Results from T2K

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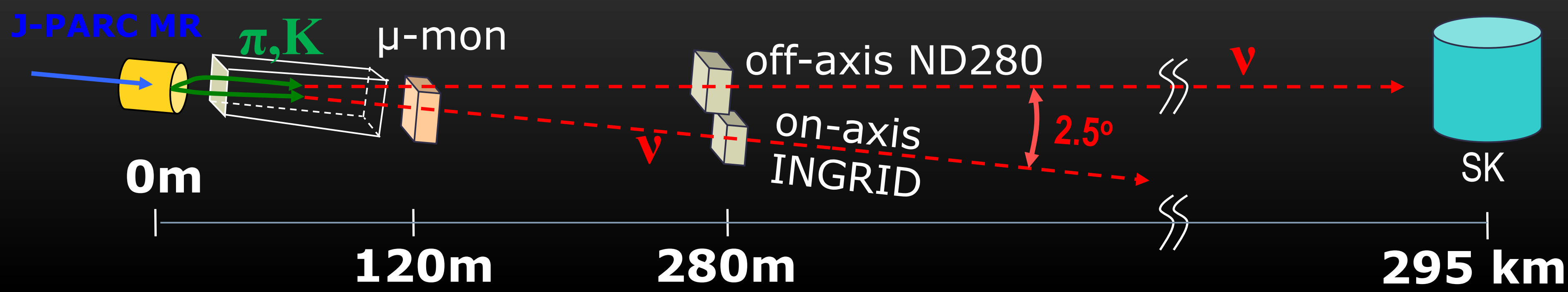
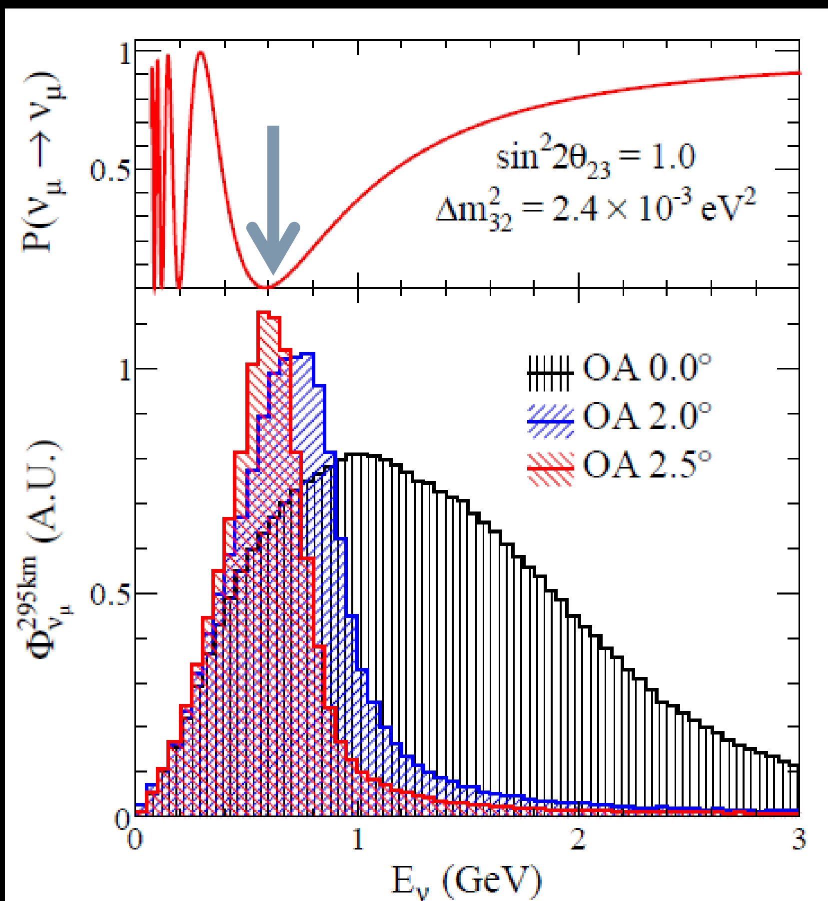
for the T2K collaboration

Outline

- Introduction
- Measurement of ν_μ disappearance
- Measurement of ν_e appearance
- Summary & conclusions

T2K neutrino beamline





- Off-axis ν_μ beam
  - Tuned to oscillation maximum (~0.6 GeV)
    → high statistics in the region of the oscillation signal
  - Low energy narrow band neutrino beam
    → less background caused by high energy neutrinos
  - Beam direction controlled to better than 1 mrad (~2% shift in peak energy) ← INGRID

