MINOS detector and tracking

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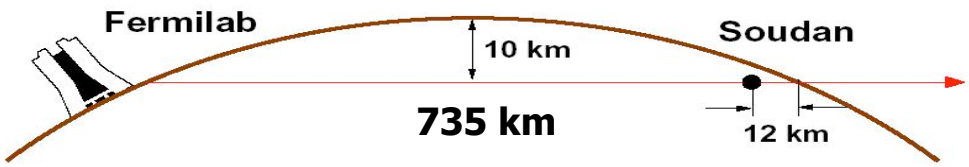
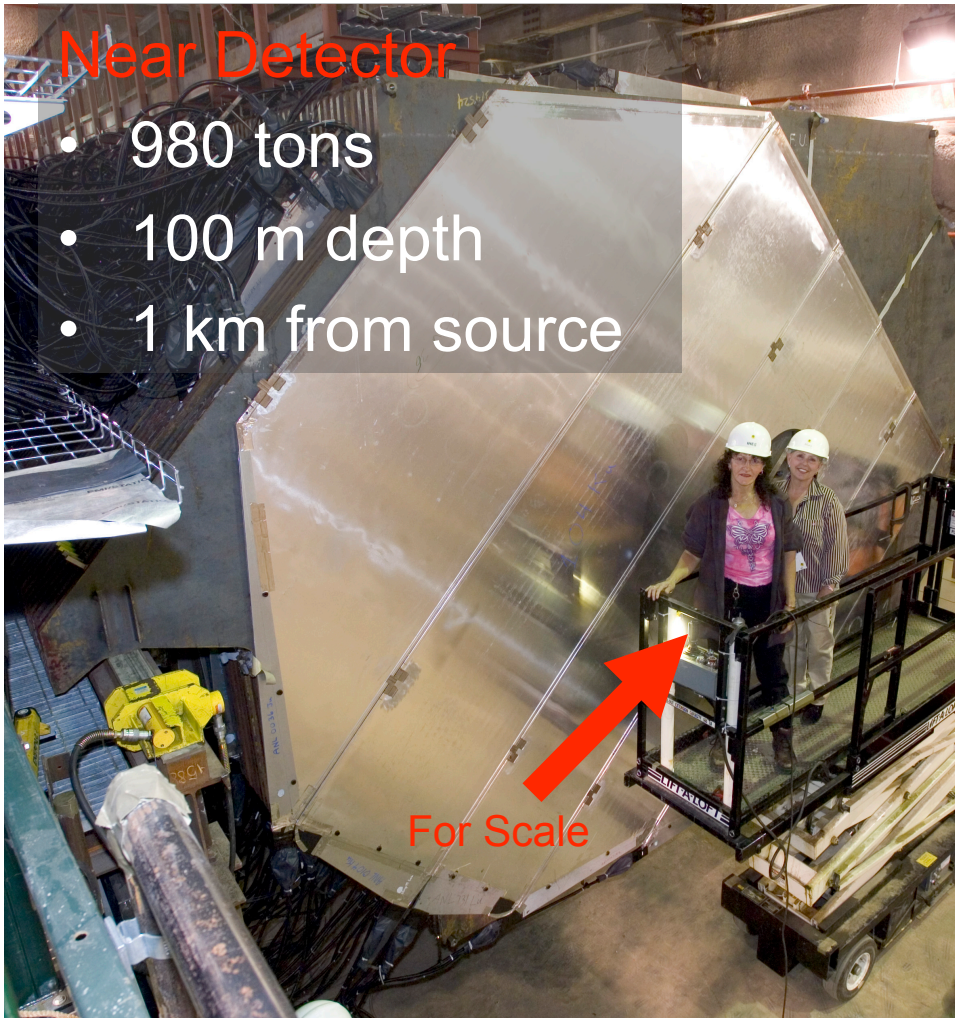
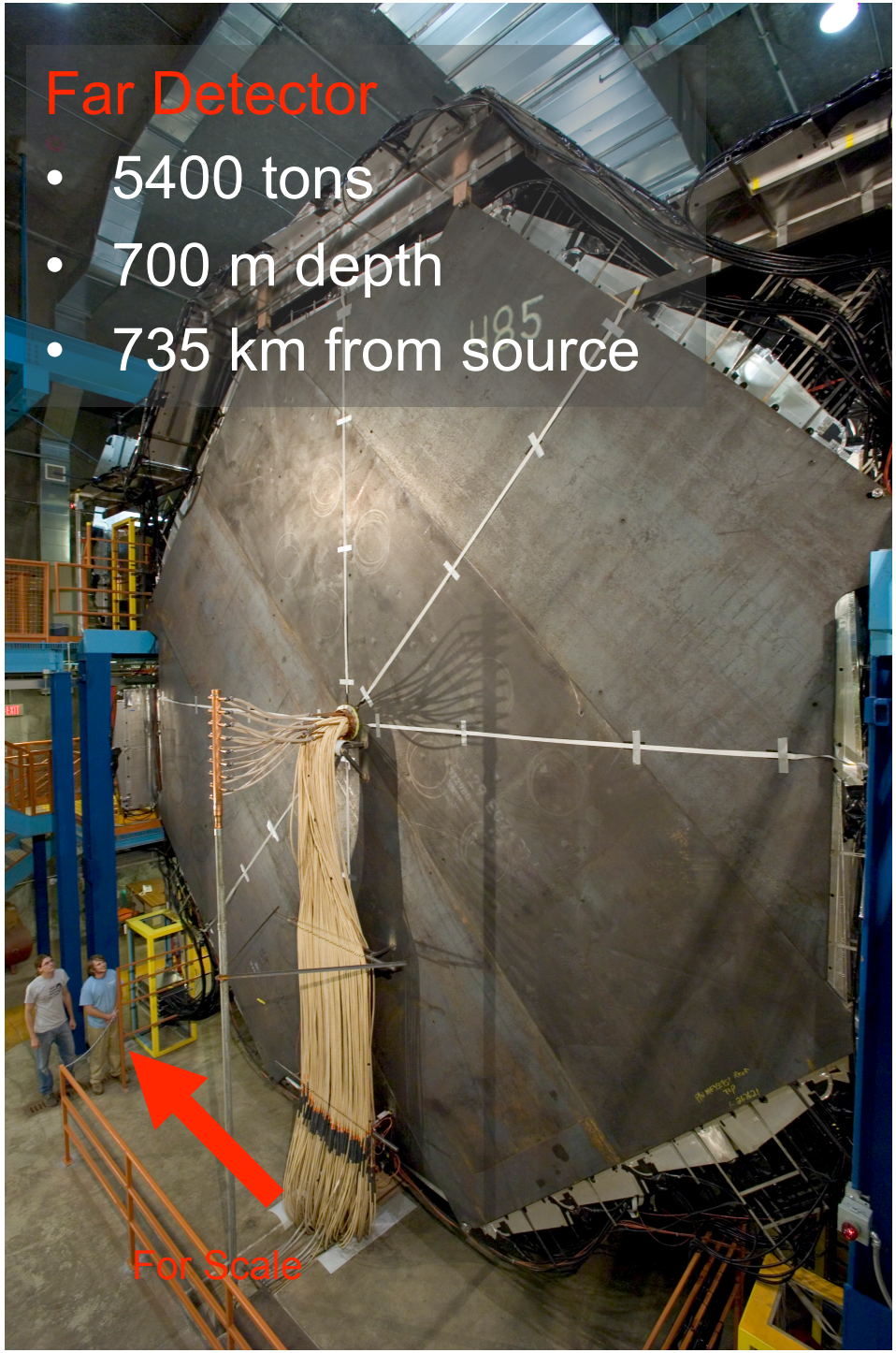
MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



