T2K実験

南野彰宏（京大）
他 T2Kコラボレーション

平成26年度宇宙線研究所共同利用成果発表会
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Outline

- Physics
- Introduction
- Experimental setup
- Analysis
- Results
- Future sensitivity

Neutrino oscillation in long-baseline accelerator experiment

- High purity ν_μ beam is produced by proton accelerator.
- Use the near detector measurement to predict the spectrum at the far detector without oscillations.

- **ν_e appearance** : sensitive to θ_{13}, δ_{CP}, Mass Hierarchy

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 + \frac{4\sqrt{2} G_F n_e E}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right)$$
$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

CP violation

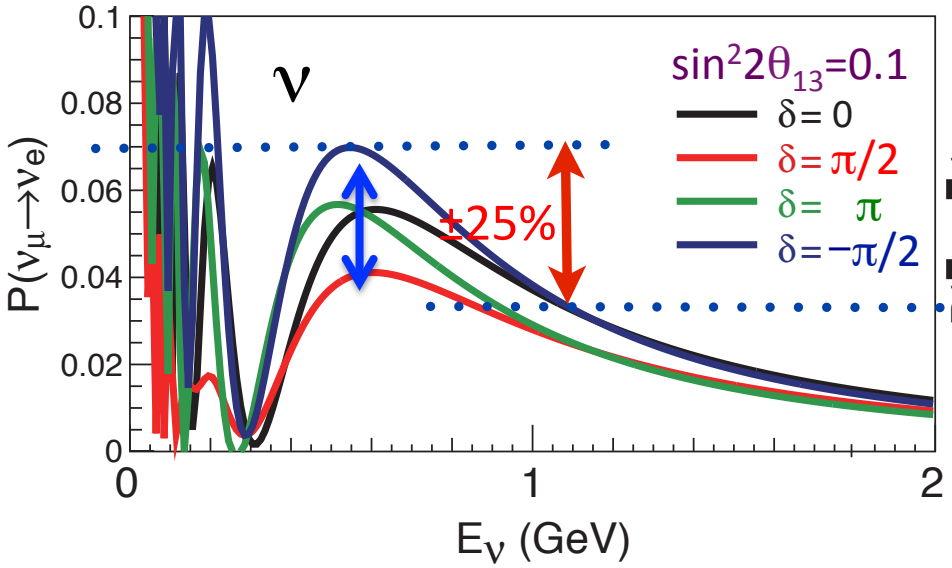
Mass Hierarchy

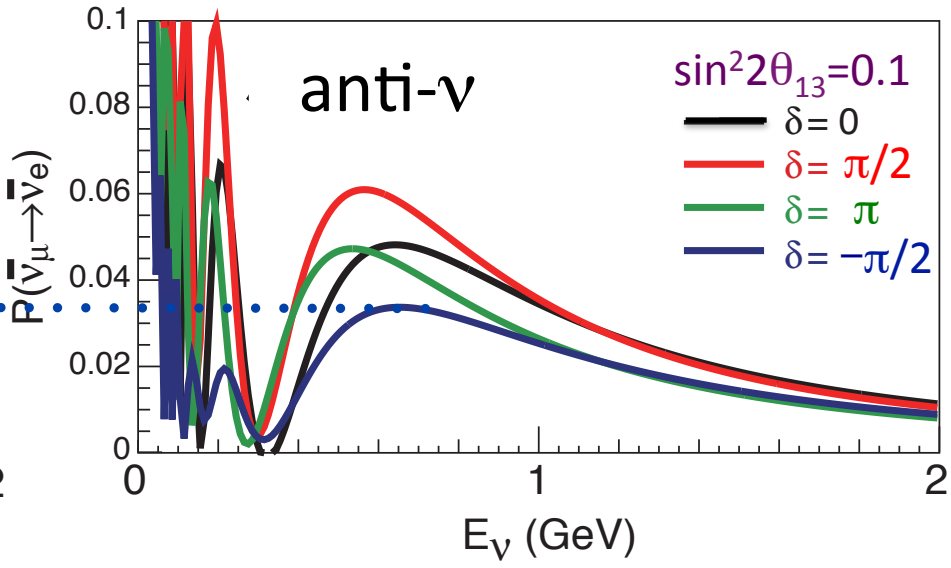
- **ν_μ disappearance**: sensitive to θ_{23} & Δm^2_{32}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4\theta_{13} \sin^2 2\theta_{23} + \sin^2\theta_{23} \sin^2 2\theta_{13}\right) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

CP violation phase, δ_{CP}

- ν_e appearance probability: sensitive to CP phase

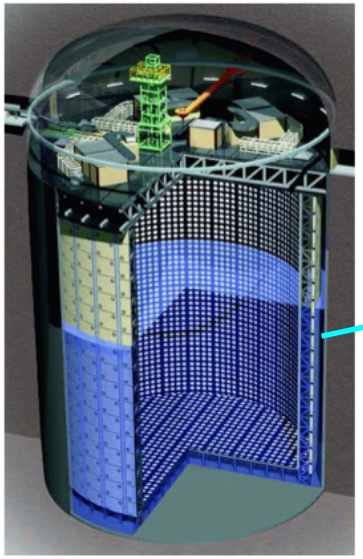


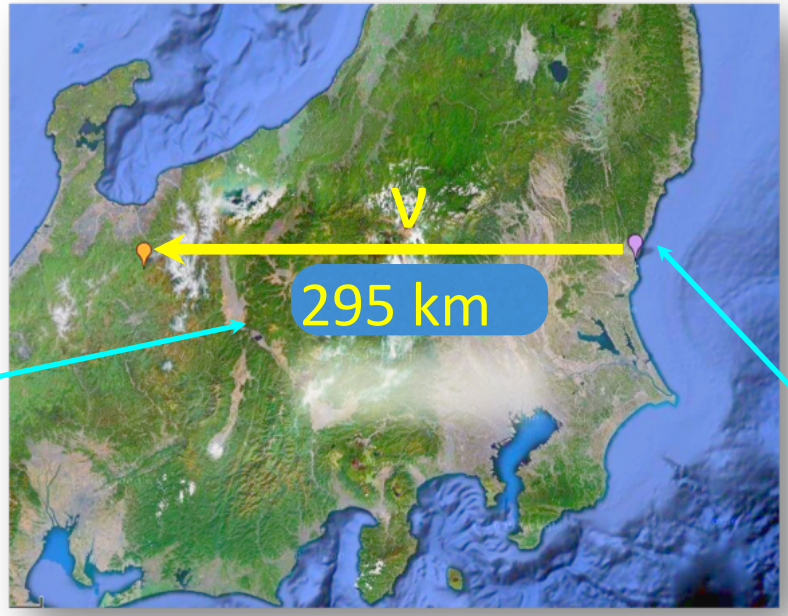


- **Comparison of ν/anti-ν mode enhances sensitivity to δ_{CP}.**
  (T2K is currently taking data with anti-ν mode in 2014.)
- **Short baseline length O(100) km**
  - small matter effect
  - Dominant contribution from δ_{CP}.

