# Recent results from T2K

Claudio Giganti
IFAE/CPAN

on behalf of the T2K Collaboration

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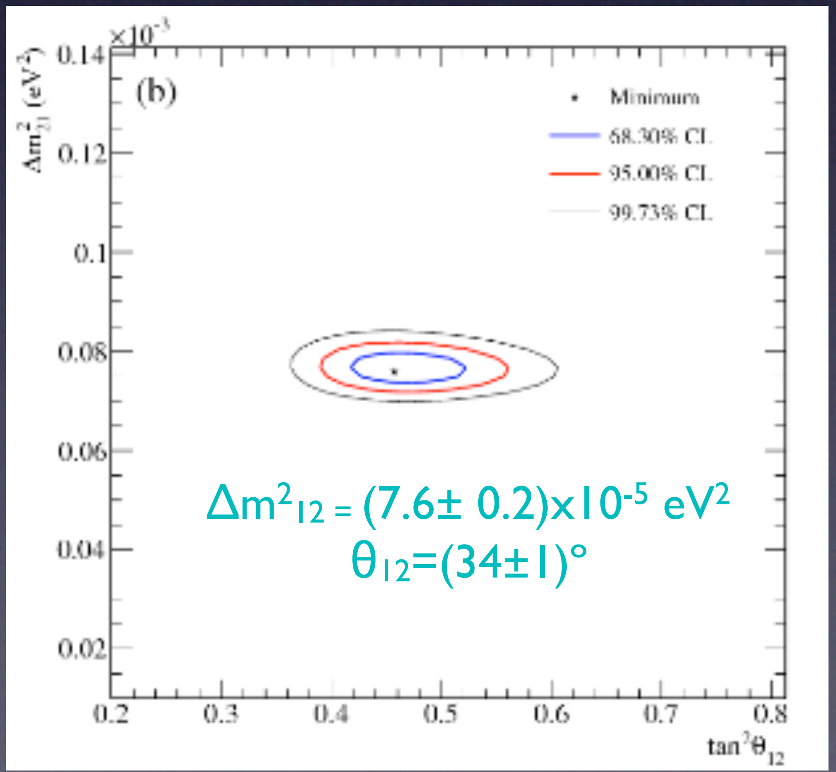
# Neutrino oscillations

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

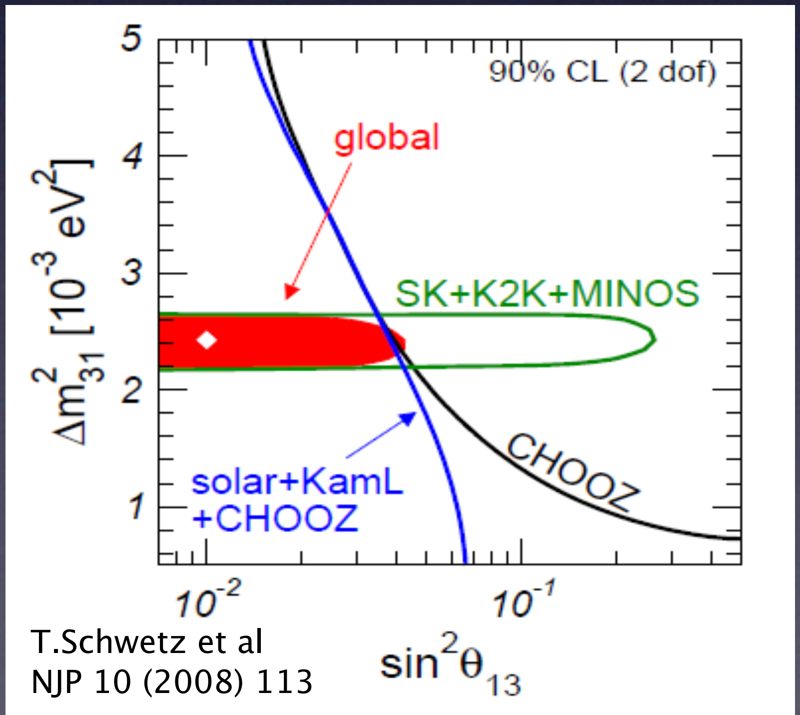
Flavor eigenstates — Mass eigenstates

- 3 angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$)
- 1 CP violation phase $\delta$
- 2 independent mass differences ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)

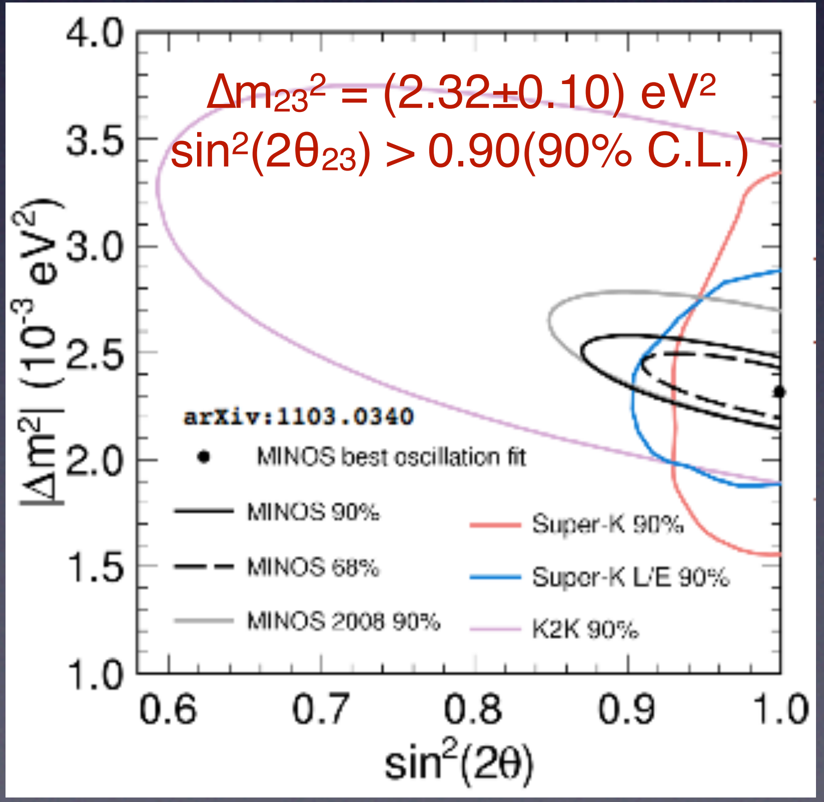
**Solar (SNO, KamLand) → $\theta_{12}$, $\Delta m_{12}$**




**Interference term → $\sin^2(2\theta_{13})<0.13$**
**$\delta$ completely unkwnown**

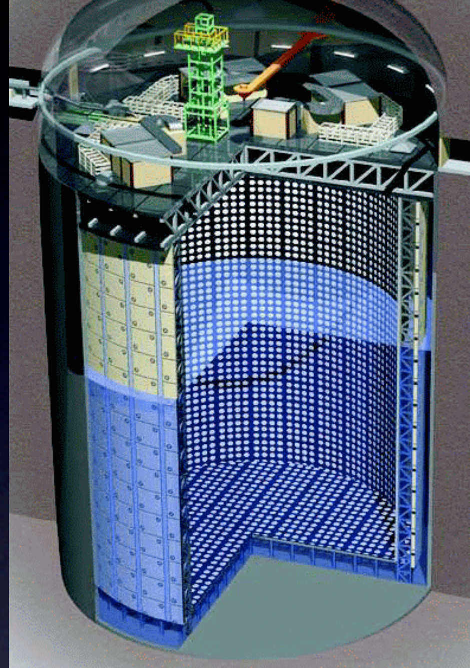



**Atmospheric (K2K, SK, Minos) → $\theta_{23}$, $\Delta m_{23}$**



# 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 $\nu_\mu$ 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 $\nu_e$ appearance → determine $\theta_{13}$ (sensitivity >10 times better Chooz limit)
  - Precise measurement of $\nu_\mu$ disappearance → Goal: $\delta(\sin^2(2\theta_{23}))\sim 0.01$, $\delta(\Delta m^2_{23})<1\times10^{-4}$ eV$^2$

# T2K Collaboration

~500 members, 59 institutes, 12 countries

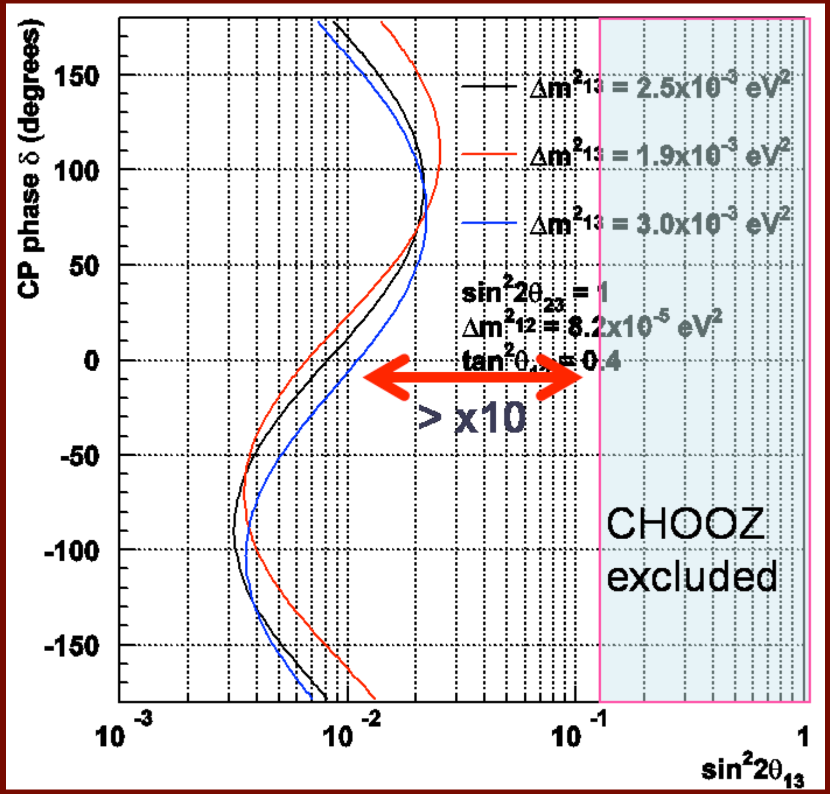
# T2K physics goals

- Expected sensitivities with $8\times10^{21}$ p.o.t. (full expected T2K data-set)
  - Today's results presented with $1.43\times10^{20}$ p.o.t. (~2% of the total)

## $\nu_e$ appearance

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

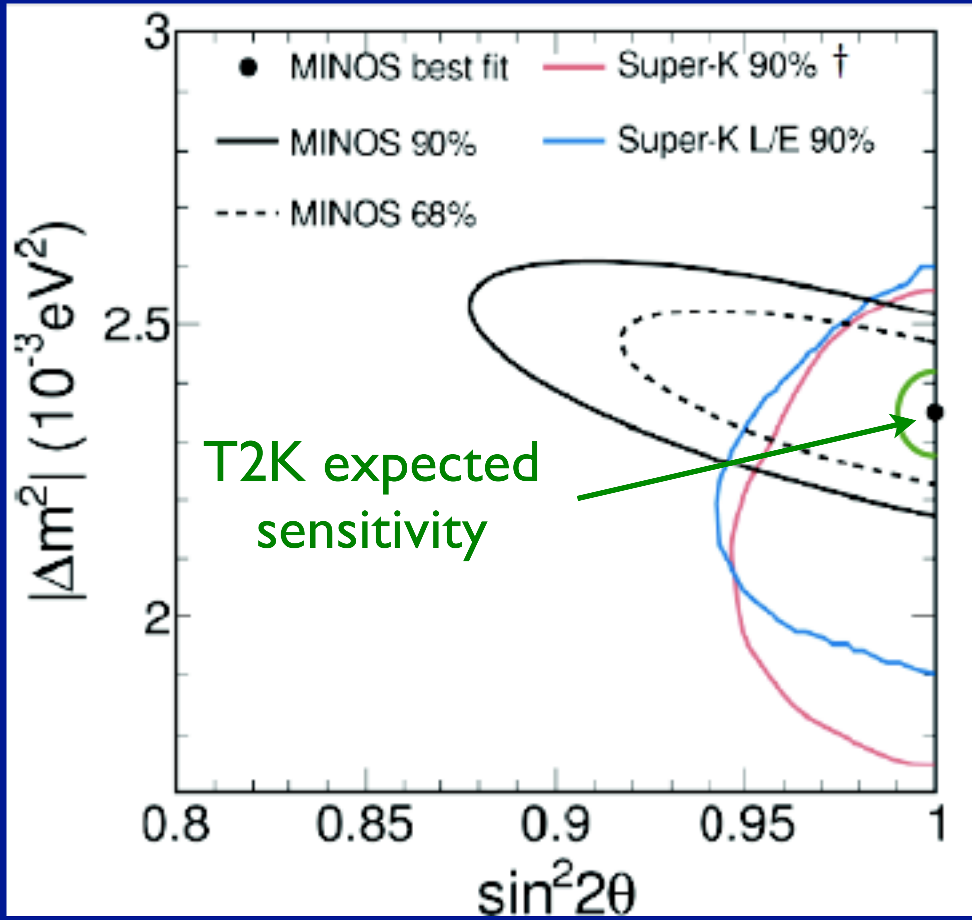
$$\Delta = 1.27\Delta m^2_{23} L/E \quad \alpha = \Delta m^2_{12}/\Delta m^2_{23} \sim 1/30$$




> 10 times improvement with respect to Chooz limit

## $\nu_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - sin^2(2\theta_{23}) sin^2(1.27\Delta m^2_{23} L/E)$$

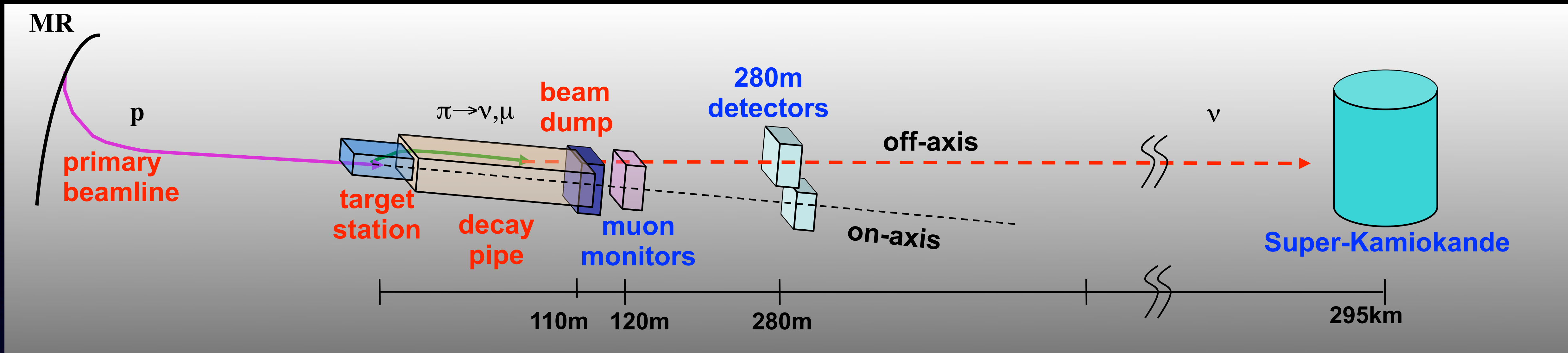



Goals: $\delta(sin^2(2\theta_{23}) \sim 0.01$

$\delta(\Delta m^2_{23}) < 1\times10^{-4}$ eV$^2$

# T2K experimental setup

# T2K experimental setup

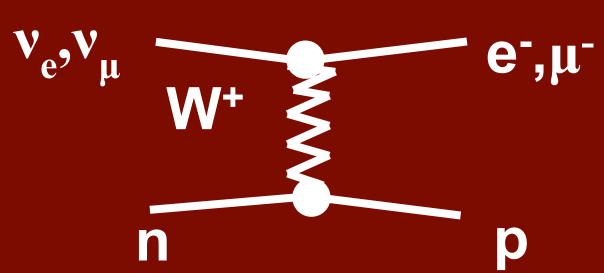



- Beamline:
  - 30 GeV proton beam from JPARC Main Ring extracted onto a graphite target
  - Pions focused and selected in charge by 3 electromagnetic horns
  - $\nu_\mu$ produced by pions decay $\pi \to \mu + \nu_\mu$
  - Off-axis beam: center of the beam 2.5° off from SK direction
- Detectors:
  - 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

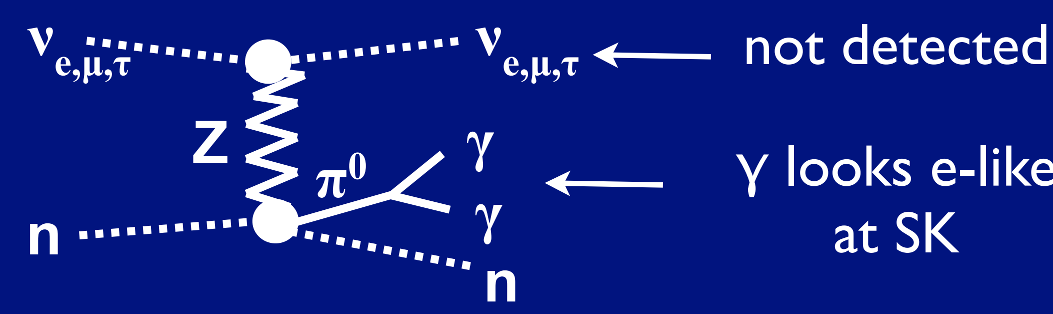
# What we are looking for

Signal at SK: CCQE interactions producing $\mu$ from $\nu_\mu$ or e from $\nu_e$




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

Backgrounds at SK:
NC1$\pi$+ interactions for $\nu_\mu$
NC1$\pi^0$ interactions for $\nu_e$

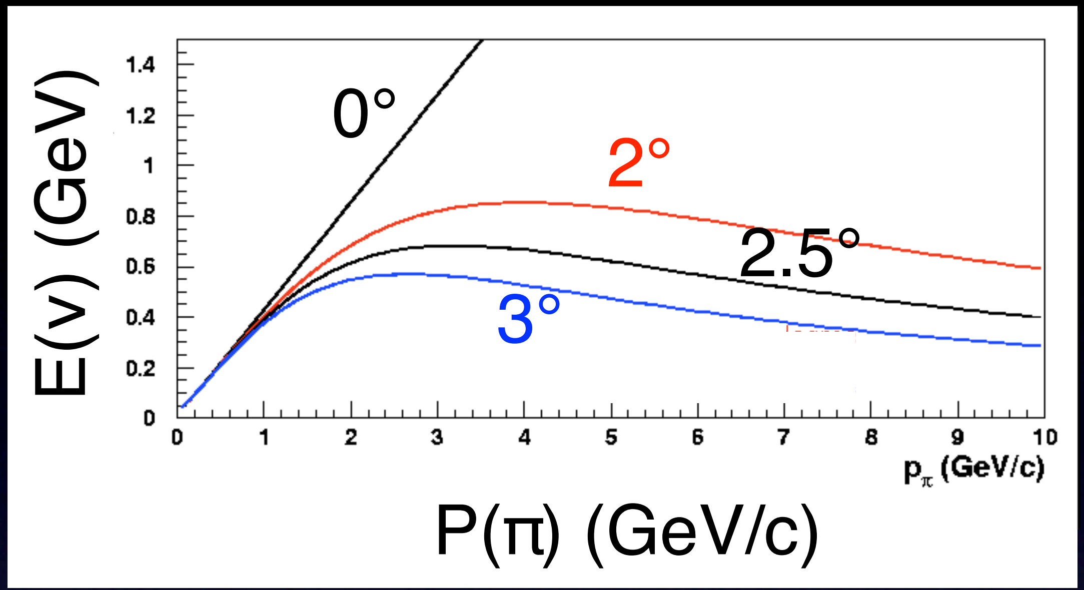


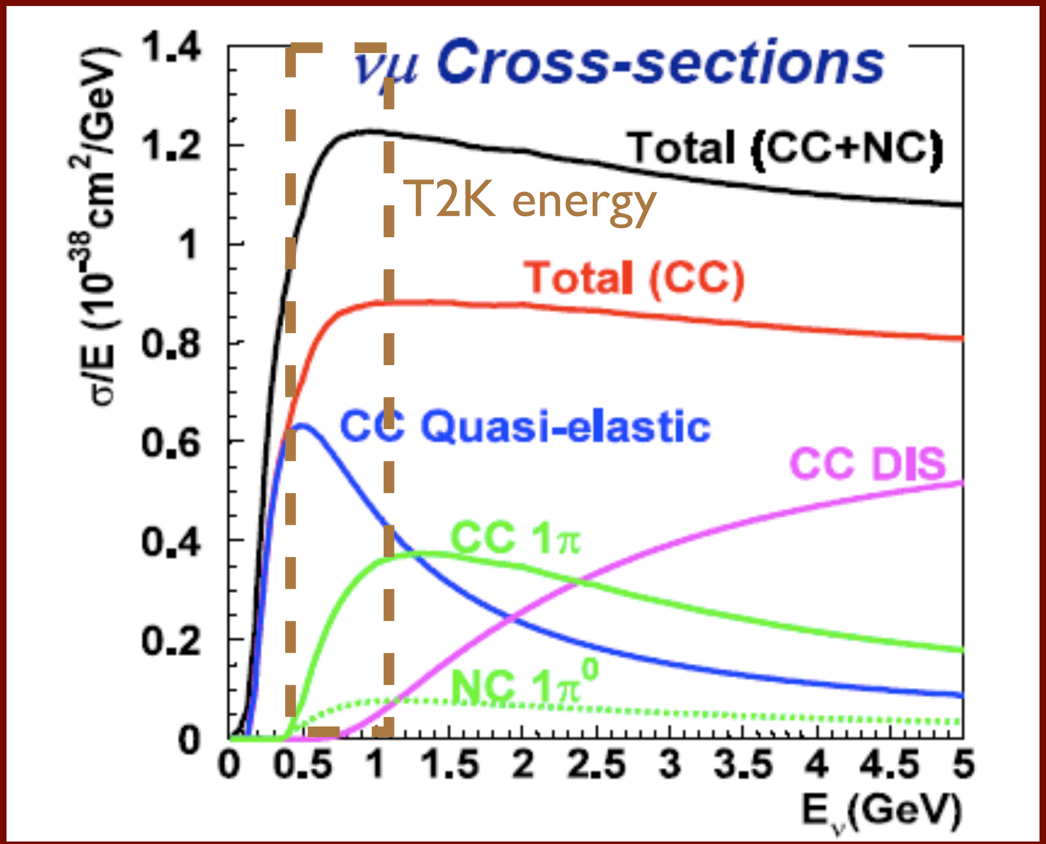

Estimated ~30% error on these processes with respect to CCQE cross-section

- Few measurements (MiniBooNE, SciBooNE, K2K) and large uncertainties in the knowledge of neutrino interactions in the 1 GeV region
  - This result in a sizeable contribution to the systematics in T2K oscillation analysis
- At ND280 we will measure the neutrino interactions

# Off-axis narrow band beam

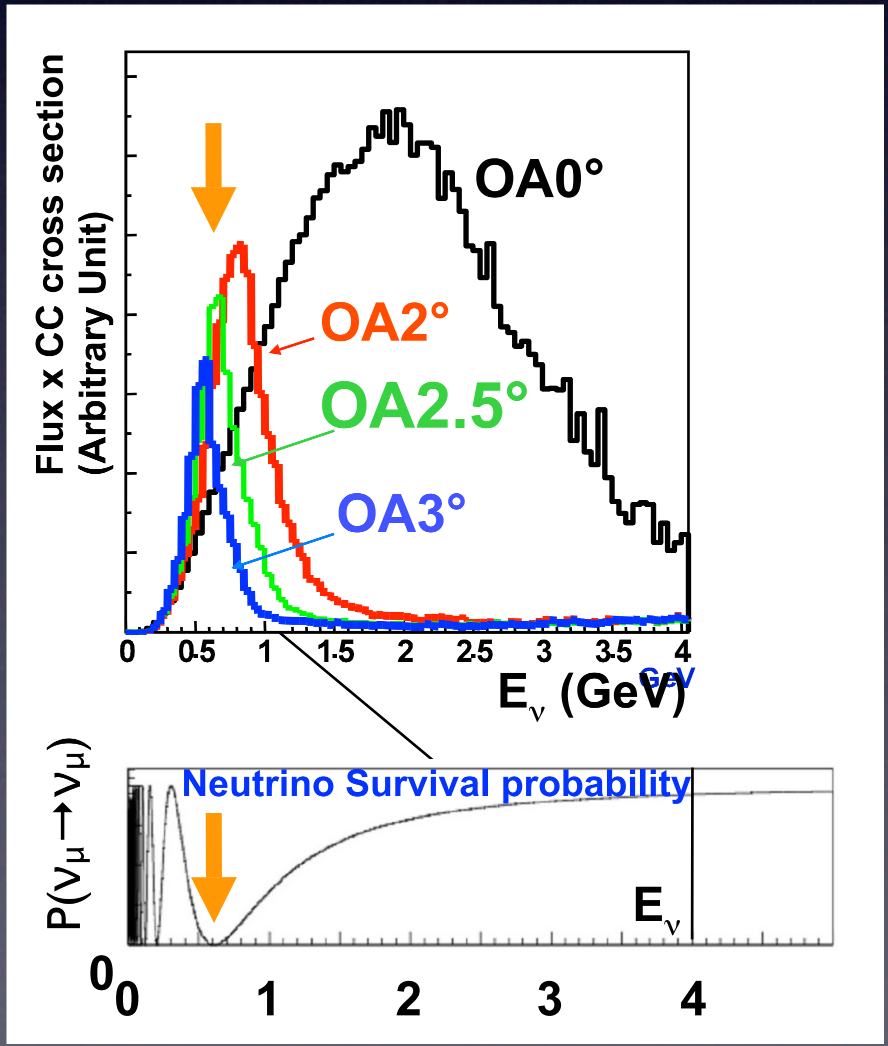
- T2K is the first long baseline experiment using off-axis technique
- Reduced dependence of $E_\nu$ from $E_\pi$
  - Intense beam where the oscillation effect is maximum (~0.6 GeV)
  - Enhance the CCQE sample, reducing the high energy tails of the beam → reduce the backgrounds to oscillation signal



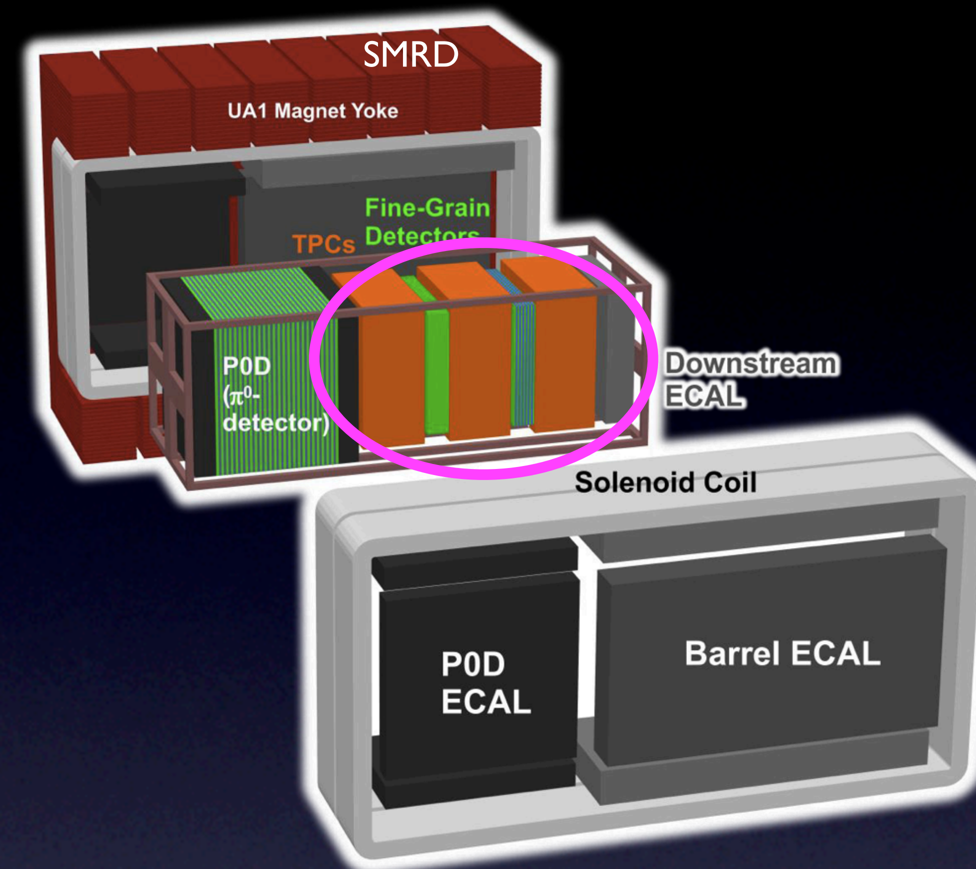

Signal: CCQE
$\nu_{e(\mu)}+n \rightarrow e(\mu)+p$

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

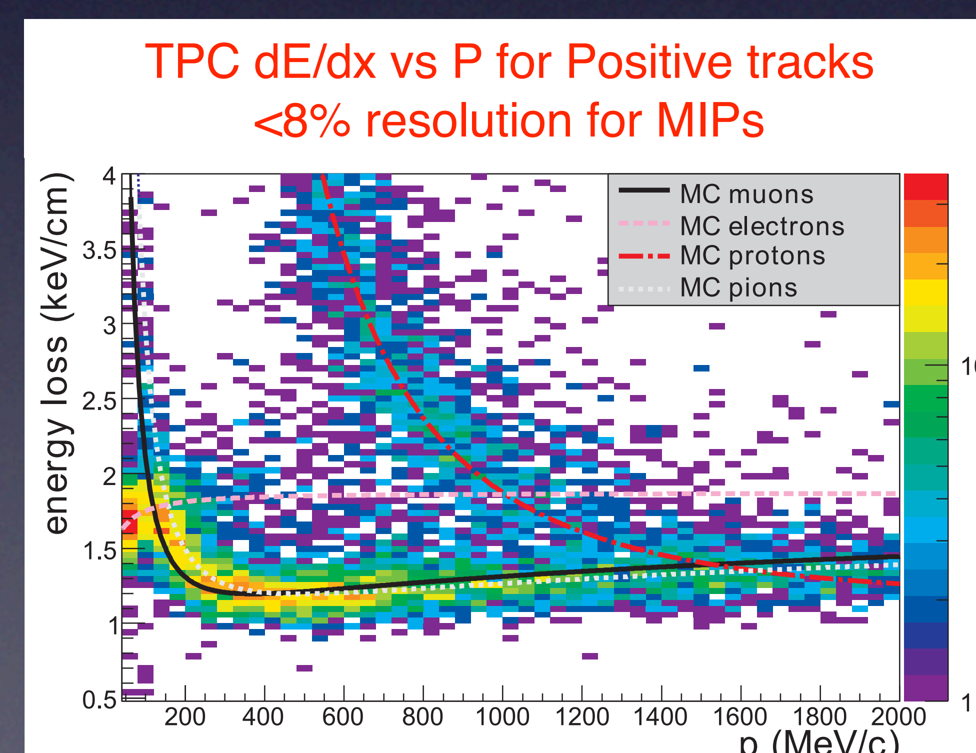


# Off-axis ND280

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



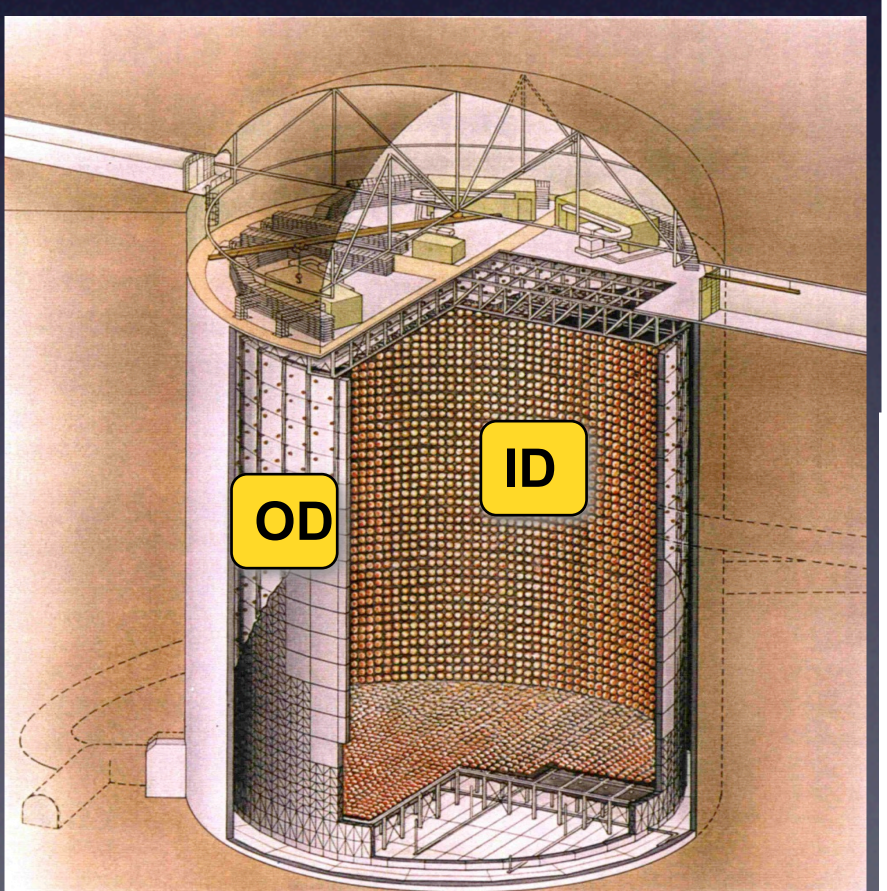

- The present analyses are based on the Tracker:
  - 2 fine grained detectors (FGD)
    - Active target for neutrino interactions (carbon and water)
    - 1.6 ton of Fiducial Volume
  - 3 time projection chambers (TPC)*
    - Instrumented with MicroMEGAS detectors
    - Reconstruct momentum and charge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

