T2K NEUTRINO EXPERIMENT RESULTS AND FUTURE PERSPECTIVES

T2K

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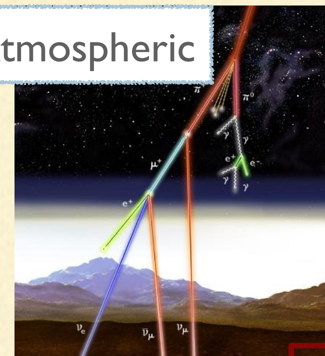
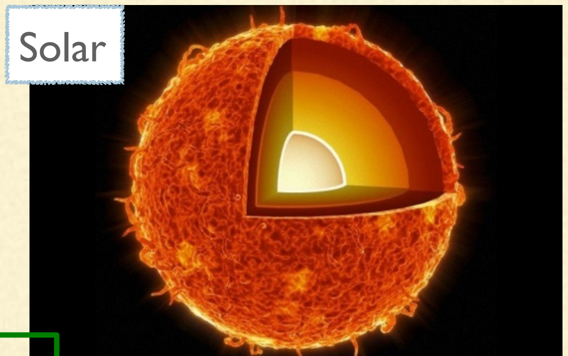
NEUTRINO OSCILLATIONS

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix





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

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillations governed by

- three mixing angles:
  - $\theta_{12} \approx 33^\circ$, $\theta_{13} \approx 9^\circ$, $\theta_{23} \approx 45^\circ$
- two mass squared differences:
  - $\Delta m^2_{21} \approx 7.5\text{x}10^{-5}\,\text{eV}^2$ and $|\Delta m^2_{32}| \approx 2.5\text{x}10^{-3}\,\text{eV}^2$
- source-detector baseline and neutrino energy

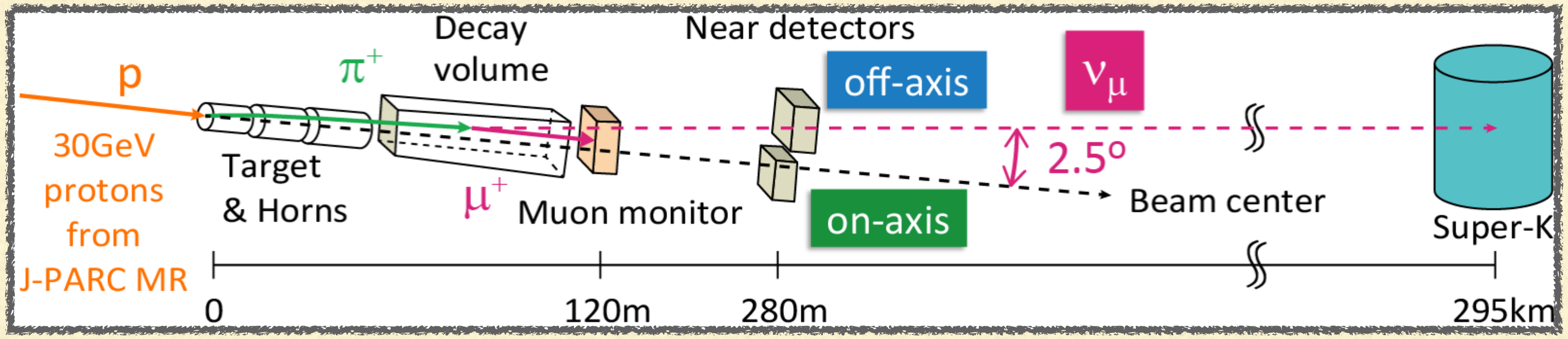
Open questions:

- CP-violation in lepton sector? δ_{CP} value?
- Mass hierarchy(MH), "normal" (NH) or "inverted"(IH):
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$?
- Octant of θ_{23}: <, > or = 45°?
- Dirac/Majorana, steriles, CPT…

T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- Long-baseline neutrino oscillation experiment in Japan
- International collaboration:
  - ~500 members, 63 institutes, 11 countries

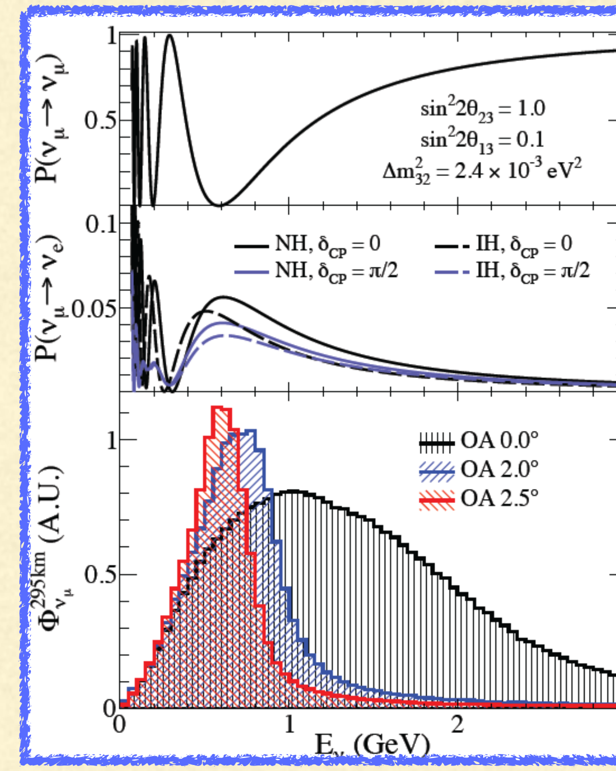
T2K DESIGN



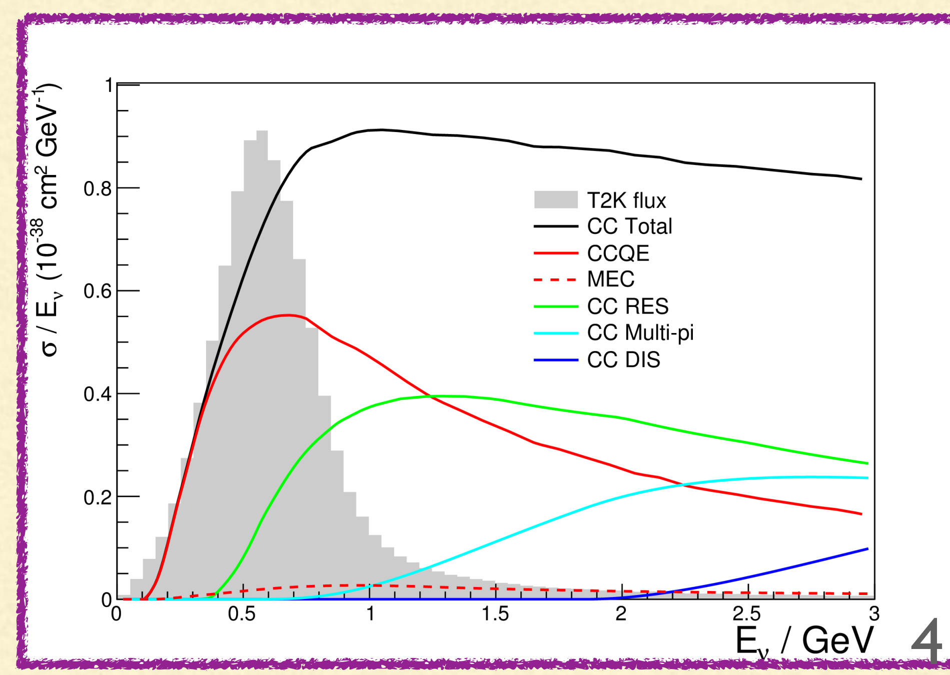
$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Observable Flux Cross section Detector response

$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc}$$



- Near and Far detectors
- Off-axis (anti)muon neutrino beam
- Energy peaked at oscillation maximum (E~0.6 GeV)
- Dominant process: charge current quasi-elastic interactions (CCQE)
- Reduced intrinsic ν_e contamination (≲1%)
- Reduced backgrounds from high-energy tail



NEUTRINO OSCILLATIONS IN T2K

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

- Precise measurement of $\sin^2 2\theta_{23}$ and CPT test via ν vs anti-ν disappearance analysis

From Phys. Rev. D64 (2001) 053003

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

Leading term

CP-violating

"+" sign for anti-ν

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

CP-conserving

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

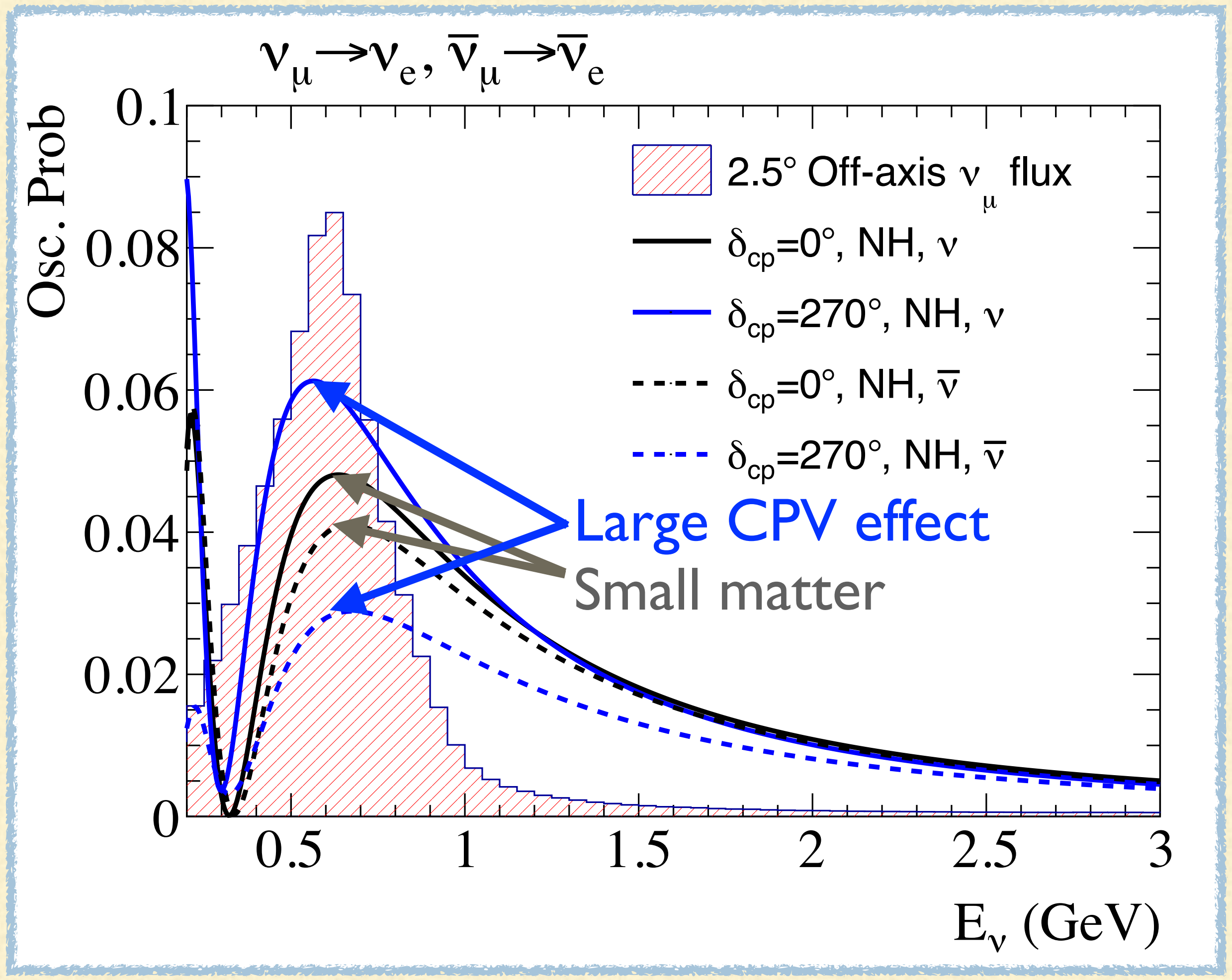
$$+O(\alpha^2)$$

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

- Leading term defines the octant of θ_{23}: <, > or = 45°
- Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data

NEUTRINO OSCILLATIONS IN T2K

δ_{CP} and MH affect differently neutrino and antineutrino oscillations



CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

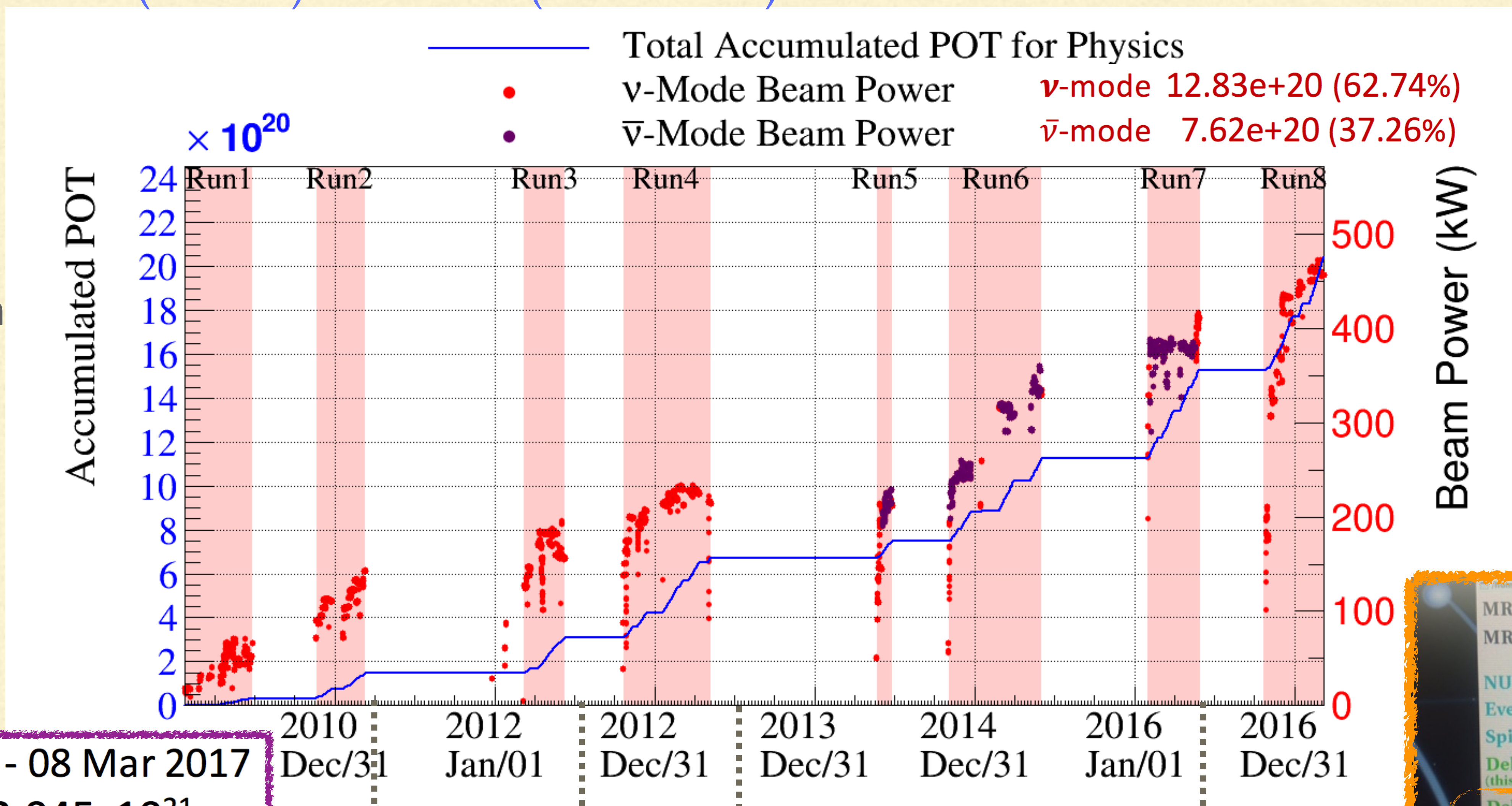
At T2K baseline (L~295km, E~0.6GeV):

- CPV: ≈ ±30% effect
- Mass hierarchy: ≈ ±10% effect

T2K DATA TAKING

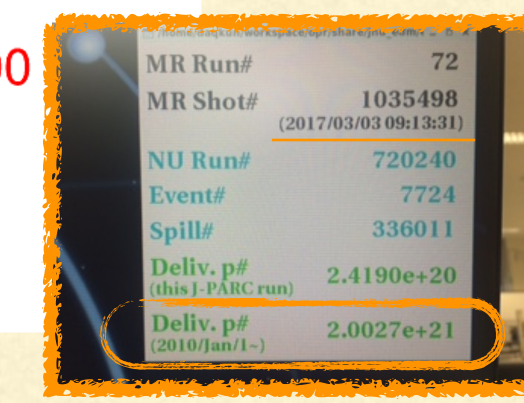
- POT (Protons on Target) for present results (Jan 2010 - May 2016):
  - 7.48×10^{20}(ν mode) + 7.47×10^{20}(anti-ν mode) POT

2010: start operation



2017: stable operation at ~460 kW

2×10^{21} POT milestone passed!