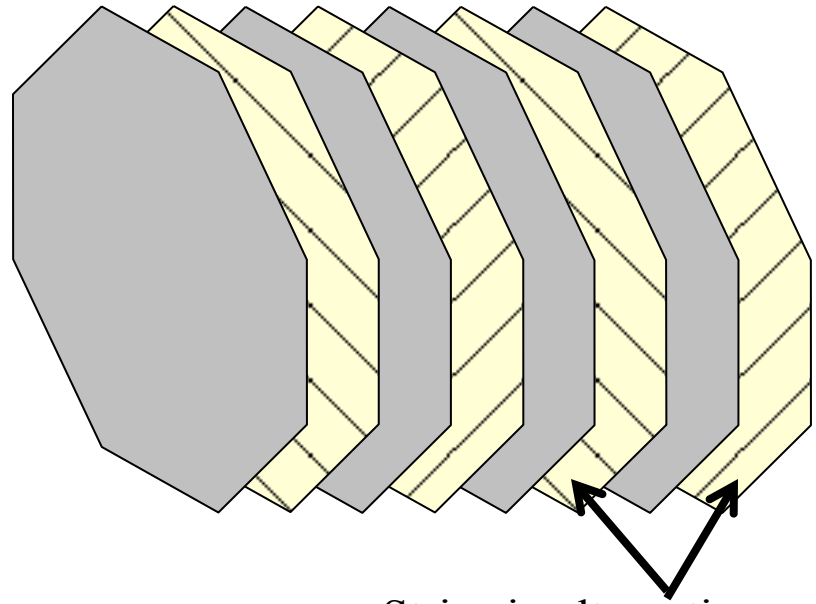
MINOS Detectors



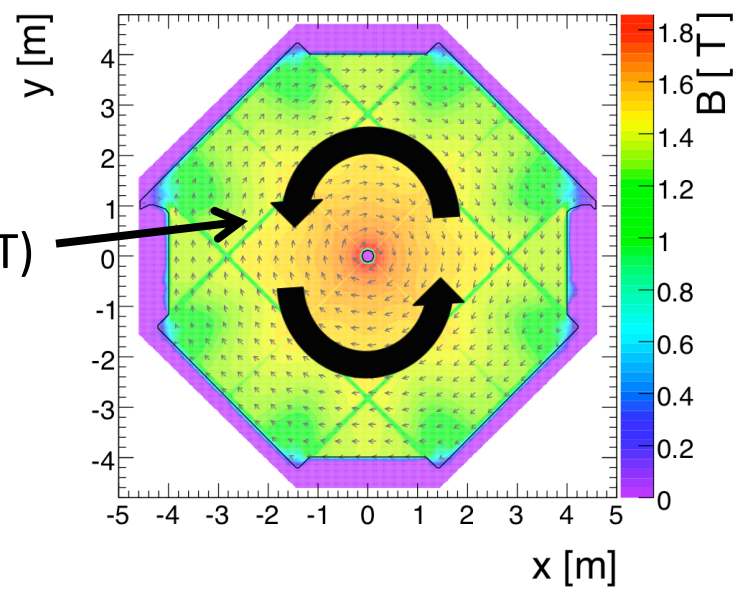


MINOS Detectors

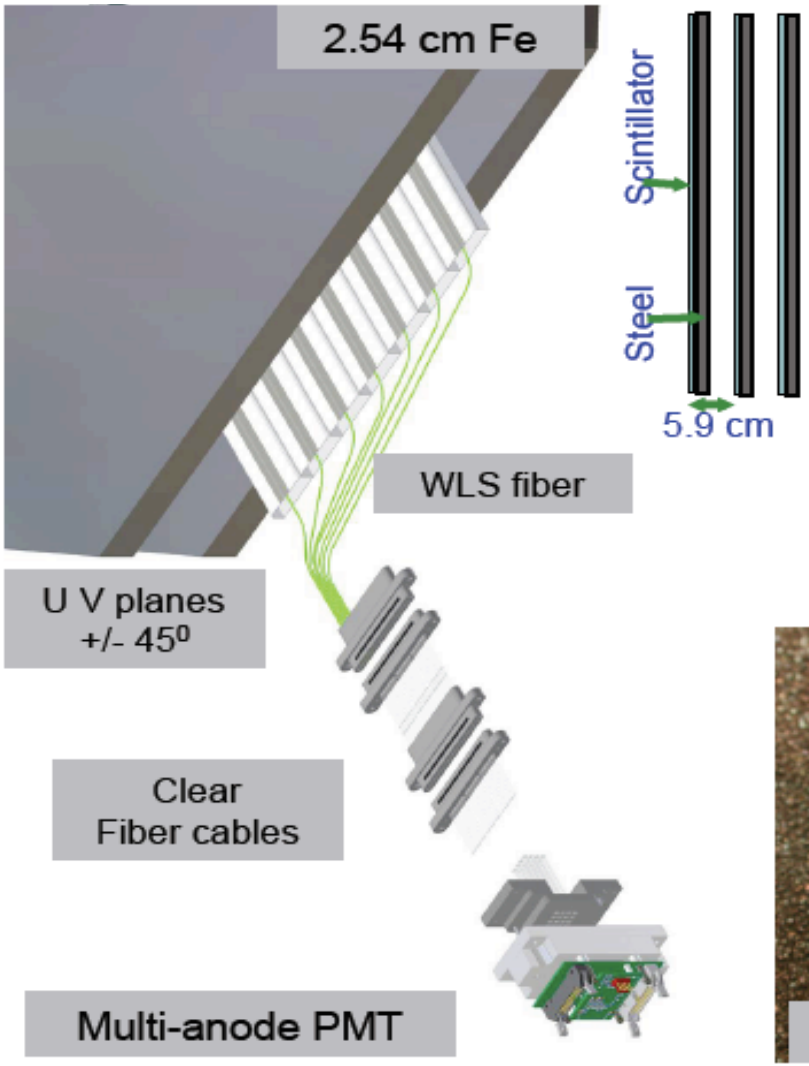
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1 cm thick) (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - distinguish μ^+ from μ^-
  - muon energy from range/curvature
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



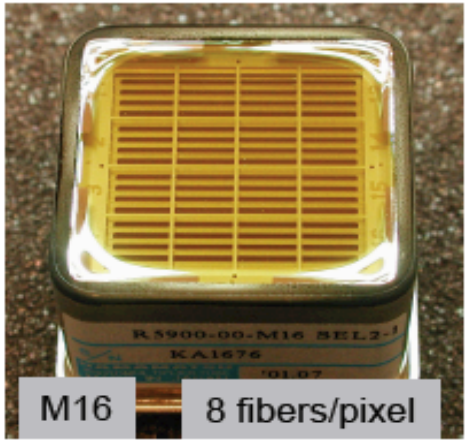
Strips in alternating directions allow 3D event reconstruction



