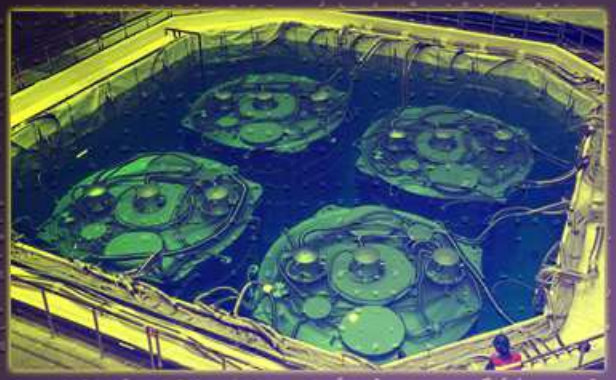


International Workshop on Neutrino Factories, Super Beams and Beta Beams

NUFACT 2013

August 19-24,2013,IHEP,Beijing,China

T2K Neutral Current Elastic Scattering Cross Section

Daniel Ruterbories
for the T2K Collaboration

NuFact2013, Beijing
August 21st, 2013

Colorado State University

On Behalf Of

~500 people, From 59 institutes, In 11 countries

T2K

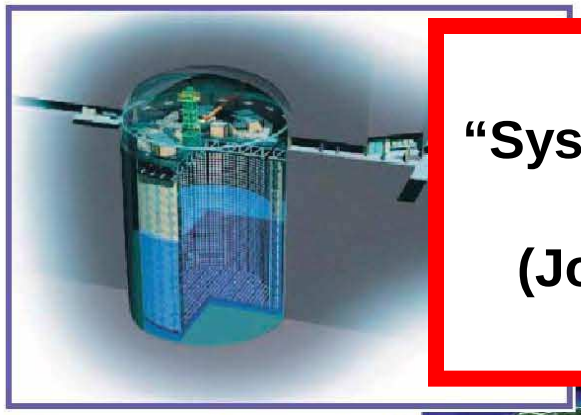
Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

Long baseline neutrino oscillation experiment designed to

- measure oscillation parameters (θ_{13}, θ_{23}, Δm^2_{32})
- neutrino-nucleus interaction cross sections …

T2K



“Systematics for Oscillation Analyses at T2K”
by Asher Kaboth at 13:30 Aug 20th
(Joint session on oscillation systematics)

See “T2K 2013 Neutrino Oscillation Results and Future Sensitivity”
by Megan Friend at 11:20 Aug 20th

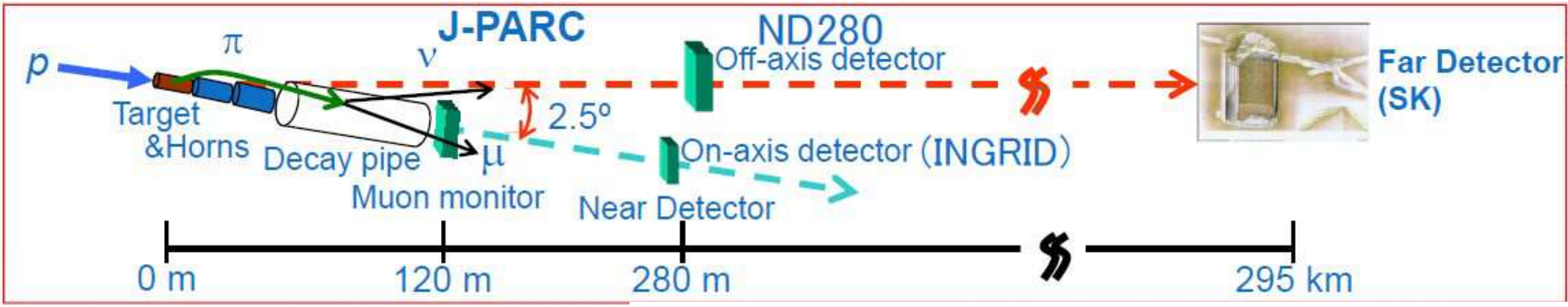
“CC cross section measurements at T2K”
by David Hadley at 10:55 Aug 20th

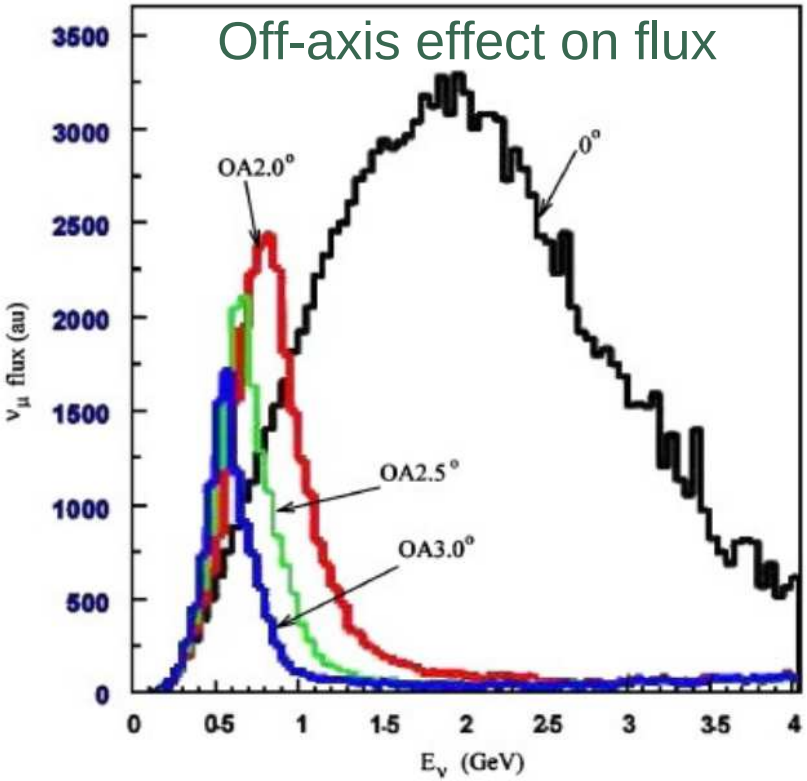
Long baseline neutrino oscillation experiment designed to

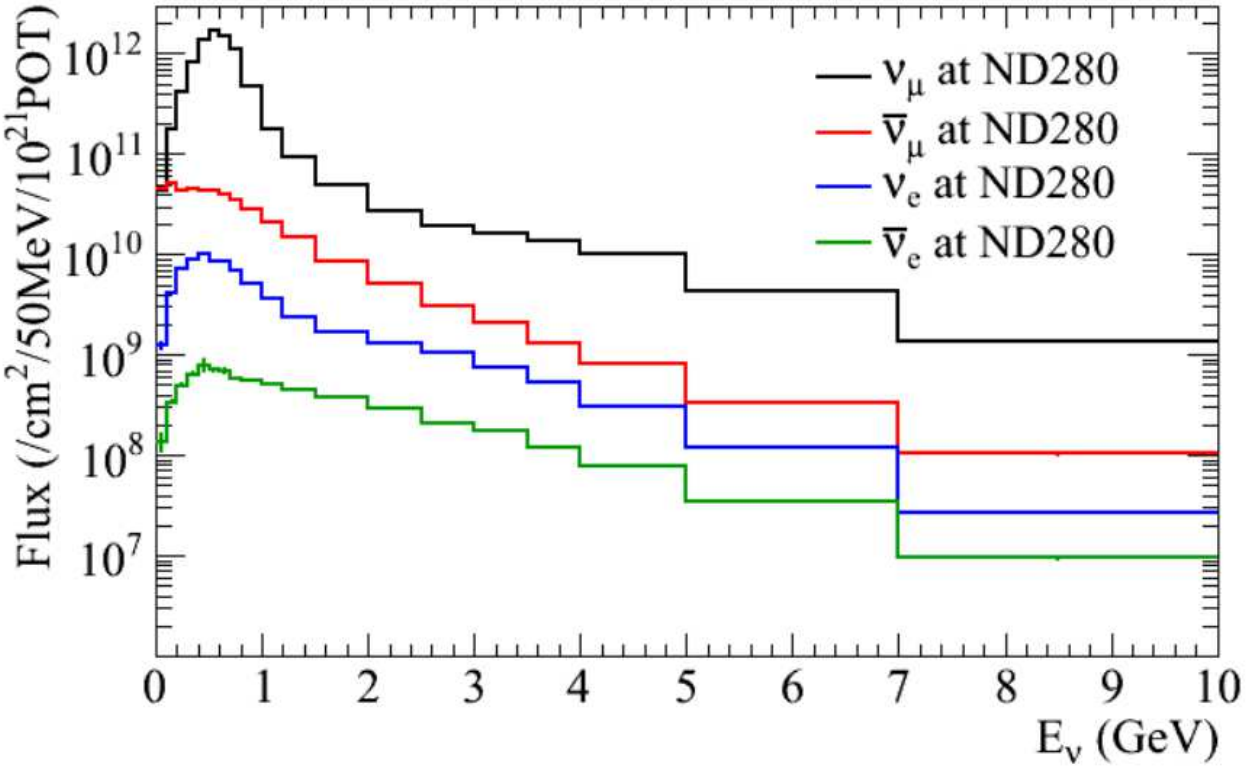
- measure oscillation parameters (θ_{13}, θ_{23}, Δm^2_{32})
- neutrino-nucleus interaction cross sections …

