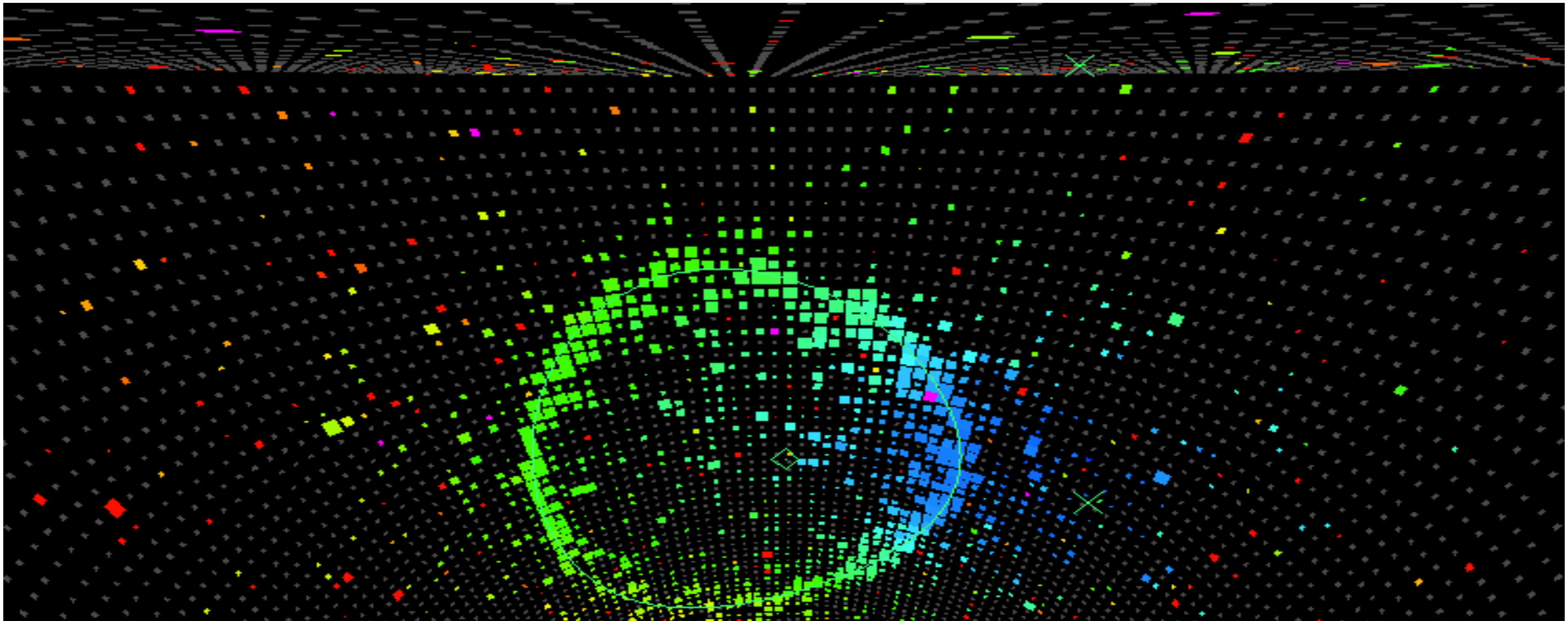
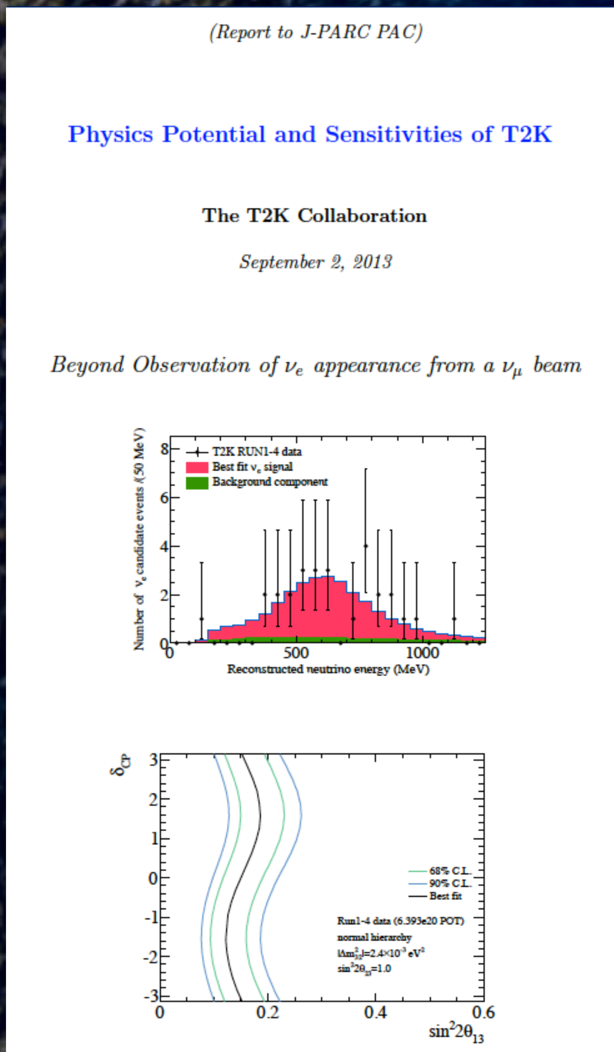


Observation of ν_e Appearance from a ν_μ Beam and more

Chang Kee Jung
Stony Brook University

J-PARC PAC Meeting
September 26, 2013

T2K Report to J-PARC PAC


(Report to J-PARC PAC)

Physics Potential and Sensitivities of T2K

The T2K Collaboration

September 2, 2013

Beyond Observation of ν_e appearance from a ν_μ beam

- Introduction, Summary of Data Taking and New (official) Results
  - – ckj
- Future Sensitivity Study Report
  - – Megan Friend (KEK)
- Summary and Beam Request
  - – Takashi Kobayashi (KEK)
- New "Work-in-Progress" Results
  - – ckj, in closed session

T2K (E11) Physics Goals based on T2K LOI and J-PARC P11

1. Discovery of $\nu_\mu \rightarrow \nu_e$ appearance by extending the search down to $2\sin^2 2\theta_{\mu e} \sim \sin^2 2\theta_{13} = 0.006$, thereby probing that $\theta_{13} \neq 0$;
2. Precision measurement of oscillation parameters in the ν_μ disappearance with precision of $\delta(\Delta m^2_{32}) \sim 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) \sim 0.01$ (~1% level); and
3. Search for sterile components in the ν_μ disappearance.

➔ Approved data taking: 5 years (5×10^7 s) @ 750 kW corresponding to 7.8×10^{21} POT with a 30 GeV beam

➔ T2K Report to J-PARC PAC provides a comprehensive status update of the experiment and present updated physics goals in light of the recent advancements

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Lepton Mixing Matrix (a la CKM matrix)

weak eigenstates
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
mass eigenstates

1 Dirac Phase ⇒ CPV

Three Angles

$$\mathrm{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij}),\quad s_{ij} = \sin(\theta_{ij})$

atm/accelerator accelerator/reactor solar/reactor

If ν is majorana particle, 2 more extra (Majorana) phases
\# of extra phases = N - 1 (w/ N = 3)

CPV in lepton sector could be A KEY to understand the origin of matter dominant universe (LEPTOGENESIS)

3-flavor Neutrino Oscillations (in Vacuum)

In general,

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

For three generation, ν_e appearance (accelerator experiments)

$$P(\nu_\mu\to\nu_e)=\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}+\text{subleading terms}$$

Sensitivity to θ_{23} octant

Full appearance probability includes term that goes as sin(δ):

CPV term $\propto \pm\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

Sensitivity to CPV-δ

Sign flip for neutrino vs. antineutrino

Need non-zero value for all three mixing angles including θ_{13}

Complementary

For anti-ν_e disappearance (reactor experiments)

$$P(\nu_e\to\nu_e)=1-4C^2_{13}S^2_{13}\cdot\left(C^2_{12}\sin^2\Delta_{13}+S^2_{12}\sin^2\Delta_{23}\right)+4S^2_{12}C^2_{12}C^4_{13}\sin^2\Delta_{12}$$

No CPV-δ dependence, Pure θ_{13} measurement

Full 3-flavor ν_μ Disappearance Probability (in Vacuum)

- For a precision measurement, the next-to-leading term must be included in the fit due to the non-zero and relatively large θ_{13}

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\underbrace{c_{13}^4 \ \sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{s_{23}^2 \ \sin^2 2\theta_{13}}_{\text{Next-to-leading}}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

non-zero

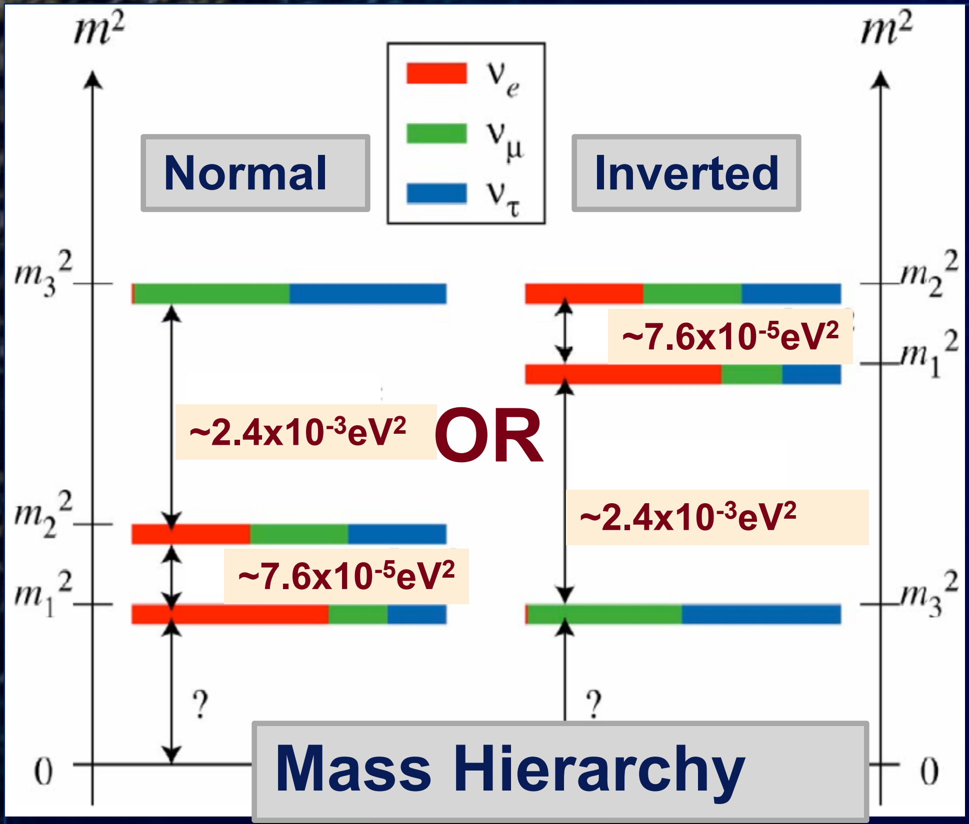
is different between 1st/2nd octants

- The next-to-leading term contains $\sin^2\theta_{23}$ while the leading term contains $\sin^2 2\theta_{23}$

