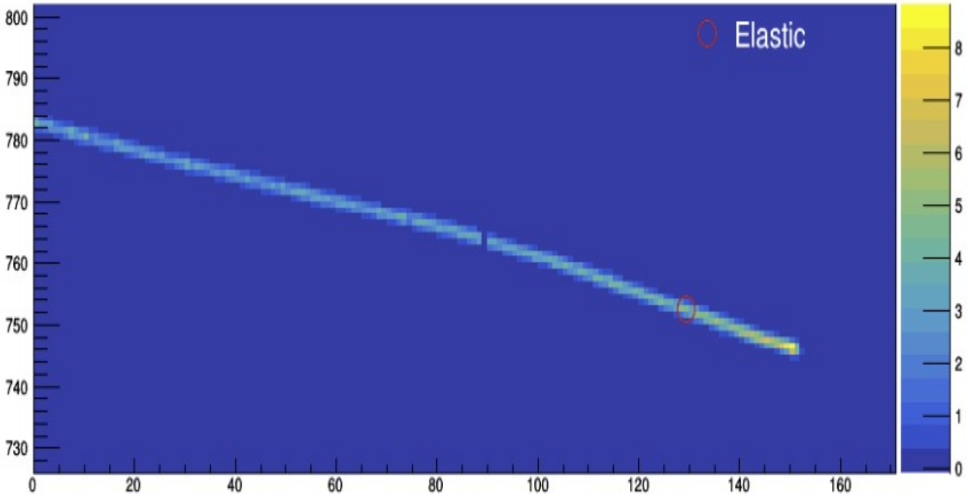
Proton Analysis

Measuring proton-argon cross section

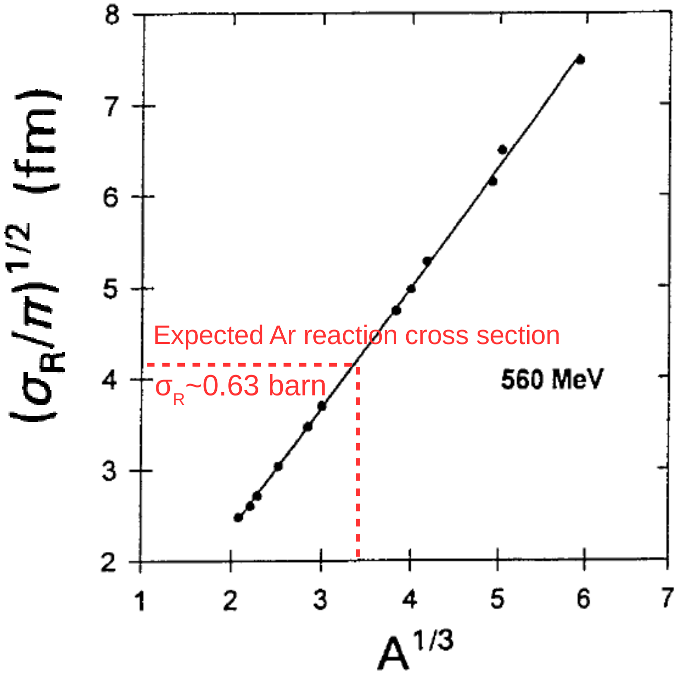


Heng-Ye Liao
ProtoDUNE Analysis Workshop
Jan 26, 2020

Outline

- Proton-Argon cross-section
- Reconstruction
  -Algorithms for vertex recognition
  -Proton kinetic energy recognition
- Reconstructed cross section (MC)

Motivation



R. F. Carlson, “Proton-nucleus total reaction* cross sections and total cross sections up to 1 GeV”, Atomic data and nuclear data tables 63, 93-116 (1996)

- Motivations of proton-argon cross section (XS)

  - Hardly find any proton-argon measurement in our energy region (~400 MeV - ~6.2 GeV)†

  - Predictions come from interpolation between heavier and lighter nuclei

  - Validate nuclear structure models (important input for study final state interactions!)

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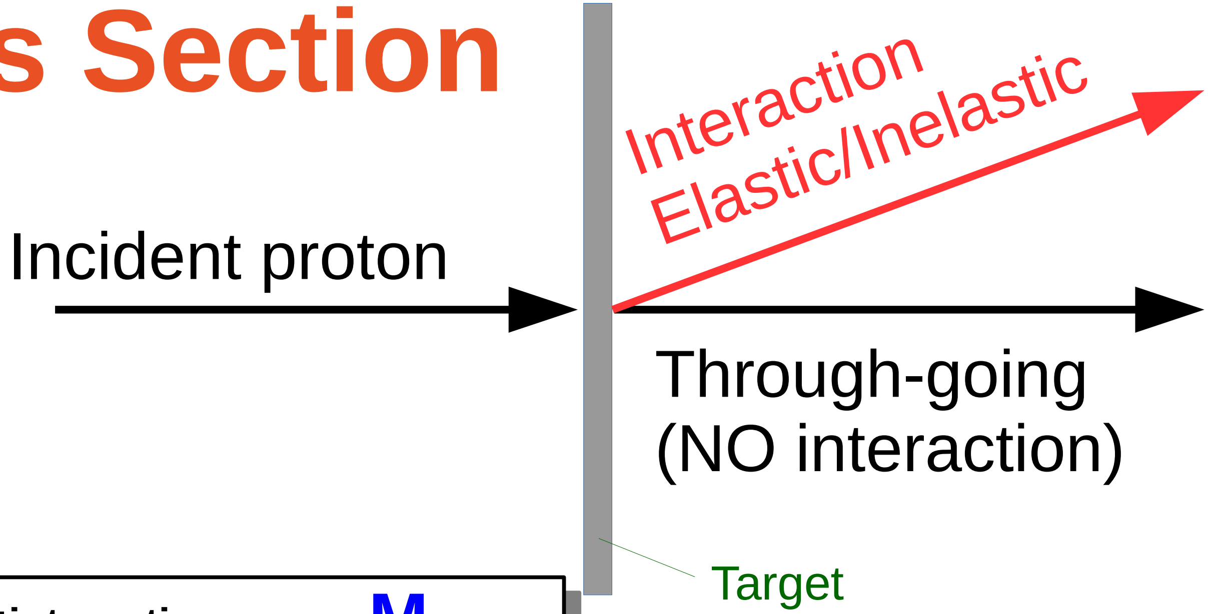
* “Reaction” XS in literature = “Inelastic” XS in Geant4

† See page 28 for more references

Cross Section


Incident proton

Interaction
Elastic/Inelastic

Through-going
(NO interaction)

Target

$$\mathbf{XS} = \frac{N^{interacting}}{N^{incident}} \cdot \frac{M_a}{d \cdot L \cdot N_a}$$

- $N^{interacting}/N^{incident}$: “Profile” of cross section
- Scaling factor **($S_f := M_a/d \cdot L \cdot N_a$)** : constant

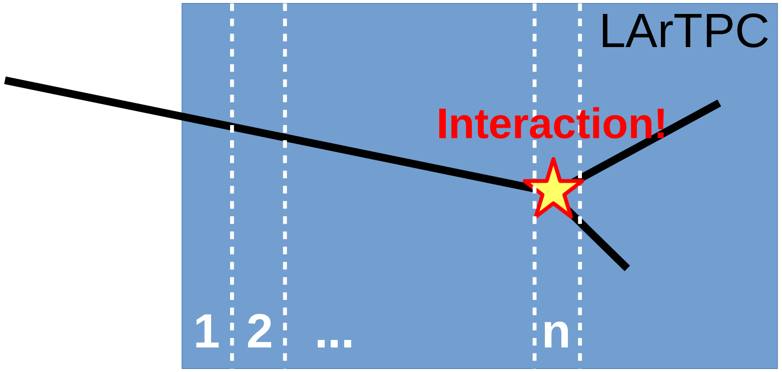
$N^{incident}/N^{interacting}$: Number of incident/interacting protons

N_a: Avogadro’s number

M_a: Atomic mass of argon

d/L: Density/thickness of argon target

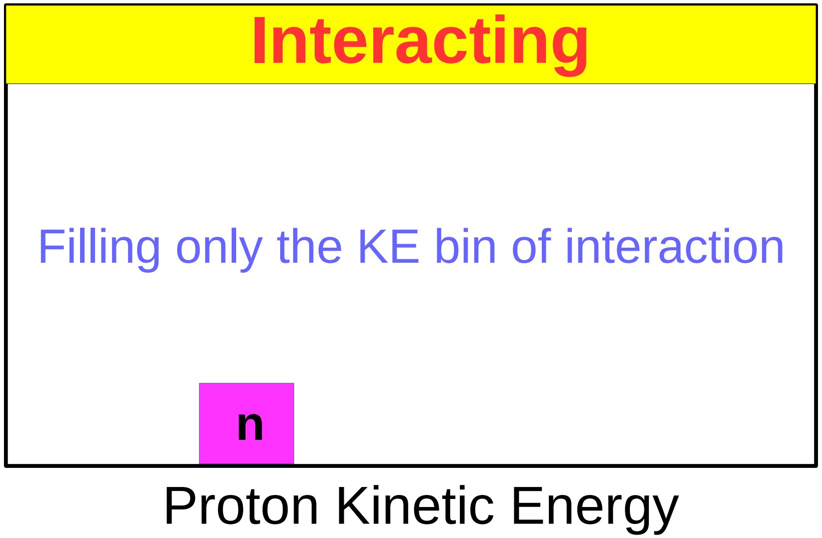
Thin Slice Method



- The thin slice method was developed by the LArIAT experiment
- Use the granularity of LArTPC
  → Treat wire-to-wire spacing as a series of “thin-slab” targets. Each thin-slab is an independent measurement.
- Cross section

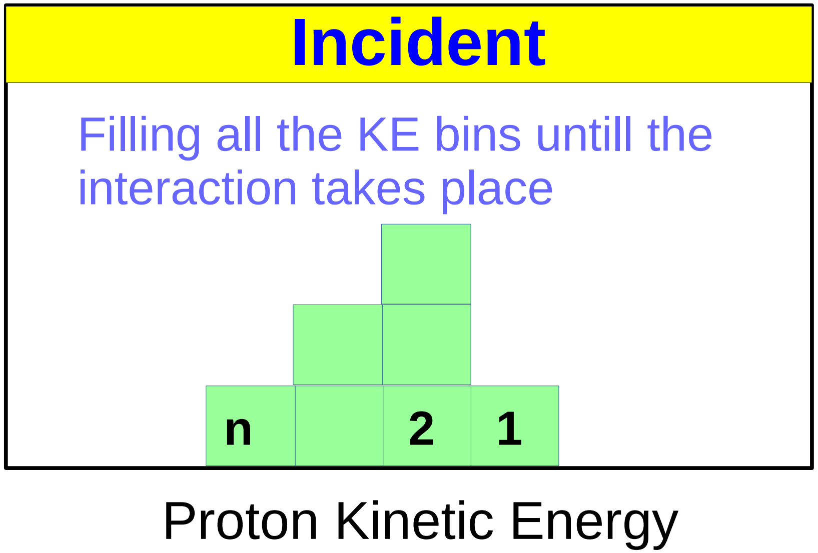
$$\boxed{XS(KE) = S_f \cdot \frac{N(KE)^{interacting}}{N(KE)^{incident}}}$$

* S_f ~ 100 barn in our experiment (Argon target & slab thickness~0.5 cm)



Interacting

Filling only the KE bin of interaction



Incident

Filling all the KE bins untill the interaction takes place

MC Setup

- MC setup for the XS study

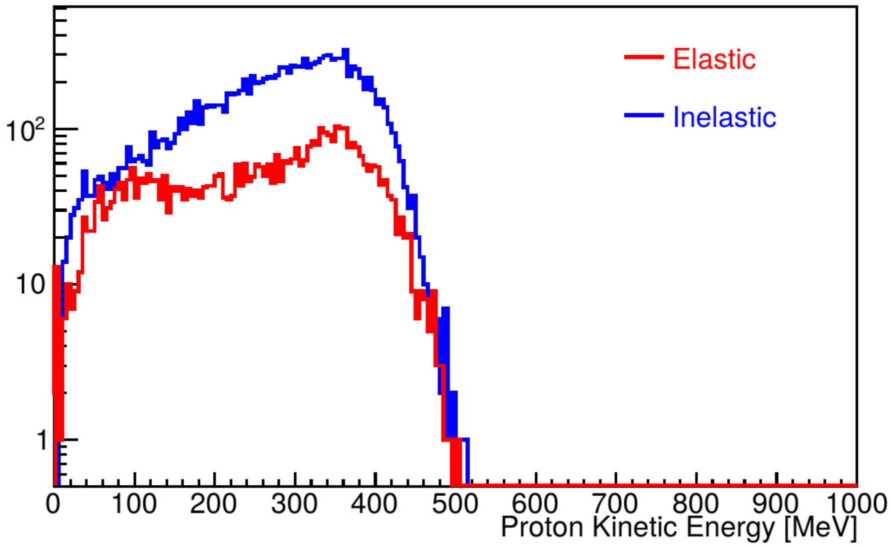
  [1] Generate the proton beam close to the TPC front face

