ETH
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Results of T2K

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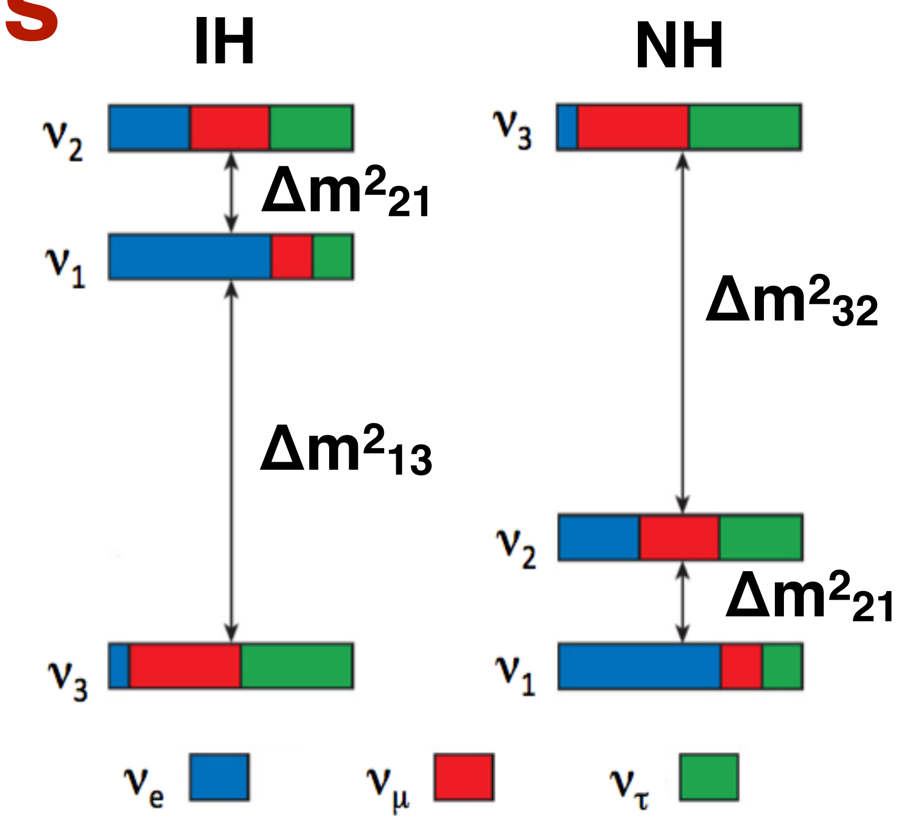
on behalf of the T2K collaboration

Rencontres de Blois, May 20th 2014

Neutrino oscillations

$$P(\overset{(-)}{\nu_\alpha} \rightarrow \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\overset{+}{\scriptstyle (-)} 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$



L: neutrino flight path

E: neutrino energy

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

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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

atmospheric/ accelerator	$\sin^2(2\theta_{23}) > 0.95$ (90%CL)	SK, MINOS, K2K, T2K	Majorana phases (no effects)
reactor/ accelerator	$\sin^2(2\theta_{13}) > 0.098 \pm 0.013$	T2K, MINOS, DB, RENO, DC	
Solar/ reactor	$\sin^2(2\theta_{12}) > 0.857 \pm 0.024$	KamLAND, SNO, SK	

$$\Delta m^2_{21} = 7.58^{+0.22}_{-0.26} \times 10^{-5}\mathrm{eV}^2/\mathrm{c}^4$$

$$|\Delta m^2_{32}| = 2.35^{+0.12}_{-0.09} \times 10^{-3}\mathrm{eV}^2/\mathrm{c}^4$$

Oscillation probabilities at T2K

Open questions:

- Is CP symmetry violated in lepton sector ($\delta_{CP} \neq 0$)?
- Mass hierarchy (sign of Δm^2_{31})?
- Is θ_{23} maximal (or which octant)?

At T2K:
$E_{peak} \sim 0.6$ GeV,
L ~ 295 km (baseline)

ν_μ disappearance → measure θ_{23} and Δm^2_{32}

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Leading term

ν_e appearance → measure θ_{13} and δ_{CP}

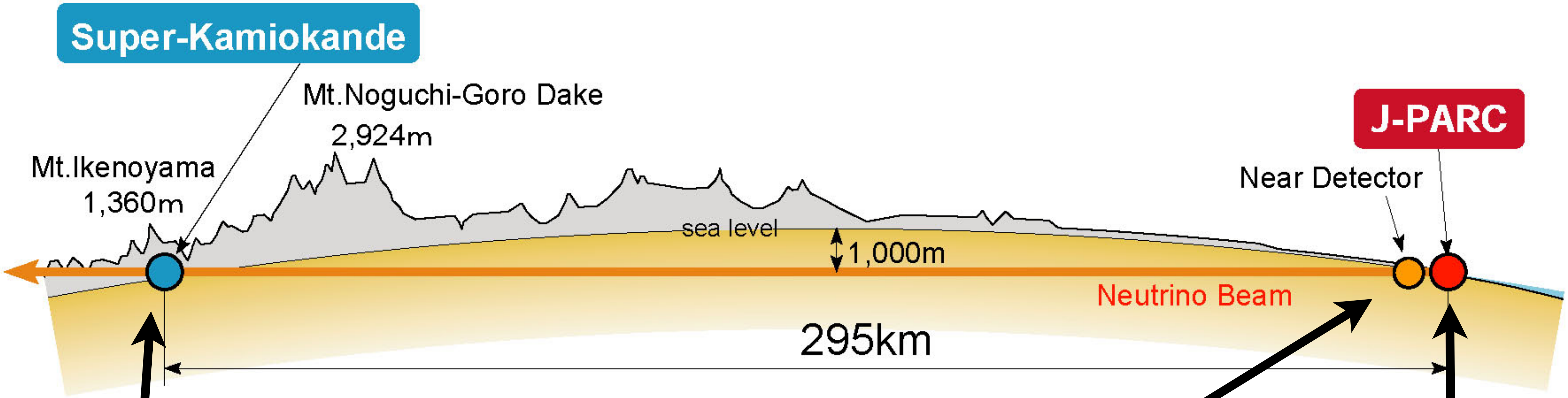
Can solve the octant

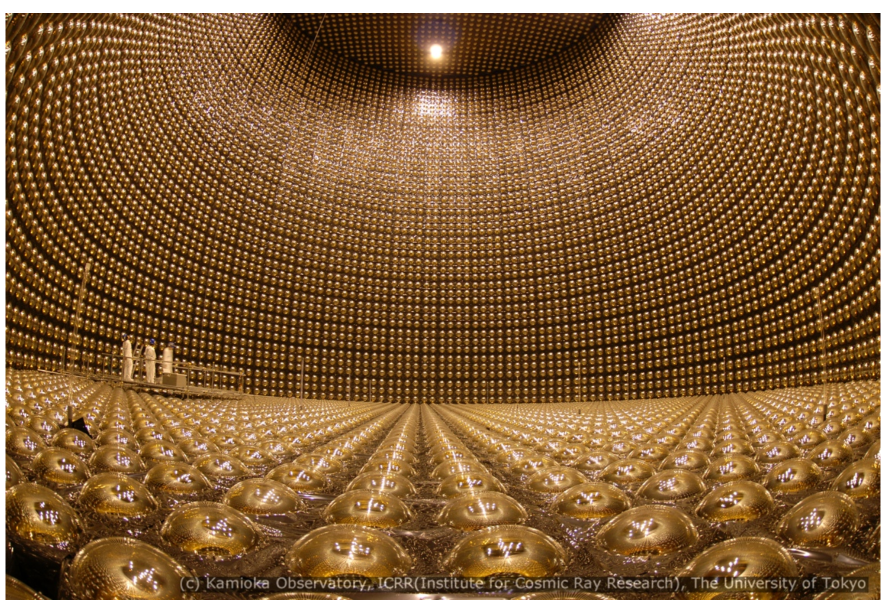
δ_{CP} can be measured since $\sin^2 2\theta_{13} > 0$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

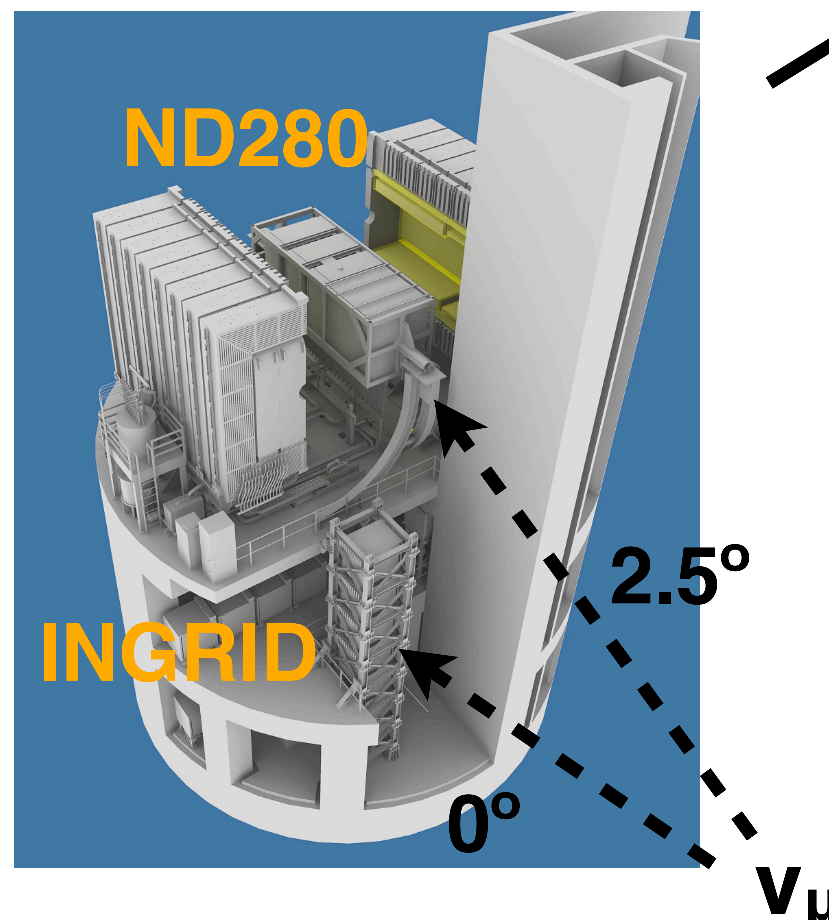
$$-\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\left(\frac{\Delta m^2_{21} L}{4E}\right)\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E}\sin\delta_{CP}$$

The T2K Experiment





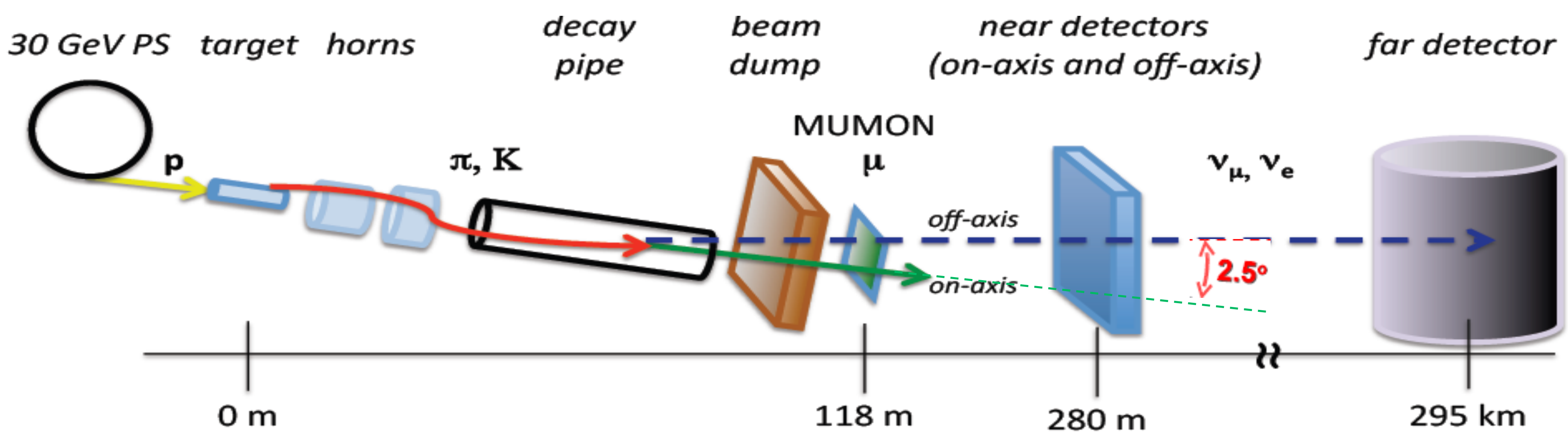
Super-Kamiokande



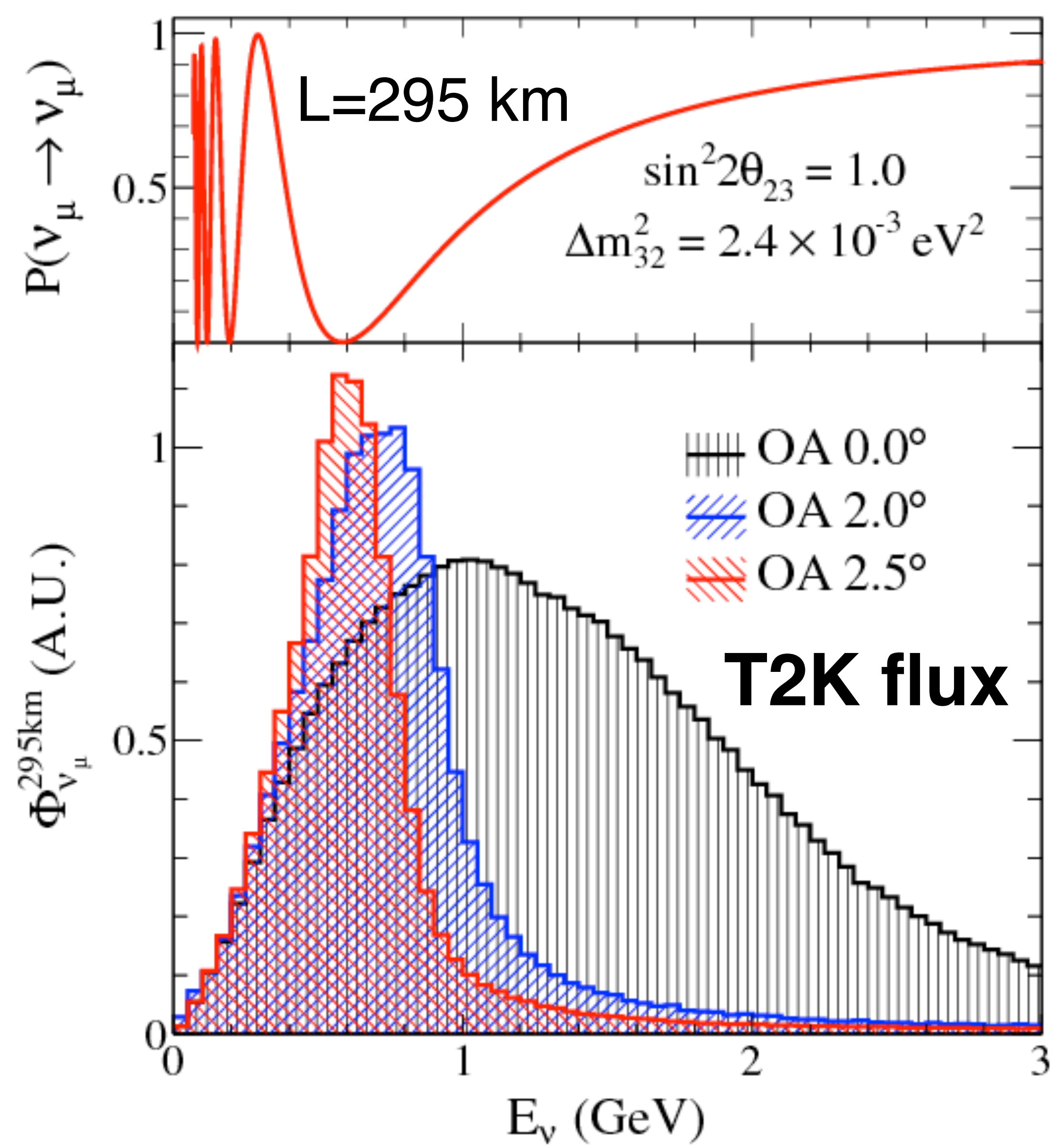
INGRID (on-axis) and ND280 (off-axis)

Neutrino beam created at J-PARC main ring

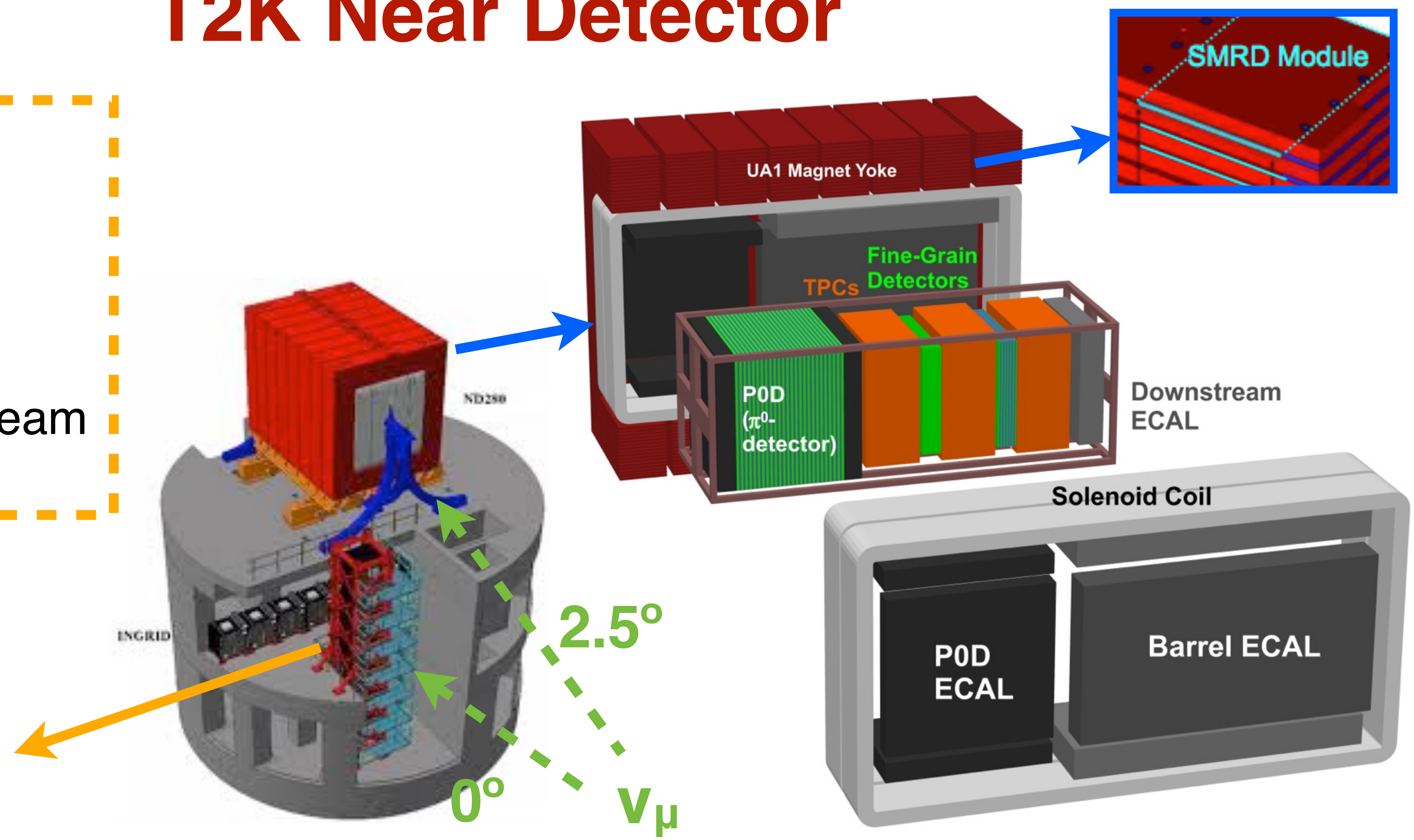
T2K Neutrino Beam



- 30 GeV proton beam on C target (90 cm)
- 3 magnetic horns (250kA)
- **ν_μ from π^+ decay (~96m decay pipe)**
- **Small ν_e contamination from μ and K**
- **Muon Monitor (MUMON)**
  - measure the beam profile and intensity
  - monitor the on-axis beam direction
- Beam dump to stop hadrons
- **2.5° off-axis neutrino beam**
  - low-energy narrow band
  - peak at oscillation maximum
  - decrease high-energy background
- **Hadron production measured by NA61/SHINE experiment (CERN)**
  - tune the flux and reduce the uncertainties

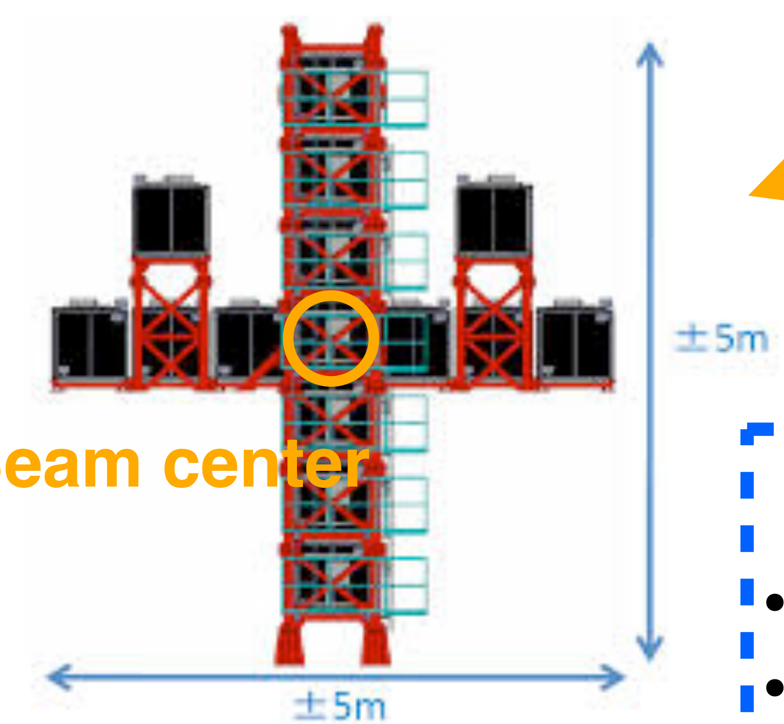


T2K Near Detector



INGRID (on-axis)

- Iron/scintillator tracking calorimeters
- 16 modules
- Measure the neutrino beam intensity and direction

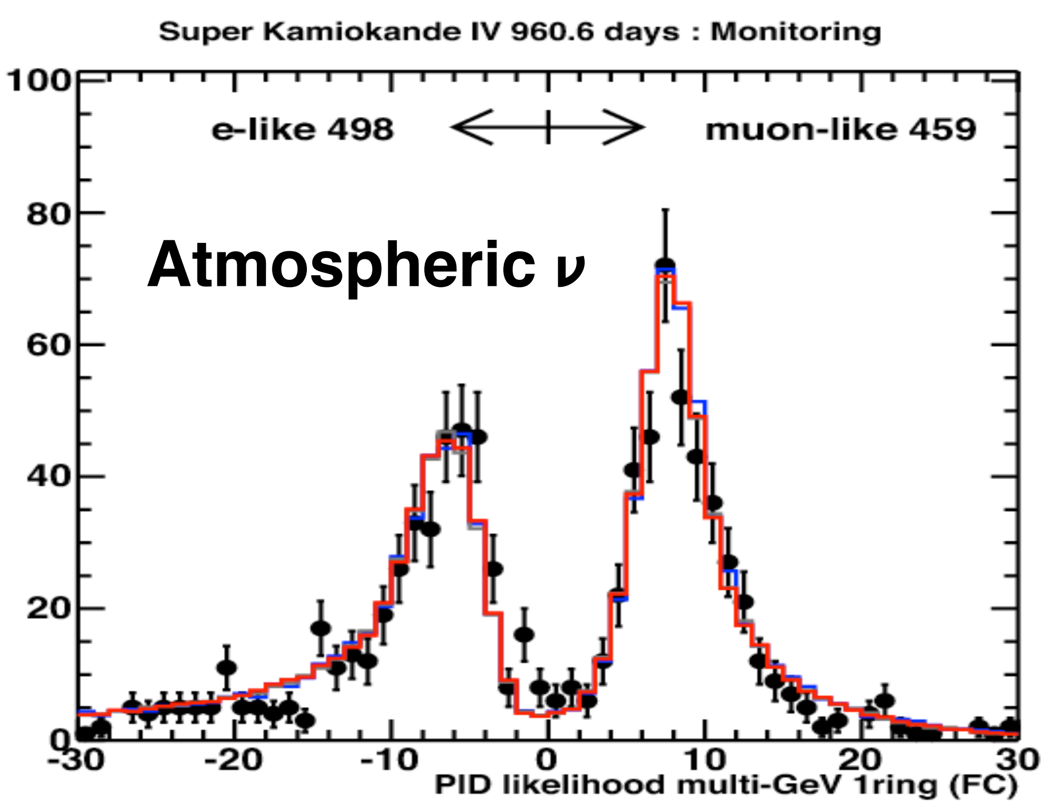


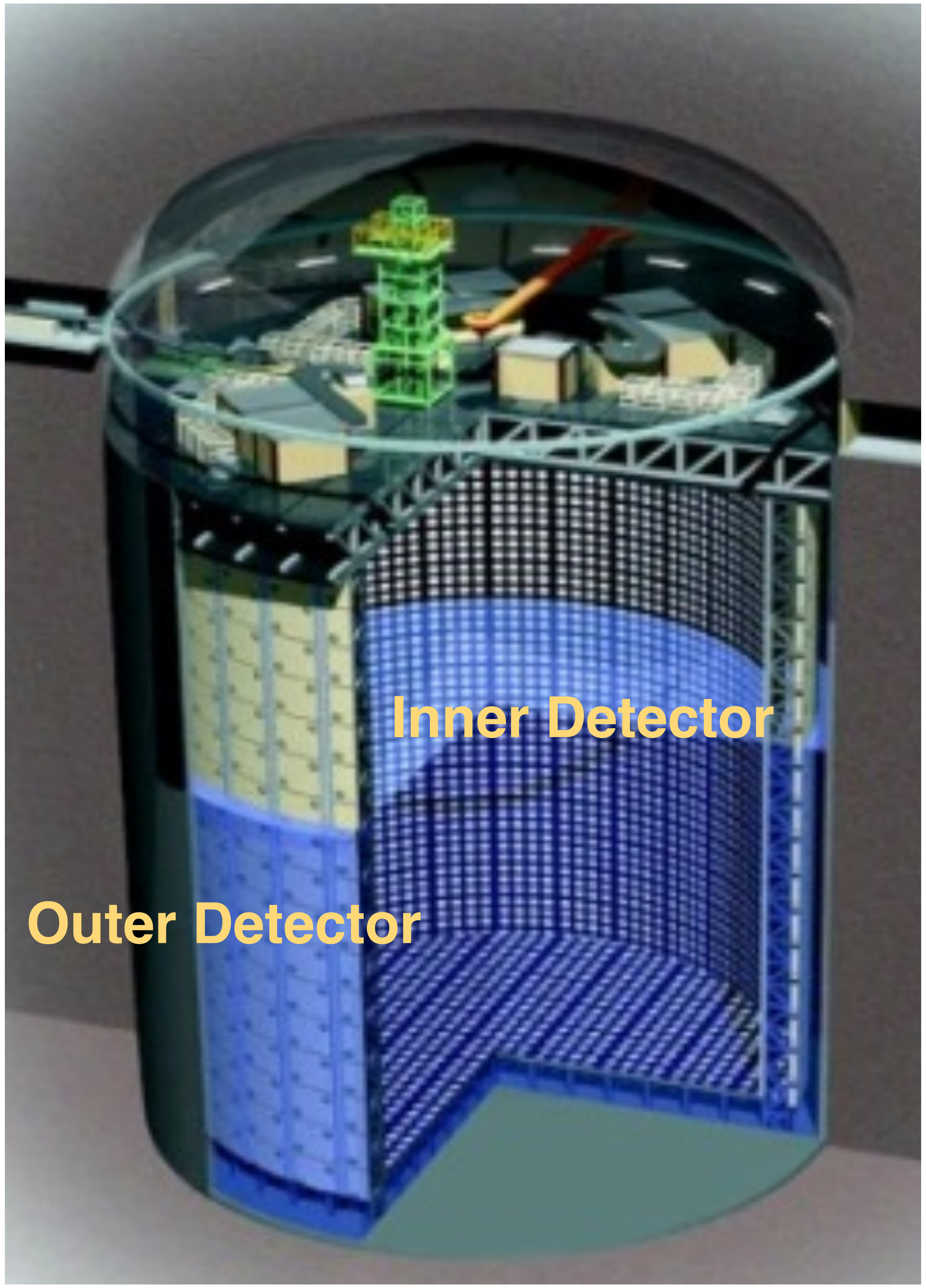
ND280 (2.5° off-axis)

- UA1 dipole magnet (0.2T)
- ECAL (Electromagnetic Calorimeter)
- P0D (π^0 detector)
- SMRD (Side Muon Range Detector)
- 2 Fine Grain Detectors (FGDs)
  - Active target mass
  - Vertex reconstruction
- 3 TPCs (Time Projection Chamber)
  - PID (dE/dx)
  - momentum reconstruction

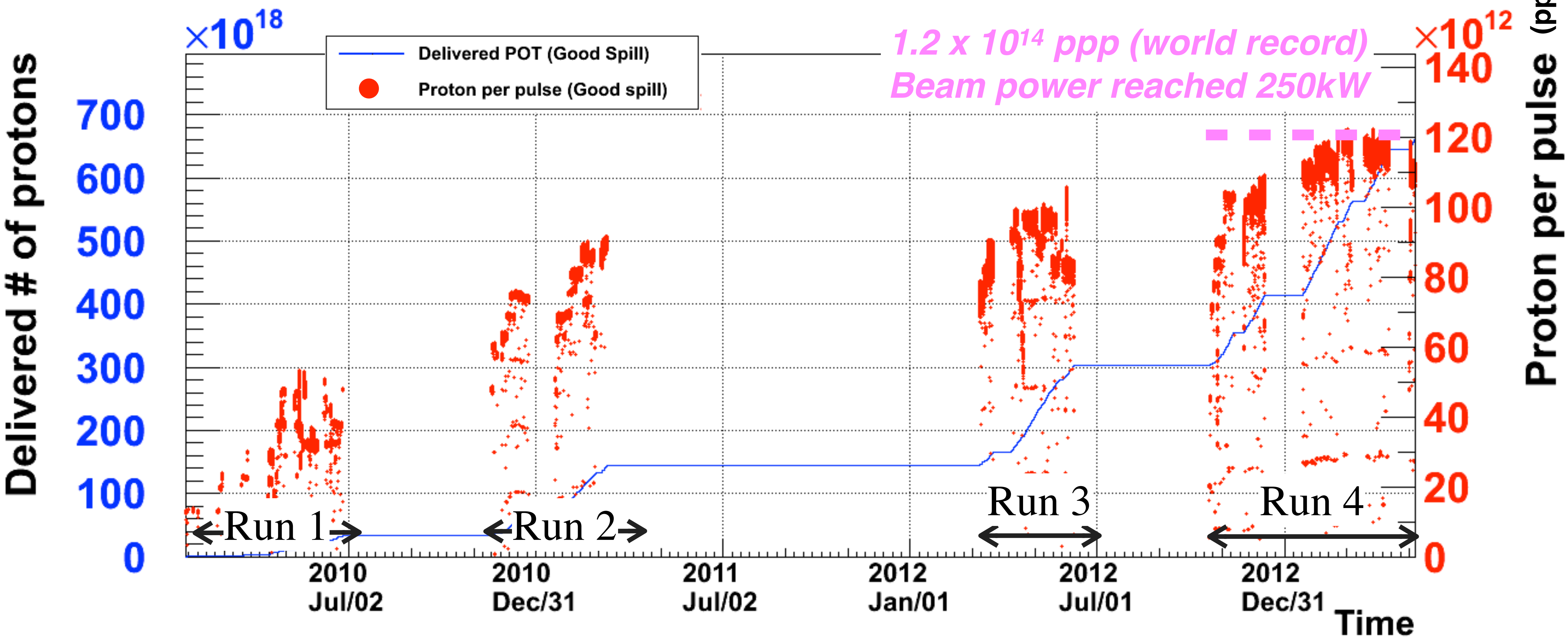
T2K far detector: Super-Kamiokande

- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector (~11k PMTs)
- Outer detector (2k PMTs) determine fully contained events
- Very good e/μ separation
- Muons misidentified as electron <1%





Data collected and analyzed



- We collected 6.63 x 10^{20} protons on target (p.o.t.) so far (~8% target total p.o.t.)
- Beam power has been increased up to 220kW
- Operation with a world record of 1.2x10^{14} proton per pulse
- <1mrad beam direction stability (<2% beam energy shift)

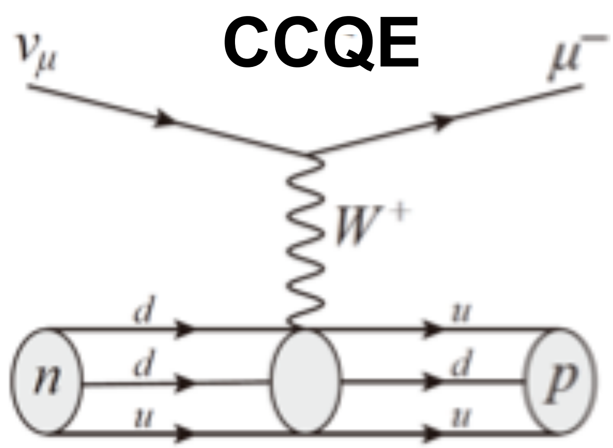
ND280 selected samples

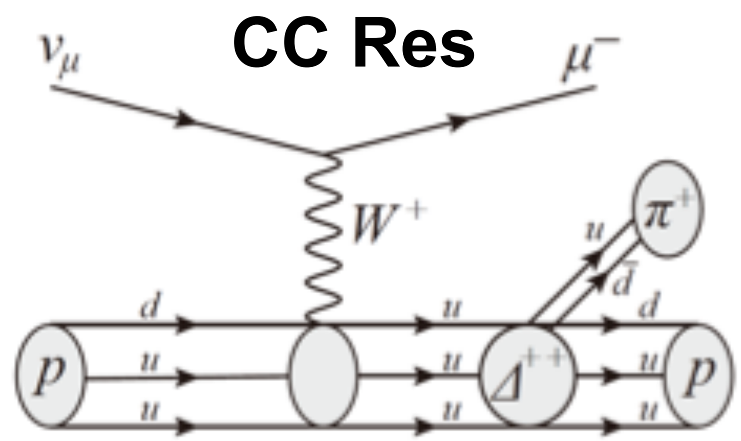
- ND280 is used to constrain the systematic uncertainties at SK
- Select events w/ ND280 Tracker
- Separate into 3 samples by topology :
  - CC0π: no pions in the final state
  - CC1π+: only 1π+ in the final state
  - CCother: >1π+ or >0π - or >0 tagged photons

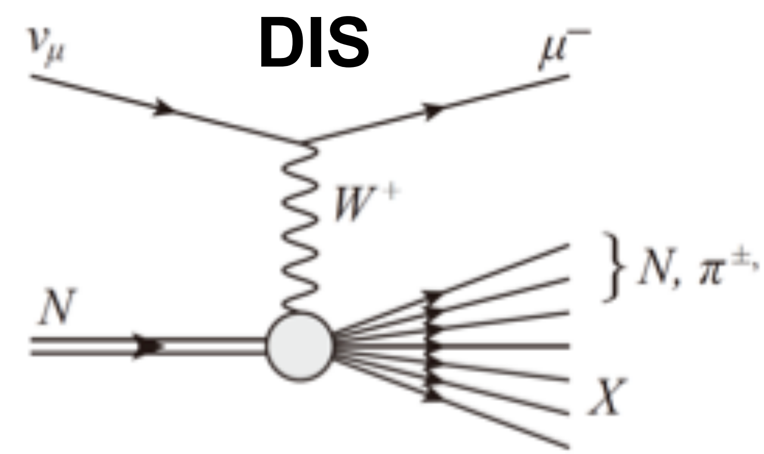
Run1-4 (5.9×10^{20} p.o.t.)

