Pion-Nucleus Interactions

Libo Jiang for pion analysis group

Outline

- Introduction to Pion Analysis Group
- Physics Interaction Simulation
- Hadronic Scattering Simulation in GEANT4
- Opening questions of nuclear effects and Previous experimental results
- Particle Identifications Strategy in protoDUNE
- Data vs MC of selected pion absorption processes
- Research Plan & Summary

Pion Analysis Group

Michigan State University

Jake Calcutt

- Pion Absorption+cex Cross Section

Supervisor: Kendal Mahn

University of Bern / CERN

Francesca Stocker

- Pion Absorption Cross Section

Supervisor: Stefania Bordoni (MSU & CERN)

Virginia Tech Group

Libo Jiang

- Particle identification
- Nuclear Effect

Supervisor: Camillo Mariani (VT)

FNAL:

Tingjun Yang(FNAL)

Physics Process Simulation

- Simulation of neutrino nucleus interaction

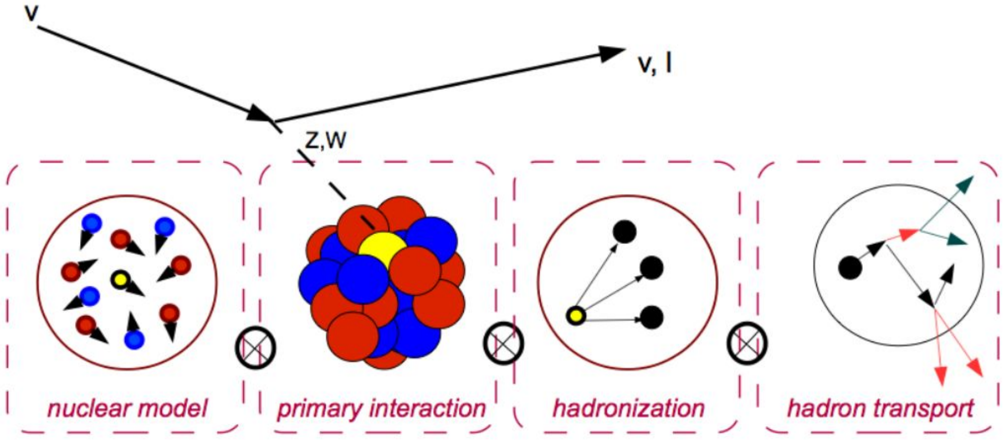


Figure by C. Andreopoulos

- Hadron nucleus scattering is treated in similar way

Physics Process Simulation

Nuclear Model

- Describe the nucleon states in nucleus
  - momentum(Local Fermi Gas Model: the fermi energy is calculated in a local density approximation)
  - Binding/removing energy(Kummer mass formula)
  - Correlation between nucleons
  - Initialization: fixes the nuclear radius and momentum according to the Fermi Gas model and atom number

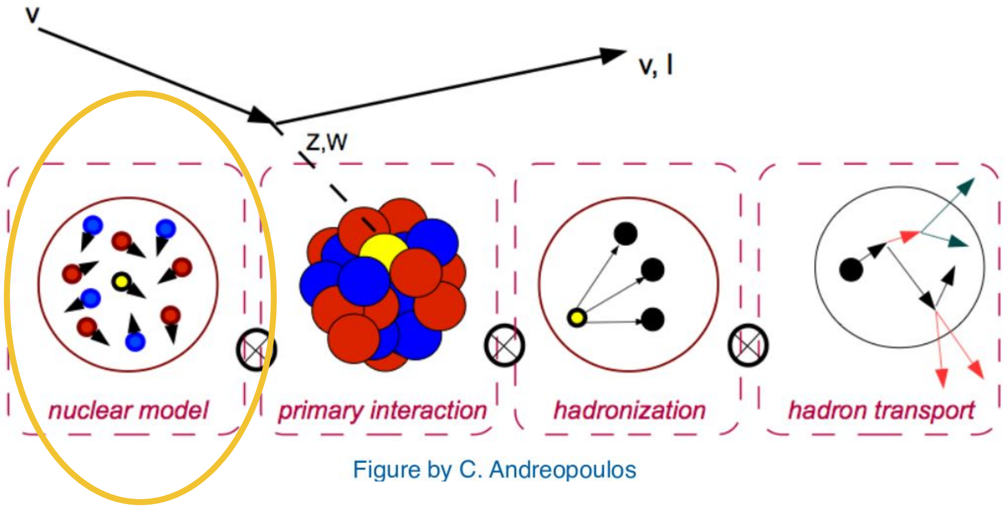


Figure by C. Andreopoulos

Physics Process Simulation

Hadron Transportation

- (Classic) Intra - Nuclear Cascade(INC) Model
    - The spatial point is selected uniformly over the projected area of the nucleus
    - Free particle-particle cross sections and region dependent nucleon densities are used to select the path length for the projectile particle

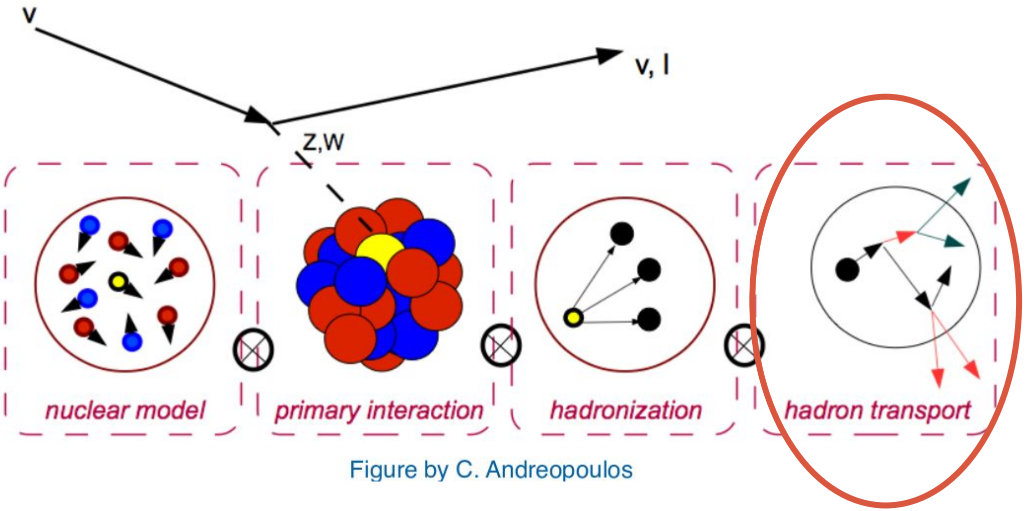


Figure by C. Andreopoulos

- Bertini nuclear model
    - Relativistic kinematics is applied through out the cascade and the cascade is stopped when all the particles which can escape the nucleus have done so
    - Pauli exclusion principle is applied

Ref: A.S. Iljinov, M.V. KazarnovskyandE.Ya. Paryev,Intermediate-energyNuclearPhysics,CRCPress, BocaRaton,Florida(USA).(1994).