→ Natural to fit $\sin^2\theta_{23}$ not $\sin^2 2\theta_{23}$

- Oscillation maximum occurs at $\theta_{23} \sim 45.74^\circ \neq 45^\circ$ maximal mixing

Current Status of Neutrino Oscillation Parameter Measurements



Critical for the ν-less double-β decay searches that would determine the Majorana-nature of ν

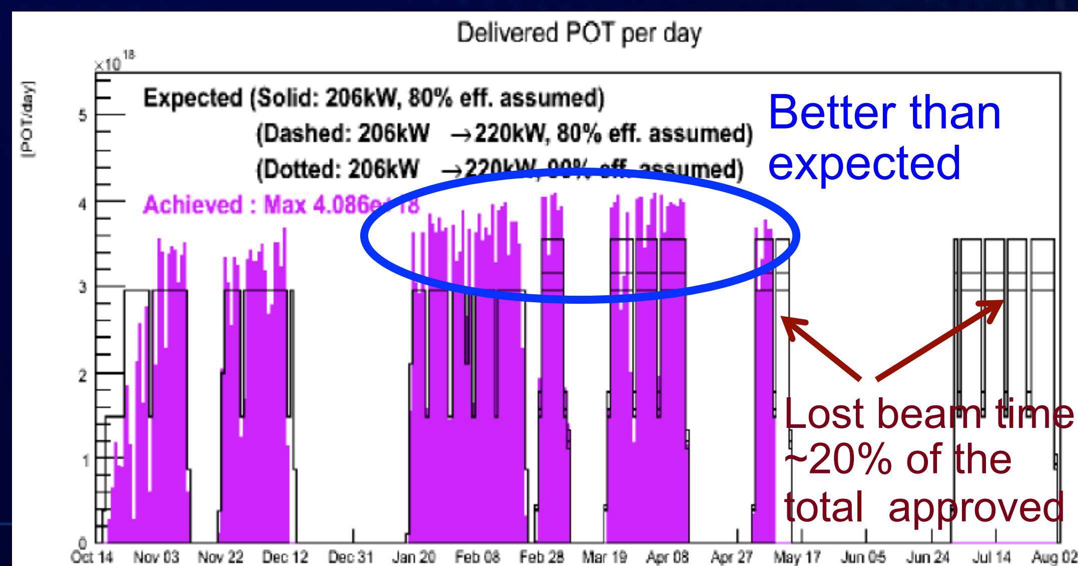
- Known Mixing Angles
  - $\theta_{12} = 33.6^o \pm 1.0^o$
  - $\theta_{13} = 9.1^o \pm 0.6^o$
  - $\theta_{23} = 45^o \pm 6^o$ (90% C.L.) → largest uncertainty
- Remaining Unknowns
  - δ_{CP} ($\neq 0$, i.e. CPV?)
  - Mass ordering (NH or IH?)
  - $\theta_{23} > 45^o$, $= 45^o$ (maximal) or $< 45^o$

    → maximal mixing may indicate a profound hidden symmetry
- T2K contributes to measurements of:
  - Δm^2_{32}, θ_{23}, θ_{13}, δ_{CP} and mass ordering

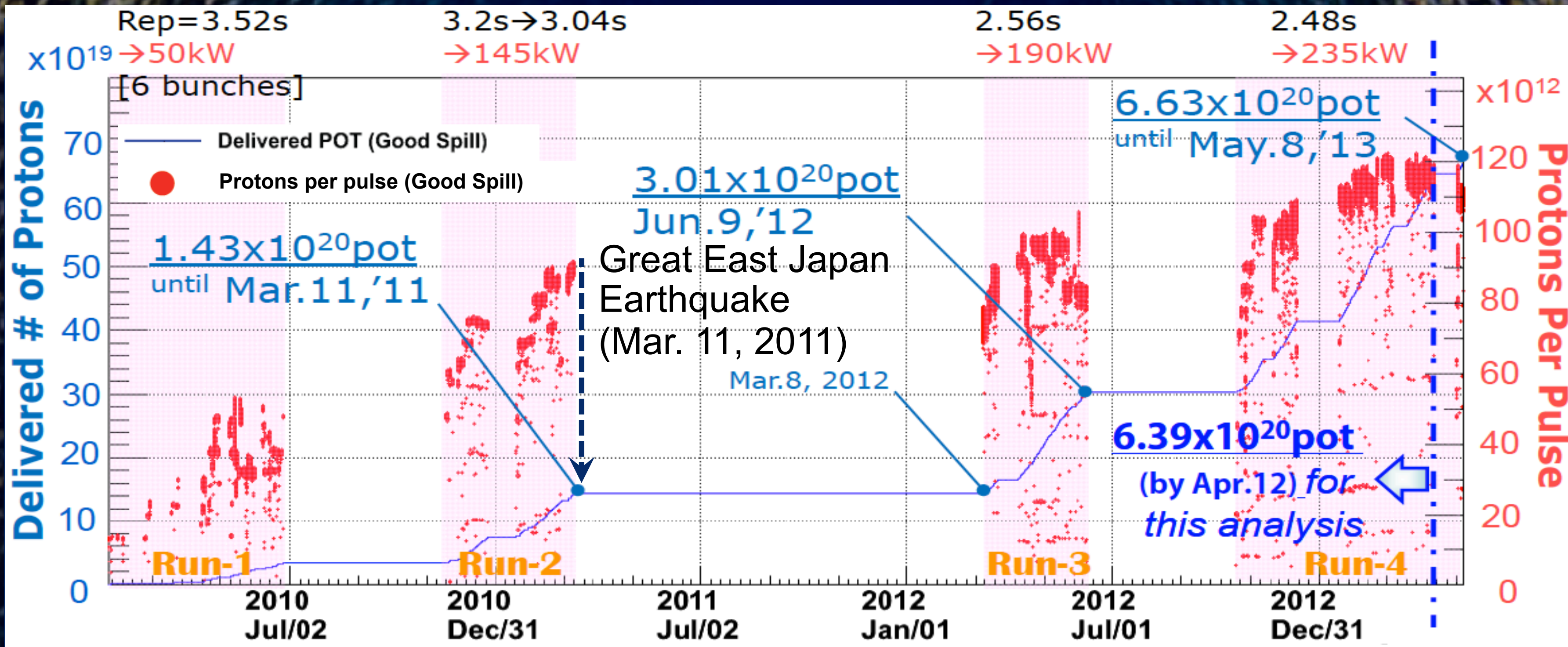
Running Status During Run 4 (Oct. 2012 ~ May 2013)

- T2K Physics runtime fraction was 82.6%
  - Accelerator trouble (11.2%), Accelerator tuning/study (1.3%)
  - NU trouble (3.0%), NU tuning/study (2.1%)
    - NU trouble was much smaller, compared to the previous runs
- Total delivered POT is 6.72×10^{20} (6.63×10^{20} for physics run)
  - Increase in this period (by May) is 3.62×10^{20} POT (very close to the expectation)

The T2K collaboration thanks the J-PARC accelerator division for their hard work to provide excellent accelerator performance



Protons on Target (POT) Delivered, Beam Power, and Data Collected



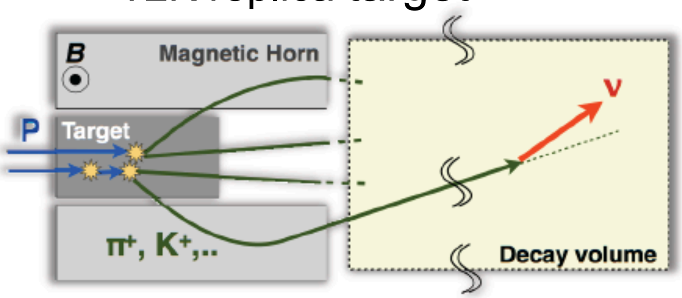
- Stable operation at ~220 kW achieved at the end of Run 4
  - World record proton per pulse (> 1.2 x 10^{14}) extracted for a synchrotron
- Total POT delivered: 6.72 (6.63 for physics run) x 10^{20} POT
  → ~ 8.6% of the total approved POT
  - Data analyzed for this presentation: 6.39 x 10^{20} POT (by April 12, 2013)

Strategy for predicting E_ν and N_{SK} at the Far Detector

A. Interaction of primary beam in the target [FLUKA2008.3d]

← π/ K production (Mainly CERN NA61)

T2K replica target



B. Tracking inside horns and He vessel [GEANT3+GCALOR]

Evaluate Neutrino flux and neutrino interaction model based on experimental data as much as possible

ν flux

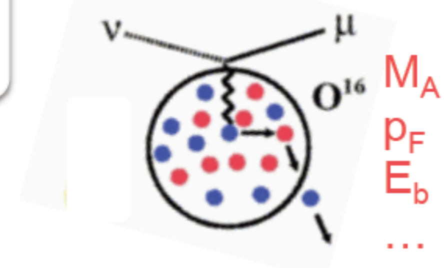
ν cross section

Near detector constraints

Prediction at far detector

$$\Phi^{SK} \cdot P_{osc} \cdot \sigma^{H2O}_{reaction} \cdot \varepsilon_{SK} dE_\nu$$

Neutrino-Nucleus interactions in a few GeV region [NEUT]



- Based on νflux ⊗ cross section MC models.
- Weighted by using as many of external data as input.
- Further constrain these predictions by the near detector measurements.

Results from the T2K ν_μ disappearance Oscillation Analyses

- 2011 results based on Run 1 + 2 (1.43 x 10^{20} POT)
  - 2 flavor oscillation analysis, fitting $\sin^2 2\theta_{23}$ and Δm^2_{32}
  - Phys. Rev. D 85, 031103(R), 2012 (arXiv:1201.1386)
- 2012 results (PRL paper) based on Run1 – 3 data (3.01 x 10^{20} POT)
  - Use event rate and E_{rec} spectrum (Same as before)
  - New analysis w/ spectrum constraint by ND280
  - 3 flavor oscillation analysis, still fitting $\sin^2 2\theta_{23}$ and Δm^2_{32}
  - Initially assumed $\theta_{23} \leq 45^o$ (1st octant)
  - Found that fitting with the 2nd octant assumption results in significantly different allowed region contour

    → Two contours for both octant assumptions (for summer conferences)
  - Final results with fitting $\sin^2\theta_{23}$, NOT $\sin^2 2\theta_{23}$ (for PRL)
- 2013 results based on Run 1 – 4 data (6.39 x 10^{20} POT)
  - 3 flavor oscillation analysis, fitting $\sin^2\theta_{23}$
  - On-going investigation of multi-nucleon knock-out processes