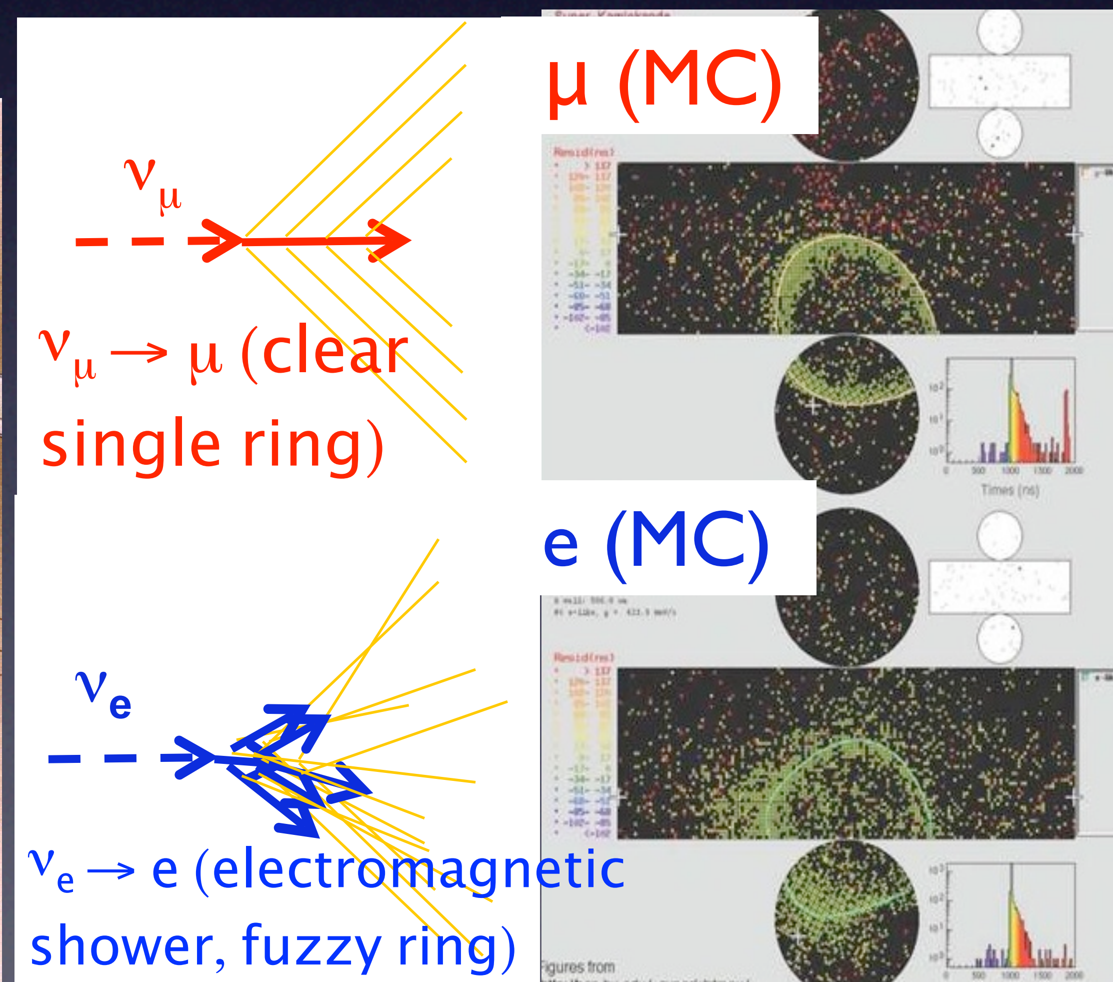



*NIM, A **637** (2011) pp. 25-46

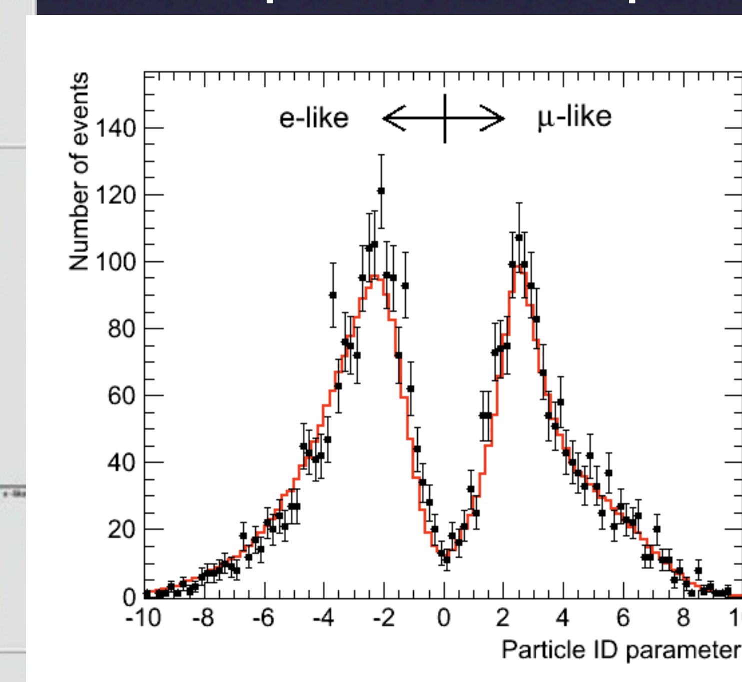
# Far Detector: Super-Kamiokande

- 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 $\nu$ sample



# T2K oscillation analysis

# T2K Oscillation analysis method

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

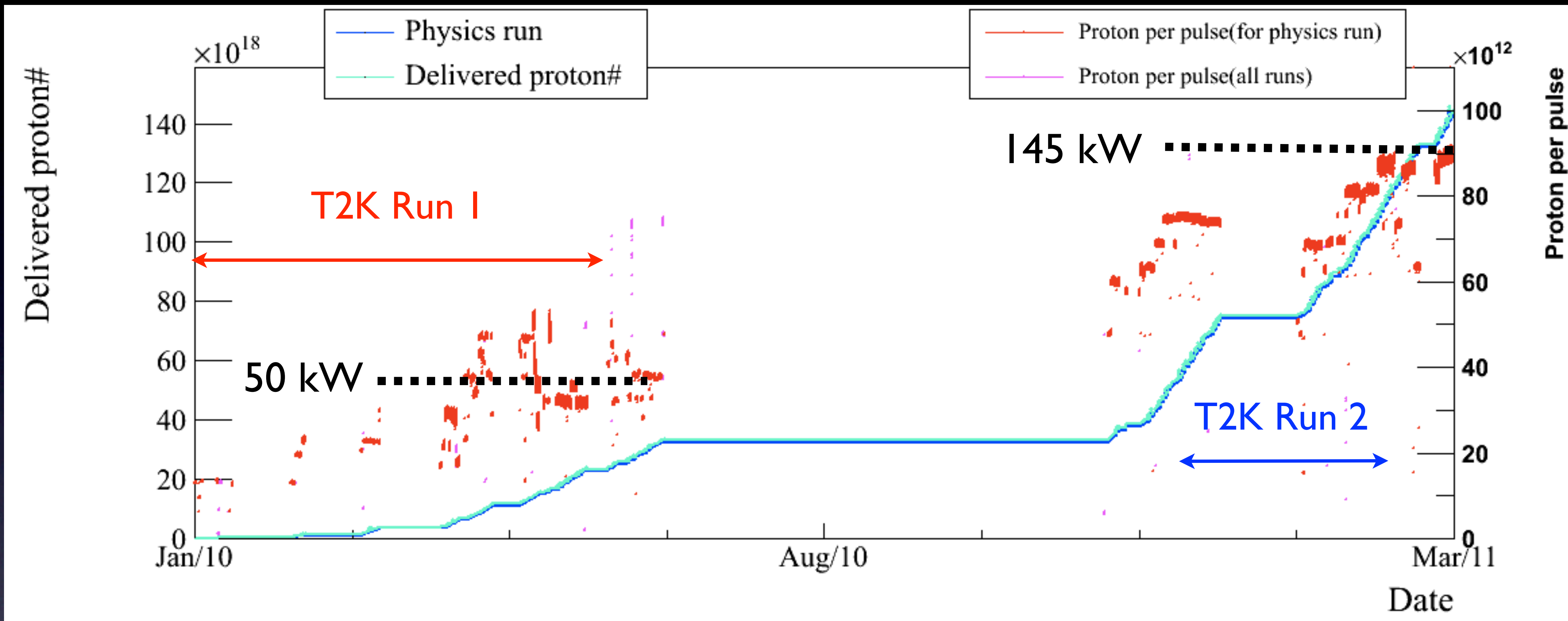
**ND280 measurements:**
- Inclusive CC $\nu_\mu$ measurement:
  - Output: $R_\mu^{ND,data}/R_\mu^{ND,MC}$
- Cross-check: $N(\nu_e)/N(\nu_\mu)$

**Super-Kamiokande measurements:**
- Select CC $\nu_\mu$ and $\nu_e$ 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

$\nu_e$ analysis → 1 single bin (counting)
$\nu_\mu$ analysis → number of events and shape information combined

# Run1+Run2 data set



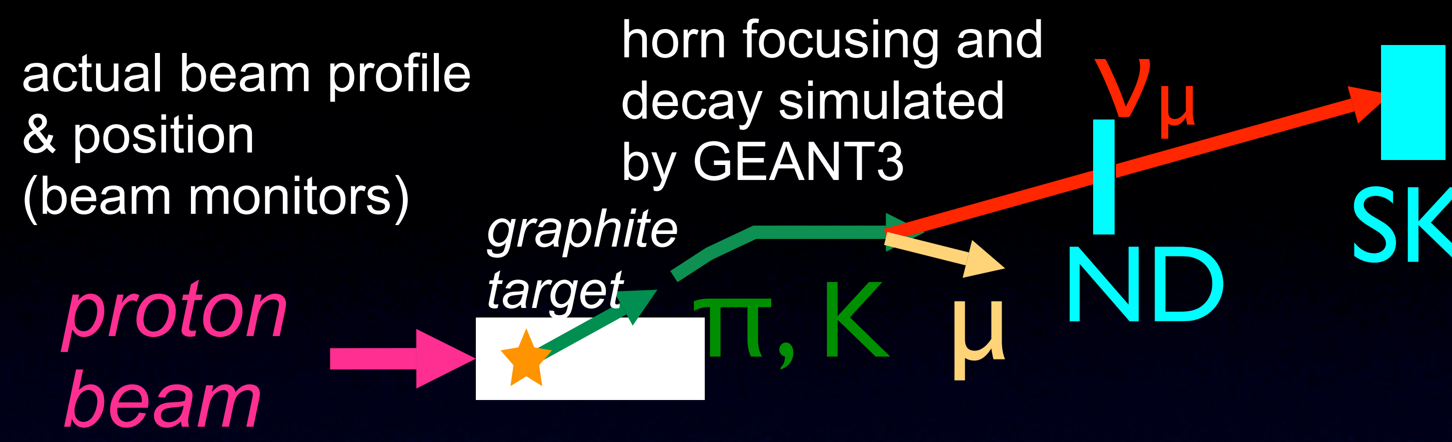

Run1 (Jan-Jun 2010)
$3.23 \times 10^{19}$ p.o.t for analysis
50 kW stable beam operation

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

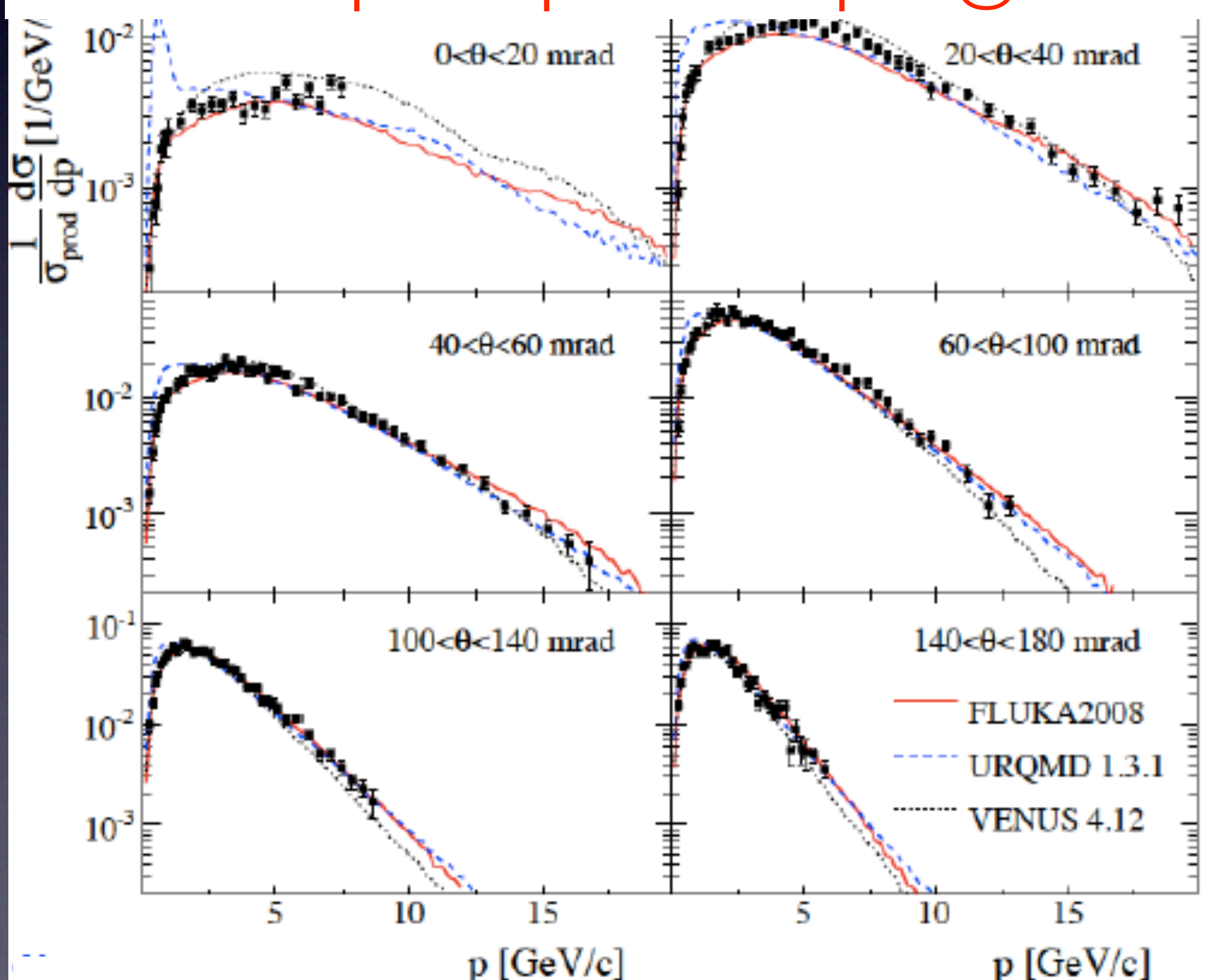
- The total number of protons used for this analysis is $1.43 \times 10^{20}$ p.o.t → 2% of the T2K final physics goal

# 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)

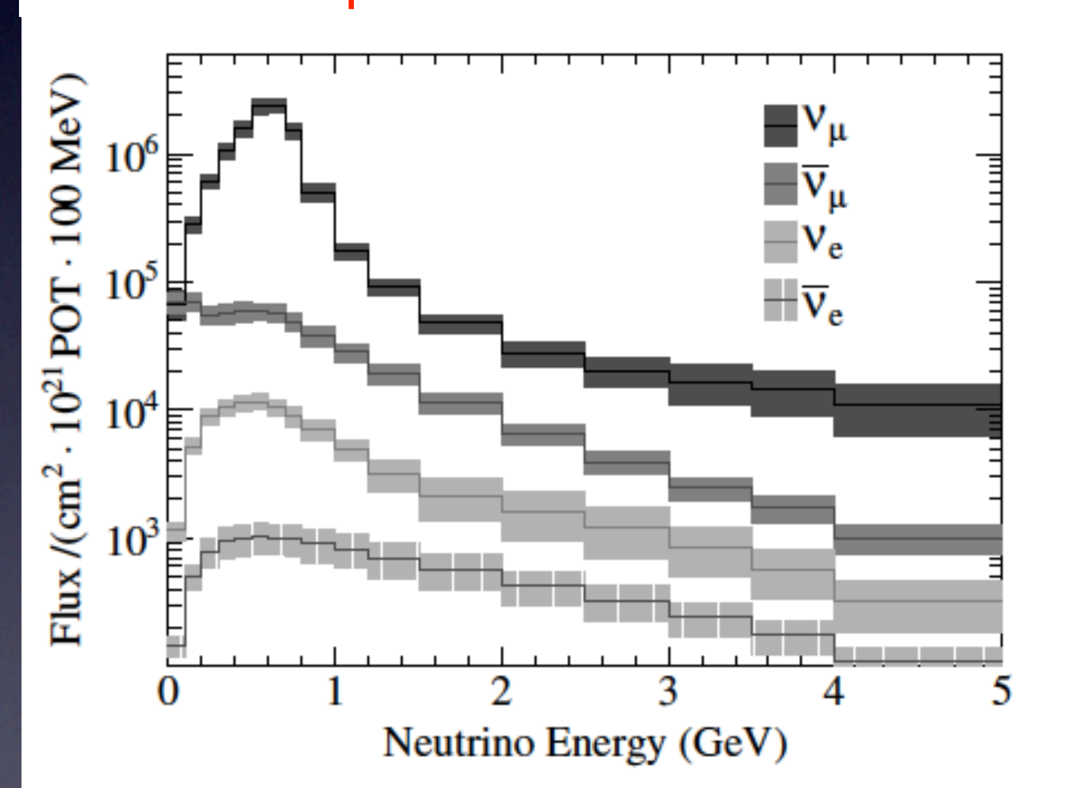



NA61: dσ/dp for π produced in p+C @31GeV




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

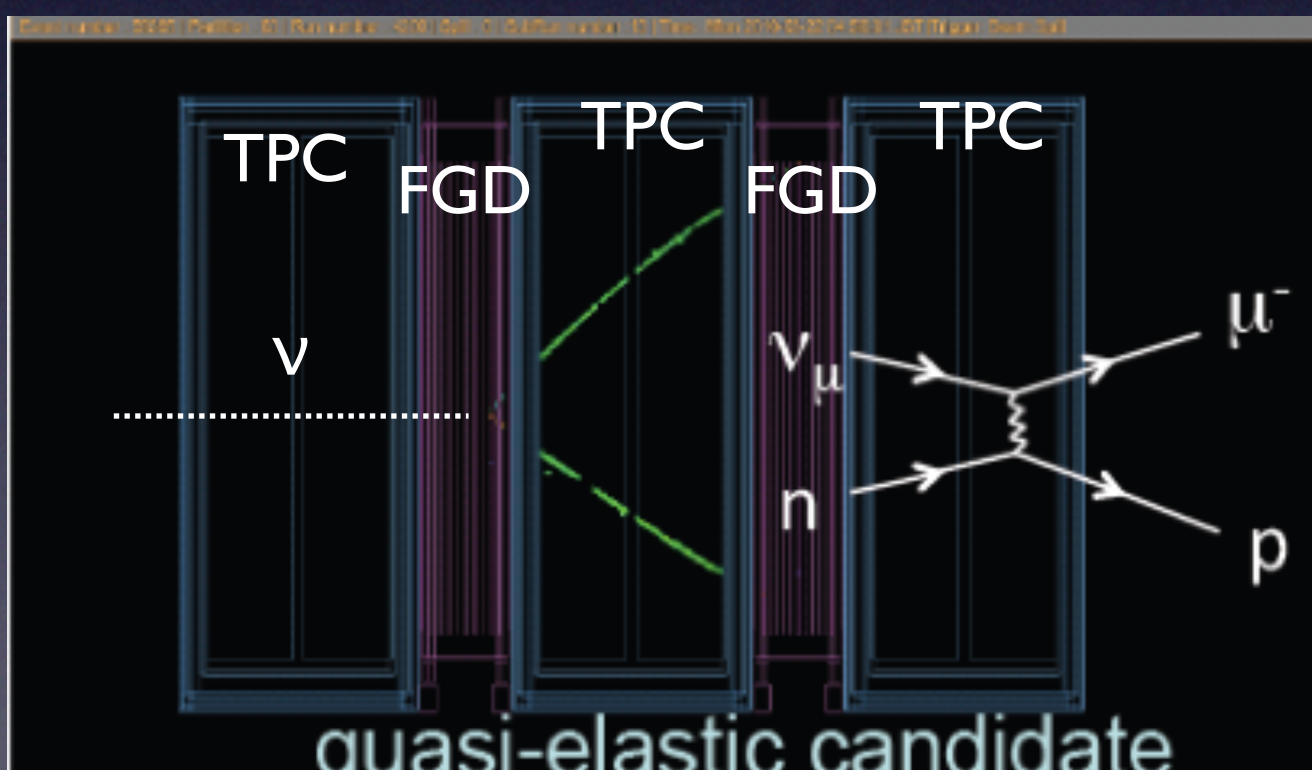
Expected ν fluxes at SK

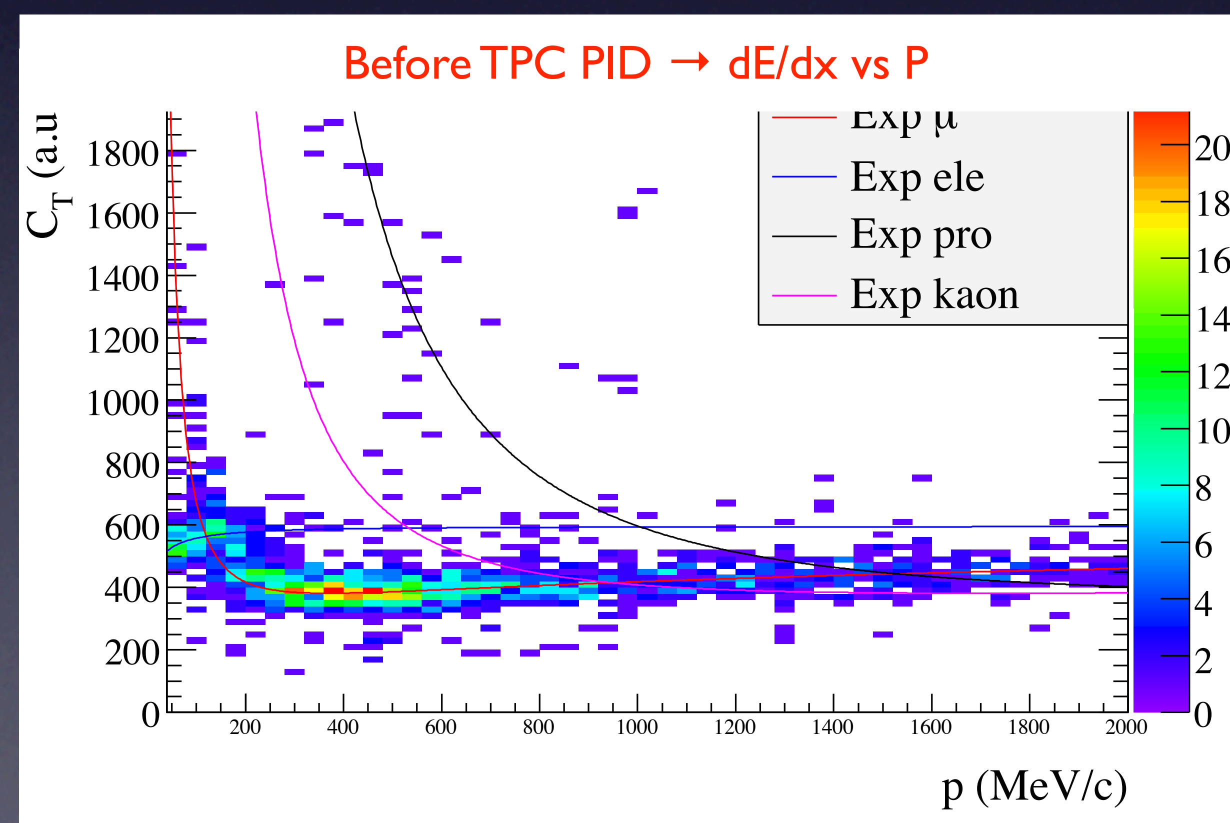



Expected beam $\nu_e$ contamination: ~1% of the total flux in the oscillation region

# ND280 analyses

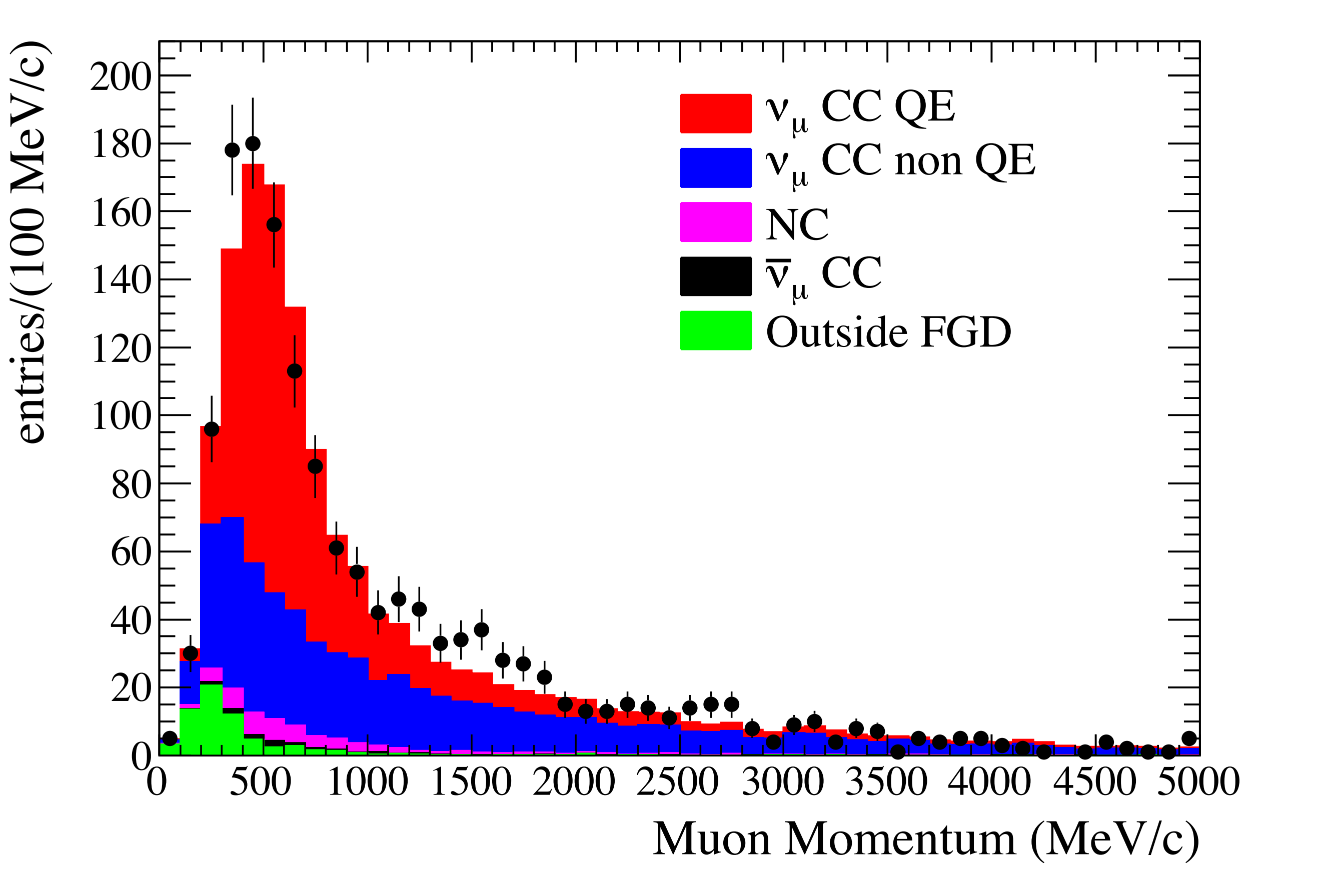
- ND280 analyses done on Run1 ($2.9 \times 10^{19}$ p.o.t)
- Measure inclusive CC$\nu_\mu$ event rate and $\nu_e$ beam component
- Select interactions in the Tracker: starting in the FGD FV producing at least 1 negative track in the downstream TPC → lepton candidate
- Measure track's momentum in the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

