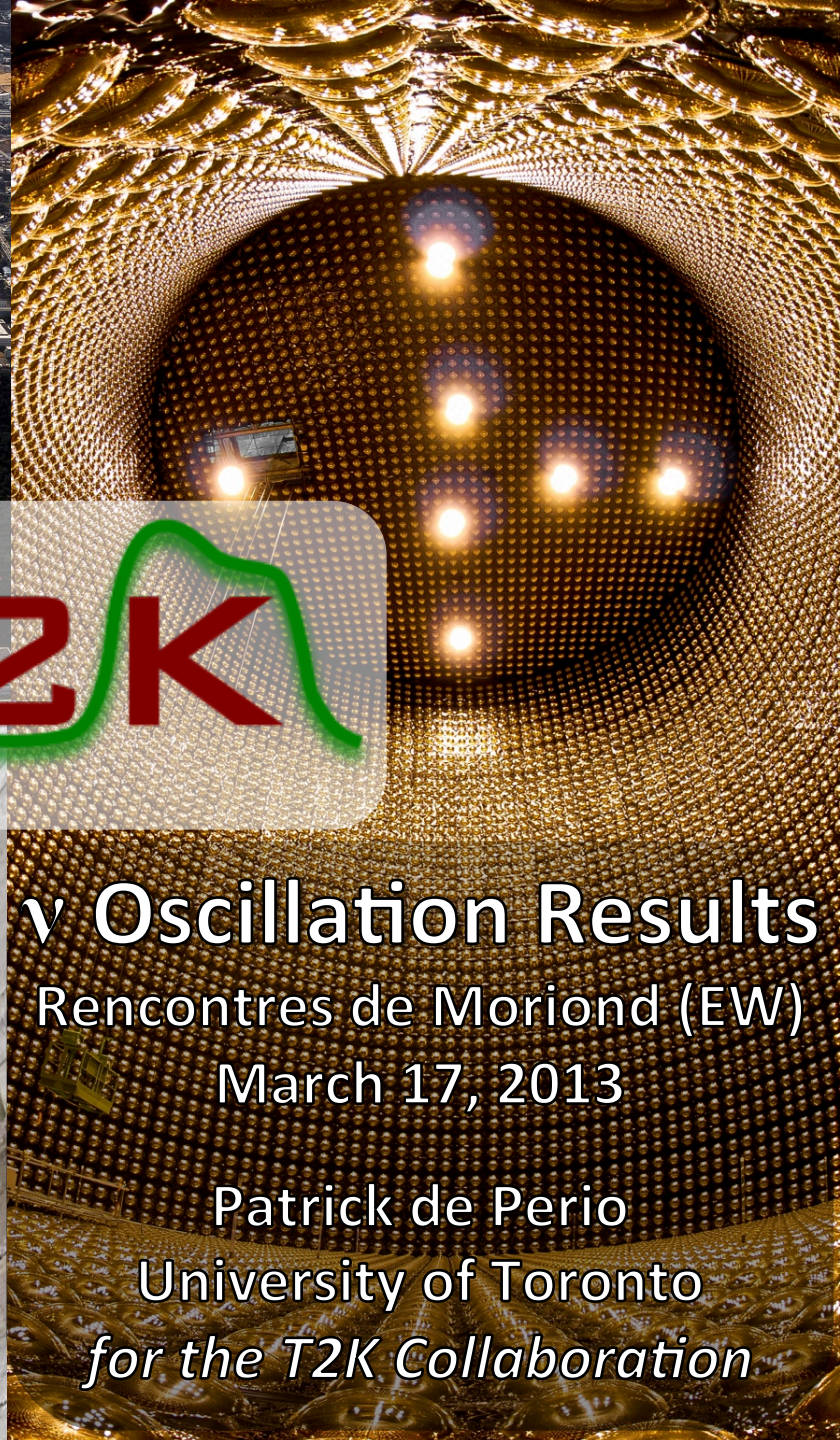
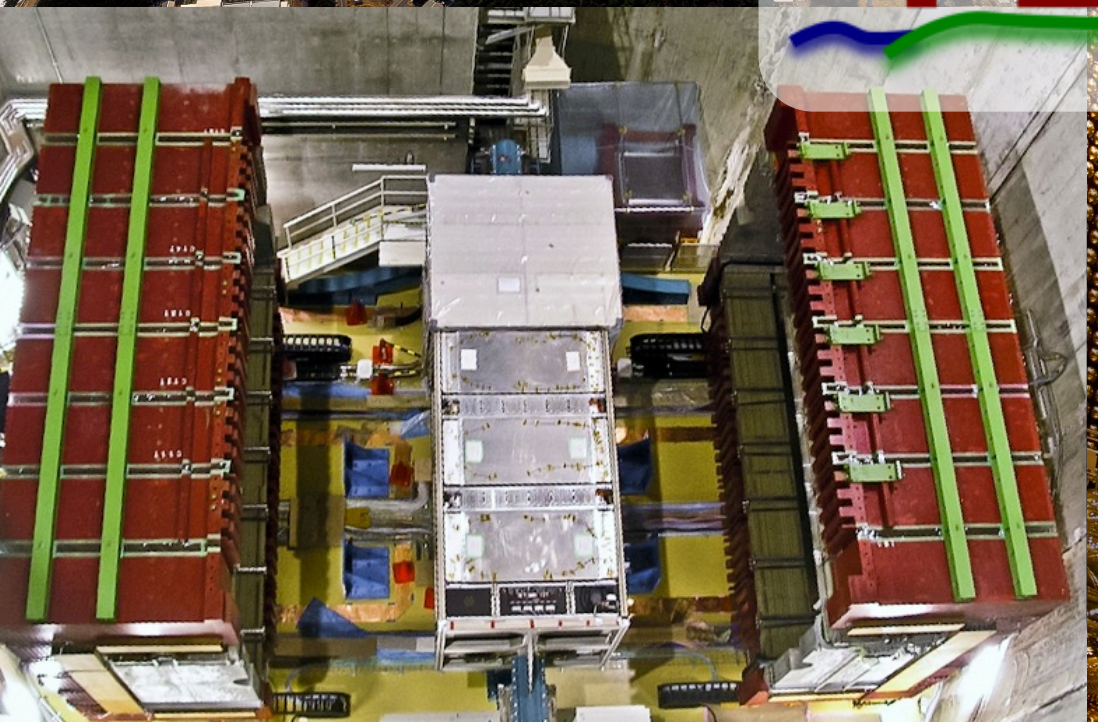




T2K

ν Oscillation Results

Rencontres de Moriond (EW)

March 17, 2013

Patrick de Perio

University of Toronto

for the T2K Collaboration

Outline

- Neutrino oscillation review
- The T2K experiment
- Results this winter
  - Update to ν_μ disappearance: $\sin^2 2\theta_{23}$ and Δm^2_{32}
  - Finalized $\nu_\mu \rightarrow \nu_e$ appearance observation
  - New joint ν_μ + ν_e analysis released for the first time
- Future prospects

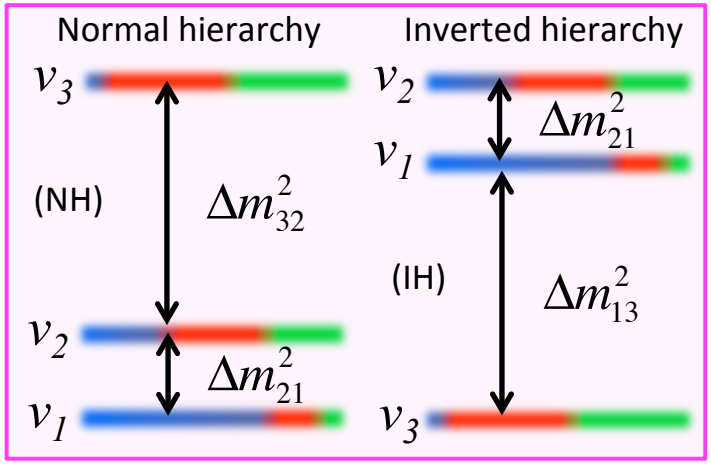
Neutrino Oscillations: Current Status

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\tfrac{1}{4}\Delta m^2_{ij}\frac{L}{E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\tfrac{1}{2}\Delta m^2_{ij}\frac{L}{E}\right)$$

Oscillation Probability

L: source-detector distance

E: neutrino energy

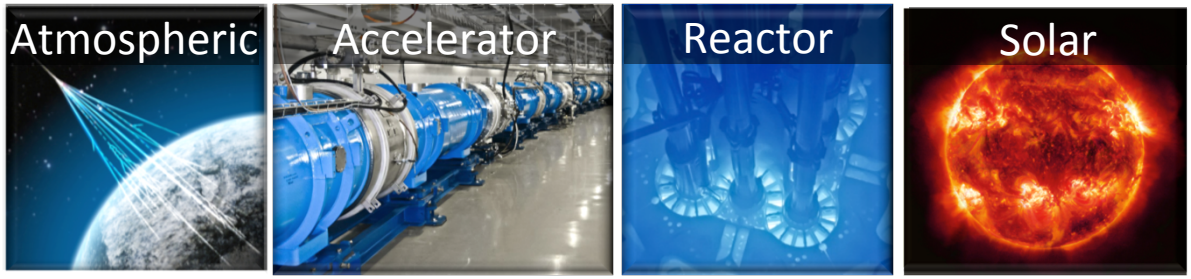


$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

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

$$\Delta m^2_{21} = 7.58^{+0.22}_{-0.26} \times 10^{-5}\,\mathrm{eV}^2$$

$$|\Delta m^2_{32}| = 2.35^{+0.12}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2$$



SK, MINOS, K2K, *T2K*: **$\sin^2(2\theta_{23}) > 0.95$ (90% CL)**

T2K, MINOS; DB, RENO, DC: **$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$**

KamLAND; SNO, SK: **$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$**

Neutrino Oscillations: Remaining Questions

- Mass hierarchy, sign(Δm^2_{31})?
  - Sensitivity from matter effect → $x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$
- Is θ_{23} maximal? If not, which octant?
- CP violation in the lepton sector?

Combination of different baseline experiments and anti-neutrino measurements will help lift parameter degeneracies

T2K producing precision measurements of…

- ν_μ *Disappearance*

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta$$

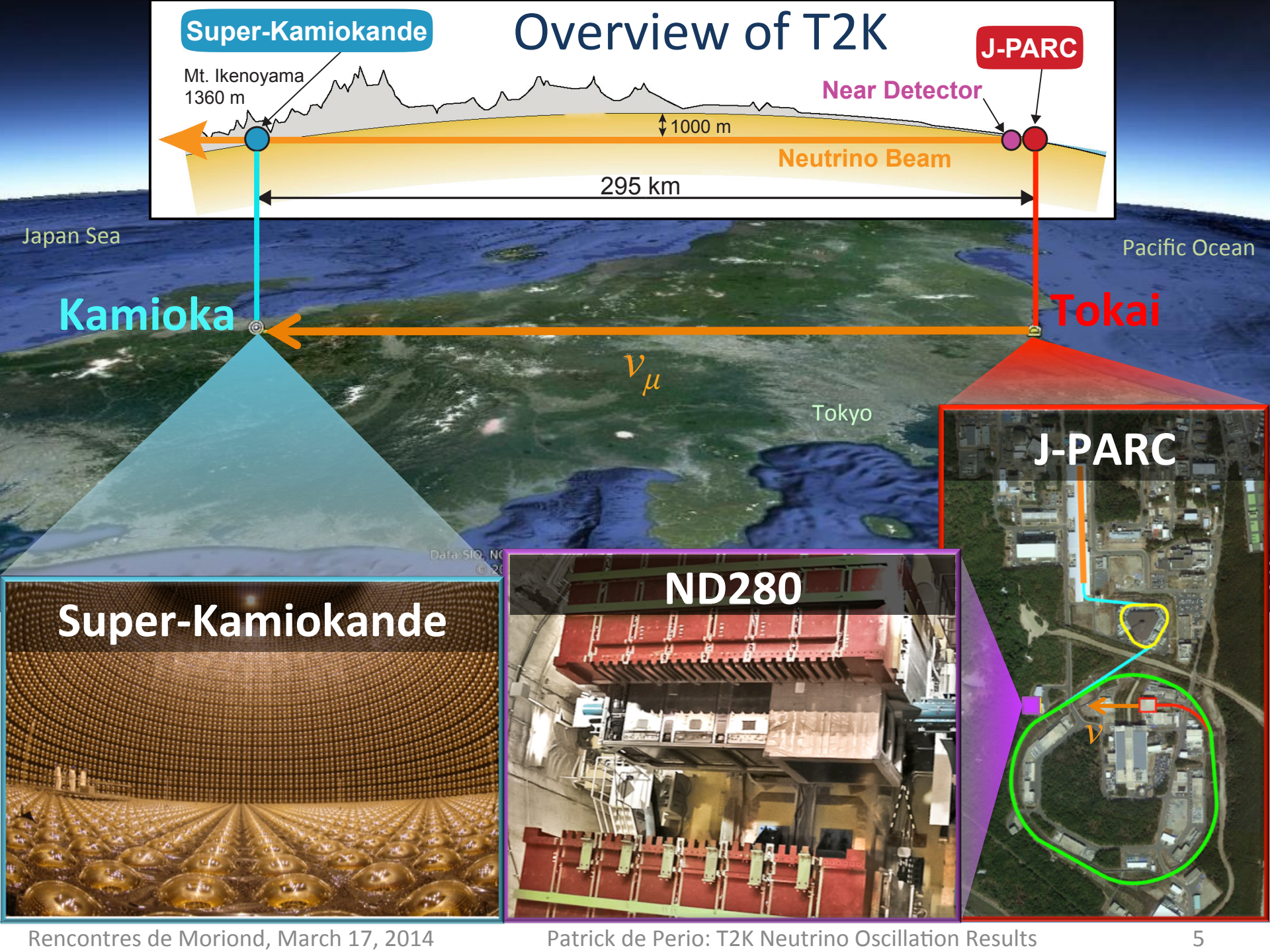
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

- *and* $\nu_\mu \to \nu_e$ *Appearance*

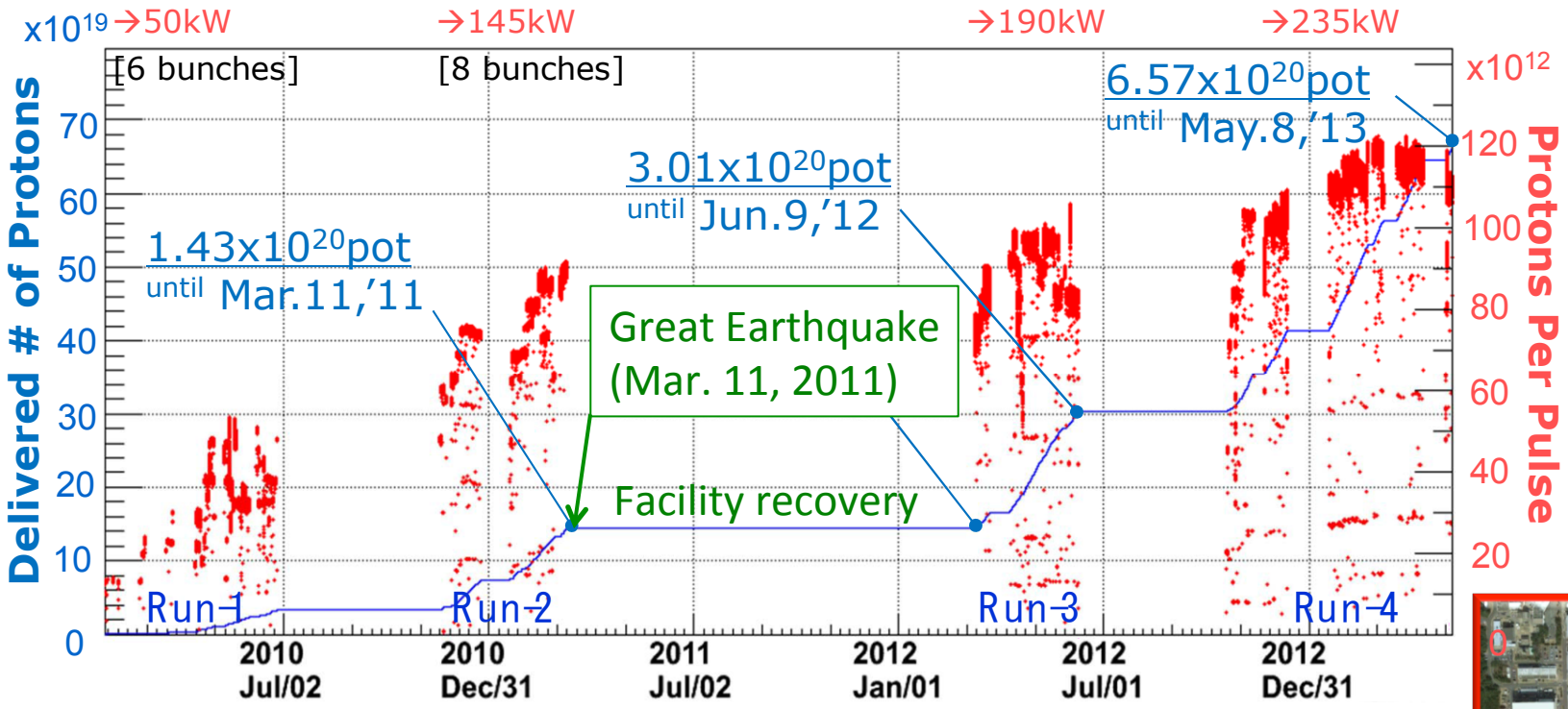
$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx \sin^2 2\theta_{13} \times \sin^2\theta_{23}\frac{\sin^2[(1\mp x)\Delta]}{(1\mp x)^2} \mp \sin\delta_{CP}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\Delta\frac{\sin(x\Delta)}{x}\frac{\sin[(1\mp x)\Delta]}{(1\mp x)}\frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

