Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Neutrino oscillations at T2K

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ETH Institute for
Particle Physics

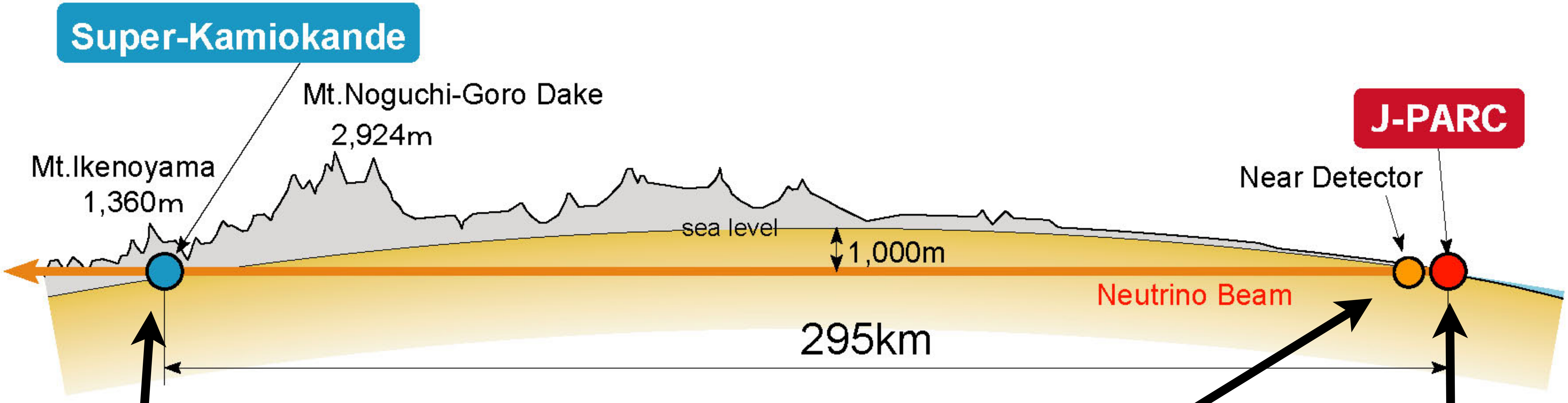
T2K experiment

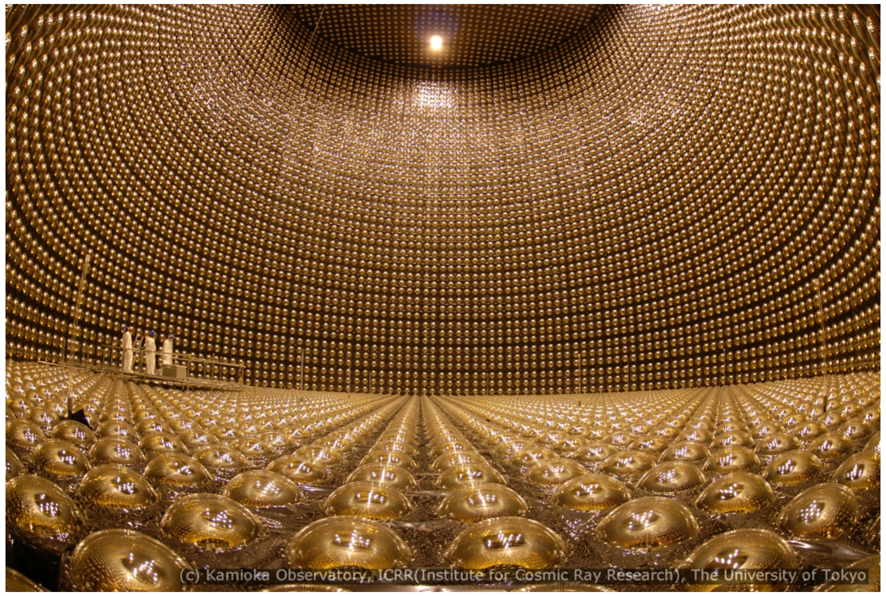
- Neutrino long-baseline experiment (295 km)
- Neutrino flux produced with proton on Carbon target at 30GeV interactions (1/100 ν_e - ν_μ ratio)
- Near Detector (ND280) to measure the neutrino flux and cross sections
- Far detector (Super Kamiokande) measure $\nu_\mu \rightarrow \nu_e$ oscillation
- Recent results:

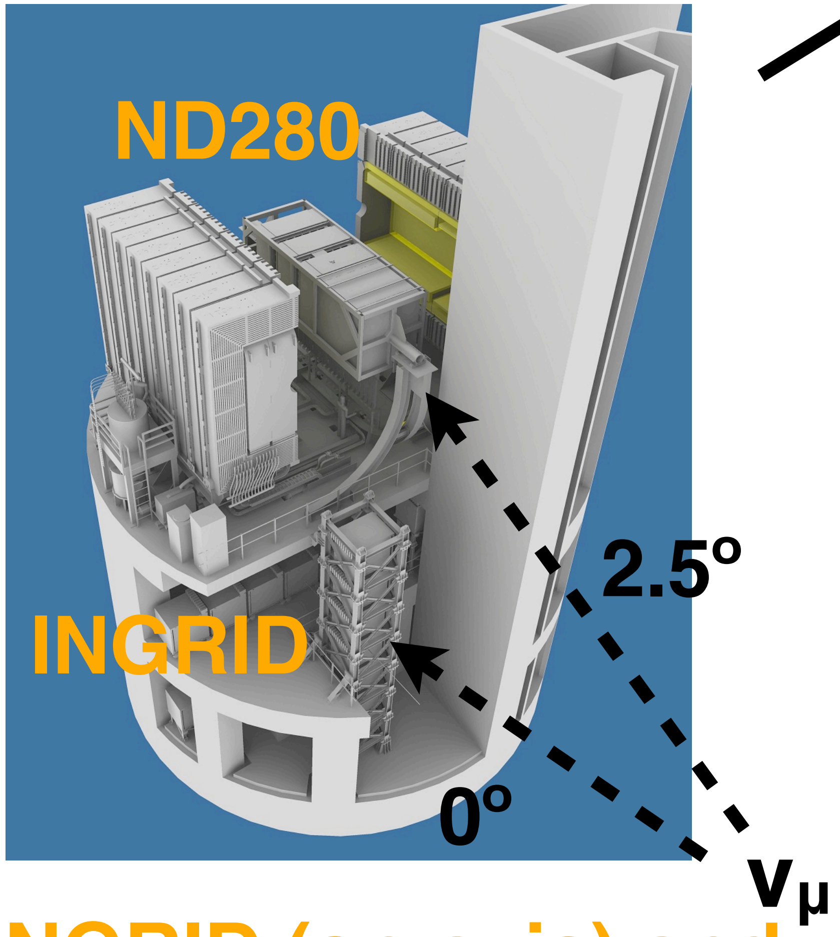
  - Discovery of $\nu_\mu \rightarrow \nu_e$ appearance w/ a significance of 7.5σ to $\theta_{13}>0$

  - First hint of CP violation in the lepton sector

T2K Experiment




(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

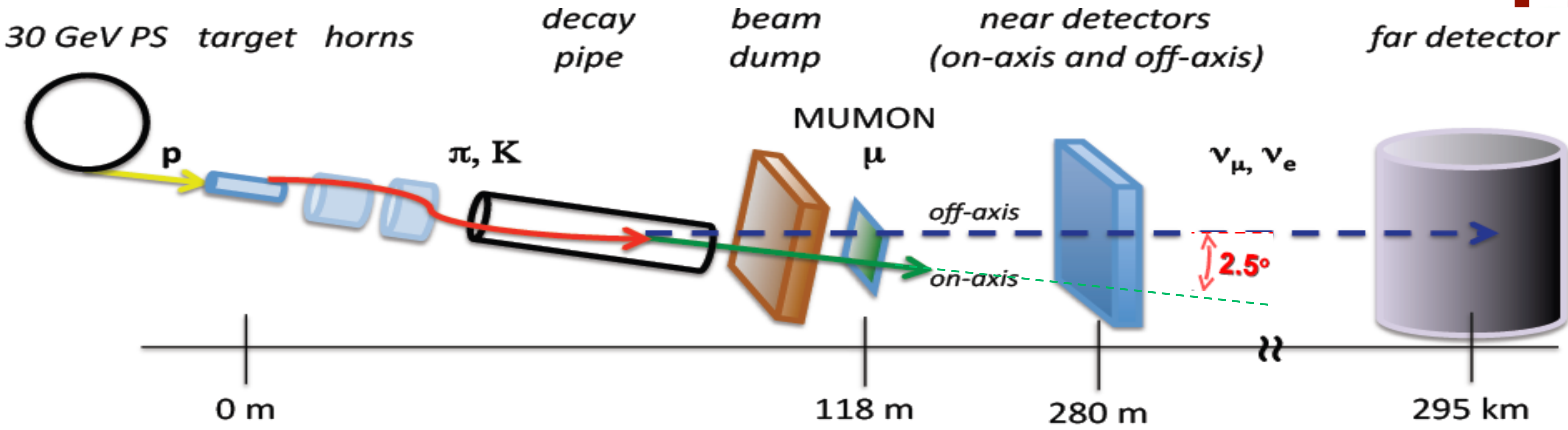


Super-Kamiokande

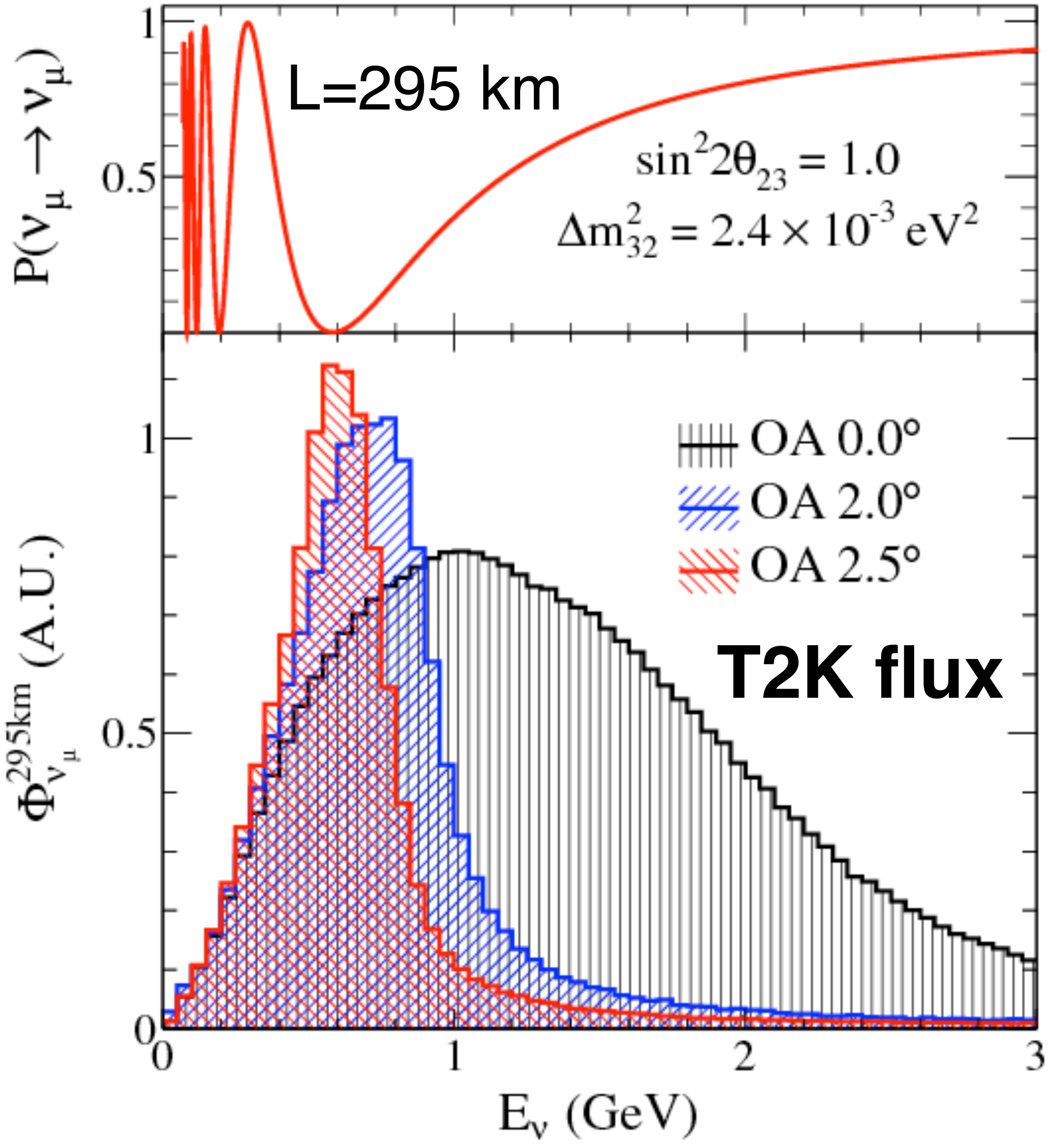
INGRID (on-axis) and ND280 (off-axis)

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)**
- **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

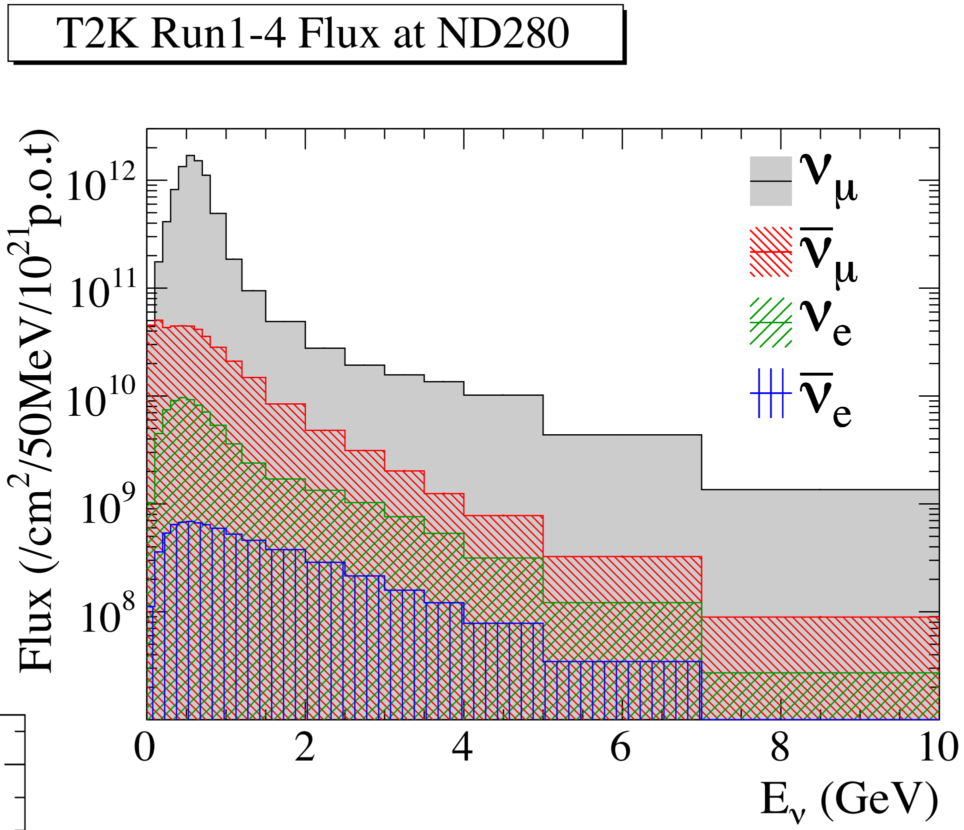


Beam flux prediction

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

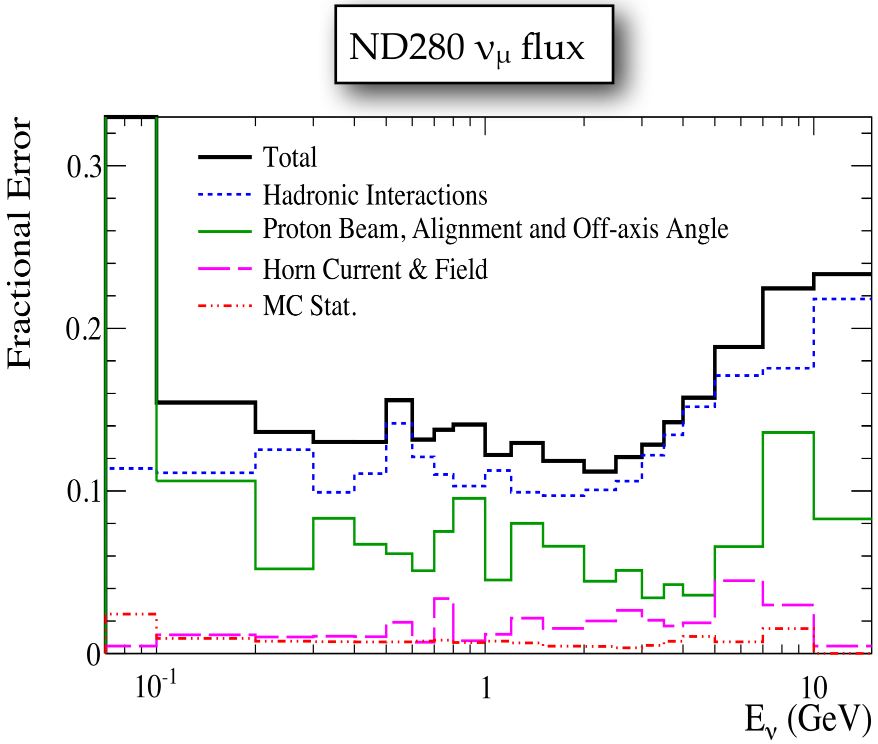
- Fundamental are NA61 hadronic production measurements (pC 30GeV as T2K):
  - Interaction rate (production cross section)
  - **σ_{prod} = 233.5 ± 2.8 (stat) ± 2.4 (det) ± 3.6 (mod) mb**
  - Pion production
  - Kaon production
- External data : NA61/SHINE (CERN) [1][2],

