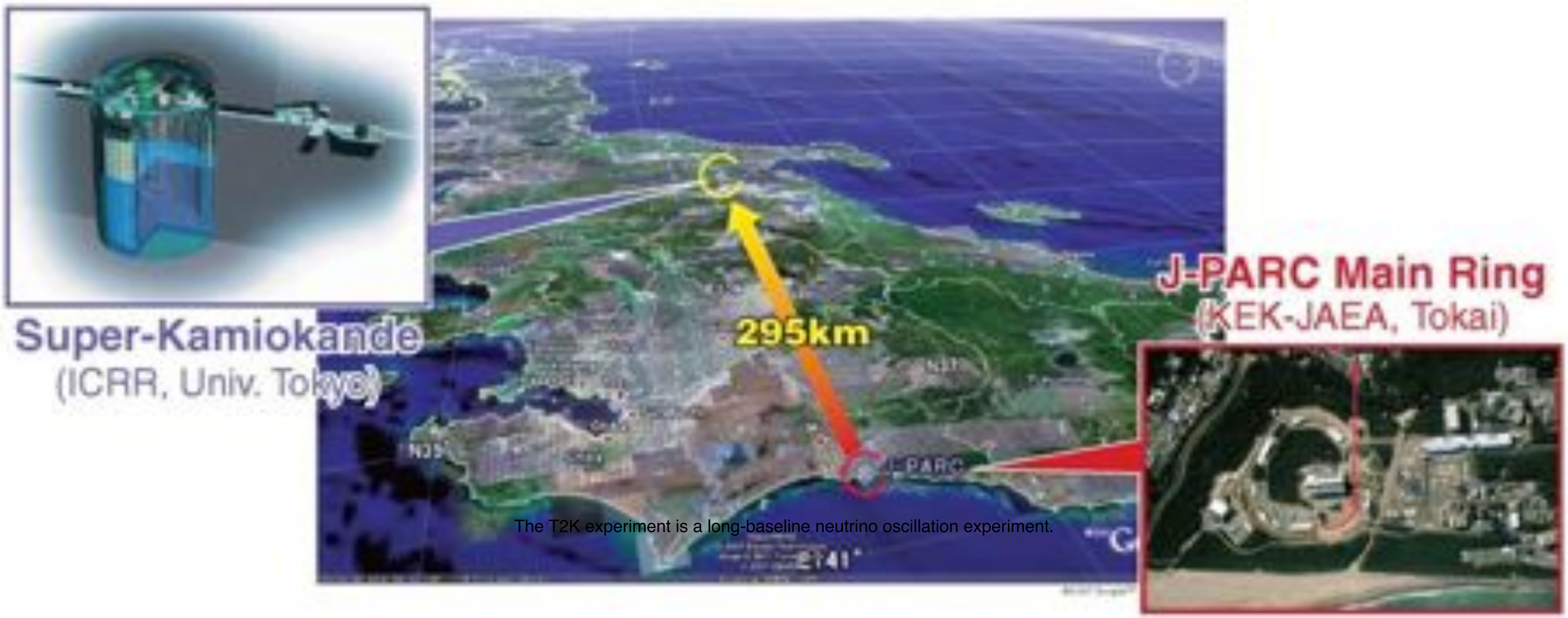
The T2K experiment

Lorena Escudero
(IFIC, Valencia)
on behalf of the T2K collaboration

Understanding Neutrinos 2012, Prague

The Tokai-To-Kamioka Experiment

T2K is a long-baseline neutrino oscillation experiment

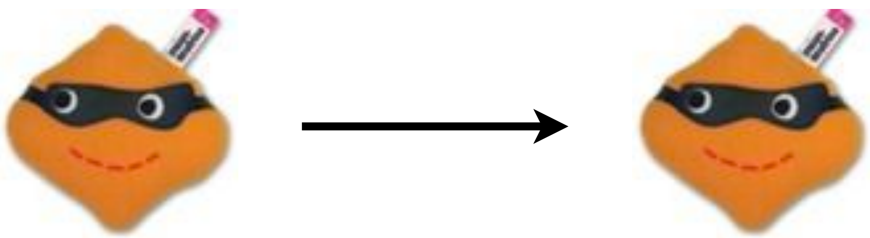


Proton beam (30Gev)

Proton beam incident on **graphite target**: **pions** produced decay into **muons** and **muon neutrinos** (T2K neutrino beam with $E_\nu \sim 1$ GeV).

T2K's Physics Goals

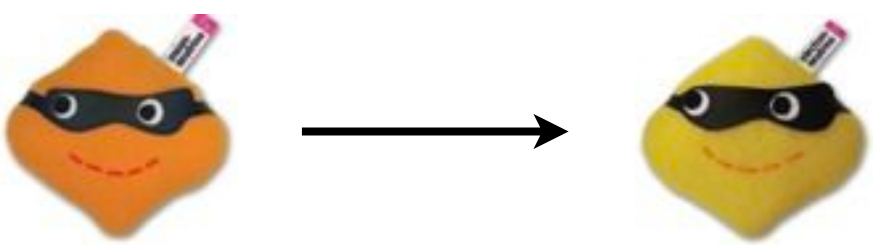
Via ν_μ disappearance studies



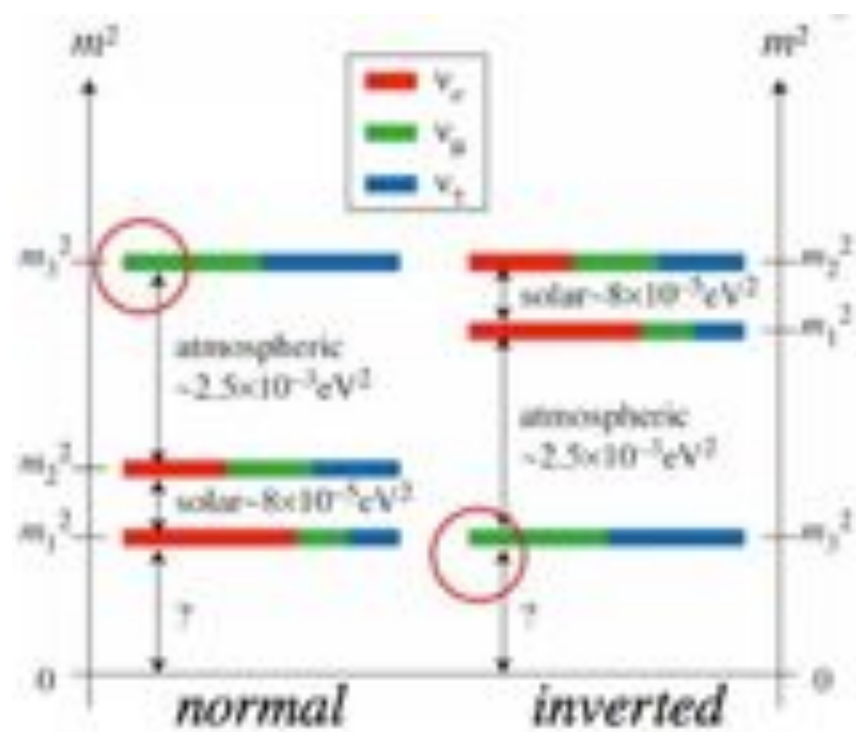
- Precise measurement of atmospheric oscillation parameters: θ_{23}, Δm^2_{23}

$$\delta(\sin^2 2\theta_{23}) \sim 0.01$$
$$\delta(\Delta m^2_{23}) \sim 10^{-4}\, eV^2$$

Via ν_e appearance studies:



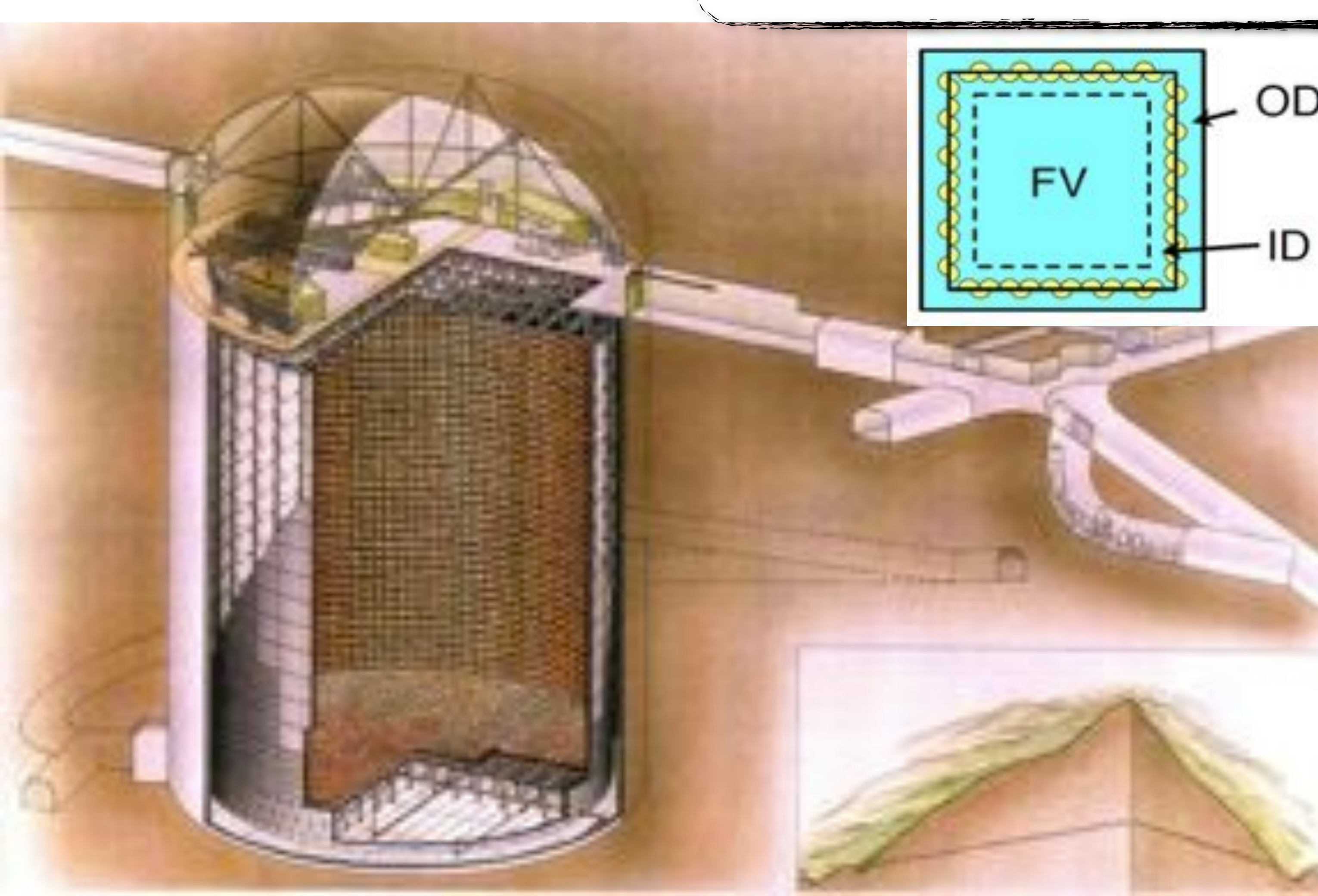
- Measure the mixing angle θ_{13}
- Possibility to measure CPV in lepton sector: δ_{CP}
- Study mass hierarchy

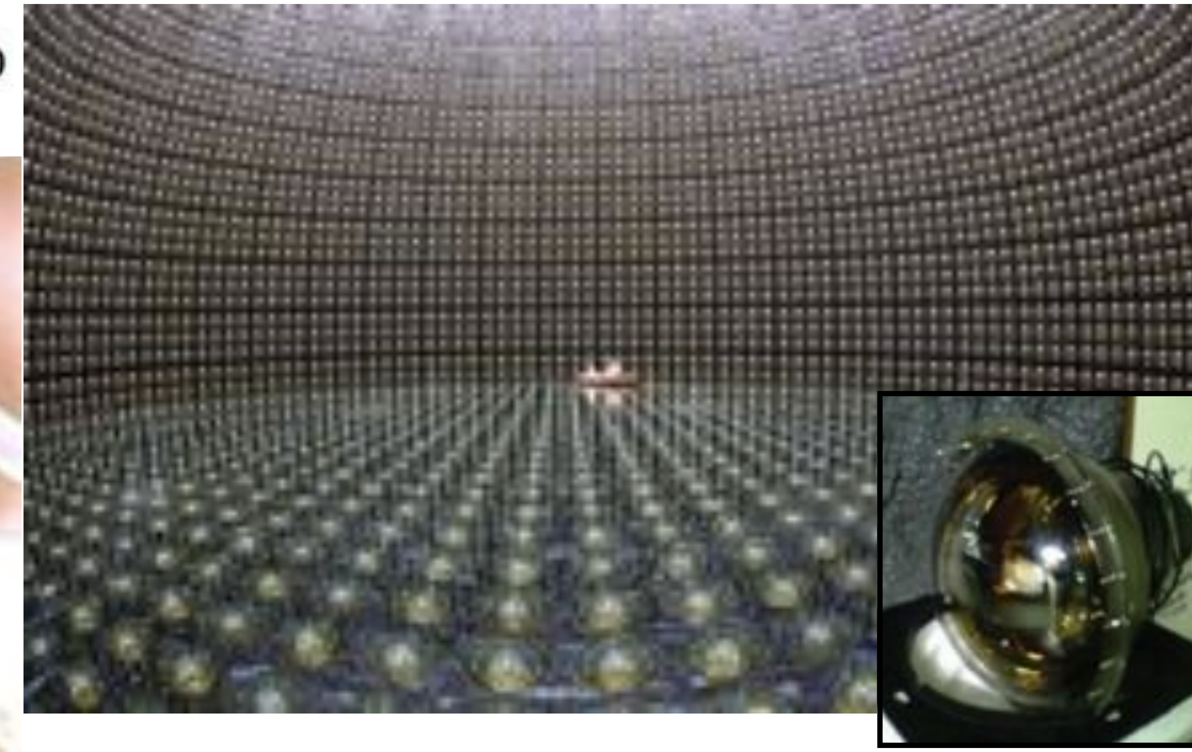


Other studies:

- Neutrino cross section measurements.
- Sterile neutrino searches.

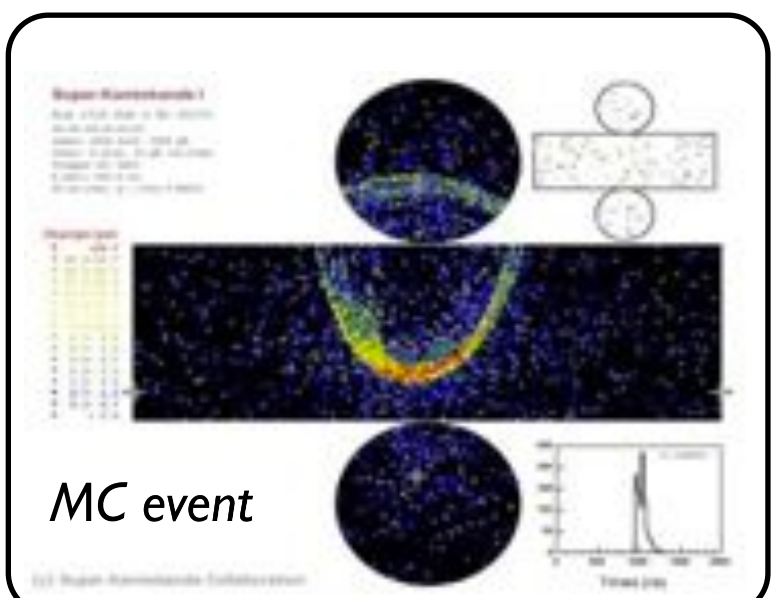
The Far Detector: SK





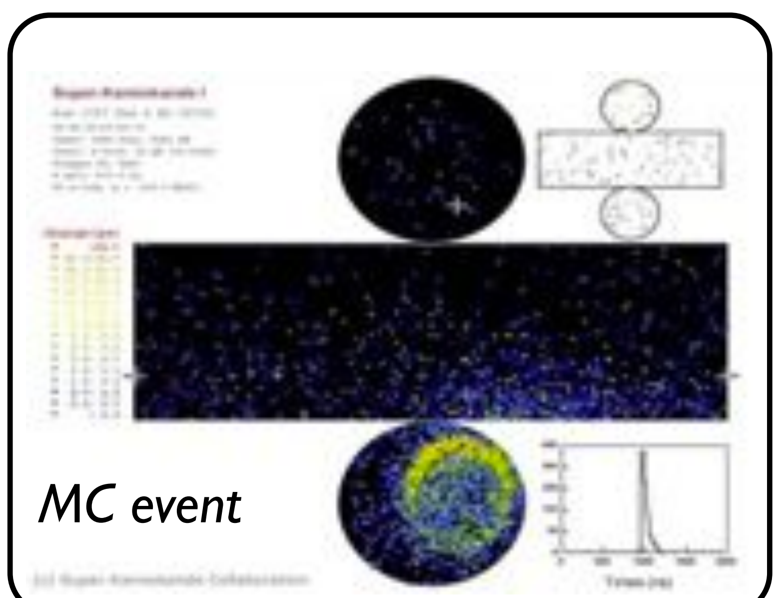
Muon neutrino event

($\nu_\mu \rightarrow \mu$ clear single ring)



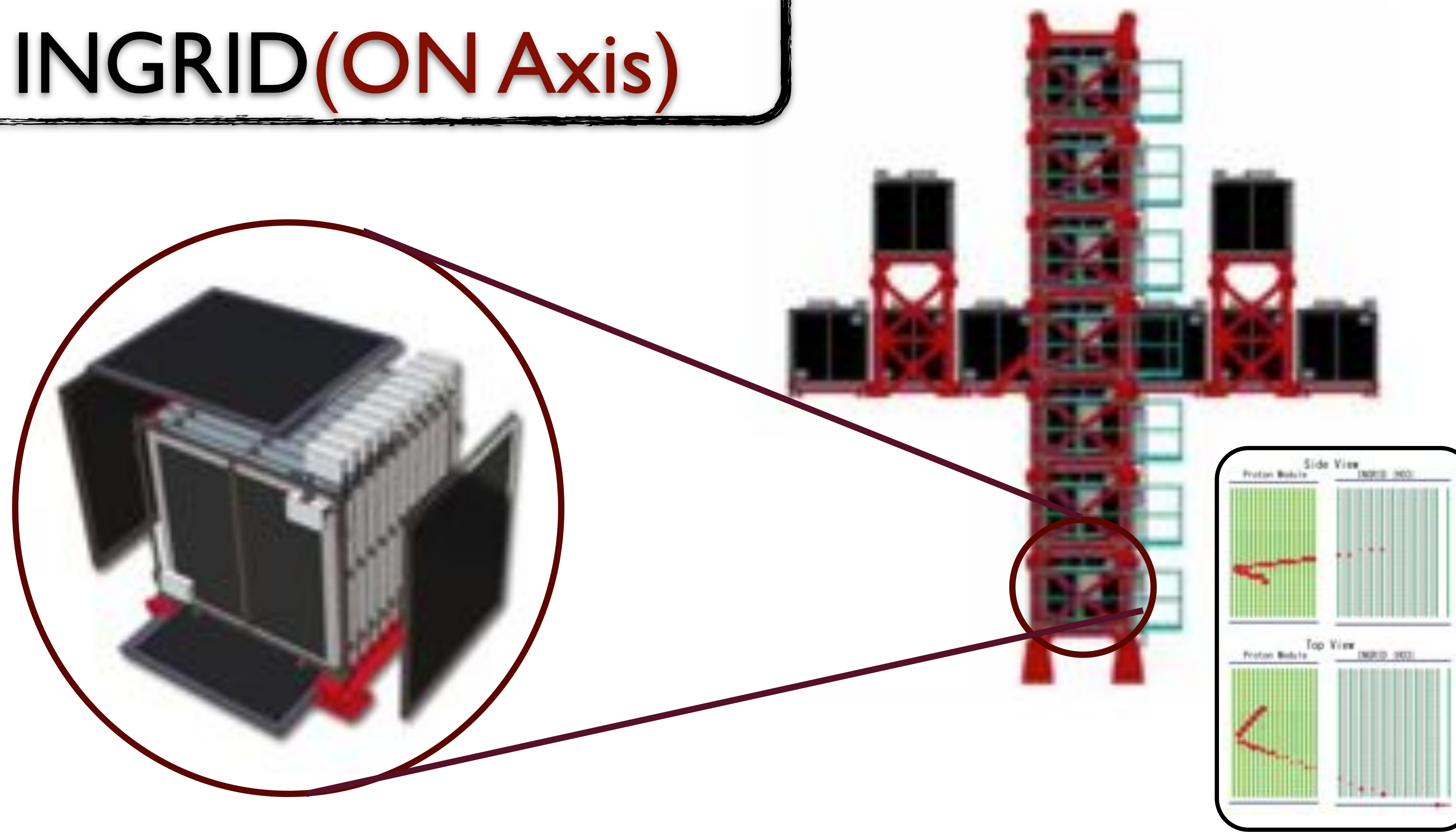
Electron neutrino event

($\nu_e \rightarrow e$ EM shower, fuzzy ring)



- **22.5kton water Cherenkov detector.**
- Cherenkov photons reach **PMTs** and produce ring-shaped hit pattern

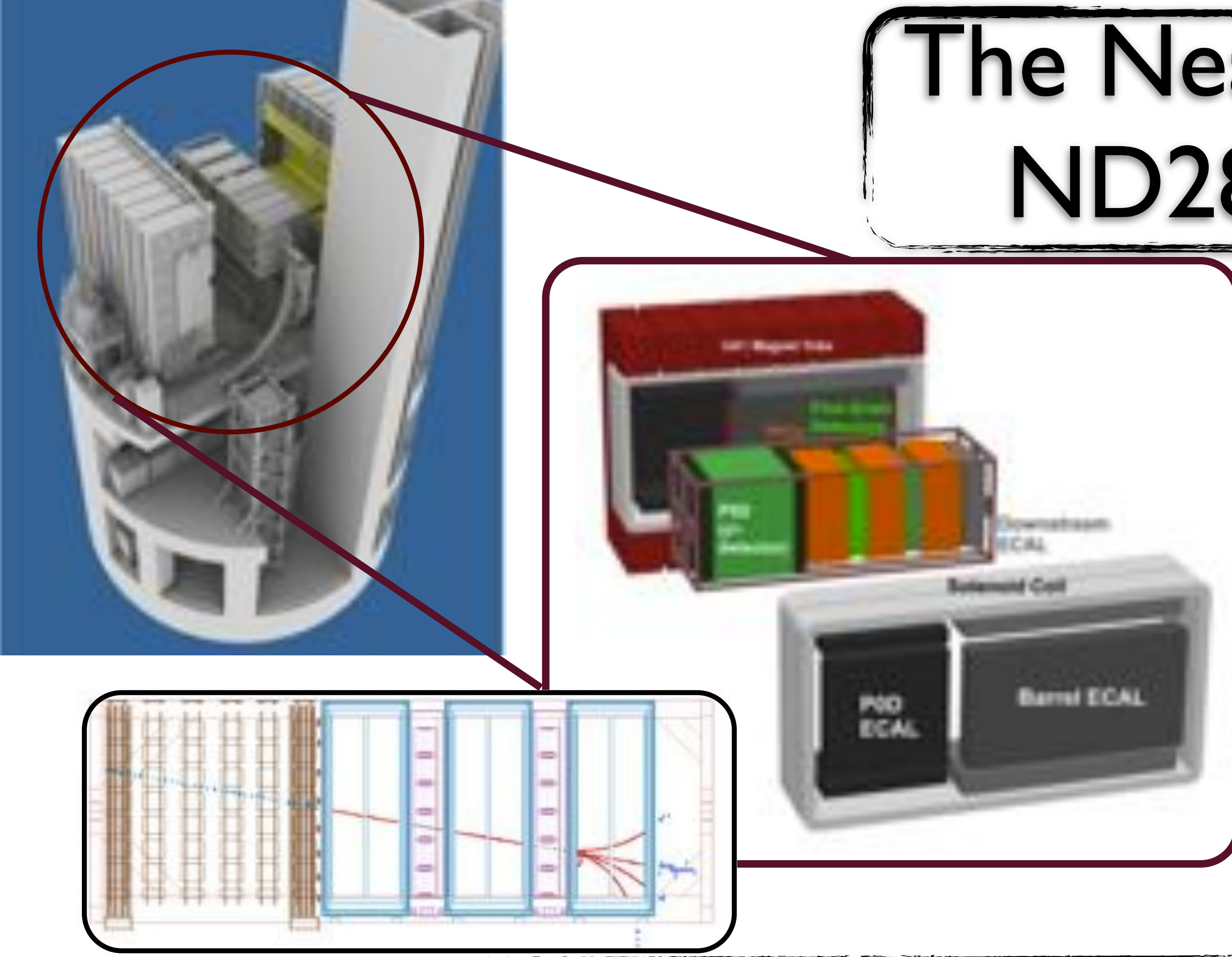
The Near Detectors I: INGRID(ON Axis)



- INGRID (Interactive Neutrino GRID) monitors directly the neutrino beam direction and intensity by means of neutrino interactions in iron.

- Each INGRID module is composed of **iron plates + scintillator layers** in a sandwich.

The Near Detectors II: ND280(OFF Axis)



ND280 goal is to measure the **flux, energy spectrum and ν_e contamination.** Cross section studies are also performed.

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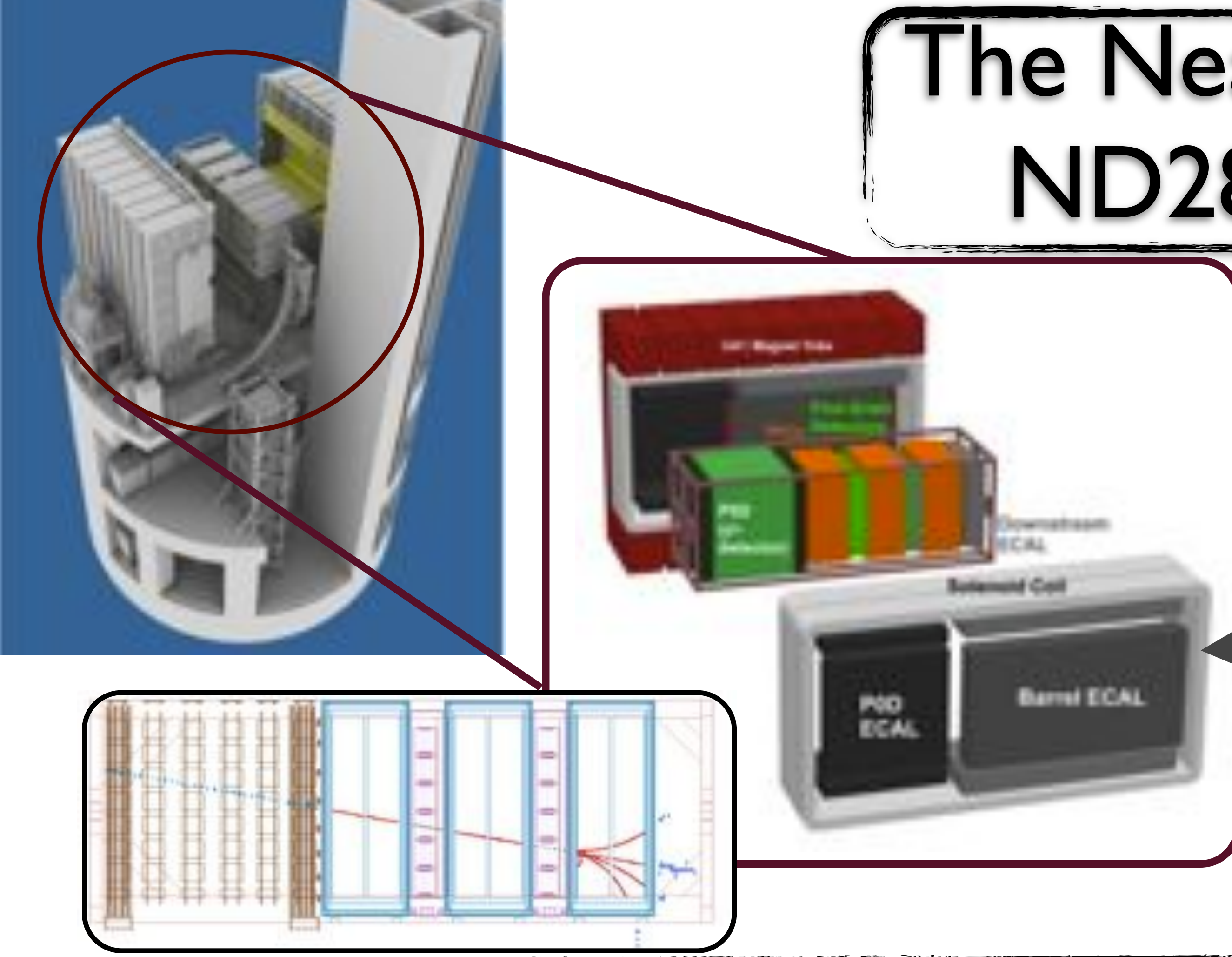

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ECAL

Electromagnetic calorimeters (plastic scintillator).

