Calibration of DUNE Far Detector using cosmic-ray muons

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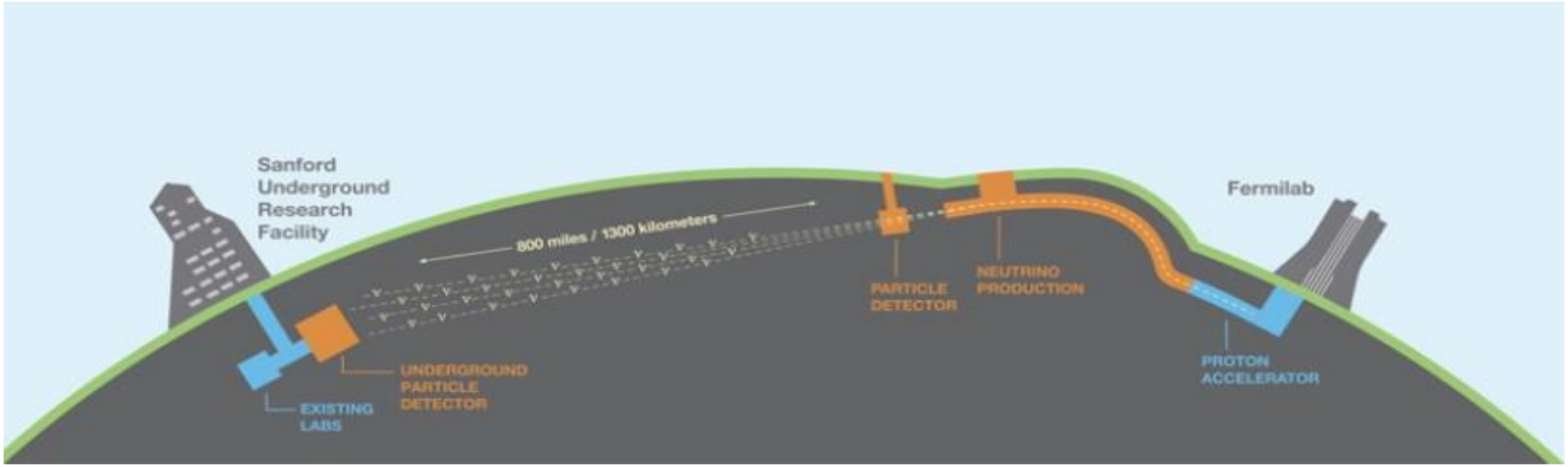
Outline

- Overview of DUNE
- LArTPC calibration
- Simulated cosmic muon events
- π^0 analysis
- dE/dx calibration

DUNE Experiment

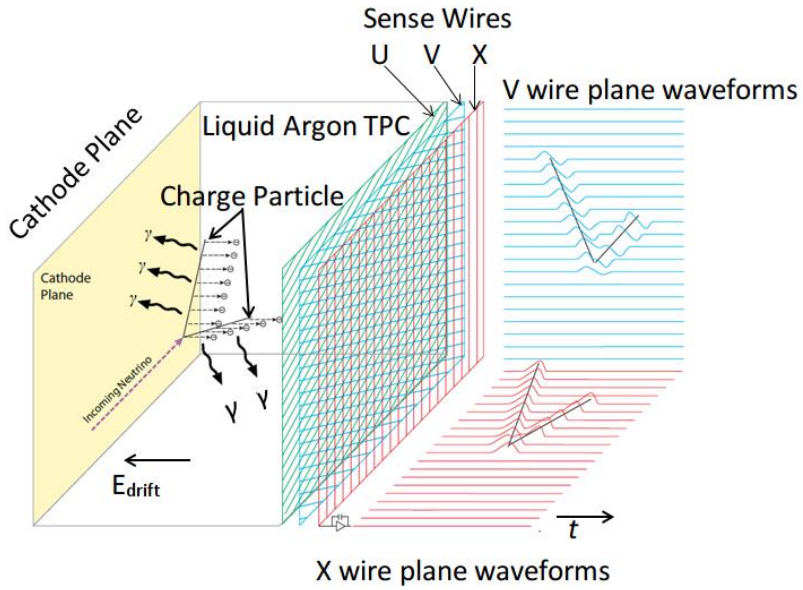


- The DUNE science program includes:
  - Neutrino oscillations
  - Detection of supernova neutrinos
  - Beyond standard model searches

Far Detector (FD)
- At SURF, SD, USA
- LArTPC
- 1.5 km underground
- 4 × 17 kt modules

Near Detector (ND)
- At Fermilab
- 3 components
- LArTPC, GArTPC, non-TPC
- Neutrino beam source

Liquid Argon Time Projection Chamber (LArTPC)