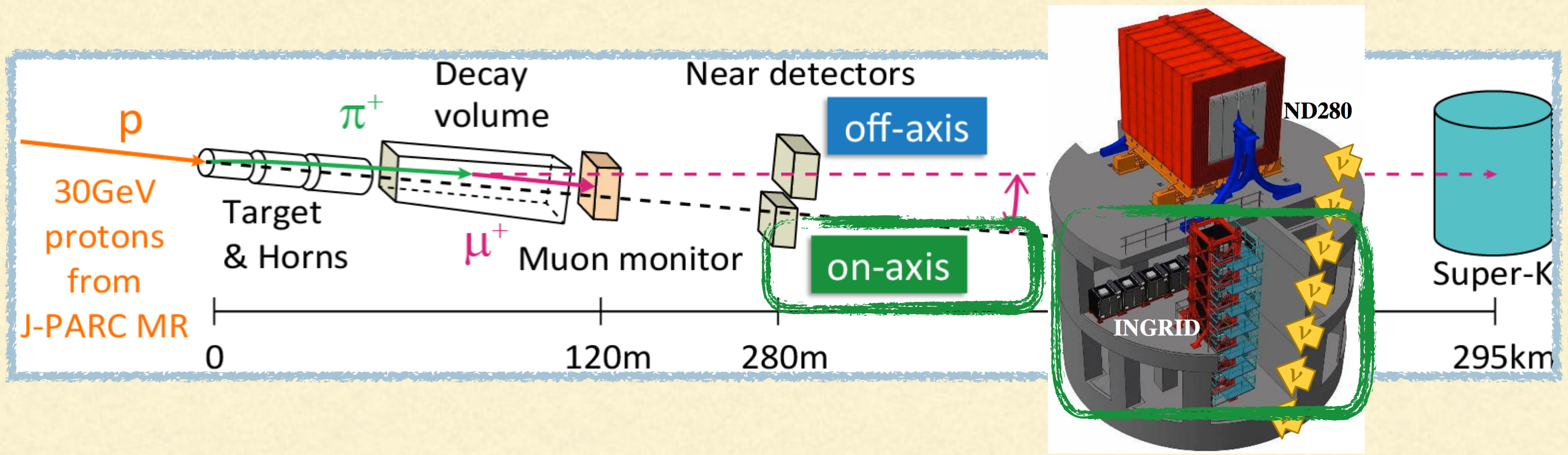
23 Jan 2010 - 08 Mar 2017
POT total: 2.045×10^{21}

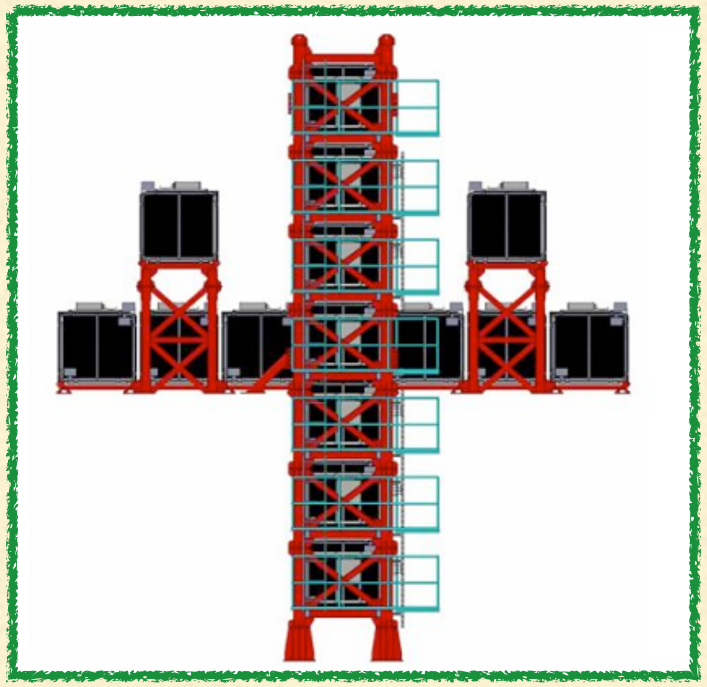
T2K results release:

- ν_e app 2.5σ; ν_μ 1st release
- ν_e app 3.1σ
- ν_e app 7.3σ; 1st constraint on δ_{CP}; ν_μ highest precision on θ_{23}
- Current ν + anti-ν joint analysis results

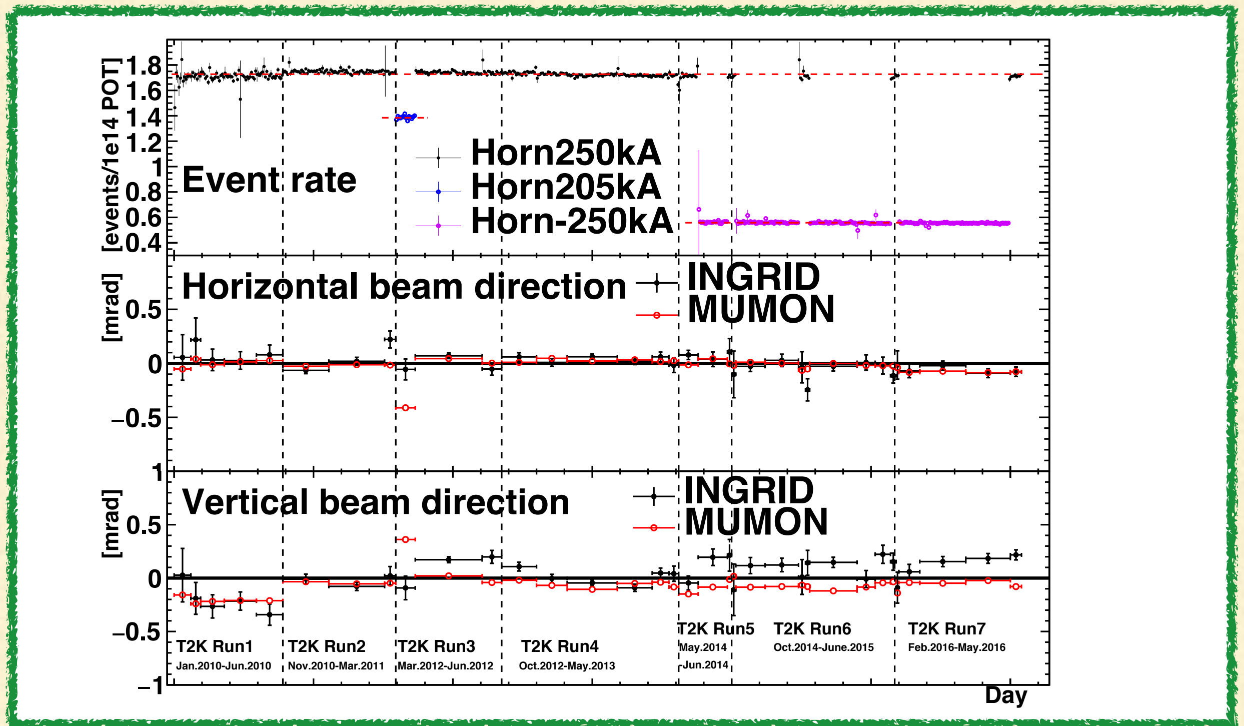
PRE-OSCILLATION MEASUREMENTS

ON-AXIS NEAR DETECTOR INGRID

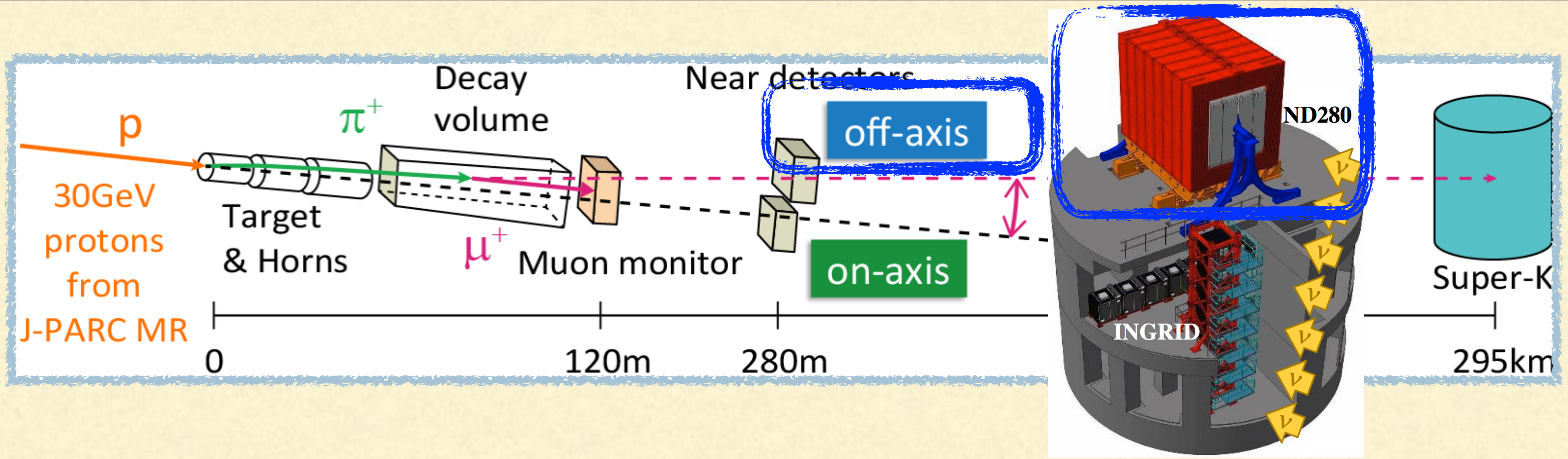


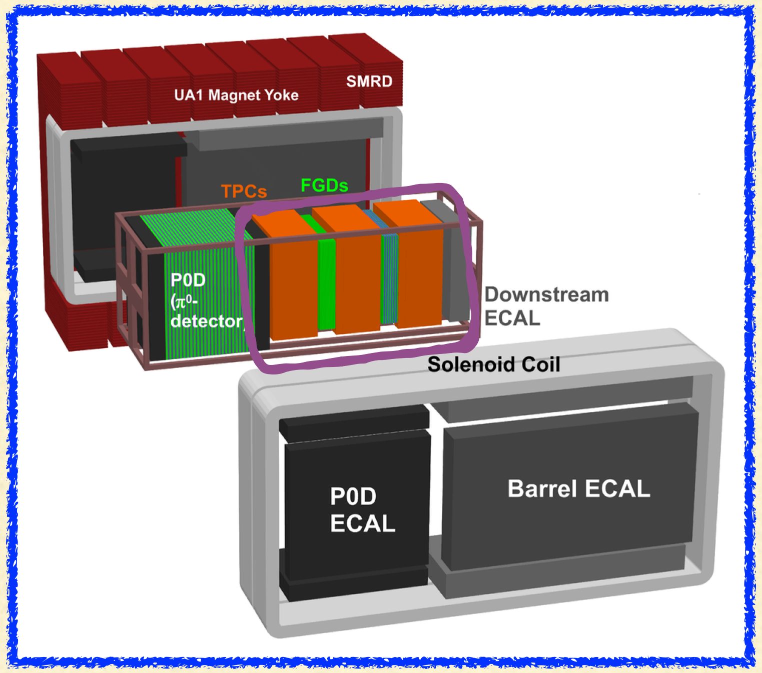


- T2K utilises off-axis neutrino beam:
  - Important to monitor beam intensity and direction
- Iron/scintillator detector to measure beam profile and rate
- Day-by-day monitoring
- Direction stable within 1 mrad (~2% shift in peak energy)

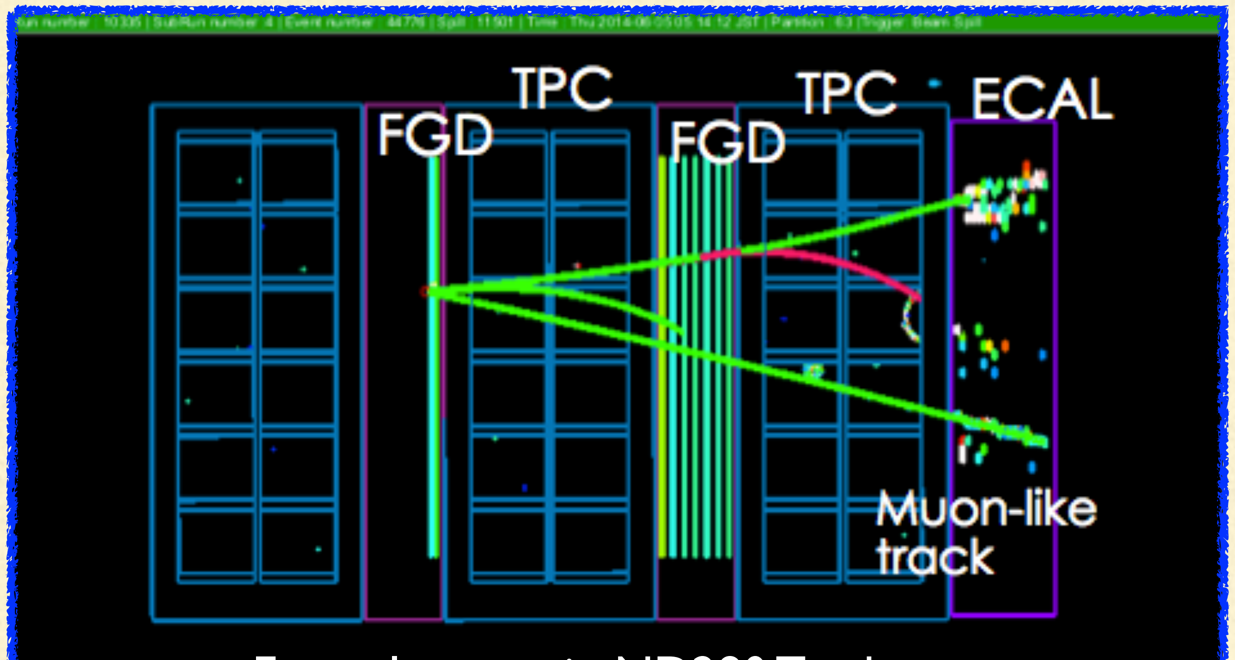


OFF-AXIS NEAR DETECTOR ND280





- Detectors inside refurbished UA1 magnet: 0.2 T
  - Tracker:
    - 3 Time-Projection Chambers (TPCs)
    - 2 Fine-Grained Detectors (FGDs):
      - scintillator (FGD1)
      - scintillator/water (FGD2)
  - Calorimeters and muon range detectors

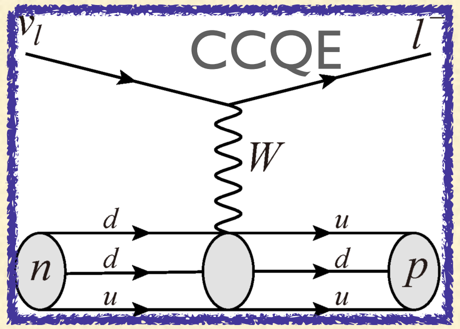


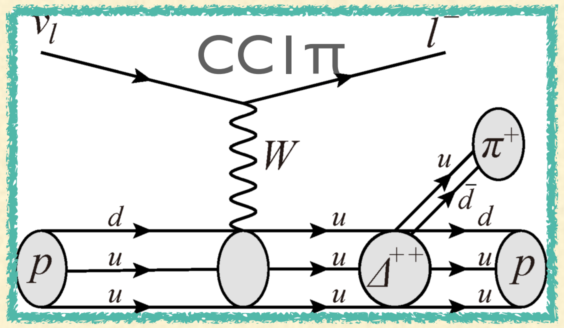
Example event in ND280 Tracker

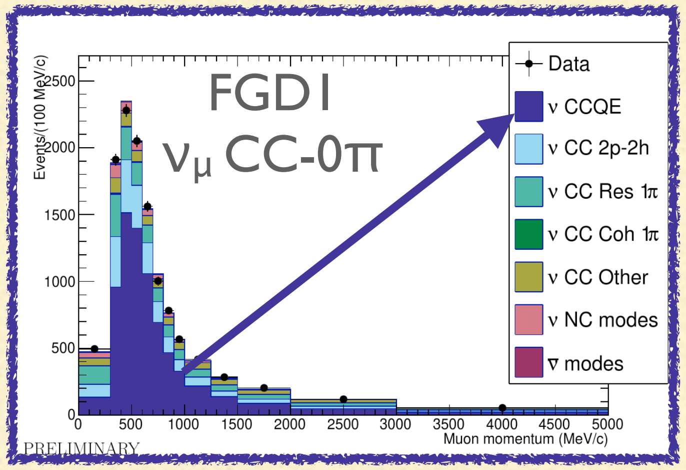
Many studies on neutrino interactions:
talk by M.Malek on March 16

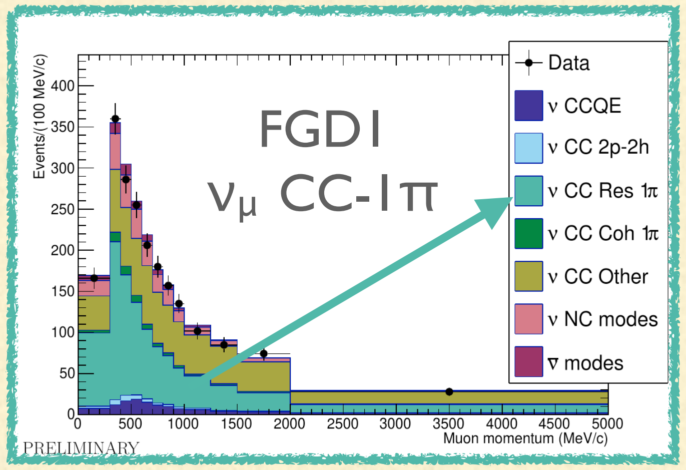
ND280 ANALYSIS

Example samples

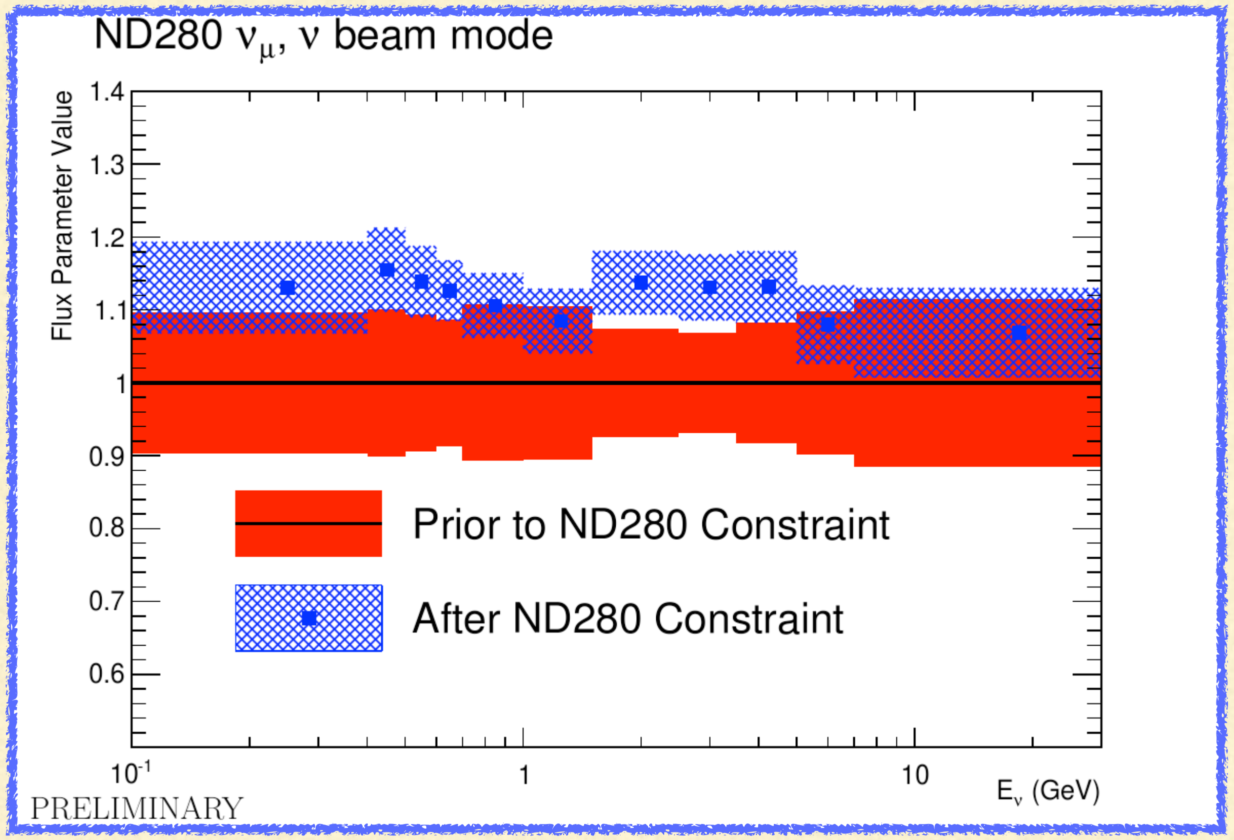








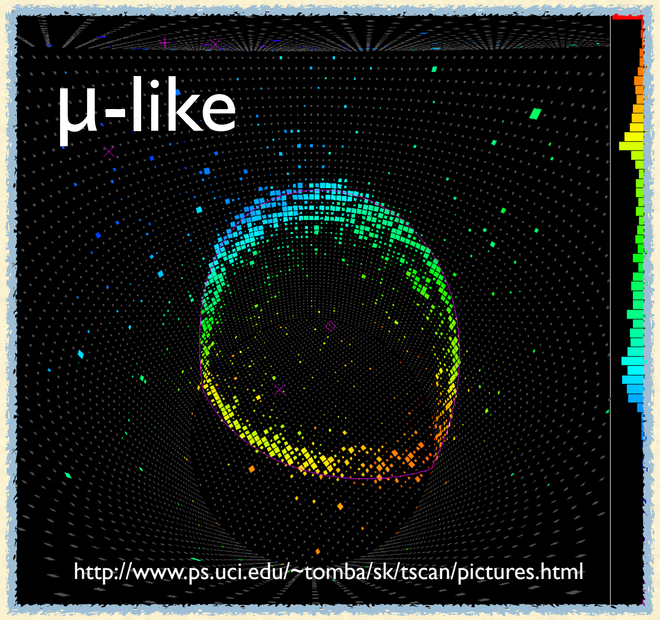
- Fit to ND280 samples constrains neutrino flux and cross-section model
- Reduce systematic uncertainty for oscillation analysis: ≈12%→≈6%

