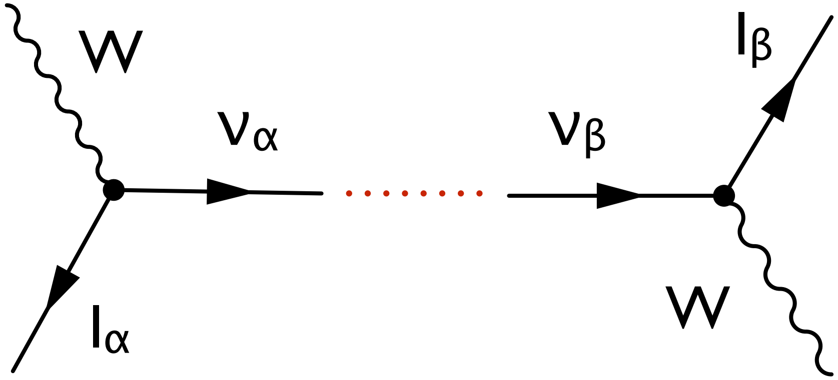
Search of neutrino CPV with the T2K experiment

Lorenzo Magaletti (Politecnico di Bari & INFN Bari)
On behalf of the T2K collaboration

La Thuile 2018: XXXII Rencontres de Physique de la Vallée d'Aoste

27th February 2018

Mixing of three neutrinos



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix

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

Super-K, K2K, MINOS, OPERA, NOνA, **T2K**

DChooz, Daya Bay, RENO MINOS, NOνA, **T2K**

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

(PMNS Neglecting possible Majorana phases)

Current knowledge:

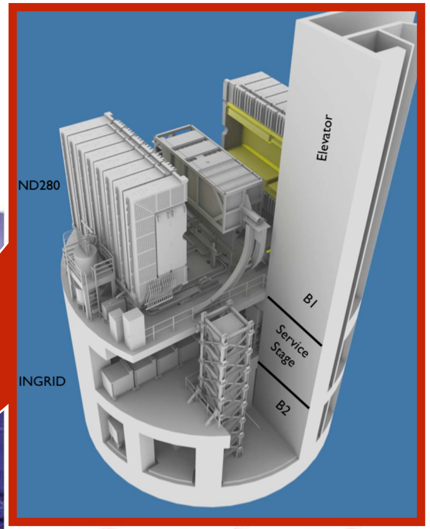
- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

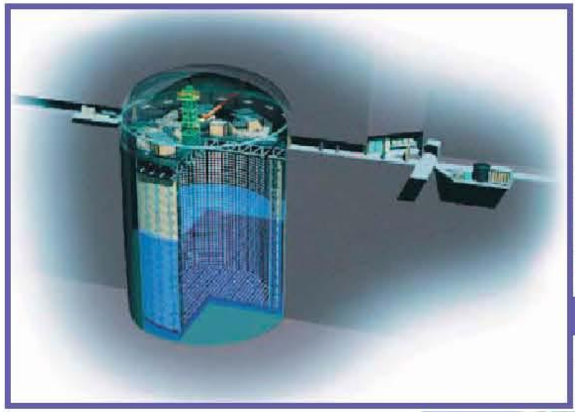
Open questions:

- CP violation?
- Mass hierarchy ($m_{1,2} \gtrless m_3$)?
- Is $\theta_{23} = 45^\circ$? If not is θ_{23} greater or lower than 45°?
- Majorana/Dirac?

Neutrino oscillations at T2K

Near detector complex
at 280 m from the target





Super-Kamiokande
(ICRR, Univ. Tokyo)

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

Intense high purity muon (anti)neutrino beam from J-PARC to Super-K to study:

- Muon (anti) neutrino disappearance $\nu_\mu \nrightarrow \nu_\mu$ ($\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
- Electron (anti) neutrino appearance $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- Rich program of:
  - neutrino cross sections studies with near detectors
  - "exotic" physics: sterile neutrinos, etc…

Big international collaboration of neutrino LBL

~500 physicists, 64 institutions, 12 countries

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

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
Wrocław U.

Russia
INR

Germany
Aachen U.

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

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

Switzerland
ETH Zurich
U. Bern
U. Geneva

Vietnam
IFIRSE
IOP, VAST

Neutrino oscillations at T2K

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

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with anti-neutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned}P(\nu_\mu \to \nu_e) = \; & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu}\times\left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-s^2_{13})\right] && \text{θ13 driven}\\ & +8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E\nu} && \text{CP even}\\ & \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E_\nu} && \text{CP odd}\\ & +4s^2_{12}c^2_{13}(c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin\frac{\Delta m^2_{12}L}{4E_\nu} && \text{Solar driven}\\ & \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\frac{aL}{4E_\nu}(1-2s^2_{13}) && \text{Matter effect (CP odd)}\end{aligned}$$

Change sign by changing ν with $\bar{\nu}$

B. Richter, SLAC-PUB-8587

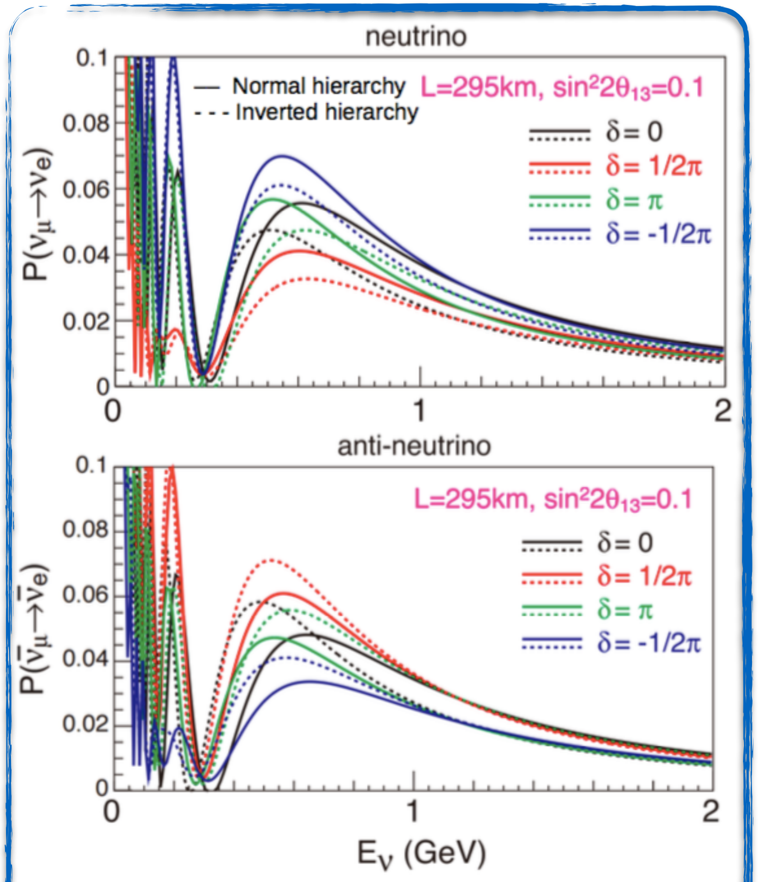
$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$

- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term (θ_{23}=45° or $\theta_{23}\gtrsim$45°?)
- CP odd phase delta: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass hierarchy

Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$
  - Enhance/suppress both ν_e and $\bar{\nu}_e$ appearance

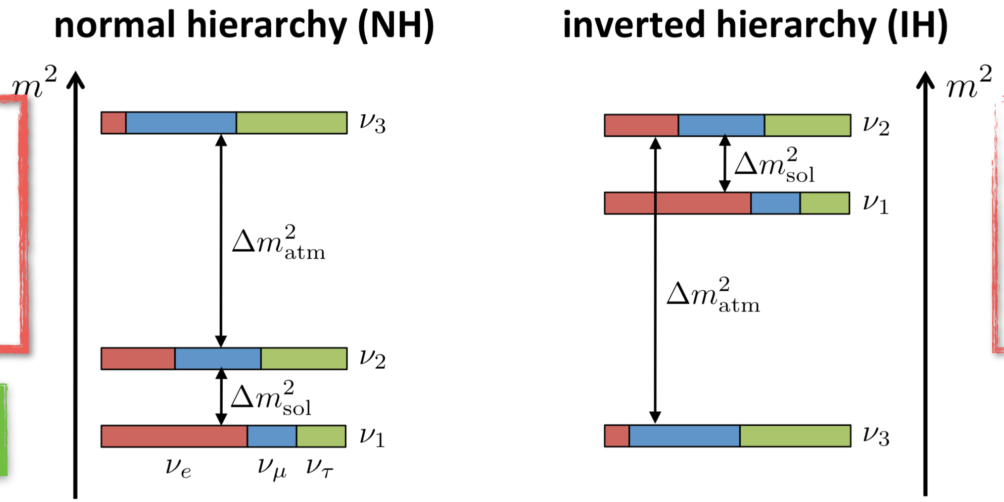
- CP-violating phase δ_{CP} (**up to ±30% effect at T2K**)
  - **δ_{CP} = 0, π** ⇒ no CP violation: $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ in vacuo
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu \rightarrow \nu_e$ and suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu \rightarrow \nu_e$ and enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



PTEP 2015 (2015) 053C02

Normal hierarchy
- Enhance $\nu_\mu \rightarrow \nu_e$
- Suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

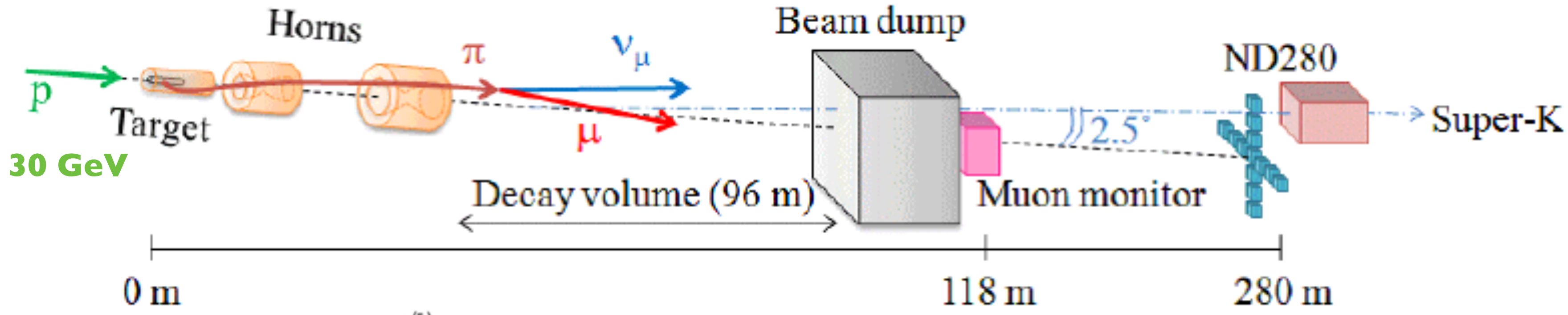
±10% effect at T2K

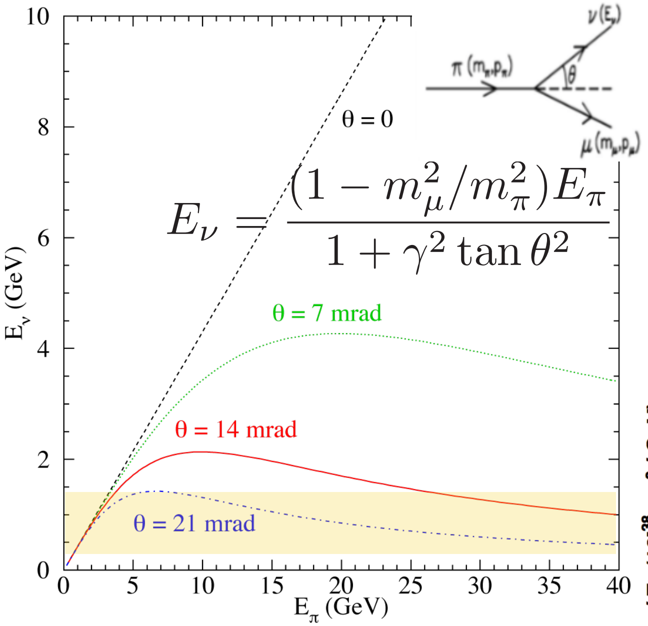


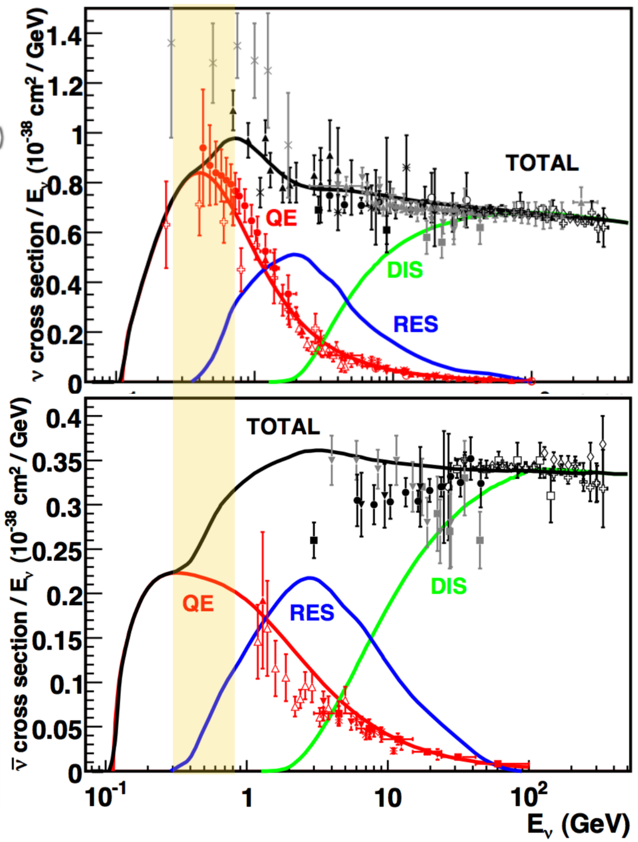
Inverted hierarchy
- Suppress $\nu_\mu \rightarrow \nu_e$
- Enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

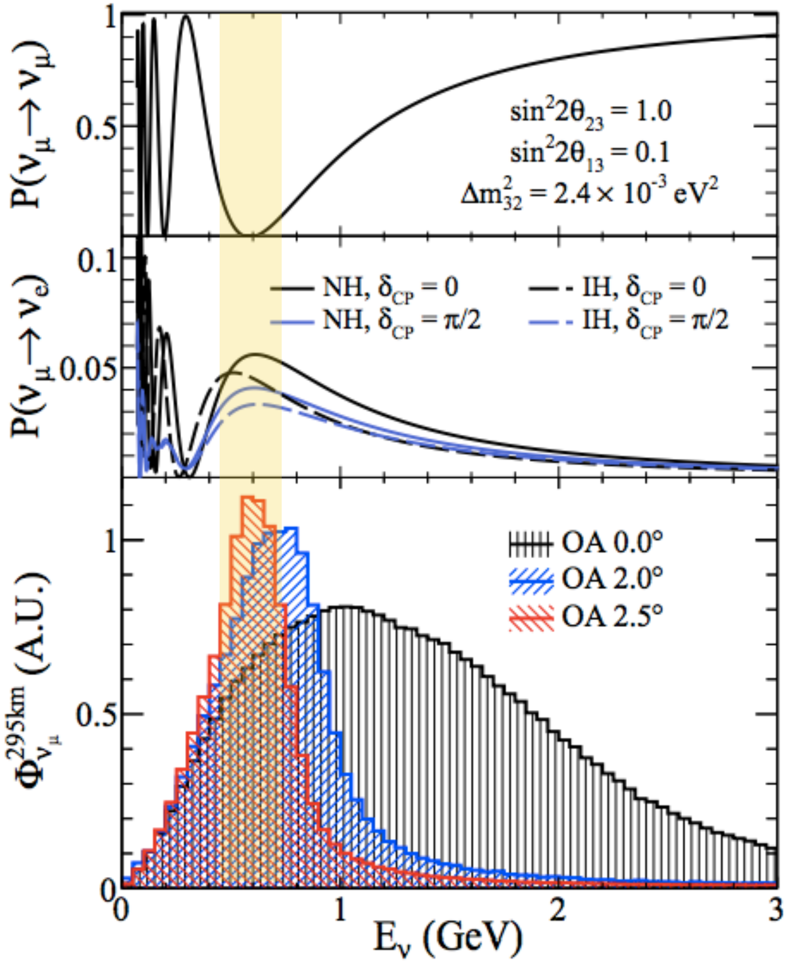
T2K experimental setup

The off-axis neutrino beam









Charged Current Quasi-Elastic (CCQE)

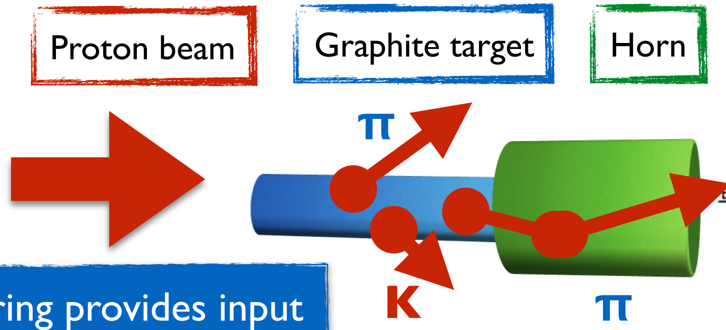
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

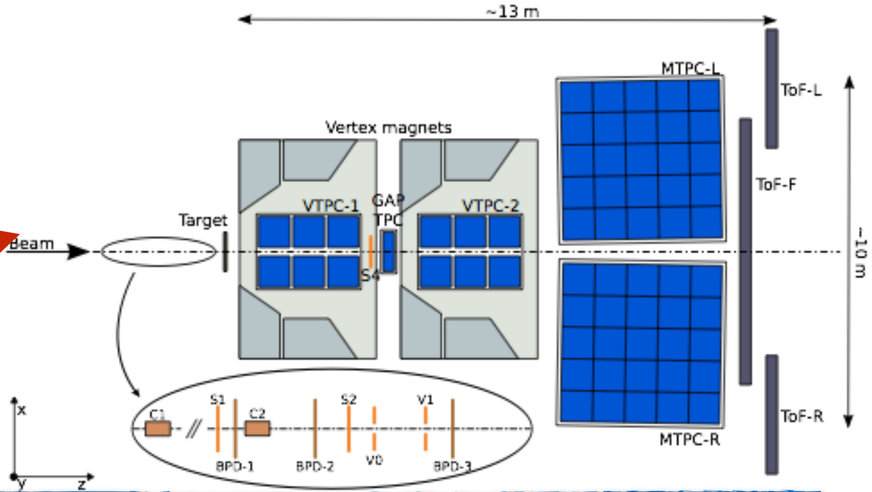
- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduces background from π^0 interactions

The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation→**NA61/SHINE experiment** measures hadron production cross sections using a thin carbon and a T2K replica target

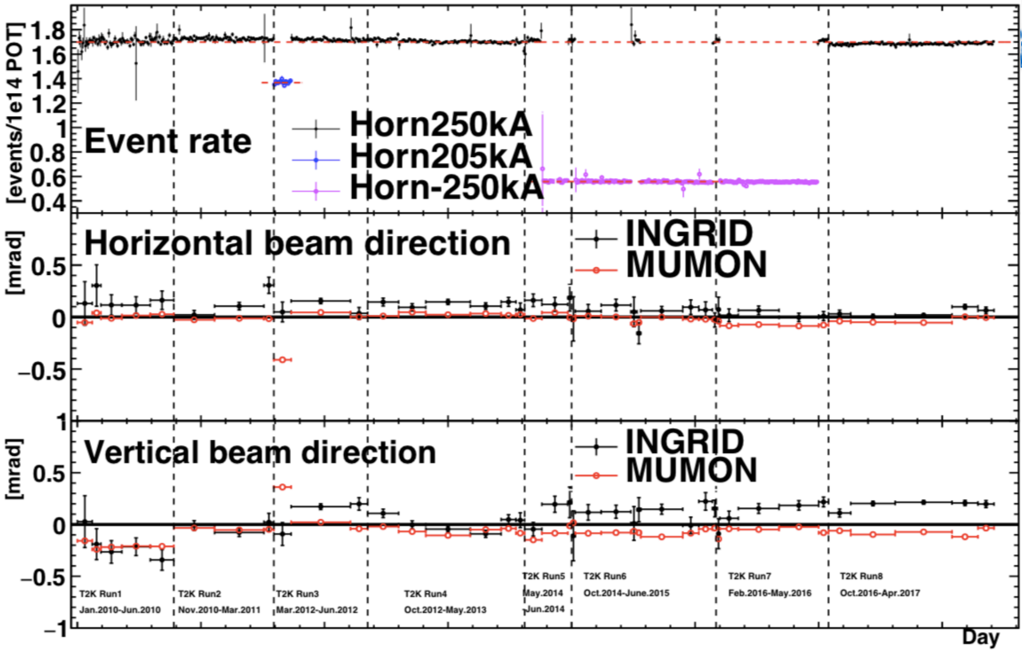
Flux error reduction from ~25% to ~10%





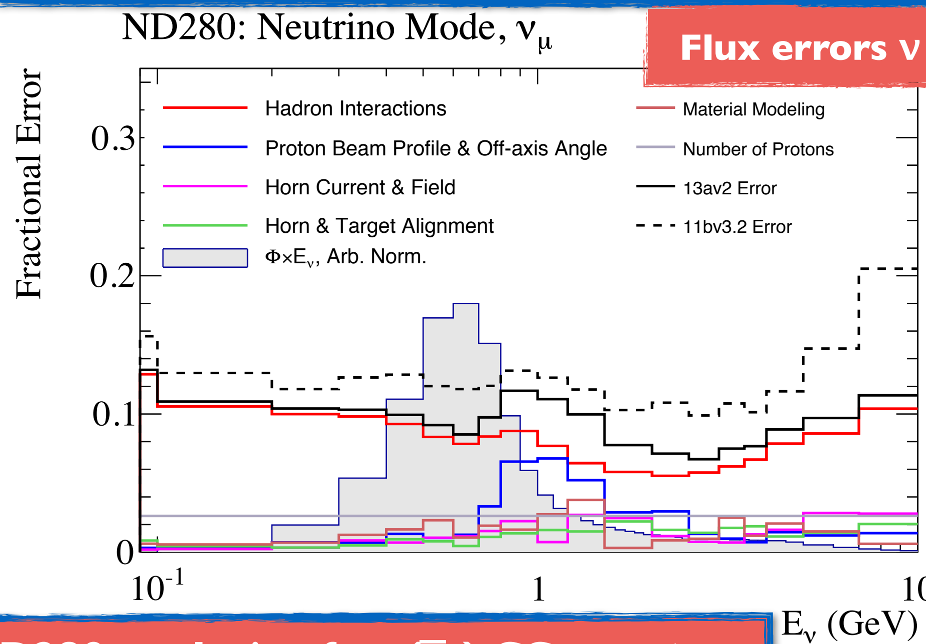
- Beam alignment monitoring provides input to estimations of beam systematics

ν daily event rate



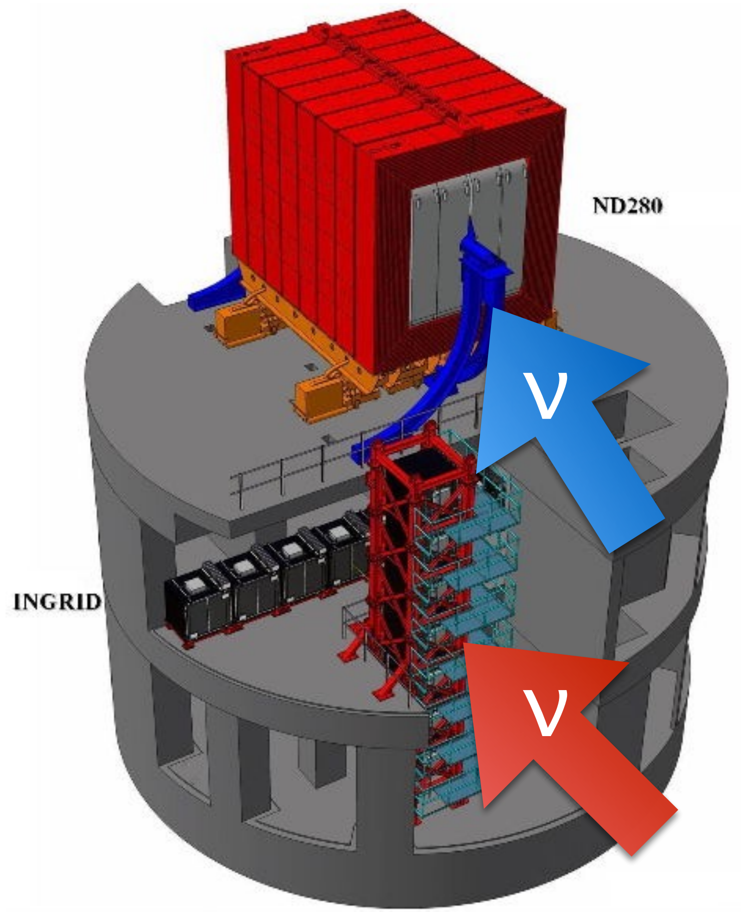
- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability

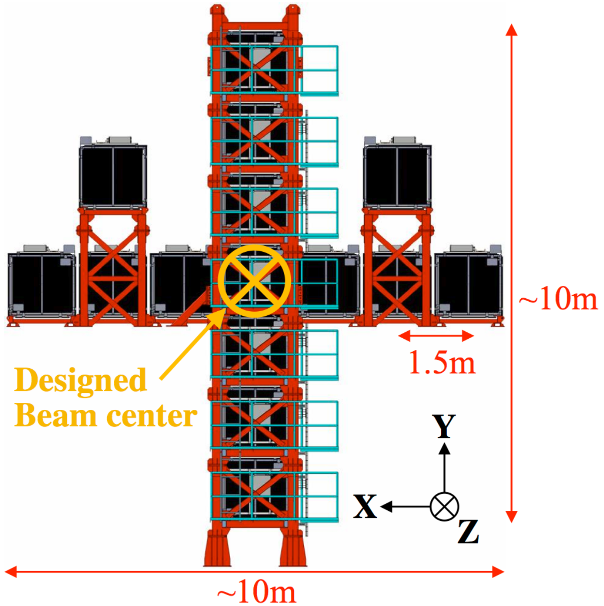
Flux errors ν mode

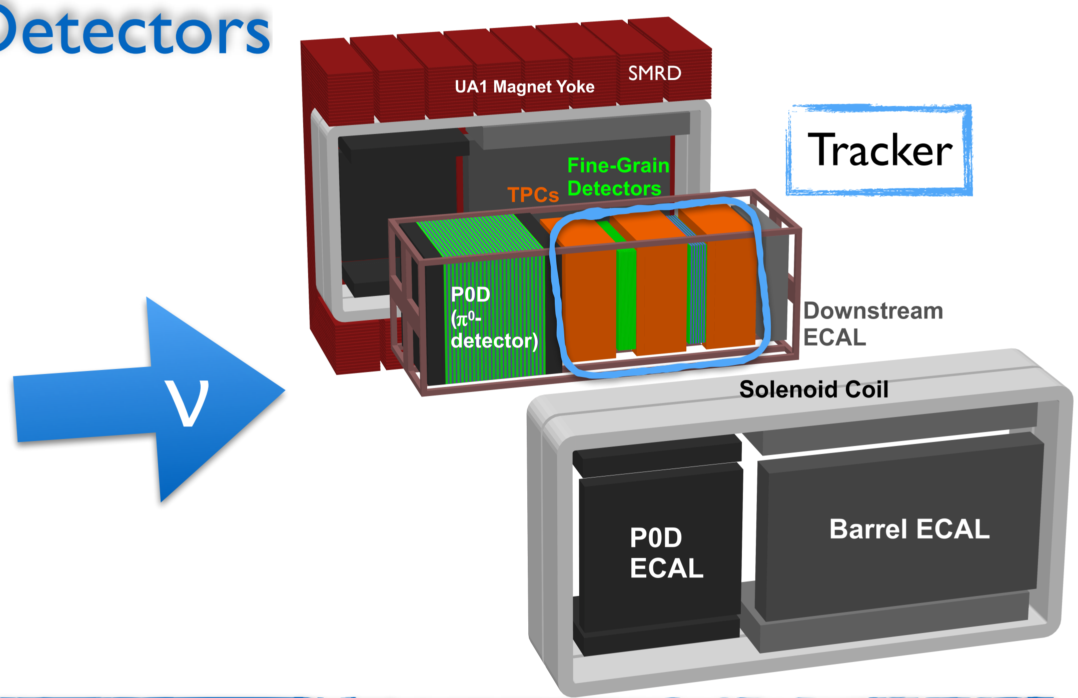


Flux errors are further constrained with the ND280 analysis of ν_μ ($\bar{\nu}_\mu$) CC events

Near Detectors







ND280 (off-axis)

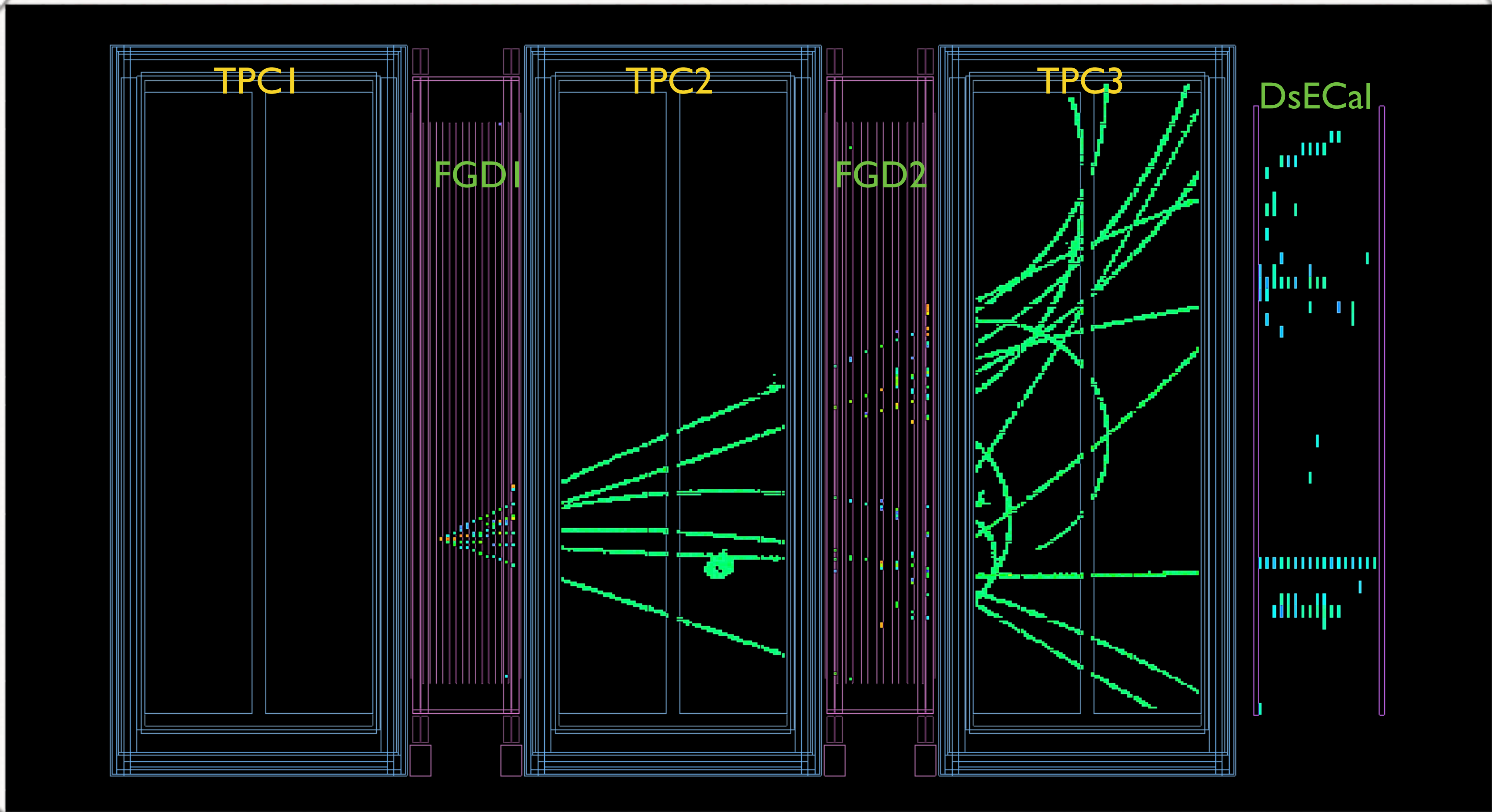
- **Magnet:** B = 0.2 T
- **TPC:** p measurement + particle-ID with dE/dx
- **FGD:** Fine-grained detectors (2 x 0.8 t) → FGD1 (C), FGD2 (C+H_2O)
- **SMRD:** magnetized muon range detector
- **P0D:** pi-zero detector (Pb/brass-H_2O-scintillator)
- **ECal:** electromagnetic calorimeter

INGRID (on-axis)

- **ν_μ CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (16 Fe/Scint modules + 1 central one made of scintillator only)

The T2K off-axis near detector: ND280

The T2K off-axis near detector: ND280

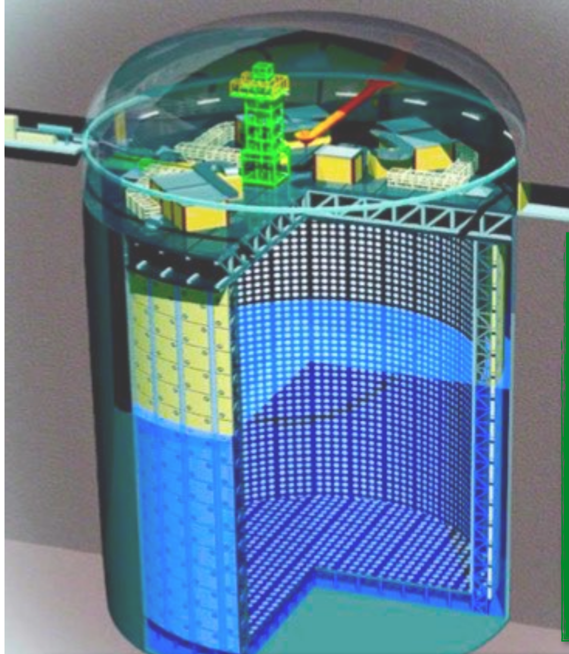


- ND280 **samples of ν_μ ($\bar{\nu}_\mu$) interactions in Carbon (FGD1) and water (FGD2)** have been employed **in the near detector analysis**.