  - Incident proton beam: P=1 GeV/c; σP=0.05 GeV/c
  - $(\Theta_{xz}, \Theta_{yz})=(0°, 0°)$ & $(x_0, y_0, z_0)=(-80, 420, -10)$ cm
  - 50,000 events generated
  - Electron lifetime: 3 ms
  - Only the truth info, no reconstruction

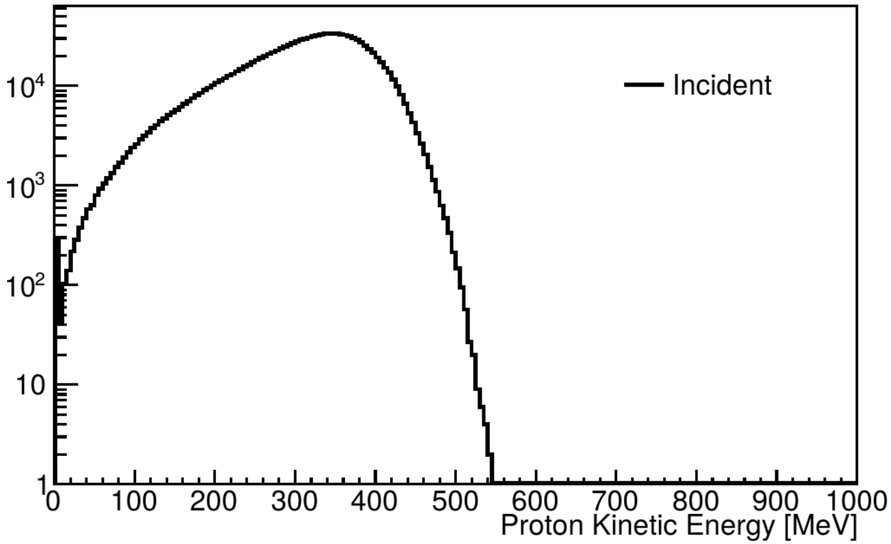
  [2] Apply the thin slice method to derive the proton-argon XS (collection plane only)

Proton Kinetic-Energy Distributions (MC)

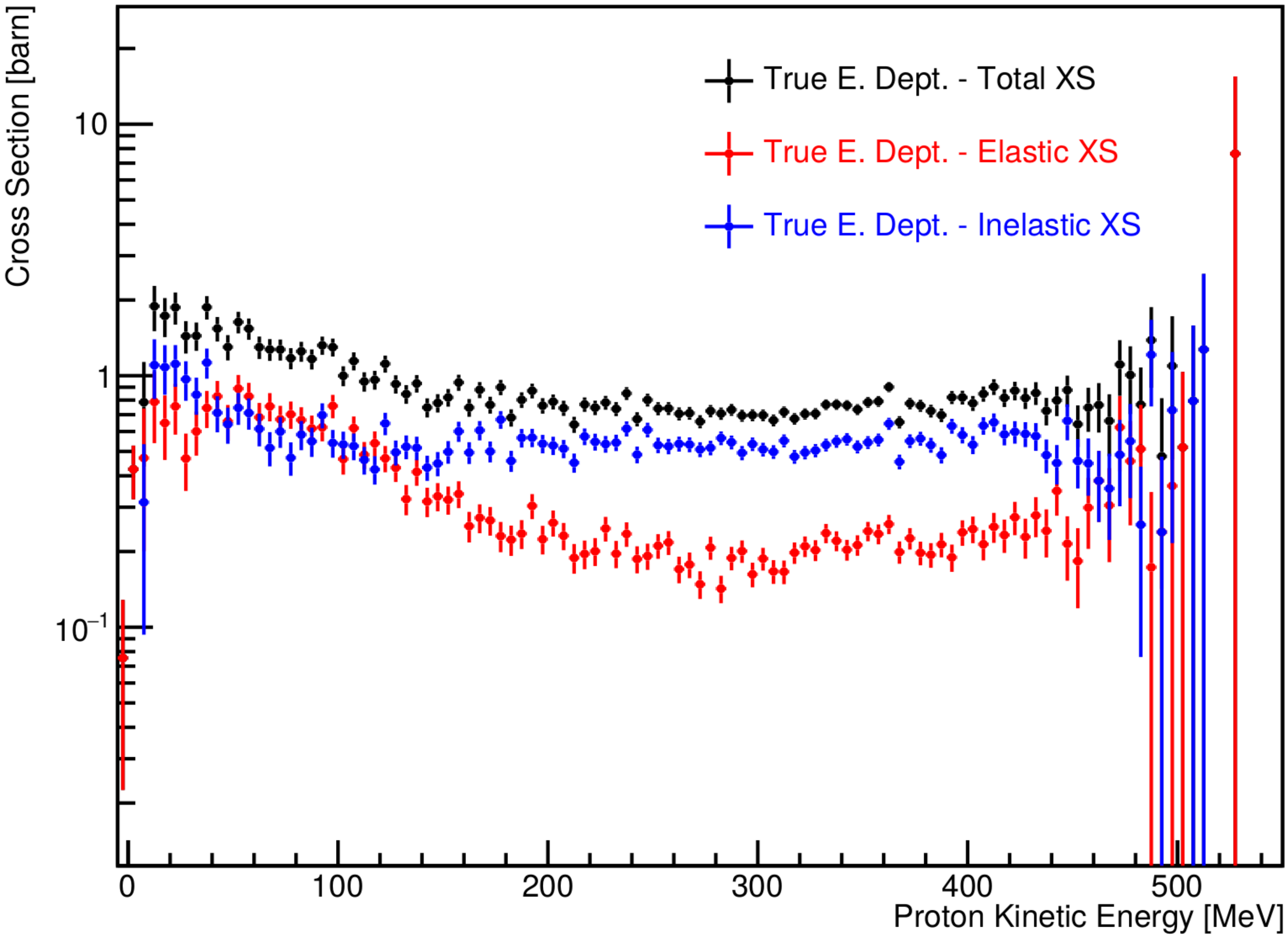
Interacting



Incident

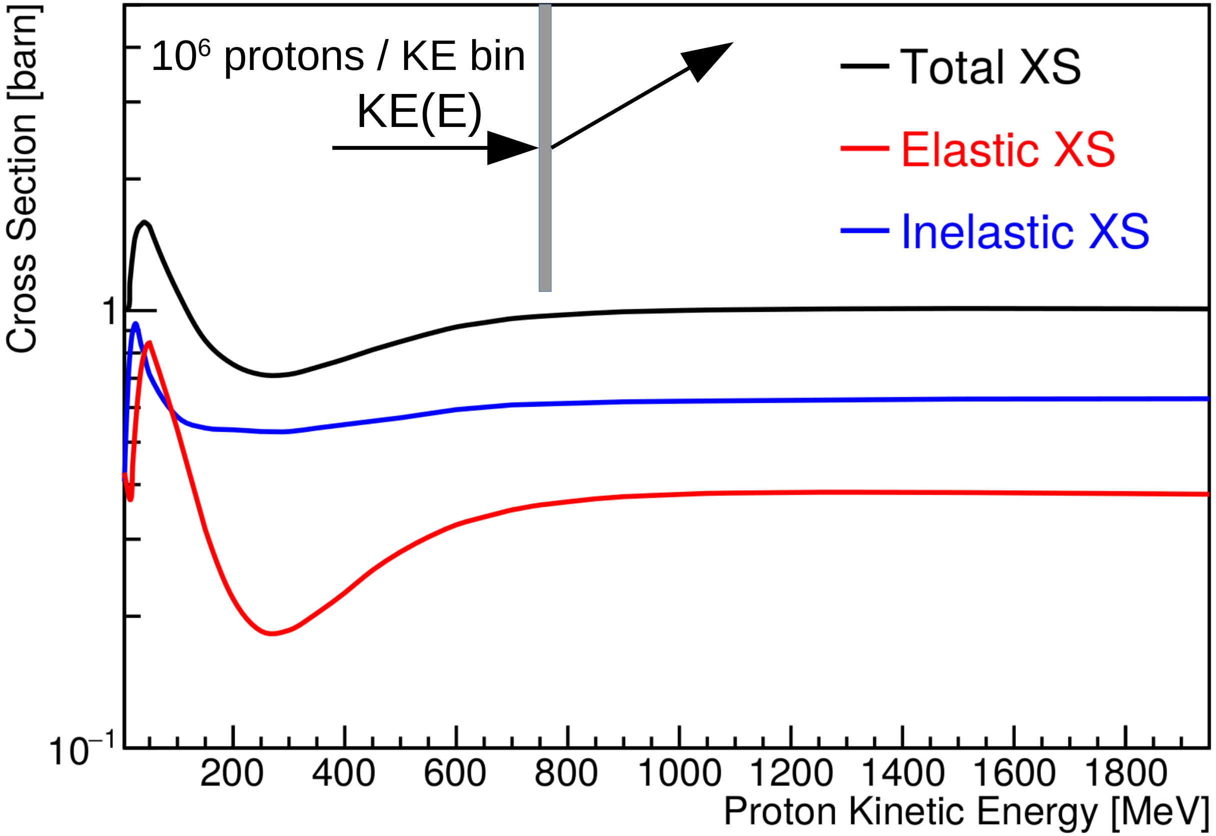


Proton-Ar Cross Sections (MC Truth)



LArSoft Geant4 version: 10.3

Geant4 Cross Sections (G4HadStudies)

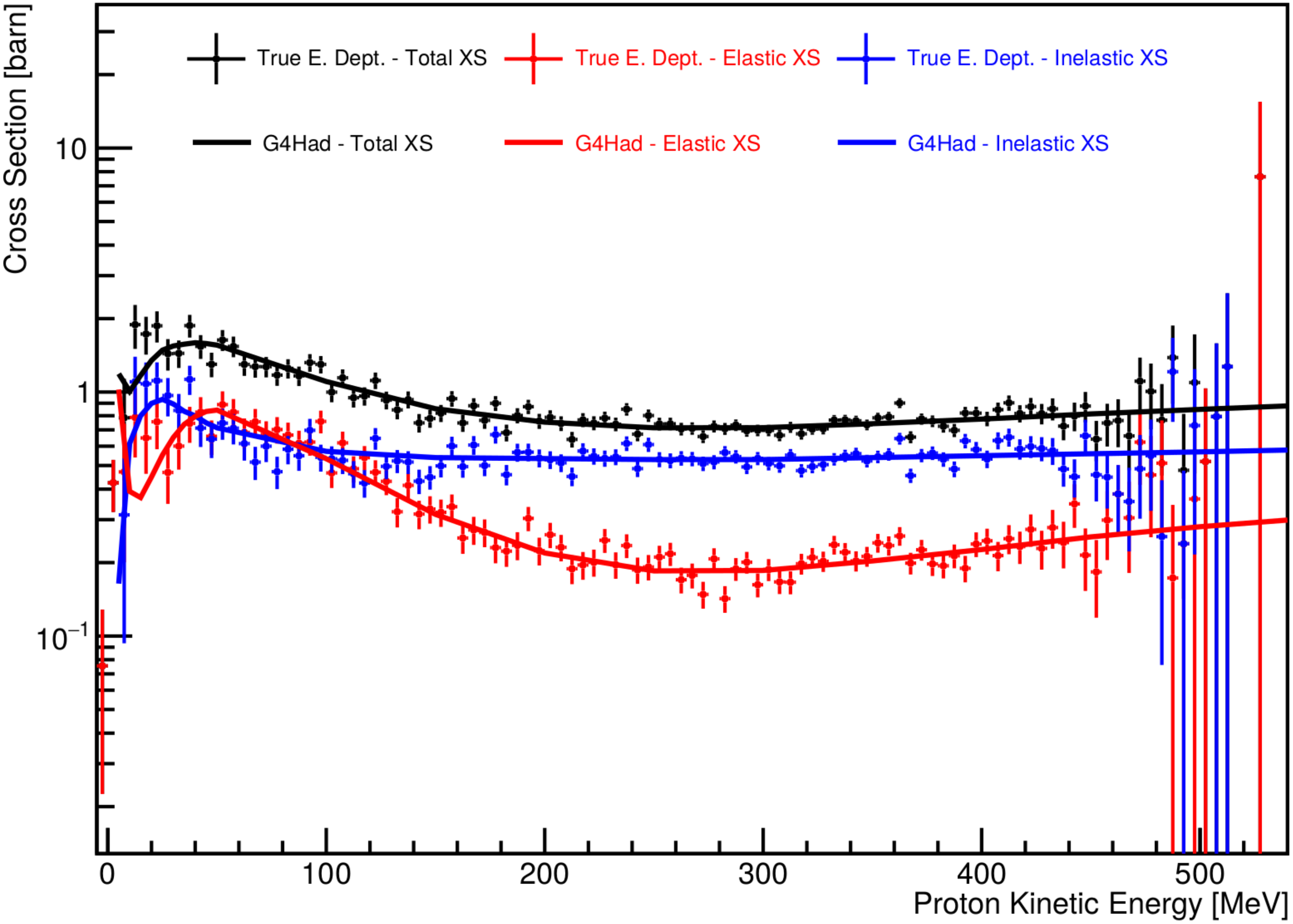


- Proof-of-principle of the thin slice method
  - Use a stand-alone Gean4 application to test if the method works
  → G4HadStudies* (Developed by Hans Wenzel)
  - To verify the cross section result from the implemented LArSoft module