T2K Beam Configuration

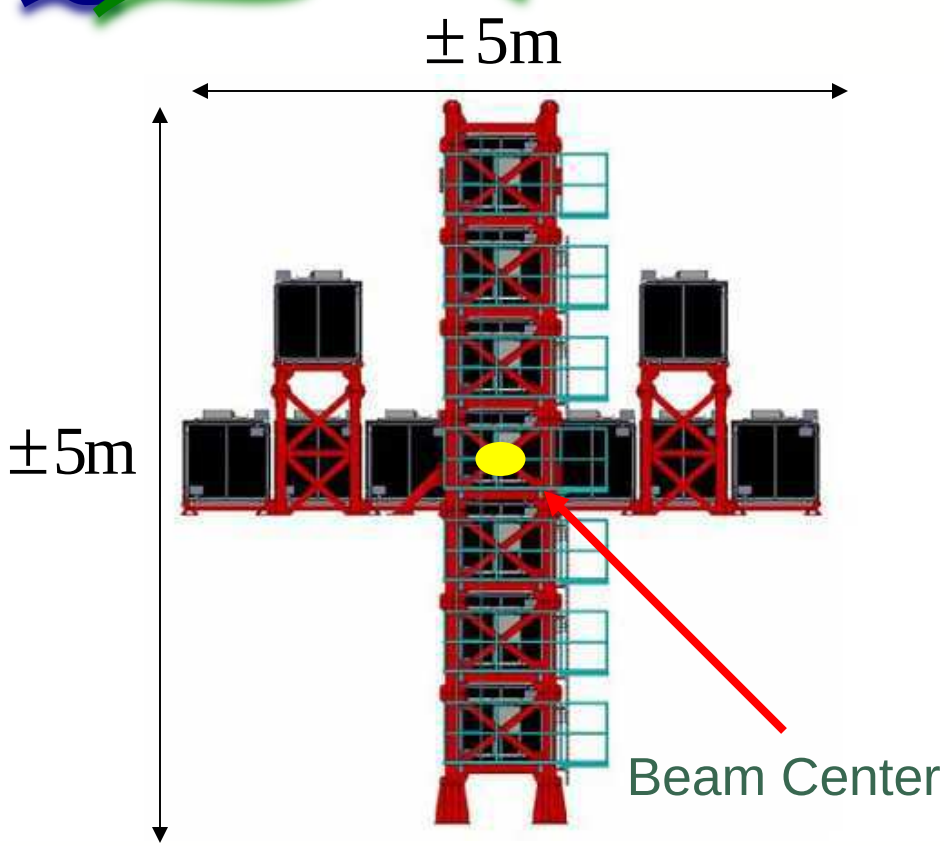
- Predominately ν_μ narrowband off-axis







INGRID



- 16 plastic scintillator + iron detectors
  - 7 vertical, 7 horizontal and 2 off axis
- 1 additional module
  - Finer grained, all scintillator
  - Designed to measure the protons from CCQE interactions
- Measures flux normalization and profile

Upcoming Analyses

Current analyses include:
CC inclusive cross section from flux variation across detector and CCQE measurements on scintillator and iron

Off-axis detector

Magnetized detector at 0.2T

SMRD (Side Muon Range Detector):

• Scintillator planes in the magnet yoke to measure muon momenta

P0D (π^0-Detector):

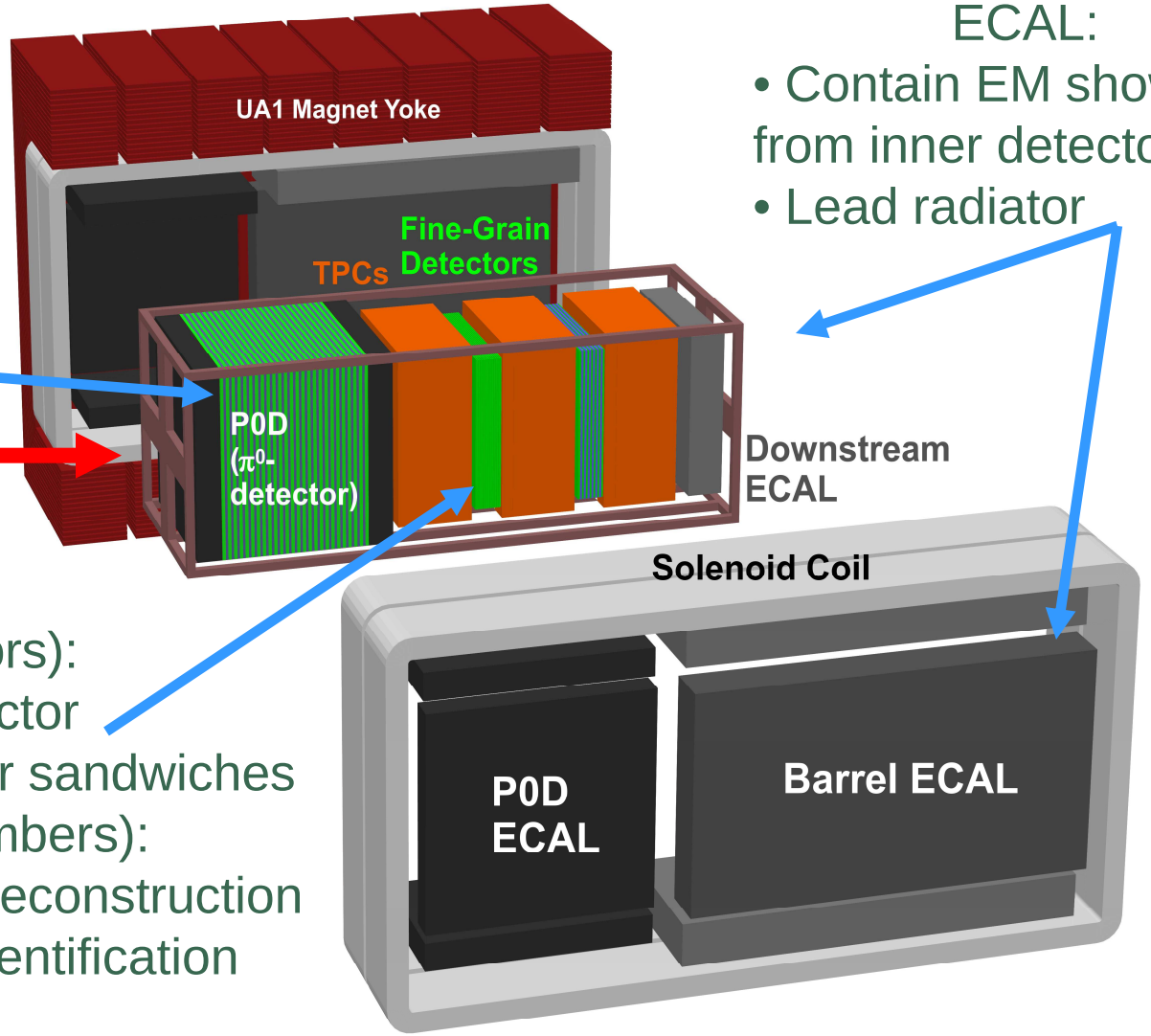
• 2 ECal sections sandwiching a removable water target

• Scintillator with brass and lead radiators

ECAL:

• Contain EM showers from inner detectors

• Lead radiator



ν beam

Tracker Section:

2 FGDs (Fine Grained Detectors):

1 fully scintillator detector

1 water and scintillator sandwiches

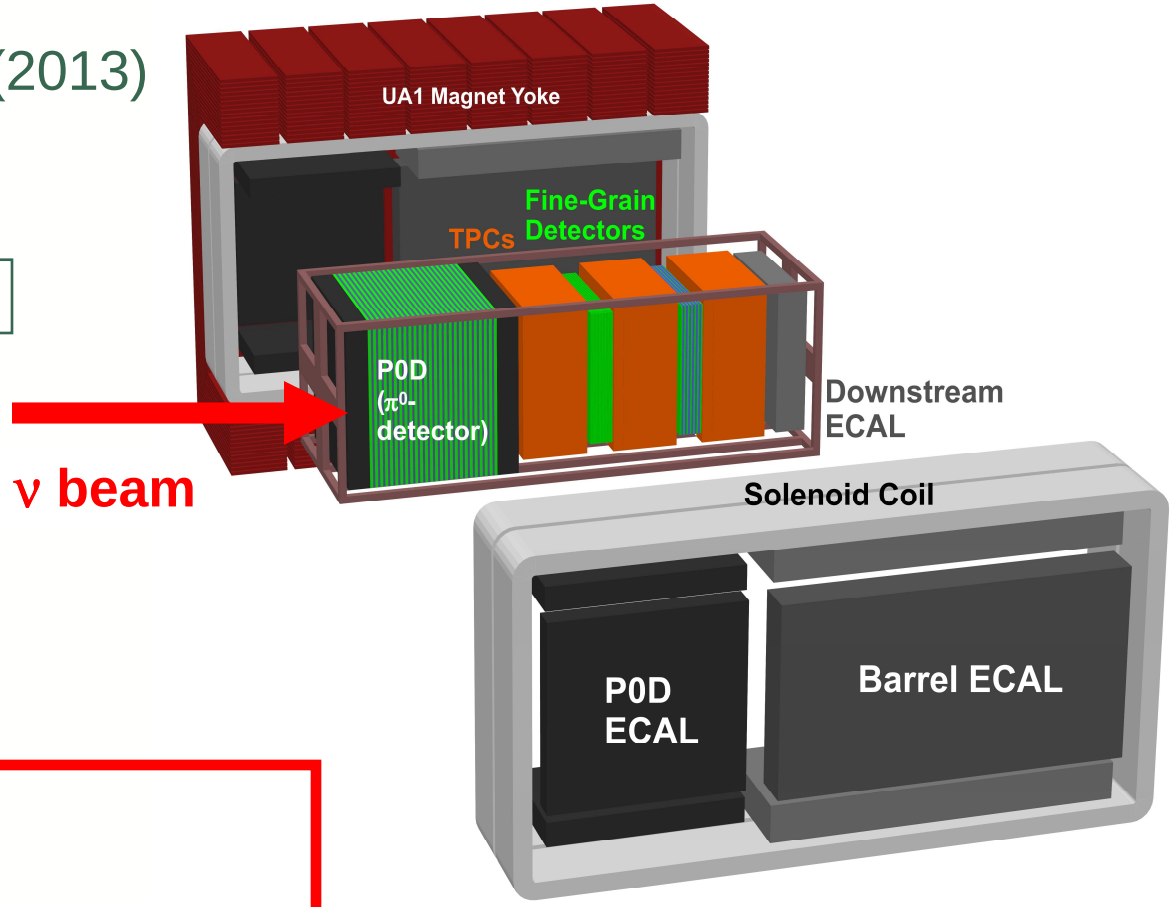
3 TPCs (Time Projection Chambers):