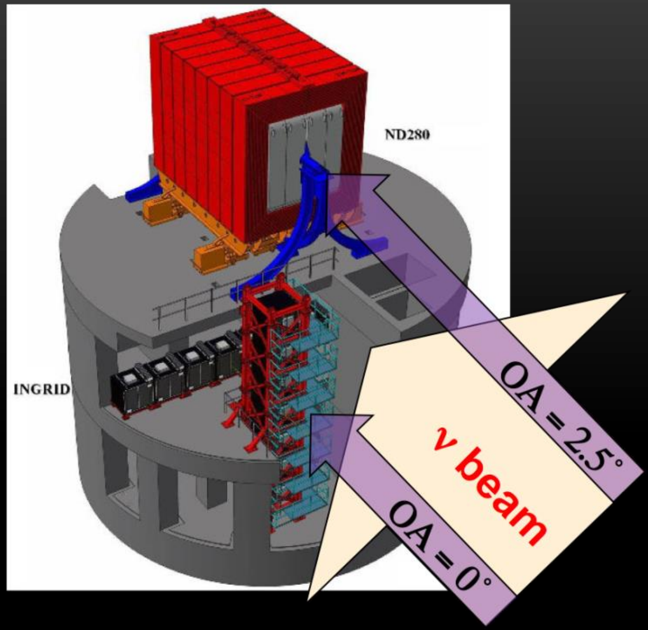
Near detectors

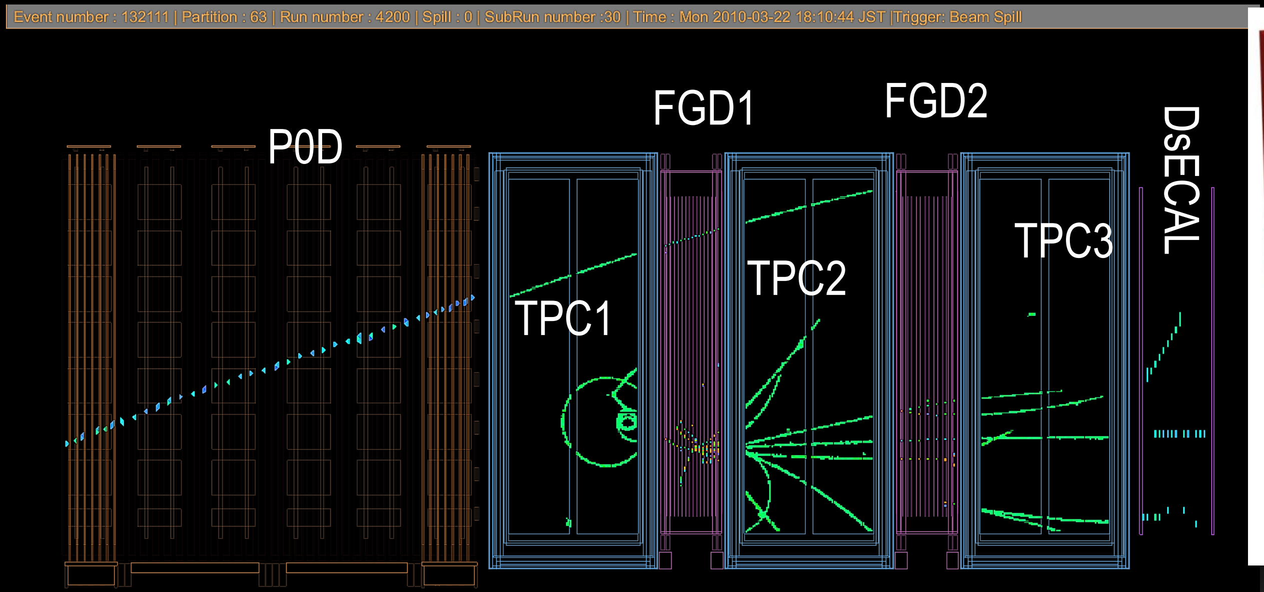
INGRID (on-axis)

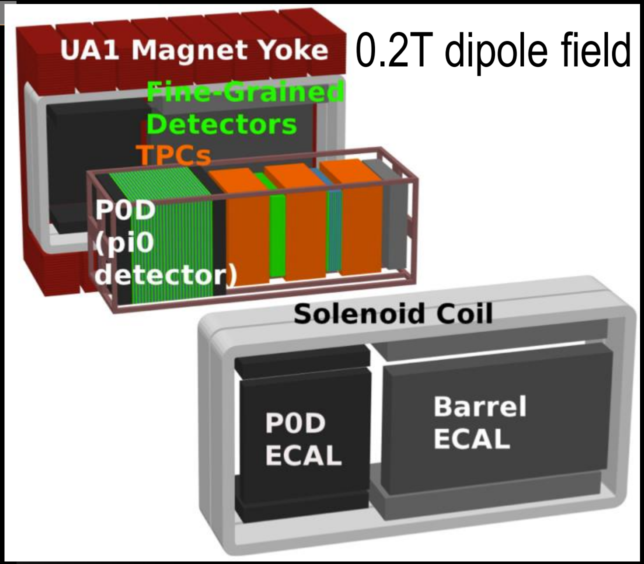
- Measure beam direction
- Monitor ν beam stability

ND280 (off-axis)

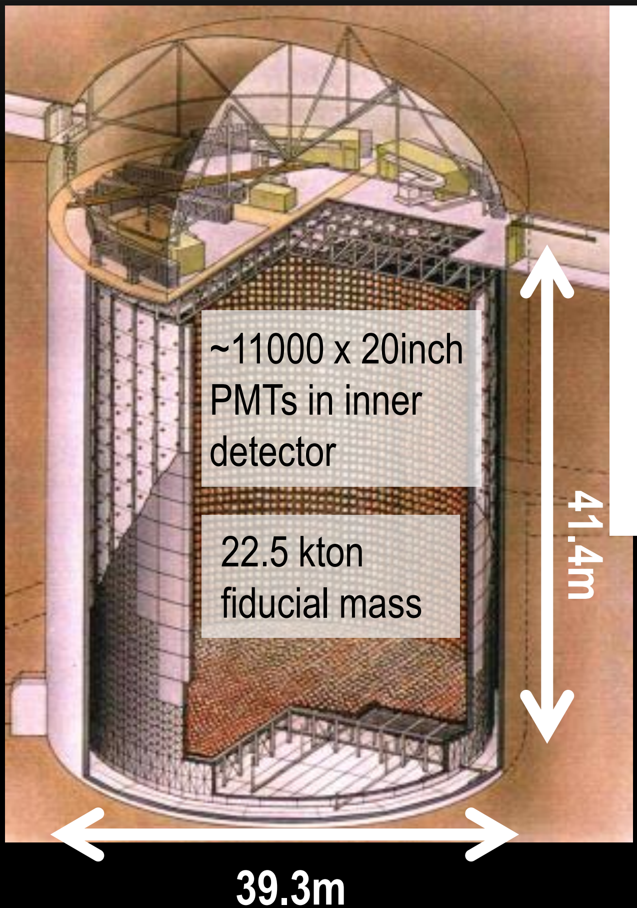
- Measure ν beam composition and energy spectrum in direction of the far detector
- Measure interaction cross sections for different channel

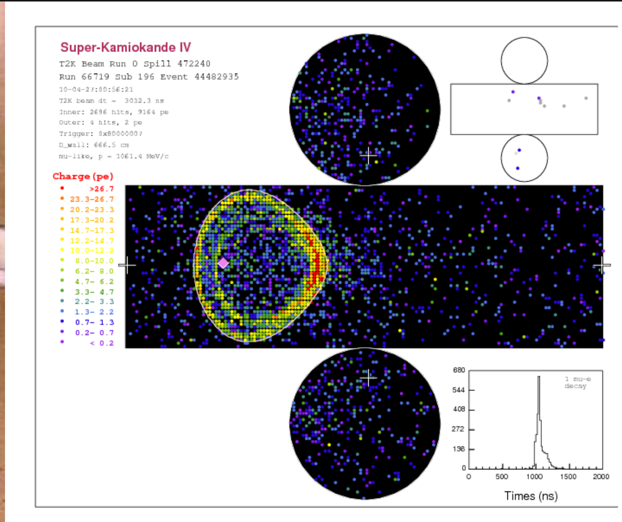


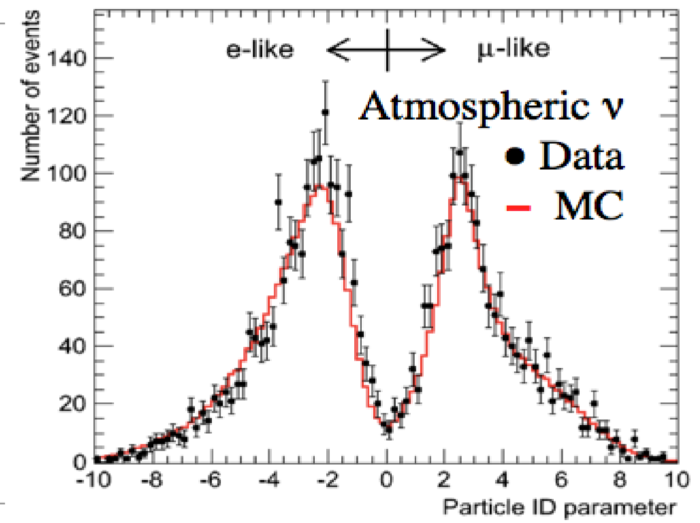




Far detector: Super-Kamiokande (SK)



