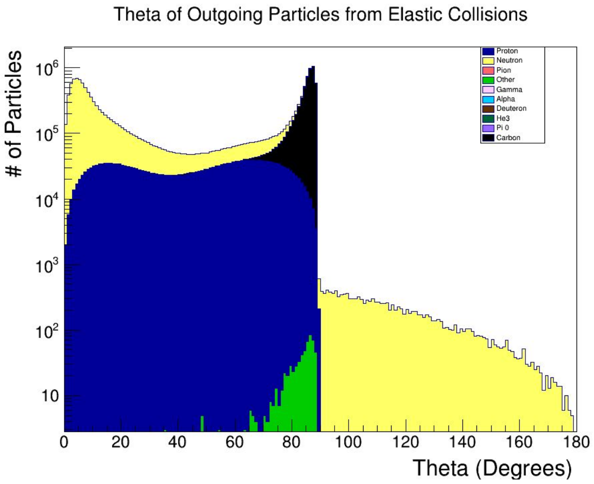
Carbon Target



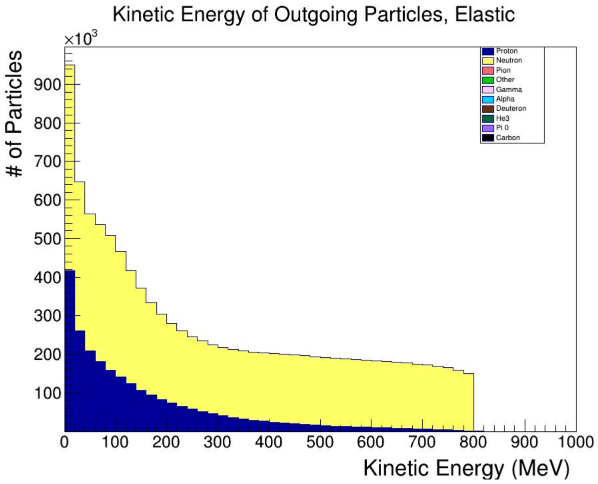
Hydrogen Target

Outgoing Particles from Elastic collisions on CH

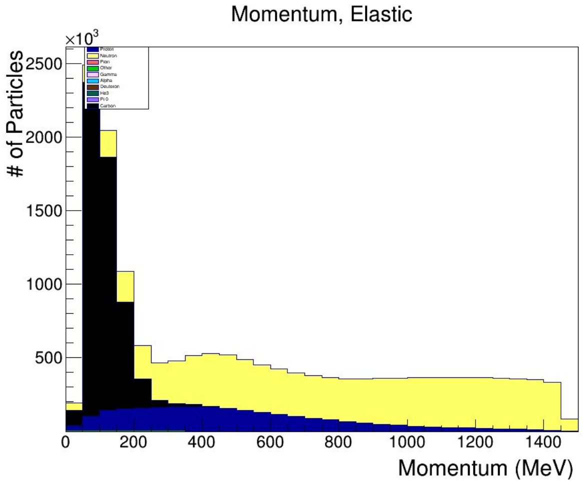
(Stacked)



θ



Kinetic Energy



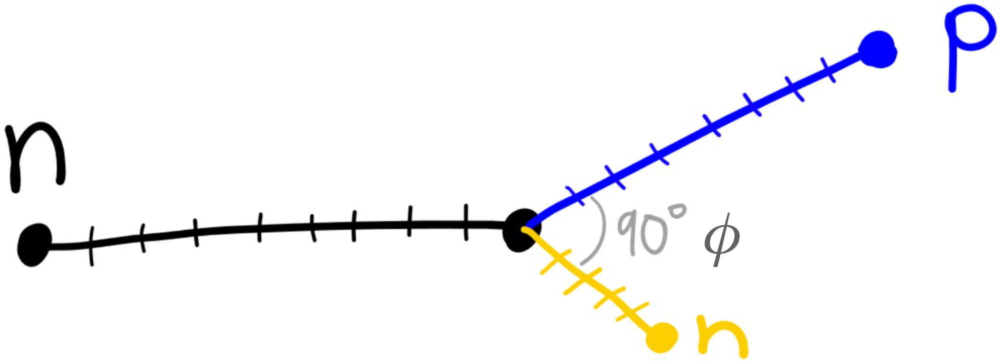
Momentum

Neutron Elastic Interactions on Hydrogen

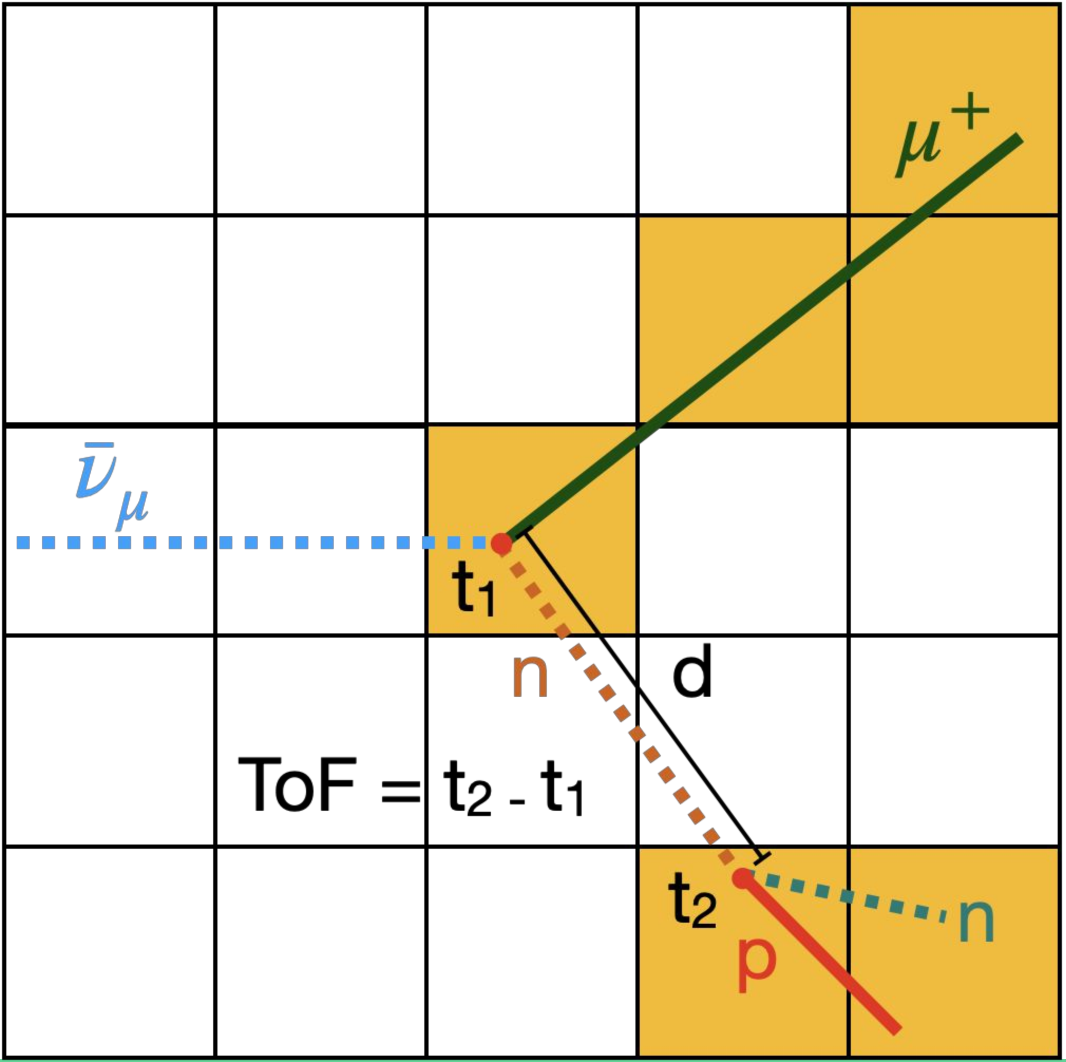
- $m_n \cong m_p \rightarrow \phi$=90°

$$Q_{Max} = \frac{4m_1m_2E}{(m_1+m_2)^2}$$

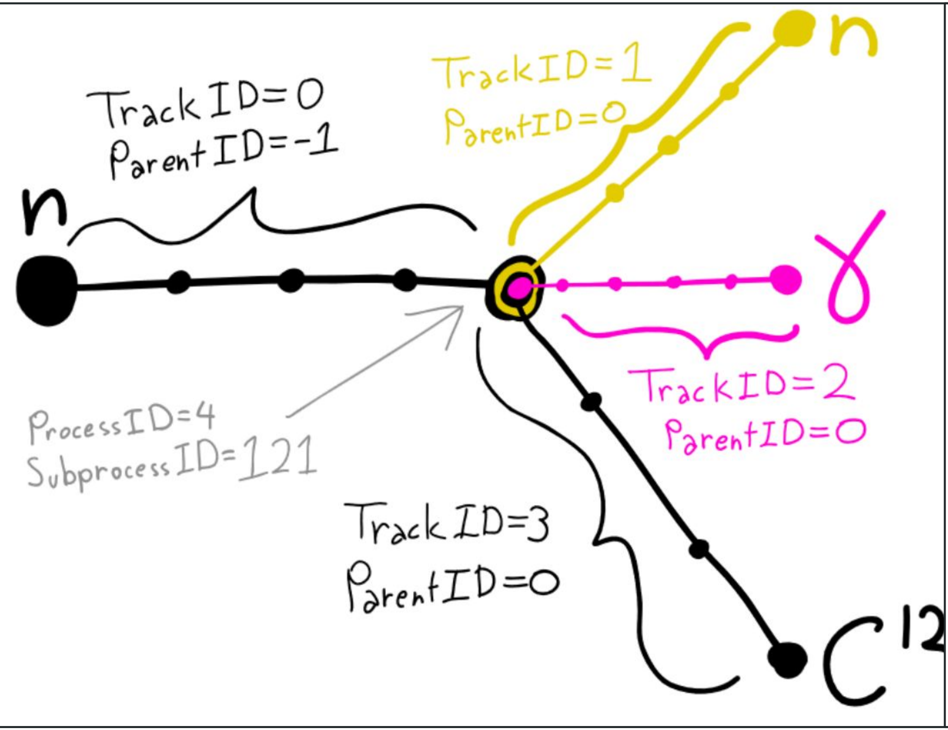
- $Q_{Max} \cong 0.99E$
- Similar N and P Kinetic Energy distributions
- Similar N and P angle w.r.t beam (θ) distributions
  - 90° difference in notable features