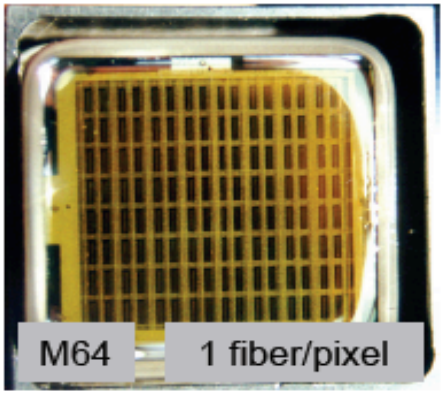
MINOS Detector Technology



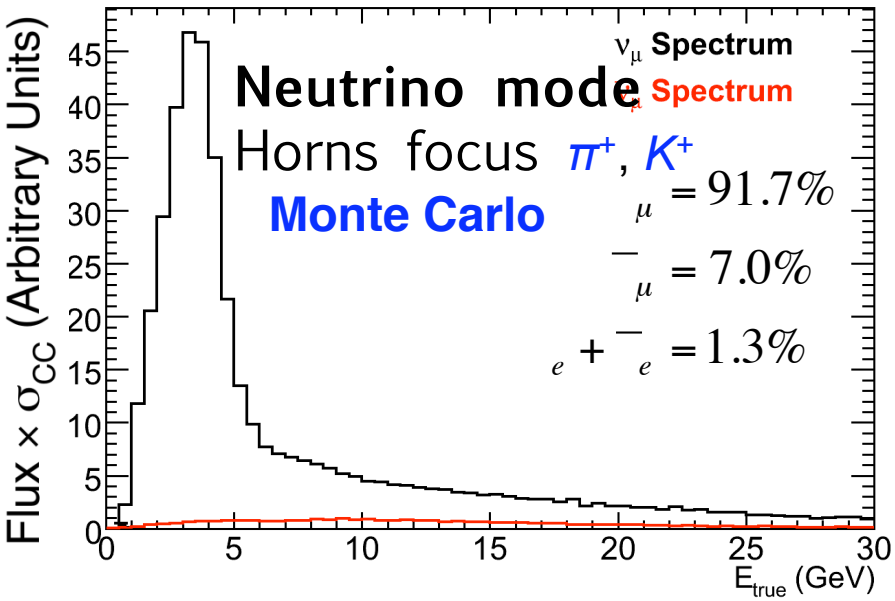
Far Det

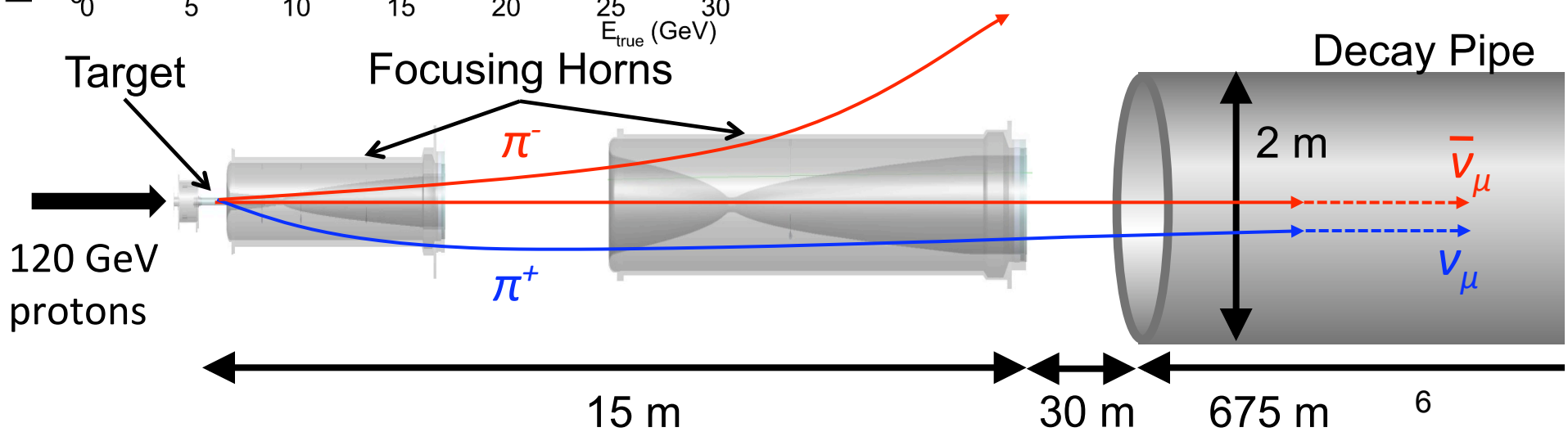


Near Det

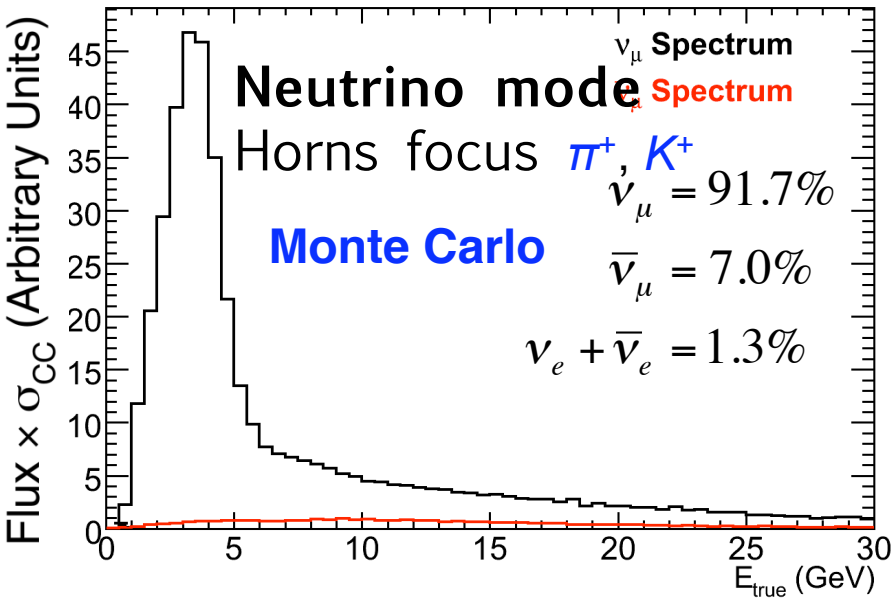


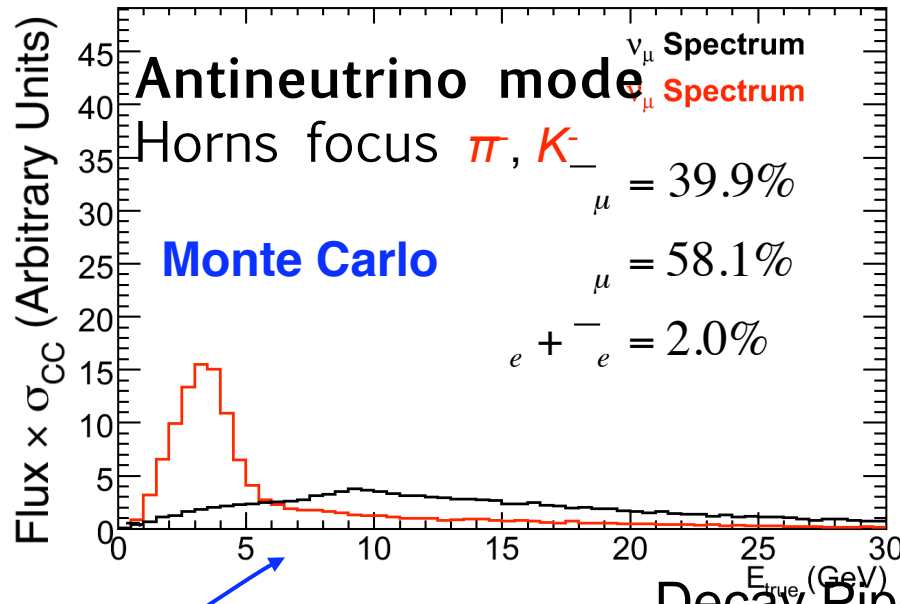
Neutrino Mode

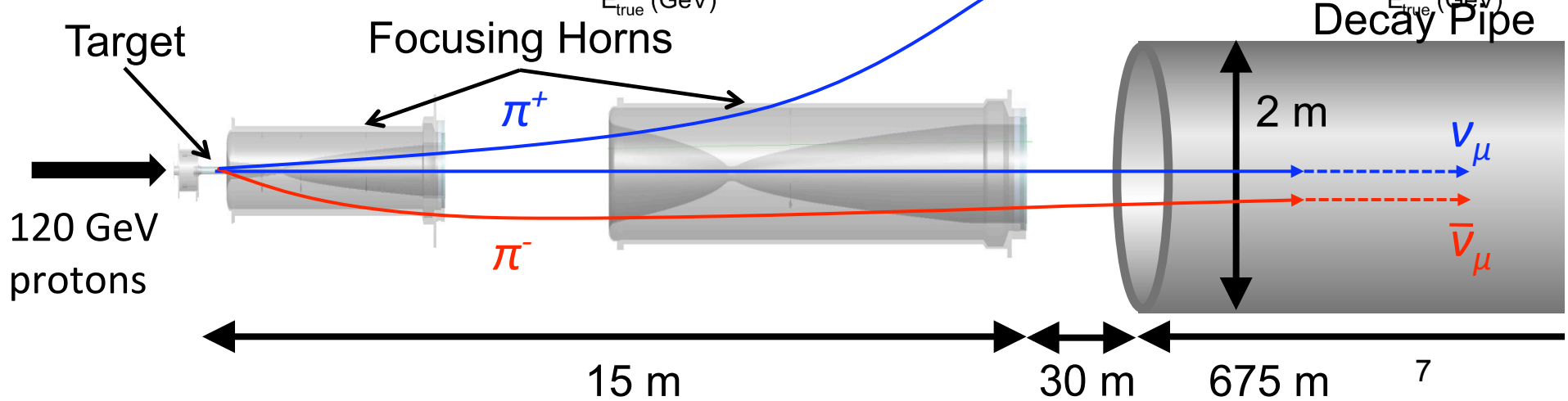




Anti-neutrino Mode

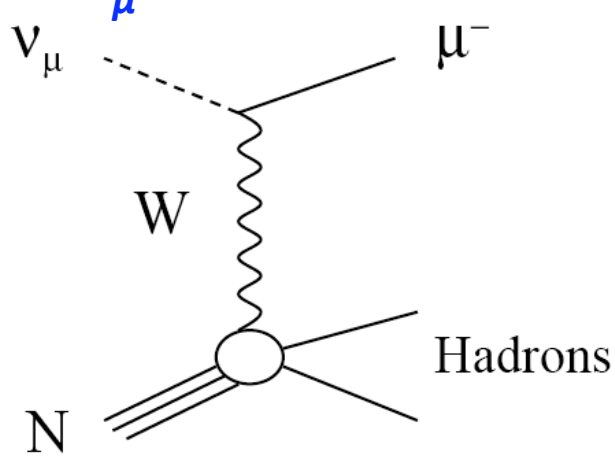




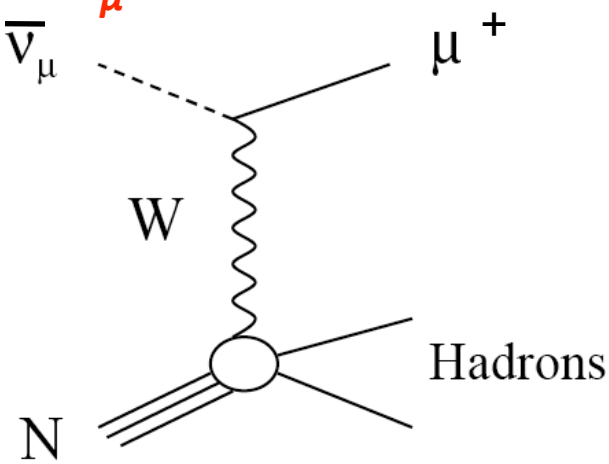


MINOS Event Topologies

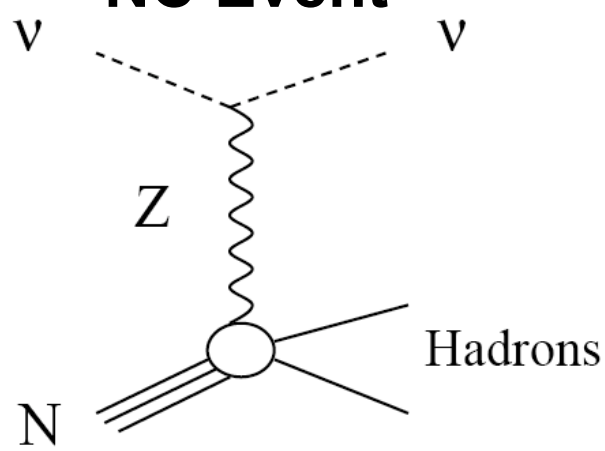
ν_μ CC Event

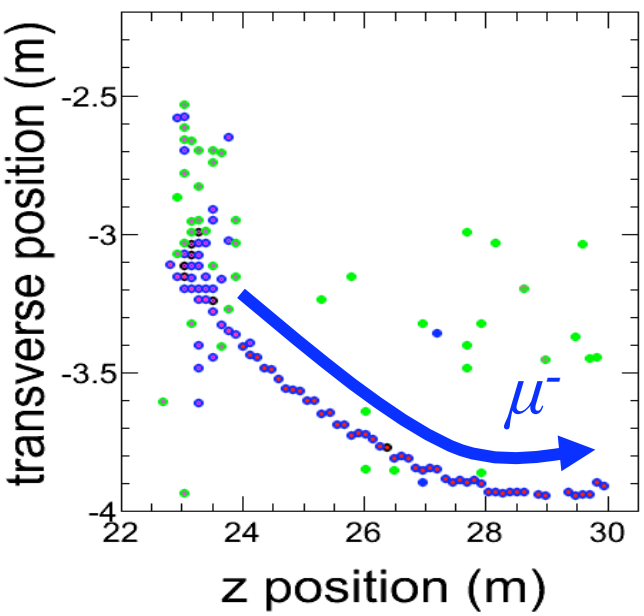


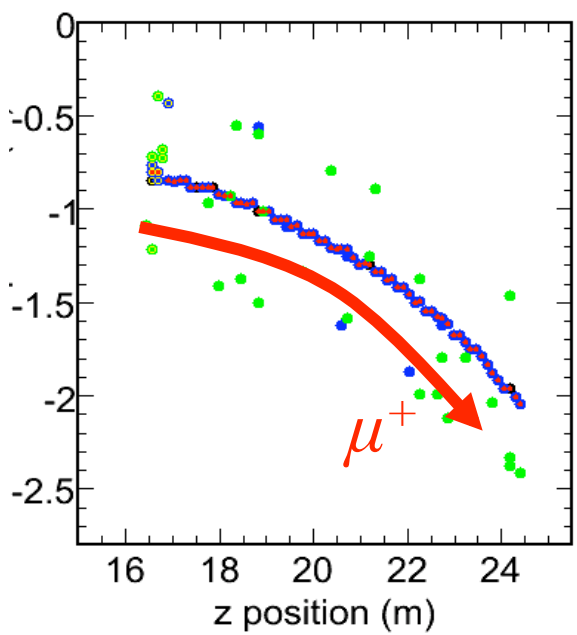
$\bar{\nu}_\mu$ CC Event

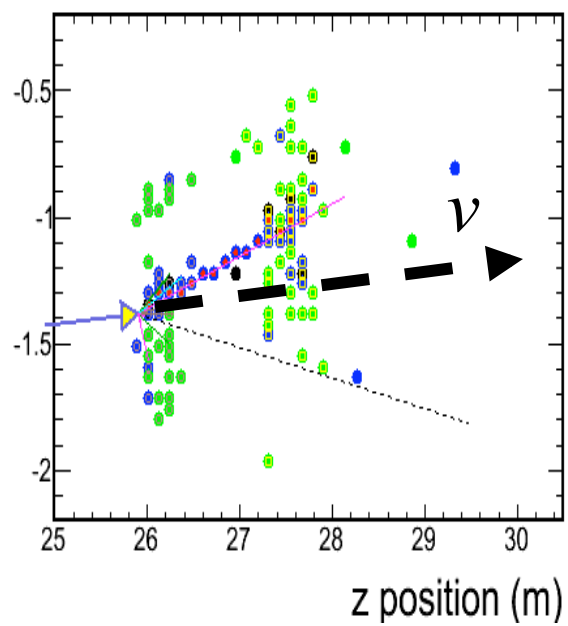


NC Event







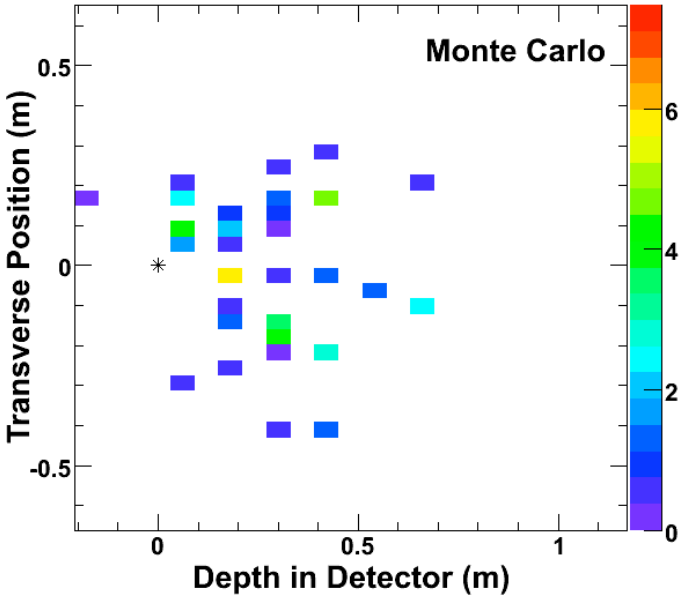


Simulated Events

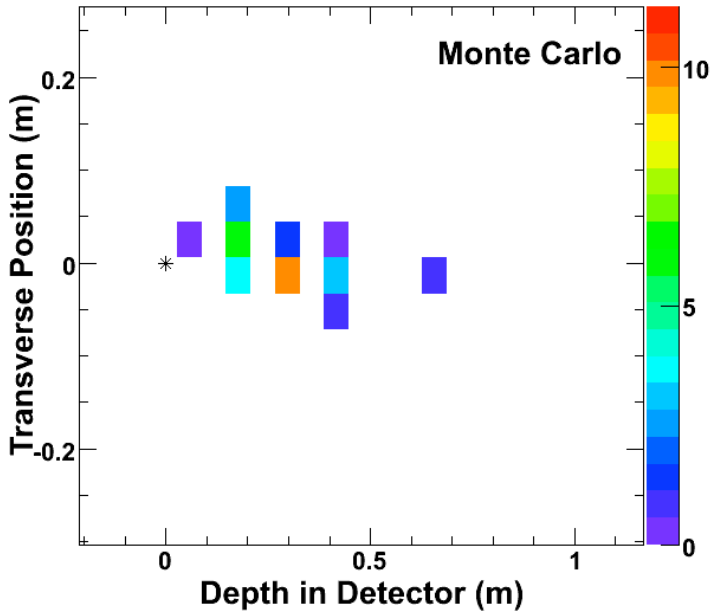
- Deposition < 2.0 pe
- 2.0 < Deposition < 20.0 pe
- Deposition > 20.0 pe

More Event topologies

