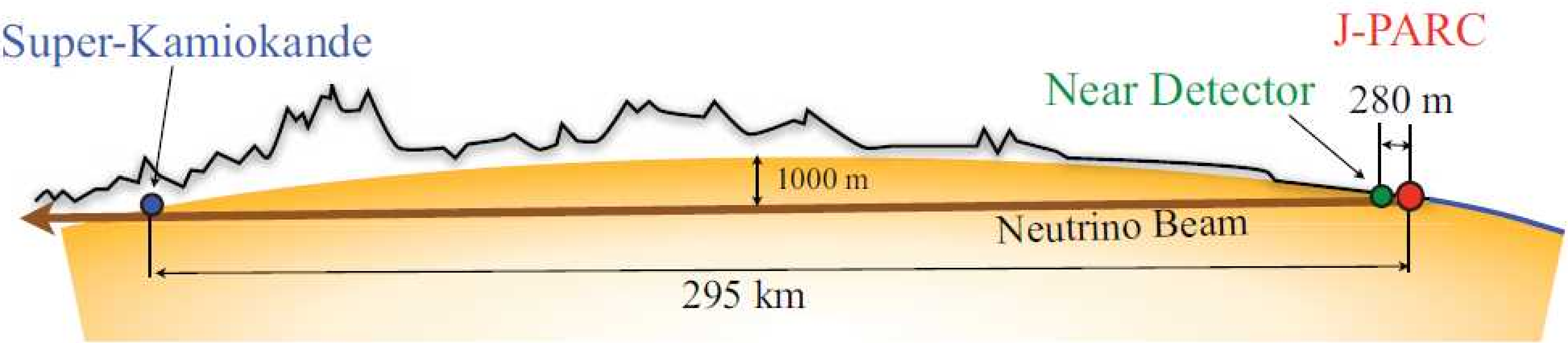
Charged Current Quasi-Elastic Scattering of Muon Neutrinos at the T2K Near Detector

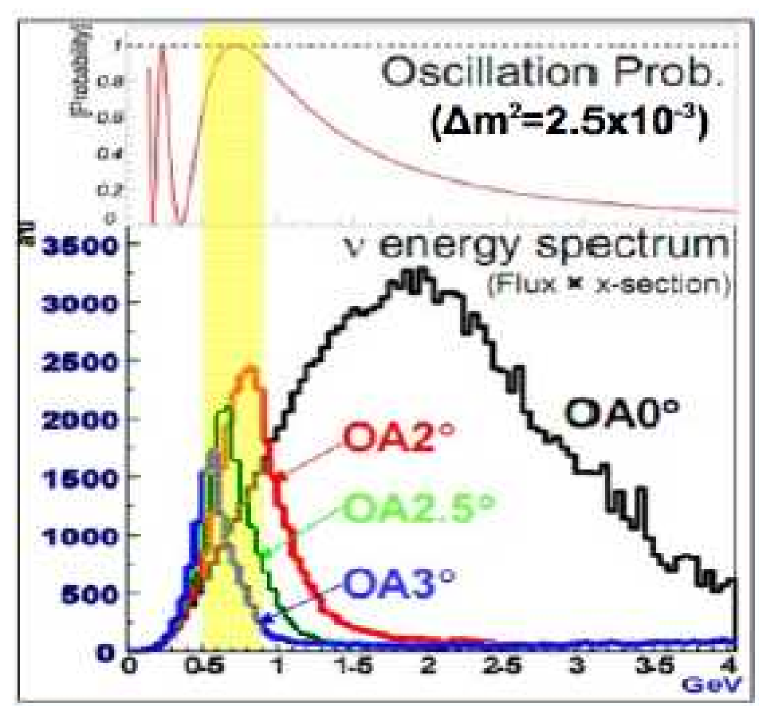
Brian Kirby (UBC, Canada) on behalf of the T2K Collaboration

APS DPF, Providence RI, August 10th 2011

The T2K Experiment



- 295km long baseline neutrino oscillation experiment using an intense off-axis muon neutrino beam produced at J-PARC
- Proton beam and off-axis angle tuned to produce a narrow energy spectrum peaked at 600 MeV
- Searching for ν_e appearance in a ν_μ beam due to neutrino oscillations, measuring unknown neutrino mixing angle θ_{13}
- Improve precision in Δm^2_{23}, $\sin^2 2\theta_{23}$ by factor of 10 over previous estimates through ν_μ disappearance
- Goal: $\delta(\Delta m^2_{23}) \sim 10^{-4}$ eV^2, $\delta(\sin^2 2\theta_{23}) \sim 0.01$,



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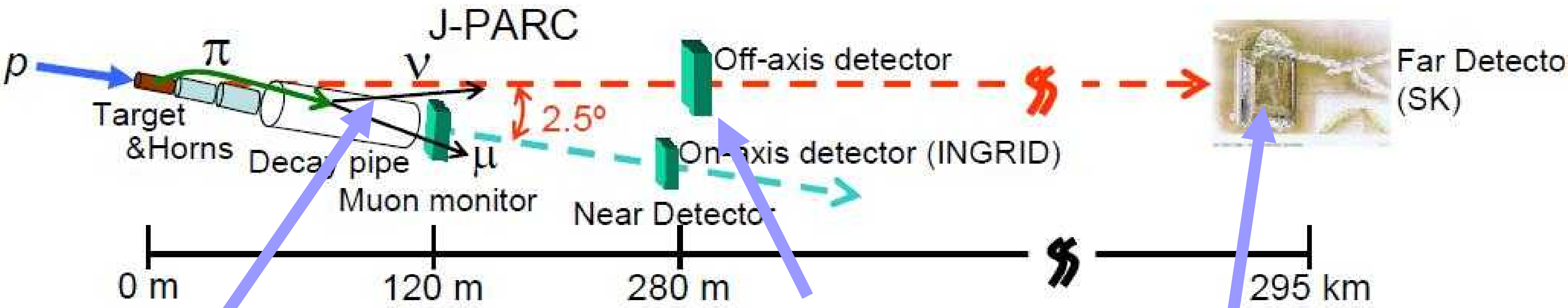
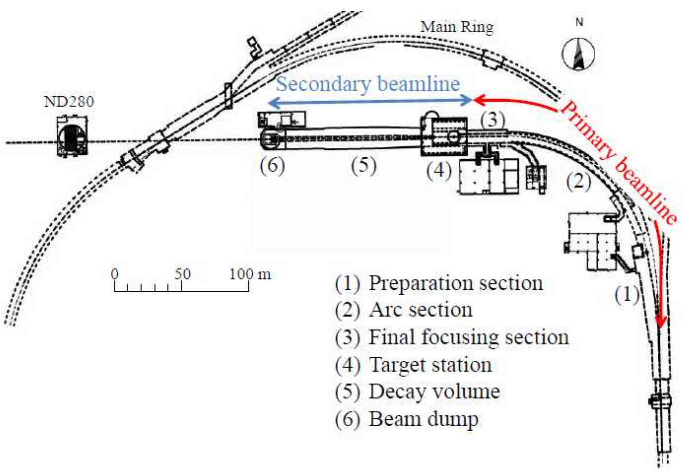
The T2K Beam and Detectors

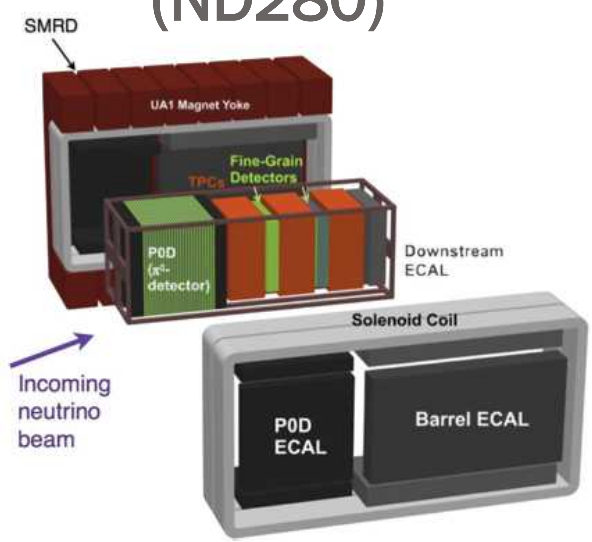


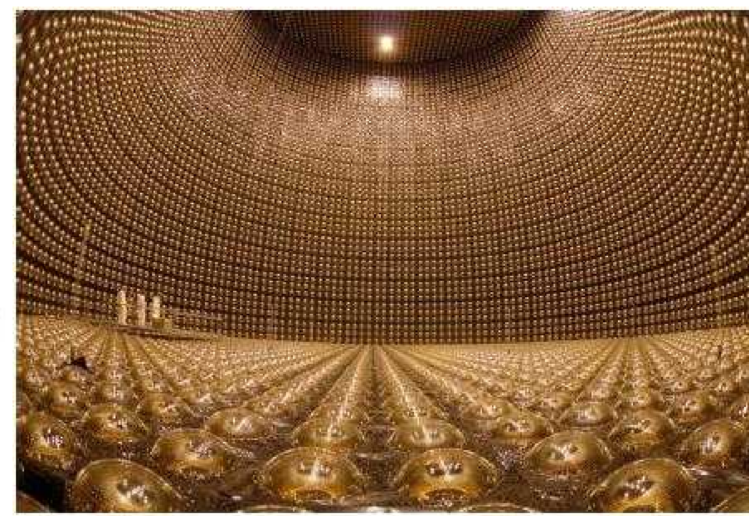
JPARC Off-Axis Neutrino Beam

Off-Axis Near Detectors (ND280)

Far Detector (Super K)

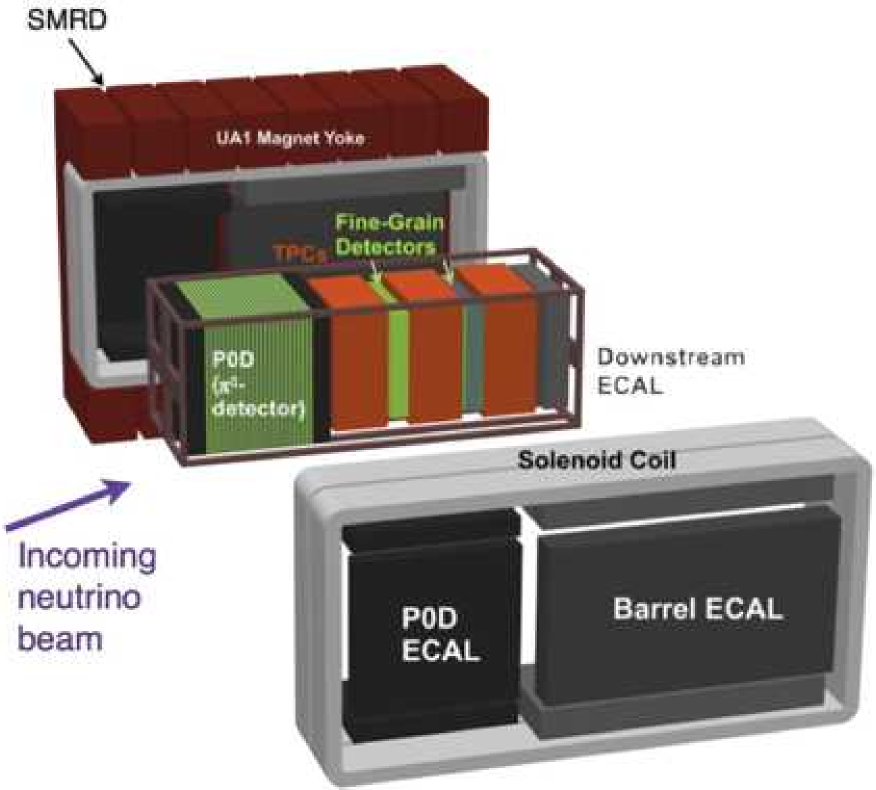




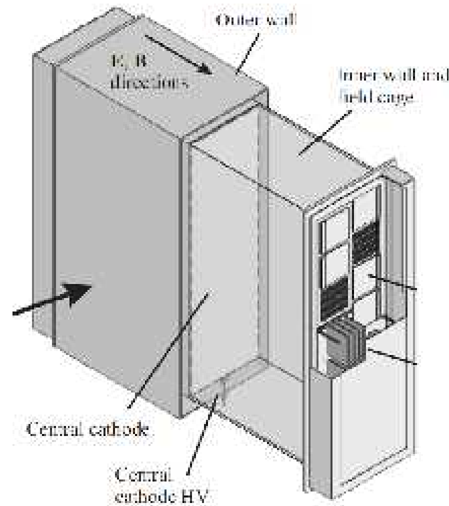


- Off-axis near detectors (ND280) reconstruct neutrino interactions, measures unoscillated flux and energy spectrum as well as cross-sections for several processes
- Super-Kamiokande is 295 km away in off-axis direction, measures oscillated flux

