UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

T2K

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

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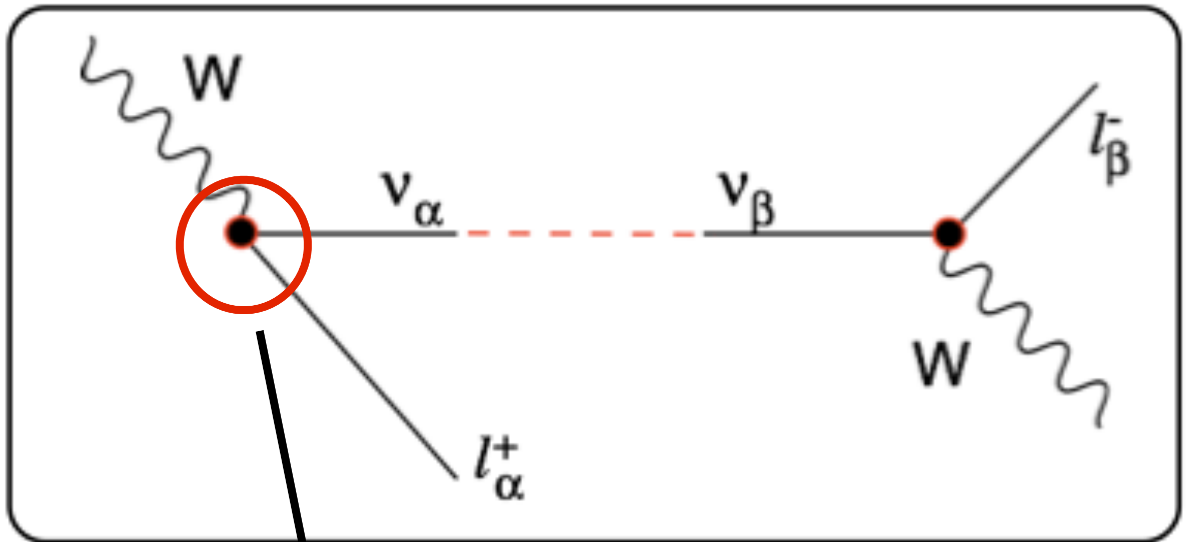
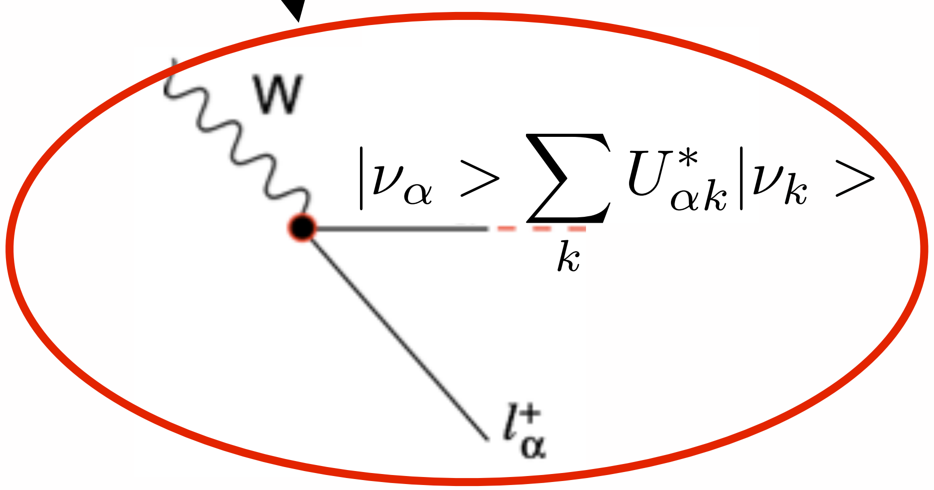
(University of Geneva)

CERN EP Seminar, 29th November 2016

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 $\Delta m^2_{ij} = m^2_i - m^2_j$

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

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

L: neutrino flight path
E: neutrino energy

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

Oscillation parameters: mixing matrix

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

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

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

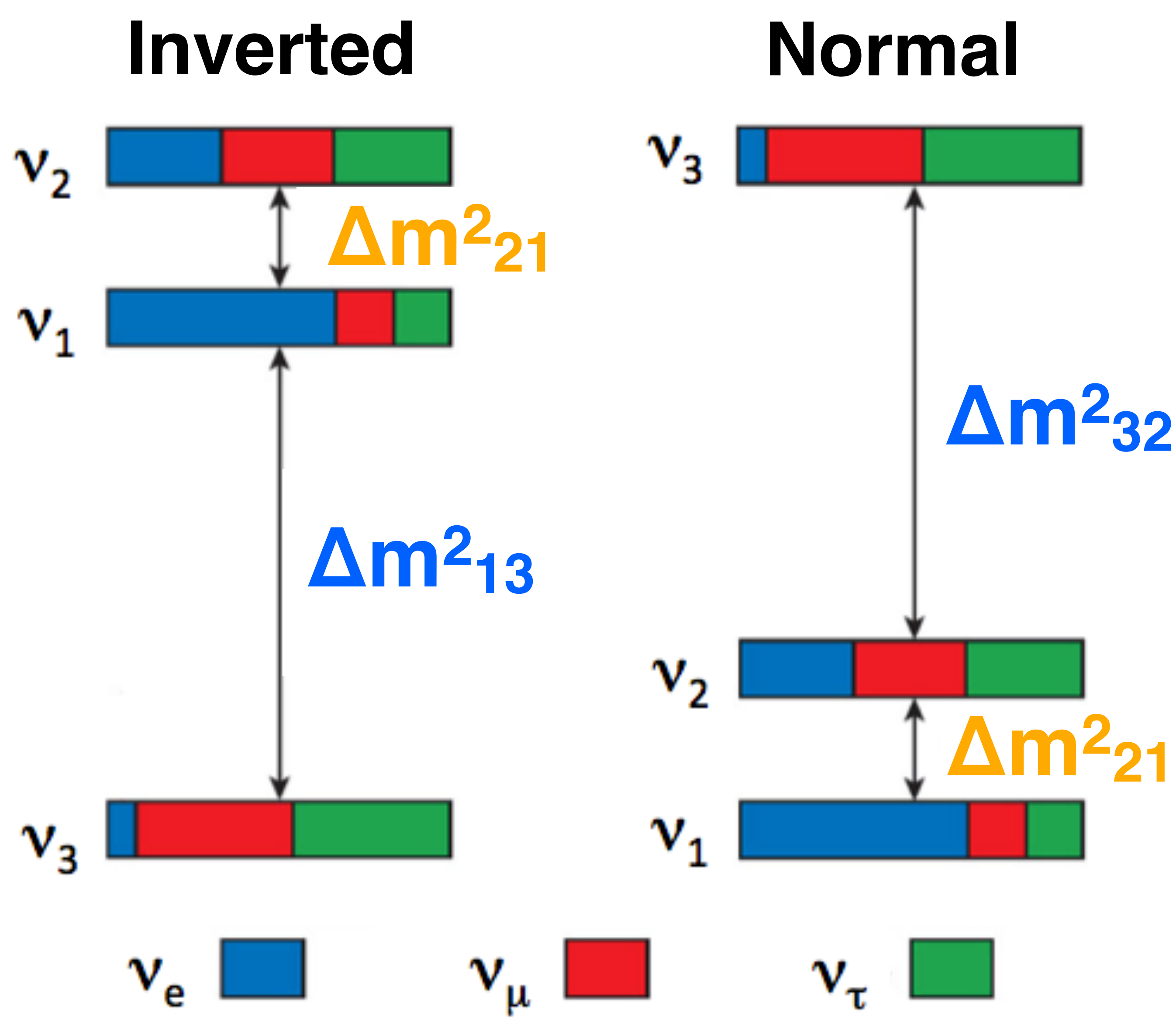
$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

δ_{CP} unknown

$\delta_{CP} = 60°$

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

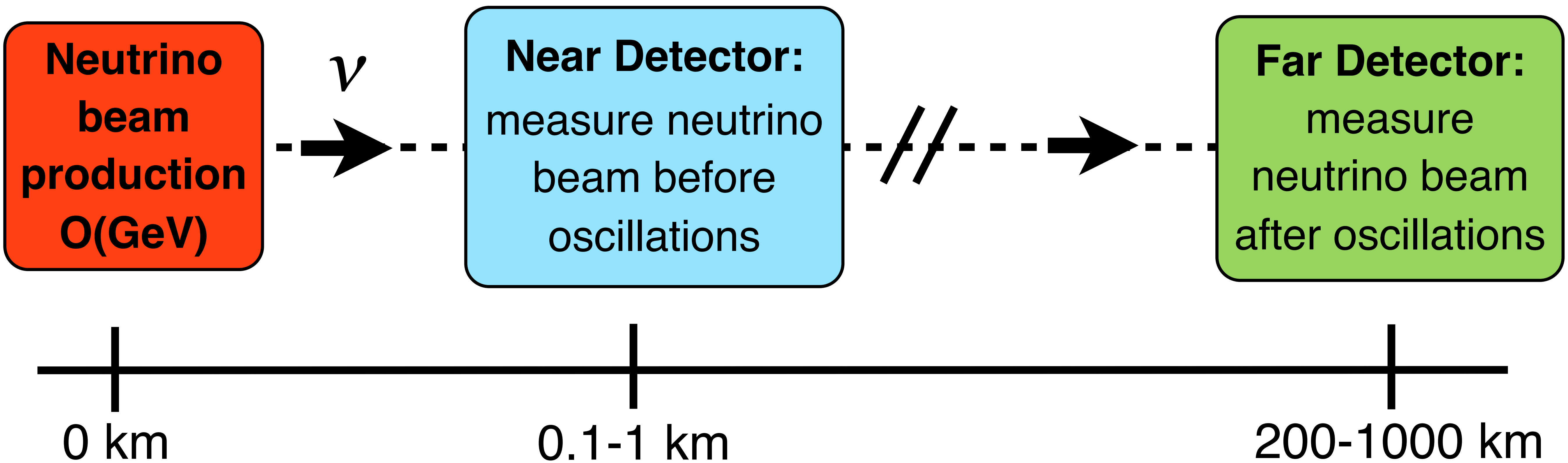
Mass hierarchy (MH) → sign of Δm^2_{32}

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

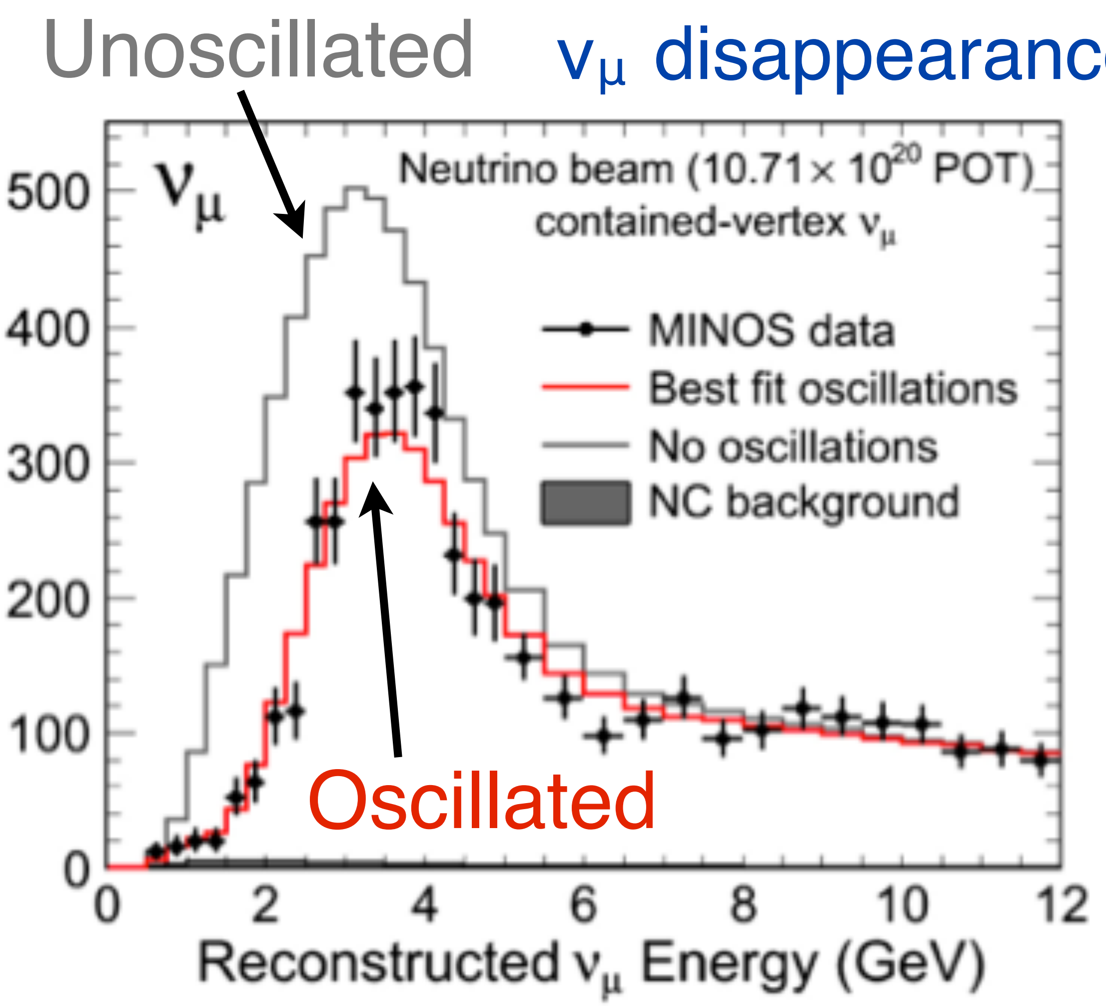
Flux | Cross Section | Detector Efficiency | Oscillation probability

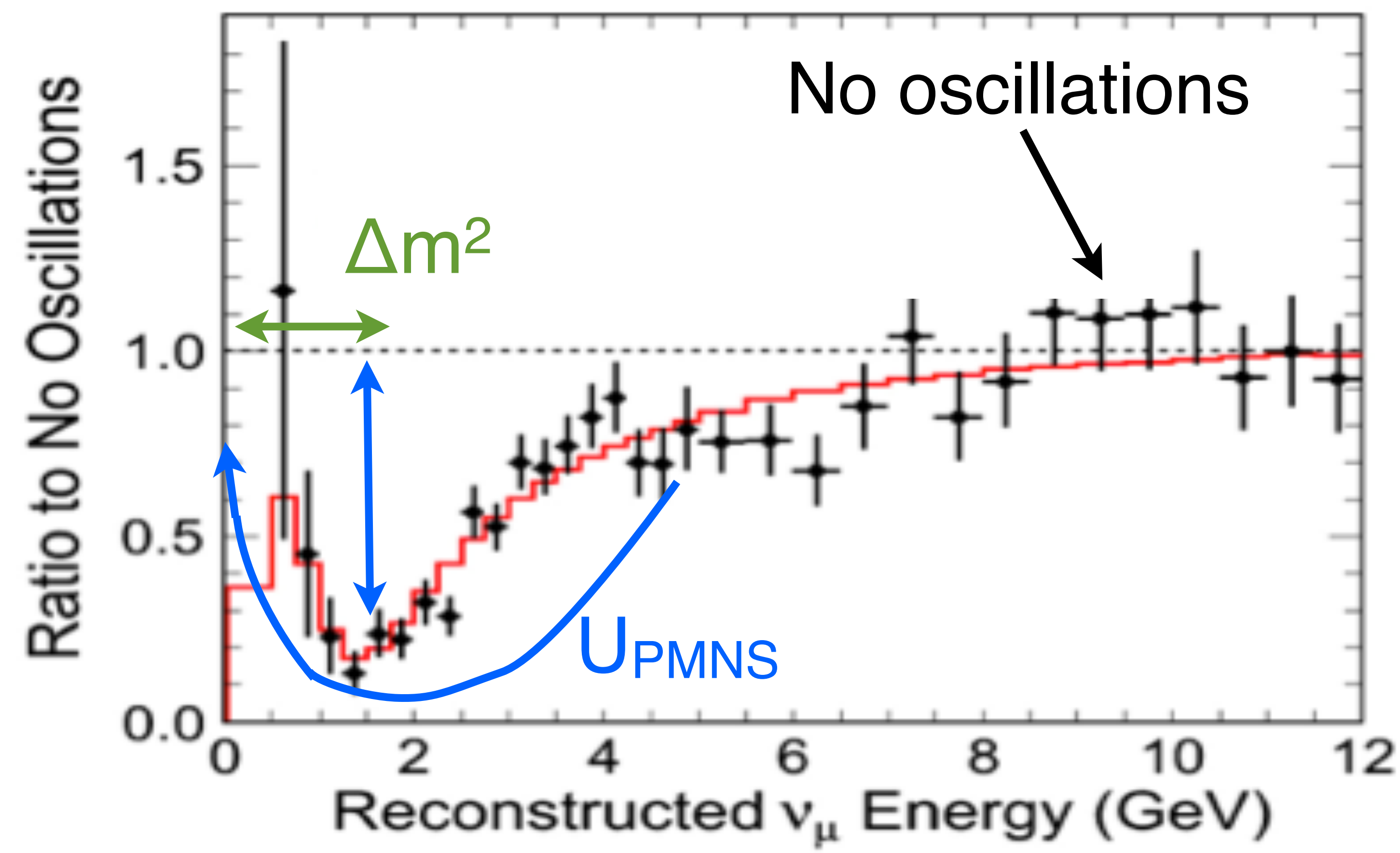
Far Detector: $N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD} P_{osc}(E_\nu)$

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))





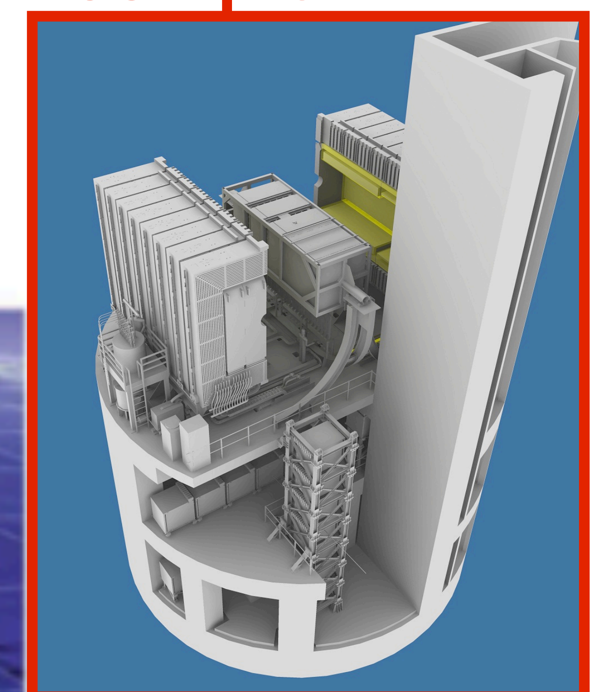
Measure $\begin{cases} \nu_\mu \rightarrow \nu_x \text{ disappearance} \\ \nu_\mu \rightarrow \nu_e \text{ appearance} \end{cases}$ ➡ Infer the oscillation parameters

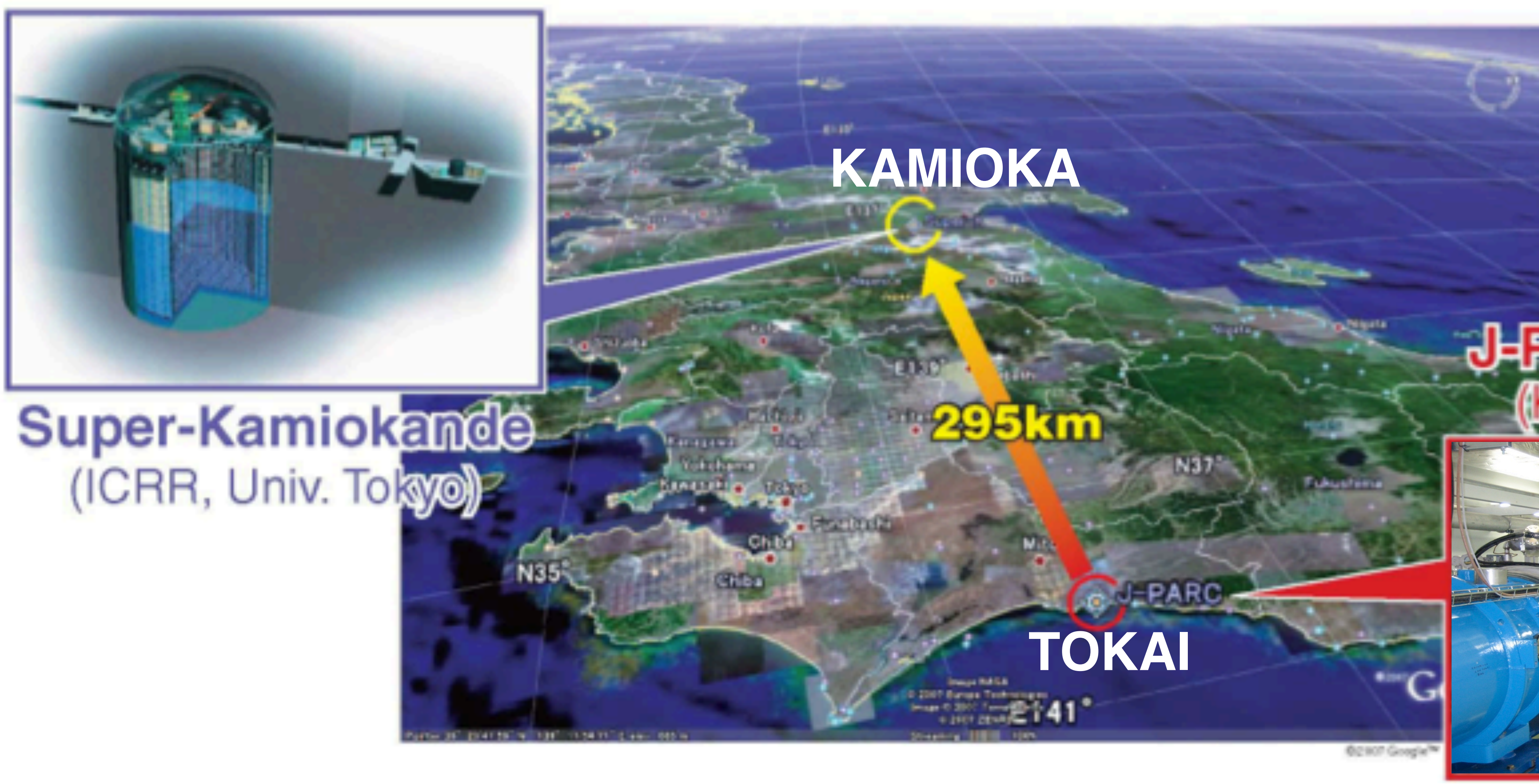
The T2K collaboration

~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





Neutrino oscillations at T2K

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

E ~ 0.6 GeV
L ~ 295 km

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

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

Phys. Rev. D64 (2001) 053003

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

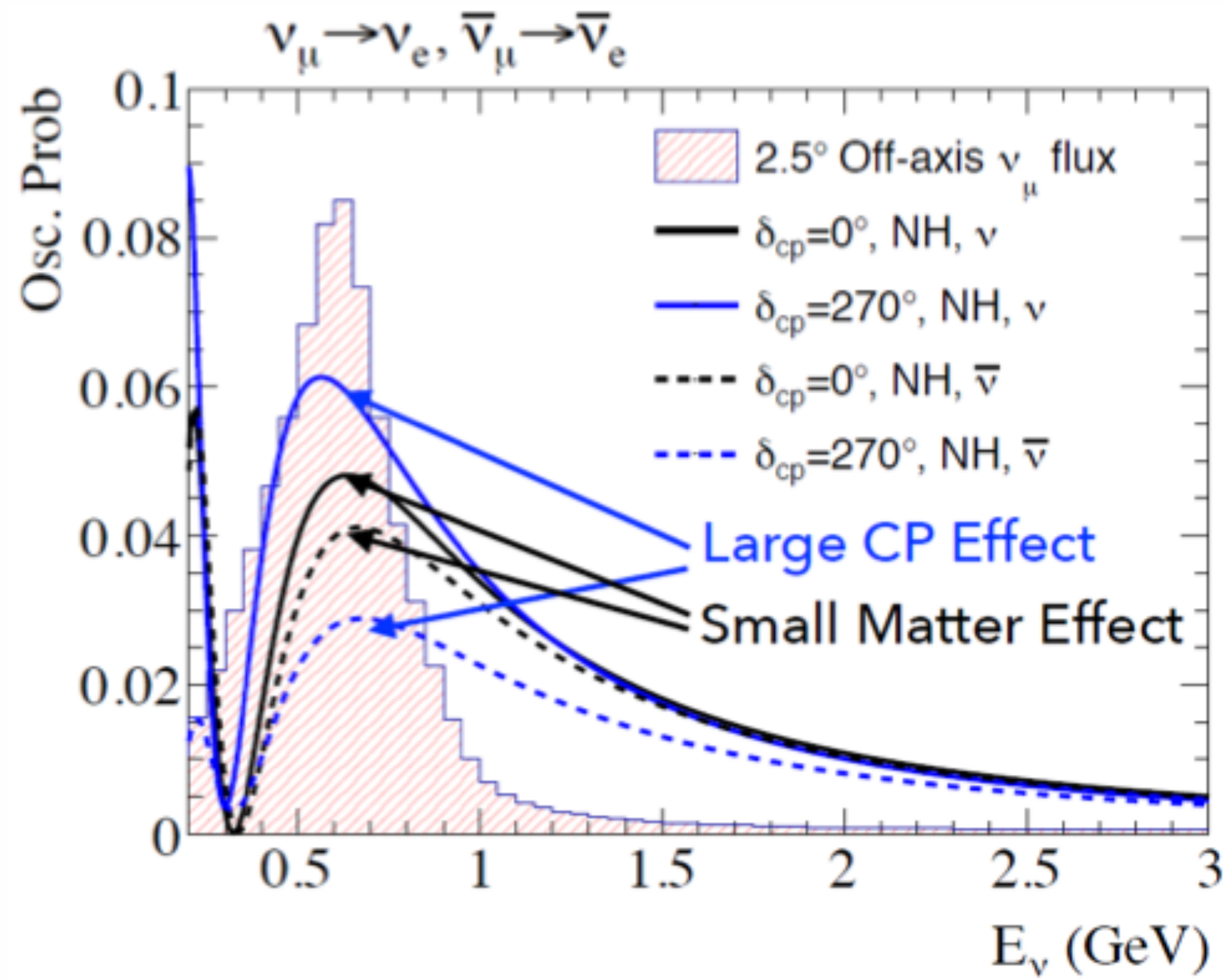
CP conserving
$$\alpha\cos\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

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

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

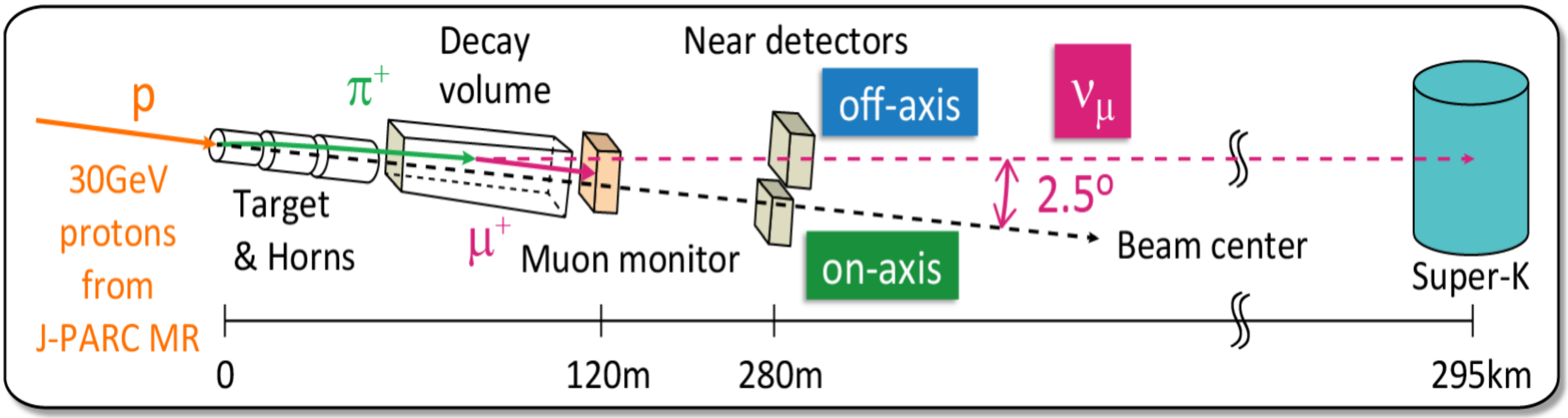
- The leading term defines the octant $\Theta_{23}>45°$ or $\Theta_{23}<45°$
- All mass splittings and mixing angles have been measured to be non-zero:
  second order term can violate the CP symmetry if $\sin\delta_{CP} \neq 0$

Effect of CP violation at T2K

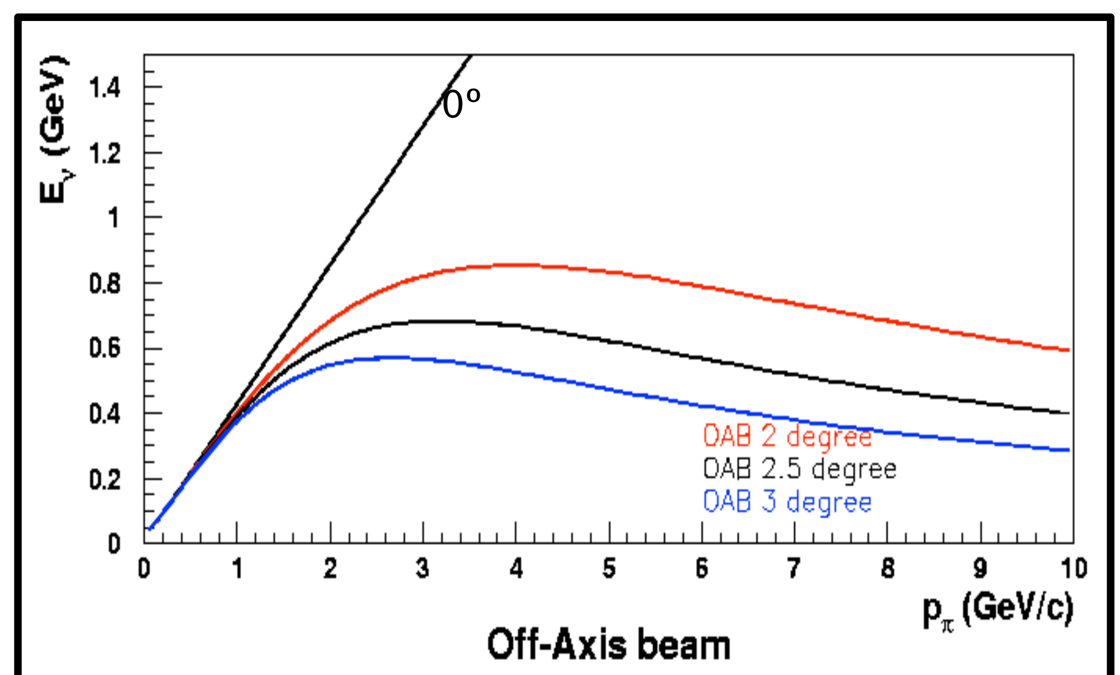


- Asymmetric effect on P($\nu_\mu \to \nu_e$) and P($\bar{\nu}_\mu \to \bar{\nu}_e$):
  - δ_{CP} = -π/2 → maximizes P($\nu_\mu \to \nu_e$) and minimizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
  - δ_{CP} = +π/2 → minimizes P($\nu_\mu \to \nu_e$) and maximizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
- δ_{CP} and 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



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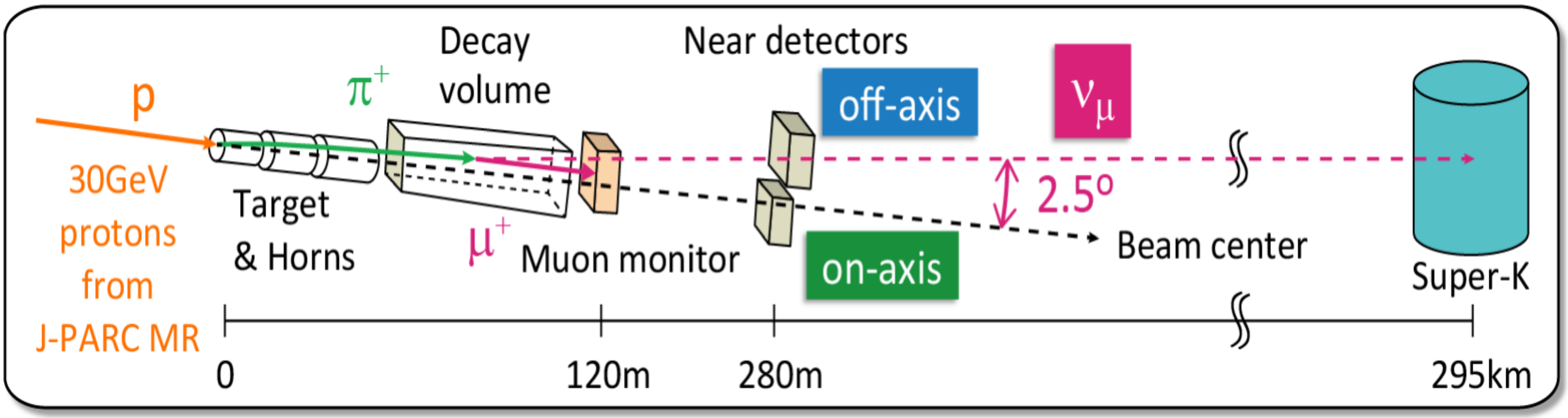

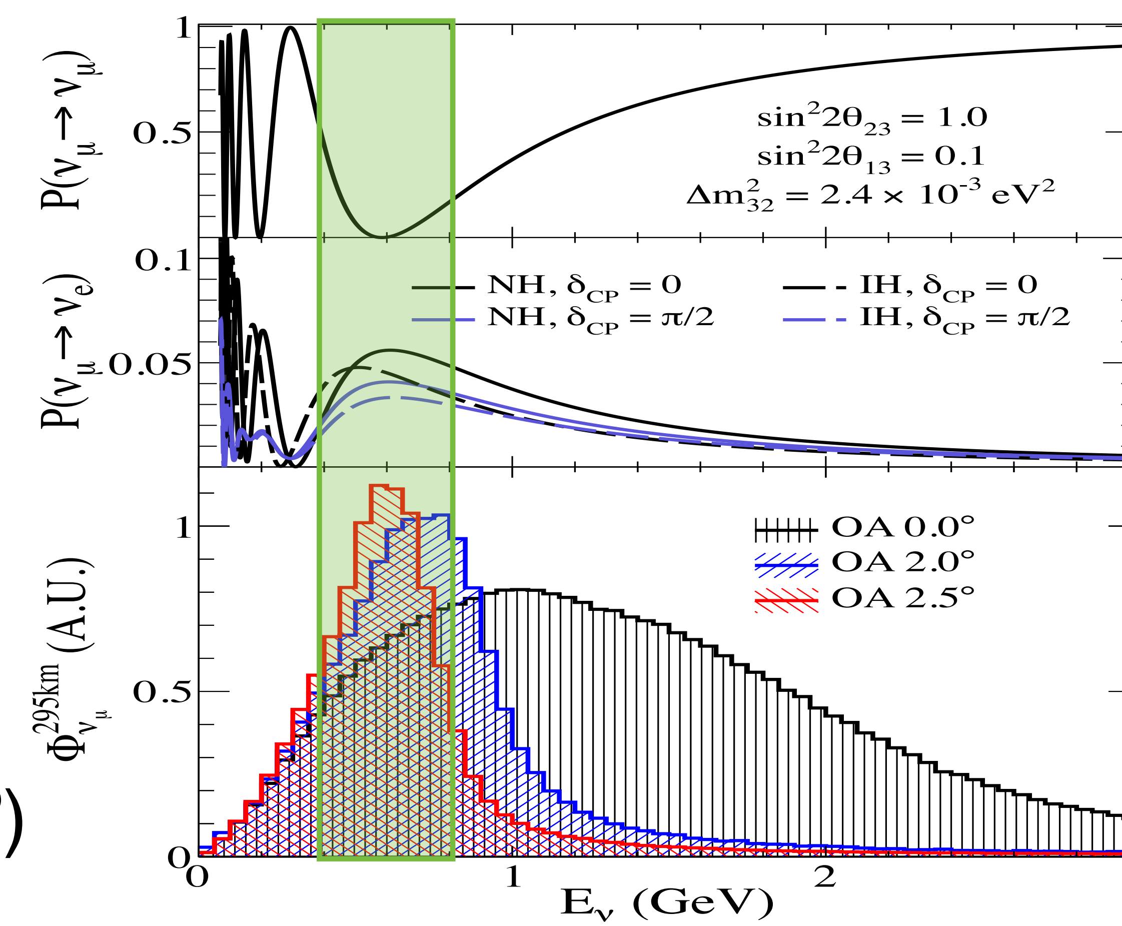

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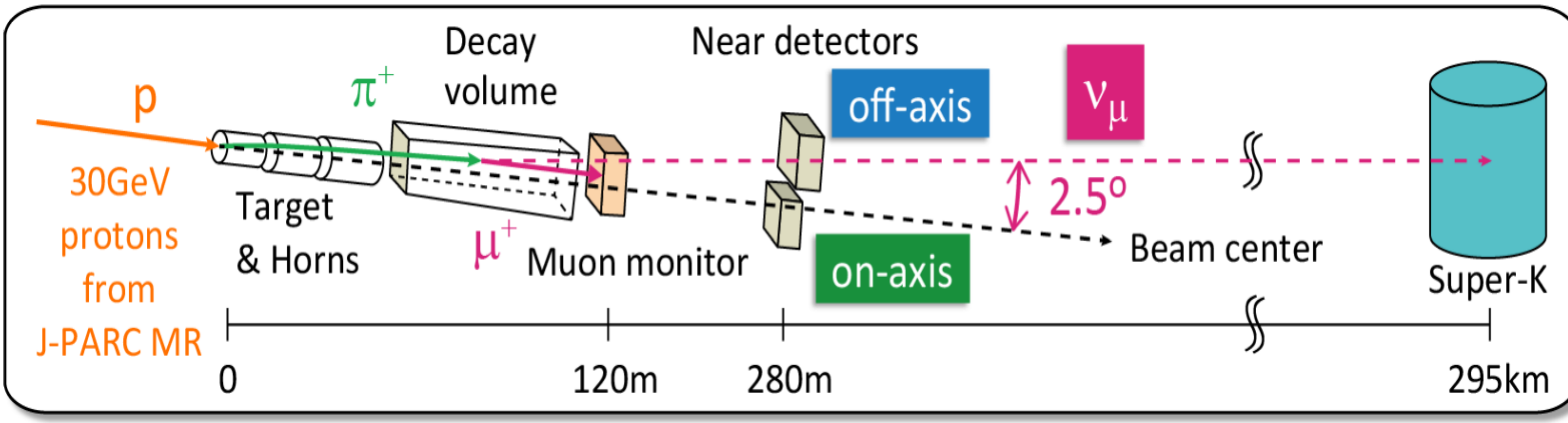

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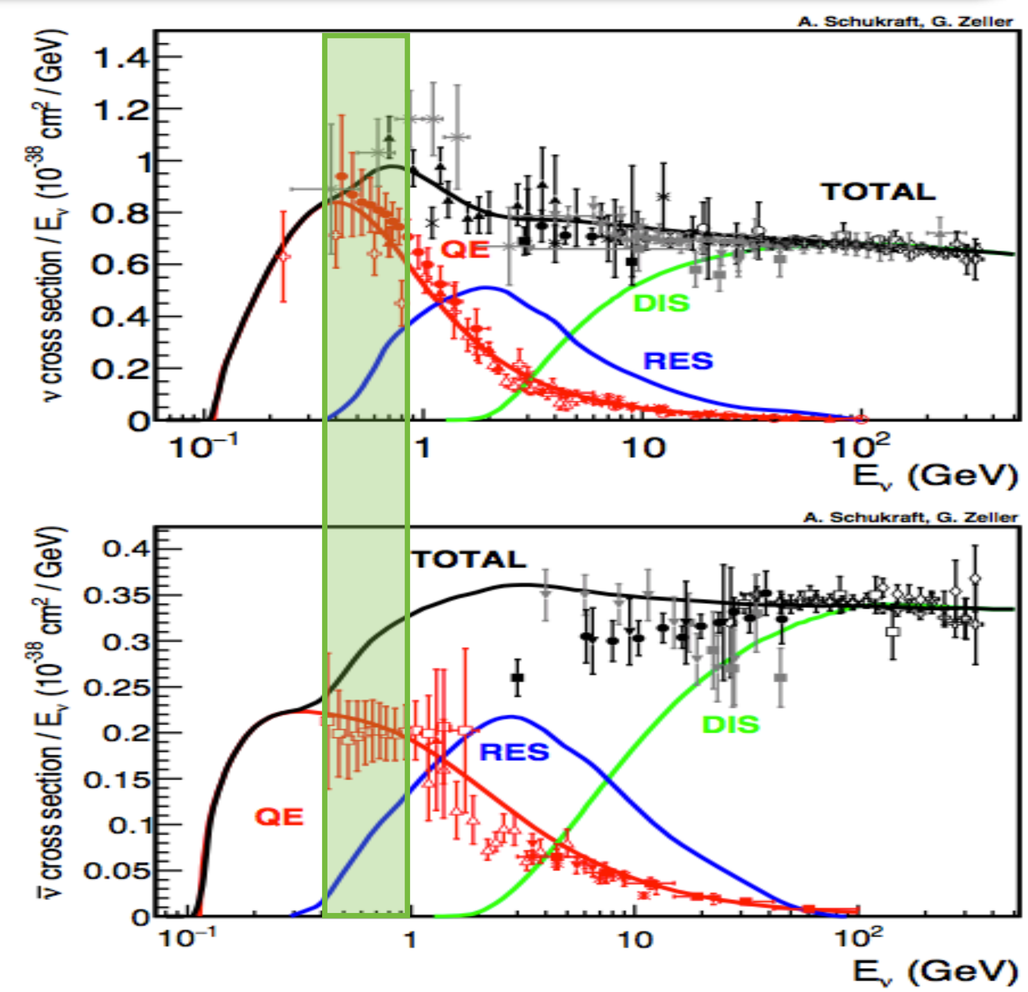
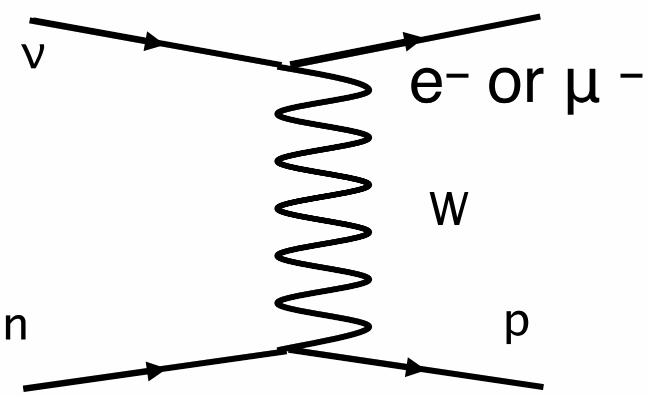