*Github link: https://github.com/hanswenzel/G4HadStudies

Geant4 version: 10.4

Cross Sections - Comparison



*Geant4 versions: LArSoft: 10.3 <> G4Had: 10.4

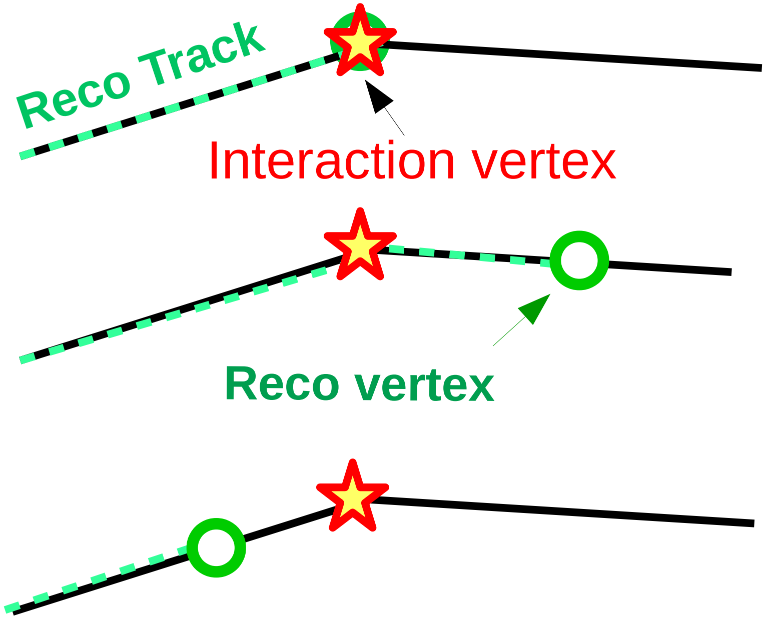
Kinetic Energy Reconstruction

- Definition of reconstructed kinetic energy:

$$KE = KE_{FF} - \sum_j \Delta E_j = KE_{FF} - \sum_j \frac{dE_j}{dx_j} dx_j$$

+ KE_{FF}: KE at front face of TPC/ ΔE_j: Energy loss at each step

- Interaction vertex recognition is a critical part of the XS analysis



$KE_{True} = KE_{Reco}$ (Perfect reco!)

$KE_{True} > KE_{Reco}$

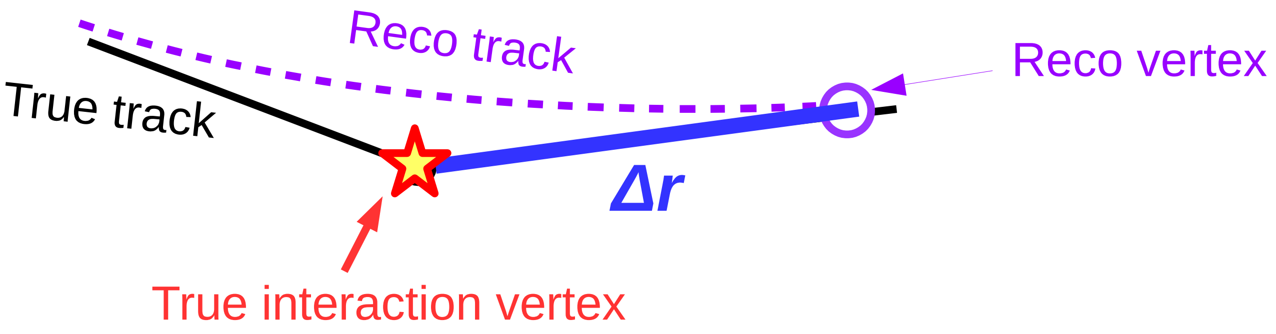
Reco track length longer than true track length

$KE_{True} < KE_{Reco}$

Reco track length shorter than true track length

Vertex Reconstruction

- Vertex reconstruction using Pandora & convolutional neutral network (CNN)
- Metric of vertex reconstruction:
  Δr := Distance between true vertex and reco vertex



- Pandora & CNN vertex identification:
  - Pandora: Assume reconstructed primary track end has interaction
  - CNN: Choose the highest CNN score as interaction vertex (elastic / inelastic score)

p.s. Sometimes the beginning of track gets a higher score, skipping the scores of first few wires (≥3 cm in Z) for the entire analysis

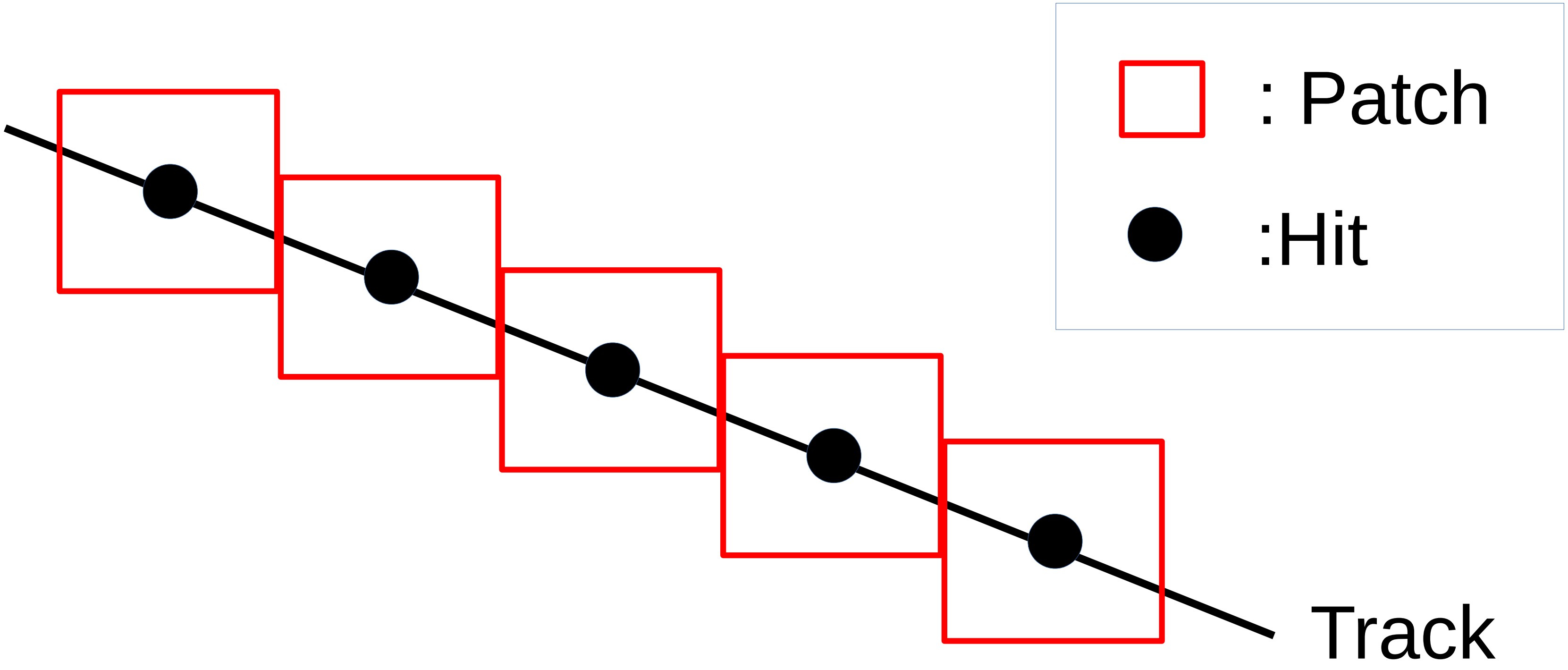
CNN for Vertex Finding

- Basic structure of CNN

1. **Convolution layer** (extract feature of input image)
2. **Pooling layer** (dimensionality reduction, prevent over-fitting)
3. **Fully-connected layer (dense layer)** (Output result)

- Modifying the current existing network of finding neutrino vertices original developed by Robert Sulej and Dorota Stefan
- Give each hit in a track the scores of elastic and inelastic scattering
  → The initial idea is triggered by Leigh
- Structure of Convolutional Neural Network
  → Tingjun and Aidan made major contribution for building the framework

Patches

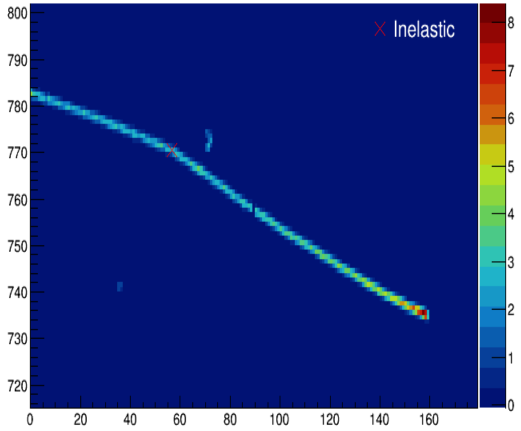


- Network training not using the entire image but using patches instead
- Advantages of using patches:
  Save memory, save time, and make the training possible

Training Sample & Procedure

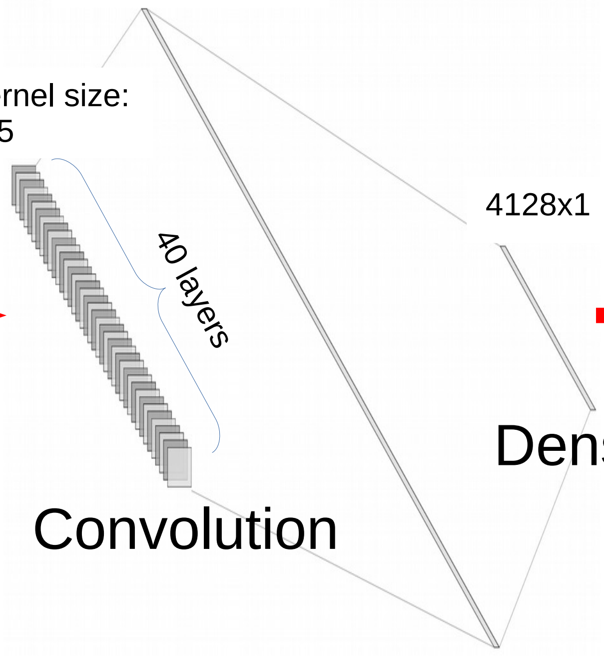
- Training sample: Single proton MC, SCE OFF
- Procedure:

Patch size: 44x48



Input:
Image with labels
(elastic/inelastic/none)

[Only collection plane Images]