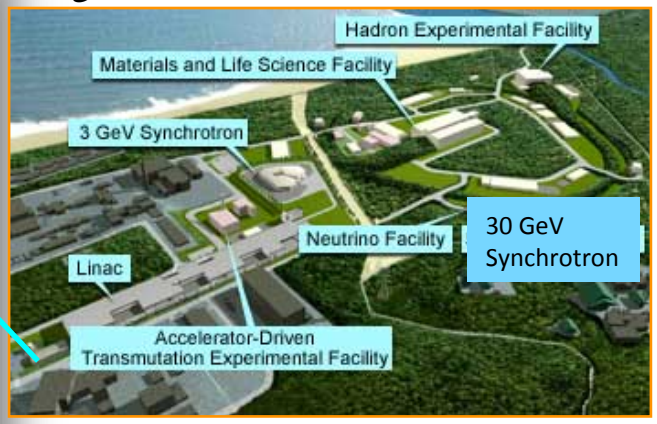
The T2K Experiment

Super-Kamiokande





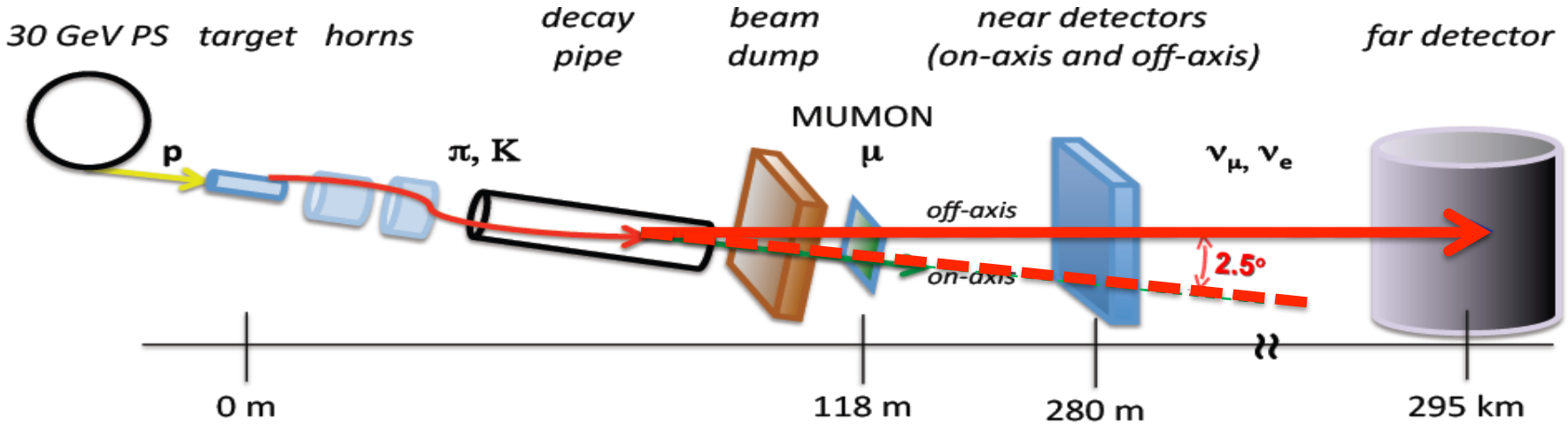
J-PARC Accelerator



- Searches for neutrino oscillations in an intense **high purity ν_μ beam**
  - Intrinsic beam ν_e from μ, K decays ~1%
- The neutrinos travel 295 km to the Super-K detector
  - ν_e appearance (sensitive to θ_{13} & δ_{CP})
  - ν_μ disappearance (sensitive to θ_{23} & Δm^2_{32})

T2K Collaboration

T2K neutrino beam

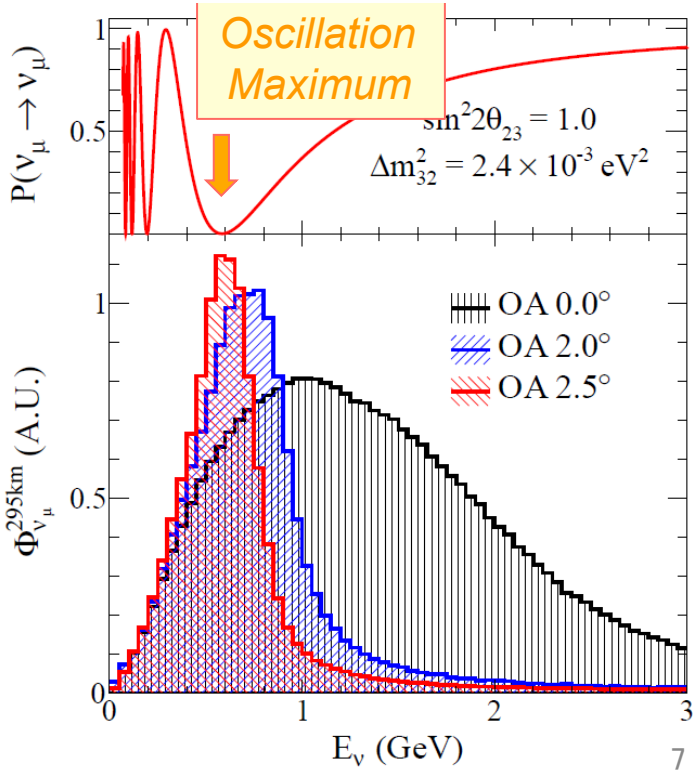


High intensity beam

- 30GeV, ~10^{14} protons/spill.
- Pure ν_μ beam from π, K decay (~99%)

Off-Axis (2.5°) ν_μ beam

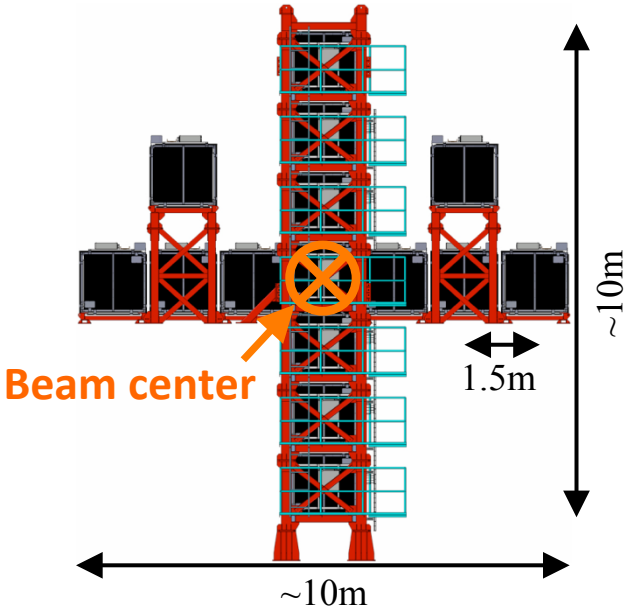
- Intense, low energy narrow-band beam.
  - E_ν peak at oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail.
- Small ν_e fraction (~1%).



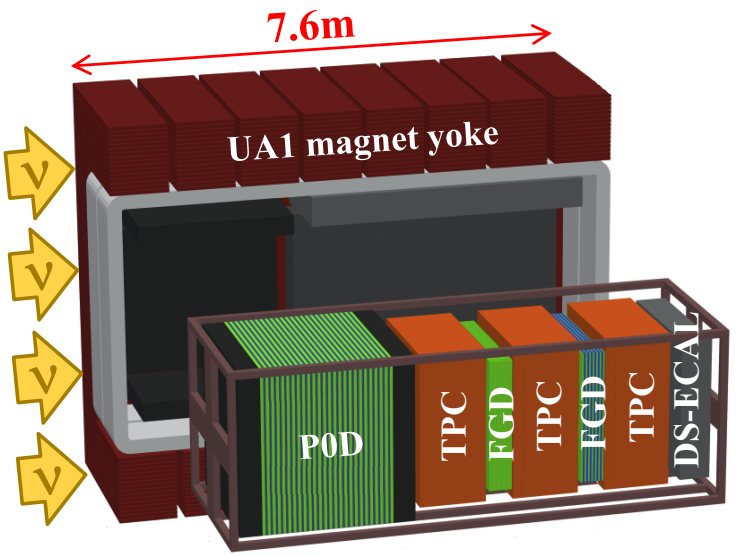
Near detectors

- Located 280 m downstream of the target
- Measure unoscillated neutrinos

INGRID @ on-axis (0°)



ND280 @ 2.5° off-axis

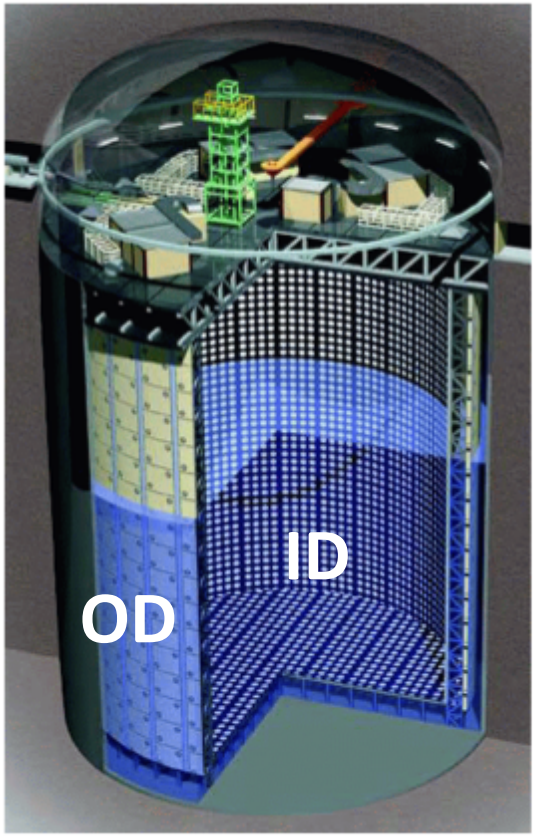


- 16 identical modules (14 in cross)
- Iron/scintillator layers
- Monitor n beam profile/rate

