Neutrino Oscillations:
Experimental Review and Prospects
Dawn of the CP searches era

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The "standard" 3 neutrino picture

- Production, detection: weak eigenstates ν_e, ν_μ, ν_τ
- Propagation: mass eigenstates ν_1, ν_2, ν_3
- 3x3 unitary mixing matrix (PMNS, like CKM)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle; \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} e^{-\iota\omega_1} & 0 & 0 \\ 0 & e^{-\iota\omega_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Majorana phases

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{\Delta m^2 L}{4E}\right) + 2\sum_{i>j} \Im\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{\Delta m^2 L}{2E}\right)$$

Sensitivity to oscillations depends on matching L/E to Δm^2

Mixing parameters

$s_{ij} = \sin\vartheta_{ij}$
$c_{ij} = \cos\vartheta_{ij}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

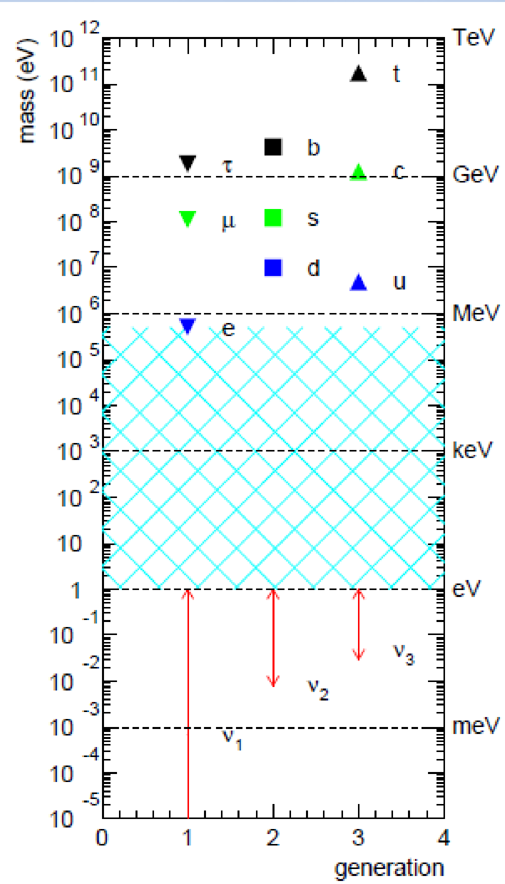
Atmospheric (+ ν_μ Long BL) | ν_μ Long BL reactor Short BL | Solar (+ reactor Long BL) | Majorana ??

- Fundamental parameters of Nature in the absence of a bigger theory:
  - 3 mixing angles
  - CP-violating phase δ
  - 3 masses
- Must be measured experimentally

The big picture

Empirical puzzles:

- Baryon asymmetry



$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

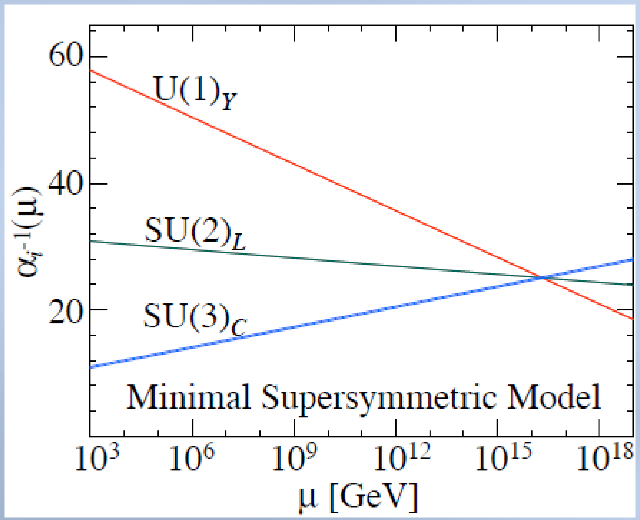
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- Mass hierarchy
- Different mixing matrices

Is there a pattern?

Exciting coincidences:

- Unification
- Inflation



- Forces unify at ~10^{16}
- Inflation: spinless field ~10^{13}
- Seesaw: RH neutrino ~10^{14}

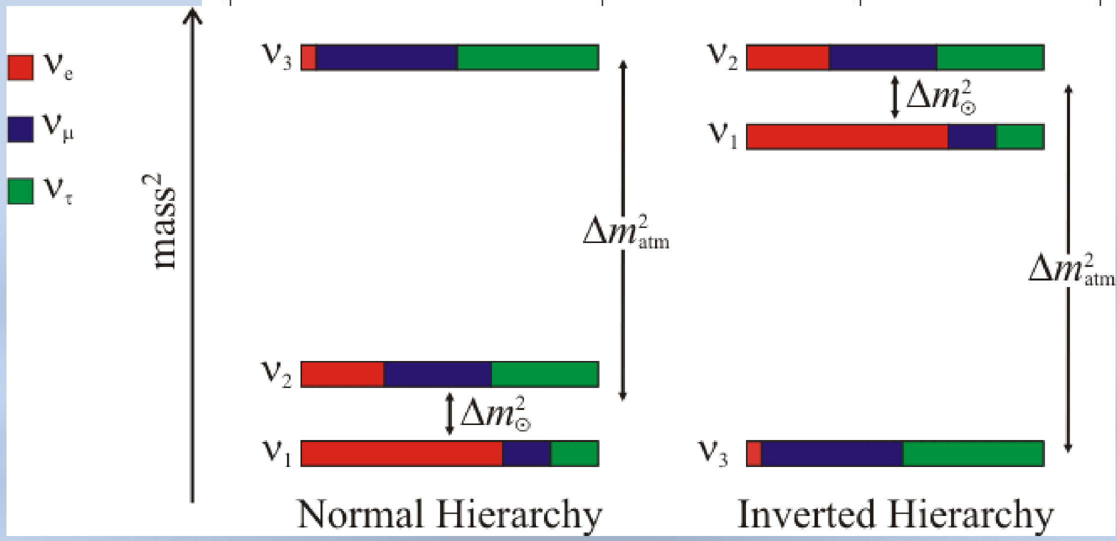
Is this accidental?

Open questions

- θ_{13}
- CP Violation ($\delta \neq 0$)?
- Mass hierarchy
- θ_{23} exactly 45°?
- *Anything else?*
  - *Steriles, CPT, ...*

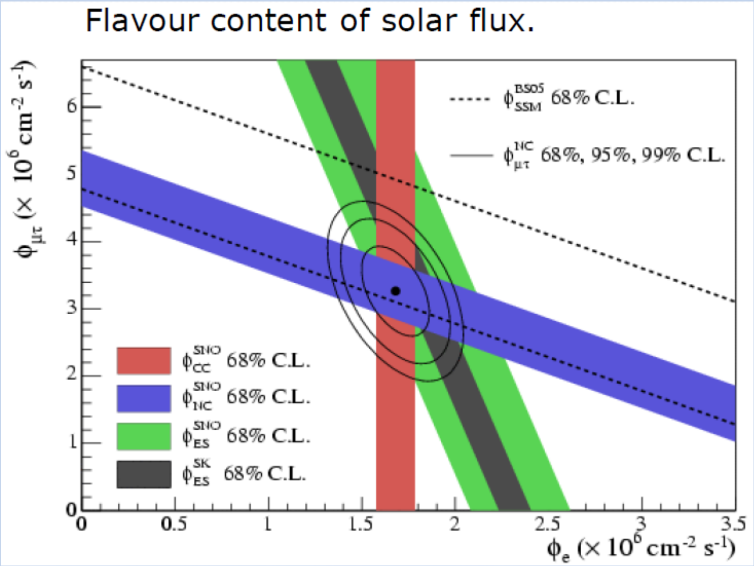
- Not in this talk:
  - Majorana?
  - Absolute mass scale

parameter	best fit	2σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.23}_{-0.18}$	7.22–8.03
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63



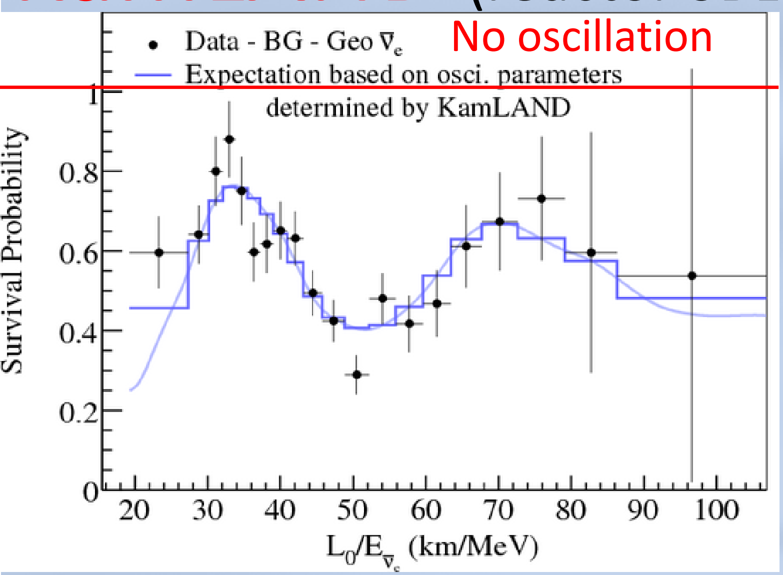
“Solar” sector (*12* mixing)