…towards an understanding beyond the Standard Model;
mixing matrix structure, origin of ν mass m_i, leptogenesis…

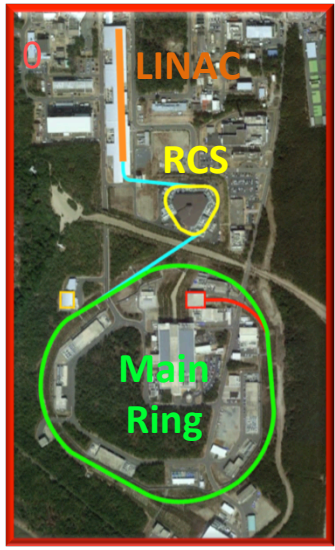
Overview of T2K



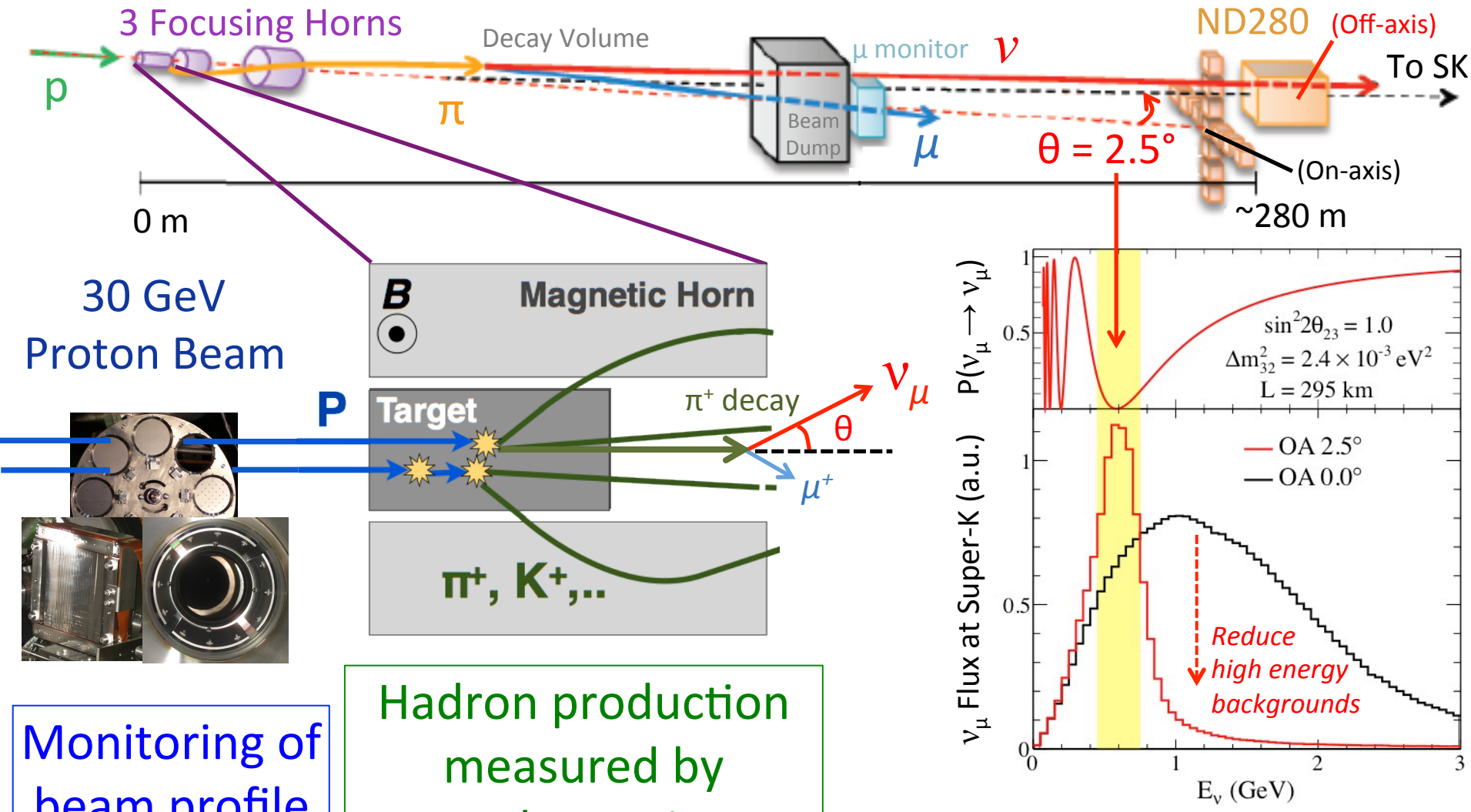
T2K Data Set



- Today's results stem from the great efforts of the J-PARC accelerator division
- Total delivered beam: 6.57 × 10^{20} protons on target
  - 8% of ultimate goal



Neutrino Beamline



Monitoring of beam profile and intensity

Hadron production measured by external experiments (NA61 @ CERN)

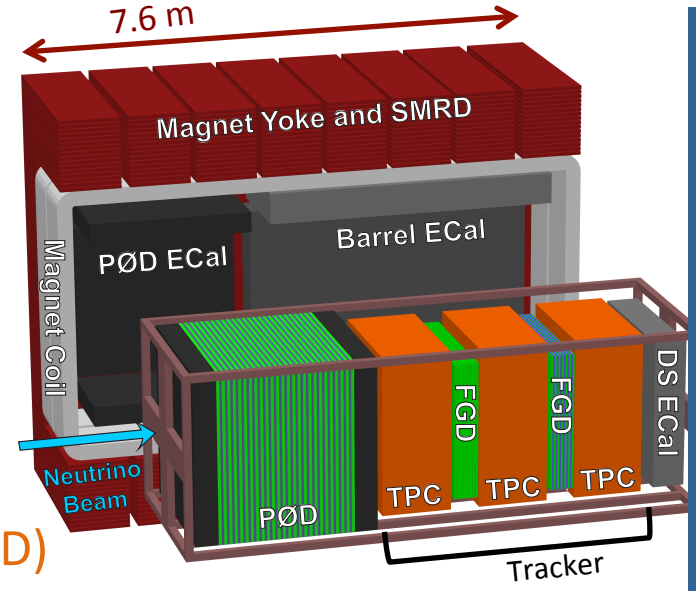
Off-axis neutrino beam
Narrow band @ osc. maximum

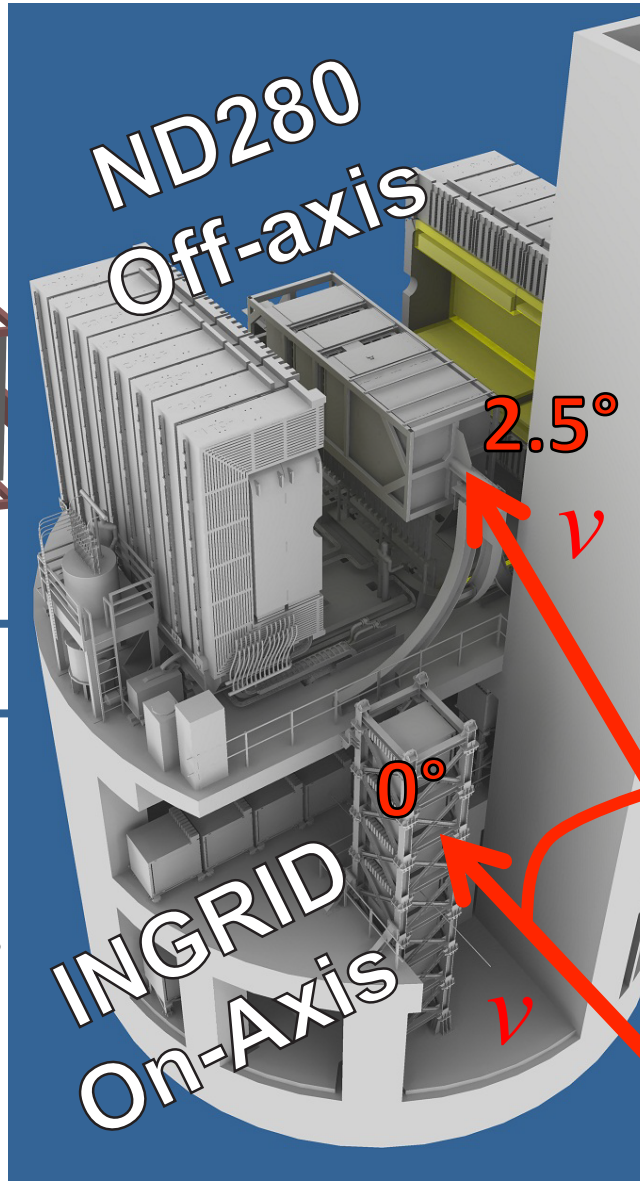
Near Detectors

Tracker Section

Fine Grained Detectors
- Active target mass
- Vertex reconstruction

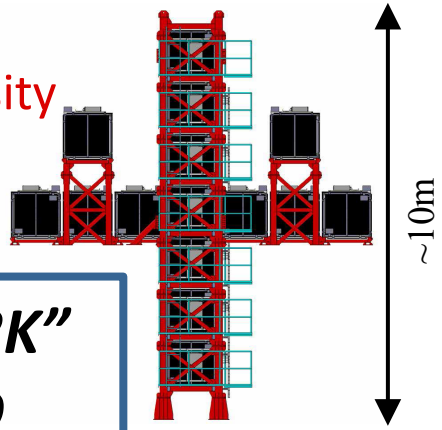
Time Projection Chambers
- Momentum reconstruction
- Particle identification (PID)





Measure ν flux and interaction cross sections

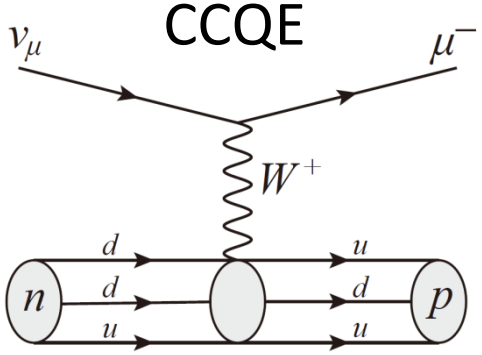
INGRID
- Monitor ν beam direction θ & intensity
- $\delta\theta < 1$ mrad $\rightarrow \delta E_\nu < 3\%$
- Very stable!



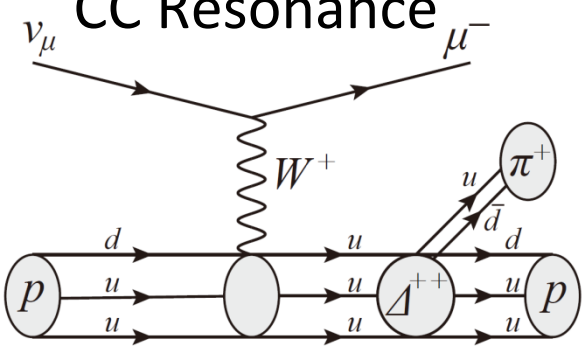
"Neutrino Interactions at T2K"
K. Suzuki @ Moriond QCD

ND280 Tracker Event Selection

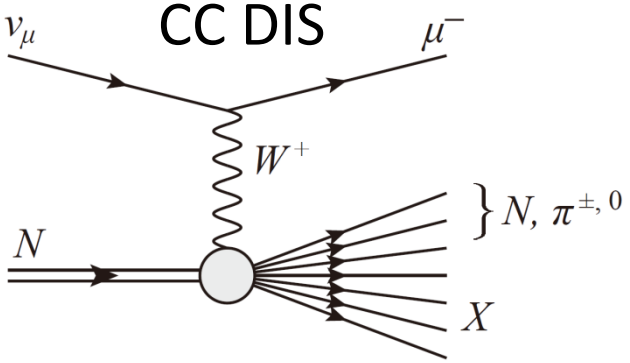
CCQE



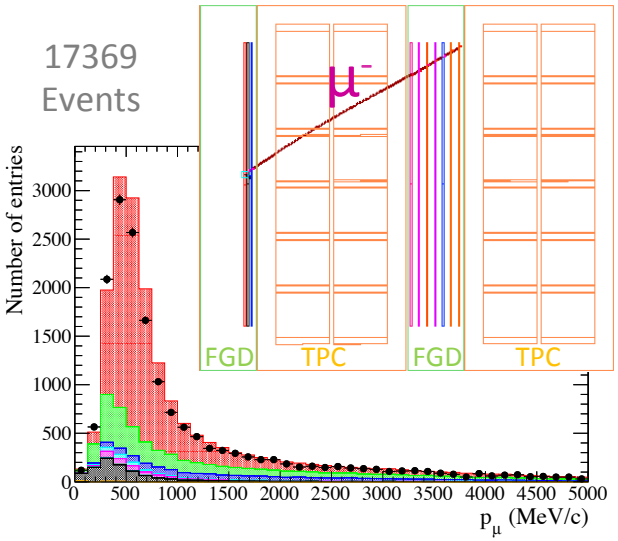
CC Resonance



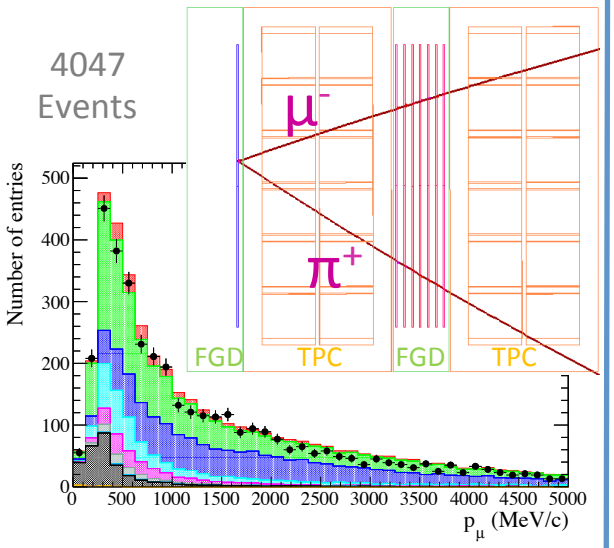
CC DIS



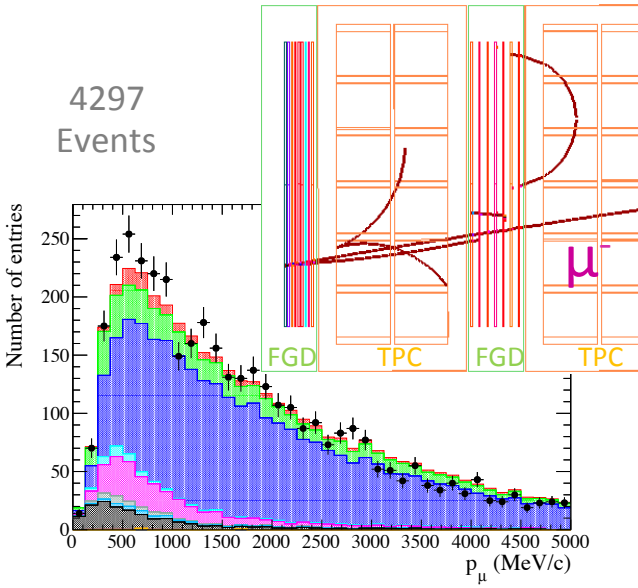
CC 0π Enriched
(CCQE Purity: 63%)