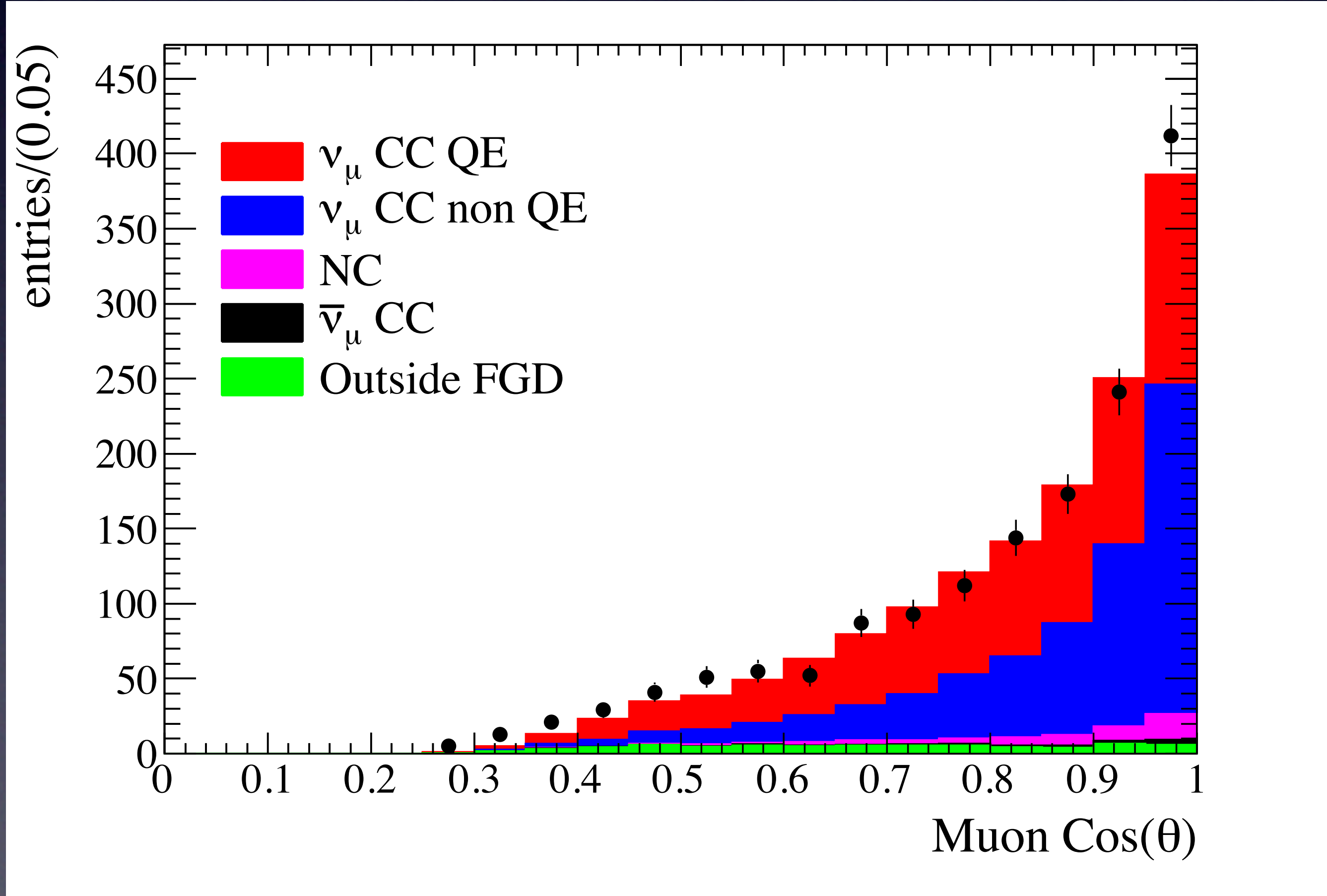


# Inclusive CC $\nu_\mu$ analysis

- 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

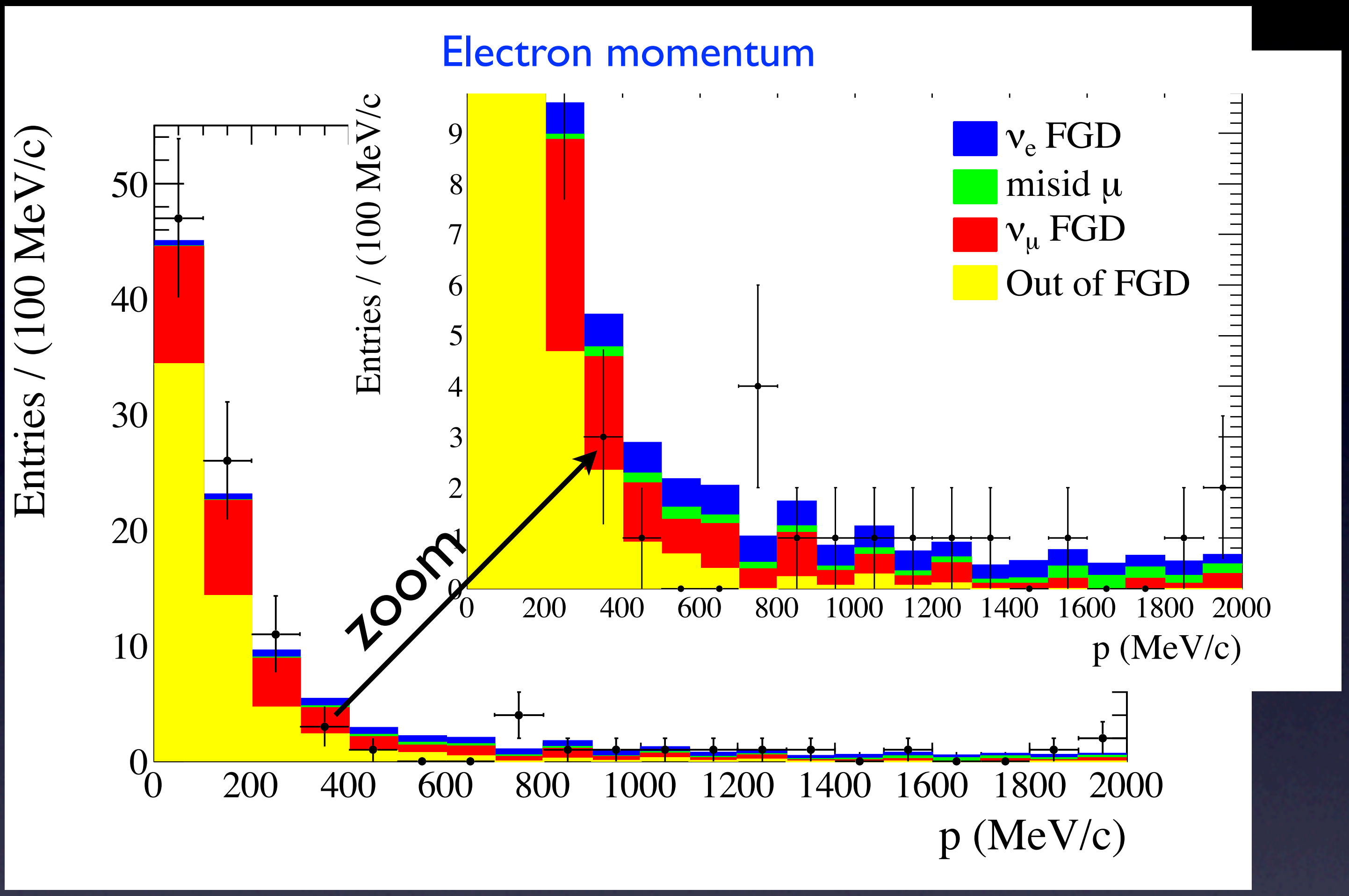



$$R(data/MC) = 1.036 \pm 0.028(stat)^{+0.044}_{-0.037}(det.\ syst) \pm 0.038(phys.\ model)$$

# ND280 beam $\nu_e$ measurement

- Beam $\nu_e$ 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($\nu_e$)
- The observed $\nu_e/\nu_\mu$ ratio at ND280 is consistent with the MC expectation confirming our beam prediction



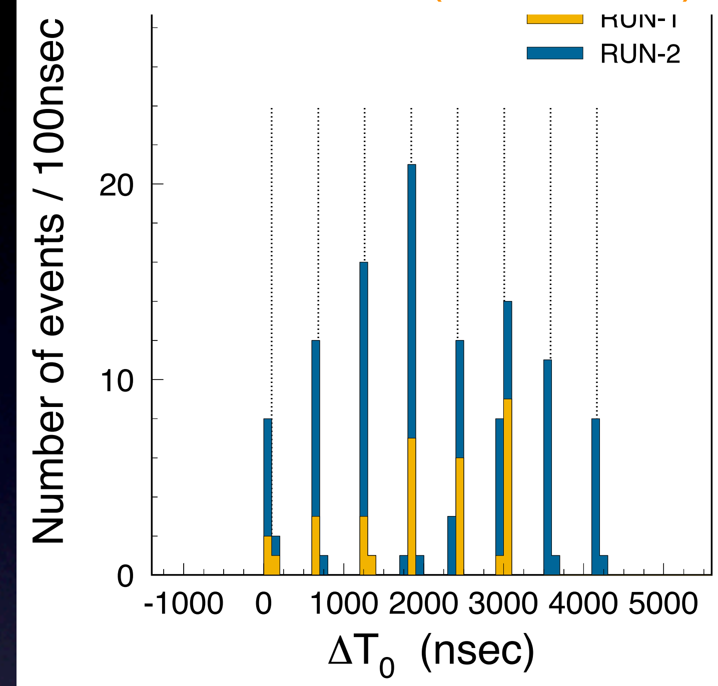

$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(stat) \pm 0.3(syst))\%$$
$$< 2.0\% \text{ @ } 90\% \ C.L.$$

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

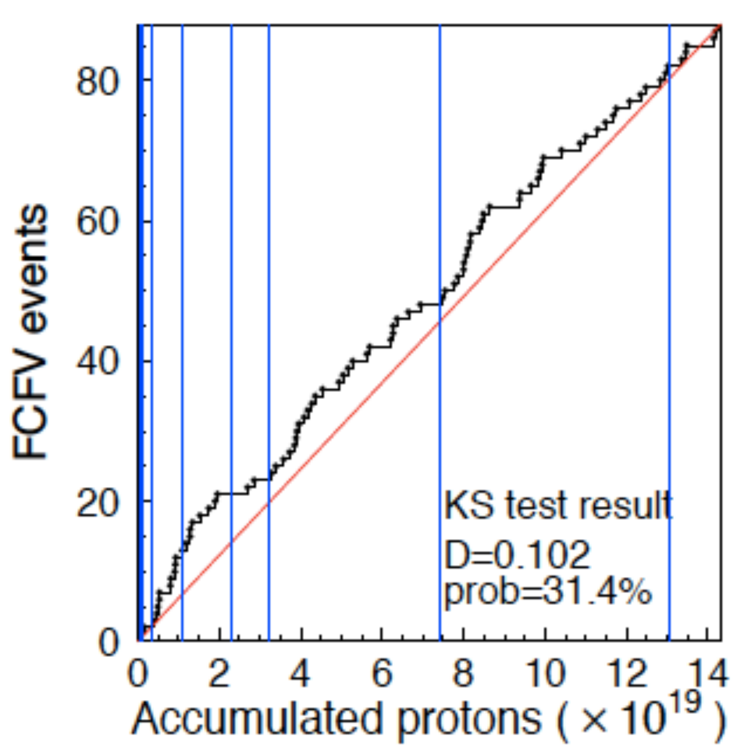
# Super-Kamiokande event selection

- Predefined event selection for $\nu_\mu$ and $\nu_e$
- 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

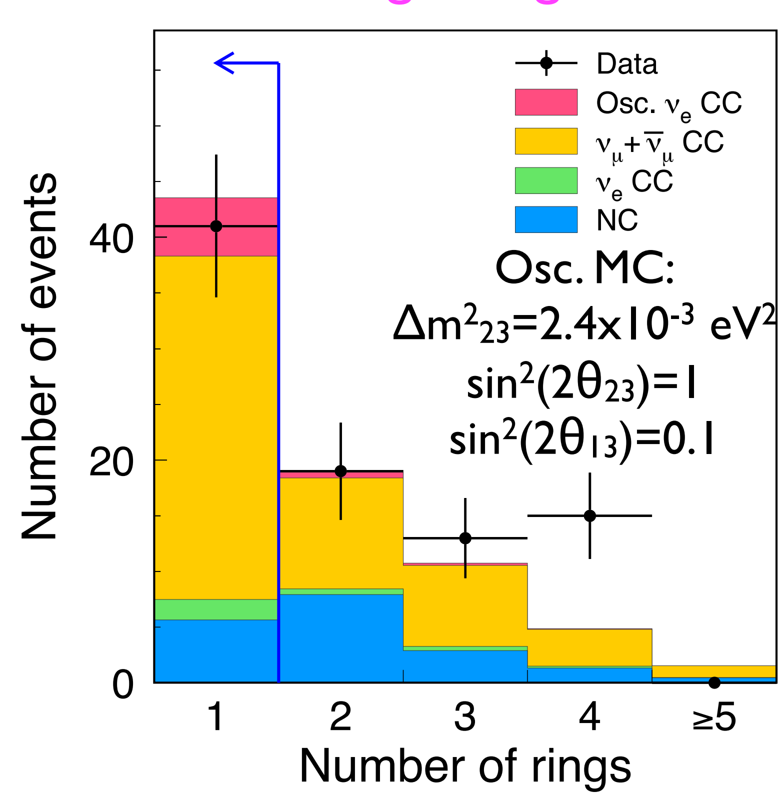
121 FC events (8 bunches)



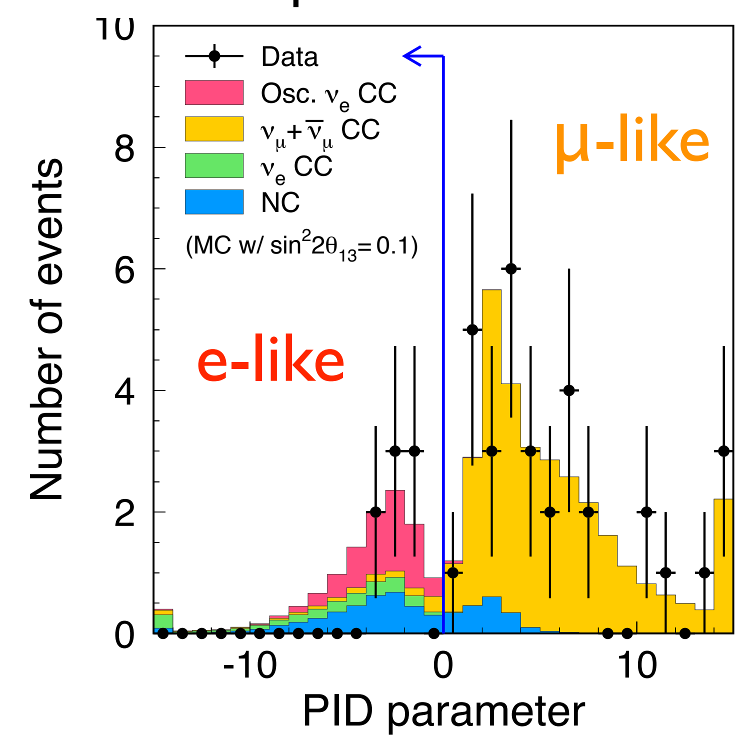

88 FCFV events



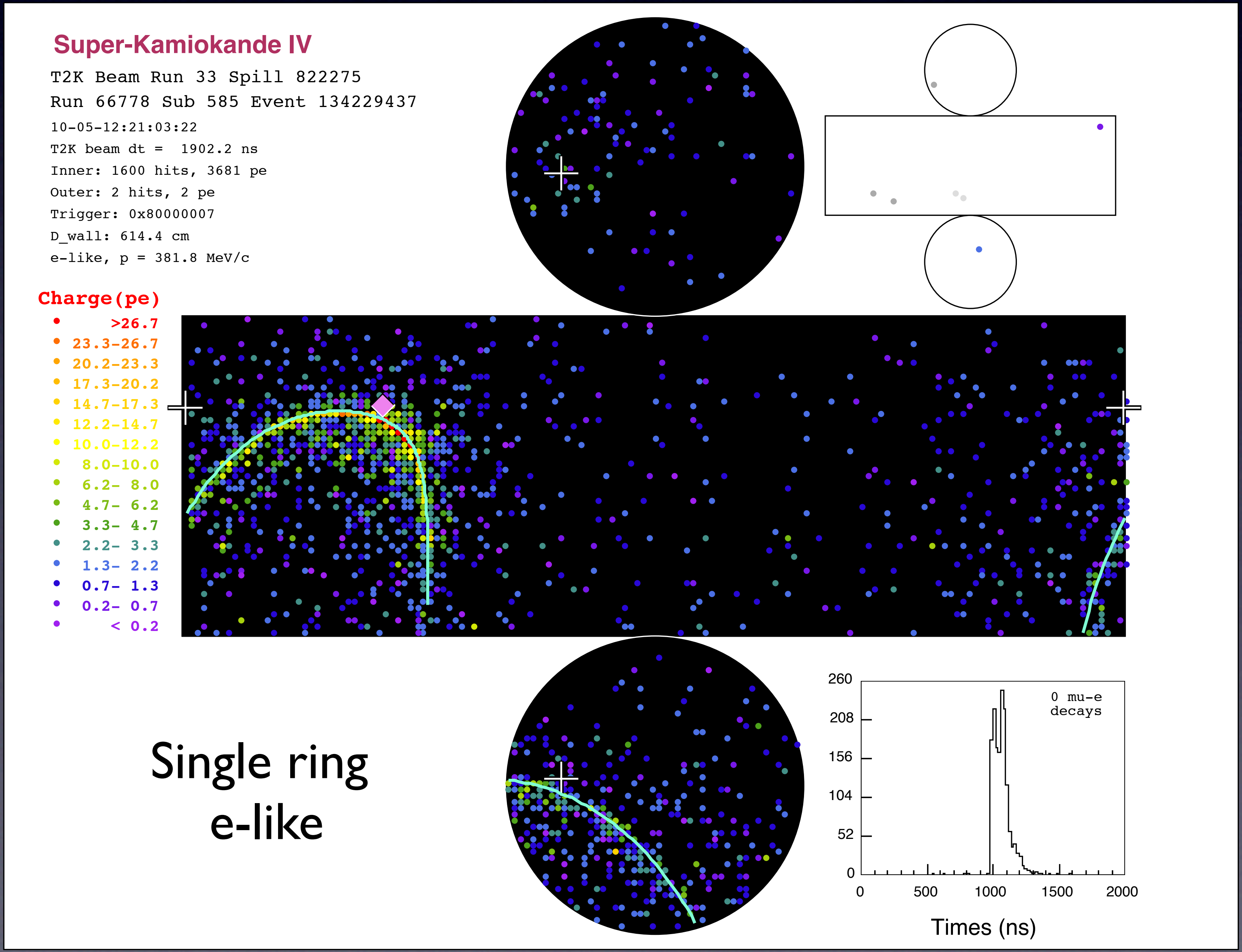

41 single ring




8 e-like events
33 μ-like events



# $\nu_e$ appearance results



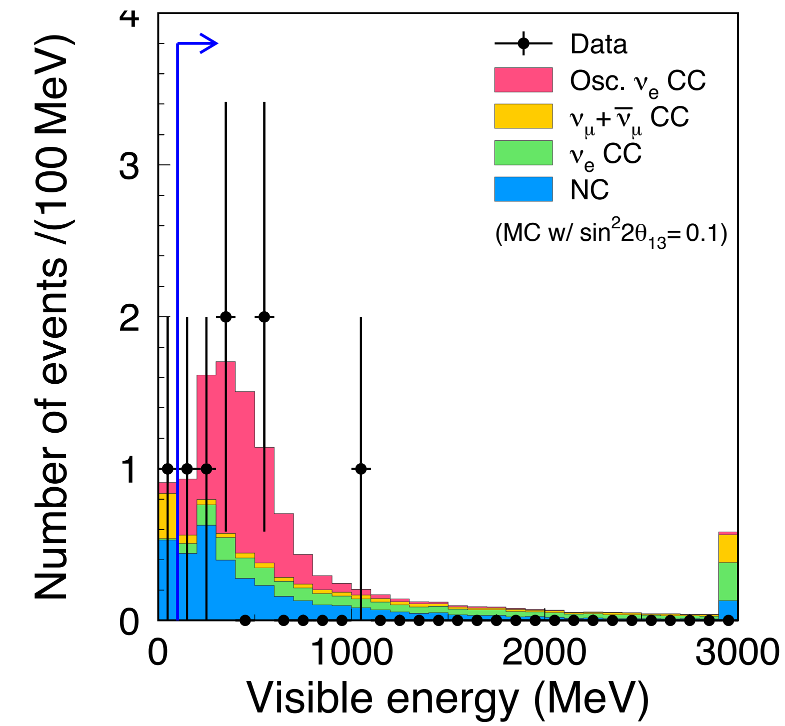

Single ring
e-like

# SK $\nu_e$ event reduction

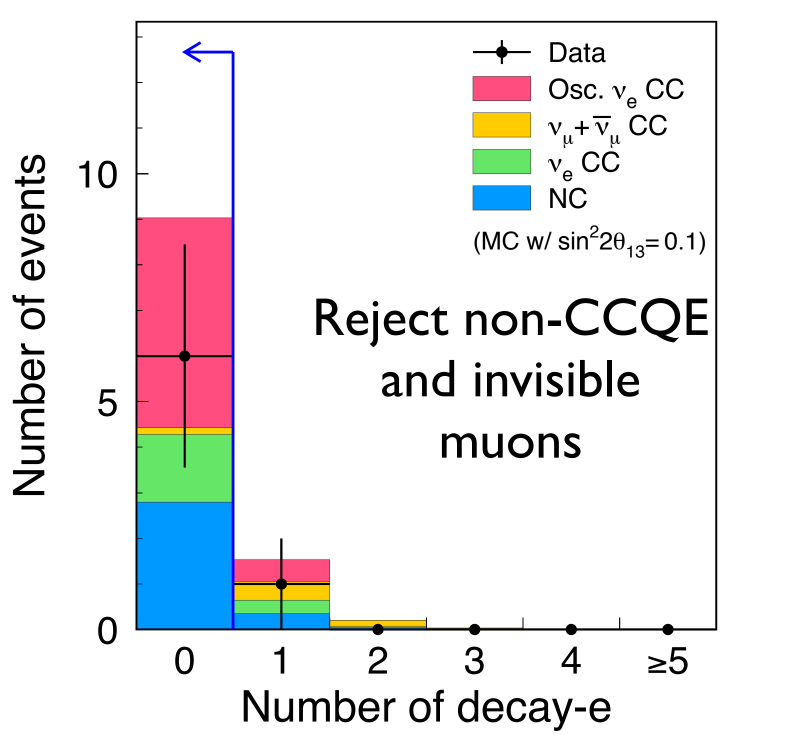
- After ring counting 8 single ring e-like events are selected
- SK "tight" cuts are applied to further reject the background
- 6 events passing all the selection

Signal efficiency: 67%
Bkg rejection: 99% for NC,
77% for beam $\nu_e$

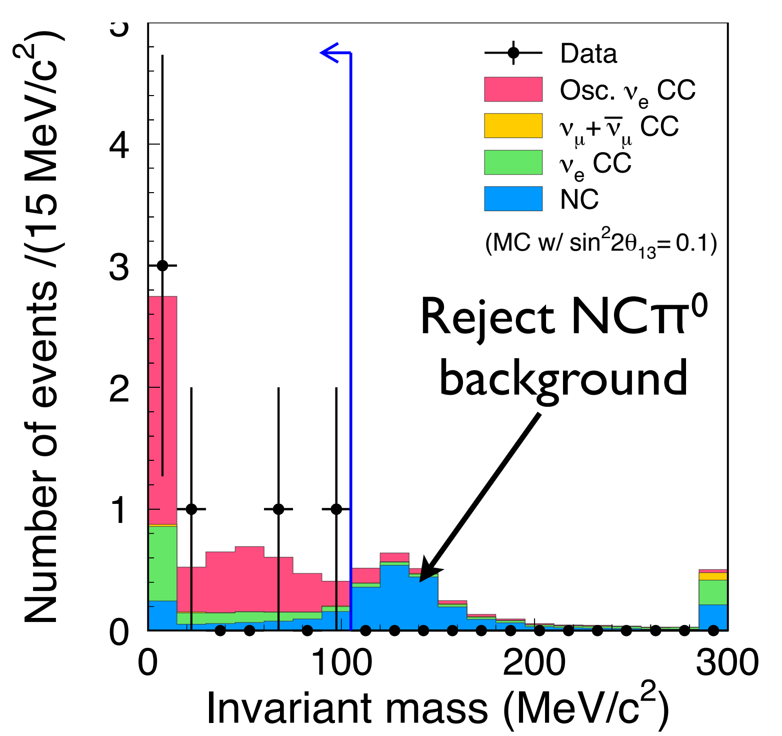
1) E(vis)>100 MeV → N=7



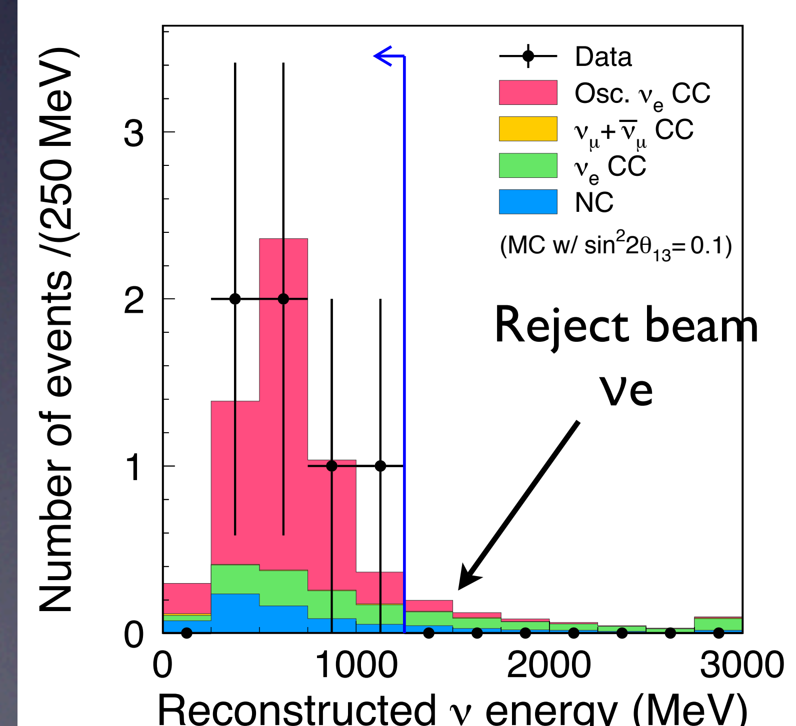

2) No decay electrons → N=6




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

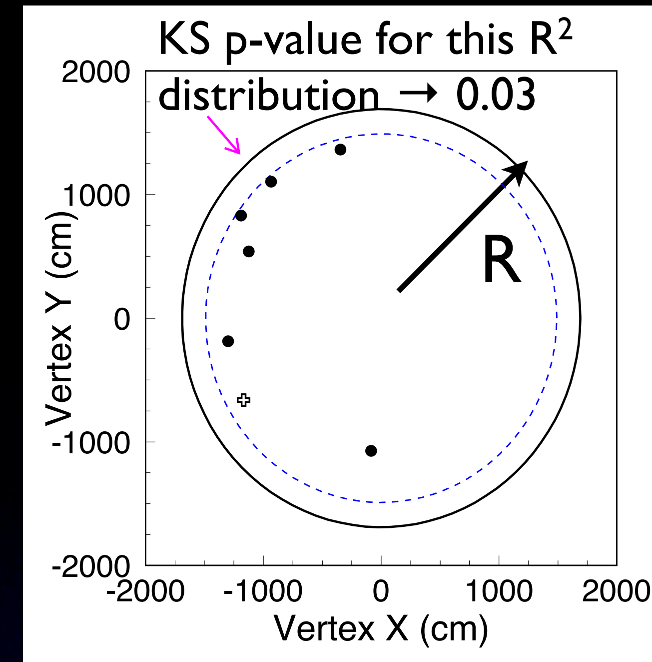



4) Rec neutrino energy <1250 MeV → N=6

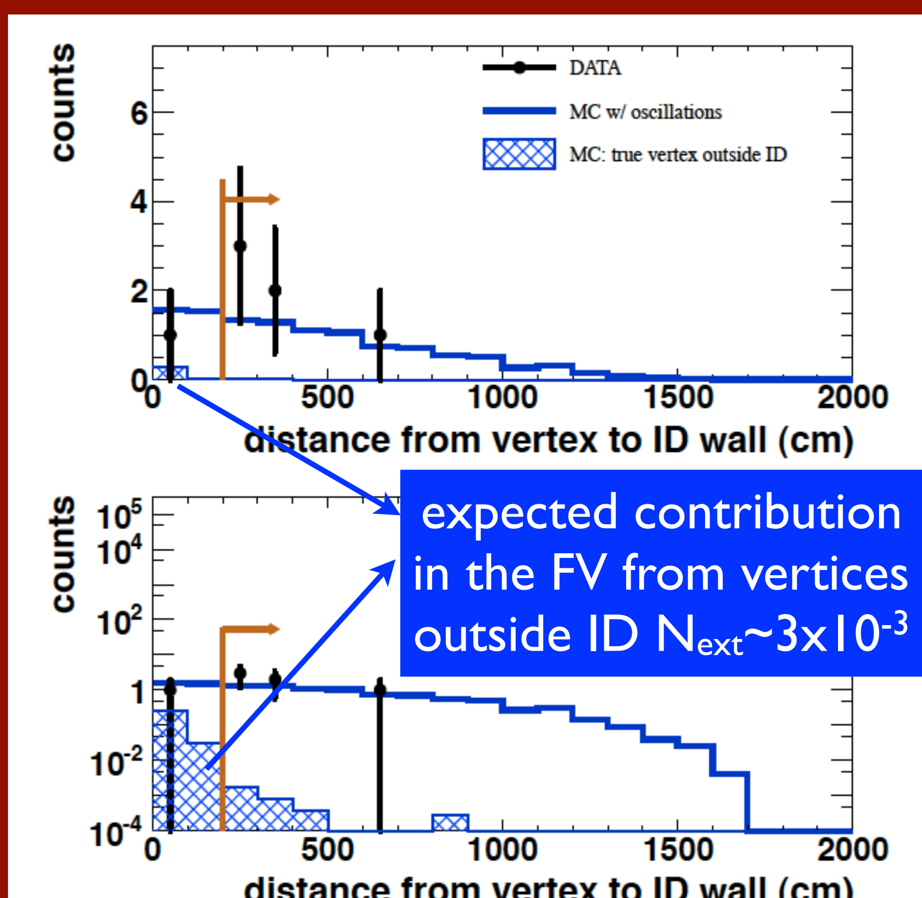


# Vertex distribution

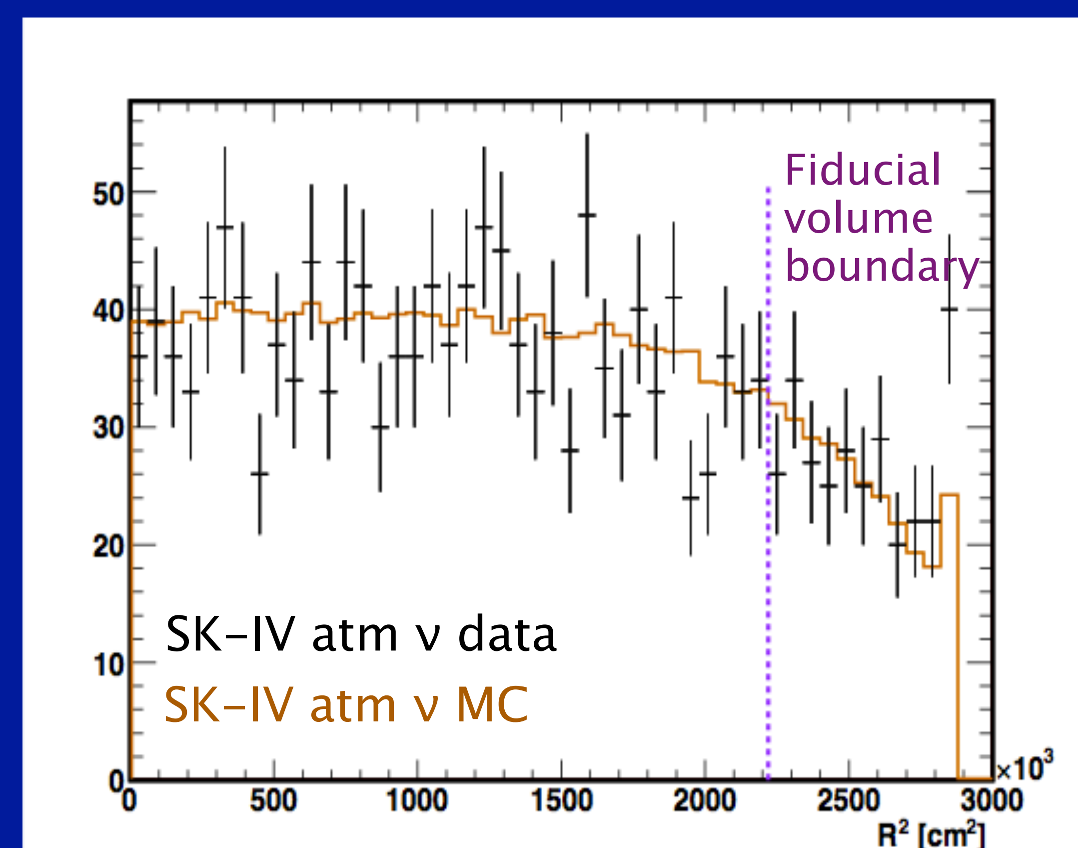
- The 6 observed events tends to cluster to high value of $R^2$
- A posteriori test of vertex distributions give P-values~(0.14-5.8)%
- More inclusive samples and atmospheric data show no anomalies near the edge of the Fiducial Volume