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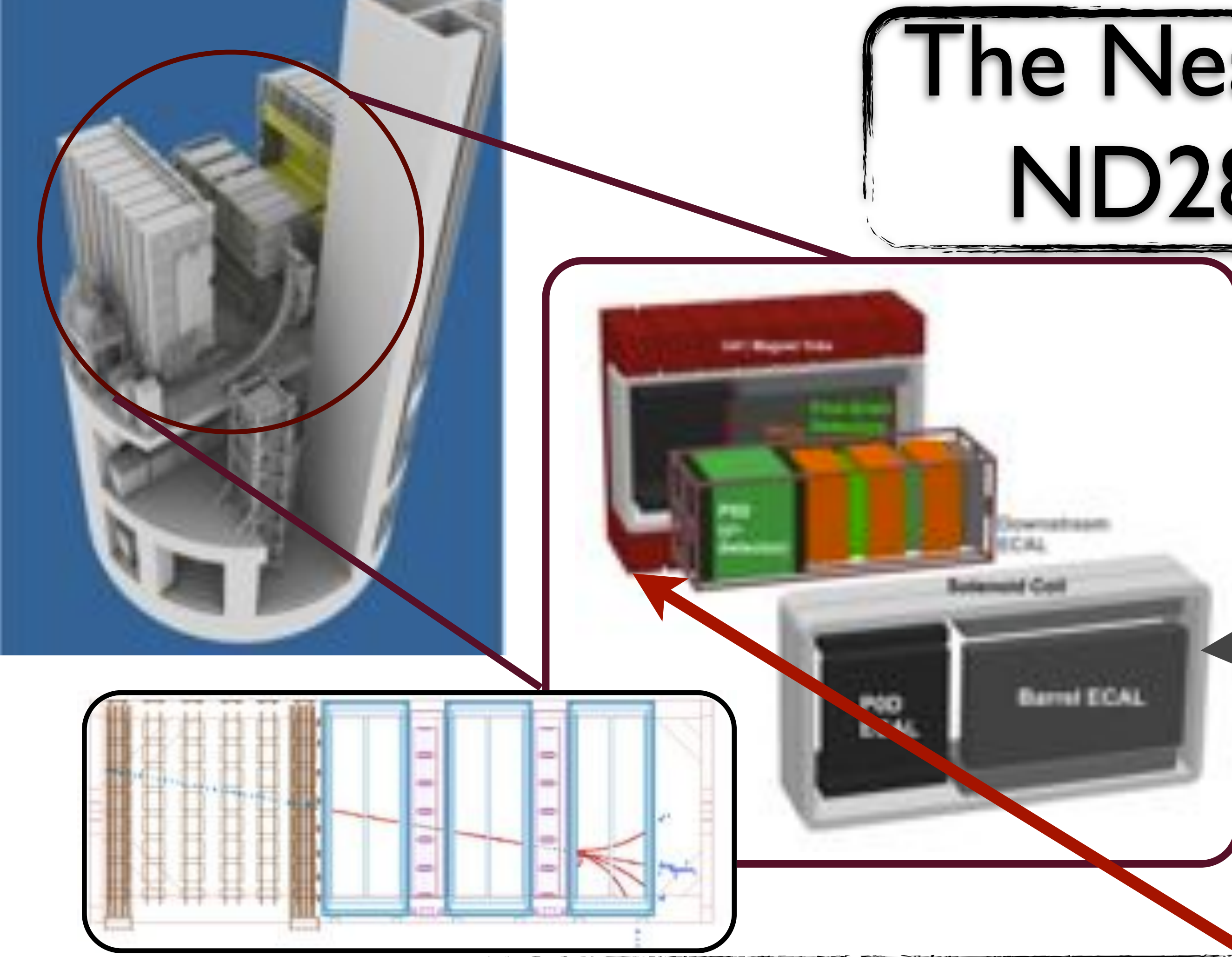

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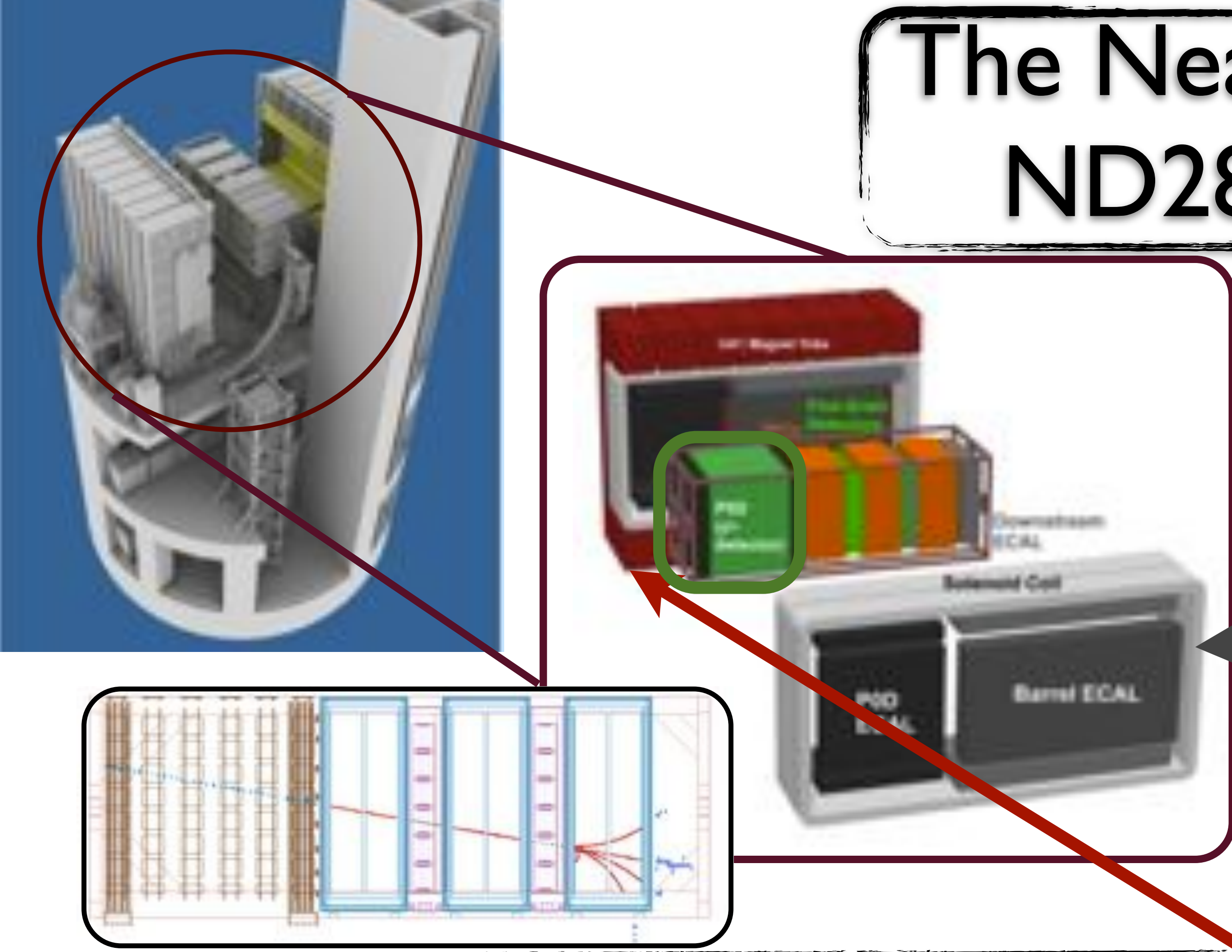

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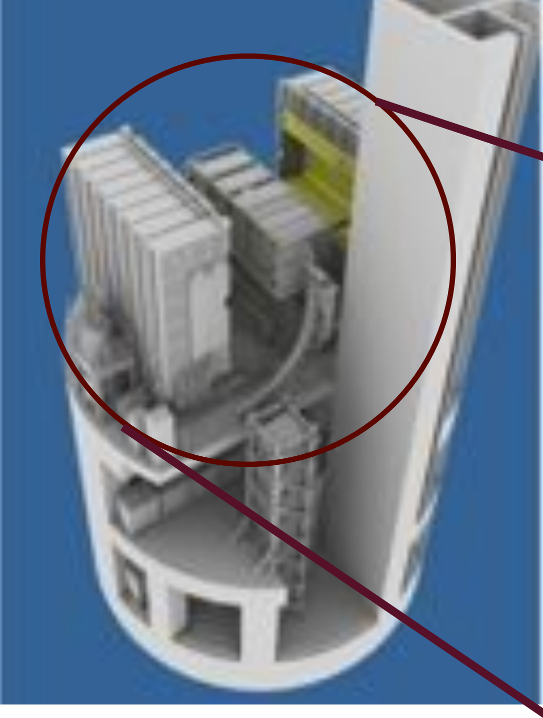

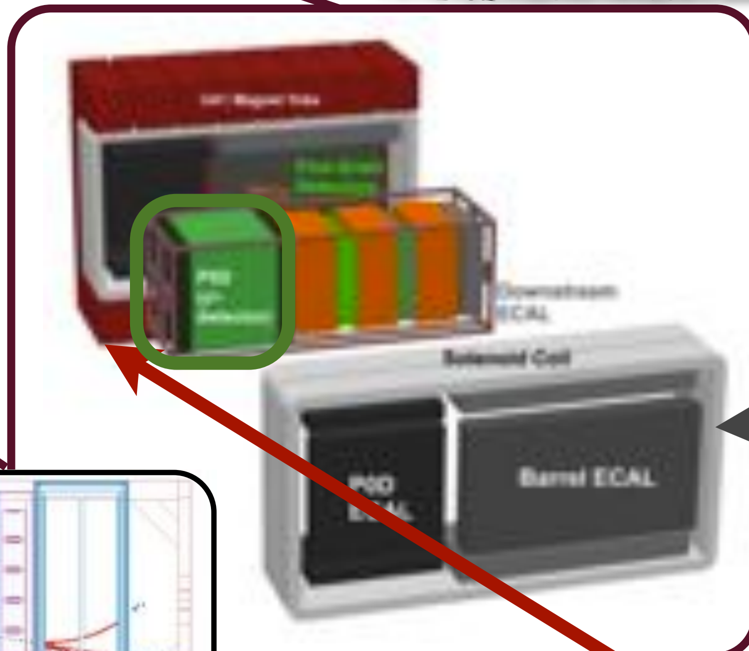

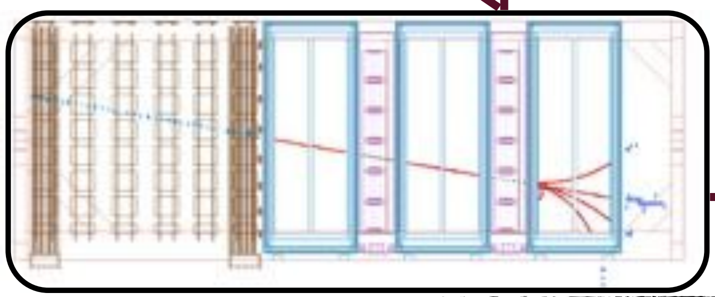

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- **3 Time Projection Chambers (TPCs)**
  - They reconstruct momentum and charge of particles.
- **2 Fine Grained Detectors (FGDs)**
  - Active target for neutrino interactions: carbon + water.

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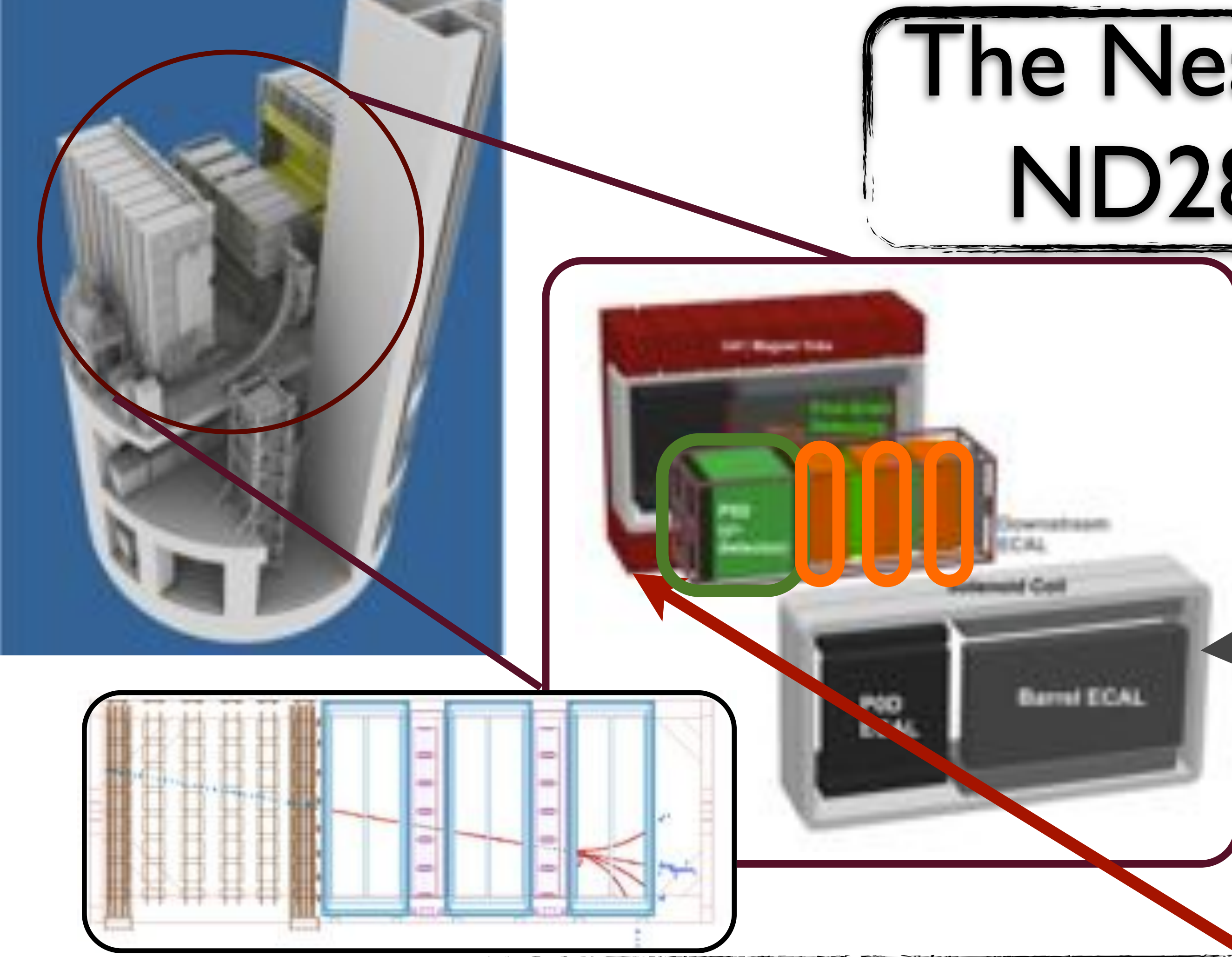

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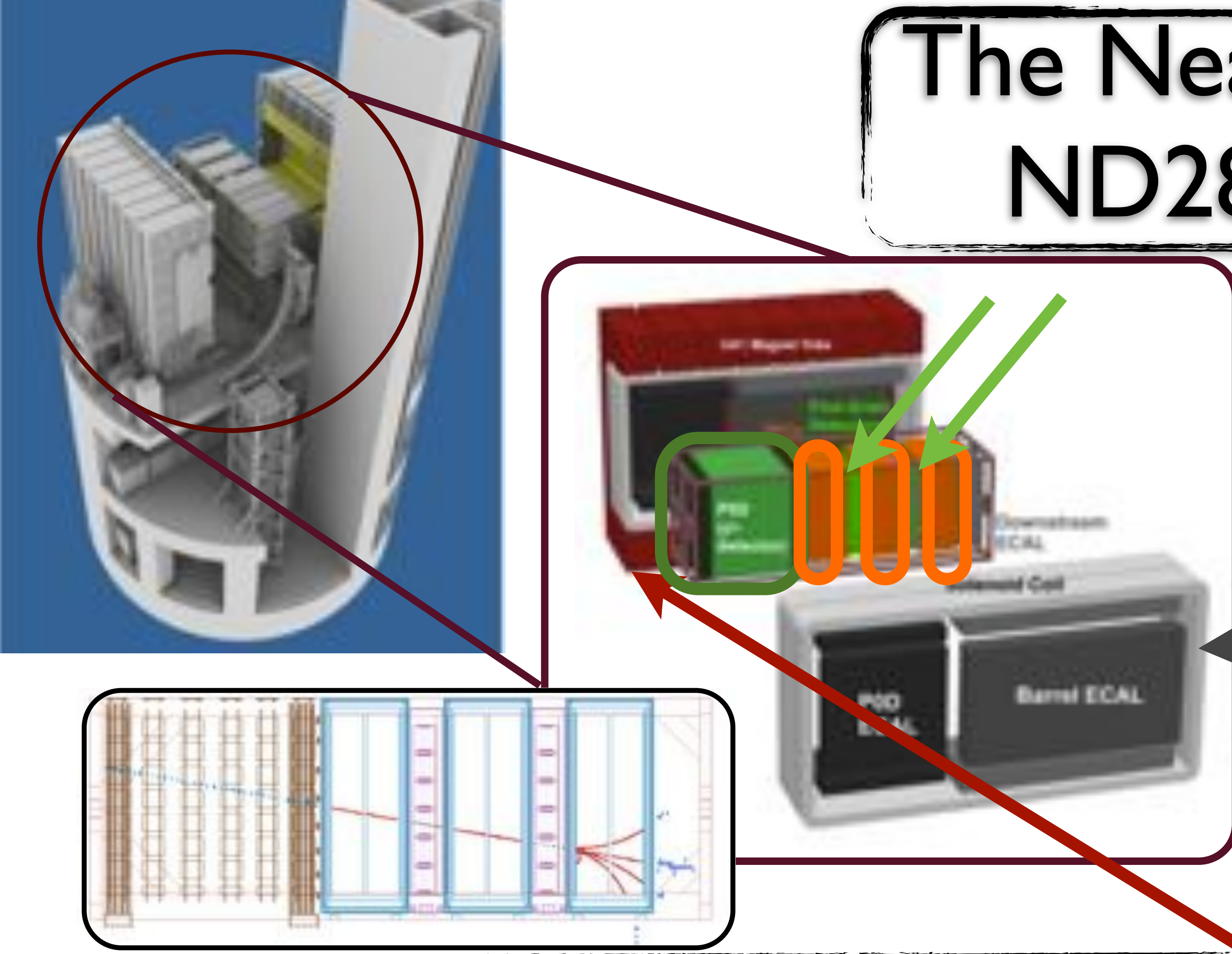

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Oscillation Analysis Method

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Flux prediction
- Beam MC
- Hadron production (NA61)

ND280 analysis
- Detector MC
- ν_μ measurements in CC QE and nonQE samples

ν cross sections
- NEUT MC model
- Uncertainties set from external data

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Extrapolation
Propagate using data/MC ratio and near/far flux transfer matrix

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MC Prediction
- SK detector MC
- Calculate prediction (event rates, spectra) at different osc. hypotheses

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Data
- T2K event candidates

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Data

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Oscillation FIT

Compare data and expectations to extract the values of the oscillation parameters

other uncertainties

2010 ν_μ Disappearance Analysis: SELECTION

RUN1+2 = 1.43 E20 POT

At the far detector a ν_μ CCQE enriched sample is selected.

CUT	EVENTS (DATA)
FCFV (+beam timing)	88
Single Ring	41
PID (μ-like)	33
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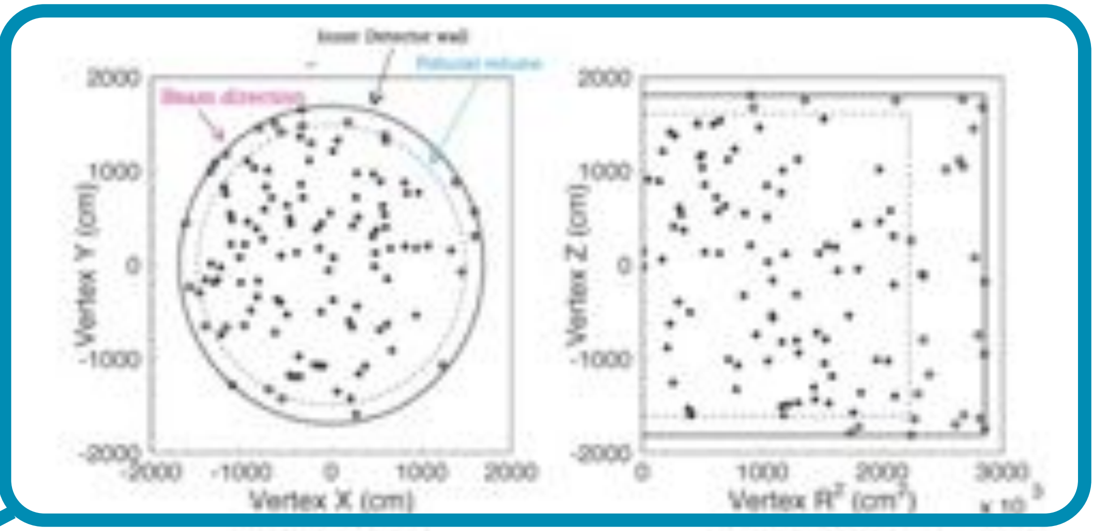

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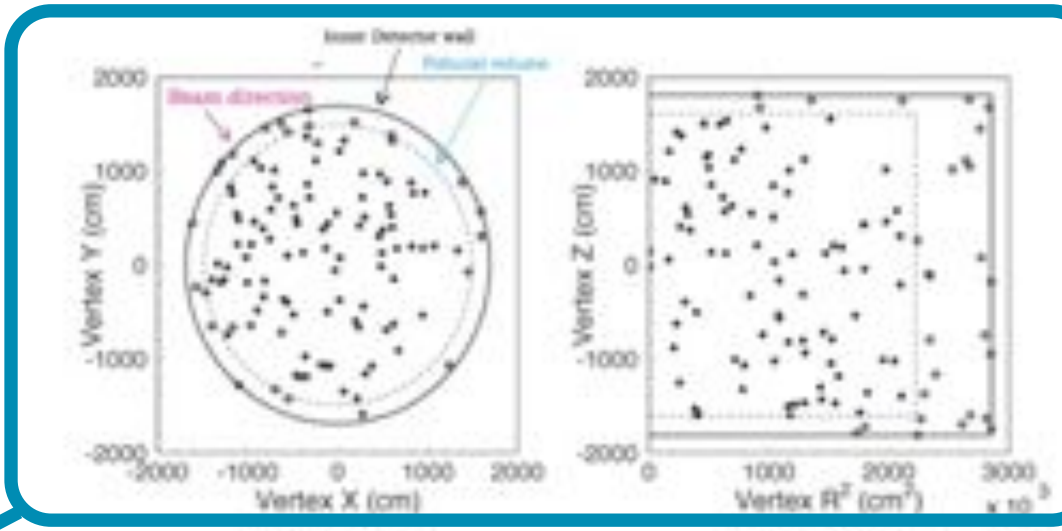

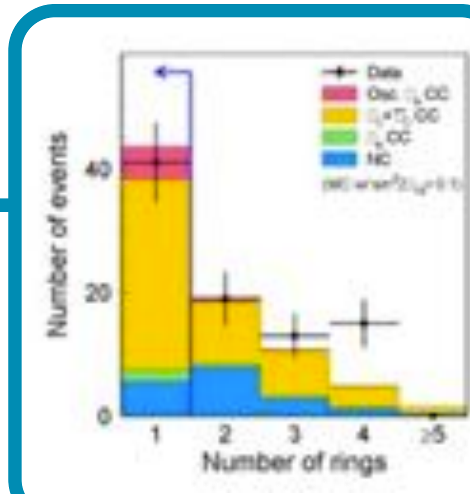

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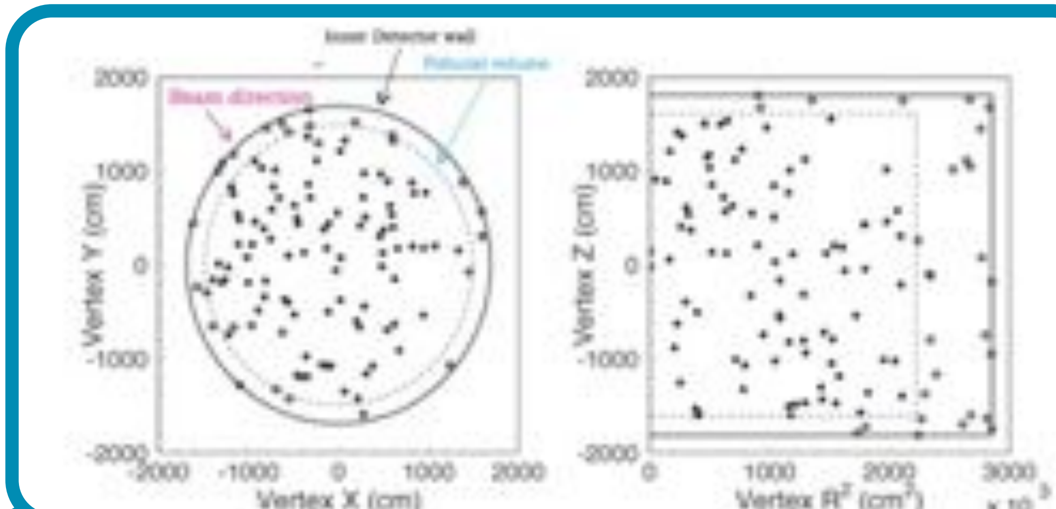

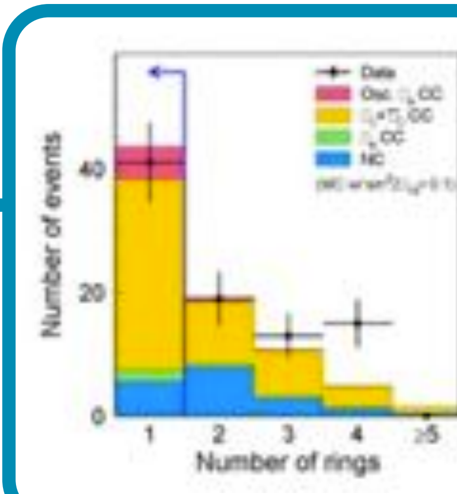

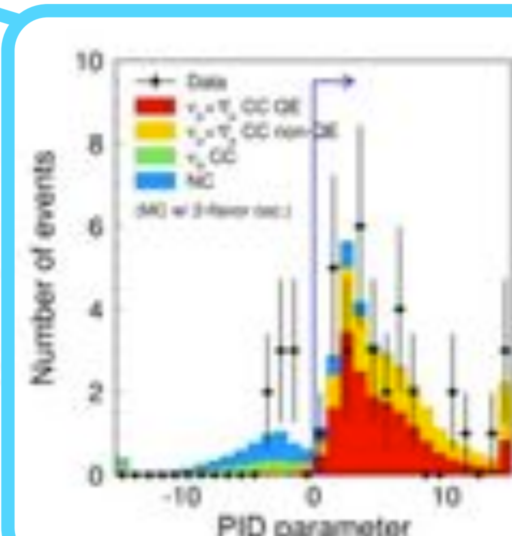

Based on shape of ring

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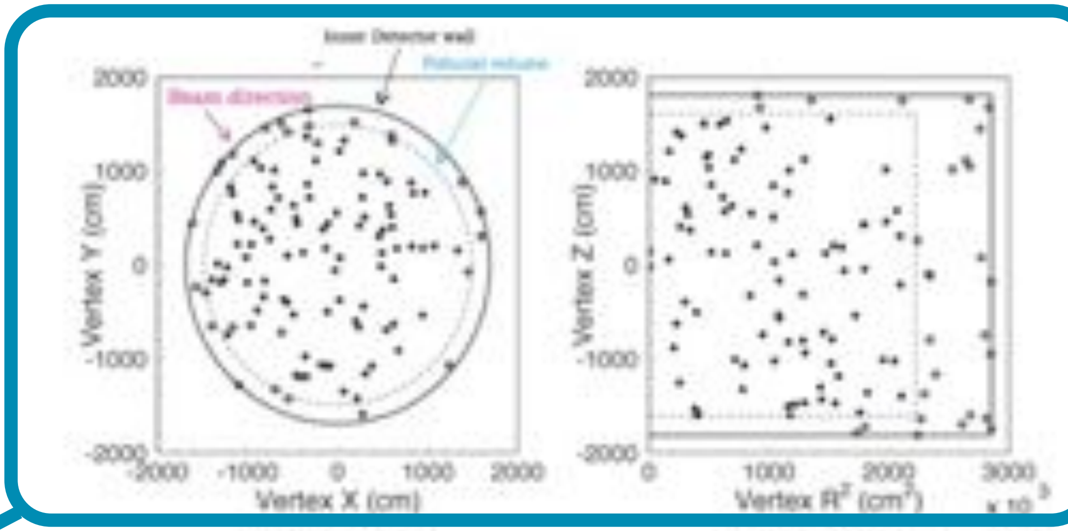

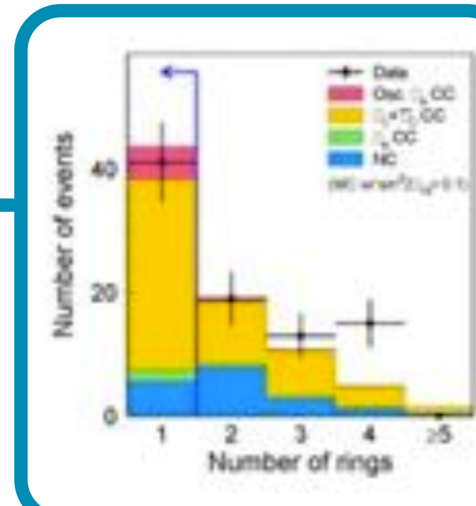

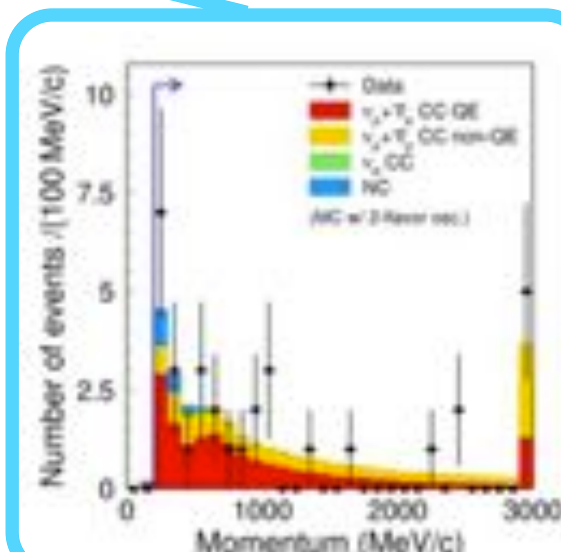

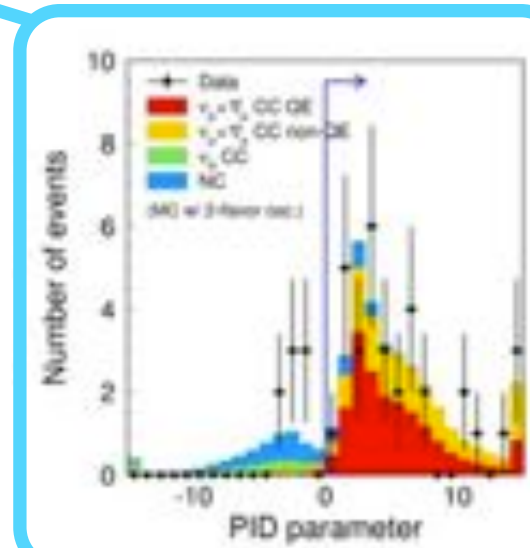

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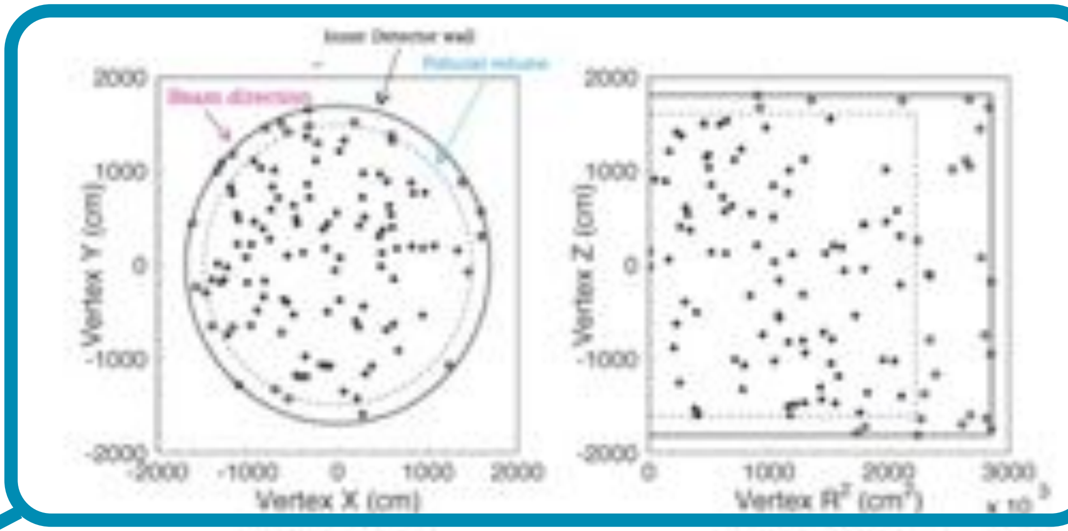