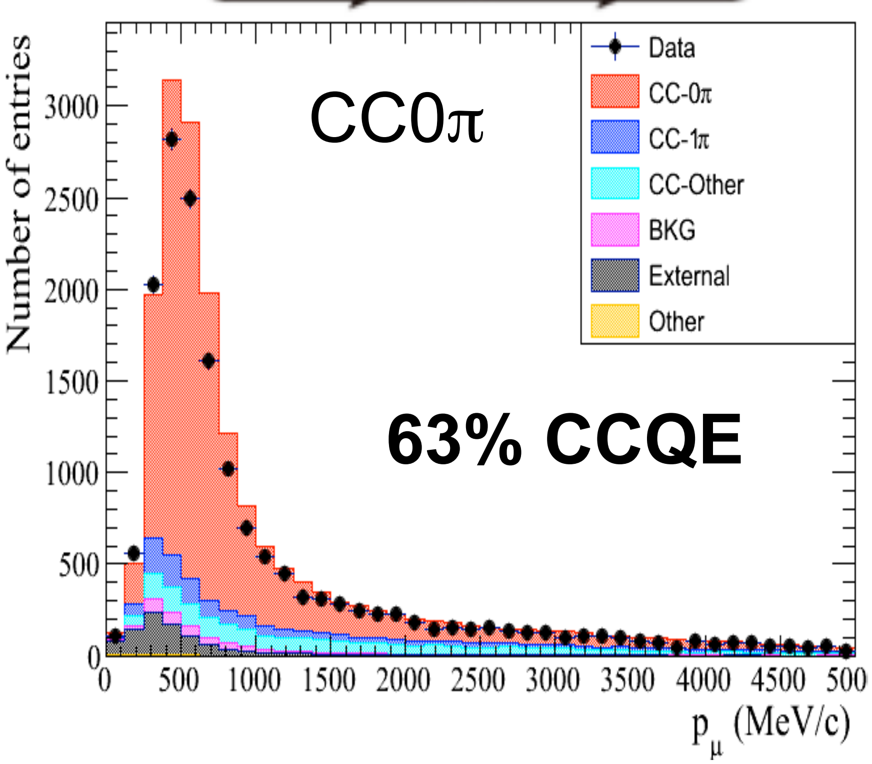
Measured ν_e flux normalization agrees with expectation: **$R(\nu_e) = 1.01 \pm 0.10$**

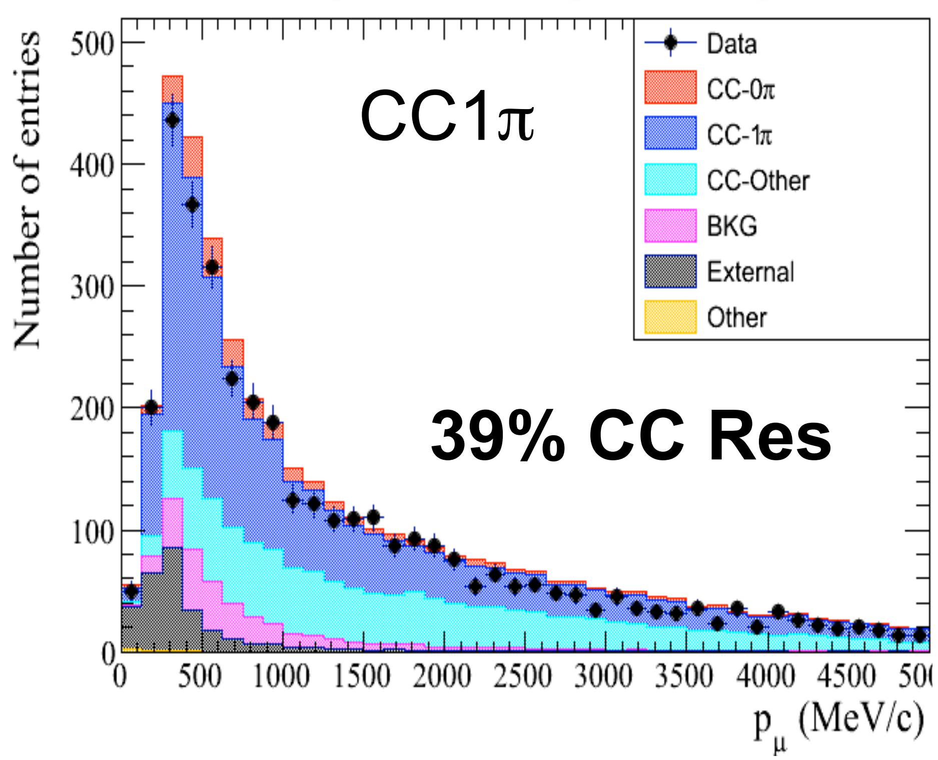
PRD 89 092003, arXiv:1403.2552

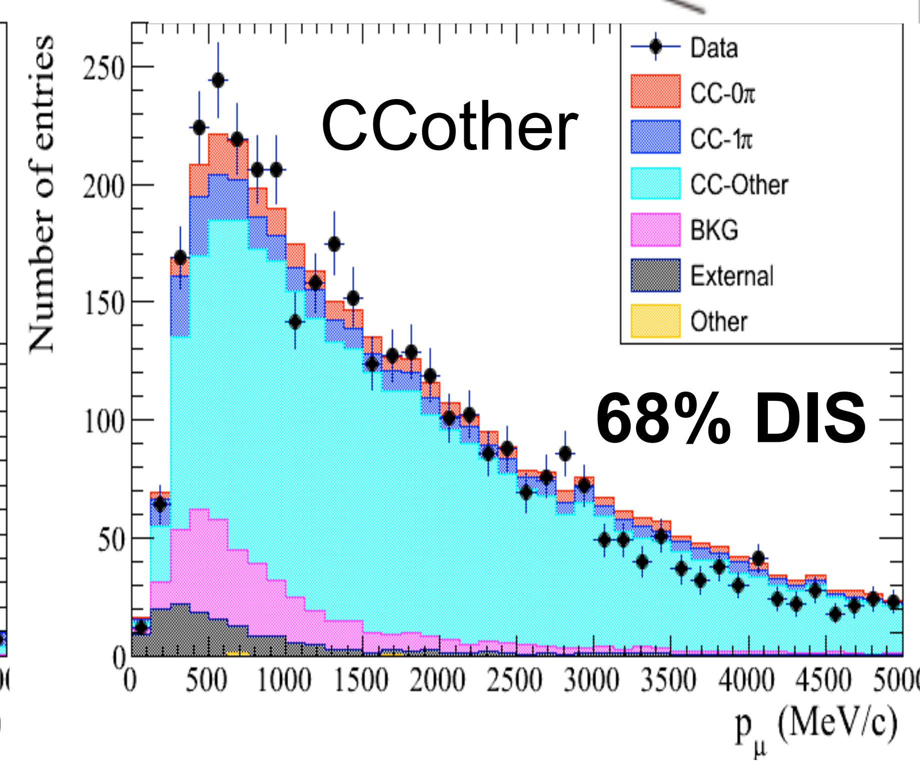










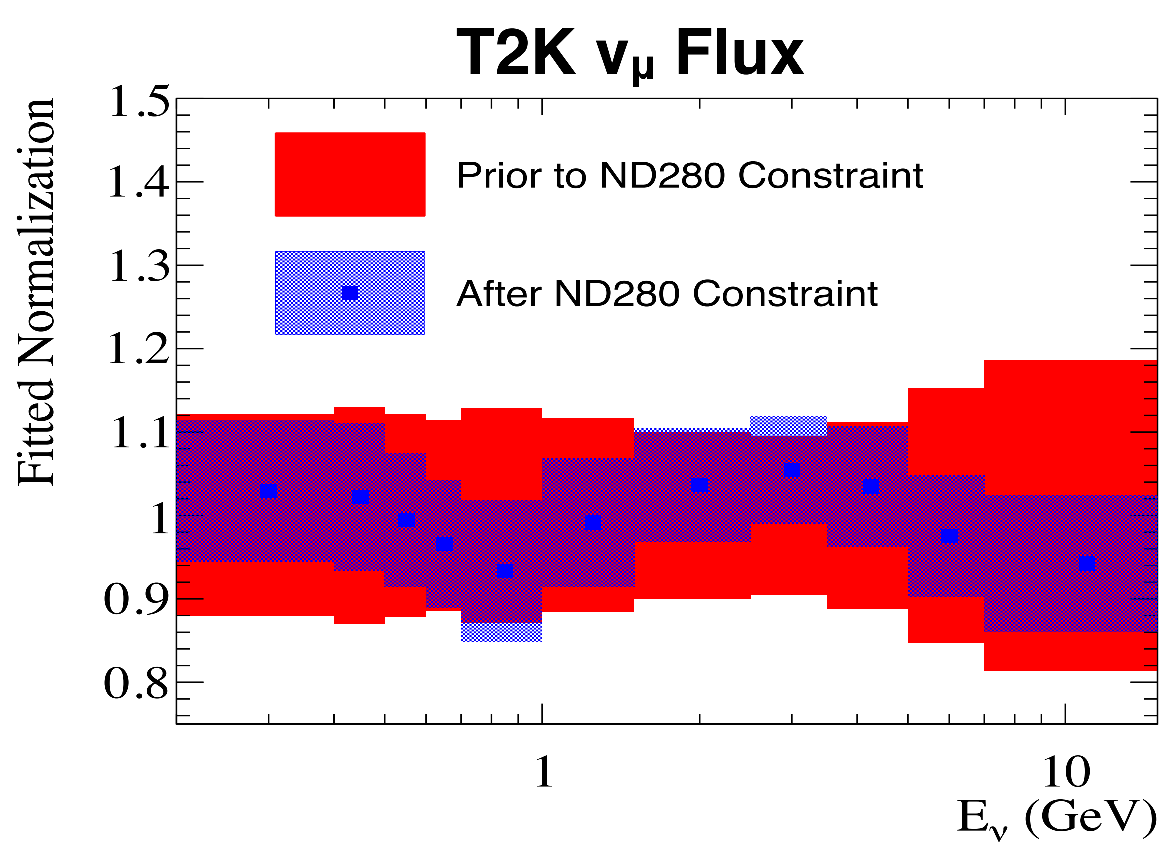


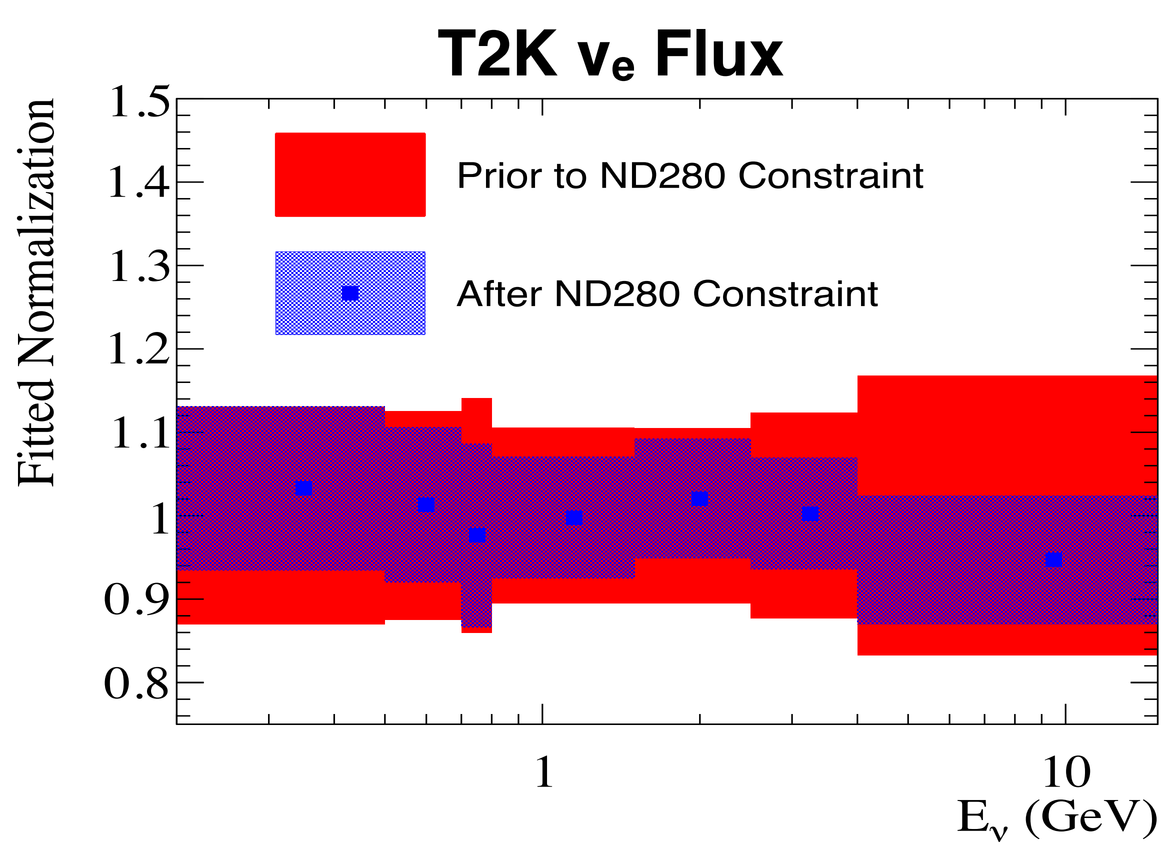
ND280 constraint

- In the fit data are binned in $\{p_\mu, \theta_\mu\}$
- Only ν_μ data sample is used
- From ~12% to ~7% uncertainty on flux
- Reduce the correlated flux and cross section (Xsec) systematic uncertainties at the far detector

Systematic uncertainties	% variation of Tot # of ν_e events	% variation of Tot # of ν_μ events
T2K corr. Flux-Xsec (w/o constraint)	2.9 (25.9)	2.7 (21.6)

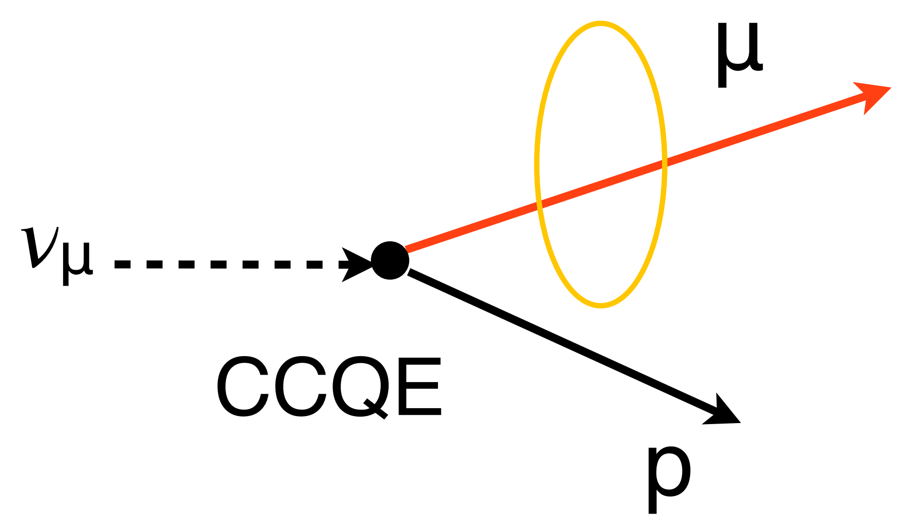
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25





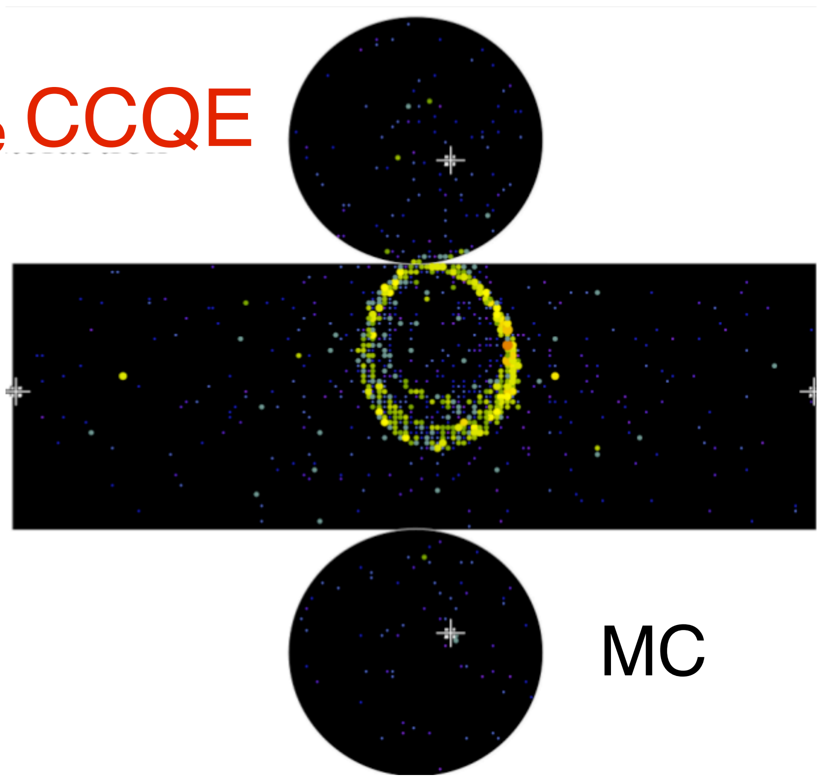
T2K events

ν_μ SIGNAL

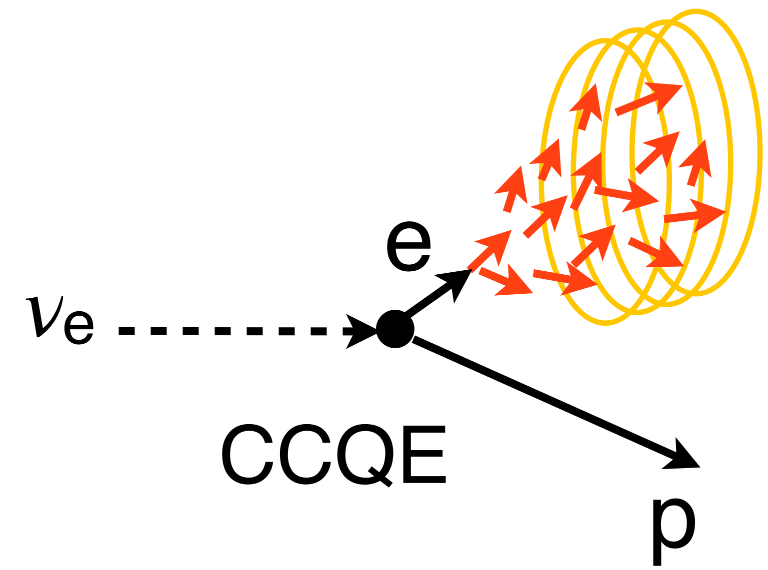


- Low scattering
- Ring with sharp edge

ν_e CCQE

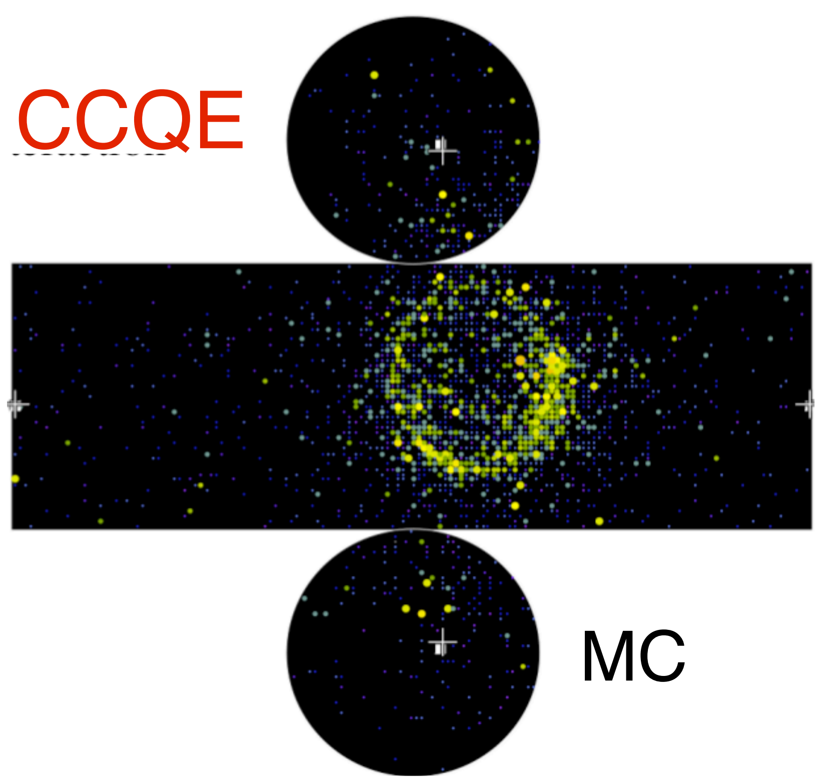


ν_e SIGNAL

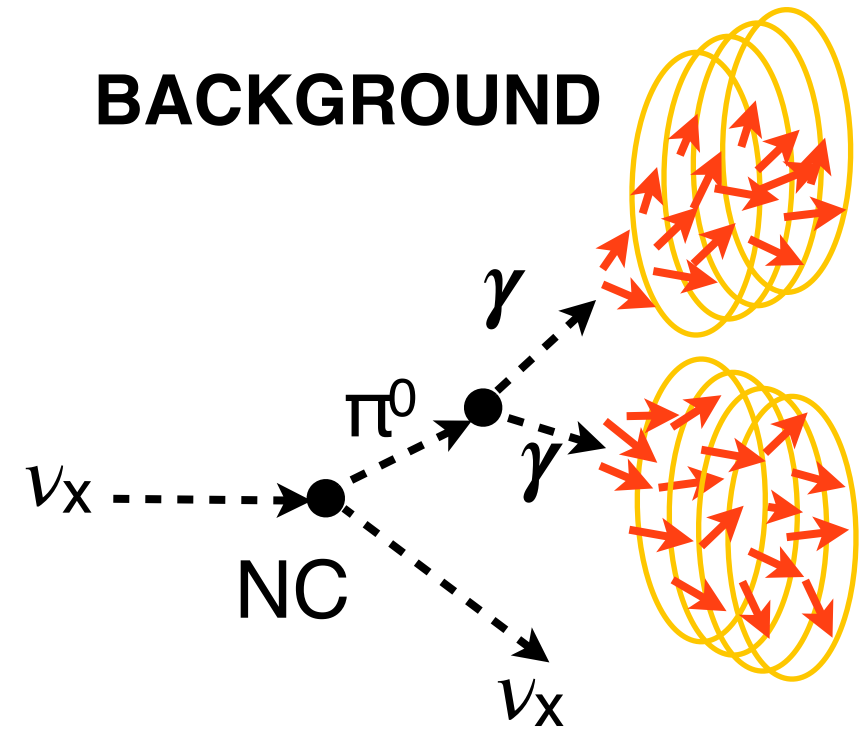


- Multiple scattering
- EM shower
- Ring with “fuzzy” edge

ν_μ CCQE

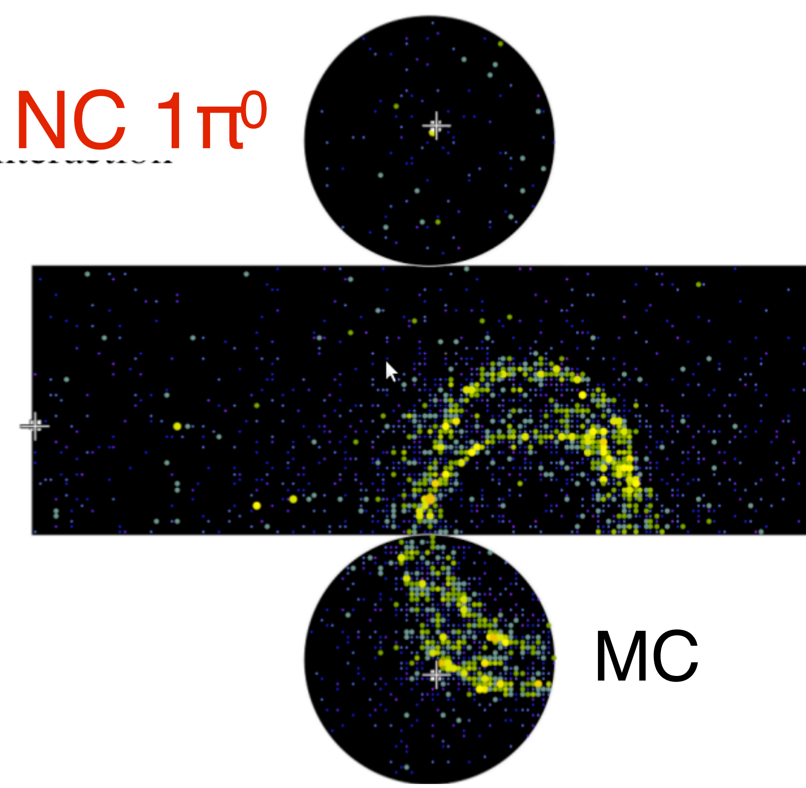


BACKGROUND



- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron
- Intrinsic ν_e component <1%

ν NC $1\pi^0$



T2K selected samples

ν_μ event selection

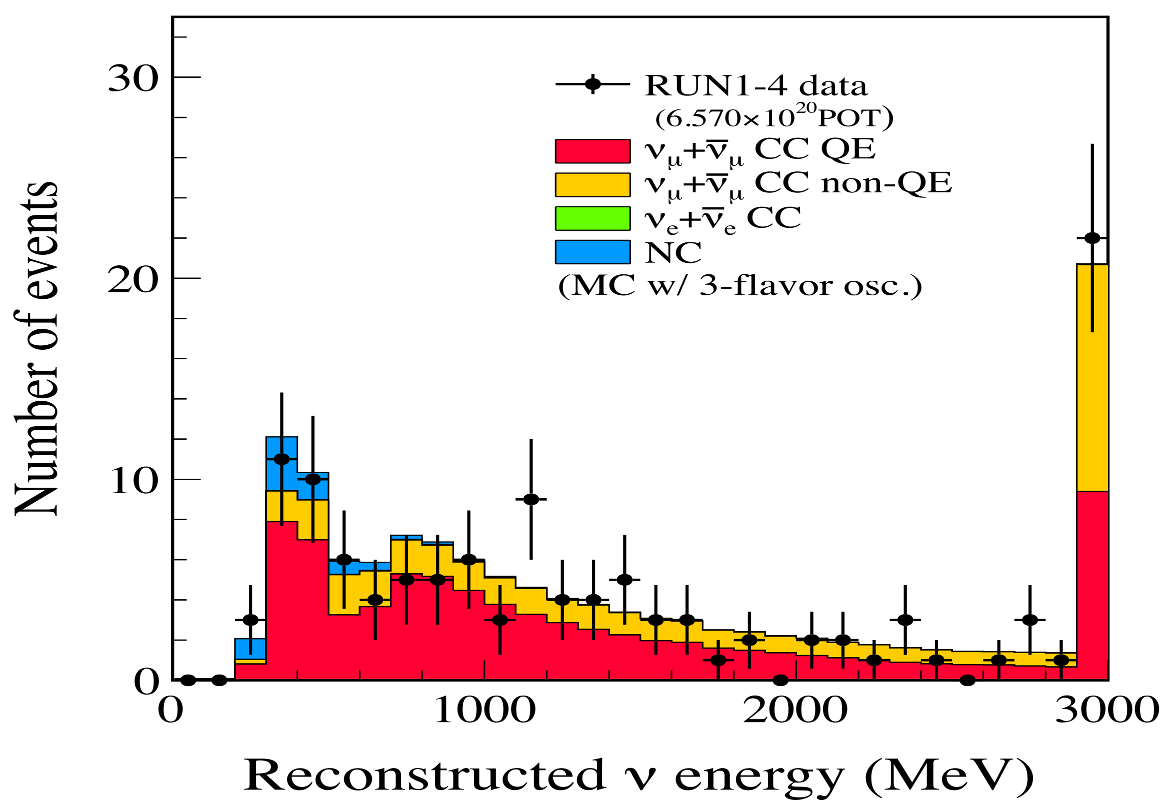
- Fully contained fiducial volume
- Single ring μ-like event
- $E_{visible}$ > 200 MeV
- # decay electron ≤ 1

ν_e event selection

- Fully contained fiducial volume
- Single ring e-like events
- $E_{visible}$ > 100 MeV
- No decay electron
- 0 < E_{rec} < 1250 MeV
- π^0 rejection cut

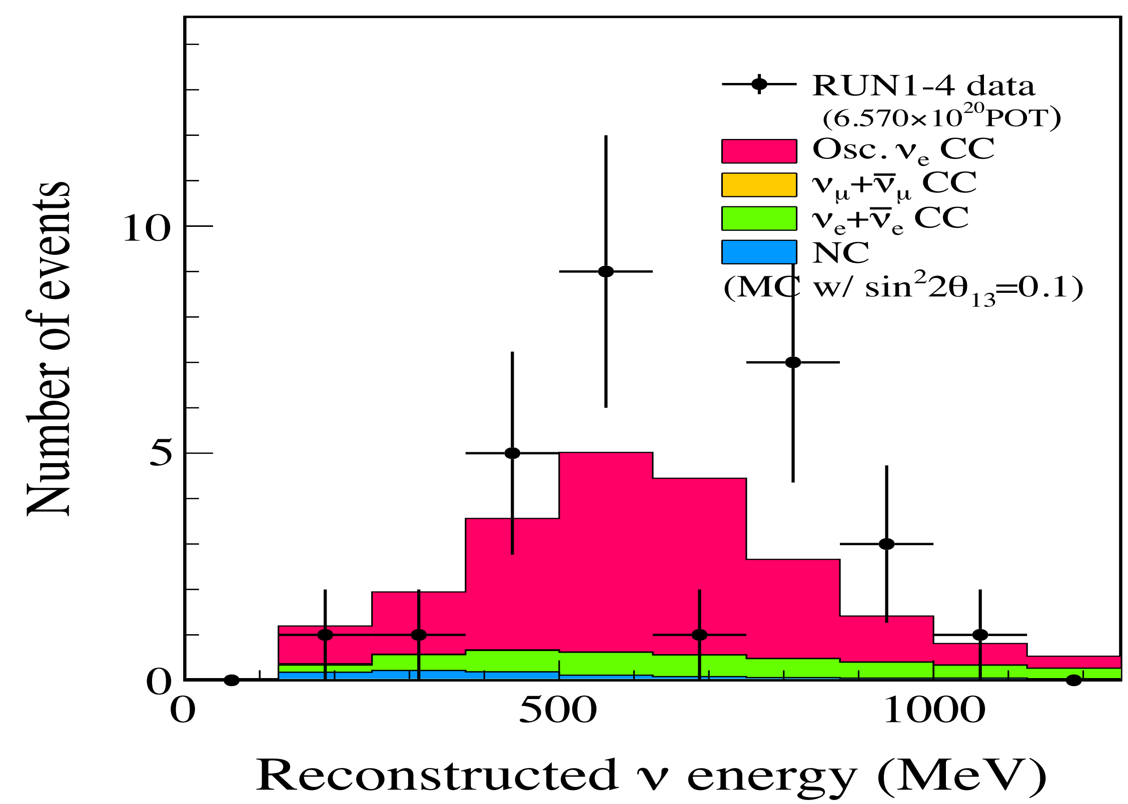
Selected events = 120

Exp. ν_μ events (w/o osc) = 446 ± 23 (syst)



Selected events = 28

Exp. Bkg. events = 4.9 ± 0.6 (syst)



$\nu_\mu \rightarrow \nu_\mu$ disappearance

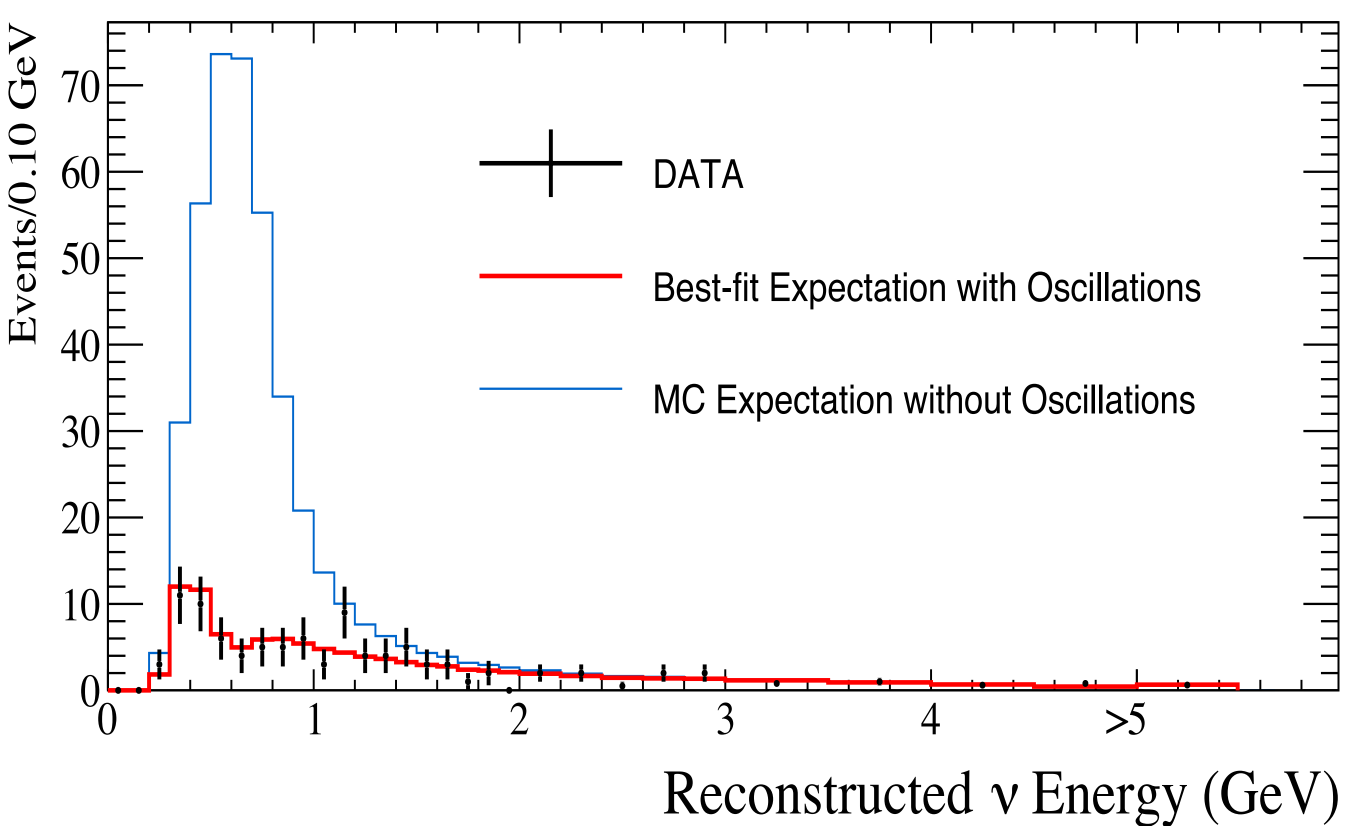
Exp. ν_μ events (w/o osc) = 446 ± 23 (syst)