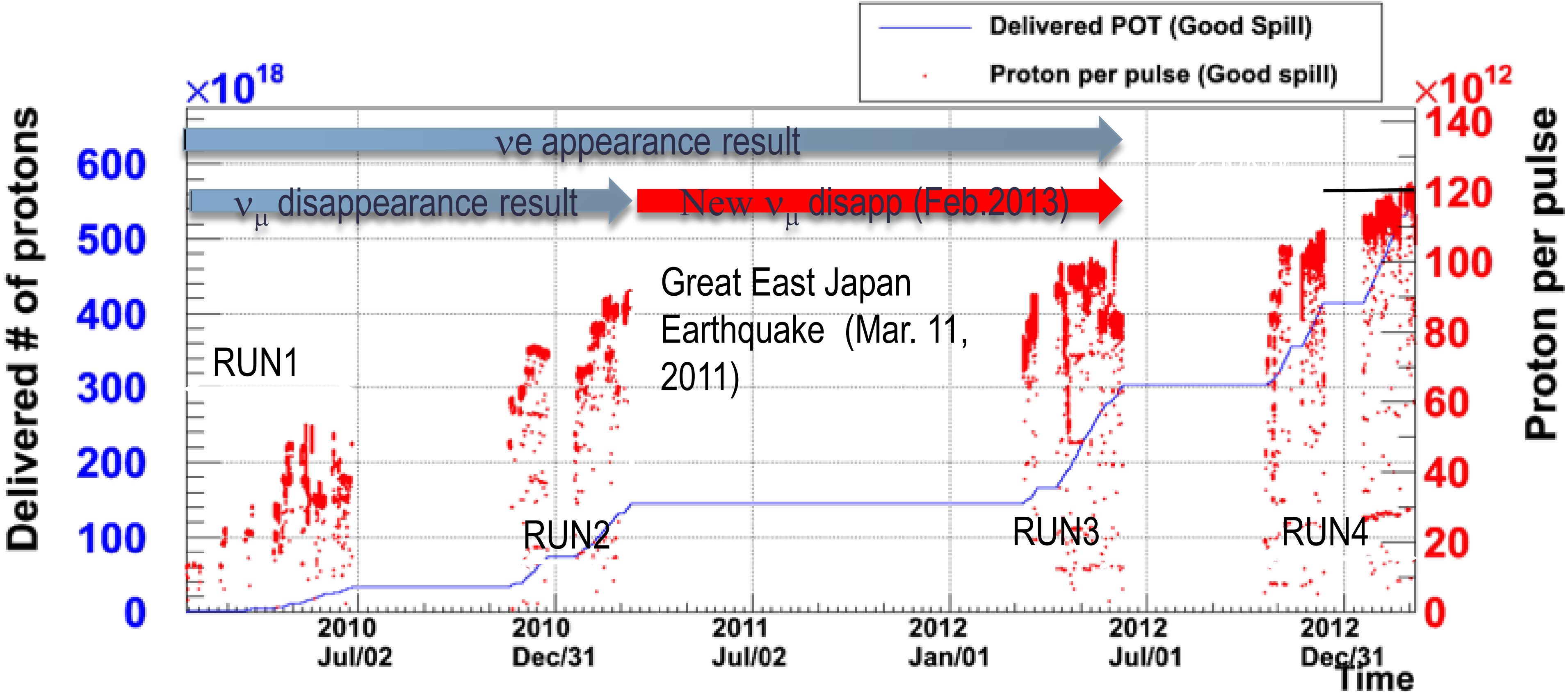




- Good separation between μ and e by Cherenkov ring profile (mis-identification probability ~1%)
- All events are recorded within ±500 μsec window synchronized to the beam arrival time

History of data-taking

Reached 230 kW stable operation ($>10^{14}$ protons per pulse)

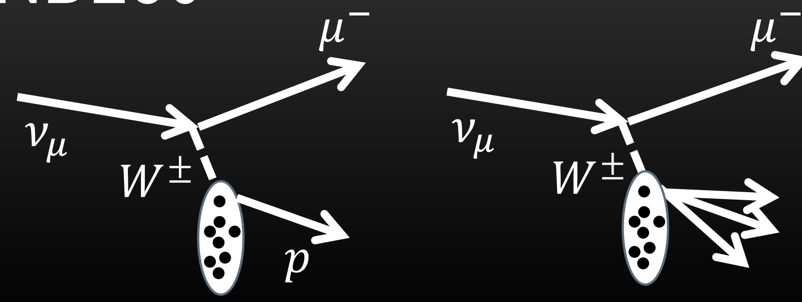


Run 1 + Run 2: 1.43×10^{20} POT

Run 3 1.58×10^{20} POT

Results shown in this talk are based on 3.01×10^{20} POT ← ~4% of total T2K approved POT 7.8×10^{21}

Constraining flux $\times$ ν xsec with ND280



CCQE

CCnonQE

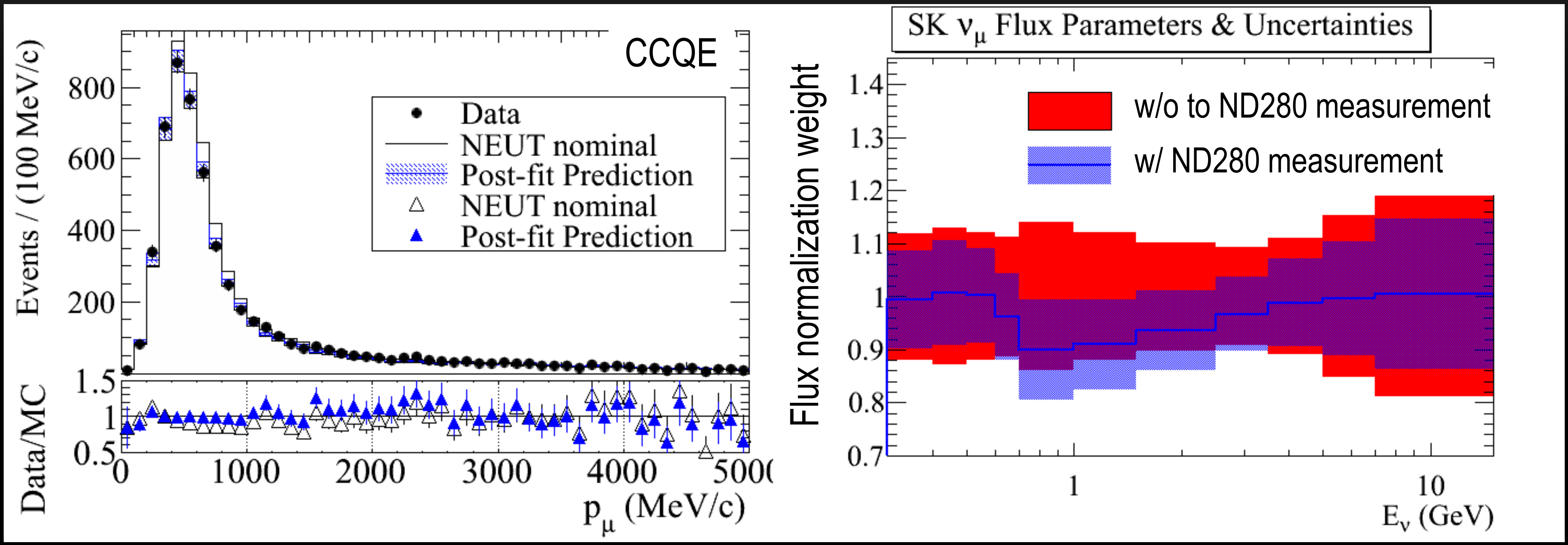
Predicted neutrino flux
[arXiv:1211.0469, PRD 87 (2013) 012001]
tuned w/ hadron production measurements from NA61 @ CERN