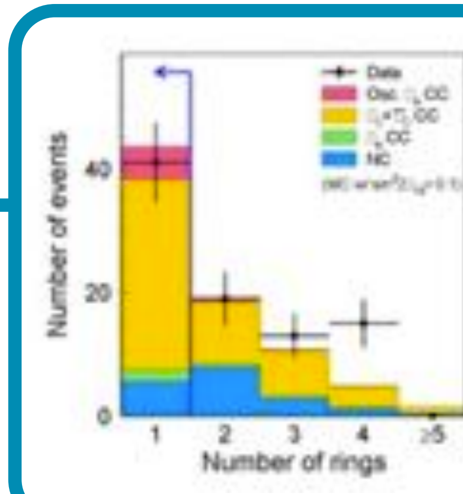

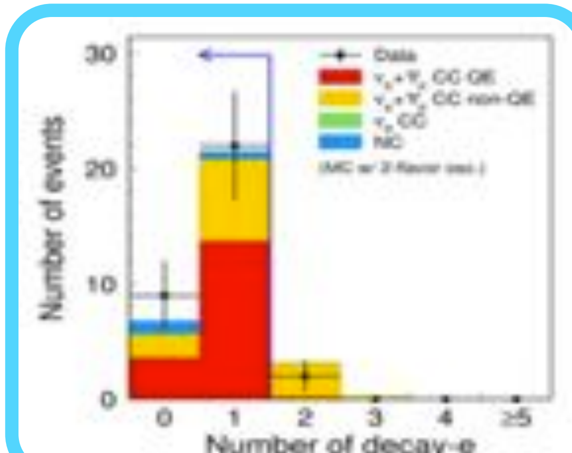

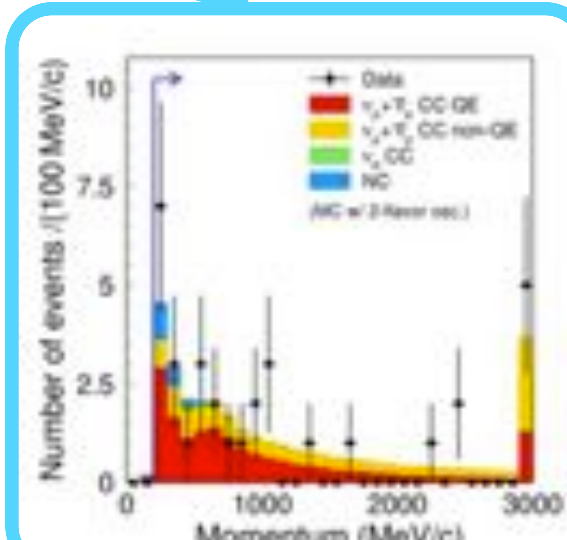

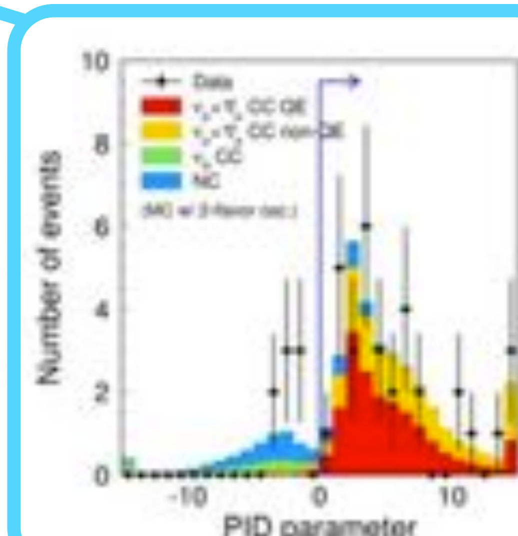

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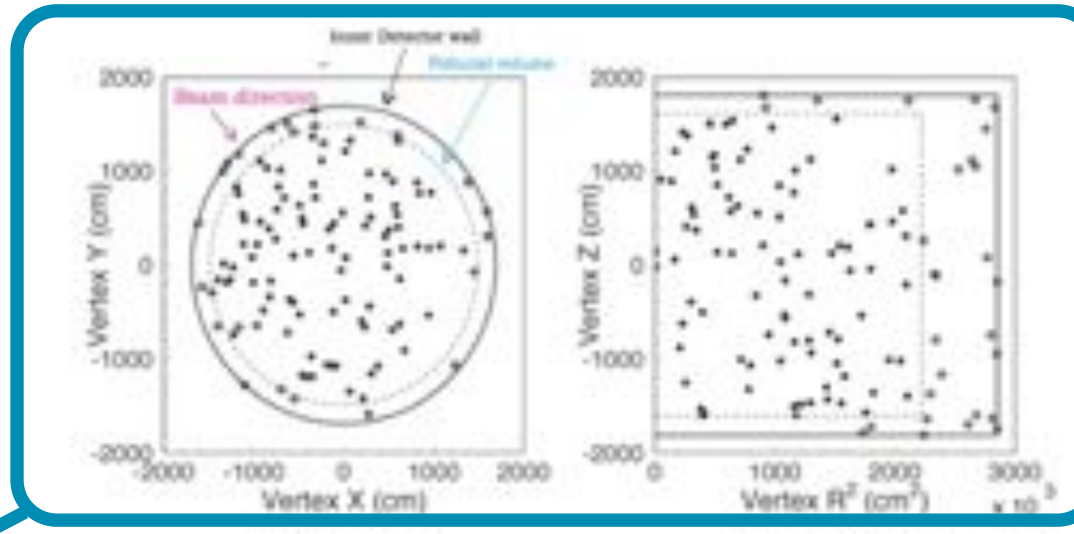
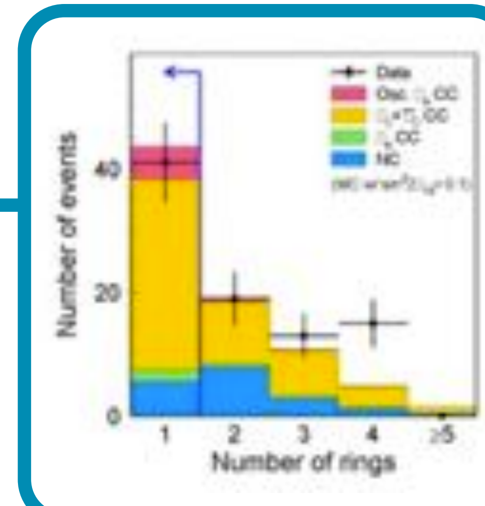
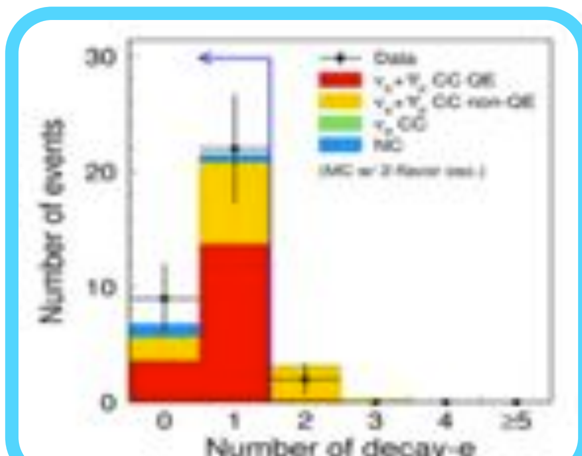
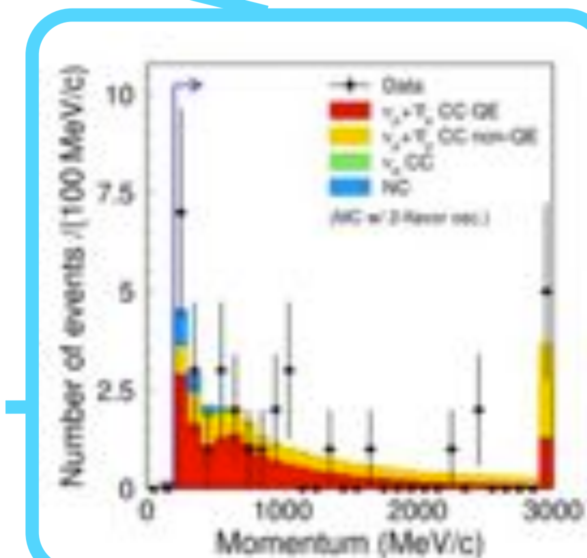
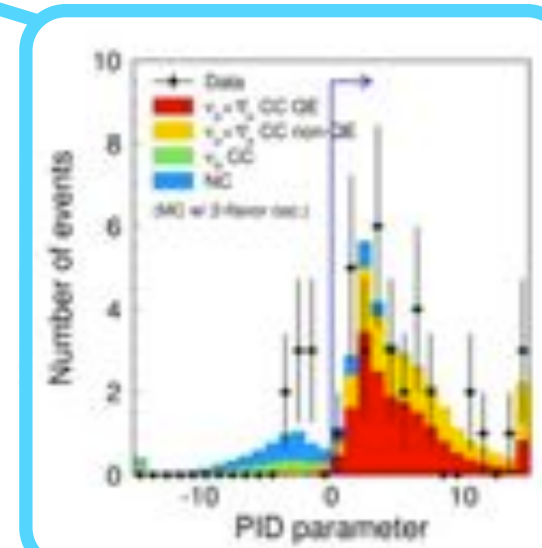






Last two vetoes reject events with unseen muons and pions





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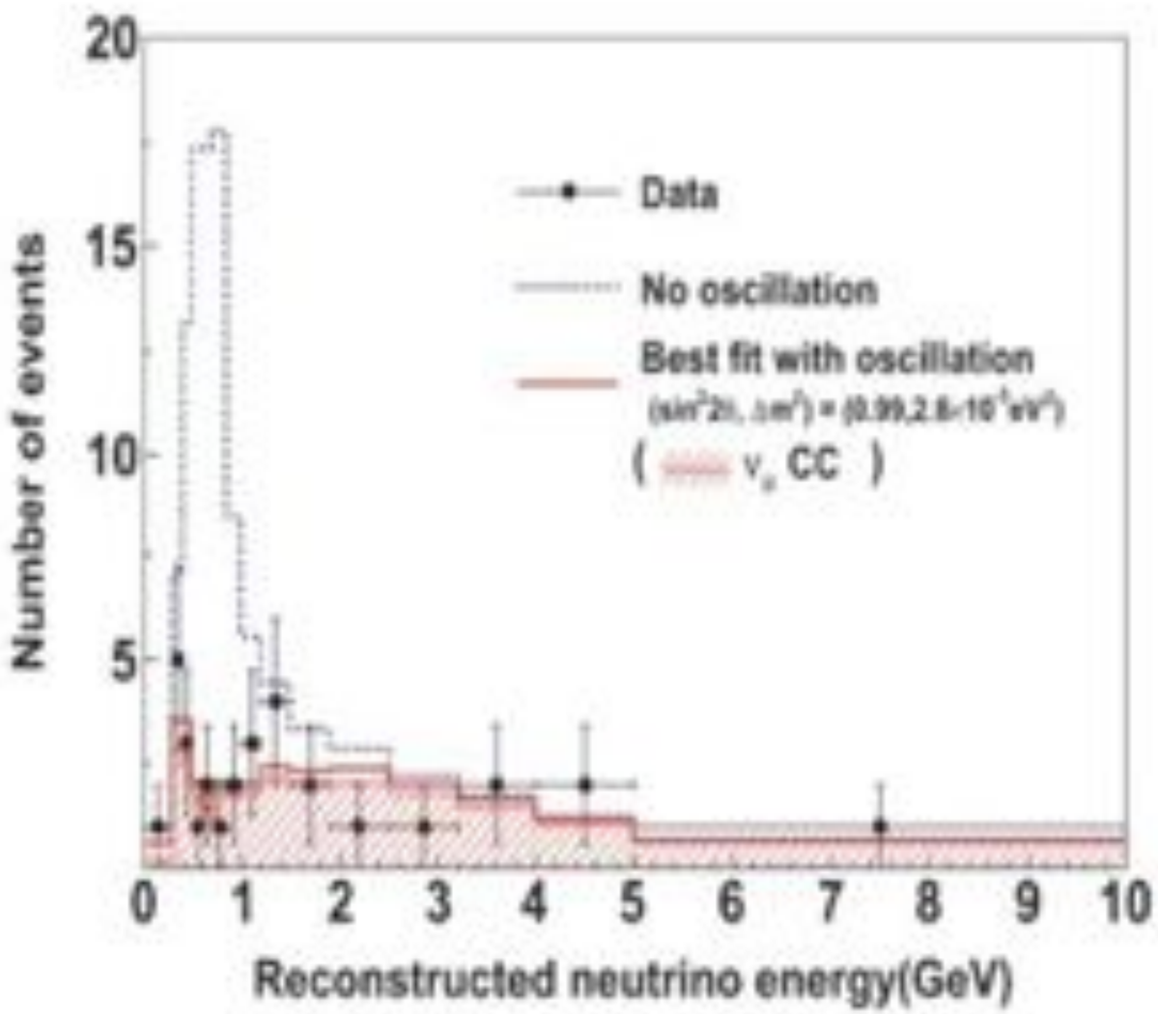
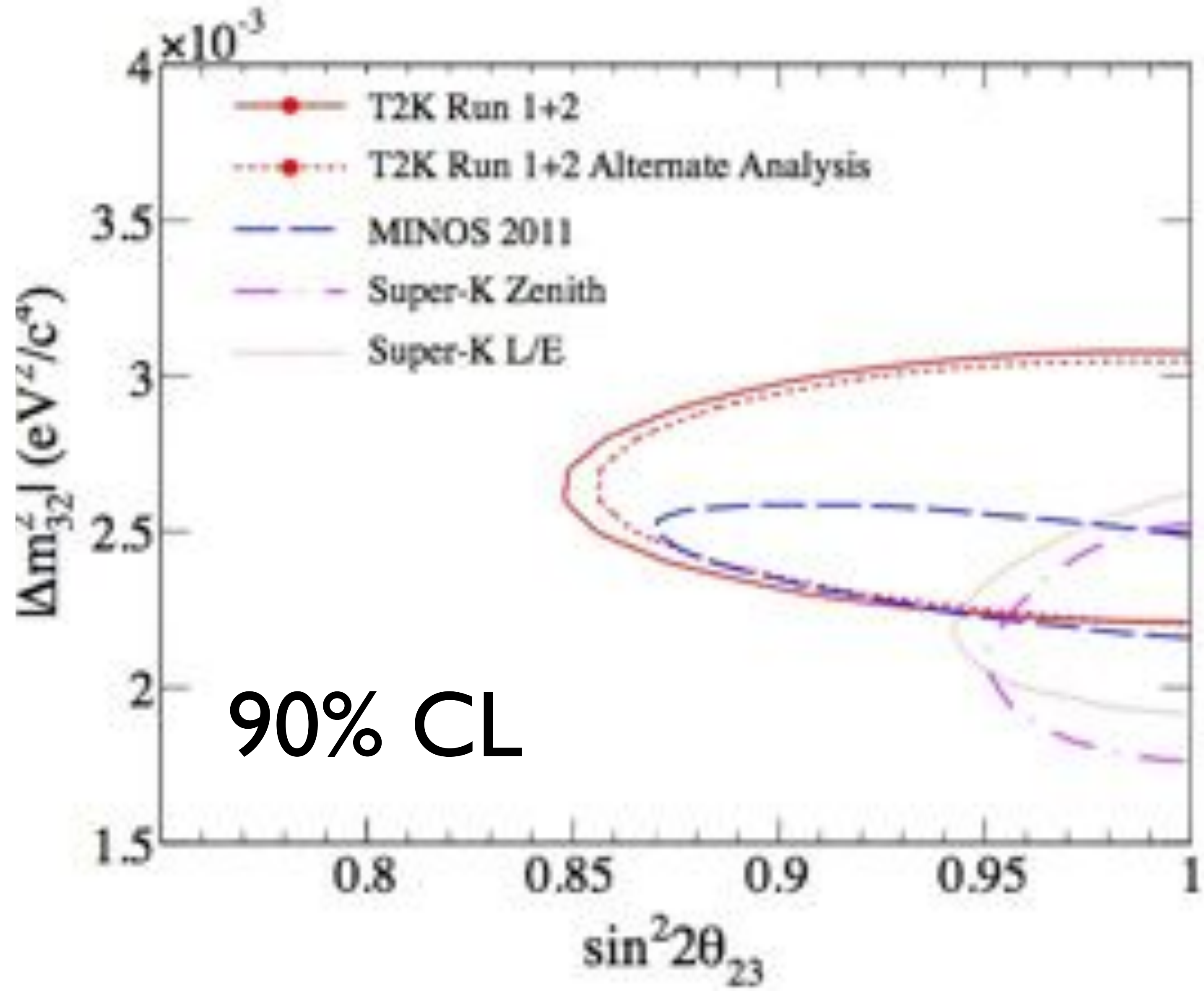
2010 ν_μ Disappearance Analysis: RESULTS





EVENTS EXPECTED

- No oscillation: **106**
  (No oscillation excluded at **4.5σ**)
- Maximal oscillation ($\sin^2(2\theta_{23})=1$, Δm^2_{23} = 2.4E-3eV^2): **28.3**

EVENTS OBSERVED: 31

- Two independent analyses done, with consistent results
- Results in full agreement with MINOS, SK

2012 ν_e Appearance Analysis: SELECTION

RUN1+2+3 = 3E20 POT

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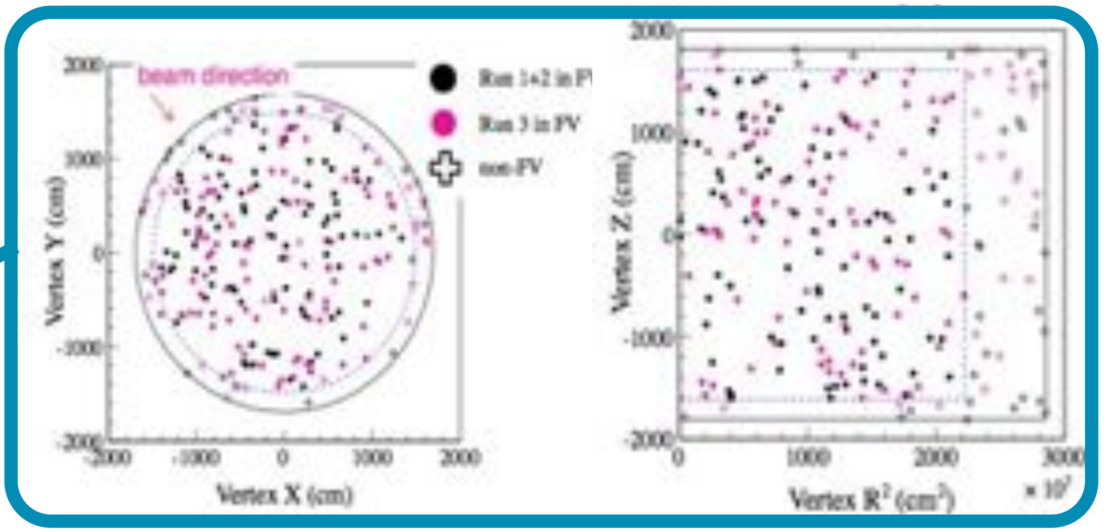

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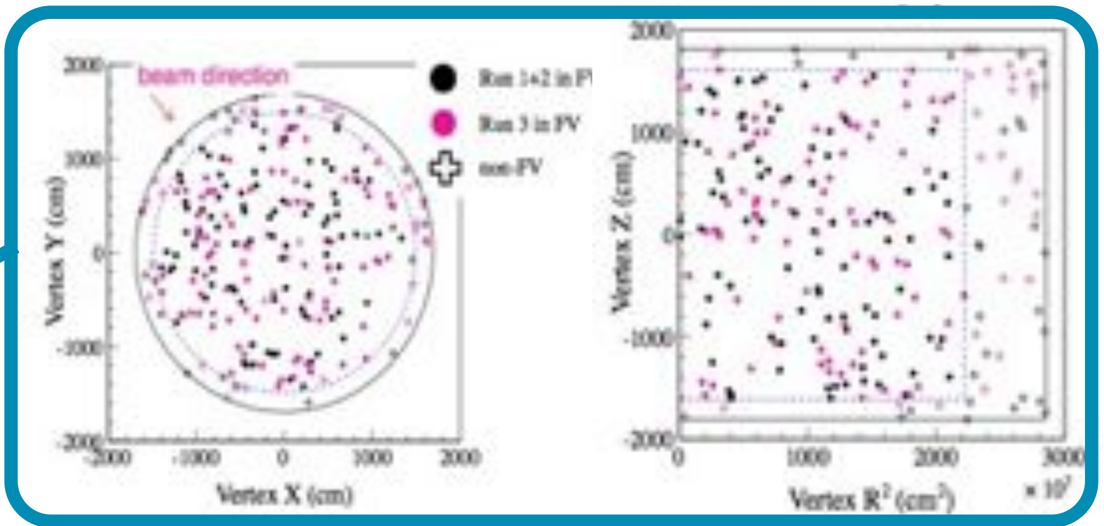

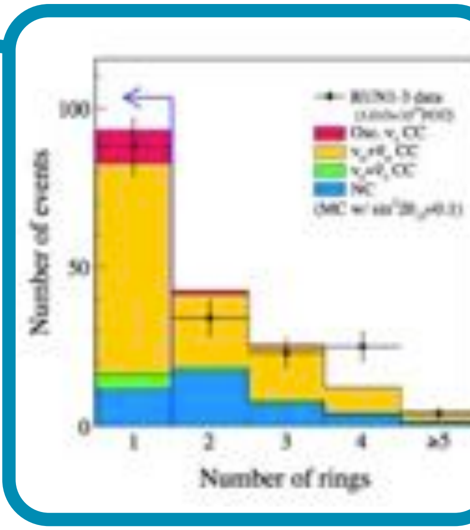

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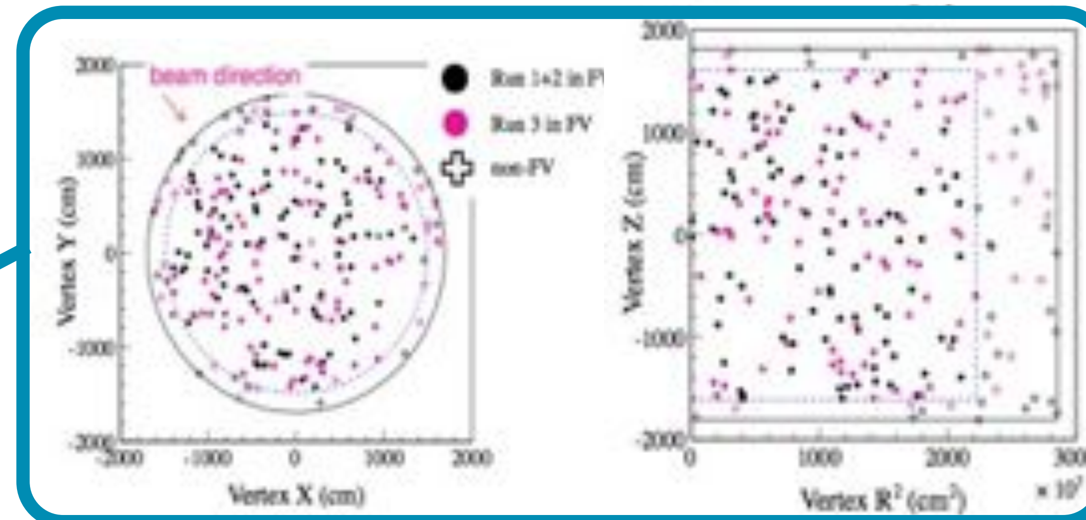

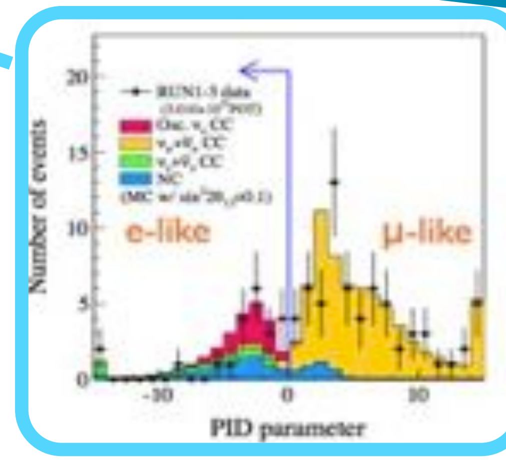

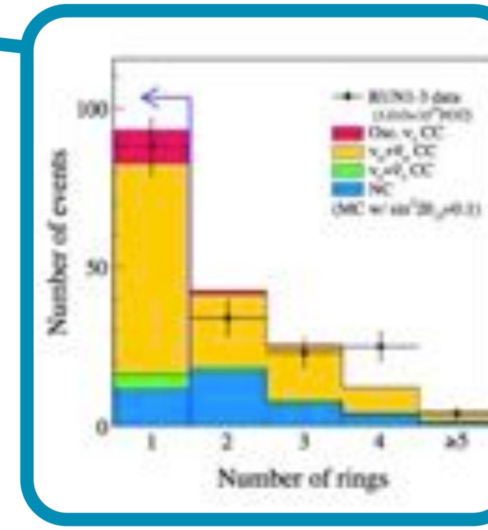

2012 ν_e Appearance Analysis: SELECTION

RUN1+2+3 = 3E20 POT

CUT	EVENTS (DATA)
FCFV (+beam timing)	174
Single Ring	88
PID (e-like)	22
E_{vis} > 100MeV	21
No decay e^-	16
Inv. mass cut	11
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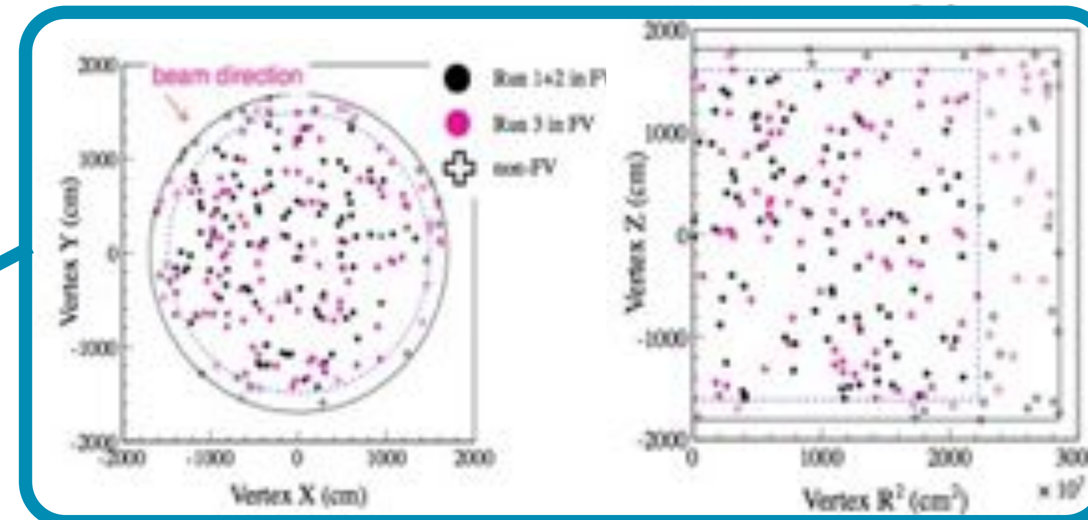

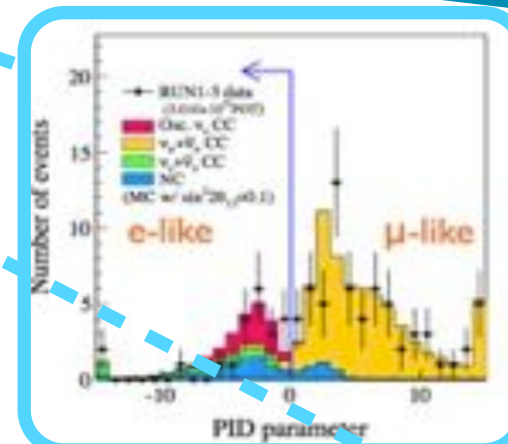

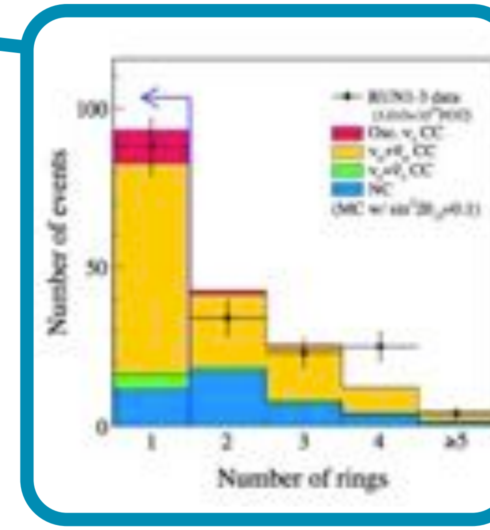

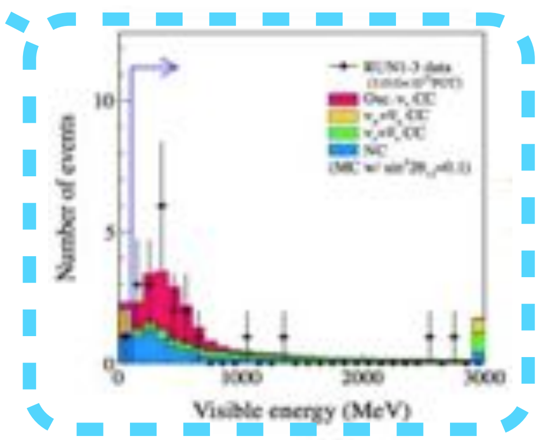

Detector performance (rejects noise)