- **FGD2** samples are useful for a **better cancelation of systematic uncertainties** caused by nuclear effects on neutrino-water cross-sections.

- Possibility to add the **"wrong sign"** samples to better constrain the ν_μ contamination in $\bar{\nu}$ beam mode

Far detector: Super-Kamiokande



Super-K (off-axis)

- Water Cherenkov (22.5 kt fiducial volume, > 11k PMT, ~40 m x 40 m)
- Excellent μ/e separation and π^0 detection (2 e-like rings)
- ΔE/E ~10% for Quasi-Elastic (QE) events

SIGNALS

$$\nu_l + n \rightarrow l^- + p \qquad \bar{\nu}_l + p \rightarrow l^+ + n$$

- Single μ/e like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics

$$\nu_e + p \rightarrow e^- + \pi^+ + p$$

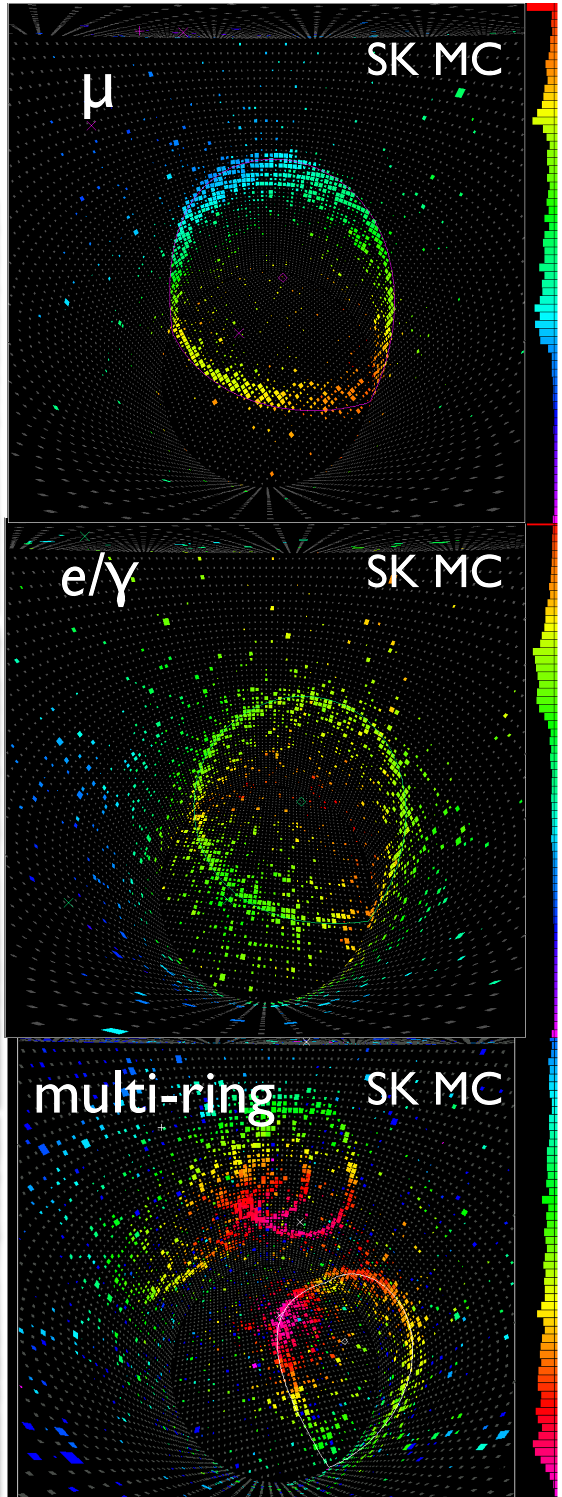
- Single e like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics with a Δ^{++} recoil
- One decay electron

BACKGROUNDS

$$\nu_l + (n/p) \rightarrow \nu_l + (n/p) + \pi^0$$

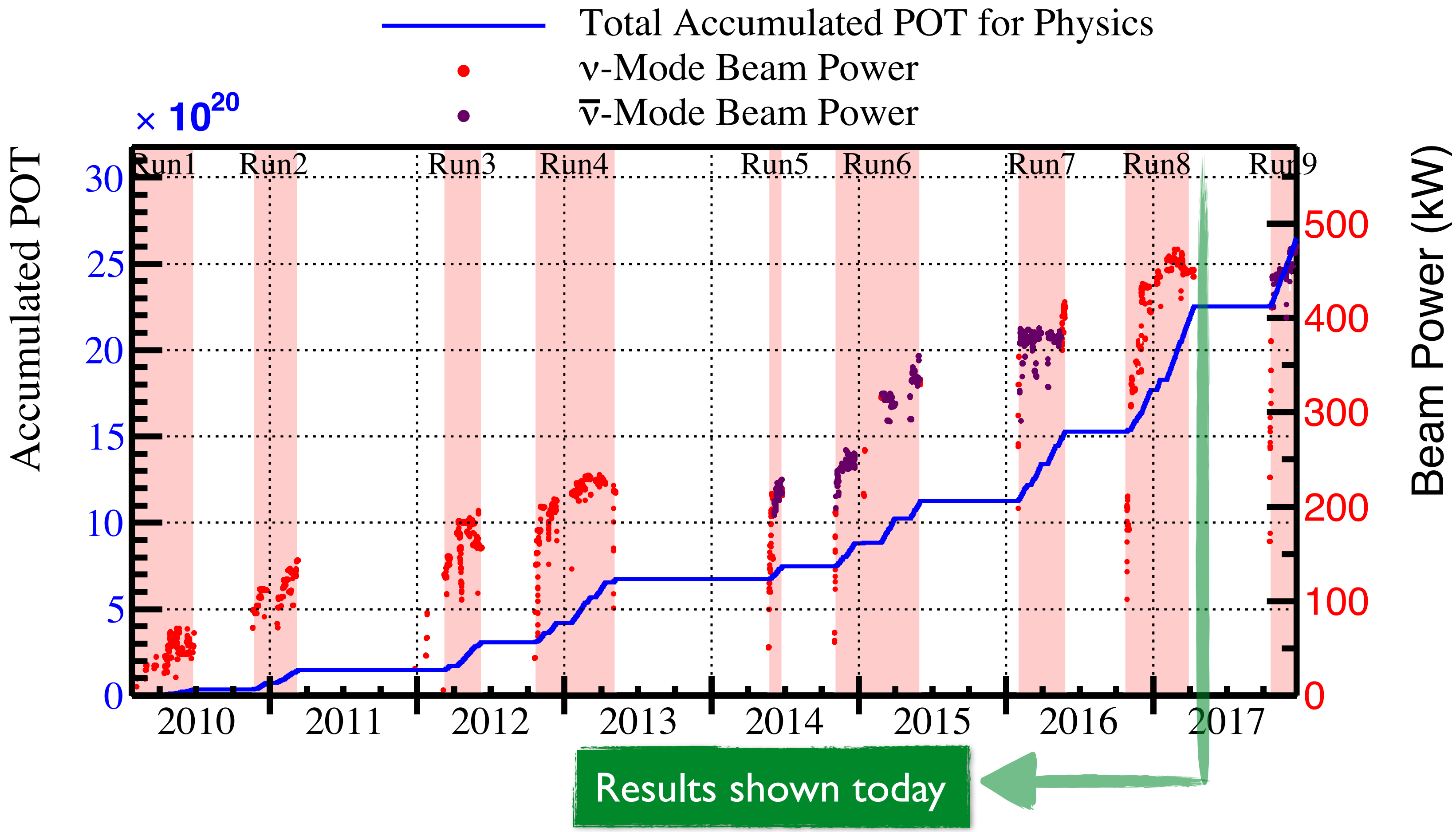
$$\nu_l + (n/p) \rightarrow l^- + (n/p) + \pi$$

- $\pi^0 \rightarrow \gamma\gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- Ring counting, decay electron cut to reject non-CCQE interactions



T2K oscillation results

Collected data



23 Jan. 2010 - 22 Dec. 2017

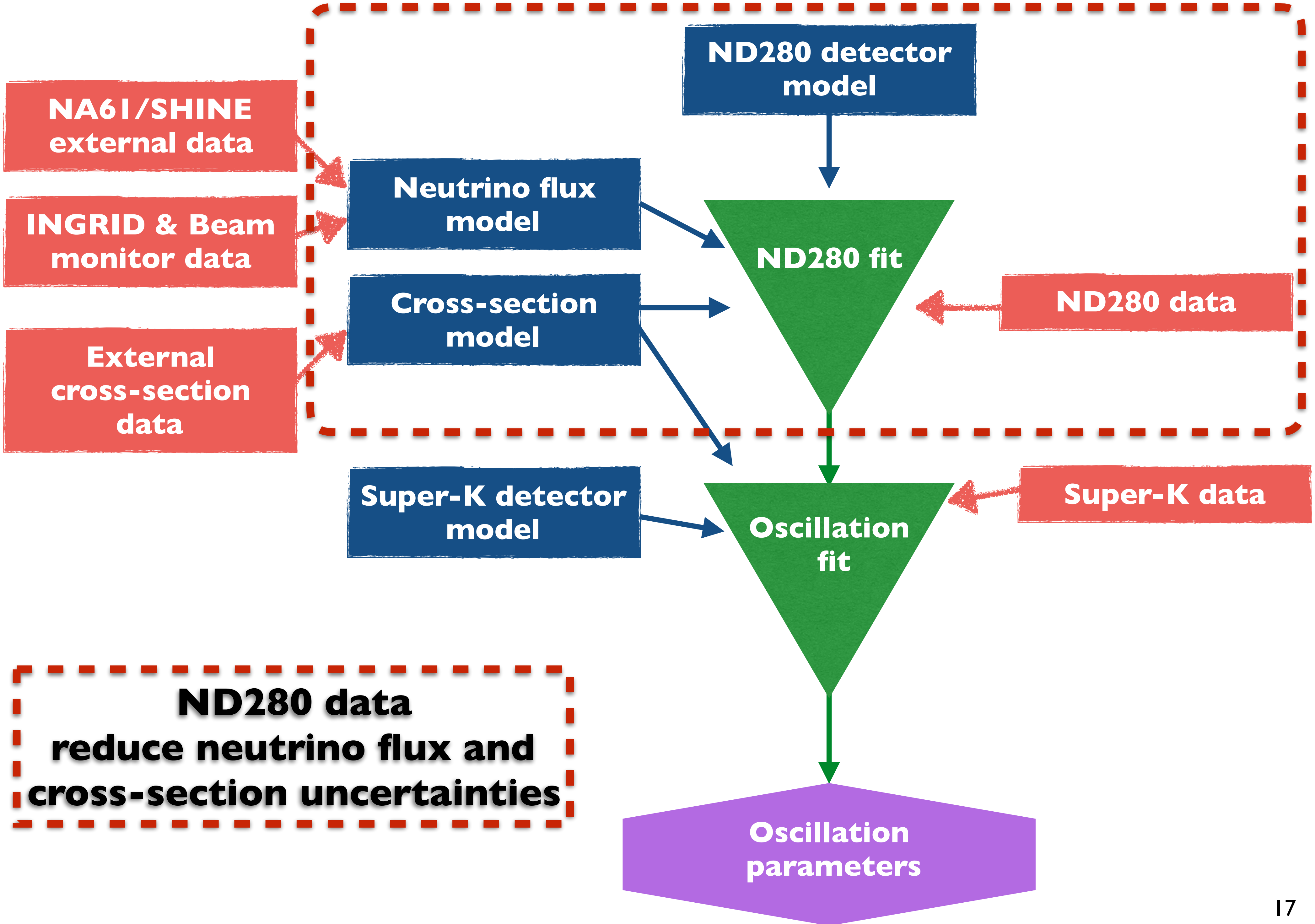
POT total: 2.65×10^{21}

ν-mode 1.51×10^{21} (57.14%)

$\bar{\nu}$-mode 1.14×10^{21} (42.86%)

- Results shown today with **22.5×10^{20} POT** (protons on target)
  - **2/3 ν-mode and 1/3 $\bar{\nu}$-mode**
  - **30% T2K total-statistical sample**
- Stable operation with **470 kW beam power ⇒ double neutrino data in 1 year!**

Analysis strategy

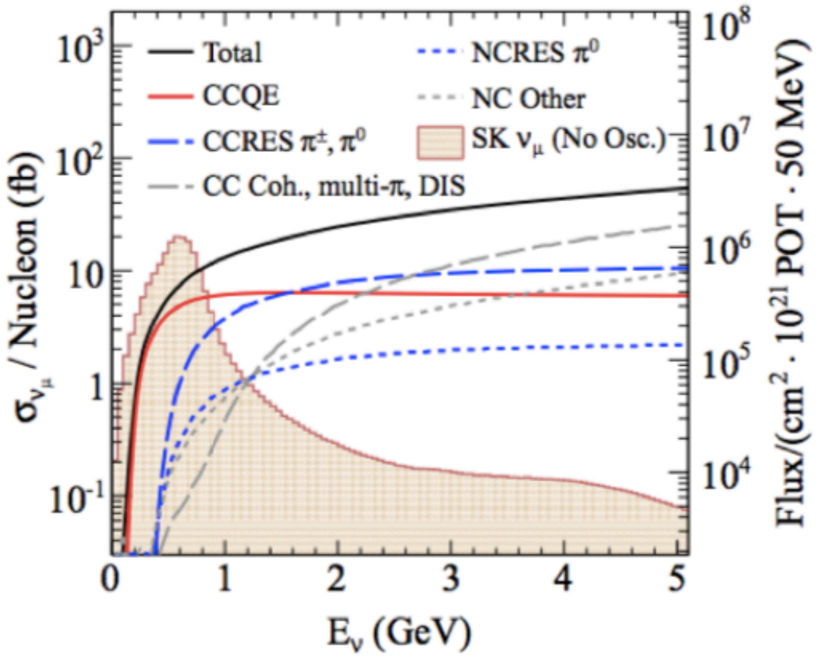


ND280 data reduce neutrino flux and cross-section uncertainties

Neutrino cross sections at T2K energies

- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction

- **Mimic CCQE interactions:**
  - Neutrino scatters on a correlated pair of nucleons (called multi-nucleon or 2 particle-2 hole, **2p-2h**)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion absorbed by the detector

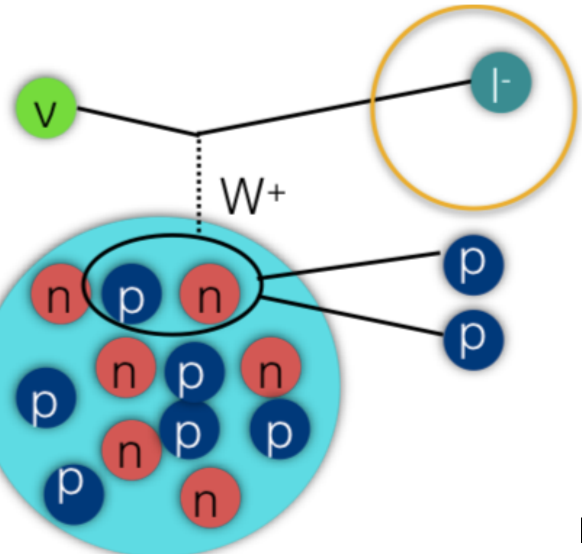


Improvements of neutrino interaction model in NEUT:

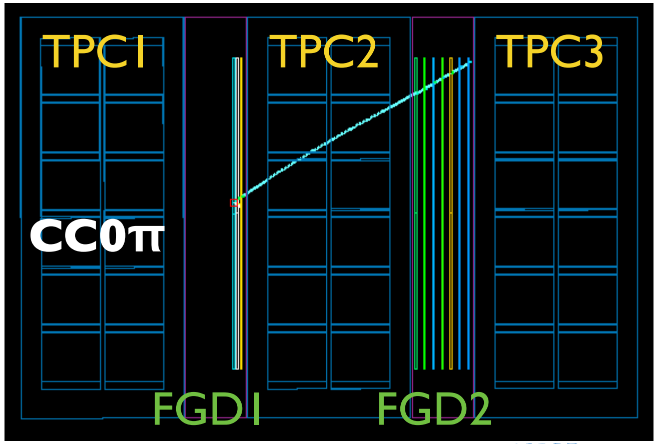
- **Improved pion production model** with tuning to data on hydrogen and deuterium

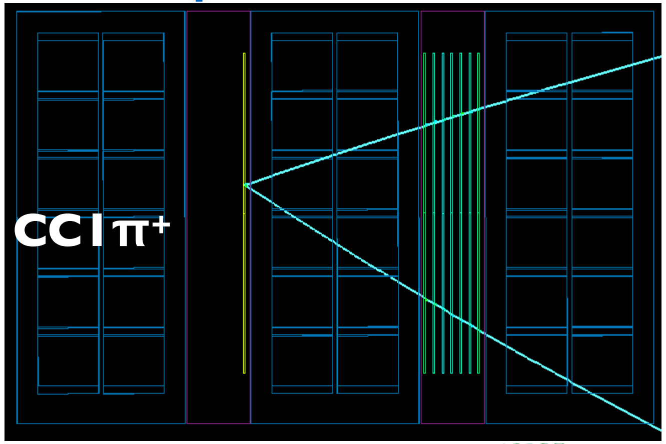
- **Inclusion of a model for multi-nucleon scattering processes**: Valencia 2p-2h model (Phys. Rev. C83 (2011) 045501)

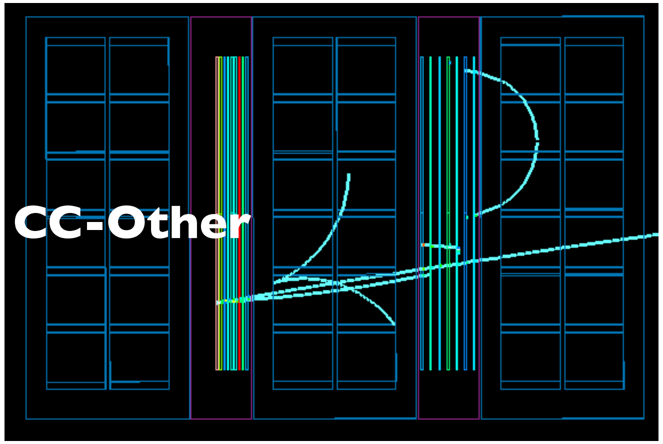
- Improved the CCQE model by including the effect of **long-range correlations in the nucleus** (calculation technique called random phase approximation, **RPA**)



ND280 FGD2 samples in neutrino beam mode





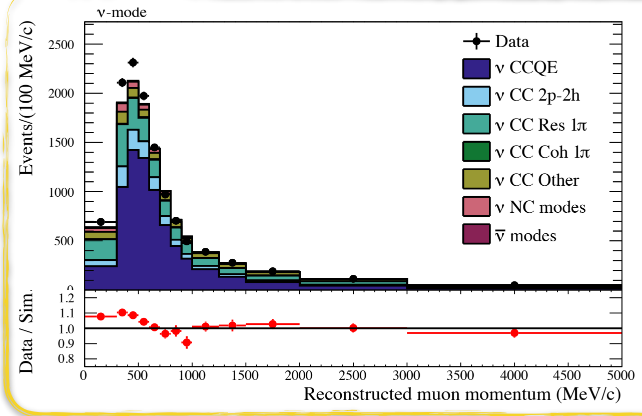


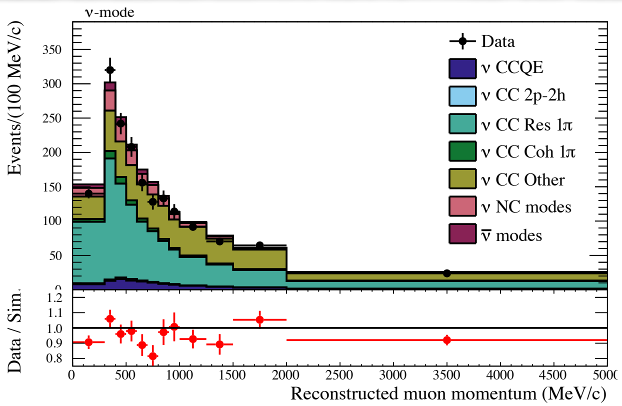
CC interaction with NO π in final state

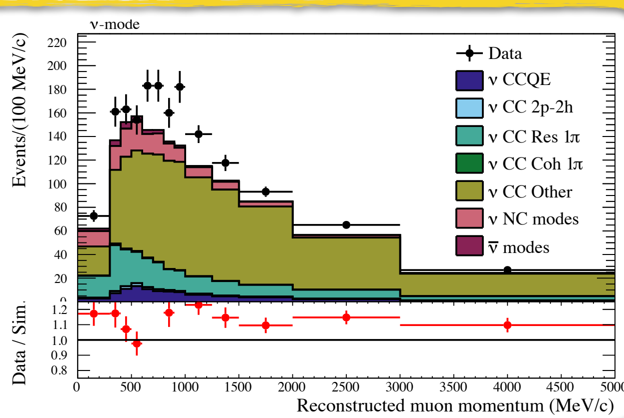
CC interaction with ONE π⁺ in final state

Other CC interactions

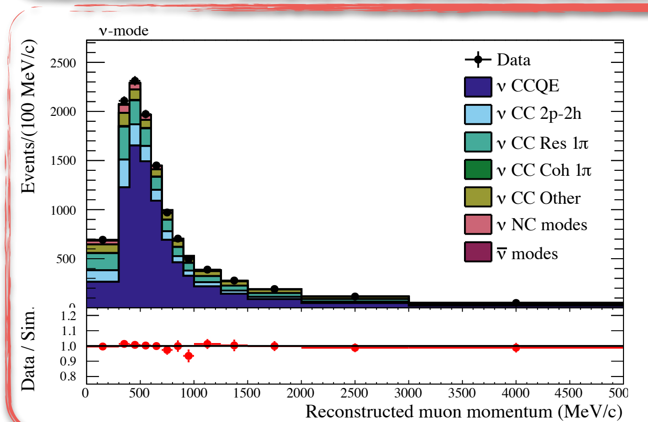
pre-ND280 fit

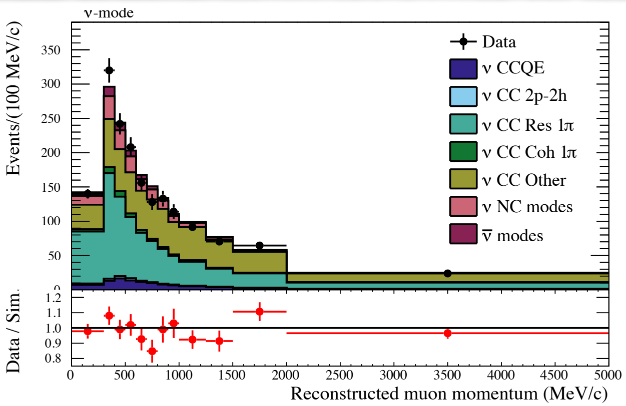


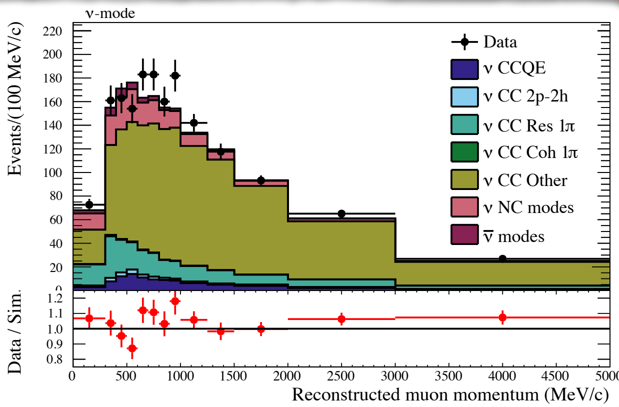




post-ND280 fit



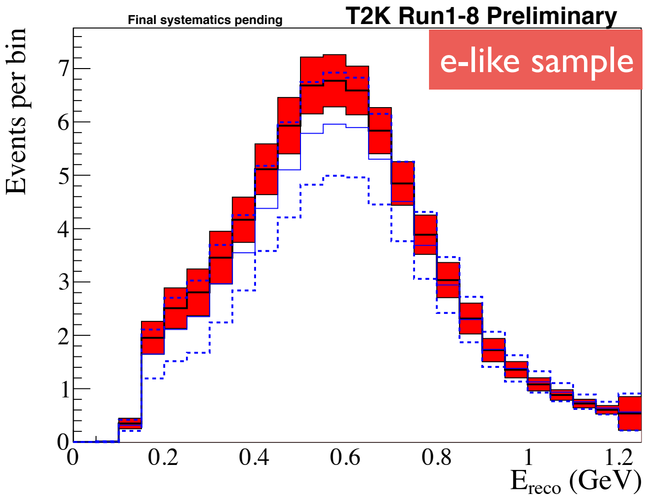


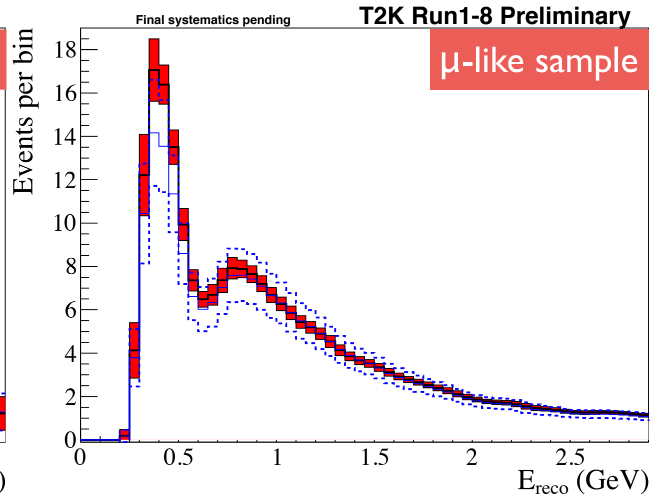


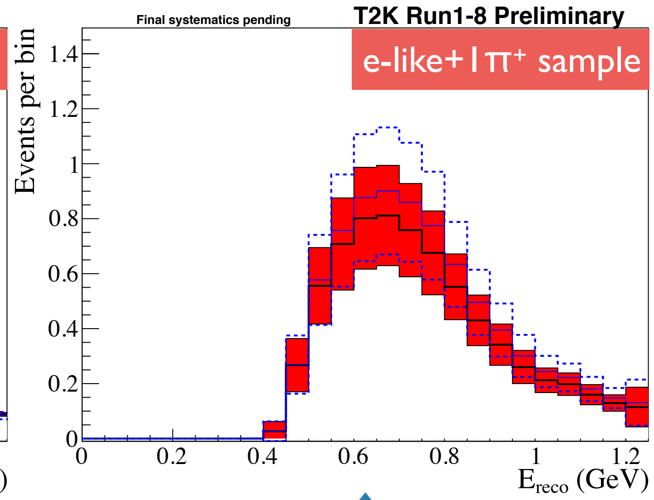
PRELIMINARY PRELIMINARY Phys.Rev. D96 (2017) no.9, 092006 ELIMINARY

ND280 constraints for Super-Kamiokande

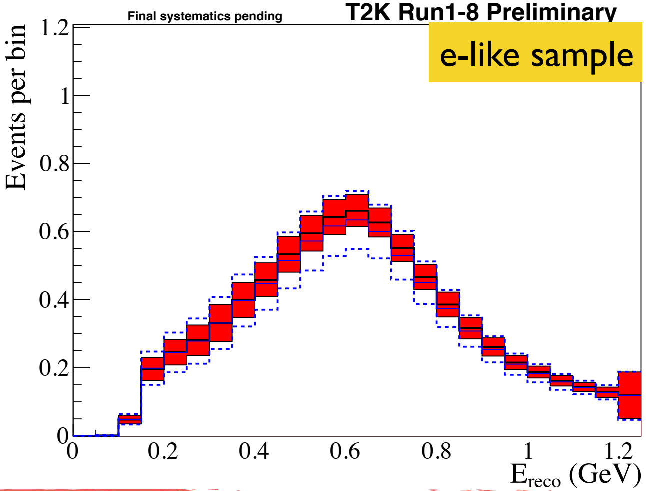
ν beam mode

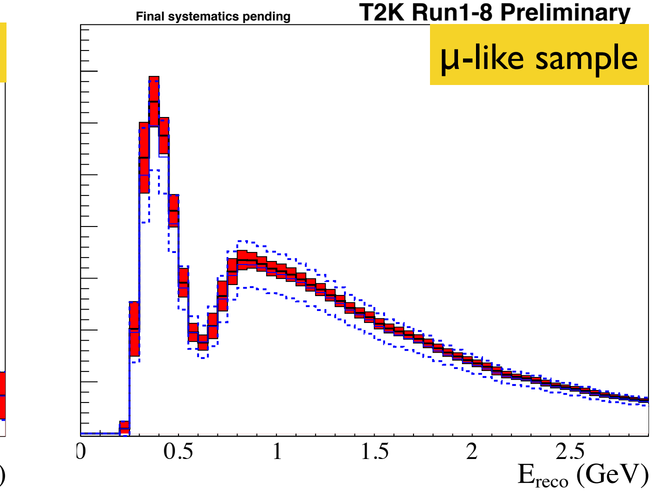






$\bar{\nu}$ beam mode





New Super-K e-like+1π+ sample

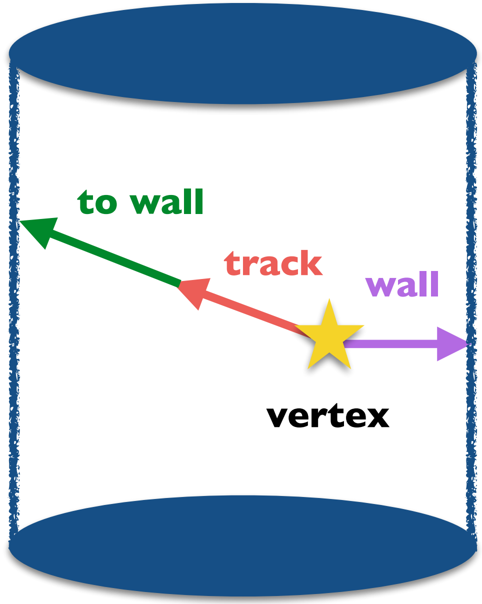
- Predicted number of events at Super-K slightly increased due to small excess of events in ND280
- Errors reduced from ~15% to ~4-7% thanks to ND280 fit
- Large uncertainty in e-like+1π+ sample mainly due to Super-K systematics

Total $\delta N_{SK}/N_{SK}$

Beam mode	sample	ND280 constrained	w/o ND280
neutrino	μ-like	4.3%	13.9%
neutrino	e-like	7.3%	15.9%
neutrino	e-like+1π+	20.9%	23.4%
anti-neutrino	μ-like	3.8%	11.7%
anti-neutrino	e-like	7.7%	13.7%

Super-Kamiokande reconstruction

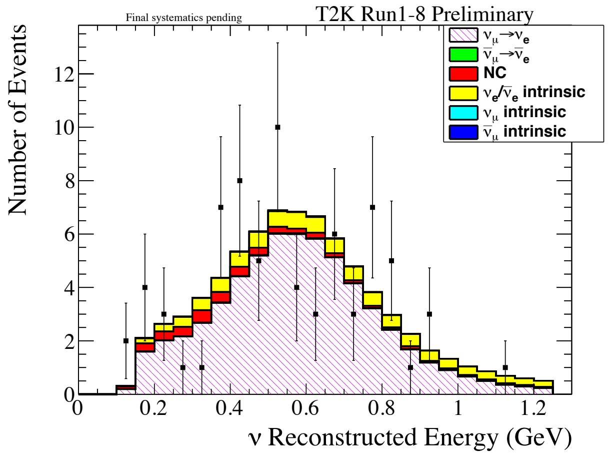
- New Reconstruction algorithm is used for Super-Kamiokande reconstruction
- This algorithm, previously used only to reject π^0, combines time and charge likelihood for a given ring hypothesis
- **New definition of Fiducial Volume** combining distance of the vertex from the wall and direction to the wall (previously only distance from the wall was used)
  - **~30% more statistics for ν-mode e-like samples (including e-like+1π+ sample)**
  - **~20% more statistic for $\bar{\nu}$-mode e-like**
  - **Better purity for μ-like samples**

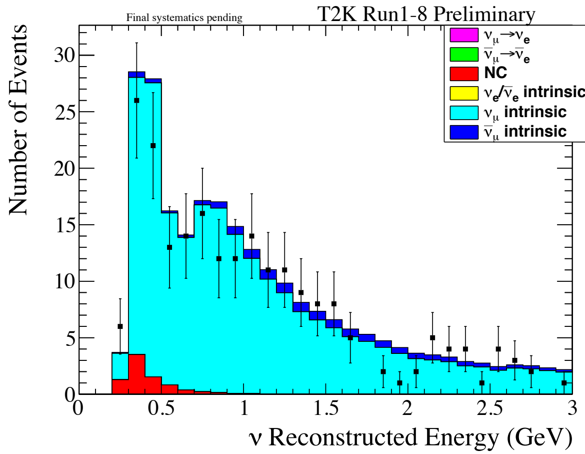


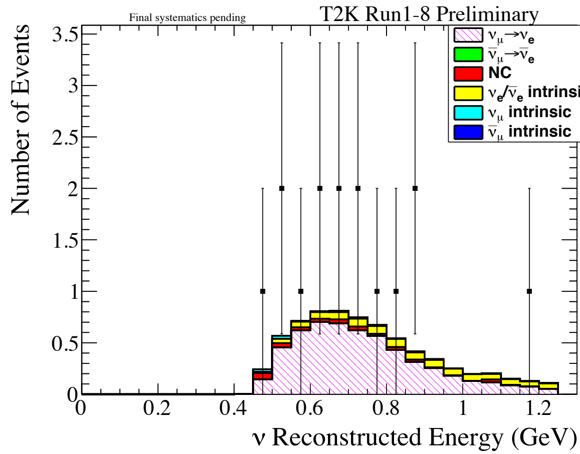
Sample	NEW Super-K selection		OLD Super-K selection	
	Candidates	Purity	Candidates	Purity
ν-mode e-like	69.5	81%	56.5	81%
ν-mode e-like+1π^+	6.9	79%	5.6	72%
$\bar{\nu}$-mode e-like	7.6	62%	6.1	64%
ν-mode μ-like	261.6	80%	268.7	68%
$\bar{\nu}$-mode μ-like	62	80%	65.4	71%