Selected events = 120

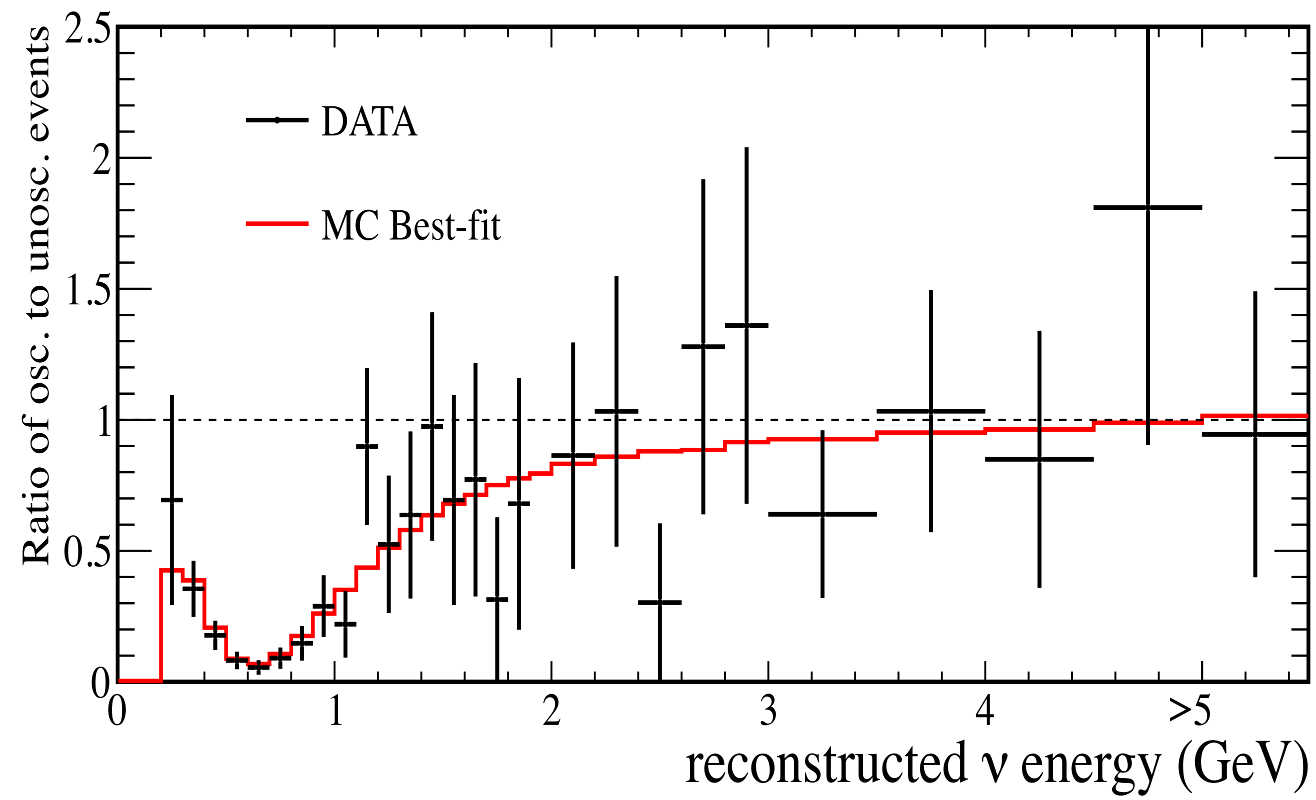
- Single-ring μ-like sample
- Use E_{reco} distributions
- Unbinned maximum likelihood fit
- Simultaneous fit of $\sin^2\theta_{23}$, Δm^2_{32} (Δm^2_{13} for IH)

Oscillation parameters	Best-fit value
$\sin^2\theta_{23}$ [NH]	0.514
Δm^2_{32} [NH] (eV^2/c^4)	2.51×10^{-3}
$\sin^2\theta_{23}$ [IH]	0.511
Δm^2_{13} [IH] (eV^2/c^4)	2.48×10^{-3}

E_{reco} distribution



Ratio wrt no oscillation



$\nu_\mu \rightarrow \nu_\mu$ disappearance

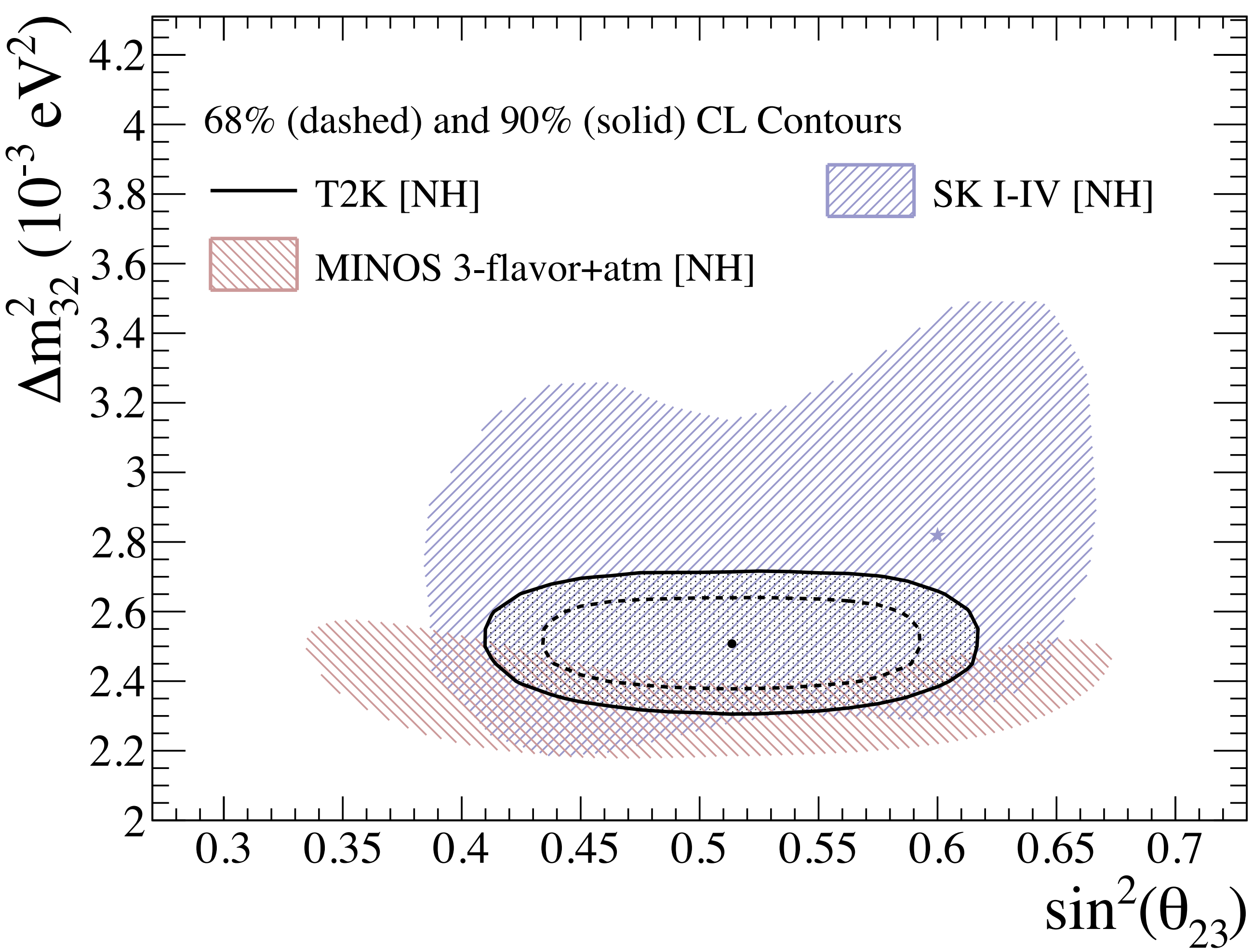
- Confidence intervals performed with the Feldman-Cousins method
- T2K data prefer maximal mixing
- **(Phys. Rev. Lett. 112, 181801 (2014), arXiv:1403.1532)**

90% 1D confidence intervals

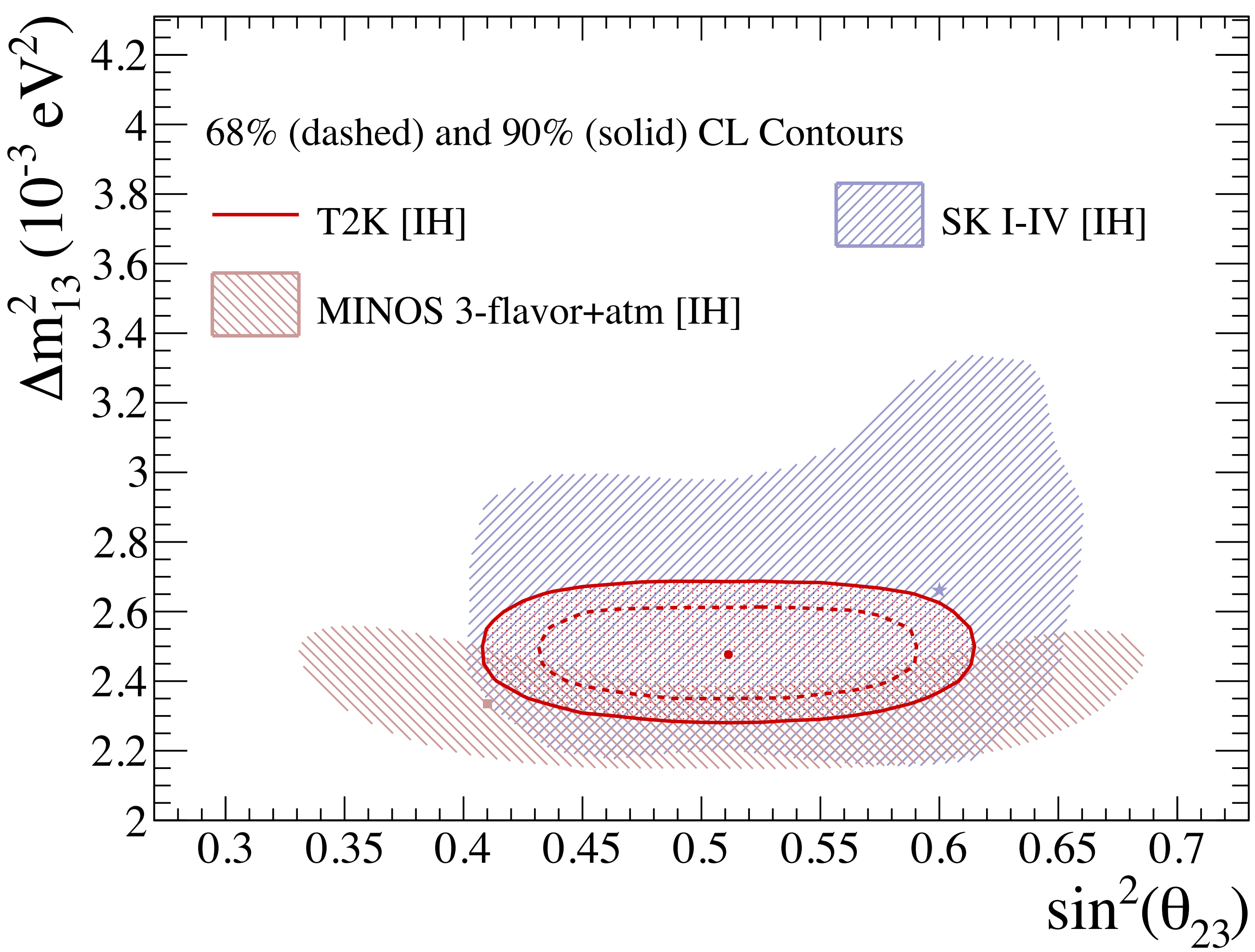
NH: $0.428 < \sin^2\theta_{23} < 0.598$
$2.34 < \Delta m^2_{32}\ (\mathrm{eV^2/c^4}) < 2.68\ (\times 10^{-3})$

IH: $0.427 < \sin^2\theta_{23} < 0.596$
$2.31 < \Delta m^2_{13}\ (\mathrm{eV^2/c^4}) < 2.64\ (\times 10^{-3})$

Normal Hierarchy

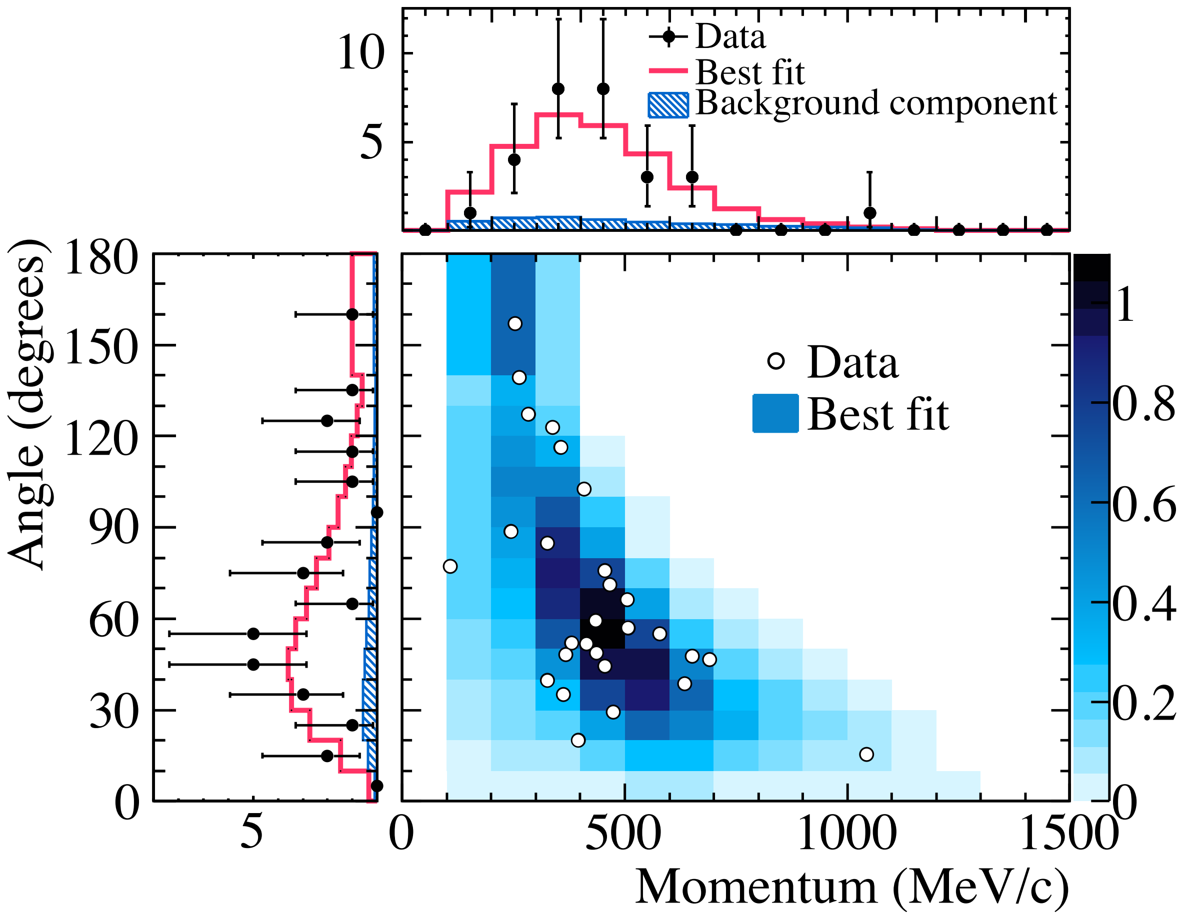


Inverted Hierarchy



World's best measurement of θ_{23}!

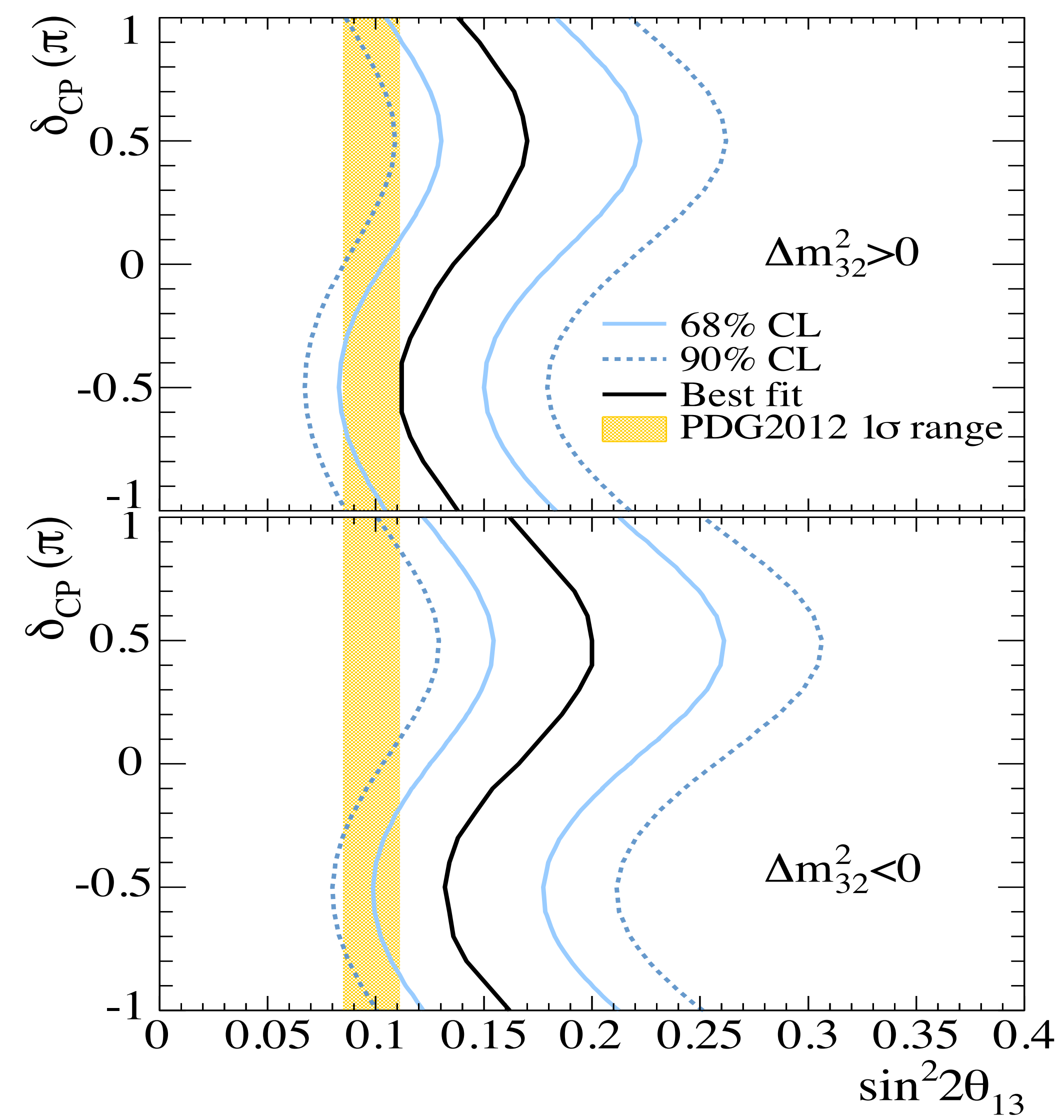
$\nu_\mu \rightarrow \nu_e$ appearance



- Maximum likelihood fit in $\{p_e, \theta_e\}$
- Consistent w/ E_{reco} alternative analysis

Phys. Rev. Lett. 112, 061802 (2014)

- Marginalize $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$ w/ T2K Run1-3 ν_μ results
- Raster scan: fit $\sin^2 2\theta_{13}$ for fixed δ_{CP}



Best-fit value

NH: $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$

IH: $\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$

$\Delta m^2_{21} = 7.60 \times 10^{-5}$ eV^2/c^4, $\sin^2\theta_{12} = 0.306$, $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2/c^4, $\delta_{CP} = 0$

7.3σ significance to non-zero θ_{13}
Discovery of ν_e appearance!

Tension with reactors for certain values of δ_{CP}

$\nu_\mu + \nu_e$ joint fit: frequentist approach

- Simultaneous fit of ν_μ-like and ν_e-like events at T2K
- Taken into account correlations between all the oscillation parameters
- Improvement wrt the stand-alone ν_e appearance analysis
- Confidence intervals performed with Feldman-Cousins

Constraint from reactors (PDG 2013):

$\sin^2 2\theta_{13} = 0.095 \pm 0.010$

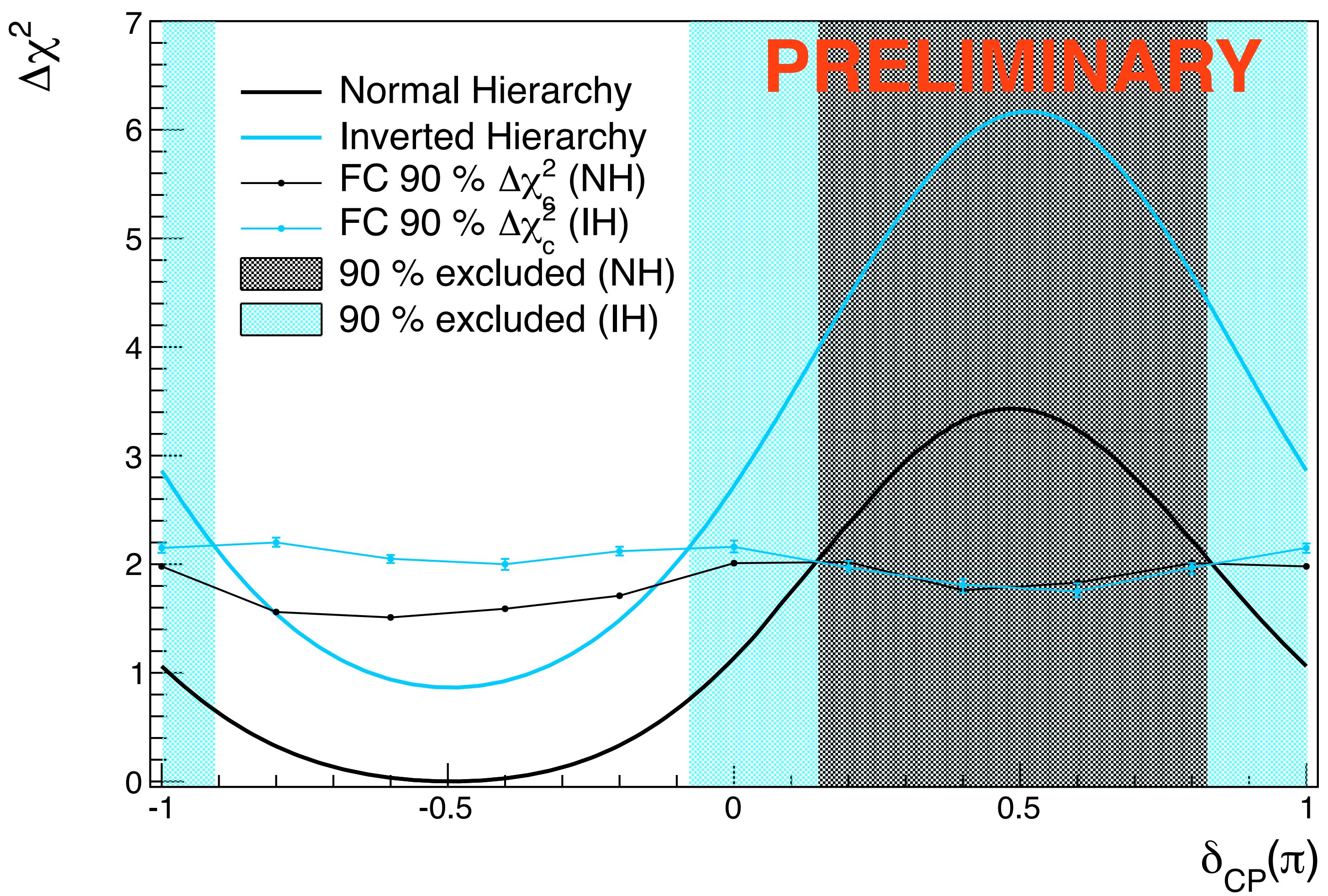
90% CL allowed intervals

NH: $-1.18\pi < \delta_{CP} < 0.15\pi$

IH: $-0.91\pi < \delta_{CP} < -0.08\pi$

Best-fit at $\delta_{CP} = -\pi/2$

90% CL excluded regions (NH-IH)



$\nu_\mu + \nu_e$ joint fit: bayesian approach

- Also a bayesian analysis has been performed
- Markov Chain MC (MCMC) method
- Marginalization of the fit parameters
- Include simultaneously T2K far and near samples
- Assumed flat prior of $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$ and P(NH) = P(IH) = 0.5

Constraint from reactors (PDG 2013):

$\sin^2 2\theta_{13} = 0.095 \pm 0.010$

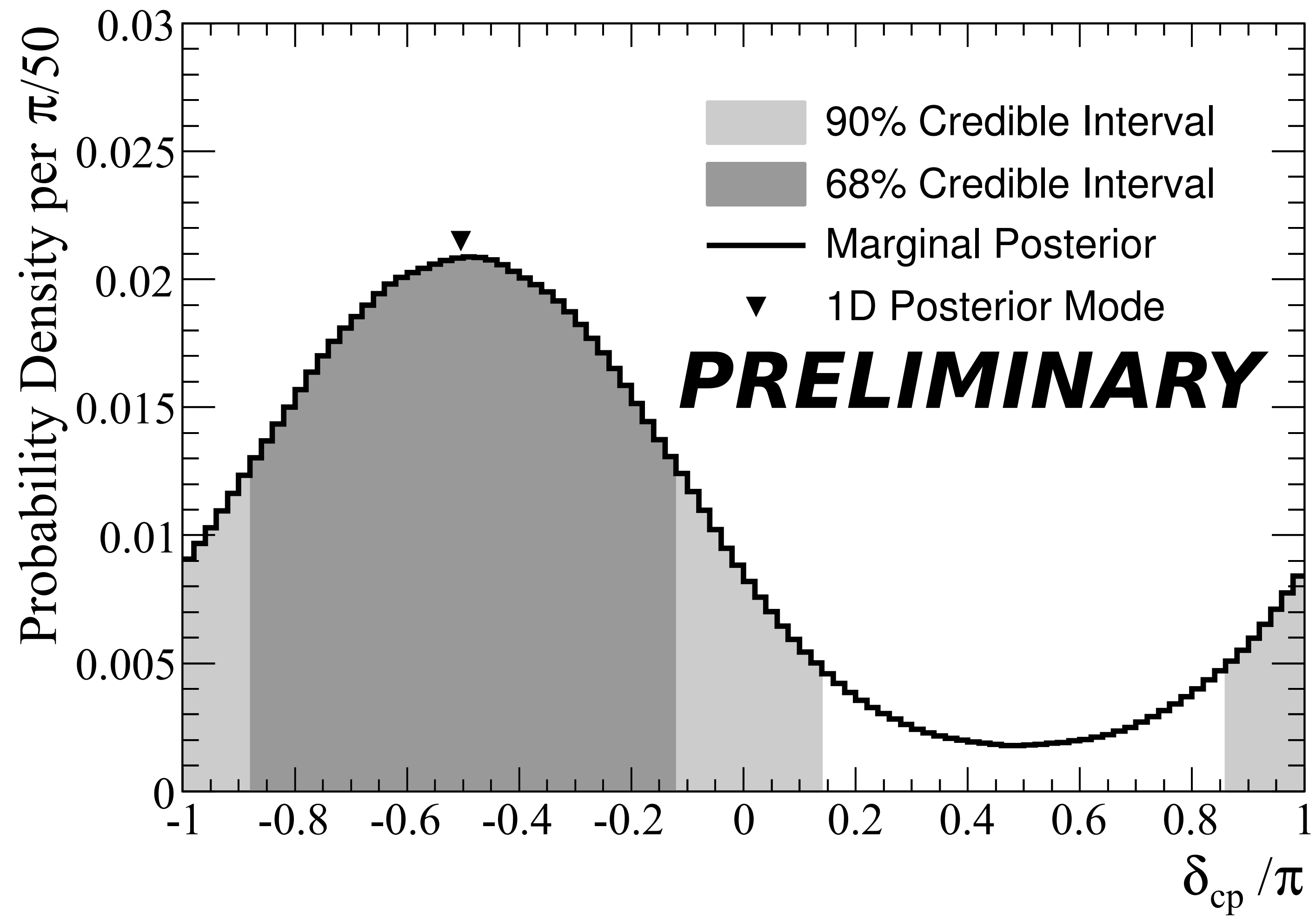
Marginalize over mass hierarchies

90% credible intervals

$-1.13\pi < \delta_{CP} < -0.14\pi$

Prefers Normal Hierarchy (68%)

Credible intervals



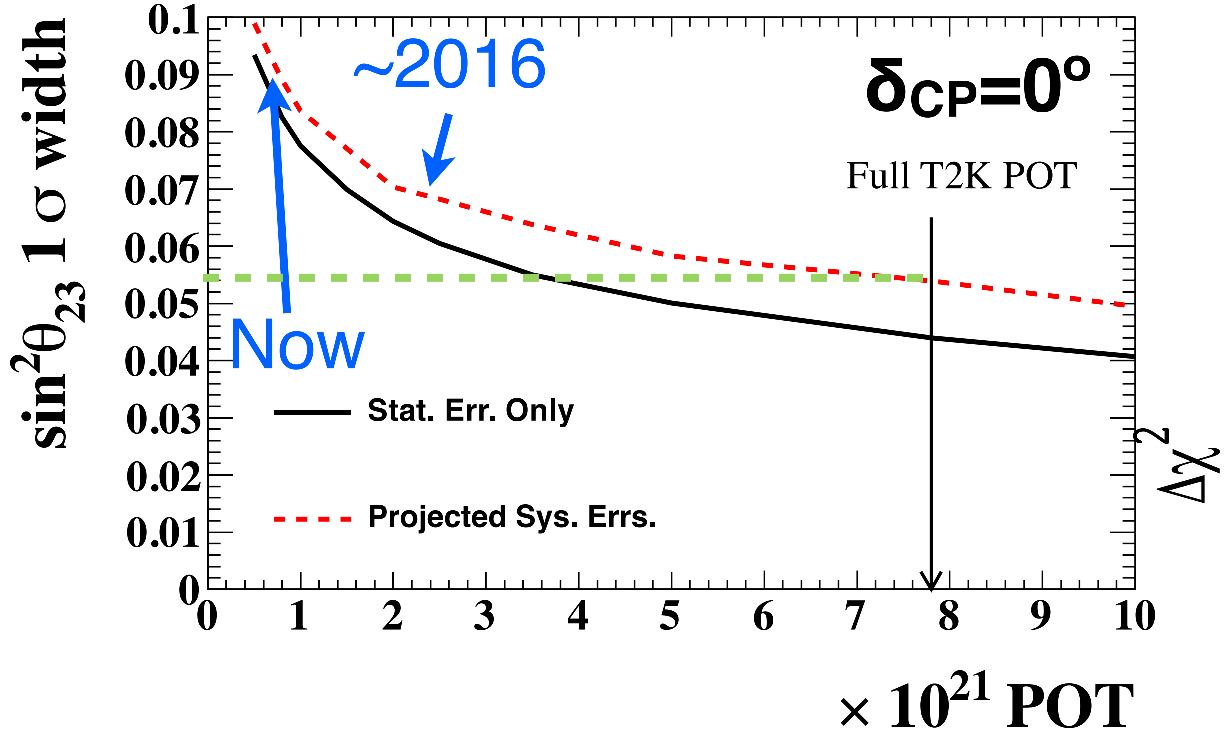
Future sensitivity studies

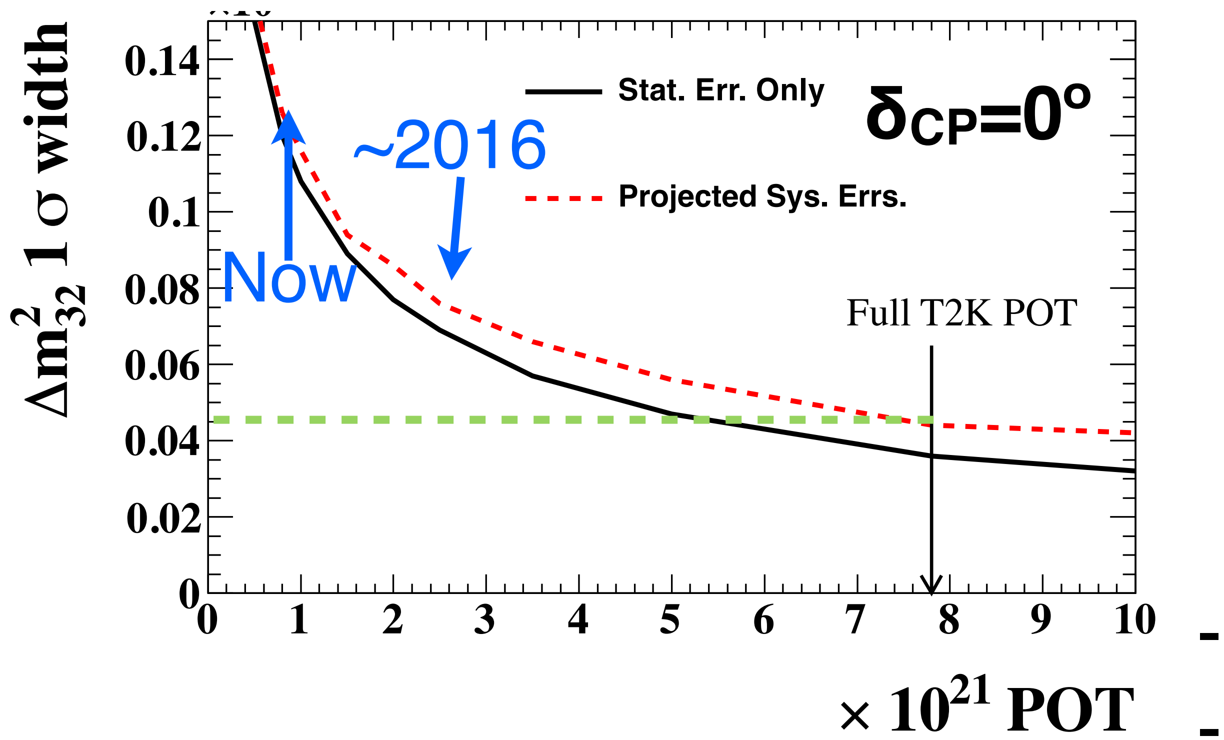
50% POT ν + 50% POT anti-ν

reactor constrain:
$\delta(\sin^2 2\theta_{13}) = 0.005$

Solid lines: no sys. err.