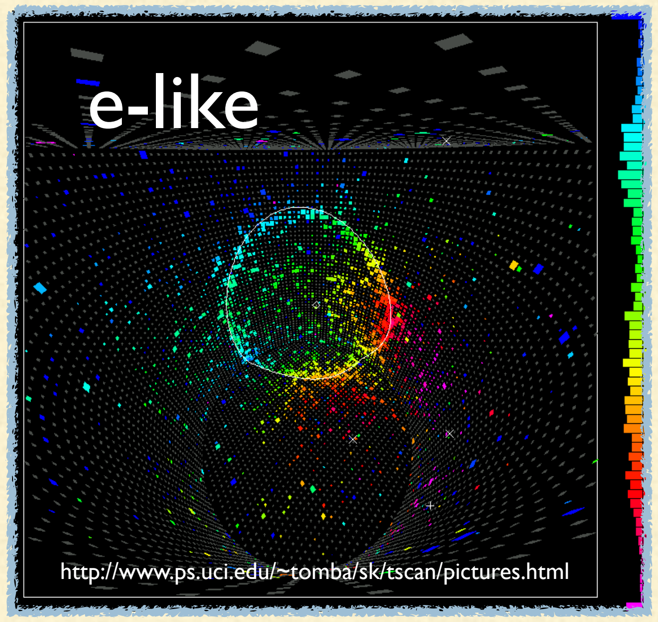


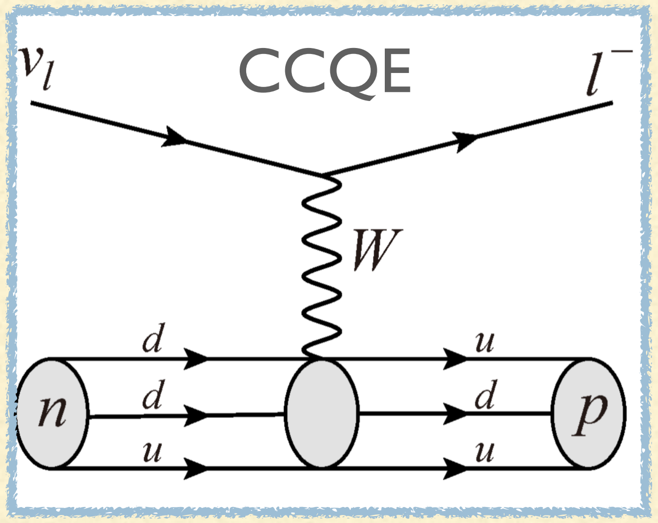
POST-OSCILLATION MEASUREMENTS

POST-OCILLATION MEASUREMENTS: SUPER-KAMIOKANDE

- 50(22.5 FV) kton water-Cherenkov tank
- Separate e/μ-like rings:
  - <1% misidentified μ as e
- π^0 rejection
- No magnetic field





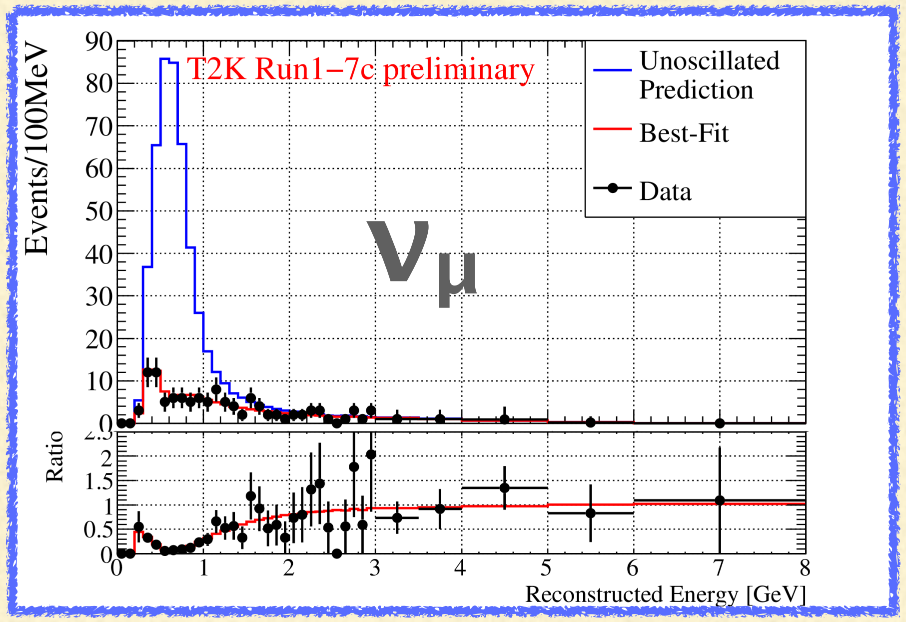


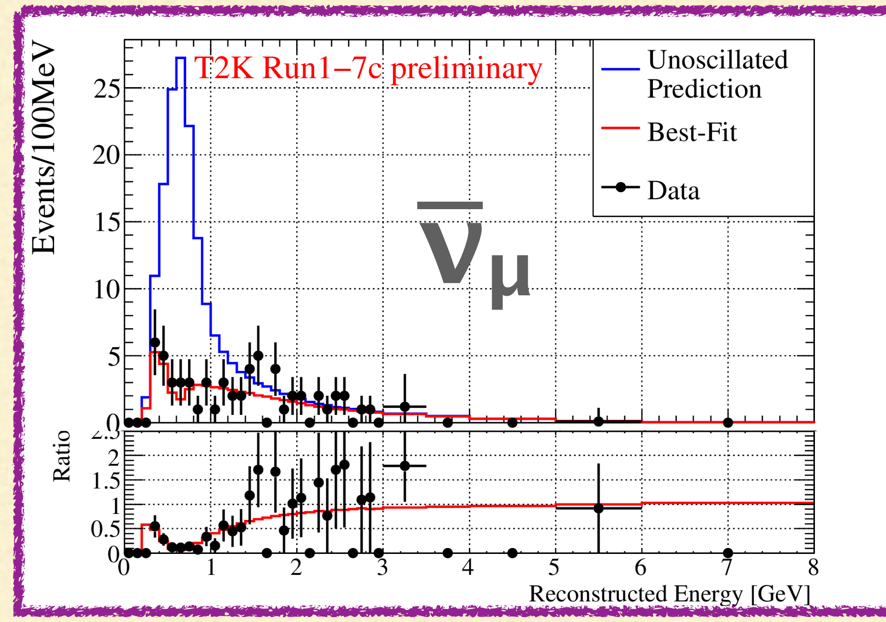
- T2K signal: single ring events
- CCQE kinematics for energy reconstruction
- Neutral current (NC) π^0 background for appearance search

$$E_{CCQE} = \frac{m_p^2 - m_n'^2 + 2m_n' E_l - m_l^2}{2(m_n' - E_\mu + p\cos\theta_\mu)}$$

SUPER-KAMIOKANDE SAMPLES

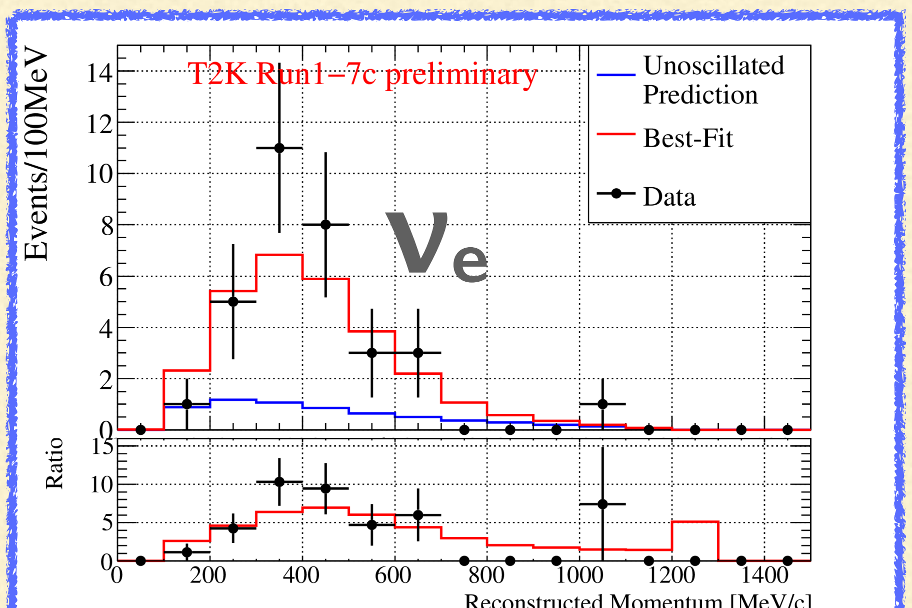
135 events

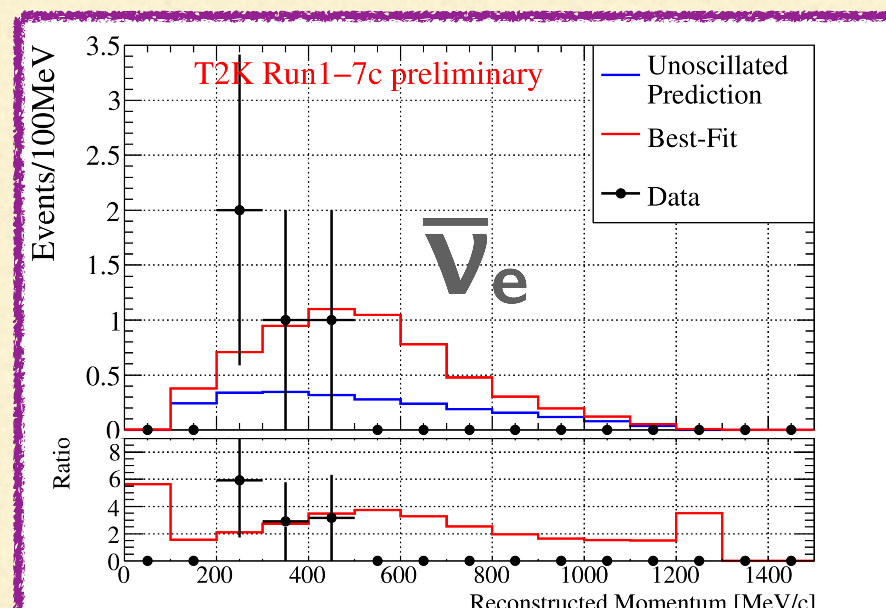




66 events

32 events





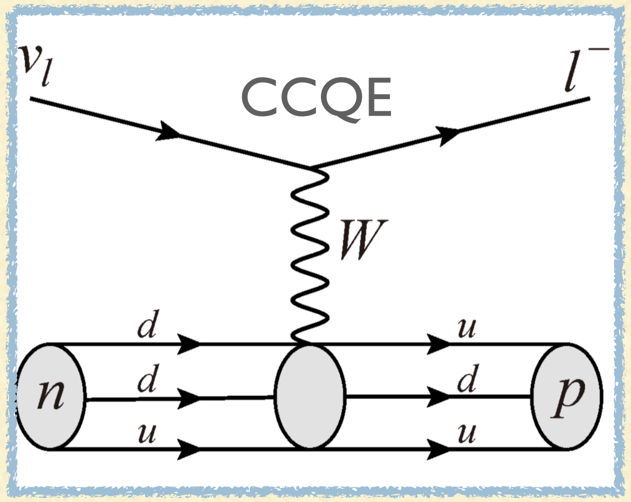
4 events

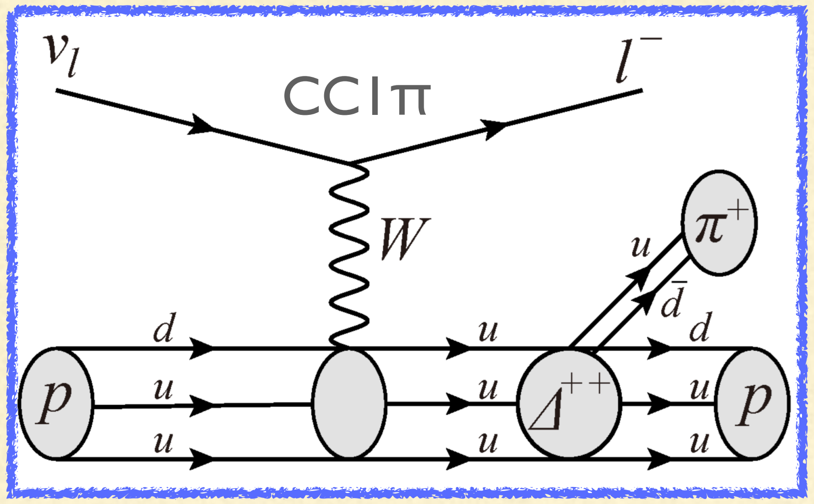
ν-mode

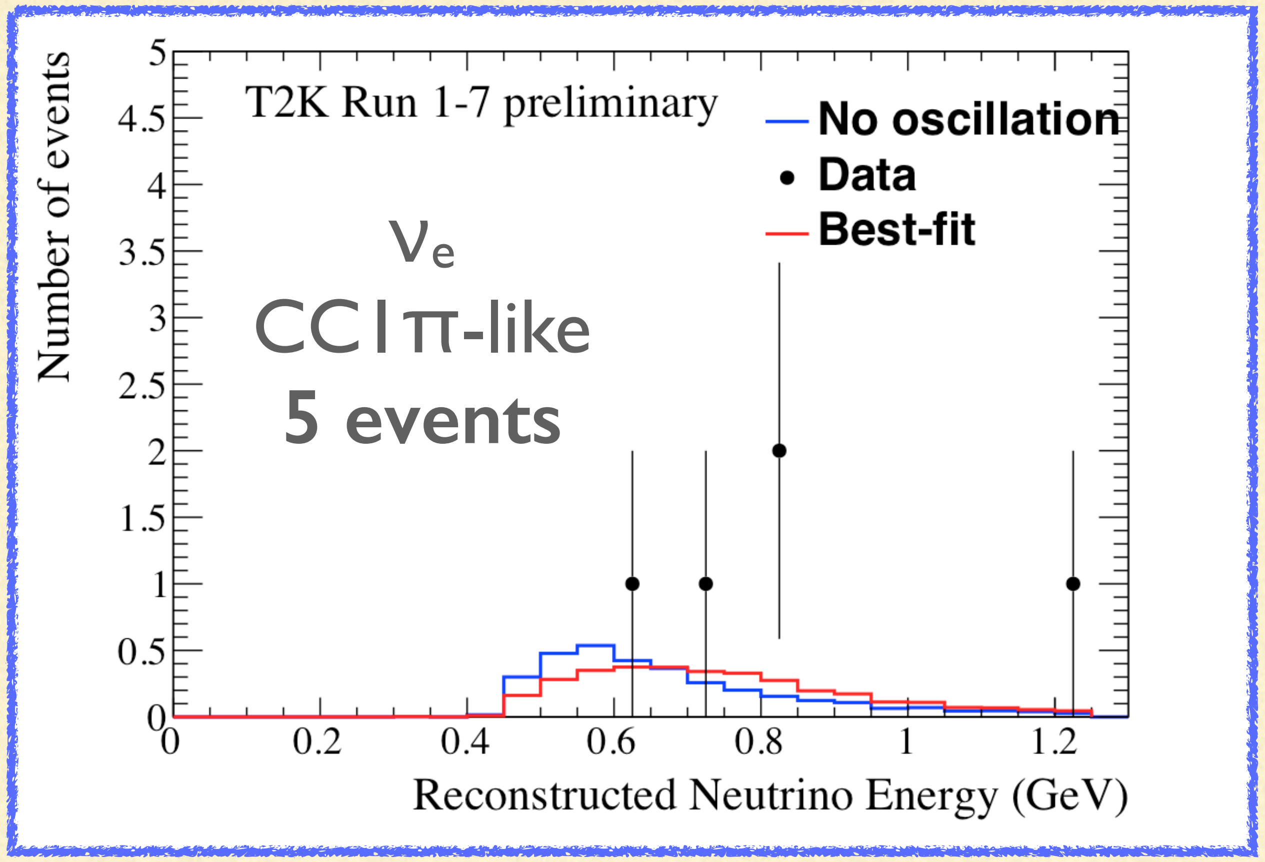
anti-ν-mode

NEW SAMPLE: CC1π

- ν_e e-like single ring events
- Require additional ring from Michel electron
- Energy with 2-body kinematics with Δ baryon
- Applied only for ν-mode running
  - Gain ~10% more statistics
  - 5 events observed
- Total 5 samples available for T2K analysis

