UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

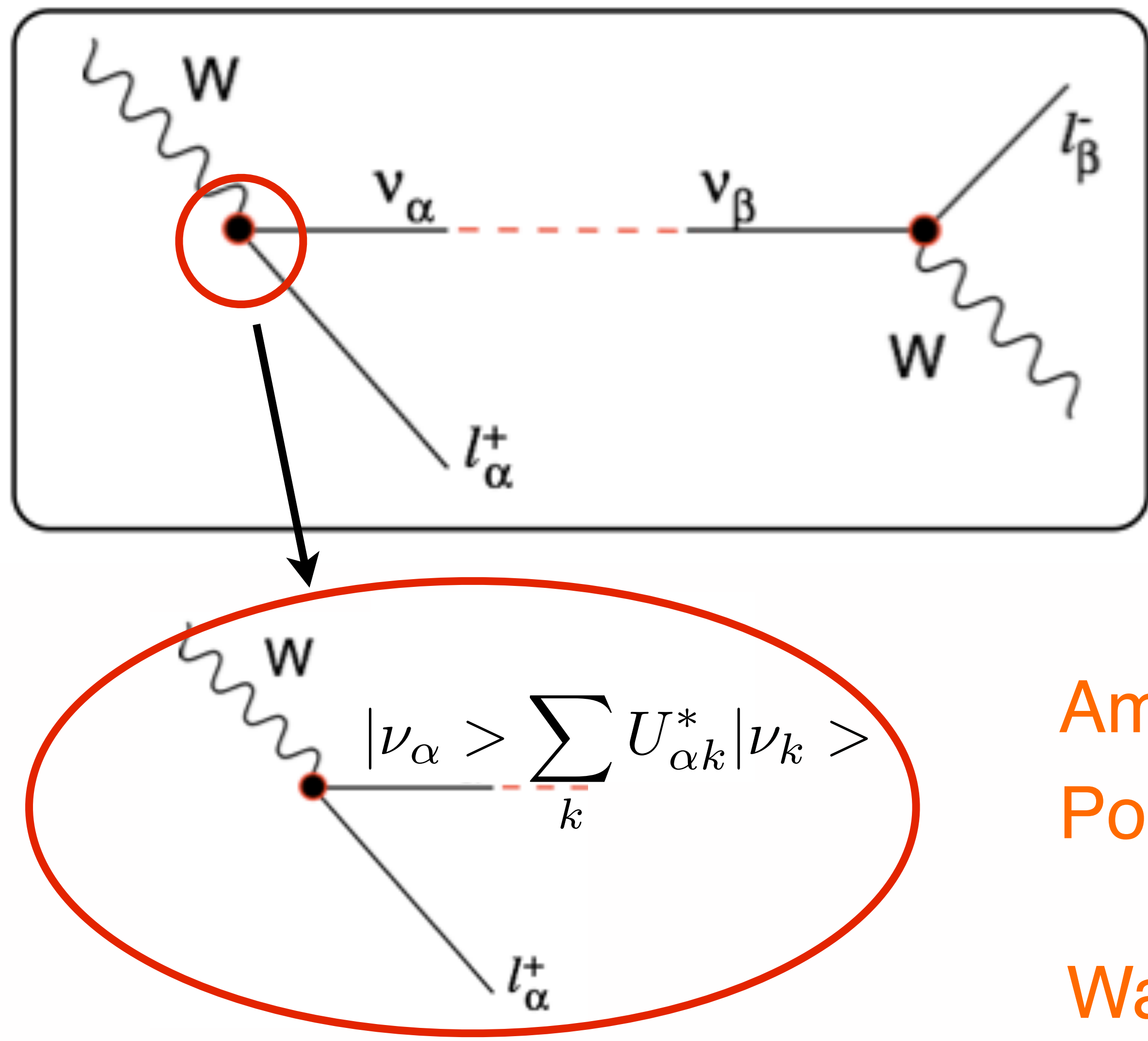
T2K

New (anti)neutrino results from the T2K experiment on CP violation in the leptonic sector

Davide Sgalaberna, University of Geneva

IPHC Seminar, 10th March 2017

Neutrino oscillations



- A neutrino mass eigenstate can be described as a linear combination of neutrino flavor eigenstates
- Fraction of each flavor varies in L(distance) / E(energy)

Amplitude: determined by mixing matrix $U_{\alpha i}$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Wavelength: determined by $\Delta m^2_{ij} = m^2_i - m^2_j$

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

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

L: neutrino flight path

E: neutrino energy

Neutrinos oscillate ($\Delta m^2_{ij} \neq 0$) → neutrinos have non-zero mass

Oscillation parameters: mixing matrix

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

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

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

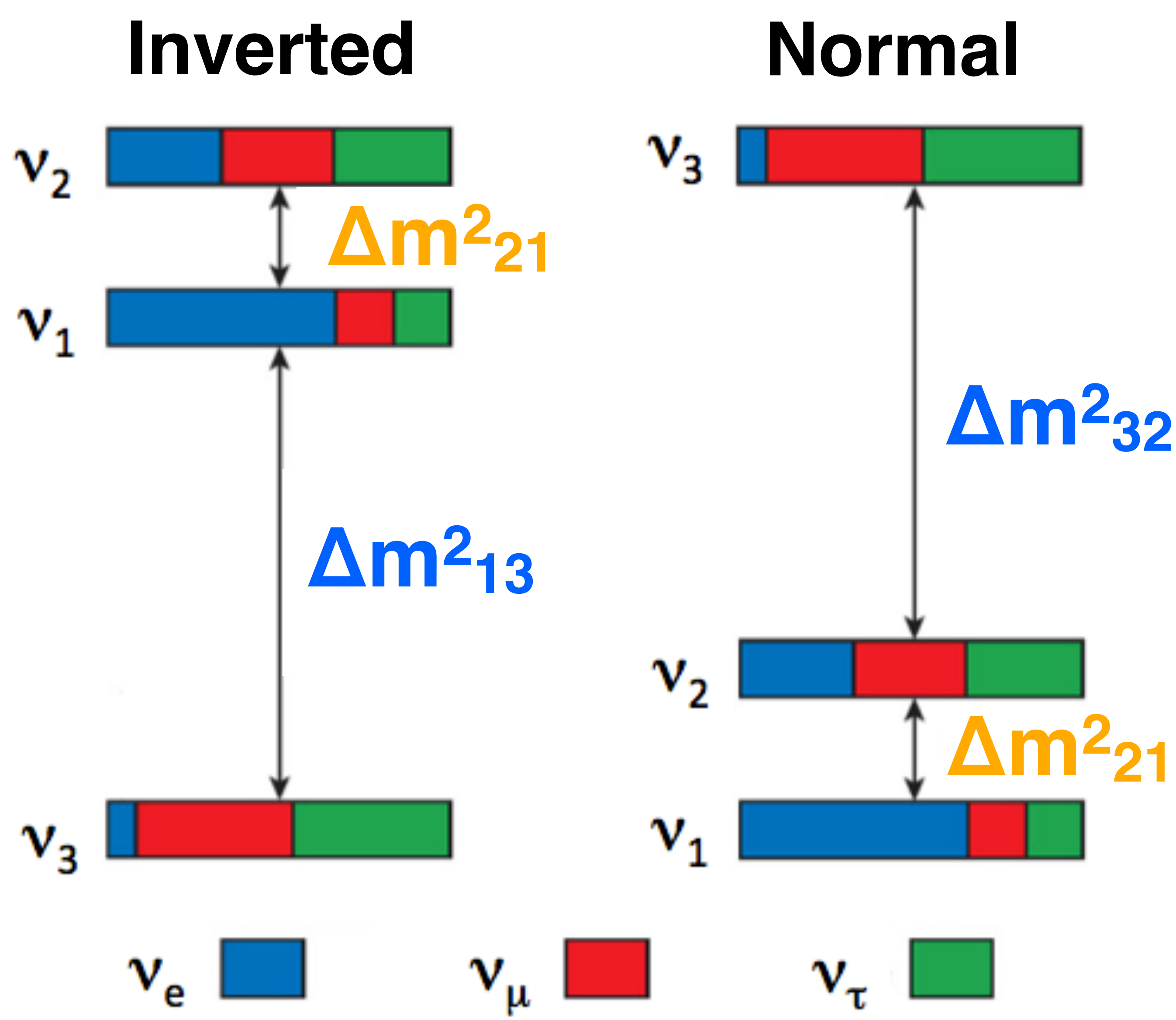
$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

δ_{CP} unknown

$\delta_{CP} = 70°$

CP symmetry is violated in lepton sector if $\delta_{CP} \neq 0,\pi$

Oscillation parameters: mass squared difference



Solar, Reactors

Accelerators, Atmospheric

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Sign of Δm^2_{21} is known

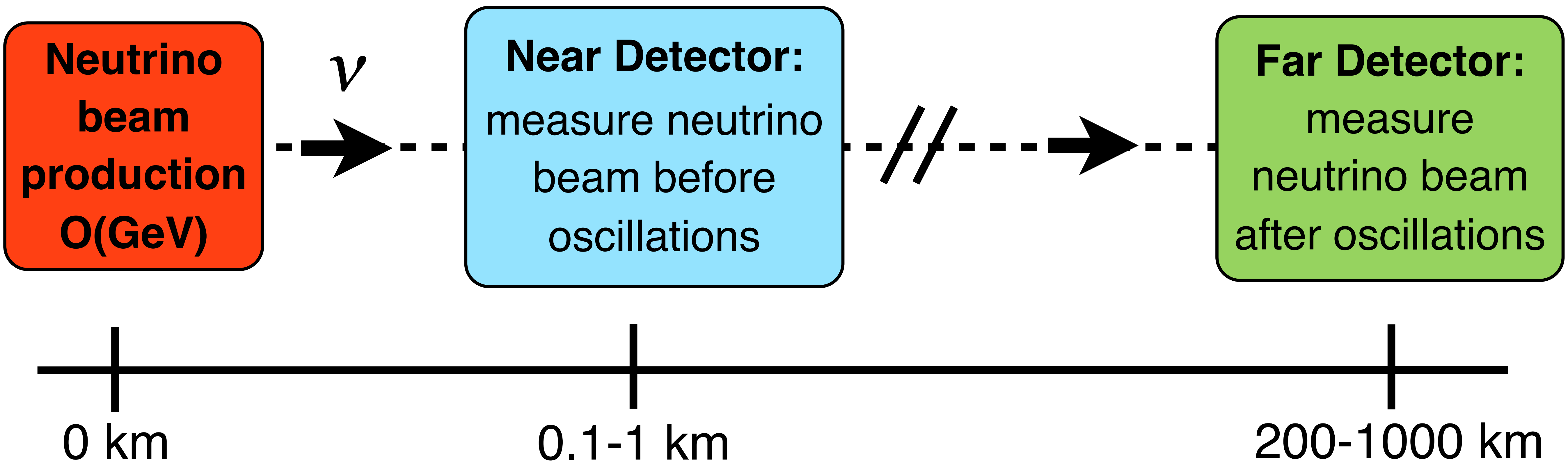
Mass hierarchy (MH) → sign of Δm^2_{32}

Normal (NH): $m_3>m_2>m_1$

Inverted (IH): $m_2>m_1>m_3$

Mass hierarchy is not yet known

Long-baseline experiments concept



Near Detector: $$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

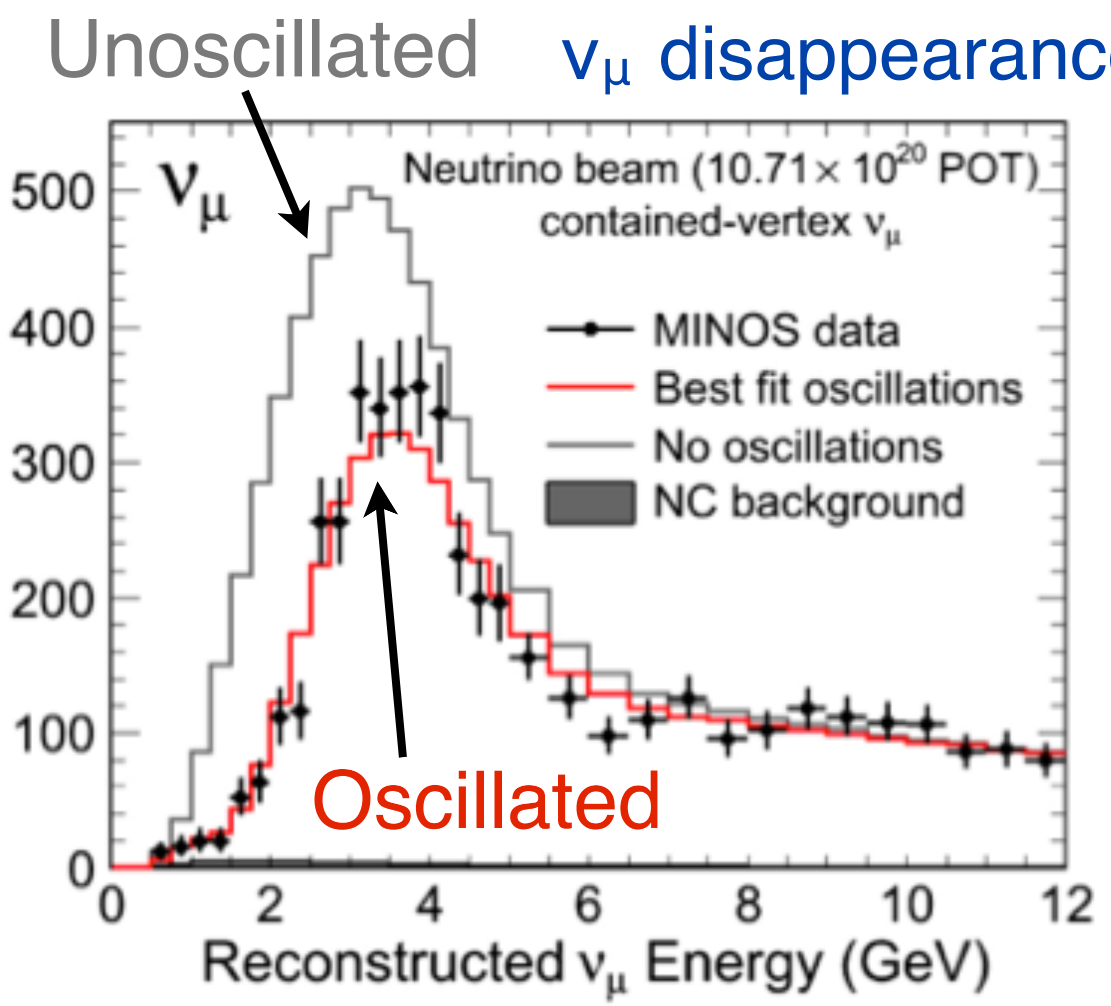
Flux | Cross Section | Detector Efficiency | Oscillation probability

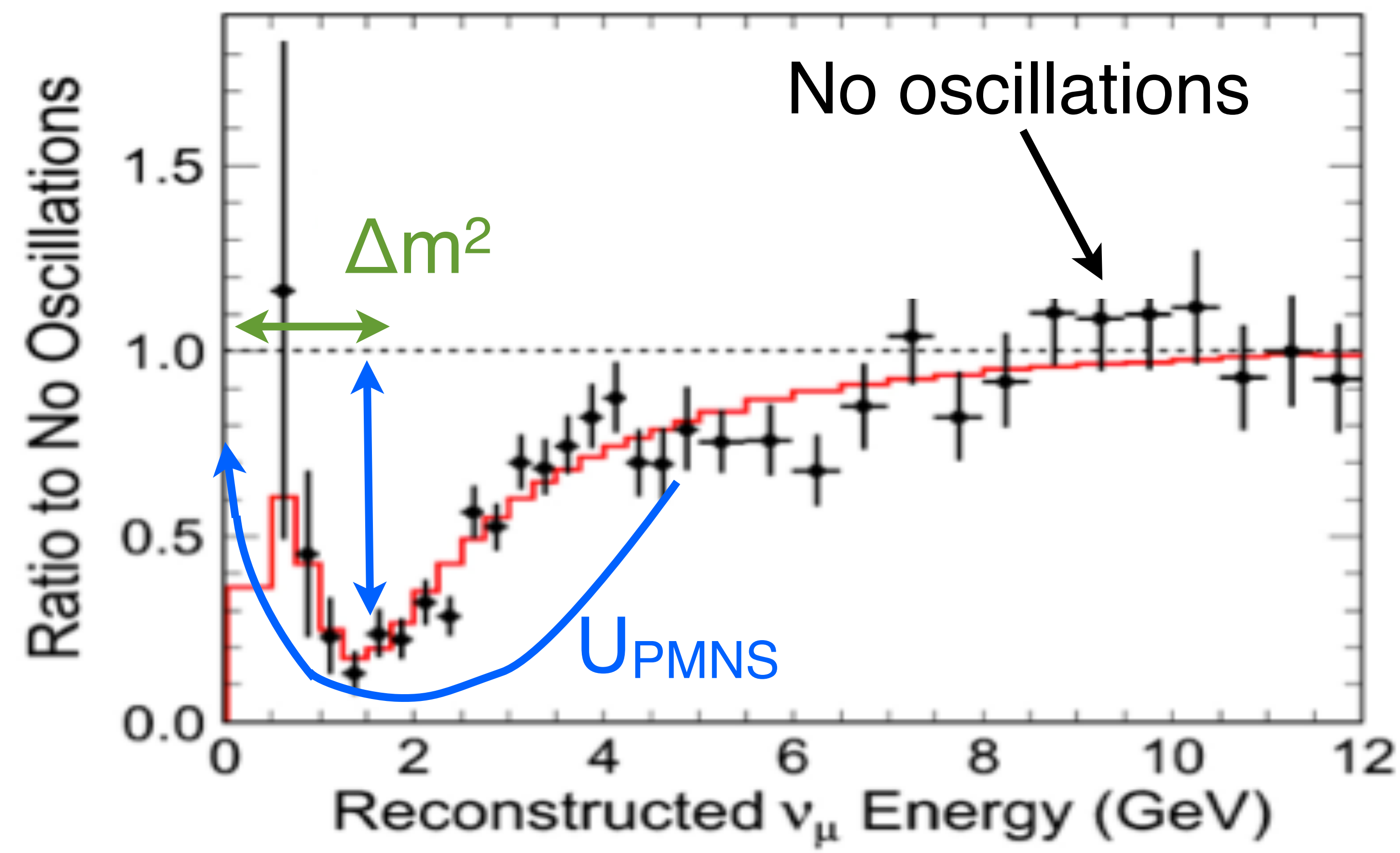
Far Detector: $$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P_{osc}(E_\nu)$$

Long-baseline experiments concept

- $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_x)$: deficit on the number of events (disappearance)
- $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$: excess of events (appearance)

ν_μ disappearance at MINOS experiment (PRL 110, 251801 (2013))





Measure $\begin{cases} \nu_\mu \rightarrow \nu_x \text{ disappearance} \\ \nu_\mu \rightarrow \nu_e \text{ appearance} \end{cases}$ ➡ Infer the oscillation parameters

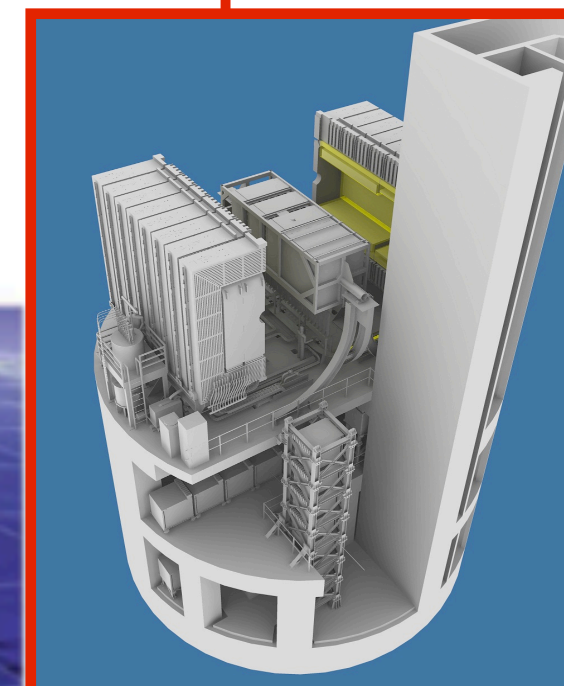
The T2K collaboration

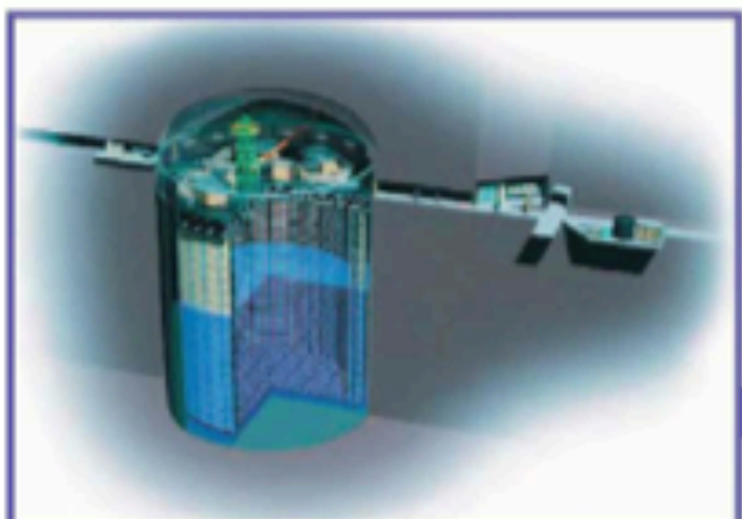
~500 researchers, 62 institutes, 11 countries

The T2K experiment

- Intense muon (anti)neutrino beam from J-PARC to Super-Kamiokande (295 km from target production): measure oscillated neutrino flux
- Unoscillated neutrino flux is measured at the near detector (~280m)
- Precise measurements of
  - muon (anti)neutrino disappearance
  - electron (anti)neutrino appearance

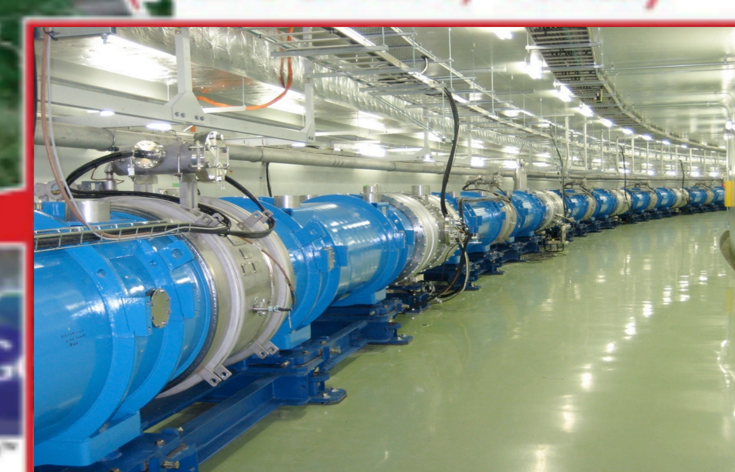
Near detector complex





Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)



Neutrino oscillations at T2K

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

E ~ 0.6 GeV
L ~ 295 km

- Precise measurement of $\sin^2 2\Theta_{23}$
- Test of CPT by comparing measured $\nu_\mu \to \nu_\mu$ with $\overline{\nu}_\mu \to \overline{\nu}_\mu$

Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Leading term

CP violating

$$-\alpha\sin\delta_{CP} \times \sin^2 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

"+" for antineutrino

CP conserving

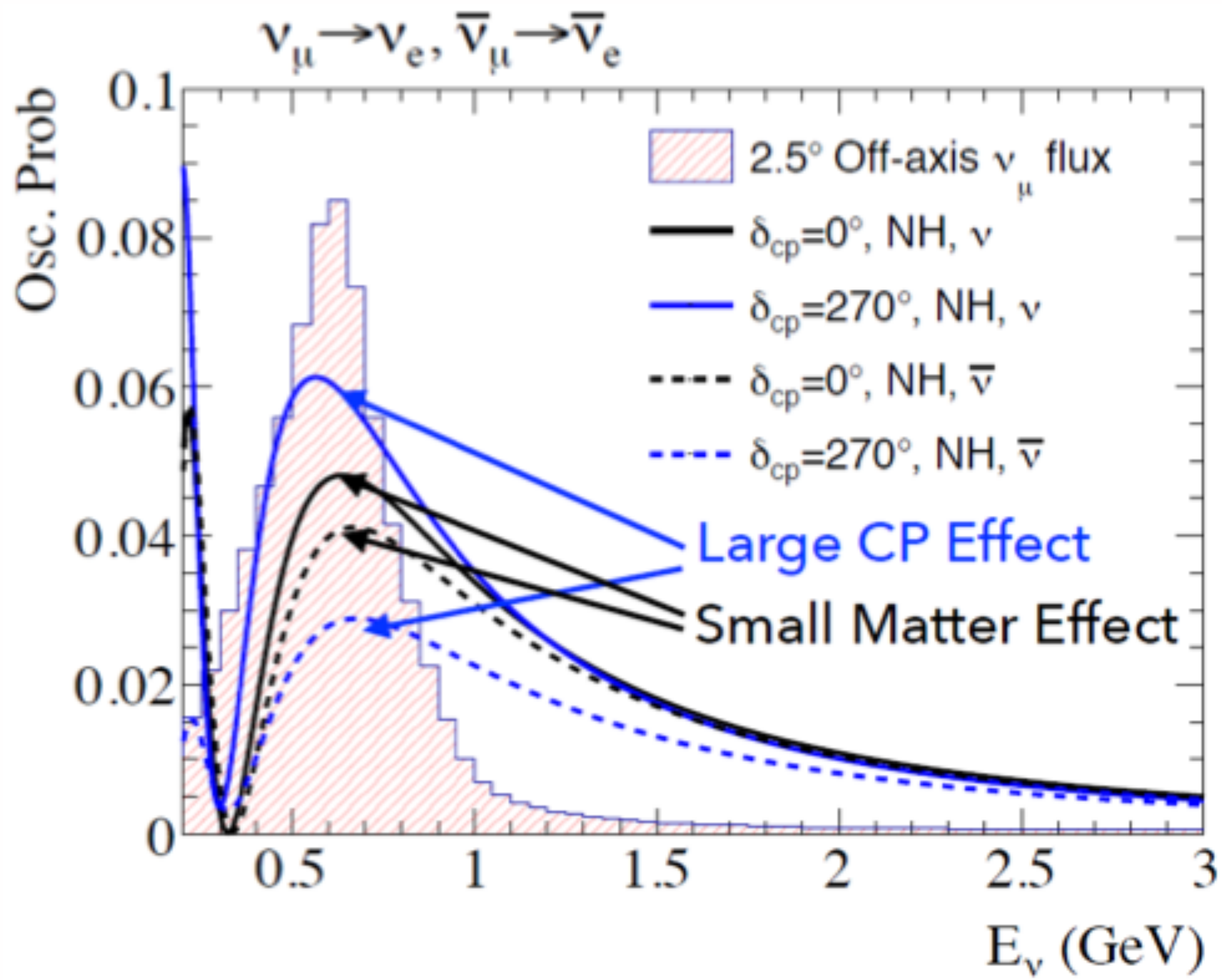
$$\alpha\cos\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+ O(\alpha^2)$$

$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \qquad \alpha = |\frac{\Delta m^2_{21}}{\Delta m^2_{31}}| \sim \frac{1}{30} \qquad \Delta = \frac{\Delta m^2_{31}L}{4E}$$

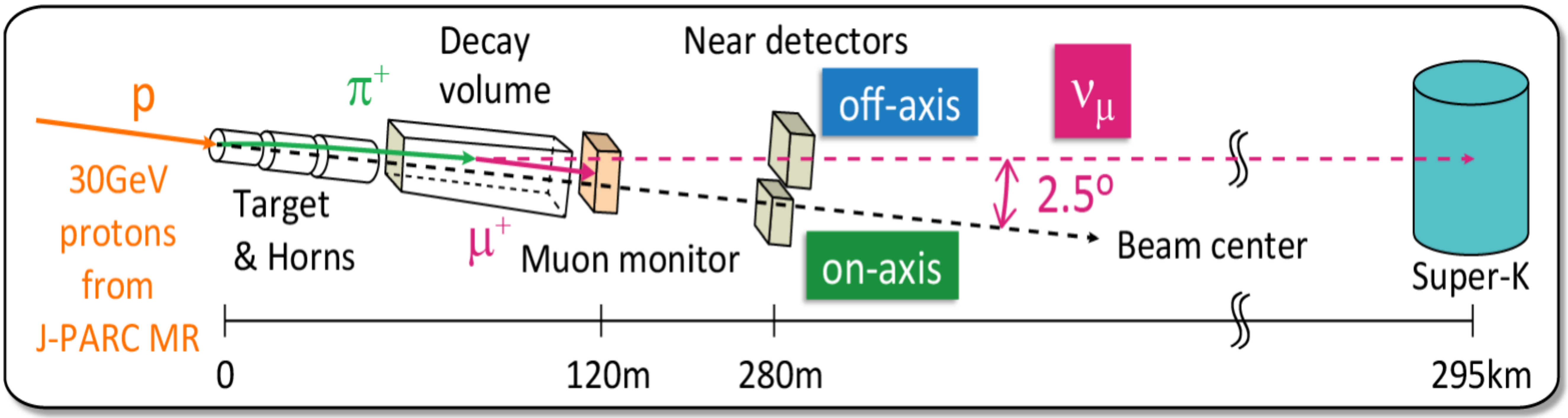
- The leading term defines the octant $\Theta_{23}>45°$ or $\Theta_{23}<45°$
- All mass splittings and mixing angles have been measured to be non-zero:
  second order term can violate the CP symmetry if $\sin\delta_{CP} \neq 0$

Effect of CP violation at T2K

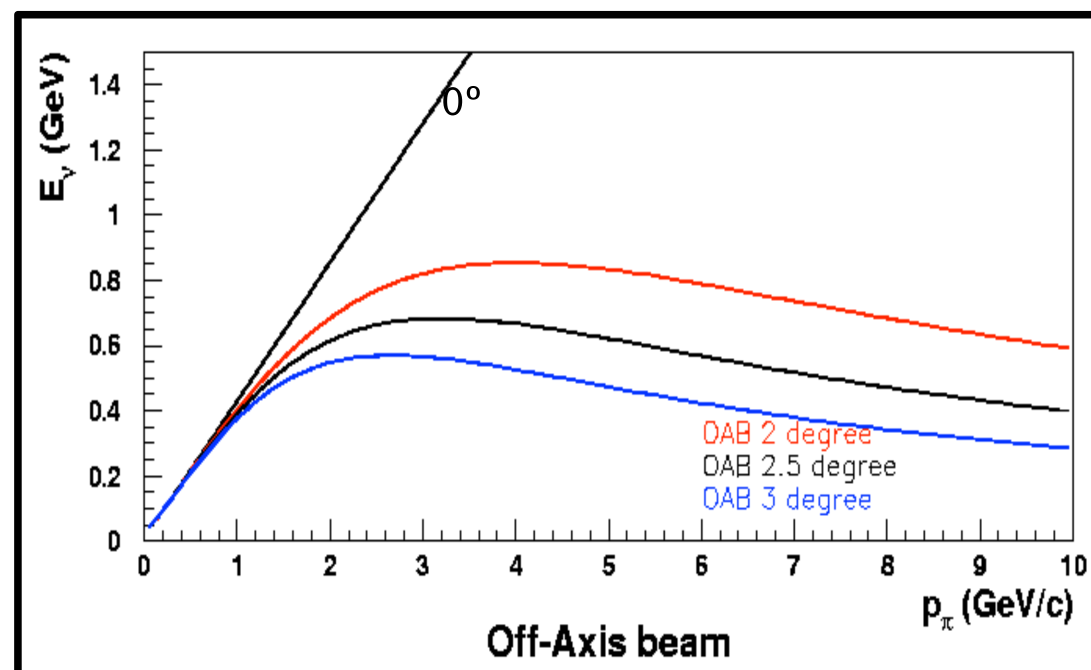


- Asymmetric effect on P($\nu_\mu \to \nu_e$) and P($\bar{\nu}_\mu \to \bar{\nu}_e$):
  - δ_{CP} = -π/2 → maximizes P($\nu_\mu \to \nu_e$) and minimizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
  - δ_{CP} = +π/2 → minimizes P($\nu_\mu \to \nu_e$) and maximizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
- δ_{CP} and Mass Hierarchy have similar effects
- Effect of δ_{CP} on $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ is about ±20-30%
- Effect of Mass Hierarchy is about ±10%

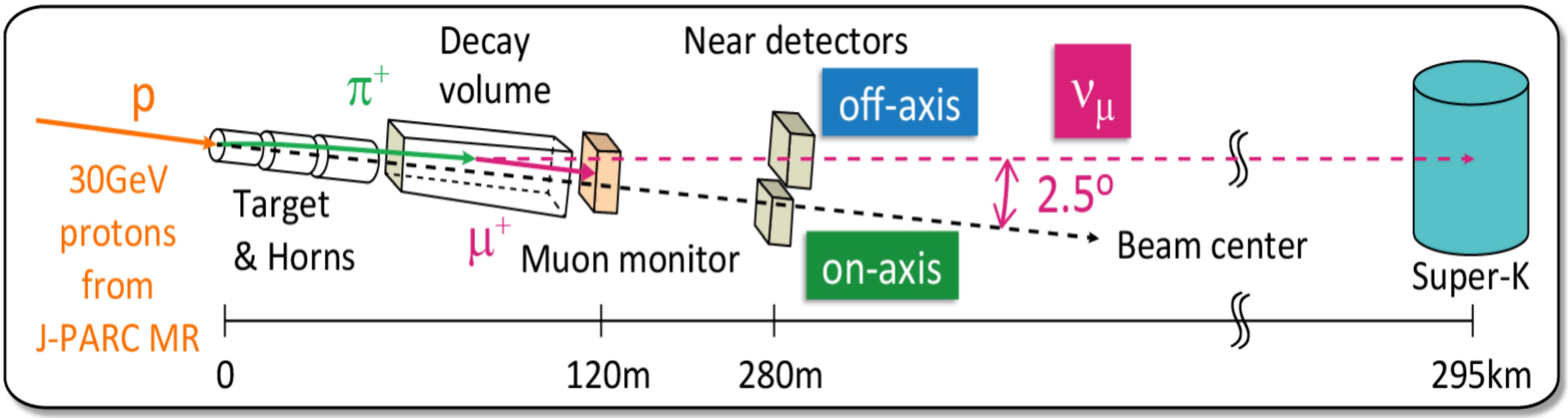
Design principle: the off-axis angle



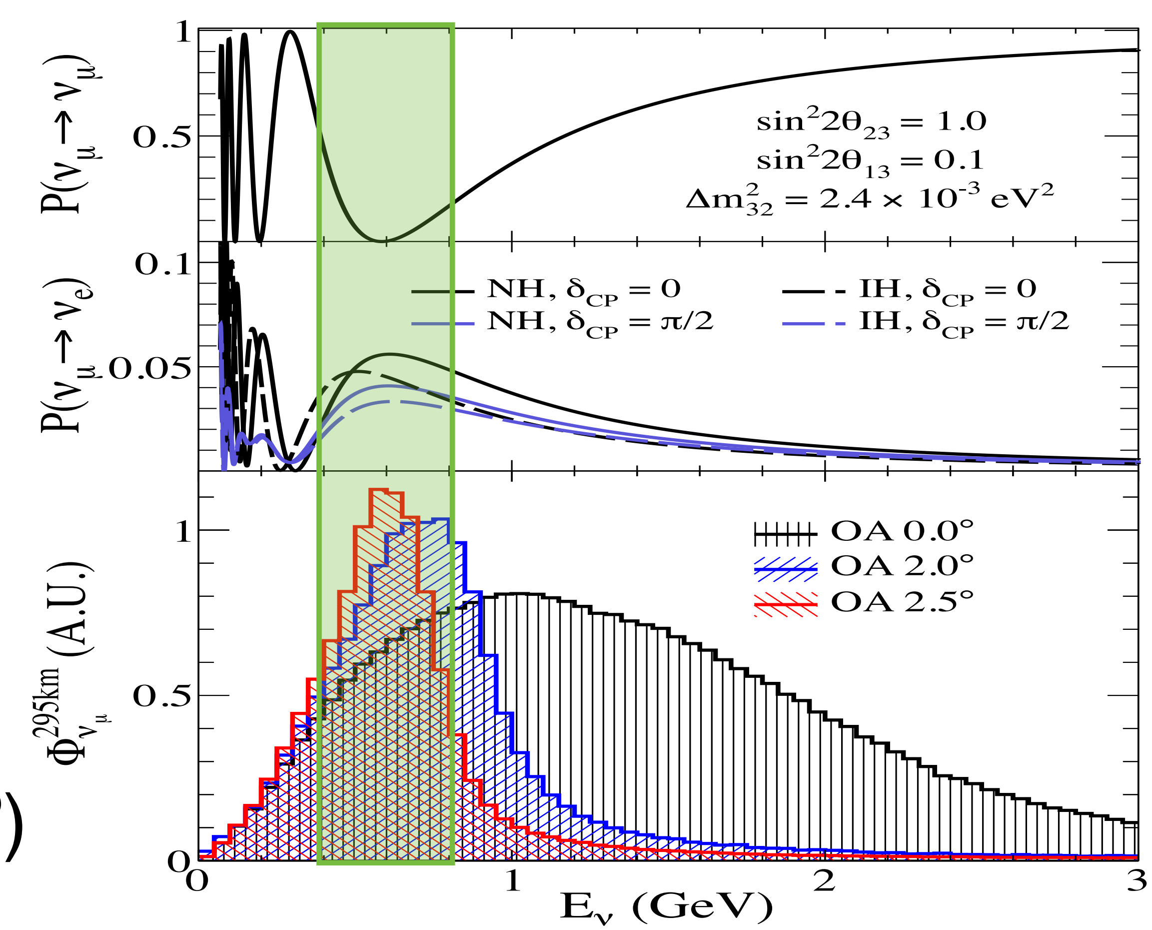
- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\overline{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Invert magnet polarity to produce a $\overline{\nu}_\mu$ beam
- First off-axis neutrino beam experiment (2.5°)
  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum



Design principle: the off-axis angle

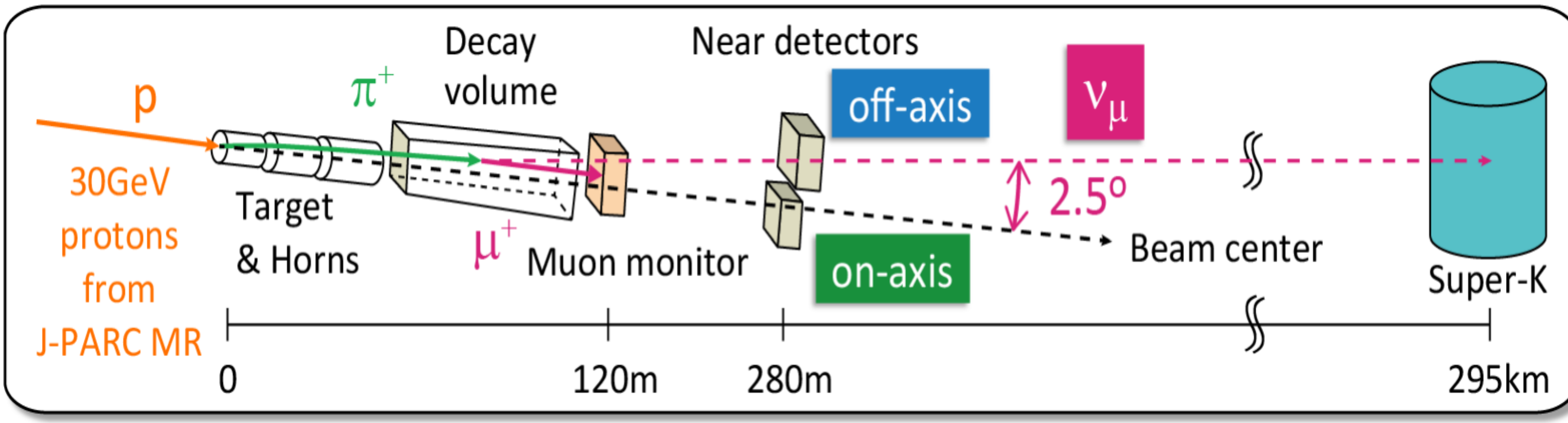


- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\overline{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Invert magnet polarity to produce a $\overline{\nu}_\mu$ beam
- First off-axis neutrino beam experiment (2.5°)

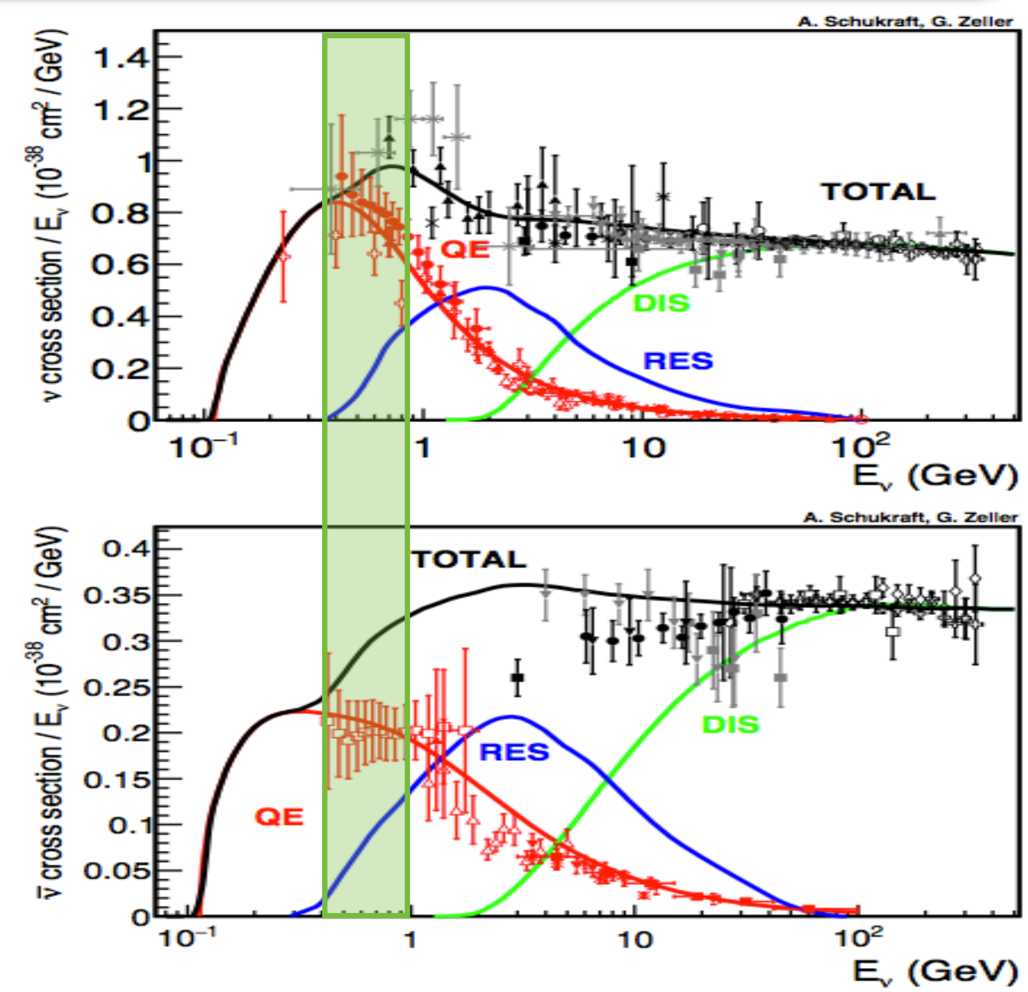


  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum

Design principle: the off-axis angle



- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\bar{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Invert magnet polarity to produce a $\bar{\nu}_\mu$ beam
- First off-axis neutrino beam experiment (2.5°)
  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum

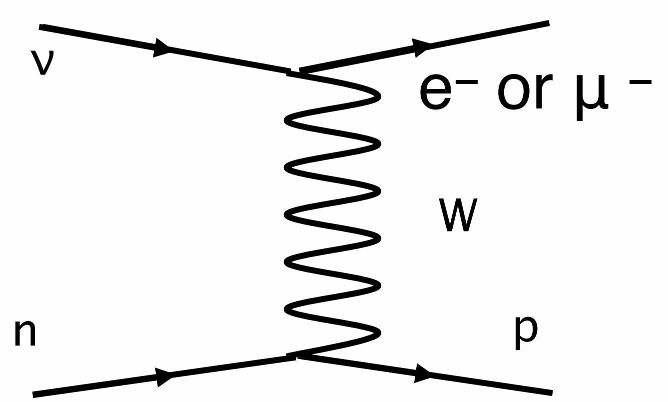


(Anti)Neutrino interactions at T2K

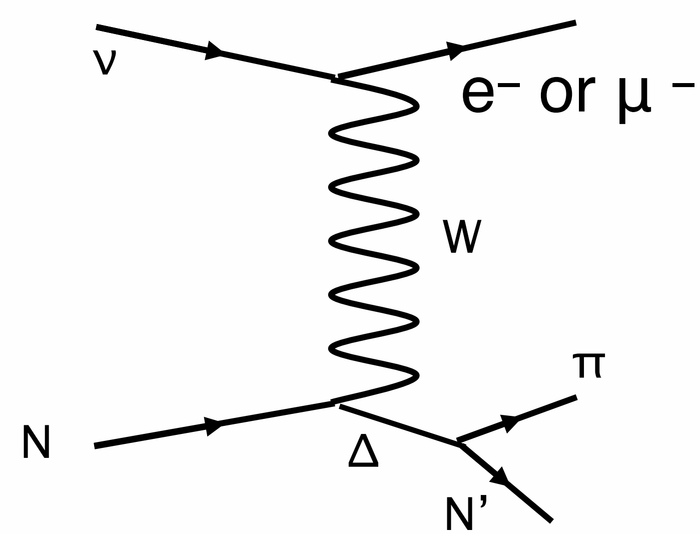
- The dominant neutrino interaction mode is Charge-Current Quasi-Elastic

Neutrino energy from lepton momentum and angle in CCQE hypothesis:
- 2 body kinematics
- assume target nucleon at rest

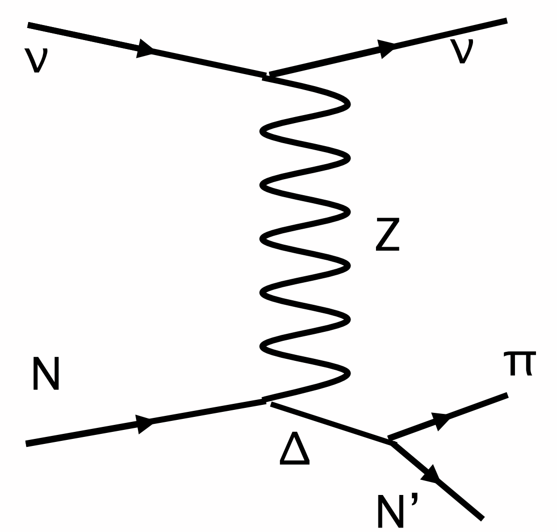
Charged-Current Quasi-Elastic (CCQE)



