Journal Club

"Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam"

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Article Topic and Structure

Topic

- Experimental Particle Physics
- Neutrino Particle Properties

Structure

- 20 Pages
  - 5 Authors, 1 Abstract, 11 Content, 3 Bibliography;
- Divided by paragraphs no sectioning.

Importance

- Submitted to PRL;
- First time measurement of relevant Physics Quantity

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Paragraph Topics

- Search Context
- Beam Characteristics
- Accelerator Description
- Near Detector Description
- Far Detector Description
- Analyzed Data
- Background and Selection Criteria
- Neutrino Flux Modulation and Simulation
- Neutrino Beam Profile and Errors
- Neutrino Event Simulation and Errors
- Neutrino Event Simulation and Errors
- FD constrains by ND ν_μ measurements
- FD measurements and selection cuts
- Properties of events passing selection
- Event Expectations and Associated Errors
- Oscillations predictions study
- Results and conclusions
- Acknowledgements

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T2K Experiment

- Uses J-PARC beam oriented 2.5º off axis to SK (L=295km) of ν_μ tuned at first oscillation maximum.
- Aimed at measuring neutrino properties like oscillations $\nu_\mu \rightarrow \nu_e$ (with previous most stringent limit $\sin^2 2\theta_{13} < 0.15$ (90%C.L.)
- Near Detector complex located at 280m:
  - On-axis Interactive Neutrino GRID (beam characteristics)
  - Off-axis detector (neutrino properties corresponding to expected FD)
- Far Detector located at 295km
  - Fiducial Volume 22kton of water with 2m outer detector.
  - Timing by GPS with <150ns precision

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Data, Backgrounds & Flux Modulation

Data

- Run 1 (Jan-Jun 2010) & Run 2 (Nov 2010-Mar 2011).
- Target efficiency +99%.
- 2.474.419 spills with a total of 1.43e20 p.o.t.

Main backgrounds

- Intrinsic ν_e contamination in the beam (from kaos).
- And NC interactions with a misidentified π^o .

Neutrino Flux Modulation

- Pion production tunned NA61 (5-10% uncertainty).
- Pions (50% uncertainty) and Kaons (15-100% uncertainty) with FLUKA.
- GEANT3 with GCALOR for hadronic interactions and particle propagation.
- Additional errors associated with beam quantities.

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Beam Properties and Event Simulation

Neutrino Beam Properties

- @INGRID rate 1.5 events/10^{14} p.o.t. was stable stable and consistent.
- Beam steering better then ±1mrad (error ±0.33(0.37) h(v))
- Error alignment SK-Beam calculated via GPS survey and is negligible.
- Errors on intrinsic ν_e flux under 1GeV estimated around 14% while above 1GeV are dominated by uncertainty on Kaon production rate (20-50%)

Event Simulation

- Used NEUT MC event generator which was tuned with SciBoone and MiniBooNE Data
- GENIE event generator used for cross checks.

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Event Simulation Uncertainties

Summary of systematic uncertainties for the relative rate of different CC and NC reactions to the rate of 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% (upper limit from [27])
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)

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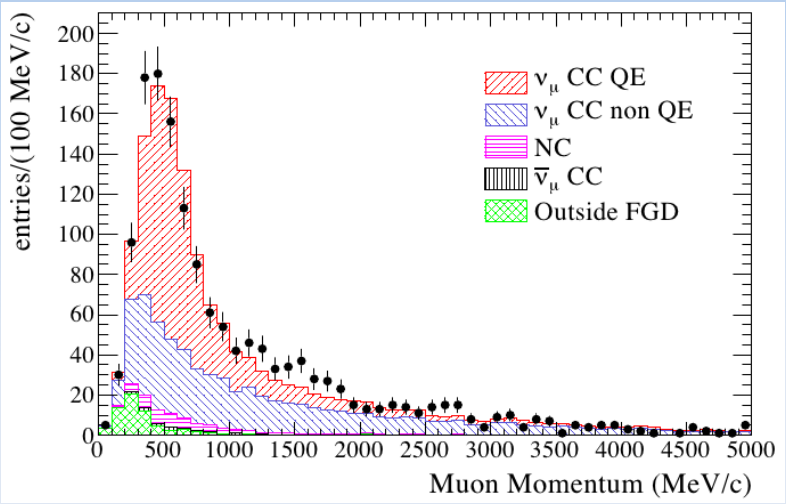
Using ND inclusive ν_μ CC measurment to contrain FD predictions

Data & Selection

- Data from Run 1 corresponding to 2.88e10[28]p.o.t. After quality cuts.
- Selection of events compatible with $\nu_\mu \rightarrow \mu$
- This analysis selects 1529 events (38% CC efficiency for 90% purity, estimated from MC).
- Which can be used to validate MC and then extrapolate to FD.



