University of Pittsburgh

T2K

High-Angle ν_μ CCQE Measurements at T2K Using the P0D (Pi-zero Detector) for Low-Energy Events

DPF Santa Cruz
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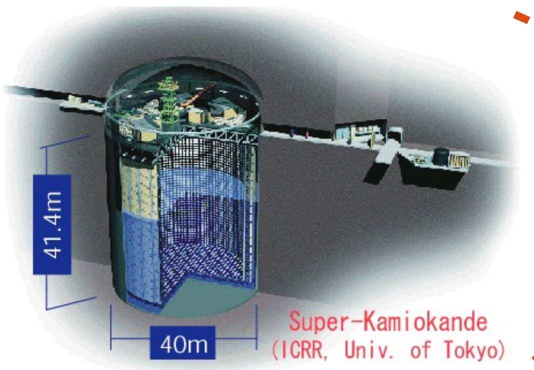
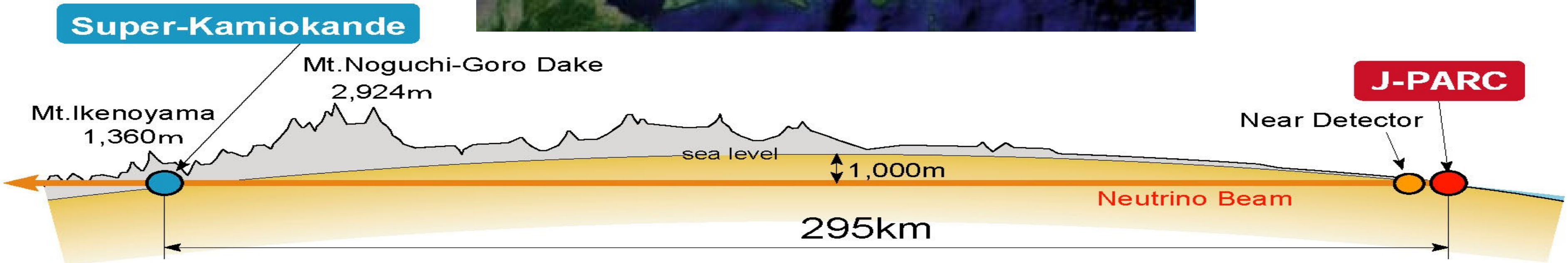
The T2K Experiment



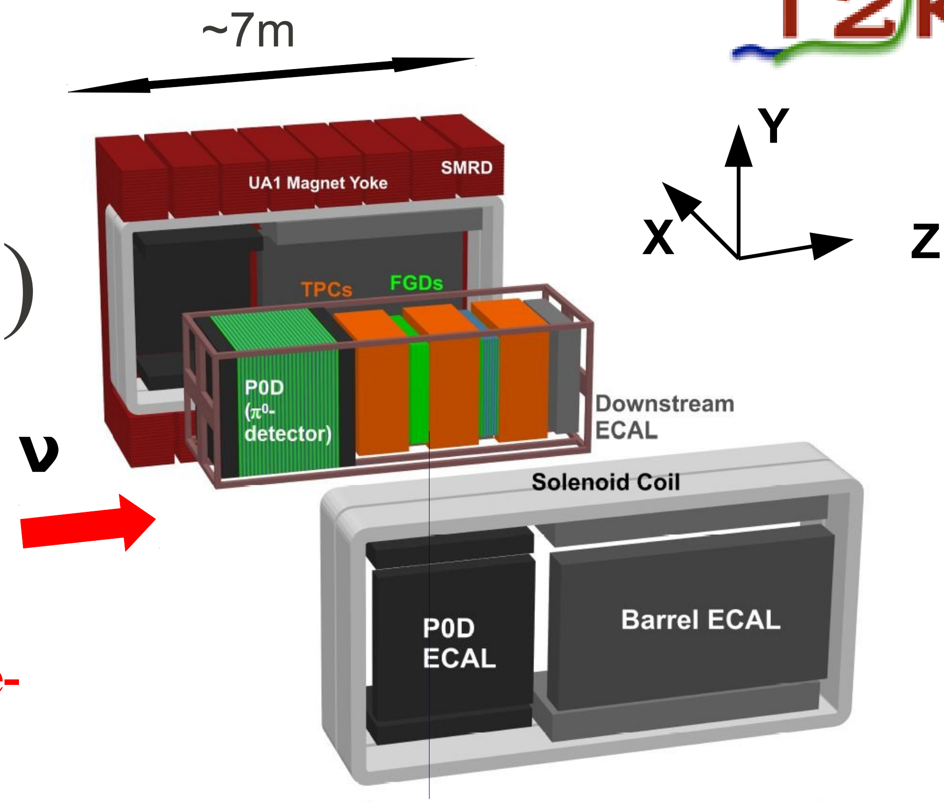


- Long-baseline accelerator neutrino experiment
- ν_μ disappearance / ν_e appearance
- Observed ν_e apperance at the 7.5σ level

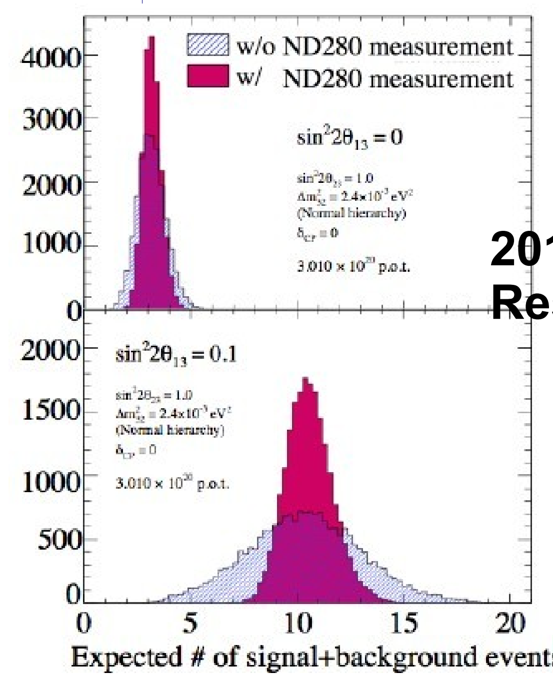
Physics goals:

- Precision measurements of neutrino oscillation parameters and cross-sections

Off-Axis Near Detector (ND280)



- **Pi-Zero Detector (P0D)**
  - Optimized for NCπ^o detection
  - Alternating layers of plastic scintillators and water targets
- **Tracker: Fine-Grain Detectors (FGD) &Time-Projection Chambers (TPC)**
  - Uses high-resolution scintillators and gas chambers for particle ID and momentum reconstruction
- **ECAL**
  - Detects EM (e's, π's) particles exiting the P0D/Tracker
- **Side Muon Range Detector**
  - Measures momenta of lateral muons by range



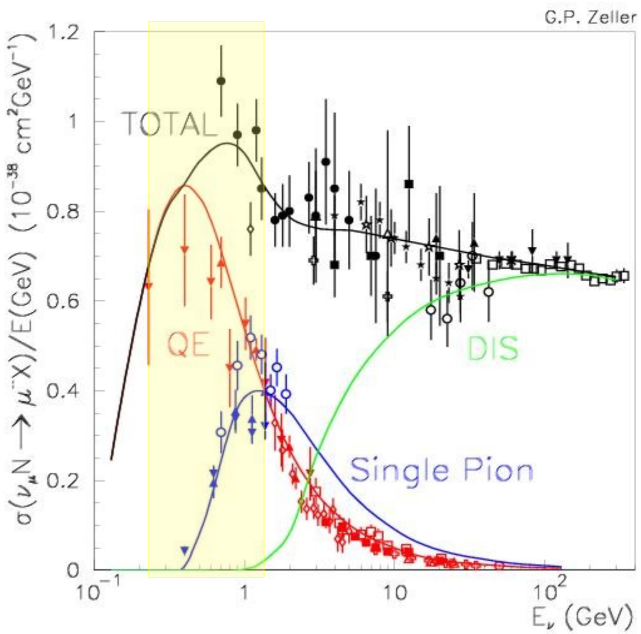
2012 Results

Where will this analysis fit into T2K's goals?

