T2K Status and Prospects

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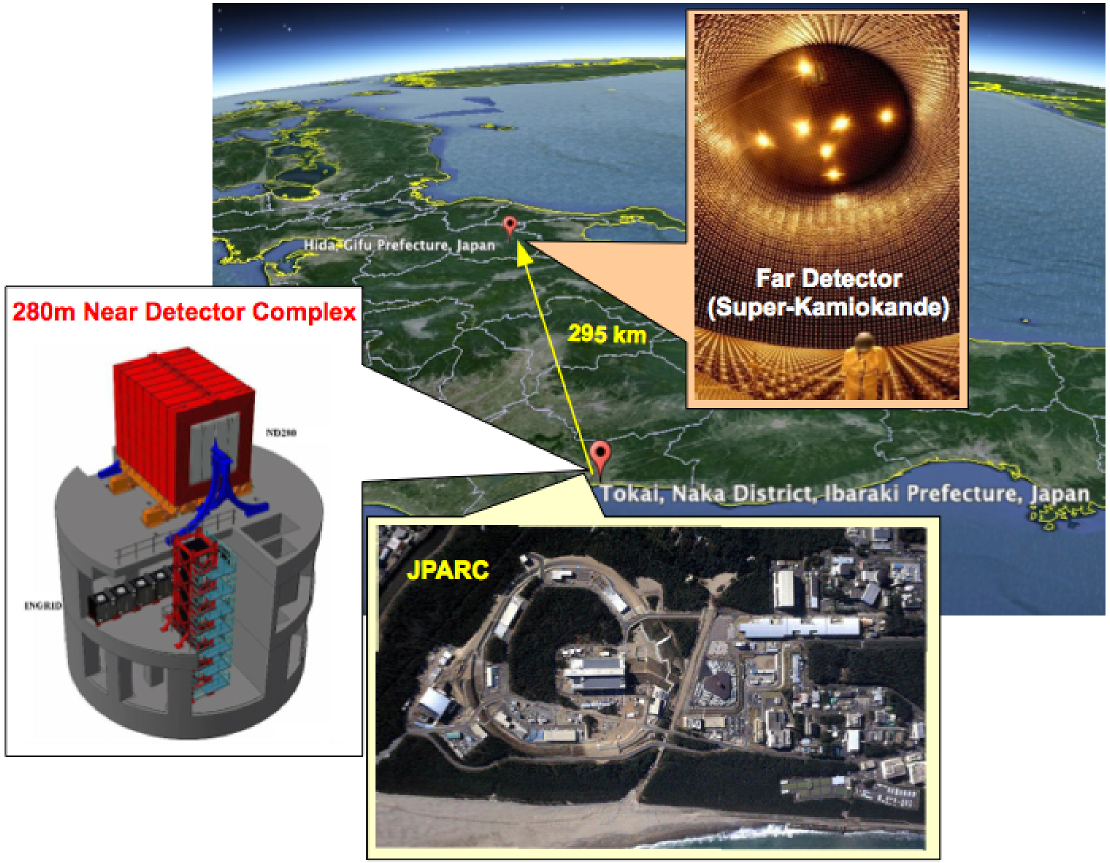
presented at the ICFA European Neutrino Town Meeting, Paris Diderot University

January 8, 2014

Outline

- **T2K - A very brief introduction**
- **Oscillation results**
  - ν_e appearance (accepted by PRL; arXiv:1311.4750)
  - ν_μ disappearance (PRL 111 (2013) 211803; arXiv:1308.0465)
- **Future prospects**
- **Summary**

T2K Experiment Overview



- Pure ν_μ beam.
- Produced using the 30-GeV proton beam at J-PARC
- Design power of 750 kW (230 kW achieved to date)
- Near detectors: on-axis and off-axis at 280 m to monitor and constrain flux characteristics and interaction rates.
- Far detector: SuperK 50-kton (22.5 kton fiducial) water Cherenkov detector, 2.5 degrees off-axis, 295 km away.
- Neutrino flux at SuperK peaked at $\sim$0.6 GeV.
- L/E tuned to the 'atmospheric' Δm^2 ($\sim 2.4 \times 10^{-3}$ eV^2/c^4).

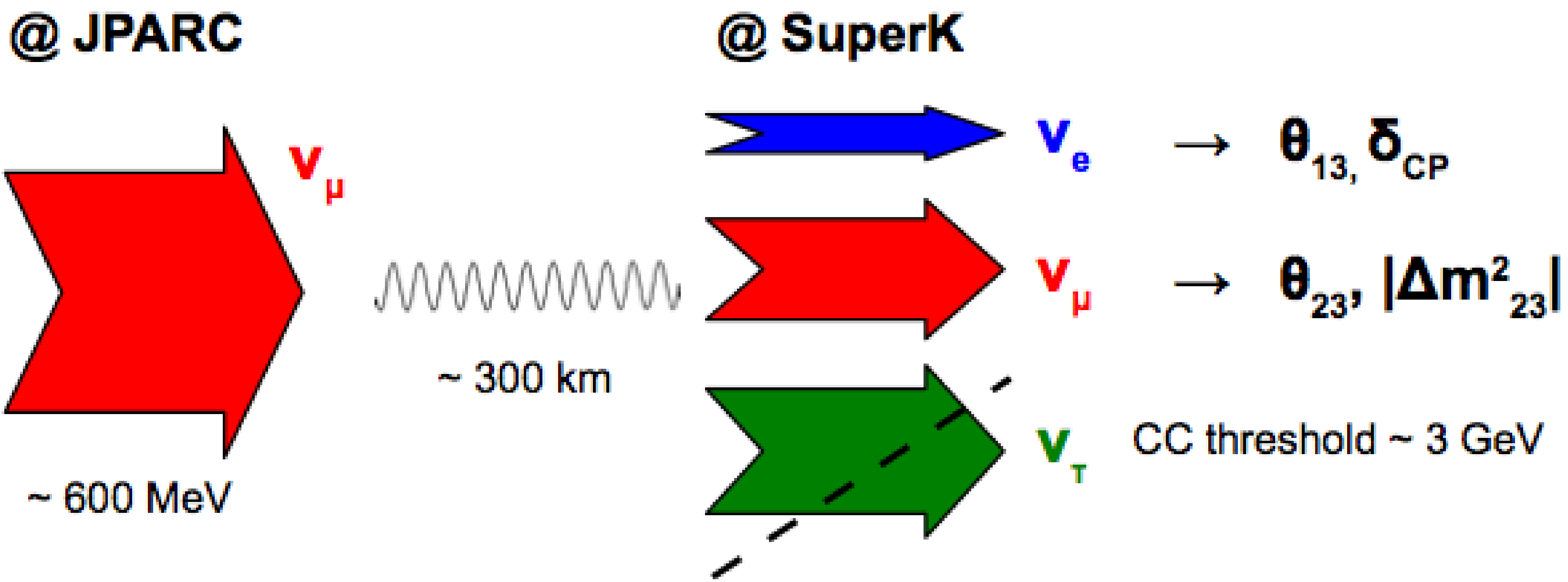
Neutrino oscillation signatures in T2K

Muon-neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$)

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - cos^4\theta_{13} \cdot sin^2 2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$

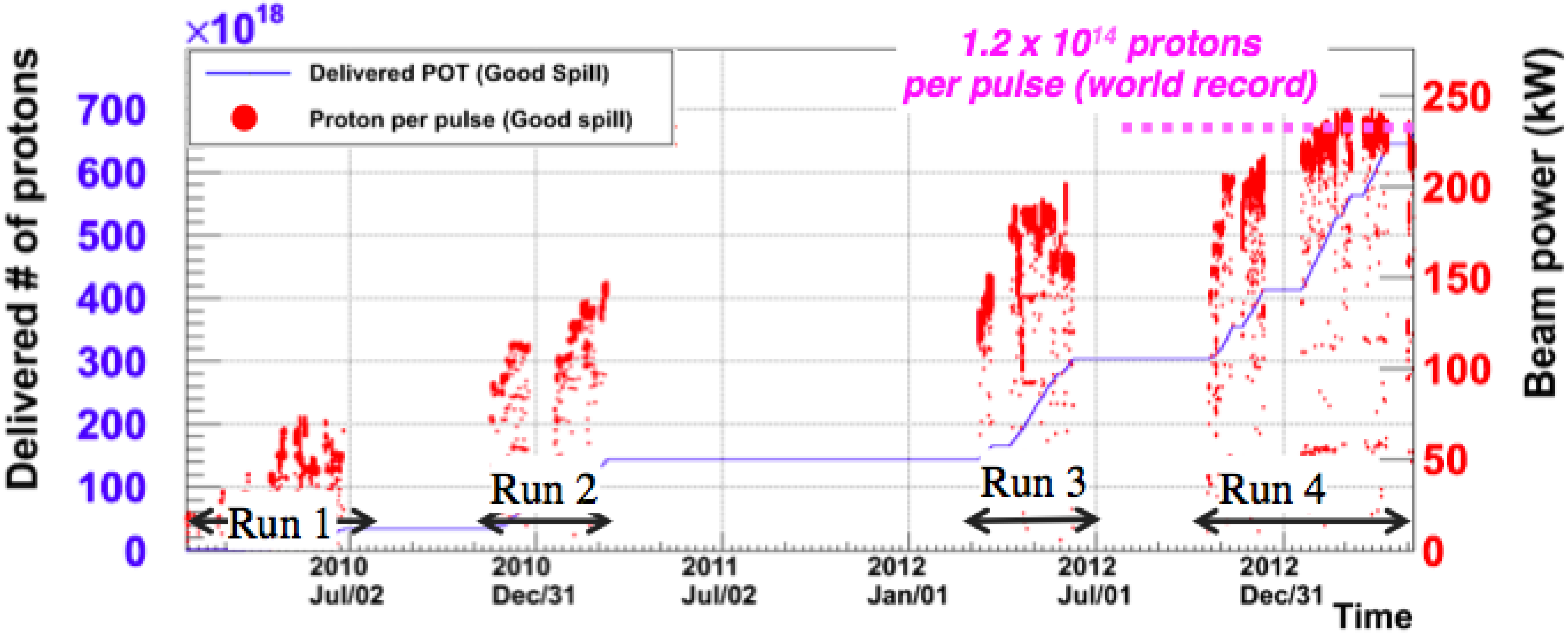
Electron-neutrino appearance ($\nu_\mu \rightarrow \nu_e$)

$$P(\nu_\mu \rightarrow \nu_e) = 4 \cdot cos^2\theta_{13} \cdot sin^2\theta_{13} \cdot sin^2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$



T2K Datasets

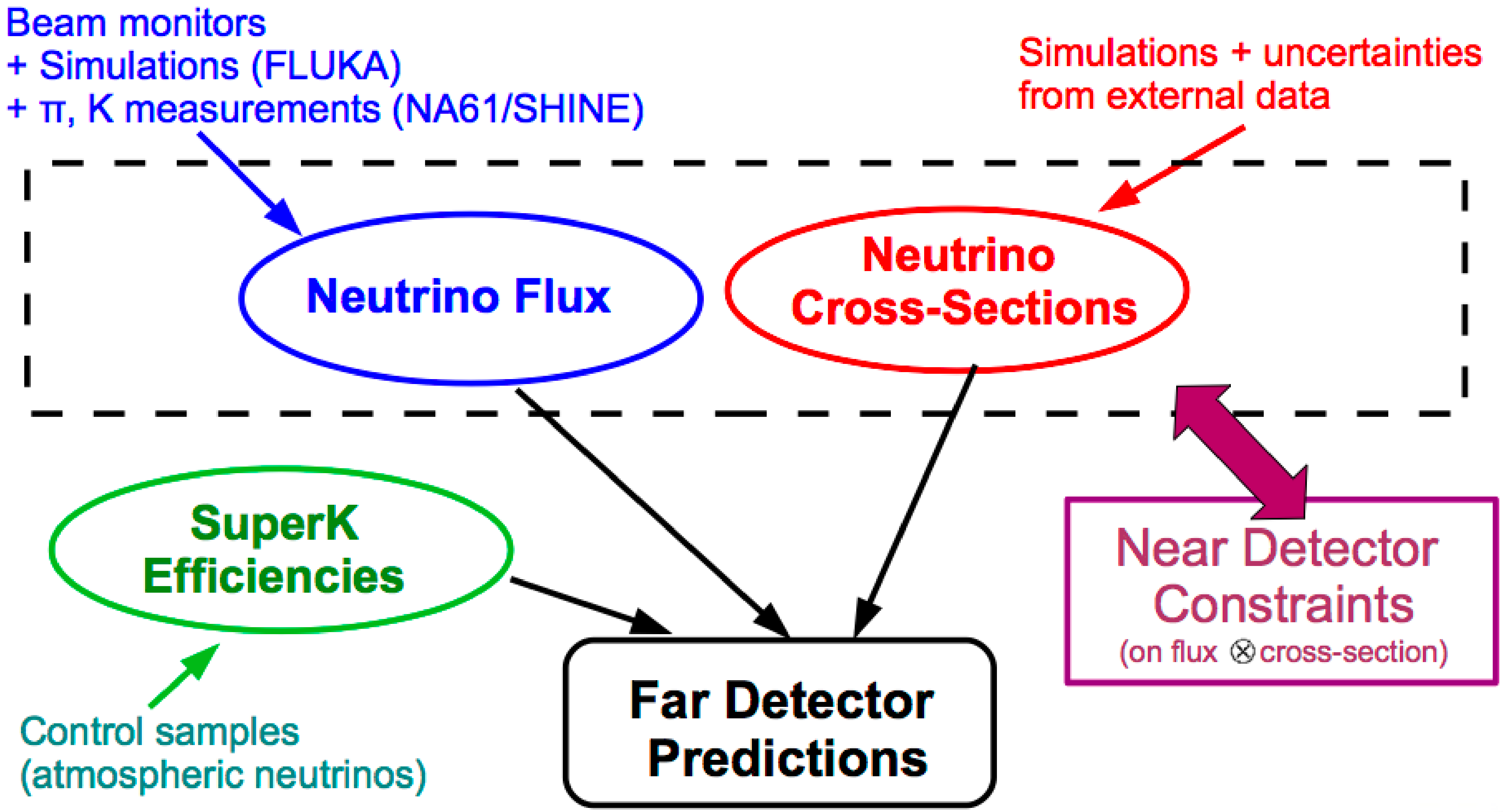
Data-taking started in January 2010. Data have been collected in 4 running periods.



Period	Exposure (proton on target) for oscillation physics analyses
Run 1	0.323×10^{20}
Run 1-2	1.431×10^{20}
Run 1-3	3.010×10^{20}
Run 1-4	6.570×10^{20}

- Steady improvement of beam power
- Run 4: Routine operation at ∼230 kW.
- Total exposure of 6.570×10^{20} protons on target for physics analysis

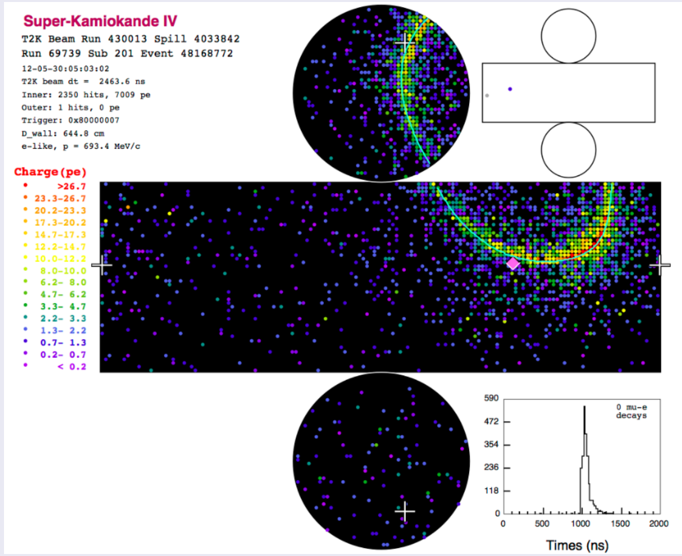
Oscillation analysis method



ν_e event selection at SuperK

- **FCFV** event in-time with expected beam arrival
- **Single electron-like** ("fuzzy") Cherenkov **ring**
- **Reconstructed momentum $>$ 100 MeV/c**
  - Eliminates decay e from stopping μ's produced by ν_μCC and NC$\pi^\pm$ interactions.
- **Reconstructed energy $<$ 1250 MeV**
  - Reduces intrinsic ν_e bkg from Kaon decays.
  - $\nu_\mu \rightarrow \nu_e$ signal <1250 MeV (unoscillated ν_μ flux peak at ~600 MeV).
- **Pass fiTQun π^0 rejection cuts**
  - Cut expressed in terms of the reconstucted mass (m_{π^0}) for the π^0 hypothesis and the ratio of the likelihoods of the electron and π^0 hypotheses ($\ln(L_{\pi^0}/L_e)$).