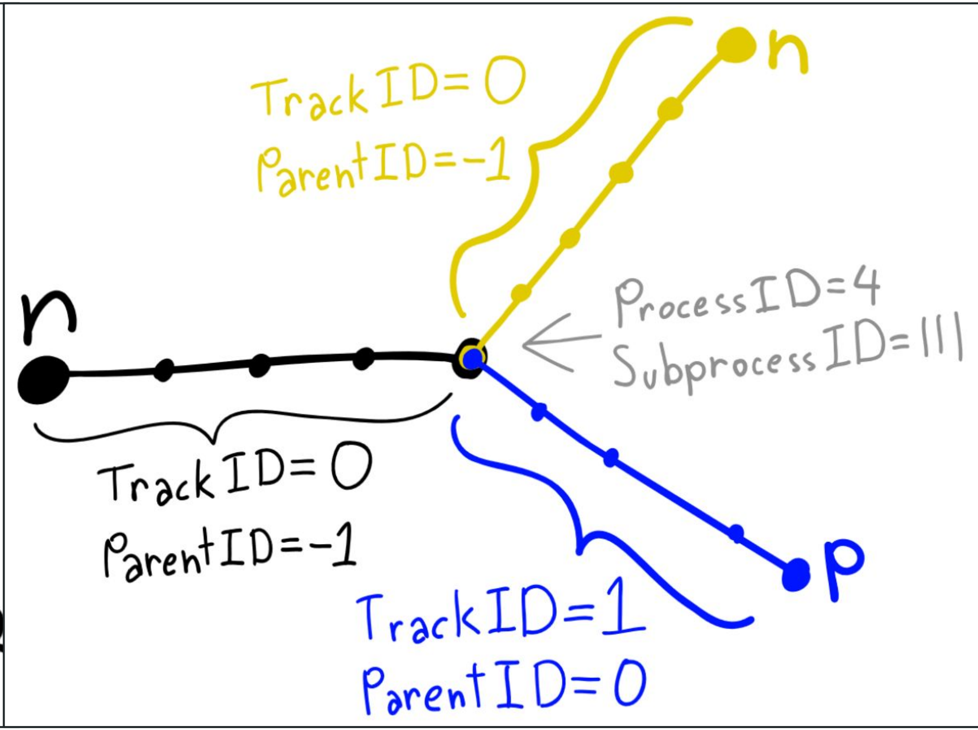


Neutrino Interactions in a Cubic Detector



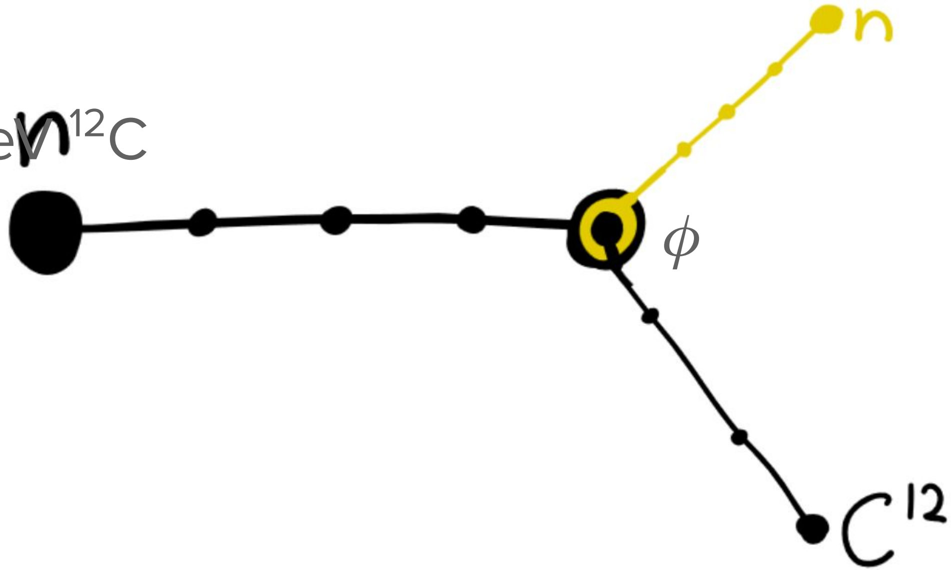
Geant4 Interaction Process Examples



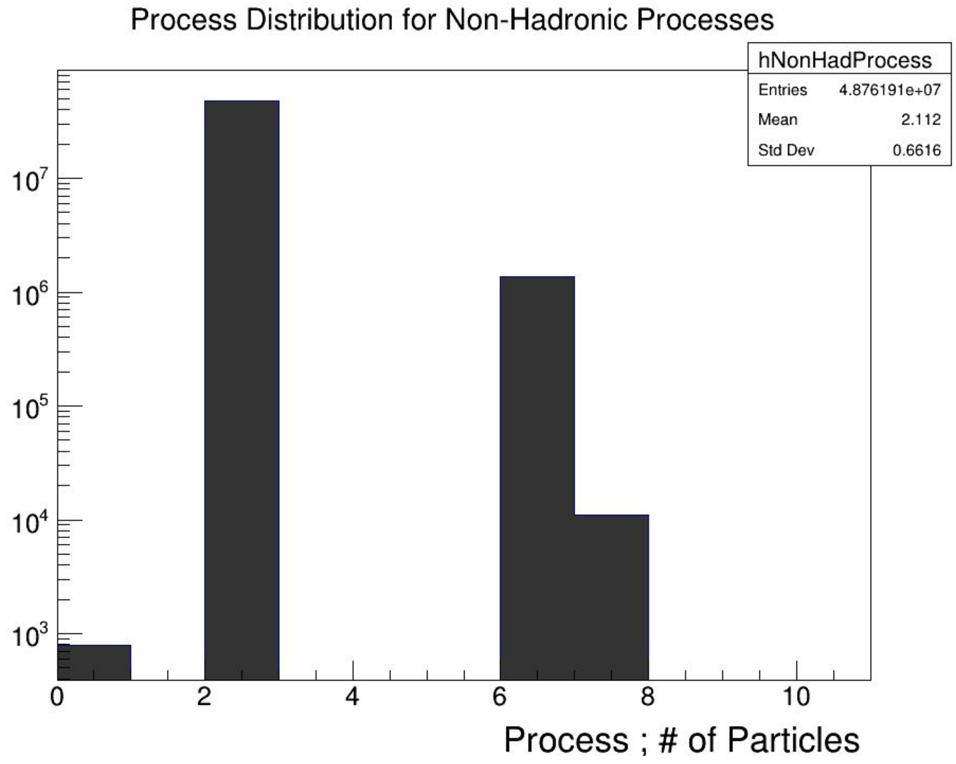


Neutron Elastic Interactions on Carbon

- $m_n << m_{12C}$ ➔ $\phi \in [90°, \sim 148°]$
  - Assuming max energy transfer
  - Lower energy transfer ➔ $\phi \in [90°, \sim 180°)$
- $Q_{Max} \cong 0.28E$
  - 800 MeV neutron ➔ ~227 MeV ^{12}C
- ^{12}C Max Energy ≅ 227
- $\theta_n \in (0°, \sim 180°)$
- $\theta_{12C} \in [0°, 90°)$
  - Mass difference