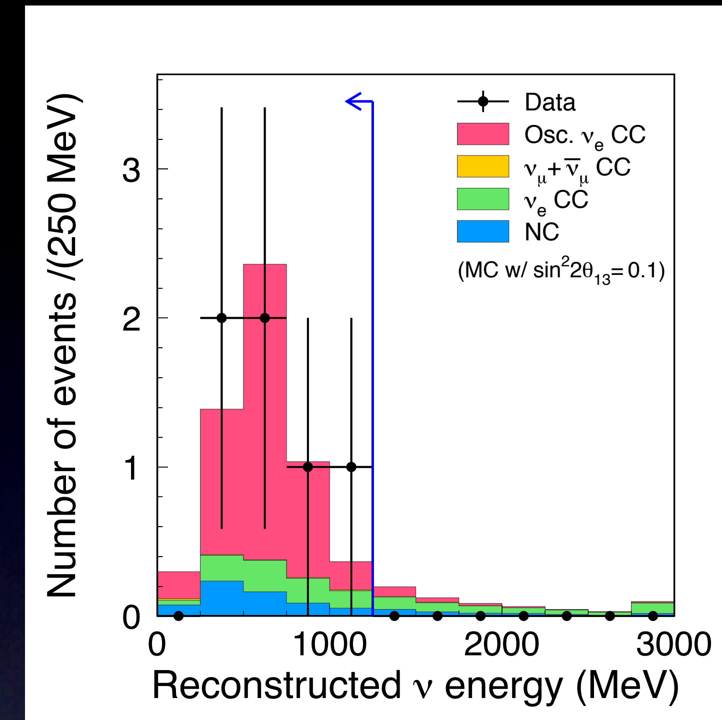

Selection of events passing all the $\nu_e$ cuts except the FV → no excesses outside the FV → no indication of not accounted entering background




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



# T2K physics results: $\nu_e$ appearance

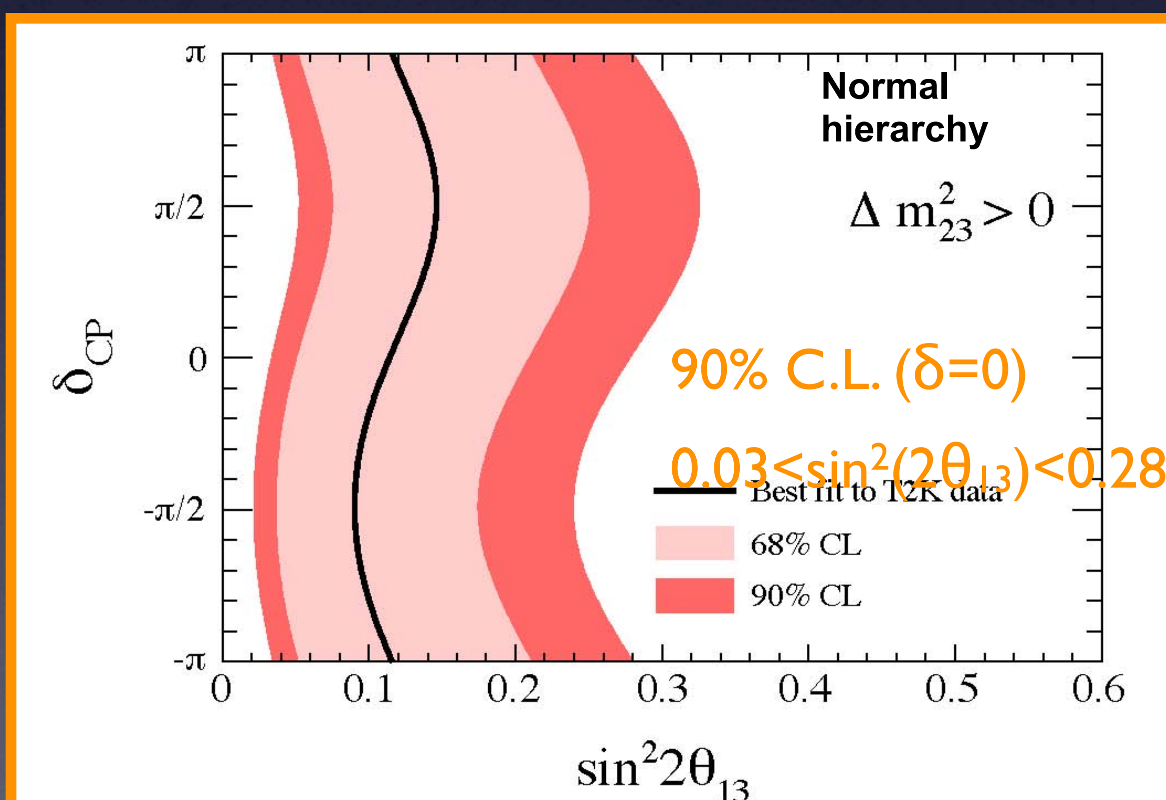



- 6 e-like events compatible with $\nu_\mu \to \nu_e$ oscillation
  - Expected background → 1.5±0.3 events
  - Background coming from beam $\nu_e$ and $\nu$ producing $\pi^0$
- Probability of observing N=6 if $\sin^2(2\theta_{13})=0$ → 0.7% (2.5σ)

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

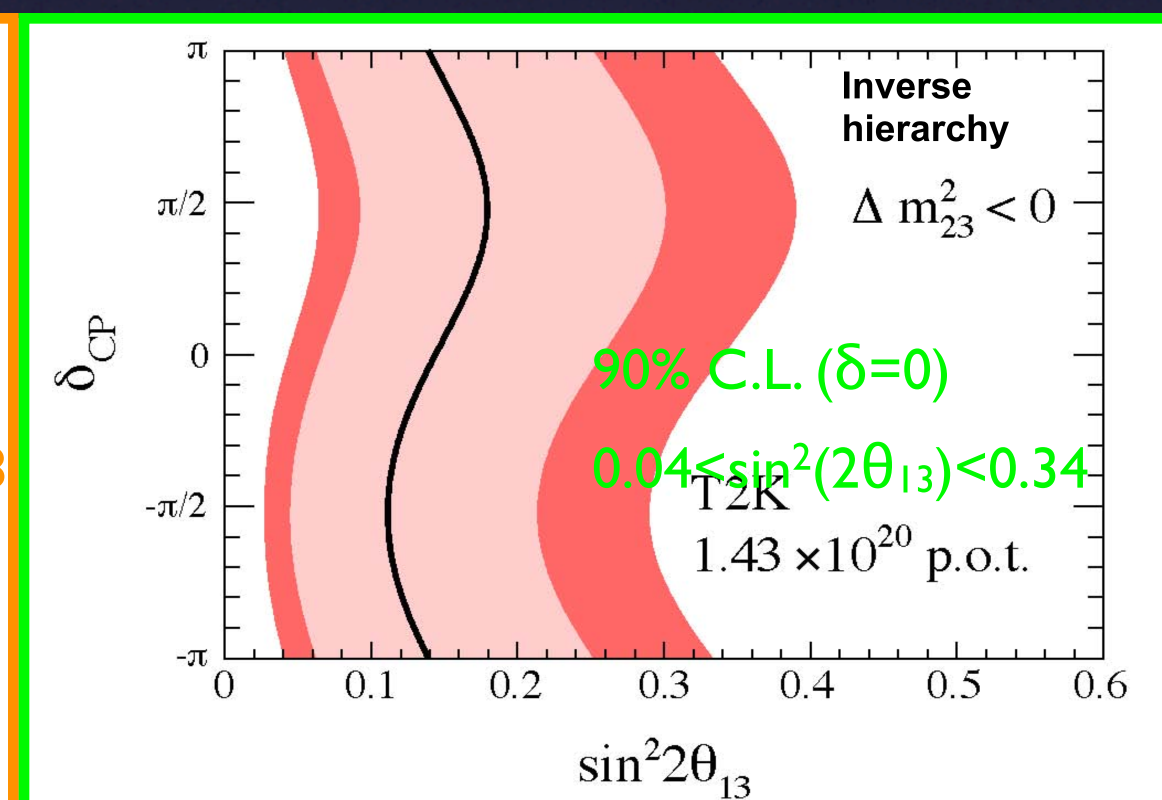
$$\Delta = 1.27\Delta m^2_{23} L/E \quad \alpha = \Delta m^2_{12}/\Delta m^2_{23} \sim 1/30$$

- Indication of $\nu_e$ appearance in $\nu_\mu$ beam!




90% C.L. (δ=0)

$0.03<\sin^2(2\theta_{13})<0.28$

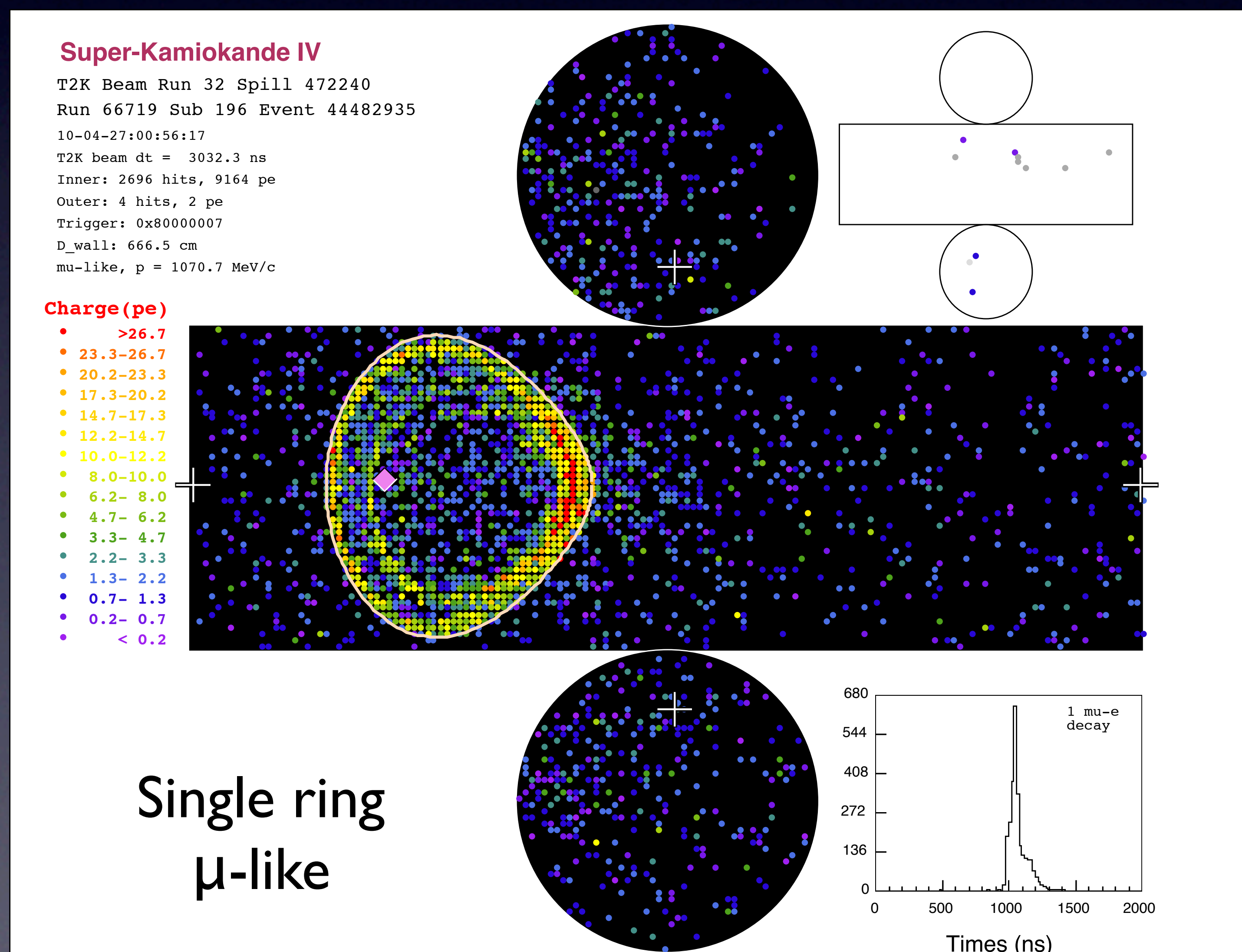



90% C.L. (δ=0)

$0.04<\sin^2(2\theta_{13})<0.34$

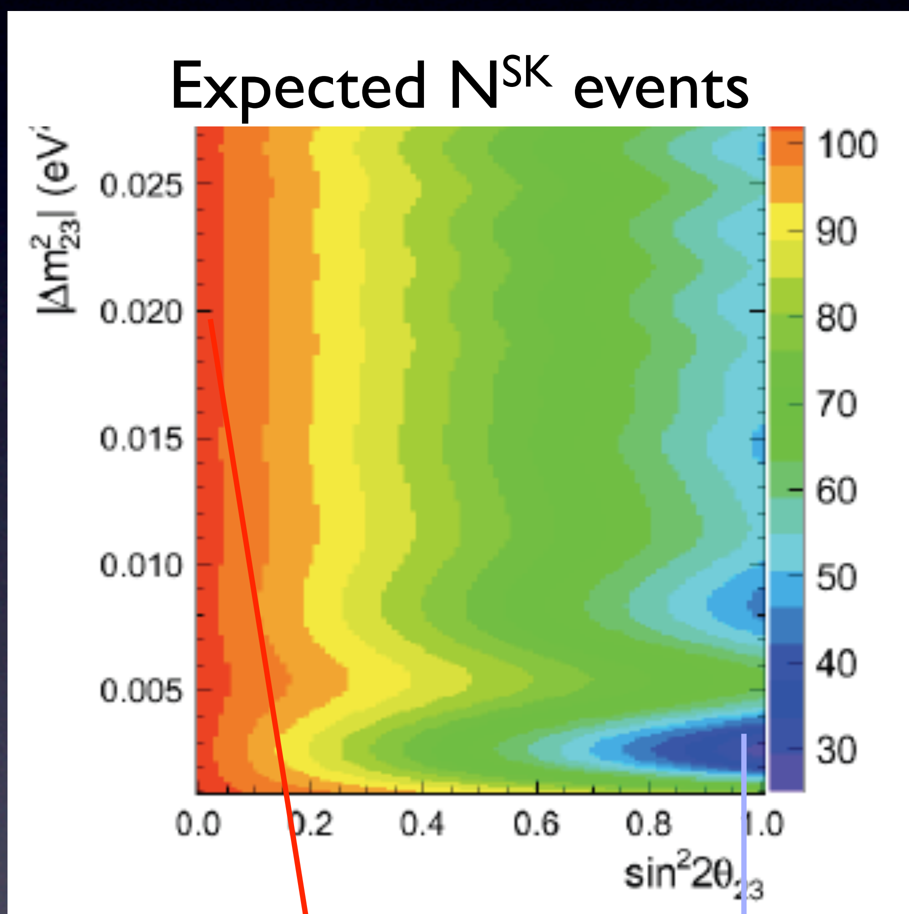
Published in Phys. Rev. Lett. 107, 041801 (2011)

# $\nu_\mu$ 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
$\sin^2 2\theta=1$, $\Delta m^2=2.4\text{x}10^{-3}$ eV$^2$

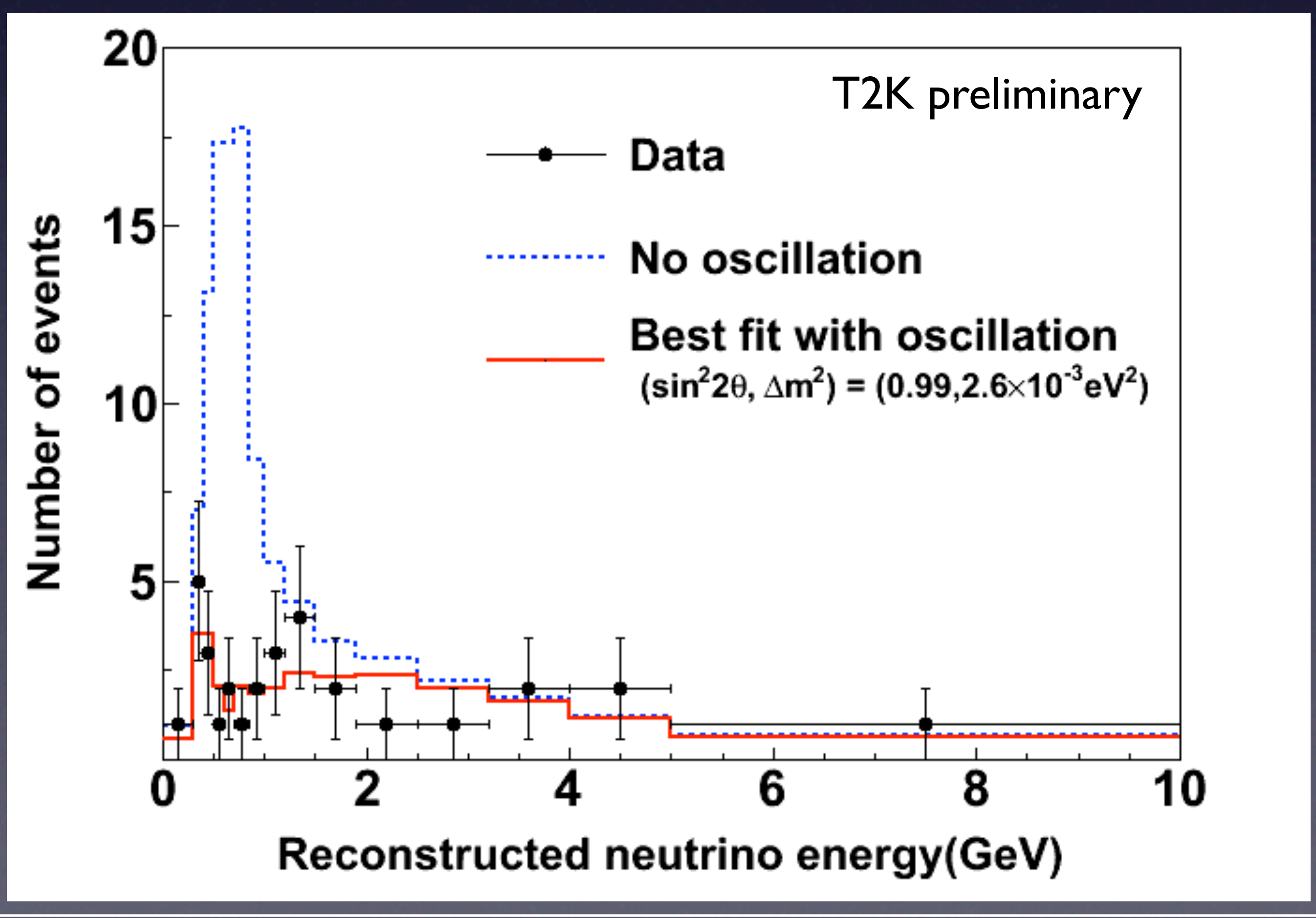
Systematics for $N_{exp}^{SK}$ for different oscillation parameters

| Error source | $\sin^2 2\theta=1$, $\Delta m^2=2.4\text{x}10^{-3}$ | 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% |

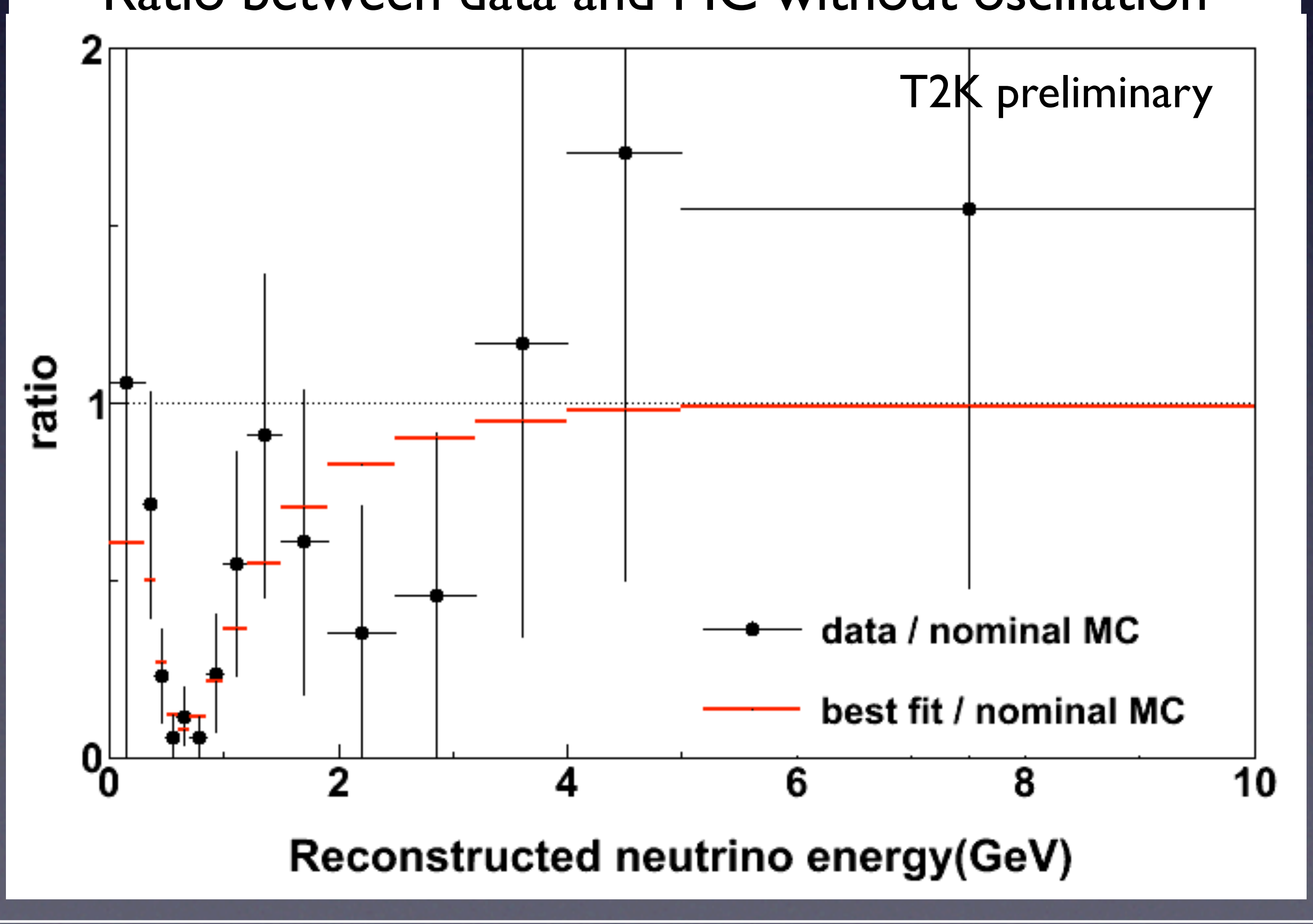
- Null-oscillation hypothesis excluded at 4.5 σ (only from $N^{obs}$)

# Neutrino energy spectrum

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




Ratio between data and MC without oscillation

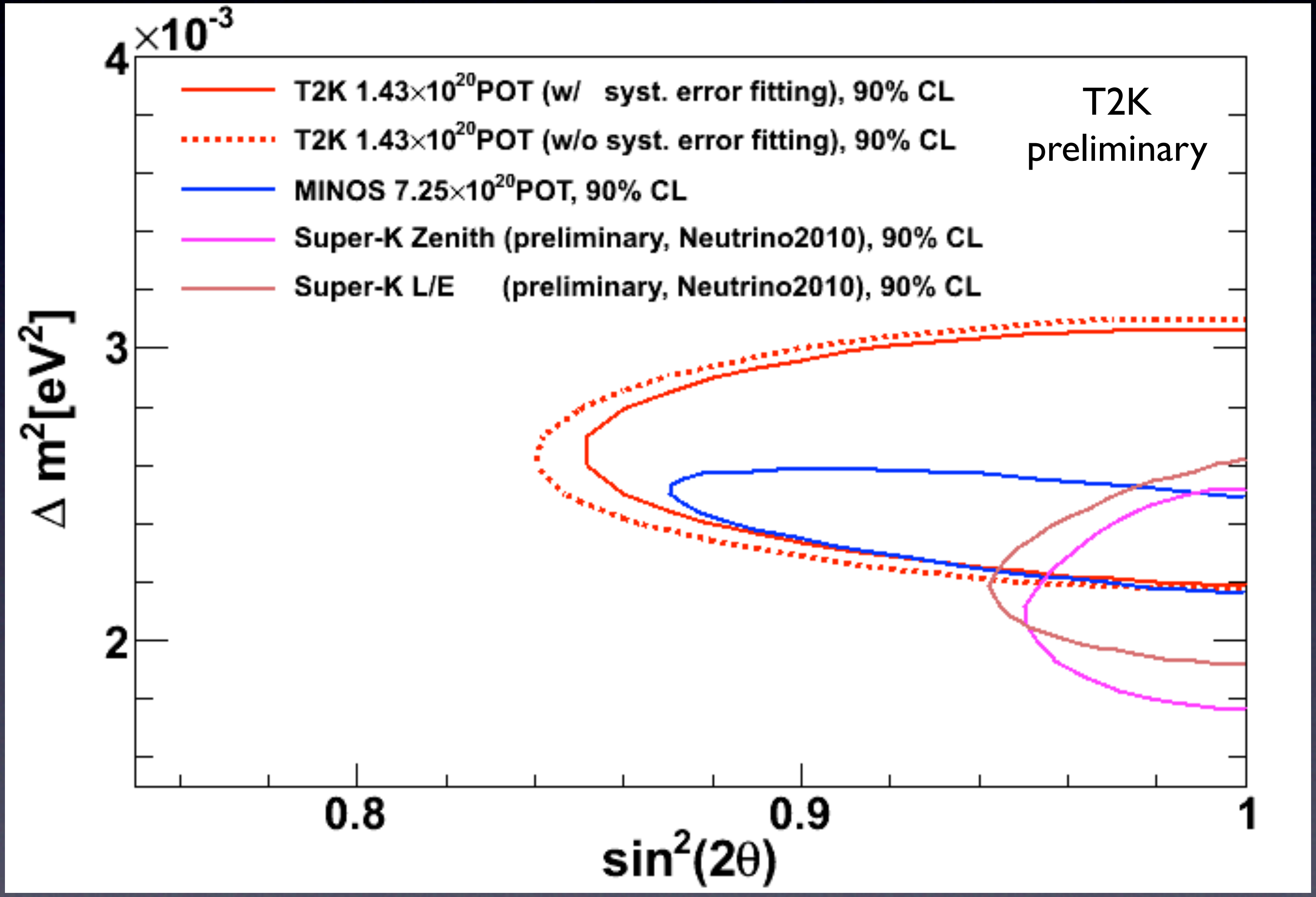


# Comparison with SK and MINOS

- T2K results are in good agreement with results from SK and MINOS

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

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

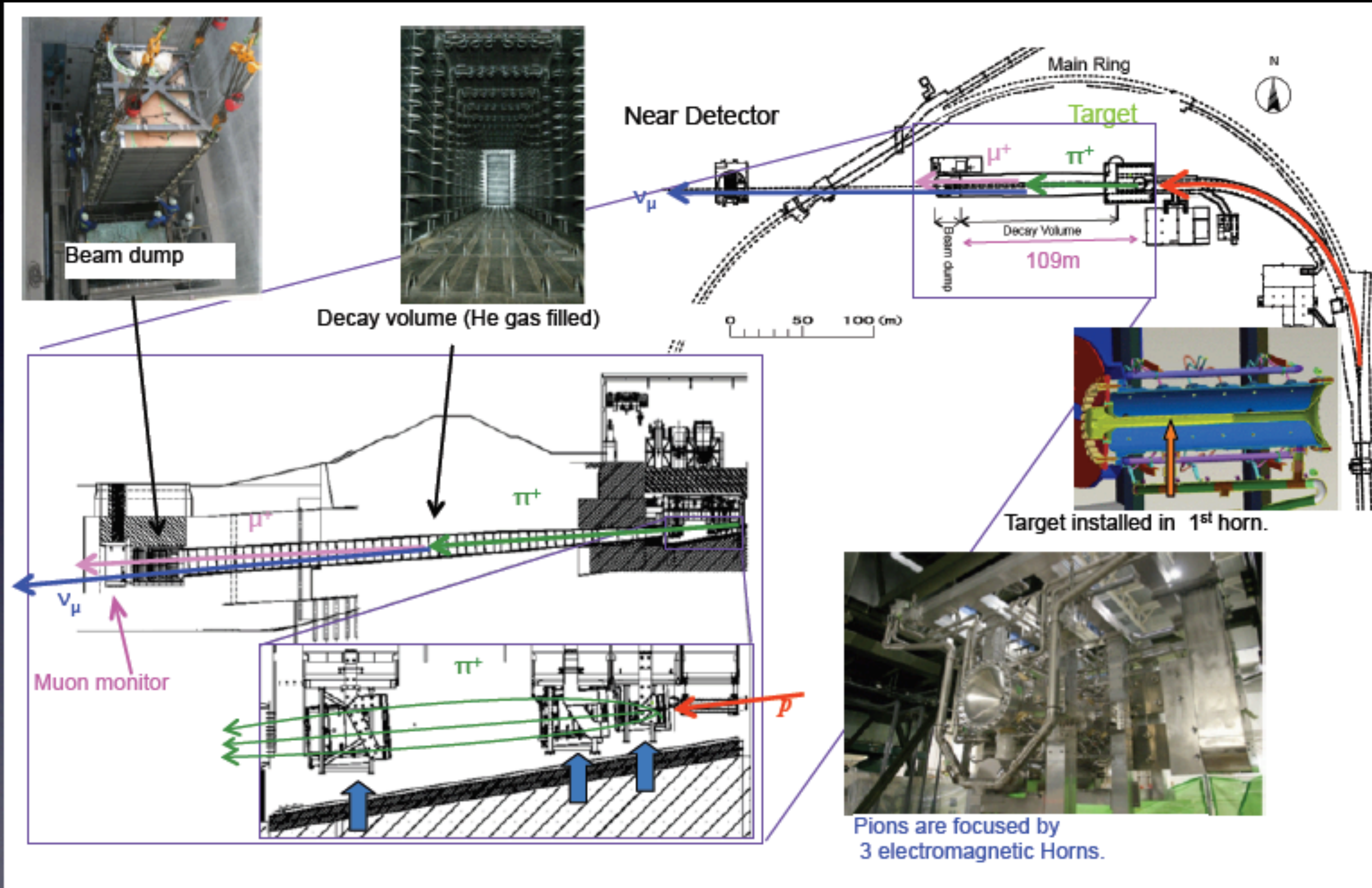


# Conclusions

- The T2K experiment has completed two oscillation analyses based on $1.43\times10^{20}$ p.o.t (2% of T2K's goal)
- $\nu_e$ appearance analysis:
  - 6 events have been observed (1.5±0.3 expected)
  - The probability of 6 events with $\theta_{13}=0$ is 0.7% (2.5$\sigma$ 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
- $\nu_\mu$ disappearance analysis:
  - No oscillation hypothesis excluded at 4.5$\sigma$
  - $\sin^2(2\theta_{23})>0.85$ 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
  - Investigations done so far indicate that all damage is repairable
  - Aim to restart JPARC operation in December 2011

# Back up slides

# JPARC beamline overview



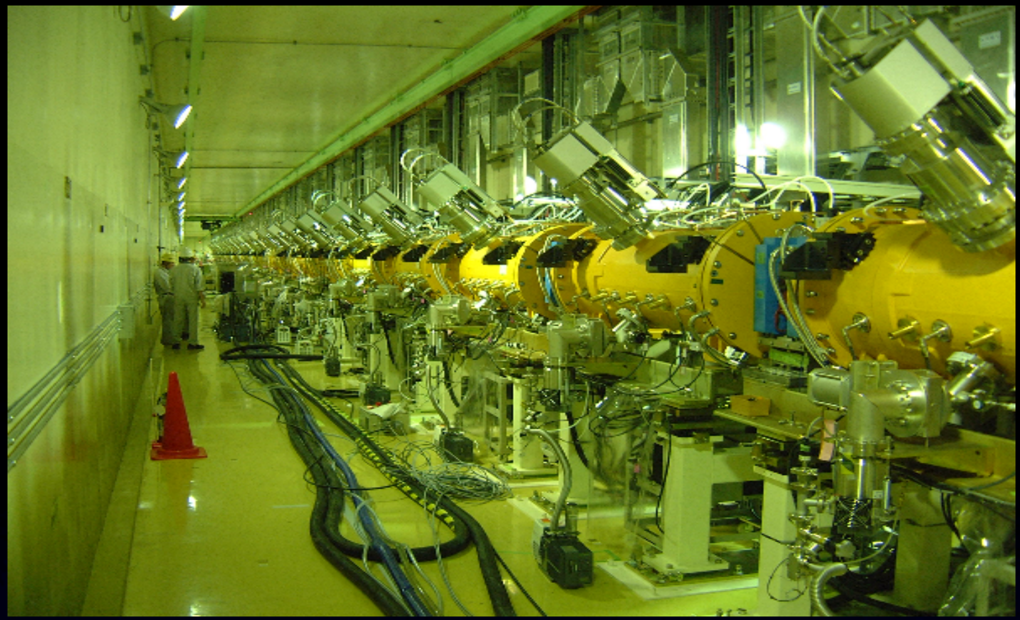
## Linac

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.