Typical event:



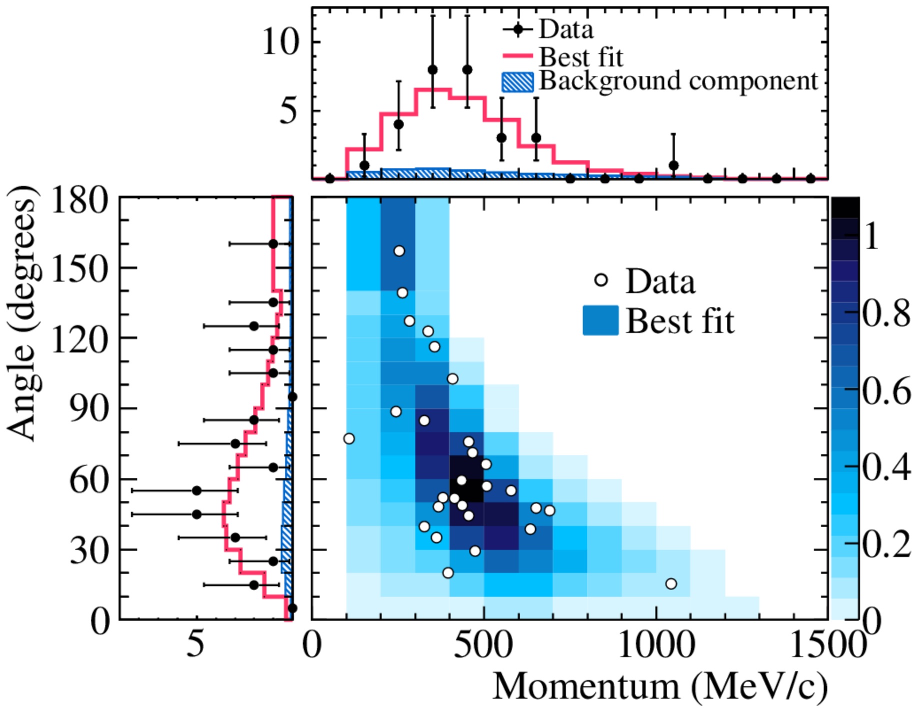
Signal sample CCQE-enhanced.
- Neutrino energy reconstruction from reconstructed electron kinematics

Main backgrounds:
- intrinsic ν_e from Kaons and muons
- ν_μ NCπ^0 with missed γ ($\pi^0 \rightarrow \gamma\gamma$)

For typical oscillation parameters (NH, $sin^2 2\theta_{13}$=0.1, δ_{CP}=0, $sin^2\theta_{23}$=0.5, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2/c^4) ~66% of the FCFV osc. signal is accepted and ~99% of the bkg is rejected

T2K ν_e appearance with Run 1-4 data

28 single-ring e-like events were observed, with an expected bkg of 4.92 $\pm$ 0.55 (syst) events. The significance of the excess is 7.3σ (first ever observation of an explicit appearance signal).



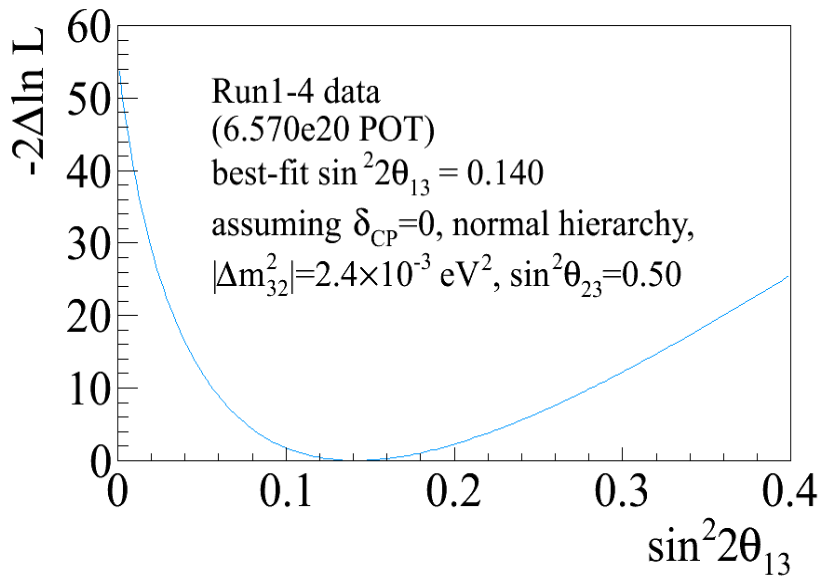
Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	4.92	21.56
ν_e signal	0.40	17.30
ν_e background	3.37	3.12
ν_μ background	0.94	0.94
$\bar{\nu}_\mu$ background	0.05	0.05
$\bar{\nu}_e$ background	0.16	0.15

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
BANFF	21.7	4.8	25.9	2.9
ν int. (other than BANFF)	6.8	6.8	7.5	7.5
SK+FSI	7.3	7.3	3.5	3.5
Total	24.0	11.1	27.2	8.8
2012 analysis	21.0	13.0	24.2	9.9

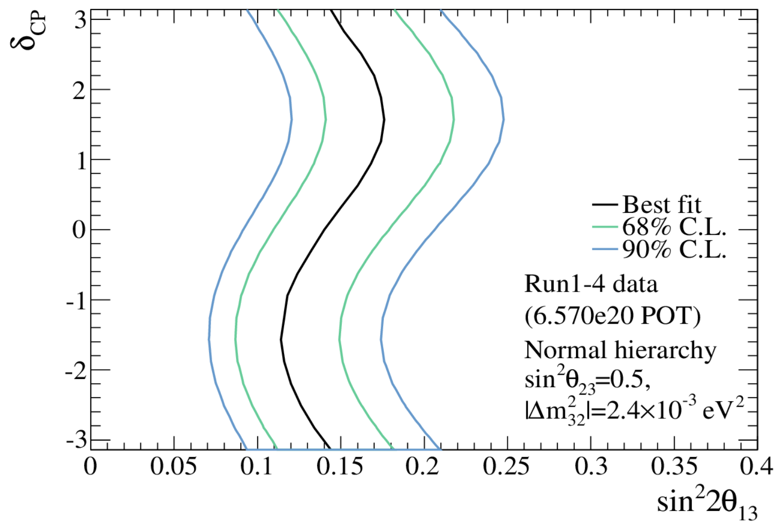
Best fit value of $\sin^2 2\theta_{13}$ (for $\delta_{CP} = 0$, $|\Delta m^2_{32}| = 2.4\times10^{-3} eV^2/c^4$ and $\sin^2\theta_{23} = 0.5$):

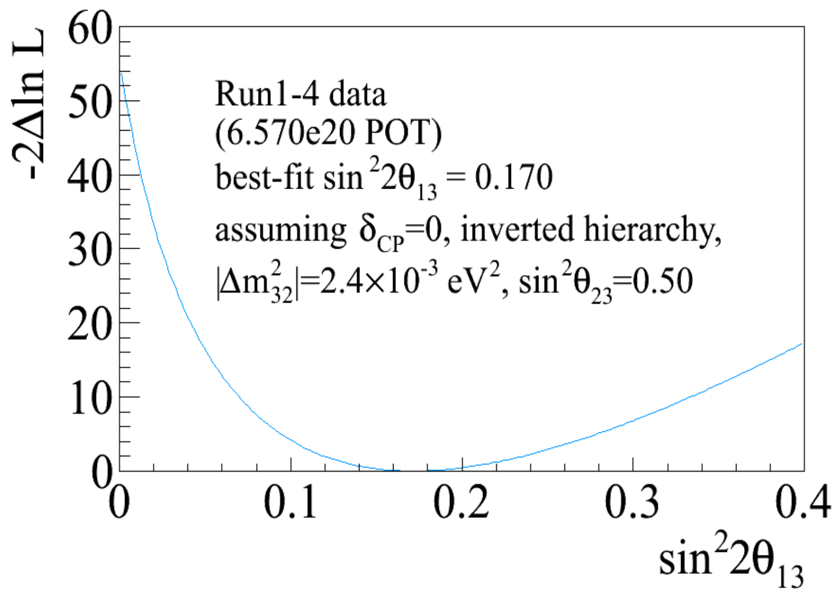
- $\sin^2 2\theta_{13} = 0.14$ (Normal)
- $\sin^2 2\theta_{13} = 0.17$ (Inverted)

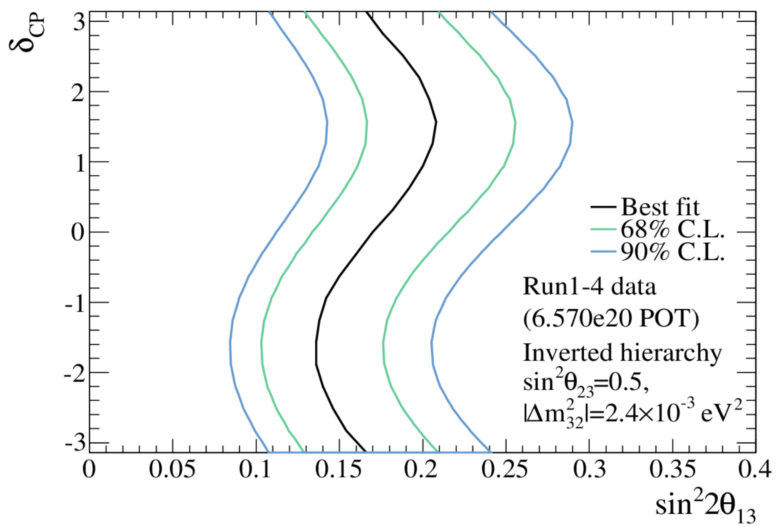
T2K constraint on θ_{13}



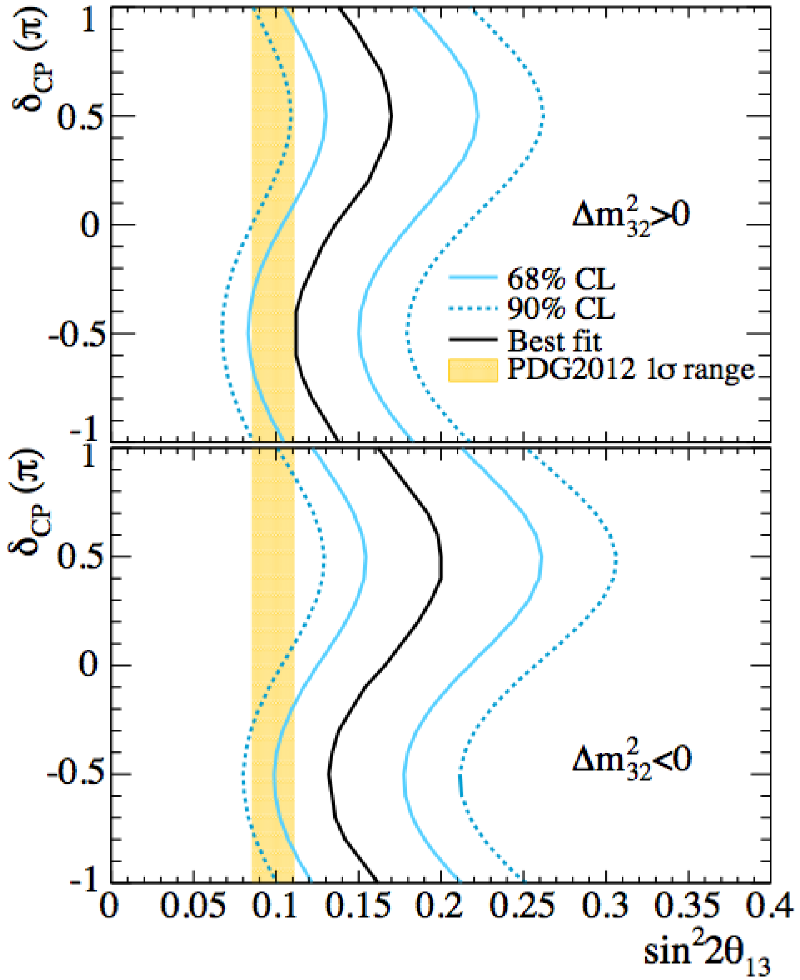
θ_{13} limit has a weak dependence on δ_{CP}
(note: 'raster scan' plots shown below)



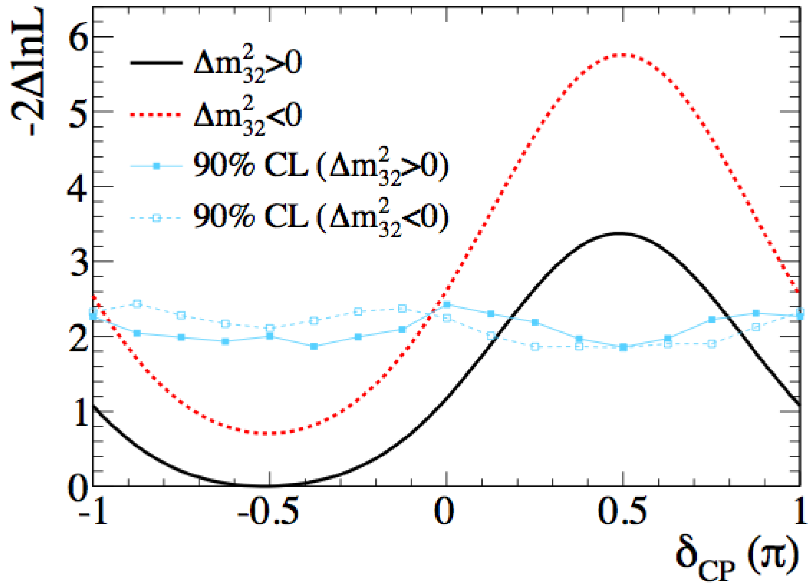




First constraint on δ_{CP}



- The T2K appearance contour depends on the values of $|\Delta m^2_{32}|$ and θ_{32}. These parameters were marginalized using the T2K disappearance measurement (left).
- Difference in reactor ($\bar{\nu}_e$ disappearance) and T2K ($\nu_\mu \to \nu_e$ appearance) best-fit values of θ_{13}.
- Using the precise reactor value of θ_{13} (PDG12: 0.098 $\pm$ 0.013) we can start constraining δ_{CP}.

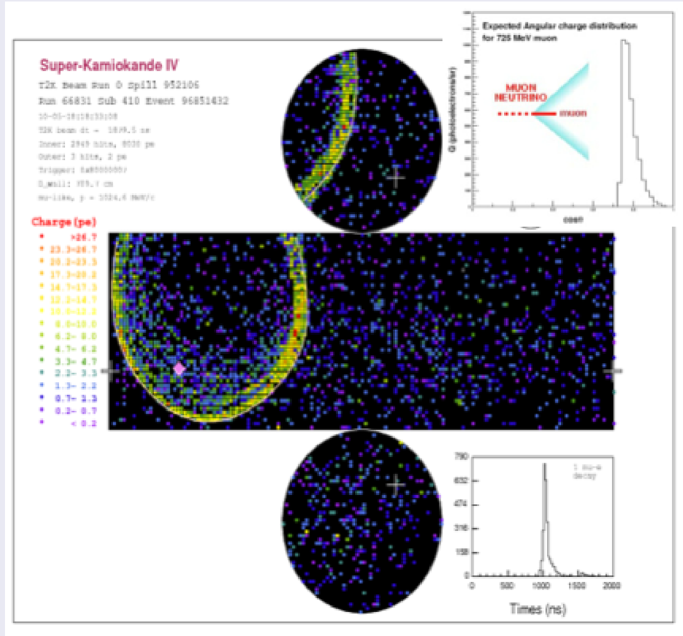


$sin^2\theta_{23}$ and Δm^2_{32} were varied in the fit using the constraint from the T2K ν_μ disappearance measurement (with Run 1-3 data).