} closed session

T2K Run 1-3 Results on ν_μ Disappearance Compared to other Results

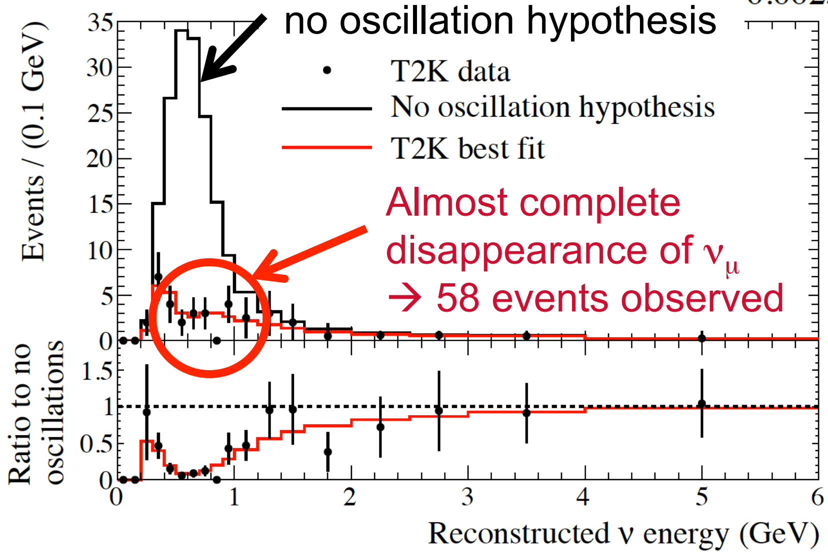
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}\right)\sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

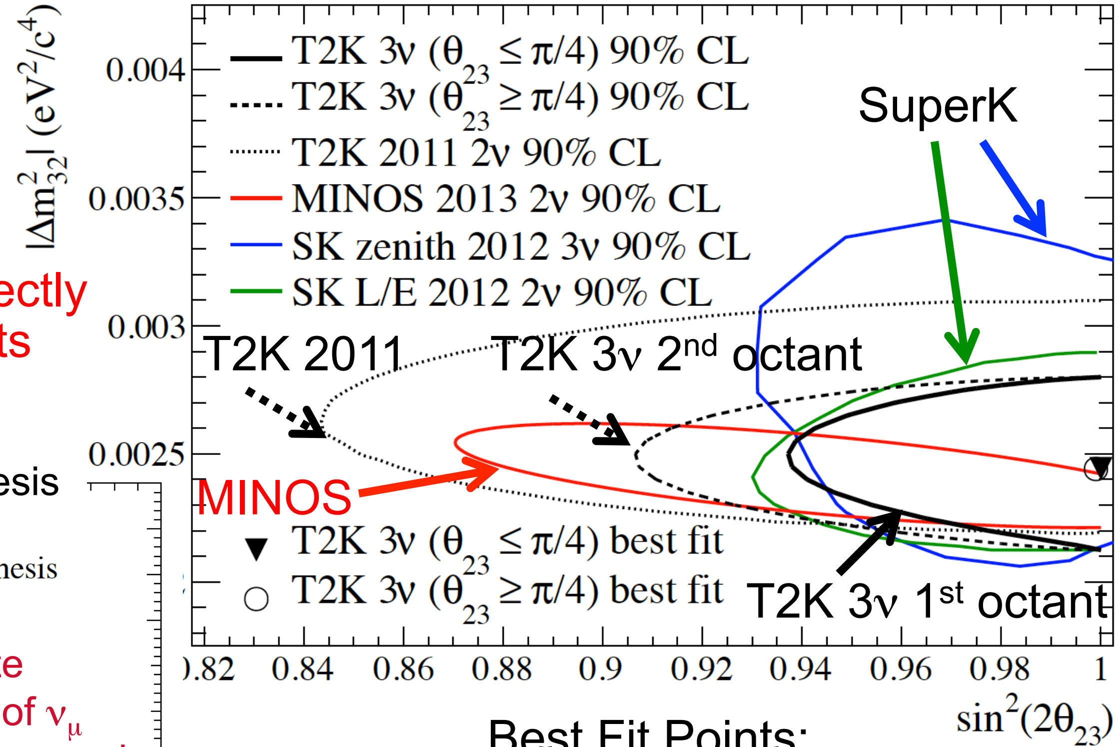
Initially fit $\mathbf{\sin^2 2\theta_{23}}$

→ choice of octant was necessary

These are not directly comparable results

205 events expected no oscillation hypothesis





Best Fit Points:

	$\sin^2 2\theta_{23}$	Δm_{32}^2	χ^2 / ndf
$\theta_{23} \le \pi/4$	1.000	2.44e-3	56.04 / 71
$\theta_{23} \ge \pi/4$	0.999	2.44e-3	56.03 / 71

Results from the T2K ν_e Appearance Oscillation Analyses

- 2011 PRL based on Run 1 & 2 (1.43 x 10^{20} POT)
  - 2.5σ "Indication" of non-zero θ_{13} / ν_e appearance
    - → This was really the first evidence of non-zero θ_{13} by a single measurement
  - Phys. Rev. Lett. **107**, 041801 (2011) → 658 citations as of 9/21/2013
- 2013 PRD paper based on Run1 – 3 data (3.01 x 10^{20} POT)
  - 3.1σ "Evidence" of ν_e appearance
  - New analysis w/ spectrum constraint by ND280
  - Phys. Rev. **D88**, 032002 (2013)
- 2013 results based on Run 1 – 4 data (6.39 x 10^{20} POT)
  - Improved near detector constraint
  - Employ an advanced fitting procedure (fiTQun) to greatly reduce the pi-zero background
  - 7.5 σ "Observation" of ν_e appearance

ν_e Candidate Events at SuperK
Selection Criteria Summary

(1) Event time within the T2K beam time window & Fully Contained (FC) Event

(2) Event vertex in the Fiducial Volume (FV)

→ (1) & (2) (= FCFV events) Common for ν_e and ν_μ

(3) Number of rings = 1

(4) Electron-like PID

(5) Visible energy > 100 MeV

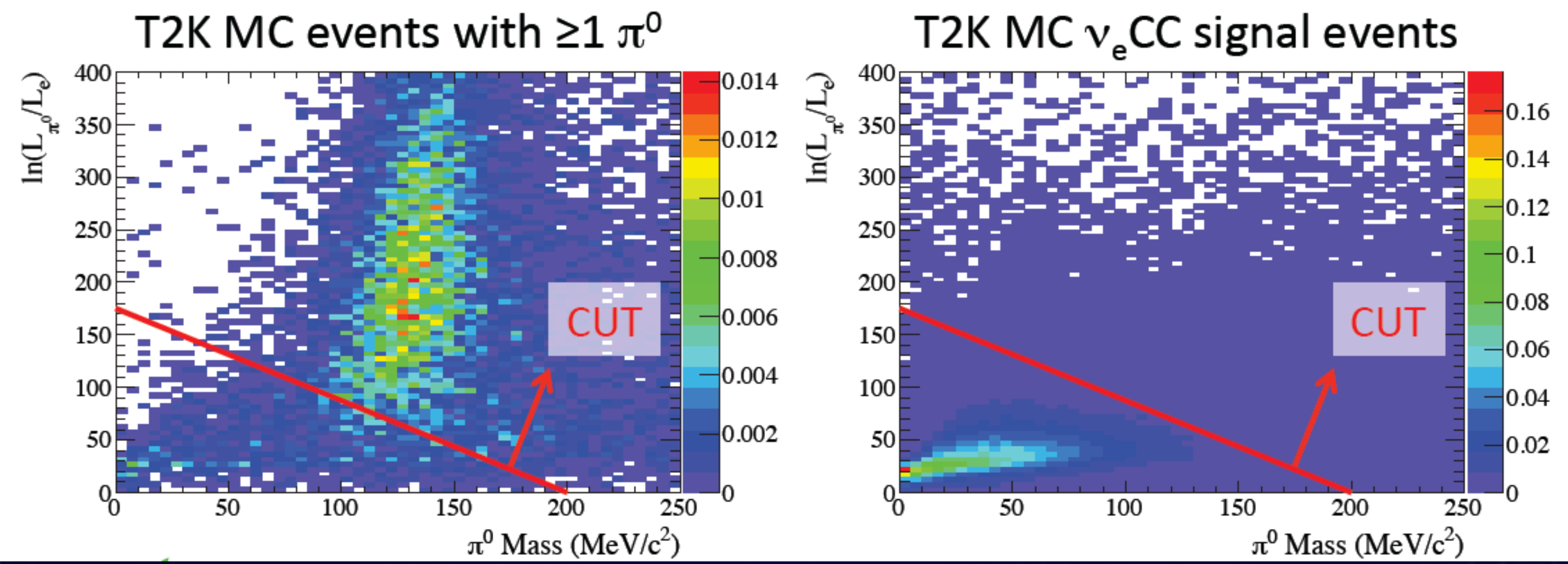
(6) No accompanying decay electron signal

(7) Reconstructed energy (E_{rec}) < 1,250 MeV

(8) π^o rejection (improved by employing new algorithm)

All cuts were predetermined before looking at the data

fiTQun π^0 rejection



- New π^0 rejection cut
  - Employ fiTQun likelihood ratio of 1-ring electron and π^0 fits in addition to reconstructed mass
  - 70% reduction of π^0 background with comparable signal efficiency
  - Total background is reduced by 27%

Predicted Number of ν_e Events and Systematic Uncertainties

Predicted # of events w/ 6.393×10^{20} p.o.t.

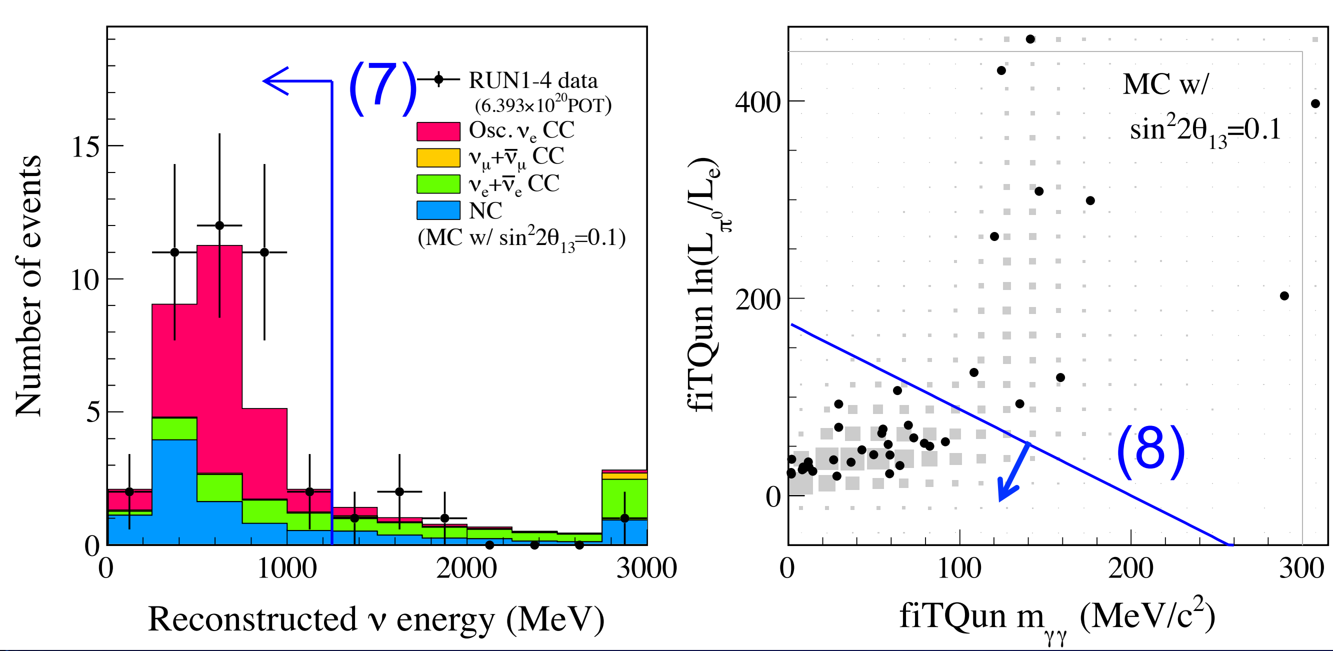
Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
ν_e signal	0.38	16.42
ν_e BG	3.17	2.93
ν_μ BG	0.89	0.89
$\bar{\nu}_\mu+\bar{\nu}_e$ BG	0.20	0.19
Total	**4.64 ± 0.52**	**20.44 ± 1.80**

