Measurement of Neutral Current π^0 Production with the T2K π^0 Detector (PØD)

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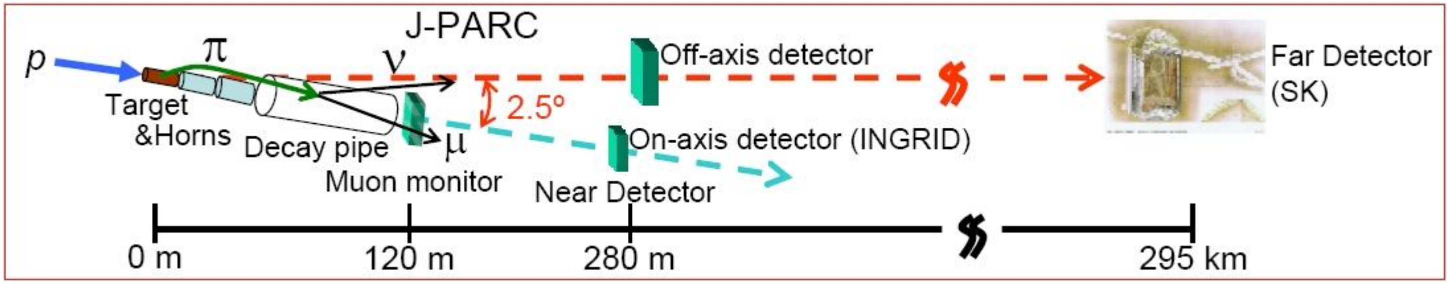
Outline

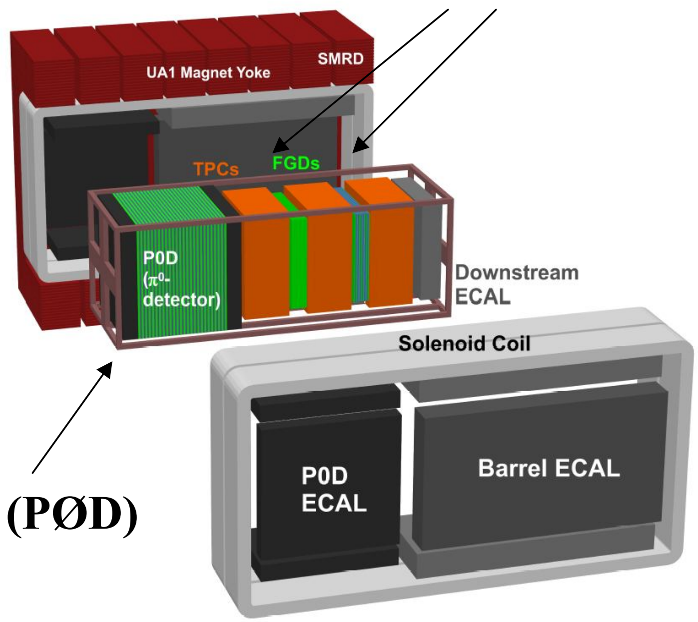
- T2K overview
- Neutral Current single π^0 (NC1π^0) production overview
- T2K PØD
- NC1π^0 measurement
  - Event Selection
  - Likelihood fit results
  - Systematic errors

T2K Experiment



- ν_μ beam produced at J-PARC in Tokai, Japan
  - 2.5 degree off axis to exploit π decay kinematics → narrow band beam
- Super Kamiokande serves as the far detector
- Primary physics goals:
  - Discovery of ν_e appearance → non-zero θ_{13} *
  - Precision measurement of ν_μ disappearance → θ_{23}, Δm^2_{23}

TPCs + FGDs (Tracker)



π^0 Detector (PØD)