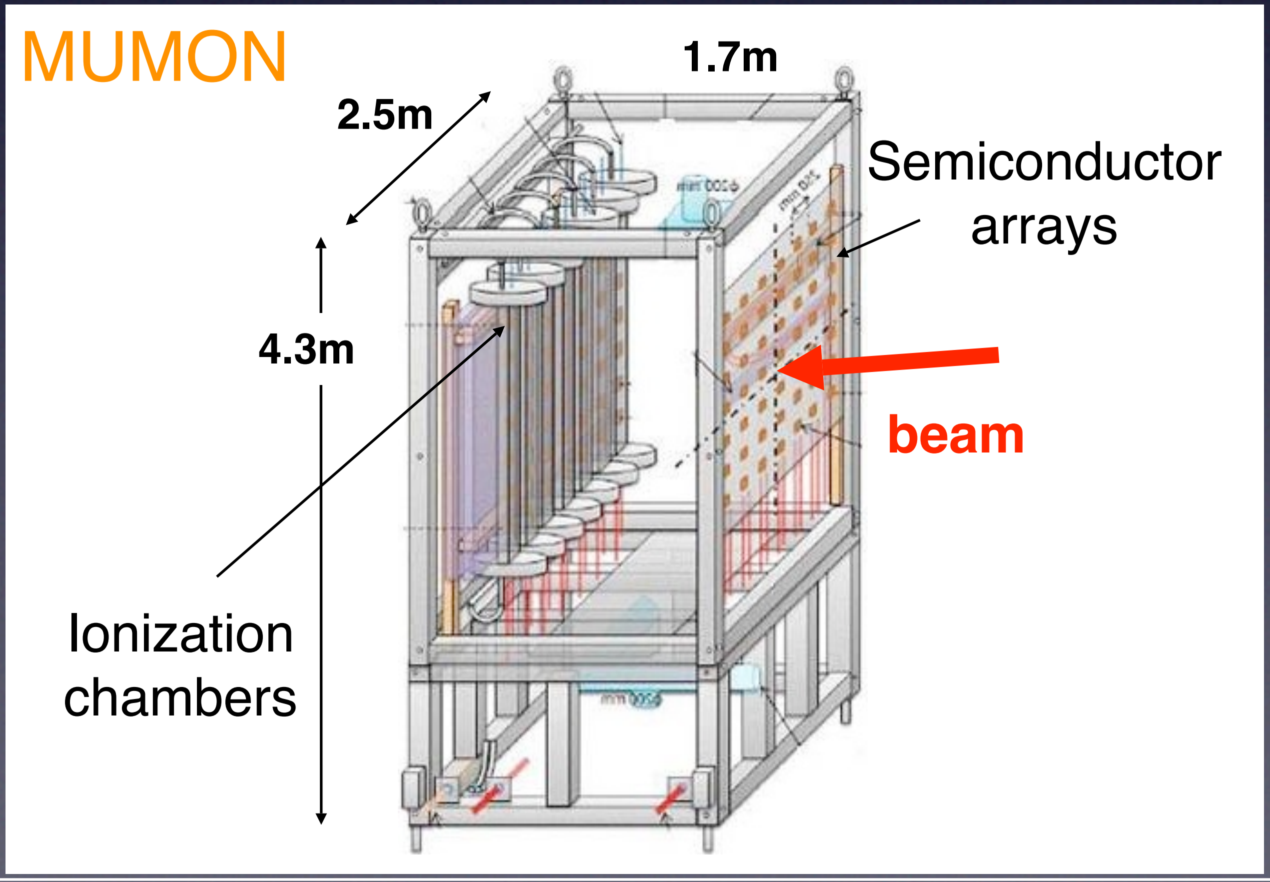
## Main Ring

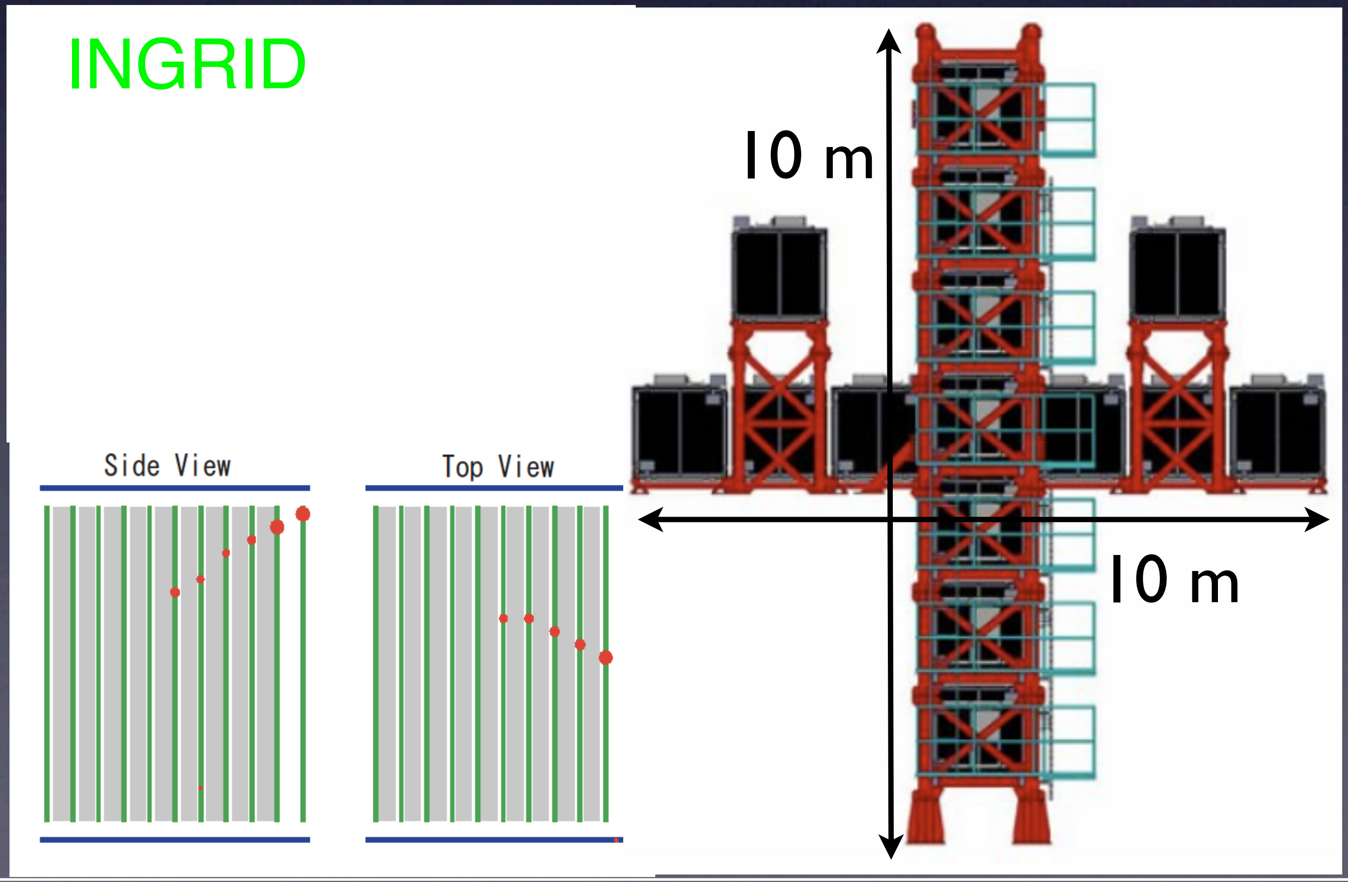
Third (and final) stage accelerator. Proton Synchrotron of 1568m circumference.

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

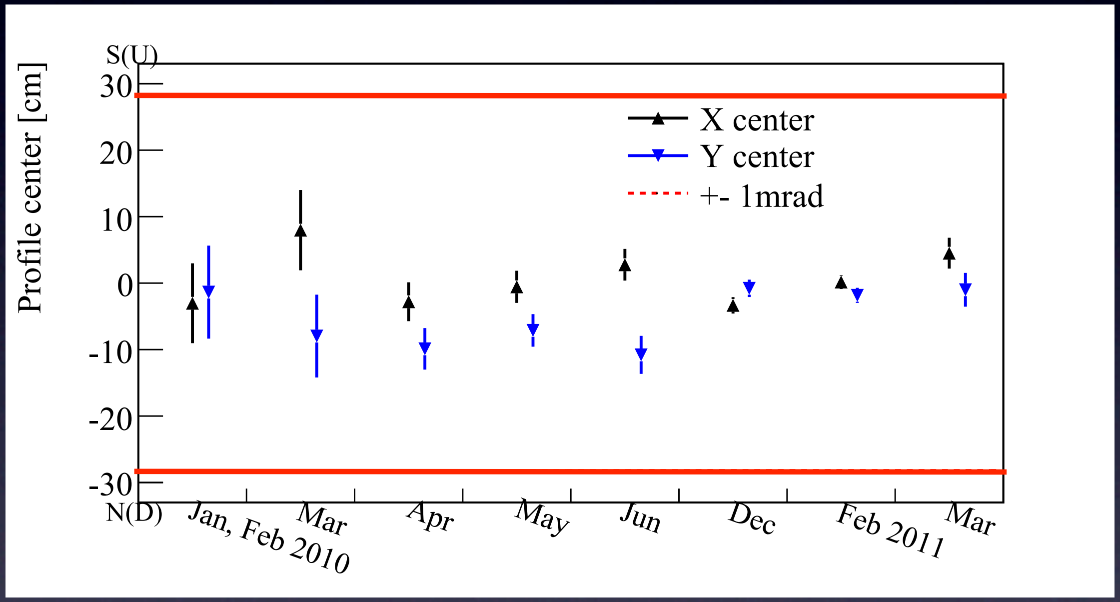


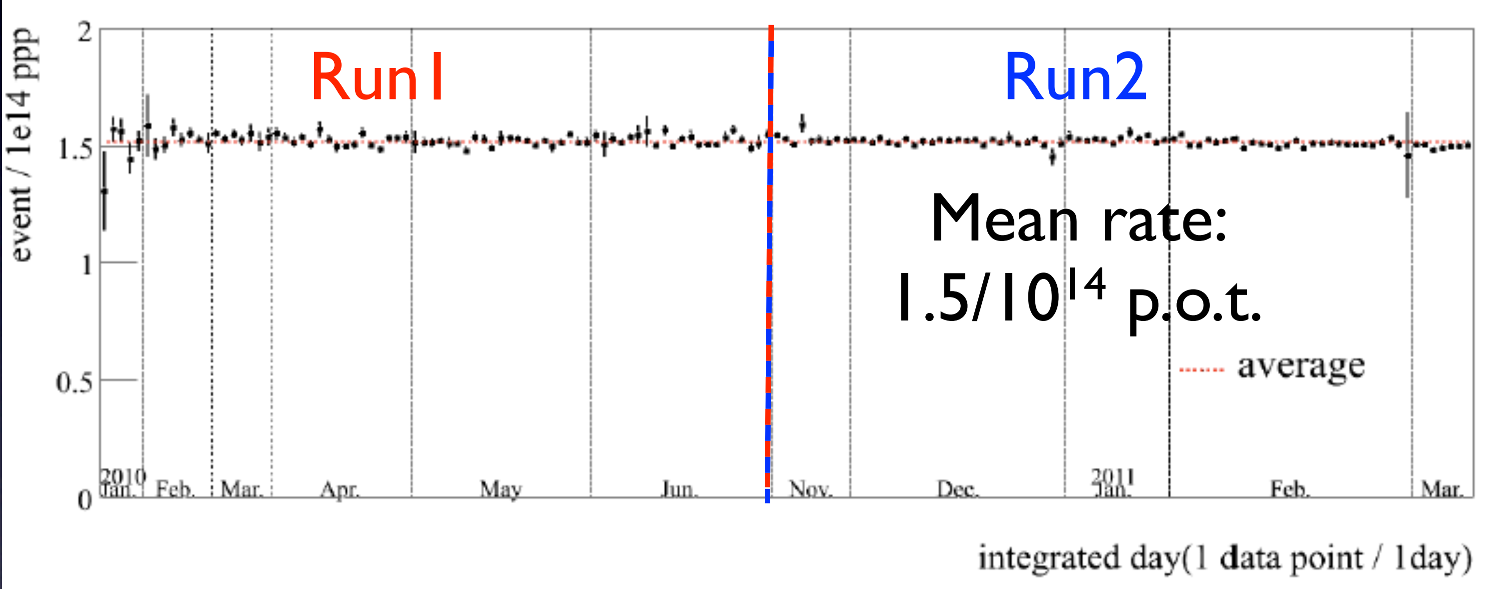
# Beam stability

- 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

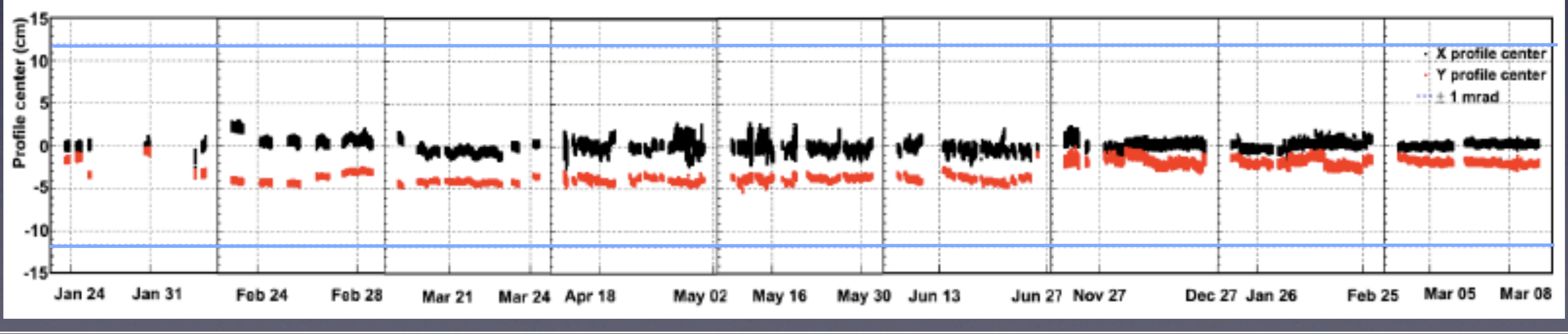
Beam center measured at INGRID well within 1 mrad




INGRID interaction rate stable for Run1 and Run2

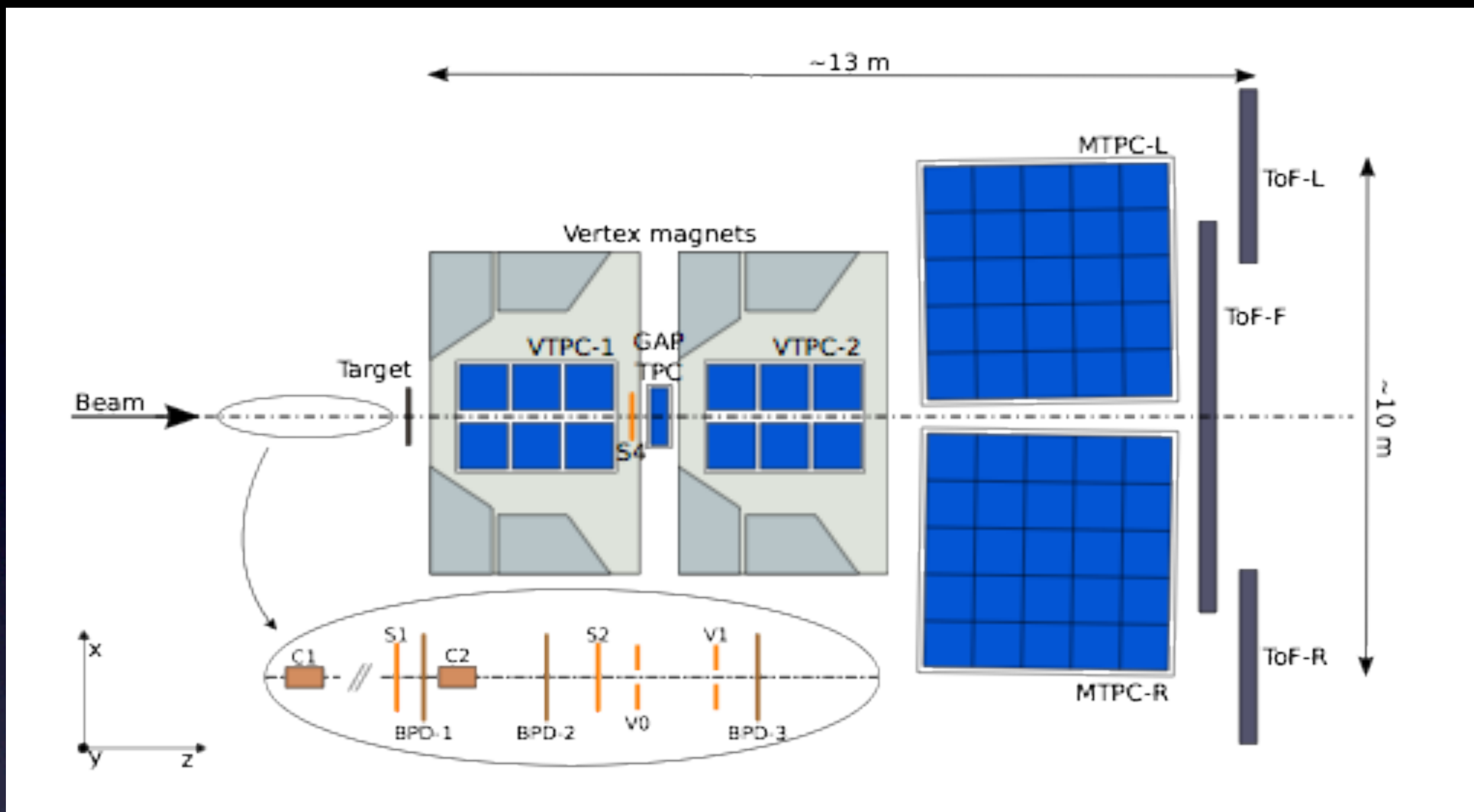


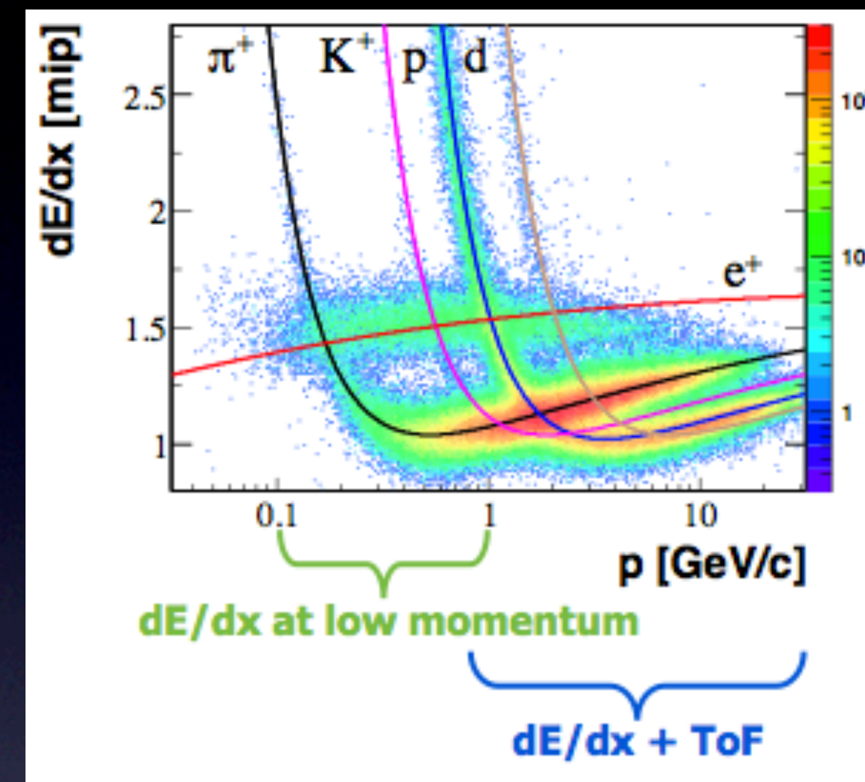

Beam center measured at MUMON well within 1 mrad



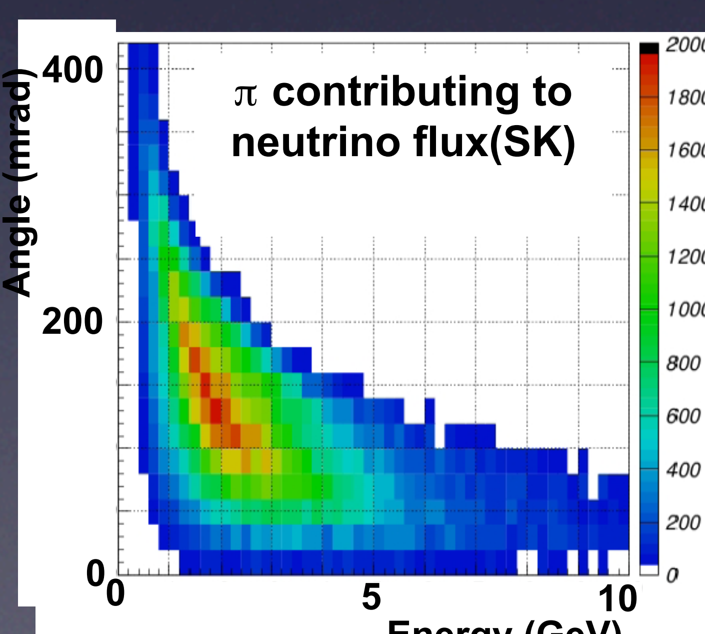
# CERN NA61/SHINE experiment

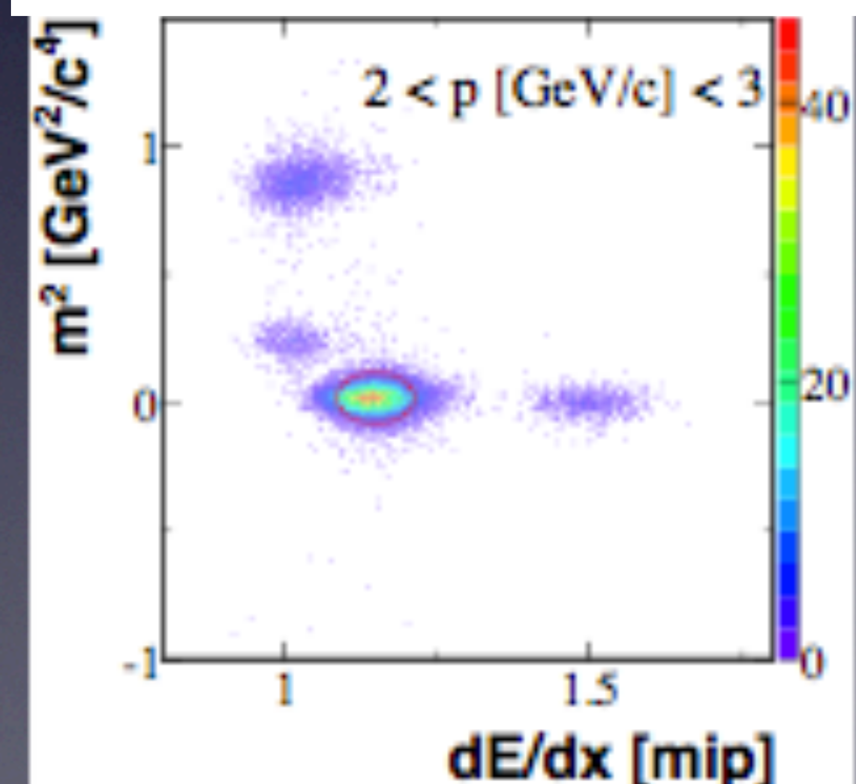
*$\pi^+$ production: Two analysis for different momentum region*



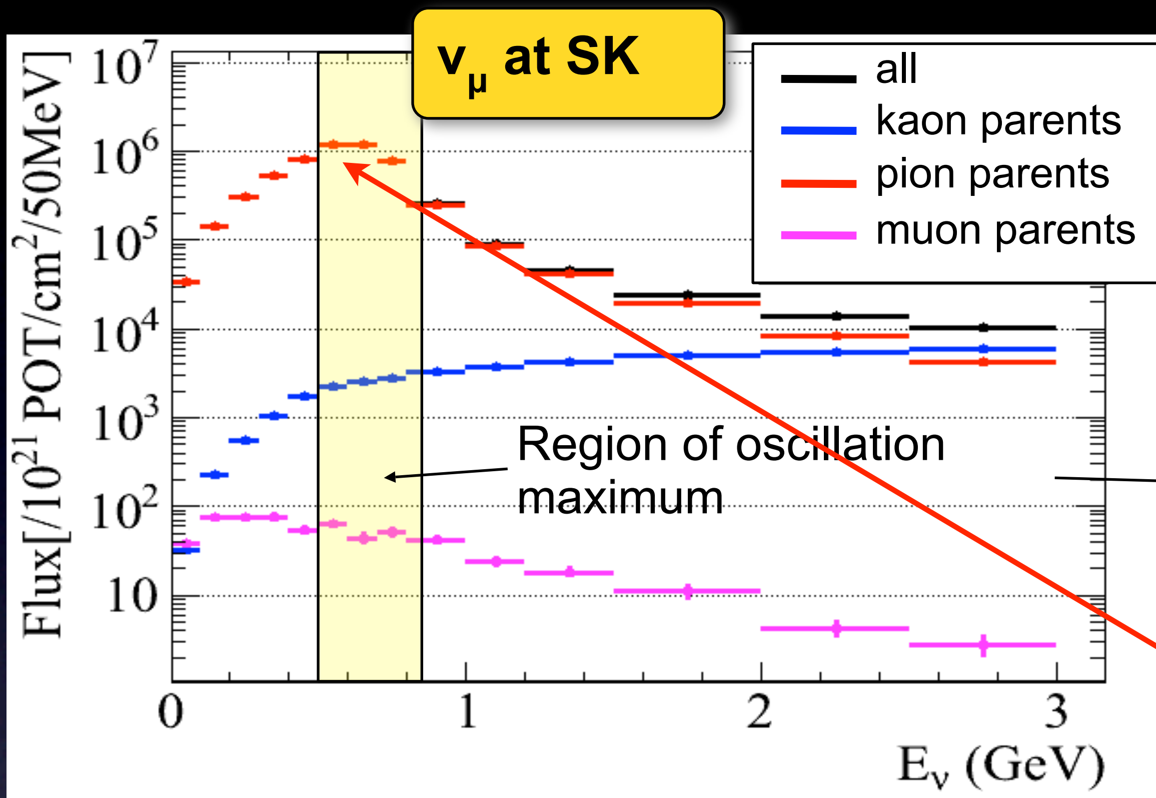



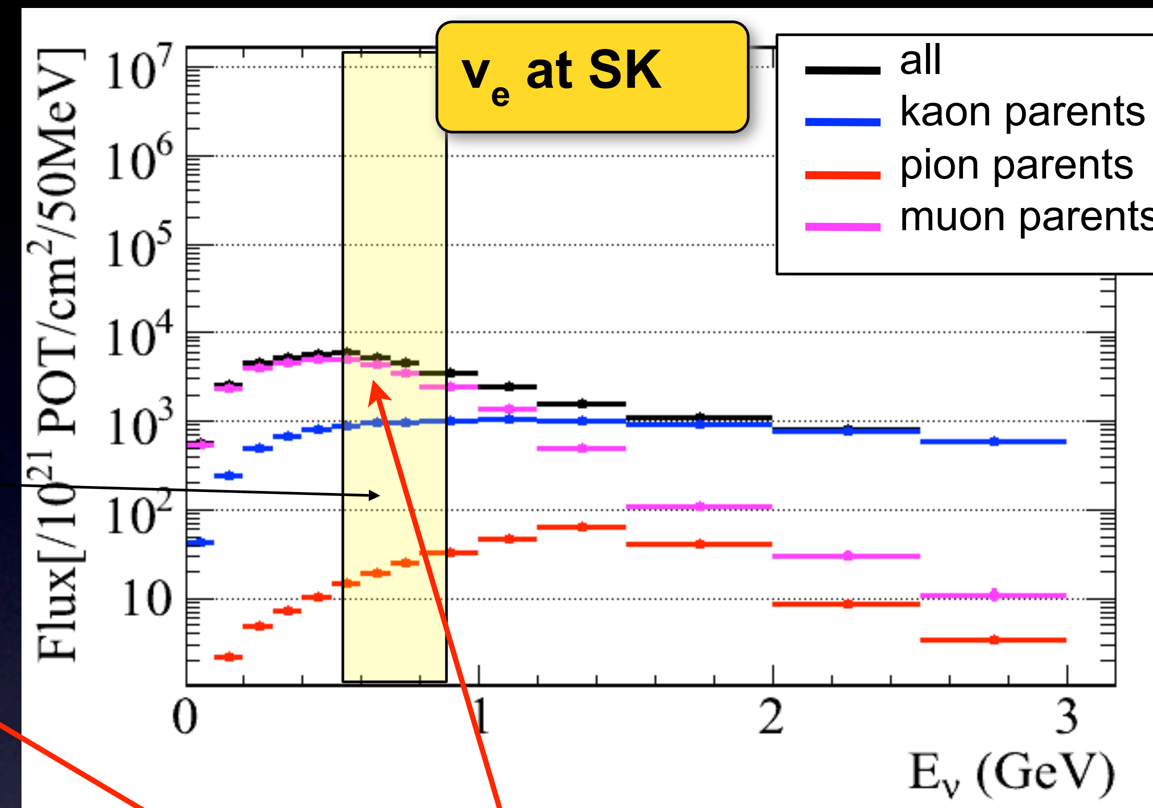

- Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction
- Thin target + T2K replica target