Fitted spectra at Super-Kamiokande

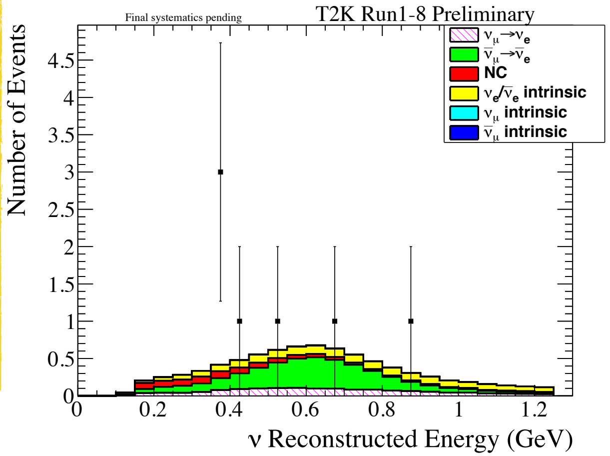
ν beam mode

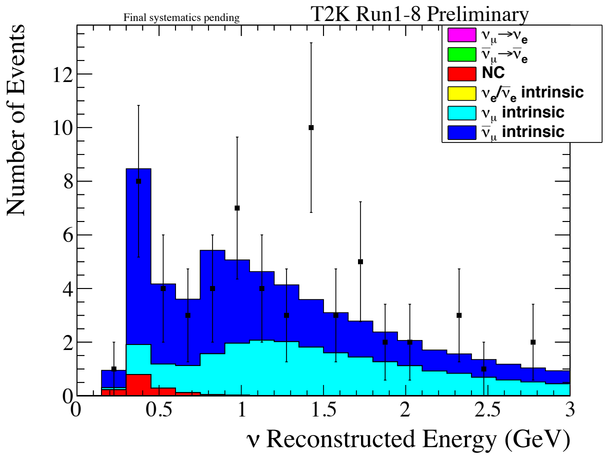






ν̄ beam mode





- **Data prefer δ_{CP} inducing the largest ν-ν̄ asymmetry: -π/2**
- **Larger effect in the e-like+1π⁺ sample** (2.5% probability of observing 15 events when 6.9 are expected)
- **Differences in μ-like events** are **consistent with statistical and systematic errors**

Normal Hierarchy

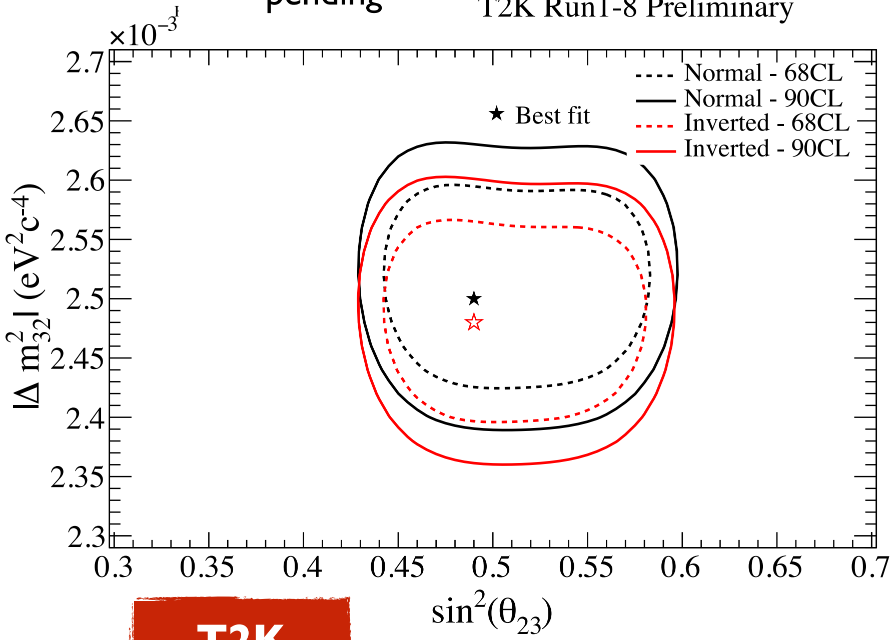
Beam mode	Sample	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π	Observed
neutrino	μ-like	267.8	267.4	267.7	268.2	240
neutrino	e-like	73.5	61.5	49.9	62	74
neutrino	e-like+1π⁺	6.9	6	4.9	5.8	15
anti-neutrino	μ-like	63.1	62.9	63.1	63.1	68
anti-neutrino	e-like	7.9	9	10	8.9	7

- **Oscillation and systematic parameters are shared between the 5 samples**
- **Fit simultaneously the 5 samples to maximize the sensitivity to the oscillation parameters**

Sensitivity: θ_{23} vs Δm^2_{23} confidence regions

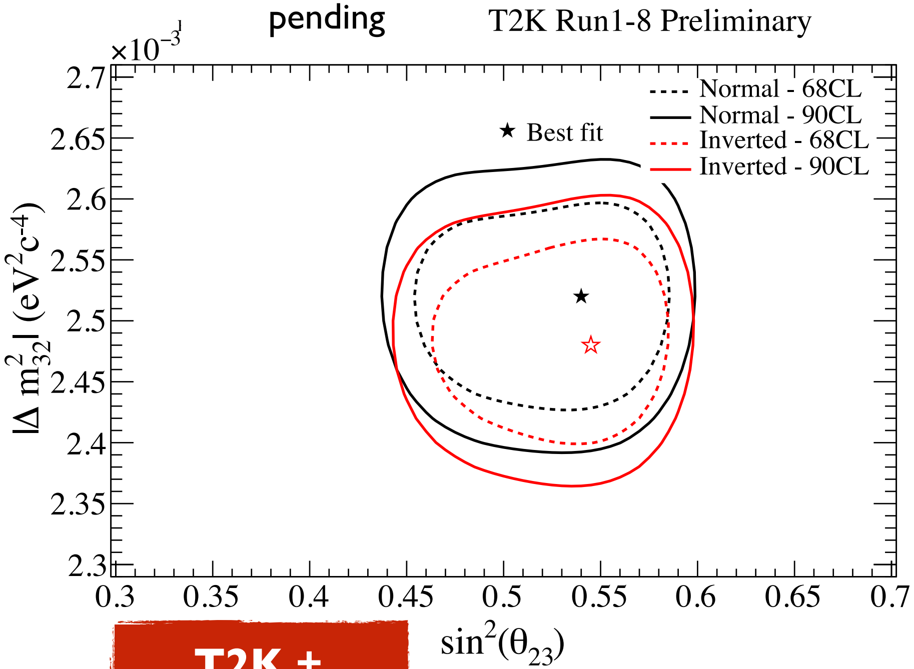
Run1-8 Sensitivity

Final systematics pending



T2K only

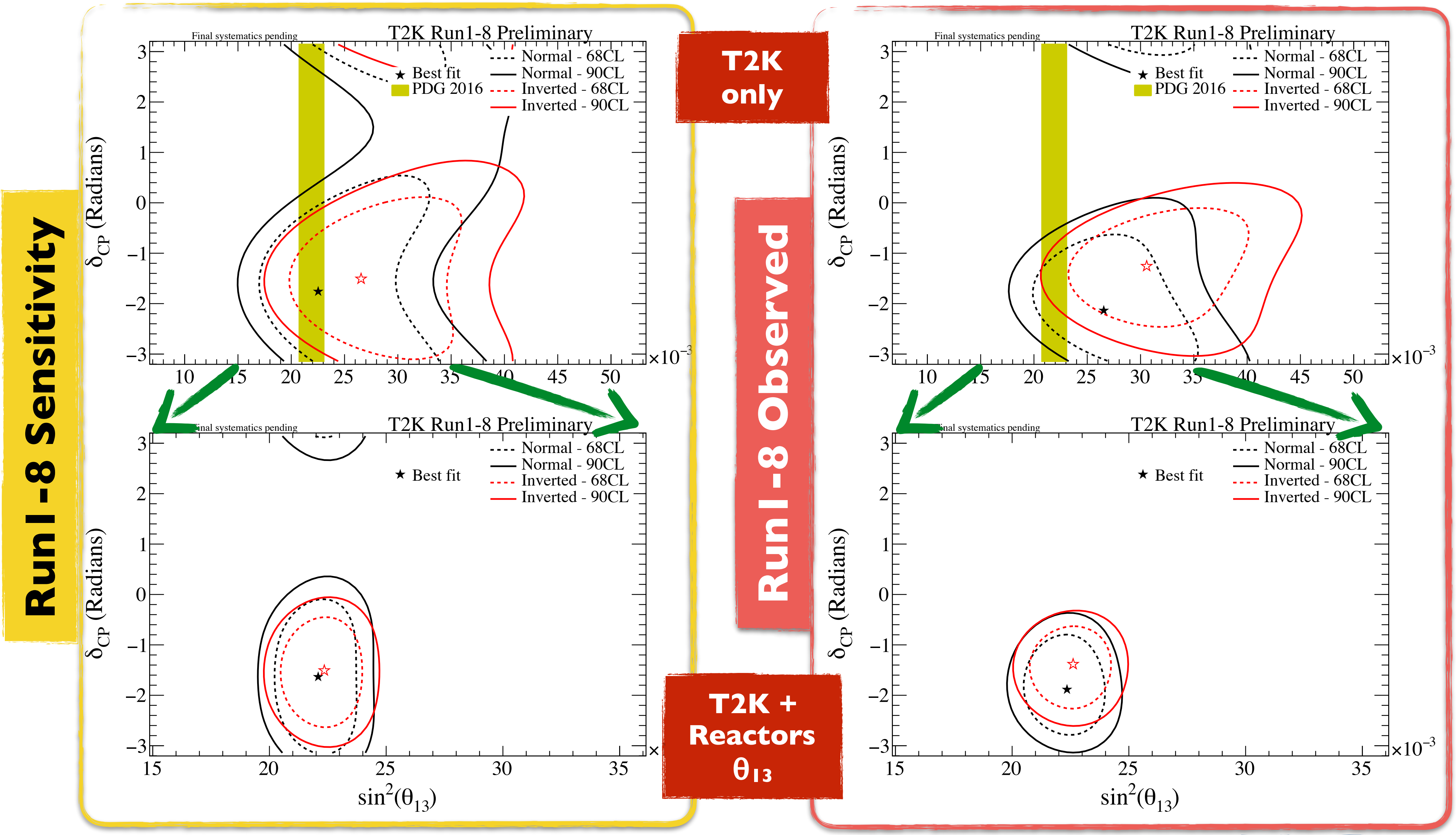
Final systematics pending



T2K + Reactors θ_{13}

- **World-leading measurement of $\sin^2 \theta_{23}$**
- Sensitivity results continue to be **consistent with maximal mixing/ oscillation**
- **Currently finalising the study of the impact of different cross-section model on these contours**

Results: δ_{CP} vs θ_{13} confidence regions



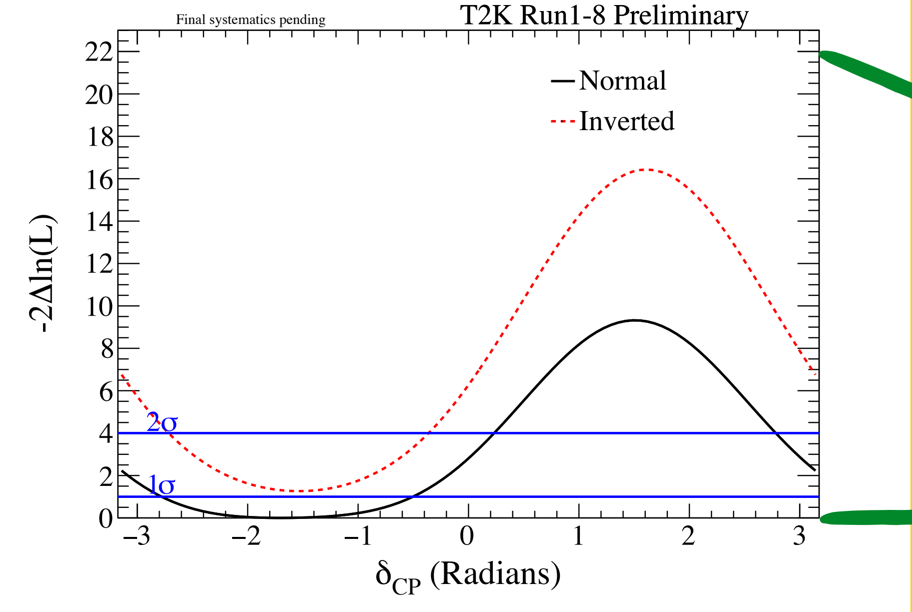
- **T2K only results are consistent with θ_{13} measured by reactors**
- **Maximal CPV: data prefer $\delta_{CP}=-\pi/2$ ($\bar{\nu}_e$ data confirm the tendency observed for ν_e data)**
- **Favours the scenario of a small θ_{13} and large CPV**

Results: δ_{CP} confidence regions

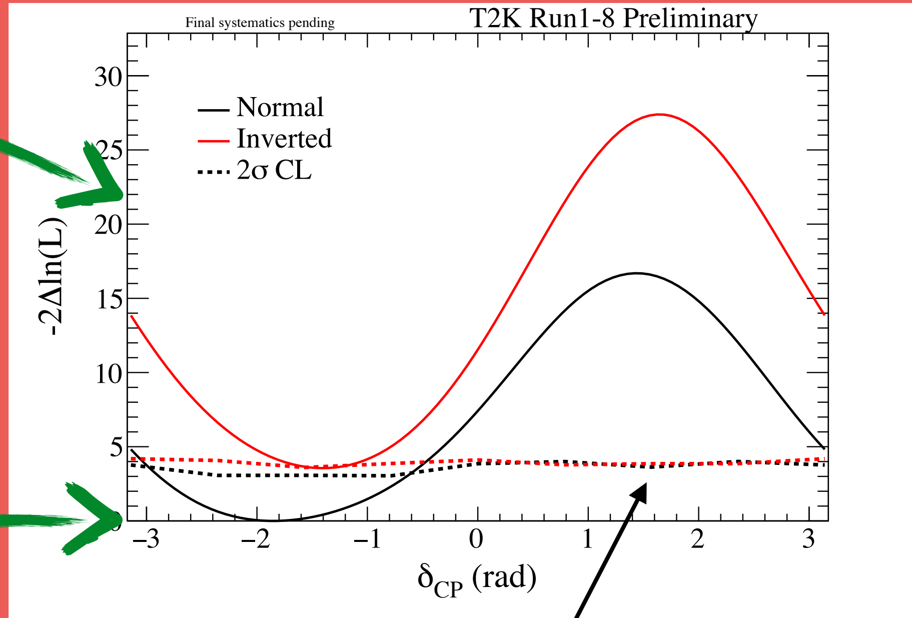
T2K + Reactor θ_{13} (PDG 2016)

$\sin^2\theta_{13}=0.022$, $\sin^2\theta_{23}=0.528$, NH, $\delta_{CP}=-1.601$

Run 1-8 **sensitivity**



Run 1-8 **observed**



Feldman-Cousins critical $\Delta\chi^2$ values for 2σ C.L.

CP conservation (δ_{CP} = 0,π) excluded at 2σ C.L.

Toy MC: if nature is NH and $\delta_{CP} = -\pi/2$ the probability for excluding $\delta_{CP} = 0$ or π at 2σ C.L. is 30% and 20% respectively

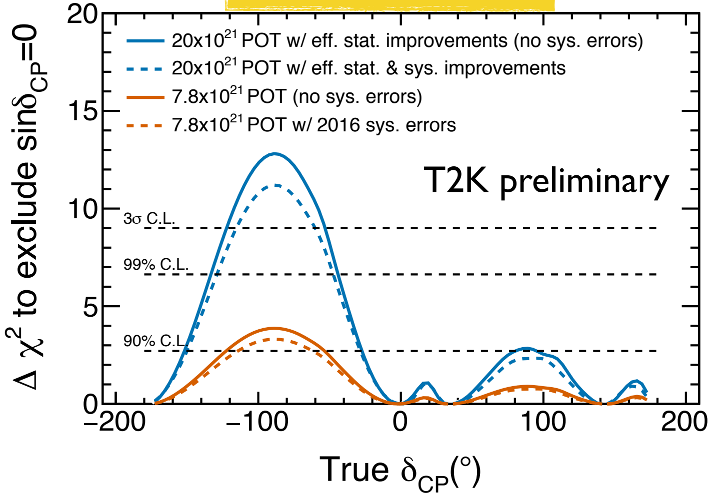
	NH	IH
68% C.L.	[-2.49, -1.23]	✗
90% C.L.	[-2.80, -0.83]	✗
2σ C.L.	[-2.98,-0.60]	[-1.53, -1.19]

Prospects

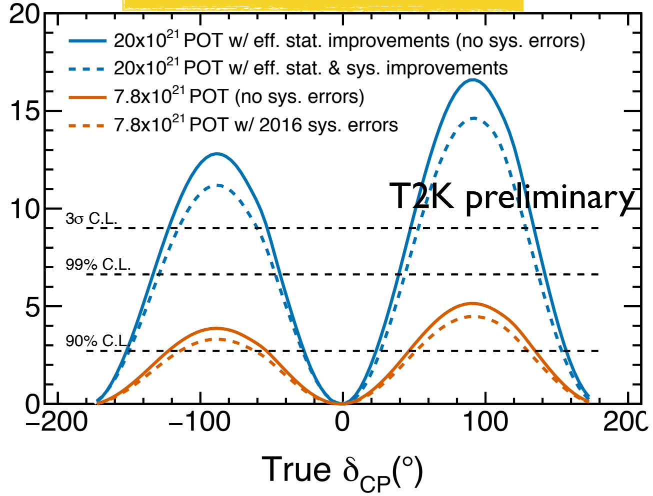
Towards T2K phase II

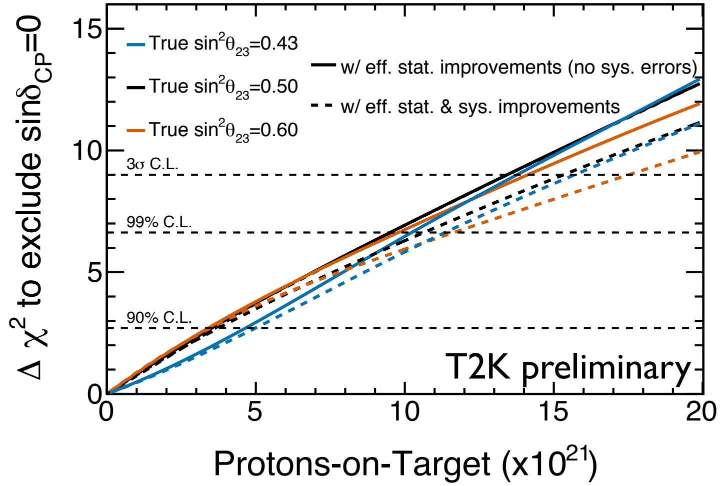
- Future: proposal for T2K phase II: Extension of collected POT from 7.8×10^{21} (T2K) to 20×10^{21} (T2K-II)
- Analysis and operation improvements to achieve another 50% in experimental sensitivity
  - **~30% already achieved**
- Super-Kamiokande upgrade with Gadolinium (start preparation work in June 2018)

hierarchy unknown

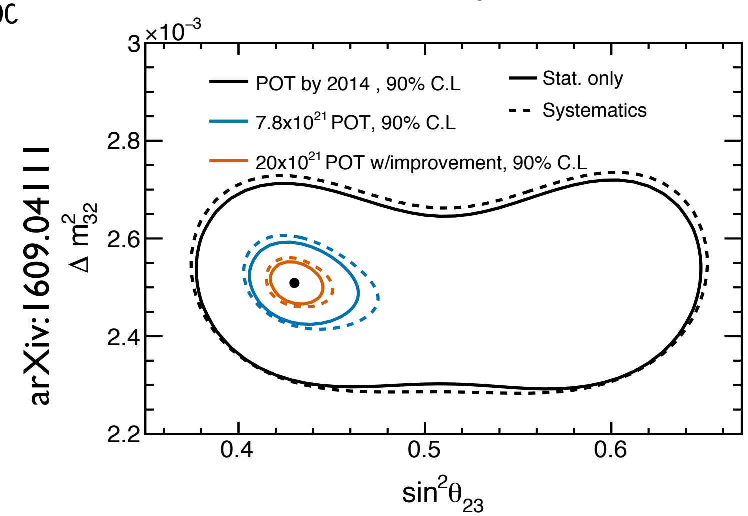


external hierarchy input



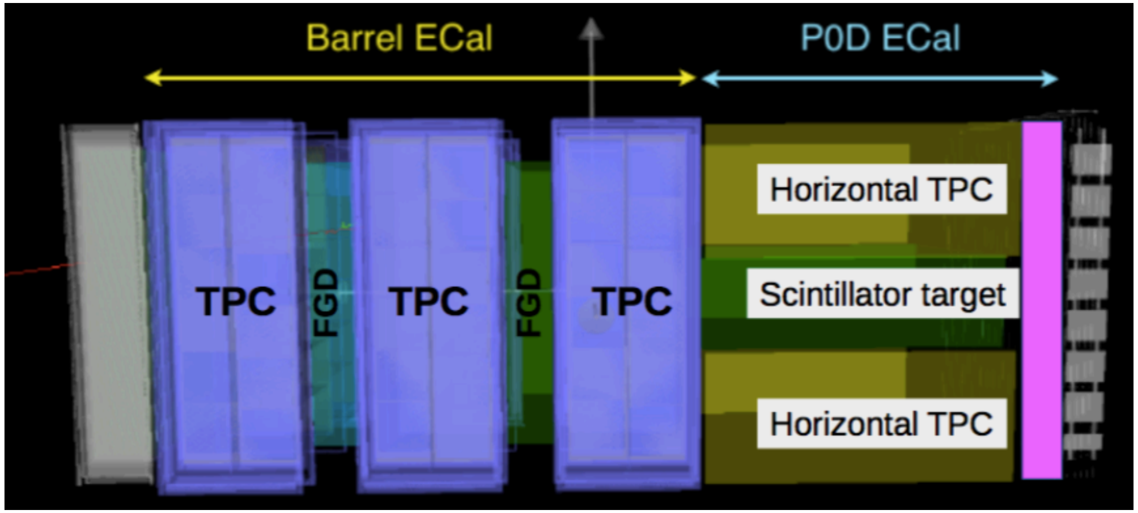


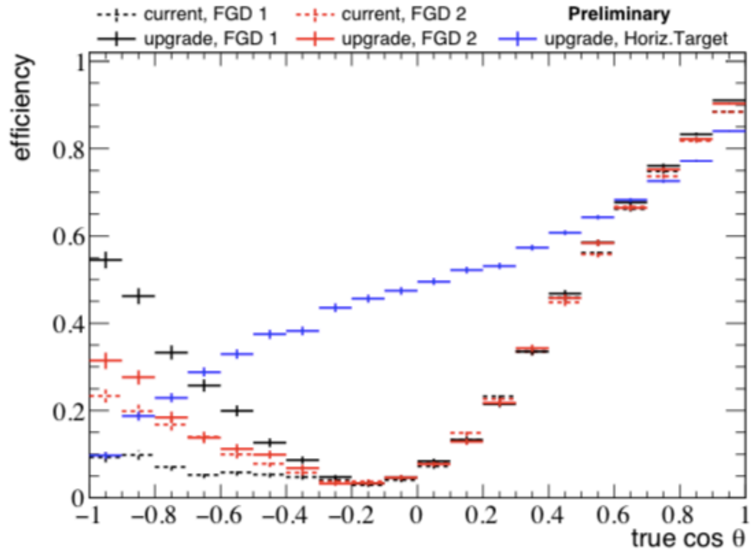
- **~3σ sensitivity to CP-violation for favorable (and currently favored) parameters**
- **precise measurement of θ_{23}:**
  - octant resolution if θ_{23} at the edge of currently allowed values
  - otherwise, measure θ_{23} to ~1.7° or better



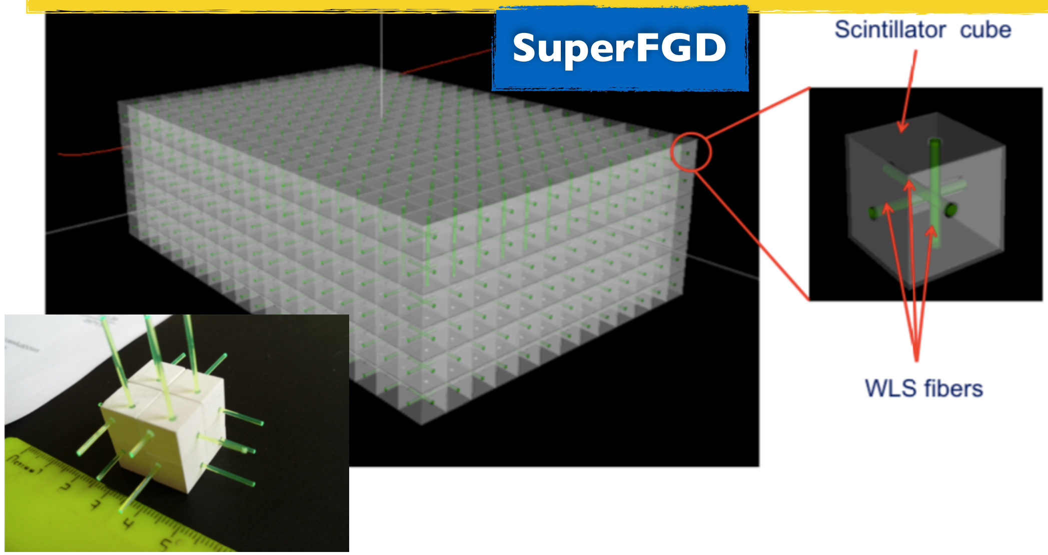
New collaborators are welcome to join the T2K phase II

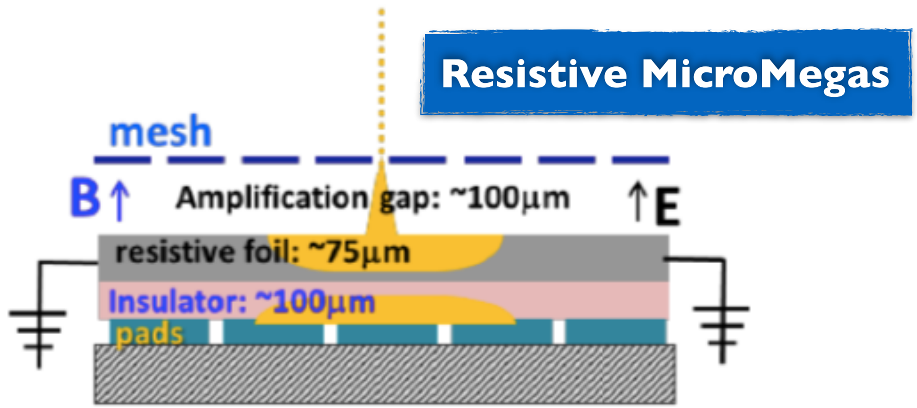
Towards T2K phase II: ND280 upgrade





- Goal of the upgrade project: replace the P0D with an **horizontal totally active target** (SuperFGD) and **2 horizontal TPCs** equipped with resistive MicroMegas by 2021
- Increase the current phase-space and reduce the cross-section systematics
- Currently working on R&D and prototypes + simulations



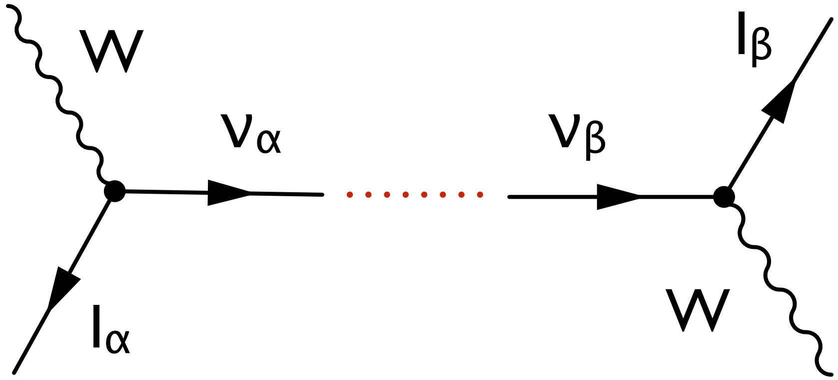


Conclusions

- **Steadily improving beam power with 480 kW stably achieved this winter**
  - T2K released results with 2.2×10^{21} POT (2/3 ν-mode and 1/3 $\bar{\nu}$-mode) ~30% of T2K total-statistical sample
  - Updated results including Run 9 (2.65×10^{21} POT, 57%ν-mode and 43% $\bar{\nu}$-mode) will be public next summer
- **Several improvements in the oscillation analysis**
  - New cross-section model constrained with ND280 data
  - New Super-K reconstruction algorithm ⇒ increase of ~30% the expected number of e-like events
- **Data continue to prefer maximal θ_{23} mixing, δ_{CP} ~$-\pi/2$ and NH**
  - CP conserving values are excluded at more than 2σ C.L.
  - δ_{CP} = [-2.98,-0.60] assuming NH, [-1.53, -1.19] assuming IH at 2σ C.L.
- **Propose to extend T2K with:**
  - Running to ~2026 to accumulate 20×10^{21} POT (3 times the currently approved POT)
  - In order to fully profit of the additional statistics need to reduce systematics ⇒ ND280 upgrade project launched
  - Primary goals aimed at more than 3σ sensitivity to CPV, θ_{23} measured to ~1.7°

Backup

Neutrino oscillations



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matr

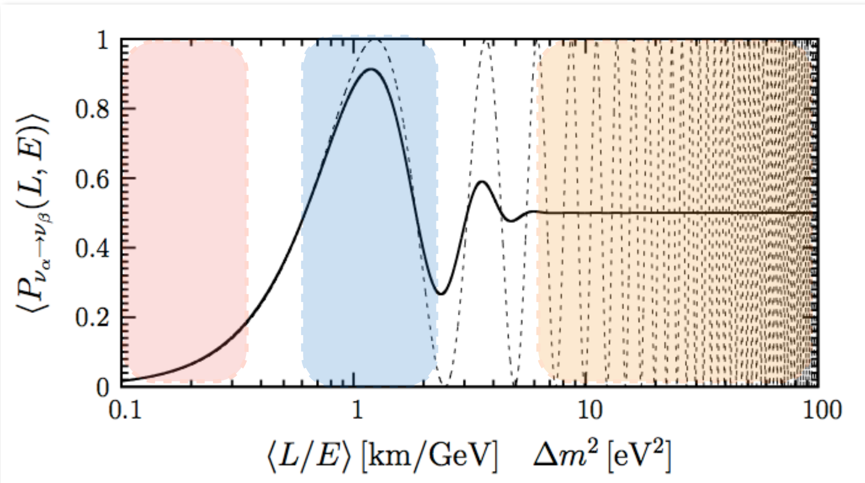
Time evolution: flavor content "oscillates" in L(distance)/E(neutrino)

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left[1.27\Delta m^2_{ij}(L/E)\right] + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin\left[2.54\Delta m^2_{ij}(L/E)\right]$$

oscillation amplitude

oscillation frequency

Parameters controlled by experiments

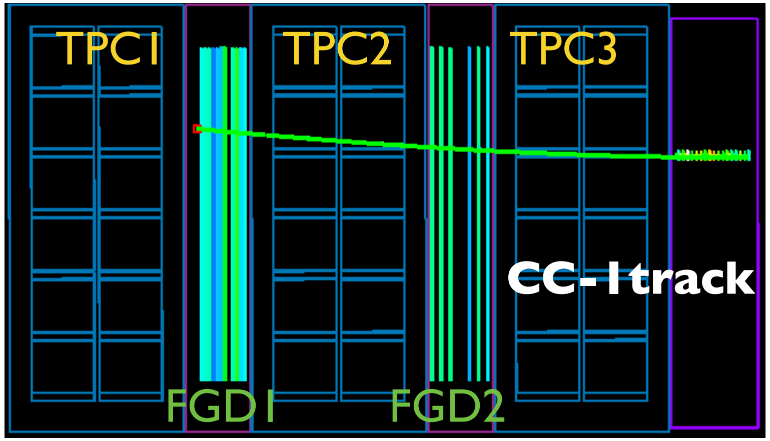


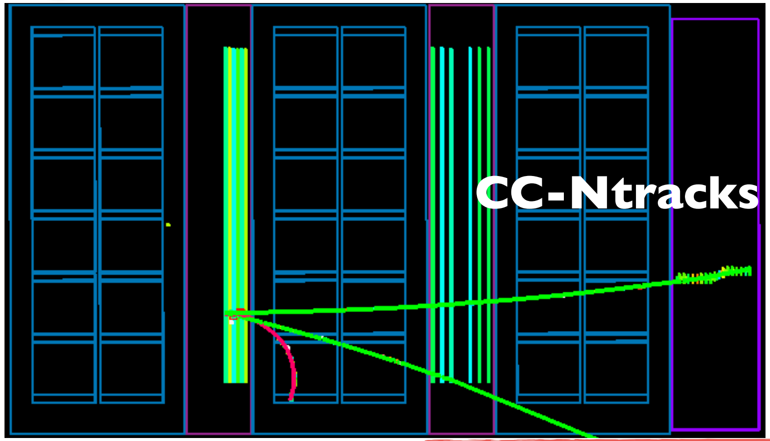
L/E << Δm^2 no time for the oscillation to develop