- Tracker (FGDs*1+TPCs*2) in a 0.2 T magnet
- Principal n target is plastic scinti. in FGDs
- Measures n flux/spectrum

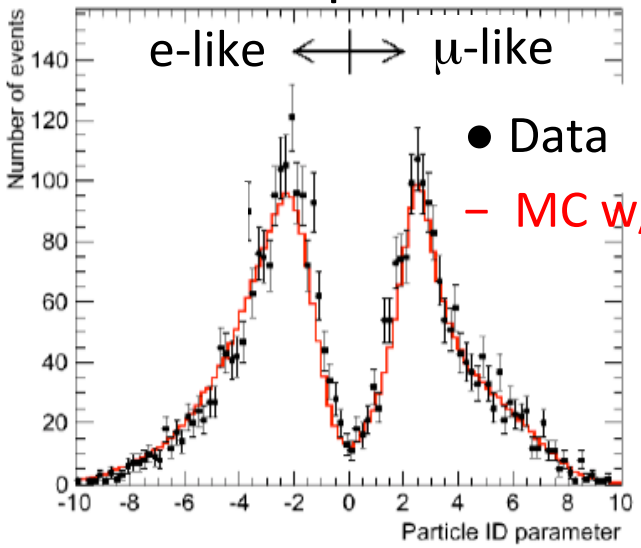
*1 FGD: Fine-Grained Detector, *2 TPC: Time Projection Chamber

Super-K (Far) detector

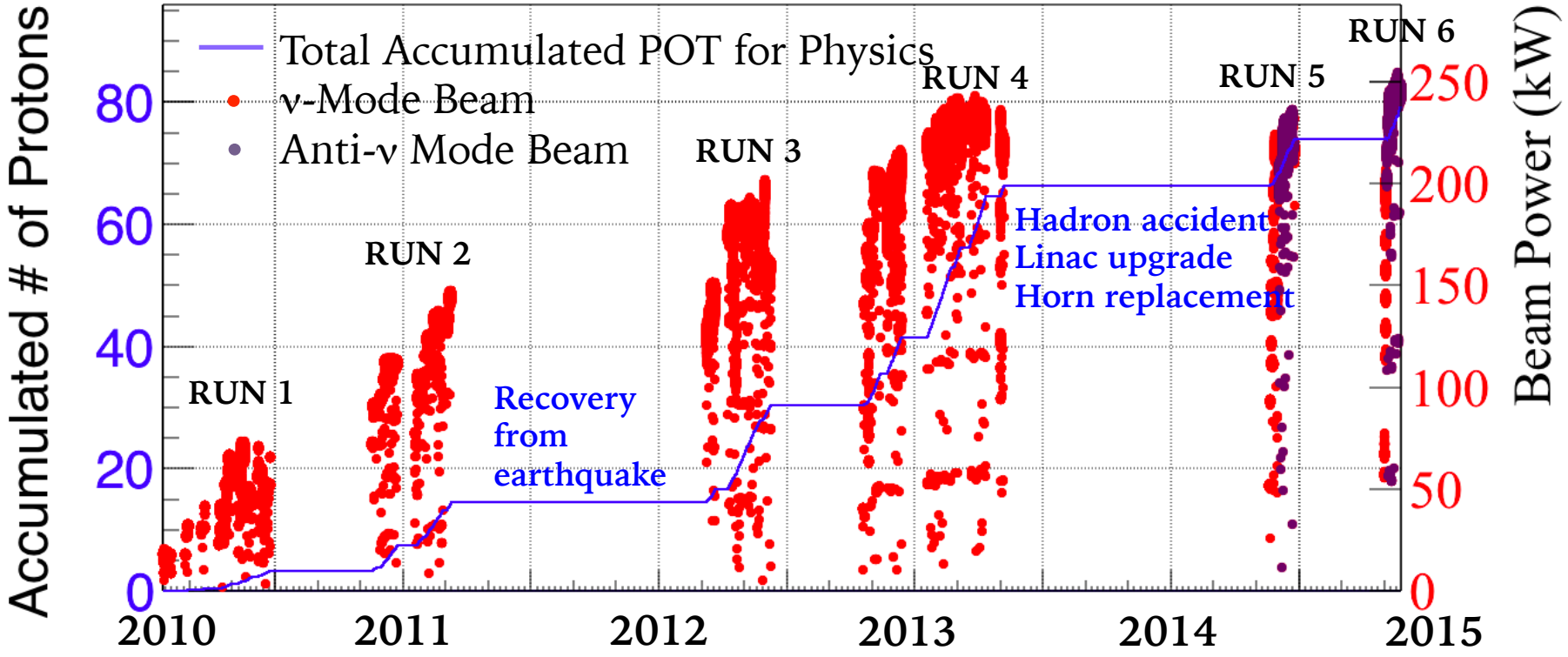


- 50 kton Water Cherenkov detector
  - 22.5 kton Fiducial volume
- Good performance for sub-GeV neutrinos
  - Good e/μ separation from ring shape topology
- T2K recorded events
  - All interactions in ±500μsec around ν arrival time