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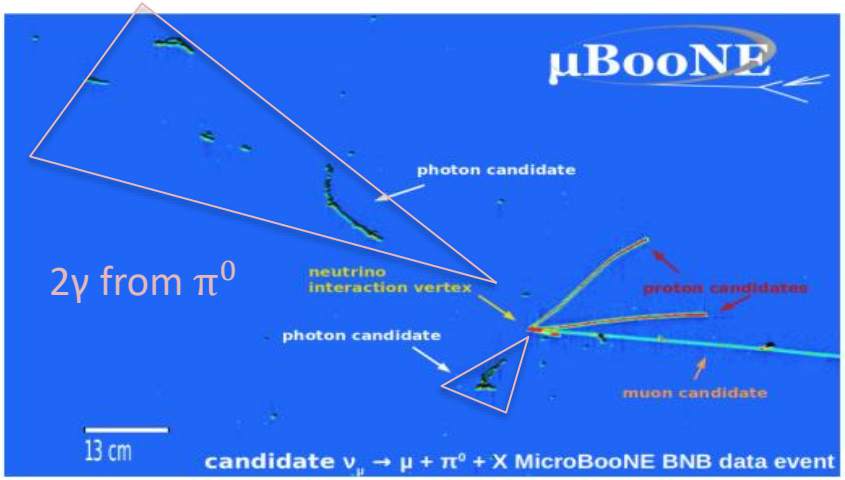
Operating principle of the Horizontal Drift (HD) Single-phase (SP) LArTPC:

- LArTPC has excellent imaging, tracking and particle identification capabilities
- A total of 200 TPCs in one HD SP module



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ν_μ CC π^0 event from MicroBooNE data

Reconstructed tracks and showers in LArTPC. Photons produce electromagnetic showers and muons produce long straight tracks

LArTPC Calibration

- **Motivation**
  - Calibrate energy scale
  - Energy resolution
  - Low energy reconstruction

- **Calibration Sources**
  - **Existing sources**
    - Cosmic muons
    - Atmospheric neutrinos
    - Accelerated neutrinos
    - Intrinsic radioactive isotopes
  - **Dedicated calibration system**
    - Ionisation laser system
    - Pulsed neutron source

- **Calibration with cosmic muons**
  - Abundant natural source
  - Well known dE/dx vs kinetic energy distribution
  - Can be used in different measurements:
    - Energy calibration
    - Electric field calibration
    - Electron lifetime for argon purity measurements

Cosmic Muon Production

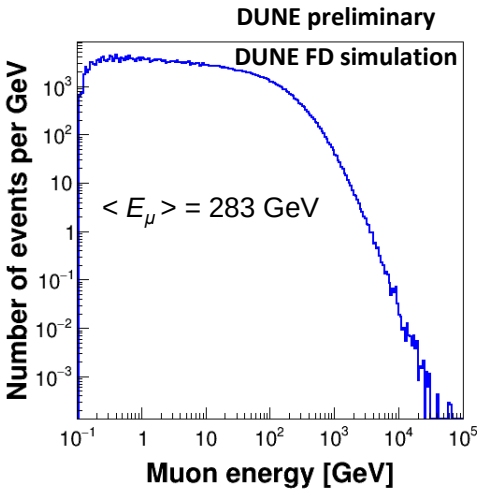
- Cosmic muon events are generated using Muon Simulation Underground (MUSUN) generator
- Total of 1.85×10^6 simulated events corresponding to 131 days of DUNE FD data

Statistics

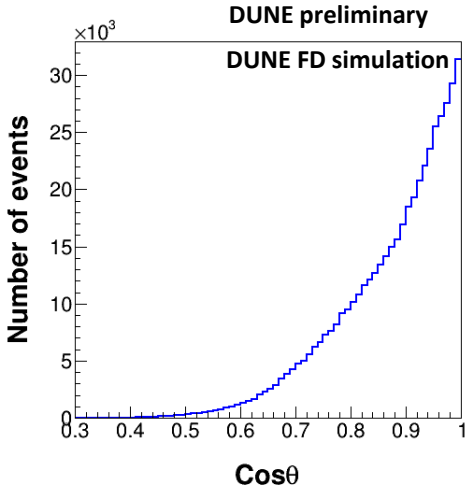
Characterisation	Total number	Per day	Fraction [%]
Total generated events	1.85×10^6	1.41×10^4	
Primary μ in active volume	**6.24×10^5**	**4.76×10^3**	**33.72 ± 0.04**
Any stopping μ in active volume	2.28×10^4	174	3.65 ± 0.02
Primary stopping μ in active volume	**1.13×10^4**	**86**	**1.81 ± 0.02**
π^0 in active volume	**2.76×10^4**	**210**	**4.42 ± 0.03**
Events in which π^0 produced	4.89×10^3	37	0.78 ± 0.01