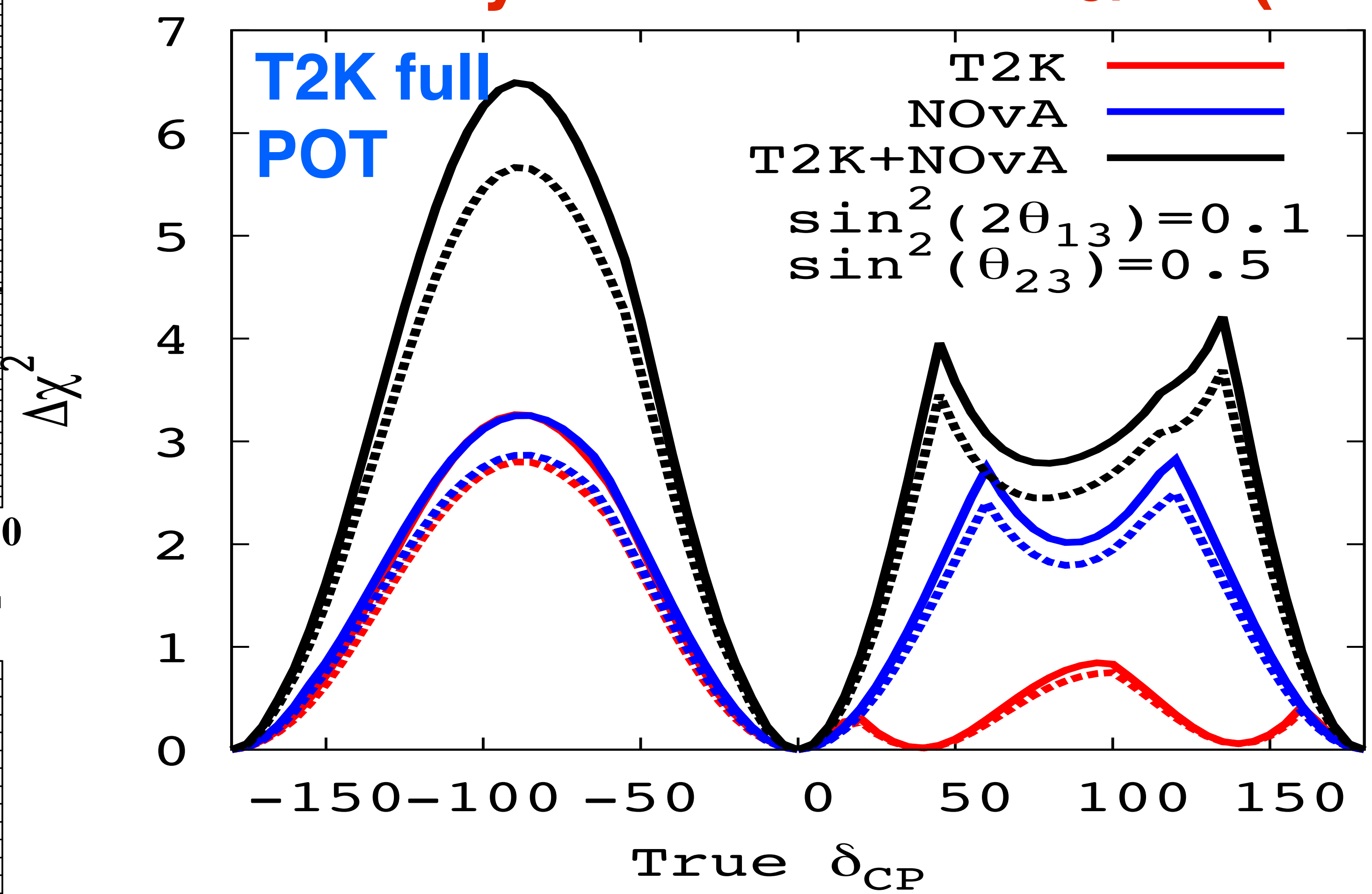
Dashed lines: sys. err. (~7%ν, ~14%anti-ν)





True values: $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5,
$|\Delta m^2_{32}|$ = 2.4x10^{-3}eV^2/c^4, [NH]

Sensitivity to resolve $\sin\delta_{CP}$=0 (NH)



5% (10%) of normalization uncertainty on signal (background)

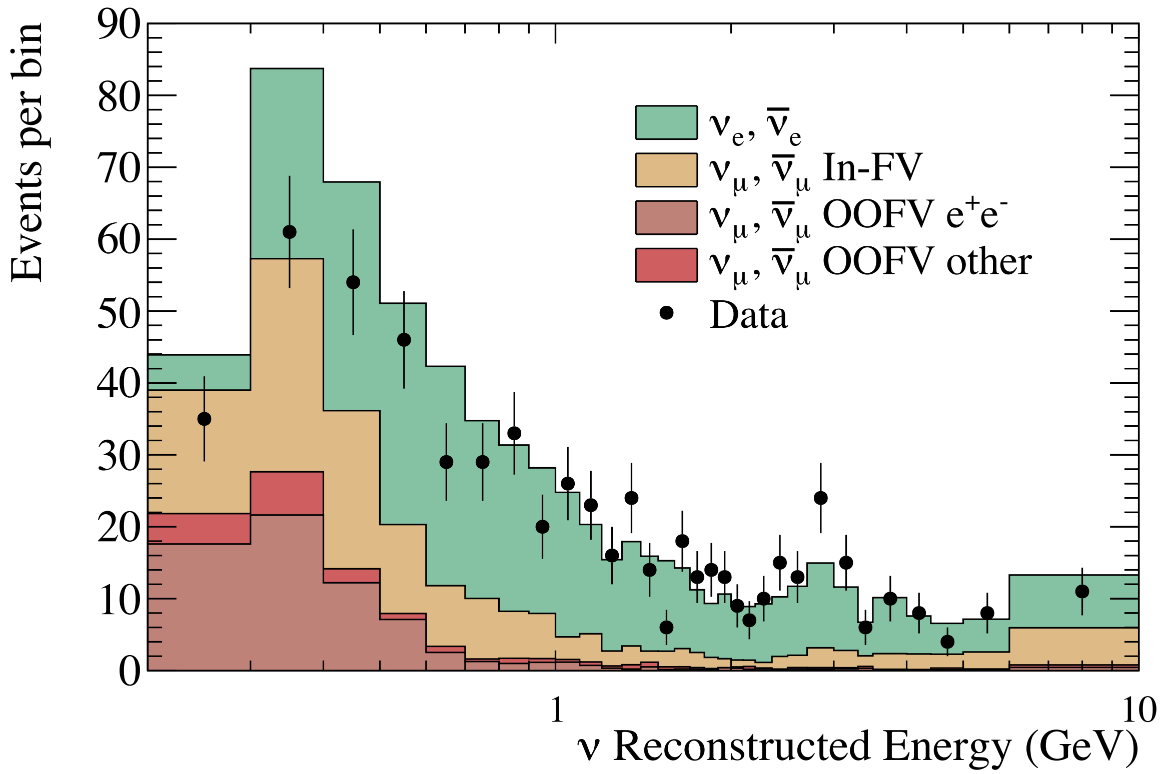
Solid lines: no syst err
Dashed lines: w/ sys. err.

- Now only ~8% target total p.o.t.
- anti-neutrino run before summer shut down
- Big improvement combining T2K and NOVA

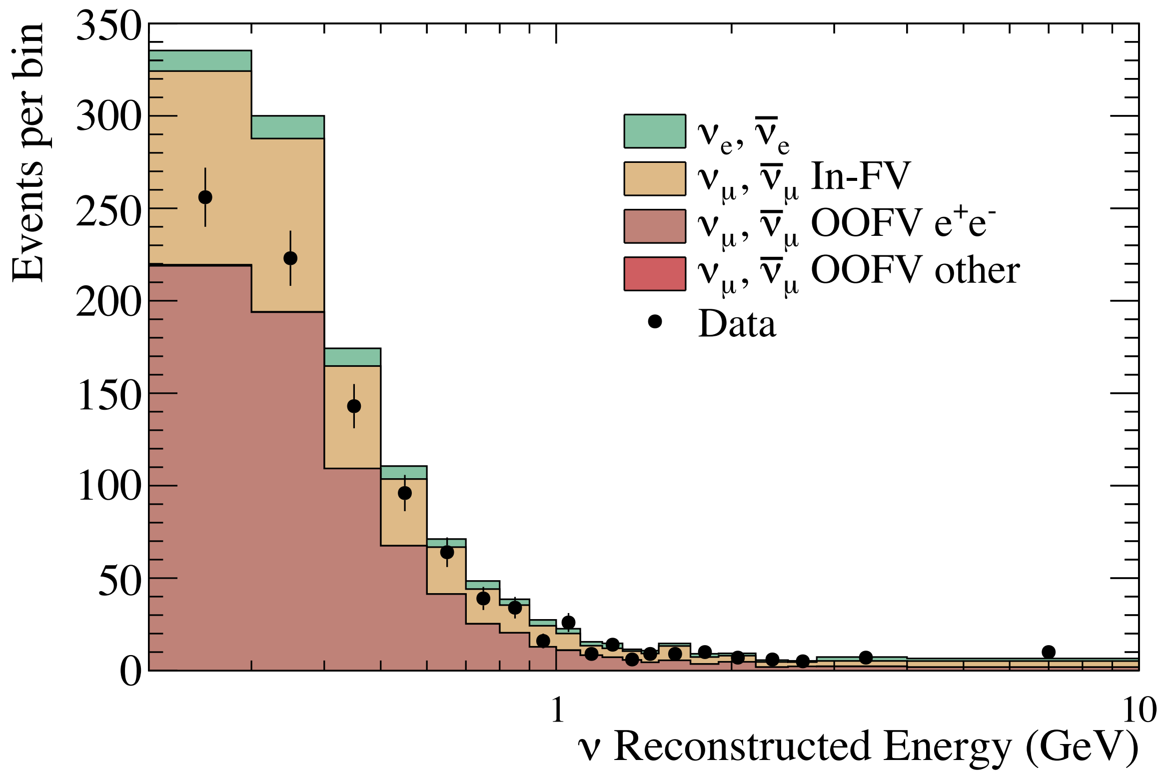
Sterile searches at ND280

- Used the near detector for sterile searches
- 3+1 sterile neutrino framework $P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \cdot \sin^2 \left(\frac{1.267 \Delta m^2_{41} L_\nu}{E} \frac{\text{GeV}}{\text{eV}^2 \text{km}} \right)$
- No hints of ν_μ disappearance → $\sin^2 2\theta_{\mu\mu} = 0$
- Look for ν_e disappearance $\{\sin^2 2\theta_{ee}; \Delta m^2_{41}\}$ → study gallium and reactor anomalies
- Fit E_{reco} distributions
- Use the constrained flux and cross section systematics by the ν_μ sample (slide 10)
- Log-likelihood ratio method

CC inclusive ν_e selection



Control sample to constrain γ bkg and out-FV component (OOFV)



Sterile searches at ND280

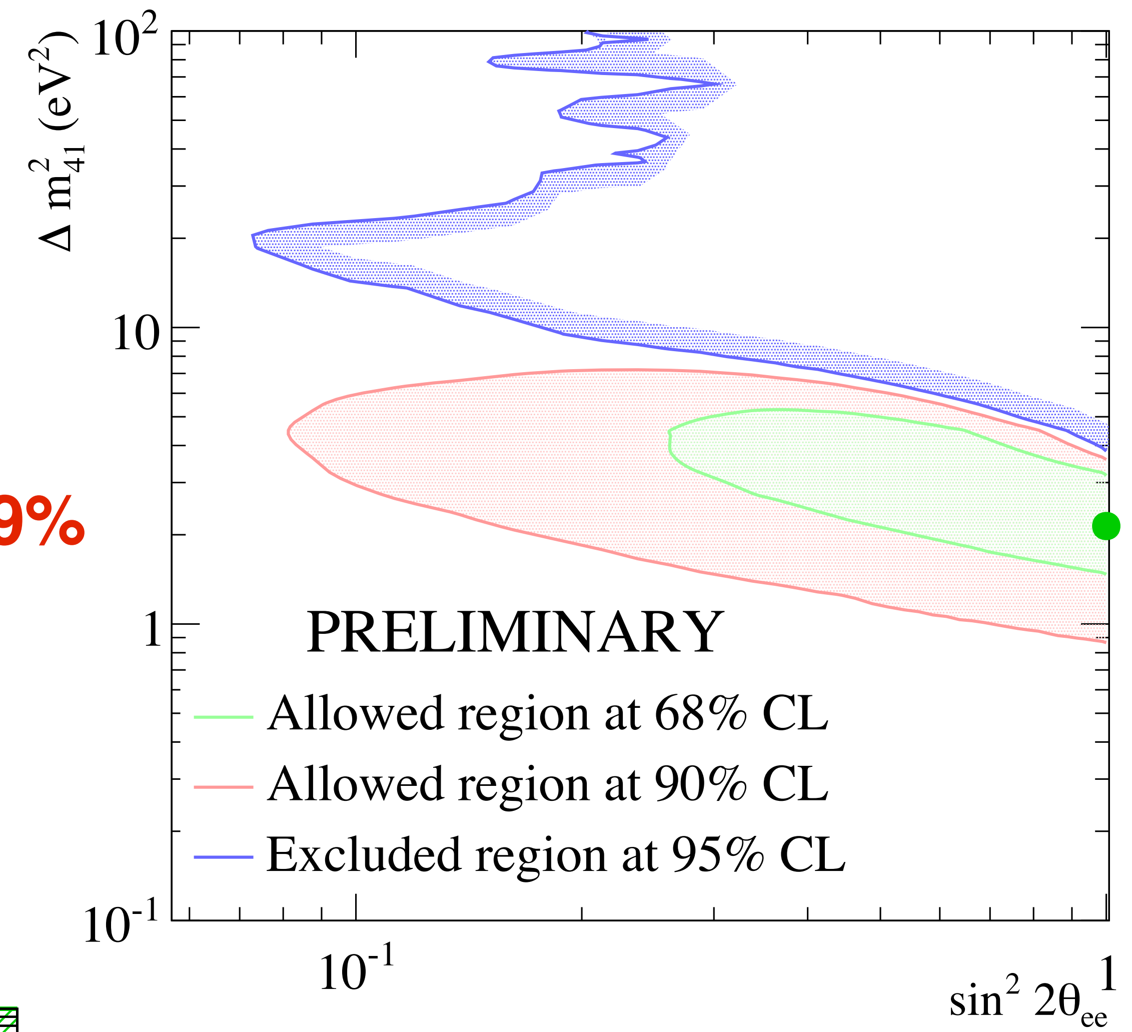
- Frequentist method for confidence intervals
- Out-FV rescaled of ~30% (1**σ**)

Best-fit values:

$\sin^2 2\theta_{ee} = 1$

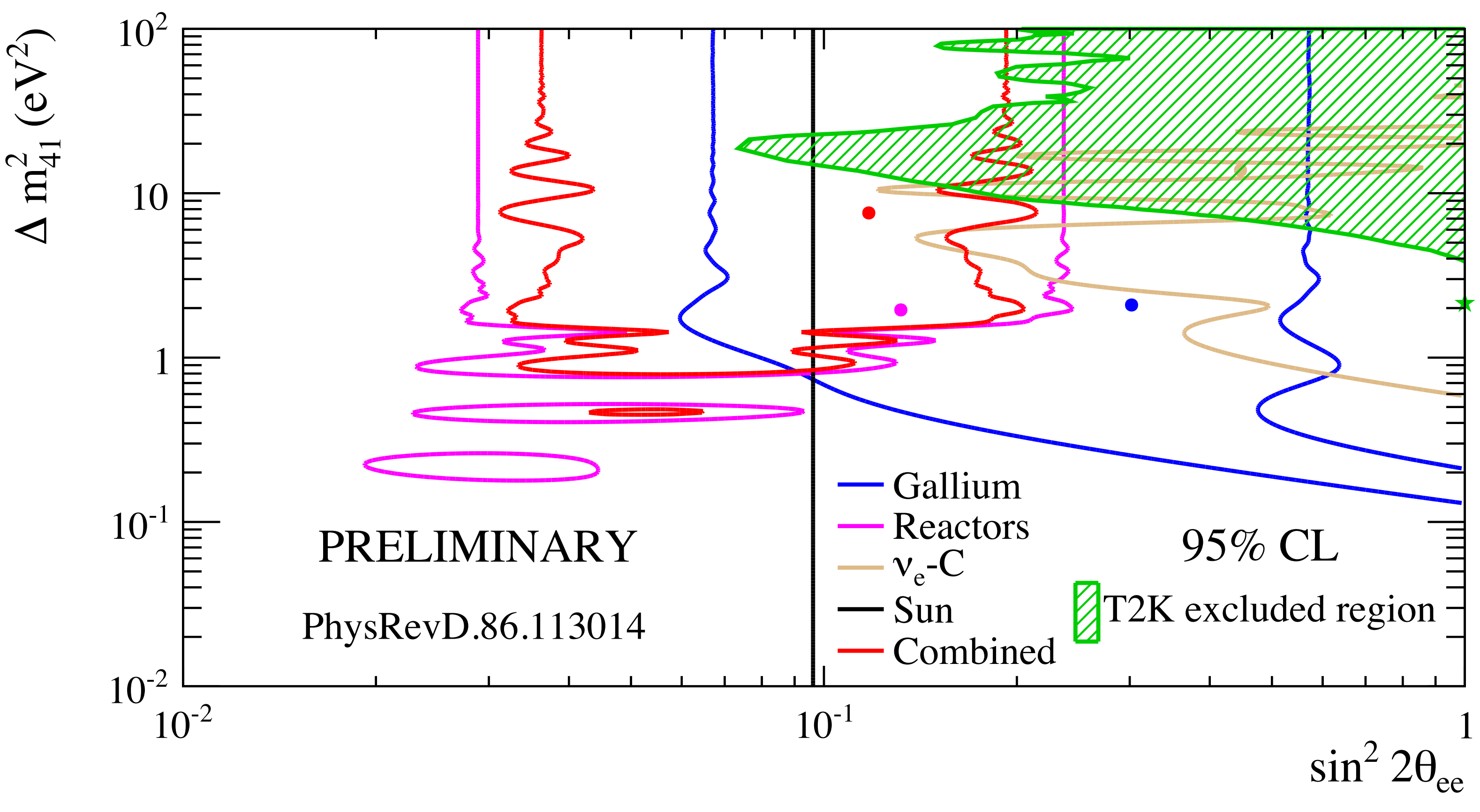
$\Delta m^2_{41} = 2.14\ eV^2/c^4$

Observed p-value wrt null oscillation hypothesis is 6.069%



95% CL excluded intervals

$\sin^2 2\theta_{ee} > 0.2\ \&\&\ \Delta m^2_{41} > 8\ eV^2/c^4$

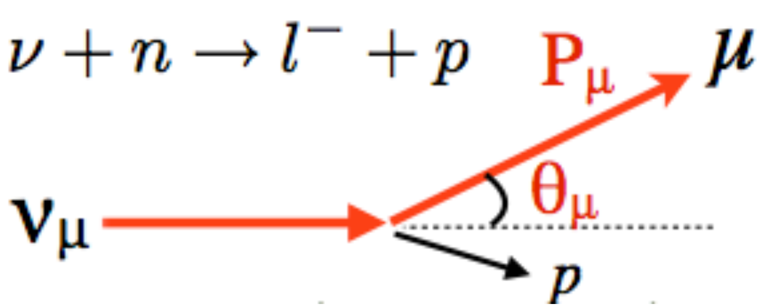


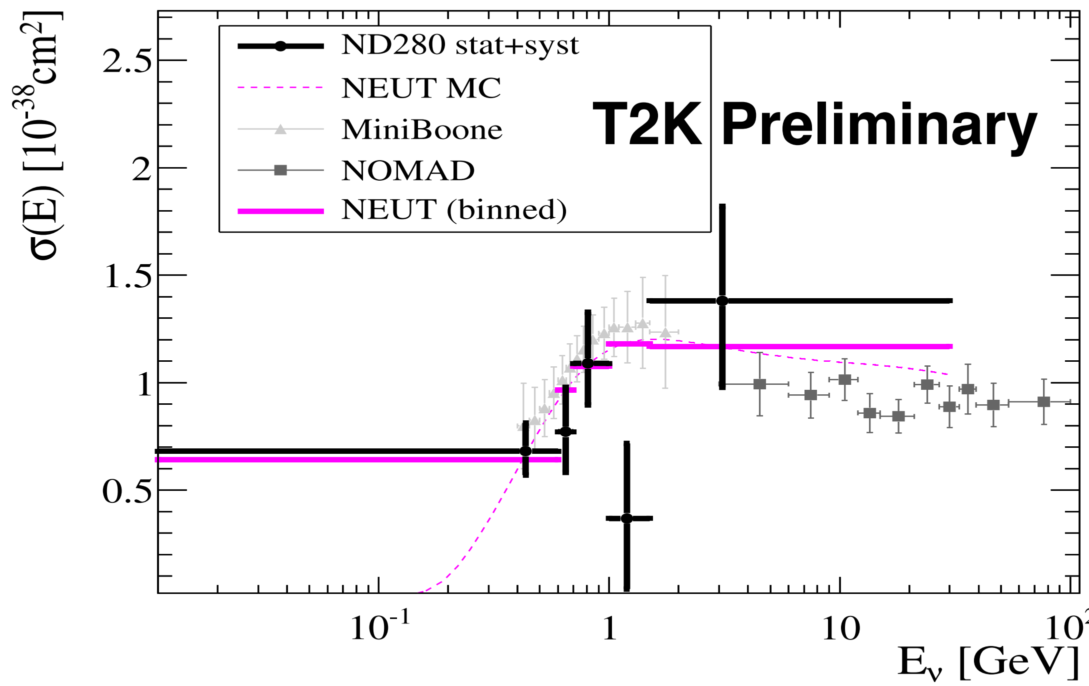
Large part of the gallium anomaly is excluded as well as a small part of the reactor anomaly

More data are needed to get conclusions

Cross section measurements

- ν_μ CC-inclusive cross section with ND280 Tracker (**PRD 87, 092003 (2013)**)
- ν_μ CCQE with ND280 Tracker (2.63x10^{20} p.o.t.)

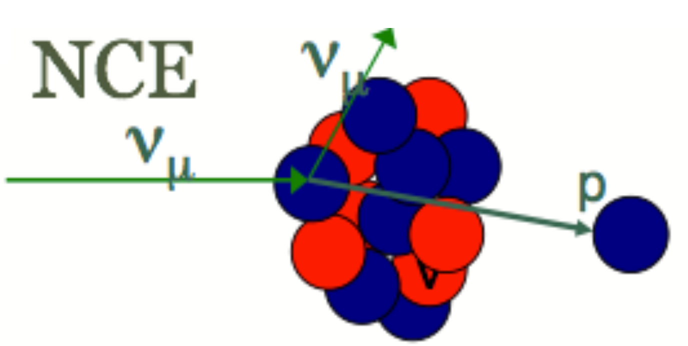




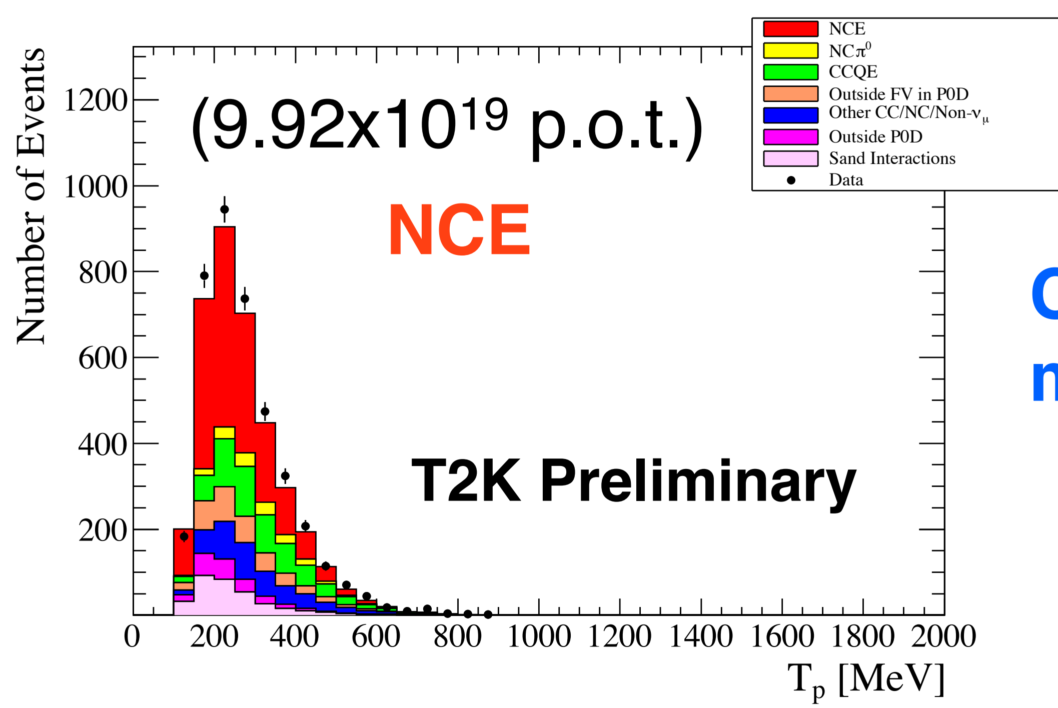
M_A^{QE} consistent with NEUT

- Neutral Current Elastic (NCE) cross section with P0D

$$< \sigma >_{flux} = 2.24 \times 10^{-39} \pm 0.07(\text{stat.}) {}^{+0.53}_{-0.63}(\text{sys.}) \frac{\text{cm}^2}{\text{nucleon}}$$



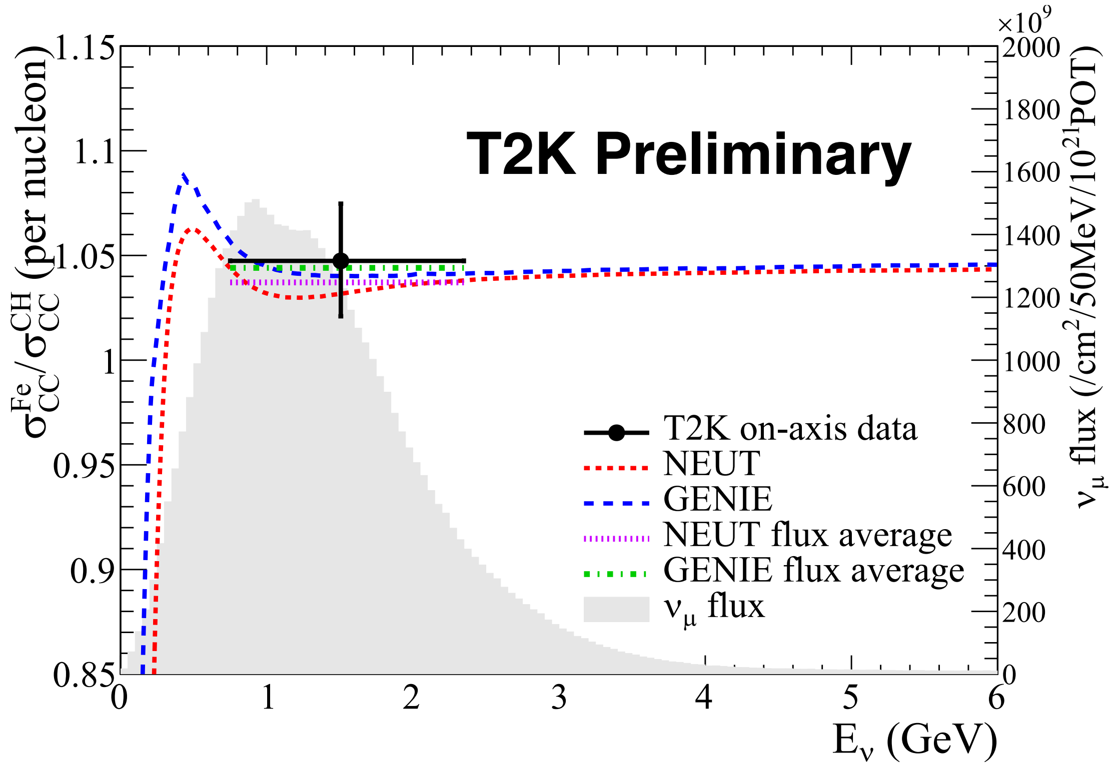
ν+N → ν+N



Consistent with neutrino models (GENIE, NEUT)

Cross section measurements

- ν_μ CC-inclusive cross section ratio (Fe/C) with INGRID 6.04×10^{20} p.o.t.



proton module (Carbon) before INGRID (Iron)

$$\frac{\sigma^{Fe}_{CC}}{\sigma^{CH}_{CC}} = 1.0474 \pm 0.0067(\mathrm{stat}) \pm 0.0284(\mathrm{syst})$$

Consistent with models

- First measurement ν - O^{16} neutral current quasi-elastic (NCQE) cross section at SK (**arXiv:1403.3140**) 3.01×10^{20} p.o.t.

  - Look to nuclear de-excitation gamma rays

$$< \sigma^{obs} >_{flux} = 1.35 \times 10^{-38} \mathrm{cm}^2$$

Obs events = 43

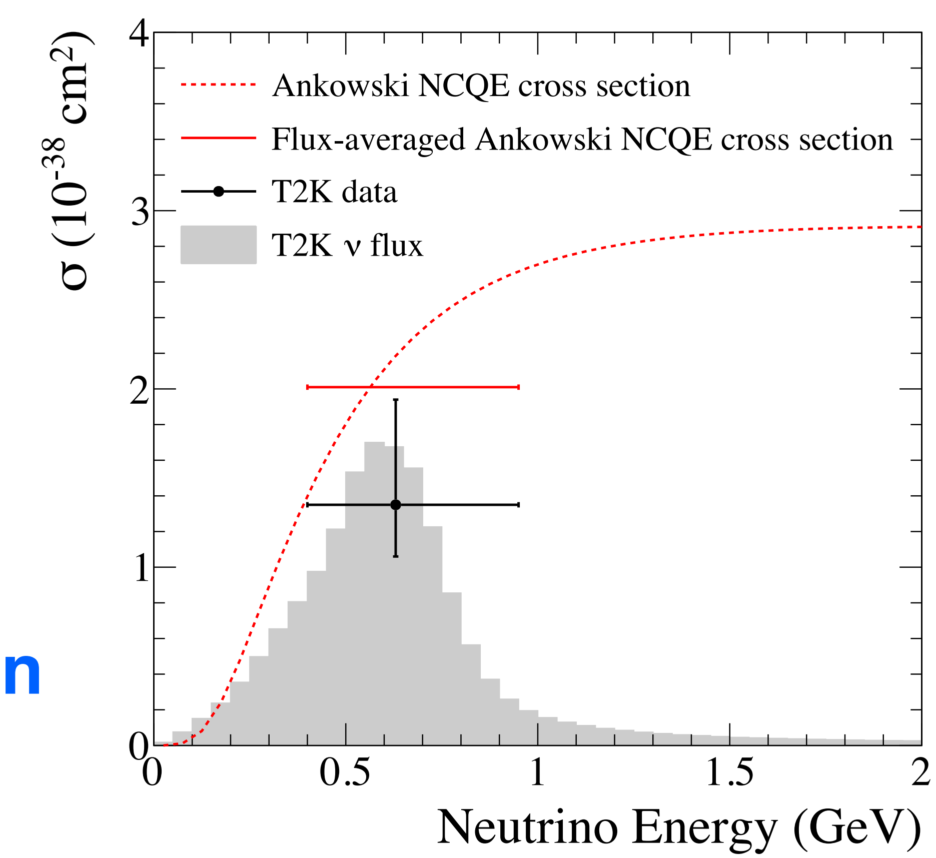
Exp events = 55.7

$$68\%\mathrm{CL} : [1.06; 1.94] \times 10^{-38} \mathrm{cm}^2$$

$$90\%\mathrm{CL} : [0.84; 2.34] \times 10^{-38} \mathrm{cm}^2$$

Smaller but consistent with theoretical prediction

$$< \sigma^{theory} >_{flux} = 2.01 \times 10^{-38} \mathrm{cm}^2$$



Summary

- Finalized oscillation results for the full Run 1-4 data set
  - Best world measurement of θ_{23}!!! (**arXiv:1403.1532**)
  - 7.3σ significance to non-zero θ_{13}!!! (**PRL 112, 061802 (2014)**)
  - New T2K joint fit: hint of $\delta_{CP}=-\pi/2$ at 90%CL with reactor constraint:

NH: $-1.18\pi < \delta_{CP} < 0.15\pi$

IH: $-0.91\pi < \delta_{CP} < -0.08\pi$

(*Preliminary*)

- First sterile search at the near detector in the 3+1 model:

  $\sin^2 2\theta_{ee} > 0.2$ && $\Delta m^2_{41} > 8$ eV^2/c^4 excluded at 95%CL (*Preliminary)*

- Several cross section measurements are released and show good agreement w/ models (many others are ongoing)

- Very important to increase the statistics

- Short anti-neutrino run before summer shutdown

Very interesting new results in the next future!!!