The 280m Near Detectors

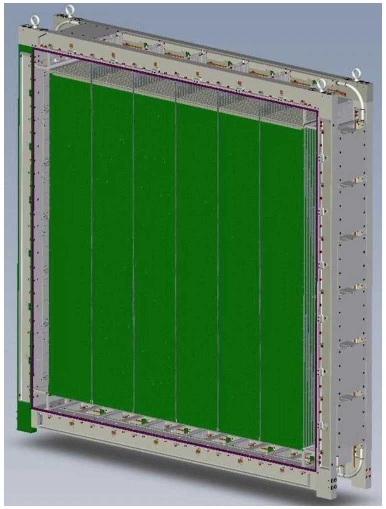


- Central tracker includes 3 Time Projection Chambers (TPCs) and 2 segmented scintillator detectors (FGDs)



TPCs

- Drift gas detector with 300-700 um spatial resolution
- Measures track curvature, charge and momentum
- Track dE/dx measurement used in PID



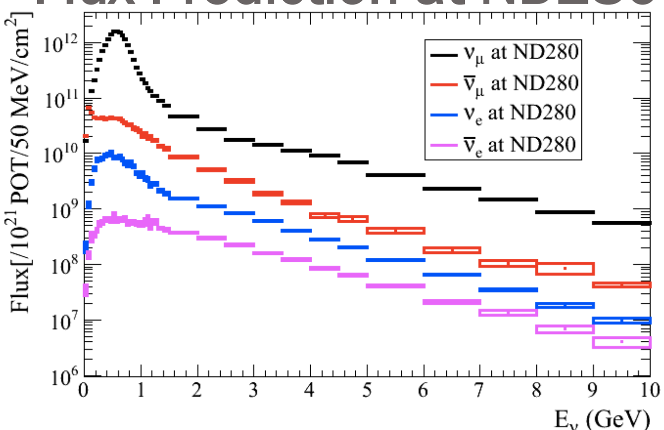
FGDs

- Scintillator detectors with 1.1 tonnes target mass
- 1cm square bar layers stacked in alternating XY orientations for 3D tracking
- FGD2 contains water layers between plastic to measure oxygen/carbon relative rates

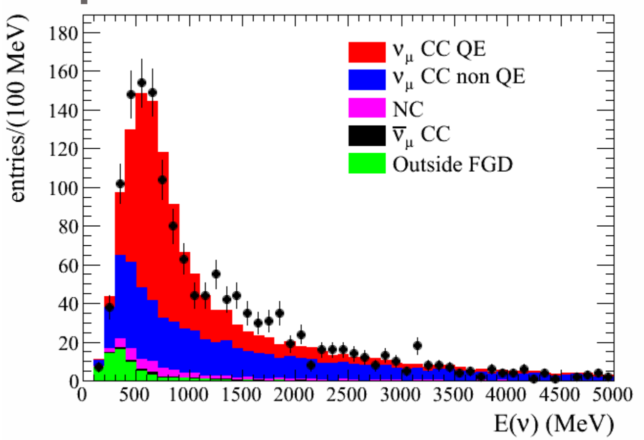
- Reused UA1 magnet holds ND280 detectors in 0.2T magnetic field, allowing momentum and charge measurements
- Electromagnetic calorimeters (ECAL) and pi-zero (P0D) detectors surround central tracker subdetectors

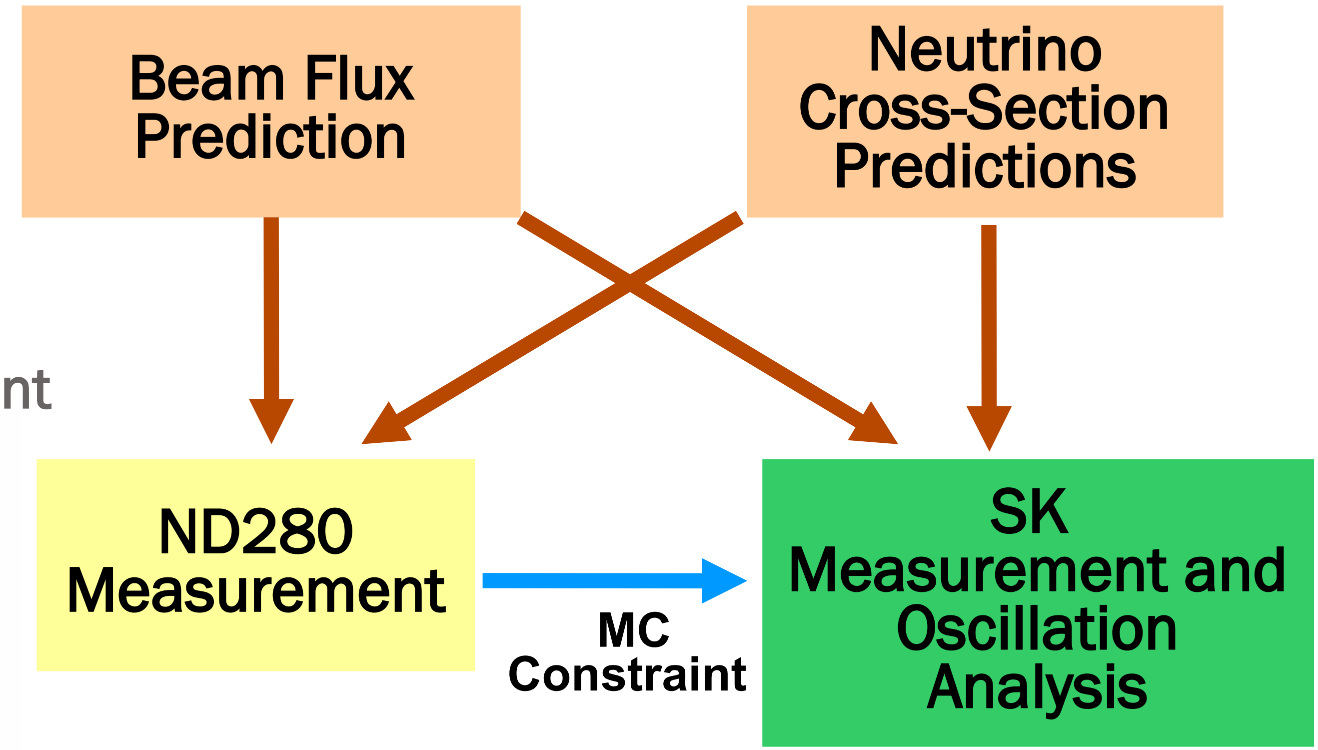
ν_μ Oscillation Analysis and ND280

Flux Prediction at ND280



Example ND280 Measurement



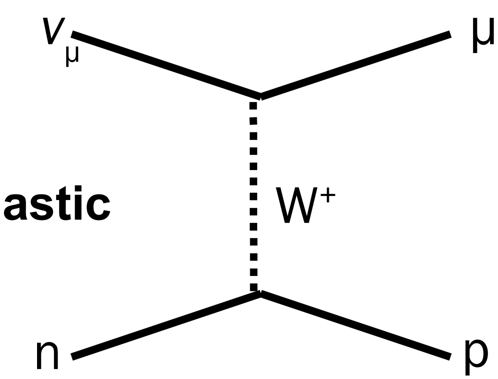


- ND280 data compared to MC prediction to constrain beam flux and cross-sections
  - In 2010 analysis ND280 measured data/MC flux normalization ratio, 2011 analysis will include spectral information
  - Including ND280 information in SK fit reduces systematic error in oscillation measurement due to flux uncertainties

Neutrino Interactions

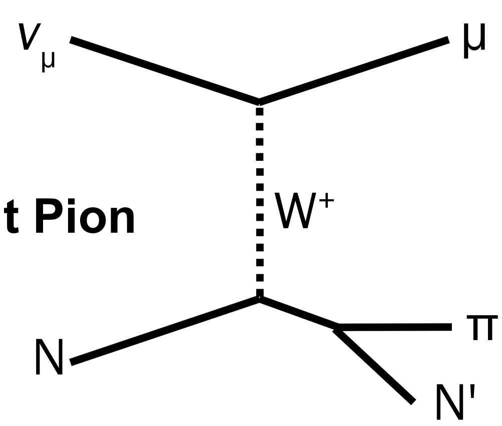
CCQE:
Charged-Current Quasielastic

$$\nu_\mu + n \rightarrow \mu + p$$



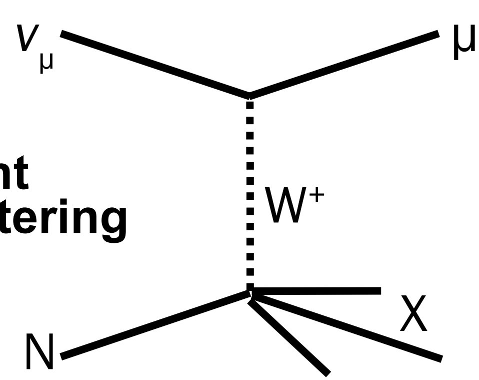
CC1π:
Charged-Current Resonant Pion

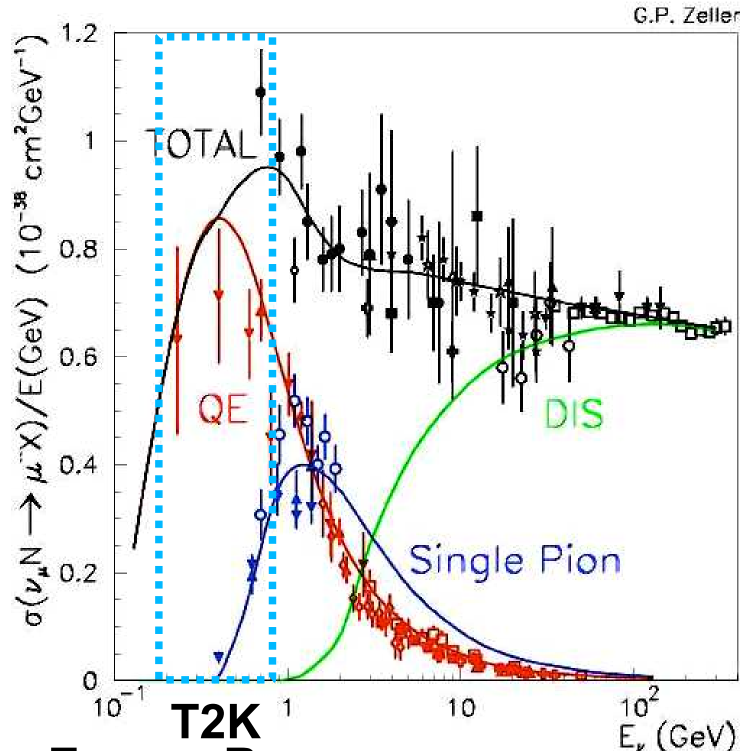
$$\nu_\mu + N \rightarrow \mu + N' + \pi$$