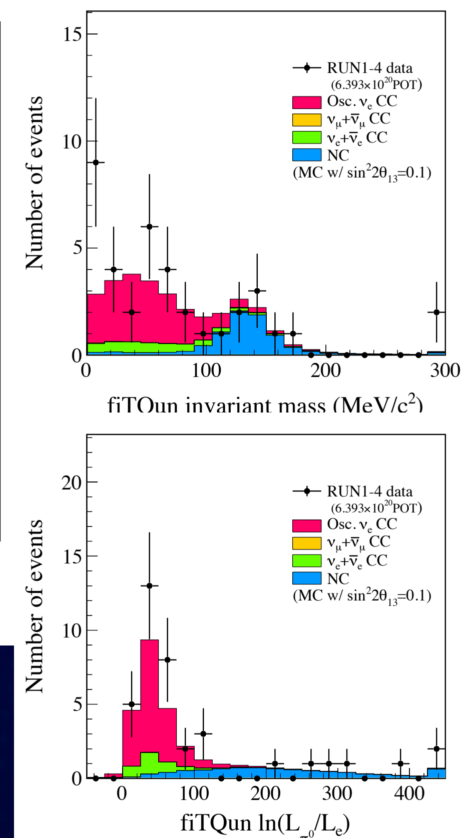
Systematic Uncertainties

Source	$\sin^2 2\theta_{13} = 0$	= 0.1
Flux + ν int. (ND meas.)	4.9 %	3.0 %
ν int. (from other exp.)	6.7 %	7.5 %
Super-K +FSI+SI+PN	7.3 %	3.5 %
Total	**11.1 %**	**8.8 %**
Total (2012)	13.0 %	9.9 %

- An excellent progress has been made in reducing systematic uncertainties
  - T2K has now essentially achieved the original sys. error goal (~10% overall)
  - Owing to the tremendous collective effort by:
    - NA61, Beam and ND280 groups
    - NIWG group
    - T2K-SK group
  - However much more effort is needed to reach ~5% level sys. error which is needed to explore CPV

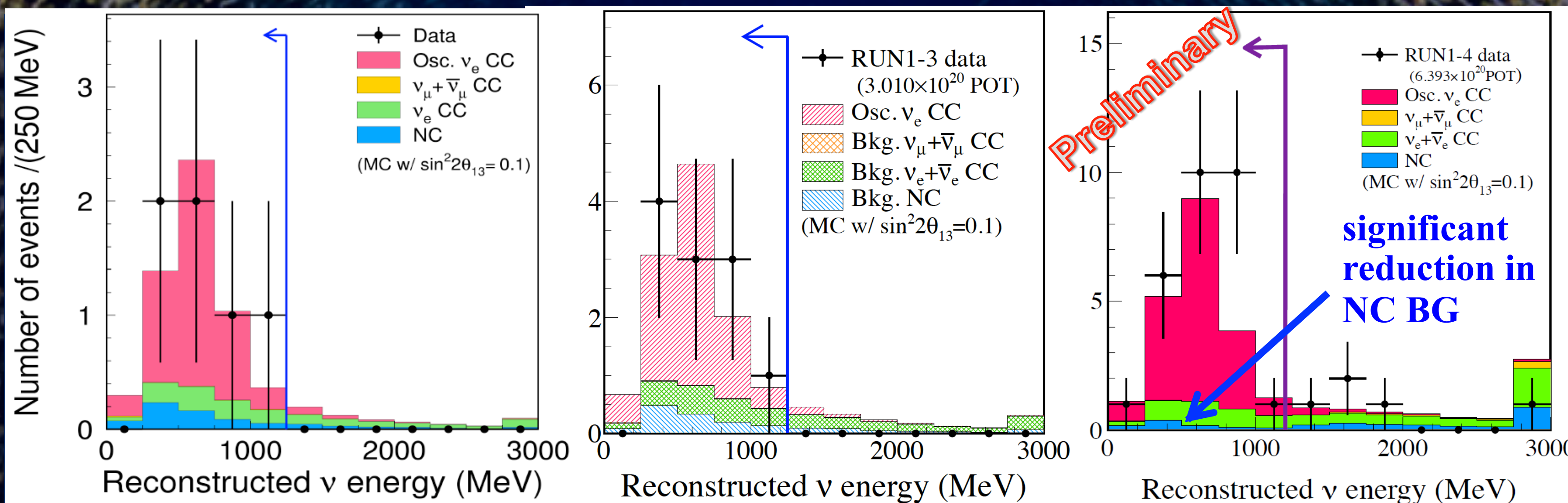
Far Detector ν_e Candidate Event Selection: (7) Reconstructed E_ν Cut & (8) π^0 Inv. Mass Cut





- (43 →) 38 events
  - Remove high energy intrinsic beam ν_e backgrounds from kaon decays
- (38 →) 28 events (final)
  - Remove remaining π^0 background

Reconstructed E_ν Spectrum of the Final Selected Events Compared to the Previous Years



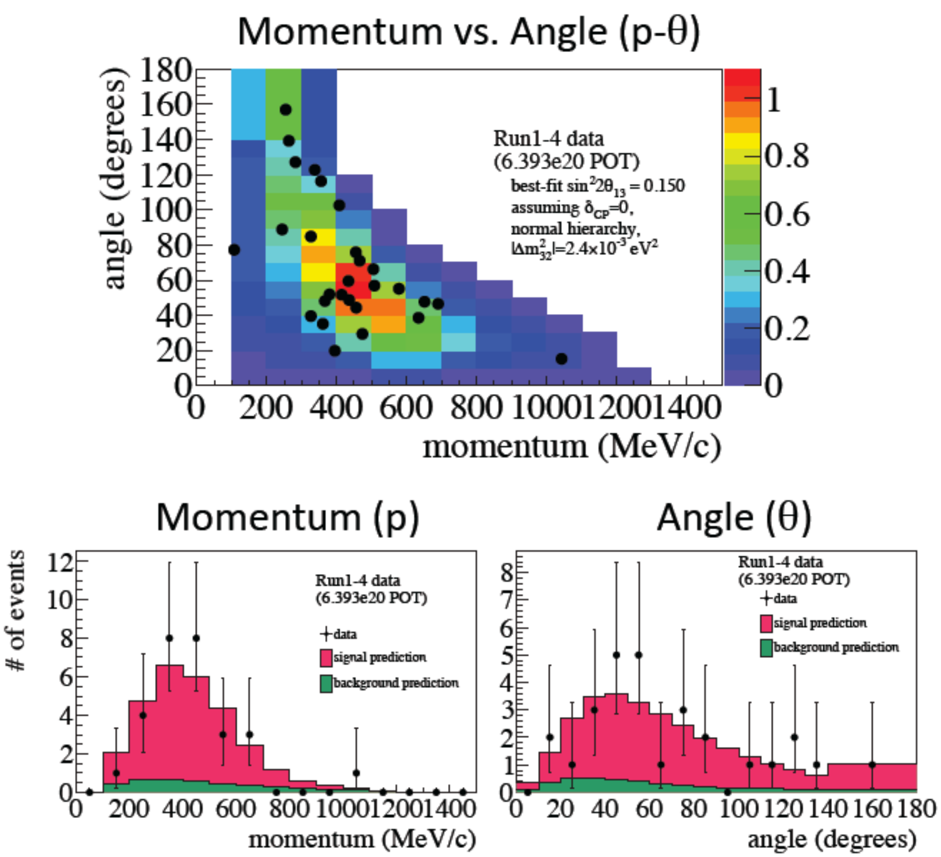
Year	2011	2012	2013
POT (10^{20})	1.43	3.01	6.39
$N^{obs.}_{\nu_e}$	6	11	28
N^{exp}_{BG}	1.5 ± 0.3	3.3 ± 0.4	4.6 ± 0.5
$\sin^2 2\theta_{13}$(T2K)	0.11	$0.088^{+0.049}_{-0.033}$	$0.150^{+0.039}_{-0.034}$
Significance	2.5σ	3.1σ	7.5σ
Systematic Error (%) on N^{exp}_{tot}	17.5	9.9	8.8

- θ_{13}= 0 is excluded at 7.5σ level of significance

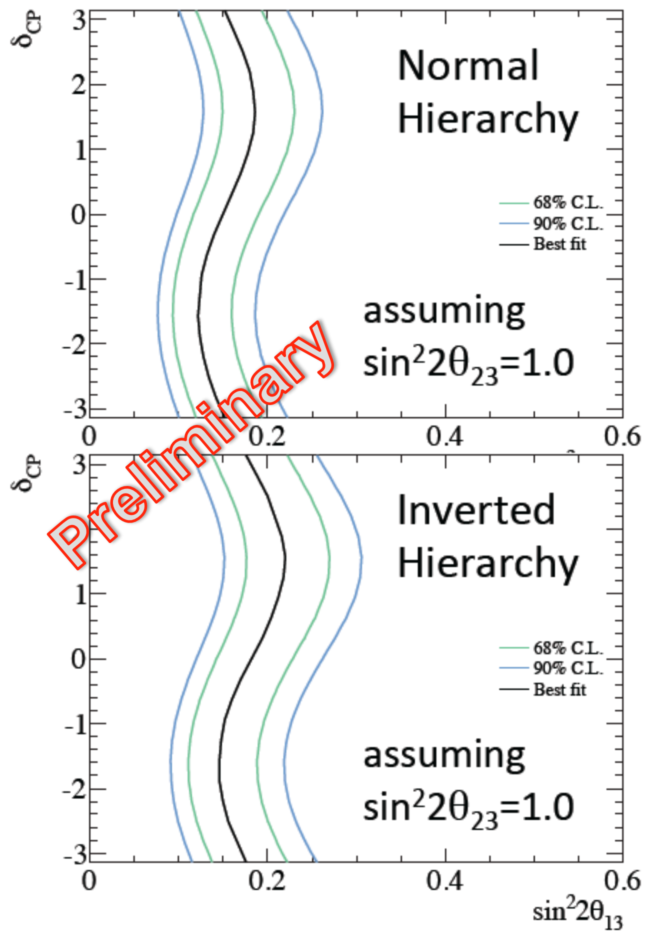
→ Observation of ν_e appearance from a ν_μ beam!