Measured muon momentum of ν_μ CC candidates reconstructed in the FGD target. Only statistical error presented.

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

FD Basic Event Selection

FD Event Selection Conditions

- Fully-Contained Fiducial Volume sample
- No activity in the outer detector on the event and 100μs before the event trigger
- At least 30MeV electron-equivalent energy deposited.
- Reconstructed vertex in the fiducial volume.

Results

- 88 events pass this requirements all within -2 to 10μs around the beam trigger.
- Expected contamination of 0.003 determined from sidebands.
- Events compatible with const. rate normalized by p.o.t via Kolmogorov-Smirnov test with (p-value=32)

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Further FD event selection

Signal Selection Cuts

- Event reconstructed with **single ring** (41 events)
- Event being **electron like** (8 events)
- **E_{vis}>100MeV** and **no delayed electron signal** (6 events)
  - Suppress $\nu_\mu \rightarrow \mu \rightarrow e$ events
- Force reconstruction of **2 rings** and cut on **M_{inv}<105MeV/c^2** (6 events)
  - Suppress π^0 events
- **E_ν^{rec}<1260MeV** assuming quasi-elastic kinematics
  - Suppress intrinsic ν_e events from from kaon decays

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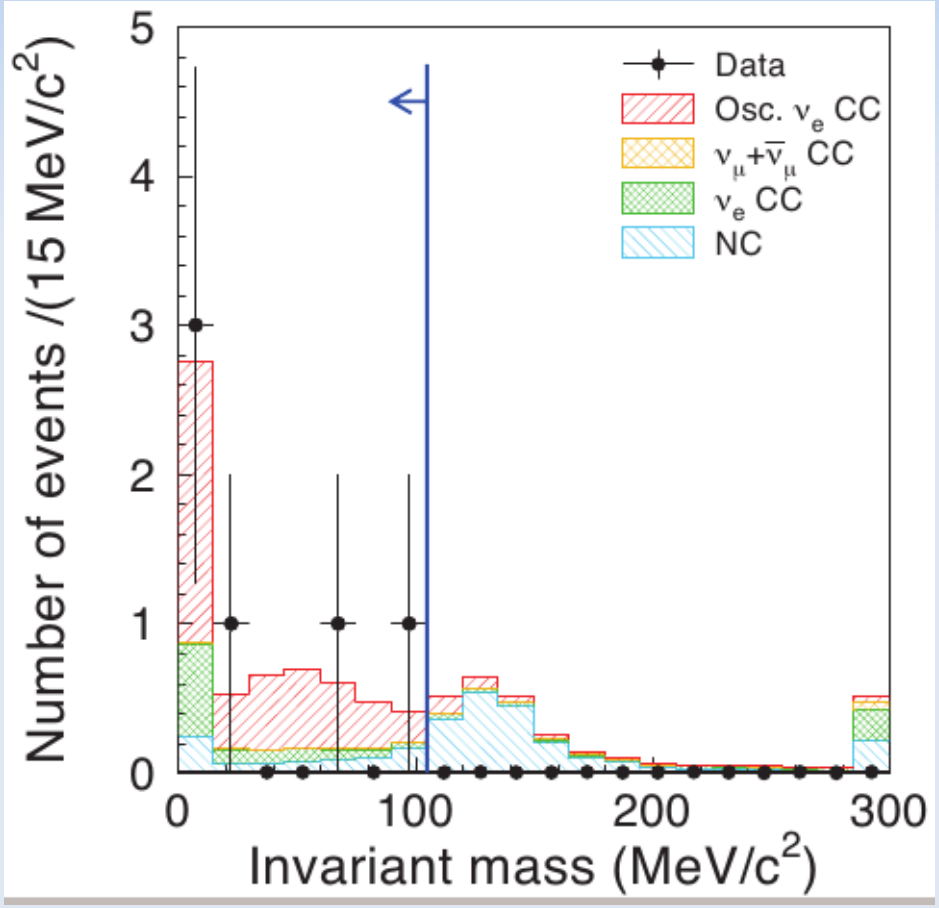
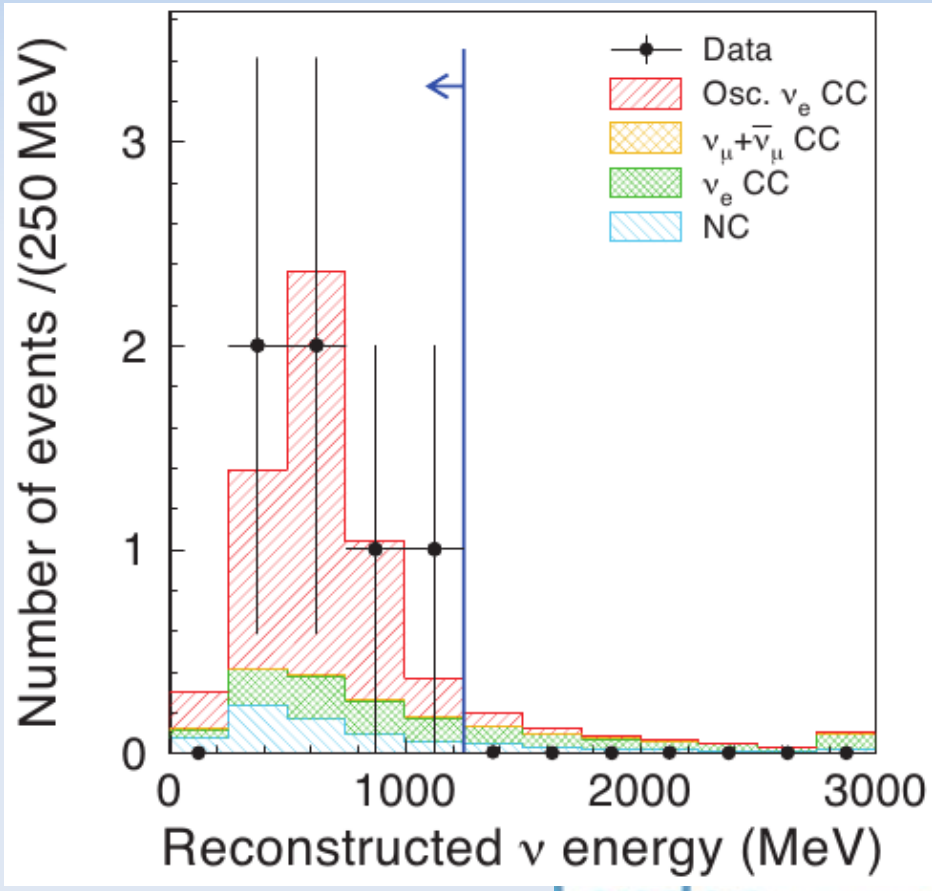
Cut Illustration Plots