CC-DIS:
Charged-Current
Deep Inelastic Scattering

$$\nu_\mu + N \rightarrow \mu + X$$

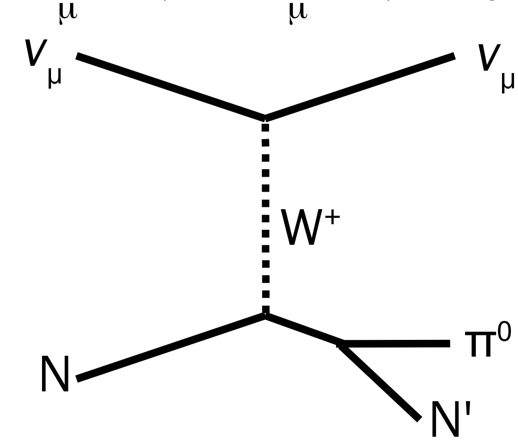




T2K
Energy Range

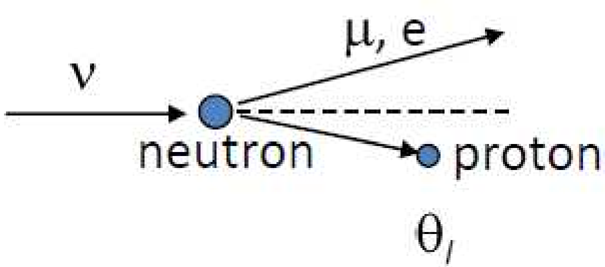
NCπ⁰:
Neutral-Current Resonant Pion

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$$



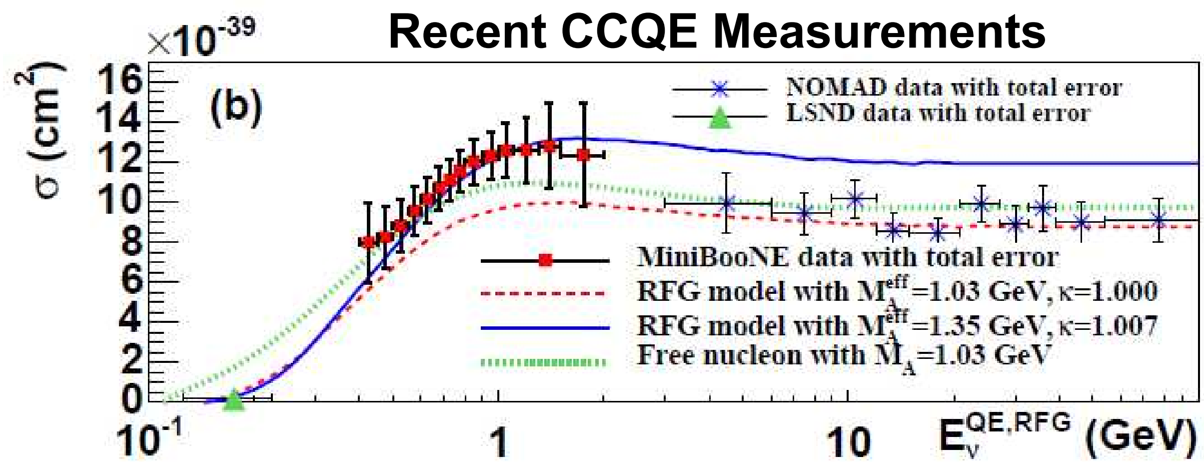
- Several neutrino interaction modes at T2K energy, additional nuclear interactions affect final observed state in detector

CCQE Interactions



$$E_\nu = \frac{m_N E_l - m_l^2}{m_N - E_l + p_l \cos\theta_l}$$

Recent CCQE Measurements

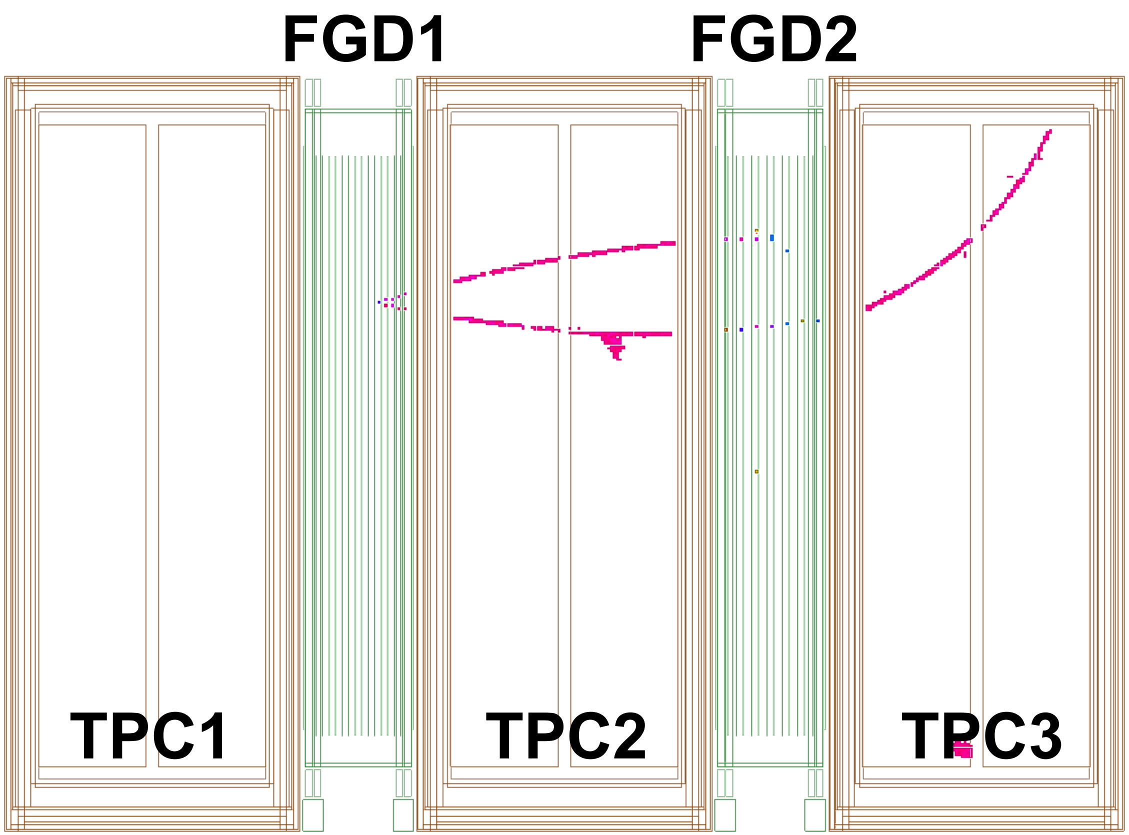


- Charged Current Quasi-Elastic (CCQE) is dominant interaction at T2K beam peak energy
  - Neutrino energy calculated from 2-body kinematics assuming neutron is at rest
  - ND280 CCQE sample used to measure beam flux, energy and flavor
- Main backgrounds includes CC resonant and DIS processes, NC and anti-neutrino processes
- Significant systematic errors estimated in relative rates of different processes

Systematic Error in Reaction Rates Relative to CCQE

Process	Systematic error
CCQE	energy-dependent (7% at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent $\pi^\pm$	100%
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
FSI	energy-dependent (10% at 500 MeV)

CC Inclusive Measurement in ND280 Tracker: 2010 Analysis Overview

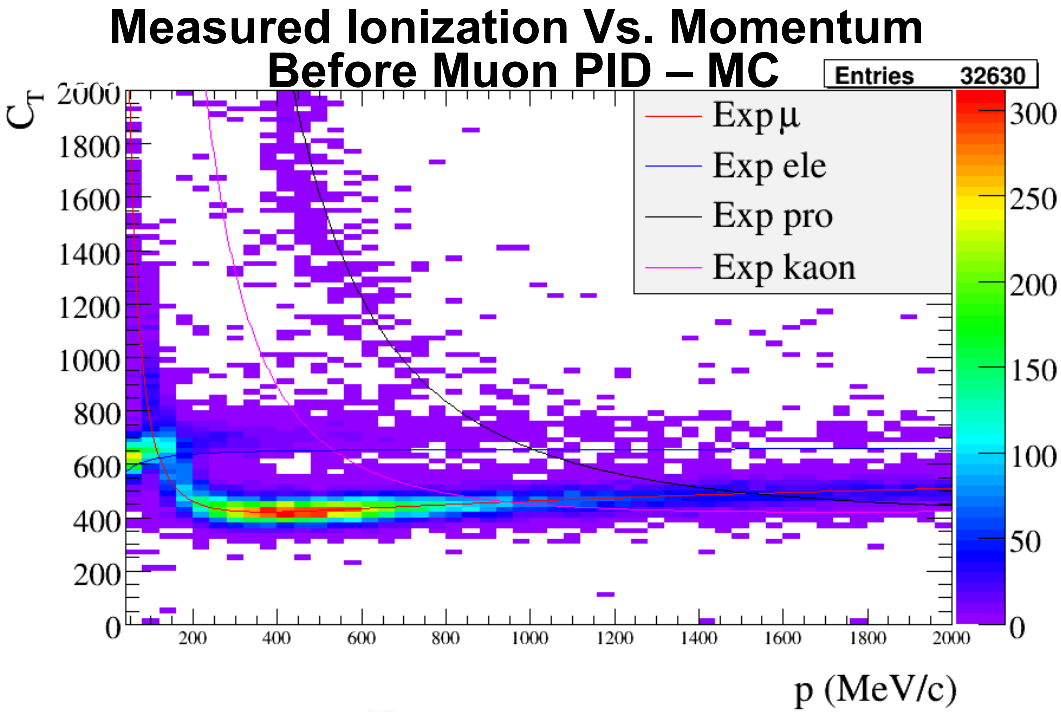


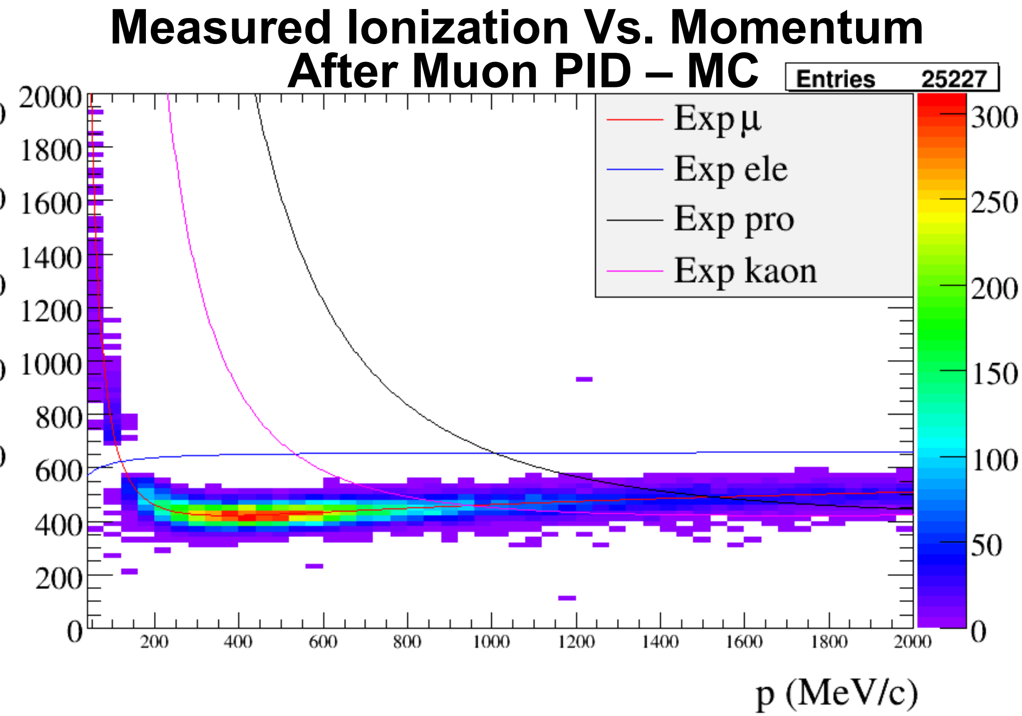
2010 CC Inclusive Cuts:

1) No track in upstream TPC
2) TPC quality: >18 Hits to consider TPC track
3) >0 Tracks in TPC2 or TPC3
4) >0 TPC tracks extrapolated to hits in upstream FGD
5) Extrapolated track with highest momentum is negatively charged
6) Negatively charged track TPC PID is muon-like

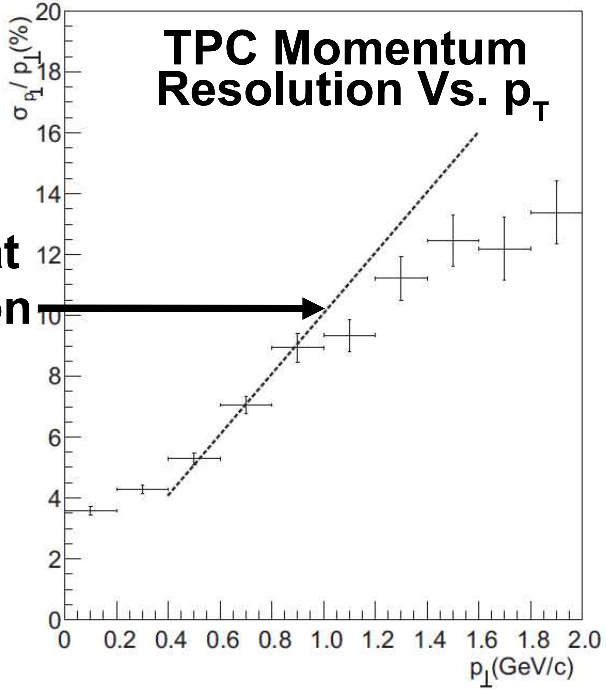
- CC inclusive sample is starting point for CCQE selection
- 2010 analysis CC inclusive measurement was first ND280 result, will be reused in 2011 with updates
- Event selection requires TPC tracks extrapolated to hits in FGD, use reconstructed momentum and PID information to select CC muon