# Expected ν fluxes and uncertainties




Systematics for $\nu_e$ 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 $\nu_e$ contamination: ~1% of the total flux in the oscillation region

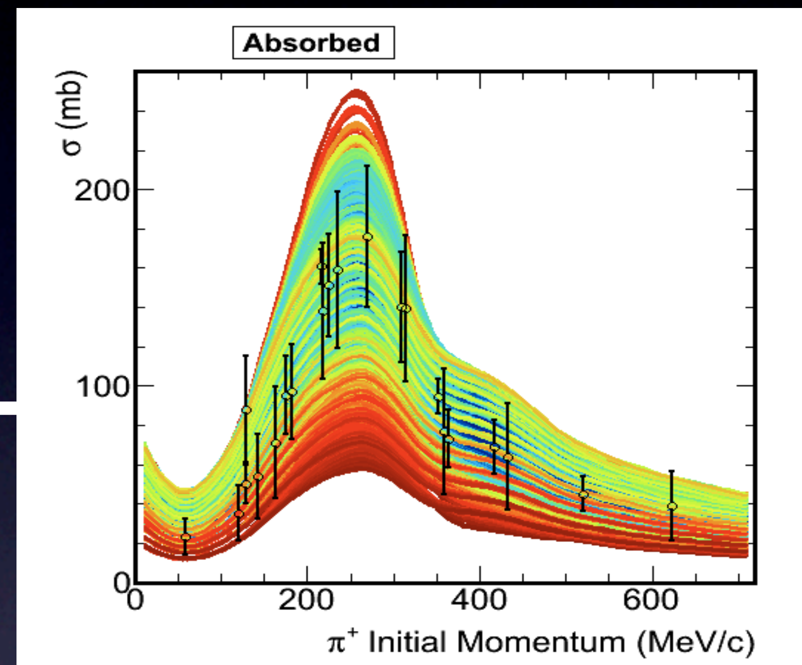
The uncertainty on the fluxes is significantly reduced when the expected event rate at the near detector is used

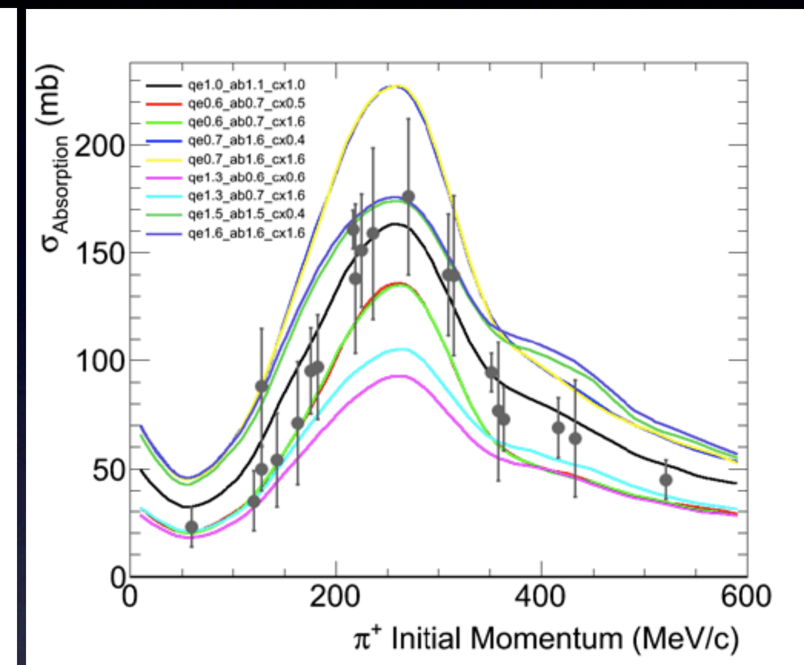
# FSI tuning

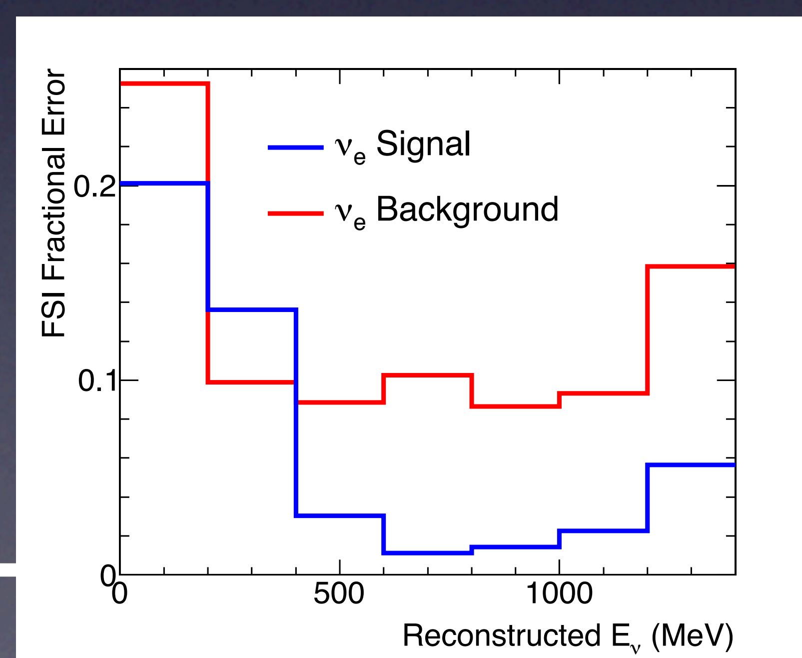
- 14% of the systematic on the background to the $\nu_e$ appearance, 8% to the $\nu_\mu$ disappearance
- Principal source of uncertainty: pion final state interaction (FSI)

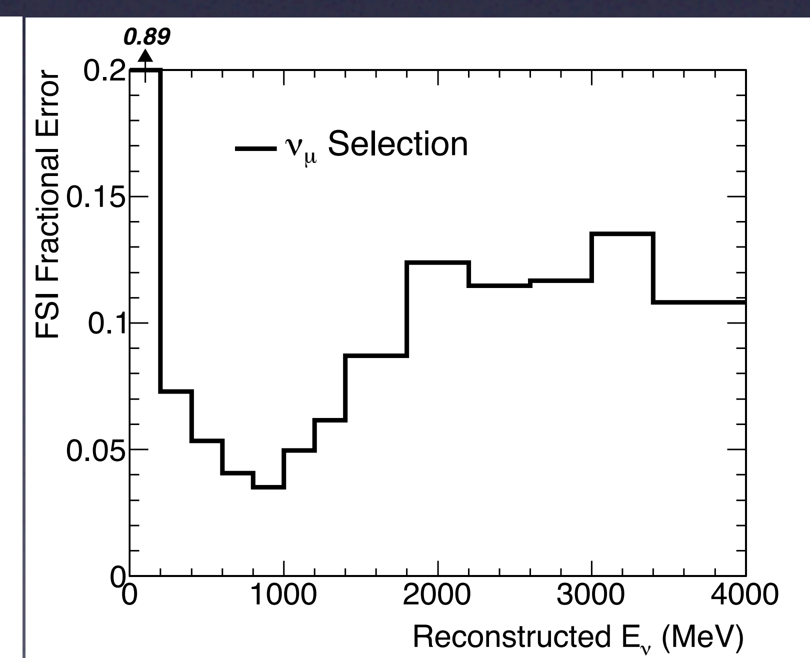
| Error source | $N^{exp}$(SK) |
|---|---|
| CCQE shape | 3.1% |
| CC1π | 2.2% |
| CC coherent π | 3.1% |
| CC other | 4.4% |
| NC1π0 | 5.3% |
| NC coherent | 2.3% |
| NC other | 2.3% |
| σ(νe) | 3.4% |
| FSI | 10.1% |
| Total | 14.0% |

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



# Off-axis ND280

- Same off-axis angle as Super-Kamiokande (2.5 degrees)
- Measure $\nu_\mu$ and $\nu_e$ spectrum before the oscillation → TPCs + FGDs
- Measure background processes to oscillation ($NC\pi^0$, $NC1\pi$, $CC1\pi$...)

ND280 installed in ex-UA1 magnet (0.2 T) 3.5x3.6x7.3 m

**SMRD (Side Muon Range Detector):** scintillator planes in magnet yokes. Measure high angle muons

**P0D (π0 detector):** scintillator bars interleaved with fillable water target bags and lead and brass sheets. Optimized for γ detection

**2 FGDs (Fine Grained Detector):** active target mass for the tracker, optimized for p/π separation
Carbon+Water target in FGD2

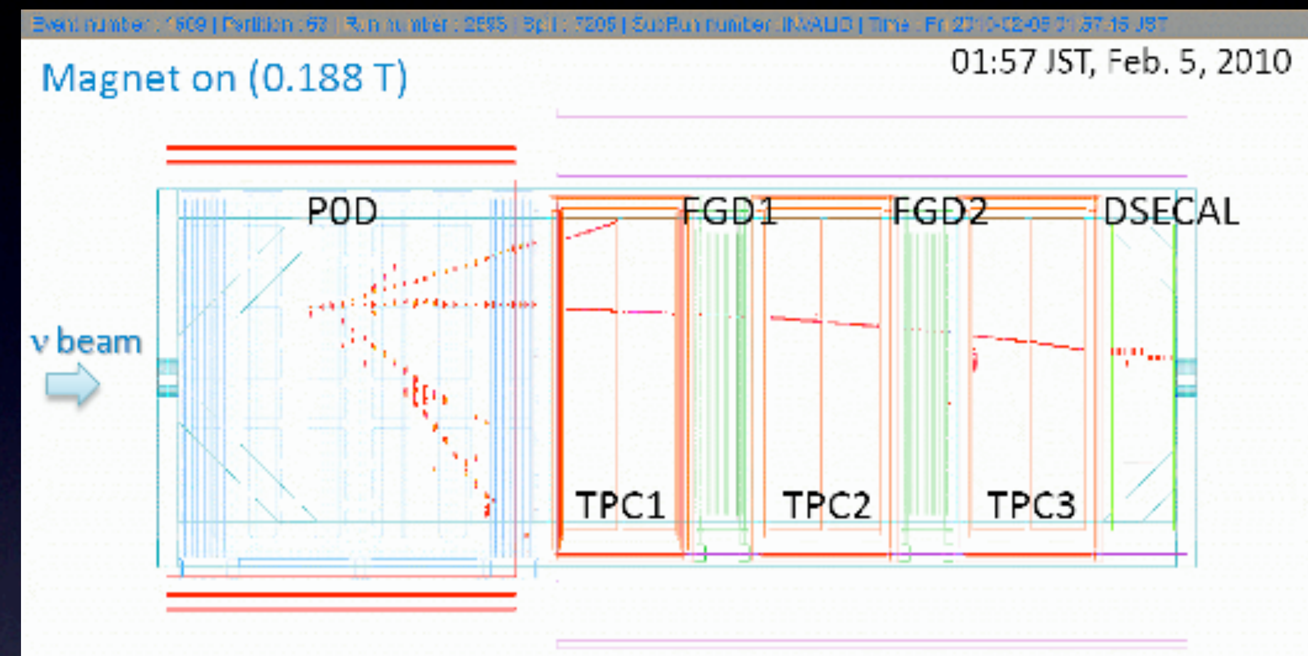
**3 TPCs (Time Projection Chambers):** measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

**P0D, Barrel and Downstream ECAL:** scintillator planes with radiator to measure EM showers

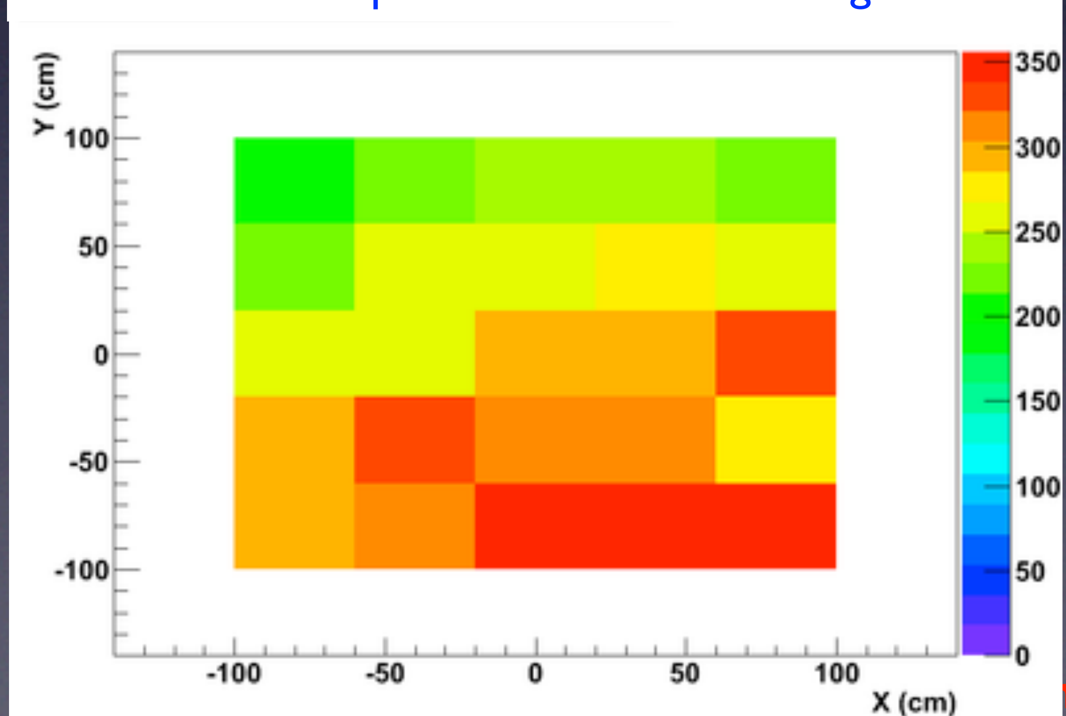
# ND280 scintillator detectors

- The ND280 detectors except the TPCs use Multi-Pixel Photon Counters (MPPCs)
  - 1.3 x 1.3 mm, 667 pixels
  - ~60000 MPPCs used in ND280

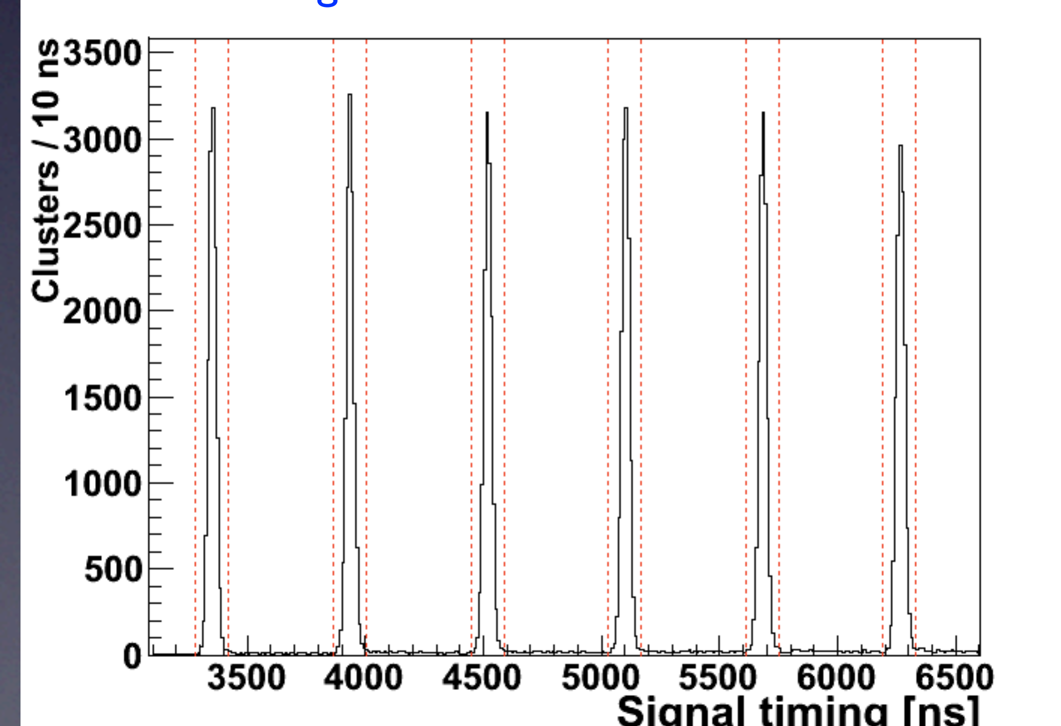
The ND280 TPCs will be described with more details in the next slides




P0D vertex XY position → off-axis configuration

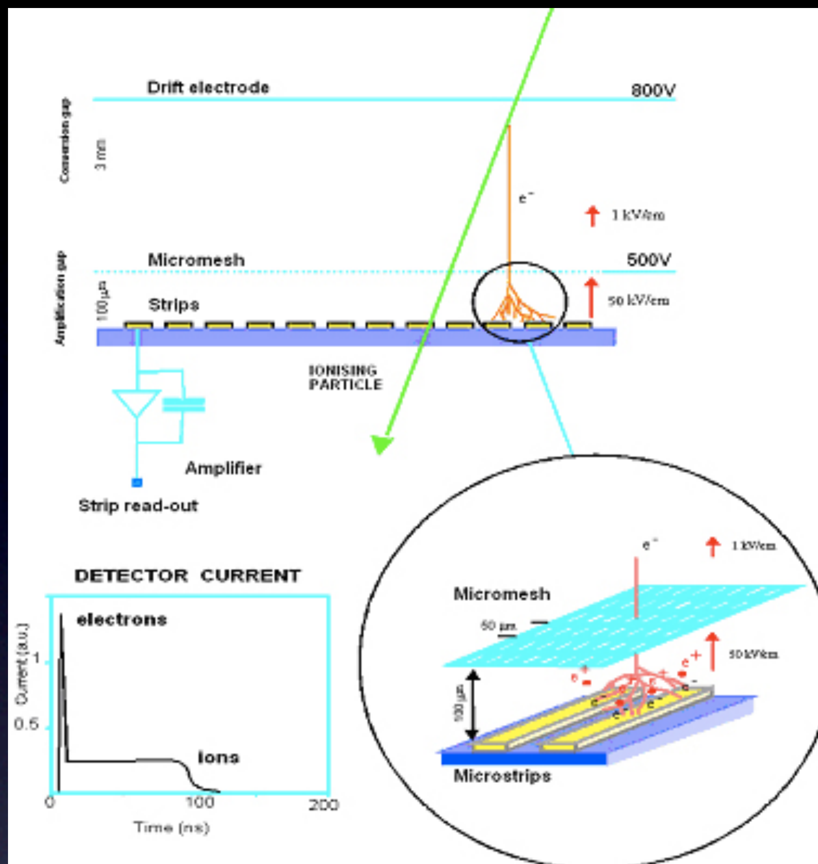



FGD timing distribution → 6 bunch structure

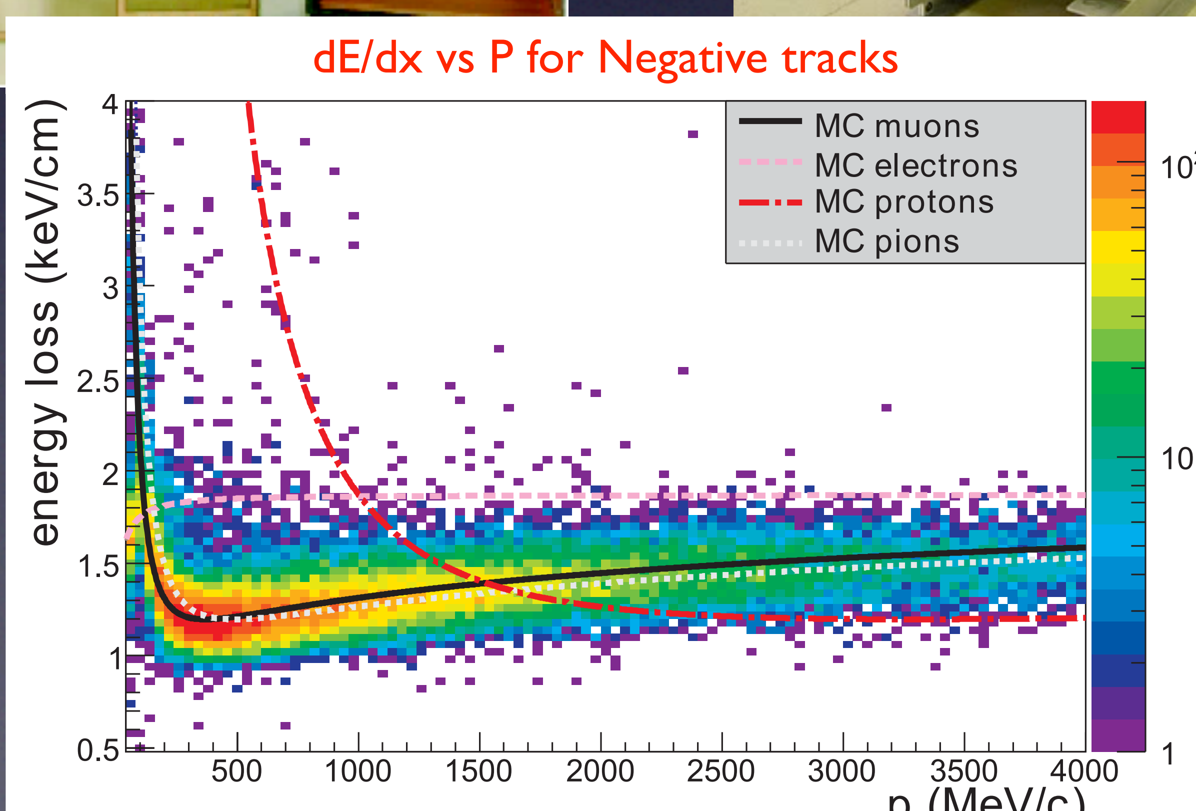



n center
→ off axis

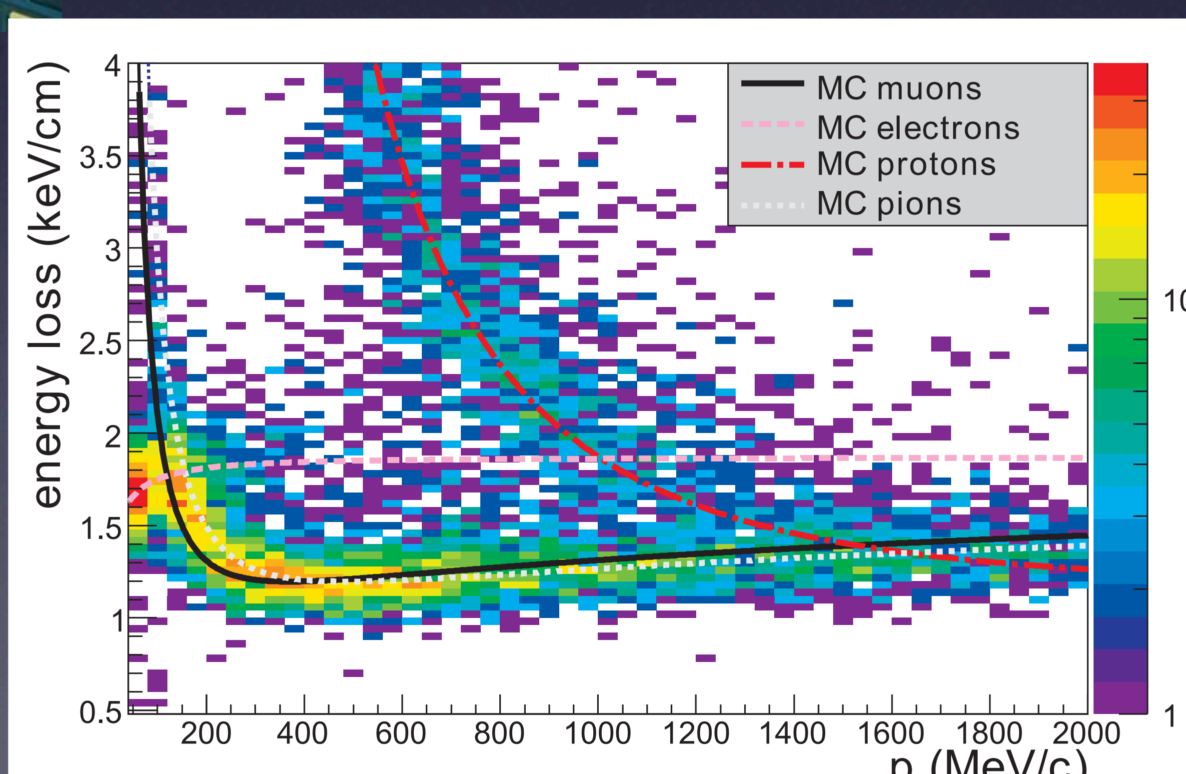
# ND280 TPC



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

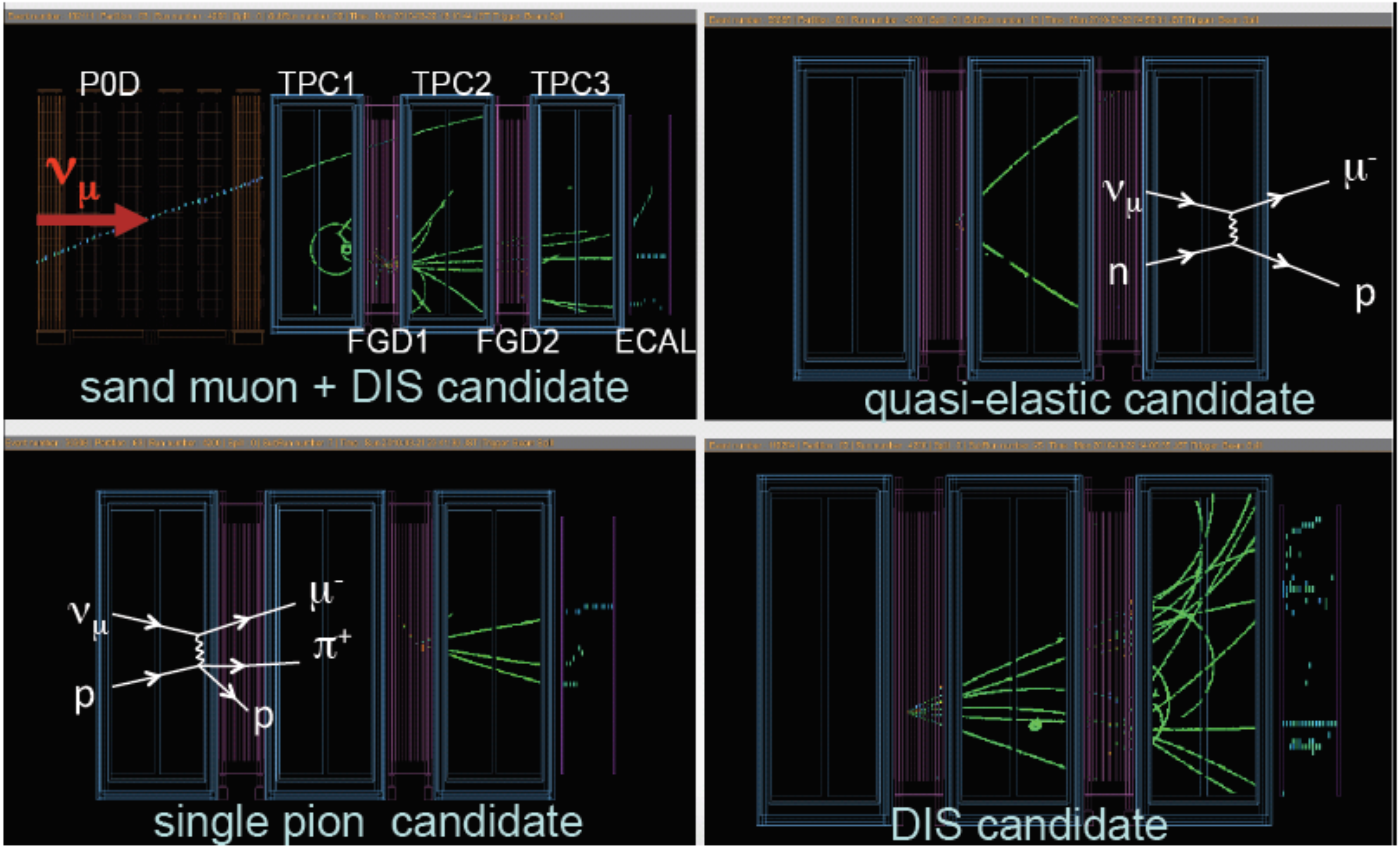



dE/dx vs P for Negative tracks
energy loss (keV/cm)
p (MeV/c)
MC muons
MC electrons
MC protons
MC pions