- (some) Existing P0D analyses
  - NC π^0
  - NC Elastic
  - NuE CCQE
  - P0D to Tracker CCQE & CC inclusive

- (some) Existing (non-P0D) T2K analyses
  - Tracker NuMu CCQE-like
  - Tracker NuMu non-CCQE-like
  - Tracker NuE flux measurement

At T2K accessible energies, the dominant interaction mode is CCQE. P0D-to-Tracker is focused towards higher energy, forward-going events. Adding a low-energy, high-angle sample will improve ND → FD fits, extend angular reach for x-sections, and significantly increase ND statistics.

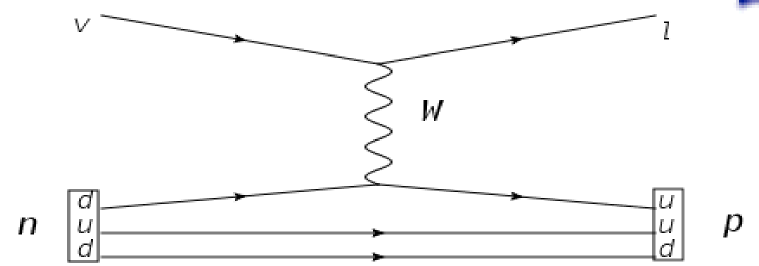


A note on interaction modes:

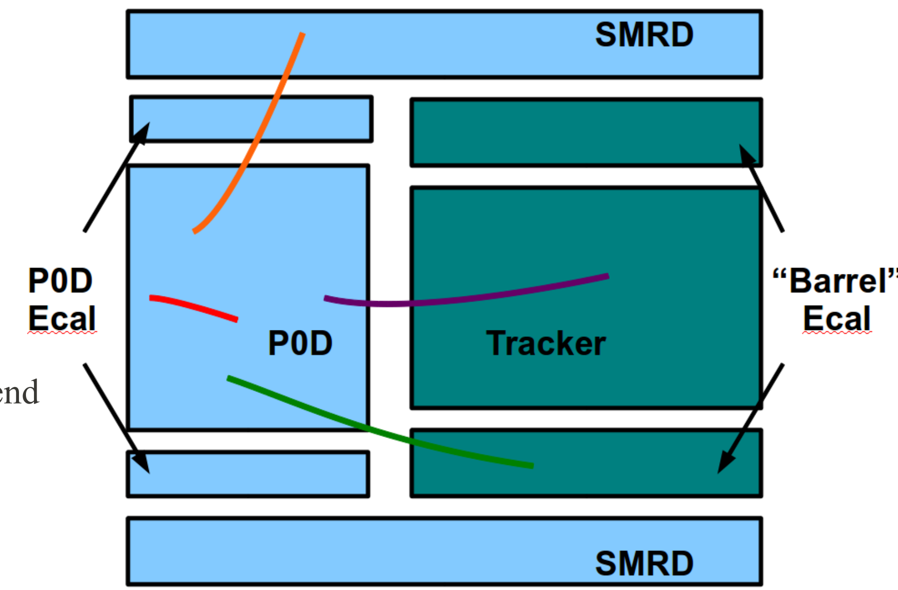
- Defined here by particles leaving the interaction vertex (i.e. by particles which are possible to detect)
- Related but not equivalent to true interaction mode with nuclear target

CCQE	1 muon No other leptons
CC 1-π	1 muon 1 charged pion
CC π^0	1 muon neutral pion
NCE	No leptons
NC 1-π	No muons 1 charged pion
NC π^0	No muons neutral pion

Event Selection



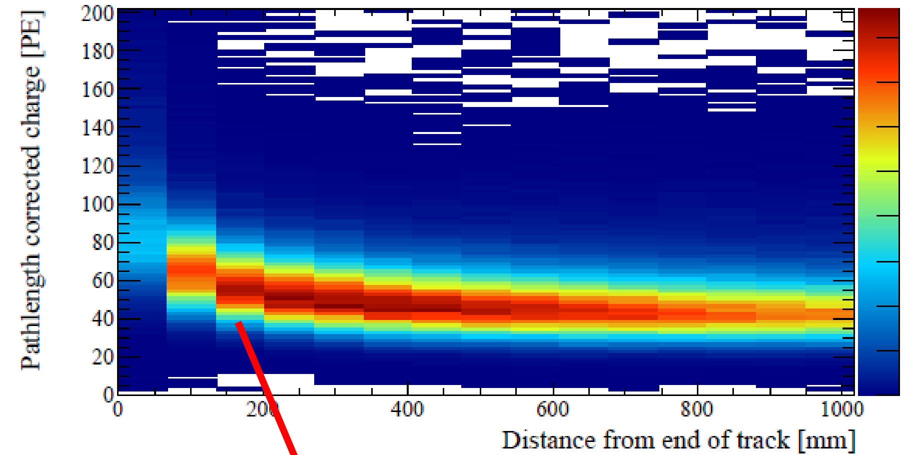
- NuMu CCQE events characterized by μ- and p final state particles; looking for event topologies compatible with this interaction mode:
- **P0D Contained**
  - Single vertex inside P0D fiducial volume (~25 cm from edge)
  - 1 or 2 tracks associated with this vertex
  - All tracks contained within the P0D active volume
    - No activity within 3 bars from the edge (~7 cm)
  - Longest track consistent with a μ
  - 2 Tracks: Shortest track consistent with a proton
- **Side-Exiting**
  - Track exits through the side of the P0D, but not out the downstream end
  - Must have matching P0D-ECal object: matching criteria shown later
  - Matching SMRD object not required, but used when present.
- **P0D → Tracker**
  - Existing analysis currently being included into the ND → FD fitting
- **P0D → Anything Else**
  - Not excluded for physics reasons: just too much for 1 person!
  - Hope to eventually have a complete sample of all NuMu CC events originating in the P0D

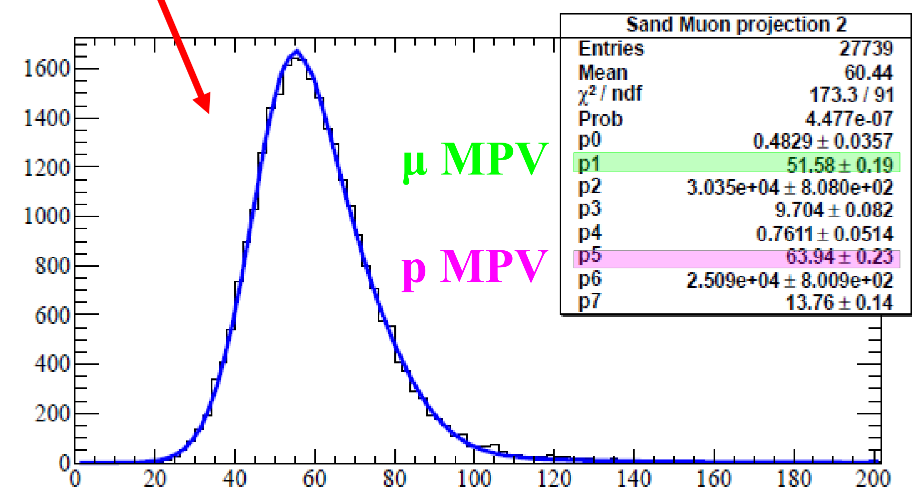


Particle ID

- Tracks in the P0D are most often μ-, but can also be p, e, π^0, $\pi^\pm$
- Proton/Muon PID (developed for NCE selection)
  - A profile of expected charge deposition from stopping muons developed from sand muon data
  - Use Most Probable Values and Gaussian sigma for each distance bin to discriminate muons & pions from protons
  - Can be used to separate NC elastic from CCQE in the 1-track contained sample and CC1Pi from CCQE in the 2-track contained sample
  - Can use the profile from the start or the end of the track: Necessary since P0D reconstruction treats all single tracks as "forward going"
  - Veto Out of P0D events for side-exiting sample?