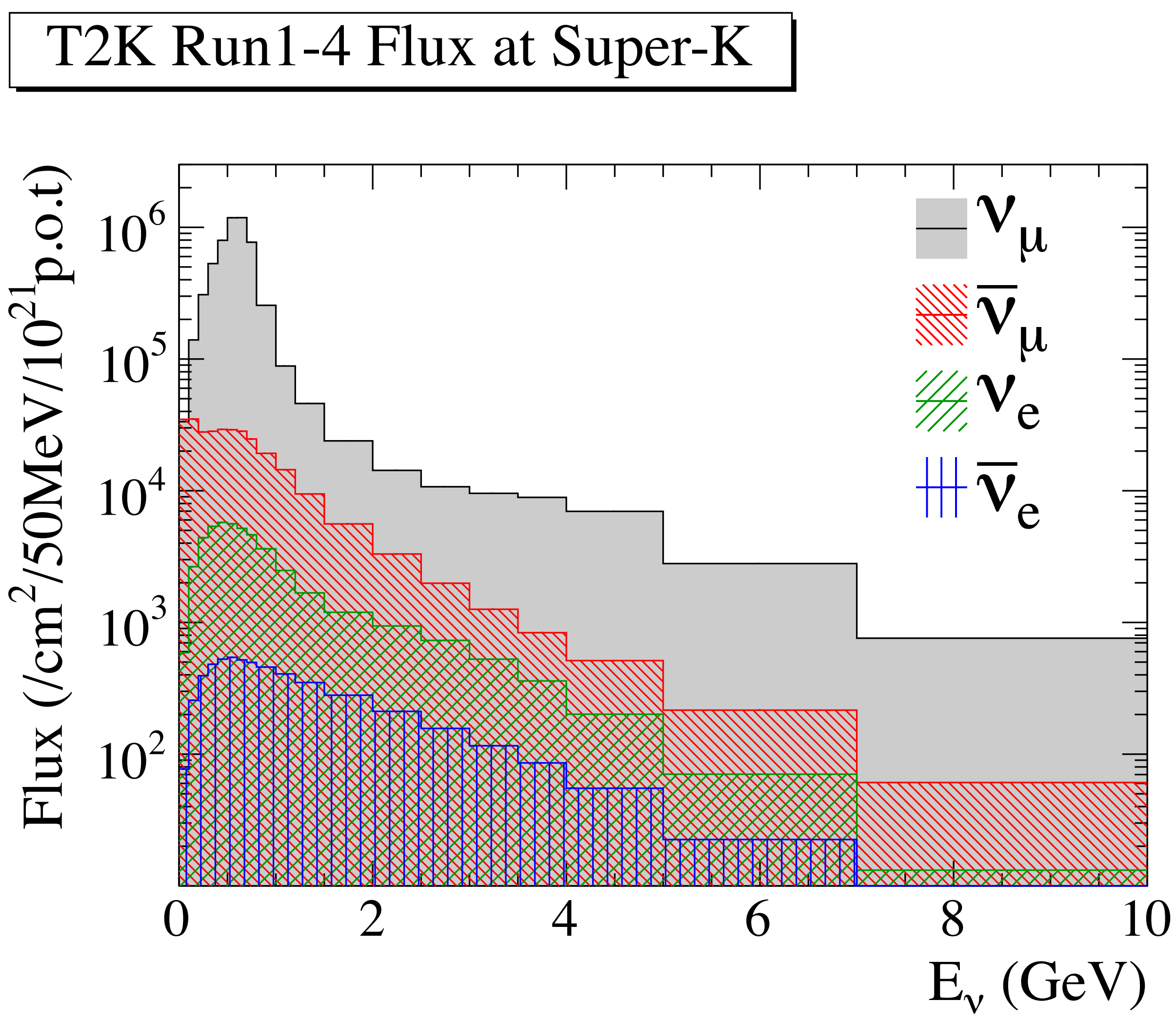
The T2K Collaboration

- 344 researchers from 11 countries
- 59 institutes

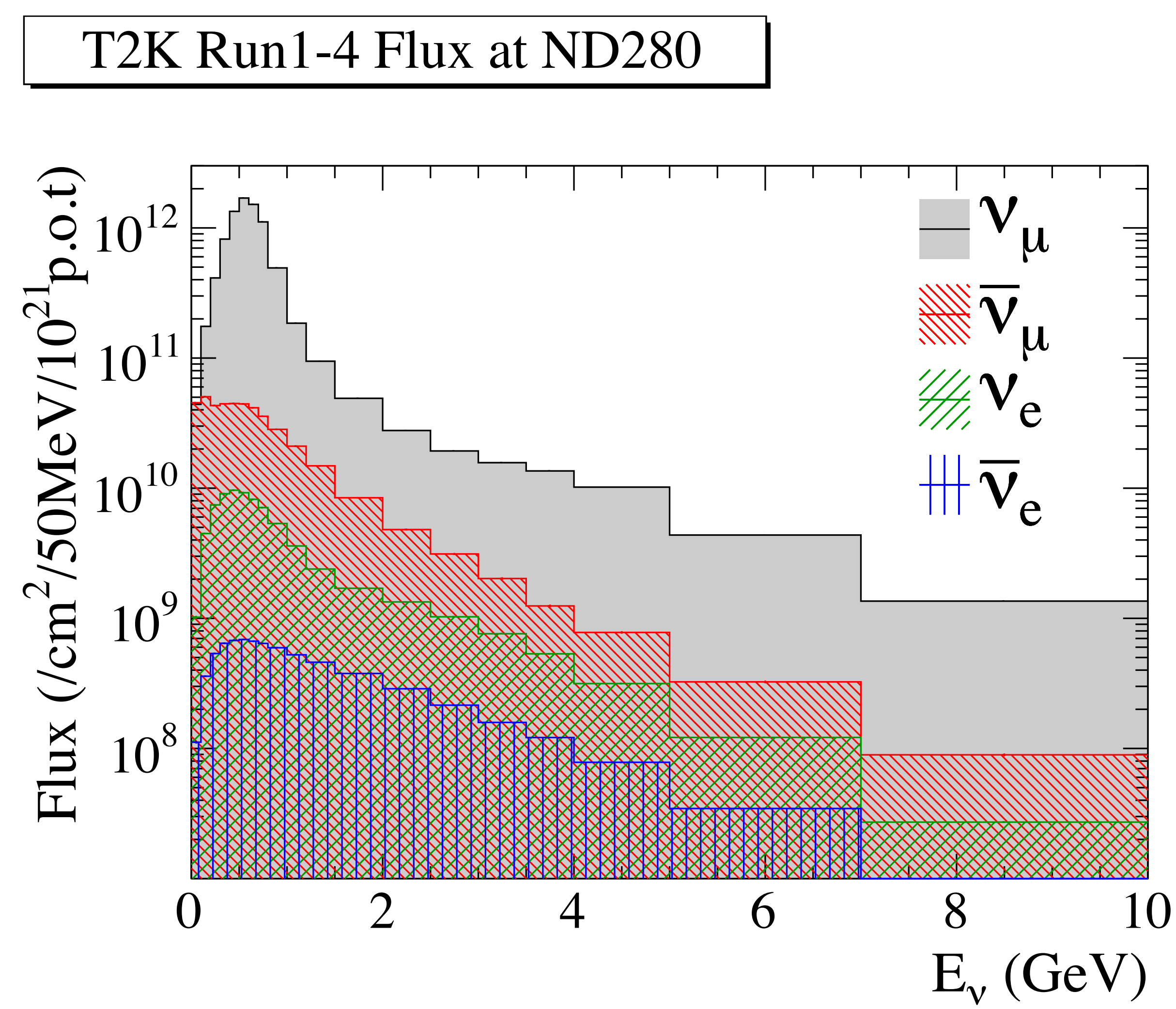
BACKUP

Beam flux prediction

Beam flux is predicted based on NA61/SHINE π, K production measurements and T2K proton beam measurements



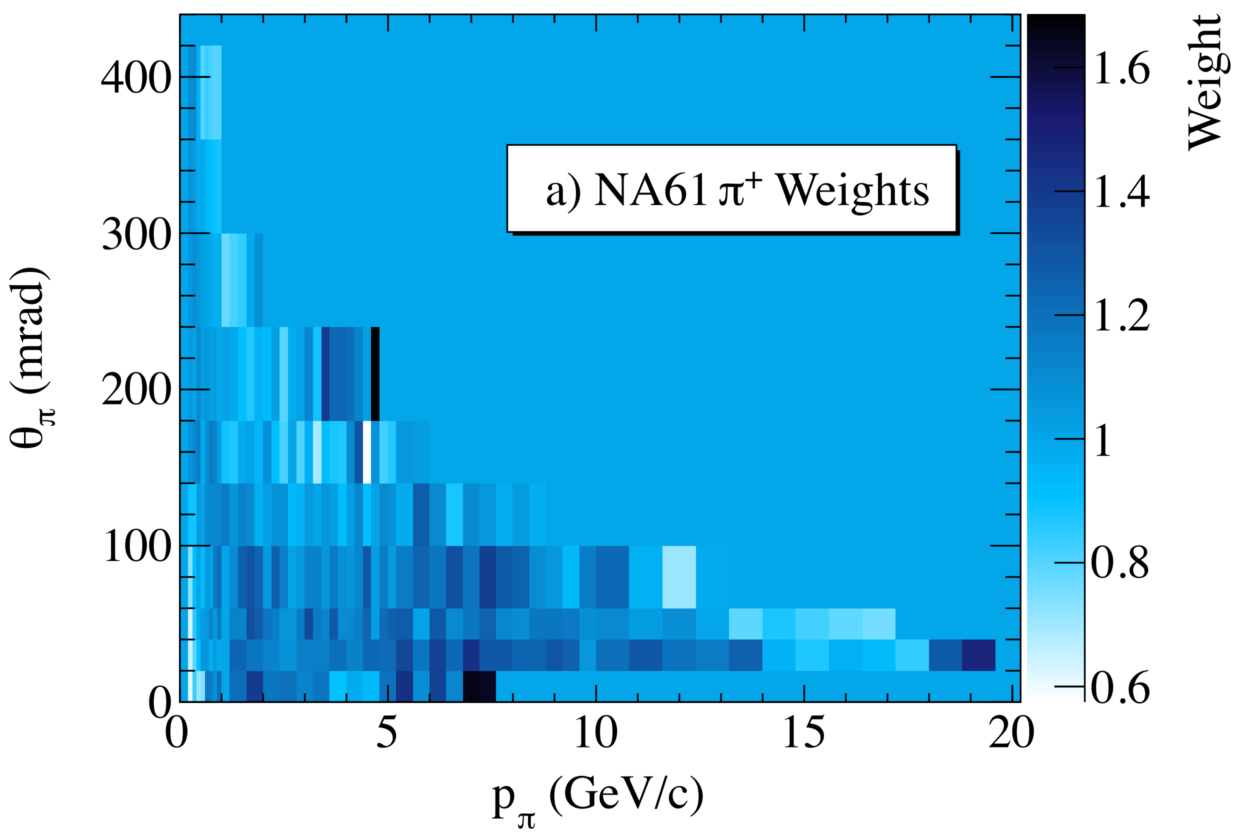
overlaid plot

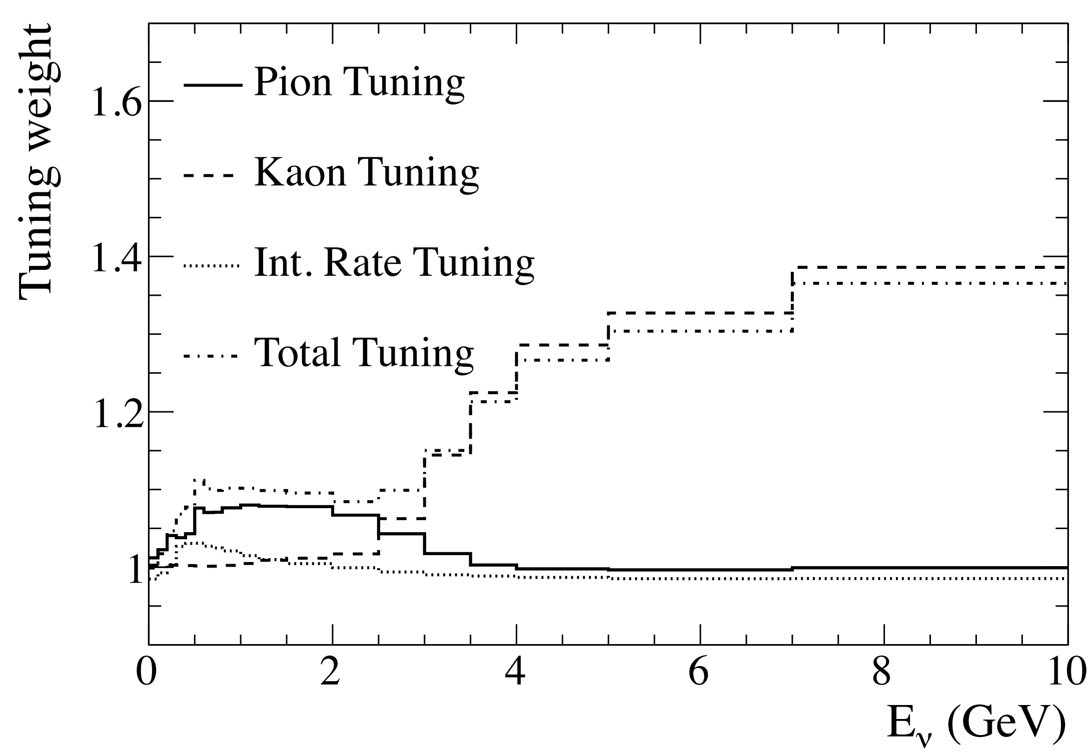


overlaid plot

Hadron production with external data

- Apply weights to the flux for each energy so that MC prediction matches data
  - The weights are calculated at each production step occurred inside the target (C) or the horn conductor (Al) by using external data
    - Interaction rate (production cross section)
    - Pion production
    - Kaon production
- External data : NA61/SHINE (CERN) **[1][2]**, Eitchen *et al*. **[3]** , and Allaby *et al*. **[4]**

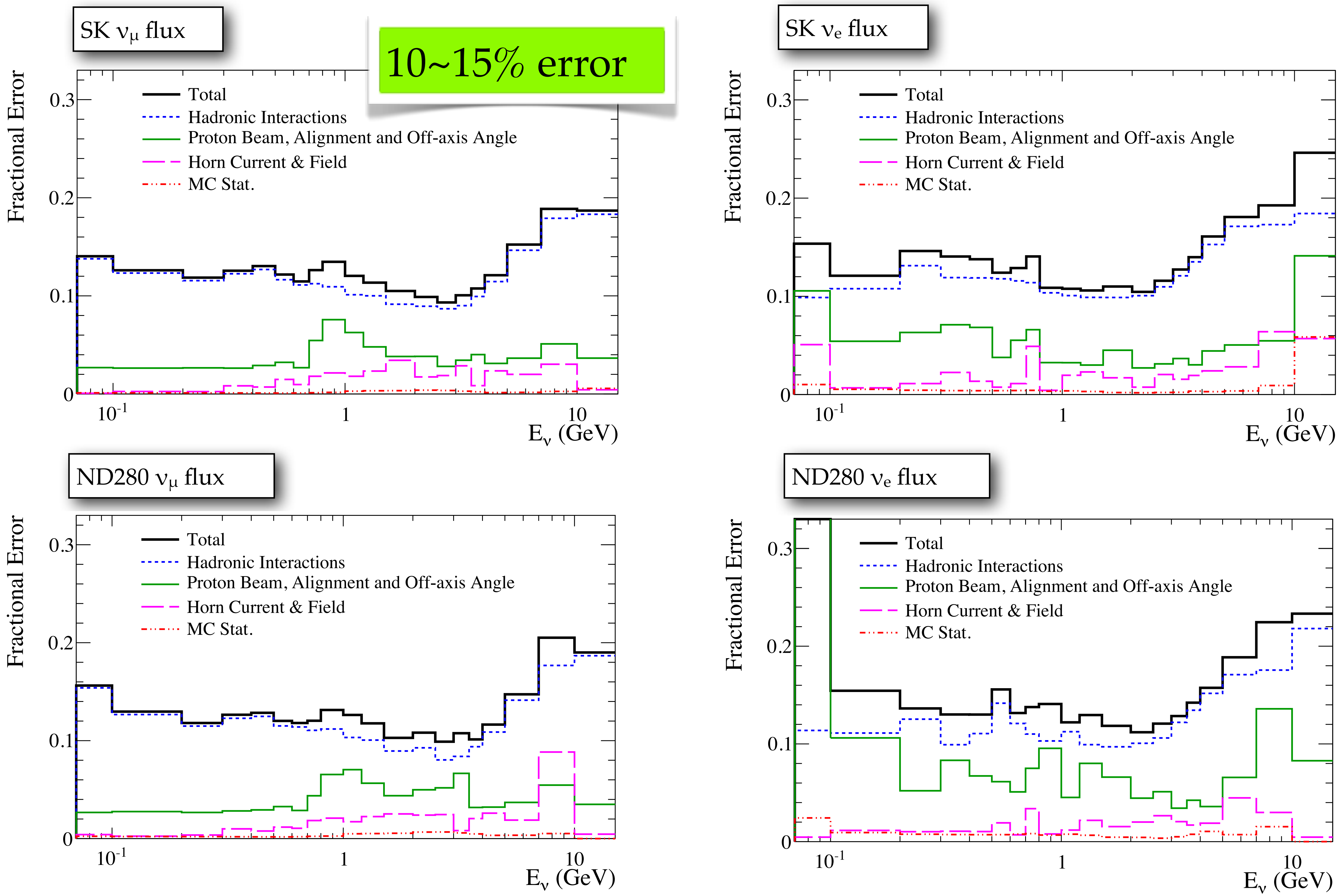




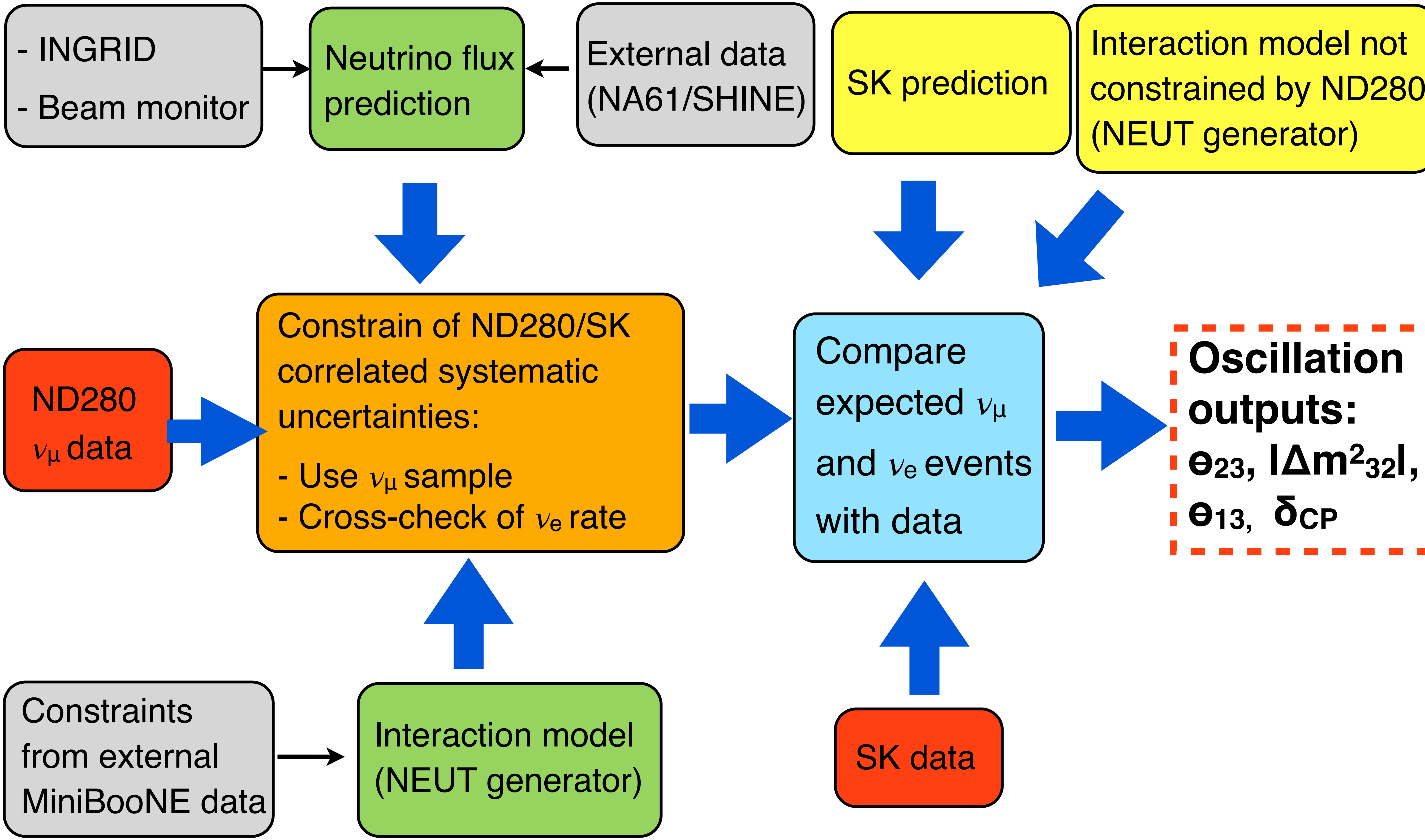
[1] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[2] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[3] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

Flux uncertainty as a function of energy

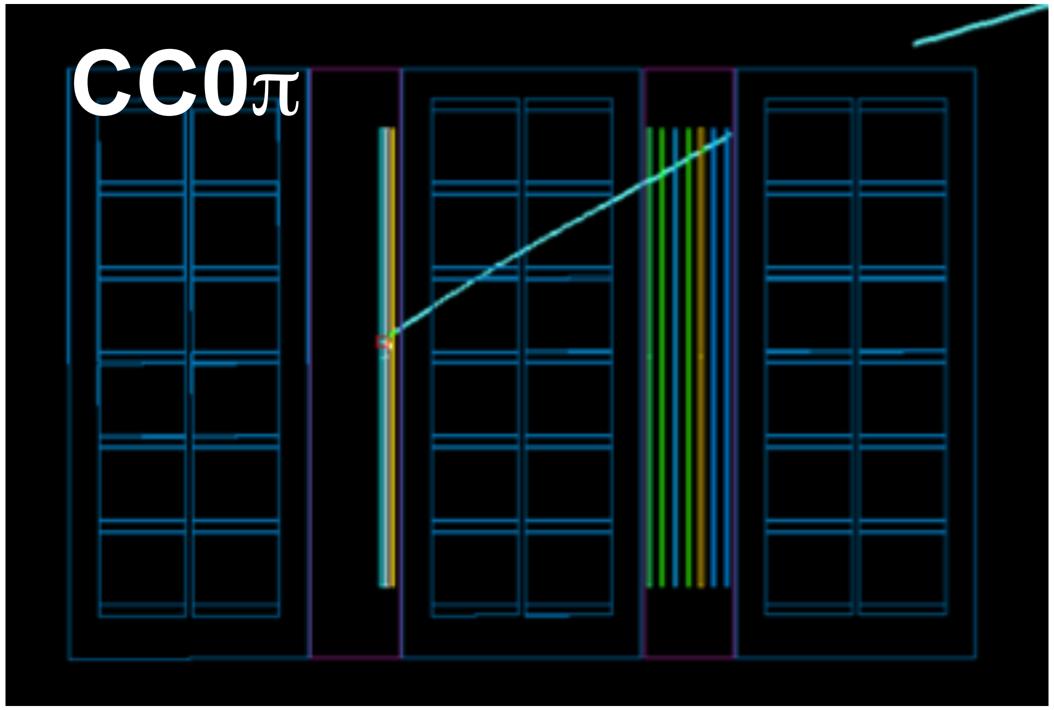
uncertainties are evaluated based on NA61 measurements and T2K beam monitor measurements

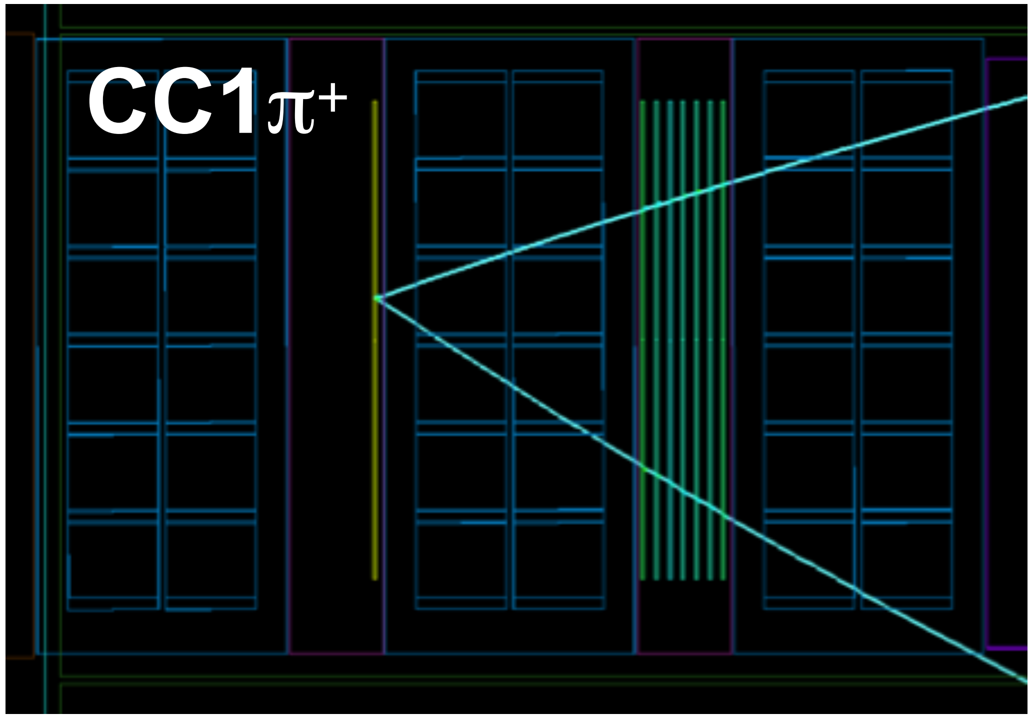


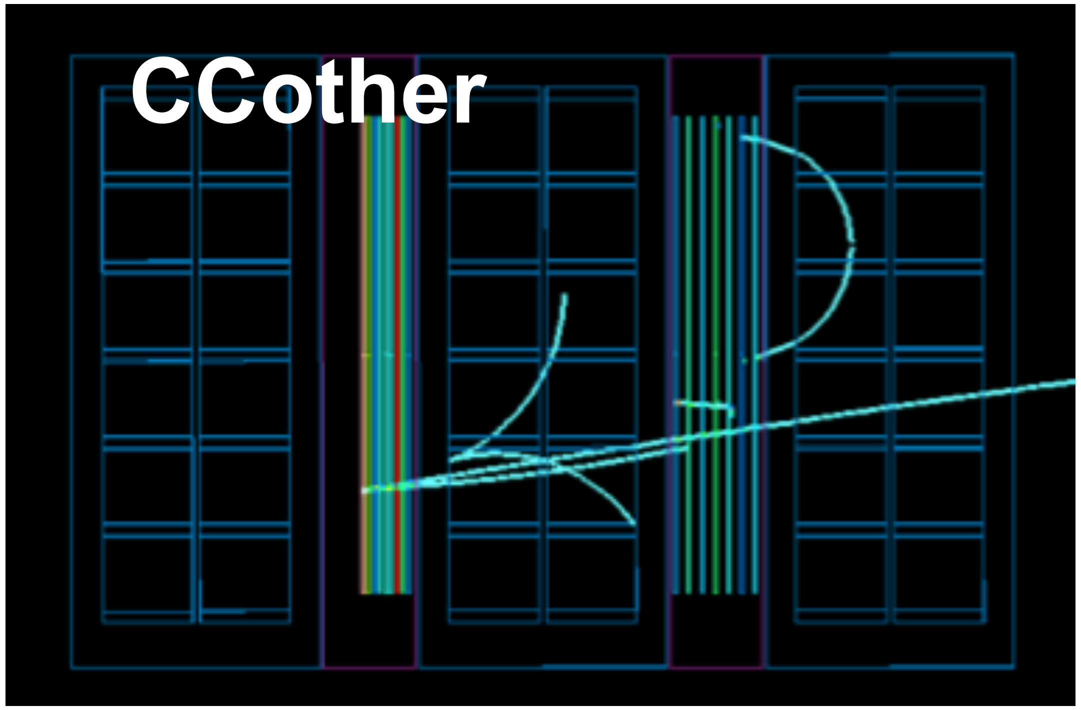
Strategy for oscillation analyses



ND280 selected samples







	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	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

Intrinsic electron neutrino

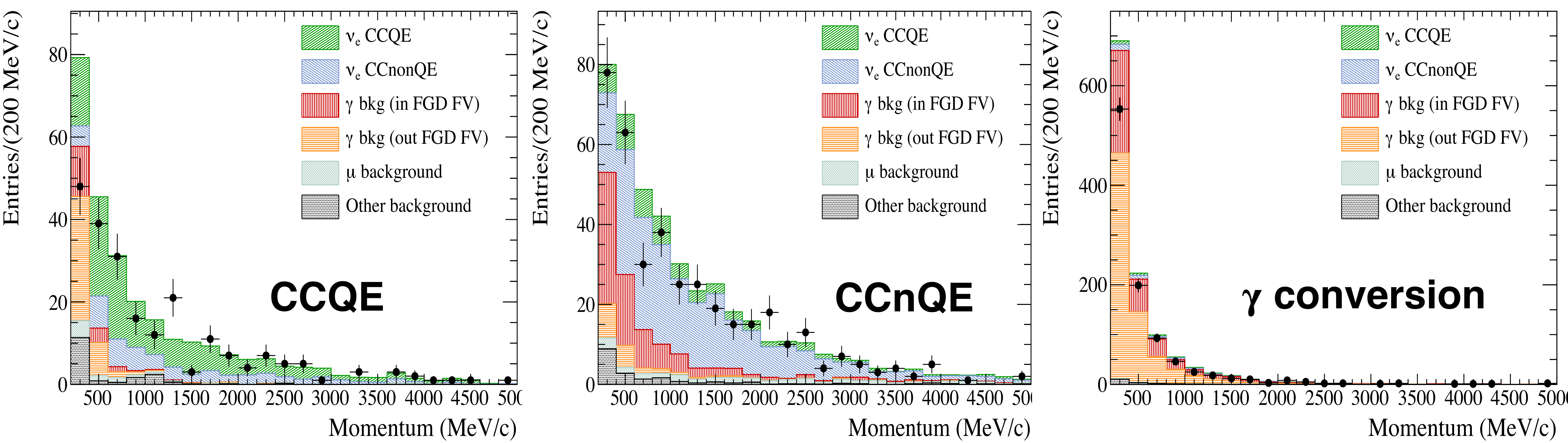
- Intrinsic ν_e beam component is ~1.2% of the beam
- CCQE & CCnQE selection (>65% purity)

Full T2K available data set:

RunI-IV (5.9×10^{20} p.o.t.)

- Control sample for γ background. Control the Out-FV background (30% systematic uncertainty)
- Use the systematics constrained by the ν_μ sample fit
- Agrees with expectation with an uncertainty of 10%: **R(ν_e) = 1.01 ± 0.10**
- Out-FV background rescaled: 0.64 ± 0.10 (within 1σ systematic uncertainty)

Accepted for publication by PRD (arXiv:1403.2552)



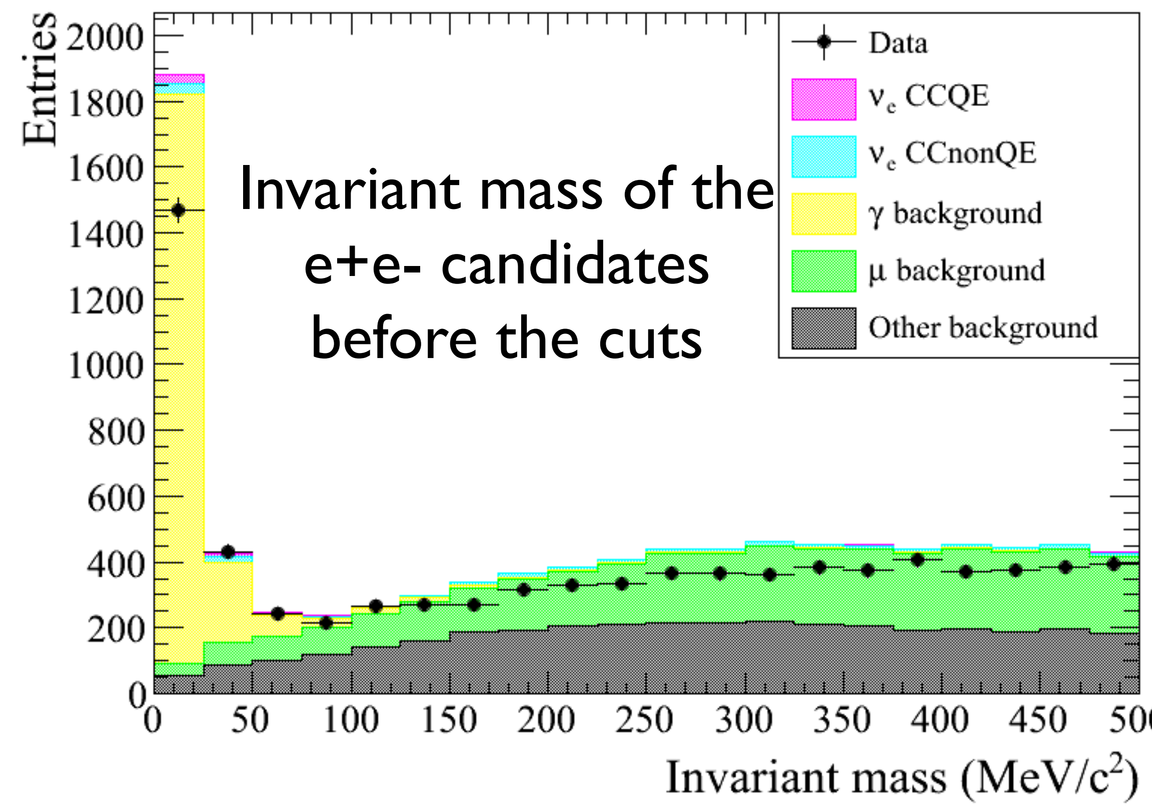
ND280 γ conversion selection

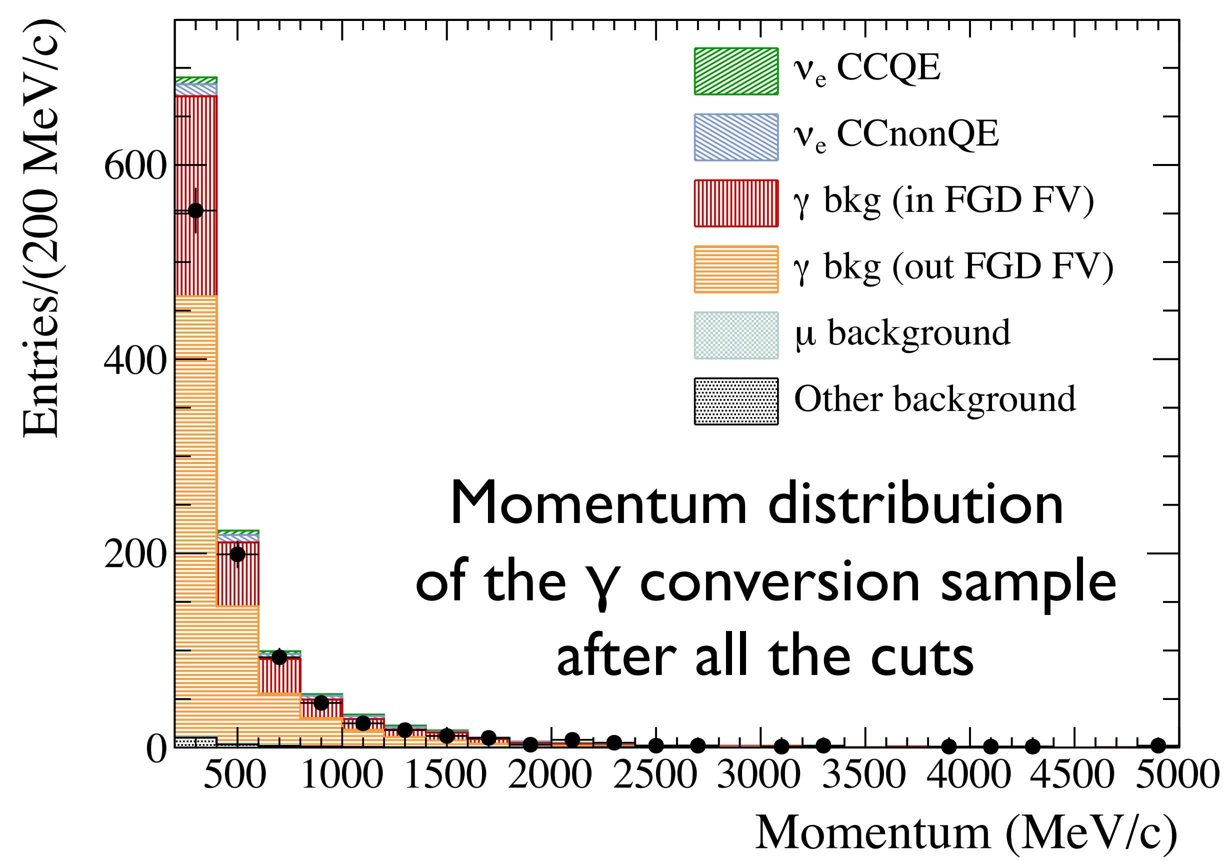
✓Most of the background selected in the analysis comes from γ conversions in the FGD producing electrons entering the tracker