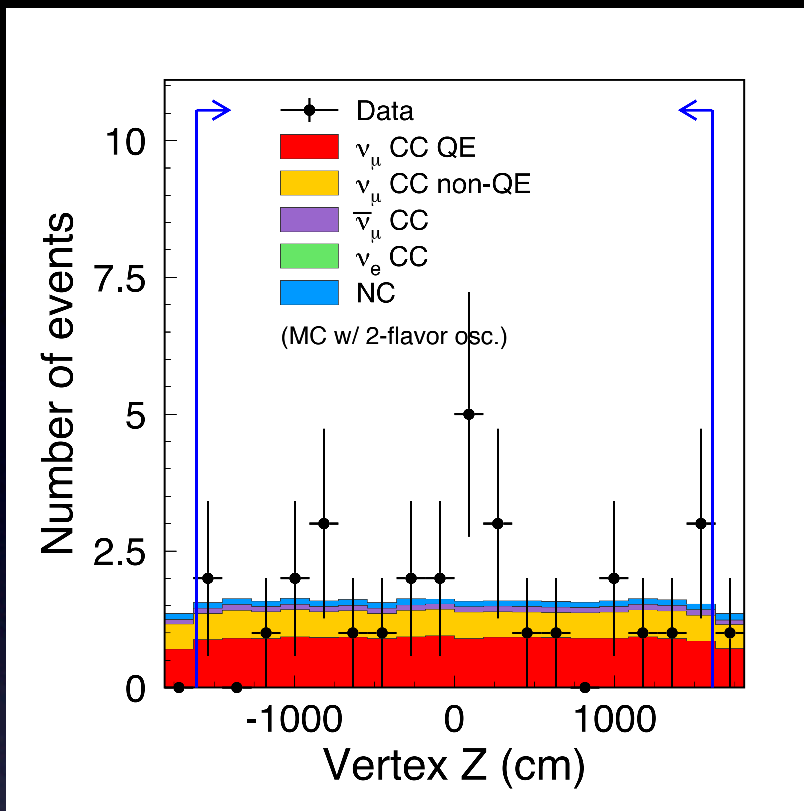



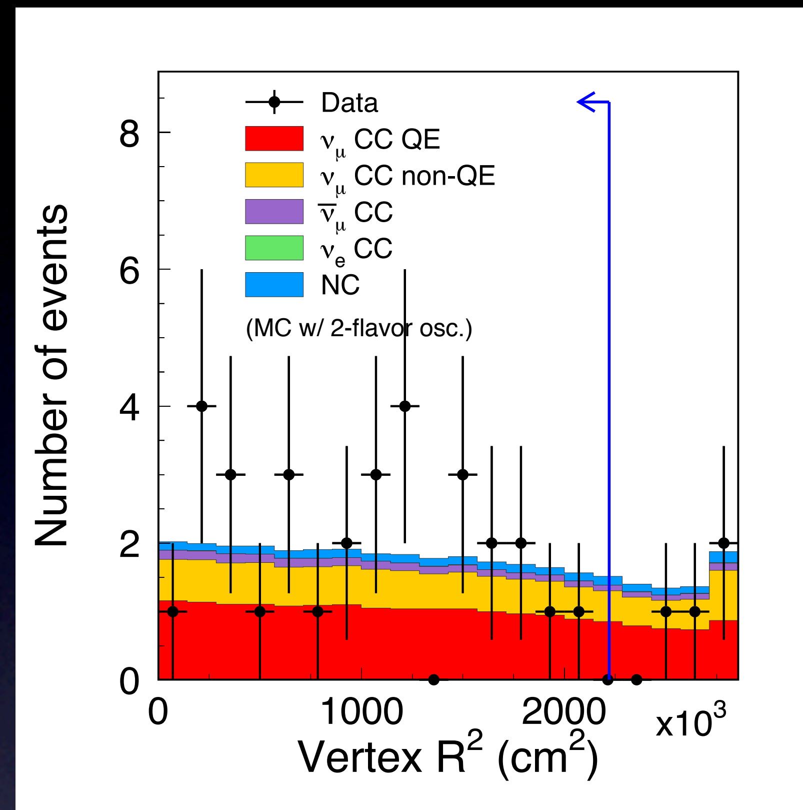
energy loss (keV/cm)
p (MeV/c)
MC muons
MC electrons
MC protons
MC pions

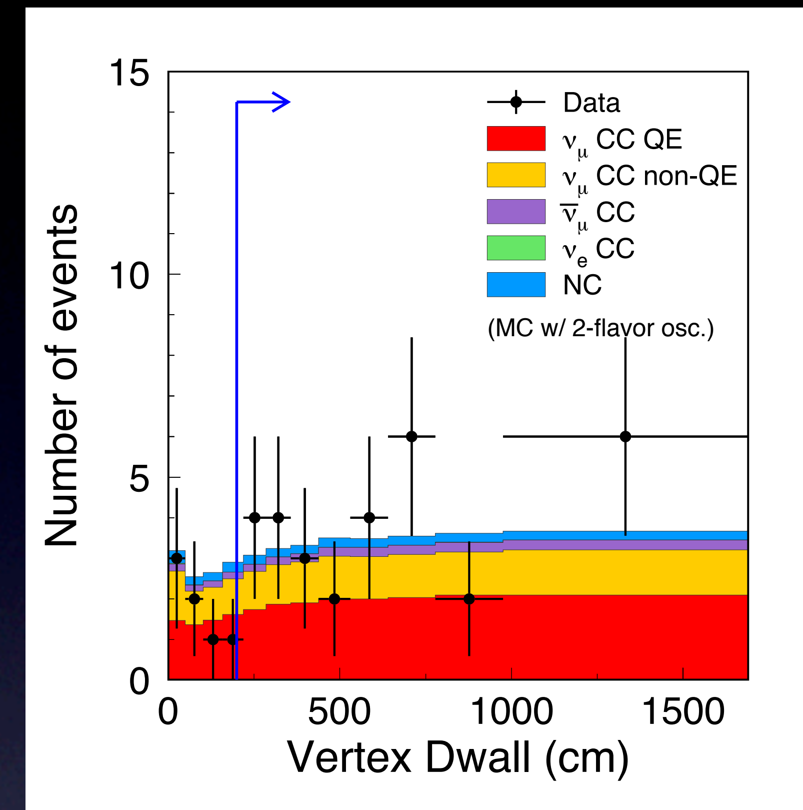
# ND280 tracker event gallery

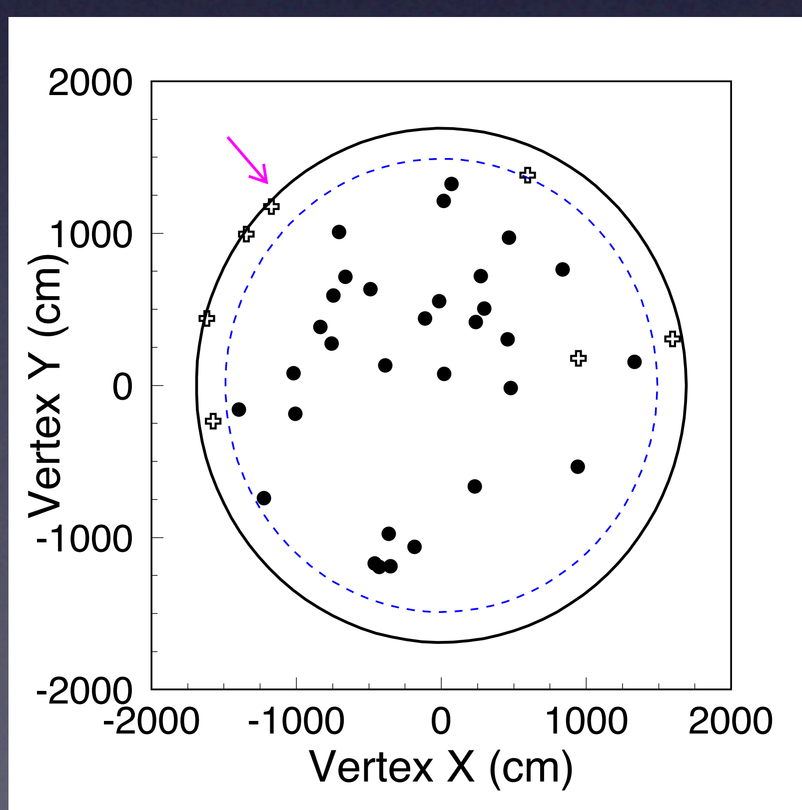


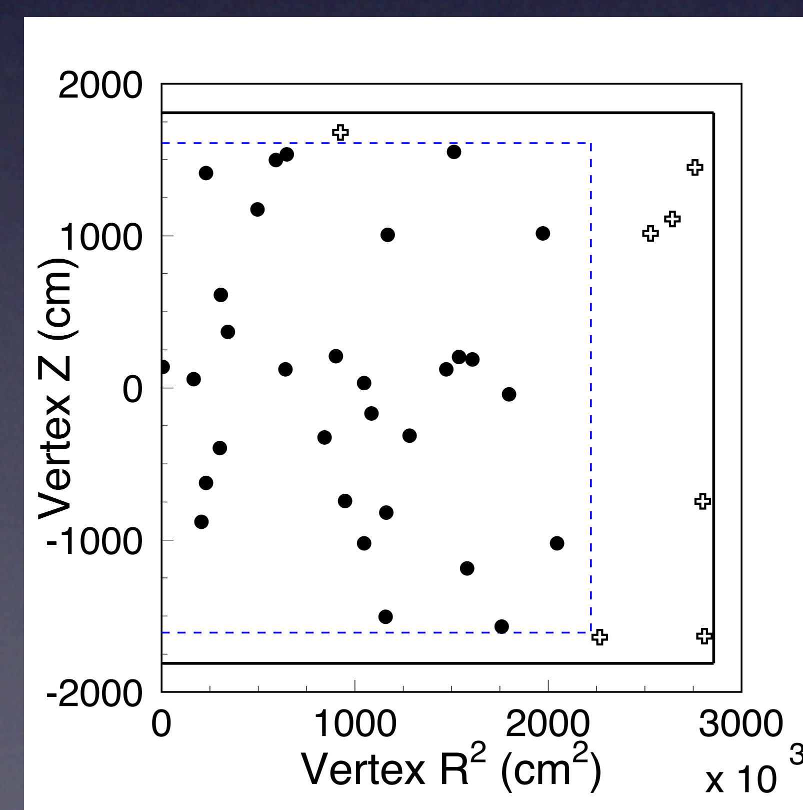
# $\nu_\mu$ disappearance vertex position



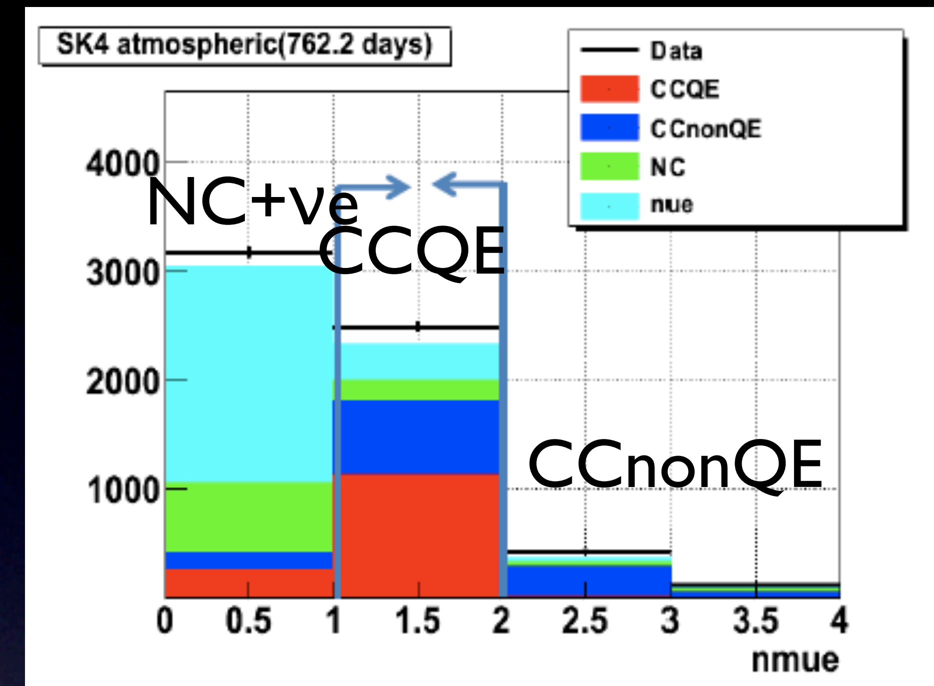



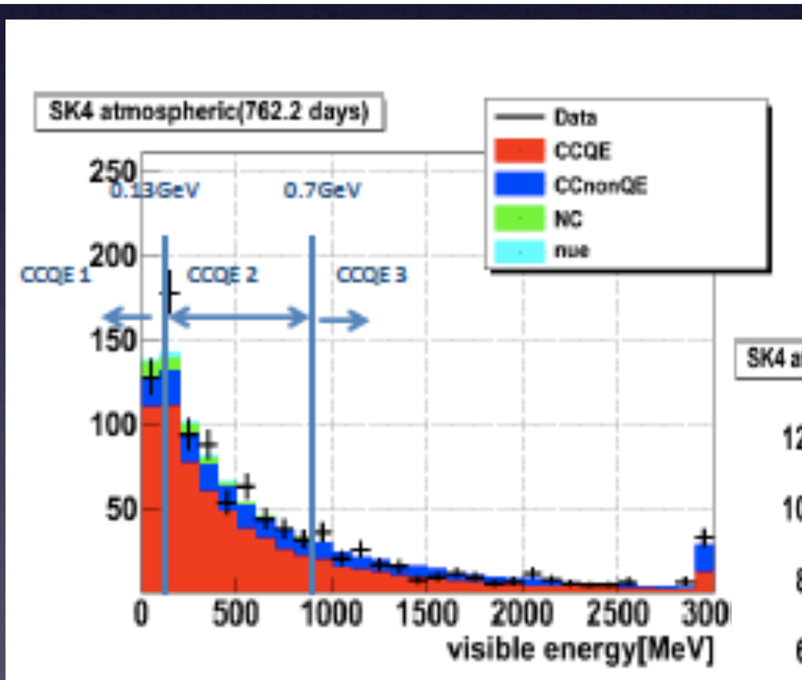



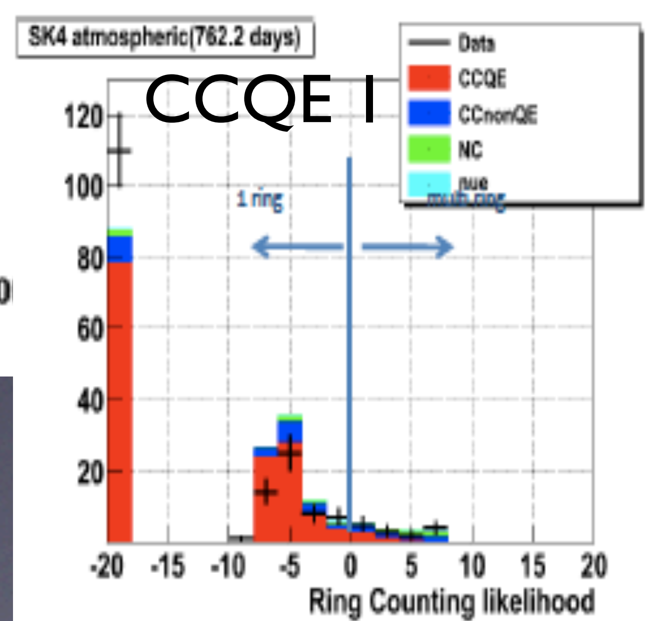



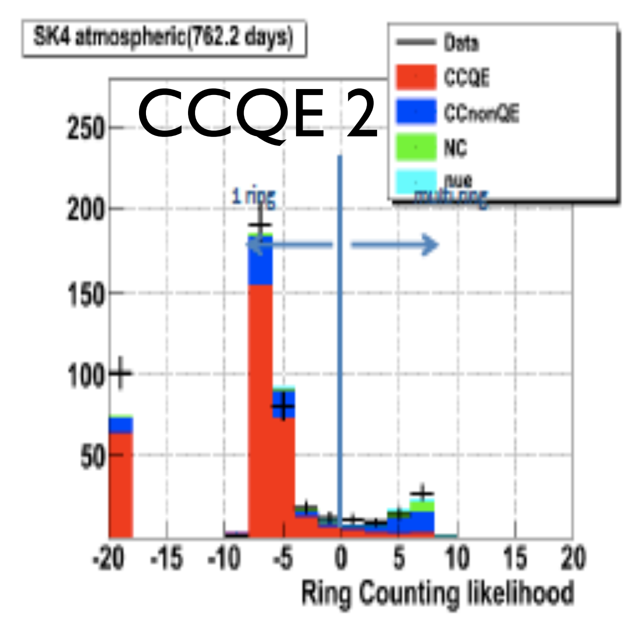
# SK $\nu_\mu$ systematics

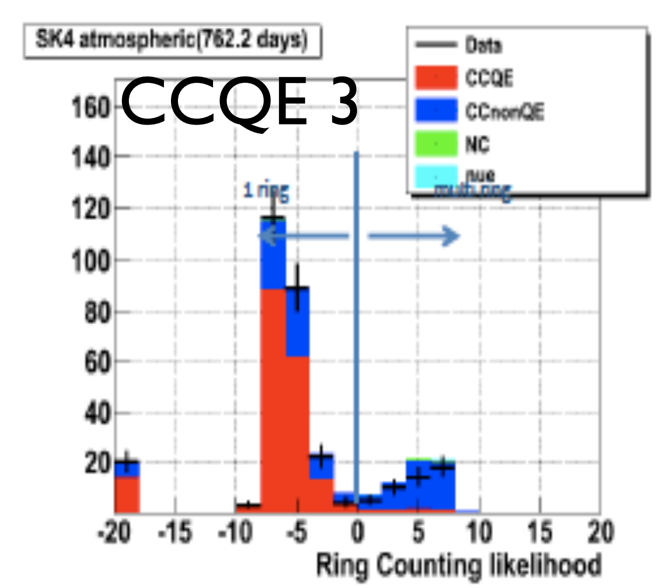
| Name of Samples | selection criteria |
|---|---|
| $\nu_\mu$ CCQE enriched sample 1 | # of decay electrons = 1<br>distance from the muon stopped point to decay electron < 80 cm<br>$E_{vis.} < 0.13$GeV |
| $\nu_\mu$ CCQE enriched sample 2 | # of decay electrons = 1<br>distance from the muon stopped point to decay electron < 80 cm<br>$E_{vis.} = 0.13 \sim 0.7$GeV |
| $\nu_\mu$ CCQE enriched sample 3 | # of decay electrons = 1<br>distance from the muon stopped point to decay electron < 80 cm<br>$E_{vis.} > 0.7$GeV |
| $\nu_\mu$ CC non-QE enriched sample | # of decay electrons > 1<br>distance from the muon stopped point to nearest decay electron < 160 cm |
| NC enriched sample | # of decay electrons = 0<br>not $\nu_e$ sample |
| $\nu_e$ CC enriched sample | brightest ring is e-like<br>$E_{vis.} > 100$MeV<br>POLfit mass < 105 MeV |