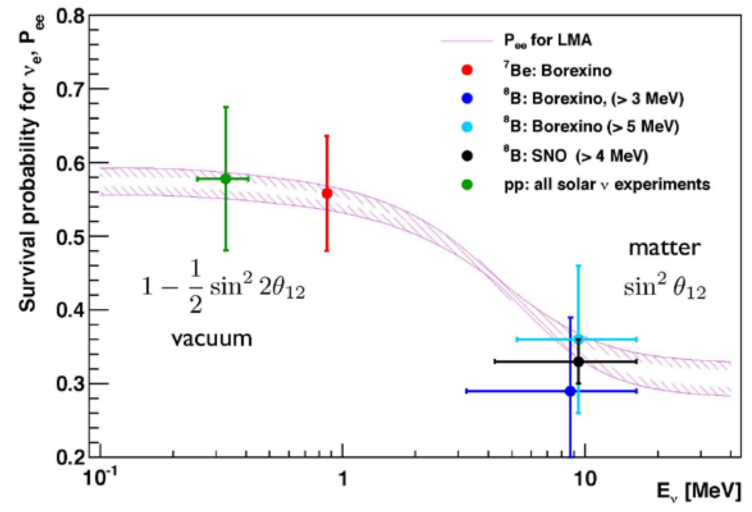
SNO (solar)



- Low Energy region:
- Borexino
  - first observation of ^{7}Be neutrinos
- SNO+, KamLAND II

KamLAND (reactor SBL)

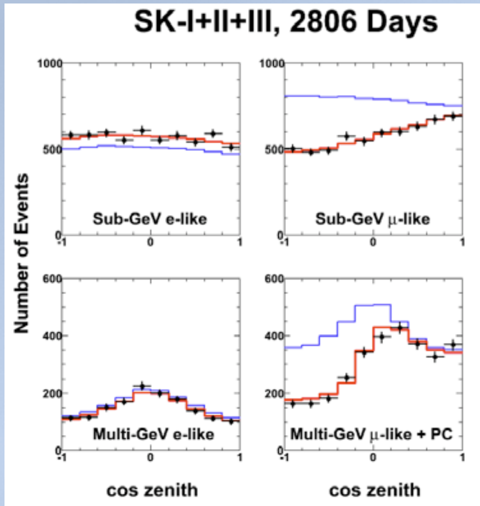


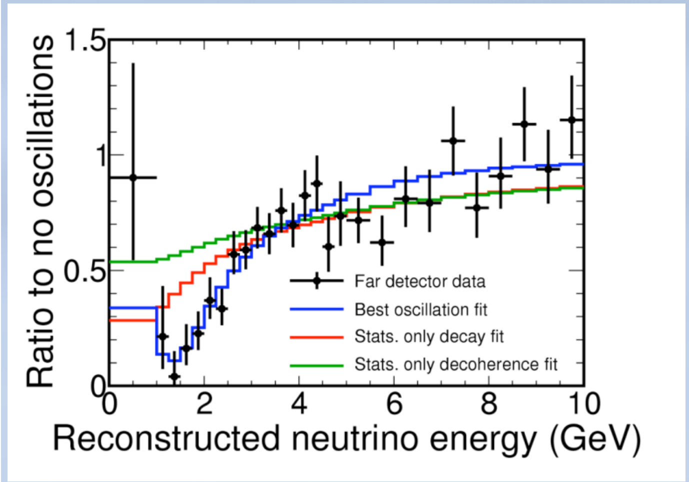


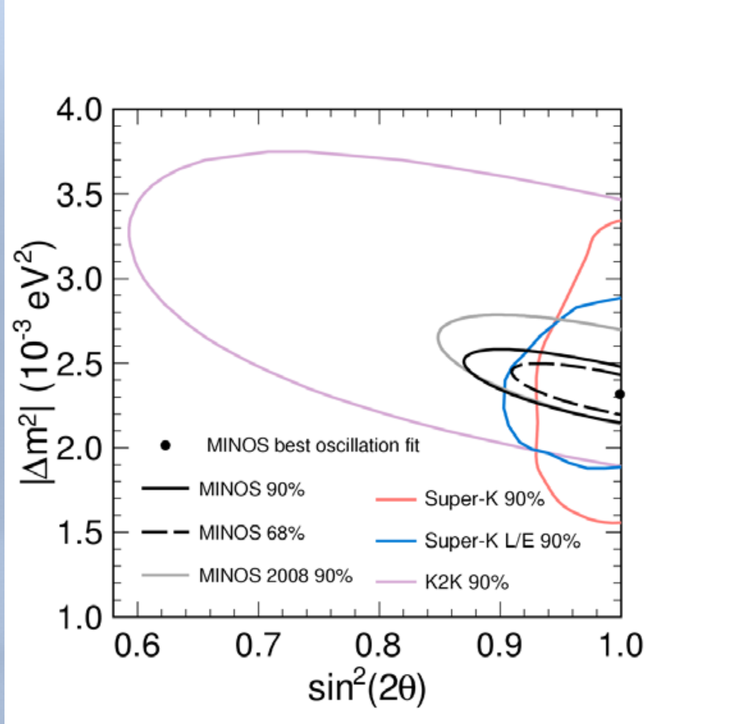
matter effects inferred previously, but this is a direct demonstration

"Atmospheric" sector (23 mixing)

- Atmospheric ν_μ disappearance
  - Departure from ν_μ/ν_e ratio 2:1
  - Zenith dependence (L/E)
  - Studied by Super-Kamiokande
  - No ν_τ appearance ruled out at 3.8σ
- Accelerator ν_μ disappearance
  - K2K, deficit + spectrum distortion
  - MINOS with 7x10^{20} pot neutrinos







A consistent picture built on a multitude of significant results from different techniques and experiments

BUT

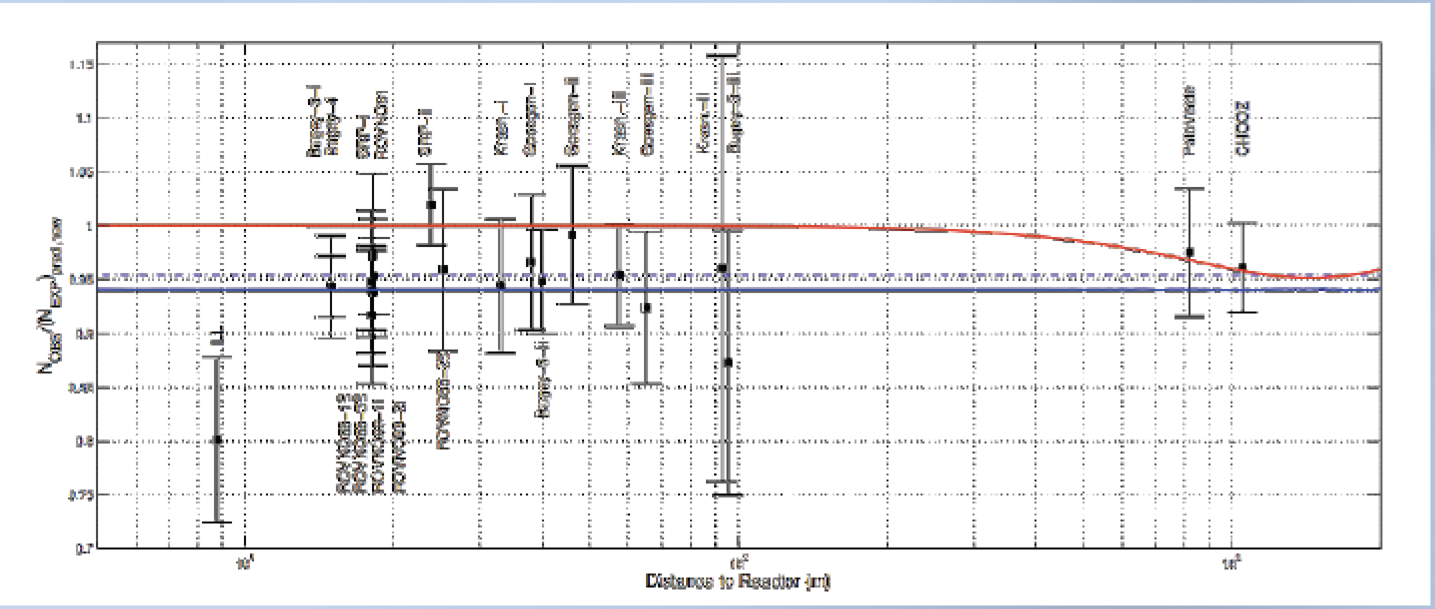
Anomalies are coming back with a vengeance

LSND, MiniBoone anomalies

- LSND: 3.8σ anti-ν_e excess from anti-ν_μ
- MiniBoone: 2.7σ anti-ν_e excess from anti-ν_μ, near the LSND preferred L/E
- MiniBoone: 3.0σ ν_e excess appearance from ν_μ, not compatible with their anti-ν_e excess under single oscillation hypothesis
- MiniBoone antineutrino results statistics limited, more data being analyzed
- Possibilities:
  - Experimental effects, single photon excess (MB neutrinos, low E), cross-sections, fluctuations
  - Steriles: 3+1 with Δm^2 around $1eV^2$ (only antineutrinos)
  - Steriles: (3+2) + (CPT violation OR x-dim OR decay) OR ....

