Recent Neutrino Oscillation results from T2K

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On behalf of the T2K collaboration

21ST RENCONTRES DU VIETNAM

22/07/2025 – Quy Nonh

Laboratoire Leprince-Ringuet

ÉCOLE POLYTECHNIQUE

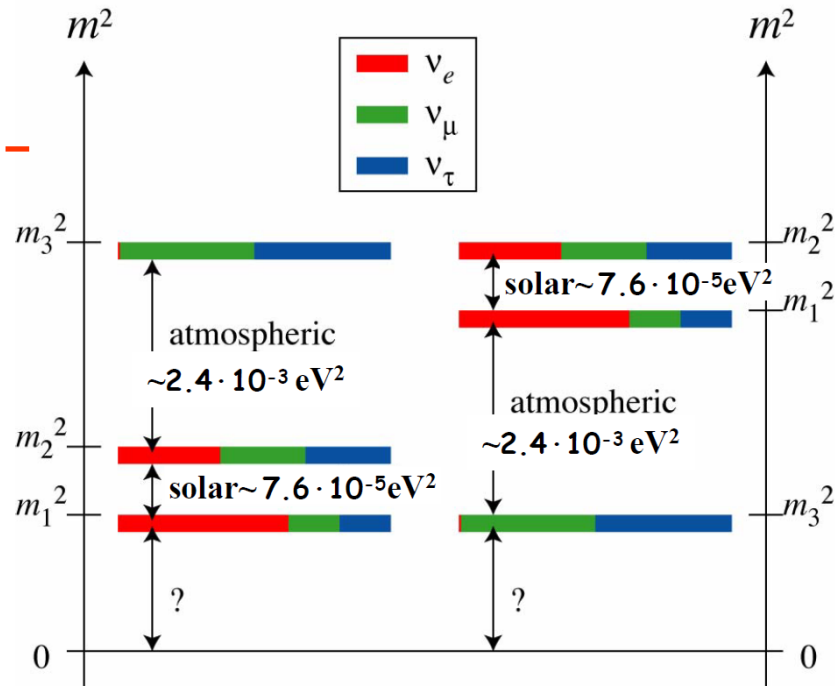
IP PARIS

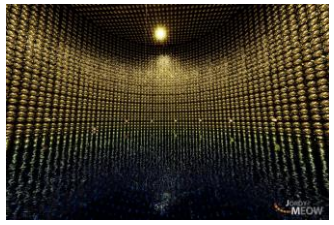
cnrs

T2K

Neutrino oscillation parameters

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





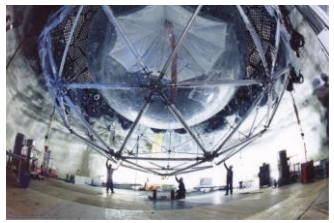
« Atmospheric »

$\theta_{23} = 48.6^{+1.0}_{-1.2}\,°$

$|\Delta m^2_{32}| = 245.4^{+2.9}_{-3.1} \times 10^{-5}\ \text{eV}^2$

« Reactor »

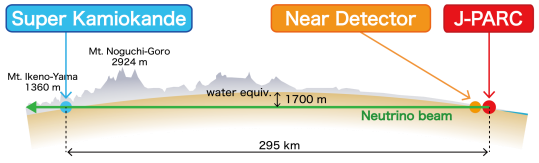
$\theta_{13} = 8.60 \pm 0.13\,°$



« Solar »

$\theta_{12} = 33.8^{+0.8}_{-0.8}\,°$

$\Delta m^2_{12} = 7{,}39^{+2.1}_{-2,0} \times 10^{-5}\ \text{eV}^2$



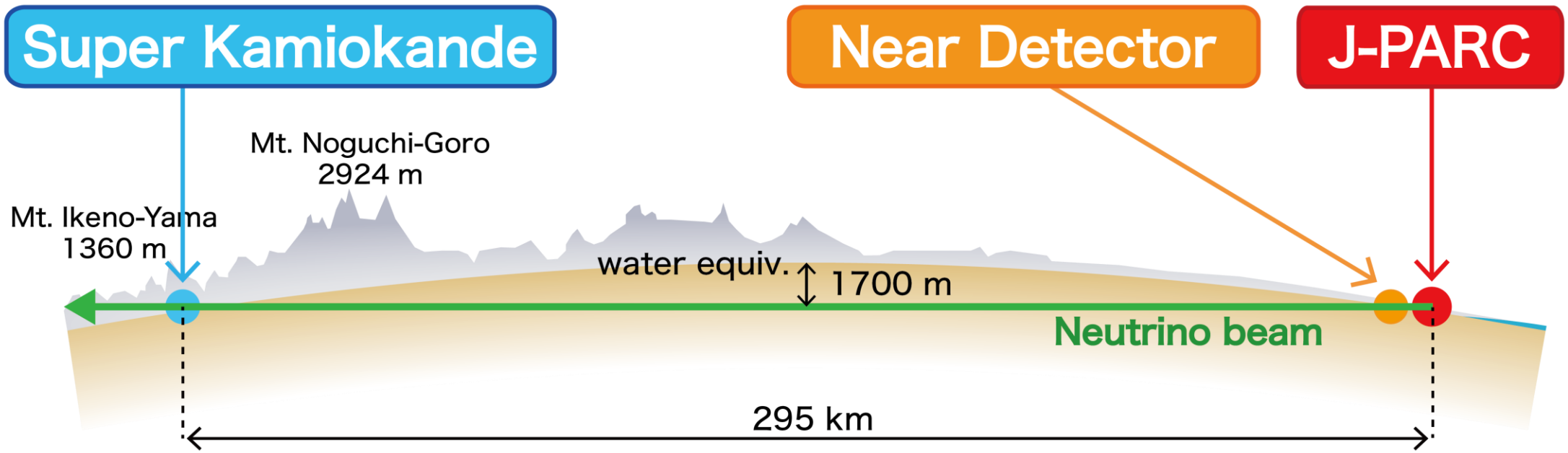
« Accelerator »

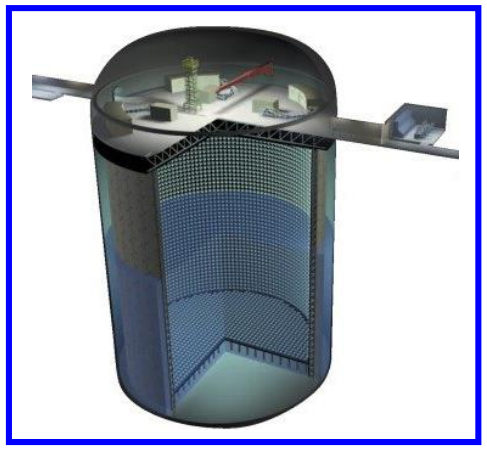
δ_{CP}

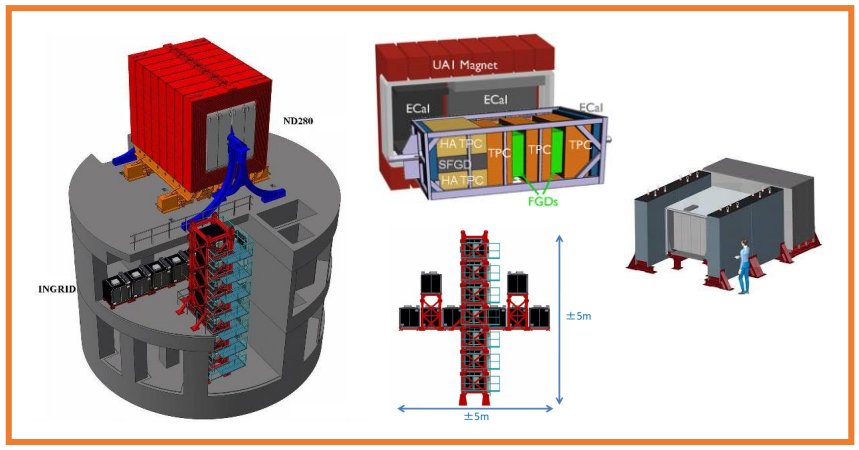
θ_{23} θ_{13}

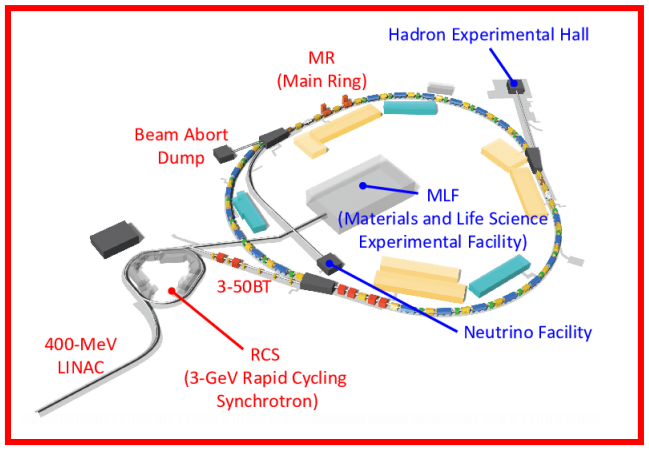
Δm^2_{atm}

THE T2K EXPERIMENT

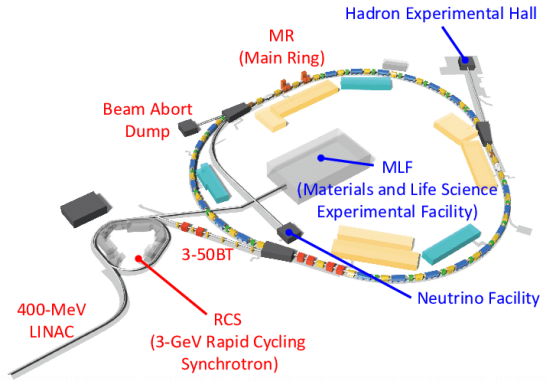

Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Neutrino beam
295 km



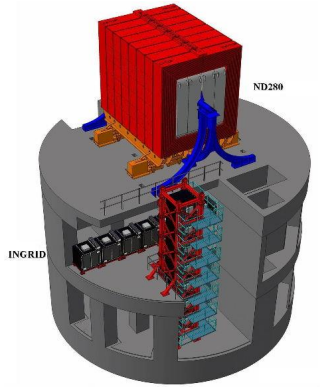

ND280
INGRID
UA1 Magnet
ECal
ECal
ECal
HA TPC
TPC
TPC
TPC
SFGD
HA TPC
FGDs
±5m
±5m


Hadron Experimental Hall
MR
(Main Ring)
Beam Abort
Dump
MLF
(Materials and Life Science
Experimental Facility)
3-50BT
Neutrino Facility
400-MeV
LINAC
RCS
(3-GeV Rapid Cycling
Synchrotron)

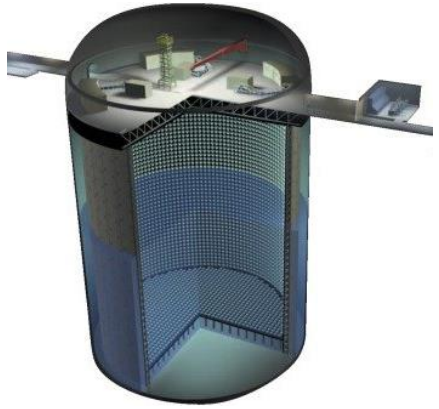
NEUTRINO BEAM



NEAR DETECTOR



FAR DETECTOR



No of ν events
function of energy

$=$

Neutrino flux
ν flux model

$\otimes$

Neutrino oscillation
PMNS model

$\otimes$

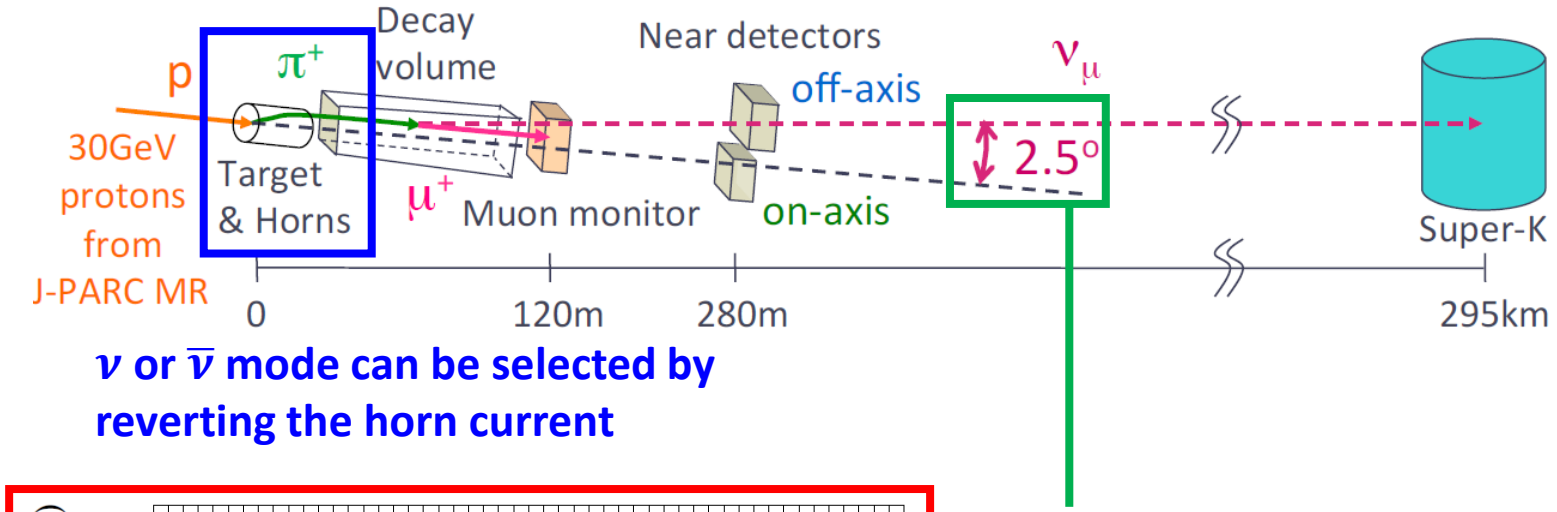
Neutrino interactions
ν cross-section models