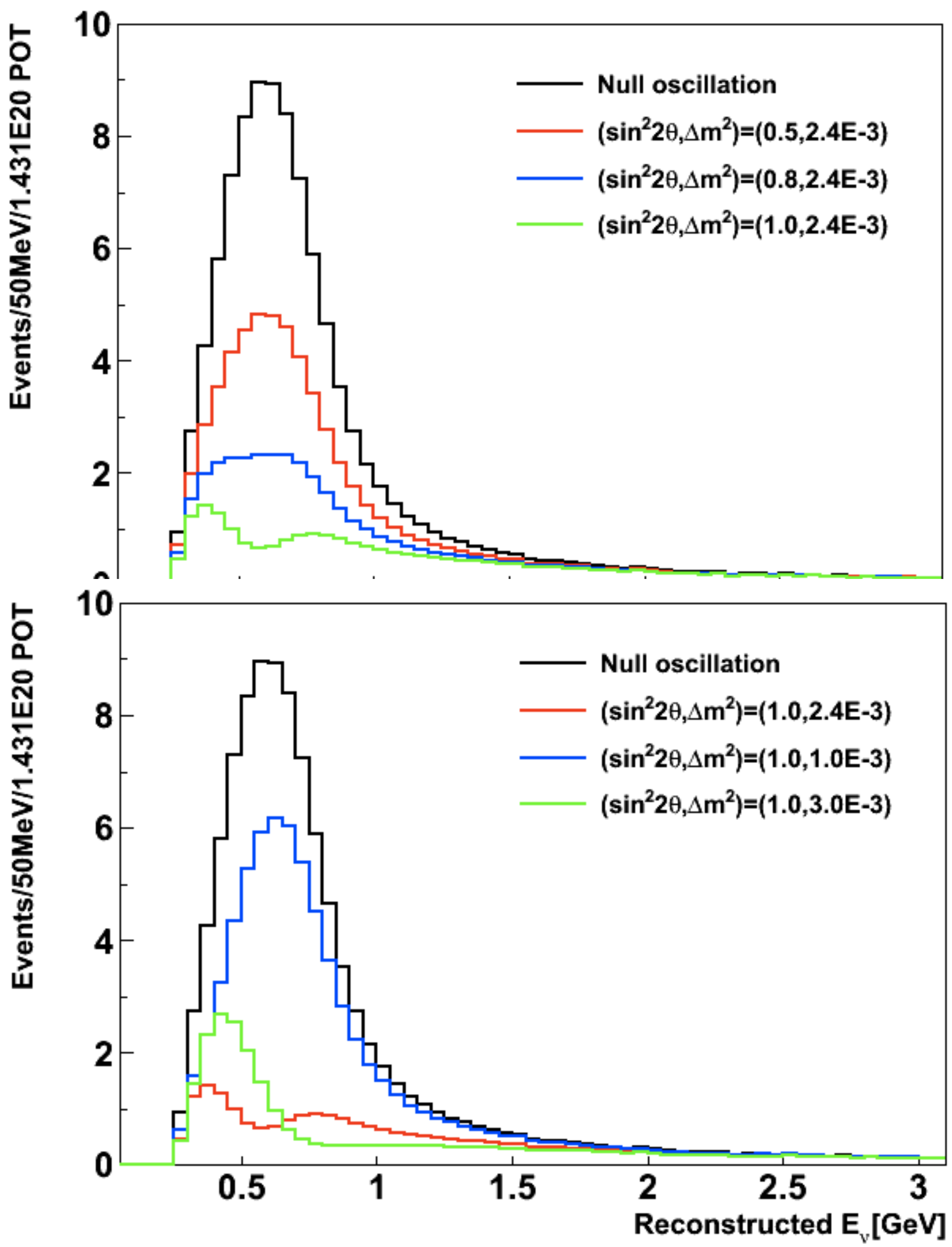



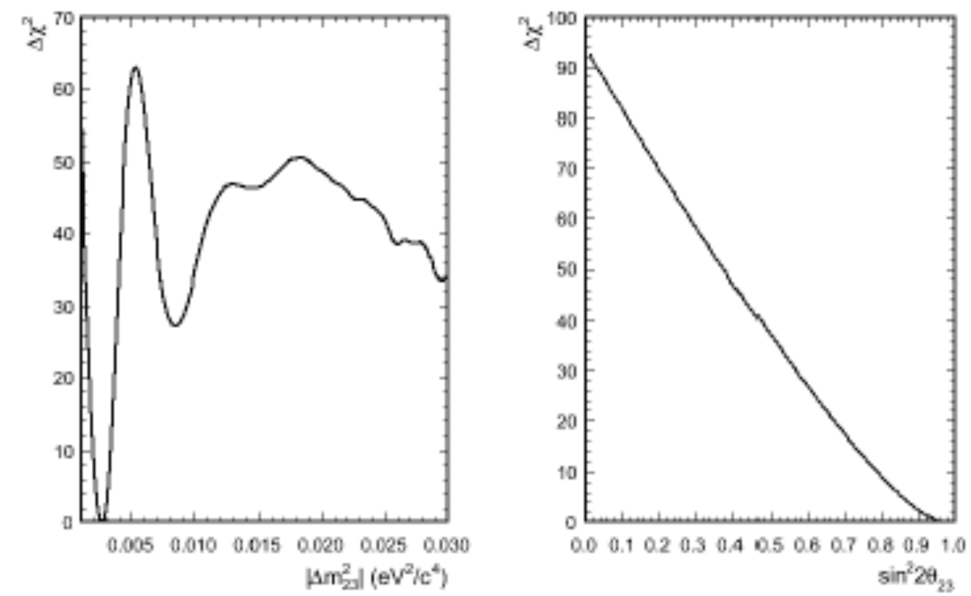



# $\nu_\mu$ disappearance

Expected spectrum

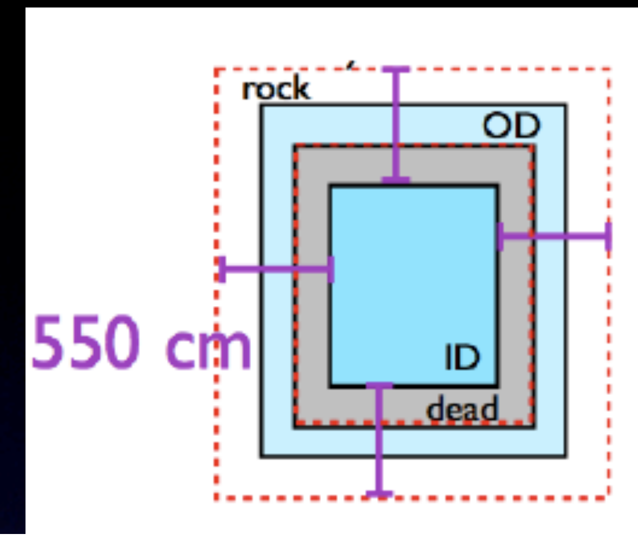


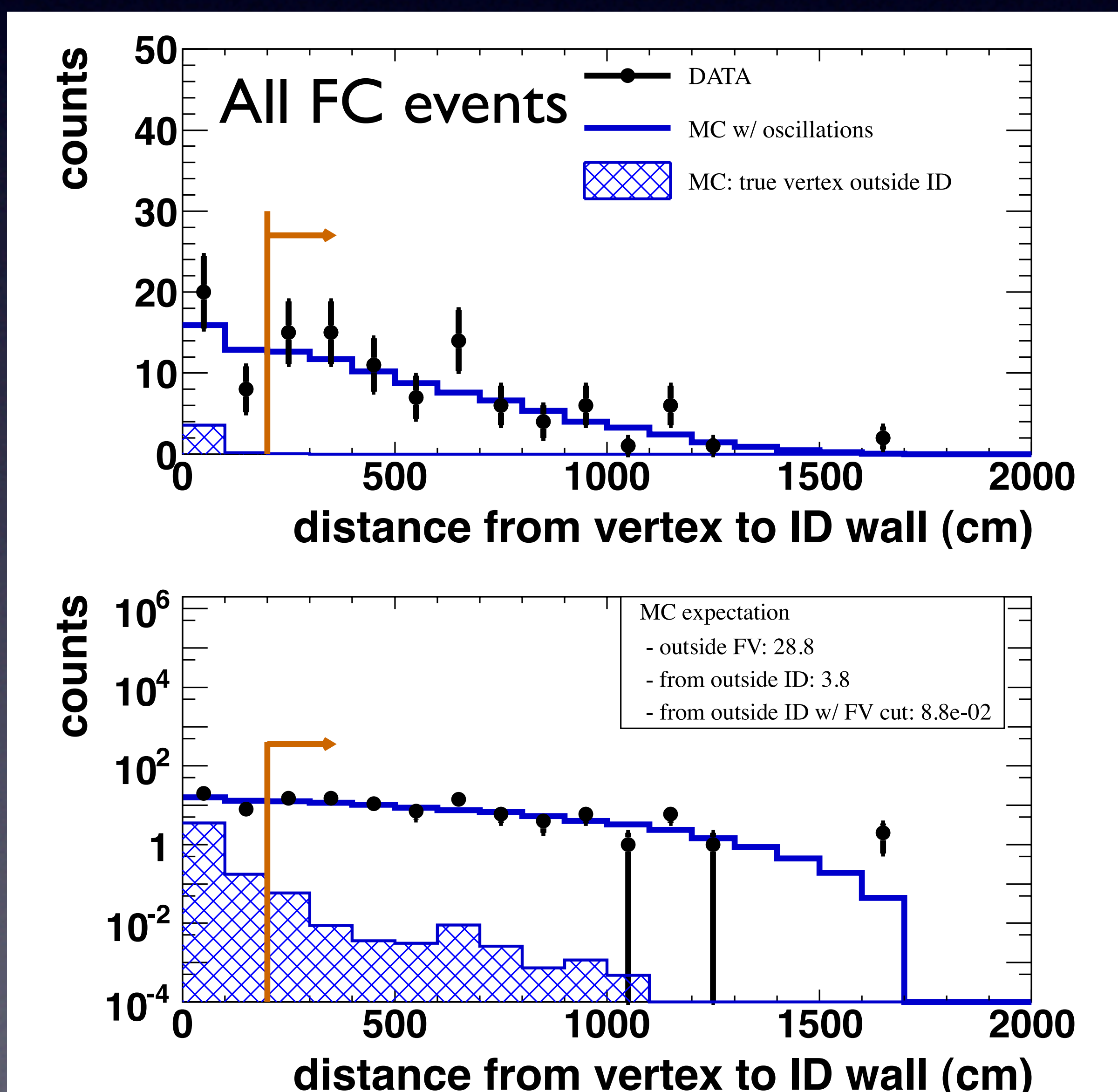

$\Delta\chi^2$ for $\Delta m^2$ and $\sin^2 2\theta$

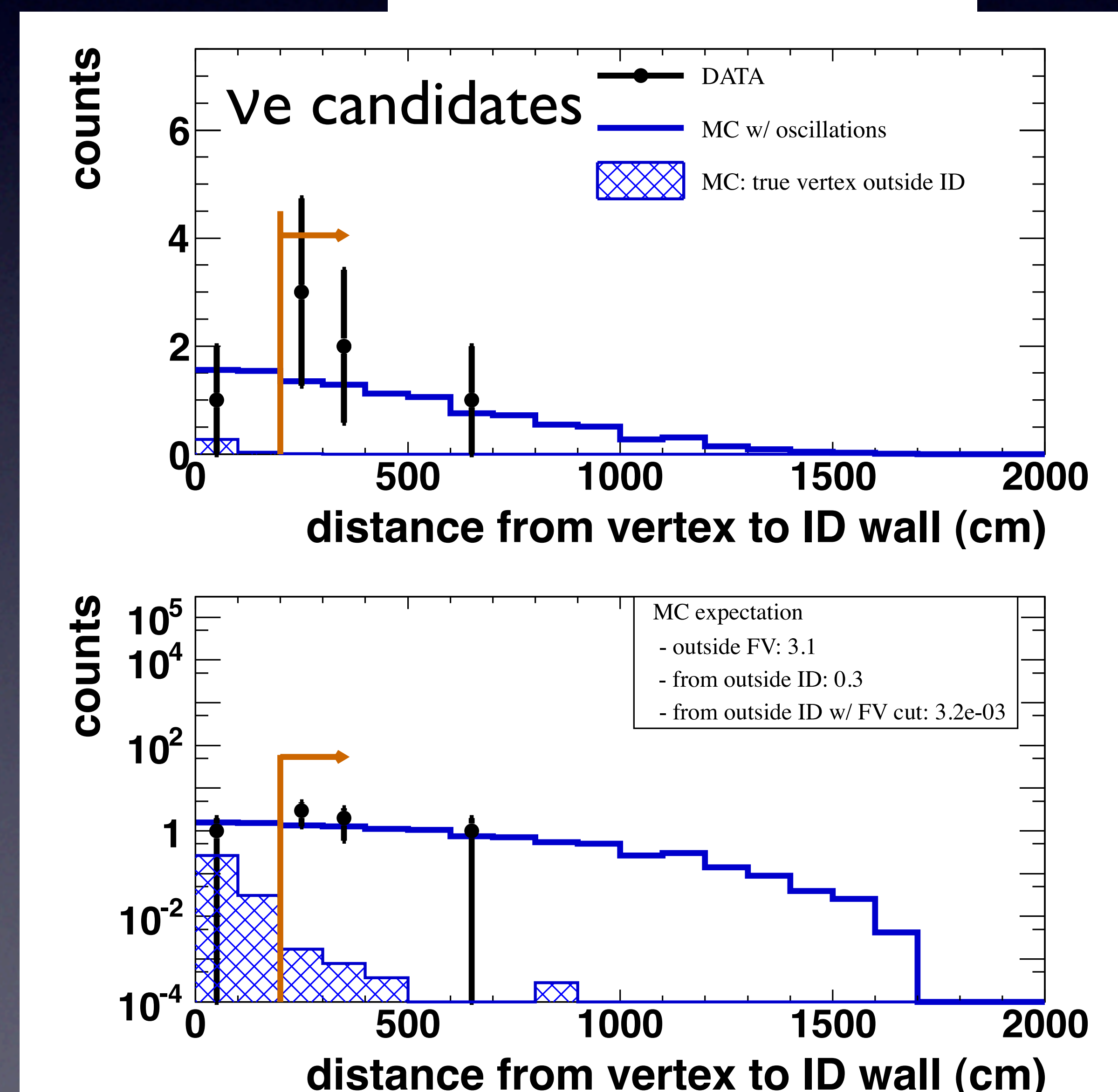


# Out of FV contamination

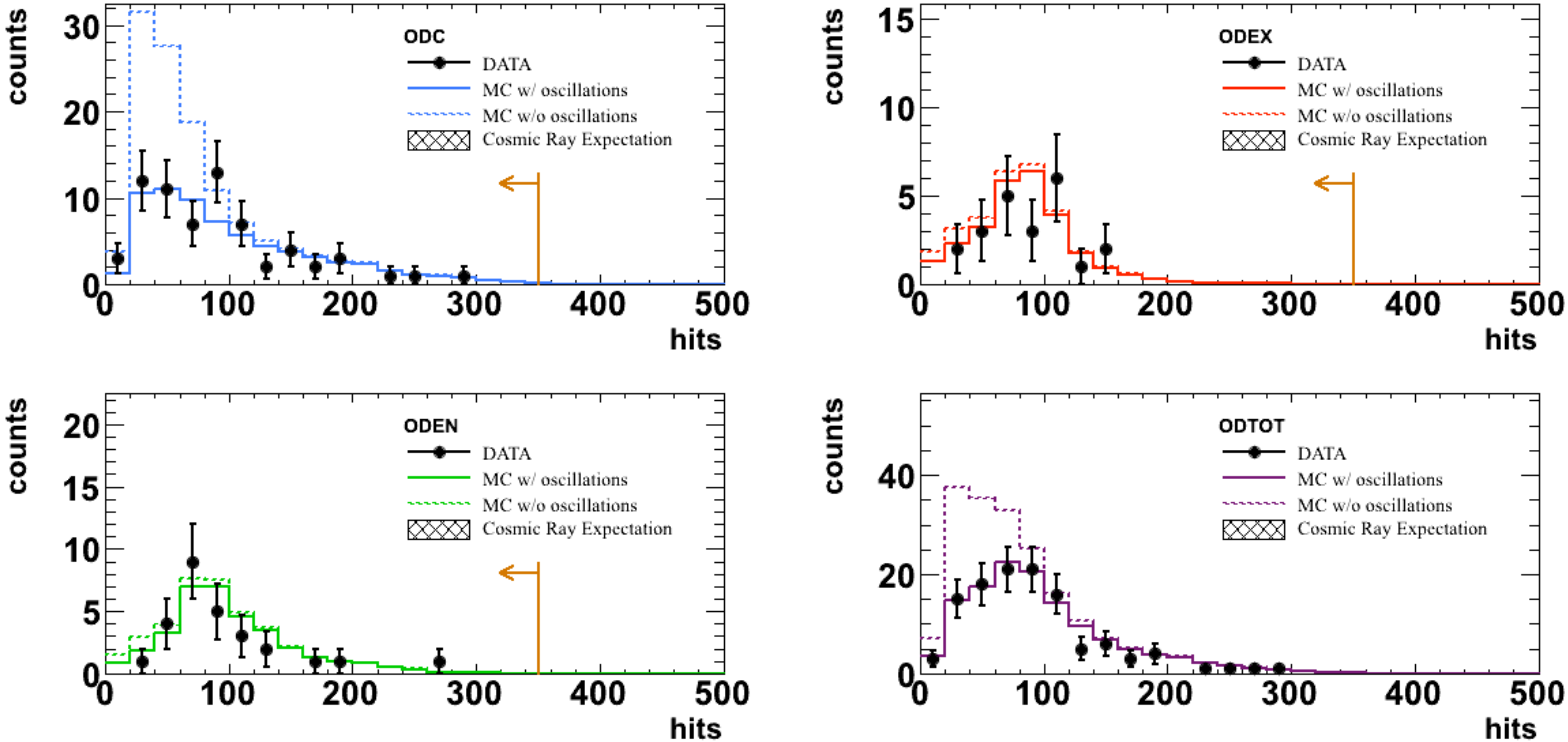
- Number of selected events with the exception of the fiducial volume cut
- Hatched histograms represent the contribution from vertices outside the ID



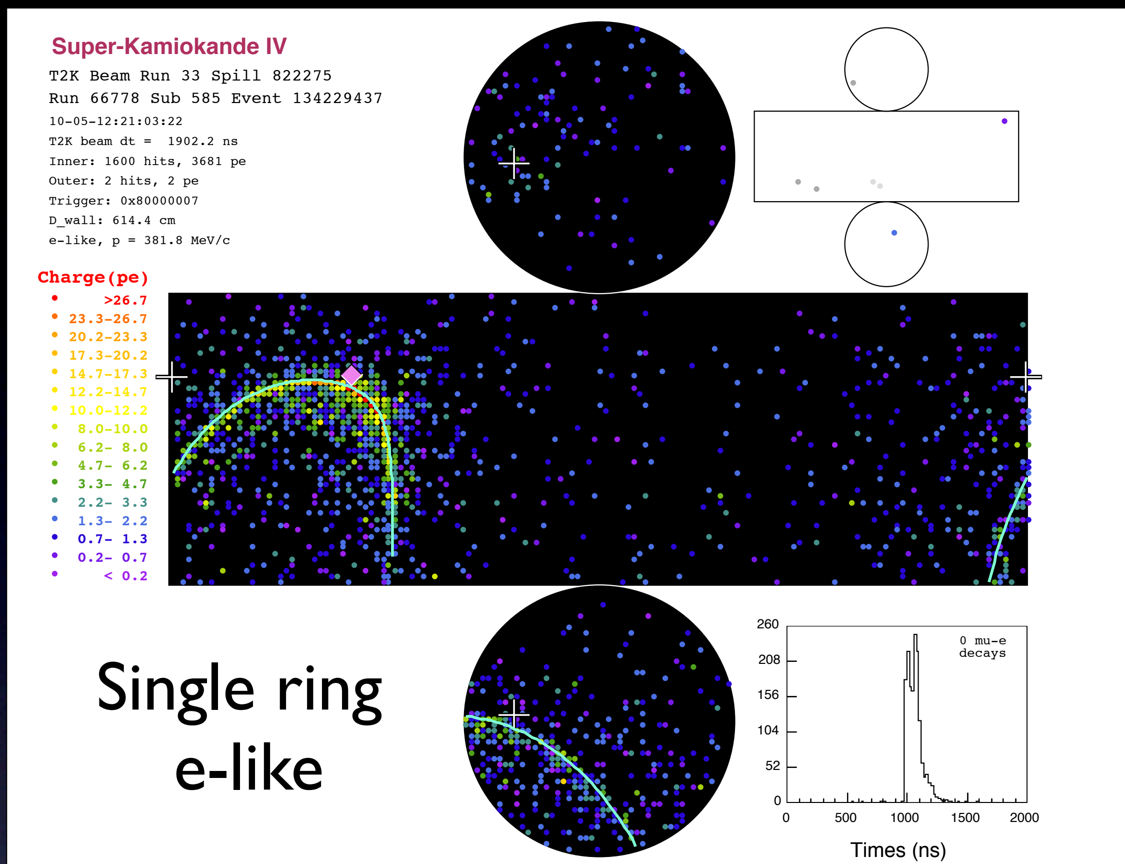



# SK Outer Detector analysis

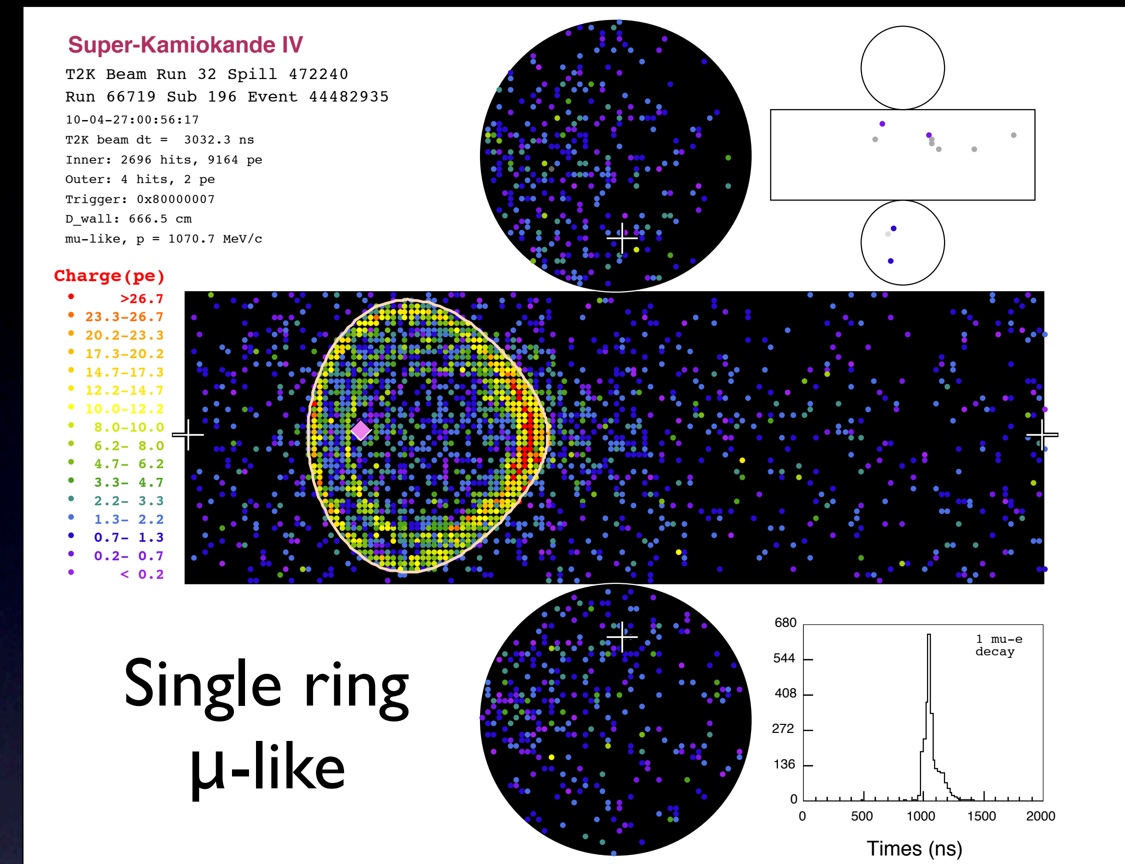



- Number of events observed in the OD compatible with the expected events from oscillations

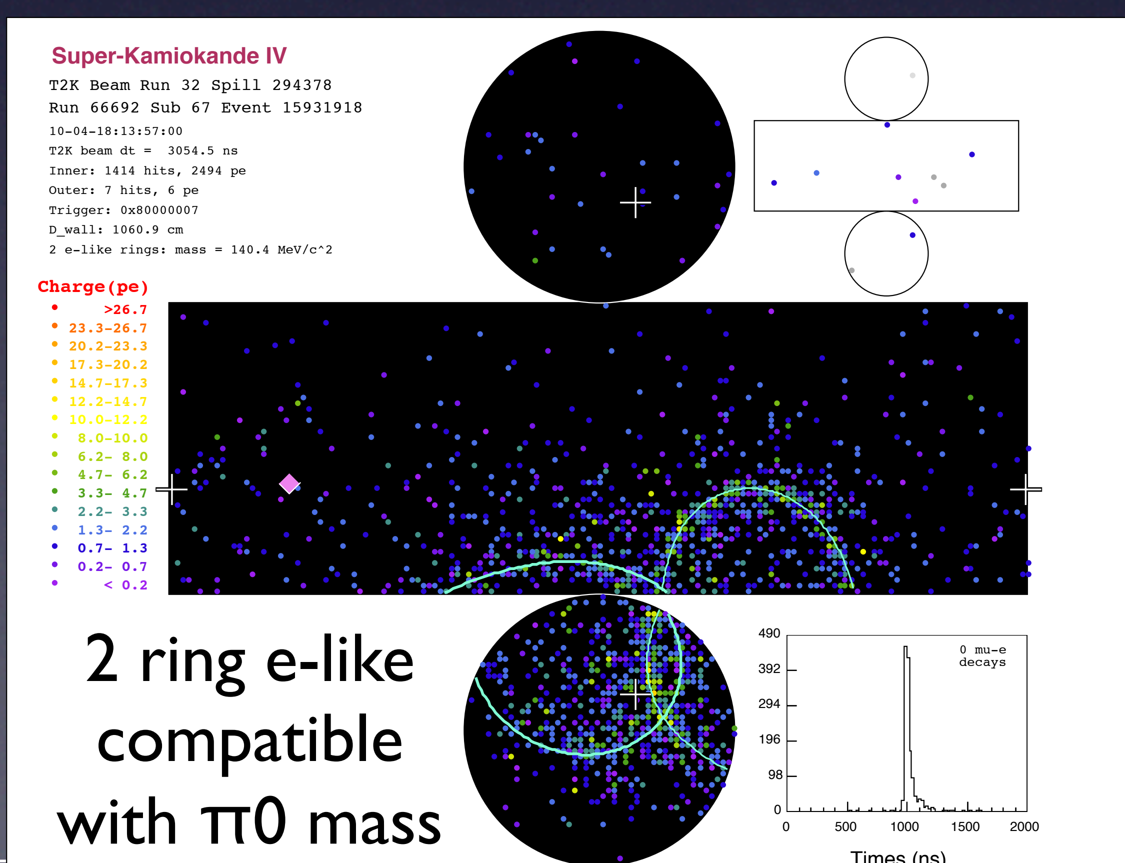
# SK event display



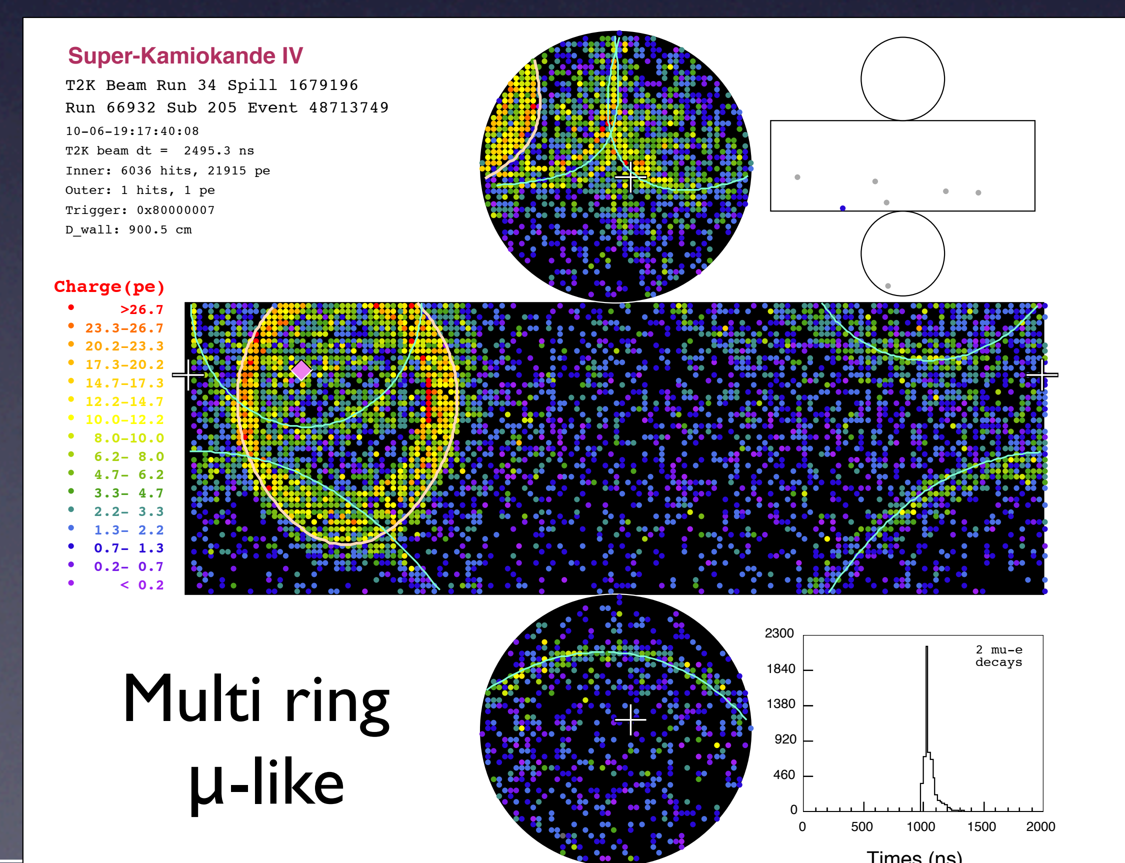

Single ring e-like




Single ring μ-like



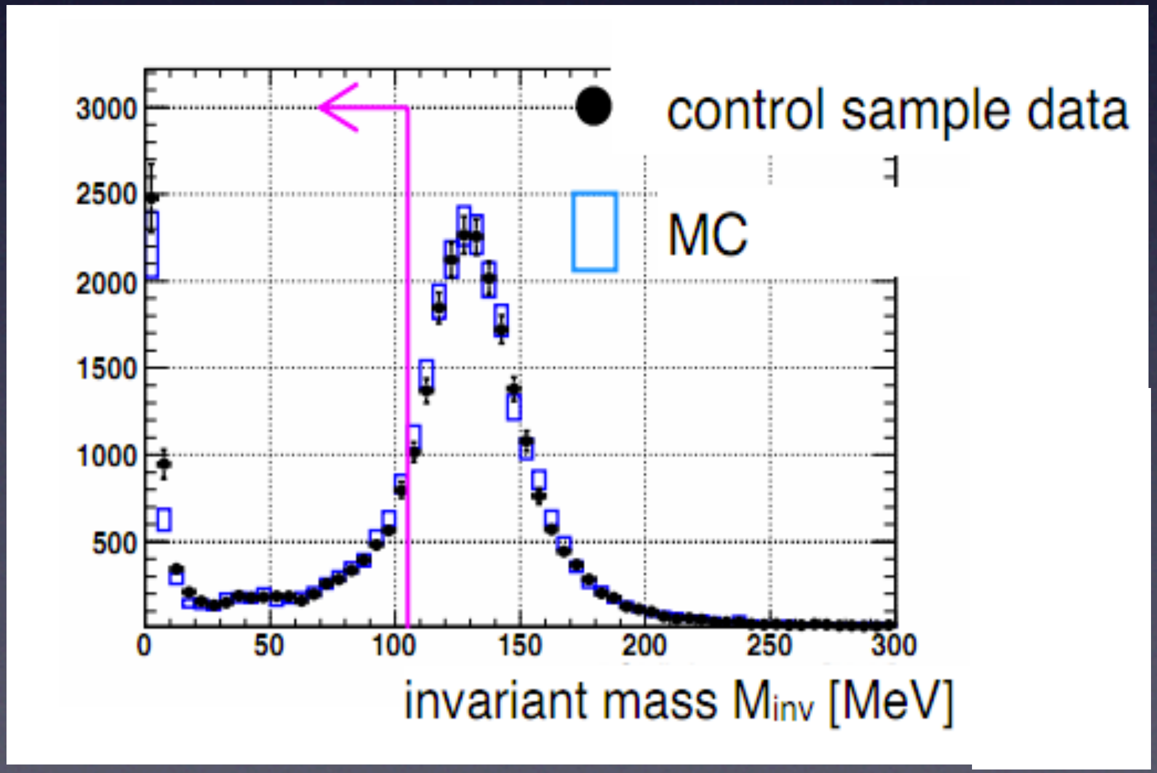

2 ring e-like compatible with π0 mass




Multi ring μ-like

# SK π0 control sample

- Control sample to evaluate the uncertainties on the π0 mass reconstruction
- Take 1 e-like events from atmospheric sample
- Add 1 simulated γ




Compare the hybrid π0 sample to a pure MC sample

Differences in the efficiency between data and MC give the systematic on the π0 mass cut

# Number of expected events

- We observed 6 $\nu_e$ candidates
- The expected number of events from un-oscillated neutrinos is 1.5

| Source | Nexp |
|---|---|
| Beam $\nu_e$ | 0.8 |
| $\nu_\mu$ Neutral Current | 0.6 |
| $\nu_\mu$ Charged Current | 0.1 |
| Total | 1.5±0.3 |

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

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

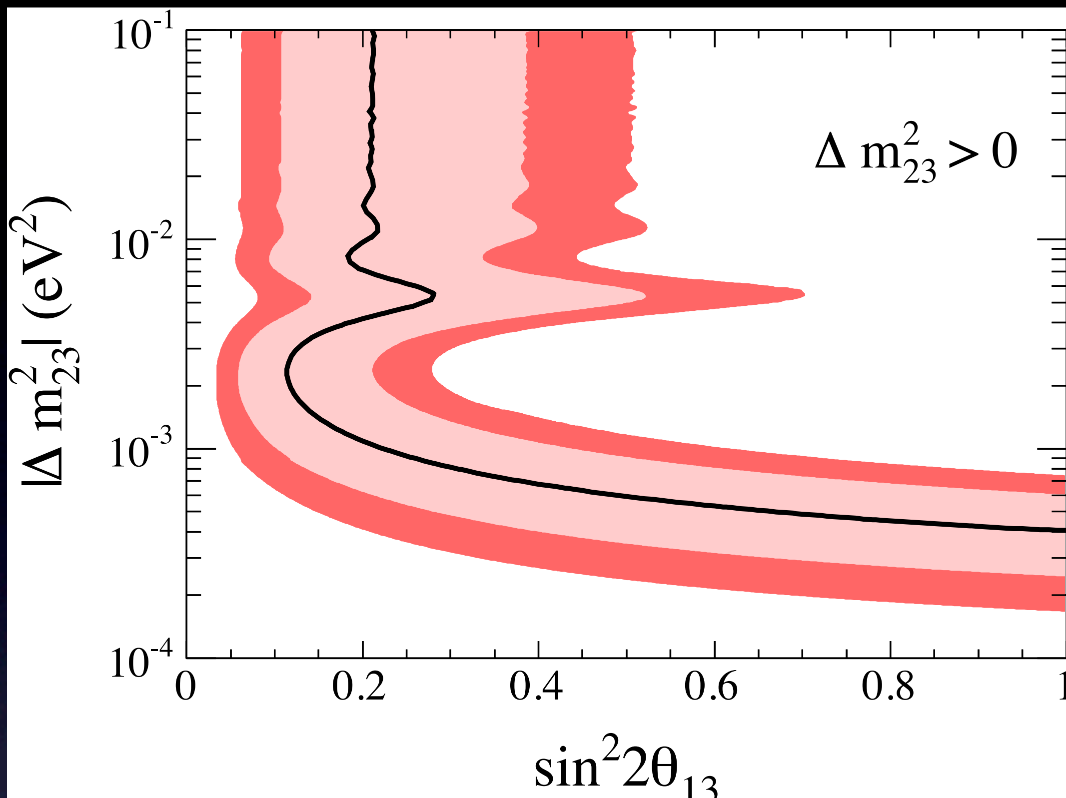
Dominated by hadron production

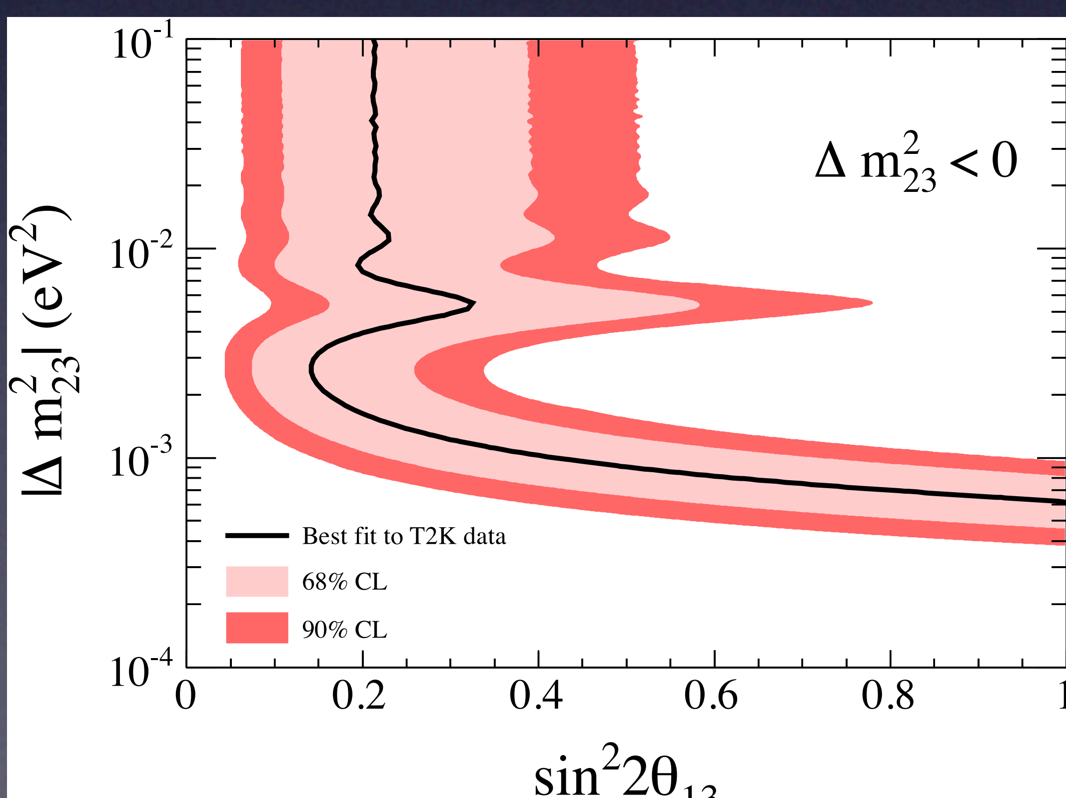
Dominated by FSI and NCπ0 cross-section uncertainties

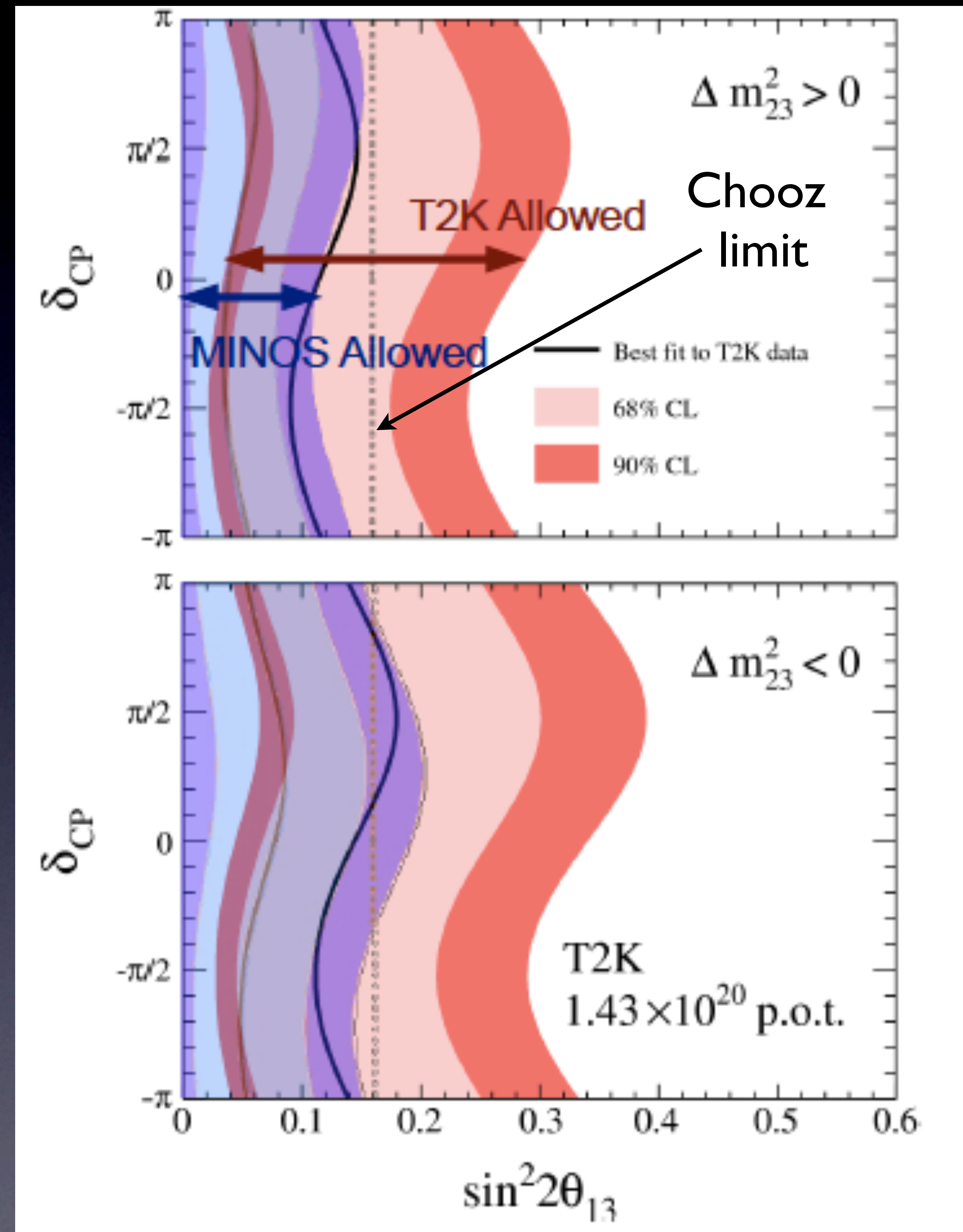
ND280 dominated by TPC tracking efficiency and ionization in the gas

SK dominated by ring counting, PID and $\pi^0$ mass systematics

# $\nu_e$ appearance



# $\nu_\mu$ disappearance analysis method

- 2 flavor neutrino oscillation fit: $P(\nu_\mu \rightarrow \nu_\mu) = 1 - sin^2(2\theta_{23}) sin^2(1.27\Delta m^2_{23} L/E)$
- 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

# JPARC status after Earthquake

- Ground level damages → rapidly repaired
- Equipments → no fatal damages
- LINAC floor, MR tunnel side pit, Near Detector bottom floor submerged under water
  - Fixed in few weeks
  - No serious damages on components
- Tunnel moved or bent of ~ several cm
  - Major alignment of many components need to be done

- We plan to resume JPARC beam operation in December 2011
- Two physics runs (~1 month each) for users before March 2012

- Future milestone:
  - 0.5 MW x $10^7$ s ($1 \times 10^{21}$ p.o.t.) in Summer 2013
    - Conclude θ13 different from 0 (more than 5 σ at present T2K best fit