Sand Muon Data



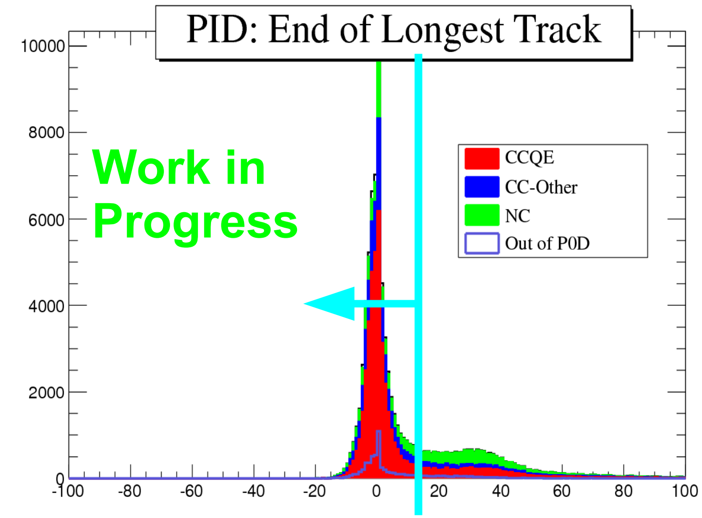


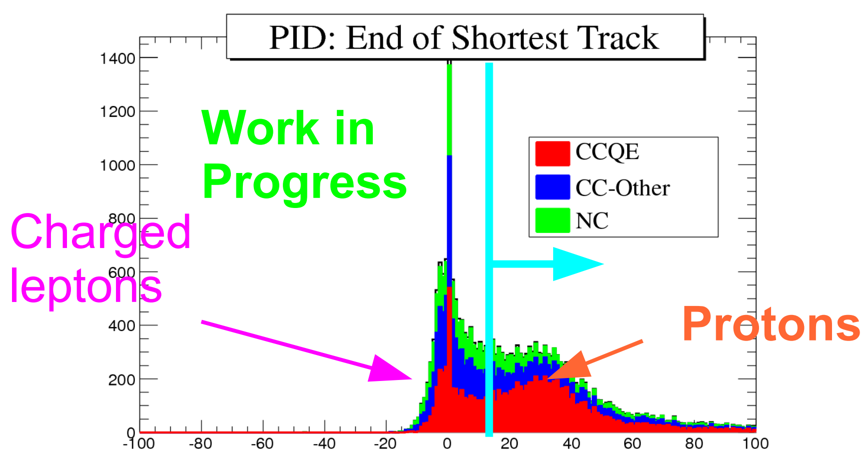
$$Pull_{PID} = \sum_{node=0}^{node=N and \Delta X <= 410mm} \frac{x_{measure} - \bar{x}_{exp,\Delta X bin}}{\sigma_{exp,\Delta X bin}}$$

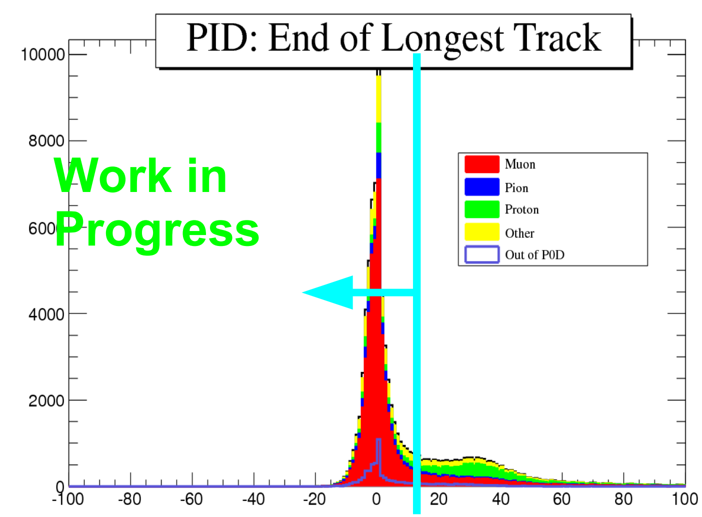
Particle ID:

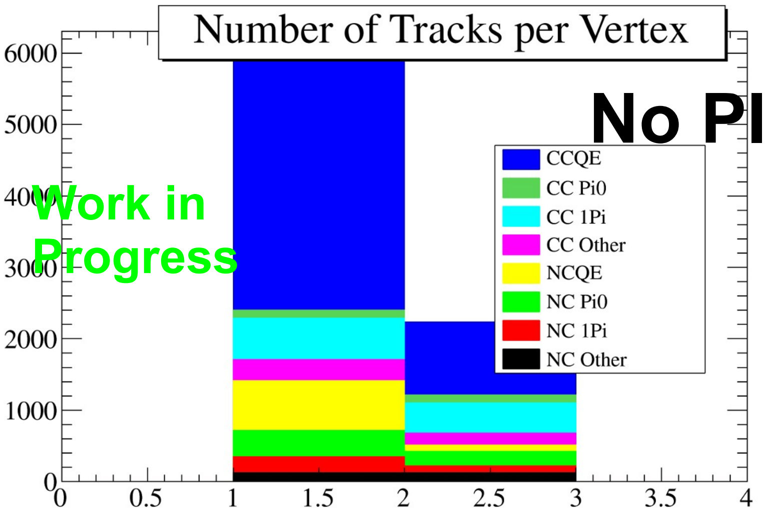
What does this PID look like for the contained sample?

- Strong discrimination between CC & NCE
- Longest track PID does little for CC backgrounds
  - CC1Pi produces μ^-
  - Charged π's are effectively identical to μ's
- A simultaneous PID on shortest track in 2 Track sample can reduce CC-other backgrounds