Muon Distributions

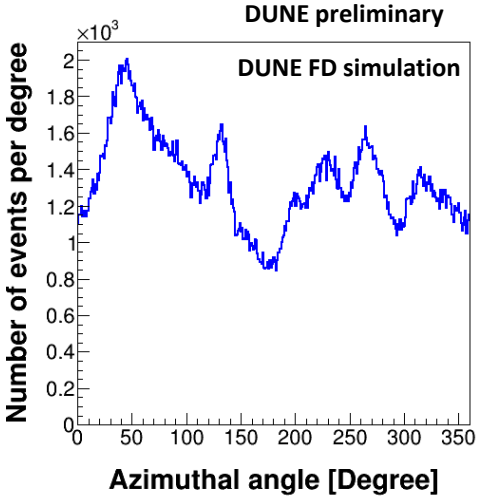
Energy of primary μ in TPC



Zenith angle



Azimuthal angle



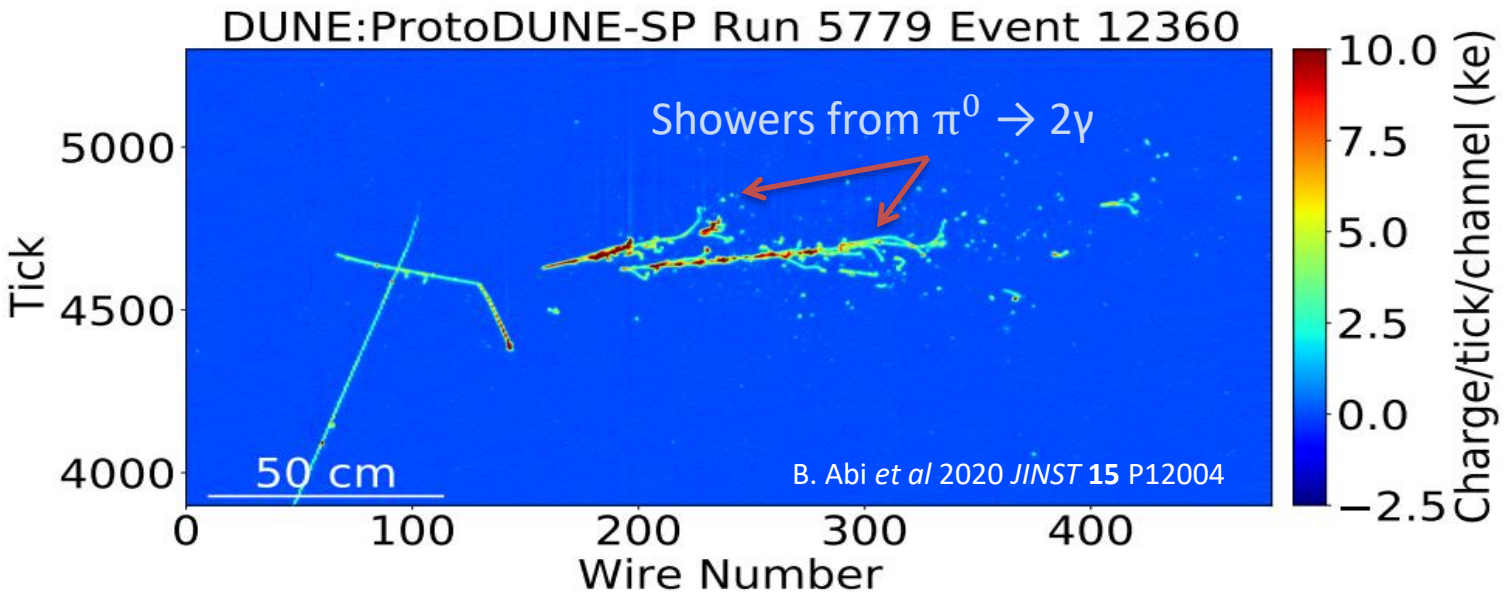
- 1.42×10^6 generated events
- 4.81×10^5 primary μ in active volume
- 101 days of data at DUNE FD
- Zenith distribution tells us the muons are mostly going downwards
- Azimuthal distribution depicts the surface profile above the DUNE FD

π^0 Analysis

- π^0 are useful for calibrating the detector to electromagnetic activity response
- The (γ,γ) invariant mass is given by:

$$M_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta)}$$

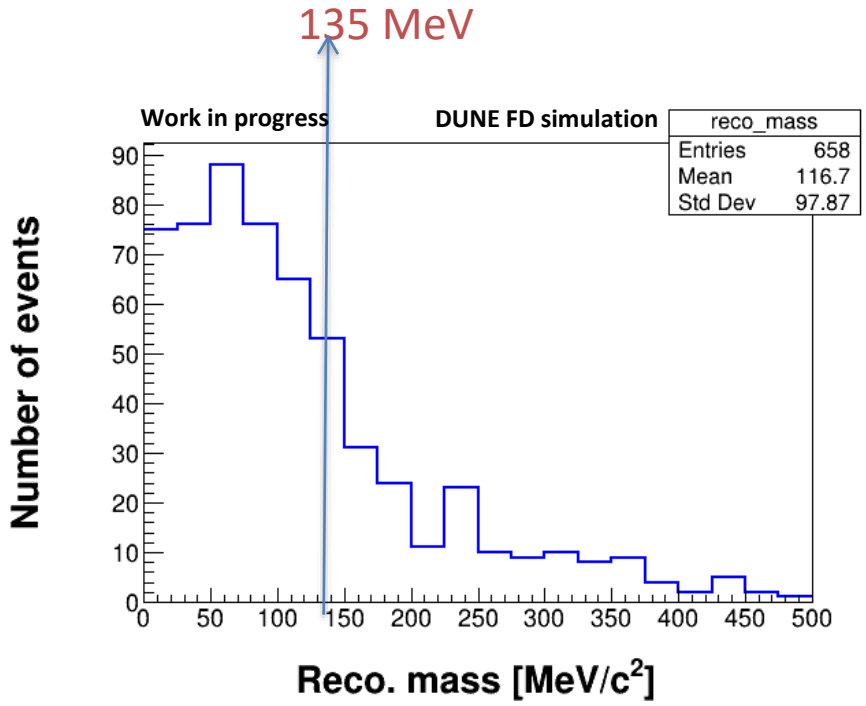
(where E_1 and E_2 are the photon energies and θ is the angle between the two photons)