L/E >> Δm^2 only average oscillation probability can be measured

L/E ≈ Δm^2 best sensitivity to oscillation

ND280 FGD2 samples in anti-neutrino beam mode

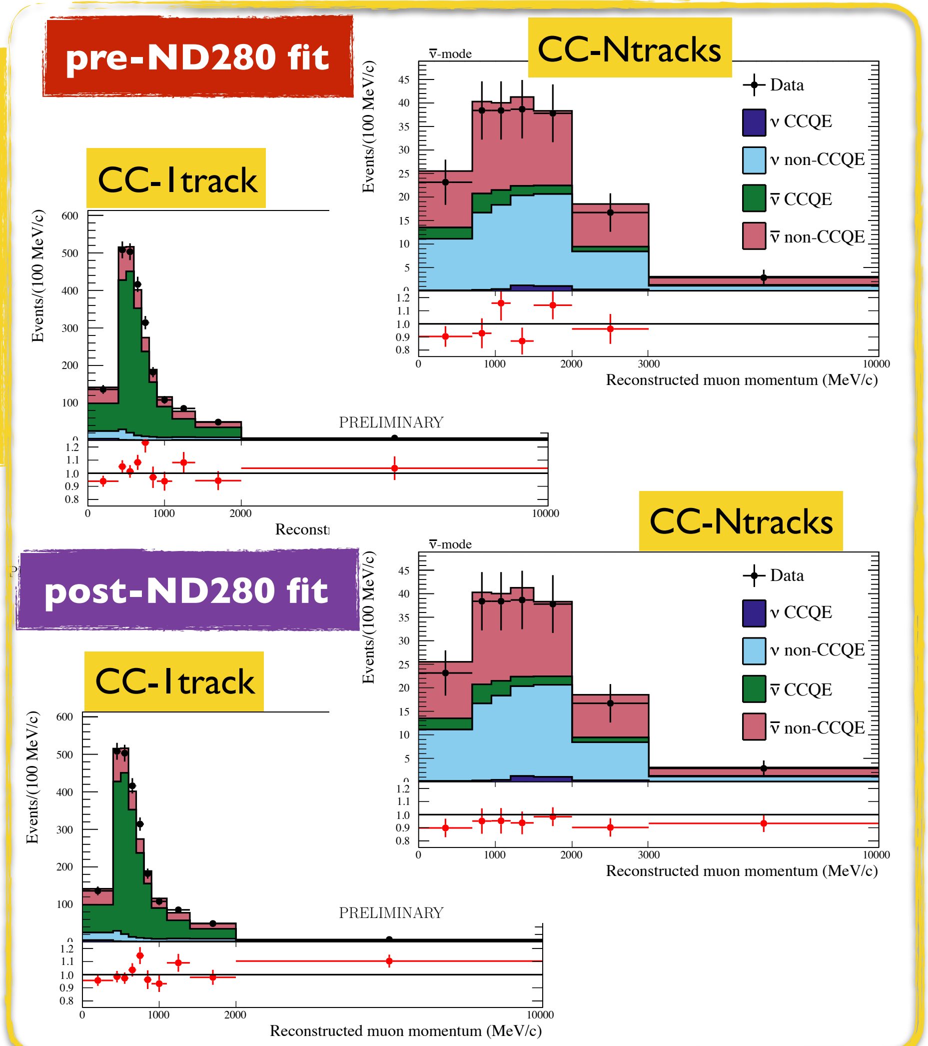




Selected both $\bar{\nu}_\mu$ and ν_μ CC events to better constrain the "wrong sign" contamination in $\bar{\nu}$ beam mode

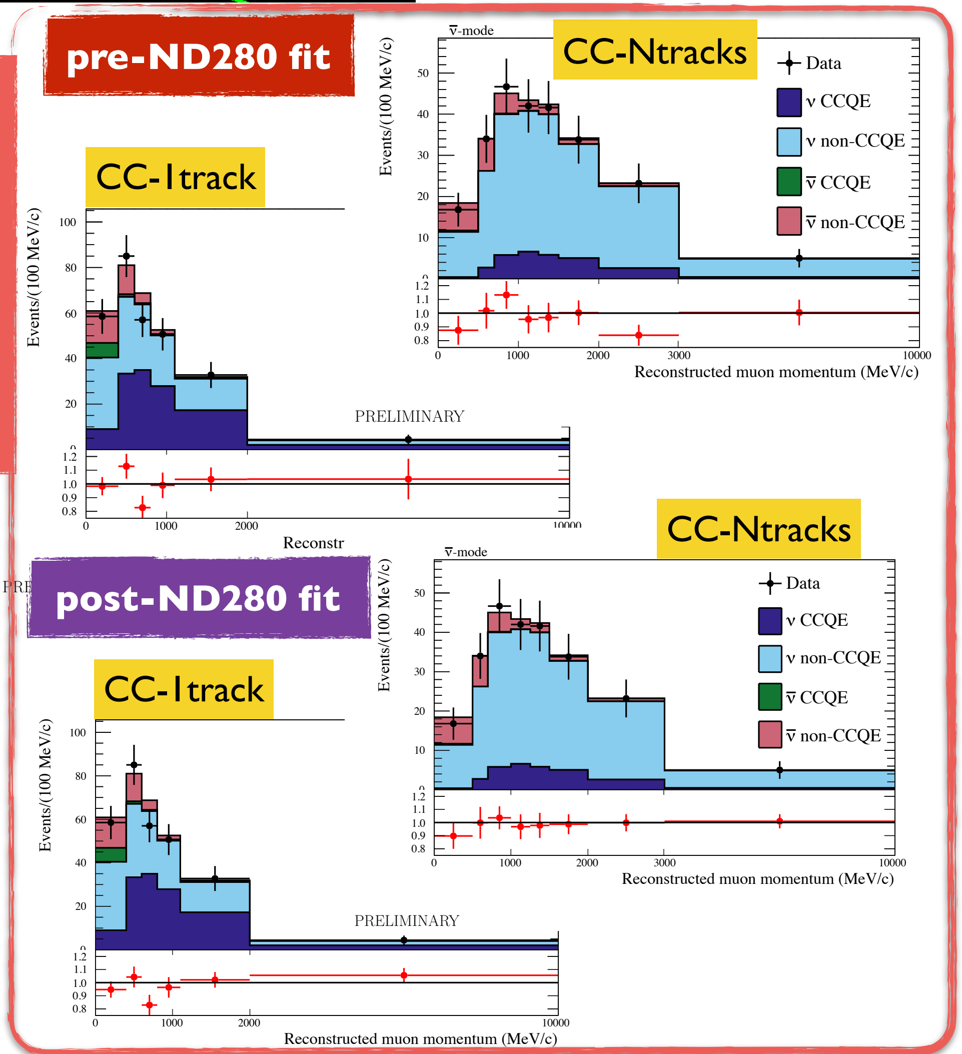
$\bar{\nu}_\mu$ signal

Phys.Rev. D96 (2017) no.9, 092006



ν_μ background

Phys.Rev. D96 (2017) no.9, 092006



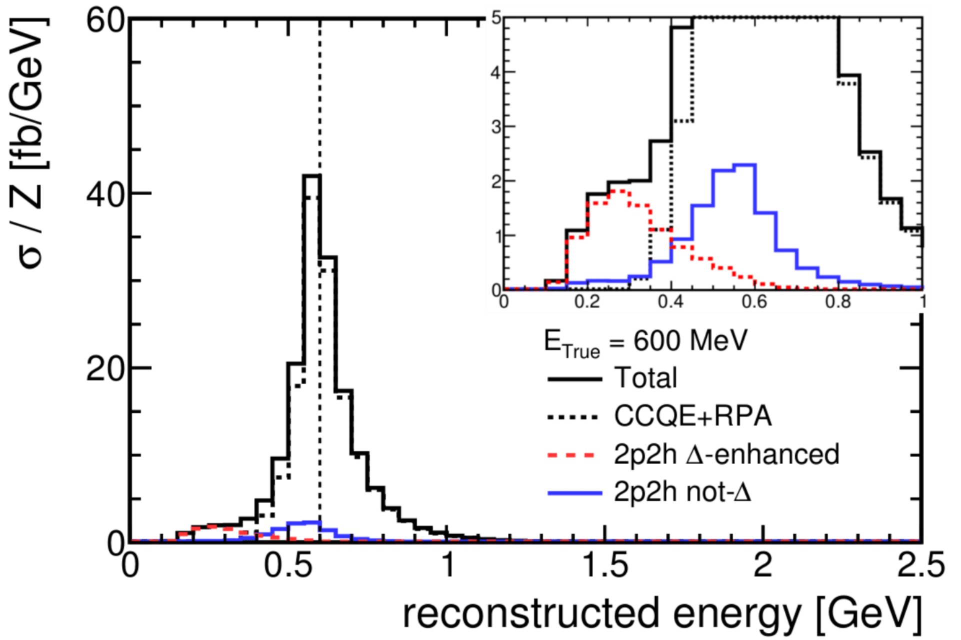
Neutrino cross sections at T2K energies

This analysis: developed new parameterisations of the uncertainties in multi-nucleon and RPA modelling:

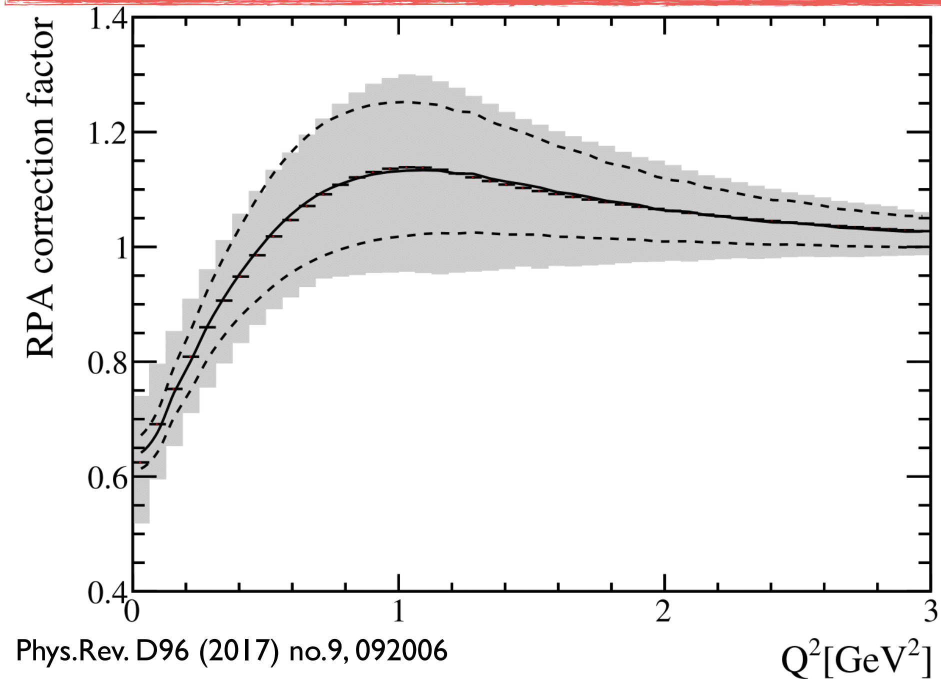
- Model the energy reconstruction error: allow strength of the 2p-2h cross-section to vary between all Δ-enhanced and all not-Δ-enhanced
- Also allow normalisation for 2p-2h to vary separately for neutrinos and antineutrinos

- Introduced a parametrisation for the RPA correction in Q^2 in order to cover the theoretical uncertainty on the RPA correction factor

2p-2h affect the neutrino energy reconstruction

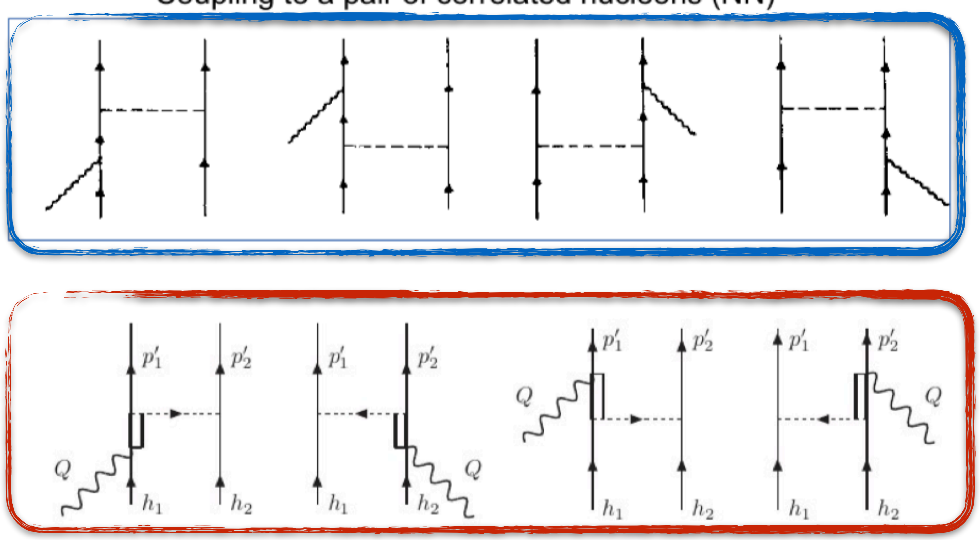


Random Phase Aprroximation (RPA) can change the Q^2 dependency of neutrino cross-section



Phys.Rev. D96 (2017) no.9, 092006

Coupling to a pair of correlated nucleons (NN)

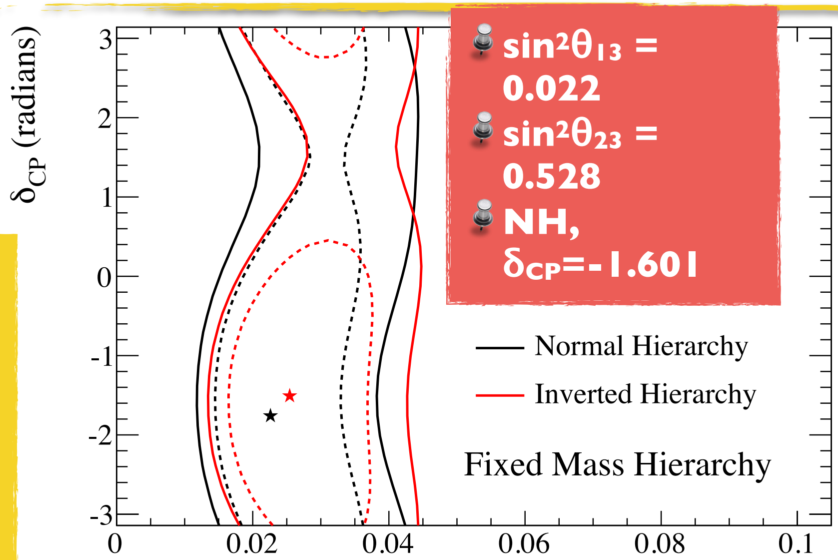


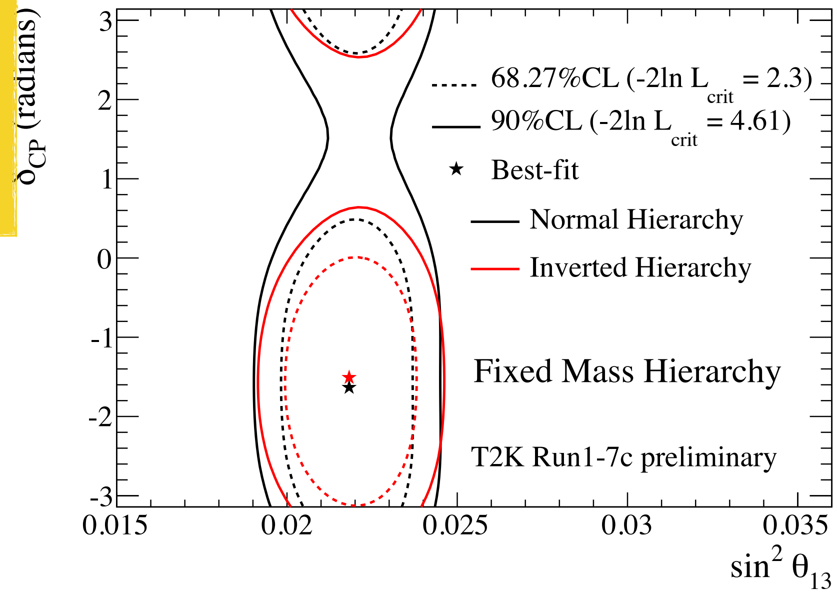
Coupling to a Δ-resonance (Δ-pole)

Results: δ_{CP} vs θ_{13} confidence regions

Run1-7 Sensitivity

- $\sin^2\theta_{13}$ = 0.022
- $\sin^2\theta_{23}$ = 0.528
- NH, δ_{CP}=-1.601

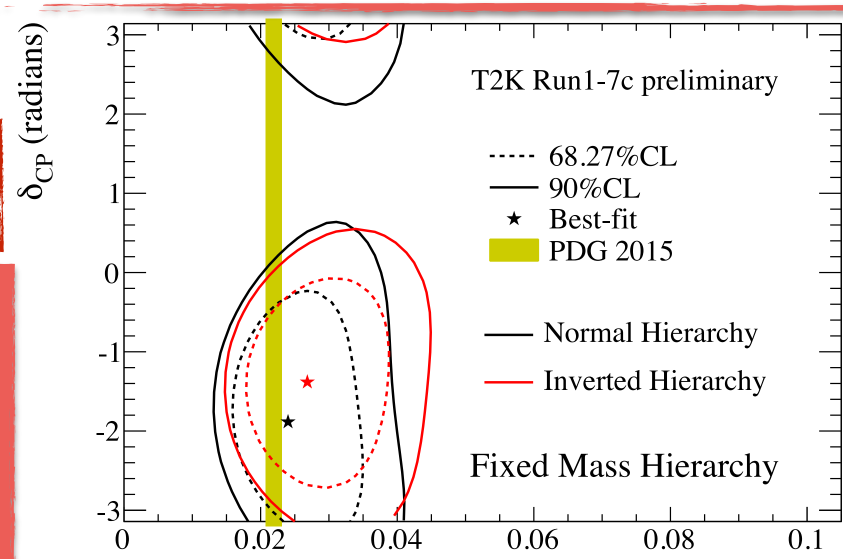


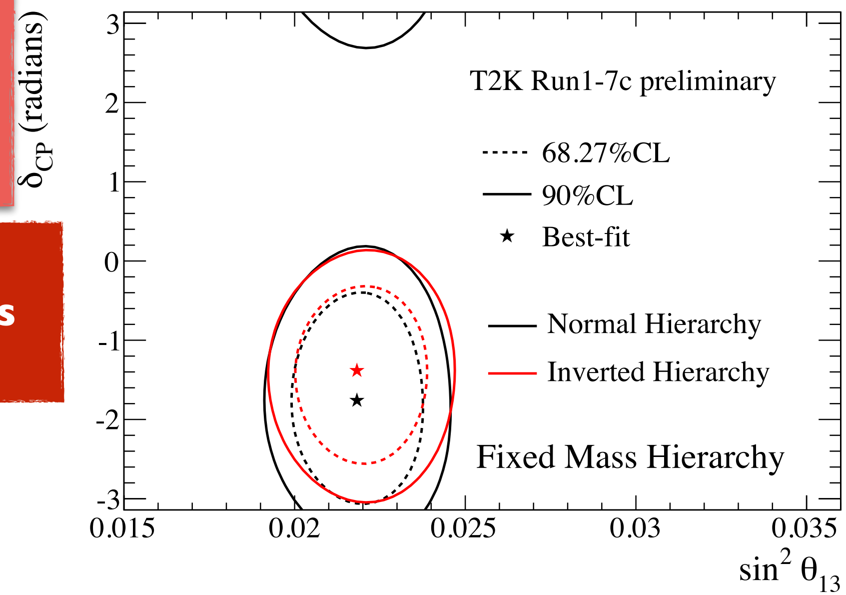


T2K only

Run1-7 Observed

T2K + Reactors θ_{13}





- **T2K results consistent with reactor results**
- **Maximal CPV: data prefer $\delta_{CP}=-\pi/2$ ($\bar{\nu}_e$ data confirm the tendency observed for ν_e data)**
- **Favors the scenario of a small θ_{13} and large CPV**

$\overline{\nu}_e$ appearance search

- <u>Motivations :</u> $\nu_\mu \rightarrow \nu_e$ has been observed @T2K, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ has never been observed !

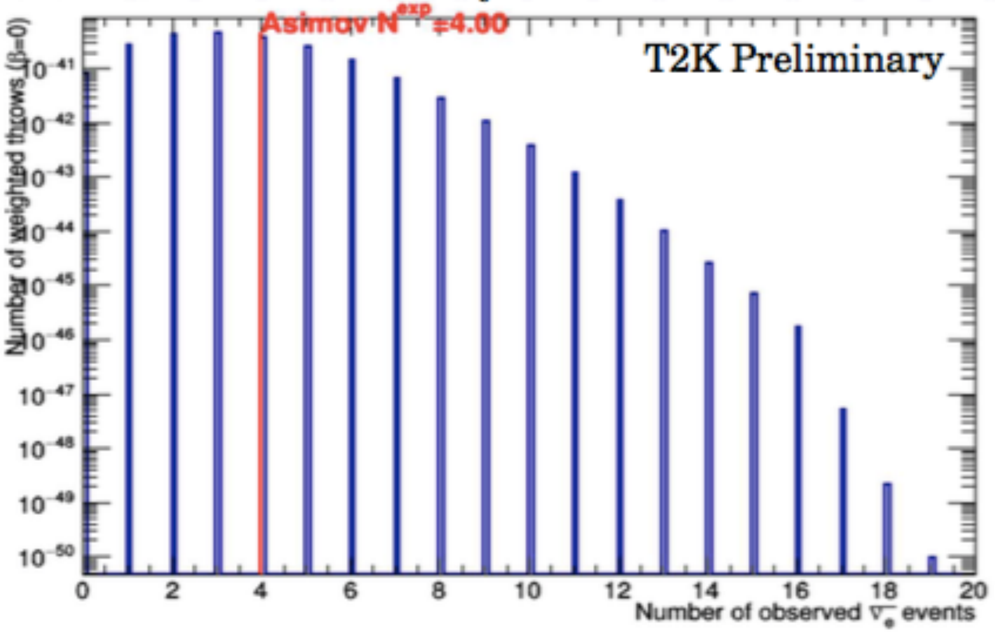
- To test the $\overline{\nu}_e$ appearance only : $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ [PMNS]$\rightarrow \beta \times P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$, $P(\nu_\mu \rightarrow \nu_e)$ unchanged.
β=0 → No $\overline{\nu}_e$ appearance, β=1 → $\overline{\nu}_e$ appearance predicted by PMNS

- <u>Null hypothesis testing :</u> no $\overline{\nu}_e$ appearance (β=0) + PMNS model testing (β=1).

<u>2 analyses :</u> (results are shown for β=0 hypothesis in the toy generation)

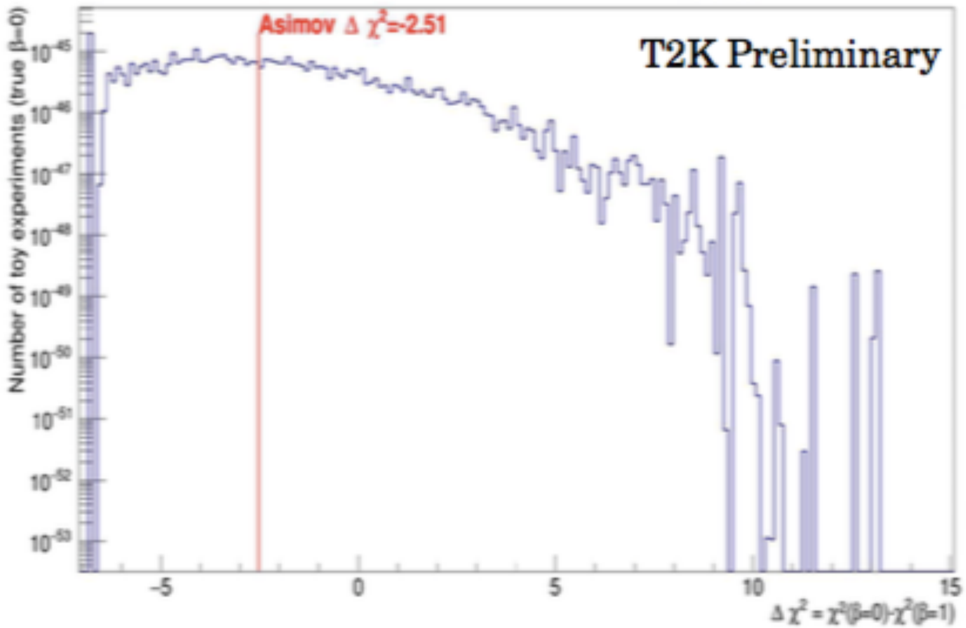
<u>Rate-only :</u>

Number of observed $\overline{\nu}_e$ events @SK.



<u>Rate+shape :</u>

$$\Delta\chi^2 = \chi^2(\beta = 0) - \chi^2(\beta = 1)$$



$\overline{\nu}_e$ appearance search: interpretation of the results

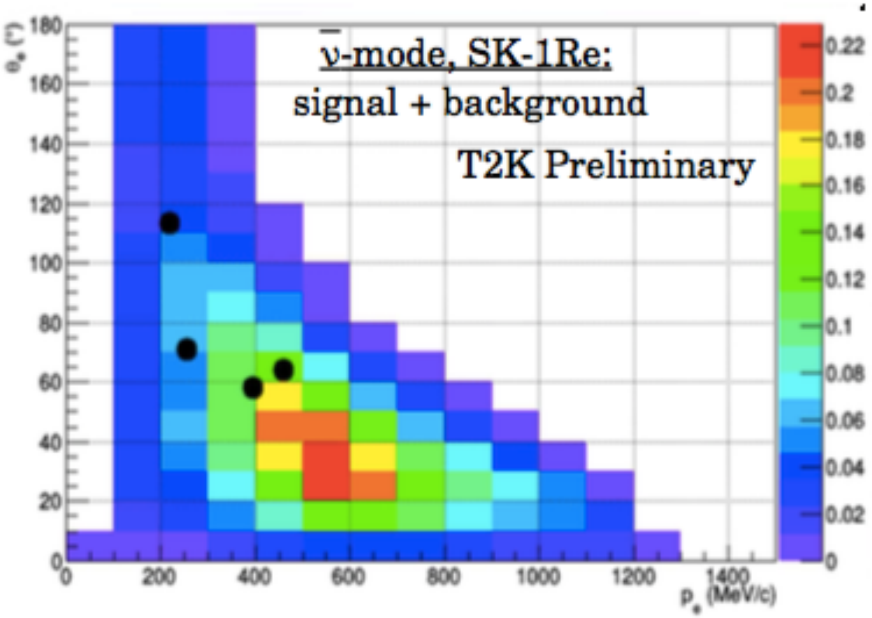
- Results summary :

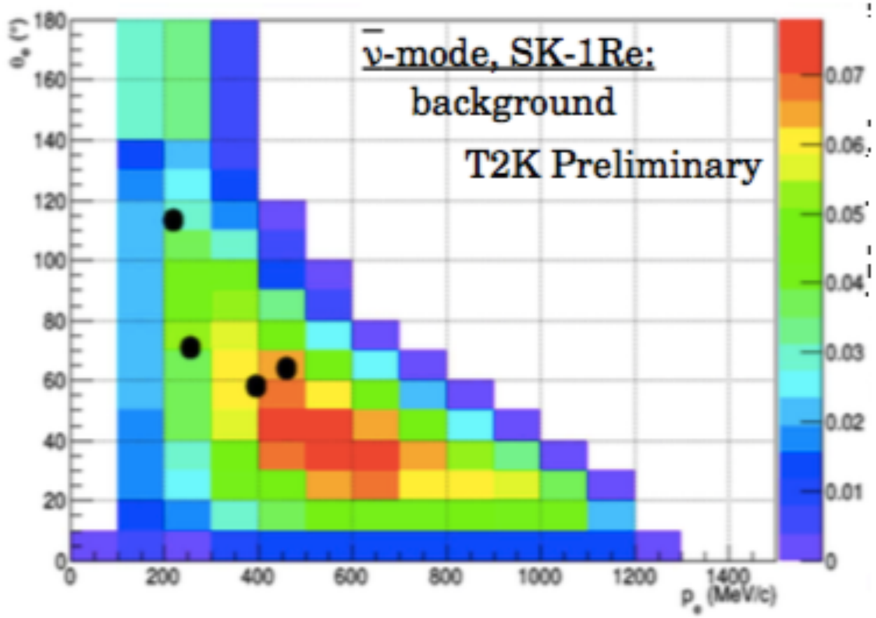
	P-value (β=0)	P-value (β=1)
Rate-only	0.41	0.21
Rate+shape	0.46	0.07

- Data set favours the « no $\overline{\nu}_e$ appearance » hypothesis → $N^{obs}_{\overline{\nu}e} = 4$

($N^{exp}_{\overline{\nu}e}$ =6.0 expected even if NH & δ_{CP} =-π/2).

- Data are in mild tension with the PMNS model → The rate+shape analysis shows almost 2σ deviation from PMNS !
  → Not only rate, but shape also increases the disagreement.

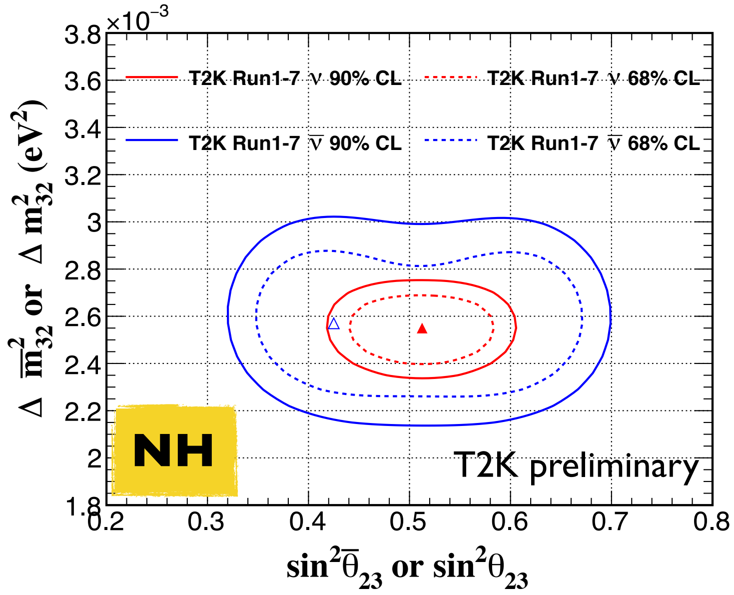


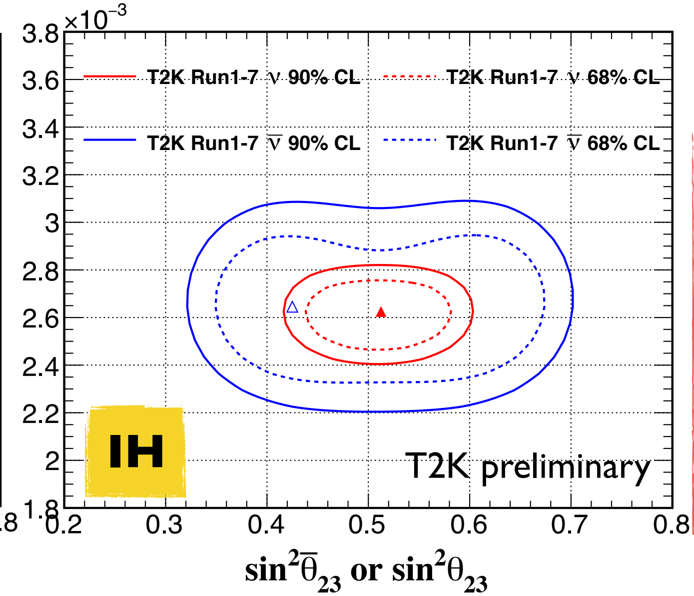


- Not only the rate is low, but the shape of $\overline{\nu}_e$ events looks like background !