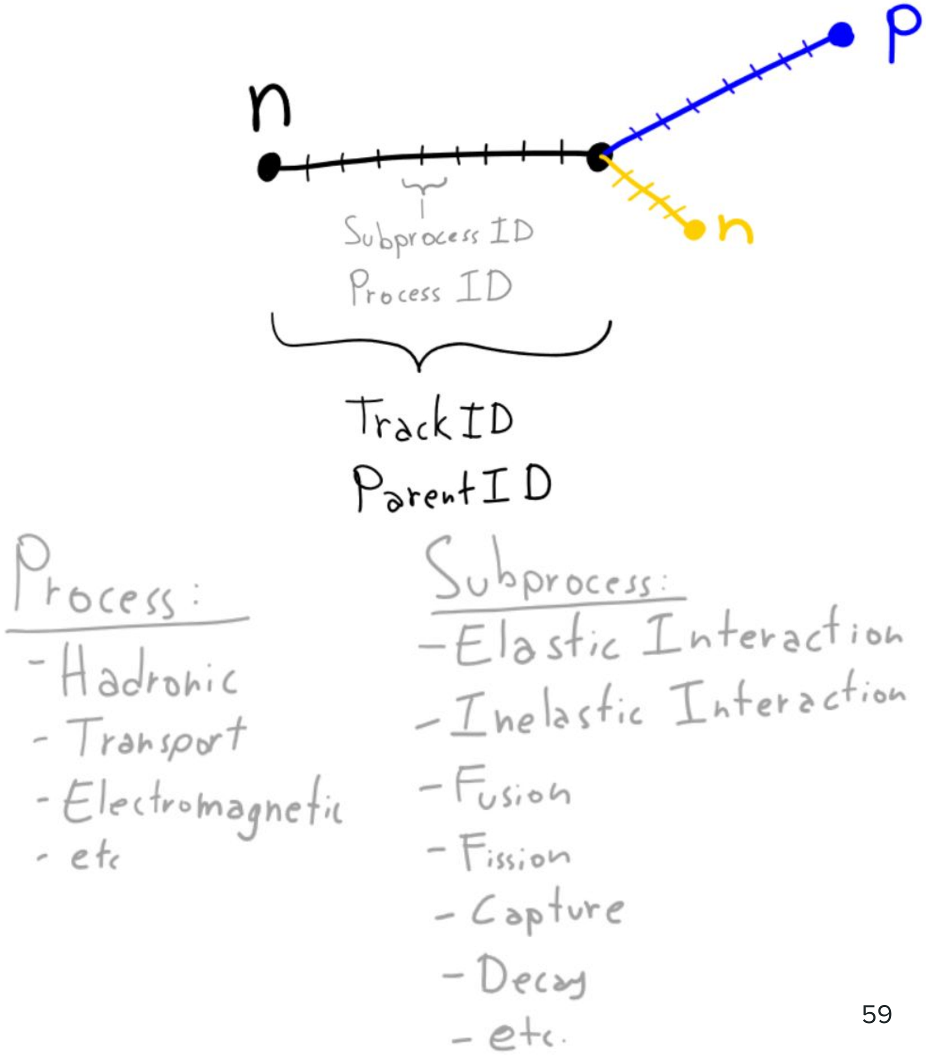


Non-Hadronic Process Interactions for Incoming Neutrons

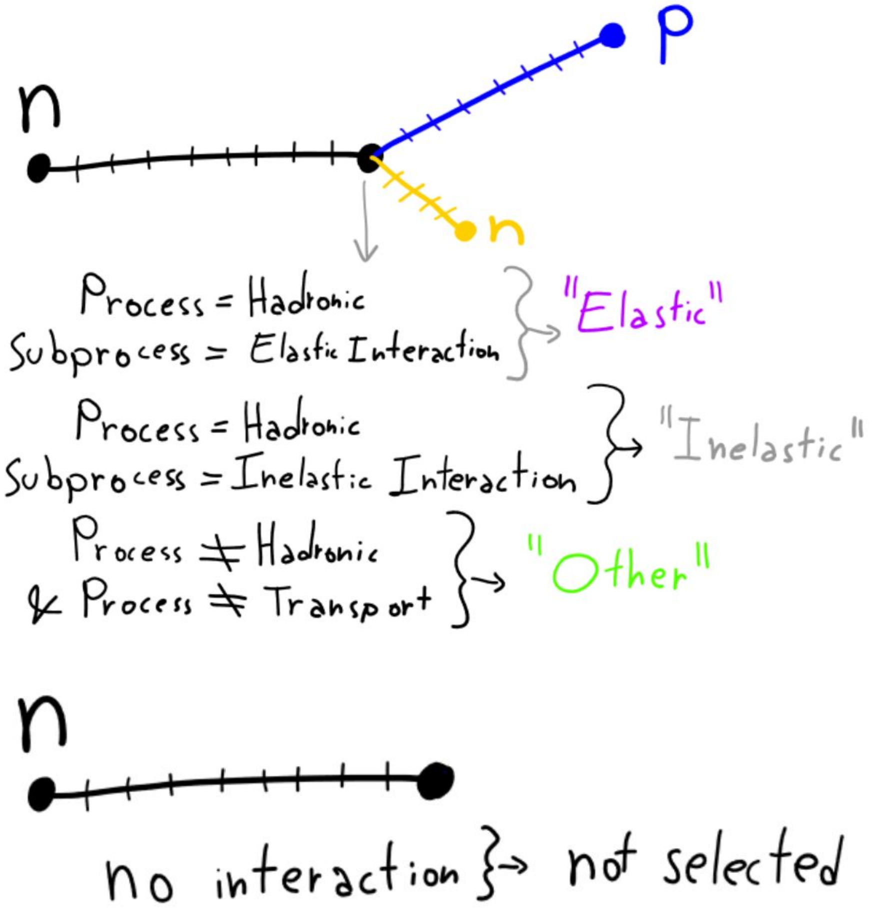


Process ID	Process Type
0	NotDefined
1	Transportation
2	Electromagnetic
3	Optical
4	Hadronic
5	Photolepton_hadron
6	Decay
7	General
8	Parameterisation

- Consider the case of neutron elastic scattering on free proton (hydrogen)
- We have 3 Trajectories, one for each particle: **Incoming Neutron**, **Outgoing Neutron**, **Outgoing Proton**
- Each trajectory has a TrackID and a ParentID; these index the particle as well as it's parent
- Each trajectory has multiple points, and each point has a Subprocess ID and a Process ID
- The Process ID tells us the **interaction process** (Hadronic Interaction, Electromagnetic Interaction, etc.)
- The Subprocess ID tells us the **interaction type** (Elastic Scattering, Inelastic Scattering, Fusion, Capture, etc.)

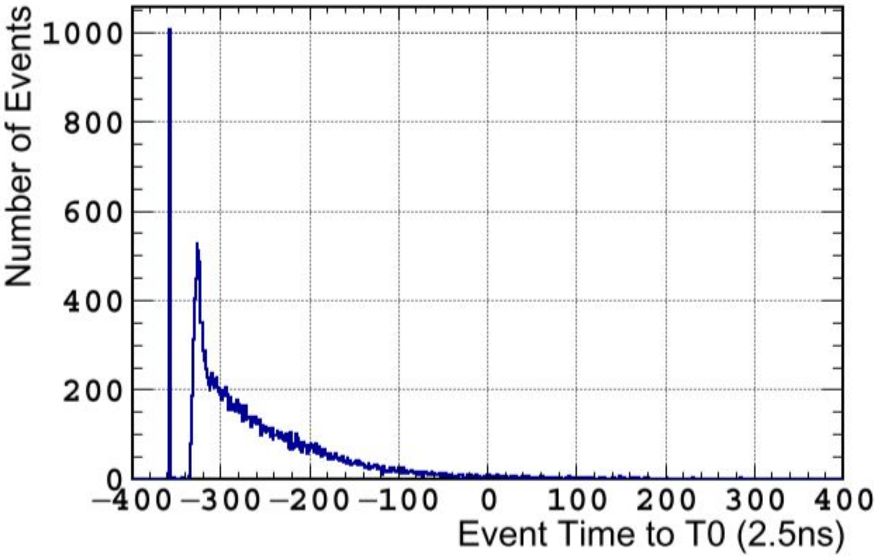


- For our selection, we only look at outgoing particles from the first Hadronic interaction from the incoming neutron
- If the incoming neutron has:
    - An Elastic Hadronic interaction, we classify this as "**Elastic**"
    - An Inelastic Hadronic interaction, we classify this as "**Inelastic**"
    - An Non-Hadronic interaction, we classify this as "**Other**"
    - **No interaction** (if we only have Transport), we do not consider these events
- Since we don't store the events with no neutron interaction, our stacked histogram for incoming neutron energy is not flat
    - If we were to store these in another category, we would have a flat stacked distribution



LANL Beam Test Results

- Improvements to measurements of neutron cross section for 500-688 MeV
  - $\sigma_{99\text{-}688MeV}$ = 0.36±0.05 barn
  - χ^2/d.o.f = 22.03/38
- Proved Capability of SuperFGD to measure neutron kinematics using ToF
- First physics result!

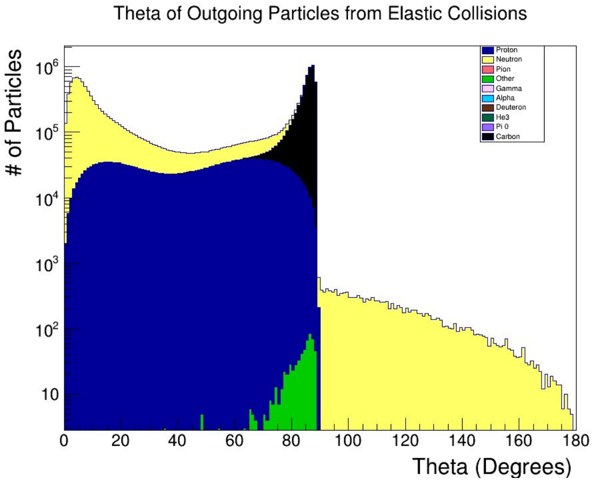


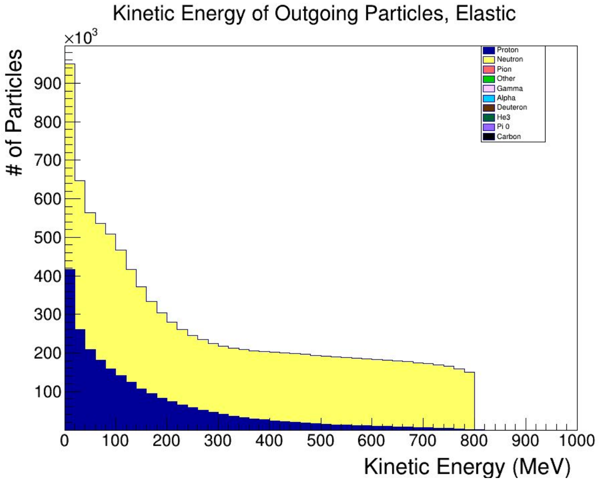
A. Agarwal et al. Total neutron cross-section measurement on CH with a novel 3D-projection scintillator detector. Phys. Lett. B, 840:137843, 2023.

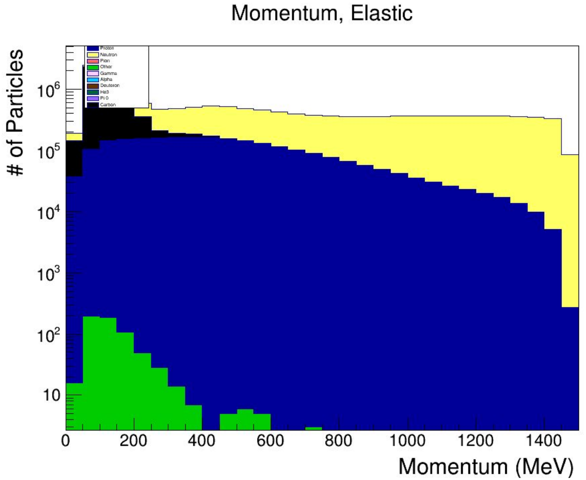
Backup: Why are neutrino oscillations described by the PMNS matrix?