✓To constrain this background we have developed a control sample of γ conversions in the FGD:

- ✓Select 2 tracks with opposite charge
- ✓Reconstruct their invariant mass (assuming the electron mass)
- ✓If the two tracks come from a gamma conversion M_{inv} should be ~0
- ✓Select γ conversion sample by requiring M_{inv}<50 MeV/c^2

✓Pure sample of γ conversions (>95% purity)

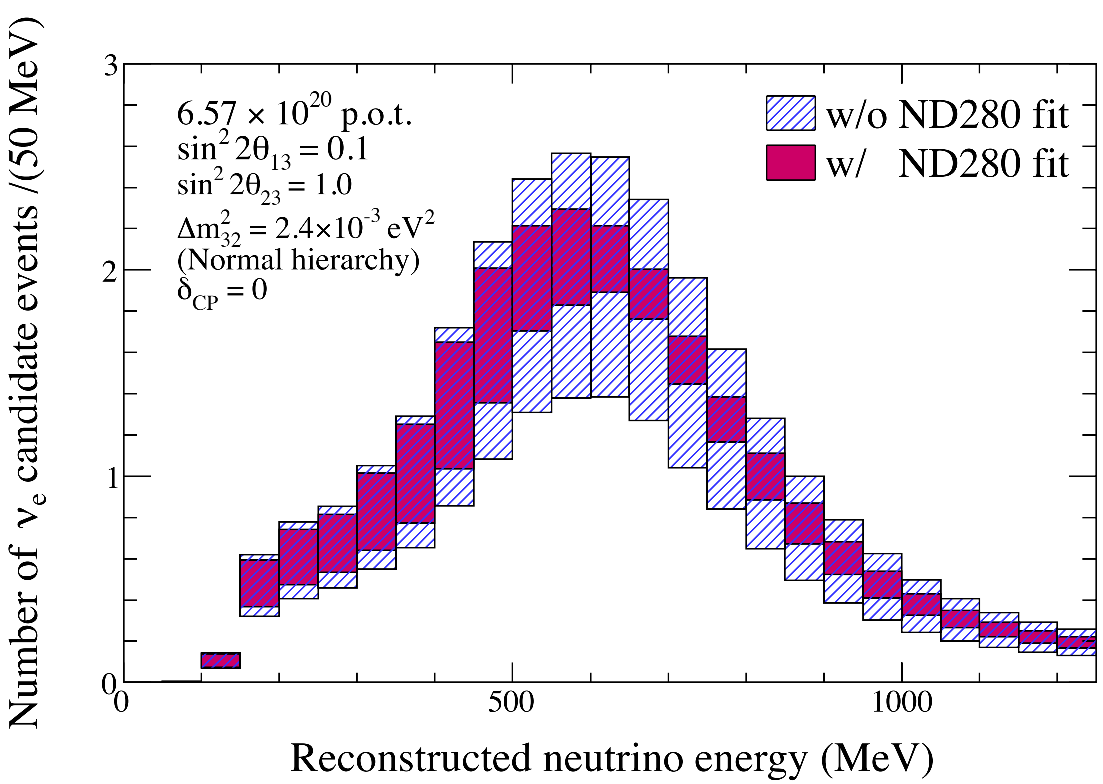


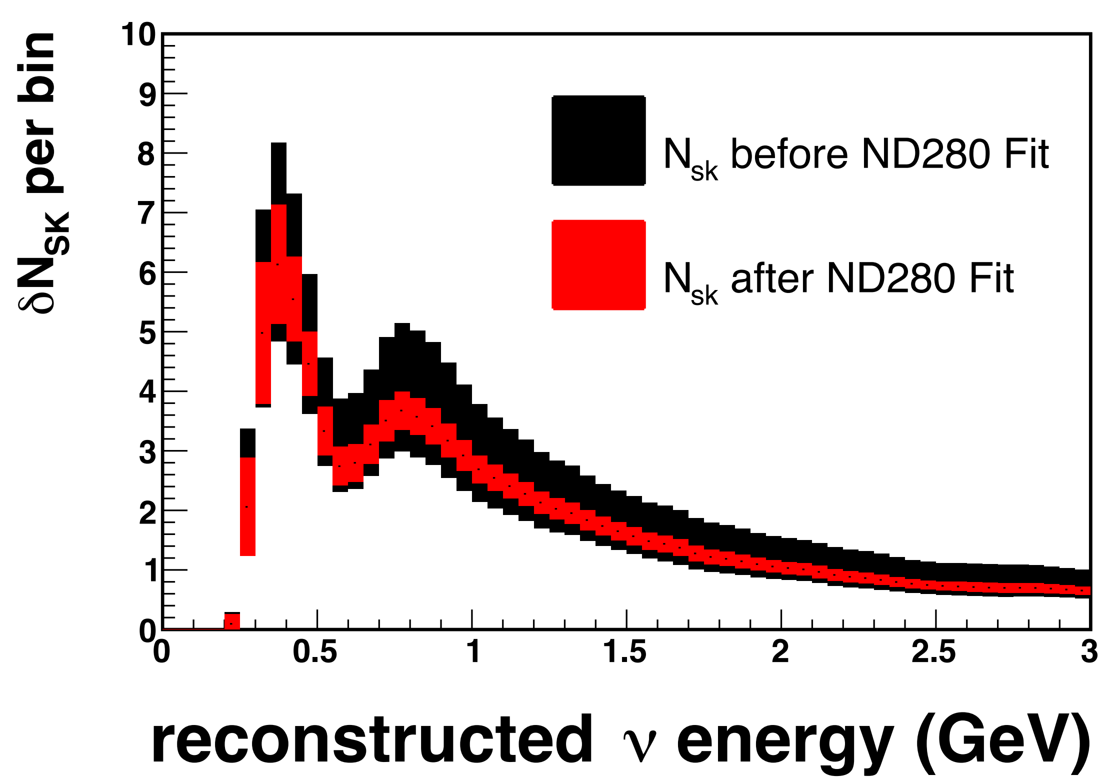


Systematic uncertainties at T2K

Systematic uncertainties	% variation of Tot # of events (electron neutrino)	% variation of Tot # of events (muon neutrino)
ND280 corr. Flux-Xsec (unconstrained)	2.9 (25.9)	2.7 (21.6)
ND280 uncorr. Xsec	7.5	4.9
SK detector + Hadronic intearctions	3.5	5.6
Total	8.8	8.1

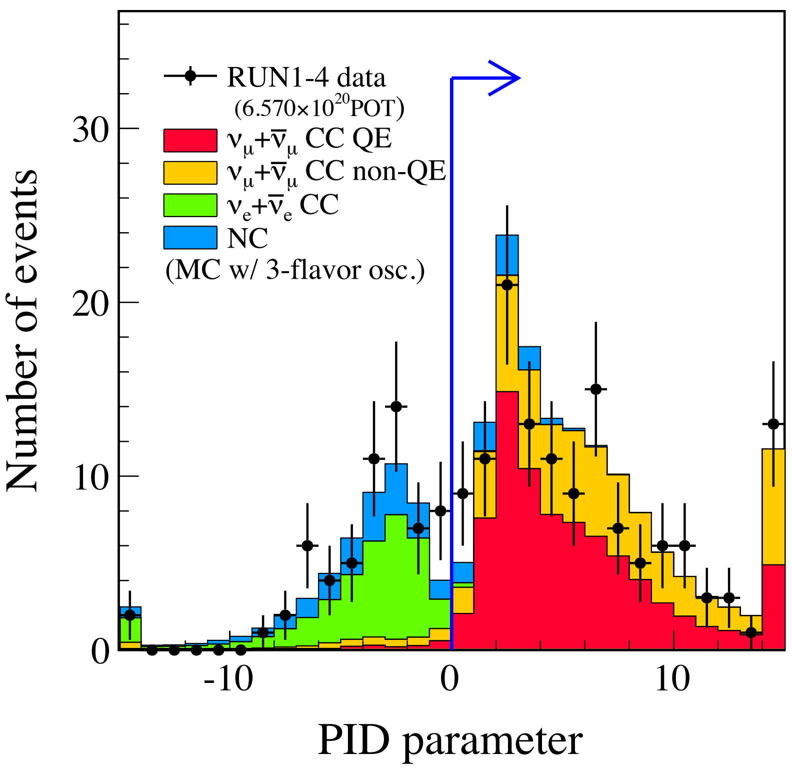
$\sin^2\theta_{13}=0.1$ - $\sin^2\theta_{23}=0.5$ - $|\Delta m^2_{32}| = 2.40\times10^{-3}\ eV^2/c^4$ - NH - $\delta_{CP}=0$



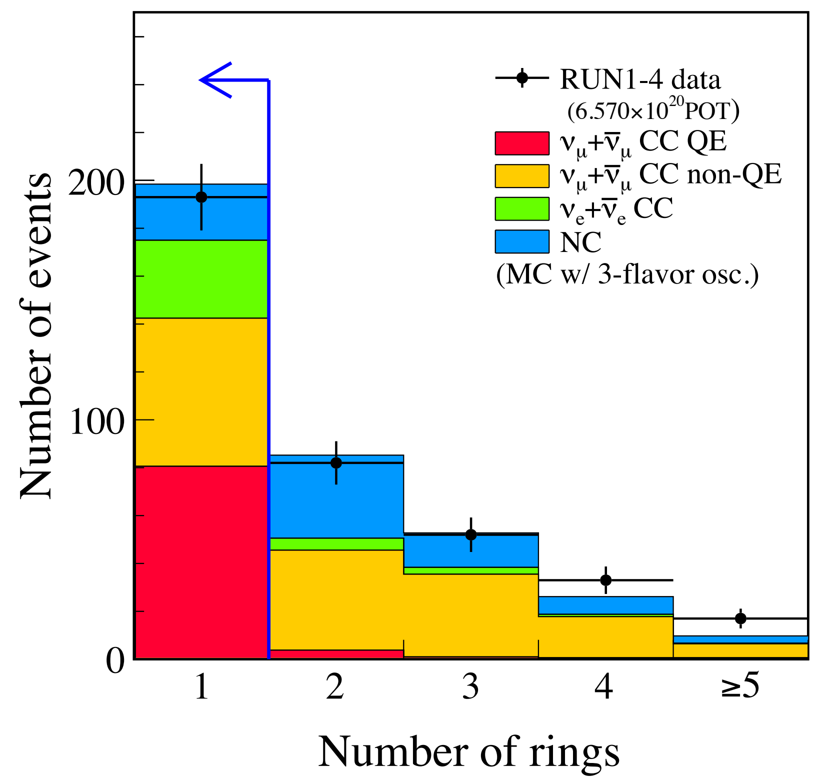


T2K selection Ring-μ

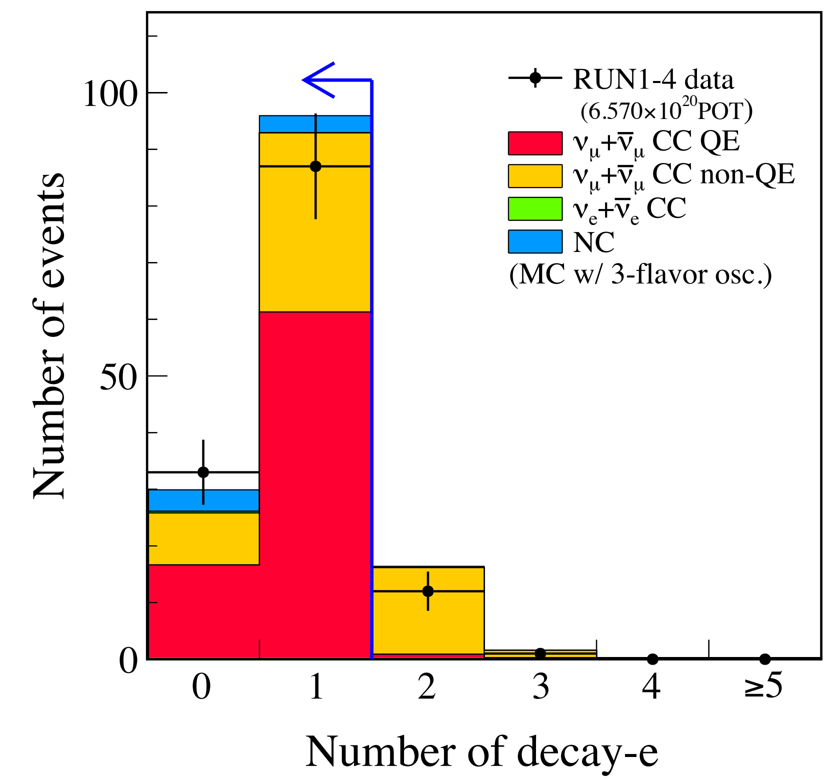
PID cut



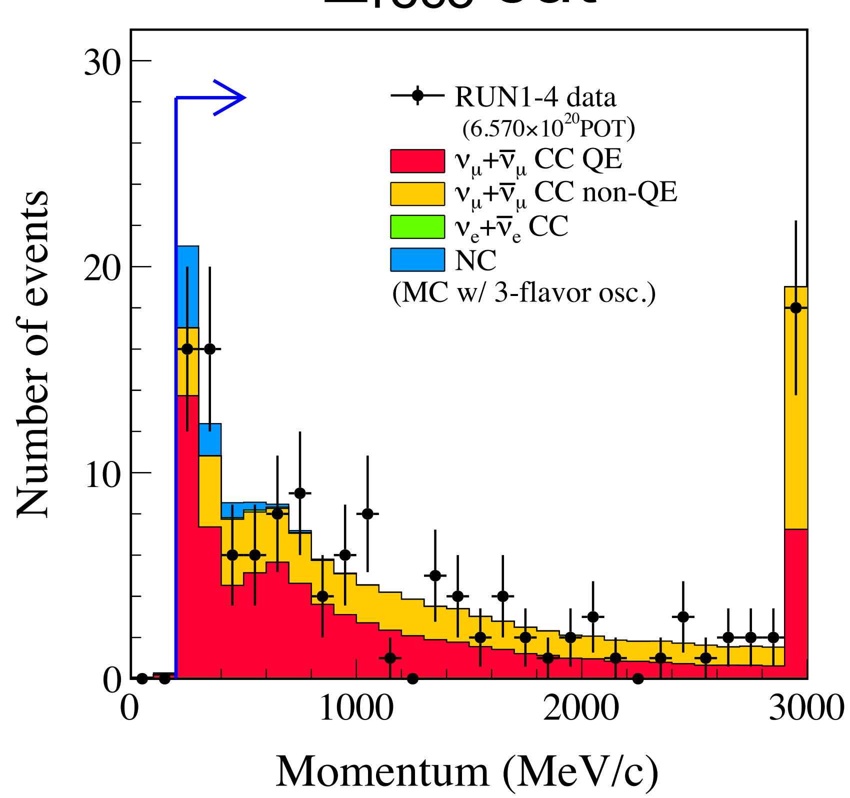
of Rings cut



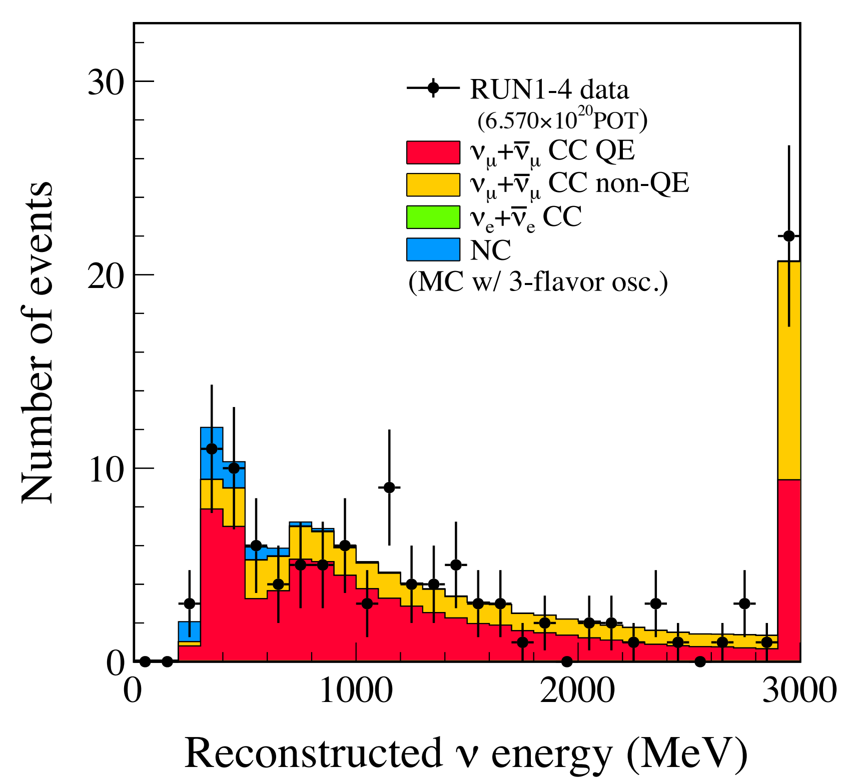
After e-like PID

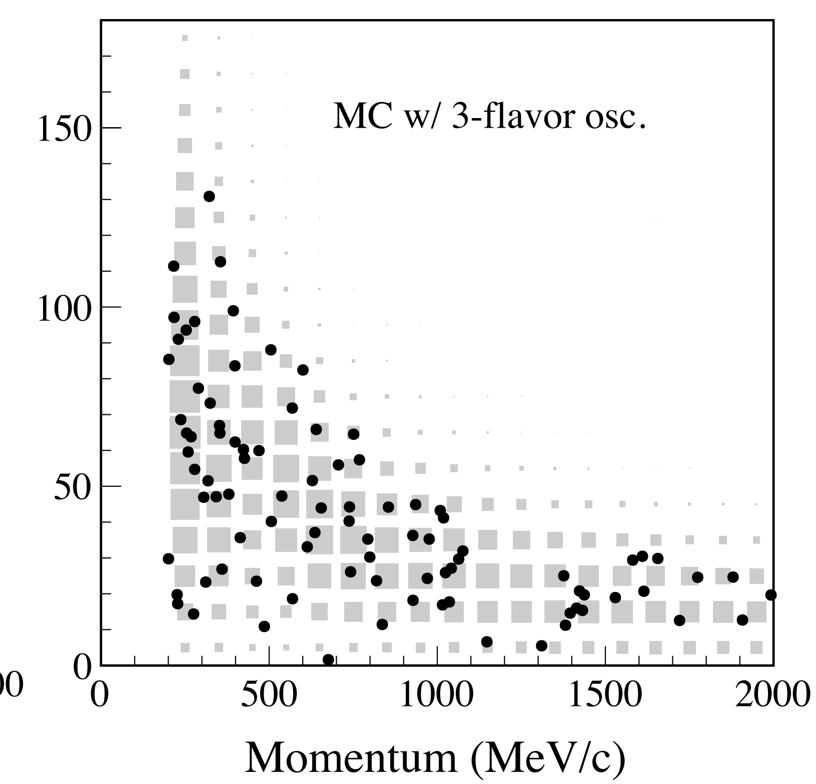


E_{reco} cut



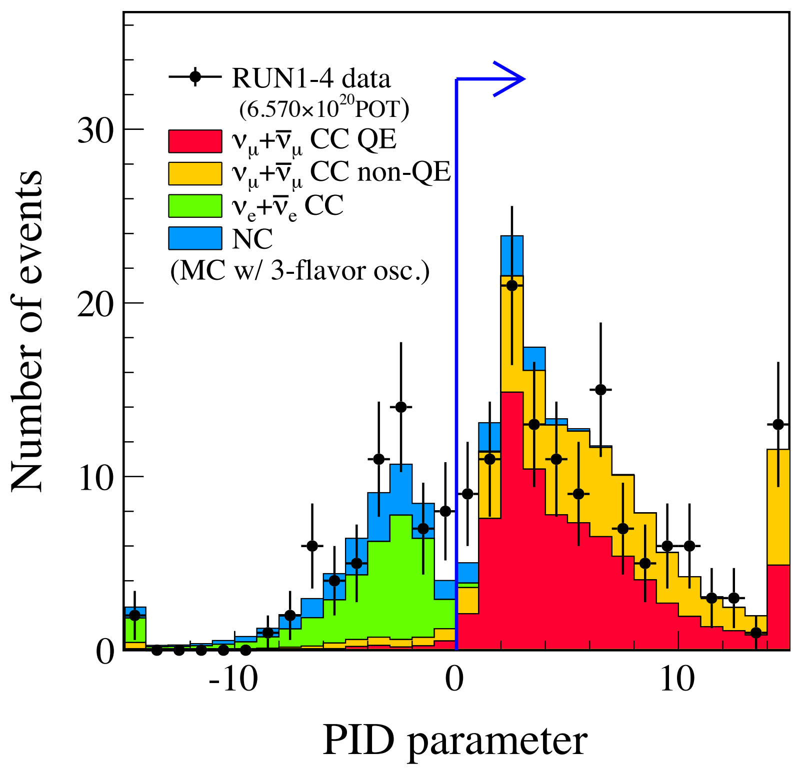
Selected samples



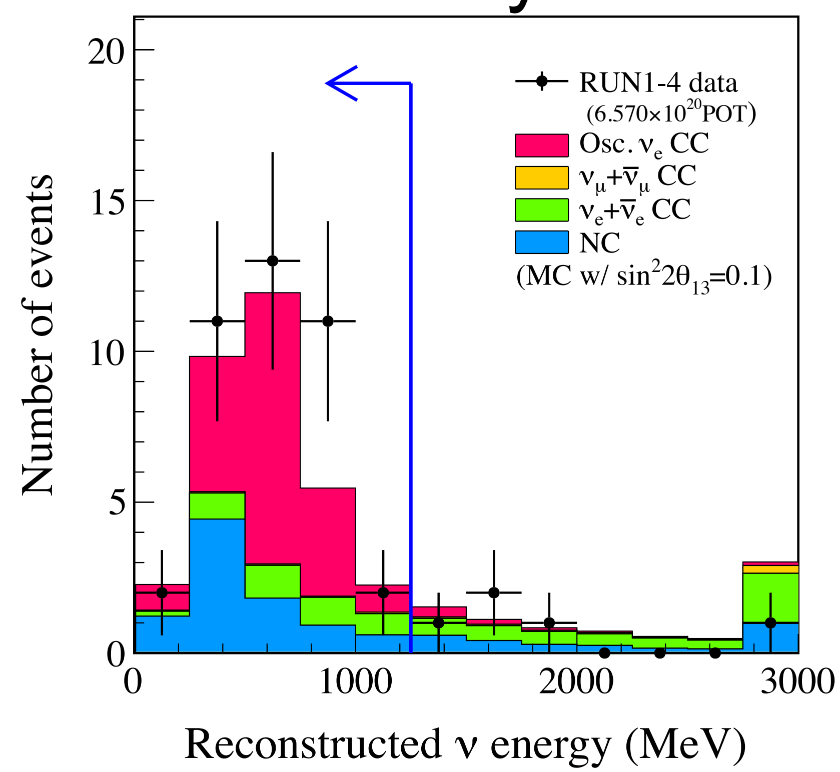


T2K selection Ring-e

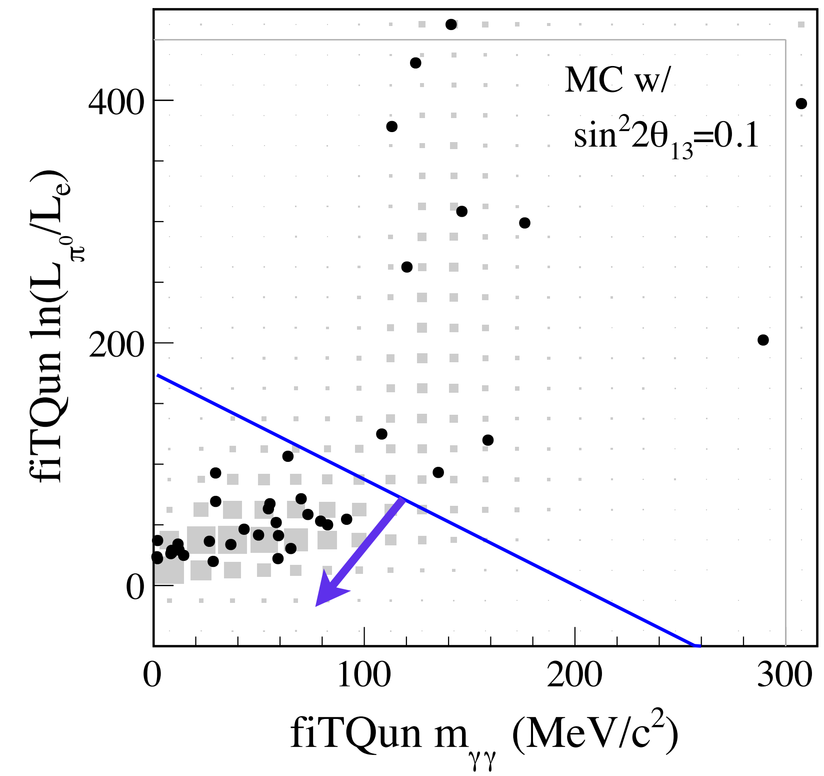
PID cut



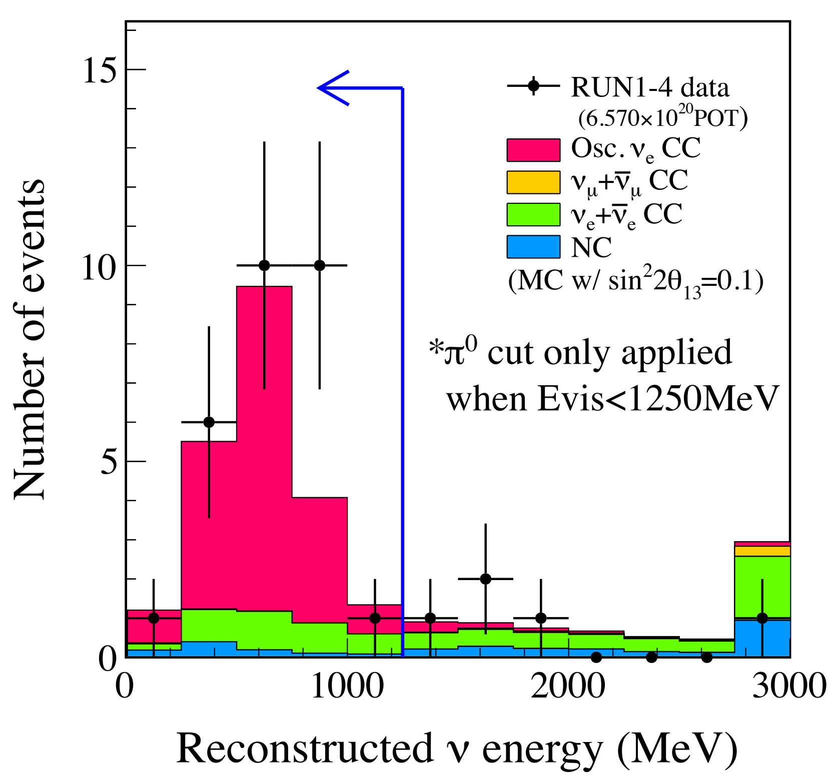
After e-like PID & no decay-e



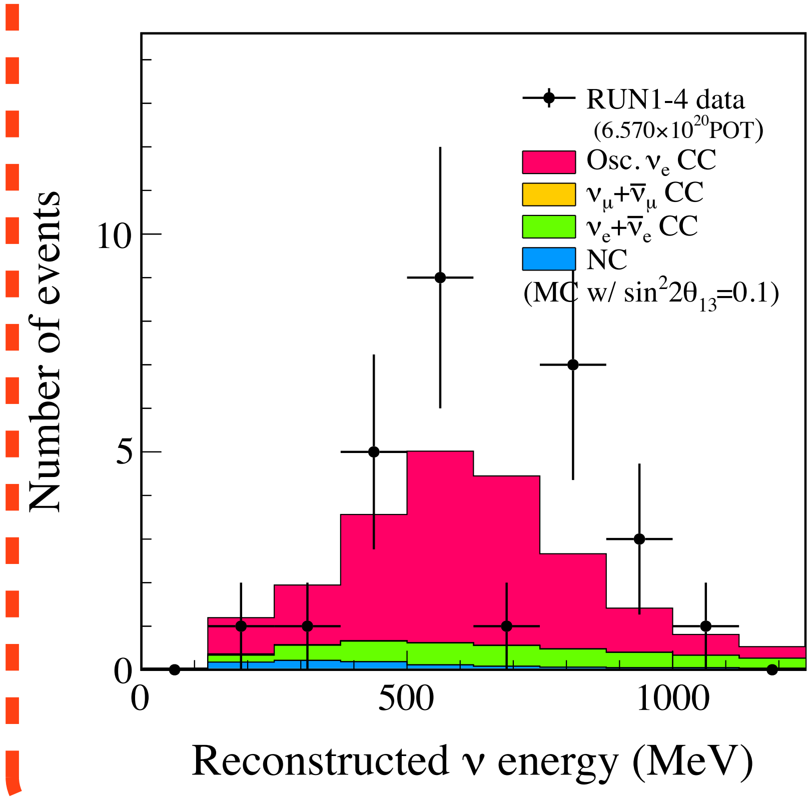
π^0 rejection cut

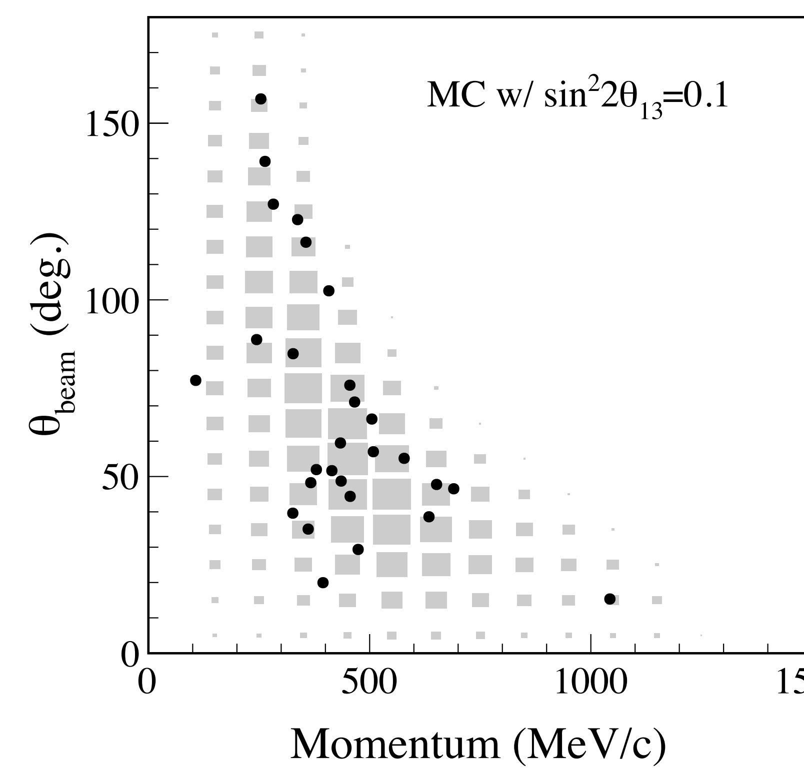


E_{reco} cut



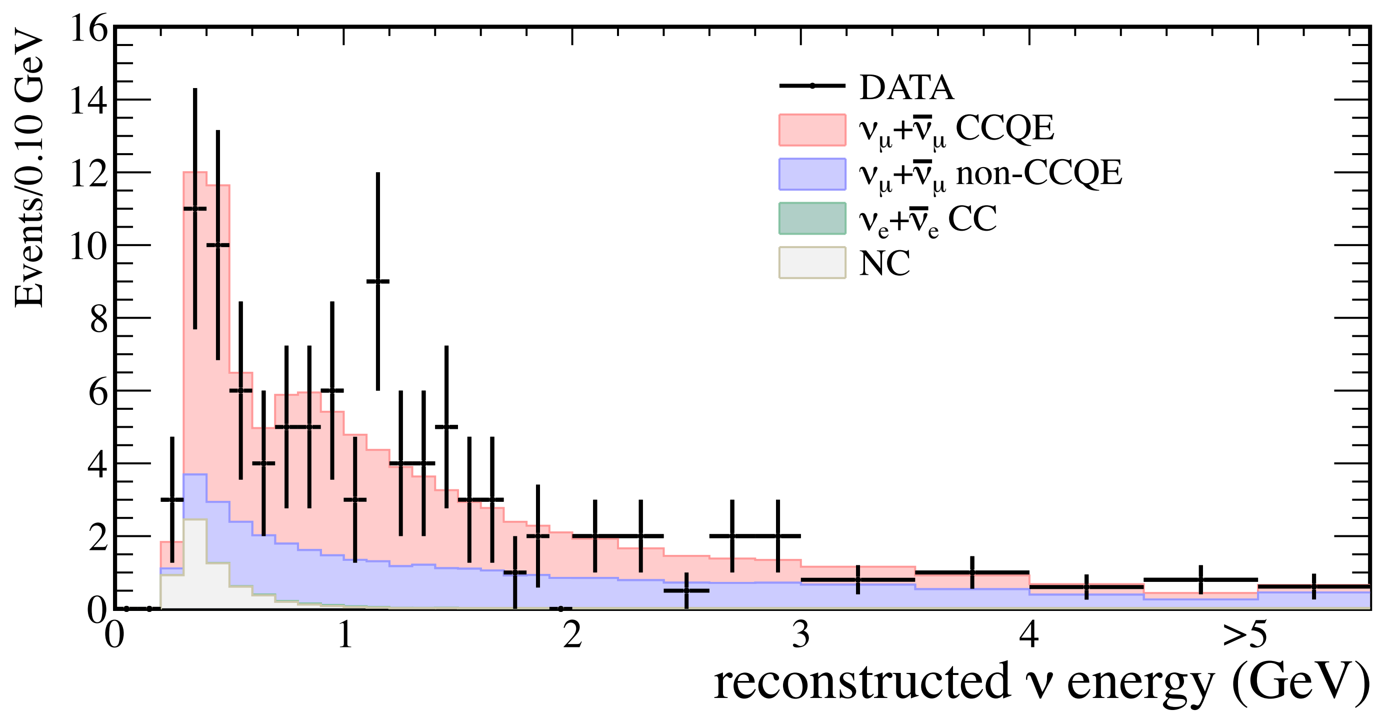
Selected samples





$\nu_\mu \rightarrow \nu_\mu$ disappearance

Neutrino reconstructed energy in CCQE hypothesis



PDG (2012):