Distribution of M_{inv} when each event is force to be reconstructed into 2 rings. Error bars only statistical.



Reconstructed neutrino energy spectrum and the applied cut.



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Event Characteristics and FD extrapolation

Selected event characteristics

- Consistent with CCQE events
- Events are clustered at large R, near the edge of the FV in the upstream beam direction.
- Inconsistency with contamination from penetrating particles from rock-neutrino interactions (no OD activity).

FD Extrapolation

- To extrapolate we can use ND data to normalize MC predictions for the FD:

$$N_{SK}^{exp} = \left(R_{ND}^{\mu,Data} / R_{ND}^{\mu,MC} \right) \cdot N_{SK}^{MC},$$

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Event Yield Table

	Data	ν_μCC	ν_eCC	NC	$\nu_\mu \rightarrow \nu_e$CC
(0) interaction in FV	n/a	67.2	3.1	71.0	6.2
(1) fully-contained FV	88	52.4	2.9	18.3	6.0
(2) single ring	41	30.8	1.8	5.7	5.2
(3) e-like	8	1.0	1.8	3.7	5.2
(4) $E_{vis} > 100$ MeV	7	0.7	1.8	3.2	5.1
(5) no delayed electron	6	0.1	1.5	2.8	4.6
(6) non-π^0-like	6	0.04	1.1	0.8	4.2
(7) $E_\nu^{rec} < 1250$ MeV	6	0.03	0.7	0.6	4.1

- Event reduction for the neutrino appearance search at the far detector. After each selection criterion is applied, the numbers of observed data and main backgrounds are given.
- At cut seven data seams clearly to favor osculation scenario.