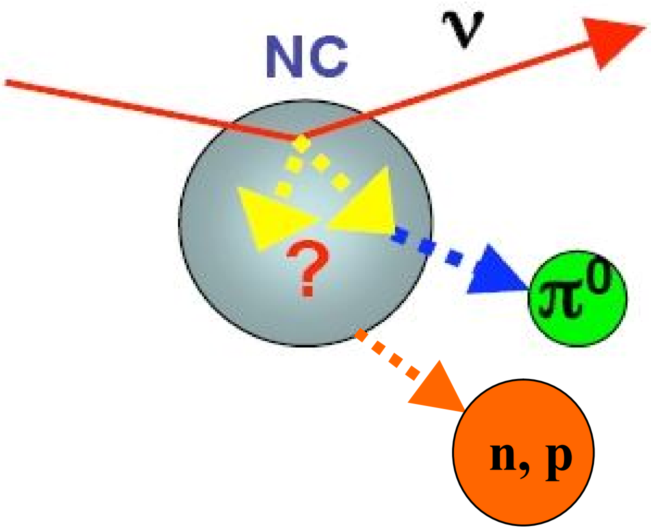
Current measurements from off-axis detector at 280 m

- Measure neutrino beam prior to oscillation (Tracker)
- Measure background to ν_e appearance search
  - PØD NC1π^0 measurement
  - PØD and Tracker intrinsic beam ν_e measurement (see poster session)

* first indications from T2K published in P.R.L. 107 2011
updated results presented by K. Sakashita, ICHEP 2012

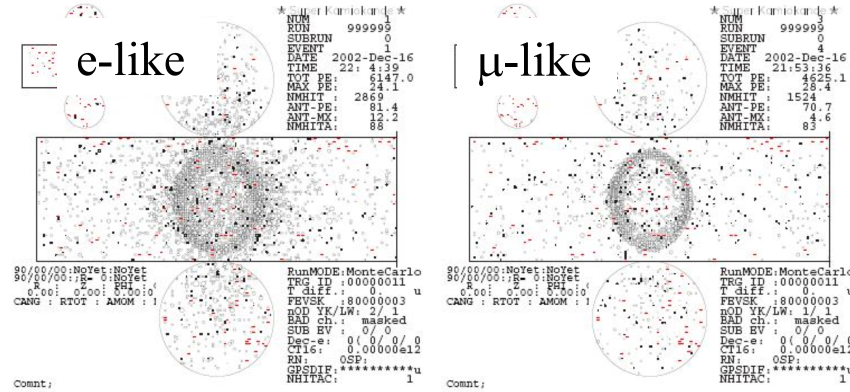
NC1π^0 Production Definition

- NC1π^0 Definition:
  - Neutral current (no outgoing charged lepton)
  - 1 π^0 exiting the nucleus after final state interactions
  - Allow any number of protons and/or neutrons
  - No other particles exiting the nucleus
- Includes π^0 production via delta resonances
  - $\nu + p(n) \rightarrow \nu + \Delta^{+(0)}$
  - $\Delta^{+(0)} \rightarrow p(n) + \pi^0$
- Includes coherent π^0 production
- Includes π^0 production from nuclear effects
  - $\pi^+ \rightarrow \pi^0$ charge exchange possible



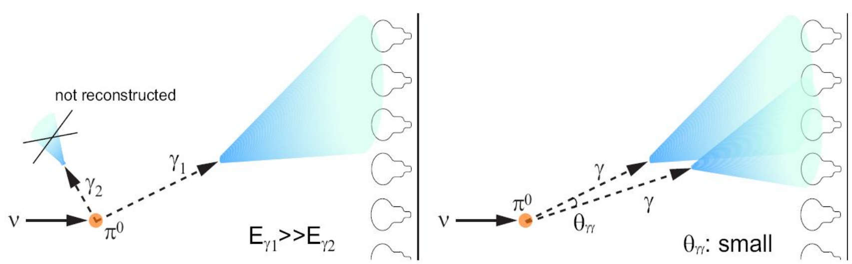
Why Measure NC1π^0 Production?