CC 1π⁺ Enriched
(CC Res. Purity: 39%)



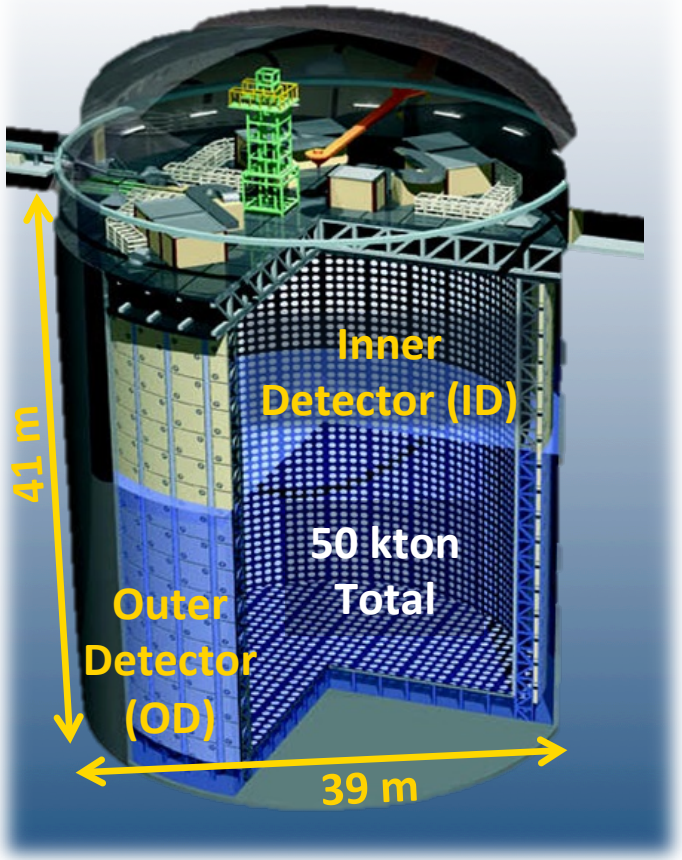
CC Other Enriched
(CC DIS Purity: 68%)

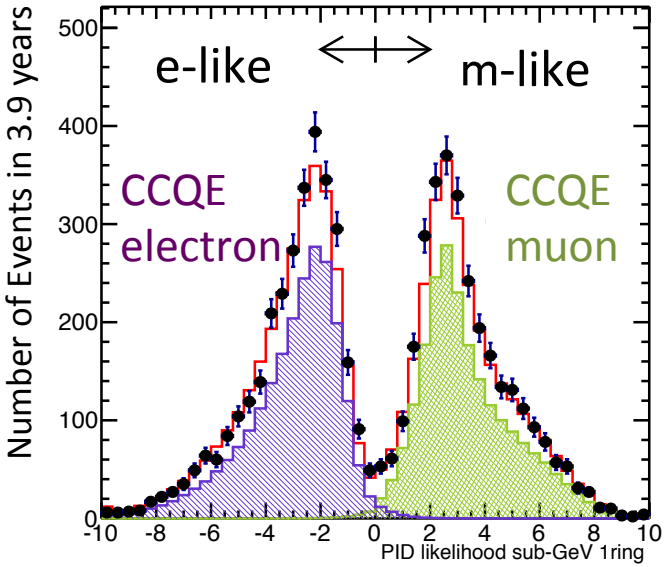


MC Legend: **CCQE** | Out-of-FGD | CC Coherent | **CC Res.** | NC | **CC DIS**

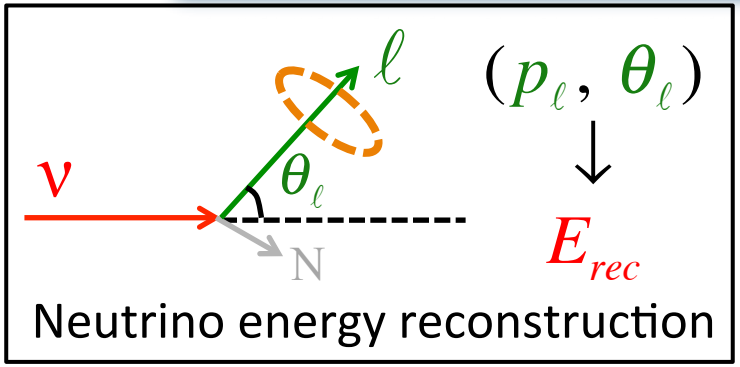
Super-Kamiokande

- 22.5 kton fiducial volume water Cherenkov detector
- Inner detector with ~11k PMTs
- Outer detector determines fully contained events
- Very good e/μ separation





Atmospheric ν
- Data
- MC



T2K-SK Event Selection

Fully Contained & Fiducial Volume & 1-Ring

PID: *e*-like

p_e > 100 MeV/*c*

No decay-*e*

New π^0 Rejection

E_{rec} < 1250 MeV

28 Events

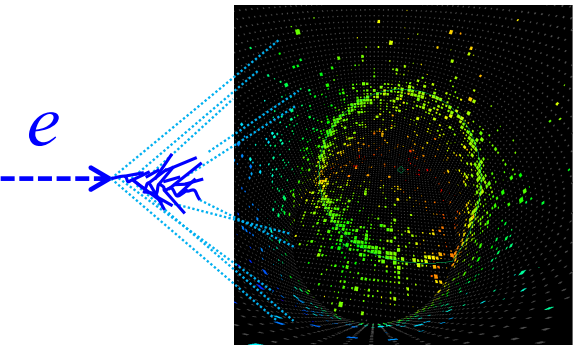
PID: μ-like

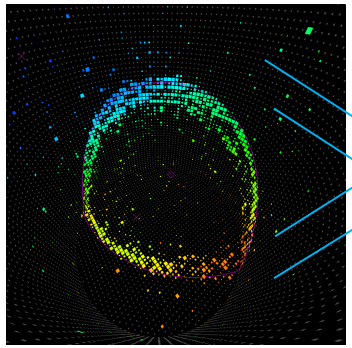
p_μ > 200 MeV/*c*

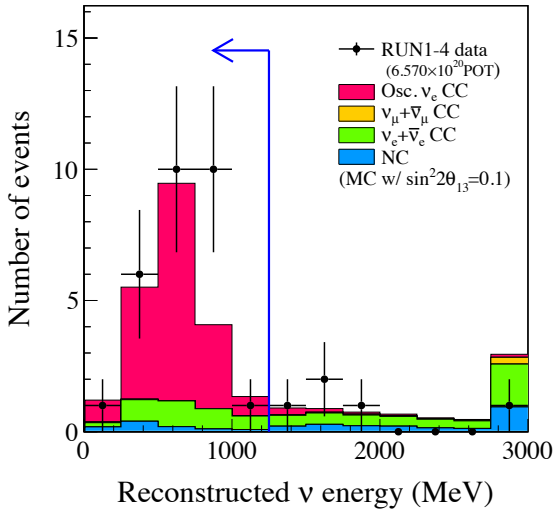
Decay-*e* ≤ 1

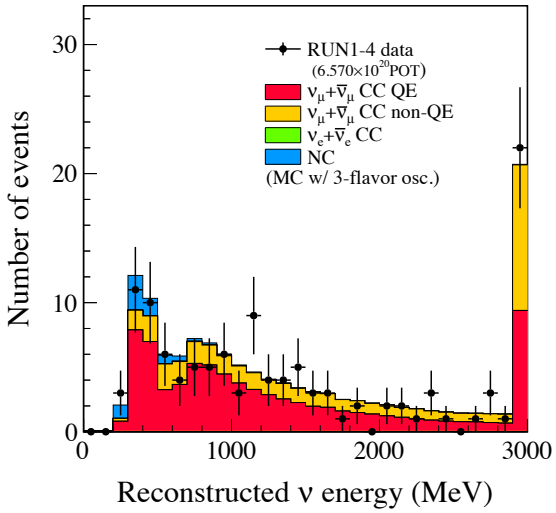
All E_{rec}

120 Events









Beam ν_e

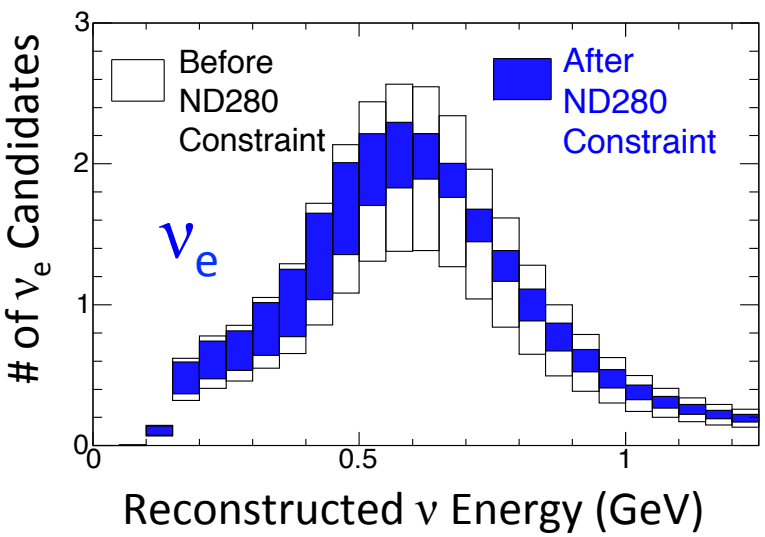
NC π^0

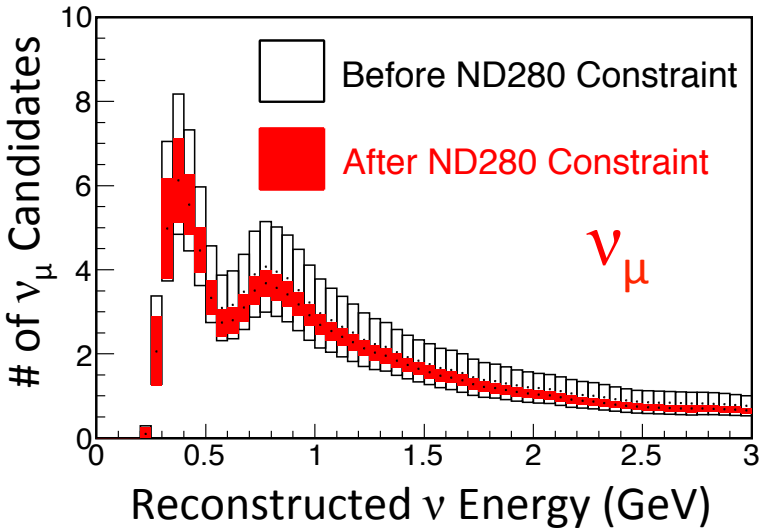
Backgrounds

CC non-QE

NC $\pi^\pm$

Systematic Errors





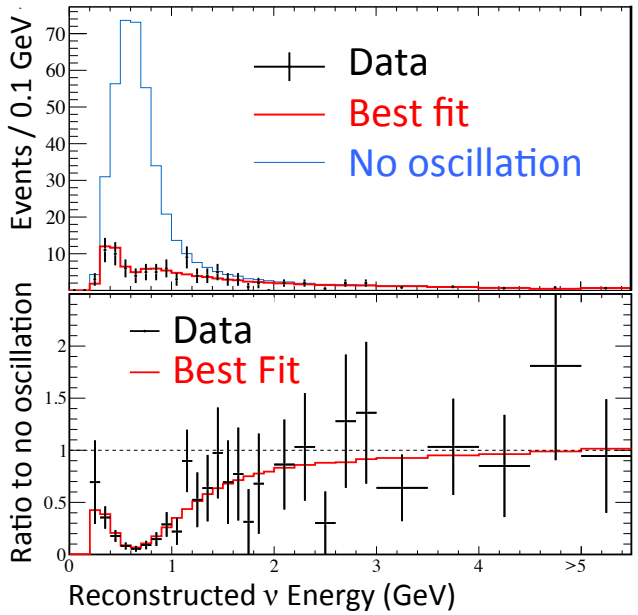
Relative Uncertainty in # of ν_e Candidates (%)	**Systematic Error Source**	Relative Uncertainty in # of ν_μ Candidates (%)
2.9	Flux ✤ Xsec. (ND280 constrained)	2.7
4.7	Xsec. (ND280-independent)	4.9
2.3	π Hadronic Interactions	3.5
2.6	SK Detector	4.4
6.8	**Total**	**8.1**

✤: Correlated

$\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1$, $\Delta m_{32}^2 = 2.4\times10^{-3}$ eV^2, NH, $\delta_{CP}=0$

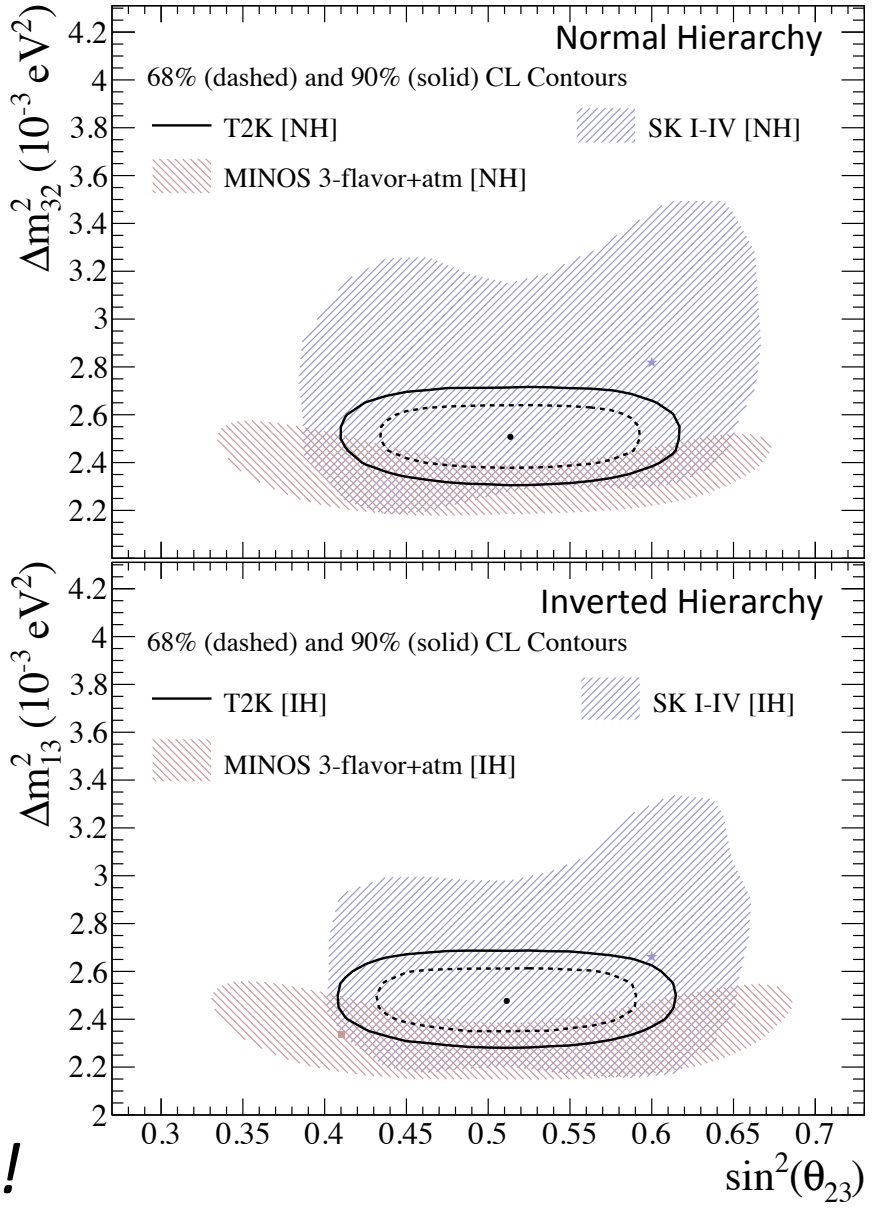
Precision ν_μ Disappearance Measurement

Maximum likelihood fit in E_{rec}



arXiv:1403.1532 (2014)