$\otimes$

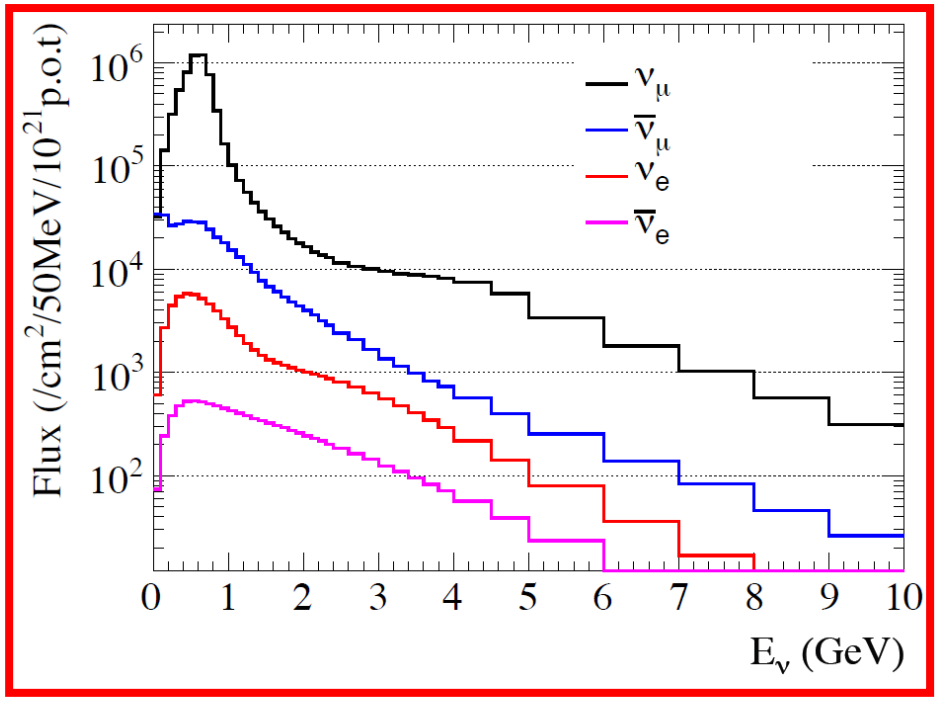
Neutrino detection
SK detector model

OSCILLATION PARAMETERS

THE T2K FLUX



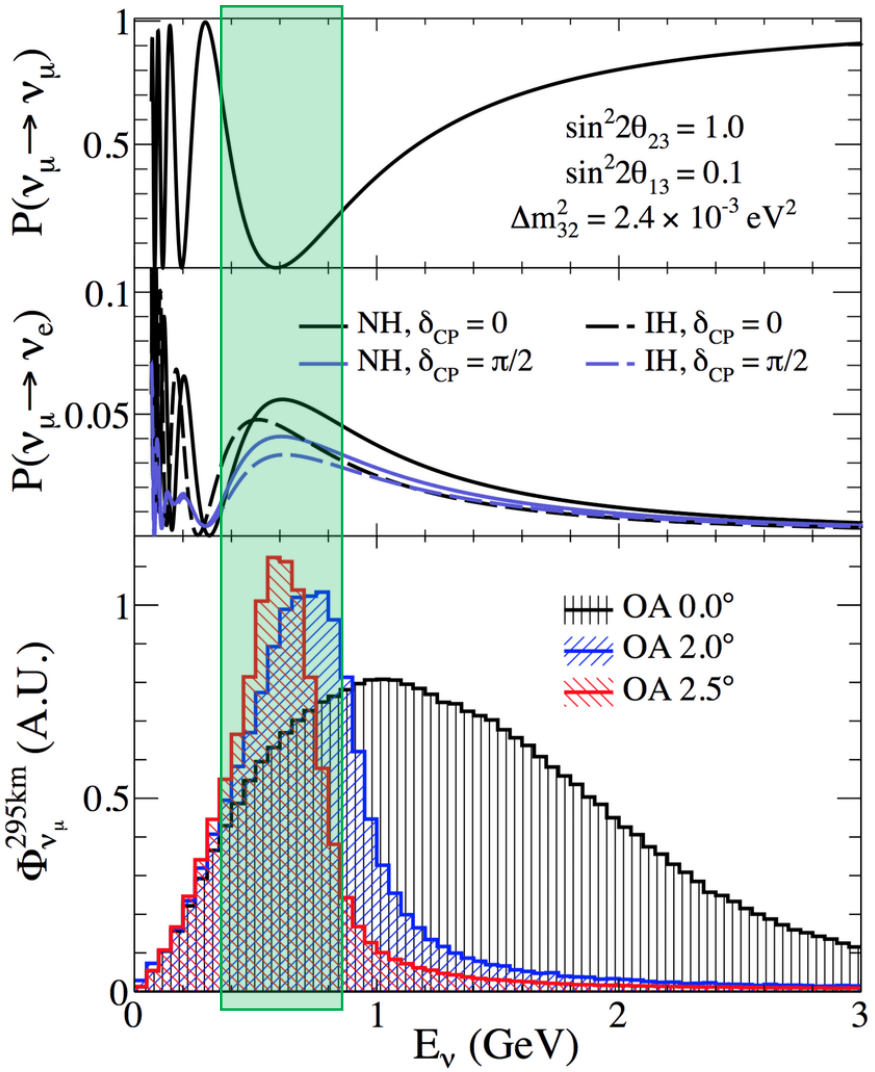
ν or $\bar{\nu}$ mode can be selected by reverting the horn current



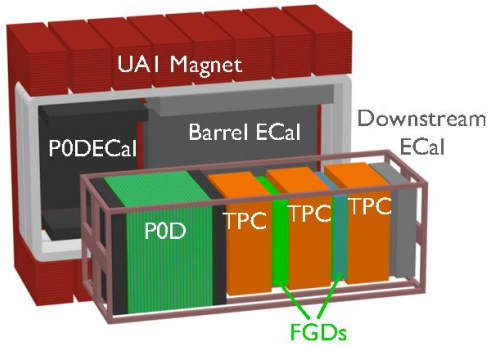
Optimization to match the flux with the oscillation maximum

Still, some contamination remains…

Neutrino flux at Far Detector



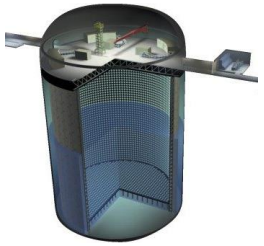
Near Detector



Included in current analysis

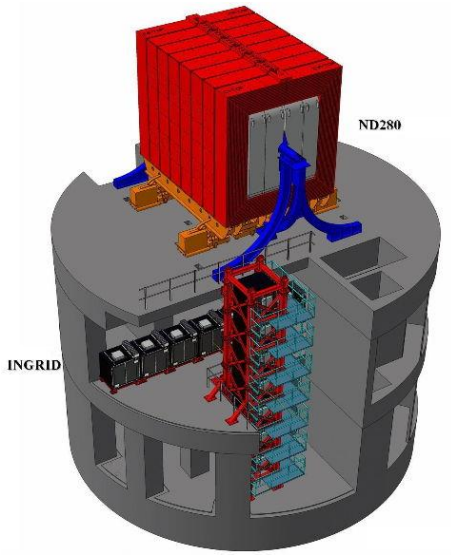
ND280
- 2.5° off-axis: $E_\nu \sim 0.6$ GeV
- **Constrains $(\nu/\bar{\nu})_\mu$ flux & cross-section systematics**

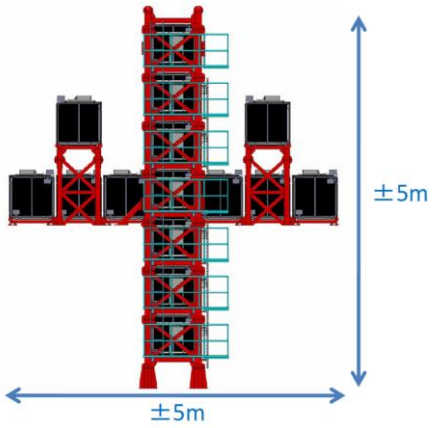
Super-Kamiokande
(2.5° off-axis)



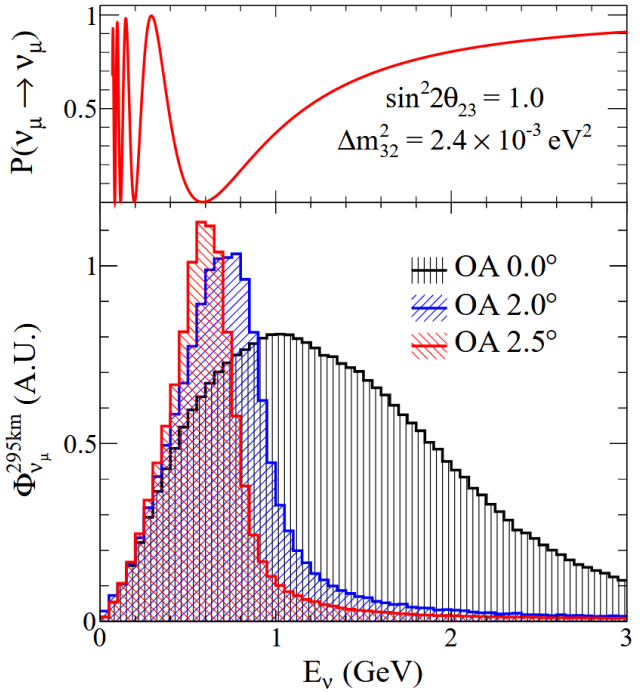
- Upgrade finalized in 2024

WAGASCI
- 1.5° off-axis: $E_\nu \sim 1$ GeV
- Cross-sections on water
- Installed in 2019





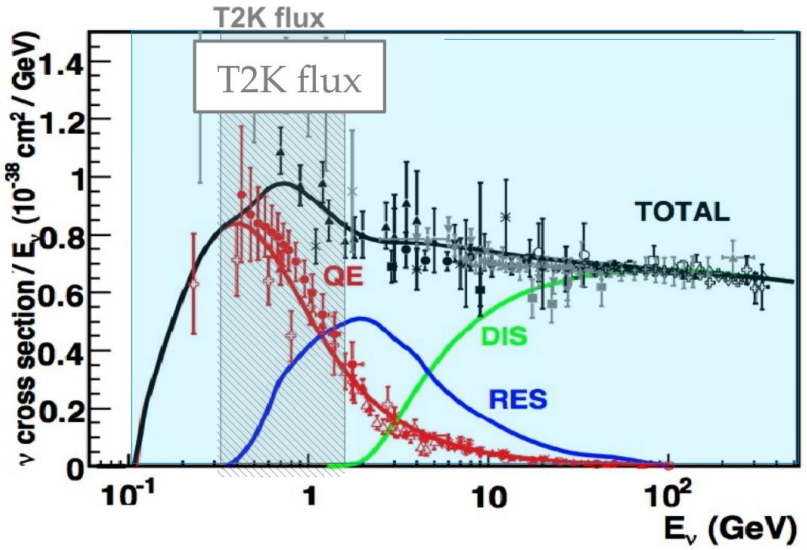
INGRID
- On-axis: $E_\nu \sim 1.5$ GeV
- Monitor ν_μ beam intensity and direction
- Used to build & prior-constrain the beam model



Selections at Near Detector

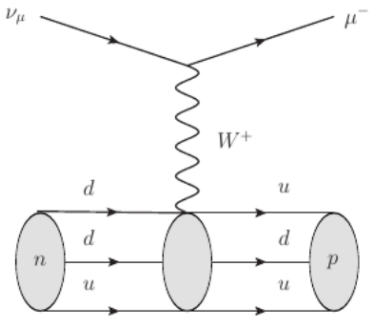
Samples based on the **event topology**
→ **Target different ν interactions**

CCQE: Charged Current Quasi-Elastic
CCRes: Charged Current Resonant Pion production
CCDIS: Charged Current Deep Inelastic Scattering

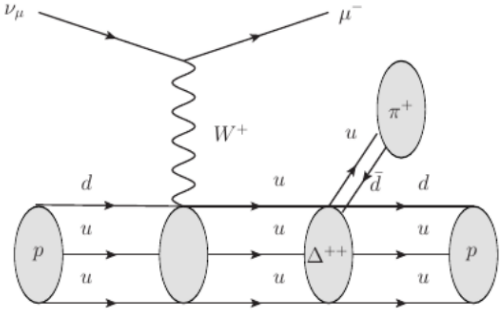


Each event topology is enriched with a specific interaction

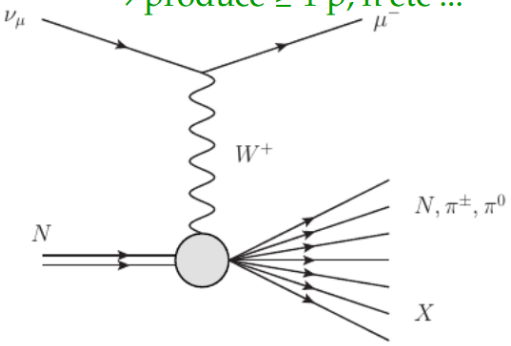
CCQE
Low q^2 (< M_p)



CCResonant
Large enough q^2 to produce Δ (1230 MeV), ou others.

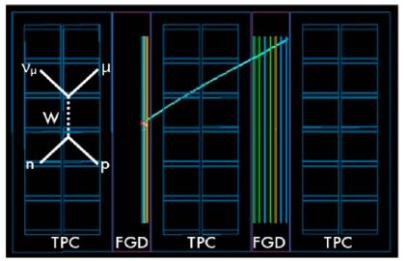


CCDIS
Large enough q^2 to see quarks
→ produce ≥ 1 p, n etc ...

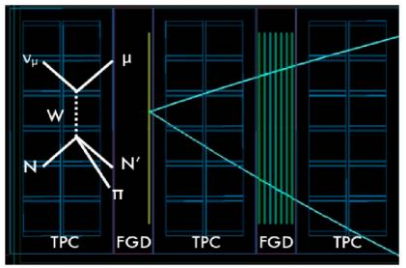


INTERACTIONS

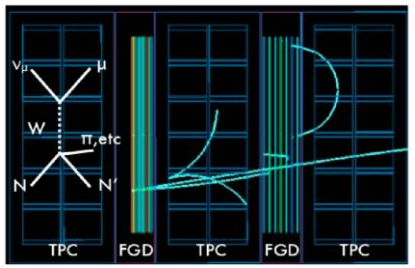
CC0π



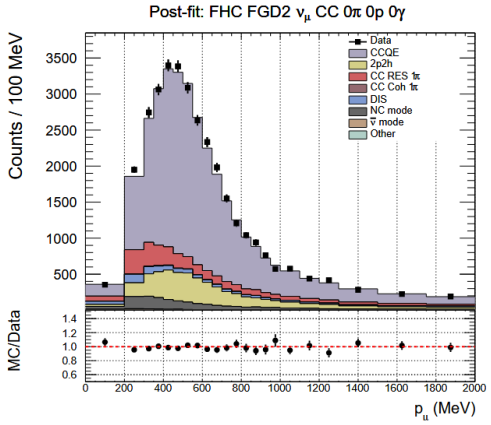
CC1π⁺

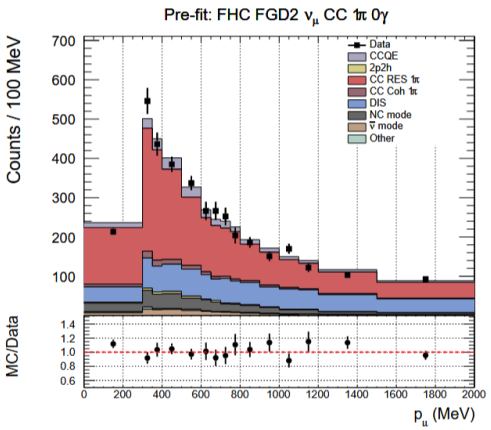


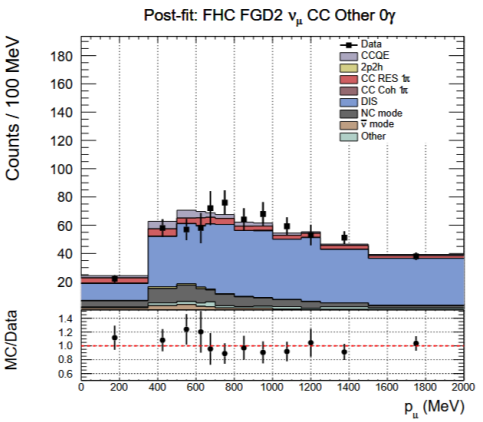
CC other



TOPOLOGIES

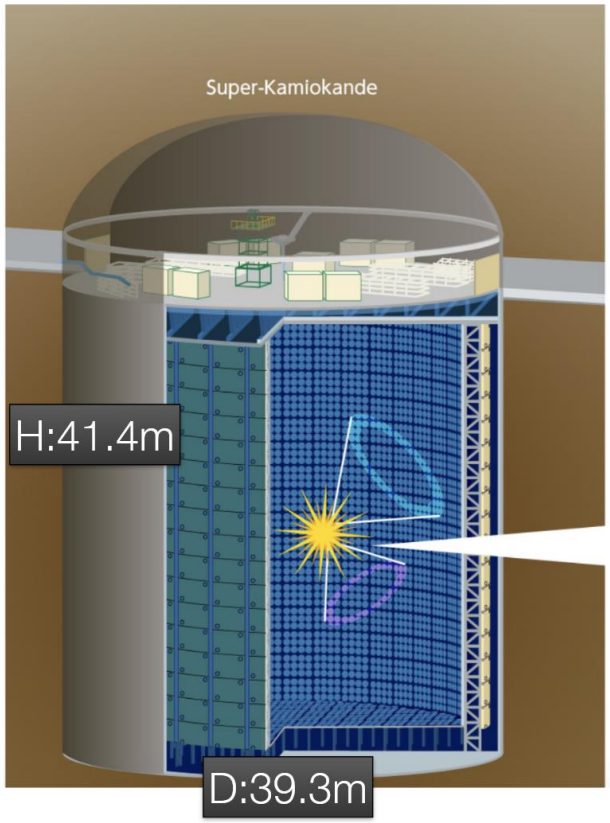






DATA FIT

Far Detector: Super-Kamiokande



Number of ID PMTs	11,129
Photo-coverage	40%
Mass	50 kton

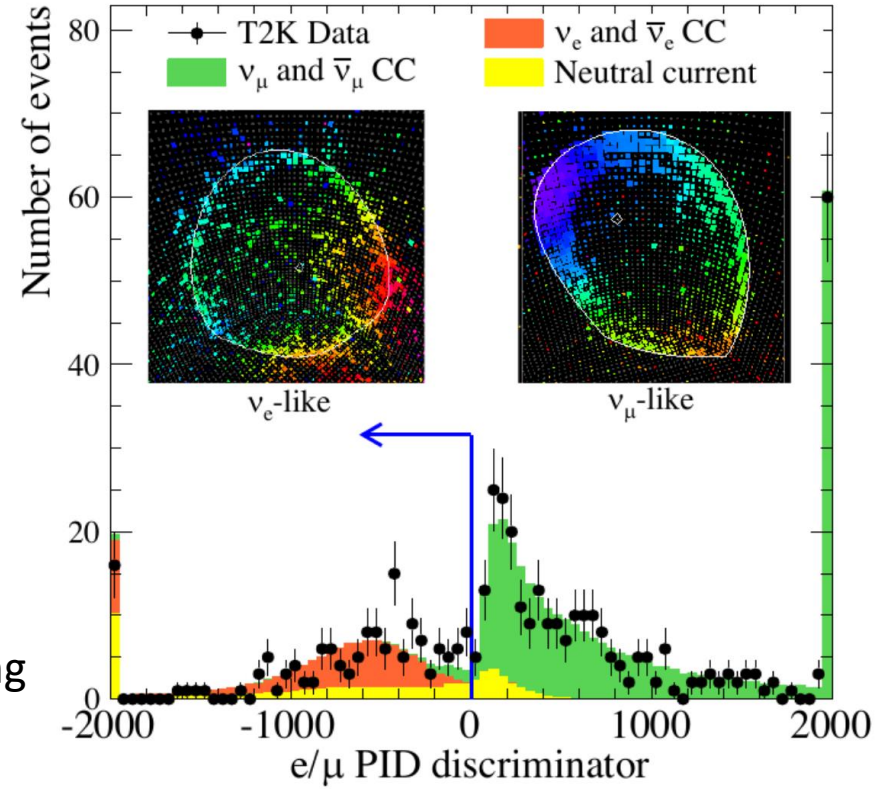
Particle identification

- $e^{\pm}$ and γ produce fuzzy rings
- $\mu^{\pm}$ and $\pi^{\pm}$ produce sharp rings (+ decay $e^{\pm}$)