Nuclear Model in GEANT4

- Cross Section - Interaction Probability
  - No cross section model totally independent from experiment
  - Some parameters come from tuning against experimental data
  - Geant 4 sample the angular distribution of final state particles in pion absorption according to experimental data
  - Need to be tested by comparing with experimental result

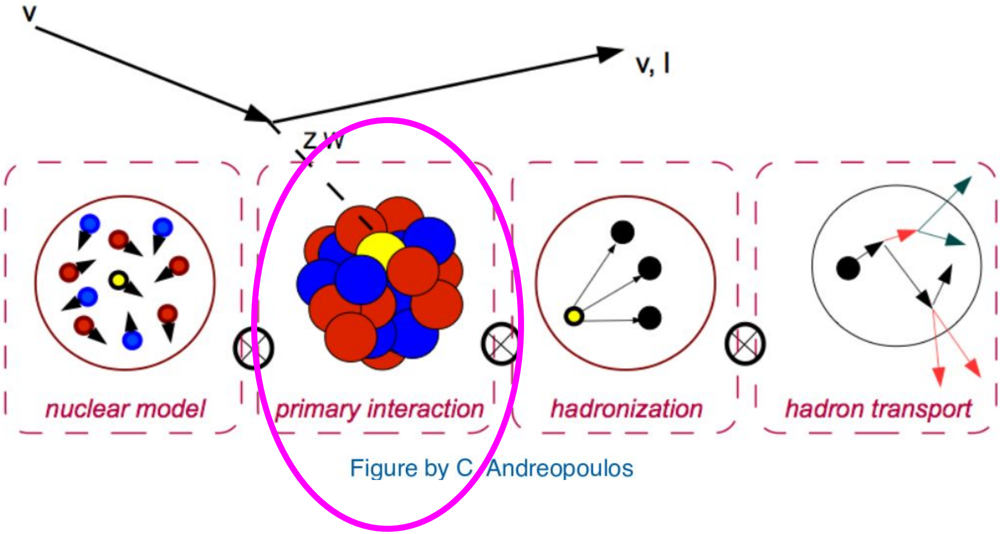
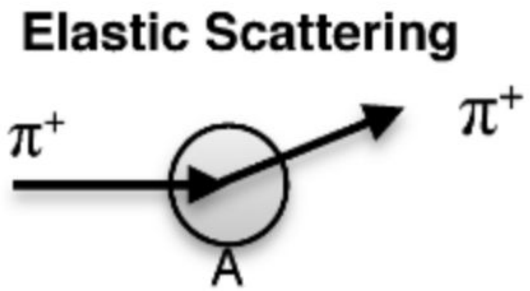


Figure by C. Andreopoulos

Pion Nucleus Interactions - Categories

- Total - calculated from attenuation of initial beam
- Elastic Scattering
  - Nucleus stays intact
- Inelastic Scattering
  - Nucleus in excited state /broken
- Charge Exchange
  - Single Charge Exchange (π^+ -> π^0)
  - Double Charge Exchange (π^+->π^-) - Need to distinguish π^+ and π^- - difficult for LArTPC
- Absorption
  - No pions in the final state - need to distinguish pions from nucleons
  - Subtraction of other processes



Dominant pion-nucleus interactions in sub-GeV region (Ref: arxiv 1611.05612)

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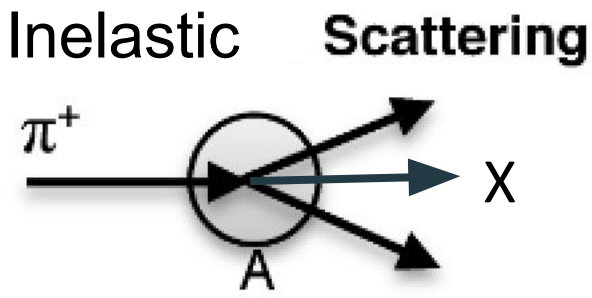

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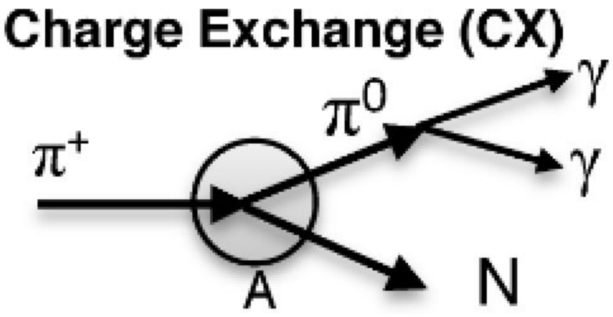

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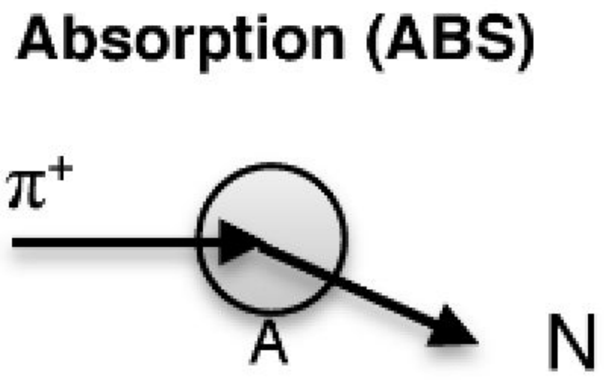


Dominant pion-nucleus interactions in sub-GeV region (Ref: arxiv 1611.05612)

Pion Absorption Reaction

- Pion Absorption:
  - Absorption on a single nucleon is forbidden due to momentum and energy conservation
  - Two body process - give insight into two body (nucleon-nucleon) correlations
    - In Geant 4 only two nucleon process simulated (details in next page)
  - Multi-nucleon absorption is still an open question
  - Mechanism is not well understood; No satisfactory theory describing pion absorption, especially for the heavier nuclei
- <u>Cross Section Measurement</u>
  - Select non-pion/only nucleon events
  - Subtract xsec of other processes from total eve $\sigma_{total} = \sigma_{abs} + \sigma_{cex} + \sigma_{inel} + \sigma_{elas}$

Pion Absorption Reaction in GEANT4

The primary process for pion absorption on heavy nuclei (A>0) is thought to be the absorption on two nucleons (2NA, I=0 pn pair)