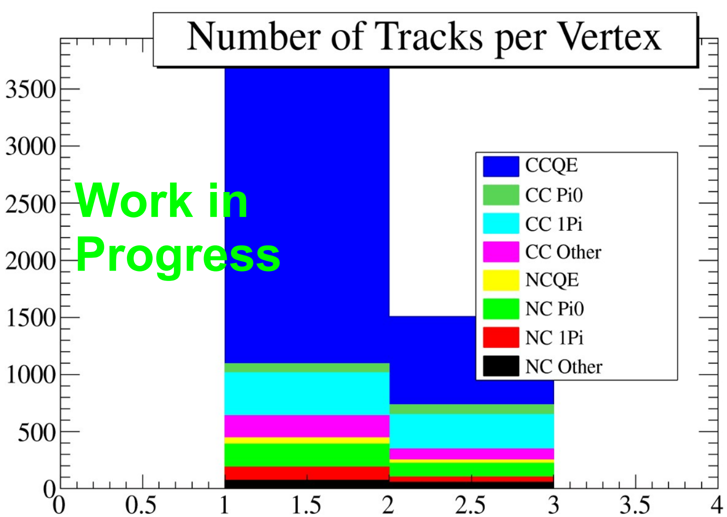




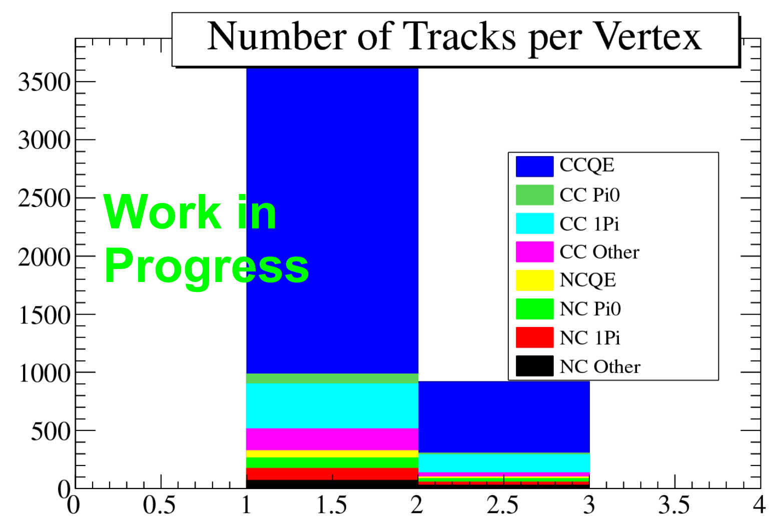
No PID

Relative sizes of each interaction mode in events passing selection

Longest Track PID = μ

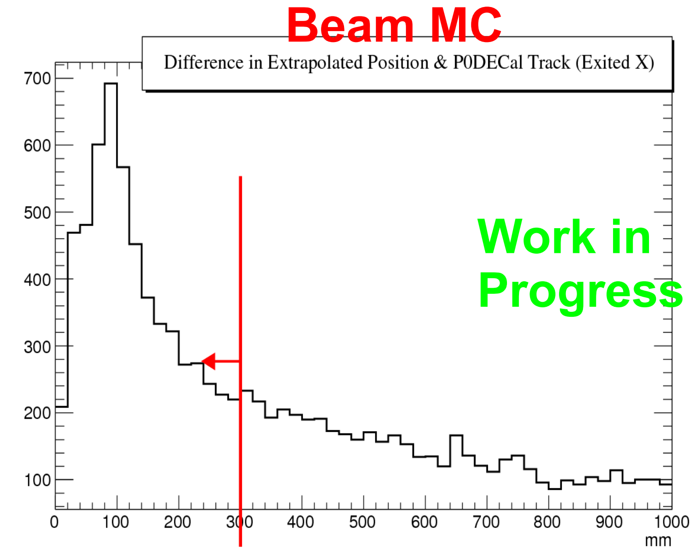


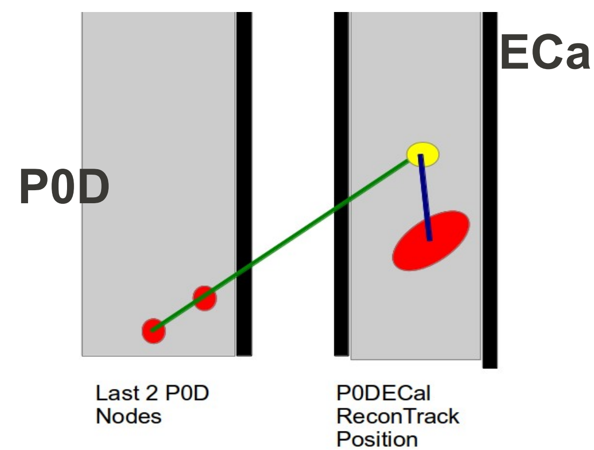
Longest track PID = μ
Shortest track PID = p



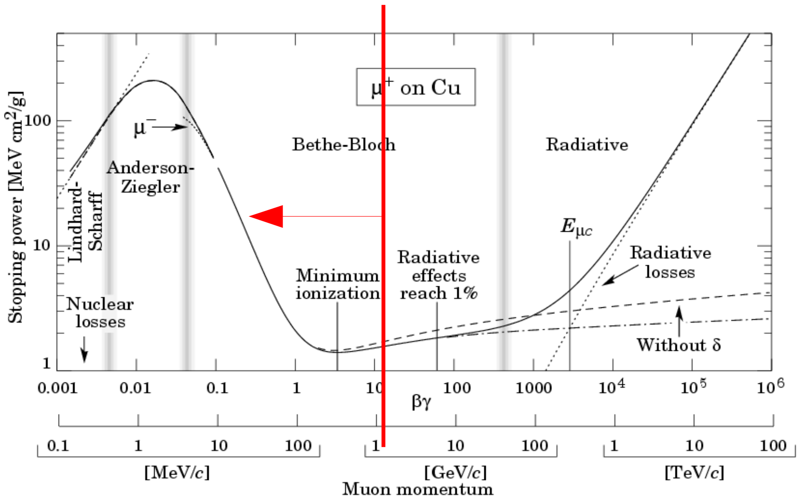
Track Matching

- P0D to P0D-ECal :
  - Fit a line to last two nodes inside the P0D; extrapolate across the gap between the two sub-detectors
  - Difference between extrapolated point and reconstruction object in P0D-ECal < 30 cm
- P0D/P0D-ECal to SMRD:
  - Time difference between P0D Vertex and SMRD object < 100ns
  - SMRD object on same side of detector as P0D-ECal object