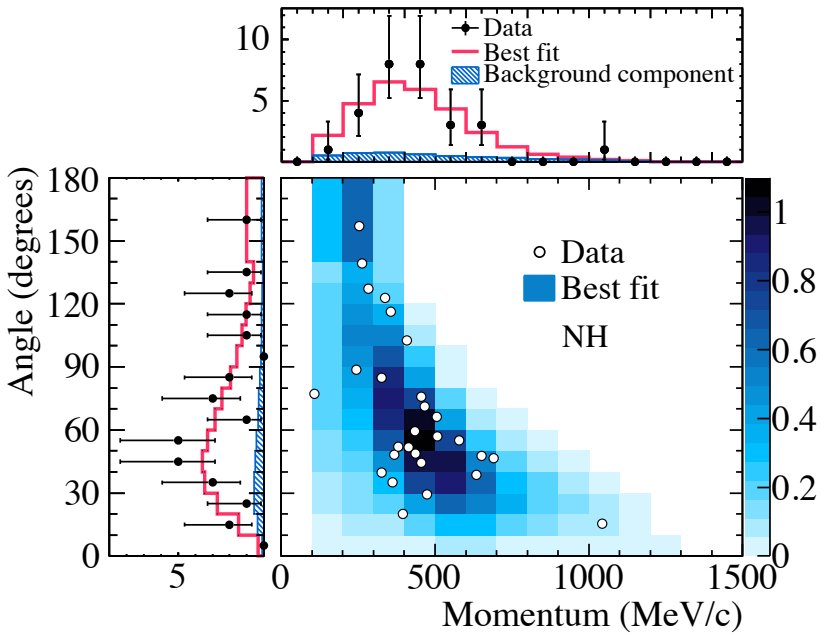
		Best-fit ± FC 68% CL
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32} $(10^{-3}\ eV^2)$	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{32} $(10^{-3}\ eV^2)$	2.48 ± 0.10



Most precise measurement of θ_{23}!

Observation of $\nu_\mu \rightarrow \nu_e$ Appearance

Maximum likelihood fit in (p_e, θ_e)

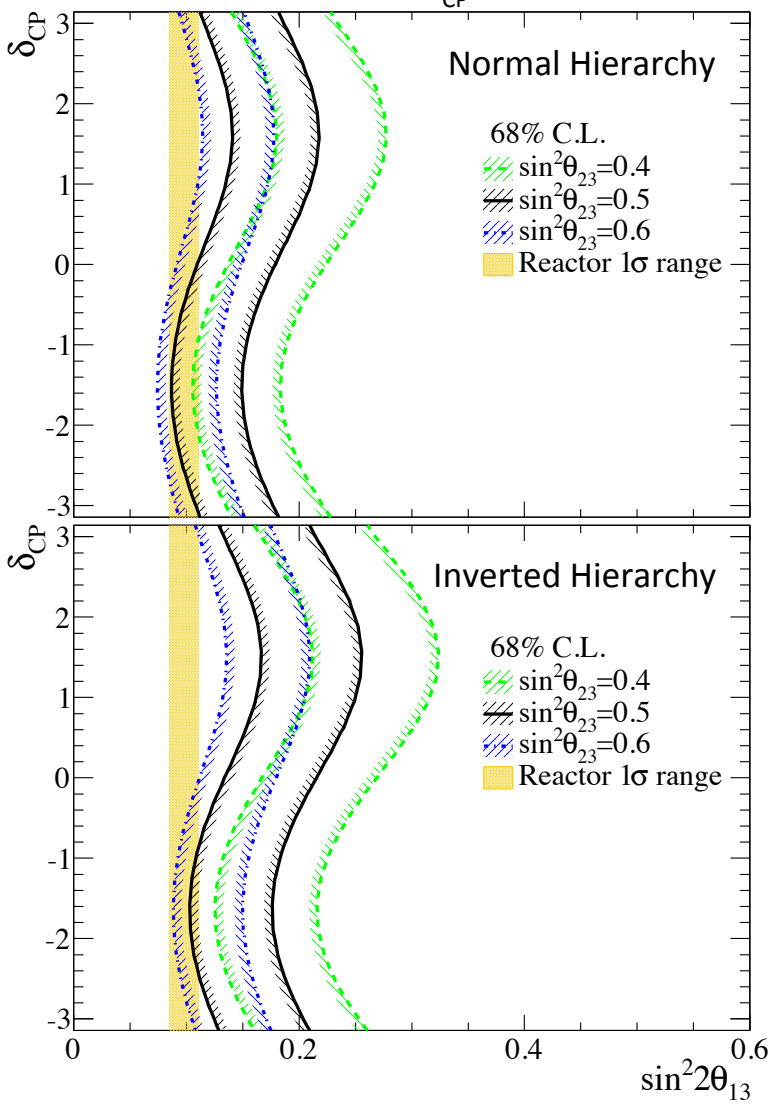


PRL 112, 061802 (2014)

		Best-fit ± 68% CL
$\sin^2 2\theta_{13}$	NH	$0.140\ ^{+0.038}_{-0.032}$
	IH	$0.170\ ^{+0.045}_{-0.037}$

@ $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$

1D contours at various δ_{CP}



Discovery of ν_e Appearance at 7.3σ!

Dependence on θ_{23} motivates a joint $\nu_\mu + \nu_e$ fit…

Joint $\nu_\mu + \nu_e$ Analysis: Constraints on δ_{CP}

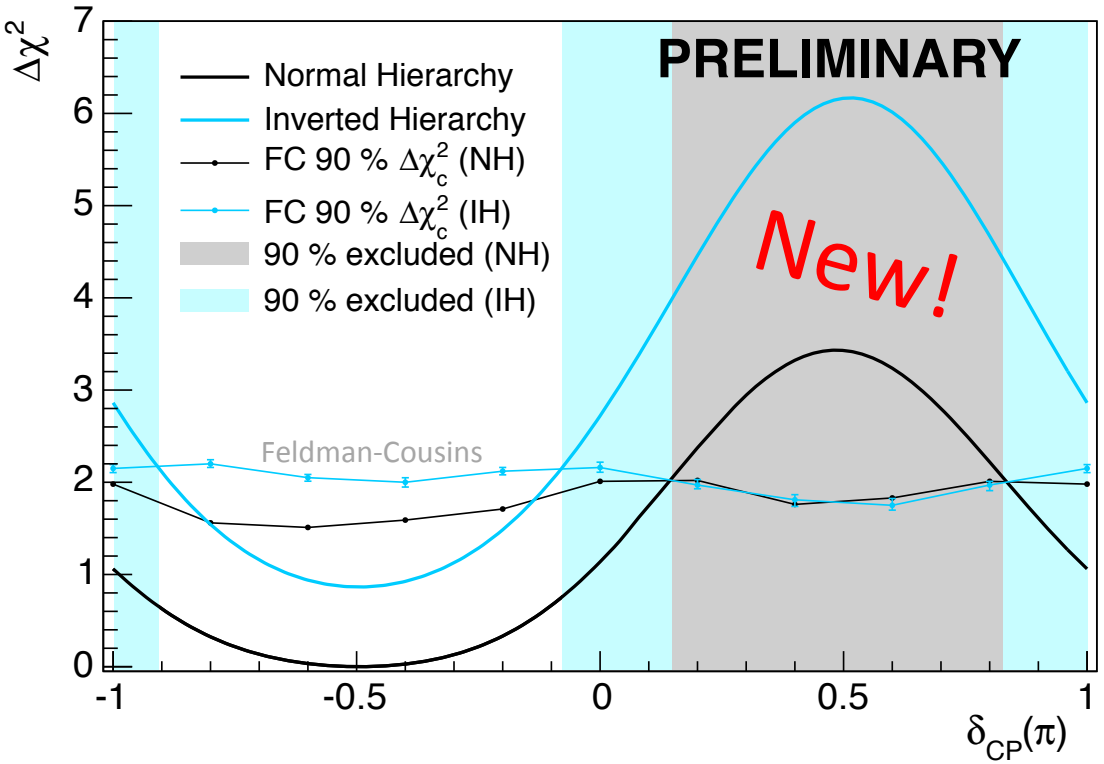
Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Accounting for correlations in the parameter space

$(\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32})$

Including constraint from reactor experiments *Daya Bay, RENO, Double Chooz*

$\sin^2 2\theta_{13} = 0.095 \pm 0.010$
(PDG 2013)



	90% CL Inclusion
NH	$\delta_{CP} \in [-1.18, 0.15]\pi$
IH	$\delta_{CP} \in [-0.91, -0.08]\pi$

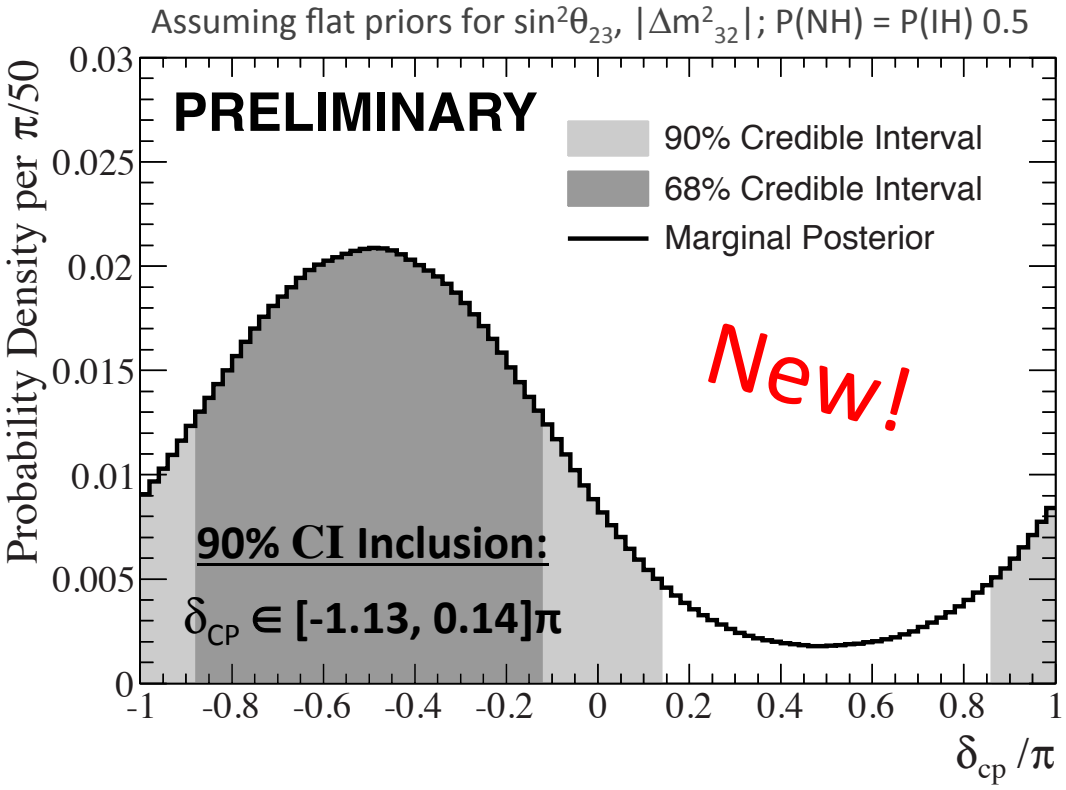
PRELIMINARY

T2K hints toward $\delta_{CP} = -\pi/2$

Joint $\nu_\mu + \nu_e$ Bayesian Analysis

Markov Chain Monte Carlo (MCMC) with both T2K-SK $\nu_\mu + \nu_e$ and ND280 samples

Can easily marginalize over e.g. mass hierarchy (MH) →



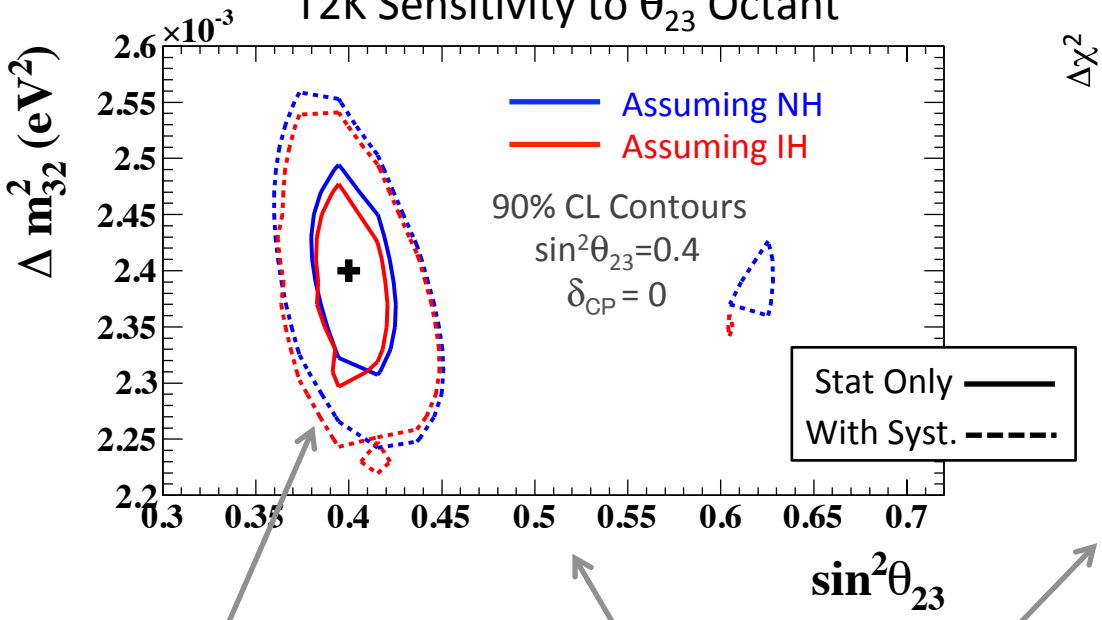
And compare the probabilities for each MH and θ_{23} octant combination →

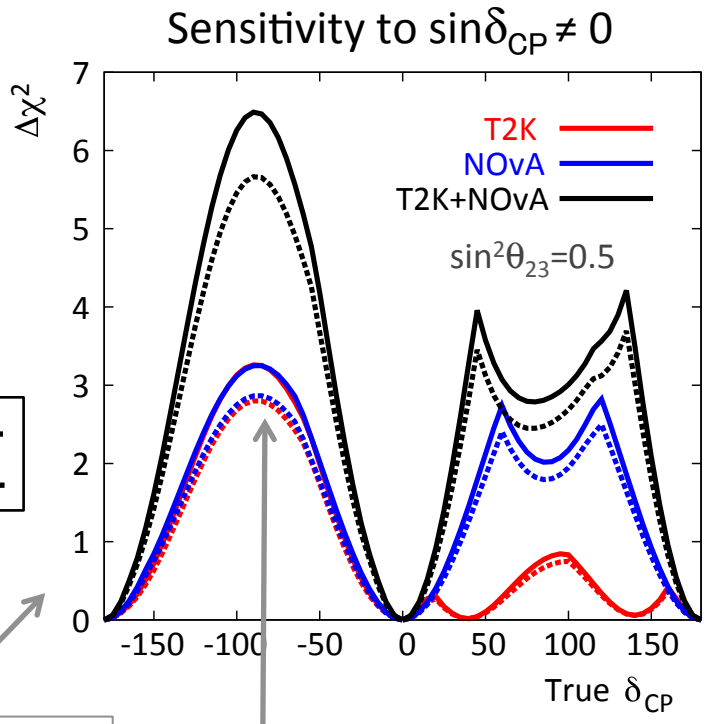
(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26
$\sin^2\theta_{23} > 0.5$	50	24	74
Sum	68	32	