Energy reconstruction

- Number of hits, hit charges, sharpness of the ring

Adapted from arXiv:1910.03887v2

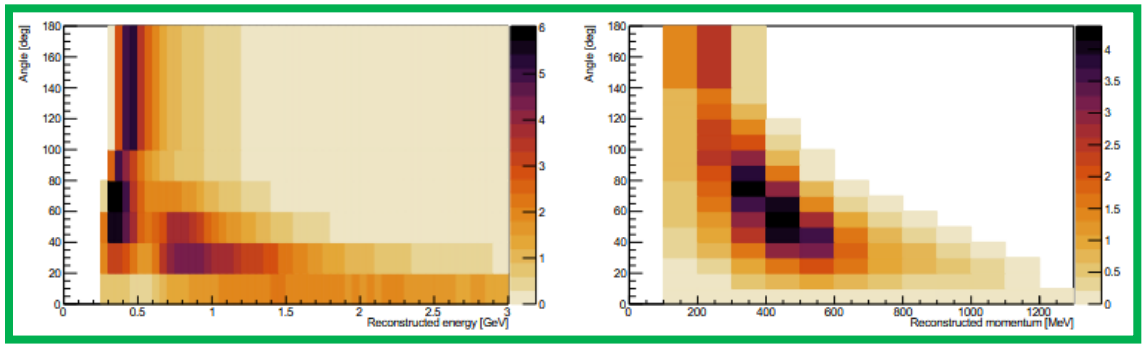


$\nu/\bar{\nu}$ identification

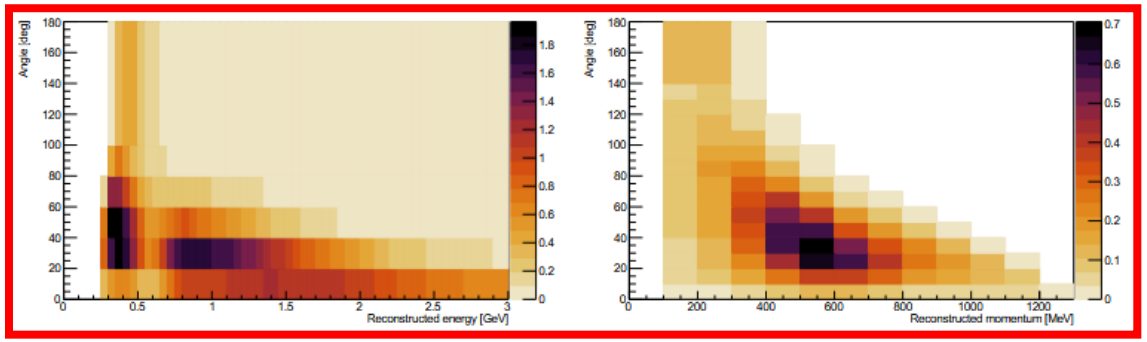
- Products of inverse beta decay: $\bar{\nu} \rightarrow \ell^+ + n \rightarrow$ neutron capture by nuclei
- Gadolinium loading since 2020: better efficiency for neutron capture detection

Six samples at far detector
Binning in reconstructed lepton momentum & angle

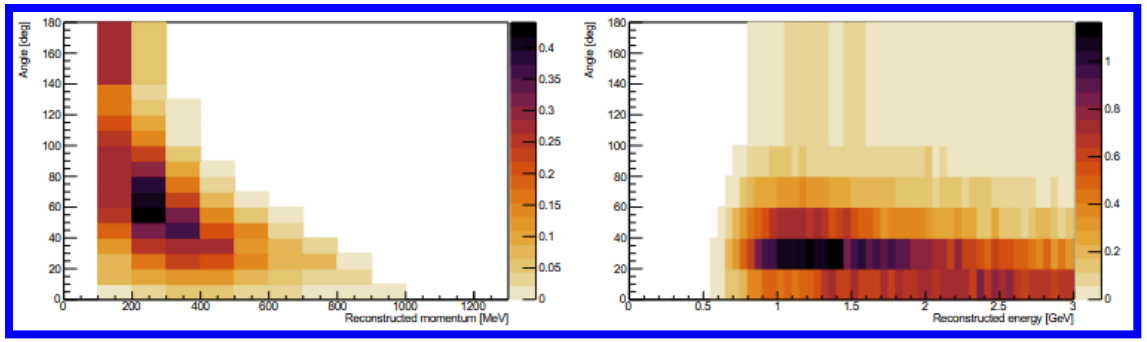
Reconstructed ν_μ **Reconstructed ν_e**



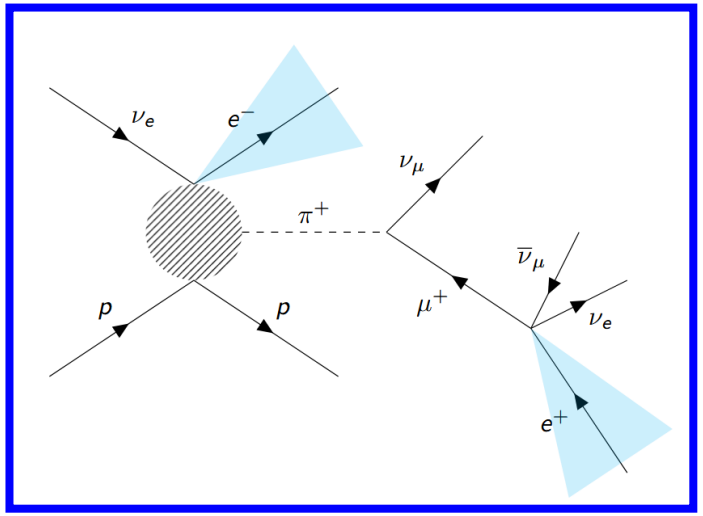
Target ν CCQE
1 ring topology in « ν beam mode »



Target $\bar{\nu}$ CCQE
1 ring topology in « $\bar{\nu}$ beam mode »



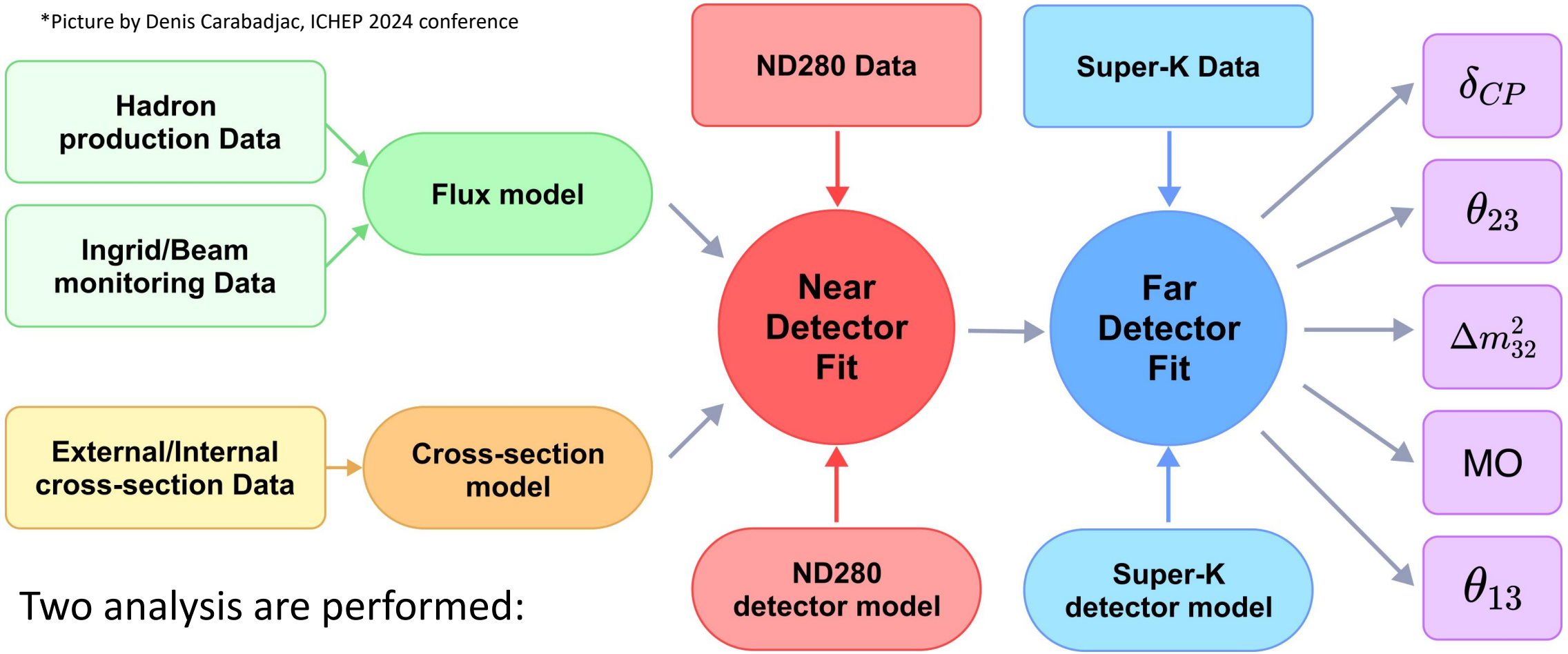
Target ν CC1π
1 main ring + 1 decay electron



Oscillation Analysis in T2K

T2K OSCILLATION ANALYSIS STRATEGY

*Picture by Denis Carabadjac, ICHEP 2024 conference



Two analysis are performed:

- **Frequentist analysis:** Feldman-Cousins method for **confidence intervals**, fitting sequentially ND and FD
- **Bayesian analysis:** Metropolis-Hastings algorithm for **credible intervals**, fitting simultaneously ND and FD

Fake data studies are made to test the robustness of the results to variations of the model

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

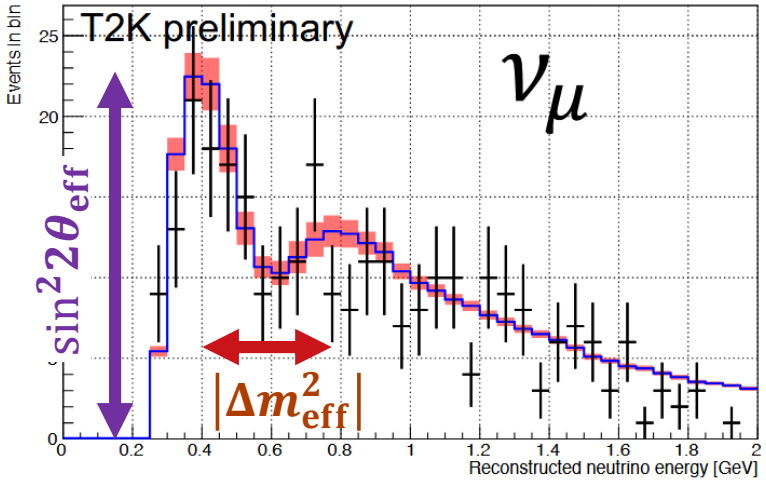
Similar to 2-flavour oscillation with effective parameters

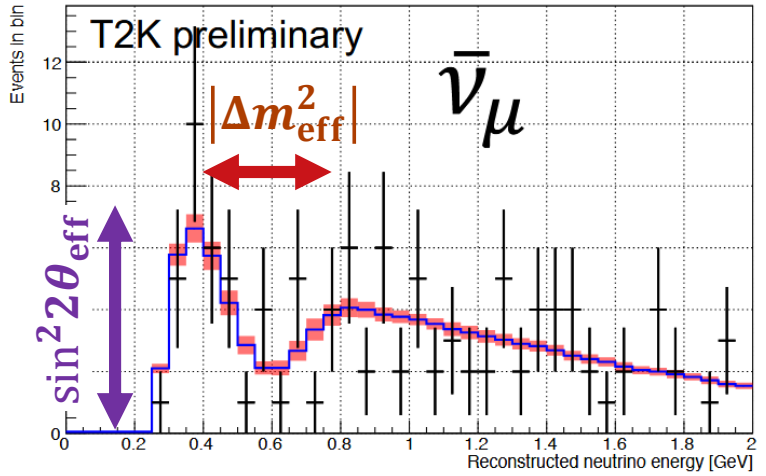
$$\sin^2 2\theta_{\text{eff}} = 4{c_{13}}^2{s_{23}}^2(1 - {c_{13}}^2{s_{23}}^2)$$

- Poor sensitivity to θ_{13} (only the cos appears)
- Good sensitivity to θ_{23}, **up to the octant!!** (two solutions for s_{23})

$$\Delta m^2_{\text{eff}} = \Delta m^2_{31} - \left({c_{12}}^2 - 2\cos\delta_{\text{CP}} s_{13} t_{23} s_{12} c_{12} \Delta m^2_{21}\right)$$

- Good sensitivity to $|\Delta m^2_{\text{atm}}|$ (= $|\Delta m^2_{32}|$[NO] / $|\Delta m^2_{31}|$[IO])
- **Mass hierarchy bias** coming from changing sign of Δm^2_{31}!





$$P(\nu_\mu \to \nu_e) = 4 s_{23}^2 s_{13}^2 c_{13}^2 \sin^2 \Delta_{31}$$ **Leading term**

$$\mp J_{\mathrm{CP}} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$ **CP-odd term**

$$\pm 8a(1-2s_{13}{}^2) s_{23}^2 s_{13}^2 c_{13}^2 \frac{\sin \Delta_{31}}{\Delta m_{31}^2} (\sin \Delta_{31} - \Delta_{31} \cos \Delta_{32})$$ **Matter effects**

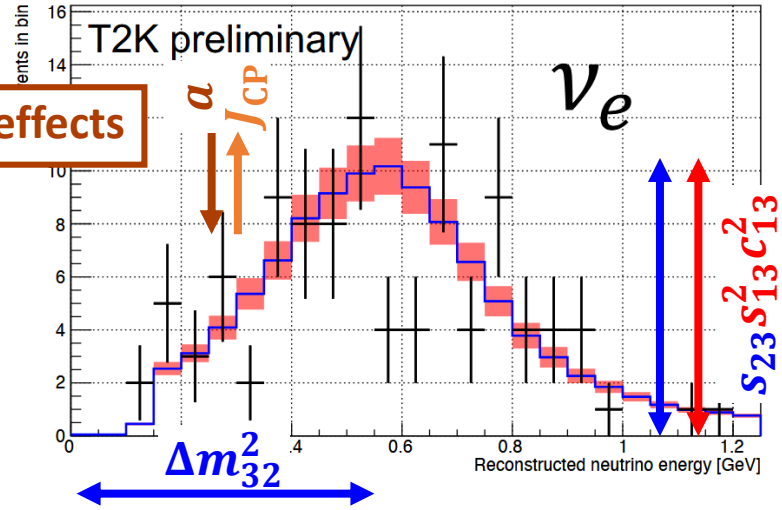
$$+\text{CP even terms} \ldots$$

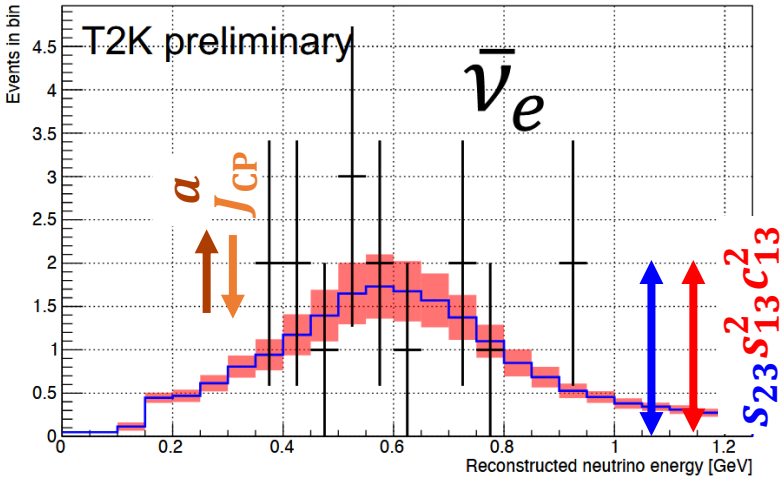
$$\Delta_{ij} = \frac{\Delta m^2 L}{4E}$$
$$a = 2\sqrt{2} G_F n_e E$$

Leading term
- Almost full degeneracy between θ_{13} and θ_{23}
- But if θ_{13} is known, ability to resolve the θ_{23} octant!