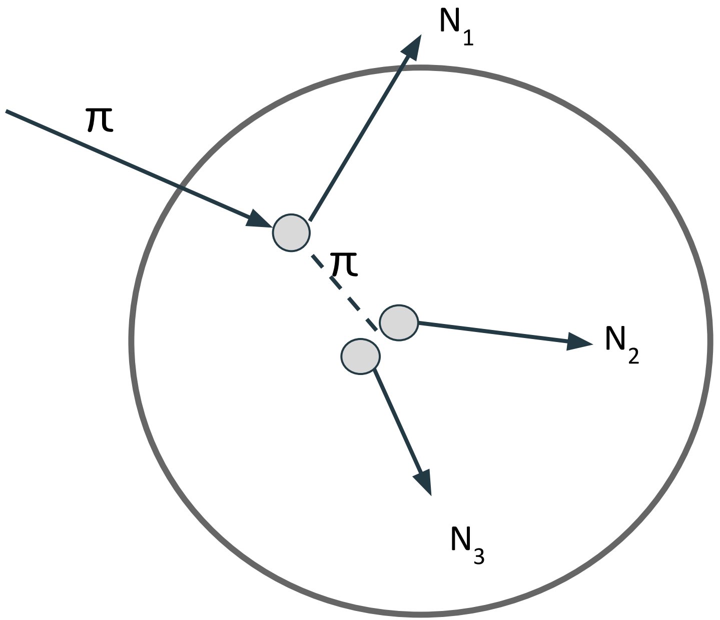
- The quasi-free absorption on two nucleons which are emitted back to back
    - Residual nucleus can be seen as spectator
- **The Pion Absorption channels are (in GEANT4)**
    - π^+nn->pn, π^+nn->pn
    - π^0nn->nn, π^0pn->pn, π^0pp->pp
    - π^-pn->nn, π^-pp->pn

Opening questions of nuclear effects in pion absorption and Previous experimental result

Pion Absorption: ISI & FSI

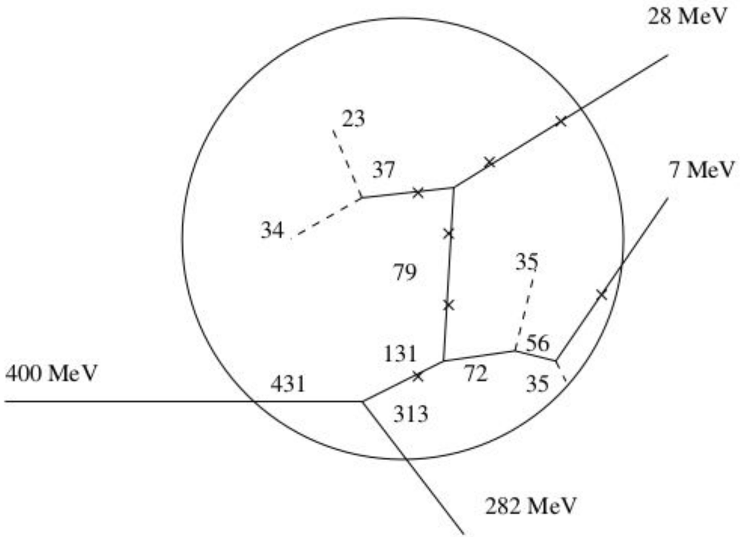
- Initial State Interaction (ISI): the pion knocks out a nucleon by quasi-elastic scattering before absorbing on two other nucleons - **WEAK**

- Final State Interaction (FSI): 2 N absorption followed by one of the two nucleons knocking out a third one in a final state interaction



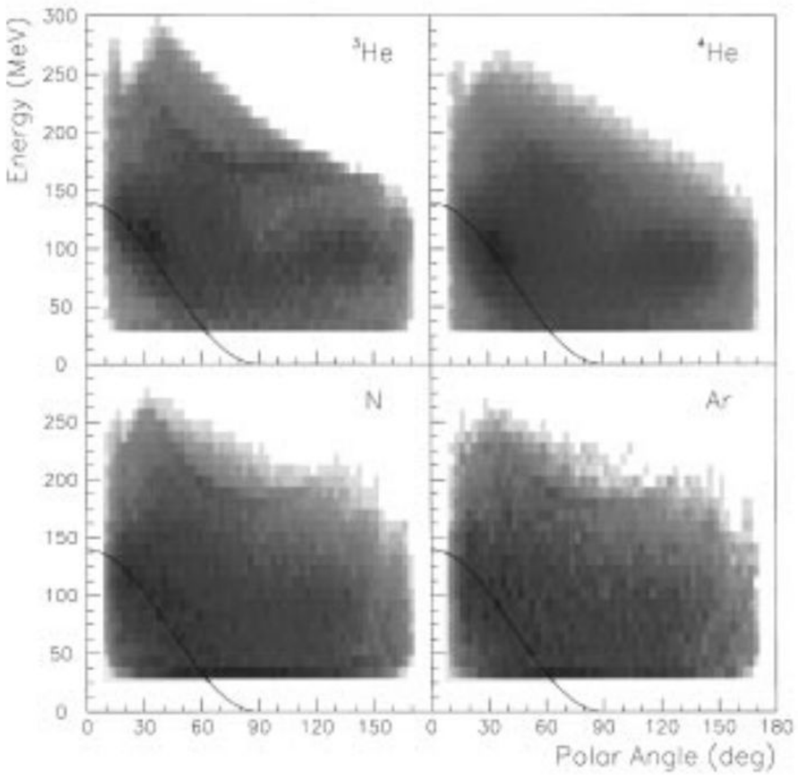
Pion Absorption: ISI & FSI

- Final State Interaction (FSI): 2 N absorption followed by more nucleons knocking out of the nucleus
  - Classic INC, bertini INC
  - Data-driven FSI model used in GENIE
- ISI: the pion knocks out a nucleon by quasi-elastic scattering before absorbing on two other nucleons - **WEAK**



Schematic presentation of intra-nuclear cascade. A hadron with 400 MeV energy is forming an INC history. Crosses present the Pauli exclusion principle in action (*Ref: A. Heikkinen, N. Stepanov, Bertini intra-nuclear cascade implementation in GEANT4*)

Evidence of ISI from LADS



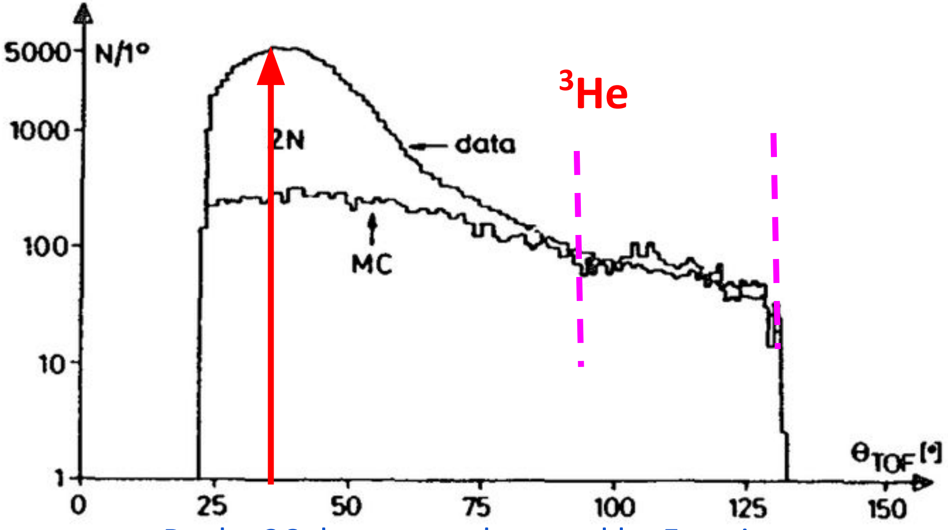
Ref. *Phy.Rev.C, 53, R2591*

- Result from Large Acceptance Detector System (LADS) experiment, **ppp results** of different targets
  - Kinetic energy of proton > 30MeV
  - Unobserved energy < 50 MeV
- The line passing through this region indicates the relationship between energy and angle for free π^+ p scattering
- ISI for Argon is weaker compared to the lighter nuclei - Hard to measure with protoDONE