In search for subdominant $\nu_\mu \longrightarrow \nu_e$ oscillations, trying to distinguish hadronic showers and electrons



Short event,
often diffuse



Compact events
EM shower profile

How do we deal with tracks in MINOS

We need to reconstruct a neutrino event:

$$E_\nu = E_\mu + E_{shower}$$

- We find a track

- We fit a track

- We find shower

1. How the track finder works

from J.Marshall thesis

General Aim:

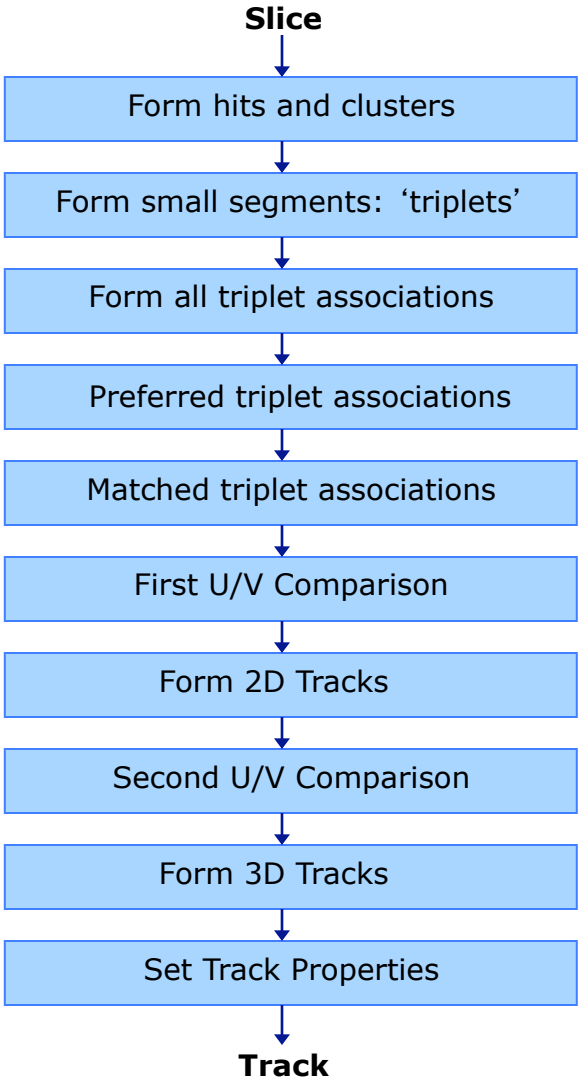
The package works by finding small segments of track.

Firstly, **Hits** with >2PEs are used to form **Clusters**. Adjacent hits on a plane are added to the same cluster.

Clusters are then linked together into small **TrackSegments**.

We choose the best segments to join together and gradually build towards the final **Track**.

Clusters could be track-like or shower-like. Densely packed clusters are fagged as shower-like.

