Recent results from T2K

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IFAE

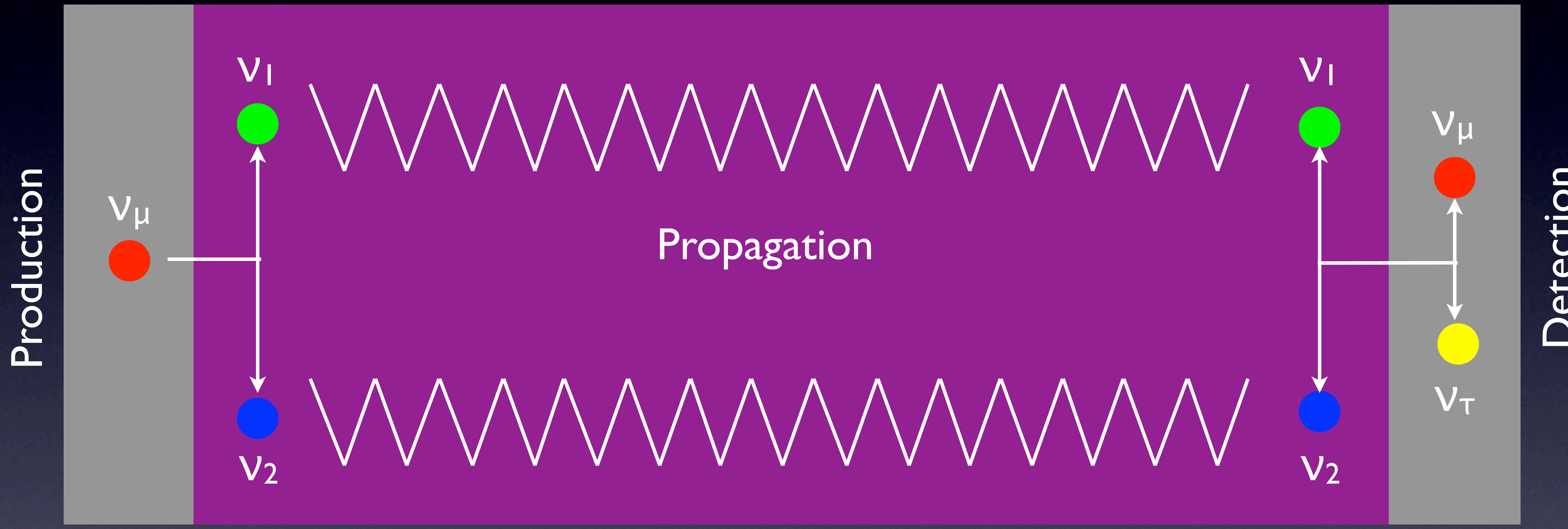
on behalf of the T2K Collaboration

Outline

- Neutrino oscillation and mixing
- How to measure the last mixing angle θ_{13}
- T2K experiment
- First T2K oscillation results
  - ν_μ disappearance
  - ν_e appearance
- Physics perspectives

Neutrino oscillation

- Neutrinos are always produced and detected in flavor eigenstate while they propagate as mass eigenstates
- Mass eigenstates are different than flavor eigenstates



- If ν_1 and ν_2 have different mass they will propagate at different speeds → interference that will change the proportion of ν_1 and ν_2 at the detection
- New flavor eigenstates might appear when neutrinos are detected
- Neutrino oscillations are, up to now, the only known phenomenon beyond the standard model

Where we were (up to ~May 2011)

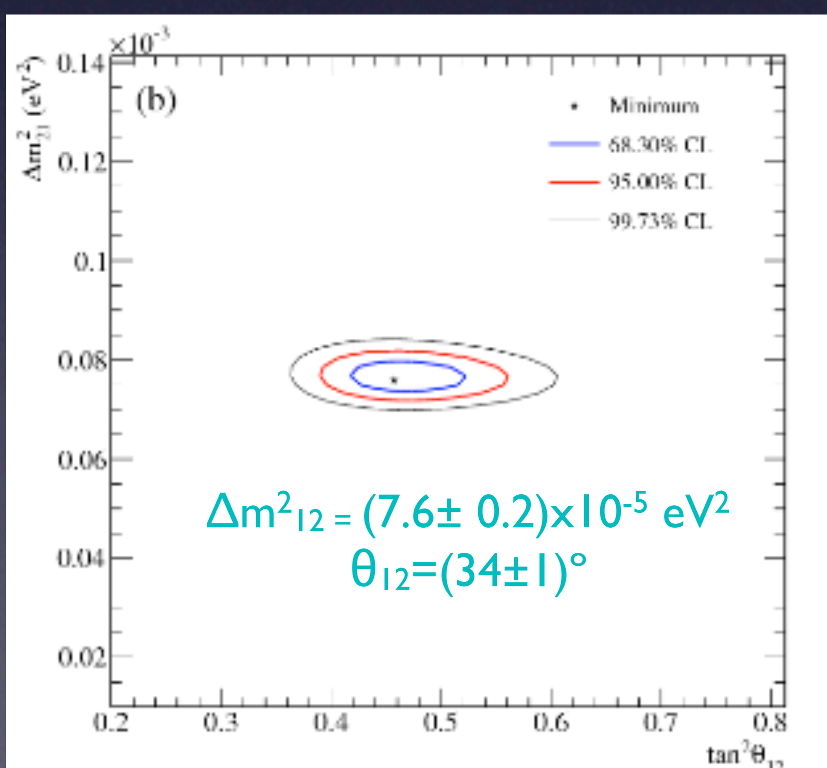
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}cos\theta_{12} & sin\theta_{12} & 0\\ -sin\theta_{12} & cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & cos\theta_{23} & sin\theta_{23}\\ 0 & -sin\theta_{23} & cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor eigenstates

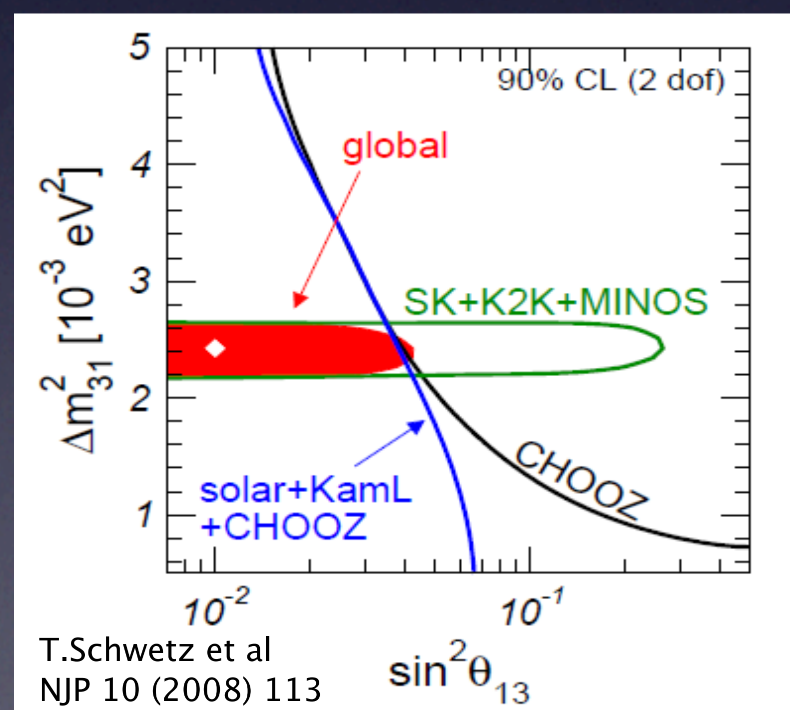
Mass eigenstates

- 3 angles (θ_{12}, θ_{23}, θ_{13})
- 1 CP violation phase δ → only if all 3 mixing angles ≠ 0
- 2 independent mass differences ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)

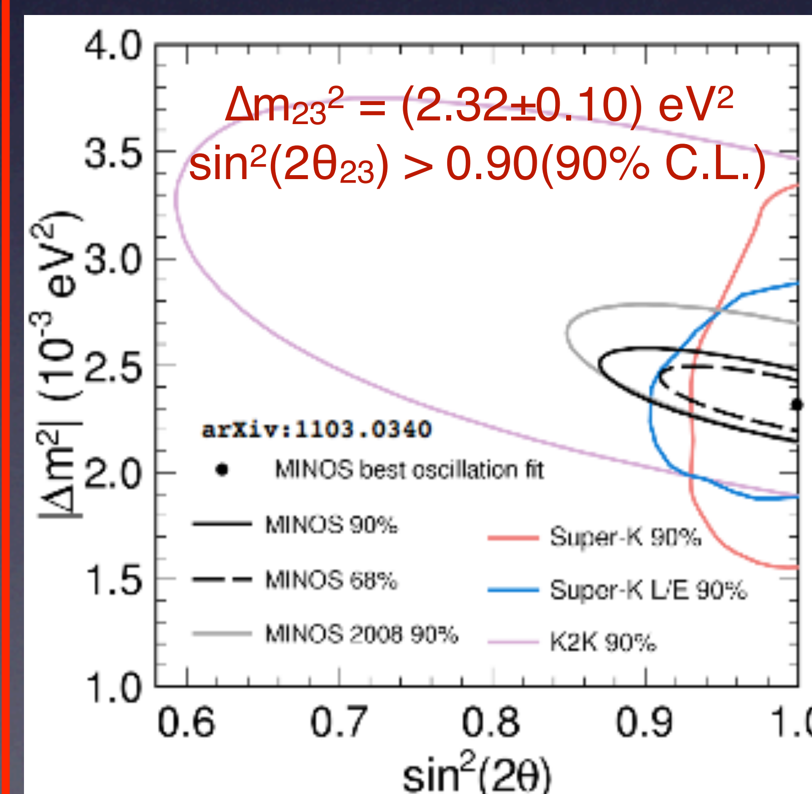
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Upper limit → $\sin^2(2\theta_{13})<0.13$
δ completely unknown



Atmospheric (K2K, SK, Minos)
→ θ_{23}, Δm_{23}



Two different approaches to θ_{13}

Reactors (DChooz, RENO, Daya Bay)

- Disappearance of anti-νe $P(\bar{\nu}_e \to \bar{\nu}_e)$
- anti-ν_e produced in nuclear reactors
  - Neutrino energy few MeV
  - Distance L ~ 1 km
- Experimental signature: disappearance of the ν_e produced in the reactor core
- Only sensible to θ_{13}

Accelerators (T2K, Minos→Nova):

- Appearance experiment: $P(\nu_\mu \to \nu_e)$
- ν_μ neutrino beam
  - Neutrino energy ~1 GeV
  - Distance L >~ 300 km
- Experimental signature: appearance of ν_e in the ν_μ beam
- Degeneracy of θ_{13} with δ, sign of δm^2

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu} \qquad \Delta_{21}/\Delta_{31} \sim 1/30$$

Clean dependence on θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - sin^2 2\theta_{13} sin^2\Delta_{13} - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{12}$$

Atmospheric baseline

$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{13} sin^2\theta_{23} \times sin^2\Delta_{13} + sin^2 2\theta_{12} cos^2\theta_{23} cos^2\theta_{13} \times sin^2\Delta_{21} + sin 2\theta_{13} cos\theta_{13} sin 2\theta_{23} sin 2\theta_{12} \times sin\Delta_{31} sin\Delta_{32} cos(\Delta_{32} + \delta)$$

Solar baseline

Interference → δ

Two different approaches to θ_{13}

Reactors (DChooz, RENO, Daya Bay)

- Sub-leading oscillation $P(\nu_\mu \rightarrow \nu_e)$
- anti-ν_e produced in nuclear react
  - Neutrino energy few M
  - Distance L ~ 1 l
- Exp
the ν_e p
- Only

Acceler →Nova):

ν_e)

signature: appearance of ν_e in
beam
- Degeneracy of θ_{13} with δ, sign of δm^2

Accelerator based experiments are needed to measure the sign of Δm_{13} and CP violation phase δ

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu} \qquad \Delta_{21}/\Delta_{31} \sim 1/30$$

dependence on θ_{13}

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2 2\theta_{13} sin^2\Delta_{13} - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{12}$$

Atmospheric baseline

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{13} sin^2\theta_{23} \times sin^2\Delta_{13} + sin^2 2\theta_{12} cos^2\theta_{23} cos^2\theta_{13} \times sin^2\Delta_{21} + sin2\theta_{13} cos\theta_{13} sin2\theta_{23} sin2\theta_{12} \times sin\Delta_{31} sin\Delta_{32} cos(\Delta_{32} + \delta)$$

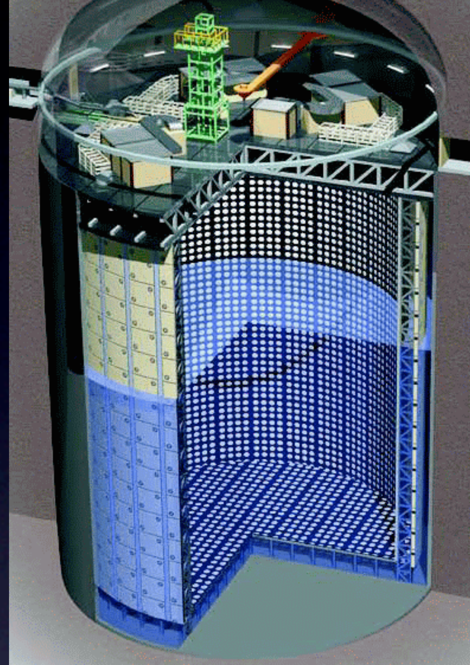
Solar baseline

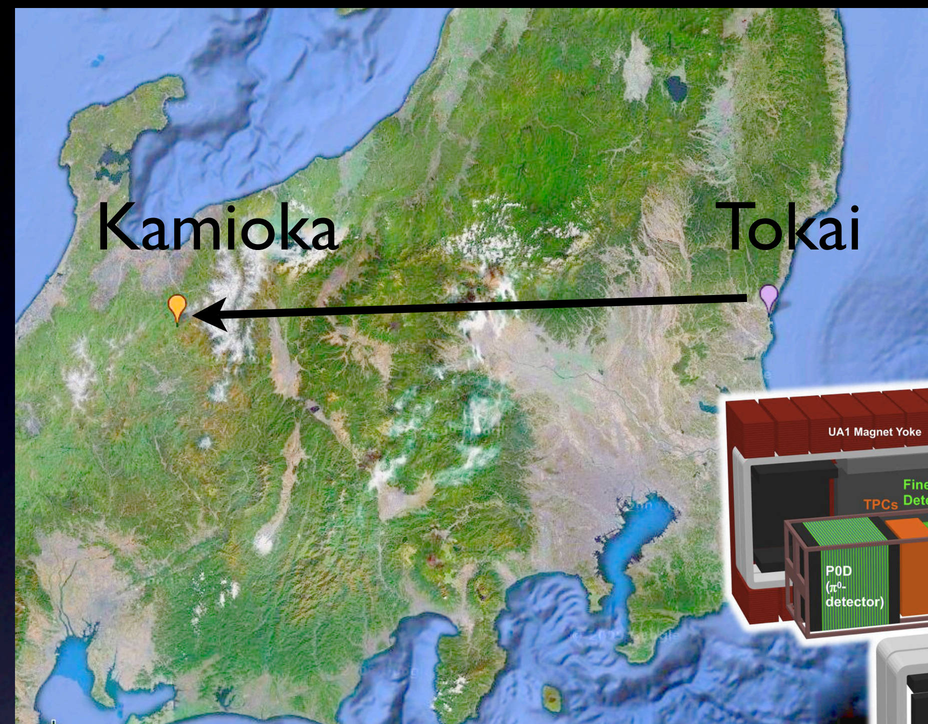
Interference → δ

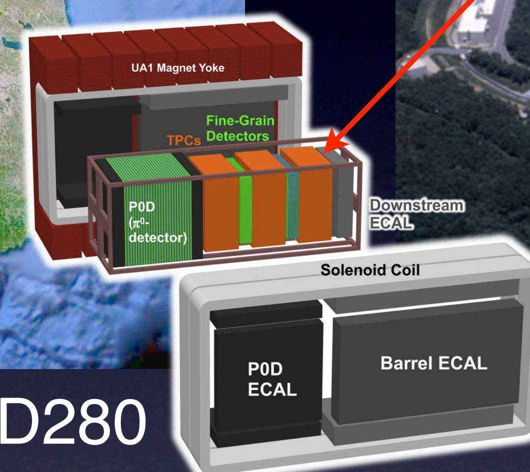
T2K experiment

T2K experiment

Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector







ND280

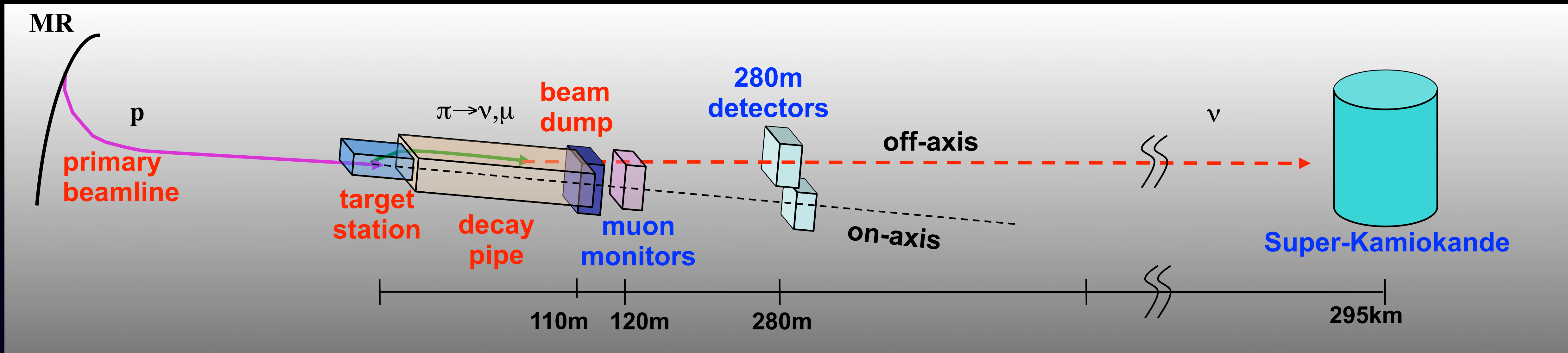
JPARC accelerator: Design power: 750 kW

- Long baseline neutrino oscillation experiment
- High intensity ν_μ beam produced at JPARC (Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) at 295 km
- Main physics goals:
  - Discovery of ν_e appearance → determine θ_{13} (sensitivity >10 times better Chooz limit)
  - Precise measurement of ν_μ disappearance → Goal: $\delta(\sin^2(2\theta_{23}))\sim0.01, \delta(\Delta m^2_{23})<1\times10^{-4}$ eV^2
- First results released with ~ 2% of the total expected T2K statistics (1.43×10^{20} p.o.t.)

T2K Collaboration

~500 members, 59 institutes, 12 countries

T2K experimental setup

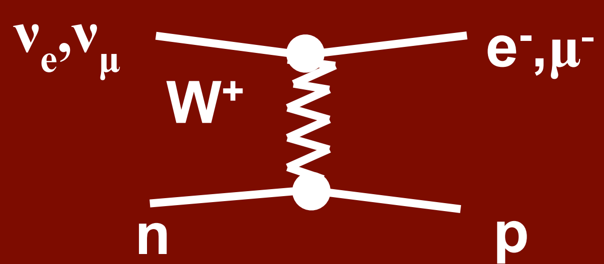


- Beamline:
  - 30 GeV proton beam from JPARC Main Ring extracted onto a graphite target
  - Pions focused and selected in charge by 3 electromagnetic horns
  - ν_μ produced by pions decay $\pi \rightarrow \mu + \nu_\mu$
  - Off-axis beam: center of the beam 2.5° off from SK direction
  - Stability and direction monitored in muon monitor (MUMON) and in INGRID (on-axis ND280)
- Detectors:
  - Off-axis Near Detector (ND280): measure ν interaction rates and flavors before the oscillation
  - Off-axis Far Detector (SK): measure ν interaction rates and flavors after the oscillation

Reference: The T2K experiment, NIM A, doi: 10.1016/j.nima.2011.06.067, arxiv 1106.1238

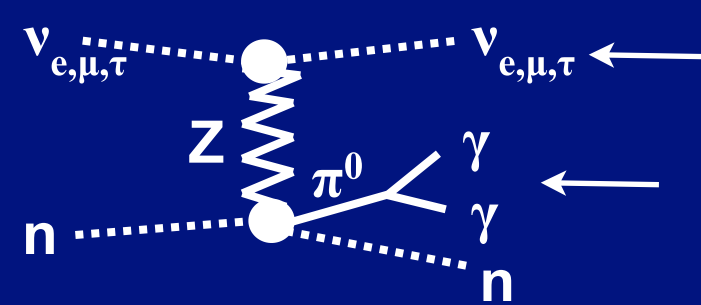
Signals and backgrounds

Signal at SK: CCQE interactions producing μ from ν_μ or e from ν_e



CCQE residual cross-section uncertainty (assuming complete far-to-near cancellation) ~7% @ 500 MeV

Backgrounds at SK:
NC1π+ interactions for ν_μ
NC1π^0 interactions for ν_e

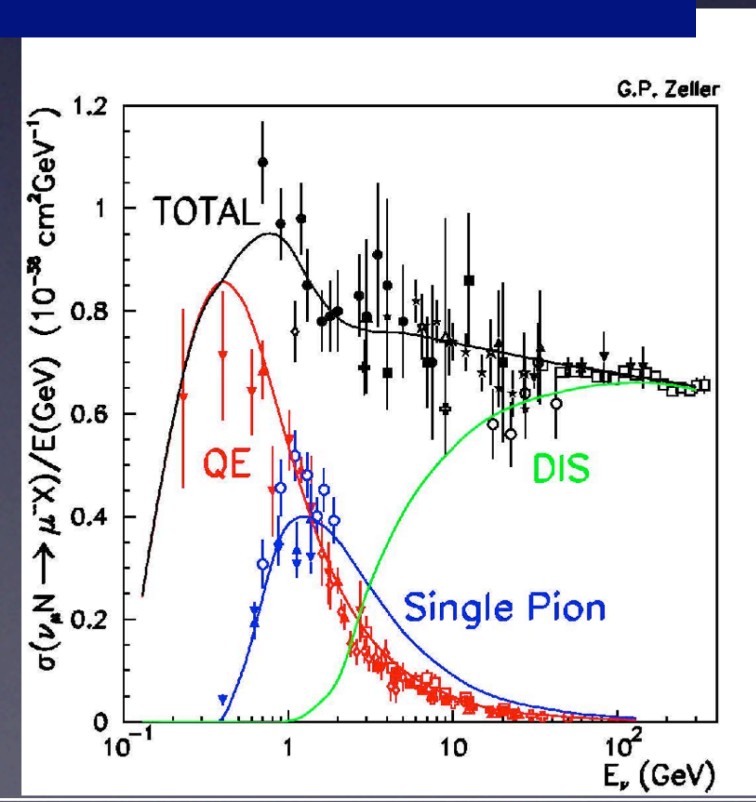


not detected

γ looks e-like at SK

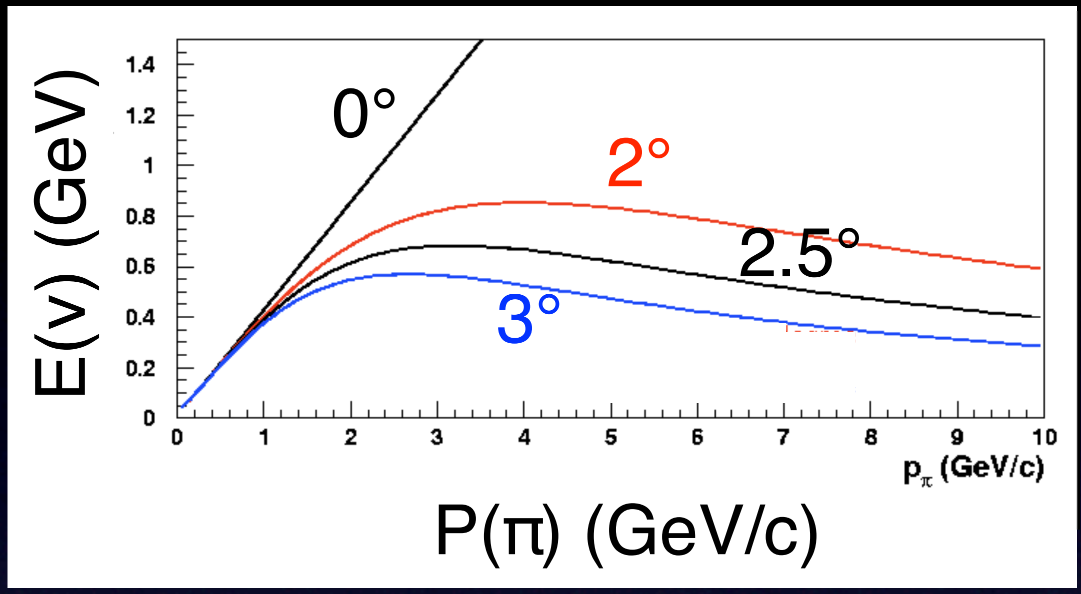
Estimated ~30% error on these processes with respect to CCQE cross-section

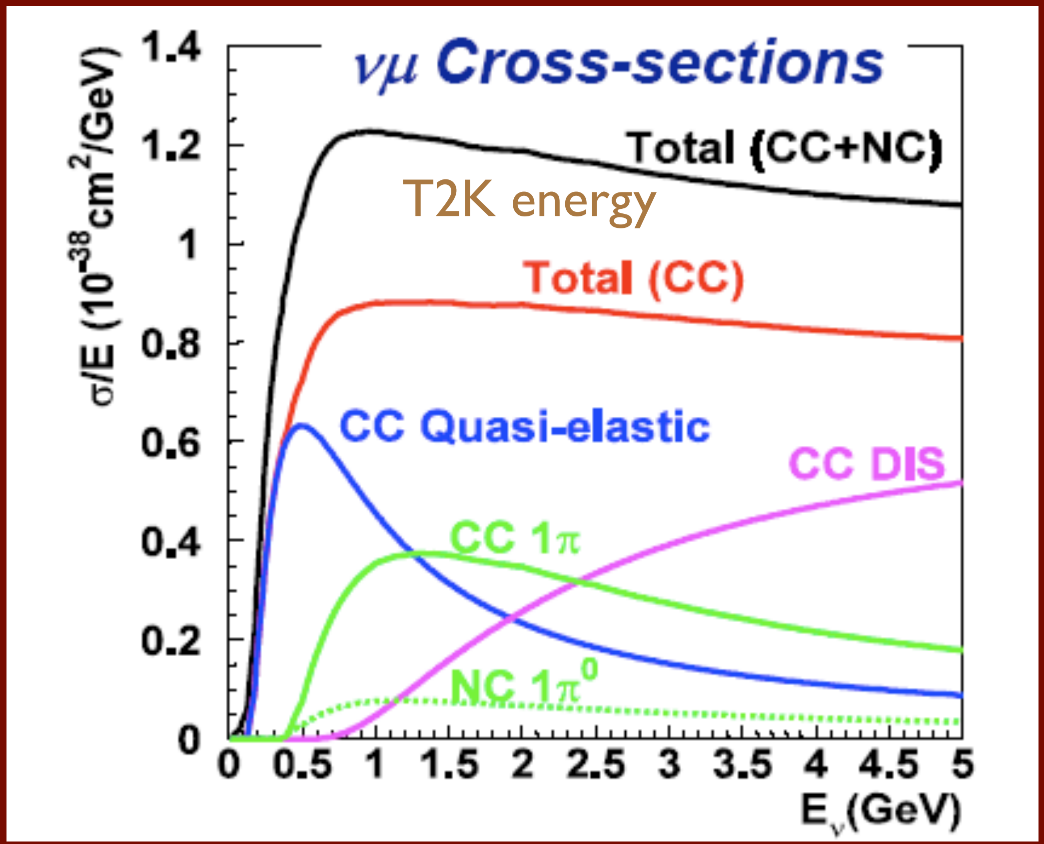
- Few measurements (MiniBooNE, SciBooNE, K2K) and large uncertainties for neutrino interactions in the 1 GeV region
    - Contribution to the systematics in T2K oscillation analysis
- One important goal of ND280 is to measure neutrino cross-sections



Off-axis narrow band beam

- T2K is the first long baseline experiment using off-axis technique
- Reduced dependence of E_ν from E_π
  - Intense beam where the oscillation effect is maximum (~0.6 GeV)
  - Enhance the CCQE sample, reducing the high energy tails of the beam → reduce the backgrounds to oscillation signal

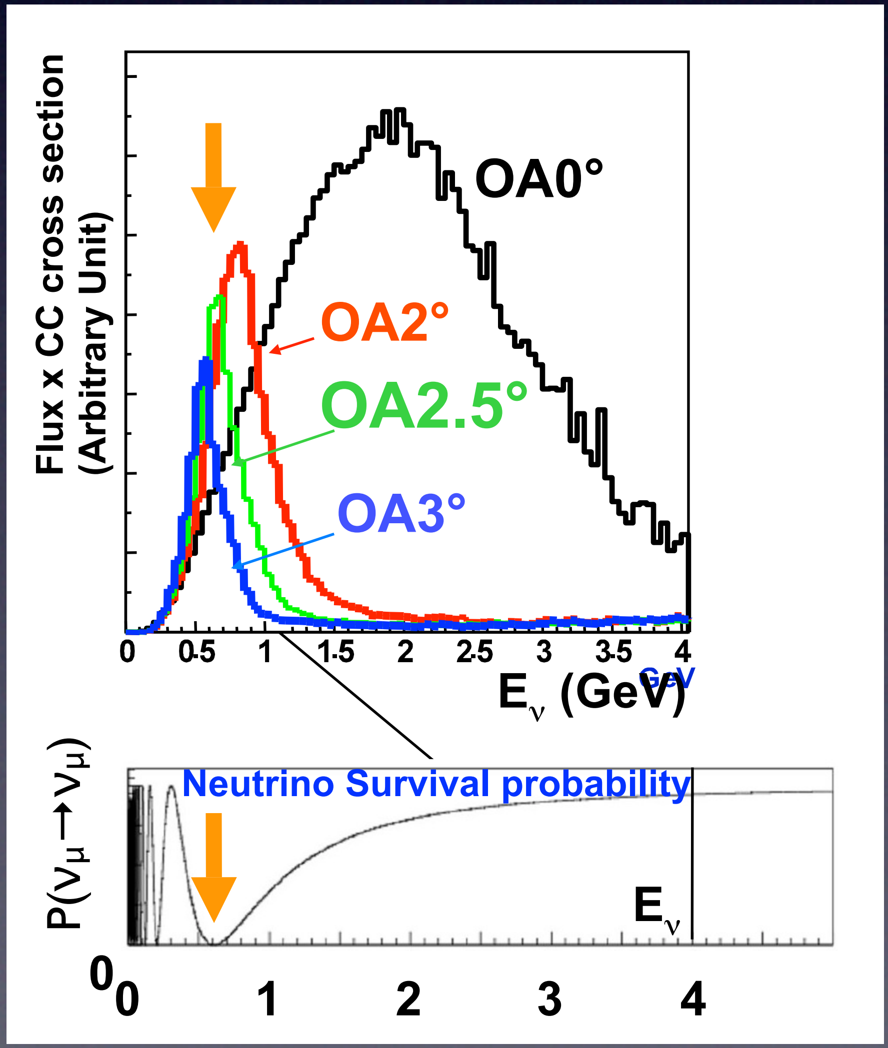




Signal: CCQE

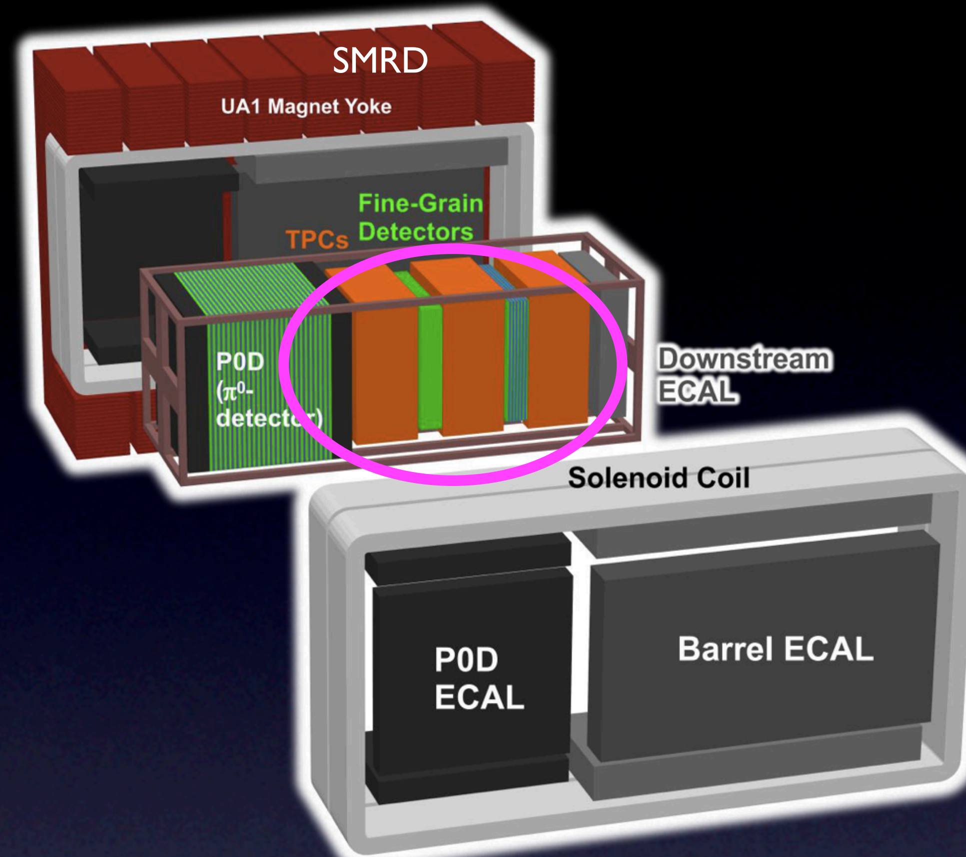
$\nu_{e(\mu)} + n \rightarrow e(\mu) + p$