- Cherenkov ring pattern for showering particles ($e^{\pm}$, γ)
- Electron neutrino appearance observed via ν_e CCQE
  - $\nu_e + n \rightarrow e^- + p$
- Appearance signal of 1 e-like ring
- π^0 can be misidentified as electron due to
  - Asymmetric decay
  - Small opening angle



•Left: ring from a showering particle ($e^{\pm}$, γ)

•Right: ring from a nonshowering particle ($\mu^{\pm}$, $\pi^{\pm}$)



Asymmetric Decay Small γγ Angle

T2K signal and background events at SK

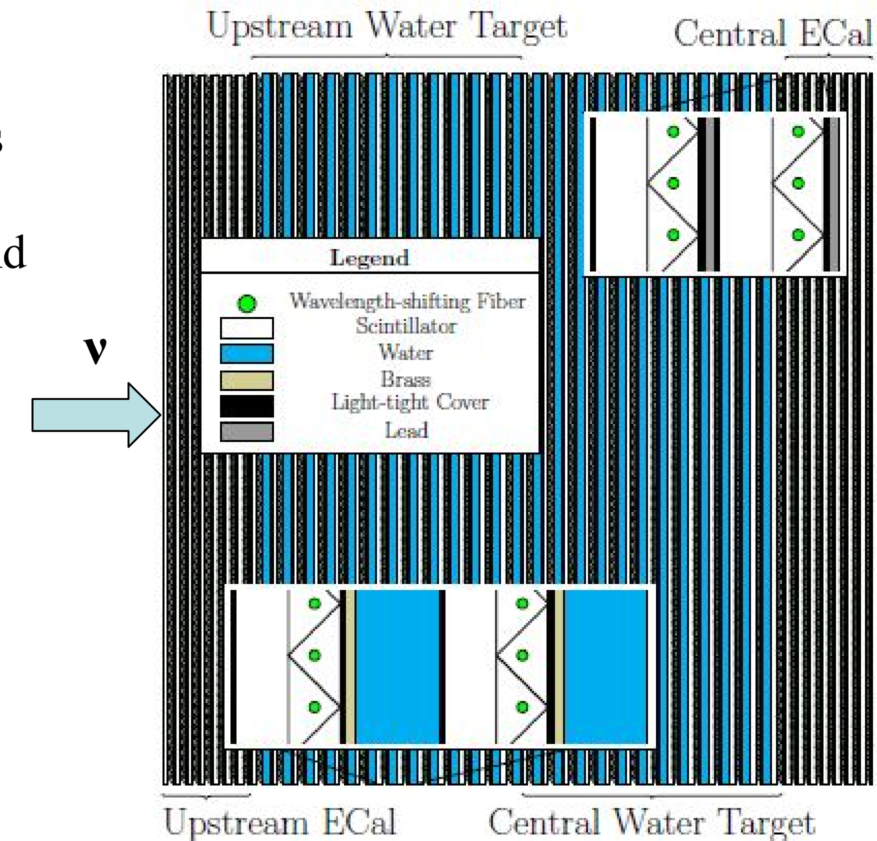
Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	2.73	9.07
ν_e signal	0.15	6.60
ν_e background	1.42	1.32
ν_μ background	1.02	1.02
$\bar{\nu}_\mu$ background	0.06	0.06
$\bar{\nu}_e$ background	0.08	0.07