10813568x1

Kernel size:
5x5

40 layers

4128x1

Convolution

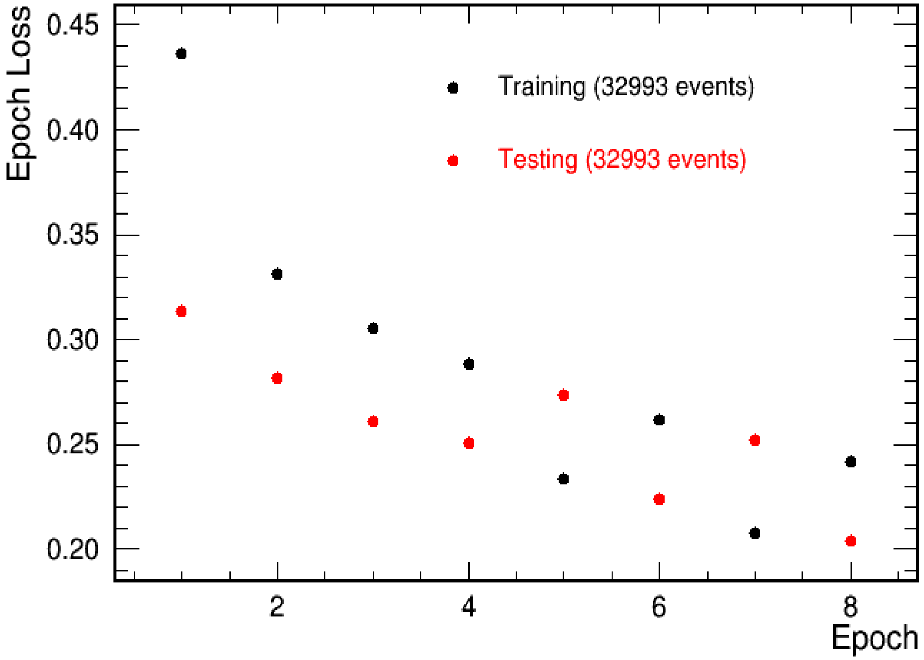
Dense

Dense

Output:

Elastic, Inelastic & none scattering score [0-1] per pixel

Loss Function



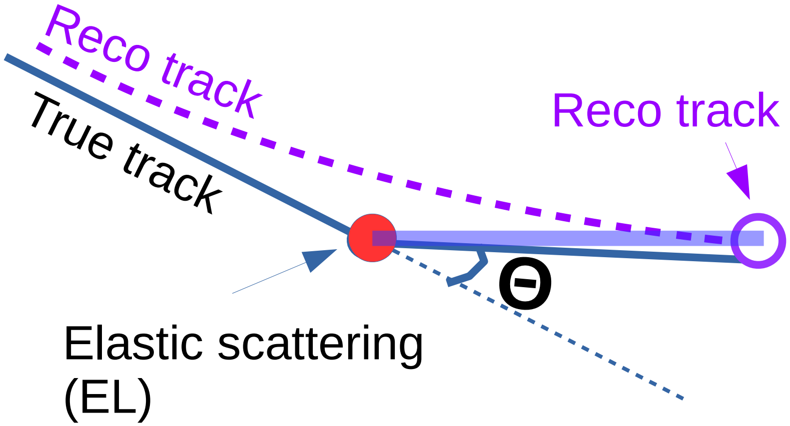
- Loss function (brief description):
A metric to measure “distance” between the ground truth and the network outputs (the lower, the better)

- Loss function of use:
Categorical cross-entropy

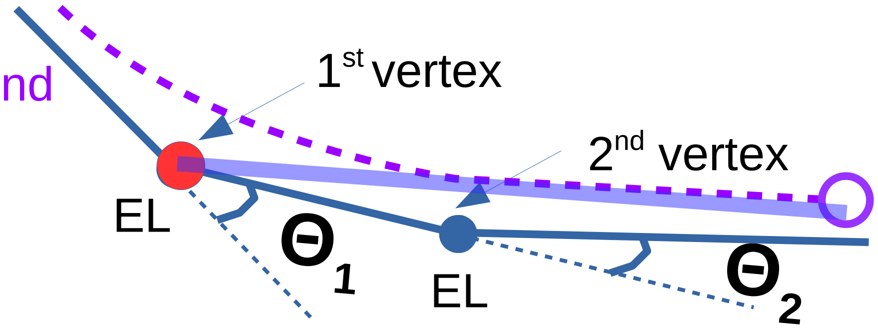
Epoch: the process of updating network parameters after forward+backward propagations

Elastic/Inelastic scattering

1 **Only one vertex**



2 **≥ 2 vertices**



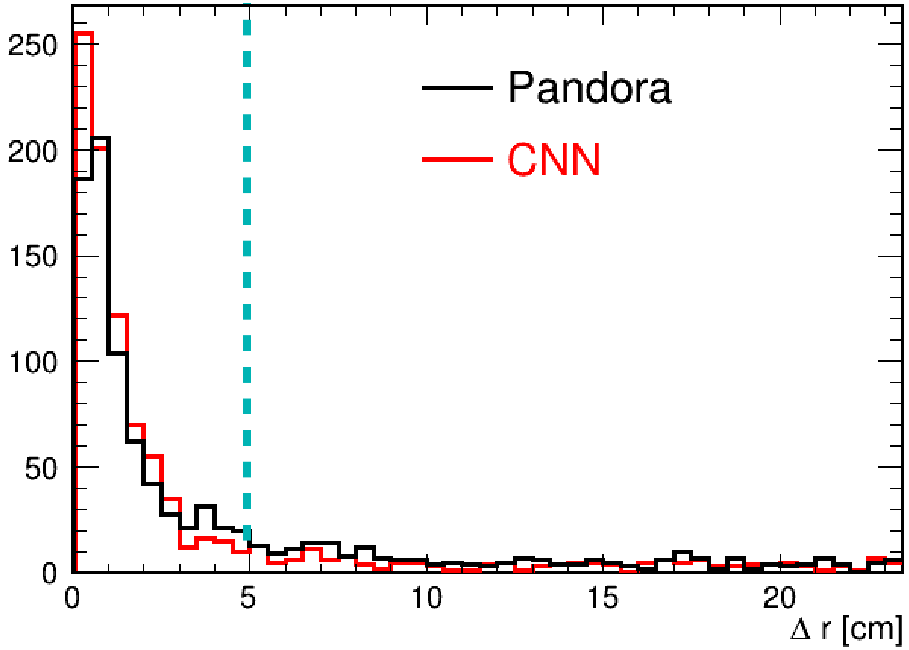
- For the XS study, we only care about where the interaction takes place
  → Looking at the first interaction vertex and see <u>how well we can identify it</u>

$$\begin{cases} \Delta r < 5 \text{ cm : good reco} \\ \Delta r \geq 5 \text{ cm : bad reco} \end{cases}$$

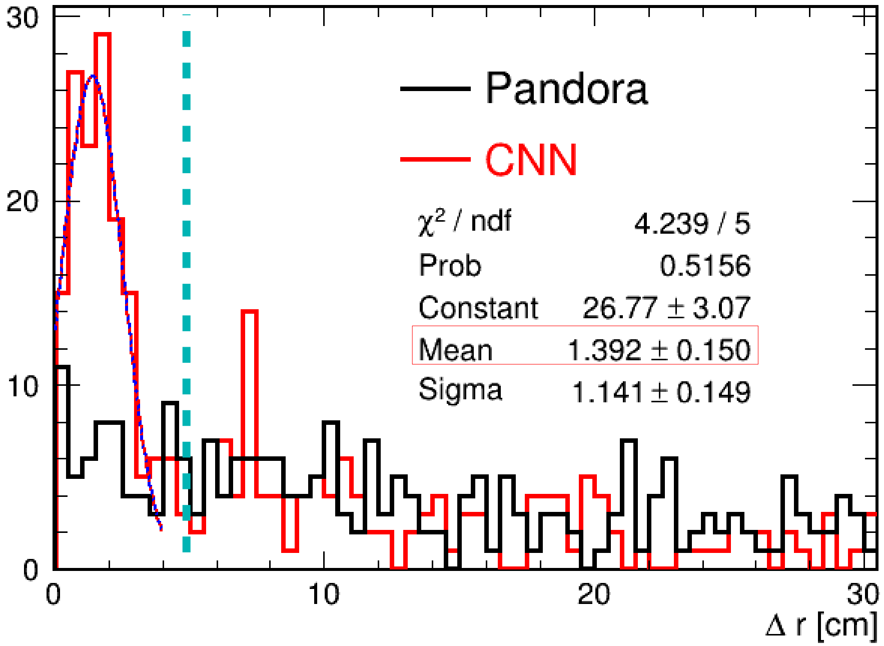
Vertex Recognition Efficiency

- How well can we identify the interaction vertex?

Inelastic

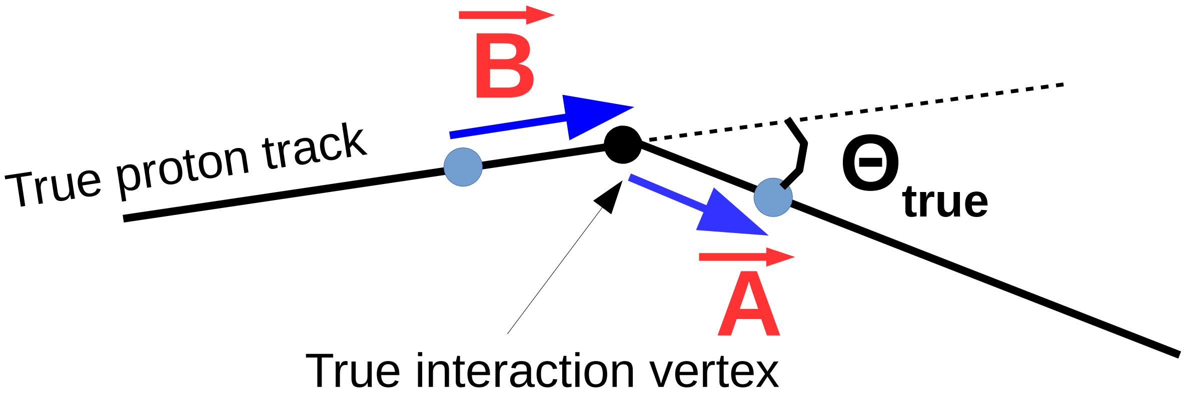


Elastic



Interaction Type	Entries of Δr ≤ 5 cm		Total Entries		Efficiency	
	Pandora	CNN	Pandora	CNN	Pandora	CNN
Elastic	67	149	488		13.7	30.5
Inelastic	734	824	1103		66.5	74.7