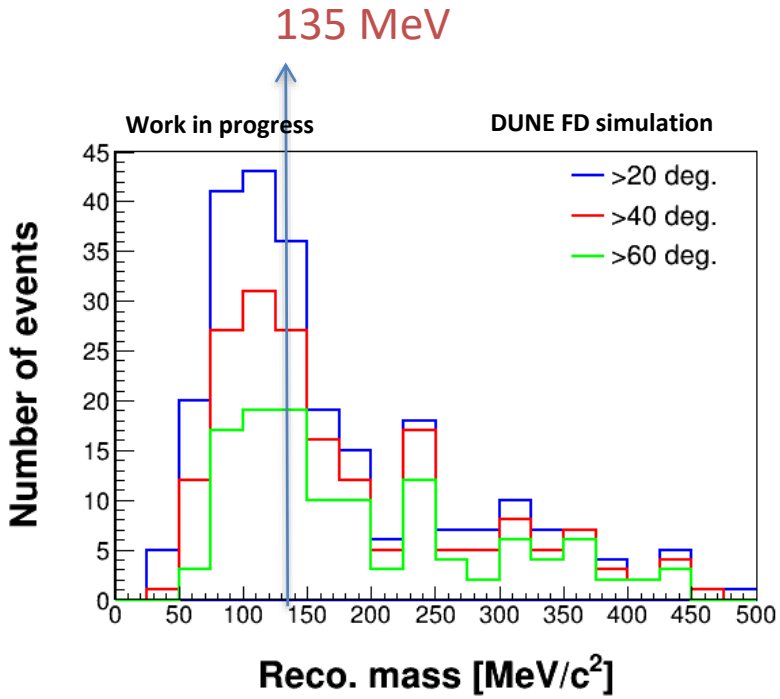


Reconstructed tracks and showers in LArTPC from protoDUNE data using Pandora reconstruction

Reconstructed Mass

$$M_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta)}$$





Selections:

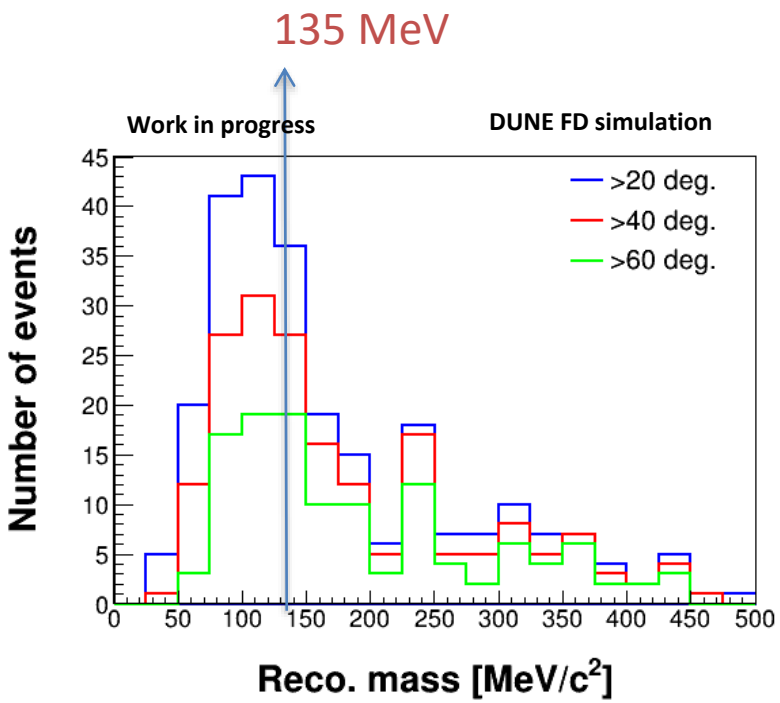
- No energy and angle selections

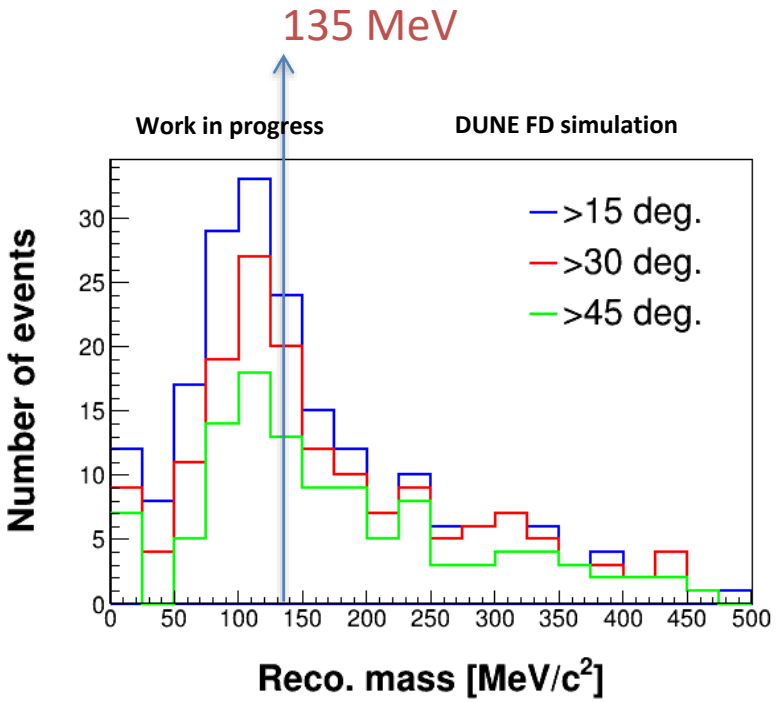
Selections:

- Leading shower energy > 60 MeV
- Sub-leading shower energy > 40 MeV

- Reconstructed mass significantly improves with the selection on higher reco. energy

Reconstructed Mass





Selections:

- Leading shower energy > 60 MeV
- Sub-leading shower energy > 40 MeV

Selections:

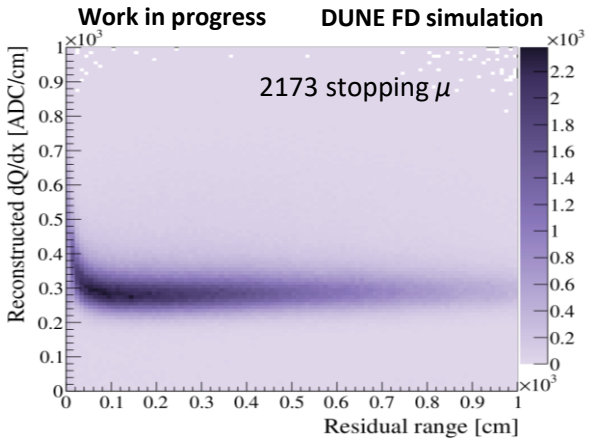
- Number of hits > 75

- Reconstruction of the invariant mass improves with the selection on no. of hits

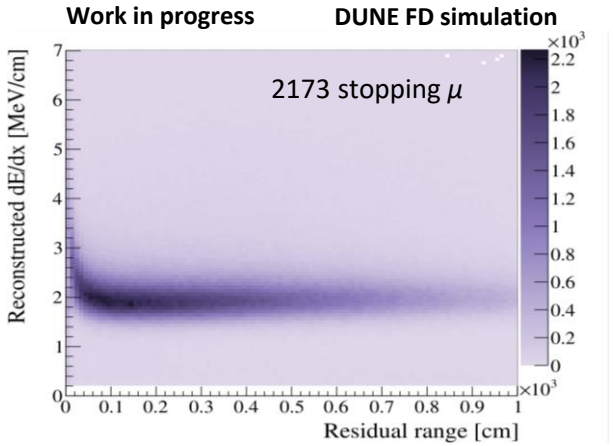
dE/dx Calibration

- Using stopping muons
  - Well-understood energy loss profile
  - Can be used as an absolute energy scale
  - Can be used for electron-ion recombination with data driven studies

Initial studies



Reconstructed dQ/dx vs. residual range



Reconstructed dE/dx vs. residual range

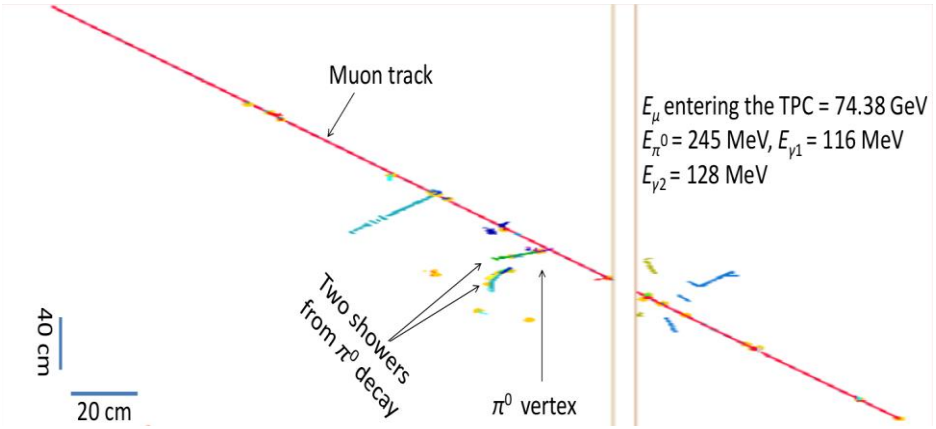
Summary

- Cosmic muon events are produced using cosmic muon generator MUSUN for the DUNE FD
- Cosmic-ray muons are valuable source for detector calibration
- Different selections on angle, energy and number of hits improve reconstruction of π^0 mass
- Studies towards energy calibration using stopping and through going muons are in progress