Significant contribution to ν_e appearance background due to NC1π^0

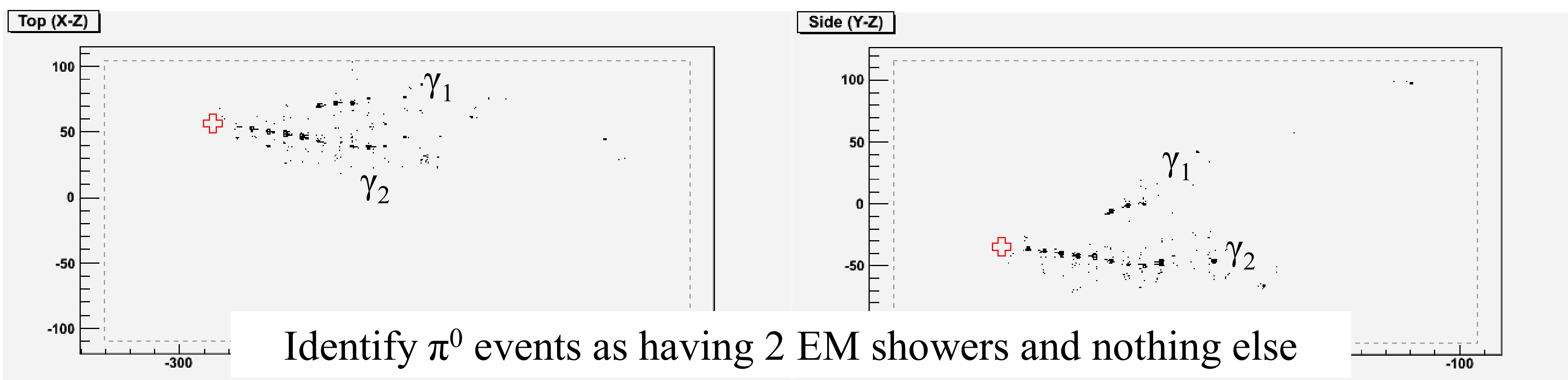
Large uncertainty in NC1π^0 cross section

T2K PØD

- EM calorimeter optimized for observing π^0 events on a water target
- 40 tracking modules with *xz*/*yz* scintillator bars and WLS fiber and MPPC readout
- Removable water targets allow measurement of cross sections on water
- US. and Cen. ECals provide energy containment
- Particles reconstructed from tracks in the active regions
- Energy-based PID provides μ/EM discrimination

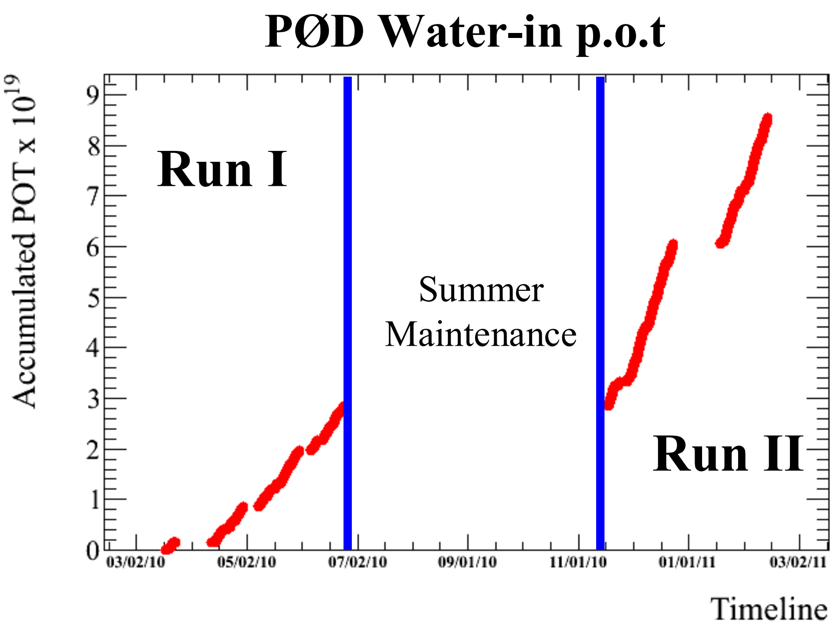


xz/*yz* projection of an NC1π^0 interaction in the PØD



Identify π^0 events as having 2 EM showers and nothing else

Summary of PØD Data and Monte Carlo



- Full water-in/out analysis requires equivalent statistics
- Water-out data taking interrupted by March 11 earthquake
- This analysis is water-in only