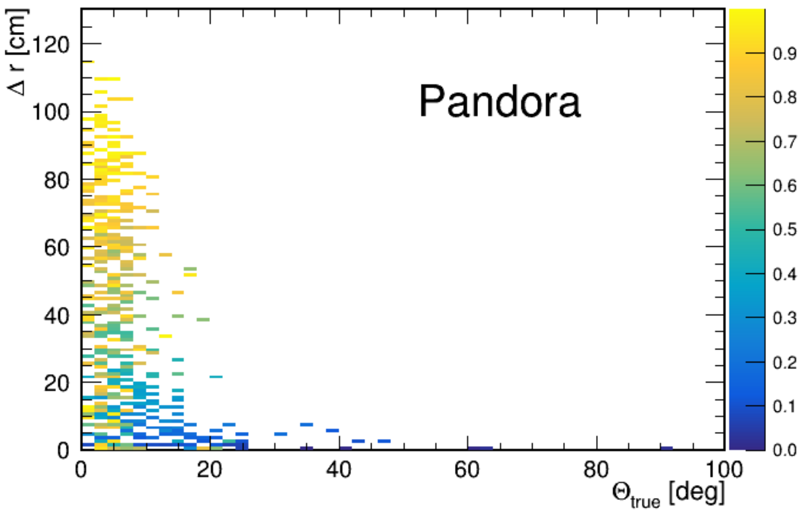
Angle Calculation

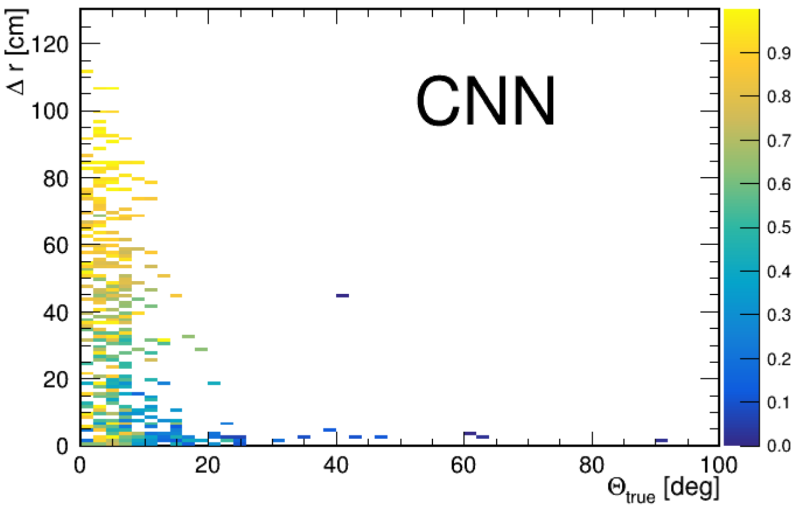


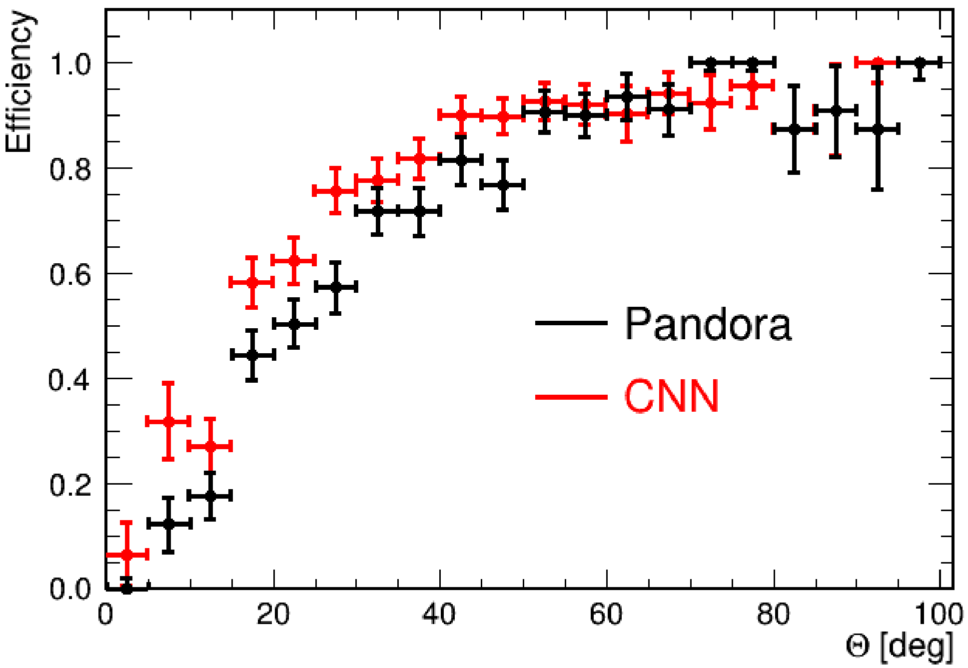
- Angle calculation for true interaction vertices:
  - Use the hits before and after the true interaction vertices
  - Definition of angle:

$$\Theta_{true} = \cos^{-1}\left(\frac{\vec{A}\cdot\vec{B}}{|\vec{A}|\,|\vec{B}|}\right)$$

Efficiency v.s. Θ [Elastic Scattering]





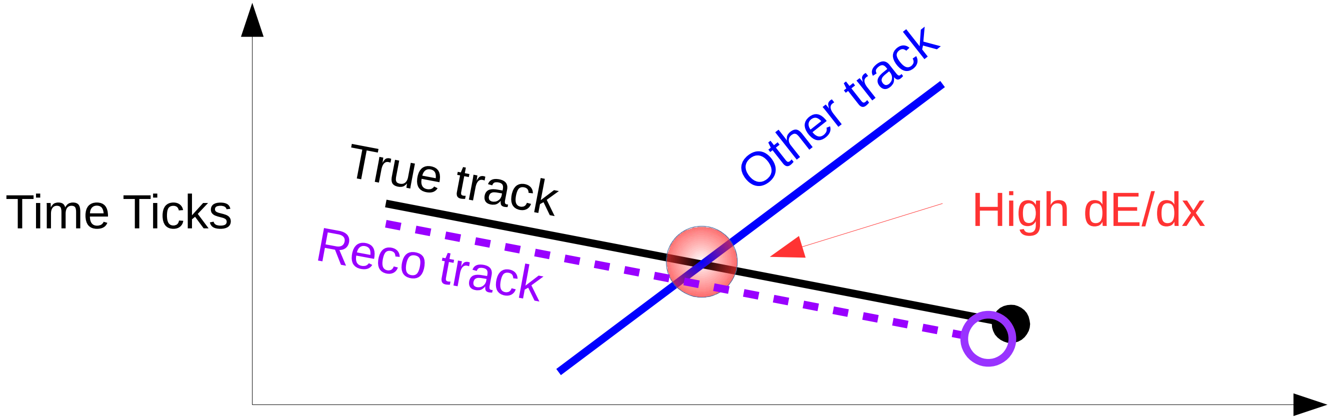


- Sensitive to Θ>40 [deg]

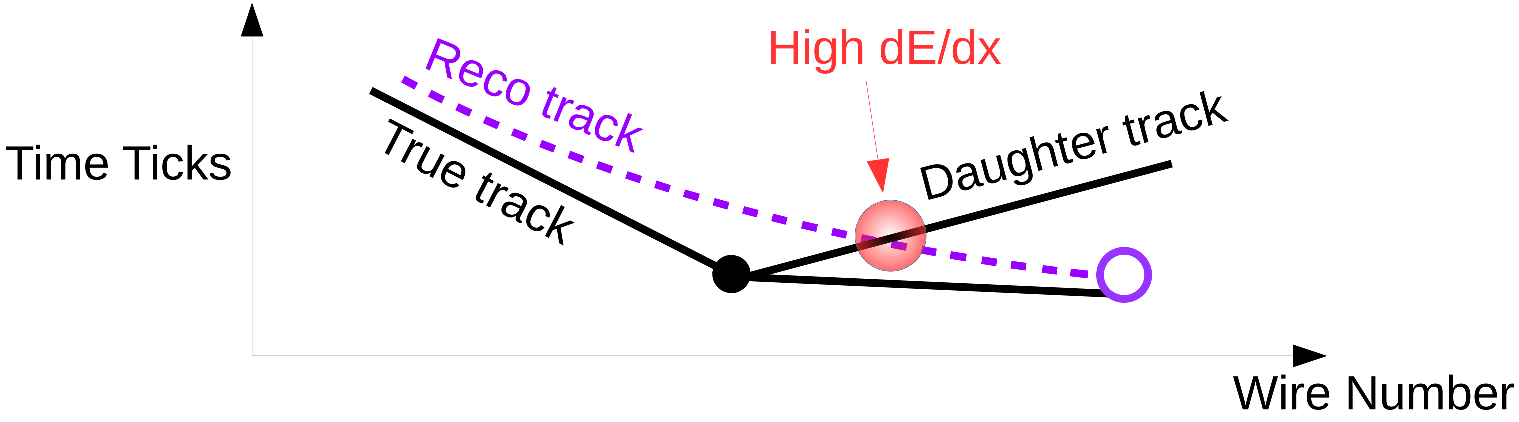
*Color code in the plots: Fraction of remaining KE before interaction vertex

dE/dx Contamination

1 Overlapping tracks*

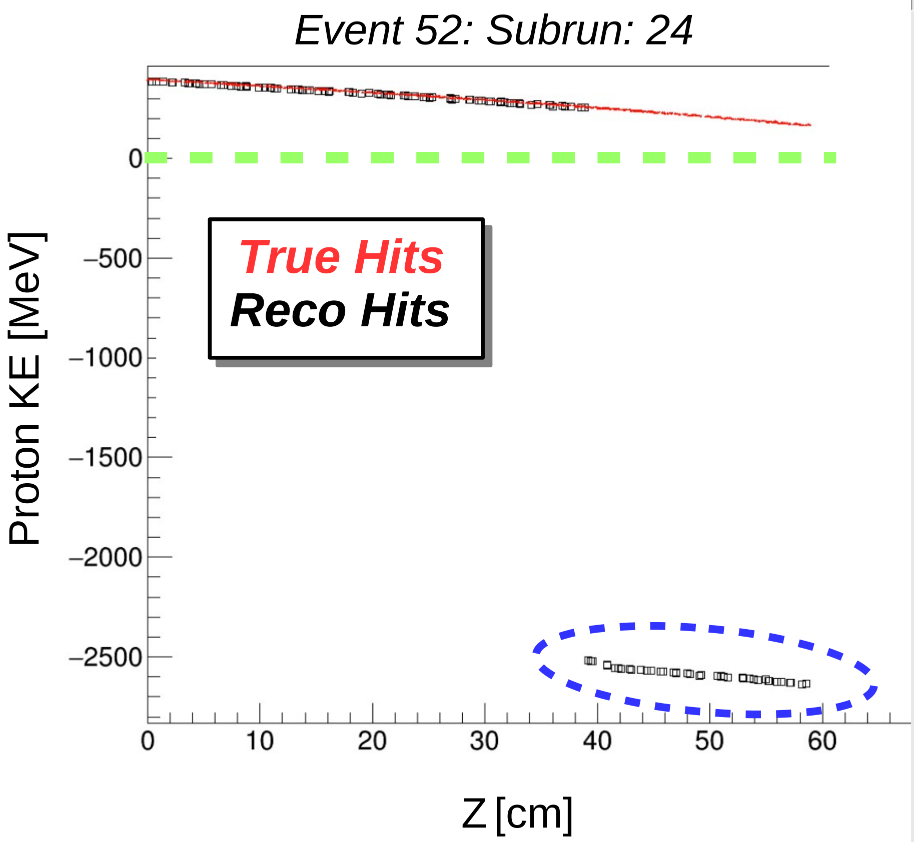


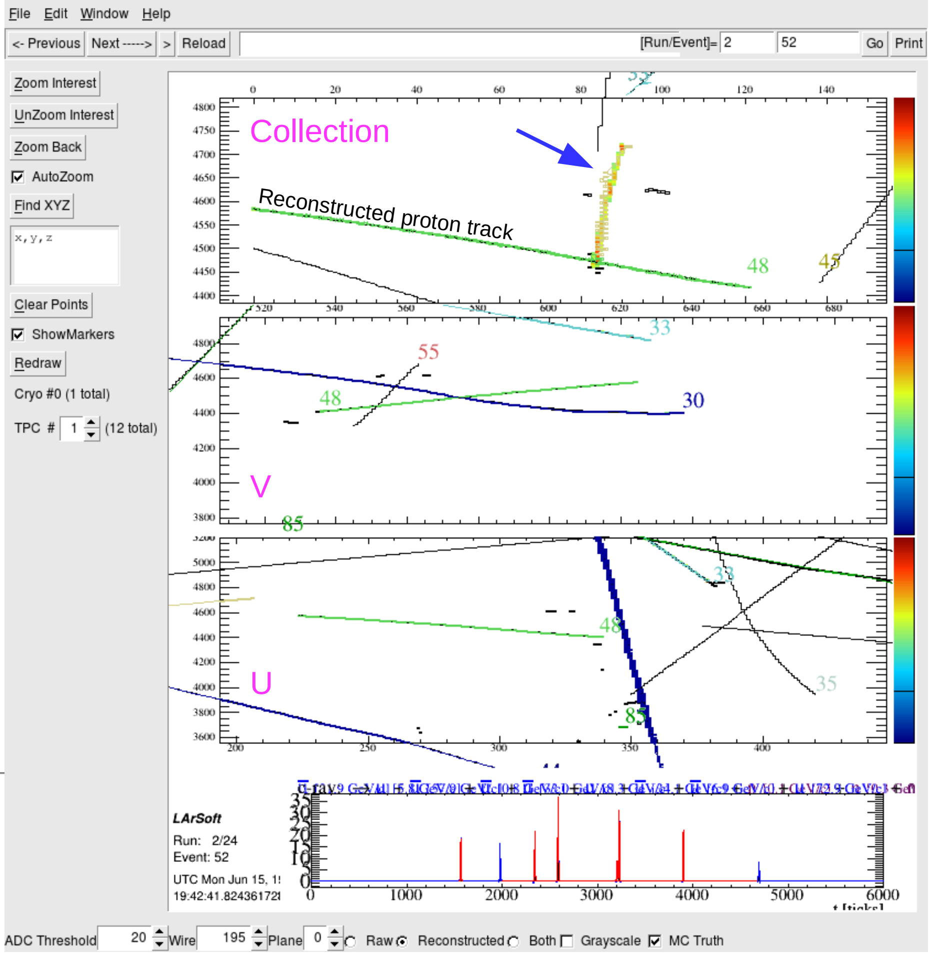
2 Daughter particles



*These issues were addressed in the pion analysis. See Ajib's talk in: https://indico.fnal.gov/event/20451/contribution/1/material/slides/0.pdf