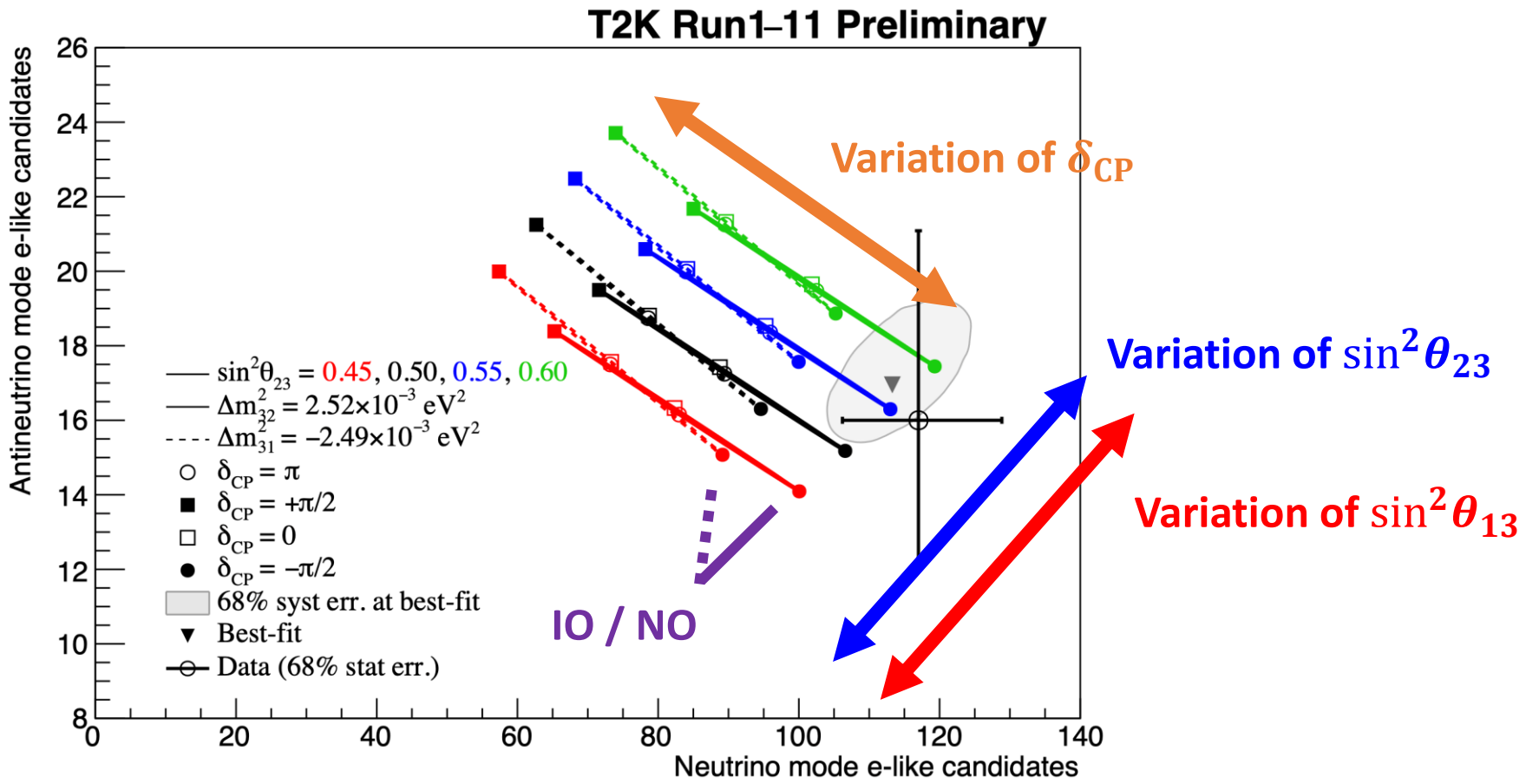
CP-odd term
- Sensitive to Jarlskog invariant $J_{\mathrm{CP}} = s_{13} c_{13}^2 s_{12} c_{12} s_{23} c_{23} \sin\delta_{\mathrm{CP}}$
- Opposite effect for ν and $\bar{\nu}$

Matter effects
- Sensitive to the sign of Δm_{31}^2, i.e. mass hierarchy!
- Opposite effect for ν and $\bar{\nu}$





DEGENERACIES IN T2K APPEARANCE CHANNEL



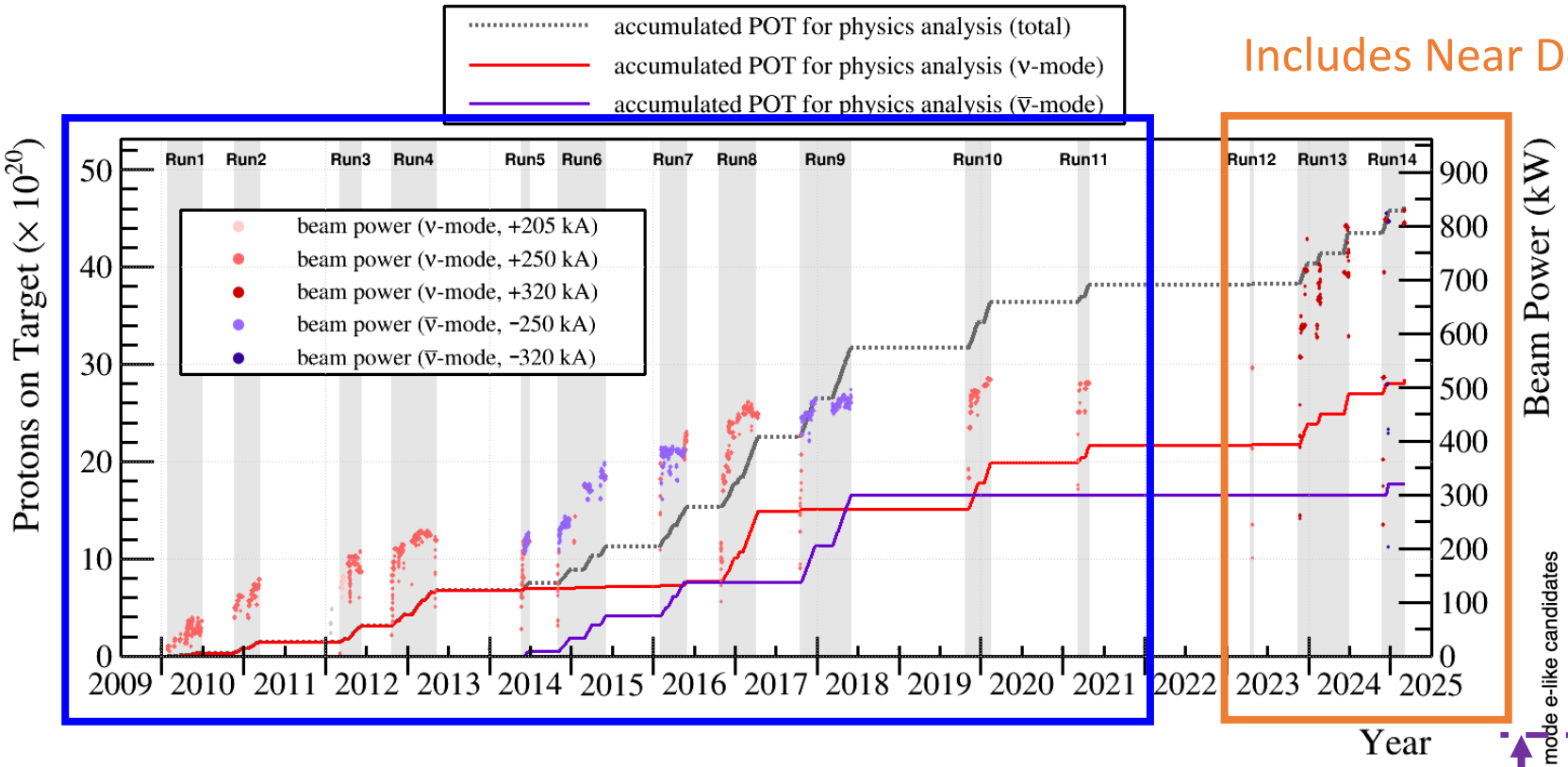
- δ_{CP} — **Mass Hierarchy** degeneracy
- δ_{CP} — θ_{23} **octant** degeneracy
- θ_{13} — θ_{23} **octant** degeneracy
- θ_{13} — δ_{CP} degeneracy

Joint fit with SK atmospheric neutrinos!

Use constraint on θ_{13} provided by reactor experiments!

Latest T2K results (with Reactor Constraint)

Analyzed data for latest results



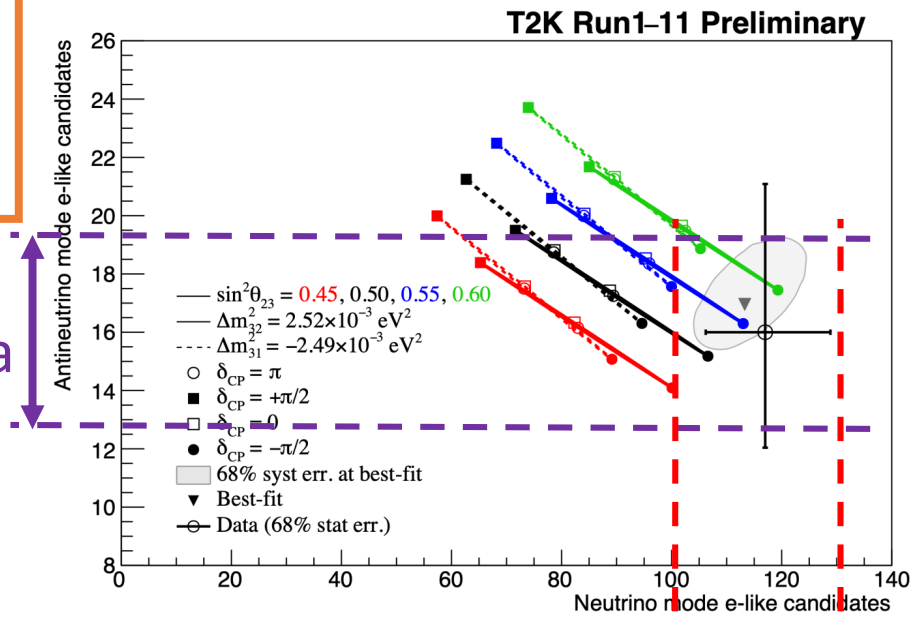
Includes Near Detector Upgrade & Flux Upgrade!