ν_μ event selection at SuperK

- FCFV event in-time with expected beam arrival
- Single muon-like ("crisp") Cherenkov ring
- Reconstructed muon momentum > 200 MeV/c
  - Rejects charged pions and mis-ID'ed electrons
- 0 or 1 reconstructed decay electrons
  - Rejects ν_μCC events accompanied by unseen charged pions

Typical event:

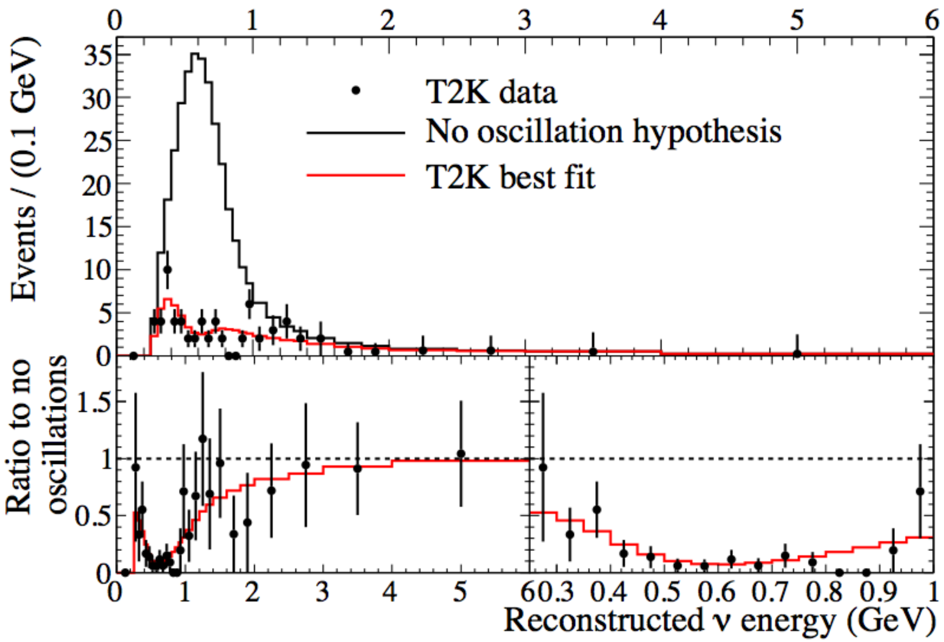


Signal sample CCQE-enhanced.
- Neutrino energy reconstruction from reconstructed muon kinematics

Main backgrounds components:
- NC (rate unaffected by active neutrino oscillations)
- ν_μ CC-nonQE (oscillates, but energy systematically mis-reconstructed)

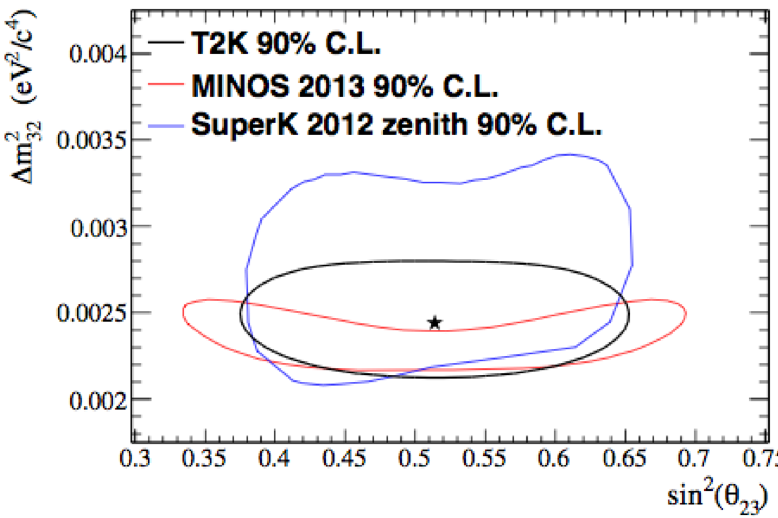
T2K ν_μ disappearance with Run 1-3 data (*)

205 $\pm$ 17 (syst.) single-ring μ-like events expected in absence of oscillations, but only 58 events were observed. The observed deficit is strongly energy-dependent.



Effect of systematics on the number of events (assuming $|\Delta m^2_{32}|$=2.4$\times 10^{-3} eV^2/c^4$, $\sin^2\theta_{23}$=0.5)
All 48 systematics were allowed to float in the fit.

Source of uncertainty (no. of parameters)	δn^{exp}_{SK} / n^{exp}_{SK}
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%



- Dramatic deficit allows us to place stringent constraints on ν_μ disappearance parameters.
- Assuming NH: $|\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3} eV^2/c^4$ and $\sin^2\theta_{23} = 0.514 \pm 0.082$

(*) Analysis of Run 1-4 data (with $\times$2 statistics) in final stages of internal T2K review. Result would be made public within the next few weeks.

Joint 3-flavour oscillation analysis for improved sensitivity

Results were presented separately for

- ν_e appearance (sensitive primarily to θ_{13} and δ_{CP})
- ν_μ disappearance (sensitive primarily to θ_{23} and $|\Delta m^2_{32}|$).

Both results were obtained in a **3-flavour oscillation framework** including matter effects.

There are ongoing efforts to perform a joint 3-flavour analysis:

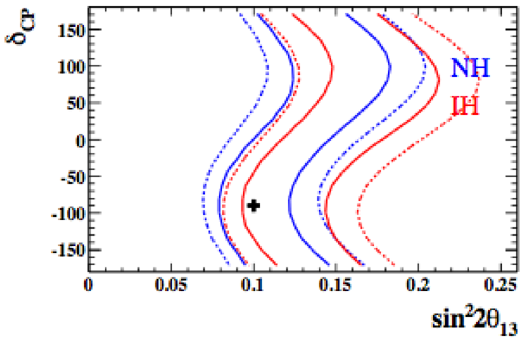
- Take fully into account all correlations and data constraints ignored in stand-alone analyses,
- Added sensitivity and degeneracy resolution
  - ν_e appearance probability depends on $sin^2\theta_{23}$, but ν_μ disappearance probability depends on $sin^2\mathbf{2}\theta_{23}$: θ_{23} octant sensitivity.

Joint oscillation analysis results will be released in the near future

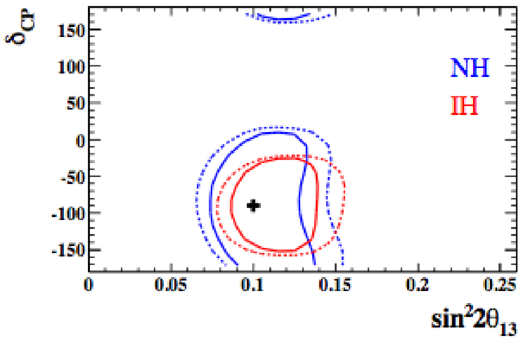
Main physics goal achieved with first 8.2% of the total approved exposure of 7.8×10^{21} protons on target ($= 750$ kW $\times$ 5 yrs $\times$ 10^7 sec/yr).

Quo vadis T2K?

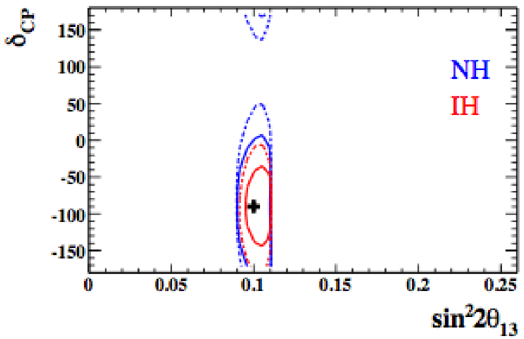
Future Sensitivity



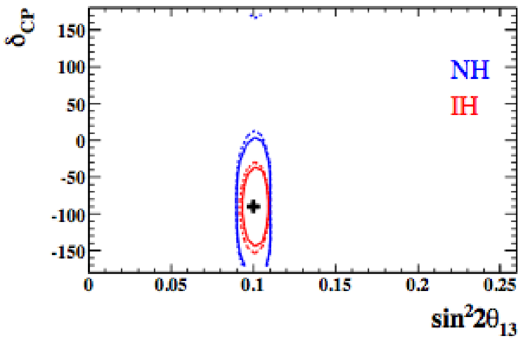
(a) 100% ν-running.



(b) 50% ν-, 50% $\bar{\nu}$-running.



(c) 100% ν-running, with ultimate reactor constraint.

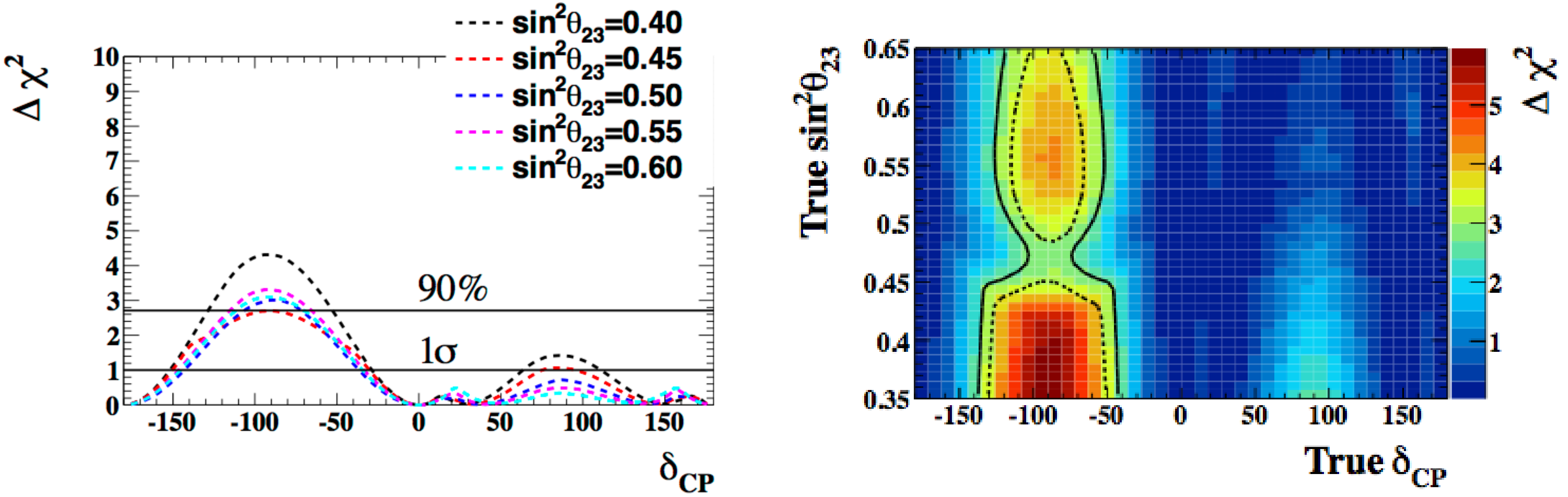


(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor constraint.

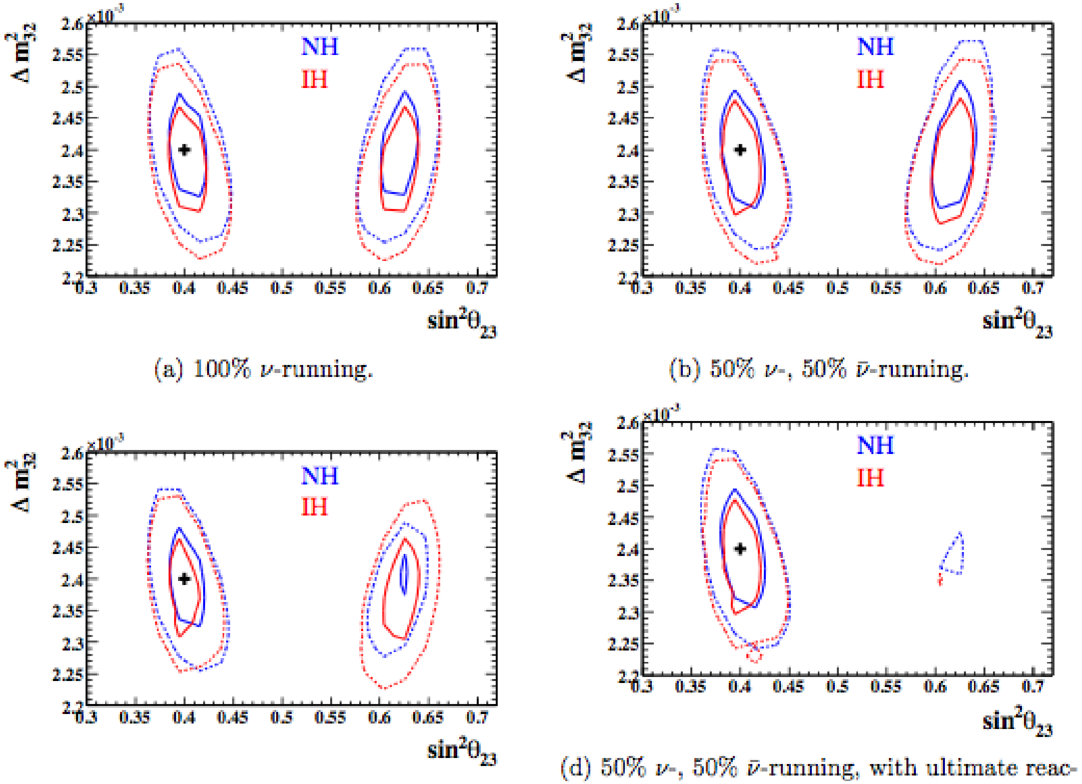
- Difference in δ_{CP} sensitivity with ν-enhanced and $\bar{\nu}$-enhanced beam running.
- Improved sensitivity with a combination of ν and $\bar{\nu}$ data.
- **$\sim$90% C.L. measurement for certain true values of δ_{CP}.**
- Similar δ_{CP} constraint with and without the reactor data: **Could start over-constraining the PMNS framework.**

90% C.L. intervals for true NH and true $\delta_{CP} = -\pi/2$, $sin^2 2\theta_{13}$=0.1, $sin^2\theta_{23}$=0.5, Δm^2_{32}=2.4$\times10^{-3}$ eV^2/c^4.
Blue: Correct hierachy, Red: Incorrect hierarchy - Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 $\times$ 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Fully correlated ν and $\bar{\nu}$ systematic errors.

Sensitivity to δ_{CP} depends strongly on its true value. Plots below show the calculated $\Delta\chi^2$ **for the** $sin(\delta_{CP}) = 0$ **hypothesis** for different values of δ_{CP} and θ_{23}.



True: NH, $sin^2 2\theta_{13}$=0.1, Δm^2_{32}=2.4×10^{-3} eV^2/c^4.
Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 × 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Assumed a ν:$\bar{\nu}$ = 1:1 running scenario with fully correlated systematic errors.



(a) 100% ν-running.

(b) 50% ν-, 50% $\bar{\nu}$-running.

(c) 100% ν-running, with ultimate reactor error.

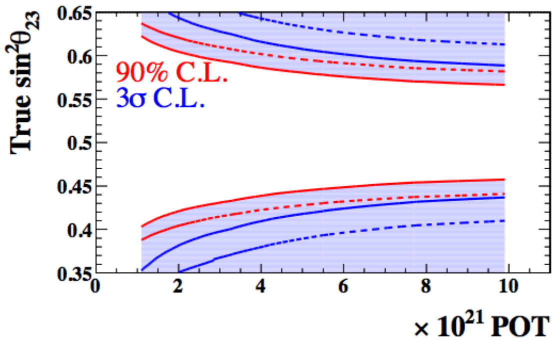
(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor error.

- Added power from combining ν and $\bar{\nu}$ data compensates for loss of statistics in $\bar{\nu}$-enhanced beam mode. There is no effect on the disappearance measurement using T2K data alone.
- Combination of T2K ν and $\bar{\nu}$ data and reactor data could allow us to resolve the θ_{23} octant.

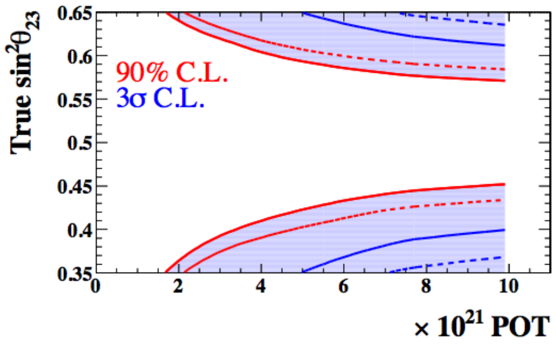
90% C.L. intervals for true NH and true Δm^2_{32}=2.4$\times10^{-3}$ eV^2/c^4, $sin^2\theta_{23}$=0.4, δ_{CP} = 0 and $sin^2 2\theta_{13}$=0.1.
Blue: Correct hierachy, Red: Incorrect hierarchy - Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 $\times$ 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Fully correlated ν and $\bar{\nu}$ systematic errors.

Future Sensitivity

Values of $sin^2\theta_{23}$ for which maximal mixing and the wrong octant can be rejected at the stated C.L.