$KE_{Reco} \neq KE_{True}$: Overlapping Tracks


Event 52: Subrun: 24

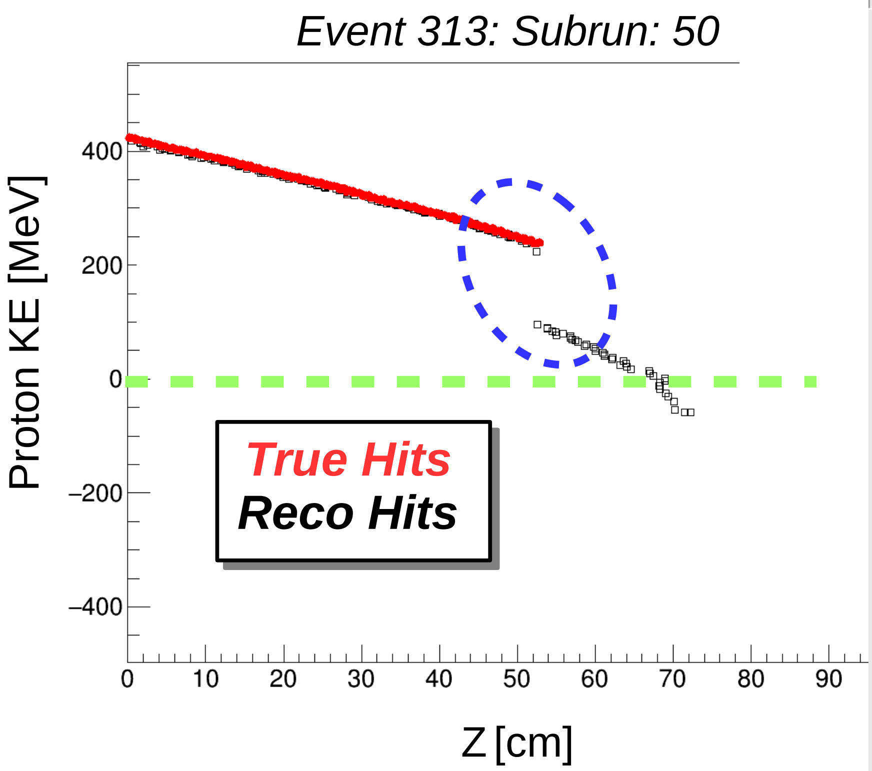

[Run/Event]= 2 52

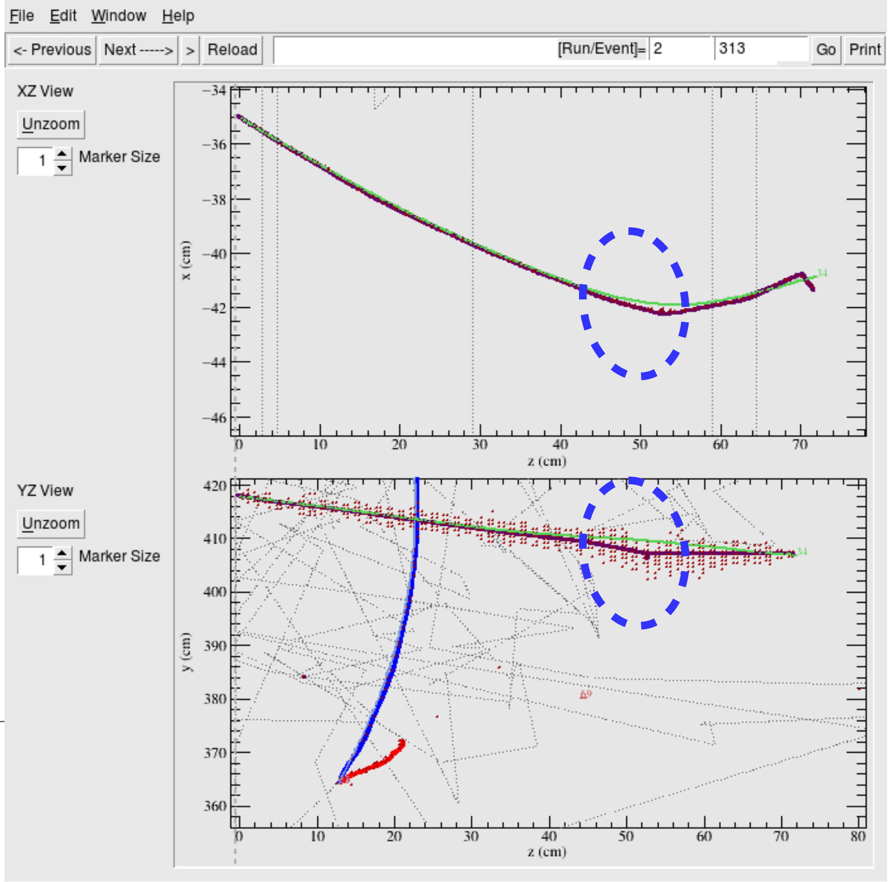
Run: 2/24
Event: 52
UTC Mon Jun 15, 1!
19:42:41.82436172

ADC Threshold 20
Wire 195
Plane 0
○ Raw ● Reconstructed ○ Both ☐ Grayscale ☑ MC Truth

☑ AutoZoom
☑ ShowMarkers
Cryo #0 (1 total)
TPC # 1 (12 total)

$KE_{Reco} \neq KE_{True}$: Daughter Particle



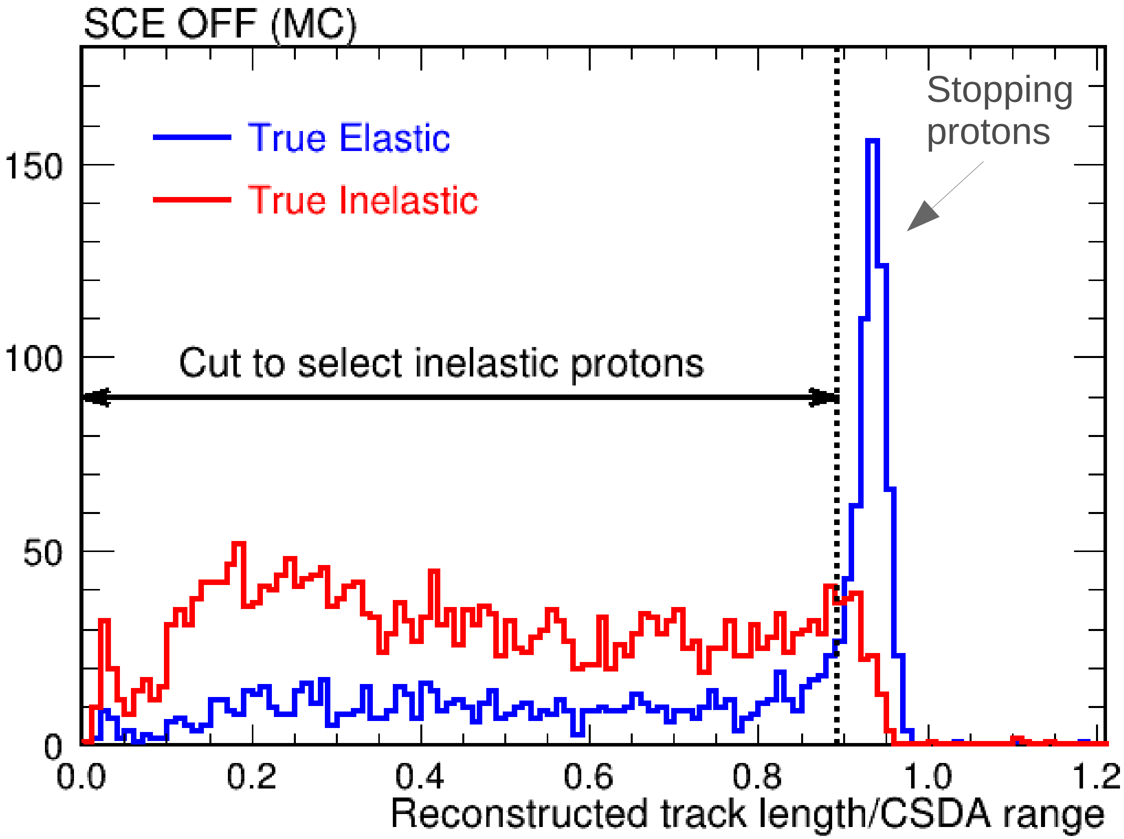


[Run/Event]= 2 313

Dark red: True proton track

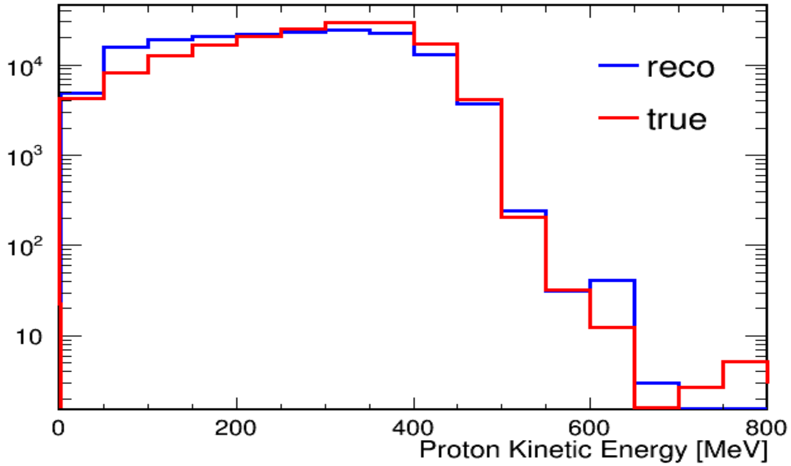
Inelastic Scattering

- Data sample (MC SCE OFF): *PDSPProd2_MC_1GeV_reco_sce_off*
- Remove over overlapping tracks & tracks with high dE/dx hits (> 30 MeV/cm)
- Event selection cuts of inelastic XS
  - Assume Pandora track end has interaction
  - Track length cut (<0.9 track length/CSDA)

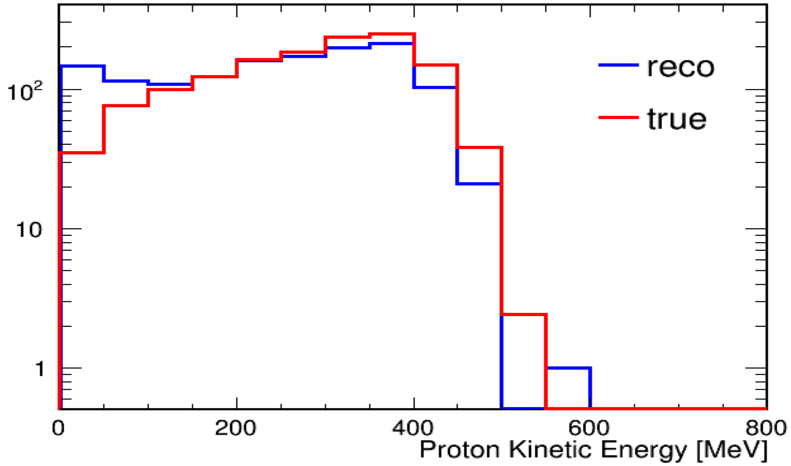


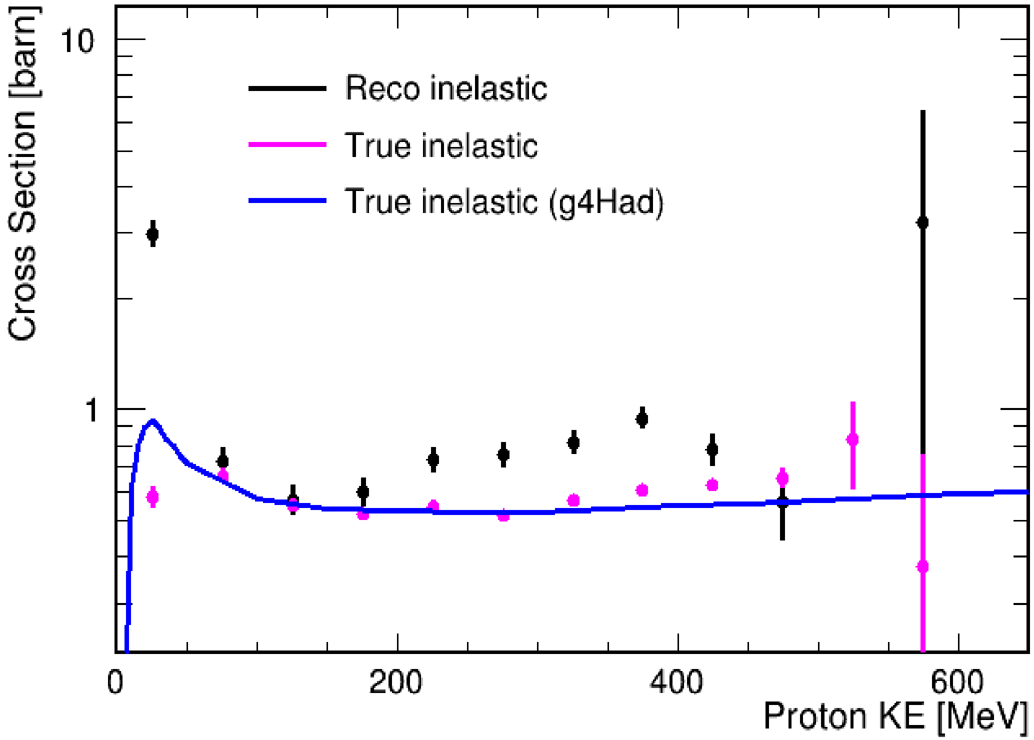
Reco. Inelastic XS (MC SCE OFF)