Atmospheric ν

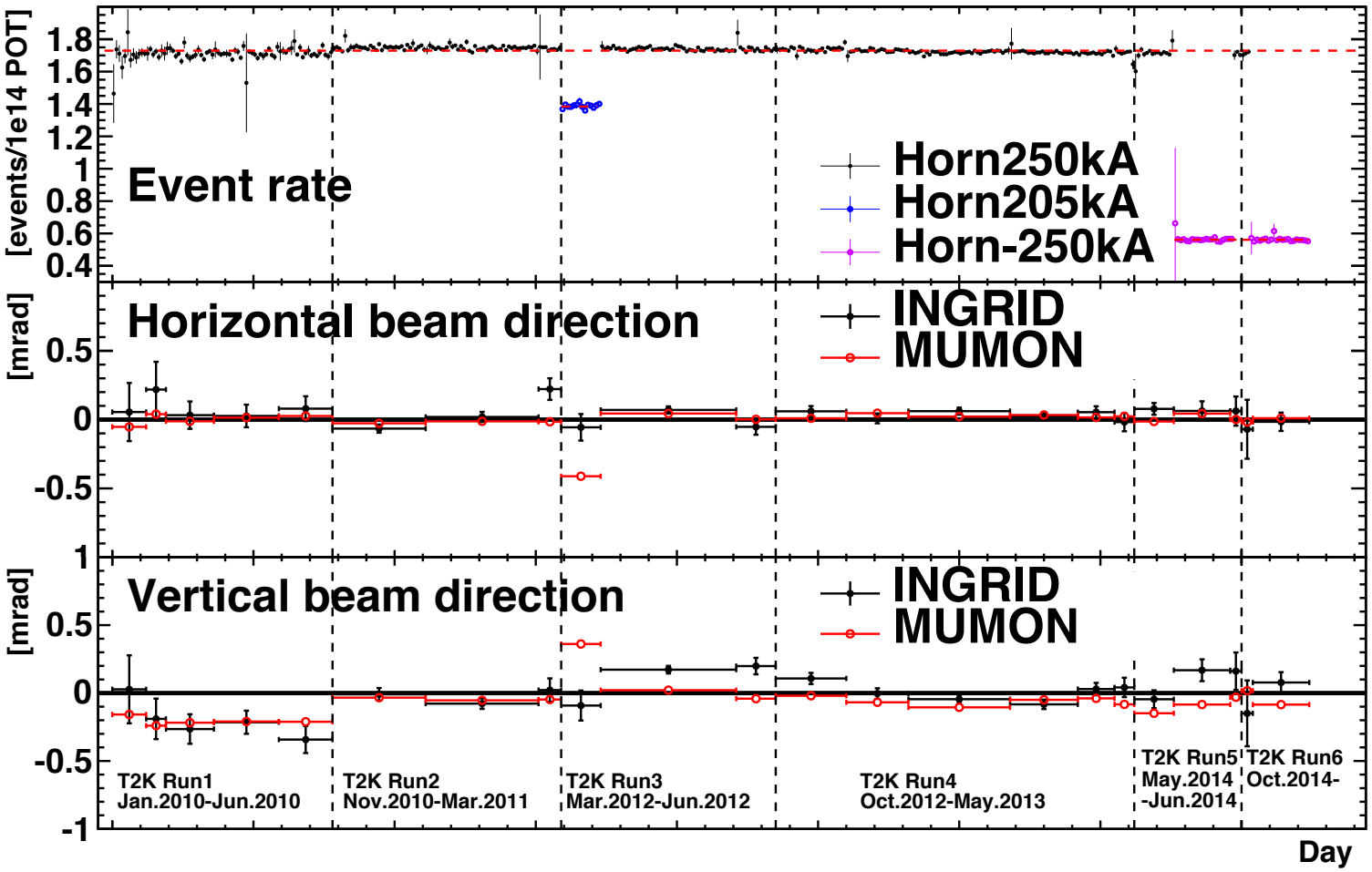


Data set (until Nov. 24, 2014)



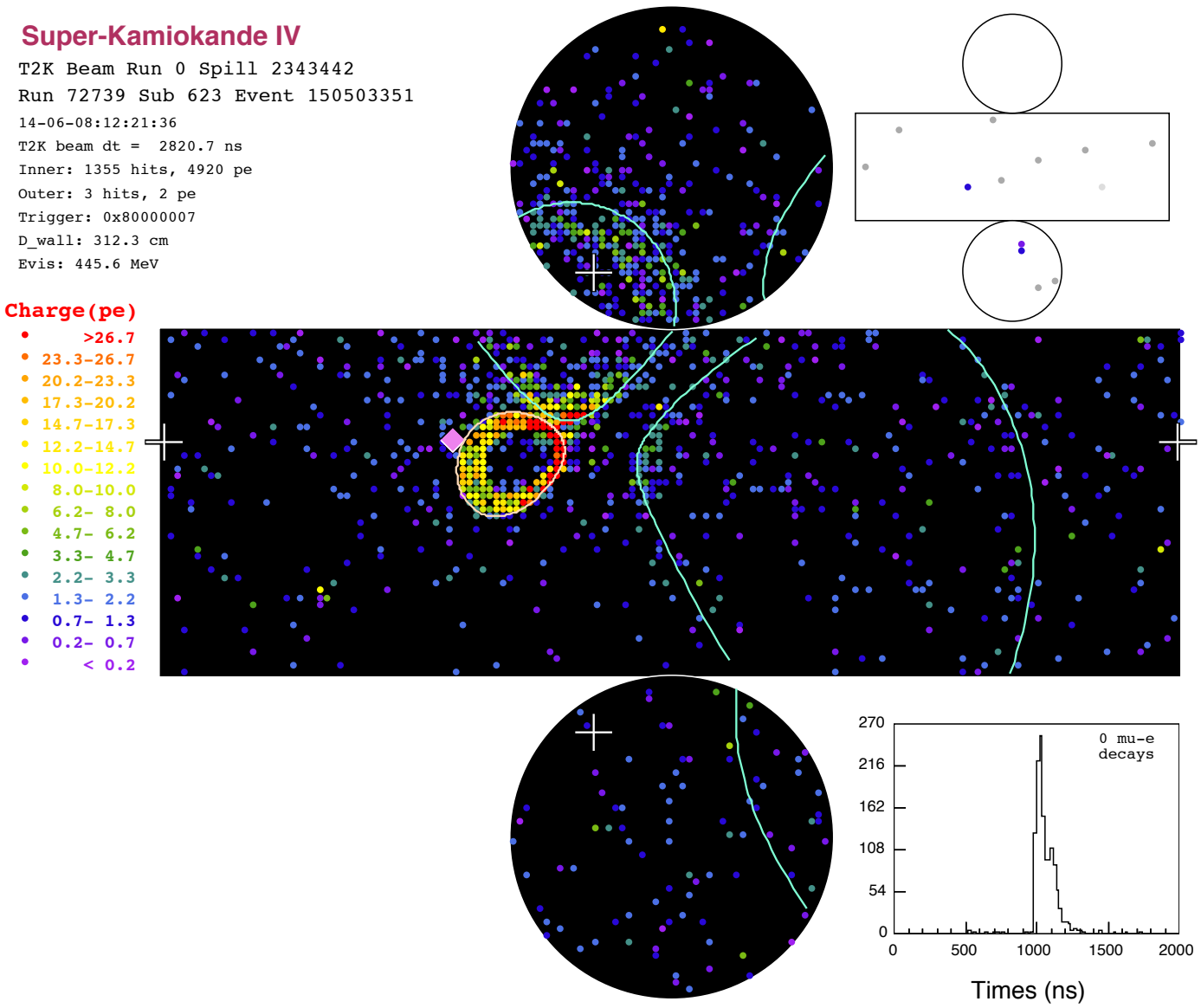
- 250 kW stable operation achieved in T2K RUN 6.
- Total delivered Proton on Target (POT): 7.9×10^{20}
  - ~10% of T2K full POT, 7.8×10^{21}
  - $6.8 \times 10^{20} / 1.1 \times 10^{20}$ POT for ν/anti-ν mode.
- Data set in T2K RUN 1-4 are used for oscillation analyses
  - 6.57×10^{20} POT for ν mode

Beam stability



- Event rate is stable over ν/anti-ν mode periods.
- Beam direction is stable < 1mrad over ν/anti-ν mode periods.

First ν event at SK in anti-ν run



What's new

- ν_μ disappearance analysis
  - Results using a data set of 6.57×10^{20} POT
- Joint ν_e + ν_μ analysis
  - Results using a data set of 6.57×10^{20} POT
  - Constraint on the CP violating phase δ_{CP} by combining our ν_e appearance/ν_μ disappearance results with θ_{13} measurements by reactor experiments
- T2K future sensitivity study
  - Resolving $\sin\delta_{CP}\neq0$
  - Determining Mass Hierarchy

Oscillation analysis principle

ν flux prediction

- Hadron production (NA61@CERN,…)
- Systematics
  - Hadron production
  - Proton/ν beam monitoring