Muon Identification with TPC PID





Target 0.1 p_T at 1GeV resolution achieved



- TPC mean energy loss measurement provides powerful particle identification method
- Measured energy loss compared with expectation for each particle hypothesis
- Muon PID requires charge deposit within 2σ of muon expectation, >2σ from electron expectation

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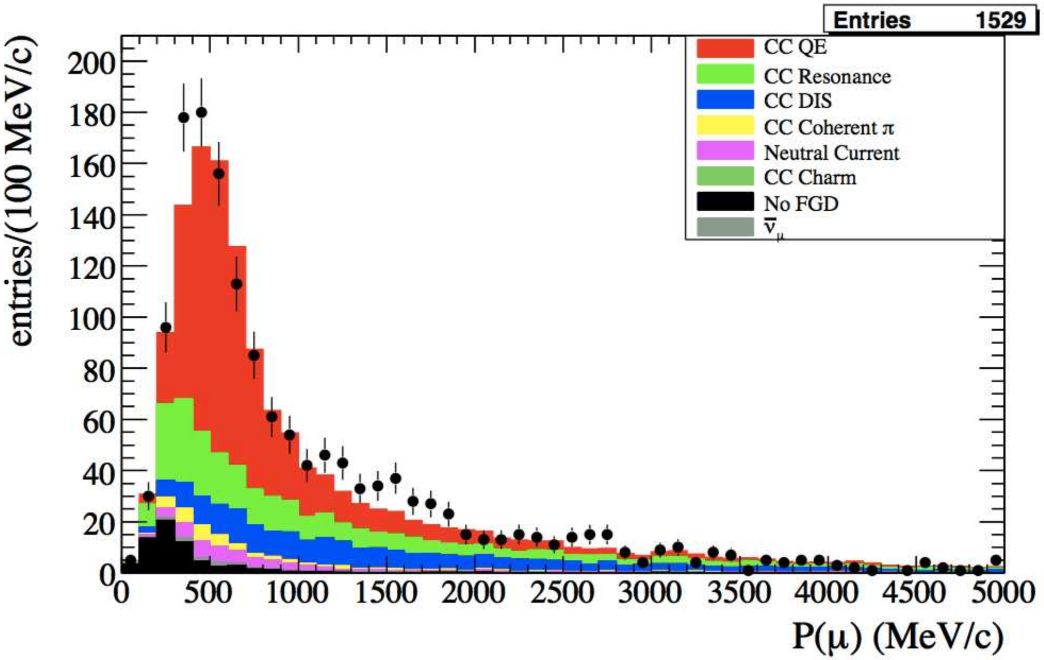
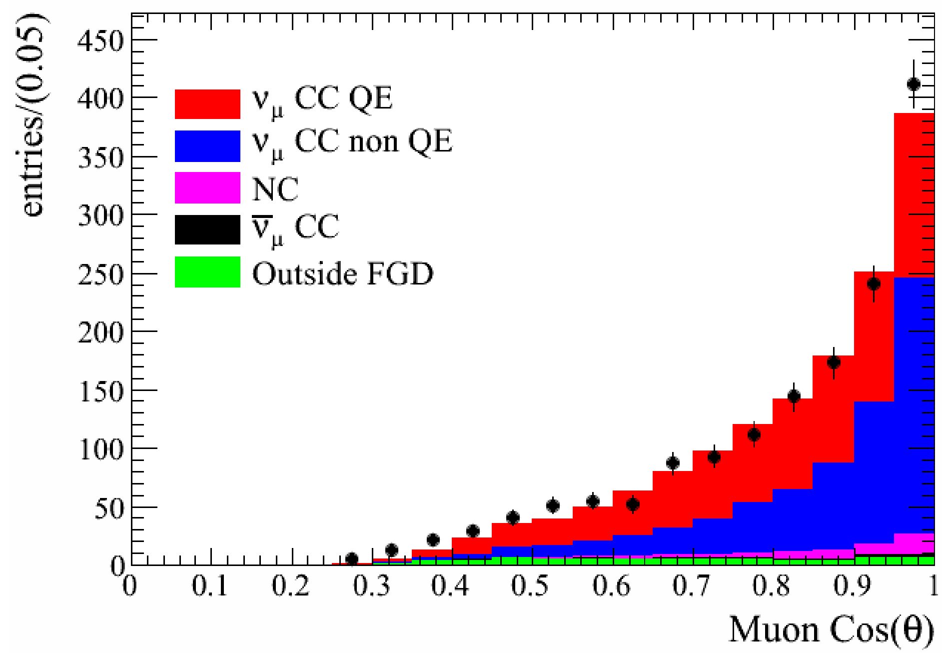
CC Inclusive Measurement in ND280 Tracker: 2010 Analysis Result

Muon Candidate Reconstructed Momentum



Muon Candidate Reconstructed Cosθ

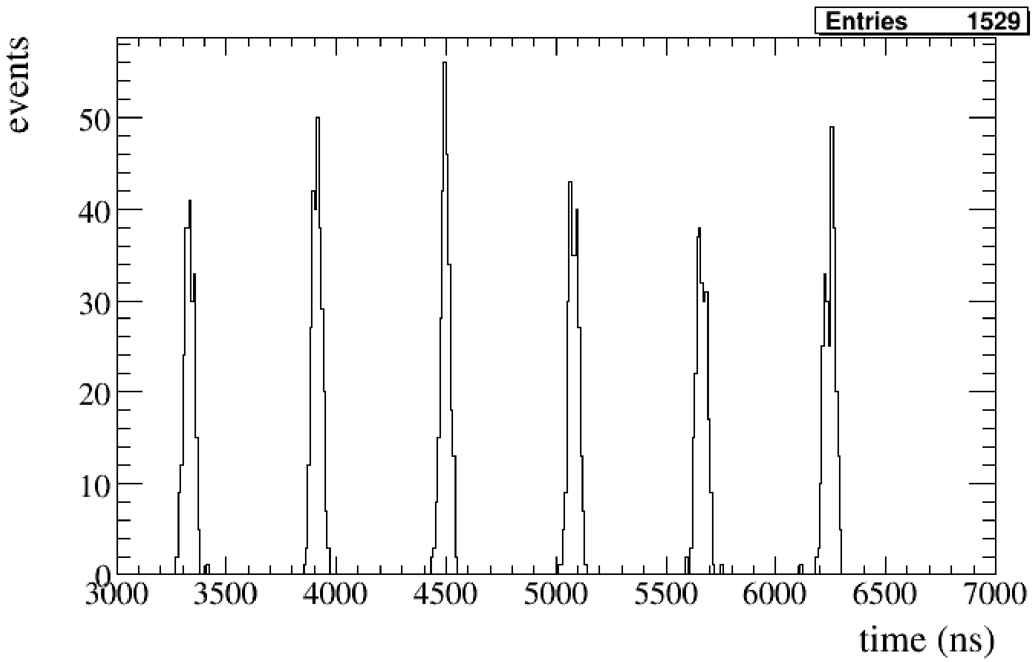


$$R_{ND}^{\mu,\,Data} / R_{ND}^{\mu,\,MC} = 1.036 \pm 0.028\,(stat.)^{+0.044}_{-0.037}\,(det.\,sys.) \pm 0.038\,(phys.\,model)$$

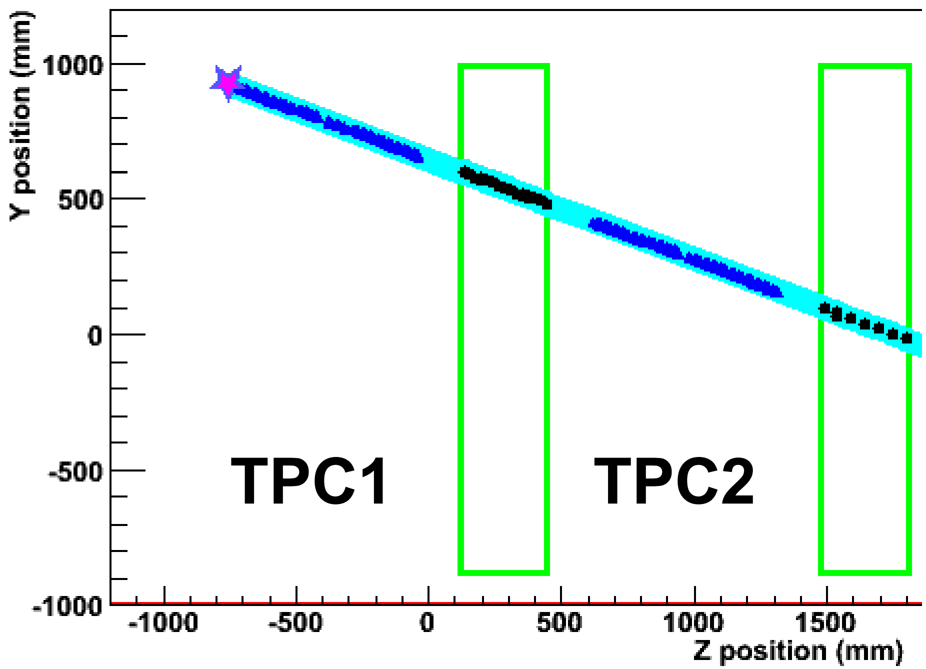
- 2010 analysis shows reasonable agreement between data and MC
  - Muon momentum and angular plots do not include systematic errors
  - Predicted ~37% efficiency for true CC-inclusive, >90% purity (~50% CCQE)
- Data/MC normalization ratio reduces flux uncertainty in v_e analysis by ~50%
- Spectral information not used in 2010 analysis

Updates in CC Inclusive Measurements for 2011 Analysis

Reconstructed Tracks Time Distribution

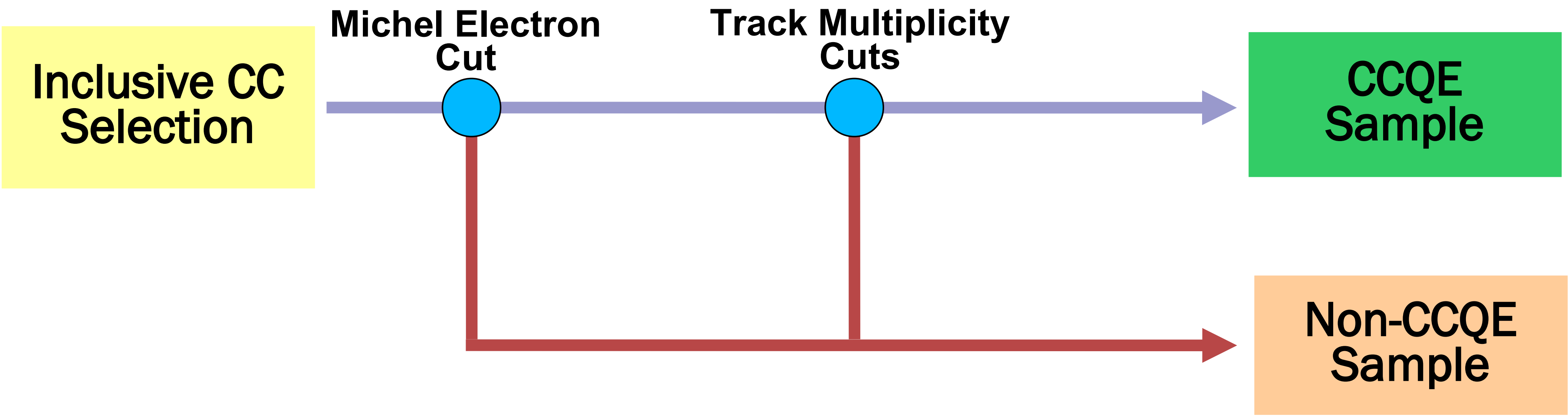


Cosmic MC Event with Incremental Matching Reconstruction Result



- Reconstructed tracks associated to a specific beam bunch using time information
  - CC inclusive selection performed on each bunch individually, reducing event pileup and external background effects
- Incremental matching reconstruction algorithm based on Kalman filter automatically connects TPC tracks to FGD hits and across subdetectors
  - Momentum estimate and TPC PID can now include information from multiple TPCs