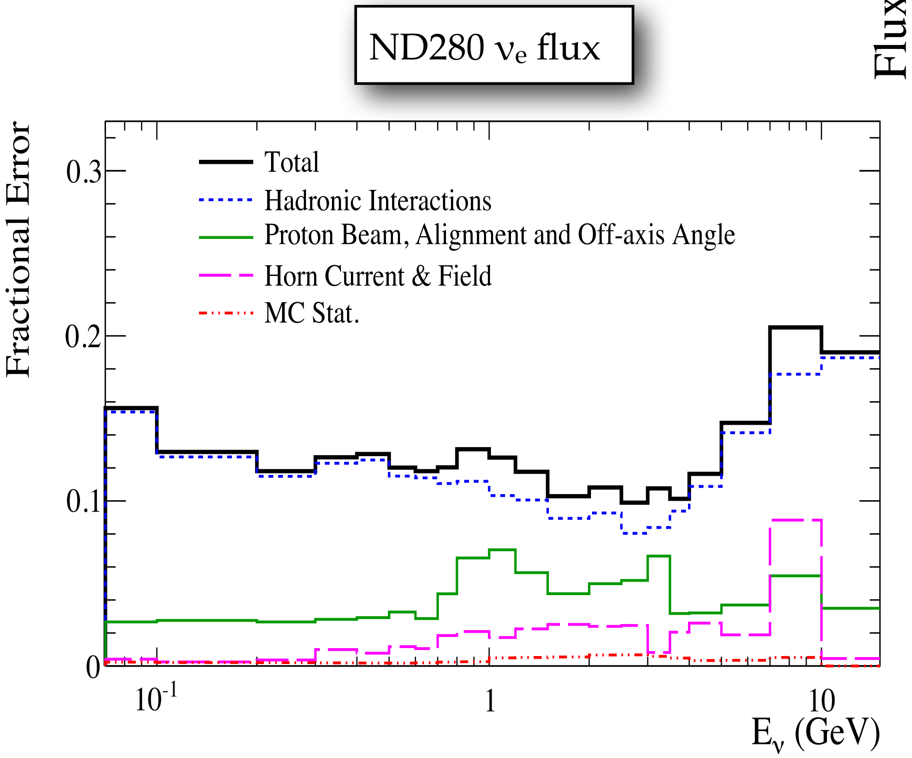
Eitchen et al. [3] , and Allaby et al. [4]



Largest uncertainty comes from hadronic interactions

NA61 new results will be released soon!!!



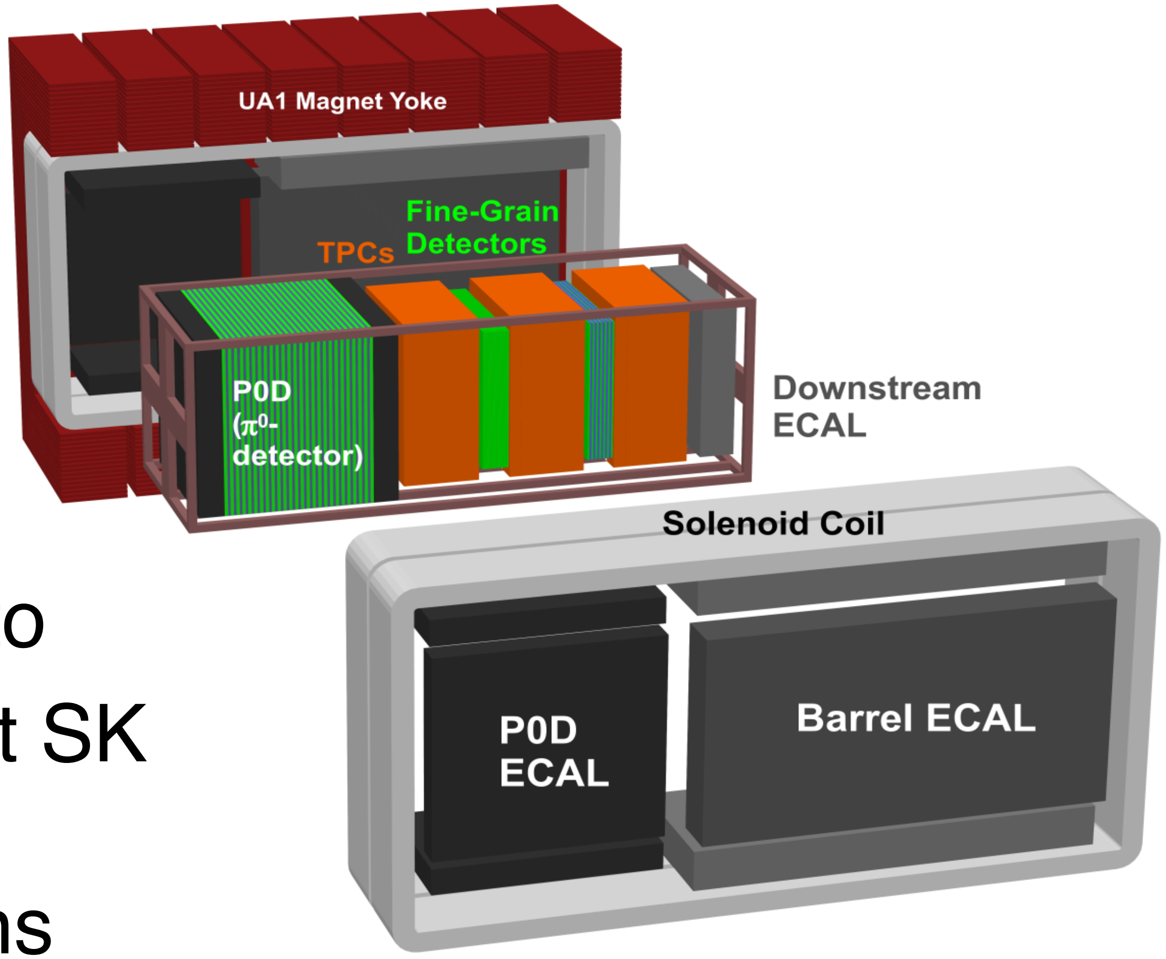


[1] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[2] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[3] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

ND280 detector

- Magnetized near off-axis detector 280 m far from the neutrino production target

- Neutrino interactions are selected in the Fine Grain Detectors, targets of both active polystyrene (CH) scintillator and passive water



- Muons and electrons are selected using the combination of the TPC and Electromagnetic CALorimeter PID

- ν_μ and ν_e fluxes are measured in order to constrain the systematic uncertainties at SK

- Measurements of neutrino cross sections are performed

3+1 neutrinos framework

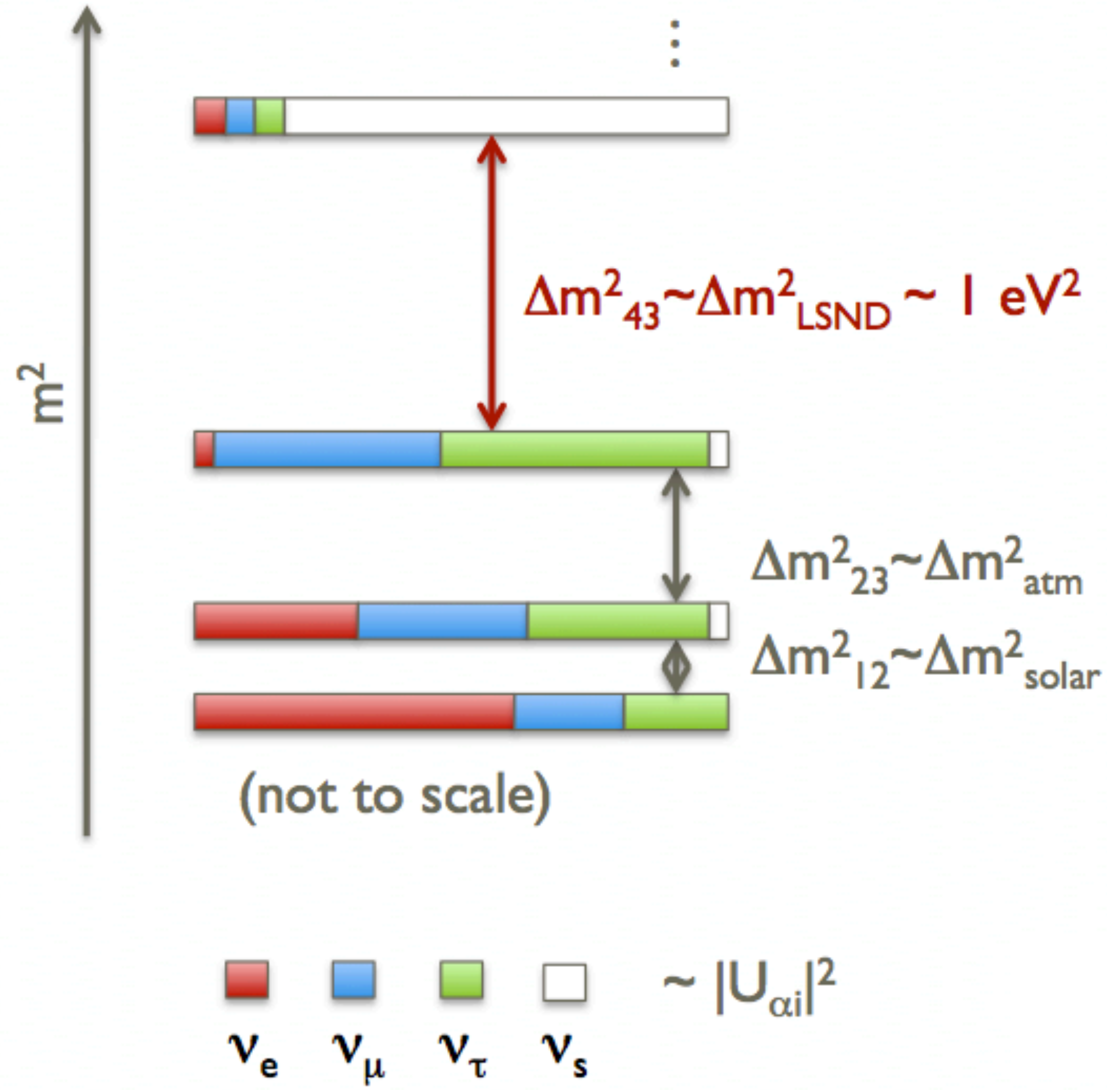
The 3+1 model is an extension of the standard three neutrino mixing

Add a right-handed neutrino (sterile) to the 3 standard flavors

Sterile neutrinos don't interact through standard interactions

Active neutrinos (ν_e ν_μ ν_τ) can oscillate into sterile neutrinos (ν_s)

$m_4 >> m_{1,2,3}$



No CP violation in 3+1 model

$$\nu_\alpha = \sum_{k=1}^{4} U_{\alpha k} \nu_k$$

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E} \right)$$

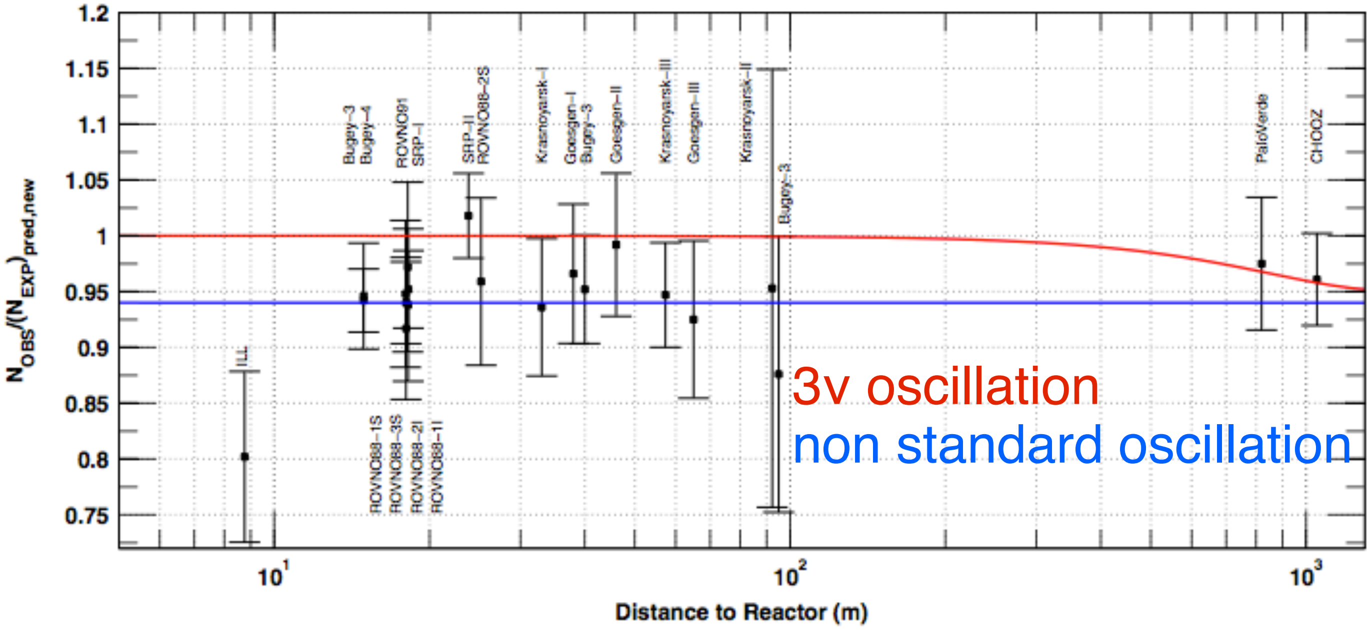
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E} \right)$$

Why sterile neutrinos?