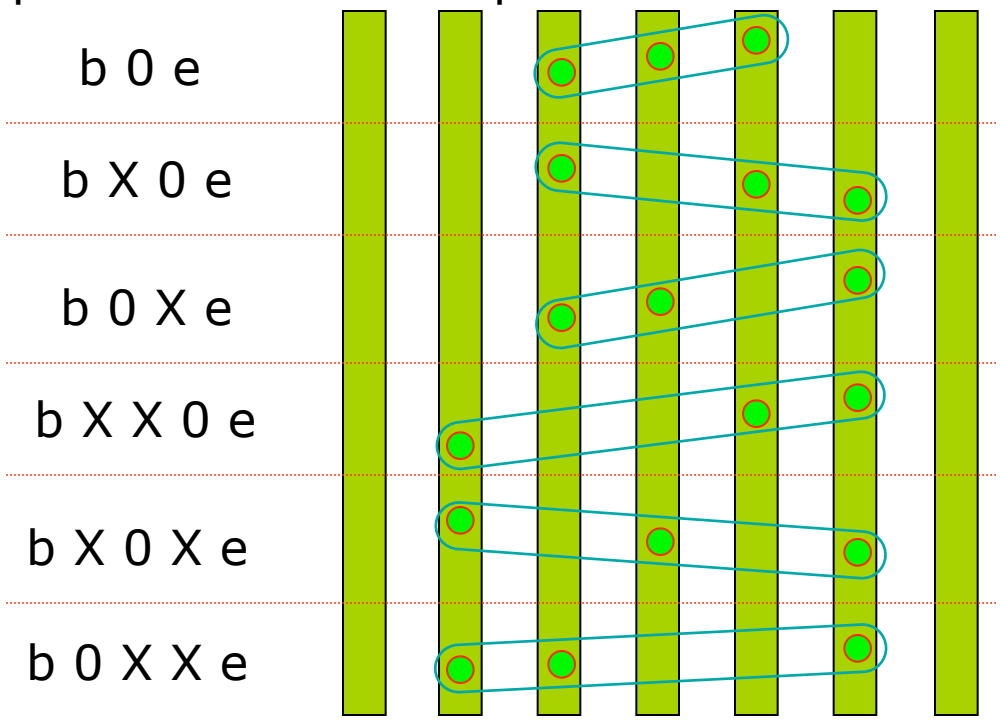


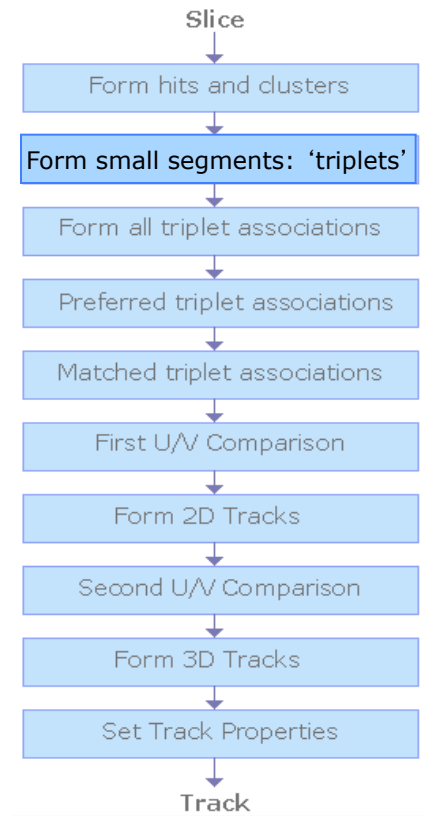
Form Triplets

- Triplets are small **TrackSegments**, each containing 3 clusters on separate planes.
- Treating U/V views separately and working separately for each FD Super Modules (we have 2 of them in FD), we create all possible forms of triplet:

Plane labels:

b: beginning
e: end
0: central
X: gap

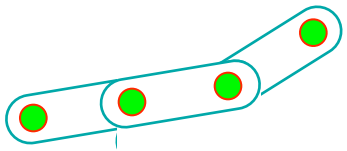




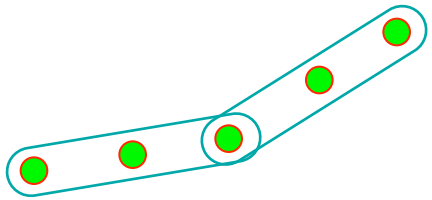
Triplets are formed separately for u and v views.

Make All Possible Associations

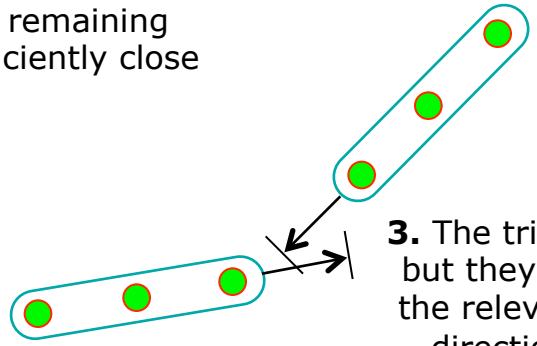
- To help choose which Triplets to join together, there are three levels of association we can make between TrackSegments.
- For the first level of association, we simply consider each triplet and find the other nearby triplets with compatible beginning/end positions and directions.
- Triplets are declared to be associated if:



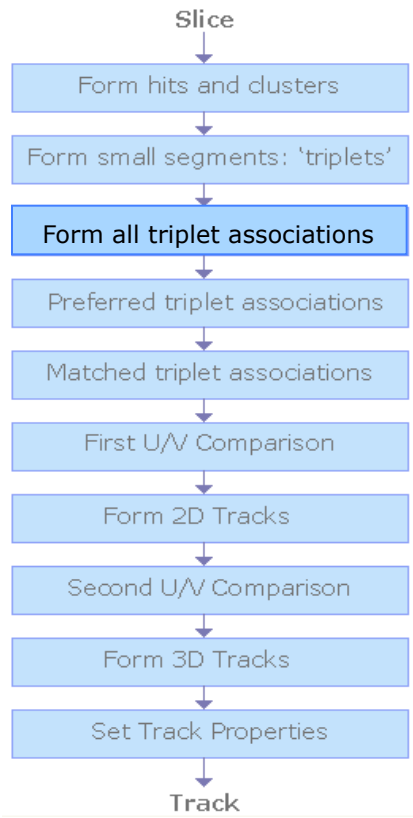
1. The two triplets share two clusters



2. The triplets share one cluster and the remaining clusters are sufficiently close

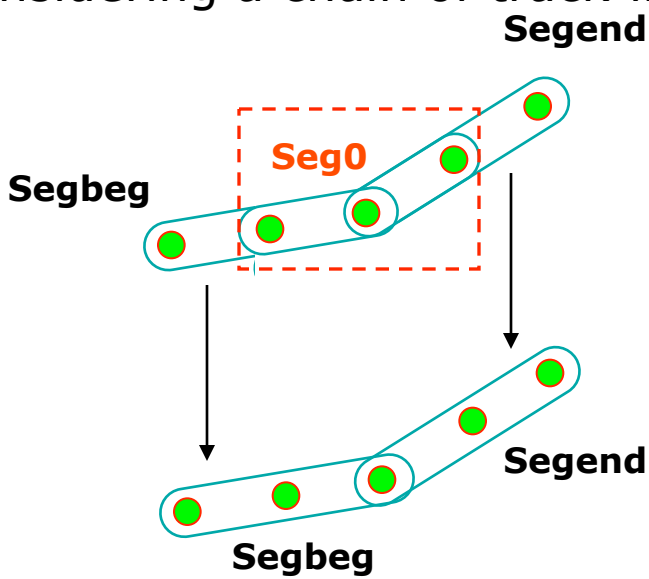


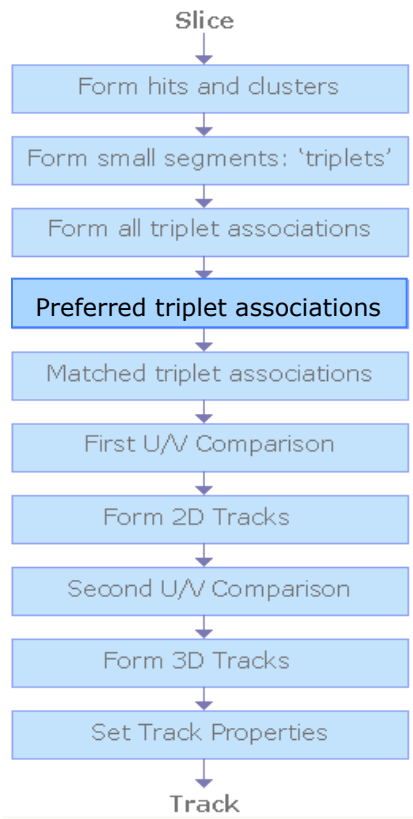
3. The triplets share no clusters, but they are suitably close and the relevant beginning and end directions are 'compatible'.



Make Preferred Associations

- From the list of simple associations, we try to select those that are most track-like and so are 'preferred'.
- For a given triplet, we know which triplets are associated with its beginning and its end.
- If these beginning and end triplets are themselves associated, then we are quite likely to be considering a chain of track-like segments.