Reactor anomaly (Mention et al, antineutrinos)

- Re-evaluation of reactor flux combining full beta-decay estimates, constrained to ILL 80-89 measurements, latest on burn-up, current neutron lifetime
- Results in a 3% downward shift for previous short-baseline reactor experiments and gets
  - seen/expected = 0.943±0.023



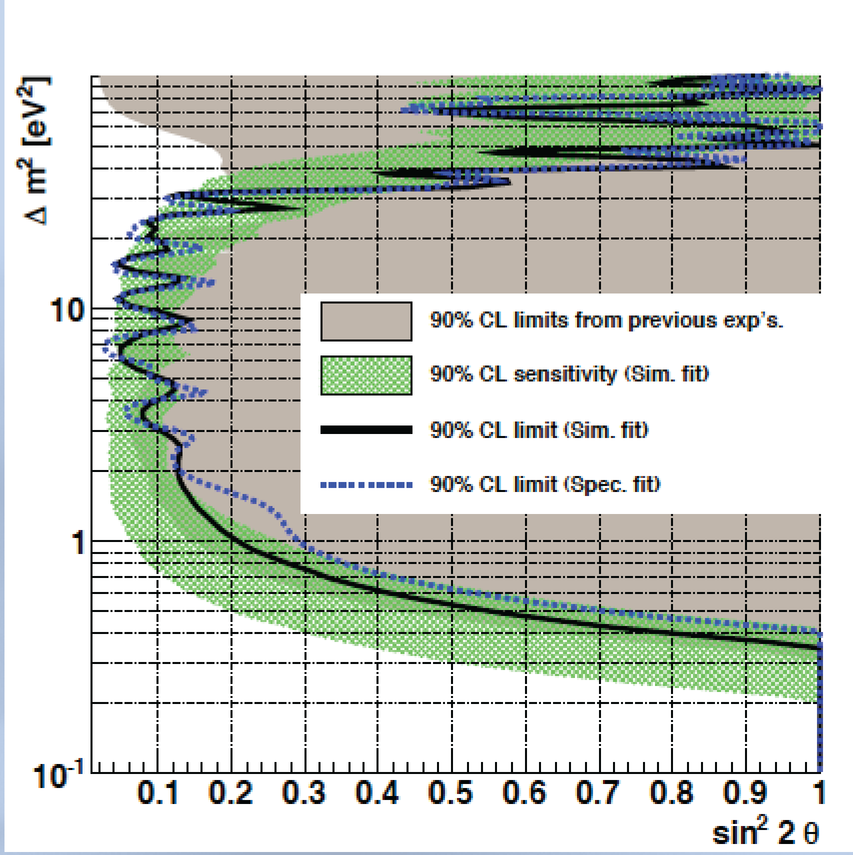
Gallium Anomaly (Giunti and Laveder, neutrinos)

- SAGE and GALLEX, ^{51}Cr and ^{37}Ar source calibrations
- Seen/expected = 0.87±0.05

- Reactor + Gallium: disappearance, common for neutrinos and antineutrinos, if oscillation then $\Delta m^2 > 1.5 eV^2$

Putting all anomalies together

- Global fits in 3+1 models not able to combine all data
- No well motivated reason for neutrino-antineutrino differences (CPT ??)
- 3+2 fits can be better, but adding enough free parameters ......
- Appearance from oscillations must have disappearance counterpart
- Common analysis of MiniBoone and SciBoone (different baseline, same beam, ν_μ disappearance) rules out high masses



A messy picture to be resolved

- More data from MiniBoone; Boone proposal
- (Very) Short Baseline reactor experiments with shape + rate analysis
- Mci sources near – inside large detectors (SNO+, Borexino, Kamland)
- C. Rubbia’s proposal (PS beam, ICARUS + ND)
- And better neutrino interaction data from dedicated experiments (e.g. Minerva) and Near Detectors (e.g. T2K ND280)

HOT NEW RESULTS

Indication for non-zero θ_{13} from T2K

Update from MINOS

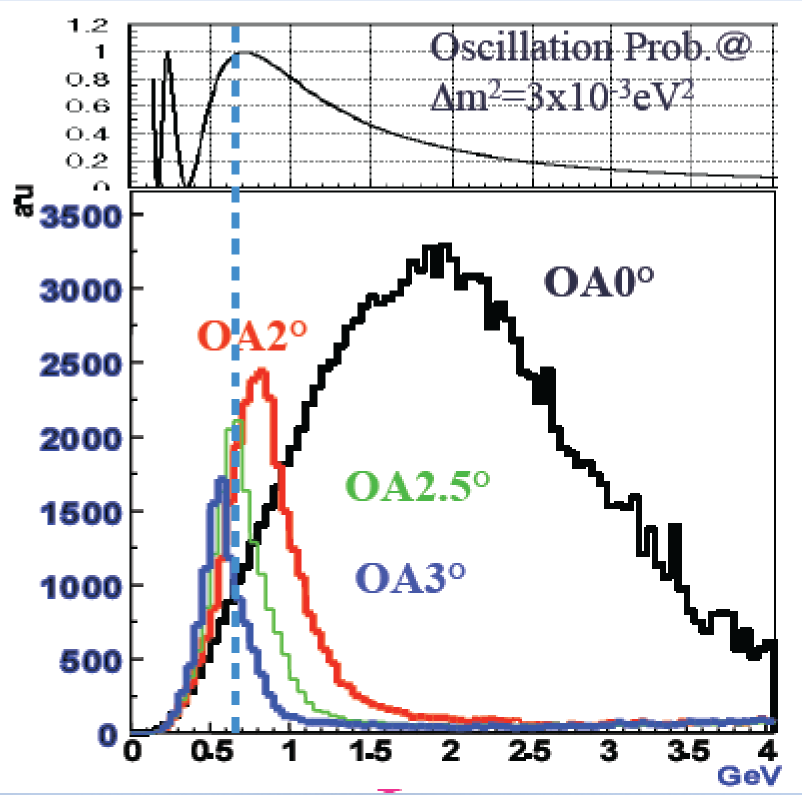
500 members, 59 institutes, 12 countries

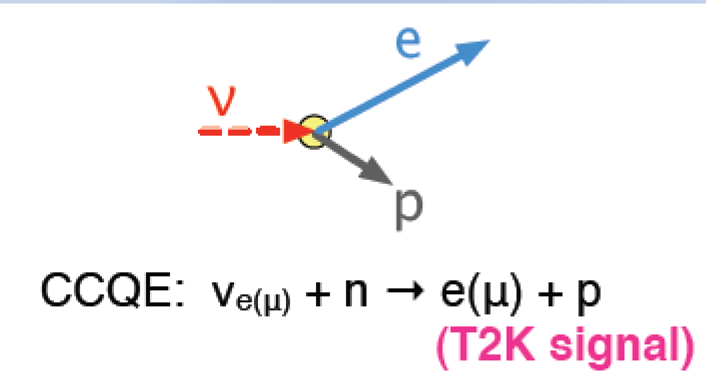
T2K

T2K Main Goals:

- ★ Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)
- ★ Precision measurement of ν_μ disappearance

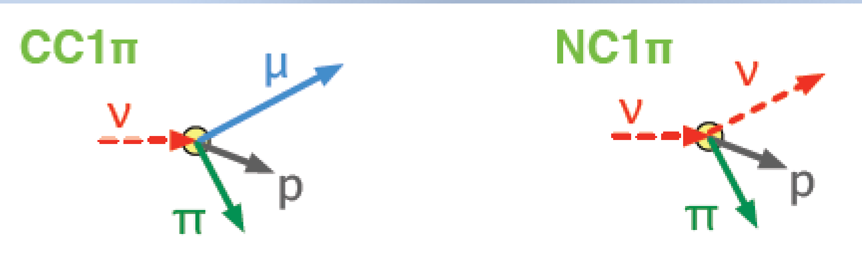
T2K: the first LBL Off-Axis experiment





Above: signal

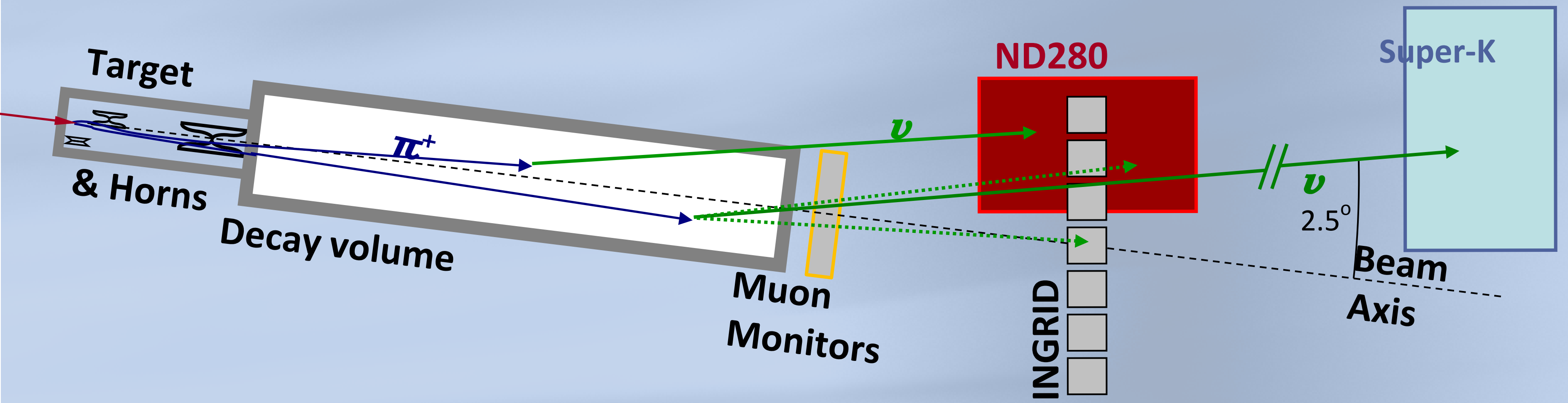
Below: backgrounds, possible fee-down from higher energies into signal region