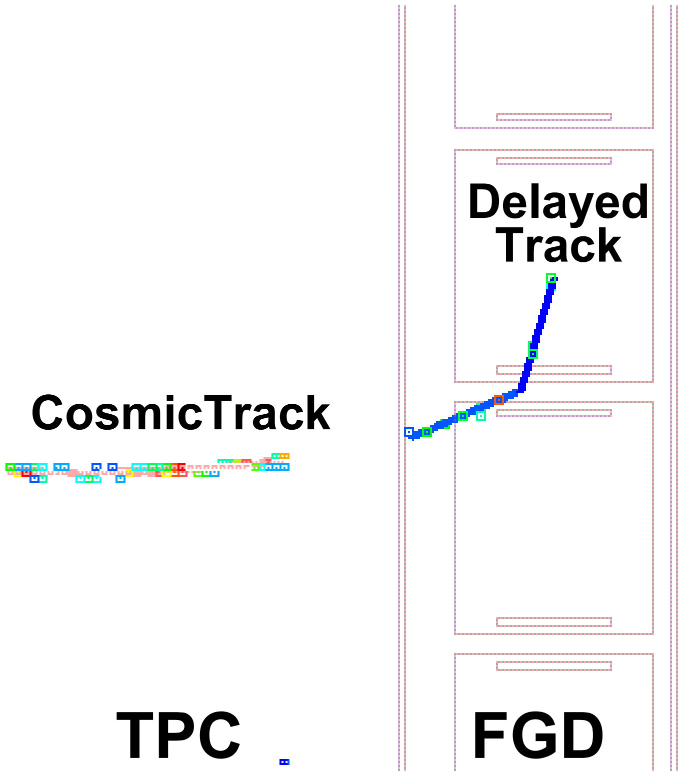
CCQE Event Selection in ND280 Tracker: Overview



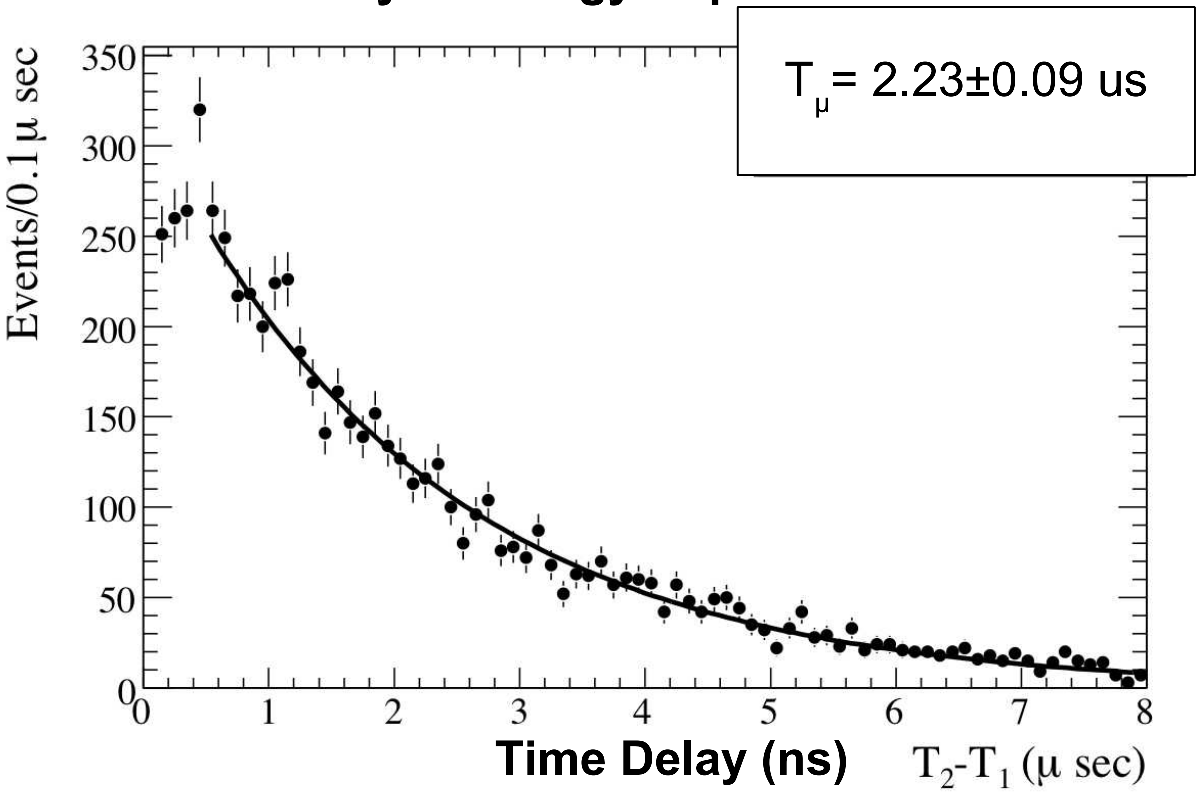
- CCQE selection is an extension of inclusive CC selection
- Additional cuts separate CC events into CCQE and non-CCQE samples
  - To simplify detector systematic error analysis, only consider FGD1 interactions
- MC predictions for both samples are fit to data to constrain beam flux parameters and provide spectral information
  - Method makes full use of CC inclusive sample, information encoded in non-CCQE events not discarded

Michel Cut: Delayed FGD Energy Deposit

Stopping Cosmic Event with Delayed Secondary Track

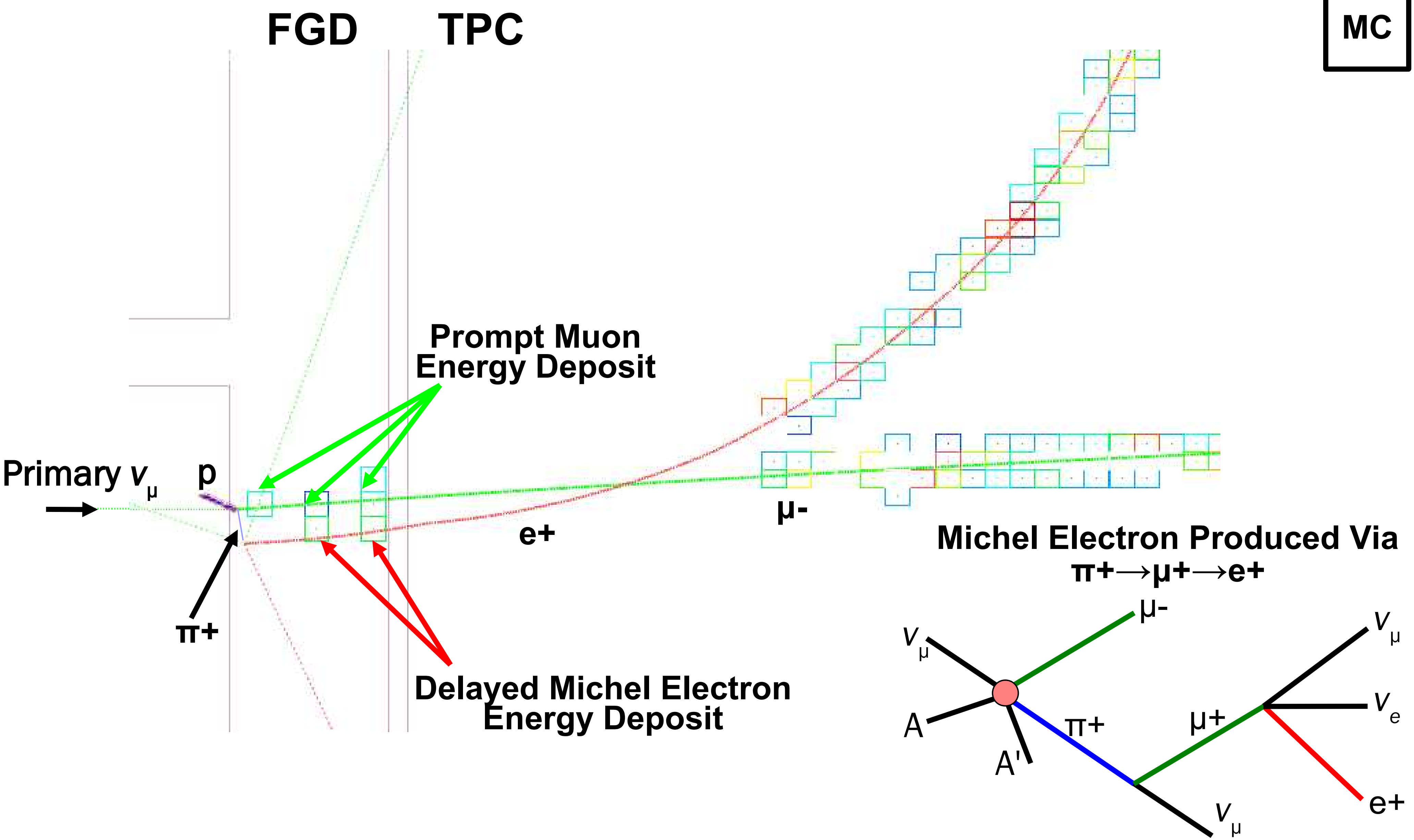


Stopping Cosmic Sample Time Distribution Of Delayed Energy Deposit Clusters



- FGD measures energy deposit up to 10us digitization window boundary
  - Hits separated by >100ns into new energy cluster
- Michel electrons from muon decay produce delayed energy deposit
  - Used to accurately measure muon lifetime in stopping cosmic events

Michel Cut: Events in Tracker



- Resonant CC pions stopping in FGD1 can be detected through delayed Michel electron energy deposit, used to identify non-CCQE interaction

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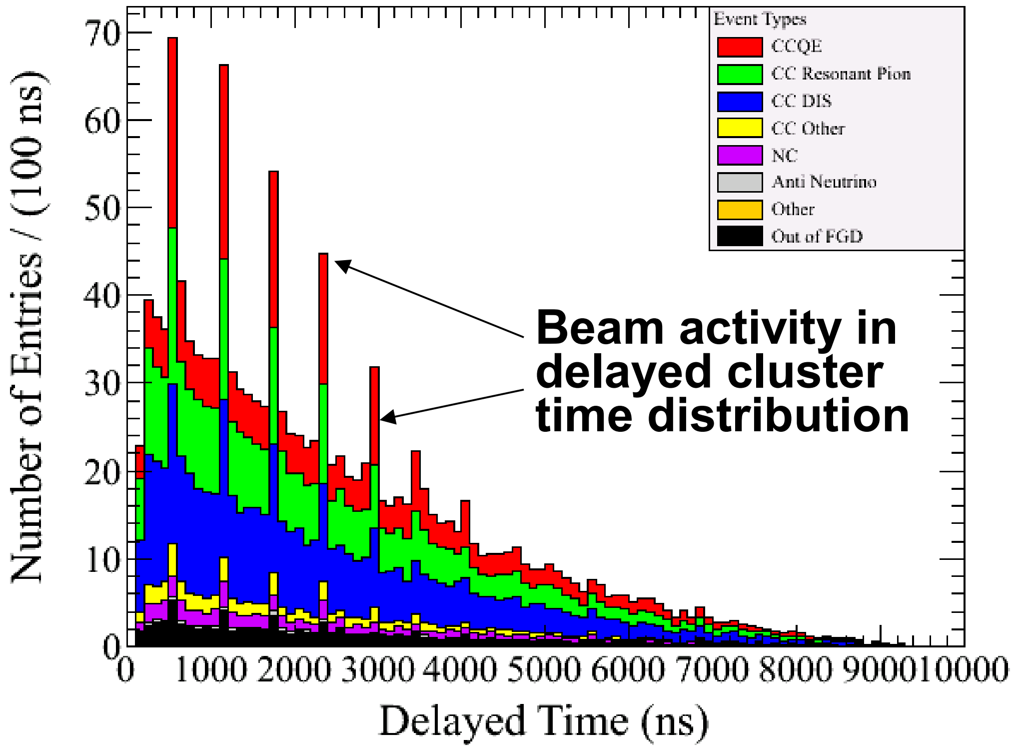
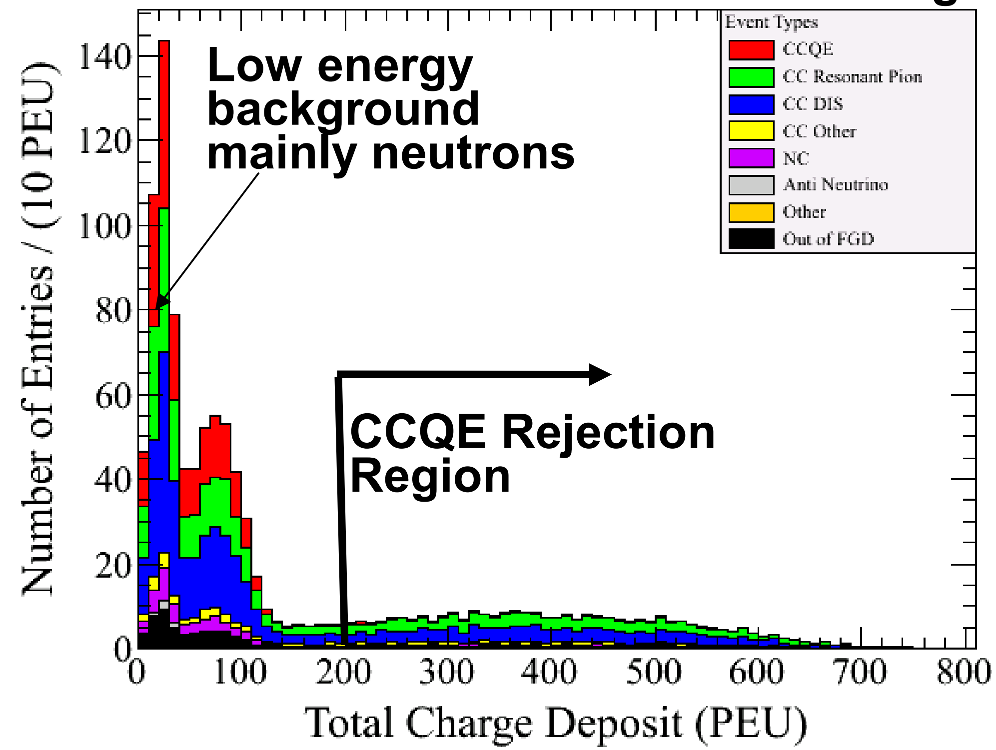
CCQE Selection: Michel Cut