(Anti)Neutrino interactions at T2K

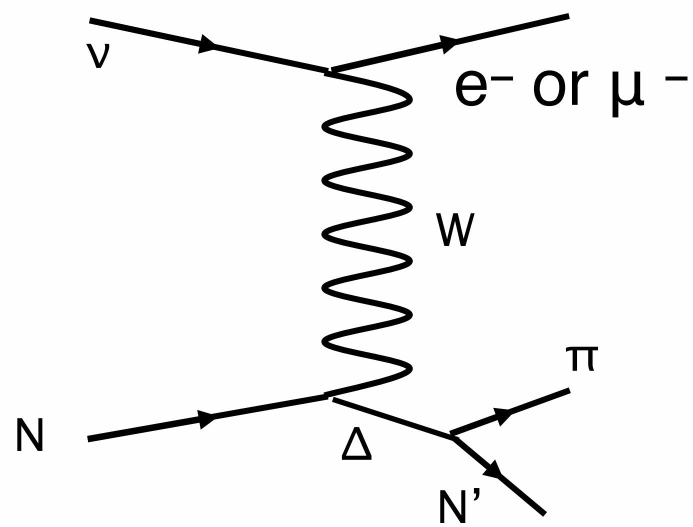
- The dominant neutrino interaction mode is Charge-Current Quasi-Elastic

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

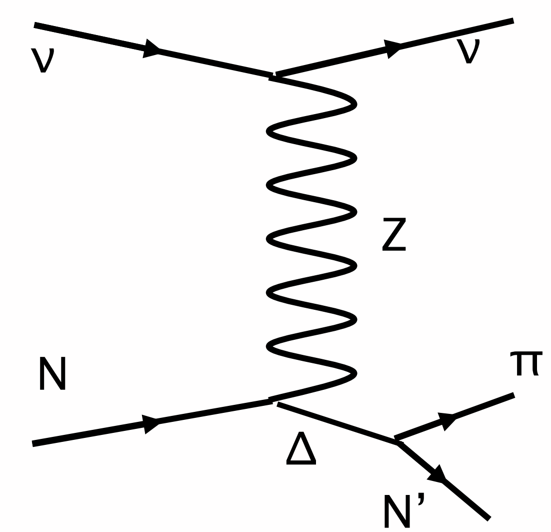
Charged-Current Quasi-Elastic (CCQE)



Charged-Current π



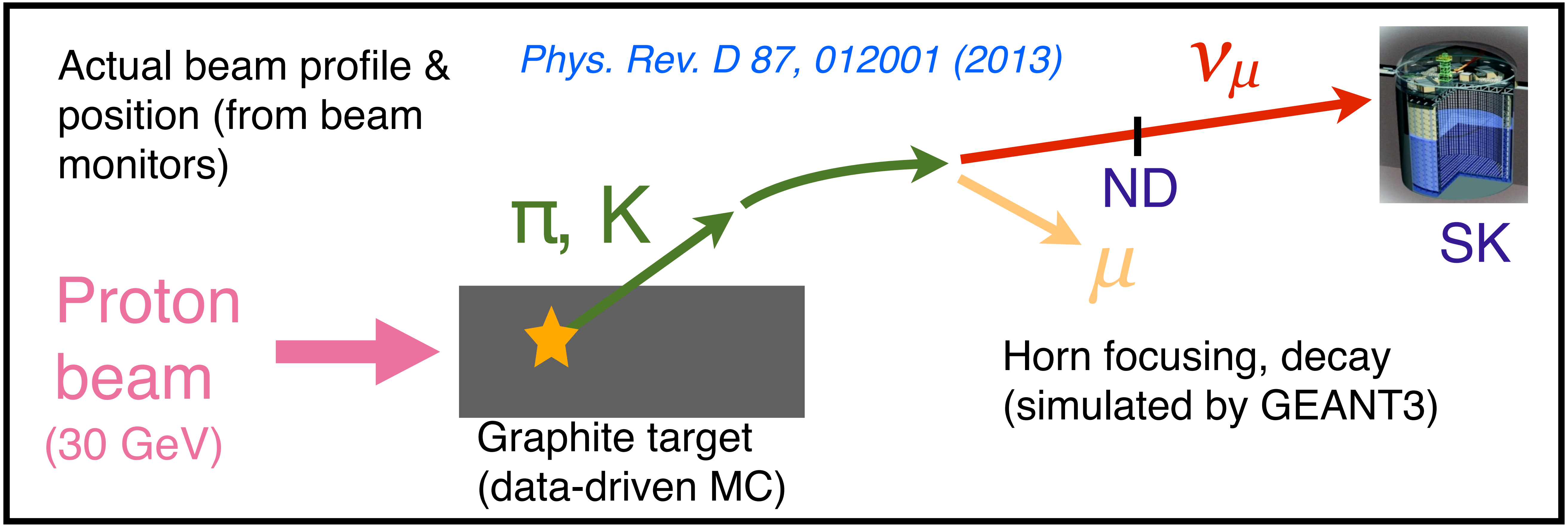
Neutral-Current π



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)

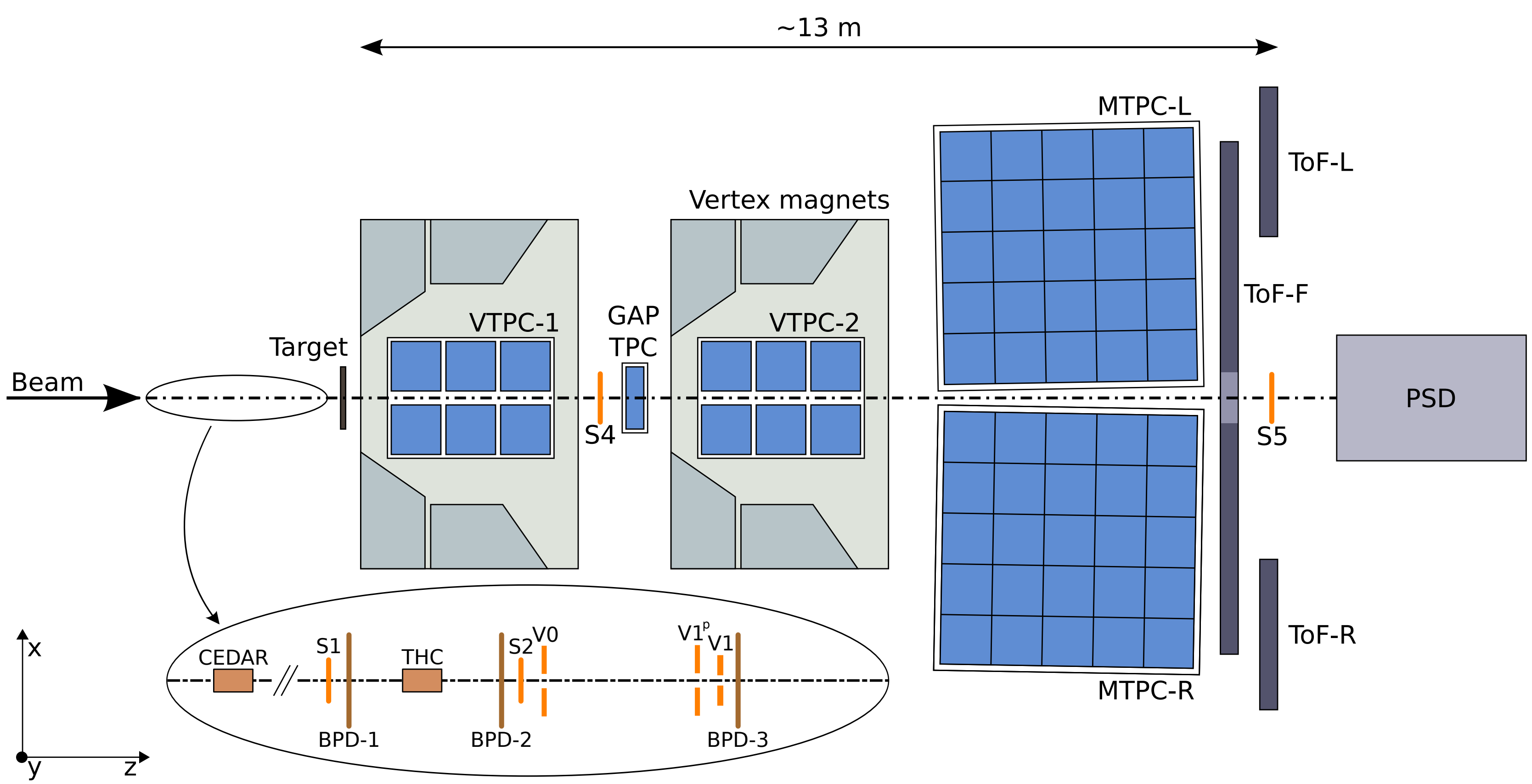
Neutrino beam production

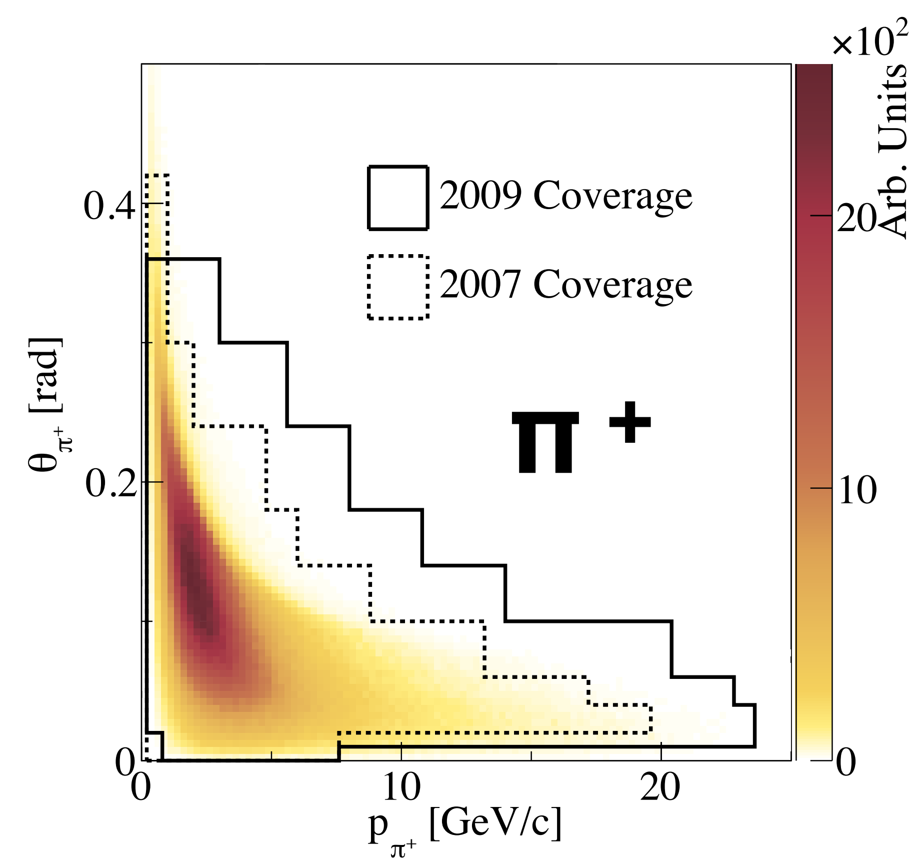


- Hadronic interactions
  - Hadron production simulated with FLUKA
  - Secondary and other interactions outside the target based on experimentally measured cross sections
- GEANT3 transport simulation used downstream of target
- Large uncertainties on forward hadron production (non-perturbative QCD)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

NA61/SHINE experiment at CERN SPS

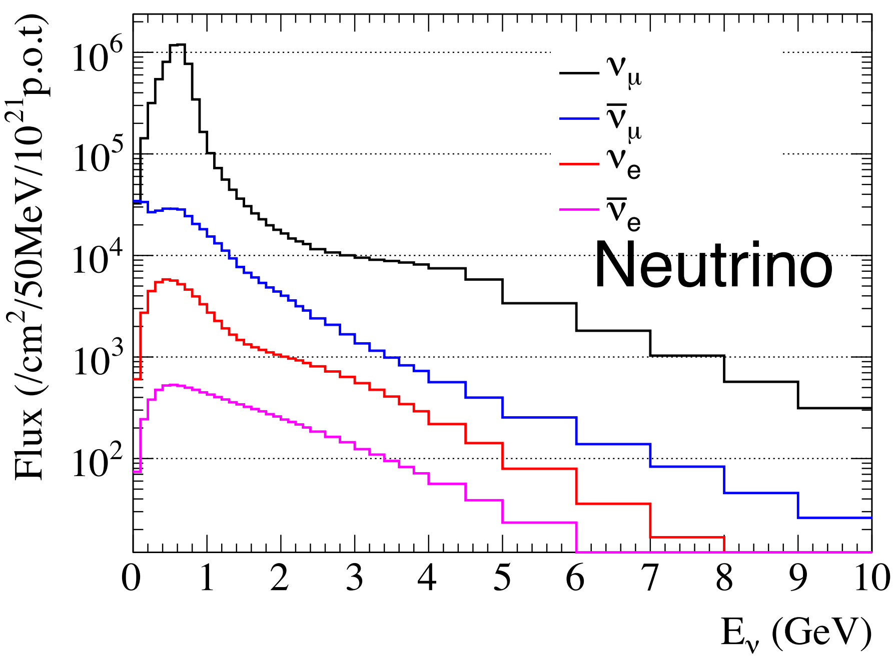
- Large-acceptance detector with very good capabilities of charge and mass measurements
- Located in the CERN North Area
- Cover almost the full {p,Θ} T2K phase space
- Measure pion, proton and kaon production with a 31 GeV/c proton beam on a carbon target
  - Thin 2cm target (4%λ_I) (*Eur. Phys. J.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

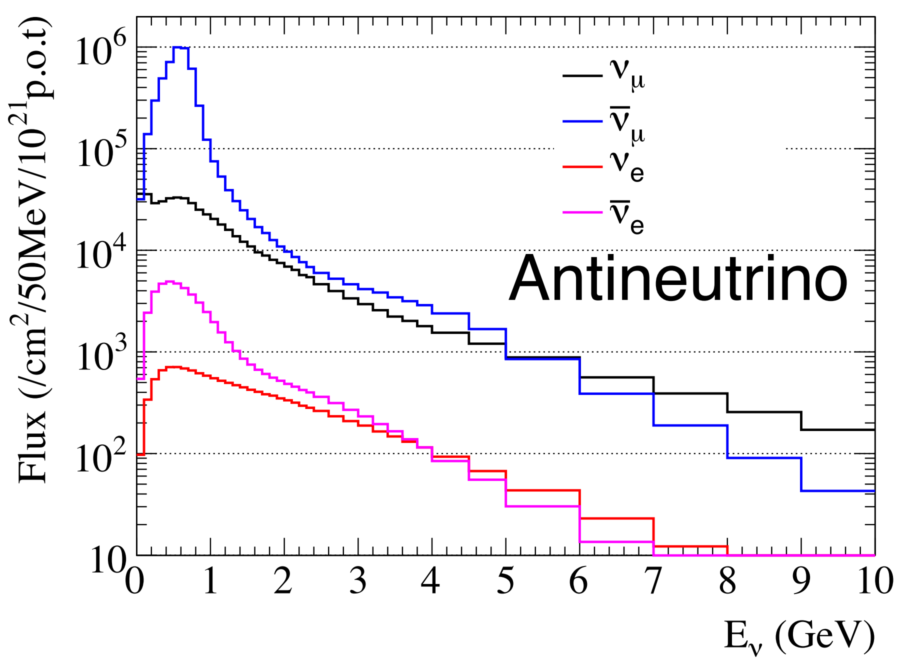


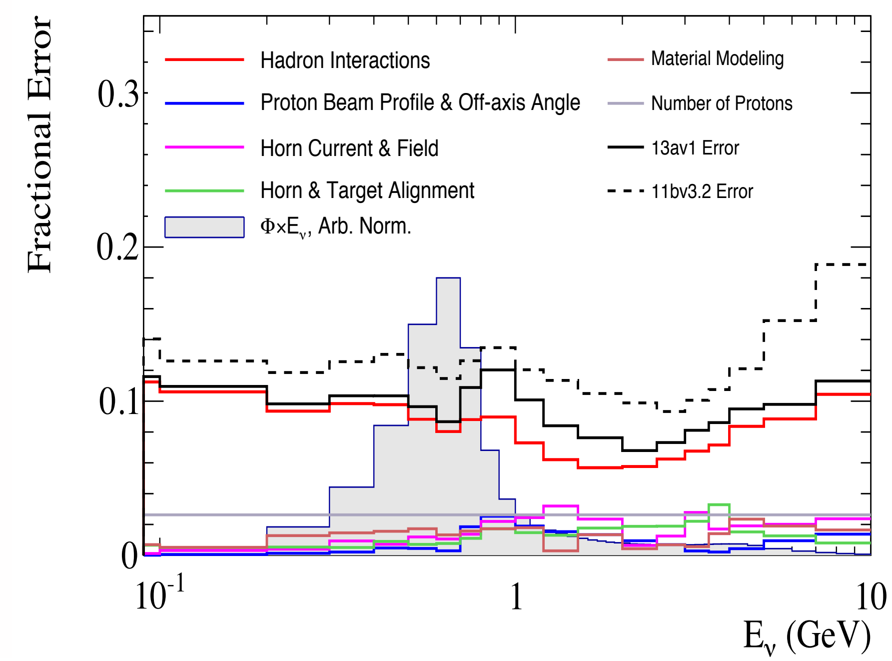


Neutrino and antineutrino flux prediction

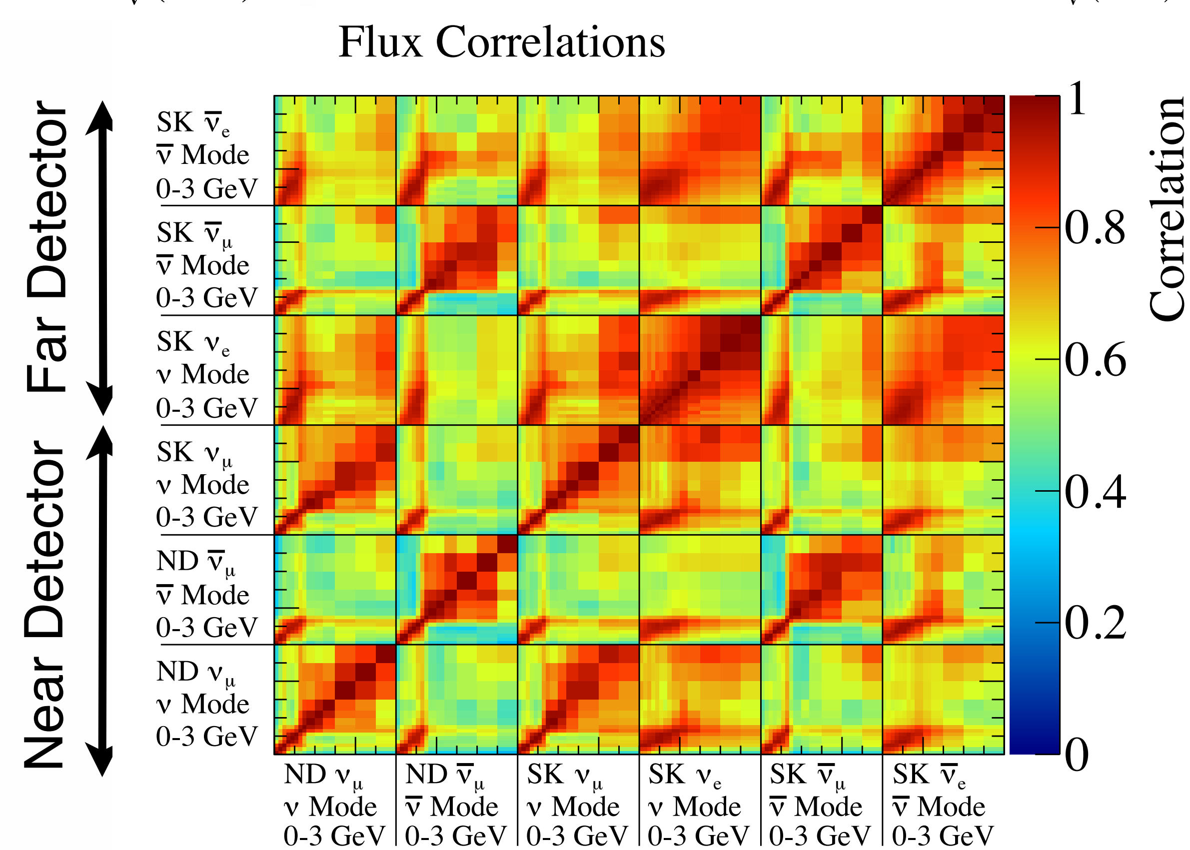
- Neutrino flux prediction tuned with hadron spectra measured at NA61/SHINE
- Flux systematic uncertainty reduced from ~30% to ~10% (thin target data)





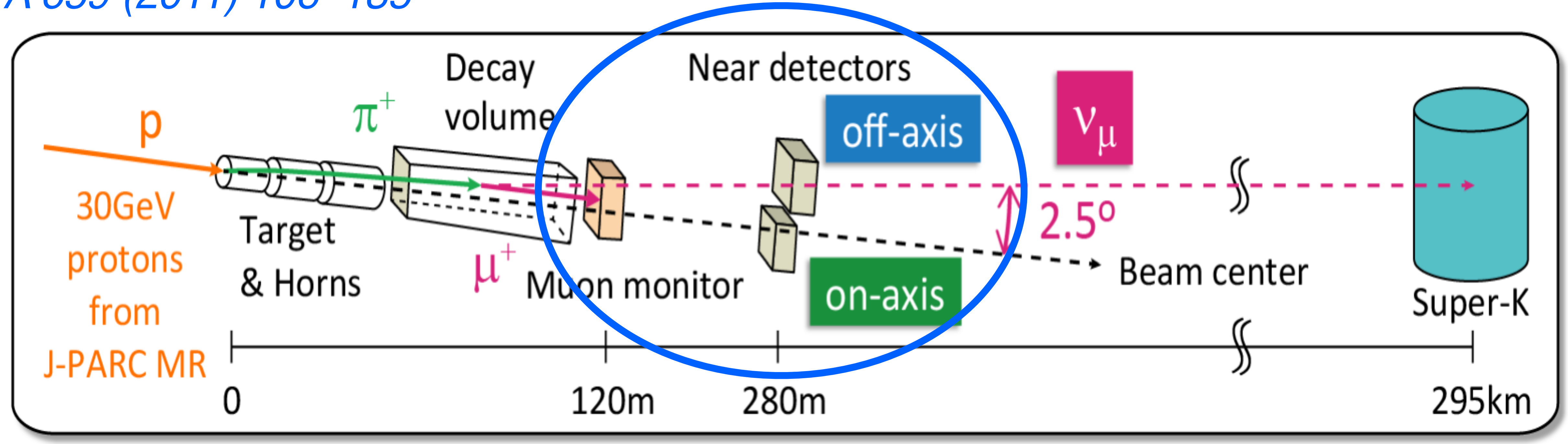


- Less than 1% intrinsic electron (anti)neutrino component at the peak
- <10% of wrong-sign background (ν_μ in $\bar{\nu}_\mu$ beam)
- Prediction of flux correlations between near / far detector, neutrino / antineutrino beam, ν_μ / ν_e is used

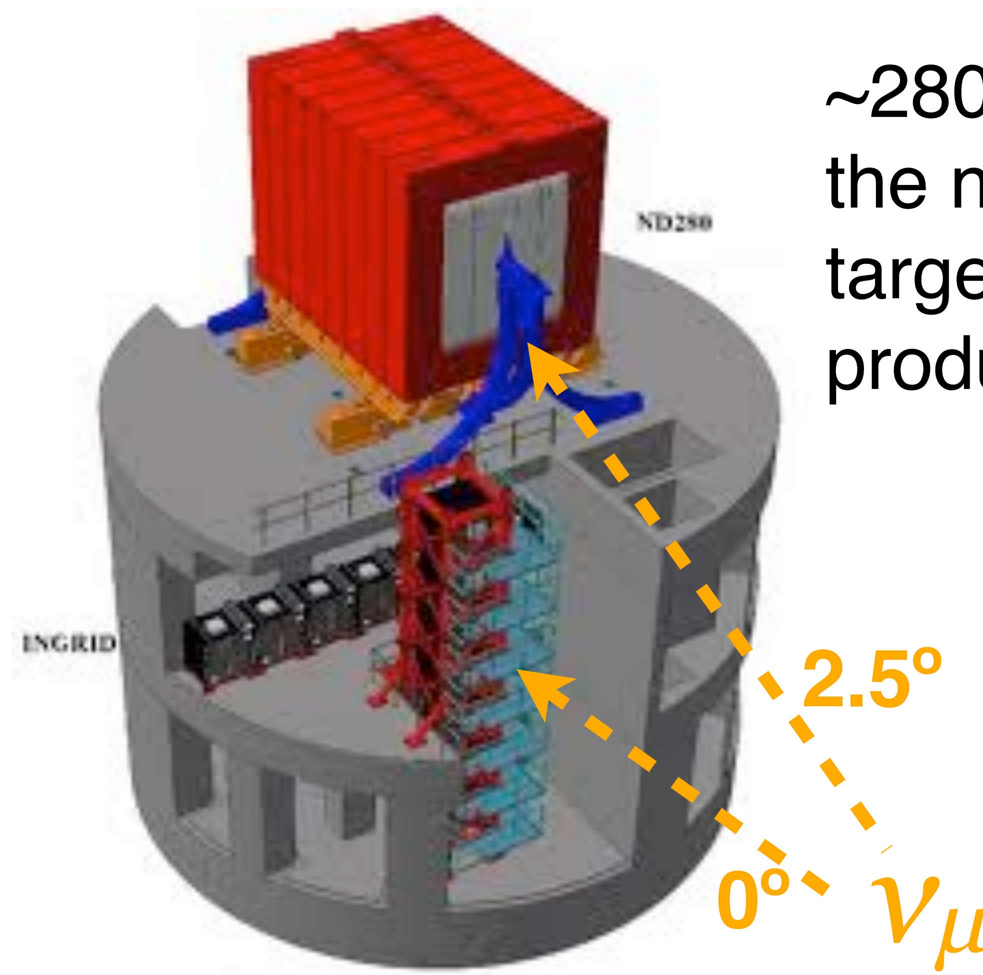


T2K near detector complex

NIM A 659 (2011) 106–135



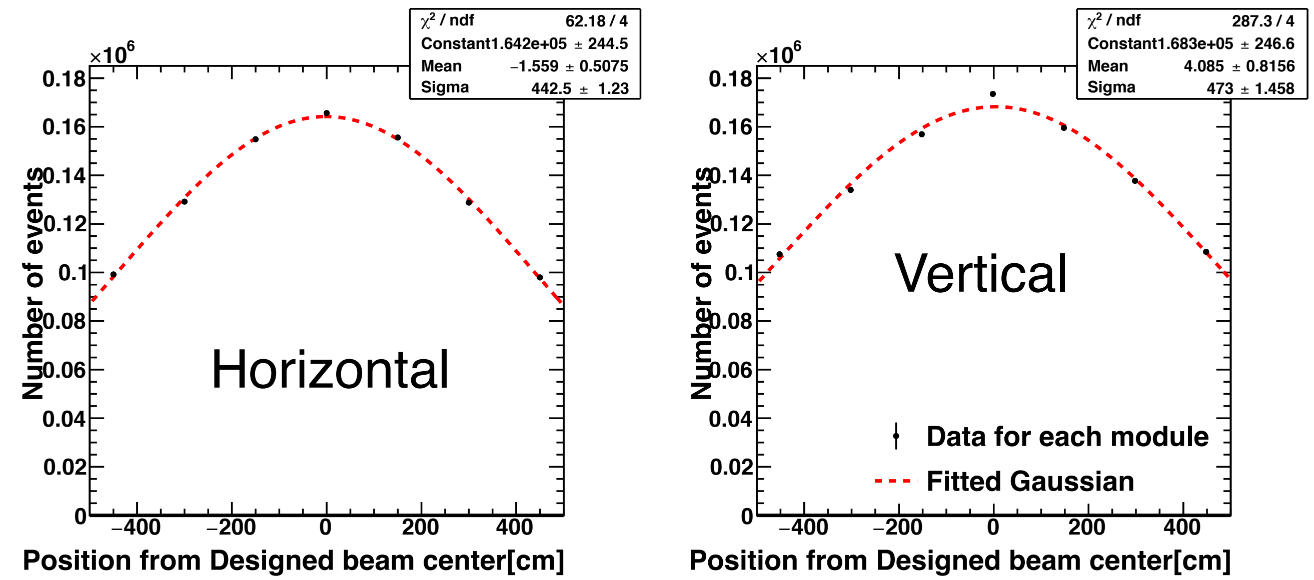
- **Muon monitor:**
  - spill-by-spill monitoring of the beam
- **On-axis detector:**
  - INGRID
  - measure beam intensity / direction
- **Off-axis detector:**
  - 2.5° off-axis magnetized detector
  - precise measurement of neutrino flux and cross section
  - measure wrong-sign background (20-30% ν_μ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



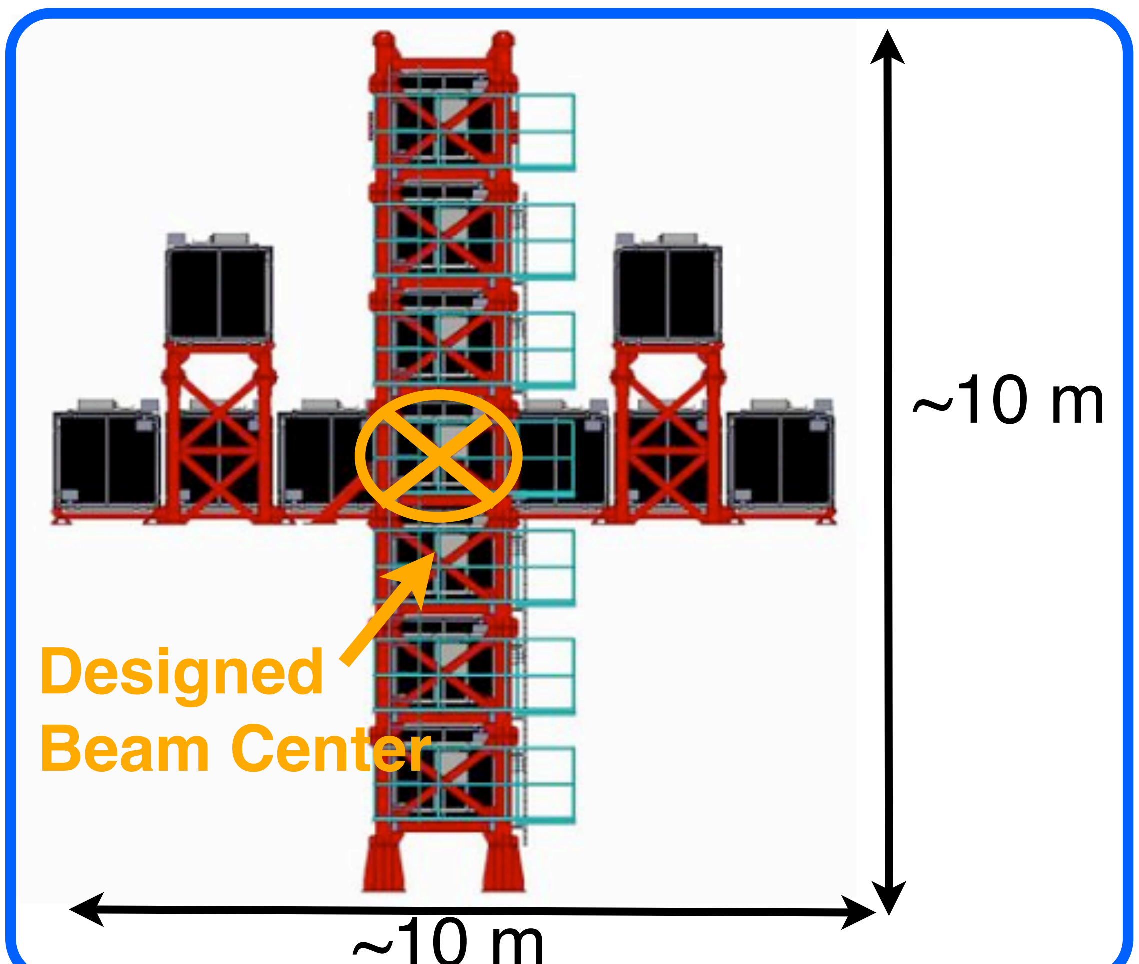
~280 m from the neutrino target production

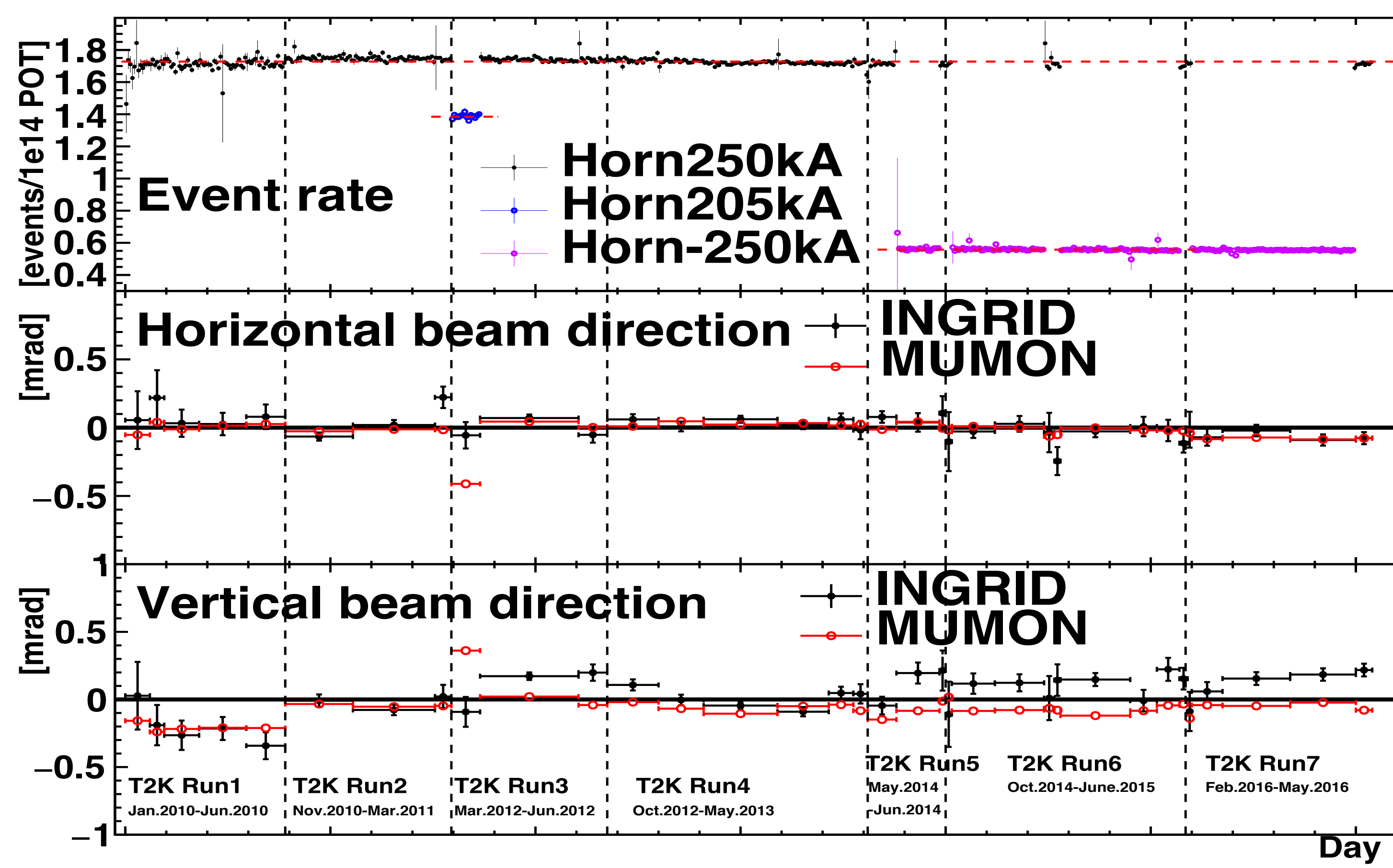
The On-Axis detector: INGRID

- 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

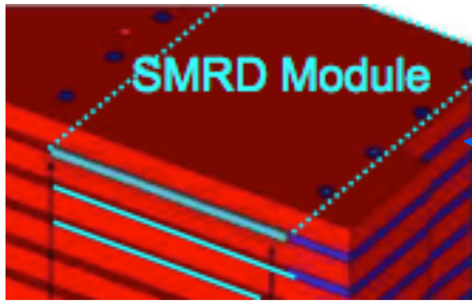


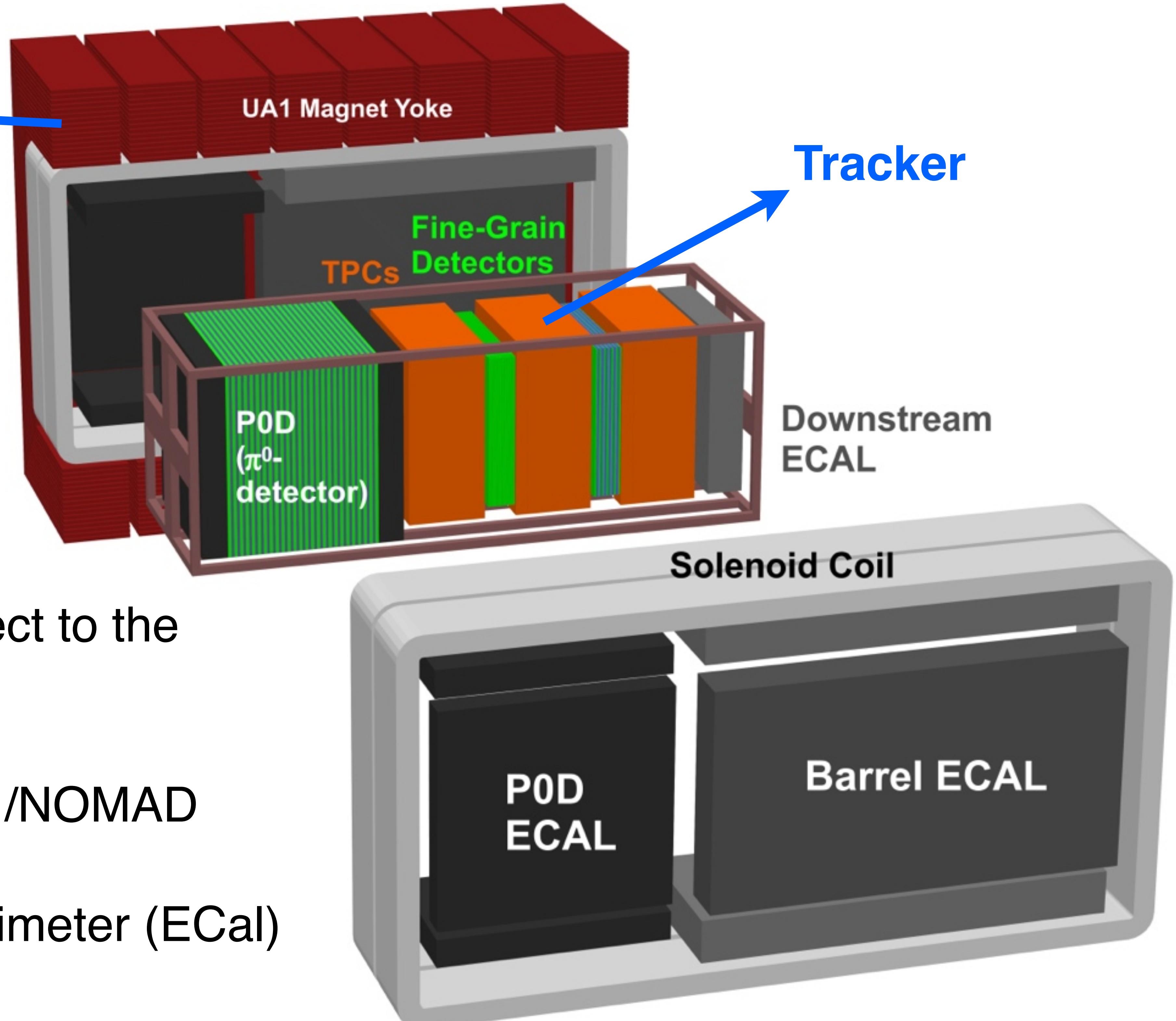
- Protons On Target (POT) normalized event rate stable better than 1%