Charged-Current π



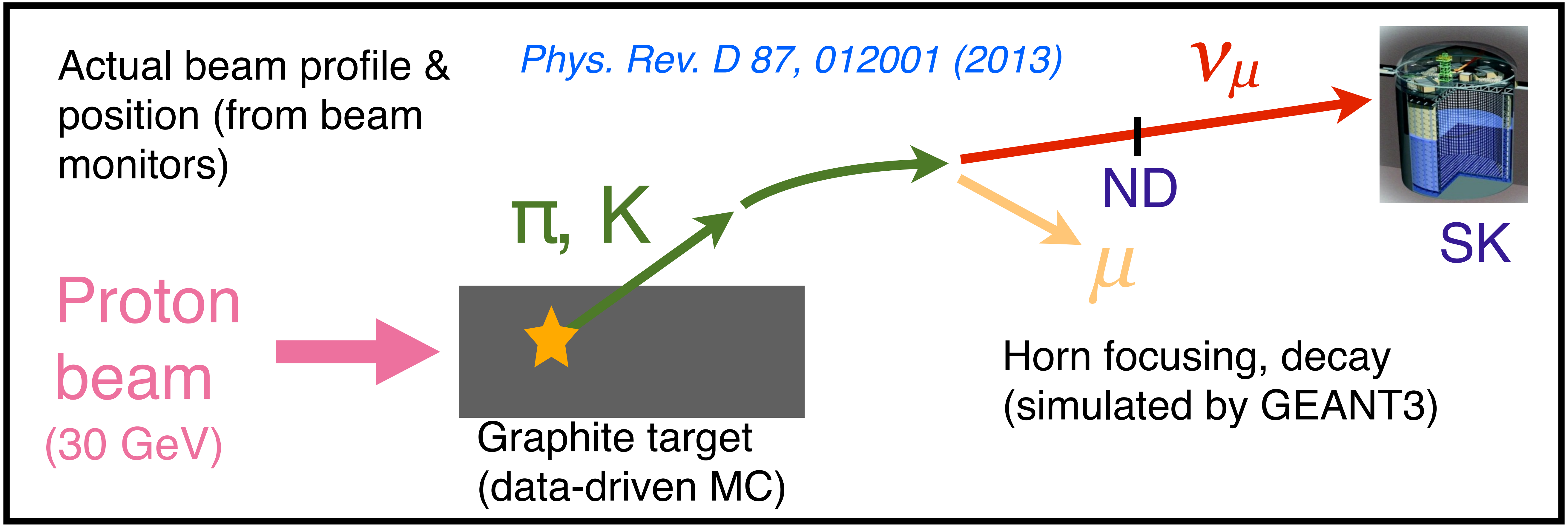
Neutral-Current π



Other cross-section components

- CCQE-like multinucleon interaction (2 nucleons in the final state)
- Charged-current single-pion production (CCπ)
- Neutral-current single-pion production (NCπ)

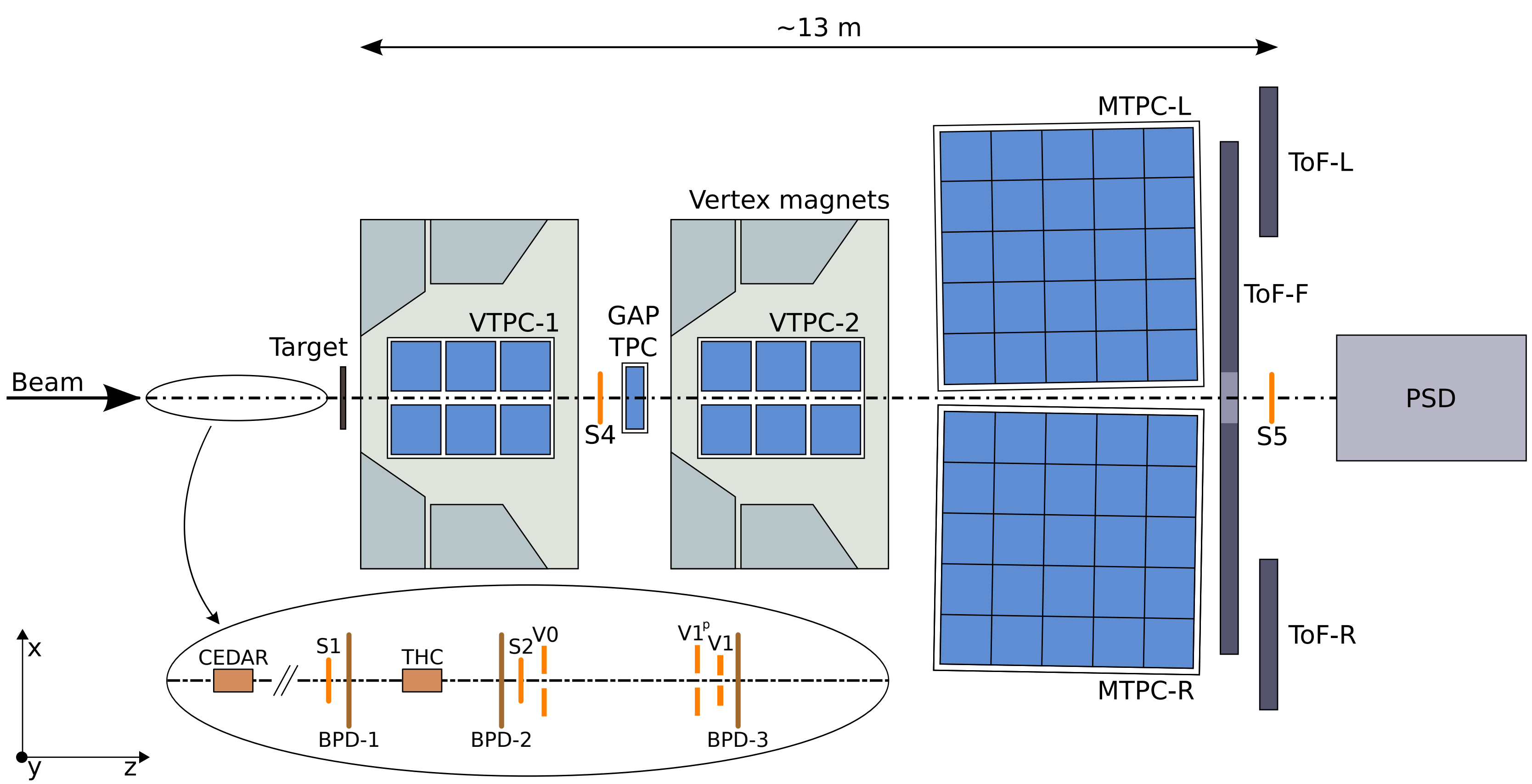
Neutrino beam production

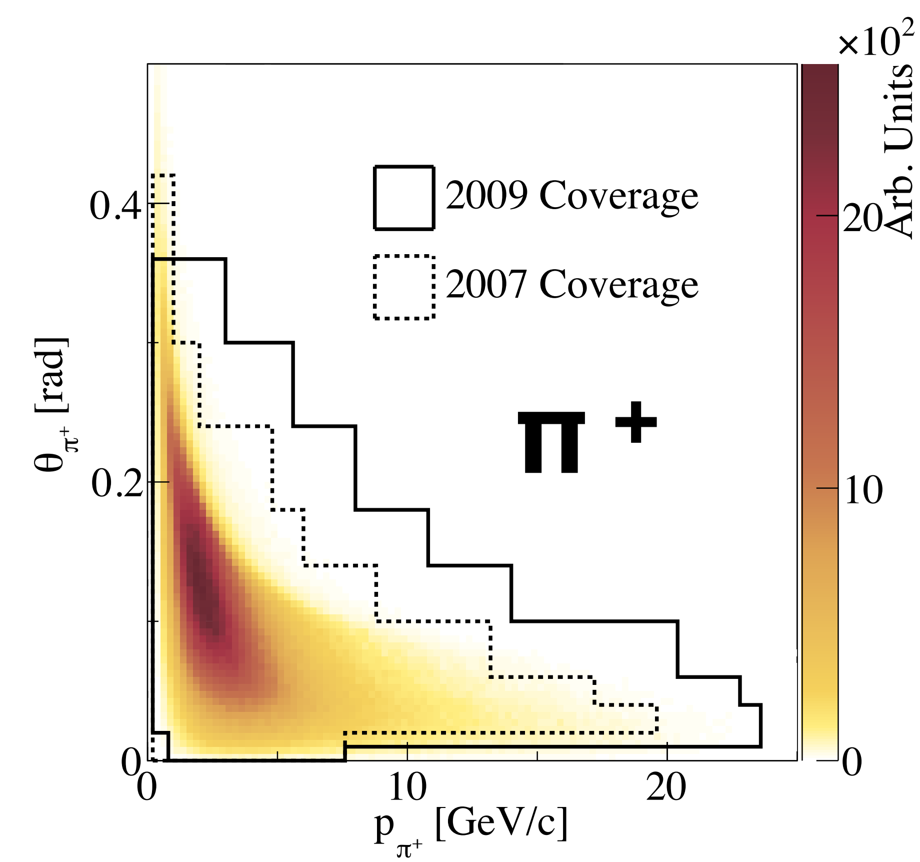


- Hadronic interactions
  - Hadron production simulated with FLUKA
  - Secondary and other interactions outside the target based on experimentally measured cross sections
- GEANT3 transport simulation used downstream of target
- Large uncertainties on forward hadron production (non-perturbative QCD)
- Need auxiliary experiment to measure pion and kaon production

NA61/SHINE experiment at CERN SPS

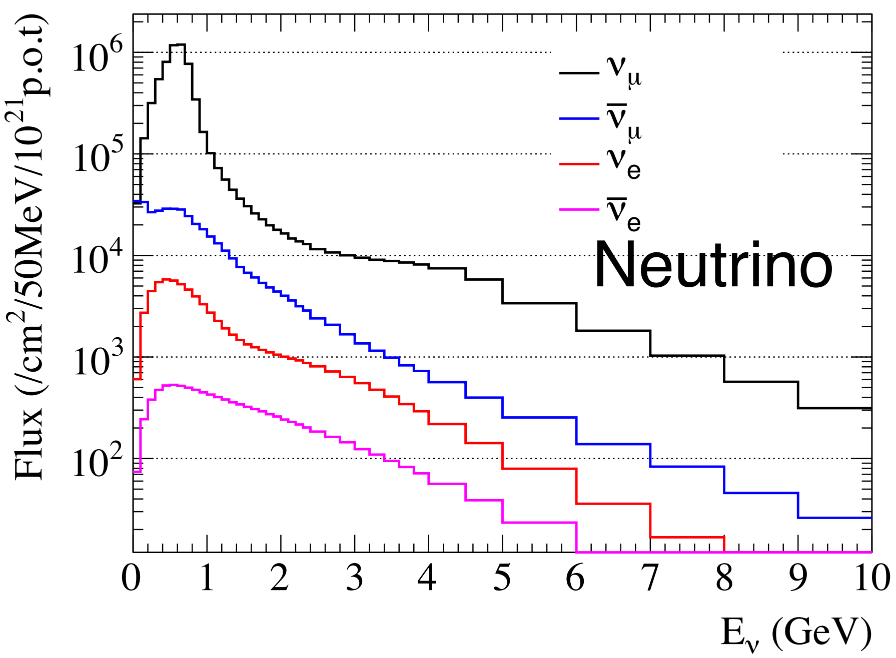
- Large-acceptance detector with very good capabilities of charge and mass measurements
- Located in the CERN North Area
- Cover almost the full {p,Θ} T2K phase space
- Measure pion, proton and kaon production with a 31 GeV/c proton beam on a carbon target
  - Thin 2cm target (4%λ_I) (*Eur. Phys. J. C 76, 84 (2016)*)
  - T2K replica target (published $\pi^{\pm}$ yields: *Eur. Phys. J. C 76, 617 (2016)*)

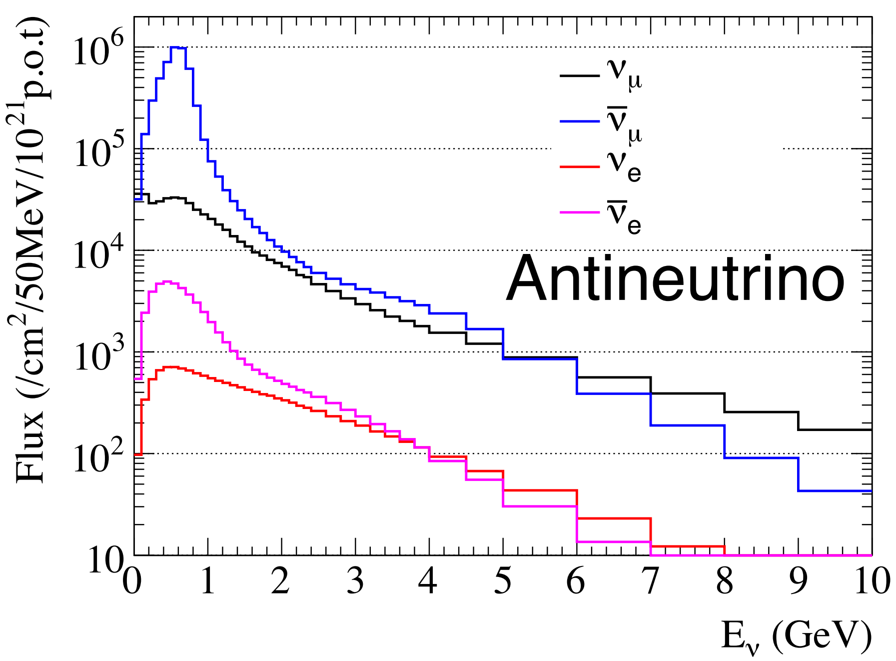


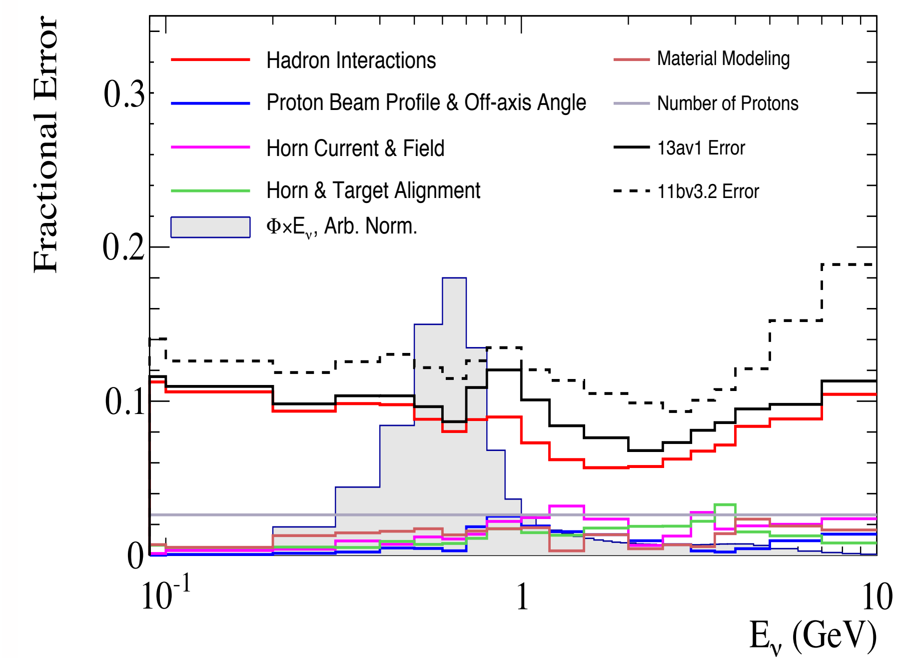


Neutrino and antineutrino flux prediction

- Neutrino flux prediction tuned with hadron spectra measured at NA61/SHINE
- Flux systematic uncertainty reduced from ~30% to ~10% (thin target data)



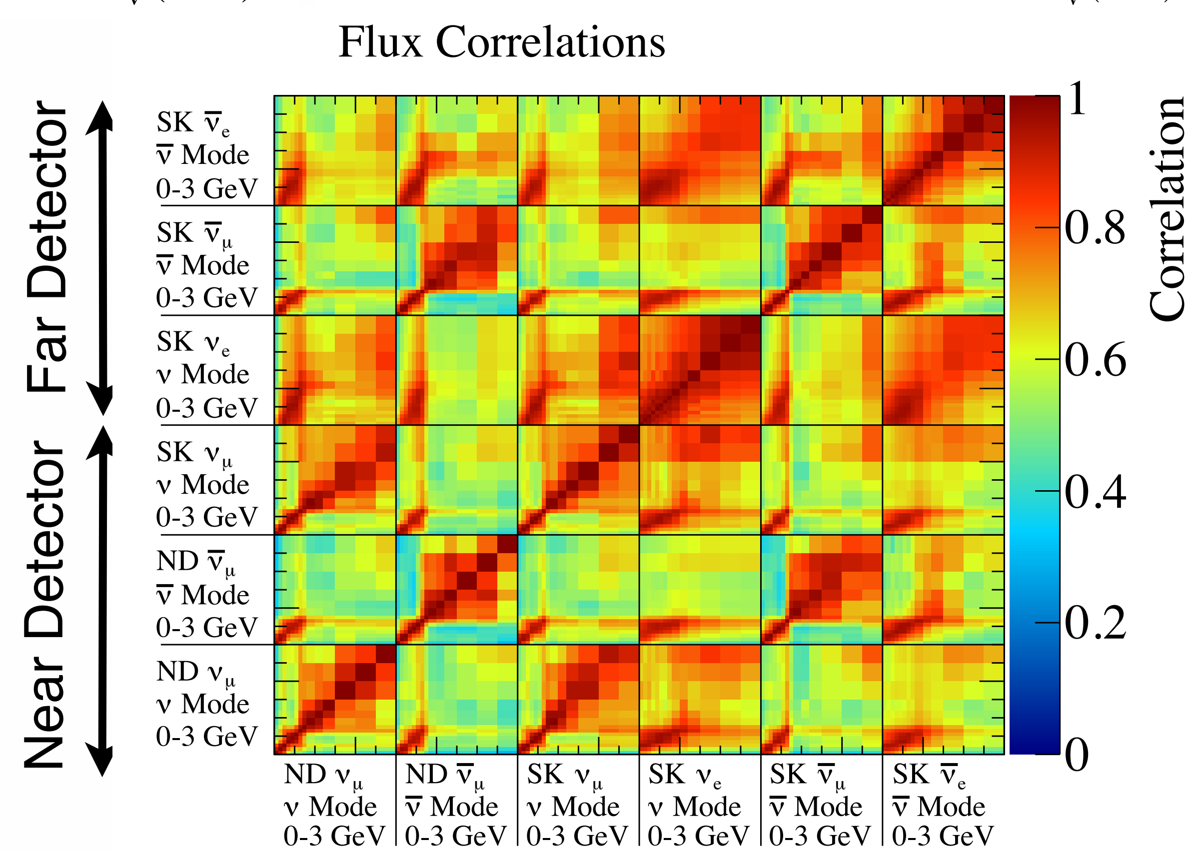




- Less than 1% intrinsic electron (anti)neutrino component at the peak

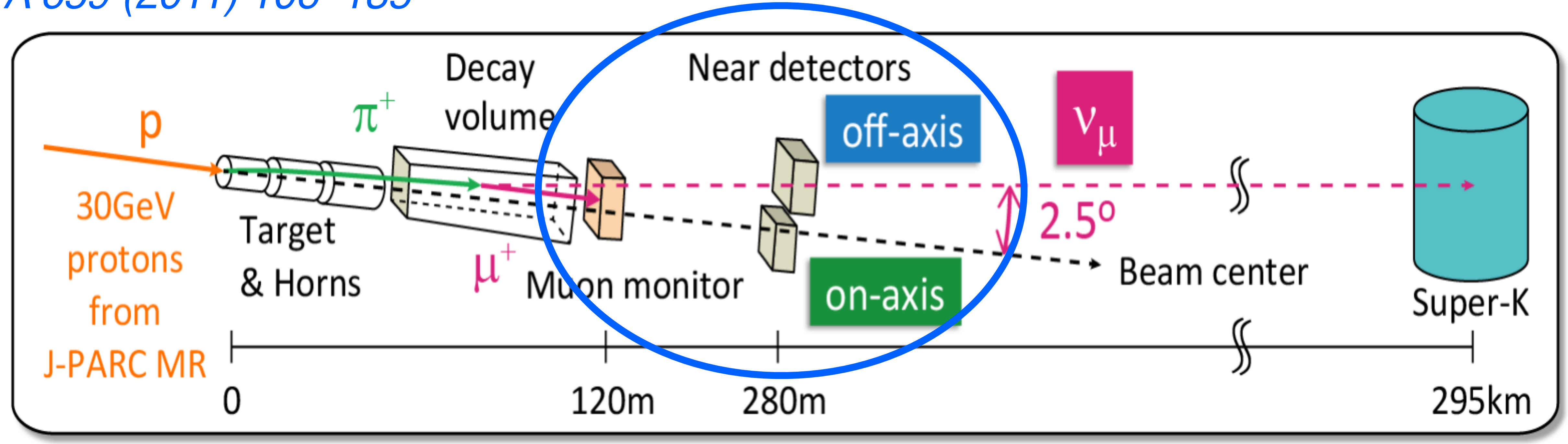
- <10% of wrong-sign background (ν_μ in $\bar{\nu}_\mu$ beam)

- Prediction of flux correlations between near / far detector, neutrino / antineutrino beam, ν_μ / ν_e is used

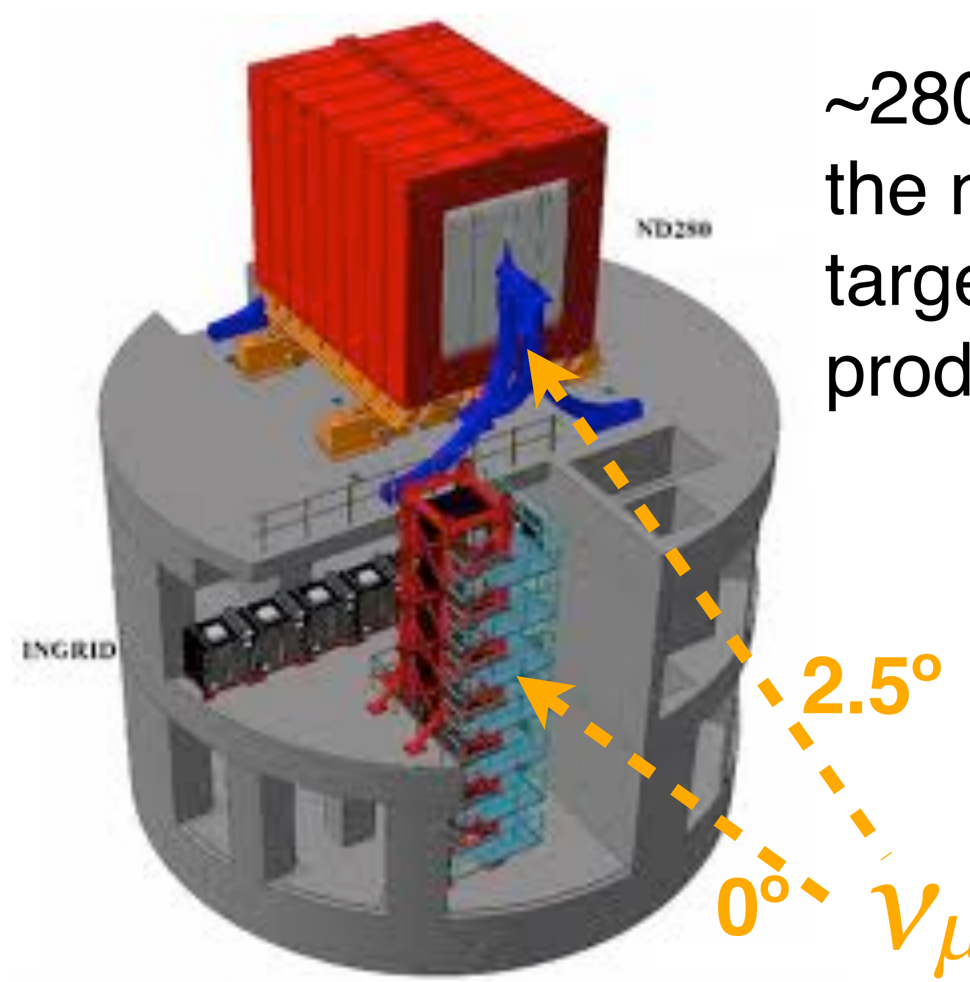


T2K near detector complex

NIM A 659 (2011) 106–135



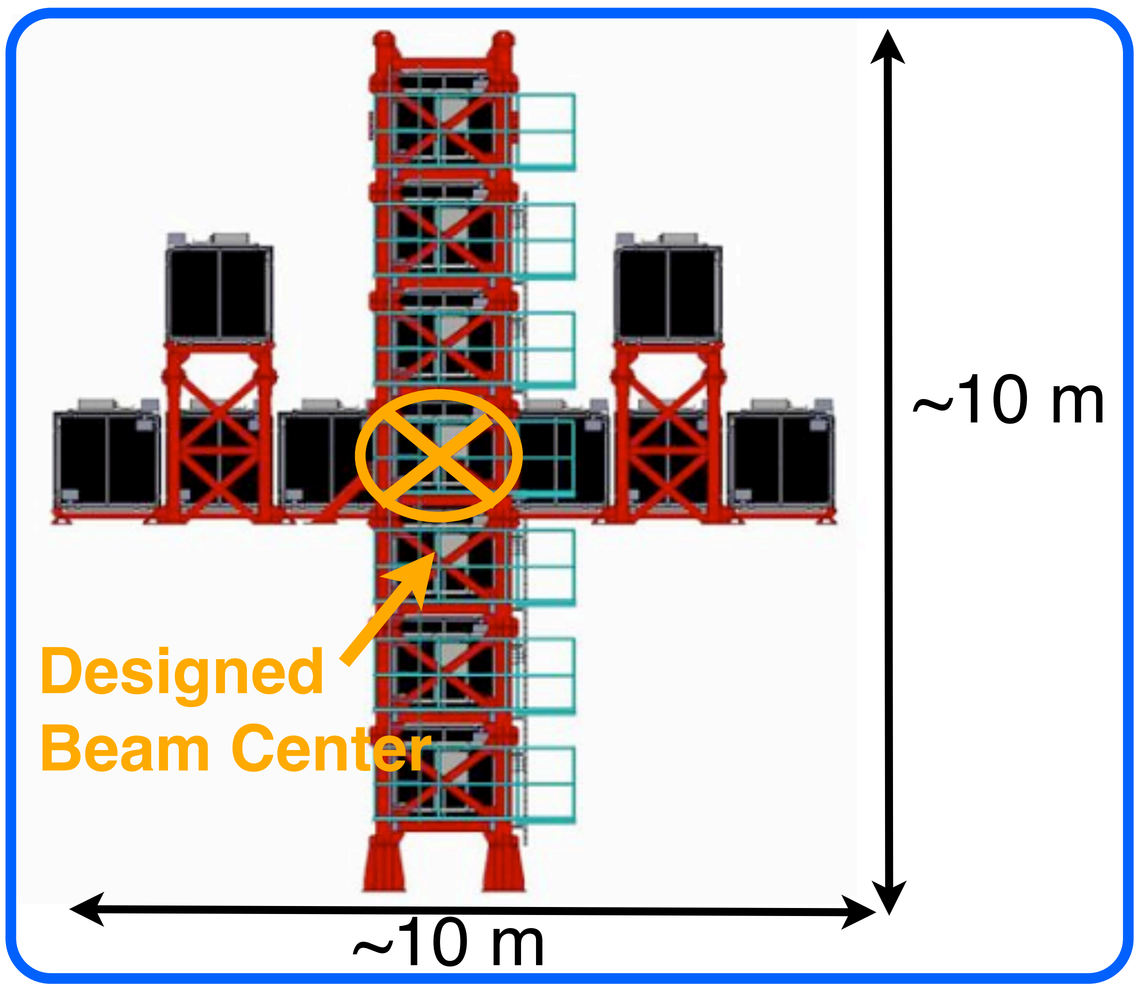
- **Muon monitor:**
  - spill-by-spill monitoring of the beam
- **On-axis detector:**
  - INGRID
  - measure beam intensity / direction
- **Off-axis detector:**
  - 2.5° off-axis magnetized detector
  - precise measurement of neutrino flux and cross section
  - measure wrong-sign background (20-30% ν_μ in $\overline{\nu}_\mu$ beam after interaction)

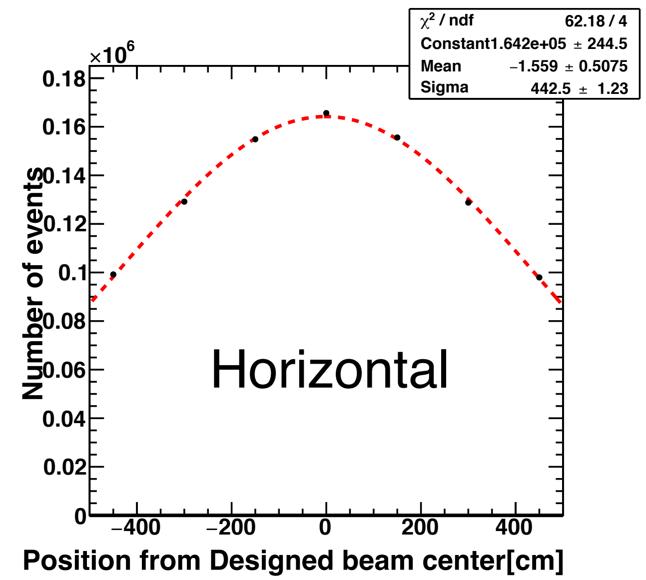


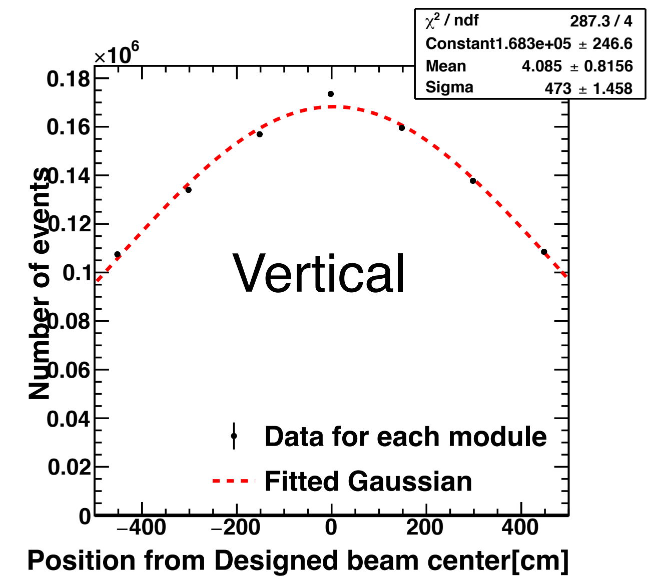
~280 m from the neutrino target production

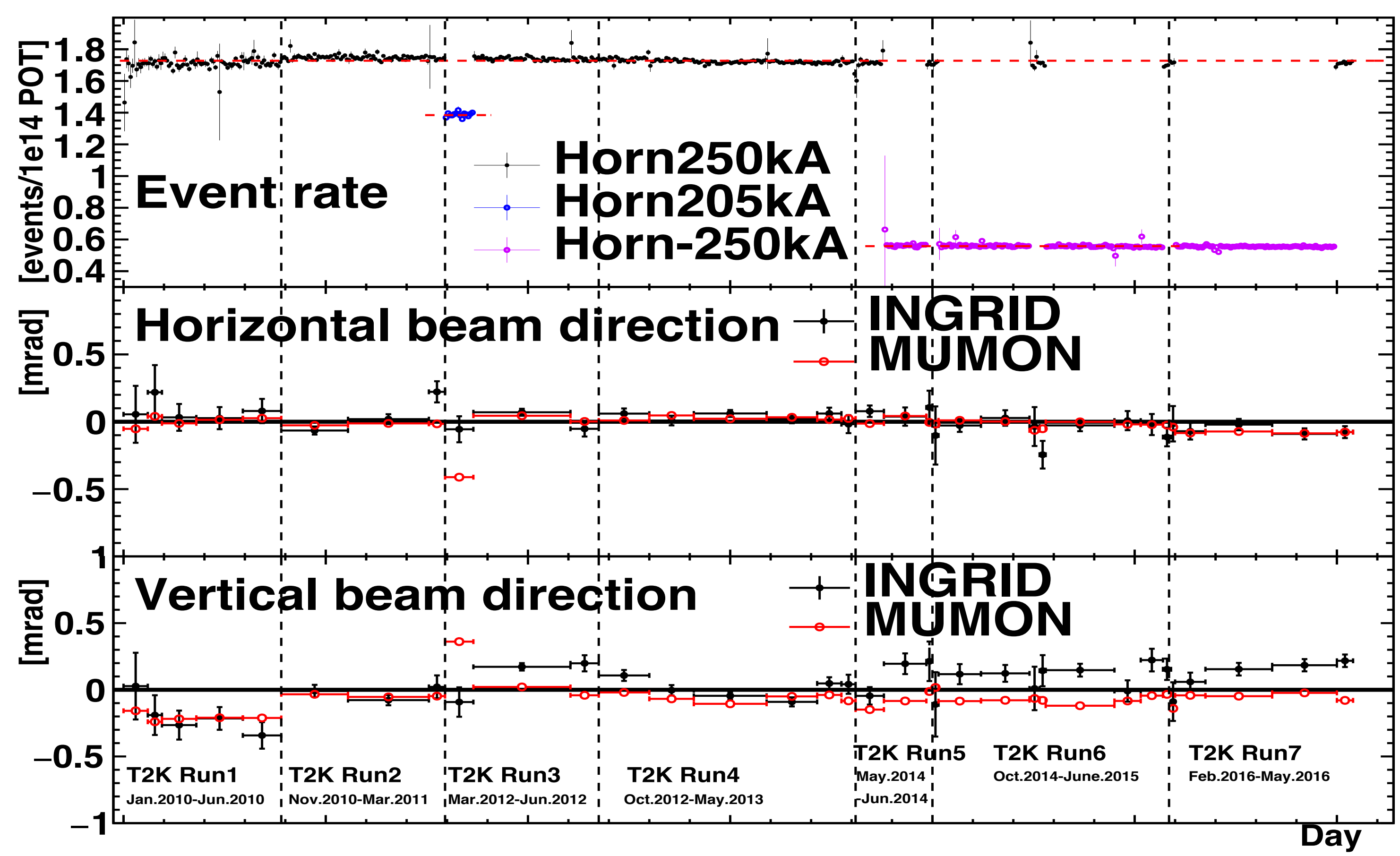
The On-Axis detector: INGRID

- 16 modules iron/scintillator tracking detectors (0-0.9° degrees off-axis)
- Measure neutrino beam profile (reconstruct muons tracks from ν_μ interactions)
- Beam direction stable within 1 mrad
  ~2% shift to peak in off-axis ν energy
- Protons On Target (POT) normalized event rate stable better than 1%

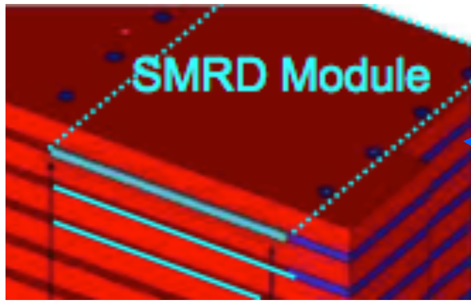


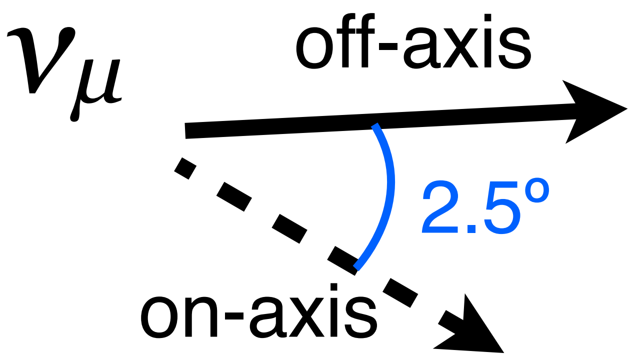


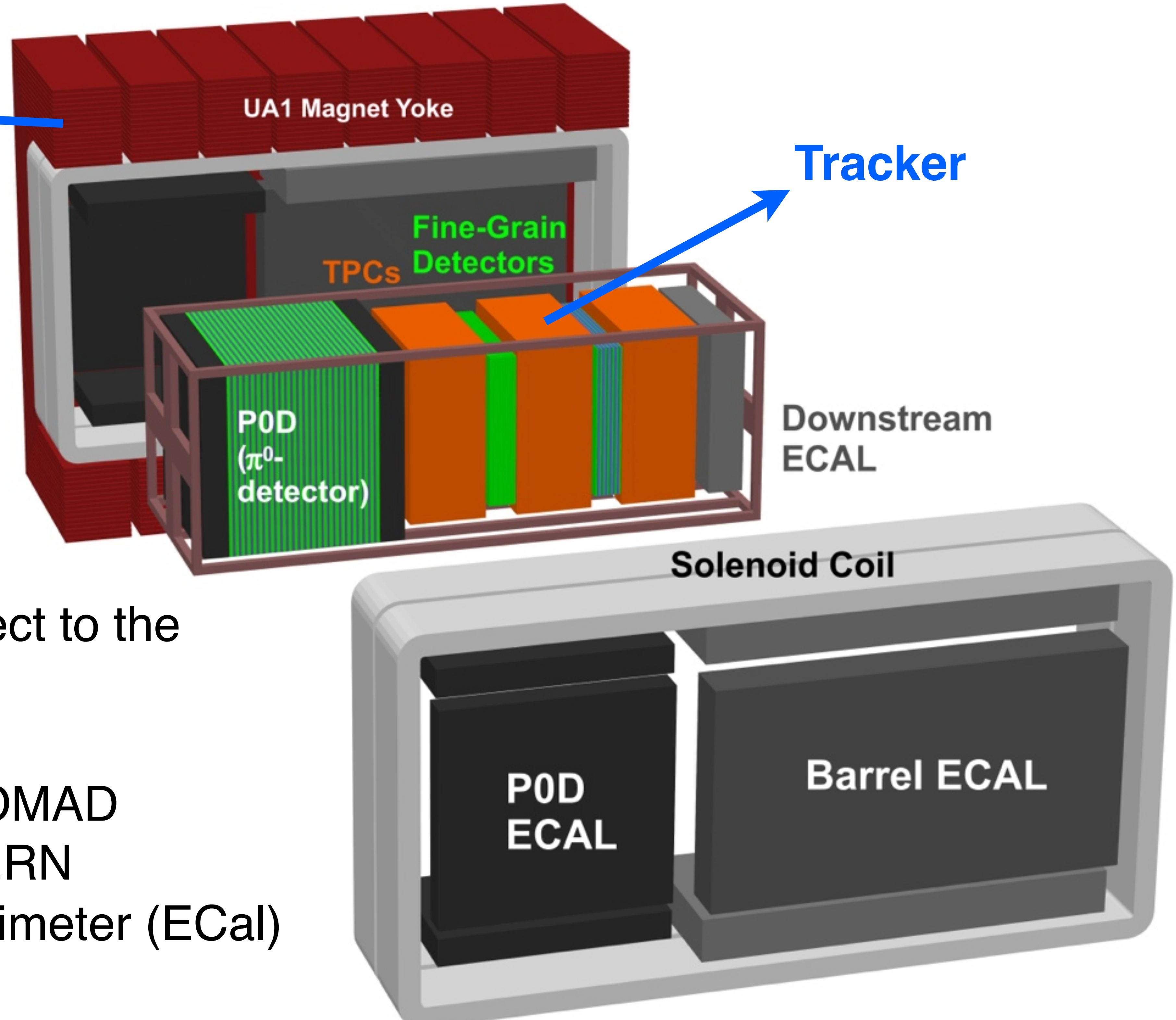




The Off-Axis detector: ND280



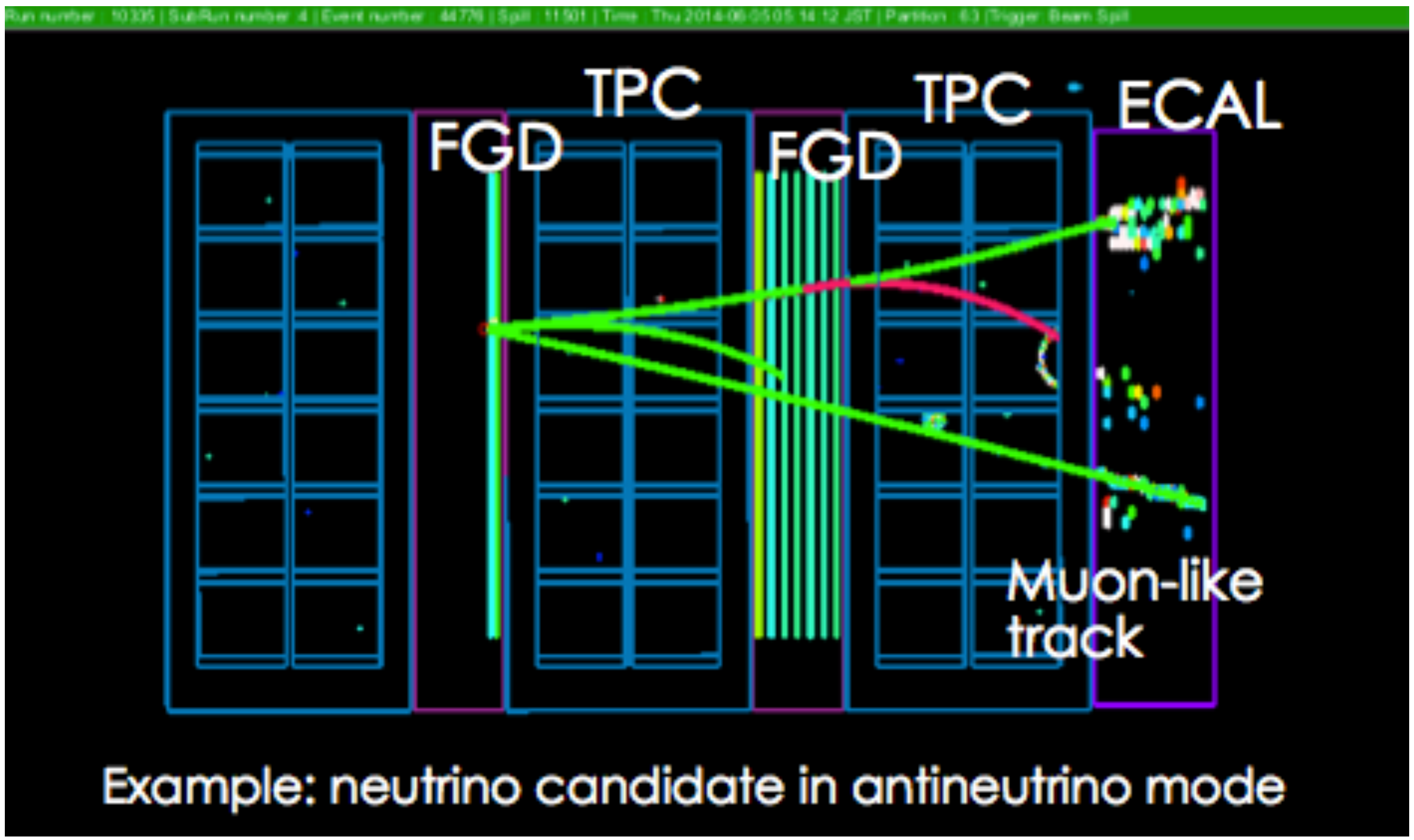


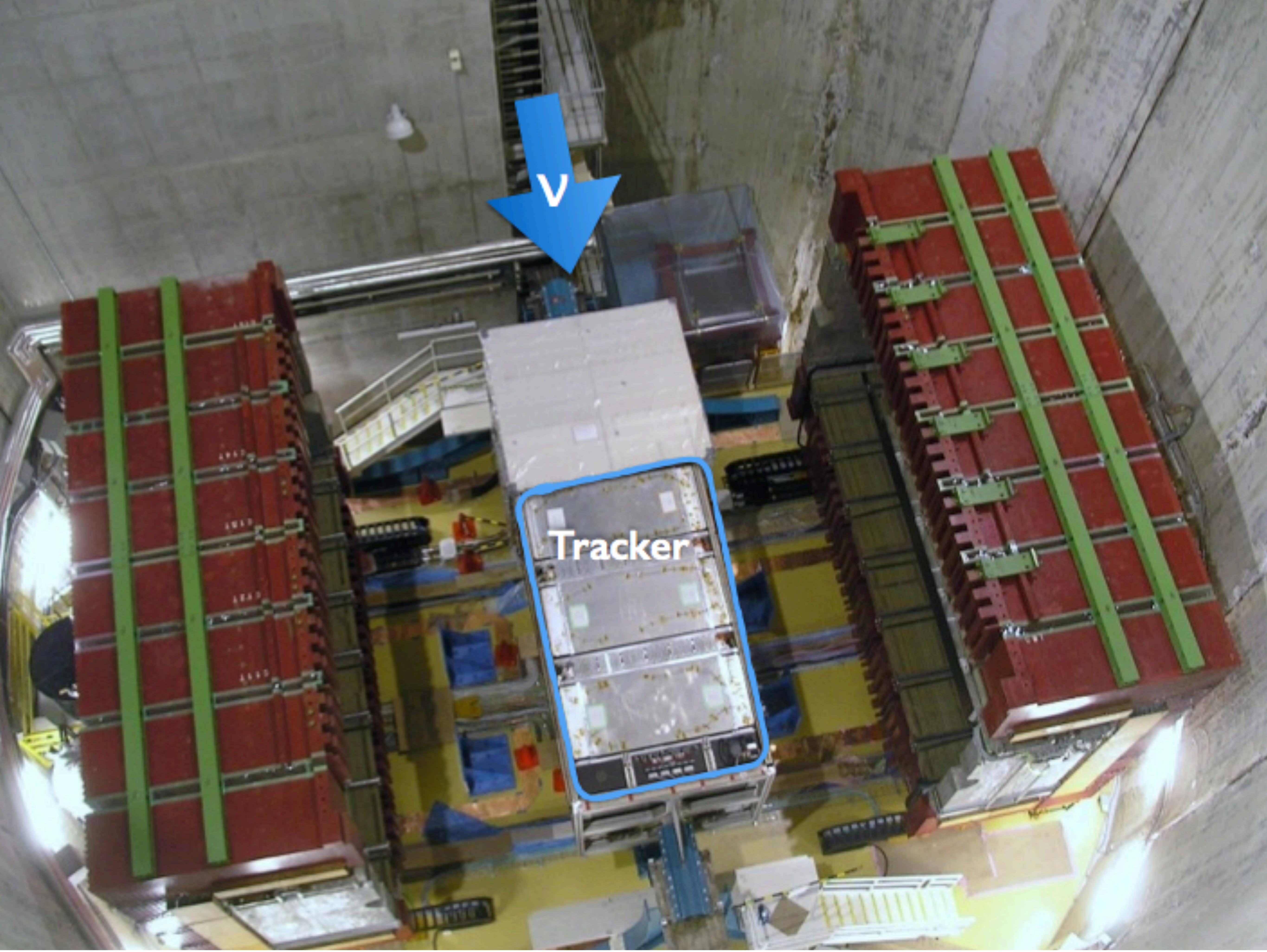


- 2.5° off-axis with respect to the neutrino beam direction
- 0.2 T dipole magnet
  - donation of UA1/NOMAD experiments from CERN
- Electromagnetic Calorimeter (ECal)
- π^0 detector (P0D)
- Side Muon Range Detector (SMRD)
- Tracker: 2 active neutrino targets + 3 Time Projection Chambers