Latest analysed data: Runs 1-11

FHC: 2.1423×10^{21} POT

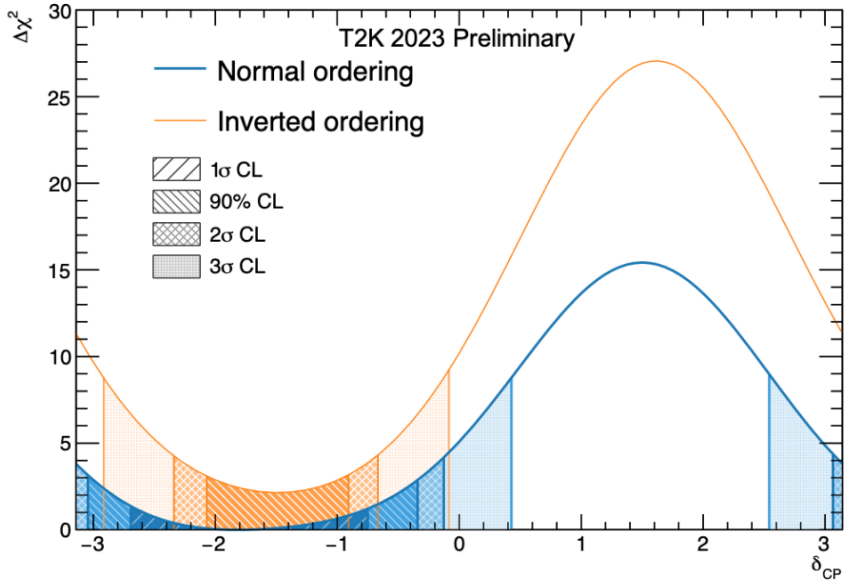
RHC: 1.6344×10^{21} POT

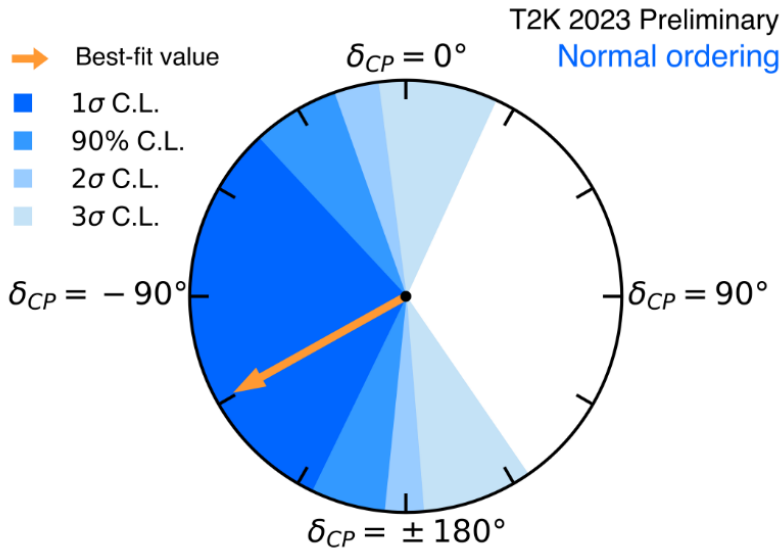
$\bar{\nu}$ mode data

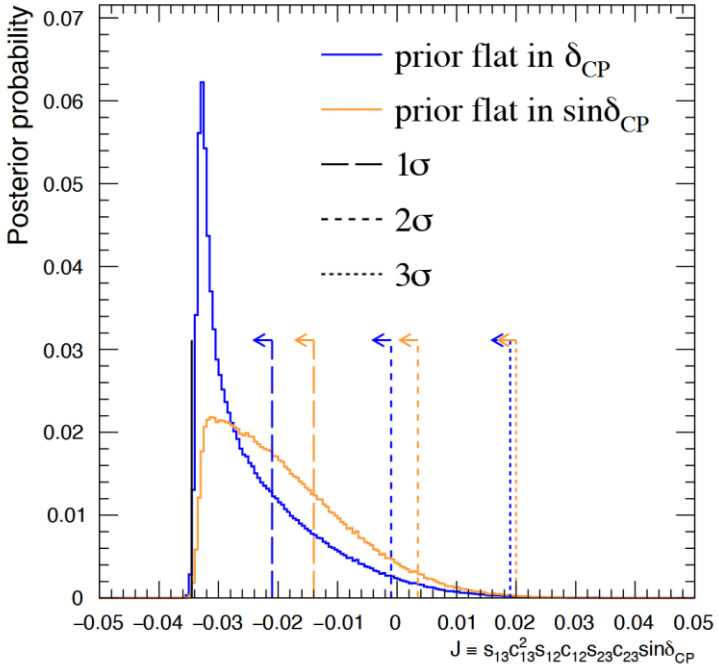


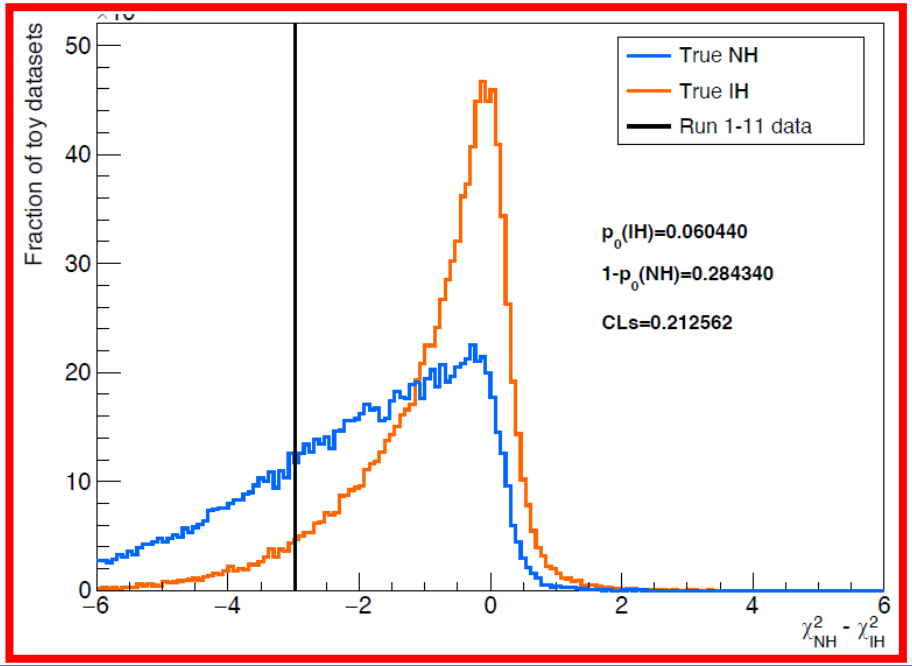
ν mode data

LATEST T2K RESULTS: CP VIOLATION AND MASS HIERARCHY







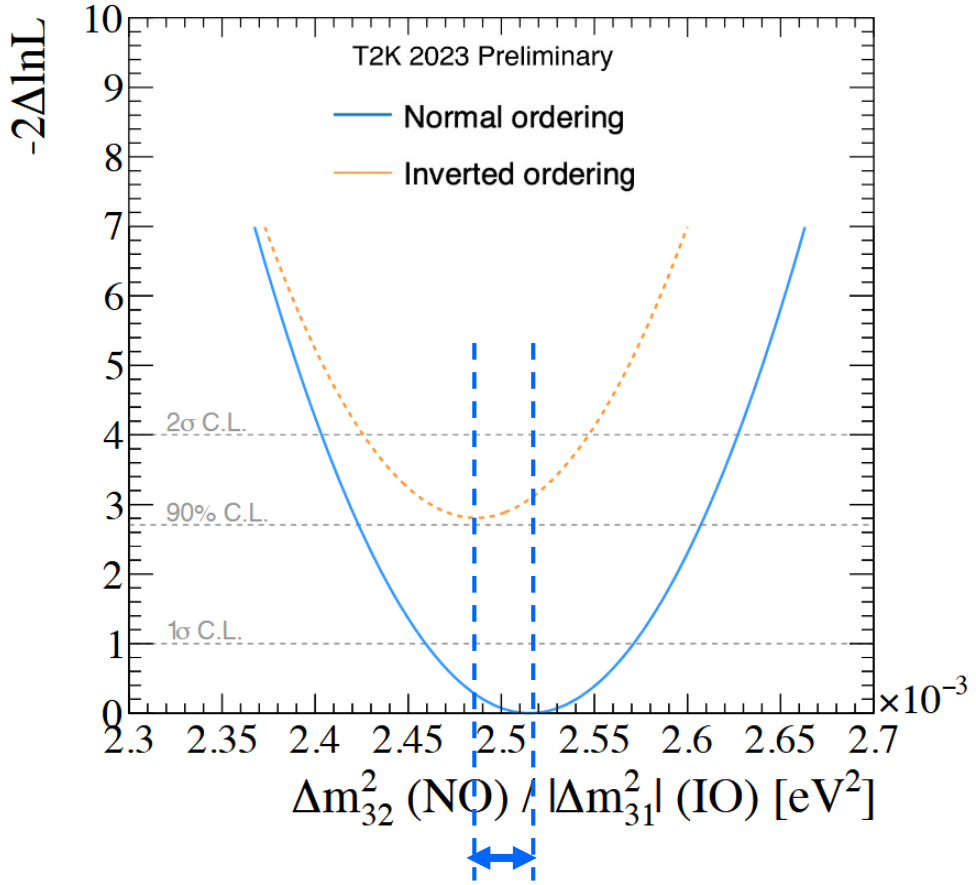


$$\delta_{CP} = -2.08^{+1.33}_{-0.61}$$

CP Conservation is excluded with 90% confidence level!

Exclusion of inverted ordering by 1.25σ (CLs method)

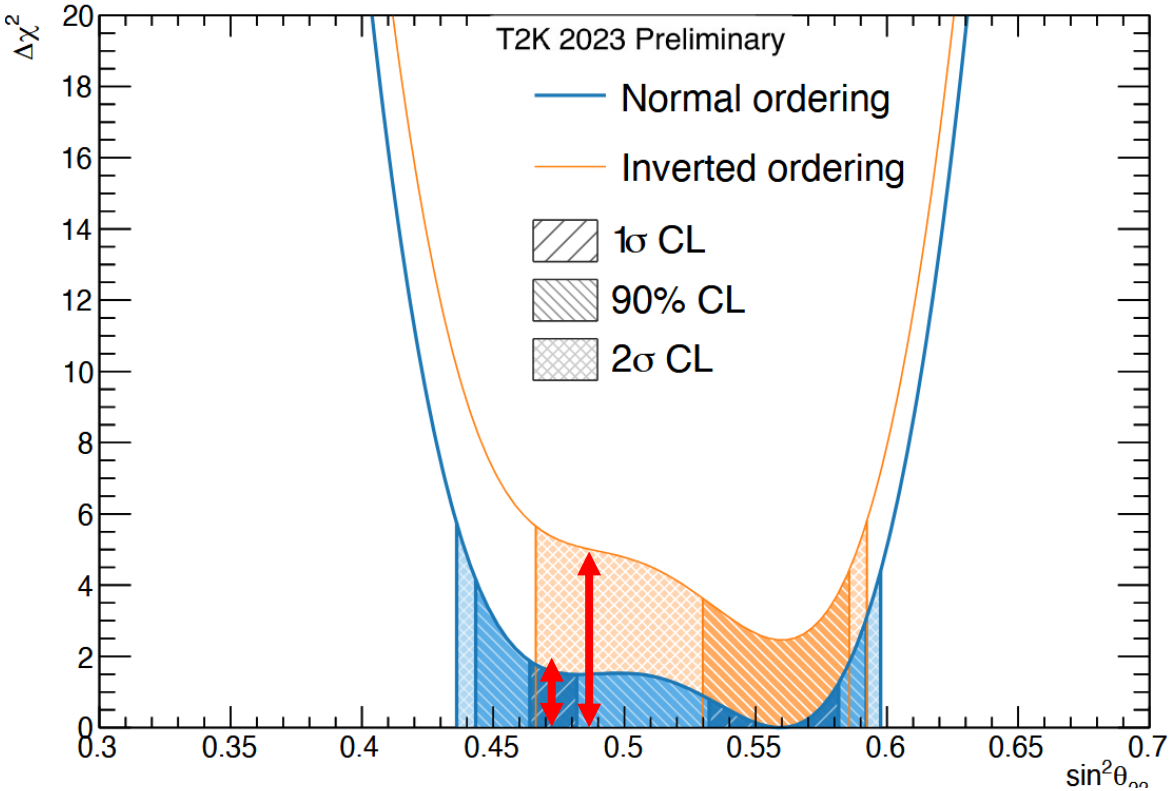
LATEST T2K RESULTS: $\Delta m^2_{\mathrm{ATM}}$ AND $\sin^2\theta_{23}$



MO Bias from disappearance channel

$$|\Delta m^2_{\mathrm{atm}}| = 2.521^{+0.037}_{-0.050} \times 10^{-3}\ \mathrm{eV}^2$$

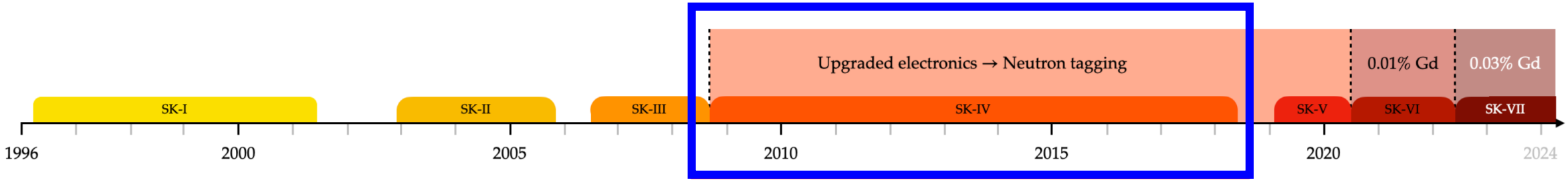
(mass hierarchy treated as nuisance)



Lower octant exclusion from appearance channel

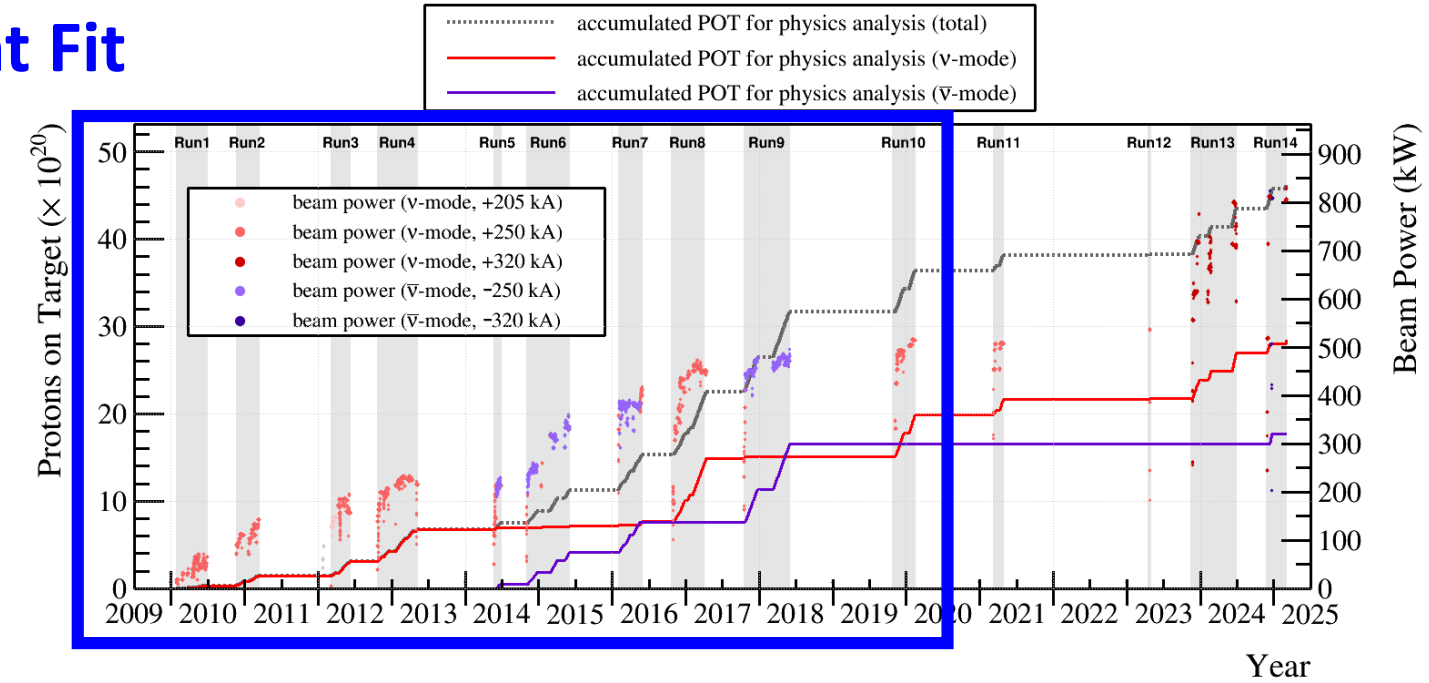
$$\sin^2\theta_{23} = \begin{cases} 0.568^{+0.014}_{-0.036} & \textbf{Upper Octant} \\ 0.475^{+0.007}_{-0.011} & \textbf{Lower Octant} \end{cases}$$

Joint fit with Super-Kamiokande Atmospherics



First iteration of the T2K+SK Joint Fit

Phys.Rev.Lett. 134 (2025) 1, 011801



Why a joint fit?

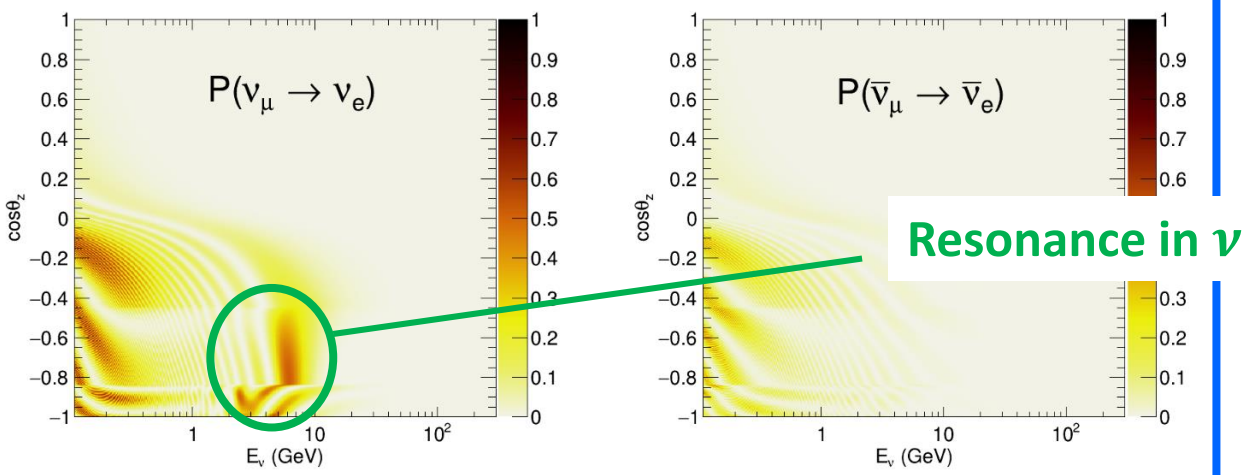
- More data
- Common systematics
- **Resolve degeneracies**

- δ_{CP} — **Mass Hierarchy degeneracy**
- δ_{CP} — θ_{23} **octant degeneracy**
- θ_{13} — δ_{CP} **degeneracy**
- θ_{13} — θ_{23} **octant degeneracy**

Joint fit with SK atmospherics!