Evidence of Multiple Nucleon Absorption

- Multi-nucleon Absorption
  - Previous experiments have
    - Shown the 2NA cross-section does not exhaust the total absorption cross sections
    - Reported 3N phase space - like contributions and associated them with 3N absorption
  - First positive indication of a 3N absorption dynamic signal

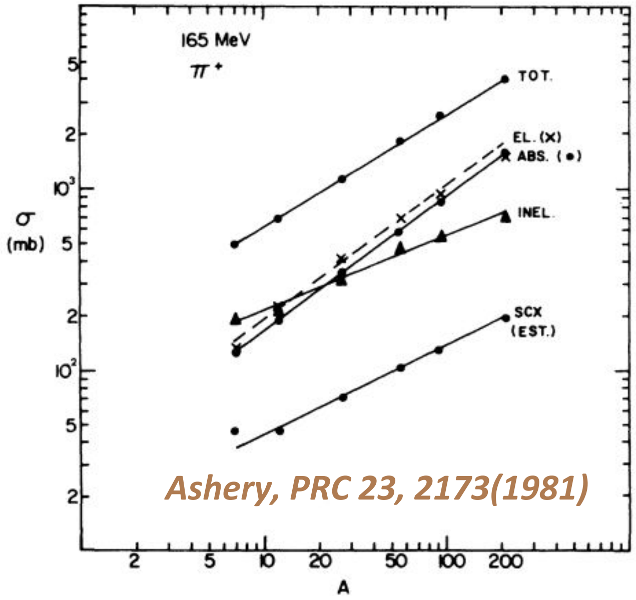
Measurement from the Swiss Institute for Nuclear Research Ring Accelerator



Peak ~36 degree, understood by Fermi Momentum

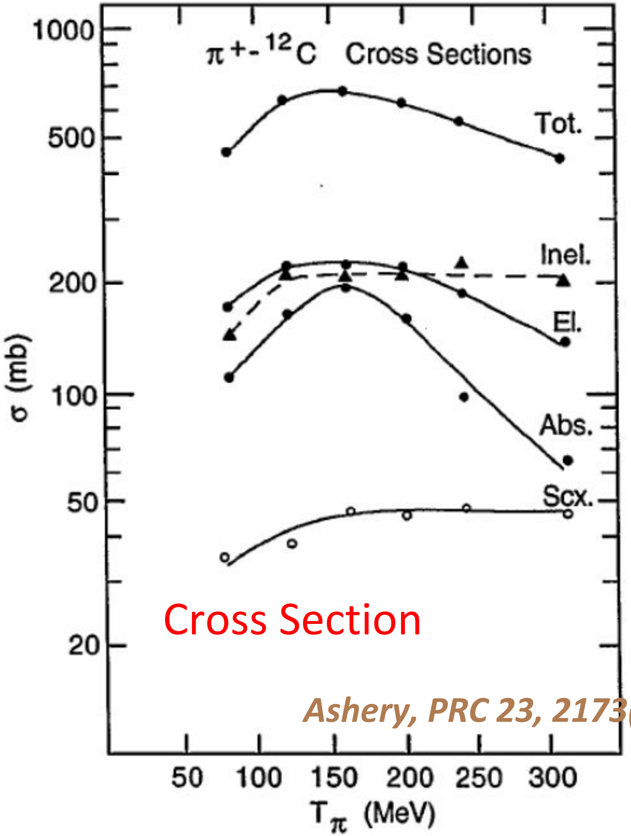
Phys. Rev. L 55, 2782 (1985).

Previous Experimental Result



Ashery, PRC 23, 2173(1981)

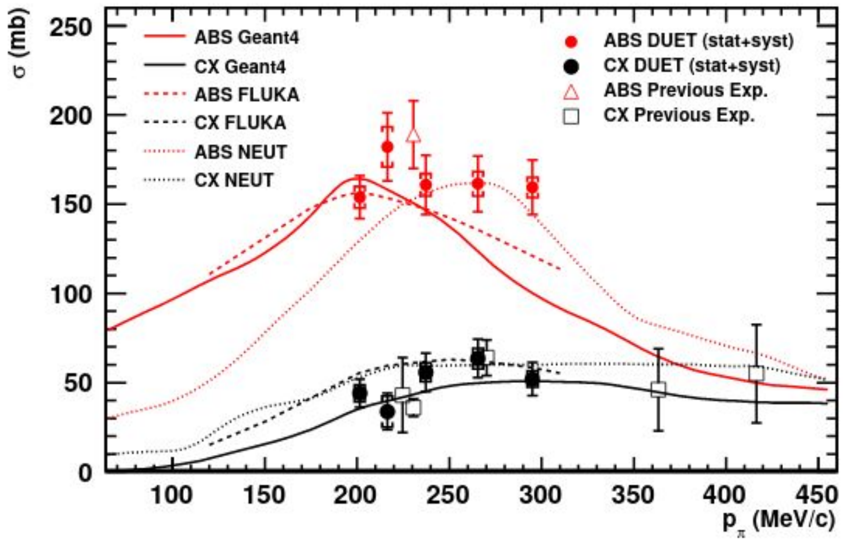
A dependance: xsec scales with power ⅔ for pion absorption



Cross Section

Ashery, PRC 23, 2173(1981)