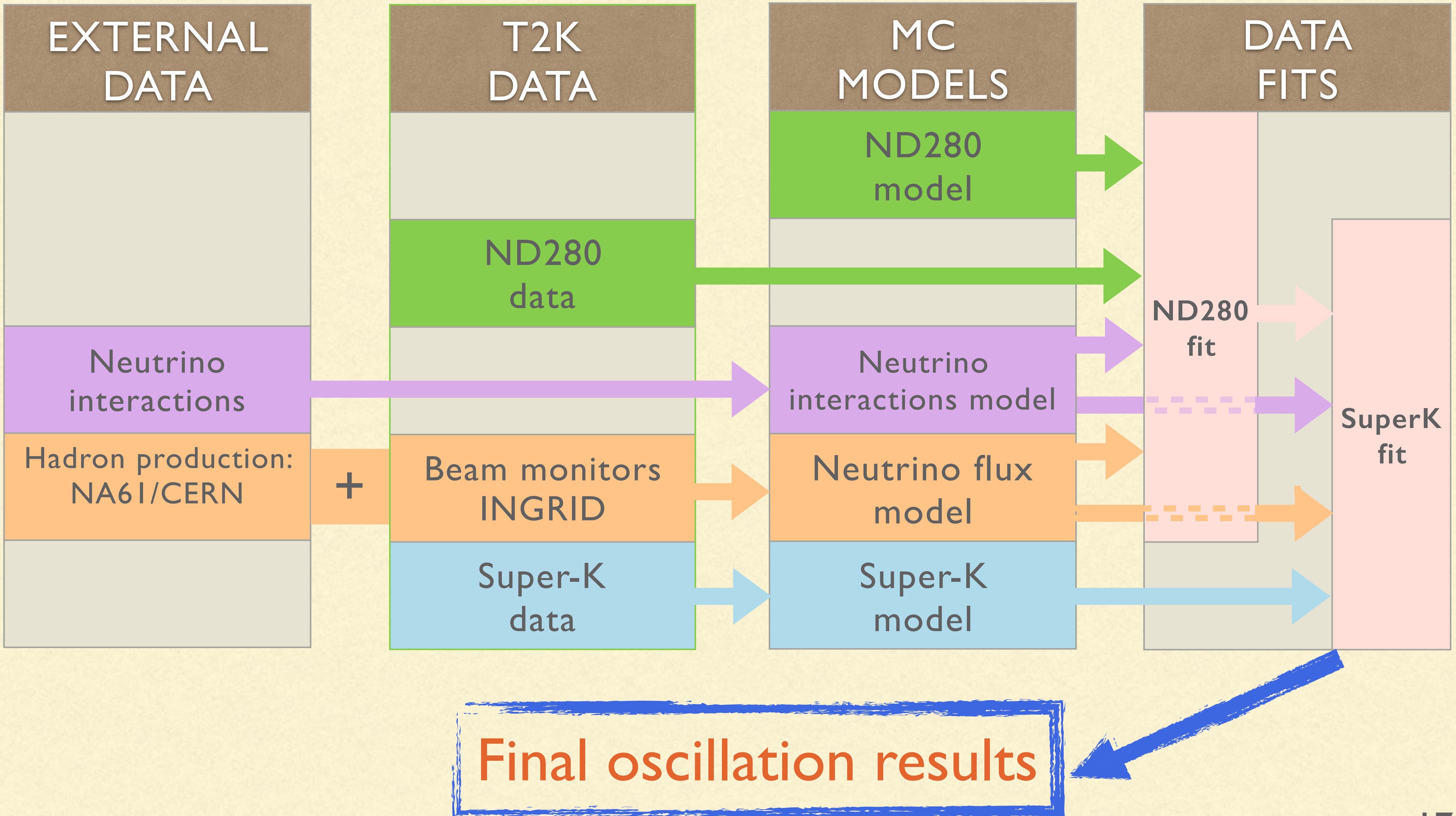




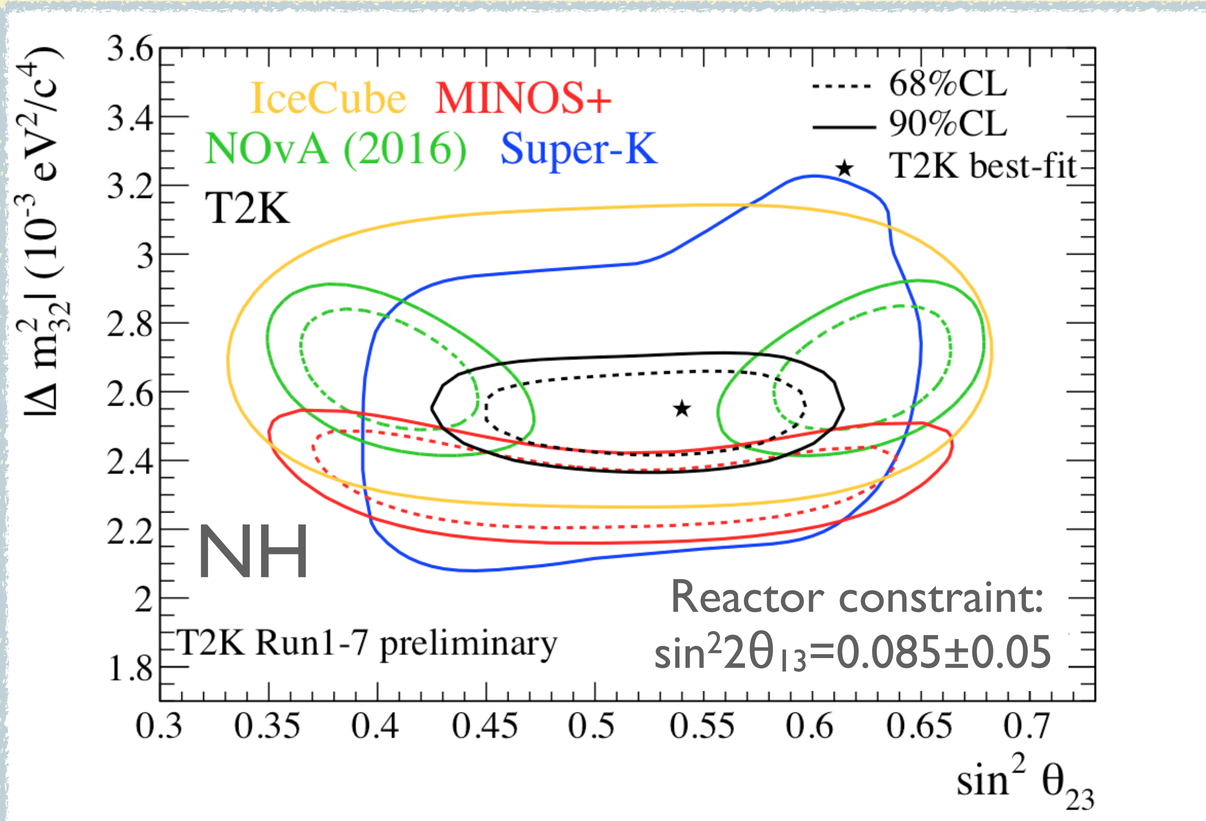


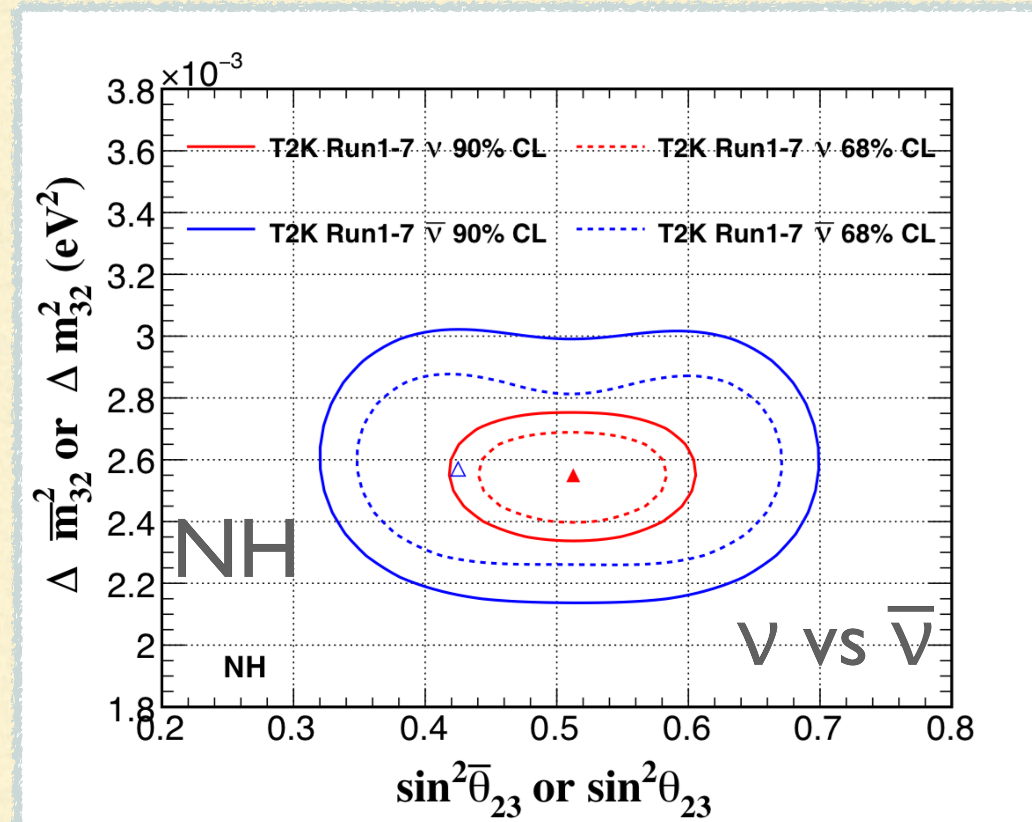
T2K ANALYSIS

T2K ANALYSIS STRATEGY



ANALYSIS RESULTS: θ_{23} AND Δm^2_{32}

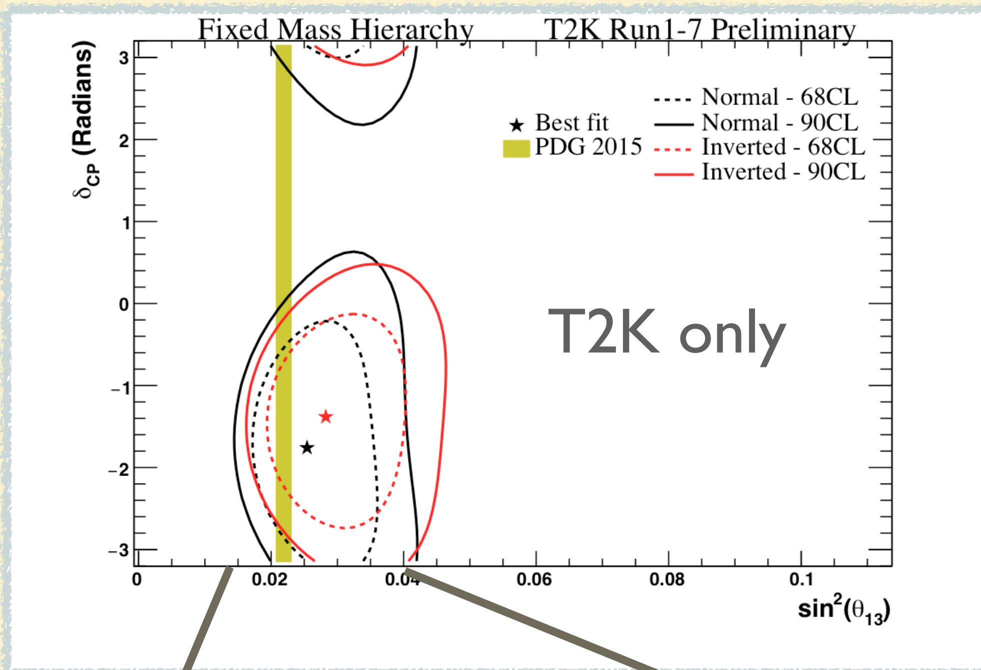




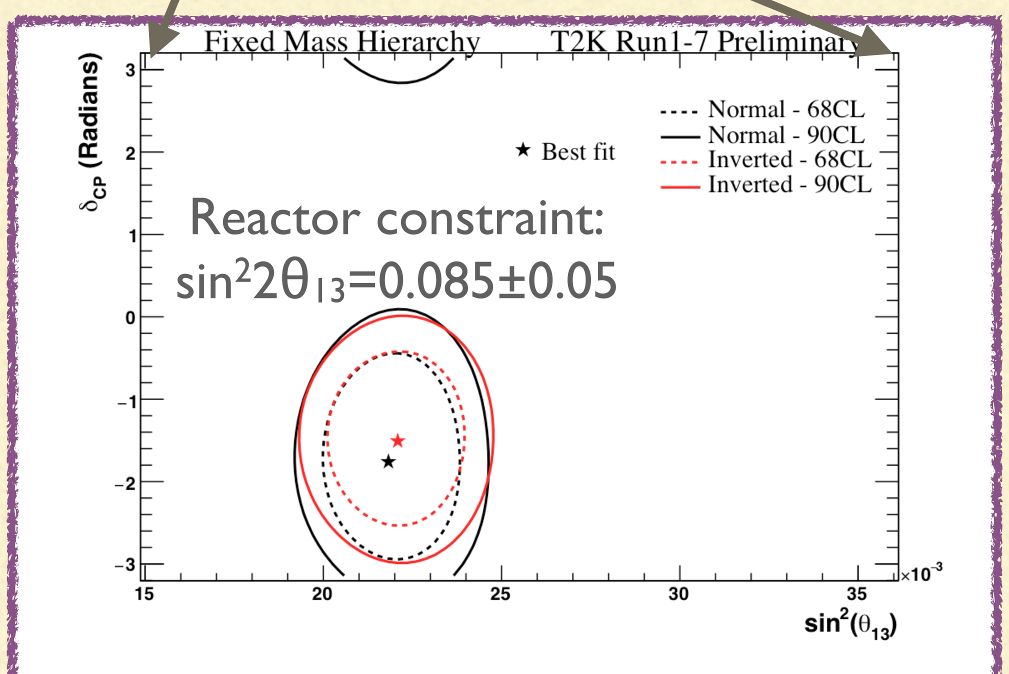
- Joint analysis with reactor constraint
- T2K data consistent with maximal mixing
- Compatible with other experiments
- Consistent results for ν and anti-ν: CPT conserved

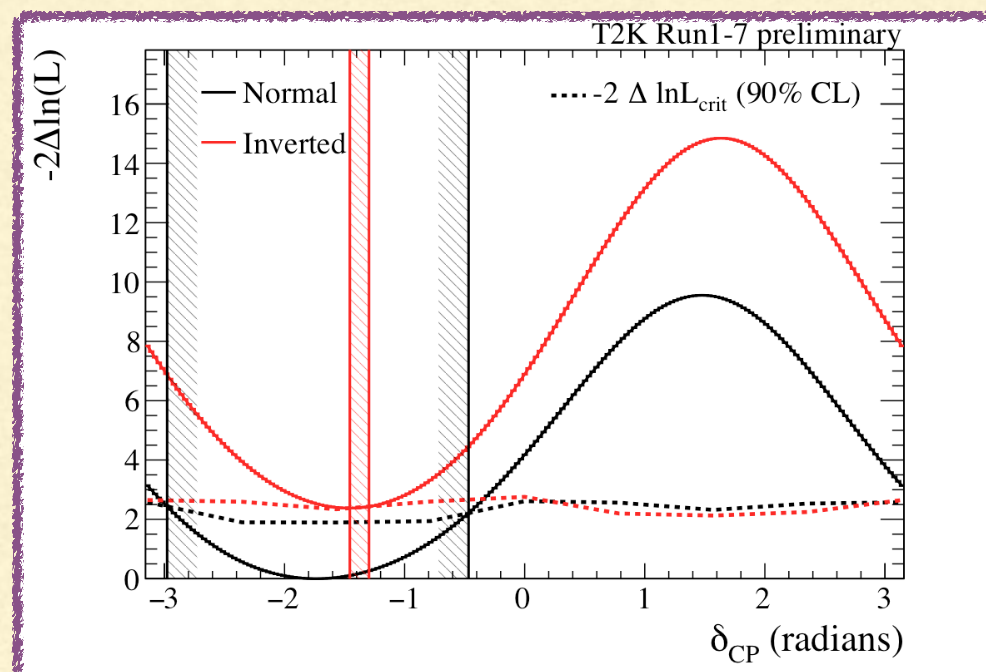
PARAMETER/MASS HIERARCHY	NORMAL MASS HIERARCHY	INVERTED MASS HIERARCHY
$\sin^2 2\theta_{32}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$\lvert \Delta m^2_{32} \rvert$ ($\times 10^{-3}$ eV^2)	$2.545^{+0.081}_{-0.084}$	$2.51^{+0.081}_{-0.083}$

ANALYSIS RESULTS: θ_{13} AND δ_{CP}

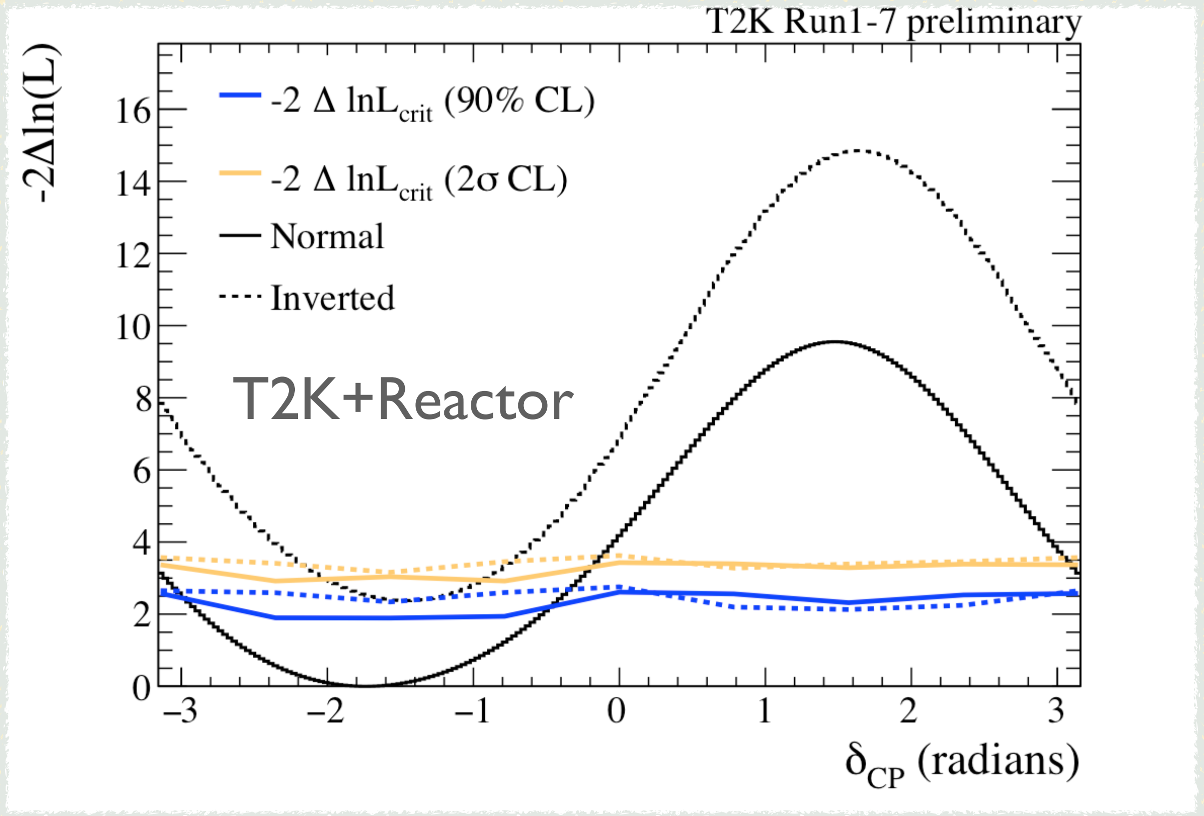


- Sensitivity to δ_{CP} with T2K data only data
- Good agreement with reactor experiments
- 90% C.L. for δ_{CP} (radians):
  - Normal mass hierarchy: [-2.948, -0.467]
  - Inverted mass hierarchy: [-1.466, -1.272]





ANALYSIS RESULTS: θ_{13} AND δ_{CP}

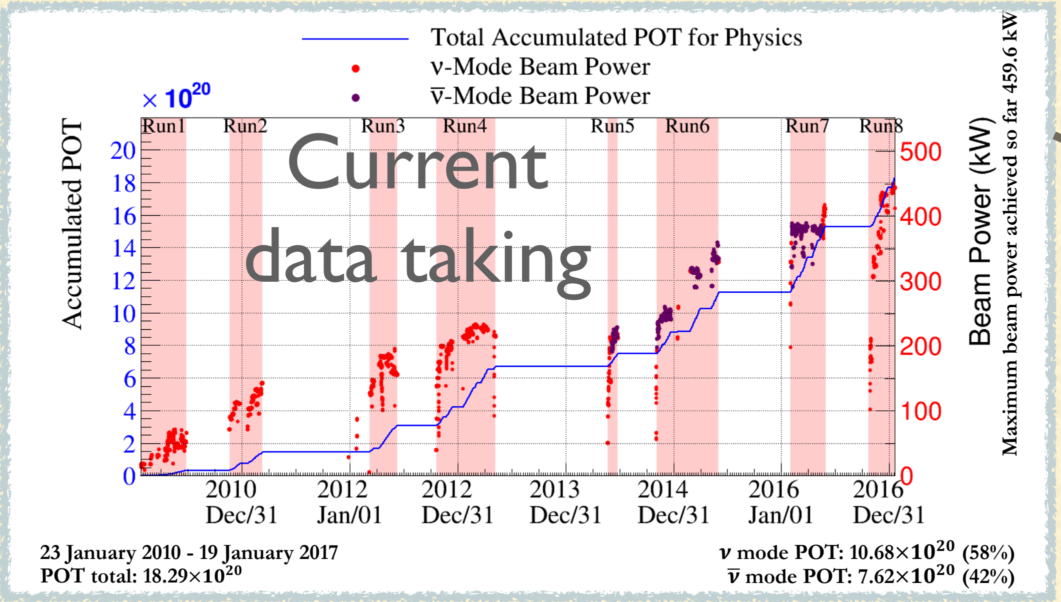


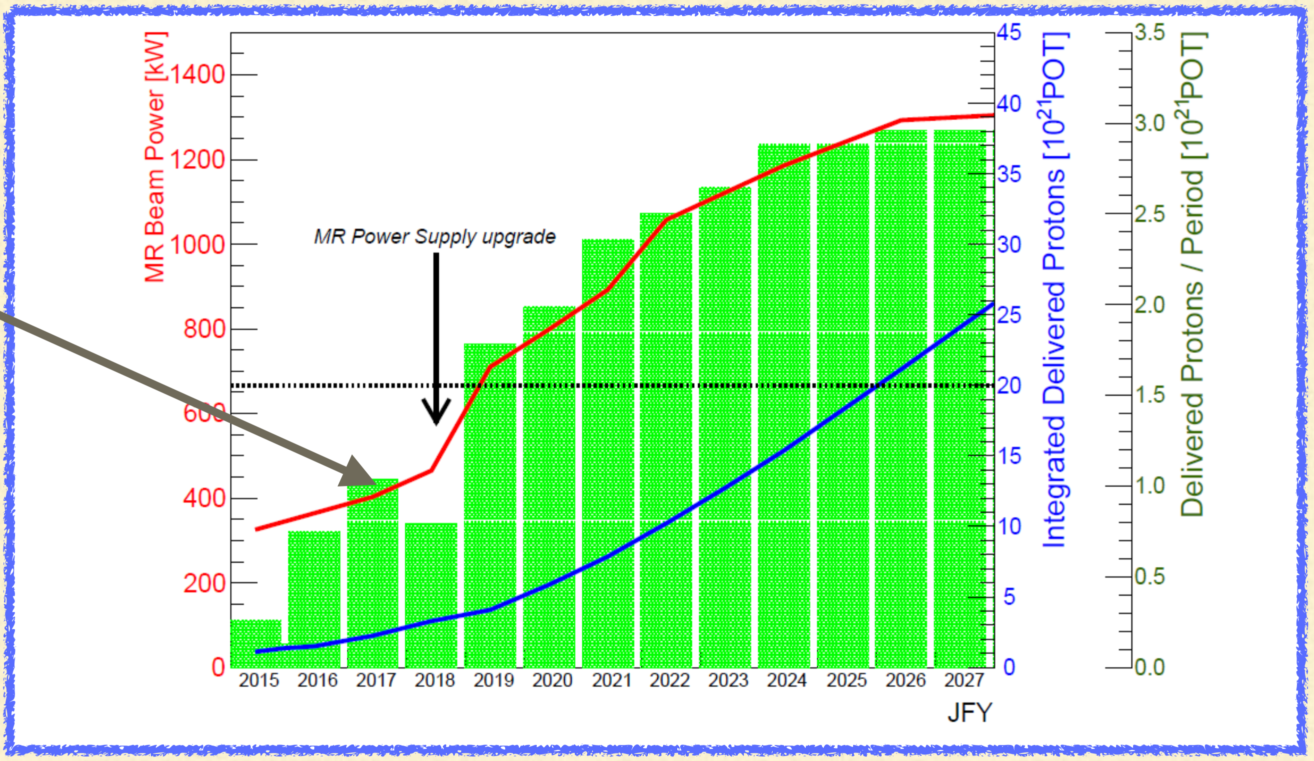
	ν_e-like		$\bar{\nu}_e$-like	
Mass hierarchy	Normal	Inverted	Normal	Inverted
δ_{CP} =-π /2	28.8	25.5	6.0	6.5
δ_{CP} =0	24.2	21.2	6.9	7.4
δ_{CP} =π/2	19.7	17.2	7.7	8.4
δ_{CP} =π	24.2	21.6	6.8	7.4
Data	**32**		**4**	