The Off-Axis detector: the tracker

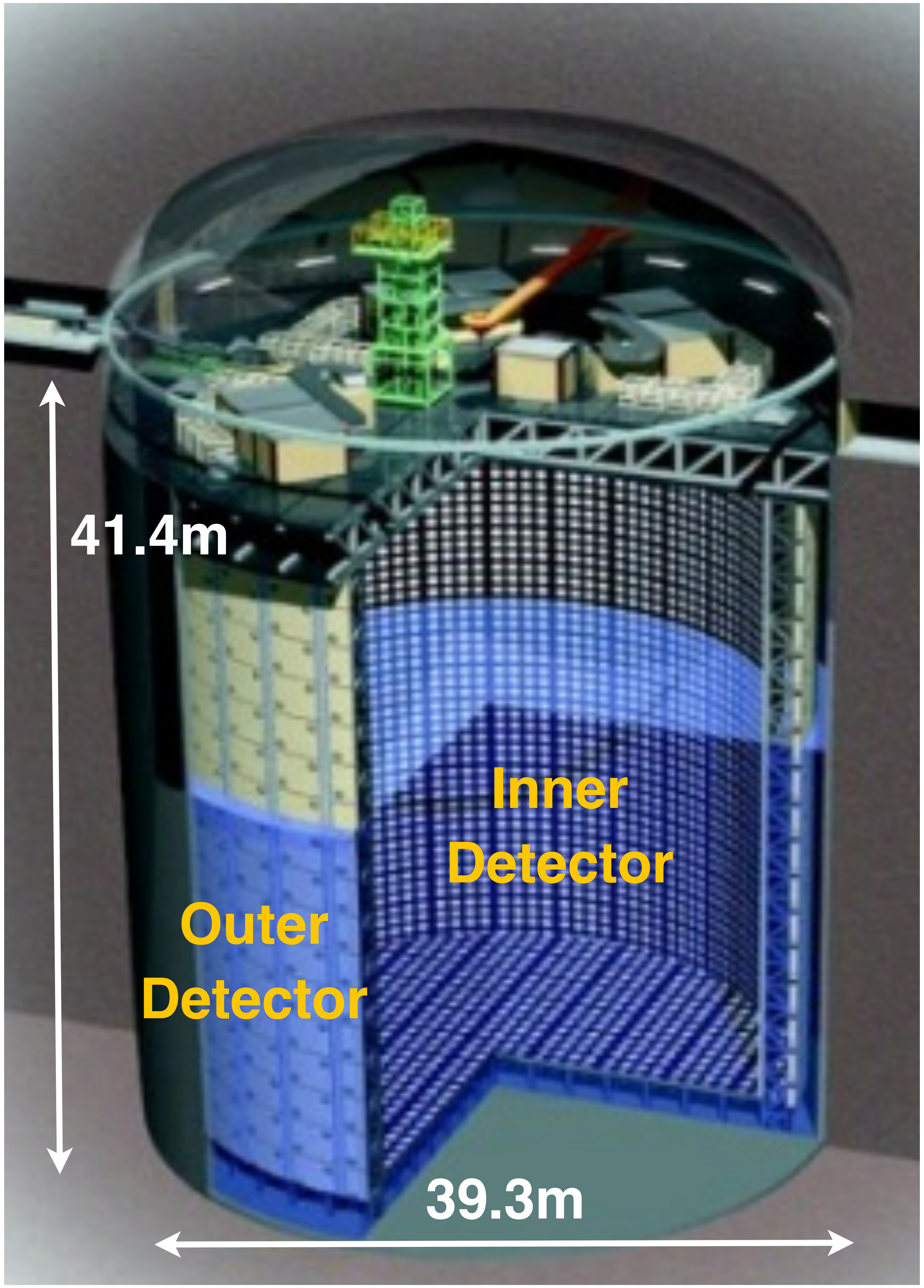
- 2 Fine-Grained Detectors (FGDs) as active neutrino target
  - FGD1 (plastic scintillator) + FGD2 (50%:50% water:scintillator)
  - 1.6 ton fiducial mass for analysis
  - constrain cross section on water with FGD2 - FGD1 subtraction
- 3 Time Projection Chambers (TPC)
  - better than 10% dE/dx resolution and 10% momentum resolution at 1GeV/c
  - measure neutrino contamination in antineutrino beam (wrong sign background)

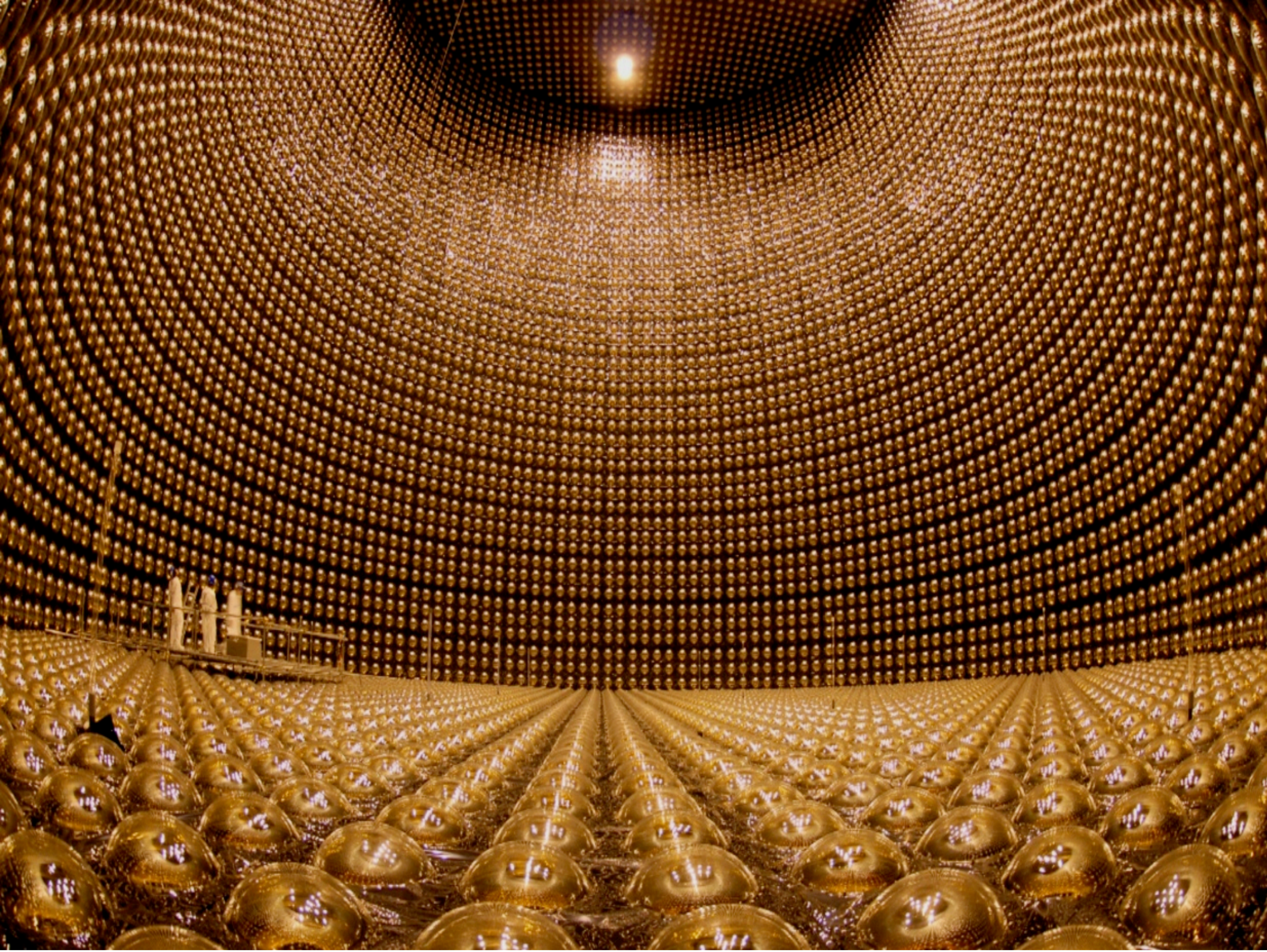


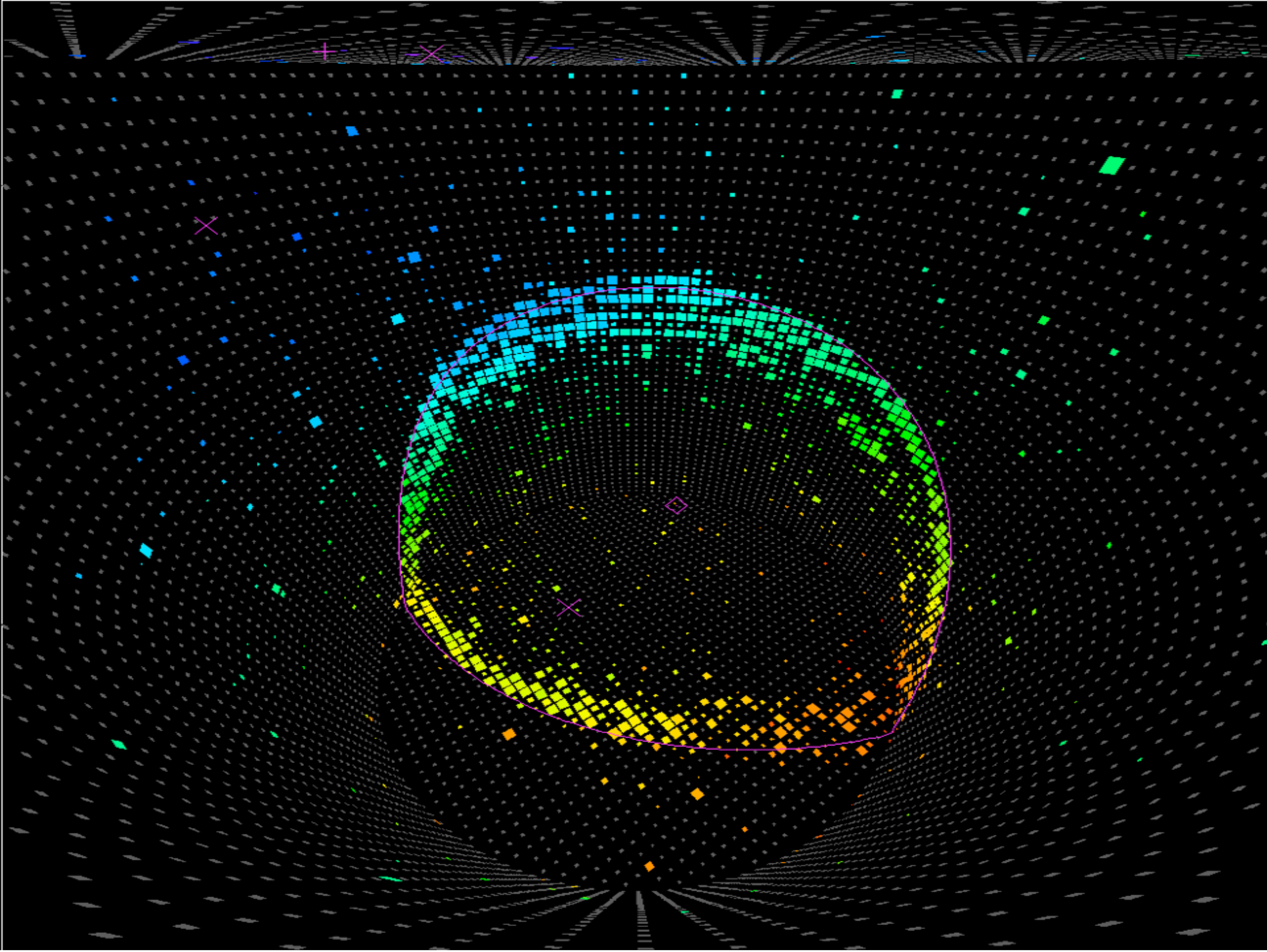

ν
Tracker

T2K far detector: Super-Kamiokande

- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events
- New DAQ system: no dead time
- T2K beam event: ±500 μs window

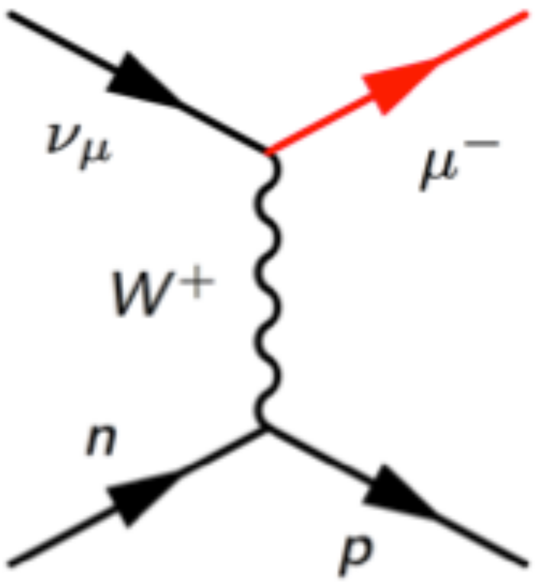




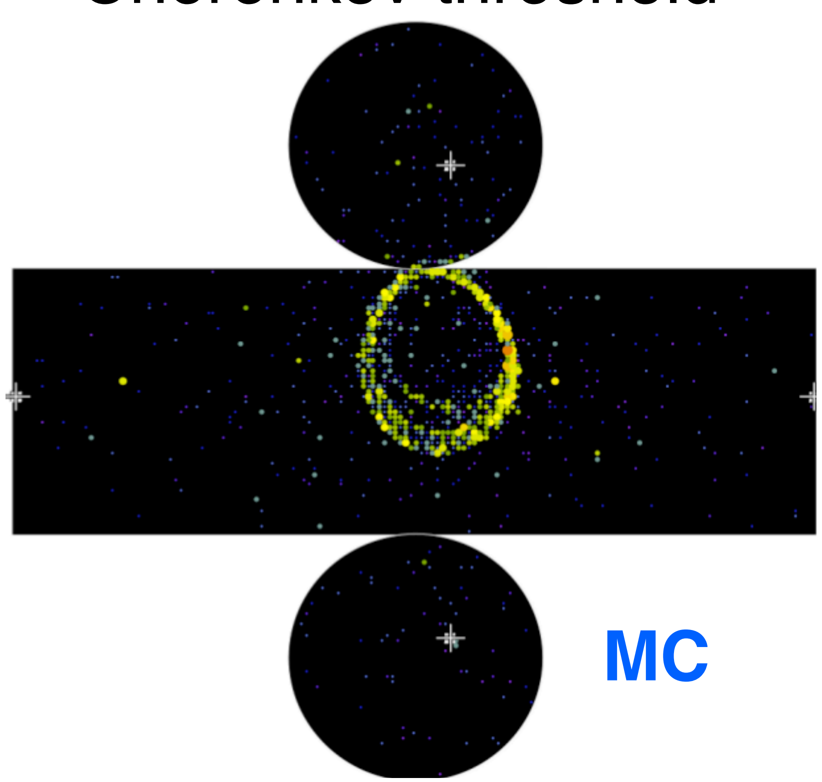


Super-Kamiokande events

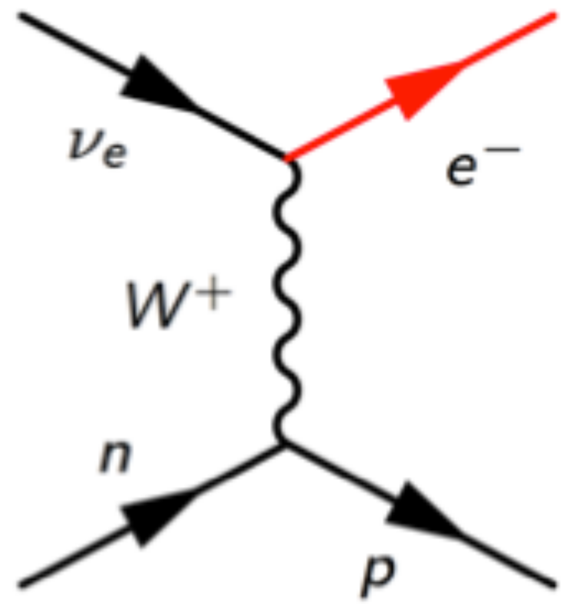
ν_μ CCQE



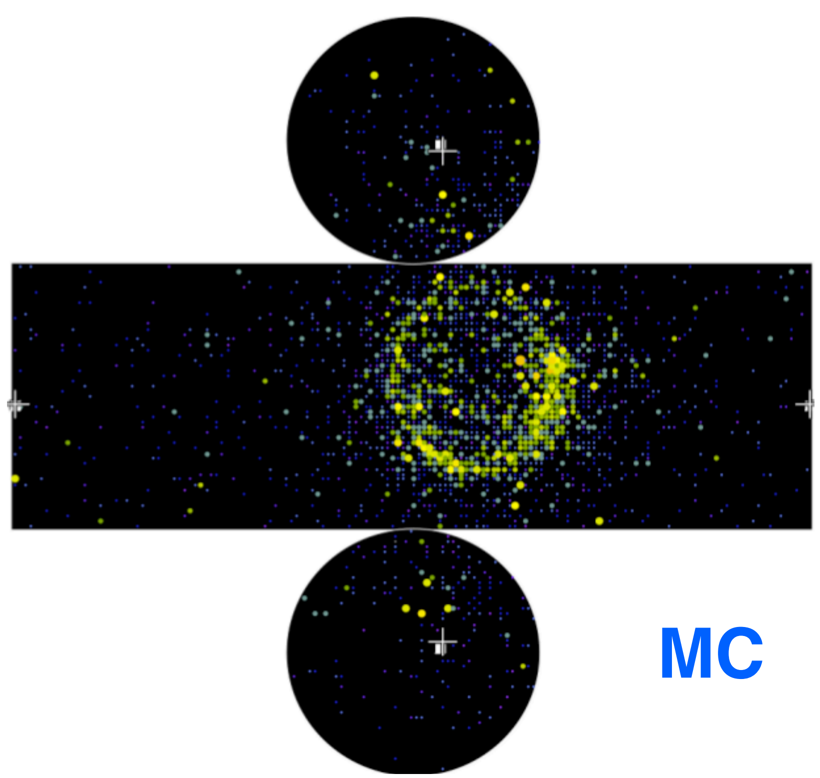
- 1 Cherenkov ring
- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold



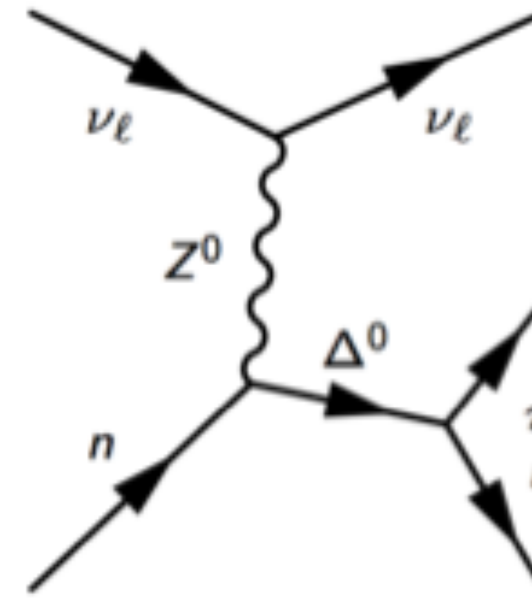
ν_e CCQE



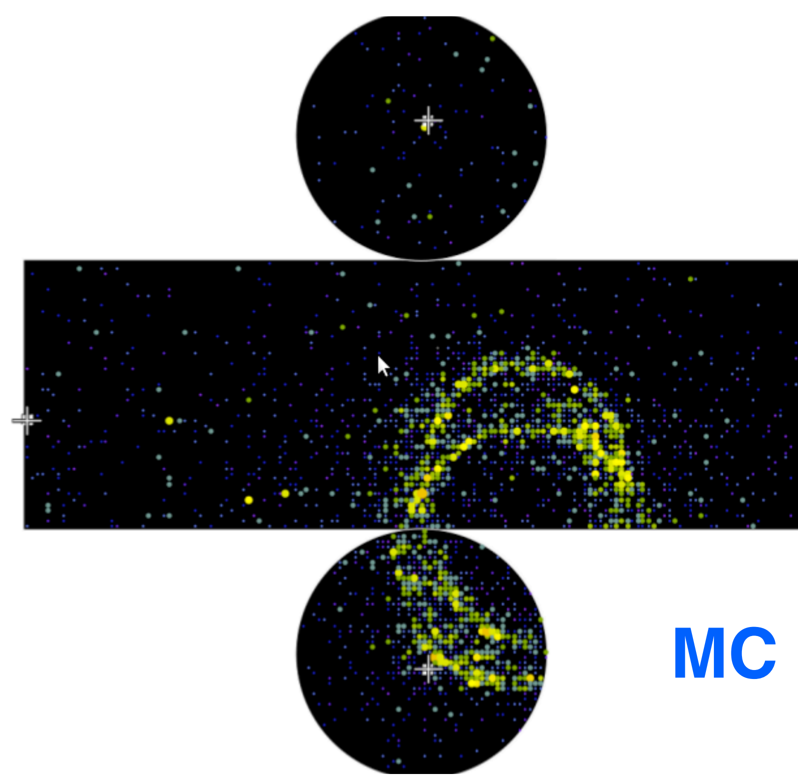
- 1 Cherenkov ring
- Multiple scattering
- EM shower
- Ring with “fuzzy” edge



Background

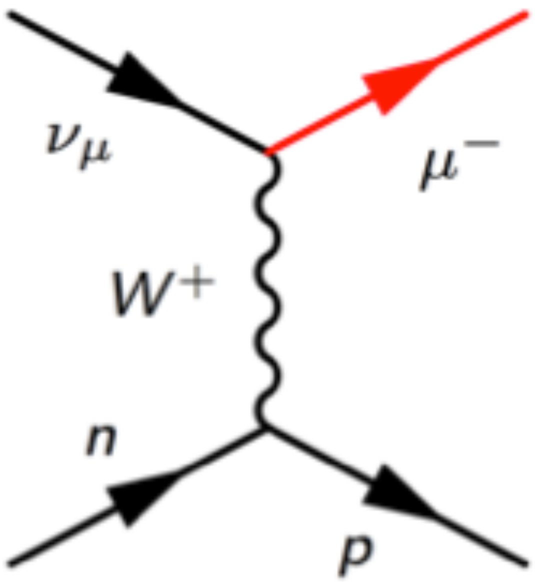


- 2 Cherenkov rings
- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron

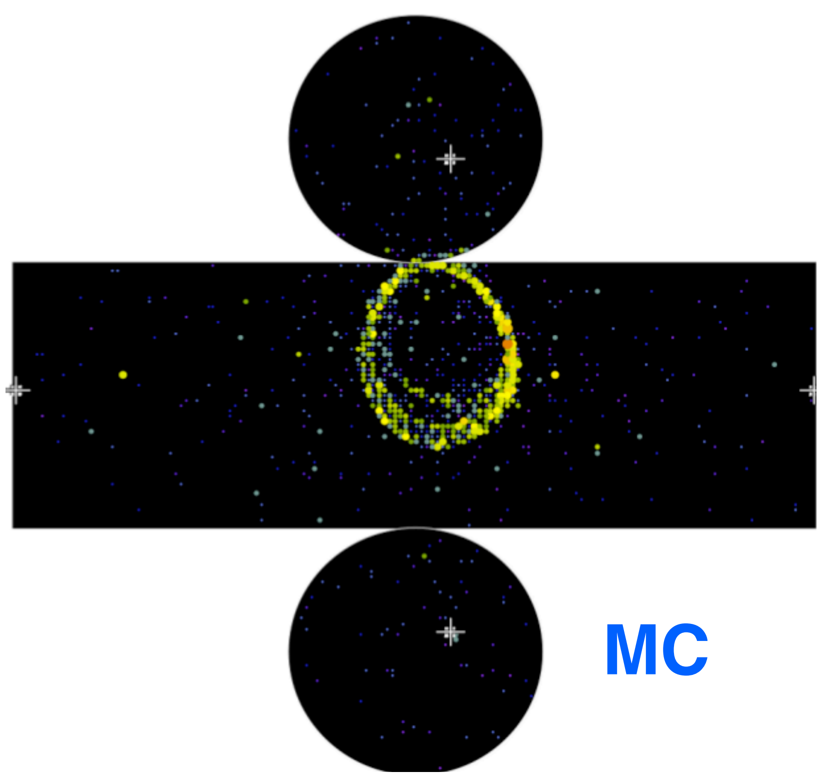


Super-Kamiokande events

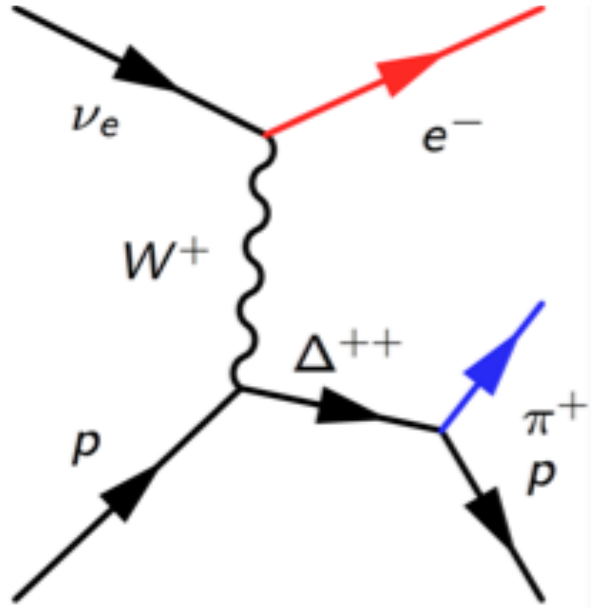
ν_μ CCQE



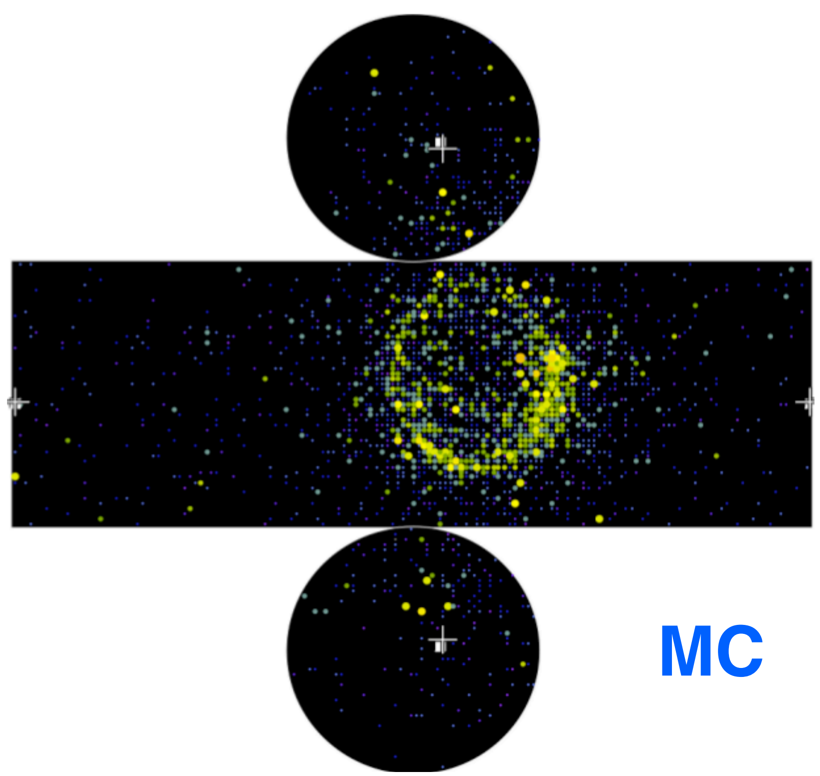
- 1 Cherenkov ring
- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold



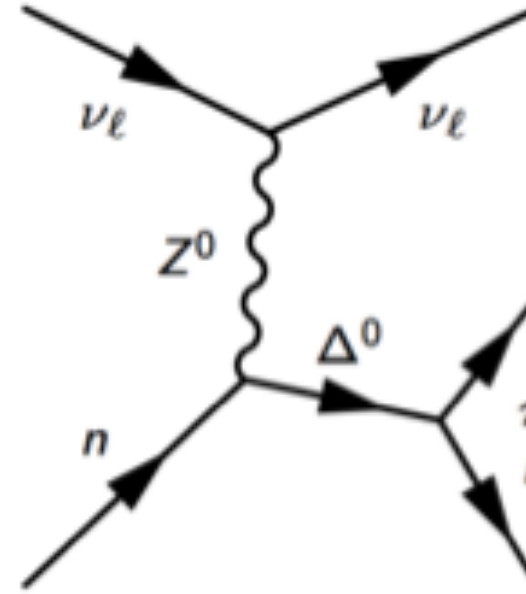
ν_e CC1π



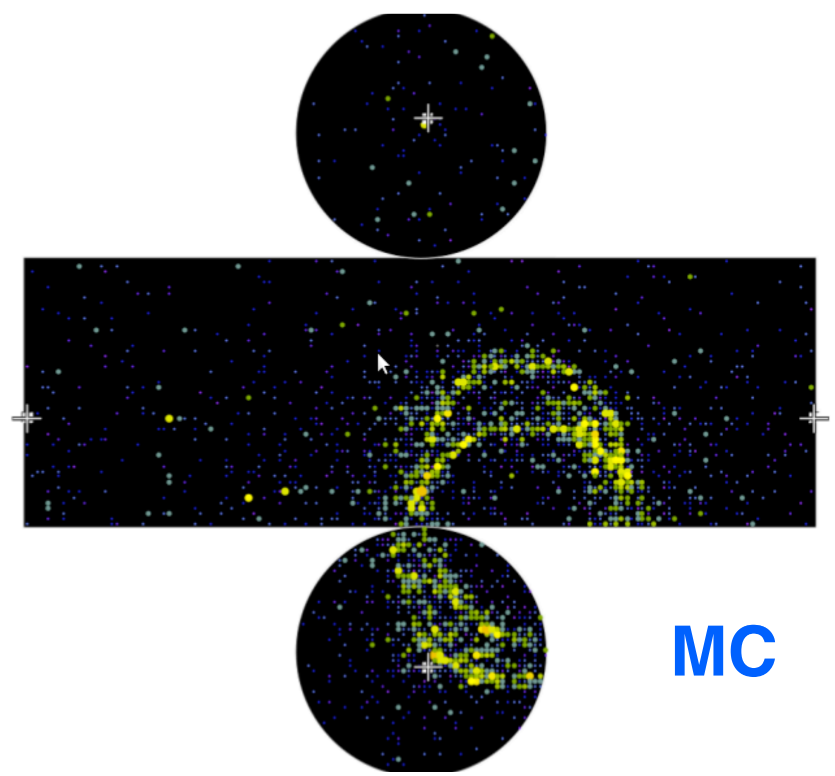
- Same as ν_e CCQE
- Delayed (~2.2 μs) electron $\pi^+ \rightarrow \nu_\mu\, \mu^+ \rightarrow e^+\, \nu_e\, \bar{\nu}_\mu$
- New sample: +10% events



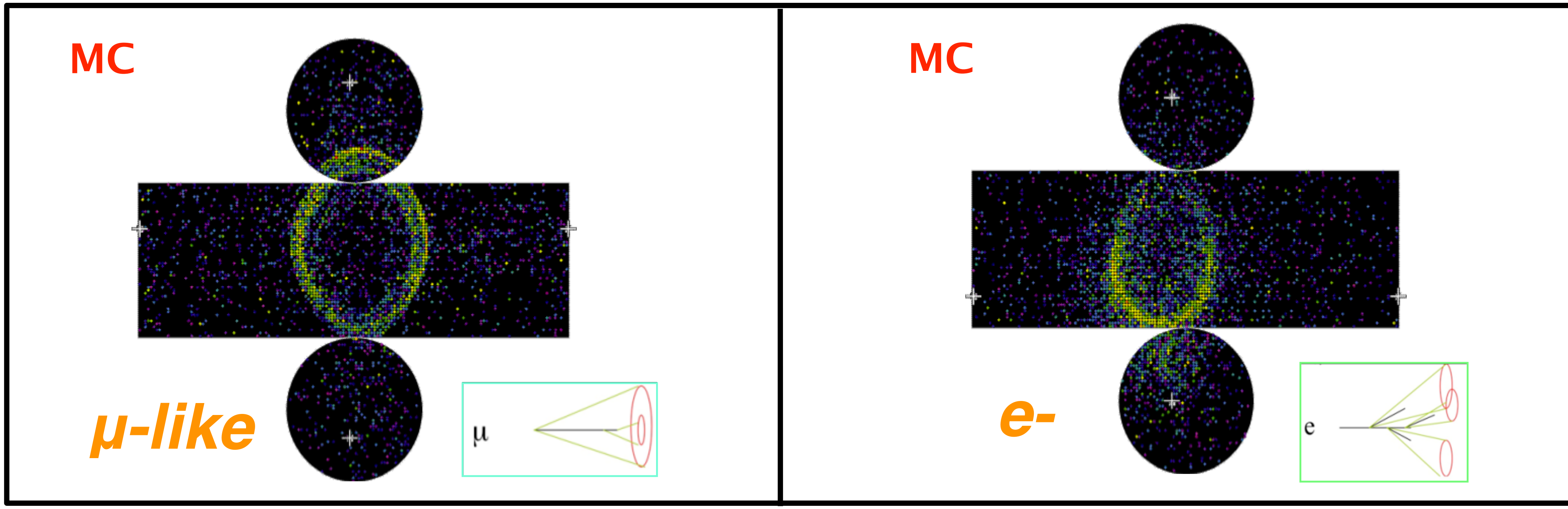
Background

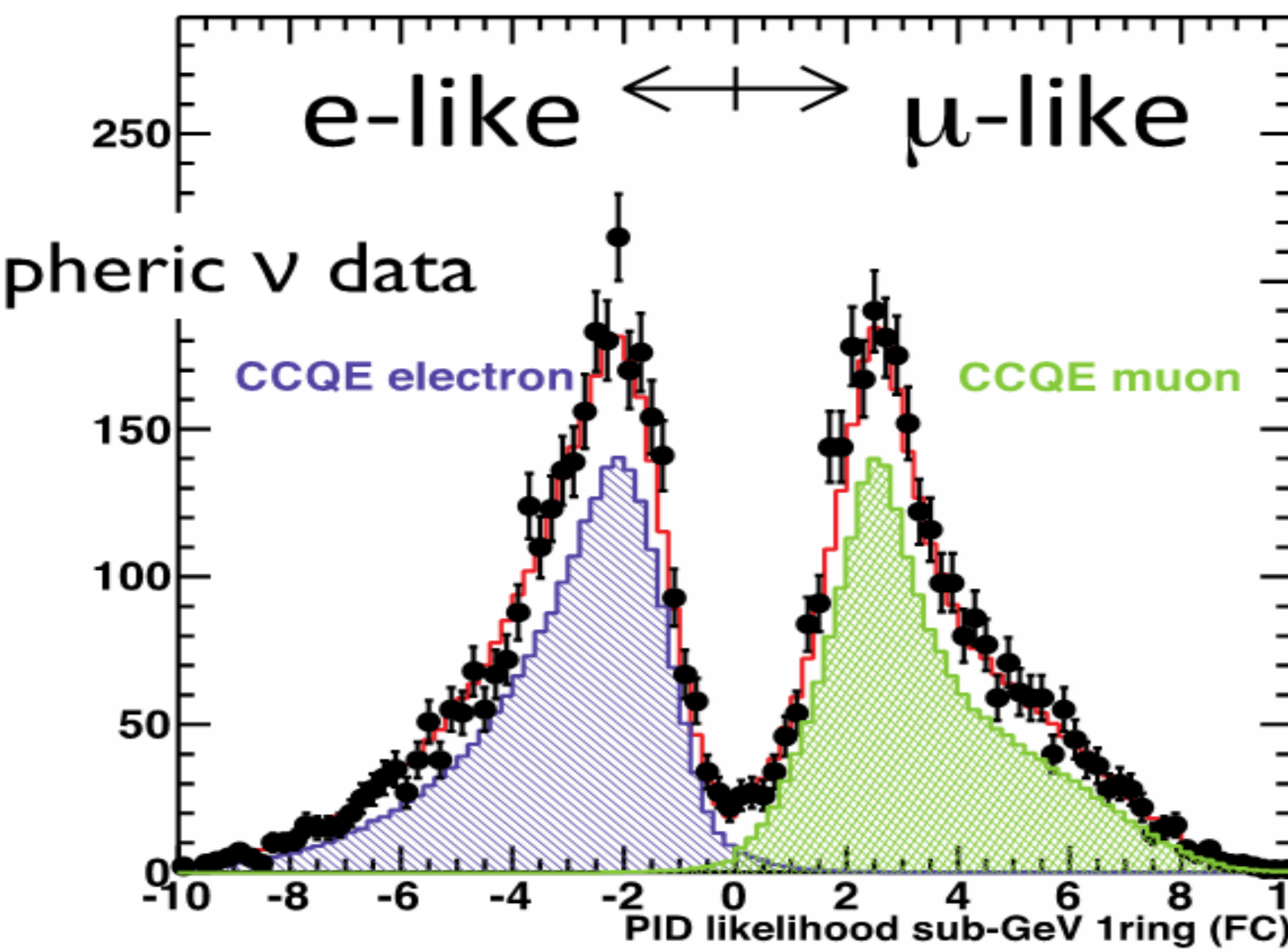


- 2 Cherenkov rings
- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron



Particle Identification at the far detector

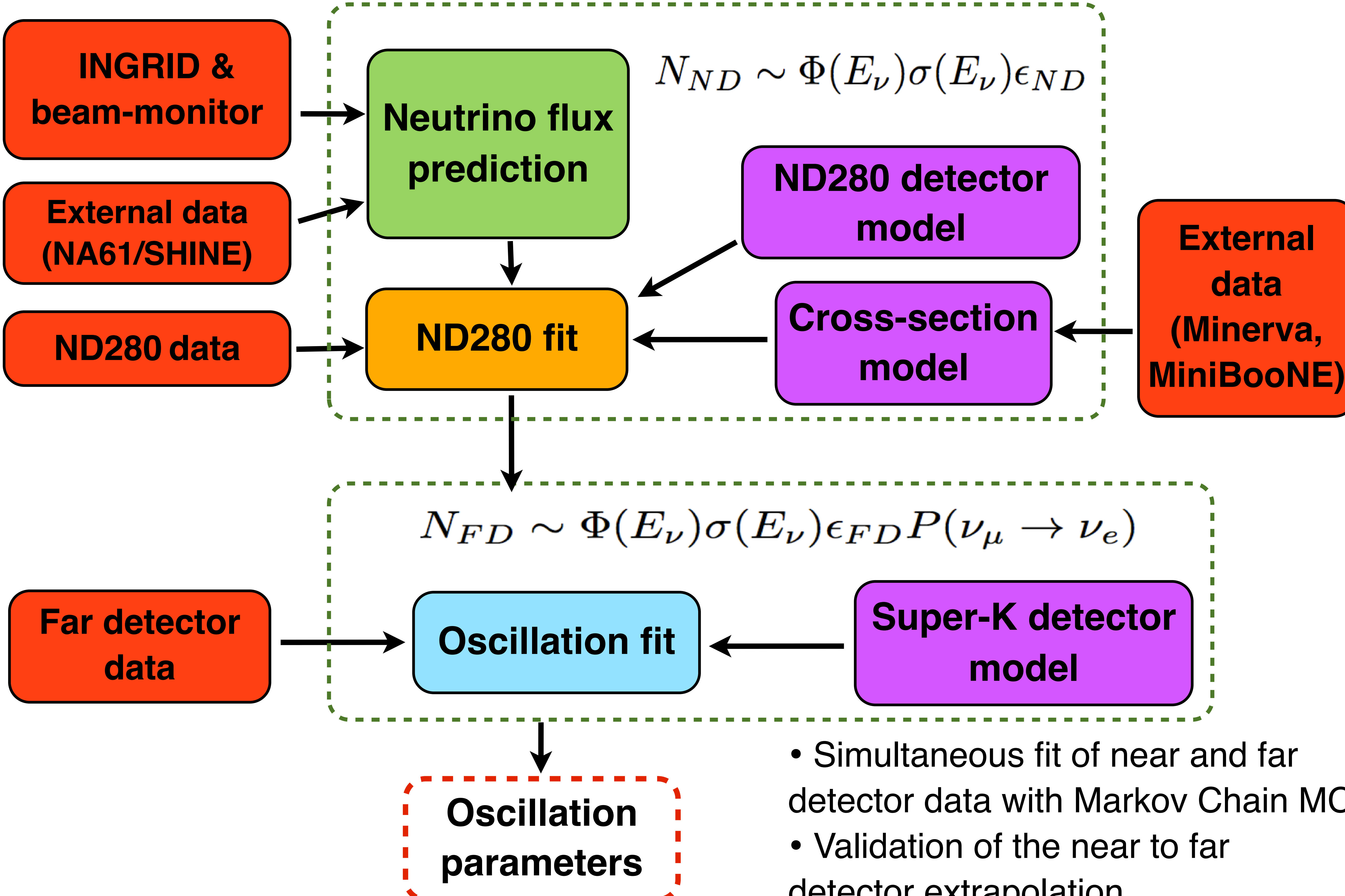




- Excellent e/μ separation

- Probability to misidentify a muon as an electron is smaller than 1%

Strategy for oscillation analyses

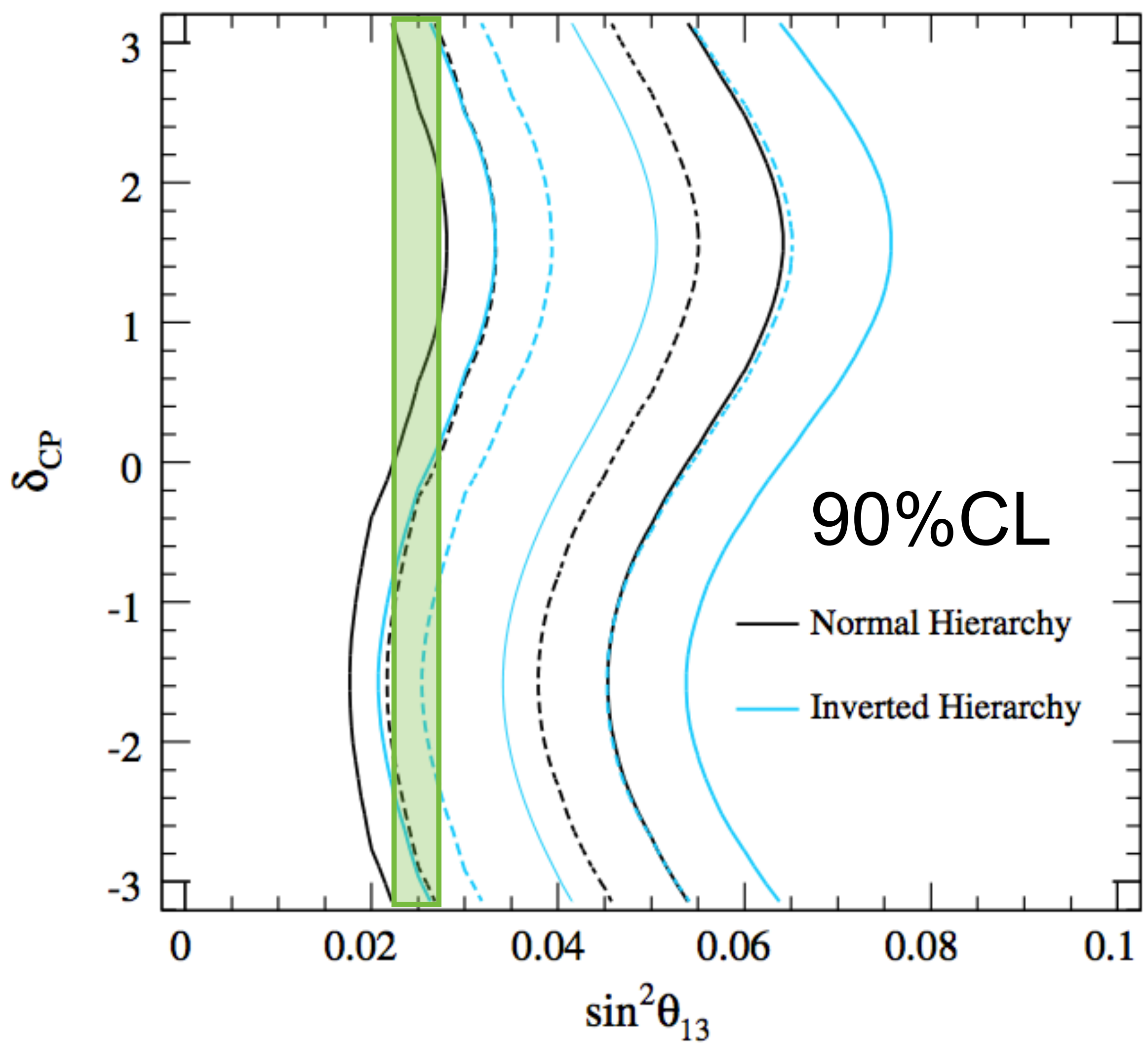


- Simultaneous fit of near and far detector data with Markov Chain MC
- Validation of the near to far detector extrapolation