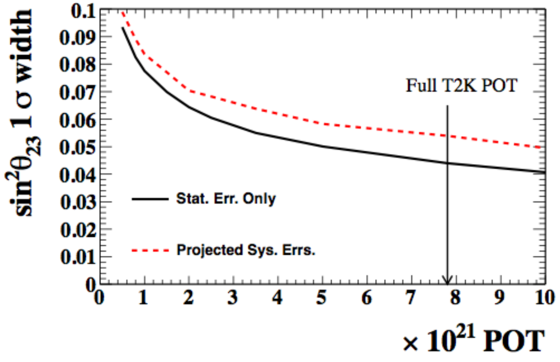
(a) $\theta_{23} \neq \pi/4$



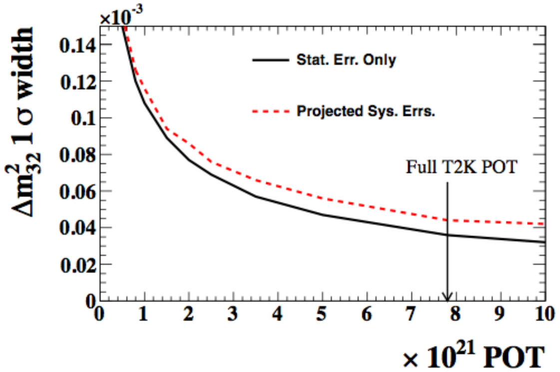
(b) θ_{23} Octant

θ_{23} octant could be determined at 90% C.L. if $|\theta_{23} - 45^o| > 4^o$.

1σ err for $sin^2\theta_{23}$ and Δm^2_{32} as function of T2K exposure.



(b) 50% ν, 50% $\bar{\nu}$-running.



$\delta(sin^2\theta_{23}) \simeq 0.045\ (2.6^o)$
$\delta(\Delta m^2_{32}) \simeq 4\times10^{-5}\ eV^2/c^4$

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2 left plots:
True: NH, $\delta_{CP} = 0$, $sin^2 2\theta_{13}$=0.1, Δm^2_{32}=$2.4\times10^{-3}\ eV^2/c^4$.
Solid: Statistical errors only, Dashed: With 2012 systematics.

2 right plots:
True: NH, $\delta_{CP} = 0$, $sin^2 2\theta_{13}$=0.1, $sin^2\theta_{23}$=0.5, Δm^2_{32}=$2.4\times10^{-3}\ eV^2/c^4$.
Solid: Statistical errors only, Dashed: With projected systematics.

All plots:
Assumed a ν:$\bar{\nu}$ = 1:1 running scenario with fully correlated systematic errors.
Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.

Updated physics goals

- **Indication/Evidence for CP violation to a level of 2.5σ.**
- **Precision measurement of ν_μ disappearance**
  - $\delta(\Delta m^2_{23}) \sim 10^{-4} eV^2/c^4$
  - $\delta(sin^2(2\theta_{23})) \sim 0.01$
  - Determination of θ_{23} octant at 90% C.L. if $|\theta_{23} - 45^o| > 4^o$
- Contribution to the determination of mass hierarchy

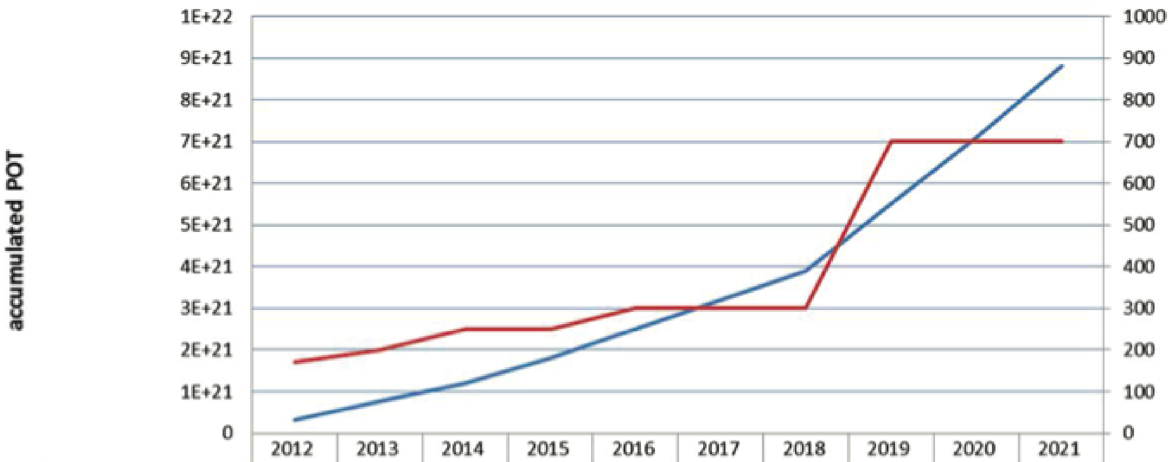
T2K plans for FY2014

Future sensitivity studies:
Large fraction of running with reversed horn current for optimal sensitivity (e.g. 50% ν-enhanced beam + 50% $\bar{\nu}$-enhanced beam).

- Currently, no agreed long-term T2K run plan.
- Crucial to have data from an $\bar{\nu}$-enhanced beam in 2014.
  - Operational experience
  - Information on event rates, spectra and systematic uncertainties.
- **Plan a 220 kW $\times$ 25 days ($\sim 10^{20}$ protons on target) anti-neutrino test run in early 2014.**
  Expected rates:
  - 500,000 ν_μ CC events in INGRID
  - 1,000 ν_μ CC events in ND280 ($\sim$90% $\bar{\nu}$)
  - 10 ν_μ CC events in SuperK ($\sim$60% $\bar{\nu}$)

J-PARC upgrades

- T2K oscillation analyses statistics limited.
- T2K beam designed for 750 kW operation.
  - Best achieved so far is ∼230 kW.
    - 1.3×10^{14} protons/pulse, 2.48 sec rep. rate.
- J-PARC upgrades (on-going LINAC upgrades, MR upgrades(2018))
  - 2.0×10^{14} protons/pulse, 1.30 sec rep. rate.



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
accumulated POT	3.1E+20	7.8E+20	1.2E+21	1.8E+21	2.50E+21	3.20E+21	3.90E+21	5.50E+21	7.10E+21	8.80E+21
beam power	170	200	250	250	300	300	300	700	700	700

Possible scenario:

- current statistics ×2 by early 2015
- current statistics ×4 by early 2017
- current statistics ×12 by end of 2020

Summary

- **Outstanding physics output from the first 8% of the approved T2K exposure.**
  - First observation of $\nu_\mu \to \nu_e$ oscillations (at 7.3σ)
  - First constraint on δ_{CP}
  - World's most stringent $\nu_\mu \to \nu_\mu$ measurement
  - *Rich near detector physics programme (not presented here)*

- **Physics potential maximized**
  - Excellent beam-line and detector performance
  - Ongoing efforts to increase the beam power
  - Impressive systematic error improvements
    - Improved understanding of neutrino flux using external data
    - Improved understanding of expected rates using near detector data
    - Improved event reconstruction and analysis techniques

- Potential to do much more than thought possible in back 2010
  - Evidence for sin(δ_{CP})$\neq$0 at 2-3σ (if lucky and nature is kind).

Supplementary slides

What are we hoping to learn?

- Discovery of neutrino masses and mixings: BSM physics!
- New physics not understood
  - What is the mass generation mechanism?
    - Could the neutrino be a Majorana particle?
    - Why are the masses so small?
  - Does it explain flavour?
    - Nearly (exactly?) maximal mixing observed: 'μ' and 'τ' flavour interchangeable in neutrino oscillations.
  - Does it provide a connection between the quark and lepton sectors?
    - Why the corresponding mixing matrices are so different?
  - What are the implications for the universe we live in?
    - Baryon asymmetry of the universe: CP violation + Majorana masses ingredients of the leptogenesis hypothesis.
    - Dark matter: Sterile neutrino is a candidate.

The study of neutrino masses and mixings the only known window to new physics.

Neutrino oscillations

Production & Detection

Flavour eigenstates

- ν_e, ν_μ, ν_τ, ...

SM:

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} j^{\mu}_{CC} W_\mu + h.c.$$

Propagation

Mass eigenstates:

- ν_1, ν_2, ν_3, ...

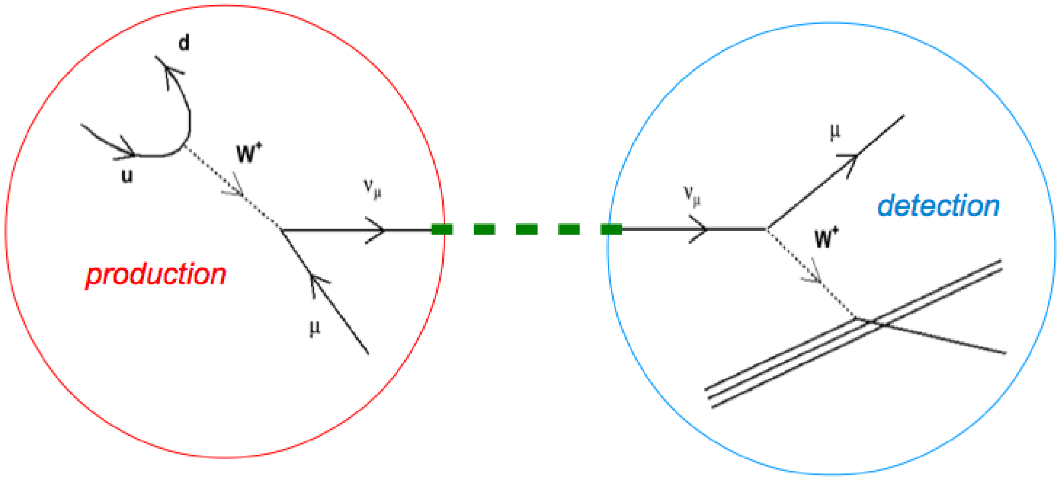
Described by plane waves:

$$|\nu_i(L)> = e^{-im_i^2 L/2E} \cdot |\nu_i(0)>$$

Each flavour eigenstate a superposition of mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

A quantum-mechanical interference effect



A neutrino state that starts its life as particular flavour eigenstate (e.g. ν_μ) may be detected as a different flavour eigenstate (e.g. ν_e).

What do we measure in neutrino oscillation experiments?

Probability for $\nu_\alpha \to \nu_\beta$ $(\alpha, \beta : e, \mu, \tau)$ flavour oscillation:

$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad - \quad 4\sum_{i>j} Re[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij})$$
$$+ \quad 2\sum_{i>j} Im[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij})$$

Sensitivity to oscillations by tuning L/E (baseline to energy ratio)

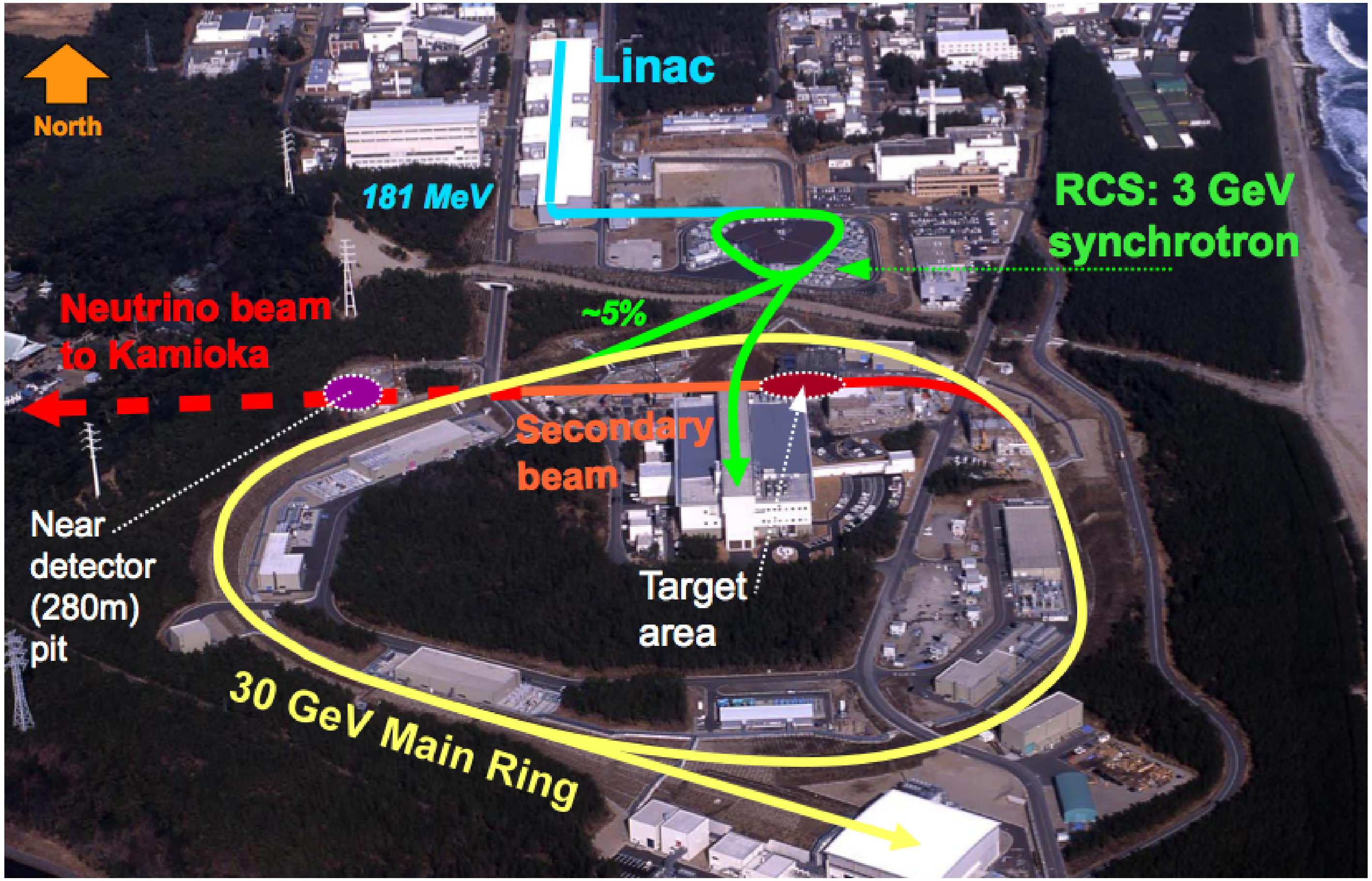
For a purely phenomenological description of neutrino oscillations, assuming 3 active neutrinos, we need:

- Any 2 squared mass splittings (e.g. Δm^2_{21},Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23})
- 1 CP invariance violating phase (δ_{CP})

T2K probes $|\Delta m^2_{32}|$, θ_{23}, θ_{13} and δ_{CP}.

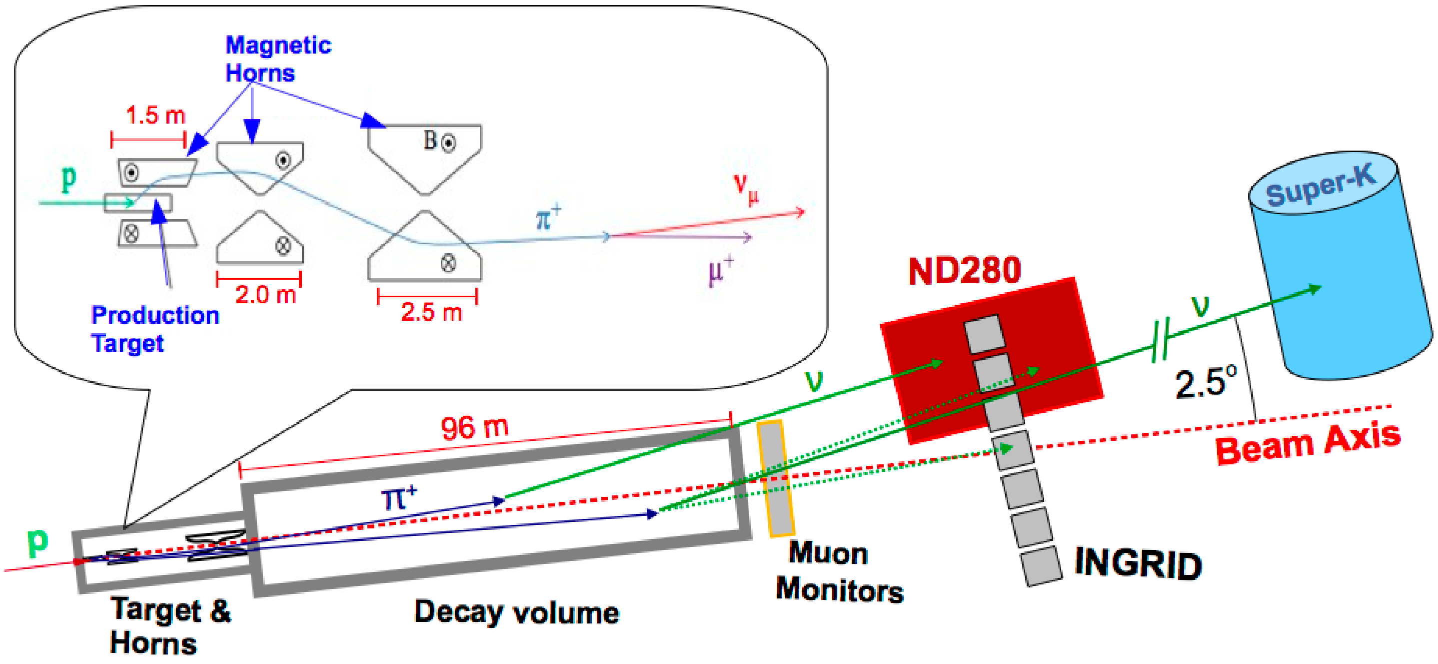
Making a neutrino beam / Primary proton beam

T2K uses the 30-GeV J-PARC proton accelerator.
Design power 750 kW (∼230 kW achieved to date)



- Fast extraction
- 3.3×10^{14} p/spill
- 0.3 Hz cycle
- 8 bunches/spill
- 581 nsec bunch interval
- 58 nsec bunch width

Currently, ∼1.3×10^{14} 30-GeV protons are extracted from the MR over a period of ∼5 μsec and transported to the neutrino beam-line. The repetition rate is ∼2.5 sec.