MC

FGD Clustered Energy Deposit Time Delay After Selected CC Inclusive Event Time



FGD Clustered Energy Deposit After CC Inclusive Event Total Charge



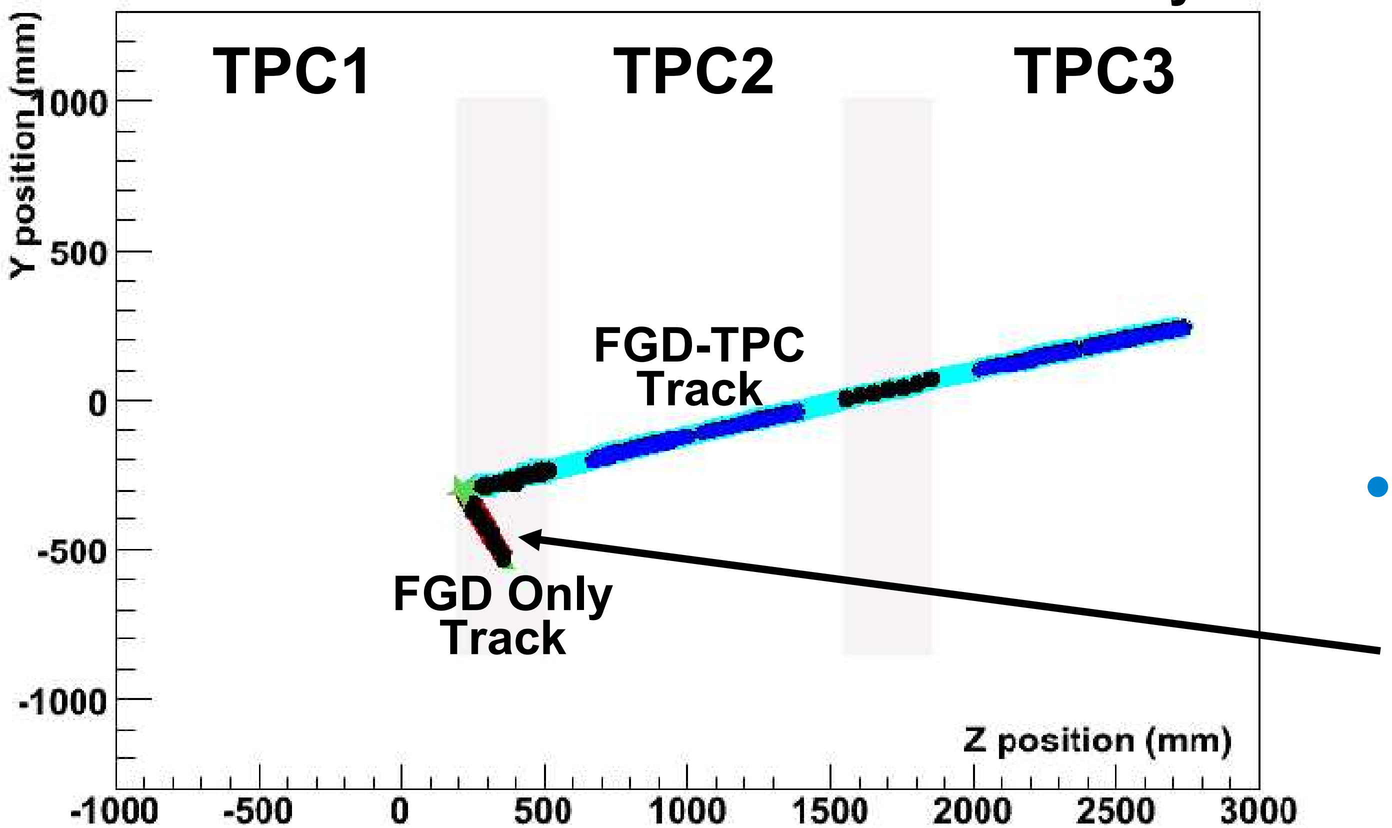
- Starting with CC inclusive sample event, check delayed energy deposit in FGD1
- Ignore activity correlated with beam or low-energy neutron induced background
- Simulation predicts ~5% increase in total CCQE purity with ~0.5% efficiency loss

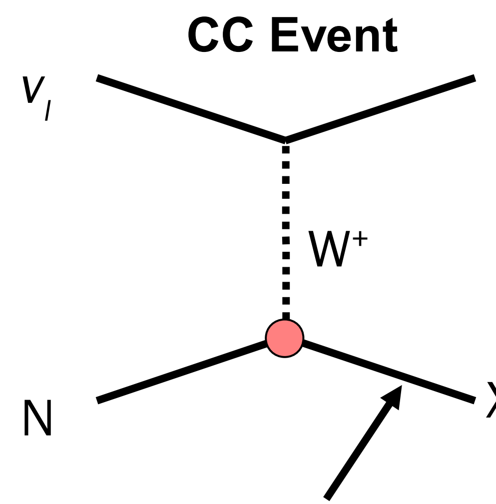
Reconstruction in ND280 Tracker

MC

- Two types of reconstructed tracks used in CCQE selection
  - Incrementally-matched FGD-TPC tracks: well suited to identify CC leptons
  - FGD-only algorithm: finds short-ranged tracks using hits in a single FGD
- CC-inclusive events classified by track topology and multiplicity, similar reconstruction systematics

CC Event with 1 FGD-TPC Track and 1 FGD-Only Track





- Non-muon tracks and energy deposit provide useful information
  - Help determine event type
  - Compare data/MC kinematic distributions

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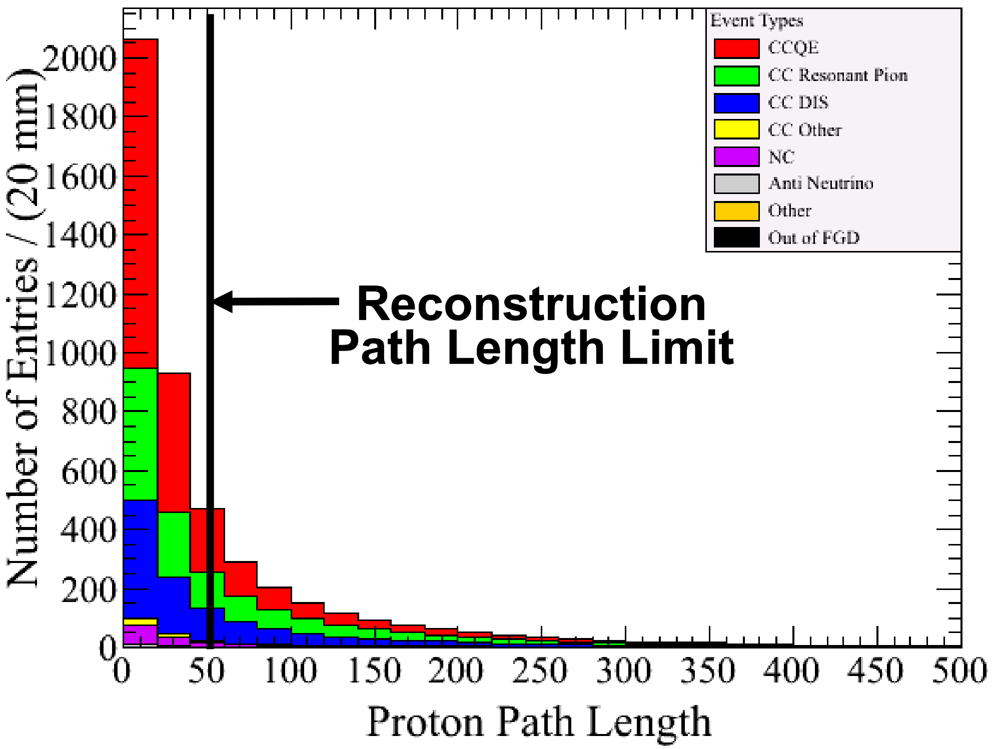
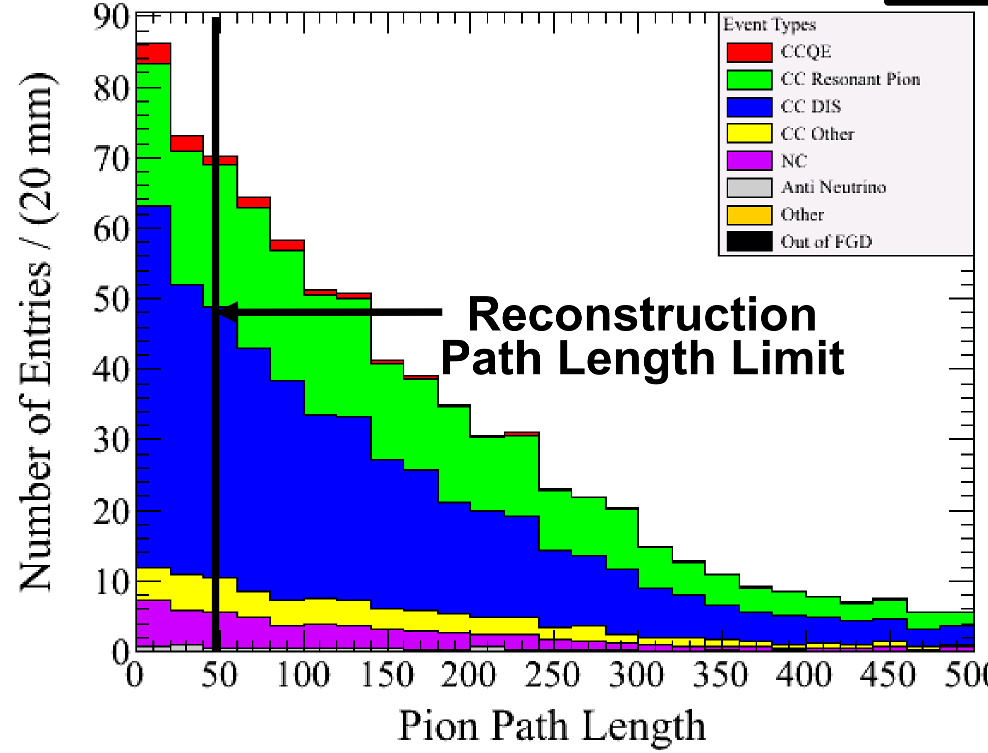
CCQE Selection: Particle Range