Main backgrounds: CC1π, NC1π, π produced in DIS → coming from high energy ν

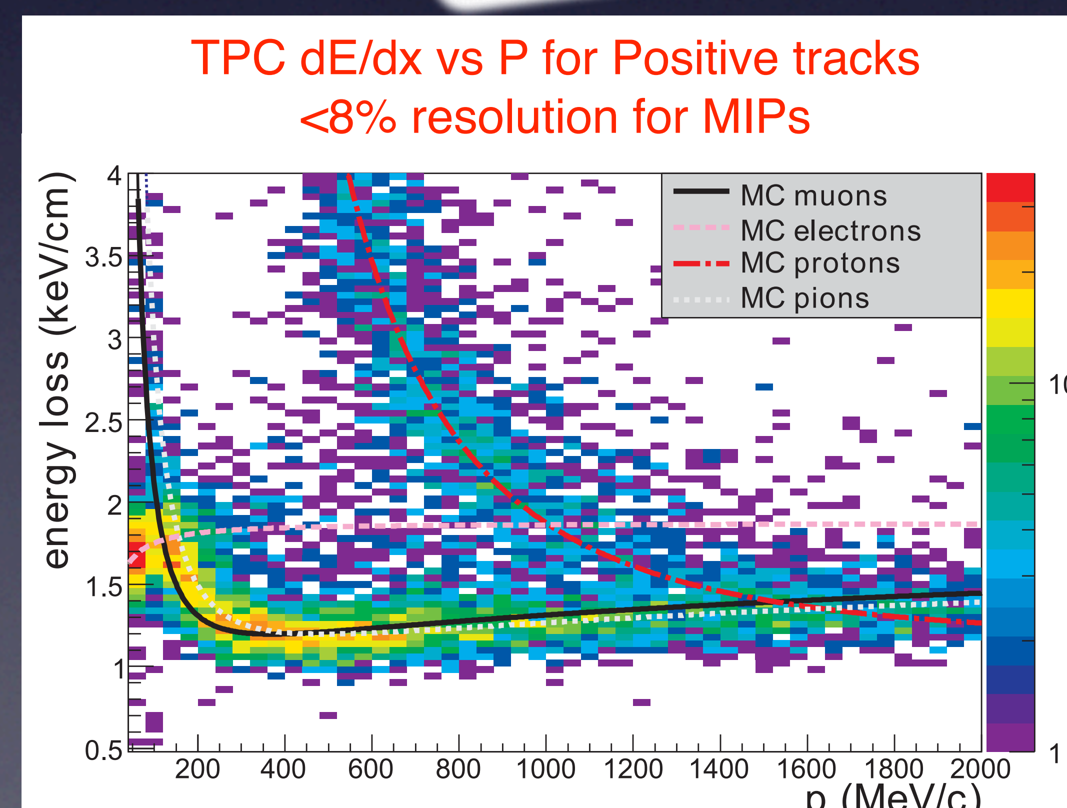


Off-axis ND280

- Set of detector installed inside the ex-UA1/NOMAD magnet (providing a 0.2 T magnetic field)
- Measure ν_μ and ν_e spectra before the oscillation
- Measure cross-sections for backgrounds to oscillation
- Dedicated π^0 detector (P0D), EM calorimeter to identify e/γ(ECAL), side muon range detector for high angle μ (SMRD)

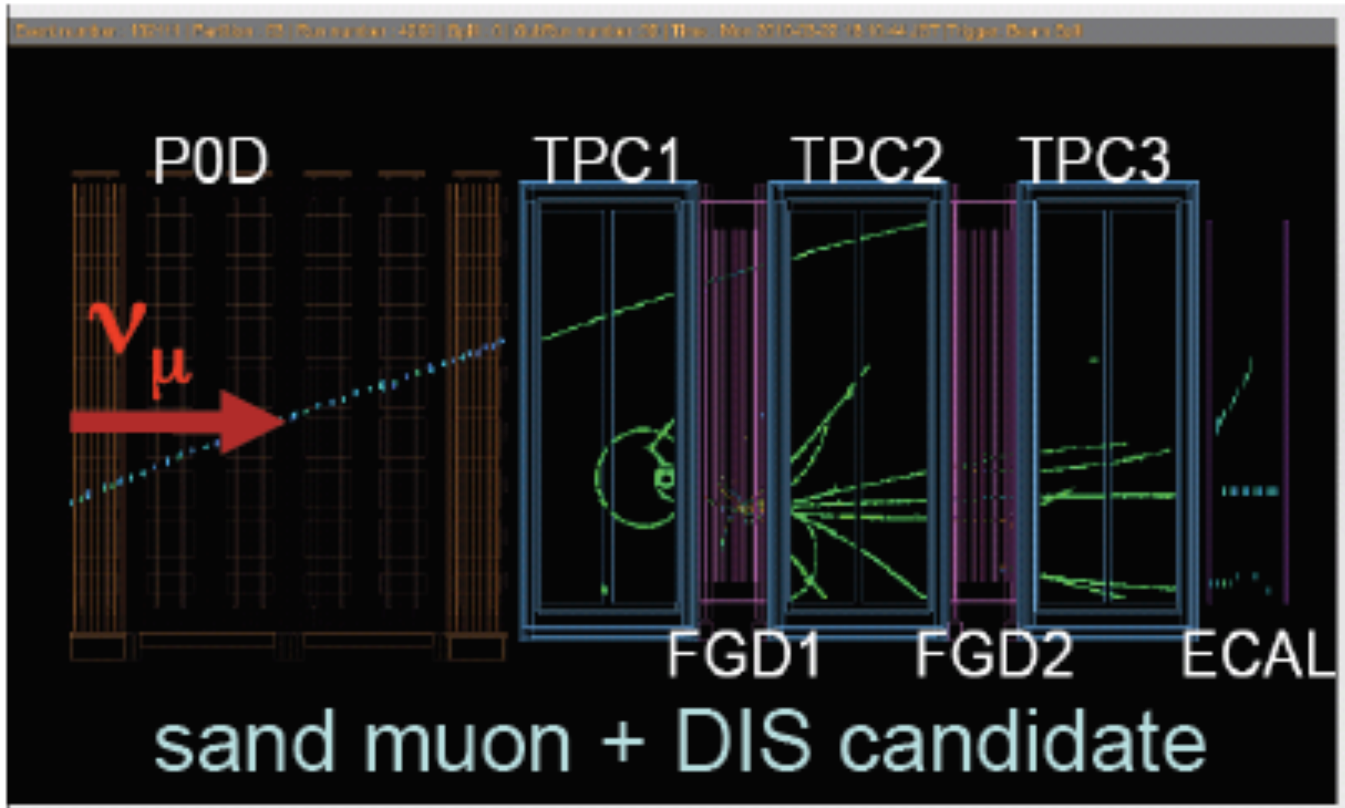


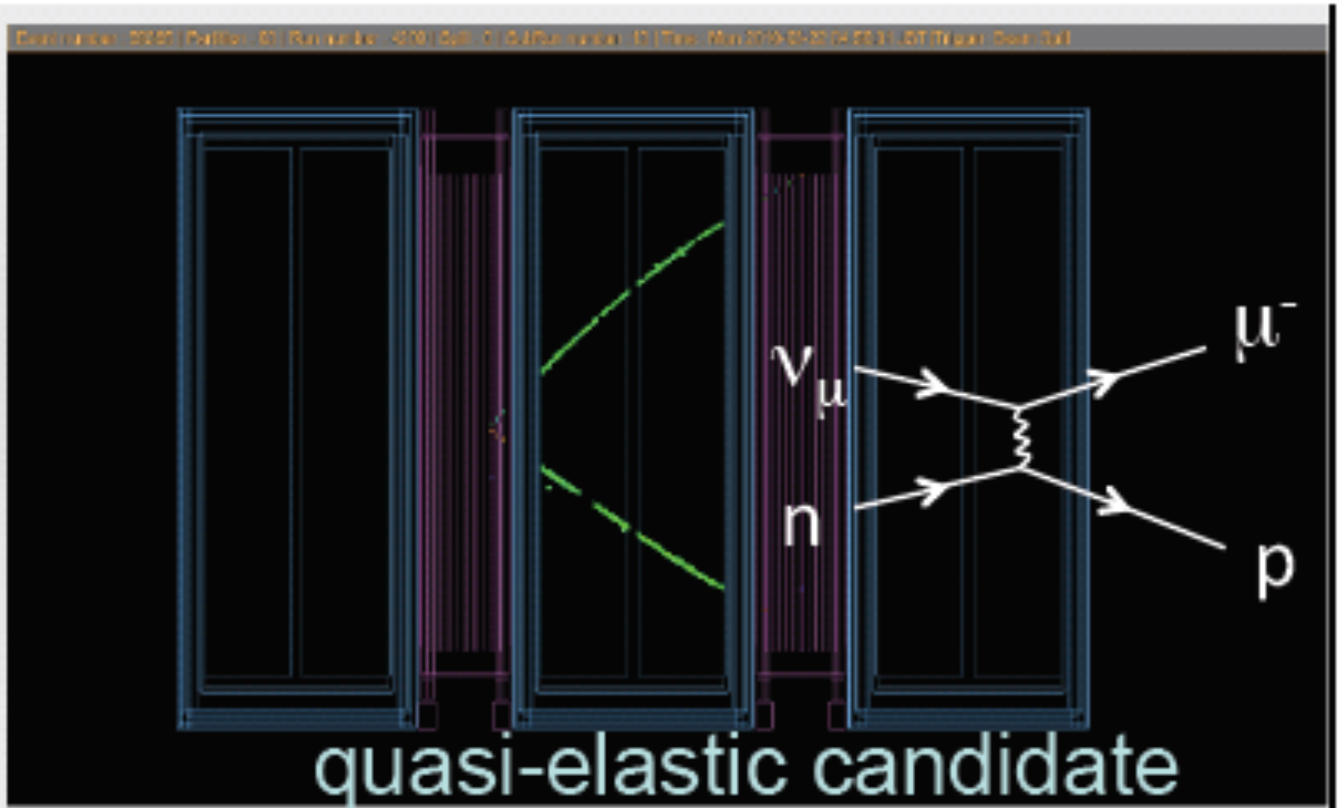
- The present analyses are based on the Tracker:
  - 2 fine grained detectors (FGD)
    - Active target for neutrino interactions (carbon and water)
    - 1.6 ton of Fiducial Volume
  - 3 time projection chambers (TPC)*
    - Instrumented with MicroMEGAS detectors
    - Reconstruct momentum and charge of the particles produced in ν interactions
    - PID capabilities measuring dE/dx in the gas

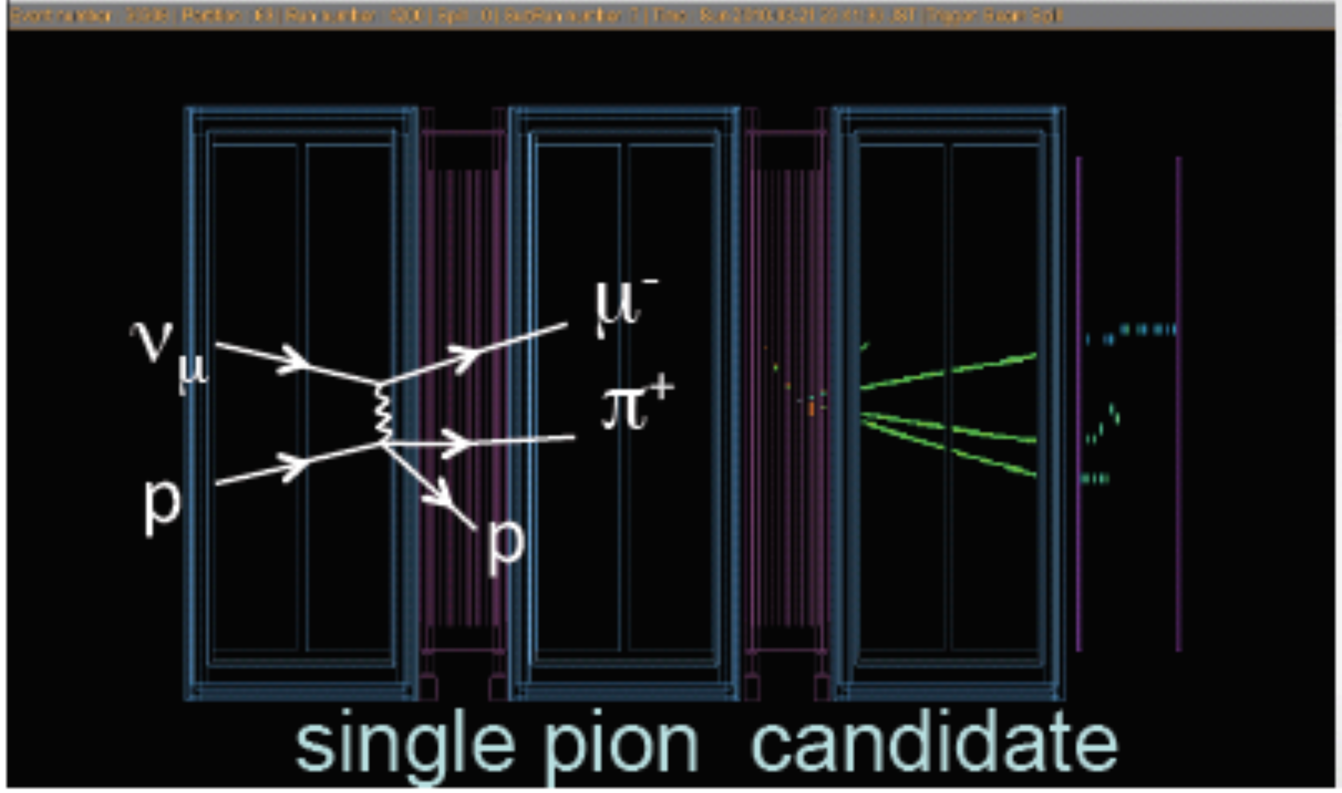


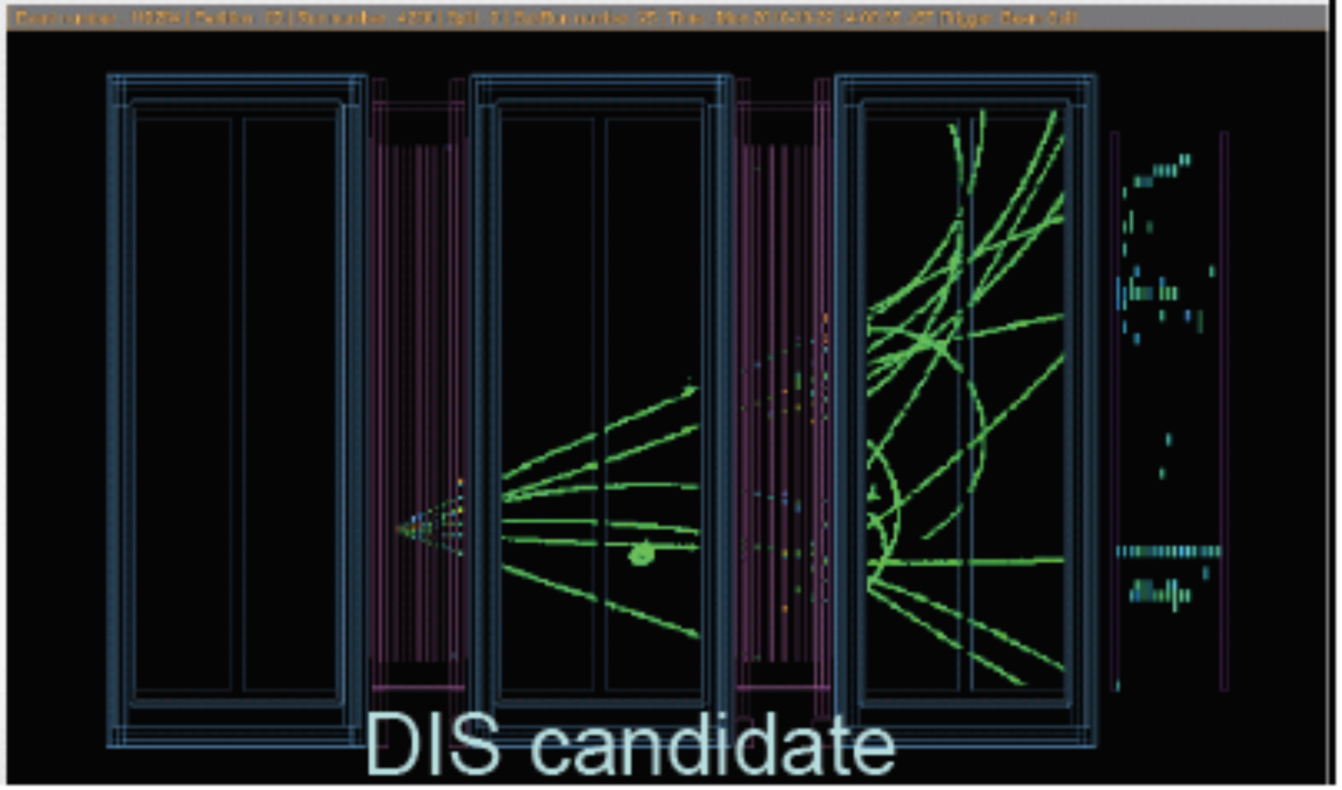
*NIM, A **637** (2011) pp. 25-46

ND280 tracker event gallery



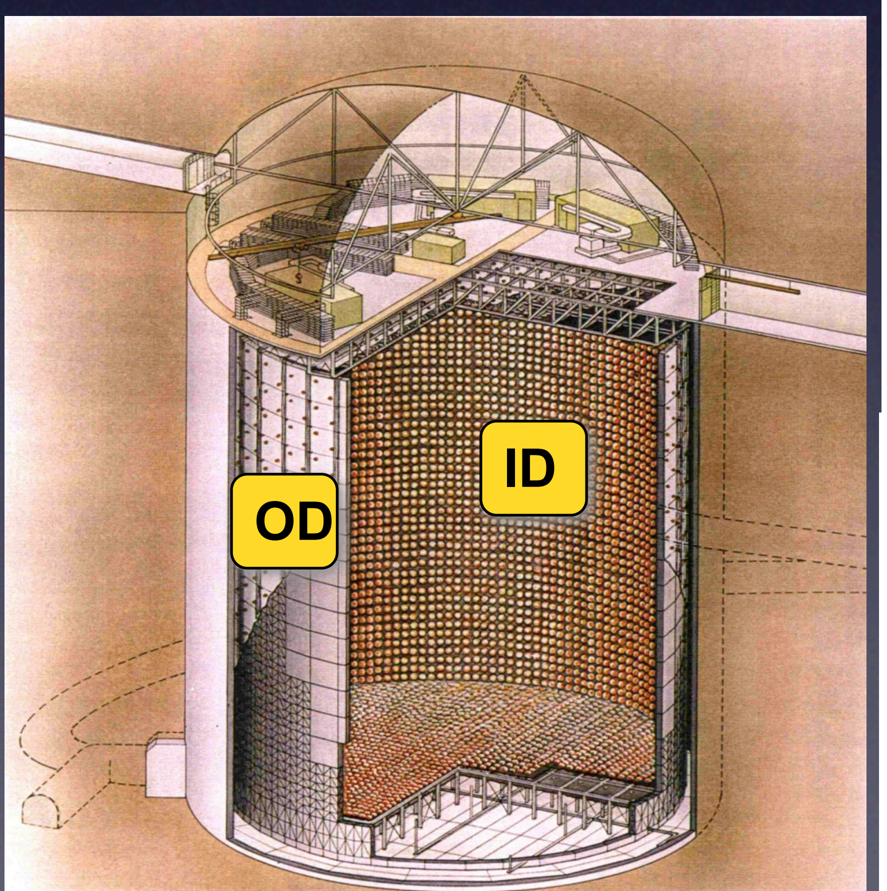


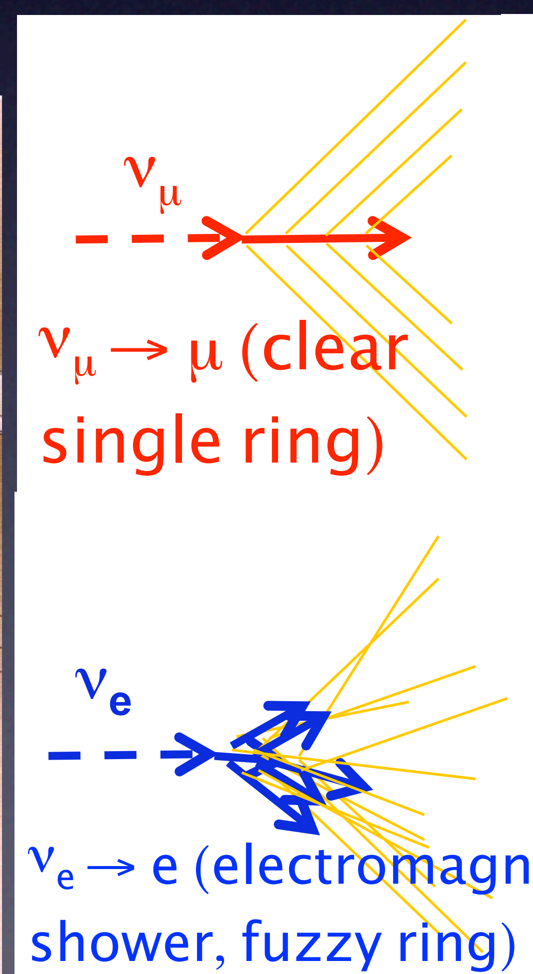


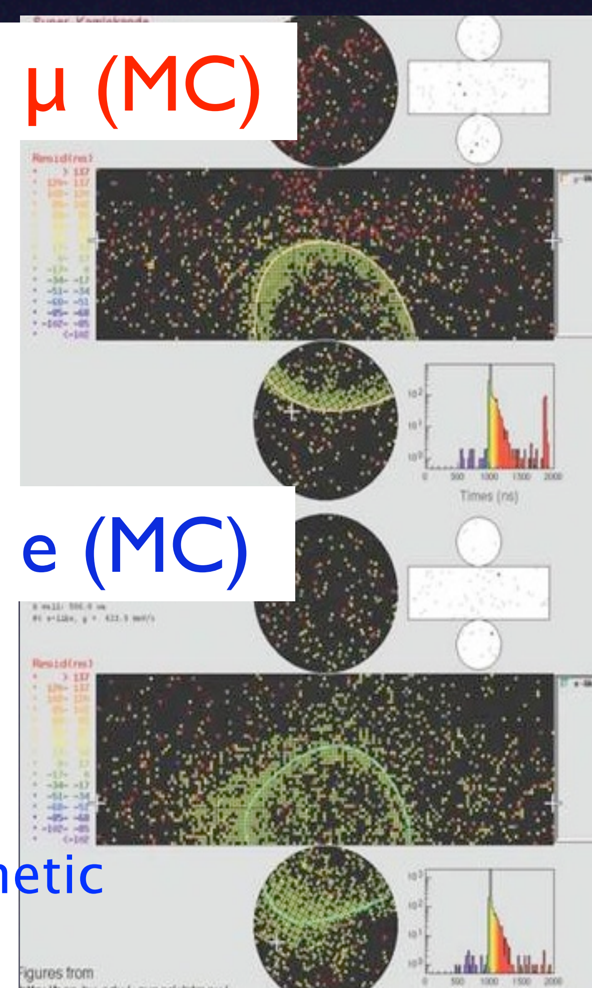


Far Detector: Super-Kamiokande

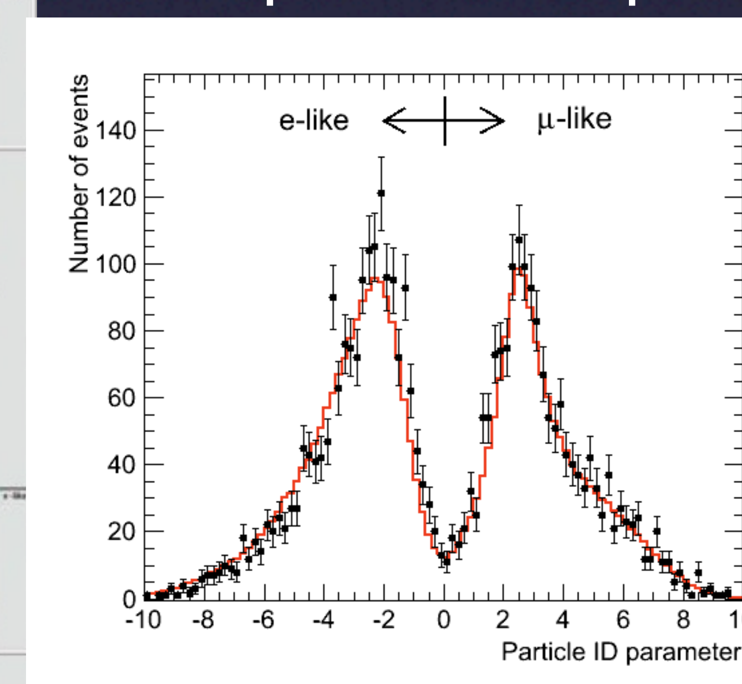
- 50 kton water Cherenkov detector (22.5 kton Fiducial Volume)
- Optically divided between an inner detector (ID) and an outer detector (OD)
  - 11129 20-inch Hamamatsu PMTs for the inner detector
- 1000 meters underground in the Kamioka mine (295 km from JPARC)
- Working since 1996, new readout electronic installed in 2006
- Very good PID capabilities: probability of a muon reconstructed as an electron of 1%







SK PID for atmospheric ν sample



T2K oscillation analysis

T2K Oscillation analysis method

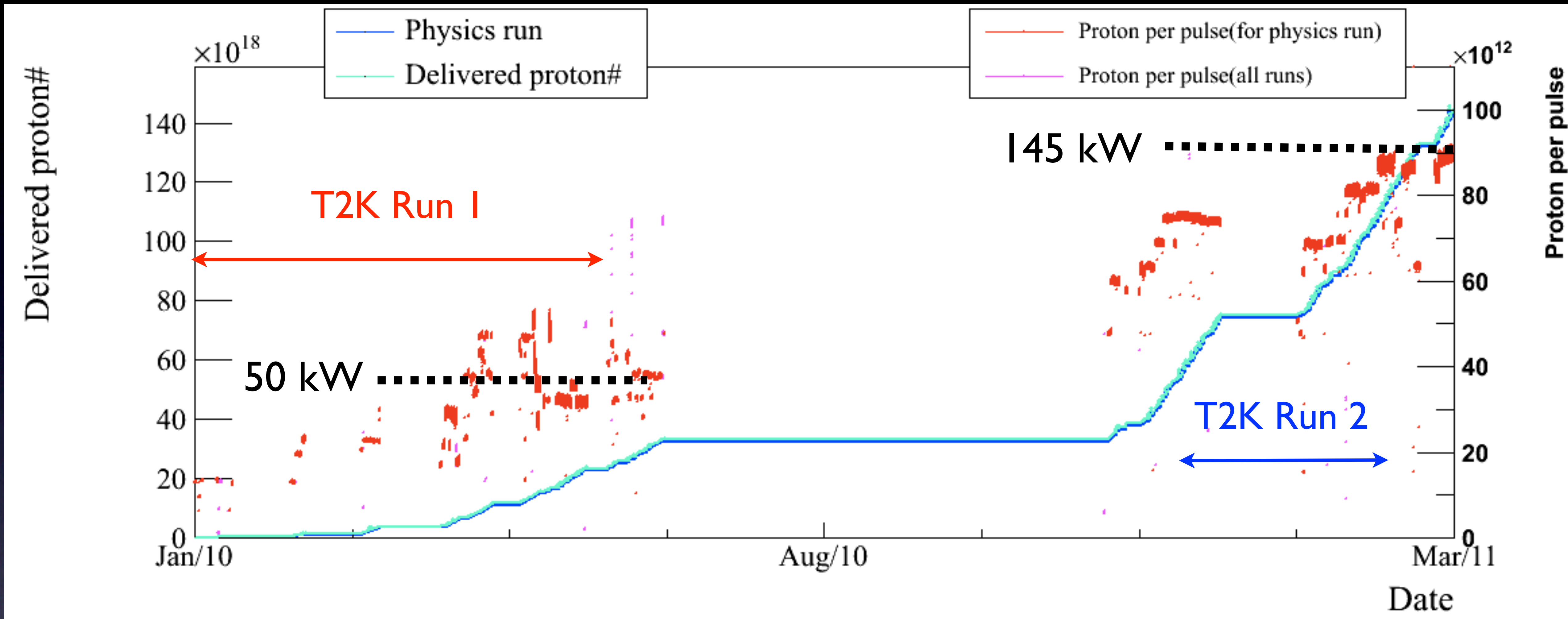
Flux prediction:
- Proton beam measurement
- Hadron production (NA61 and others external data)

ND280 measurements:
- Inclusive CC ν_μ measurement:
  - Output: $R_\mu^{ND,data}/R_\mu^{ND,MC}$
- Cross-check: $N(\nu_e)/N(\nu_\mu)$

Super-Kamiokande measurements:
- Select CC ν_μ and ν_e candidates
- Compute N_{MC}^{SK} without oscillations
- Adjust normalization with ND280:
  $N_{exp}^{SK} = (R_\mu^{ND,data}/R_\mu^{ND,MC}) \times N_{MC}^{SK}$
- Compare with N_{obs}^{SK} to evaluate oscillation parameters

Neutrino interactions:
- Interaction models
- External cross-section data

Run1+Run2 data set



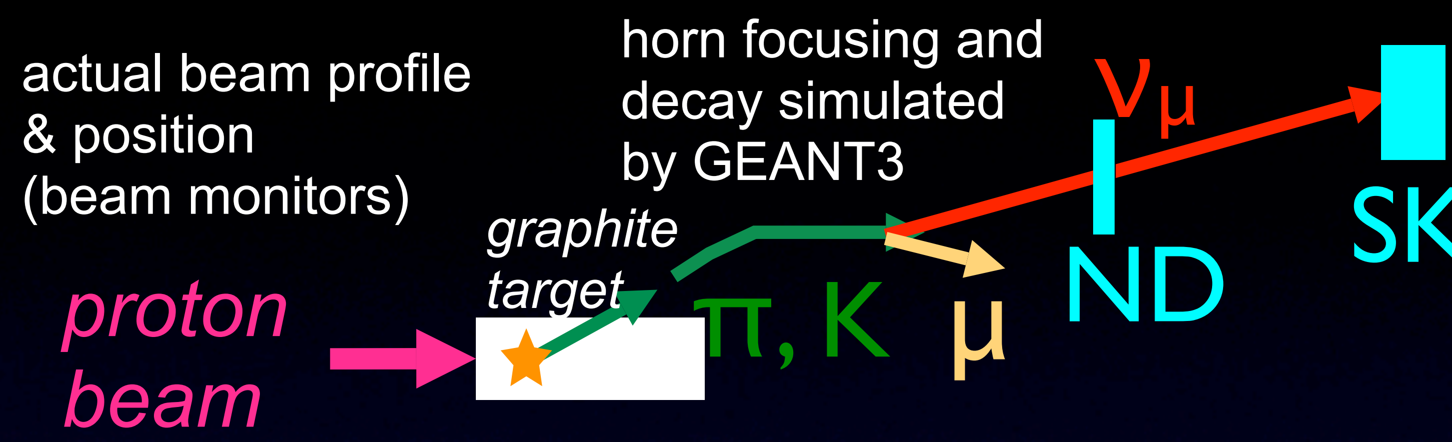
Run1 (Jan-Jun 2010)
3.23×10^{19} p.o.t for analysis
50 kW stable beam operation

Run2 (Nov 2010 - Mar 2011)
11.08×10^{19} p.o.t for analysis
145 kW stable beam operation

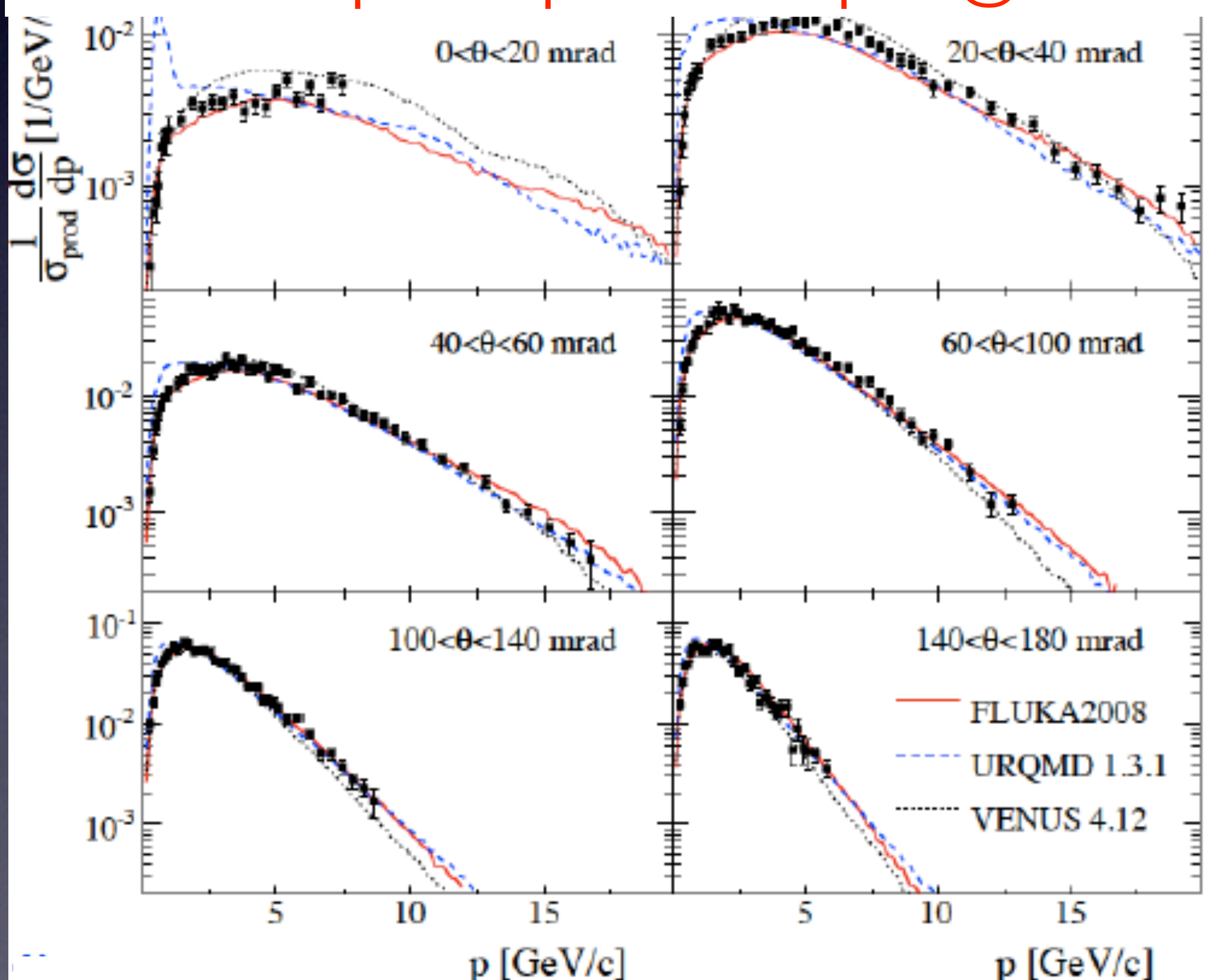
- The total number of protons used for this analysis is 1.43×10^{20} p.o.t → 2% of the T2K final physics goal

Neutrino flux prediction

- T2K beam simulation based on hadron production measurements
- NA61 experiment (@CERN) measure pion production in p+C interactions (same energy and target as T2K)