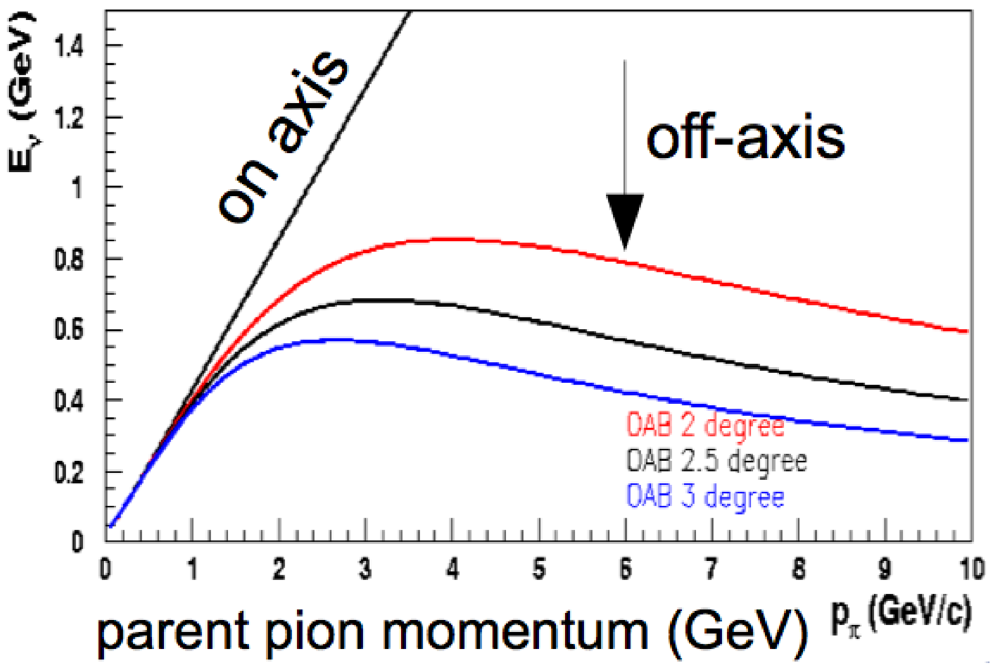


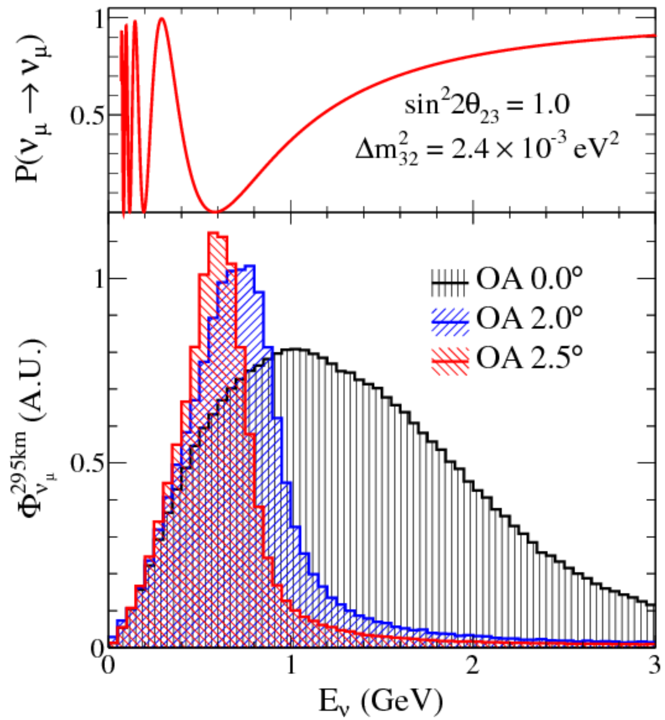
Where do our ν's come from?

$\pi^+ \rightarrow \nu_\mu + \mu^+$
$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$
$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$
$\mu^- \rightarrow \bar{\nu}_e + \nu_\mu + e^-$
$K^+ \rightarrow \nu_\mu + \mu^+$
$K^+ \rightarrow \nu_e + \pi^0 + e^+$
$K^+ \rightarrow \nu_\mu + \pi^0 + \mu^+$
$K^- \rightarrow \bar{\nu}_\mu + \mu^-$
$K^- \rightarrow \bar{\nu}_e + \pi^0 + e^-$
$K^- \rightarrow \bar{\nu}_\mu + \pi^0 + \mu^-$
$K^0_L \rightarrow \bar{\nu}_\mu + \pi^+ + \mu^-$
$K^0_L \rightarrow \nu_\mu + \pi^- + \mu^+$
$K^0_L \rightarrow \bar{\nu}_e + \pi^+ + e^-$
$K^0_L \rightarrow \nu_e + \pi^- + e^+$

Target: A 91.4 cm (1.9 int. length) long, 2.6 cm wide graphite rod.
Pion focussing: 3 magnetic horns pulsed with ∼250 kA currents (∼ 2 T field). They provide a 16× increase in ν flux w.r.t unfocussed beam.
Decay volume: A 96 m long steel decay tunnel.

T2K is the first accelerator experiment employing the off-axis trick. Exploits kinematical properties of pion decay to create a narrow-band neutrino beam peaked at an energy chosen so as to maximize the oscillation probability at the SuperK location.



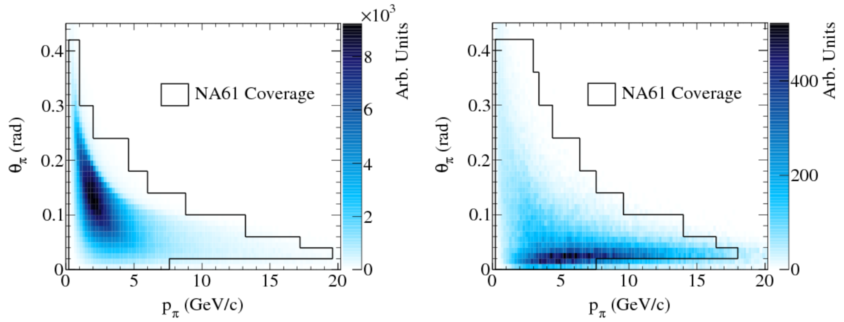


Main ingredients of Neutrino Flux Prediction

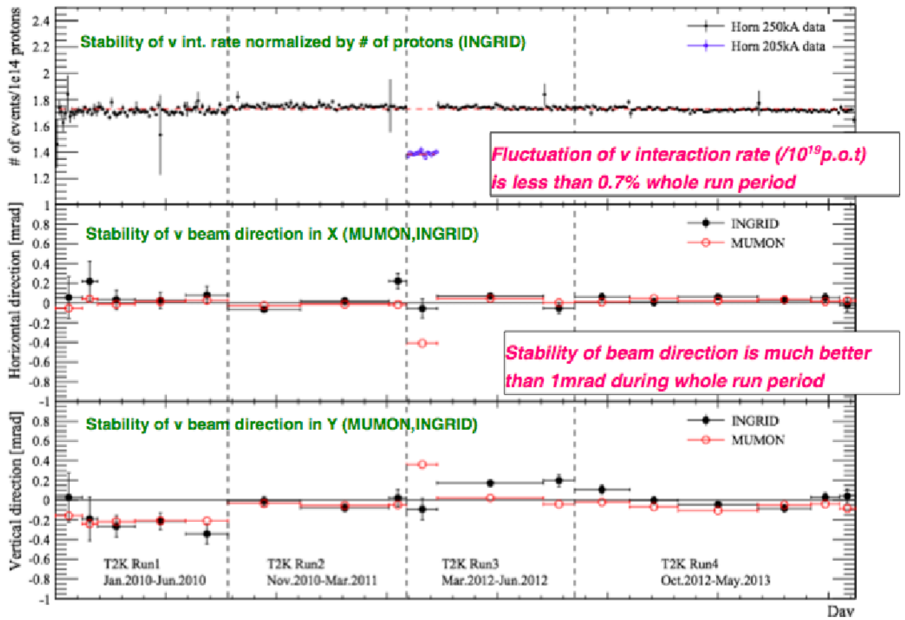
- **Hadron-production measurements**
- **Monitoring**: Primary proton beam and the neutrino beam (directly with an on-axis neutrino detector -INGRID- and indirectly using muons -MUMON-)

30 GeV p+C particle yields were measured by NA61/SHINE both with a thin target (∼4% of an interaction length) and a replica T2K target.

π^+ coverage: π^- coverage:



2007 thin target data (π^+, π^-, K$^-$) are used in present T2K analyses to tune the neutrino flux simulations.

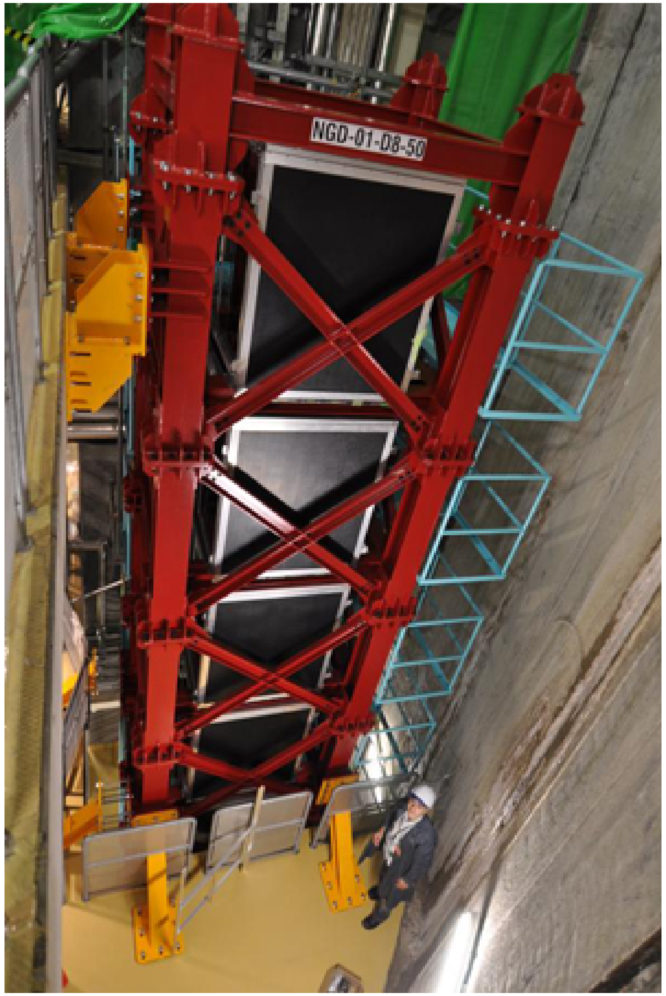


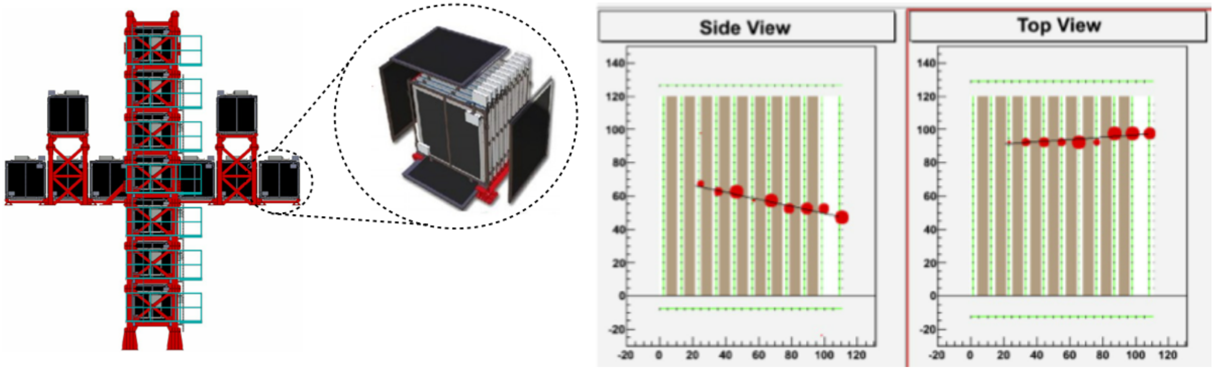
Excellent beam performance:
- Interaction rate stable within 0.7%
- Beam direction well within goal of ±1 mrad.

Total systematic error for the absolute flux prediction: 10-15%.

Uncertainty in the FAR / NEAR flux ratio: less than 2% at the flux peak.