MC



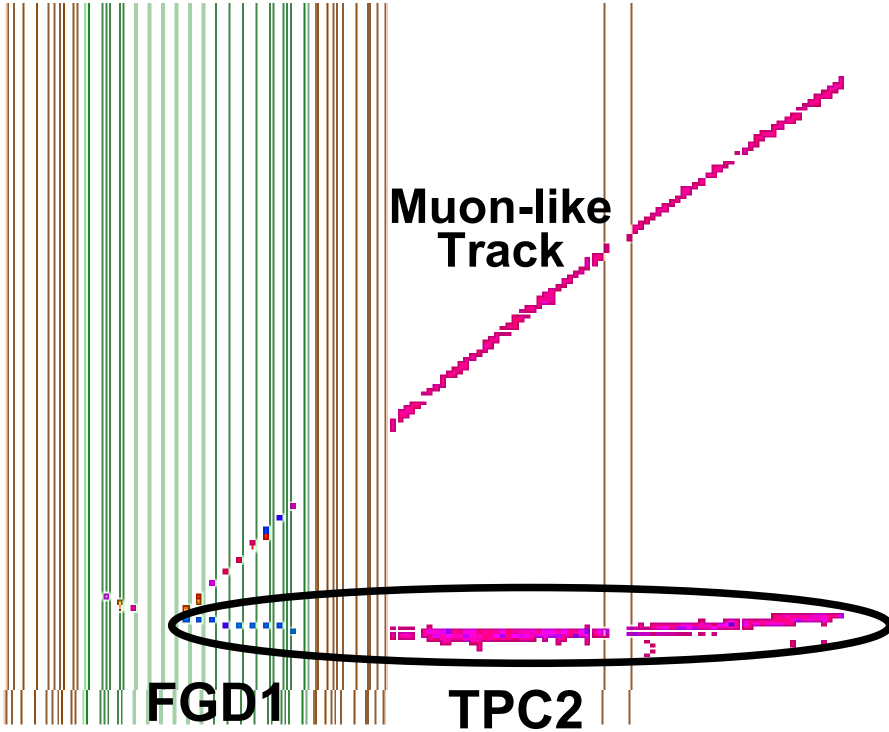


- CCQE interactions expected to have fewer long ranged protons and less pions than non-CCQE interactions
- Track length cut could help separate CCQE and non-CCQE events, but there are significant systematic uncertainties in final state kinematics
    - Tracker reconstruction generally only sensitive to tracks > ~50mm in length
- Instead examine events with specific topology and track multiplicity, non-CCQE events will preferentially have higher multiplicity

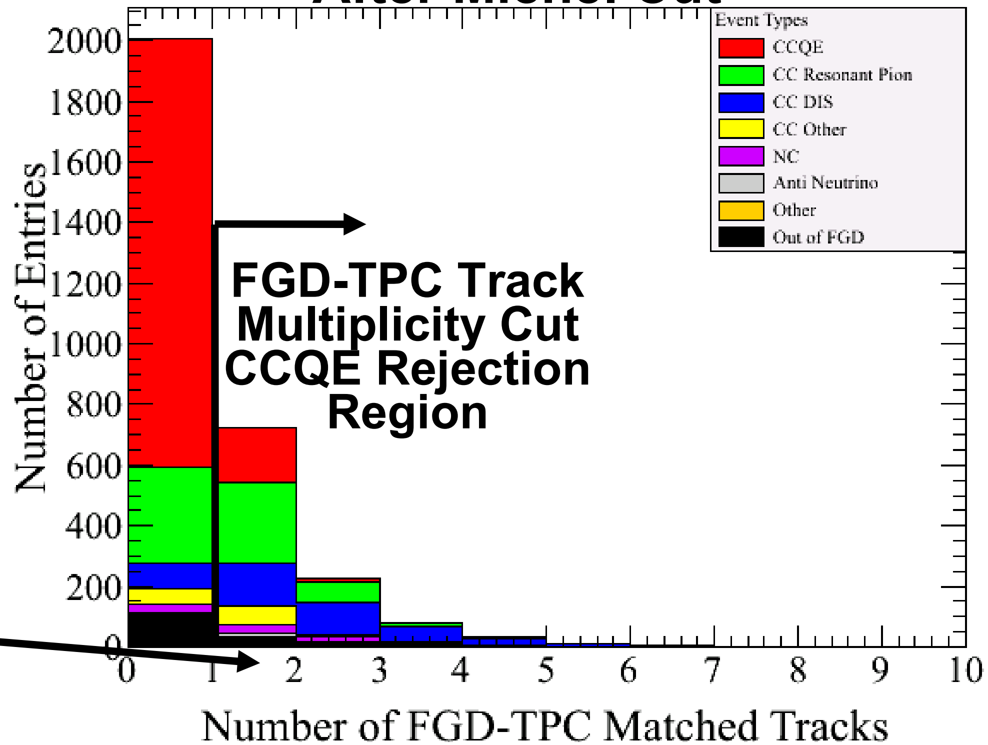
CCQE Selection: FGD-TPC Tracks

MC

CC Event with 2 FGD-TPC Tracks



Number of Non-Muon FGD-TPC Tracks After Michel Cut

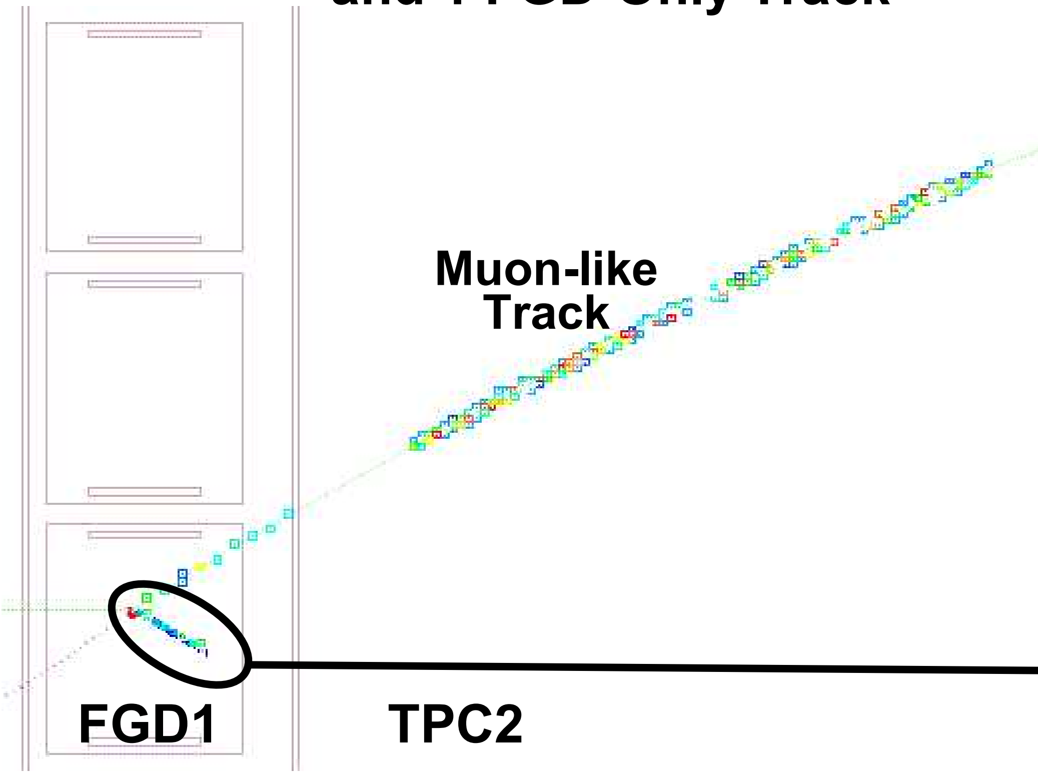


- While CCQE events produce two particles, MC predicts the proton usually doesn't reach the TPC, so events with 2 FGD-TPC tracks are usually non-CCQE
  - Consequently CCQE selection requires events contain zero non-muon FGD-TPC tracks
- TPC particle identification can help separate CCQE and non-CCQE in multi-track case, introduces extra detector systematic effects

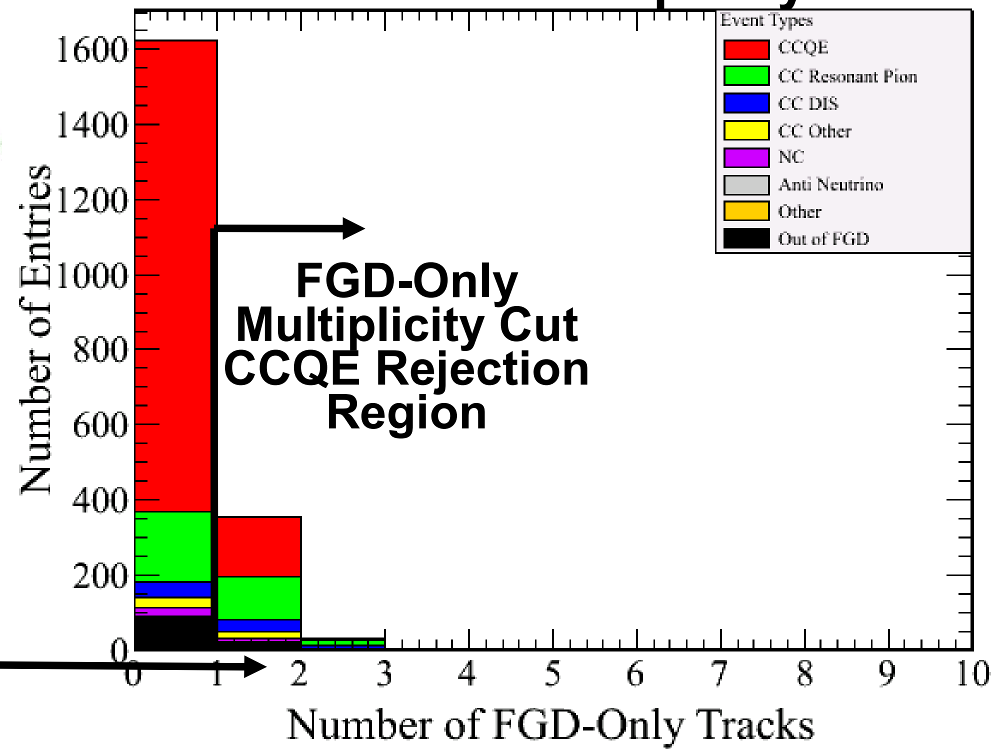
CCQE Selection: FGD-Only Tracks

MC

CC Event with 1 FGD-TPC Track and 1 FGD-Only Track



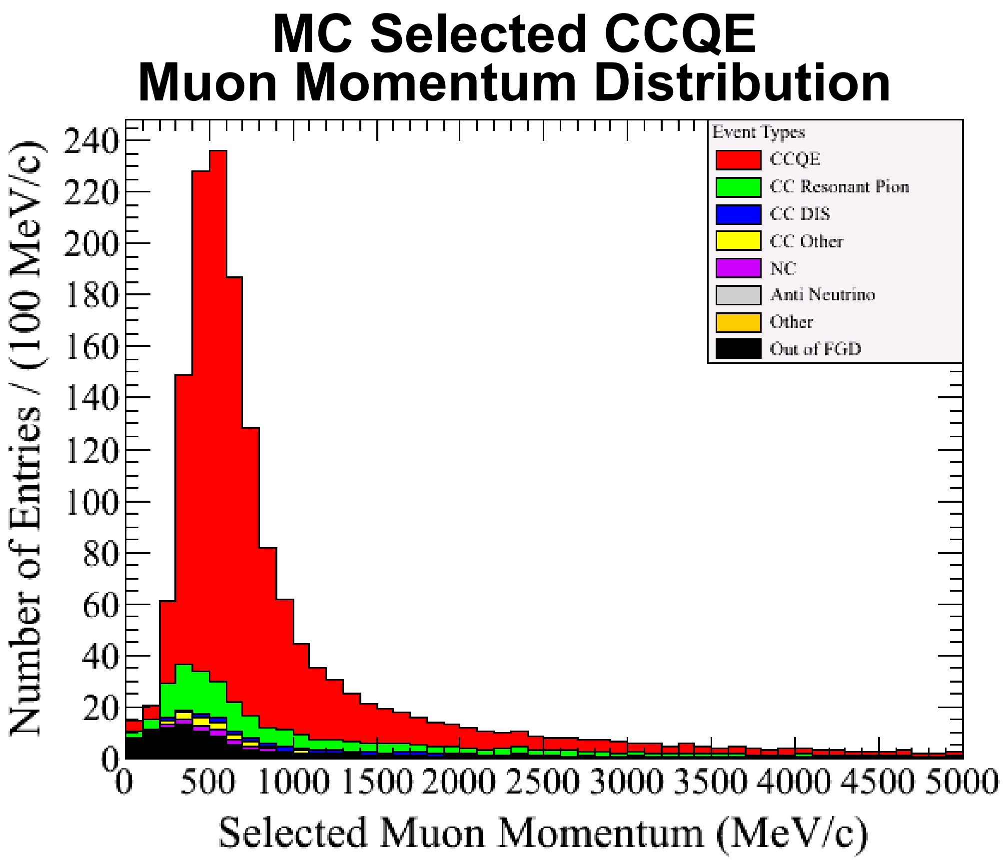
Number of FGD1-Only Tracks After FGD-TPC Multiplicity Cut