- Hints of additional non standard neutrinos
- Sterile neutrinos cannot be directly detected
- They can be seen only indirectly through appearance or disappearance of standard neutrinos

Reactor anomaly

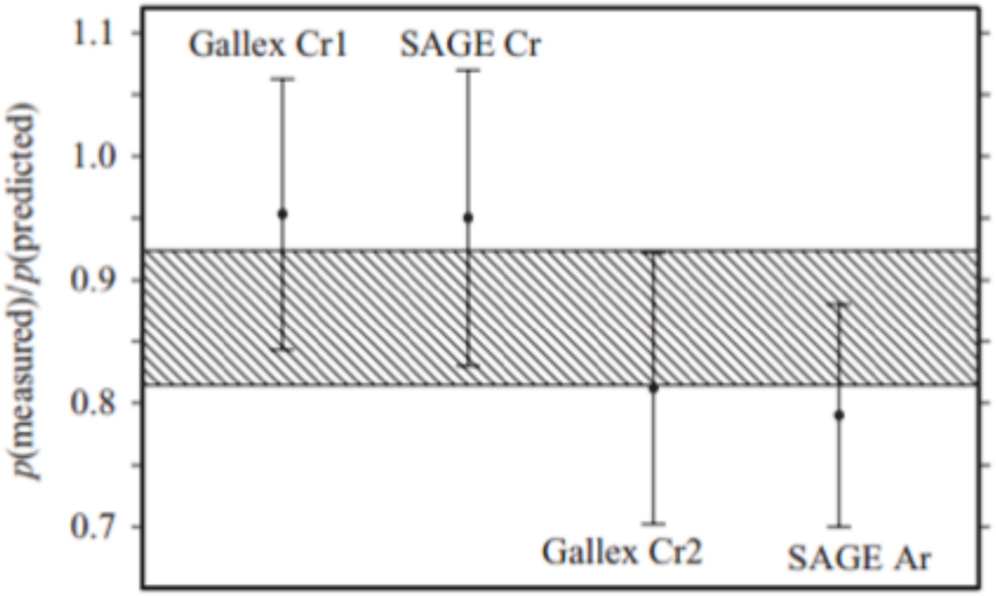
✓ New theoretical calculations of reactor anti-ν_e fluxes consistent w/ a 3σ deficit



Phys.Rev. D83, 073006 (2011)

Gallium anomaly (GALLEX, SAGE experiments)

✓ Deficit of measured anti-ν_e interaction is 2.7σ



Phys. Lett. B685, 47 (2010)

It can be explained adding a sterile neutrino of largest mass $\Delta m^2_{14} \sim O(1eV^2)$

Short base-line is needed

ν_e disappearance at ND280

Search for a deficit of ν_e at the near detector

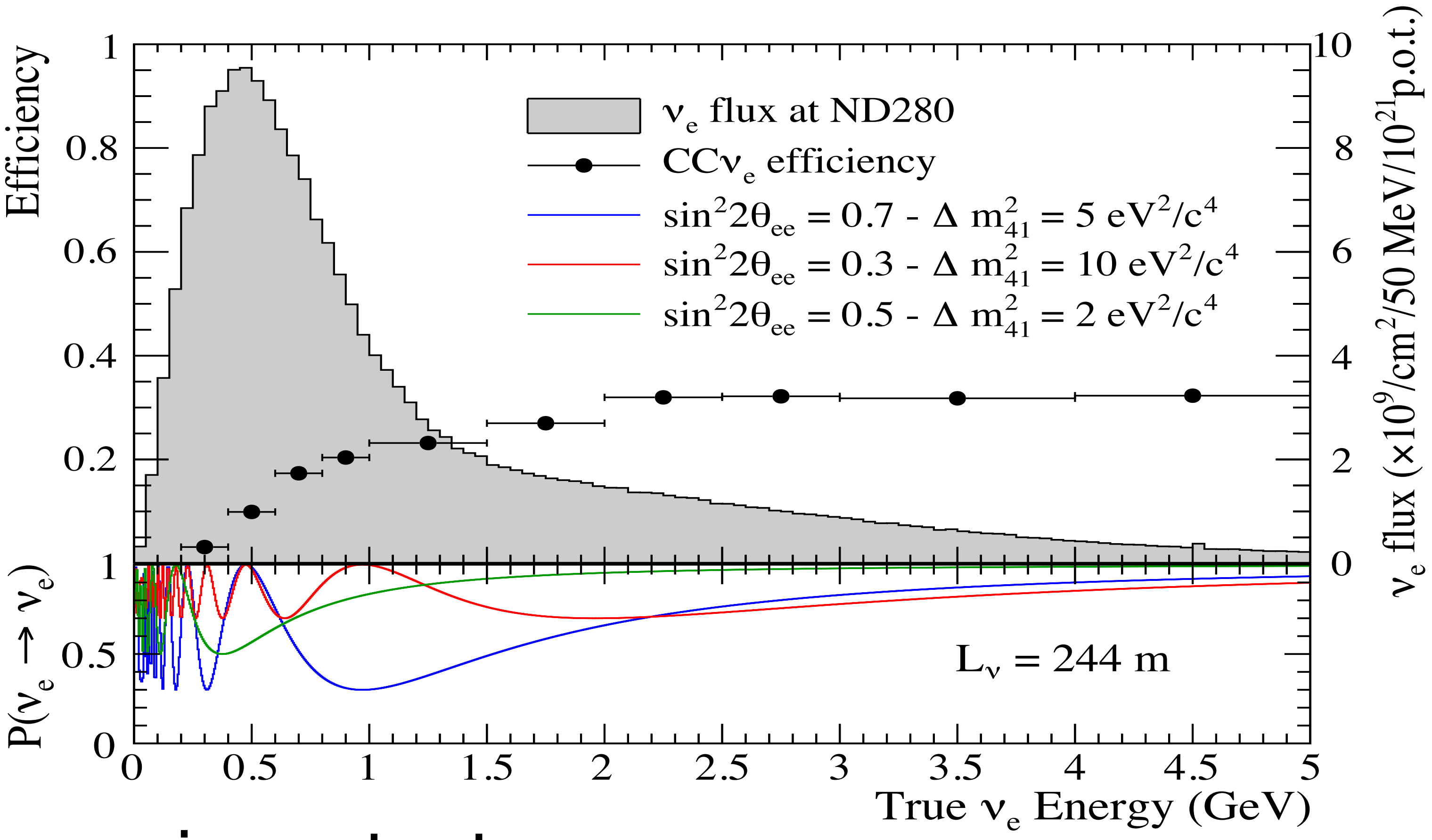
The following assumptions are done:

$$P_{surv} = 1 - sin^2 2\theta_{ee} \cdot sin^2\left(\frac{1.267\Delta m^2_{14} L_\nu}{E}\right)$$

- No experimental evidences for ν_μ disappearance
- Neglect ν_μ disappearance and ν_e appearance ($U_{\mu 4} = 0$)

- $\sin^2 2\theta_{ee}$ - Δm^2_{14} oscillation parameters for $\nu_e \rightarrow \nu_s$
- L → neutrino flight path
- E → neutrino true energy

Δm^2_{14} around >1eV^2



Knowledge of the beam flux is very important

99% are ν_μ → very good ν_e selection is needed to get a clean sample

Event selection

ν_e sample

- ✓ Tracks starting in FGD
- ✓ Electron-like PID (dE/dx TPC + EM shower ECal)
- ✓ Reject $\pi^0 \rightarrow \gamma \rightarrow e^+e^-$ (two close tracks + invariant mass < 50 MeV)
- ✓ Muon rejection factor ~99.8%
- ✓ Purity ~ 63%
- ✓ Constrain the $\pi^0 \rightarrow \gamma\ \gamma$ w/ the control sample

Obs. # of evts = 614
Exp. # of evts = 665 ± 51 (syst)

$\pi^0 \rightarrow \gamma$ control sample

- ✓ Main background from low energy photon conversions:

  $\nu_\mu N \rightarrow \pi^0 \rightarrow \gamma\ \gamma \rightarrow e^+e^-$
- ✓ Can constrain it from the data by developing a selection of a photon conversion sample
- ✓ Look for e^+e^- pair in the TPC and reconstruct the invariant mass
- ✓ Purity ~ 92%
- ✓ Not sensitive to ν_e oscillations

Obs. # of evts = 989
Exp. # of evts = 1236 ± 246 (syst)

Beam ν_e measurement: PRD 89, 092003 (2014)

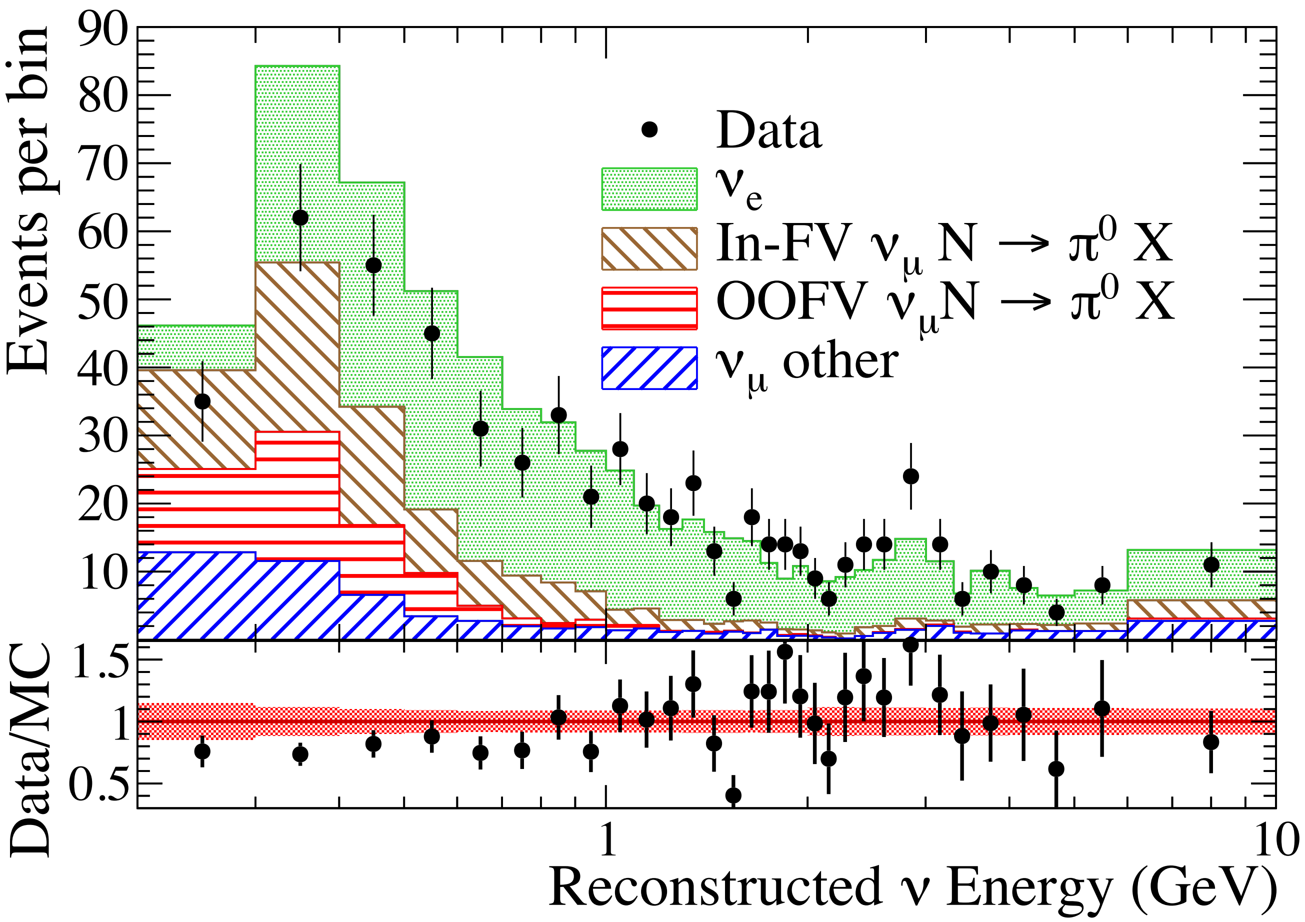
Run1-4: 5.9×10^{20} p.o.t.

Selected distributions

- ✓ Constrain systematic uncertainties fitting the ν_μ selected sample at ND280 (null oscillations hypothesis)
- ✓ Flux, XSec, Detector systematic uncertainties (55 parameters)
- ✓ Events outside the fiducial volume have large uncertainty (30%) due to interactions in heavy nuclei, not well known

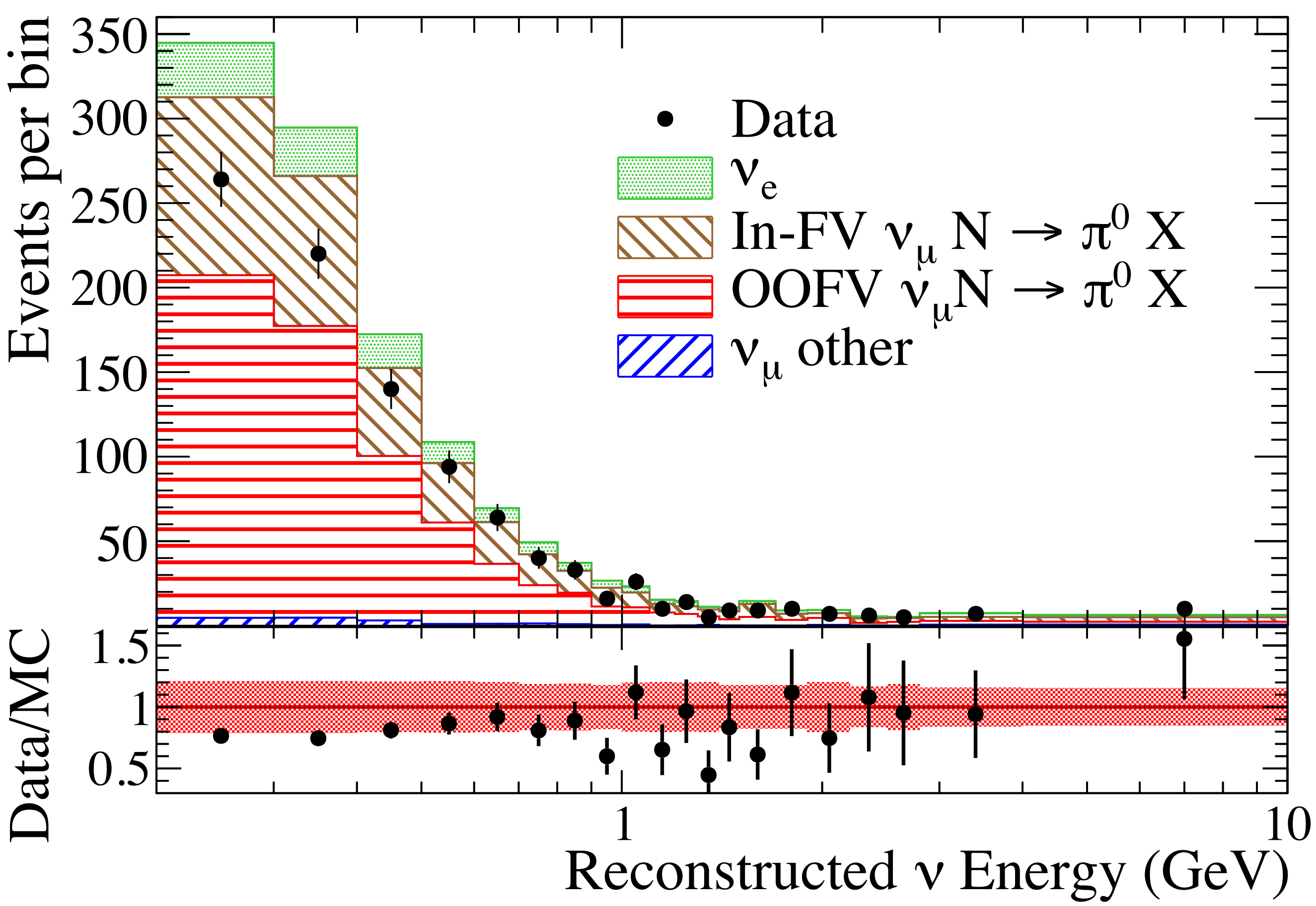
Energy reconstructed in the CCQE hypothesis