$\sin^2(\theta_{13}) = 0.0251 \pm 0.0035$

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ eV^2/c^4$

$\sin^2(\theta_{12}) = 0.312 \pm 0.016$

δ_{CP} unconstrained in $[-\pi;+\pi]$

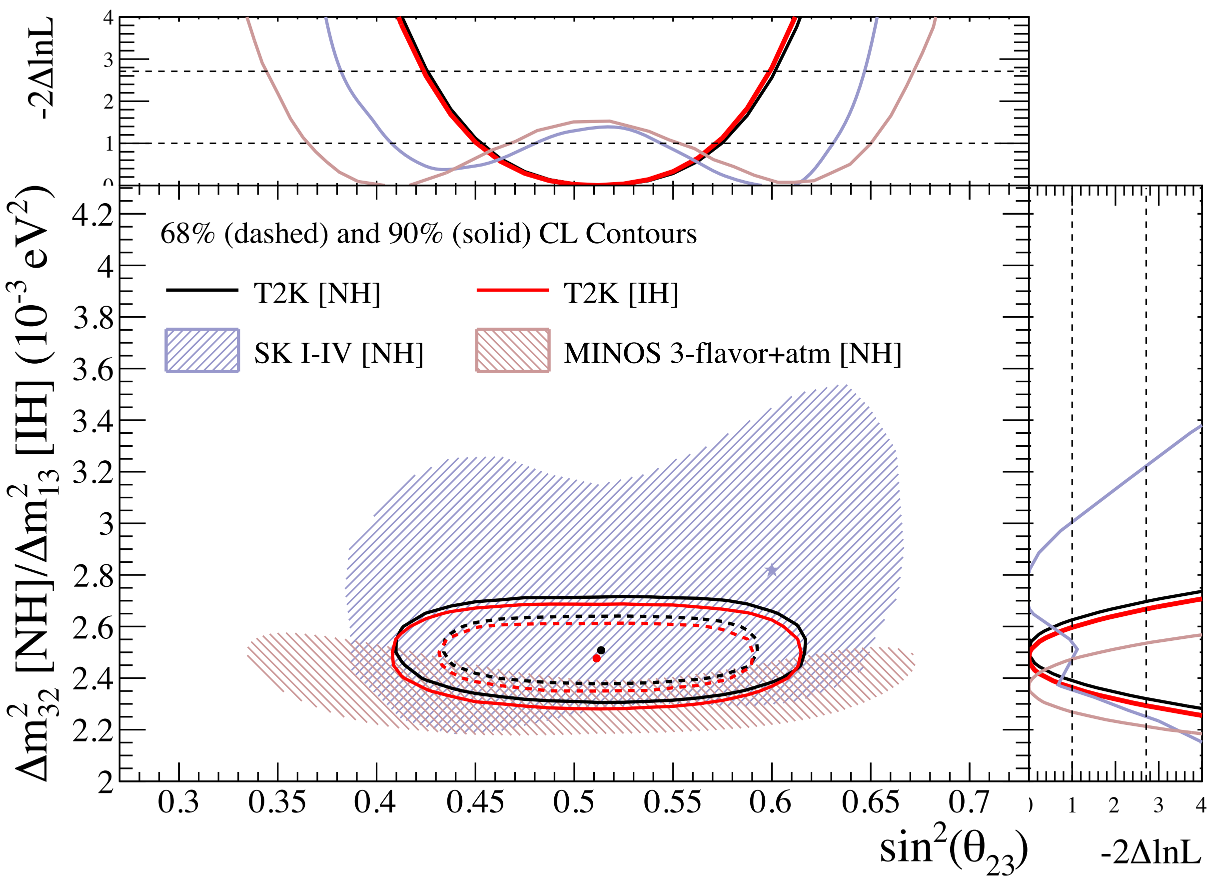
Effect on the Tot # of events = 0.2%

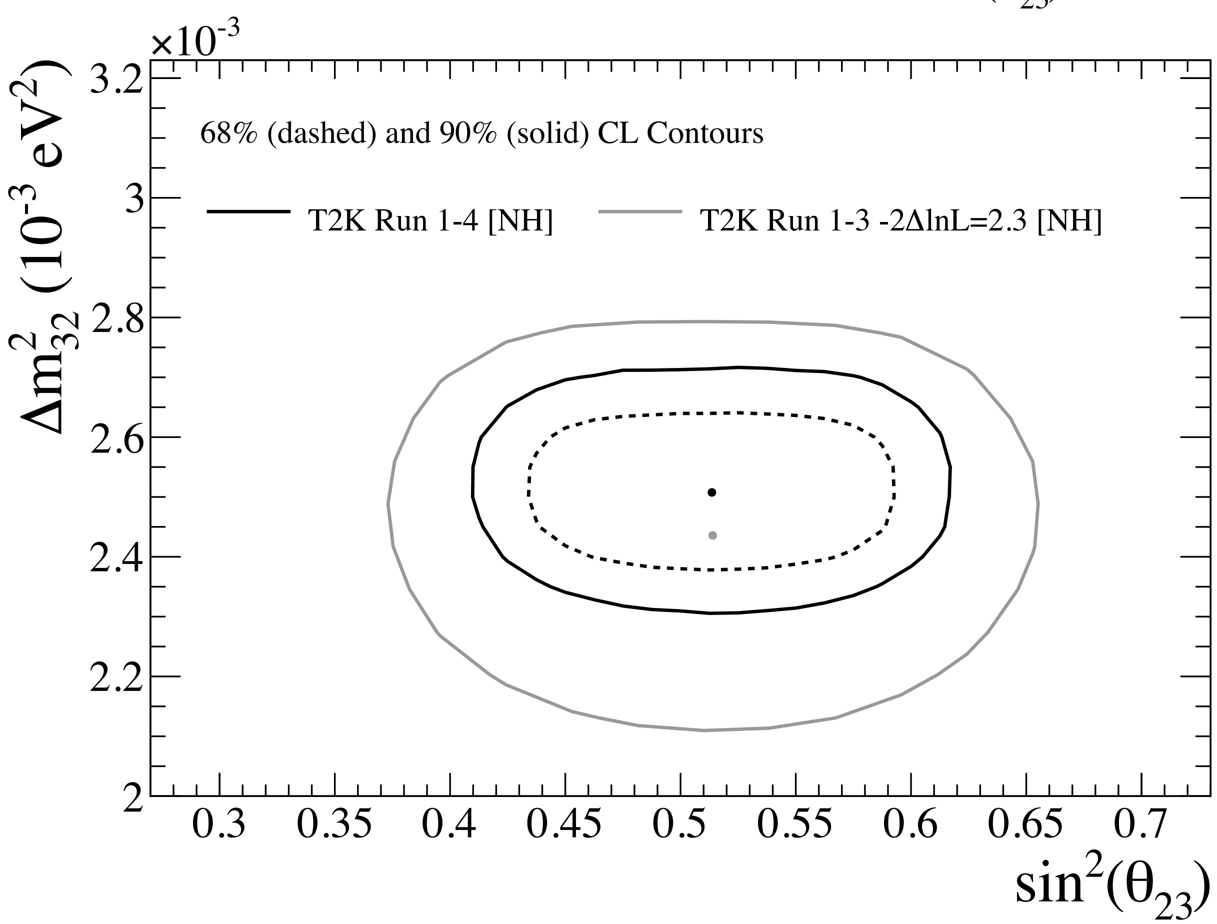
Systematics as nuisance parameters

$$L = L_{norm} \times L_{shape} \times L_{syst} \times L_{osc}$$

- L_{norm}: Poisson term
- L_{shape}: E_{reco} spectrum shape term
- L_{syst}: Penalty term w/ flux, Xsec and detector systematics
- L_{osc}: Penalty term for constrained oscillation parameters

$\nu_\mu \rightarrow \nu_\mu$ disappearance





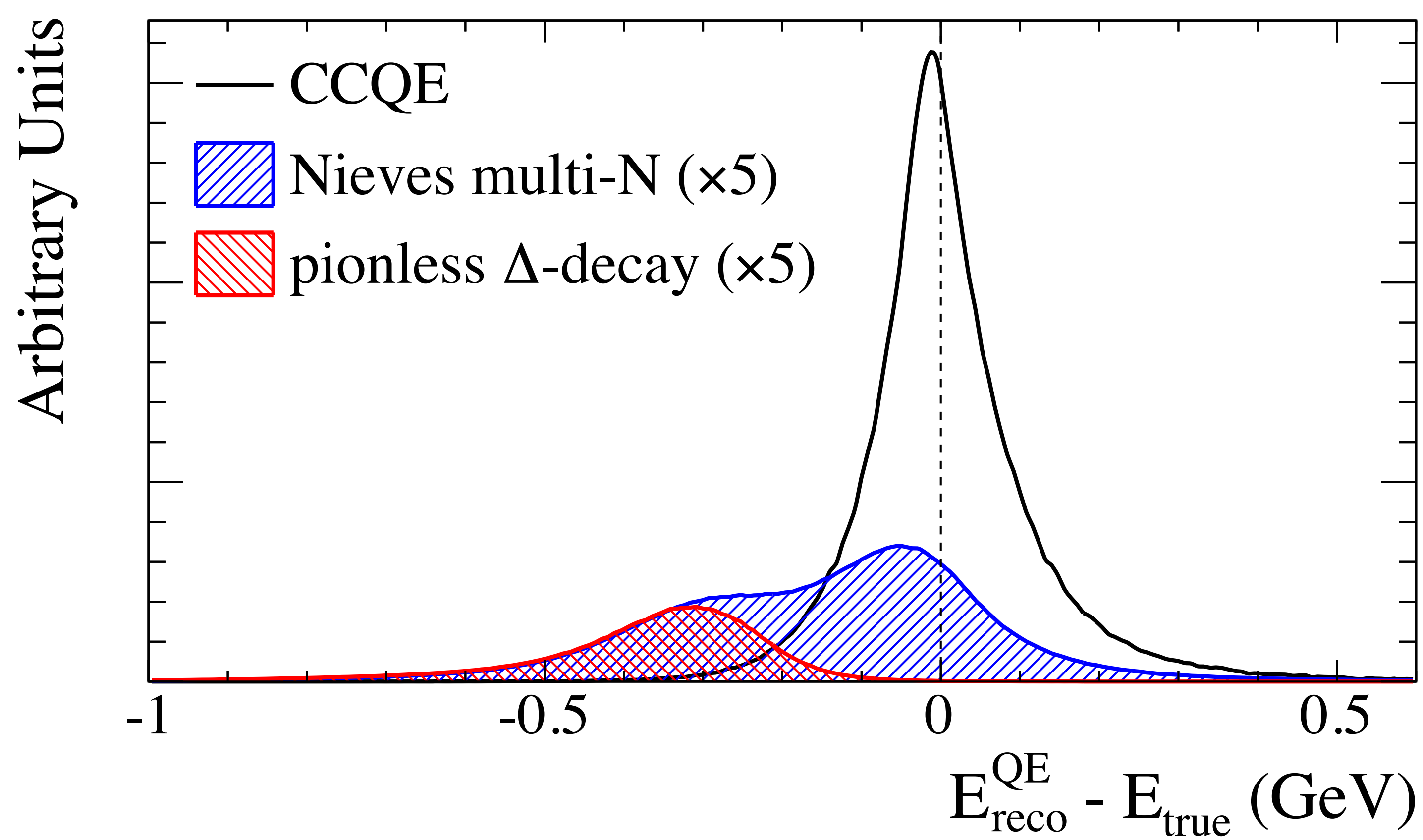
Feldman-Cousins 1D Confidence Intervals

	68% CL	**90% CL**
$\sin^2(\theta_{23})$ [NH]	[0.458,0.568]	[0.428,0.598]
Δm^2_{32} (x10^{-3}) [NH]	[2.41,2.61]	[2.34,2.68]
$\sin^2(\theta_{23})$ [IH]	[0.456,0.566]	[0.427,0.596]
Δm^2_{13} (x10^{-3}) [IH]	[2.38,2.58]	[2.31,2.64]

Great improvement from previous measurement (PRL 111, 211803 2013)

Multi-nucleon effect on ν_μ disappearance

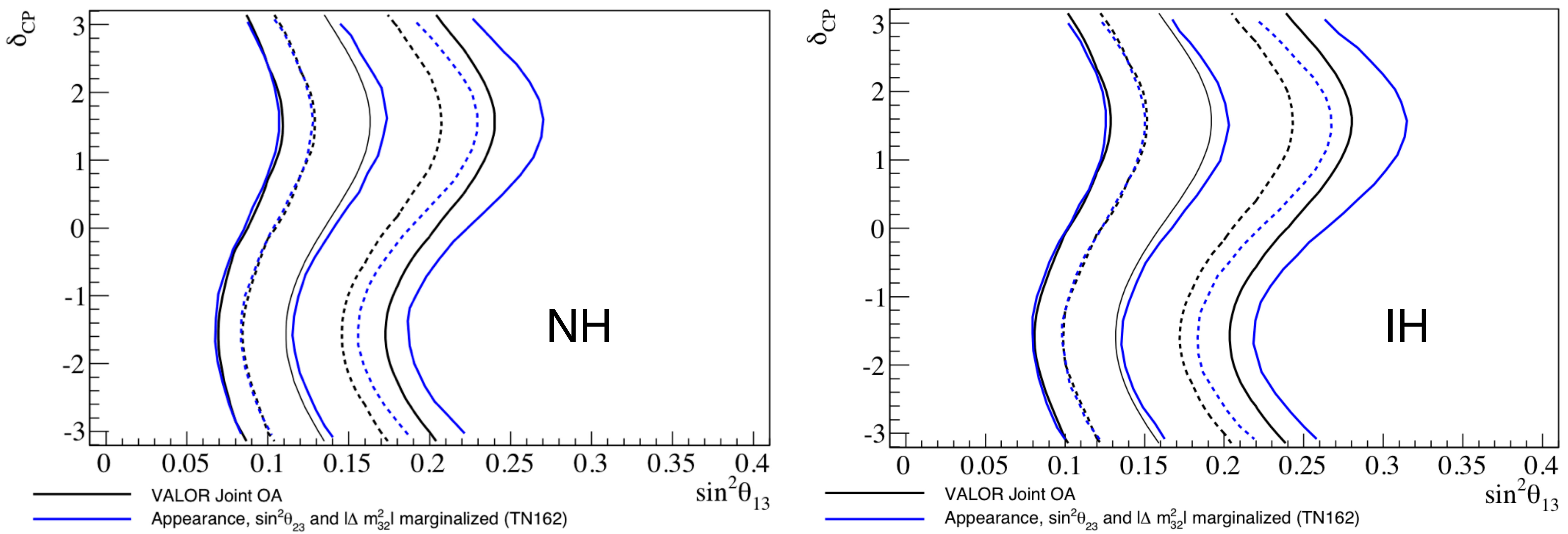
- Discrepancy of CCQE cross section between MiniBooNE and other experiments
- Multi-nucleon neutrino interaction model can explain it (Nieves et al Phys.Lett.B 707, 72 (2012). arXiv:1106.5374)
- Simulate multi-nucleon effect in the MC and fit w/ current analysis



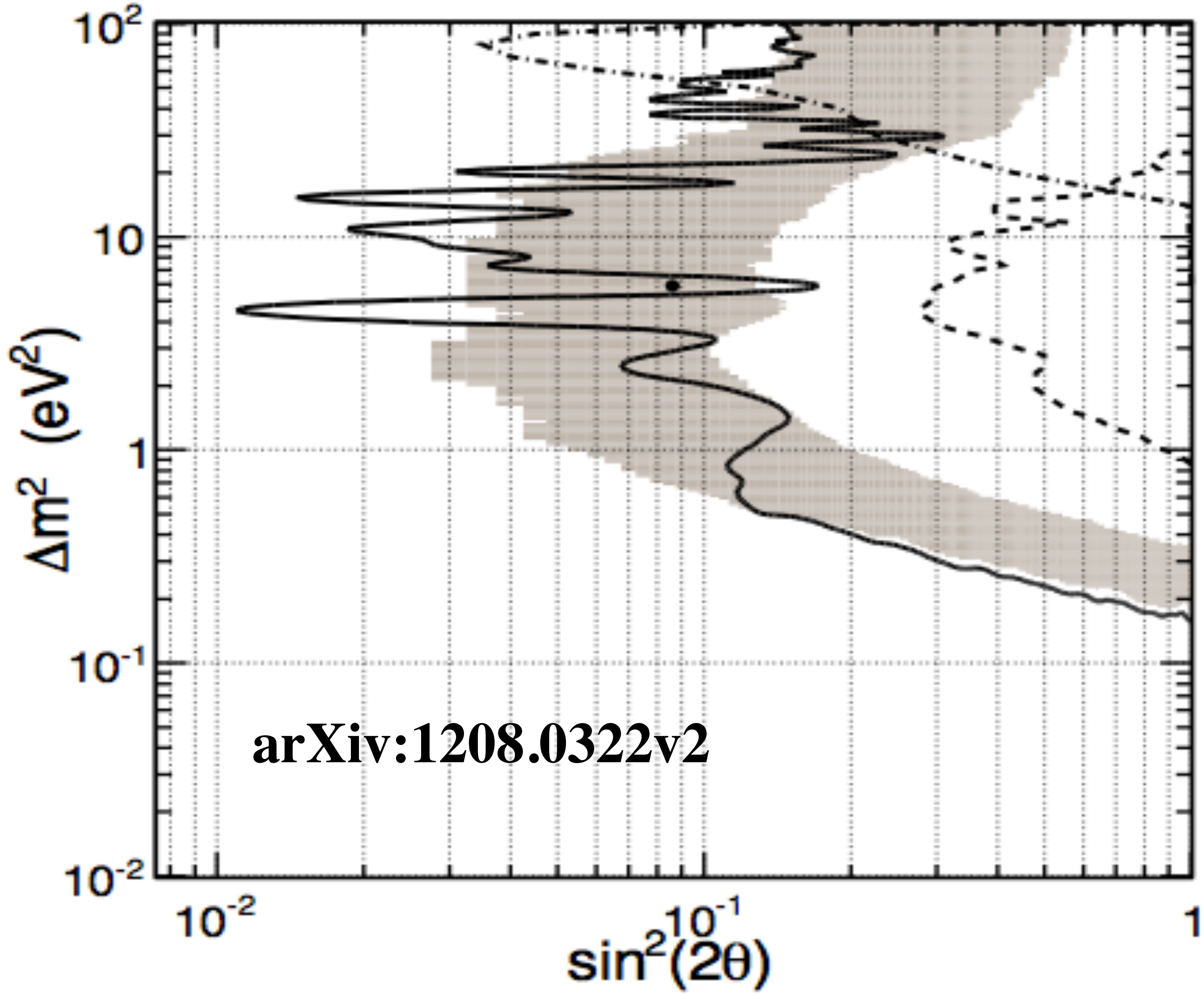
- Negligible (sub-percent) effect on $\sin^2\theta_{23}$ and Δm^2_{32}
- π-less Δ-decay has 100% systematic uncertainty in the analysis w/ a similar effect

$\nu_\mu + \nu_e$ joint fit

Mass Hierarchy	$\Delta m^2_{32}/\Delta m^2_{13}$ $10^{-3} eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
Normal	$2.512^{+0.111}_{-0.118}$	$0.524^{+0.057}_{-0.059}$	$0.042^{+0.013}_{-0.021}$
Inverted	$2.488^{+0.117}_{-0.118}$	$0.523^{+0.073}_{-0.065}$	$0.049^{+0.015}_{-0.021}$



MiniBooNE ν_μ disappearance result



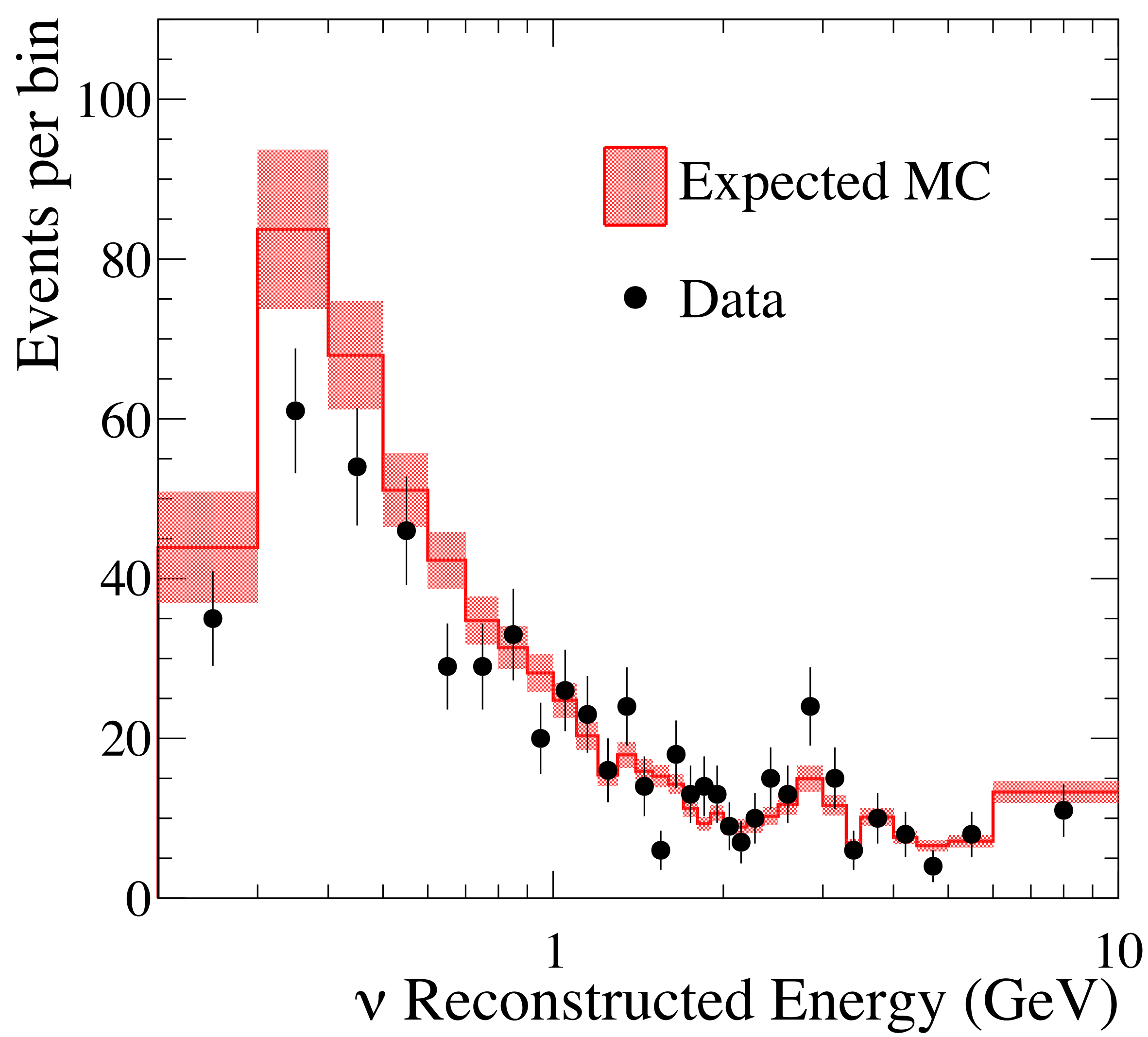
Sterile searches at ND280

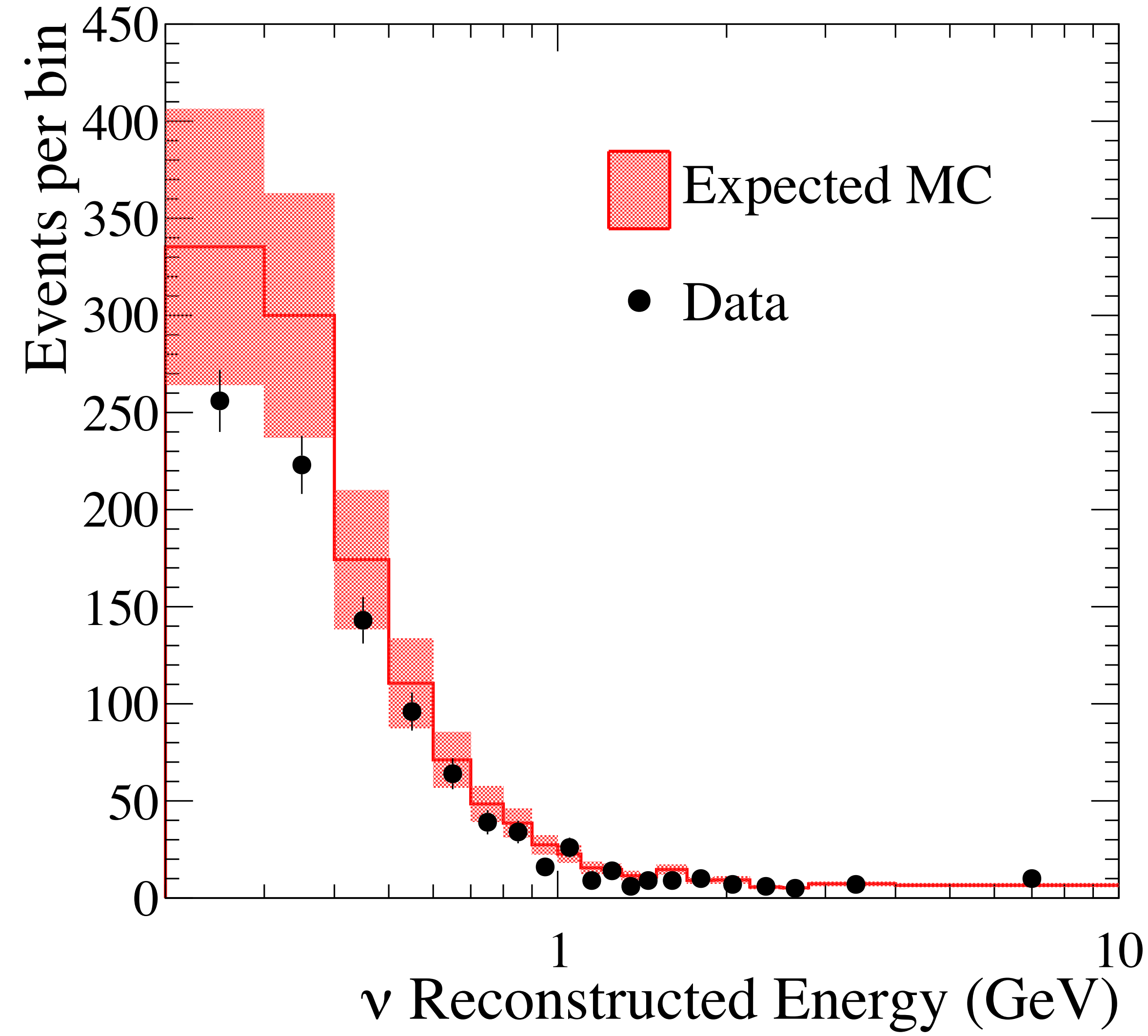
Best-fit values

$\sin^2 2\theta_{ee} = 1$

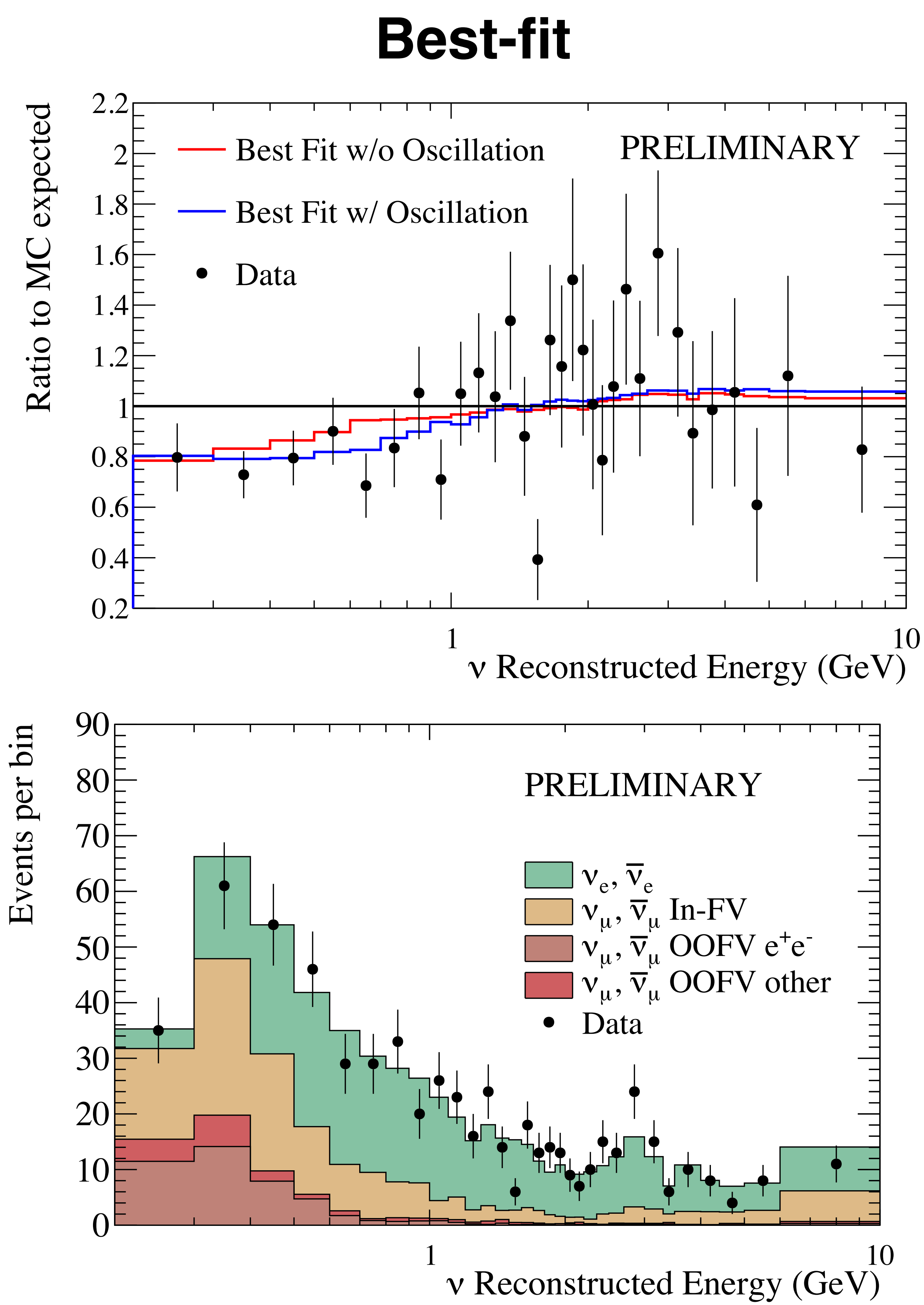
$\Delta m^2_{41} = 2.14\ eV^2/c^4$

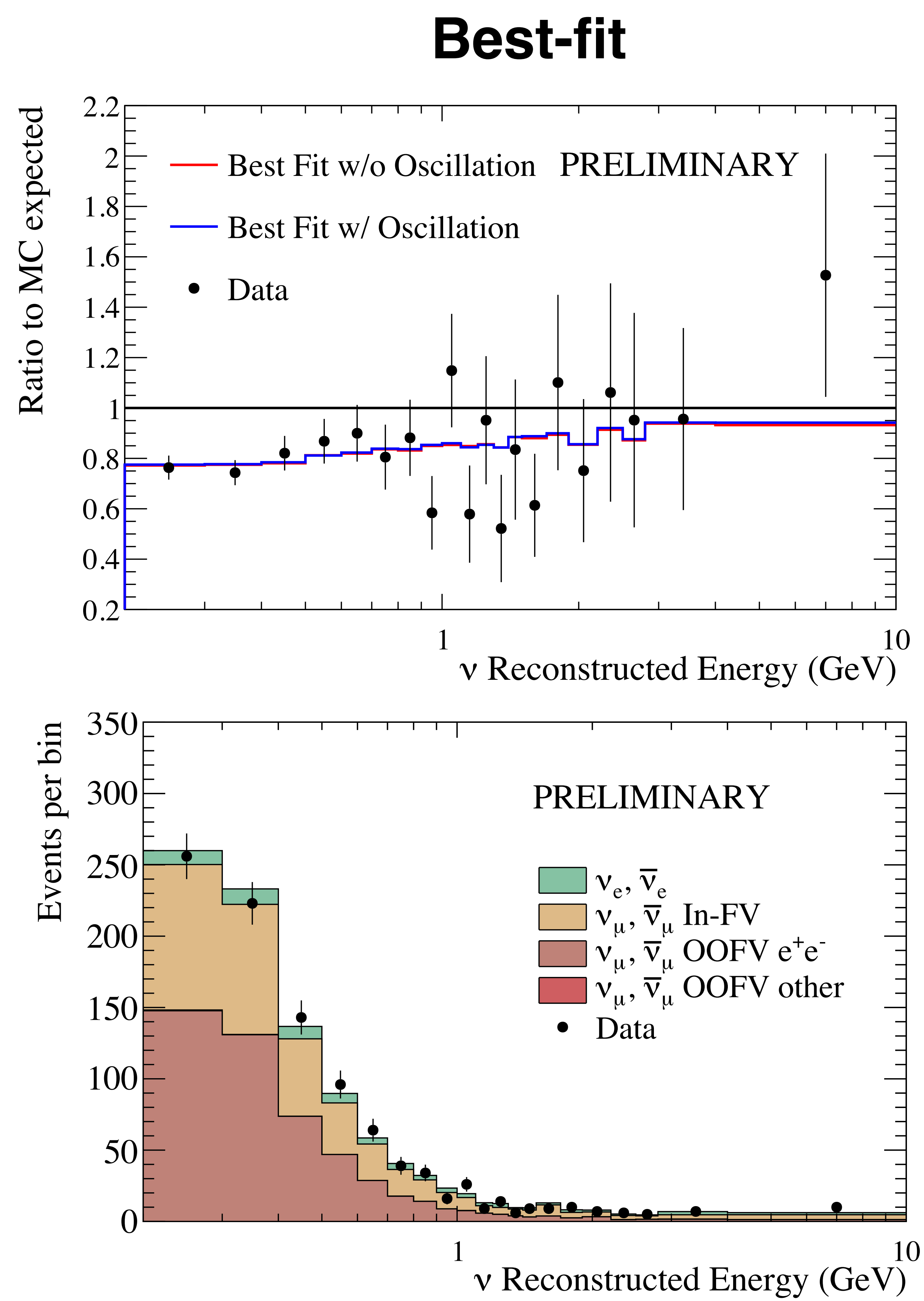
$$-2\ln\mathcal{L}_T(\sin^2 2\theta, \Delta m^2; \vec{f}) = -2\ln\mathcal{L}_{\nu_e} - 2\ln\mathcal{L}_\gamma + (\vec{f} - \vec{f}_0)^T V^{-1}(\vec{f} - \vec{f}_0)$$