Used for momentum reconstruction and charge particle identification

Ongoing Off-axis Analyses

All cross sections use the NEUT event generator
Can use GENIE as a cross check

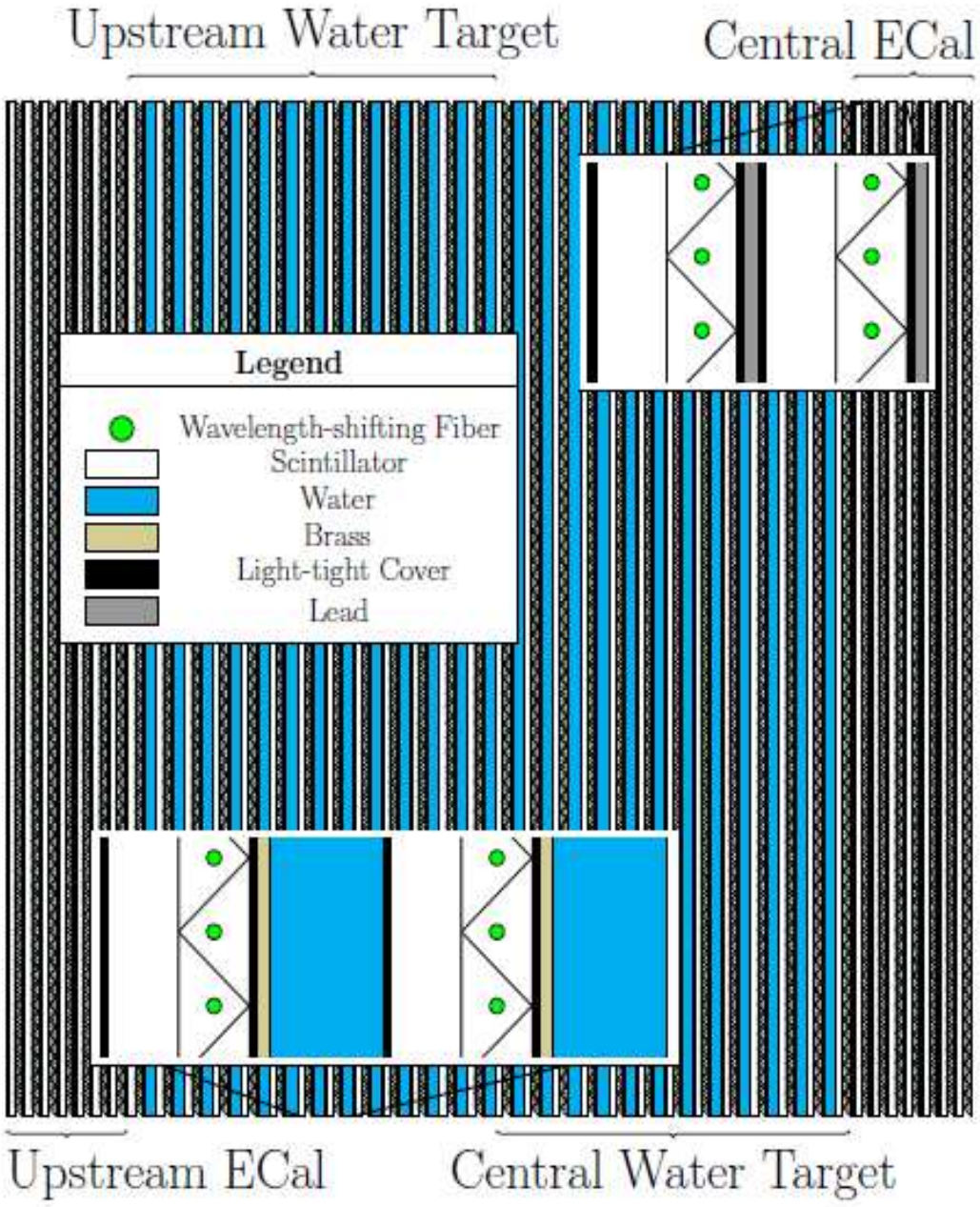
- CC Inclusive $\nu_\mu + X \rightarrow \mu^- + X$
  - On water, lead
  - Carbon published:
    Phys. Rev. D 87, 092003 (2013)
- CCQE $\nu_\mu + n \rightarrow \mu^- + p^+$
  - On carbon, water
- CC$\pi^{+/-}$ $\nu_\mu + n(p^+) \rightarrow \mu^- + p^+(n) + \pi^{-(+)}$
  - On carbon, water
- CCπ^0 $\nu_\mu + n \rightarrow \mu^- + p^+ + \pi^0$
  - On carbon
- NCπ^0 $\nu_\mu + p^+ \rightarrow \nu_\mu + p^+ + \pi^0$
  - On carbon, water



- NCE $\nu_\mu + p^+(n) \rightarrow \nu_\mu + p^+(n)$
  - On carbon, water, brass
  - *Today's result uses a combination of materials in the P0D*

π^0-detector (P0D)

- Partially active volume
- Two EM Calorimeters (ECal)
  - Scintillator + lead
  - Helps contain EM showers
- Two water targets (WT)
  - Scintillator + brass + water(air)
  - Removable water to provide measurement of neutrino cross-sections on water
  - Brass to help initiate EM showers

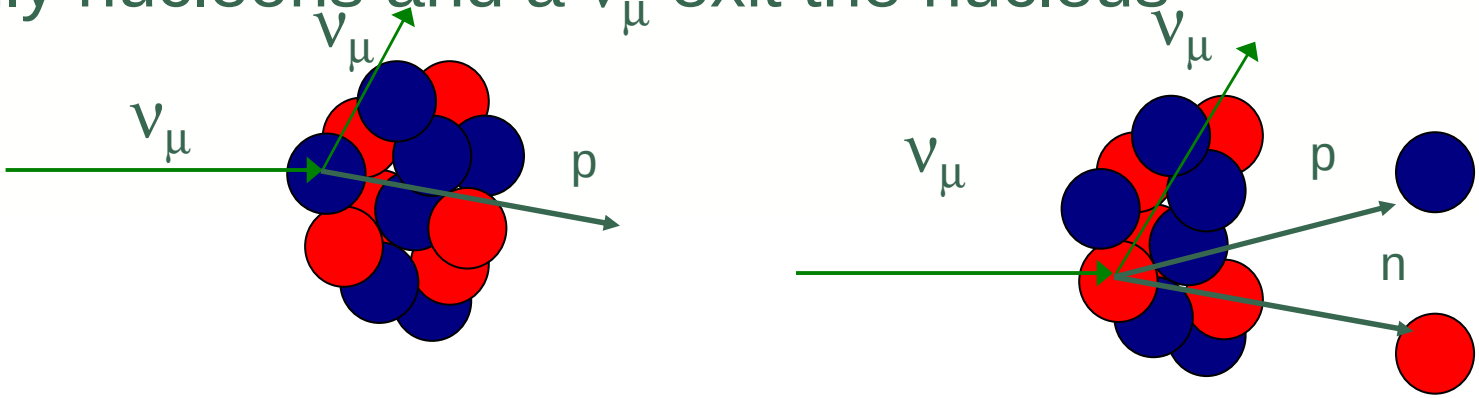


Neutral Current Elastic Interaction

- Primary Interaction:

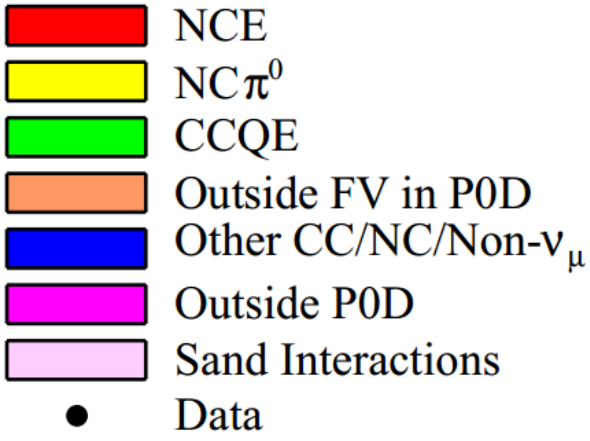
$$\nu_\mu + \mathbf{n} \rightarrow \nu_\mu + \mathbf{n}$$
$$\nu_\mu + \mathbf{p^+} \rightarrow \nu_\mu + \mathbf{p^+}$$

- With perfect reconstruction and detectors:
  - 1 track corresponding to a proton
  - Neutrons are not directly visible to the P0D
- Can produce multiple nucleons with final state interaction (FSI)
  - Cause feed down from other NC processes
- T2K's measurement investigates NCE-like events, or events where only nucleons and a ν_μ exit the nucleus



Topology Definitions

Defined by FSI topologies



NCE: Any interaction where there is a ν_μ but no mesons exiting the interaction nucleus. Any number of protons and/or neutrons are allowed in the final state.

NC π^0: Any interaction where there is only one π^0 exiting the interaction nucleus. Any number of nucleons are allowed

CCQE: Any interaction where there is a μ^- but no mesons exiting the nucleus.

Outside FV in P0D: Any interaction with a ν_μ of any interaction type that occurs within the active volume, but outside the FV of the P0D.

CC Other: Any interaction where there is a μ^- but any number of mesons exiting the nucleus.
NC Other: Any interaction where there is a ν_μ plus some number of mesons exiting the nucleus.

Other: Any non-ν_μ neutrino interaction

Outside P0D: Any interaction with a ν_μ of any interaction type that occurs outside the active volume of the P0D.