Incident KE



Inelastic KE





- Reco inelastic XS higher than the true one
  → Need to improve:
  (1) Vertex identification
  (2) Background from elastic scattering

Summary & Outlook

- MC-based study on proton-argon cross section
- Applied thin slice method to Monte Carlo simulation
- Pandora reconstruction performance for 1 GeV/c protons
  - Good elastic: Θ>40°
  - Good inelastic: 67% & good elastic: 14%
- Applied convolution neural network to identify interaction vertex
  -Improvement on elastic & inelastic scattering
  → Good inelastic: 75% & good elastic: 31%
- Issues of reconstructed proton kinetic energy
  - Vertex identification
  - Overlapping tracks/daughter particles
- First result of reconstructed inelastic XS (MC, SCE OFF)

<u>Next</u>

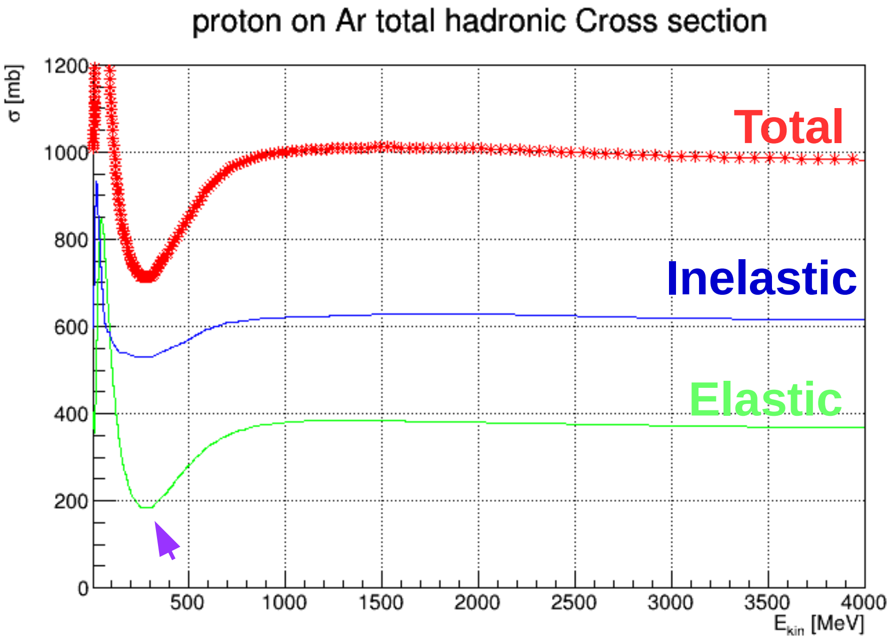
- Improve reco inelastic XS
- Improve vertex recognition using CNN

Backup

Literature Survey on Proton XS

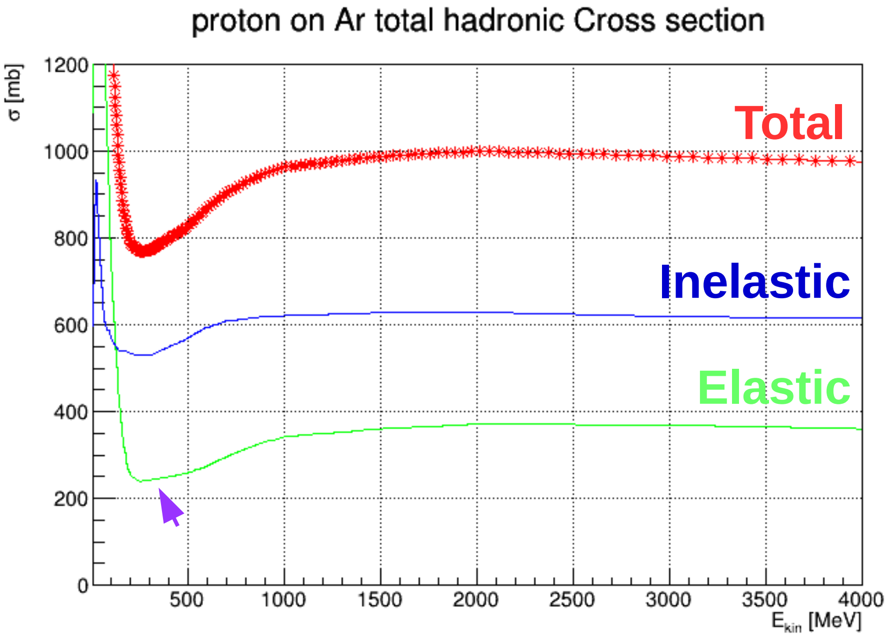
#	Title of Paper	Author(s)	Journal
1	Measurements of the proton total reaction cross section for light nuclei between 20 and 48 MeV	McGill, W.F. et al.	Phys.Rev. C10 (1974), p2237-2246
2	Proton Total Reaction Cross Sections in the 10-20-MeV Range: Calcium-40 and Carbon-12	J.F. Dicello, G. Igo	Phys.Rev.C2 (1970) , p488-499
3	Reaction cross sections for protons on C-12, Ca-40, Zr-90 and Pb-208 at energies between 80-MeV and 180-MeV	A. Auce, A. Ingemarsson et al.	Phys.Rev.C71 (2005) , p: 064606
4	Reaction cross sections for protons in the energy range 220-570 MeV	P.U.Renberg, D.F.Measday et al.	Nuclear Physics Al83 (1972) 81-104
5	Proton-nucleus total reaction cross sections and total cross sections up to 1 GeV	R. F. Carlson	Atomic data and nuclear data tables 63,93 – 116 (1996)
6	Proton-argon elastic scattering at 9.8MeV	T. HonJeong, L. Johnston et al.	Nuclear and Instruments and methods volume 28, Aug. 1964, 325-329
7	Total Reaction Cross-Section Measurements With 60 MeV Protons	J. J. H Menet, E. E. Gross et al.	Phys. Rev. Lett. 22, 1128 – Published 26 May 1969
8	Cross sections for reactions with 593 and 540 MeV protons in aluminium, arsenic, bromine, rubidium and yttrium	A. Grütter	The International Journal of Applied Radiation and Isotopes, volume 33, Issue 9, September 1982, 725-732
9	Reactions of Protons with Ni58 and Ni60	Sheldon Kaufman	Phys. Rev. 117, 1532 – Published 15 March 1960
10	Reaction Cross Sections for 30- to 60-MeV Protons on Various Elements: Comparison of Theoretical Results with Experiment	H. W. Bertini	Phys. Rev. C 5, 2118 – Published 1 June 1972
11	Proton-nucleus total crosssections in the intermediate energy range$^{*(100\text{-}2200\ \text{MeV})}$	L. Ray	Physical Review C, 1979 - APS
12	Nuclear reactions of tantalum with 5.7-Gev protons	J. R. Grover	Physical Review, 1962 - APS
13	A study of proton total reaction cross sections for several medium-mass nuclei between 20 and 48 MeV	R. H. McCamis, et al	Canadian Journal of Physics, 1986, Vol. 64, No. 6 : pp. 685-691
14	A Direct Measurement of the Proton Total Reaction Cross Section for Copper at 9.3 Mev	G. W. Greenlees and O. N. Jarvis	Proceedings of the Physical Society, 1961
15	Energy dependence of proton-nucleus reaction cross sections	A. Ingemarsson and M. Lantz	PHYSICAL REVIEW C 72, 064615 (2005)
16	Total cross section measurements with π^- , Σ^- and protons on nuclei and nucleons around 600 GeV/c	SELEX Collaboration	Nuclear Physics B Volume 579, Issues 1–2, 17 July 2000, Pages 277-312
17	Measuring system of proton total reaction cross-sections at tandem energy region	Nokumura, et al	Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

XS: Geant4 Versions



Version 10.4

(Figure credit: Hans Wenzel)



Version 10.5
(latest version*)

- Geant4 version matters
- Discrepancy in the low energy region
- Provide a validation of Geant4 models using our data!

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*Released on Dec/07/2018 (v10.4: Dec/08/2017; v10.3: Dec/09/2016)

Geant4 10.4 & 10.5: Model Comparison

10.5	10.4
Process: ***hadElastic*** Model: hElasticCHIPS: 0 eV - 100 TeV Cr_sctns: Barashenkov-Glauber: 0 eV - 100 TeV	Process: ***hadElastic*** Model: hElasticCHIPS: 0 eV - 100 TeV Cr_sctns: ChipsProtonElasticXS: 0 eV - 100 TeV Cr_sctns: GheishaElastic: 0 eV - 100 TeV
Process: ***protonInelastic*** Model: FTFP: 3 GeV - 100 TeV Model: BertiniCascade: 0 eV - 12 GeV Cr_sctns: Barashenkov-Glauber: 0 eV - 100 TeV	Process: ***protonInelastic*** Model: FTFP: 3 GeV - 100 TeV Model: BertiniCascade: 0 eV - 12 GeV Cr_sctns: Barashenkov-Glauber: 0 eV - 100 TeV Cr_sctns: GheishaInelastic: 0 eV - 100 TeV

Credit: Hans Wenzel

- According to the release notes, there were a lot of changes to the cross sections between 10.4 and 10.5. (see “Hadronic Physics” & “Physics Lists” in: http://geant4-data.web.cern.ch/geant4data/ReleaseNotes/ReleaseNotes4.10.5.html)