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Total Relative Uncertainty

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}$%	$^{+17.6}_{-17.5}$%

- Contributions from various sources and the total relative uncertainty for $\sin^2 2\theta_{13}$=0 and 0.1 and δ_{cp}

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Conclusions

- Observation of 6 single e-like events exceeds expectations of three-flavor neutrino oscillation scenario with $\sin^2 2\theta_{13}=0$. (Prob. to observe 6 or more events is 7e-3)
  - Conclude that data indicate electron neutrino appearance from a muon neutrino beam.
  - Confidence yields $0.03(0.04)<\sin^2 2\theta_{13}<0.28(0.34)$ at 90% C.L. For $\sin^2 2\theta_{23}=1.0$, $|\Delta m^2_{23}|=2.4\text{e-}3\text{eV}^2$, $\delta_{CP}=0$ and for normal(inverted) neutrino mass hierarchy. The best fit points are 0.11(0.14).
- More data are required to firmly establish ν_e appearance and to better determine the angle θ_{13}

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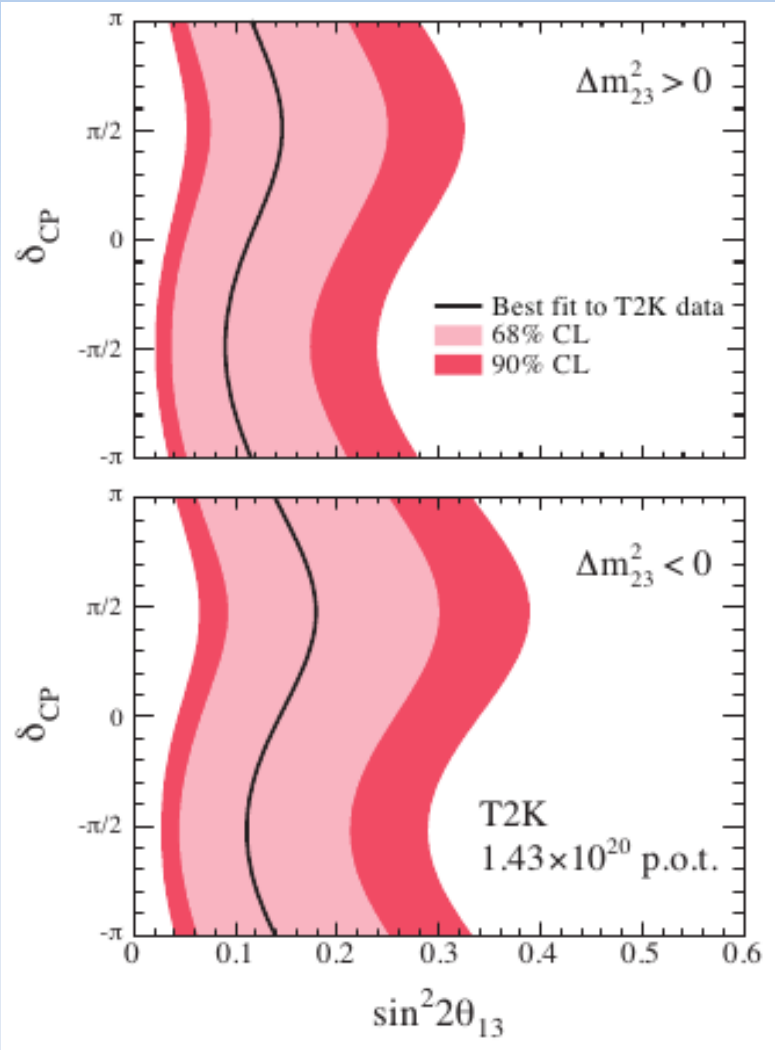
Δm^2_{23} and δ_{cp} fit



- The 68% and 90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of $\delta_{cp,}$ consistent with the observed number of events in the three-flavor oscillation case for normal (top) and inverted (bottom) mass hierarchy. The other oscillation parameters are fixed. Best fit values are shown with solid lines.

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