- Exclude $\sin(\delta_{CP})=0$ at 90% C.L.
- Observed events favour large CPV ($\delta_{CP} \approx -\pi/2$) and normal mass hierarchy
- Data implies more CPV → stronger limits than expected
    - "Statistical fluctuation"? → need further data

T2K FUTURE PROSPECTS

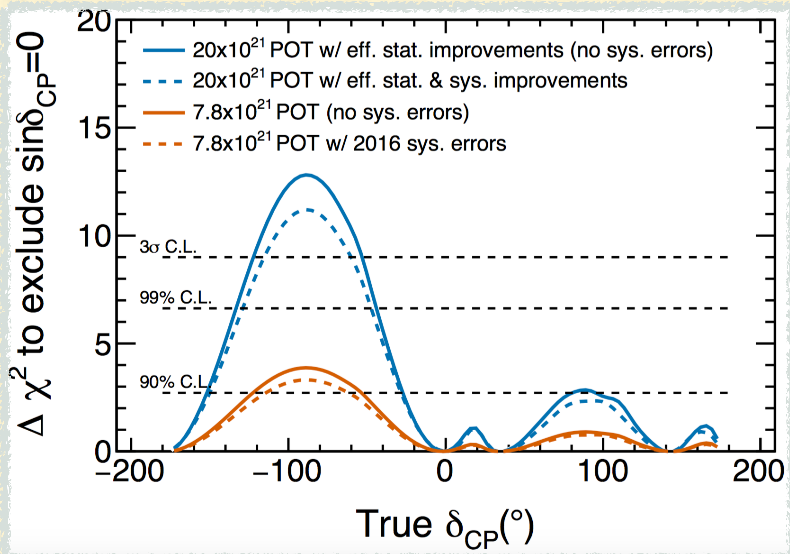
- $7.8\mathrm{x}10^{21}$ POT approved (expected by ~2021)
- Gain "effective" statistics: new CC-nonQE, multi-ring samples, expand Super-K FV
- Decrease systematic uncertainties: new ND280 samples + analysis improvements
- T2K phase-II proposal to start in ~2021 and run till 2026 (Hyper-Kamiokande time?):
    - Collect $\sim 20\mathrm{x}10^{21}$ POT
    - Increase beam power: 450 kW → 750kW → 1.3 MW
    - Horn current: 250 kA → 320 kA

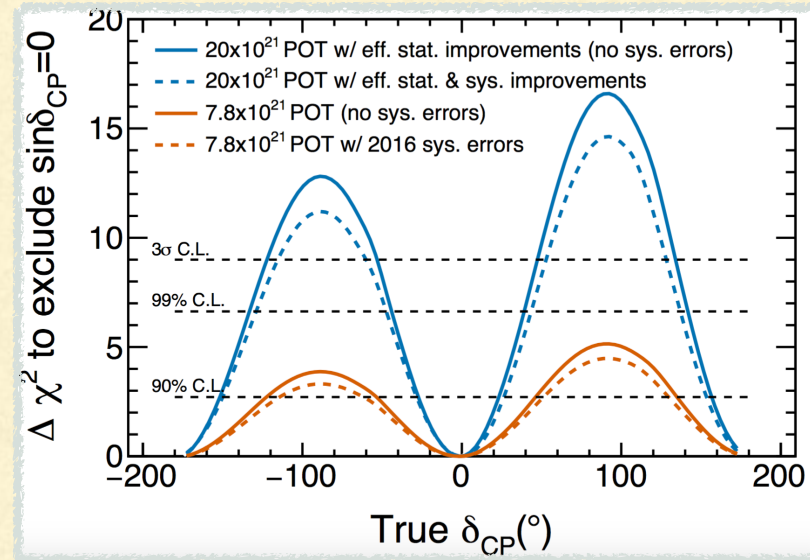




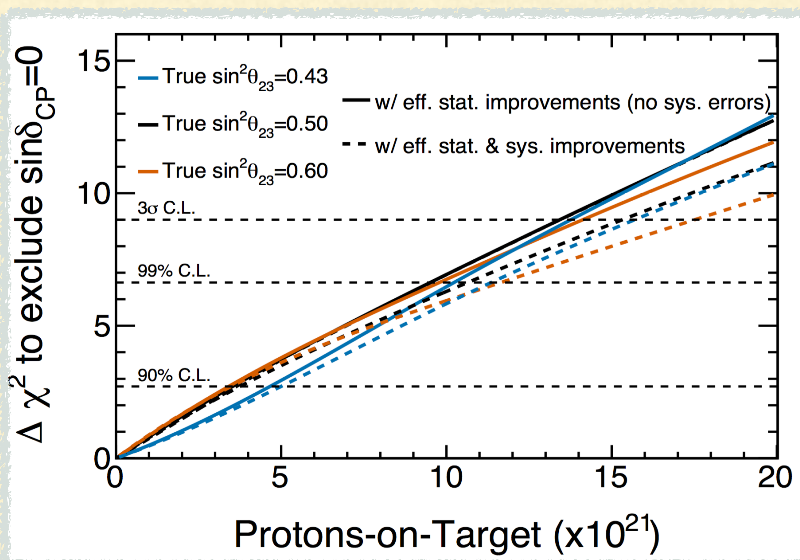
T2K FUTURE PROSPECTS: SENSITIVITY

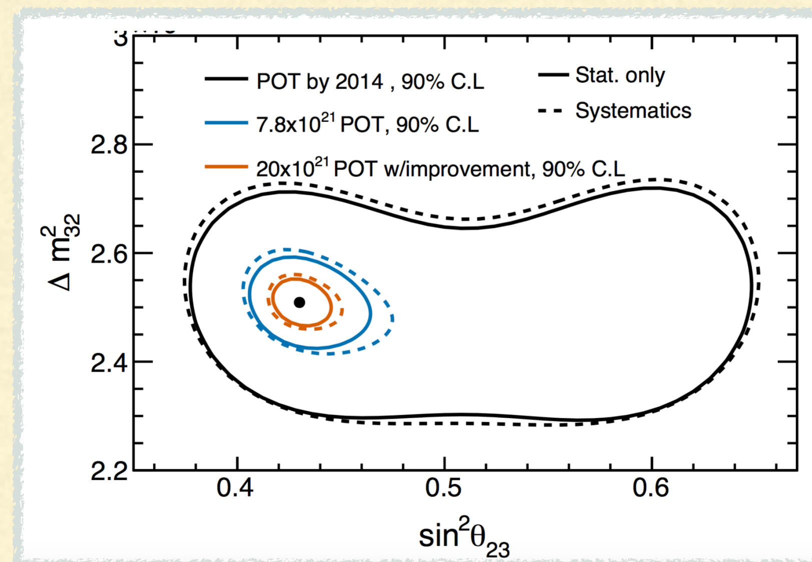
Unknown MH





Known MH

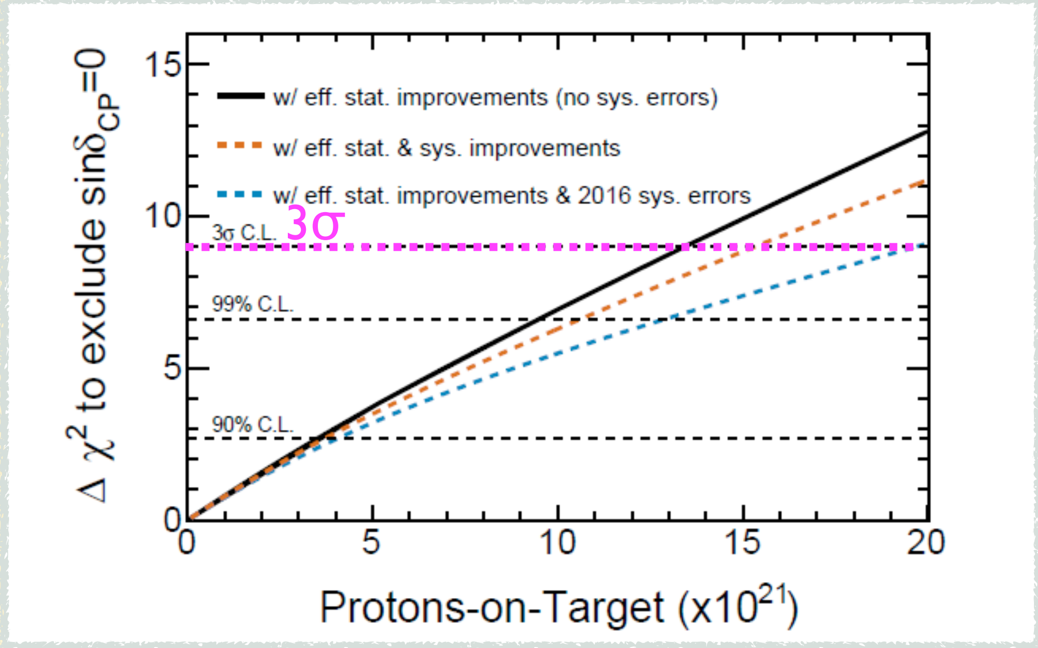




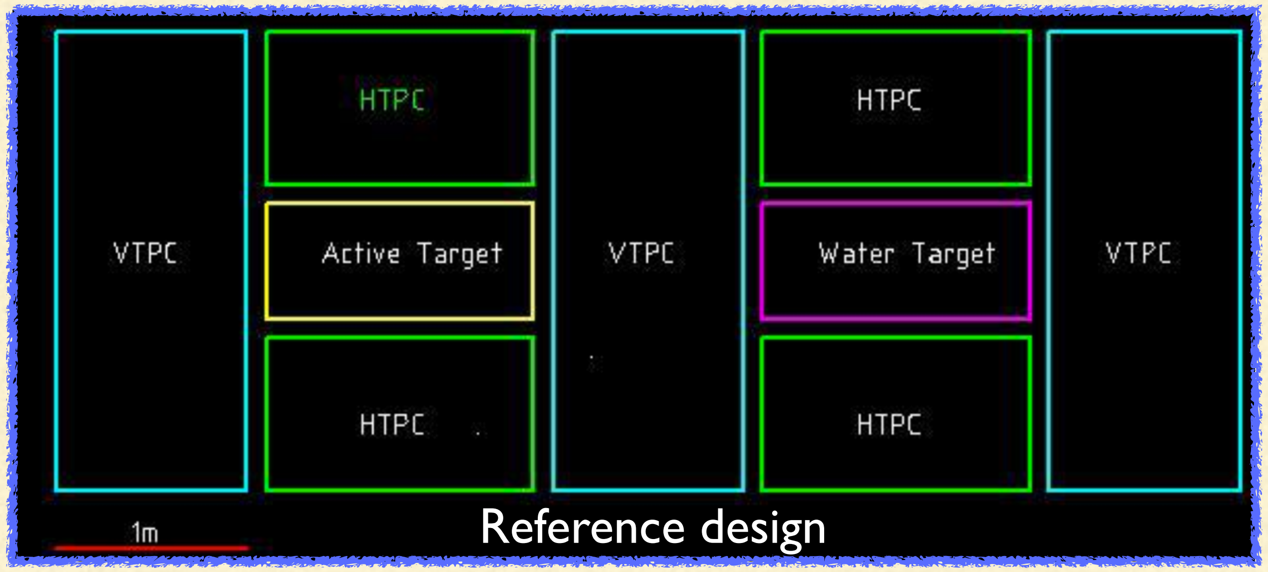
- Exclude no-CPV at more than 3σ level for δ_{CP} = -π/2 and NH.
- Measure θ_{23} with resolution of ≲1.7°

T2K FUTURE PROSPECTS: NEAR DETECTOR UPGRADE

- Reduction of systematic uncertainties is crucial
  - ~18% (2011) → ~9% (2014) → ~6% (2016) → 4%(2020..)?
- ND280 measurements are important



- Possible upgrade of T2K near detector: target date ~2020
- New design (work on-going):
  - improve acceptance
  - increase mass of water target
- Test detectors in J-PARC for target design:
  - INGRID water module (2016)
  - WAGASCI/Baby-MIND (from 2017)



Existing TPCs, New TPCs, Targets (Water) + surrounding calorimeters

SUMMARY

- <u>**T2K is working steadily on its quest on filling neutrino puzzle**</u>
- With $\simeq 15\times10^{20}$ POT (~20% expected statistics):
    - **Very precise measurements of $\sin^2 2\theta_{23}$ and Δm^2_{32}**
    - Consistent disappearance results for neutrino and antineutrino: **no CPTV**
    - Measurement of **$\sin^2\theta_{13}$ in agreement with reactor data**
    - **First! exclusion of CP-conservation at 90% C.L.**
- Short term plans:
    - Continuous data taking with beam power increase to 750 kW
    - New analysis samples in far and near detectors to increase statistics and improve systematics
- **T2K Phase-II proposed**, extended run for ~2020-2026. Smooth transition to Hyper-K time
    - Accumulate 20×10^{21} POT to reach 3σ exclusion of non-CPV for certain δ_{CP} and MH
    - Accelerator upgrade to reach 1.3 MW
    - Possible near detector upgrade to further reduce systematic uncertainties

T2K

Thank You

～500 members, 63 Institutes, 11 countries

T2K Experiment International Collaboration

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

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

Germany
Aachen

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

Japan
ICRR Kamioka
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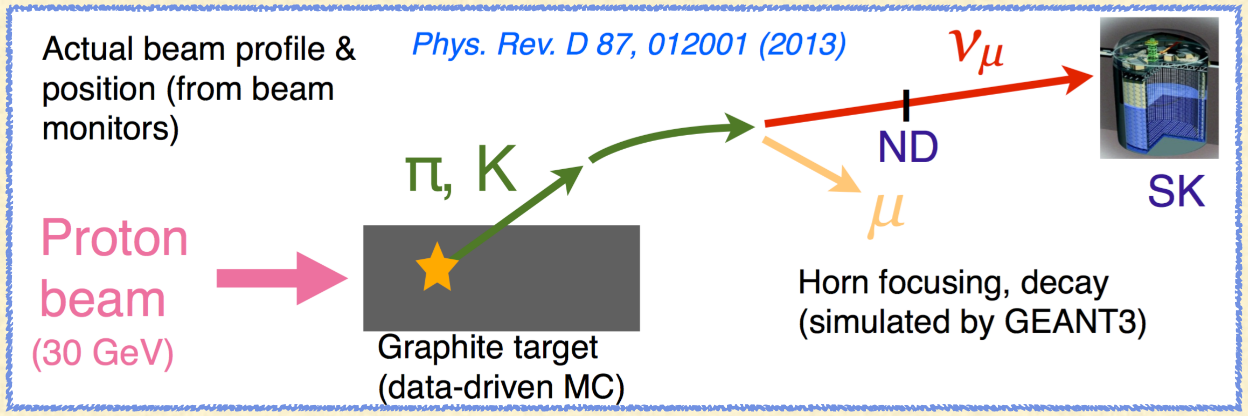
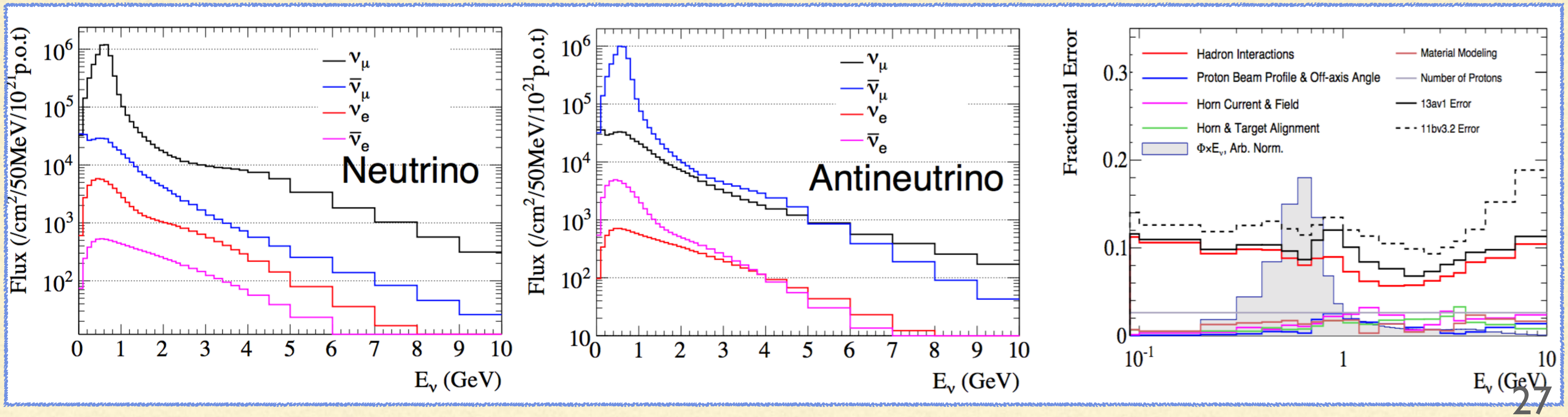
T2K NEUTRINO FLUX PREDICTION