PRELIMINARY

Future Sensitivity Studies

- T2K is aiming for 7.8×10^{21} POT (current data at ~8%)
  - Future running likely to include significant anti-ν fraction (under consideration)
- Sensitivity with T2K alone
- Enhancement with other experiments such as NOνA





T2K 2012 syst. errors

Ultimate POT (50% ν + 50% anti-ν)
True $\sin^2 2\theta_{13}$=0.1, Δm^2_{32}=2.4×10^{-3} eV^2, NH

Syst. assuming 5% (10%) normalization uncertainty on signal (background)

Summary

- Results finalized for latest analyses with 6.57×10^{20} POT
  - *ν_μ disappearance: Leading precision on θ_{23}!* [arXiv:1403.1532]
  - *$\nu_\mu \rightarrow \nu_e$ appearance observation!* [PRL 112, 061802 (2014)]

- New T2K joint ν_μ + ν_e analysis presented today
  - *Hints toward $\delta_{CP} \approx -\pi/2$ with reactor constraint:*

Feldman-Cousins 90% CL Inclusion Intervals:

NH: $\delta_{CP} \in$ **[-1.18, 0.15]**π

IH: $\delta_{CP} \in$ **[-0.91, -0.08]**π

PRELIMINARY

Bayesian 90% Credible Interval:

MH Marginalized: $\delta_{CP} \in$ **[-1.13, 0.14]**π

PRELIMINARY

- Upcoming prospects this year
  - Short anti-ν run planned this spring
  - Increasing beam power and POT from current ~8% of total
  - Tighter constraints on oscillation parameter space

The T2K Collaboration

~500 members (337 authors), 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Italy
INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
INFN, U. Bari

Japan
ICRR Kamioka
ICRR RCCN
Kavli-IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NJBC, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
U. Wroclaw

Russia
INR

Spain
IFIC, Valencia
U. A. Barcelona

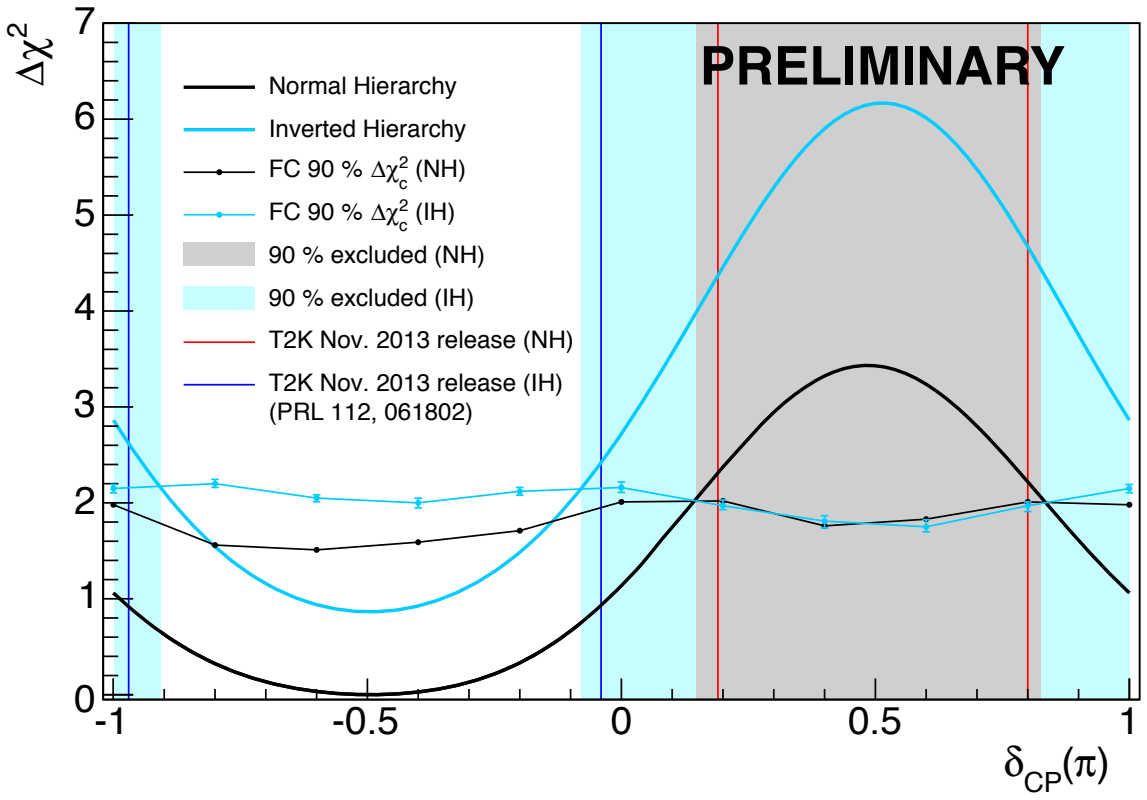
Switzerland
U. Bern
U. Geneva
ETH Zurich

United Kingdom
Imperial C. London
Queen Mary U. L.
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
STFC/Daresbury
STFC/RAL
Warwick U.

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

APPENDIX

Constraints on δ_{CP} Exclusion



T2K New Joint Analysis

δ_{CP} (π)	90% CL Excluded
NH	[0.15, 0.82]
IH	[-0.08, 1.09]

PRELIMINARY

T2K Nov. 2013 release (PRL 112, 061802)

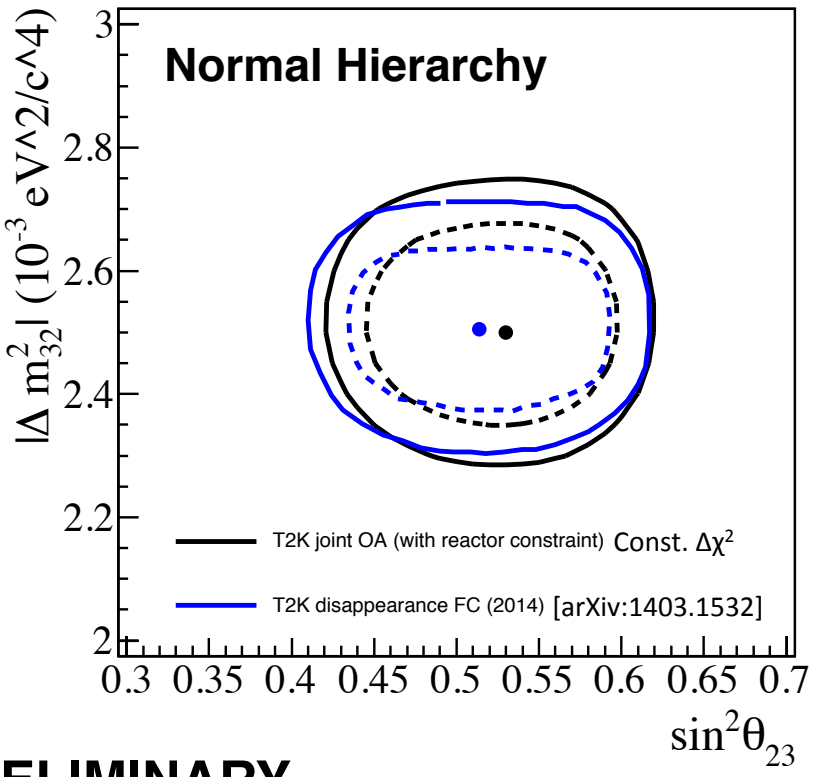
δ_{CP} (π)	90% CL Excluded
NH	[0.19, 0.80]
IH	[-0.04, 1.03]

PRELIMINARY

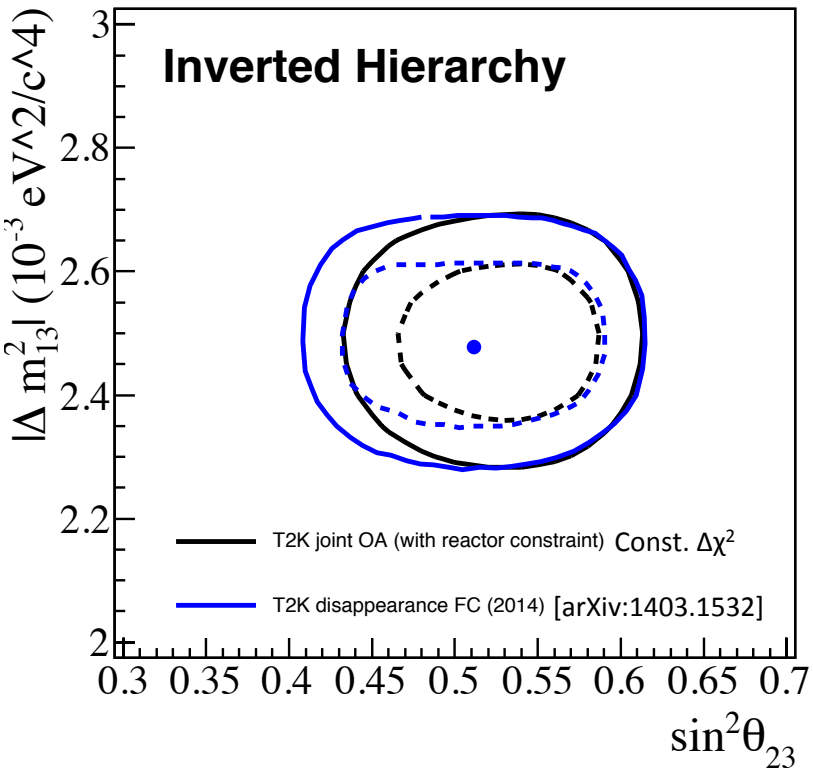
Reactor constraint	Hierarchy	$\lvert\Delta m^2_{32}\rvert(NH)$ $\lvert\Delta m^2_{13}\rvert(IH)$ $10^{-3}eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}	$N^{1R\mu}_{obs}$	$N^{1R\mu}_{exp}$	N^{1Re}_{obs}	N^{1Re}_{exp}	$\Delta(\chi^2)$
NO	NH	2.512	0.524	0.162	1.909	120	119.915	28	27.999	0.01
NO	IH	2.488	0.523	0.187	1.005	120	119.948	28	27.998	-
YES	NH	2.509	0.527	0.0967	-1.554	120	120.383	28	25.870	-
YES	IH	2.481	0.533	0.0984	-1.556	120	121.204	28	23.571	0.864

ν_μ Disappearance Parameters

PRELIMINARY



PRELIMINARY



PRELIMINARY

Reactor constraint	Hierarchy	$\lvert\Delta m^2_{32}\rvert(NH)$ $\lvert\Delta m^2_{13}\rvert(IH)$ $10^{-3}eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}	$N^{1R\mu}_{obs}$	$N^{1R\mu}_{exp}$	N^{1Re}_{obs}	N^{1Re}_{exp}	$\Delta(\chi^2)$
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YES	IH	2.481	0.533	0.0984	-1.556	120	121.204	28	23.571	0.864

MCMC Joint Analysis Results

- Constraints on ν_μ disappearance parameters

T2K-Only Model Probabilities

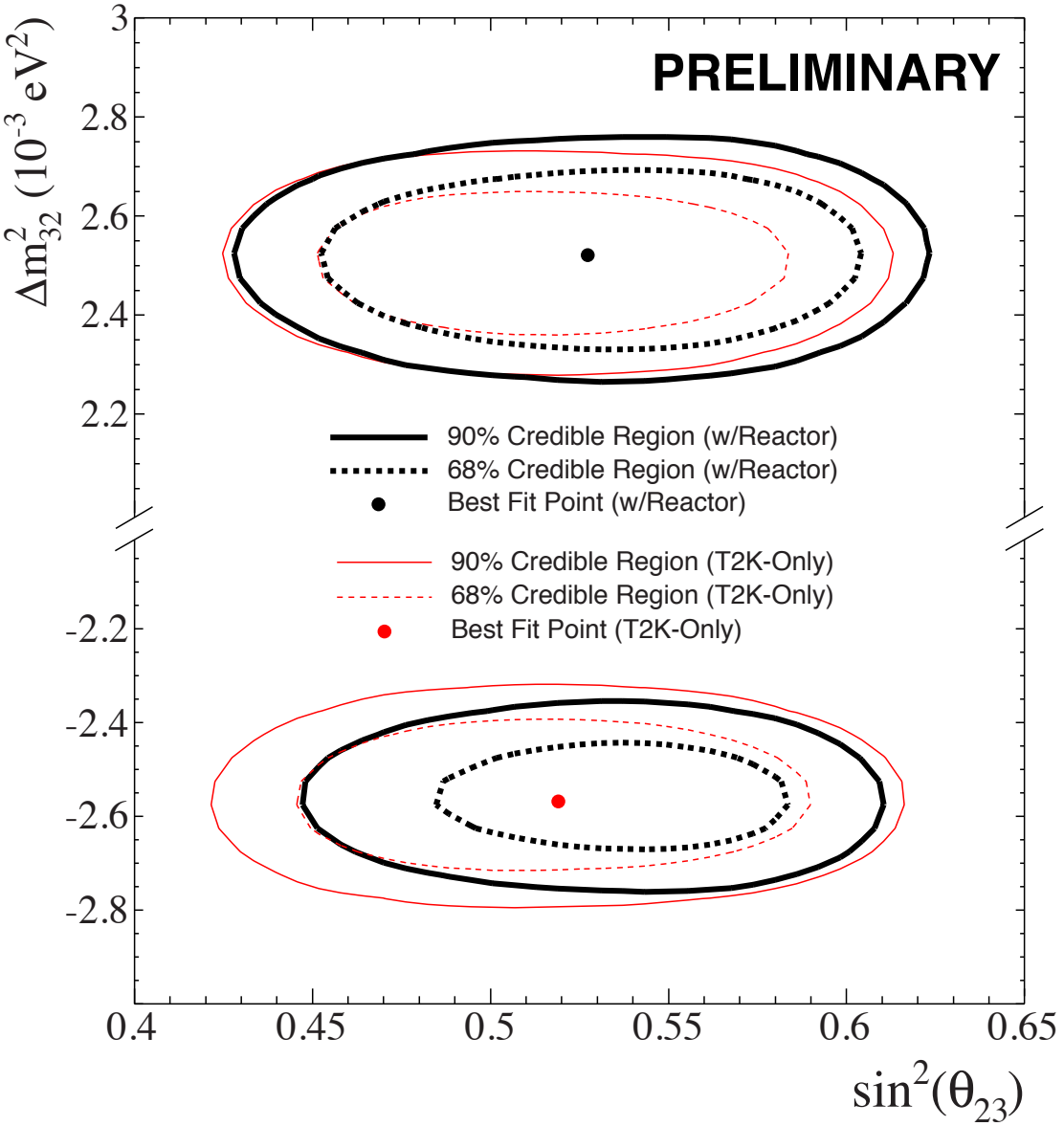
(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	16	20	36
$\sin^2\theta_{23} > 0.5$	29	35	64
Sum	45	55	

PRELIMINARY

With Reactor Constraint

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26
$\sin^2\theta_{23} > 0.5$	50	24	74
Sum	68	32	

PRELIMINARY



Constraints on δ_{CP} Exclusion Comparison

- δ_{CP} inclusion regions by:
  - Feldman-Cousins (FC)
  - Bayesian MCMC assuming prior probabilities
    - NH: P(NH) = 1
    - IH: P(IH) = 1
    - MH Marg.: P(NH) = P(IH) = 0.5