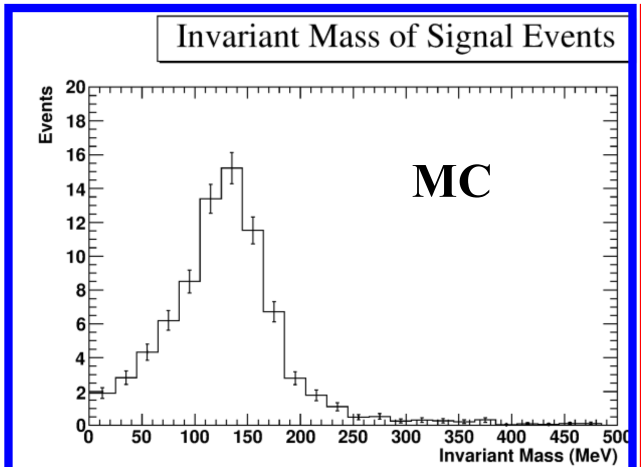
- **Data:**
  - Good beam spills were selected by requiring both the PØD and Magnet to have good detector status
  - Run I: 2.85×10^{19} p.o.t.
  - Run II: 5.70×10^{19} p.o.t.
- **MC:**
  - Use NEUT MC Generator to simulate neutrino interactions at ND280
  - Run I: (6 bunches) 55.65×10^{19} p.o.t.
  - Run II: (8 bunches) 110.15×10^{19} p.o.t.

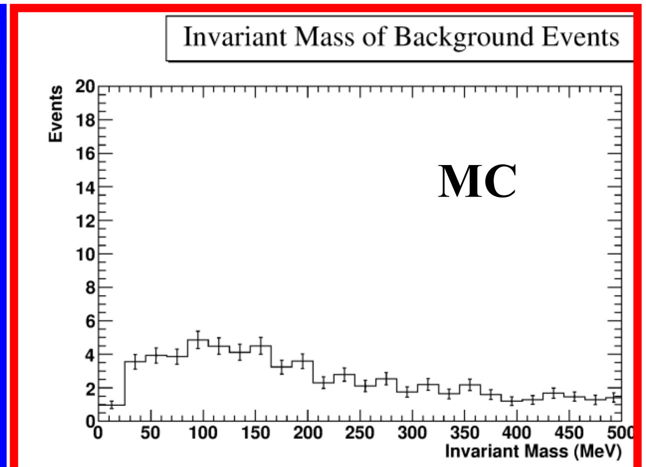
NC1π^0 Event Selection

- **Pre-selection**
  - Require event to be within beam spill
- **Fiducial**
  - Require vertex in water target
- **No μ-like**
  - Reject CC events
- **2 EM-like**
  - $\pi^0 \rightarrow \gamma\gamma$
- **No μ-decay**
  - No delayed hit clusters
- **π^0 Direction**
  - Require π^0 in forward direction
- **EM Charge**
  - Apply additional PID to EM shower
- **EM Separation**
  - Require decay γs to be separated by 50 mm

Cut	Data	Signal	Background
Pre-selection	415750	4569.1 ± 16.1	183382.2 ± 100.7
Fiducial	51736	1716.1 ± 10.3	48117.1 ± 54.1
No μ-like	11170	1185.5 ± 8.0	10571.8 ± 24.6
2 EM-like	2061	399.0 ± 4.7	1958.1 ± 10.8
No μ-decay	1536	387.9 ± 4.6	1335.1 ± 9.2
π^0 Direction	693	250.4 ± 3.7	616.6 ± 6.8
EM Charge	312	166.7 ± 3.0	223.5 ± 3.5
EM Separation	115	79.1 ± 2.1	64.5 ± 1.9

Calculate invariant mass $M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{\gamma\gamma})}$