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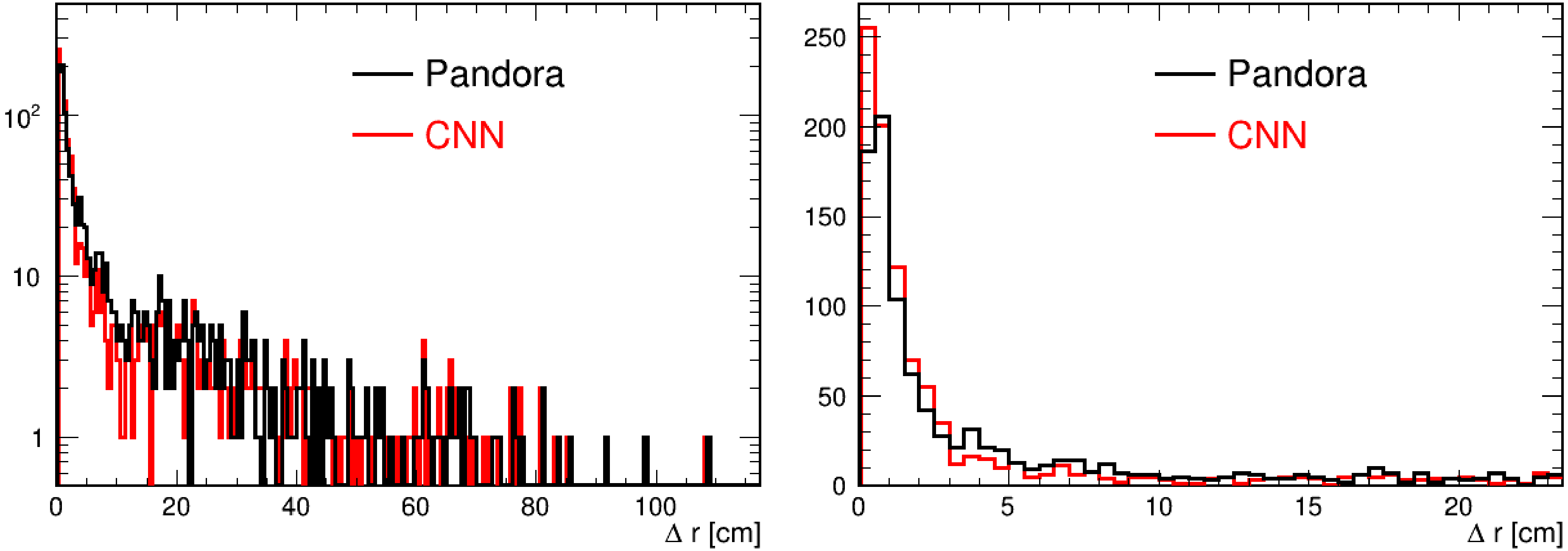
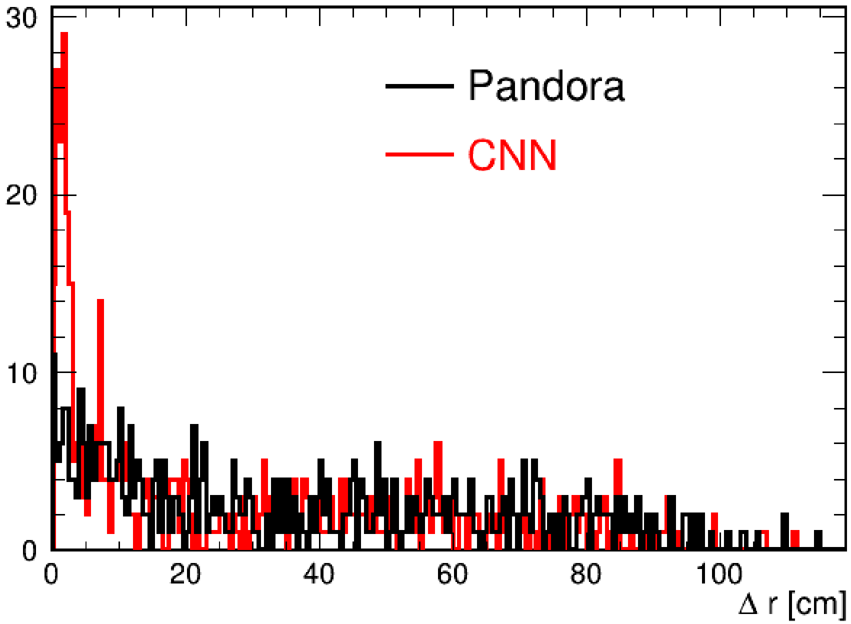
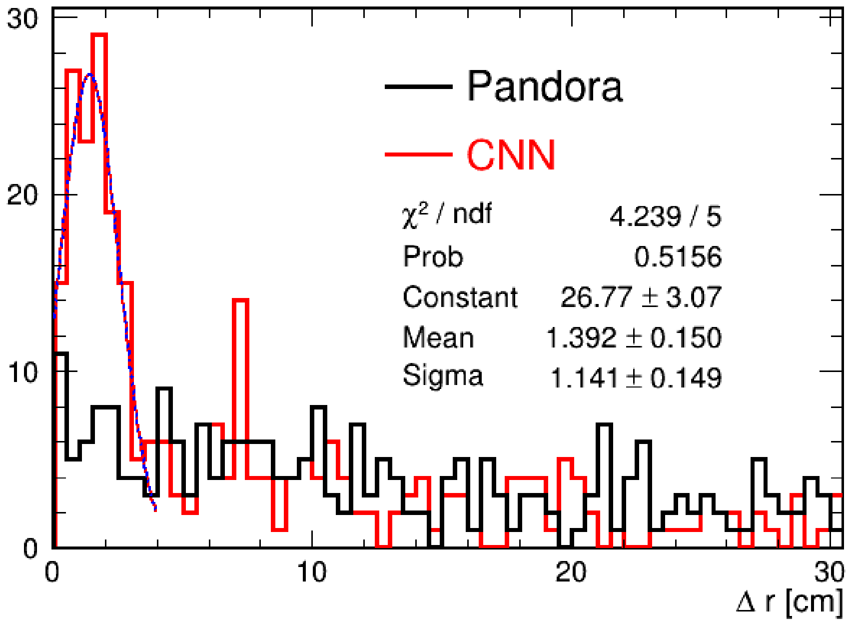
*Note. Unlike the EM physics in Geant4, 1 process has 1 model and 1 cross section, the Hadronicphysics in Geant4 has many possible models, cross sections (Cr_sctns).

Δr Distributions-Inelastic Scattering



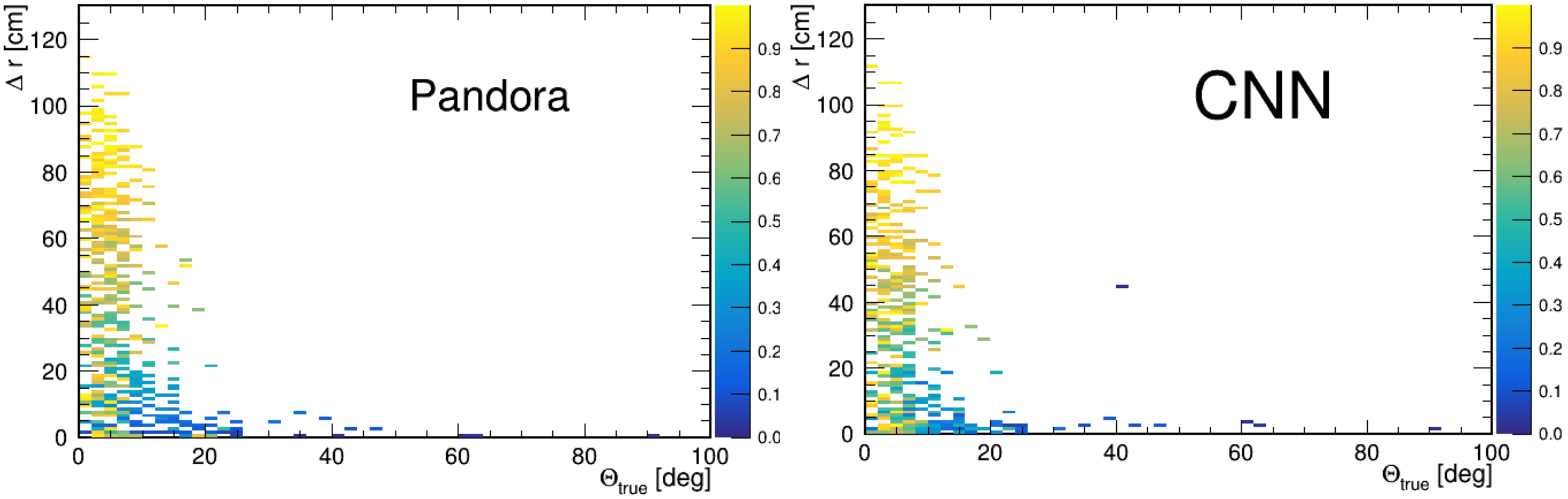
Δr Distributions – Elastic Scattering





- CNN peaking at ~1.4 cm in Δr

Δr v.s. Θ [Elastic Scattering]

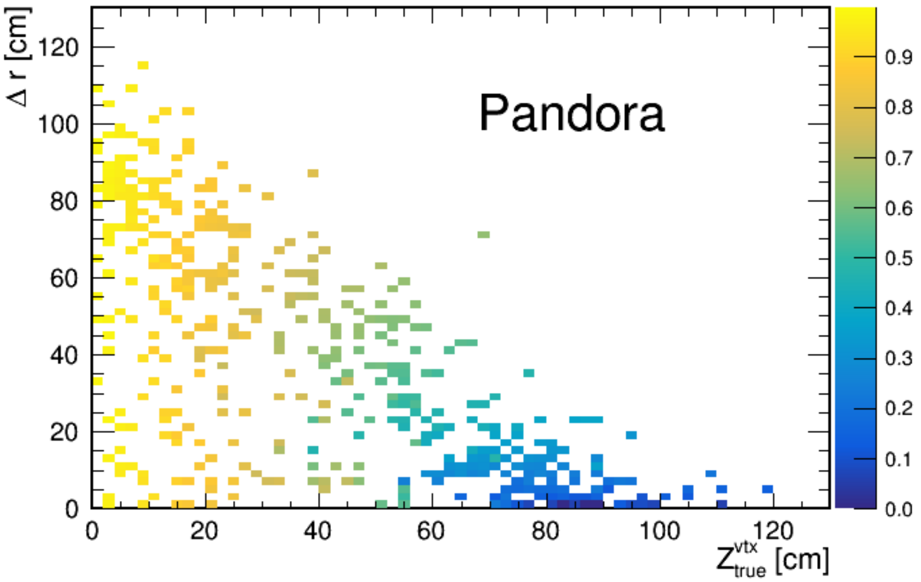


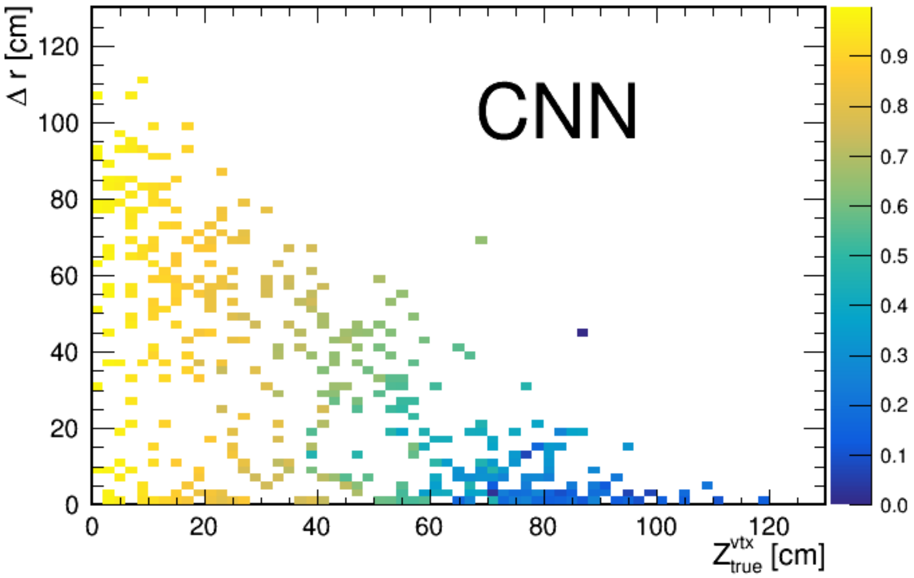
- Color code in the plots: Fraction of remaining KE before interaction vertex

$$f^{RE} = 1 - \frac{\sum_{j=1}^{vertex} \Delta E_j}{KE^{ff}}$$

ΔE_j : Energy deposition of each hit

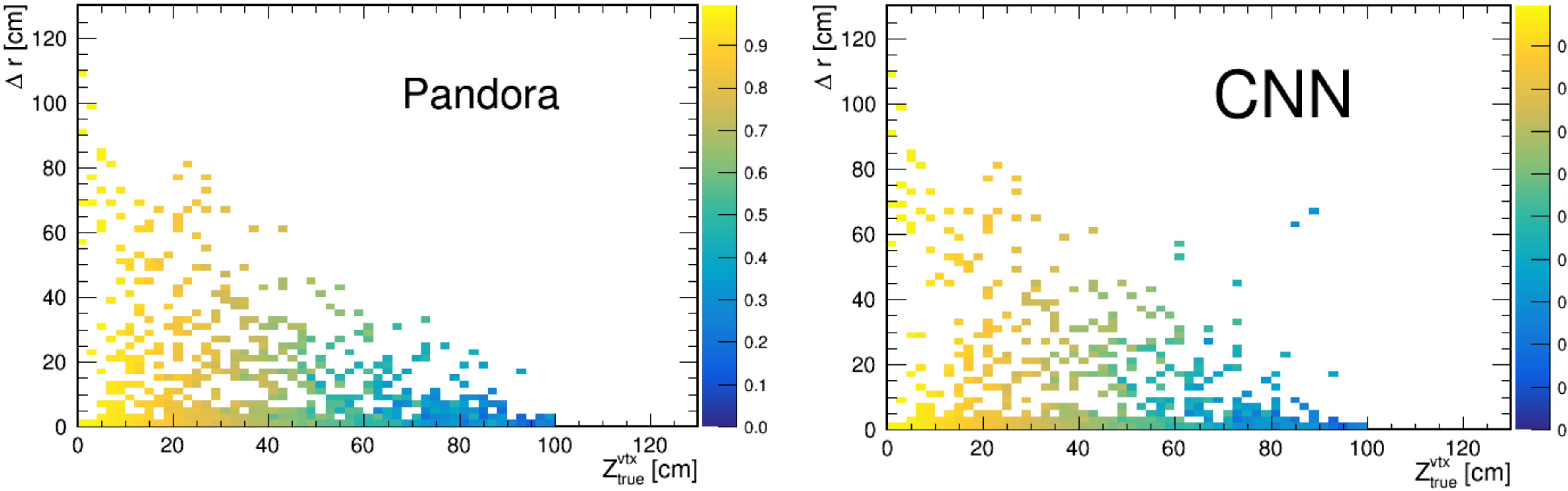
Position Dependency [Elastic]





- If the interaction vertex happens in the beginning of track (~< 20 cm)
  → Not easy to identify

Position Dependency [Inelastic]



- More uniform in Δr v.s. Z^{vtx}_{true}
- Better vertex identification for both Pandora and CNN