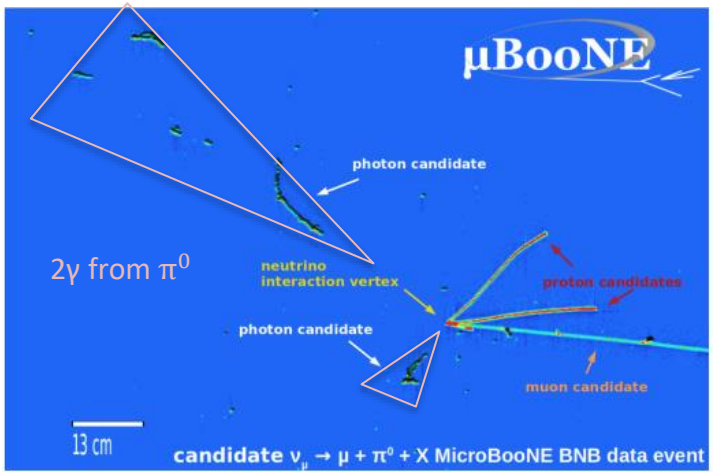
Thanks !

Backup Slides

Particle interaction in LArTPC



A simulated cosmic muon event in DUNE FD



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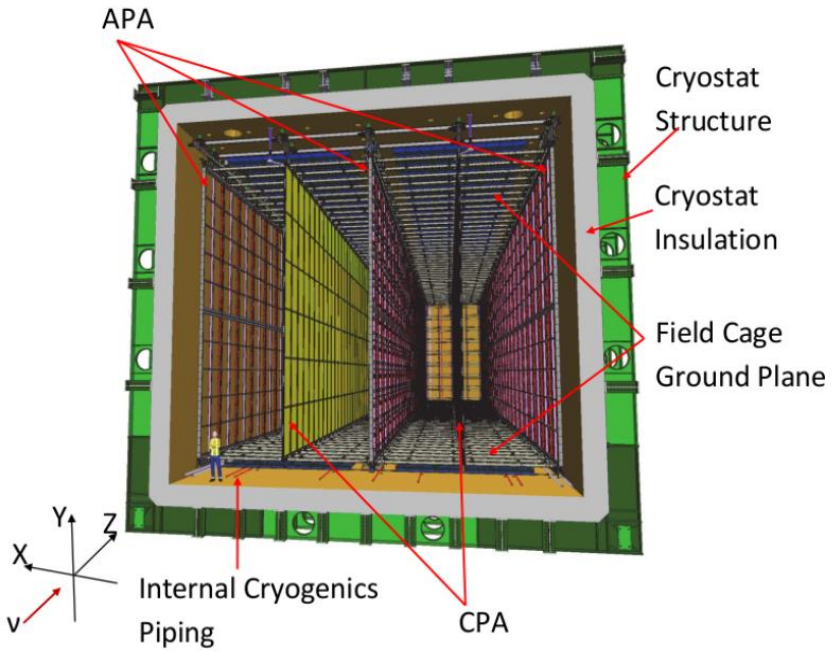
ν_μ CC π^0 event from MicroBooNE data.

Diagrams show the reconstructed event's tracks and showers in LArTPC for simulated event (left) and data (right). Photons produce em showers and muons produce long straight tracks.

DUNE Far Detector (FD)



A Horizontal Drift (HD) Single-phase (SP) LArTPC FD module:
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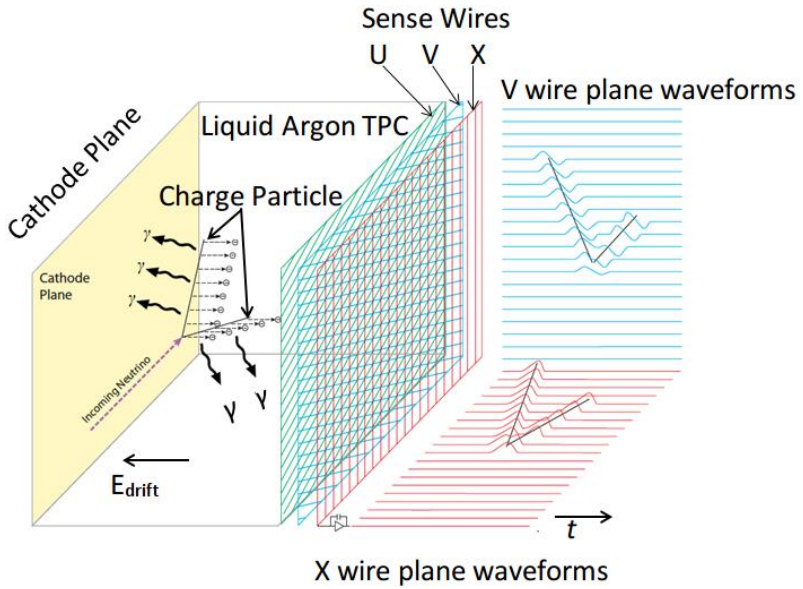

Operating principle of the HD SP LArTPC:
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- The DUNE FD consists of four 17-kt LArTPC modules
- The first FD will be Single-phase
- Largest LArTPC ever built