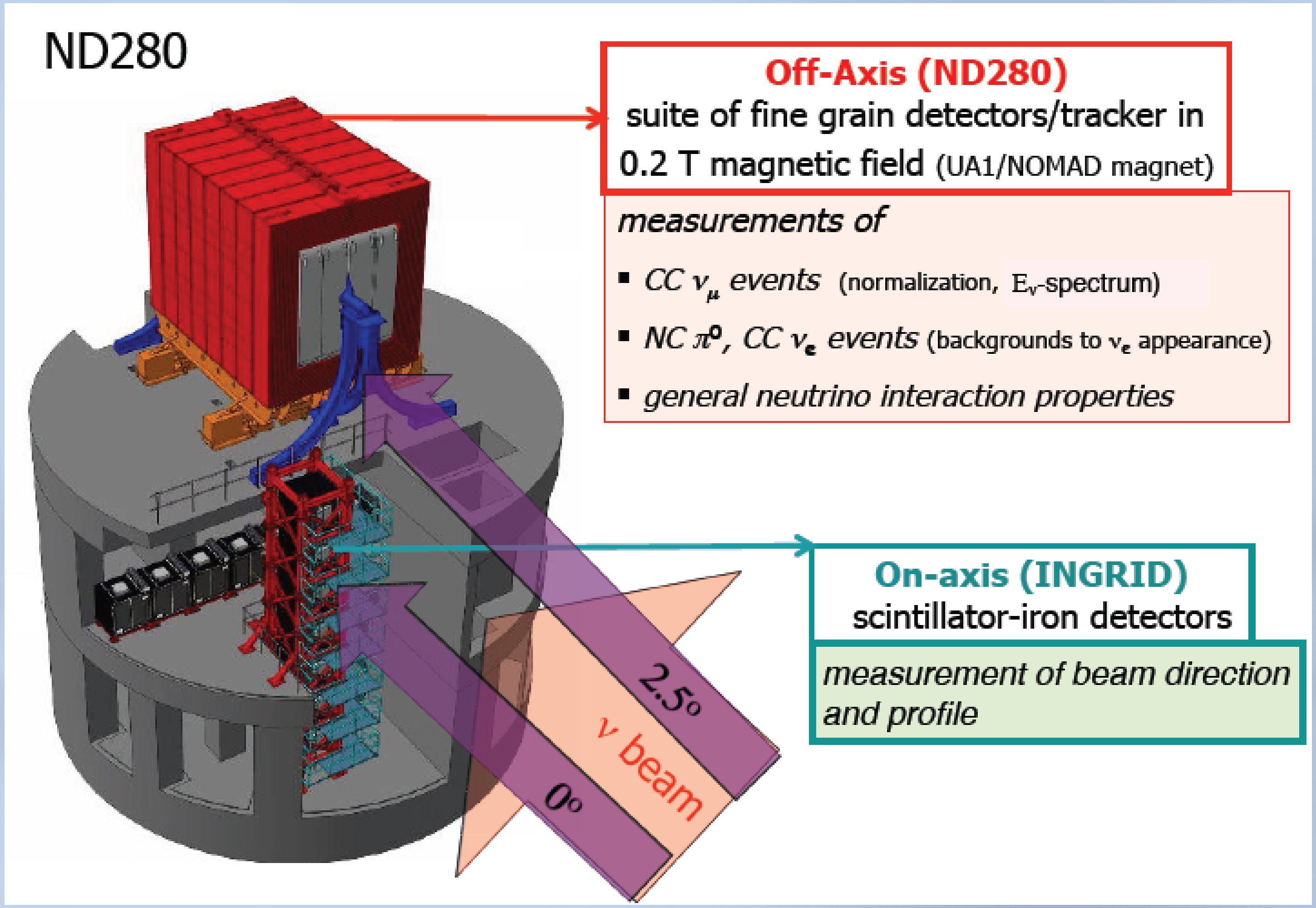
- Almost monoenergetic neutrino beam
  - Tuned exactly at oscillation maximum
- Minimization of feed-down backgrounds
- Resulting in maximum sensitivity

T2K

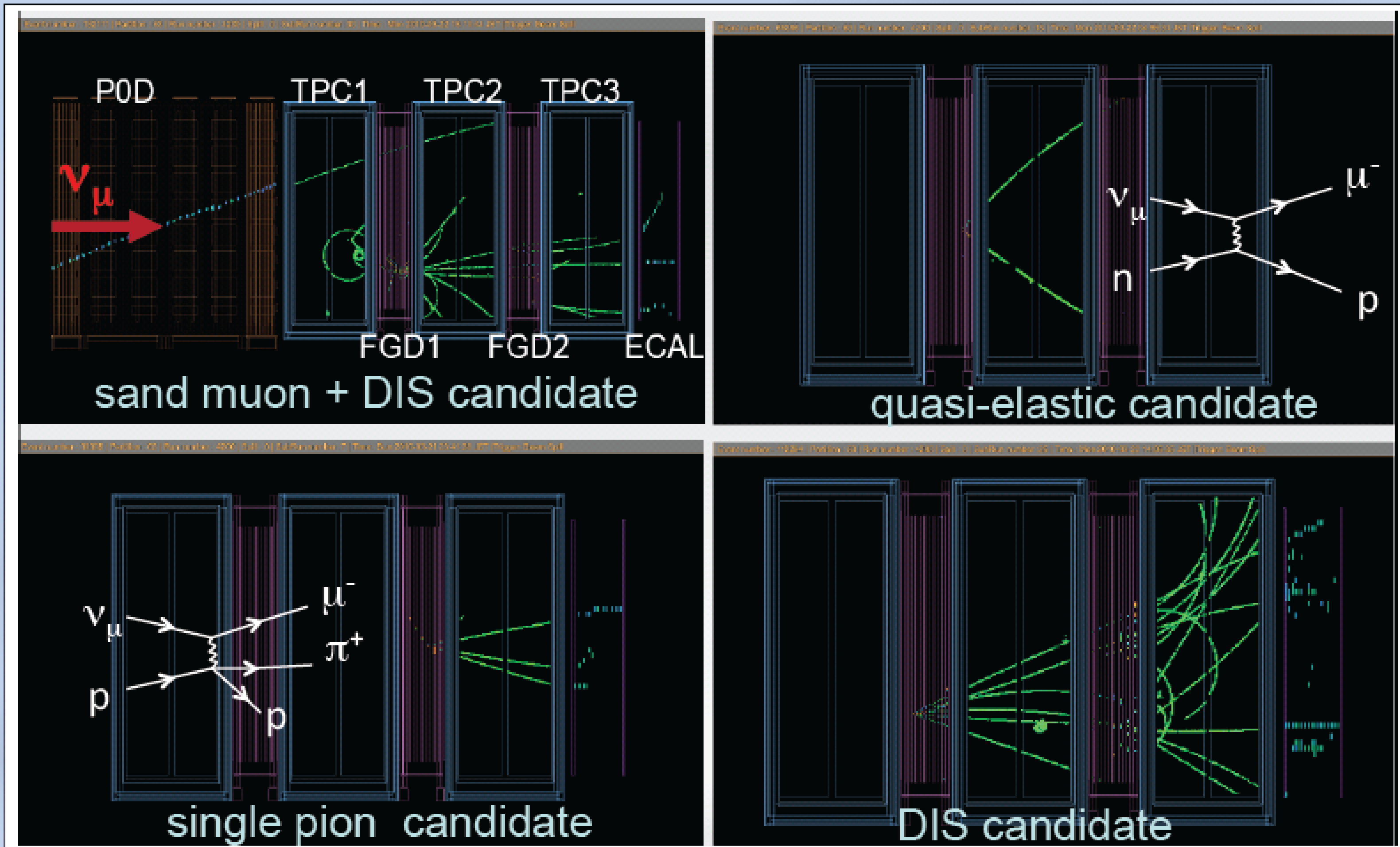
- 30GeV protons from J-PARC MR
- Target station + Decay volume
- Near Detector: ND280 (off-axis); INGRID (on-axis)
- Far Detector: Super-K (50kt water Cherenkov)



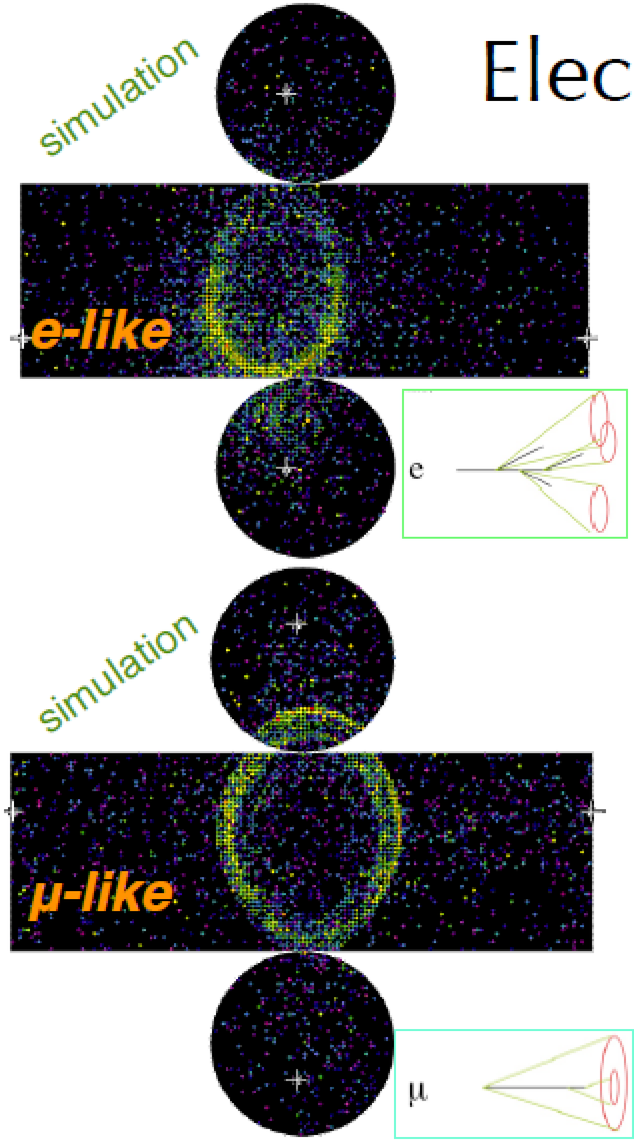
T2K Near Detectors (280m from target)