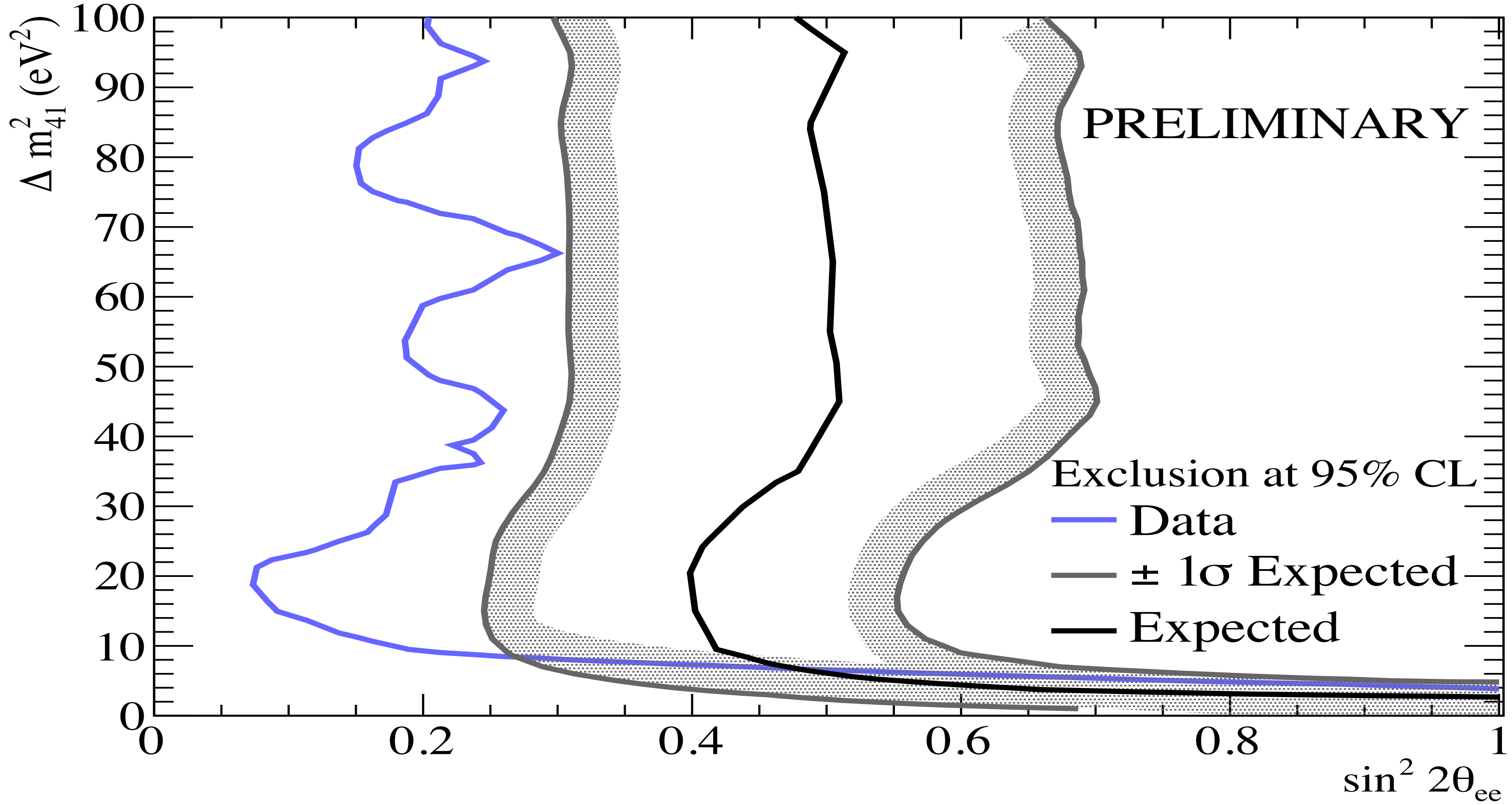
Sterile searches at ND280





Sterile searches at ND280

	$\chi^2_{bestfit}$	d.o.f.	goodness-of-fit
Osc.	43.57	49	0.75
No Osc.	47.88	51	0.63

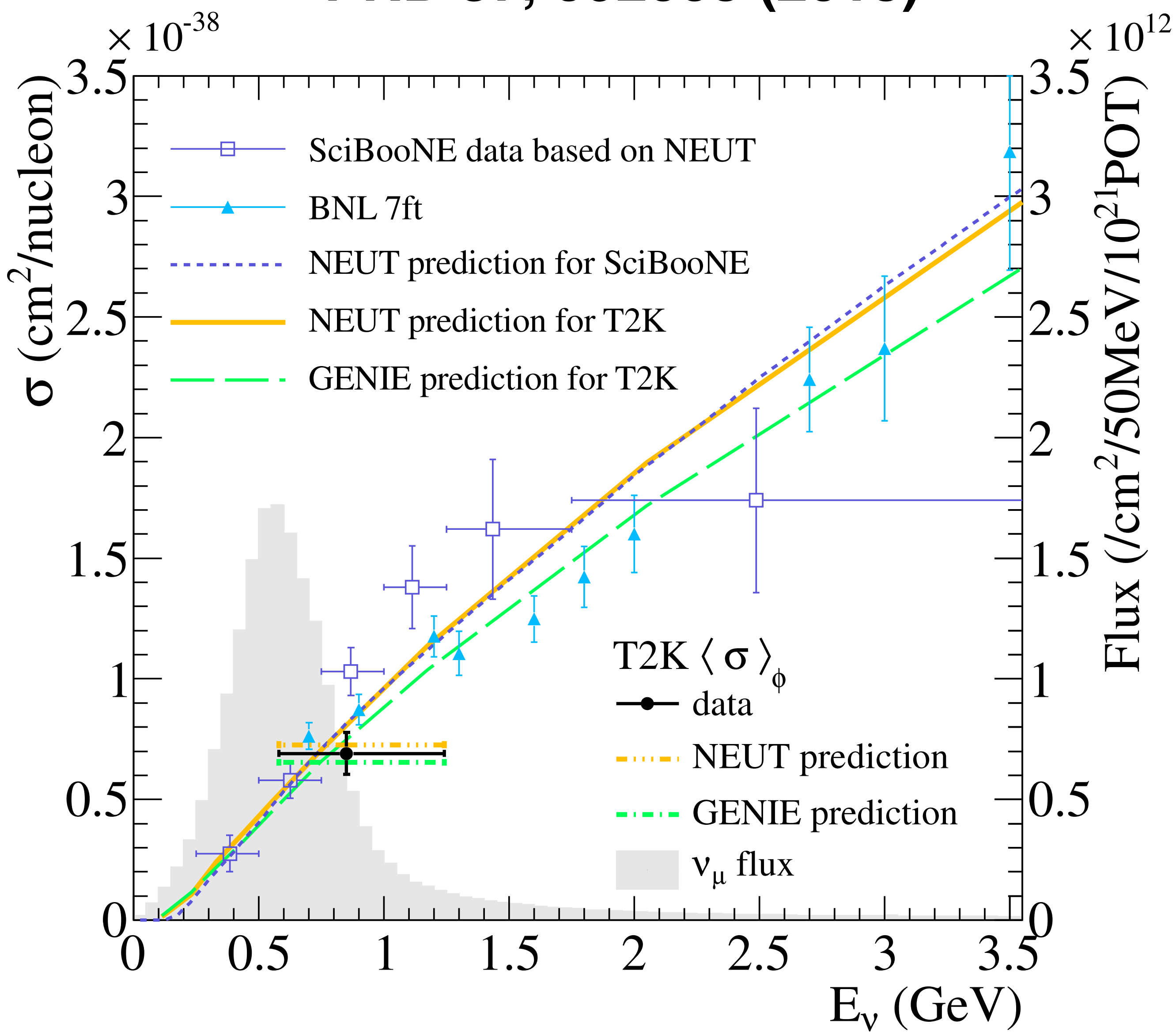


$\chi^2_{bestfit}$ w/ oscillation	$\chi^2_{bestfit}$ w/o oscillation	$\Delta\chi^2$	p-value wrt null hypothesis
43.57	47.88	4.31	0.06069

ν_μ CC-inclusive cross section

$<\sigma_{CC}> = (6.91 \pm 0.13(\text{stat}) \pm 0.84(\text{syst})) \times 10^{-39}$ cm^2/nucleon

PRD 87, 092003 (2013)

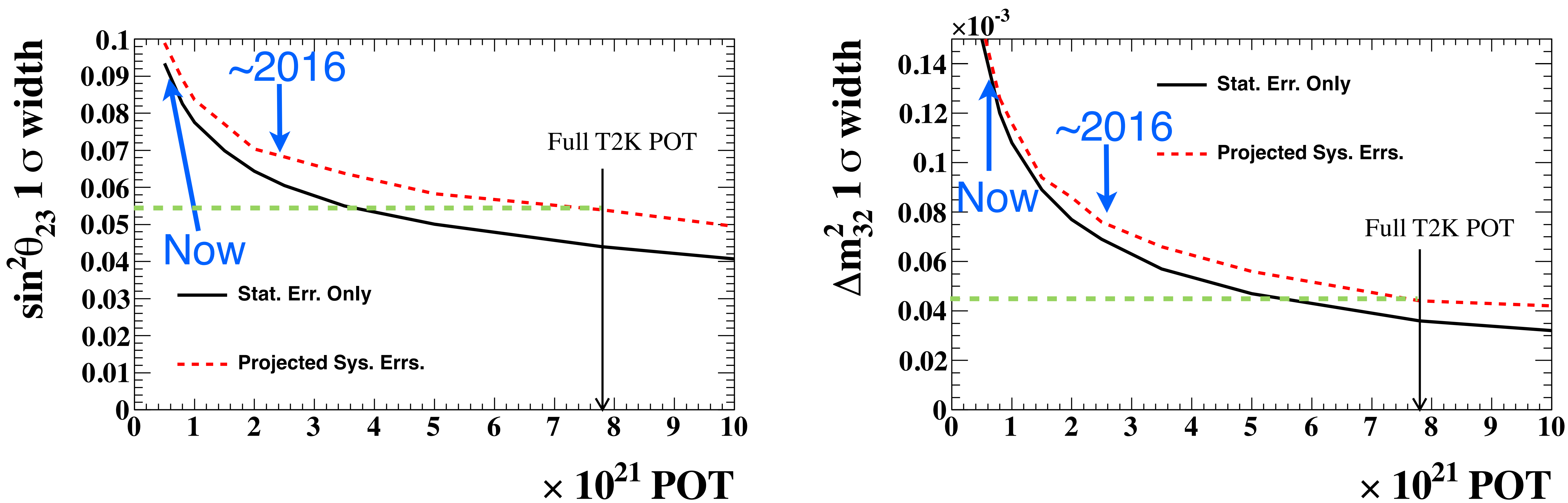


Future $\sin^2\theta_{23}$ and Δm^2_{32} 1σ precision

50% POT ν + 50% POT anti-ν

Solid lines: no sys. err.

Dashed lines: projected conservative sys. err. (~7%ν, ~14%anti-ν)



True values: δ_{CP}=0°, $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5, $|\Delta m^2_{32}|$ = 2.4×10^{-3}eV^2/c^4, [NH]

reactor constrain: $\delta(\sin^2 2\theta_{13})$ = 0.005

- Decrease uncertainties a lot in the next 2 years
- Statistical limit reached at the full T2K POT

Appearance 90%CL sensitivity

7.8×10^{21} POT (50% POT ν + 50% POT anti-ν)

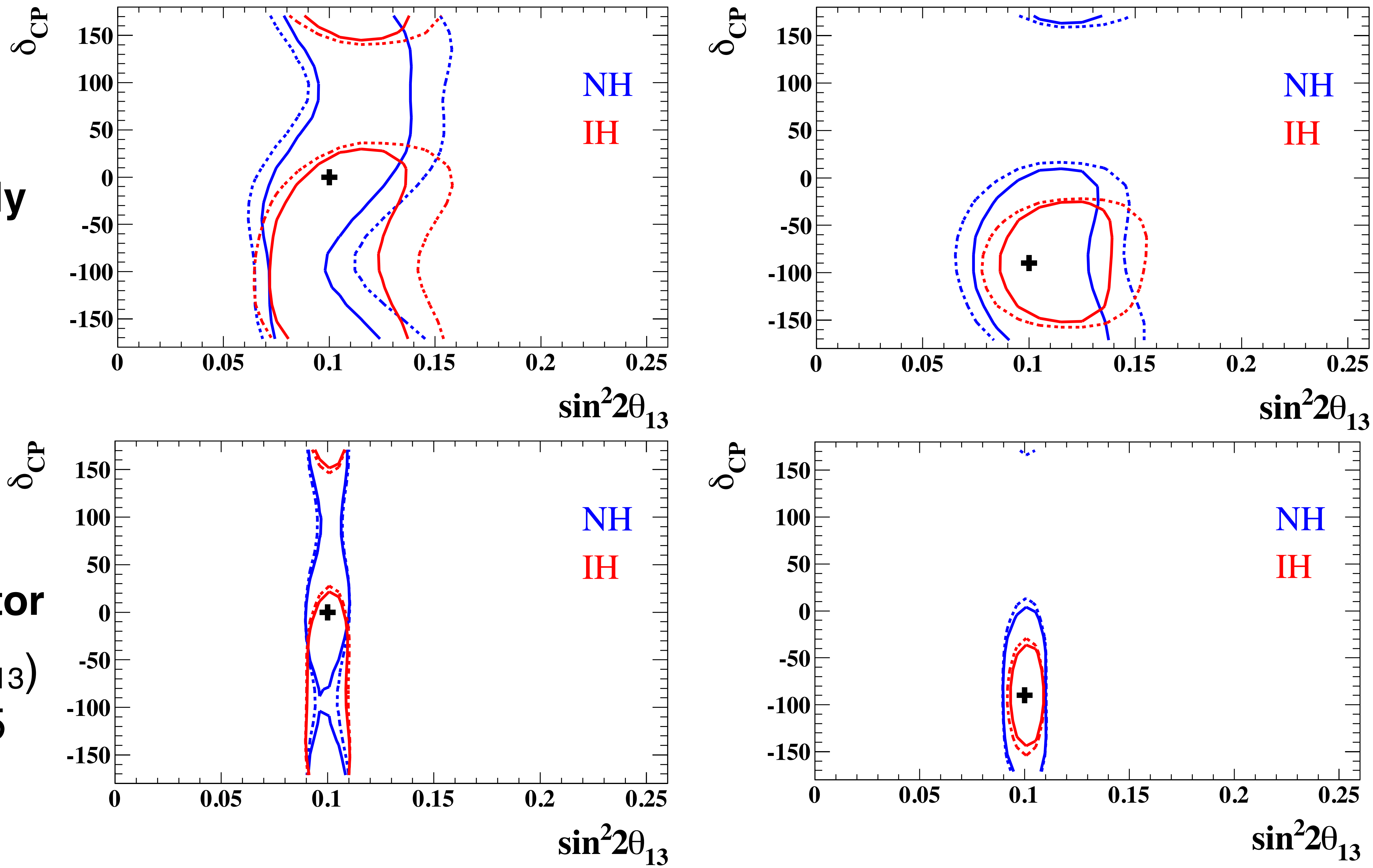
Solid lines: no syst err - Dashed lines: 2012 sys. err. (~10%ν_e, ~13%ν_μ)

True δ_{CP} = 0° | **True δ_{CP} = -90°**

T2K-only

T2K w/ Reactor

$\delta(\sin^2 2\theta_{13}) = 0.005$

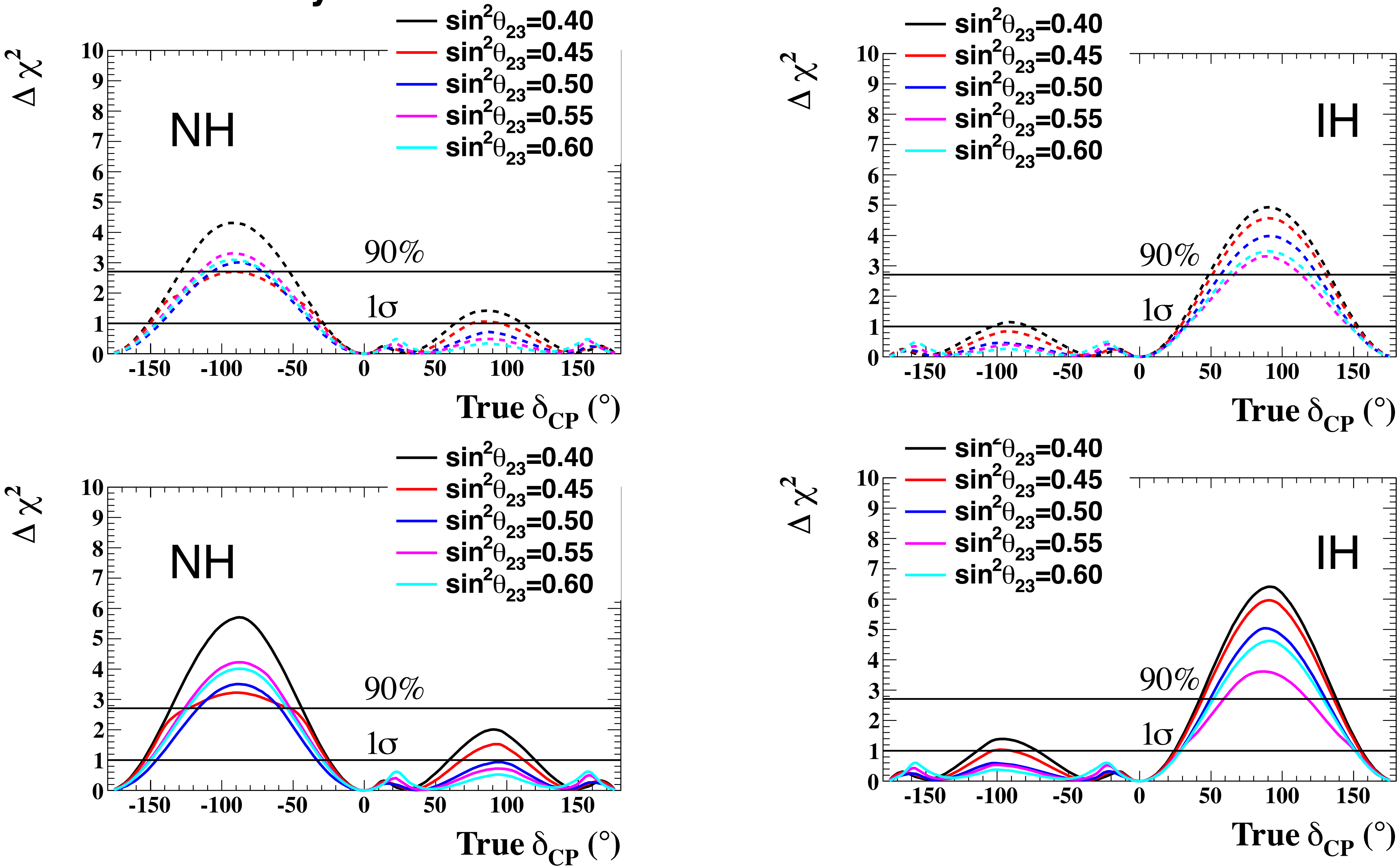


True values: $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2/c^4, [NH]

Sensitivity for resolving sinδ_{CP}≠0

50% POT ν + 50% POT anti-ν

No sys. err. **2012 sys. err. (~10% $_e$, ~13% $_\mu$)**



True values: δ_{CP}=0°, $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5, $|\Delta m^2_{32}|$ = 2.4x10^{-3}eV^2/c^4, [NH]

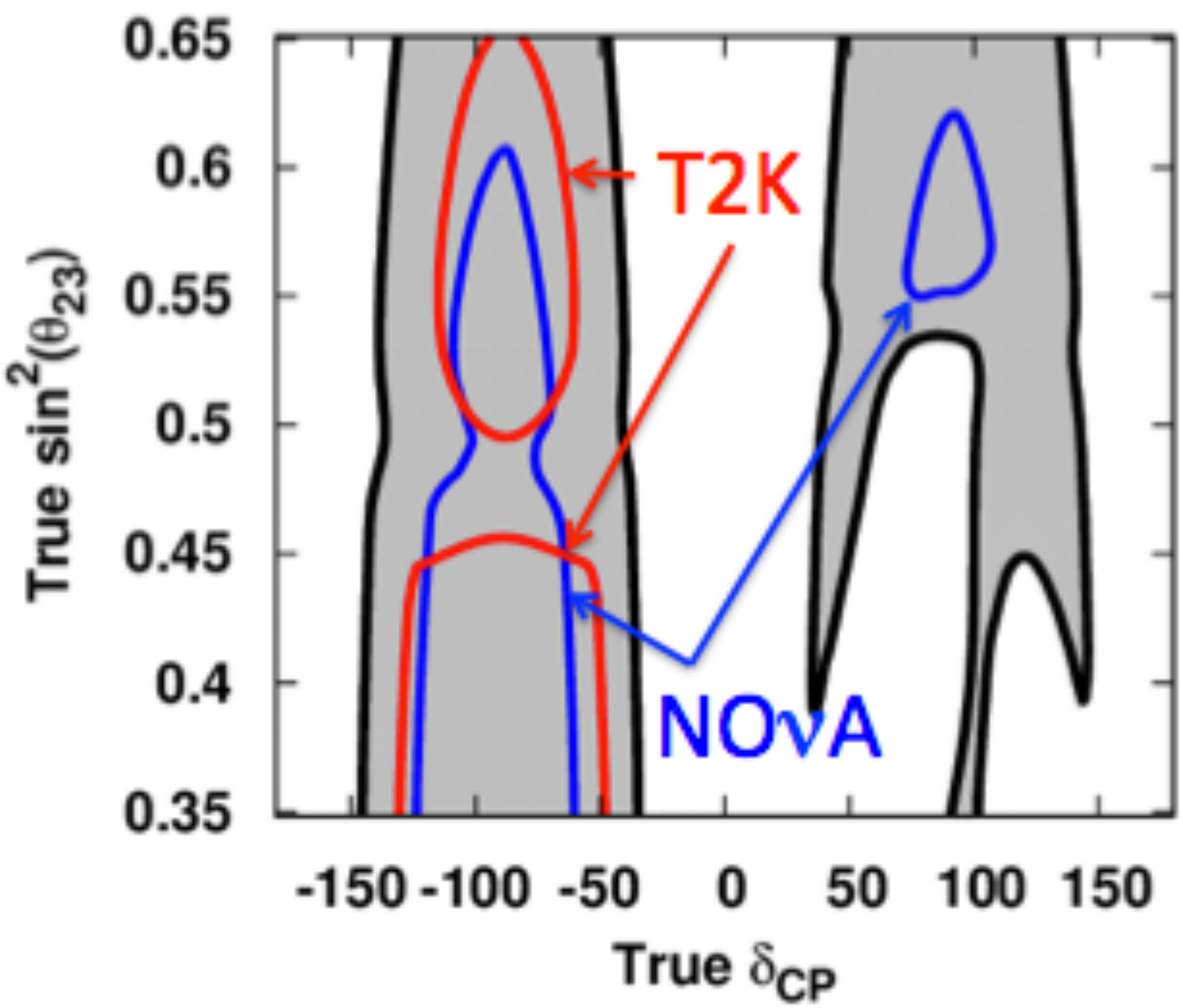
reactor constrain: $\delta(\sin^2 2\theta_{13})$ = 0.005

T2K+NOVA sensitivity to δ_{CP}

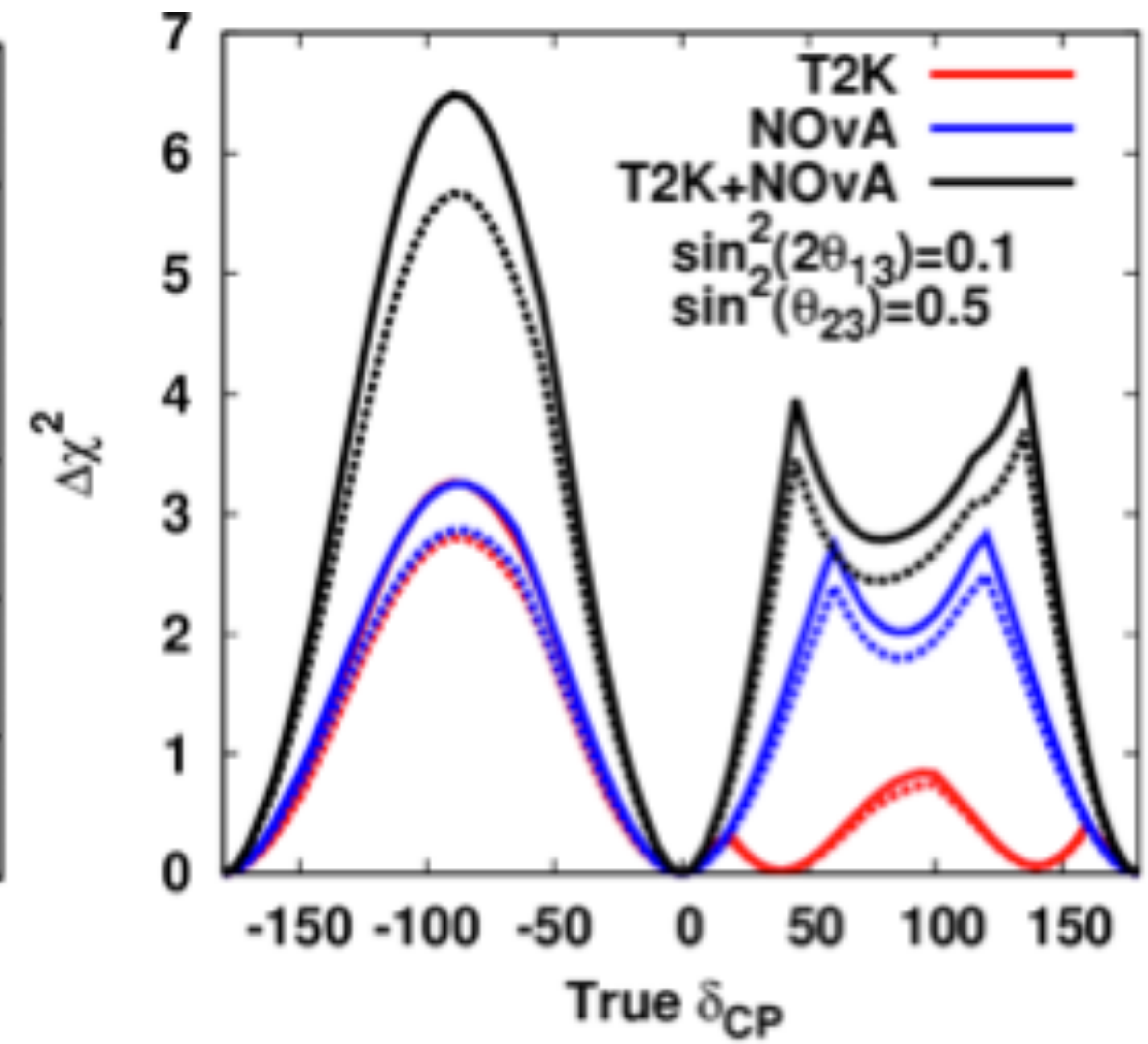
50% POT ν + 50% POT anti-ν for both T2K and NOVA (full statistics)

Solid lines: no syst err - Dashed lines: w/ sys. err.

Normal Hierarchy



90%CL exclusion region w/ sinδ_{CP}=0



Sensitivity to resolve sinδ_{CP}=0

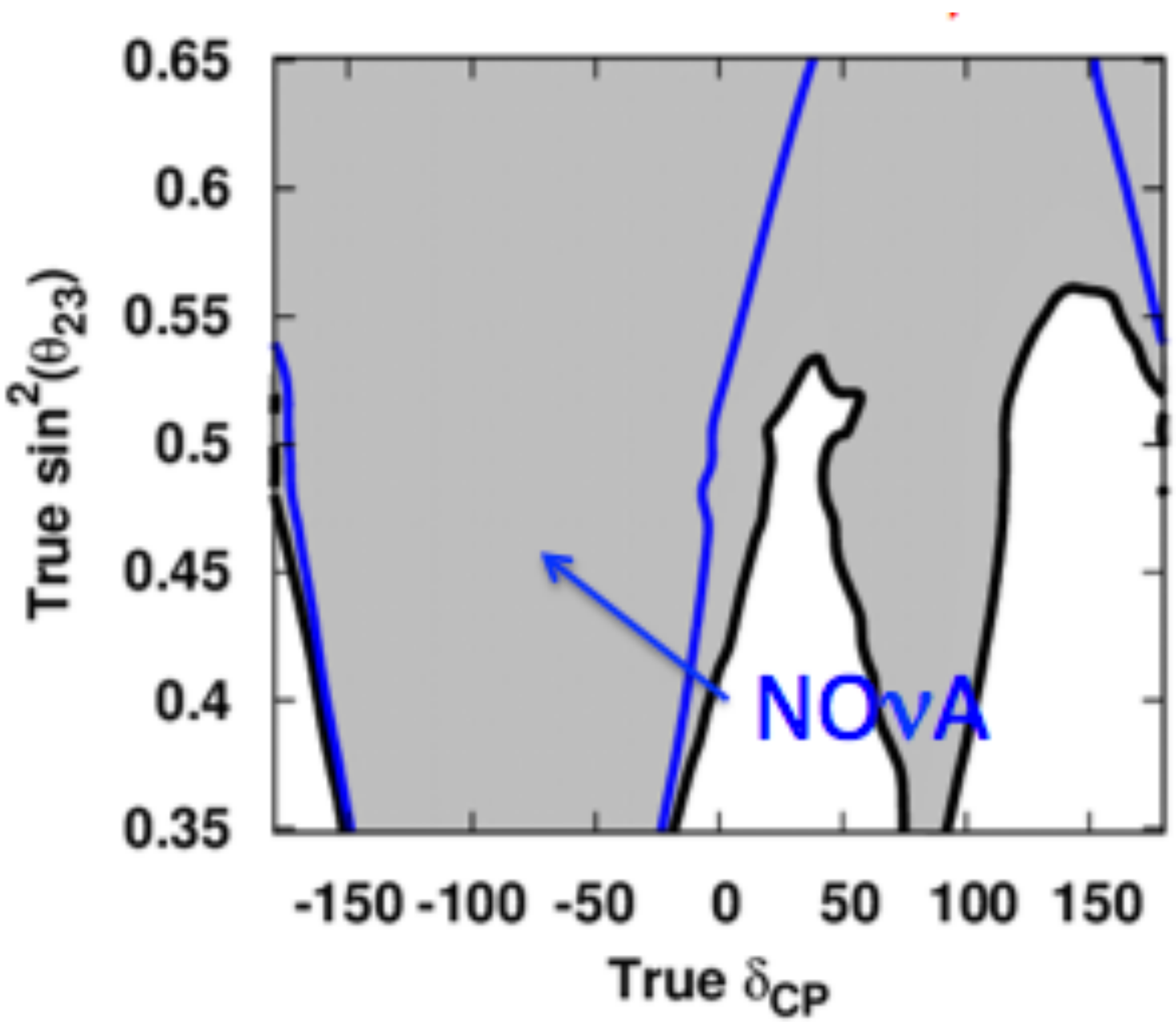
True values: $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5, $|\Delta m^2_{32}|$ = 2.4x10^{-3}eV^2/c^4
reactor constrain: $\delta(\sin^2 2\theta_{13})$ = 0.005
5% (10%) of normalization uncertainty on signal (background)

T2K+NOVA sensitivity to MH

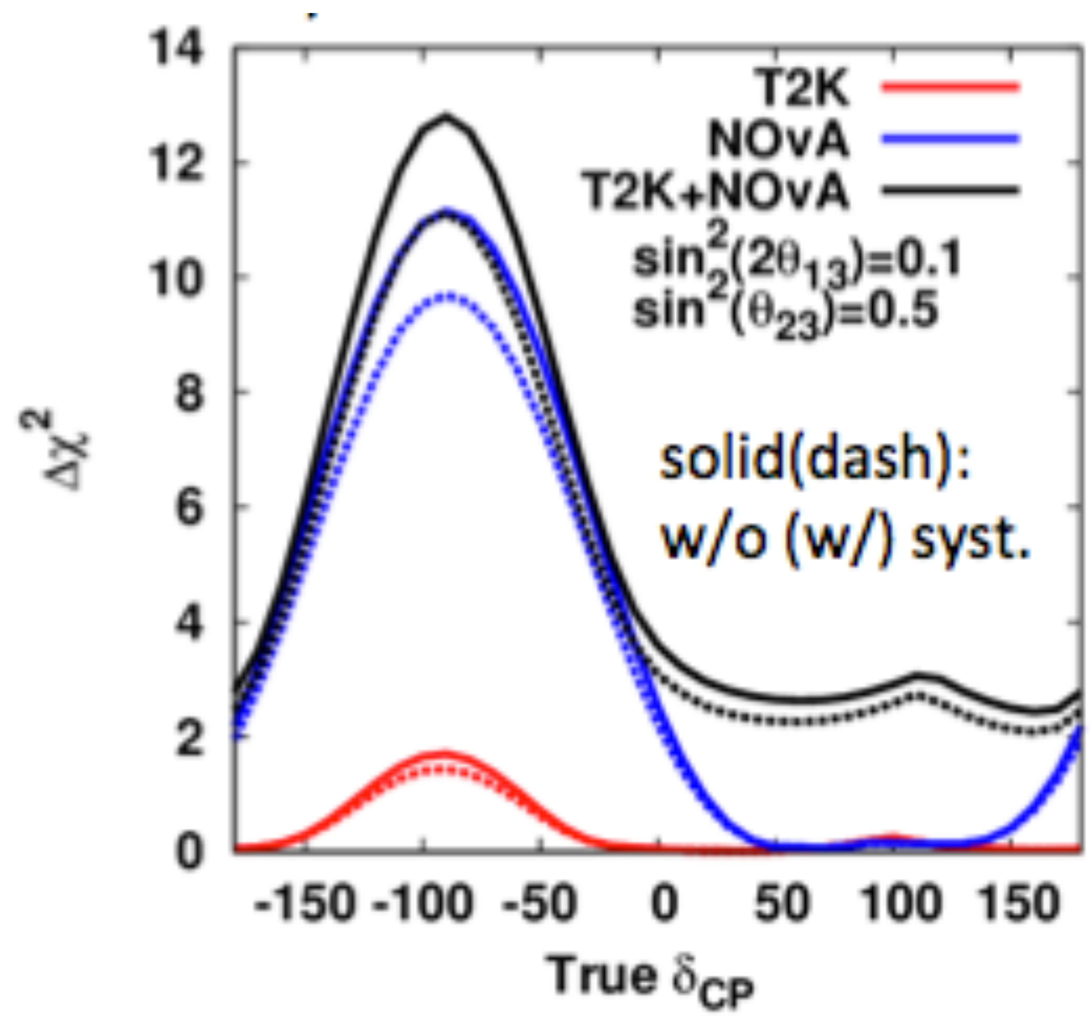
50% POT ν + 50% POT anti-ν for both T2K and NOVA (full statistics)

Normal Hierarchy

Solid lines: no syst err - Dashed lines: w/ sys. err.



90%CL exclusion region for MH



Sensitivity to resolve MH

True values: $\sin^2 2\theta_{13}$=0.1, $\sin^2\theta_{23}$=0.5, $|\Delta m^2_{32}| = 2.4\times10^{-3} eV^2/c^4$
reactor constrain: $\delta(\sin^2 2\theta_{13})$ = 0.005
5% (10%) of normalization uncertainty on signal (background)