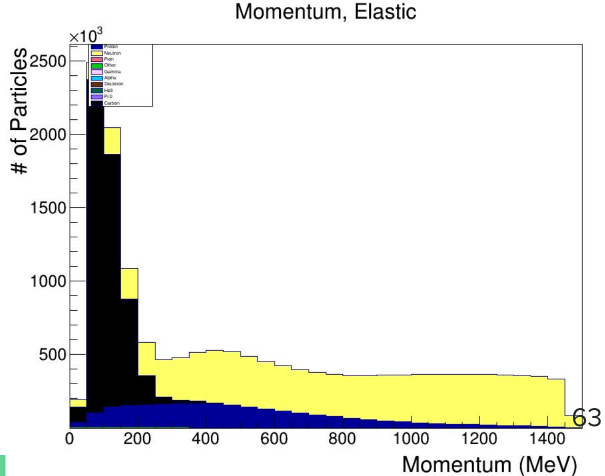
- SM ➔ ν_e , ν_μ , ν_τ
  - Neutrinos are SM particles and we have 3 flavours
- 3 flavours represented by eigenstates
  - Complete, orthonormal basis
- Also: 3 mass eigenstates
  - Complete, orthonormal basis
- Flavour eigenbasis ≠ mass eigenbasis !
- Flavour eigenbasis = mass eigenbasis * Unitary transformation
- Unitary transformation = PMNS matrix

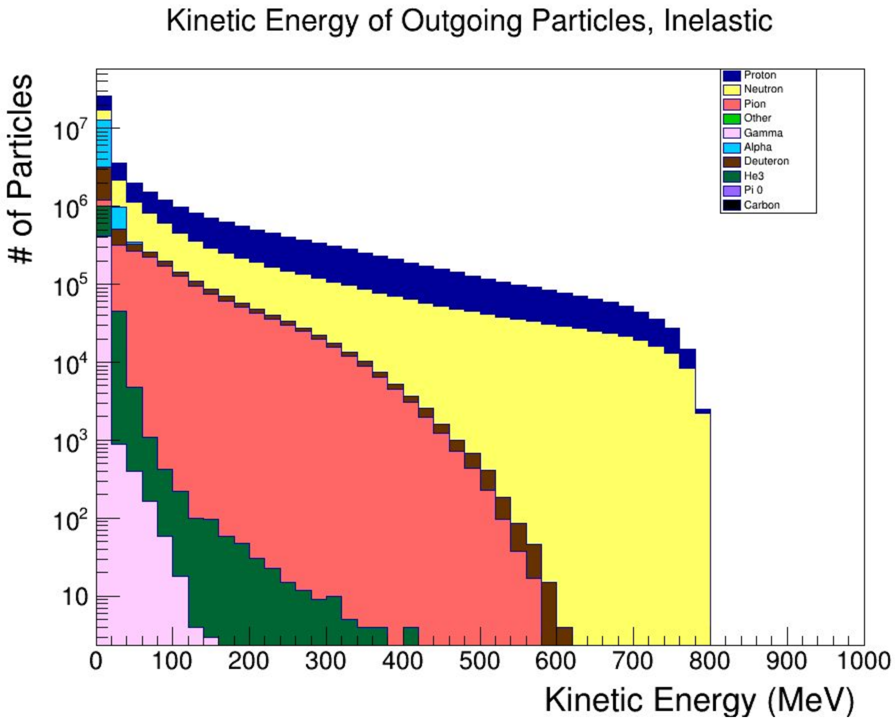
Outgoing Particles from Elastic collisions on CH

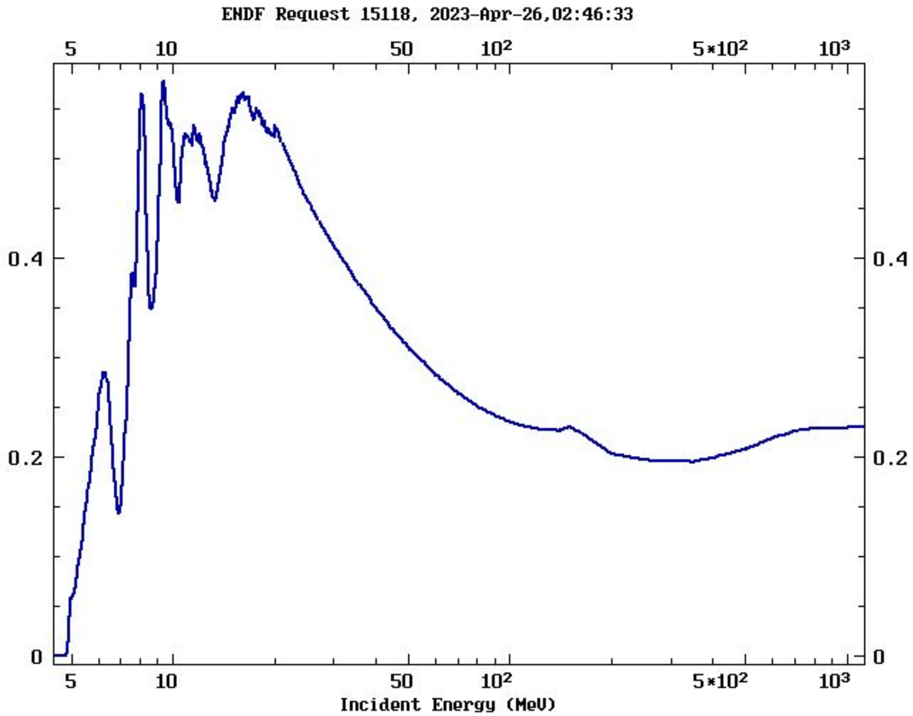


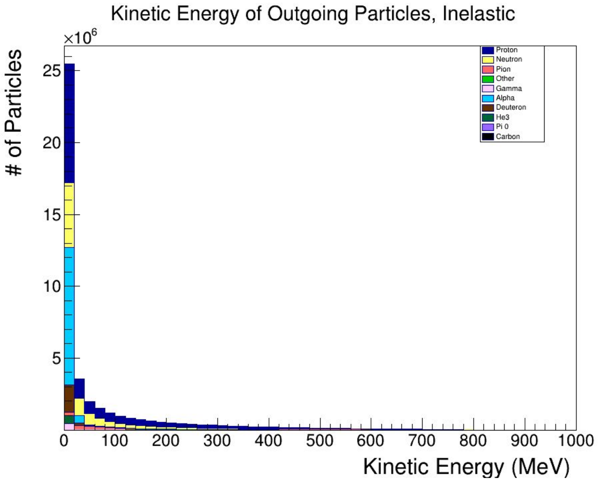


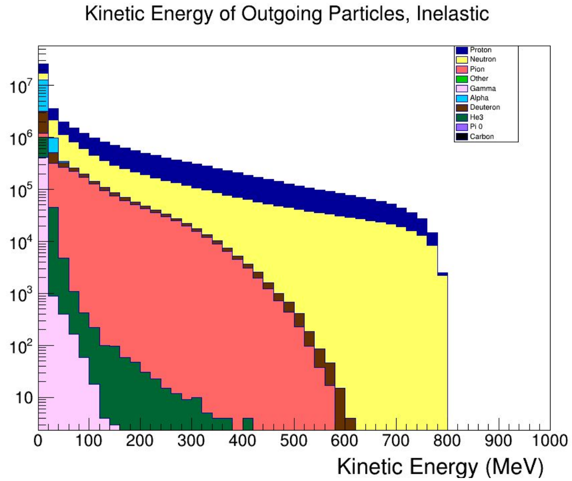


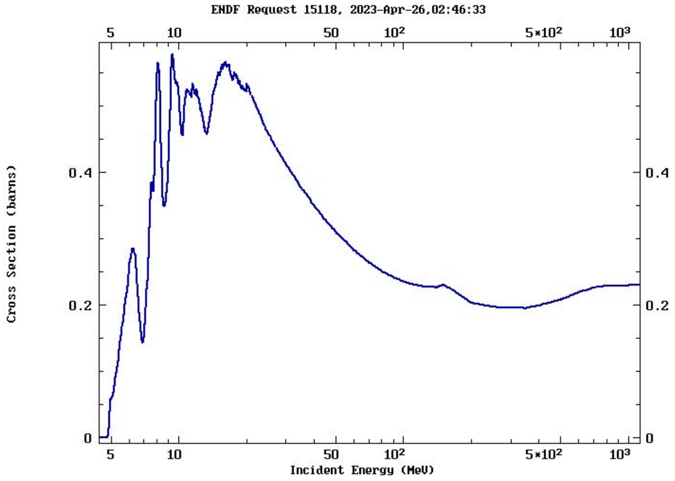


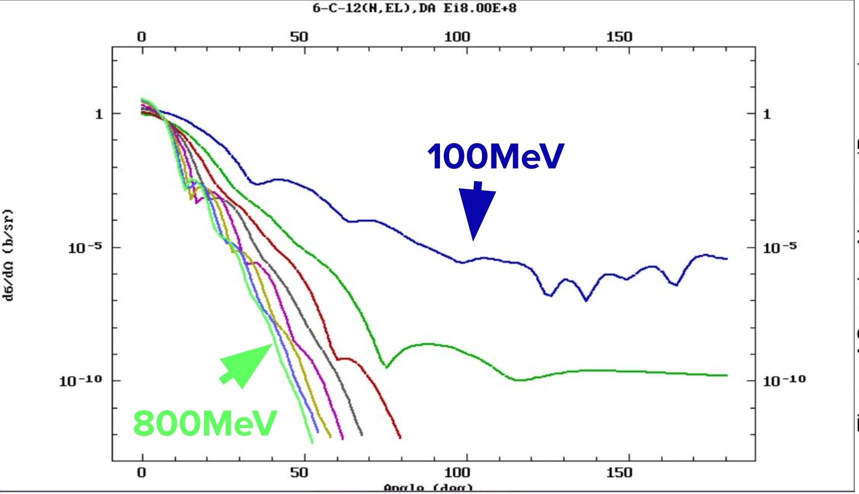

Kinetic Energy of Outgoing Particles, Inelastic
# of Particles
Kinetic Energy (MeV)
Proton
Neutron
Pion
Other
Gamma
Alpha
Deuteron
He3
Pi 0
Carbon