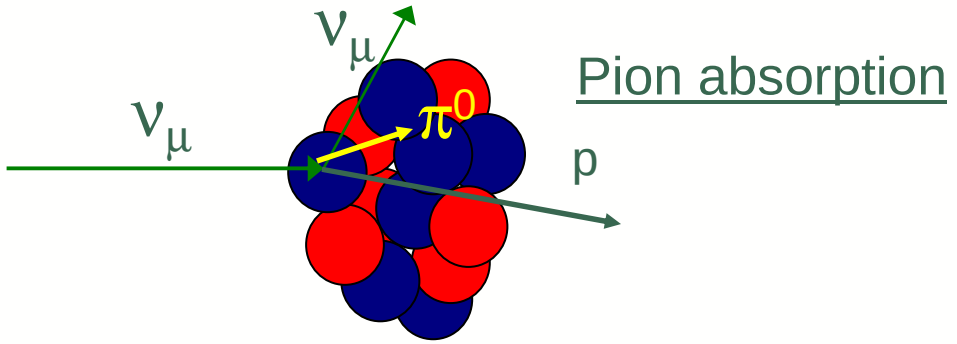
Sand Interactions: Any interaction with the interaction vertex outside the magnet volume

Signal Definition

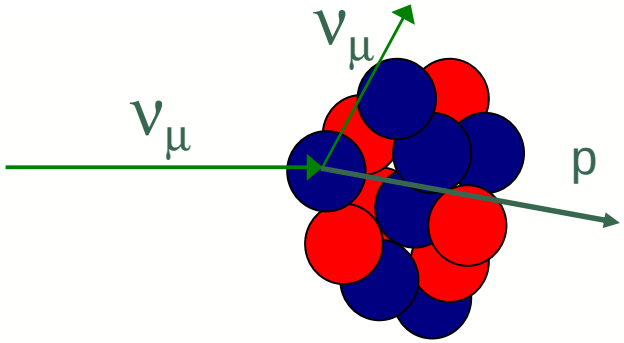
Defined by FSI topologies

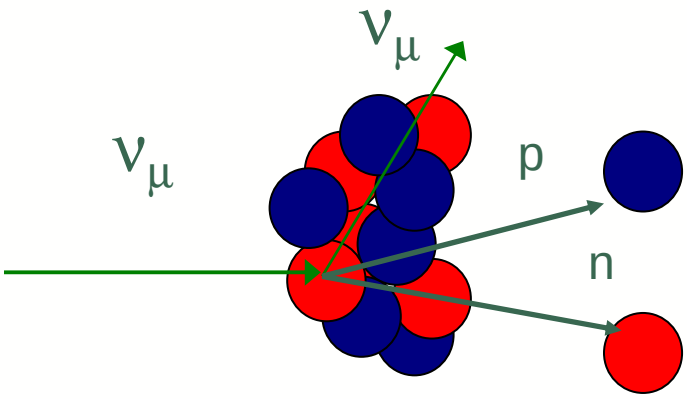
NCE: Any interaction where there is a ν_μ but no mesons exiting the interaction nucleus. Any number of protons and/or neutrons are allowed in the final state.

- NCE
- NCπ^0
- CCQE
- Outside FV in P0D
- Other CC/NC/Non-ν_μ
- Outside P0D
- Sand Interactions
- Data



Pion absorption

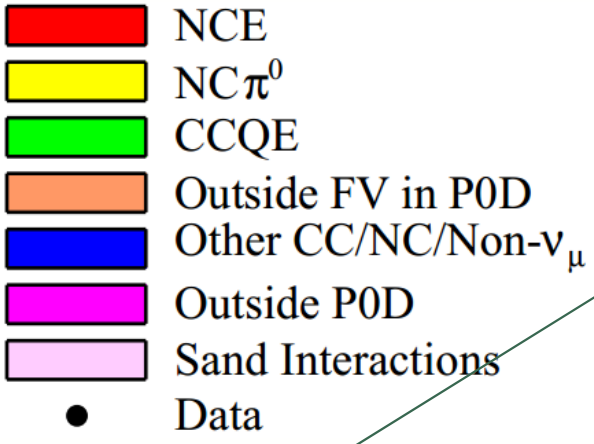




All of these types of events are signal events

Internal P0D Background

Defined by FSI topologies



Largest single channel background

Mostly neutrons from interactions upstream

Irreducible background

NC π^0: Any interaction where there is only one π^0 exiting the interaction nucleus. Any number of nucleons are allowed

CCQE: Any interaction where there is a μ^- but no mesons exiting the nucleus.

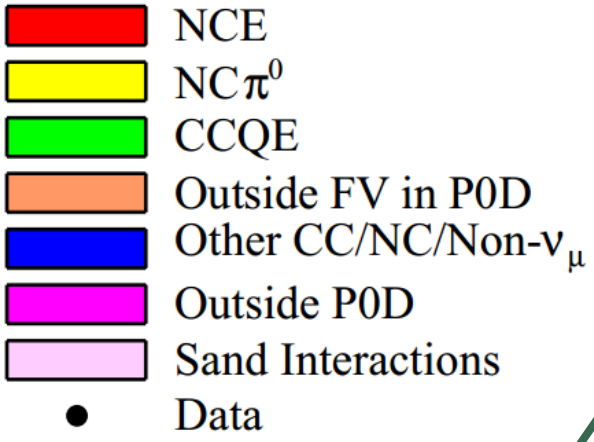
Outside FV in P0D: Any interaction with a ν_μ of any interaction type that occurs within the active volume, but outside the FV of the P0D.

CC Other: Any interaction where there is a μ^- but any number of mesons exiting the nucleus.
NC Other: Any interaction where there is a ν_μ plus some number of mesons exiting the nucleus.

Other: Any non-ν_μ neutrino interaction

External Backgrounds

Defined by FSI topologies



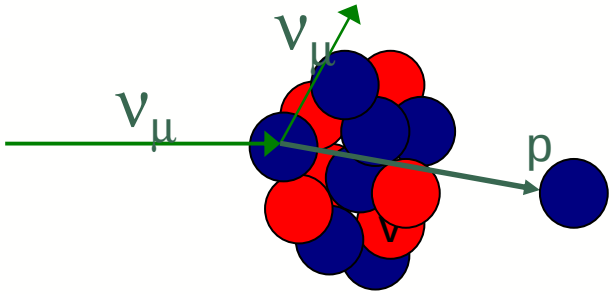
Come from upstream neutrino interactions

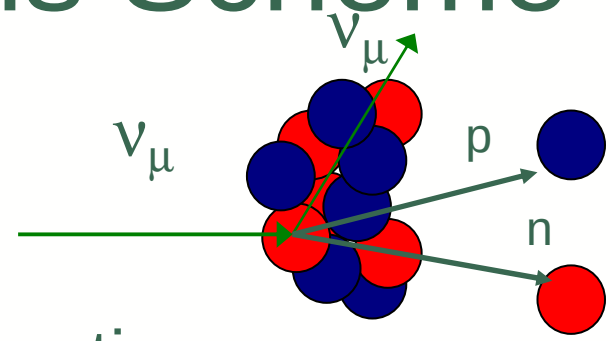
- From the wall and dirt (Sand)
- From the magnet and support structures (Outside P0D)

Outside P0D: Any interaction with a ν_μ of any interaction type that occurs outside the active volume of the P0D.

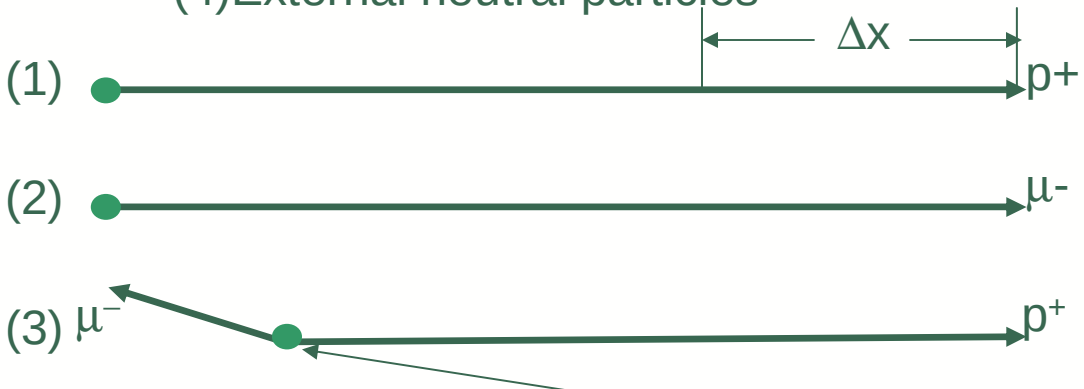
Sand Interactions: Any interaction with the interaction vertex outside the magnet volume

P0D Analysis Scheme

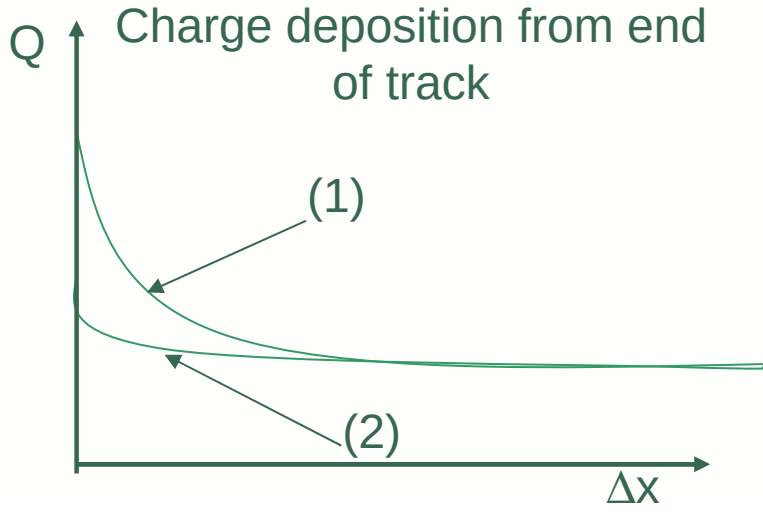




- Trying to extract the NCE neutrino interaction
  - Signal
    - (1) consists of a forward going proton contained in P0D
  - Primary Backgrounds
    - (2)consists of single track CCQE
    - (3)CCQE with a backwards going μ^-
    - (4)External neutral particles



Mis-reconstructed as single track



Flux averaged cross section

$$\langle \sigma \rangle_{flux} = \frac{N_{data} - B_{mc}}{T \Phi \varepsilon}$$

N_{data}	selected number of events in data
B_{MC}	background prediction from MC
T	total number of target nucleons
Φ	Neutrino flux
ε	Selection efficiency correction