δ_{CP} (π)	90% FC CL Interval
NH	[-1.18, 0.15]
IH	[-0.91, -0.08]*

PRELIMINARY

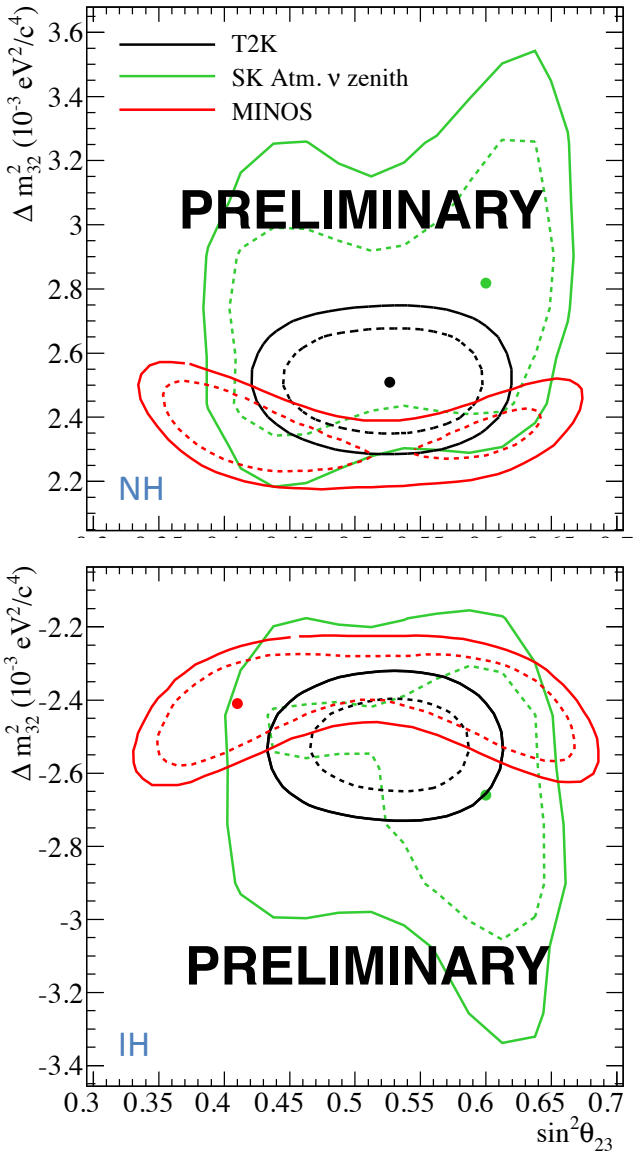
*Assuming global minimum in NH

δ_{CP} (π)	90% Bayesian Credible Interval
NH	[-1.16, 0.17]
IH	[-1.05, 0.06]
MH Marg.	[-1.13, 0.14]

PRELIMINARY

Joint Analysis Comparison

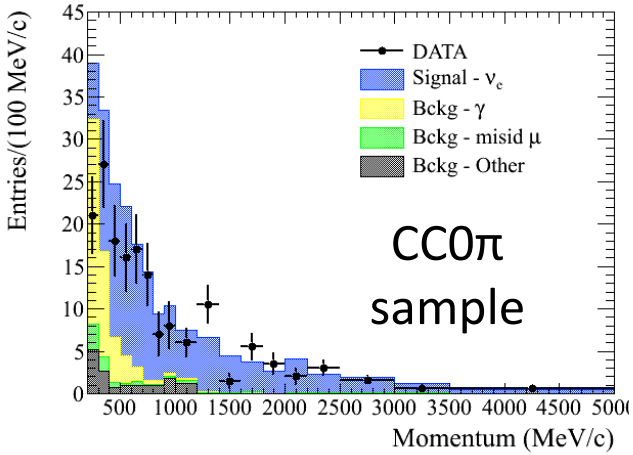
- T2K joint accelerator ν_μ disappearance + ν_e appearance
  - Fixing $\sin^2 2\theta_{13} = 0.095 \pm 0.01$ (PDG2013)
  - Constant $\Delta\chi^2$
- Super-K 3-flavor atmospheric ν analysis
  - arXiv:1310.6677
  - Independent best fits for each mass hierarchy
  - Fixing $\sin^2 2\theta_{13} = 0.098$ (PDG2012)
- MINOS combined accelerator and atmospheric analysis
  - arXiv:1403:0867
  - Fixing $\sin^2 2\theta_{13} = 0.095 \pm 0.01$ (PDG2013)

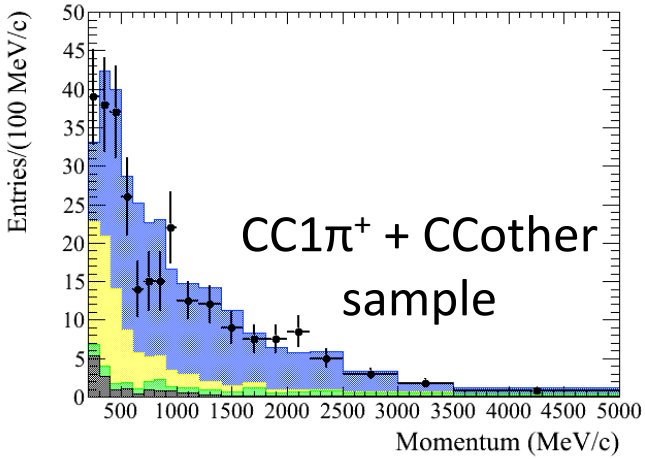


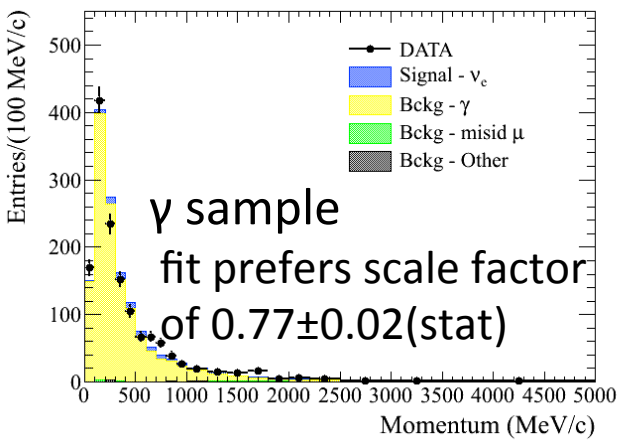
ND280 ν_e Measurement

- Interactions in FGD and particle ID in TPC
- Major background: photons from π^0 decays
- Fit CC0π, CC1π+CC Other and γ sideband

arXiv:1403.2552





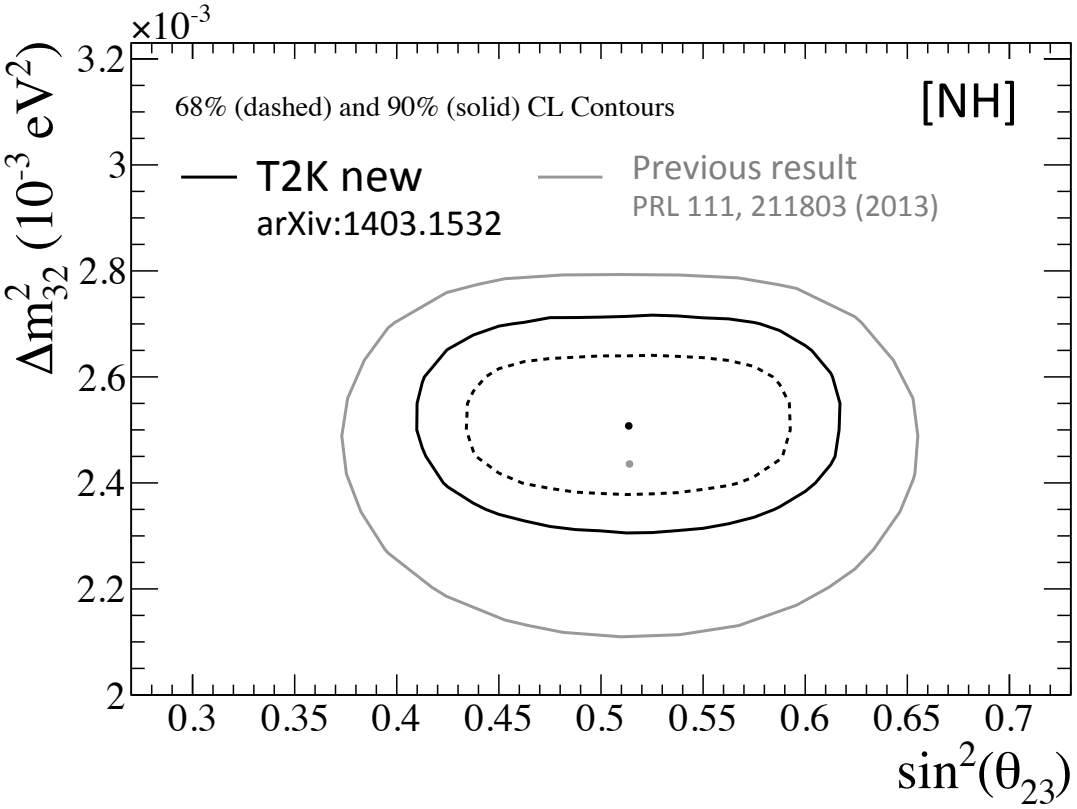


$$\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

Intrinsic beam ν_e background prediction is validated!

Results of ν_μ Disappearance Analysis

Feldman-Cousins 2D confidence regions

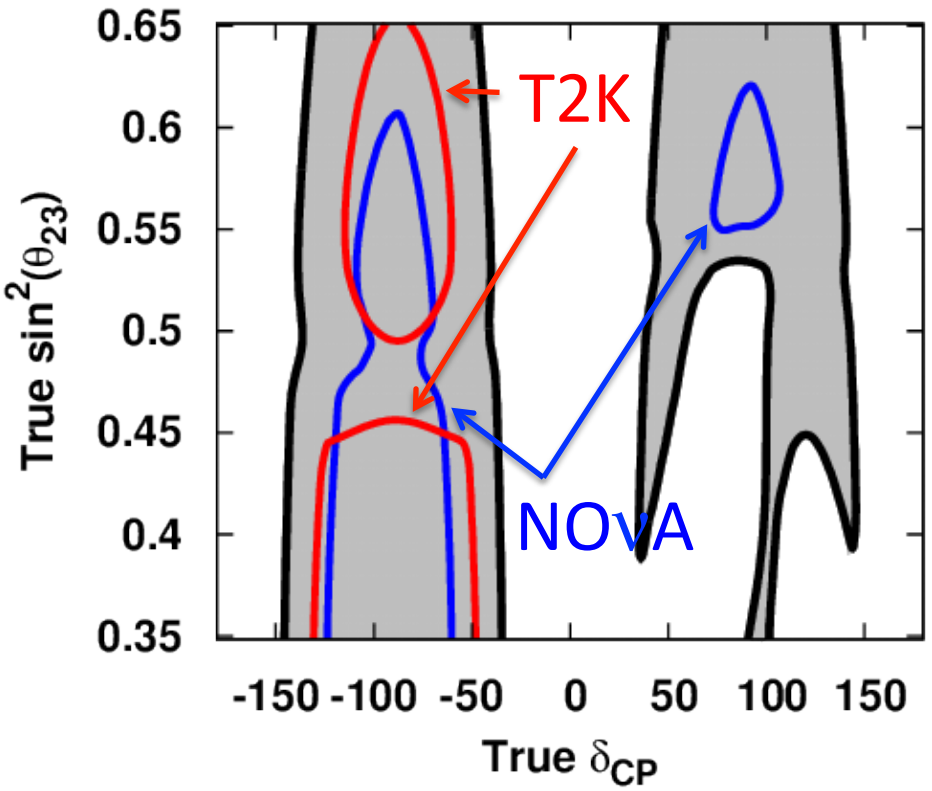


Great improvement from the previous T2K result!

T2K favors maximal disappearance

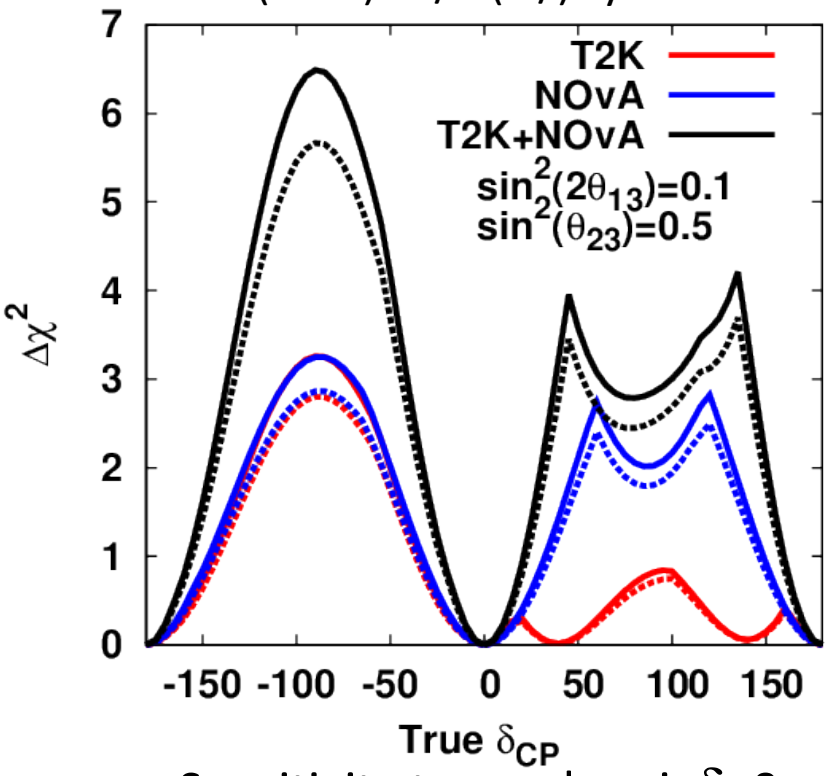
T2K + NOνA Sensitivity for Resolving $\sin\delta_{CP}\neq 0$

Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)
Shown in [NH] case.



Region where $\sin\delta=0$ can be excluded by 90% C.L.

solid(dash): w/o (w/) systematics



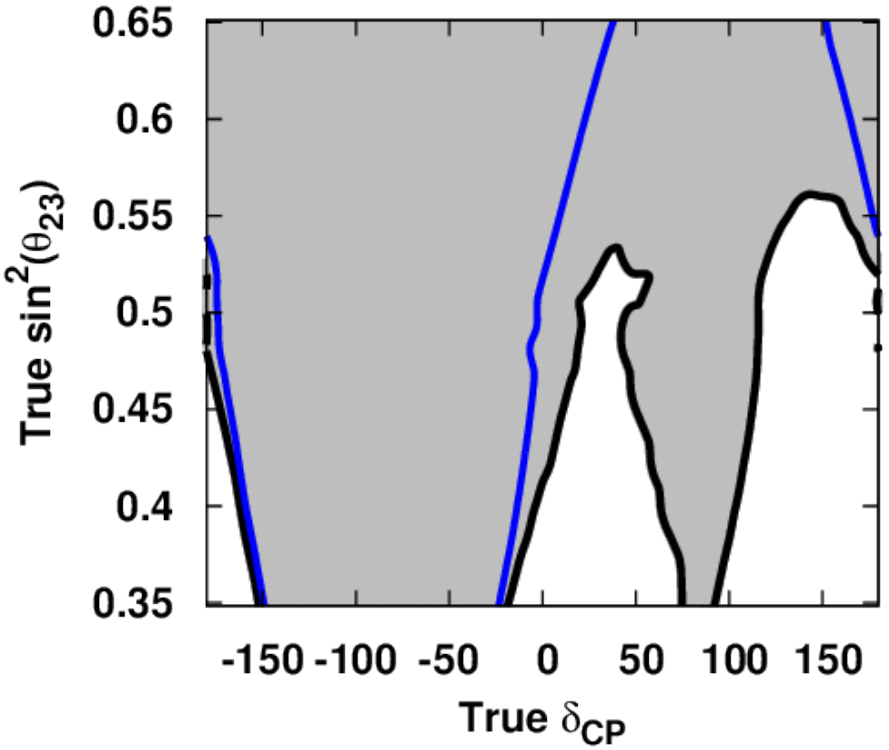
Sensitivity to resolve $\sin\delta=0$

Assuming 5% (10%) normalization uncertainty on signal (background)
Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

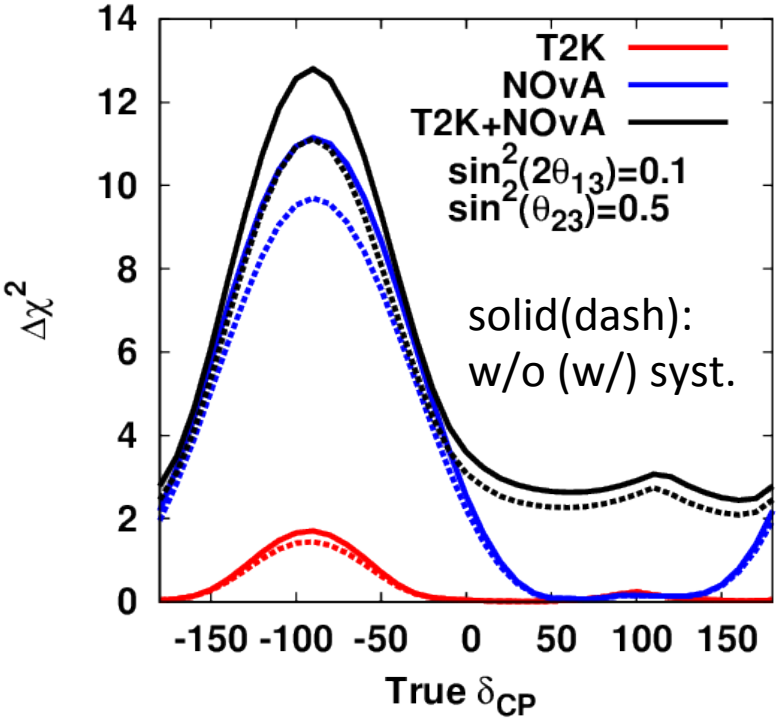
T2K + NOνA Sensitivity to Mass Hierarchy

Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)
Shown in [NH] case.