ν cross section

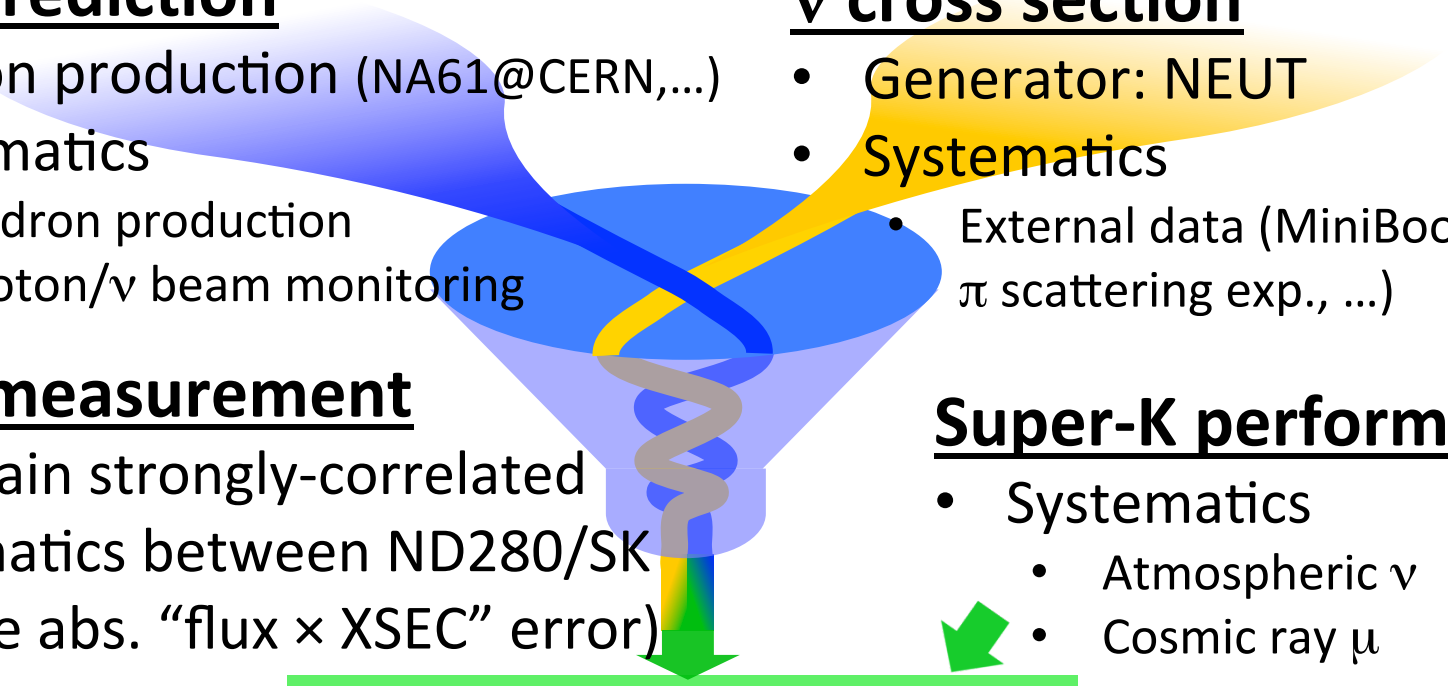
- Generator: NEUT
- Systematics
  - External data (MiniBooNE, π scattering exp., …)

ND280 measurement

- Constrain strongly-correlated systematics between ND280/SK (Reduce abs. "flux × XSEC" error)

Super-K performance

- Systematics
  - Atmospheric ν
  - Cosmic ray μ

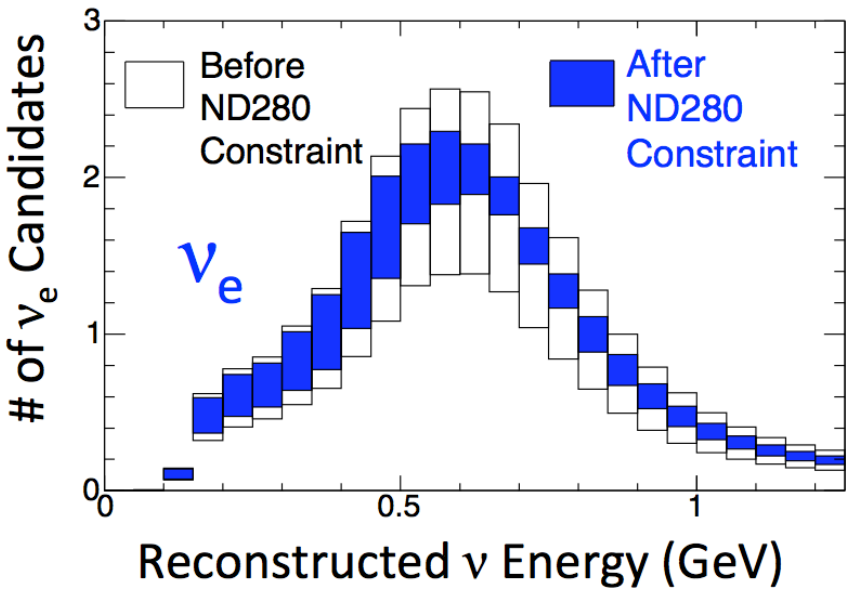


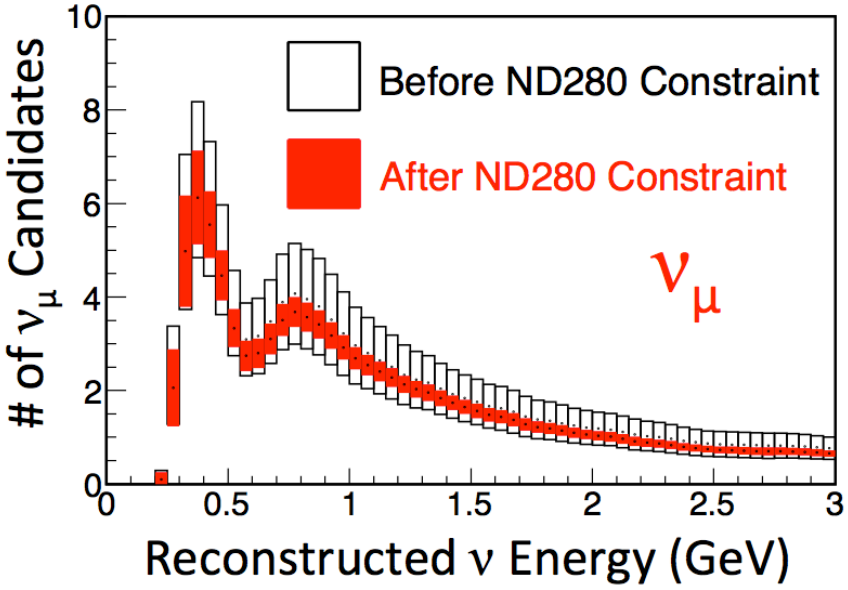
Super-K prediction
with systematics

Compare

Super-K measurement

Systematic Uncertainties





Systematic uncertainties to # of events at Super-K

		ν_μ sample	ν_e sample
ν flux and cross section	w/o ND measurement	21.8%	26.0%
	w/ ND measurement	2.7%	3.1%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%
Final or Secondary Hadronic Interaction		3.0%	2.4%
Super-K detector		4.0%	2.7%
total	w/o ND measurement	23.5%	26.8%
	w/ ND measurement	7.7%	6.8%

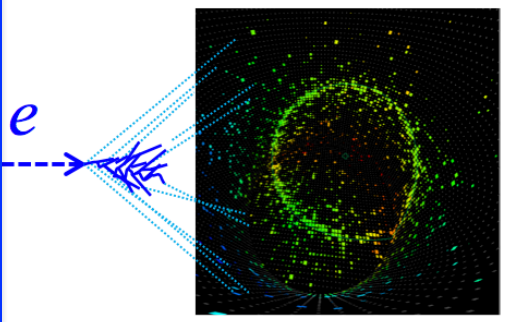
Near detector constraints strongly reduce the systematic uncertainties.

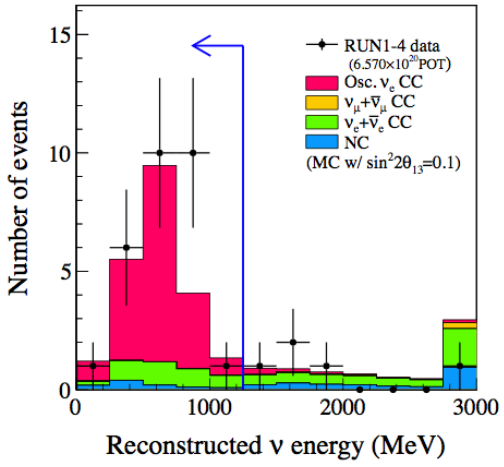
Systematic uncertainties < 10% already achieved.