- Uses data with water in the P0D
- Reported as cross section per nucleon
  - Averages over carbon, brass, water
- Background subtracted result
- Using 9.918×10^{19} POT select 3936 events with a predicted background of 2016 events

Analysis cuts

- 1 reconstructed vertex with 1 3D track
- Start position within the fiducial volume
  - 25cm from active edges in water target (XY cut)
  - Within readout planes in the water target (Z cut)
- Track is contained
- Downstream PID pull non-muon like
  - Cut results in 82% of the selected tracks having a proton at the downstream end.
- Upstream PID pull non-muon like
- No Michel decay clusters

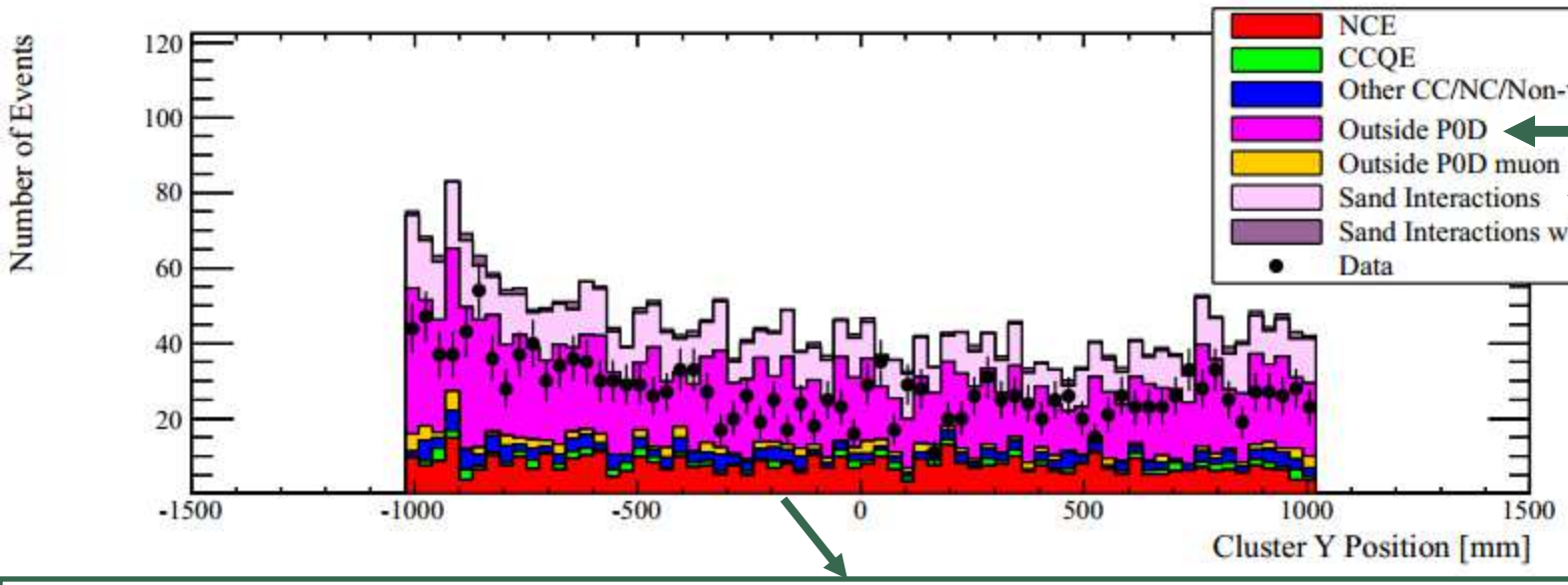
External Background Estimation

- Predominately neutrons from ν_μ interactions upstream of the detector
- Insufficient timing resolution to detect by time of flight
- Significant background with large uncertainty
  - Measure neutron flux with data

Low Energy Clustering

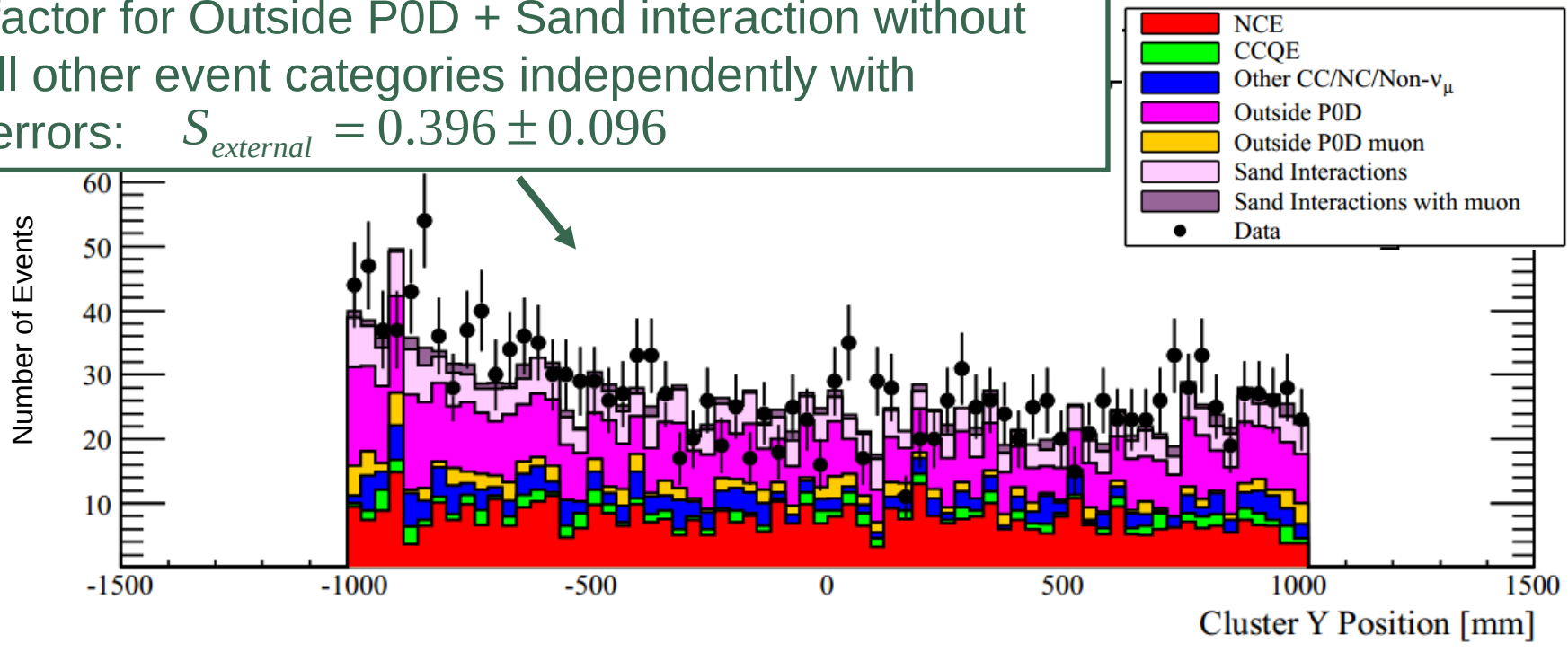
- Reconstruct low energy neutron re-interactions
- Results in an independent event sample
  - Reject events where there are other reconstructed neutrino interactions
  - Enhanced sample for external neutral particles
- Fit data for scaling factor to apply to MC