ND280 ν_μ CCQE and CCnonQE selection + detector sys. uncertainties

ν interaction cross-section models
NEUT + constraints from available data

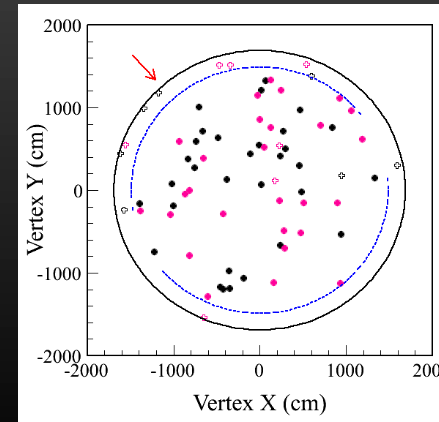
Fit measured $p_\mu - \theta_\mu$ distribution to constrain flux and cross-section model parameters

ND280 constraint

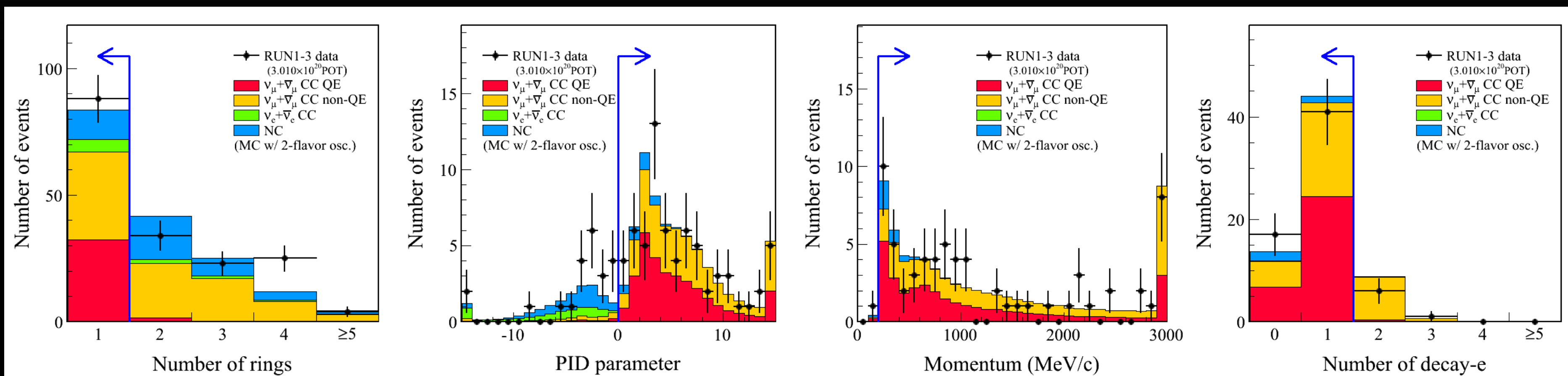


- Weights to correct the predicted event rates at the near and far detectors are obtained
- Prior systematic uncertainties are constrained

ν_μ event selection at the T2K far detector



- Event in the fiducial volume & compatible w/ beam timing
- Single ring only (CCQE-tailored, for which one can accurately recon E_ν)
- PID is μ-like
- Reconstructed momentum greater than 200 MeV/c
- Number of decay electron ≤ 1