ν_e sample



Syst variation on exp # of evts = 7.6%

$\pi^0 \rightarrow \gamma$ control sample



Syst variation on exp # of evts = 19.9%

Oscillation fit

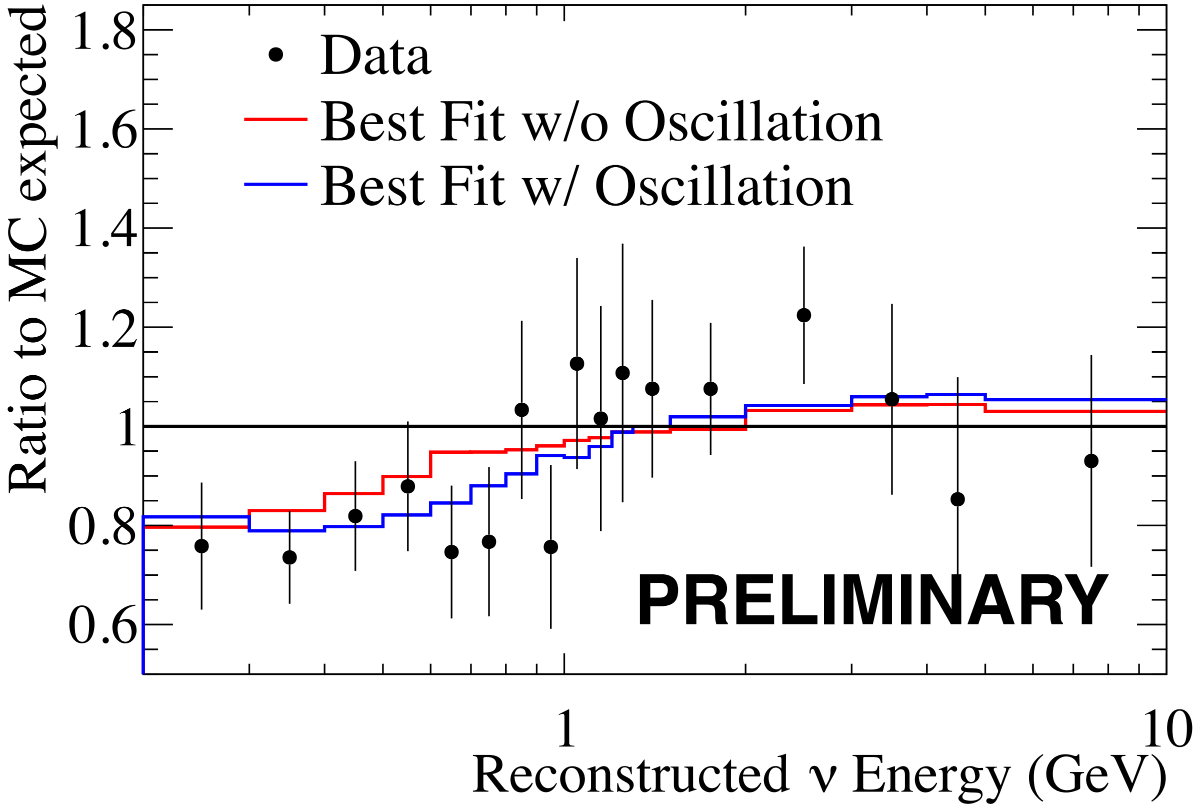
- ✓ $\sin^2 2\theta_{ee}$ and Δm^2_{41} estimated minimizing a Poisson likelihood ratio
- ✓ 55 nuisance parameters take into account the systematic uncertainties
- ✓ Constrained by a gaussian penalty term and profiled
- ✓ Calibration “in situ” of the $\pi^0 \rightarrow \gamma\,\gamma$ simultaneously fitting the ν_e and the control sample

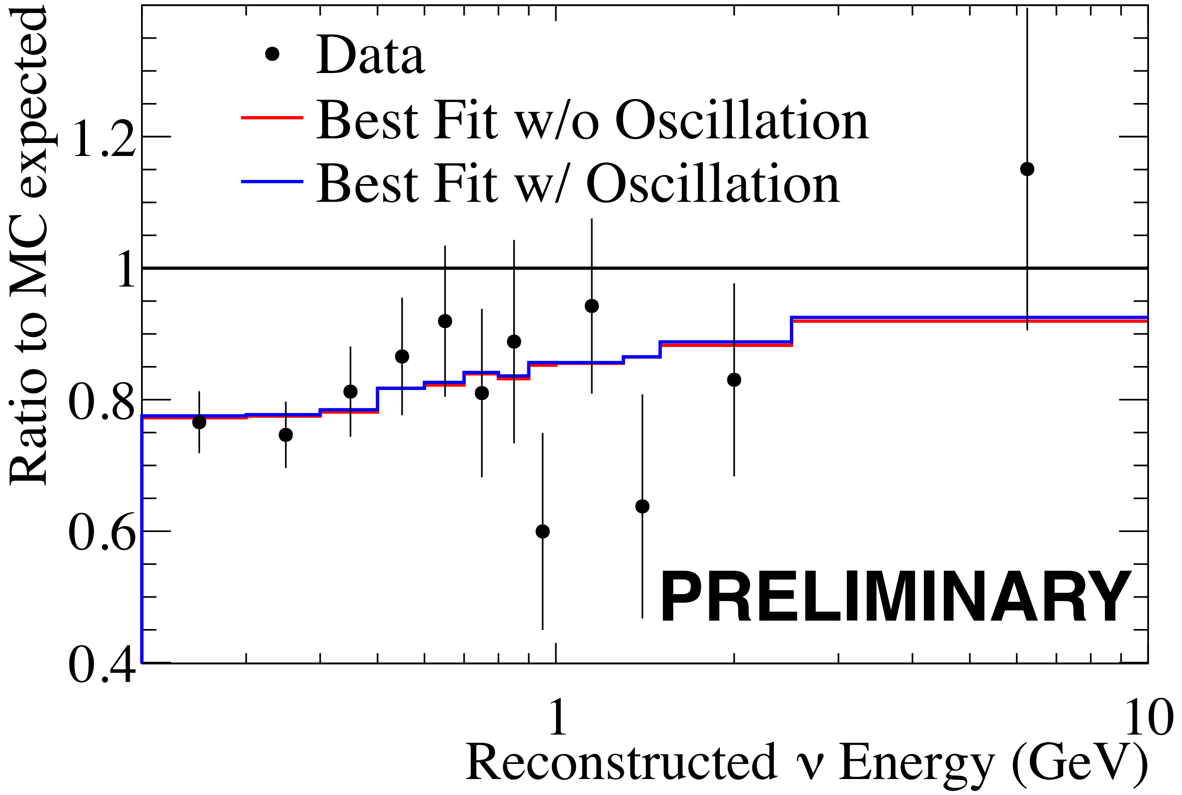
χ^2 / ndf = 45.86 / 51

Best-fit values:

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

$\Delta m^2_{41} = 2.05\ \mathrm{eV}^2/c^4$

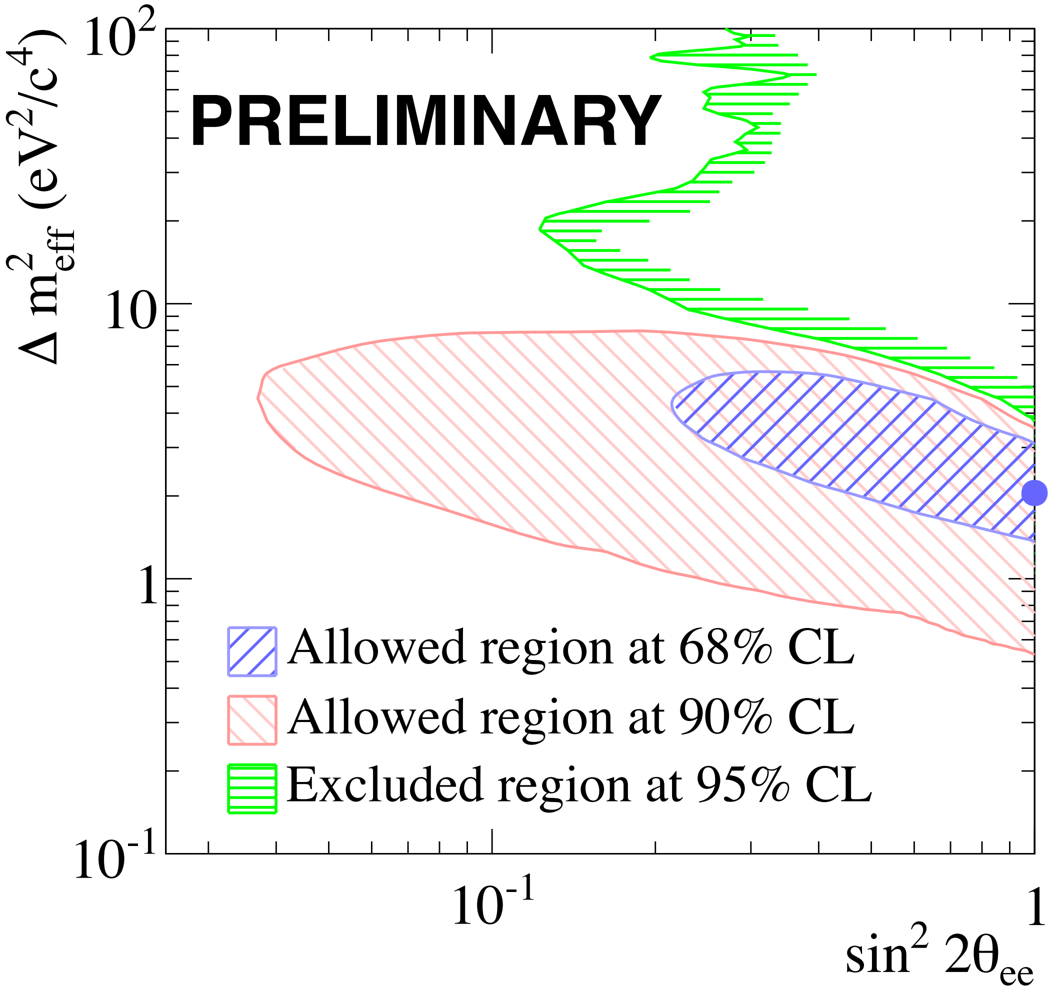




Systematic Uncertainties

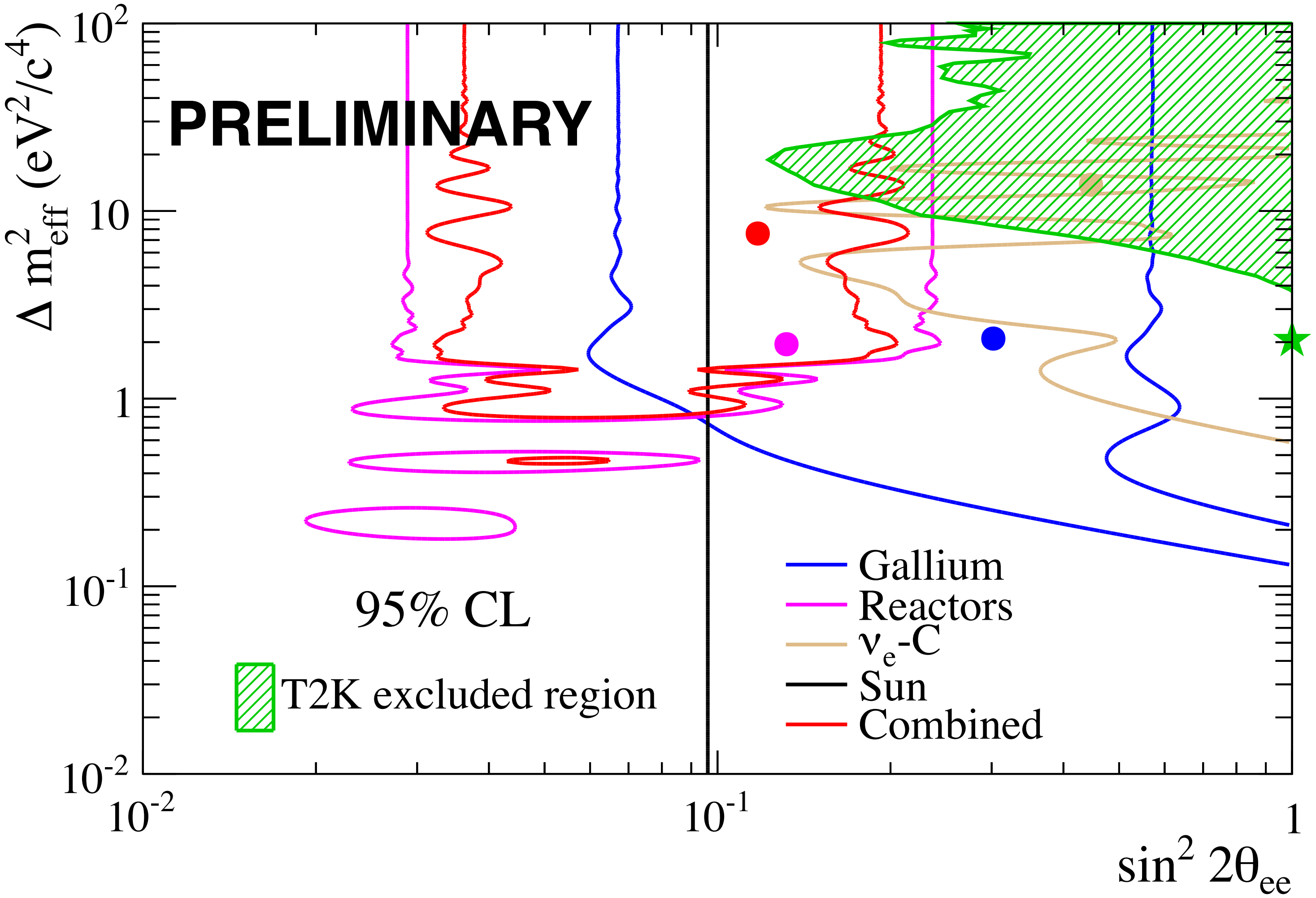
- ✓ Confidence intervals computed w/ Feldman-Cousins method

Observed p-value wrt null oscillation hypothesis is 8.4%



95% CL excluded intervals

$\sin^2 2\theta_{ee} > 0.3$ && $\Delta m^2_{41} > 8$ 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

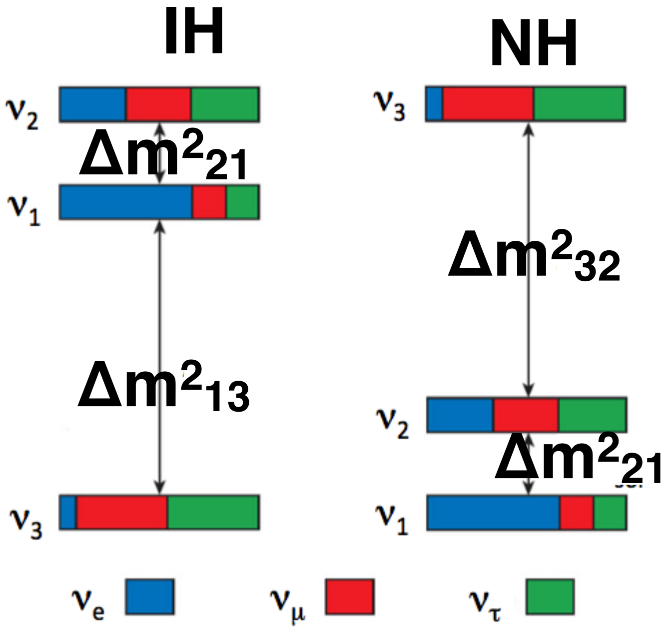
Current Status

- ✓ First sterile search at the near detector in the 3+1 model
- ✓ Analysis of $\nu_e \rightarrow \nu_s$ oscillations due to sterile neutrinos has been finalized (no ν_μ disappearance is considered)
- ✓ $\sin^2 2\theta_{ee} > 0.2$ && $\Delta m^2_{41} > 8$ eV^2/c^4 excluded at 95%CL (*Preliminary)*
- ✓ Quite large region of Gallium anomaly as well as a small part of the reactor anomaly are rejected at 95% CL
- ✓ Analysis is approved and result presented at the summer conferences (“Rencontres de Blois 2014”, “Neutrino 2014”)
- ✓ Writing the paper
- ✓ Next step is to include the numu sample in the analysis and perform a joint fit in a more complete 3+1 framework
- ✓ Extract $\sin^2 2\theta_{ee}$, $\sin^2 2\theta_{\mu\mu}$ and Δm^2_{41} fitting both ν_μ and ν_e oscillation simultaneously

Standard oscillations 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)?