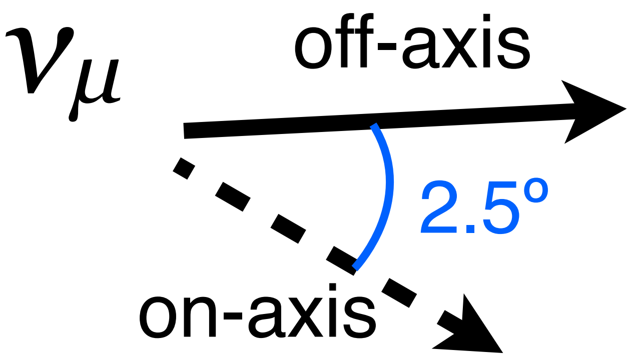




The Off-Axis detector: ND280



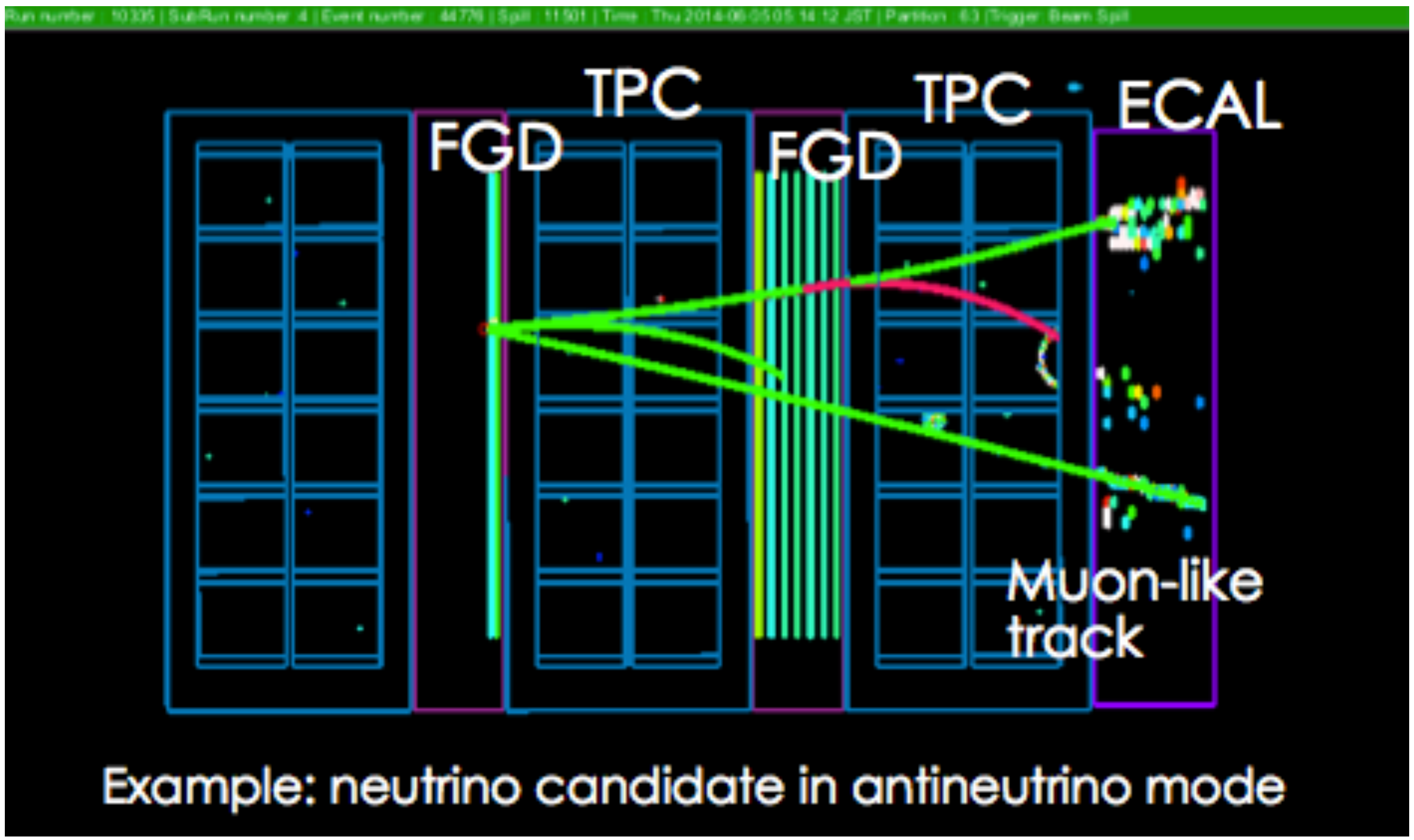


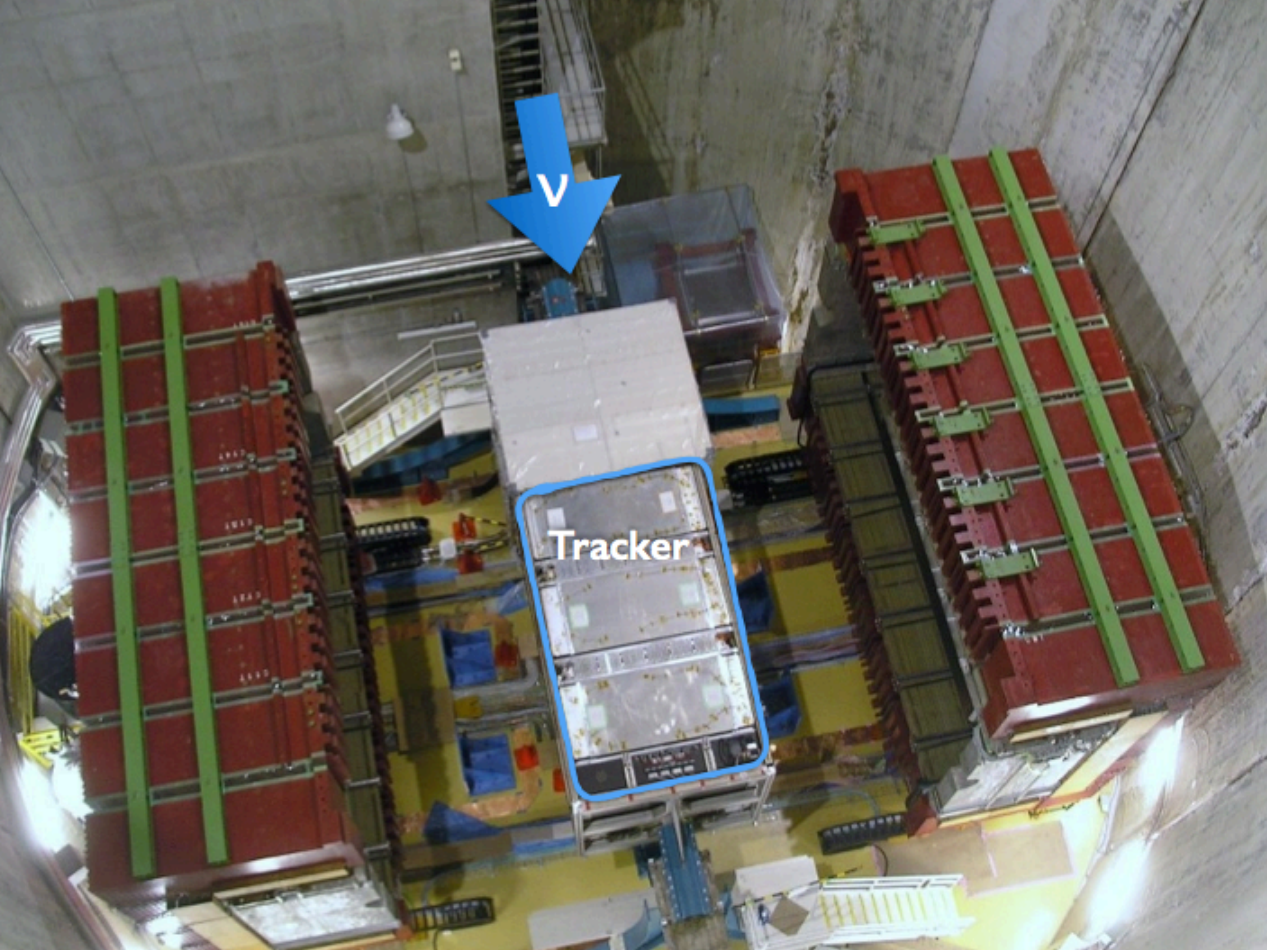


- 2.5° off-axis with respect to the neutrino beam direction
- 0.2 T dipole magnet
  - donation of the UA1/NOMAD from CERN
- Electromagnetic Calorimeter (ECal)
- π^0 detector (P0D)
- Side Muon Range Detector (SMRD)
- Tracker: 2 active neutrino targets + 3 Time Projection Chambers

The Off-Axis detector: the tracker

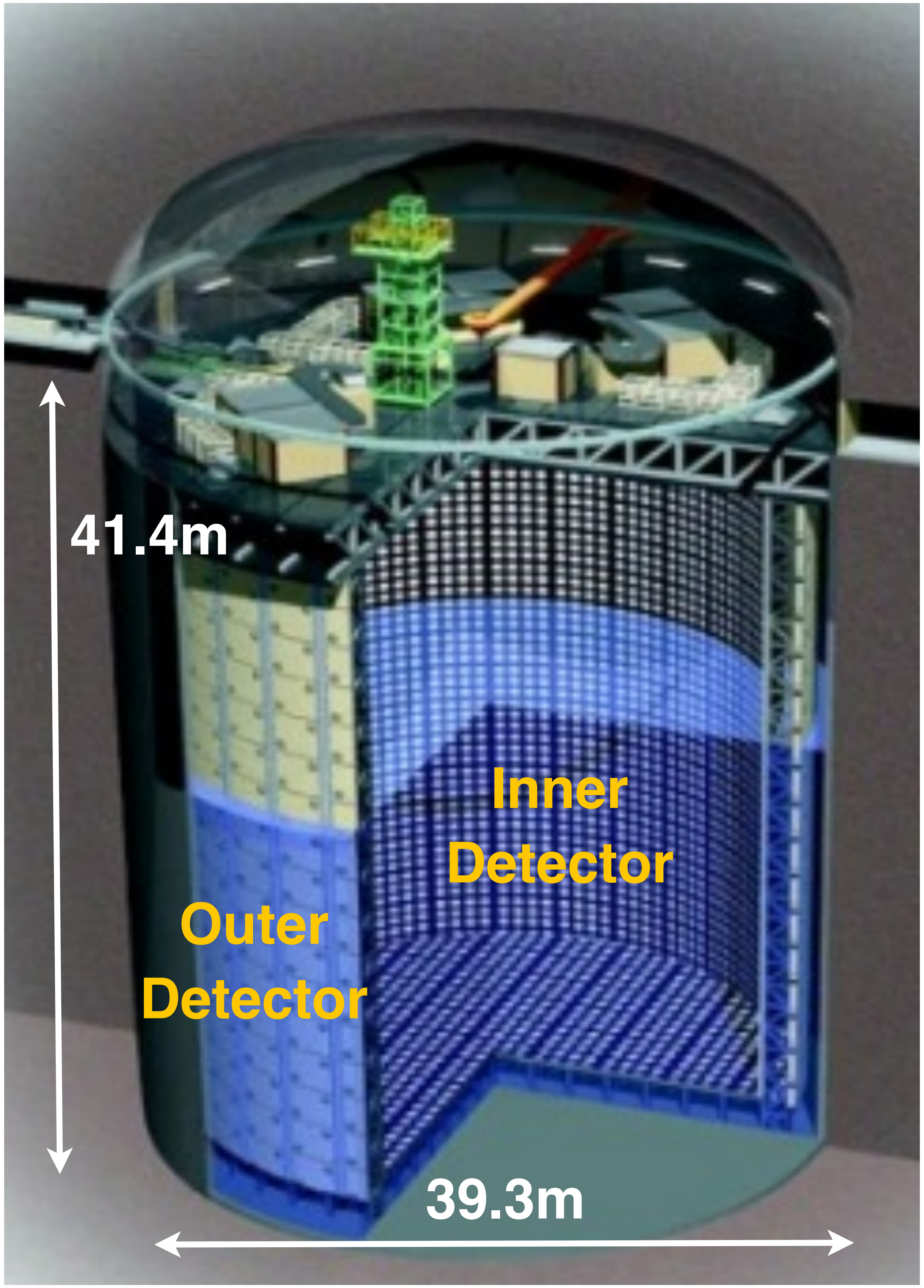
- 2 Fine-Grained Detectors (FGDs) as active neutrino target
  - FGD1 (plastic scintillator) + FGD2 (50%:50% water:scintillator)
  - 1.6 ton fiducial mass for analysis
  - constrain cross section on water with FGD2 - FGD1 subtraction
- 3 Time Projection Chambers (TPC)
  - better than 10% dE/dx resolution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

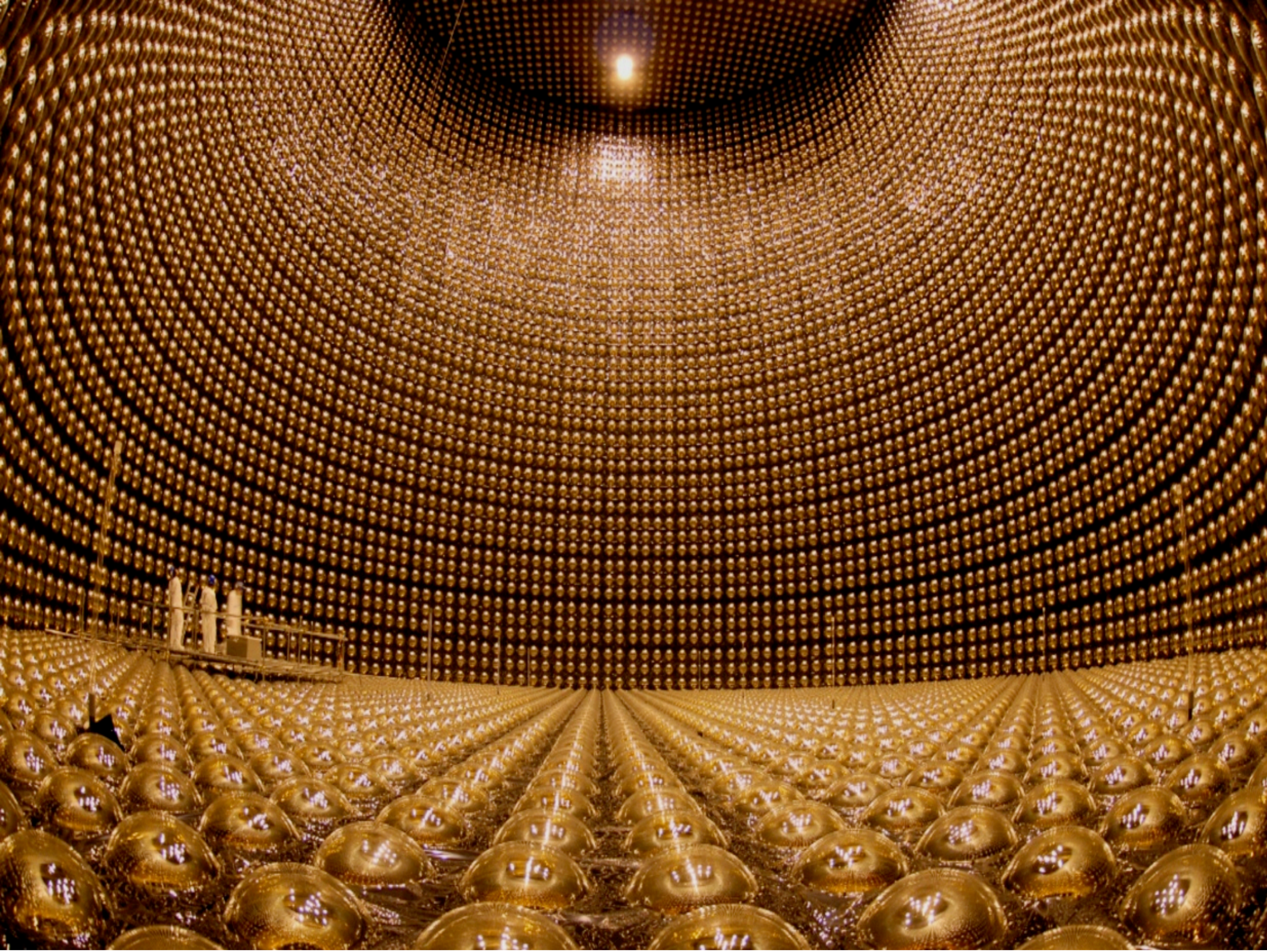


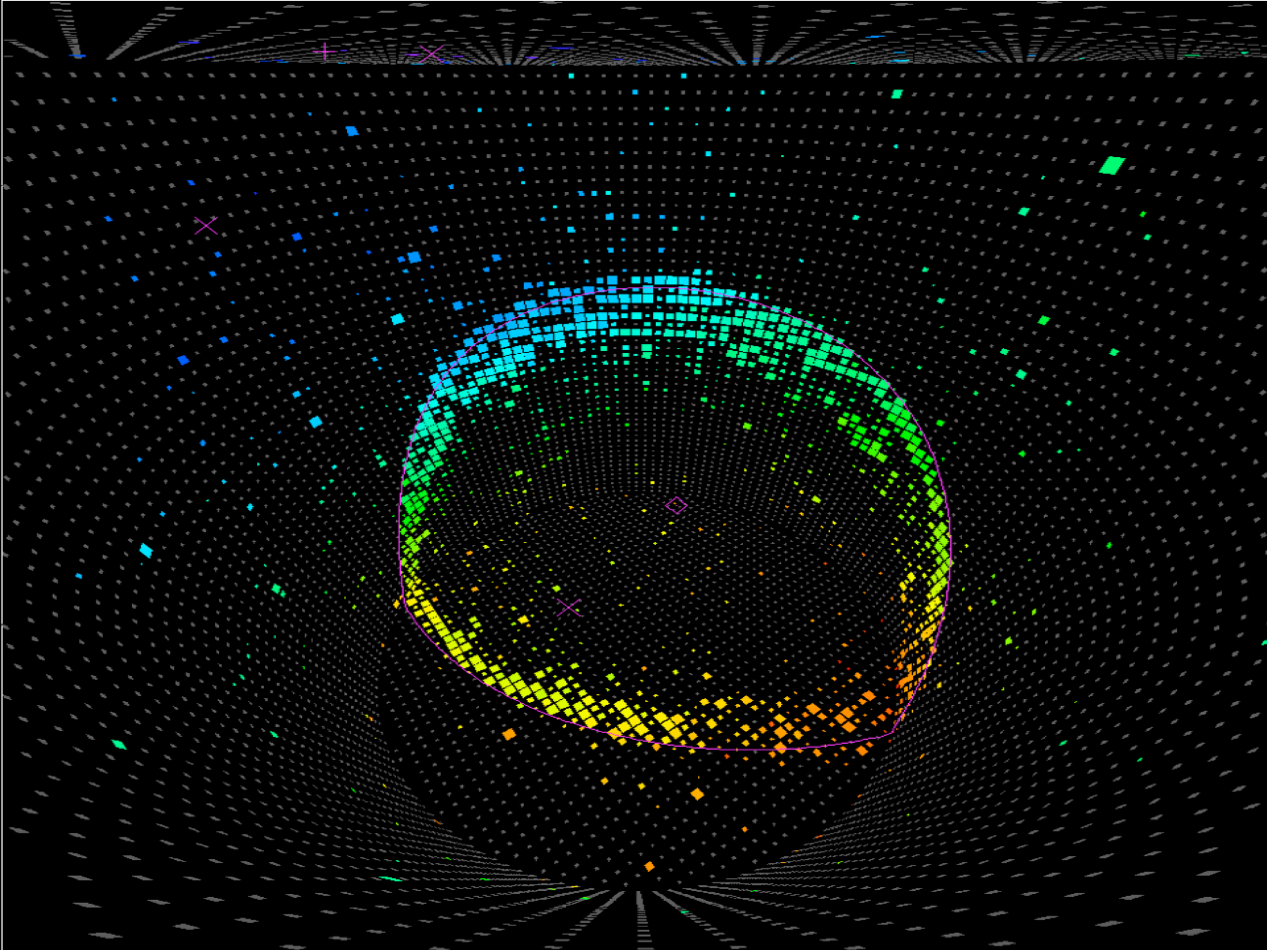

ν
Tracker

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

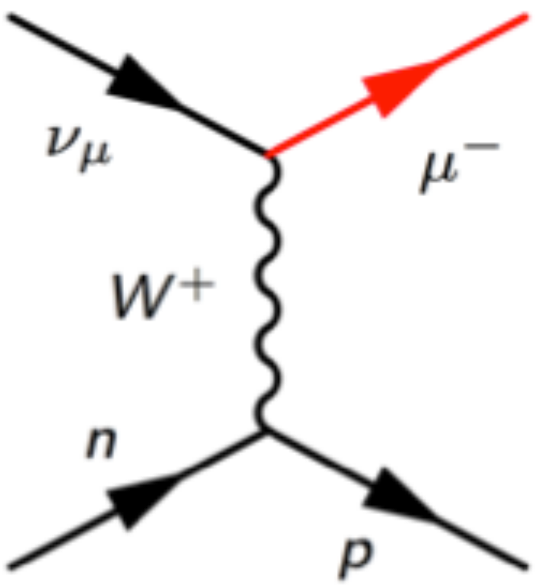




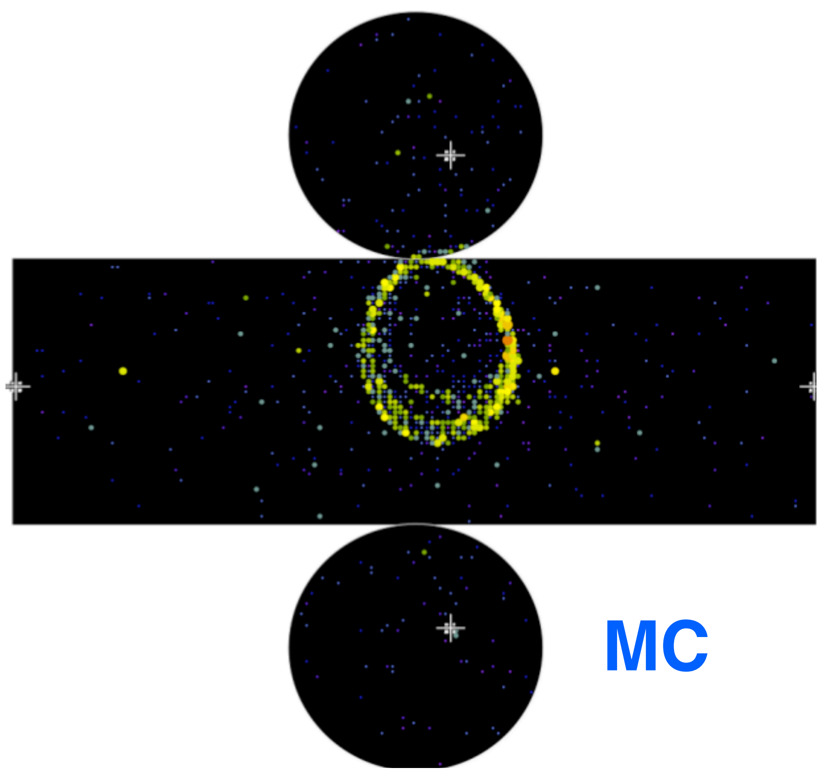


Super-Kamiokande events

ν_μ CCQE

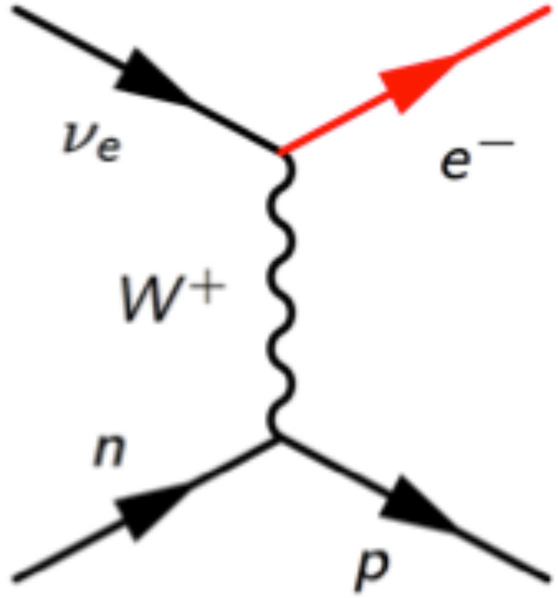


- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold

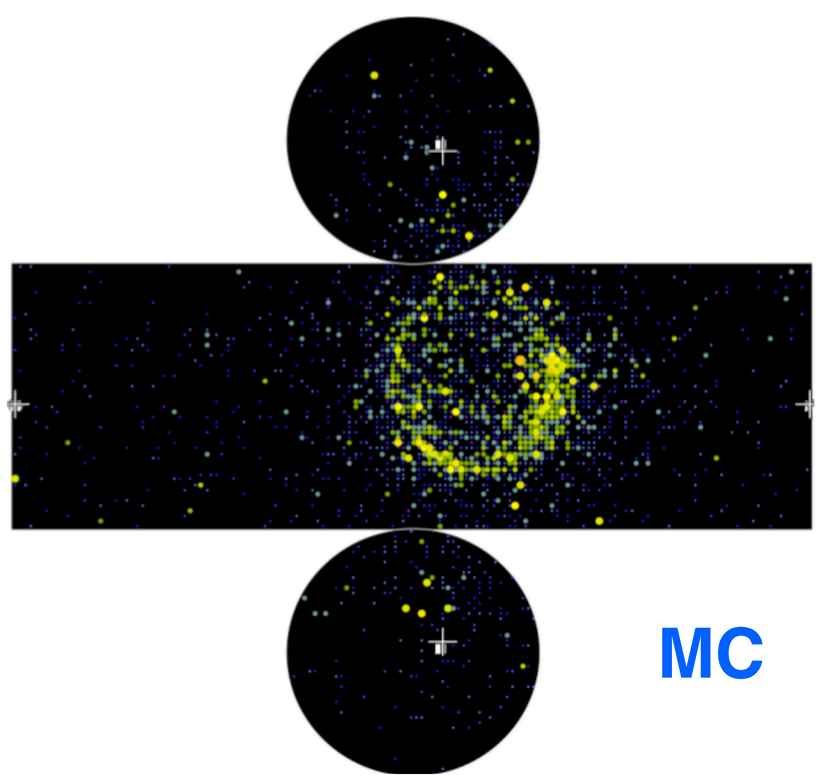


MC

ν_e CCQE

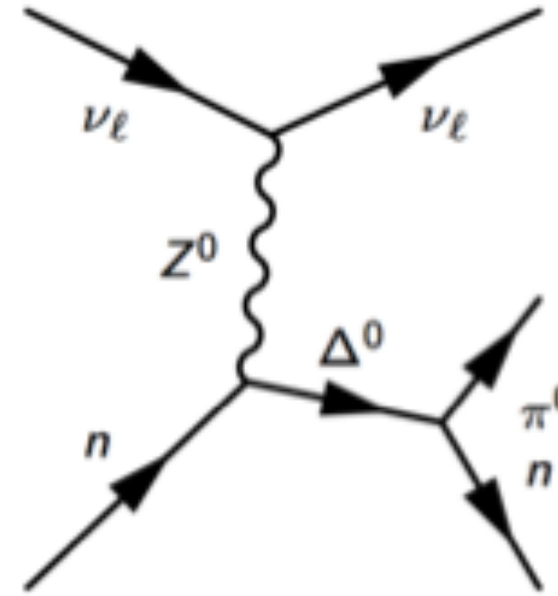


- Multiple scattering
- EM shower
- Ring with “fuzzy” edge

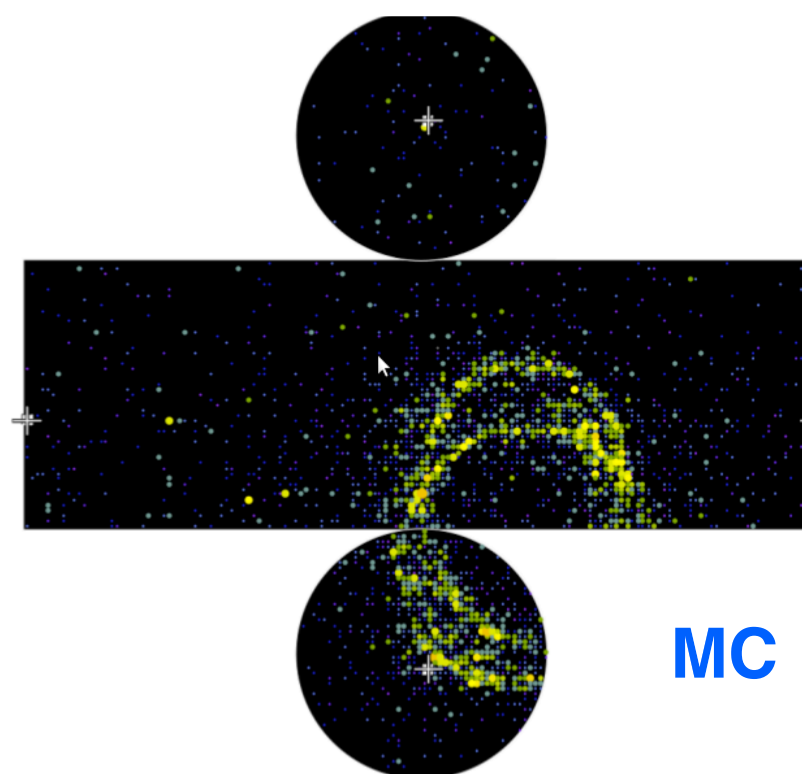


MC

Background

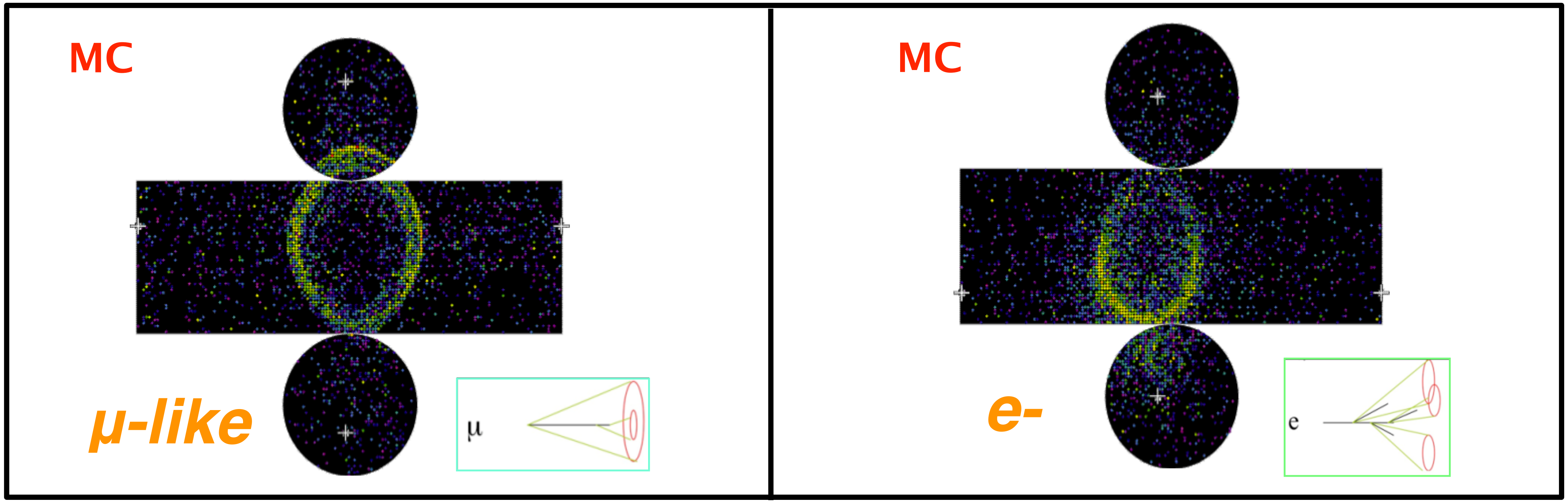


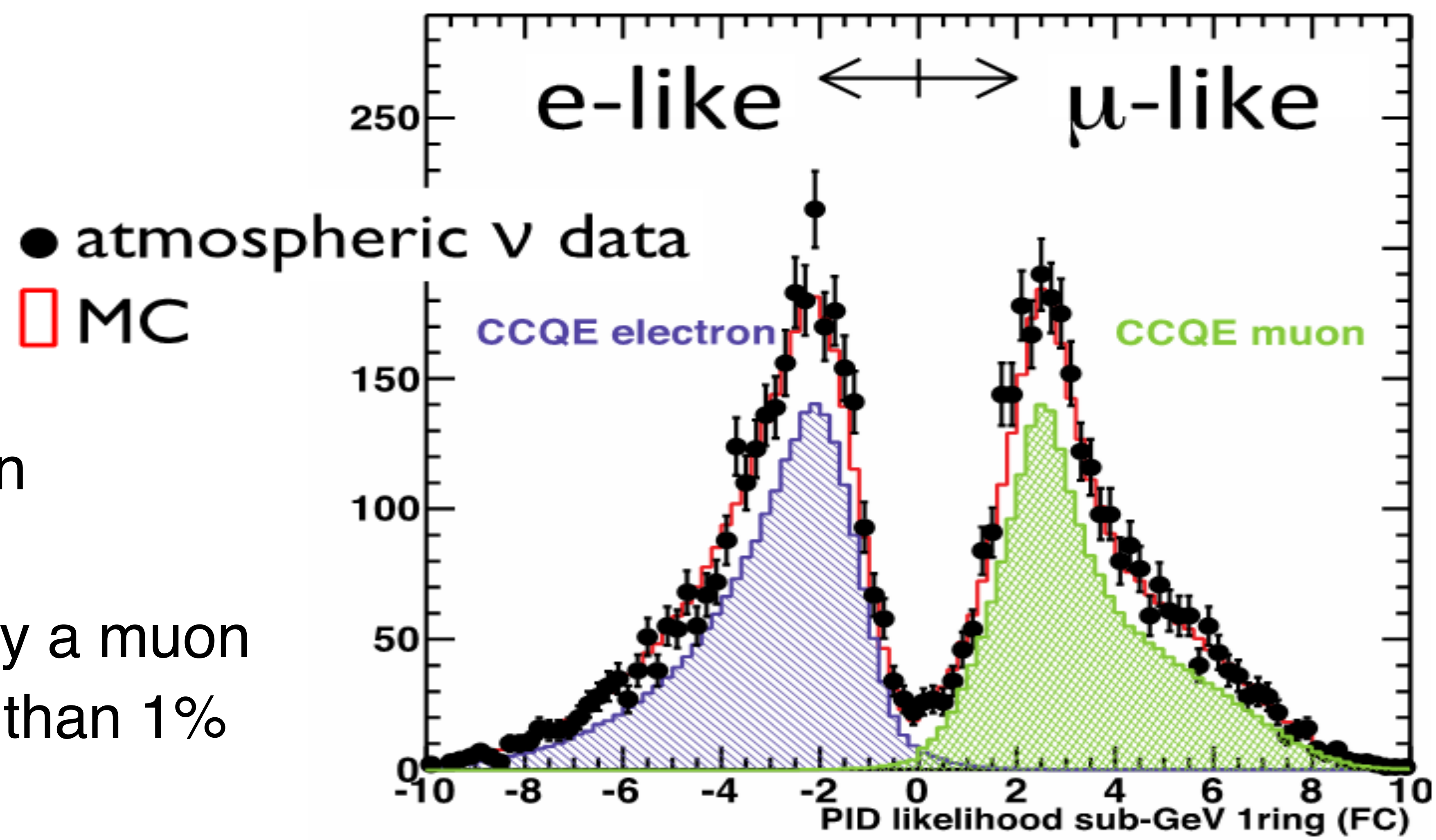
- EM shower from $\pi^0 \to \gamma\gamma$
- Can be misidentified as an electron



MC

Particle Identification at the far detector

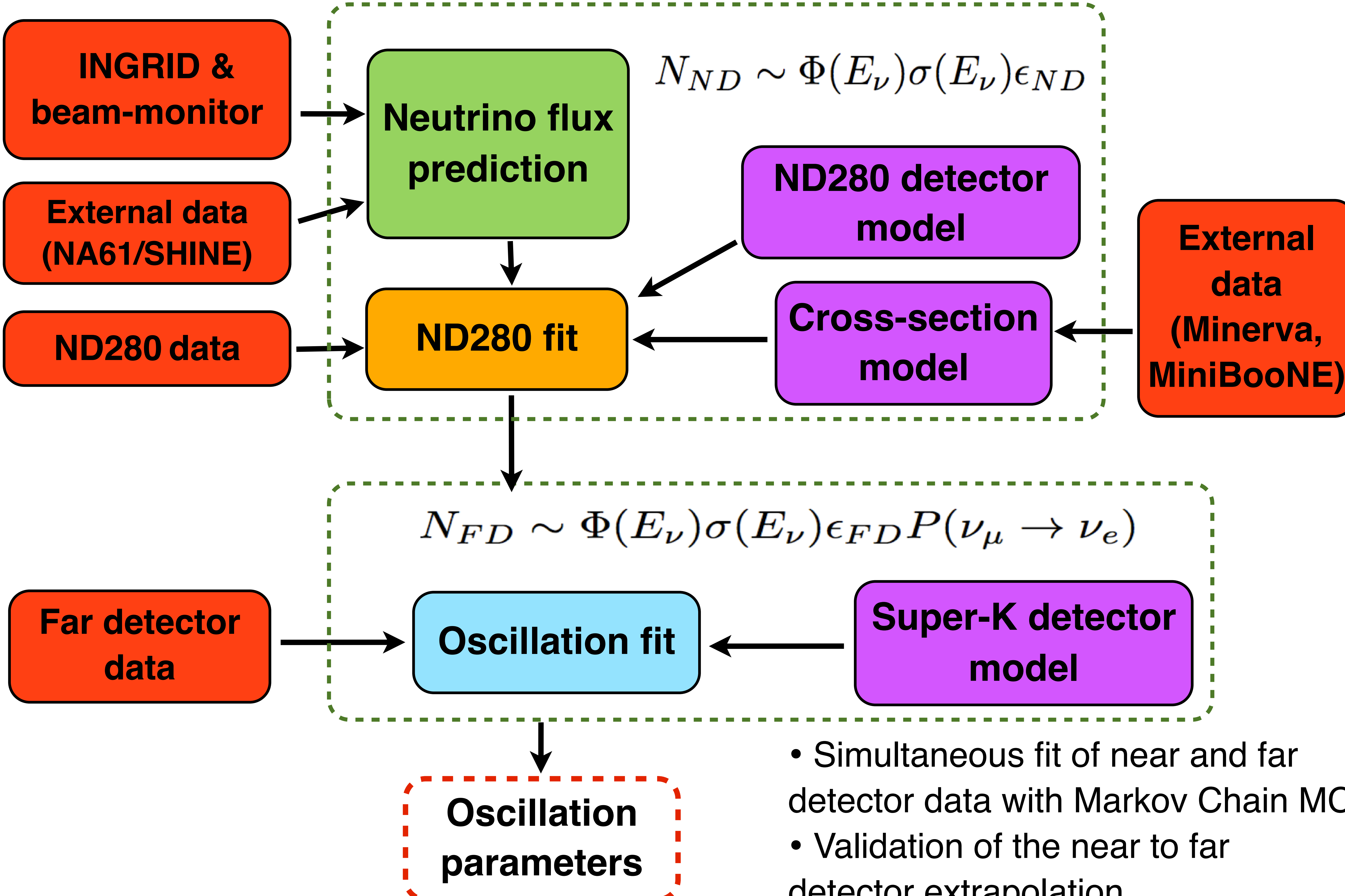




- Excellent e/μ separation

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

Strategy for oscillation analyses

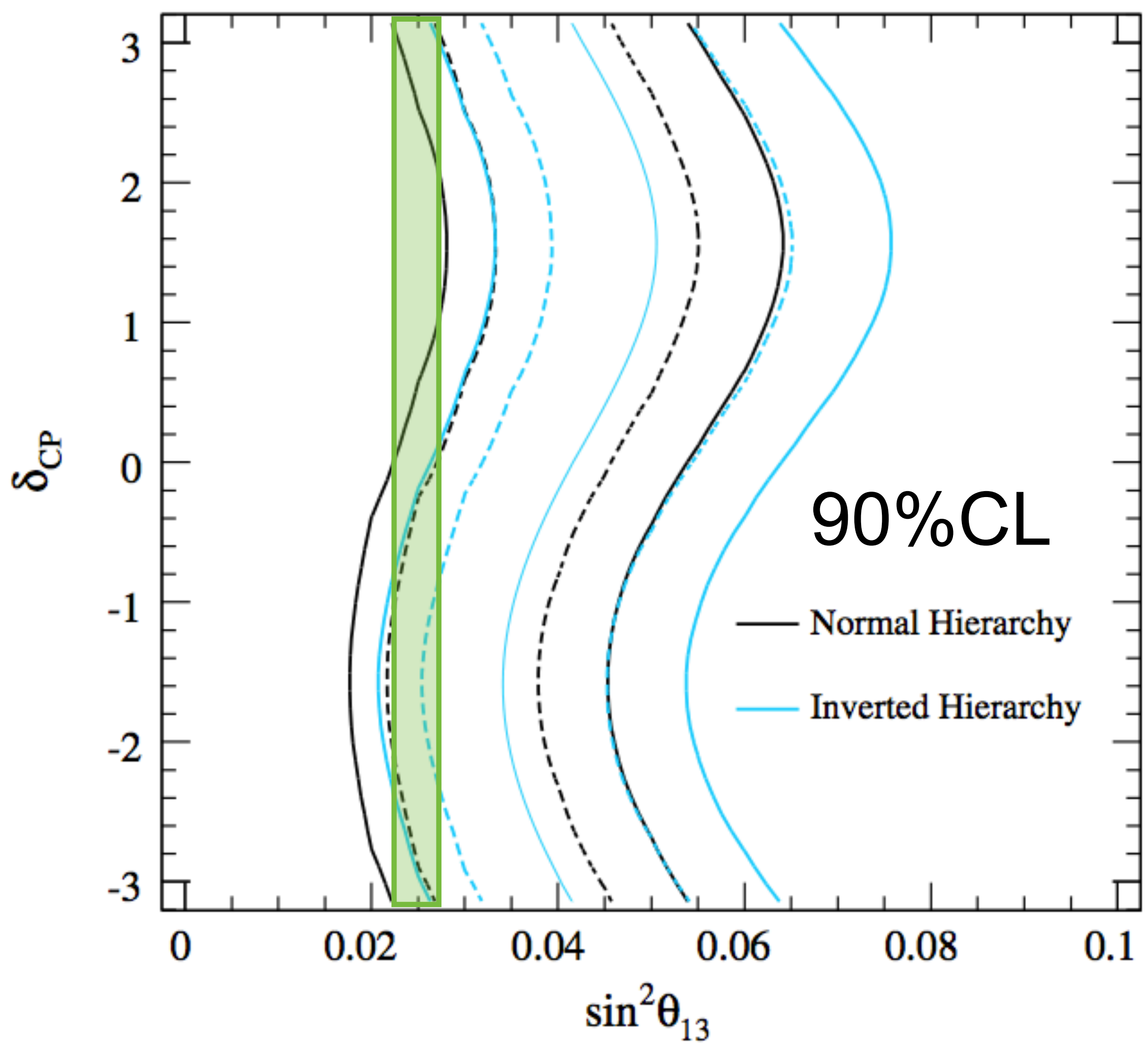


- Simultaneous fit of near and far detector data with Markov Chain MC
- Validation of the near to far detector extrapolation