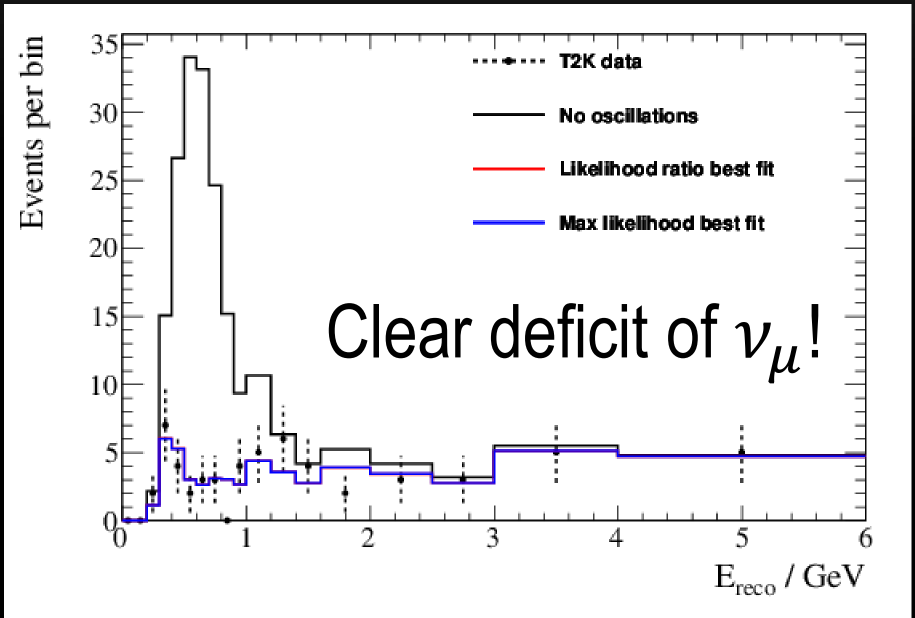


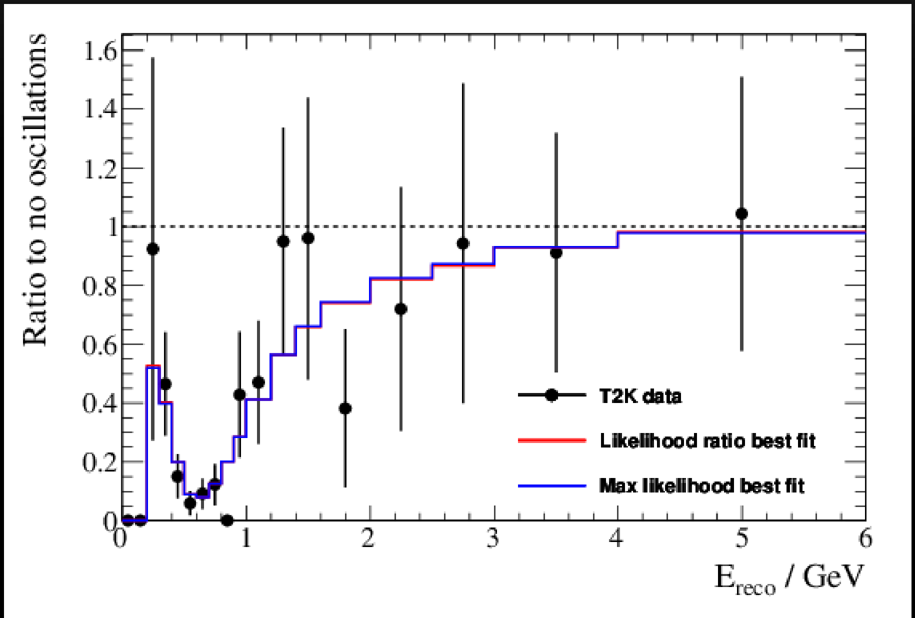
	Data	MC Total
FCVF	174	168.9
One-ring	88	85.7
μ-like	66	69.7
p_μ>200MeV/c	65	69.3
Ndcy <= 1	58	59.9

$$\sin^2\theta_{23} = 1.0$$
$$\Delta m^2_{32} = 2.4\times10^{-3}\text{eV}^2$$

57% CCQE
38% CCnonQE
5% NC

Fit results



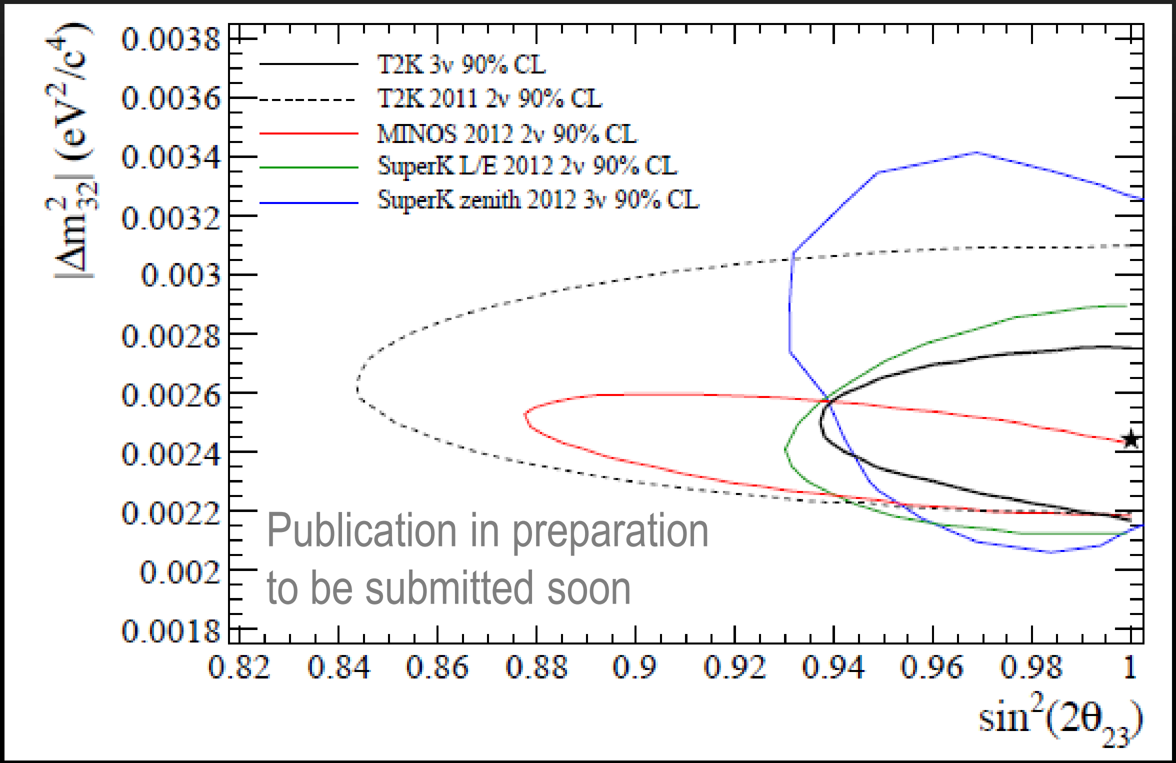


Best fit point:

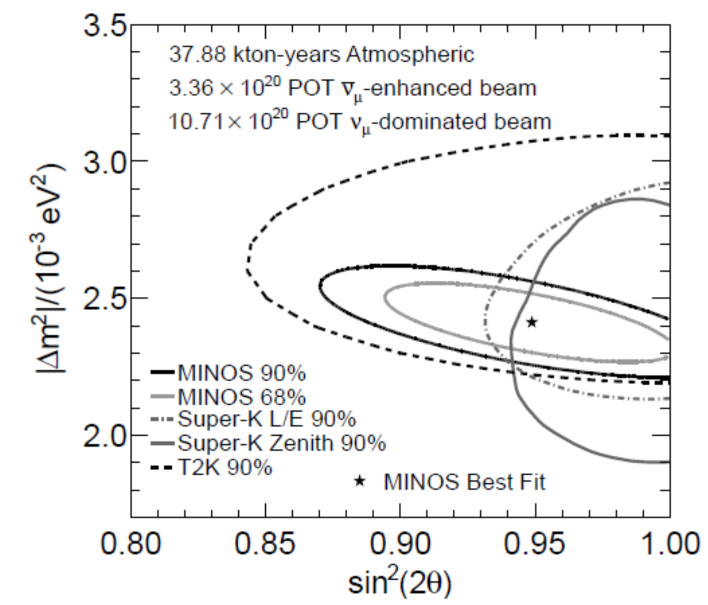
$$\sin^2 2\theta_{23} = 1.0$$

$$|\Delta m^2_{32}| = 2.44 \times 10^{-3} \mathrm{eV}^2$$

Parameter limits



New MINOS result: combined fit of beam and atm. results: hep-ex 1304.6335

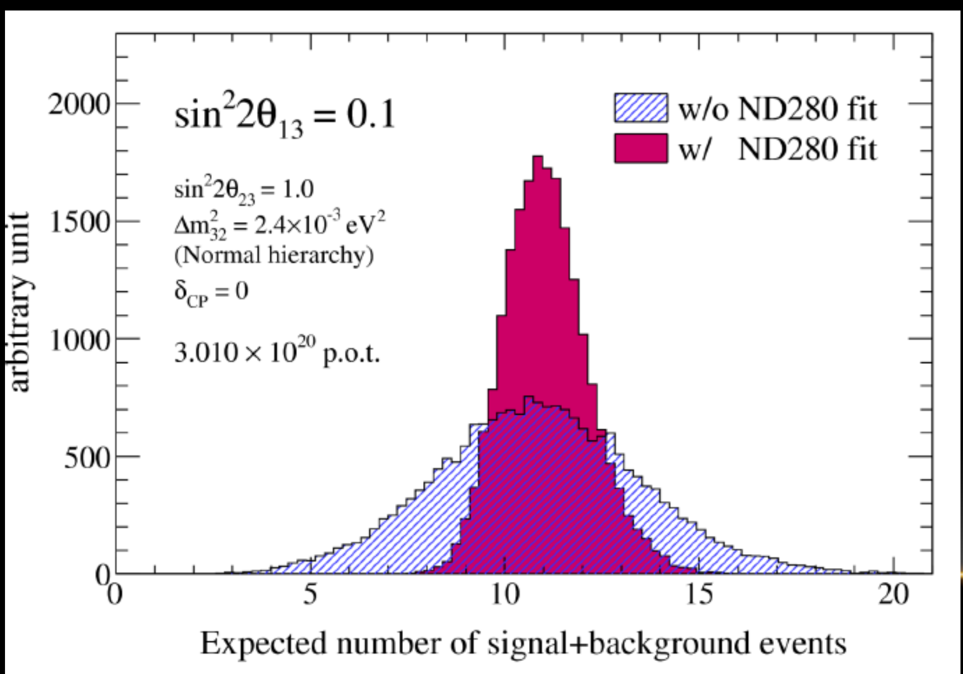


Measuring maximal mixing
Dominated by statistical uncertainty

Predicted number of ν_e events

Predicted # of events with 3.01 x 10^{20} POT

Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.28	11.16
ν_e signal	0.19	8.20
ν_e background	1.75	1.63
ν_μ background	1.18	1.18
$\overline{\nu}_\mu$ background	0.07	0.07
$\overline{\nu}_e$ background	0.09	0.09



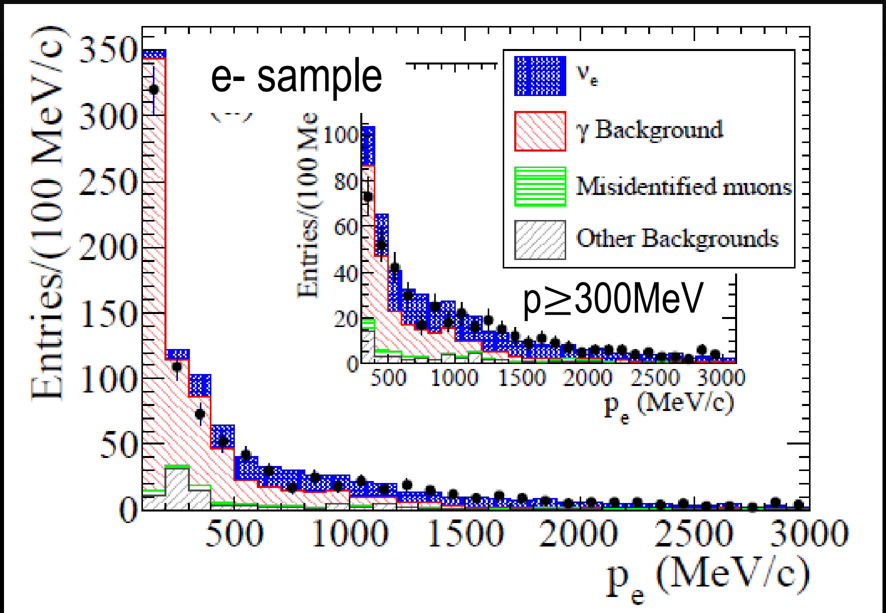
Systematic uncertainties

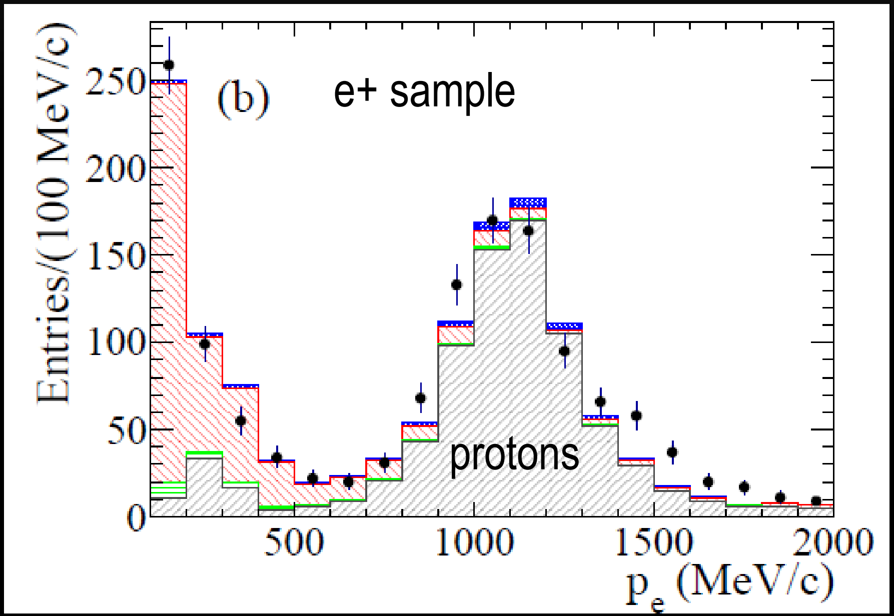
Error source	$\sin^2 2\theta_{13}$	
	0.0	0.1
Flux + xsec (w/ ND280)	8.5	5.0
xsec (from other exp.)	6.5	7.7
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0%	9.9%

Uncertainties are reduced with ND280 measurement

Beam ν_e measurement at ND280

- Intrinsic beam ν_e is the main irreducible background for $\nu_\mu \rightarrow \nu_e$
- Check whether measured ν_e rate is consistent with expectation