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

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

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

Leading term

Can solve the octant

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

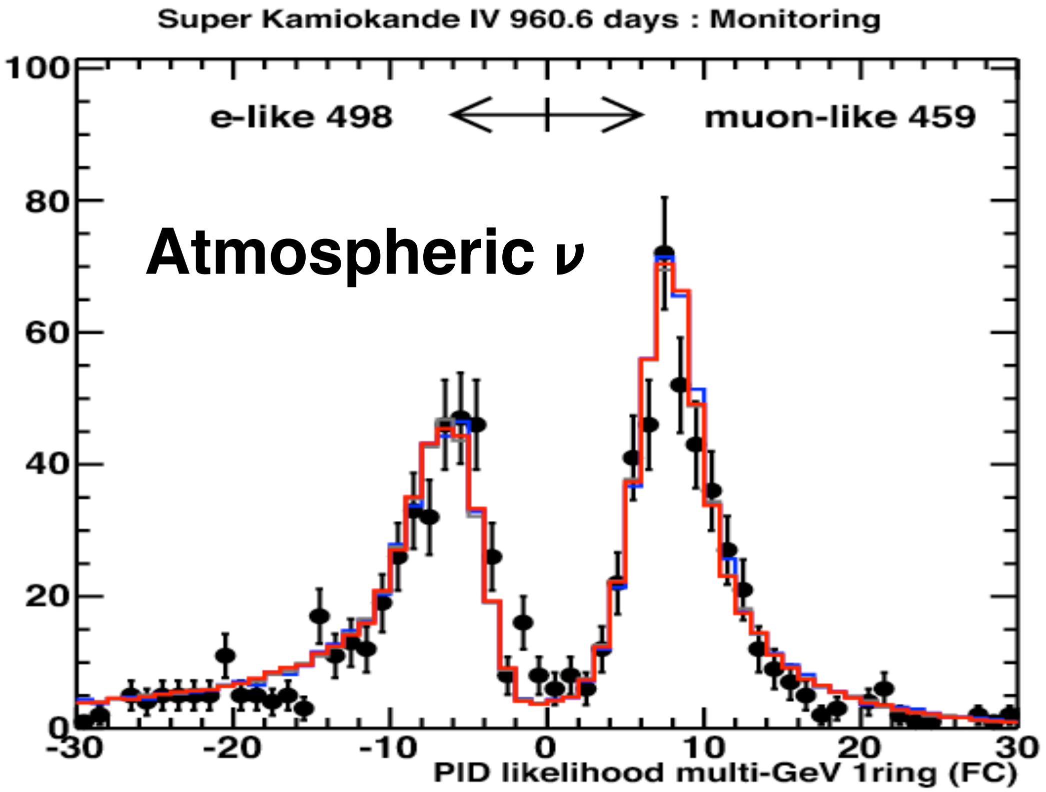
δ_{CP} can be measured since $\sin^2 2\theta_{13} > 0$

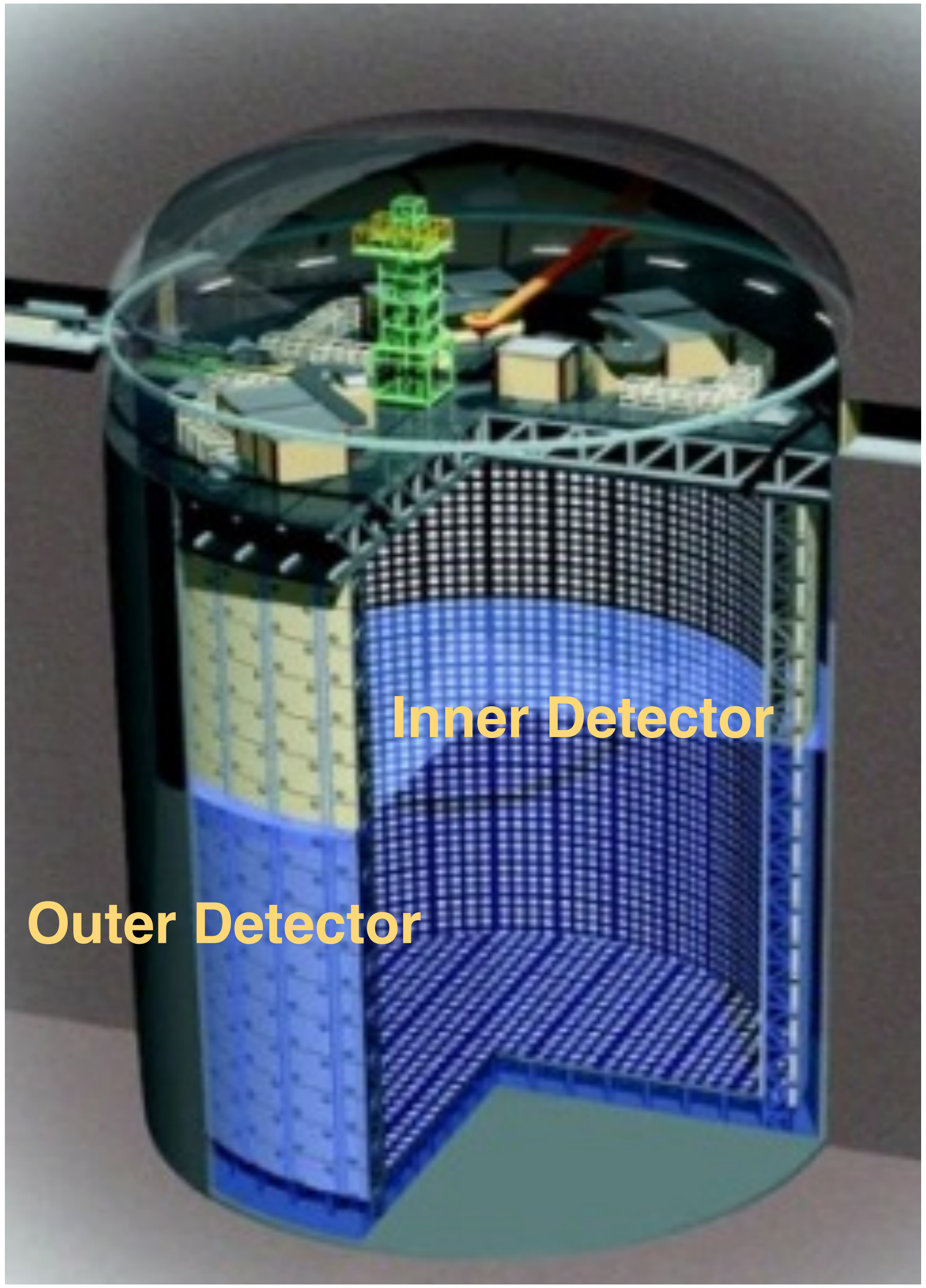
$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

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

T2K far detector: Super-Kamiokande

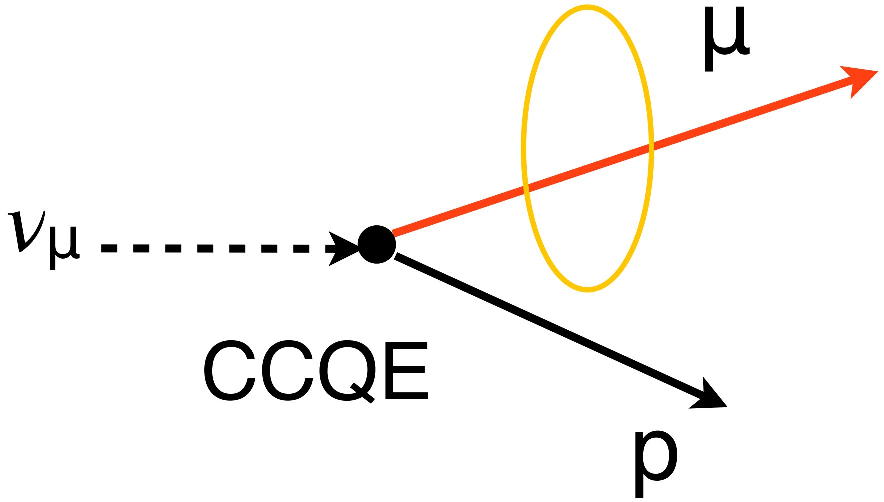
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector (~11k PMTs)
- Outer detector (2k PMTs) determine fully contained events
- Very good e/μ separation
- Muons misidentified as electron <1%



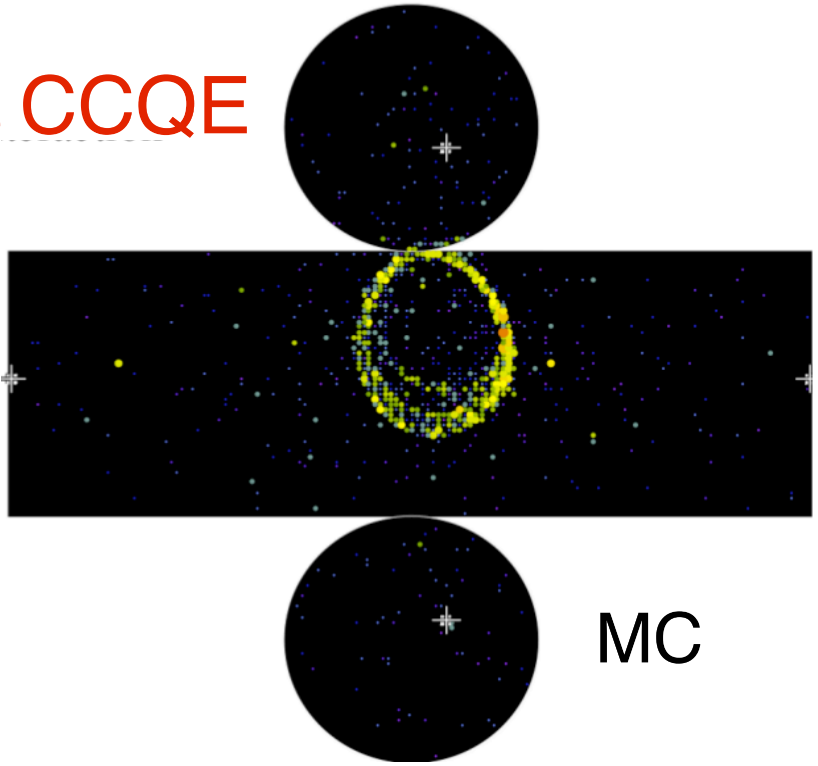


T2K events

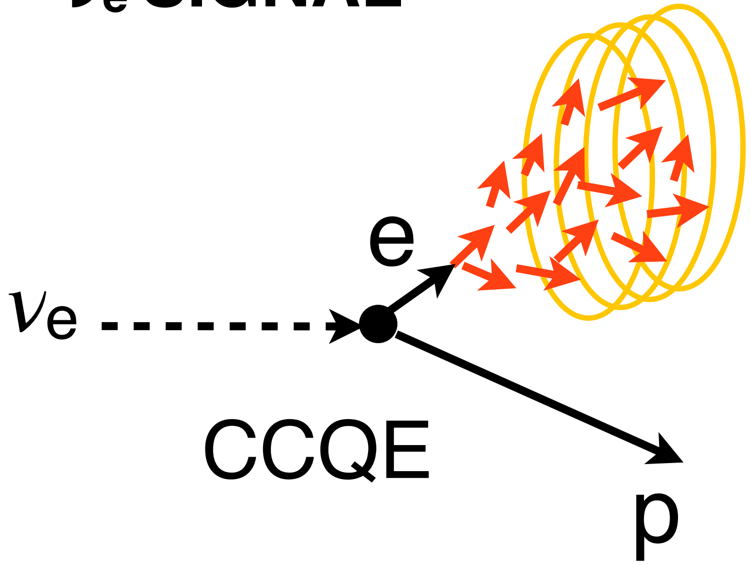
ν_μ SIGNAL



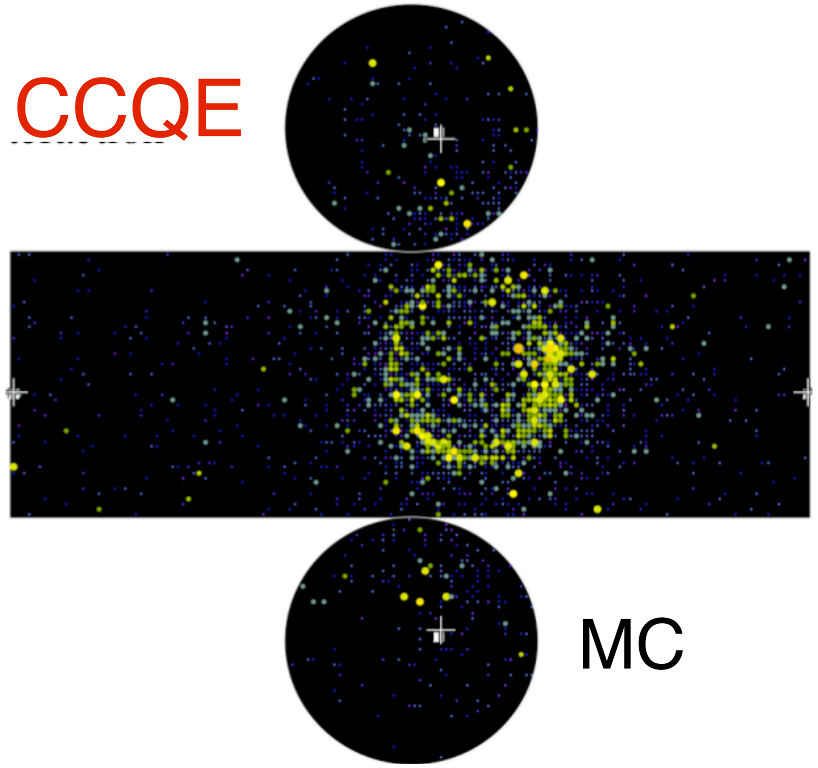
- Low scattering
- Ring with sharp edge



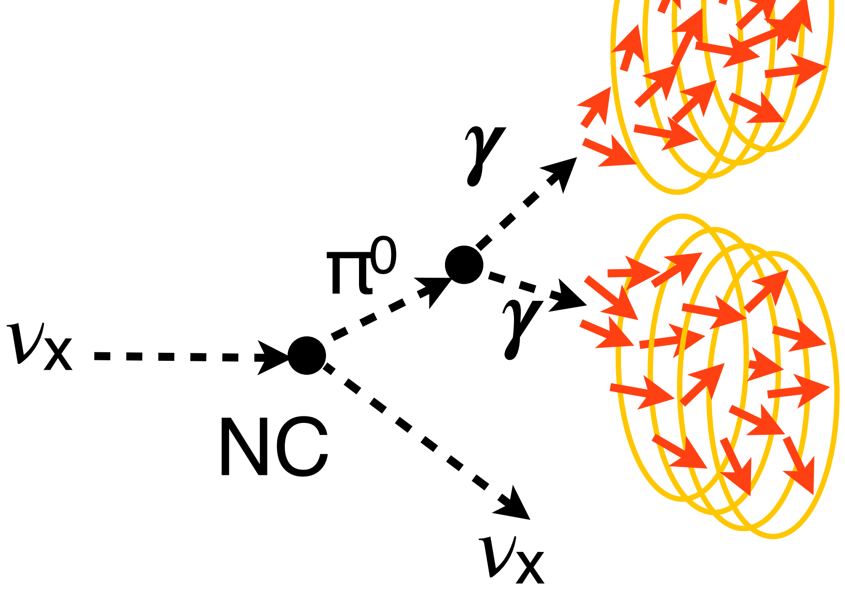
ν_e SIGNAL



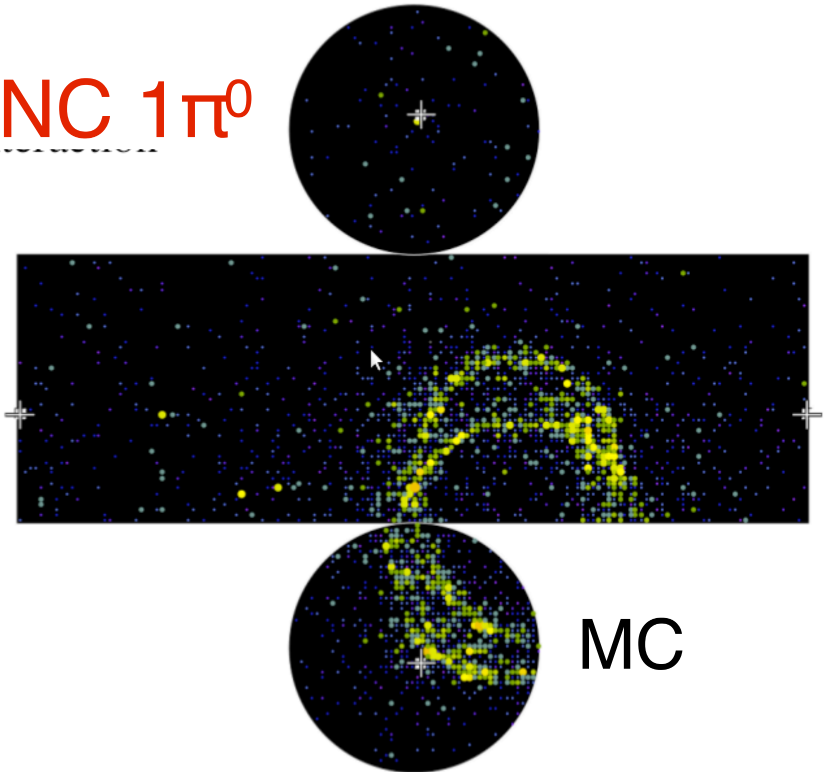
- Multiple scattering
- EM shower
- Ring with “fuzzy” edge