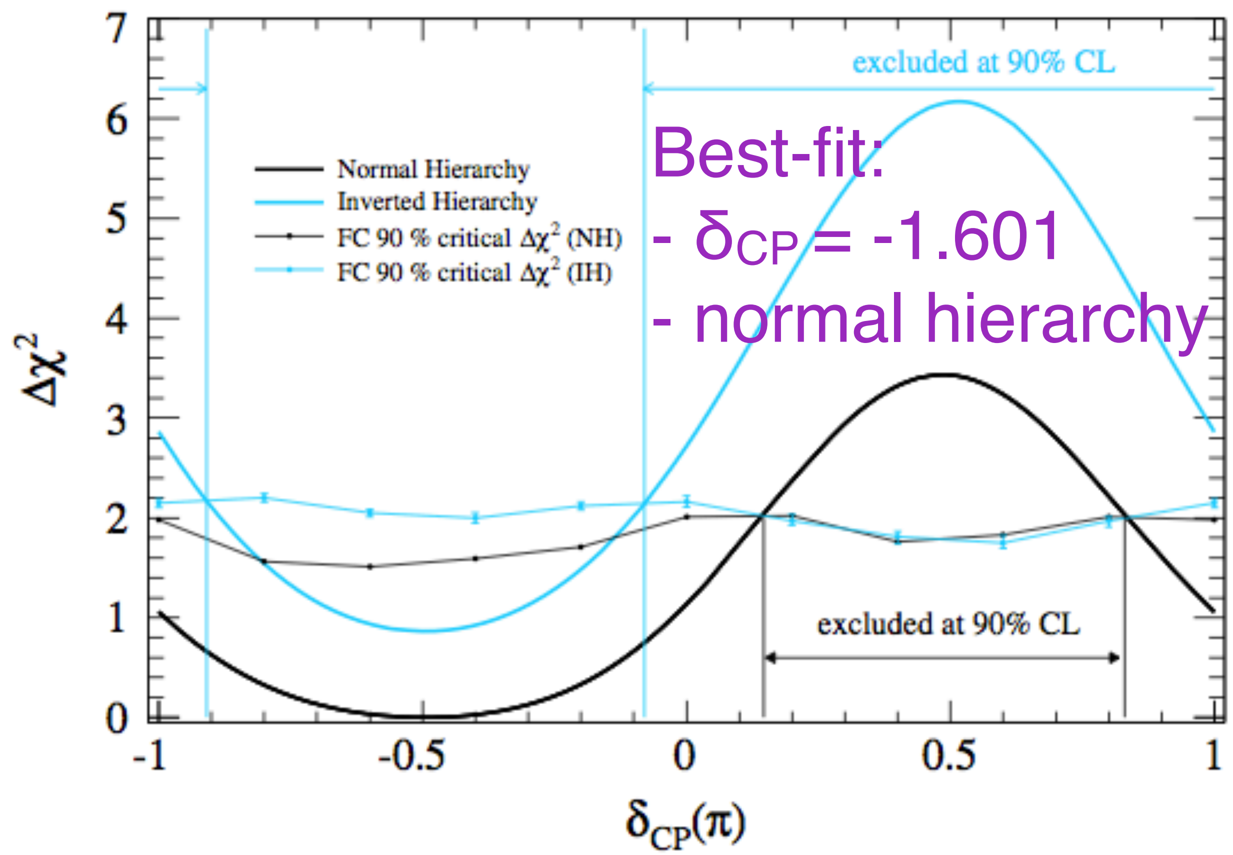
Where we were with only neutrino data

- 6.6×10^{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)
- $\sin^2\theta_{13} = 0.0243 \pm 0.0026$



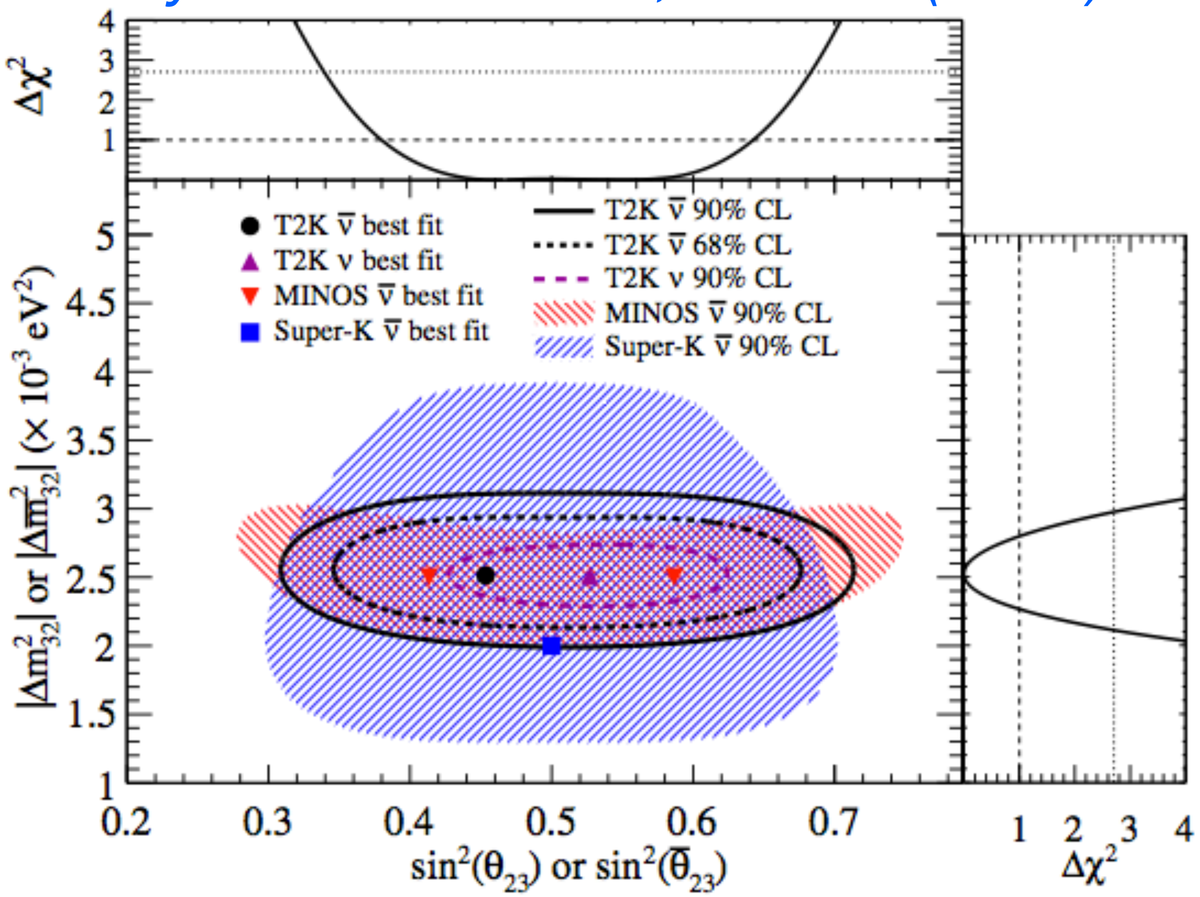
Need to directly compare neutrino and antineutrino to infer δ_{CP}

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 at CERN

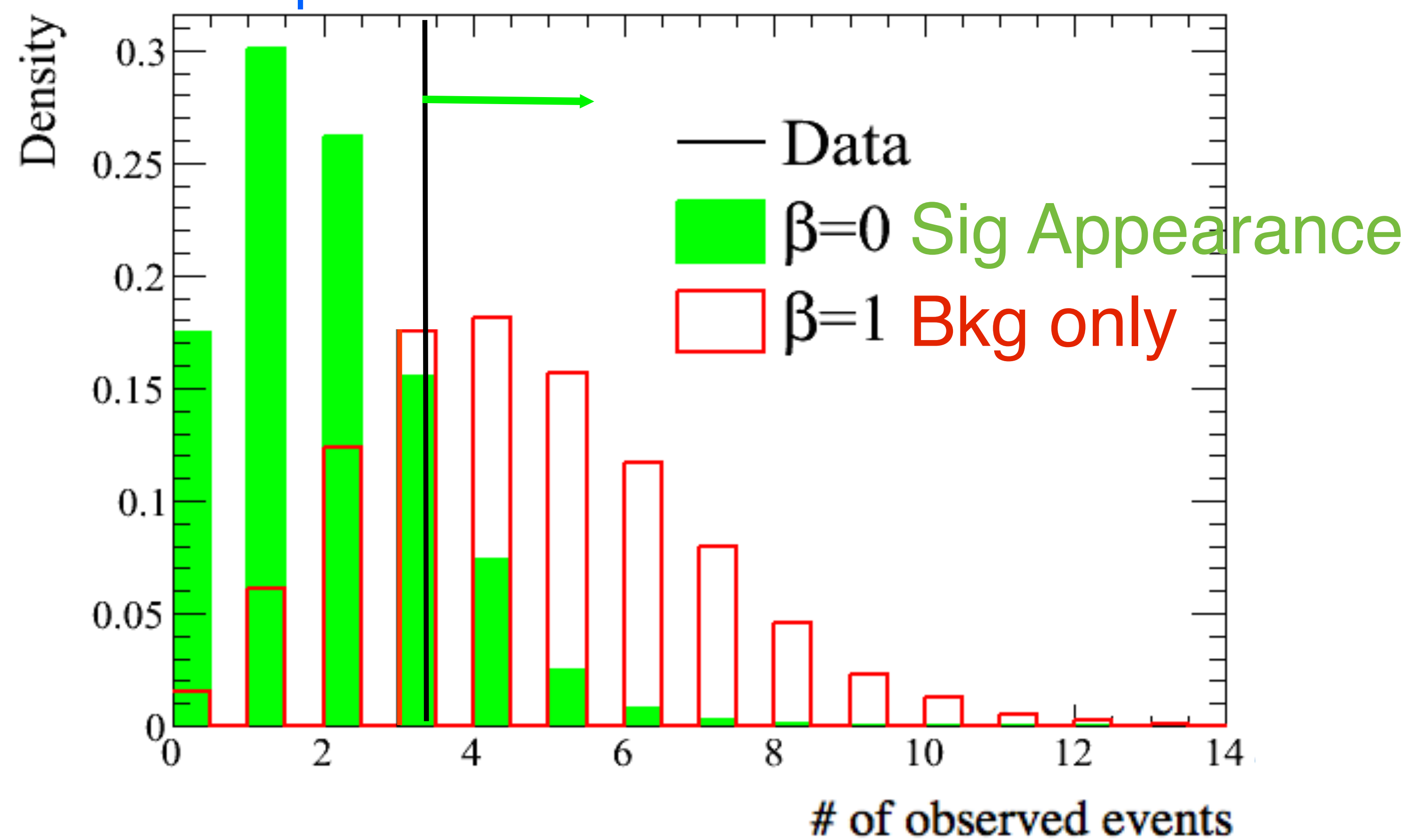
$\overline{\nu}_\mu$ disappearance

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



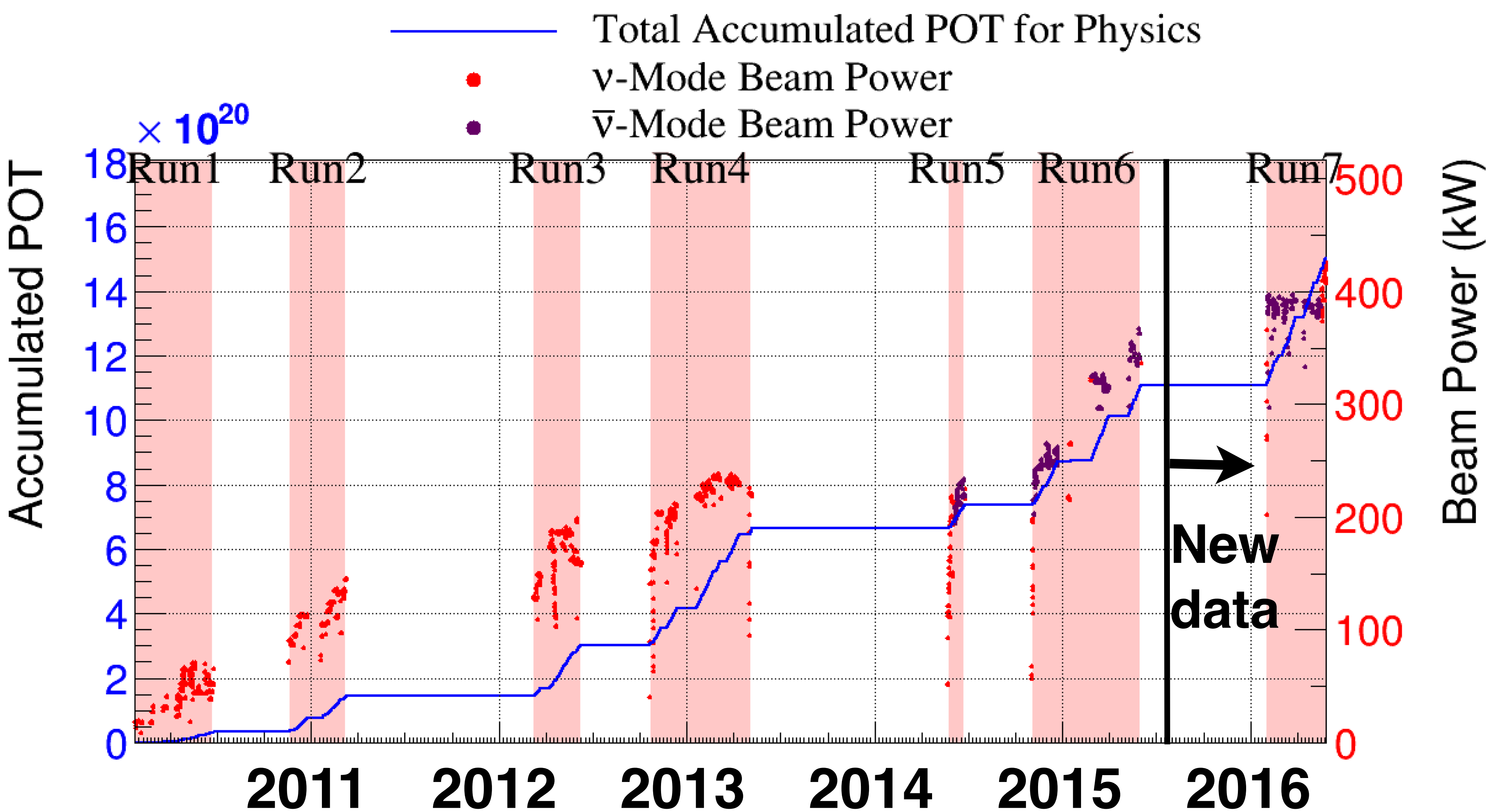
$\overline{\nu}_e$ appearance

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: 1.510×10^{21}

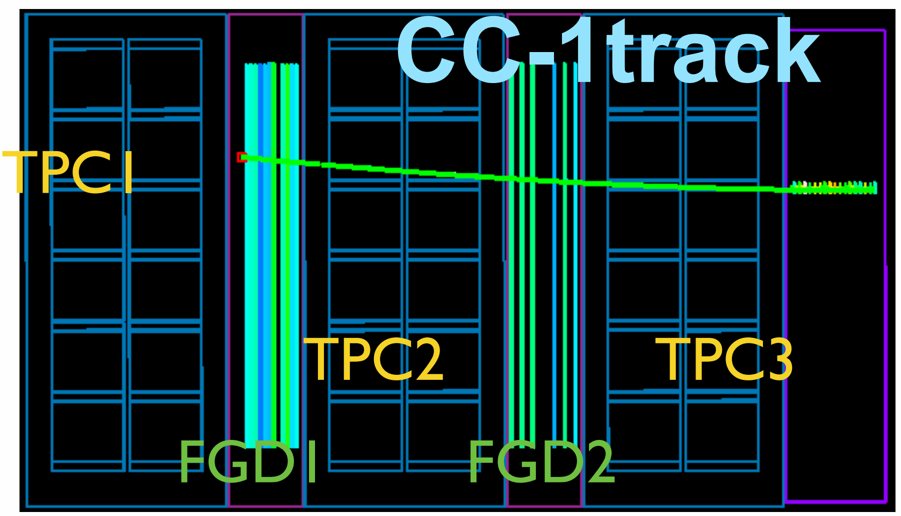
ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

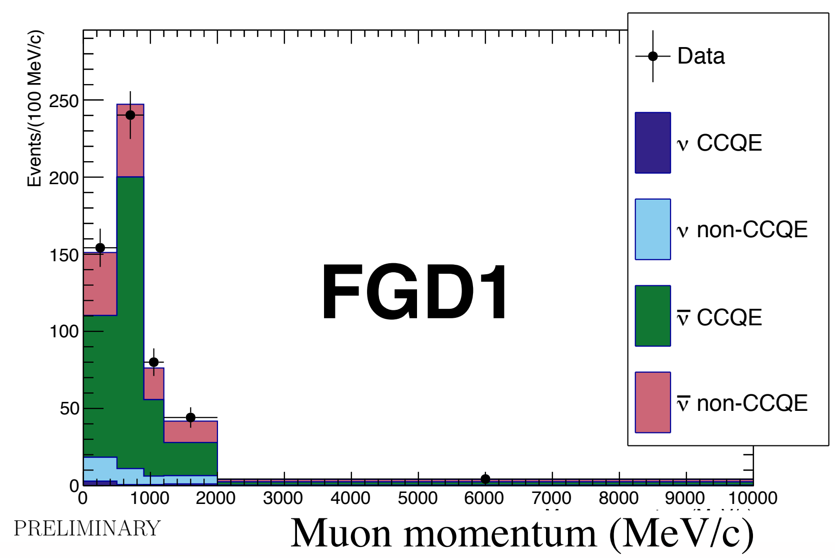
- Beam power increased up to 420 kW
- Almost doubled protons-on-target (POT) in antineutrino beam mode wrt 2015
- Almost same number of POT in neutrino and antineutrino beam mode

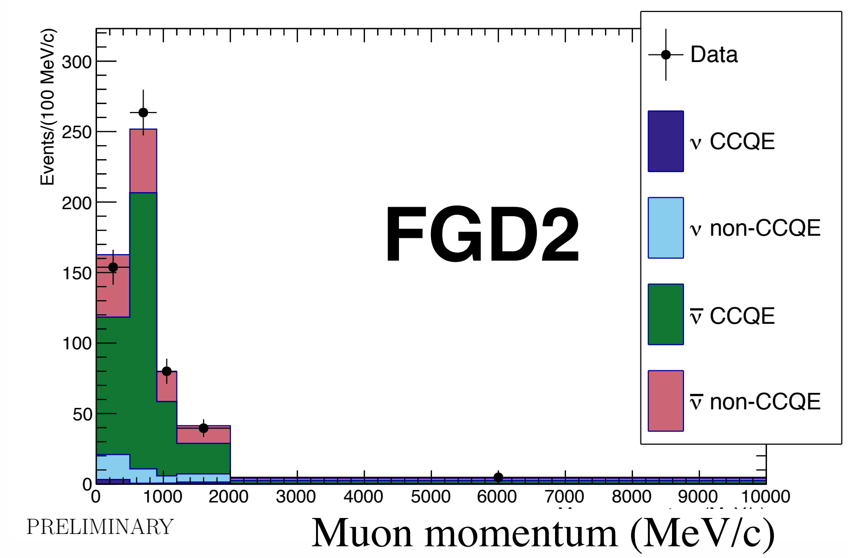
Near Detector Fit: antineutrino samples

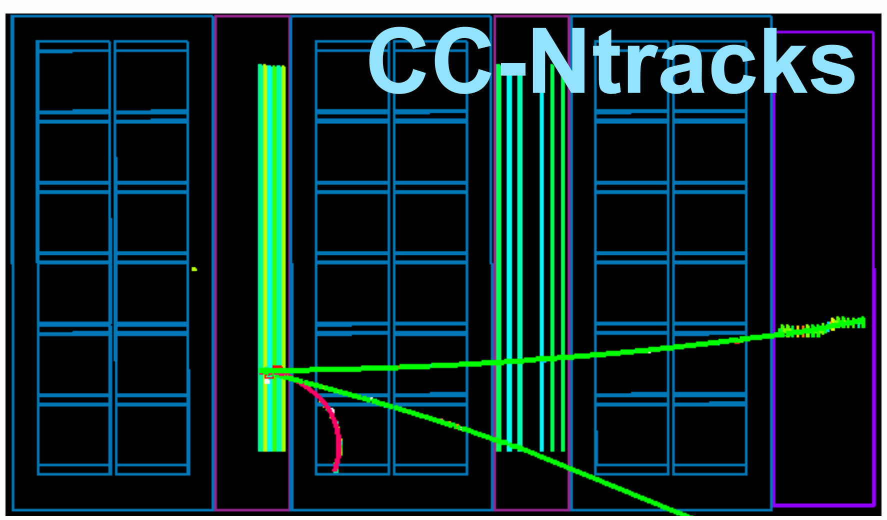
- Antineutrino samples: 1 μ^+ candidates (CC-1track) + CC-Ntracks
- Neutrino samples: 1 μ^- candidates (CC-0π) + 1π^+ (CC-1π) + CC other
- Simultaneous analysis of neutrino and antineutrino data (μ momentum/angle)

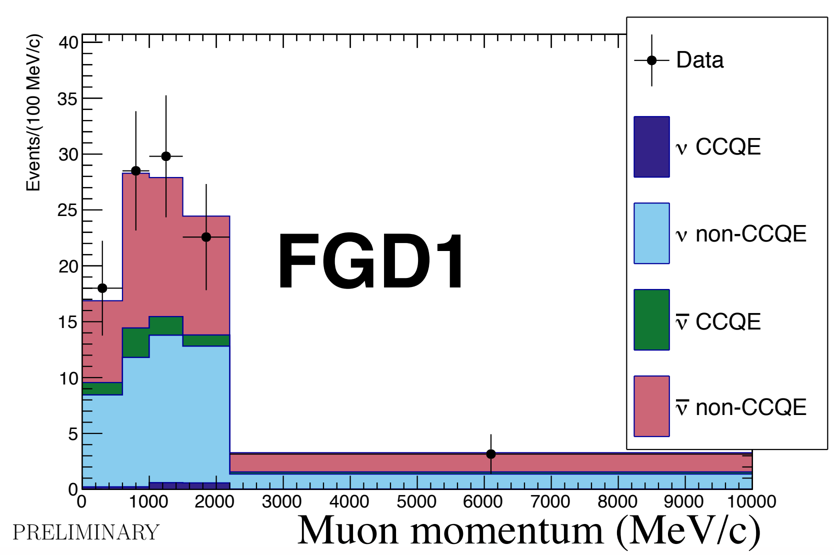
Antineutrino best-fit distributions

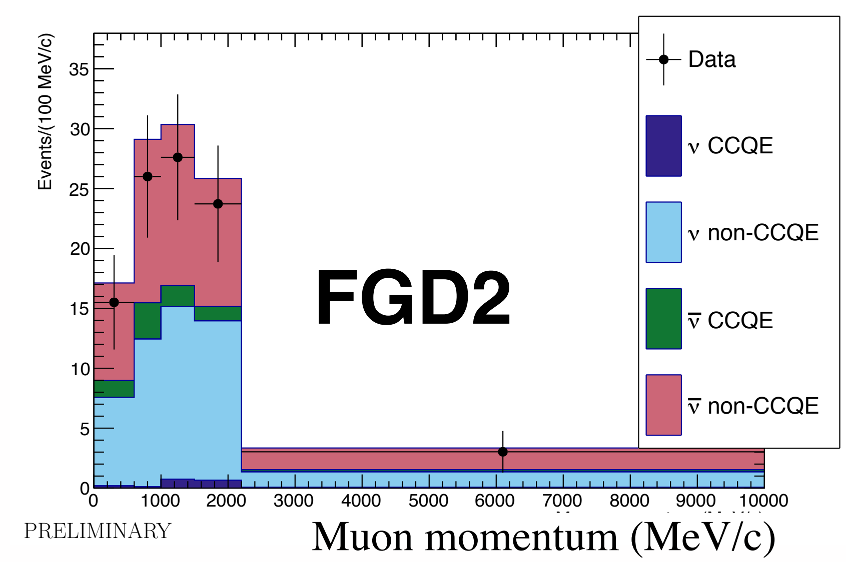








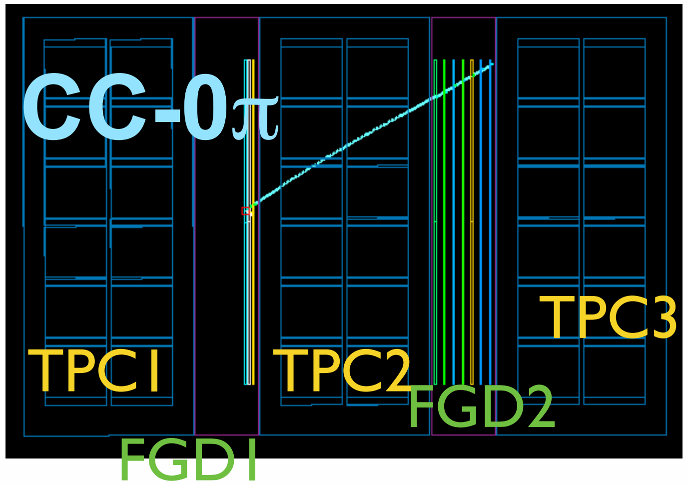


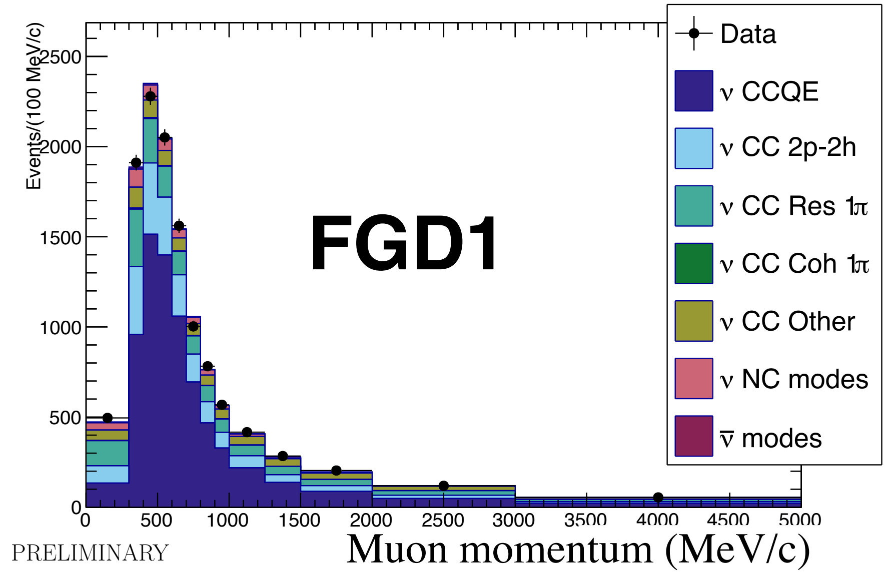


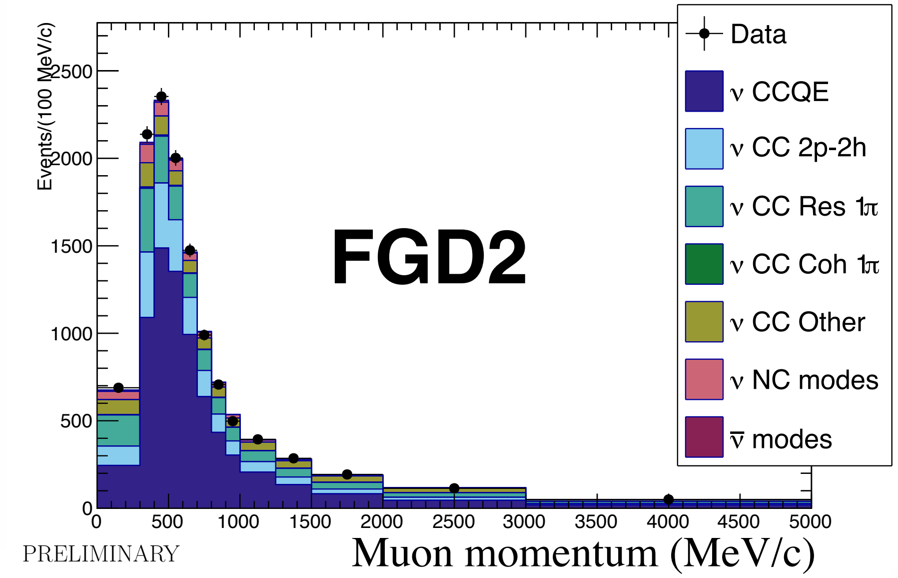
Additional samples to measure wrong-sign background (~30% of ν_μ contamination)