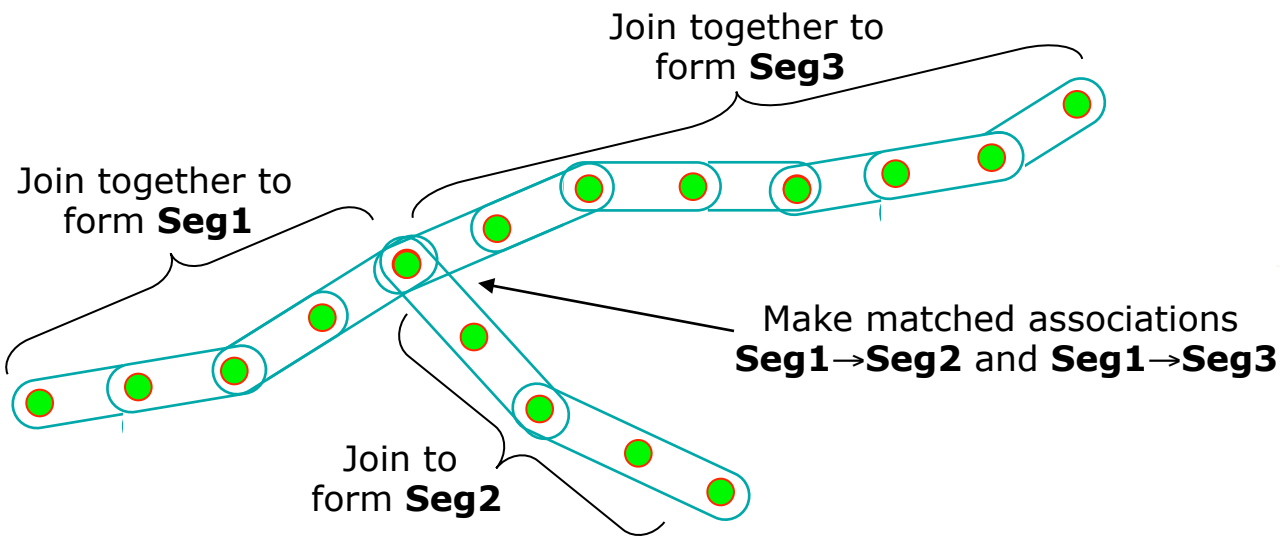


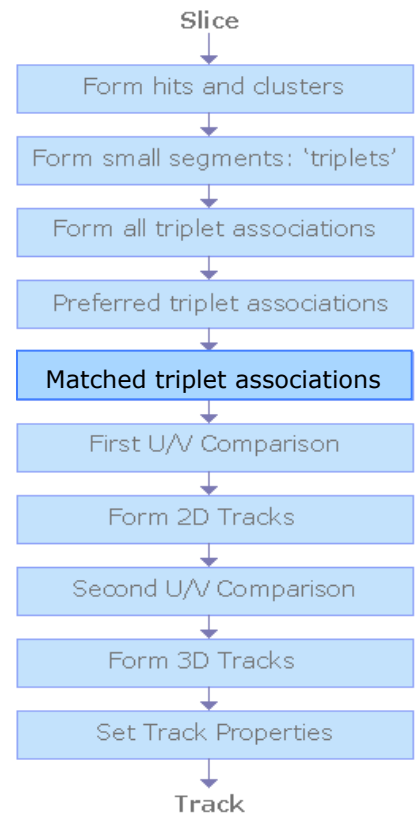


Segbeg and Segend are associated with each other, so we can make preferred associations between **Segbeg** and **Seg0**.

Make Matched Associations

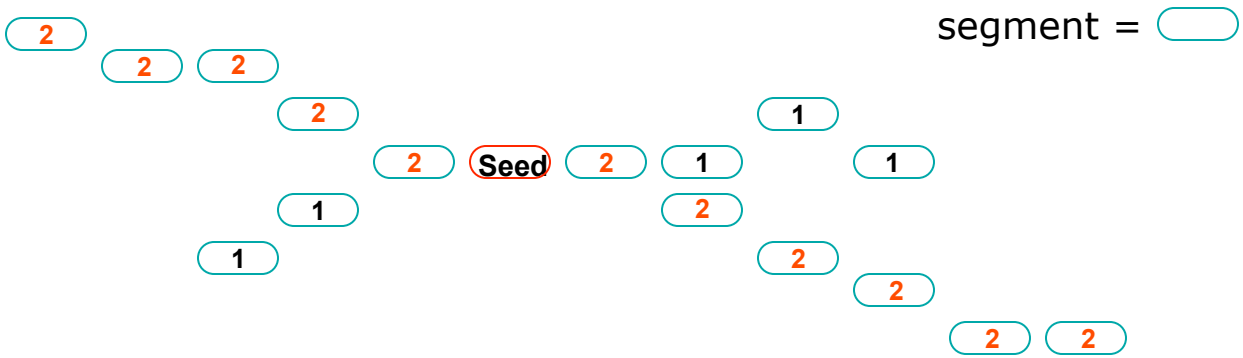
- We next look for long chains of triplets with preferred associations.
- If the triplets in these chains each have one preferred beginning association and one preferred end association, we can join them together.
- Otherwise, we make 'matched' associations between the segments in the most likely chains.
- We make matched associations between segments separated by the coil hole.





Form 2D Tracks

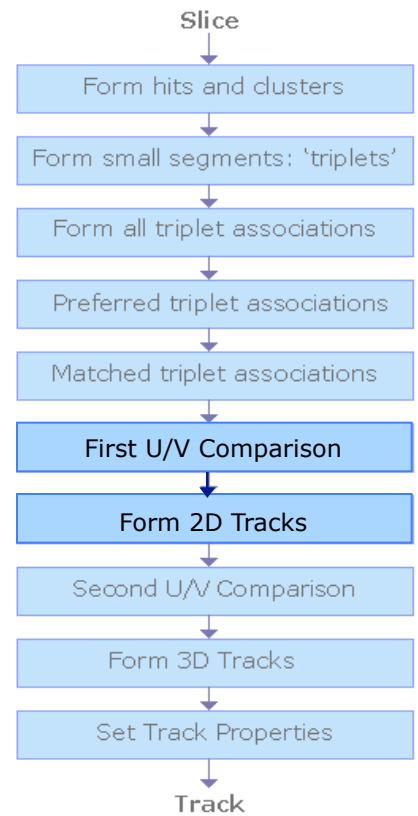
- Next, we look for the best seed segments for a track.
- These are the segments from which we can move back and forth **along a path of matched associations** to find a long track.
- For each seed segment we select, we try to propagate backwards and forwards, marking the segments we use with different 'flags'.



First we propagate outwards from the seed, along paths of matched associations, flagging the segments used with **1**

We then propagate back from the segments farthest from the seed, flagging the segments used with **2**

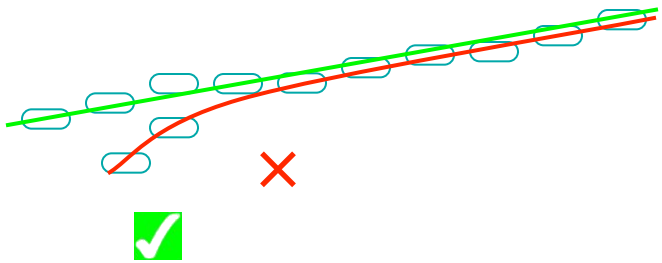
In this way, we label the segments in the longest 2D tracks.



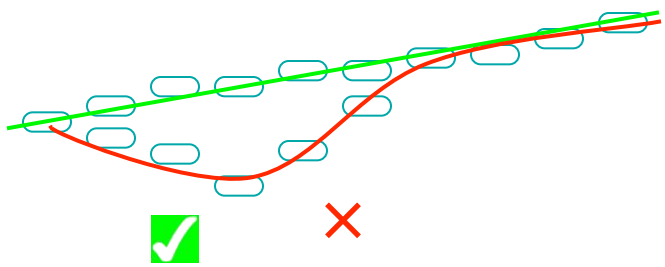
Form 2D Tracks – Cont'd

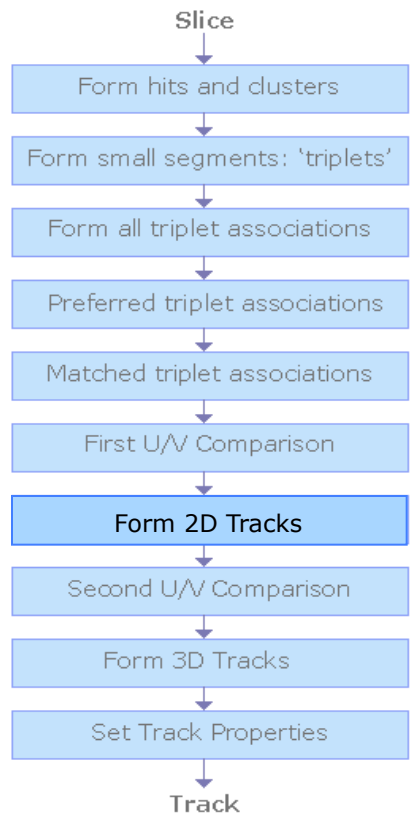
- From the selection of possible longest paths, we rate each one on its length and 'straightness' to find the best.

Each possible 2D track is given a score. The first contribution is from the number of clusters in the track.



The second contribution is a 'straightness' score. Tracks deviating from local linear fits are penalised.