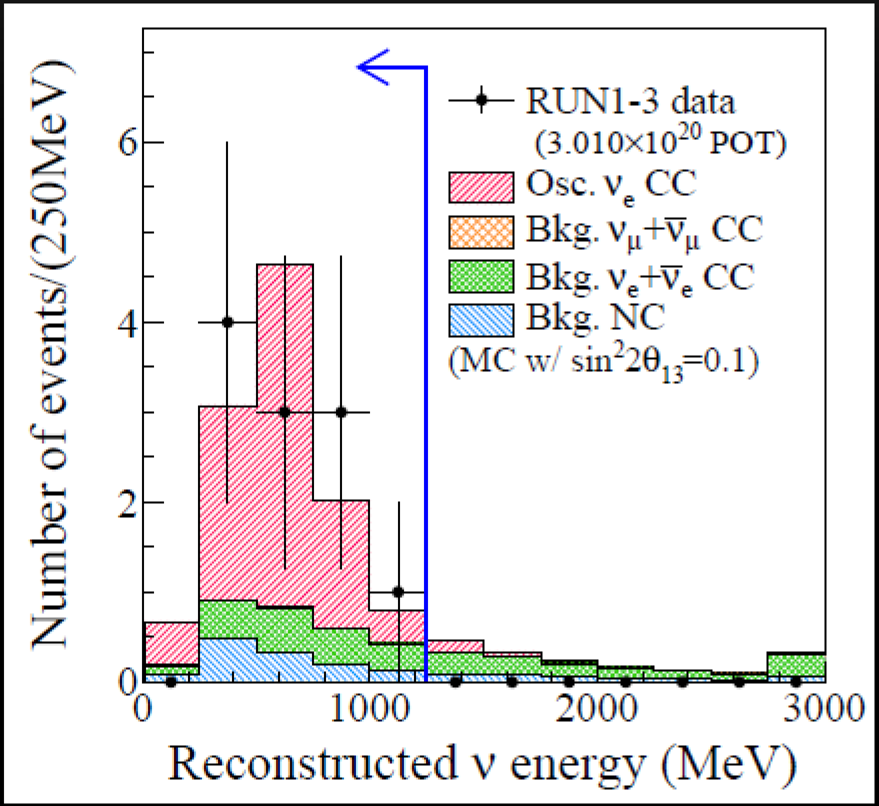


- Simultaneously fit e^- & e^+ samples to determine ν_e and γ normalizations

$$CC\ \nu_e\ Data/MC = 0.88 \pm 0.10(stat.) \pm 0.15(syst.)$$

Selection of ν_e candidates at T2K

3.01E+20 POT	Data
Fully contained FV	174
Single ring	88
e-like	22
$E_{vis} > 100$ MeV	21
No decay e	16
2γ invariant mass cut	11
$E_\nu^{rec} < 1250$ MeV	11



After selection cuts:

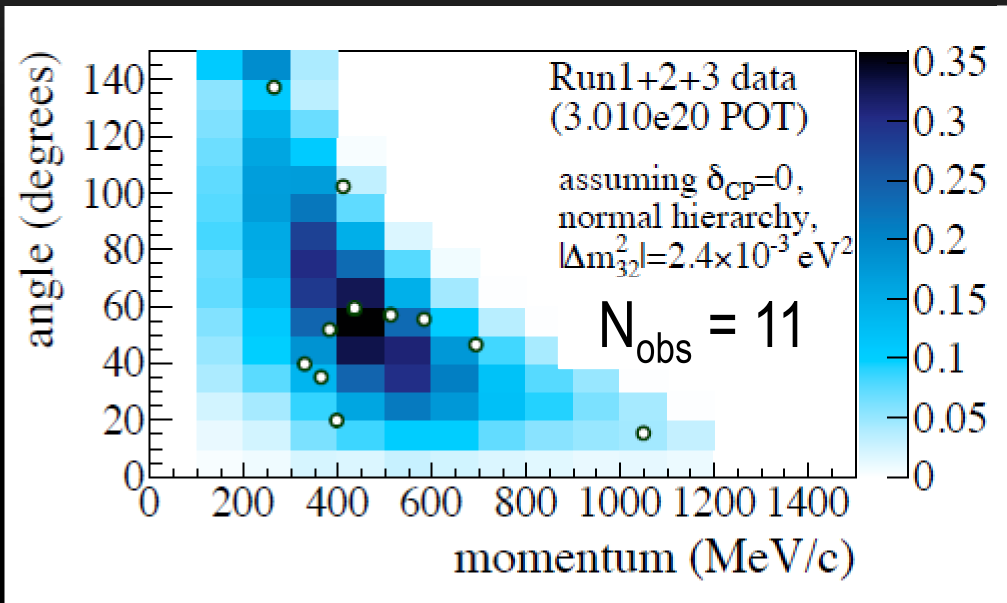
11 candidate events are observed

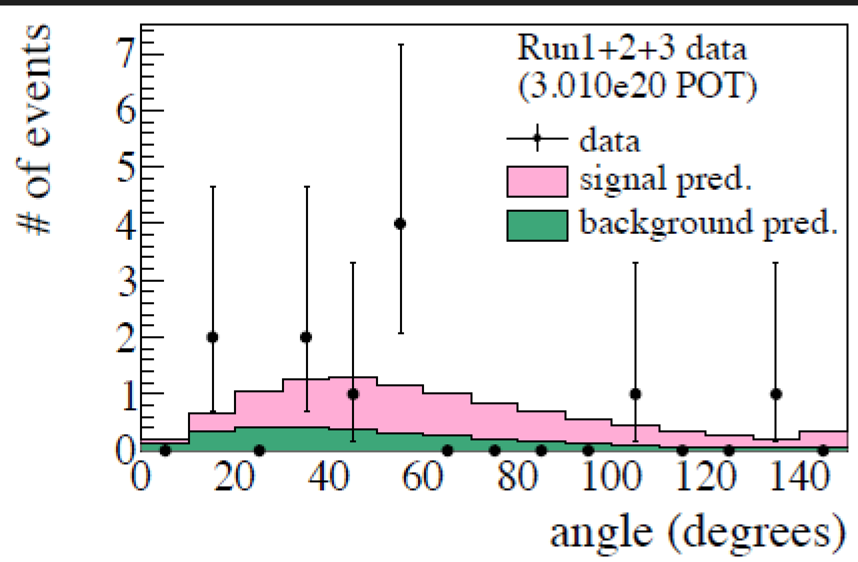
11.2 are expected for $\sin^2 2\theta_{13} = 0.1$

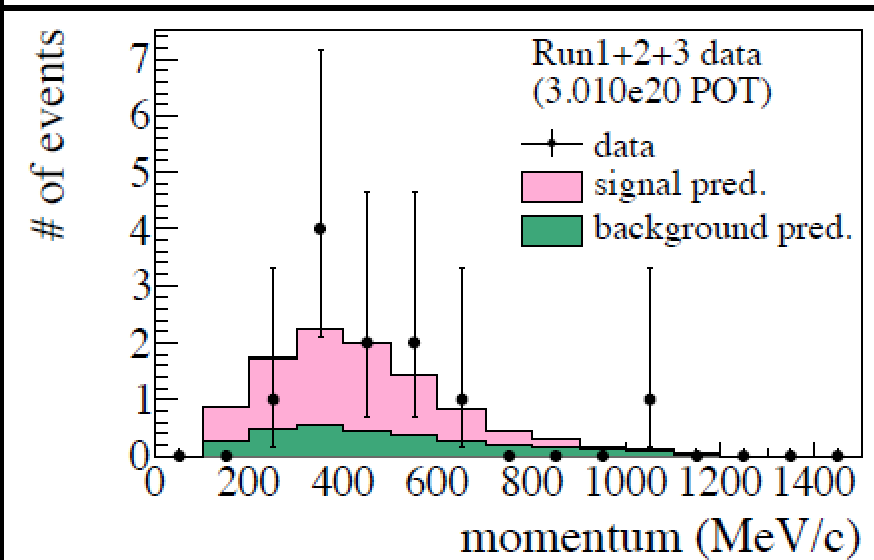
Results

$$\mathcal{L}(N_{obs.}, x; o, f) = \mathcal{L}_{norm}(N_{obs.}; o, f) \times \mathcal{L}_{shape}(x; o, f) \times \mathcal{L}_{syst.}(f)$$

Total rate — Shape of (p_e, θ_e) — Sys. param.