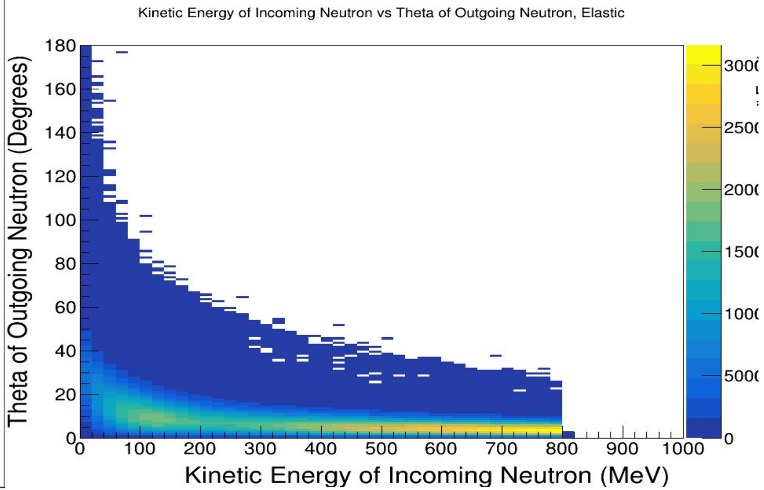

ENDF Request 15118, 2023-Apr-26,02:46:33
Incident Energy (MeV)

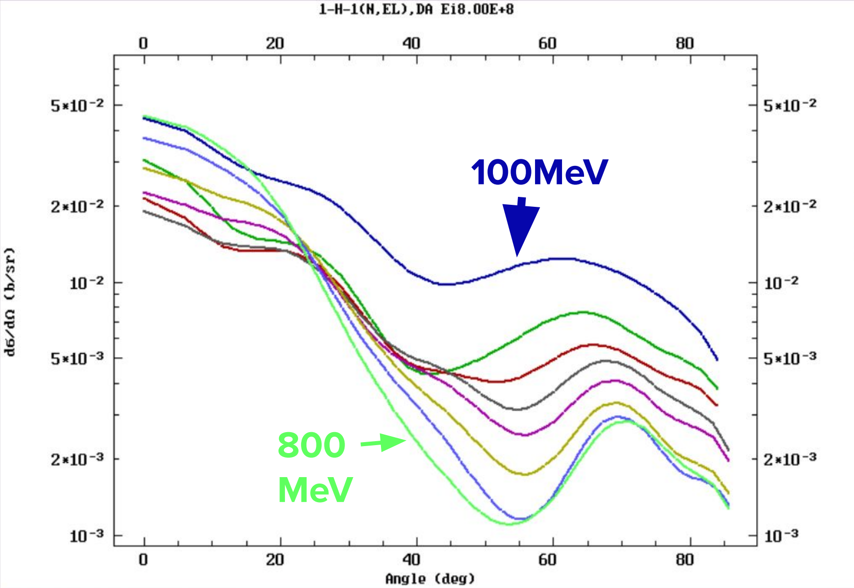

Kinetic Energy of Outgoing Particles, Inelastic
×10^6
# of Particles
25
20
15
10
5
0
100
200
300
400
500
600
700
800
900
1000
Kinetic Energy (MeV)
Proton
Neutron
Pion
Other
Gamma
Alpha
Deuteron
He3
Pi 0
Carbon

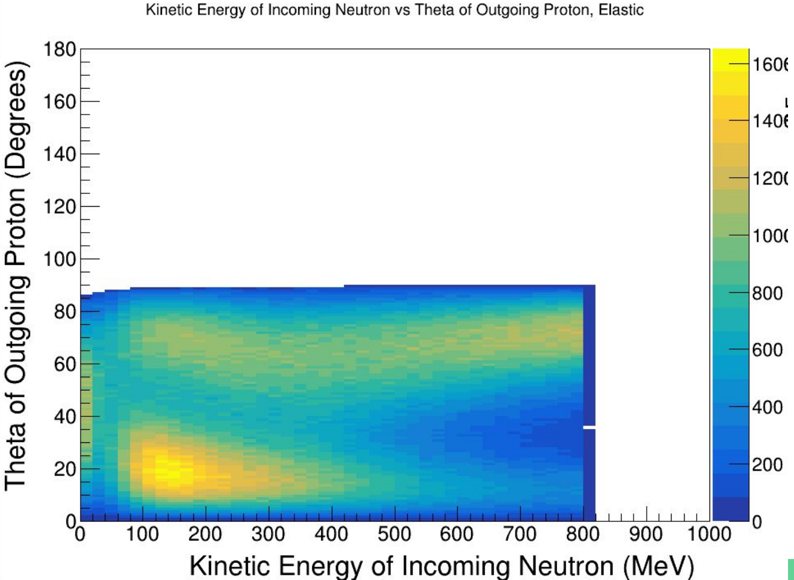

Kinetic Energy of Outgoing Particles, Inelastic
10^7
10^6
10^5
10^4
10^3
10^2
10
0
100
200
300
400
500
600
700
800
900
1000
Kinetic Energy (MeV)
Proton
Neutron
Pion
Other
Gamma
Alpha
Deuteron
He3
Pi 0
Carbon


ENDF Request 15118, 2023-Apr-26,02:46:33
Cross Section (barns)
0.4
0.2
0
5
10
50
10^2
5×10^2
10^3
Incident Energy (MeV)


6-C-12(N,EL),DA Ei8.00E+8
dσ/dΩ (b/sr)
Angle (deg)
100MeV
800MeV


Kinetic Energy of Incoming Neutron vs Theta of Outgoing Neutron, Elastic
Theta of Outgoing Neutron (Degrees)
Kinetic Energy of Incoming Neutron (MeV)


1-H-1(N,EL),DA Ei8.00E+8
dσ/dΩ (b/sr)
Angle (deg)
100MeV
800
MeV

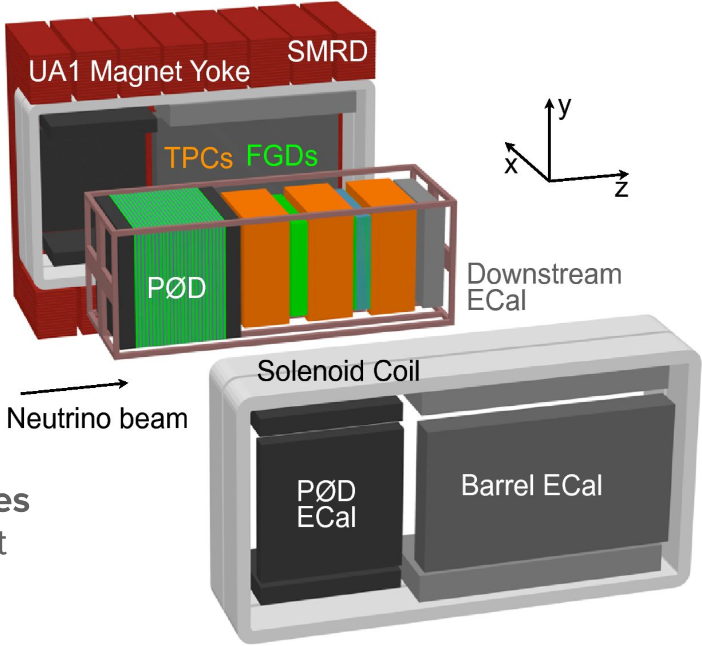

Kinetic Energy of Incoming Neutron vs Theta of Outgoing Proton, Elastic
Theta of Outgoing Proton (Degrees)
Kinetic Energy of Incoming Neutron (MeV)

How is the PMNS matrix related to the parameters we are interested in measuring?

- PMNS = 3x3 matrix; 9 d.o.f.
  - Actually we can fully describe it using four free parameters
  - Reasoning beyond the scope of this thesis
- These four free parameters are our parameters of interest
  - We can rewrite the PMNS matrix such that each of these parameters is expressed in a different matrix (shown above in presentation)

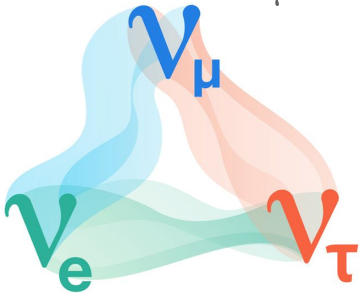
Near Detector

- UA1 Magnet
  - Measure momenta with good resolution
  - Measure sign of charged particles
- Pi-Zero Detector
  - Measures ν_μ + n → ν_μ + n + π^0 + X with the same neutrino beam flux that reach SK
- Time Projection Chamber (TPC)
  - Determines number, orientation, **momenta of charged particles**
  - Determines event rate as fxn of neutrino energy, ionization left for each particle
    - PID from ionization
- Fine Grain Detector (FGD)
  - Tracks charged particles
- Electromagnetic Calorimeter
  - Photon detection, energy and direction measurement
- Side muon range Detector
  - Records muons escaping with high angle relative to the beam (θ)
  - Identify beam-related event interactions in cavity walls and magnet



Neutrino Oscillation

SM → ν_e, ν_μ, ν_τ



$$P(\nu_\alpha \to \nu_\beta) = P(E, L, \Delta m^2, \theta)$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} θ_{13} δ_{CP} θ_{12}

Neutrino Oscillation

Atmospheric & Accelerator

Reactor & Accelerator

Solar & Reactor

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} θ_{13} δ_{CP} θ_{12}

Near Detector

- INGRID
  - Beam direction
  - Beam Profile
- ND280
  - Flux
  - Cross Sections
- Super Kamiokande
  - CC candidates
  - ν_e/ν_e candidates
  - ν_μ/ν_μ candidates