SK event selection

Fully Contained | Fiducial Volume | 1-Ring

ν_e selection





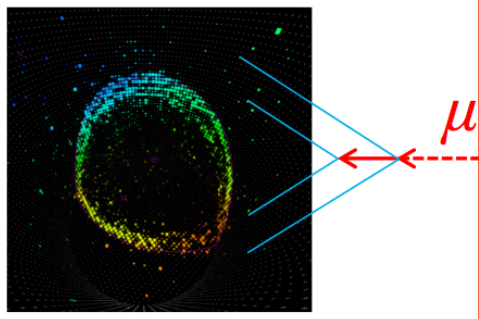
- PID: e-like
- p_e > 100 MeV/c
- No decay-e
- E_{rec} < 1250 MeV
- π_0 rejection

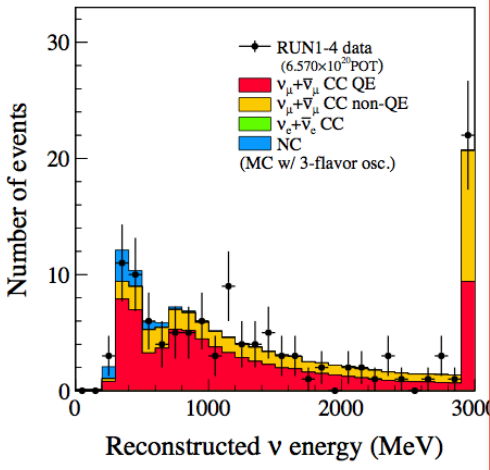
28 Events

4.9±0.6(sys.)
unoscillated

ν_μ selection

- PID: μ-like
- p_μ > 200 MeV/c
- Decay-e ≤ 1
- All E_{rec}





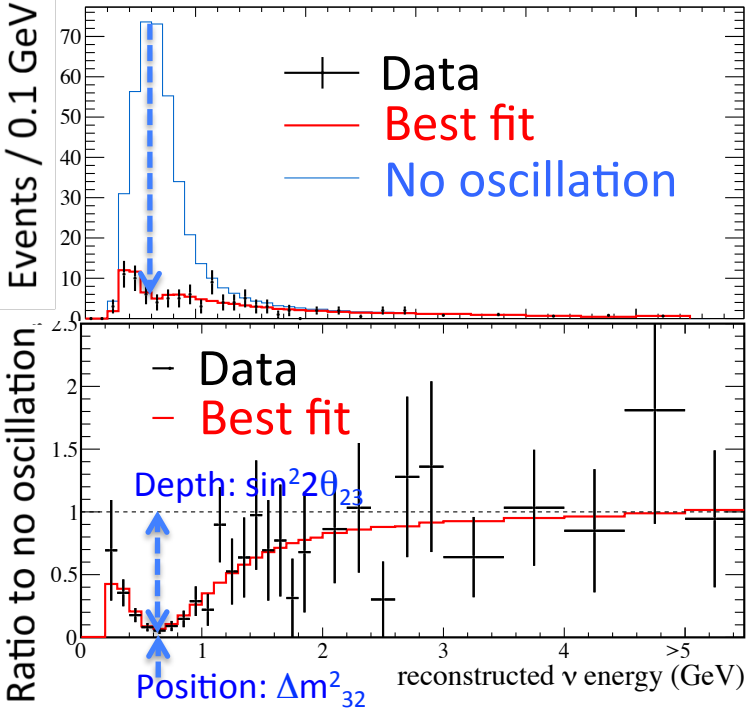
120 Events

446±23(sys.)
unoscillated

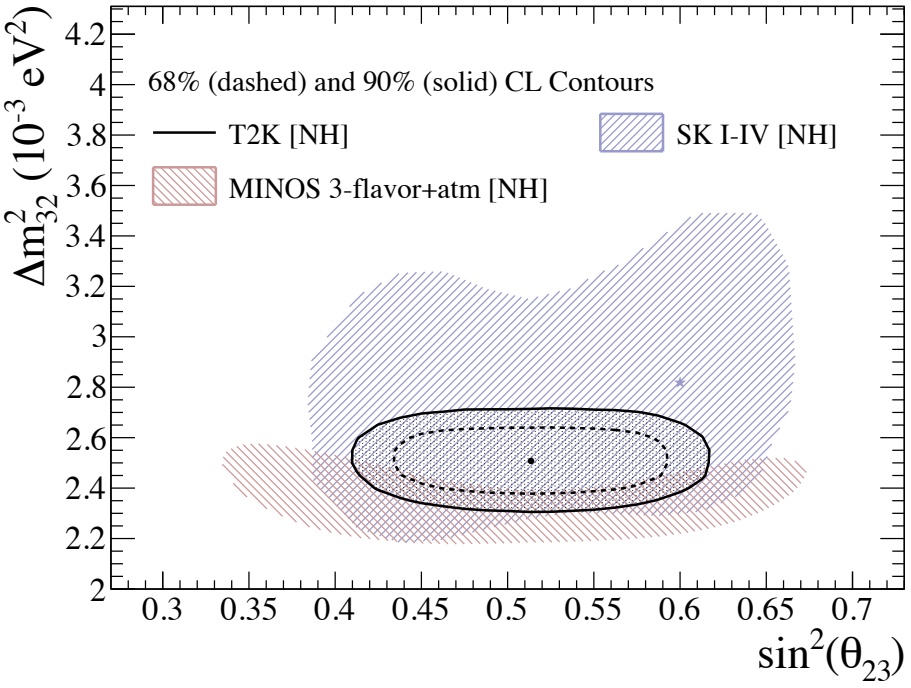
ν_μ disappearance analysis (6.57×10^{20} POT)

PRL 112 (2014) 181801

Best fit spectrum



Comparison w/ other experiments



Normal Hierarchy

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

$$\Delta m^2_{32} = 2.51 \pm 0.10\,\mathrm{eV}^2$$

Inverted Hierarchy

$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

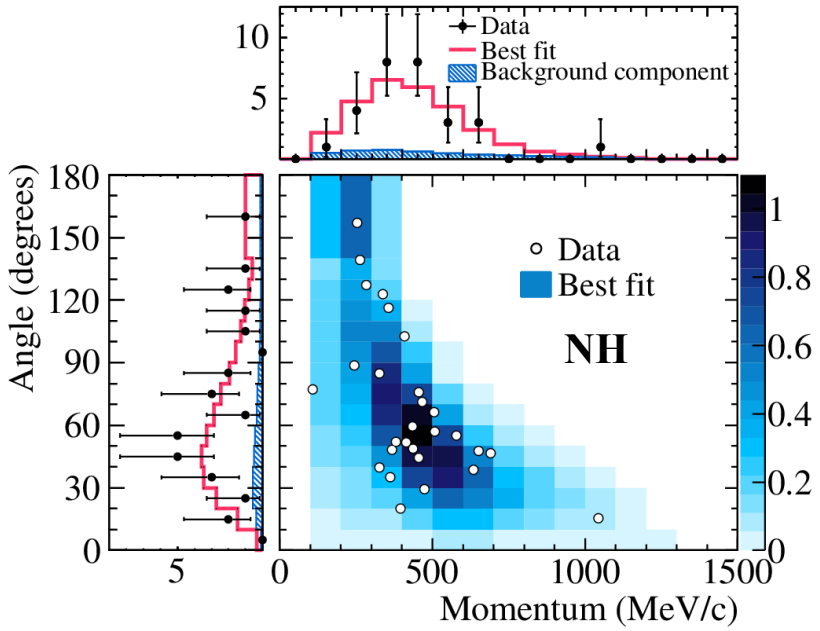
$$\Delta m^2_{13} = 2.48 \pm 0.10\,\mathrm{eV}^2$$

T2K measures θ_{23} with the world-leading precision!

ν_e appearance analysis (6.57×10^{20} POT)

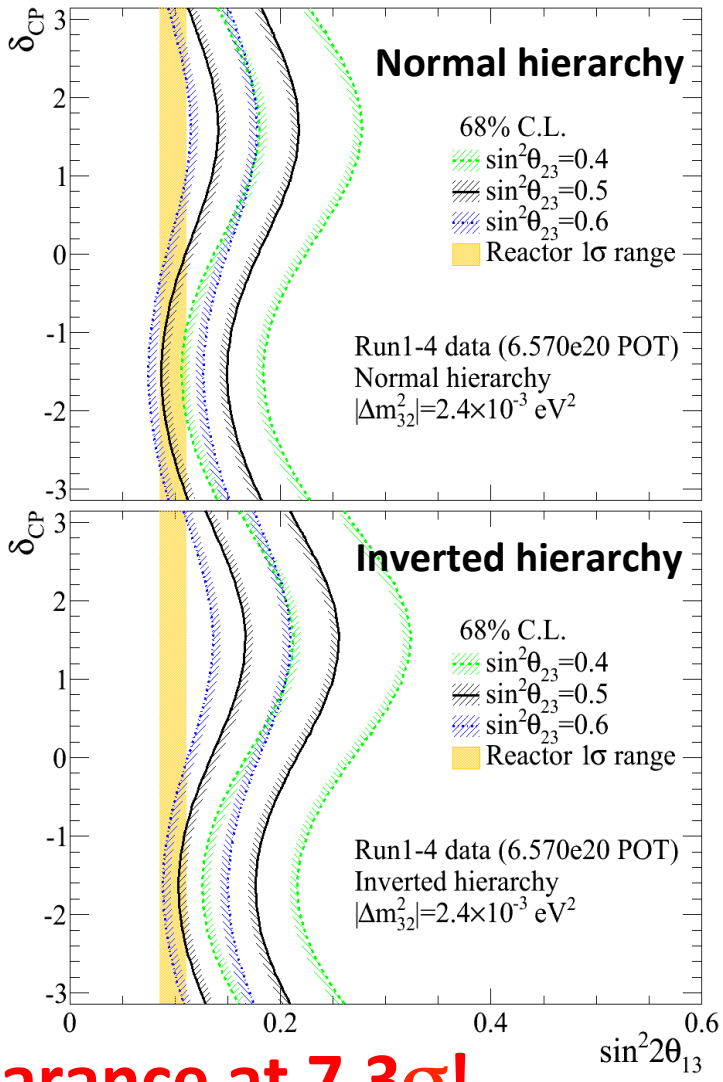
PRL 112, 061802 (2014)