Data Fit Results: Method 1 (p-θ)

Data and best-fit MC distributions



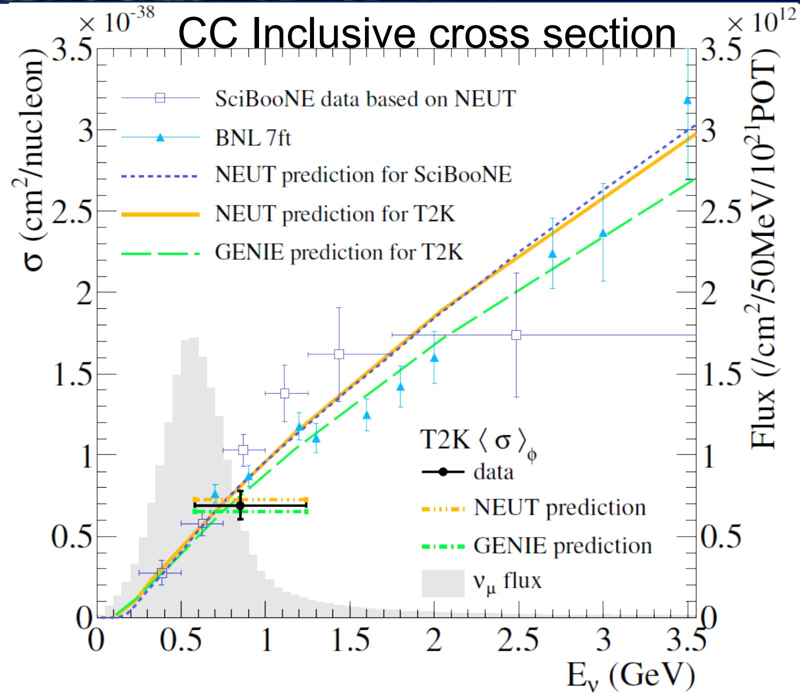
68%/90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of δ_{CP}

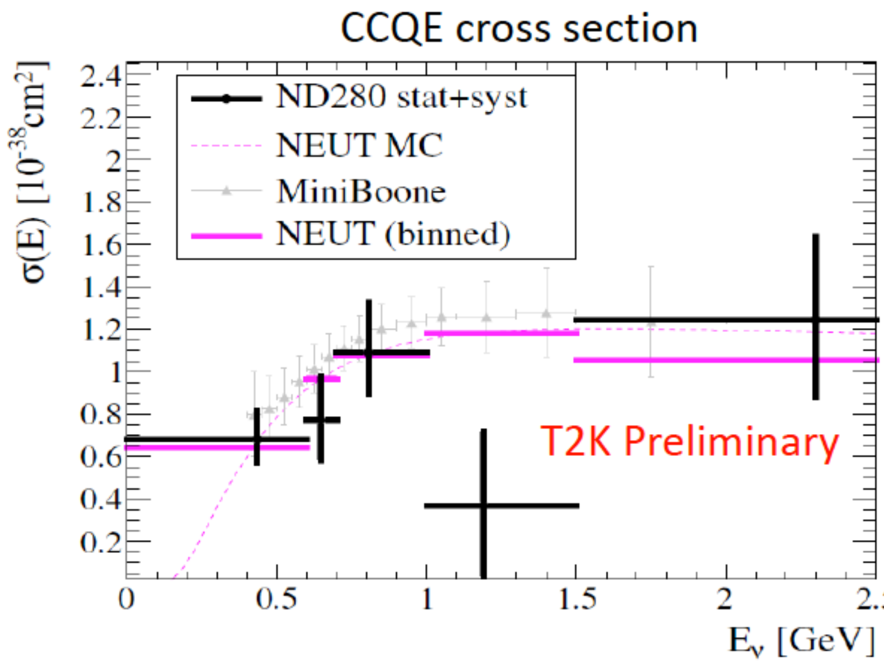


Cross-section Measurements

- Various neutrino interaction cross-section measurement (including on water) opportunities at T2K
- Currently, the largest systematic uncertainty comes from the uncertainties in the cross-sections from other experimental input
- Officialized Results
  - Measurement of the Inclusive ν_μ Charged-Current Cross Section on Carbon in the Near Detector of the T2K Experiment, Phys. Rev. D 87, 092003 (2013)
  - ν_μ CCQE Cross-section Measurement Using ND280 Tracker
  - ν_μ NC Elastic Cross-section Measurement Using ND280 P0D
- On-going Studies
  - ND280 Tracker: ν_μ CC1π^+, ν_μ CC-coherent π, ν_e CC-inc, ν_e CCQE
  - ND280 P0D: ν_μ NC1π^0, ν_e CC-inc, ν_μ CC-inc & CC1π^+ (on water)
  - INGRID: ν_μ CC-inc & CCQE, ν_μ CC-coherent π

Summary of Cross-section Measurements Results





$$\langle\sigma_{CC}\rangle_{\Phi} = \left(6.91 \pm 0.13(stat.) \pm 0.84(syst.)\right) \times 10^{-39}\,\frac{\mathrm{cm}^2}{\mathrm{nucleon}}$$

$$M_A^{QE} = 1.26^{+0.21}_{-0.18}\ \mathrm{GeV}$$

$$\langle\sigma_{NCE}\rangle_{\Phi} = \left(2.24 \pm 0.07(stat.)^{+0.53}_{-0.63}(syst.)\right) \times 10^{-39}\,\frac{\mathrm{cm}^2}{\mathrm{nucleon}}$$

Conclusions

- J-PARC accelerator has achieved steady operation at 220 kW for much of T2K Run 4
- We report a new T2K result on ν_e appearance based on 6.39×10^{20} pot (only ~8.6% exposure of T2K's design goal)
  - This is 2.1 times the Run 1-3 data used for 2012 analysis
  - 28 candidate events are observed compared to $4.6 \pm 0.5_{sys}$ expected for $\sin^2 2\theta_{13} = 0$
  - An extended M.L. analysis utilizing both the number and *p. θ* of the events excludes $\theta_{13} = 0$ at the 7.5 σ level of significance ($\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$)
    - Note: the result depends on the assumptions on other neutrino oscillation parameters, such as $\sin^2\theta_{23}$ and δ_{CP}
  - Substantial improvements in analysis have been achieved
  - This demonstrates the power and elegance of the off-axis beam technique

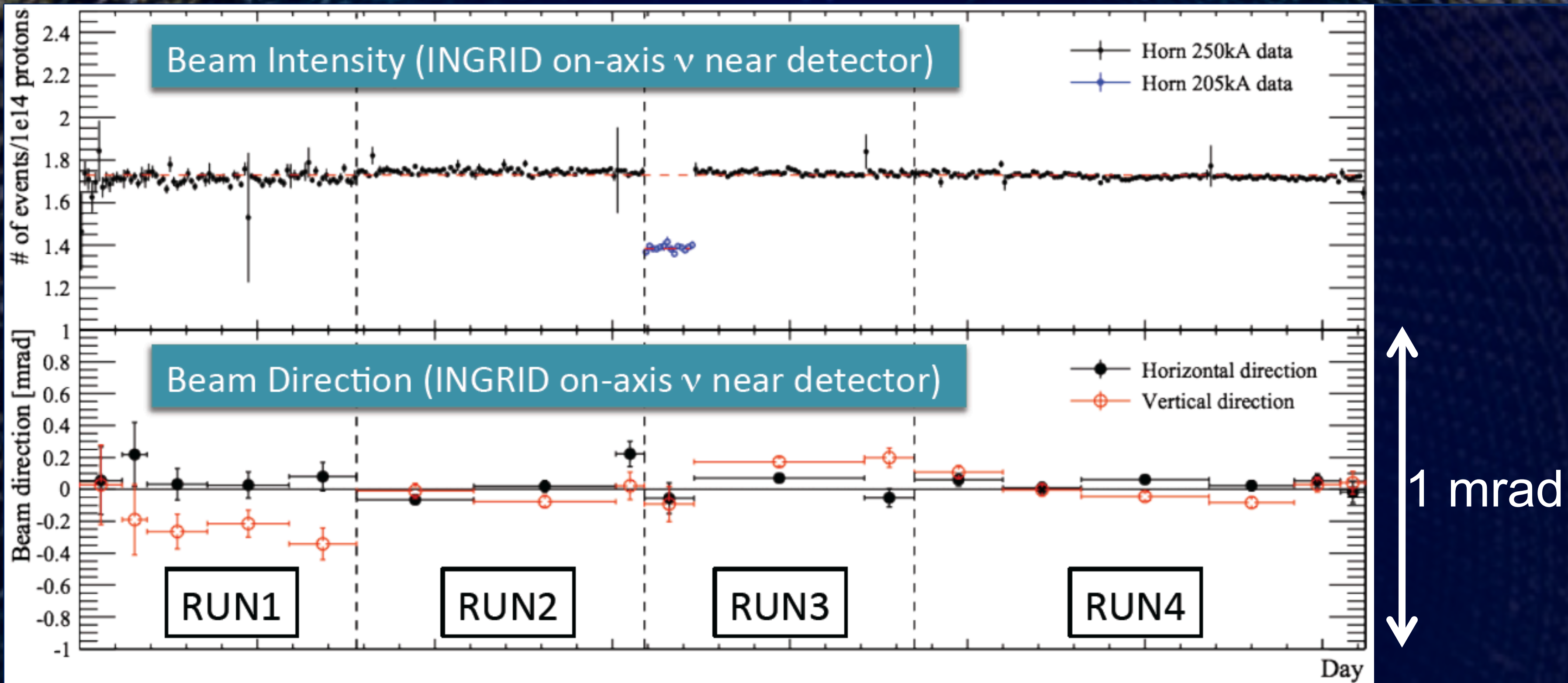
conclusion continues …

- **“Observation of ν_e appearance from a ν_μ beam”** has now been made
  - The (original) primary physics goal of T2K has been now realized
  - This is the first time neutrino oscillation is observed in an “appearance mode”, i.e. an explicit flavor appearance is observed from another neutrino flavor
  - This opens the door to study CPV in neutrinos
- Physics goals for the post non-zero θ_{13} /ν_e appearance era are now clearly defined for T2K and the world neutrino oscillation community
  - Determination of δ_{CP}, mass hierarchy and θ_{23} (=0, <45, >45?)
  - T2K along with NOvA will lead the world in determining these parameters at least for the next decade
- Non-zero neutrino mass is an indication for physics beyond the Standard Model
- Nature kindly gave us the non-zero neutrino mixing angles and **ν_e appearance** in order for us to be able to probe CP violation

May Nature be kind to us, (again)!