ν_μ and $\bar{\nu}_\mu$ disappearance results

Constraints on the atmospheric parameters: θ_{23} and Δm^2_{31}



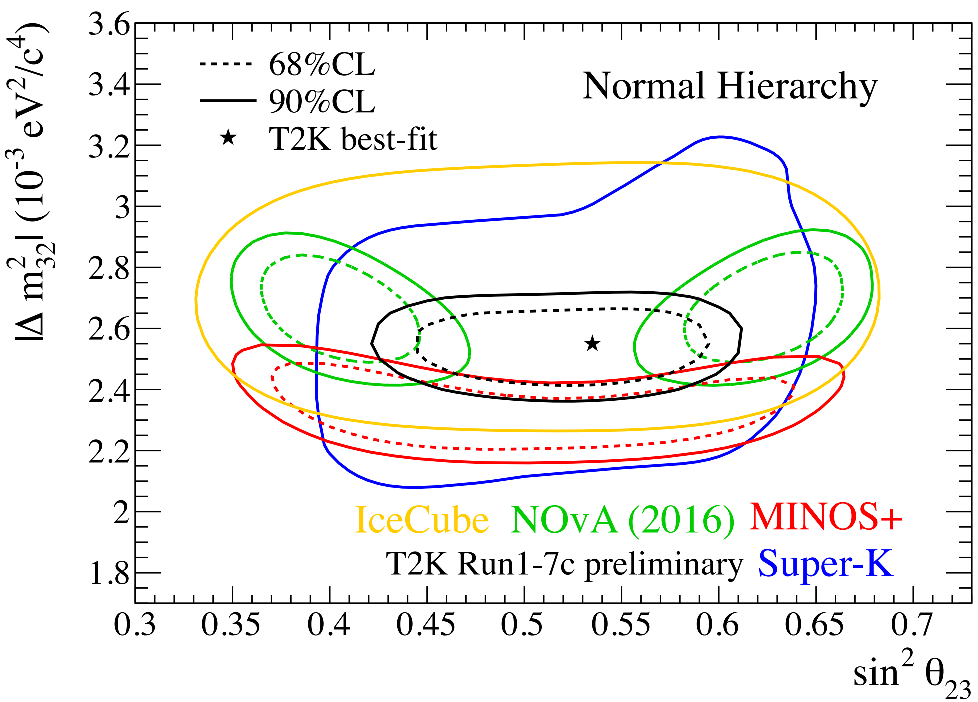


- **CPT theorem:**

$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

if $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \Rightarrow$

CPT theorem is violated



- **World-leading measurement of $\sin^2\theta_{23}$**
- **Results continue to be consistent with maximal mixing/oscillation**
- **No significant differences between ν and $\bar{\nu}$**

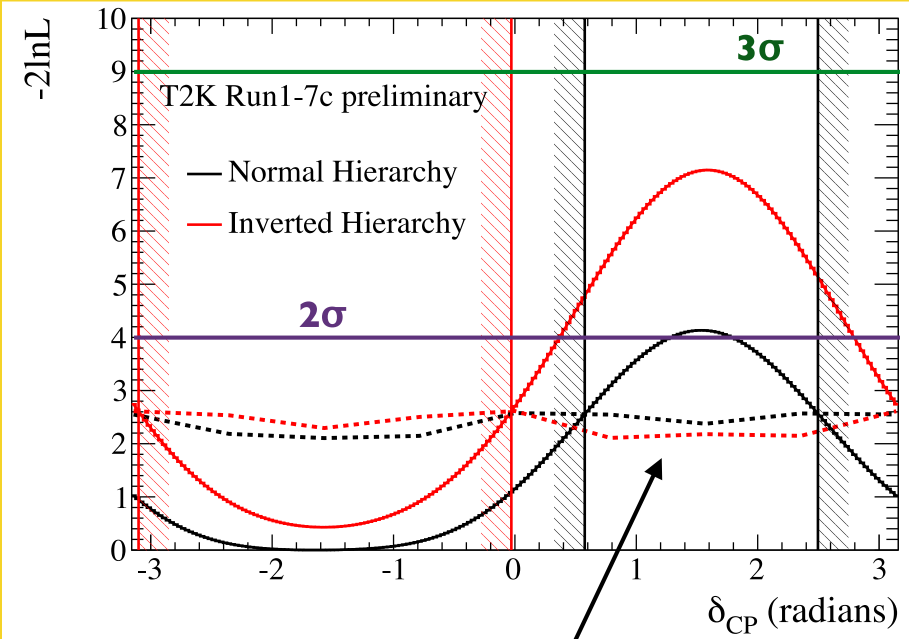
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.007}$
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-5}$ eV^2/c^4)	$254.5^{+8.1}_{-8.4}$	$251.0^{+8.1}_{-8.3}$

Results: δ_{CP} confidence regions

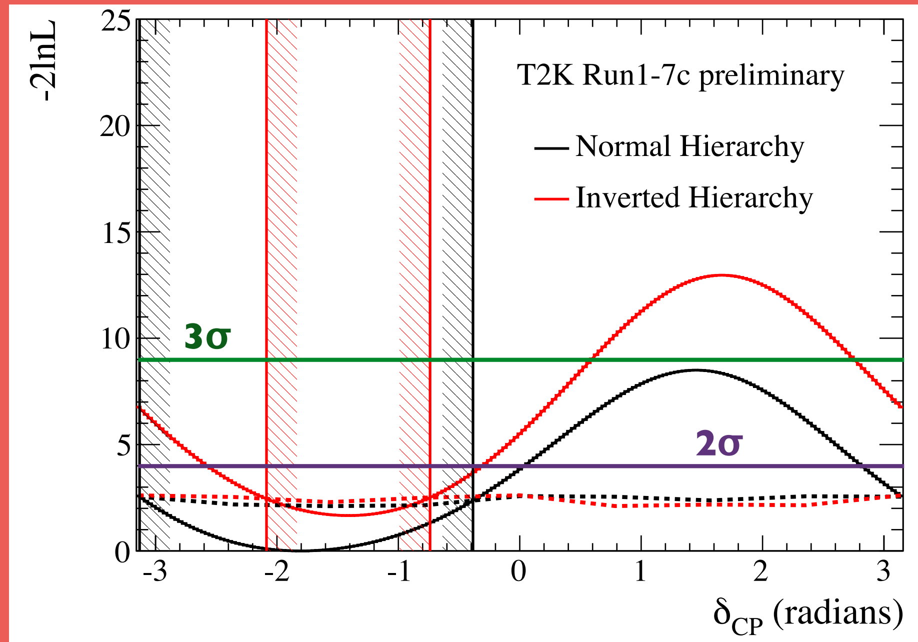
T2K + Reactor θ_{13} (PDG 2015)

$\sin^2\theta_{13}=0.022$, $\sin^2\theta_{23}=0.528$, NH, $\delta_{CP}=-1.601$

Run 1-7 **sensitivity**



Run 1-7 **observed**



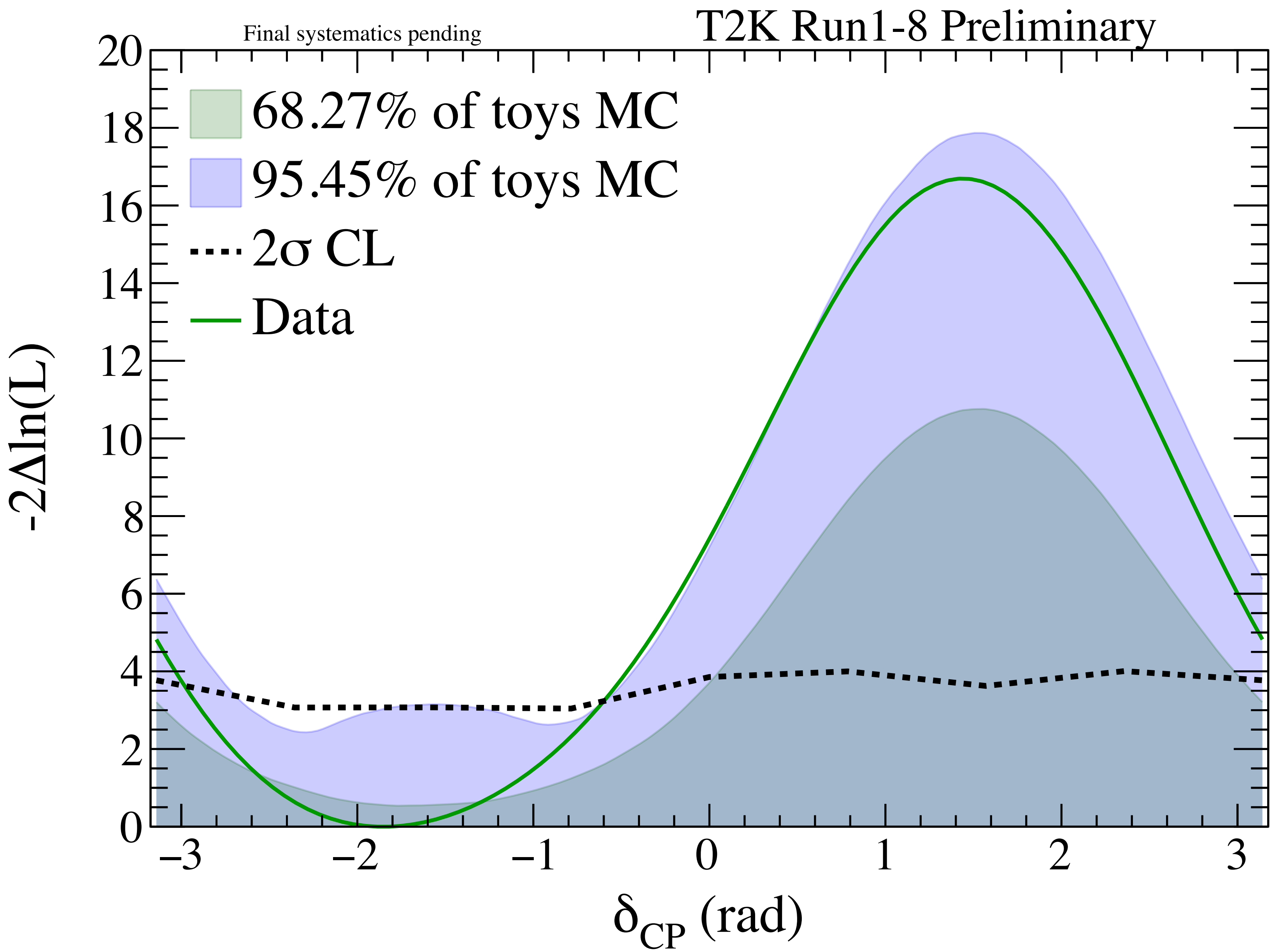
Feldman-Cousins critical $\Delta\chi^2$ values for 90% C.L.

CP conservation (δ_{CP} = 0,π) excluded at 90% C.L.

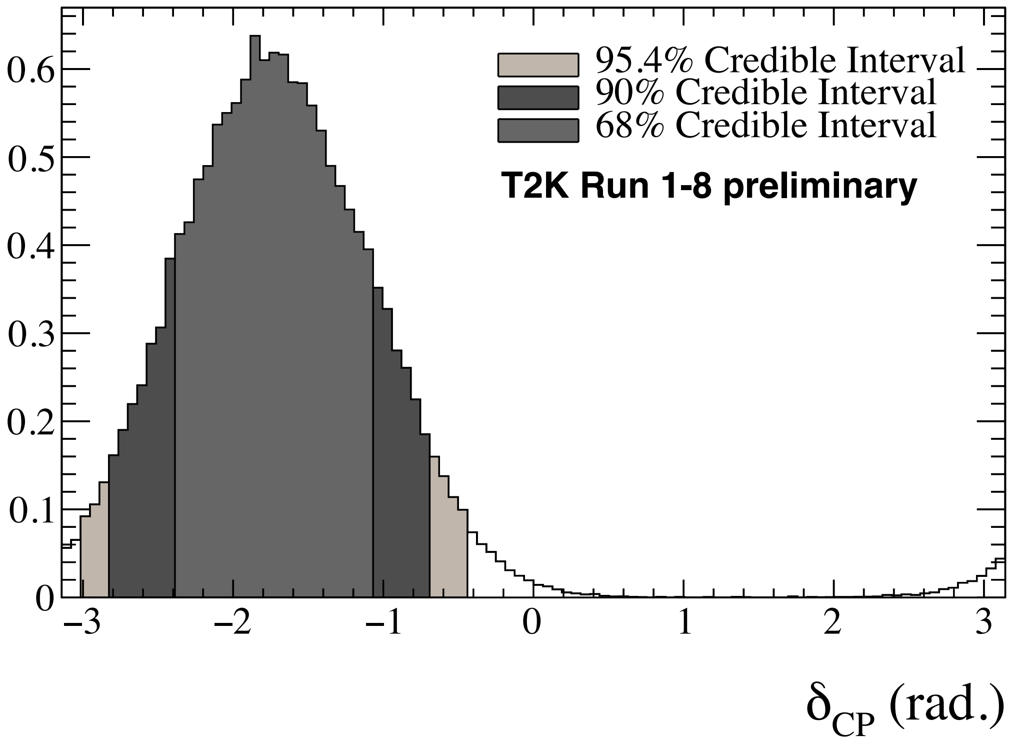
Toy MC: if nature is NH and $\delta_{CP} = -\pi/2$ the probability for excluding $\delta_{CP} = 0$ or π at 90% C.L. is19.6% and 17.3% respectively

- **δ_{CP} = [-3.13, -0.39] assuming NH**
- **δ_{CP} = [-2.09, -0.74] assuming IH**

Results: δ_{CP} confidence regions



Results: Bayesian posterior probabilities



Markov Chain Monte Carlo (MCMC)

- Posterior probability distribution in δ_{CP} marginalizing over all parameters
- Negligible dependence on priors
- Posterior probability distributions for θ_{23} octant and hierarchy with MCMC analysis

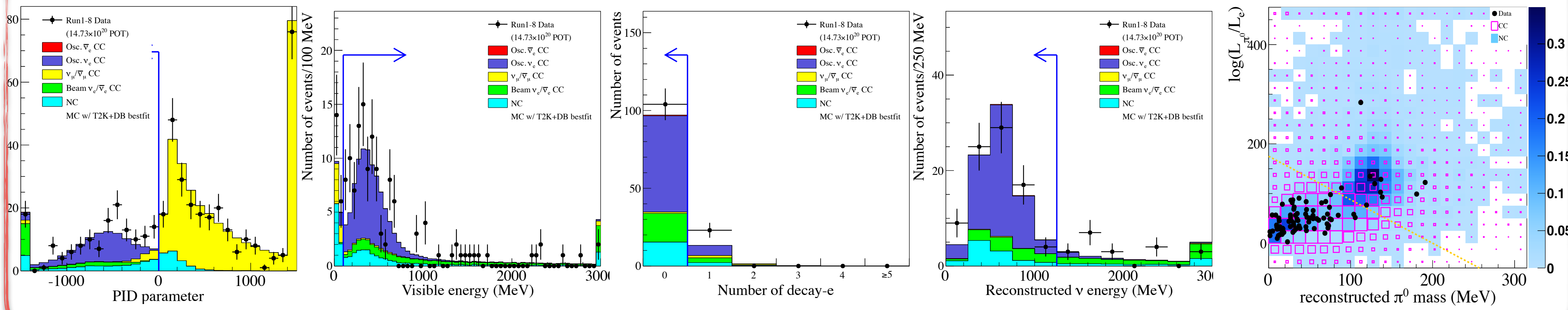
	Mass hierarchy		
Octant	NH	IH	Sum
$\theta_{23} < 45^\circ$	19,3%	2,6%	21,9%
$\theta_{23} > 45^\circ$	67,4%	10,6%	78,1%
Sum	86,8%	13,2%	100%

Weak preference for $\theta_{23} > 45^\circ$ and normal hierarchy

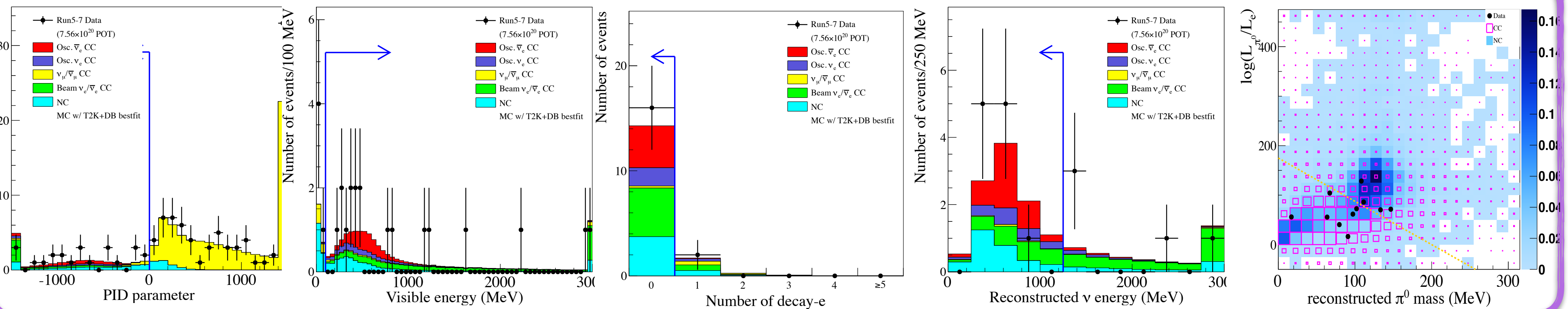
Event selection at Super-Kamiokande

1Re CCQE ν beam mode

PID | visible E | Michel Electrons | Recon. E | π^0 rejection



Selection cuts

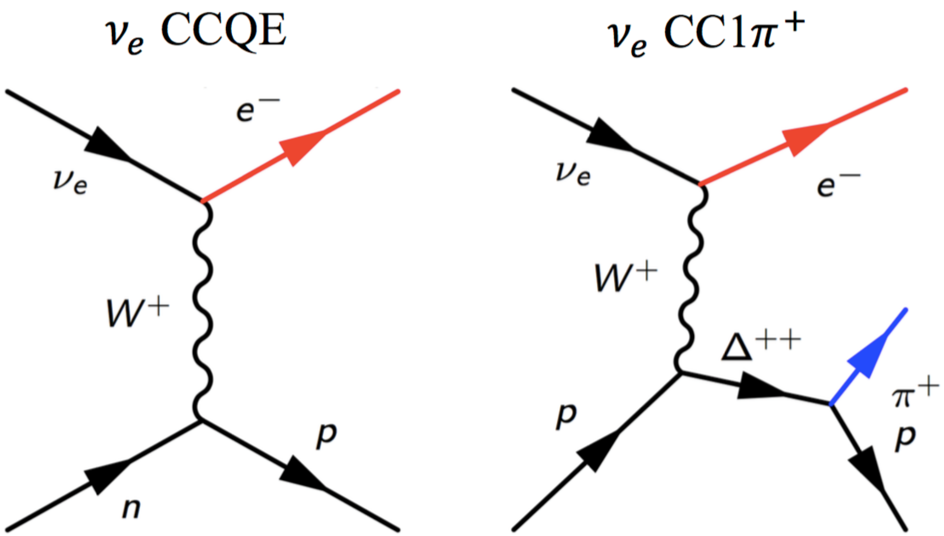


Selection cuts

1RE CCQE ν̄ beam mode

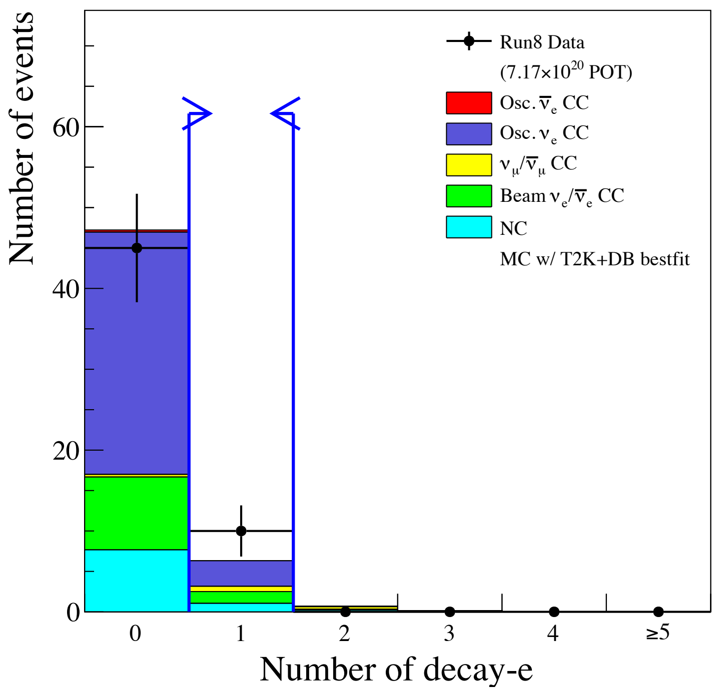
Selection of additional ν_e CC1π^+ appearance sample

Introduce ν_e single-ring, electron-like events with one Michel Electron

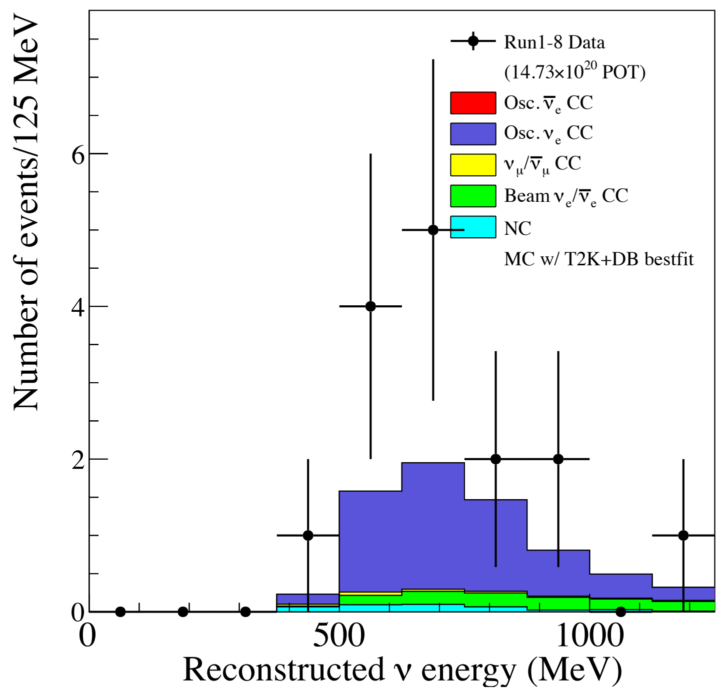


Expected number of events (for NH)

δ_{CP}			
-π/2	0	+π/2	π
6.9	6	4.9	5.8

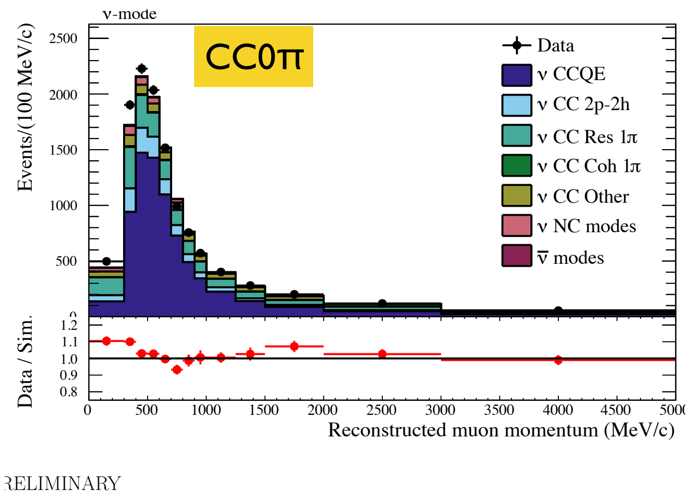


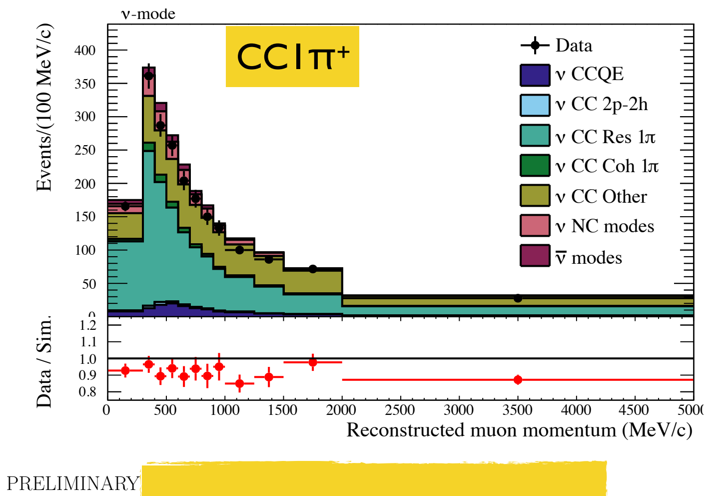
15 events observed

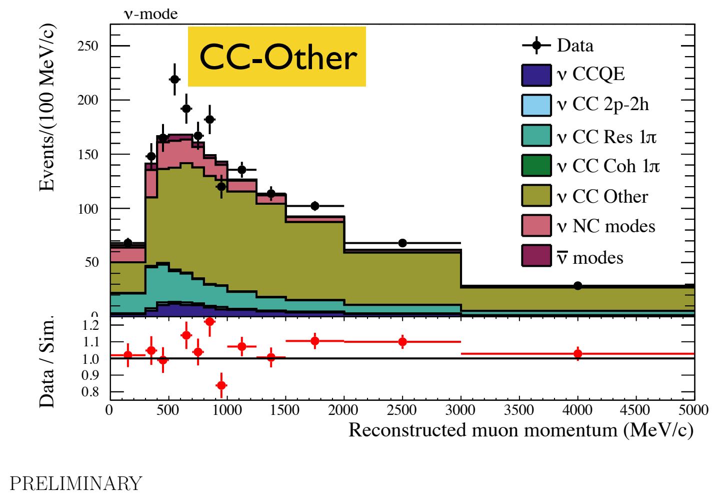


ND280 samples in neutrino beam mode (FGD1)

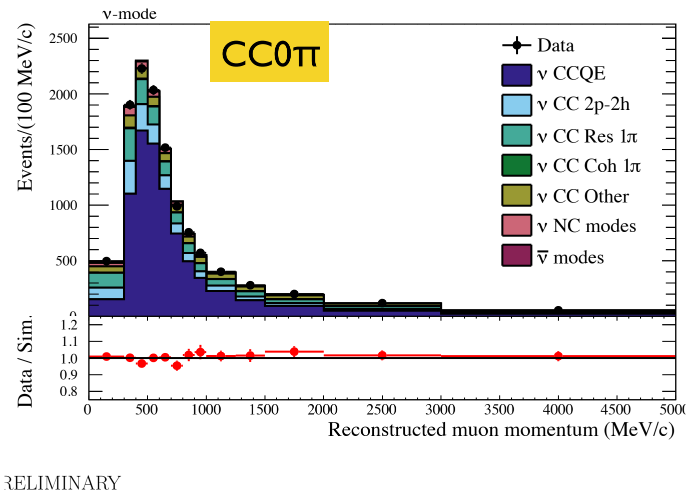
pre-ND280 fit

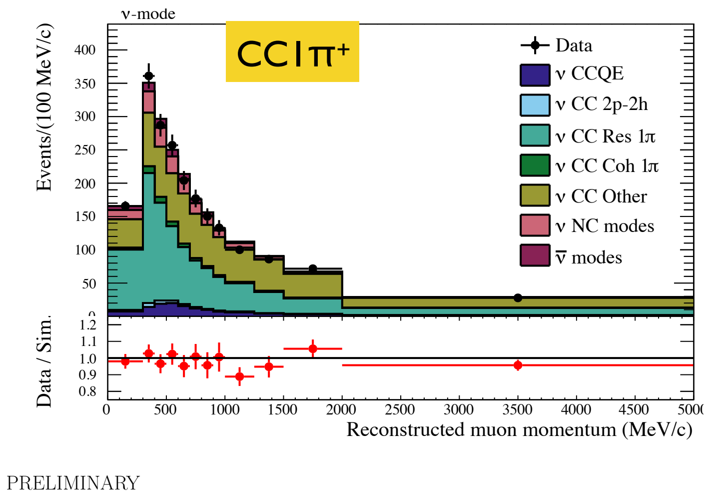


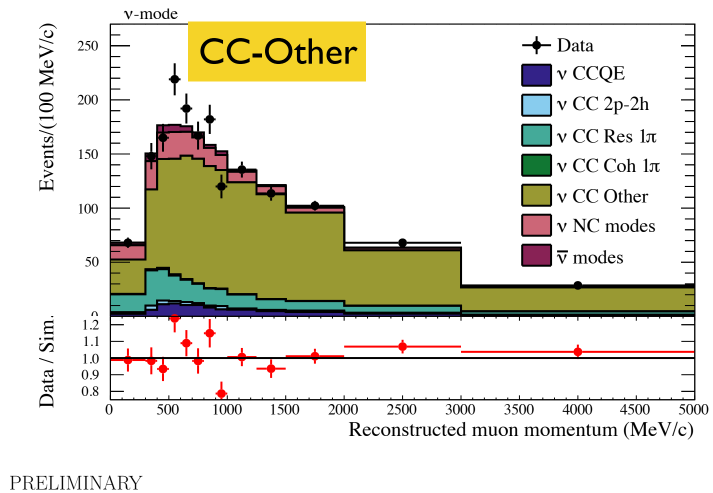




post-Nd280 fit

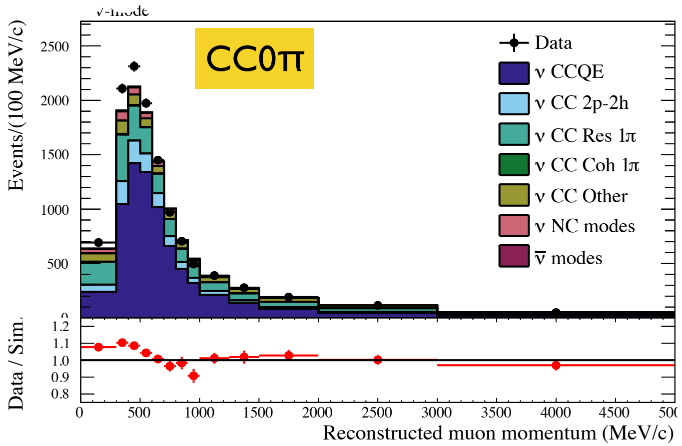




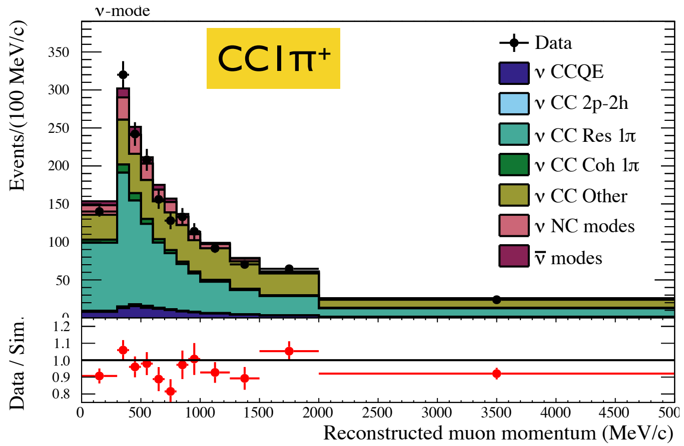


ND280 samples in neutrino beam mode (FGD2)

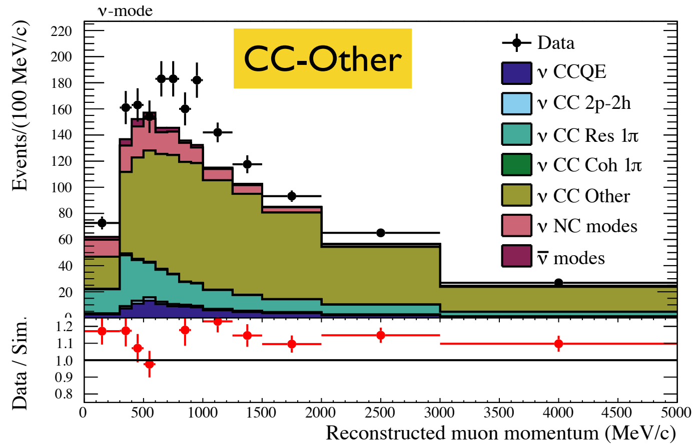
pre-ND280 fit



ELIMINARY

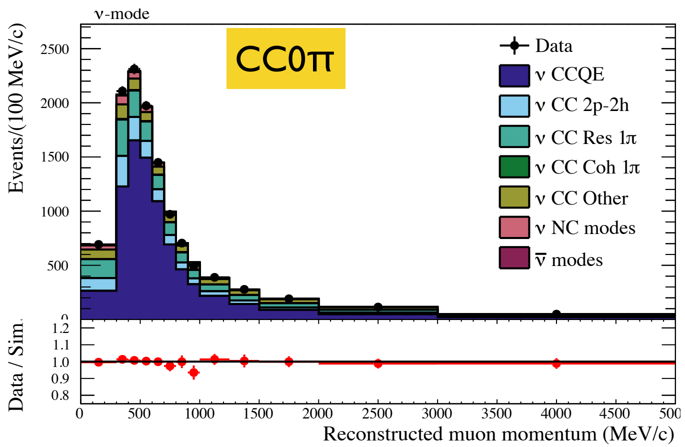


PRELIMINARY

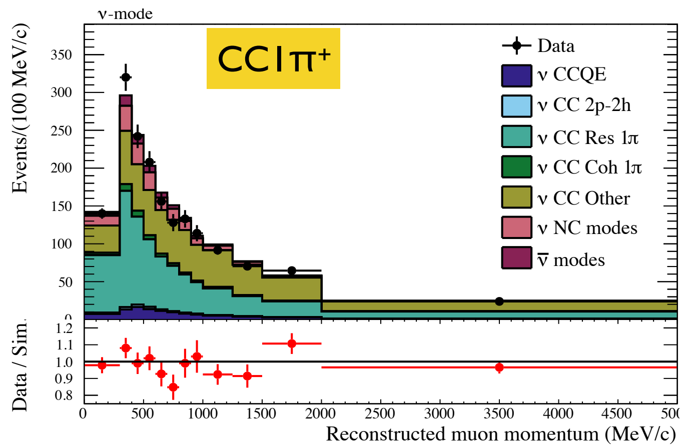


PRELIMINARY

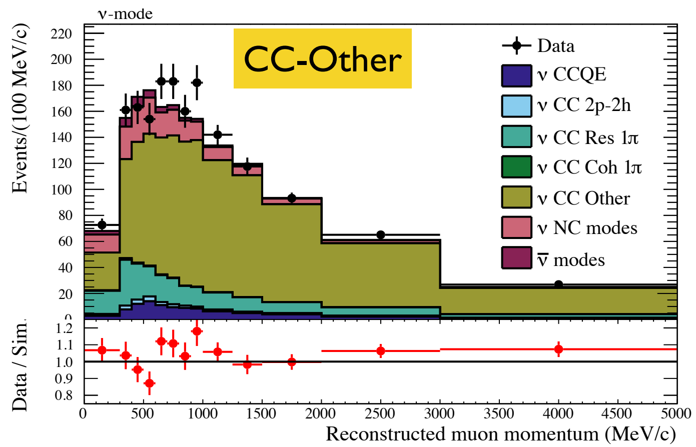
post-Nd280 fit



ELIMINARY



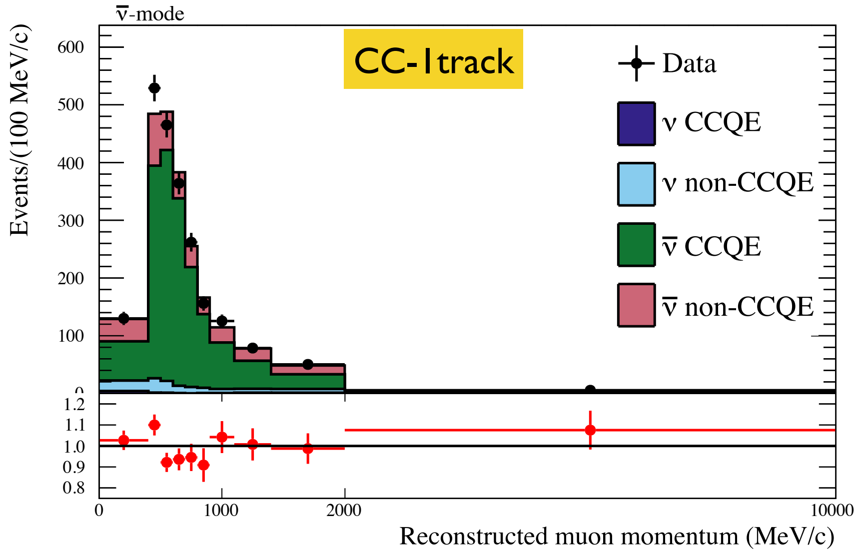
PRELIMINARY

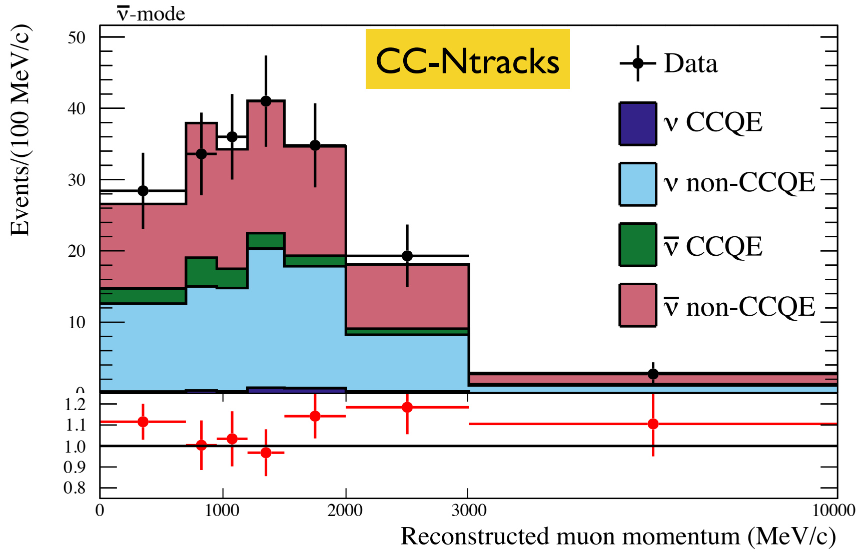


PRELIMINARY

ND280 samples in anti-neutrino beam mode ($\bar{\nu}_\mu$ FGD1)