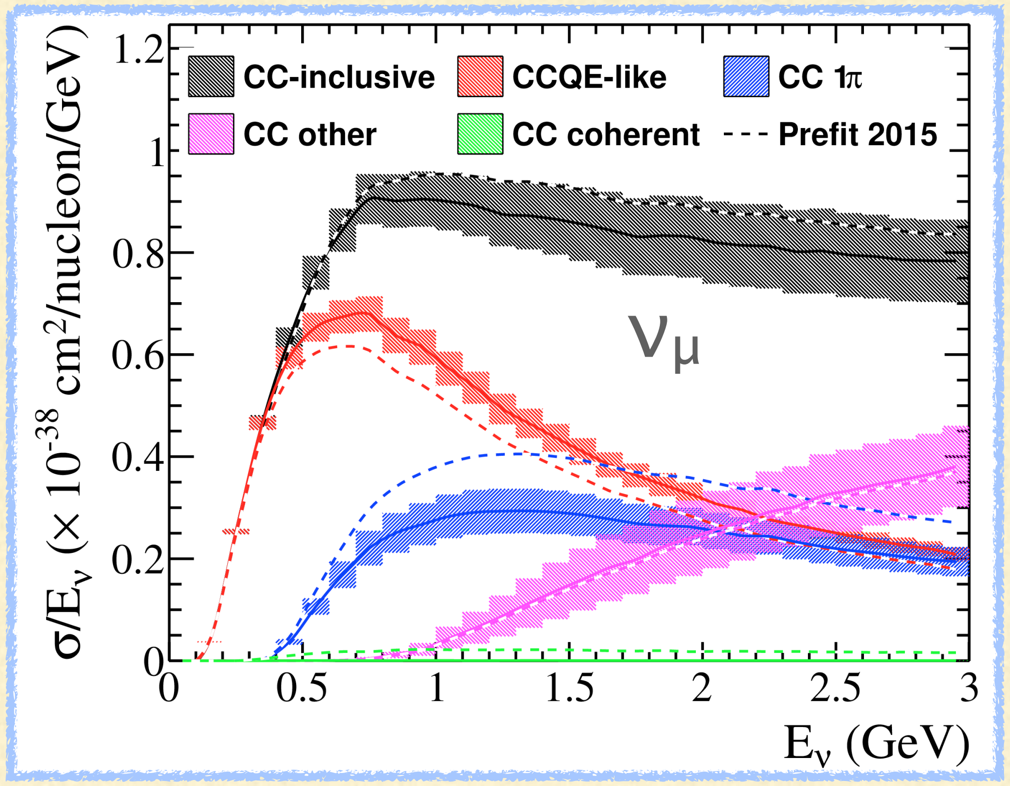
- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
  - Measurement of pion/kaon production of 31 GeV/c proton beam with carbon target
  - Thin target (4%λ) and T2K replica target
  - Reduction of uncertainties: ~30% to ~10%
- Intrinsic ν_e background at ~0.5% level

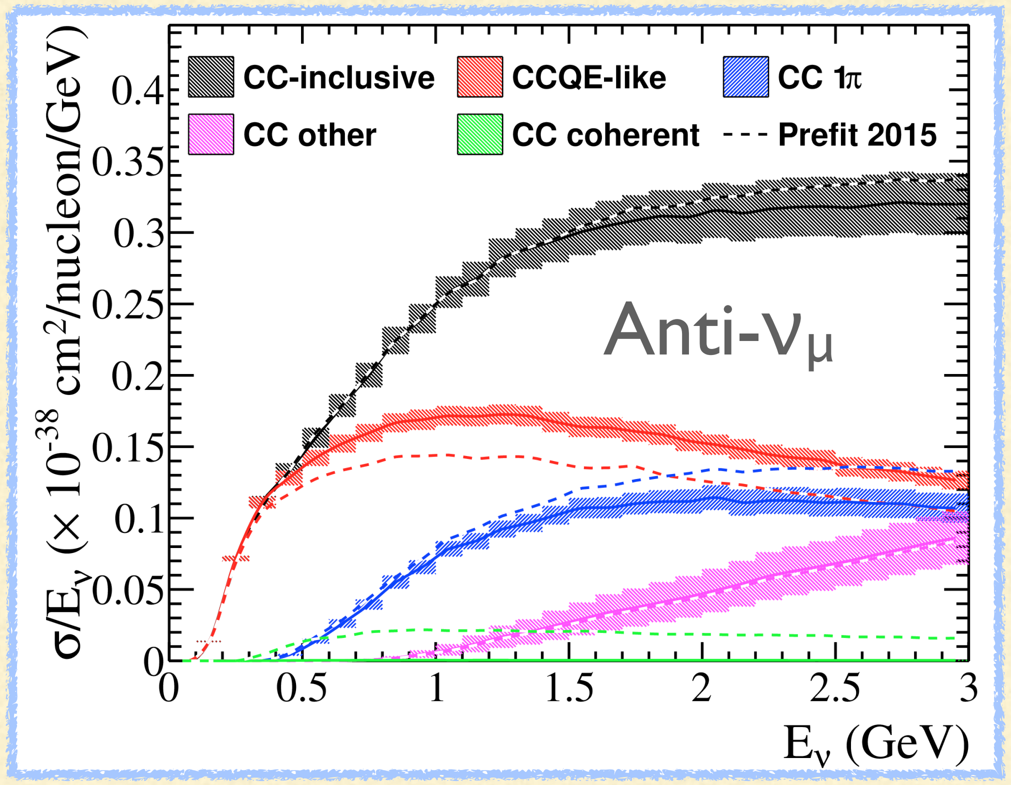




T2K NEUTRINO INTERACTION MODEL

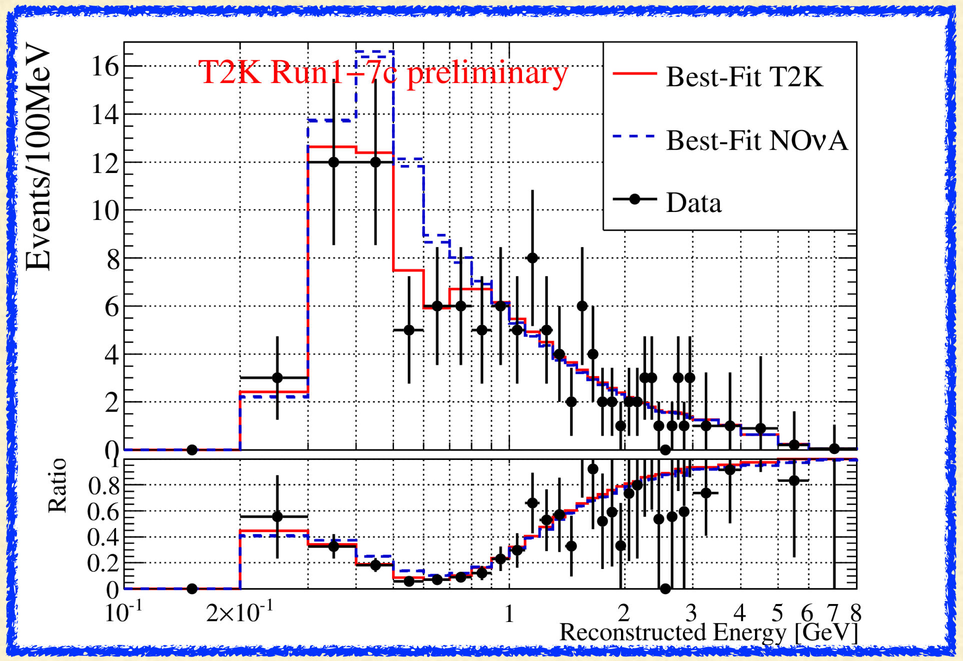
- NEUT neutrino generator
- Model tuned to external data: MiniBooNE, MINERνA, bubble chambers`
- CCQE: Relativistic Fermi Gas + relativistic Random Phase Approximation for nuclear system
- Multinucleon processes (2p2h) included based on J.Nieves model, Phys. Lett. B 707, 72 (2012)
- Pre-(ND280)fit uncertainty for Super-K: ~7.5%