Supplemental Slides

Neutrino Beam Stability Measured by INGRID

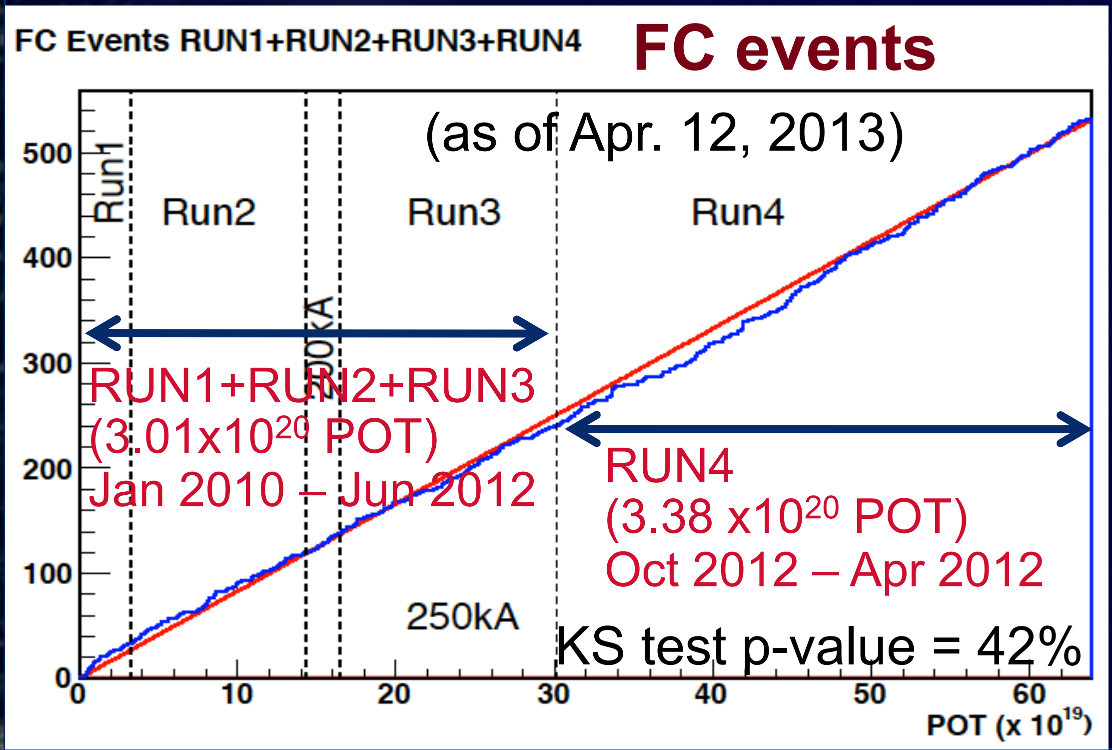


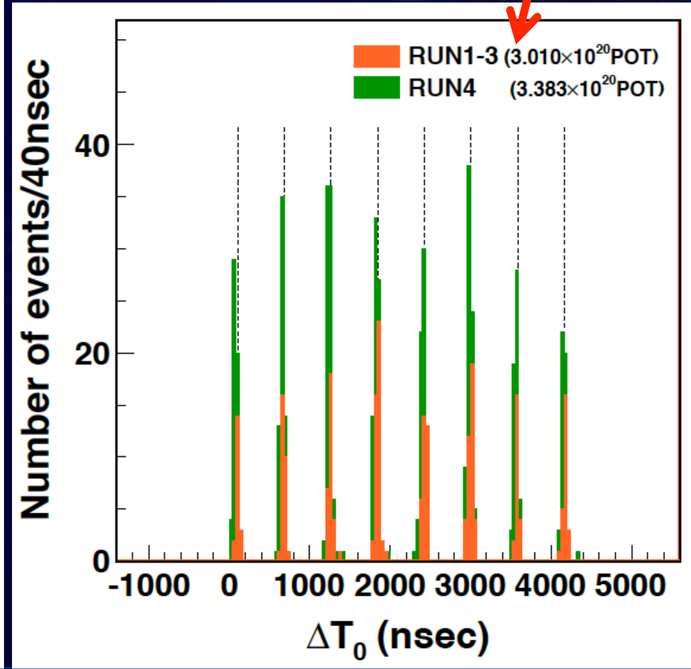
- POT normalized ν event rate is very stable (<1%)
- Beam direction is controlled well within the design requirement of 1 mrad (→ 2% shift in the peak energy of ν spectrum)

T2K Data Taking at SuperK

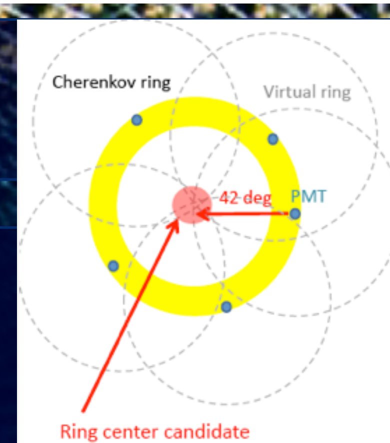
- Very smooth data taking
  - Data taking efficiency ~ 99%

Well defined beam bunch structure

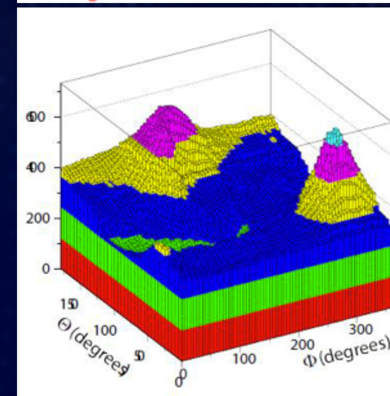


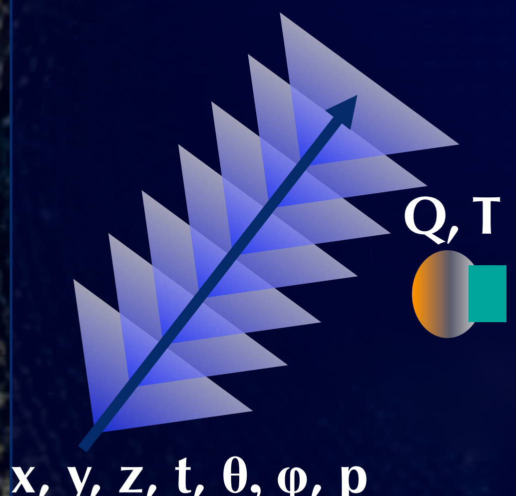


APFIT and fiTQun



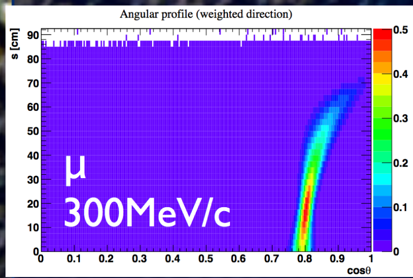
- APFIT: sequential algorithm to reconstruct general event topologies at SK
  - Time-based vertex fit
  - Hough transform to identify Cherenkov rings
    - Select signal CCQE events with 1 ring
    - Reconstruct ring direction/energy with forward hits
    - e/μ particle identification with ring sharpness
  - POLFIT: dedicated 2-ring fit to identify π^0 events

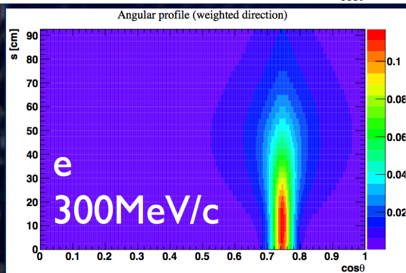




- fiTQun: new likelihood-based algorithm
- predictive model estimates Q/T at each PMT with 7 track parameters for each hypothesis (e/μ/π/p)
- Simultaneously extract parameters with likelihood fit to observed Q/T at each PMT
- Multi-ring hypothesis built by superposing contribution from individual rings

fiTQun PID and π^0 Reconstruction

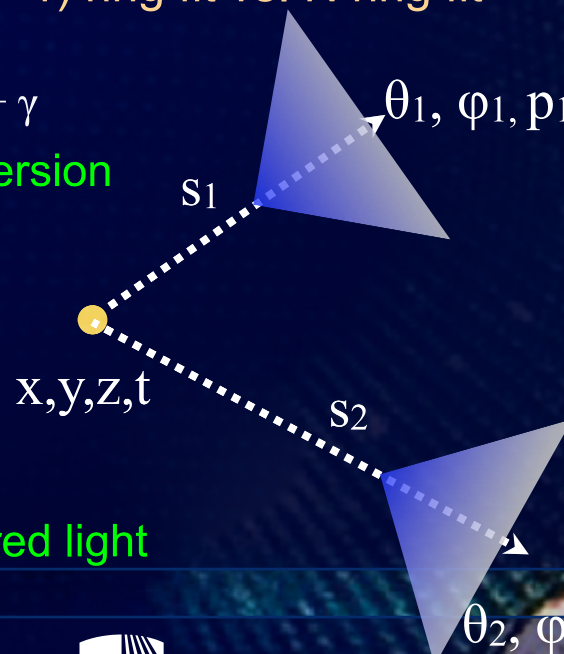




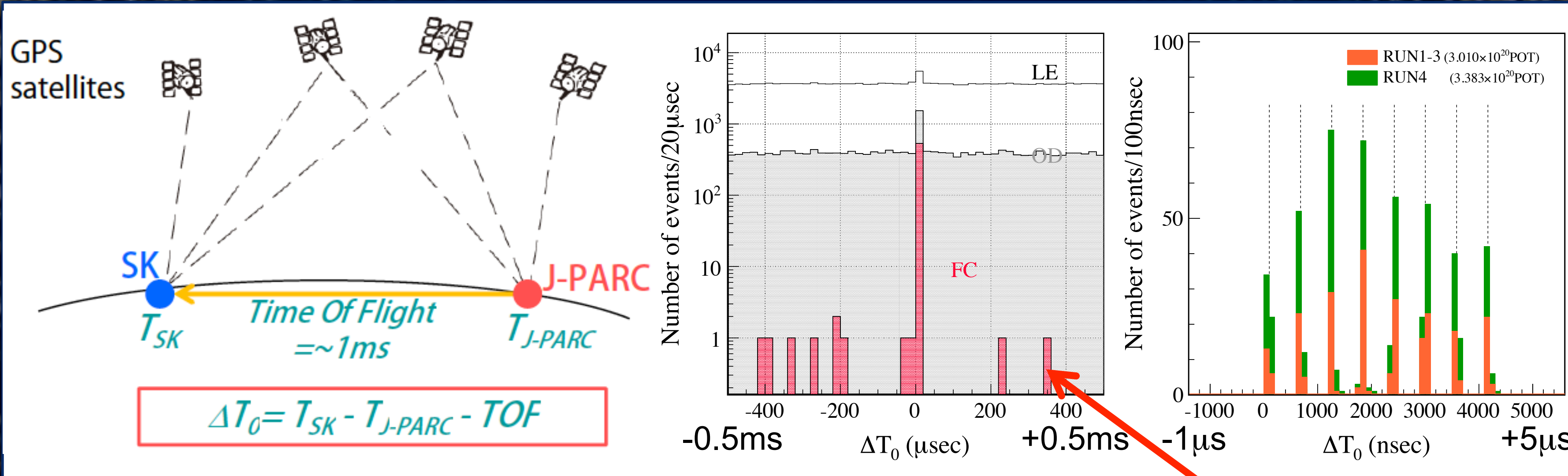
- Fitted likelihoods allow hypothesis tests
- Particle identification:
  - expected light profile from each hypothesis encoded in assumed Cherenkov profile
  - e/*μ*/π/p identification by comparing fit likelihood from each hypothesis
- Ring counting:
  - compare likelihood of (N+1) ring fit vs. N ring fit