Maximum likelihood fit in (p_e, θ_e)



$$\sin^2\theta_{13} = 0.140^{+0.038}_{-0.032} \quad (NH)$$
$$\sin^2\theta_{13} = 0.170^{+0.045}_{-0.037} \quad (IH)$$
$$68\%\ CL$$

$(\sin^2\theta_{23} = 0.5, |\Delta m^2_{23}| = 2.4\times10^{-3} eV^2, \delta_{CP} = 0)$



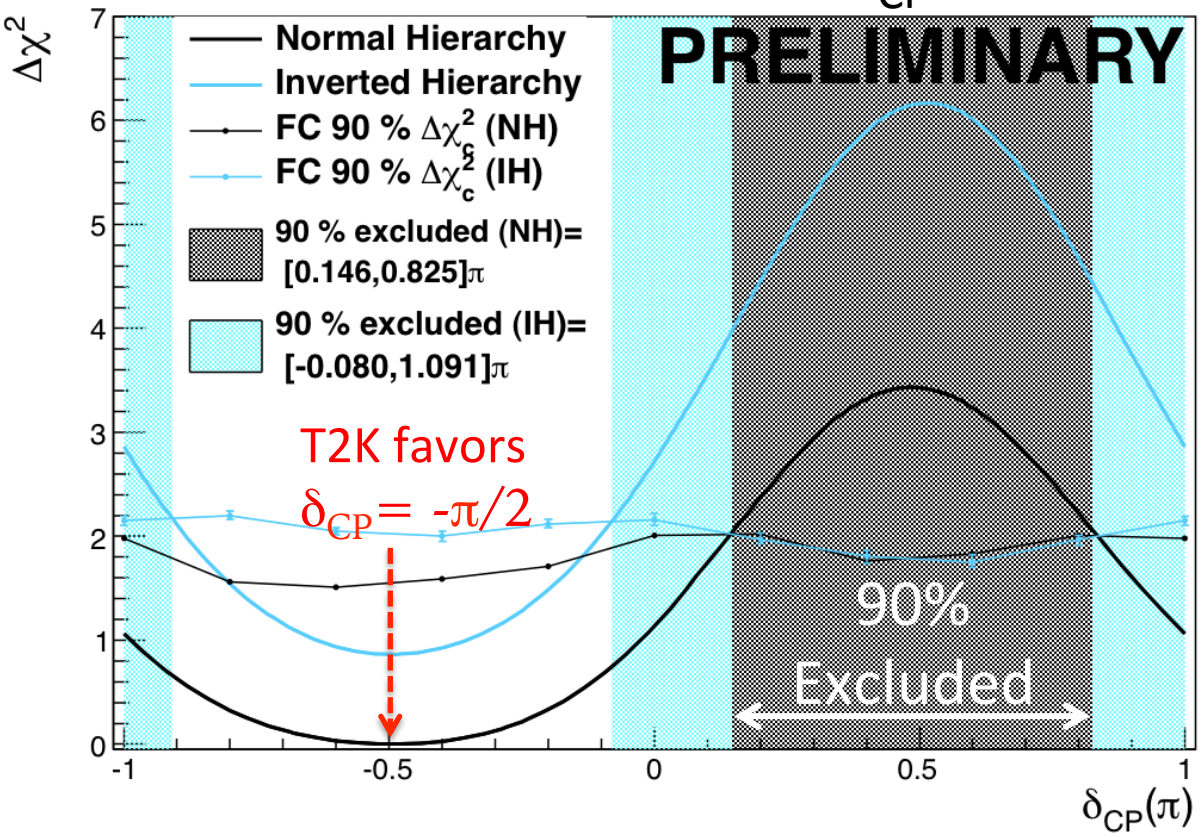
Discovery of ν_e appearance at 7.3σ!

θ_{23} dependence motivates a joint $\nu_e + \nu_\mu$ fit

Joint $\nu_e + \nu_\mu$ analysis (6.57×10^{20} POT)

- Simultaneous fit to ν_e and ν_μ data
  - 4 oscillation parameters Δm^2_{23}, θ_{23}, θ_{13}, δ_{CP}
- Reactor constraints (PDG2013): $\sin^2 2\theta_{13}=0.095\pm0.010$

Constraint on δ_{CP}

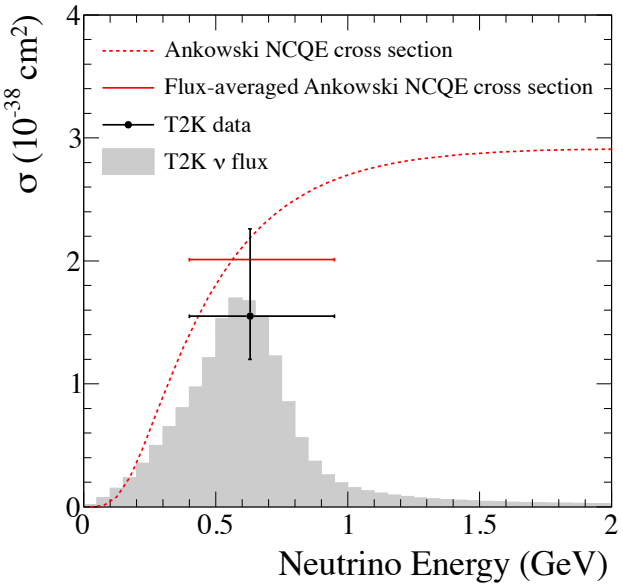


Other measurements

- T2K is not only measuring the oscillation parameters at Super-K.
- Many other interesting analyses are performed.
  - Cross section measurements
  - Measurement of the intrinsic ν_e beam component
  - Search for short baseline ν_e disappearance
- Very arbitrary choice of the results are shown here.

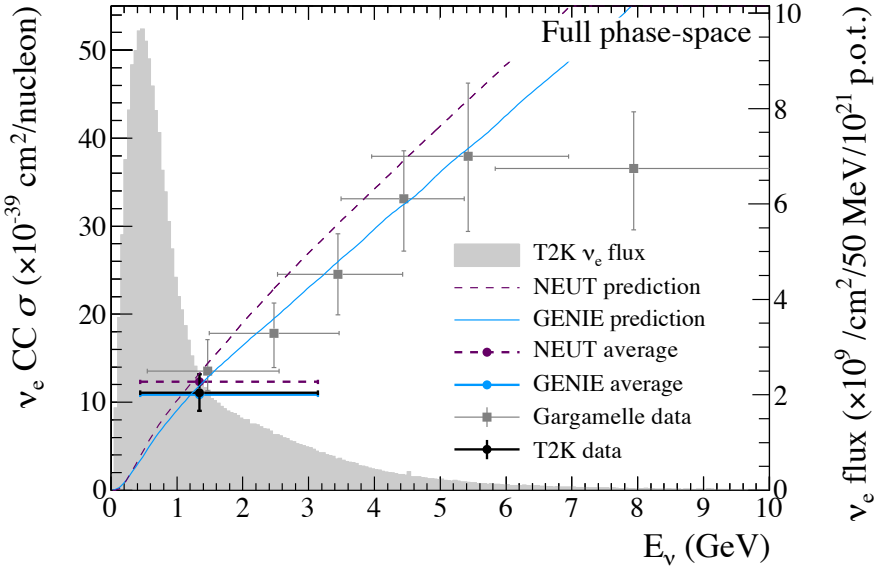
ν-oxygen NCQE cross section @ SK

Phys. Rev. D 90, 072012 (2014)