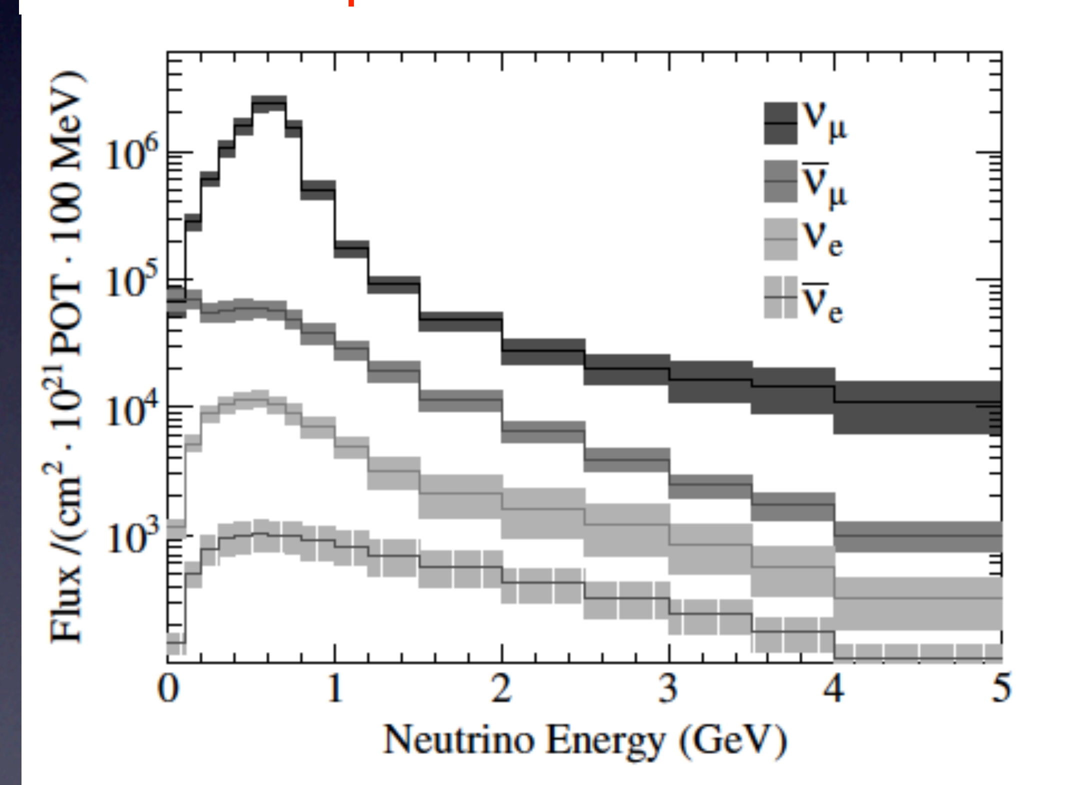


NA61: dσ/dp for π produced in p+C @31GeV



N.Abgrall et al., arXiv:1102.0983 [hep-ex], accepted by Phys.Rev.C

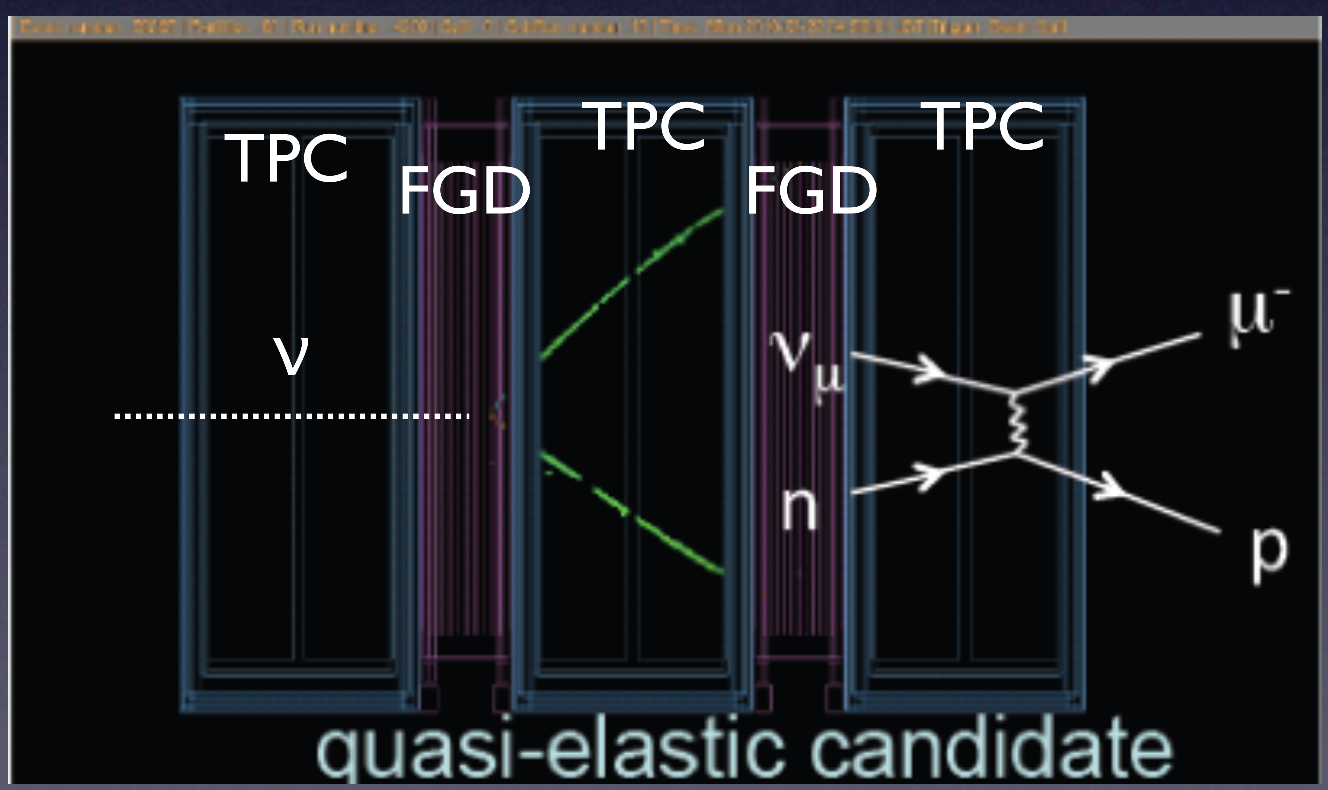
Expected ν fluxes at SK

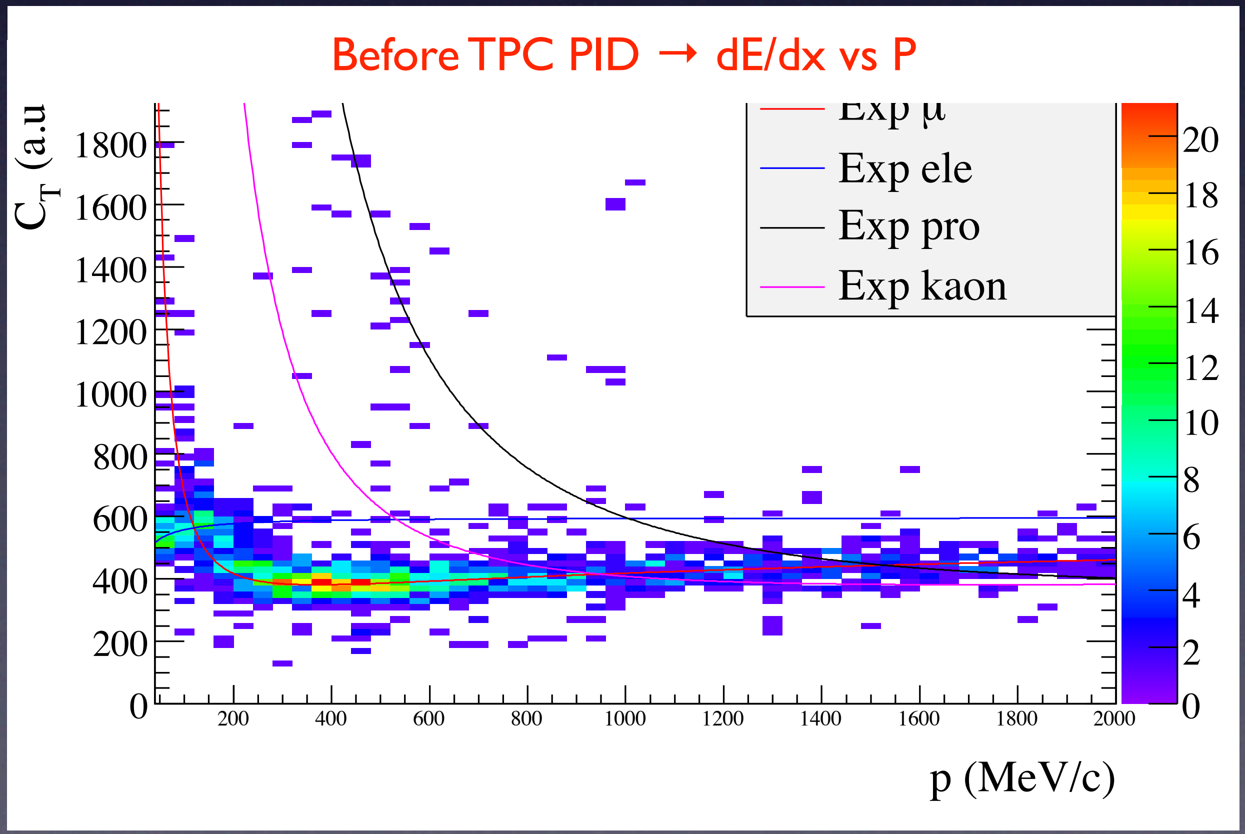


Expected beam ν_e contamination: ~1% of the total flux in the oscillation region

ND280 analyses

- ND280 analyses done on Run1 (2.9×10^{19} p.o.t)
- Measure inclusive CCν_μ event rate and ν_e beam component
- Select interactions in the Tracker: starting in the FGD FV producing at least 1 negative track in the downstream TPC → lepton candidate
- Measure track's momentum in the TPC
- Use TPC PID to select muons or electrons

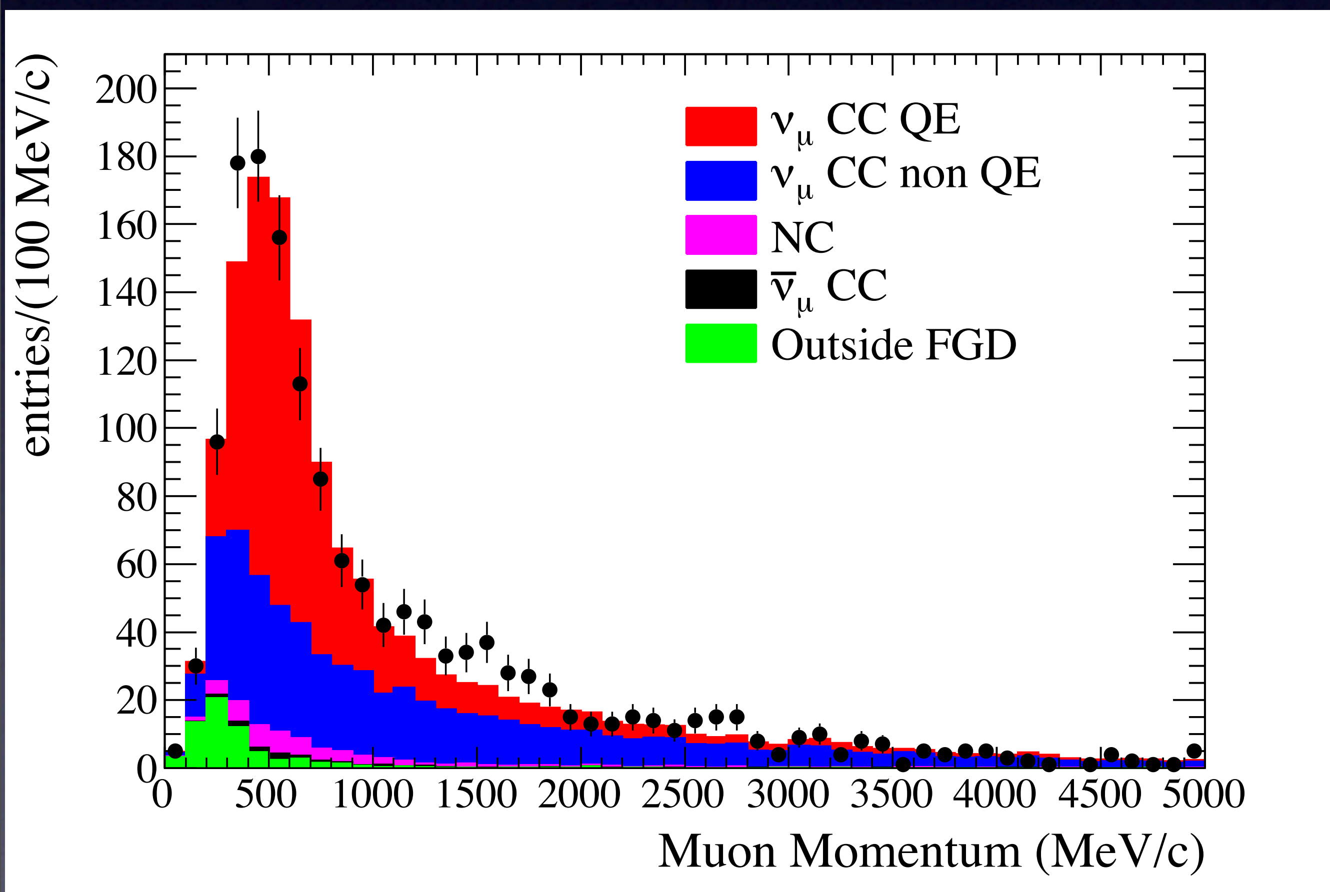




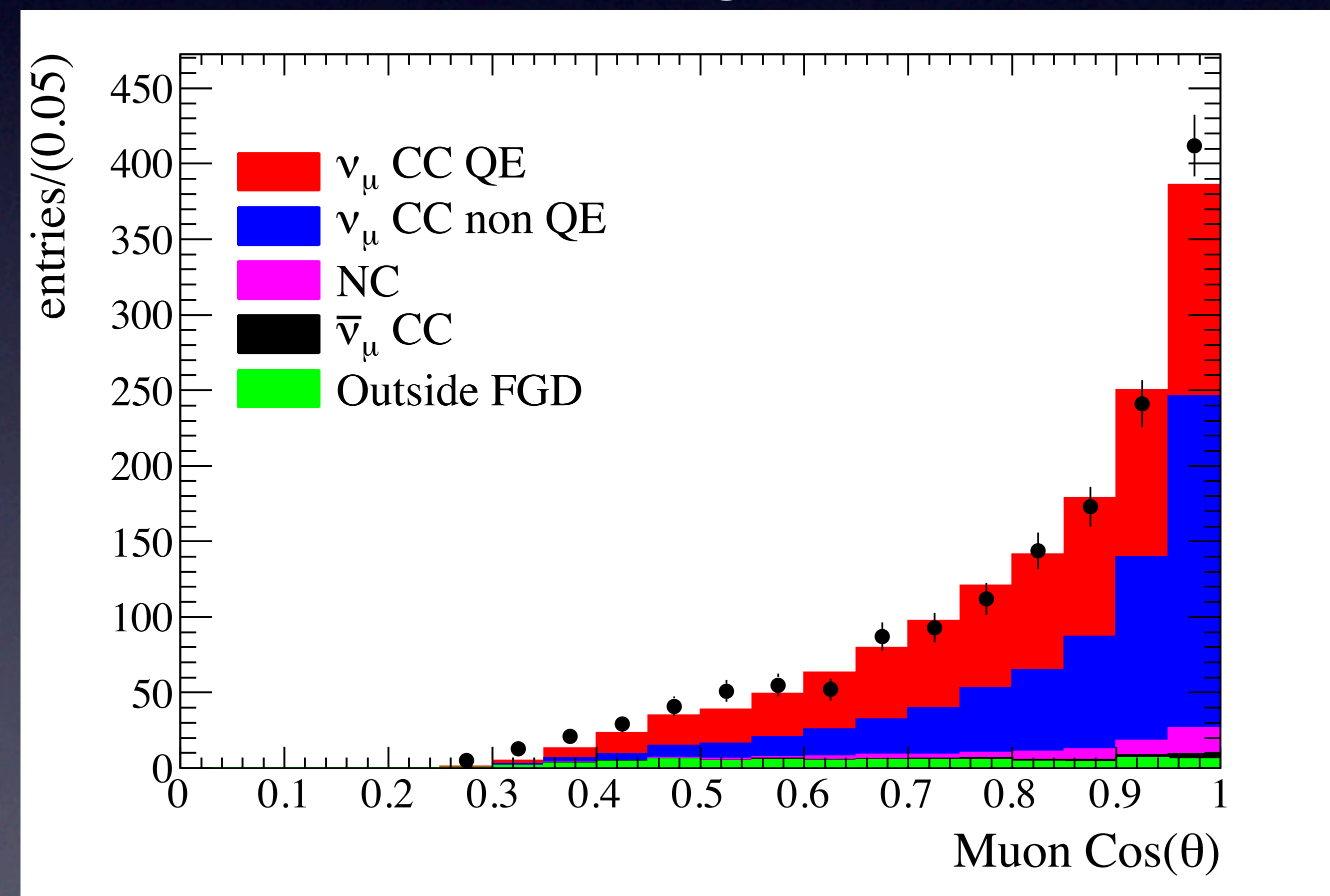
Inclusive CC ν_μ analysis

- Selection of μ-like tracks requiring dE/dx in the TPC compatible with muons
- Good agreement between data and MC (NEUT)
- 90% purity and 38% efficiency in CC selection
- Main detector systematics coming from tracking efficiency and TPC PID

Reconstructed μ momentum



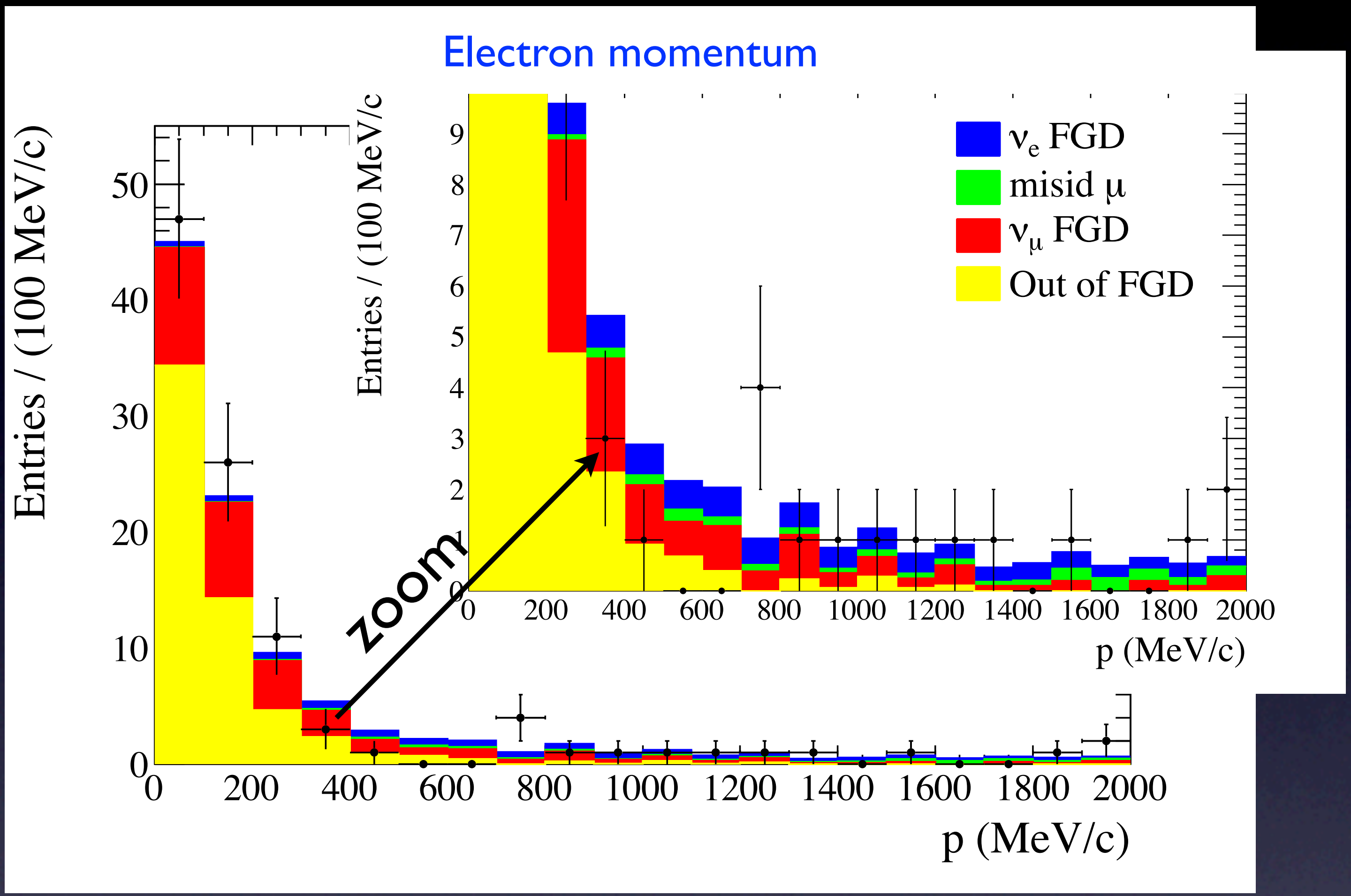
Reconstructed θ angle w.r.t. the beam



$$R(data/MC) = 1.036 \pm 0.028(stat)^{+0.044}_{-0.037}(det.\ syst) \pm 0.038(phys.\ model)$$

ND280 beam ν_e measurement

- Beam ν_e are the main background to ($\nu_\mu \rightarrow \nu_e$) oscillation signal at SK
- We measured them in the ND280 Tracker by selecting electrons via dE/dx in the TPC
- Background from misidentified μ estimated using a sample of sand muons in the data
- MC expectation for backgrounds from γ conversions constrained by control samples based on data
- Likelihood fit on the electron momentum to measure N(ν_e)
- No observed excesses in the beam ν_e component



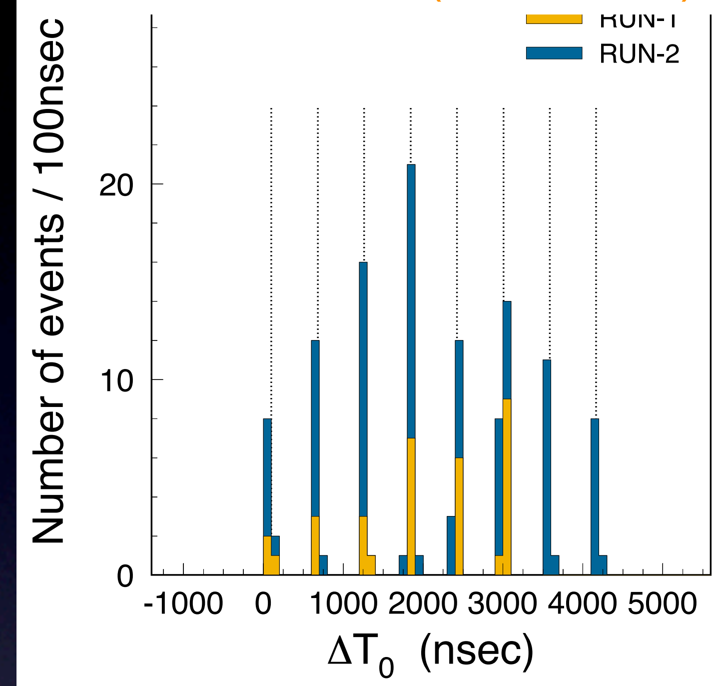
$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(stat) \pm 0.3(syst))\%$$
$$< 2.0\% \ @ \ 90\% \ C.L.$$

$$\frac{N(\nu_e)^{DATA} N(\nu_\mu)^{MC}}{N(\nu_\mu)^{DATA} N(\nu_e)^{MC}} = 0.6 \pm 0.4(stat) \pm 0.2(syst)$$

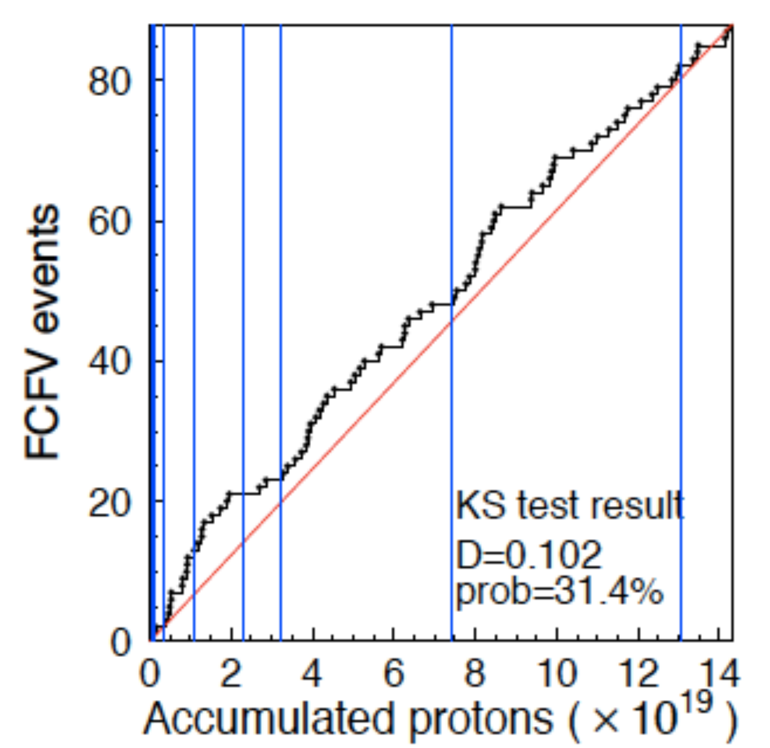
Super-Kamiokande event selection

- Predefined event selection for ν_μ and ν_e
- First steps that are common:
  - SK synchronized to beam timing using GPS
  - Fully contained events in the Inner Detector, minimal activity in the Outer Detector
  - Starting in the FV (FCFV)
  - Number of rings = 1
  - PID algorithm to distinguish e-like and μ-like events

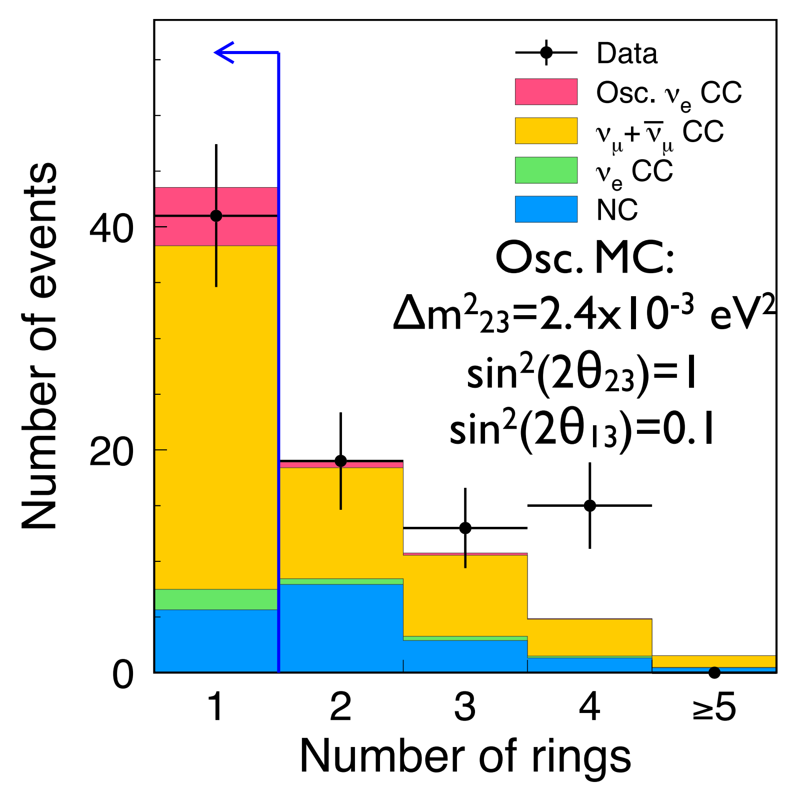
121 FC events (8 bunches)



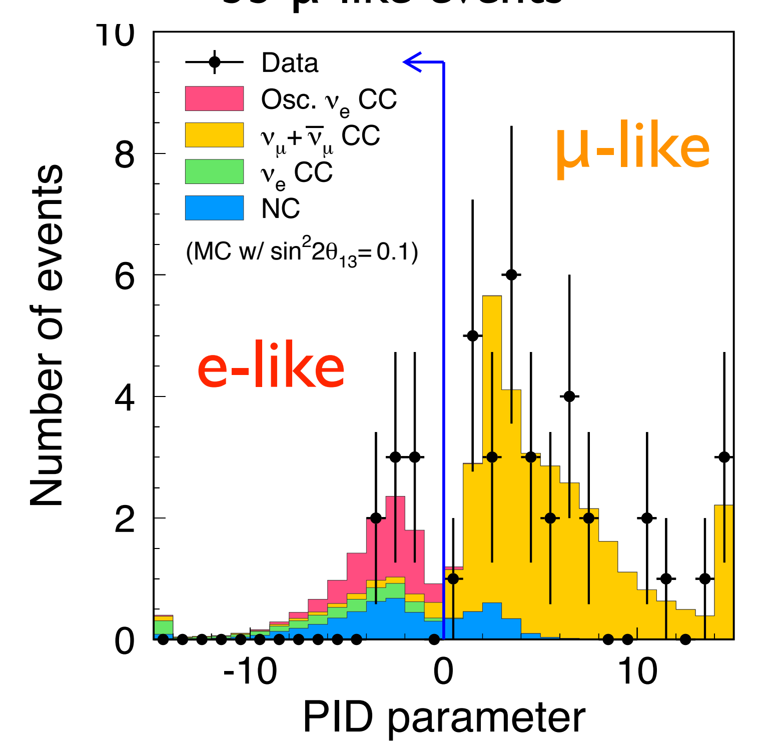
88 FCFV events



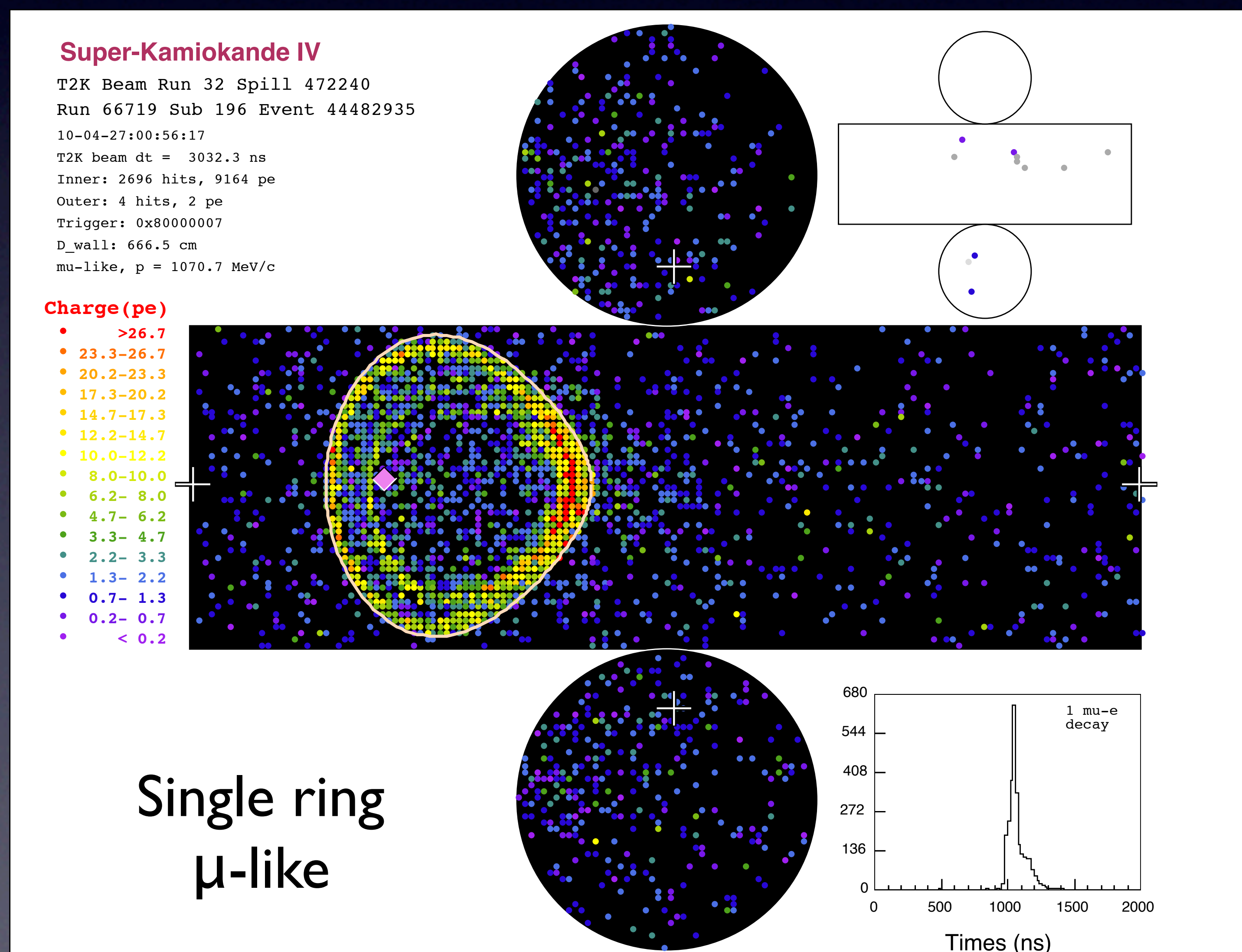
41 single ring



8 e-like events
33 μ-like events

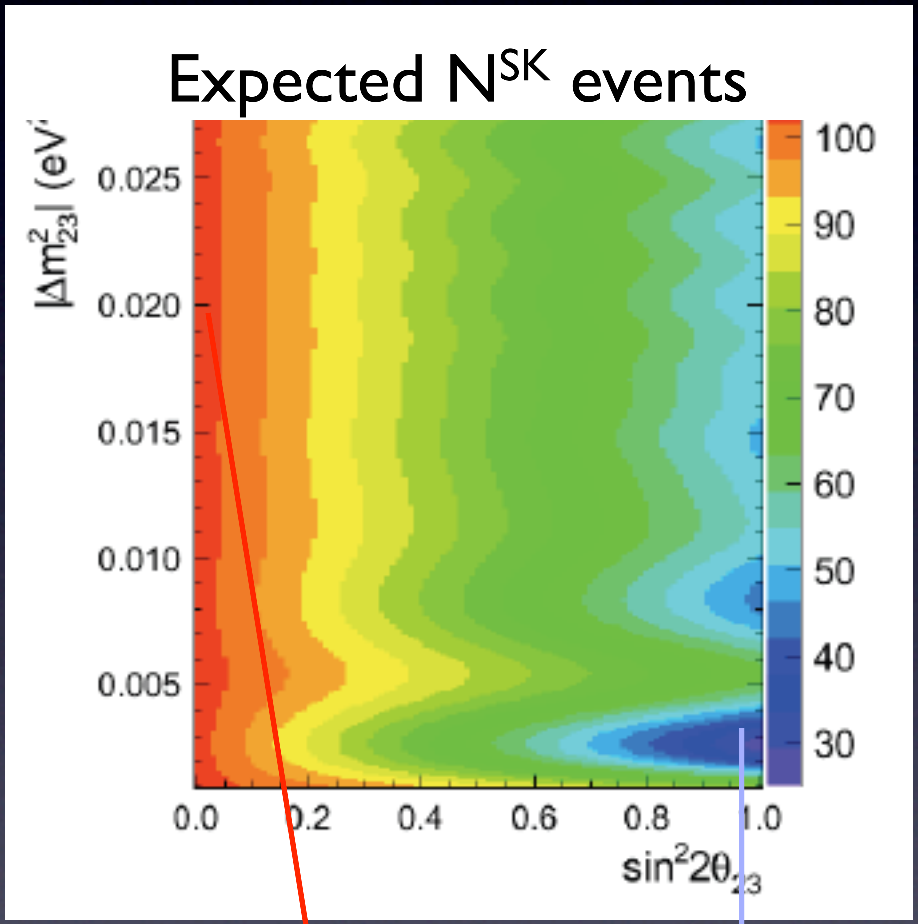


ν_μ disappearance results



Number of events at SK

- 1 single ring μ-like event with less than 2 decay electrons → 31 events passing this selection