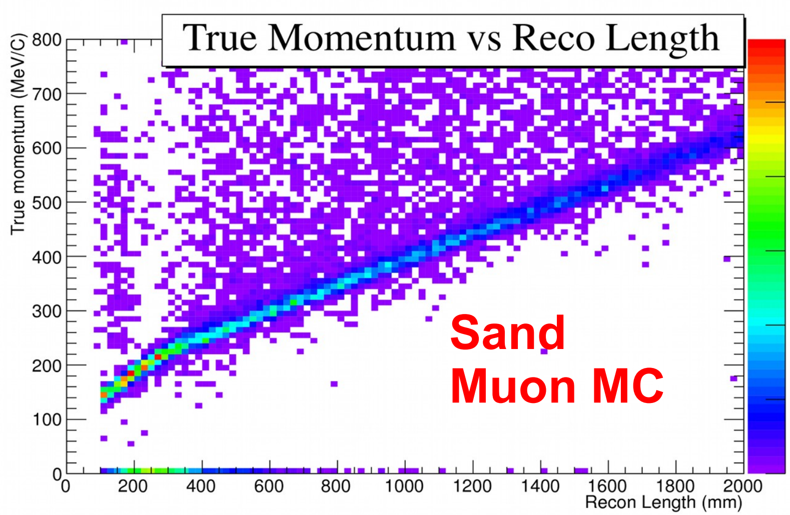


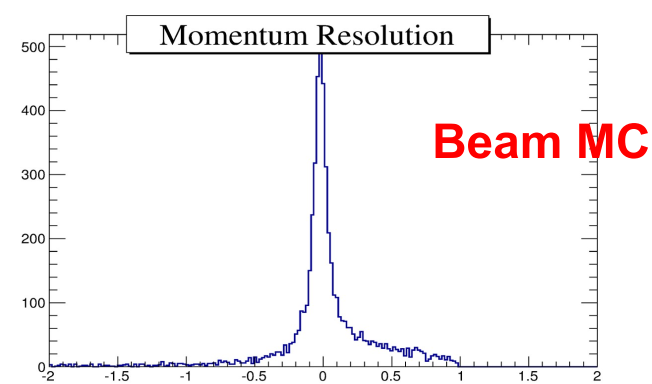


Momentum Reconstruction



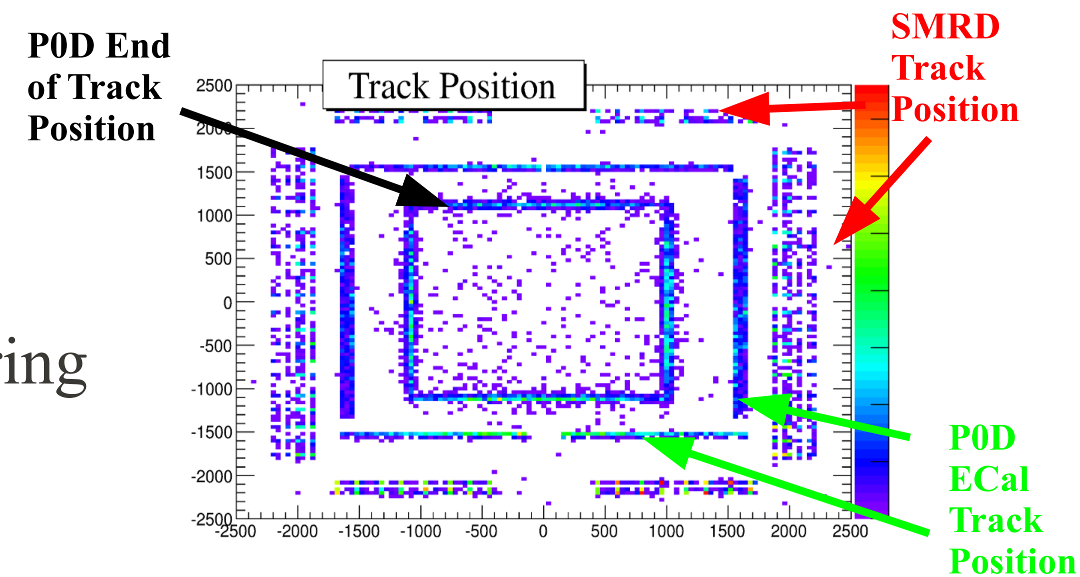
- Muons in these samples typically have momenta around 300-700 MeV/c
  - In this region, the Bethe-Bloch is effectively flat (i.e. stopping power is a constant)
- Since stopping power is approx. constant, we can reconstruct momentum loss from range
- Inside the P0D, momentum resolution ~5%

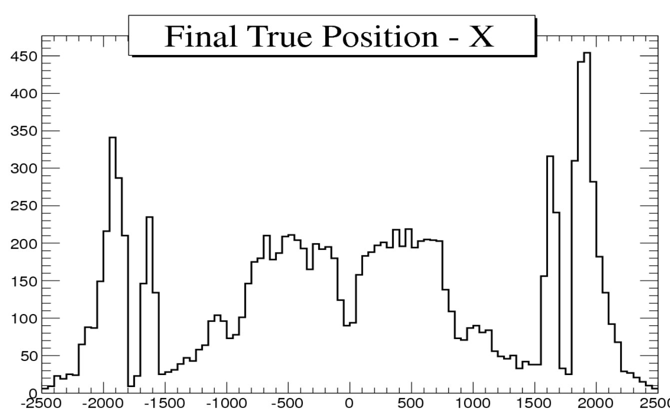




Momentum Reconstruction: Side-Exiting

- Complicated by 2 features:
  - ~80% of tracks entering the P0D-Ecal pass completely through
  - Much denser dead material and much less resolution in the SMRD
- Is track-by-track momentum reconstruction possible for this sample?





	Contained		Side-Exiting	
5×10^{20} p.o.t. Water-in MC 2x current T2K water-in data	1 Track 40379 total selected	2 Track 9694 total selected	1 Track 10243 total selected	2 Track 2989
Signal (true ν_μ CCQE in FV)	23724 (0.59)	5600 (0.58)	6201 (0.61)	1848 (0.62)
Out of Fiducial	9094 (0.23)	799 (0.08)	2926 (0.29)	313 (0.10)
Out of P0D (subset of above)	3973 (0.10)	96 (~0.01)	1721 (0.17)	81 (0.03)
ν_μ Non-CCQE (in FV)	6862 (0.17)	3122 (0.32)	657 (0.06)	709 (0.24)
Non-ν_μ CCQE (in FV)	266 (~0.01)	9 (~0.01)	104 (0.01)	13 (<0.01)
Non-ν_μ Non-CCQE (in FV)	433 (~0.01)	164 (0.02)	77 (<0.01)	48 (0.02)

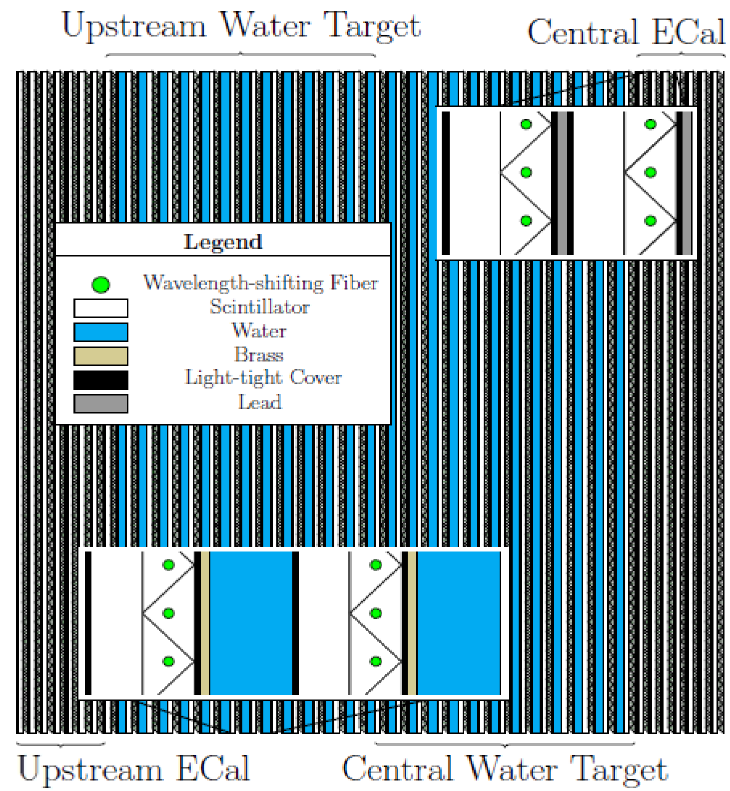
In Summary

- Despite not being designed optimally for the task, the P0D can yield a useful addition to current T2K CC analyses
- MC study shows that with a few selection criteria, we get
  - Good signal selection purity
  - Good statistics
  - A vast improvement on accessible phase-space for P0D-based ν_μ CCQE interactions
- Next steps: open this analysis to current T2K data, and integrate into the ND analysis framework.