ν_e CC cross section @ ND280

arXiV: 1407.7389 [hep-ex], Accepted by PRL



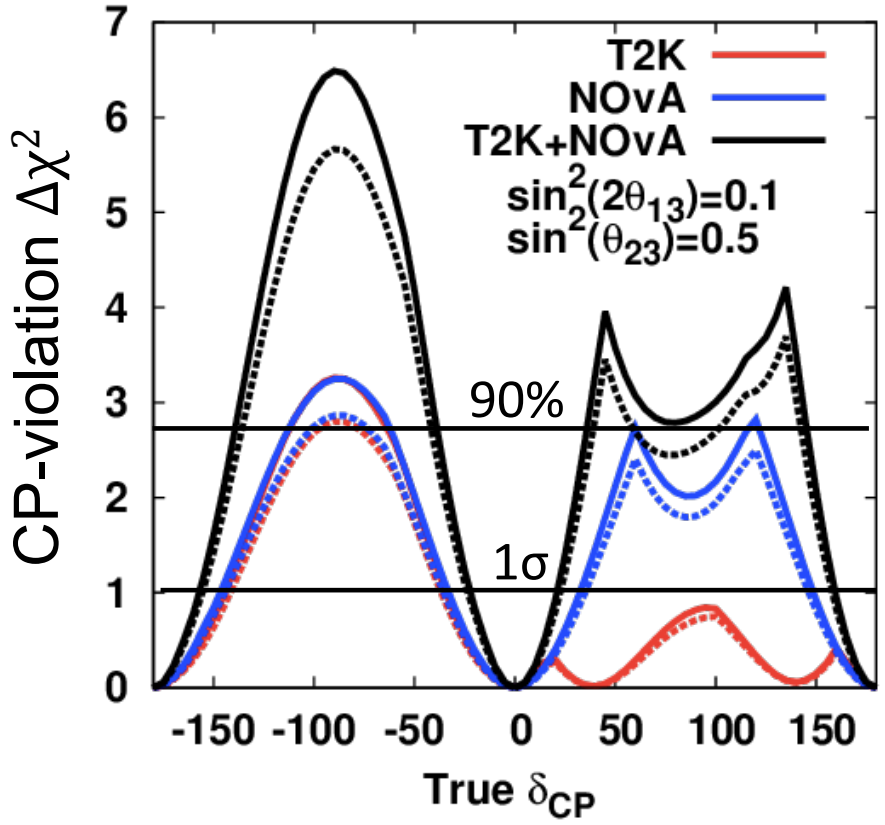
Future T2K sensitivity

Future physics goals/strategy

- Physics goals
  - Exploring lepton CPV
  - High precision ν_μ disappearance measurement
  - ν/anti-ν cross section measurements
  - Important contribution to Mass Hierarchy determination
- Strategy toward the approved 7.8×10^{21} POT
  - Run with 50% ν – 50% anti-ν mode
    - that is optimum condition to achieve the best sensitivity
    - also keeping T2K as "world-leading" experiment
  - Our short-term goal is accumulation of 5×10^{20} POT for anti-ν mode by summer 2015 -> currently taking the data
    - World-leading anti-ν_μ disappearance measurement
    - Initial anti-ν_e appearance measurement

Sensitivity for resolving $\sin\delta_{CP}\neq 0$

Submitted to PTEP, arXiv:1409.7469 [hep-ex]



Assumptions

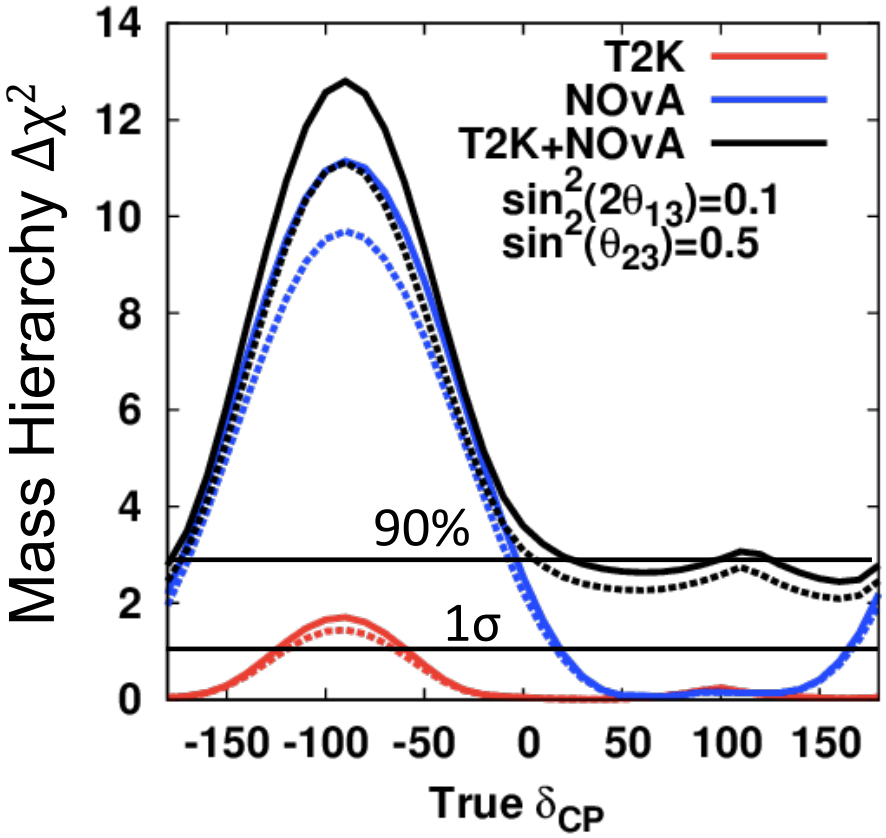
- dashed (solid): w/ (w/o) systematics
- $\sin^2 2\theta_{13}$ = 0.1 w/ ultimate reactor prec.
- $\sin^2\theta_{23}$ = 0.5
- Δm^2 = 2.4 x 10^{-3} eV^2
- Normal hierarchy
- **T2K**
  - 7.8 x 10^{21} POT (50% ν–50% anti-ν)
- **NOνA**
  - 3.6 x 10^{21} POT (50% ν-50% anti-ν)

Systematics: 5%(10%) norm. error on sig. (BG)

- T2K is exploring CPV in the lepton sector
  - Observed significance can be much better than the projected sensitivity
  - Combined fit w/ other experiments (NOνA, SK atm.) enhances the sensitivity
  - Improved systematic errors/analysis techniques also enhances the sensitivity.

Sensitivity for determining MH

Submitted to PTEP, arXiv:1409.7469 [hep-ex]



Assumptions

- dashed (solid): w/ (w/o) systematics
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- Normal hierarchy
- **T2K**
  - 7.8×10^{21} POT (50% ν−50% anti-ν)
- **NOνA**
  - 3.6×10^{21} POT (50% ν-50% anti-ν)

Systematics: 5%(10%) norm. error on sig. (BG)

- important contribution to Mass Hierarchy determination with NOνA data.
  - Combined fit w/ SK atm. data also enhances the sensitivity.

Conclusion

- T2K achievements w/ 8% of the T2K full POT
  - Discovery of $\nu_\mu \rightarrow \nu_e$ appearance with 7.3σ
  - World best precision on θ_{23}
  - Constraints on δ_{CP}

All of these are "world leading" results!

- Future T2K
  - Short term goals
    - 5×10^{20} POT for anti-ν mode by summer 2015
    - anti-ν_μ disappearance/anti-ν_e appearance measurements
  - Goals w/ the T2K full POT, 7.8×10^{21}
    - Exploring lepton CPV
    - Important contribution to Mass Hierarchy determination