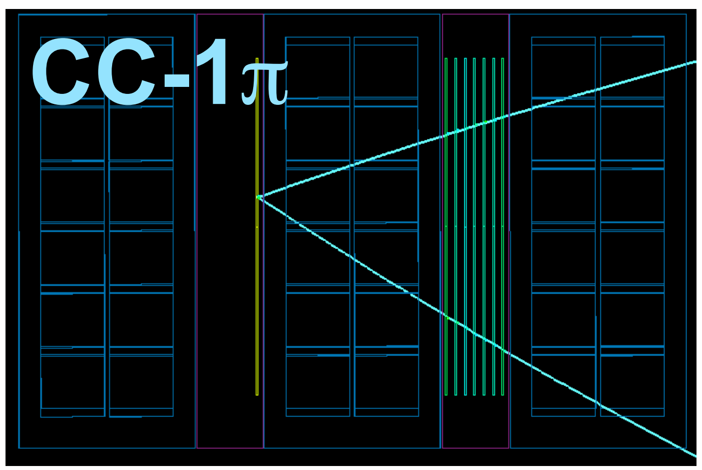
Near Detector Fit: neutrino samples

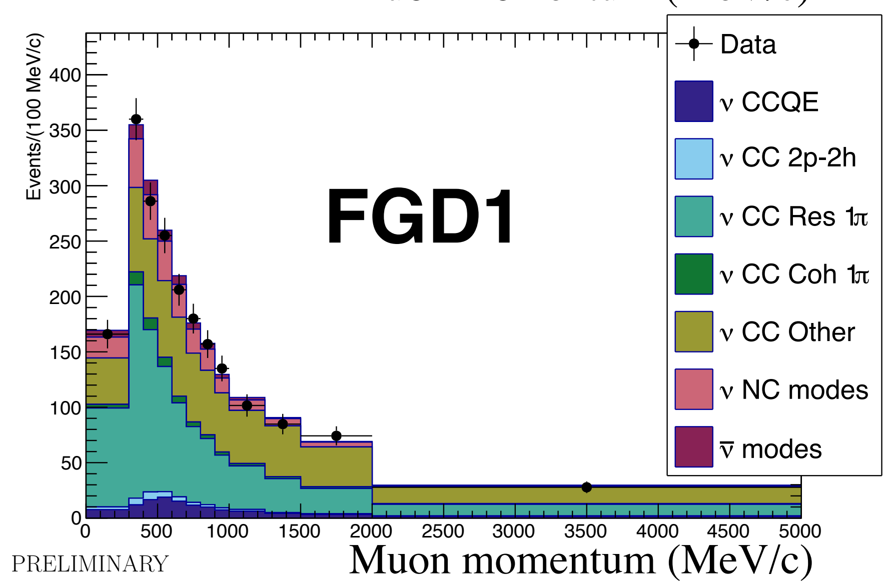
Neutrino best-fit distributions

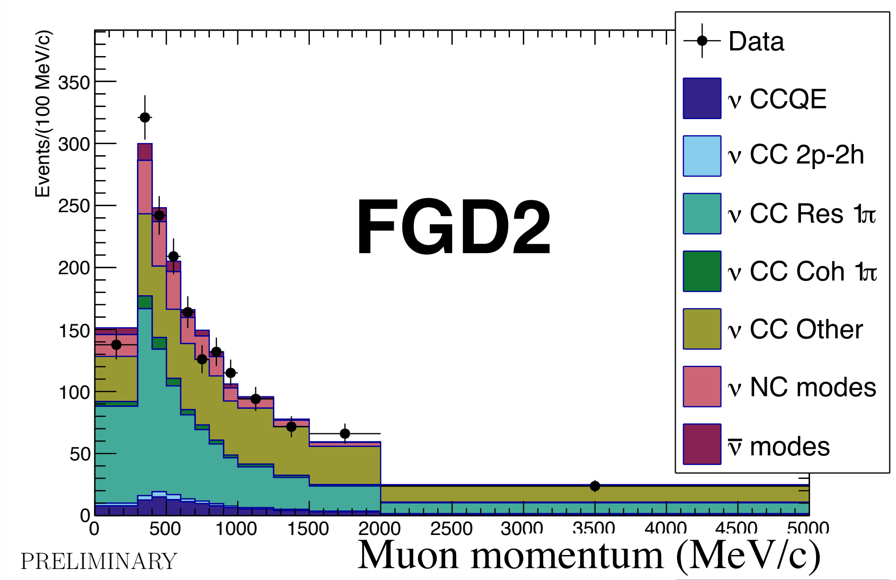


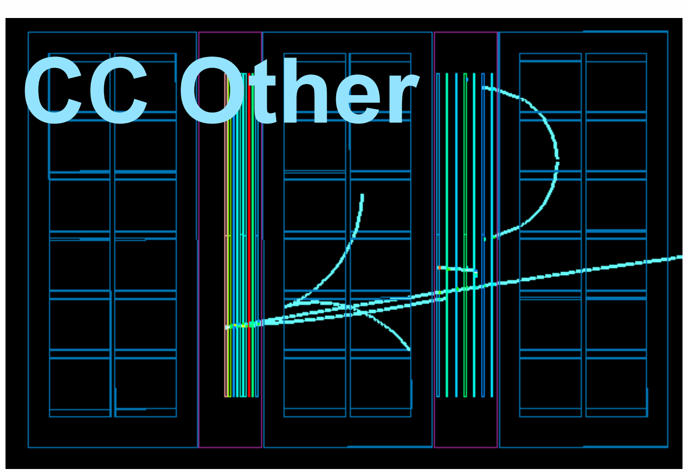


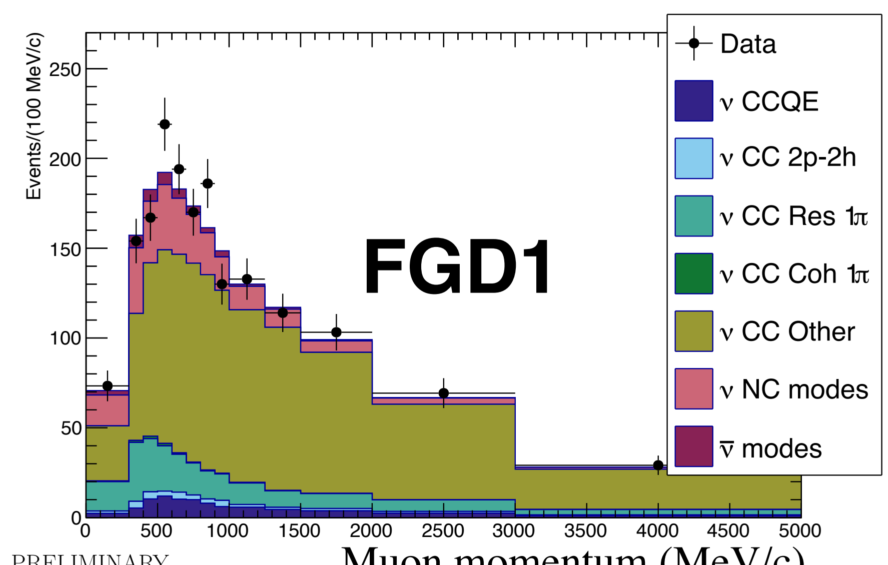


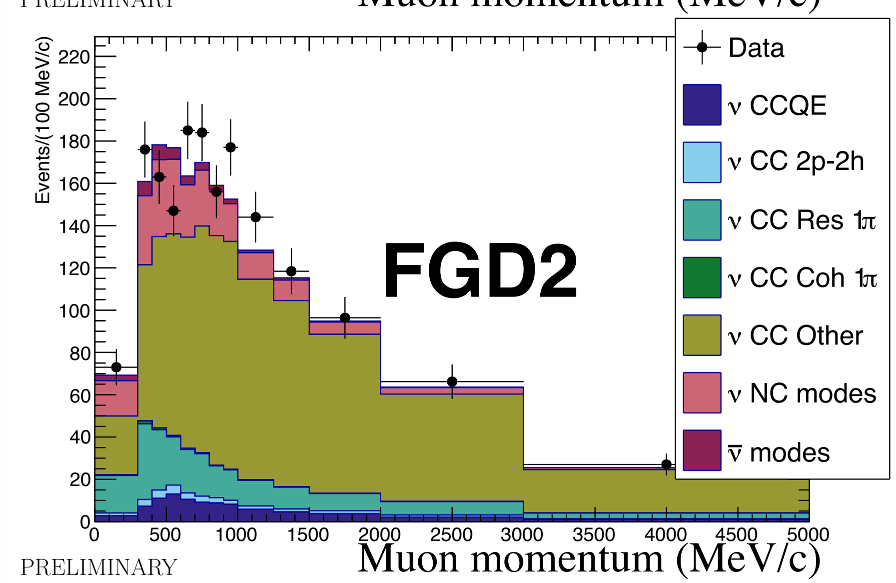






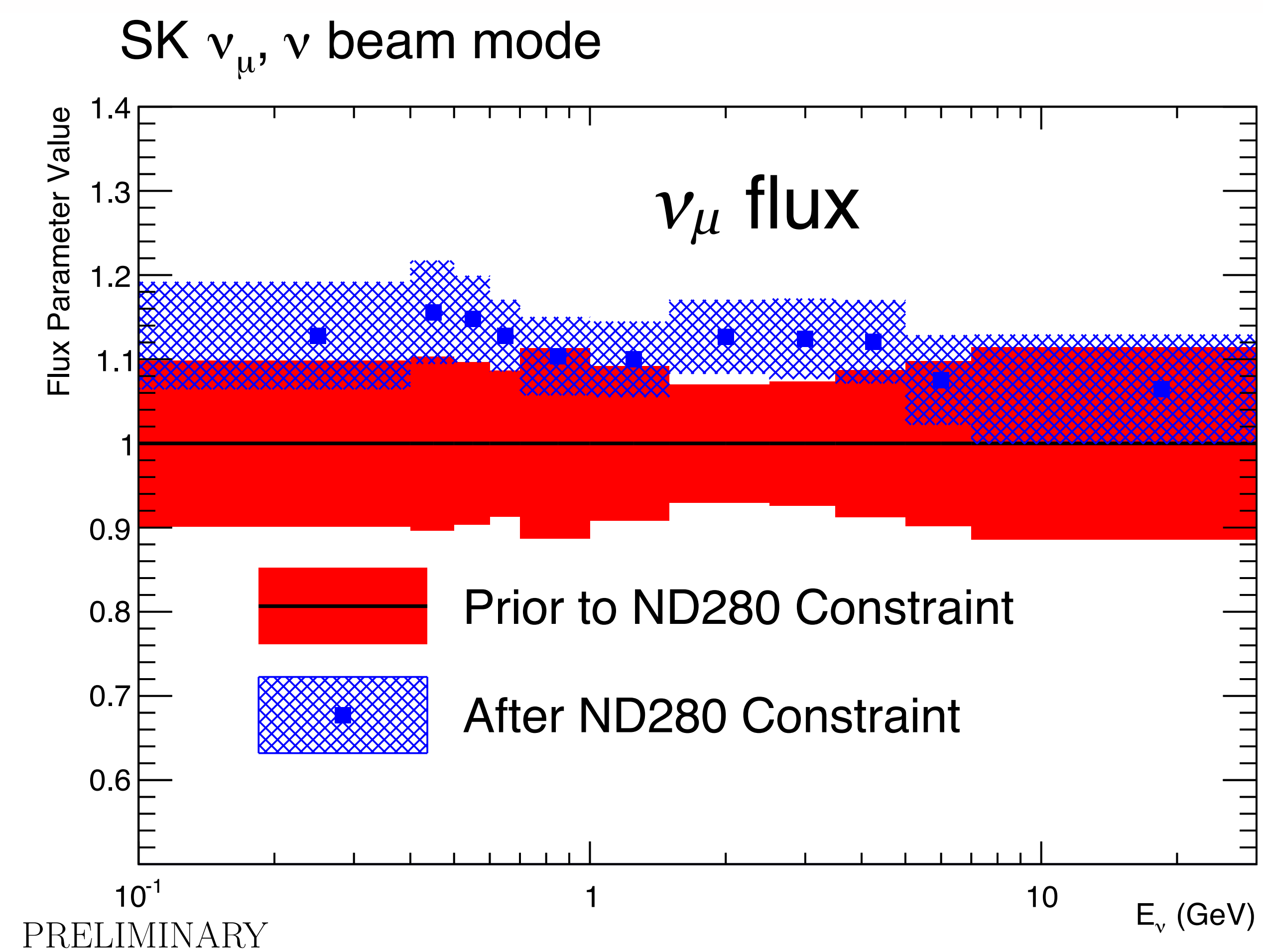


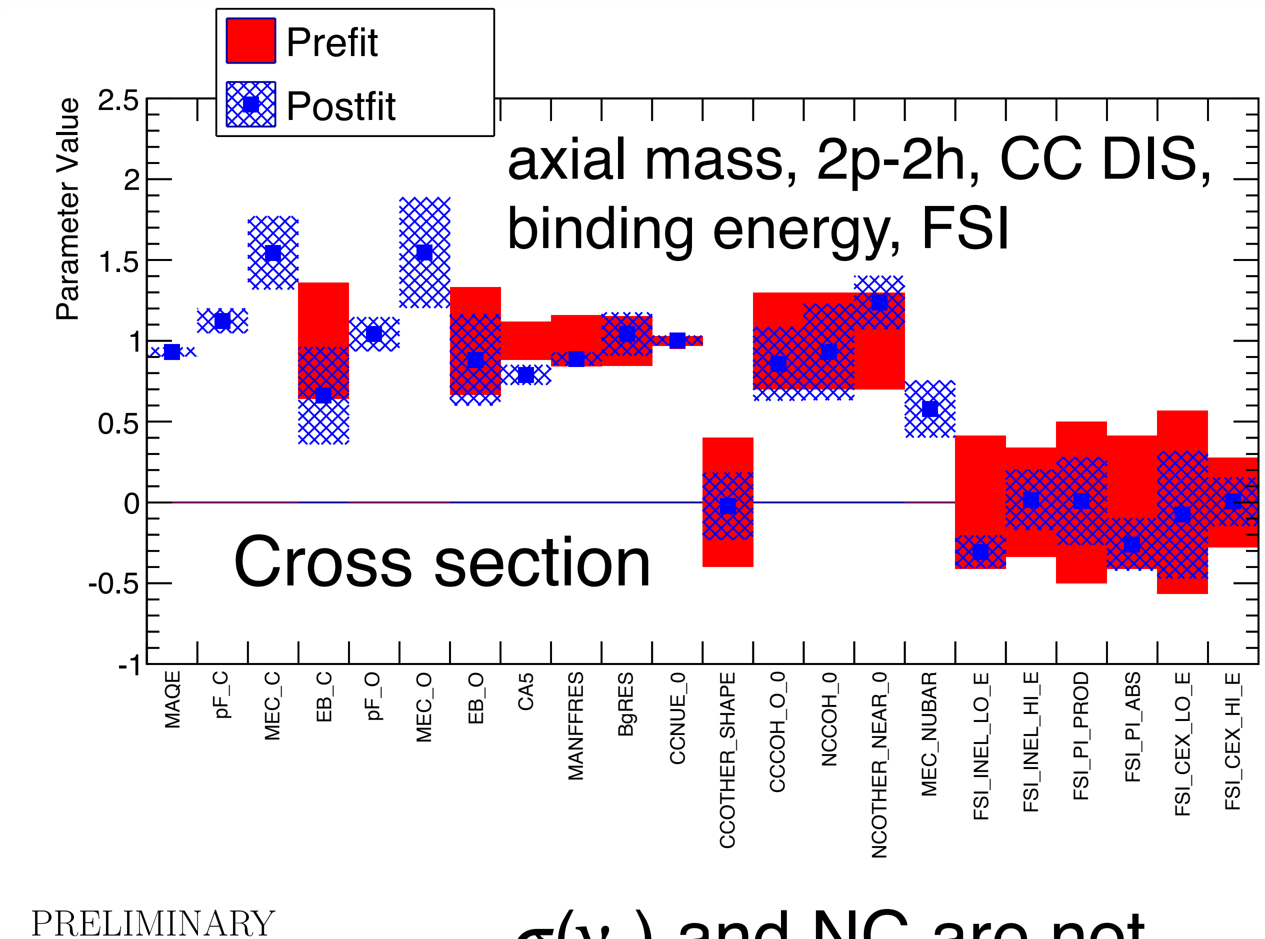




Near Detector Fit: flux and cross-section uncertainties

- Measure neutrino flux and cross section at ND280



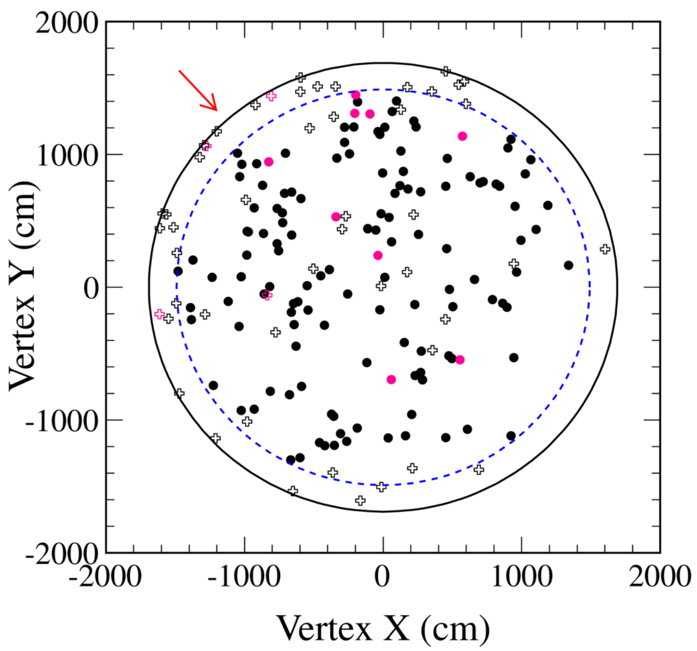


$\sigma(\nu_e)$ and NC are not measured at ND280

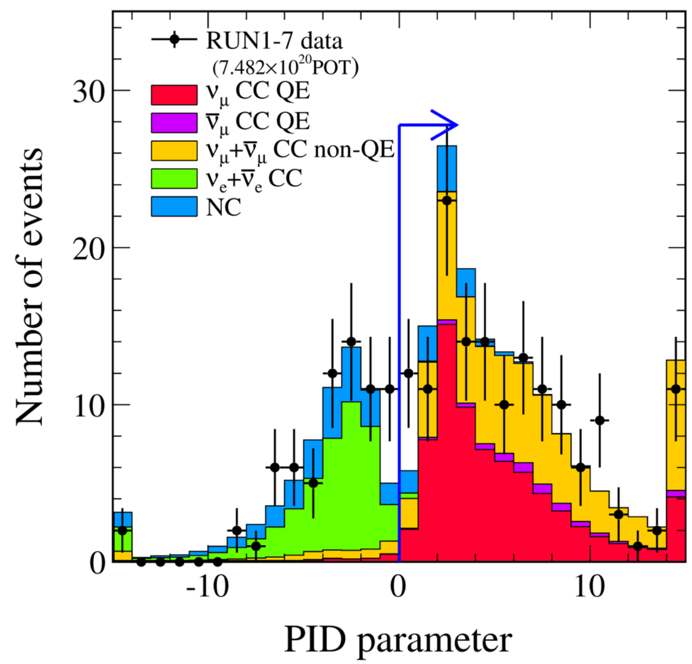
- Flux parameters increase by ~15%
- Cross sections ~ consistent with input value
- Flux and cross section highly anti-correlated after the data fit
- The p-value to the pre-fit prediction is acceptable (8.6%)
- Systematic uncertainties in neutrino oscillation analyses from 12-14% to 5-6%

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

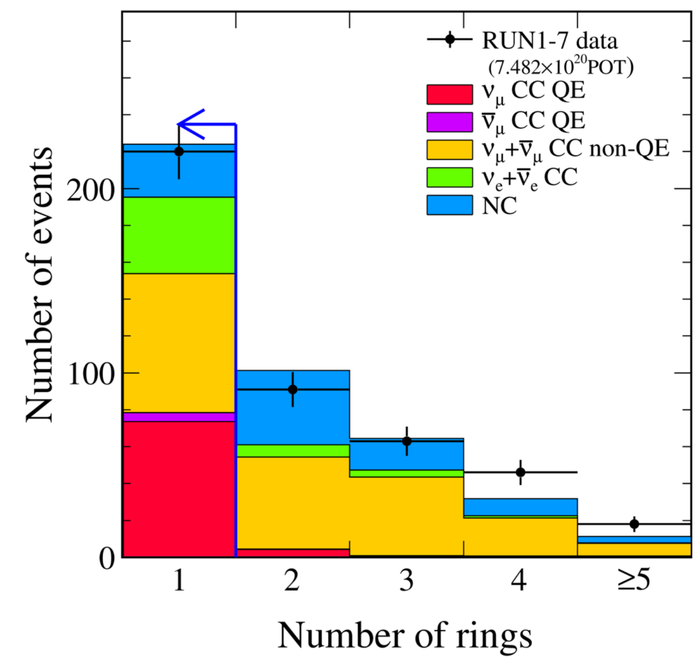
1) Fully contained in fiducial volume rings



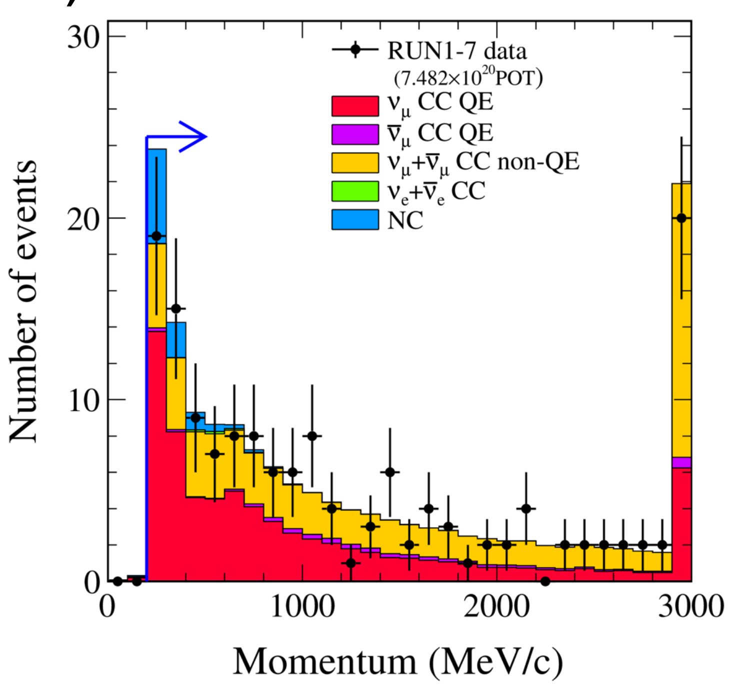
2) μ-like PID



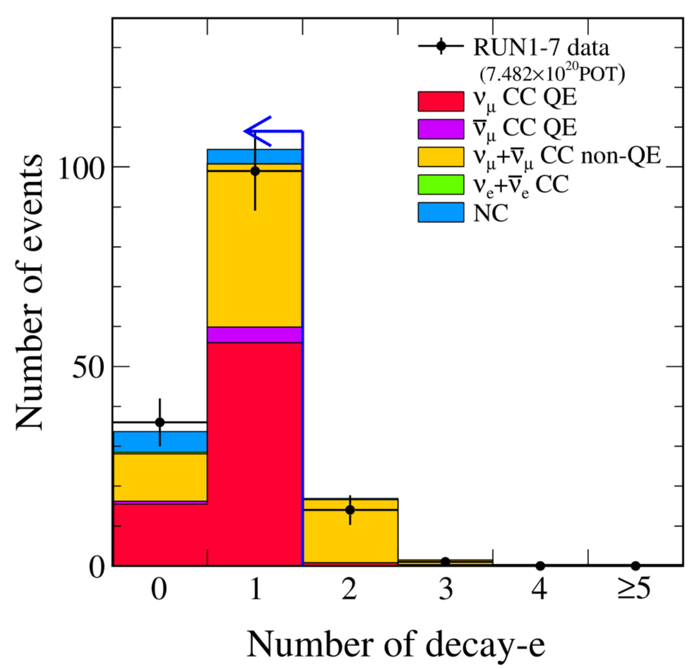
3) Single ring event

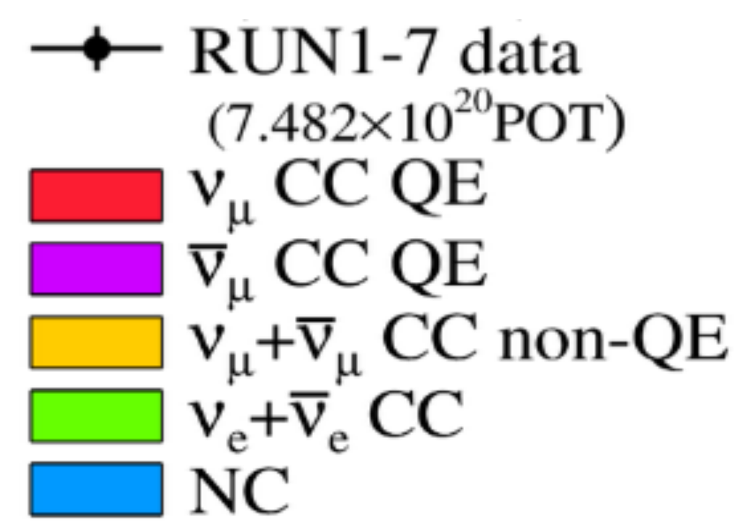


4) Momentum > 200 MeV



5) # decay electron ≤ 1



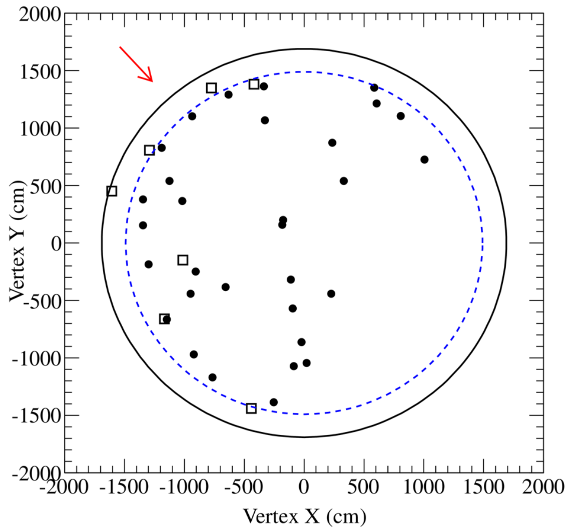


Select CCQE-like events

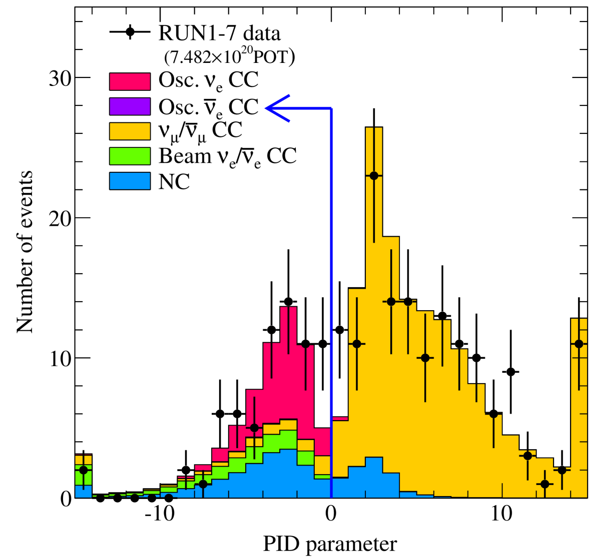
- Well understood detector/selection
- Not magnetized detector: same selection for neutrino and antineutrino beam

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

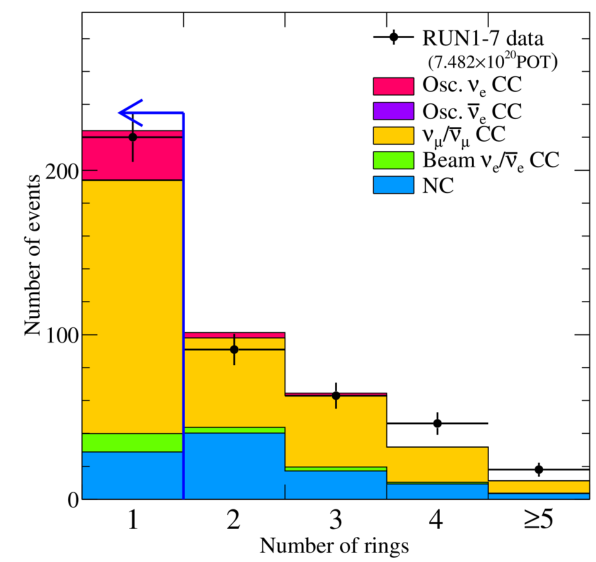
1) Fully contained in fiducial volume rings



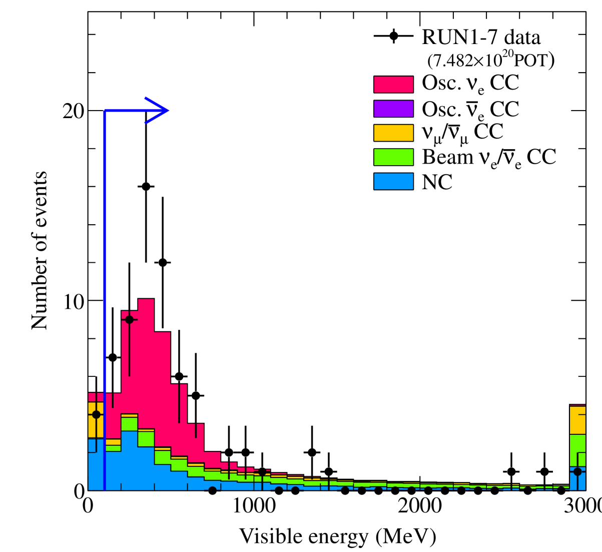
2) e-like PID



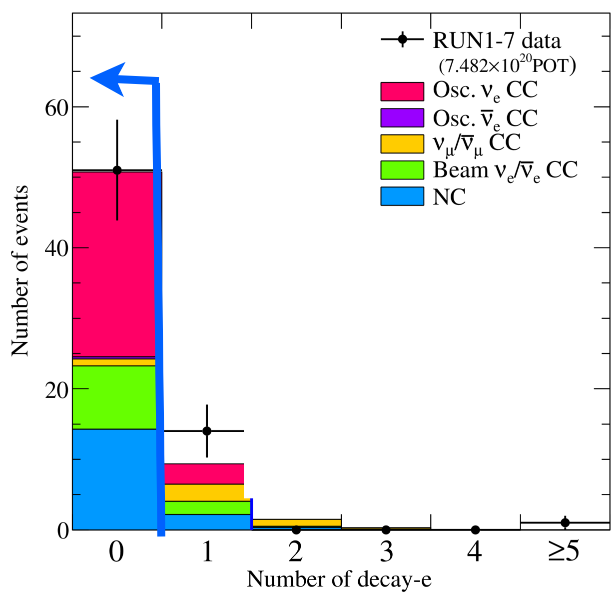
3) Single ring event



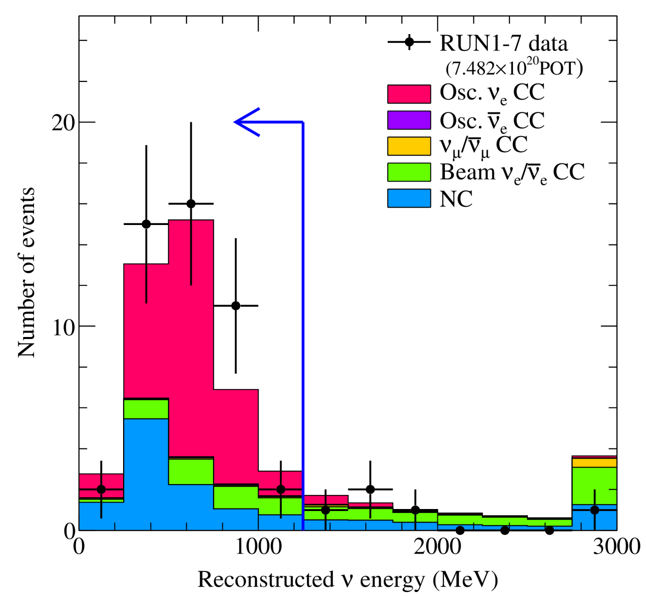
4) $E_{visible}$ > 100 MeV



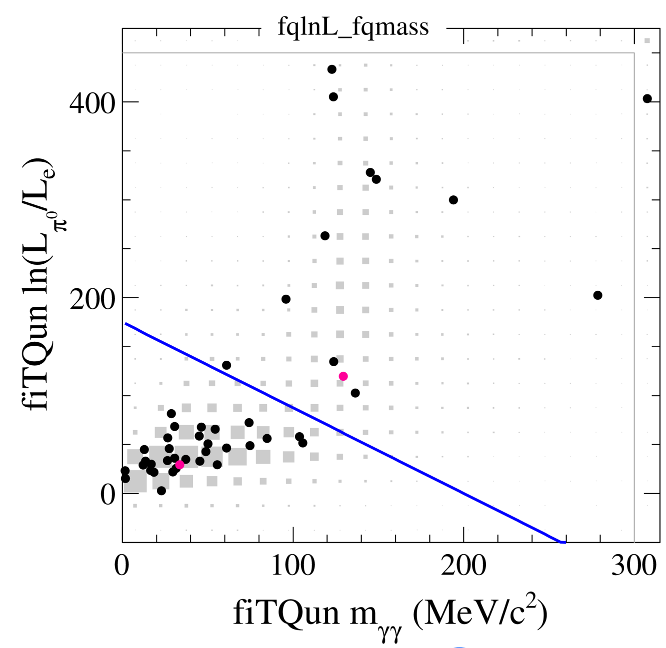
5) # decay e^- = 0

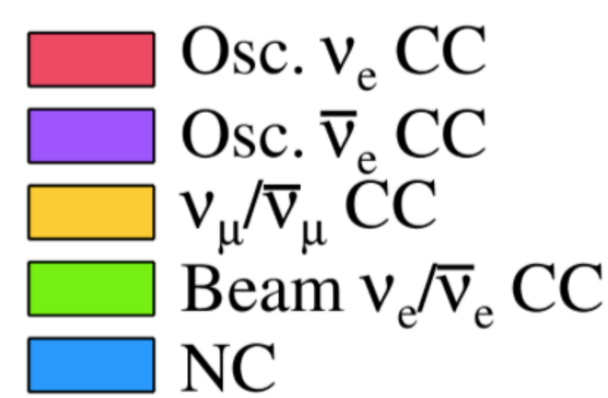


6) 0 < E_{rec} < 1250 MeV



7) π^0 rejection cut



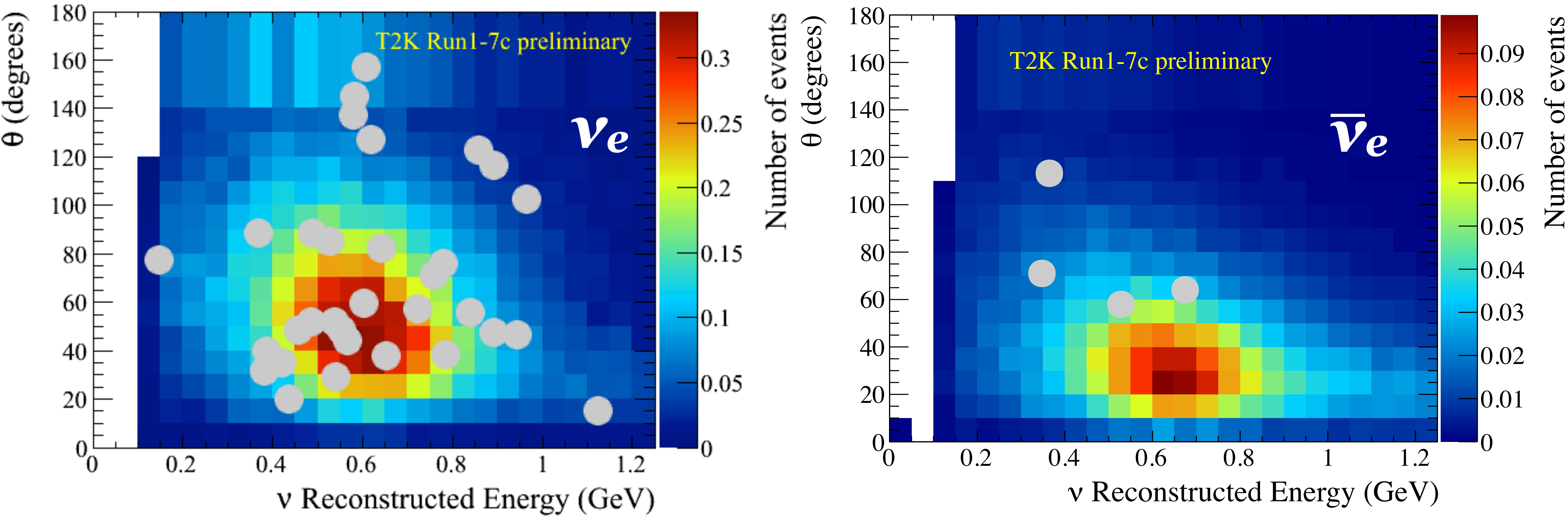


Select CCQE-like events

- Well understood detector/selection
- Not magnetized detector: same selection for neutrino and antineutrino beam

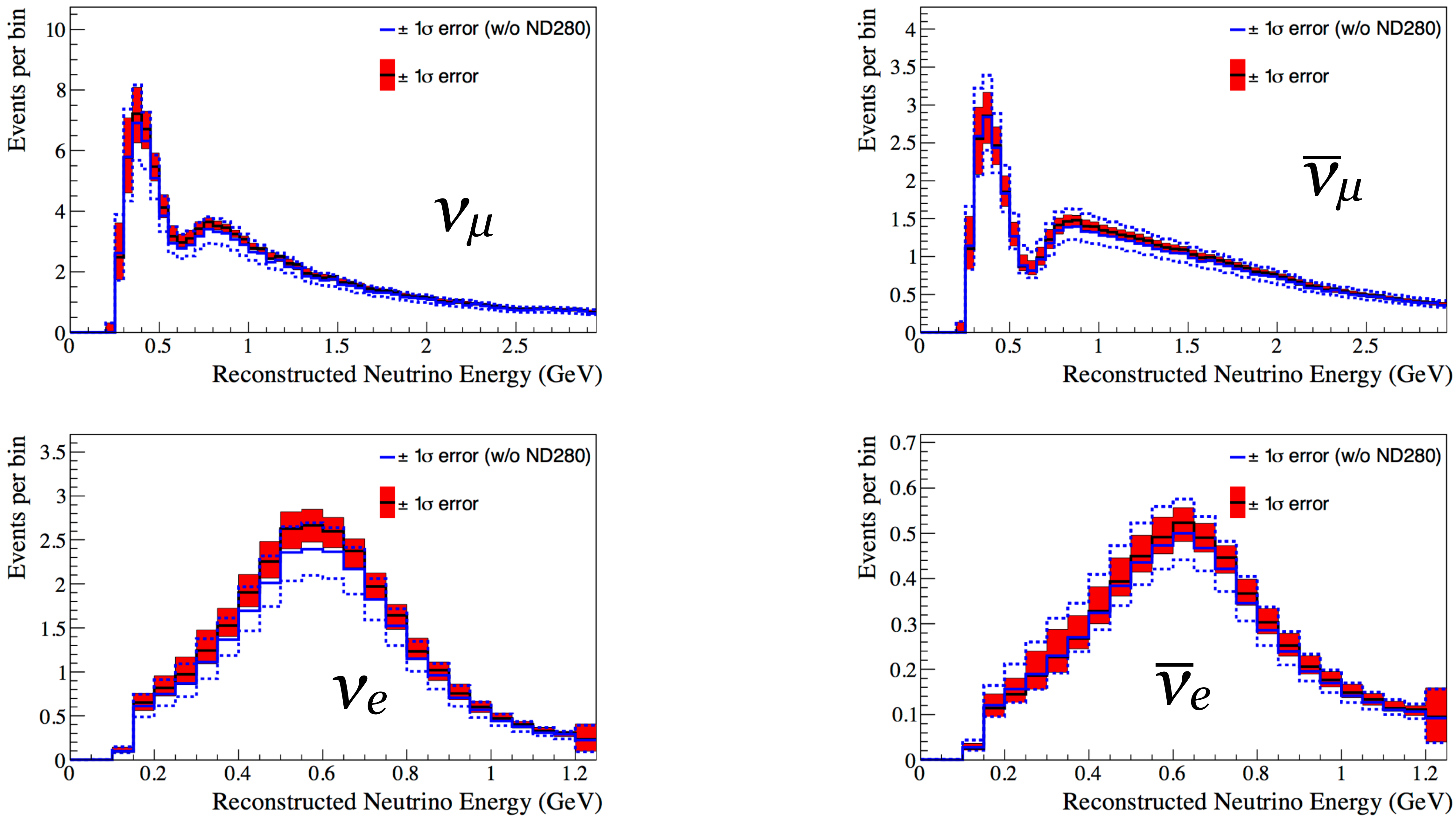
ν_e / $\bar{\nu}_e$ predicted spectra at Far Detector

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



- 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} only

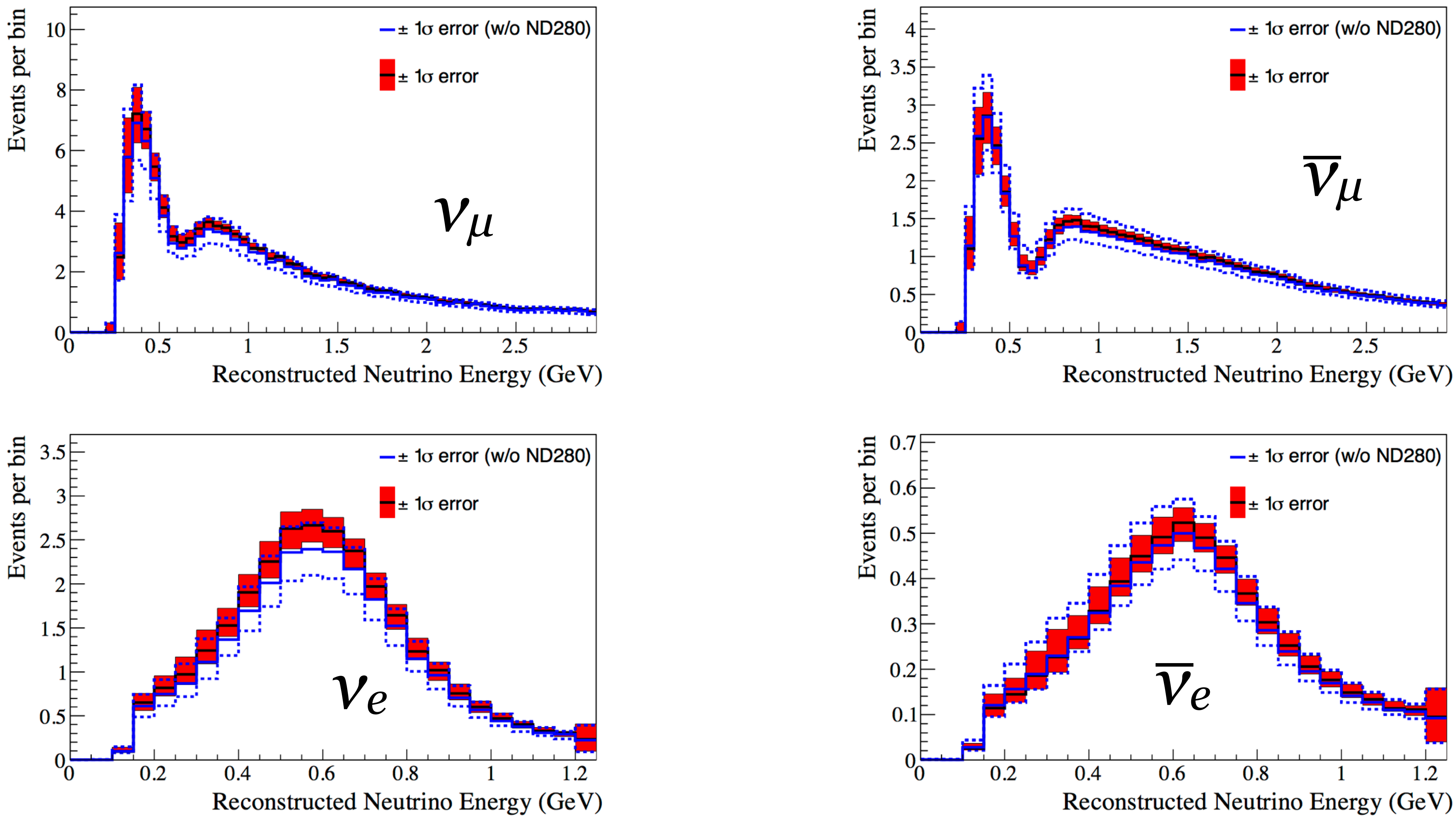
Impact of systematic uncertainties



Total $\delta N_{SK}/N_{SK}$			
Beam mode	**sample**	**w/o ND280**	**ND280**
neutrino	**μ-like**	**12.0%**	**5.0%**
neutrino	**e-like**	**11.9%**	**5.4%**
antineutrino	**μ-like**	**12.5%**	**5.2%**
antineutrino	**e-like**	**13.7%**	**6.2%**

- Improvement given by measurements with ND280 data
- Low energy: mainly NC, not measured by ND280

Impact of systematic uncertainties



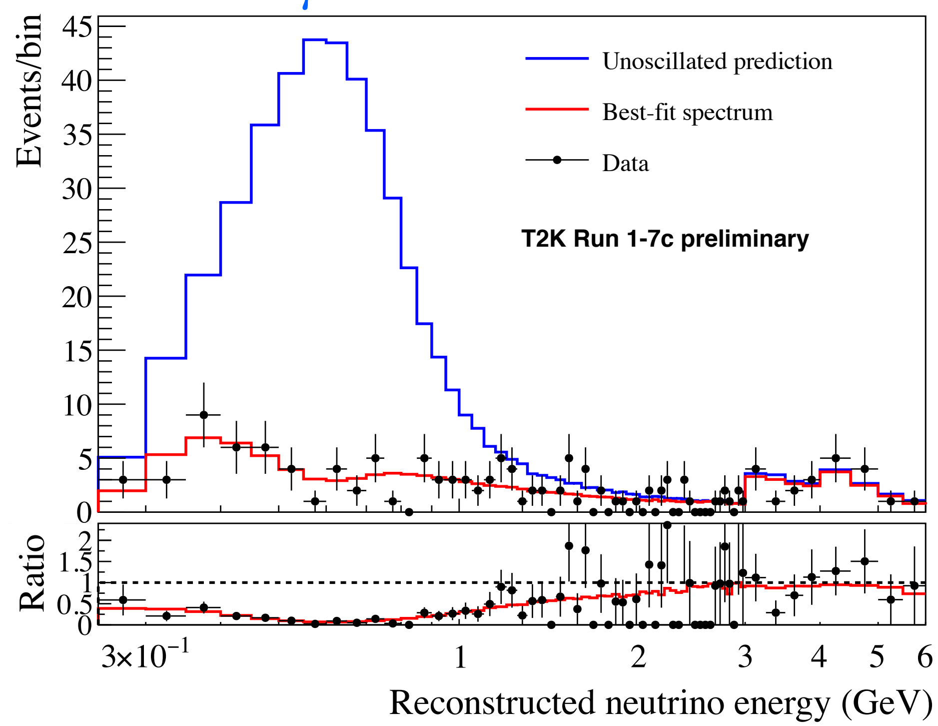
Total $\delta N_{SK}/N_{SK}$			
Beam mode	**sample**	**w/o ND280**	**ND280**
neutrino	μ-like	12.0%	5.0%
neutrino	e-like	11.9%	5.4%
antineutrino	μ-like	12.5%	5.2%
antineutrino	e-like	13.7%	6.2%

- Improvement given by measurements with ND280 data
- Low energy: mainly NC, not measured by ND280

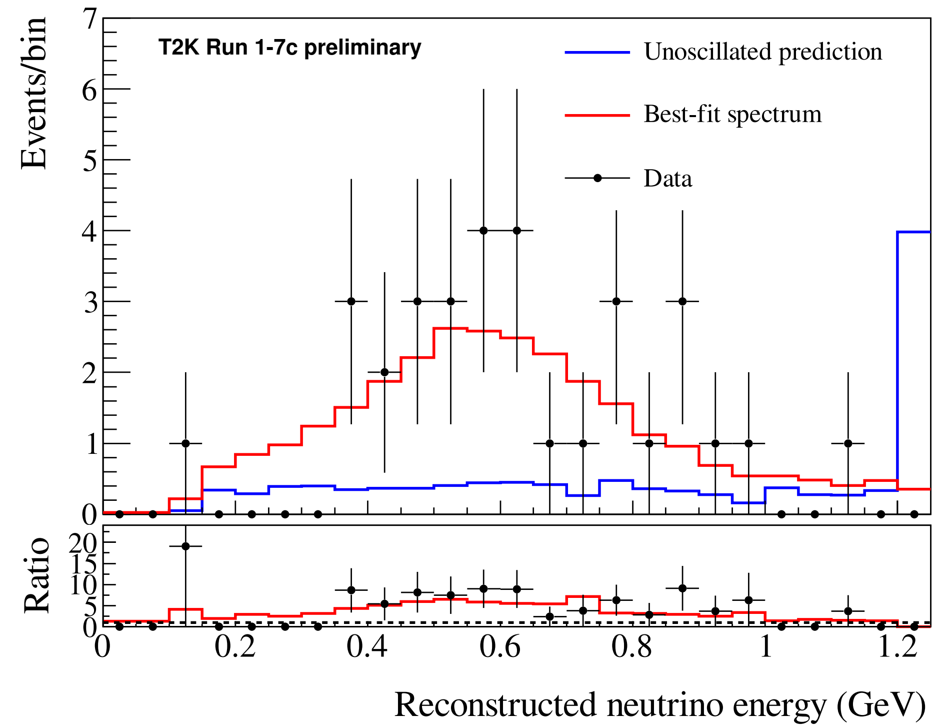
Joint neutrino and antineutrino analysis

- Joint analysis of all 4 samples at the far detector
- Both frequentist and fully bayesian analyses