Backup Slides

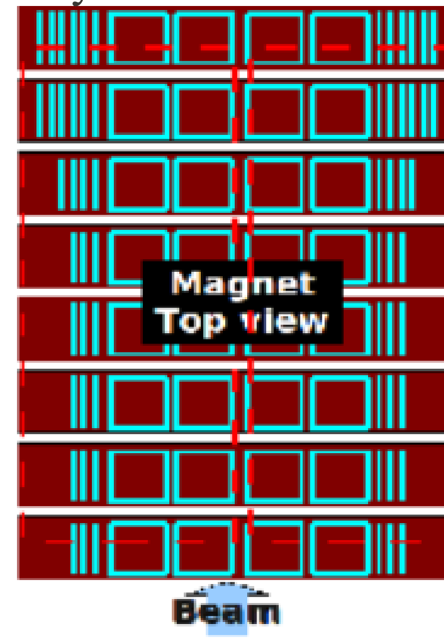
The P0D Subdetector

- P0Dules
  - Basic "unit" of the P0D
  - Composed of 2 layers of plastic scintillator bars: 1 oriented vertically (X-view) and 1 oriented horizontally (Y-view)
  - Hits in each view are reconstructed together as 3-D nodes
- 4 "Super-P0Dules"
  - 2 Ecals
    - 7 P0Dules separated by lead sheets
  - 2 Water Targets
    - 26 P0Dules separated by brass sheets and 25 layers of water bags
    - Water mass (~3,000kg) can be drained
  - 10,400 scintillator bars (33 mm x 17.5 mm)
    - Very few dead channels (~30)

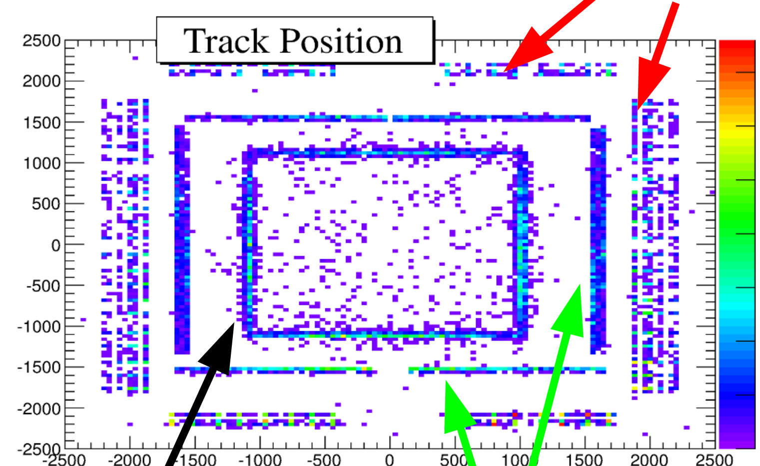


- P0D-ECal composed of 6 compartments surrounding the P0D
  - Alternating layers of plastic scintillator to lead (~ 4:1)
  - No Z reconstruction! 2D objects only.
- SMRD: the recommissioned UA1 magnet surrounds the entire Off-Axis Near Detector
  - Extremely granulated due to physical constraints of the magnet
  - Sides:
    - 3 layers for first 5 yokes
    - 4 layers for 6th yoke
    - 6 layers for last 2 yokes
  - Top/Bottom
    - 3 layers the length of the detector

SMRD Layout



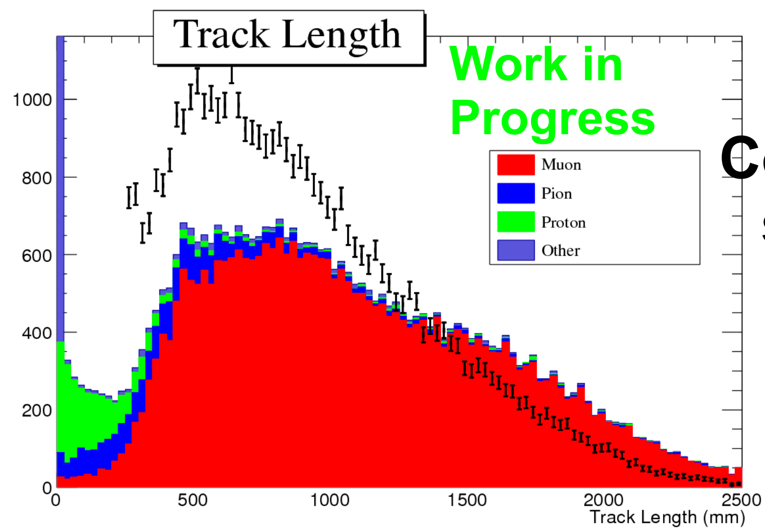
SMRD Track Position



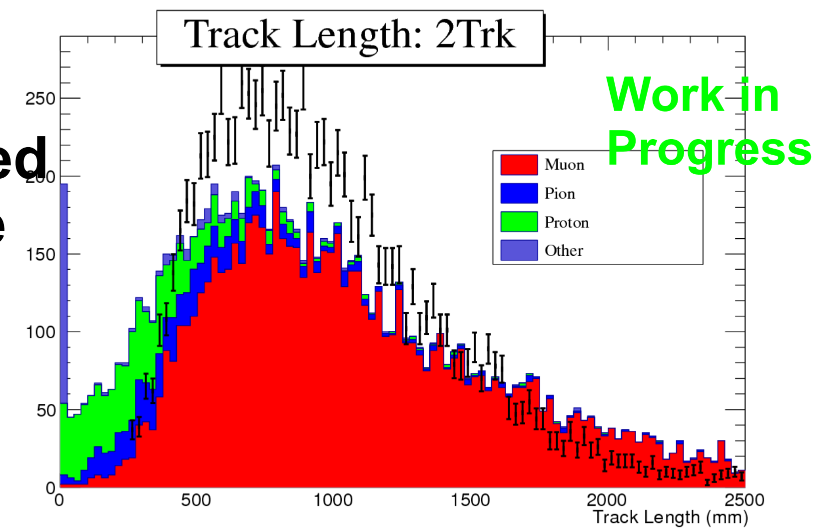
P0D Last Node Position

P0D ECal Track Position

1 vs 2 track kinematics: longest track length reconstruction



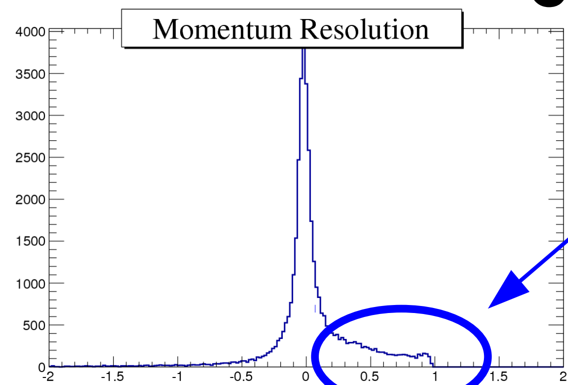
Contained sample

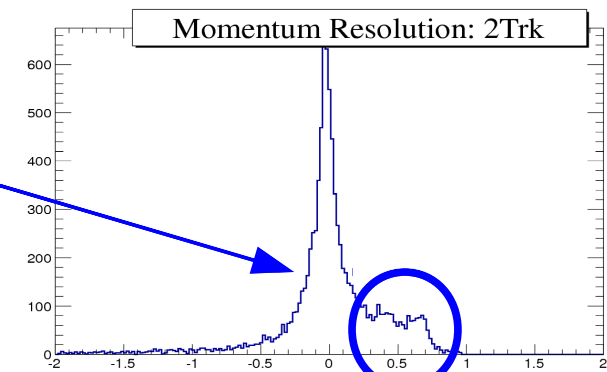


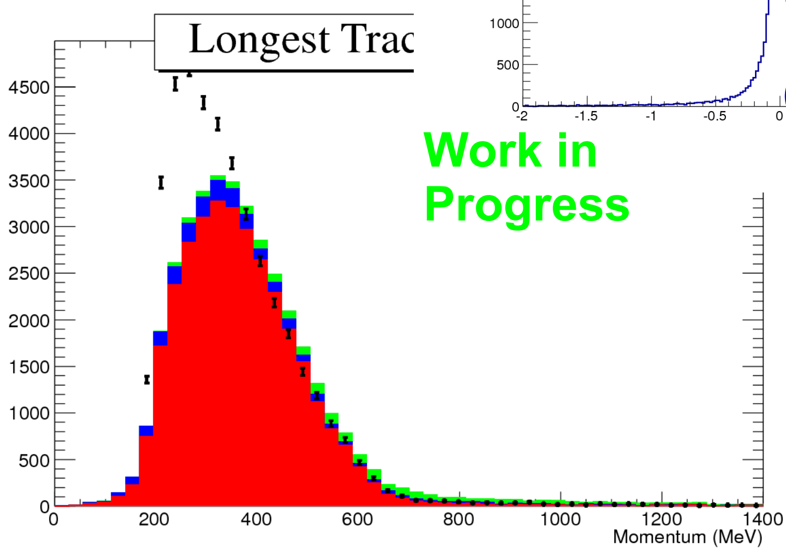
1 vs 2 track kinematics: longest track momentum reconstruction