Use mass distributions as pdfs in a likelihood fit

Fit Method

Define a likelihood function by:

$$\mathcal{L}(N_{\text{Sig}}, N_{\text{Bkg}}, E_{\text{Scale}}) = \underbrace{\mathcal{L}_{\text{EScale}} \times \mathcal{L}_{\text{Bkg}}}_{\text{Constraint Terms}} \times \underbrace{\mathcal{L}_{\text{Shape}} \times \mathcal{L}_{\text{Norm}}}_{\text{Extended Term}}$$

N_{Sig} = Number of signal events

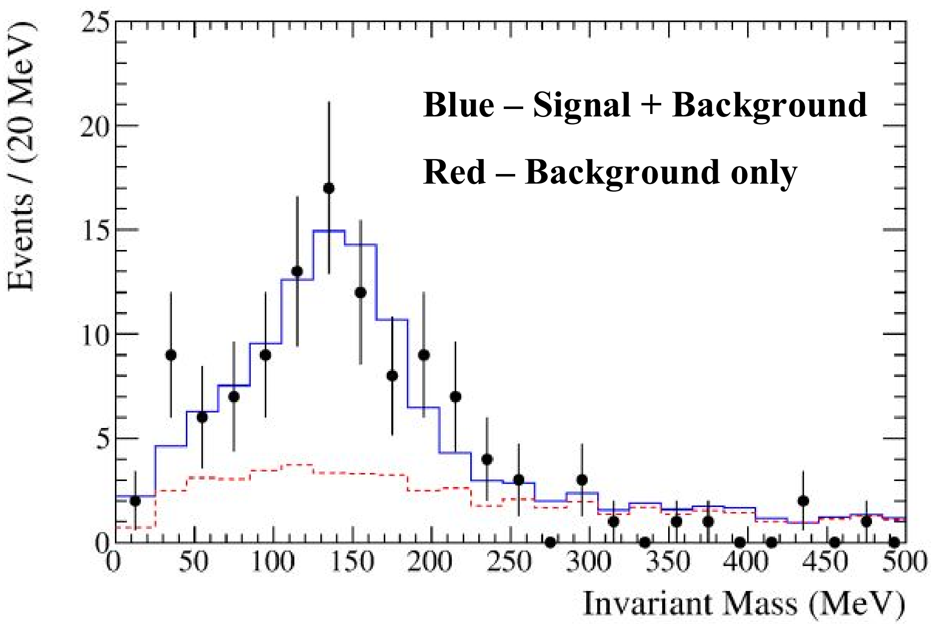
N_{Bkg} = Number of background events

E_{Scale} = Controls the ratio of photoelectrons (P.E) seen by MPPCs, attributed to a γ, to total γ energy in MeV.

- Energy Scale Term
  - Ratio of γ energy to visible energy determined from MC (0.2 P.E/MeV)
  - Systematic due to differences between real/simulated geometries
  - Total energy scale systematic of 7%
  - Gaussian with mean of 1.0 and sigma of 0.07
- Background Term
  - Apply NEUT cross section uncertainties to MC background prediction
  - Gaussian with mean of 65 and sigma of 14

Results of the Fit

Results of an unbinned likelihood fit



	Observed	Expected	Ratio
Signal	66 ± 13	79 ± 2	0.84 ± 0.16
Background	52 ± 10	65 ± 2	0.80 ± 0.16