Red: T2K alone, Blue: NOνA alone, Black: T2K + NOνA



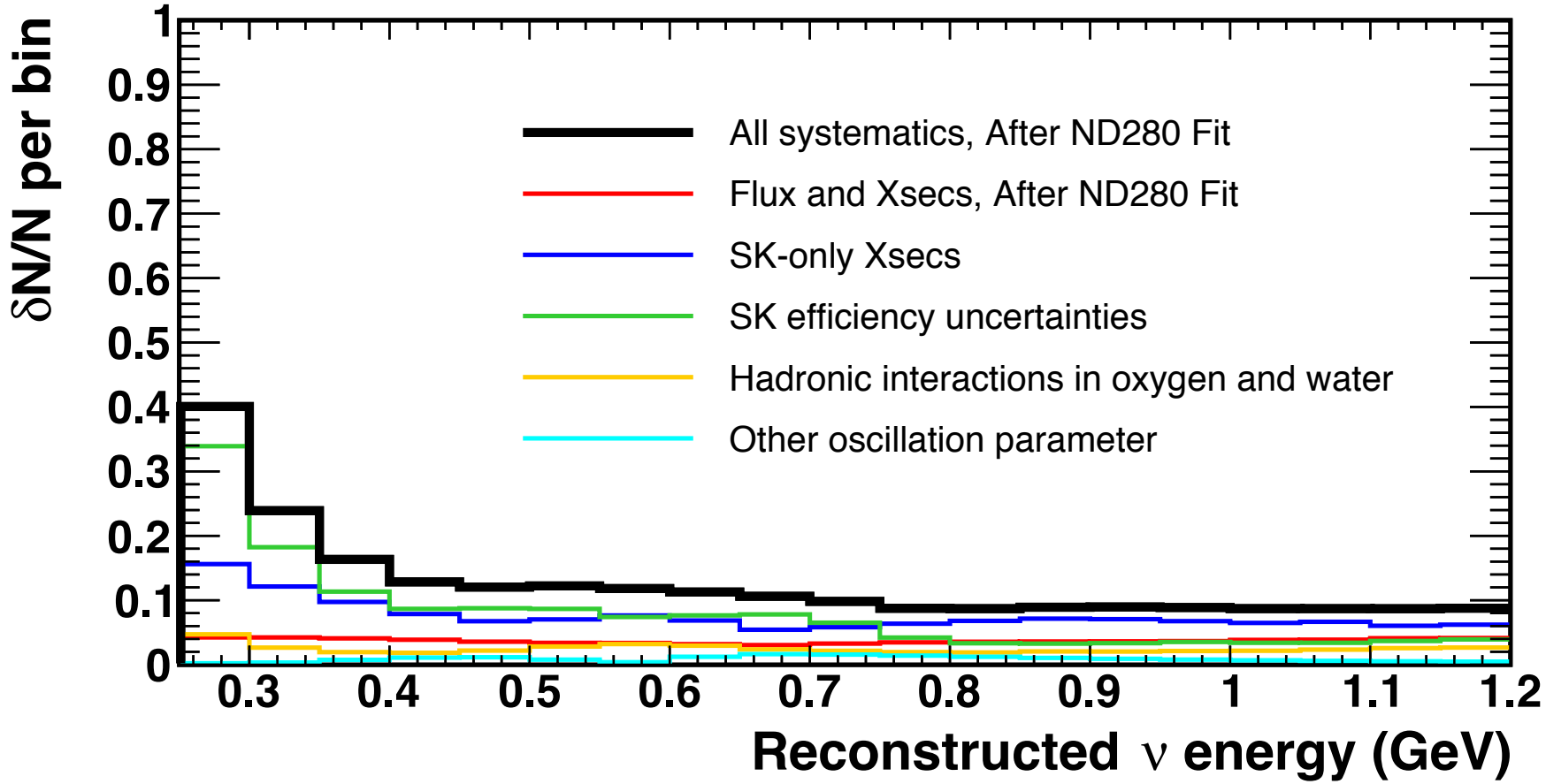
Region where MH can be distinguished by 90% C.L.



Sensitivity to resolve MH

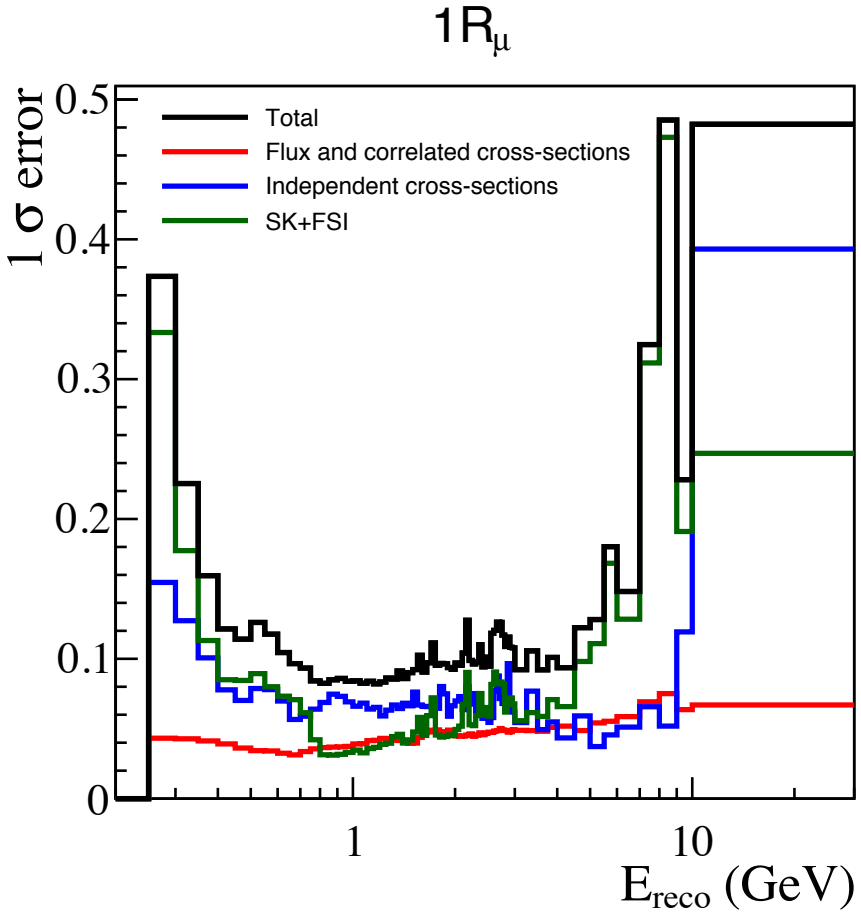
Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

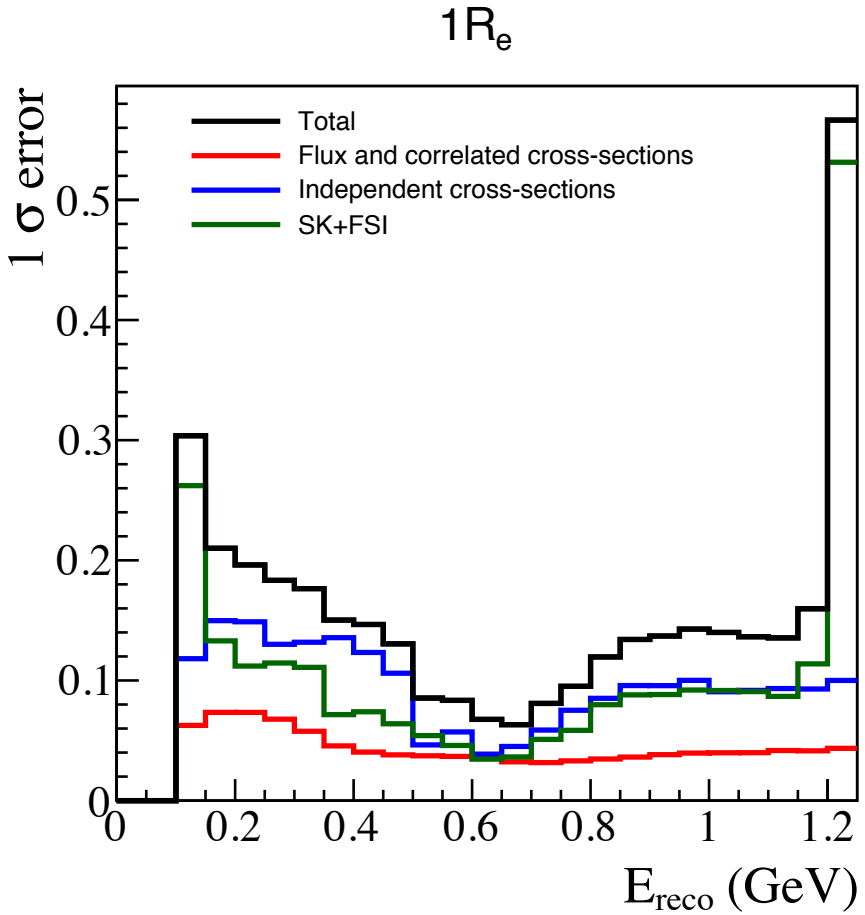
ν_μ Disappearance Systematics Summary



Summary of Systematic Errors

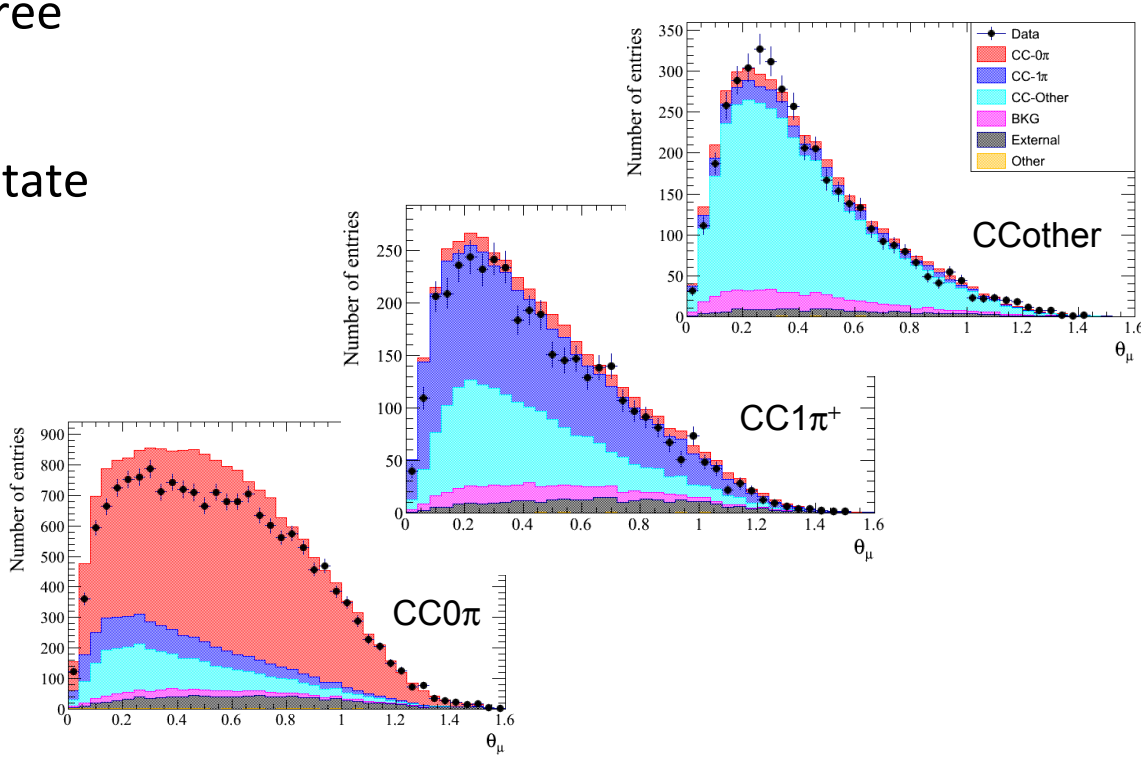
- After ND280 constraint





ND280 Tracker Analysis

- Separate the CC sample into three subsamples:
  - CC0π: **no pions** in the final state
  - CC1π$^+$: exactly **1 π$^+$** in the final state
  - CCother: **>1 π$^+$** OR **>0 π$^-$** OR **>0 tagged photons**



Data from T2K Runs 1-4:
5.9x10^{20} protons on target

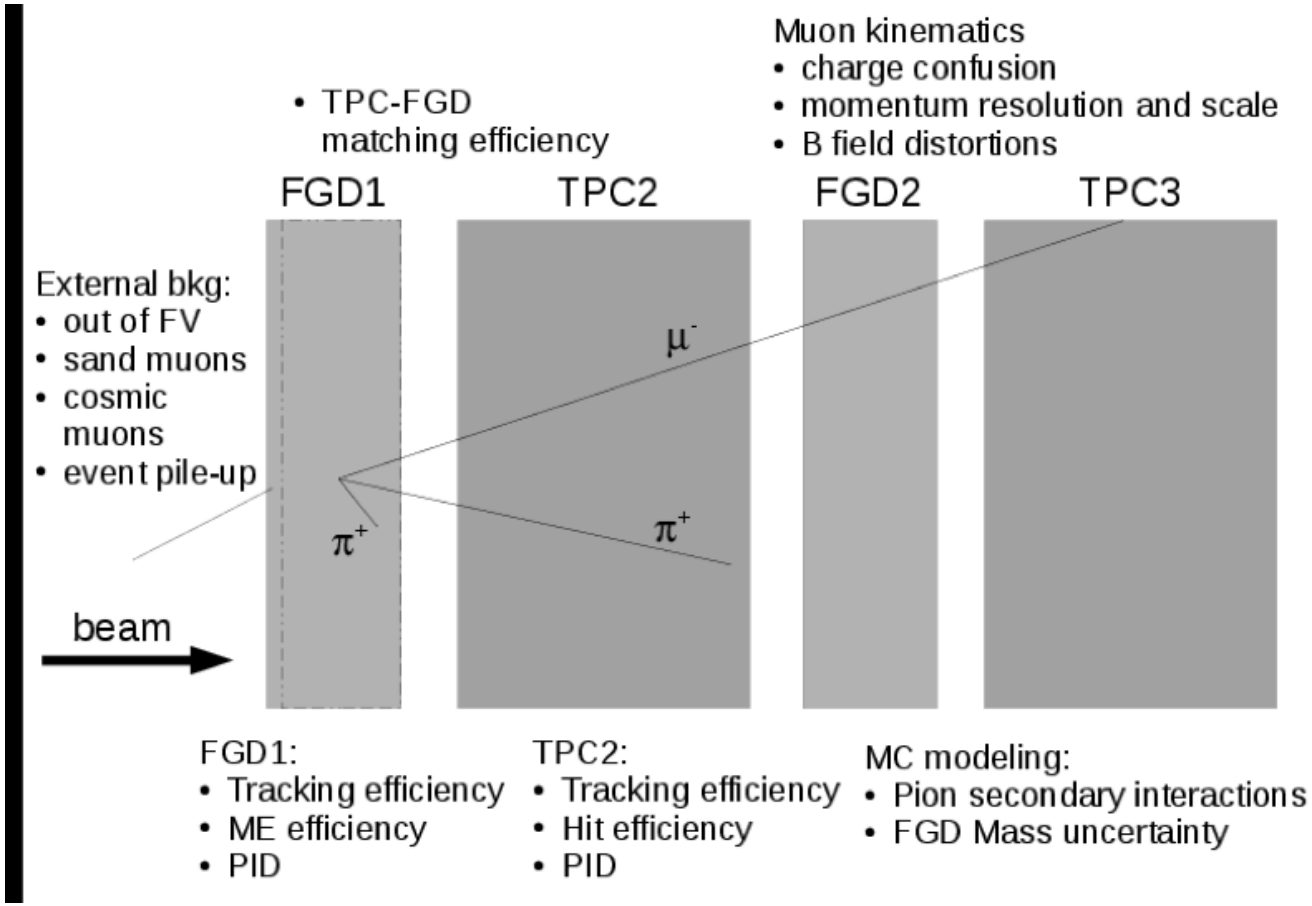
Selection	Number of Events
CC0π	17369
CC1π	4047
CC Other	4173
CC Inclusive	25589