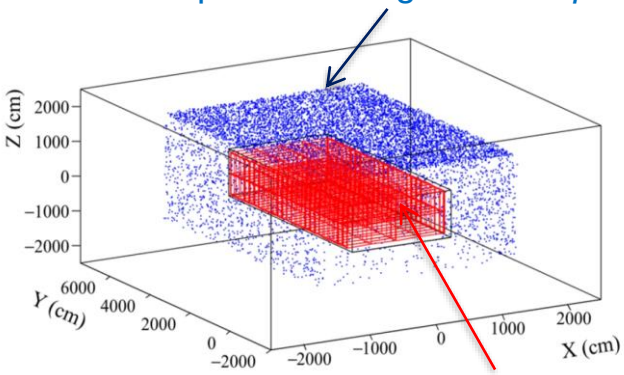
- LArTPC has excellent imaging, tracking and particle identification capabilities
- A total of 200 TPCs in one HD SP module

Cosmic muon production

- Cosmic muon events are generated using Muon Simulation Underground (MUSUN) generator.
- Muons are generated on the top and side surfaces of a box with dimensions 77.2, 29.5, 30.2 m (L, W, H) around the DUNE FD.
- Total of 1851000 simulated events corresponding to 131 days of DUNE FD data.
- **Statistics**

Characterisation	Total number	Per day	Fraction [%]
Total generated events	1851000	14118	
Primary μ in active volume	**624184**	**4761**	**33.72 ± 0.04**
Any stopping μ in active volume	22770	174	3.65 ± 0.02
Primary stopping μ in active volume	**11297**	**86**	**1.81 ± 0.02**
π^0 in active volume	**27590**	**210**	**4.42 ± 0.03**
Events in which π^0 produced	4893	37	0.78 ± 0.01

Initial positions of generated μ



Individual TPCs

π^0 Analysis

- π^0 are useful for calibrating the detector to electromagnetic activity response.
- π^0 are produced inside the LArTPC by muon nuclear interaction process and also by secondary hadrons (or photons) in the muon-induced cascades
- The (γ,γ) invariant mass is given by:

$$M_{\pi^0} = \sqrt{2E_1E_2(1 - cos\theta)}$$

(where E_1 and E_2 are the photons energies and θ is the angle between the two photons)

- Two different reconstruction methods are used:
  - Neutrino oriented reconstruction: Tune to reconstruct neutrino events from the beam, contains 104 days of data at DUNE FD
  - Cosmic oriented reconstruction: Tune to reconstruct muon track from cosmic-ray muons, contains 22 days of data at DUNE FD