ND280 events

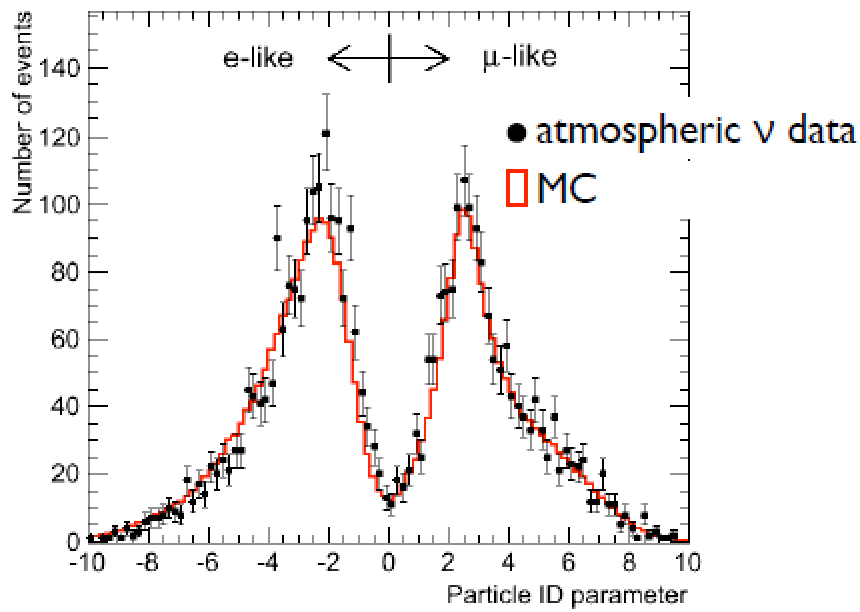


Super-Kamiokande: a well understood far detector



Electron-like and muon-like event at SK

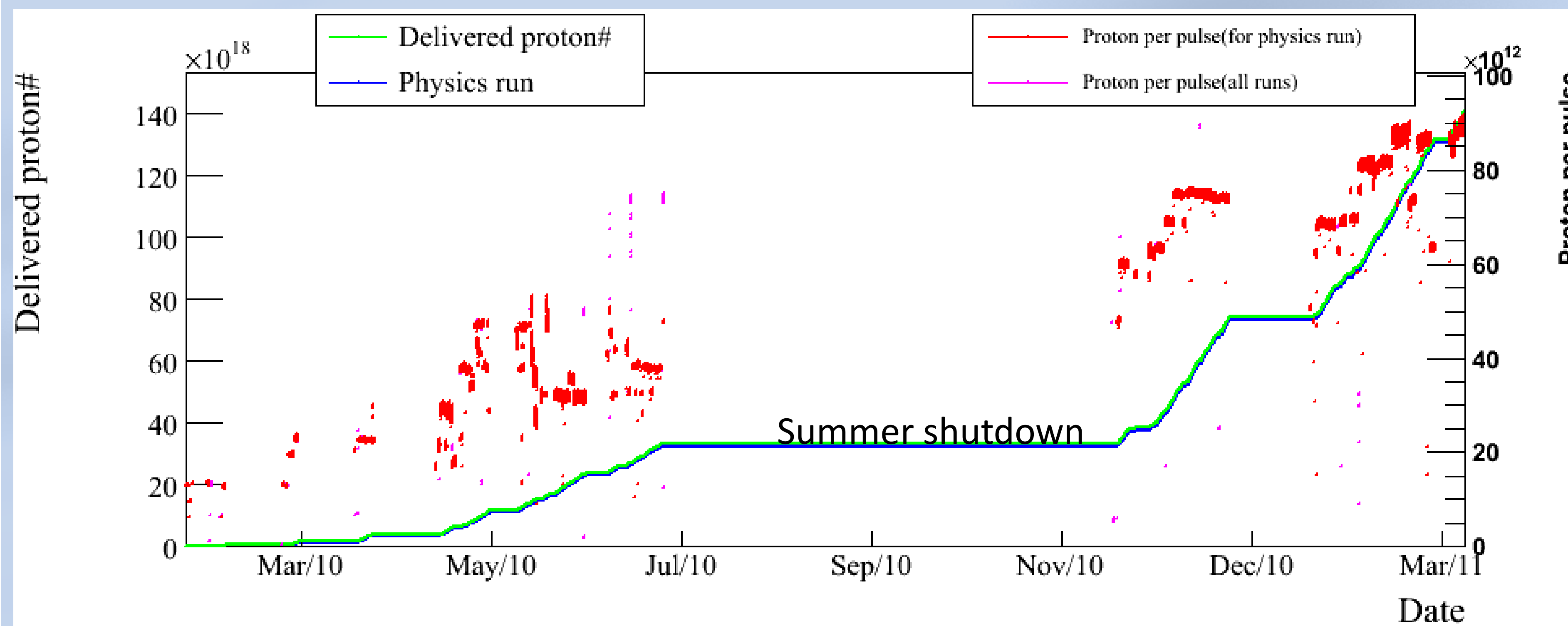
Particle identification using
ring shape & opening angle



Probability that μ is mis-identified as electron is ~1%

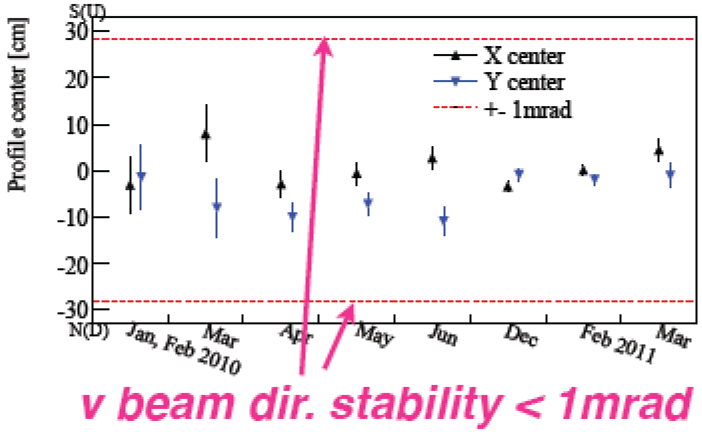
T2K

- Approved in 2004, running since December 2009
- Total accumulated before 11/03/11: 1.45×10^{20}pot
- Plan to restart taking data in January 2012
- Planned power: 750kW. Achieved: 145kW

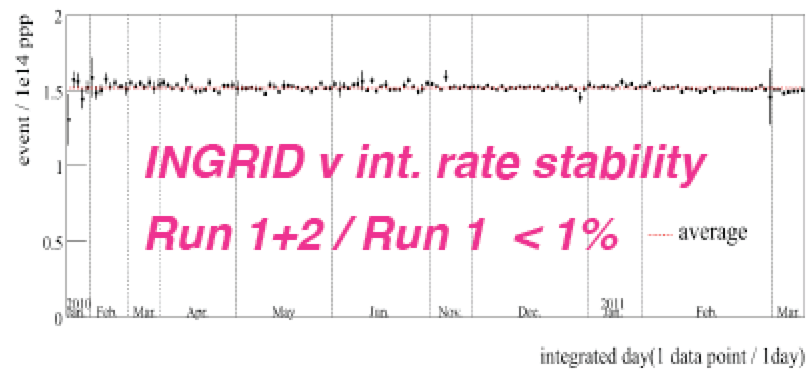


Beam stability: 1mrad on direction required for 2% neutrino energy peak stability

Stability of ν beam direction (INGRID)

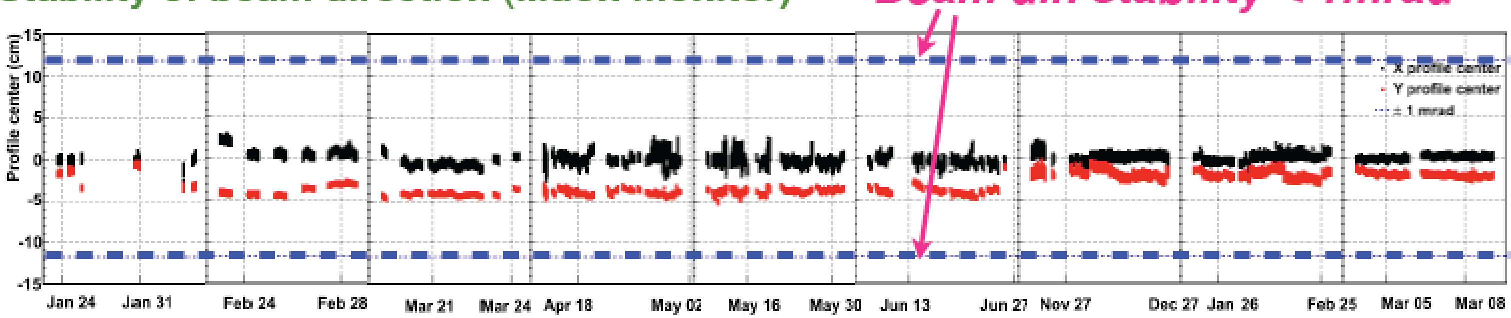


Stability of ν interaction rate normalized by # of protons (INGRID)



Stability of beam direction (Muon monitor)