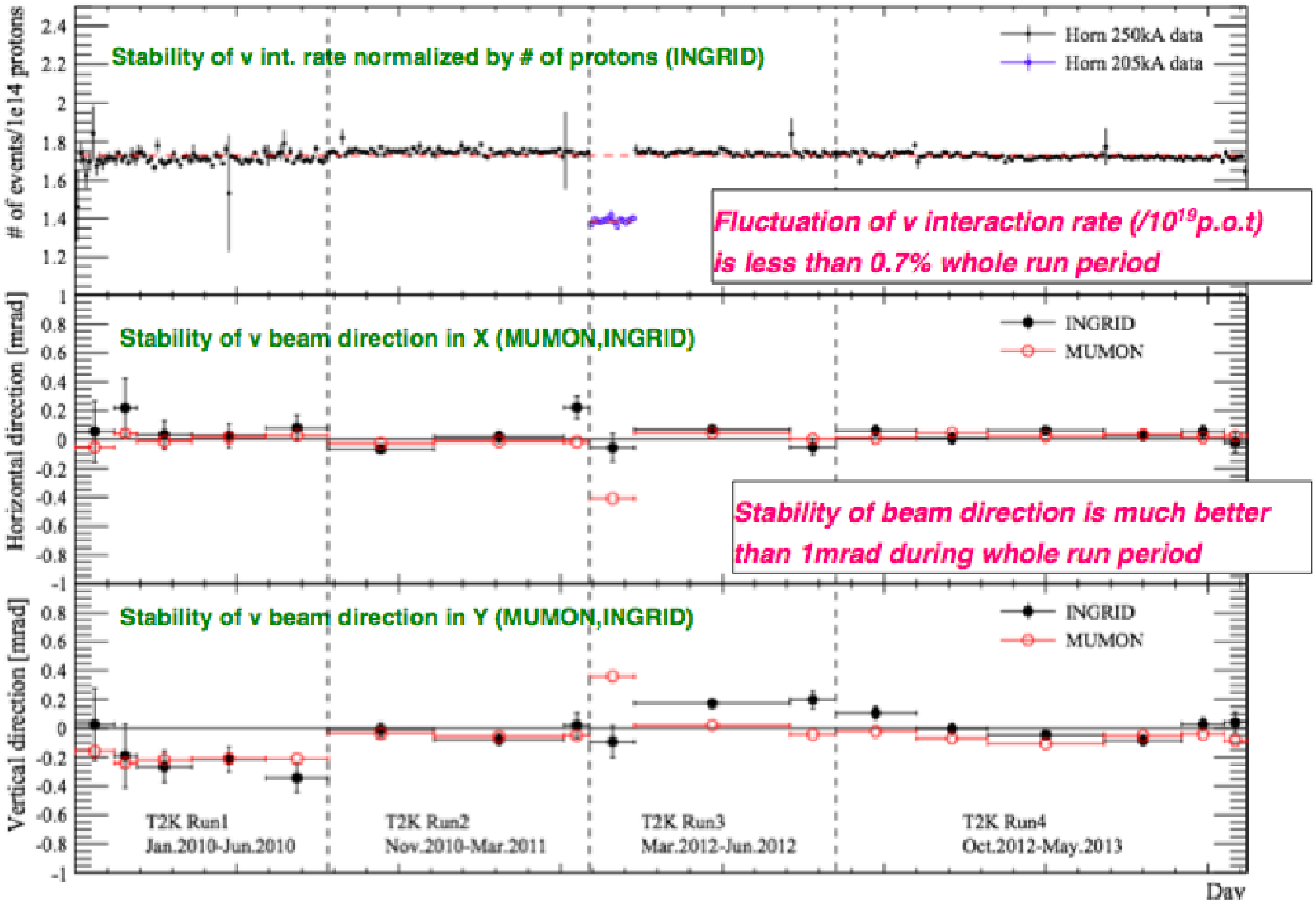
Neutrino Beam Monitoring





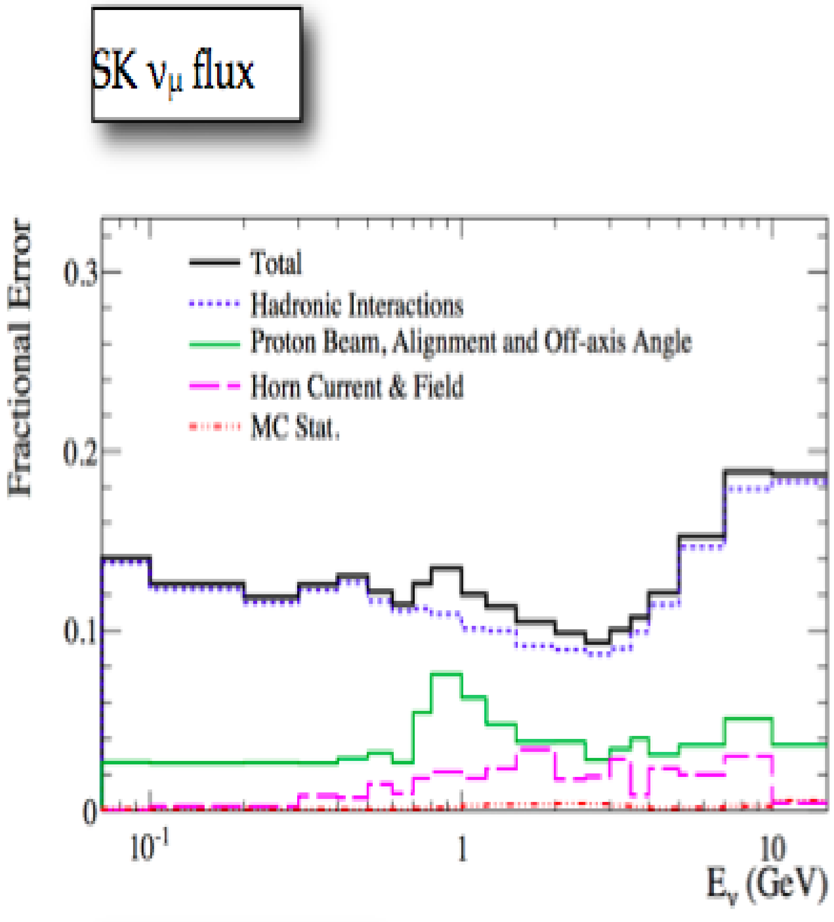
- 16 modules (14 in cross configuration).
- Each module: 7 tons, alternating scintillator / iron planes.
- 10 m × 10 m beam area coverage
- 1 event per $\sim 6 \times 10^{13}$ protons on target.
- Monitors neutrino beam rate and profile.

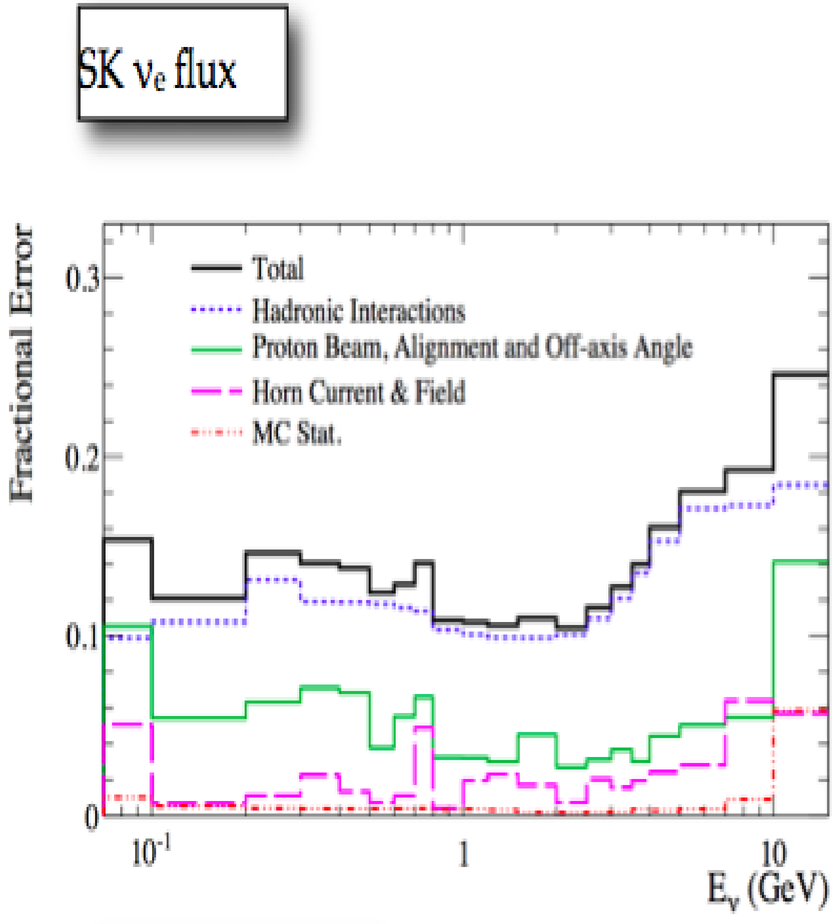
Neutrino Beam Stability



Neutrino Flux Prediction and Uncertainties

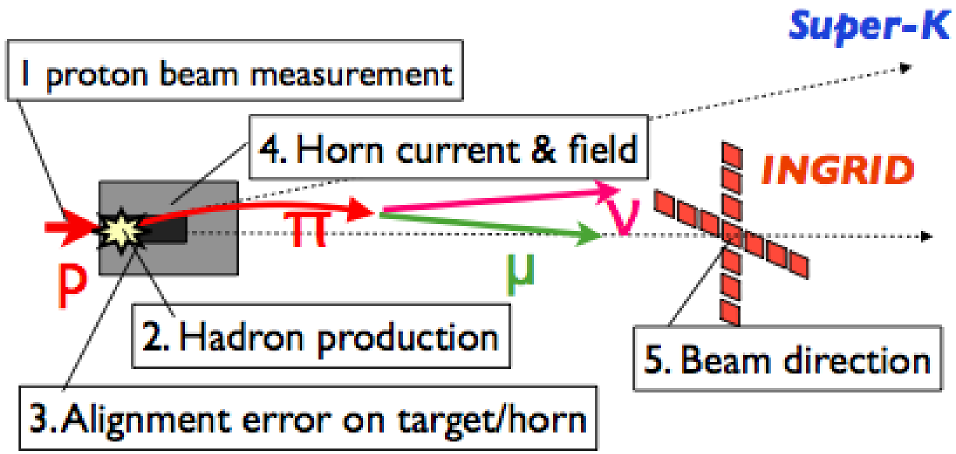
A priori prediction of flux at SuperK has uncertainties of the order of 10-15% below 5 GeV.

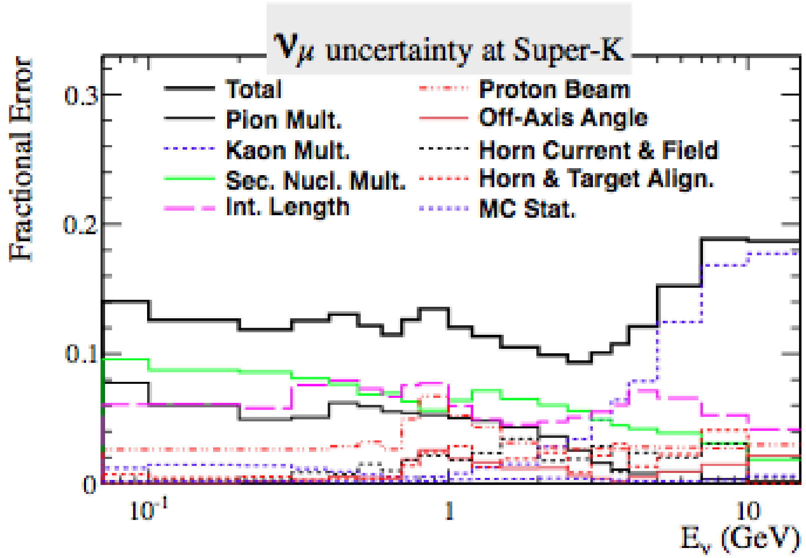




Systematic error sources for neutrino flux

1. **Measurement error on monitoring proton beam**
2. **Hadron production**
3. **Alignment error on the target and the horn**
4. **Horn current & field**
5. **Neutrino beam direction (Off-axis angle)**

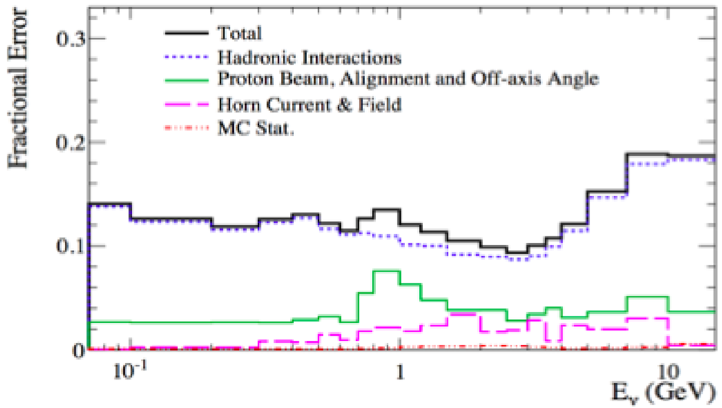




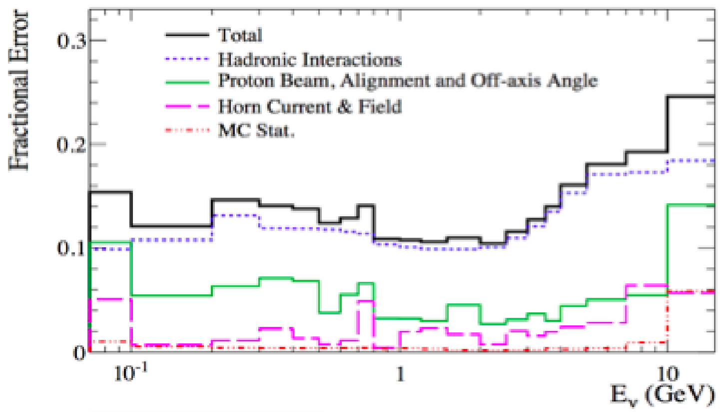
Flux uncertainty

Uncertainties are evaluated based on NA61/SHINE measurements and T2K beam monitor measurements.