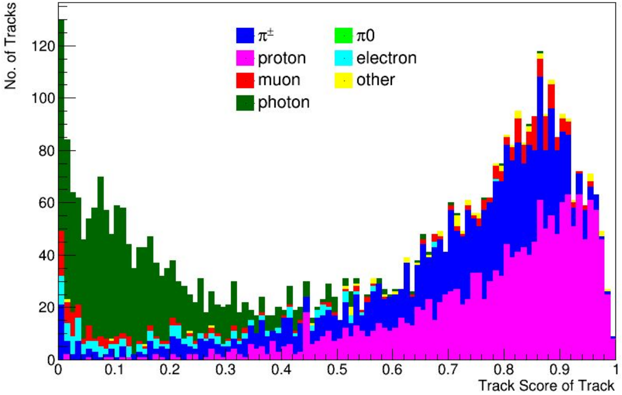
Previous Experimental Result

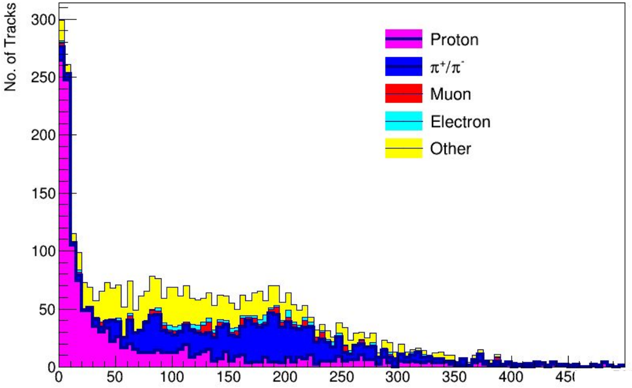


Ref: arXiv: 1611.05612

- Charge Exchange and Absorption process cross sections shown on the left with statistical and systematic error bars
- DUET vs previous experimental result
  - 265 MeV pi+ on oxygen Asheryat.al (*Phys. Rev. C, 30(3):946 (1984)*)
- NEUT v5.3.5 cascade model
- GEANT4 v9.04.04: Bertini cascade model
- FLUKA: cascade model
- **No more pion absorption experimental data above 400 MeV**

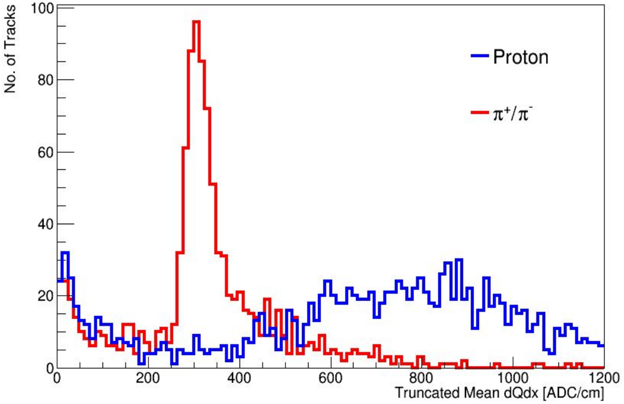
Particle Identification Strategy

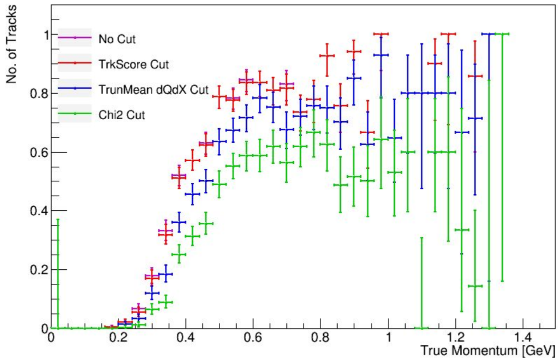


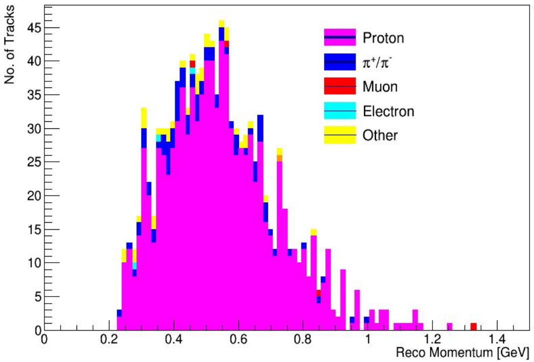


Particle Identification Strategy developed based on

- CNN Track Score
- Chi2/degree of freedom
- Truncated Mean dQdx







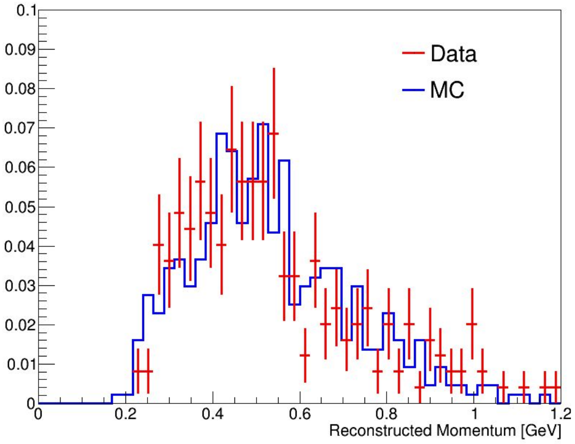
Data-MC Comparison - Area Normalized

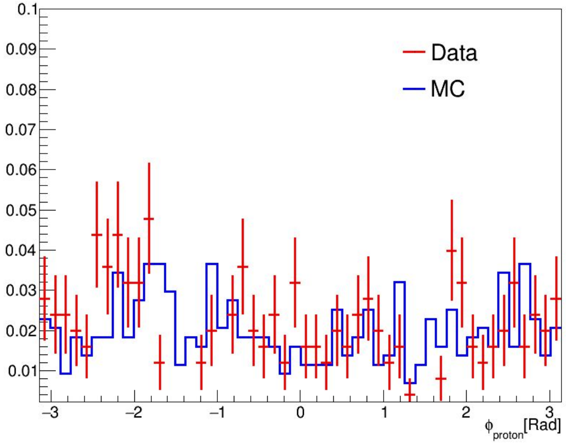
Event Selection (MC)

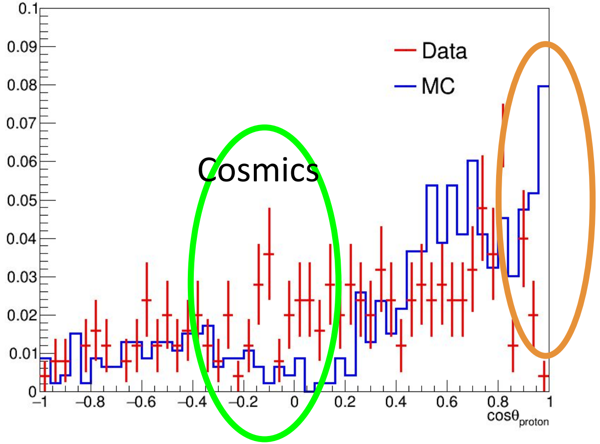
- Beam End to Track Start matching, based on Jake and Owen’s work
- Track Score + Truncated Mean dQdx +Chi2 Cut to select proton candidates

Event Selection (Data)

- Beam End to Track Start matching, based on Jake and Owen’s work
- **Removed tracks go through the TPC**
  - Further removed cosmics







Research Plan with Pion Absorption Processes

- Pion Absorption
  - Complete Event Selection
  - Characterize the kinematic distribution of the protons
  - Calculate xsec based on the event selection
- Pion Nuclear Effect Study through the pion absorption processes
  - Nucleon-Nucleon correlation
  - Neutron Energy
  - Transverse Imbalance
- Look for evidence of Multi-Nucleon processes
  - Not a easy work, but will try it