Contained sample

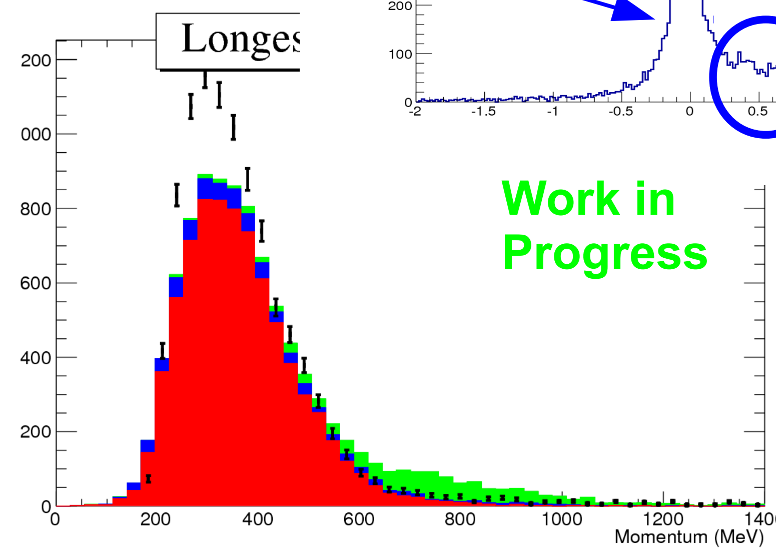
Protons mis-ID as muons



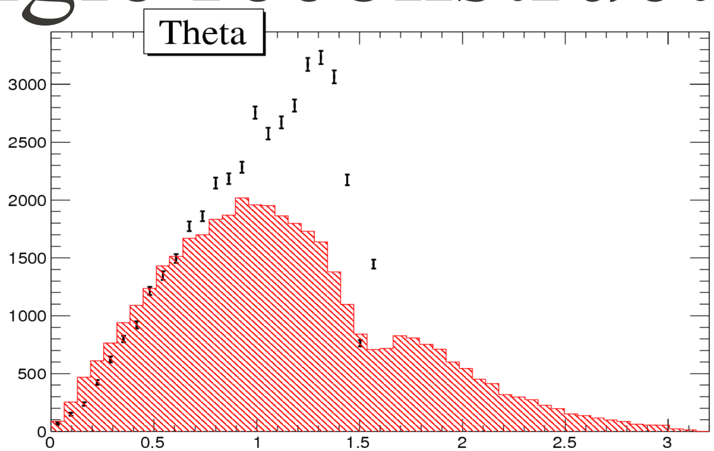


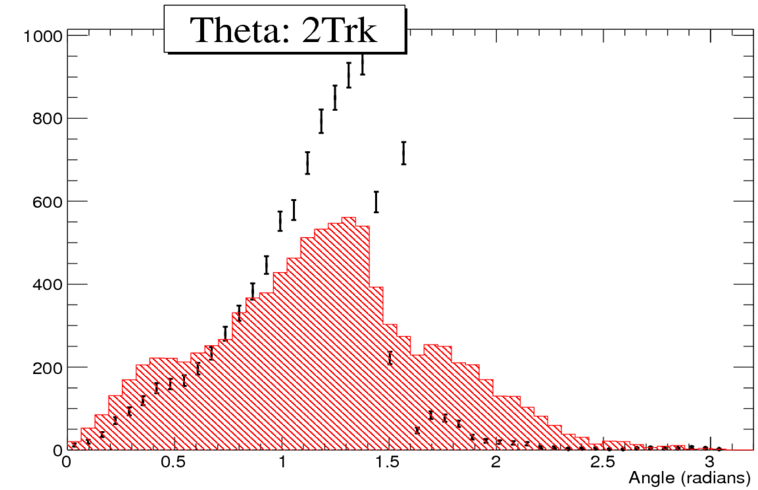


muon
pion
proton



1 vs 2 track kinematics: longest track angle reconstruction





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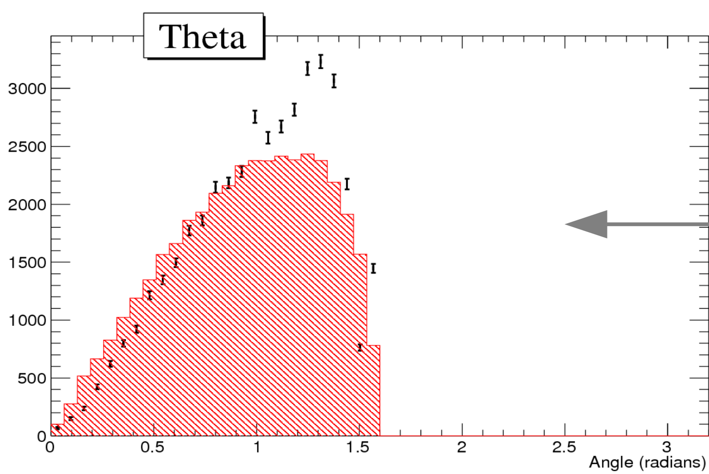

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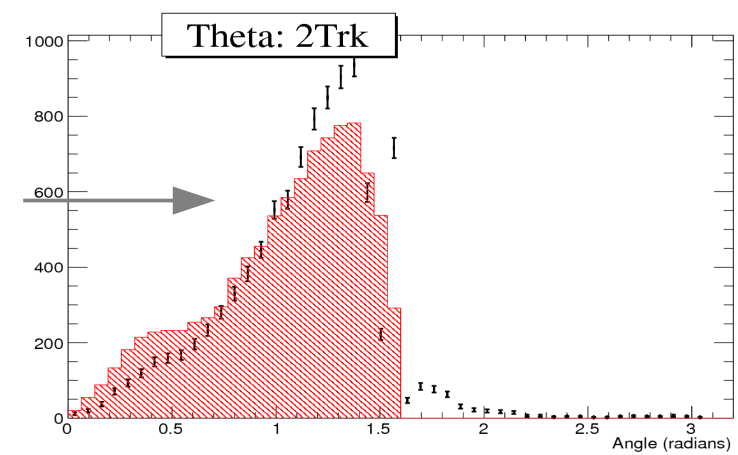