N_{exp} without oscillation: 103.6

N_{exp} with oscillation: 28.3
$\sin^2 2\theta=1, \Delta m^2=2.4\times10^{-3}$ eV^2

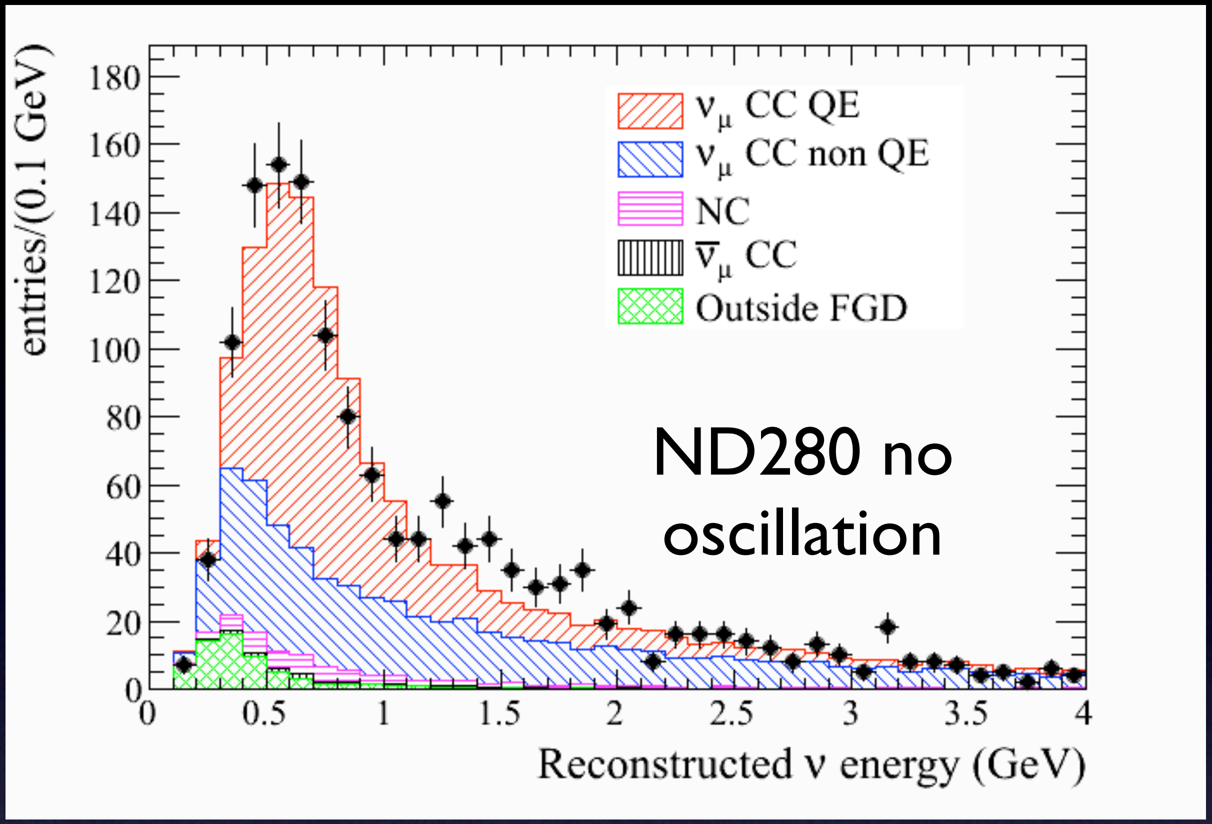
Systematics for N_{exp}^{SK} for different oscillation parameters

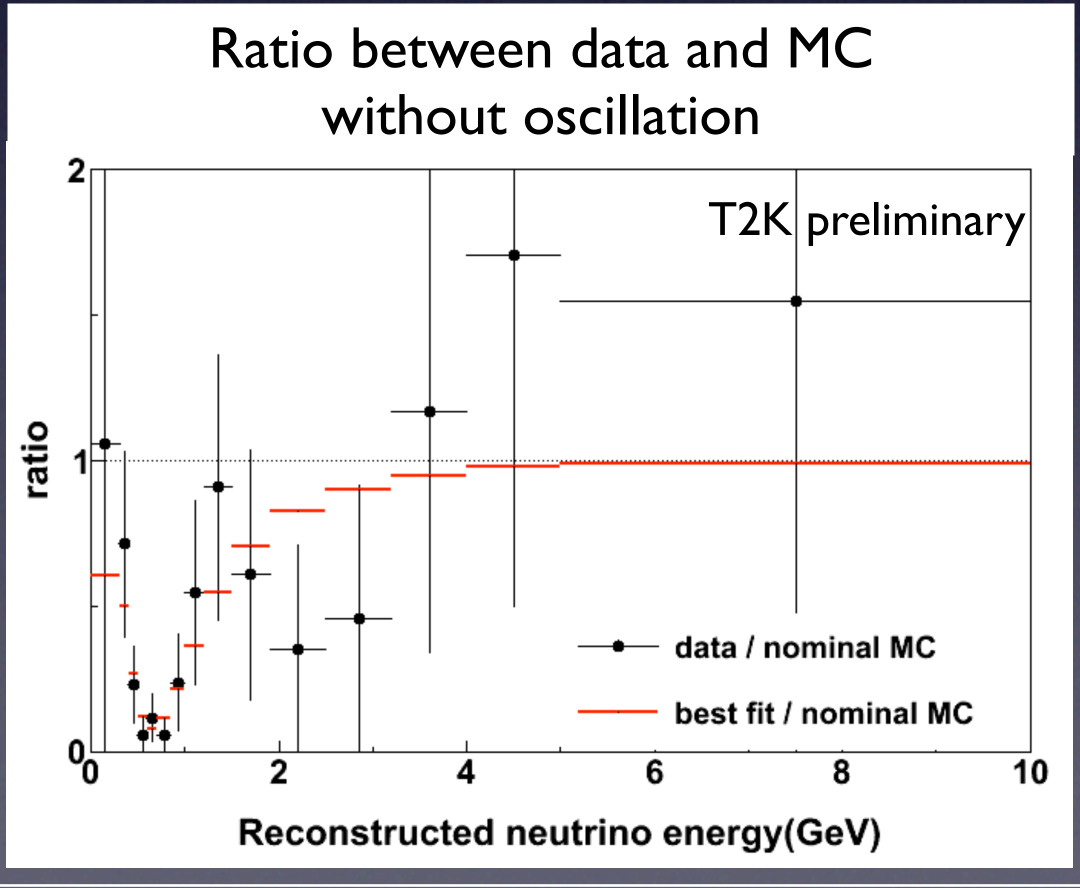
Error source	$\sin^2 2\theta=1, \Delta m^2=2.4\times10^{-3}$	No osc
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%

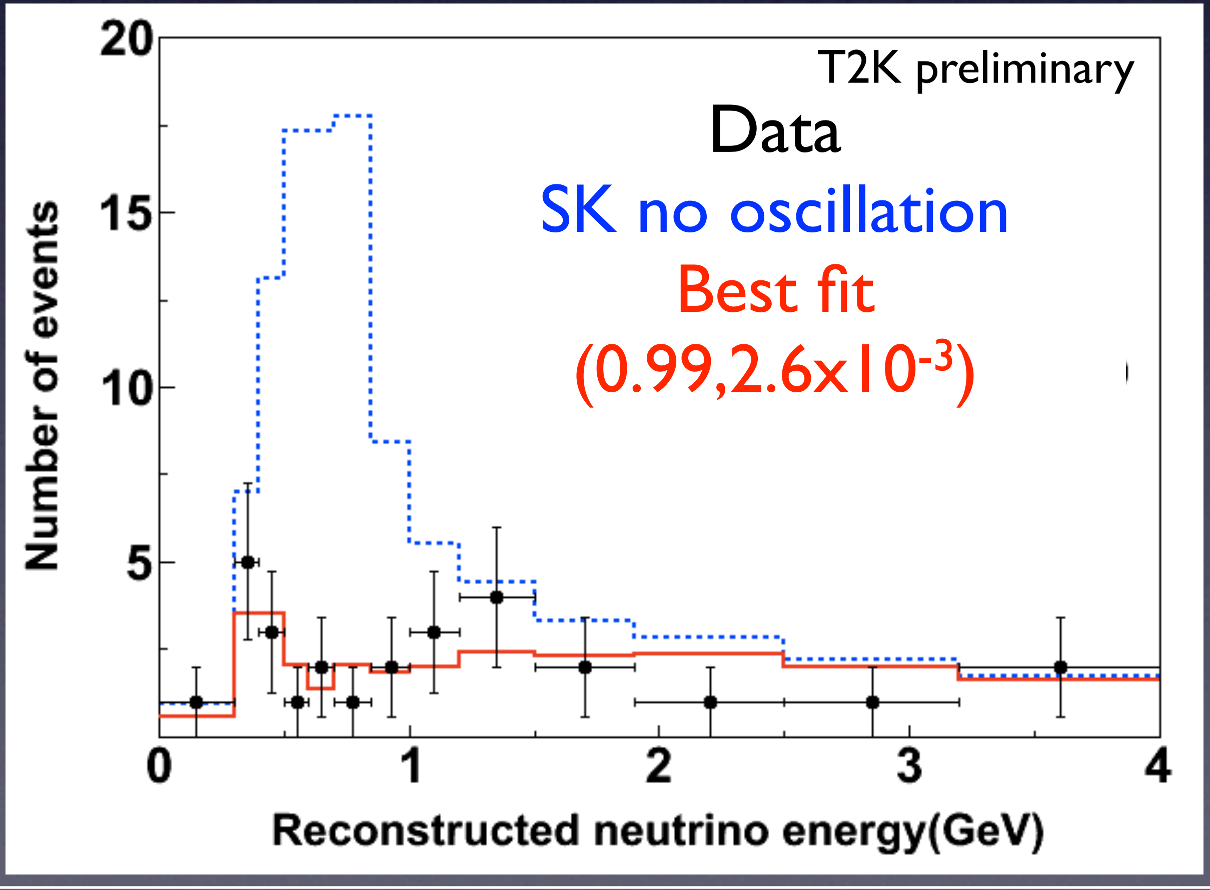
- Null-oscillation hypothesis excluded at 4.5 σ (only from N^{obs})

Neutrino energy spectrum

- Observed events at SK satisfying ν_μ disappearance criteria: 31
- Oscillation parameters extracted from an oscillation fit on $E(\nu)^{rec}$
- The oscillation pattern is clearly visible in the reconstructed energy spectrum → advantage of using off-axis configuration





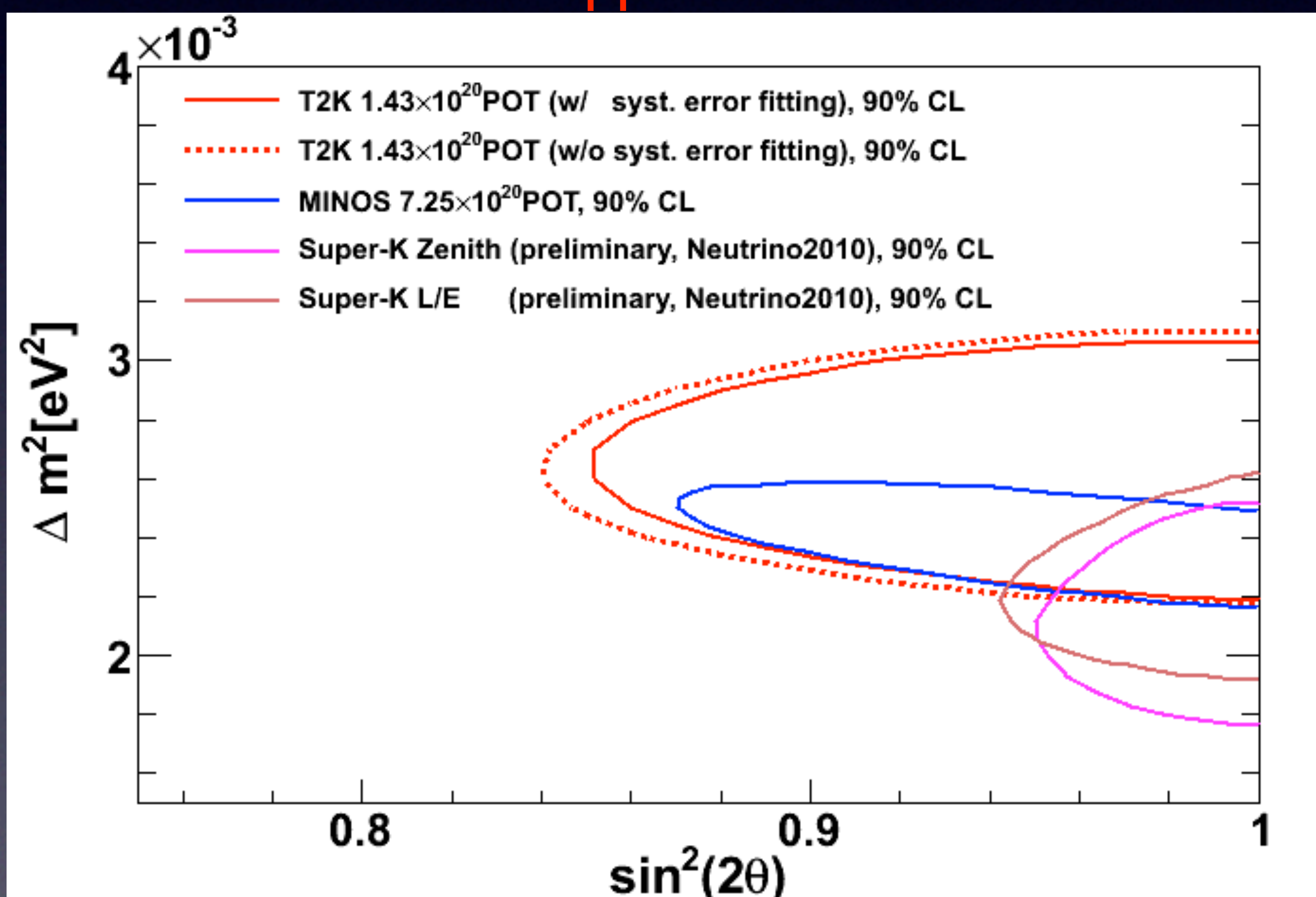


Comparison with SK and MINOS

- T2K results are in good agreement with results from SK and MINOS
  - These results have been obtained with only the 2% of the statistics we expect to have at the end of T2K

First T2K disappearance results

T2K preliminary



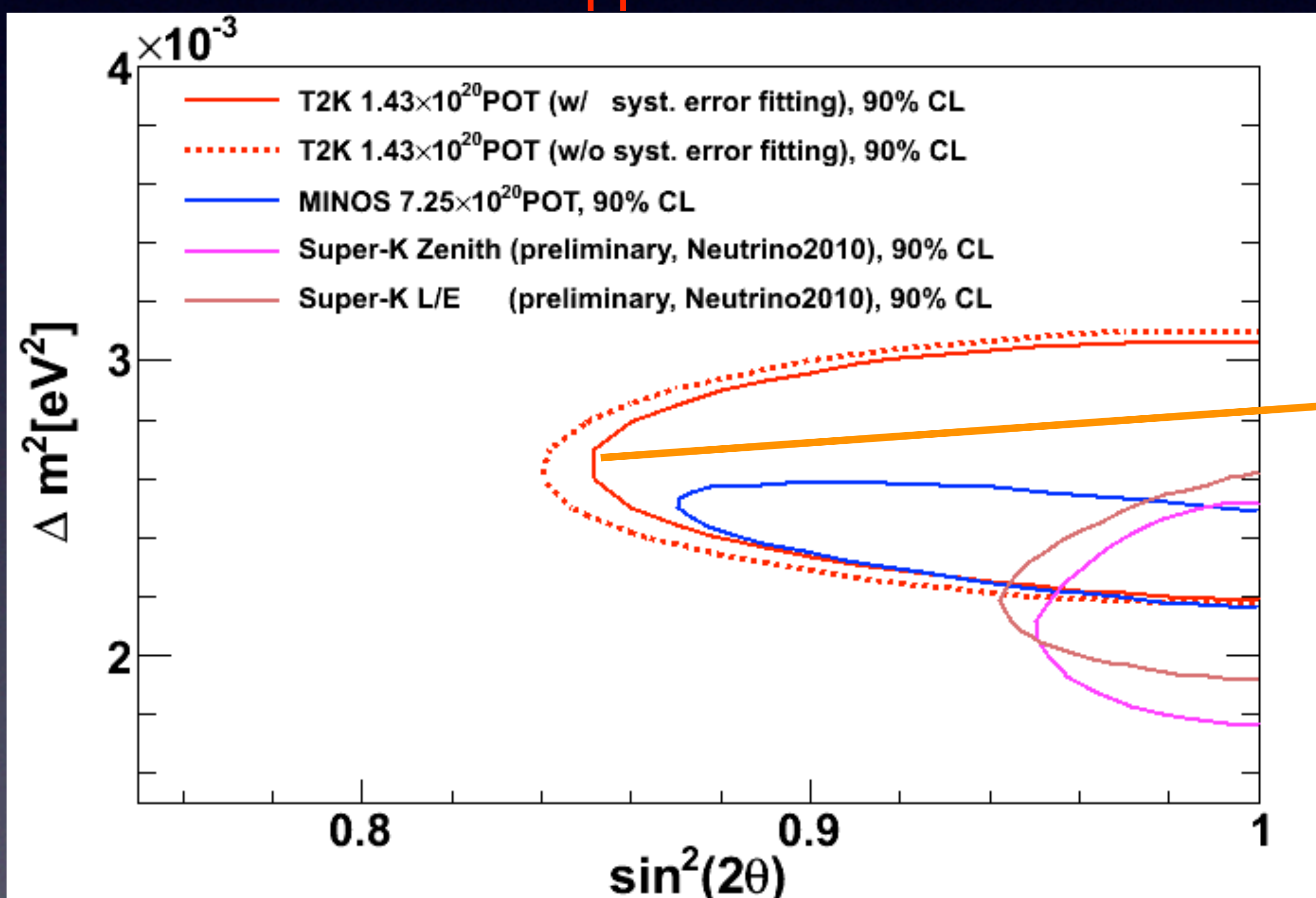
T2K results:
Best fit:
$\sin^2(2\theta_{23}) = 0.98$,
$|\Delta m^2_{23}| = 2.6\text{x}10^{-3}\ eV^2$

90% C.L.:
$\sin^2(2\theta_{23}) > 0.84$
$2.1\text{x}10^{-3} < \Delta m^2_{23}(eV^2) < 3.1\text{x}10^{-3}$

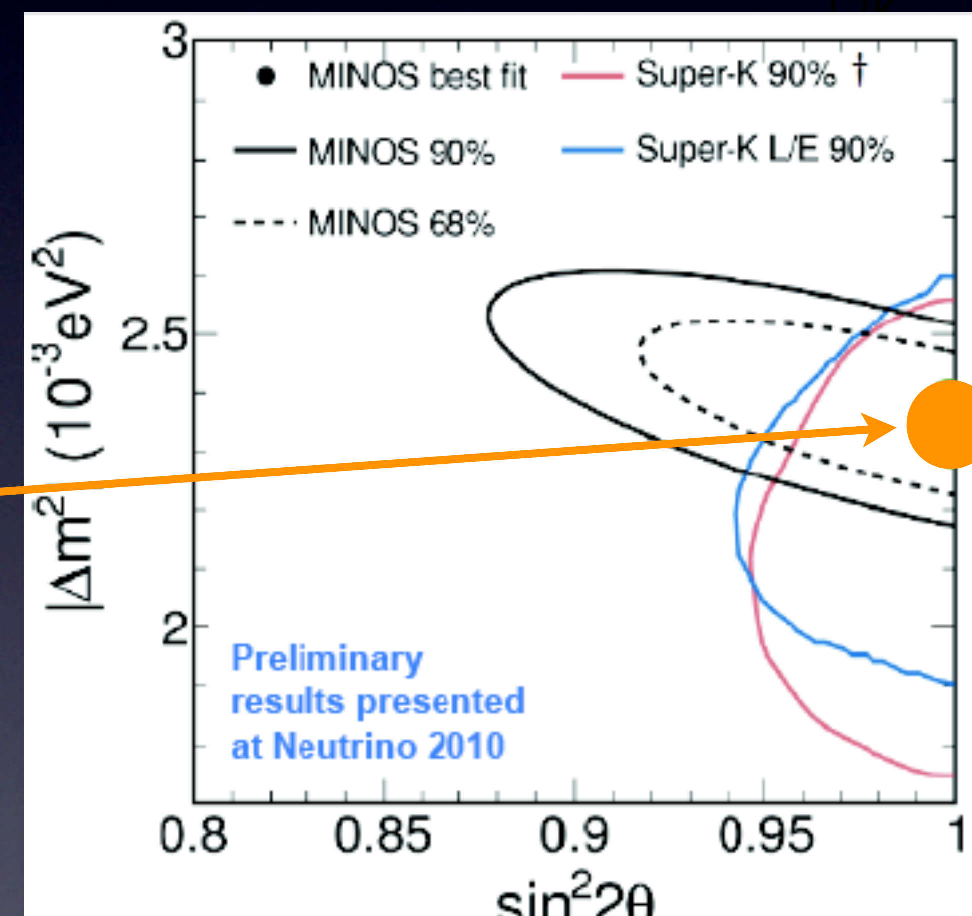
Perspectives for ν_μ disappearance

- Once all the statistics will be collected

First T2K disappearance results



T2K final goal

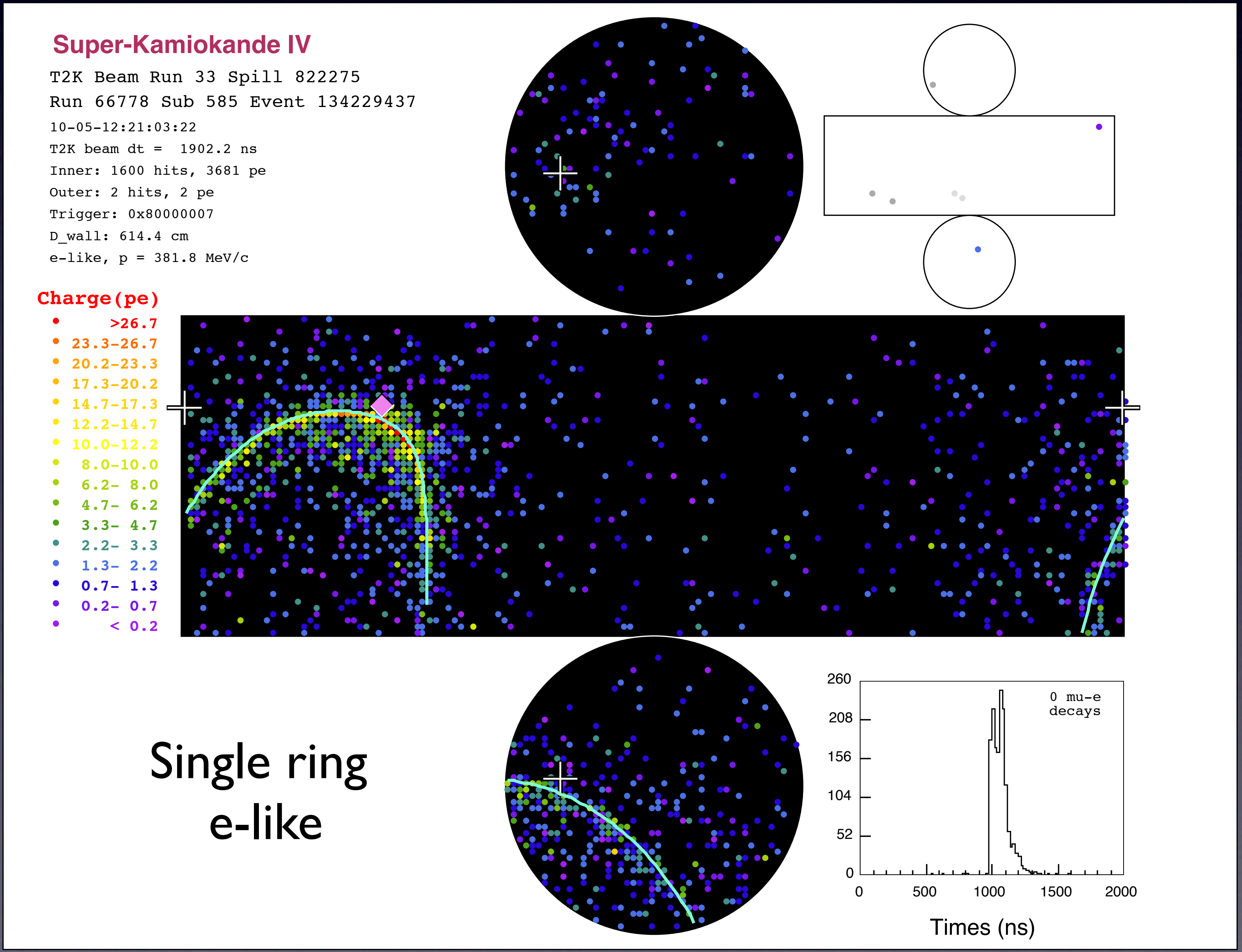


Test if θ_{23} is maximal:

$\delta(\sin^2(2\theta_{23})\sim 0.01$

$\delta(\Delta m^2_{23})<1\times 10^{-4}$ eV^2

ν_e appearance results



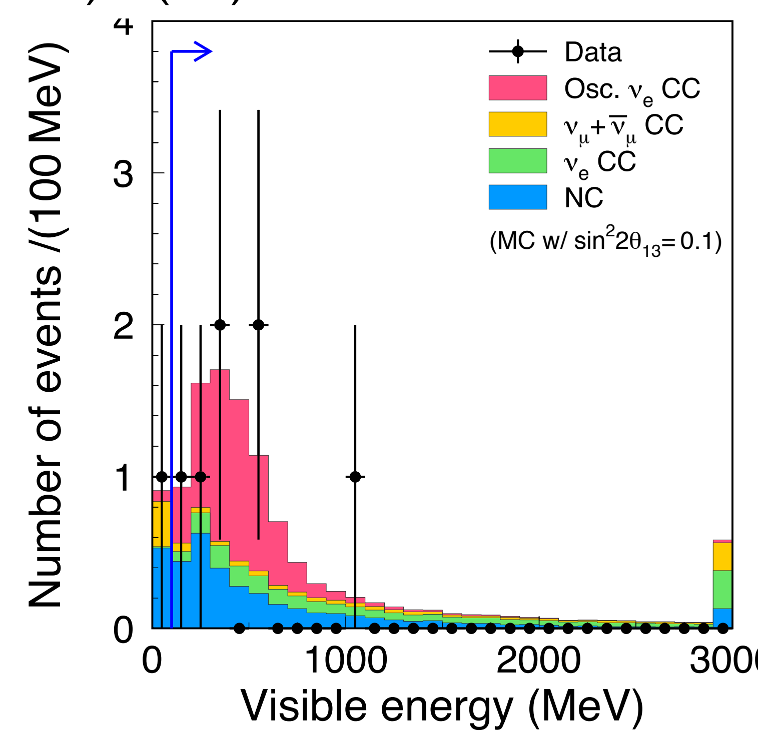
Single ring e-like

SK ν_e event reduction

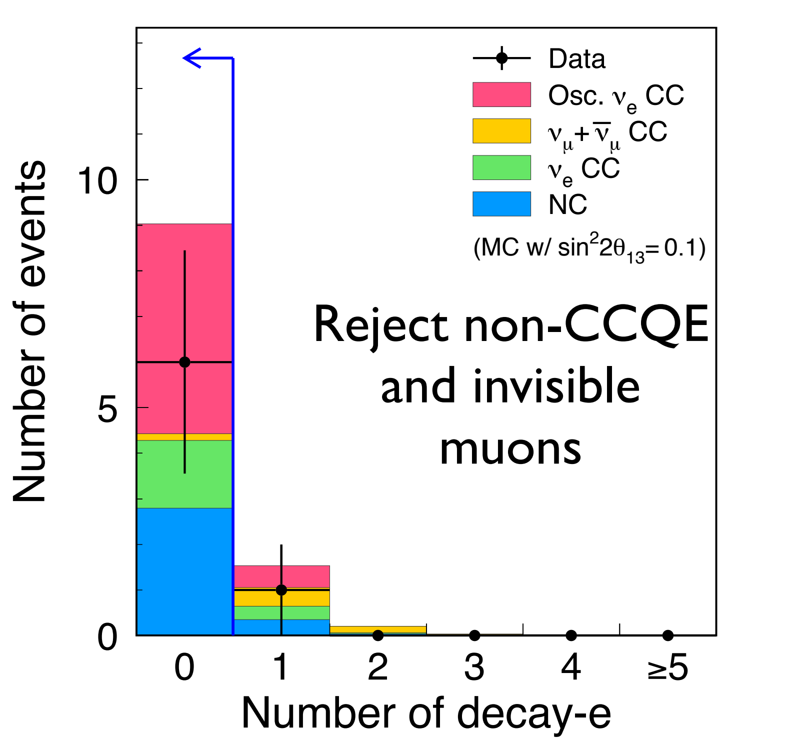
- After ring counting 8 single ring e-like events are selected
- SK "tight" cuts are applied to further reject the background
- 6 events passing all the selection

Signal efficiency: 67%
Bkg rejection: 99% for NC,
77% for beam ν_e

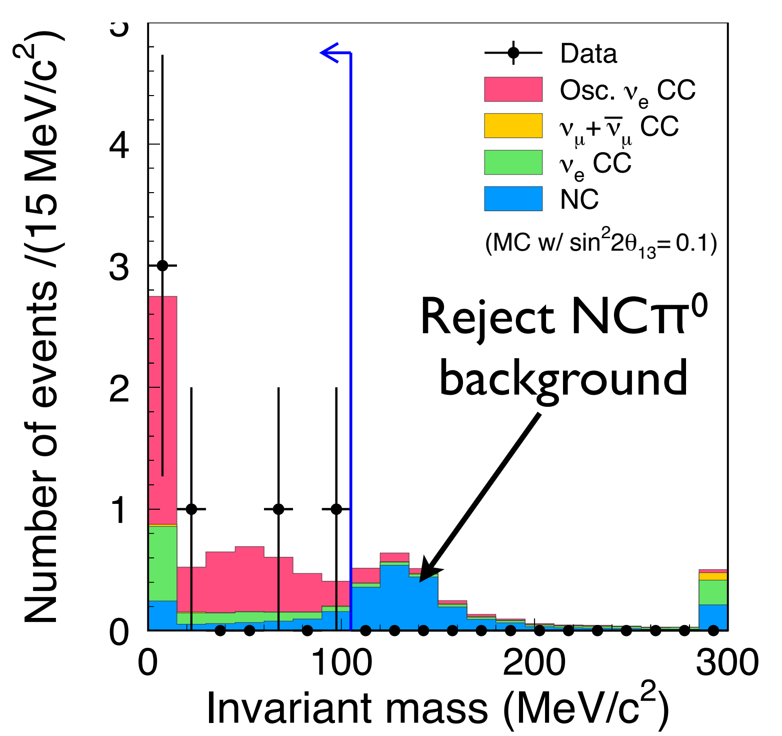
1) E(vis)>100 MeV → N=7



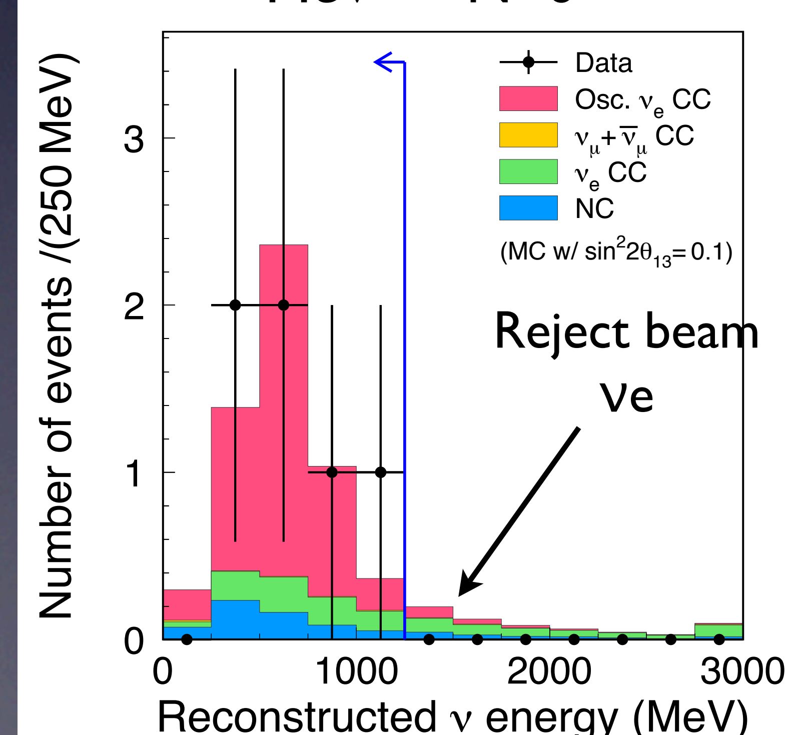
2) No decay electrons → N=6



3) M_{inv} with forced 2nd ring <105 MeV → N=6



4) Rec neutrino energy <1250 MeV → N=6



Number of expected events

- We observed 6 ν_e candidates
- The expected number of events from un-oscillated neutrinos is 1.5
- Main contribution coming from beam νe → cross-checked with an analysis at ND280

Source	Nexp
Beam ν_e	0.8
ν_μ Neutral Current	0.6
ν_μ Charged Current	0.1
Total	1.5±0.3