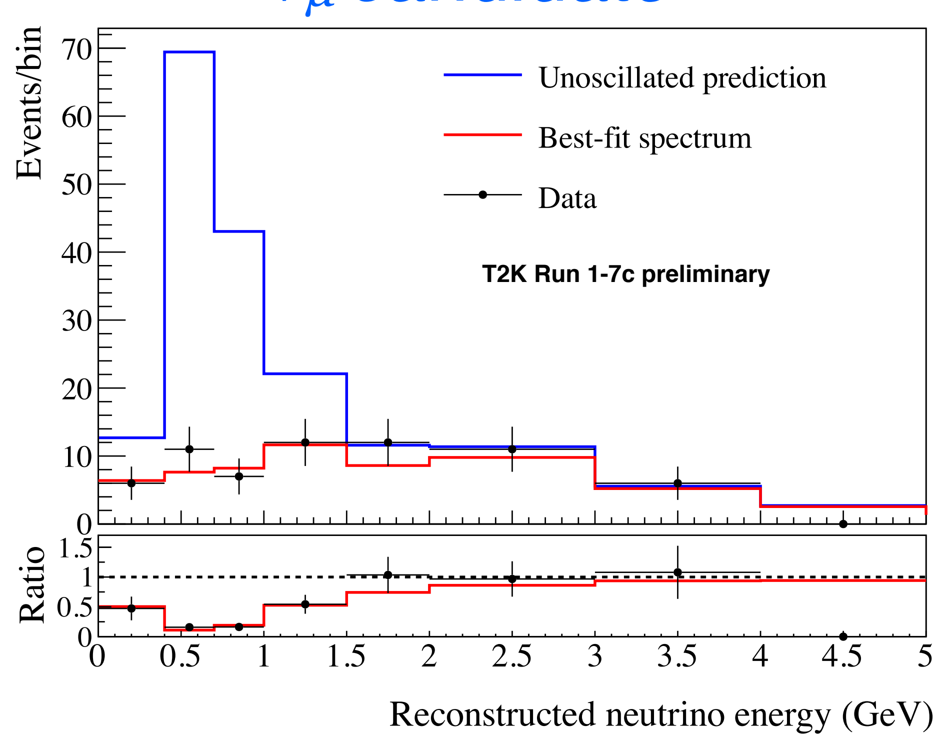
ν_μ candidate



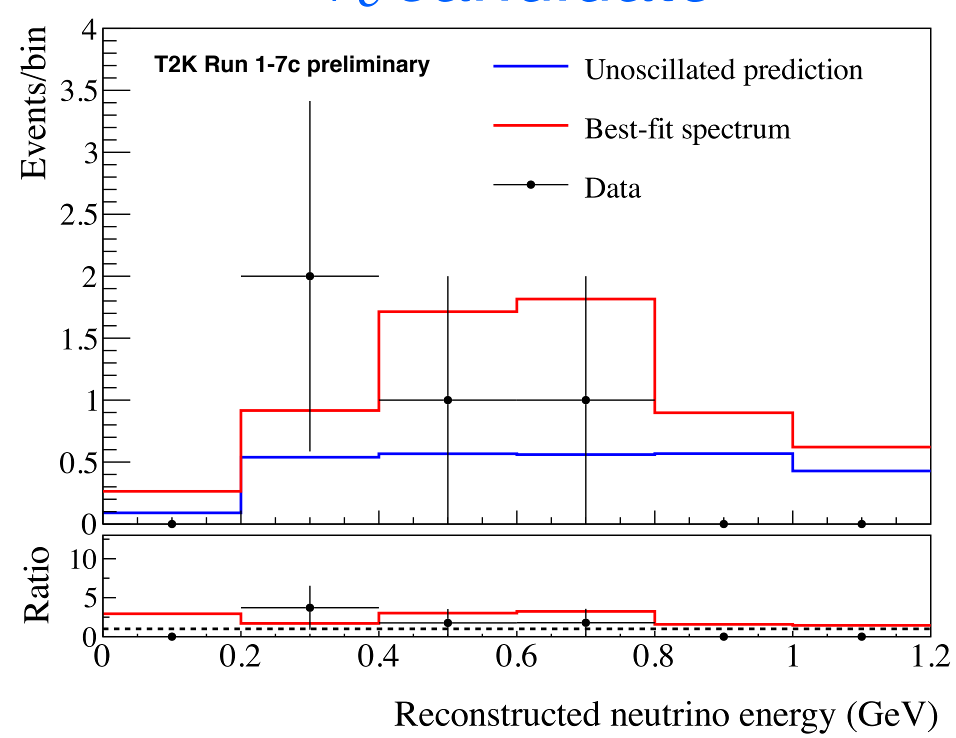
ν_e candidate



$\bar{\nu}_\mu$ candidate



$\bar{\nu}_e$ candidate



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

- In PMNS framework $P(\nu_\mu \rightarrow \nu_x) = P(\overline{\nu}_\mu \rightarrow \overline{\nu}_x)$ 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

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

- ~7.5x10[20] POT antineutrino (~3.5x10[20] POT more wrt 2015 analysis):
  - joint neutrino / antineutrino (muon (anti)neutrino samples)

ν: $\sin^2\Theta_{23}$ $|\Delta m^2_{32}|$

Vs

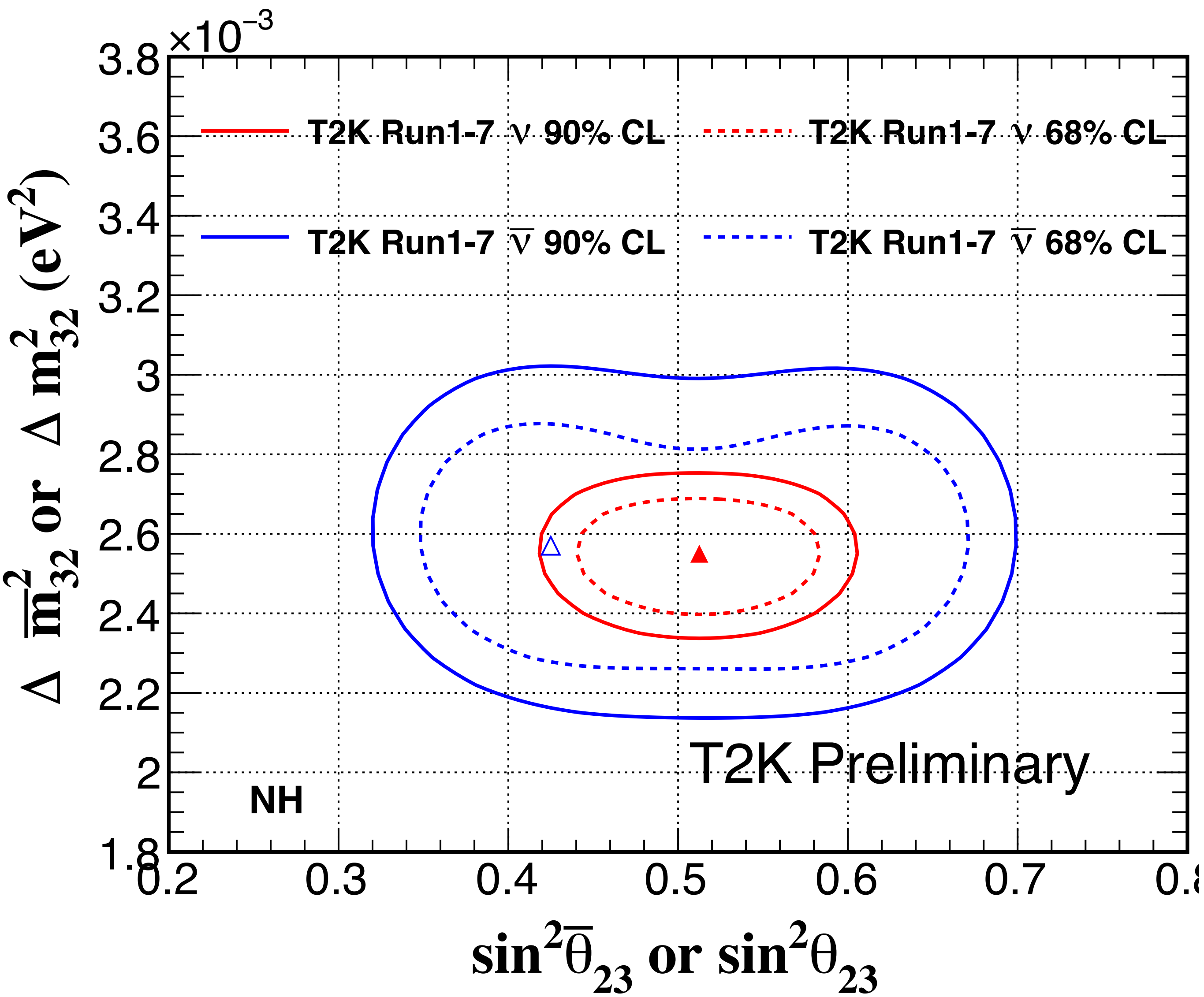
$\overline{\nu}$: $\sin^2\overline{\Theta}_{23}$ $|\Delta\overline{m}^2_{32}|$

Constrain other oscillation parameters with PDG 2015 and fix δ_{CP}=0

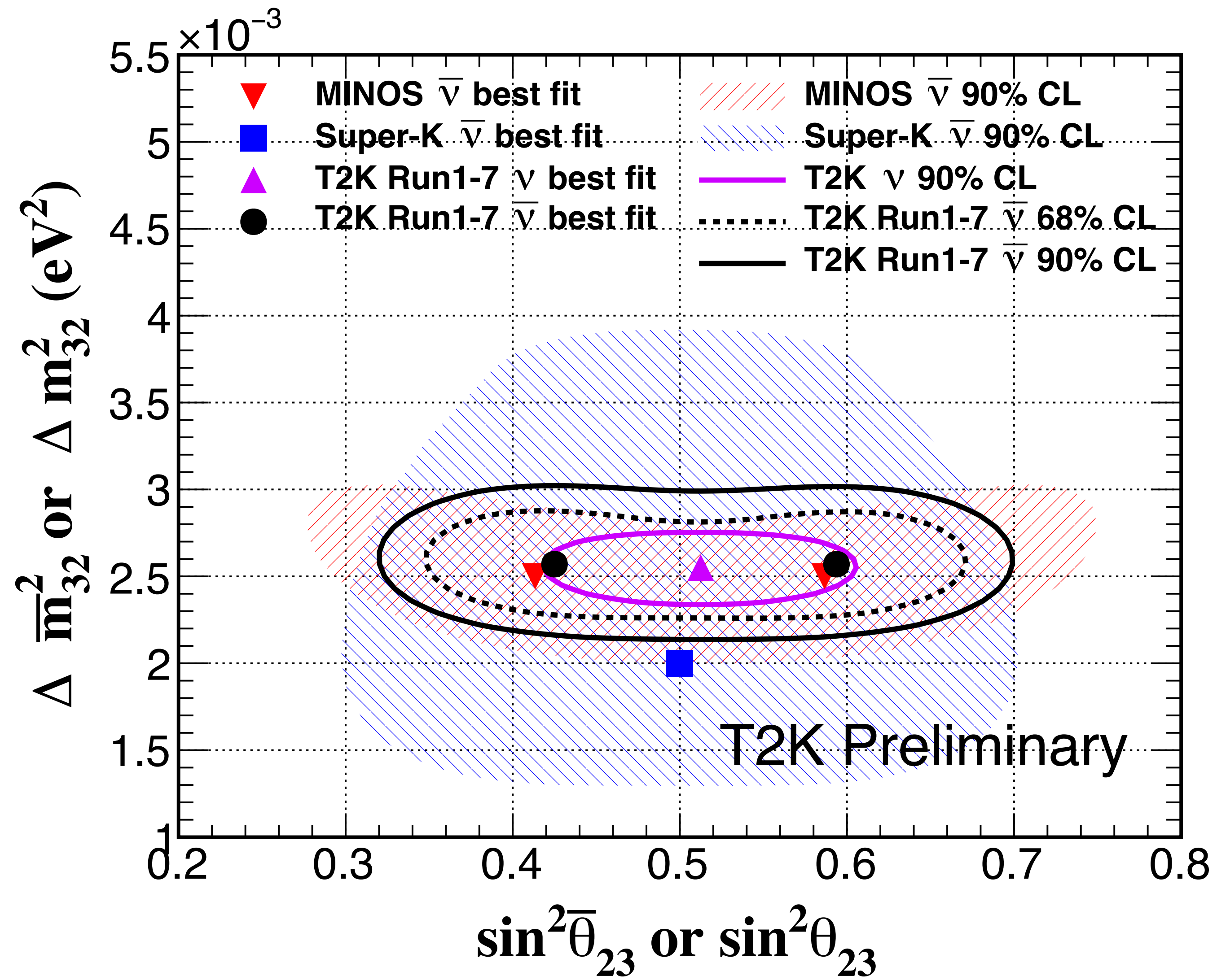
Beam mode	Expected Not Osc.	Observed
neutrino	521.8	135
antineutrino	184.8	66

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

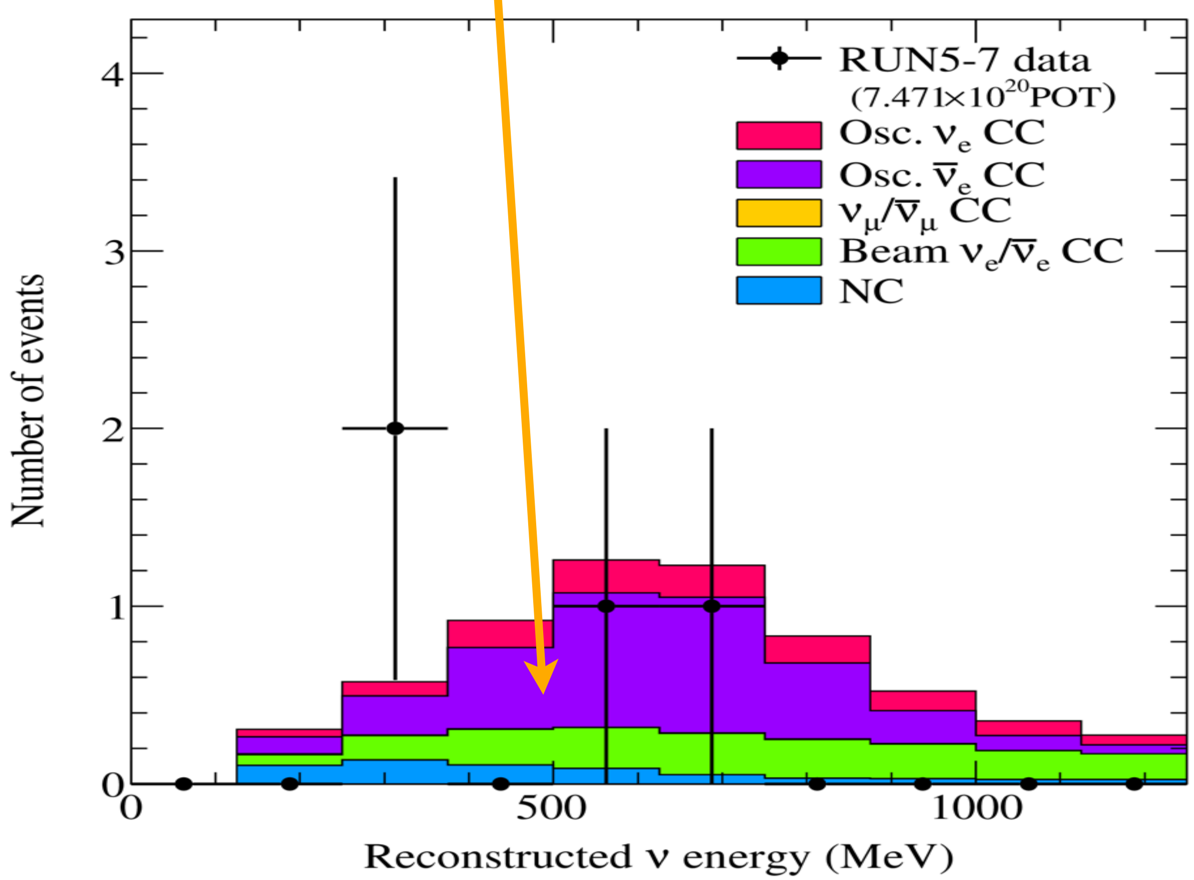
Updated $\overline{\nu}_e$ appearance results

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

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

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

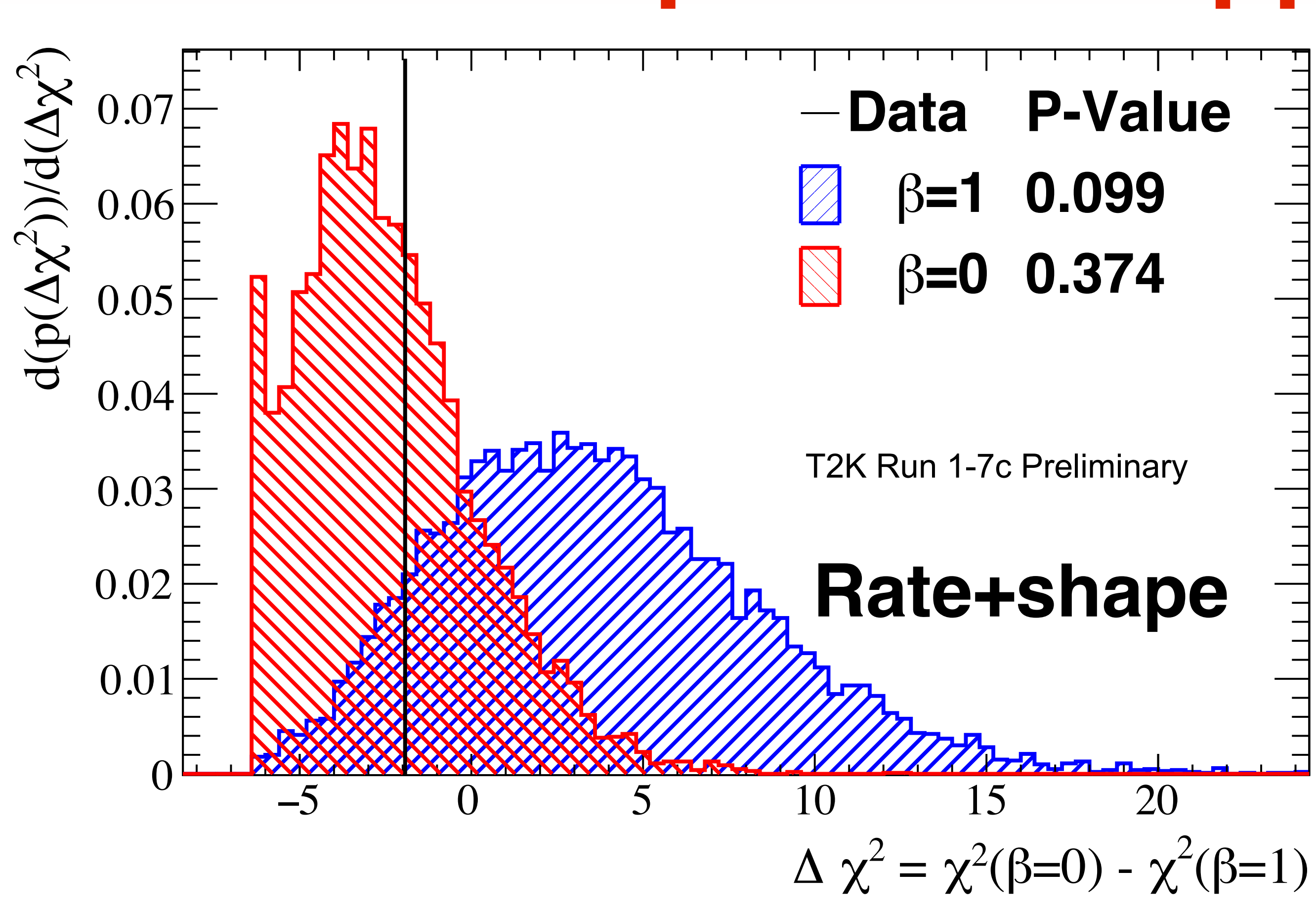


- Fit all 4 far detector samples to fully constrain the oscillation probability
- ~20% of wrong sign background ($\nu_\mu \rightarrow \nu_e$)
- Constrain $\sin^2\Theta_{13}$ with reactor measurements

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

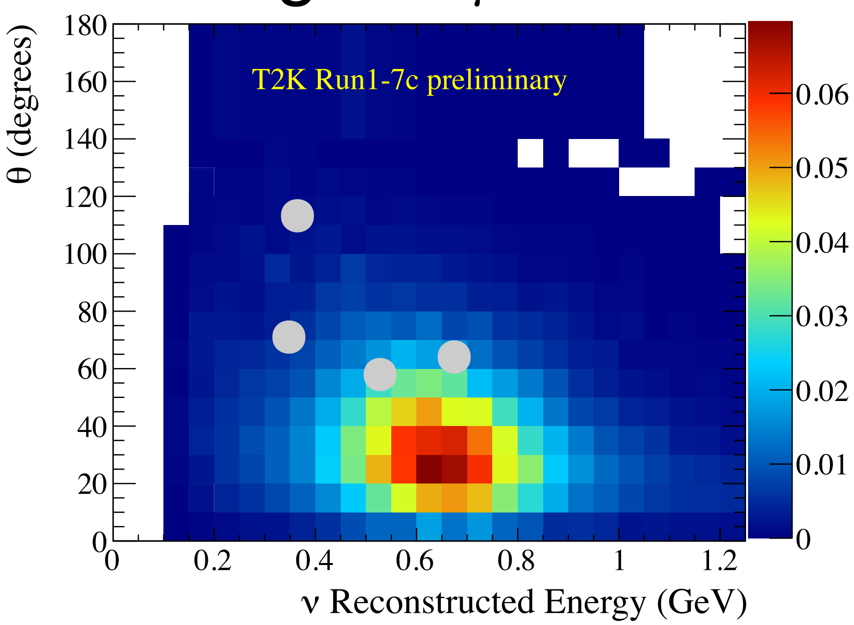
Updated $\overline{\nu}_e$ appearance results



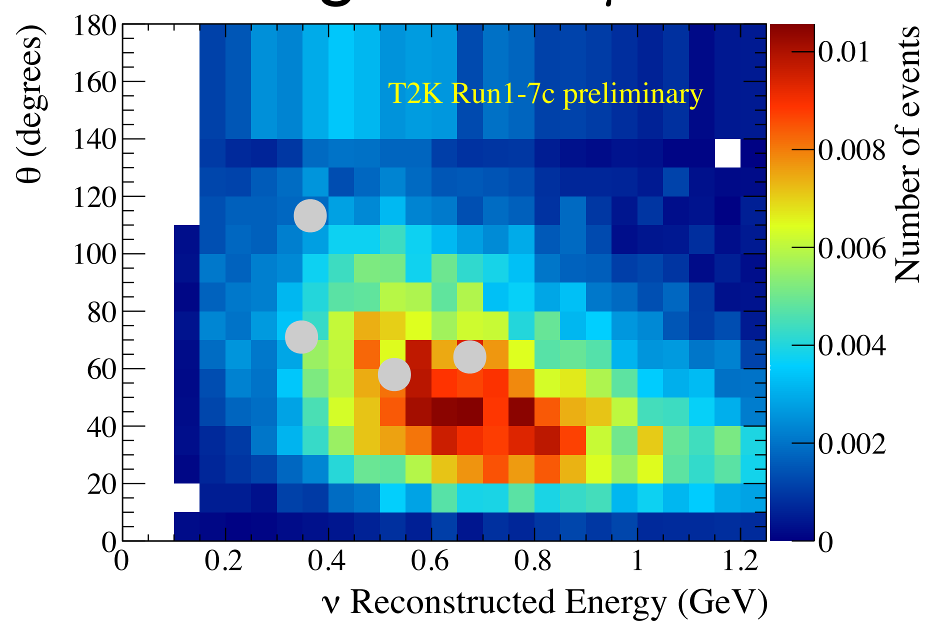
Likelihood ratio: L(β=0) / L(β=1)

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

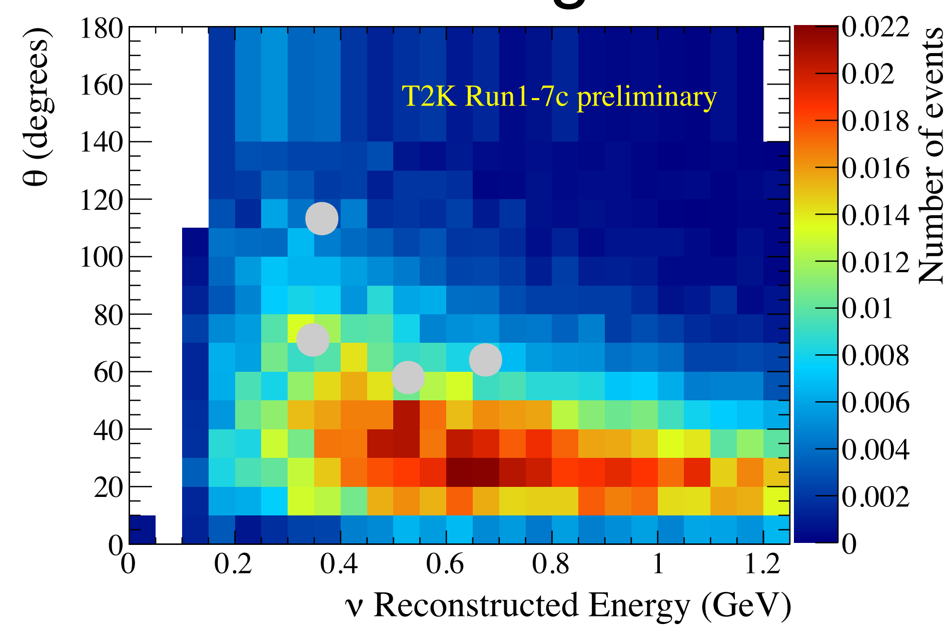
Signal $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



Background $\nu_\mu \rightarrow \nu_e$



Other Background



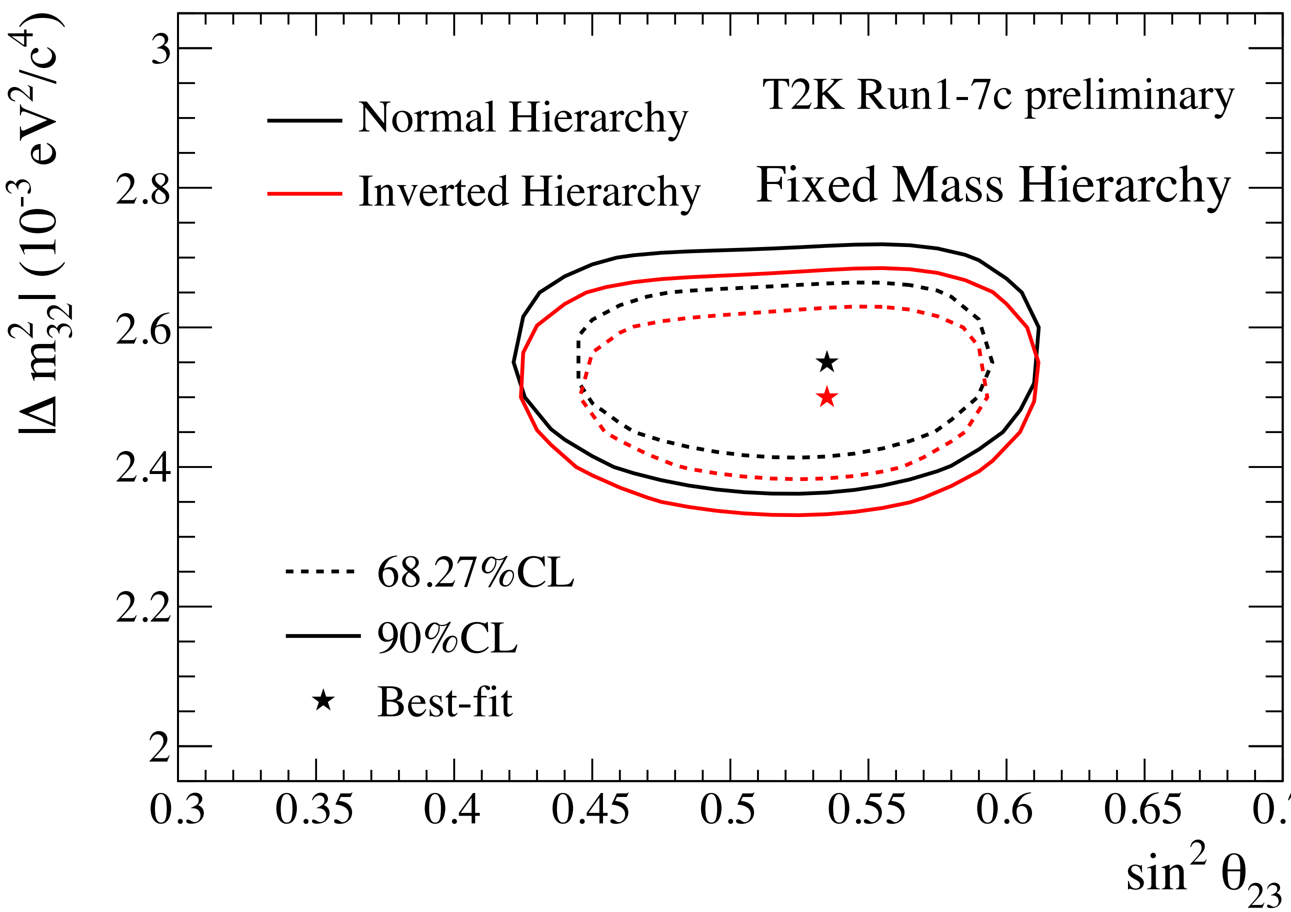
- No evidence of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with new full data set
- Shape of the spectra look more consistent with background

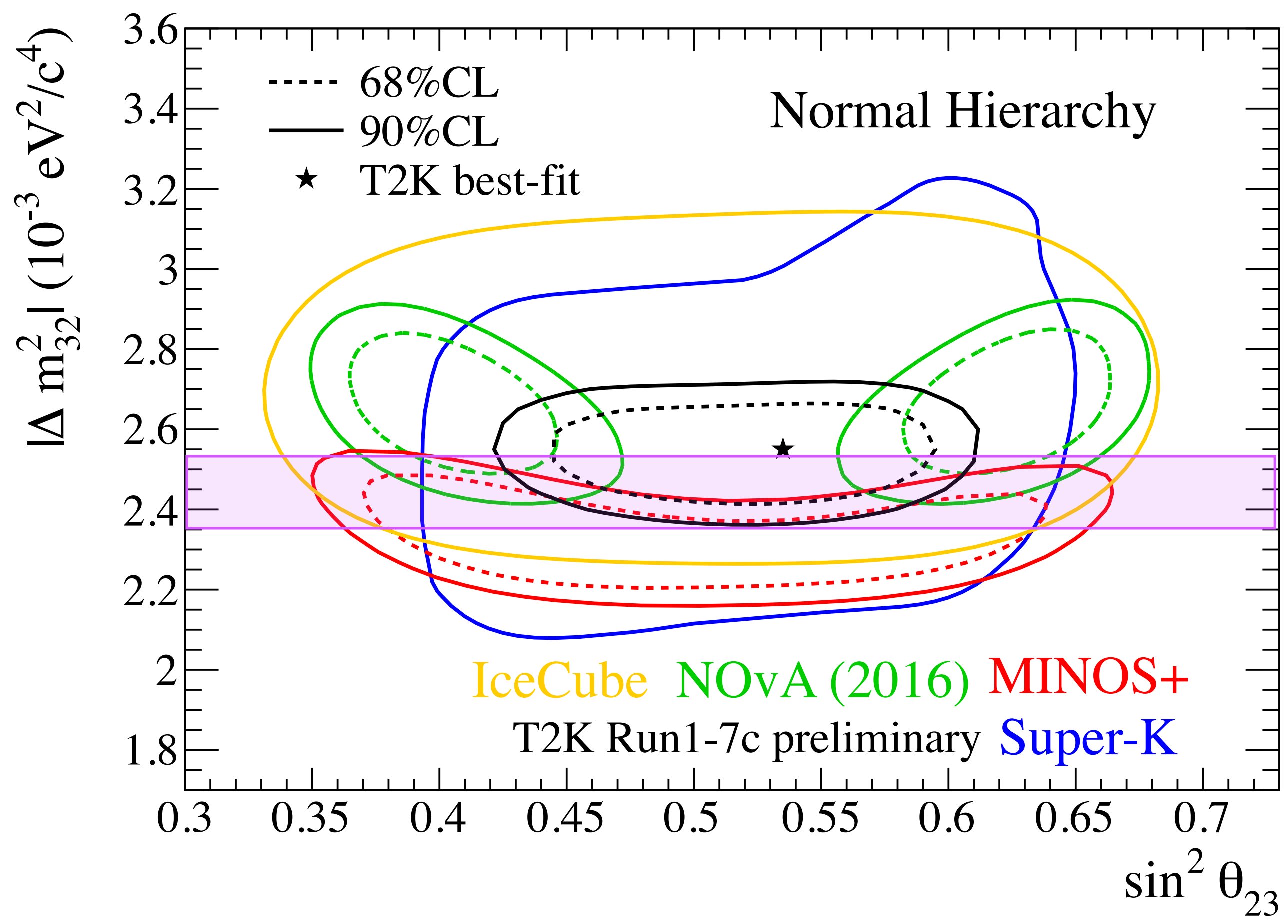
Confidence intervals $\sin^2\Theta_{23}$ and Δm^2_{32}

- Measurement of $\sin^2\Theta_{23}$ 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}



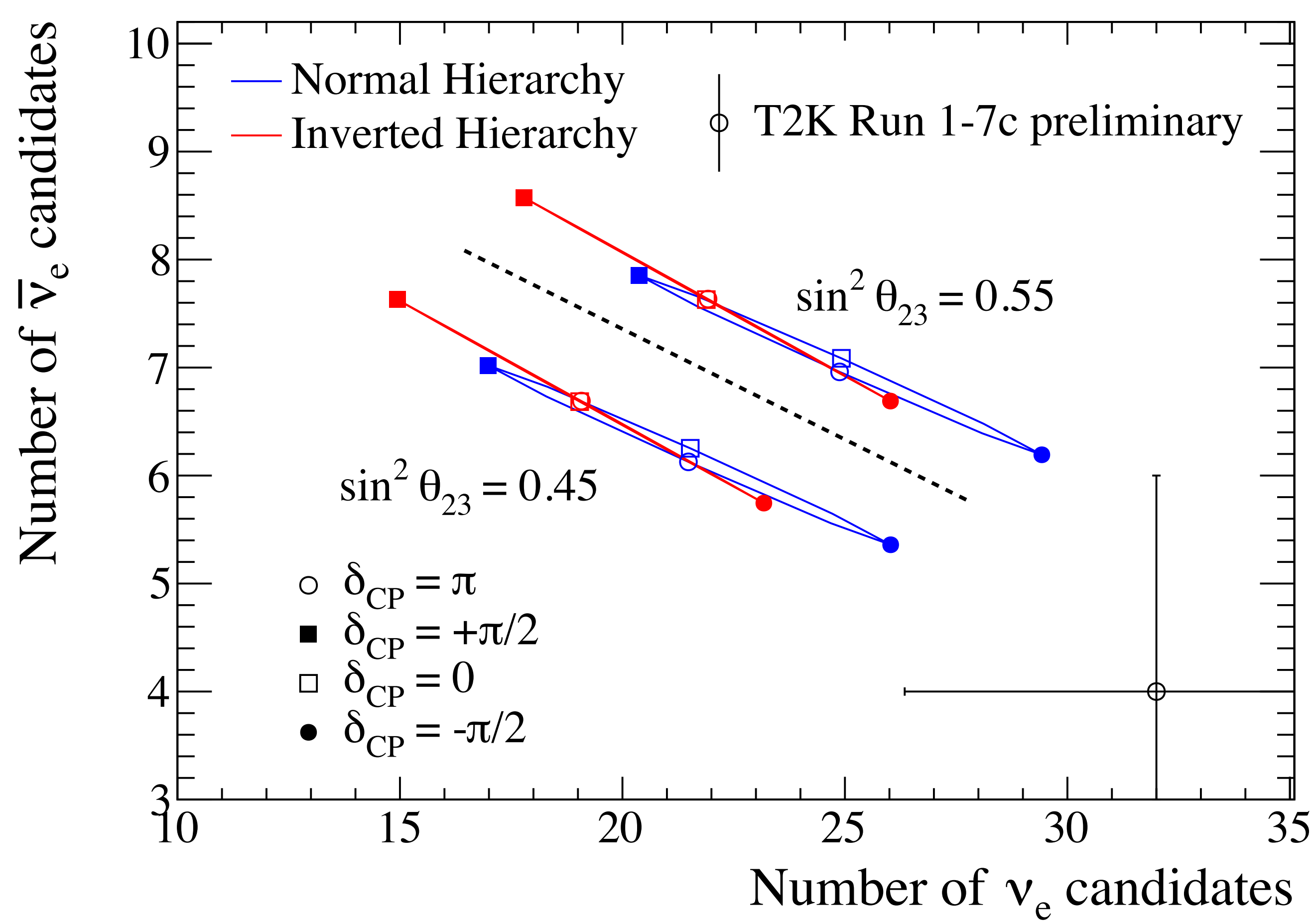


- T2K data consistent with maximal mixing as in past analysis results
- All the experiments show agreement

Best-fit	NH	IH
$\sin^2\theta_{23}$	0.532	0.534
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.545	2.510

Predicted vs observed # of events

- Compare the observed # of ν_e and $\overline{\nu}_e$ 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
- $\nu_\mu \rightarrow \nu_e$
- $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

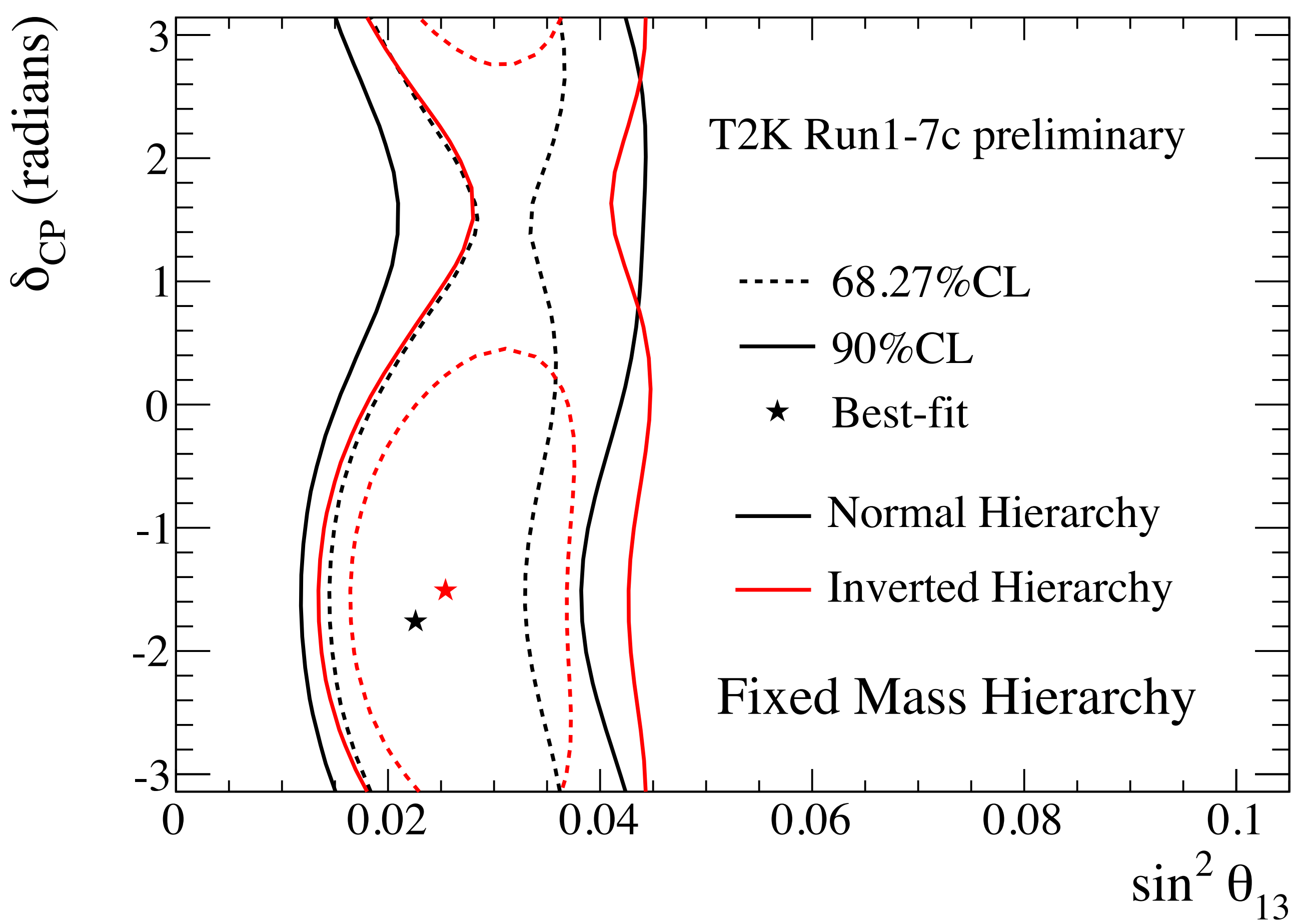
Assumption for oscillation parameters:
$|\Delta m^2_{32}|$ = 2.509 x 10^{-3}eV^2
$\sin^2\Theta_{13}$ = 0.0217 (PDG2015)

- 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 $\overline{\nu}_e$ candidates than predicted