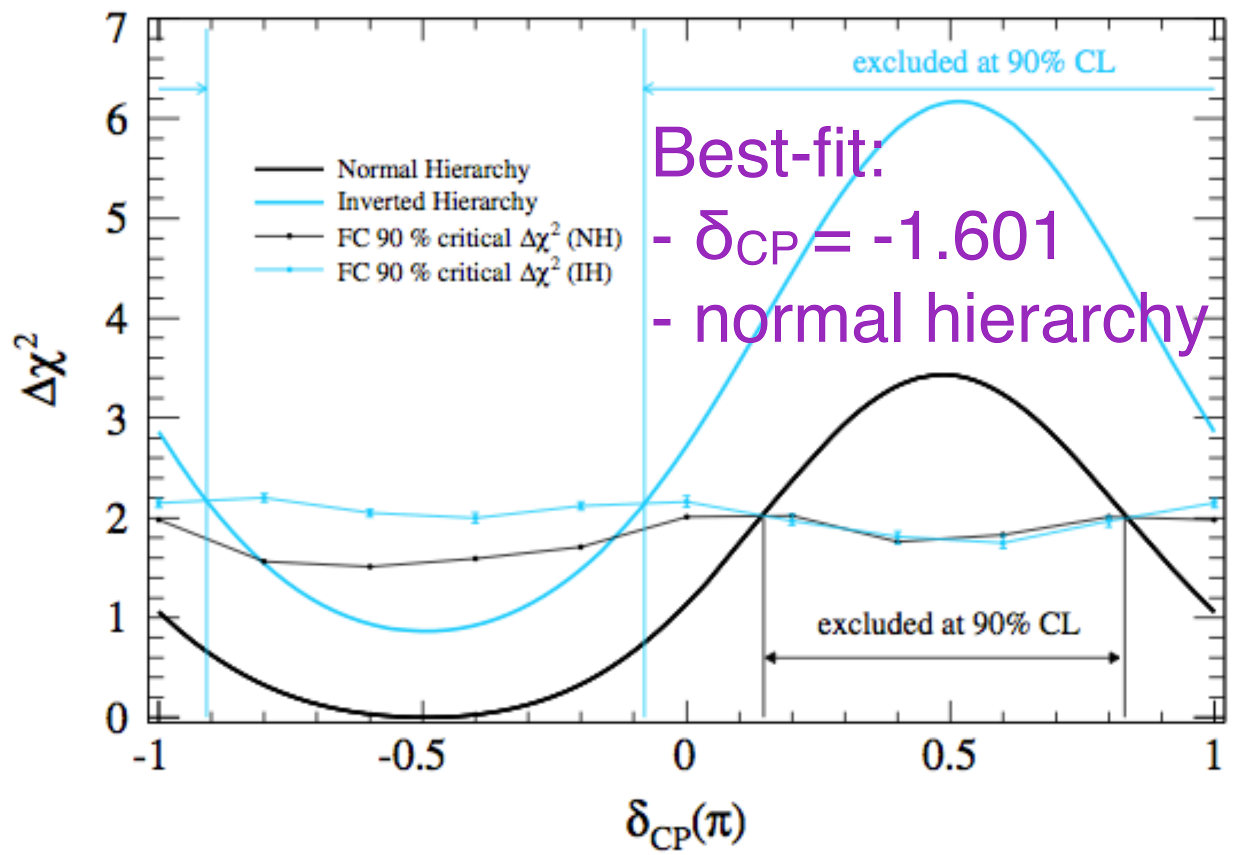
Where we were with only neutrino data

- 6.6 x 10^{20} protons on target (POT) at Super-K of neutrino beam mode data
- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance (7.3σ) (*Phys. Rev. Lett. 112, 061802 (2014)*) opens a window on the search for CP violation in leptonic sector
- Slight preference for $\delta_{CP} \sim -\pi/2$ and Normal Hierarchy

Phys. Rev. D 91, 072010 (2015)



- Θ_{13} constrained with reactor measurement (PDG2013)
- $\sin^2\theta_{13} = 0.0243 \pm 0.0026$



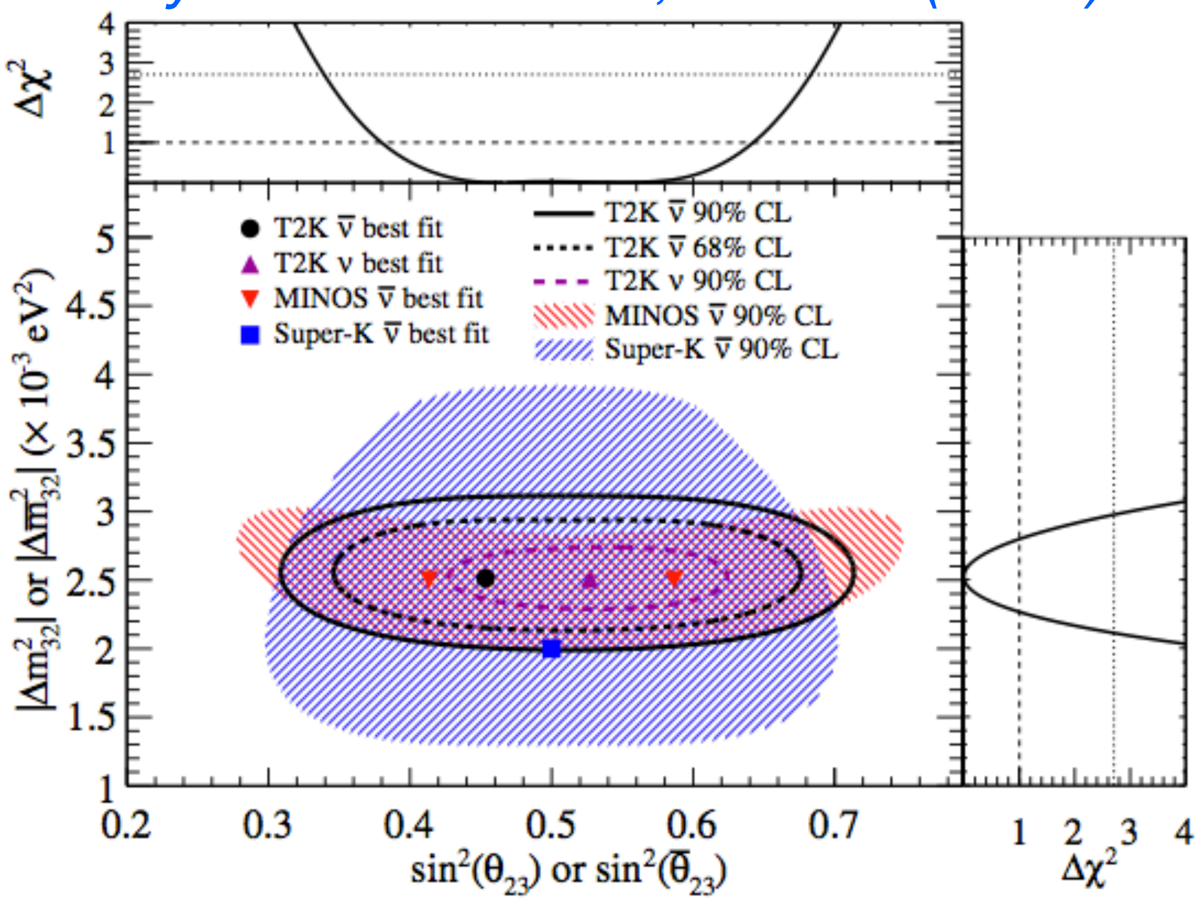
Need to directly compare neutrino and antineutrino to infer δ_{CP}

Previous T2K measurements with antineutrino data

- About half of the current statistics: 4×10^{20} POT at Super-K
- Results presented in 2015 at the main HEP conferences and laboratories

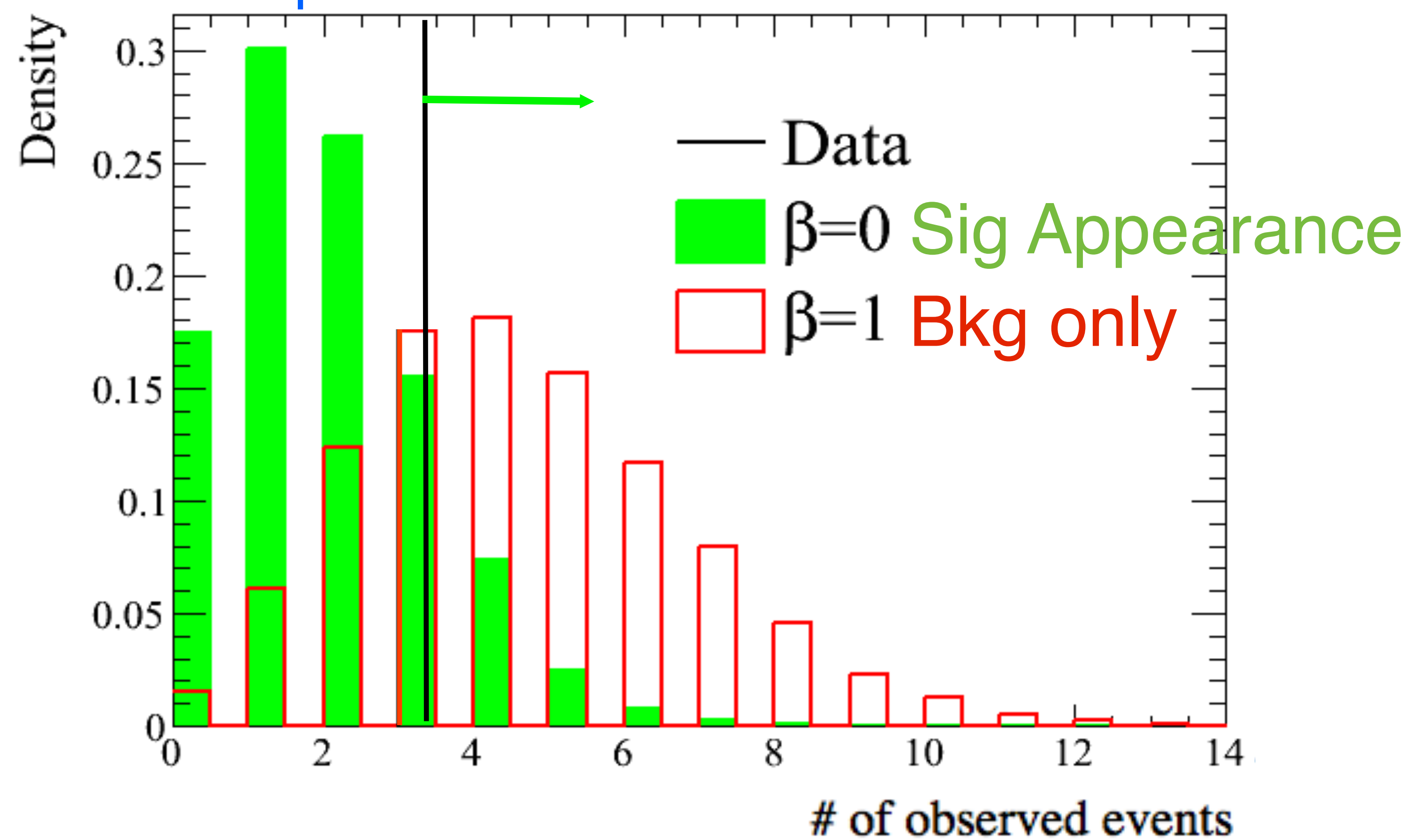
$\overline{\nu}_\mu$ disappearance

Phys. Rev. Lett. 116, 181801 (2016)



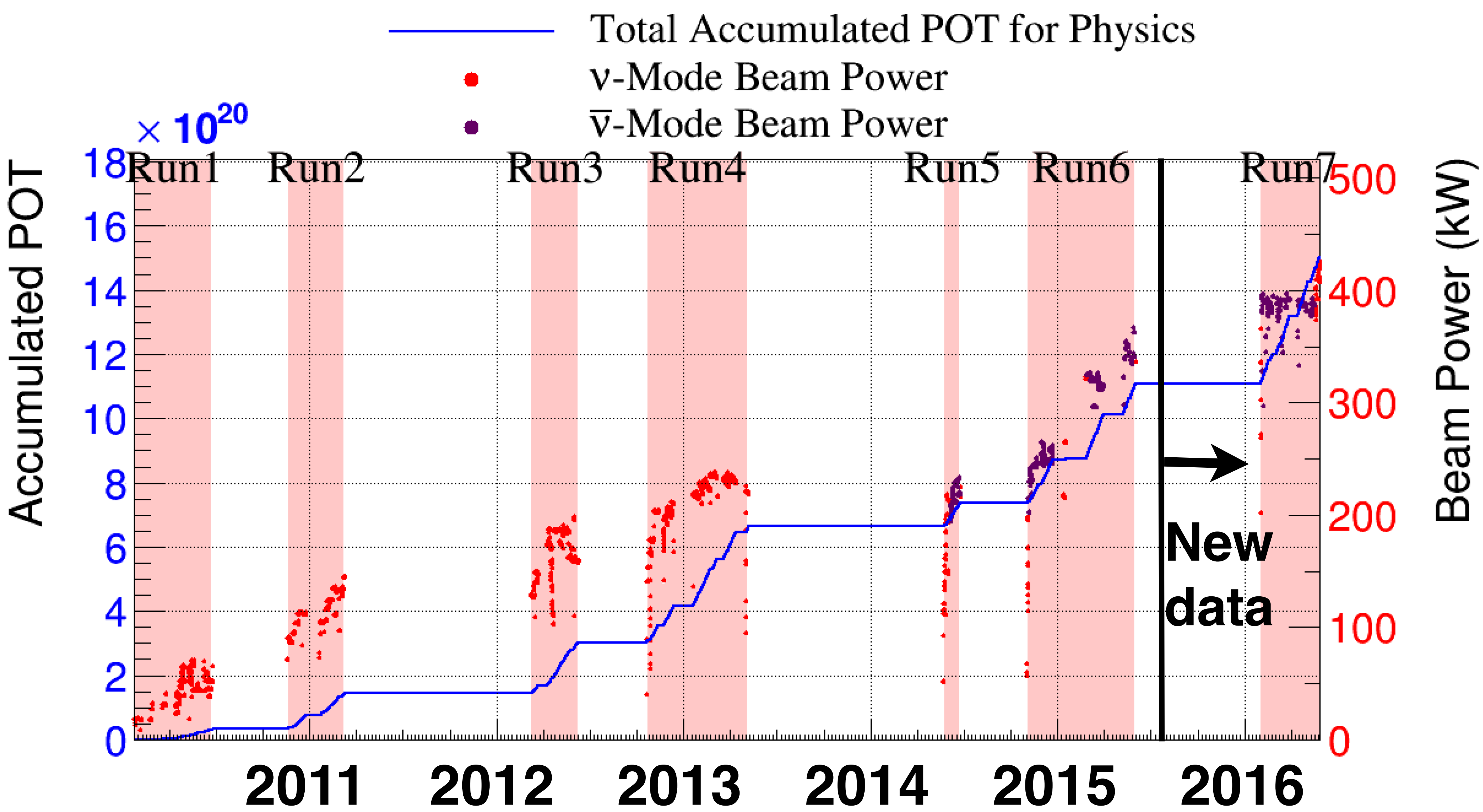
$\overline{\nu}_e$ appearance

https://indico.cern.ch/event/404254/



- No evidence for $\overline{\nu}_e$ appearance (p-value to nuebar appearance = 0.26)
- Agreement between neutrino and antineutrino data
- Joint analysis of higher statistic neutrino and antineutrino data is a necessary step toward searches for CP violation

Data taking in 2016



27 May 2016
POT total: $1.510{\times}10^{21}$

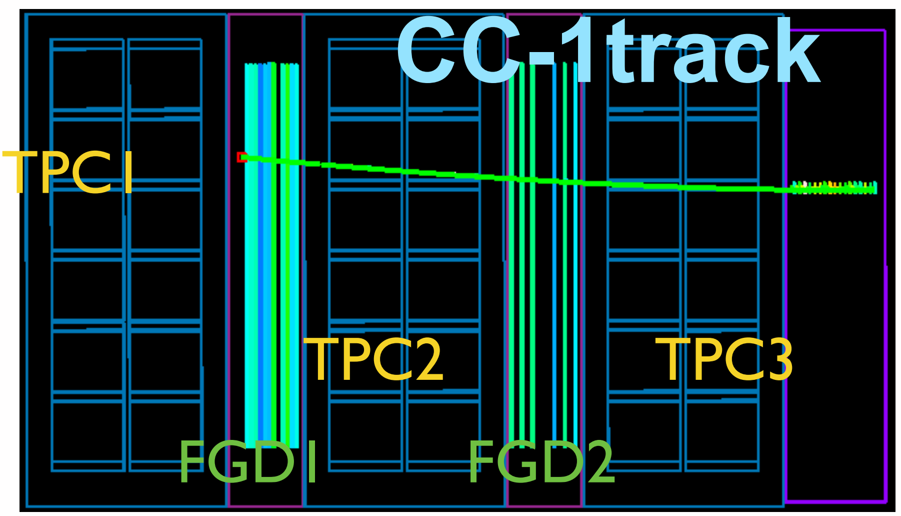
ν-mode POT: $7.57{\times}10^{20}$ (50.14%)
ν̄-mode POT: $7.53{\times}10^{20}$ (49.86%)

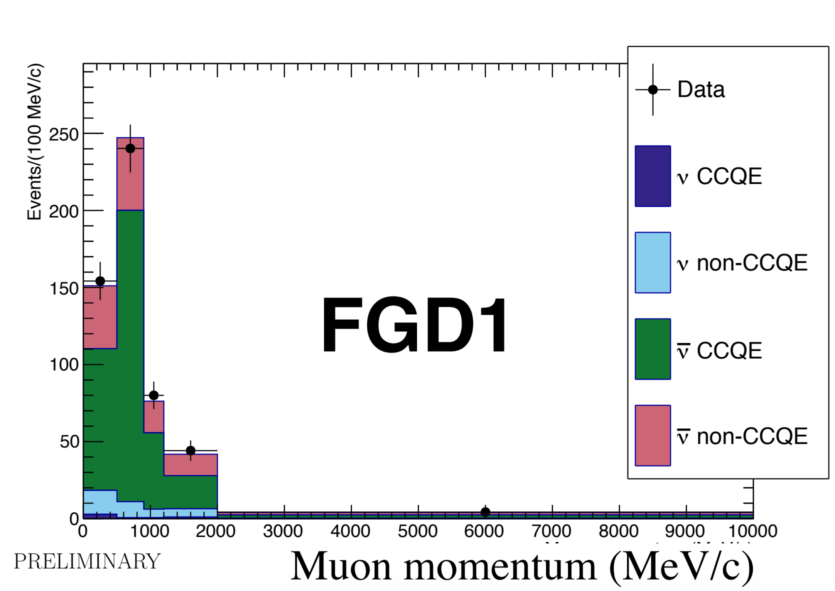
- Beam power increased up to 420 kW in 2016. Now running stable at ~470 kW
- Almost doubled protons-on-target (POT) in antineutrino beam mode wrt 2015
- Almost same number of POT in neutrino and antineutrino beam mode

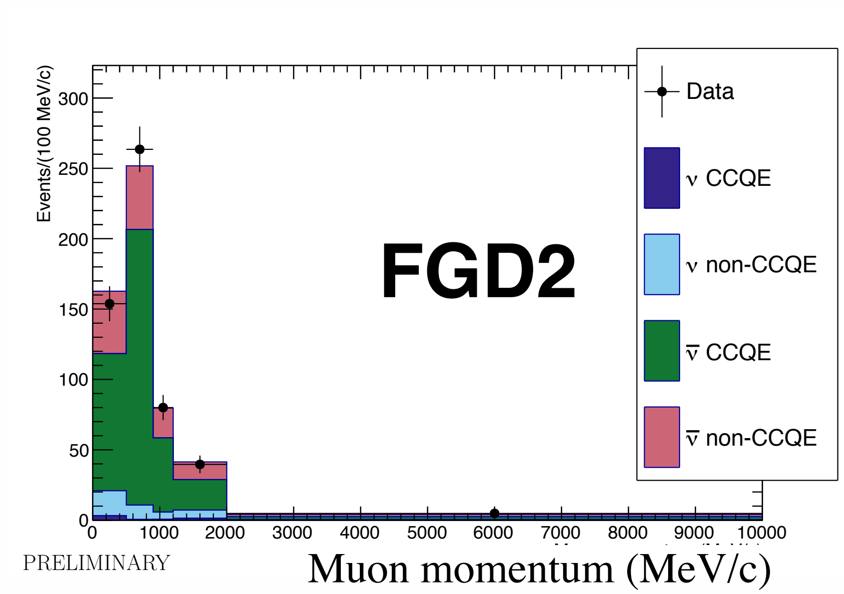
Near Detector Fit: antineutrino samples

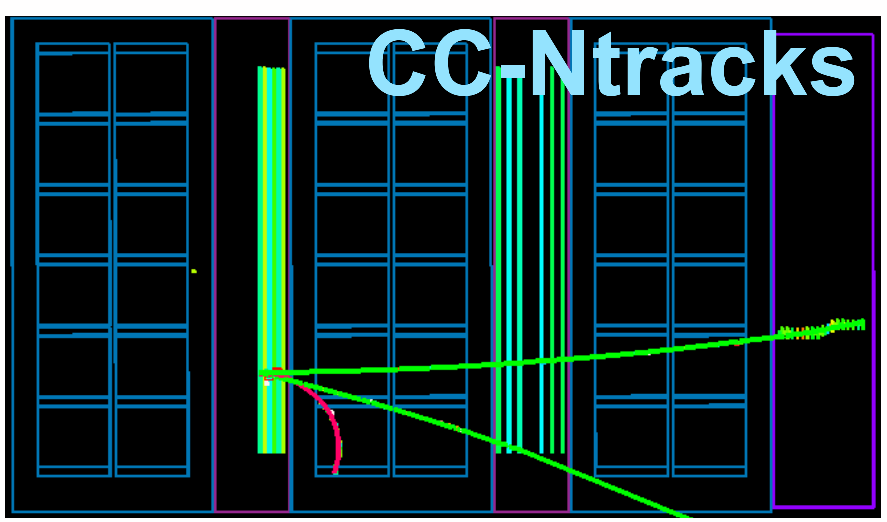
- Antineutrino samples: 1 μ^+ candidates (CC-1track) + CC-Ntracks
- Neutrino samples: 1 μ^- candidates (CC-0π) + 1π^+ (CC-1π) + CC other
- Simultaneous analysis of neutrino and antineutrino data (μ momentum/angle)

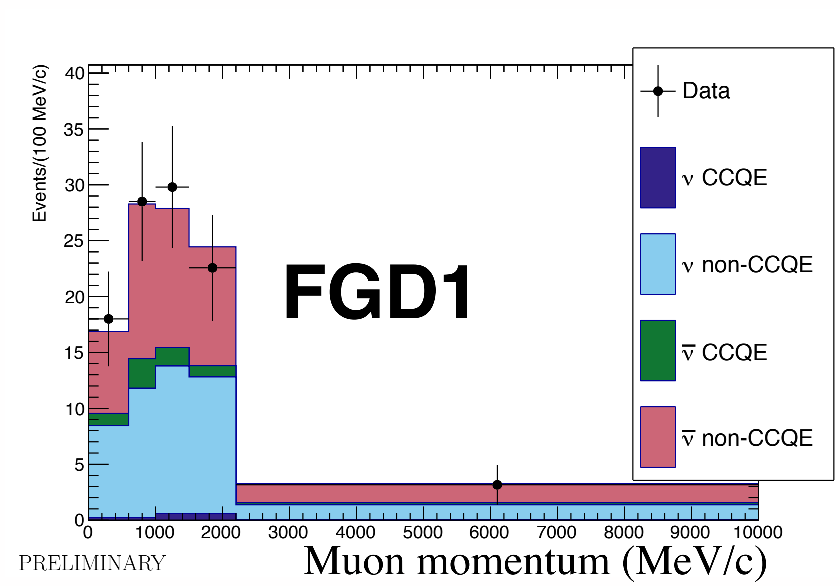
Antineutrino best-fit distributions

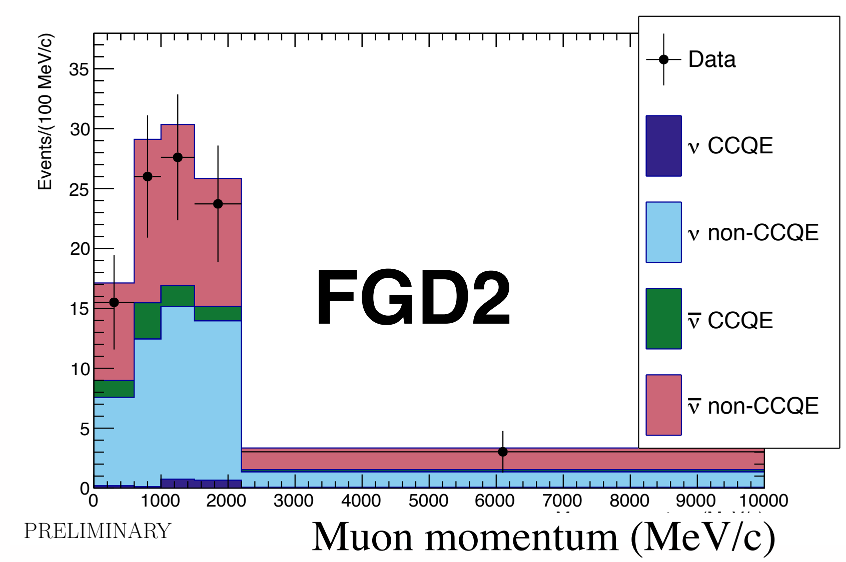








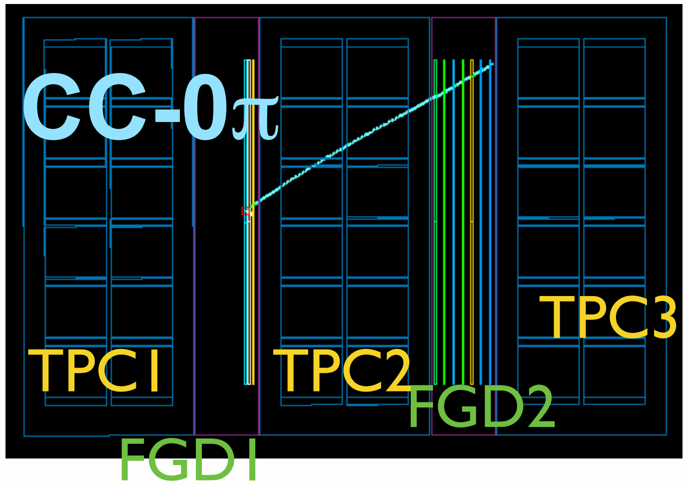


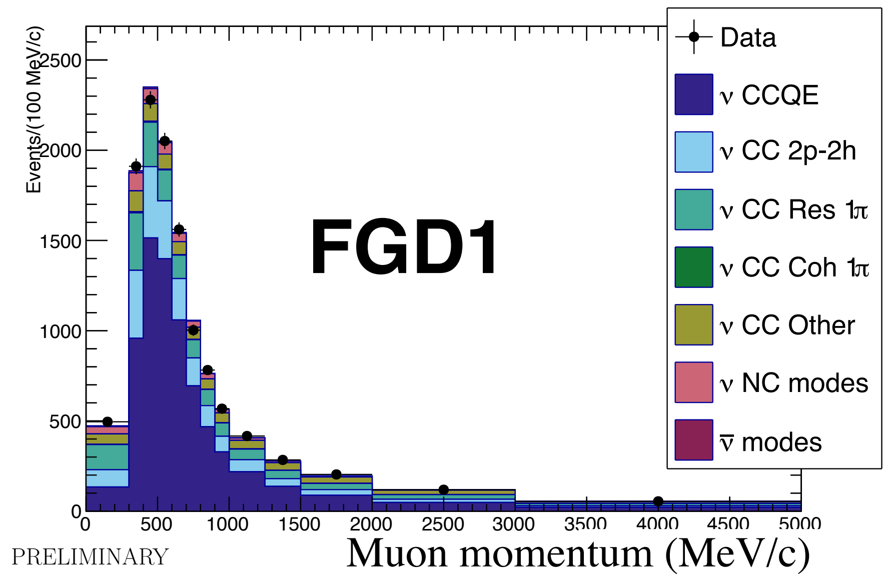


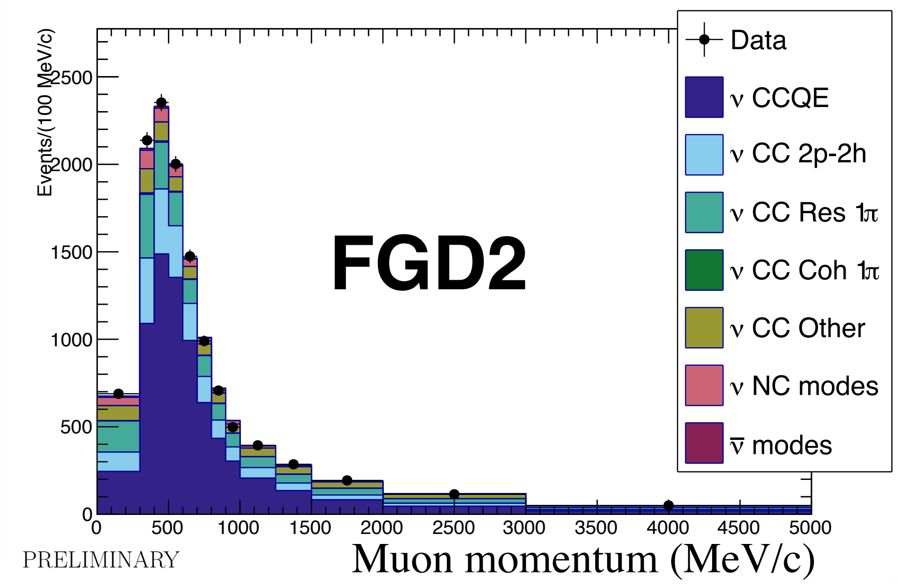
Additional samples to measure wrong-sign background (~30% of ν_μ contamination)

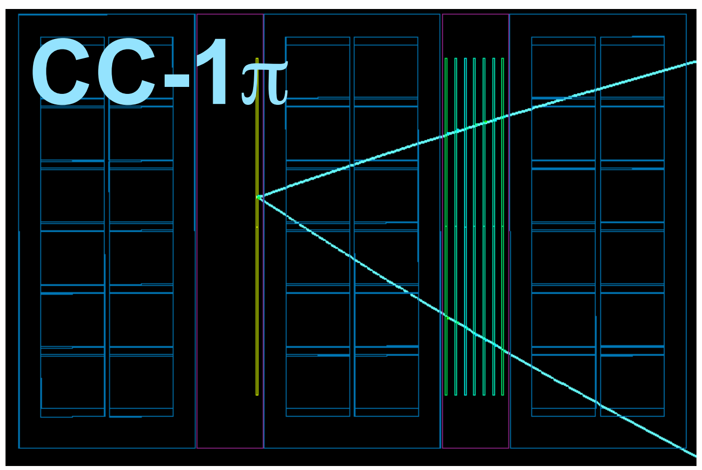
Near Detector Fit: neutrino samples

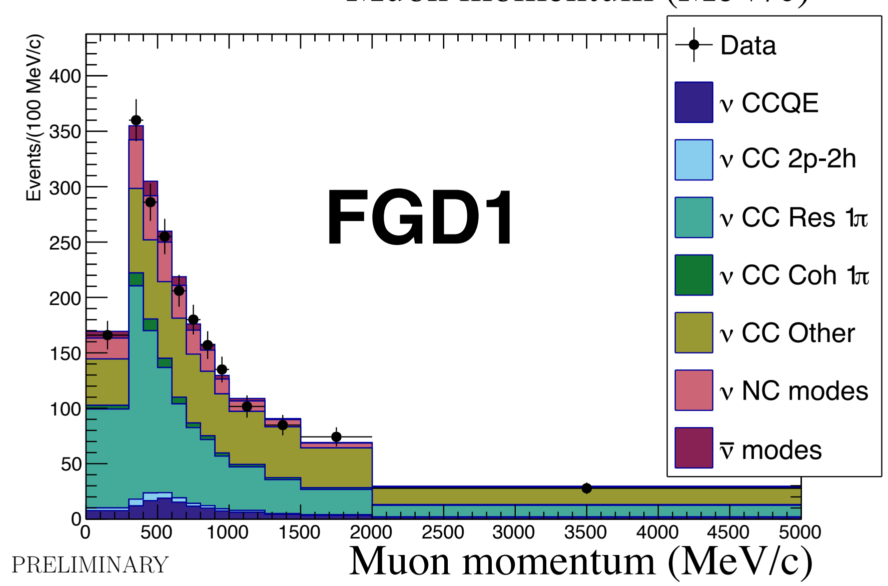
Neutrino best-fit distributions

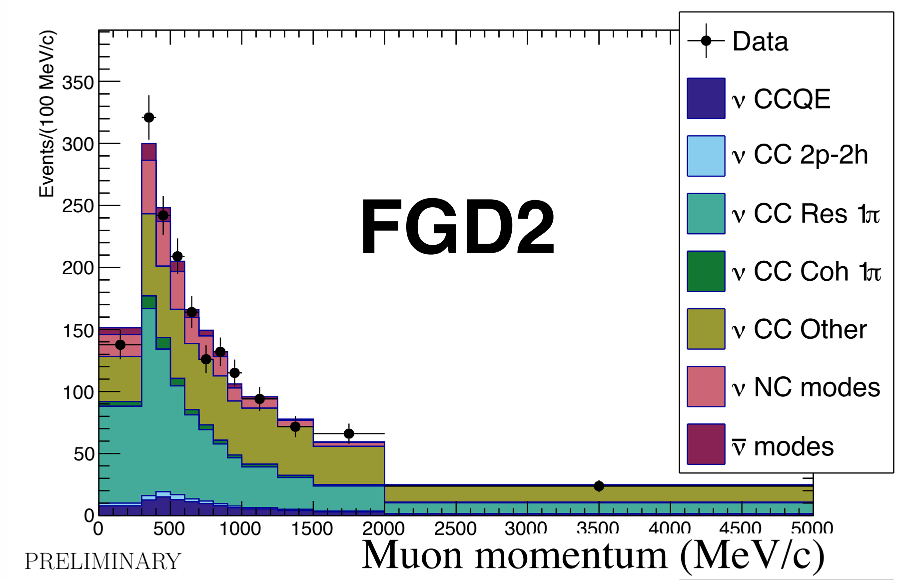


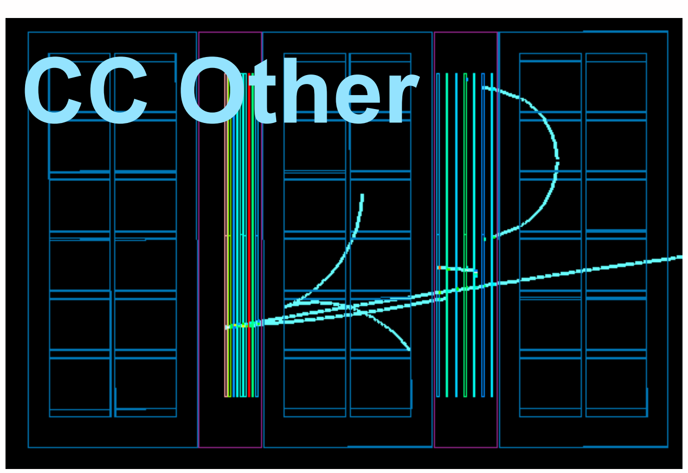


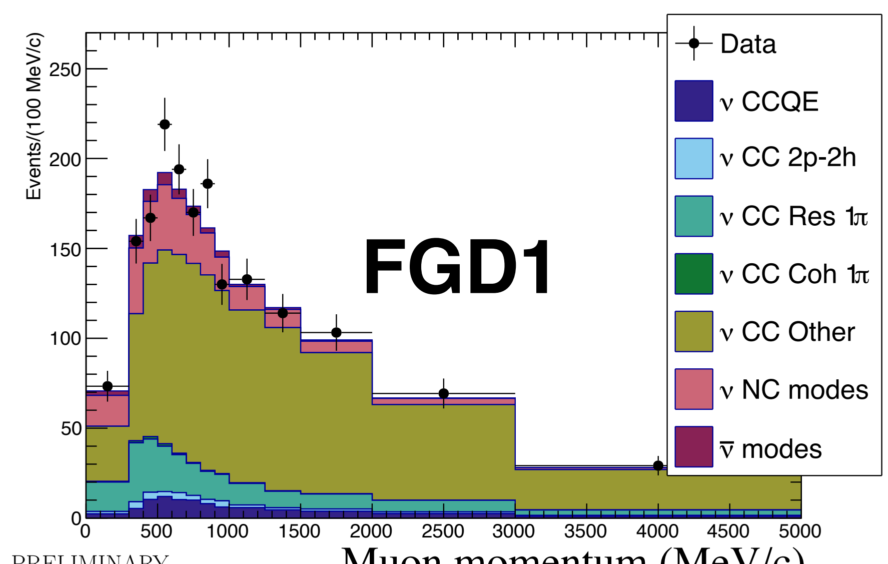


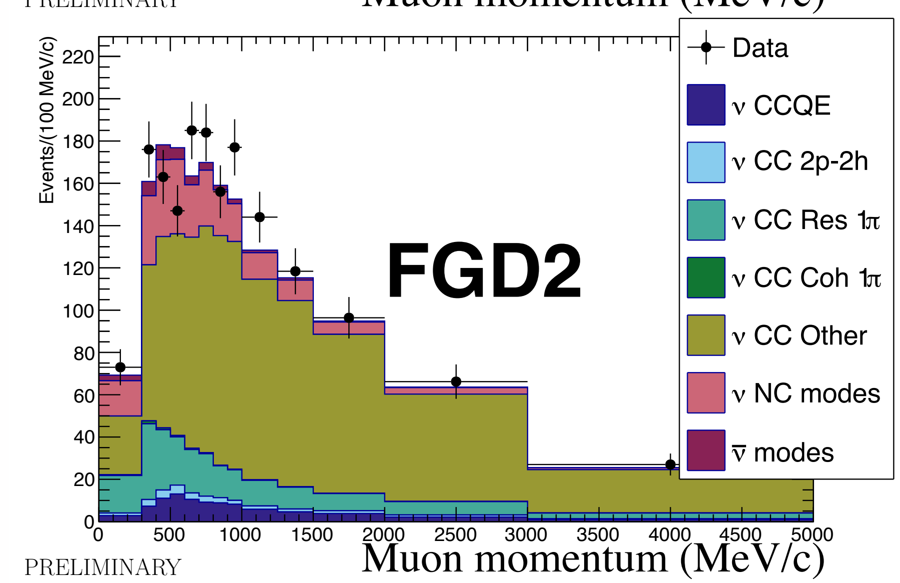






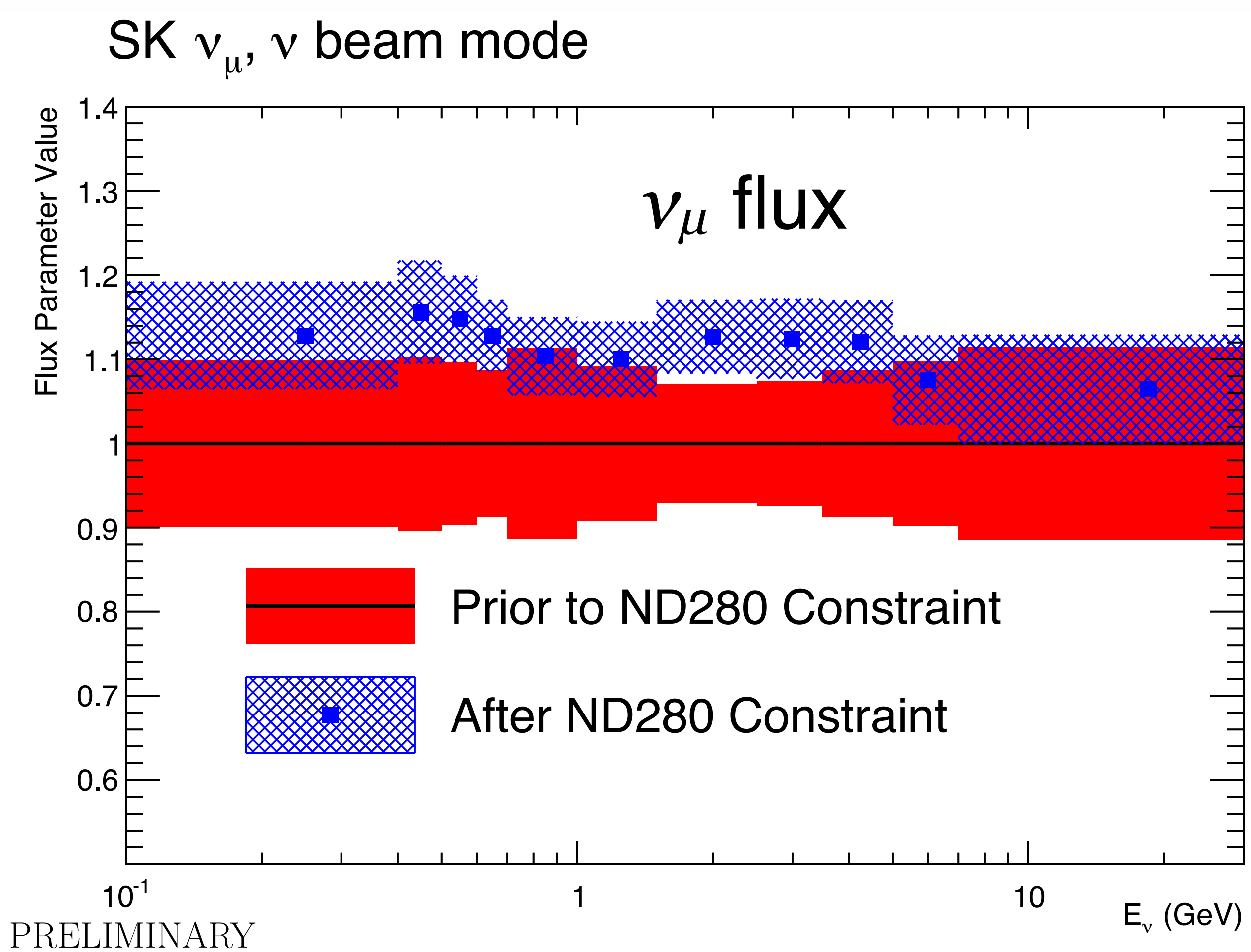


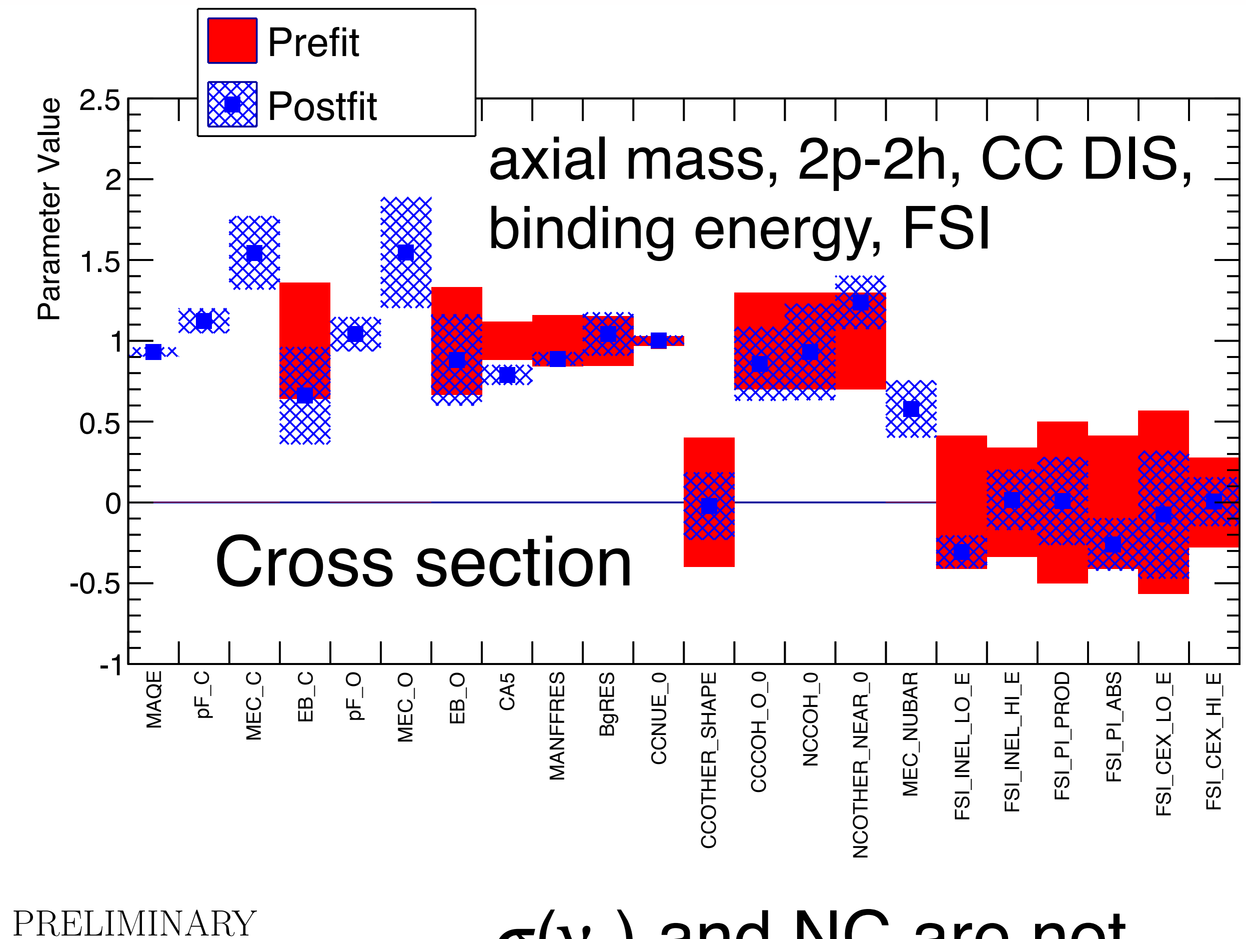




Near Detector Fit: flux and cross-section uncertainties

- Measure neutrino flux and cross section at ND280



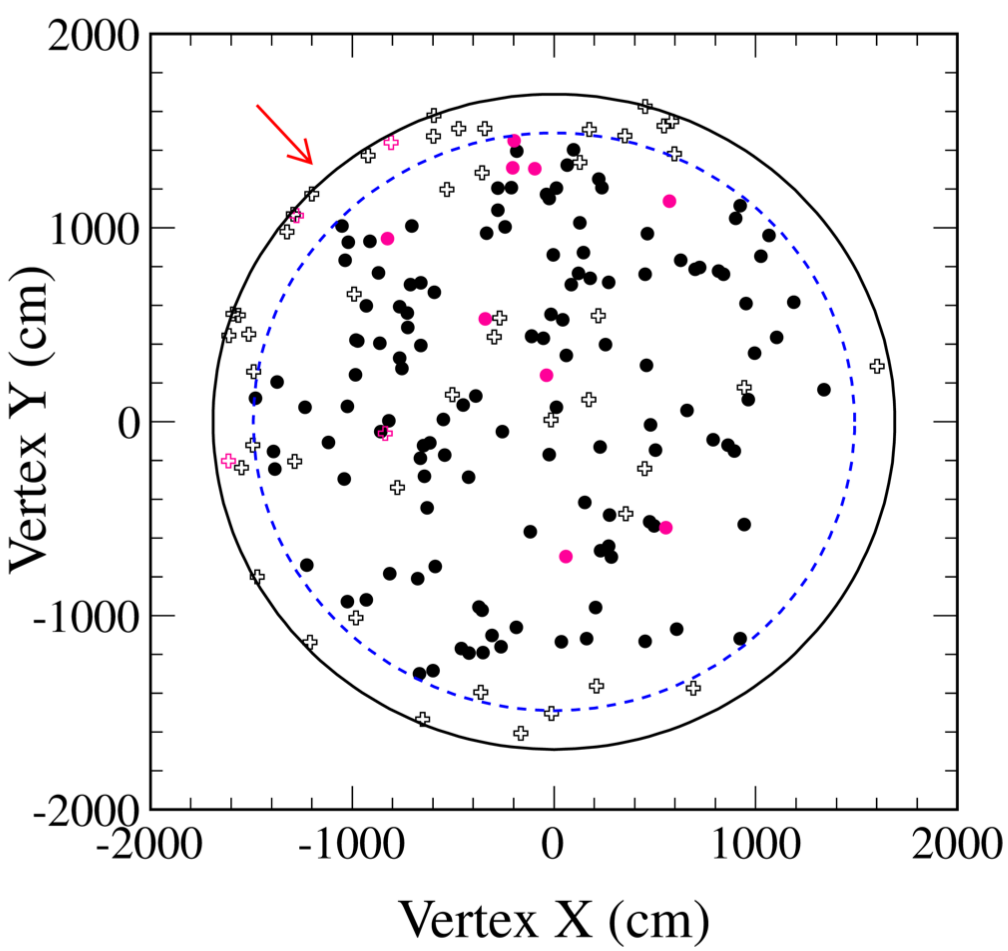


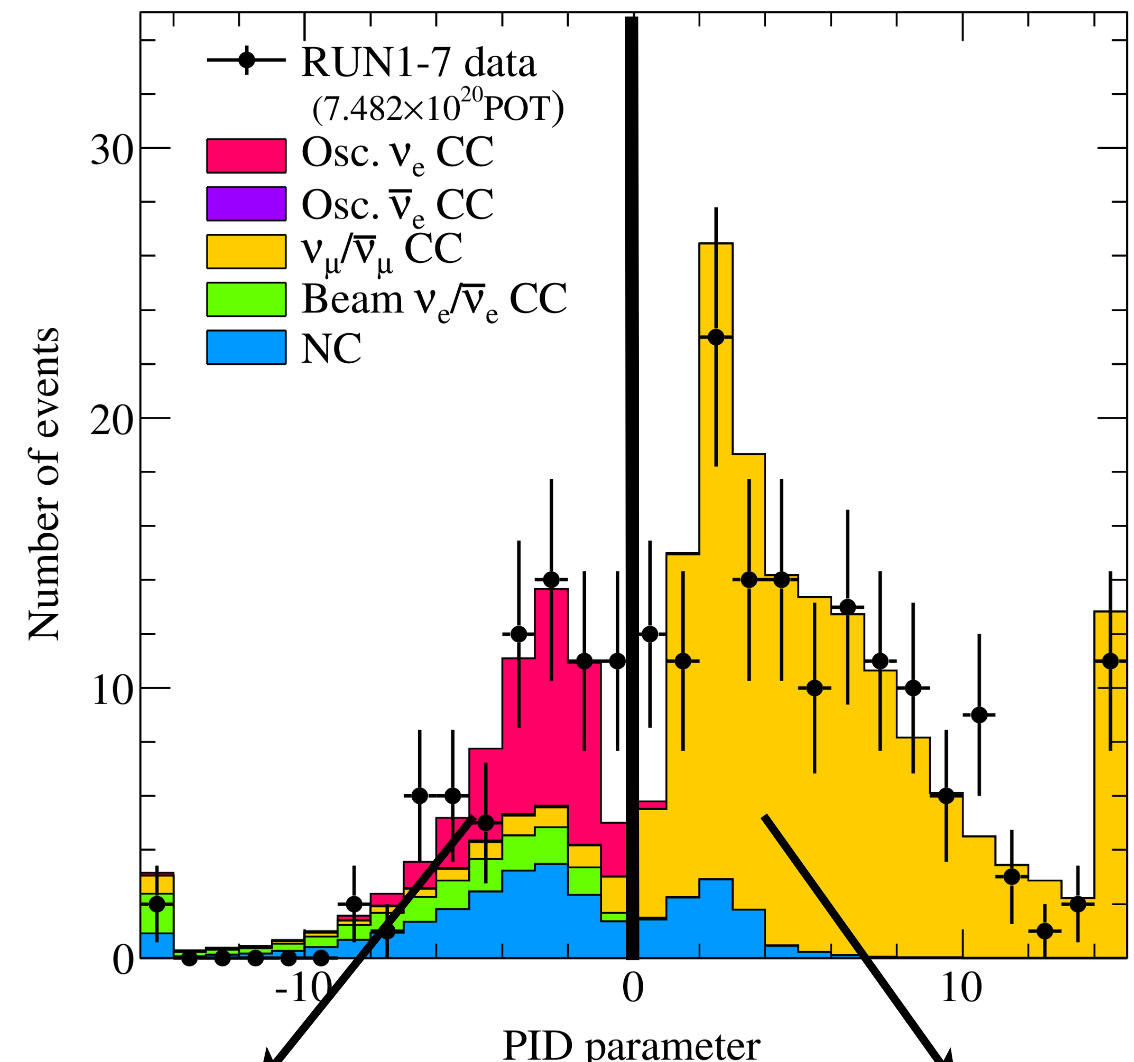
$\sigma(\nu_e)$ and NC are not measured at ND280