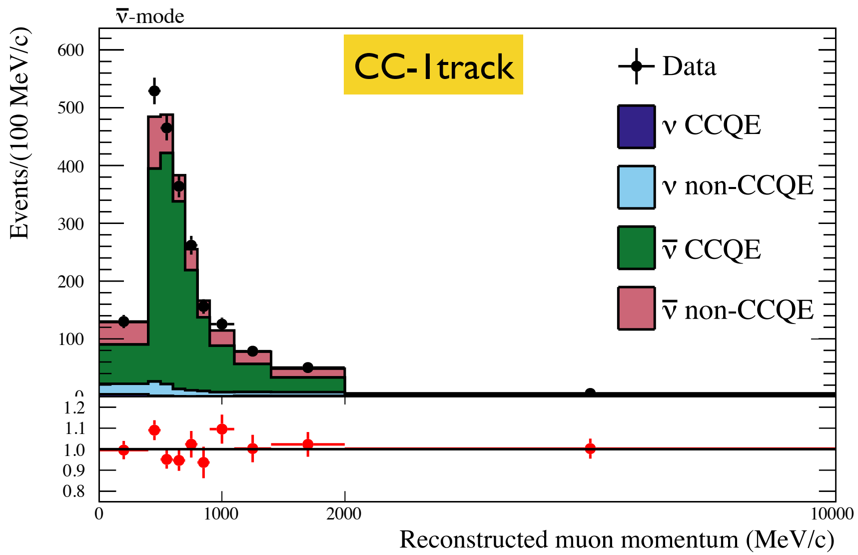
pre-ND280 fit

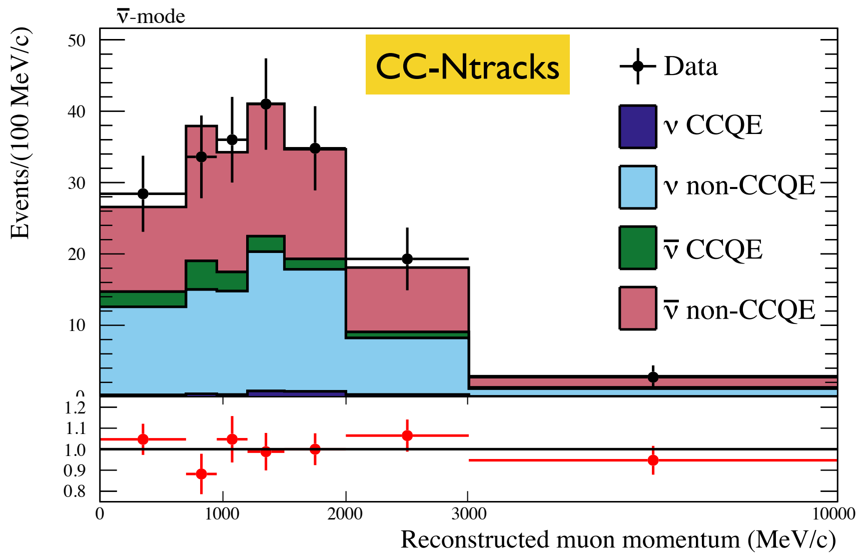




RELIMINARY

post-ND280 fit



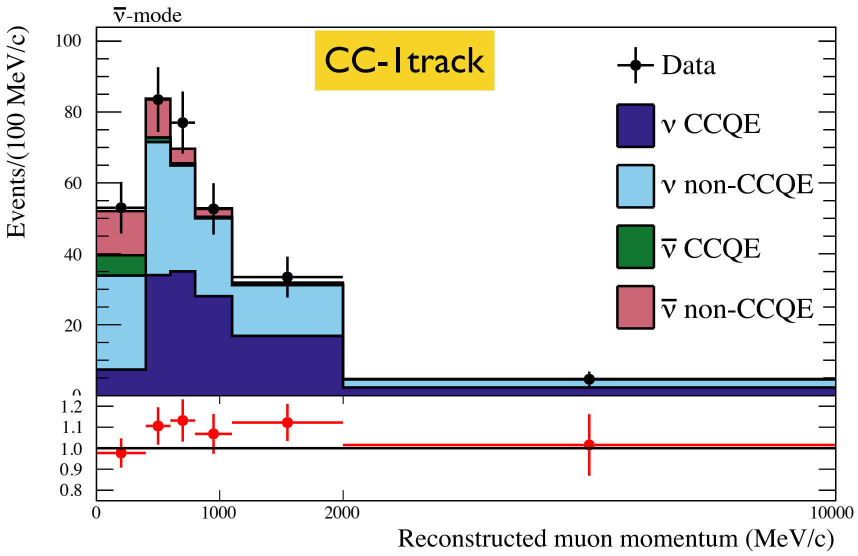


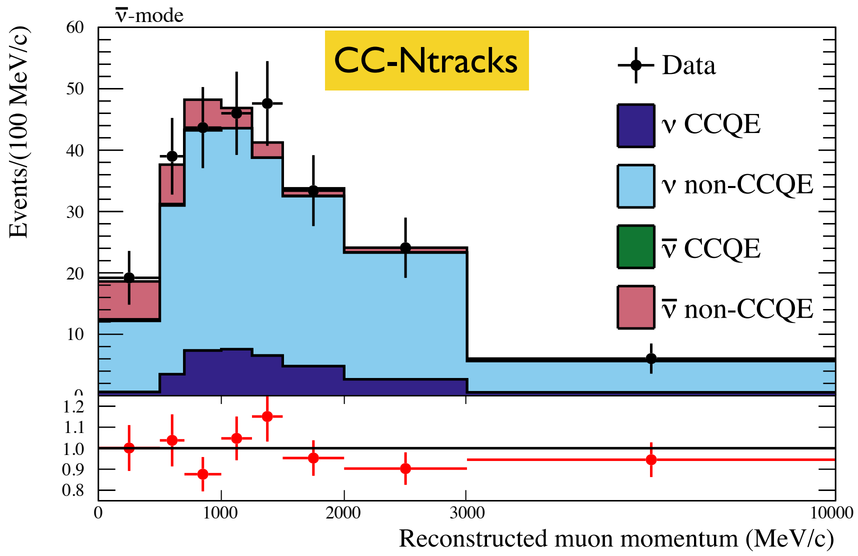
RELIMINARY

PRELIMINARY

ND280 samples in anti-neutrino beam mode (ν_μ FGD1)

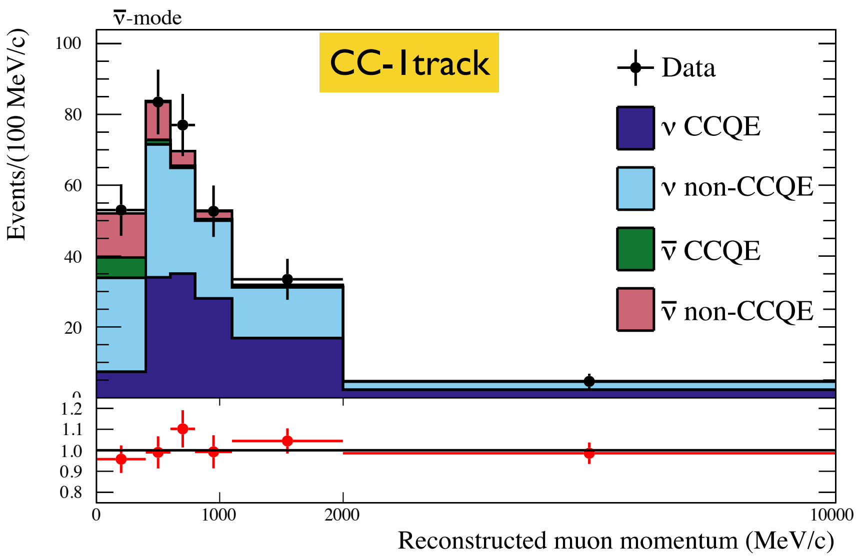
pre-ND280 fit



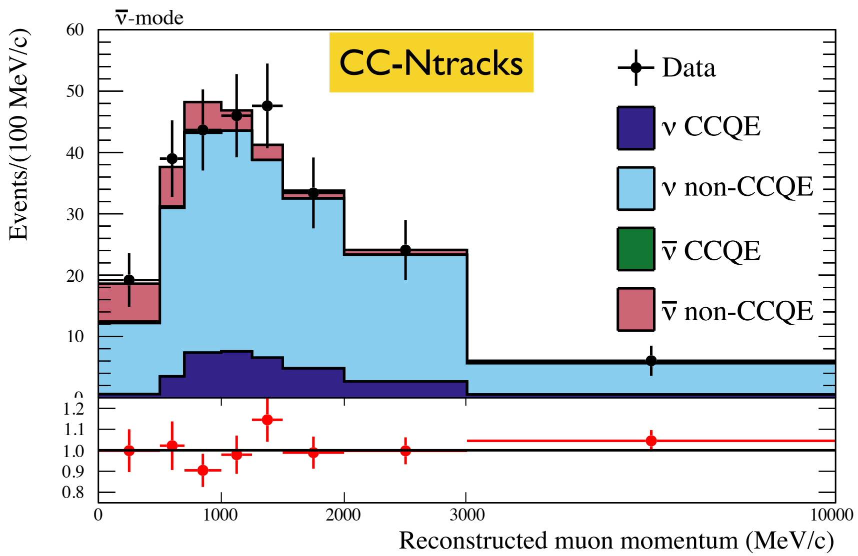


PRELIMINARY

post-ND280 fit



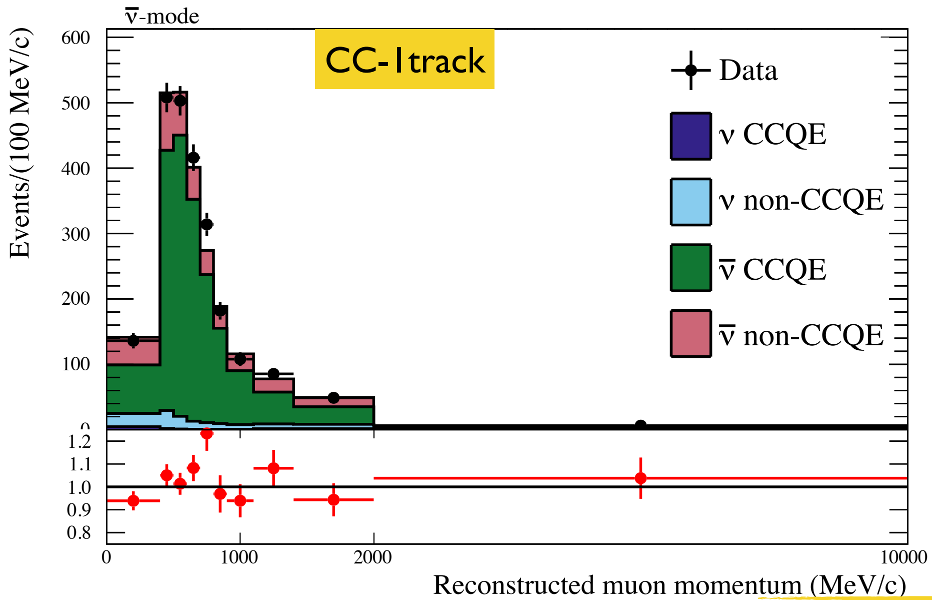
PRELIMINARY

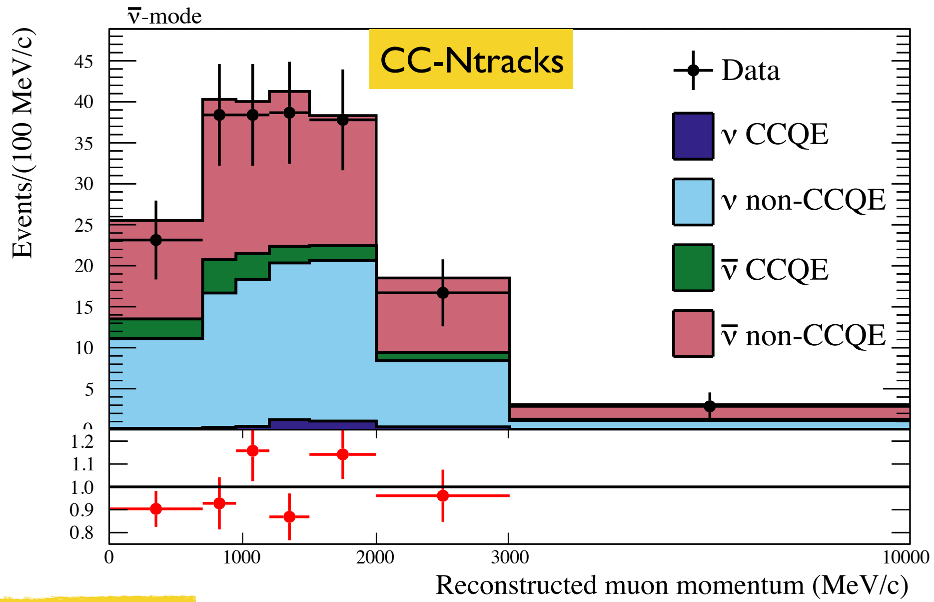


PRELIMINARY

ND280 samples in anti-neutrino beam mode ($\bar{\nu}_\mu$ FGD2)

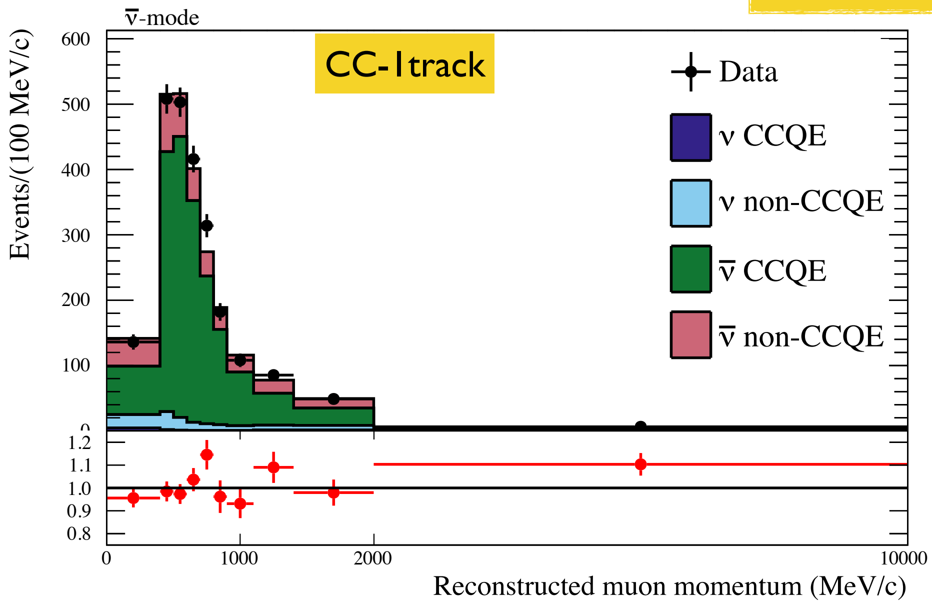
pre-ND280 fit

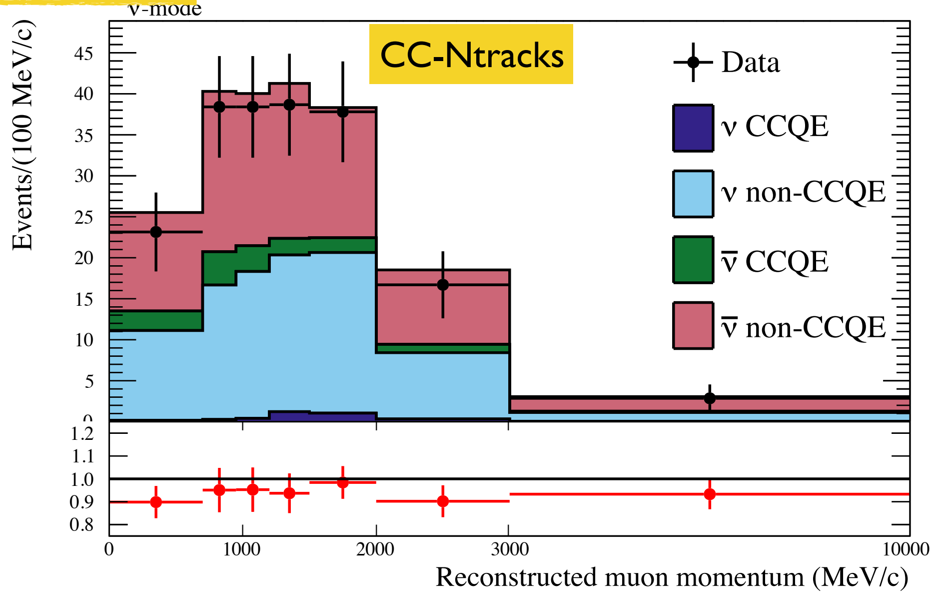




PRELIMINARY

post-ND280 fit



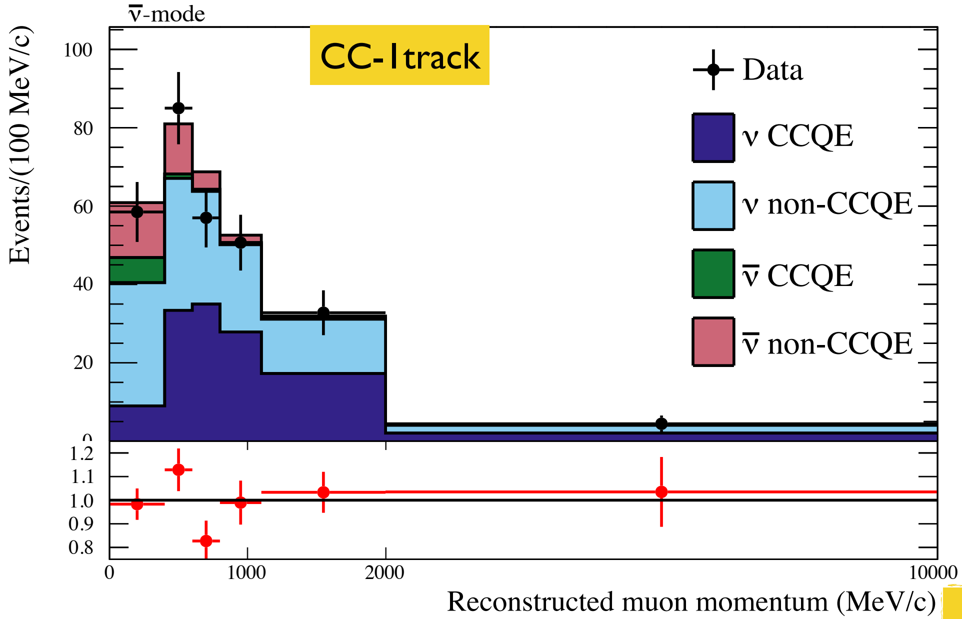


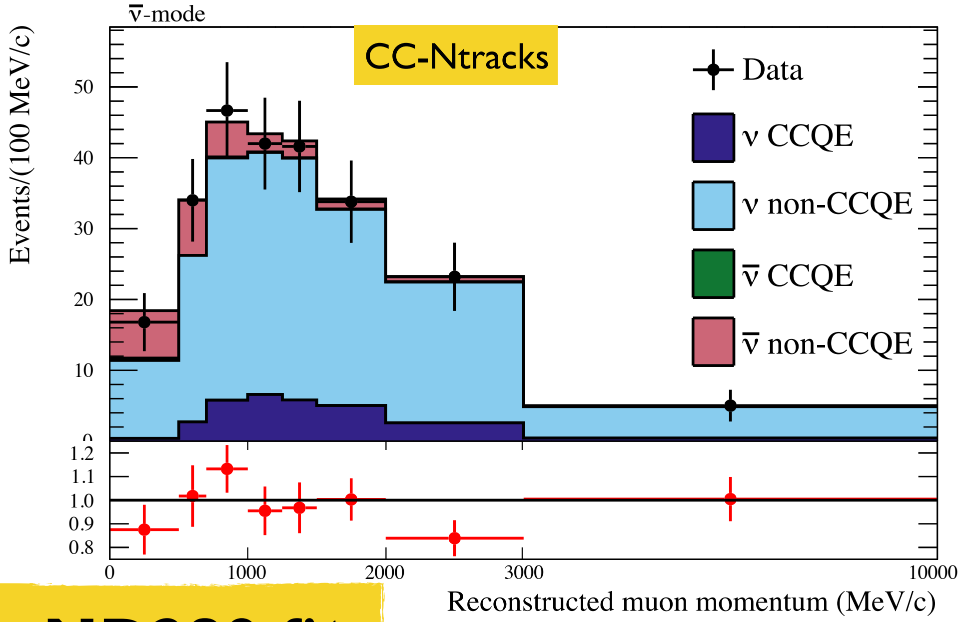
PRELIMINARY

PRELIMINARY

ND280 samples in anti-neutrino beam mode (ν_μ FGD2)