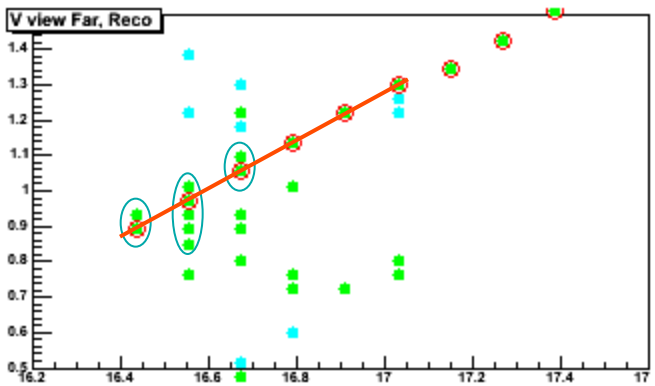


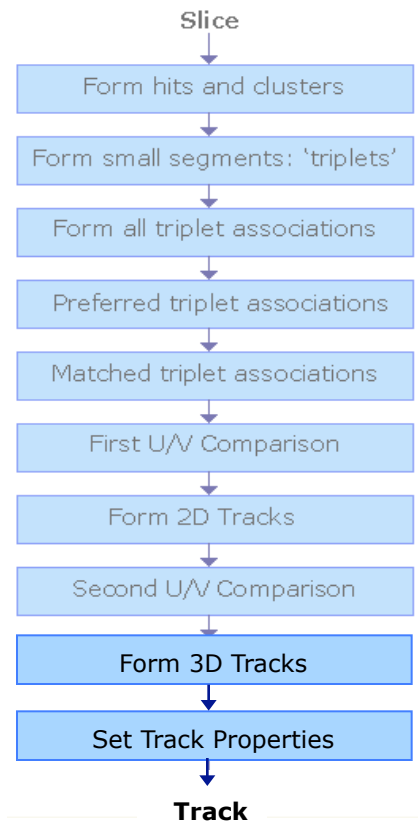
- Once we have found the best overall path, we join all the chosen segments together to form a 2D track.

Form 3D Tracks

- We finish the track finding process by selecting the best strips from the clusters, using linear fits.

Choose hits from clusters using a linear fit to 'clean' part of track.



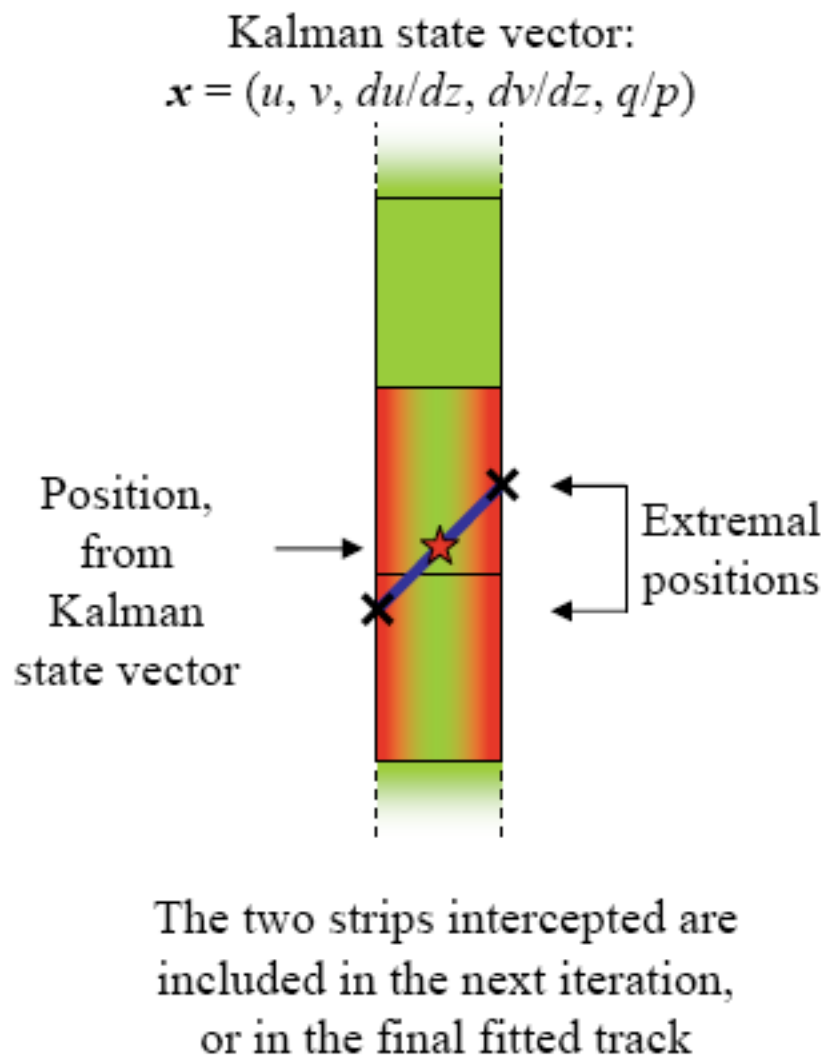


- Any obvious gaps in the track are filled and any obvious extensions at the beginning/end are made.

- Once the strips are found, we make the **final track** and pass it to the track Algorithm to set its properties (timing fits, gradients, traces, etc).

2. - Track Fitter

- Fitting algorithm uses information from the seed track and combines it with knowledge of propagation and energy loss of muons.
- Kalman filter algorithm uses the muon propagator matrix and the noise matrix.
- Set of recursive equations.
- State vector specifies the properties of the muon at a particular point on the track.
- Accounts for multiple scattering and energy loss of the muon in its motion between the planes.
- Muon Swimmer numerically calculates the new state vector at any requested z coordinate.



Kalman Filter variables

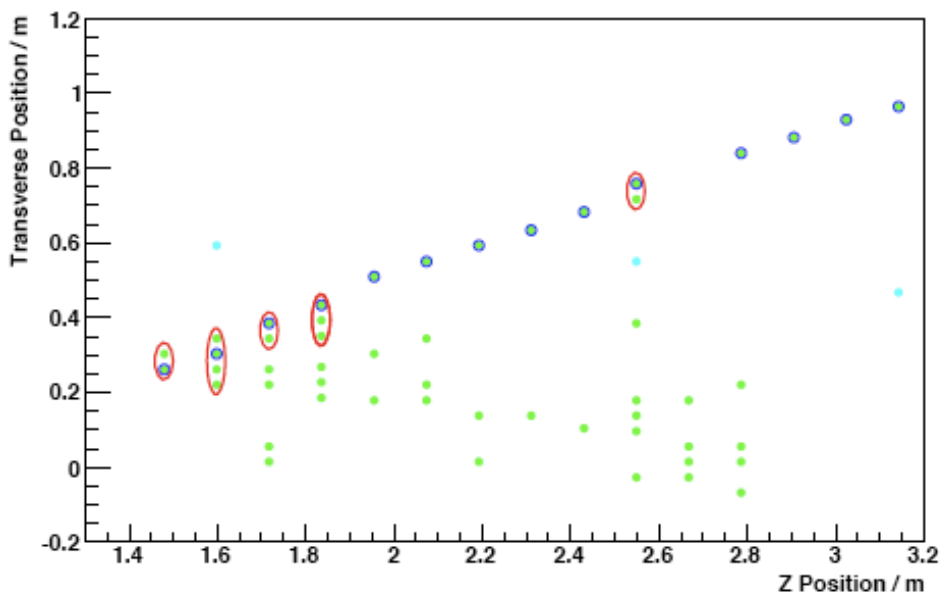
Input to filter

- List of strips is the seed track
- U & V View track's Z coord.
- Measured strip's transverse pos.
- measured error of that pos.

(charge weighted trans. Pos. of strip, helps to reduce noise)

Output

- Kalman state vectors at each plane update the list of seed strips as being most consistent with the vector.
- Vertex state vector includes q/p value at the track vertex, which defines charge sign and momentum of the muon.



Measured track strip position and errors are determined by examining the clusters of strips around the seed track strips.

Track Fitter - Cont'd

A summary diagram of how the MINOS track fitter works:

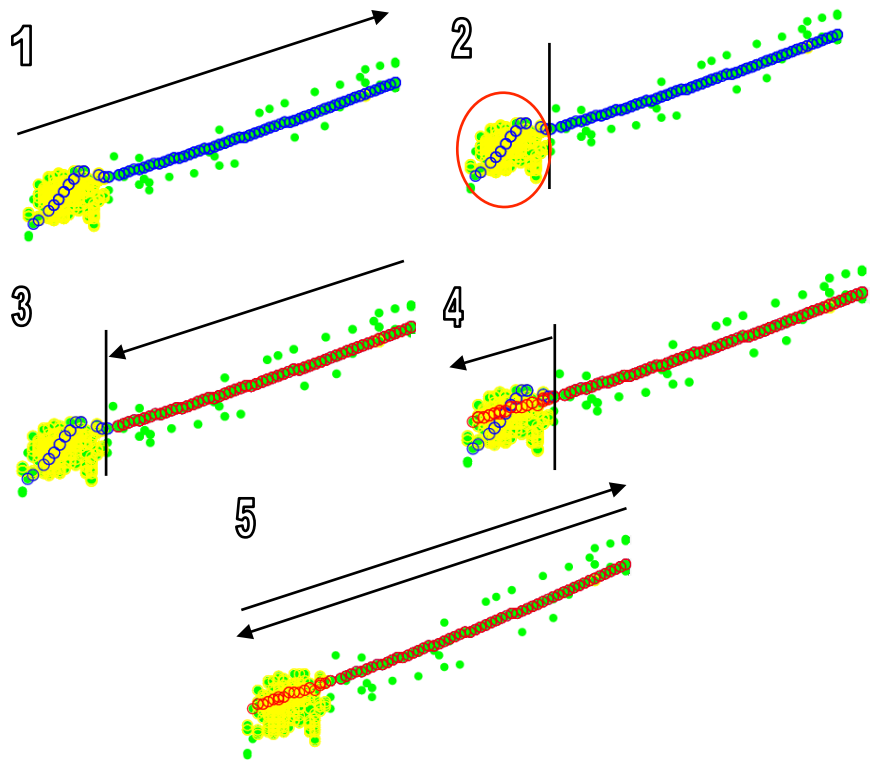
① Using finder strips, move from vtx to end.