Oscillation Parameters

θ_{23}

θ_{13}

δ_{CP}

θ_{12}

Backup: Signal Contamination

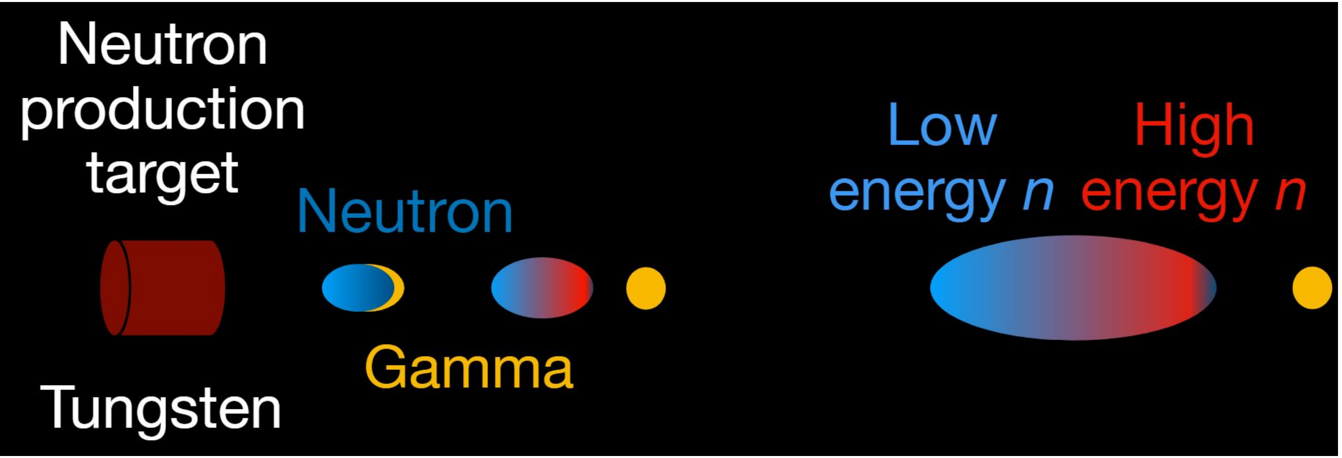


Photo Credit: Ciro Riccio, Stony Brook University | DUNE collaboration meeting

$$v_{\gamma} > v_{\text{neutron (high E)}} > v_{\text{neutron (low E)}}$$

Path

Understanding kinematics of outgoing particles from neutron interactions w/ detector

⬇

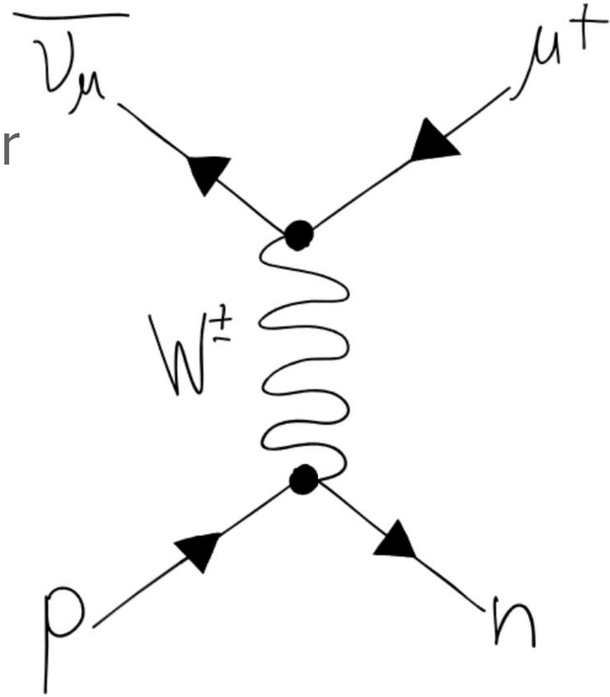
Better understanding of neutron energies