2012 ν_e Appearance Analysis: SELECTION

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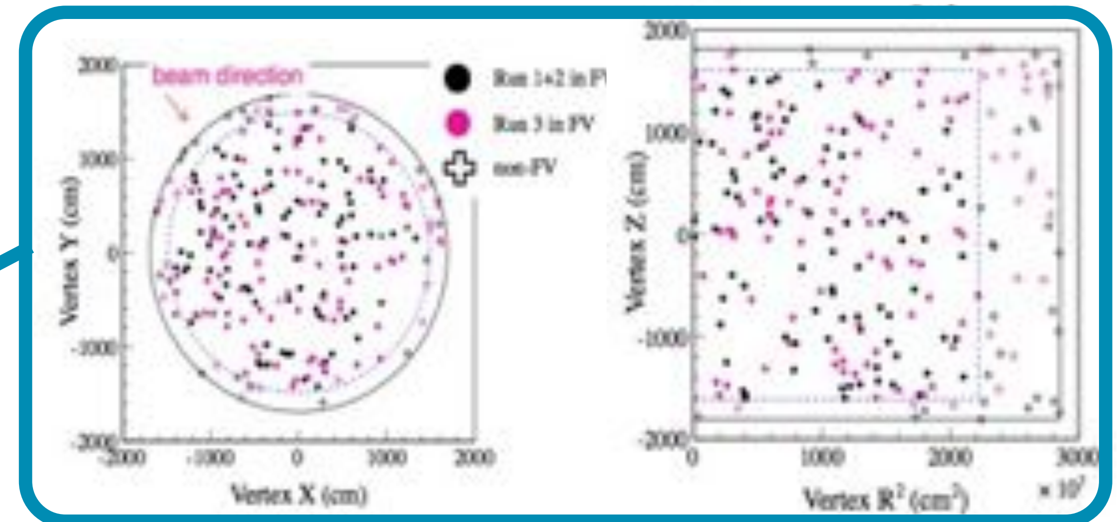
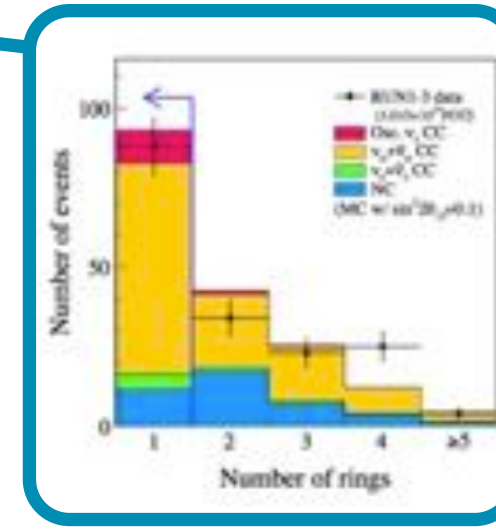
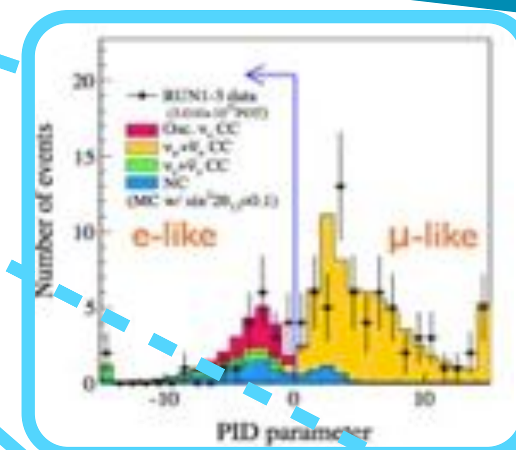
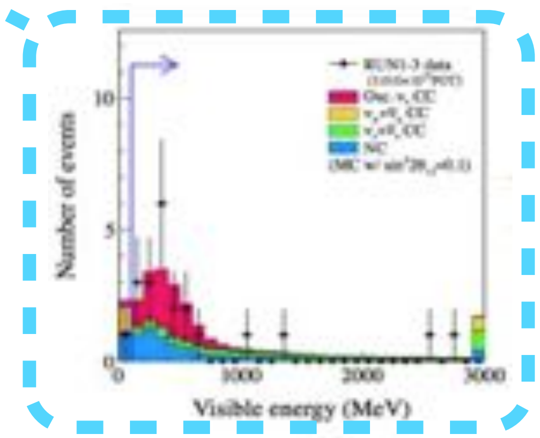
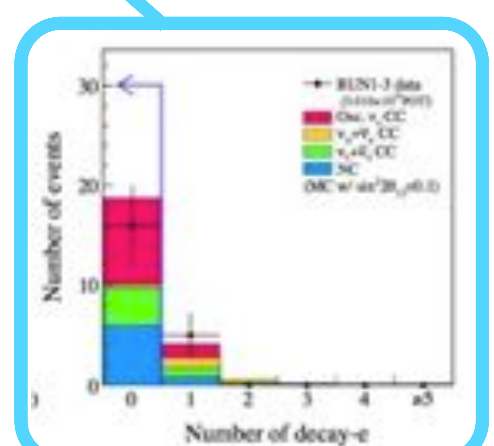








Detector performance (rejects noise)



Rejects e from μ decays

2012 ν_e Appearance Analysis: SELECTION

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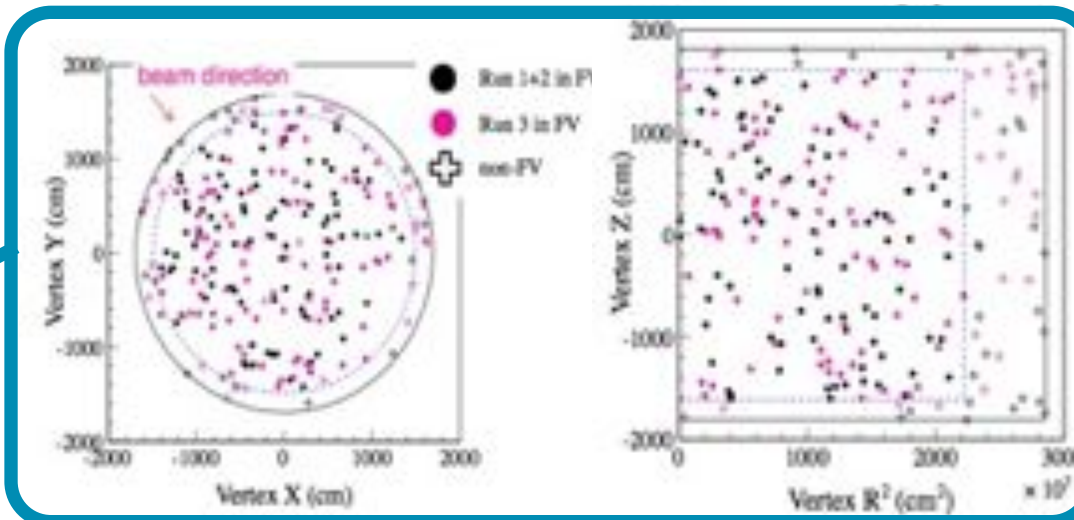
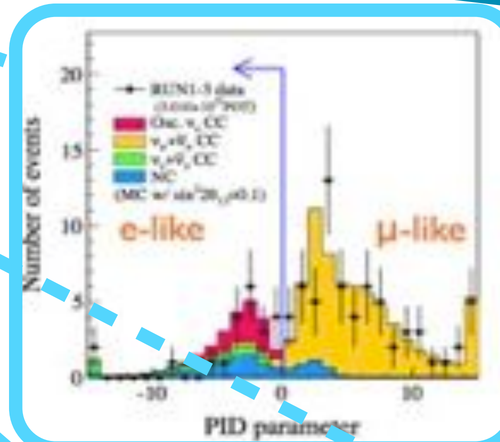
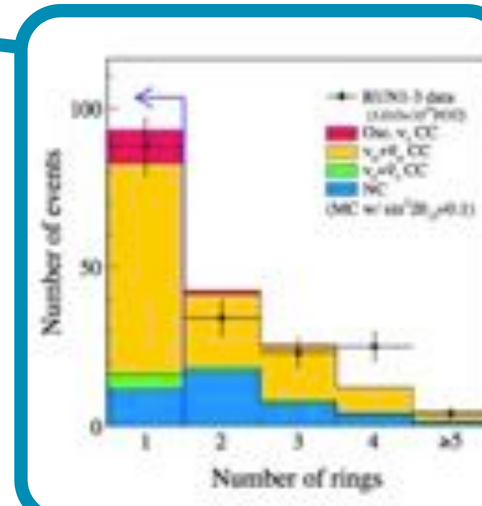
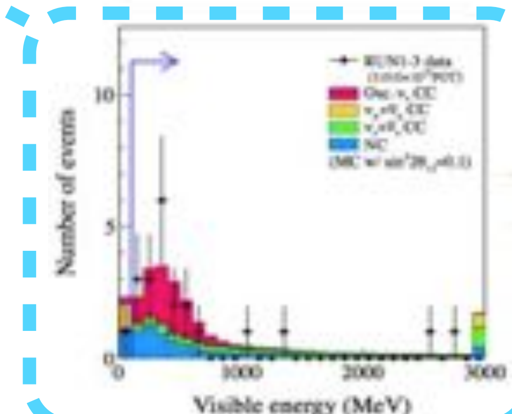
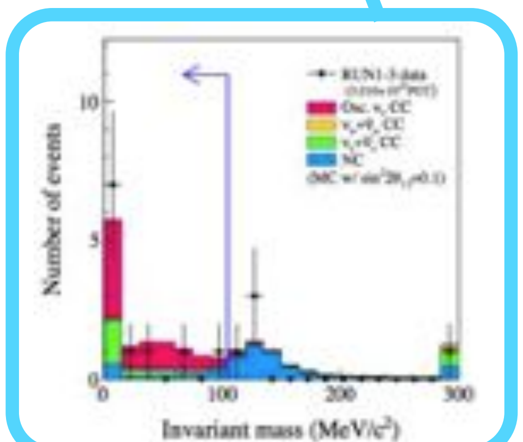


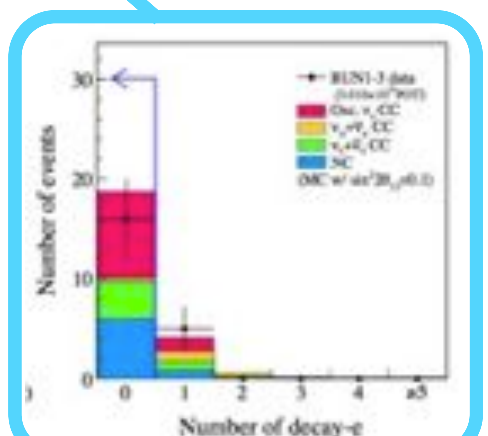






Detector performance (rejects noise)





Rejects e from μ decays

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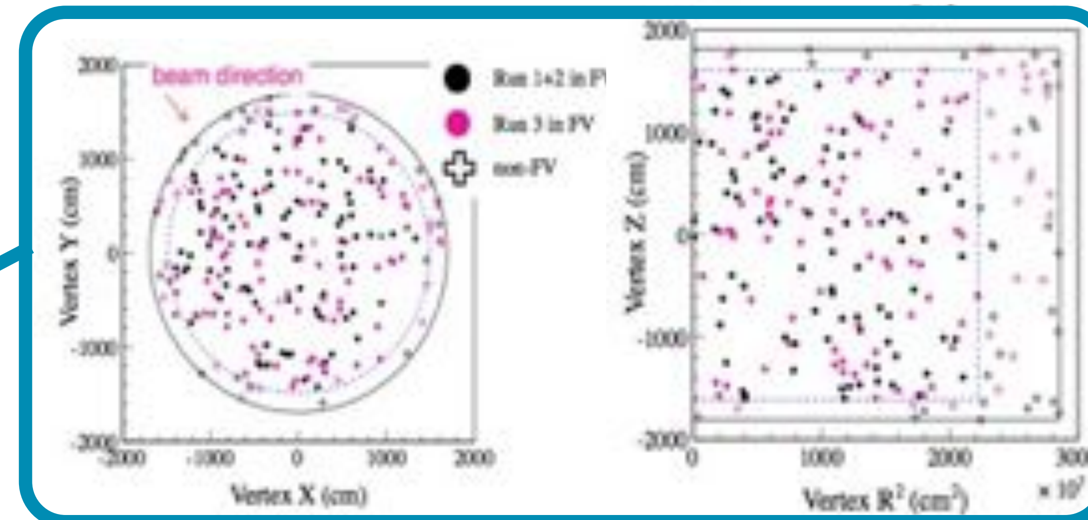
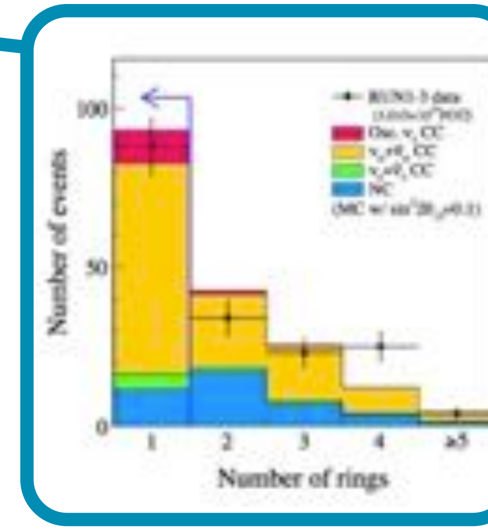
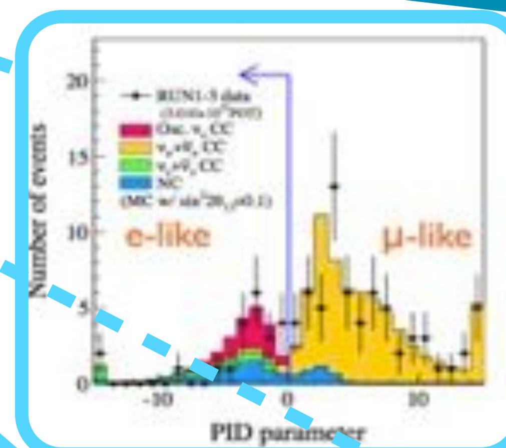
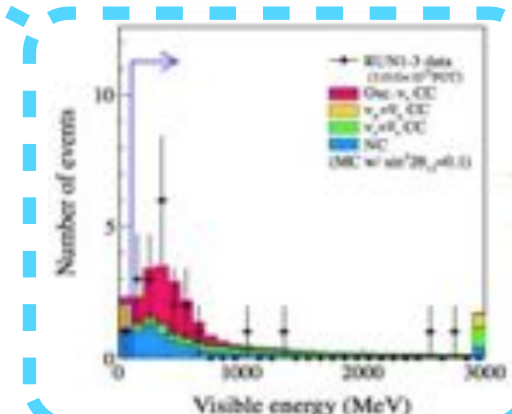
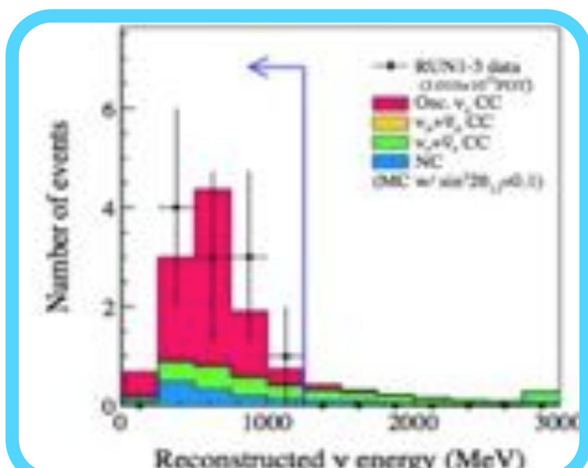


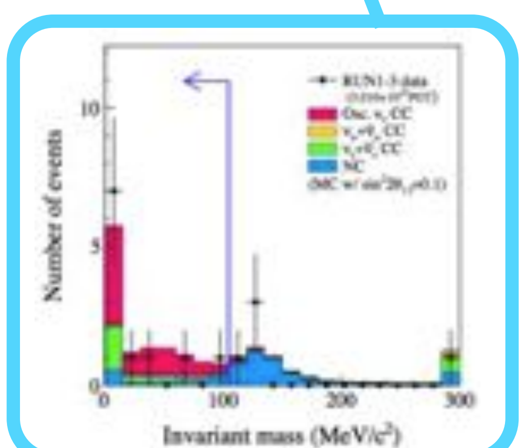


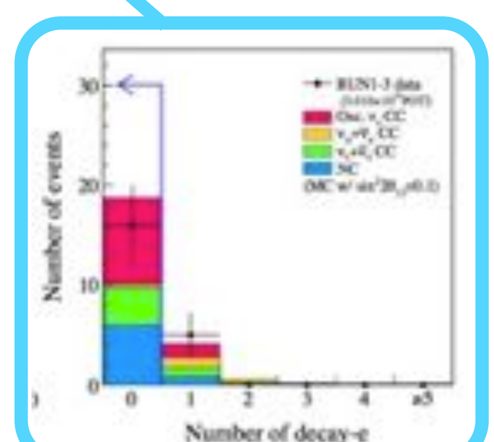




Detector performance (rejects noise)







Rejects e from μ decays

2012 ν_e Appearance Analysis: SELECTION

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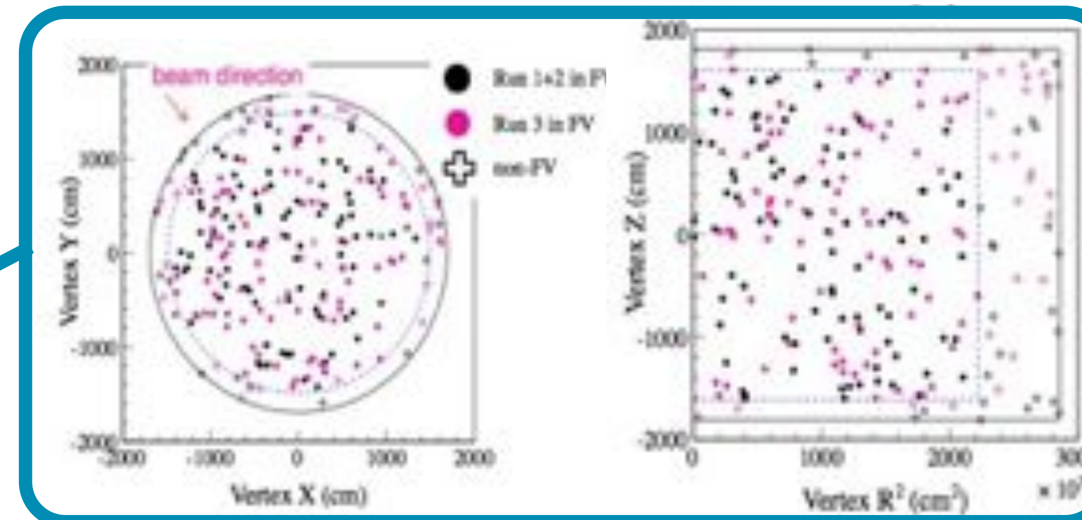
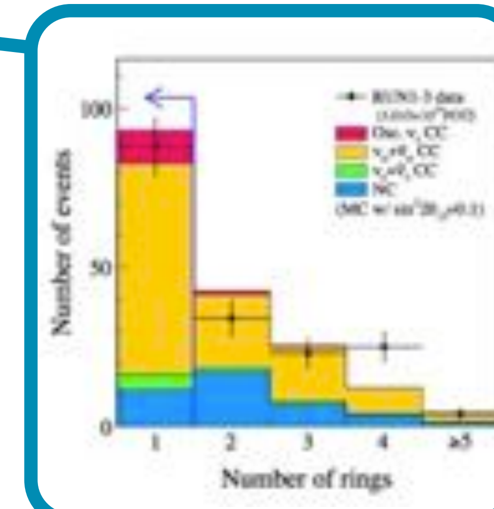
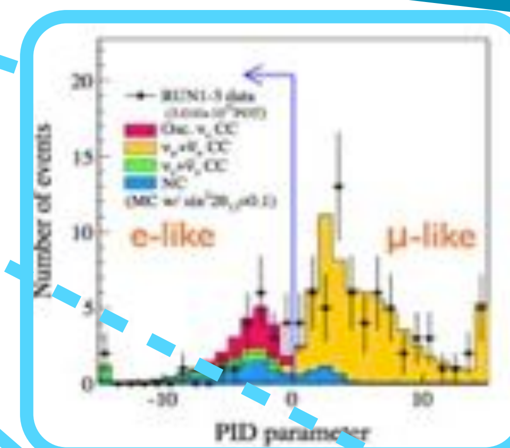
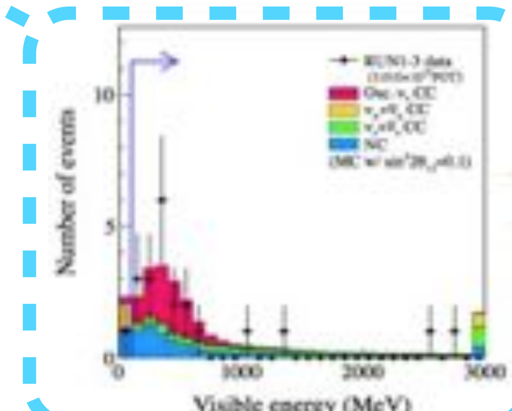
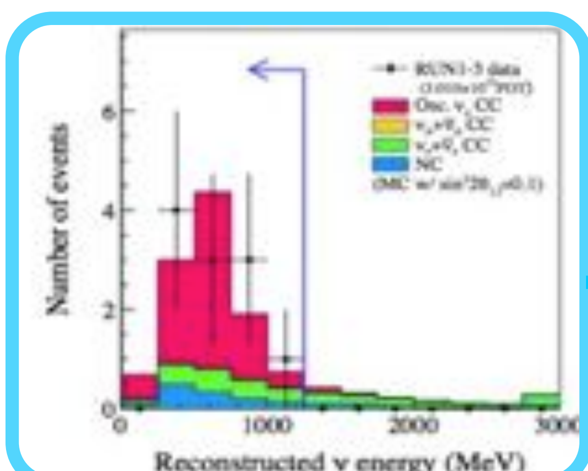




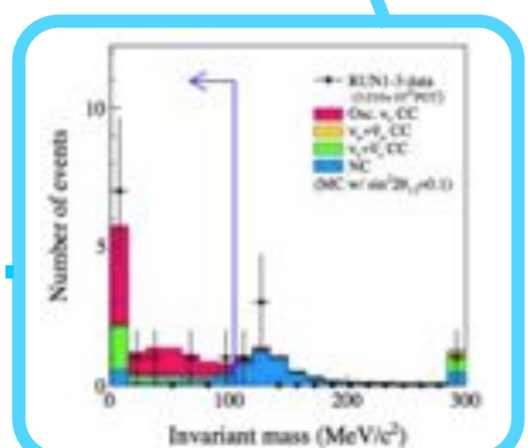


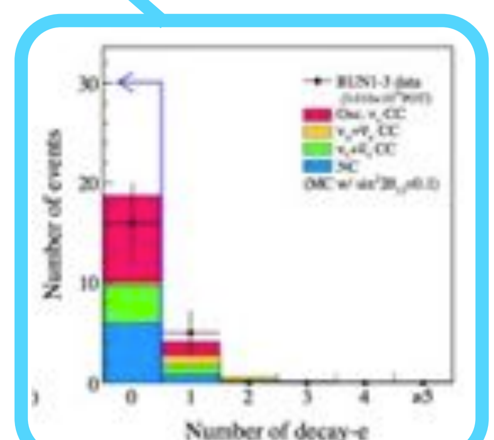


Detector performance (rejects noise)



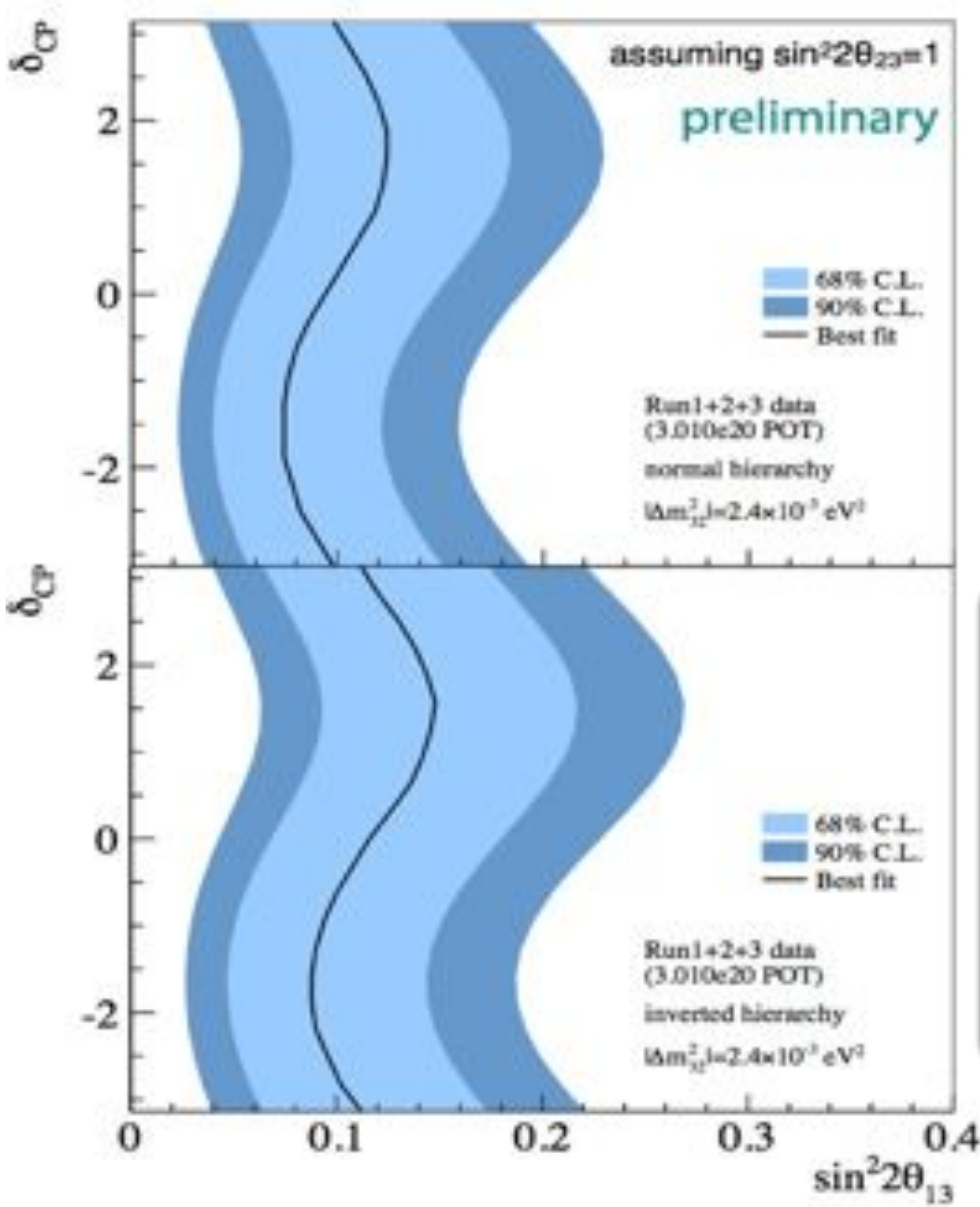
Background rejection: $NC\pi^0$ (inv. mass) beam ν_e (E_ν^{rec})

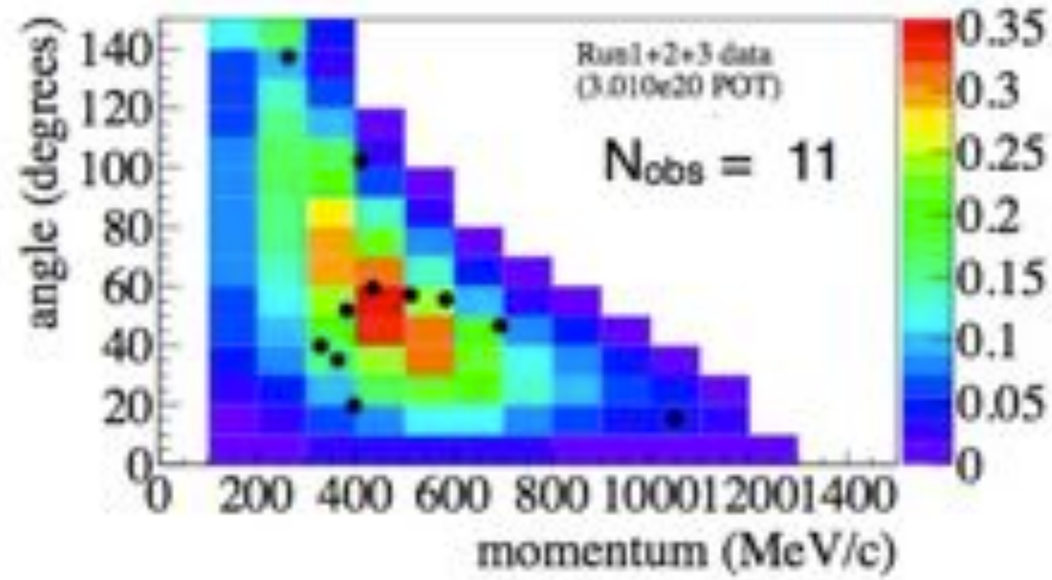




Rejects e from μ decays

2012 ν_e Appearance Analysis: RESULTS





BEST FIT
(with 68% CL error, @δ_{CP}=0)

- **Normal hierarchy**

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

- **Inverted hierarchy**

$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

Conclusions / Future Plans

- T2K has been taking data since 2010.

- We are reporting evidence of **ν_e appearance.** Latest result, based on 3E20 POT, recently reported (ICHEP 2012).
  - θ_{13} values compatible with reactor experiments.

- Updated results on **ν_μ disappearance** coming soon.
  - Current θ_{23}, Δm^2_{23} values compatible with MINOS, SK

- Summer 2012 shutdown underway.
- Data taking will be restarted in October 2012
- Planned to take more data at higher beam power

~8×10^{20} p.o.t (2013) → ~1.2×10^{21} p.o.t (2014) → ~1.8×10^{21} p.o.t. (2015)

Thanks for your attention!