External Bkg Estimation



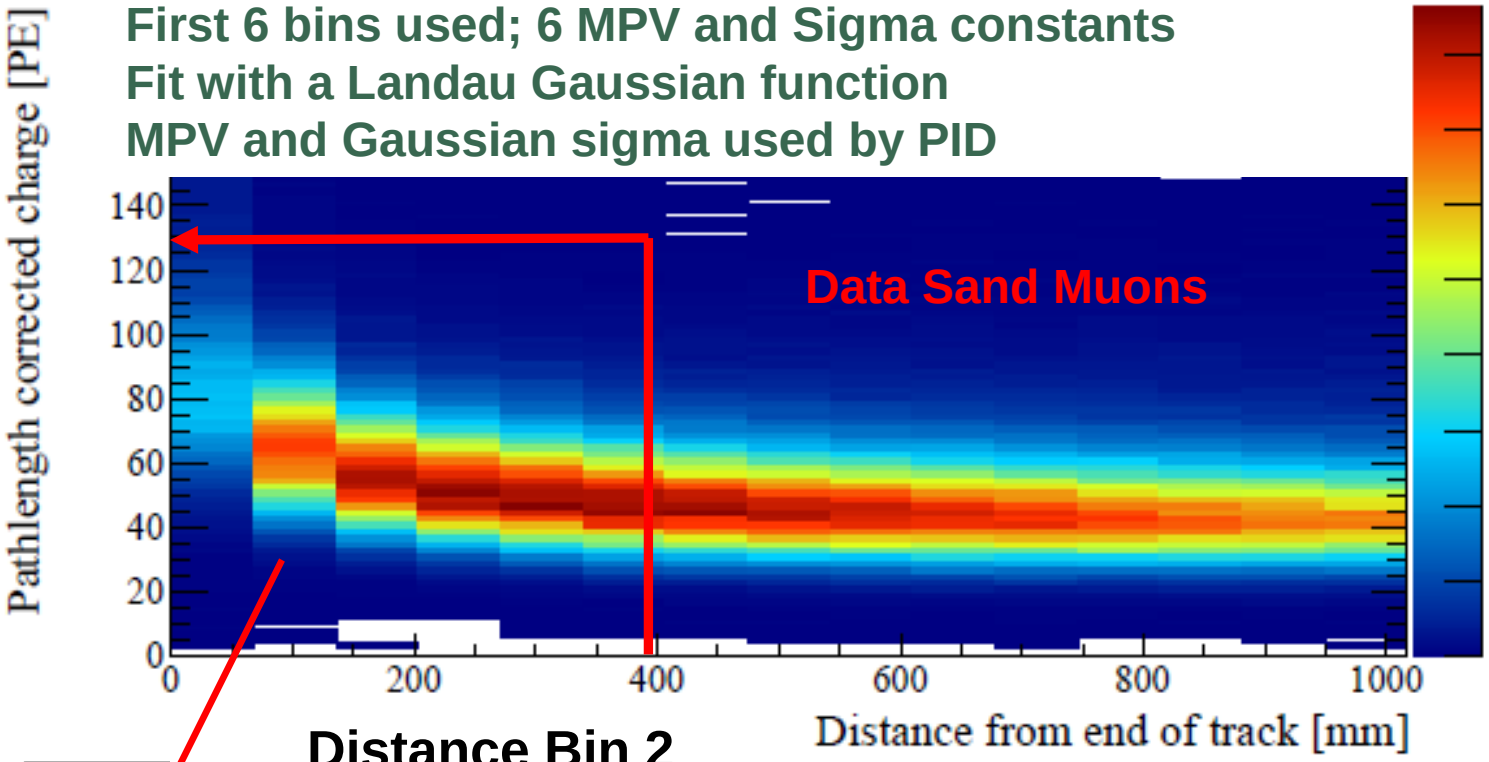
Categories to be scaled

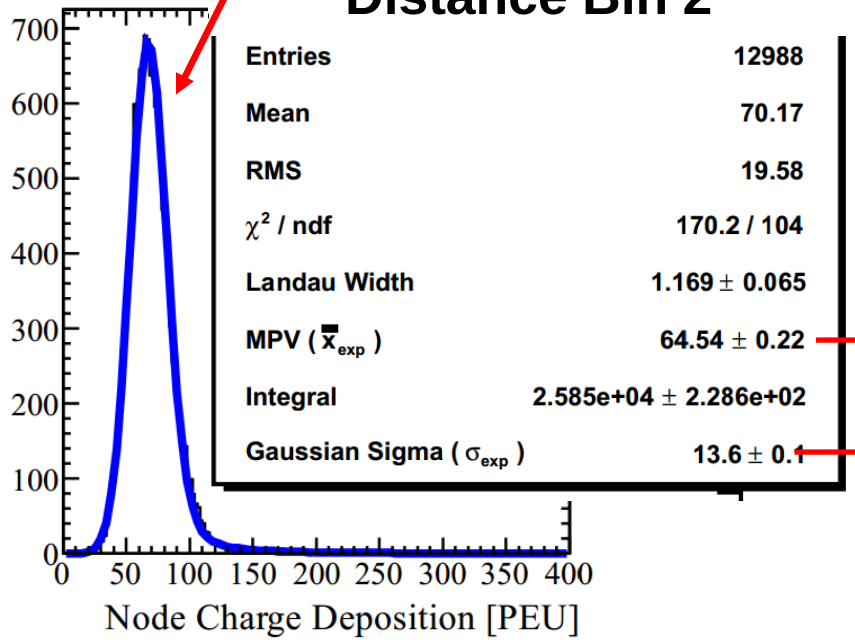
Fit for scaling factor for Outside P0D + Sand interaction without muons. Vary all other event categories independently with normalization errors: $S_{external} = 0.396 \pm 0.096$



Particle Identification

First 6 bins used; 6 MPV and Sigma constants
Fit with a Landau Gaussian function
MPV and Gaussian sigma used by PID



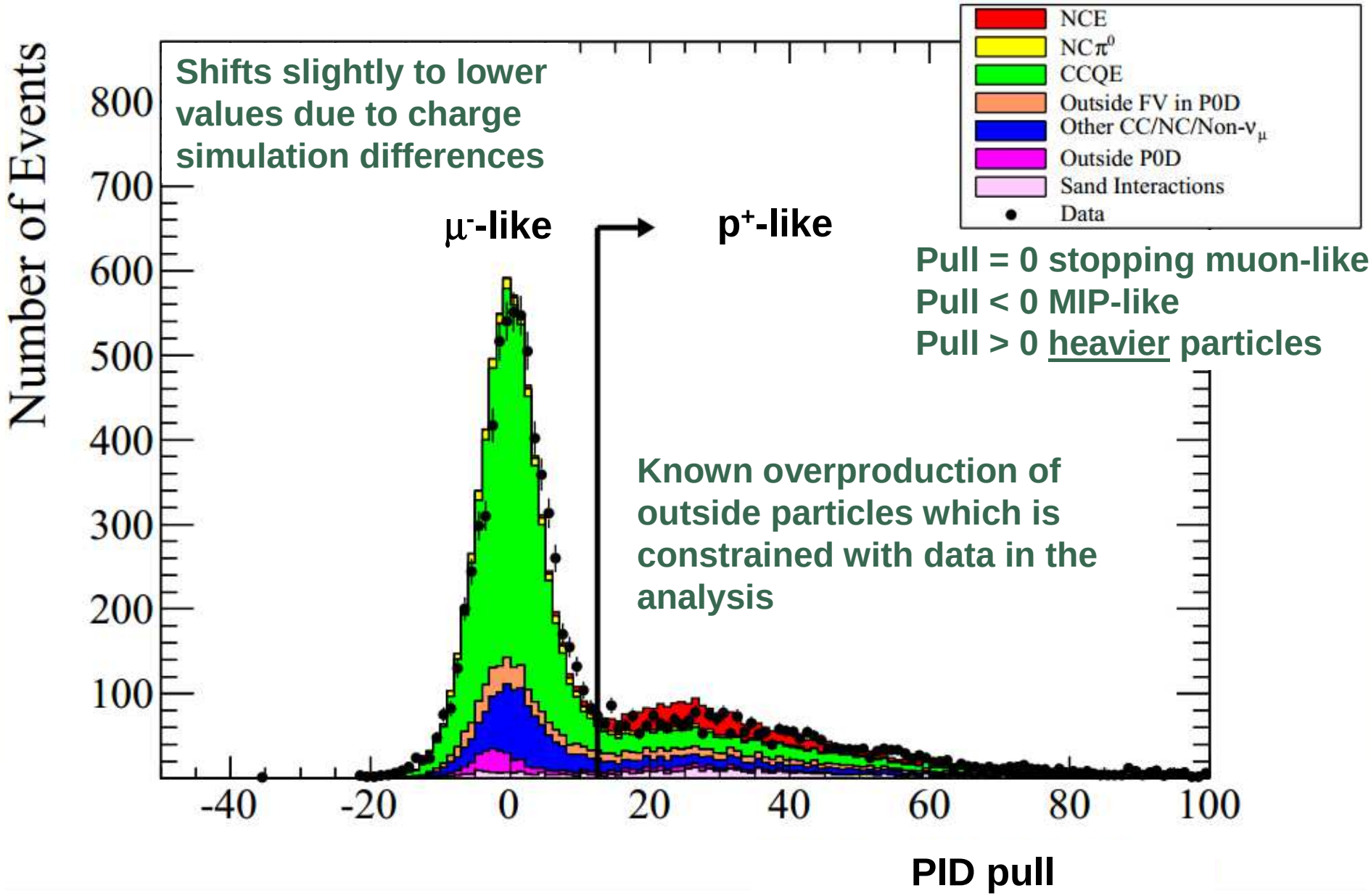


- Select, in data, all upstream entering particles which stopped at least 1 m into the detector
- The PID is applied to the end and beginning of the track resulting in 2 distributions

$$PID_{Pull} = \sum_{nodes} \frac{x_{measure} - \bar{x}_{expectation}}{\sigma_{expectation}}$$

PID applied to end of track

Cuts applied: 1 3D track, fiducial volume

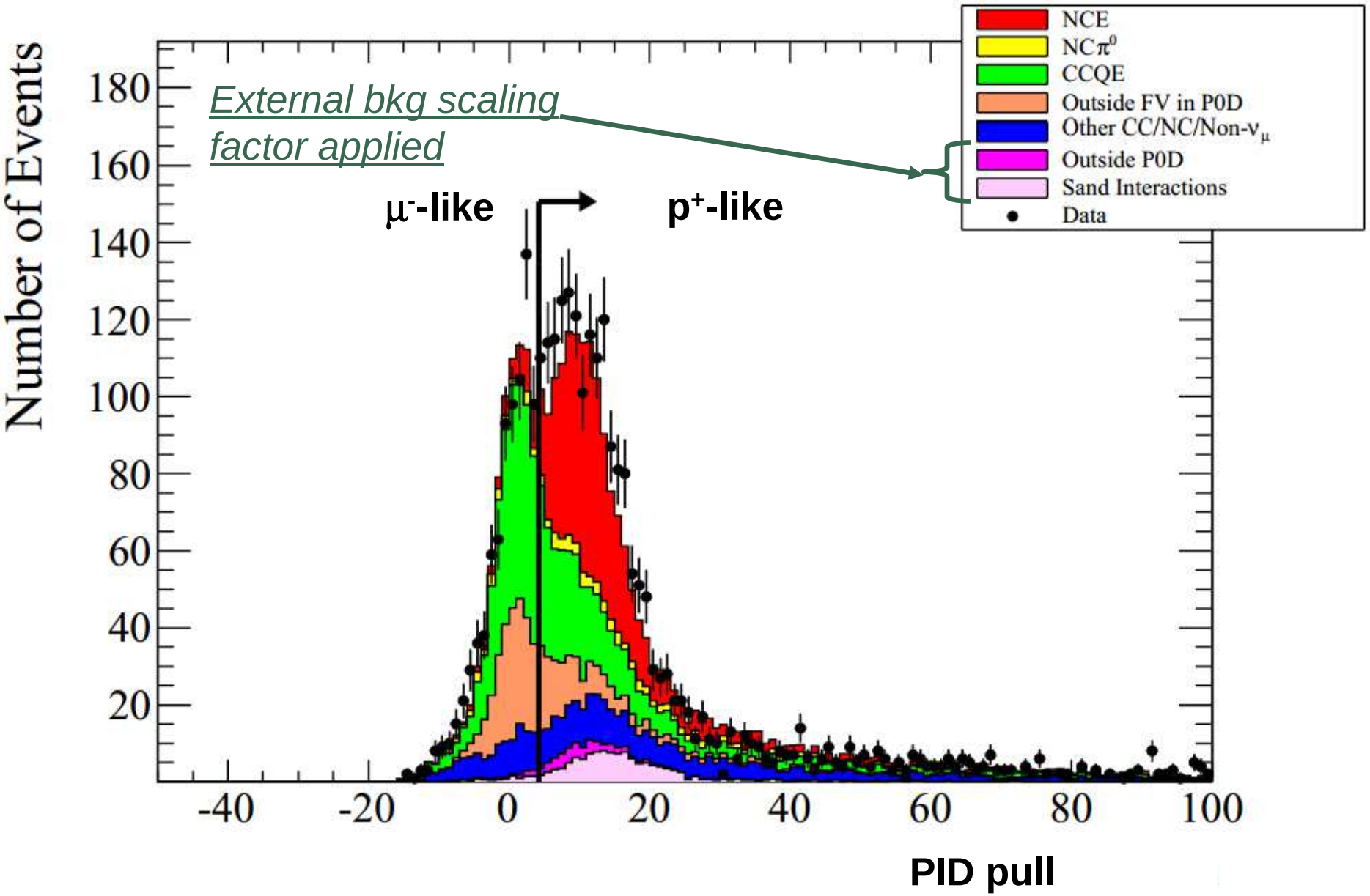


Pull = 0 stopping muon-like
Pull < 0 MIP-like
Pull > 0 heavier particles

Known overproduction of outside particles which is constrained with data in the analysis