Fitted E_{Scale} is 0.94 ± 0.03

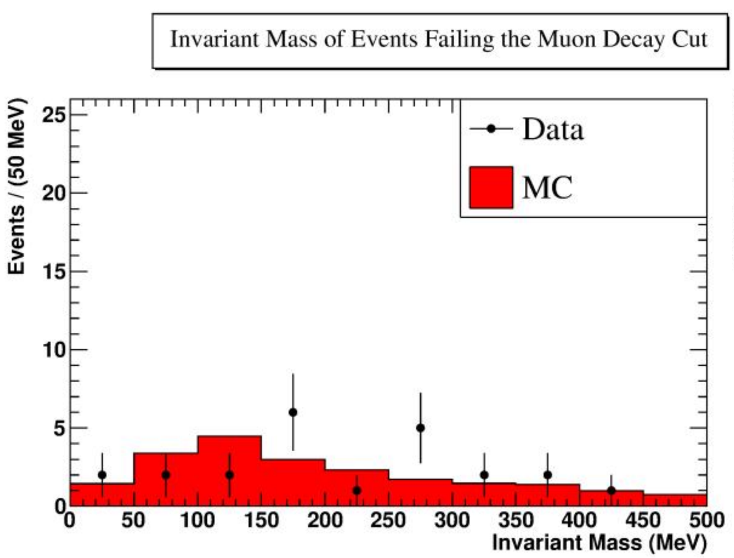
$$r = \frac{N_{\pi^0}^{Data}}{N_{\pi^0}^{MC}} = 0.84 \pm 0.16(stat)$$

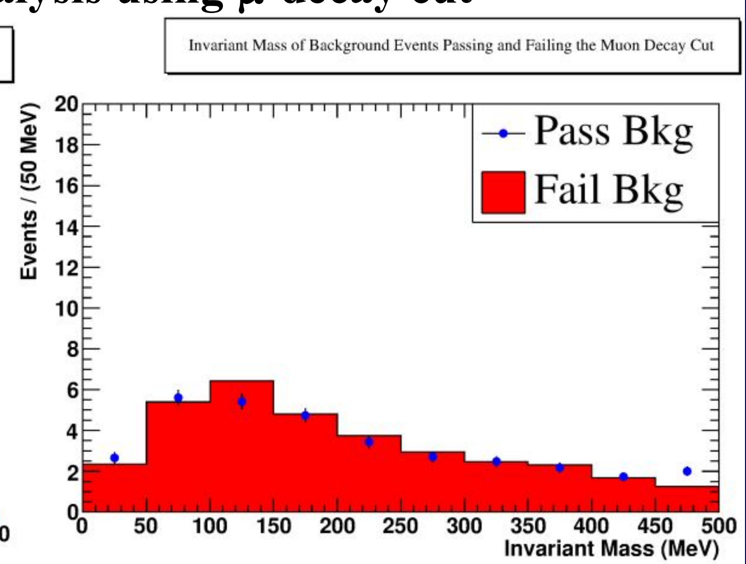
Sideband analysis using μ-decay cut

Compare events with a μ-decay signal

Check consistency of bkgd shape prediction

Repeat fitting procedure to estimate bkgd shape prediction uncertainty





Summary of Systematic Errors

Source	Error	Contribution to Ratio (%)
Target Mass Uncertainty	0.8%	0.8%
Detector Alignment	2.5 mm	$< 0.1\%$
Fiducial Volume	7%	7%
Relative Flux Uncertainty	15%	15(6.5)%
Reconstruction Uncertainties	4.7%	4.7%
Energy Resolution	10%	0.5%
Shape Uncertainty	13.7%	13.7%
Total	—	22(17)%

- **Fiducial volume uncertainty due to vertex reconstruction bias**
- **Flux uncertainty**
  - Normalize by Tracker CC inclusive measurement to reduce uncertainty

$$\frac{N_{CC}^{Data}}{N_{CC}^{MC}} = 1.036 \pm 0.028(\text{stat})\,^{+0.044}_{-0.037}(\text{det. syst}) \pm 0.038(\text{phys. model})$$

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- **Reconstruction uncertainties due to data/MC differences in the PID**
- **Shape uncertainty estimated from sideband analysis**

Summary of NC1π^0 Results

$$r = \frac{N_{\pi^0}^{Data}}{N_{\pi^0}^{MC}} = 0.84 \pm 0.16(stat) \pm 0.18(sys)$$

$$R = \frac{N_{\pi^0}^{Data} / N_{\pi^0}^{MC}}{N_{CC}^{Data} / N_{CC}^{MC}} = 0.81 \pm 0.15(stat) \pm 0.14(sys)$$