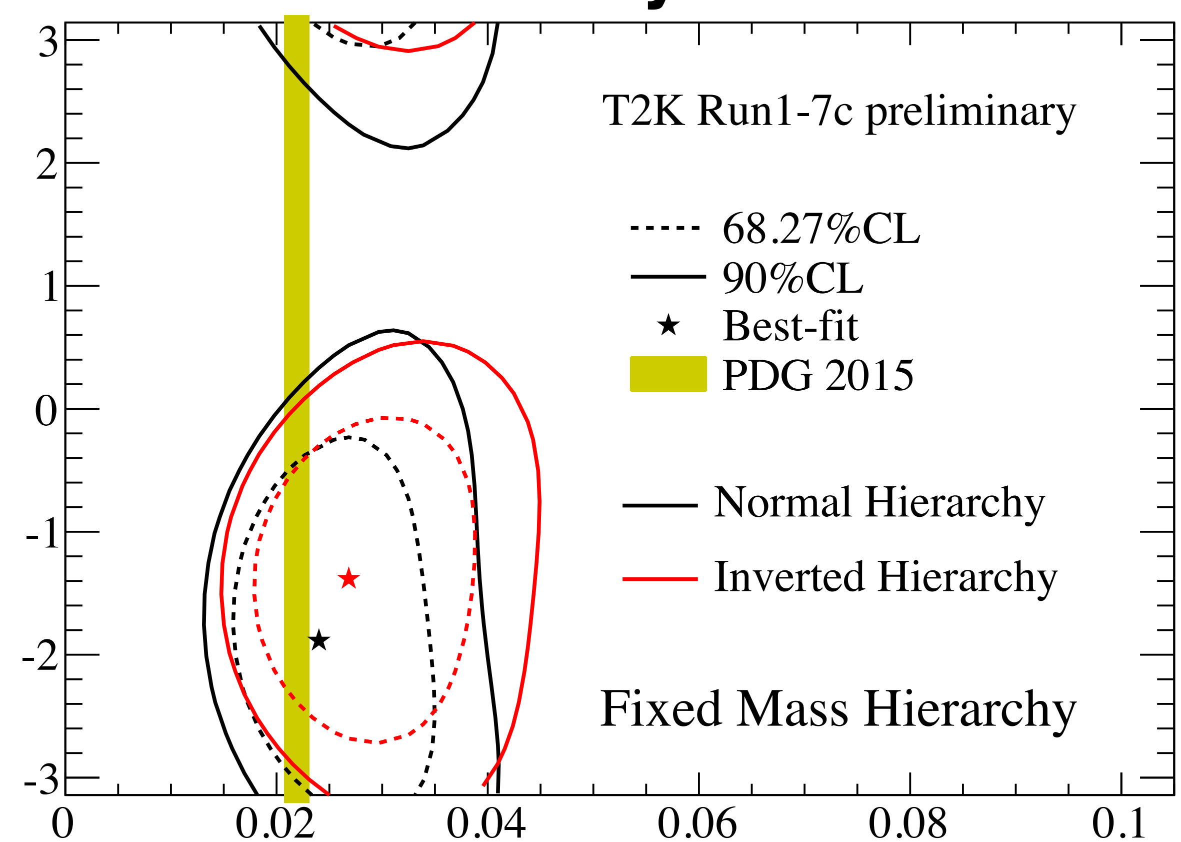
Confidence intervals $\sin^2\Theta_{13}$ and δ_{CP}

- 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

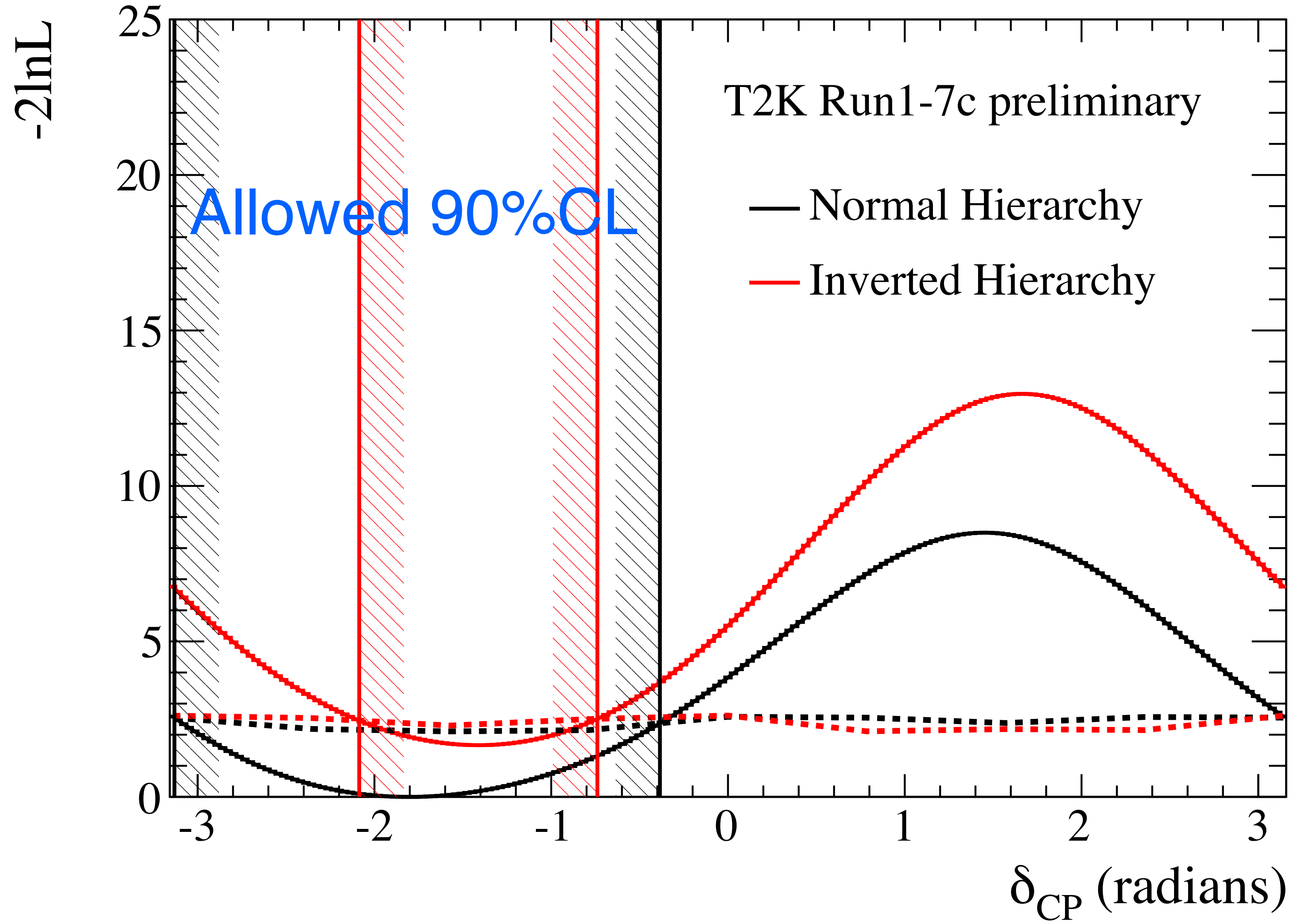


$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

- 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)



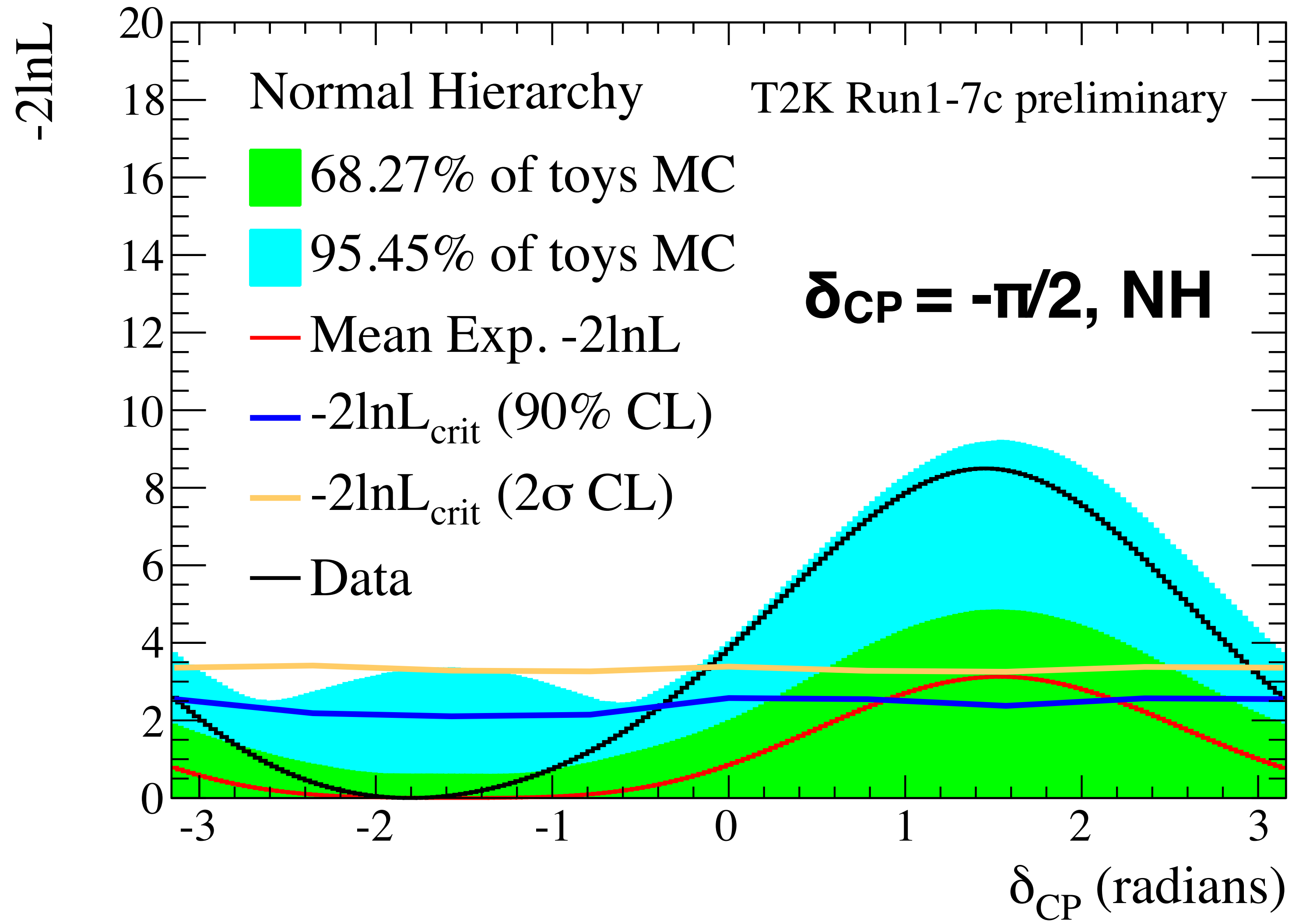
Reactors' constraint:
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$
(PDG 2015)

- Best-fit: δ_{CP} = -1.885, Normal Hierarchy
- $\delta_{CP} = 0$ is excluded at 2σ CL while $\delta_{CP} = \pi$ is excluded at 90% CL
- Allowed 90% CL region: - Normal Hierarchy: [-3.13,0.39]
  - Inverted Hierarchy: [-2.09,-0.74]

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 9.2%
  - probability to exclude $\delta_{CP}=\pi$ at 90%CL is 17.3%

Bayesian posterior probabilities

- Credible intervals using flat prior for δ_{CP}
- Mass hierarchy is marginalised
- Use momentum - lepton angle as templates

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

T2K only

T2K Run1-7c preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.19	0.22	0.40
Normal hierarchy	0.27	0.33	0.60
Column total	0.45	0.55	1

T2K + reactors

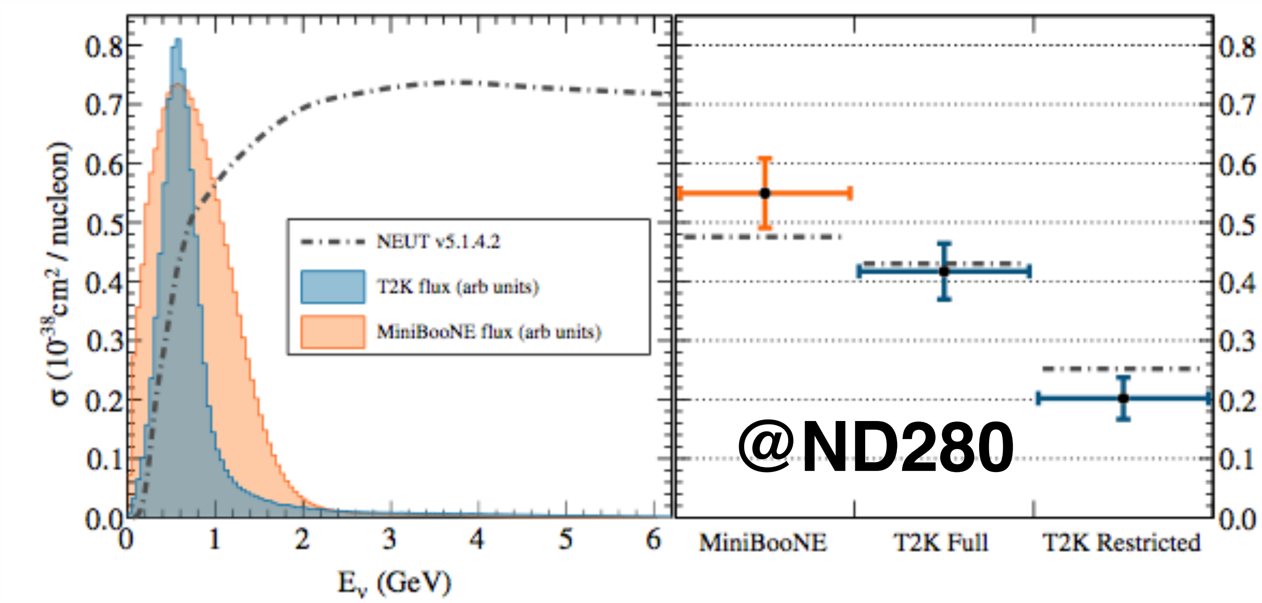
T2K Run1-7c preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Inverted hierarchy	0.10	0.14	0.25
Normal hierarchy	0.29	0.46	0.75
Column total	0.39	0.61	1

- Weak preference for Normal Hierarchy and $\Theta_{23} > \pi/4$

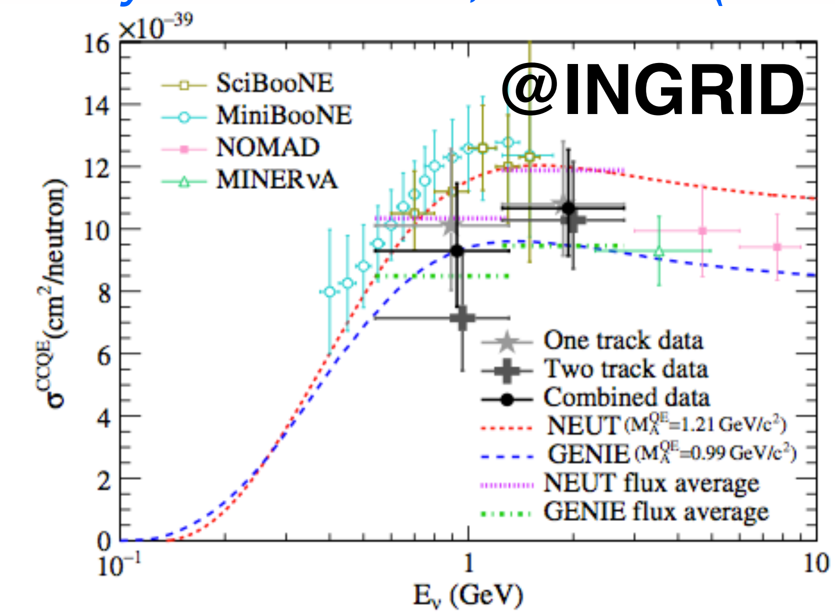
Neutrino cross-section results

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

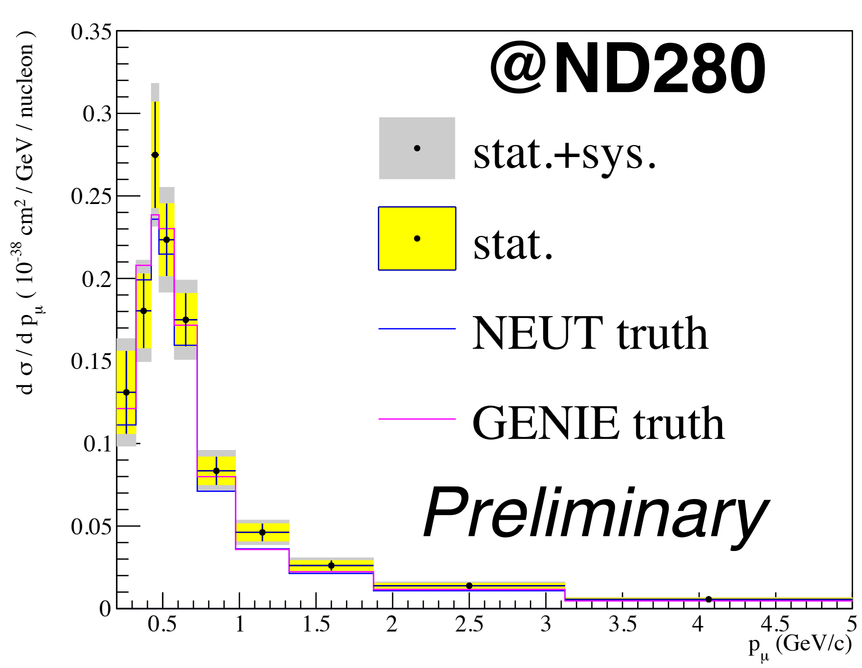
Phys. Rev. D 93, 112012 (2016)



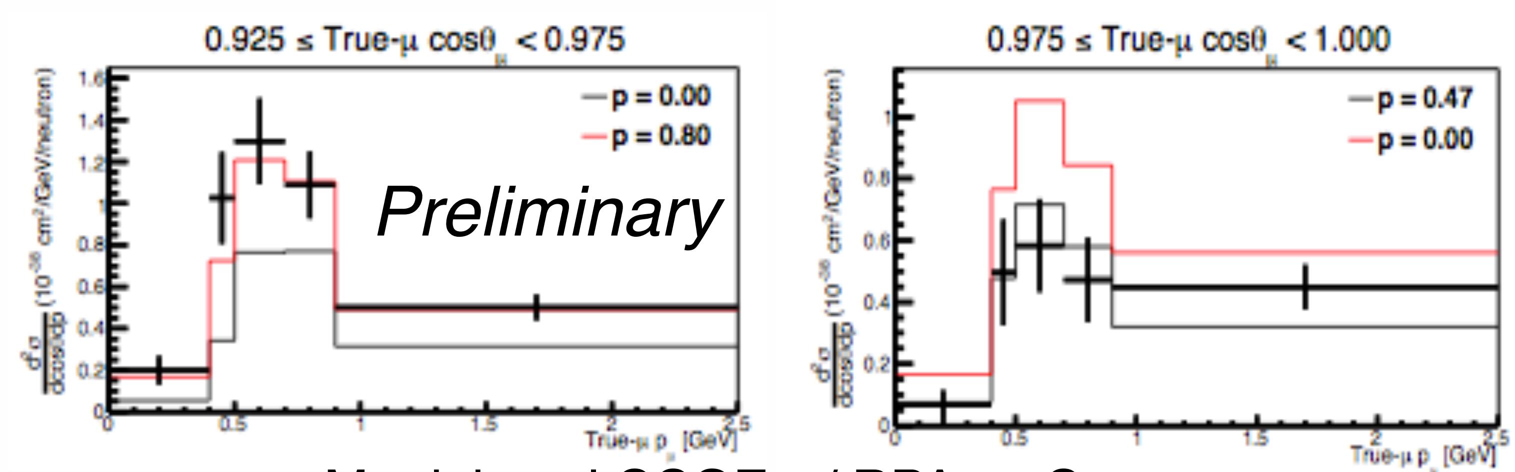
Phys. Rev. D 91, 112002 (2015)



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

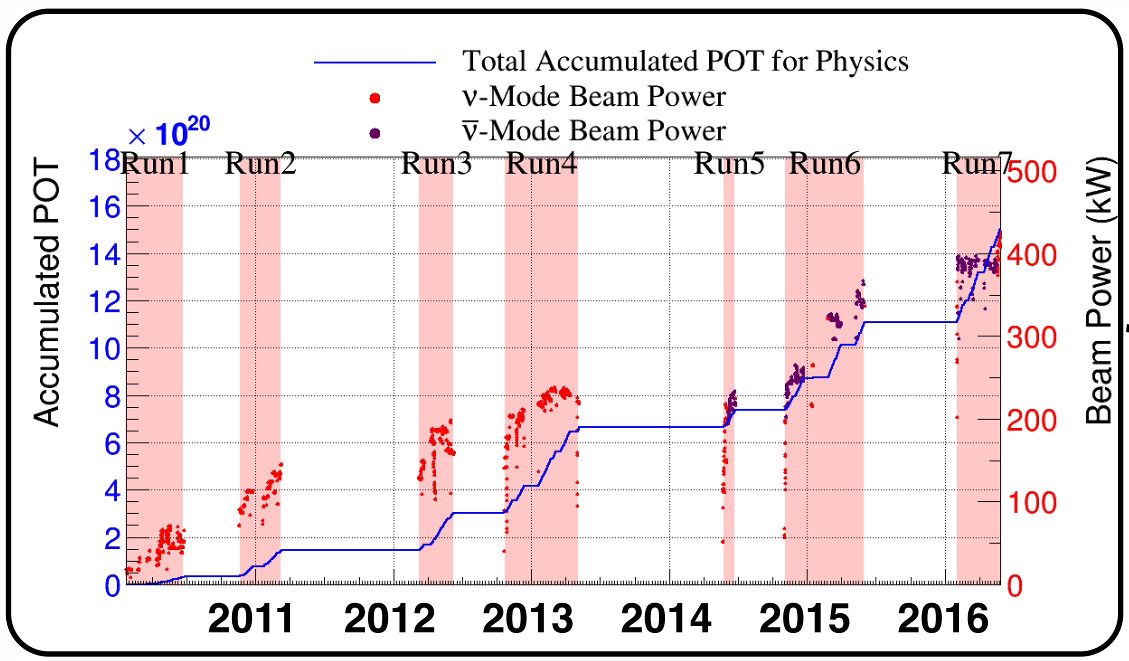
Many other results will be released soon...

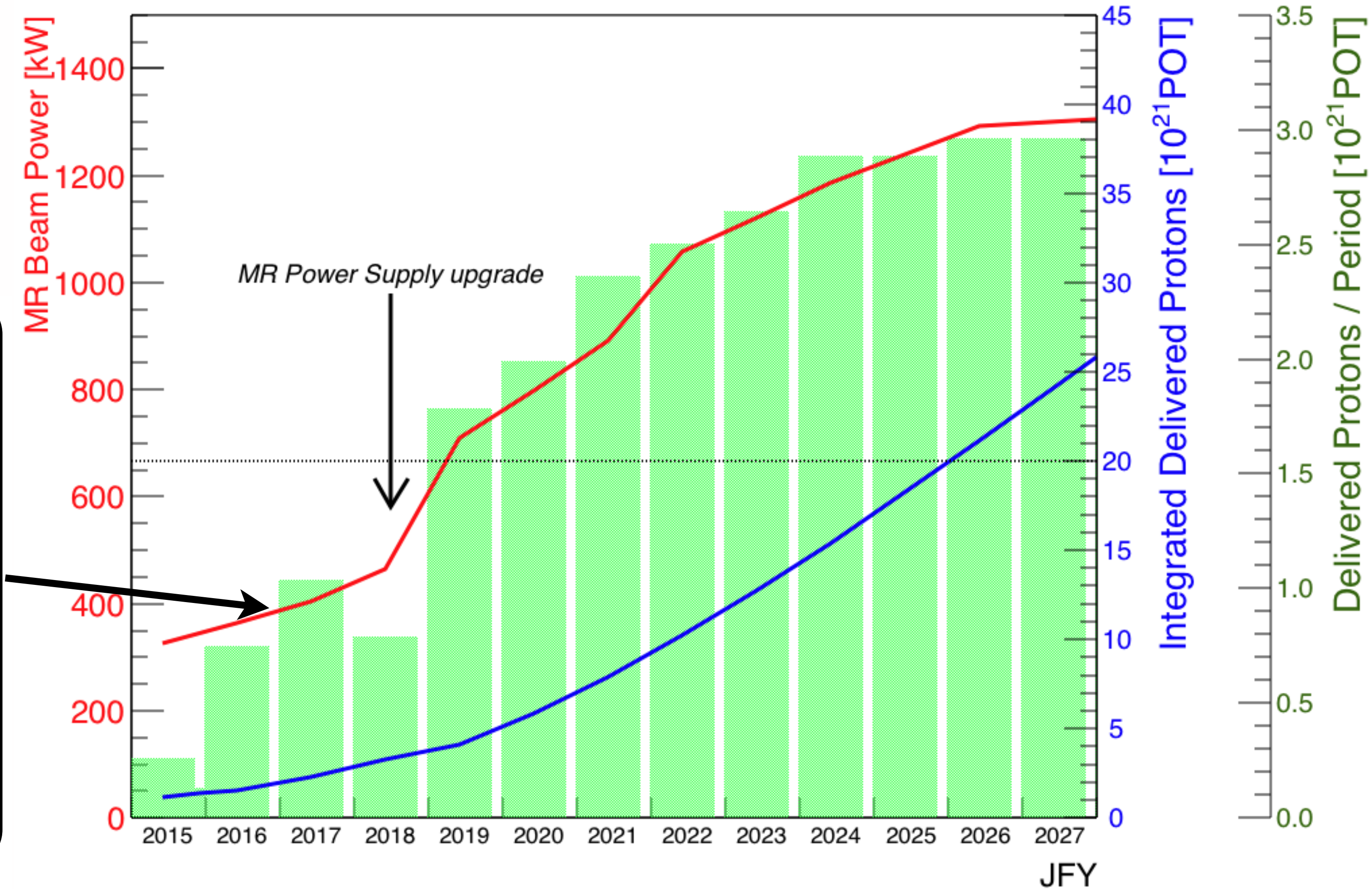
Prospects for the future: T2K-II

- 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

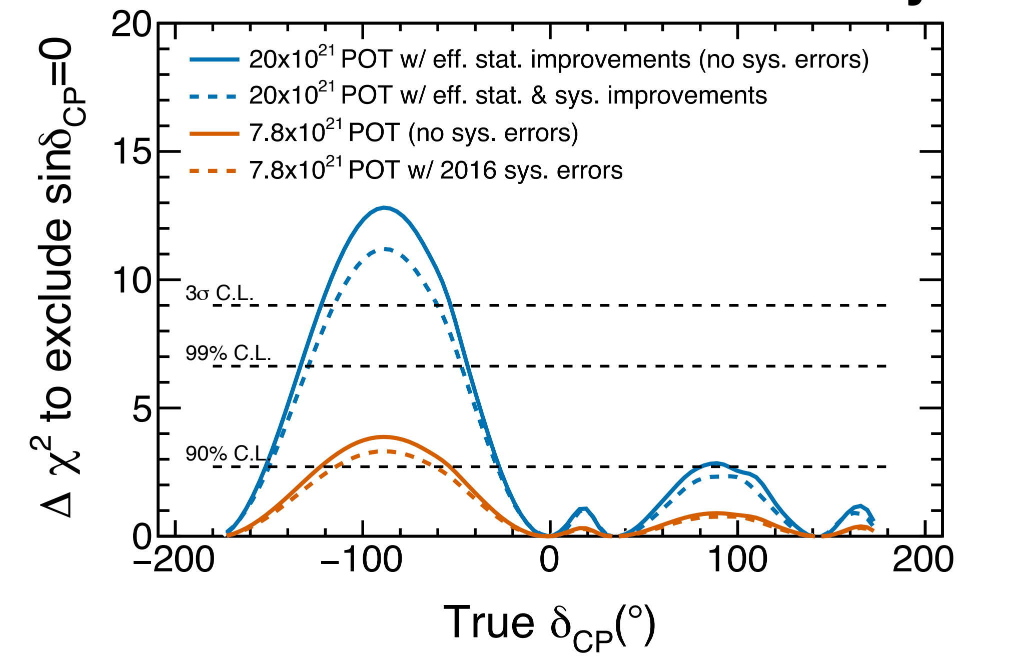
TODAY



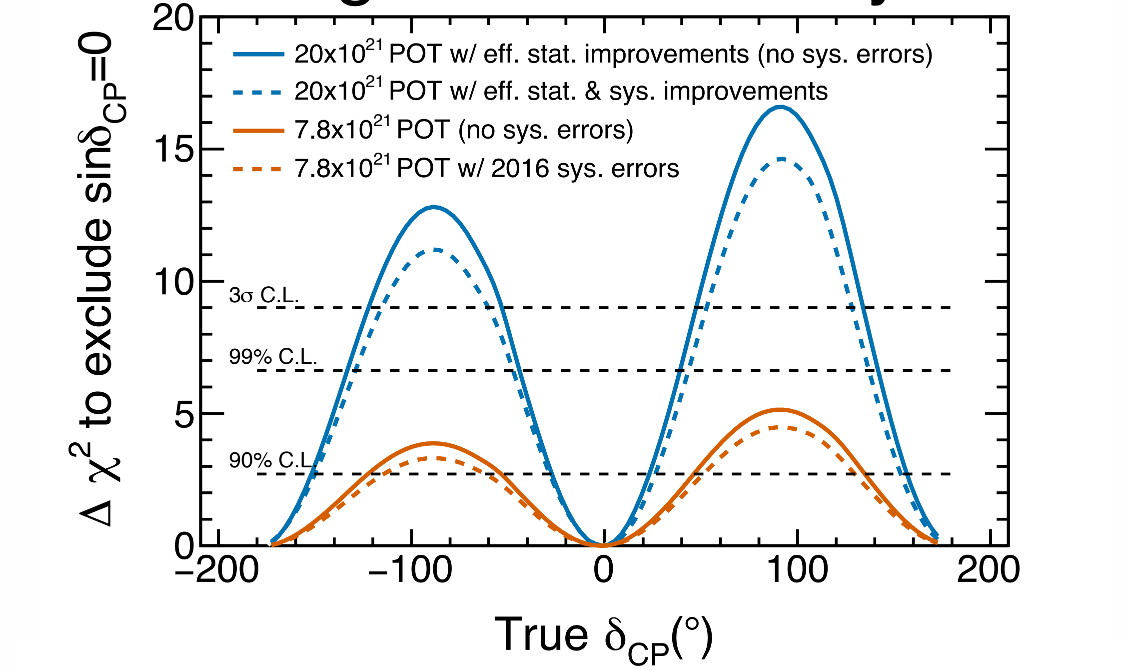


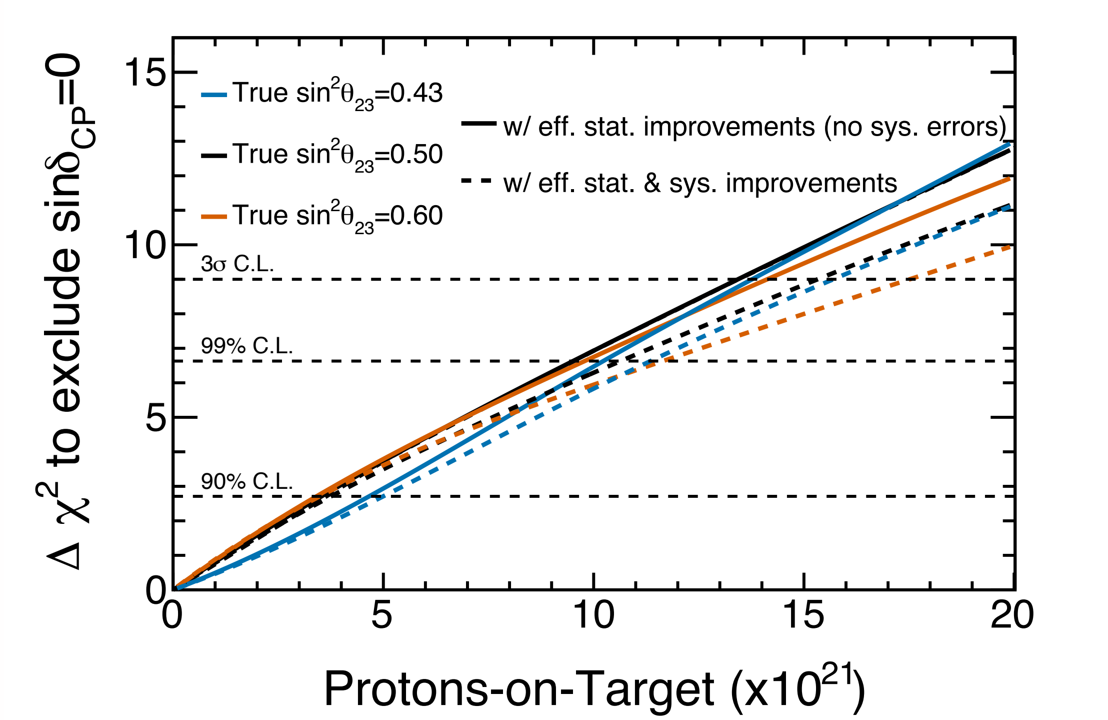
Prospects for the future: T2K-II

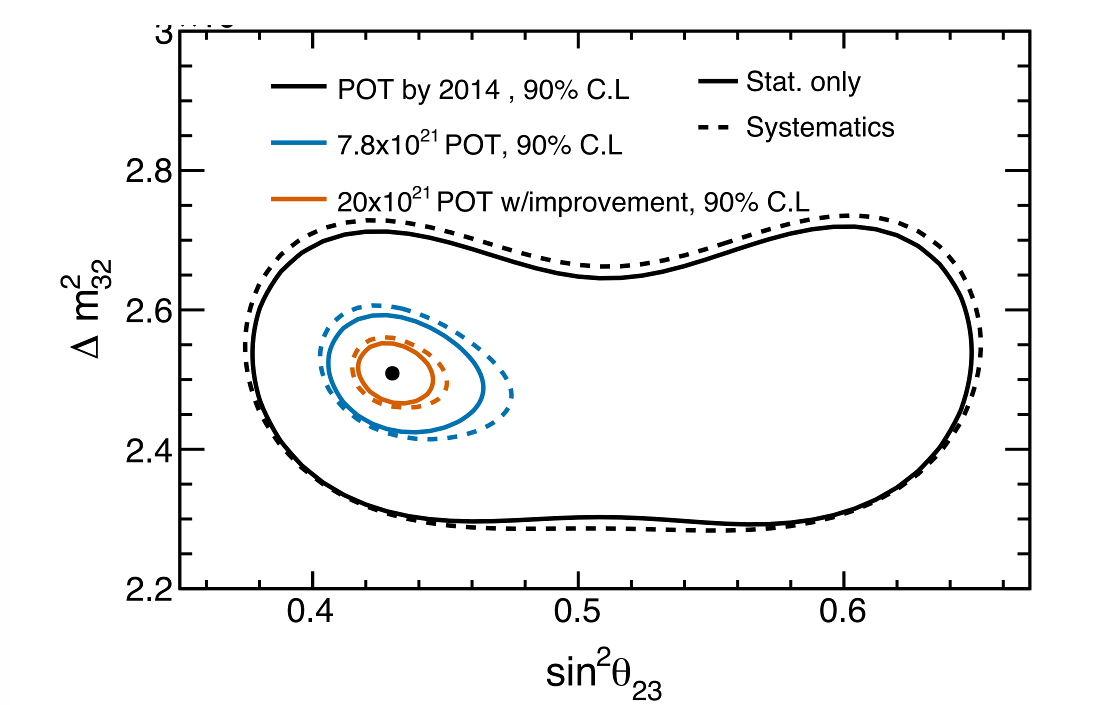
Unknown mass hierarchy



Assuming mass hierarchy known







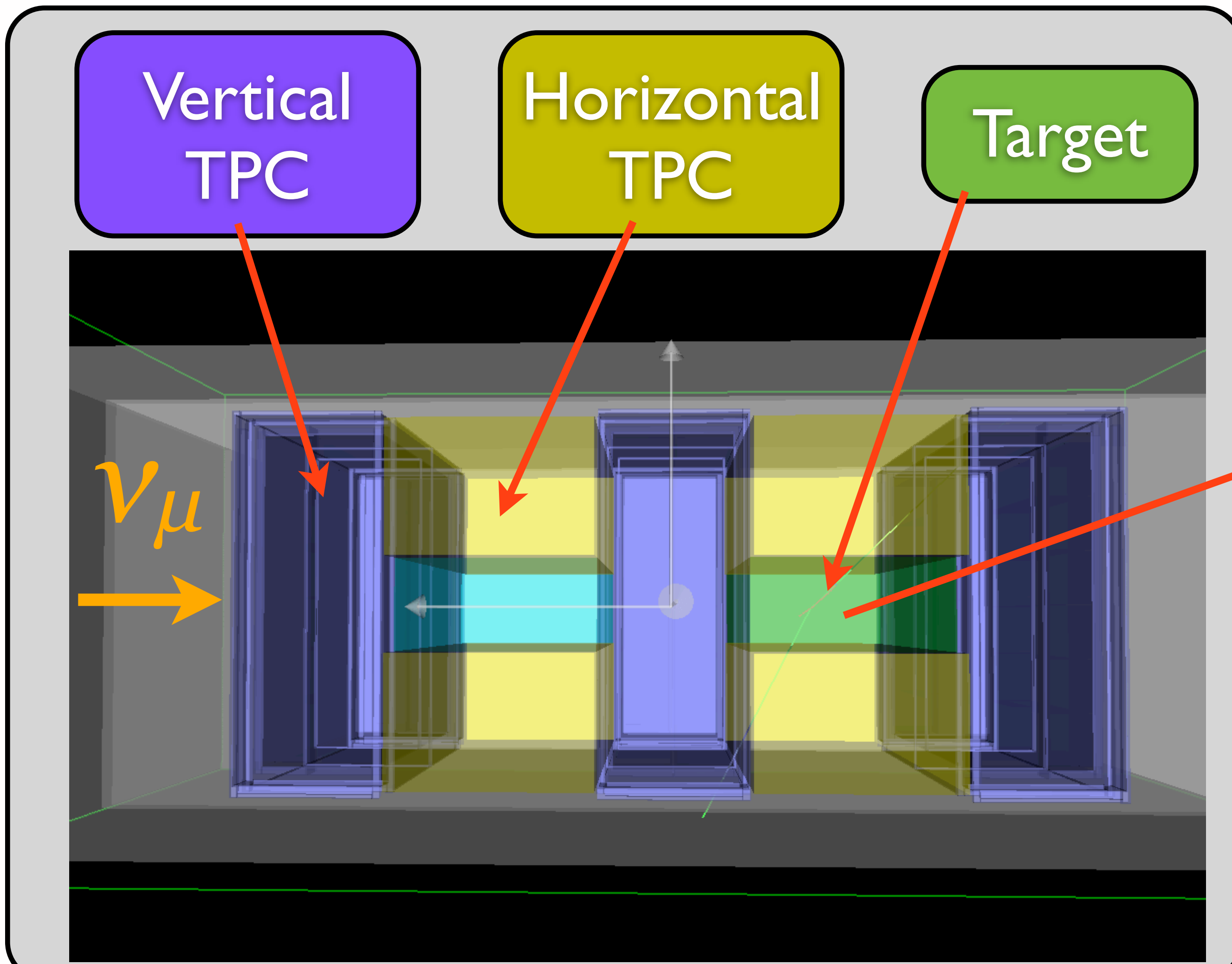
- Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \sim -\pi/2$ and NH
- Measure Θ_{23} with resolution of $\lesssim 1.7^\circ$
- Need to reduce the systematic uncertainties:
  ~18% (2011) → ~9% (2014) → ~6% (2016) → ~4% (2020) ???