ν_e BACKGROUND



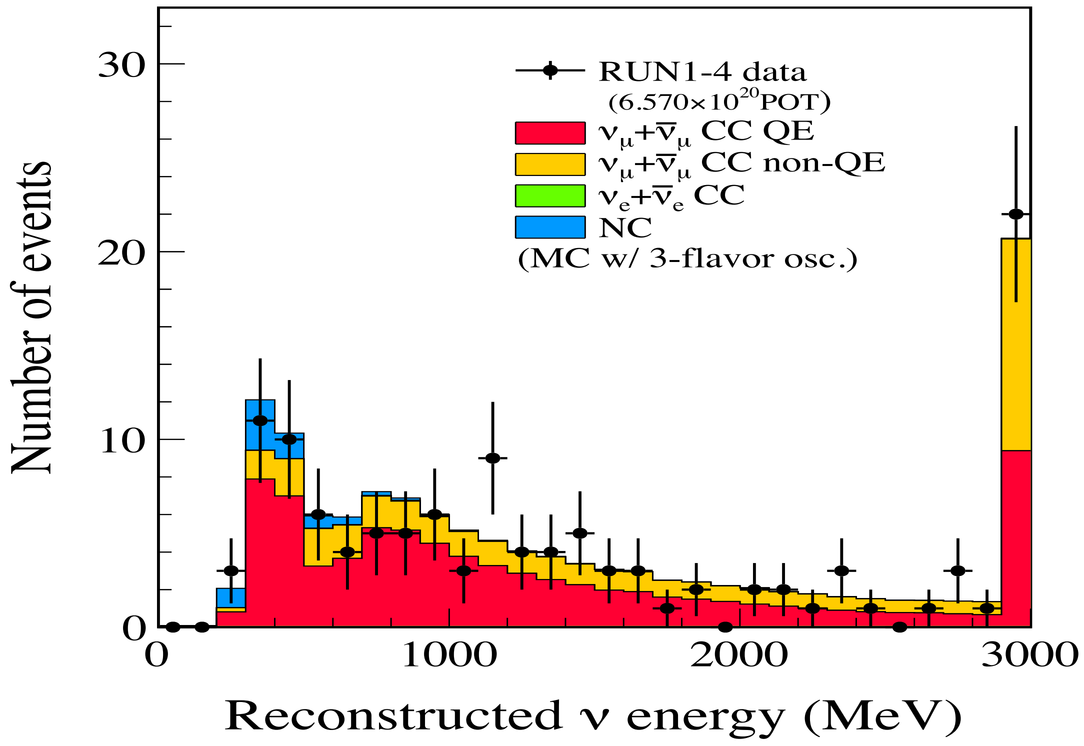
- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron
- Intrinsic ν_e component <1%



T2K selected samples

ν_μ event selection

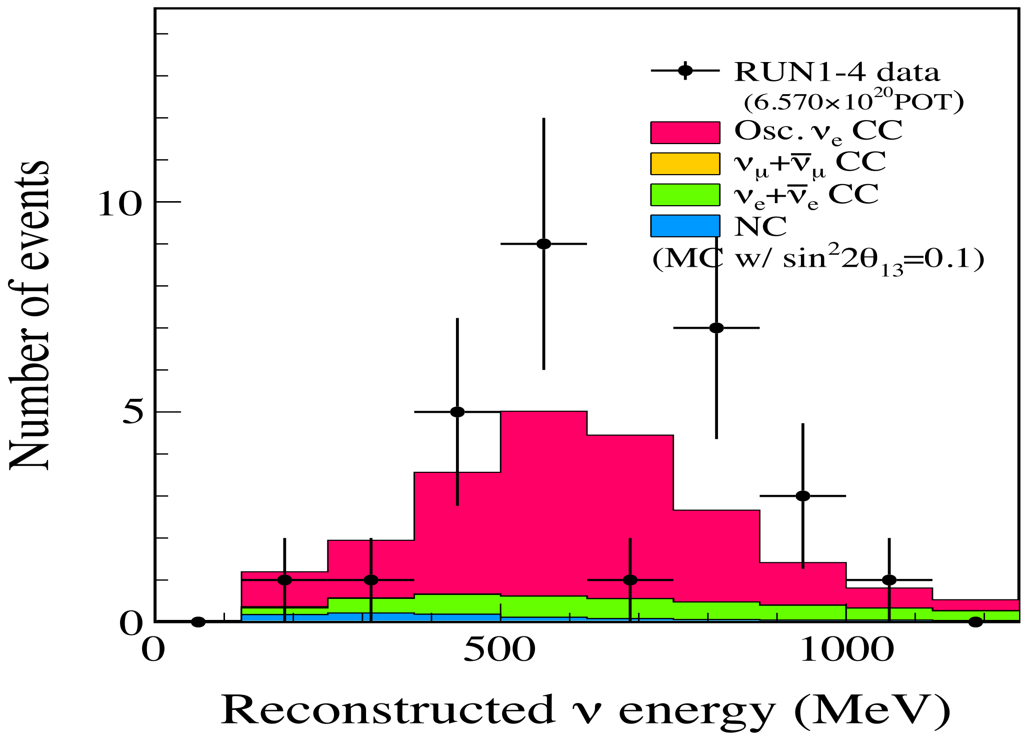
- Fully contained fiducial volume
- Single ring μ-like event
- $E_{visible} > 200$ MeV
- # decay electron ≤ 1



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

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



Look to ν_e appearance and measure θ_{13}

Fit both samples simultaneously to search for CP violation

Current status

✓ Started to work on the ν_μ - ν_e joint analysis to study δ_{CP}

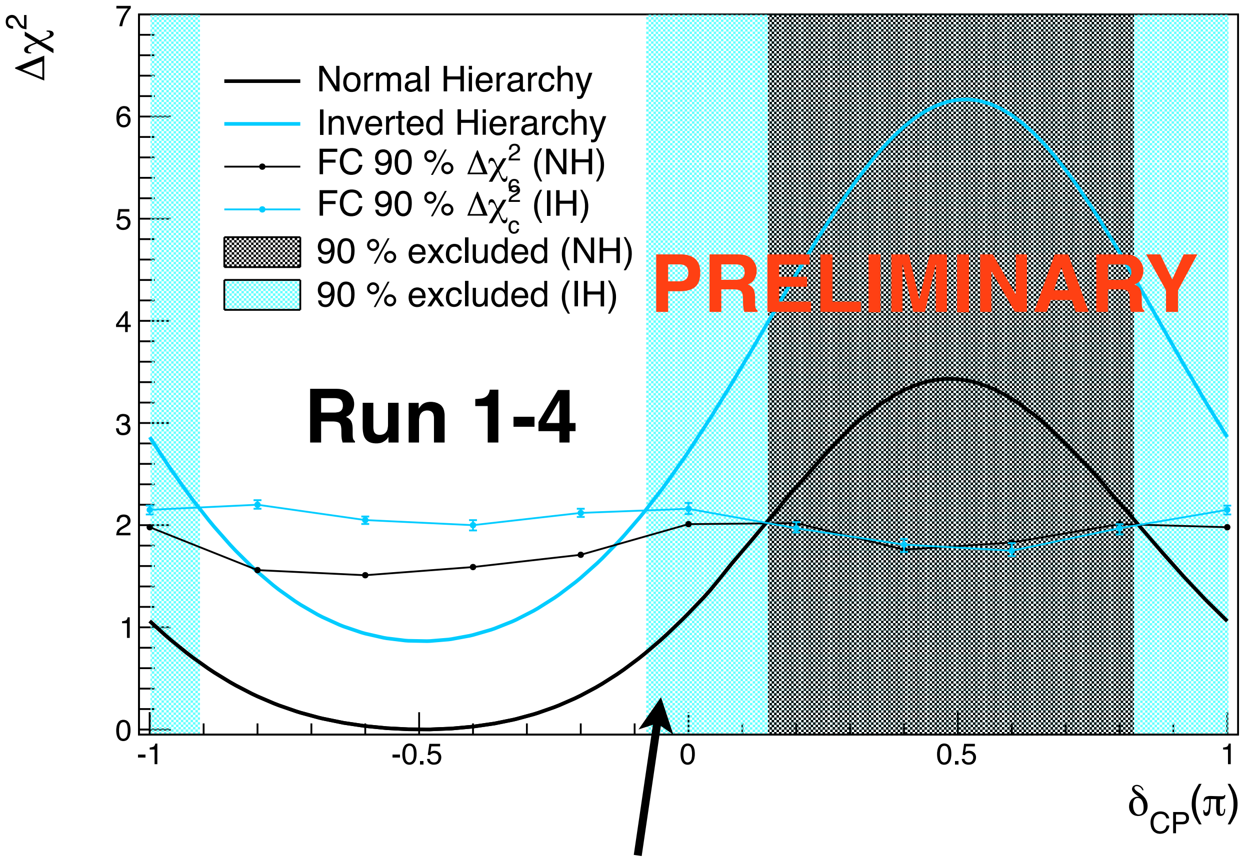
✓ Study of control samples to constrain the systematics or simply add events affected by standard oscillations. Work in progress

✓ Have new results on δ_{CP} based on the Run 1-5 data set (first time w/ anti-ν at T2K)

✓ Sensitivity studies w/ the anti-ν run are ongoing as well

✓ Anti-ν data are very important to solve the degeneracy in δ_{CP}

✓ New anti-ν run in autumn



Improve the neutrino run 1-4 measurement

Conclusions

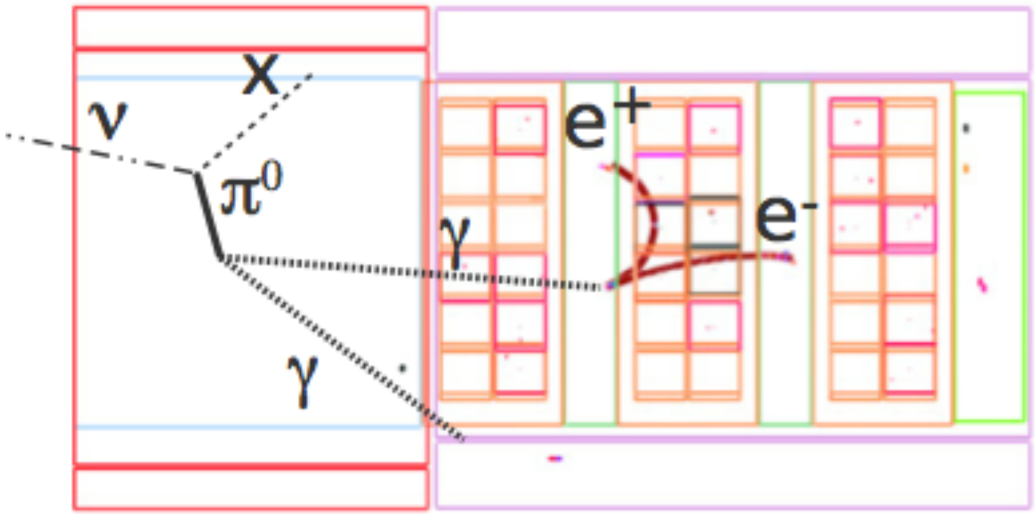
- ✓ Performed the production cross section measurement at NA61/SHINE experiment, need to constrain the flux at T2K
- ✓ Search of ν_e disappearance due to sterile neutrinos at the near detector has been finalized w/o numu oscillations
- ✓ Writing the paper
- ✓ Update the analysis introducing numu oscillations in a more complex joint fit
- ✓ Moved to standard oscillation analysis at the far detector
- ✓ Measurement of δ_{CP} and look for hints of CP violation in the leptonic sector
- ✓ Study of possible control samples
- ✓ The measurement will include the first anti-ν run at T2K, fundamental to solve the degeneracy of δ_{CP}

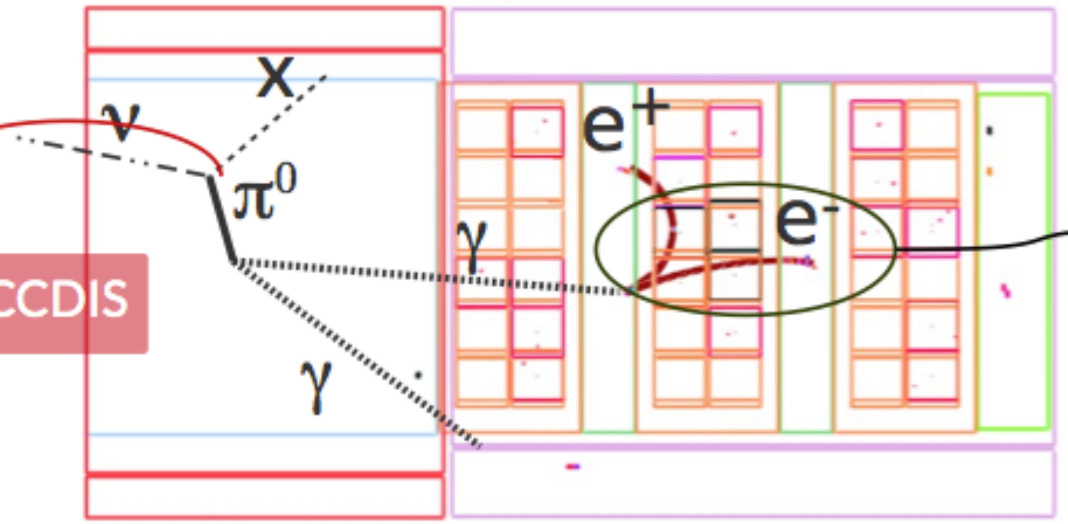
BACK UP

$$E_{Rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

Error source (# param.)	ν_e sample (sig+bkg)	ν_e sample (sig only)	control sample
ν_μ - ν_e common (40)	4.4	5.2	6.7
Unconstrained (5)	3.7	3.0	17.8
Detector + FSI (10)	5.1	5.5	5.5
Total (55)	7.6	8.1	19.9