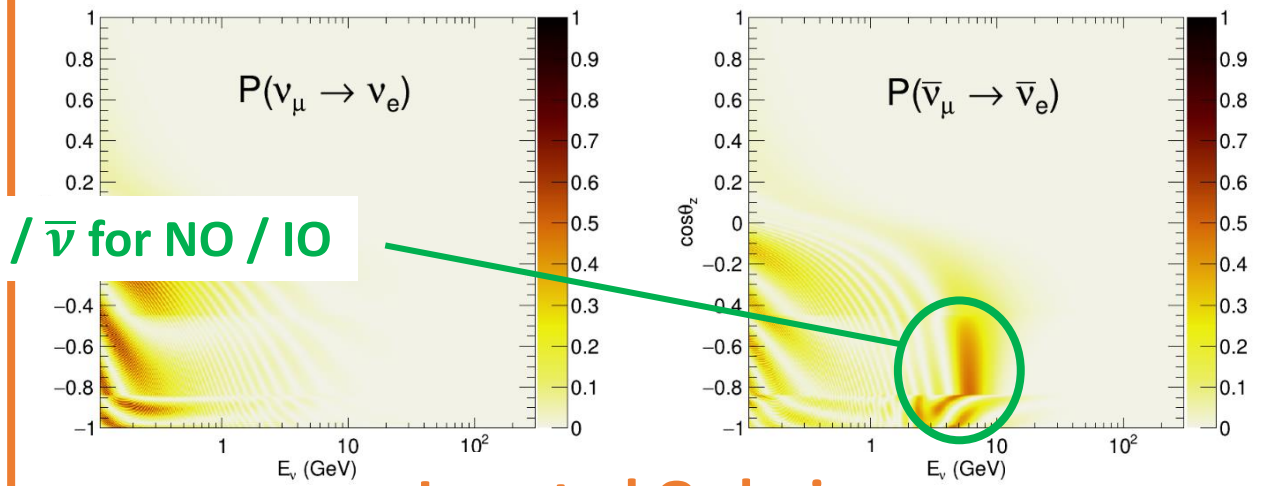
Use constraint on θ_{13} provided by reactor experiments!

Resolving the degeneracies with the joint fit

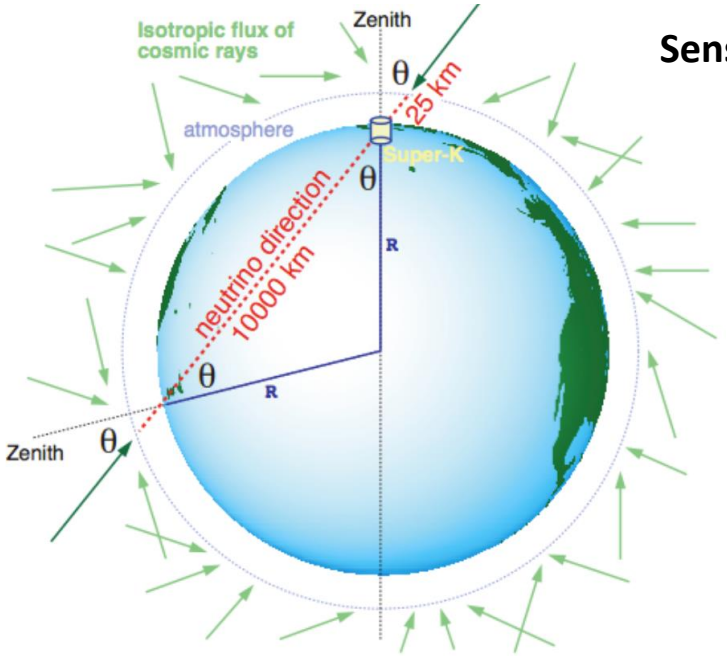


Normal Ordering

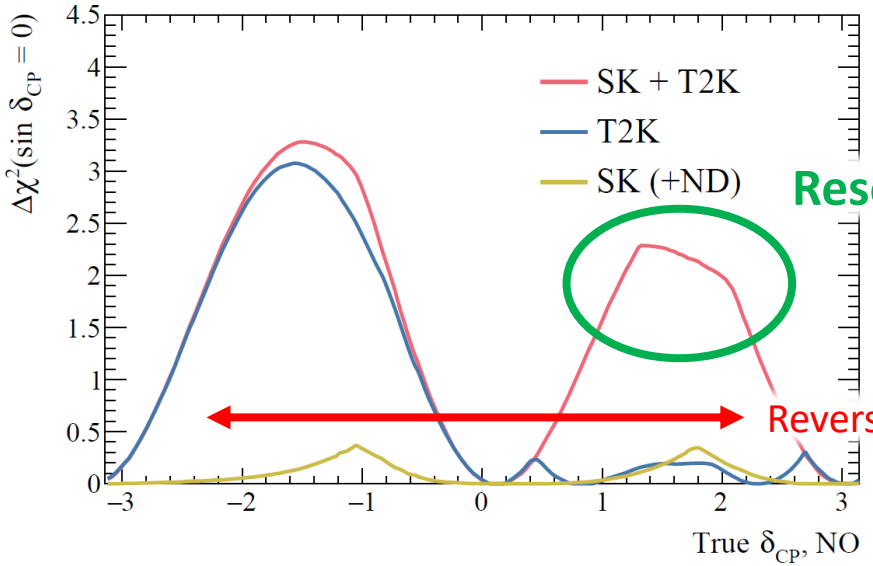
Resonance in ν / $\bar{\nu}$ for NO / IO



Inverted Ordering

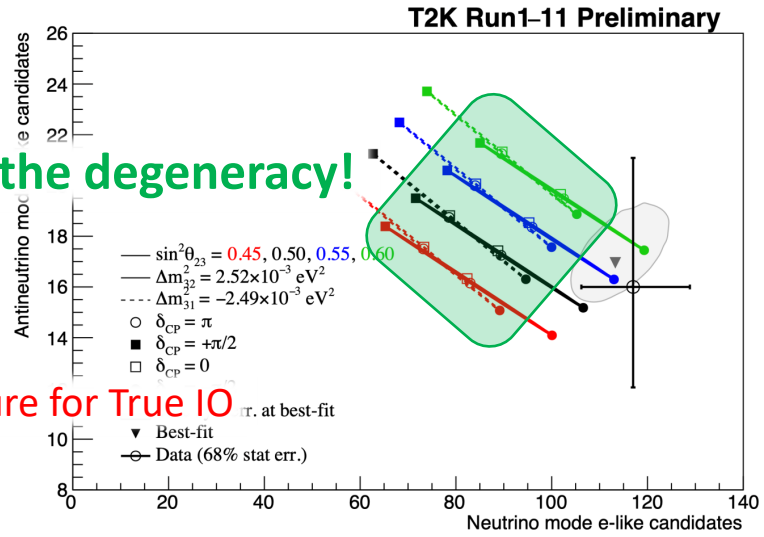


Sensitivity to exclude $\sin\delta_{CP} = 0$ as a function of True δ_{CP} (True NO)



Resolving the degeneracy!

Reversed picture for True IO



Number of neutrino events = Neutrino flux (ν flux model) ⊗ Neutrino oscillation (PMNS model) ⊗ Neutrino interactions (ν cross-section models) ⊗ Neutrino detection (SK detector model)

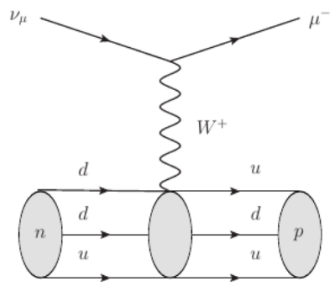
Neutrino flux models

Hadronic models could be correlated
→ Not implemented yet

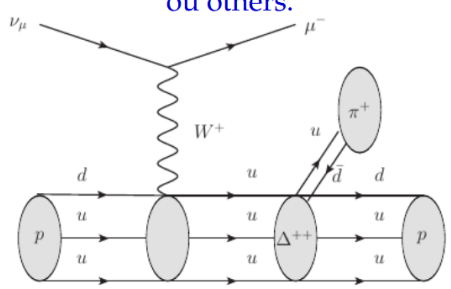
SK detector model

The systematics for atmospheric neutrinos detection and T2K neutrinos detection have been correlated

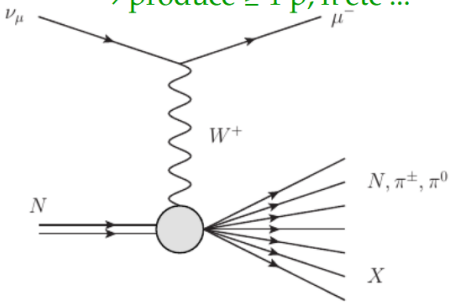
CCQE
Low q^2 (< M_p)



CCResonant
Large enough q^2 to produce Δ (1230 MeV), ou others.



CCDIS
Large enough q^2 to see quarks
→ produce ≥ 1 p, n etc ...

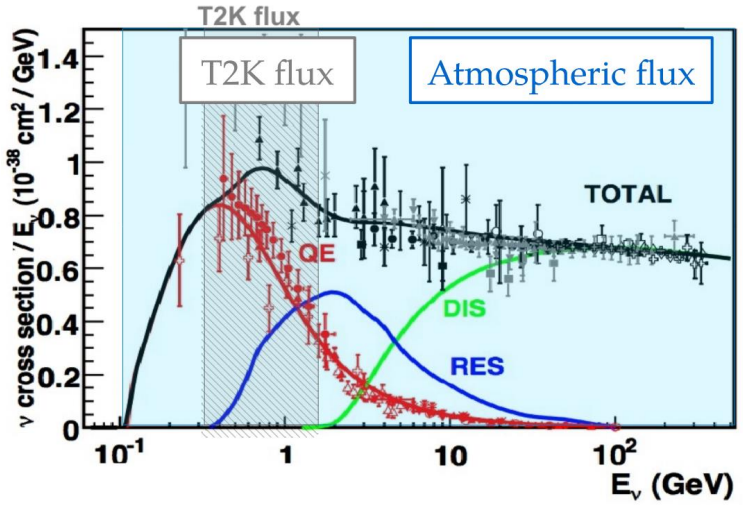


Neutrino interaction models

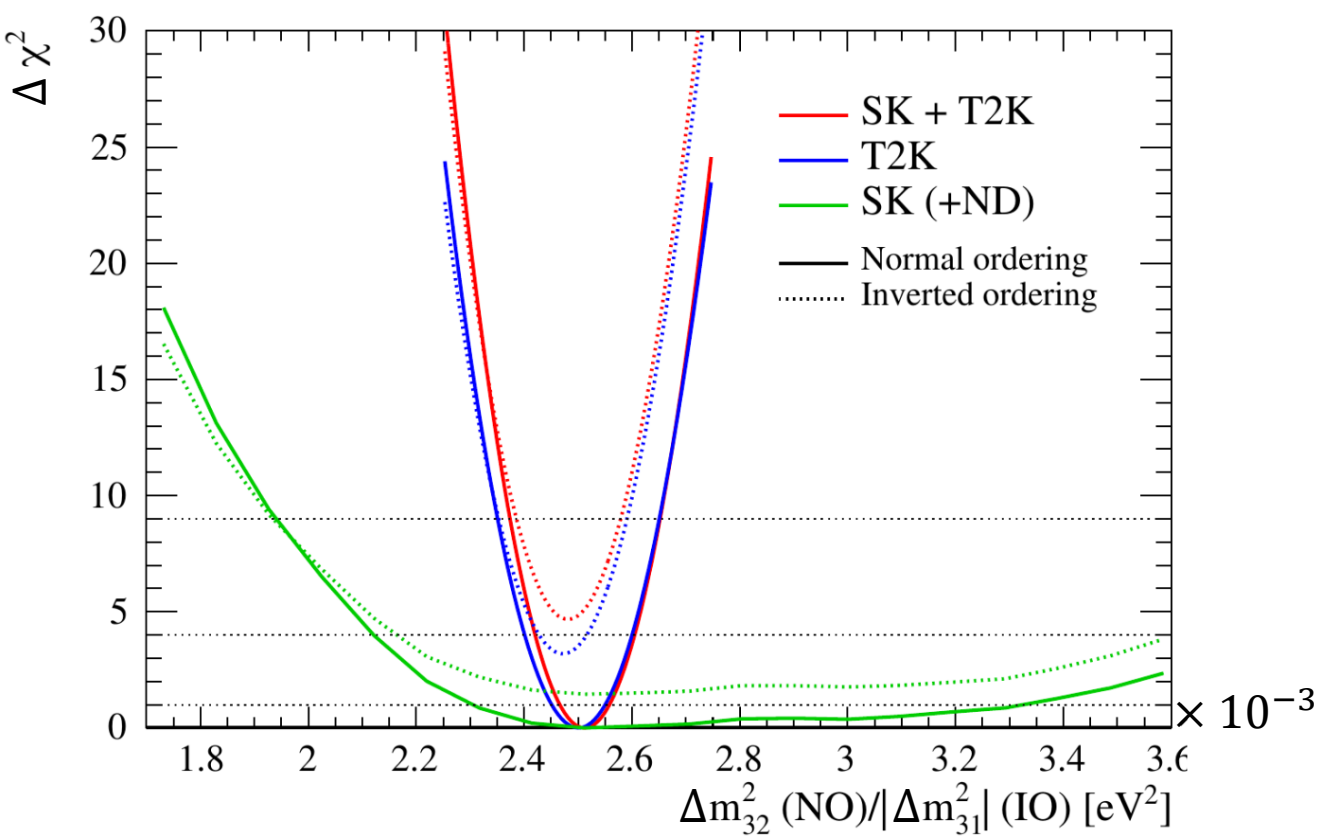
T2K interaction models:
- Very well-constrained by ND
- Robust only in 0 – 2 GeV region

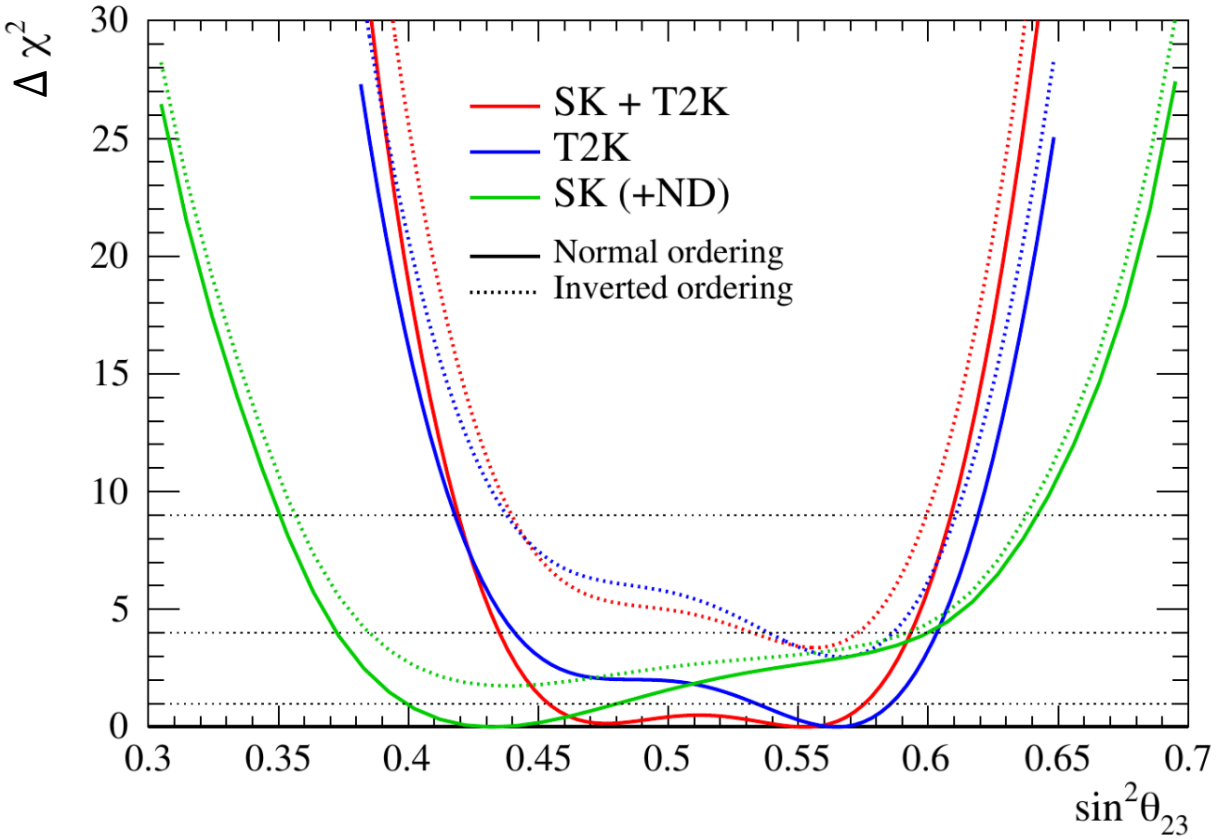
SK interaction models:
- Up to 10 TeV for atmospherics!