Syst for $\theta_{13}=0$ → Nexp = 1.5±0.3

error source	syst. error
ν flux	$\pm 8.5\%$
ν int. cross section	$\pm 14.0\%$
Near detector	$^{+5.6}_{-5.2}\%$
Far detector	$\pm 14.7\%$
Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

Dominated by hadron production

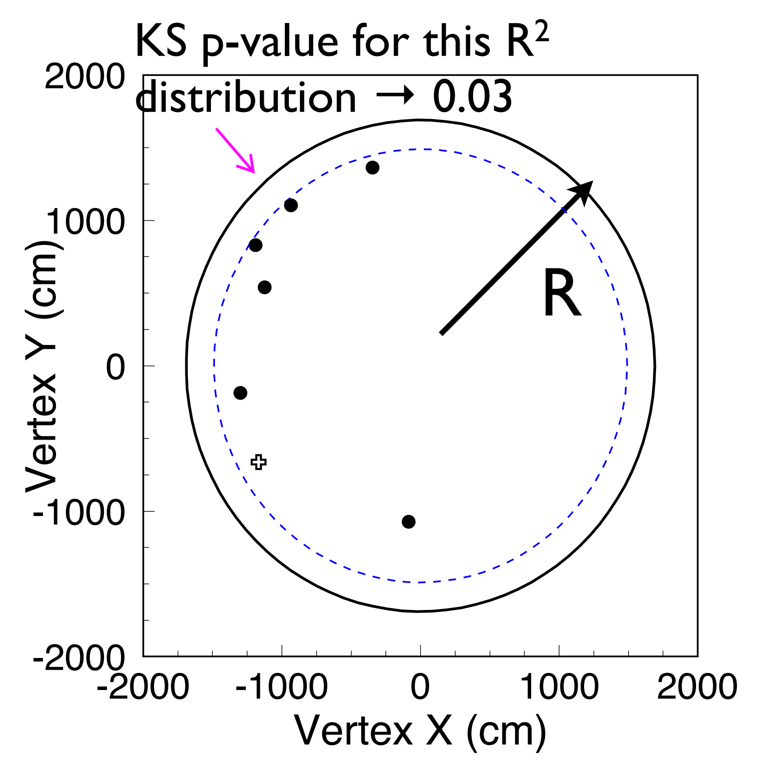
Dominated by FSI and NCπ0 cross-section uncertainties

ND280 dominated by TPC tracking efficiency and ionization in the gas

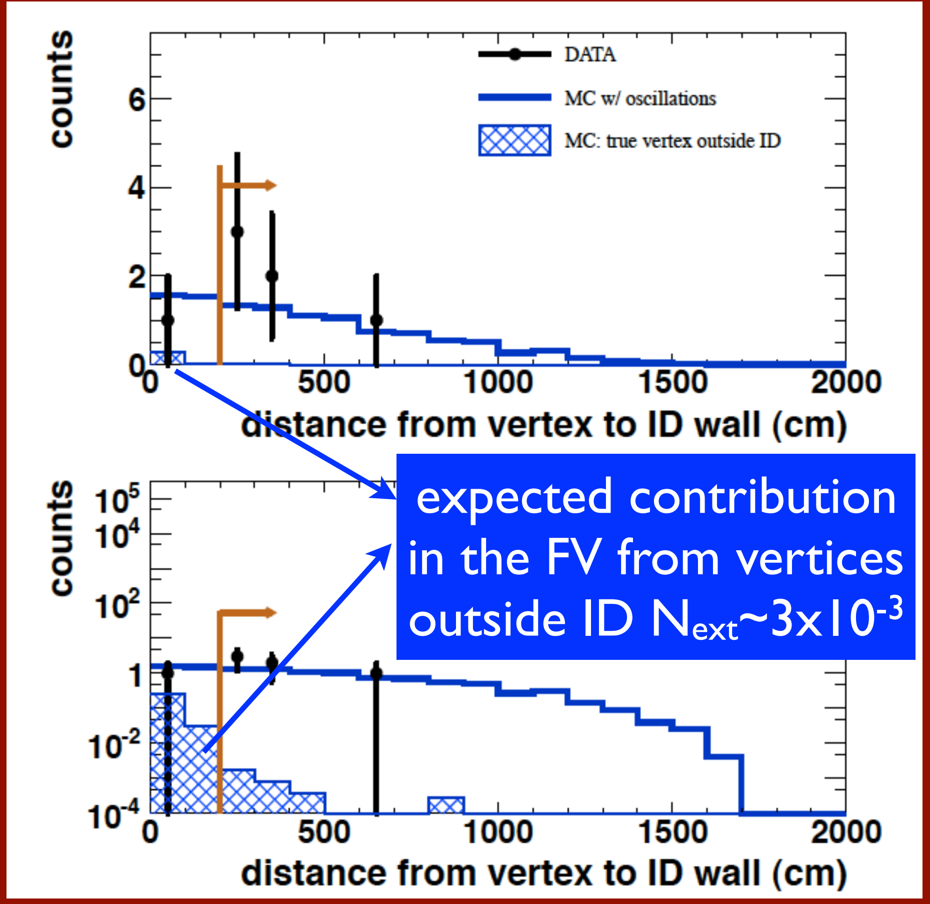
SK dominated by ring counting, PID and π^0 mass systematics

Vertex distribution

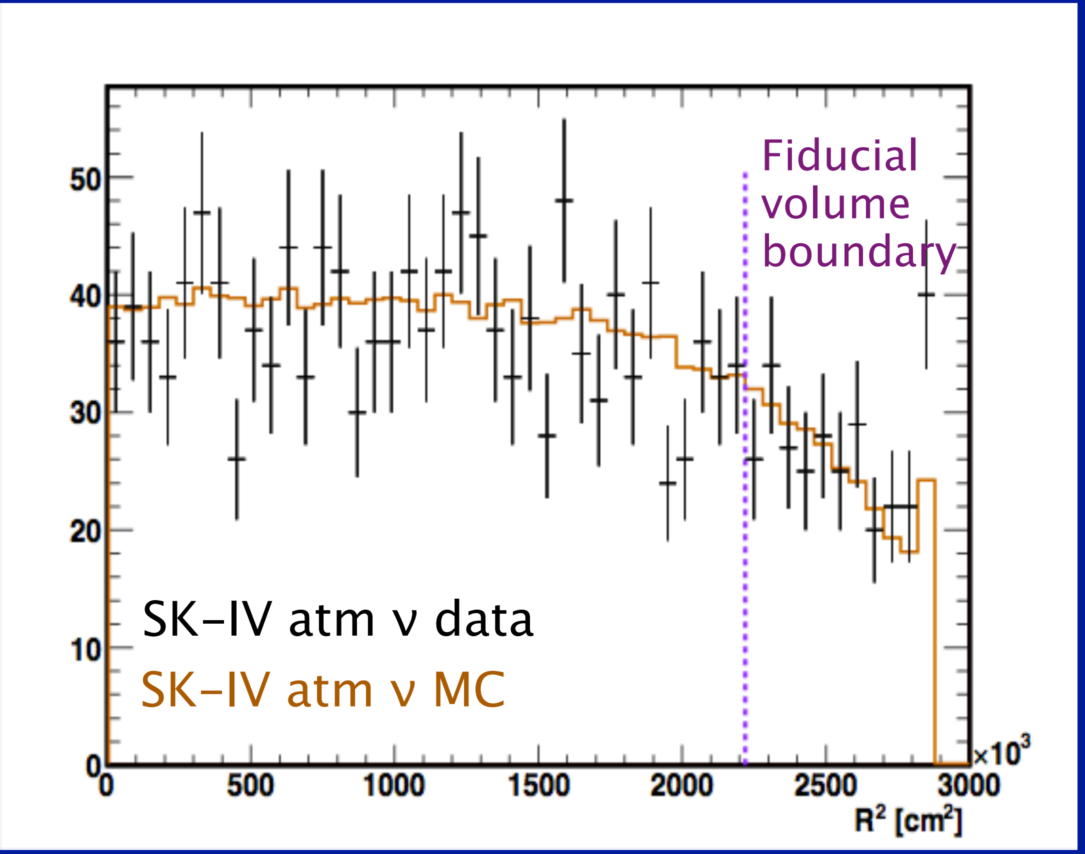
- The 6 observed events tends to cluster to high value of R^2
- Test of vertex distributions give P-values ~ (0.14-5.8)%
- More inclusive samples and atmospheric data show no anomalies near the edge of the Fiducial Volume



Events passing all the ν_e cuts except FV → no excess outside FV → no indication of entering background



SK IV Sub-GeV e-like + T2K cuts → good agreement data/MC inside and outside FV → no indication of SK reconstruction effects



T2K physics results: ν_e appearance

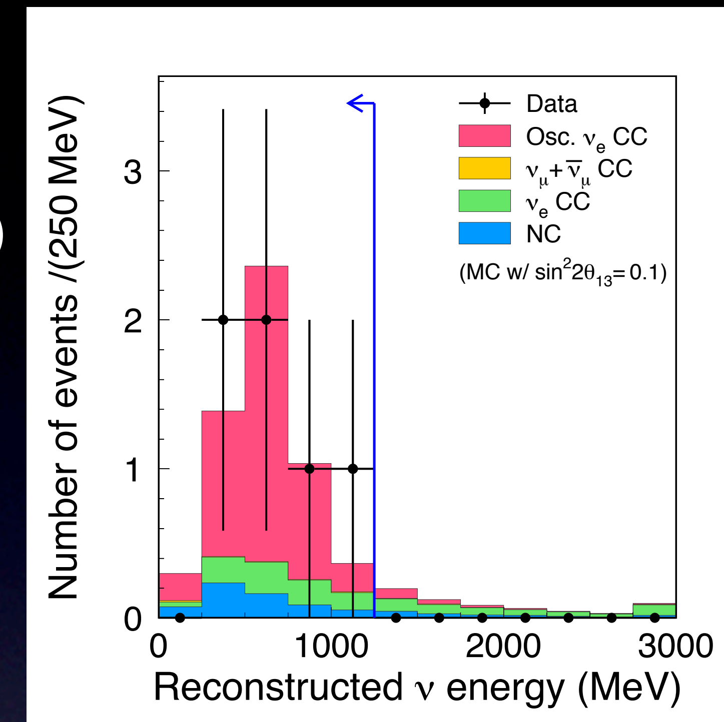
- 6 e-like events compatible with $\nu_\mu \to \nu_e$ oscillation
  - Expected background → 1.5±0.3 events (from beam ν_e and π^0)
- Probability of observing N=6 if $\sin^2(2\theta_{13})=0$ → 0.7% (2.5σ)

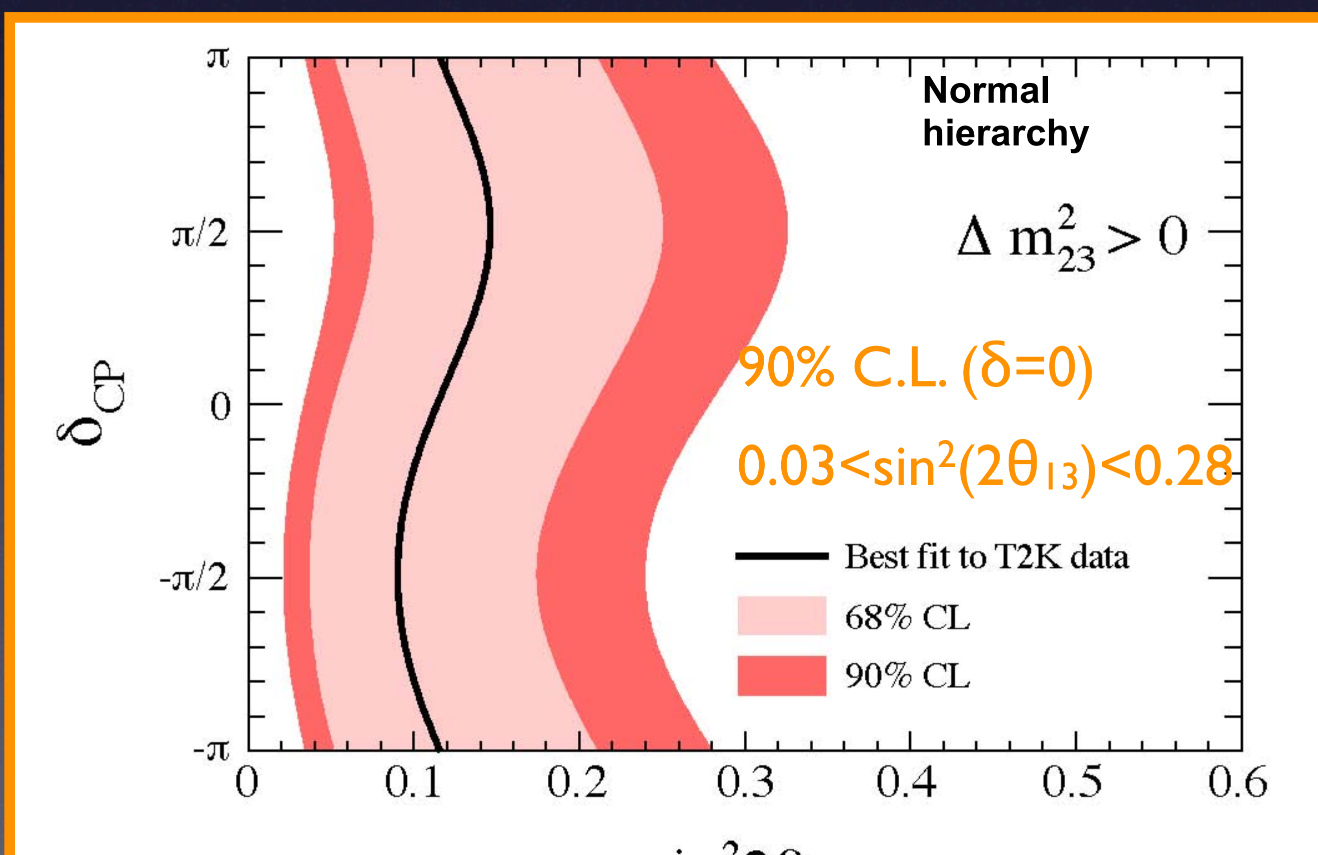
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{13} sin^2\theta_{23} sin^2\Delta + \alpha f(\delta_{CP})$$

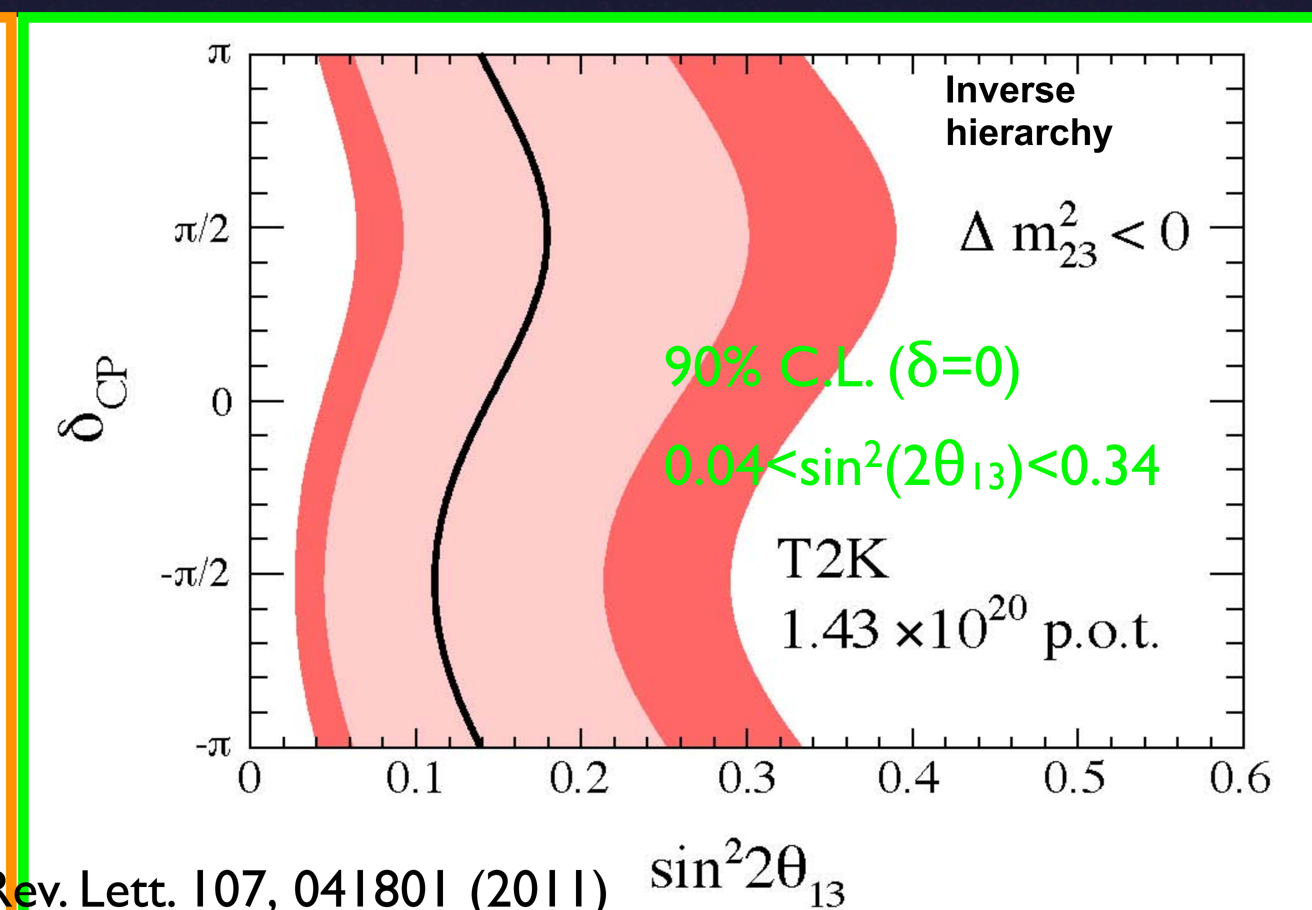
$$\Delta = 1.27\Delta m^2_{23} L/E$$

$$\alpha = \Delta m^2_{12}/\Delta m^2_{23} \sim 1/30$$

- Indication of ν_e appearance in ν_μ beam!



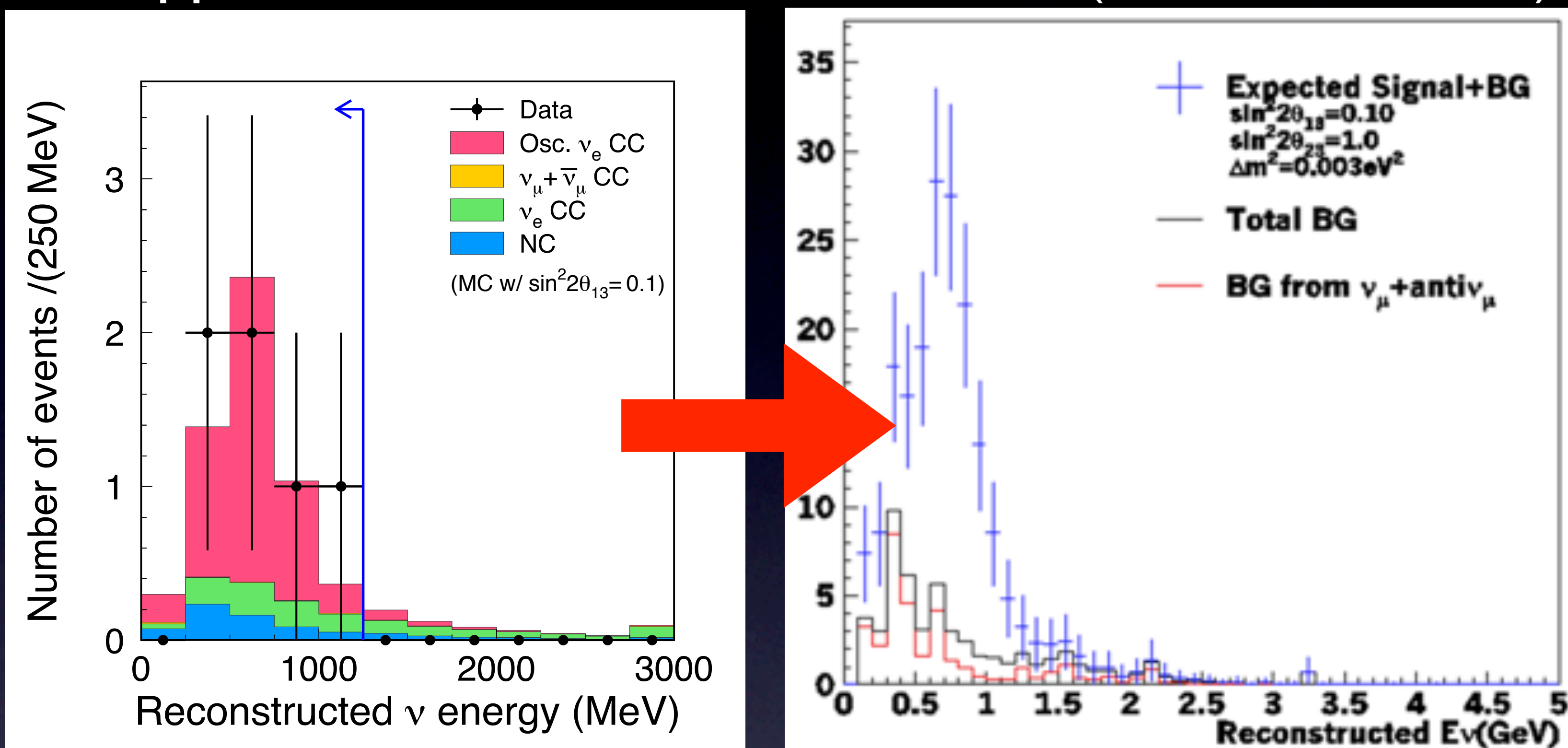


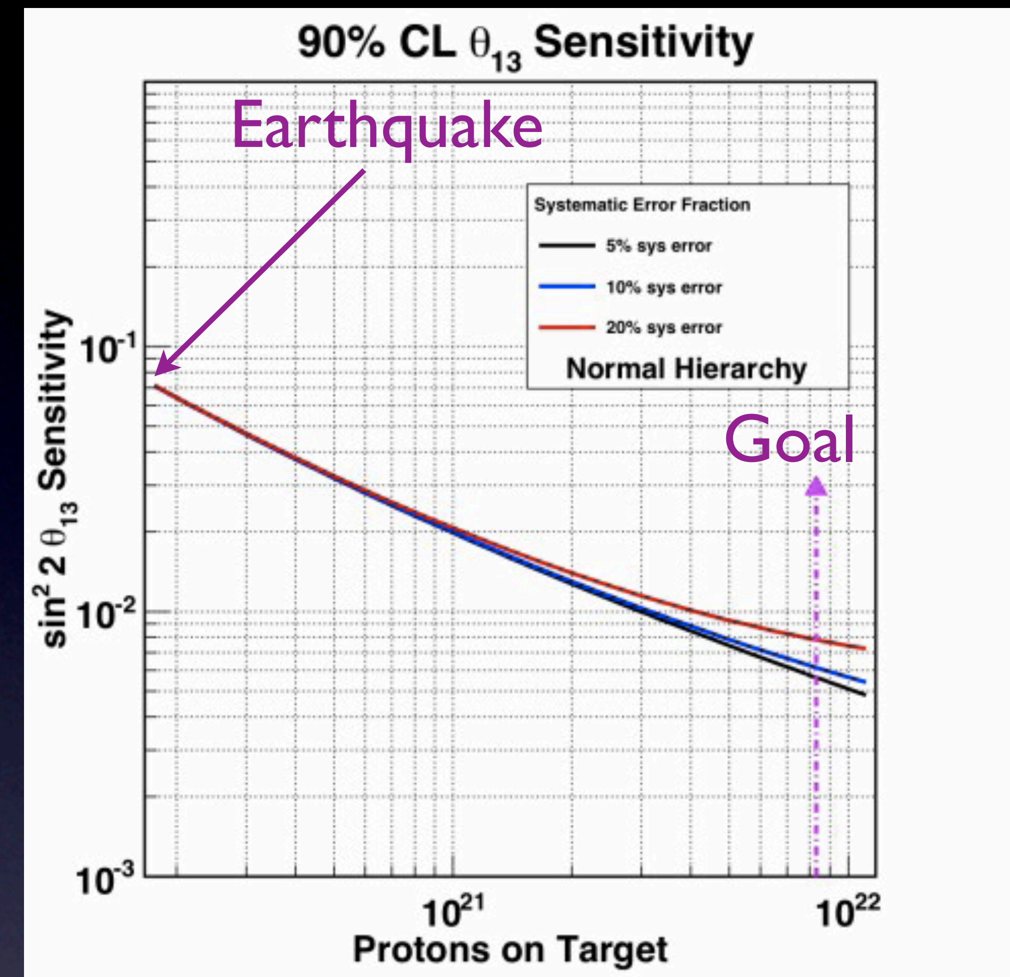


Results published in Phys. Rev. Lett. 107, 041801 (2011)

T2K ν_e appearance perspectives

ν_e appearance: from 6 events to >100 (for $\sin^2 2\theta_{13}$=0.1)

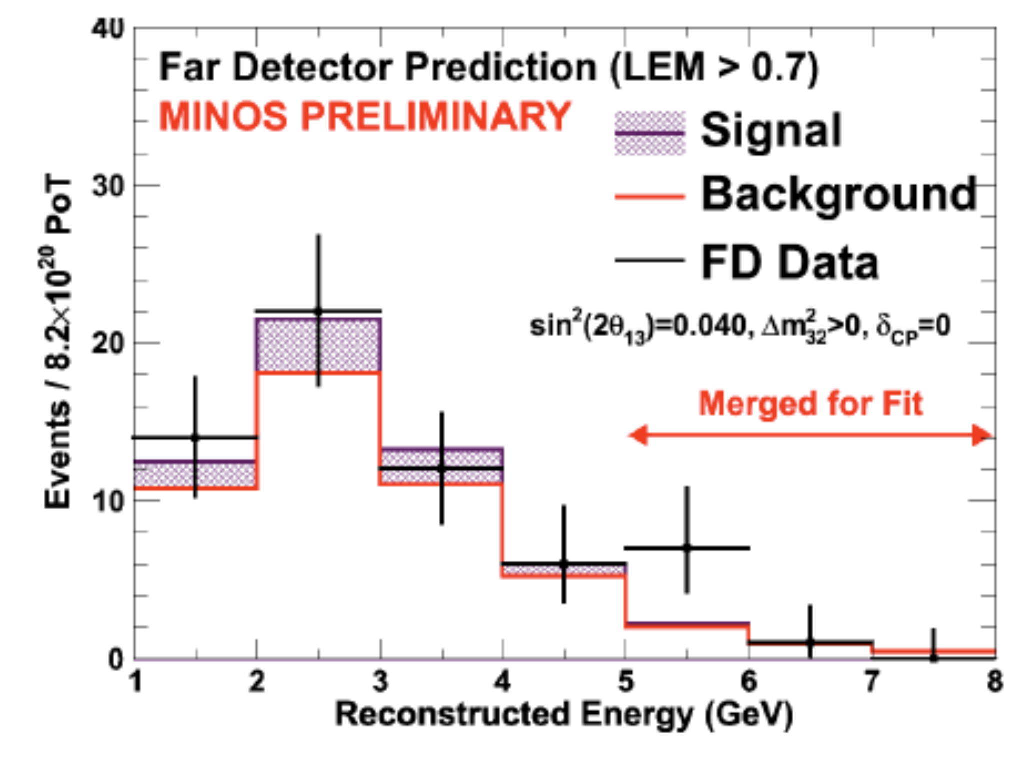




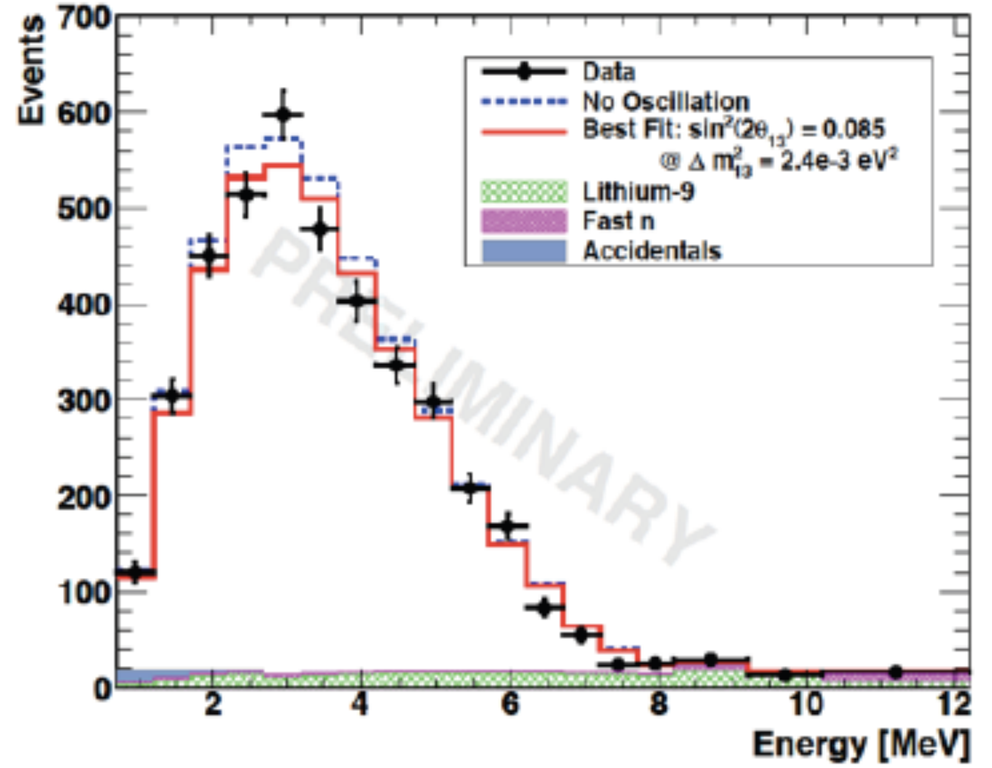
- At the end of the T2K data taking we expect to observe more than 100 events in ν_e appearance (for $\sin^2 2\theta_{13}$=0.1)
- This will allow us to make a precise measurement of θ_{13} or to set a limit on $\sin^2(2\theta_{13})\leq 0.02$

Minos and Double Chooz

- Minos: accelerator experiment
- Main goal was θ_{23} measurement
- Not optimized to track electrons → large NC background
- $N_{obs} = 62$, $N_{exp}(\theta_{13}=0) = 50$
- Best fit: $\sin^2(2\theta_{13})=0.04$ (0.08) for normal (inverted) hierarchy and $\delta=0$)
- Exclude $\theta_{13}=0$ @ 89% C.L.



- Semi-Double Chooz (only Far Det)
- Reactor experiment
- ν_e disappearance from reactors
- Rate+Shape analysis
  - $\sin^2(2\theta_{13})=0.085\pm0.029(\text{stat})\pm0.042$ (syst)
- No degeneracies with δ and hierarchy



T2K next physics run

- Our data taking was interrupted after the 11th March Big Earthquake in Japan
- Since then:
  - We released physics analyses based on the available statistics
  - We worked to recover the JPARC facility and the T2K experiment
  - Only beam and ND280 were affected by the earthquake → no problems at SK
- So far all the damages have been repaired
- We will restart the operation of the JPARC accelerators this month
- If the beam re-commissioning goes well we will start the third T2K physics run at the end of January
- We hope to present results with new data set at Neutrino12 conference at Kyoto in June 2012

Conclusions

T2K

- The T2K experiment has completed two oscillation analyses based on 1.43×10^{20} p.o.t (2% of T2K's goal)
- ν_e appearance analysis:
  - 6 events have been observed (1.5±0.3 expected)
  - The probability of 6 events with $\theta_{13}=0$ is 0.7% (2.5σ significance)
  - This lead to a 90% confidence interval of $0.03(0.04)<\sin^2(2\theta_{13})<0.28(0.34)$ for normal (inverted) hierarchy and $\delta_{CP}=0$
  - Result published in PRL
- ν_μ disappearance analysis:
  - No oscillation hypothesis excluded at 4.5σ
  - $\sin^2(2\theta_{23})>0.85$ and $2.1\times10^{-3}<\Delta m^2_{23}$ $(eV^2)<3.1\times10^{-3}$ @ 90% C.L.
- The experiment is currently recovering from the 11th March earthquake
  - Hope to start the third T2K physics run in January

Back up slides

Superluminal neutrinos & T2K

- Official statement by T2K :
  - Based on our initial assessment of our capability, at the moment T2K cannot make any definitive statement to verify the Opera measurement of the speed of neutrino (Opera Anomaly).
  - We will assess a possibility to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future.Such a measurement with an improved system, however, could take a while to achieve.

- Time of flight in T2K :
  - Baseline is shorter: 300 km vs 700 km
  - Energy is lower: $E_\nu < 10$ GeV vs $E_\nu > 20$ GeV
  - Actual GPS synchronization precission ~100 ns.

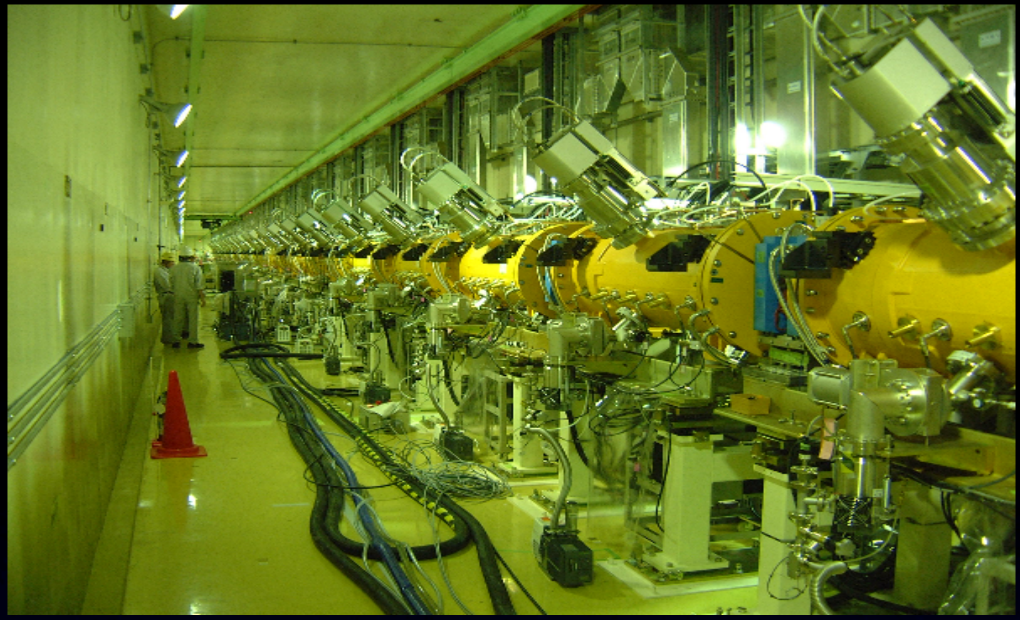
Linac

First stage accelerator, 330m in length.