Beam dir. stability < 1mrad



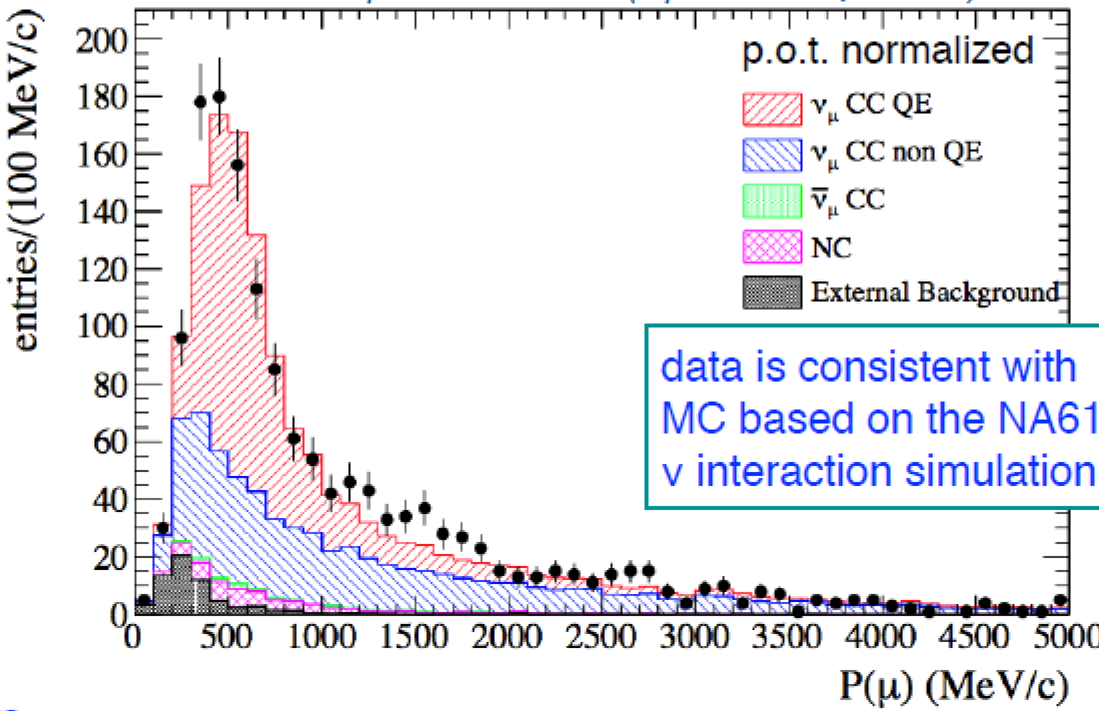
Search for ν_e appearance

- Fix Super-K event selection on atmospheric data BEFORE any beam data were collected
- Estimate expected Super-K event rates
  - Full MC simulation
  - Use hadro-production data from NA61
  - Use ND280 rates for absolute normalization
- Estimate systematic errors on the above
- Look at beam data, extract θ_{31} result

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

Neutrino flux measurement in ND280

ND Measurement of muon momentum in inclusive ν_μ CC events ($\nu_\mu + N \rightarrow \mu^+ + X$)



data is consistent with MC based on the NA61 and ν interaction simulation (w/o tuning)

Results

$$R_{ND}^{\mu,\ Data} = 1529 \ \text{events} \ / \ 2.9 \times 10^{19} \ \text{p.o.t.}$$

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

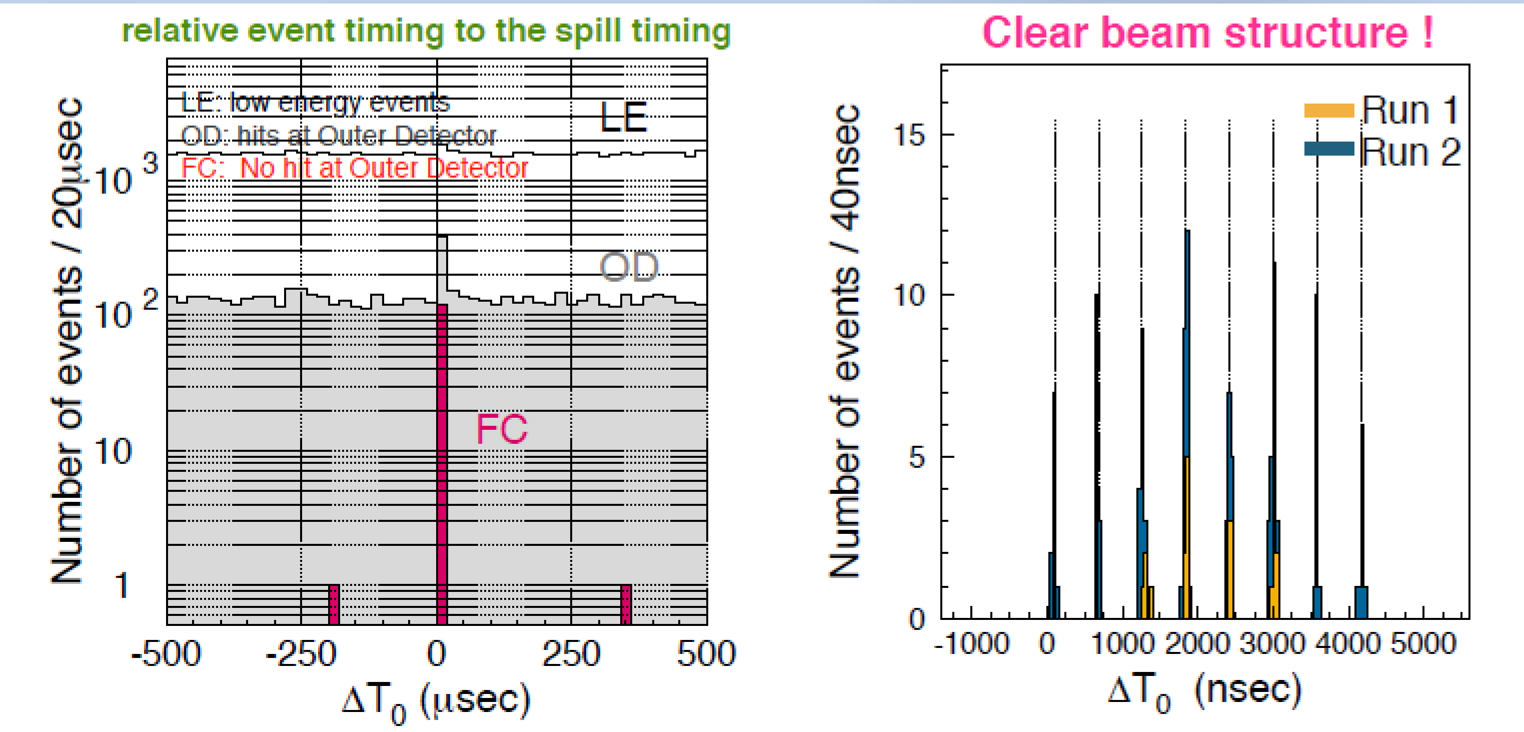
Expected signal-like events in SK, θ_{13}=0

The expected number of events with 1.43 x 10^{20} p.o.t.

$$N^{exp}_{SK\ tot.} = 1.5\ \text{events}$$

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	**0.8**	**0.6**	**0.1**	**1.5**

SK beam events: timing



$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

Systematic errors

Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}$=0 and 0.1

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

cf.
$\sin^2 2\theta_{13}$=0:
#sig = 0.1 #bkg = 1.4

$\sin^2 2\theta_{13}$=0.1:
#sig = 4.1 #bkg = 1.3

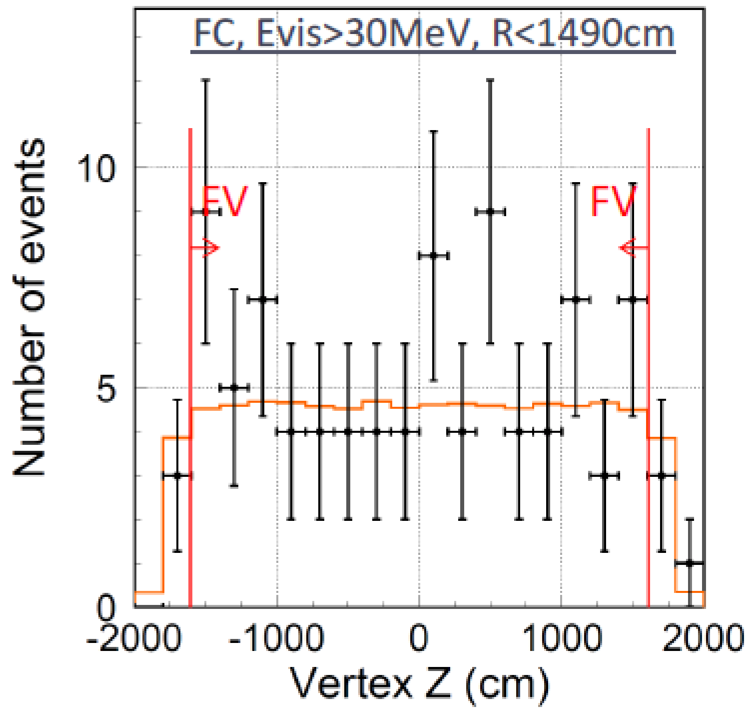
(due to small Far det. uncertainty for signal)

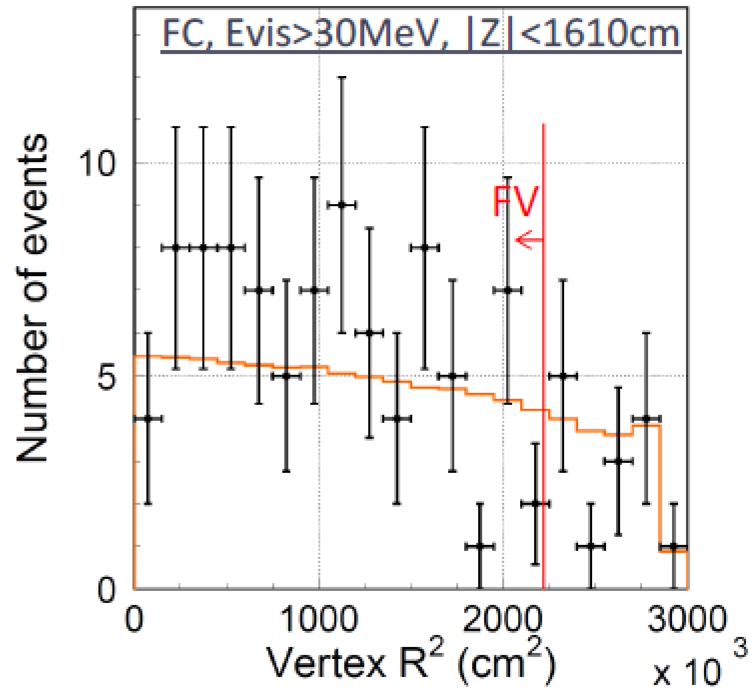
$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}$=0 (w/ 1.43×10^{20} p.o.t.)