Correlate only T2K and Sub-GeV atmospherics (with ND constraint)



JOINT FIT RESULTS: $\Delta m^2_{\mathrm{ATM}}$ AND $\mathrm{SIN}^2\theta_{23}$





$\Delta m^2_{32} = 2.520^{+0.048}_{-0.058}\ \mathrm{eV}^2$ Normal Hierarchy

$\Delta m^2_{32} = -2.480^{+0.052}_{-0.048}\ \mathrm{eV}^2$ Inverted Hierarchy

→ **Similar to T2K only**

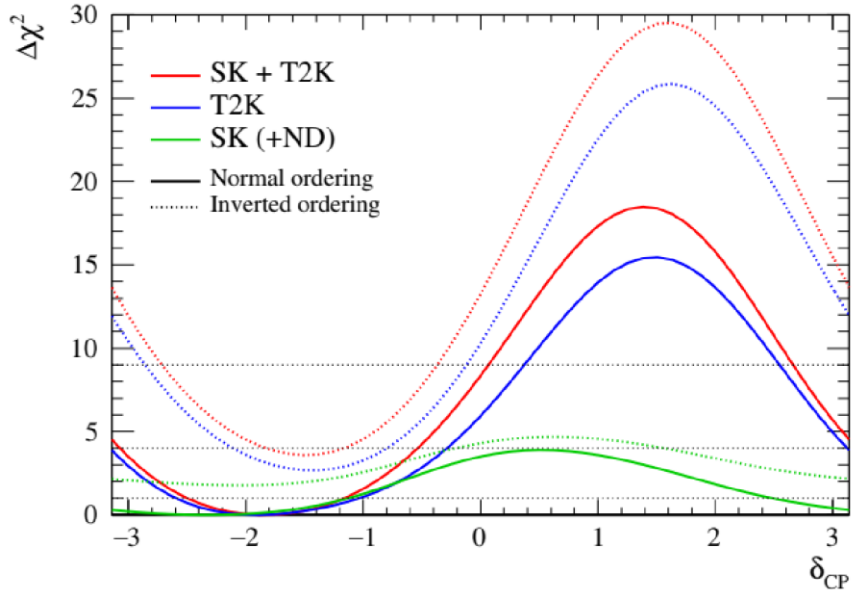
$\sin^2\theta_{23} = 0.468^{+0.106}_{-0.025}$

(mass hierarchy treated as nuisance)

→ **Different octant preferences for SK and T2K**

→ **Largely compatible with Maximal Mixing**

JOINT FIT RESULTS: CP VIOLATION AND MASS HIERARCHY

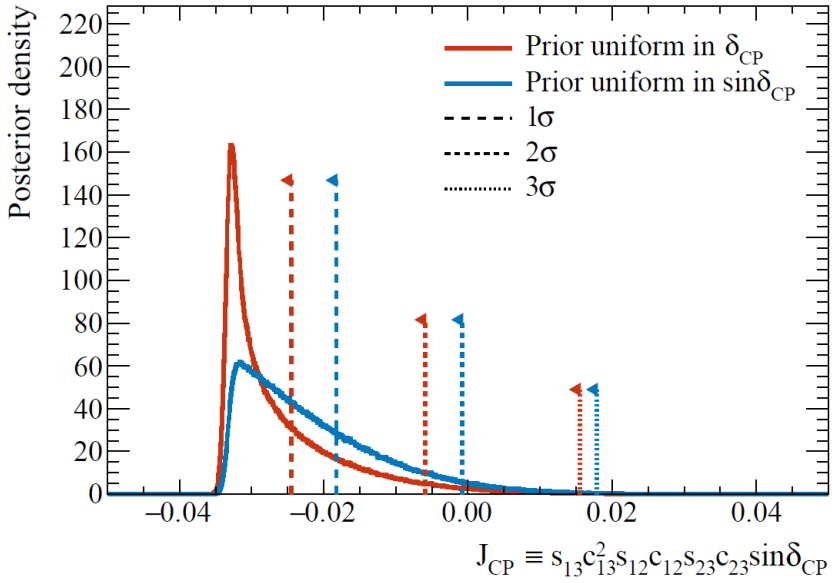


$$\delta_{\mathrm{CP}} = -1.76^{+0.73}_{-0.95}$$

→ **Both T2K and SK favor $\delta_{CP} \approx -\frac{\pi}{2}$**

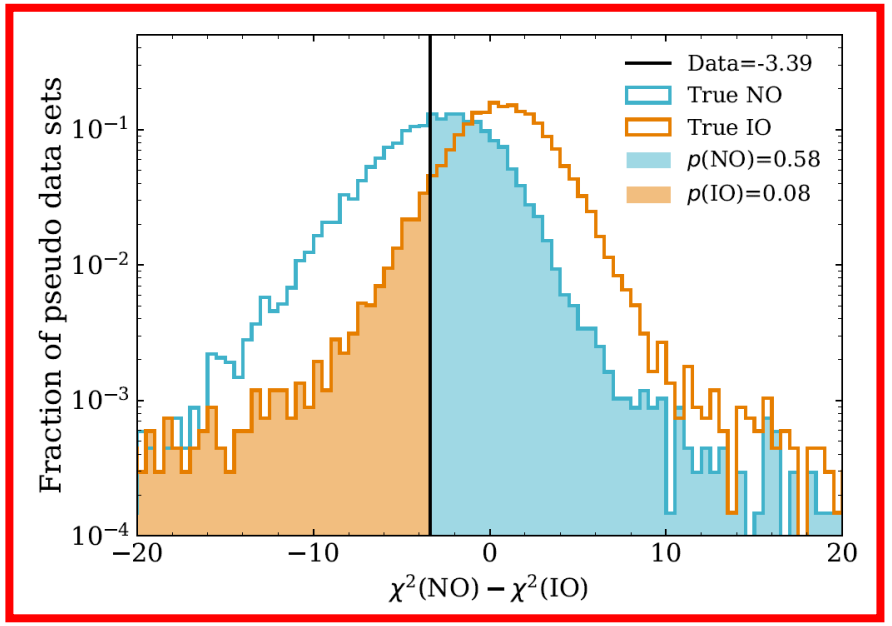
→ Clear enhancement in the exclusion of $\delta_{CP} = 0$: $\mathbf{2.5\sigma}$

→ Overall exclusion of $J_{\mathrm{CP}} = 0$: $\mathbf{1.9\sigma}$

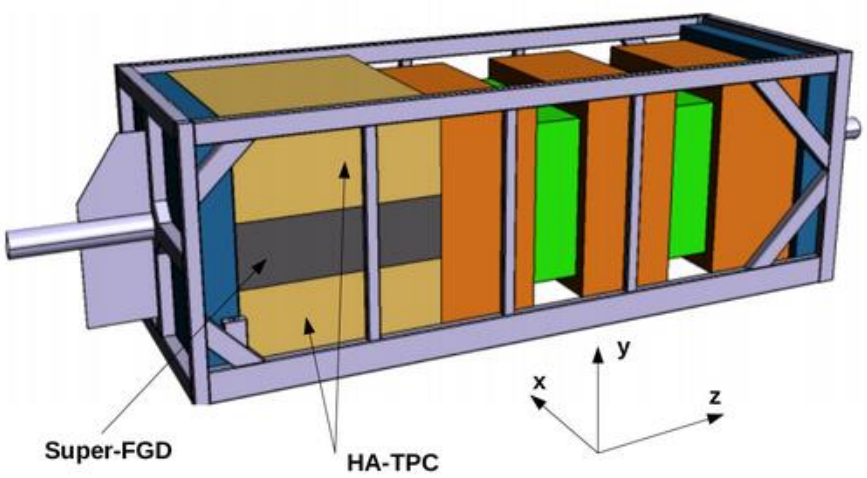


Limited preference for NO:
→ 1.2σ rejection of IO

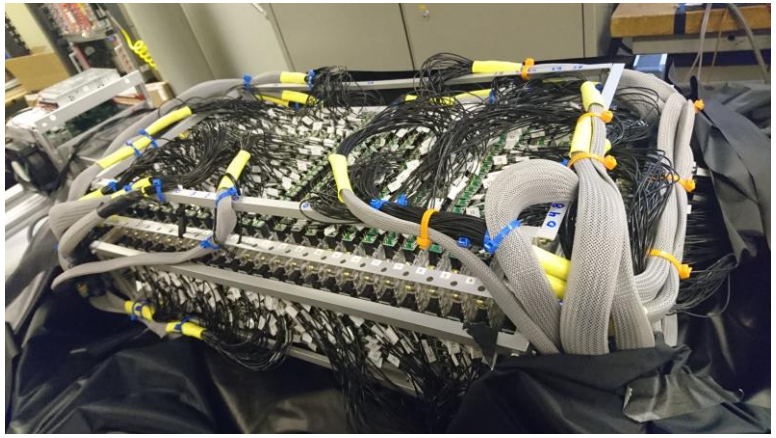
→ Large improvement expected with all SK atmospherics data



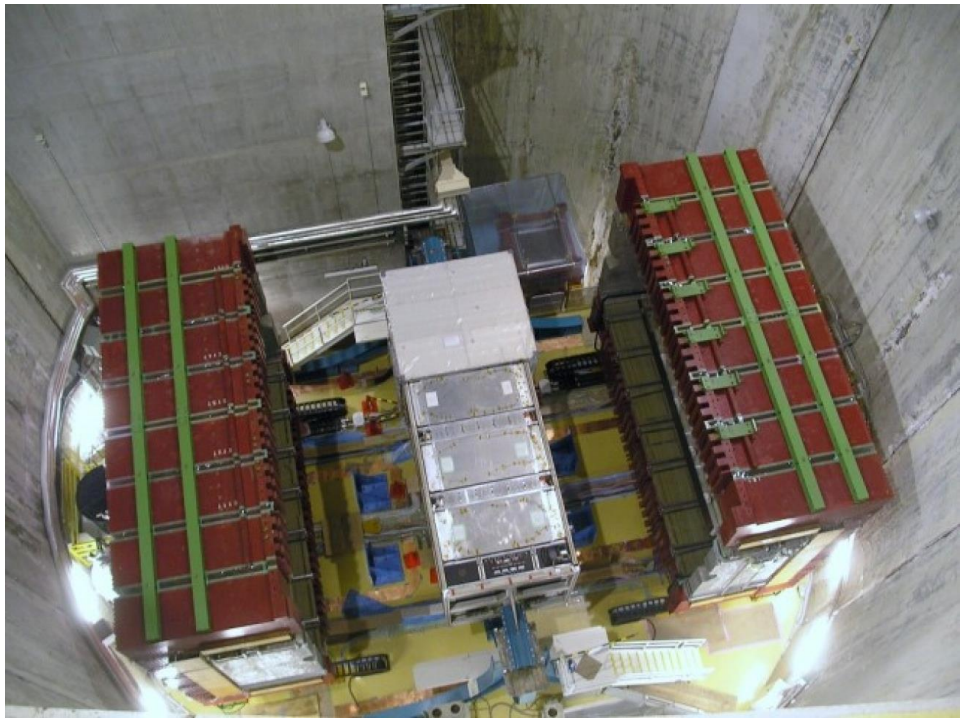
T2K Future prospects

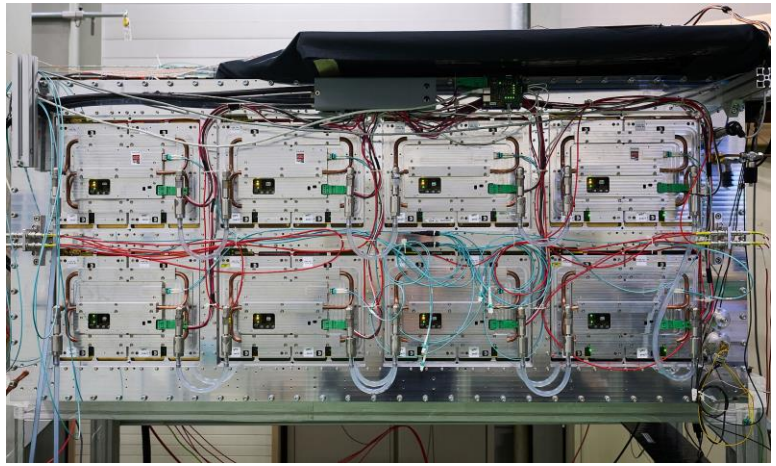


Installation of the T2K Near Detector upgrade finalized in 2024!

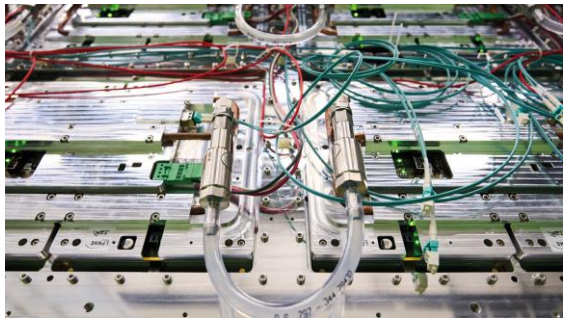


Super-FGD

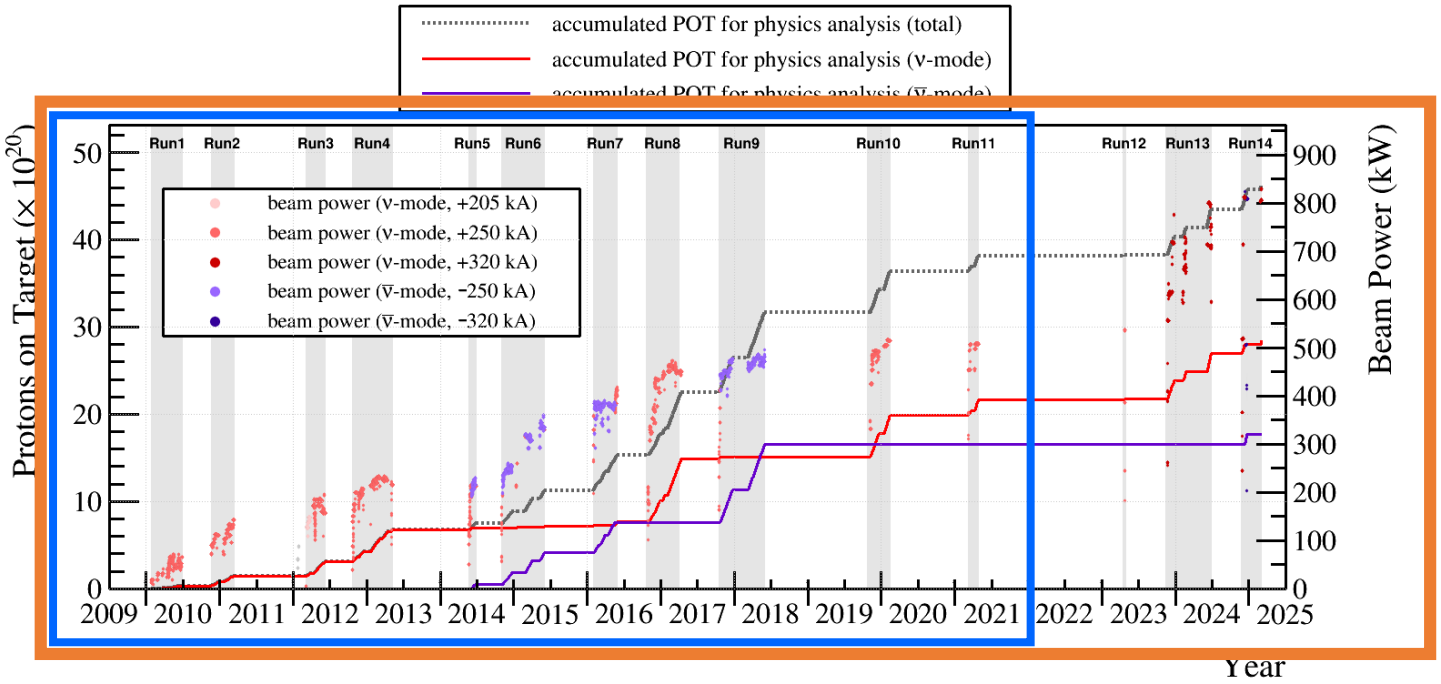




High Angle TPC



Conclusion

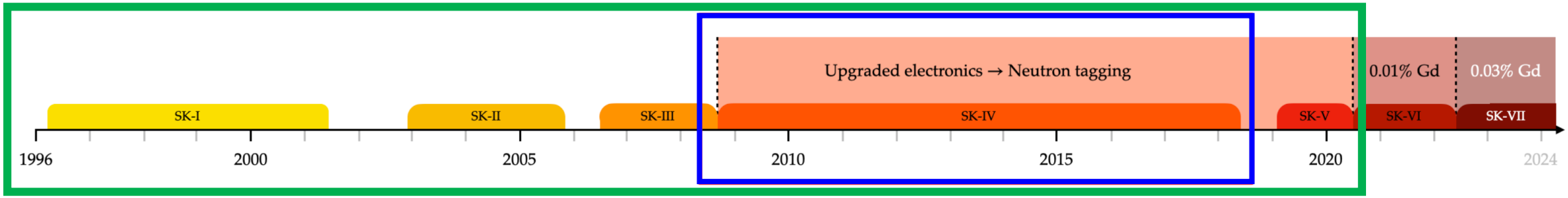


Latest analyzed data

- $\sin\delta_{CP} = 0$ excluded at 90% C.L.
- Slight preference for NO and upper octant
- Precision of 4×10^{-5} eV^2 on Δm^2_{atm}