Design energy is 400MeV.

At present, protons are accelerated to 181MeV.

Upgrade to the design energy is under preparation.



RCS (Rapid Cycling Synchrotron)

Second stage accelerator, Proton Synchrotron of 348m circumference.

The acceleration up to 3GeV is successfully working.

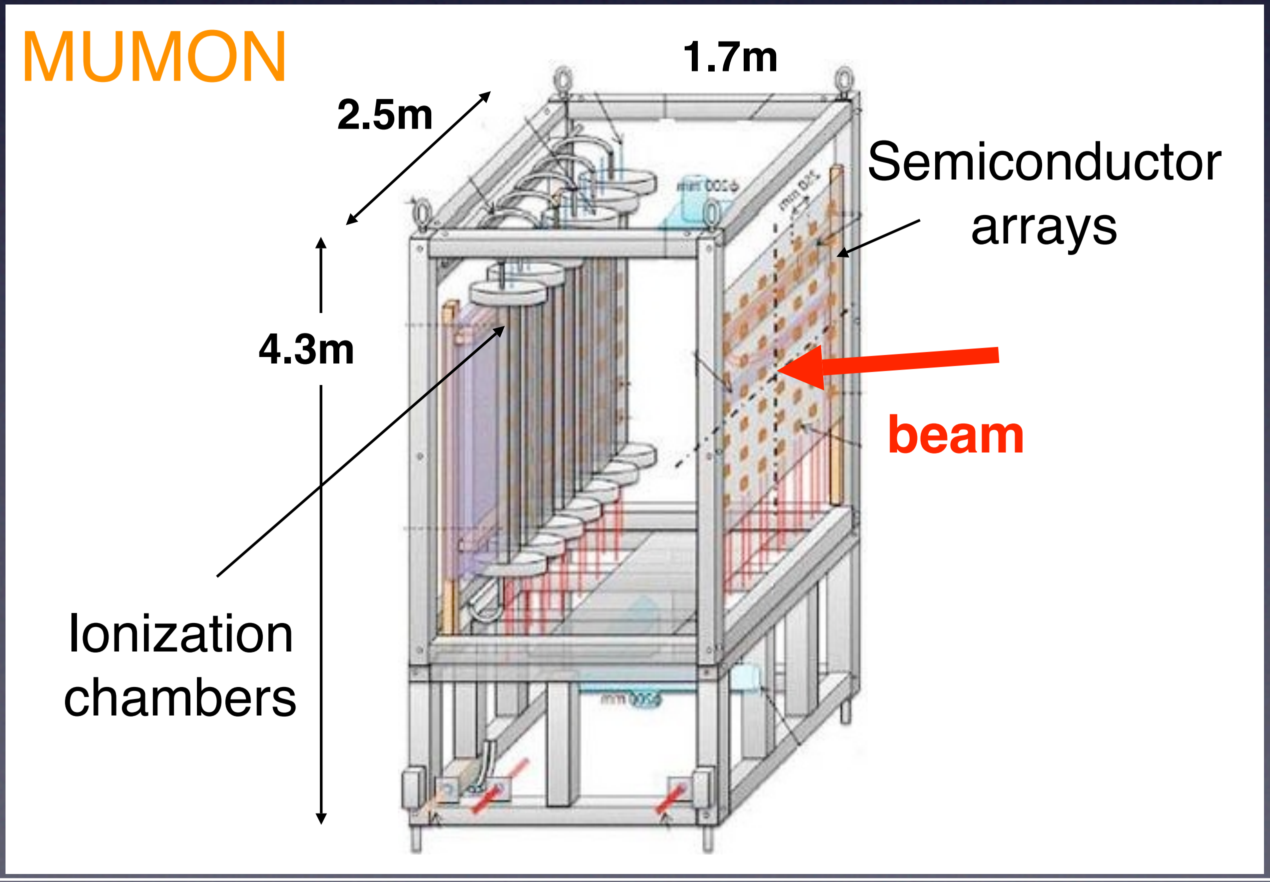
Main Ring

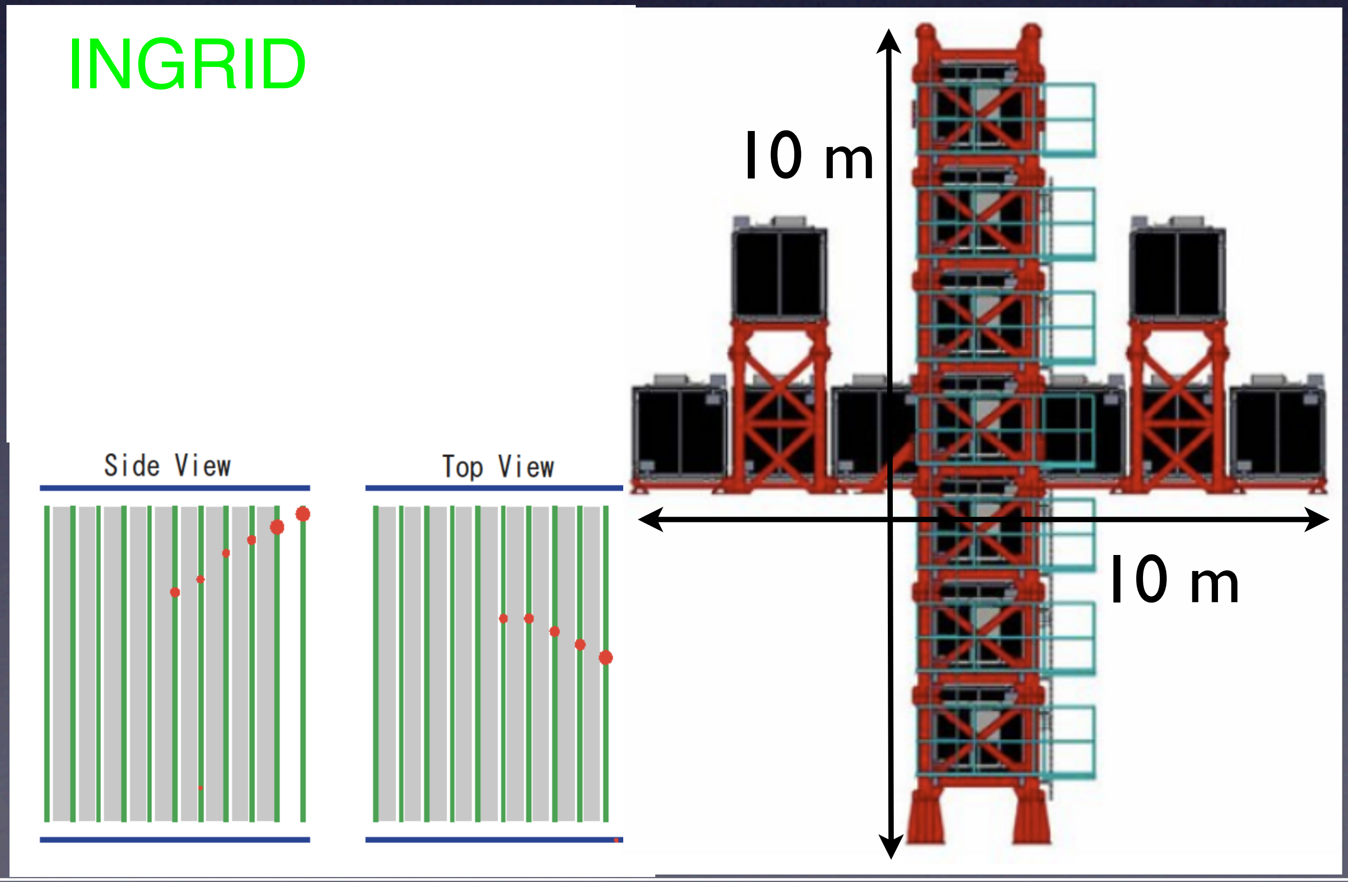
Third (and final) stage accelerator. Proton Synchrotron of 1568m circumference.

The 30 GeV proton beam is extracted to the neutrino beamline. The beam is shared by T2K and the experiments in the hadron hall.

MUMON and INGRID

- Muon monitor (MUMON): installed after the beam dump
  - Monitor the beam on a spill-by-spill basis looking at high energy muons
  - Composed by ionization chambers and semiconductor arrays
- On-axis Near Detector (INGRID): on axis in the Near Detector complex
  - Monitor the beam stability on a day-by-day basis looking at ν interactions
  - 16 cubic modules: 1 module is a sandwich of 10 iron and 11 scintillator layers

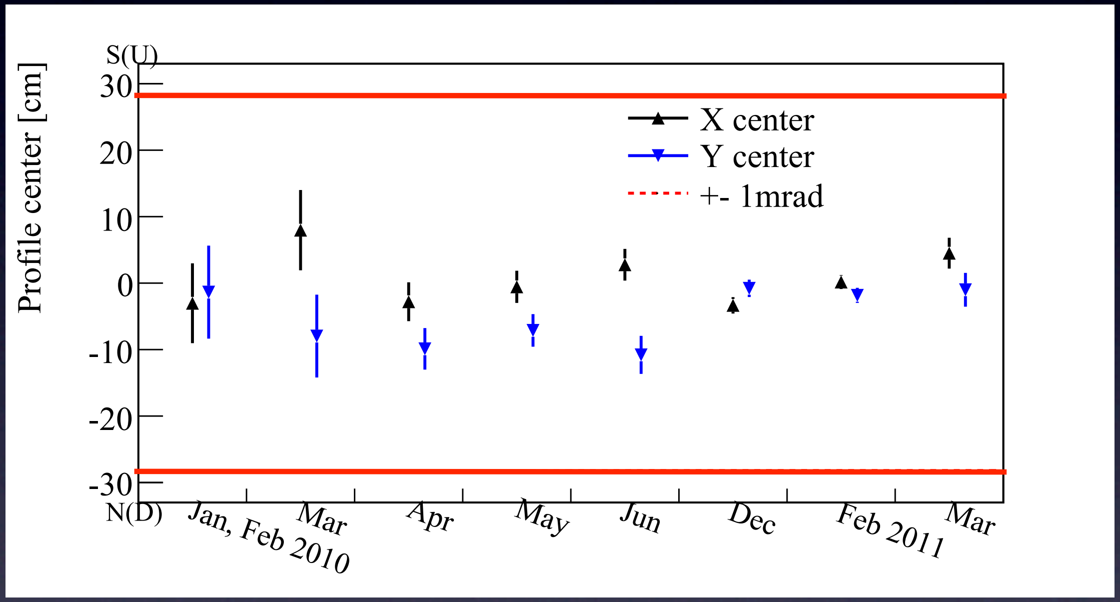




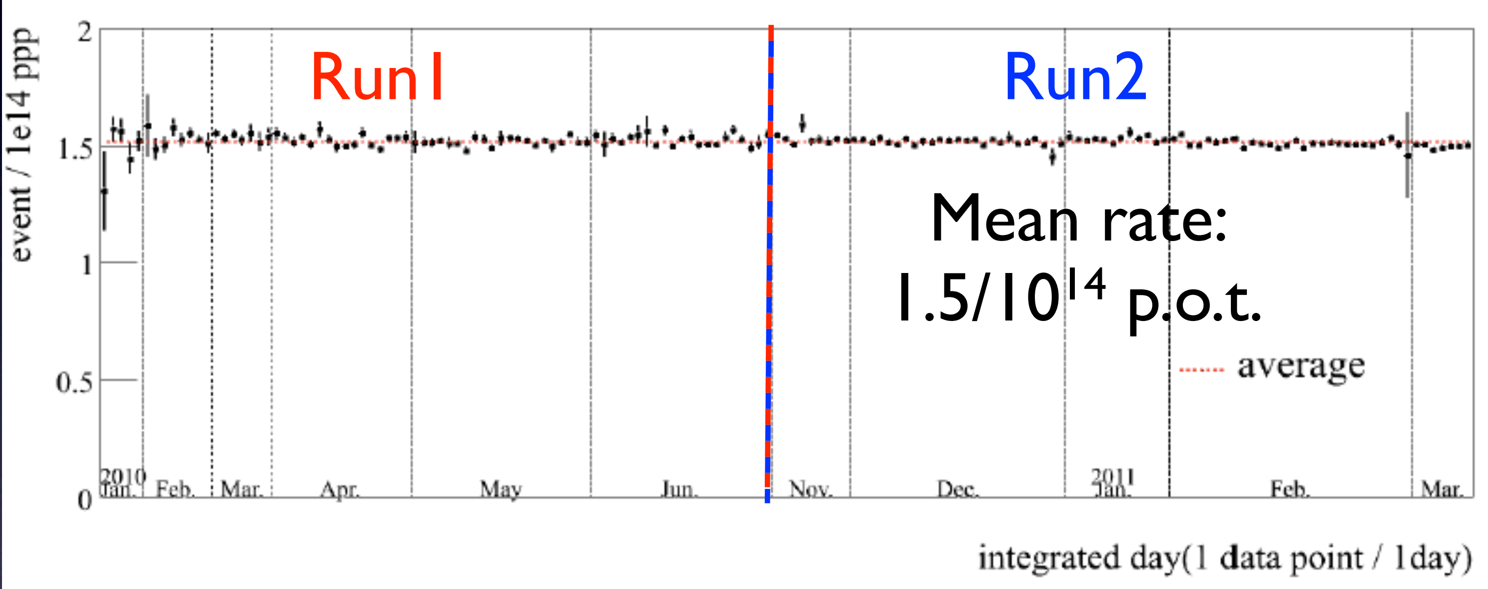
Beam stability

- Necessary to keep the beam direction stable to ensure the stability of the neutrino peak energy: δ(dir)<1 mrad → δ(E)/E<2% @ SK

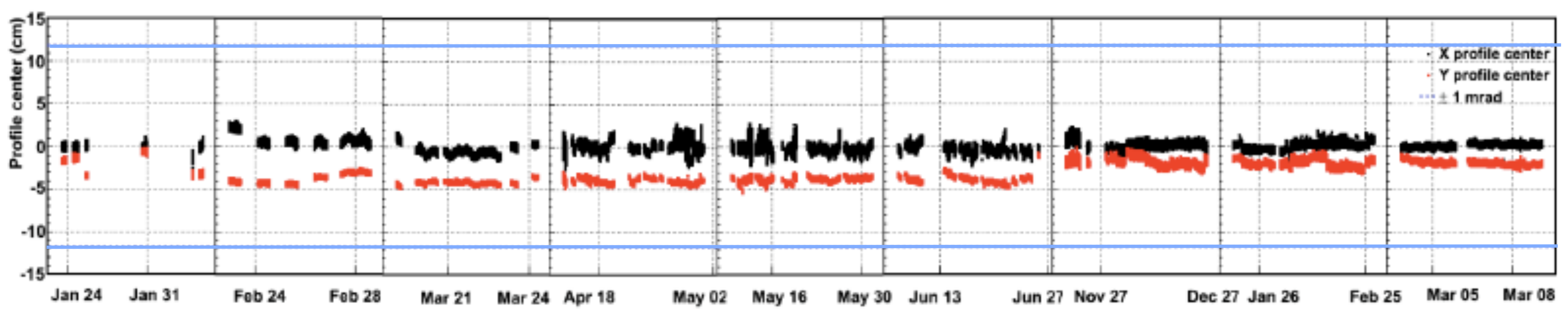
Beam center measured at INGRID well within 1 mrad



INGRID interaction rate stable for Run1 and Run2

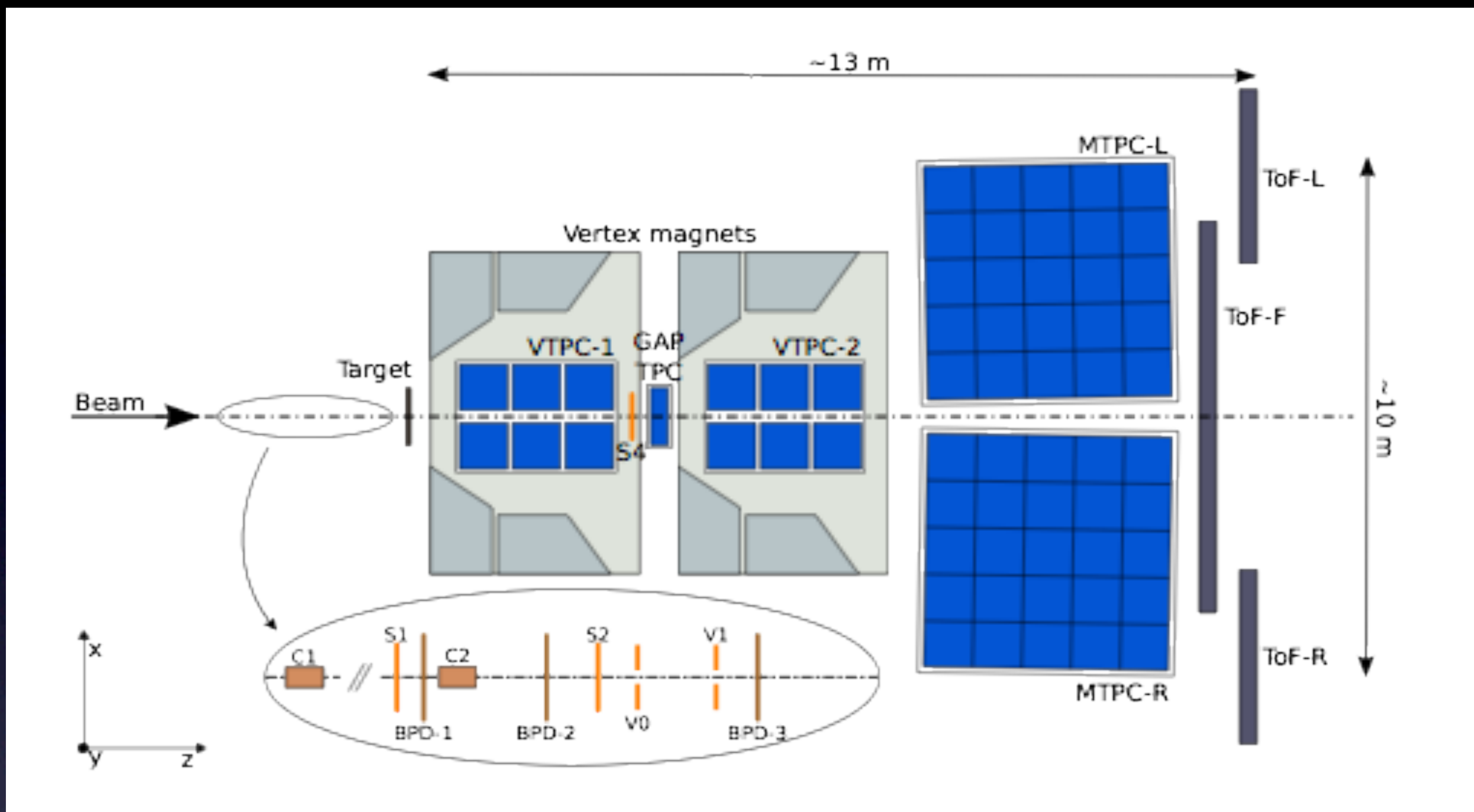


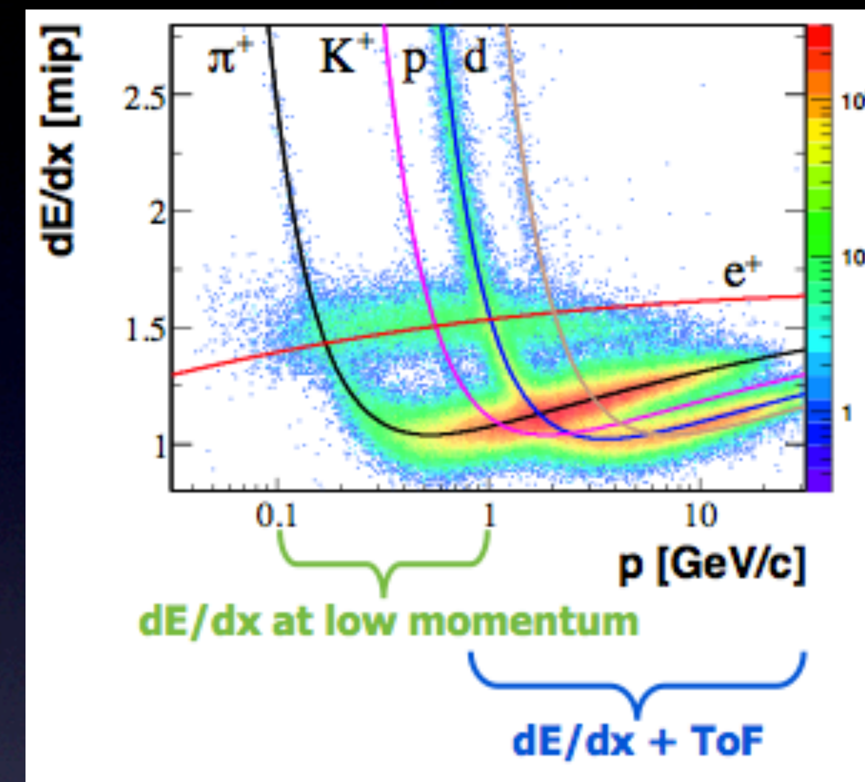
Beam center measured at MUMON well within 1 mrad

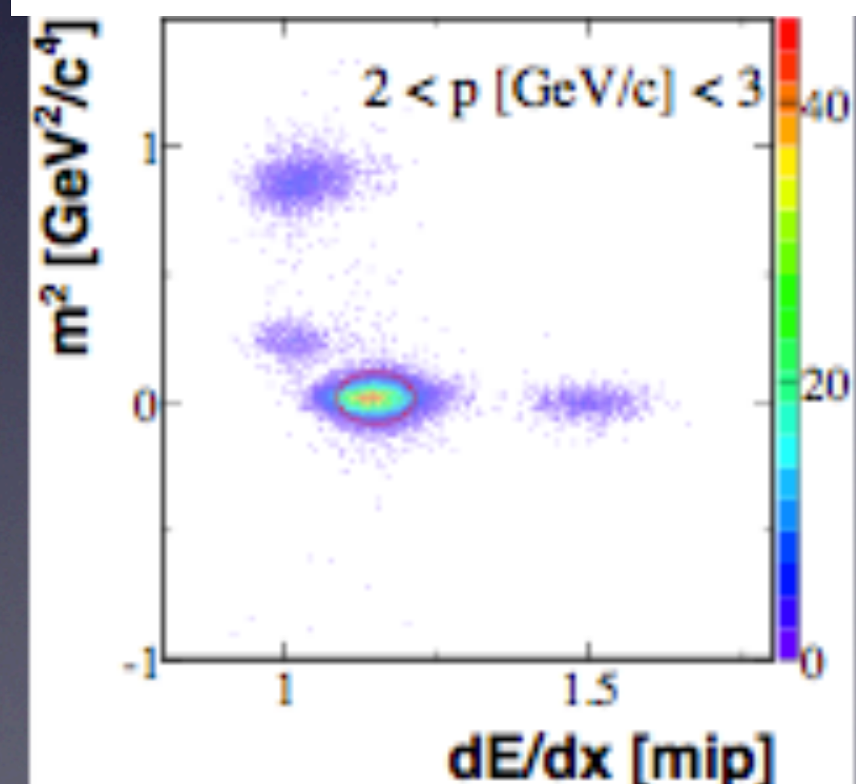


CERN NA61/SHINE experiment

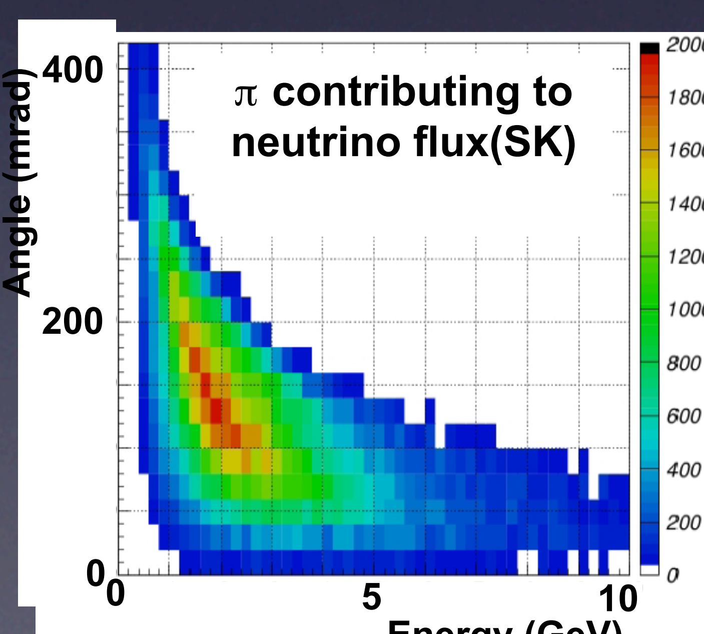
π^+ production: Two analysis for different momentum region



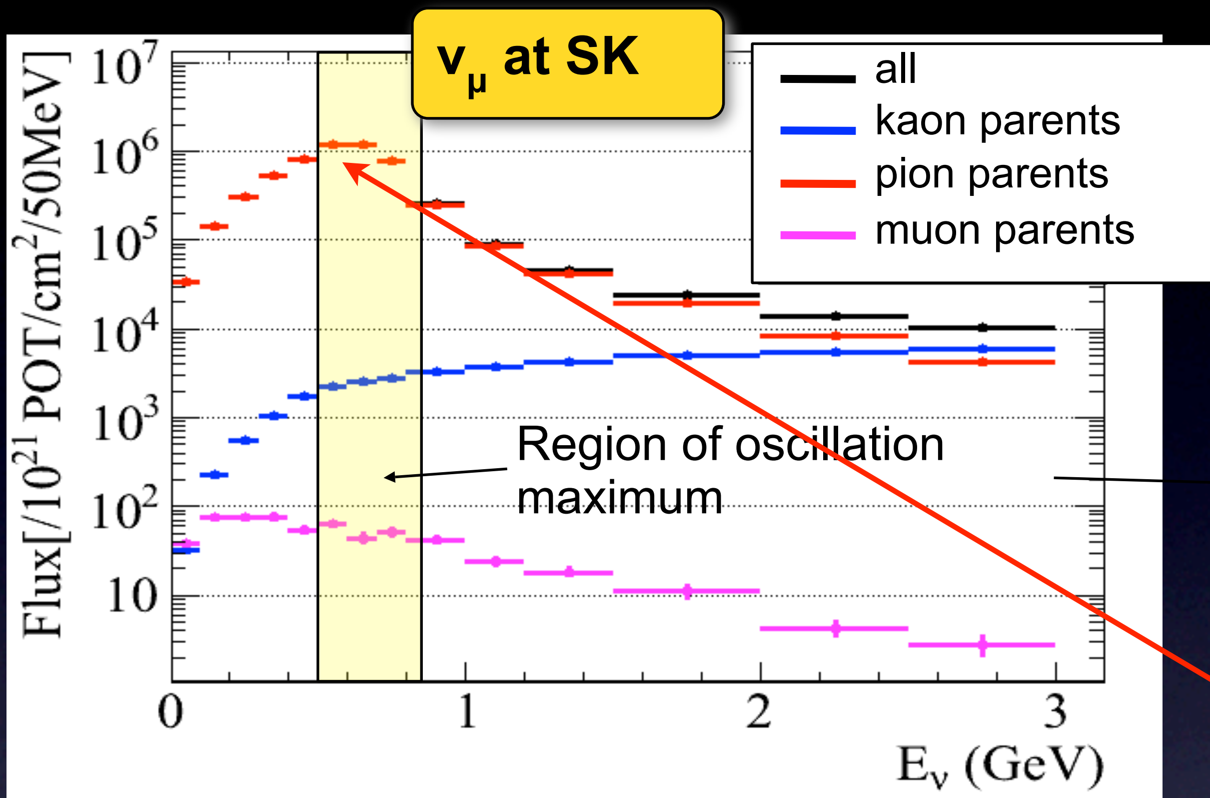


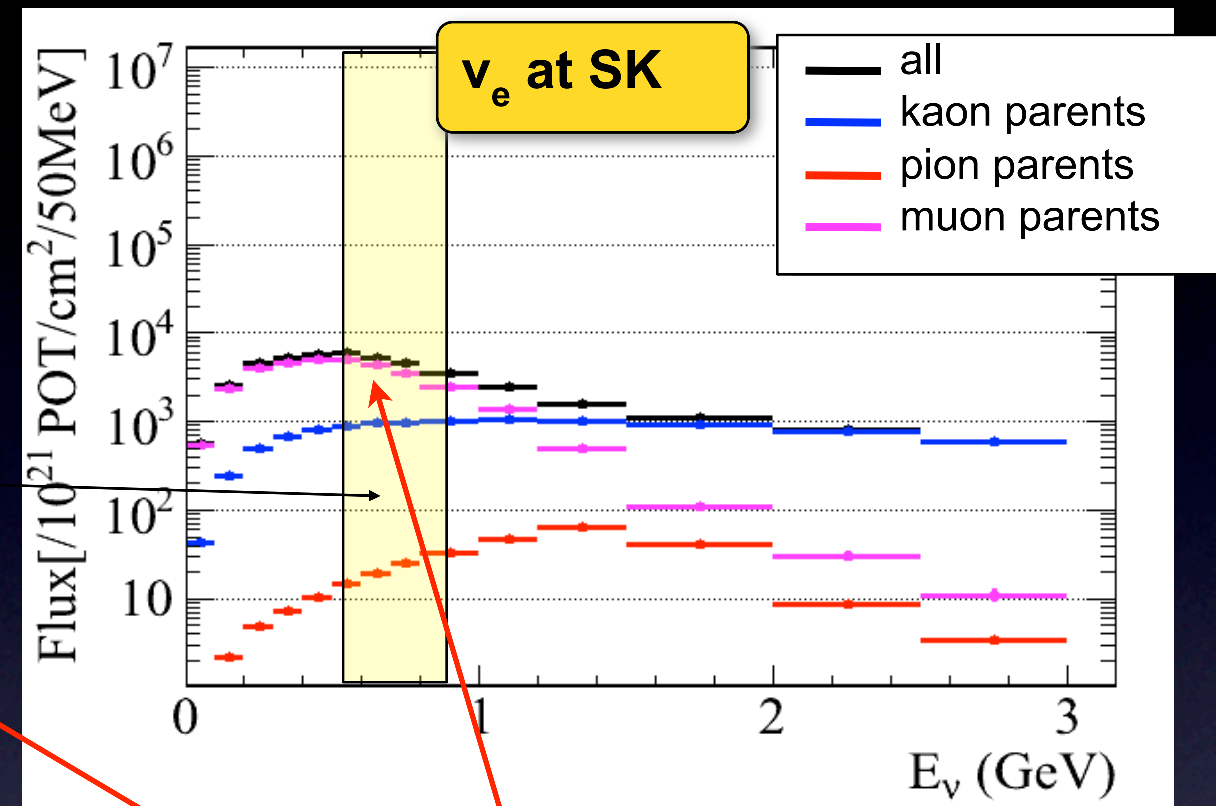


- Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction
- Thin target + T2K replica target



Expected ν fluxes and uncertainties





Systematics for ν_e appearance

Error source	$R_{ND}^{\mu, MC}$	N_{SK}^{MC}	$\frac{N_{SK}^{MC}}{R_{ND}^{\mu, MC}}$
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

Expected beam ν_e contamination: ~1% of the total flux in the oscillation region

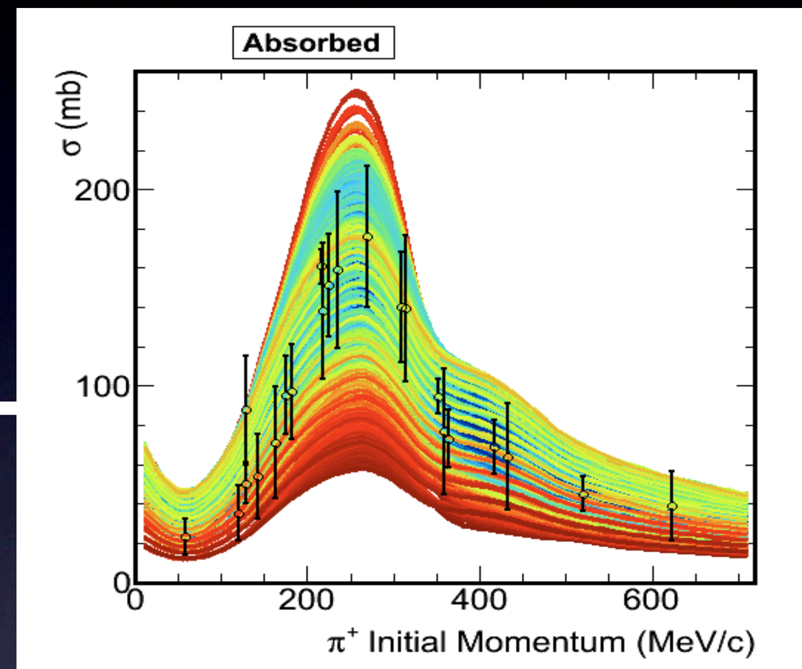
The uncertainty on the fluxes is significantly reduced when the expected event rate at the near detector is used

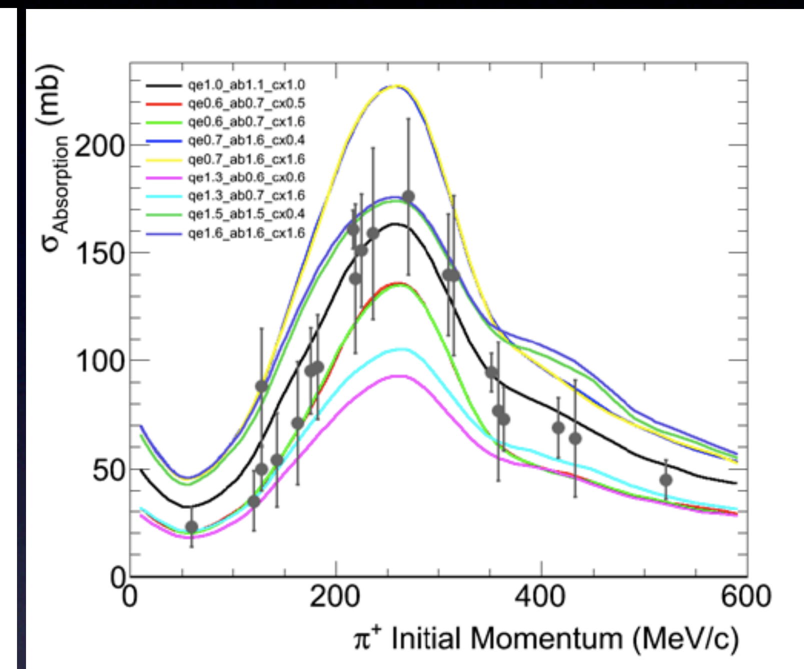
FSI tuning

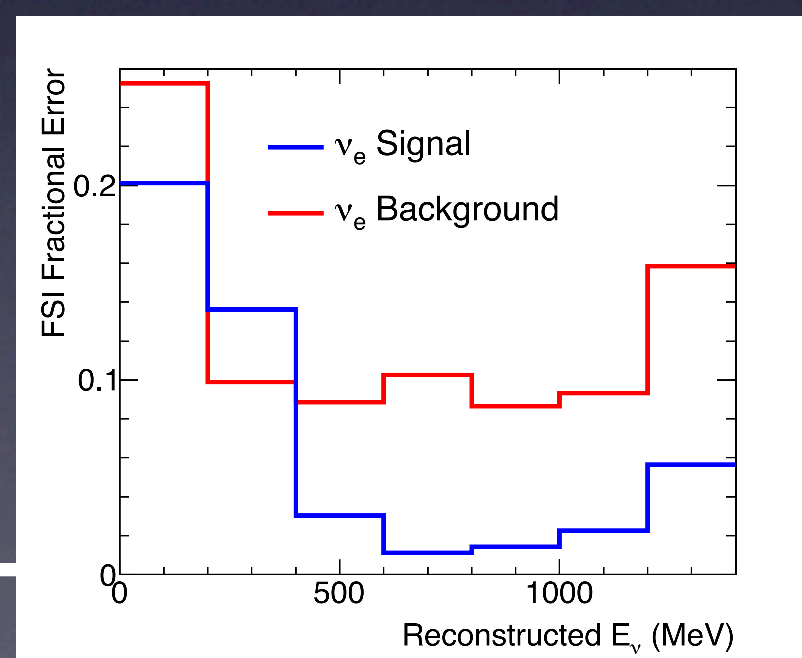
- 14% of the systematic on the background to the ν_e appearance, 8% to the ν_μ disappearance
- Principal source of uncertainty: pion final state interaction (FSI)