SK beam (in-time) events, fiducial cuts

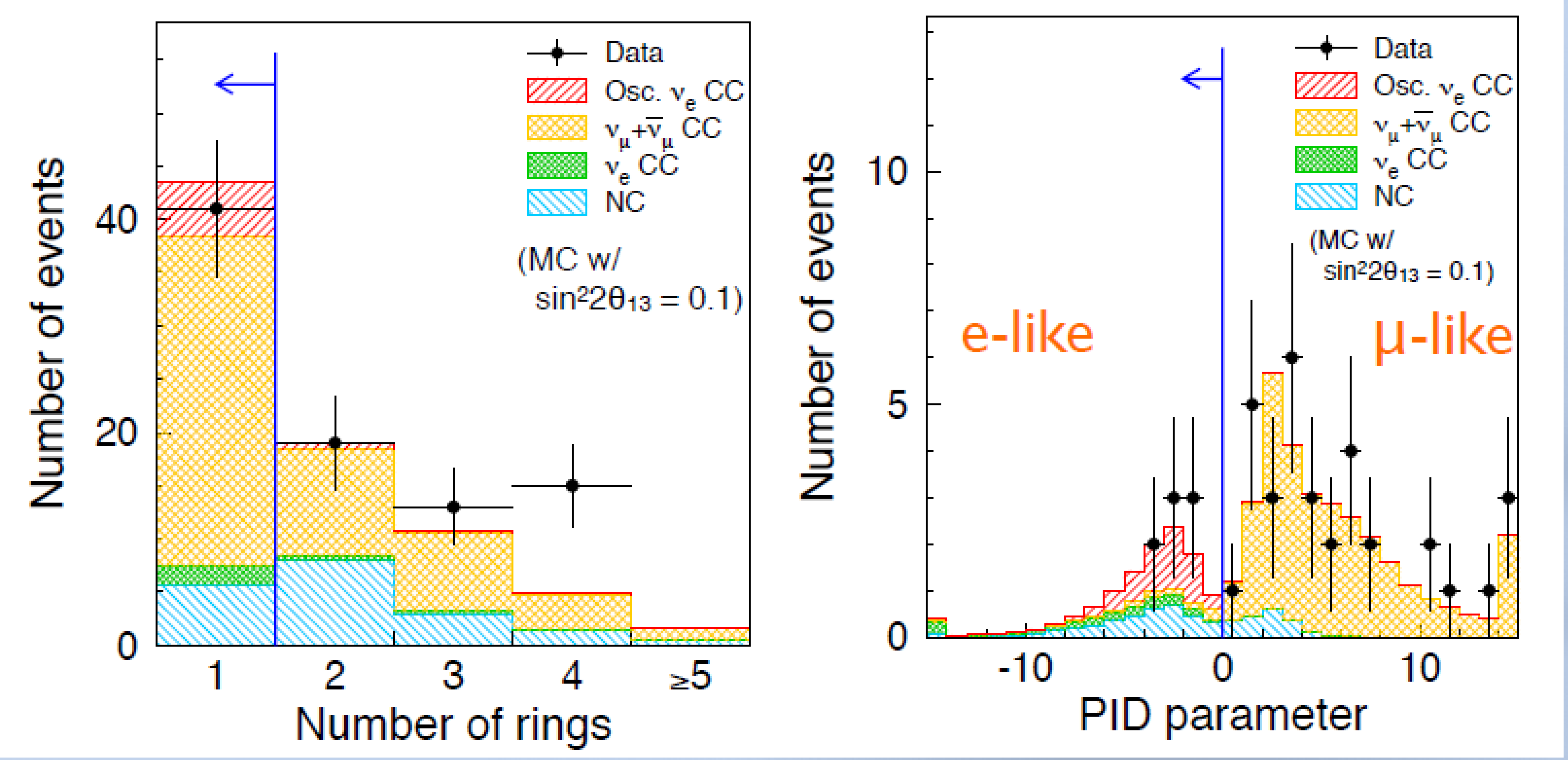
Number of events in on-timing windows (-2 ~ +10 μsec)

Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT (x 10^{19})	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

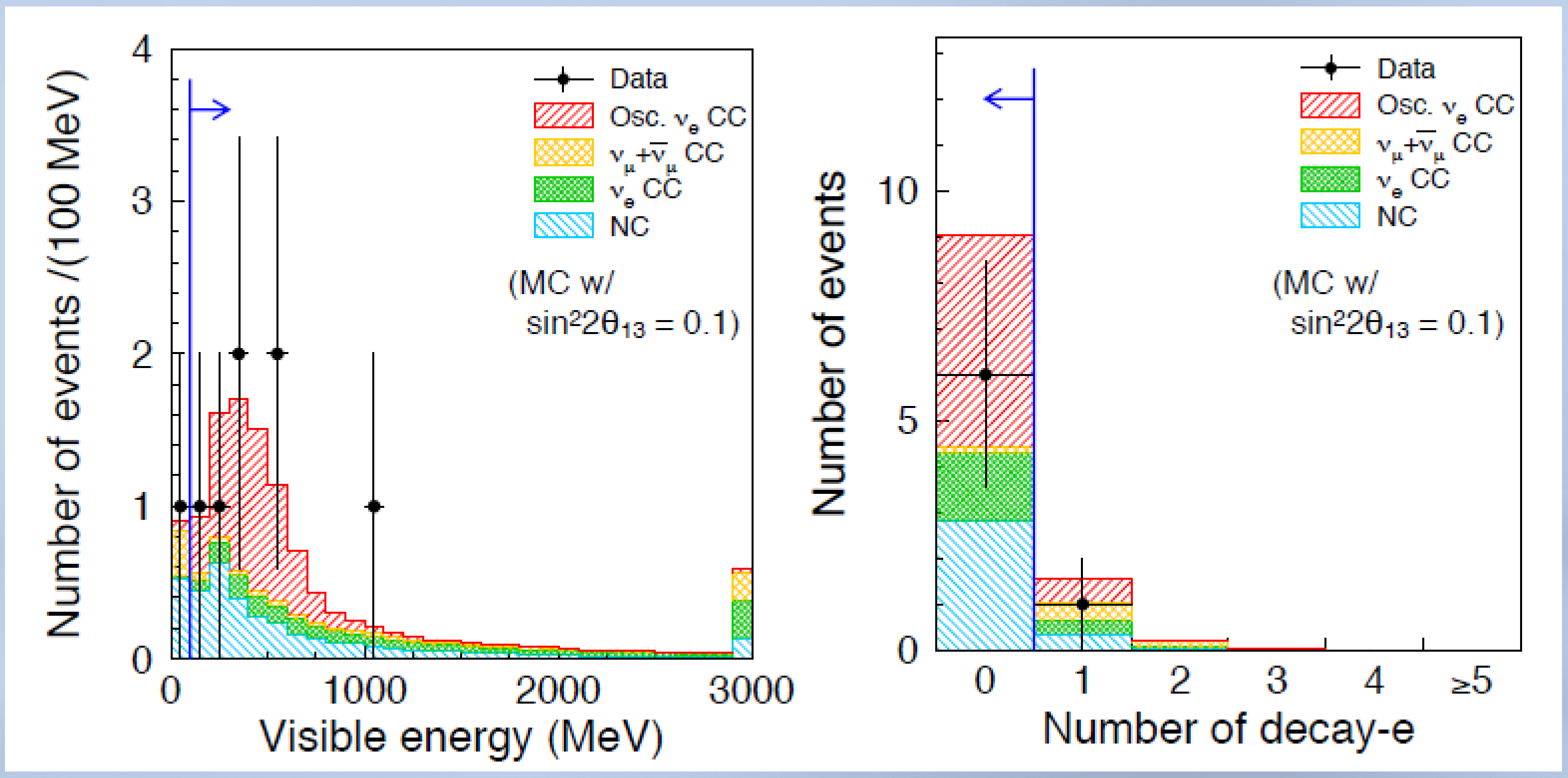




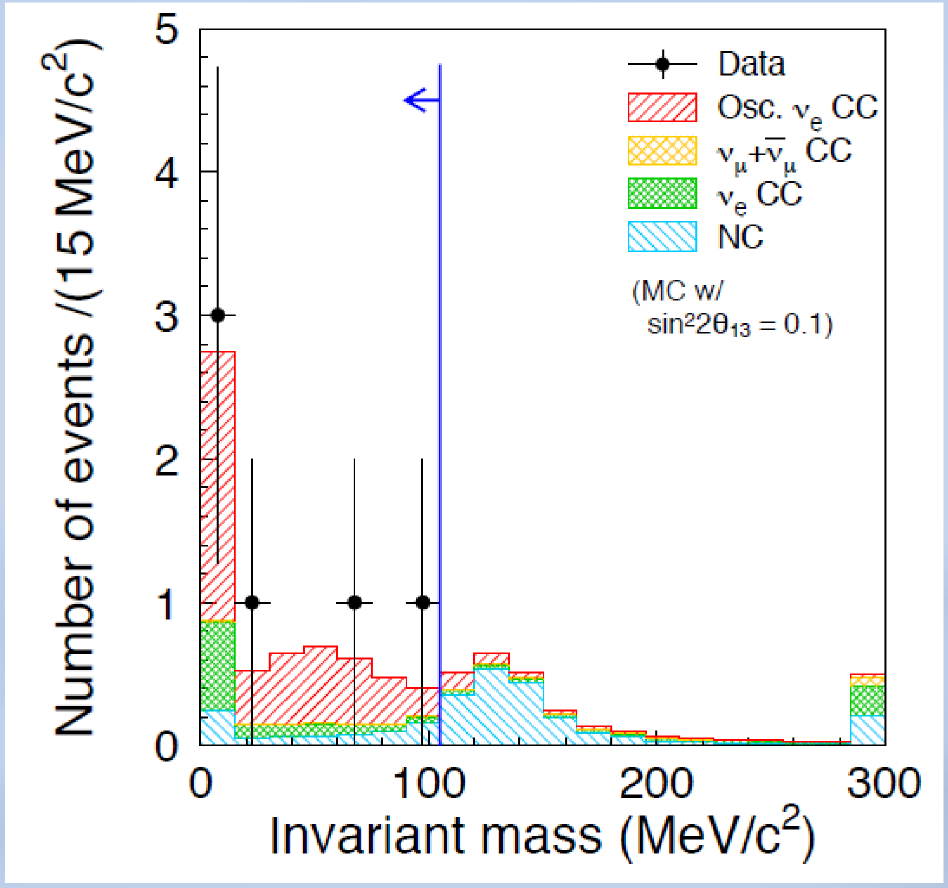
Single electron cuts (single ring, e-like)