- Flux parameters increase by ~15%
- Cross sections ~ consistent with input value
- Flux and cross section highly anti-correlated after the data fit
- The p-value to the pre-fit prediction is acceptable (8.6%)
- Systematic uncertainties in neutrino oscillation analyses from 12-14% to 5-6%

Event selection at Far Detector

- Well understood detector/selection
- Not magnetized: same selection for neutrino and antineutrino beam
- Cuts common to all event sample selections:
  1) events fully contained in fiducial volume
  2) Single ring event
  3) PID cut





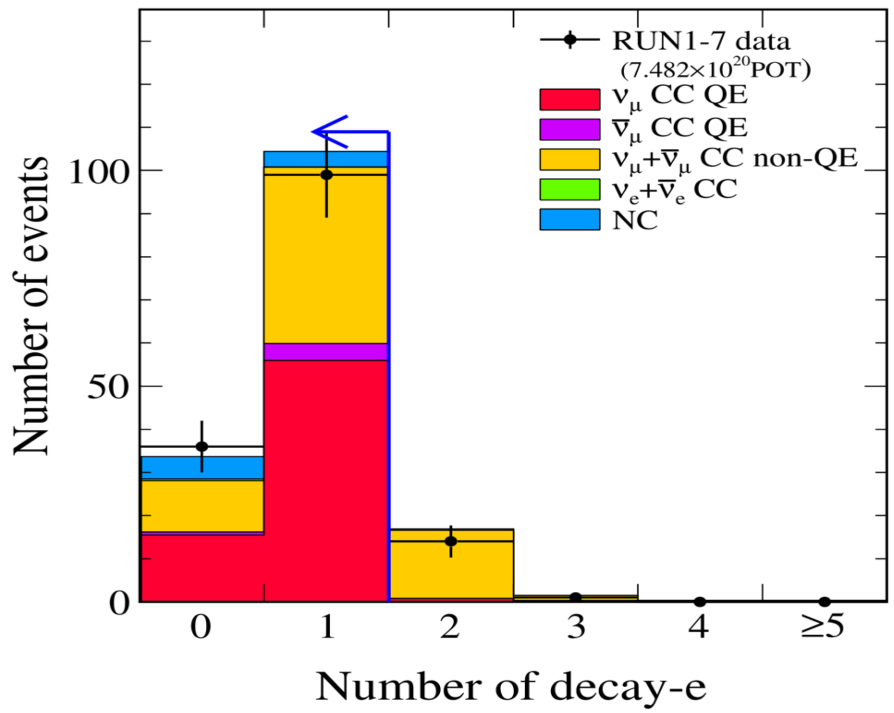
electron-like

muon-like events

ν_μ / $\bar{\nu}_\mu$ CCQE-like selection at Far Detector

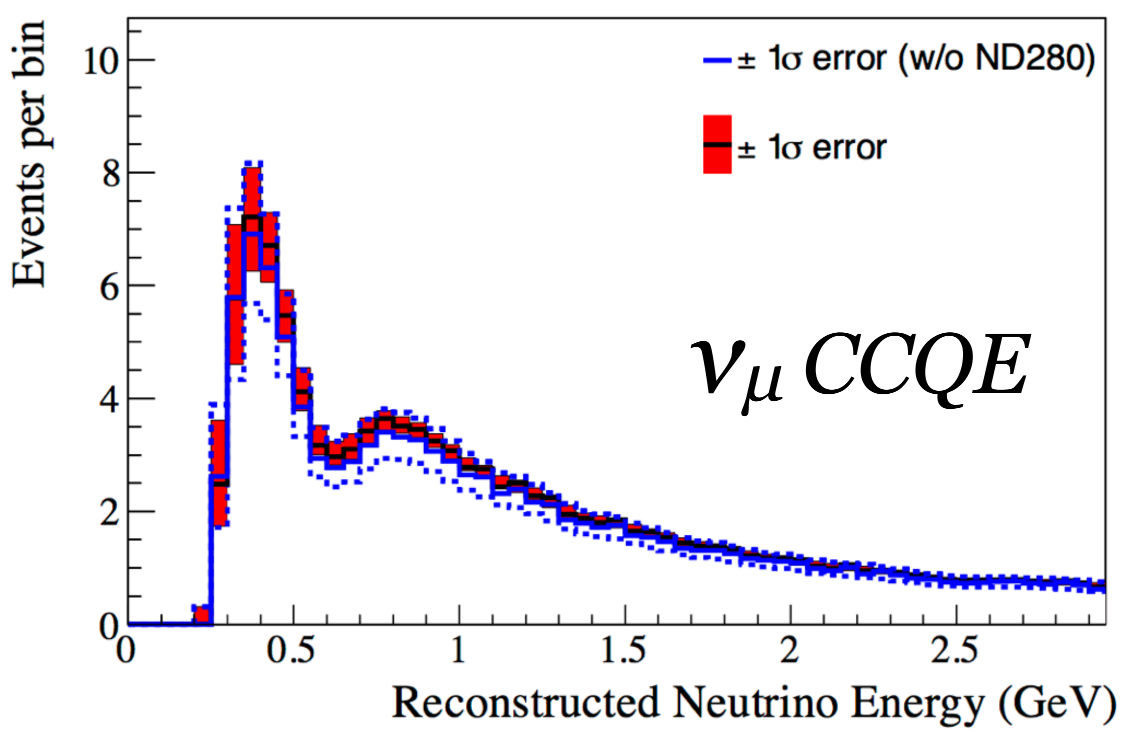
1) Momentum > 200 MeV

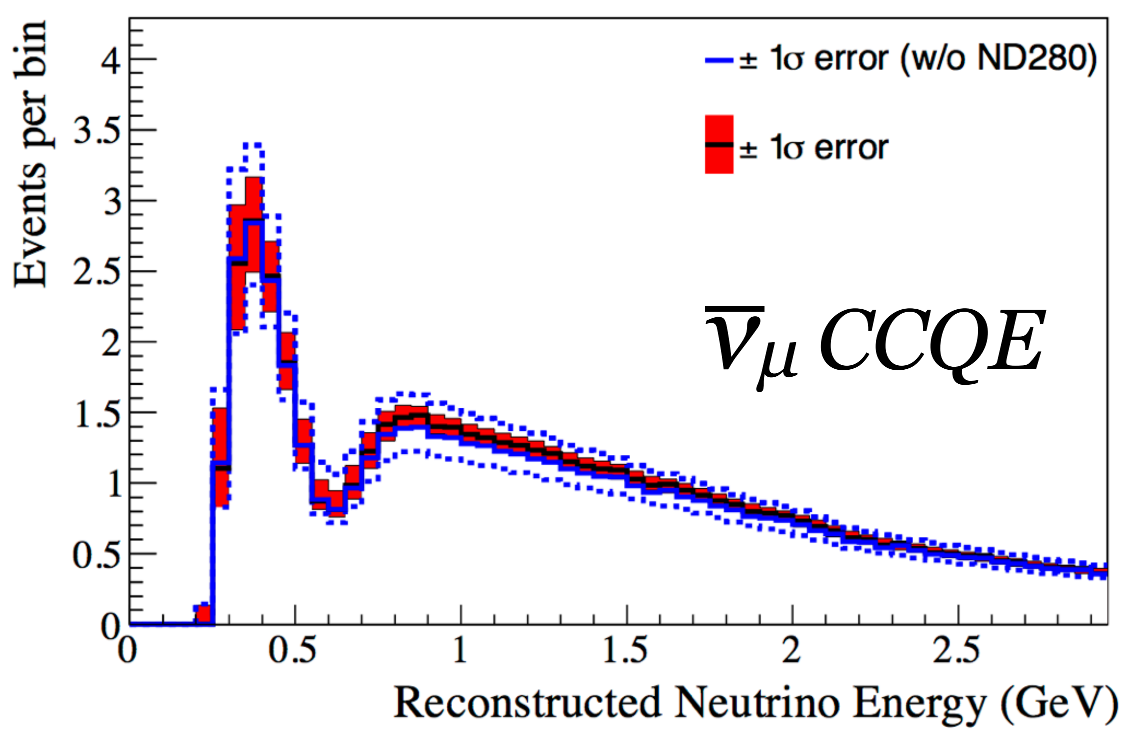
2) # decay electron ≤ 1



Event rate			
Beam mode	**Not Oscillated**	**Oscillated**	**Observed**
neutrino	**521.8**	**135.8**	**135**
antineutrino	**184.8**	**64.2**	**66**

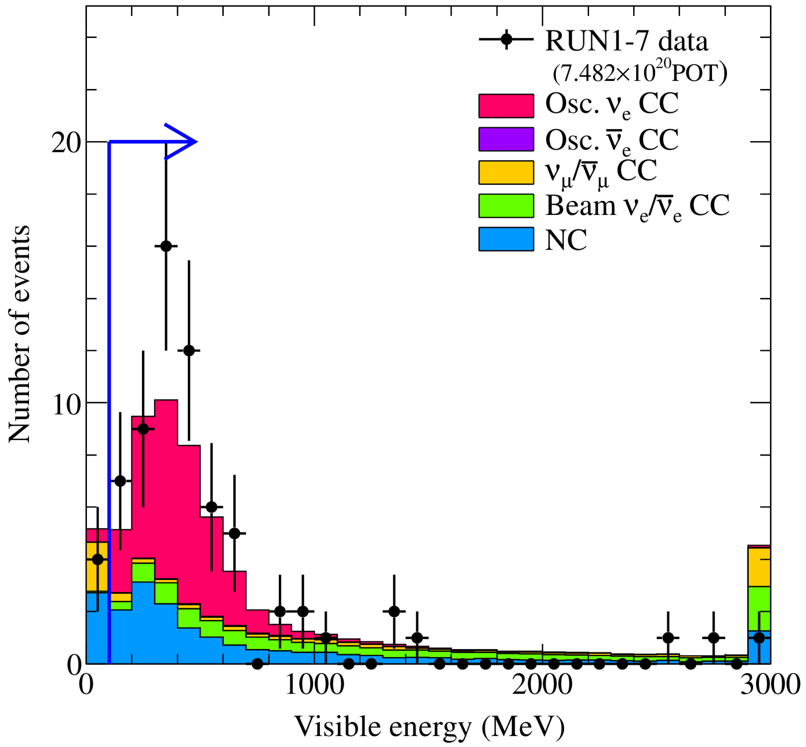
Systematic error		
Beam mode	**w/o ND280**	**ND280**
neutrino	**12.0%**	**5.0%**
antineutrino	**12.5%**	**5.2%**



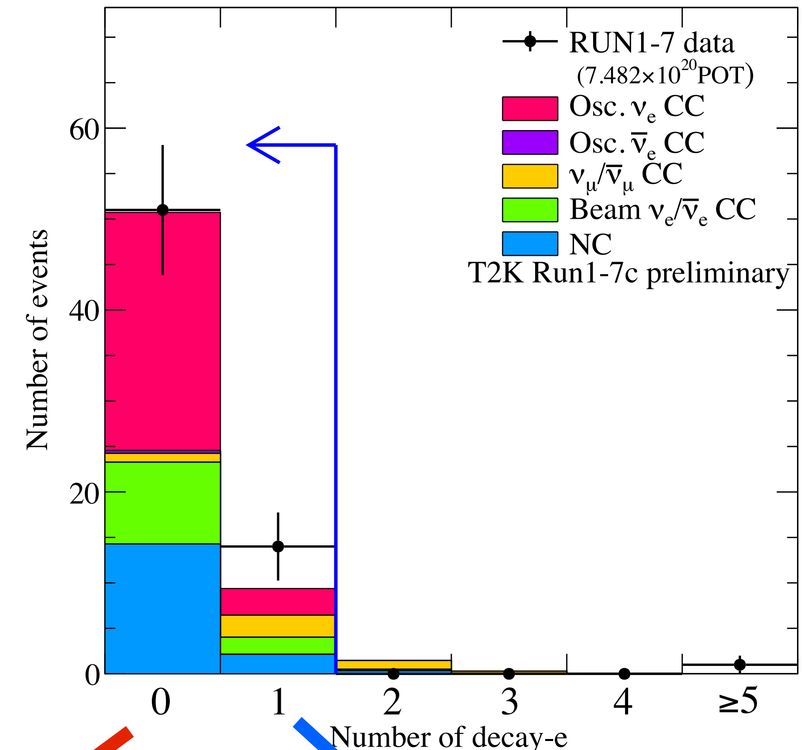


$\overline{\nu}_e$ / ν_e selection at Far Detector

1) $E_{visible}$ > 100 MeV



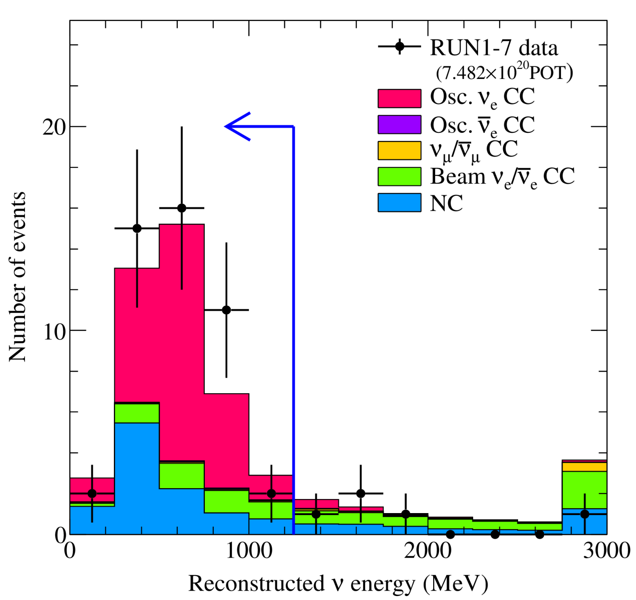
2) # decay electrons



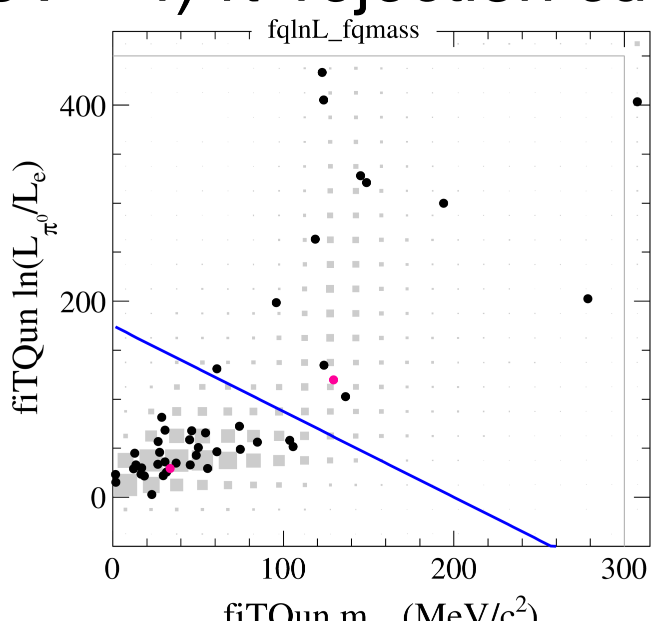
Additional CC1π-like sample increase the statistics by ~10%

0 decay e⁻ --> CCQE-like

3) 0 < E_{rec} < 1250 MeV

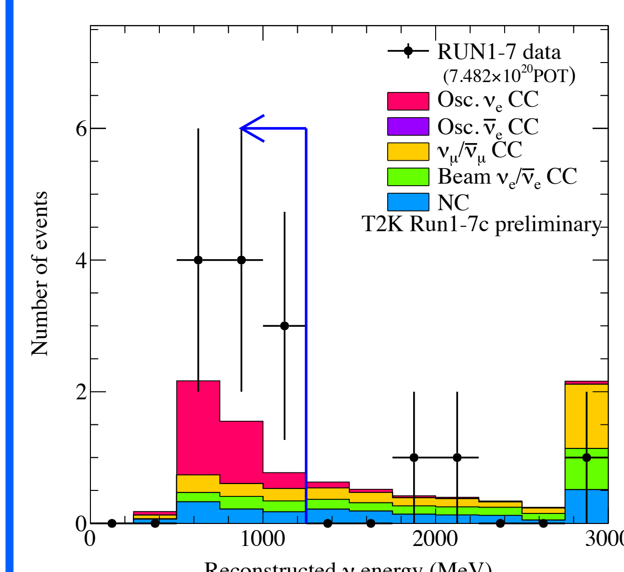


4) π^0 rejection cut

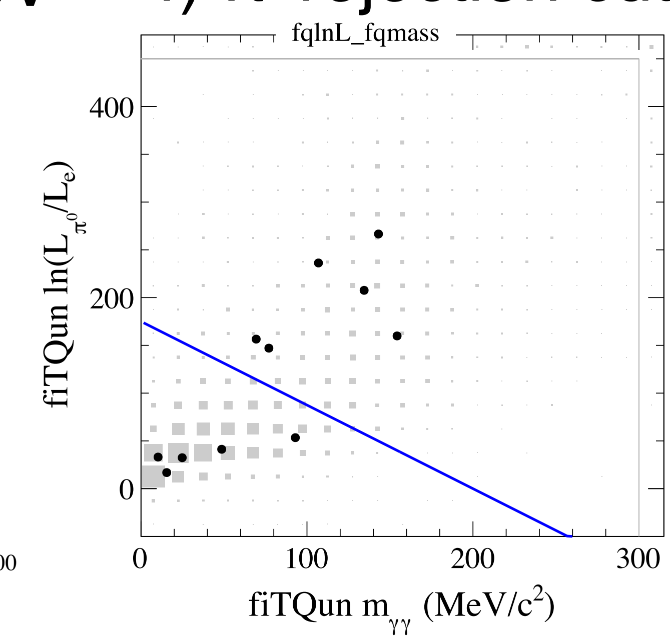


1 decay e⁻ --> CC1π-like

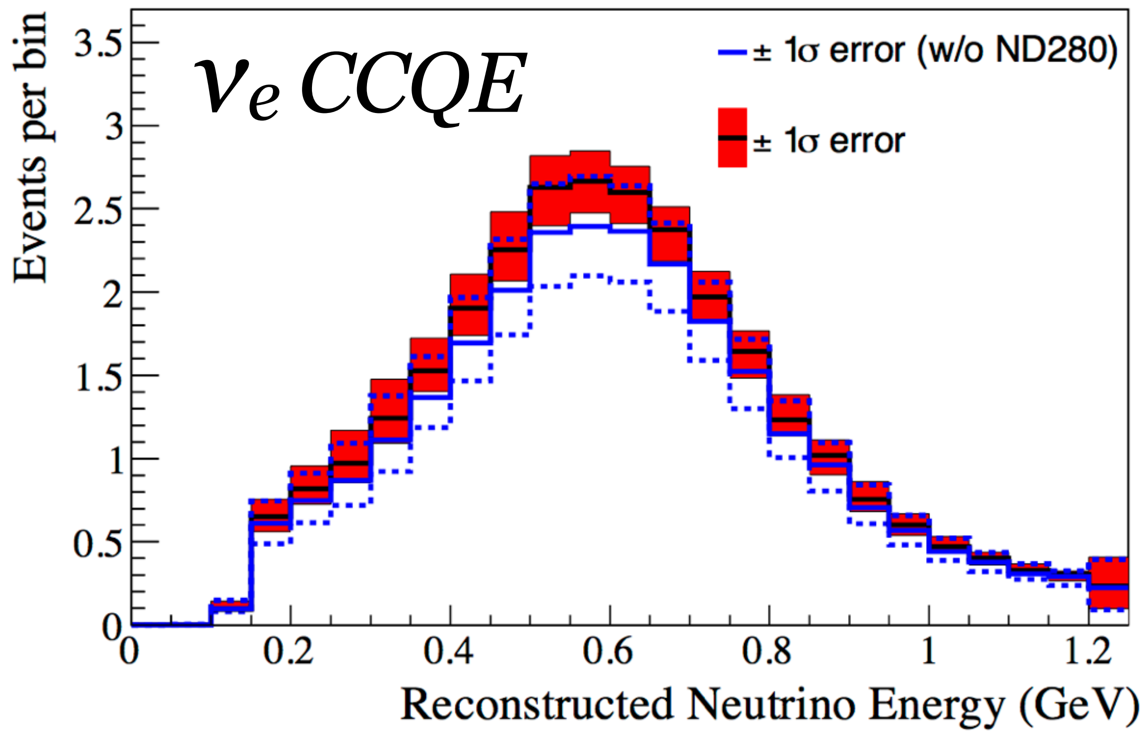
3) 0<E_{rec}<1250 MeV

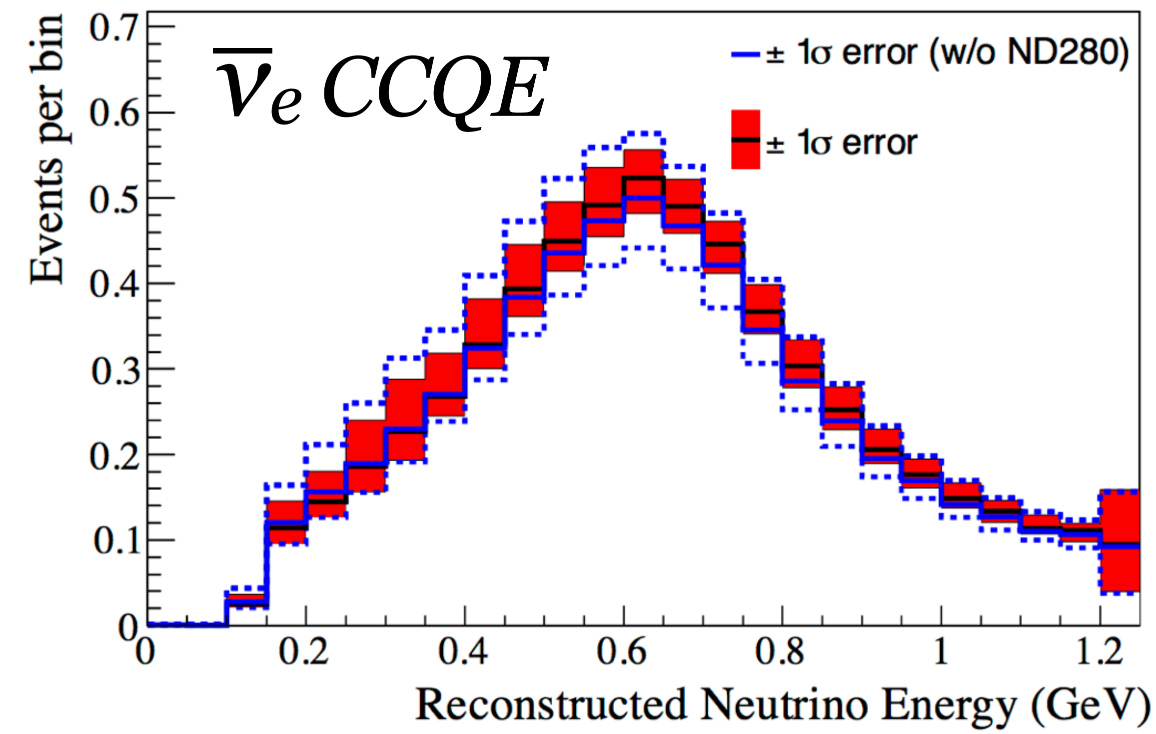


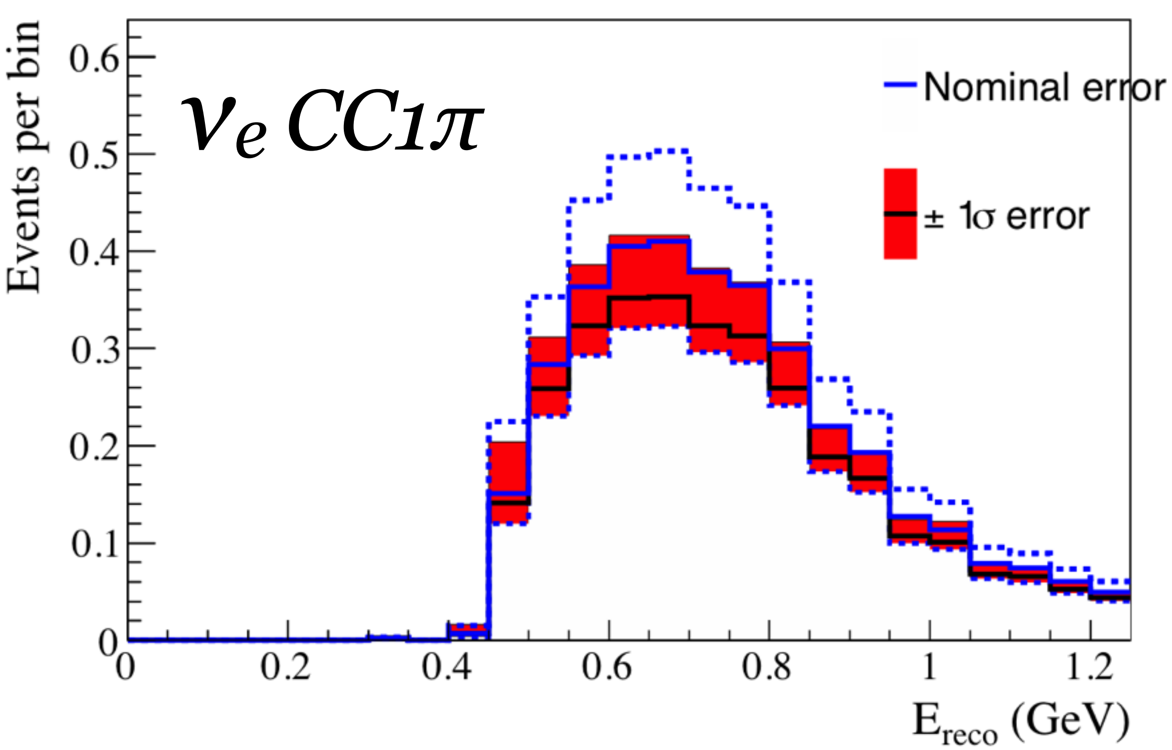
4) π^0 rejection cut



$\overline{\nu}_e$ / ν_e selection at Far Detector



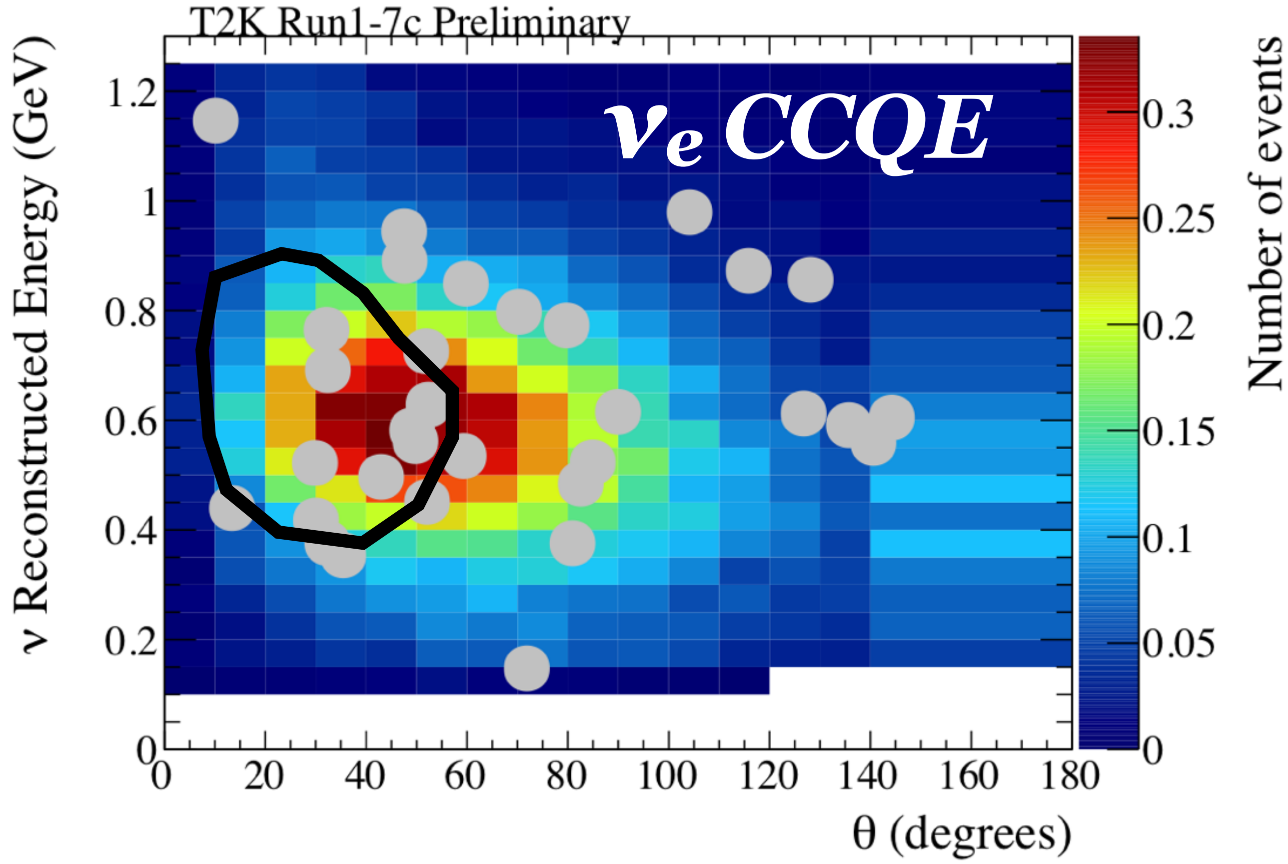


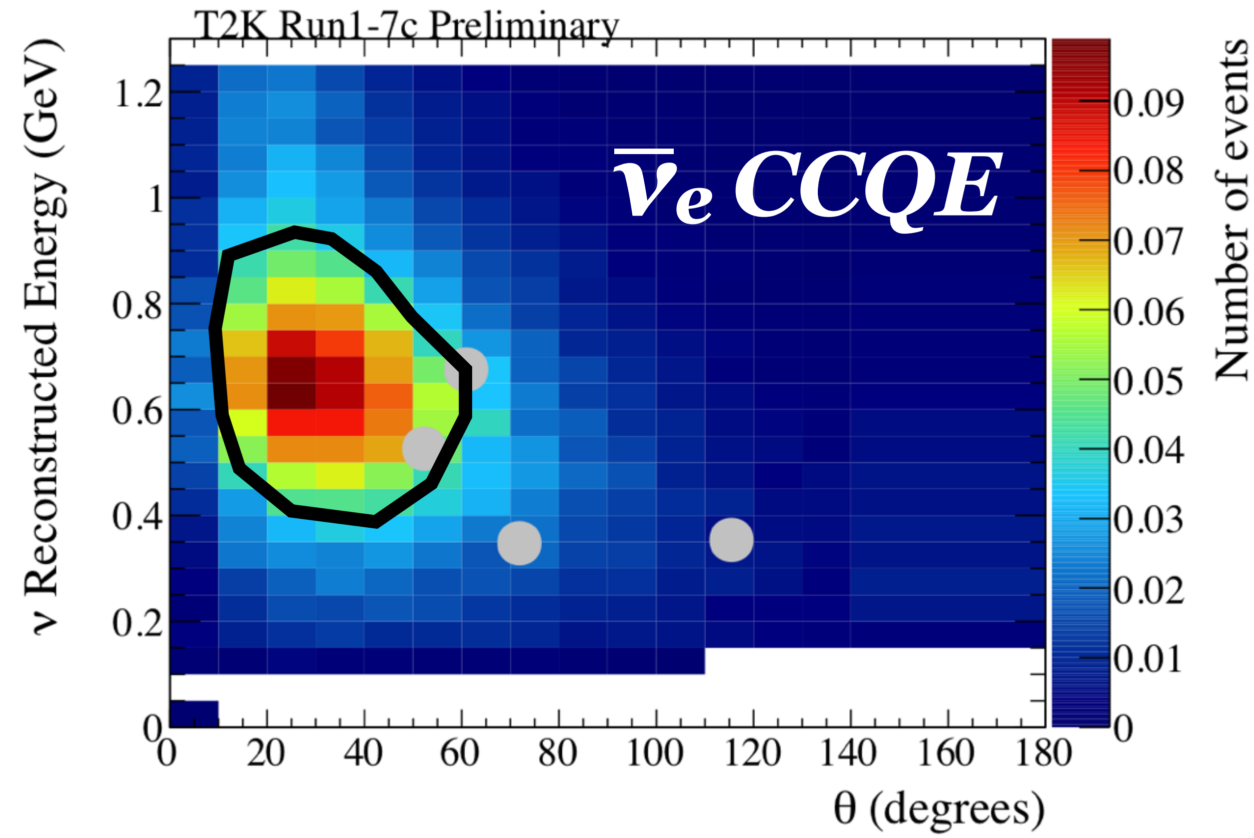


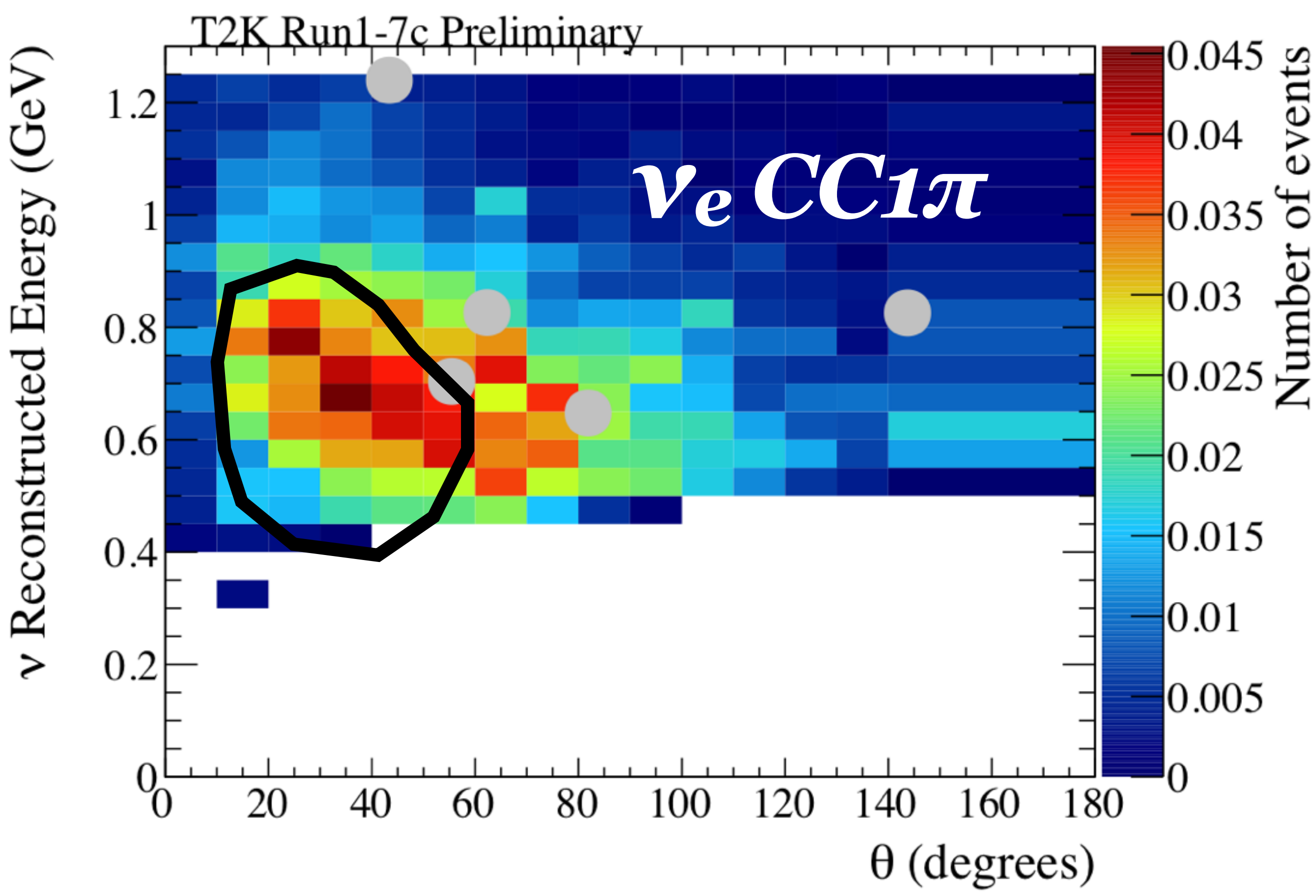
Event rate			
Sample	**Signal**	**Total**	**Observed**
neutrino CCQE	23.2	28.7	32
antineutrino CCQE	2.8	6.0	4
neutrino CC1π	2.3	3.1	5

Systematic error		
Sample	**w/o ND280**	**ND280**
neutrino CCQE	11.9%	5.4%
antineutrino CCQE	13.7%	6.2%
neutrino CC1π	21.9%	15.3%

ν_e / $\bar{\nu}_e$ predicted spectra at Far Detector





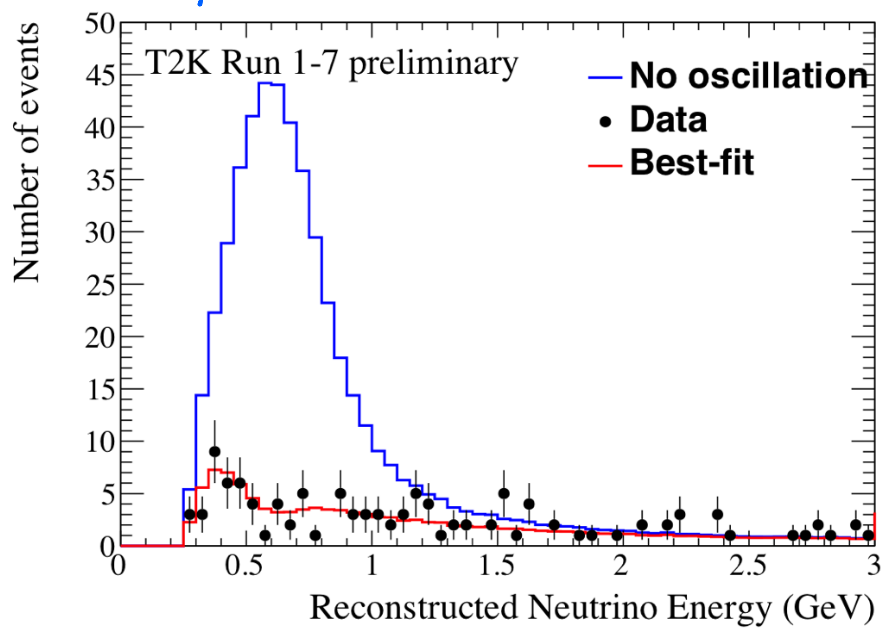


- ν_e and $\bar{\nu}_e$ cover quite different phase space:
  - different cross section between neutrino and antineutrino
  - use outgoing lepton angle (Θ): constrain wrong sign background
- Three analyses: E_{rec}-Θ, p_{lep}-Θ, E_{rec}

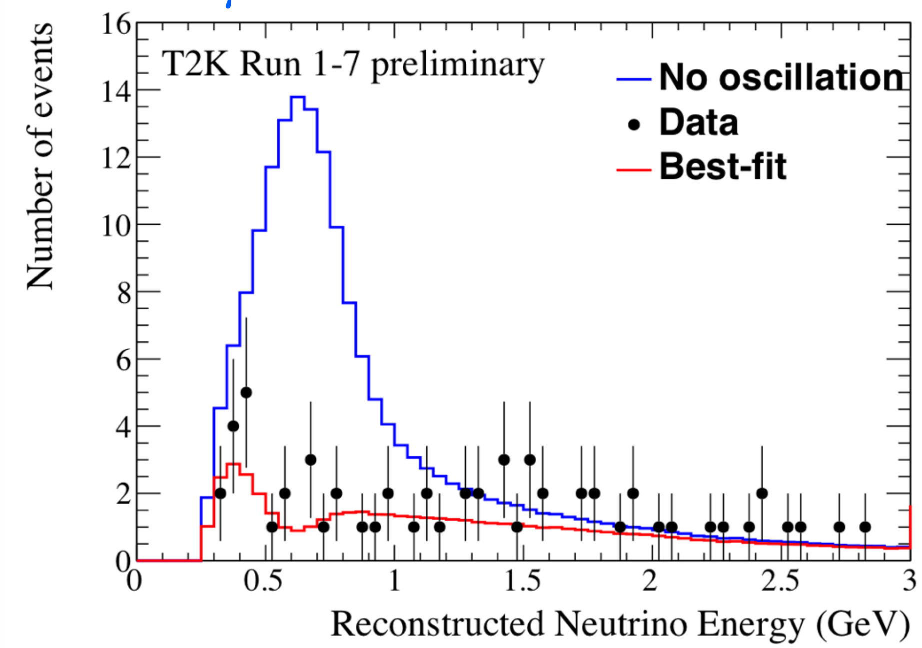
Joint neutrino and antineutrino analysis