⬇

Better understanding of antineutrino energy reconstruction

⬇

Better understanding of neutrino oscillation probabilities



CCQE

More SuperFGD Assembly Pictures

SuperFGD Assembly

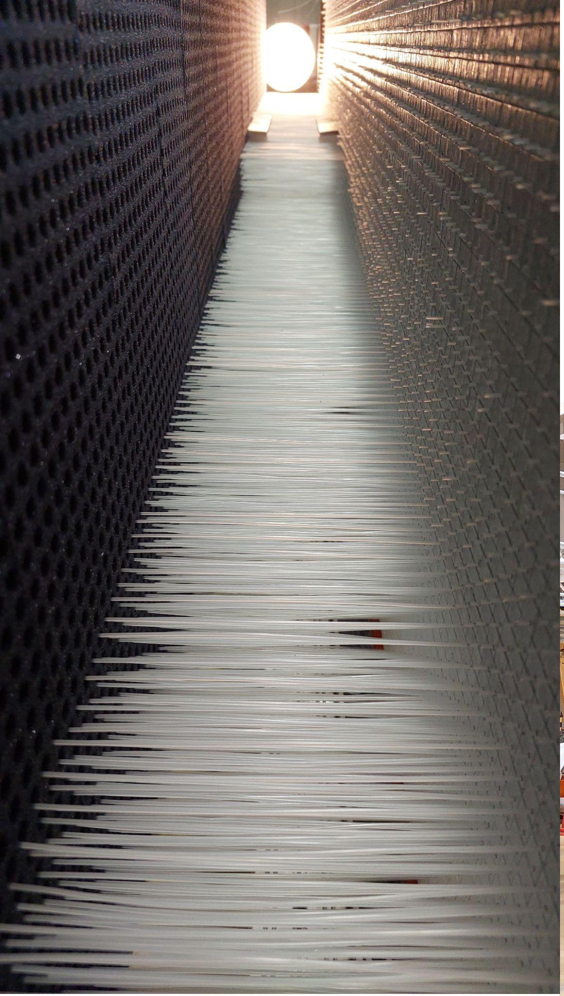
Credit: Ciro Riccio

Credit: Jiayu Ji

Credit:
Kuunal
Mahtani

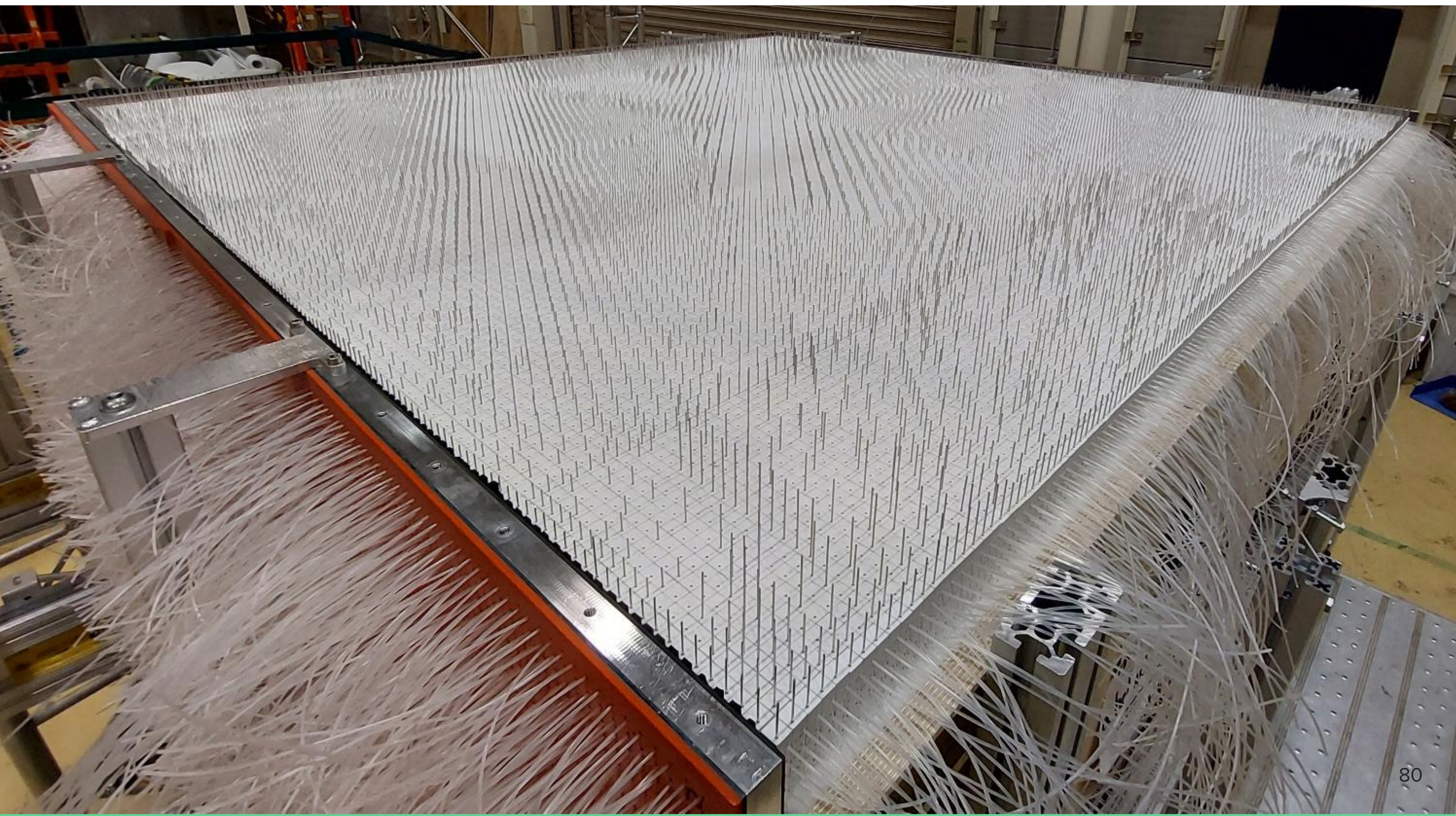
Credit: Kuunal Mahtani

Credit: Kuunal Mahtani