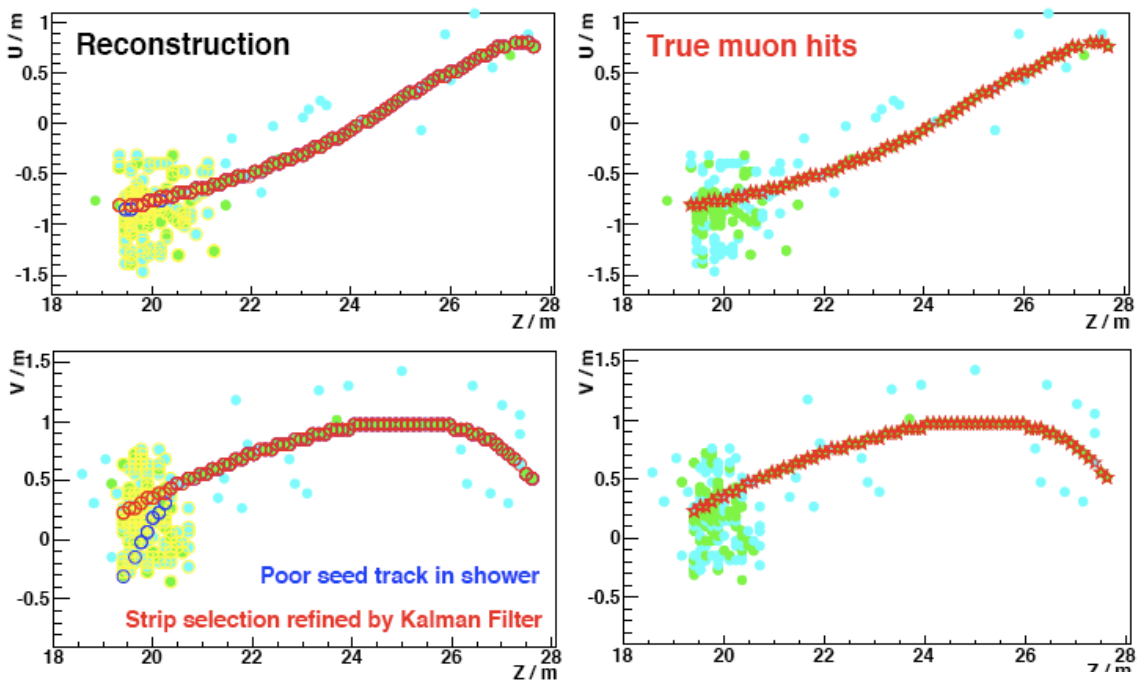
② Find large vertex shower. Discard track finder data for all planes inside shower.

③ Move from end of track to 'shower entry' plane.

④ Use swimmer to find track strips in shower. Using state vectors, find strips for next iteration.

⑤ Carry out next iteration, moving from vtx to end and back. Find final strips and set properties.



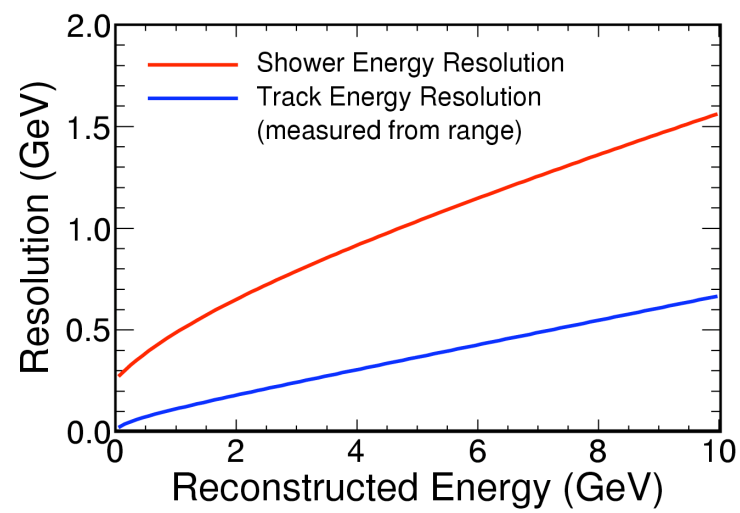


The track fitting process improves track strip identification within a large vertex shower.

Neutrino energy components:

$$E_\nu = E_{shower} \quad 40.4\%/\sqrt{E} + 8.6\% + 257\text{MeV}$$

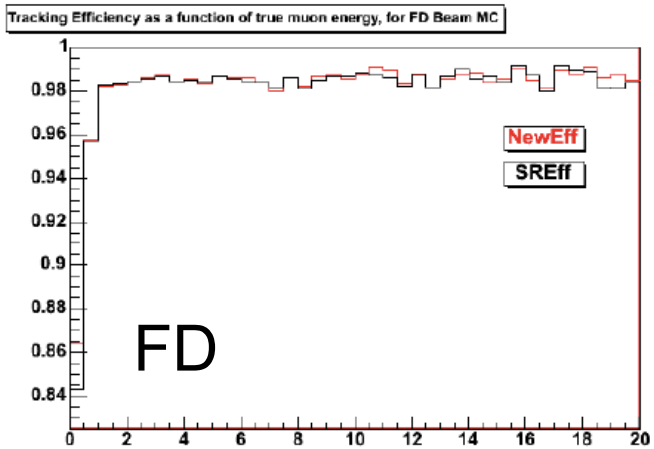
$$+E_\mu \quad 5.1\%/\sqrt{E} + 6.9\% \text{ range}$$



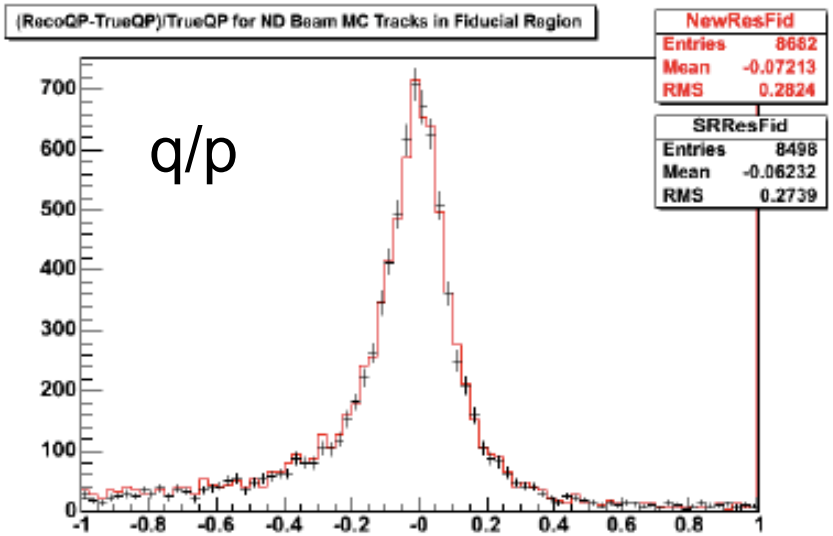
Shower vs Track Energy from range

Track reco qualities

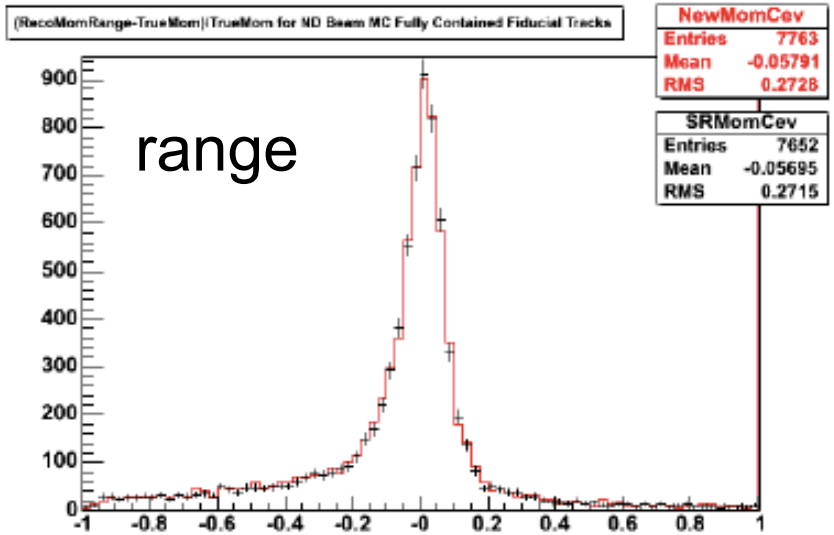
Good efficiency vs truth



Tracks in fiducial volume,
Low energy “useful” tracks.



(reco-true)/true



(reco-true)/true

Summary

- MINOS is quite mature experiment in terms of tracking and shower reconstruction techniques and methods.
- Similarity of ND and FD allows to use the same methods in both detectors.
- Magnetized detectors provide stable reconstruction of muon tracks of both signs, contributing to the adequate neutrino and antineutrino energy reconstruction in both running modes and detectors.