- Joint analysis of all 4 samples at the far detector

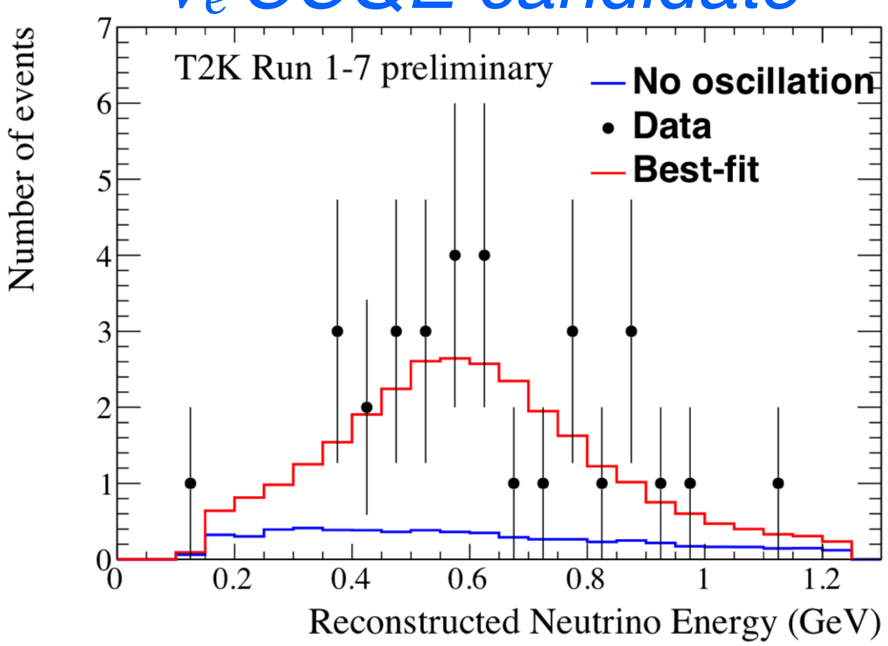
ν_μ CCQE candidate



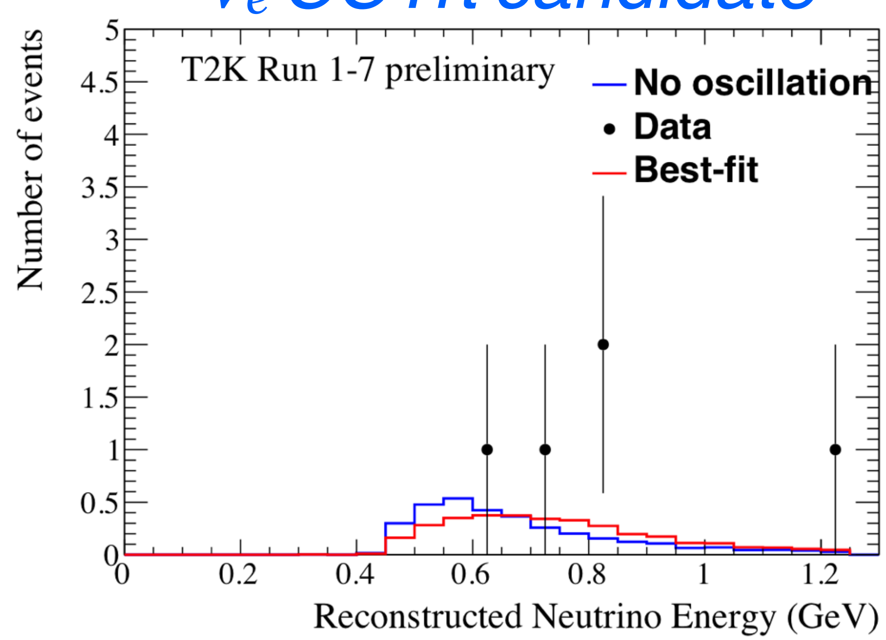
$\overline{\nu}_\mu$ CCQE candidate



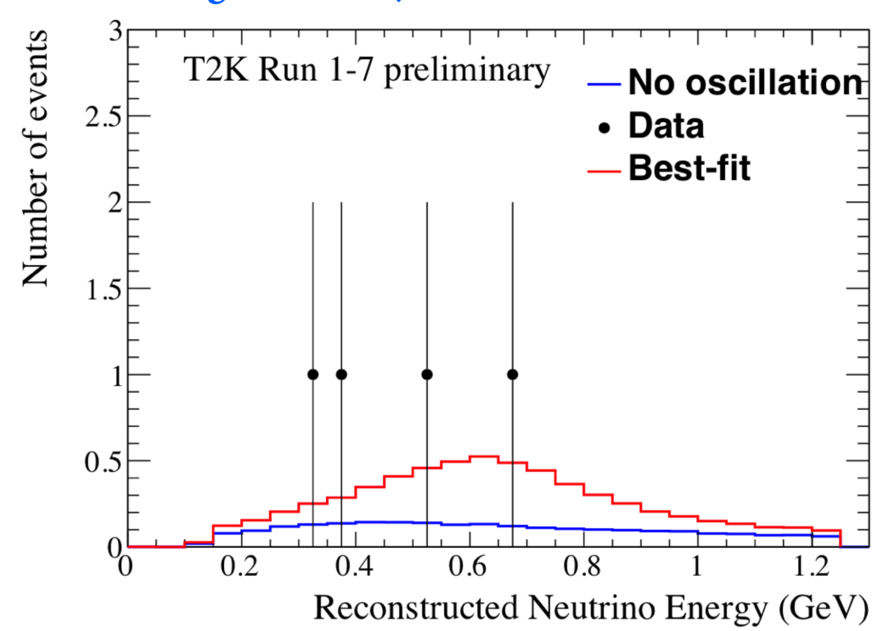
ν_e CCQE candidate



ν_e CC1π candidate



$\overline{\nu}_e$ CCQE candidate

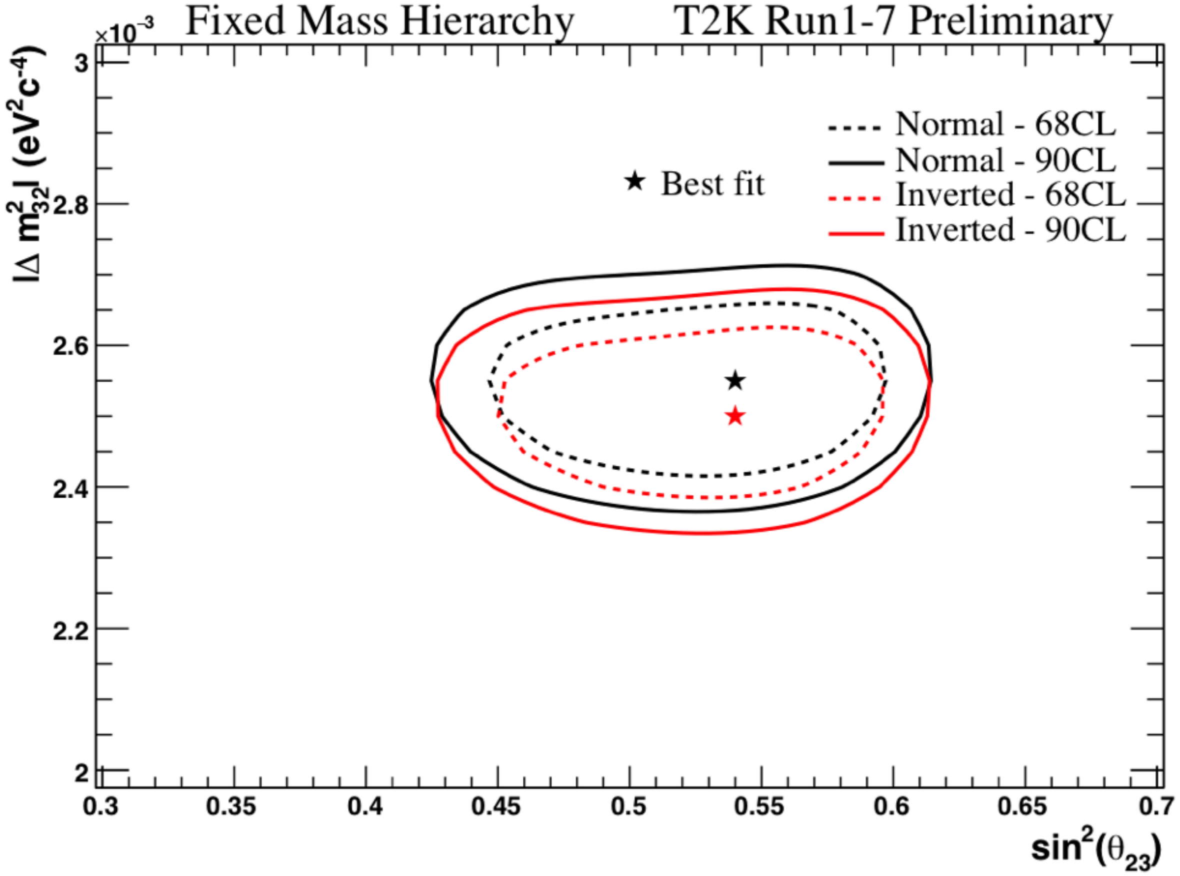


- No evidence for 3-flavor $\overline{\nu}_e$ appearance yet (p-value to bkg hypothesis ~0.37)
- $\overline{\nu}_\mu$ disappearance in good agreement with ν_μ data

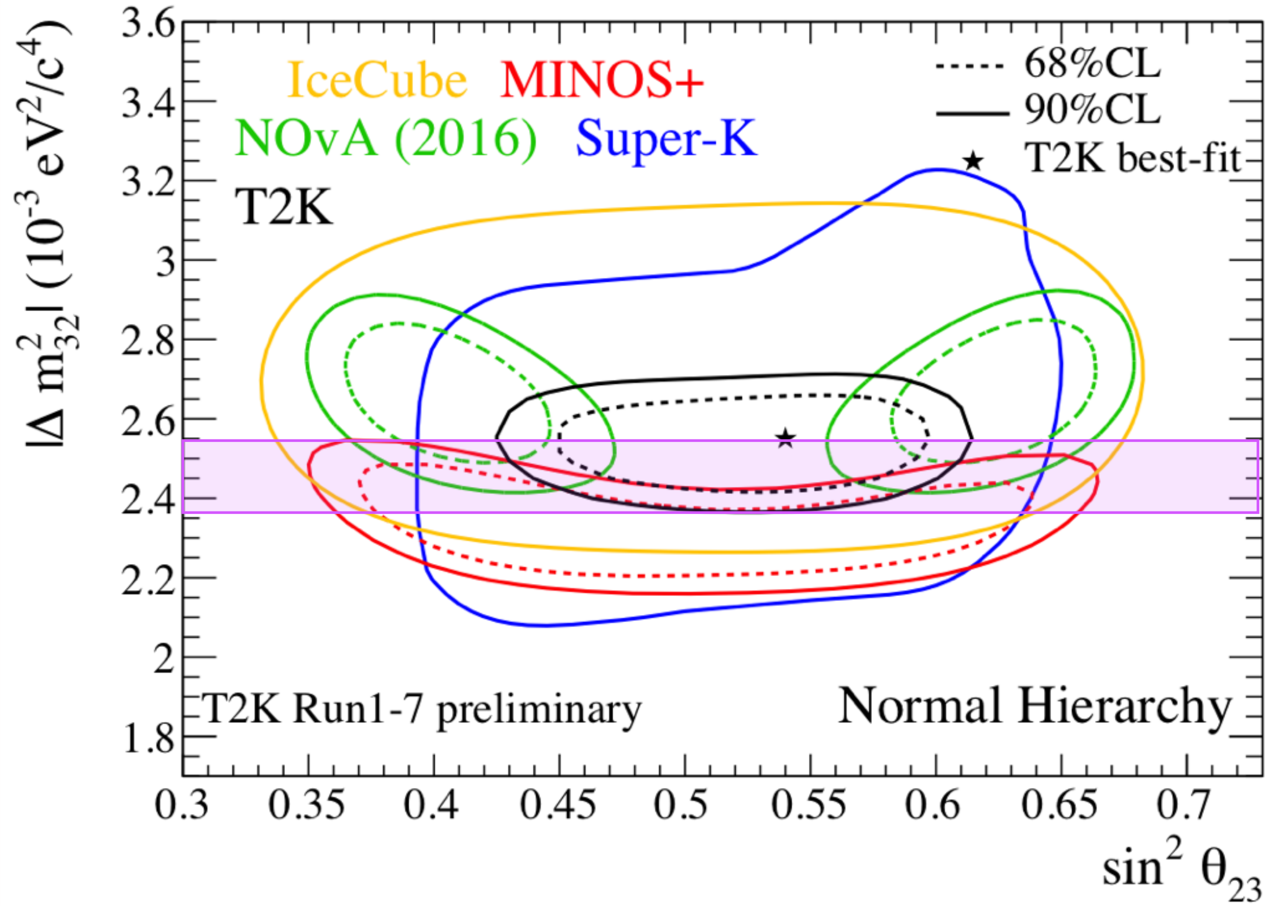
Confidence intervals $\sin^2\Theta_{23}$ and Δm^2_{32}

- ν_μ and $\bar{\nu}_\mu$ candidate samples constrain $\sin^2 2\Theta_{23}$
- ν_e and $\bar{\nu}_e$ candidate samples define the Θ_{23} octant
- Contours with constant $\Delta\chi^2$ method (gaussian approximation)

Mass Hierarchy is fixed to either Normal or Inverted



Daya Bay measures Δm^2_{ee}



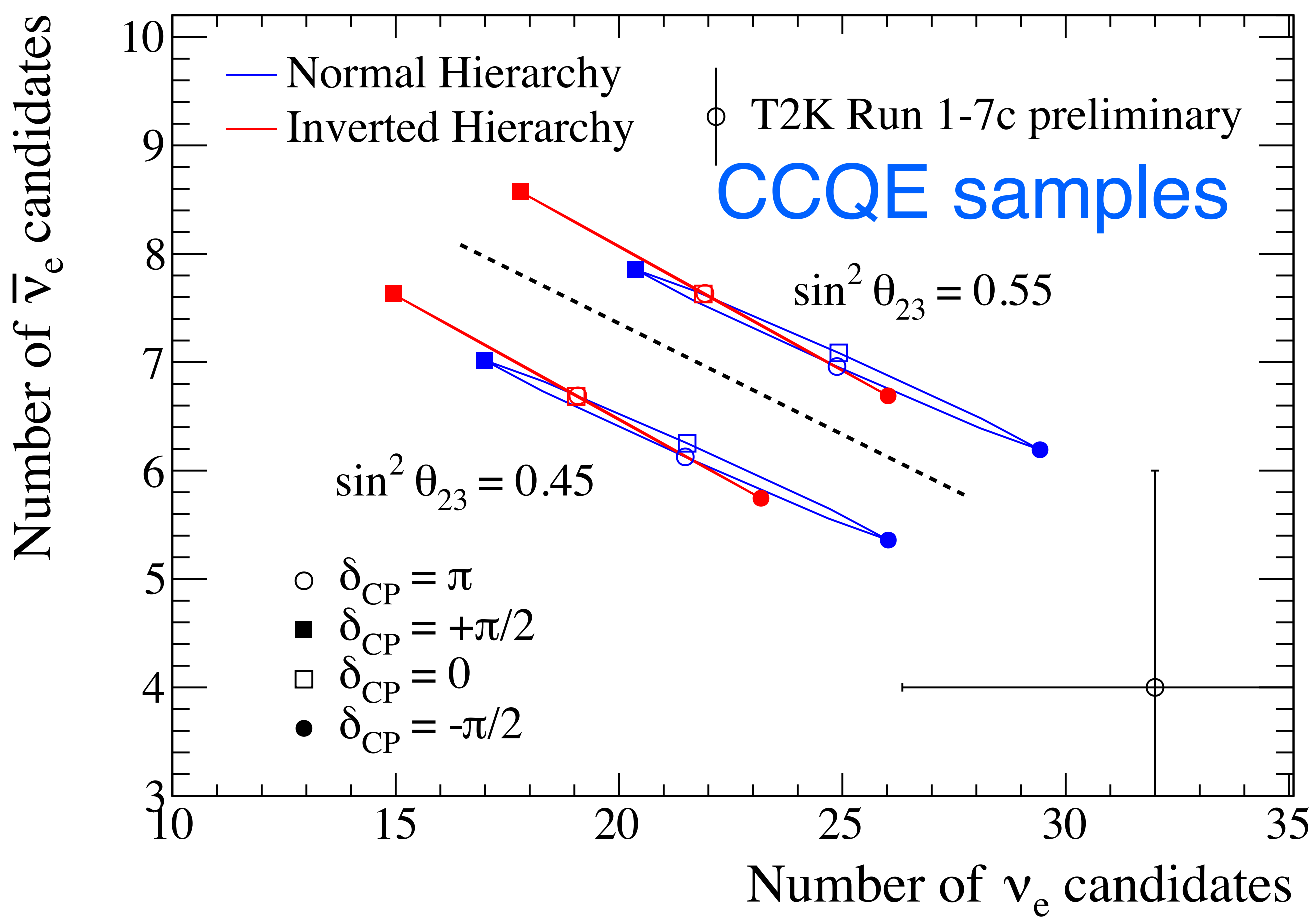
- T2K data consistent with maximal mixing as in past analysis results

- All the experiments show agreement

Best-fit	NH	IH
$\sin^2\theta_{23}$	0.550	0.553
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.54	2.51

Predicted vs observed # of events

- Compare the observed # of ν_e and $\bar{\nu}_e$ events with the prediction for:
  - δ_{CP} = -π/2, 0, π, +π/2
  - $\sin^2\Theta_{23}$ = 0.45, 0.55
  - Normal and Inverted Hierarchy



CP violation (δ_{CP}≠0,π) gives different oscillation probabilities for
- $\nu_\mu \to \nu_e$
- $\bar{\nu}_\mu \to \bar{\nu}_e$

Assumption for oscillation parameters:
$|\Delta m^2_{32}|$ = 2.509 x 10^{-3} eV^2
$\sin^2\Theta_{13}$ = 0.0217 (PDG2015)

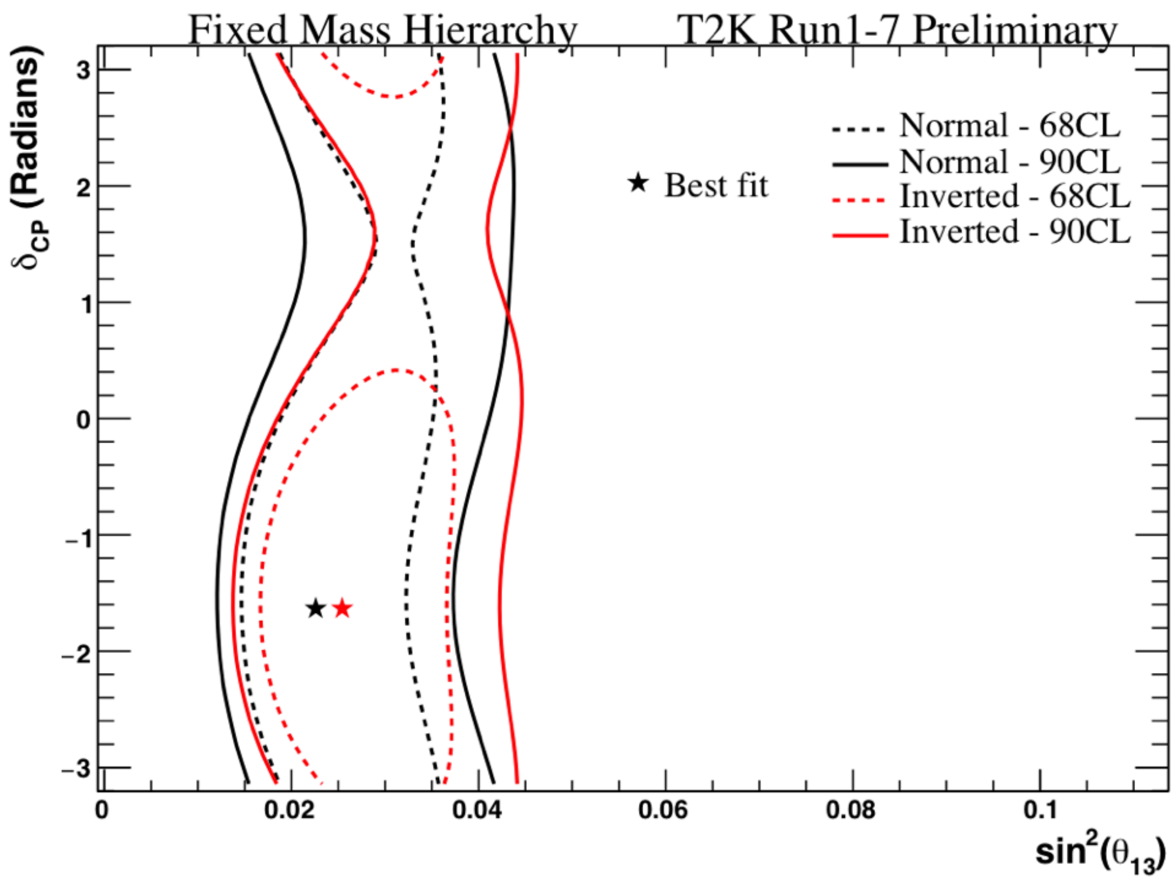
ν_e CC1π sample
Observed = 5
Expected (δ_{CP} = -π/2, NH) = 3.3

- Observed number of events shows a slightly larger asymmetry compared to the prediction for δ_{CP}=-π/2 and Normal Hierarchy
  - few more ν_e candidates than predicted
  - few less $\bar{\nu}_e$ candidates than predicted

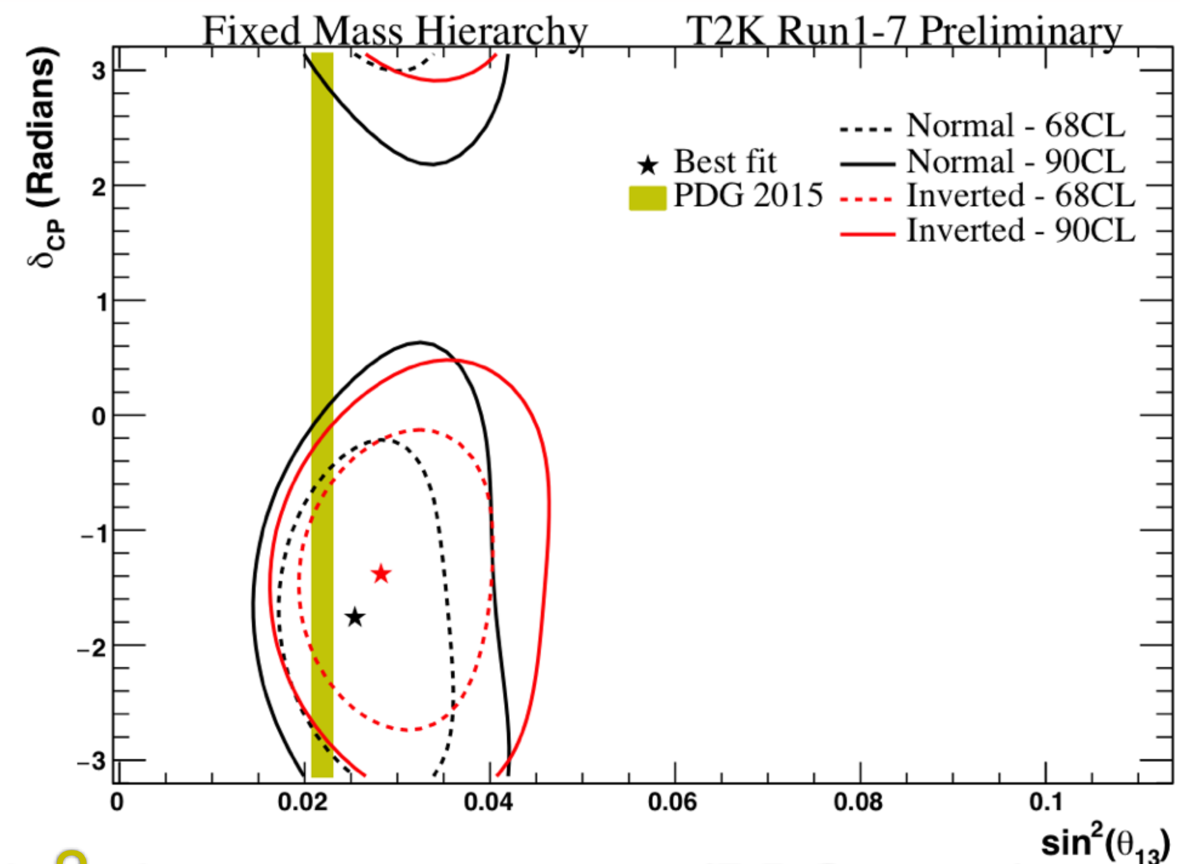
Confidence intervals $\sin^2\theta_{13}$ and δ_{CP}

- Mass hierarchy is fixed to either normal or inverted
- Contours with constant $\Delta\chi^2$ method (gaussian approximation)

T2K-only sensitivity (True δ_{CP}= -1.601)



T2K-only data fit

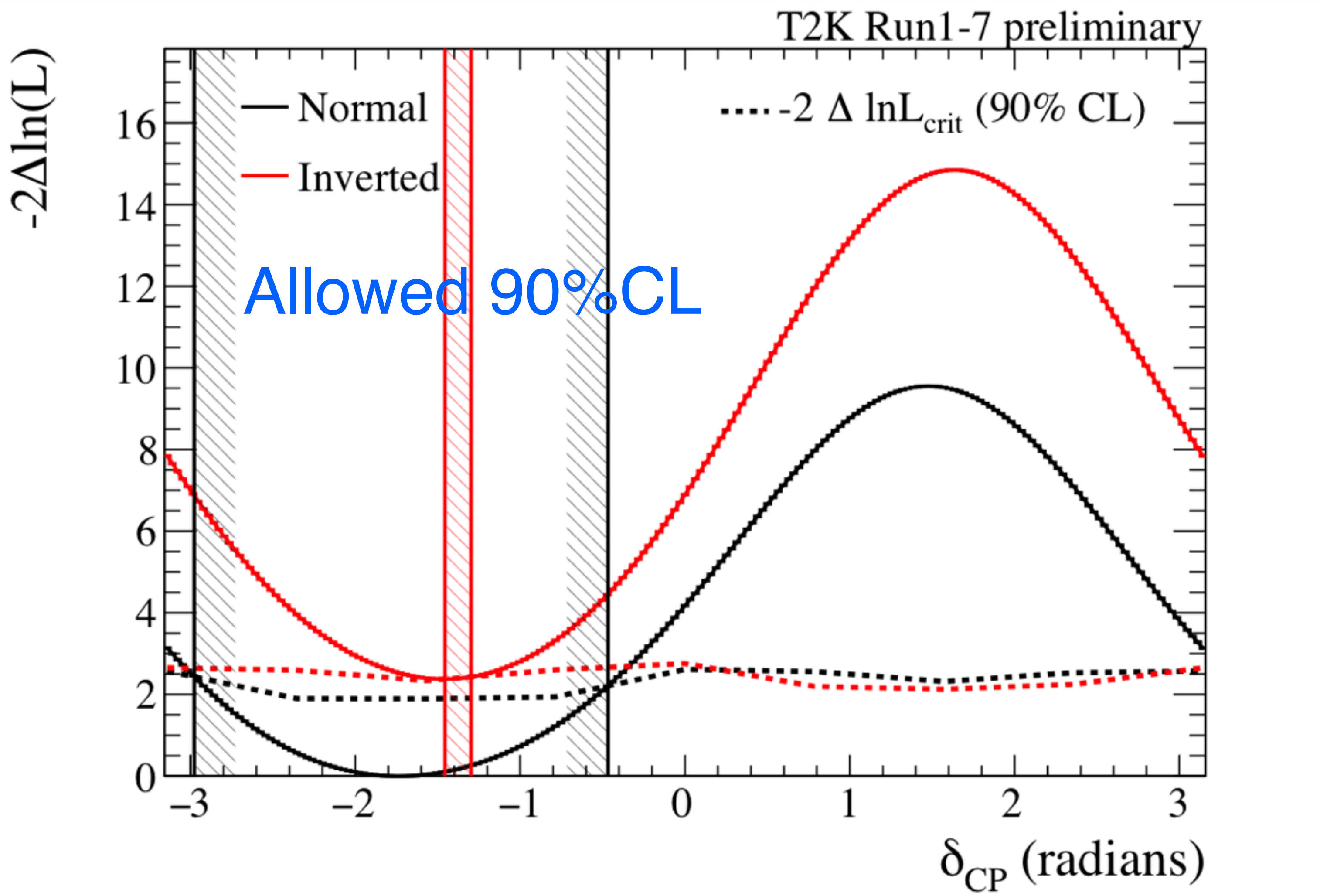


$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

- Good agreement with the reactors' measurement
- T2K-only data disfavor region of δ_{CP} at ~ $+\pi/2$
- Preference for $-\pi/2$ for both normal and inverted hierarchy
- Confidence intervals are slightly tighter than expected ones

Confidence intervals of δ_{CP}

- Confidence intervals at 90% CL computed with Feldman-Cousins method (toy MC method that provides coverage)



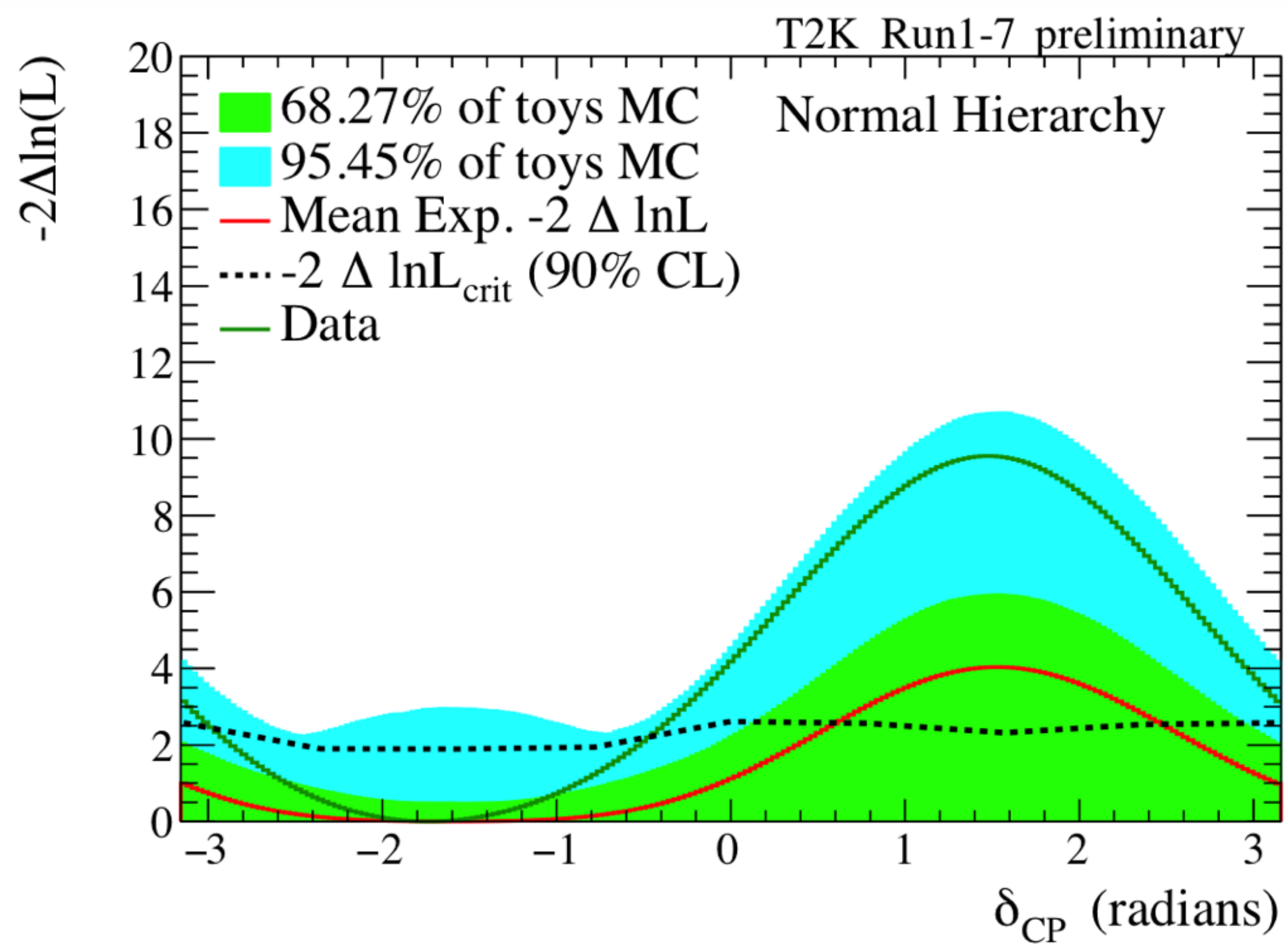
Reactors' constraint:
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$
(PDG 2015)

- Best-fit: δ_{CP} = -1.73, Normal Hierarchy
- δ_{CP} = 0 is excluded at 2σ CL while $\delta_{CP} = \pi$ is excluded at 90% CL
- Allowed 90% CL region: - Normal Hierarchy: [-2.98,-0.47]
  - Inverted Hierarchy: [-1.47,-1.27]

CP conservation hypothesis is excluded at 90%CL

Confidence intervals of δ_{CP}

- Toy MC study to estimate the probability to observe such a data set



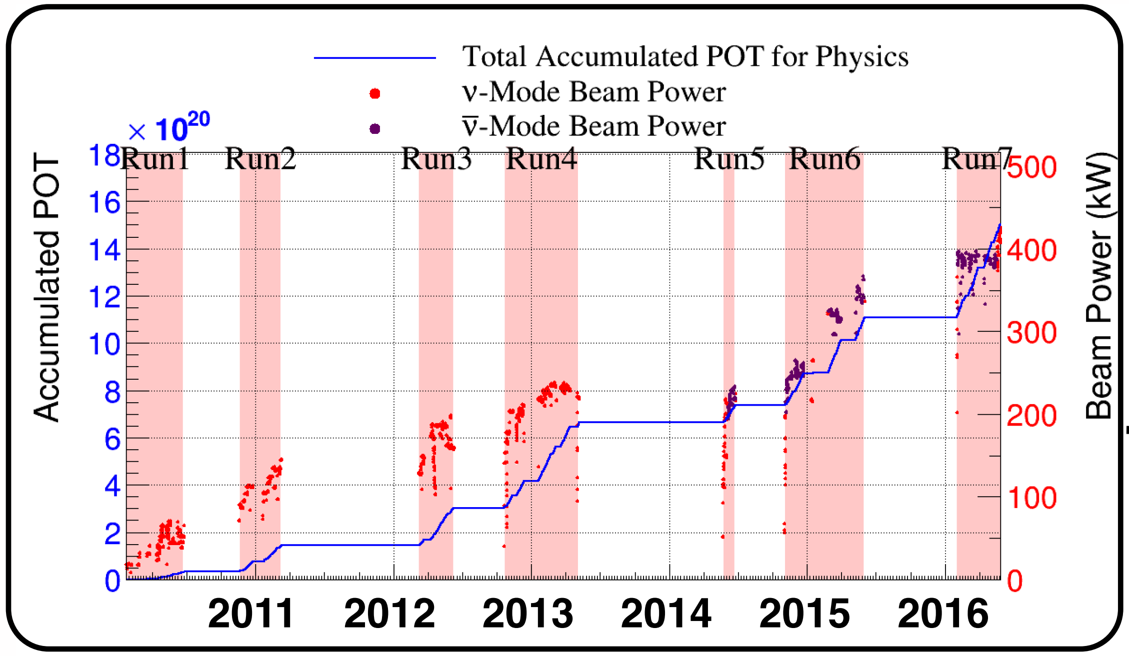
- More than ~5% of toy MC experiments show stronger exclusion than T2K data
- If nature is $\delta_{CP} = -\pi/2$ and Normal Hierarchy:
  - probability to exclude $\delta_{CP}=0$ at 2σ is 13.1%
  - probability to exclude $\delta_{CP}= \pi$ at 90%CL is 21.6%

Prospects for the future: T2K-II

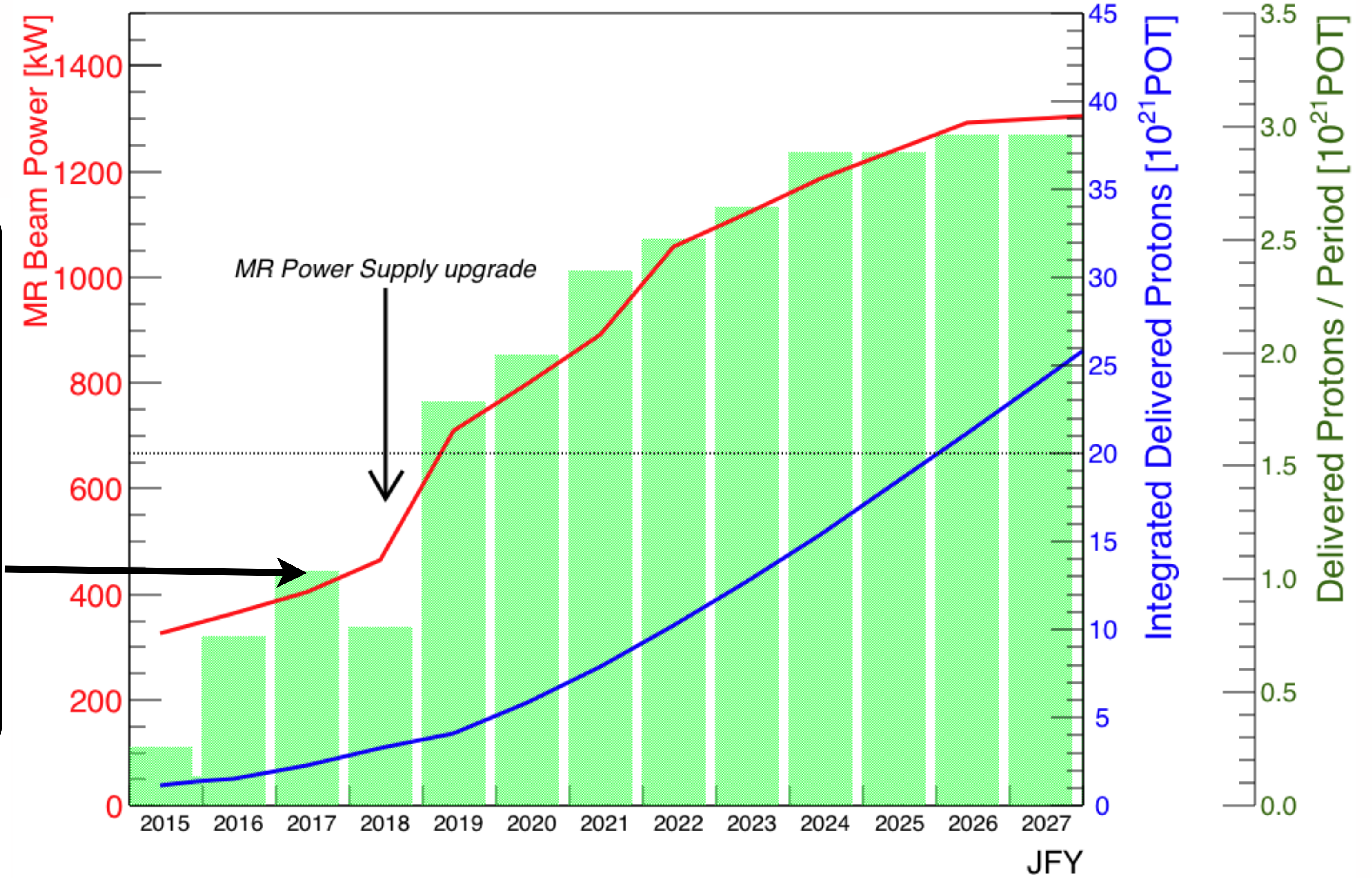
- Expect to reach the approved T2K statistics (7.8×10^{21} POT) around 2021
- **T2K-II phase**: proposed to extend T2K run to 20×10^{21} POT by 2025 (Stage-I status at summer JPARC PAC)
- Plan to gradually increase the beam intensity up to ~1 MW in 2021
- Aiming for >1 MW intensity for 2021 and 1.3 MW in ~2026: accelerator and beam-line upgrade is needed
- Demonstrated 3.41×10^{13} protons per beam operation → 1MW equivalent

arXiv:1609.04111

TODAY

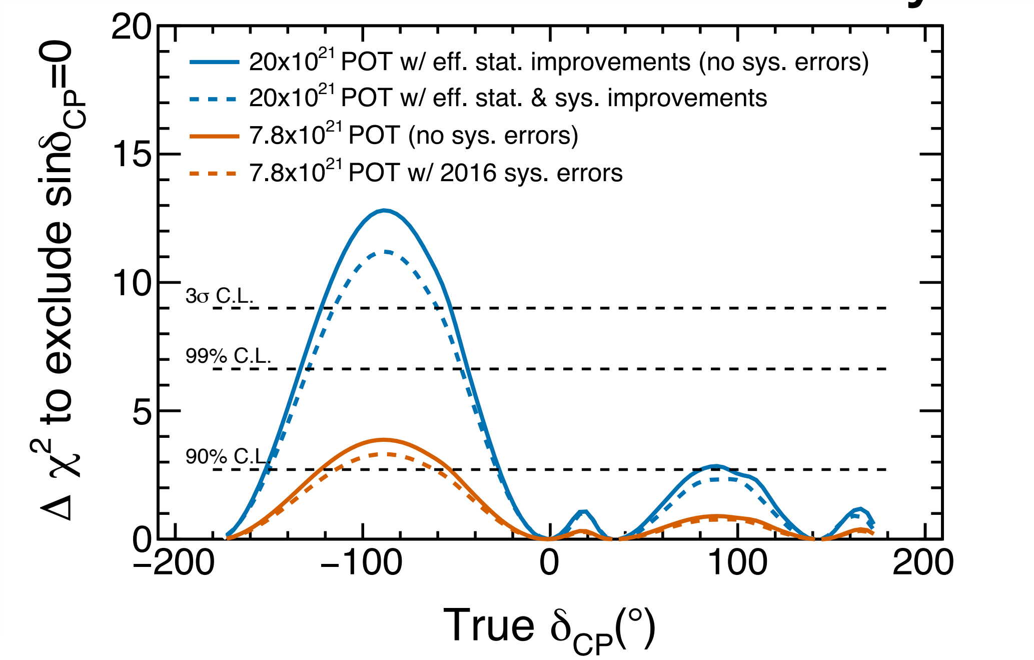


Will reach 500 kW soon

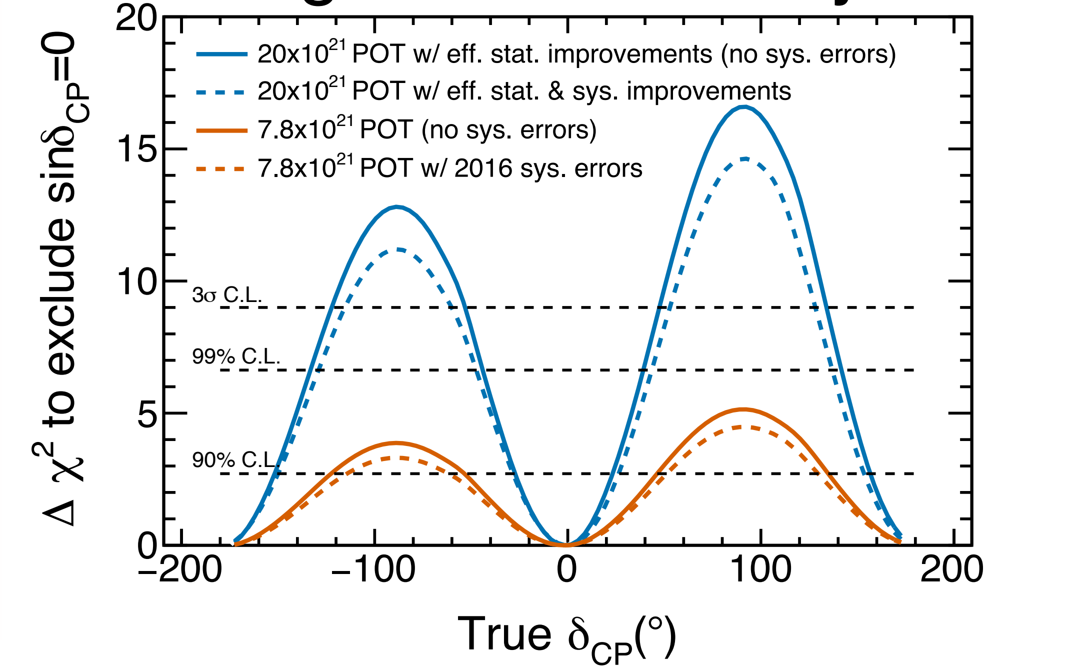


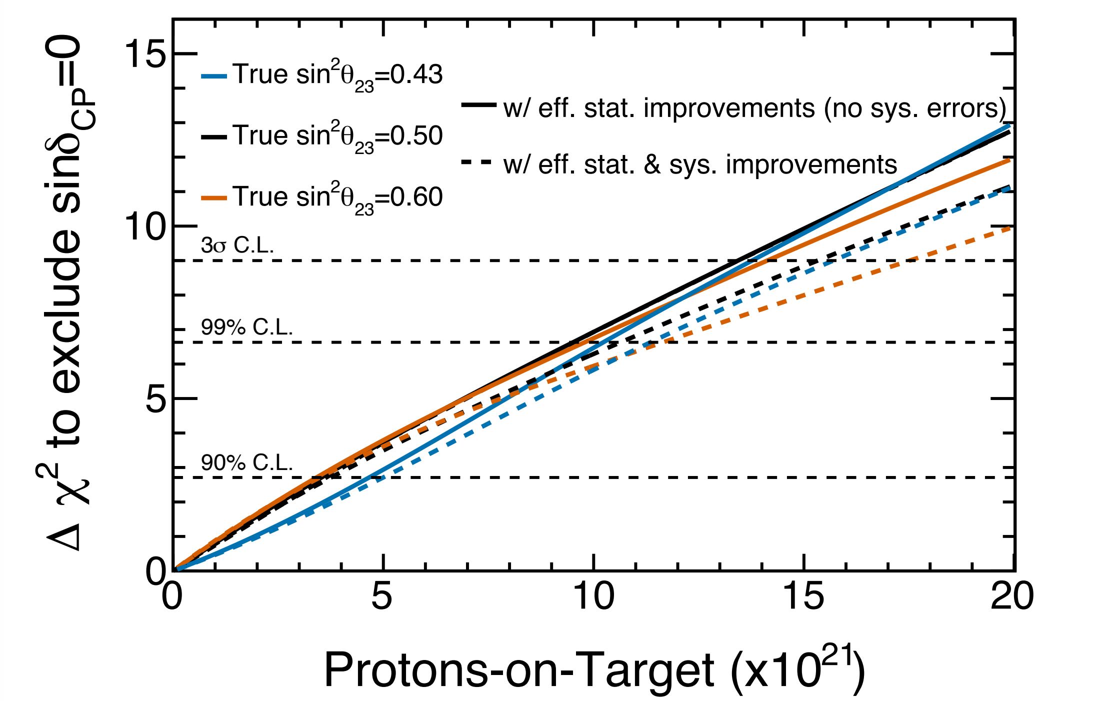
Prospects for the future: T2K-II

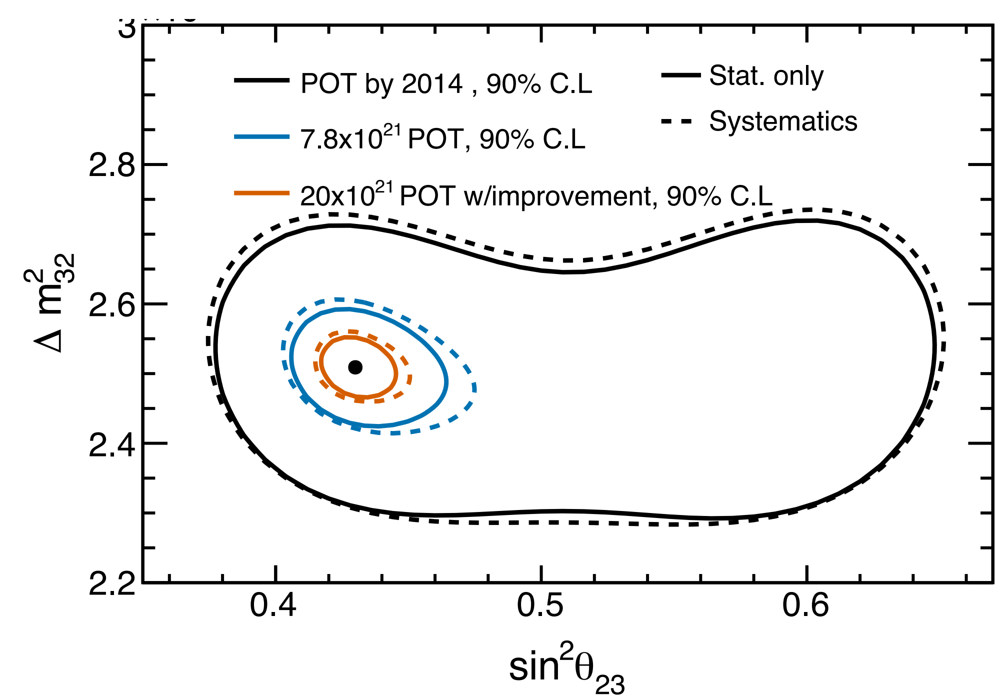
Unknown mass hierarchy



Assuming mass hierarchy known





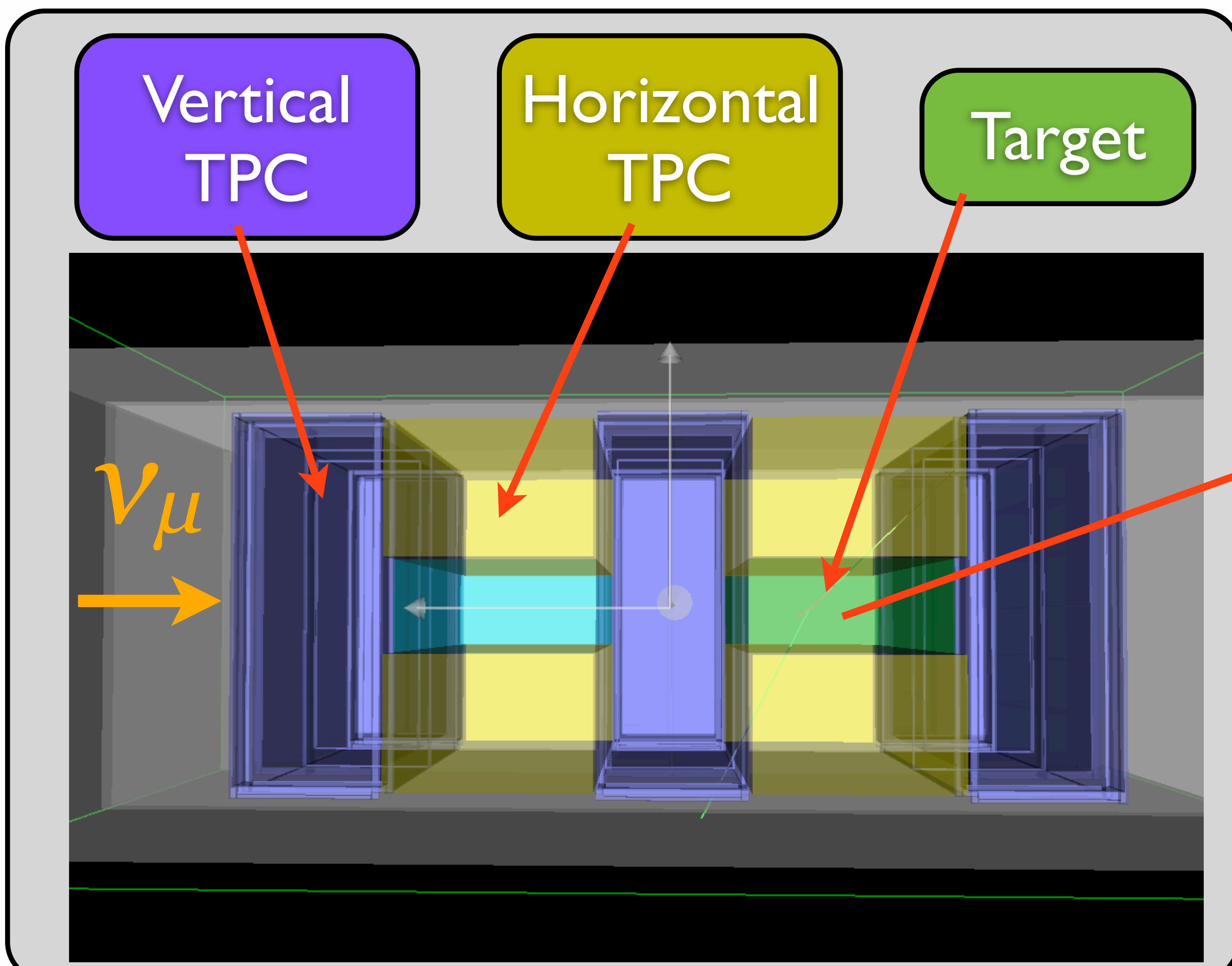


- Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \sim -\pi/2$ and NH
- Measure Θ_{23} with resolution of $\lesssim 1.7^o$
- Need to reduce the systematic uncertainties:
  ~18% (2011) → ~9% (2014) → ~6% (2016) → ~4% (2020) ???