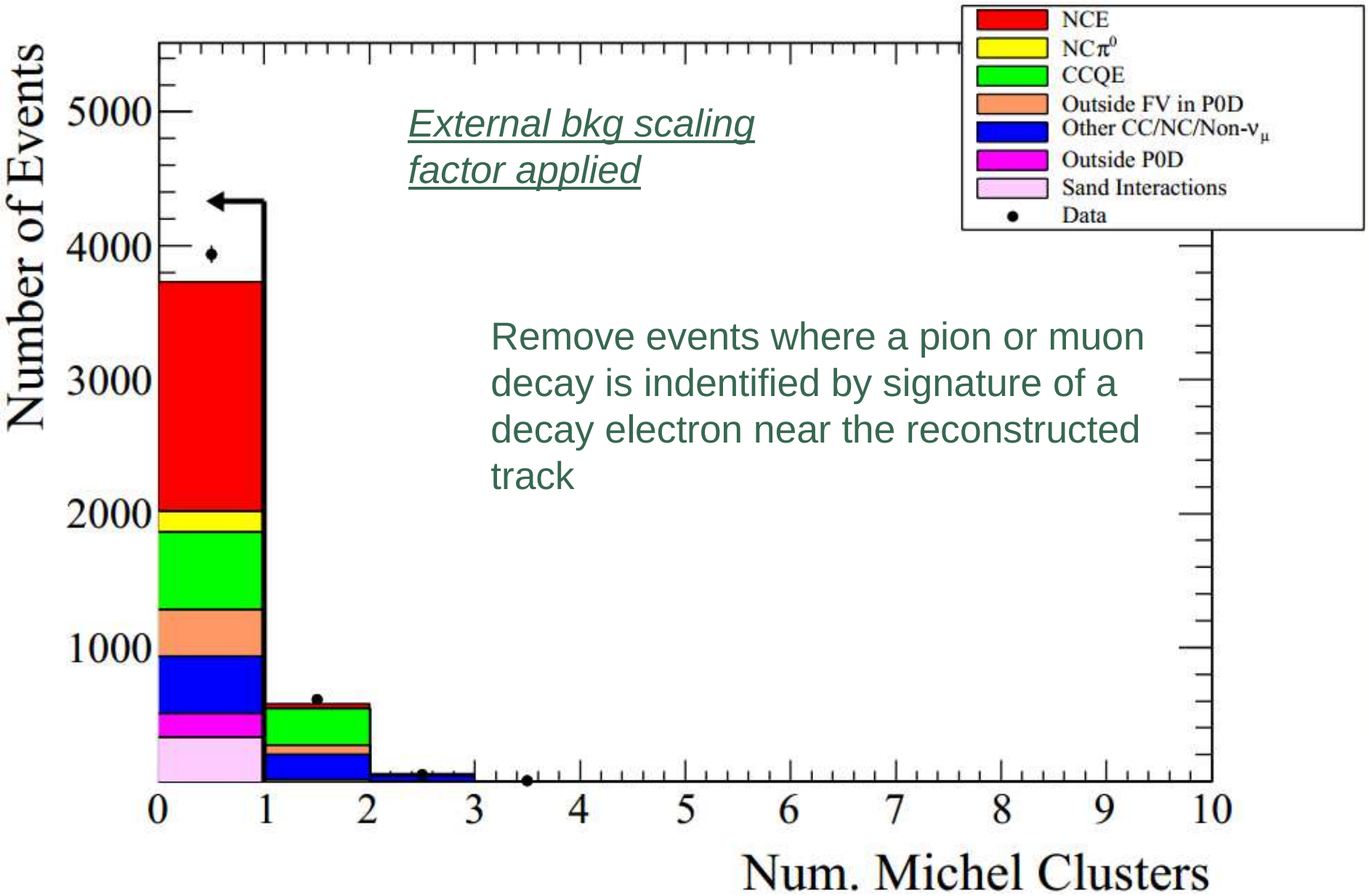
PID applied to beginning of track

Cuts applied: 1 3D track, FV, PID on track end



Remove Michel Decays

Cuts applied: 1 3D track, FV, PID on track end and beginning

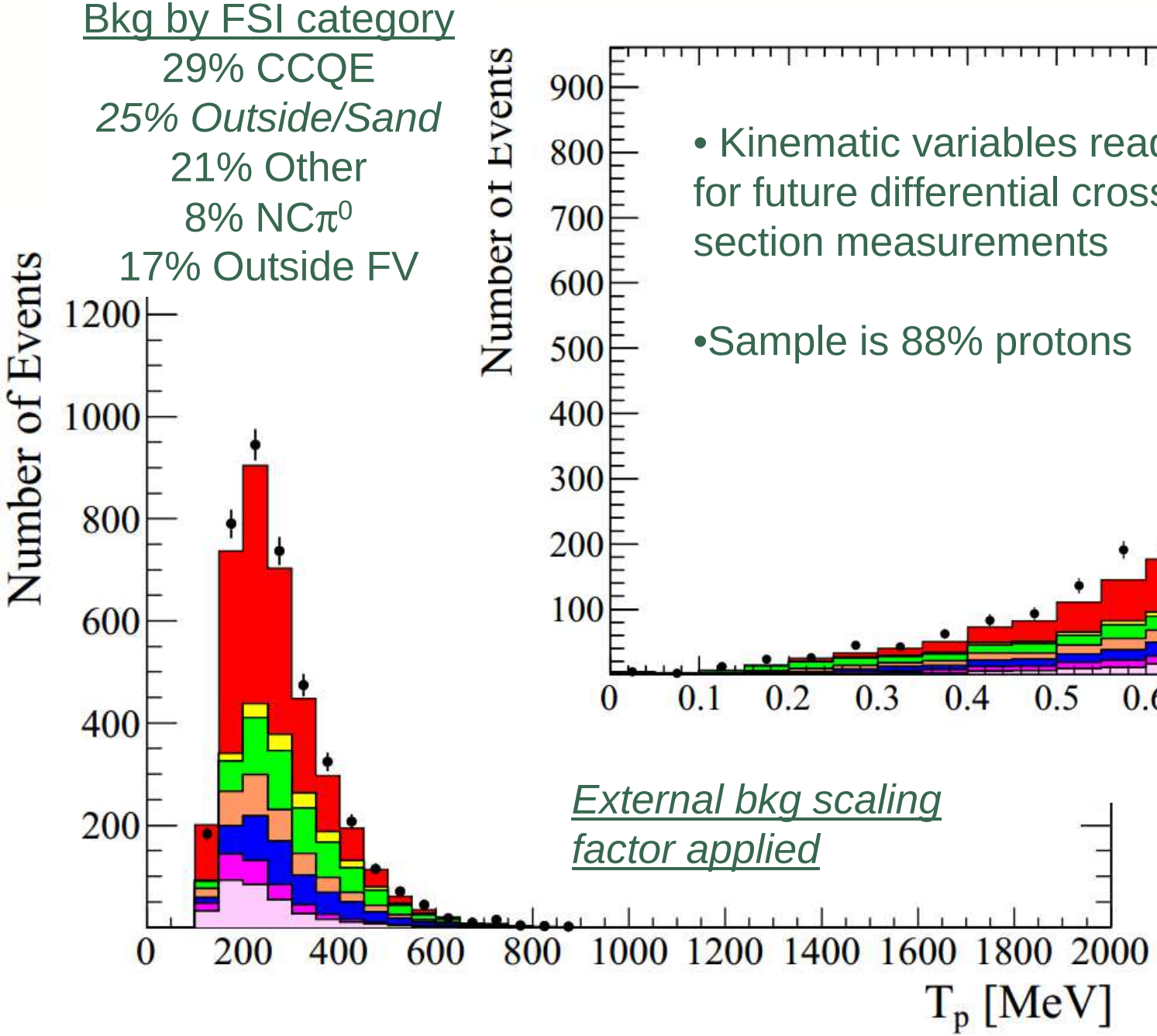


External bkg scaling factor applied

Remove events where a pion or muon decay is indentified by signature of a decay electron near the reconstructed track

Final Sample

Bkg by FSI category
29% CCQE
25% Outside/Sand
21% Other
8% NCπ^0
17% Outside FV



- Kinematic variables ready for future differential cross section measurements
- Sample is 88% protons

External bkg scaling factor applied

Systematics

Systematic Name	Error on cross section
Detector and Reconstruction	
Fiducial Volume	0.72%
PID Algorithm	1.12%
Reconstruction Road Following	1.66%
Michel Efficiency	0.98%
Number of targets	0.7%
Physics	
Cross section model parameters	+14.33%, -16.60%
Pion Absorption	2.29%
Secondary Interactions	2.5%
Outside background scaling factor	6.40%
Beam Flux	
Flux	+17.5%, -21.5%
Total Systematics	+23.88%, -28.22%
Total Statistical	±3.3%