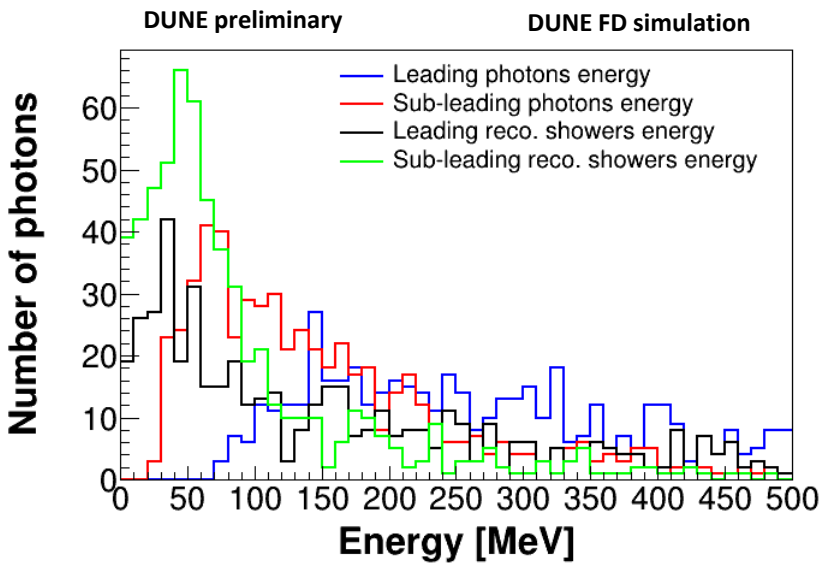
π^0 Selections

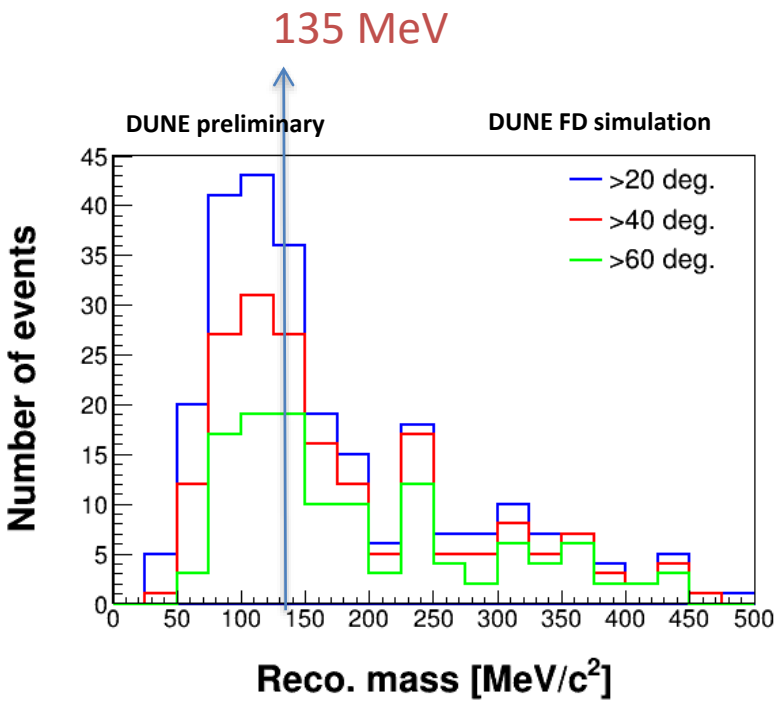
- To select π^0 events and showers, following selections are used:
  - Event with at least one $\pi^0 \rightarrow$ Selection1 (truth-level)
  - Shower matched with $\pi^0 \rightarrow$ Selection 2 (reco $\rightarrow$ truth association)
  - Only those events π^0 decay to $2\gamma \rightarrow$ Selection 3 (truth-leve)
  - Shower with maximum energy selected $\rightarrow$ Selection 4 (reco $\rightarrow$ truth association)
  - Leading and sub-leading reconstructed showers energy correspond to leading and sub-leading photon energy $\rightarrow$ Selection 5 (reco $\rightarrow$ truth association)
- Statistics:

Characterisation	Total number (Neutrino oriented)	Total number (Cosmic oriented)	Fraction [%] Neutrino oriented	Fraction [%] Cosmic oriented	Selections
Number of TPC muons	498606	108203	33.69	33.81	
No. of events at least 1 π^0 produced	3917	954	0.79	0.88	Selection 1
No. of π^0 produced	22748	4967	4.56	4.59	Selection 1
No. of reconstructed showers associated with π^0	7620	15973	1.52	14.76	Selection 1 & 2
No. of events $\pi^0 \rightarrow 2\gamma$ and shower matched with γ	625	684			Selection 1, 2 & 3

Reconstructed Mass

Neutrino oriented reconstruction





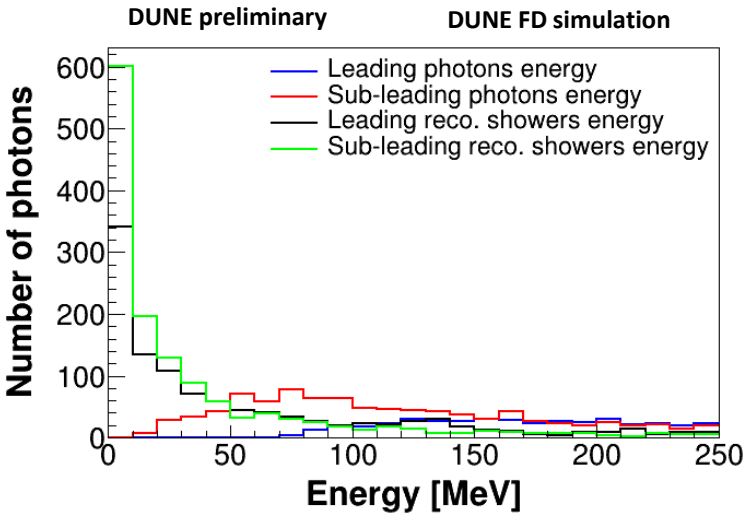
Selections:

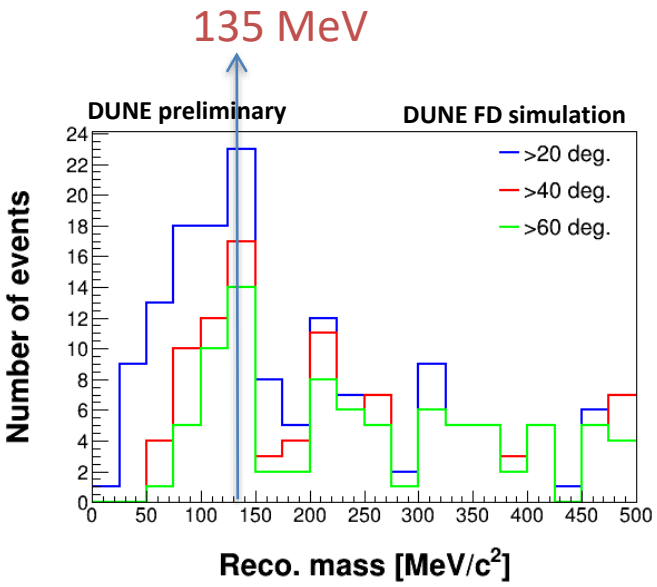
- All selections are used
- Looking around peak of leading and sub-leading shower energy, selections are made on the right plot
- Leading shower energy > 60 MeV
- Sub-leading shower energy > 40 MeV

- Reconstructed mass significantly improves with the selection on higher reco. energy

Reconstructed Mass

Cosmic oriented reconstruction





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