REFERENCES

[1] **The T2K Experiment**
NIMA, DOI number: 10.1016/j.nima.2011.06.067 (2011) arXiv:1106.1238
[2] **Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-axis Muon Neutrino Beam**:
Phys. Rev. Lett. 107, 041801 (2011)
[3] **First muon-neutrino disappearance study with an off-axis beam**
Phys. Rev. D 85, 031103(R) (2012) arXiv:1201.1386

BACKUP

Some Neutrino Physics

NEUTRINO MIXING

Matrix connecting mass and flavor eigenstates (PMNS)

We start with the PMNS matrix:
($s_{ij} = \sin\theta_{ij}$ -- $c_{ij} = \cos\theta_{ij}$)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \\ \multicolumn{3}{c}{\left[\begin{array}{ccc} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{array}\right]} \end{array}$$

Now the oscillation probability:

$$P(\nu_\alpha \to \nu_\beta) = \delta\alpha\beta - 4\sum_{i>j} \mathrm{R}[\, U_{\alpha i}{}^* U_{\beta i} U_{\alpha j} U\beta j^* \,] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{I}[\, U_{\alpha i}{}^* U_{\beta i} U_{\alpha j} U\beta j^* \,] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

6 independent parameters describing oscillations: 3 angles, 2 mass splitting parameters and one phase:

Solar parameters (very well known)
θ_{12}, Δm^2_{12}

Atmospheric parameters (well known)
θ_{23}, Δm^2_{23}

Interference parameters (unknown)
θ_{13}, δ_{CP}

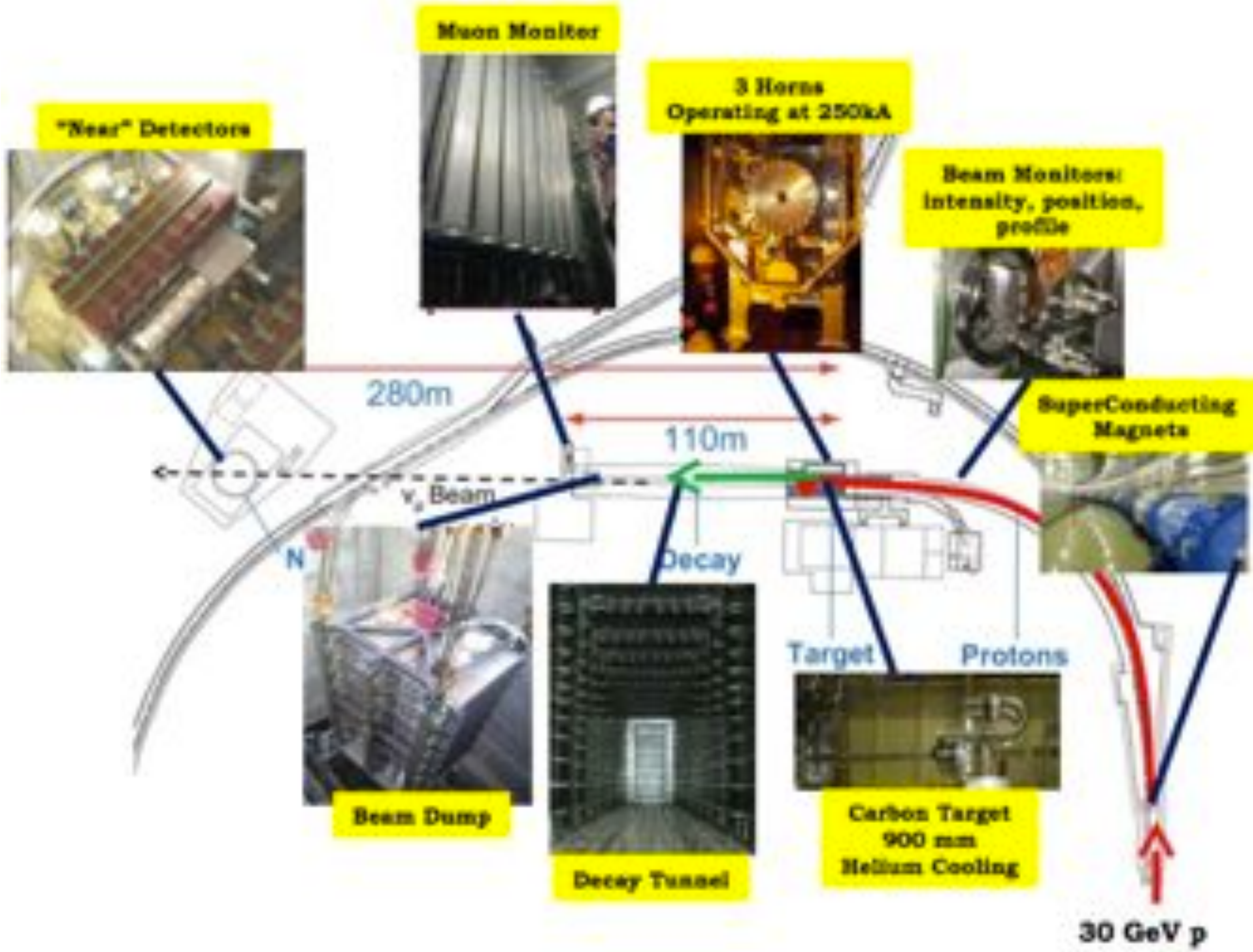
The T2K Collaboration

12 countries
61 institutions
~500 authors

Public website:
http://t2k-experiment.org/

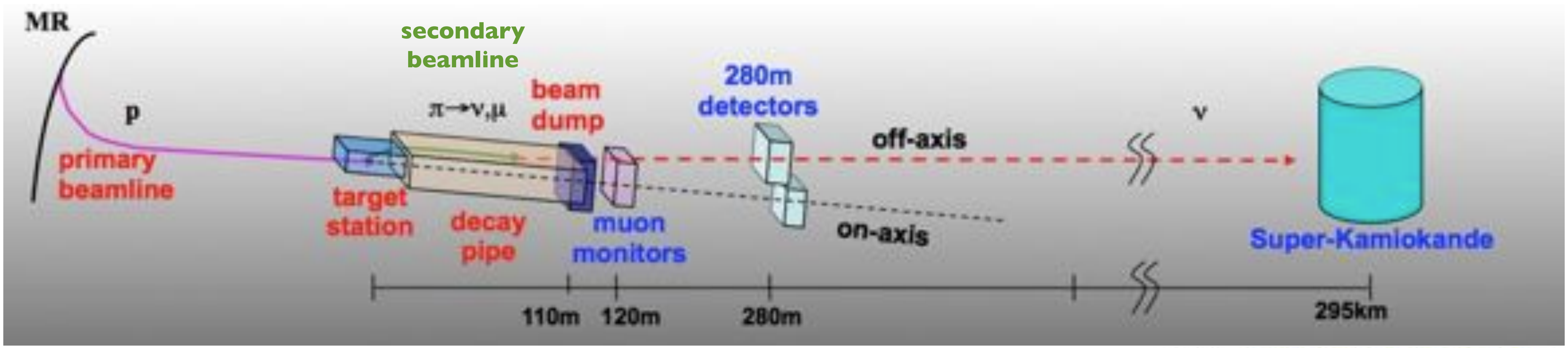

Linac
3 GeV
Synchrotron
Pacific Ocean
Near
Detector
Neutrino Beam to Kamioka
1200-year-
old temple
Design Intensity
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Construction
2001~2009
Photo: January 2008

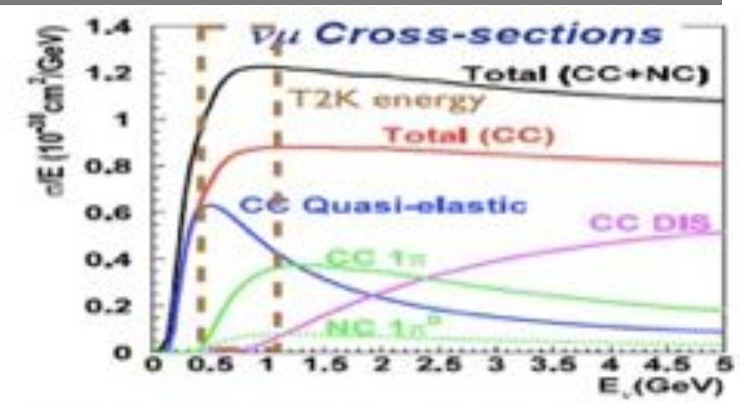
The Beam



Muon Monitor
3 Horns
Operating at 250kA
"Near" Detectors
Beam Monitors:
intensity, position,
profile
280m
110m
SuperConducting
Magnets
ν_μ Beam
N
Decay
Target
Protons
Beam Dump
Decay Tunnel
Carbon Target
900 mm
Helium Cooling
30 GeV p

The Off Axis Method

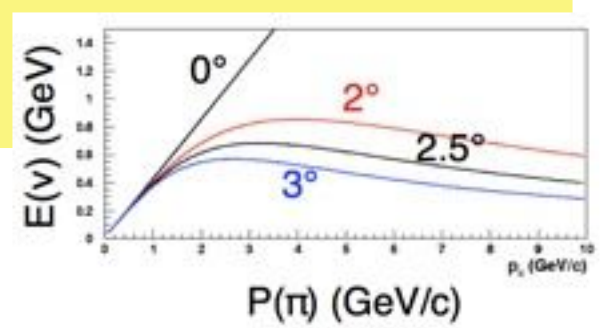


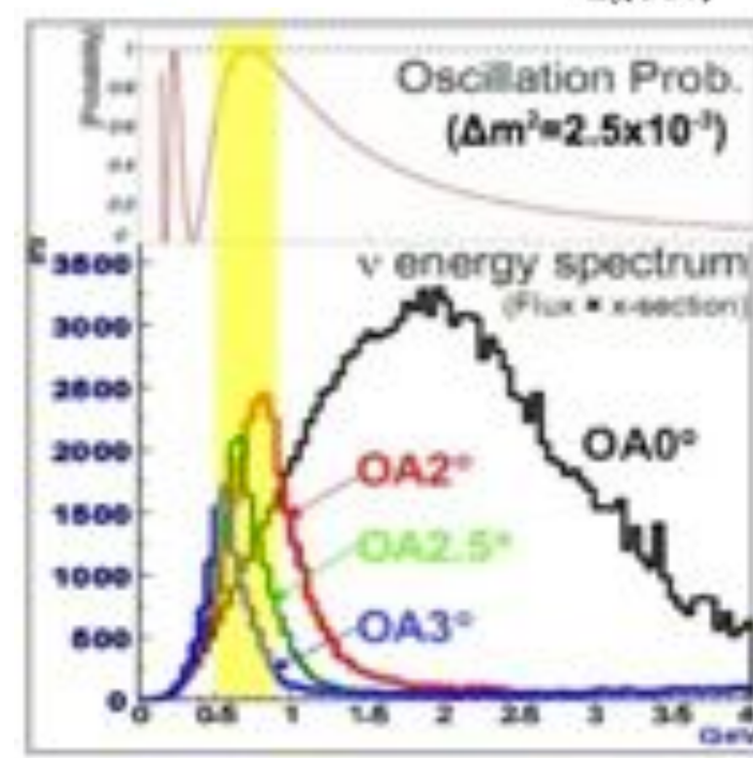


T2K is the first long baseline experiment using the off-axis technique. The current **off-axis angle is 2.5°**(2°-2.5° range allowed by the facility design).

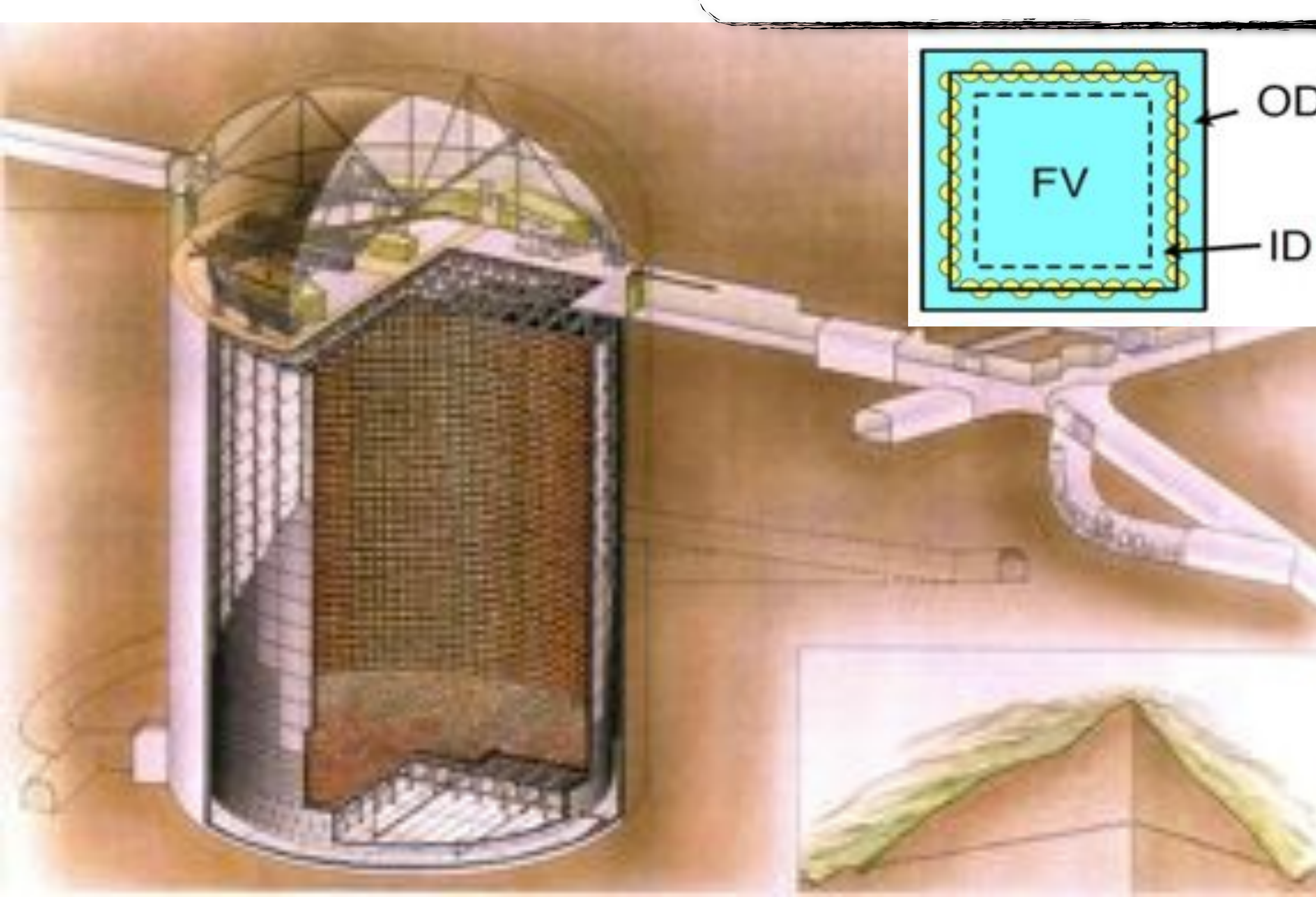
Characteristics/advantages of the off-axis method:

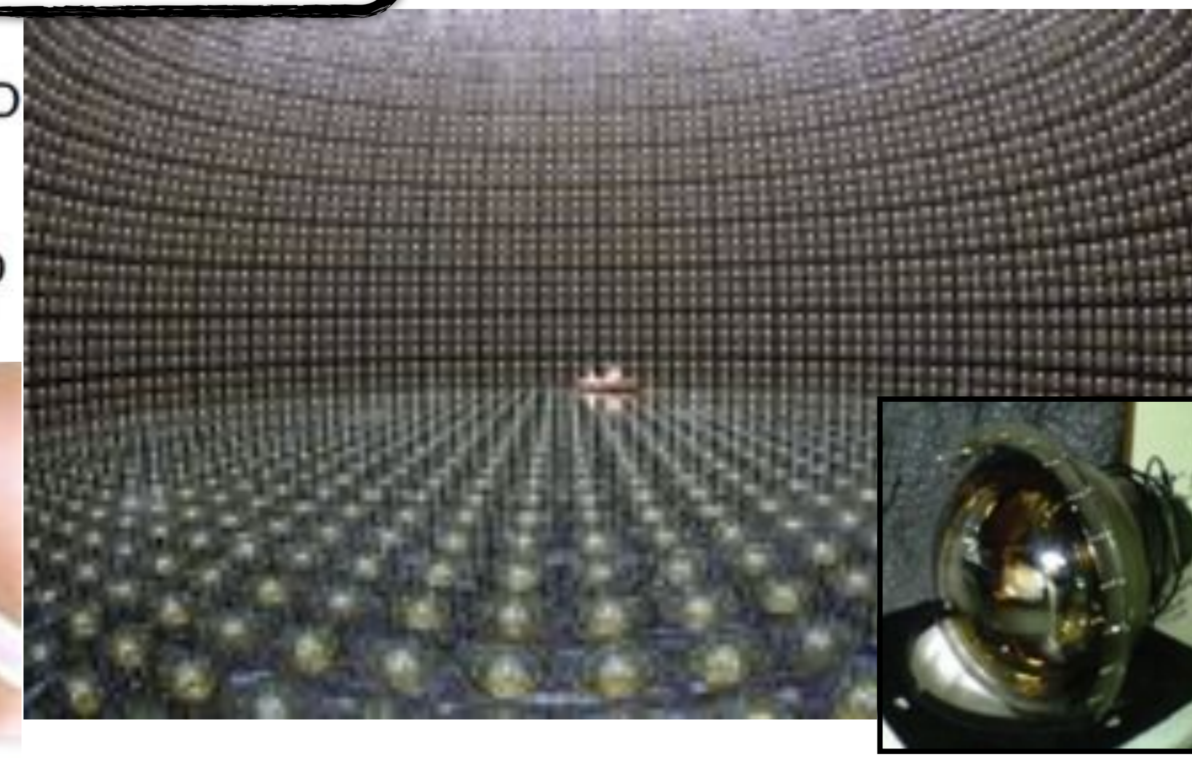
- Narrow beam with peak energy at maximum of $\nu_\mu \longrightarrow \nu_e$ oscillation (~600MeV).
- CCQE sample enhanced: high energy tails of the beam reduced (background from non-QE and NC to oscillation signal reduced).
- Dependence of E_ν from E_π reduced.





The Far Detector: SK

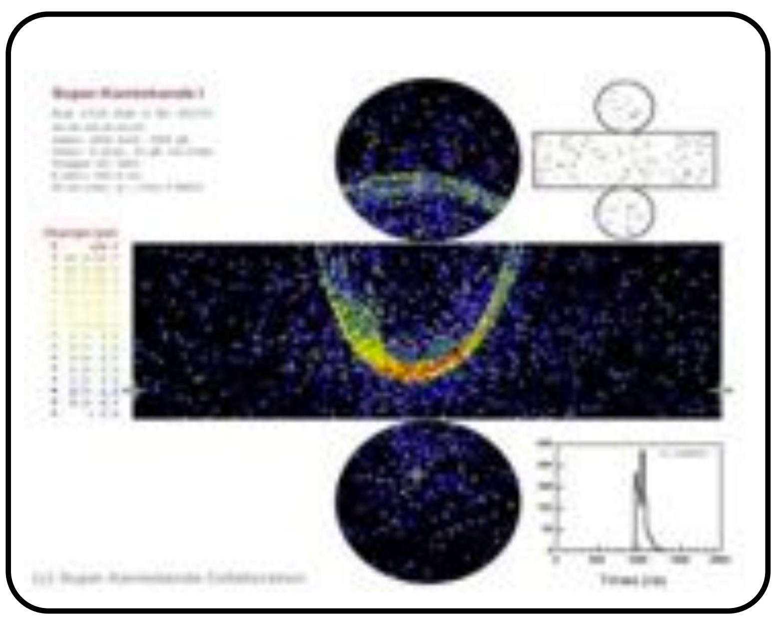




- **Water Cherenkov detector.**
- 1 km deep underground.
- Cylindrical shape with 39 m ∅ and 42 m height.
- Filled with 50 kton of pure water (fiducial volume 22.5 kton).
- **PMTs**: 11.146 in the inner region.
- Cherenkov photons reach PMTs and produce ring-shaped hit pattern
- Using the timing and charge information, the interaction vertex, ring direction and flavor of incoming particle (from the sharpness of edge of ring) are determined.

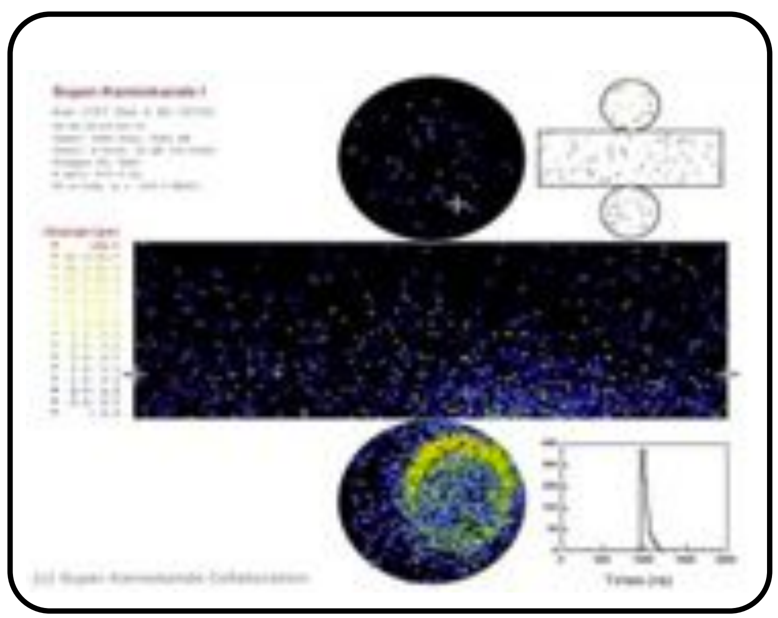
Muon neutrino event

($\nu_\mu \rightarrow \mu$ clear single ring)

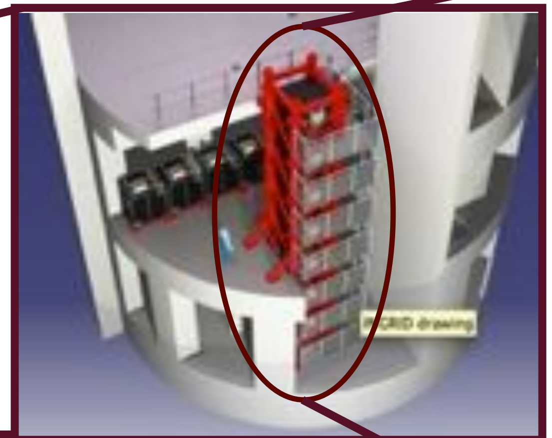


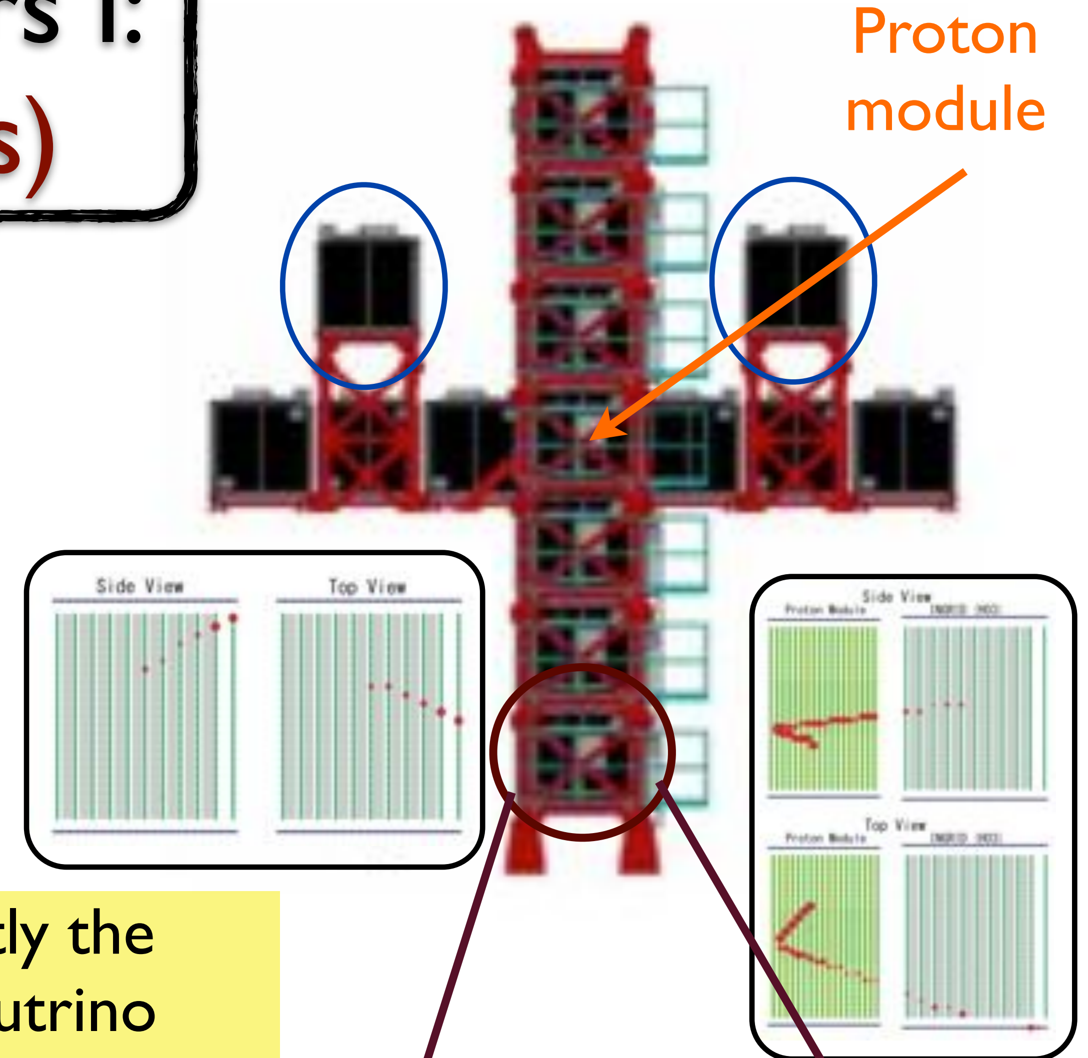
Electron neutrino event

($\nu_e \rightarrow e$ EM shower, fuzzy ring)

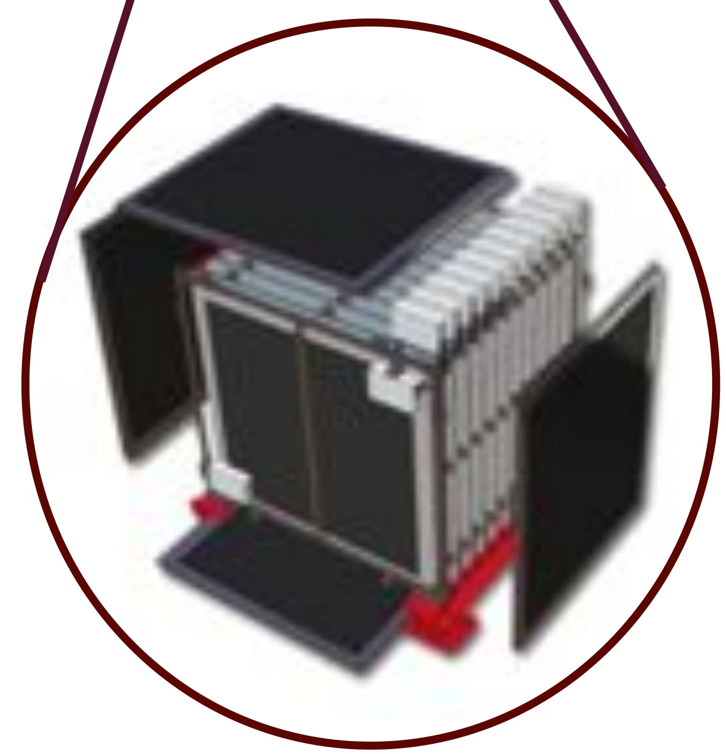


The Near Detectors I: INGRID(ON Axis)

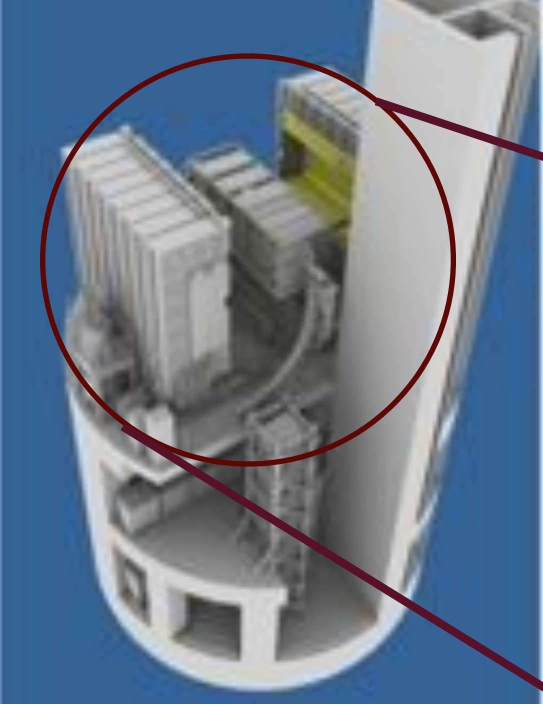


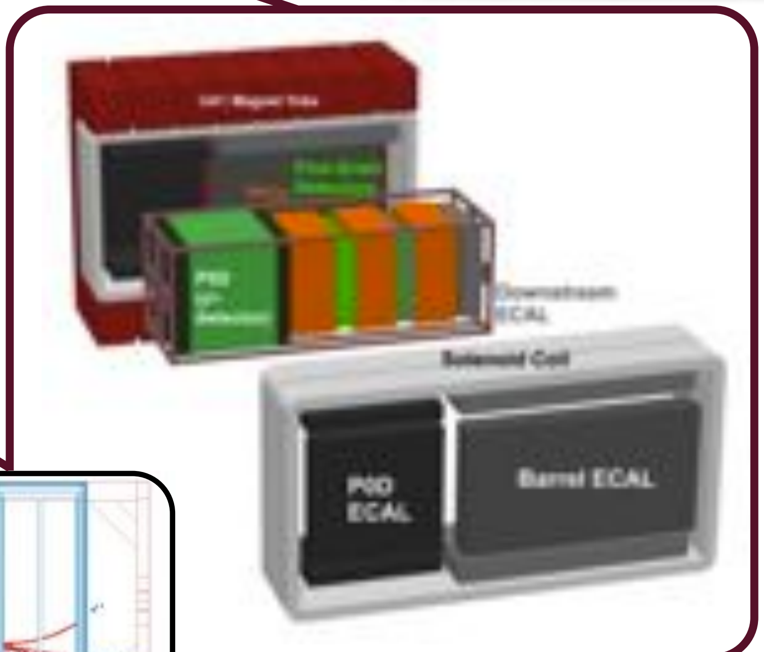


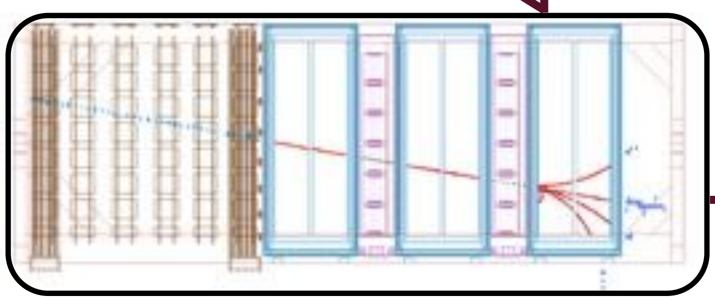
- INGRID (Interactive Neutrino GRID) monitors directly the neutrino beam direction and intensity by means of neutrino interactions in iron. The beam stability on a day-by-day basis is studied in this way.
- INGRID consists of
  - 14 on-axis modules (horizontal+vertical) forming a cross.
  - 2 extra off-axis modules used to study the axial symmetry of the beam.
  - Each module (7 ton) is composed of 9 iron plates + 11 scintillator layers in a sandwich (10mx10m).
  - An extra module, Proton Module, without iron plates is added in order to detect muons together with protons produced by the neutrino beam.