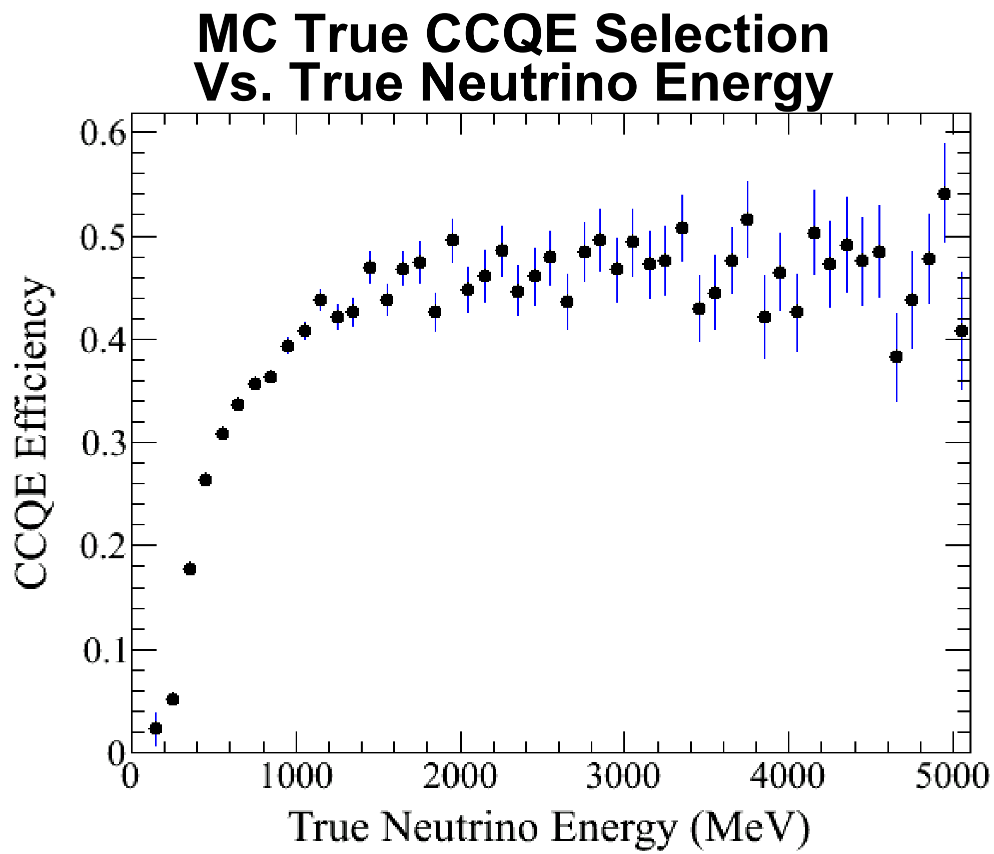


- Similarly to the FGD-TPC track distribution, events with zero FGD-only tracks predicted to contain largest CCQE fraction
  - CCQE protons often don't travel far enough to leave a reconstructible track
  - CCQE selection requires events with zero non-muon FGD-TPC tracks and FGD-only tracks, event topology with highest purity and largest sample

MC Predicted CCQE Selection for Run 1+2 Dataset

MC



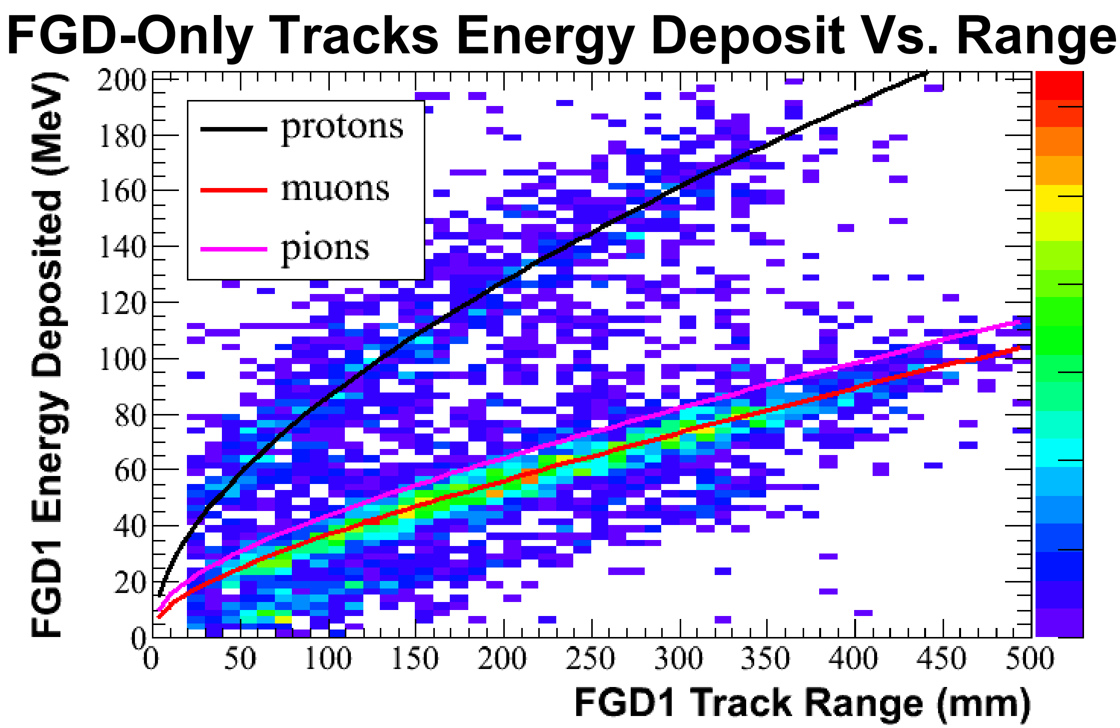


- Current T2K Run 1 + Run 2 dataset with 9.02×10^{19} POT,
- MC predicts ~1620 CCQE selected events and ~1740 non-CCQE

- CCQE selection has ~34% efficiency, >75% purity
- CCQE efficiency relatively stable at high energy

CCQE Future Plans

- Several improvements to CCQE selection possible in future:
  - POD and ECAL information provide additional means to separate channels
  - Apply PID algorithms to non-muon tracks to help distinguish between proton and pions
    - Include one muon + one proton-like track events in CCQE selection
  - Vertex activity measurement can study short ranged energy deposit directly

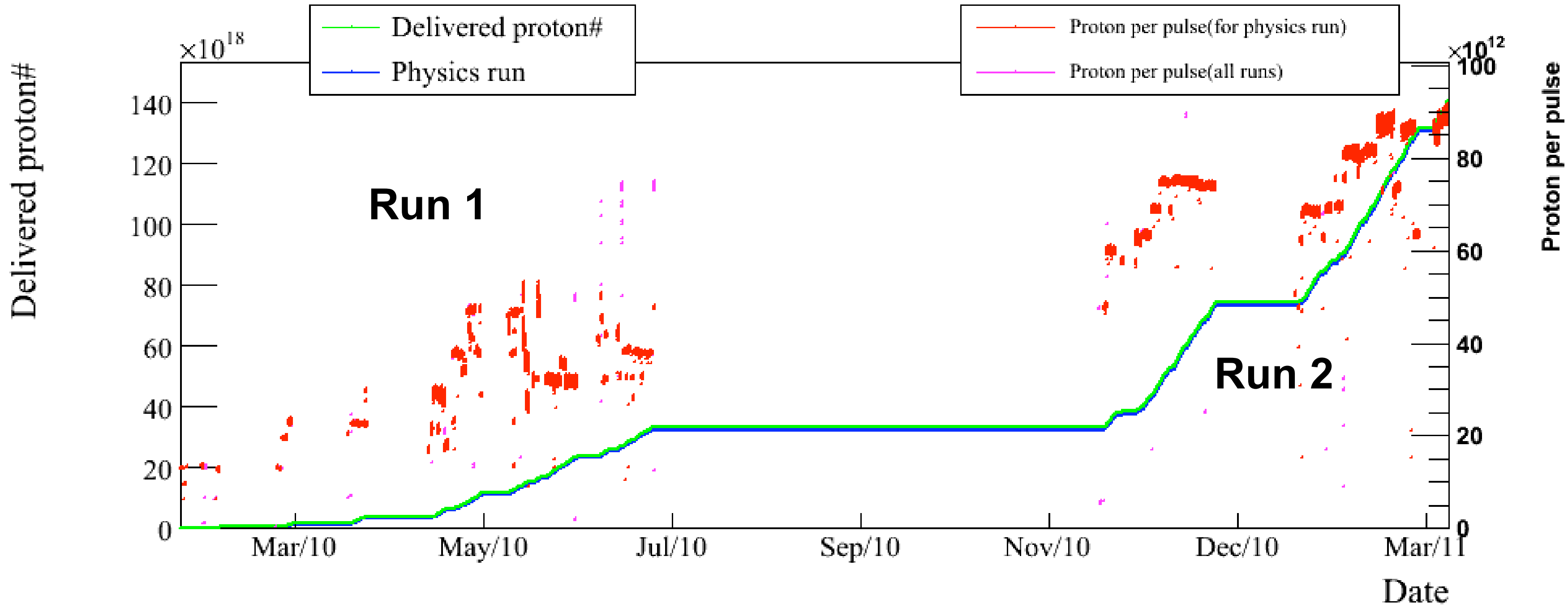


ND280 CCQE Selection Summary

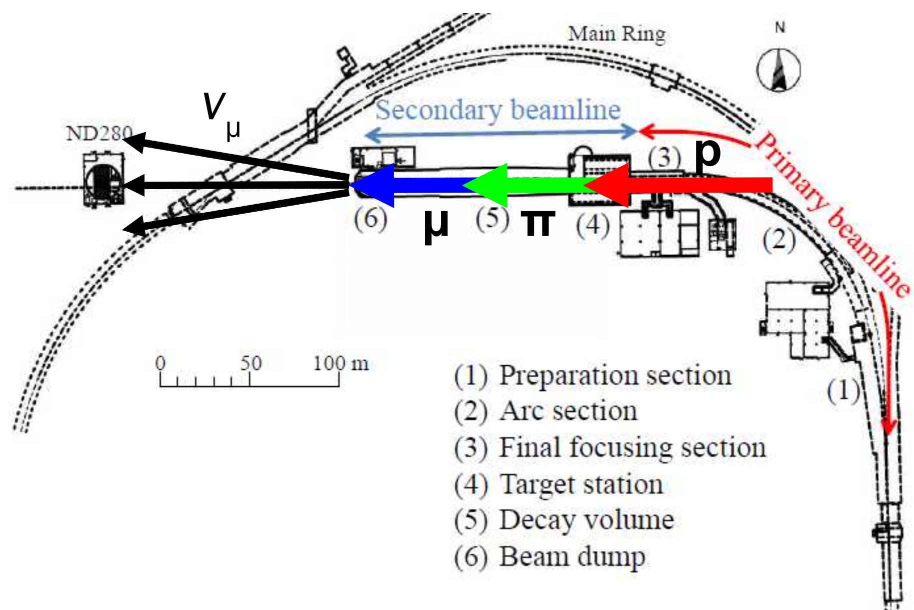
- ND280 CC inclusive selection well developed and used in initial oscillation analyses
  - Updated selection includes reconstruction tools with ability to track particles across multiple subdetectors, improving momentum resolution and PID
- High purity CCQE and non-CCQE selections defined for 2011 analysis
  - Uses Michel electron and track multiplicity cuts
  - **CCQE selection has ~34% efficiency, >75% purity (preliminary)**
  - Systematic studies and data/MC comparisons are in progress
  - ND280 measurement of neutrino beam energy spectrum will be available to oscillation analysis

Backup Slides

J-PARC Neutrino Beam



J-PARC Beamline Overview



- JPARC 30 GeV proton beam interacts with graphite target, produces neutrino beam via pion decay
- High intensity beam designed to run at 750 kW will allow higher statistical precision than previous experiments
- Run 1 stable operation at 50 kW, Run 2 operation at 145 kW