- fiTQun π^0 fit
  - Reconstruct by identifying two rings from $\pi^0 \rightarrow \gamma + \gamma$
    - 12 parameter fit hypothesis includes two conversion lengths (s_1, s_2)
  - Previous algorithm:
    - 3 free parameter (2nd ring energy fraction and direction)

      other parameters fixed from single ring fit
    - charge-only fit with simplified model for scattered light



Far Detector ν_e Candidate Event Selection: (1) Beam Timing & FC



- Clear beam bunch timing of J-PARC beam observed (GPS sync)
- 532 FC in-time events detected
  - 0.7 expected background events

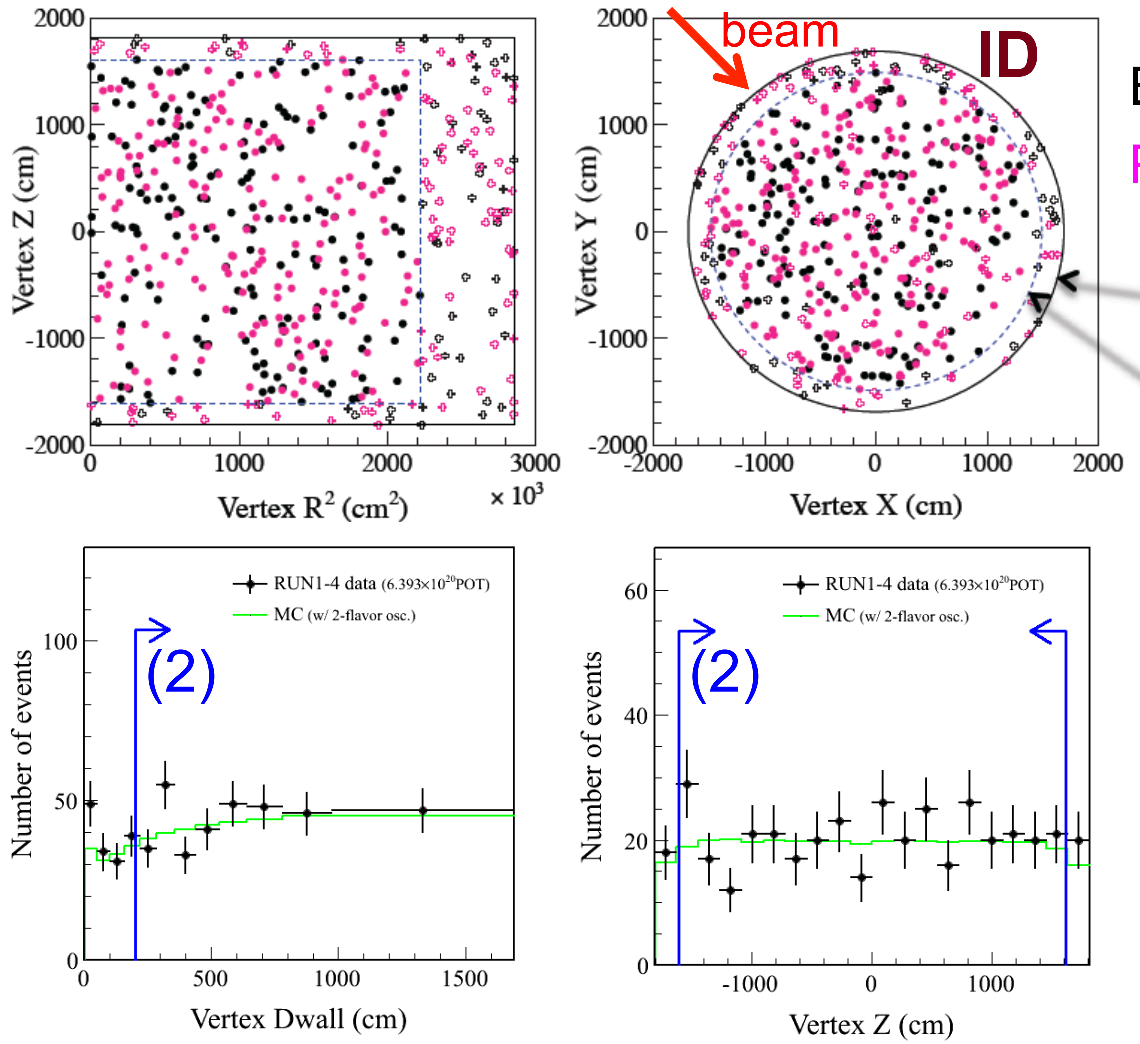
Off-Timing FC

Observed : 11

Expected BG: 5.8

p-value (>11) : 3.5%

Far Detector ν_e Candidate Event Selection: (2) Within FV



Black dots: Run 1-3

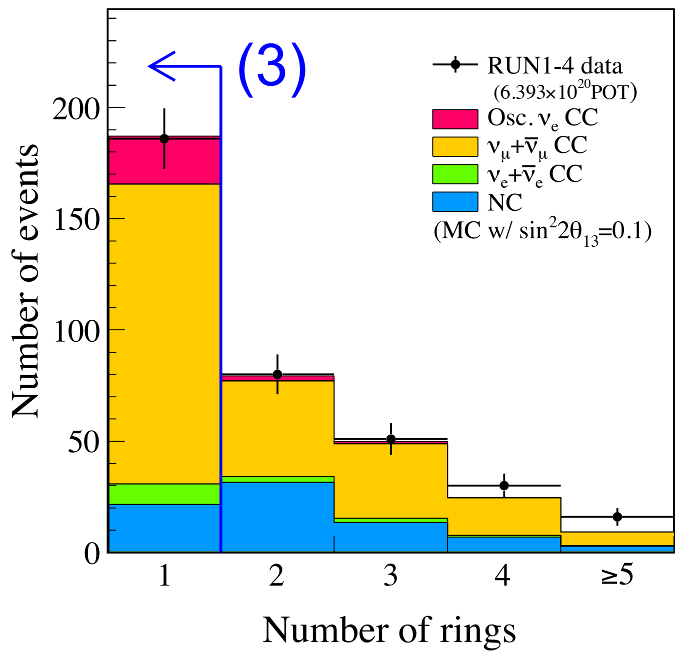
Pink dots: Run 4

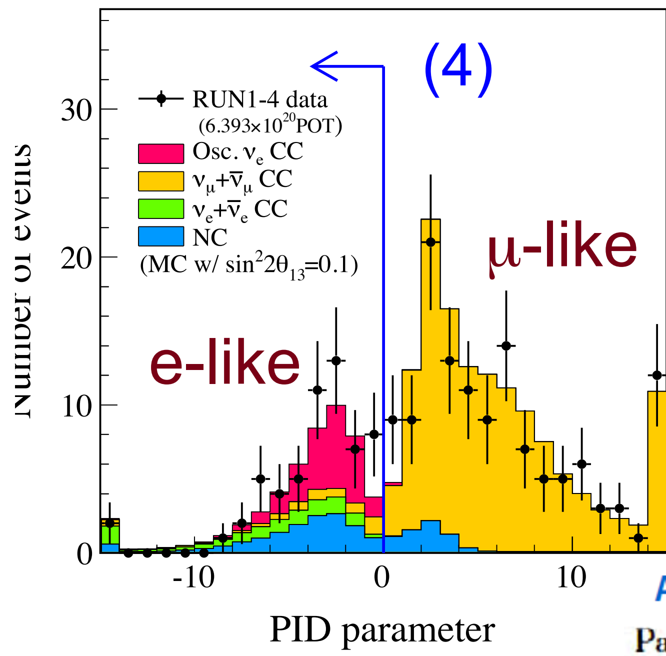
Inner detector wall

FV boundary (2m from wall)

- (532 →) 363 FCFV events detected
  - 0.008 expected background events
  - Reduce event reconstruction systematic errors

Far Detector ν_e Candidate Event Selection: (3) Single Ring & (4) Electron-like PID





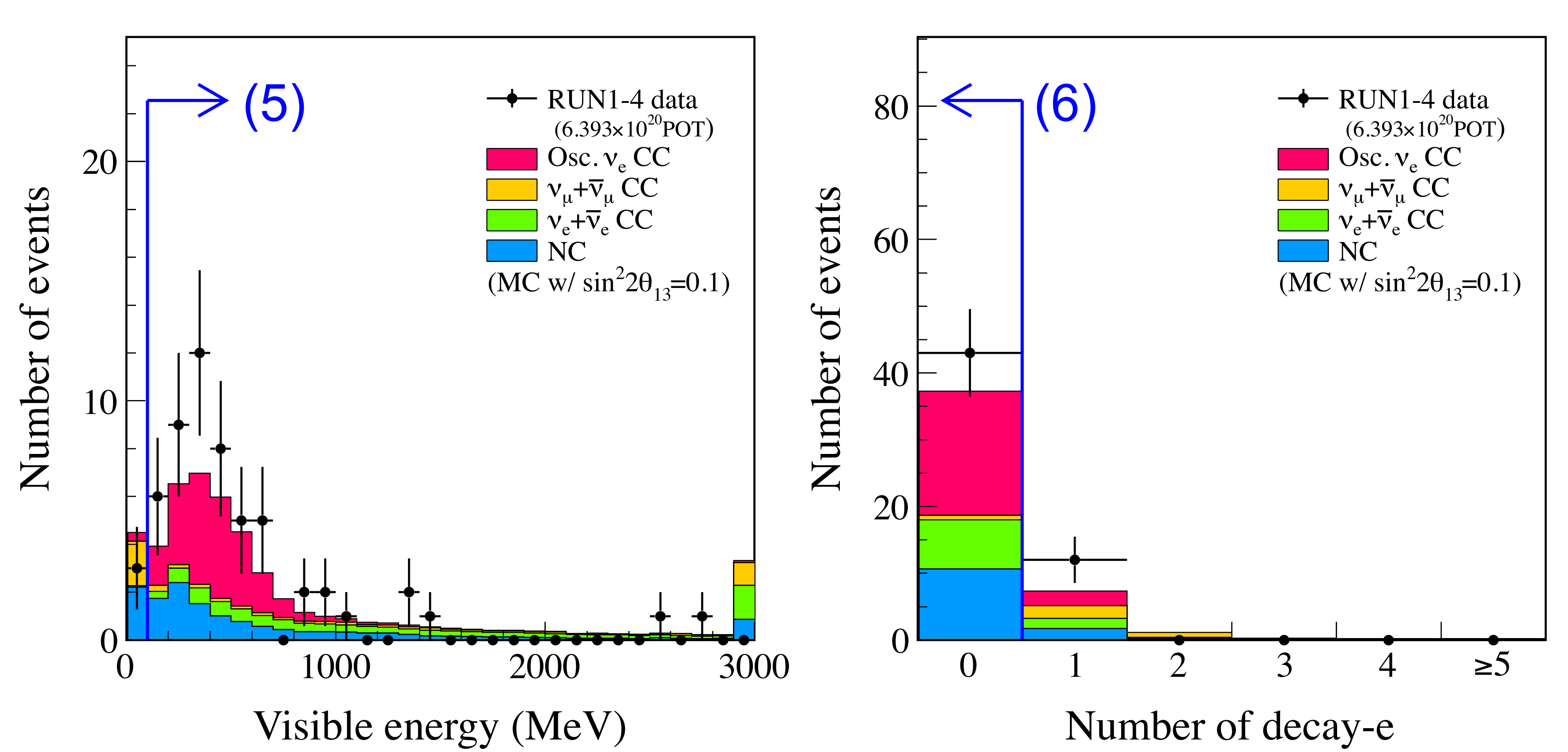
MC distributions w/ $\sin^2 2\theta_{13}$=0.1 is not a fit. It is just for a reference.