The Near Detectors II: ND280(OFF Axis)







- ND280 goal is to measure the flux, energy spectrum and ν_e contamination before oscillation.
- General purpose to measure: CCν_μ events, used for flux normalization and spectrum prediction for the oscillation analysis and detailed cross section studies; and CCν_e events, background to ν_e appearance.

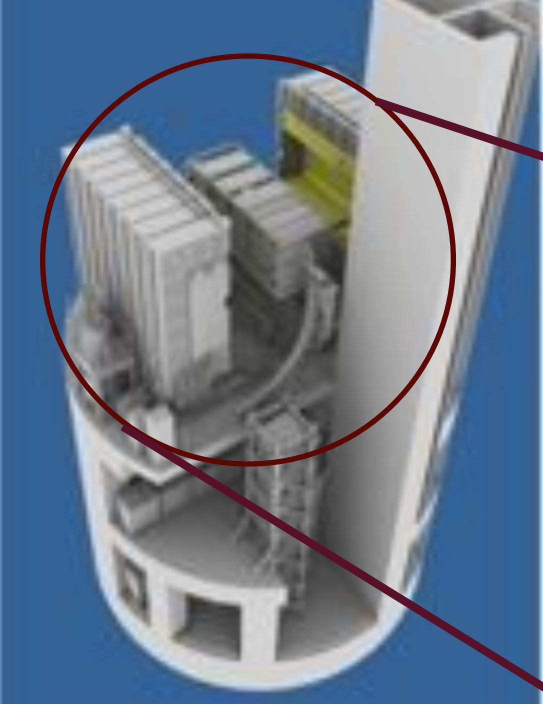
ND280 Magnet & SMRD

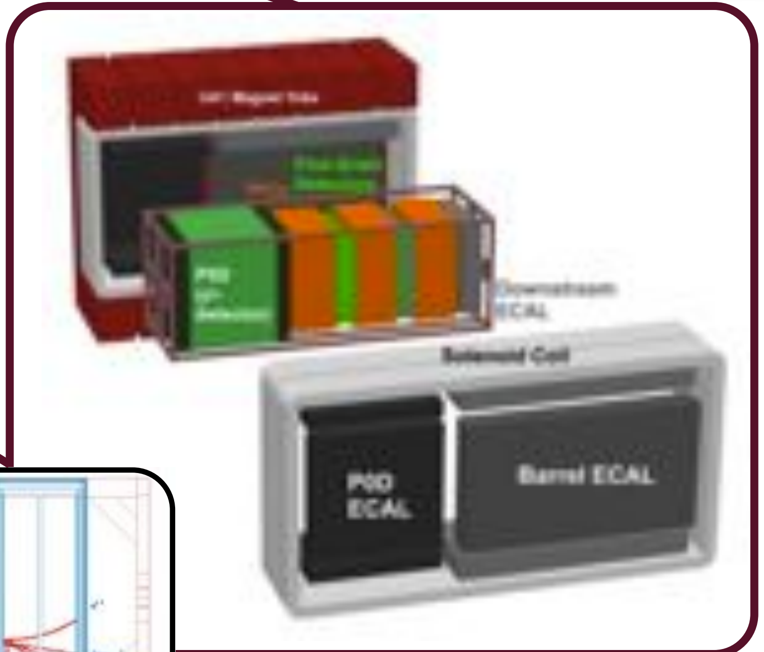
- ND280 is built inside the old CERN UA1/NOMAD magnet that provides a dipole magnetic field of 0.2 T.
- SMRD (Side Muon Range Detector) consists of 440 scintillator modules inserted in the air gaps of the magnet. It records muons escaping with high angles, triggers on cosmic ray muons and helps identifying interactions in the surrounding cavity.

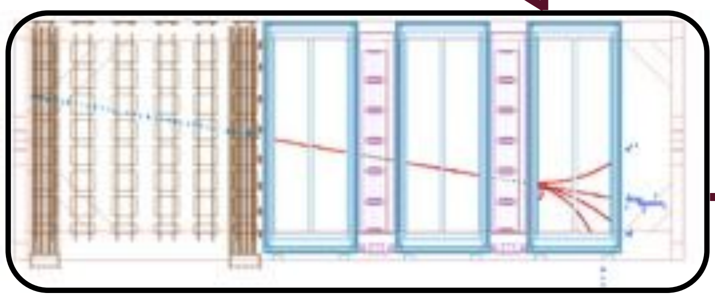
ECAL

- 3 different types depending on the position: DSEcal, BarrelEcal, P0DEcal.
- These modules are electromagnetic calorimeters using layers of plastic scintillator. Its role is to detect photons complementing the inner detectors in full event reconstruction. The information provided by the Ecals is relevant for particle identification and key in the pi0 reconstruction.

The Near Detectors II: ND280(OFF Axis) II



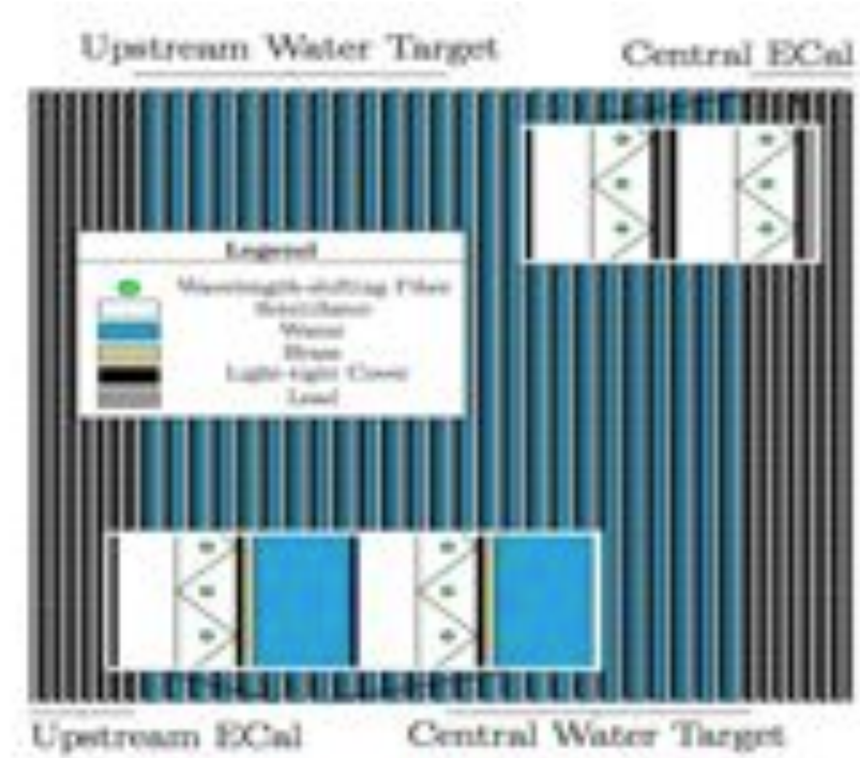




Tracker

- 3 Time Projection Chambers (TPCs)
  - MicroMegas detectors. Tracking devices. They reconstruct momentum and charge of particles. *(See next talk: "Calibration and Performance of the T2K TPCs" by Lorena Escudero).*
- 2 Fine Grained Detectors (FGDs)
  - Thin, wide planes of scintillator bars.
  - Active target for neutrino interactions: carbon + water (only in the second FGD).
  - Charged particle tracking.

Pi 0 detector (P∅D)

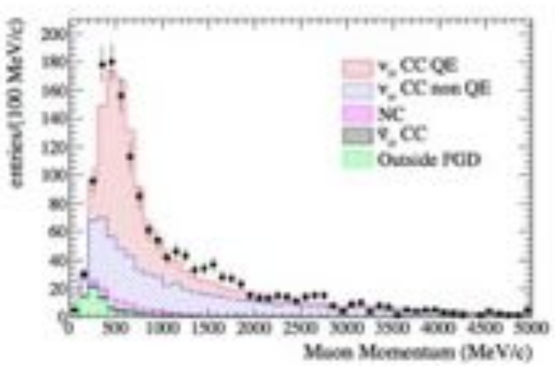


- Scintillator + water detector
- Optimized for γ detection and π0 reconstruction (neutrino NC process)
- Water can be subtracted.
- Study of water cross section.

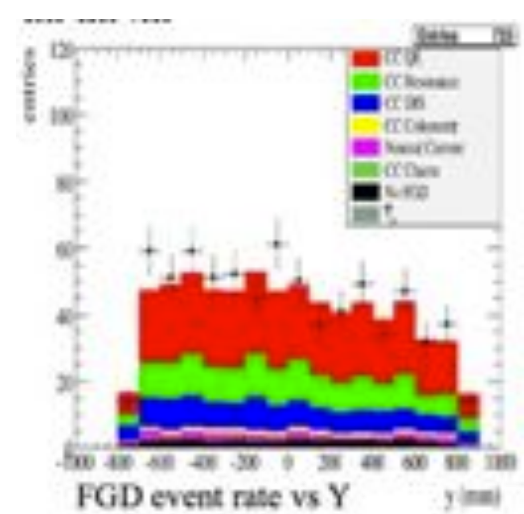
Neutrino Interaction Event Rates

TPC: negligible.
INGRID: 1.5 evts/10^{14} POT
FGD: from the plot:

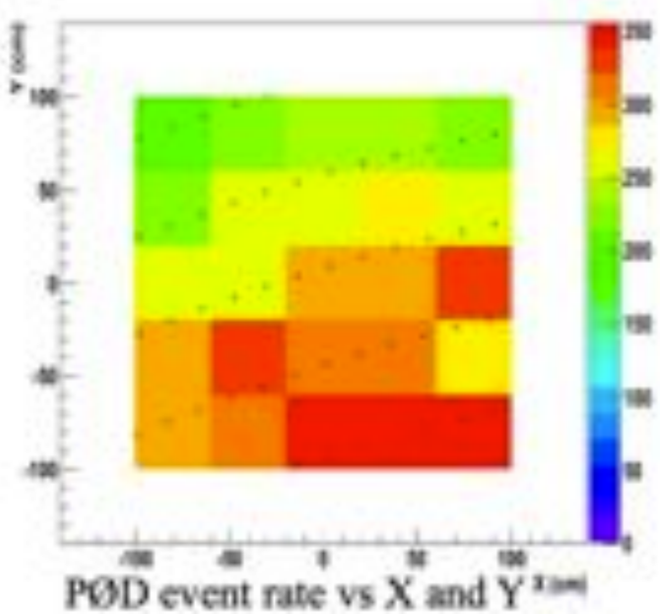
1529 evts in 2.88×10^{19} POT
event rate = 5.3evts/10^{16} POT



also...



P0D:



SK: Predicted from MC models

NEUT

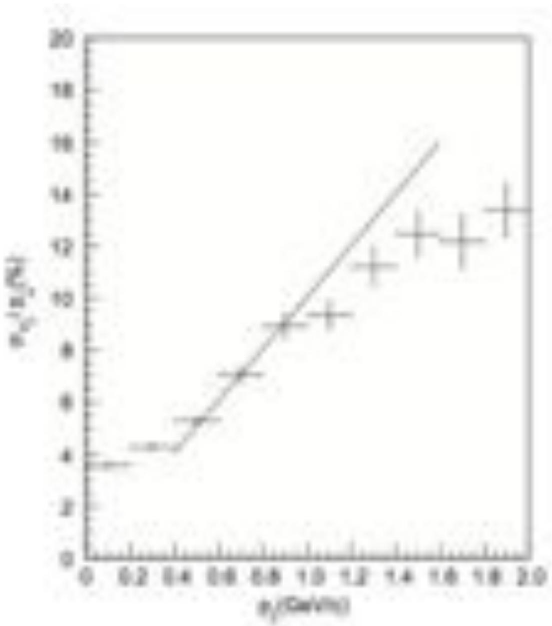
- **QE**
  - Llewellyn Smith, Smith-Moniz
  - M_A = 1.2 GeV/c^2
  - P_F = 217 MeV/c, E_B = 27 MeV (for Carbon)
- **Resonant π**
  - Rein-Sehgal (2007)
  - M_A = 1.2 GeV/c^2
- **Coherent π**
  - Rein-Sehgal (2006)
  - M_A = 1.0 GeV/c^2
- **DIS**
  - GRV98 PDF
  - Bodek-Yang correction

Mix of Features

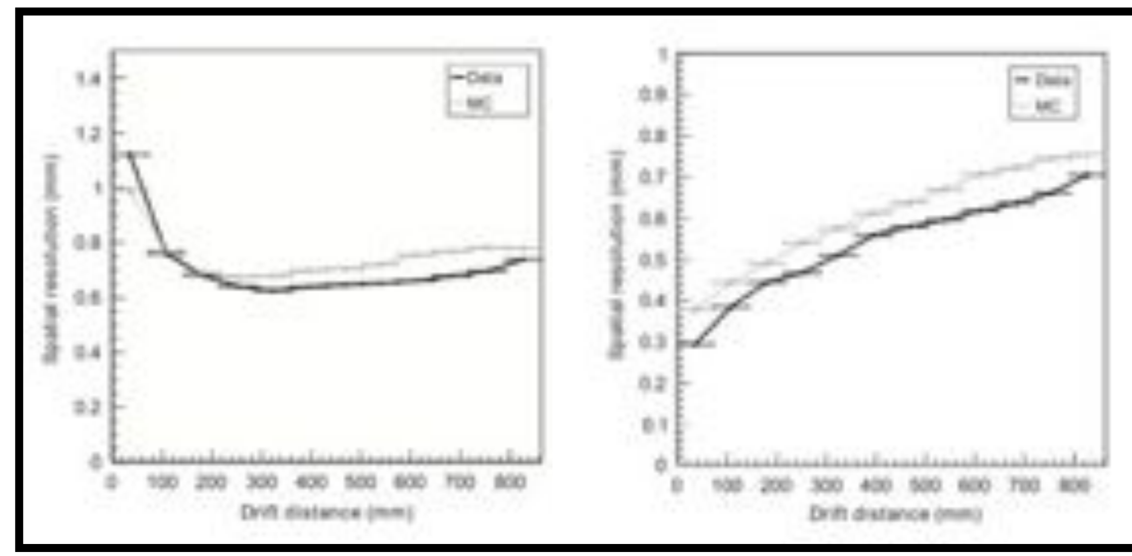
Dimensions

TPC (Active): 1,8 m (X) x 2,1 m (Y) x 0.772 m (Z)
FGD (Active): 1,864 m (X) x 1,864 m (Y) x 0,33 m(Z)

TPC Resolutions

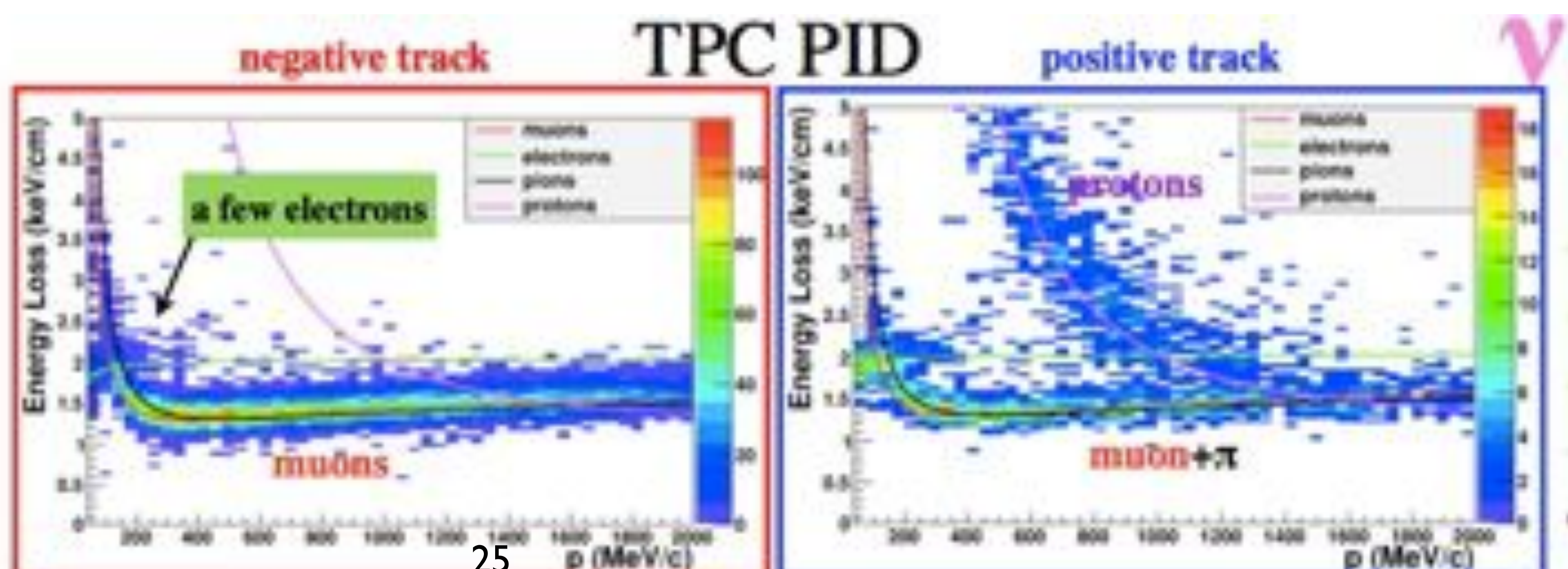


Momentum resolution

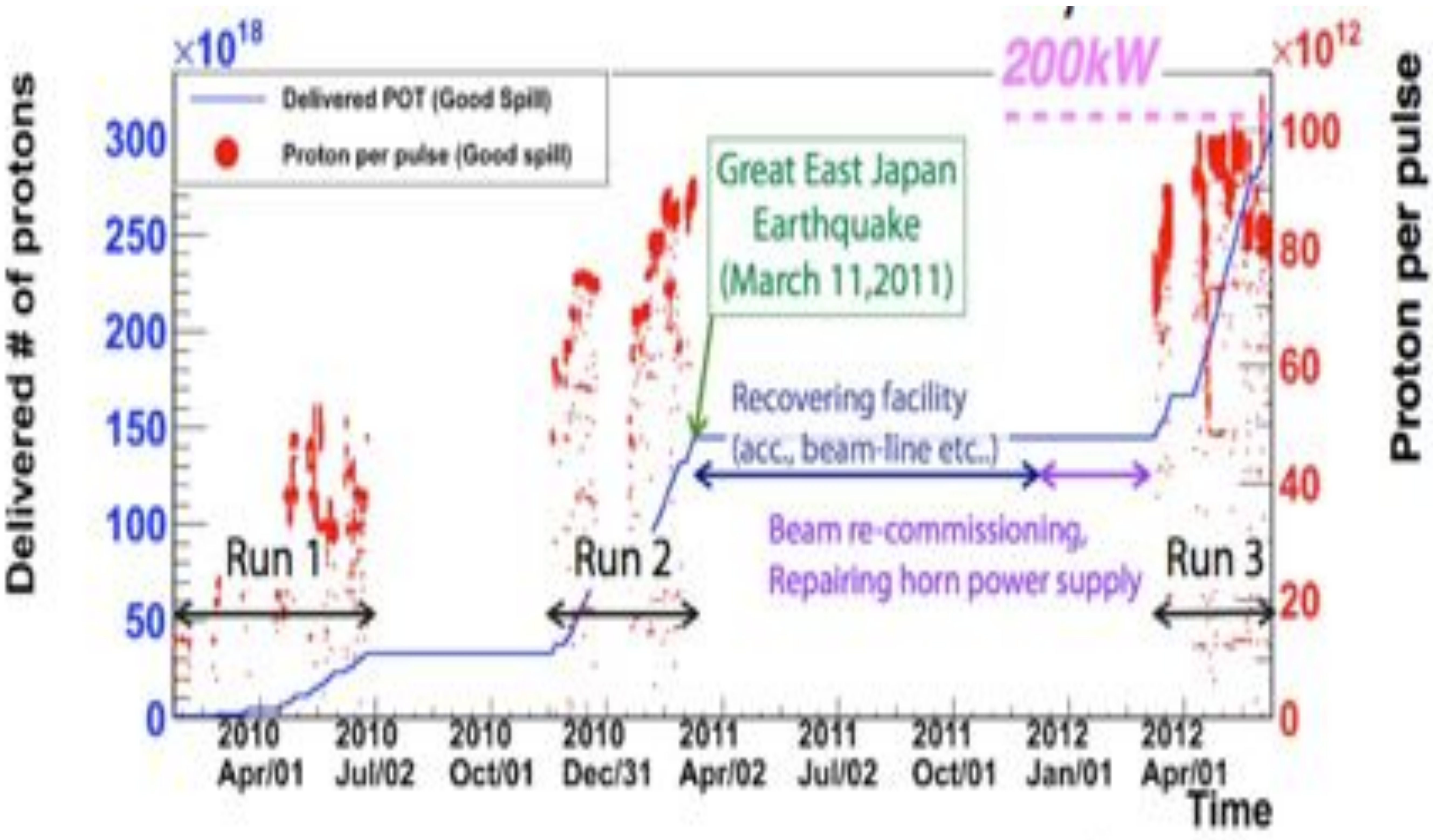


Spatial resolution

TPC PID



Data Sets



×10^18
Delivered POT (Good Spill)
Proton per pulse (Good spill)
Great East Japan
Earthquake
(March 11,2011)
200kW
×10^12
Delivered # of protons
Proton per pulse
300
250
200
150
100
50
0
100
80
60
40
20
0
Recovering facility
(acc., beam-line etc.)
Beam re-commissioning,
Repairing horn power supply
Run 1
Run 2
Run 3
2010 Apr/01
2010 Jul/02
2010 Oct/01
2010 Dec/31
2011 Apr/02
2011 Jul/02
2011 Oct/01
2012 Jan/01
2012 Apr/01
Time

2010 ν_μ Disappearance Analysis

Event Reduction

TABLE I. Event reduction at the far detector. After each selection criterion is applied, the number of observed (Data) and MC expected events of ν_μ CCQE, ν_μ CC non-QE, intrinsic ν_e, and neutral current (NC) are given. The columns denoted by ν_μ include $\bar{\nu}_\mu$. All MC CC samples assume $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2(2\theta_{23})$=1.0 and $|\Delta m^2_{32}|$=2.4 × 10^{-3}eV^2.

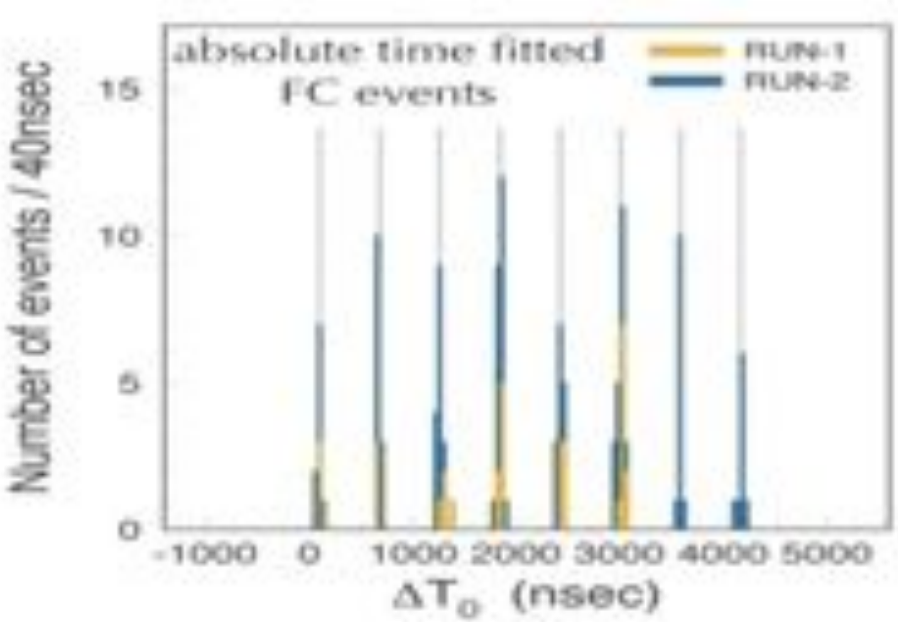
	Data	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC
FV interaction	n/a	24.0	43.7	3.1	71.0
FCFV	88	19.0	33.8	3.0	18.3
single ring	41	17.9	13.1	1.9	5.7
μ-like	33	17.6	12.4	<0.1	1.9
p_μ > 200 MeV/c	33	17.5	12.4	<0.1	1.9
0 or 1 delayed e	31	17.3	9.2	<0.1	1.8

Uncertainties

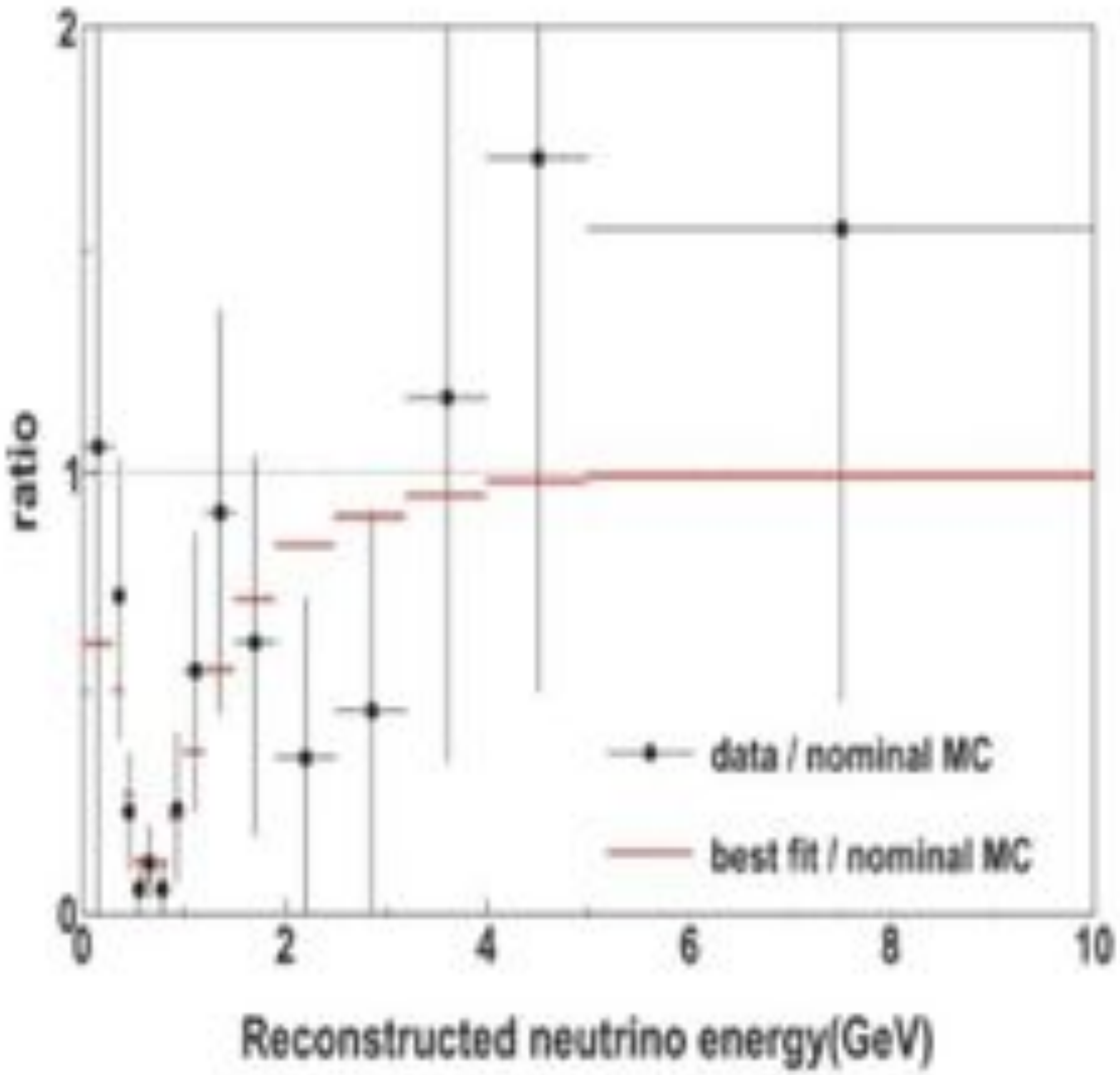
TABLE II. Systematic uncertainties on the predicted number of SK selected events without oscillations and for oscillations with $\sin^2(2\theta_{23})$ = 1.0 and $|\Delta m^2_{32}|$ = 2.4 × 10^{-3} eV^2.