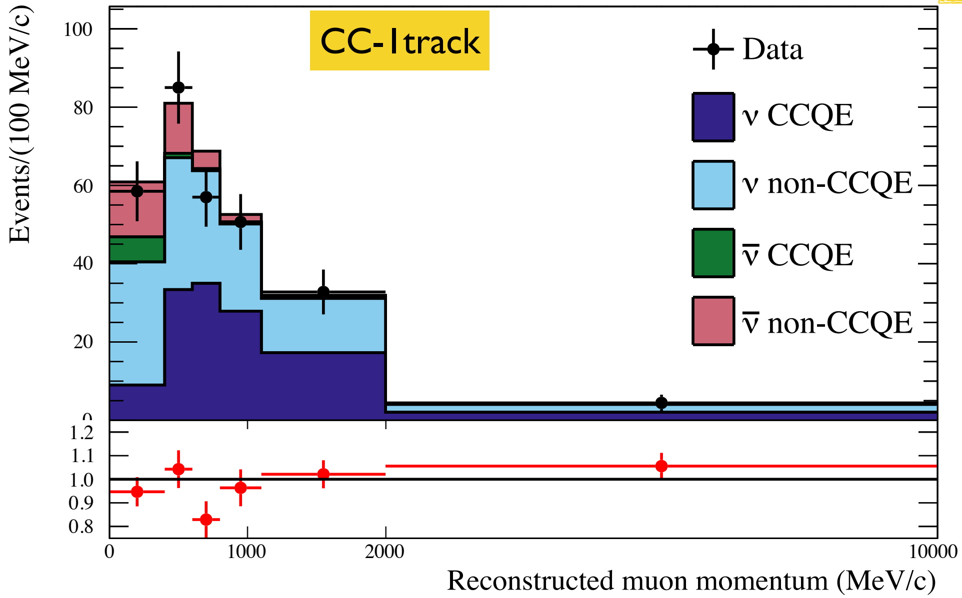
pre-ND280 fit

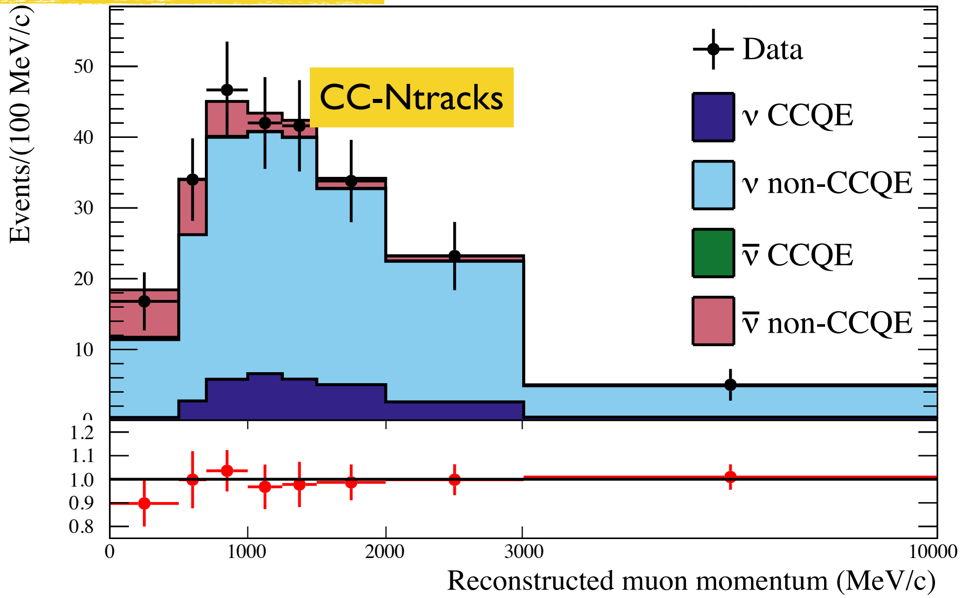




post-ND280 fit

PRELIMINARY

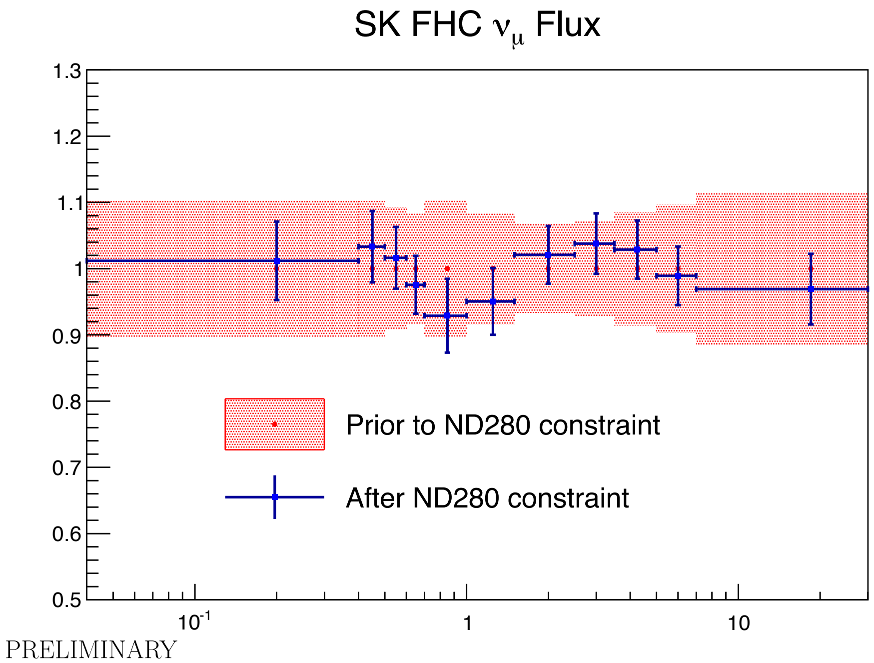


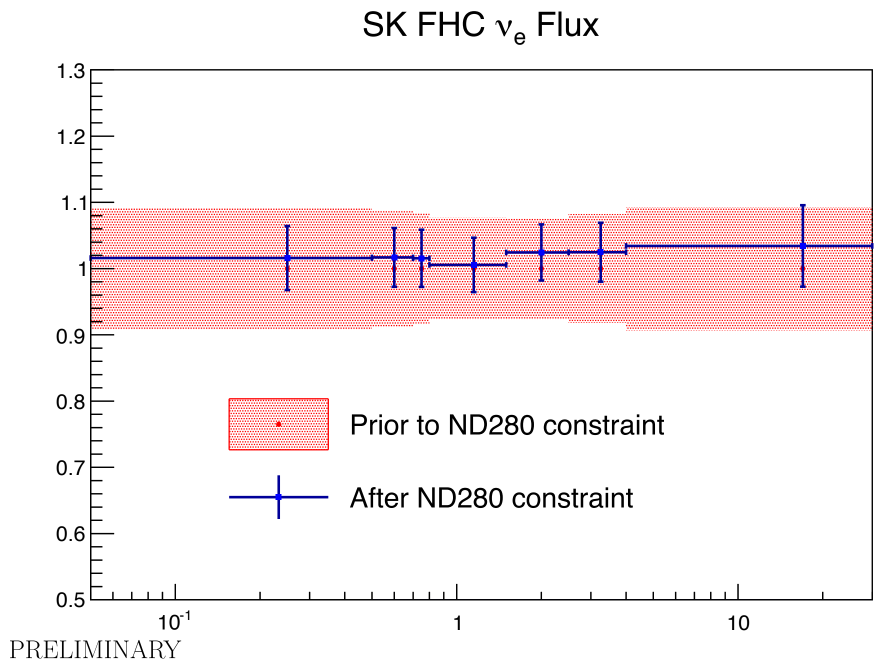


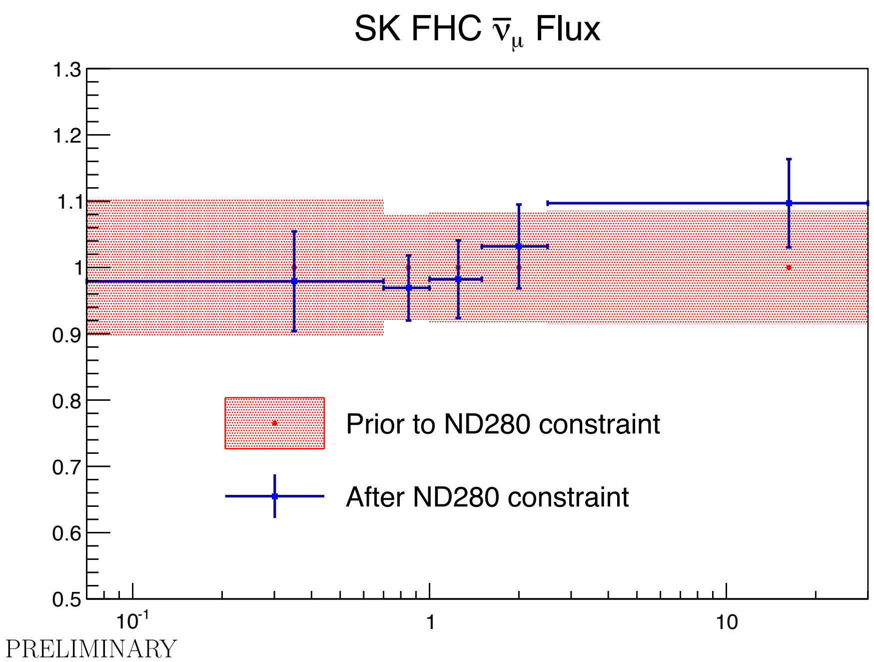
PRELIMINARY

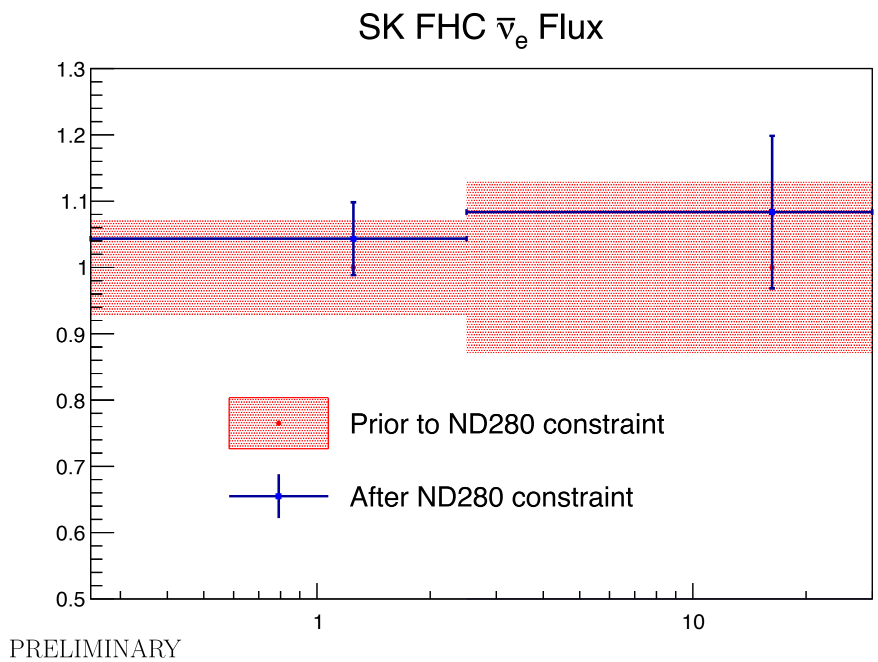
PRELIMINARY

ND280 constraints on flux

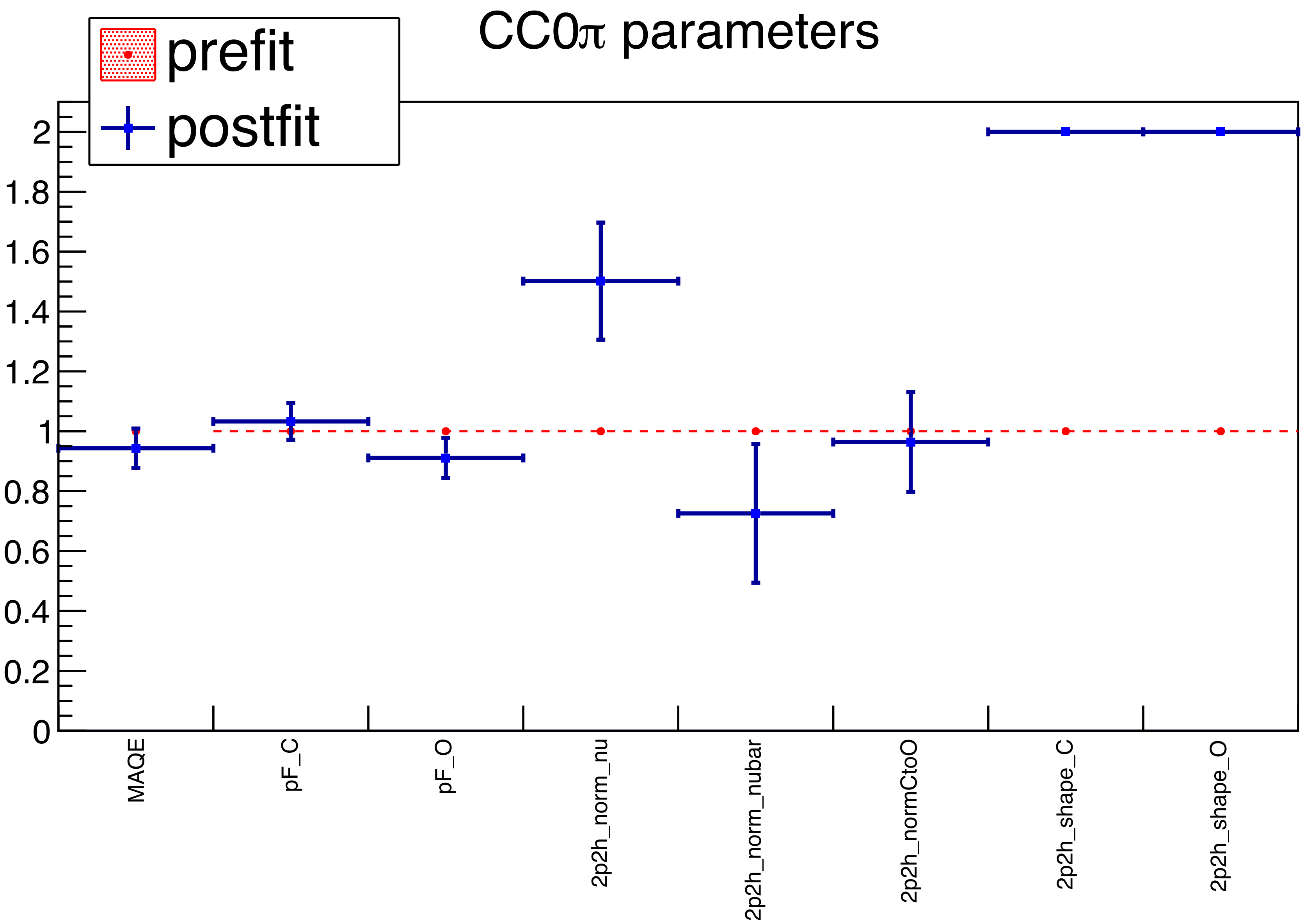








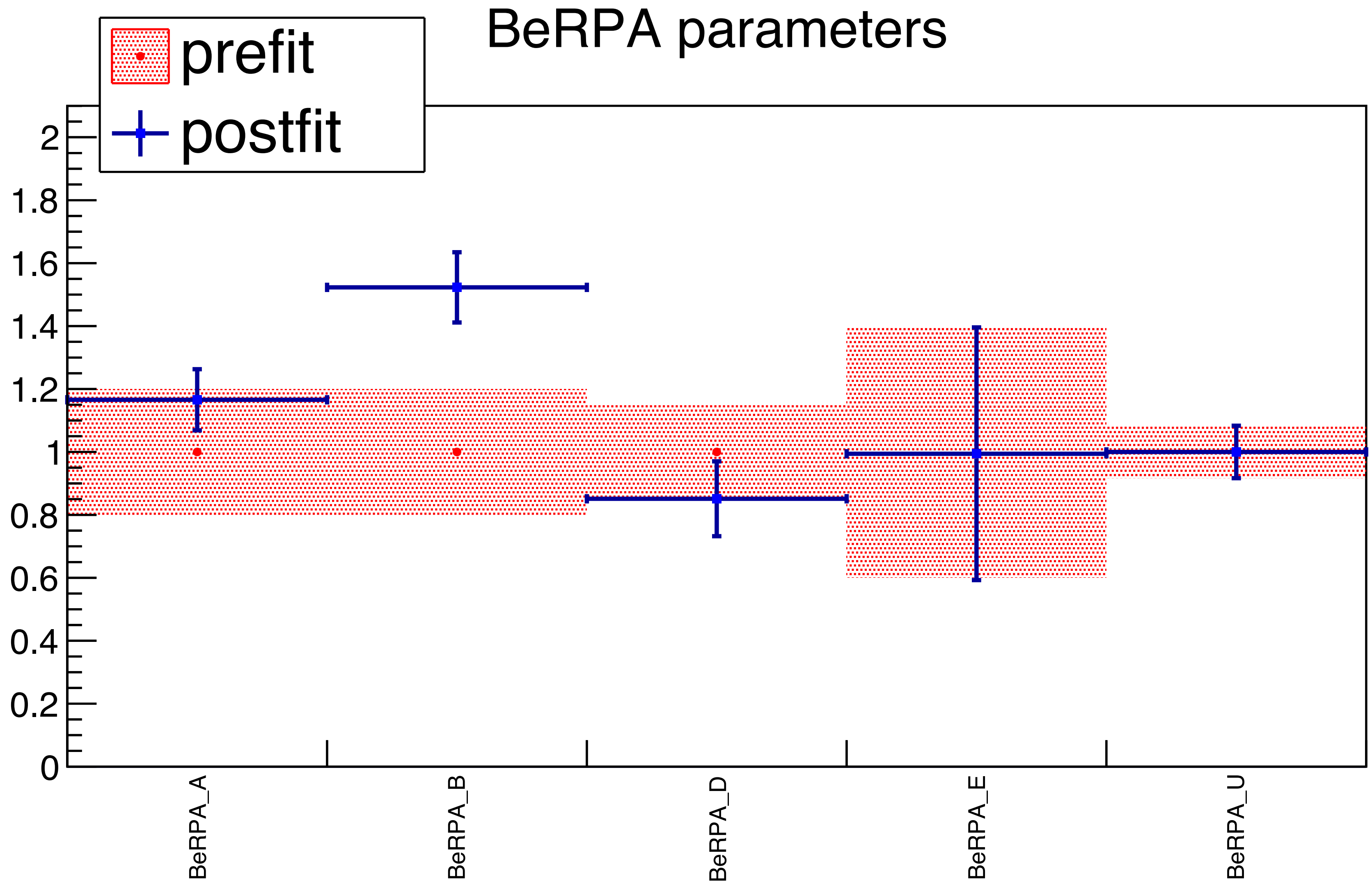
ND280 constraints on cross-section parameters



PRELIMINARY

Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters

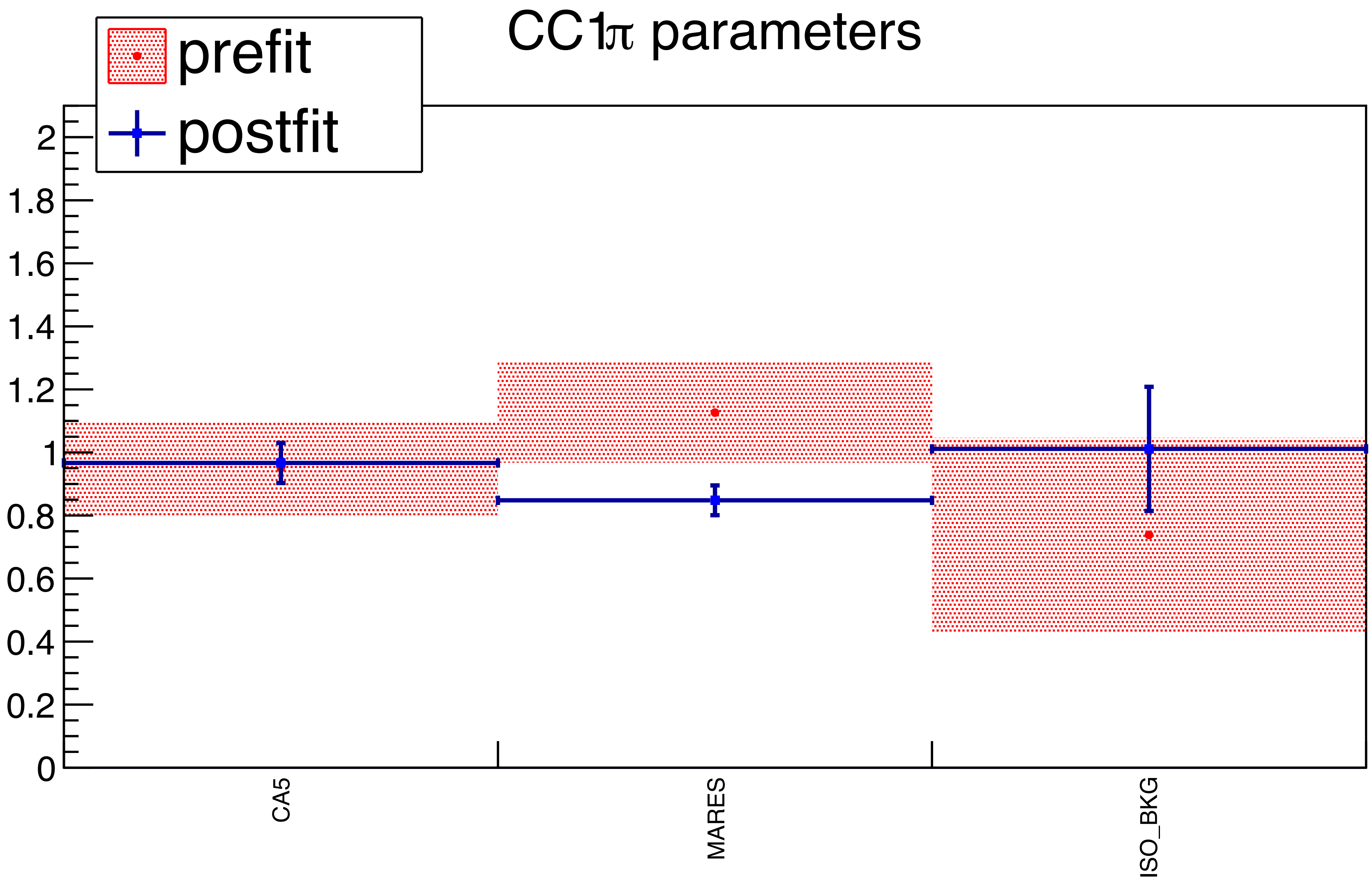
ND280 constraints on cross-section parameters



PRELIMINARY

Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters

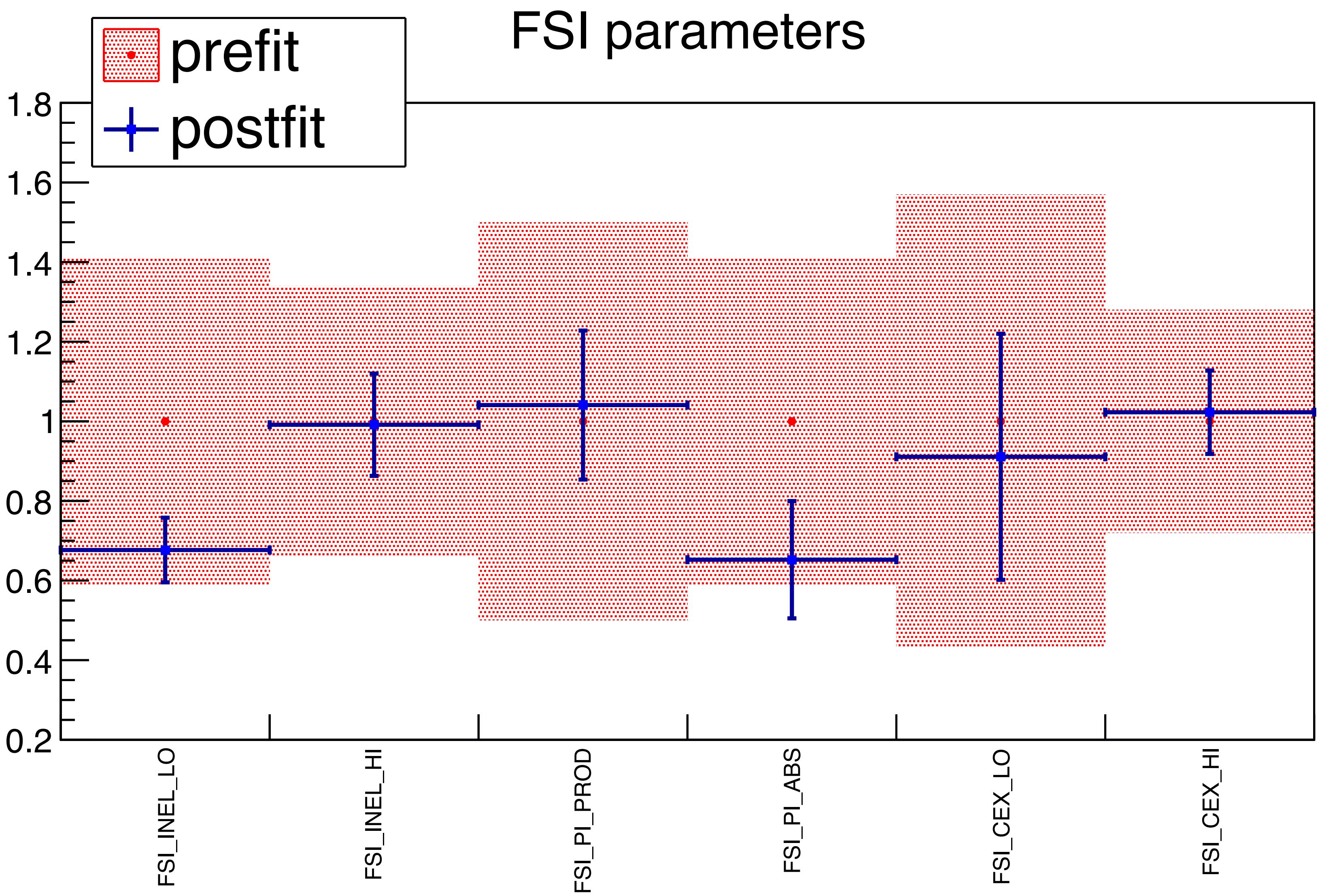
ND280 constraints on cross-section parameters



PRELIMINARY

Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters

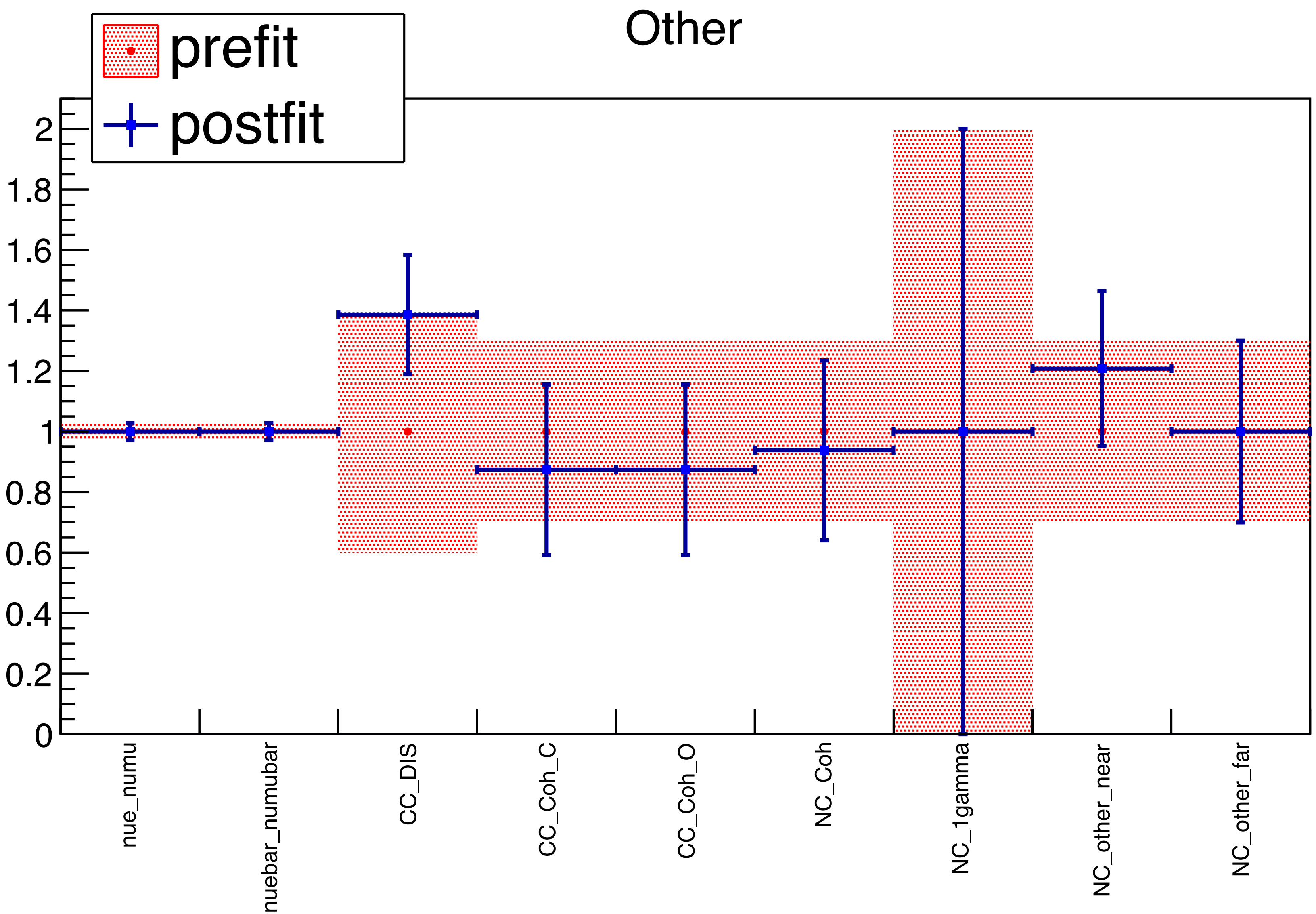
ND280 constraints on cross-section parameters



PRELIMINARY

Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters

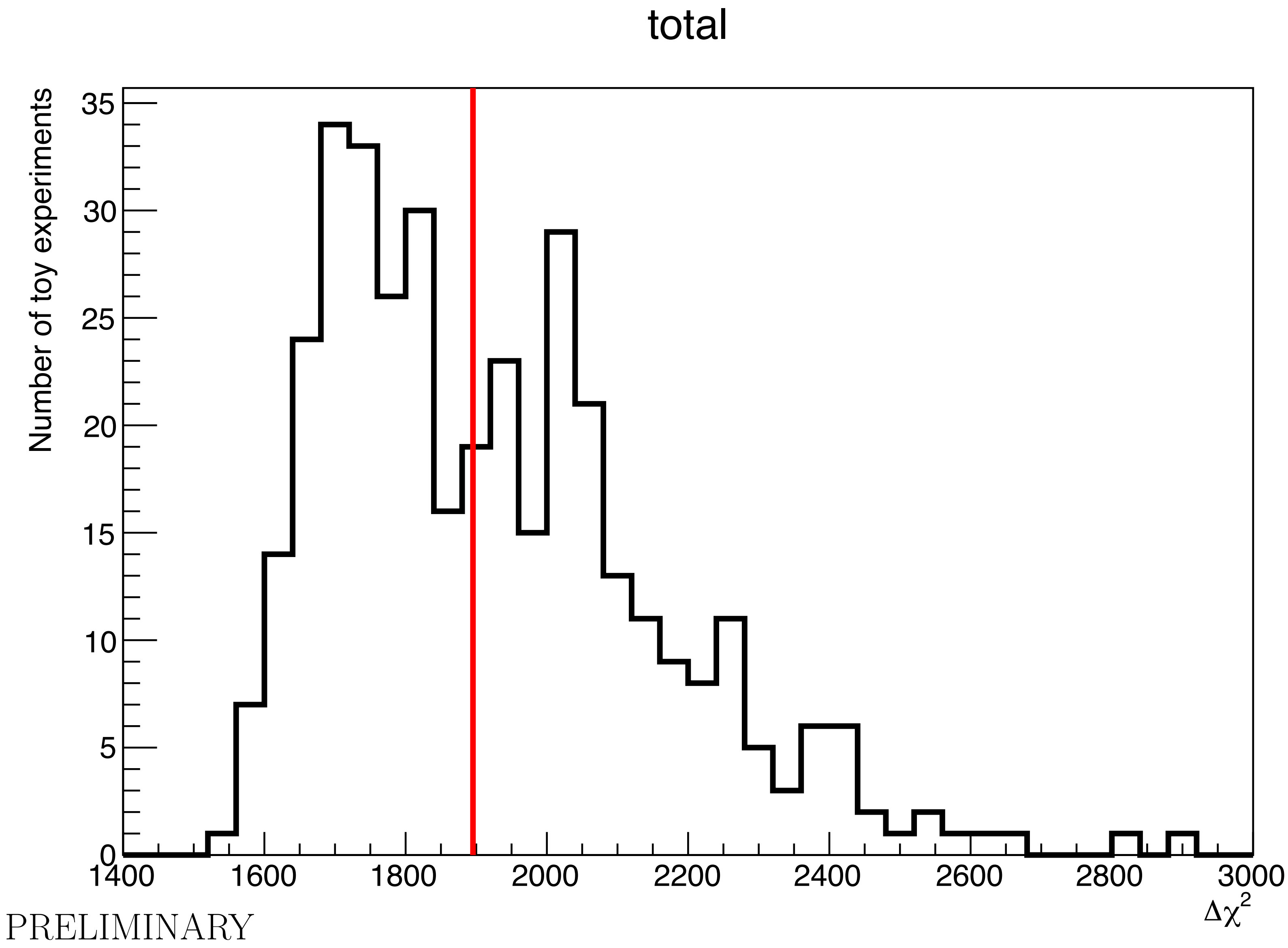
ND280 constraints on cross-section parameters



PRELIMINARY

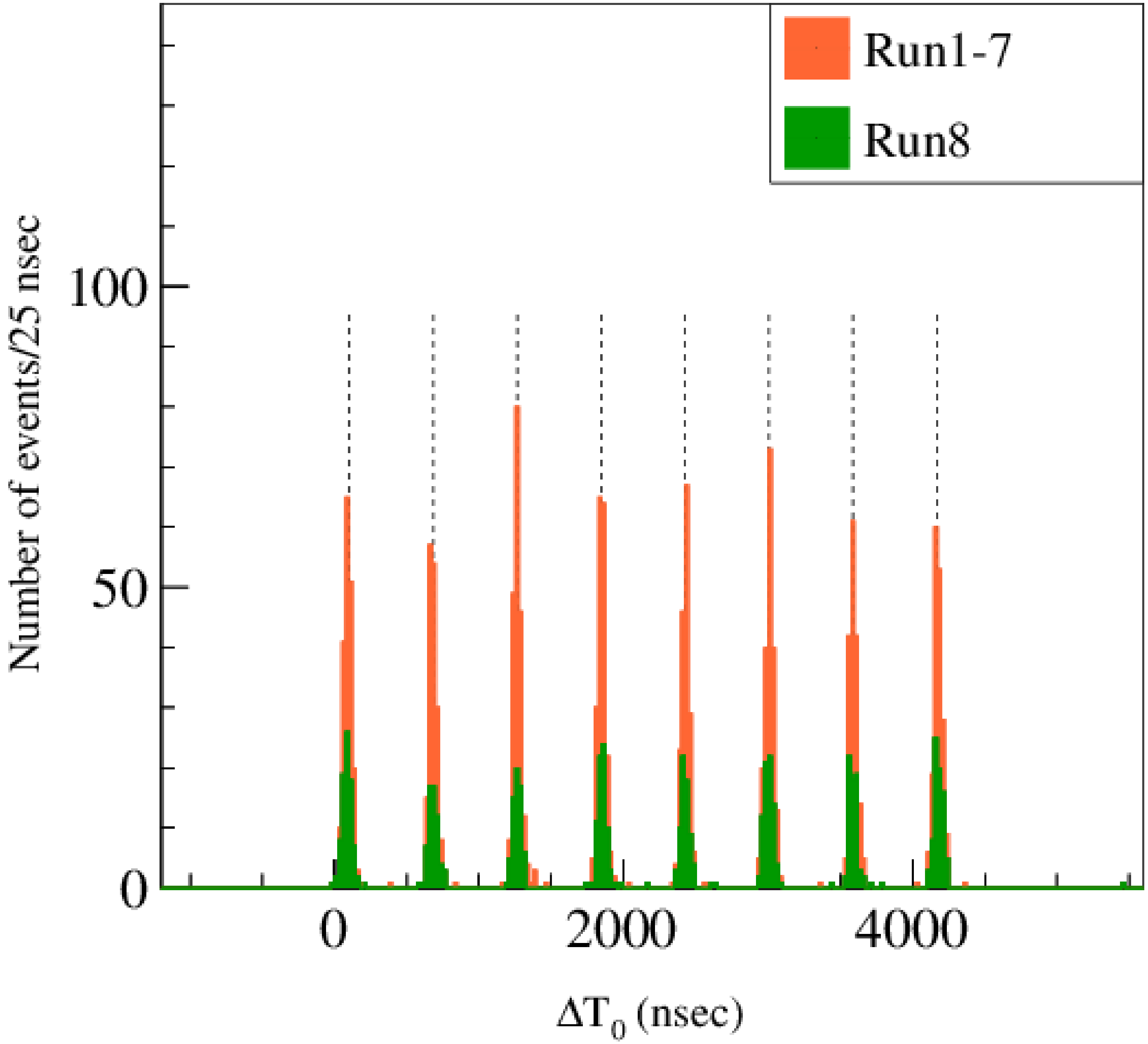
Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters

ND280 fit : p-value



Systematic uncertainties

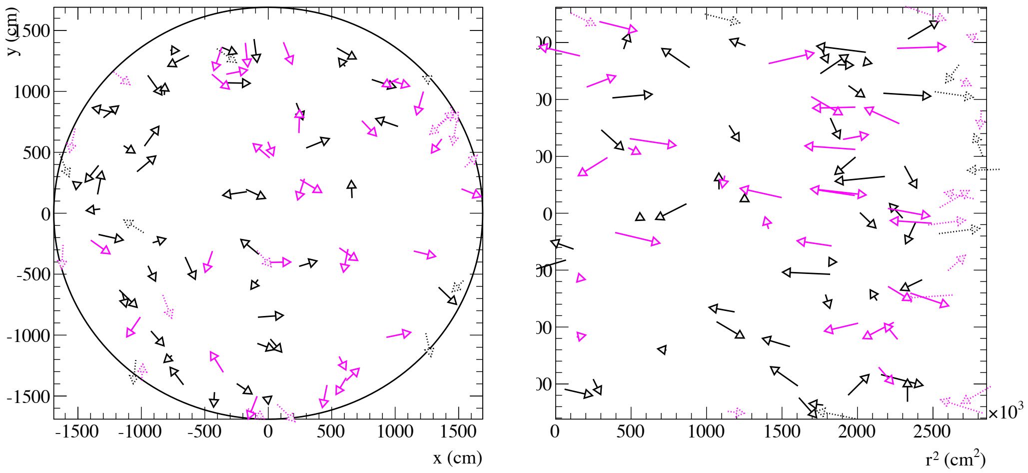
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
Flux + Xsec constrained	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Osc	0.04	0.03	3.86	3.60	3.78	0.79
All Systematics	4.40	3.76	6.10	6.51	20.94	4.77
All with osc	4.40	3.76	7.27	7.44	21.24	4.85


Run1-7
Run8
Number of events/25 nsec
100
50
0
0
2000
4000
ΔT_0 (nsec)

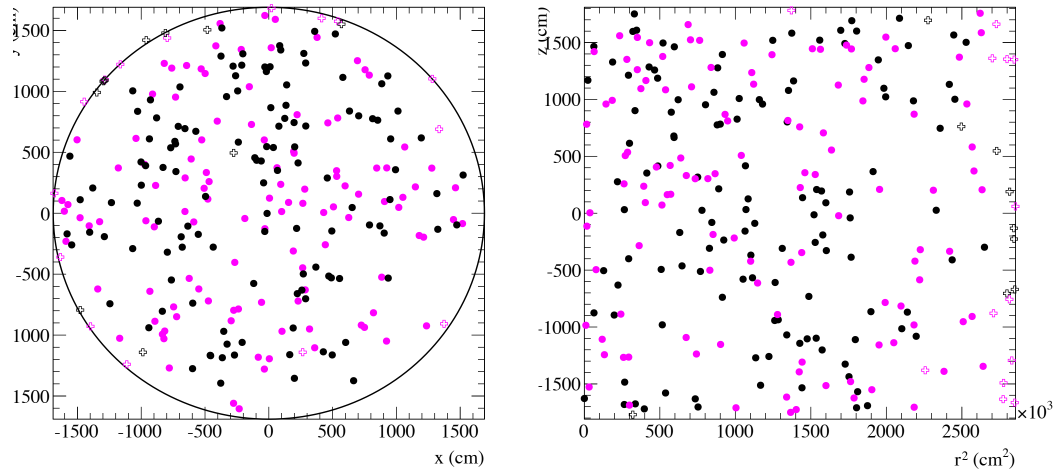
Vertex distributions at Super-Kamiokande

ν beam mode

e-like sample

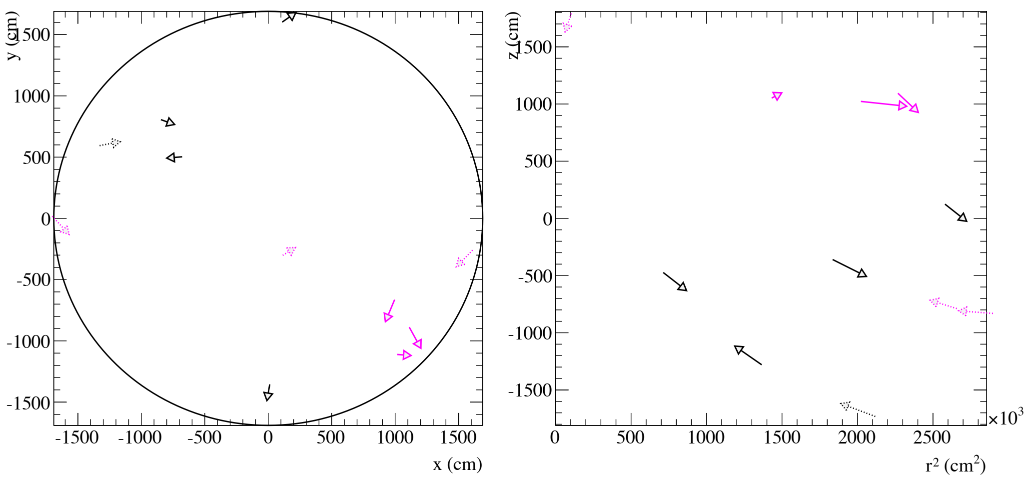


μ-like sample

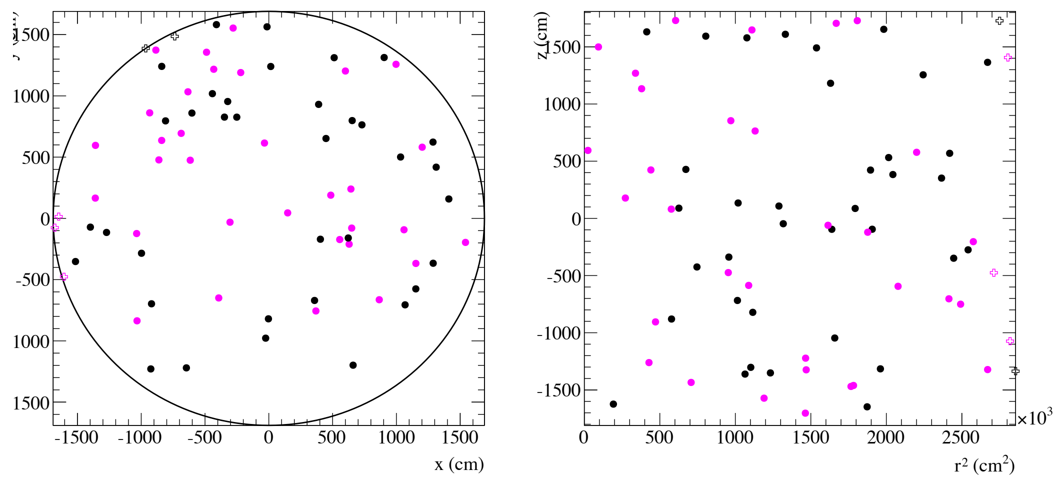


$\bar{\nu}$ beam mode

e-like sample



μ-like sample



Event reduction at Super-Kamiokande in appearance analysis

CCQE ν beam mode

Runs 1-8	Expected						Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	Beam $\nu_e + \bar{\nu_e}$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu_\mu} \to \bar{\nu_e}$	
Floor-FCFV	636.832	38.902	234.163	909.898	83.988	0.738	999
Sample-FCFV	681.329	42.525	238.660	962.514	83.429	0.753	1059
Single Ring	300.618	21.880	43.704	366.202	69.982	0.571	441
Electron-like PID	8.477	21.864	26.014	56.355	69.887	0.571	147
Evis > 100 MeV	3.183	21.708	18.199	43.090	68.515	0.568	127
No Decay-e	0.864	18.478	15.361	34.703	61.869	0.550	104
Erec	0.547	9.754	11.480	21.781	59.774	0.406	84
π^0 rejection cut	0.266	8.670	4.150	13.087	56.086	0.350	74
Efficiency from FCFV	0.000	0.204	0.017	0.014	0.672	0.465	-