Assumed Parameter Values

Parameter	Value
Δm^2_{21}	7.6×10^{-5}eV^2
Δm^2_{32}	2.4×10^{-3}eV^2
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	2.6g/cm^3

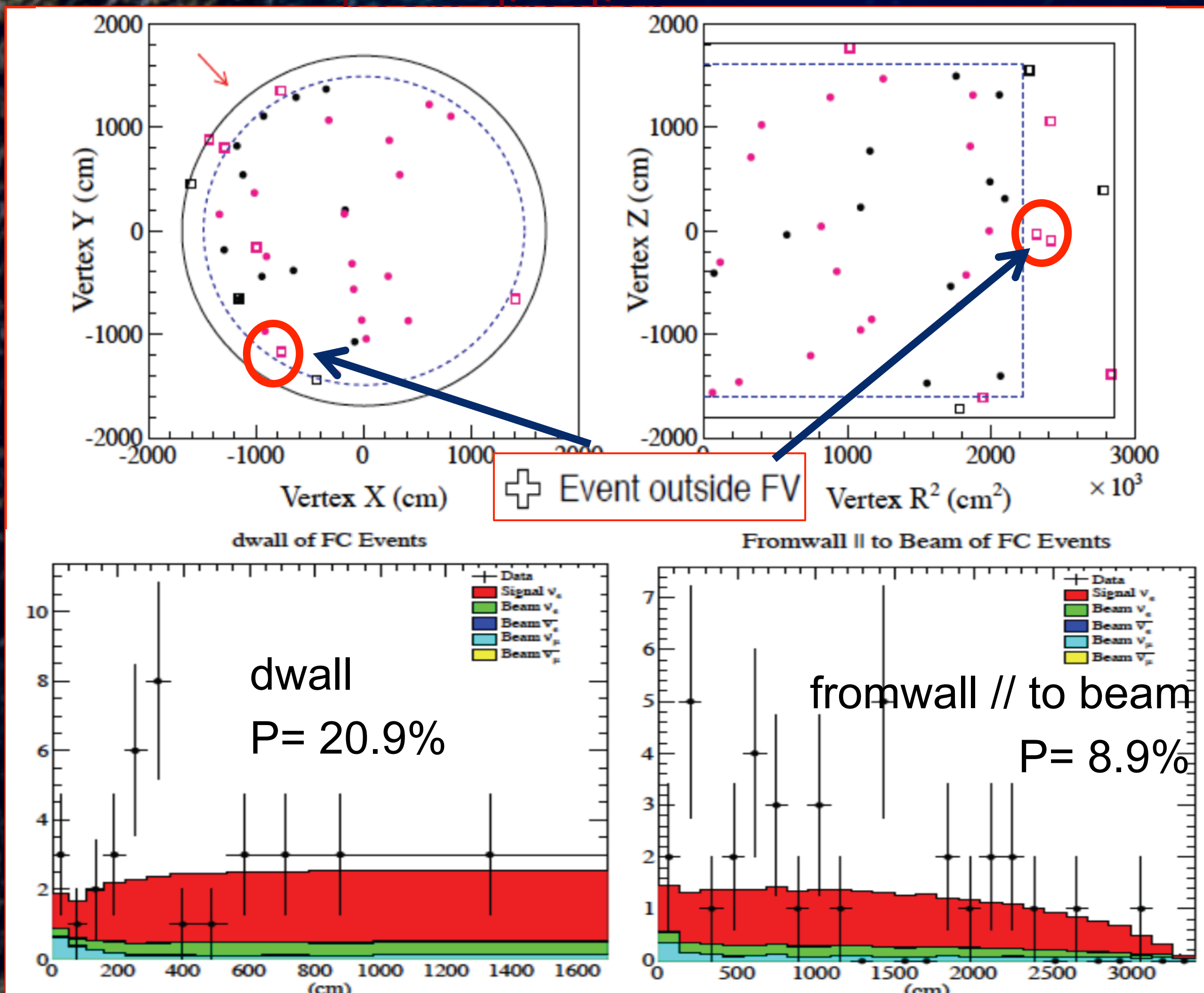
- (363 →) 186 single ring events
  → 58 single ring e-like events
  - Enhance ν_e CCQE events

Far Detector ν_e Candidate Event Selection: (5) Visible E>100 MeV & (6) No Decay Electron



- (58 →) 55 events
  - Suppress NC background and decay electrons
- (55 →) 43 events
  - Suppress invisible π or μ

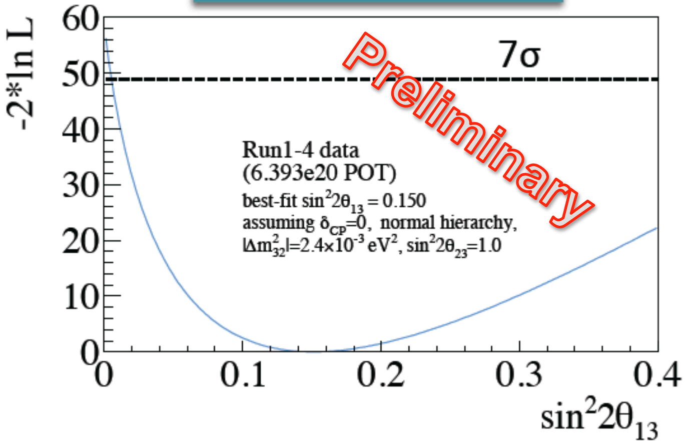
Vertex Distribution of the Final ν_e Sample



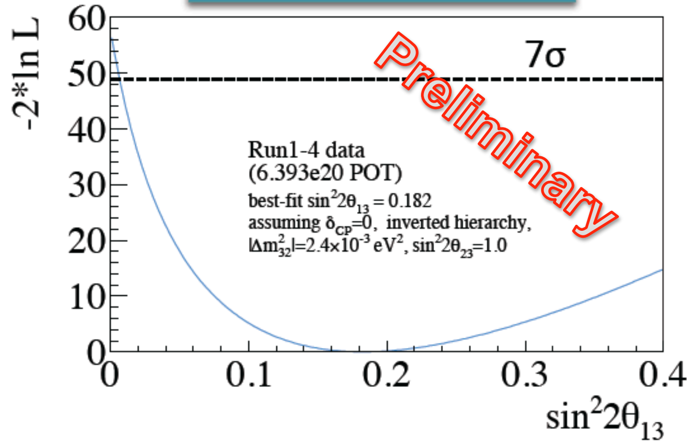
- Entering BG events from interactions in OD is estimated to be:
  - 0.03±0.009 events
  - O(0.1%) of FCFV ν_e candidates

Data Fit Results: Method 1 (p-θ)

Normal Hierarchy



Inverted Hierarchy



Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$

$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$ Best-fit values w/ 68% confidence intervals $0.182^{+0.046}_{-0.040}$

Parameter	Value
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$
Δm^2_{32}	$2.4 \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1 (or 0)
δ_{CP}	0

Assumed Parameter Values

- θ_{13}= 0 is excluded at 7.5σ level of significance

➔ Observation of ν_e appearance from a ν_μ beam!

Effect of θ_{23} Uncertainty

$$P_{\nu_\mu \rightarrow \nu_e} \approx \boxed{\sin^2\theta_{23}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

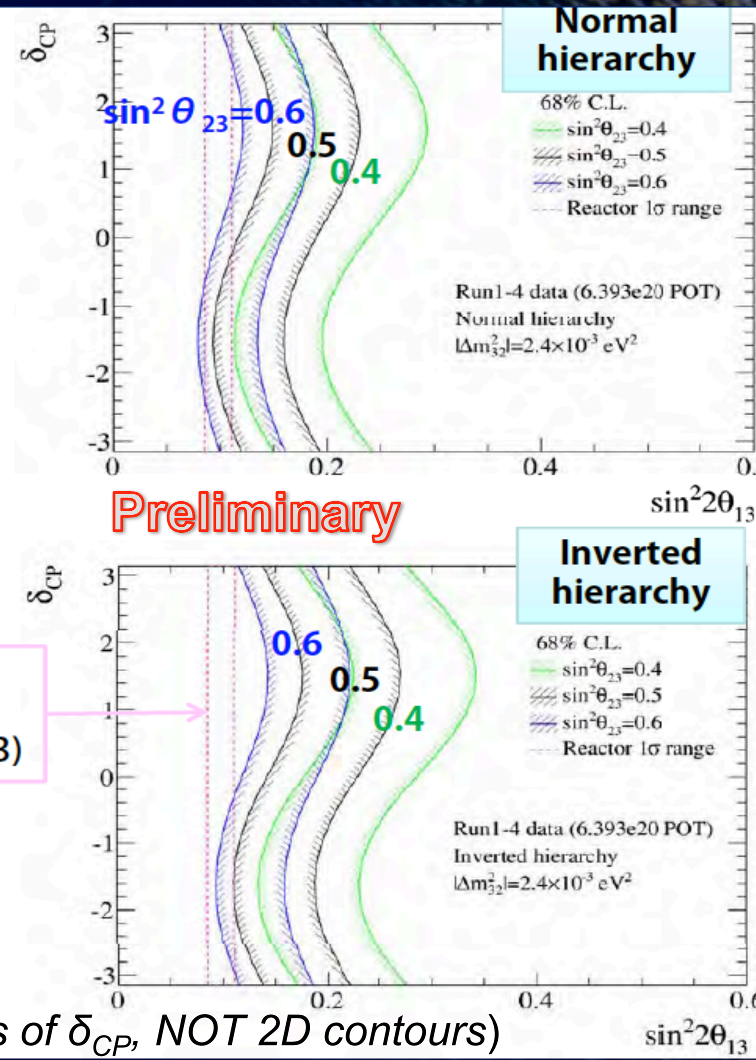
- Oscillation probability depends on $\sin^2\theta_{23}$ (octant)

  PDG2012: $\sin^2(2\theta_{23}) > 0.95$
  - $\sin^2\theta_{23} \sim 0.50 \pm 0.11$
  - $\theta_{23} \sim 45 \pm 6.5°$

  Reducing uncertainty on $\sin^2\theta_{23}$ is critical for further improvements

PDG2012 reactor average value (0.098±0.013)

T2K's ν_μ disappearance study will play a leading role.



(NOTE: These are 1D contours for various values of δ_{CP}, NOT 2D contours)