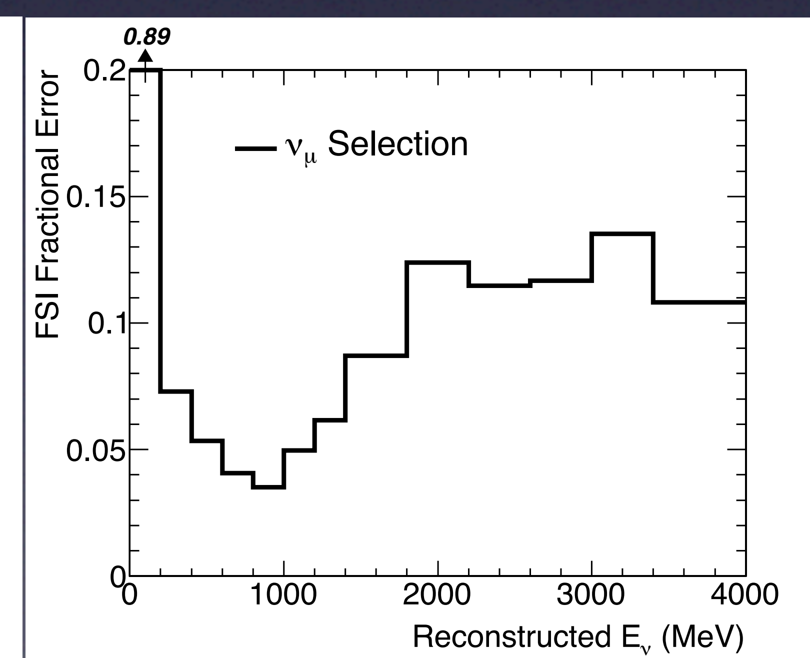
Error source	N^{exp}(SK)
CCQE shape	3.1%
CC1π	2.2%
CC coherent π	3.1%
CC other	4.4%
NC1π0	5.3%
NC coherent	2.3%
NC other	2.3%
σ(νe)	3.4%
FSI	10.1%
Total	14.0%

Studied by adjusting NEUT microscopic pion cross section model and comparing to pion cross section data

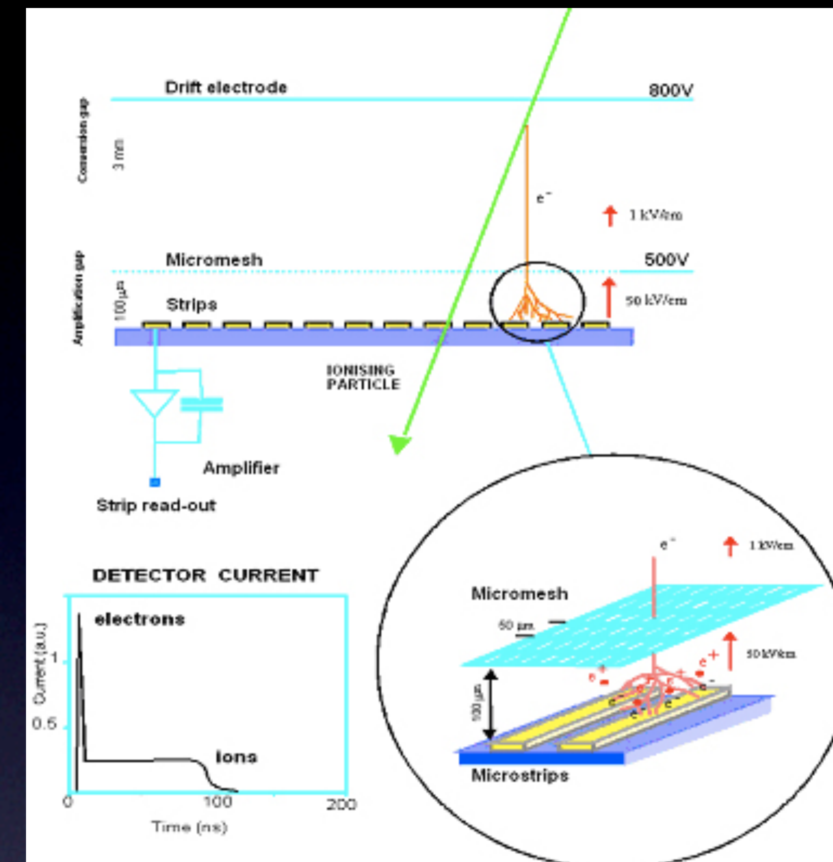




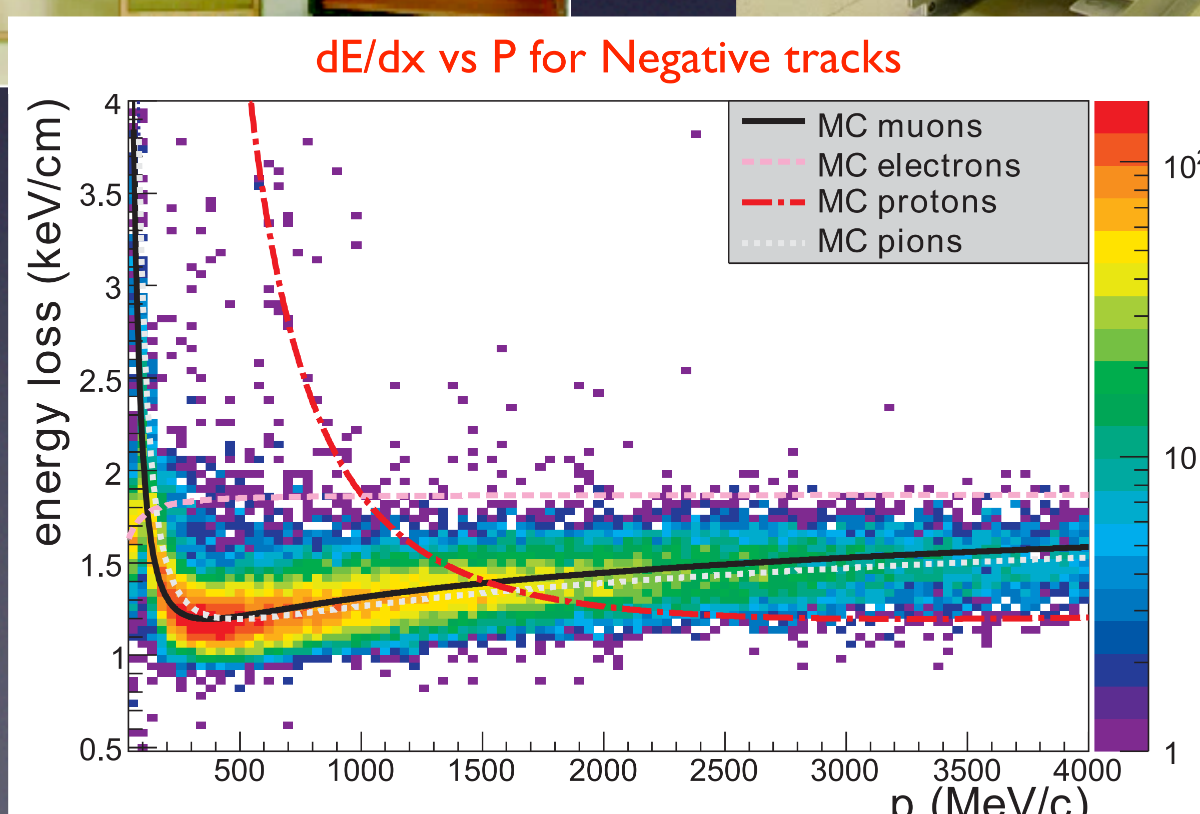




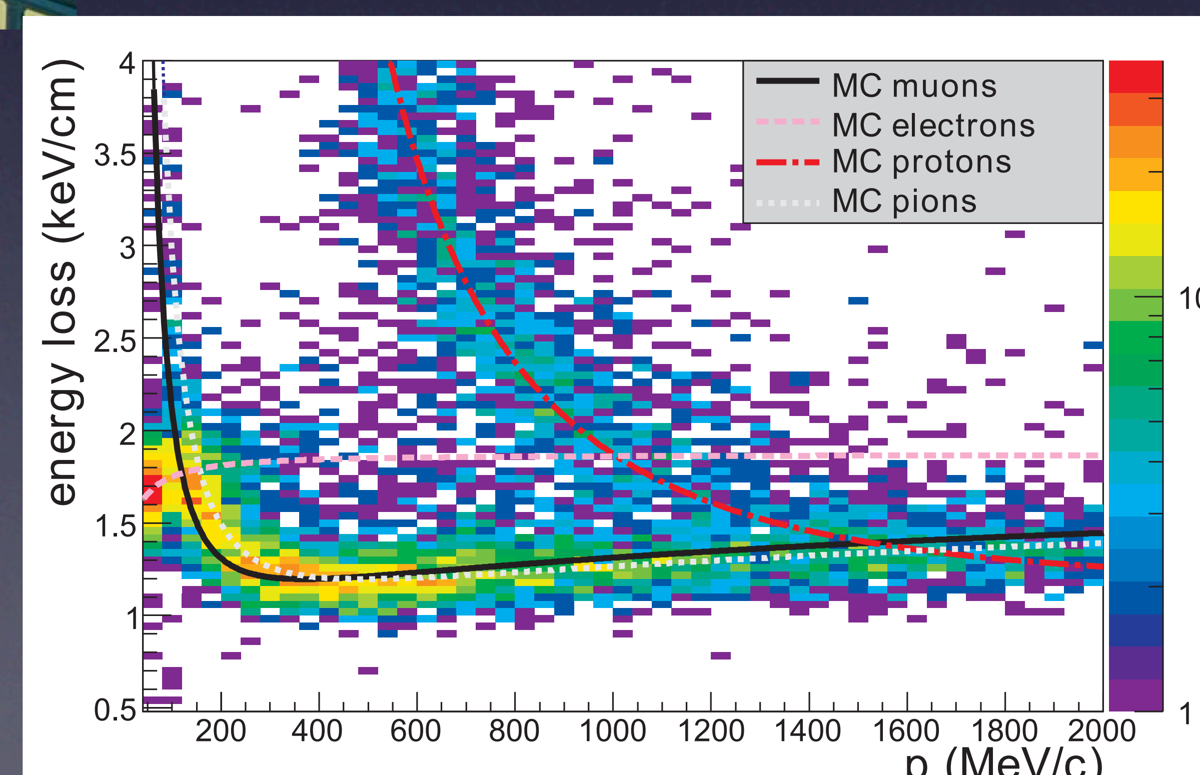
ND280 TPC



Drift electrode
800V
Micromesh
500V
Strips
IONISING PARTICLE
Amplifier
Strip read-out
DETECTOR CURRENT
electrons
ions
Time (ns)
Micromesh
Microstrips

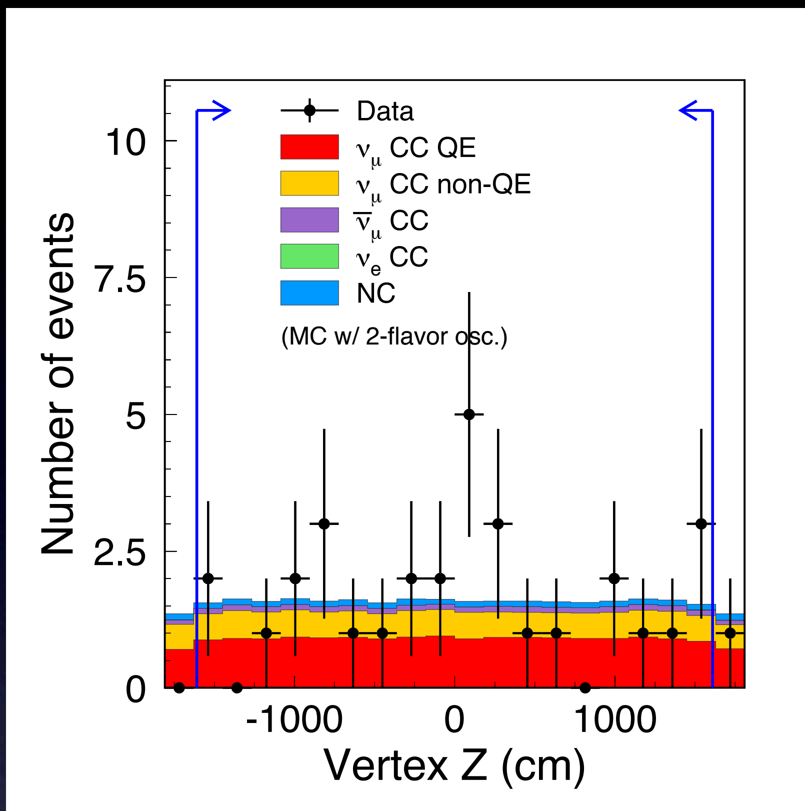


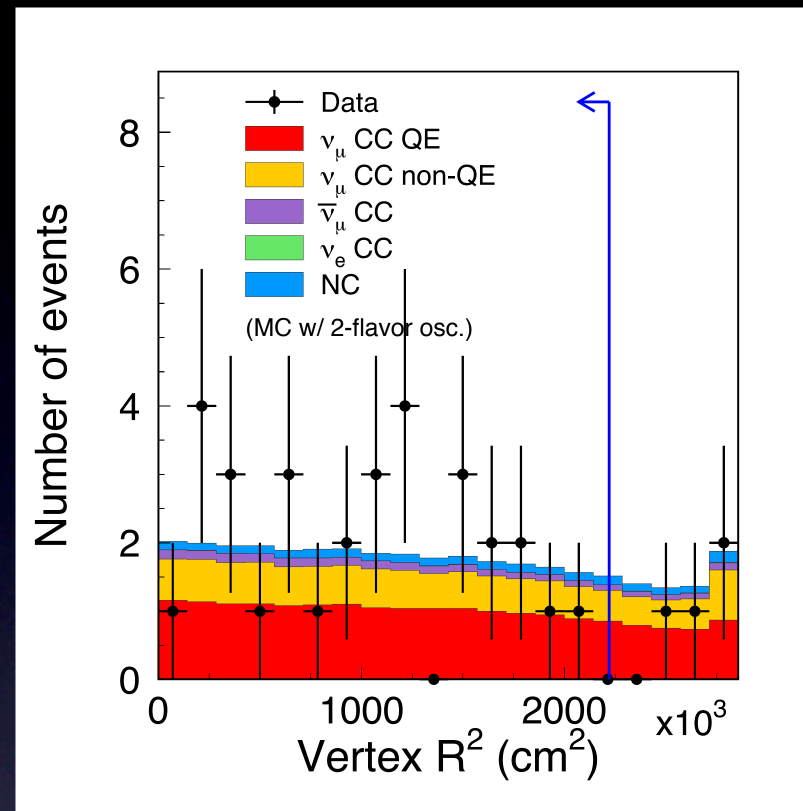
dE/dx vs P for Negative tracks
energy loss (keV/cm)
p (MeV/c)
MC muons
MC electrons
MC protons
MC pions

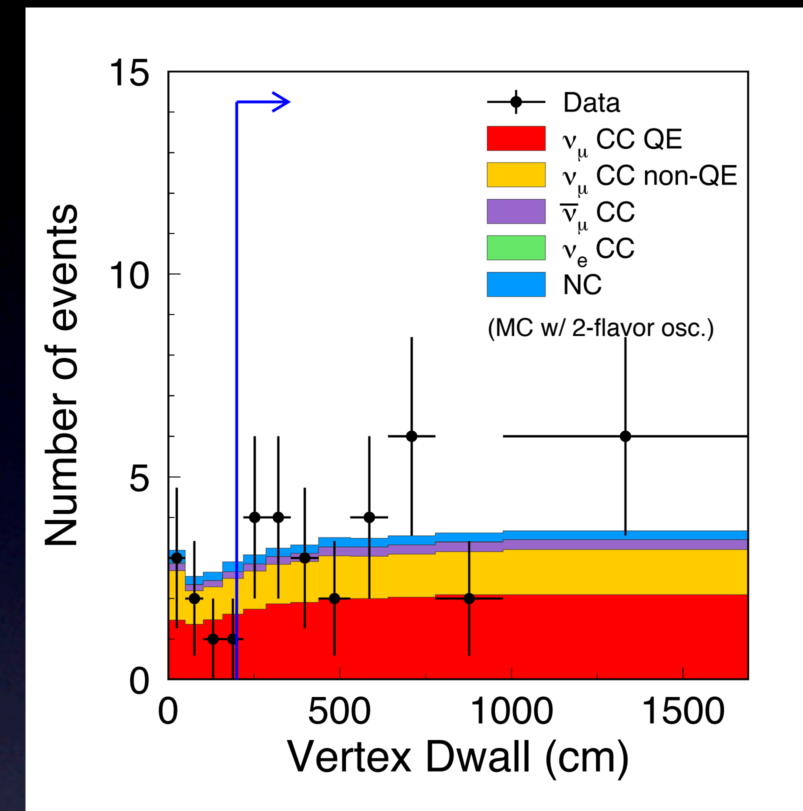


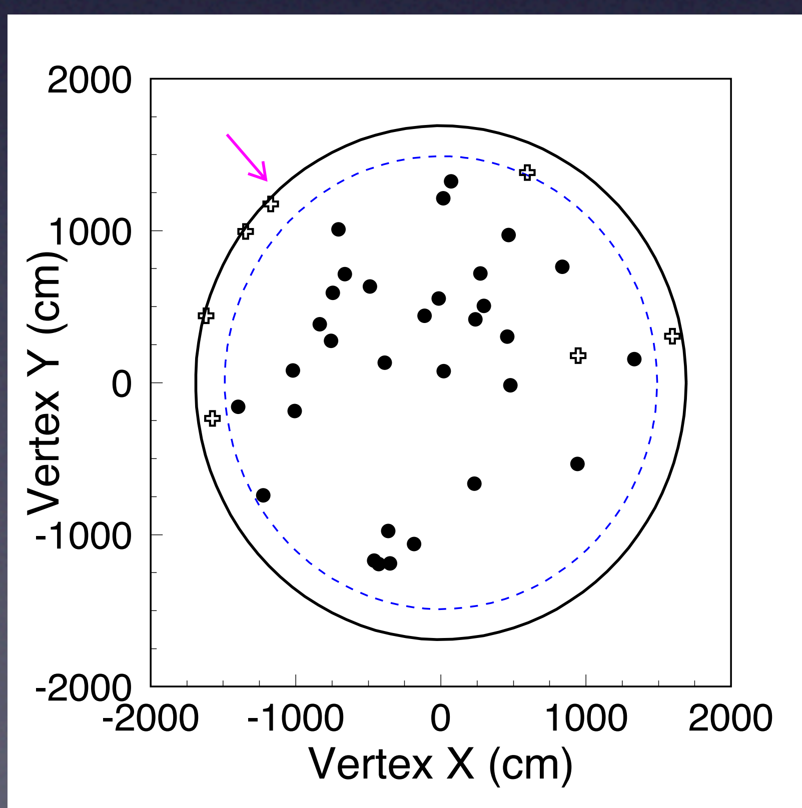
energy loss (keV/cm)
p (MeV/c)
MC muons
MC electrons
MC protons
MC pions

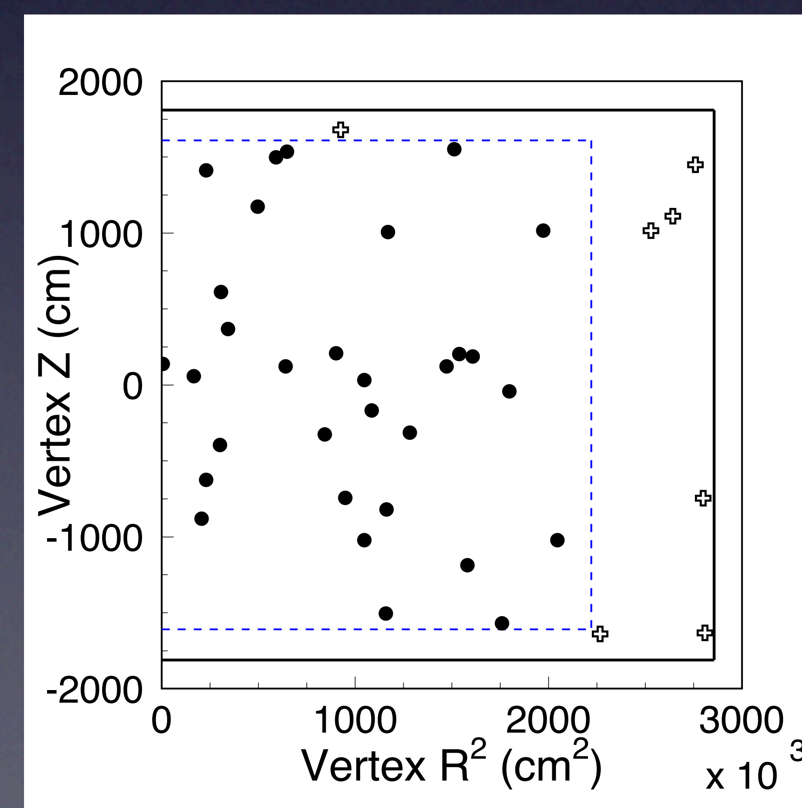
ν_μ disappearance vertex position





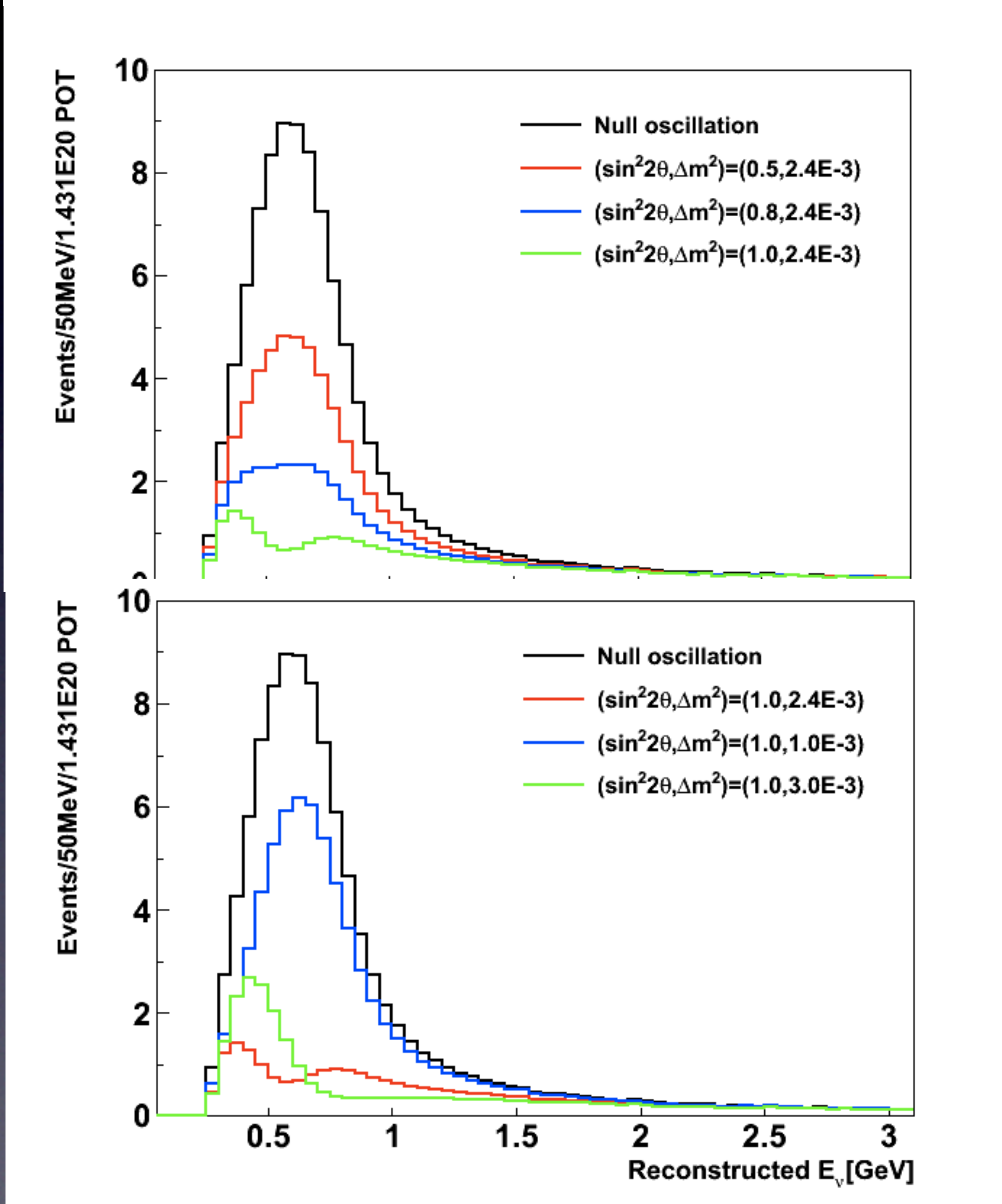




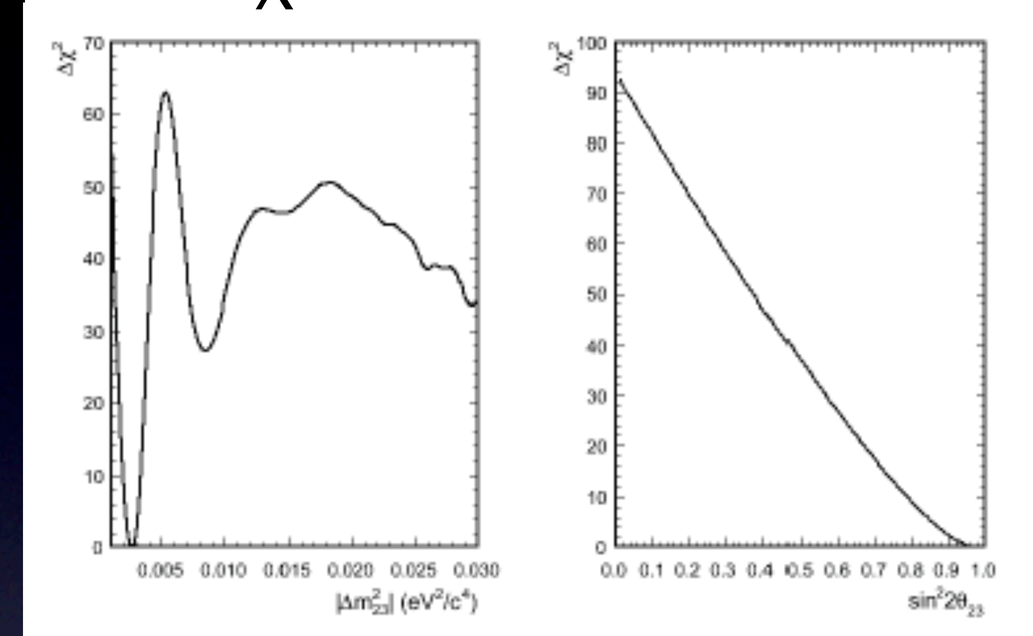


ν_μ disappearance

Expected spectrum

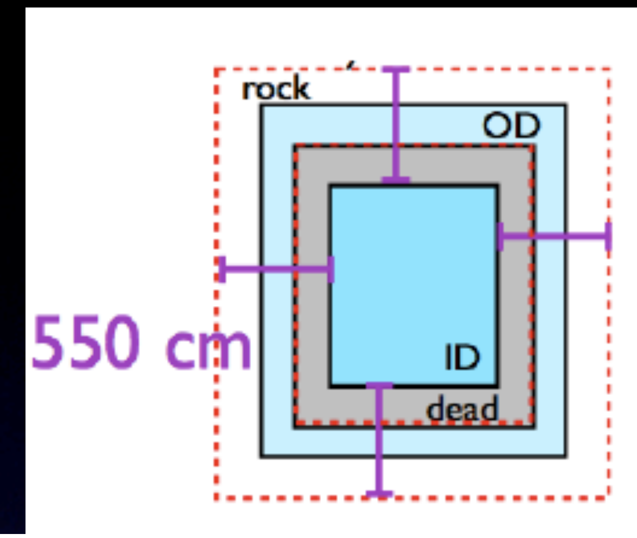


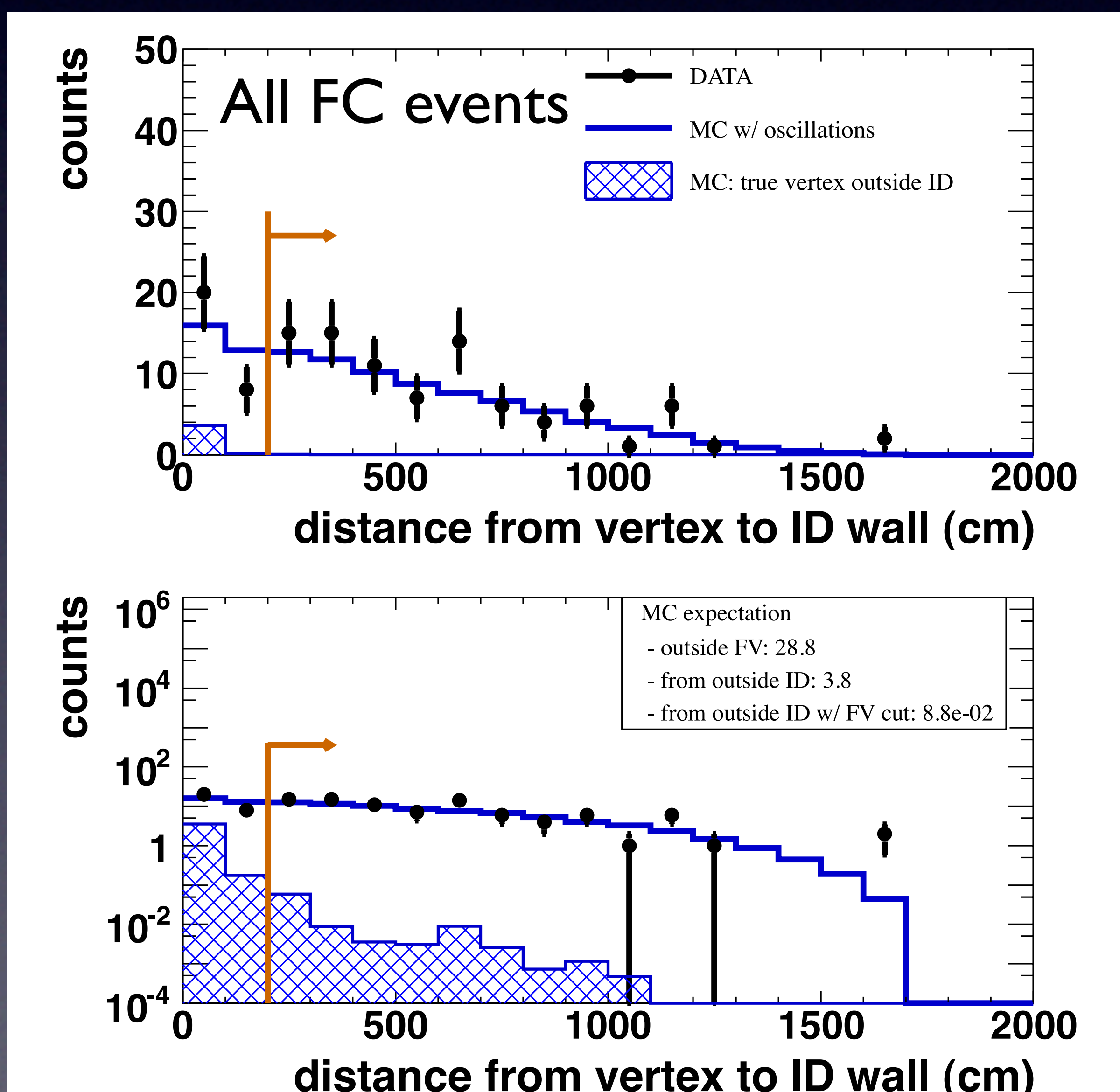
$\Delta\chi^2$ for Δm^2 and $\sin^2 2\theta$