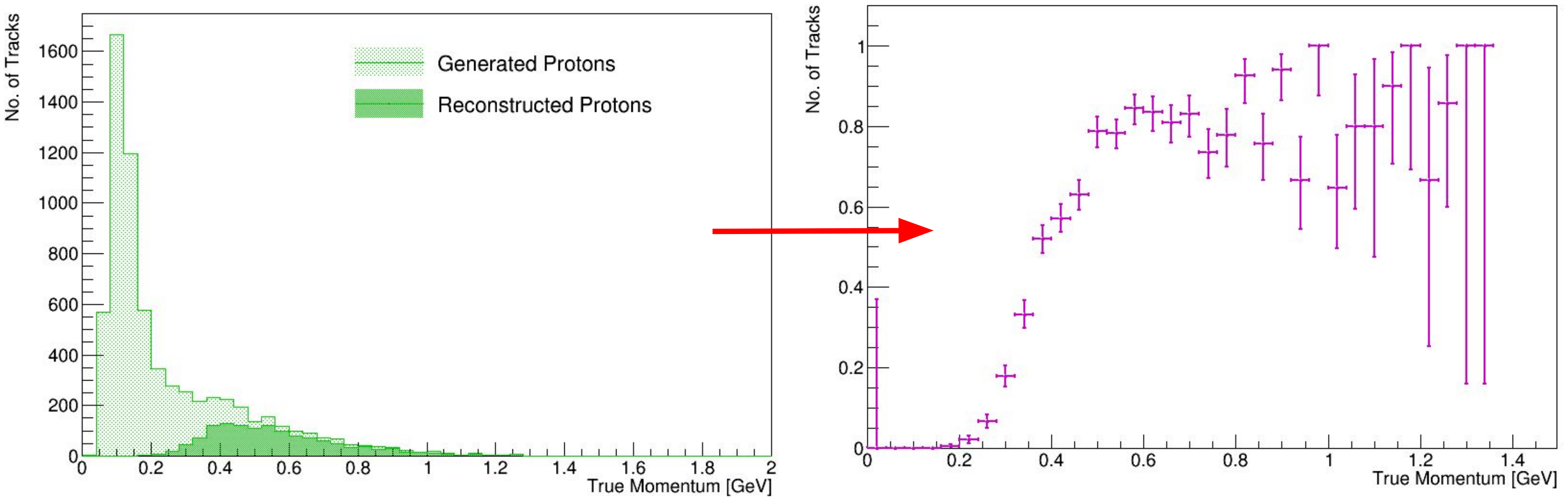
Summary & Conclusion

- Factorization Method is widely used in simulation/event generator
- There are still many opening questions in modeling pion absorption process, no satisfactory models to describe this process
- No pion absorption/charge exchange measurement above 300 MeV
  - Any measurement will be very valuable
- Pion Analysis Group are planning to do pion absorption/charge exchange event selection, cross section measurement and nuclear effect study
- (more details will be shown in Jake and Francesca's talk)

BackUp Slides

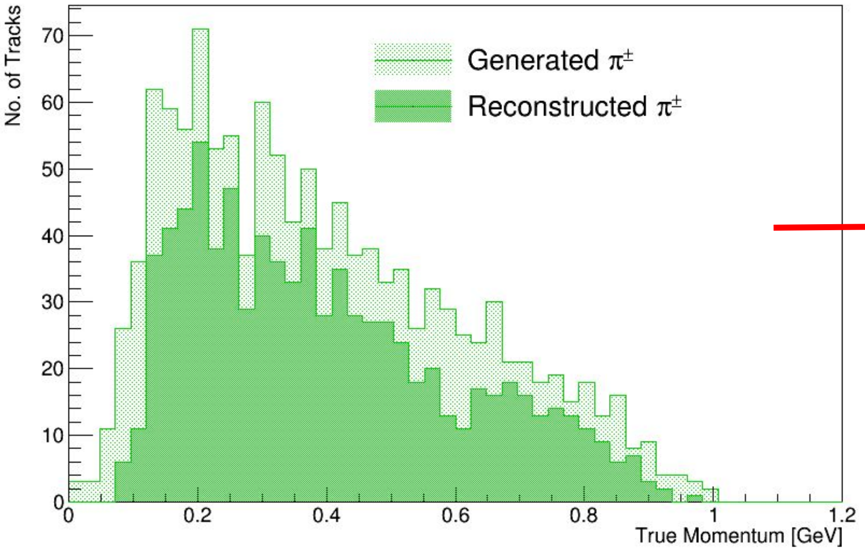
Proton Reconstruction Efficiency

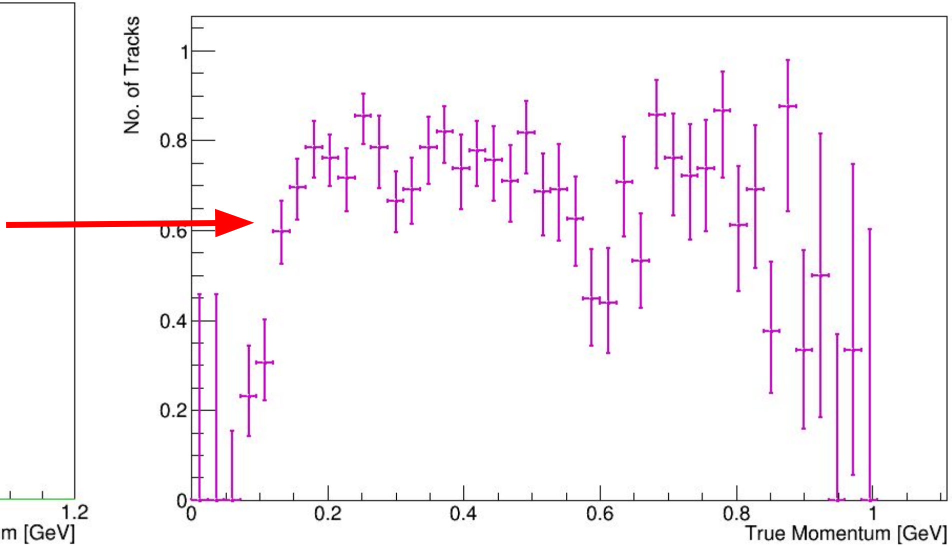
- All the particle identification results come from 1GeV pion MC sample with SCE on
- Left: True Momentum distribution of generated protons vs reconstructed protons
- Right: Reconstruction efficiency of protons (calculated from the true momentum distributions at the left side)