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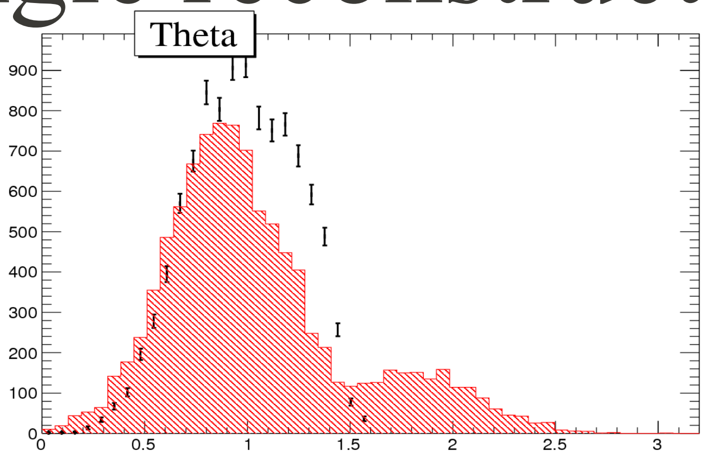
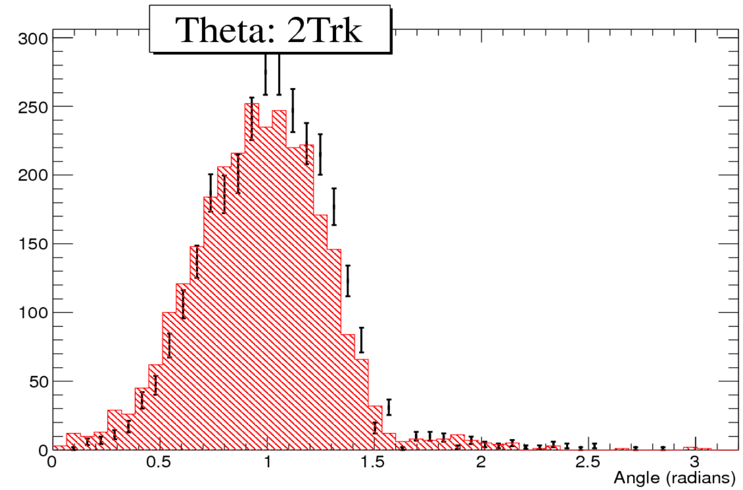
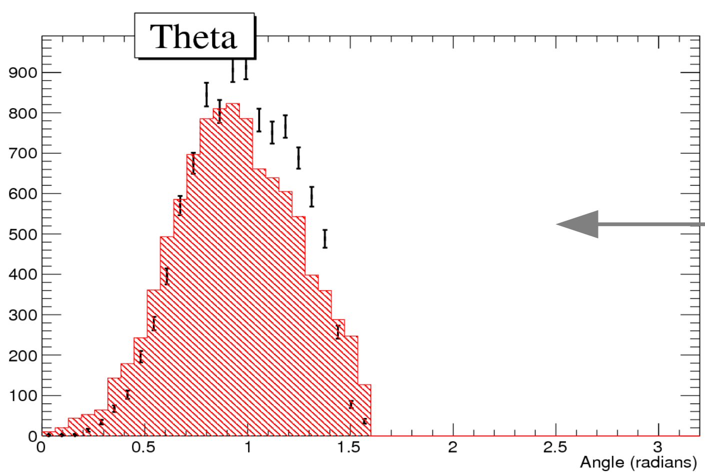


Exiting sample





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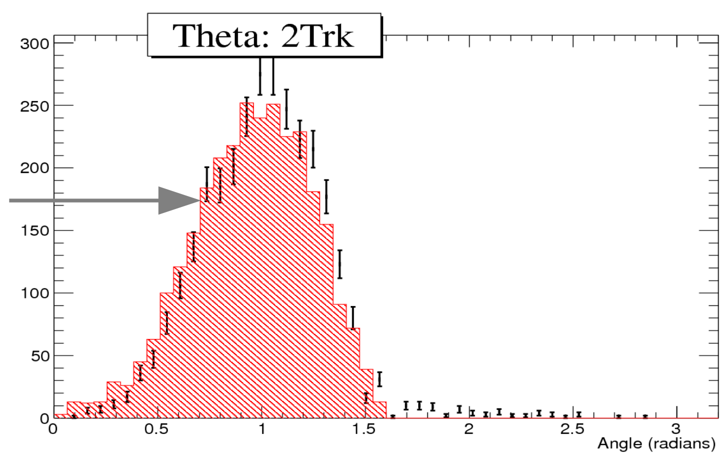
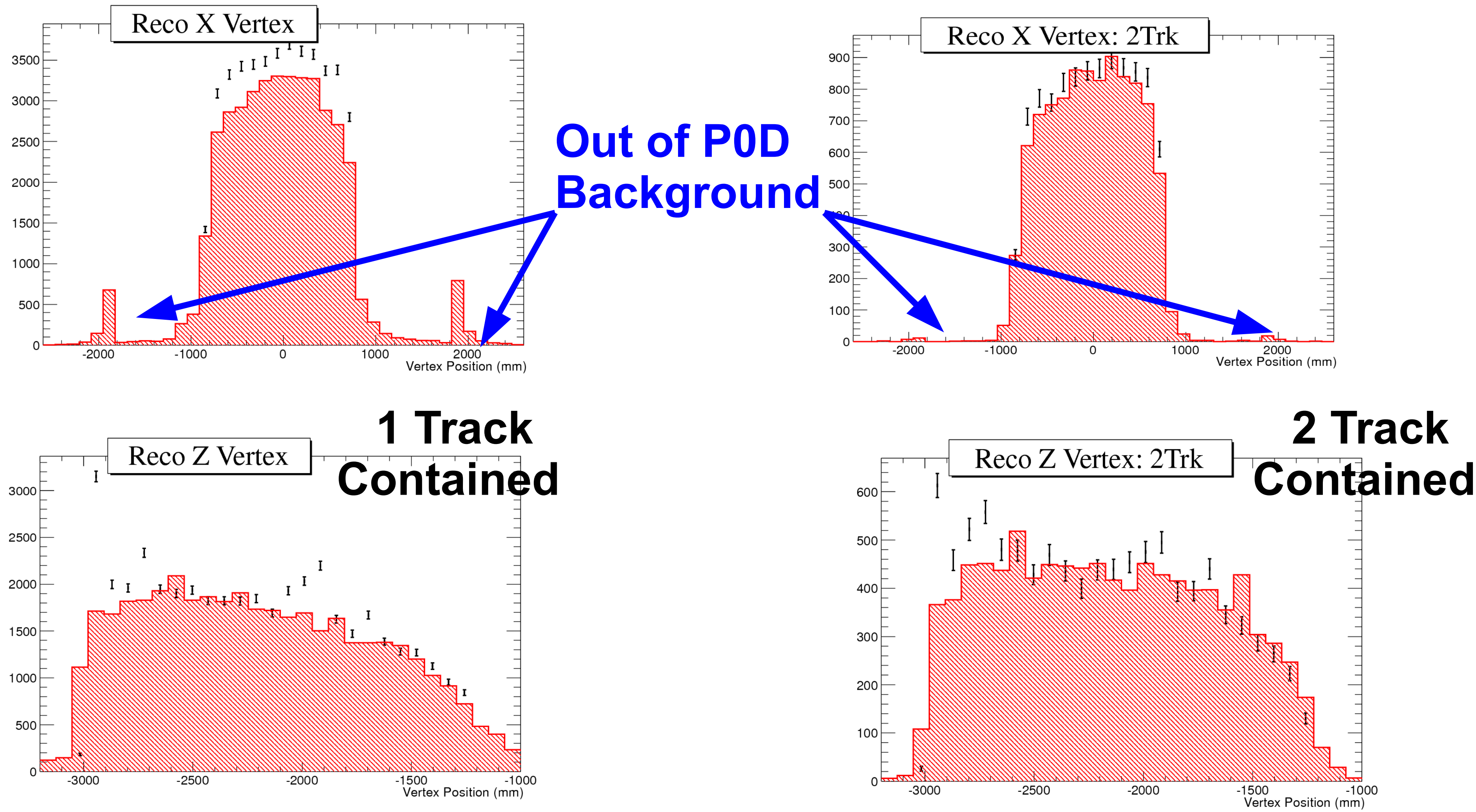


Vertex Reconstruction



Vertex Reconstruction