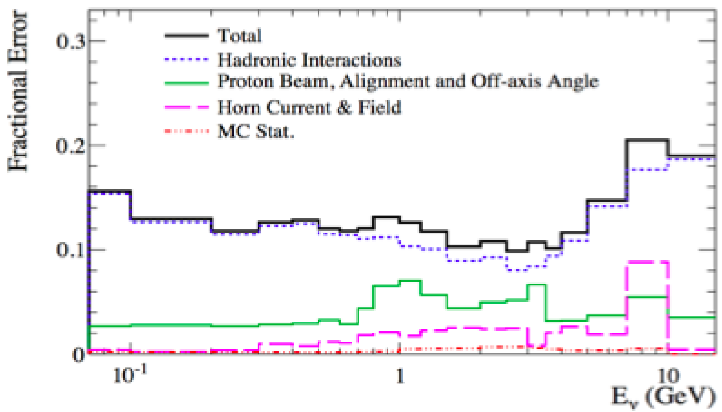
SK ν_μ flux



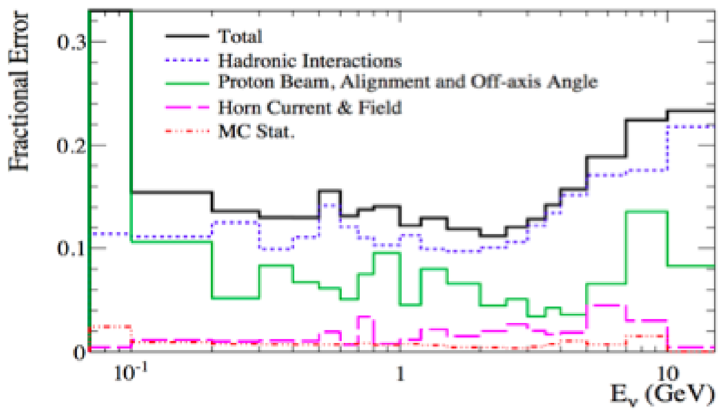
SK ν_e flux



ND280 ν_μ flux

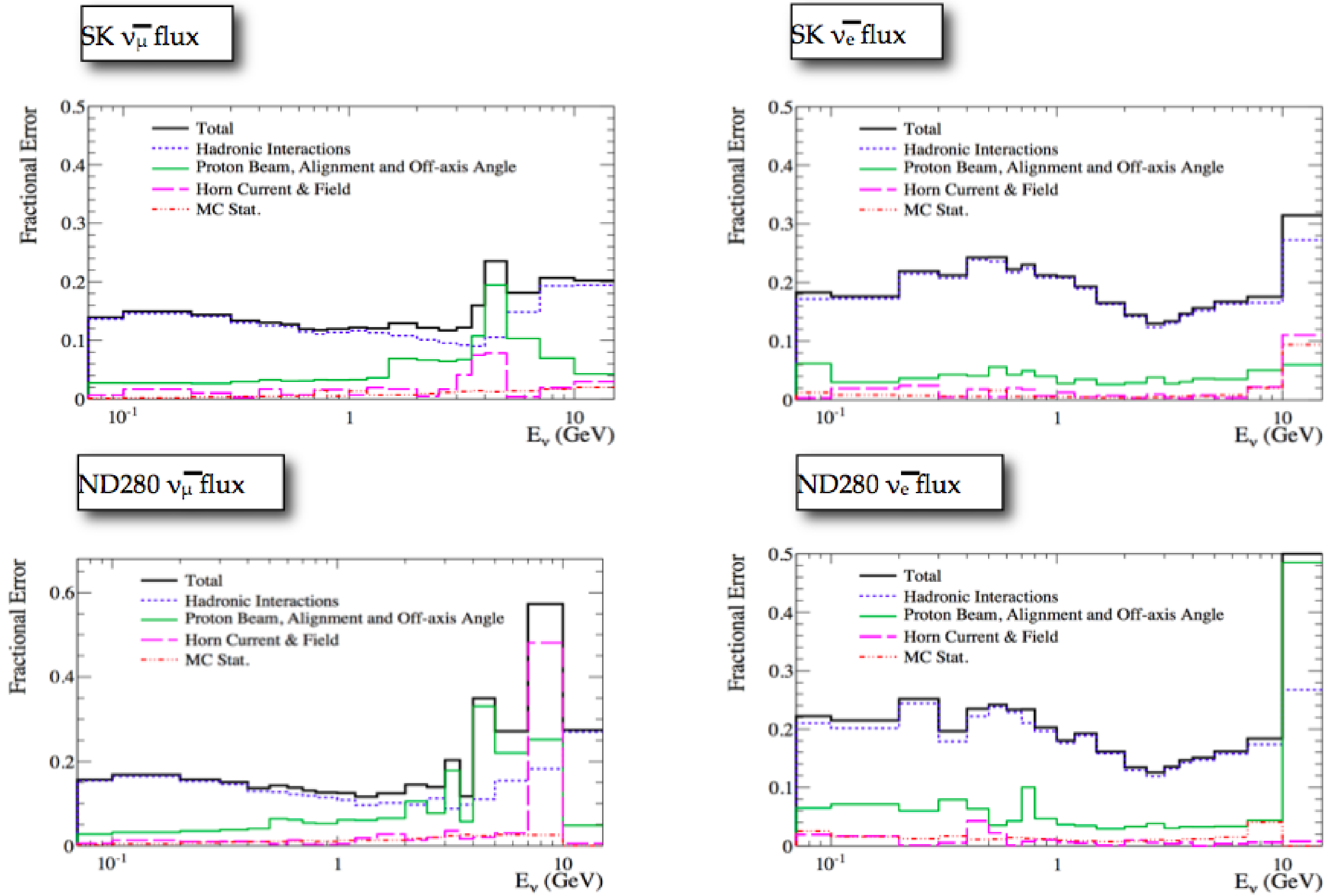


ND280 ν_e flux

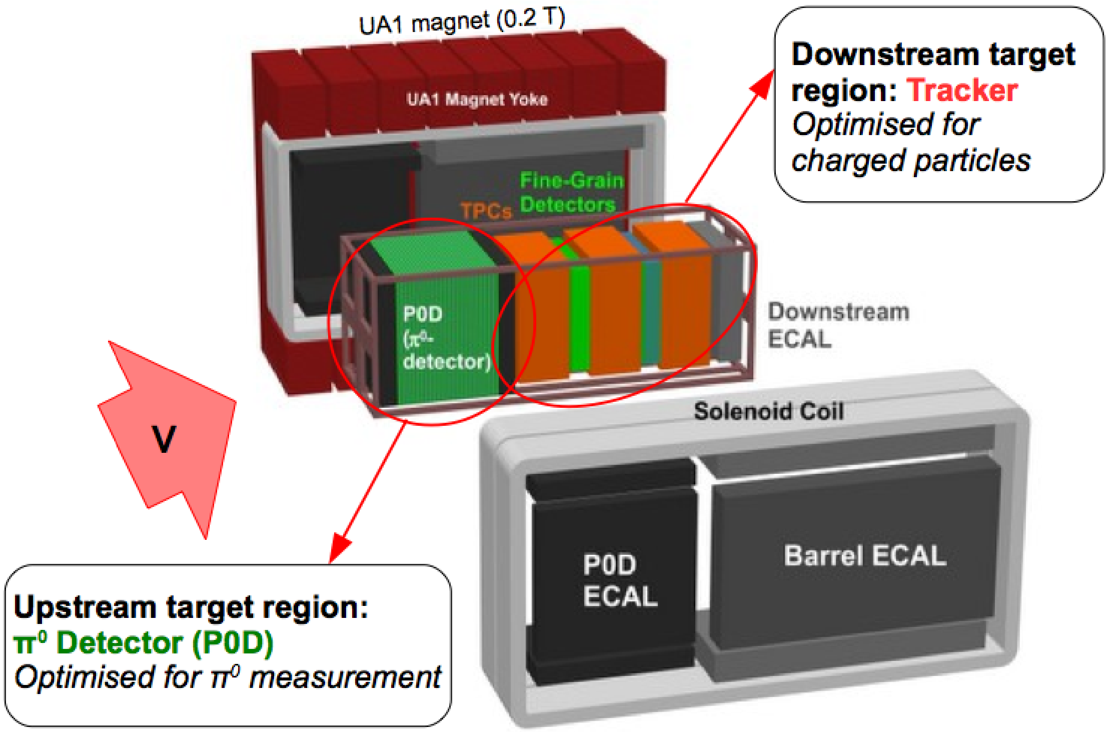


Flux uncertainty

Uncertainties are evaluated based on NA61/SHINE measurements and T2K beam monitor measurements.



The Off-Axis Near Detector at 280 m



Provides measurements of ν flux characteristics and ν+nucleus cross-section measurements.

Fined-grained Scintillator Tracking Calorimeters and Time Projection Chambers in a 0.2T magnetic field.

Polystyrene (Carbon) and water (Oxygen) targets.

Sees a line source, not a point source (range of off-axis angles). Location chosen so that spectrum is similar to the expected unoscillated spectrum at SuperK.

Tracker

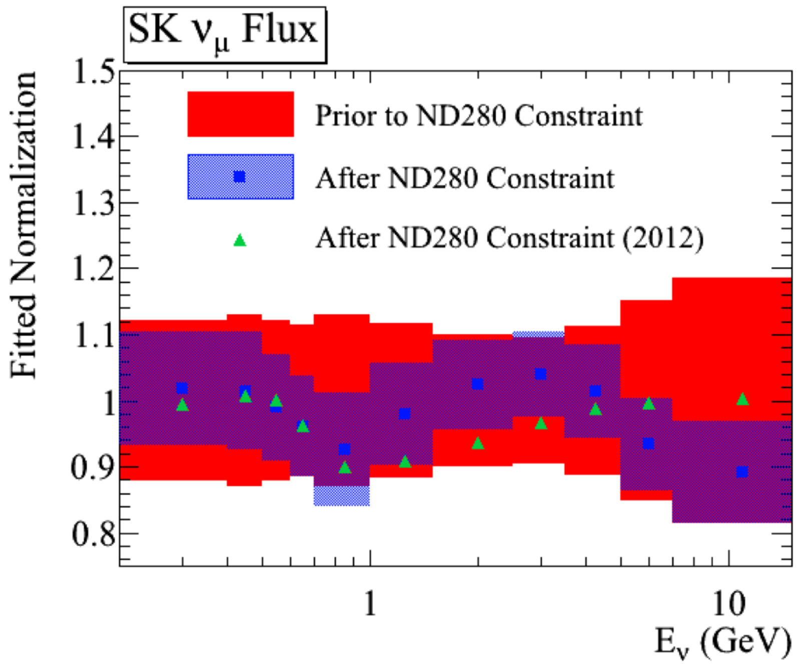
- 2 fine-grained scintillator detectors (FGDs) + 3 time projection chambers (TPCs)
- FGDs provide the target mass (FGD1: 1 ton scintillator, FGD2: 0.5 ton scintillator + 0.5 ton water)
- Momentum measurement of charged particles, PID via dE/dx.

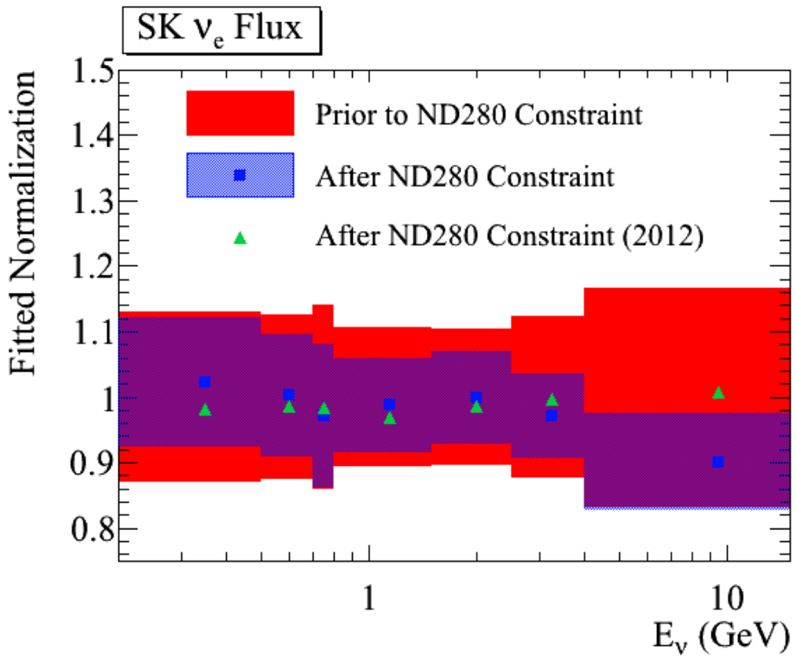
P0D

- Scintillator planes interleaved with lead and water layers.
- 13 tons of lead + 3 tons of water.
- Optimized for γ detection.

Flux and Cross-Section Errors after ND280 Constraint

$\nu_\mu CC0\pi$ (17.5k events) $\nu_\mu CC1\pi^+$ (4k events) $\nu_\mu CCother$ (4k events) samples obtained in the ND280 tracker. Muon angle-momentum distributions fit for a number of flux normalization and cross-section parameters, marginalizing over detector systematics. Constrained parameters reduced uncertainty on SuperK predictions.



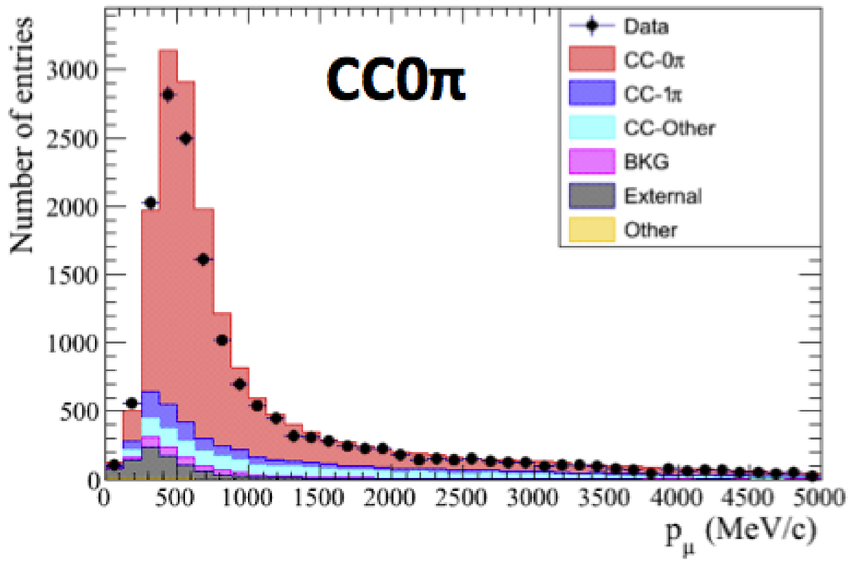


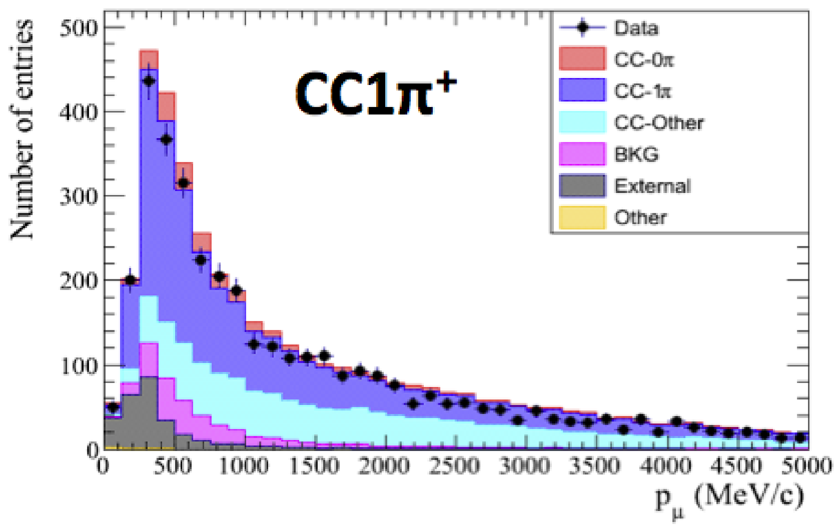
- ND280 constraint reduces both flux and cross-section model uncertainties
  - Uncertainty on number of 1-ring e-like events at SuperK: 27% $\rightarrow$ 9%
  - Uncertainty on number of 1-ring μ-like events at SuperK: 23% $\rightarrow$ 8%
- Flux and cross-section parameters are anti-correlated as a result of imposing the ND280 constraint (constraint is a rate measurement)
  - Correlations fully taken into account in the oscillation fits.

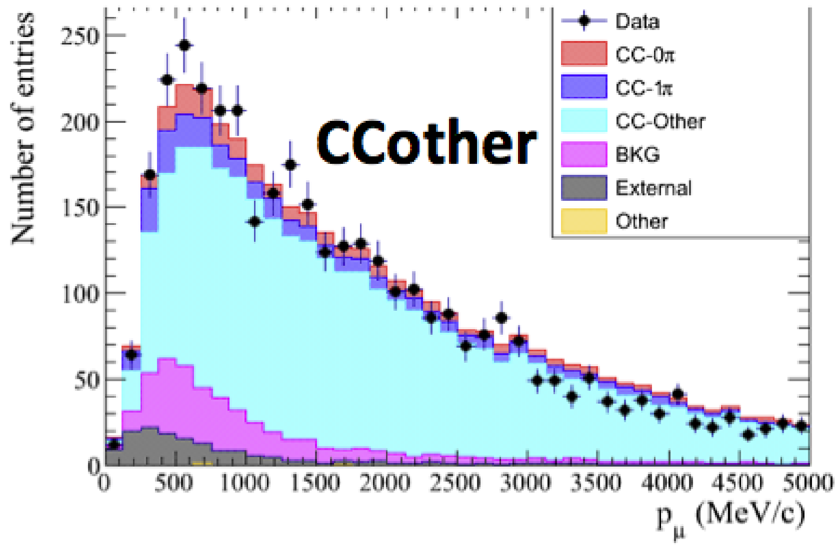
Near Detector Samples for Oscillation Analyses

- Exclusive ν_μCC samples based on final state hadronic topology

True identification of interaction	CC0π sample	CC1π sample	CCother sample
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out of FGD1 Fid Vol	5.1%	6.5%	3.9%

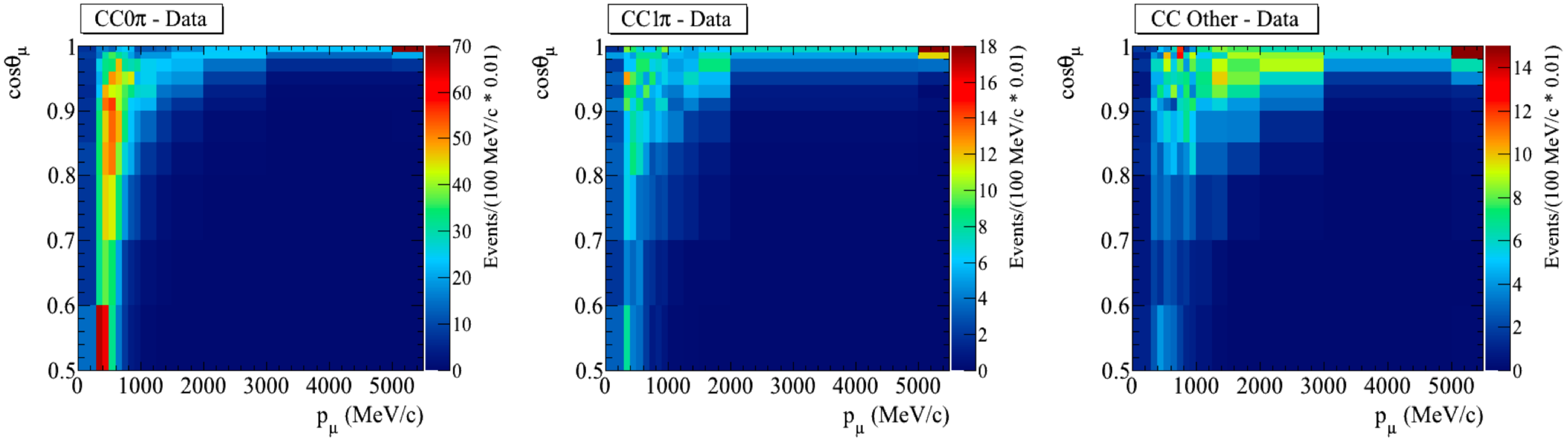






Near Detector Samples for Oscillation Analyses

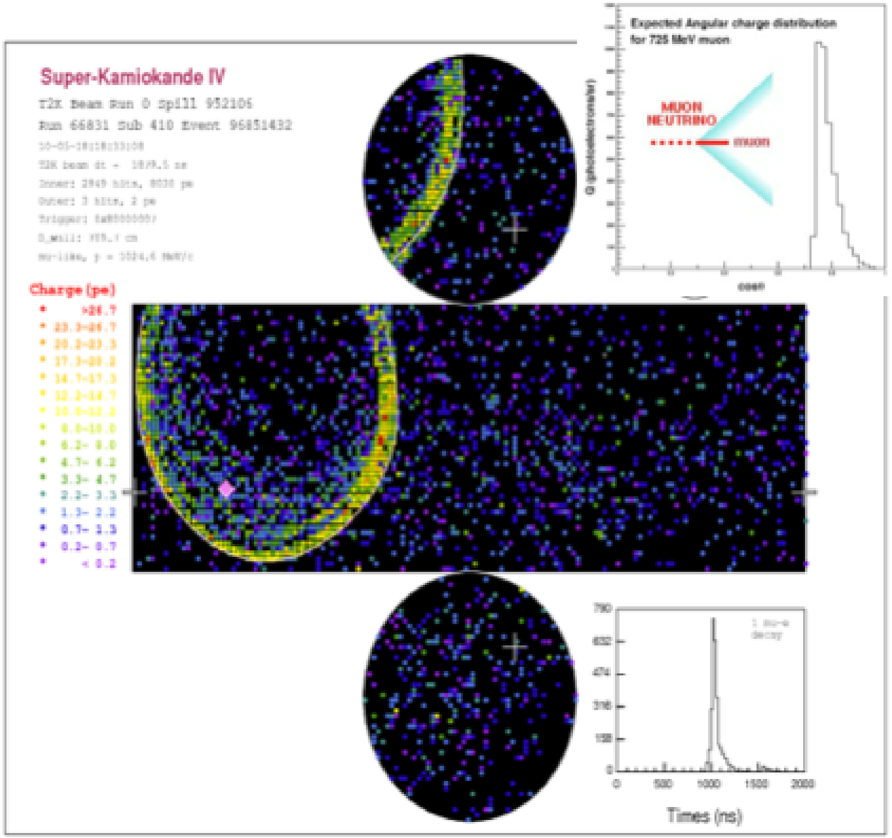
Run 1-4 data binned in muon momentum (p_μ) and angle ($cos\theta_\mu$)