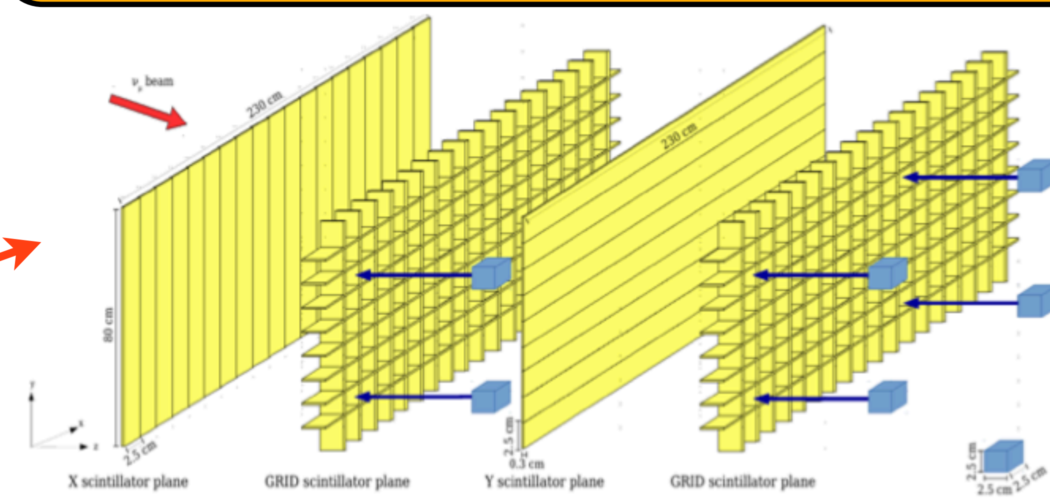
Prospects for the future: near detector upgrade

- Goal is to reduce the cross section systematics
- Need more precise measurements at ND280
  - better efficiency for low momenta π and p
  - 4π acceptance

It would be the magnetized detector also for Hyper-Kamiokande



WAGASCI detector:
- water-in → ~70% of water
- water-out → low momentum π



We are studying also other options

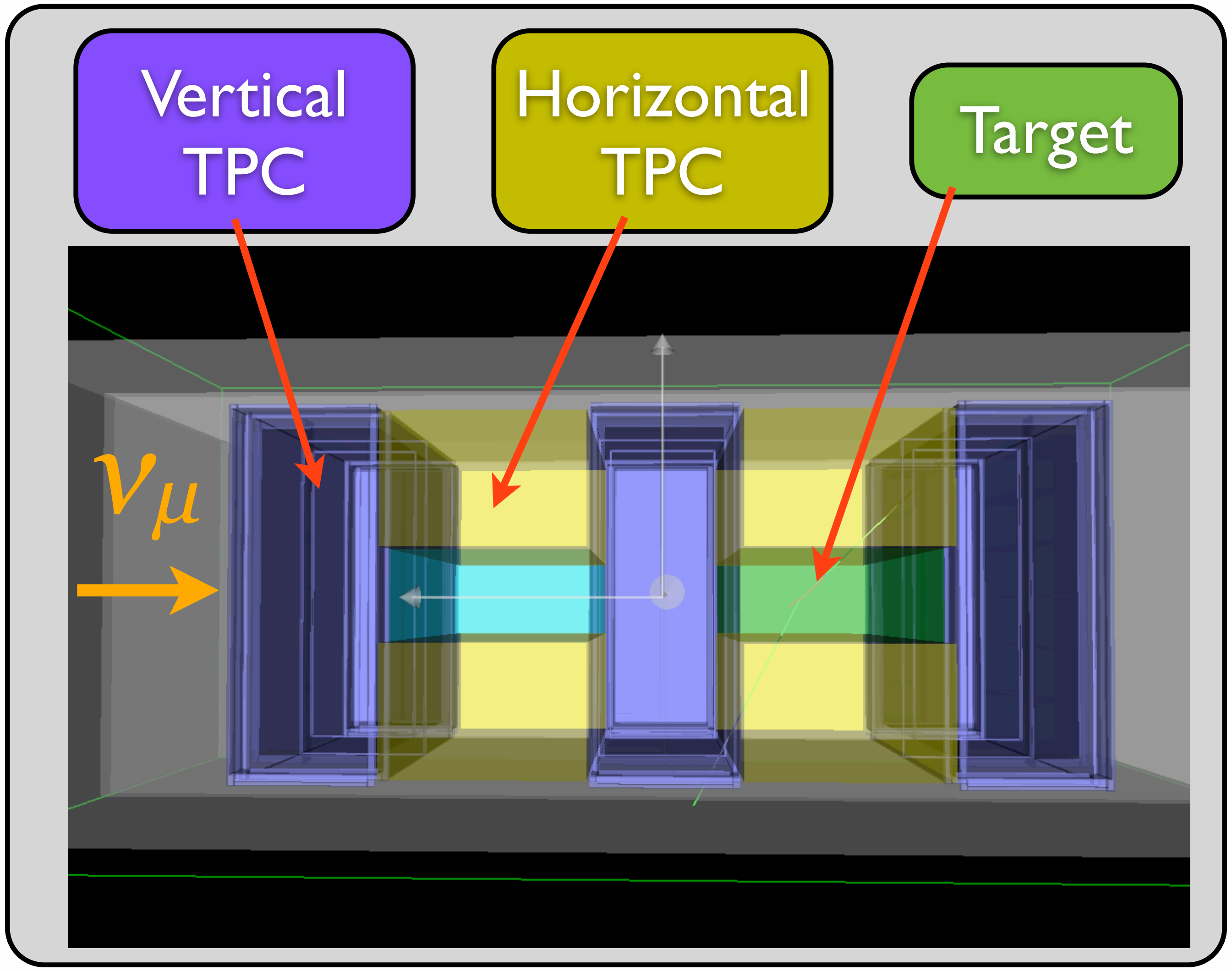
Workshop on “Neutrino ND based on gas TPCs” @CERN: https://indico.cern.ch/event/568177/
https://indico.cern.ch/event/61307/

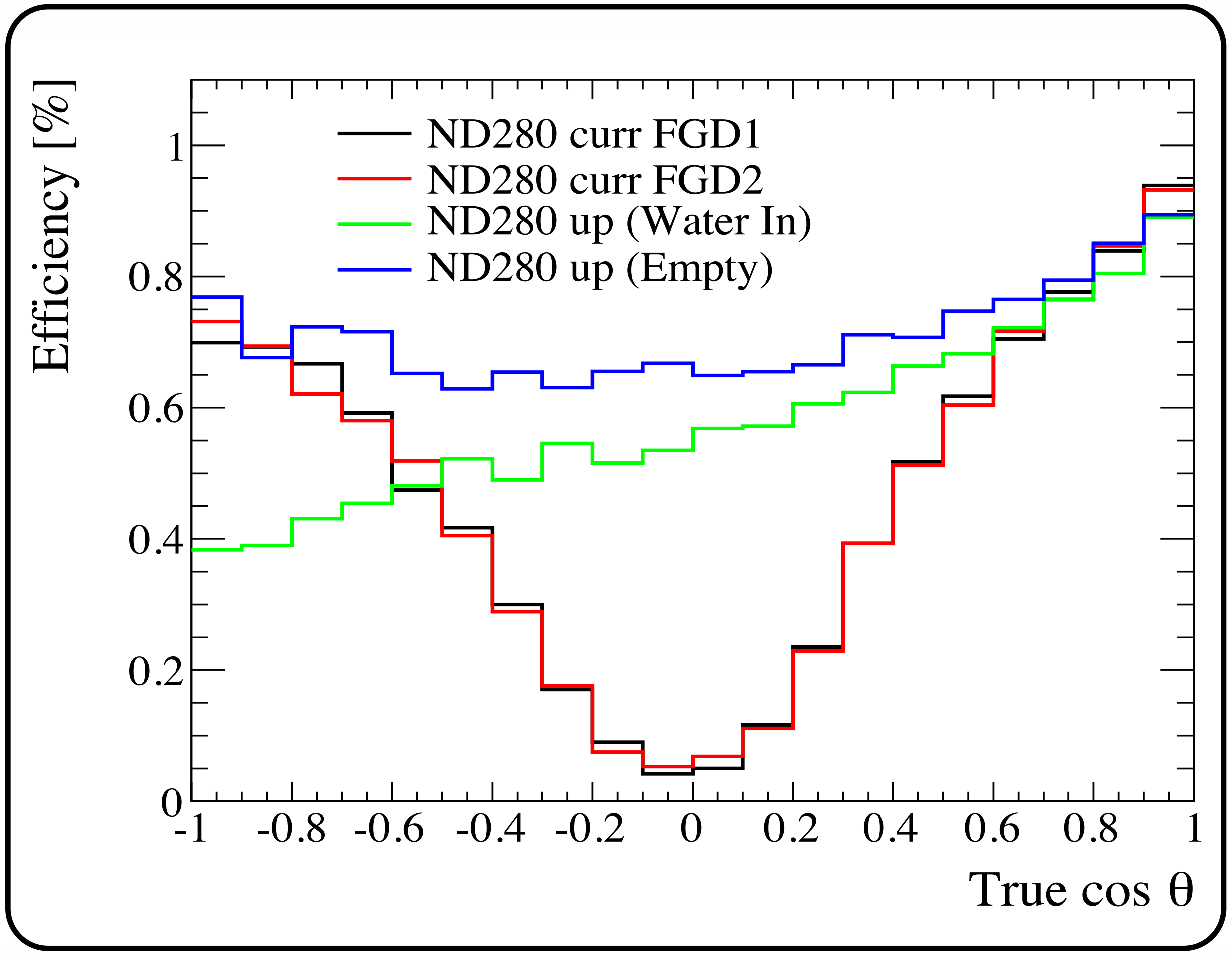
Alternative configurations to the reference design are being studied

Prospects for the future: near detector upgrade

- Goal is to reduce the cross section systematics
- Need more precise measurements at ND280
  - better efficiency for low momenta π and p
  - 4π acceptance

It would be the magnetized detector also for Hyper-Kamiokande





Workshop on "Neutrino ND based on gas TPCs" @CERN: https://indico.cern.ch/event/568177/
https://indico.cern.ch/event/61307/

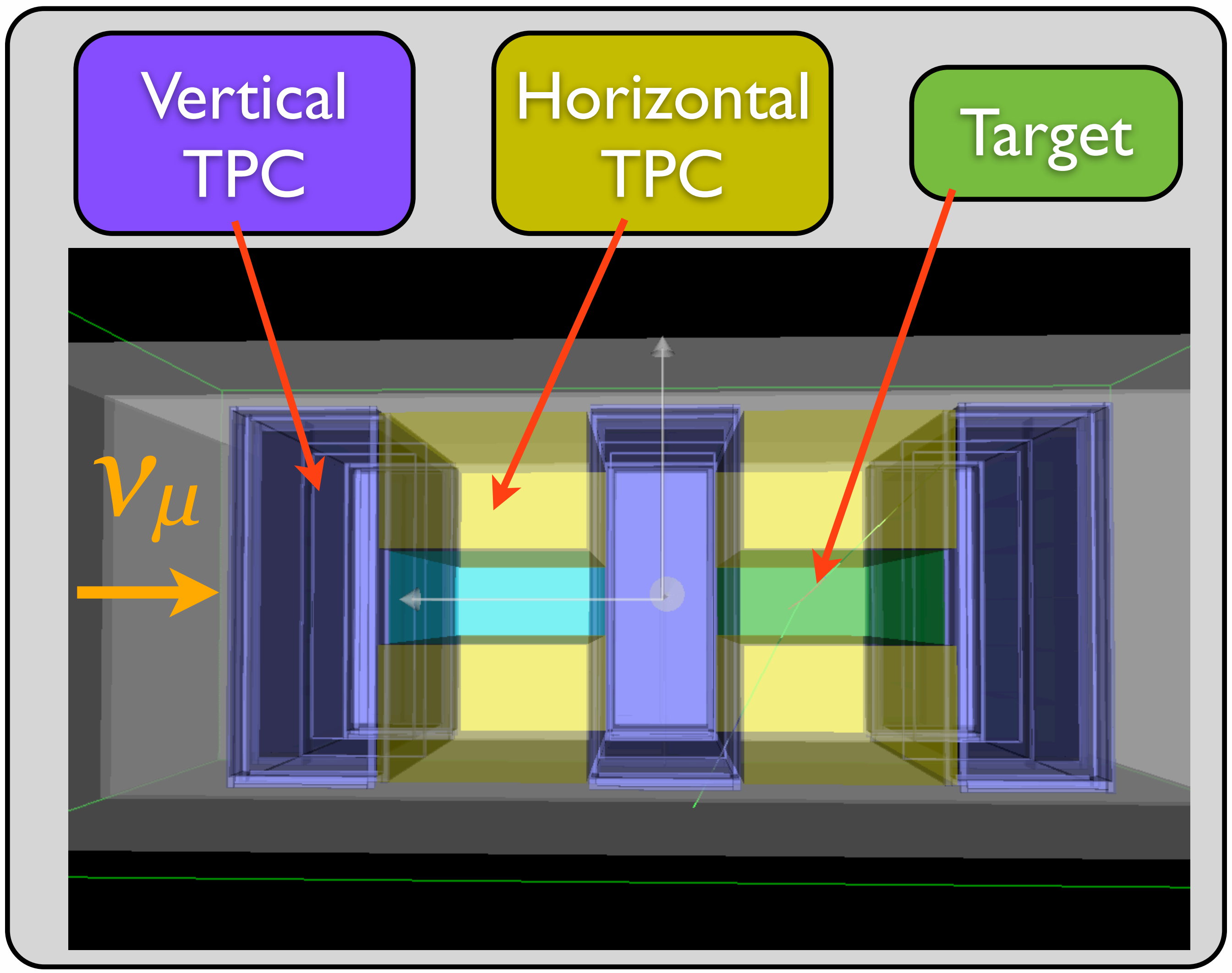
Alternative configurations to the reference design are being studied

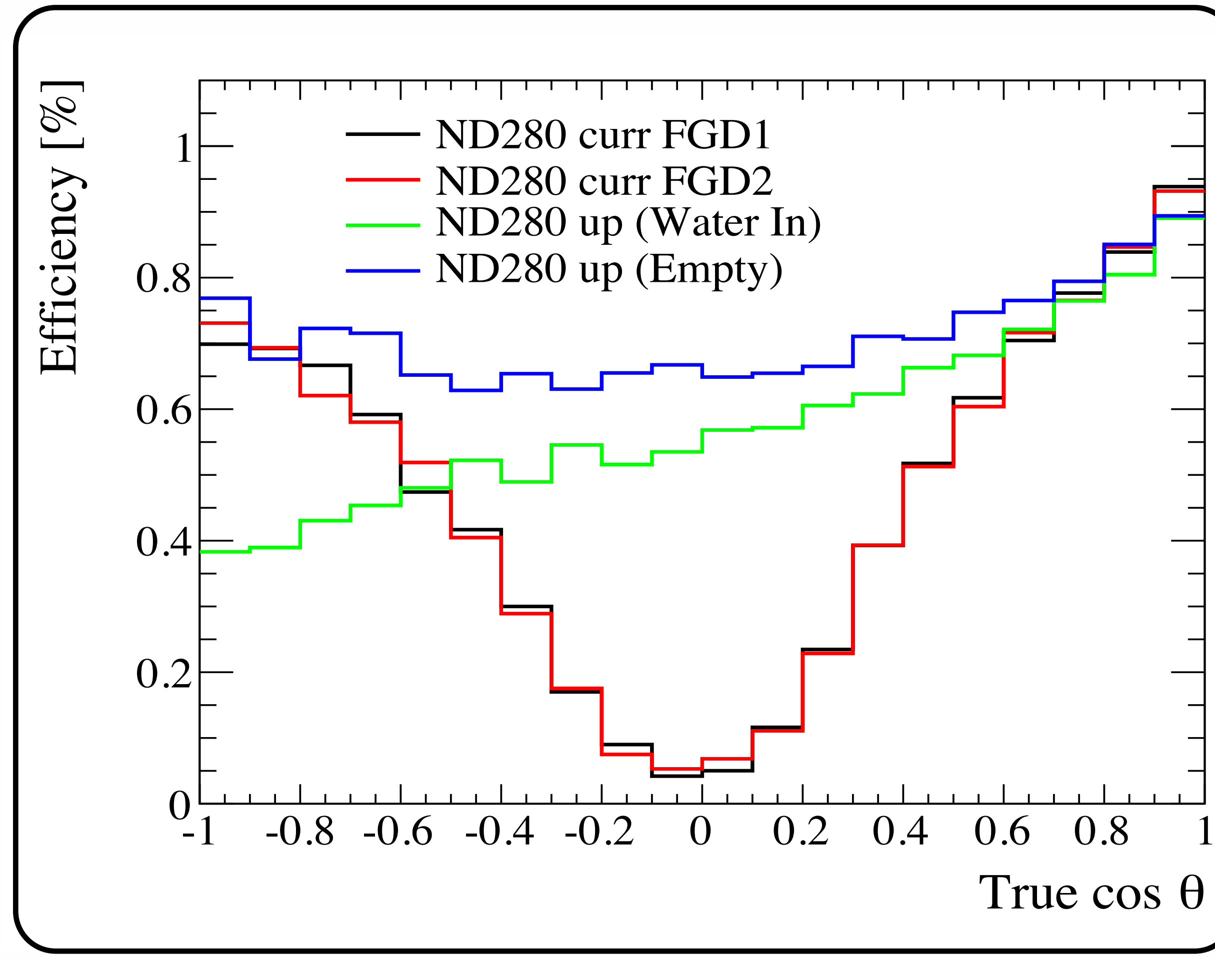
Prospects for the future: near detector upgrade

The upgrade of ND280 is now a T2K project

- 13 working packages have been established
- full proposal by end of 2017
- CERN EOI: CERN-SPSC-2017-002 / SPSC-EOI-015

It would be the magnetized detector also for Hyper-Kamiokande





Workshop on "Neutrino ND based on gas TPCs" @CERN: https://indico.cern.ch/event/568177/
https://indico.cern.ch/event/61307/

Alternative configurations to the reference design are being studied

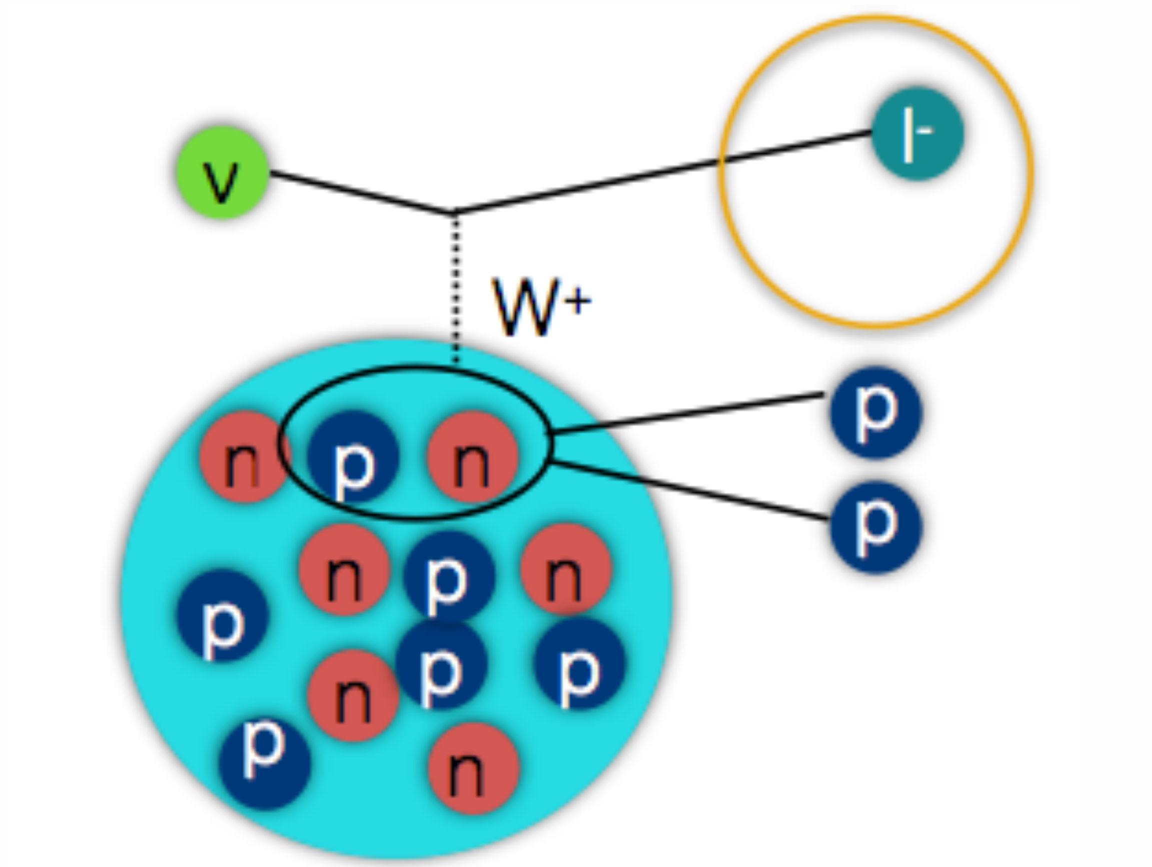
Summary

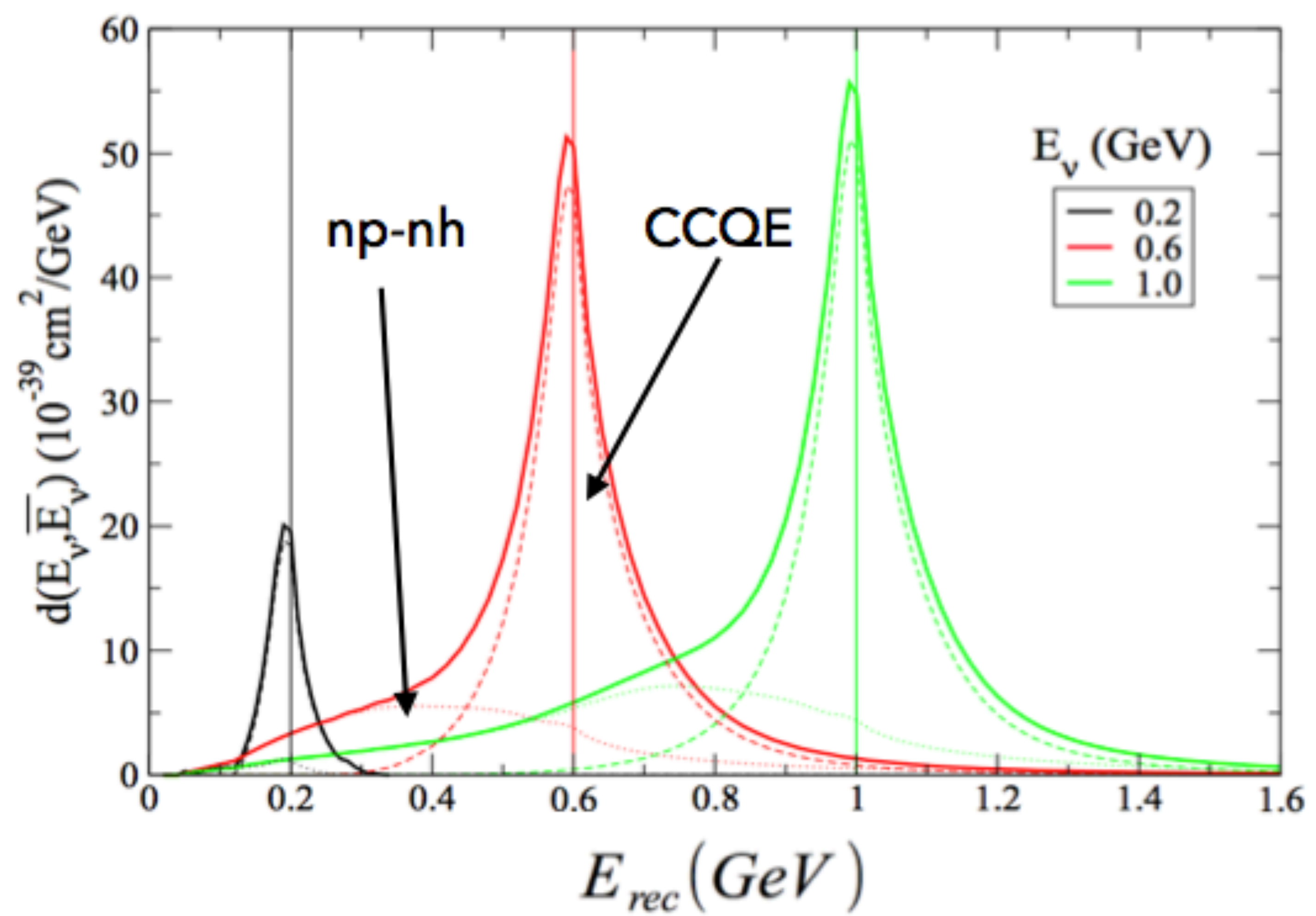
- New neutrino oscillation results from T2K (7.5 ν + 7.5 $\overline{\nu}$ x 10^{20} POT)
- First search for CP violation in the leptonic sector with neutrino & antineutrino
- Added the CC1π^+ - ν_e candidate sample (~10% more ν_e data)
  - data prefer maximal $\nu_\mu/\overline{\nu}_\mu$ disappearance
  - CP conservation excluded at 90% CL
  - δ_{CP} = [-2.98,-0.47] (NH), [-1.47,-1.27] (IH) @ 90% CL
- Two publications will be released soon:
  - first $\nu + \overline{\nu}$ oscillation analysis (arXiv:1701.00432, submitted to PRL)
  - same analysis with additional ν_e CC1π^+ sample (to be submitted to PRD)
- Expect to double neutrino data by summer 2017
- The goal (7.8x10^{21} POT) is expected by 2021
- Proposal for extending T2K to reach 3σ sensitivity to $\delta_{CP} \sim -\pi/2$ and NH
  - running until ~2025 to accumulate up to 20x10^{21} POT
  - the upgrade of the near detector is an official T2K project

BACKUP

Non-CCQE interactions

- Often only the lepton in the final state is visible
- Neutrino interaction observed as CCQE-like but it's non-CCQE
- More nucleons interact with the neutrino: multi-nucleon (np-nh)





Nieves et al. PRC 83 045501 (2011)
Martini et al. Phys.Rev. D87 (2013) 013009

- The final state kinematic is different → bias in neutrino energy reconstruction
- Analogous bias can be observed if the outgoing pion is absorbed
- Important for future detectors to improve sensitivity to these interactions

Impact of systematic uncertainties

Fractional error on the number of expected events at SK

	ν_μ sample 1R$_\mu$ FHC	ν_e sample 1R$_e$ FHC	$\bar{\nu}_\mu$ sample 1R$_\mu$ RHC	$\bar{\nu}_e$ sample 1R$_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

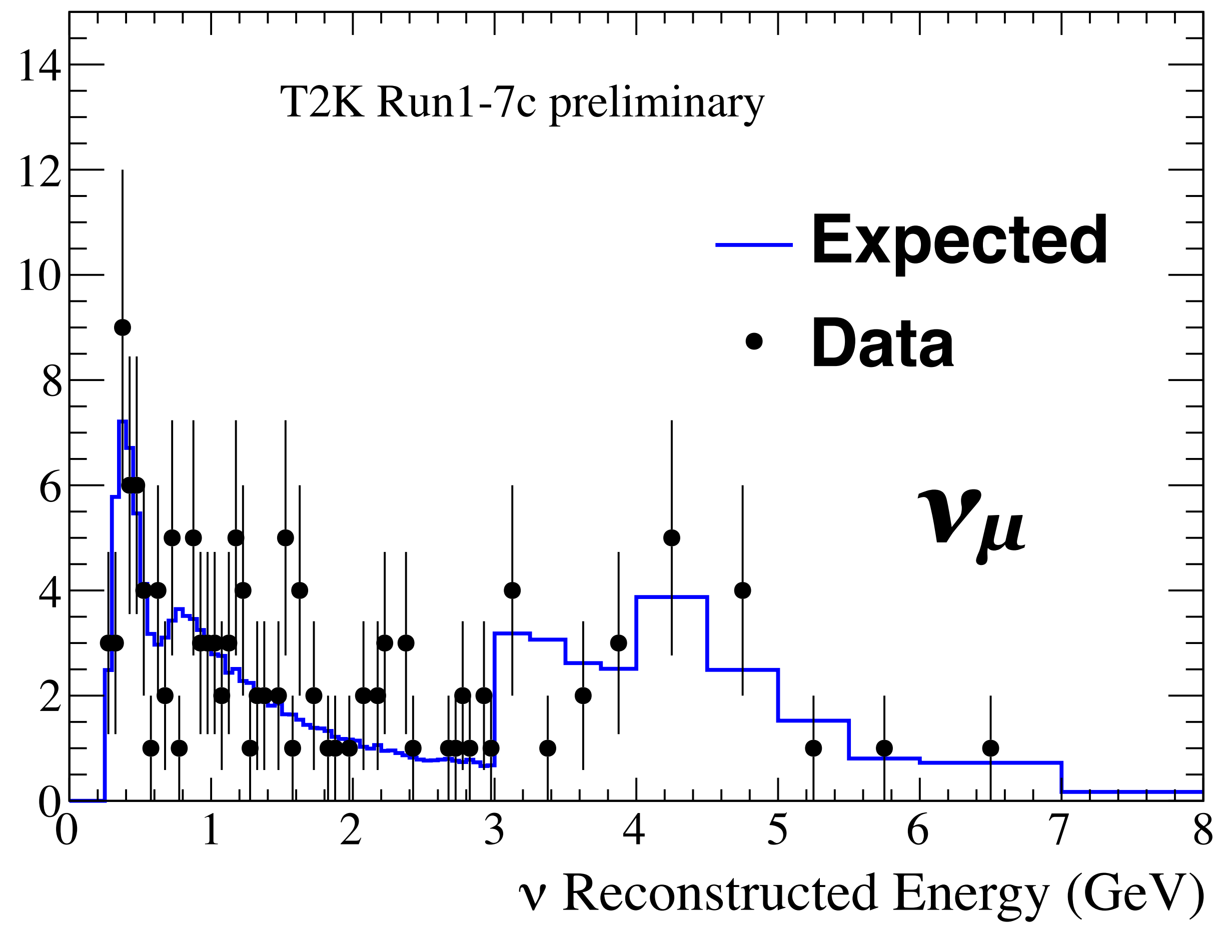
	ν_μ sample 1R$_\mu$ FHC	ν_e sample 1R$_e$ FHC	$\bar{\nu}_\mu$ sample 1R$_\mu$ RHC	$\bar{\nu}_e$ sample 1R$_e$ RHC	1R$_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%	1,5%
NC other	0,8%	0,2%	0,8%	0,3%	0,2%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%	3,6%
Super-K detector	3,9%	2,4%	3,3%	3,1%	1,6%
Total	**5,0%**	**5,4%**	**5,2%**	**6,2%**	**5,8%**

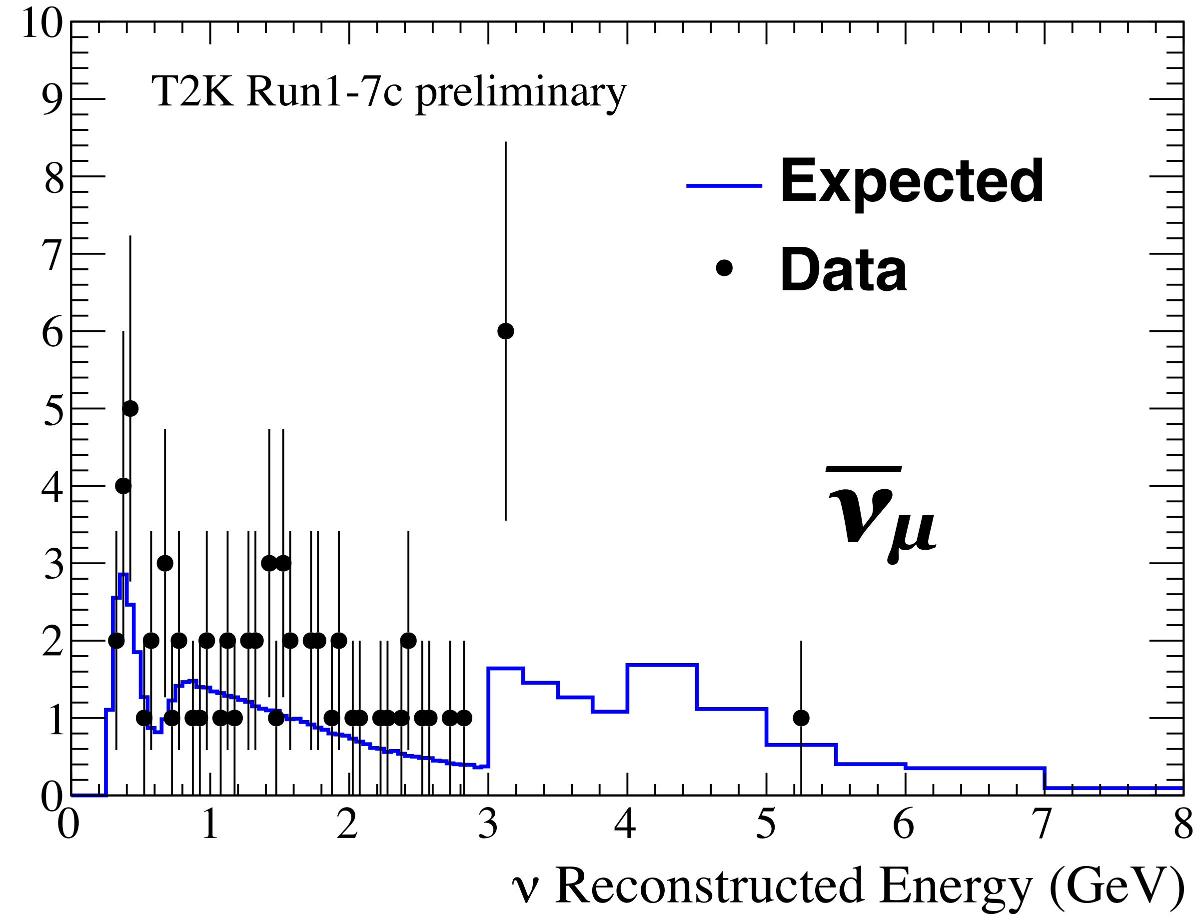
Neutrino reconstructed energy

$$E^{\text{Rec}}_{\nu_e CCQE} = \frac{2(M_n - V_{\text{nuc}}) * E_e + M_p^2 - (M_n - V_{\text{nuc}})^2 - M_e^2}{2((M_n - V_{\text{nuc}}) - E_e + p_e \cos\theta_e)}$$

$$E^{\text{Rec}}_{\nu_e CC\Delta} = \frac{2M_p E_e + M^2_{\Delta^{++}} - M_p^2 - M_e^2}{2(M_p - E_e + p_e \cos\theta_e)}$$

ν_μ / $\bar{\nu}_\mu$ predicted spectra at Far Detector





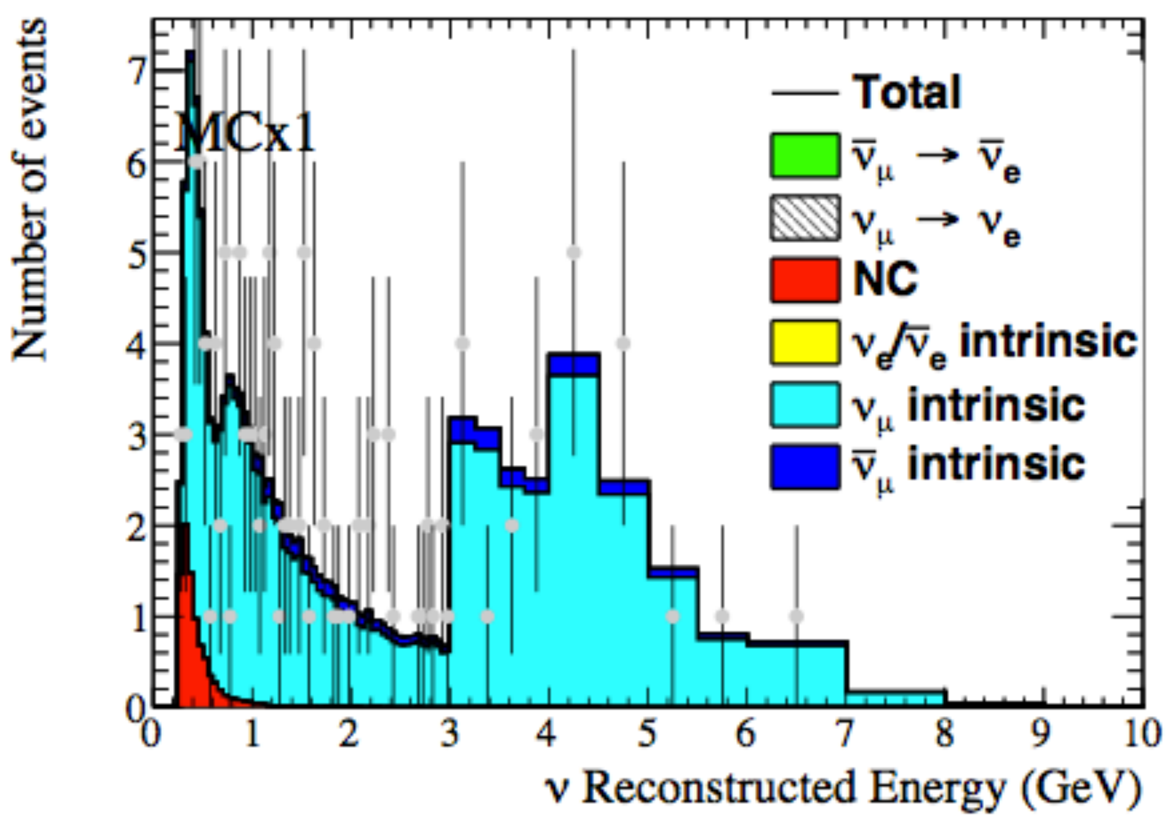
$\sin^2\Theta_{23} = 0.528$
$|\Delta m^2_{32}| = 2.509 \times 10^{-3} eV^2$
$\sin^2\Theta_{13} = 0.0217$
$\delta_{CP} = -1.601$
Normal Hierarchy

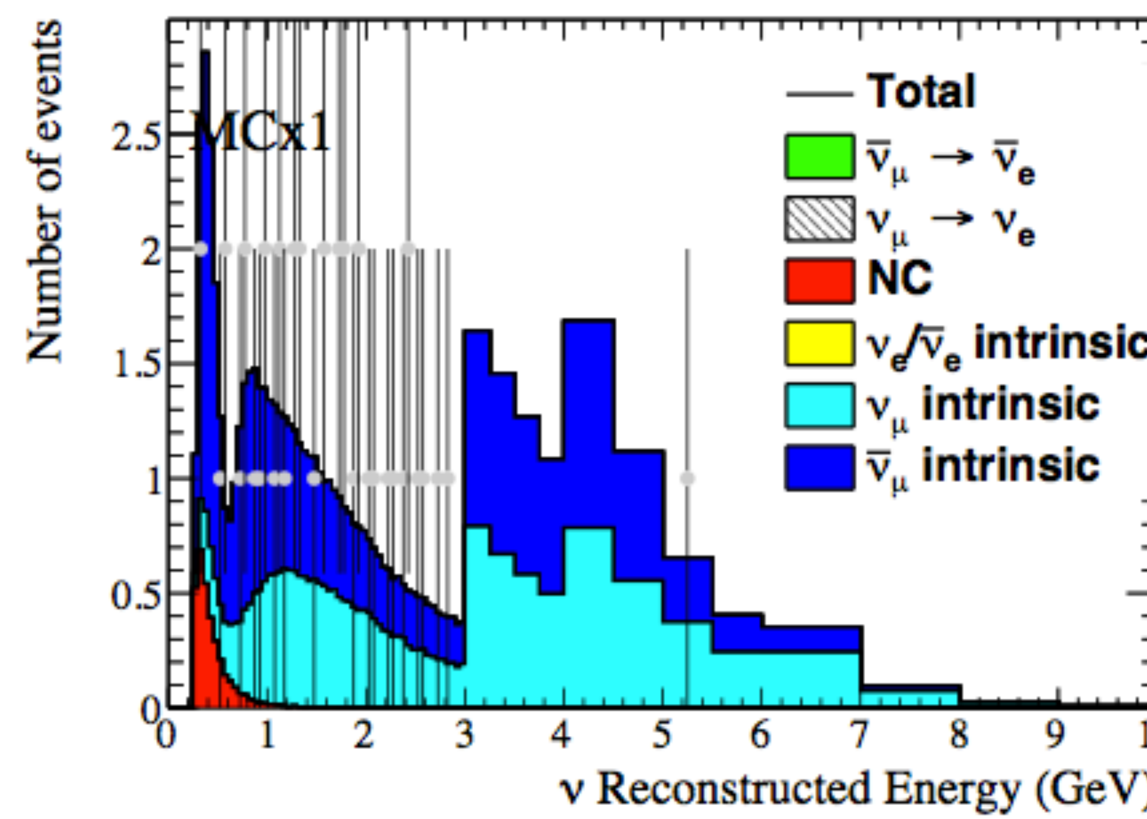
Beam mode	Expected Not Oscillated	Expected Oscillated	Observed
neutrino	521.8	135.8	135
antineutrino	184.8	64.2	66

- Reconstructed energy (E_{rec}) distributions assuming 2-body ("QE") kinematics

Event rates

Beam mode	Signal	Wrong-sign background	Total	Observed
numu CCQE	126.9	8.2	135.8	135
numubar CCQE	36.6	27.4	64.2	66
nue CCQE	23.2	0.2	28.7	32
nuebar CCQE	2.8	1.0	6.0	4
nue CC1π	2.3	0.0	3.1	5





Updated $\overline{\nu}_\mu$ disappearance results

- In PMNS framework $P(\nu_\mu \to \nu_x) = P(\overline{\nu}_\mu \to \overline{\nu}_x)$ for any value of δ_{CP}
- No "± terms" for neutrino / antineutrino

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

~~CPT~~

Non-standard matter interactions

$\}\longrightarrow P(\nu_\mu \to \nu_\mu) \neq P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$

- ~7.5×10^{20} POT antineutrino (~3.5×10^{20} POT more wrt 2015 analysis):
  - joint neutrino / antineutrino (muon (anti)neutrino samples)