From Tracker CC measurement

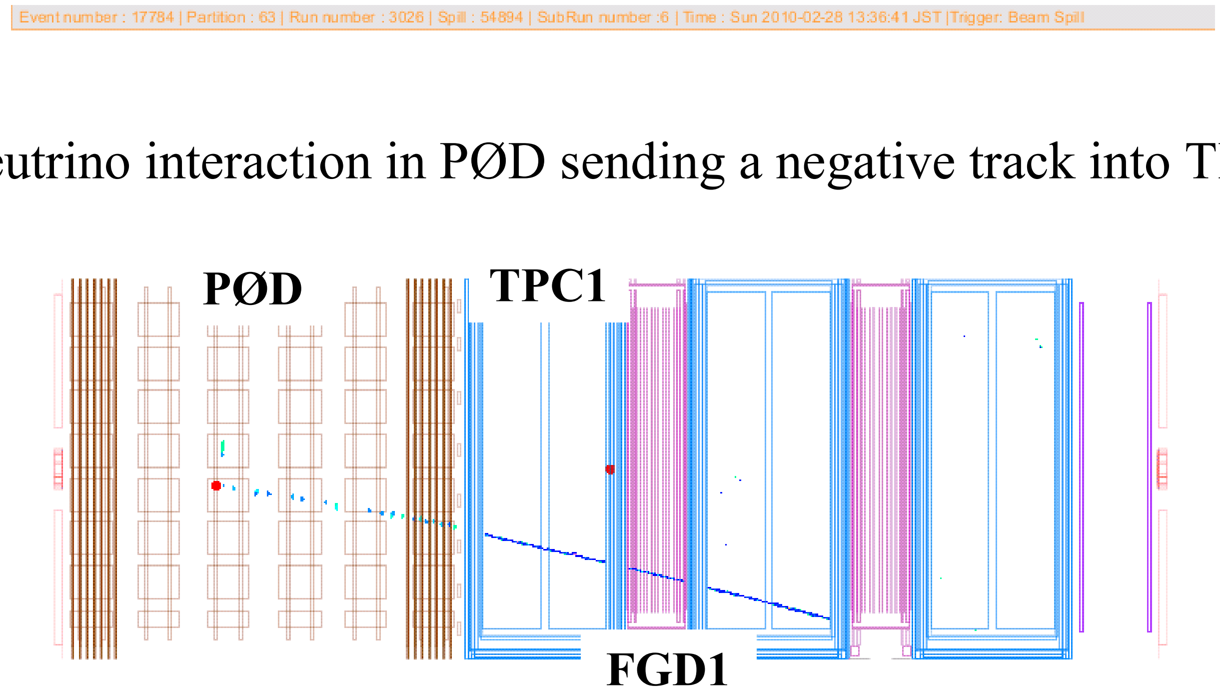
Measurement of NC1π^0 production on composite target

H_2O (~1900 kg), Scintillator (~2675 kg), Brass (~750 kg)

Summary

- We present a measurement of NC1π^0 production using 8.55x10^{19} p.o.t. of run 1 and run 2 data with the PØD in the water-in configuration
  - First half of the cross section measurement on water
  - Water out data has been taken, stay tuned for results
- We measure the ratio of the observed number of NC1π^0 events to the NEUT prediction
  - **r = 0.84 ± 0.16 (stat) ± 0.18(sys)**
- The ratio of the observed number of NC1π^0 events to the NEUT prediction normalized by the tracker CC inclusive measurement is
  - **R = 0.81 ± 0.15 (stat) ± 0.14(sys)**

CC Interaction Study



Neutrino interaction in PØD sending a negative track into TPC

Event Selection

- Highest momentum negative track used as candidate
- Track position located in PØD fiducial volume
- Good TPC momentum measurement

Need to incorporate reconstruction information from multiple detectors

Analysis still being finalized