Data are binned in two dimensions: muon momentum (p) and angle (cosθ)

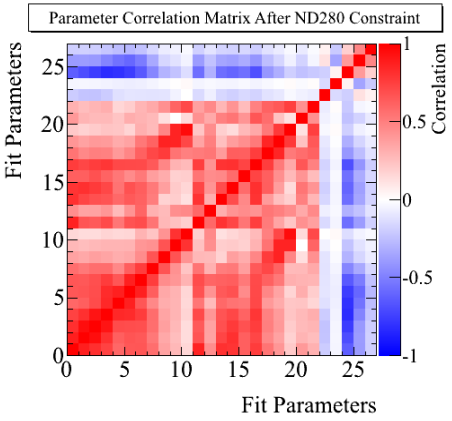
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-ν)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

ND280 Systematic Errors

- Many sources of systematic error have been evaluated for the ND280 constraint
  - All errors are assigned using data control samples

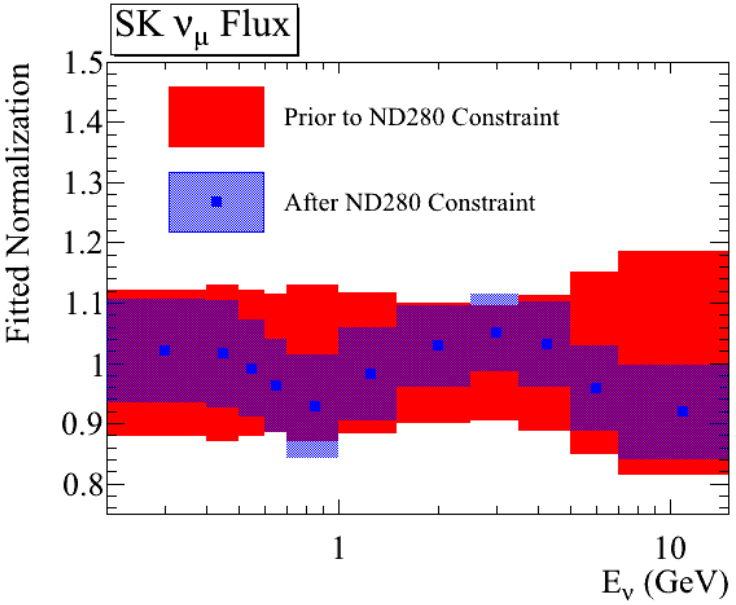


ND280 Fit Results

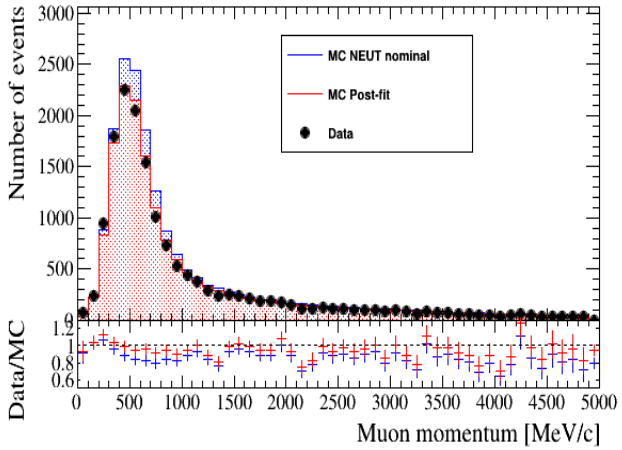


Strong reduction in uncertainties, especially through flux/xsec anti-correlation

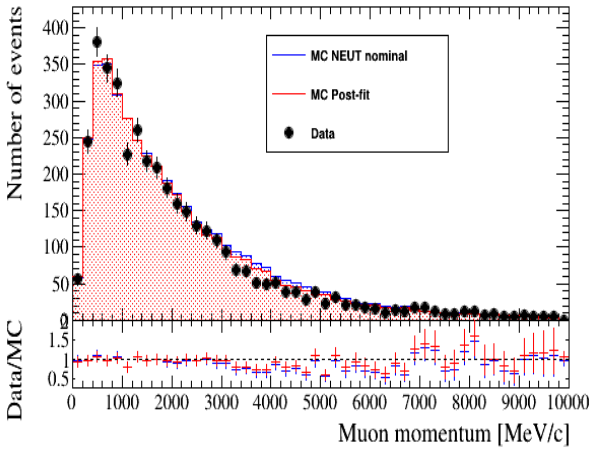
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.22 ± 0.07
CCQE Norm.	1.00 ± 0.11	0.96 ± 0.08
M_A^{RES} (GeV)	1.41 ± 0.22	0.96 ± 0.06
CC1π Norm.	1.15 ± 0.32	1.22 ± 0.16



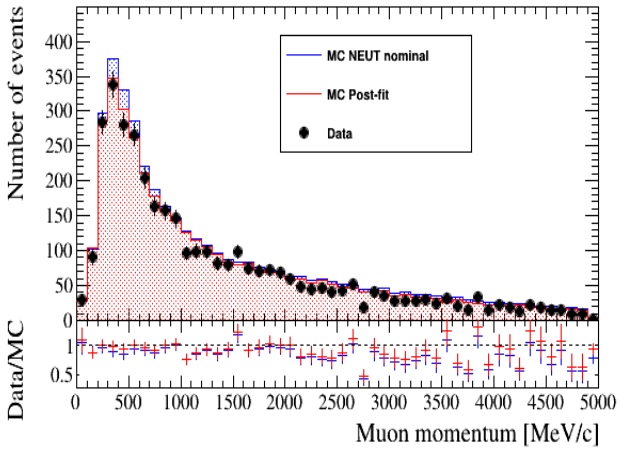
CC 0π Sample



CC 1π⁺ Sample



CC Other Sample

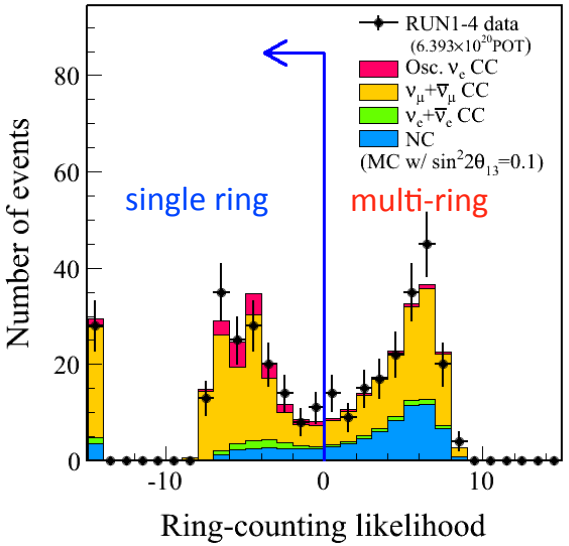


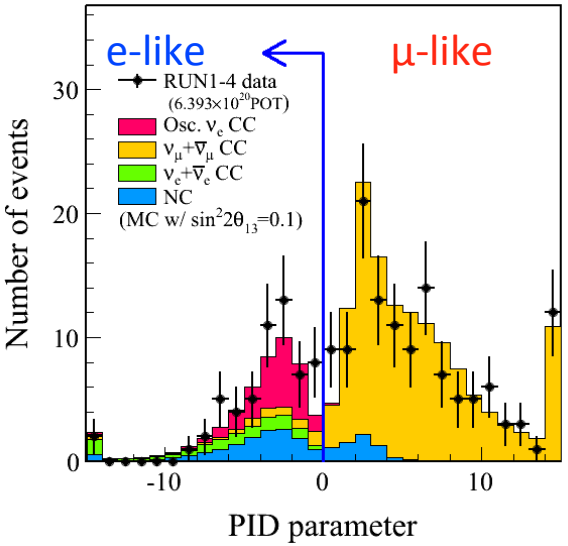
SK ν_e Appearance Event Selection

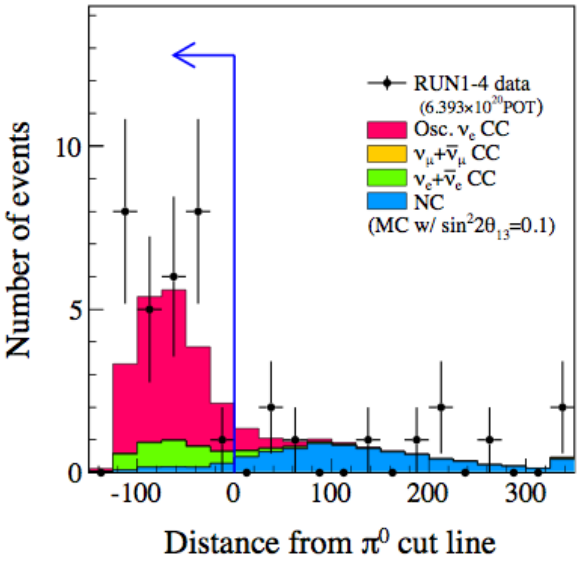
ν_e Selection Cuts

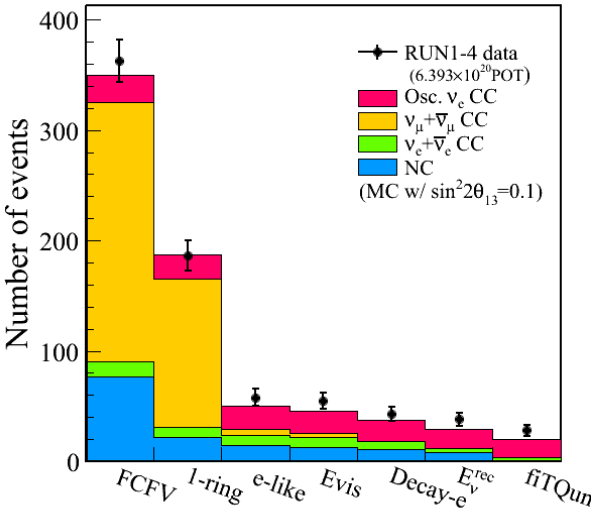
- Veto hits < 16
- Fid. Vol. = 2 m
- Single ring

- e-like
- $E_{visible}$ > 100 MeV
- no Michel $e^{\pm}$
- π^0 rejection
- $0 < E_\nu < 1250$ MeV







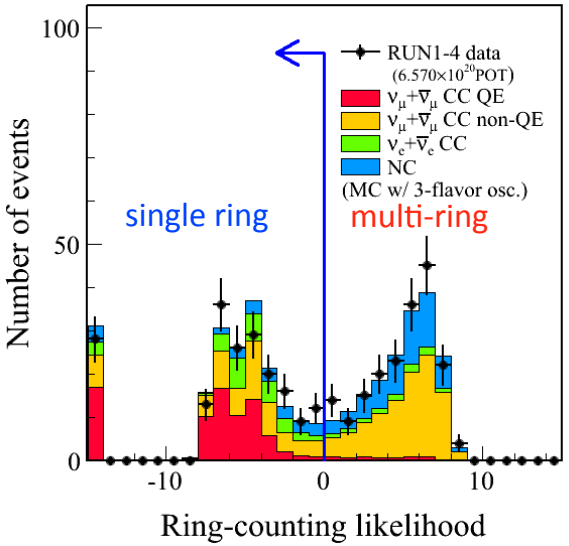


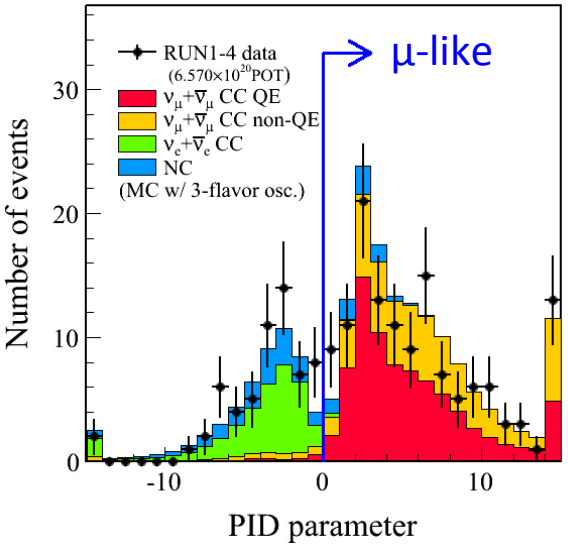
SK ν_μ Disappearance Event Selection

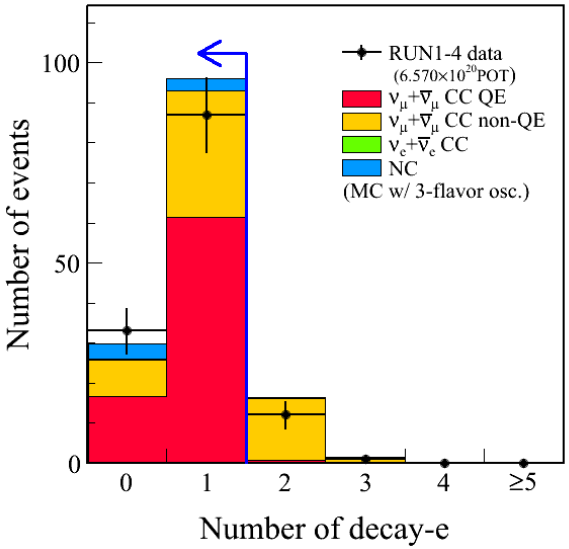
ν_μ Selection Cuts

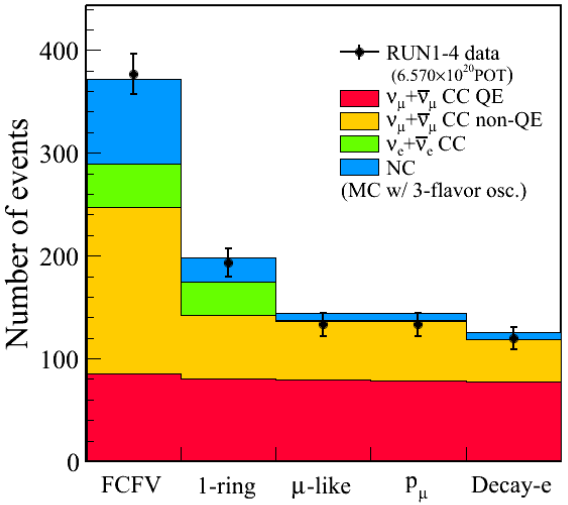
- Veto hits < 16
- Fid. Vol. = 2 m
- Single ring

- muon-like
- p_μ > 200 MeV/c
- 0 or 1 Michel $e^{\pm}$









Predicted Number of Events

$\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1$, $\Delta m_{32}^2 = 2.4\times10^{-3}$ eV^2, NH, $\delta_{CP}=0$

ν_e Selection	MC Expectation
ν_e CC Signal	17.32
ν_e + anti-ν_e CC	3.24
NC	0.96
ν_μ + anti-ν_μ CC	0.07
Total	**21.59**

ν_μ Selection	MC Expectation
ν_μ + anti-ν_μ CCQE	77.93
ν_μ + anti-ν_μ CCnQE	40.78
NC	6.78
ν_e + anti-ν_e CC	0.35
Total	**125.85**

ν_μ MC Components