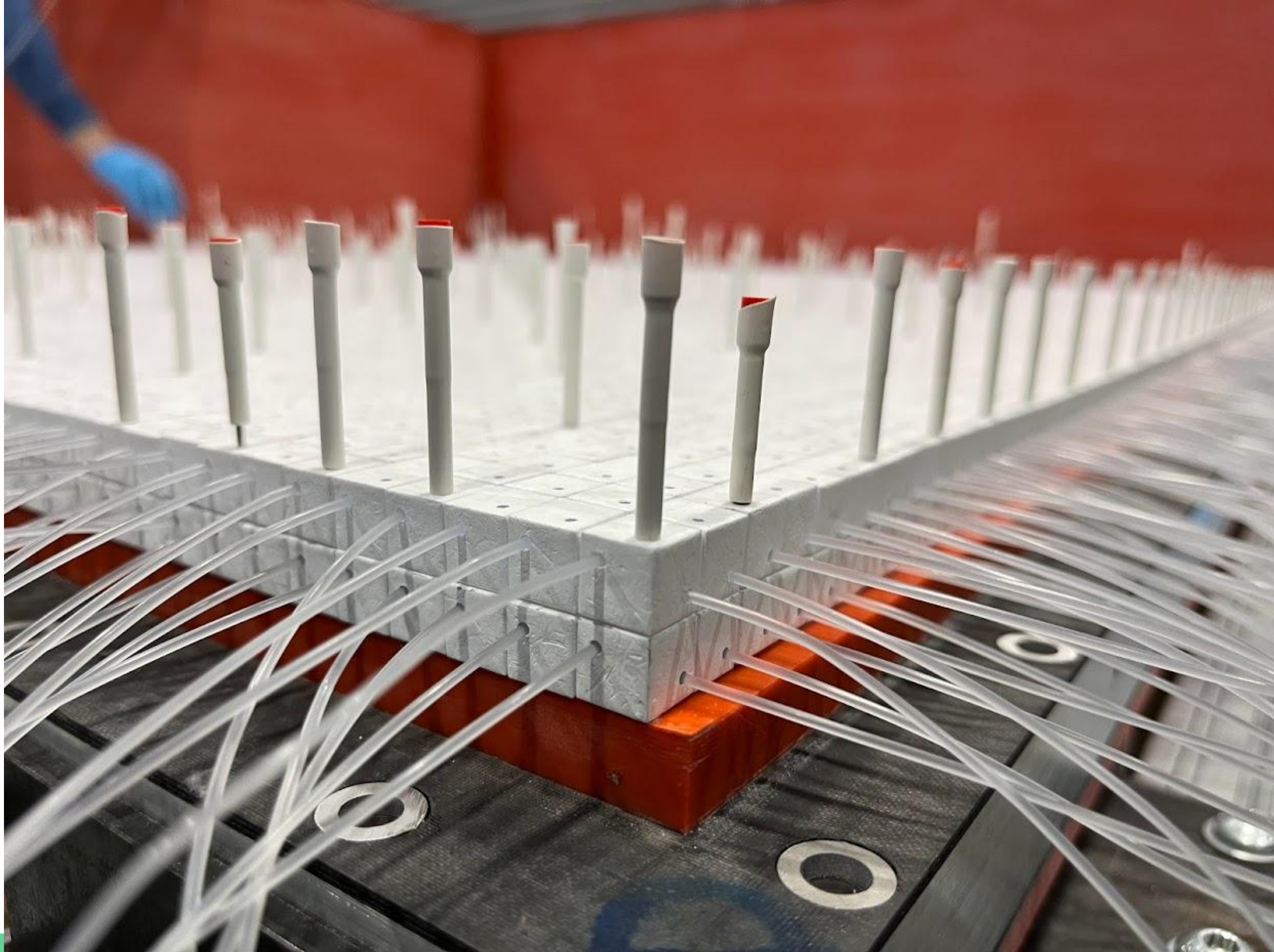


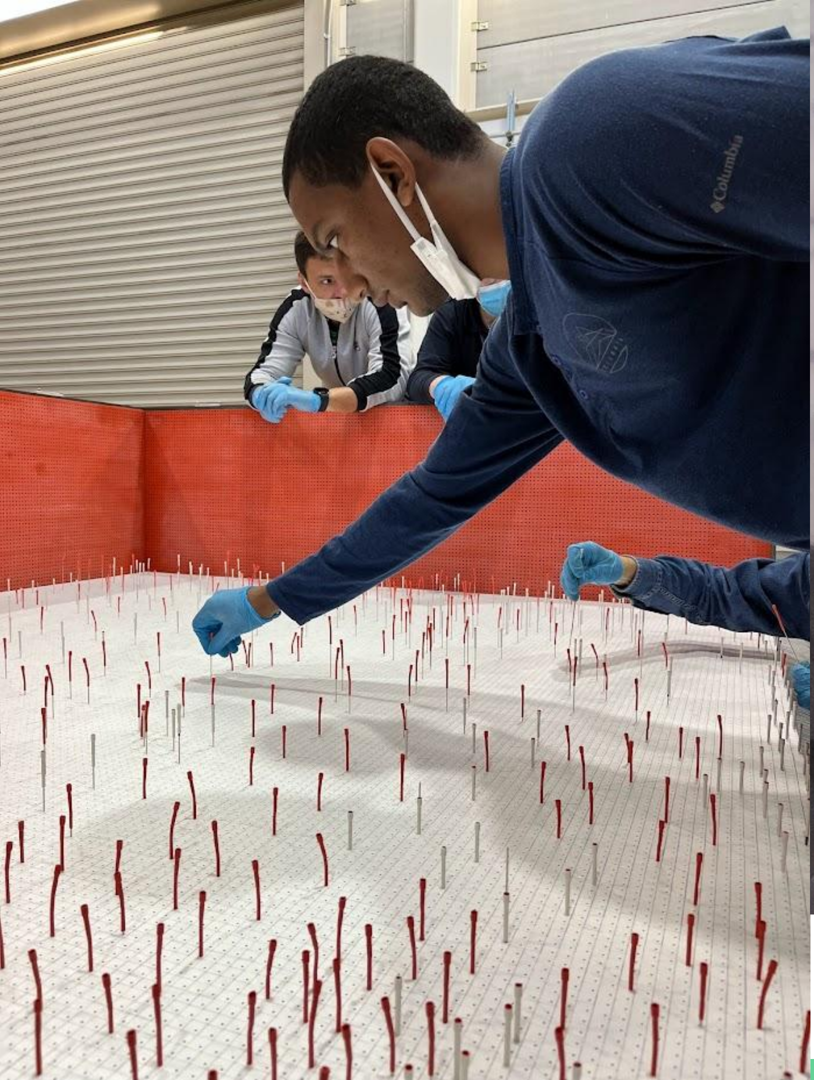
Credit: Kuunal Mahtani

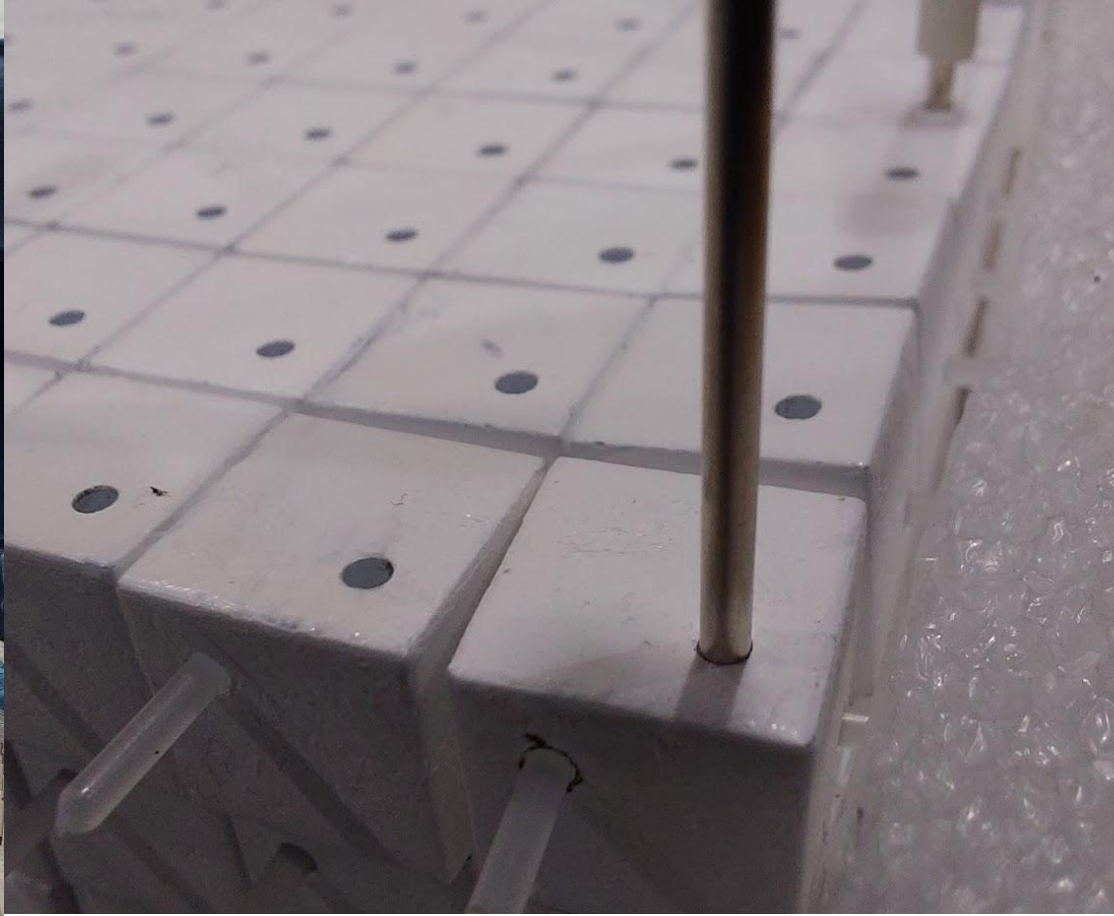
Credit: Kuunal Mahtani

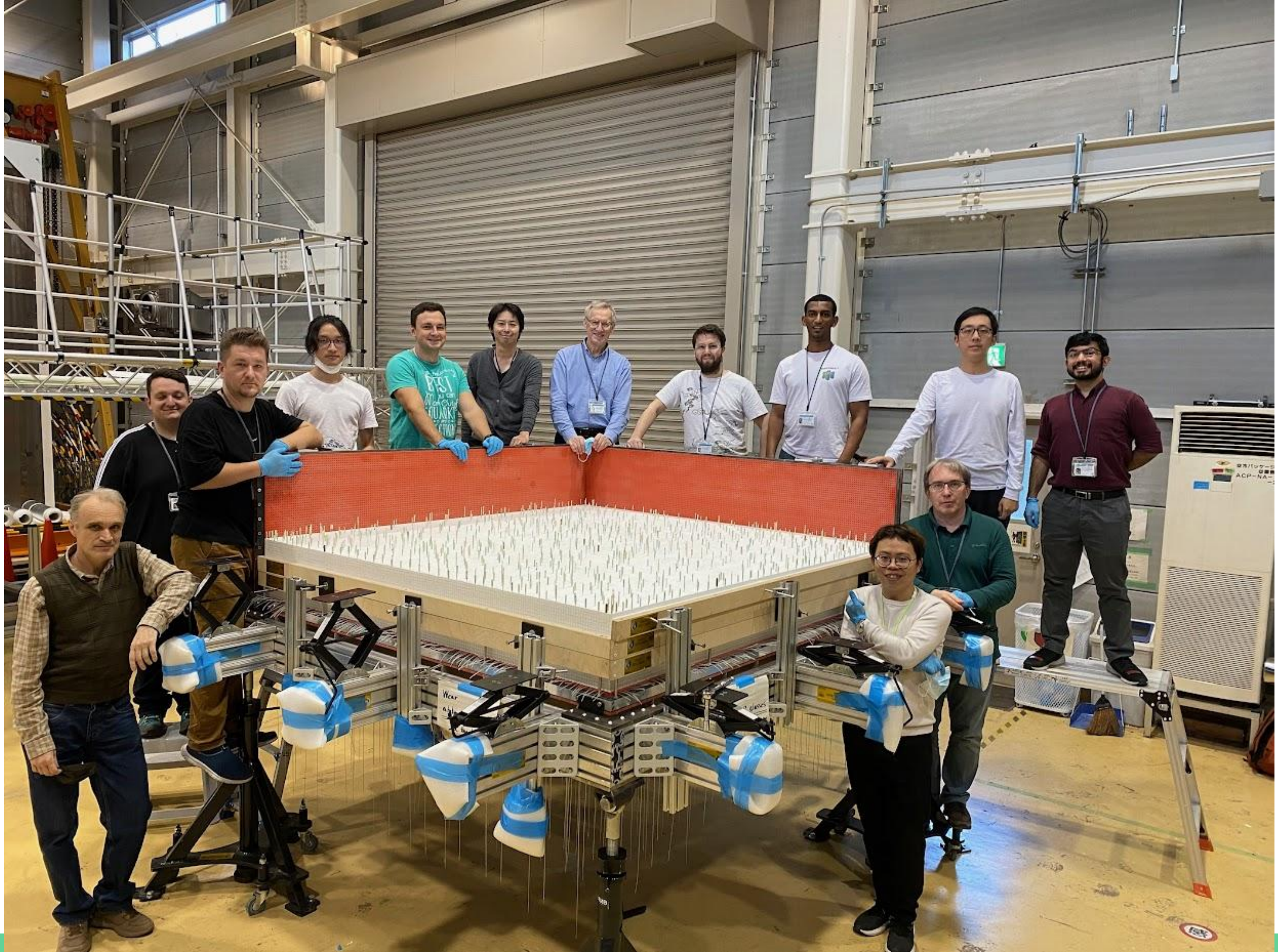


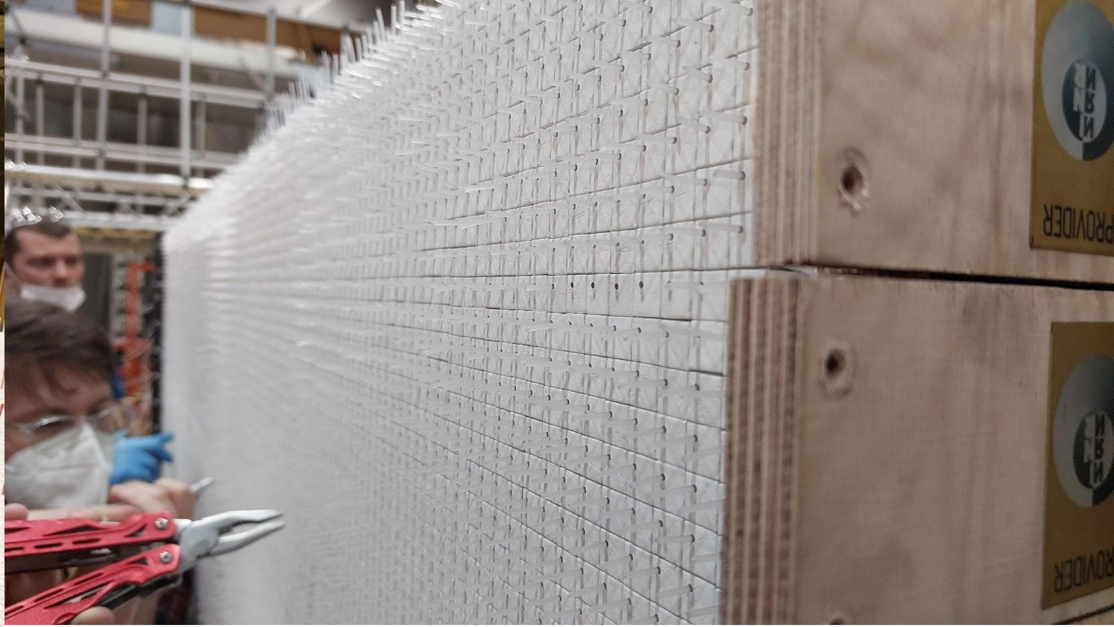

AED




Columbia

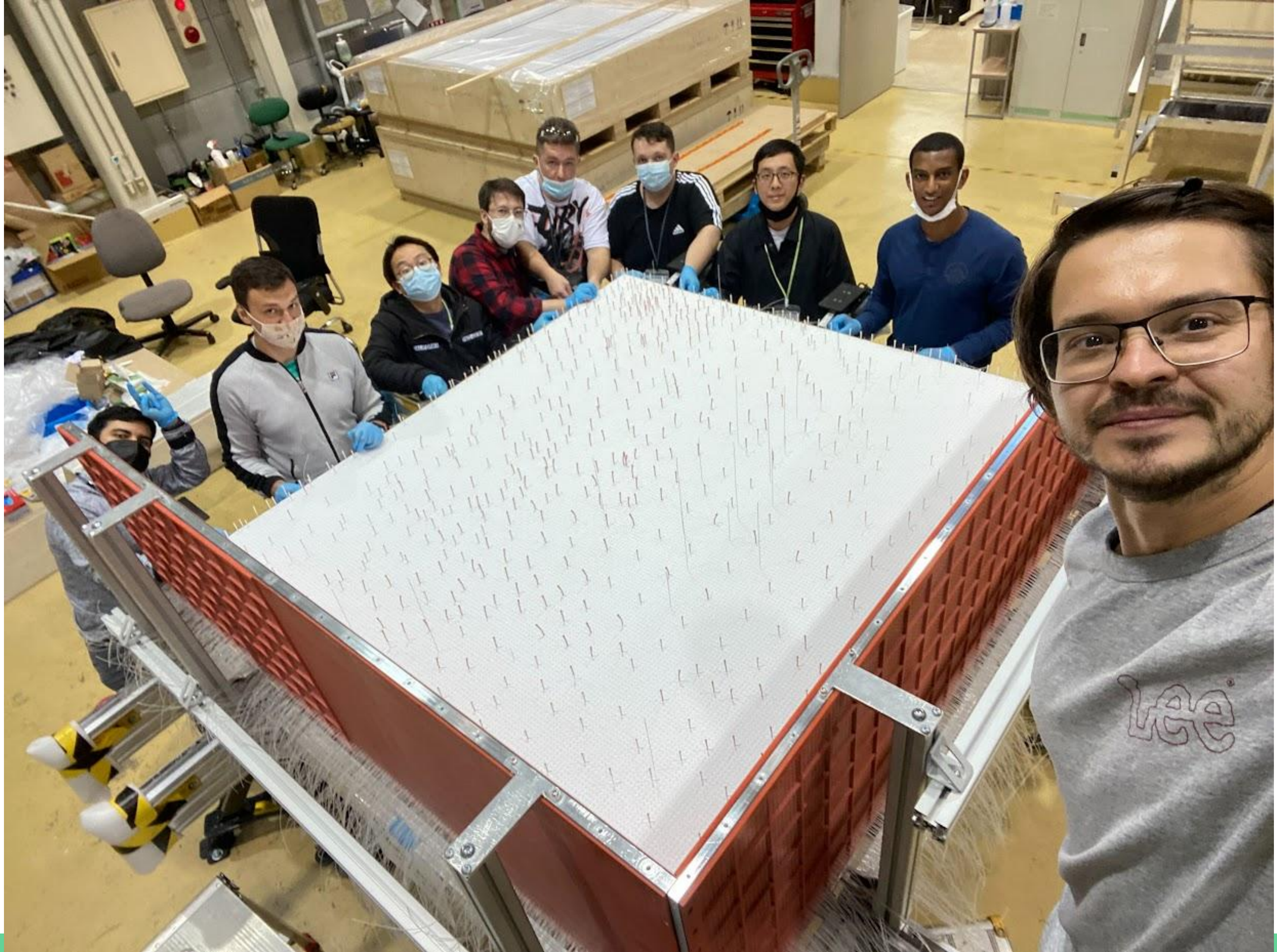






Credit: Kuunal Mahtani

Credit: Ciro Riccio


Lee