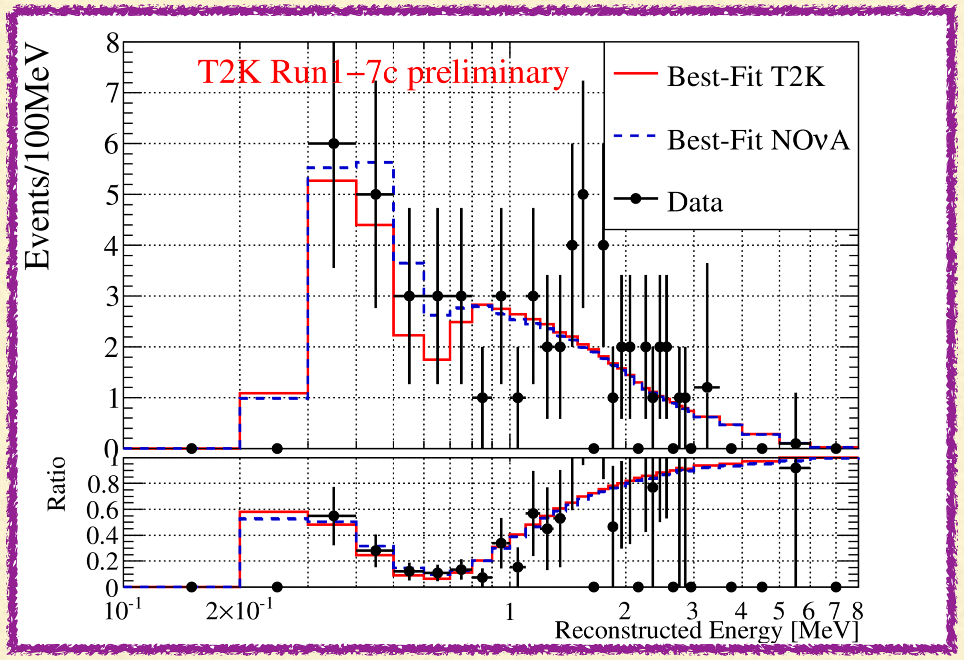




COMPARISON WITH NOVA BEST-FIT

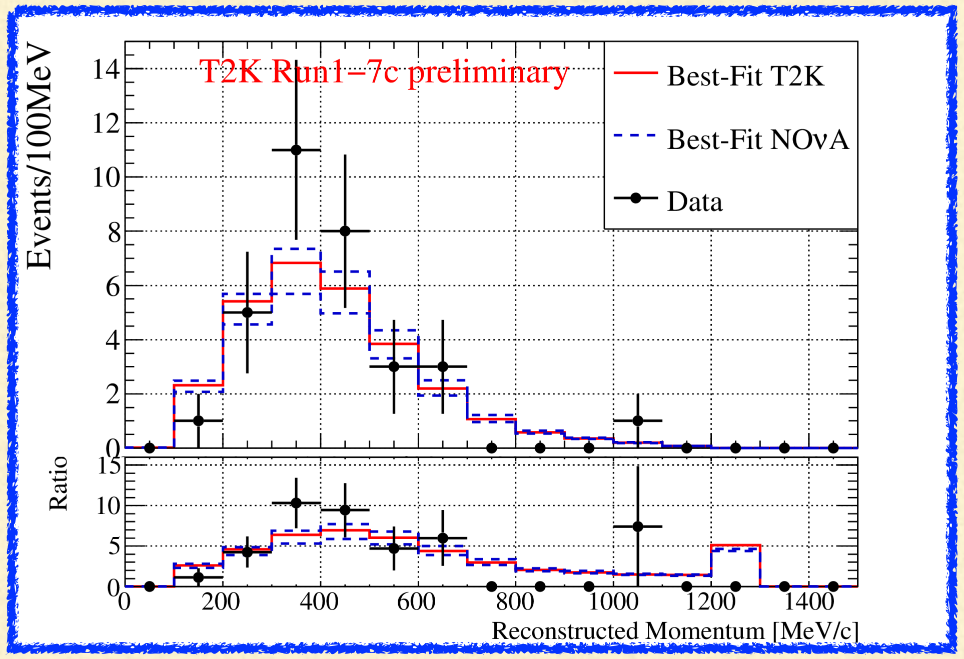
ν_μ
μ-like

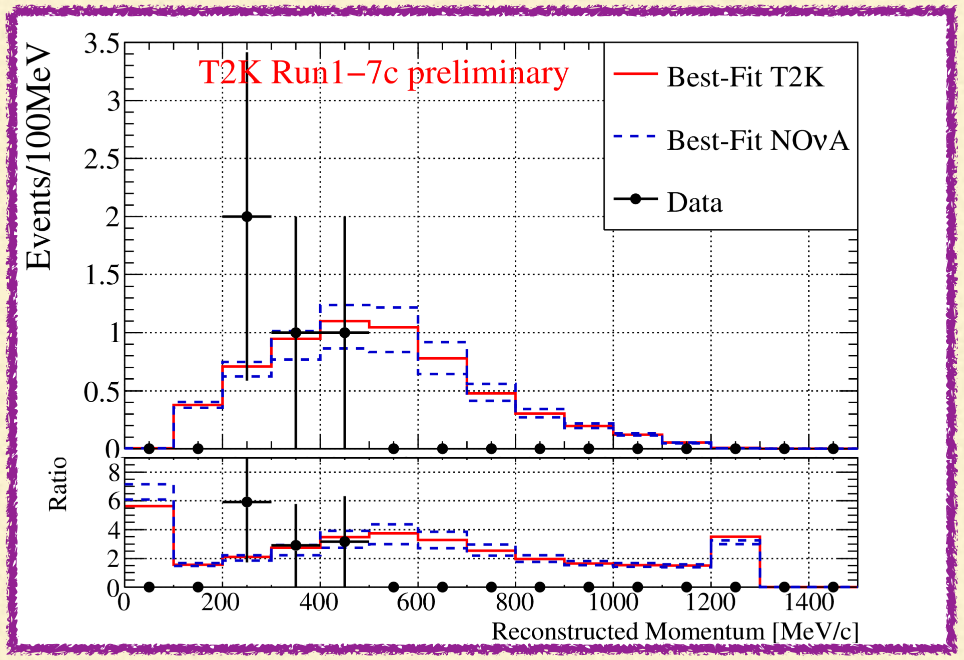




anti-ν_μ
μ-like

ν_e
e-like



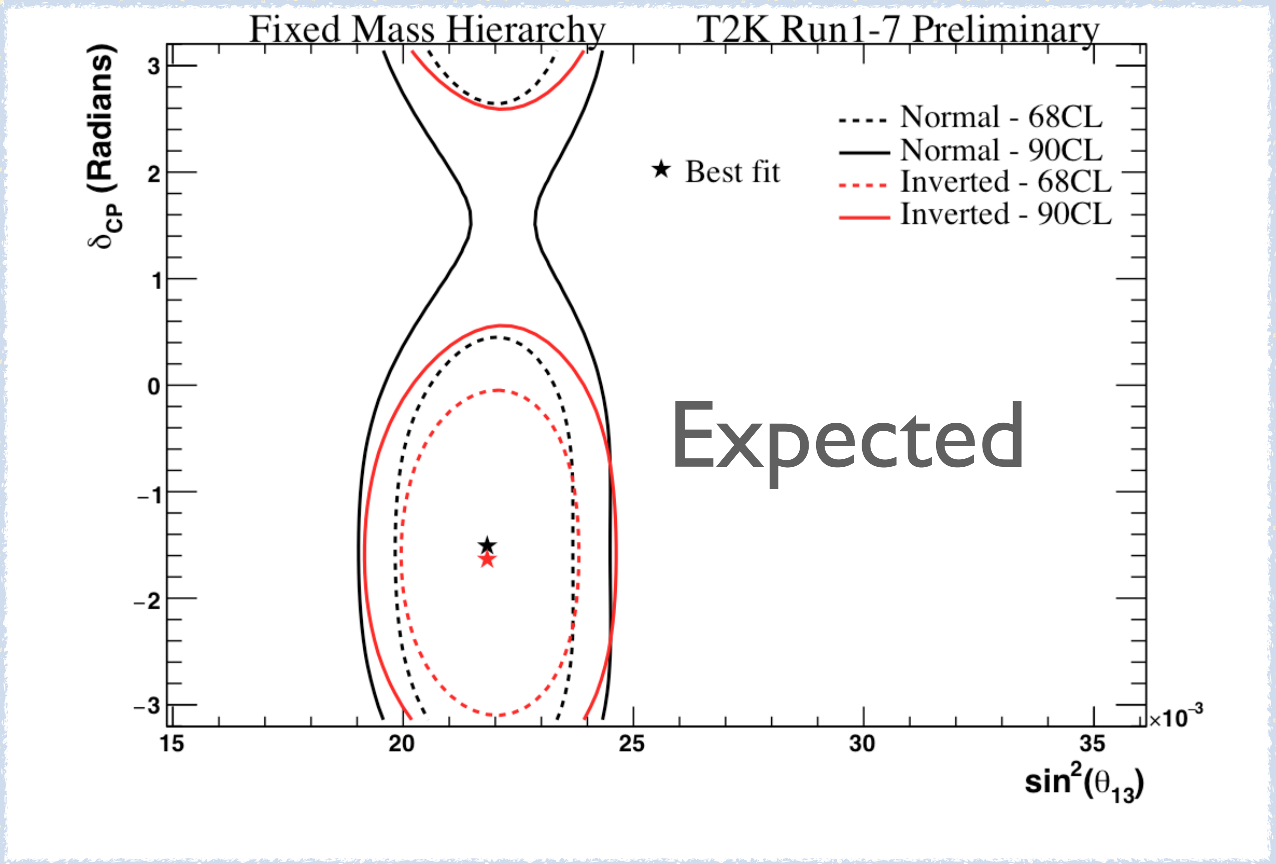


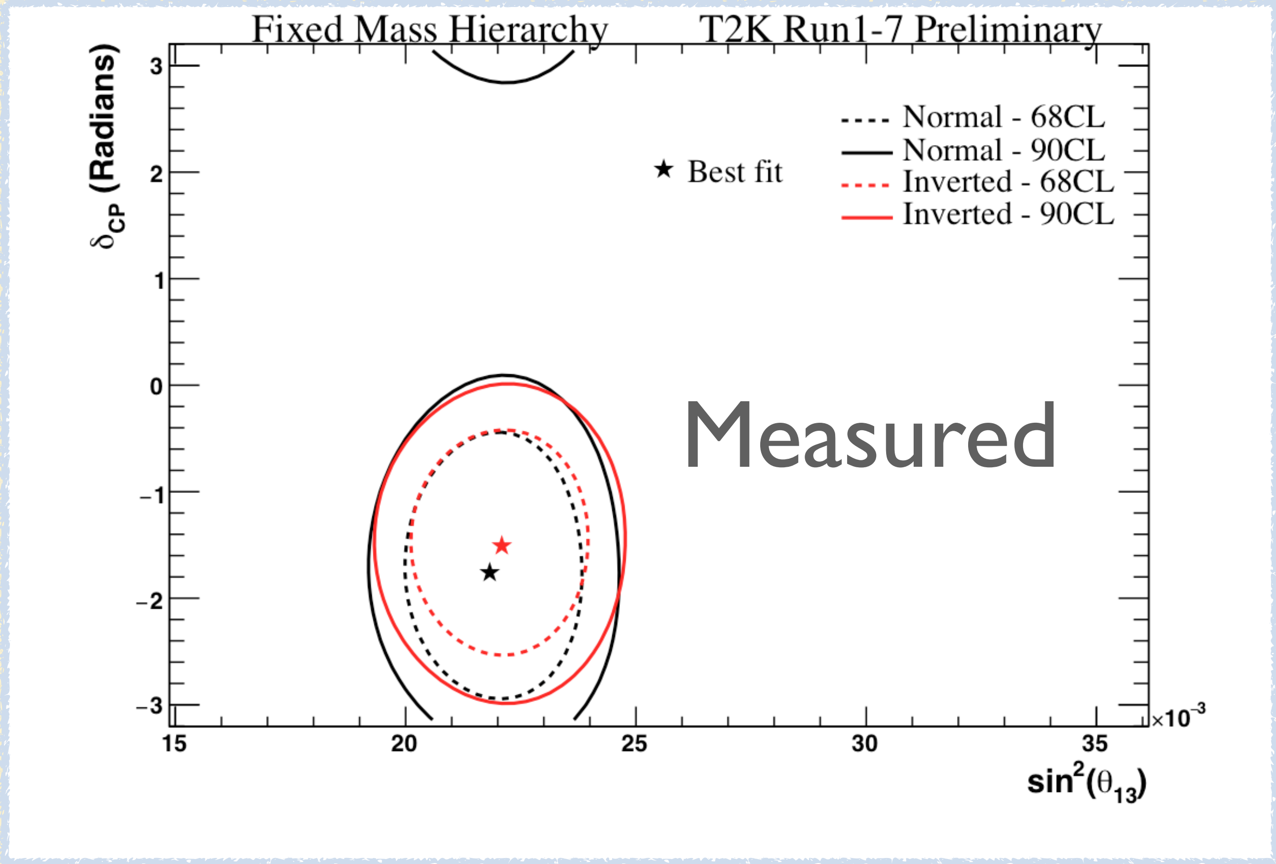
anti-ν_e
e-like

ν-mode

anti-ν-mode

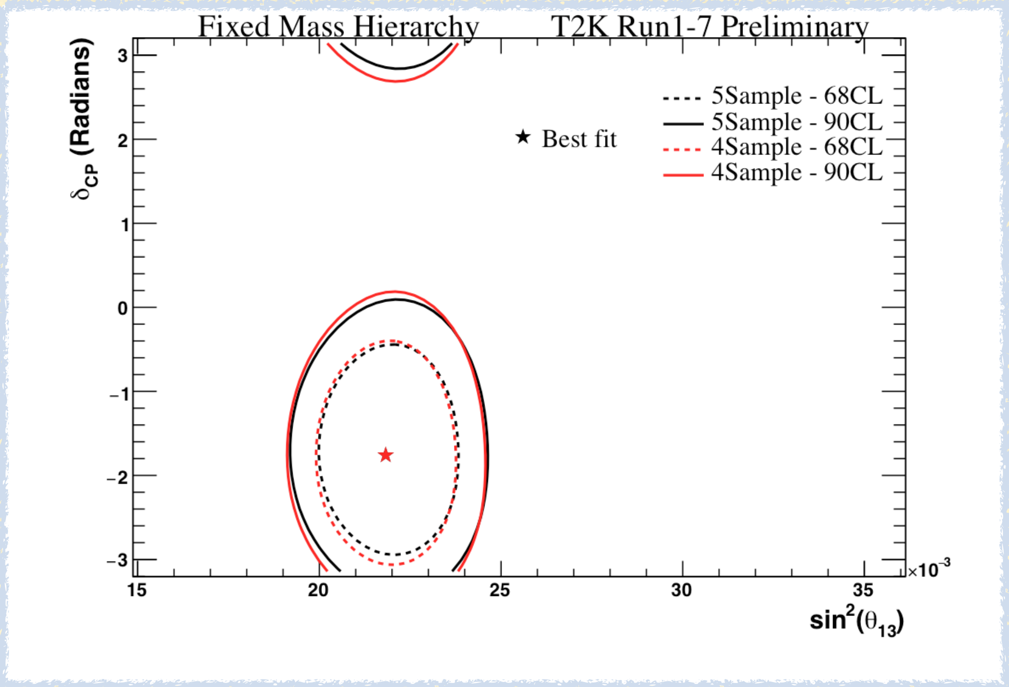
ANALYSIS RESULTS: θ_{13} AND δ_{CP} EXPECTED SENSITIVITY

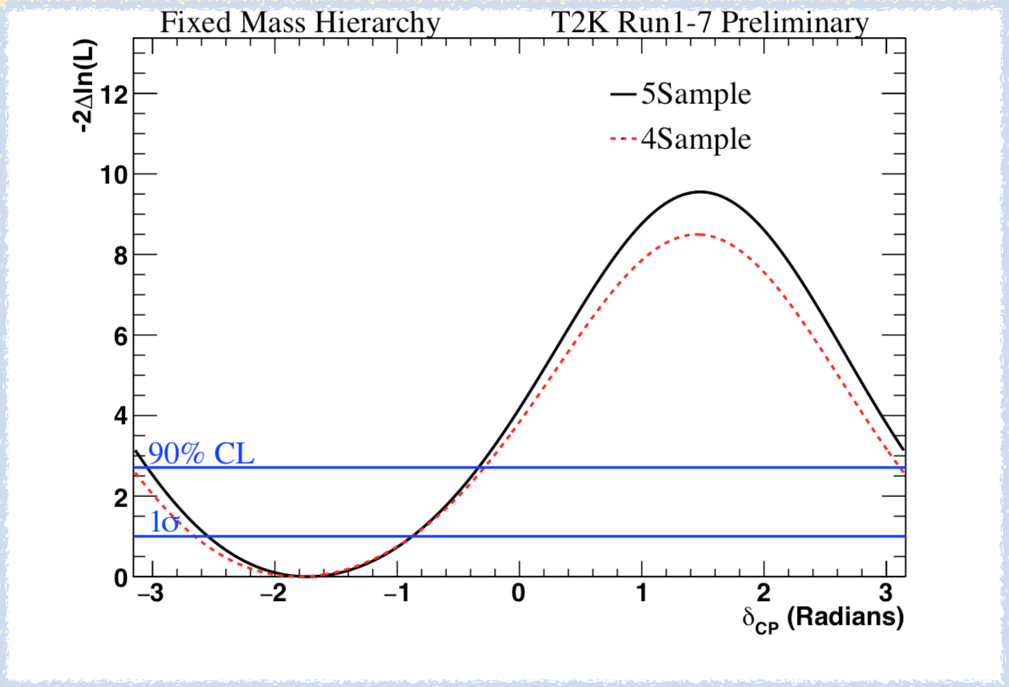


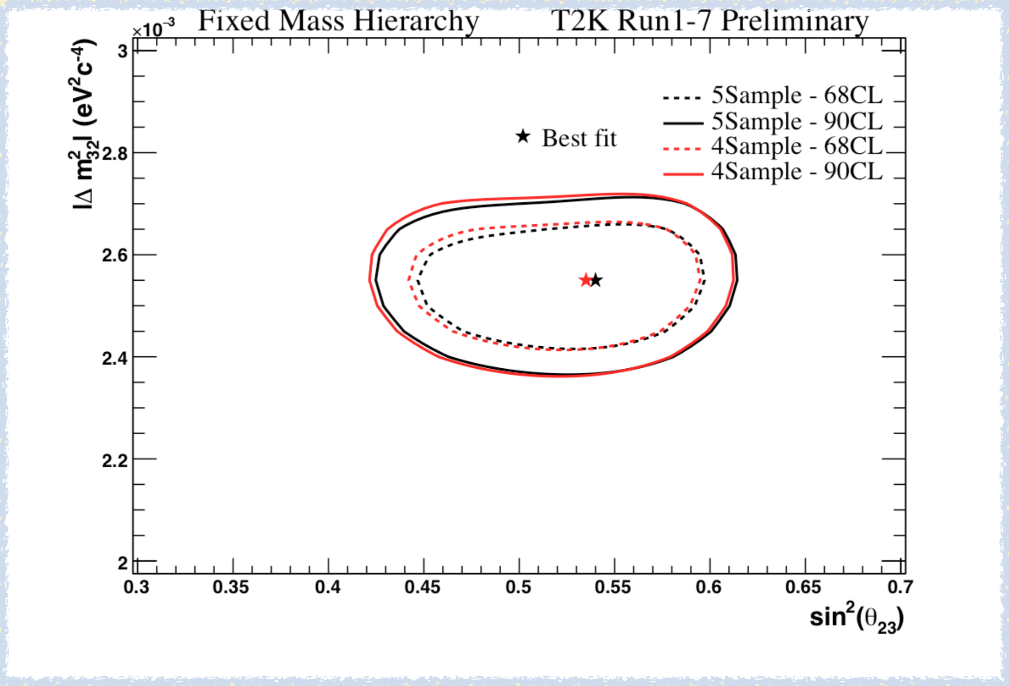


- Expected sensitivity for $\delta_{CP} = -1.601$ and $\sin^2\theta_{13} = 0.0217$ Asimov dataset
- Reactor constrain applied

EFFECT OF CC1π SAMPLE



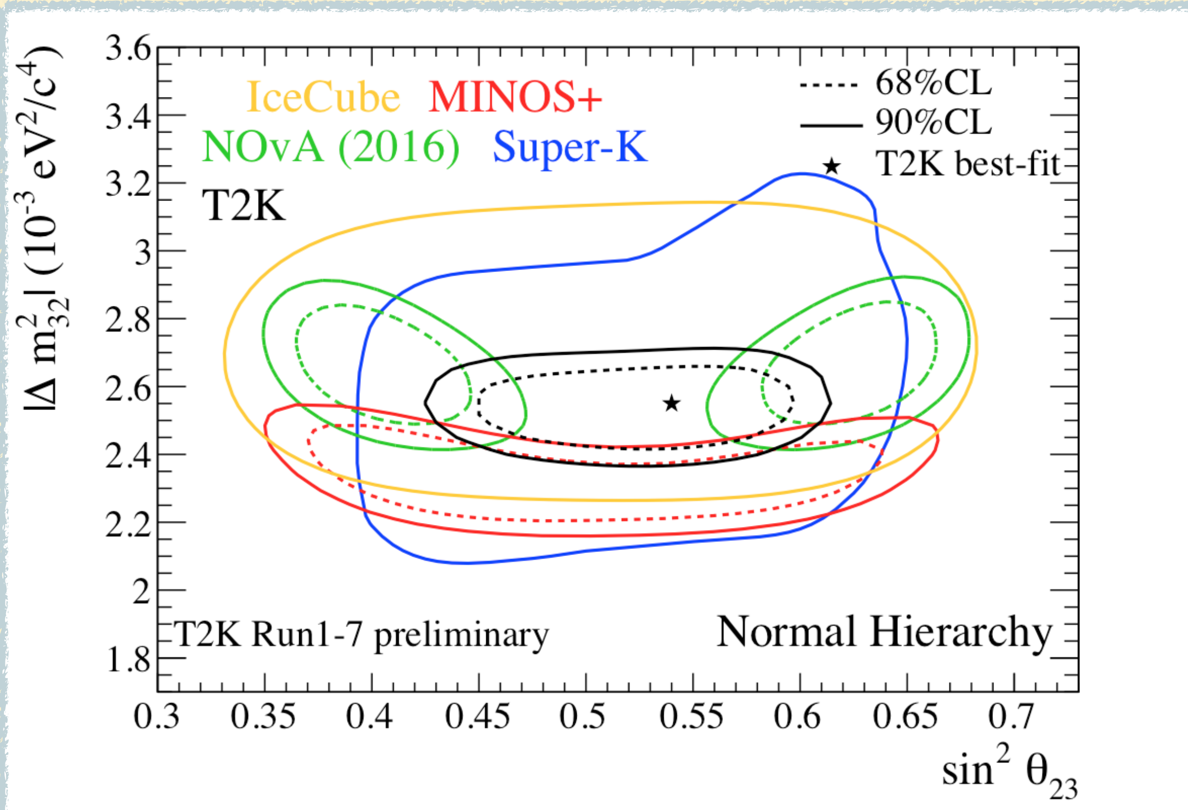


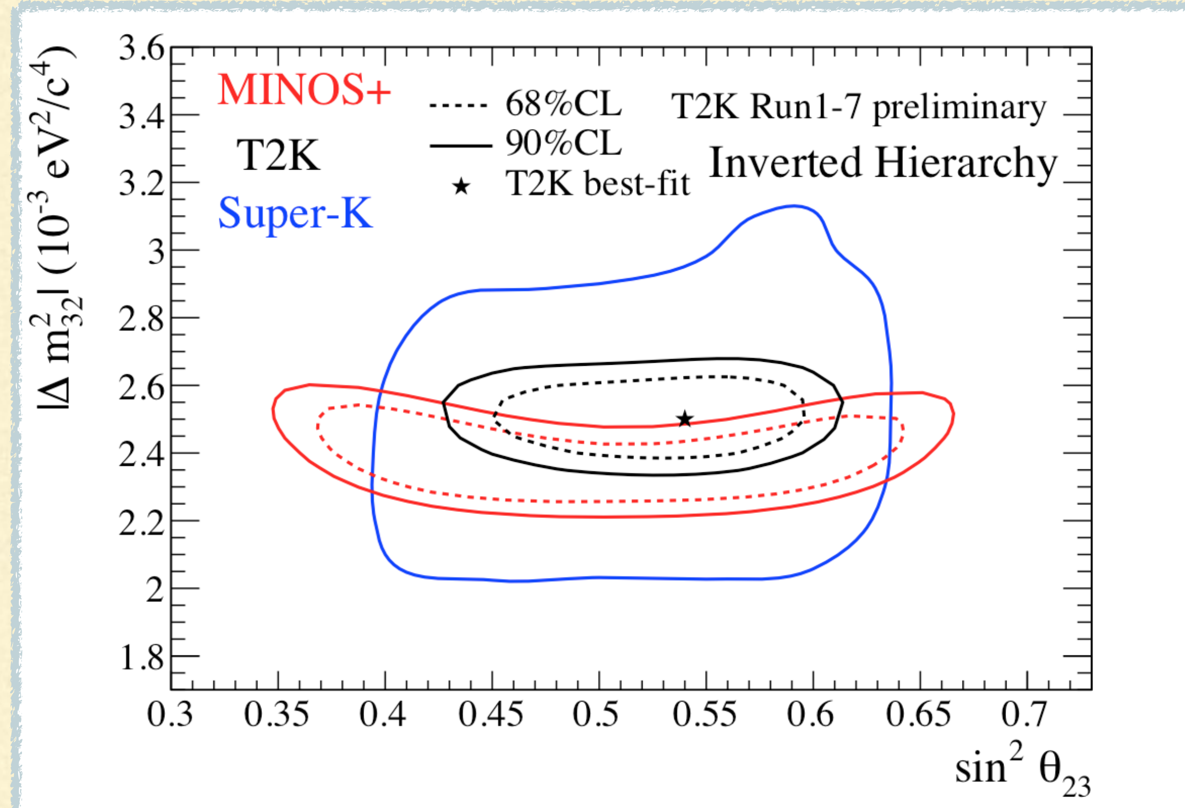


Normal mass hierarchy
Reactor constrain applied

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e CCQE	28.7	24.2	19.6	24.1	32
$\nu_e CC1\pi^+$	3.1	2.8	2.3	2.7	5

ANALYSIS RESULTS: θ_{23} AND Δm^2_{32}



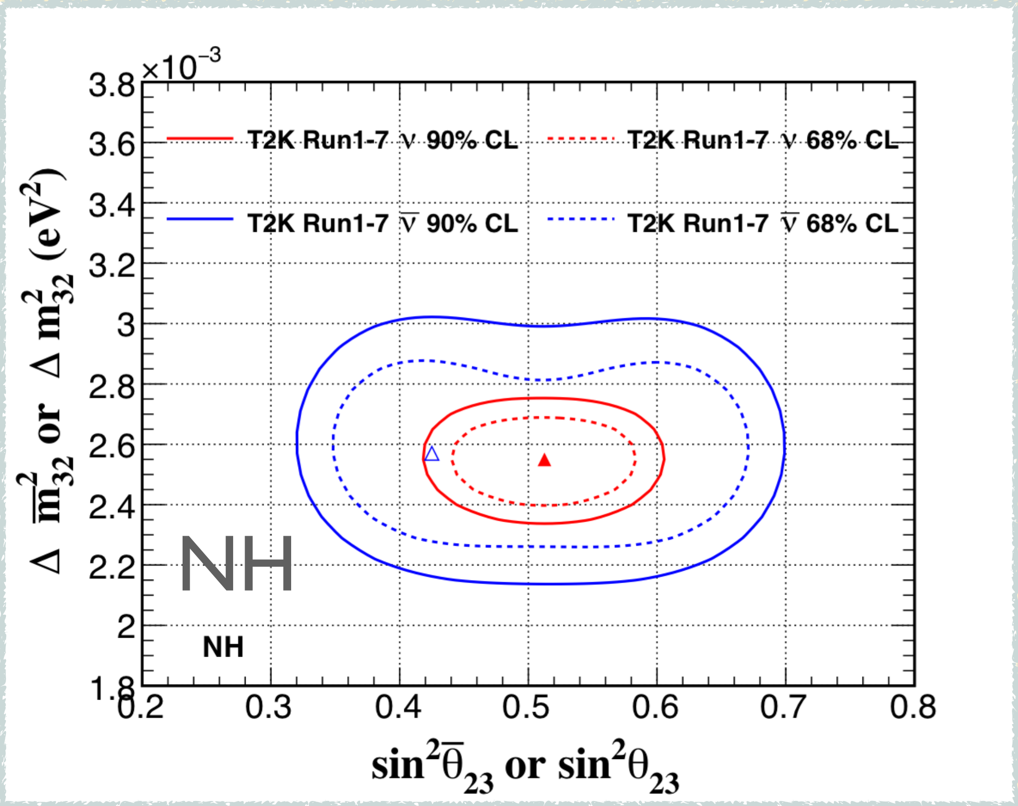


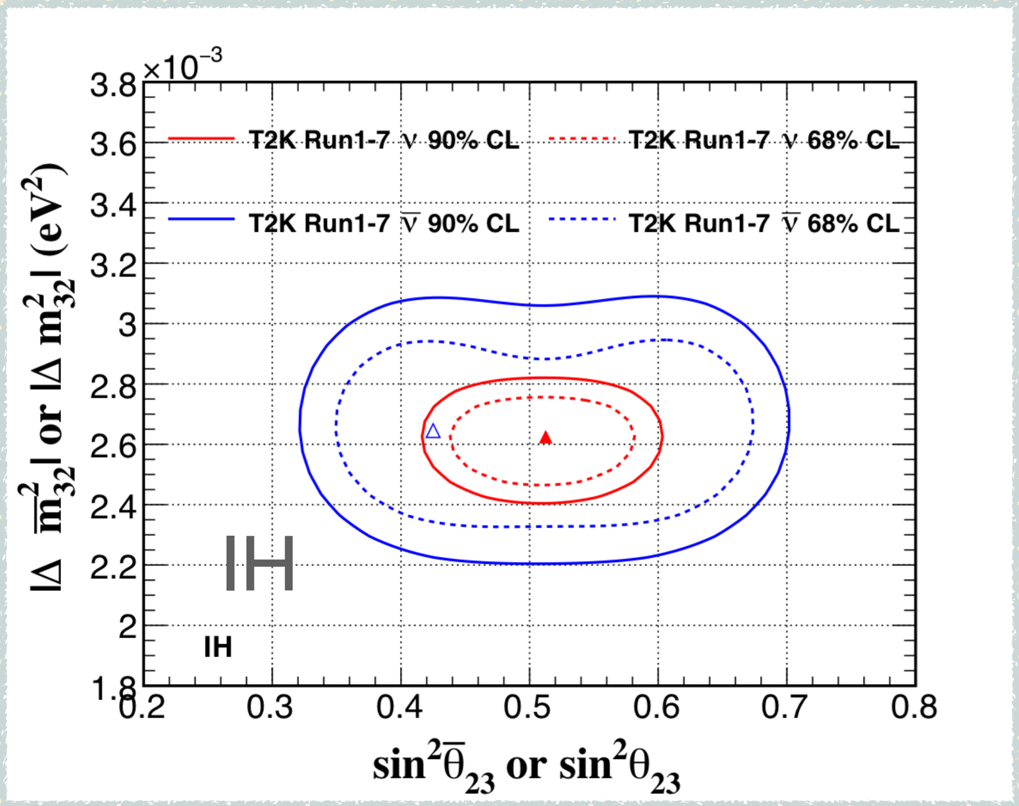
- Joint analysis with reactor constraint: $\sin^2 2\theta_{13}=0.085\pm0.05$
- T2K data consistent with maximal mixing
- Compatible with other experiments (intervals for fixed mass hierarchy)