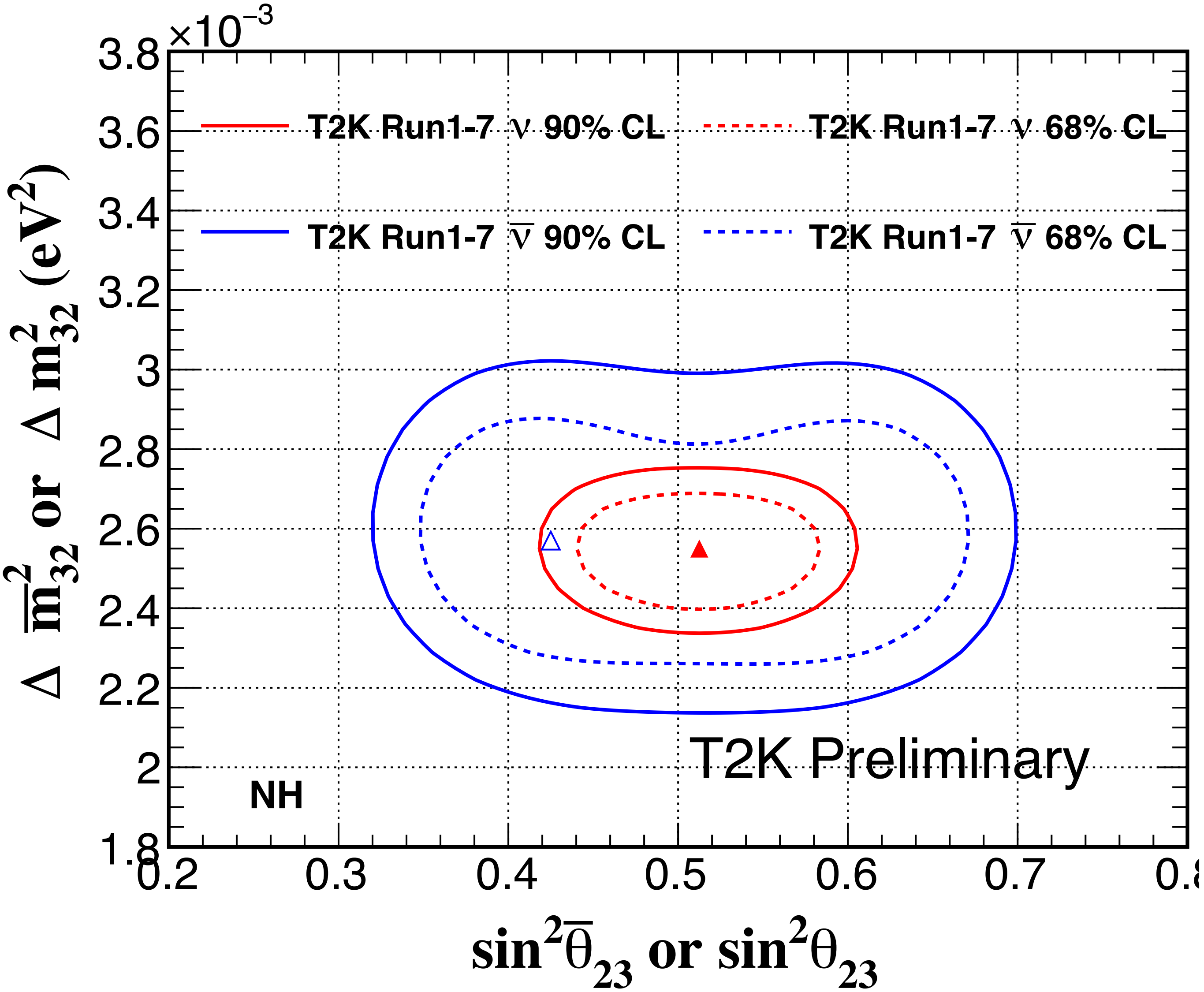
ν	Vs	$\overline{\nu}$
$\sin^2\Theta_{23}$ $\lvert\Delta m^2_{32}\rvert$		$\sin^2\overline{\Theta}_{23}$ $\lvert\Delta\overline{m}^2_{32}\rvert$

Constrain other oscillation parameters with PDG 2015 and fix $\delta_{CP}=0$

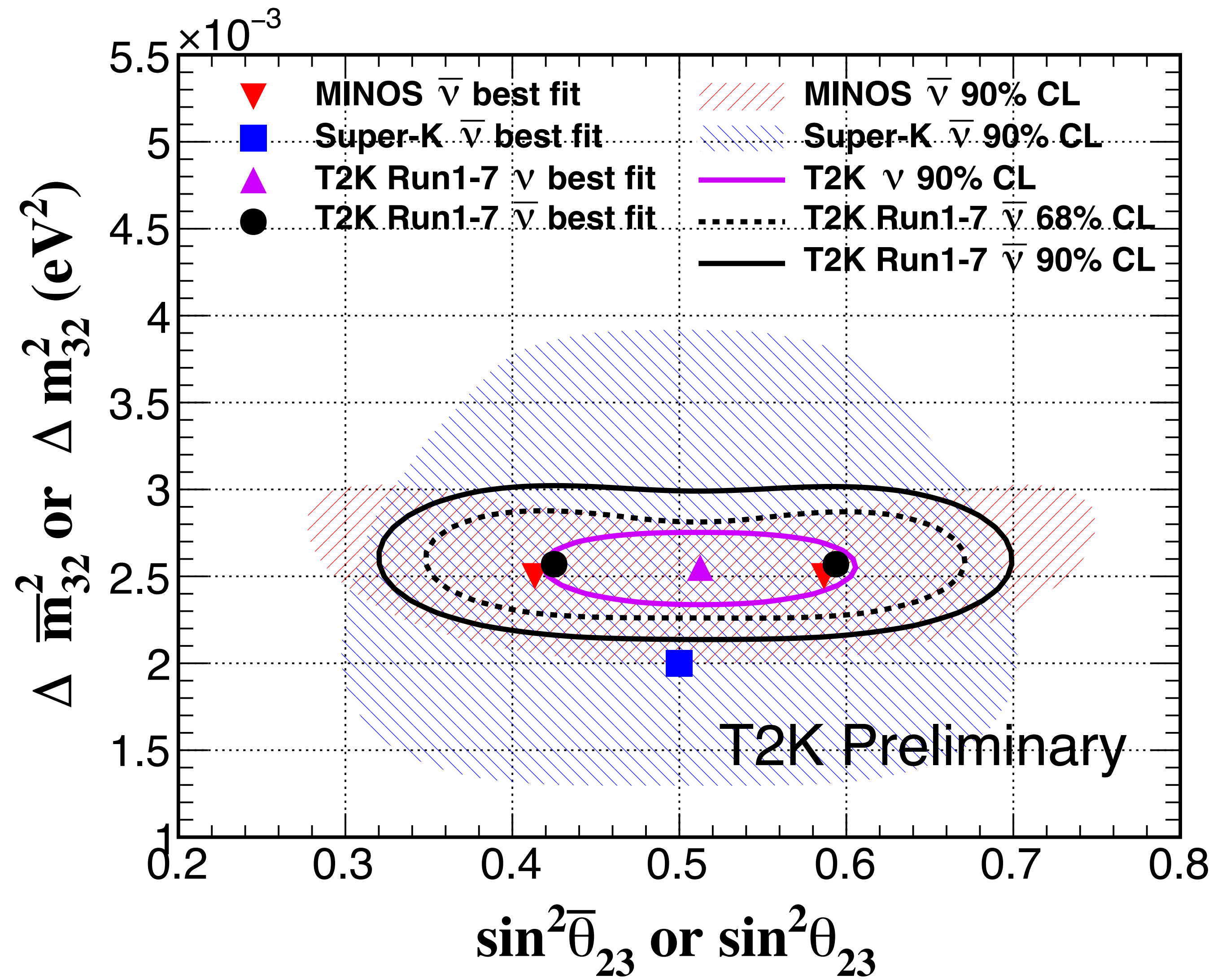
Beam mode	Expected Not Osc.	Observed
neutrino	521.8	135
antineutrino	184.8	66

Updated $\overline{\nu}_\mu$ disappearance results

Neutrino Vs antineutrino



Comparison with other experiments



- No discrepancy between neutrino and antineutrino data
- Best measurement of the oscillation parameters with antineutrino data only
- Good agreement with antineutrino data from other experiments

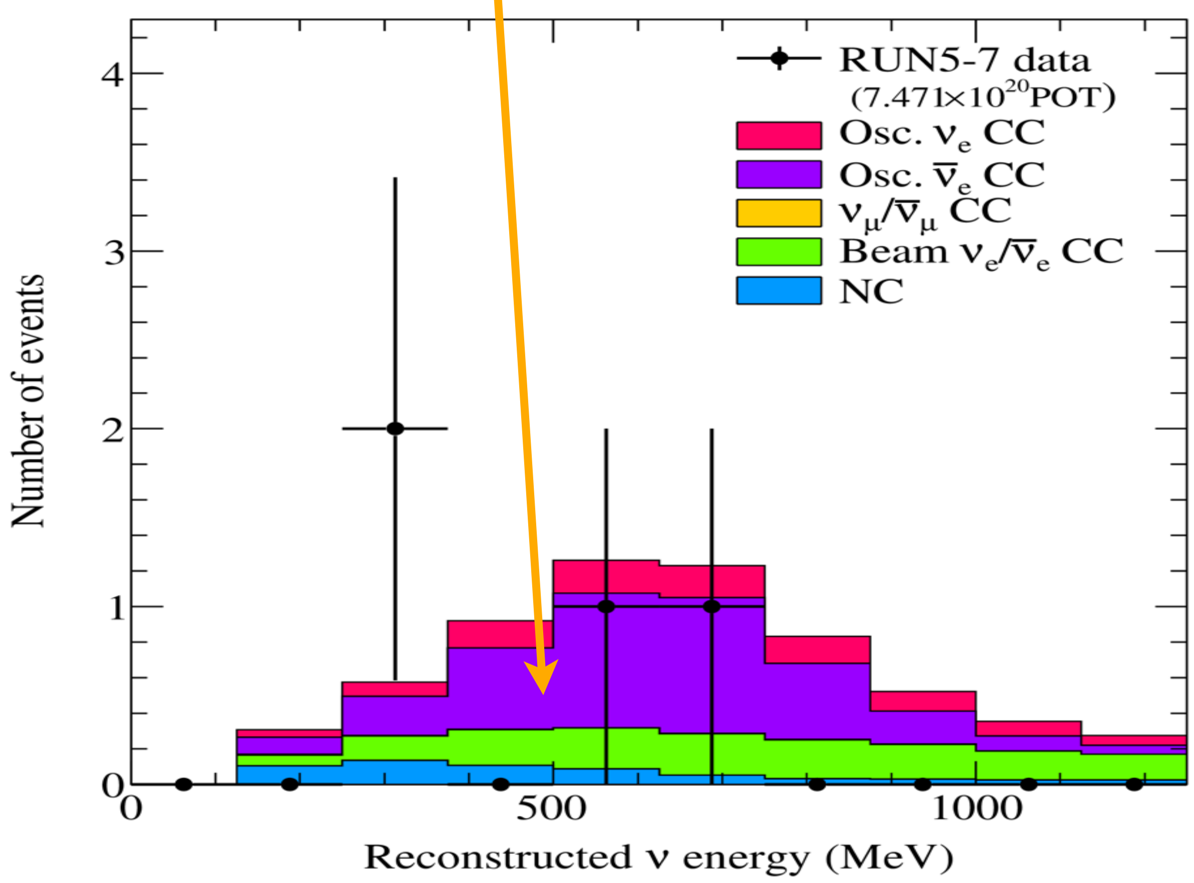
Updated $\overline{\nu}_e$ appearance results

Test of electron antineutrino appearance hypothesis:

- β = 0 → no $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance
- β = 1 → $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance consistent with PMNS framework

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\rm PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

β add / remove the $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signal component

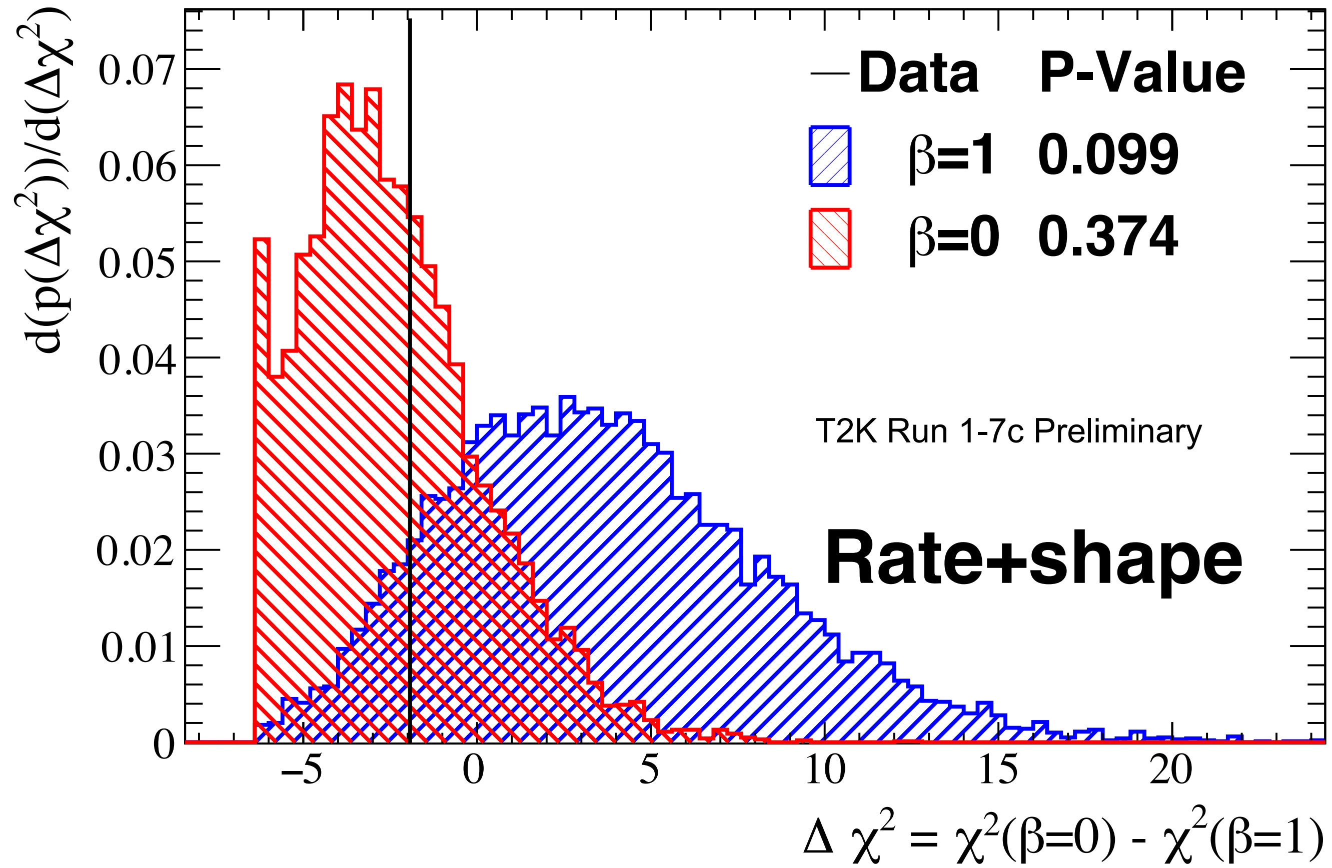


- Fit all 4 far detector samples to fully constrain the oscillation probability
- ~20% of wrong sign background ($\nu_\mu \rightarrow \nu_e$)
- Constrain $\sin^2\Theta_{13}$ with reactor measurements

True δ_{CP} - Normal Hierarchy					
	-π/2	0	π	+π/2	Observed
ν_e	28.7	24.1	24.2	19.6	32
$\overline{\nu}_e$	6.0	6.9	6.8	7.7	4

Sensitivity to appearance depends on the true value of δ_{CP} and the mass hierarchy

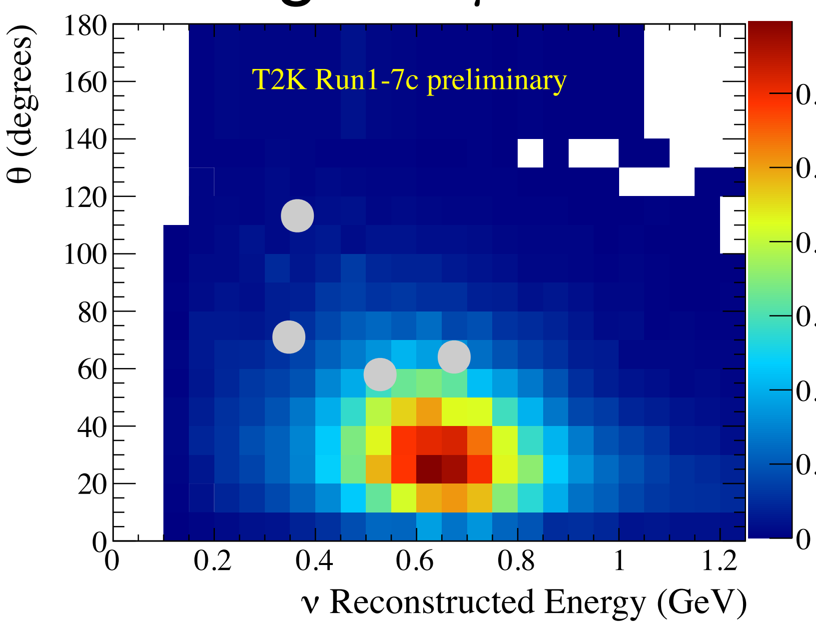
Updated $\overline{\nu}_e$ appearance results



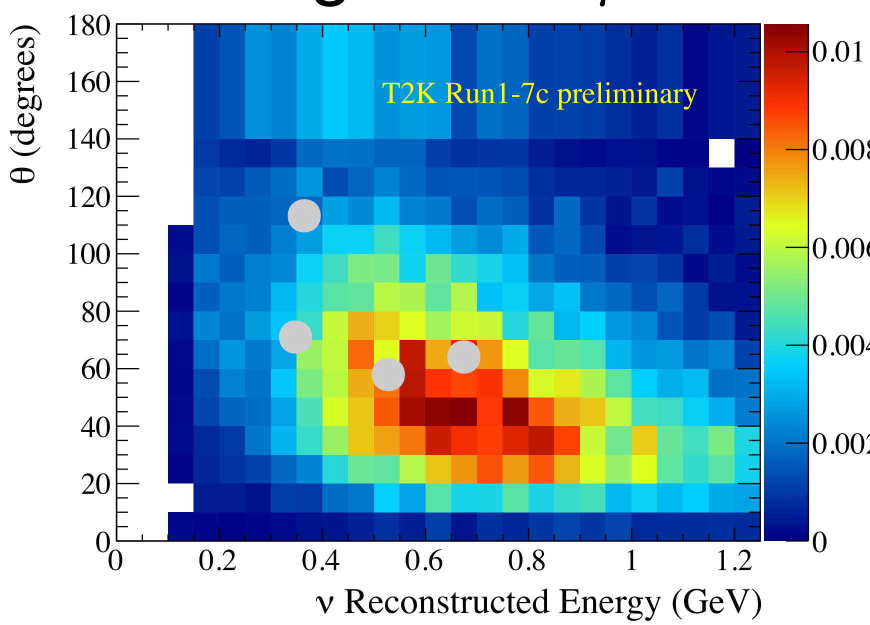
Likelihood ratio: L(β=0) / L(β=1)

P-value	Signal	Background
rate-only	0.22	0.41
rate+shape	0.10	0.37

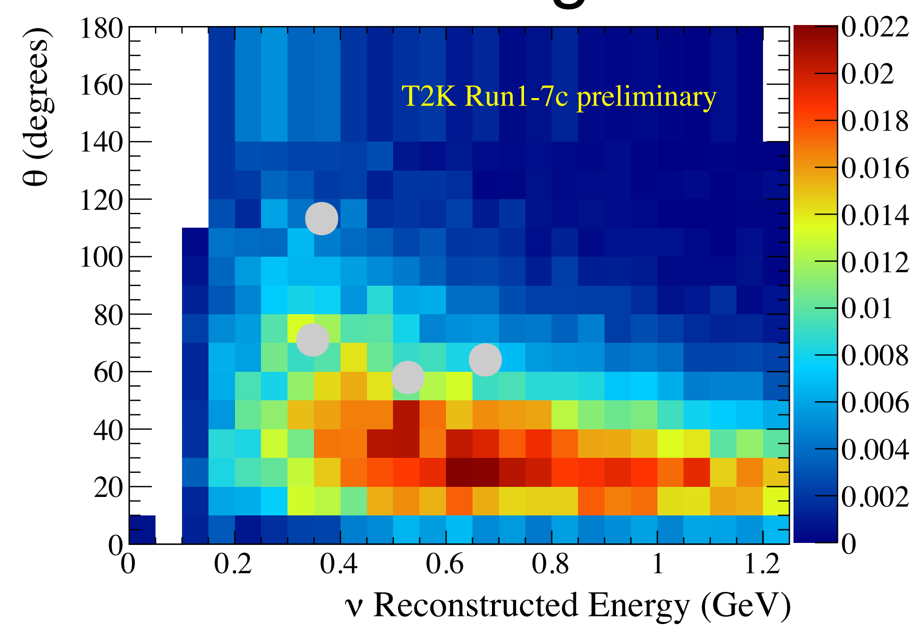
Signal $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



Background $\nu_\mu \rightarrow \nu_e$



Other Background

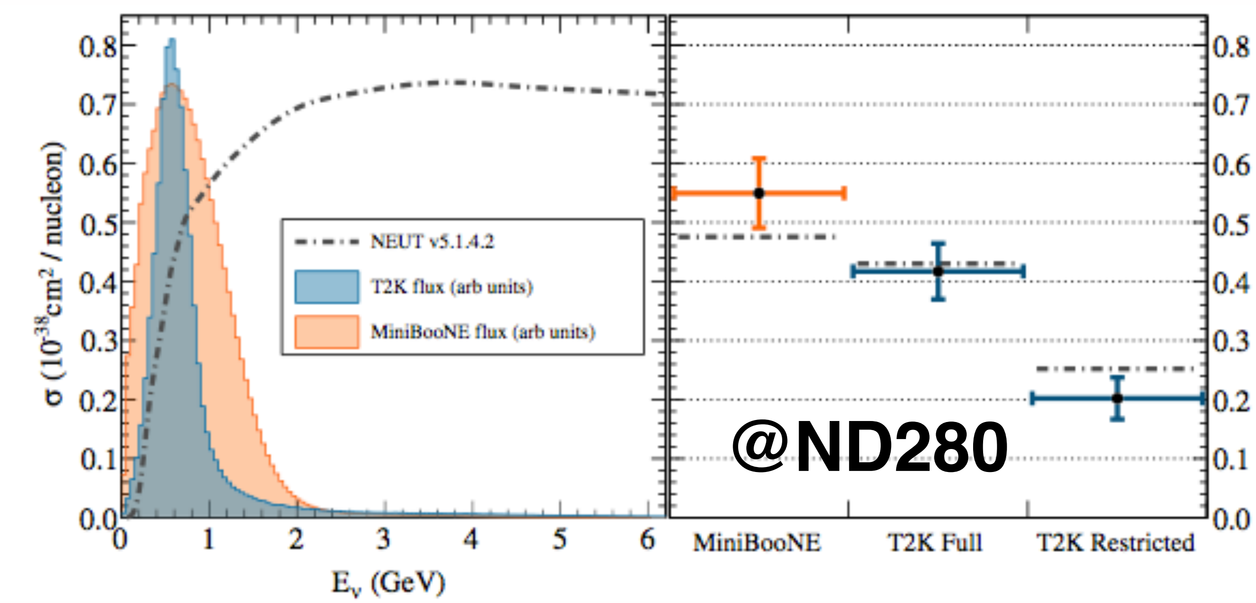


- No evidence of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with new full data set
- Shape of the spectra look more consistent with background

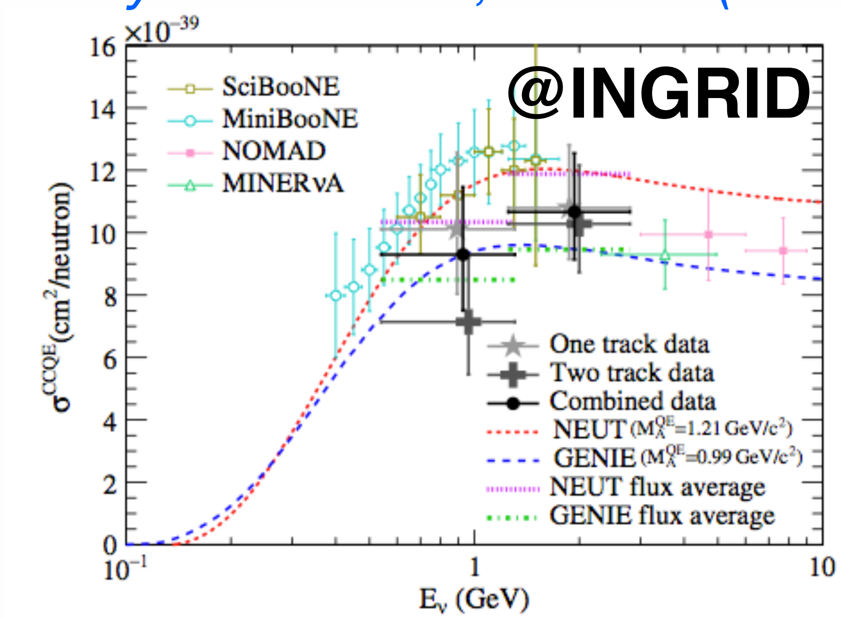
Neutrino cross-section results

- Understanding of neutrino cross section is fundamental for a precise measurement of the oscillation probability
- ν_μ CCQE-like cross section on C^{12}

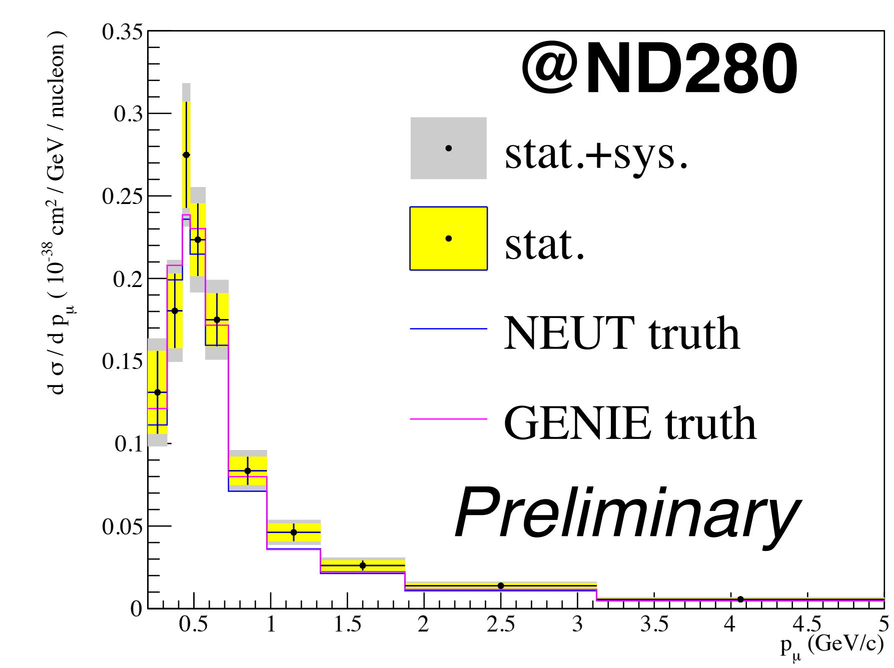
Phys. Rev. D 93, 112012 (2016)



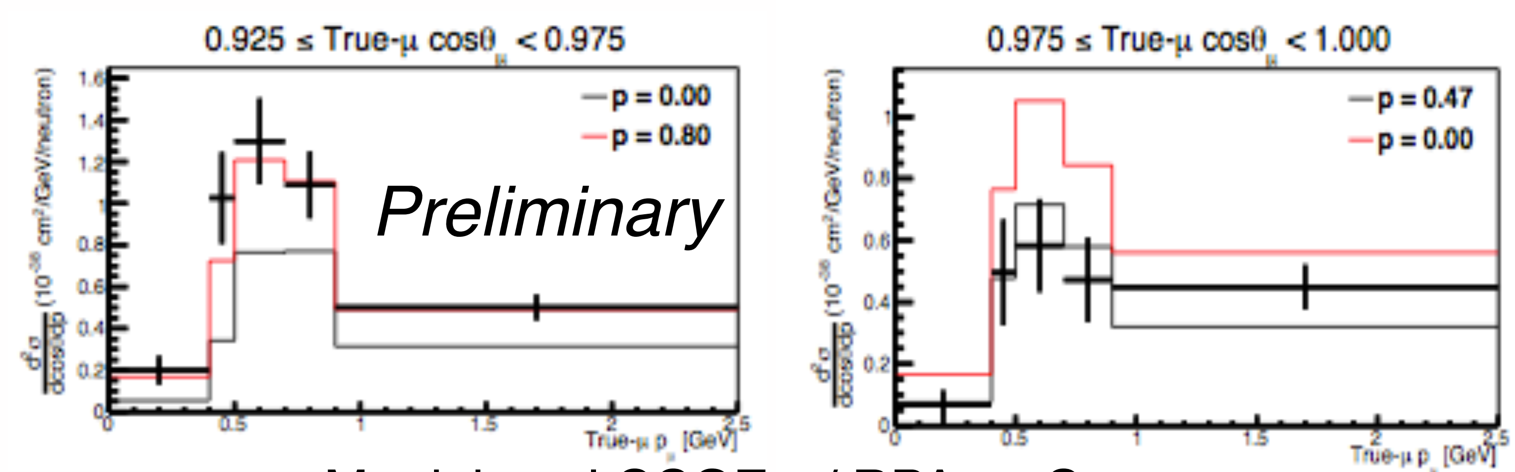
Phys. Rev. D 91, 112002 (2015)



- $\bar{\nu}_\mu$ CC cross section on C^{12}



- ν_μ CCQE on water with the P0D



- Martini et al CCQE w/ RPA on C
- Martini et al CCQE w/ RPA+2p2h on C

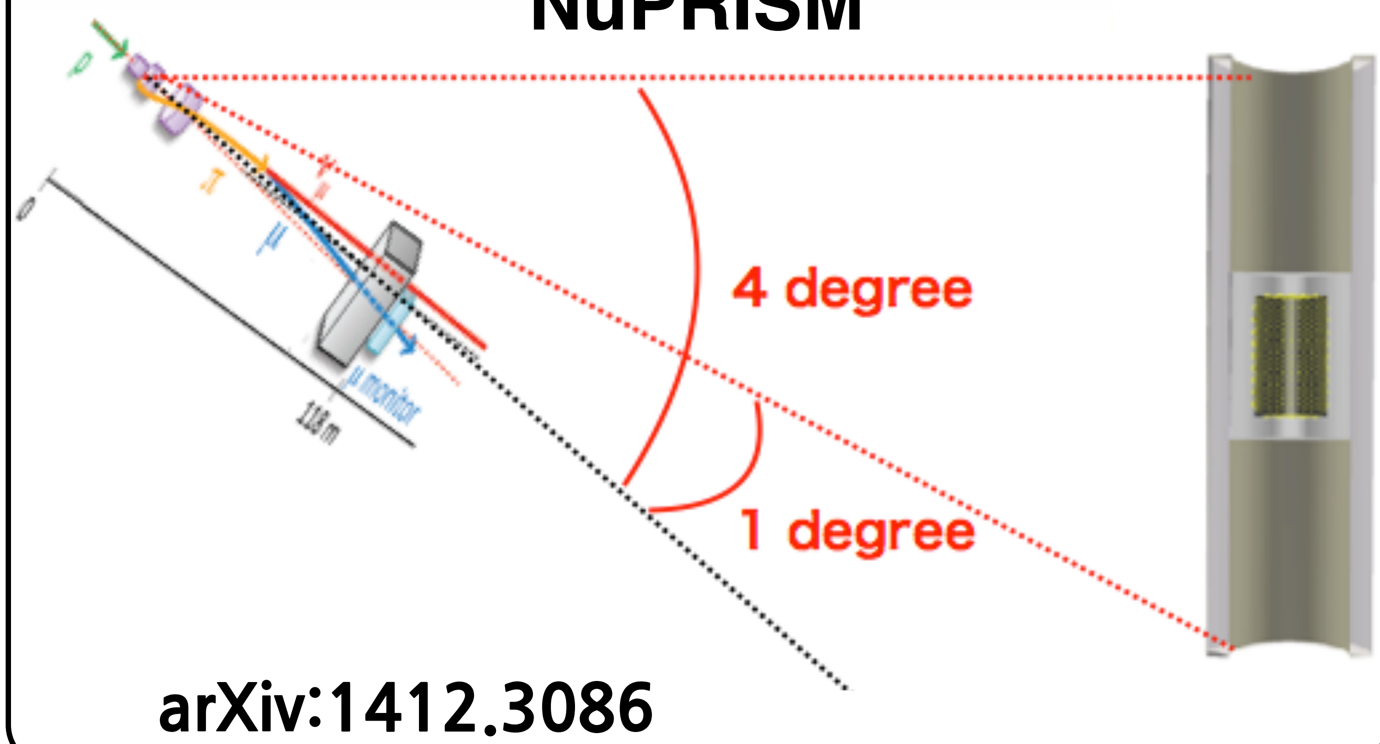
Many other results will be released soon...

Possible further upgrade: intermediate detector

• Water Cherenkov detector at intermediate distance (>1 km from target) with a high-intensity neutrino beam
• Same neutrino cross section as at the far detector
• Complementary to the upgrade of ND280 (magnetized)

Hyper-Kamiokande intermediate detectors optimized for T2K-II too

NuPRISM



TITUS

• Spans off-axis 1°/4°
• Mono-chromatic neutrino beam
• Study energy dependence to neutrino interactions

• 2.5° off-axis detector with 1.27 Kton FV
• Long geometry to contain high- momentum muons
• Gadolinium loading for neutron detection
• Magnetized muon range detector

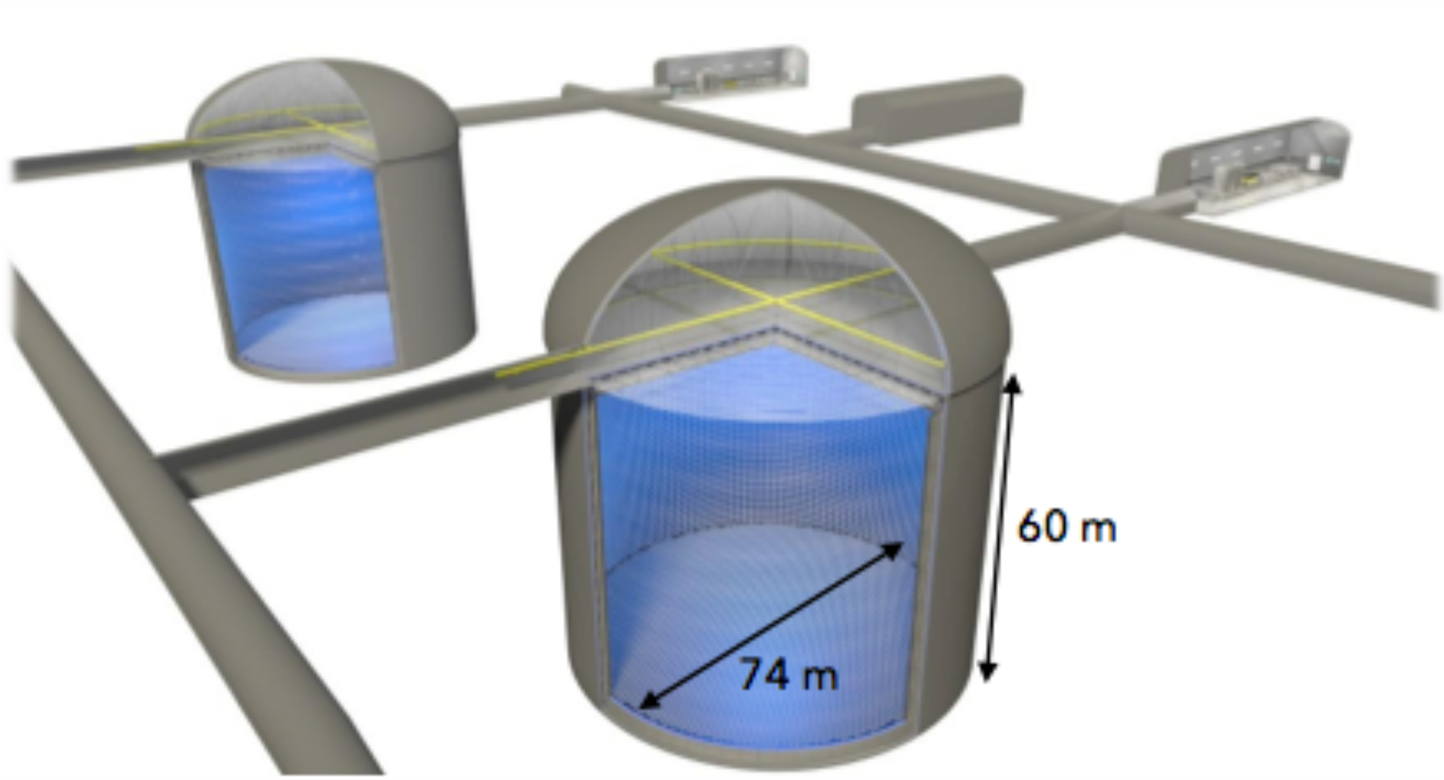
Process for merging the two proposals into a single detector design

Hyper-Kamiokande

- 2 tanks 60 m height x 74 m diameter
- 40,000 50cm PMTs → 40% photo-coverage
- 260 kton mass (187 kton fiducial volume is ~10x larger than Super-K)
- Same off-axis angle as Super-K
- Staged construction of the tanks with the second tank 6 years after first tank

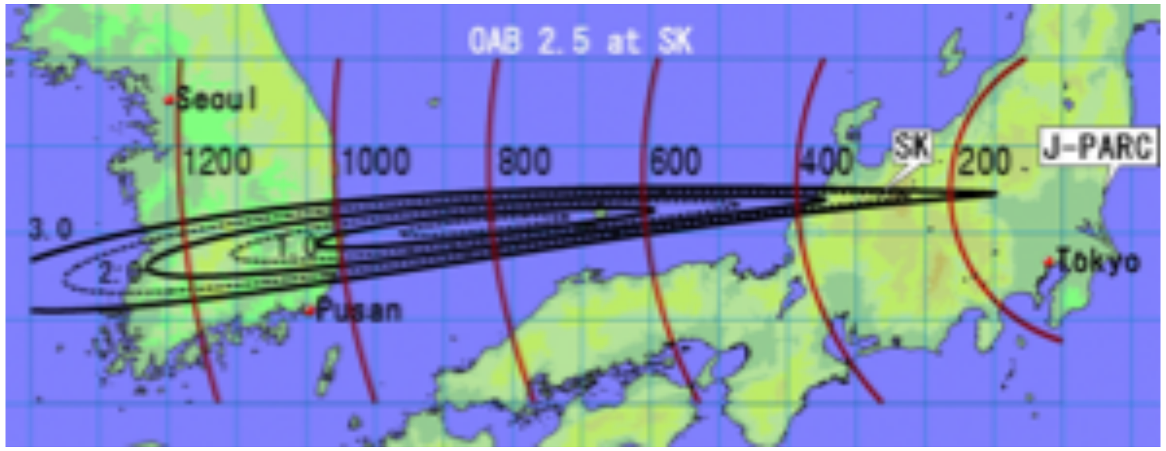
Physics program:

- Long-baseline neutrinos
- Atmospheric neutrinos
- Solar, astrophysical, supernova neutrinos
- Proton decay



LOI: 1109.3262 [hep-ex]
Physics potential: 1309.0184 [hep-ex]

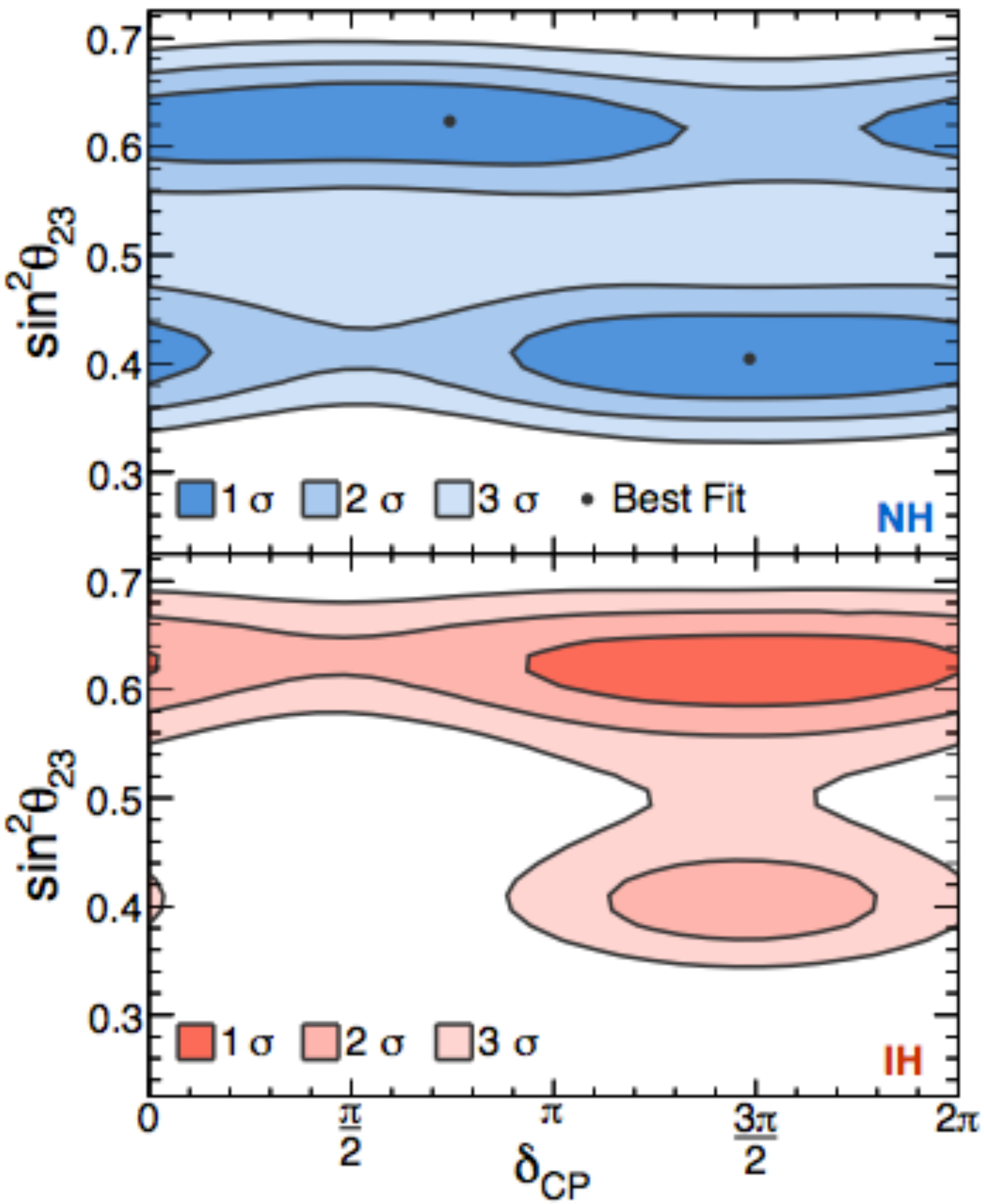
- Also proposal to have the 2nd tank in South-Korea to measure the 2nd oscillation maximum

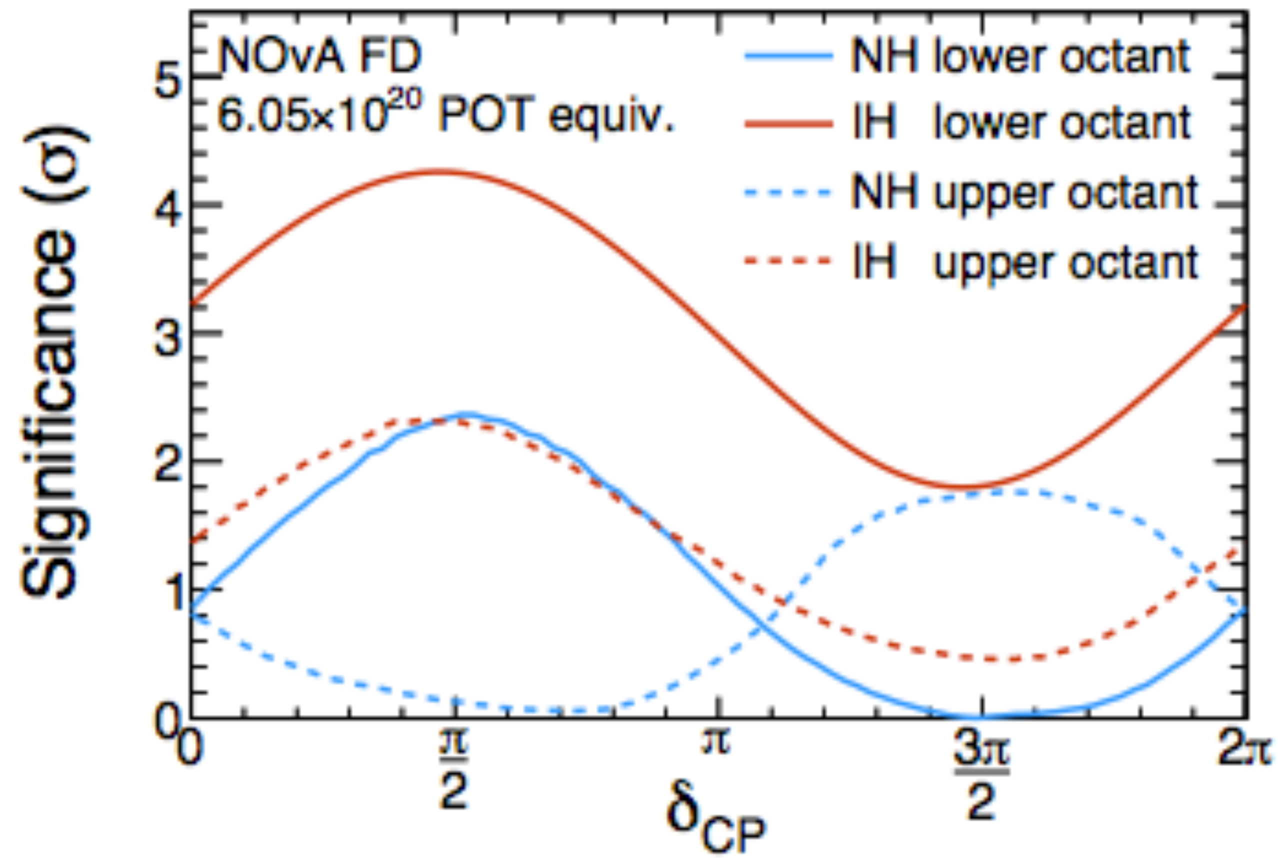


arXiv:1611.06118v1

NOVA

arXiv:1703.03328





$\Delta m^2_{ee} \rightarrow \Delta m^2_{32}$ at Daya Bay

arXiv:1610.04802

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$
$$- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E} \qquad \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$$

$|\Delta m^2_{ee}| \sim |\Delta m^2_{32}| \pm 0.052 \times 10^{-3}$ eV^2 ("-" for NH, "+" for IH)

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}$ eV^2

IH: $\Delta m^2_{32} = [-2.56 \pm 0.08] \times 10^{-3}$ eV^2