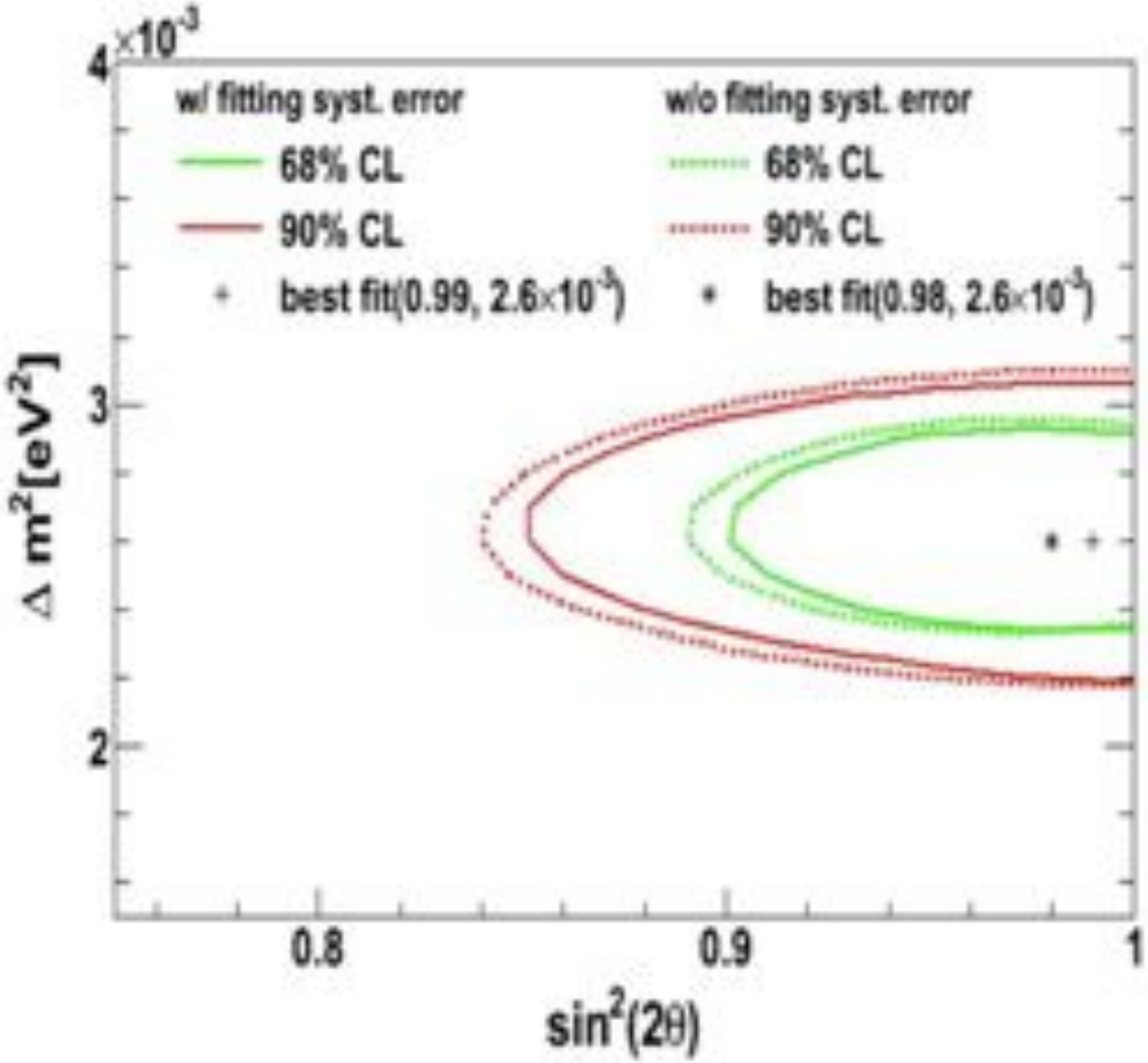
Source	$\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, no osc)	$\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, with osc)
SK CCQE efficiency	±3.4	±3.4
SK CC non-QE efficiency	±3.3	±6.5
SK NC efficiency	±2.0	±7.2
ND280 efficiency	+5.5 -5.3	+5.2 -5.3
ND280 event rate	±2.6	±2.6
Flux normalization (SK/ND280)	±7.3	±4.8
CCQE cross section	±6.1	±7.5
CC1π/CCQE cross section	+2.2 -1.9	+0.4 -0.5
Other CC/CCQE cross section	+5.3 -4.7	+4.1 -3.6
NC/CCQE cross section	±0.8	±0.9
Final-state interactions	±3.2	±5.9
Total	+13.3 -13.0	+15.0 -14.8

Cut1: Timing



2010 ν_μ Disappearance Analysis

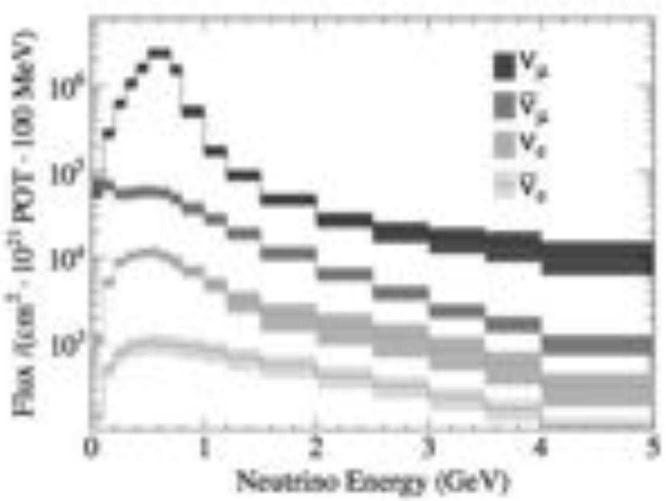




Phys. Rev. Lett. 107, 041801 (2011)

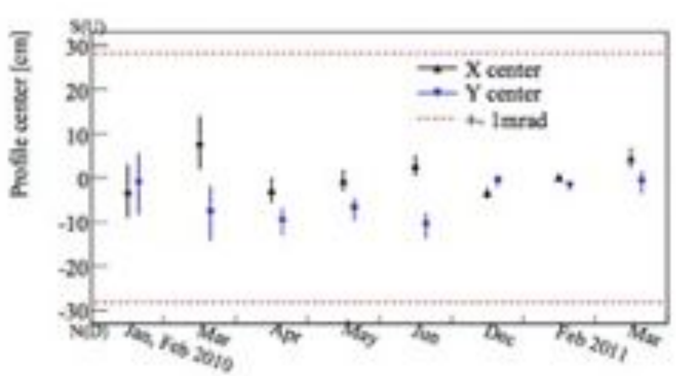
2010 ν_e Appearance Analysis

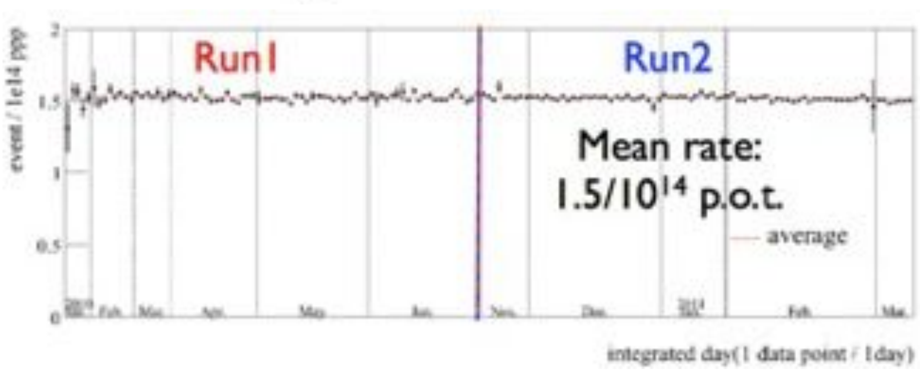
Predicted flux



-Pion production in (p,θ) bins is based on the NA61 experiment (CERN) measurements, typically with 5-10% uncertainties.
-Pions produced outside the experimentally measured phase space, as well as kaons, are modeled using FLUKA (MC).
-Systematic uncertainties of 50% assigned for pions.
-Systematic uncertainties for kaons of 15-100% from comparison with data from:
T. Eichen et al., Nucl. Phys. B 44, 333 (1972)
-GEANT3 and GCALOR for hadronic interactions to handle particle propagation through magnetic horns, target hall, decay volume and beam dump.

Beam profile





The neutrino beam profile and its absolute rate (1.5 evts/10^14 POT) as measured b INGRID were stable and consistent with expectations.

FC in SK

An event is categorized as FC if the maximum number of photoelectrons on a single PMT at the exit direction of the most energetic particle is less than 200.

Phys. Rev. Lett. 107, 041801 (2011)

2010 ν_e Appearance Analysis

T2K

- Results based on two physics runs RunI (Jan.-Jun. 2010) and RunII (Nov.-Mar. 2011).
  Total 1.43x10^20 POT (protons on target).
- Sample of CCQE events enhanced.
- Main backgrounds:
  - Intrinsic νe contamination in the beam.
  - NC π0 events.
- Observed number of events compared to signal and background expectations based on neutrino flux and cross-section predictions, corrected with near detector info.

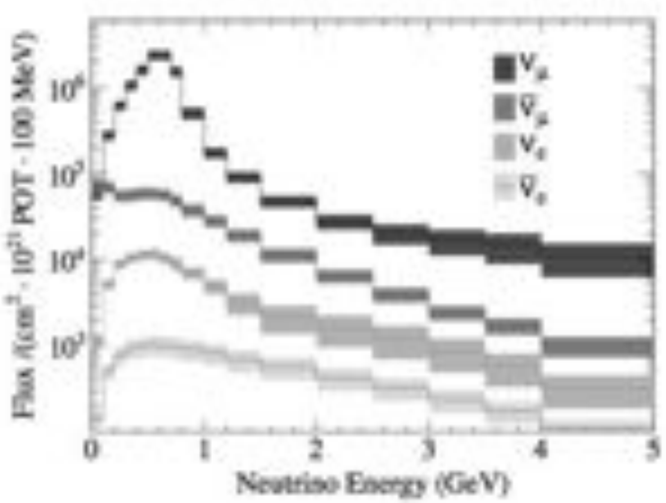
Oscillation Analysis

- Select CC νe candidates
- Compute N^{SK}_{MC} without oscillations.
- Normalization with ND280 ratio:

$$N^{SK}_{\exp} = (R^{ND,data}_{\mu} / R^{ND,MC}_{\mu}) \, x \, N^{SK}_{MC}$$

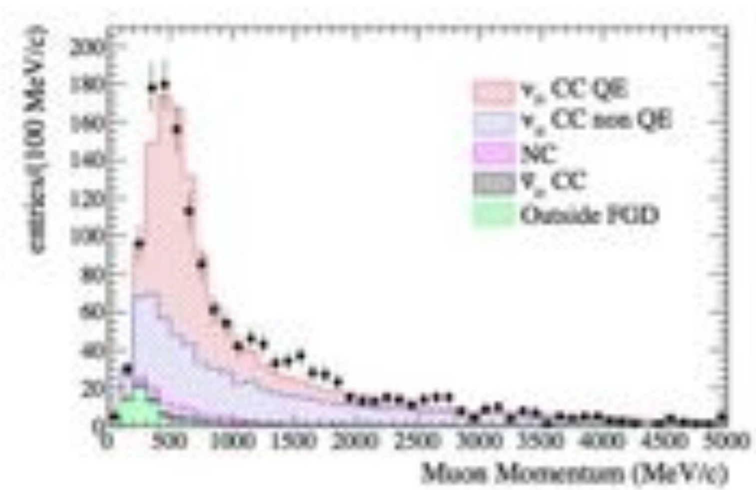
- Compare with N^{SK}_{obs} to evaluate oscillation parameters.

1.- Predicted flux



Fluxes computed starting from models and tuning them to experimental data.

2.- ND280 Ratio



Data sample from RunI

NEUT MC
(GENIE for xcheck)

Neutrino interaction in the FGDs entering following TPC (and not in first TPC)

90% purity & 38% efficiency

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

(Rs = POT normalized rates of νμ CC interactions)

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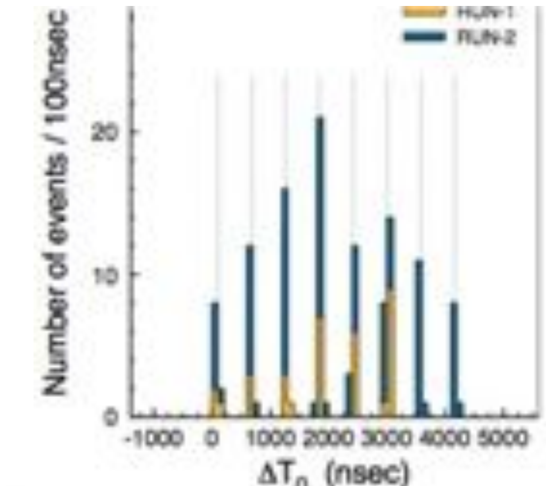
2010 ν_e Appearance Analysis

3.- T2K Event Selection

1


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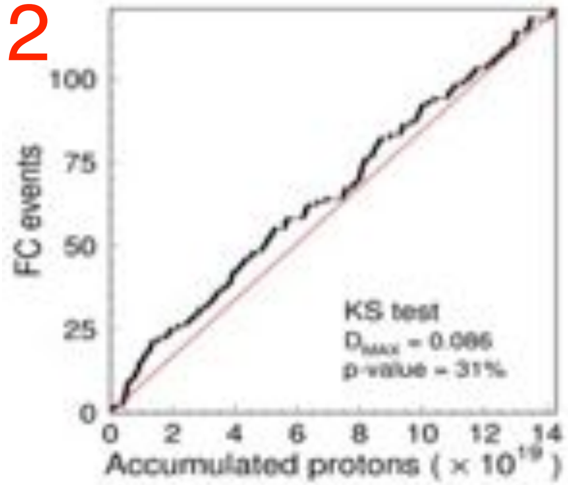
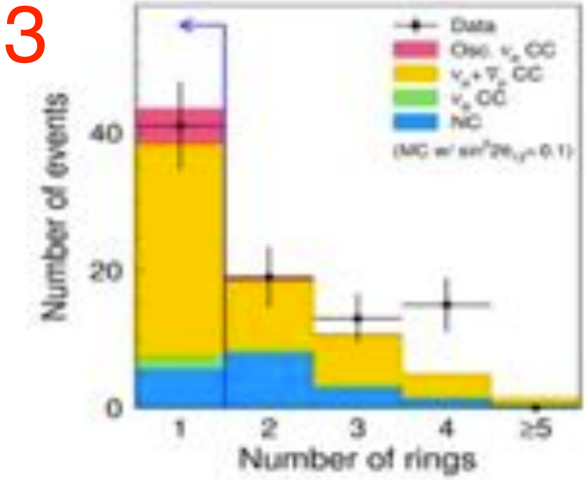


3


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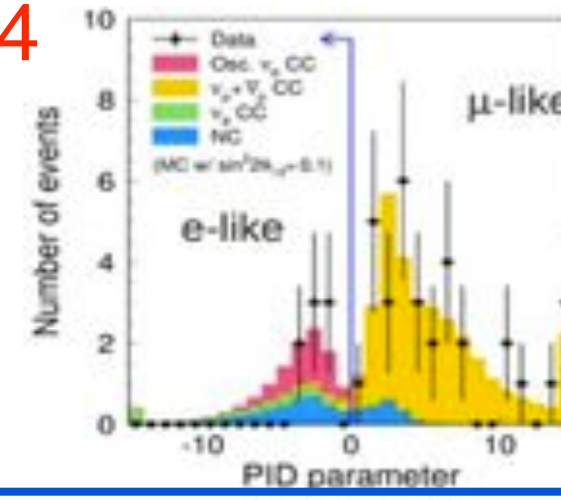

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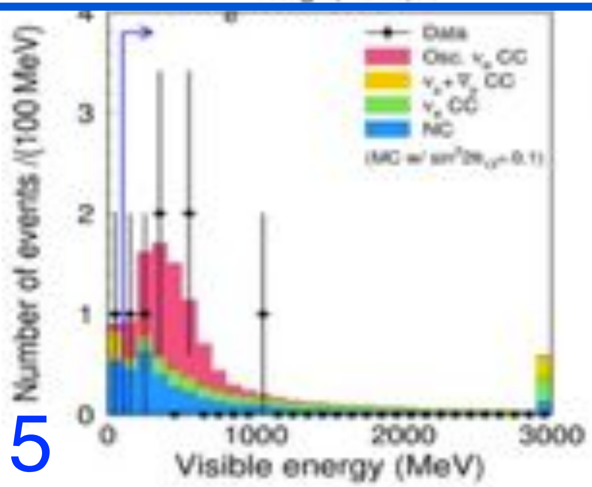
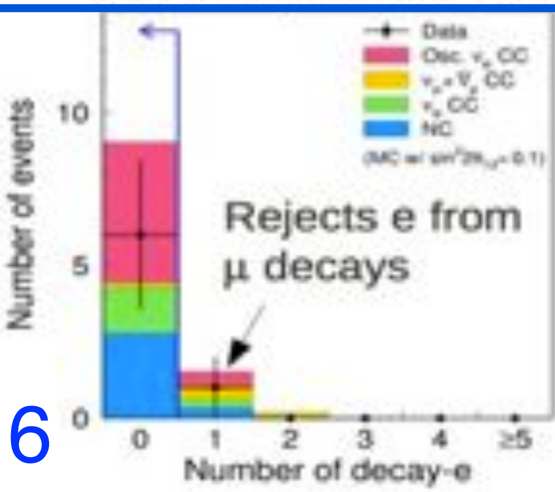
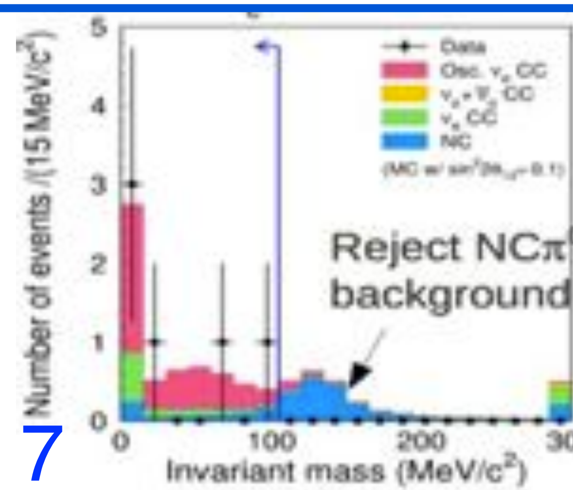
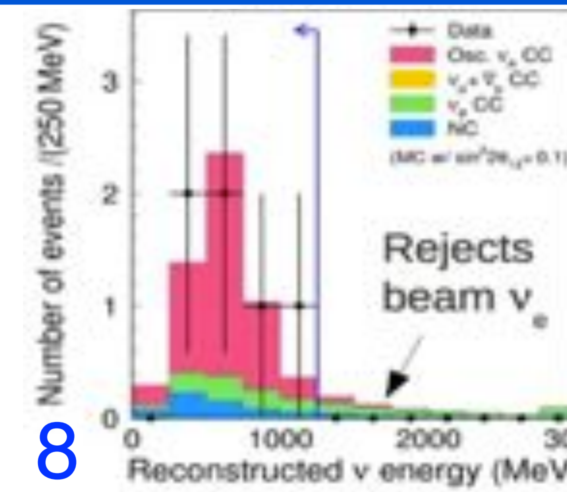


6


7


8


Cut	# evts selected
1 - FC events	121
2 - FCFV events	88
3 - One ring events	41
4 - Electron-like ring events	8

specific for νe event reduction

Cut	# evts selected
5 - Visible E > 100 MeV	7
6 - No decay electrons (delayed)	6
7 - Invariant Mass < 105 MeV (with forced second ring)	6
8 - Rec. ν E < 1250 MeV	6

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2010 ν_e Appearance Analysis

4.- Expected

$$N_{exp}^{SK} = (R_{\mu}^{ND,data} / R_{\mu}^{ND,MC}) \, x \, N_{MC}^{SK}$$

Event rates computed incorporating 3-flavor oscillation probabilities and matter effects with:

$$\Delta m_{12}^2 = 7.6\text{x}10^{-5} eV^2 \qquad \sin^2 2\theta_{12} = 0.8704$$

$$\Delta m_{23}^2 = 2.4\text{x}10^{-3} eV^2 \qquad \sin^2 2\theta_{23} = 1.0$$

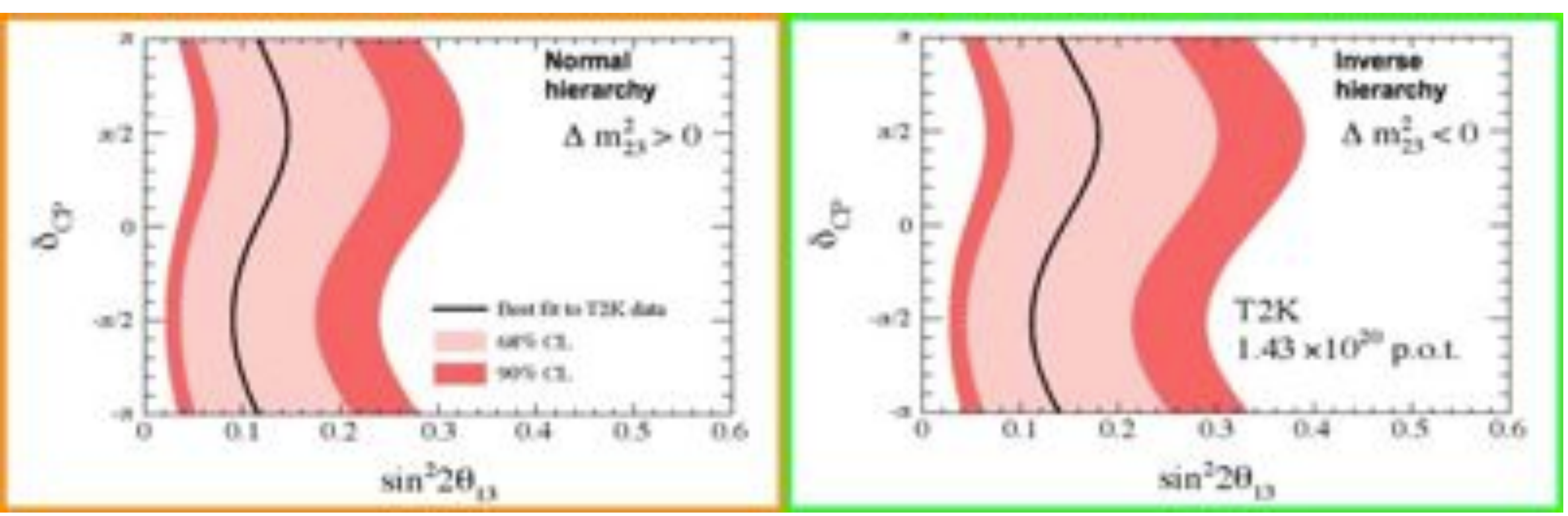
$\boxed{\sin^2 2\theta_{13} = 0}$

Source	Nexp
Beam νe	0.8
νμ NC	0.6
νμ CC (νμ→νe)	0.1
Total	1.5+-0.3

5.- RESULTS!

Observation exceeds the expectation:

Probability to observe 6 events with $\sin^2 2\theta_{13} = 0$ is 0.7% (2.5 σ significance)



Feldman-Cousins unified method:

Normal hierarchy, δ=0

$0.03 < \sin^2 2\theta_{13} < 0.28$ at 90% C.L

Best fit: $\sin^2 2\theta_{13} = 0.11$

$0.04 < \sin^2 2\theta_{13} < 0.34$ at 90% C.L

Best fit: $\sin^2 2\theta_{13} = 0.14$

Inverse hierarchy, δ=0

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2010 ν_e Appearance Analysis

T2K

Uncertainties

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)

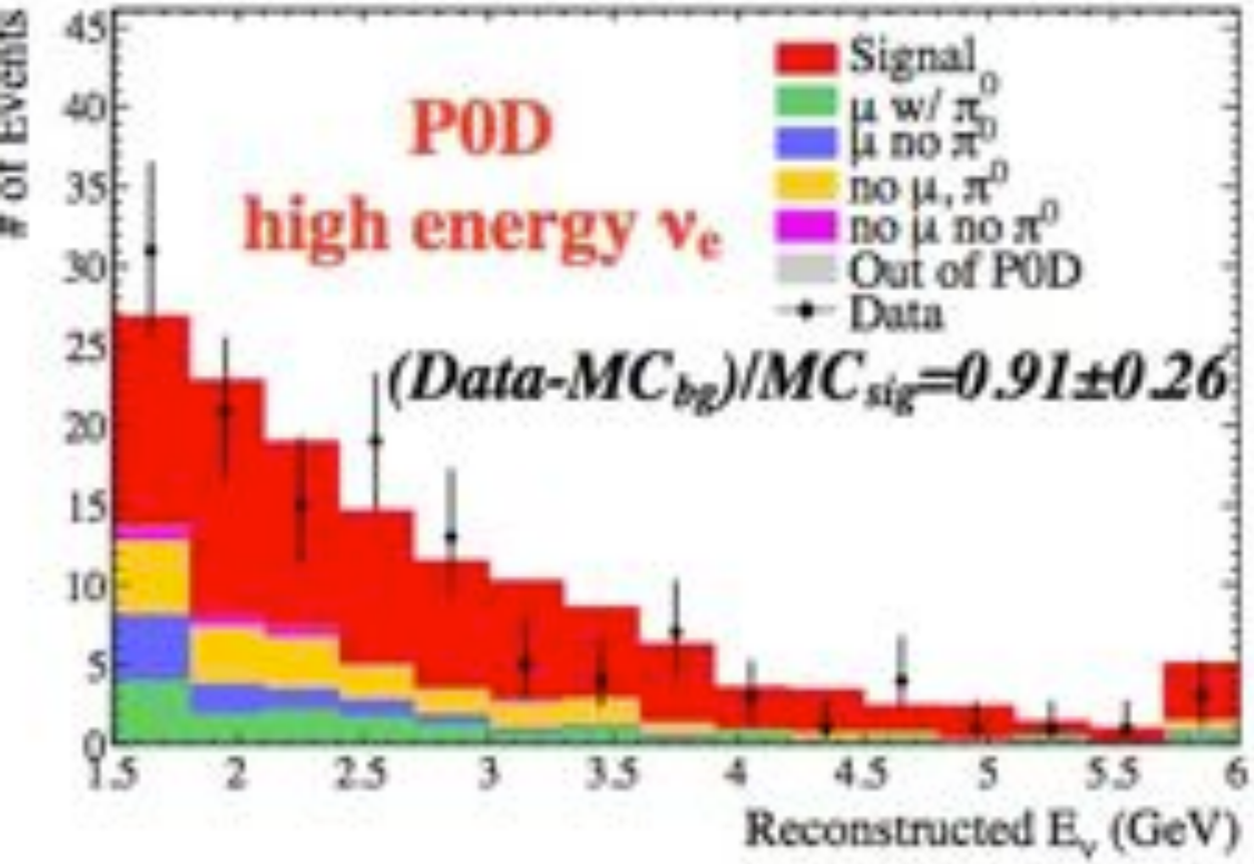
Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$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

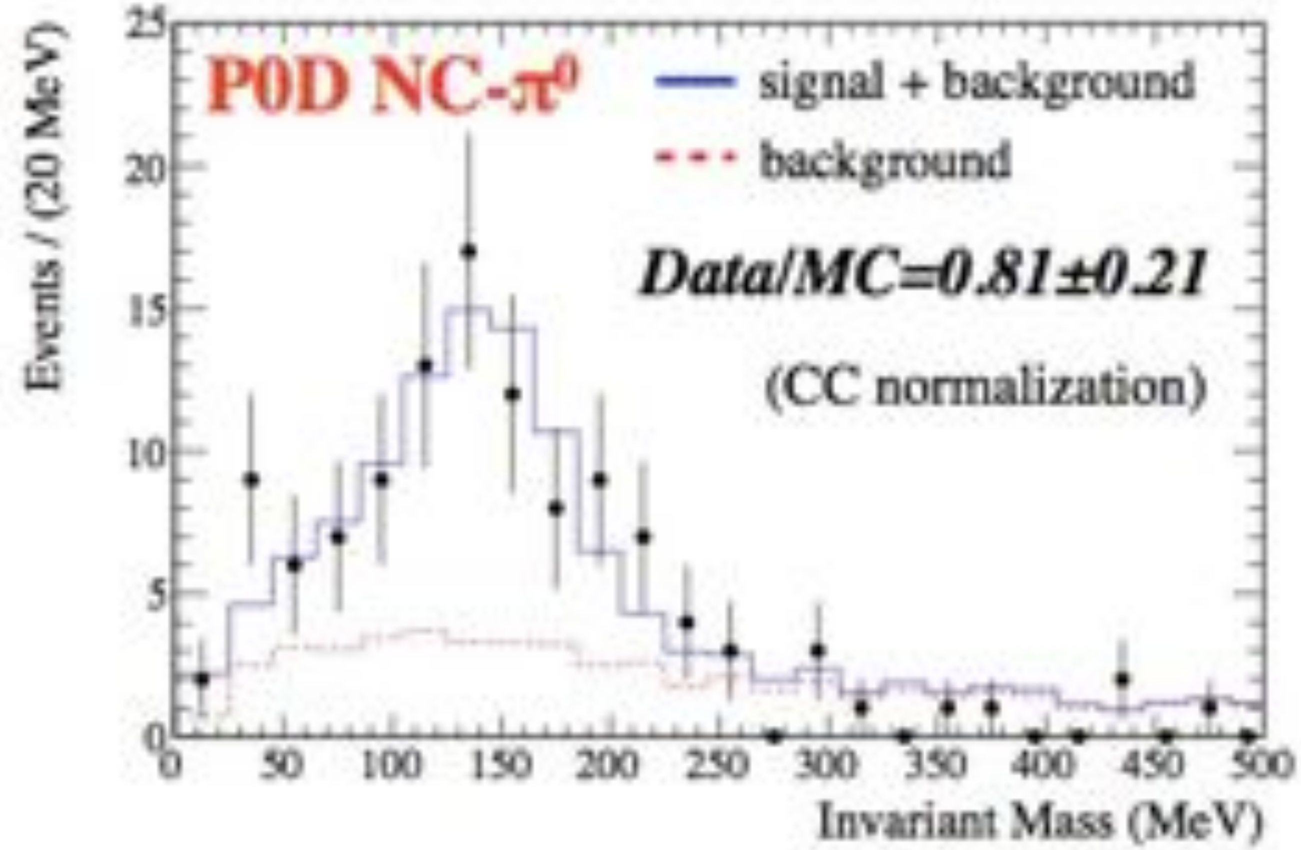
Event Reduction

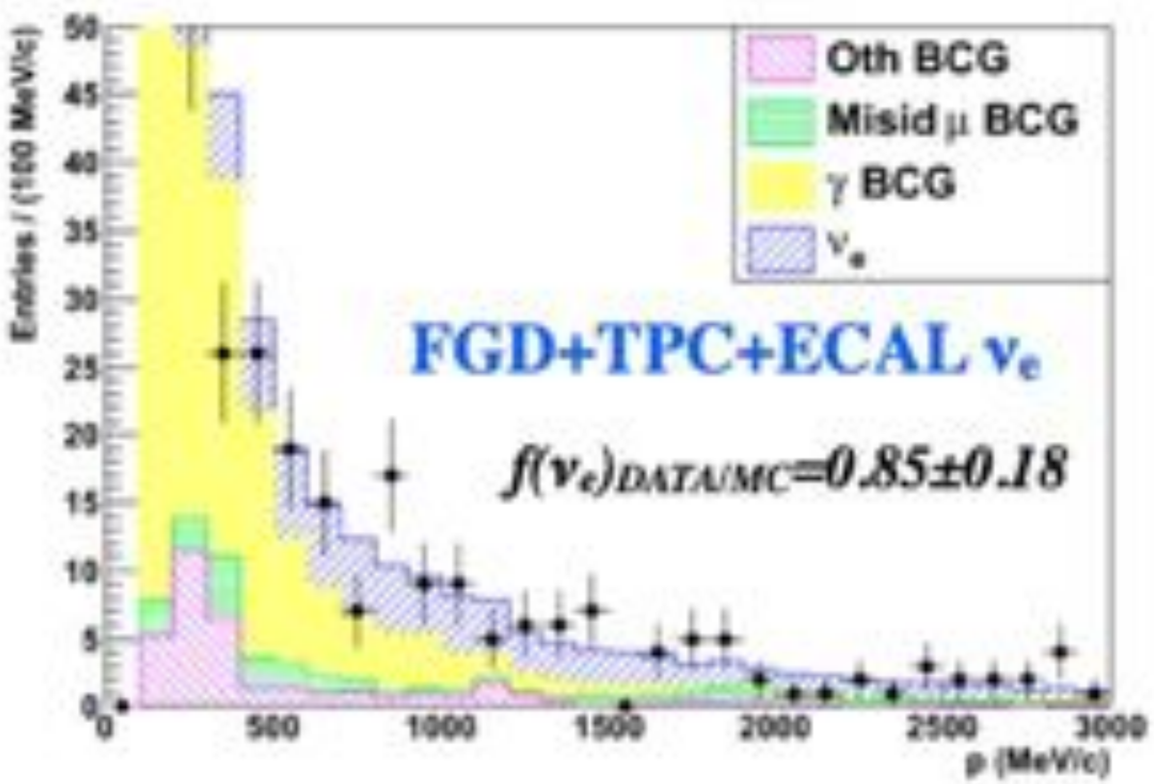
	Data	ν_μCC	ν_eCC	NC	$\nu_\mu \to \nu_e$CC
(0) interaction in FV	n/a	67.2	3.1	71.0	6.2
(1) fully-contained FV	88	52.4	2.9	18.3	6.0
(2) single ring	41	30.8	1.8	5.7	5.2
(3) e-like	8	1.0	1.8	3.7	5.2
(4) $E_{vis} > 100$ MeV	7	0.7	1.8	3.2	5.1
(5) no delayed electron	6	0.1	1.5	2.8	4.6
(6) non-π^0-like	6	0.04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