Assuming $\delta_{CP} = 0$, normal mass hierarchy, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV², $\sin^2 2\theta_{23} = 1$

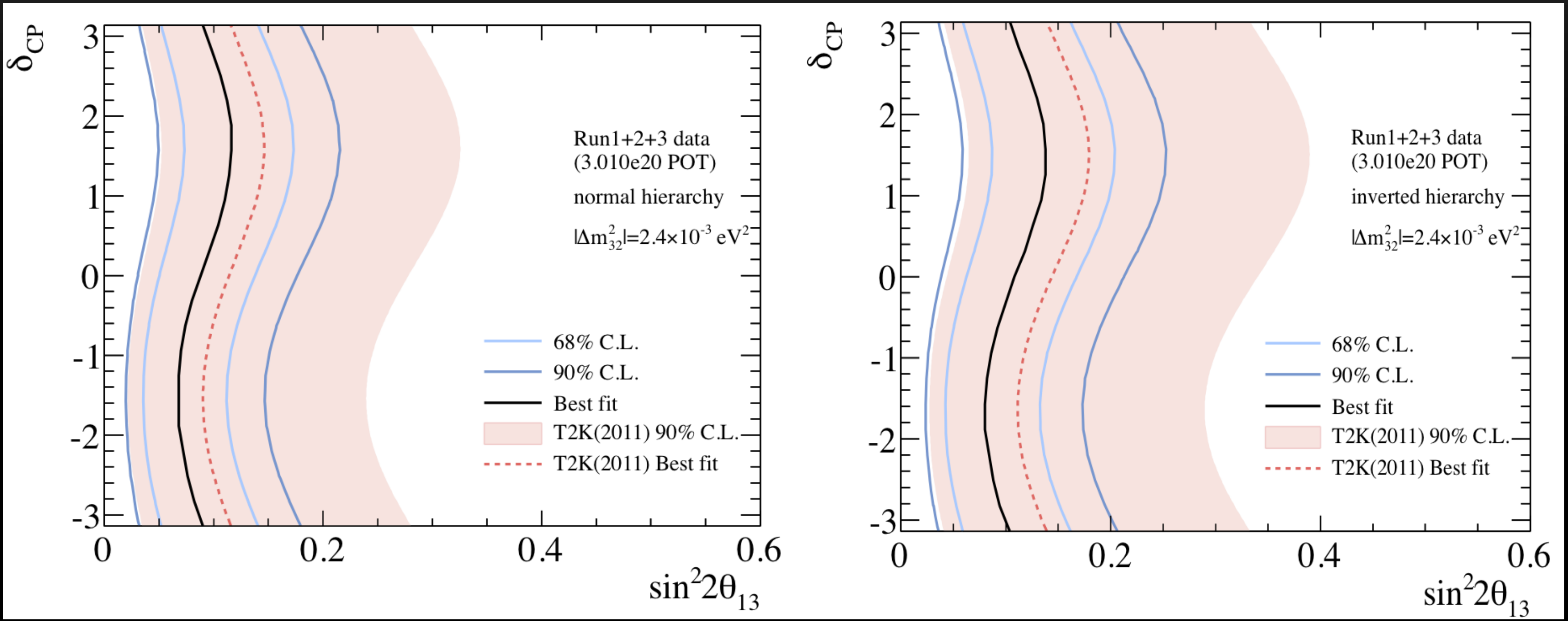
w/ the above osc. parameters fixed:

Best fit w/ 68% C.L. errors:

$$\sin^2 2\theta_{13} = 0.088^{+0.049}_{-0.039}$$

Allowed regions of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

ArXiv 1304.0841, submitted to PRD



Best fit @ δ_{CP} = 0.0:

Normal hierarchy:

$$\sin^2 2\theta_{13} = 0.088^{+0.049}_{-0.039}$$

$$0.030 < \sin^2 2\theta_{13} < 0.175$$

Inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.108^{+0.059}_{-0.046}$$

$$0.038 < \sin^2 2\theta_{13} < 0.212$$

In summary …

- With ~4% of the total POT we plan to collect:
  - T2K has already the world's best precision on θ_{23}
  - Observed 11 ν_e candidate events → $\sin^2 2\theta_{13} = 0$ excluded at 3.1σ
- Data taking is on-going and the goal is to collect $\sim 8 \times 10^{20}$ POT by July 2013 ← almost 3x more than what was shown today

T2K program

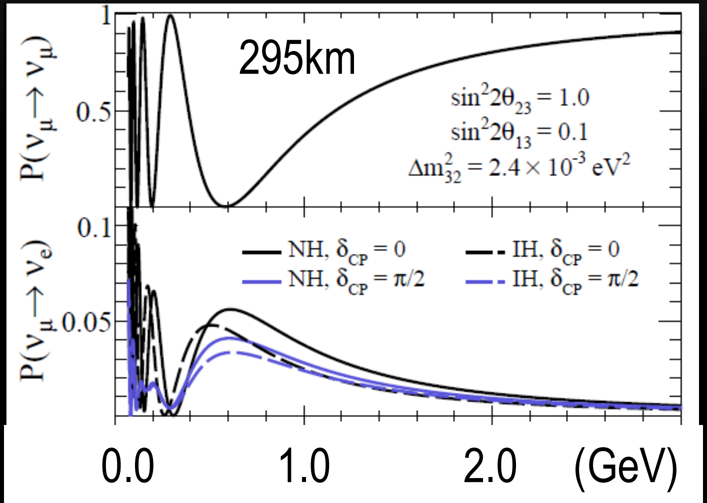
- Precision measurement of disappearance
  - Is θ_{23} really maximal?
  - Precise measurement is also important for probing CPV
- Precision measurement of ν_e appearance
  - Try to see first hints of CPV
- Cross-section measurements at ND280
- Explore possibility of measurements with anti-nu beam

Extra

PMNS matrix elements and mass differences in long baseline neutrino oscillation experiments

❖ ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



❖ ν_e appearance:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + (CPV\ term) + (Subleading\ terms)$$

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

Sensitive to the CPV phase δ. All mixing angles need to be non-zero

Through matter effects sensitive to the sign of Δm^2_{31} →MH

Numu events @ SK

RUN1+2+3 3.010×10^{20}POT	Data	MC Expectations w/ oscillation				
		MC total	$\nu_\mu+\bar{\nu}_\mu$ CCQE	$\nu_\mu+\bar{\nu}_\mu$ CC non-QE	$\nu_e+\bar{\nu}_e$ CC	NC
True FV	-	299.35	49.67	109.50	8.62	131.56
FCFV	174	168.86	37.60	82.80	8.24	40.23
One-ring	88	85.65	35.27	33.67	5.28	11.43
μ-like	66	69.67	34.58	31.61	0.04	3.43
p_μ>200MeV/c	65	69.25	34.34	31.54	0.04	3.33
N_{dcy-e}<=1	58	59.86	33.90	22.73	0.04	3.19
Efficiency [%]	-	20.0	68.2	20.8	0.4	2.4