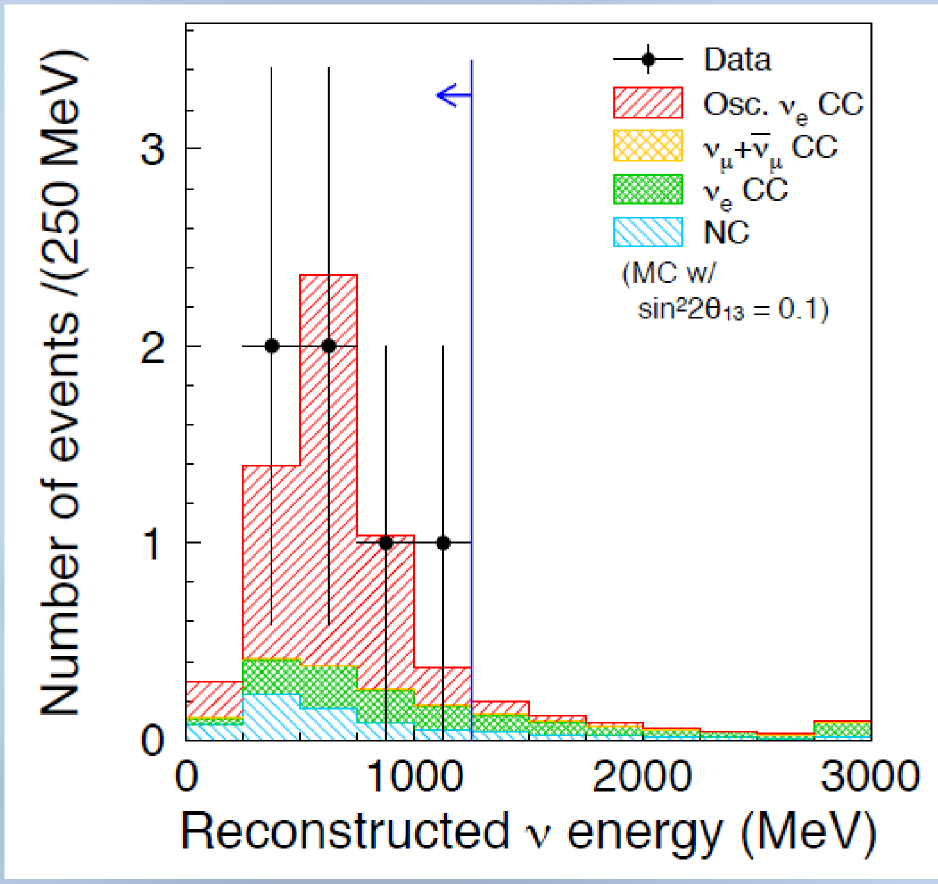


E>100MeV, no decay electron



π^0 rejection, total energy cut

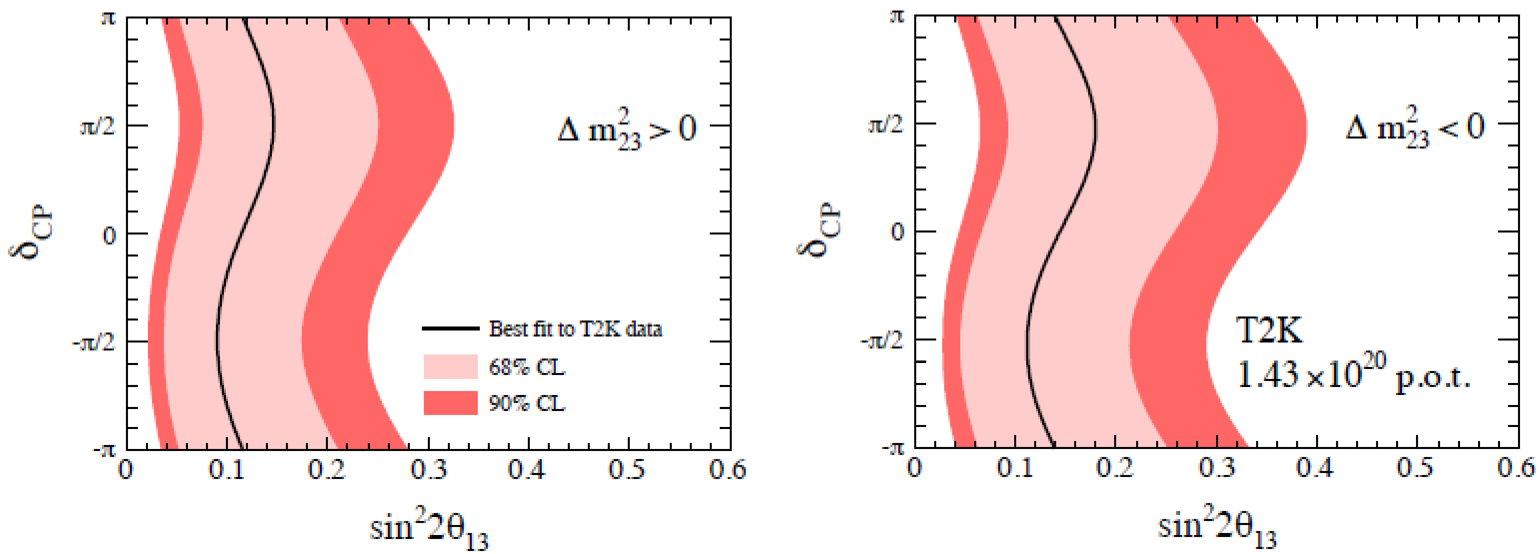




RESULT from 1.43×10^{20} POT

- 6 events found, 1.5±0.3 expected for $\theta_{13}=0$
- Probability to observe ≥6 events for $\theta_{13}=0$: 0.007
- PRL paper in print

(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)



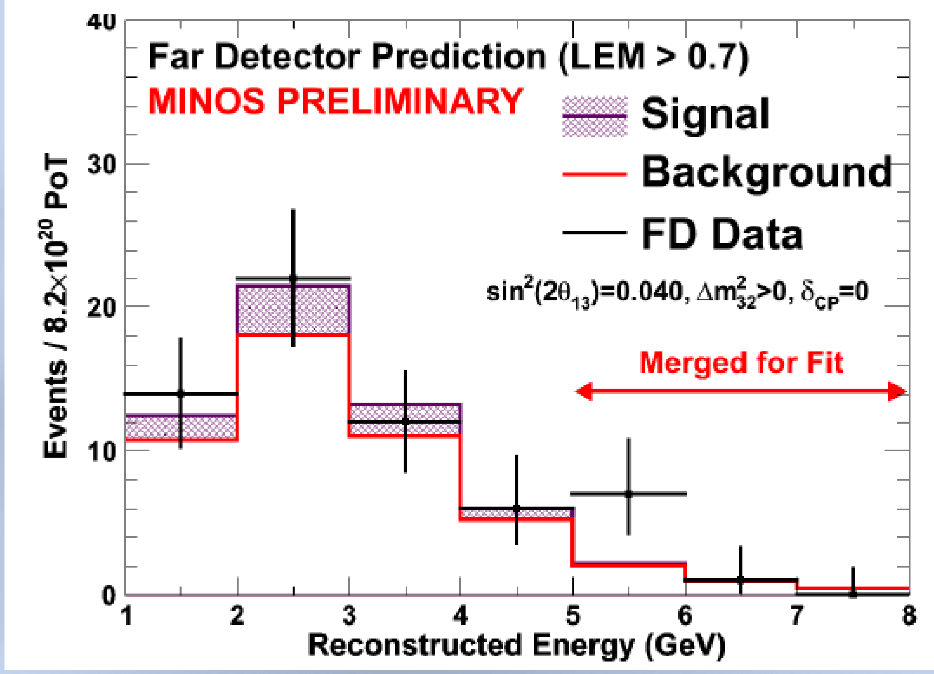
90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

MINOS update, 24 June 2011

- 8.2×10^{20} POT
- Improved sensitivity using Library Event Matching
- Analysis of ND data, prediction for FD for $\theta_{13}=0$:
  - 49.5 ± 2.8(syst) ± 2.8(stat)
- Events observed: 62
- $\theta_{13}=0$ excluded at 89%
- $\sin^2(2\theta_{13}) < 0.12$ (0.19)

for normal (inverse) MH



Next steps

- T2K to restart by January; data shown only **2%** of approved pot
- MINOS to collect and analyze more data
- NOVA to start with full detector in 2014
- Double Chooz running; second detector in 2012
- RENO starting up
- Daya Bay filling detectors
- CP search superbeam options:
  - JPARC to Okinoshima, 100kt Lar OR Hyper-K, Mton WC
  - LBNE
  - LAGUNA-LBNO option from CERN (SPS) to Finland

Summary

- **T2K** presented first indication for electron neutrino appearance; θ_{13}=0 excluded at **99.3%**
- **MINOS** update excludes θ_{13}=0 at **89%**
- A value of θ_{13} around 5-10 degrees opens up exciting options for CP search
- Many results expected in next two years
- And programmes to elucidate anomalies
- The neutrino community is busy....

......watch this space!