γ event



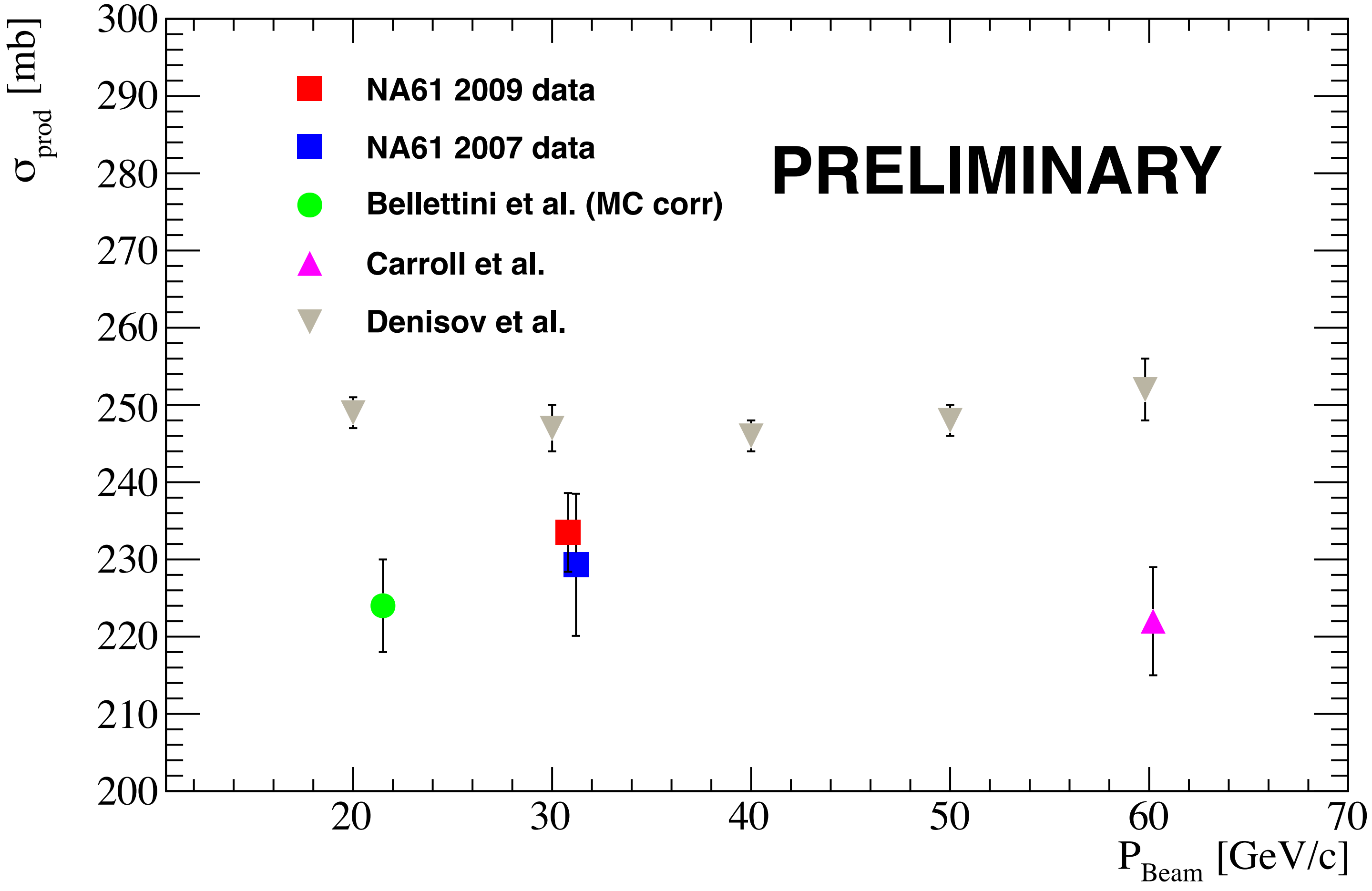


Mainly ν_μNC or ν_μCCDIS

Misidentified as ν_eCC

New measurement of production cross section reduced the total uncertainty from 4% to 2%

$$\sigma_{prod}^{2009} = 233.5 \pm 4.2\ (\text{model}) \pm 1.0\ (\text{trigger})\ \text{mb}$$



Future results of NA61 experiments will have a statistical precision improved of 2-3 times

Likelihood fit

Oscillation parameters $\sin^2 2\theta_{ee}$ and Δm^2_{41} are estimated through the minimization of the likelihood ratio

$$-2\ln L_{tot} = \underset{\substack{\uparrow \\ \nu_e \text{ selection}}}{-2\ln L_{\nu_e}} \underset{\substack{\uparrow \\ \gamma \text{ selection}}}{-\, 2\ln L_{\gamma}} + \underset{\substack{\uparrow \\ \text{penalty term}}}{(\vec{f} - \vec{f_0})^T V^{-1} (\vec{f} - \vec{f_0})}$$

$$-2\ln L = 2 \times \sum_{i}^{E_{reco}} \left\{ n^i_{exp} - n^i_{data} + n^i_{data} \times \ln\left(\frac{n^i_{data}}{n^i_{exp}}\right) \right\}$$

V → the covariance matrix that contains the systematic uncertainties and the correlations

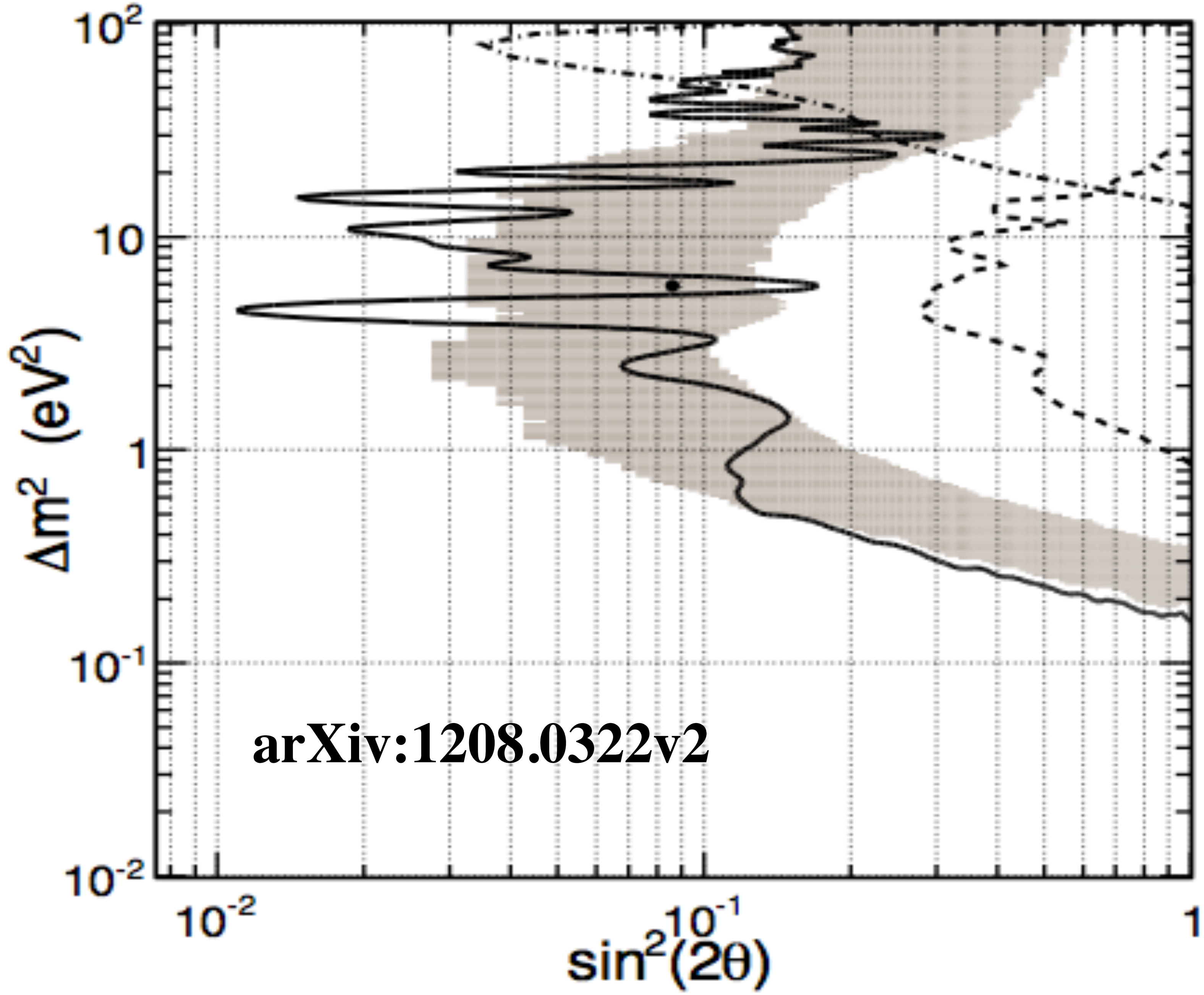
f → vector of nuisance parameters

f_0 → nominal value of systematic parameter

ν_e and γ terms have the same form and are treated in the same way

Nuisance parameters are constrained trough a penalty term

MiniBooNE ν_μ disappearance result



arXiv:1208.0322v2

ND280 selected samples

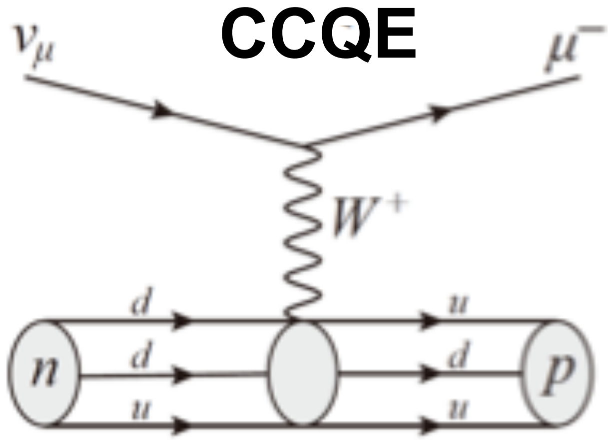
- ND280 is used to constrain the systematic uncertainties at SK

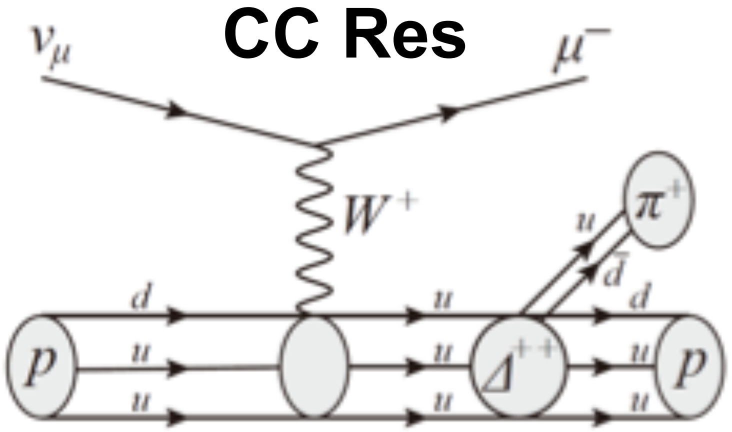
Run1-4 (5.9×10^{20} p.o.t.)

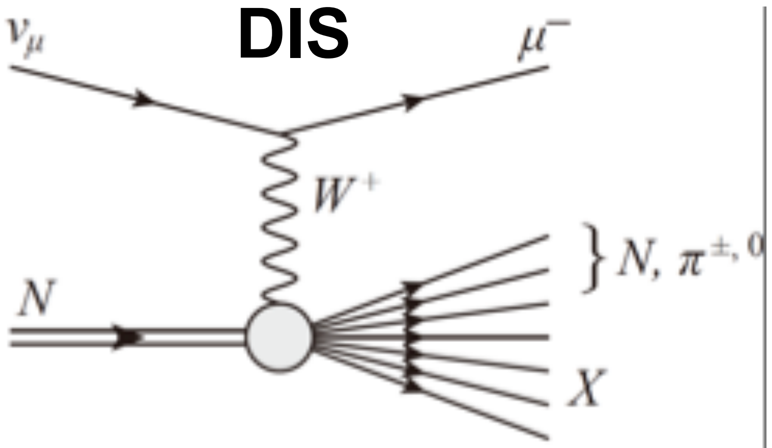
- Select events w/ ND280 Tracker
- Separate into 3 samples by topology :
  - CC0π: no pions in the final state
  - CC1π$^+$: only 1π$^+$ in the final state
  - CCother: >1π$^+$ or >0π$^-$ or >0 tagged photons

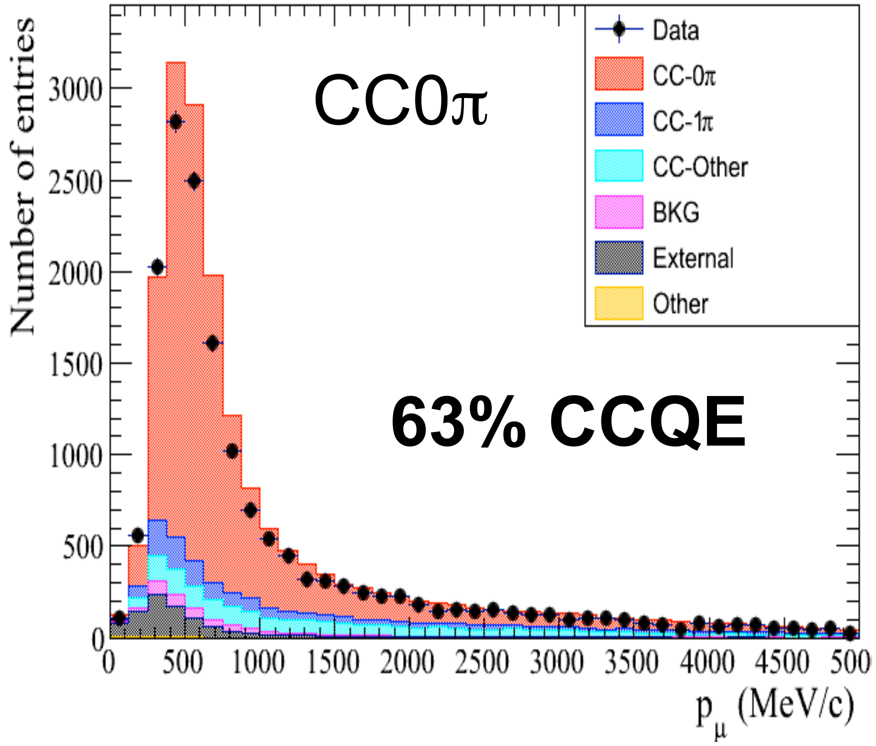
Measured ν_e flux normalization agrees with expectation: **$R(\nu_e) = 1.01 \pm 0.10$**