CC1π⁺ ν beam mode

Runs 1-8	Expected						Data
	ν_μ+$\overline{\nu}_\mu$	ν_e+$\overline{\nu}_e$	NC	BG Total	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	
Floor-FCFV	636.832	38.902	234.163	909.898	83.988	0.738	999
Sample-FCFV	686.941	43.278	244.103	974.321	83.538	0.759	1067
Singe Ring	296.945	21.938	43.785	362.668	69.736	0.571	433
Electron-like PID	8.211	21.922	26.606	56.739	69.655	0.571	144
Evis > 100,MeV	2.778	21.753	18.476	43.006	68.206	0.567	125
1 Decay-e	1.338	2.995	2.150	6.483	6.505	0.016	23
Erec	0.456	1.083	0.998	2.538	5.996	0.008	19
π^0 rejection cut	0.161	0.914	0.378	1.453	5.396	0.007	15
Efficiency from FCFV	0.000	0.021	0.002	0.001	0.065	0.009	-

Event reduction at Super-Kamiokande in appearance analysis

$\bar{\nu}$ beam mode

Runs 5-7	Expected						Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	$\nu_e + \bar{\nu_e}$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu_\mu} \to \bar{\nu_e}$	
Floor-FCFV	139.629	9.117	52.839	201.585	2.731	4.802	216
Sample-FCFV	149.778	10.263	53.852	213.893	2.757	4.788	228
Singe Ring	69.757	5.235	9.644	84.635	2.003	4.106	107
Electron-like PID	1.344	5.231	5.958	12.533	2.000	4.103	23
Evis $>$ 100 MeV	0.687	5.211	4.363	10.262	1.972	4.079	18
No Decay-e	0.196	4.628	3.732	8.556	1.732	3.999	16
Erec	0.133	2.049	2.882	5.064	1.439	3.779	11
π^0 rejection cut	0.063	1.779	1.062	2.905	1.307	3.430	7
Efficiency from FCFV	0.000	0.173	0.020	0.014	0.474	0.716	-

Event reduction at Super-Kamiokande in disappearance analysis

ν beam mode

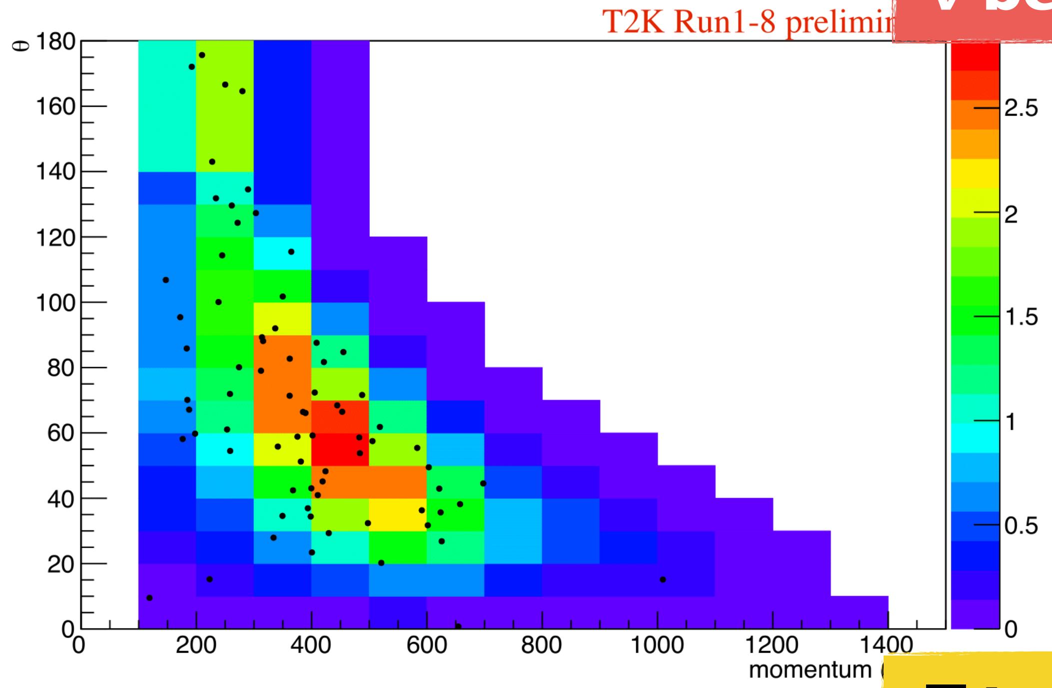
Runs 1-8	Expected						Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	
sample-FCFV	120.805	230.800	370.306	721.911	244.720	14.051	985
Single Ring	89.591	42.697	62.594	194.883	213.979	12.400	419
Muon-like PID	0.095	17.534	58.632	76.261	209.809	12.308	279
Momentum $>$ 200 MeV	0.095	17.413	58.594	76.103	209.613	12.306	278
0 or 1 Decay-e	0.095	16.834	37.795	54.723	207.419	12.179	249
π^+ rejection cut	0.077	8.193	36.562	44.833	204.713	12.053	240
Efficiency from FCFV	0.001	0.035	0.099	0.062	0.837	0.858	-

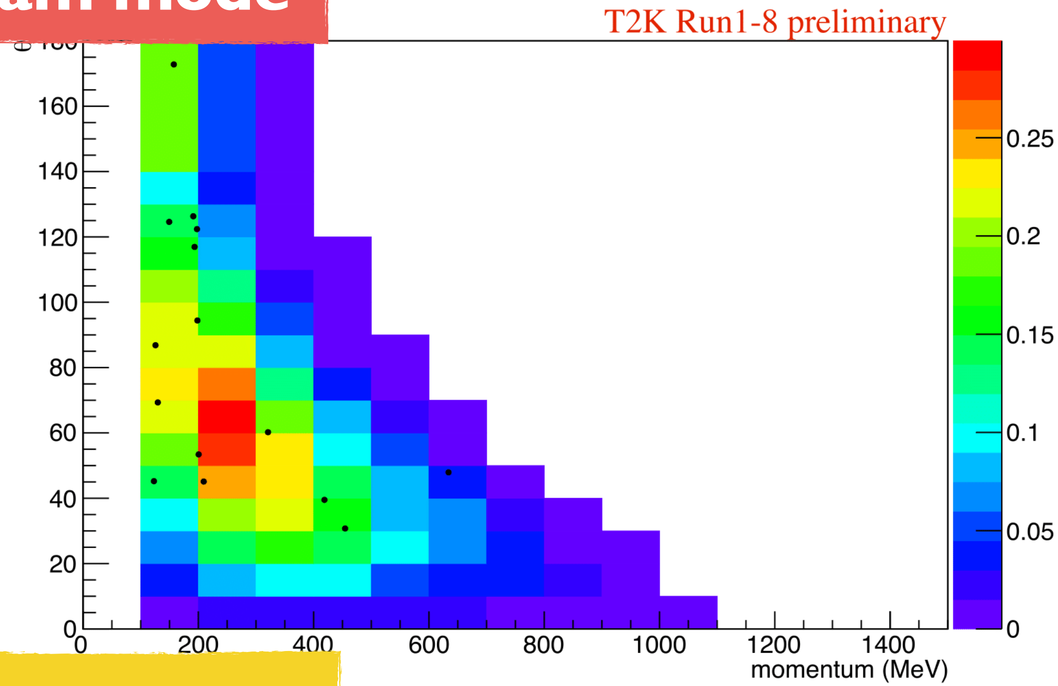
$\bar{\nu}$ beam mode

Runs 5-7	Expected						Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	
sample-FCFV	16.403	52.052	80.048	148.503	21.824	36.333	213
Single Ring	10.825	9.432	15.596	35.853	17.732	33.502	99
Muon-like PID	0.008	3.660	14.942	18.610	17.562	33.035	77
Momentum $>$ 200 MeV	0.008	3.623	14.938	18.570	17.556	33.017	77
0 or 1 Decay-e	0.008	3.503	11.227	14.737	17.347	32.656	69
π^+ rejection cut	0.006	1.596	10.982	12.585	17.151	32.305	68
Efficiency from FCFV	0.000	0.031	0.137	0.085	0.786	0.889	-

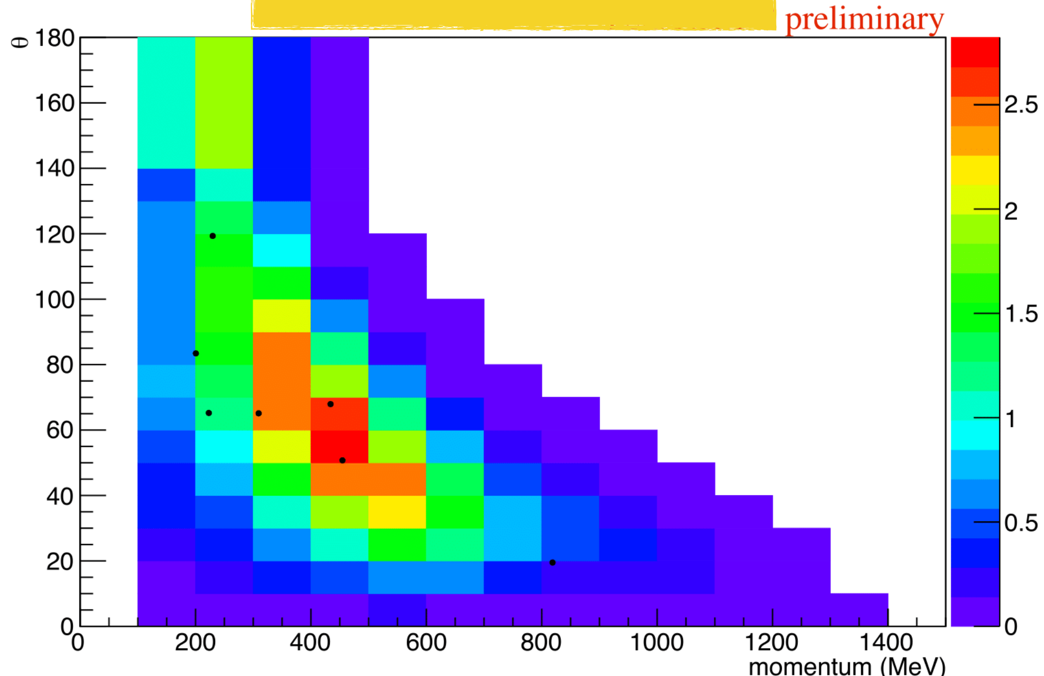
p-θ distributions of selected 1R e-like events at SK

ν beam mode

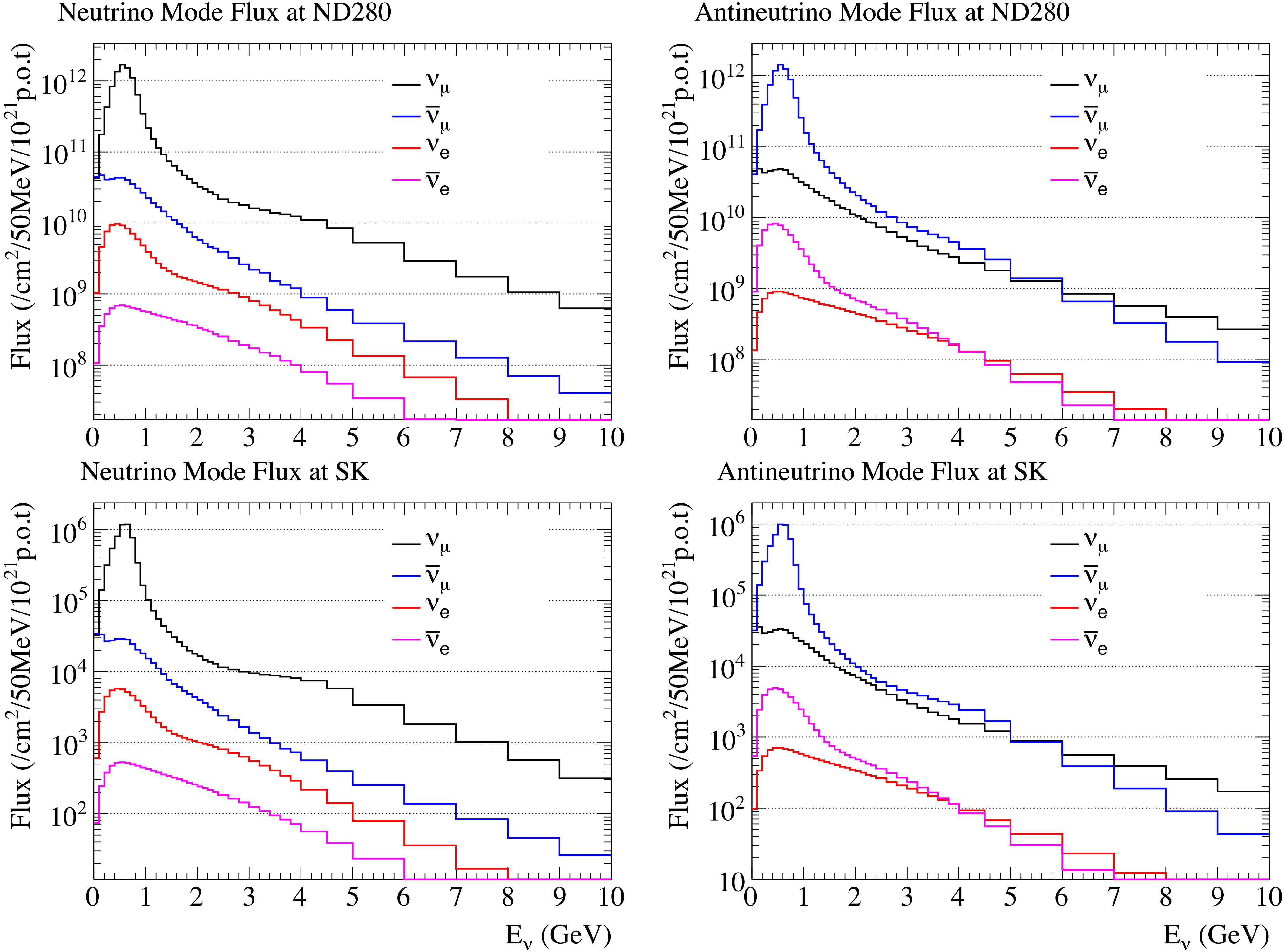




ν̄ beam mode



Neutrino flux



Discovery of $\nu_\mu \rightarrow \nu_e$ appearance

Phys. Rev. Lett. 112 (2014) 061802

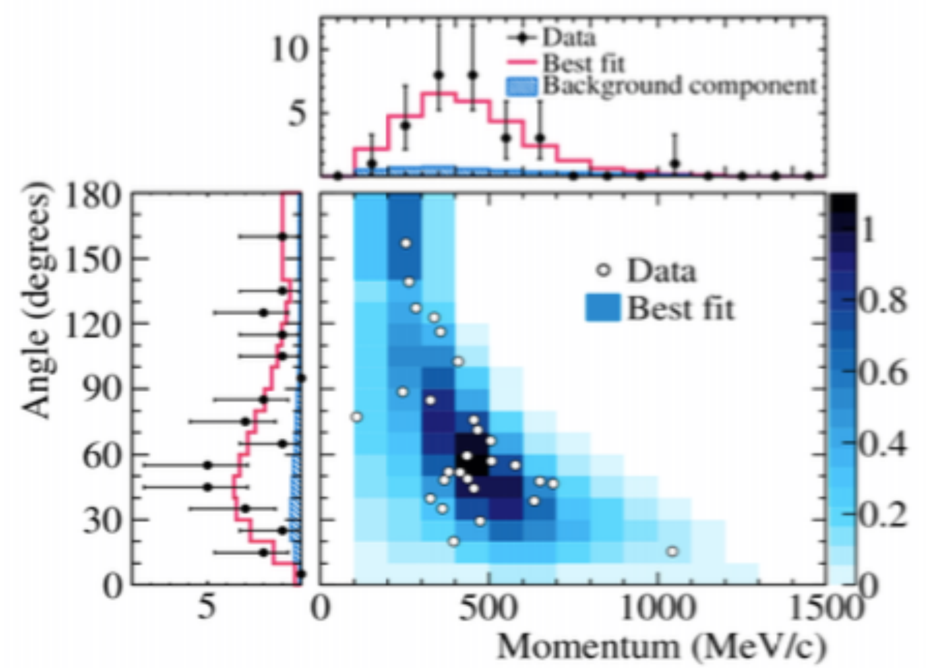
Based on 6.57×10^{20} p.o.t.

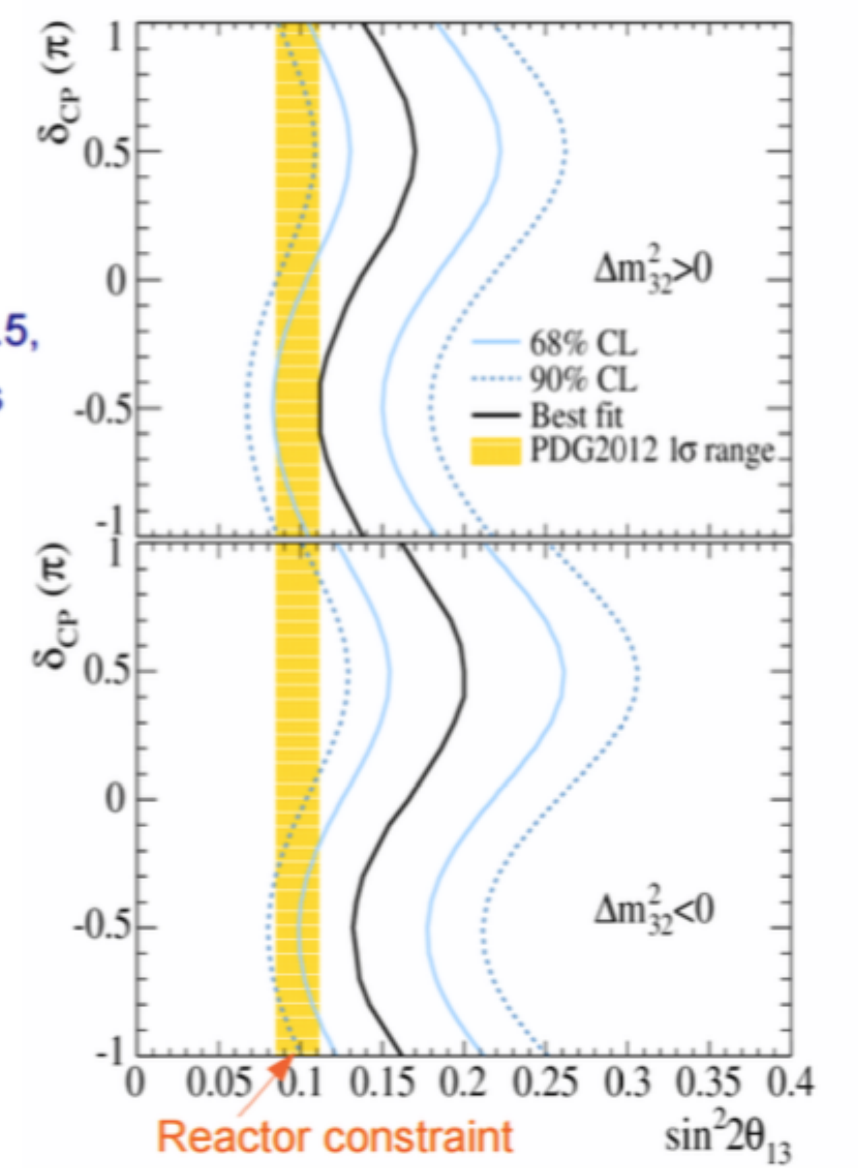
28 events observed while expected background is 4.92 ± 0.55

First observation of neutrino appearance with a significance of 7.3σ

Assuming $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = 0$, and $\Delta m^2_{32} > 0$ ($\Delta m^2_{32} < 0$) a best fit is

$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ $(0.170^{+0.045}_{-0.037})$





Precise measurement of ν_μ disappearance

Phys. Rev. Lett. 112 (2014) 181801

Based on 6.57×10^{20} p.o.t.

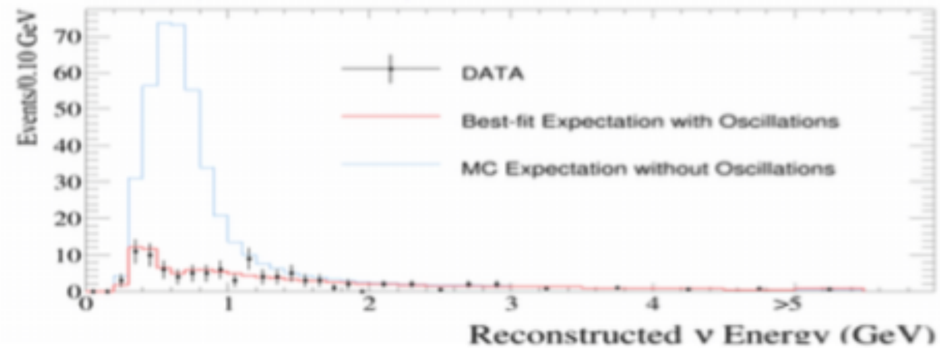
120 events observed while expectation without oscillations is 446 ± 22.5

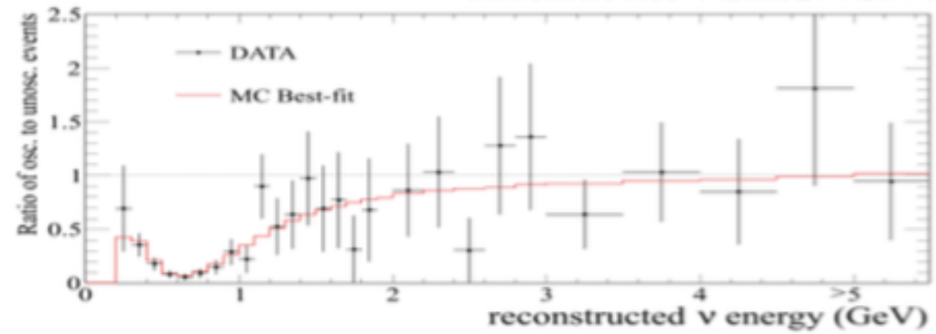
World best measurement of θ_{23}

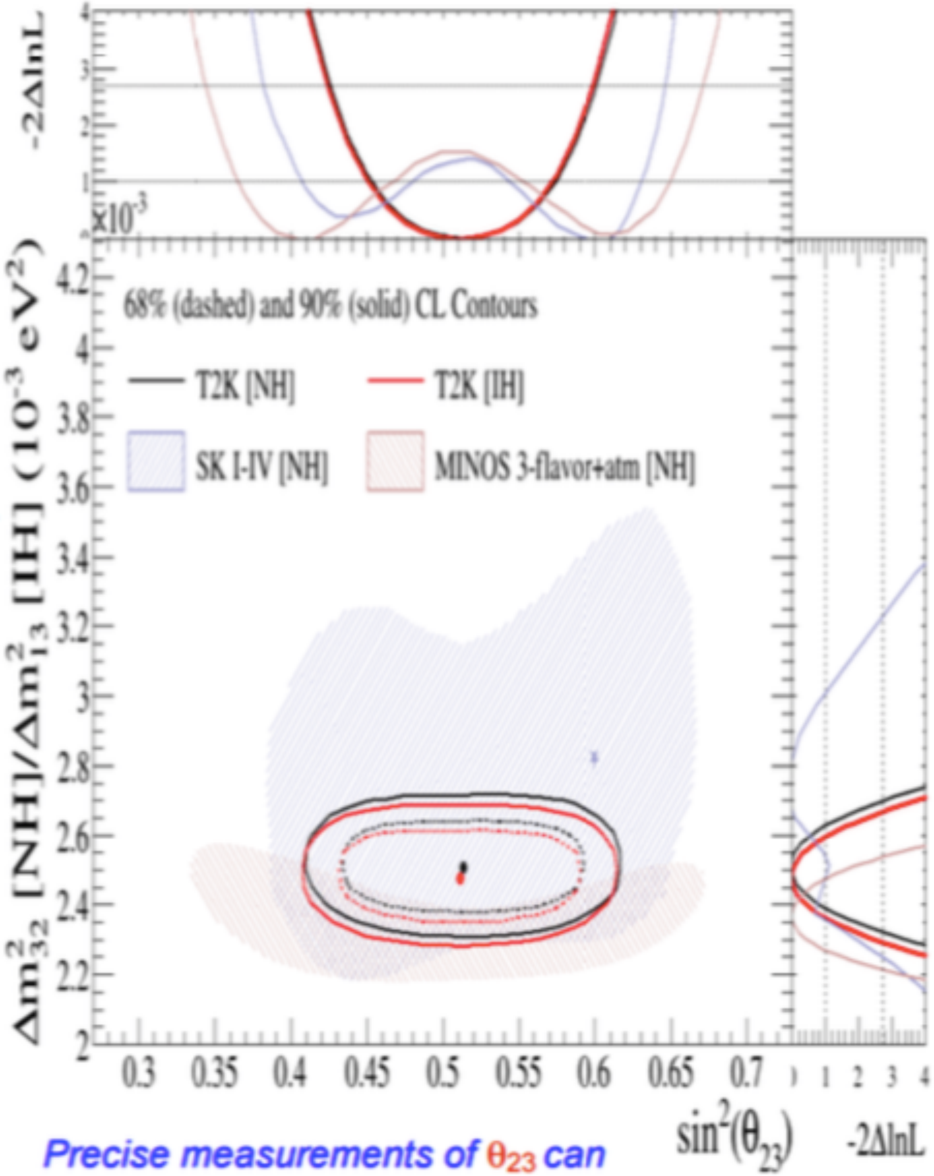
The 68% C.L. on $\sin^2\theta_{23}$ is $0.514^{+0.055}_{-0.056}$ (0.511±0.055) assuming normal (inverted) mass hierarchy (MH).

$\Delta m^2_{32}=(2.51\pm0.10)\times10^{-3}$ eV^2 for normal MH;

$\Delta m^2_{13}=(2.48\pm0.10)\times10^{-3}$ eV^2 for inverted MH.







Precise measurements of θ_{23} can constrain models of neutrino mass generation

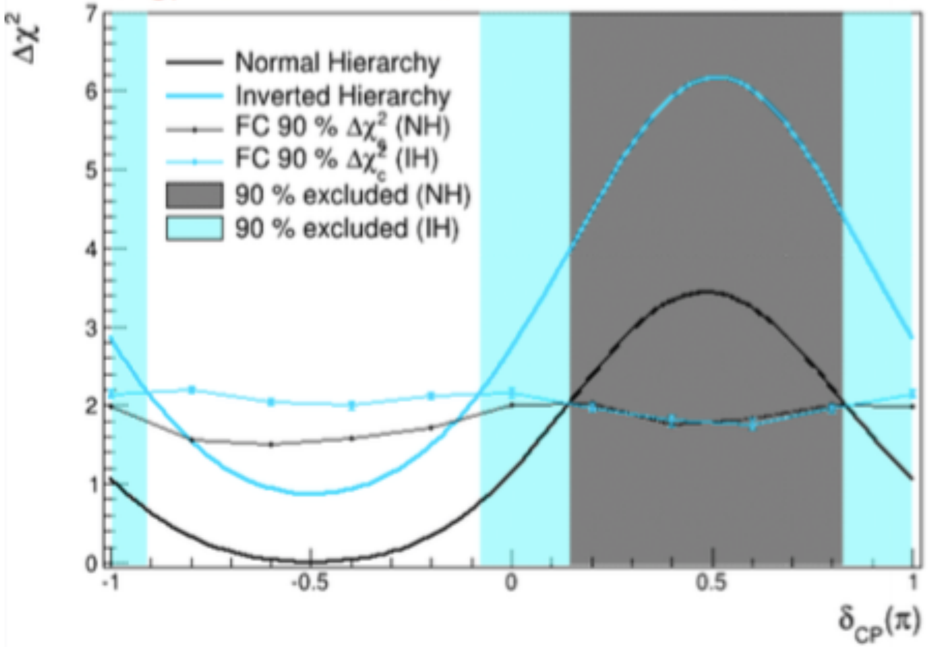
Combined $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$

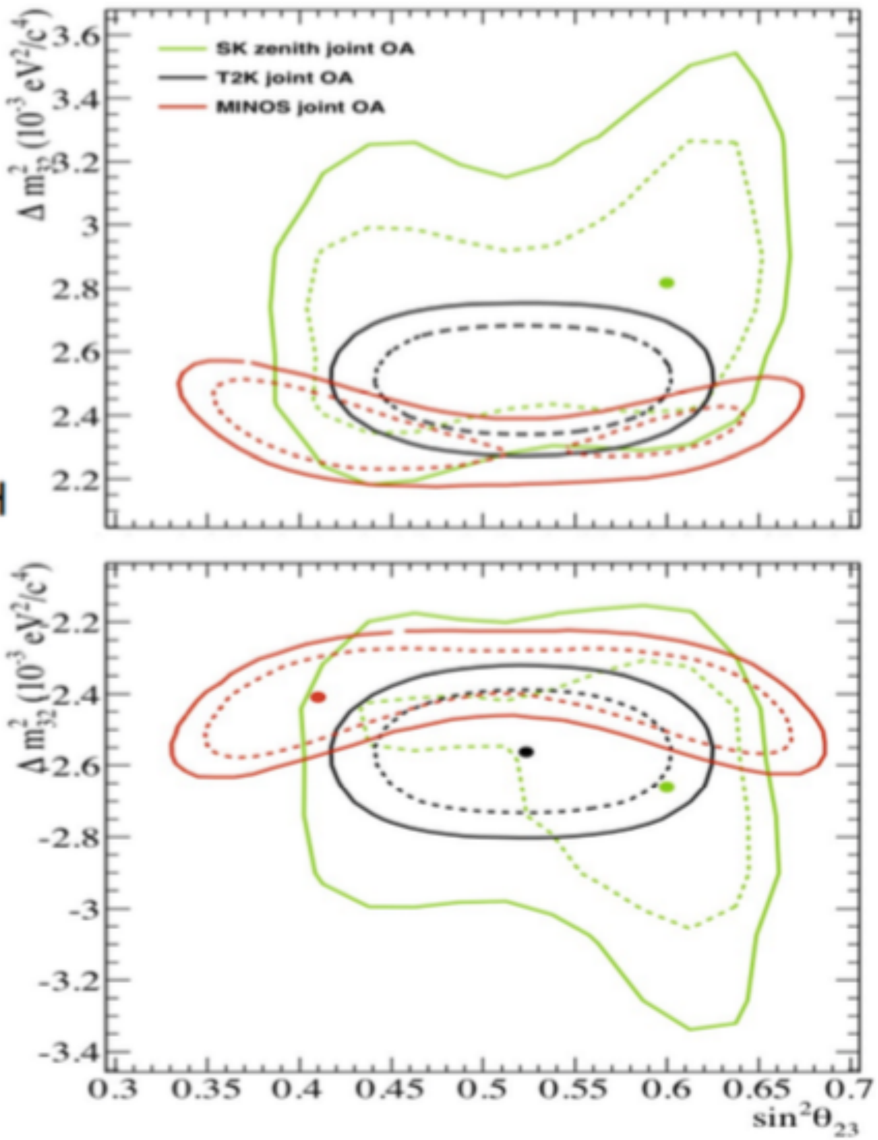
Phys. Rev. D 91 (2015) 072010

Based on 6.57×10^{20} p.o.t.

Combined analysis of ν_e appearance and ν_μ disappearance to estimate the four oscillation parameters - $|\Delta m^2|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP}, and the mass hierarchy (MH).

At 90% C.L. including reactor results we exclude the region $\delta_{CP}=[0.15,0.83]\pi$ ($\delta_{CP}=[-0.08,1.09]\pi$) for normal (inverted) MH





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

Phys. Rev. Lett. 116 (2016) 181801

Since 2014 T2K started running in anti-neutrino mode

First analysis of $\bar{\nu}_\mu$ disappearance:

Based on 4.01×10^{20} p.o.t.

34 events observed

Best-fit:

$\sin^2\bar{\theta}_{23} = 0.45$, $|\Delta \overline{m}^2_{32}| = 2.51\times10^{-3}\ \mathrm{eV}^2$

Parameter	ν	$\bar{\nu}$
$\sin^2\theta_{23}$	0.527	fit 0 - 1
Δm^2_{32} (10^{-3} eV^2)	2.51	fit 0 - 20
$\sin^2\theta_{13}$	0.0248	
$\sin^2\theta_{12}$	0.304	
Δm^2_{21} (10^{-5} eV^2)	7.53	
δ_{CP} (rad)	-1.55