Charged Pion Reconstruction Efficiency

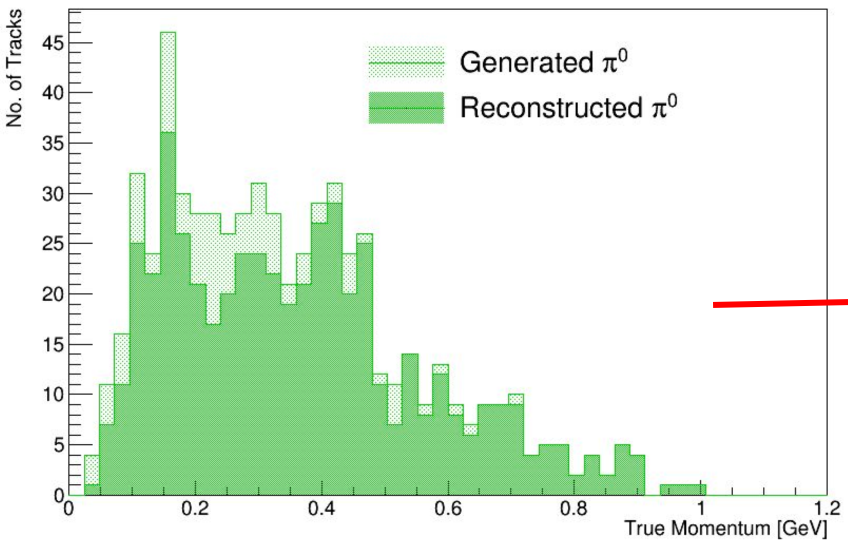
- Fewer low momentum pions produced in the Pion Argon interaction
- Reconstruction efficiency decrease to ~0 with the true momentum < 0.1 GeV

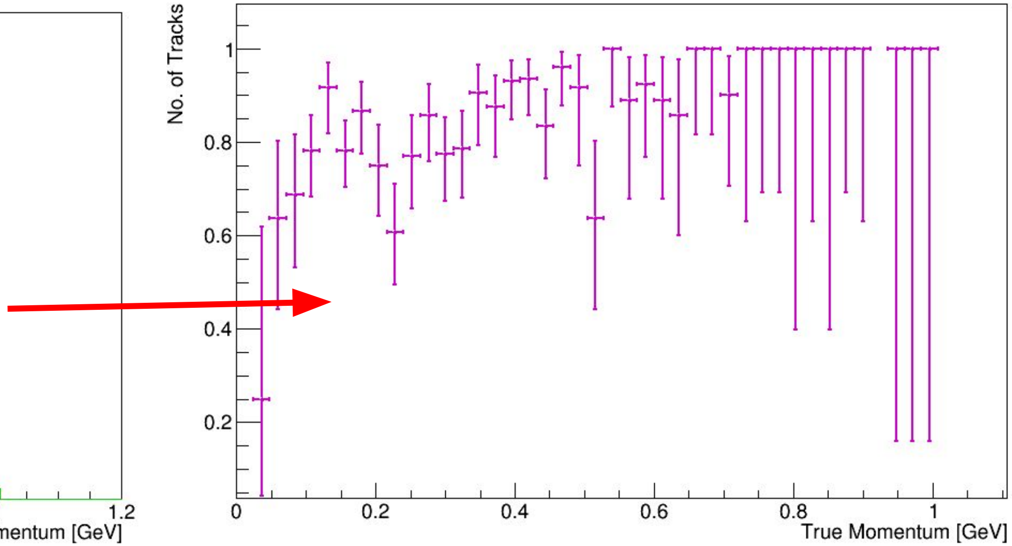




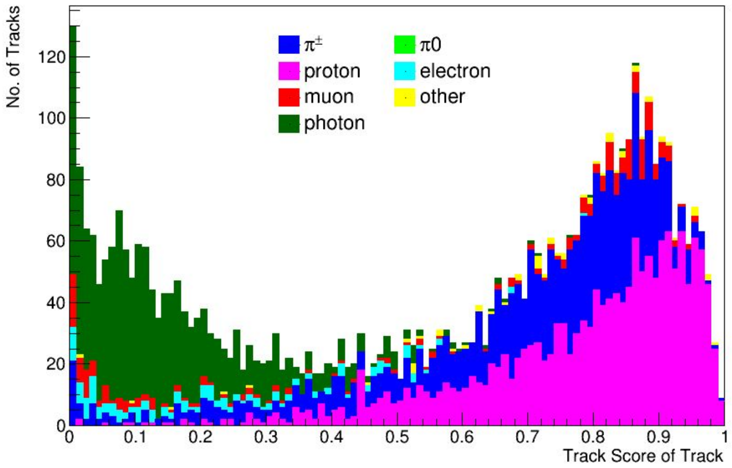
π^0 Reconstruction Efficiency and Identification

- Better neutral pion shower reconstruction efficiency in protoDUNE
- Reconstruction efficiency is low in the low momentum region dune to the low statistics





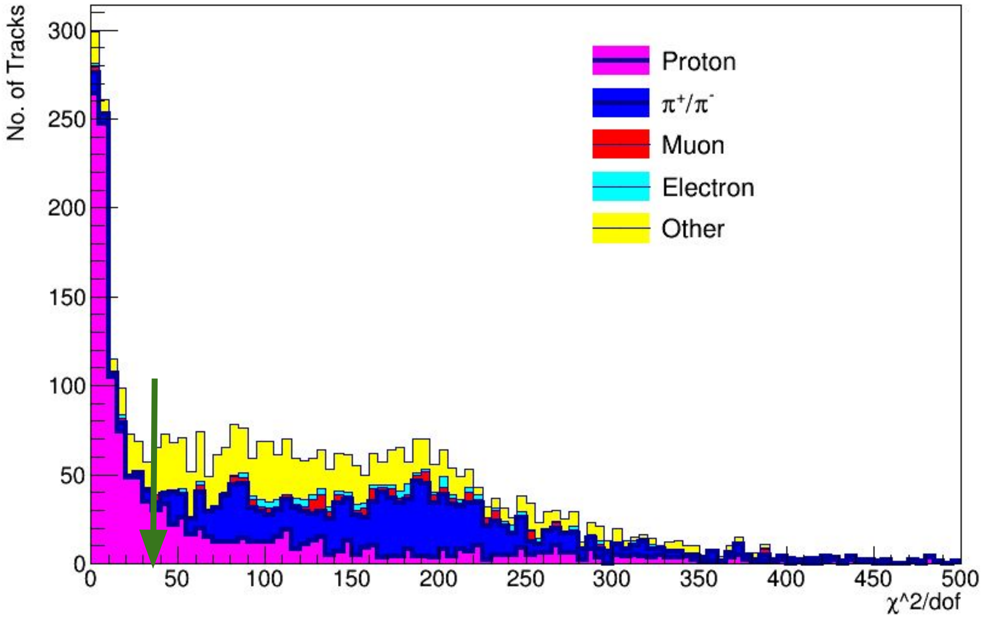
Proton Identification - Track Score



- Good track/shower separation with the CNN track score
- Most of the PF particles with shower less than 0.3 are photons
- Cut value 0.3 was used for the track shower separation