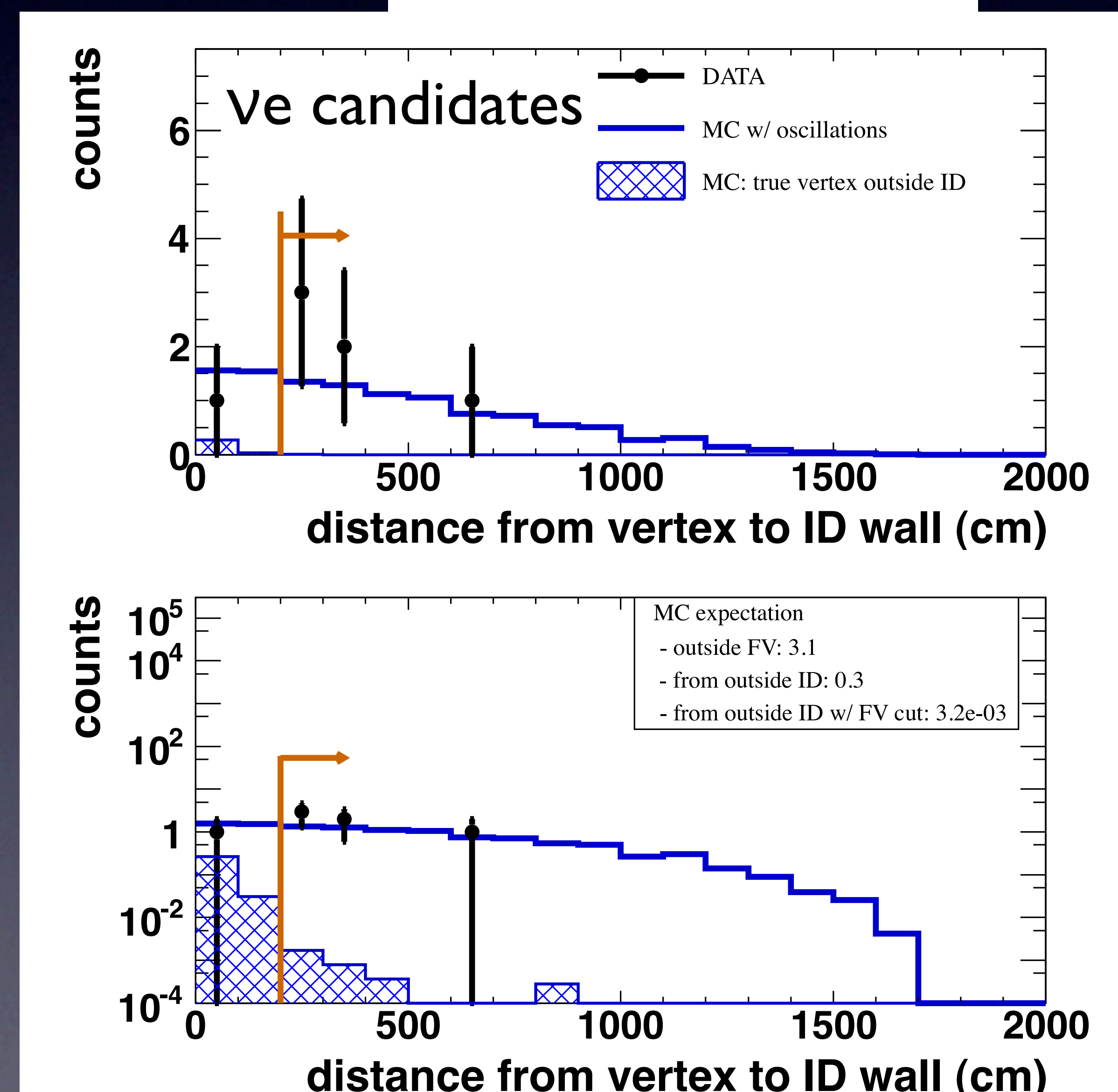


Out of FV contamination

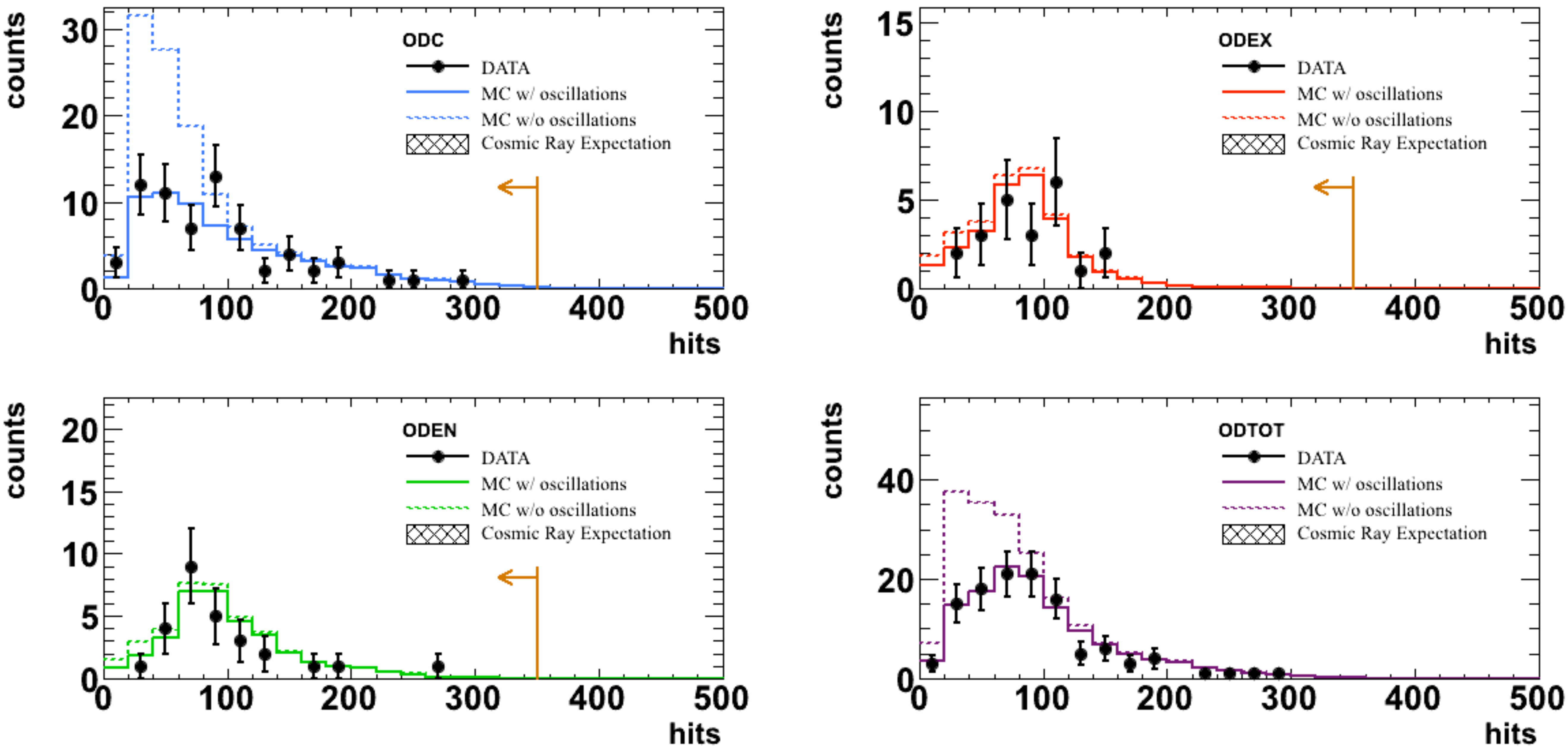
- Number of selected events with the exception of the fiducial volume cut
- Hatched histograms represent the contribution from vertices outside the ID





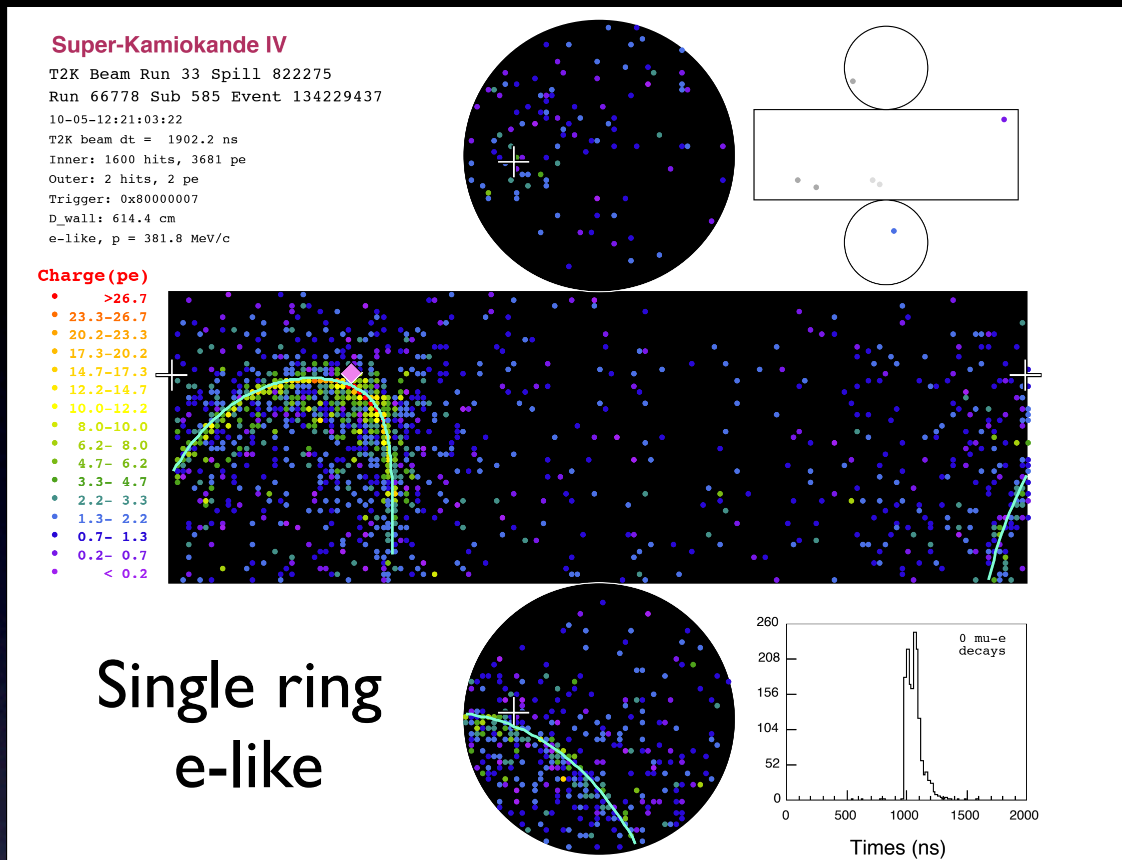


SK Outer Detector analysis

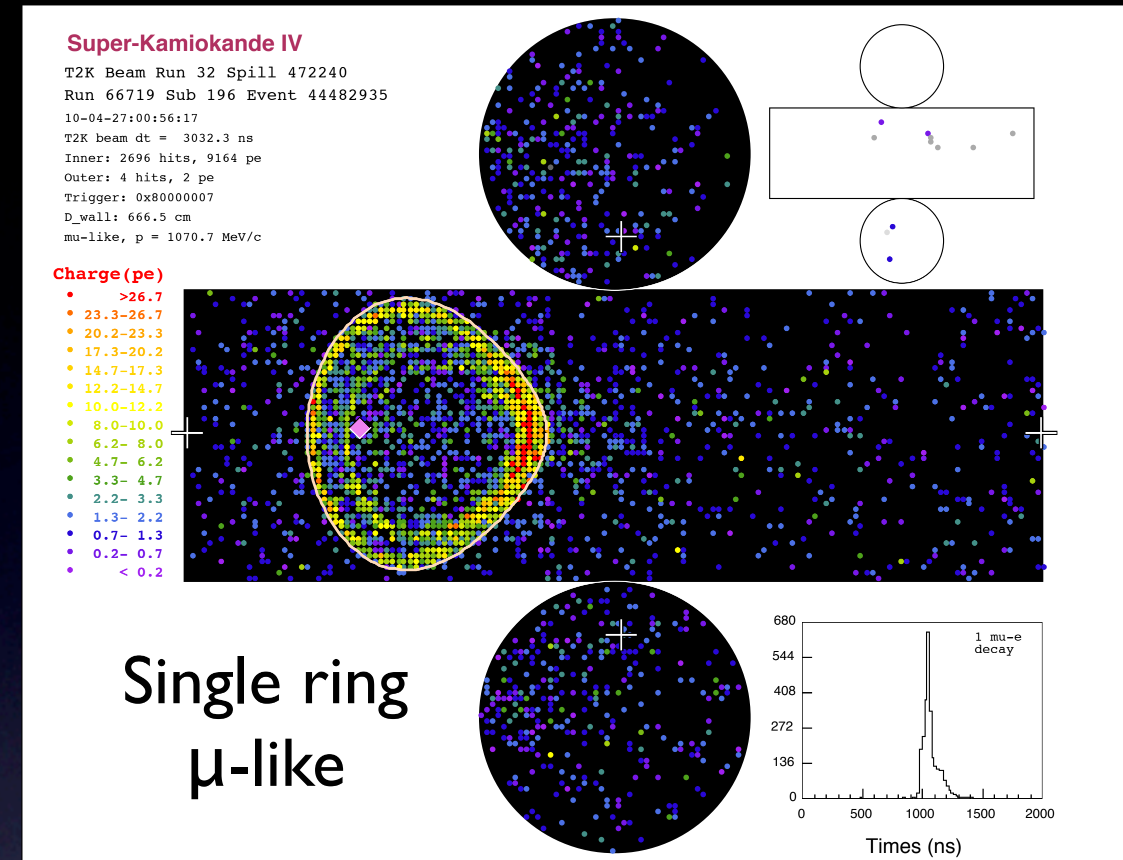


- Number of events observed in the OD compatible with the expected events from oscillations

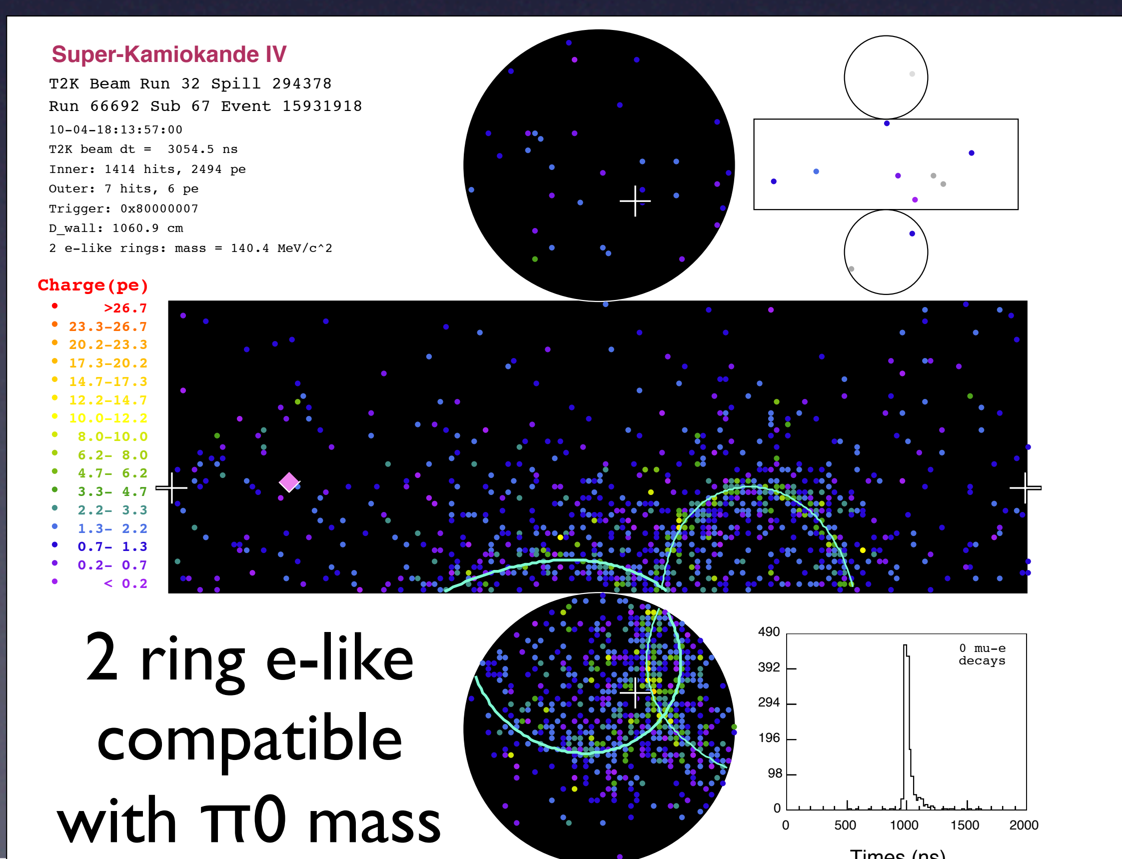
SK event display



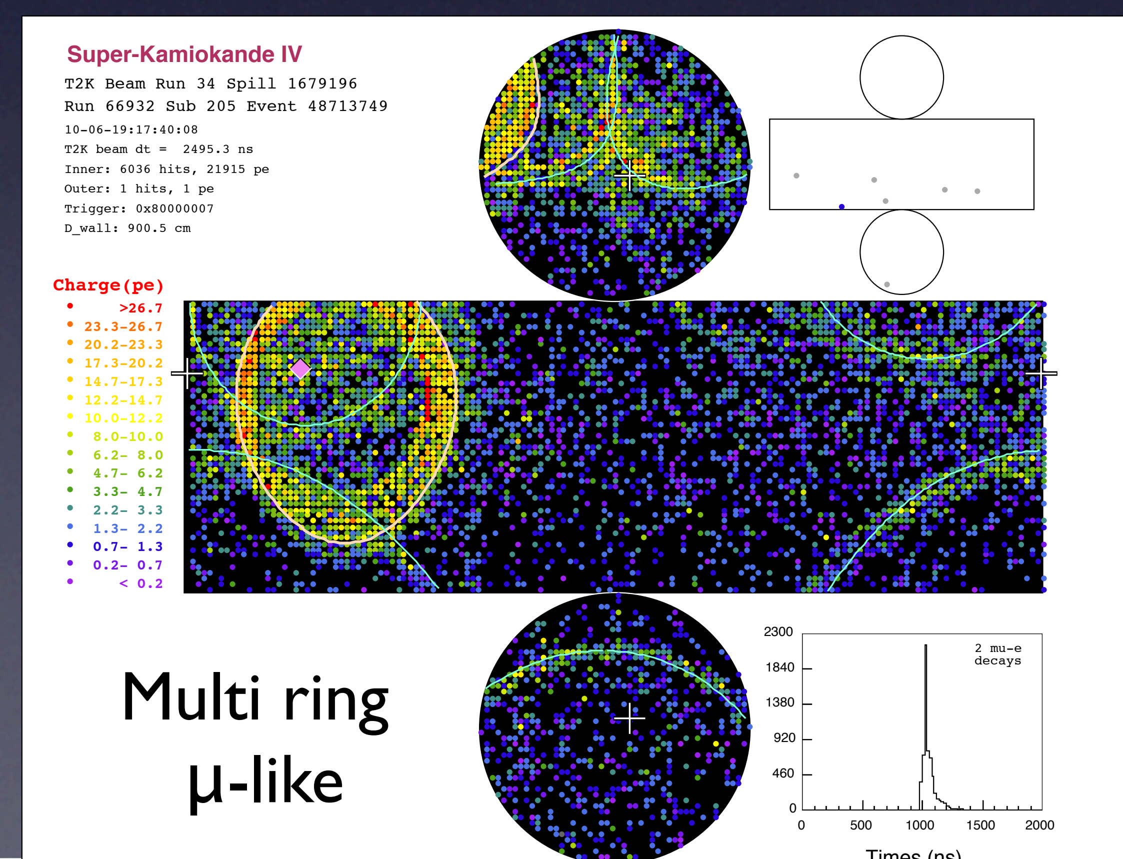
Single ring e-like



Single ring μ-like

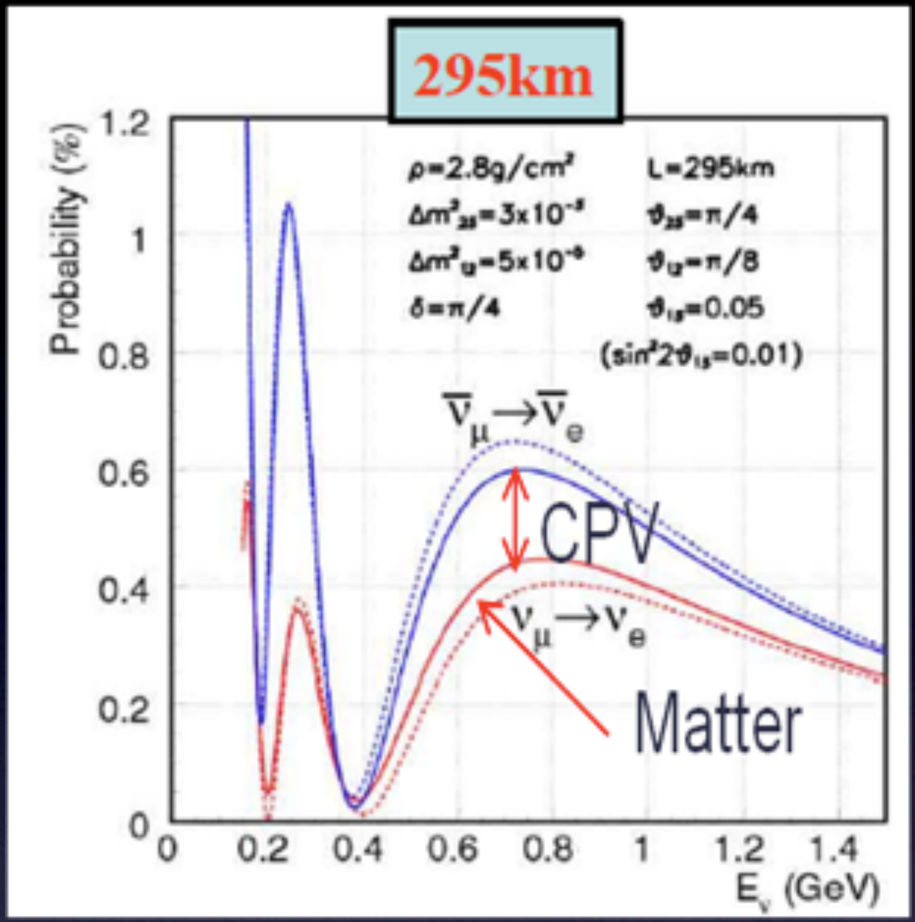


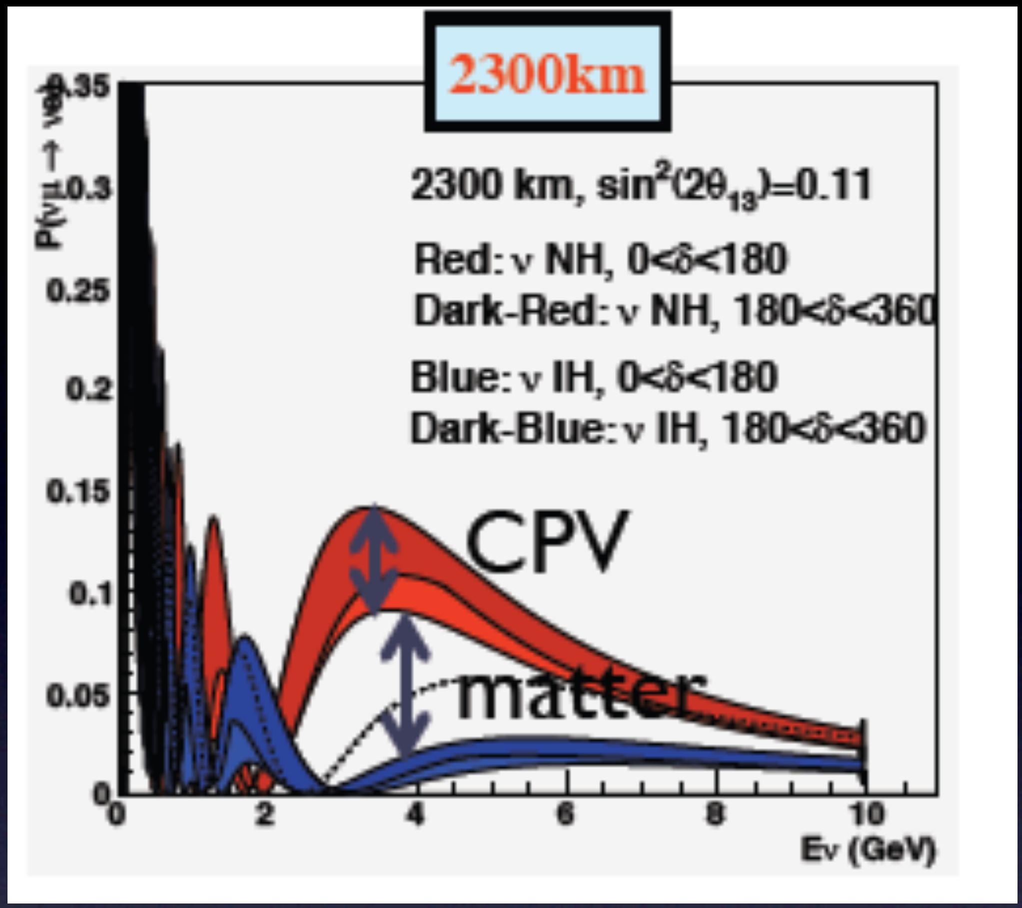
2 ring e-like compatible with π0 mass



Multi ring μ-like

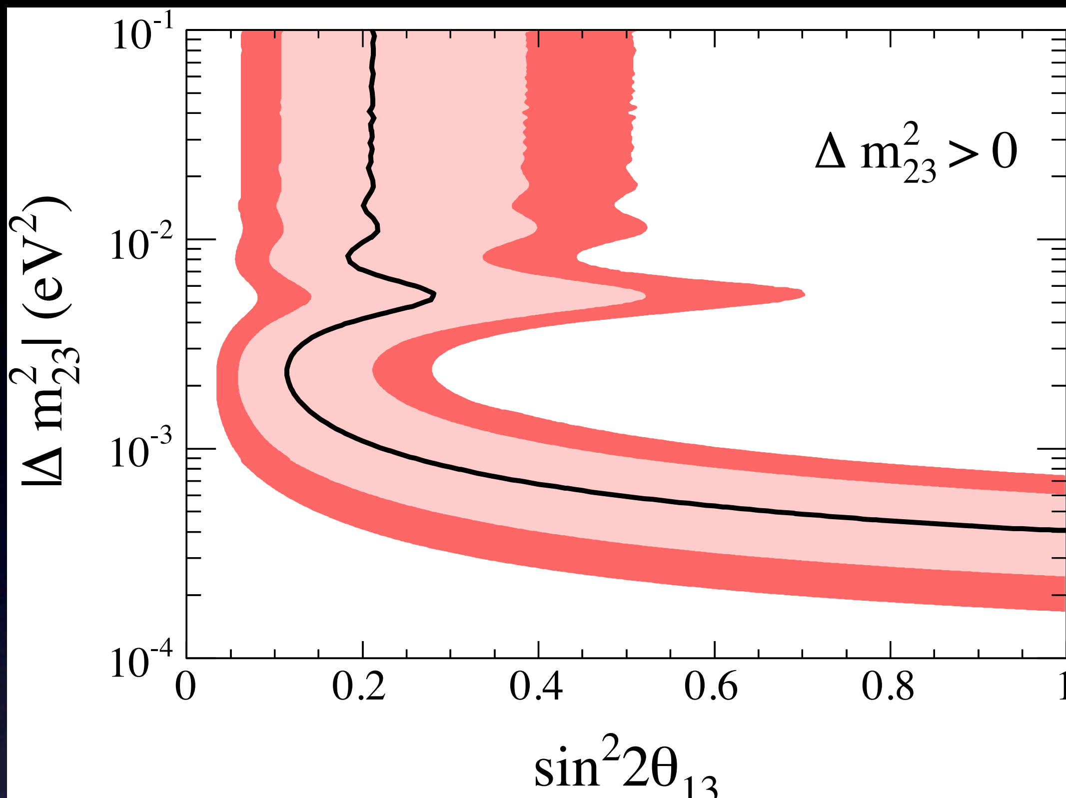
Measuring δ

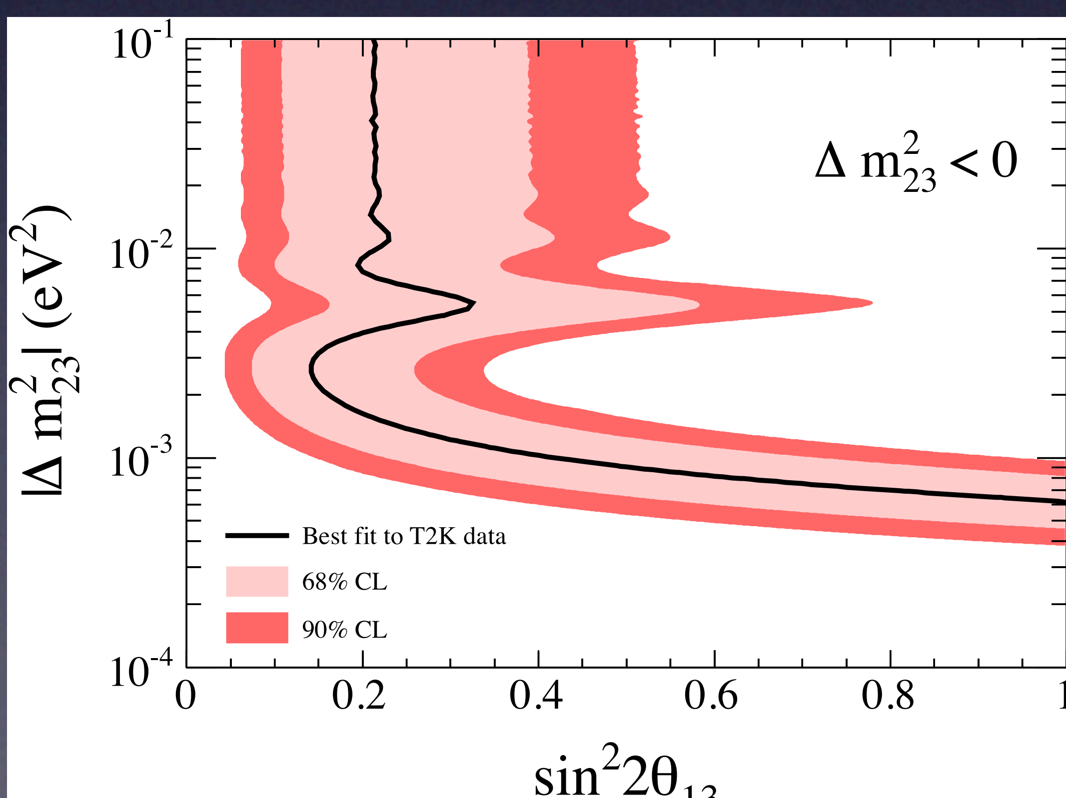


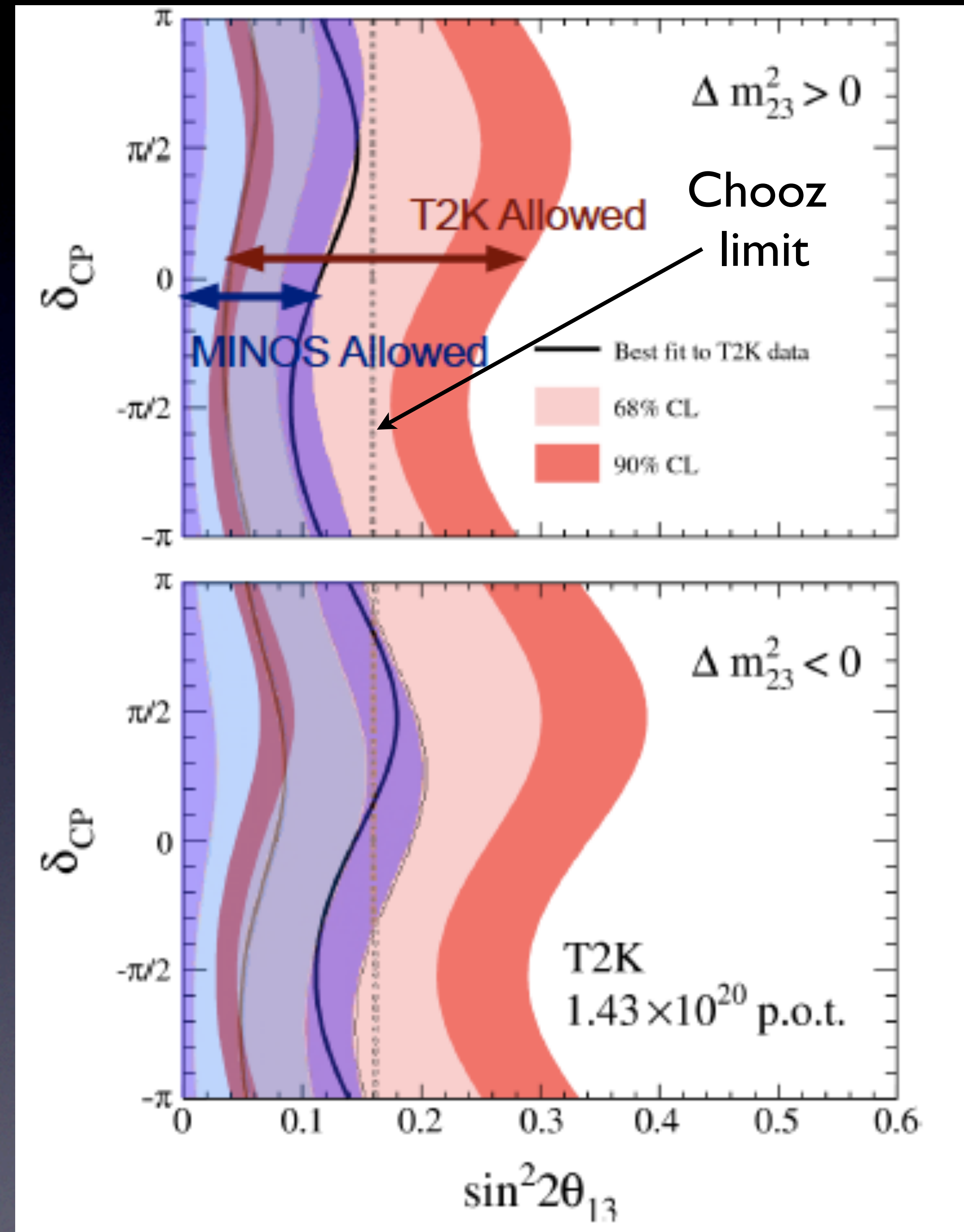


- ν_e appearance in Wide Band Beam at fixed L
  - Look at the first 2 oscillation maximum → need very good energy resolution
  - Long distances to decouple CP violation and matter effects
  - Investigate CP with ν run only
- Difference between νe and anti-νe appearance
  - Also in Narrow Band Beam at relatively short distances → small matter effects
  - Need a lot of statistics for both, neutrinos and antineutrinos (~1/6 or the neutrinos)

ν_e appearance







ν_μ disappearance analysis method

- 2 flavor neutrino oscillation fit: $P(\nu_\mu \to \nu_\mu) = 1 - sin^2(2\theta_{23}) sin^2(1.27\Delta m^2_{23} L/E)$
- We developed 2 independent oscillation analysis to extract the oscillation parameters

Method A:
Maximum likelihood with fitting of the systematics parameters:

$$L(sin^2 2\theta, \Delta m^2, \vec{f}) = L_{norm}(sin^2 2\theta, \Delta m^2, \vec{f}) \cdot L_{shape}(sin^2 2\theta, \Delta m^2, \vec{f}) \cdot L_{syst}(\vec{f})$$

L_{norm} → Poisson distribution of the total number of events
L_{shape} → un-binned spectrum shape

Method B:
Comparison of the observed spectrum with the expected spectrum varying oscillation parameters to minimize:

$$\chi^2 = 2 \sum_{i=1}^{N} \left[n_i^{obs} \cdot ln \left(\frac{n_i^{obs}}{n_i^{exp}} \right) + n_i^{exp} - n_i^{obs} \right]$$

i = bin number in SK energy
$n_i^{obs(exp)}$ number of observed (expected) events in the i-th bin
In this method systematic *f* parameters are not fitted