Prospects for the future: near detector upgrade

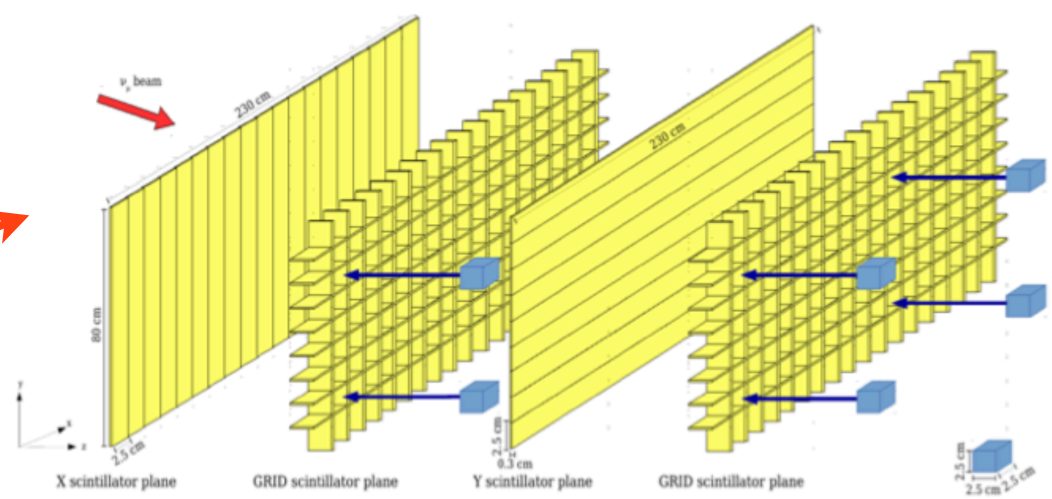
• Discussions within the collaboration about a possible upgrade of ND280 to reach the following goals:

- better efficiency for low momenta π and p
- 4π acceptance
- increase water target mass

It could be used as a magnetized detector for Hyper-Kamiokande



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



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

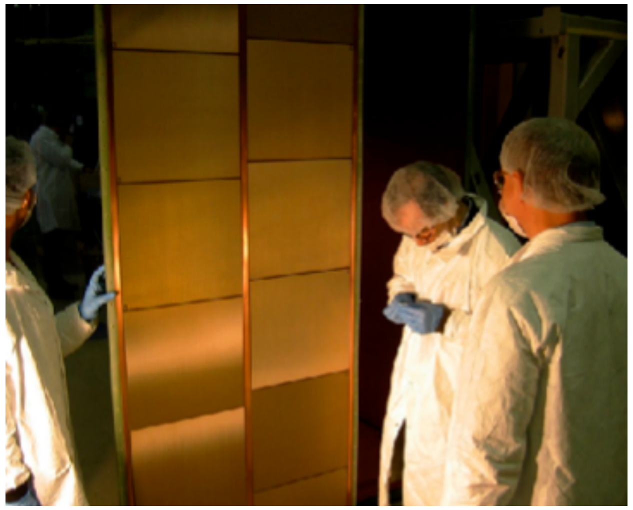
Plan to build new horizontal TPCs to detect high angle tracks

Synergy between CERN and T2K

T2K is a recognized experiment at CERN (RE13)

CERN contributions to T2K:

- UA1/NOMAD magnet
  - And infrastructure
- Production and testing of MicroMegas
  - TS/DEM group
- NA61/SHINE experiment
  - Hadron production measurements
- CERN-KEK cooperation on superconducting magnets
  - For neutrino beam line
- Test beams
  - For near detector components



We hope the synergy between CERN and T2K will continue in the future

Summary

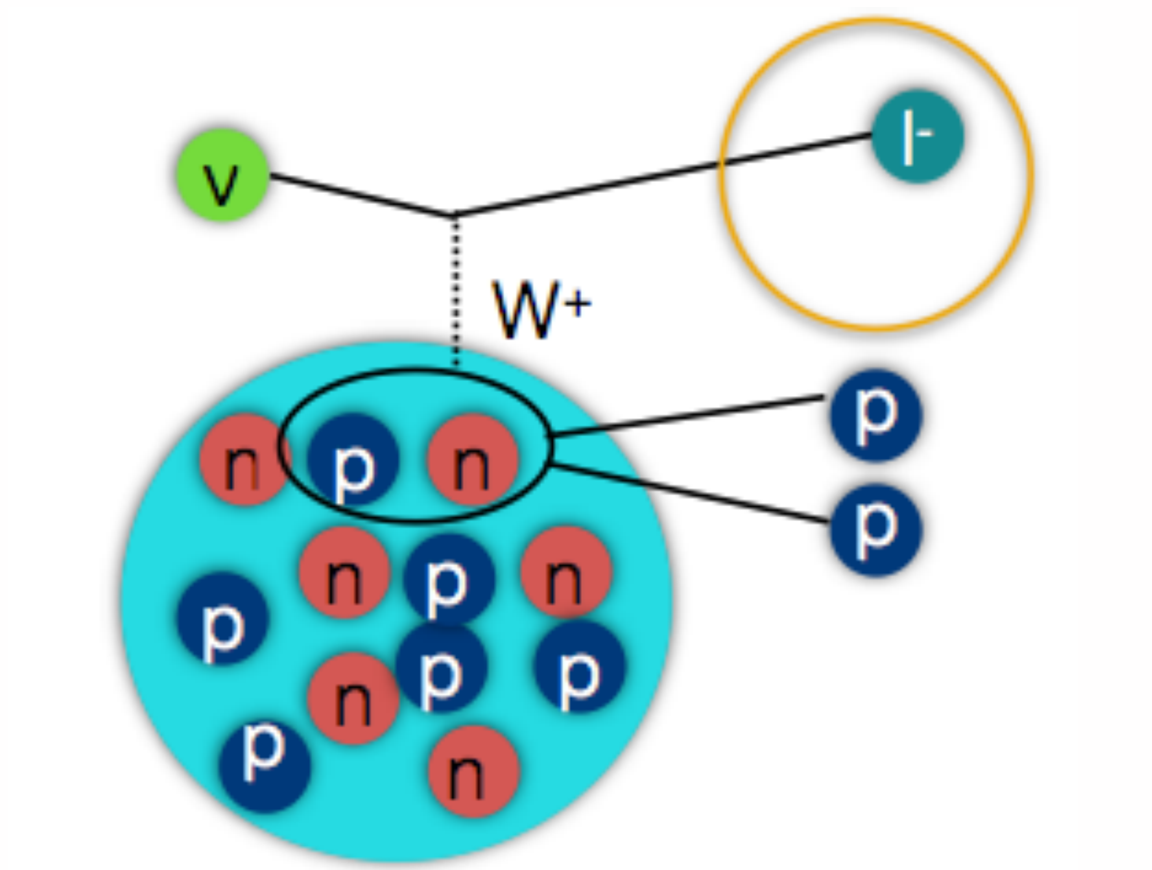
- New neutrino oscillation results from T2K (7.5 ν + 7.5 $\overline{\nu}$ x 10^{20} POT)
- First search for CP violation in the leptonic sector with neutrino & antineutrino
    - data prefer maximal $\nu_\mu/\overline{\nu}_\mu$ disappearance
    - CP conservation excluded at 90% CL
    - δ_{CP} = [-3.13,0.39] (NH), [-2.09,-0.74] (IH) @ 90% CL
- Working to add the CC1π^+ - ν_e candidate sample (~10% additional ν_e data)
- 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 δ_{CP} ~ -π/2 and NH
    - running until ~2025 to accumulate up to 20x10^{21} POT
    - possibility for an upgrade of the near detector to reduce systematics
- CERN contributions: NA61/SHINE, UA1 magnet, MicroMegas, test beam

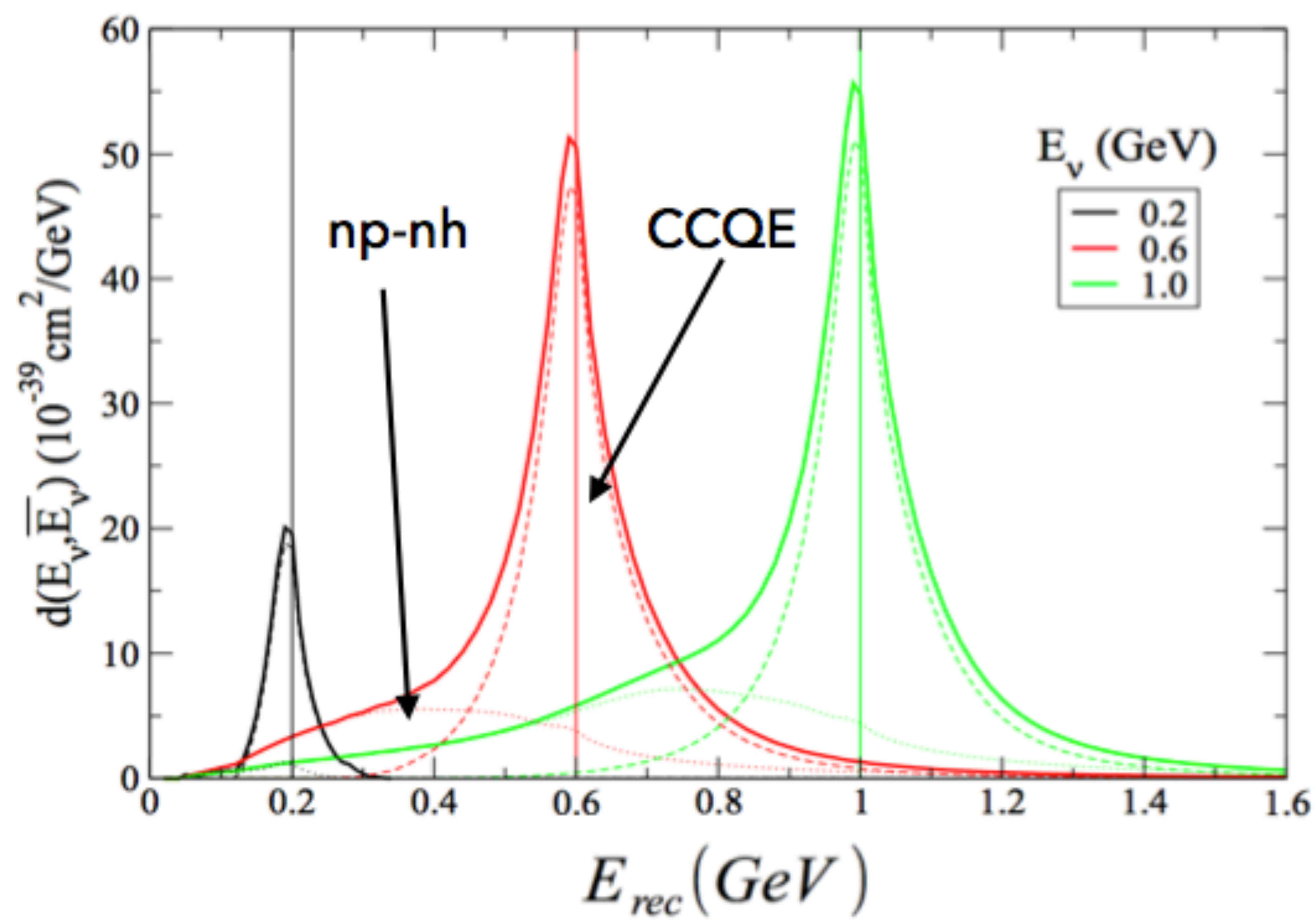
Good timing for new collaborators to join T2K

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

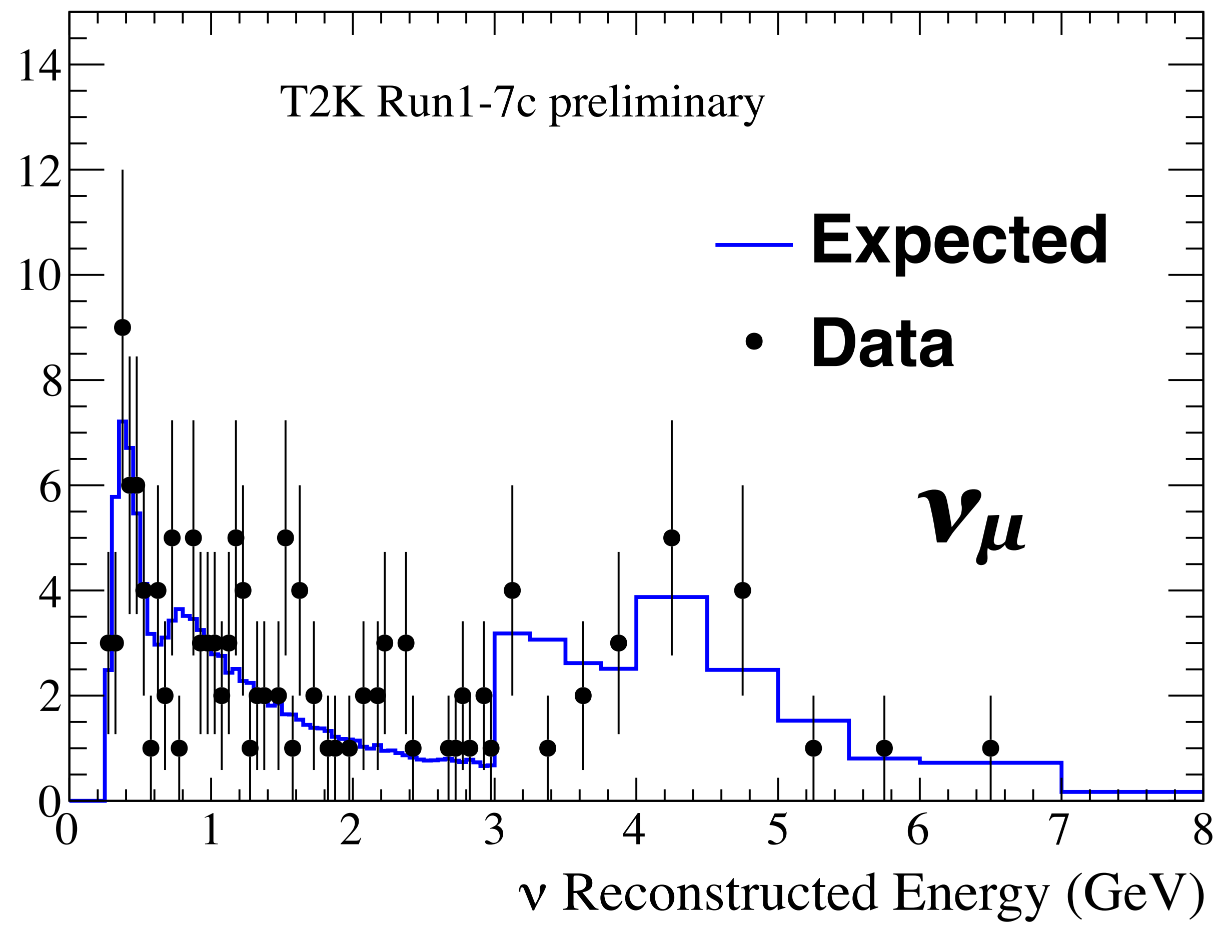
Impact of systematic uncertainties

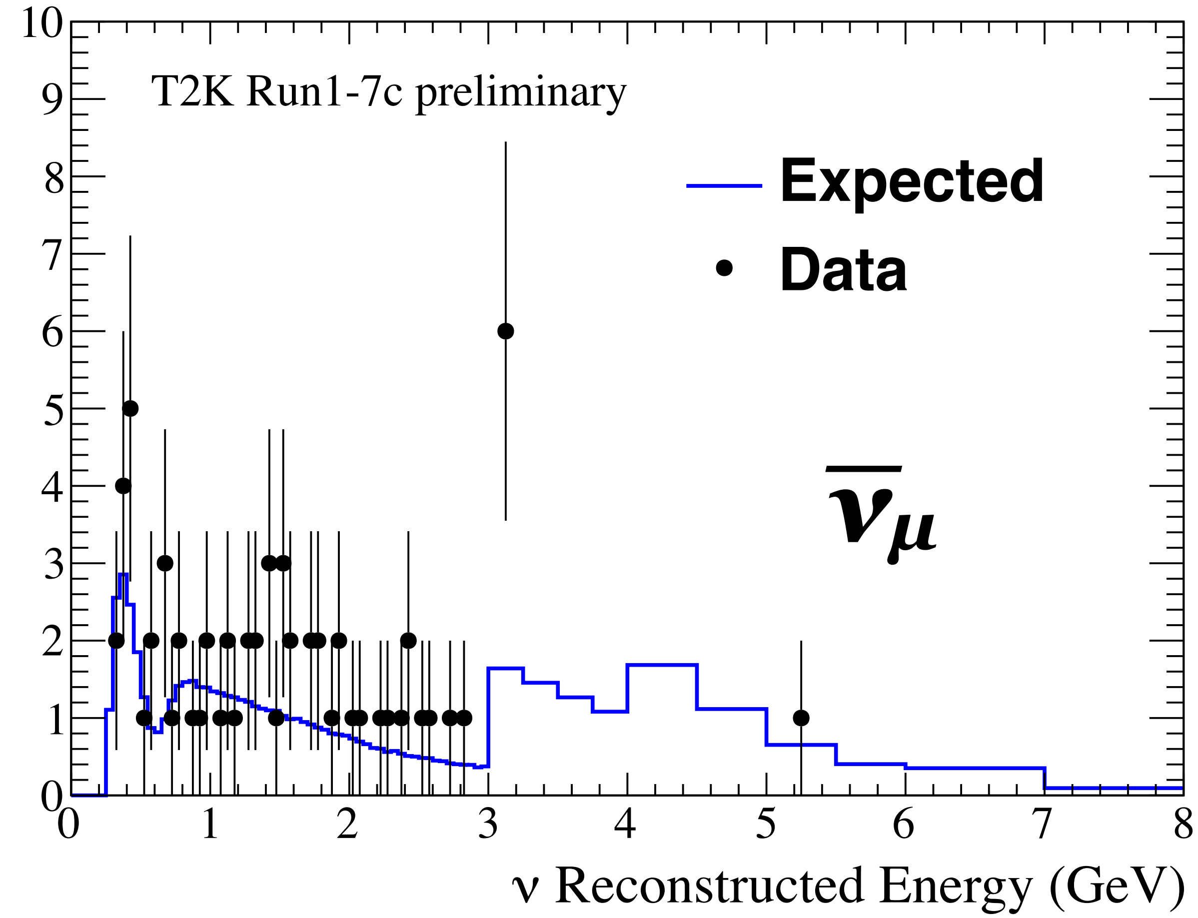
Fractional error on the number of expected events at SK

	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%**

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

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

arXiv:1610.04802

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E} \qquad \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

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

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

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

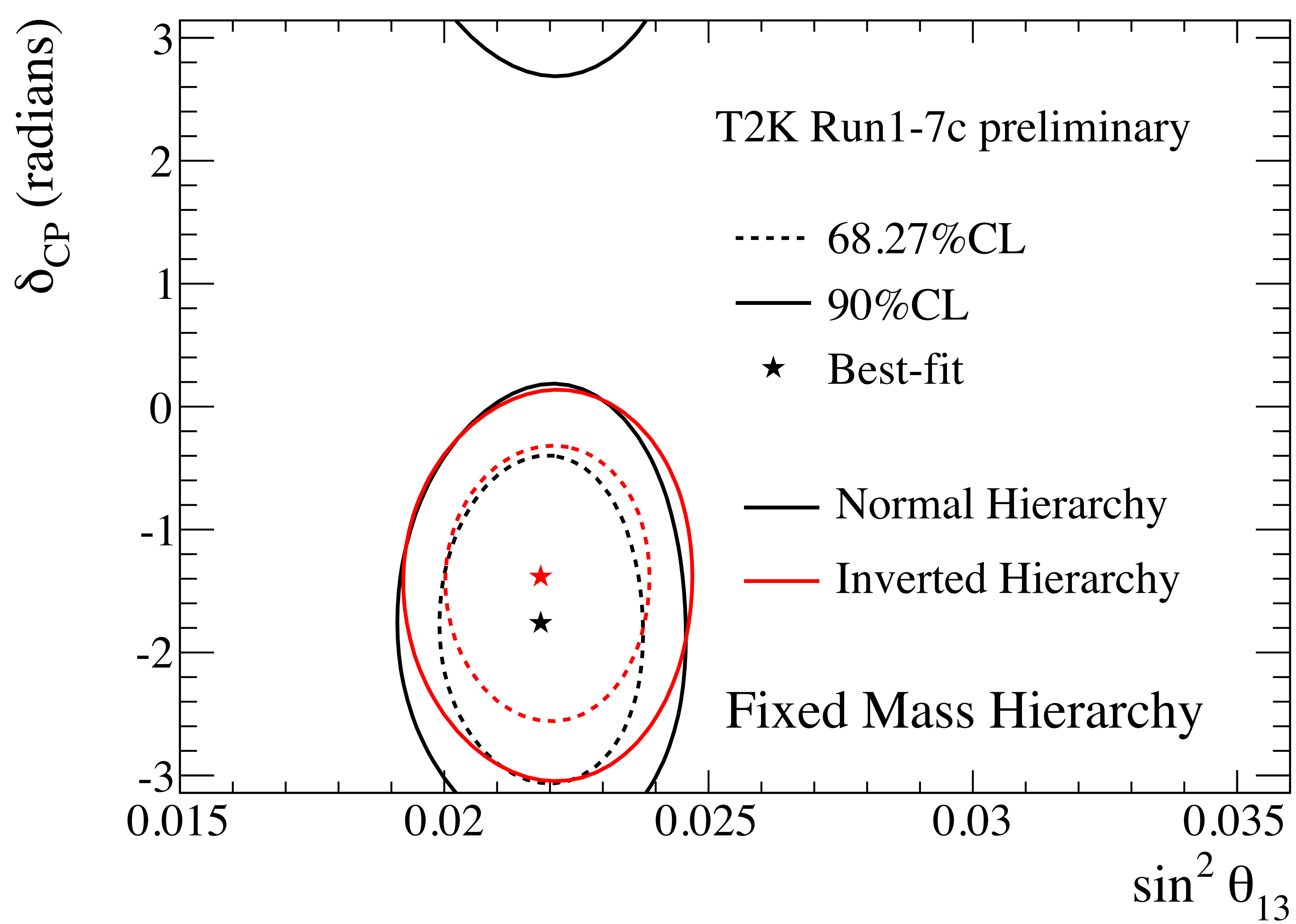
IH: $\Delta m^2_{32} = [-2.56 \pm 0.08] \times 10^{-3}$ eV^2

T2K+reactors: $\sin^2\theta_{13}$ and δ_{CP}

- Mass hierarchy is fixed to either normal or inverted
- Reactor constraint: $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

sensitivity assumptions:

- $\sin^2 2\theta_{13} = 0.085$ (PDG 2015)
- $\sin^2\theta_{23} = 0.528$
- NH, $\delta_{CP} = -1.601$



T2K+reactors: $\sin^2\theta_{13}$ and δ_{CP}

- Mass hierarchy is fixed to either normal or inverted
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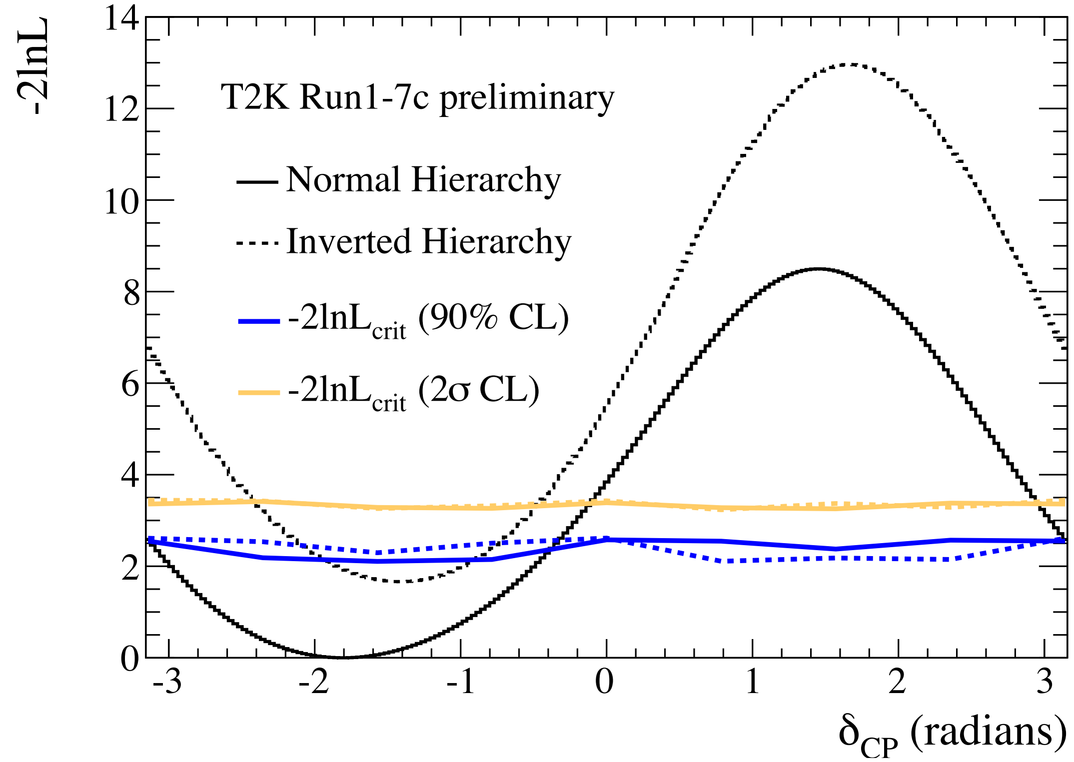
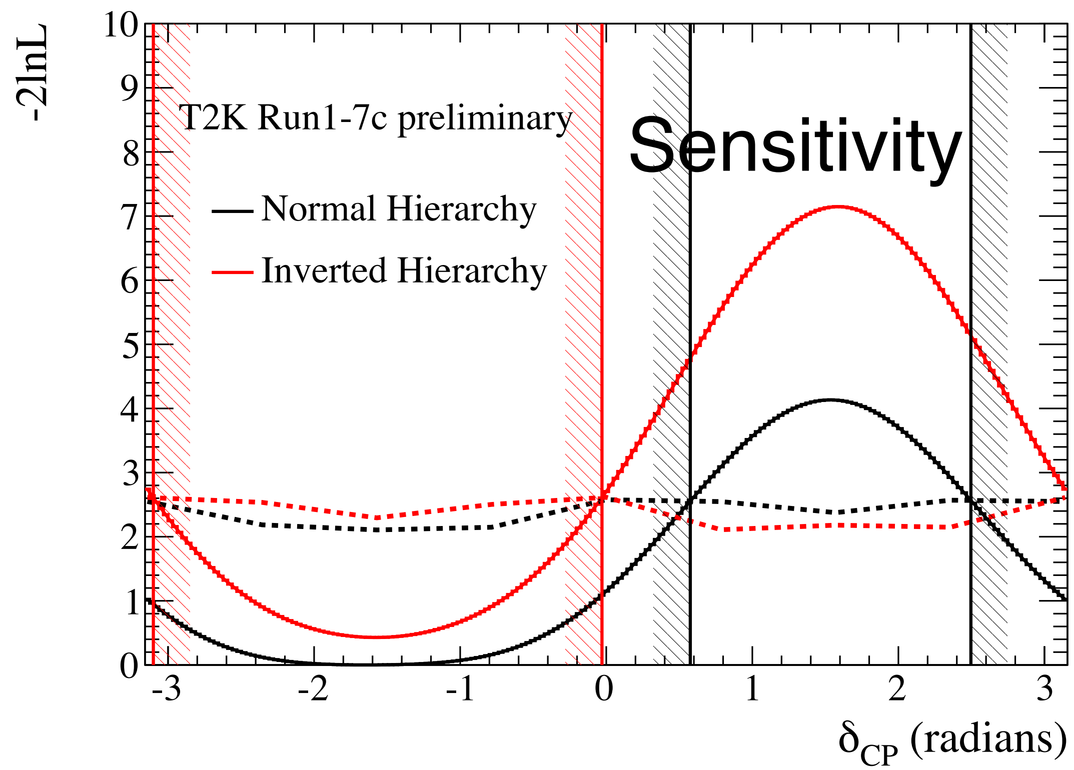
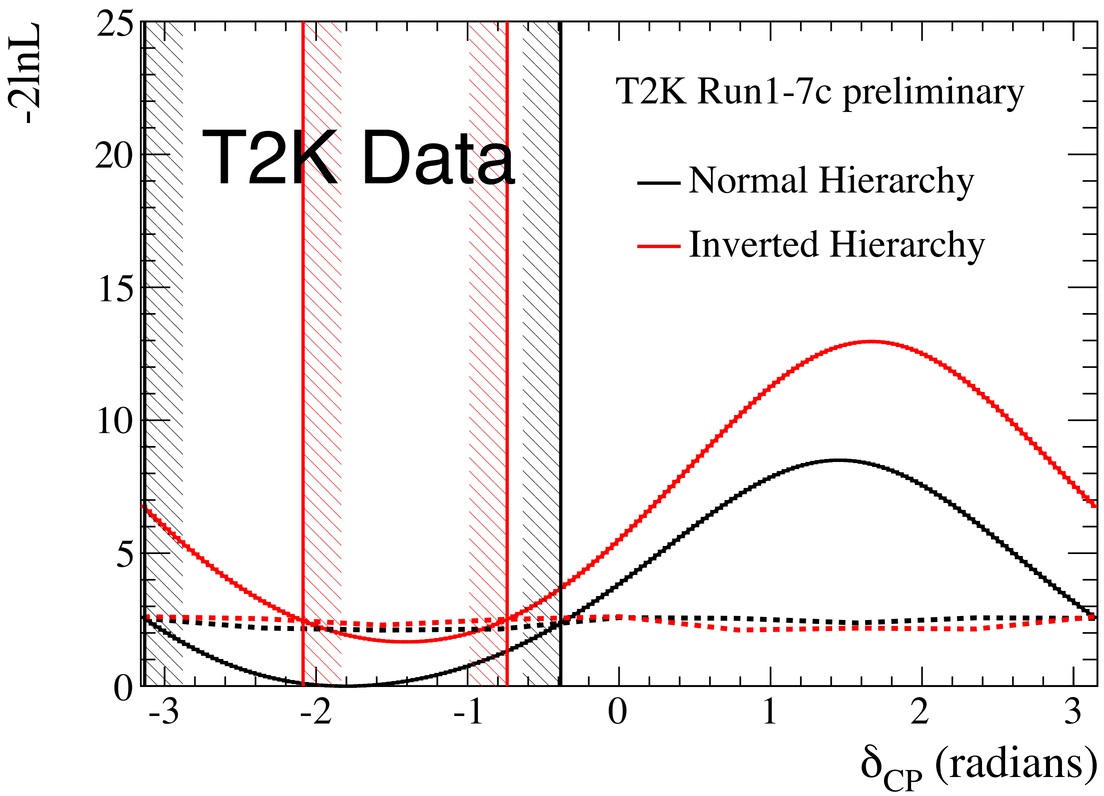
sensitivity assumptions:
- $\sin^2 2\theta_{13} = 0.085$ (PDG 2015)
- $\sin^2\theta_{23} = 0.528$
- NH, $\delta_{CP} = -1.601$



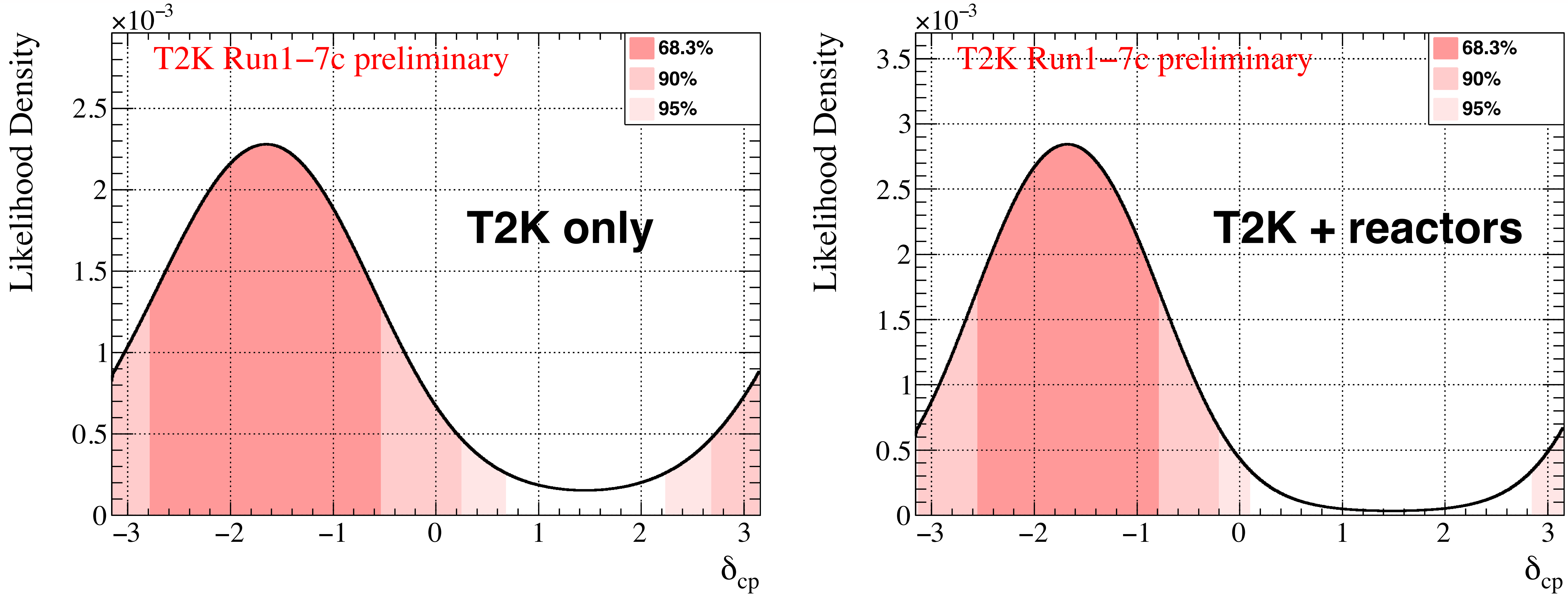




Bayesian posterior probabilities

- Credible intervals using flat prior for δ_{CP}
- Mass hierarchy is marginalised
- Use momentum - lepton angle as templates

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



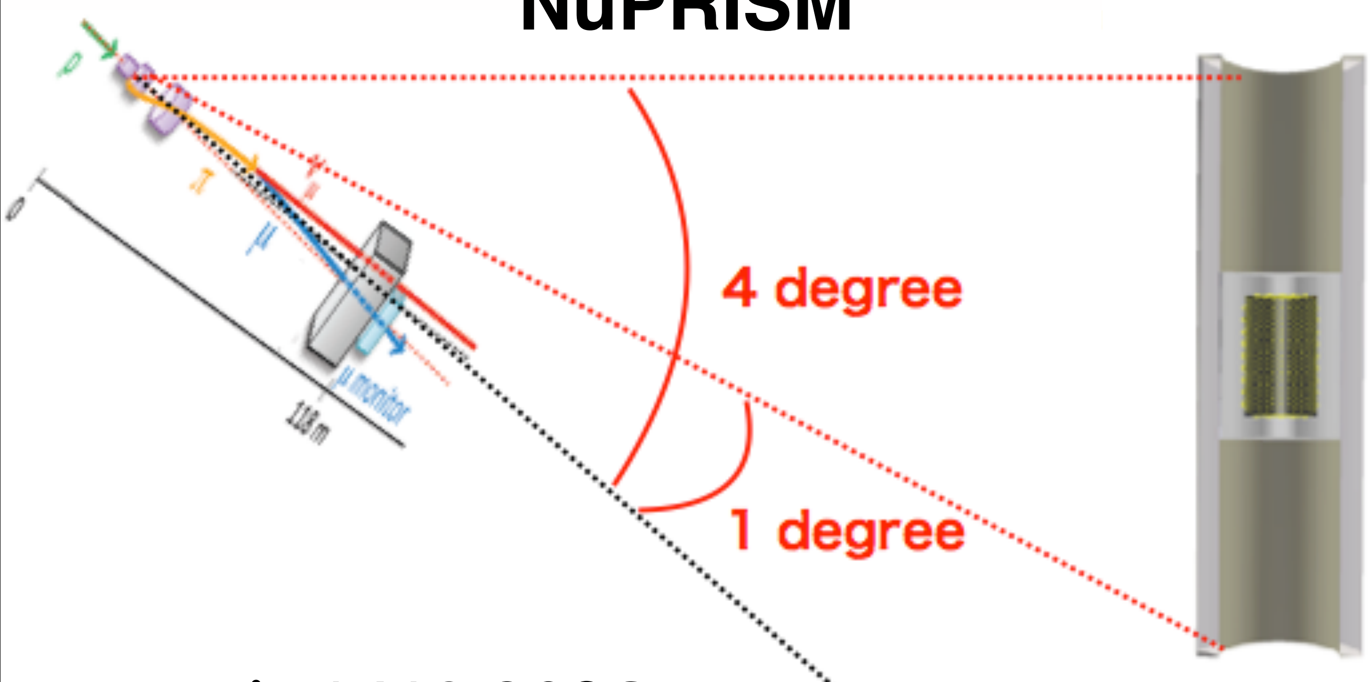
- $\delta_{CP} = -\pi/2$ is driven by the T2K-only data
- Reactors' constraint don't change the result but improves the sensitivity

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



arXiv:1412.3086

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

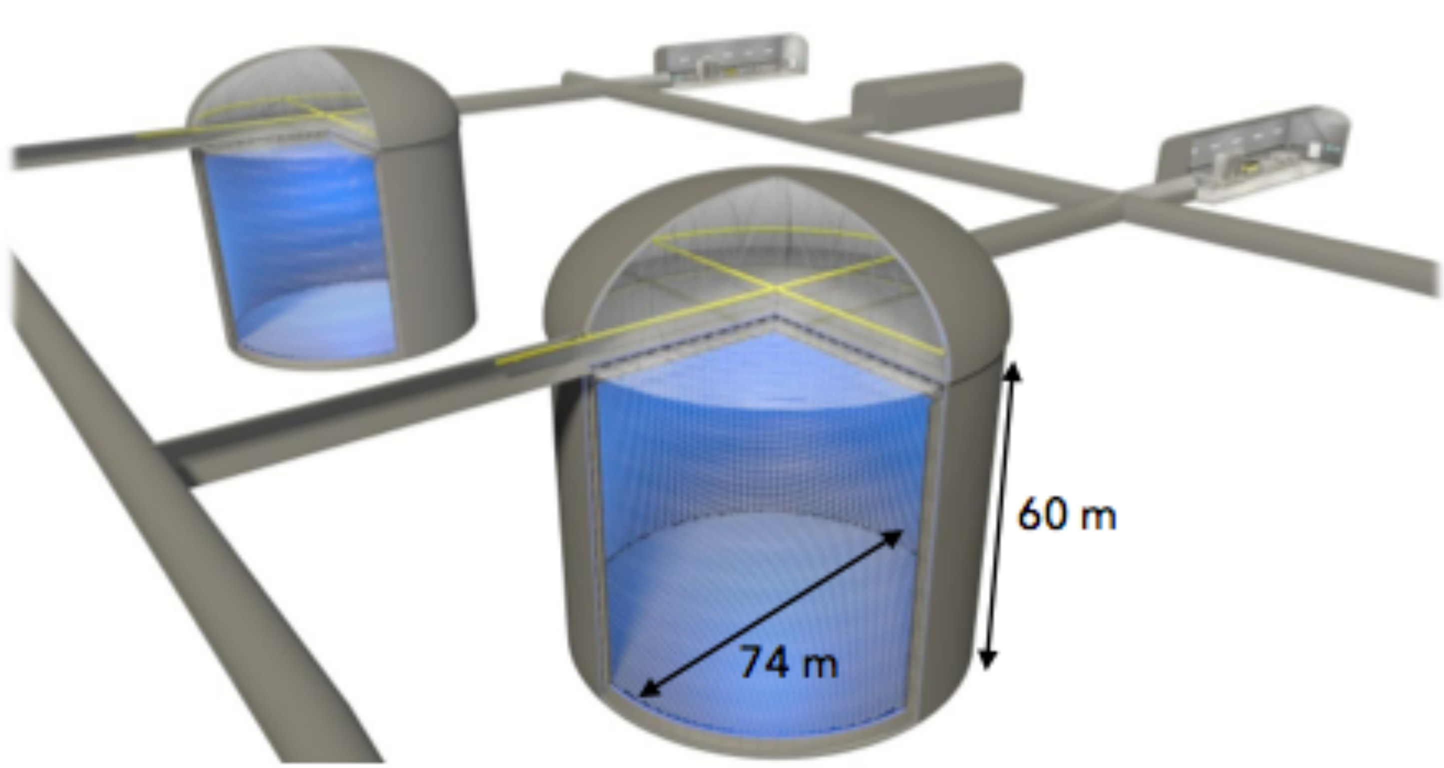
Process for merging the two proposals into a single detector design

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

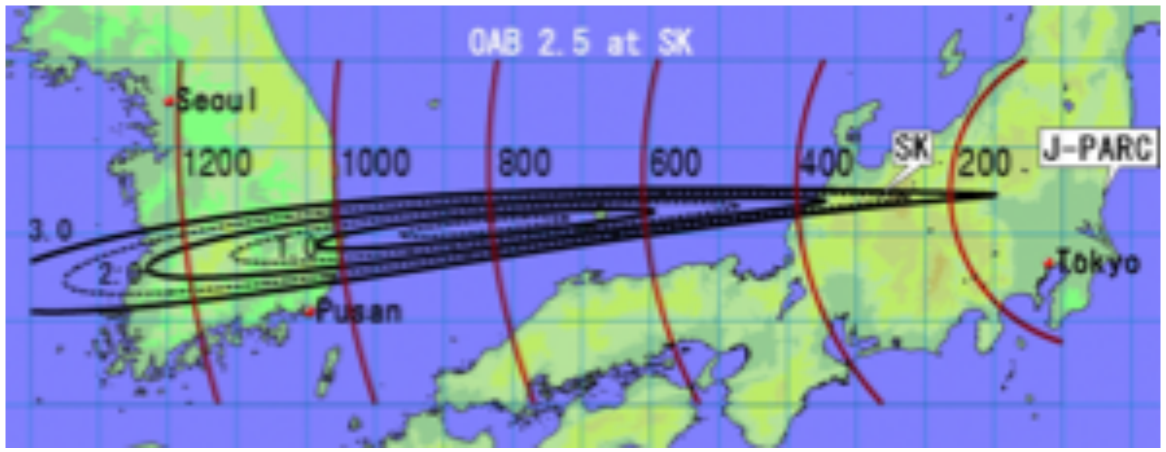
Physics program:

- 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