PARAMETER/MASS HIERARCHY	NORMAL MASS HIERARCHY	INVERTED MASS HIERARCHY
$\sin^2 2\theta_{32}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$\lvert \Delta m^2_{32} \rvert$ ($\times 10^{-3}$ eV^2/c^4)	$2.545^{+0.081}_{-0.084}$	$2.51^{+0.081}_{-0.083}$

CPT INVARIANCE TEST: ν_μ AND anti-ν_μ DISAPPEARANCE

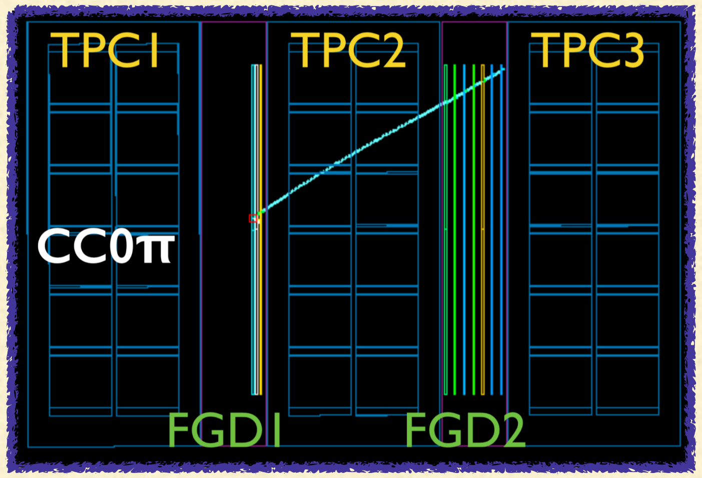
- Strategy
  - Assign independent oscillation parameters for antineutrinos
  - Neutrino samples constrain "wrong-sign" background
  - Test CPT: $\theta_{23} \neq \bar{\theta}_{23}$ and $\Delta m^2_{32} \neq \Delta \bar{m}^2_{32}$
- Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved

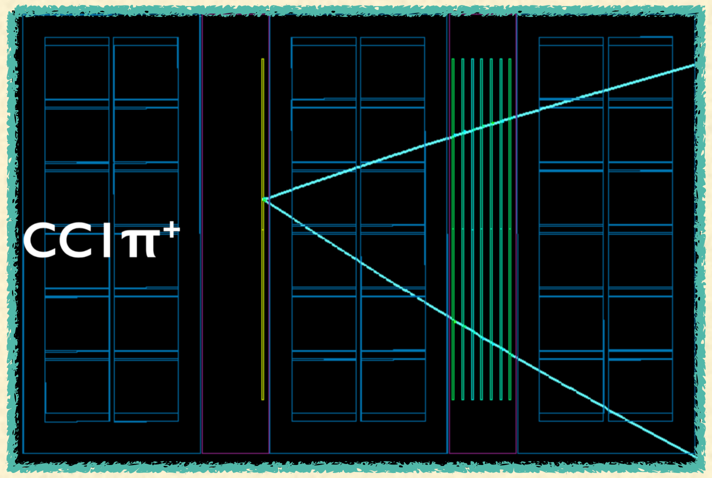


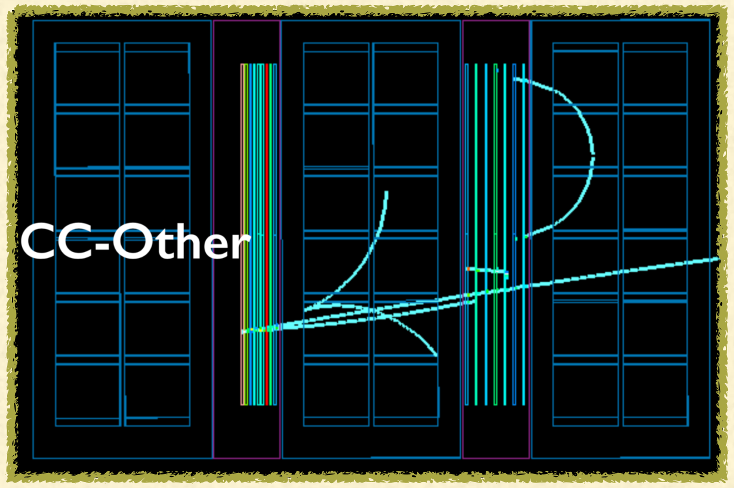


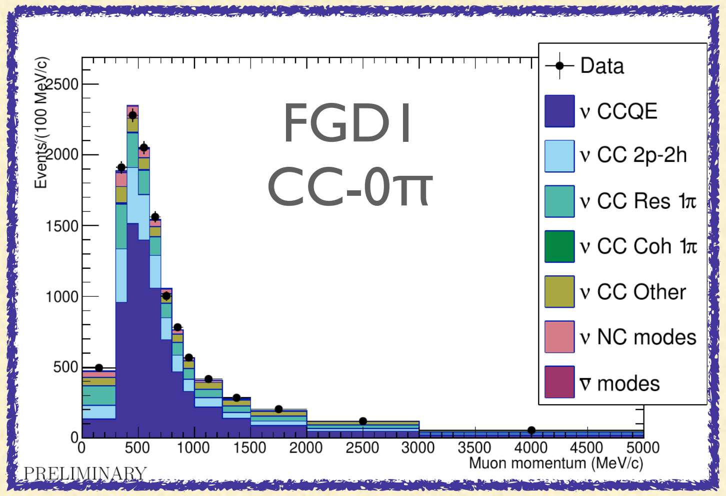
ND280 ANALYSIS: ν-MODE

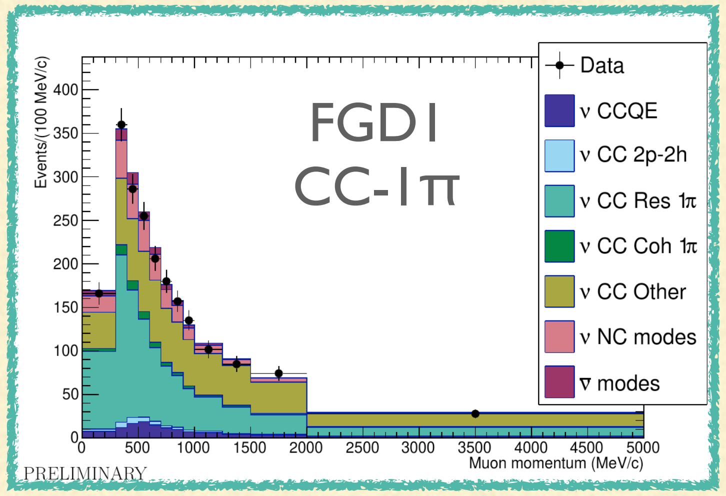
- ND280 samples in FGD1 and FGD2: ν_μ interactions in ν mode running
  - CC-0π: muon and no pions in the final state
  - CC-1π: muon and π^+ in the final state
  - CC-Other: all other CC interactions (DIS dominated)

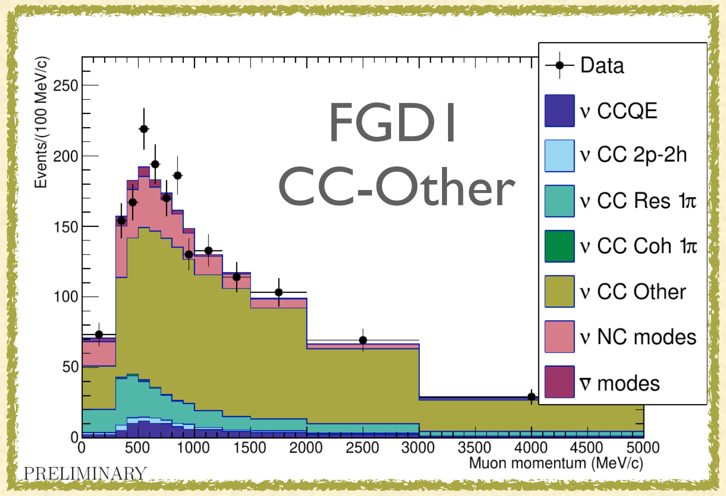






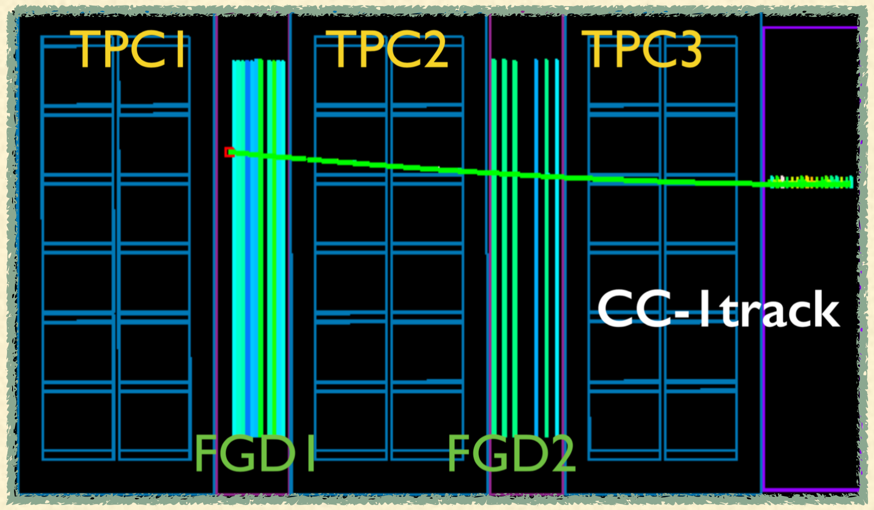


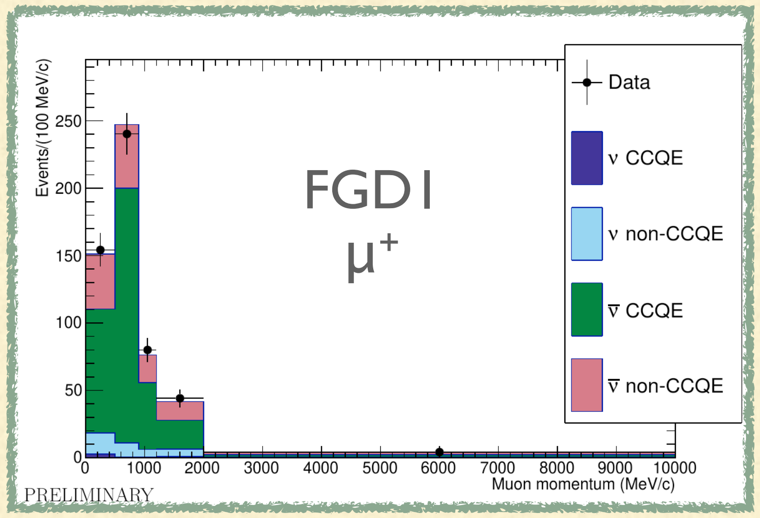


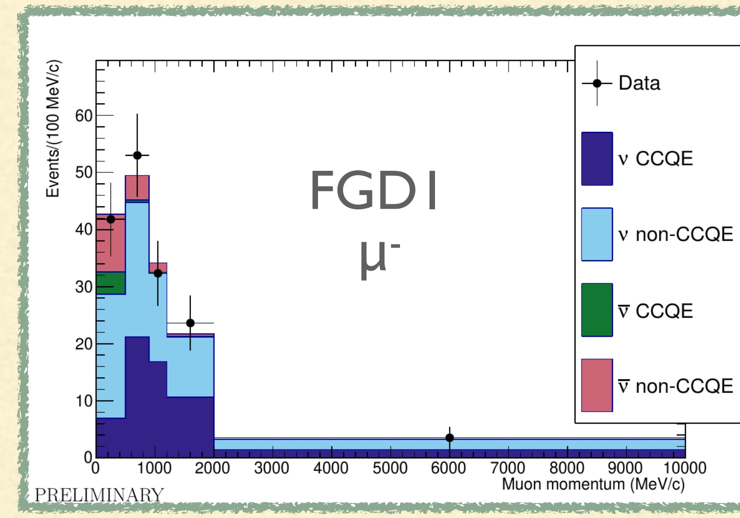


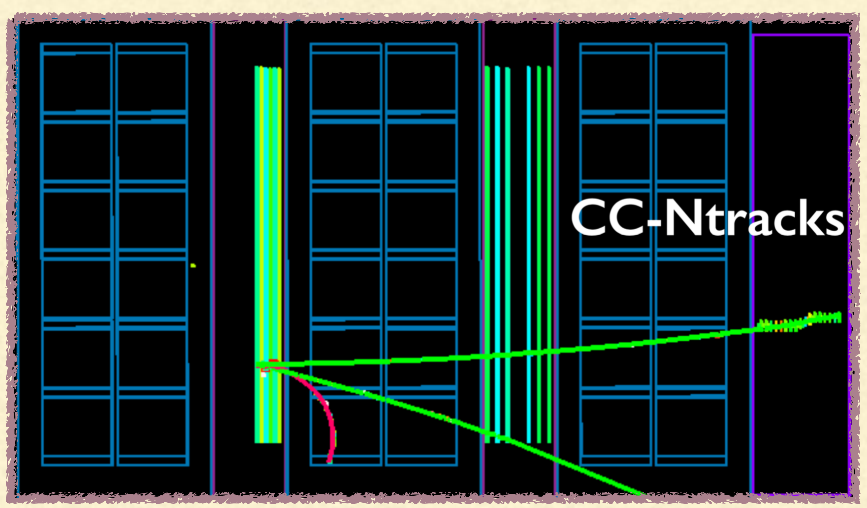
ND280 ANALYSIS: ANTI-ν-MODE

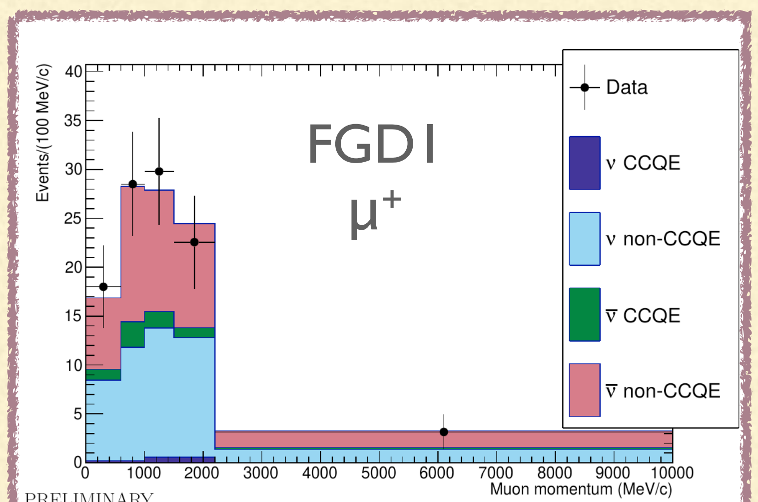
- ND280 samples in FGD1 and FGD2
- CC-1tracks and CC-Ntrack samples
- μ^+ samples and μ^- to constrain “wrong-sign” background

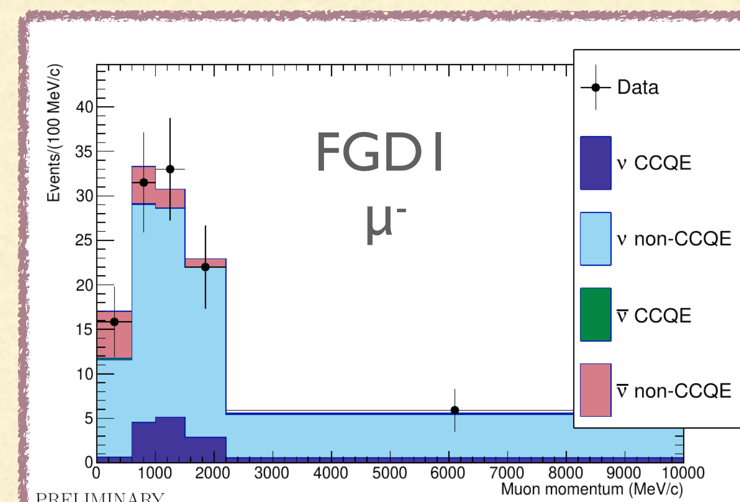






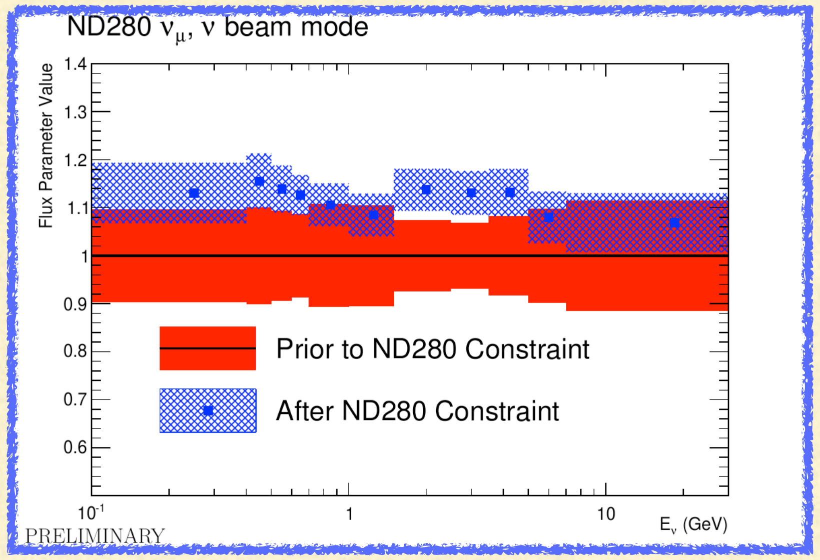


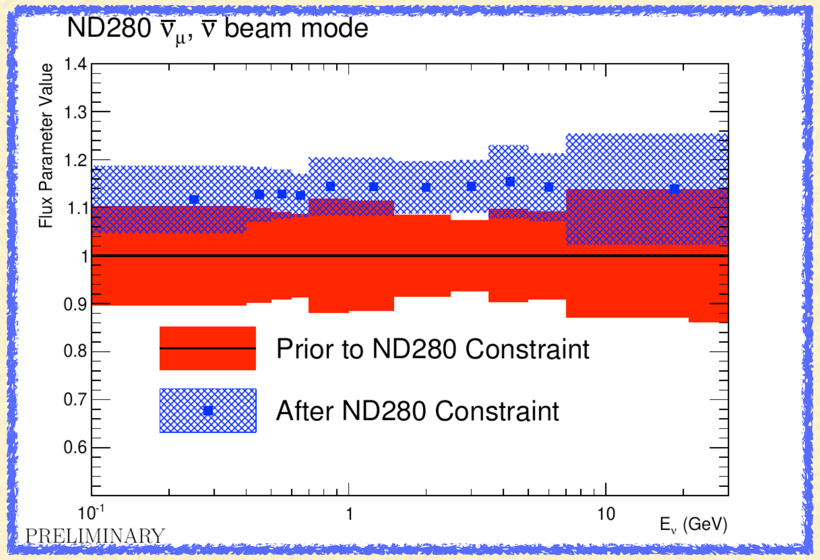




ND280 INPUTS TO OSCILLATION ANALYSIS

- Each model parameter (flux + neutrino interactions) has its uncertainty
- Fit to ND280 data constrains flux and cross-section model, uncertainties propagated to SK as covariance
    - Significant reduction of systematic uncertainties





Total N_{SK} Fraction Uncertainty, %		ν_μ	ν_e	ainti-ν_μ	anti-ν_e
Flux	W/O ND280	7.6	8.9	7.1	8.0
Cross section	W/O ND280	7.7	7.2	9.3	10.1
Flux and cross section	**W/ ND280**	**2.9**	**4.2**	**3.4**	**4.6**
Final/sec. hadronic interactions	—	1.5	2.5	2.1	2.5
Far detector	—	3.9	2.4	3.3	3.1
Total	W/O ND280	12.0	11.9	12.5	13.7
Total	**W/ ND280**	**5.0**	**5.4**	**5.2**	**6.2**