Error source @ SK	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot}}{N^{MC}_{SK\ bkg.\ tot}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

ND280 Measurements



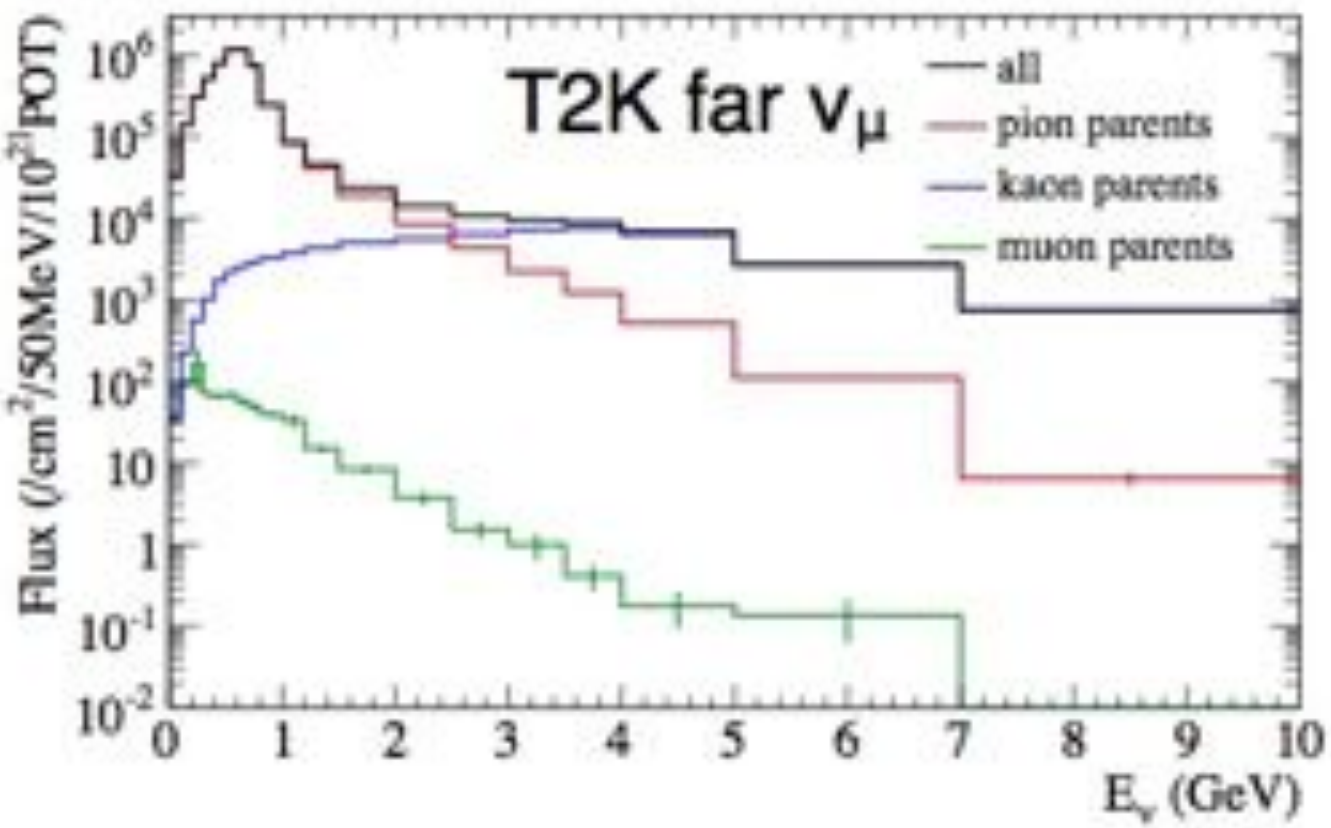




Background events for ν_e appearance are measured at the near detector ND280:

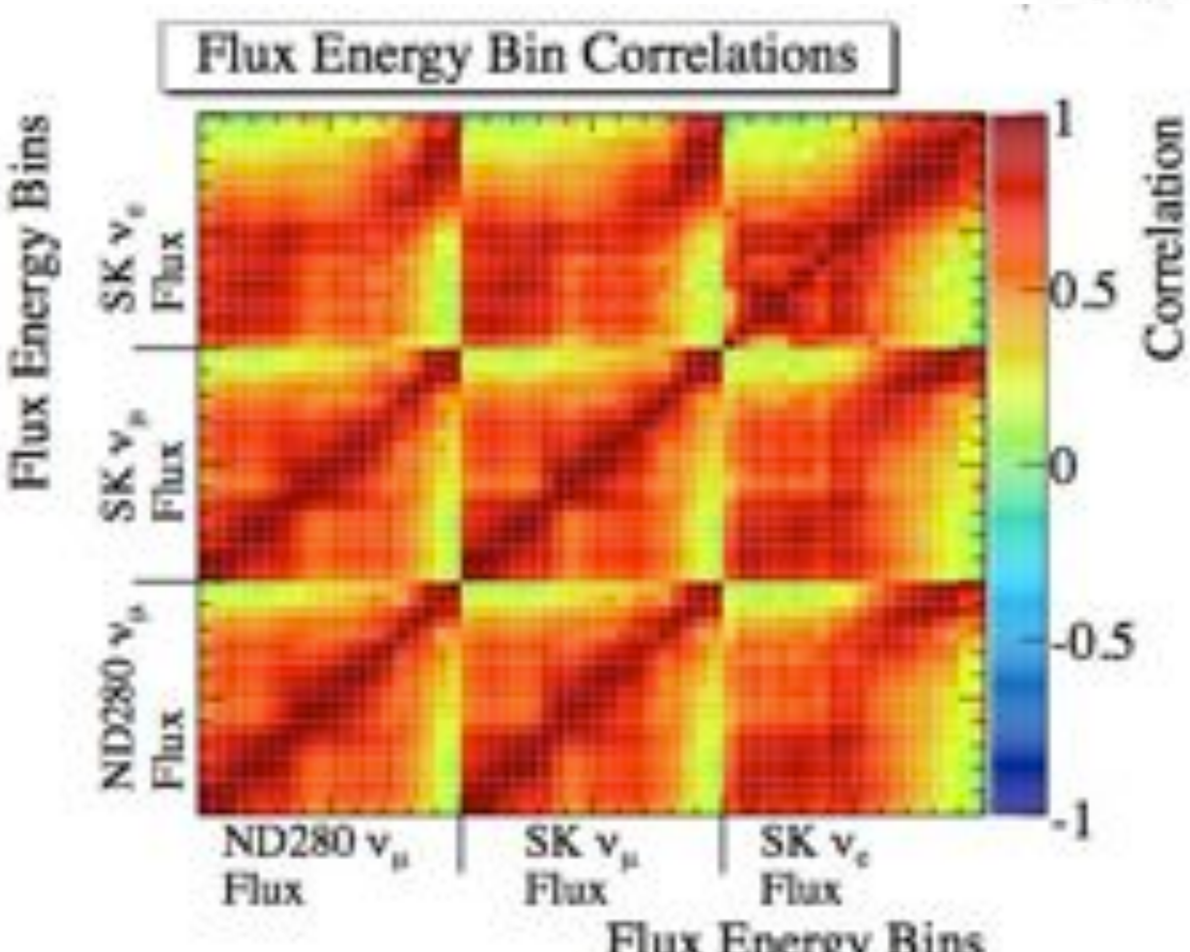
ν_e CC events
NCπ^0 events

2012 Beam Flux Prediction



Beam flux is predicted based on:

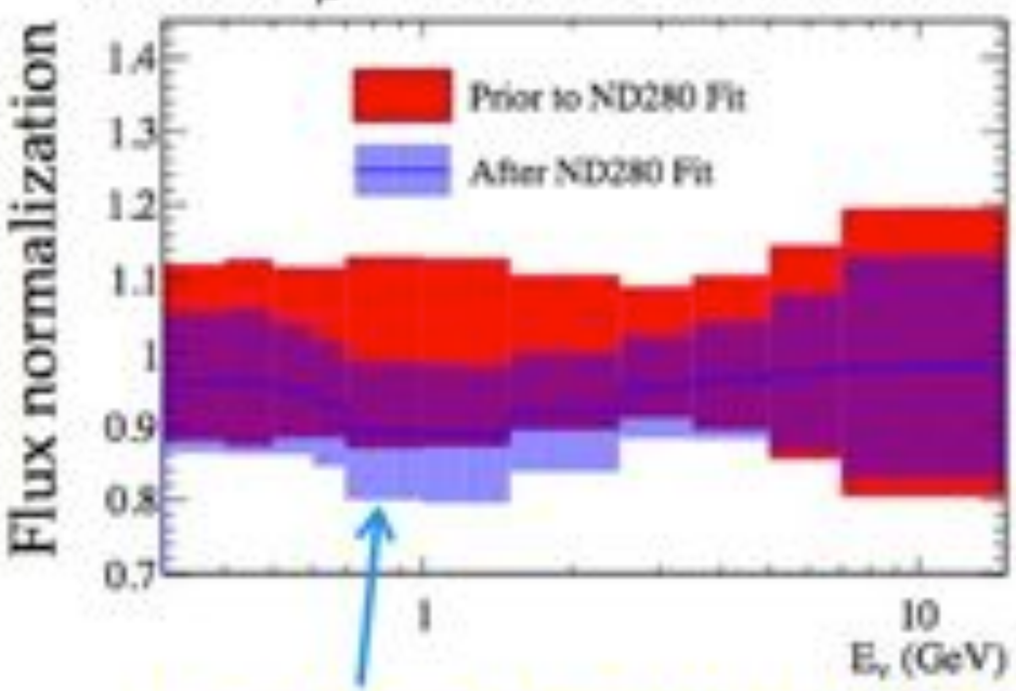
- NA61 π,K measurements
- T2K proton beam measurements

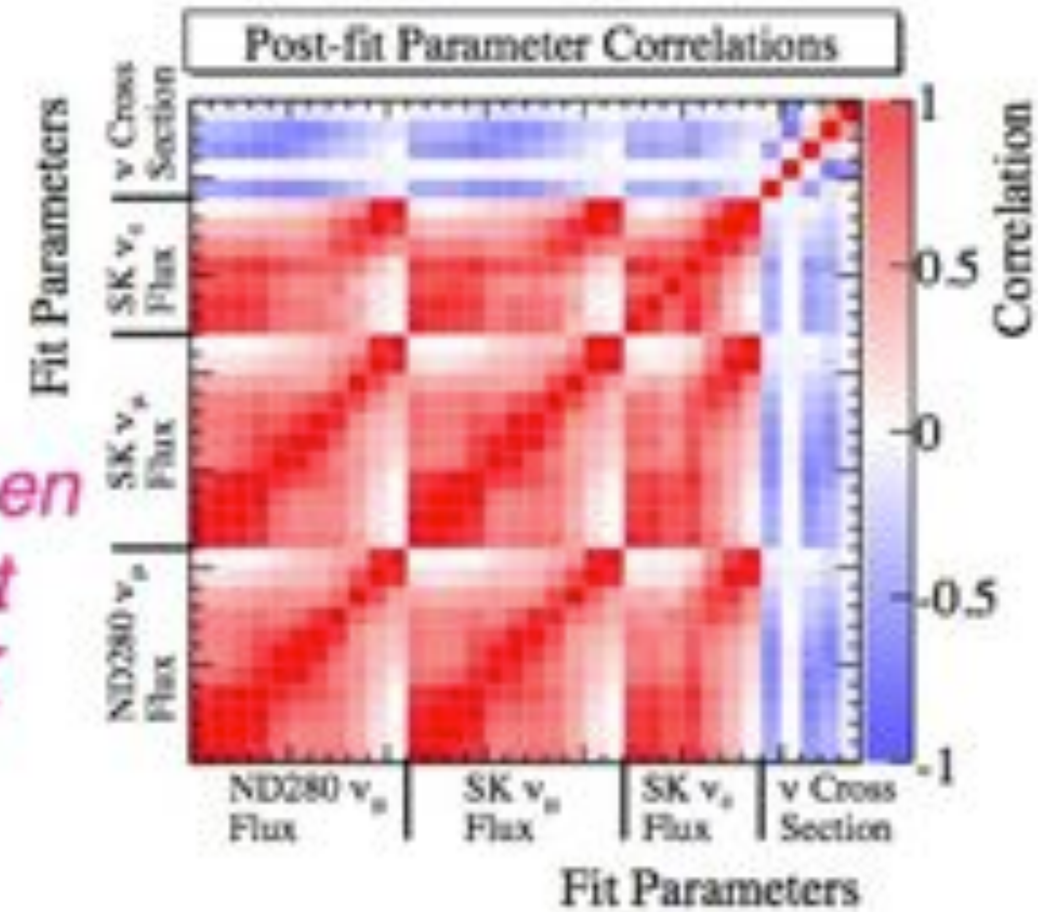


Matrix built with the correlation between energy bins for different neutrino types, detectors.

2012 Flux + Cross Section Fit

ND280 ν_μ Flux normalization & uncertainties

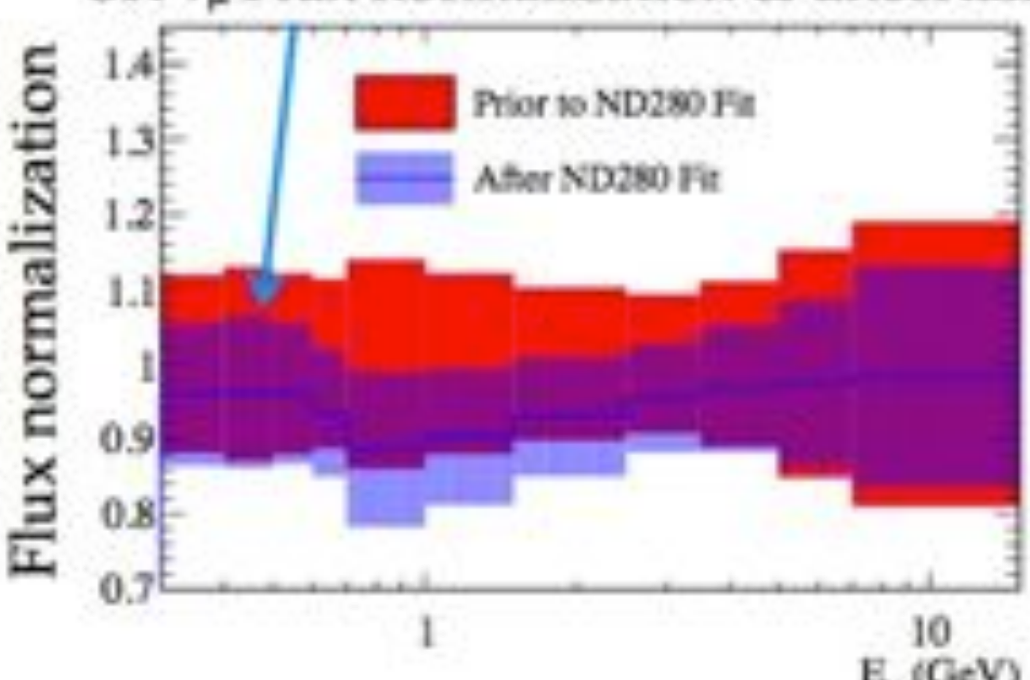




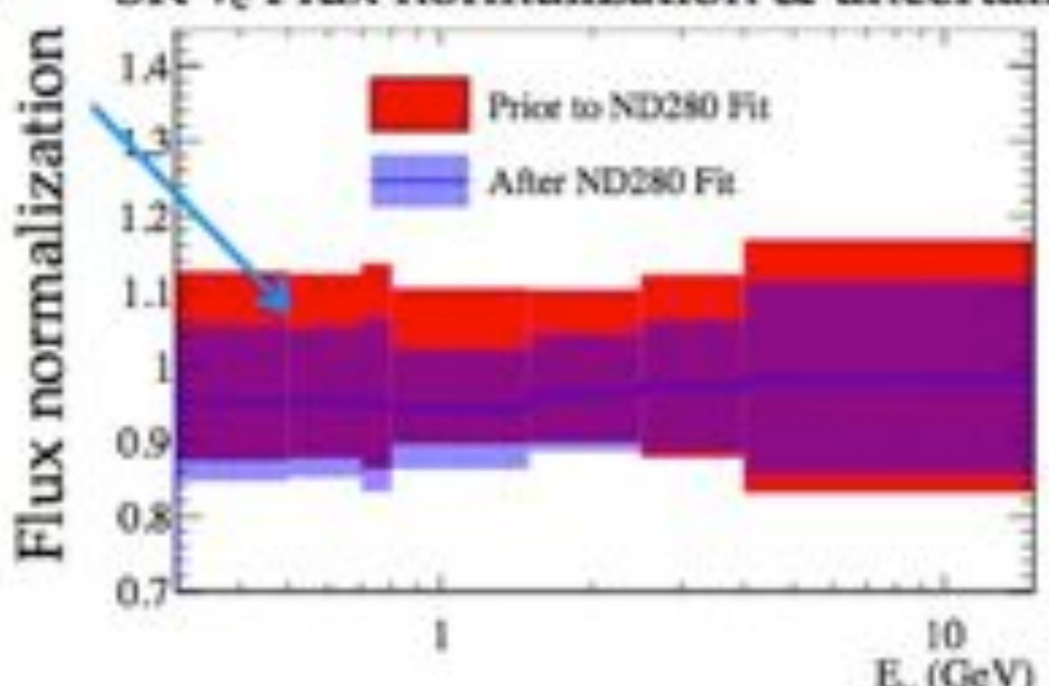
correlation between flux and xsec at ND280 and SK

uncertainties were reduced

SK ν_μ Flux normalization & uncertainties



SK ν_e Flux normalization & uncertainties



2012 Cross Section Uncertainties

T2K

Parameters in the cross section's models are fitted to ND280 measurements

model parameters	Before FIT	After FIT (w/ ND280 measurement)
CCQE M_A [GeV]	1.21±0.45	1.19±0.19
CC1π(resonance) M_A [GeV]	1.16±0.11	1.14±0.10
Fermi momentum surface P_F [MeV]	217±30	224.6±23.5
Spectral Function	0[off] - 1[on]	0.04±0.21
CC-other cross section shape	0.0±0.4	-0.05±0.35
CCQE E-dependence	1.0±0.11, 1.0±0.11, 1.0±0.11	0.94±0.09, 0.92±0.23, 1.18±0.25
CC1π(resonance) E-dep.	1.63±0.43, 1.0±0.4	1.67±0.28, 1.10±0.30
NC-π^0 cross sections	1.19±0.43	1.22±0.40
CC-coherent π cross section	1–1	same (no additional ND280 constrained)
NC-coherent π cross section	1.0±0.3	same (no additional ND280 constrained)
NC other cross section	1.0±0.3	same (no additional ND280 constrained)
W shape in resonance model [MeV]	87.7±45.3	same (no additional ND280 constrained)
π-less Δ decay	0.0±0.2	same (no additional ND280 constrained)
CC-1π,NC-1π^0 energy shape	0.0±0.5	same (no additional ND280 constrained)
$\sigma_{\nu e}$ / $\sigma_{\nu\mu}$	1.0±0.03	same (no additional ND280 constrained)

Parameter correlated between ND280 and SK

2012 Systematic Errors

T2K

Contribution from systematic errors to the predicted number of events (appearance analysis)

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND measurement	$\sin^2 2\theta_{13} = 0$ w/ ND measurement	$\sin^2 2\theta_{13} = 0.1$ w/o ND measurement	$\sin^2 2\theta_{13} = 0.1$ w/ ND measurement
Beam only	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3

Numbers are percentiles (%)

2012 ν_e Appearance Analysis

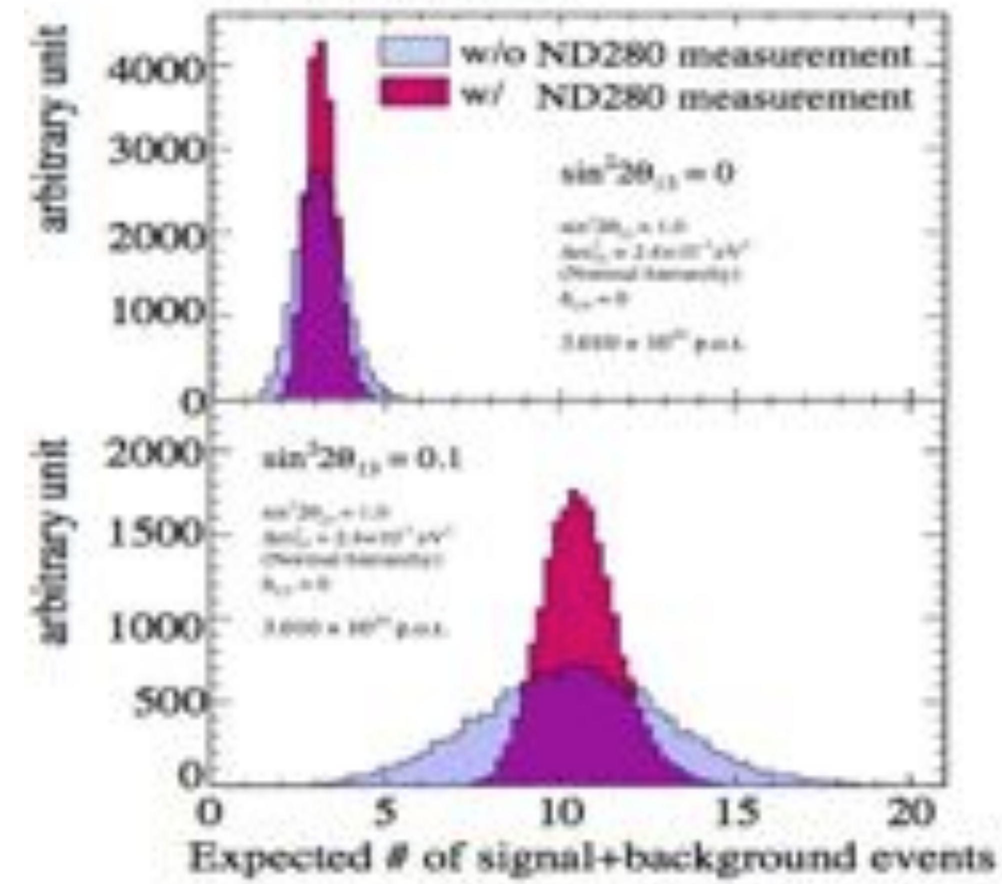
The predicted # of events w/ 3.01 x 10^{20} p.o.t.

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

the predicted # of event distribution



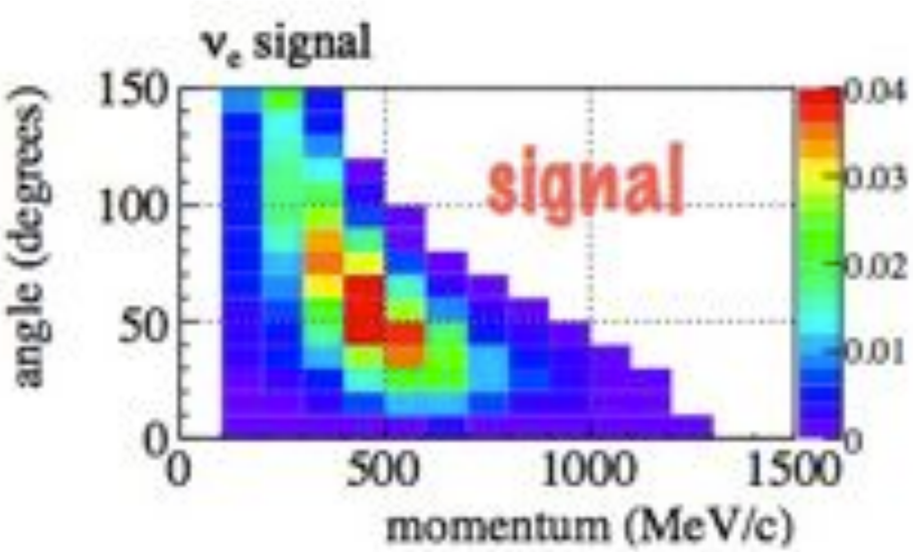
RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}$=0.1				
		Signal $\nu_\mu \to \nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e-like	22	10.27	15.60	2.72	4.79	8.10
E_{vis}>100MeV	21	10.04	13.53	1.76	4.75	7.01
No decay-e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}$=0 case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9

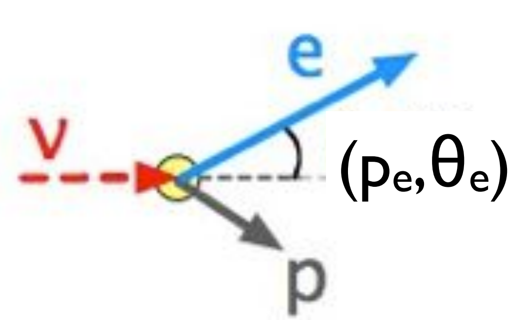
2012 ν_e Appearance Analysis: FIT

Three independent analyses done,
with consistent results.

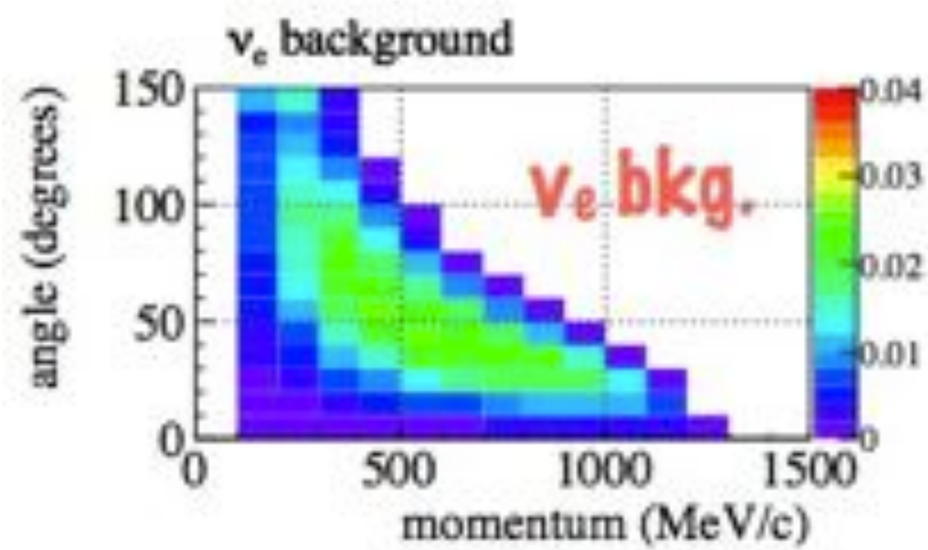
One method is based in **(p-θ) distribution:**

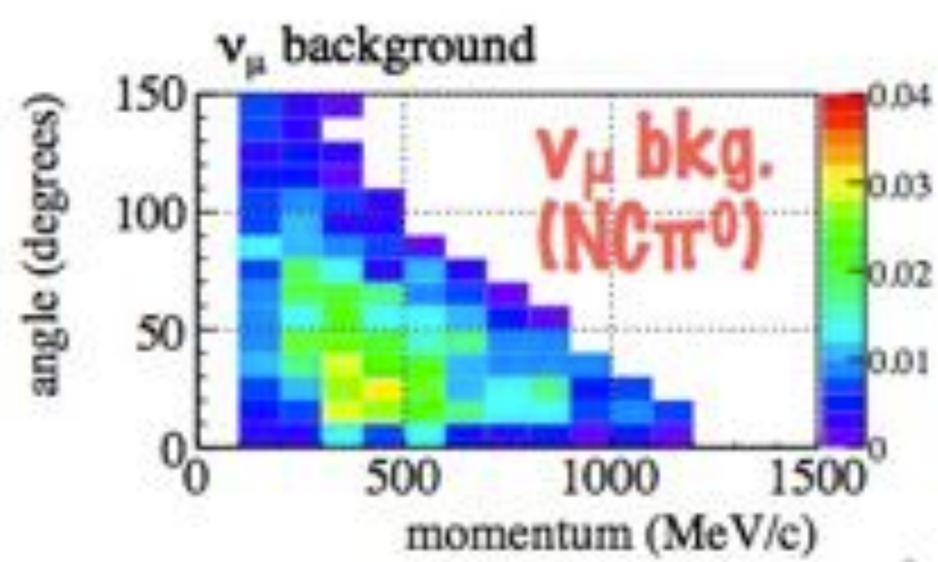
- Extended maximum likelihood fit
- Data fitted with rate + (p_e,θ_e) shape
- Differences in the 2D distribution improve the discrimination of signal events from background





BACKGROUNDS





+ anti-ν_e, anti-ν_μ bkg.

The Earthquake

• Big **earthquake and tsunami** occurred near the pacific coast of Japan on 11/3/2011.

• Combined with the Fukushima plant destruction and pollution, it is a *grave national disaster* for Japan.

• J-PARC was not affected directly by the tsunami (although on the coast)
• Structural damage to infrastructure quickly repaired over summer.
• More detailed tests and controls (e.g. alignment) underway