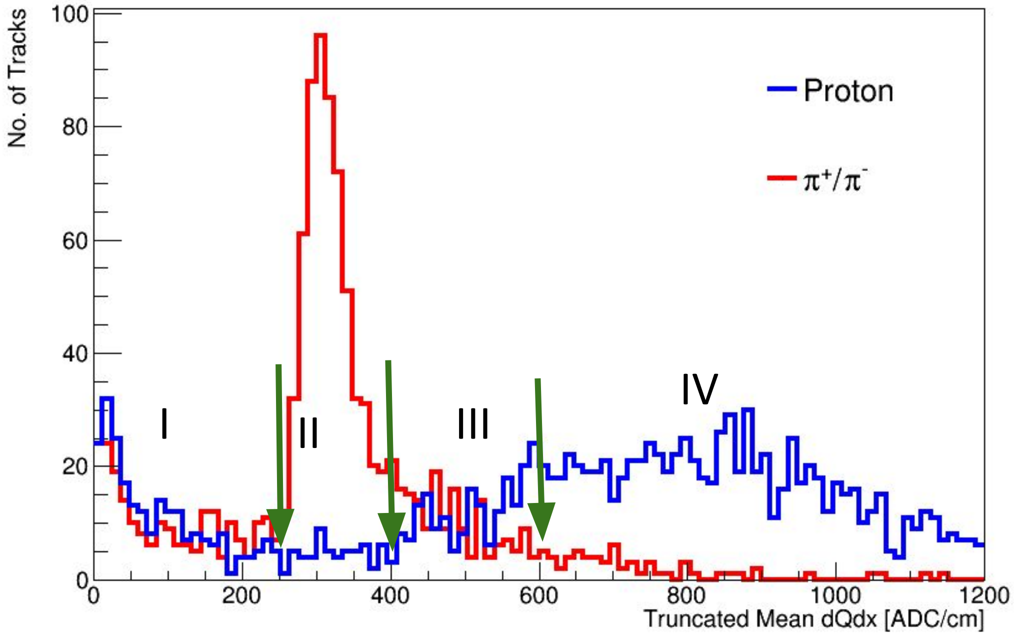
Add a fraction of photons come from pi0 decay of all the photon !!!!

Particle Identification - Chi2



- Chi2/ndof distributions (Left)
  - Ndof: number of hits on collection plane
  - No other cuts performed
- Chi2 with proton hypothesis is was used to selected protons in MicroBooNE
- Cut value ~40 suggested in the pion beam events at 1 GeV

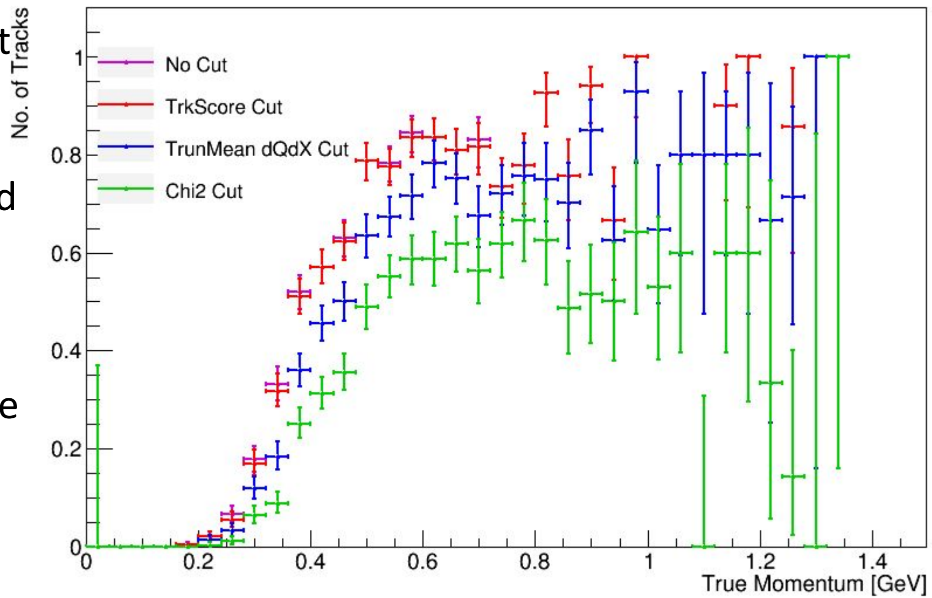
Pion Identification - Truncated Mean dQdx



- Truncated Mean dQdx distribution after track score cut
- Protons and pions are separated by truncated mean dqdx at a good level
- All the tracks are divided into 4 regions according to the truncated mean dqdx
  - I and III transition region
  - II -- pion region
  - IV -- proton region

Particle Identification - Protons

- Lots of low momentum protons can not be reconstructed due to low momentum
- A scheme of proton identification based on track score, truncated mean dQdx and chi2 cut
  - More complex particle identification scheme means more systematic uncertainties



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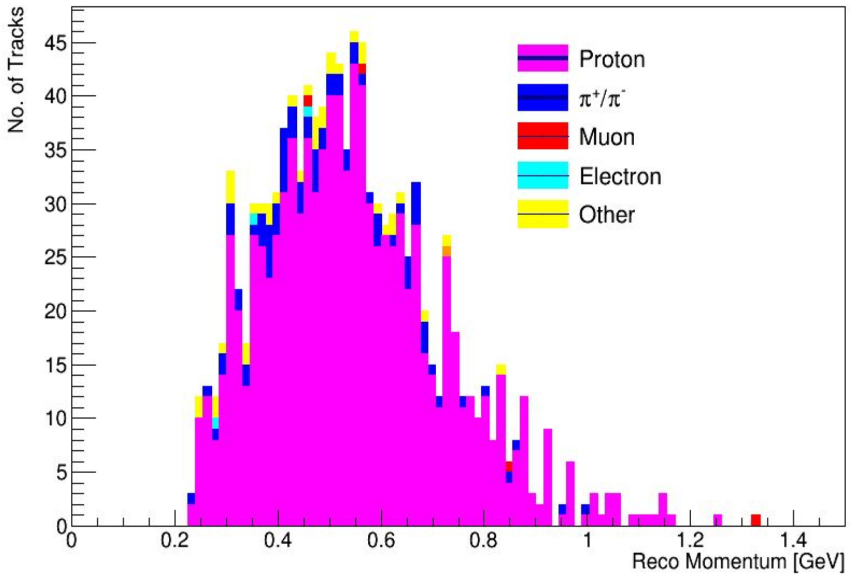

- A scheme with the combination of Track score+truncated mean dqdx+chi2 cut is performed to selected proton candidates
- The figure (Left) shows the reconstructed momentum distribution of selected proton candidate
- The proton purity is ~90%

Particle Identification - Pions

- Track score + truncated mean dqdx + chi2 cut cut off part of the proton backgrounds for pion identification
- Further background subtraction still needed, such as track range cut