See next slide

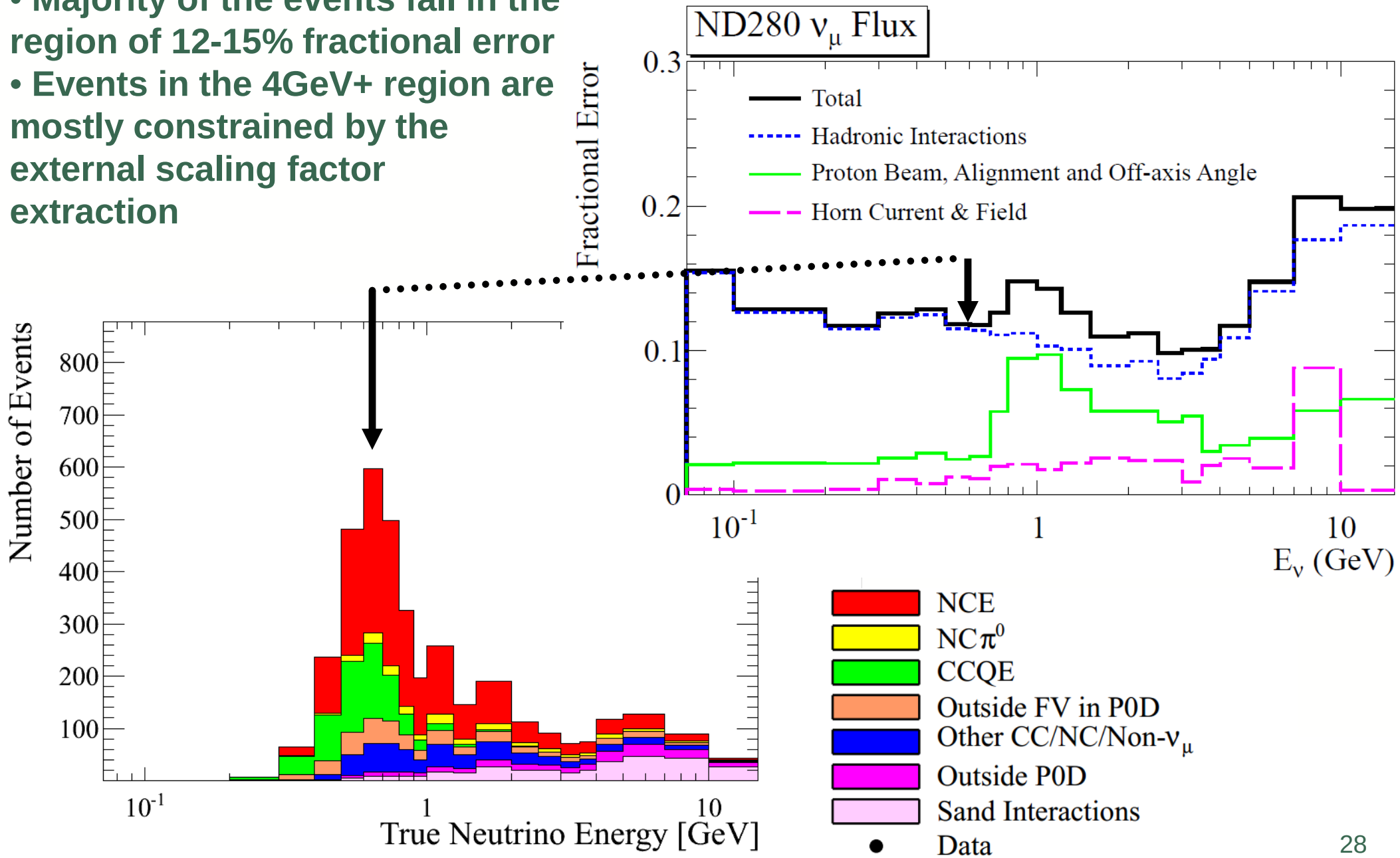
See later slide

Model Uncertainty

- Uncertainty dominated by background channels
- 3 largest contributors:
  - Pionless delta decay
  - NCπ^0 normalization
  - CCQE uncertainty modeled by varying M_A^{QE}
    - ~30% of the background

T2K Flux Uncertainty

- **Majority of the events fall in the region of 12-15% fractional error**
- **Events in the 4GeV+ region are mostly constrained by the external scaling factor extraction**



Flux averaged cross section

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- Uses data with water in the P0D
- Reported as cross section per nucleon
  - Averages over carbon, brass, water
- Background subtracted result
- Using 9.918 x 10^{19} POT select 3936 events with a predicted background of 2016 events

$$\langle \sigma \rangle_{flux} = 2.24 \times 10^{-39} \pm 0.07(\text{stat.}) \, {}^{+0.53}_{-0.63}(\text{sys.}) \frac{\text{cm}^2}{\text{nucleon}}$$

$$\text{NEUT}: \langle \sigma \rangle_{flux} = 2.02 \times 10^{-39} \frac{\text{cm}^2}{\text{nucleon}}$$

$$\text{GENIE}: \langle \sigma \rangle_{flux} = 1.78 \times 10^{-39} \frac{\text{cm}^2}{\text{nucleon}}$$

Future

- Currently in the works:
  - Data driven background fit
    - Reduction in flux and model systematics
    - Goal is to reduce from 25% level to ~15%
  - Full T2K data set
    - Higher statistics for differential measurement with respect to proton kinematics
      - Uses ~1/3 of water-in data and none of water out
      - ~40% water-in, 60% water-out at just over 6E20 POT
  - Water-in - water-out measurement
    - Differential measurements on water only
    - Differential measurements on carbon + brass

Conclusion

- The preliminary T2K ND280 NCE flux averaged cross section per nucleon has been measured

$$< \sigma >_{\text{flux}} = 2.24 \times 10^{-39} \pm 0.07(\text{stat.}) \, {}^{+0.53}_{-0.63} (\text{sys.}) \frac{\text{cm}^2}{\text{nucleon}}$$

  - Future improvements in background prediction will reduce systematics significantly
- Future NCE differential cross section measurements on water
- Active cross section program using the on and off axis detectors using a variety of nuclear targets

Backups

BNL 734

–L.A. Ahrens et al., Phys. Rev. D 35, 785 (1987)

- In the end after bkg subtraction 951(776) elastic events for 0.55(2.5)E19 POT for ν_μ(ν_μ-bar) respectively

$$R_\nu = \frac{\sigma(\nu_\mu p \to \nu_\mu p)}{\sigma(\nu_\mu n \to \mu^- p)} = 0.153 \pm 0.007(\text{stat}) \pm 0.017(\text{syst}),$$

$$R_{\bar{\nu}} = \frac{\sigma(\bar{\nu}_\mu p \to \bar{\nu}_\mu p)}{\sigma(\bar{\nu}_\mu p \to \mu^+ n)} = 0.218 \pm 0.012(\text{stat}) \pm 0.023(\text{syst}),$$

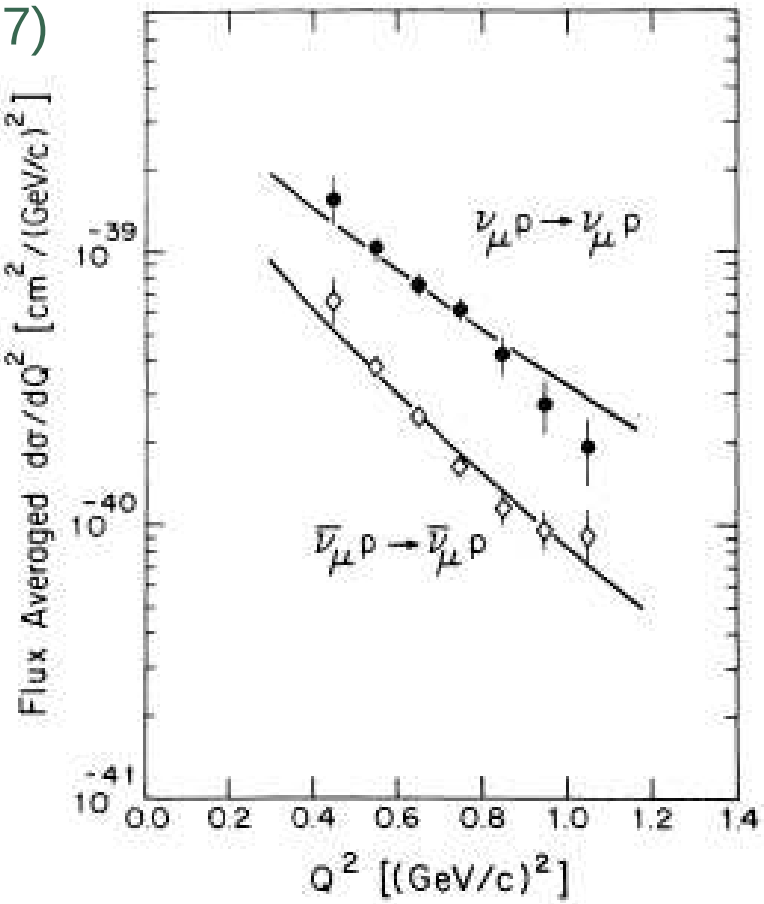

FIG. 35. The data points are the measured flux-averaged differential cross sections for $\nu_\mu p \to \nu_\mu p$ and $\bar{\nu}_\mu p \to \bar{\nu}_\mu p$ from this experiment. The solid curves are best fits to the combined data with the values $M_A = 1.06$ GeV/c^2 and $\sin^2\theta_W = 0.220$. This fitting procedure imposes adjustment of the solid curves by scale factors of 1.05 for $\nu_\mu p$ and 1.09 for $\bar{\nu}_\mu p$ consistent with the absolute scale uncertainty of approximately 11% in each of the individual cross sections which was included in the fitting procedure. The error bars represent statistical error and also include Q^2-dependent systematic errors (see Table IX).

MiniBooNE

- 94,531 events pass the cuts for 6.46E20 POT
  - World's largest NCE sample

PRD 82, 092005 (2010)