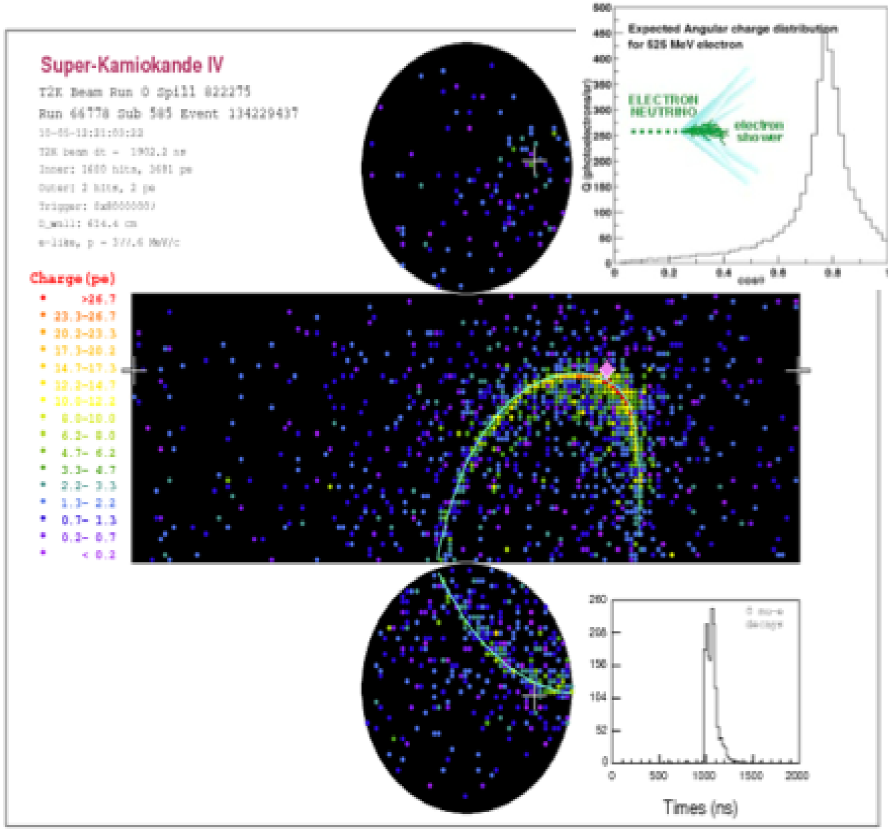


Cherenkov cone opening angle: $cos\theta = 1/\beta n$

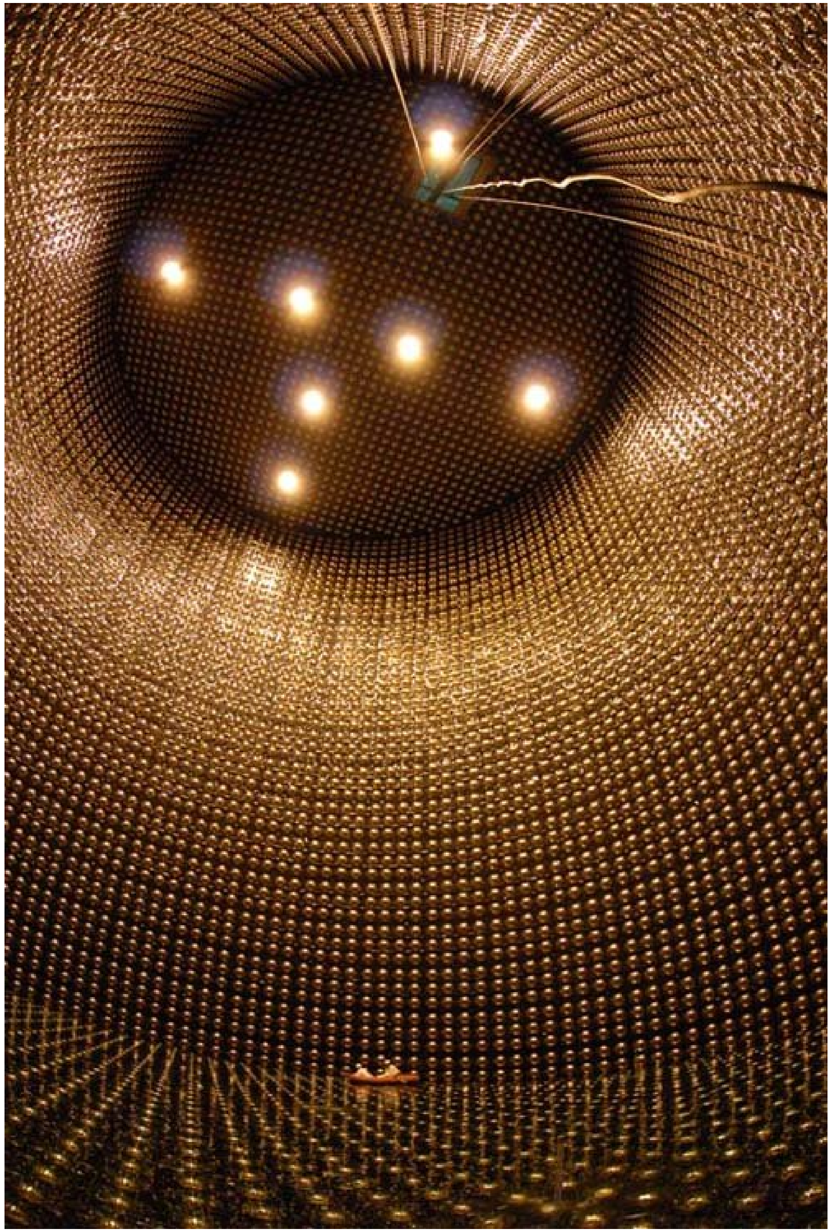
For water $n = 1.33$ (refractive index)

For a highly relativistic particle ($\beta = u/c = 1$) $\theta = 42$ **degrees**

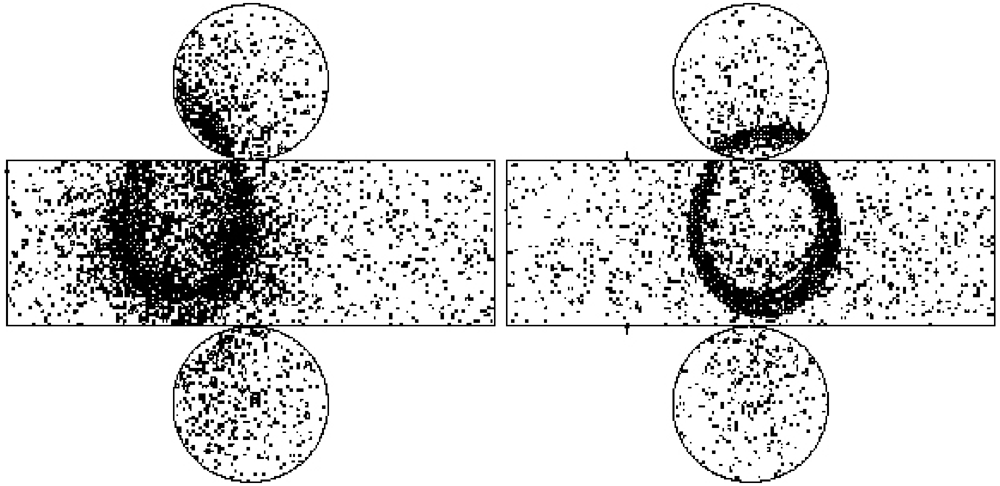




The Far Detector (Super-Kamiokande IV)



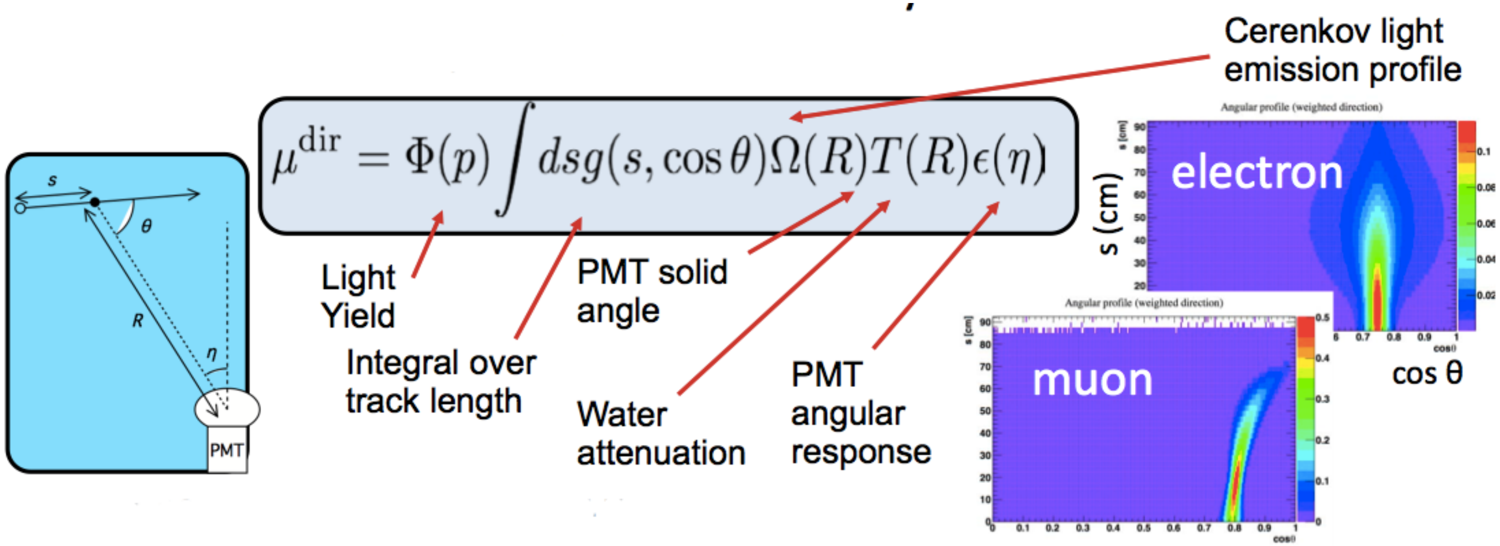
- 50 kt Water Cherenkov detector (22.5 kton fiducial)
- Overburden (shielding): 2700 mwe
- Inner Detector (ID): 11,129 20" PMTs (40% photo-cathode coverage)
- Outer Detector (OD): 1,885 8" PMTs
- Energy threshold: $\sim$ 4.5 MeV



SuperK event reconstruction improvements (fiTQun)

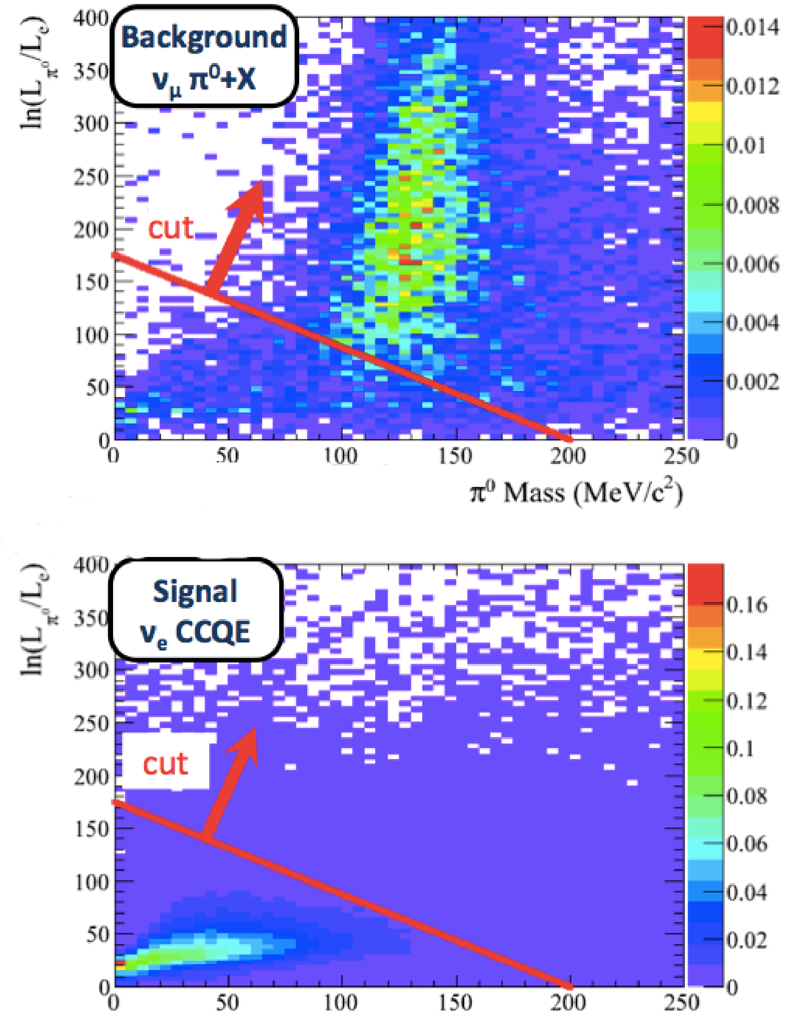
- Each SuperK event: **Charge** and **time** recorded for every PMT.
- Charge and time PDFs can be produced for each PMT for each event topology hypothesis
  - Based on the MiniBooNE reconstruction algorithm (NIM A608, 2006 (2009))
- Fit determines parameters for each hypothesis (for 1-ring hypotheses: vertex (x,y,z,t), momentum (p), direction (θ, ϕ))
- Event hypotheses distinguished by **comparing best-fit likelihoods**.
- The main challenge in producing the charge and time PDFs is to predict the number of photons at the PMT (predicted charge)

Calculation of predicted charge from *direct* light (charge from *in-direct* light is also taken into account in the PDF calculation):



SuperK event reconstruction improvements (fiTQun)

Likelihood ratio vs π^0 mass (MC)

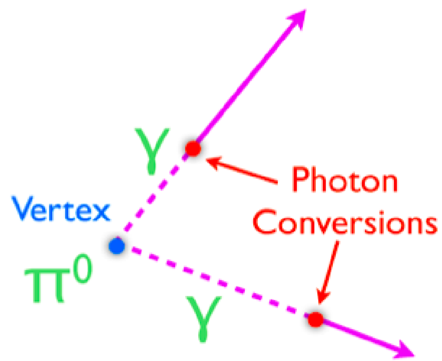


The new reconstruction algorithm was applied in the ν_e appearance analysis and provided an **enhanced π^0 rejection**.

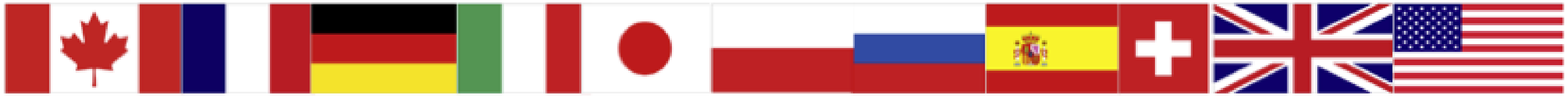
Much better π^0 rejection efficiency for events with a low energy photon.

Removes 70% more π^0 background than previous algorithm with only a 2% additional signal efficiency loss.

π^0 fitter: The new reconstruction assumes two e-like rings at a common vertex. It determines 12 parameters (vertex (x,y,z,t), directions (θ_1, ϕ_1, θ_2, ϕ_2), momenta (p_1, p_2), conversion lengths (L_1, L_2))



The T2K Collaboration



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