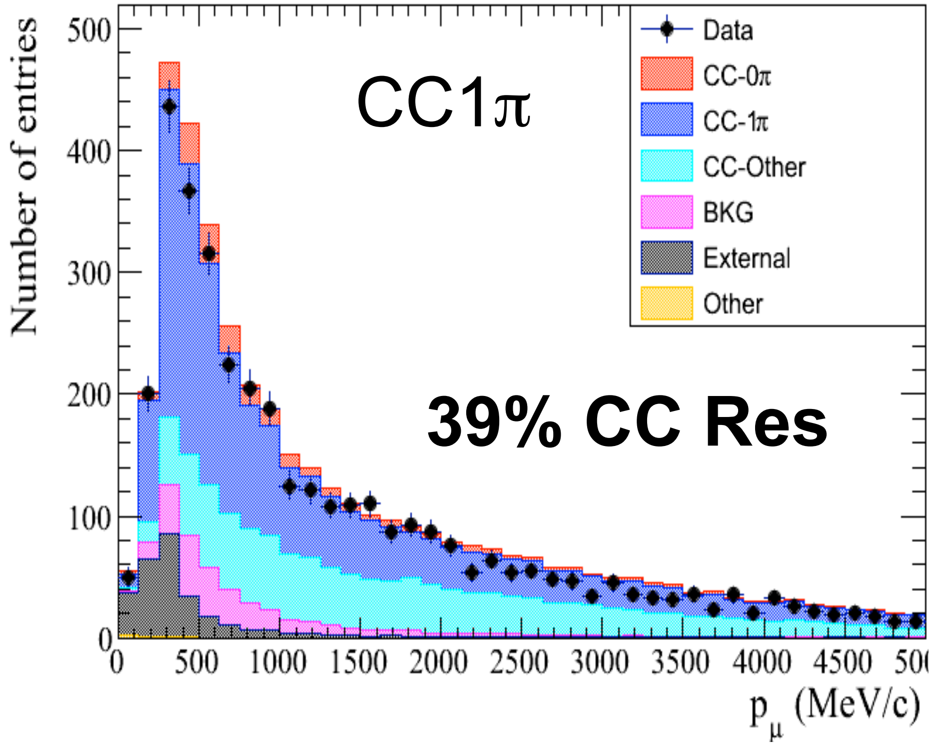
PRD 89 092003, arXiv:1403.2552

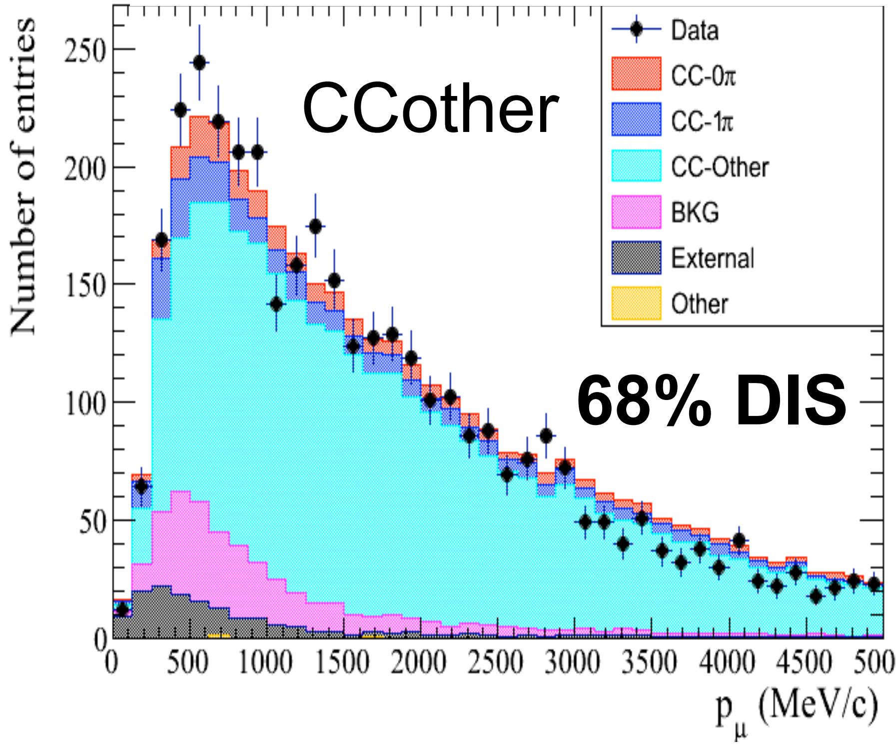












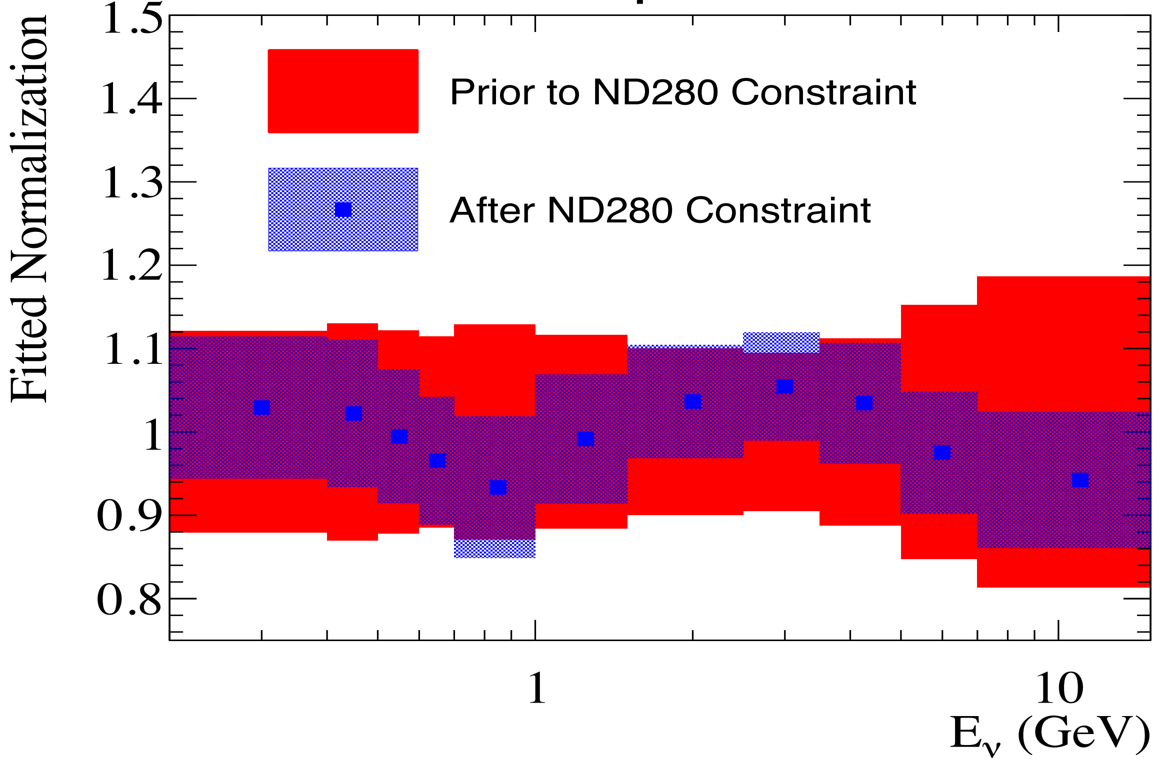
ND280 constraint

- 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

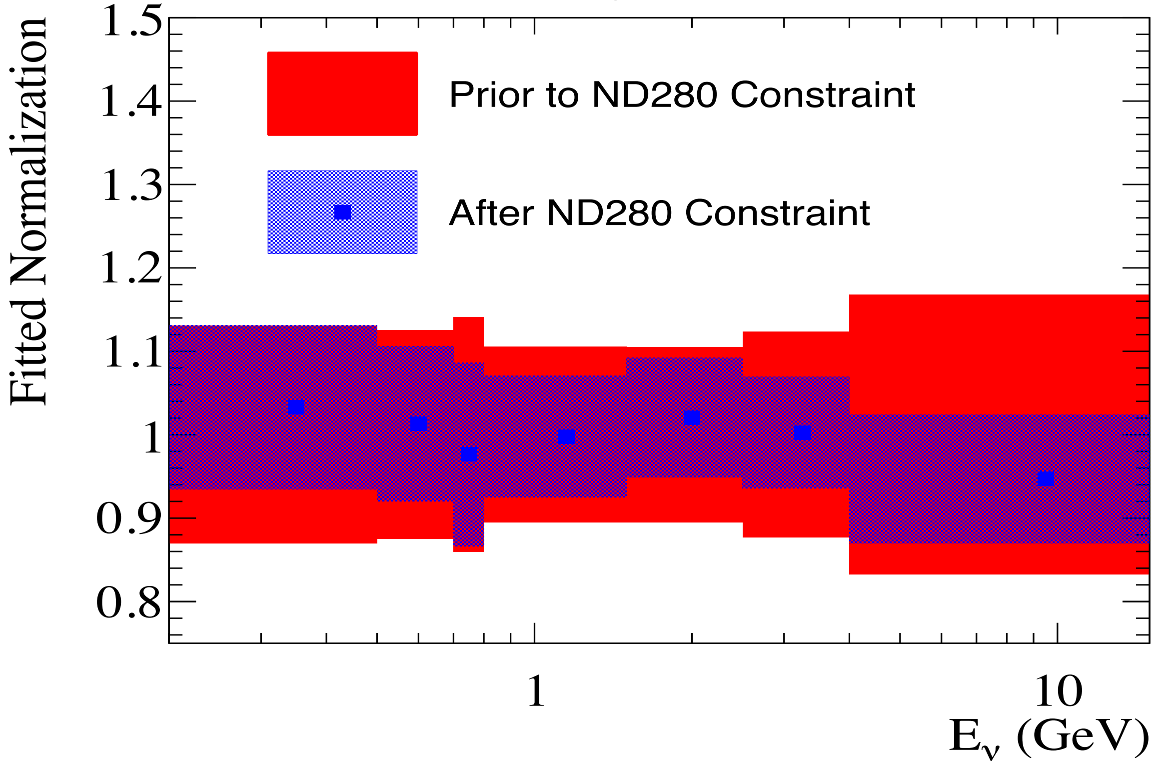
Systematic uncertainties	**% variation of Tot # of ν_e events**	**% variation of Tot # of ν_μ events**
T2K corr. Flux-Xsec **(w/o constraint)**	2.9 (25.9)	2.7 (21.6)

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 ν_μ Flux



T2K ν_e Flux



$\nu_\mu + \nu_e$ joint analysis

- 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
- Result obtained w/ Run 1-4 data set (6.57×10^{20} POT)

Constraint from reactors (PDG 2013):

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

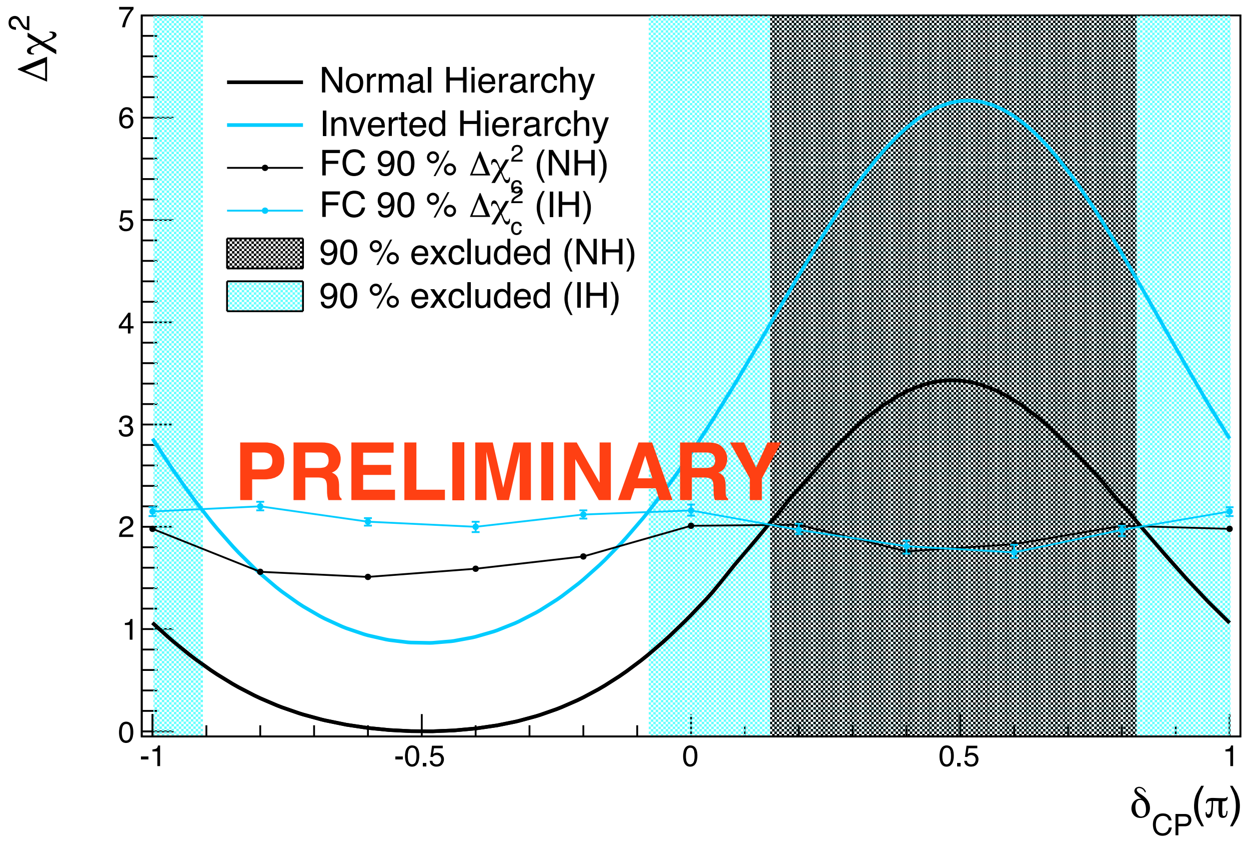
90% CL allowed intervals

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)

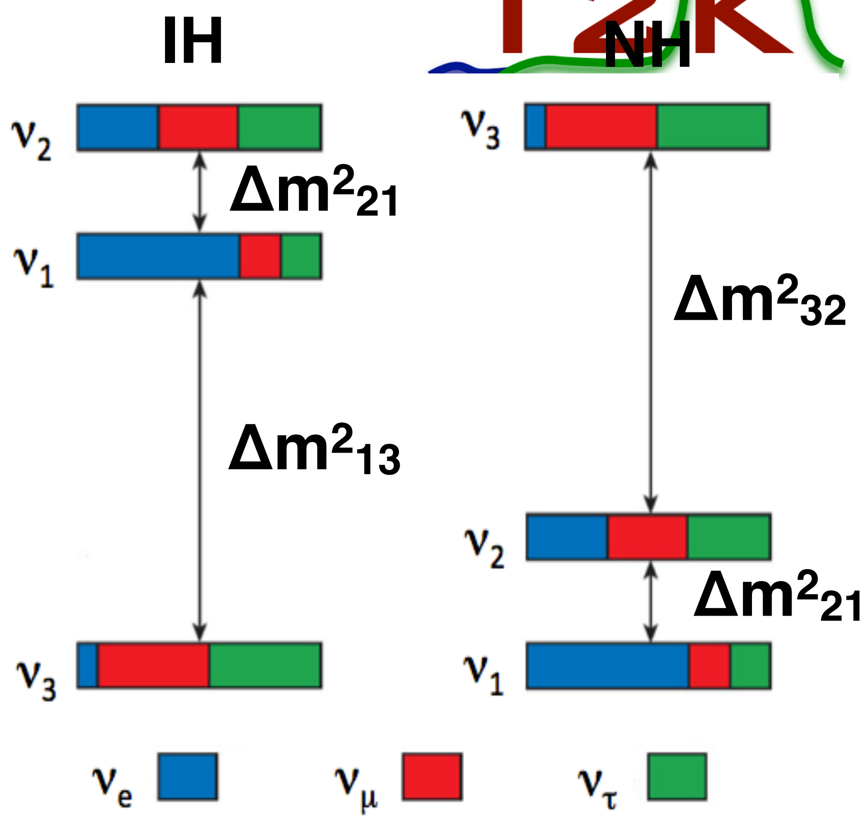


Standard neutrino oscillations

ETH Institute for Particle Physics

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

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



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**
reactor/ accelerator	**$\sin^2(2\theta_{13}) > 0.098\pm0.013$**	**T2K, MINOS, DB, RENO, DC**
Solar/ reactor	**$\sin^2(2\theta_{12}) > 0.857\pm0.024$**	**KamLAND, SNO, SK**

Majorana phases (no effects)

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

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

T2K selected samples (Run 1-4)

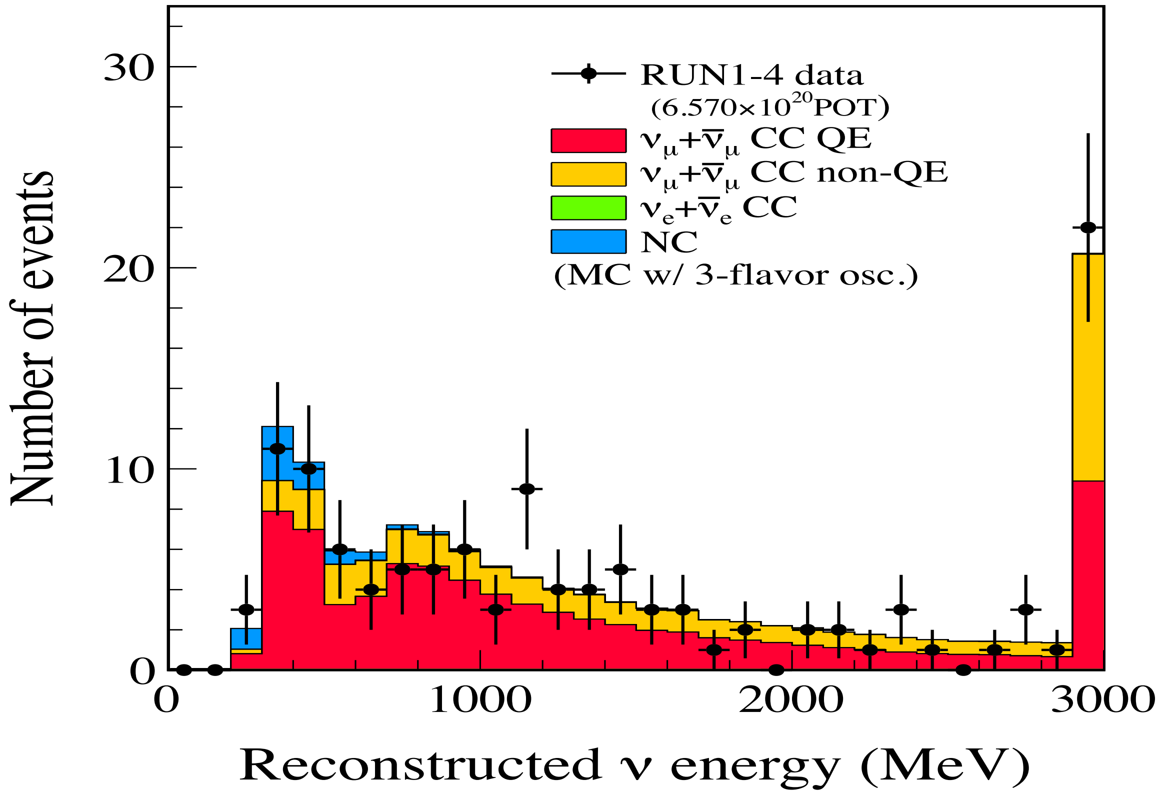
Run 1-4 (6.57×10^{20} POT)
neutrino data sample

ν_μ event selection

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

Selected events = 120

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



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 = 28

Exp. Bkg. events = 4.9 ± 0.6 (syst)