Future analyses

- Upgraded focusing horns: less flux contamination
- ND Upgrade: More fiducial mass, better resolution
- Increased beam power: more POT per year



First iteration of the T2K+SK Joint Fit

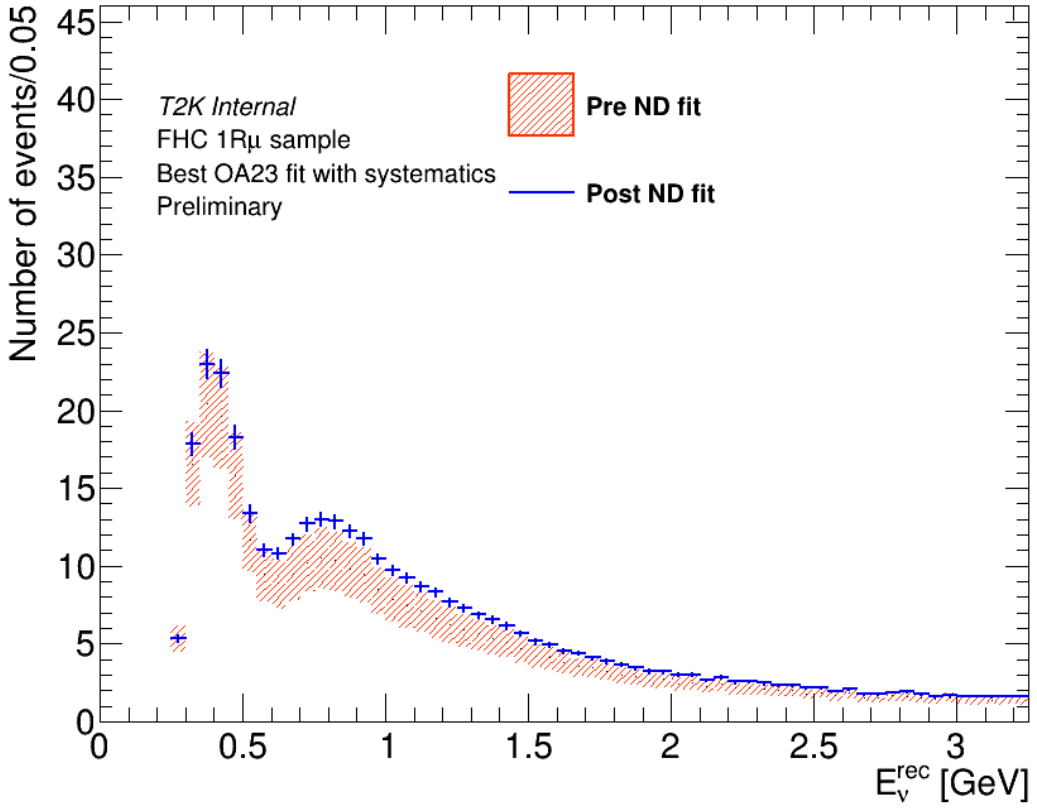
- $J_{CP} = 0$ excluded at 2σ
- Slight preference for NO
- No octant preference

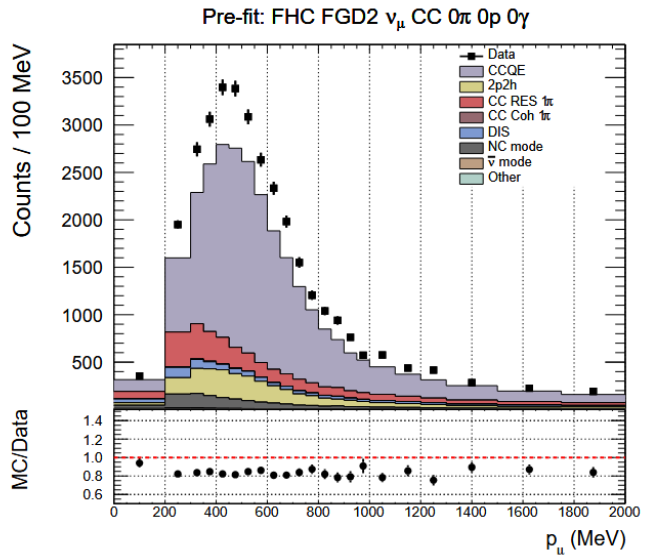
Second iteration of the T2K+SK Joint Fit

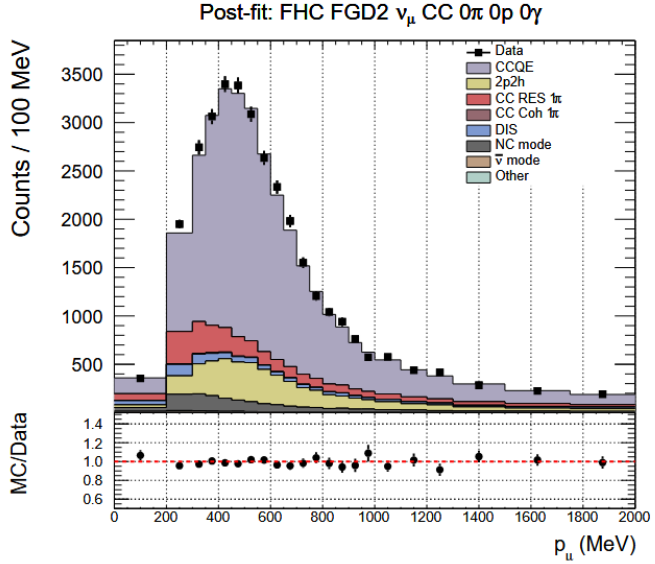
- Even more data! (× 2 SK, +9% T2K)
- New accelerator samples
- New cross-section model

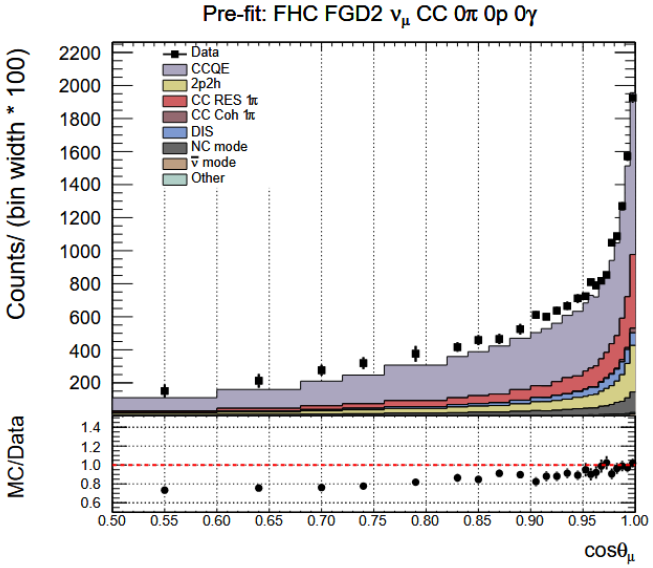
BACKUP

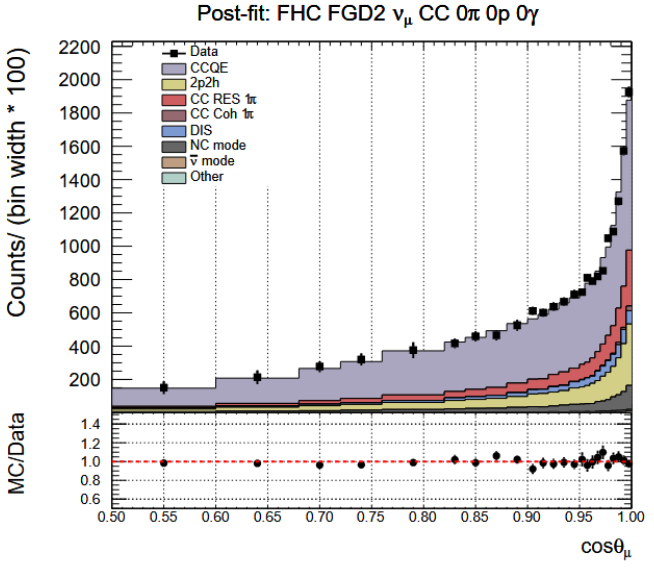
Near Detector Fit



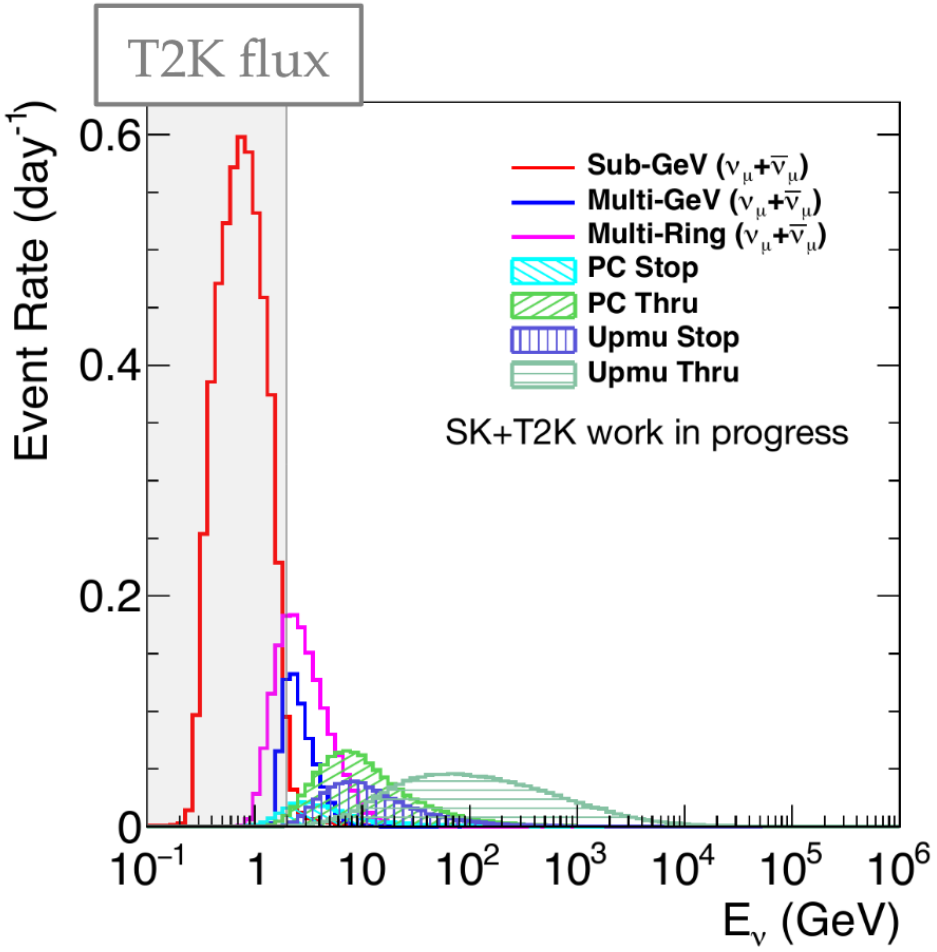








Number of neutrino events = Neutrino flux (ν flux model) ⊗ Neutrino oscillation (PMNS model) ⊗ Neutrino interactions (ν cross-section models) ⊗ Neutrino detection (SK detector model)



Neutrino flux models

T2K flux model:
- Hadronic models
- NA61/SHINE tuning

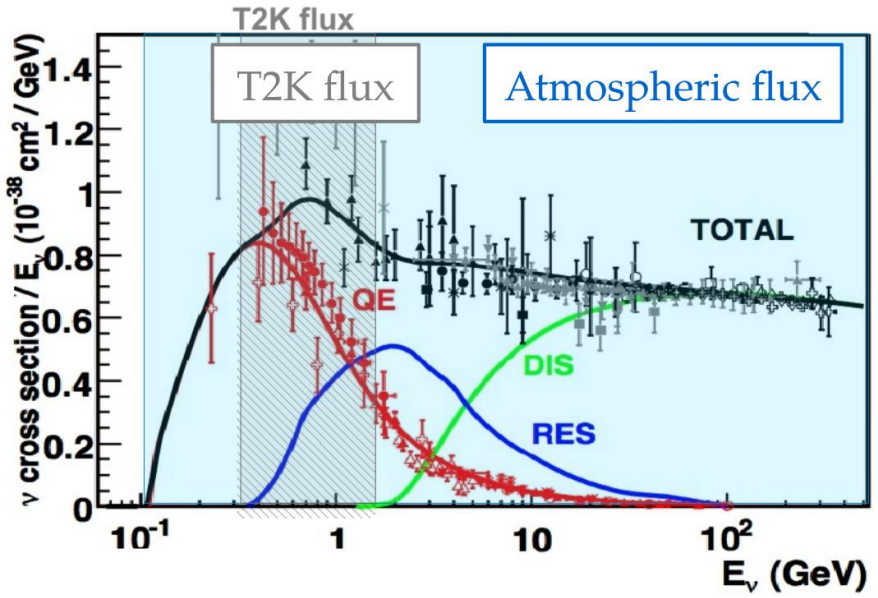
SK atmospheric flux model:
- Honda flux (HESS & AMS data) *(Phys.Rev.D 70 (2004) 043008)*
- Muon flux measurements

Hadronic models could be correlated below ~1 GeV

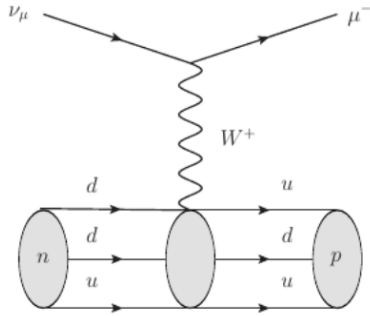
Not in the first Joint Fit result
→ Future work!

Number of neutrino events = Neutrino flux (ν flux model) ⊗ Neutrino oscillation (PMNS model) ⊗ Neutrino interactions (ν cross-section models) ⊗ Neutrino detection (SK detector model)

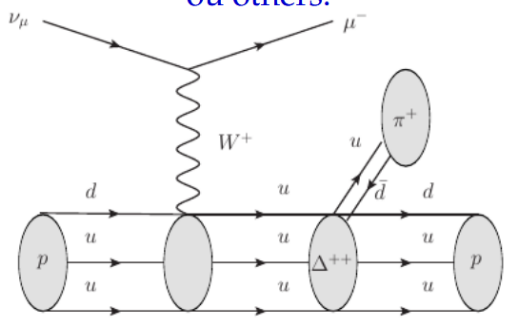
Neutrino interaction models



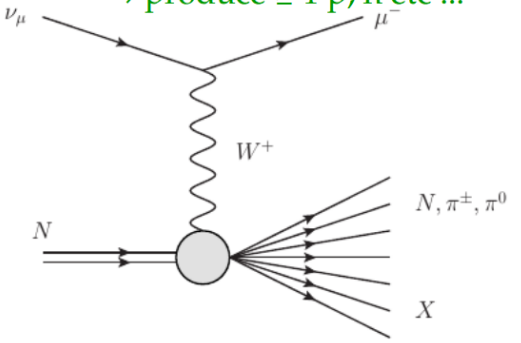
CCQE
Low q^2 (< M_p)



CCResonant
Large enough q^2 to produce Δ (1230 MeV), ou others.



CCDIS
Large enough q^2 to see quarks → produce ≥ 1 p, n etc ...

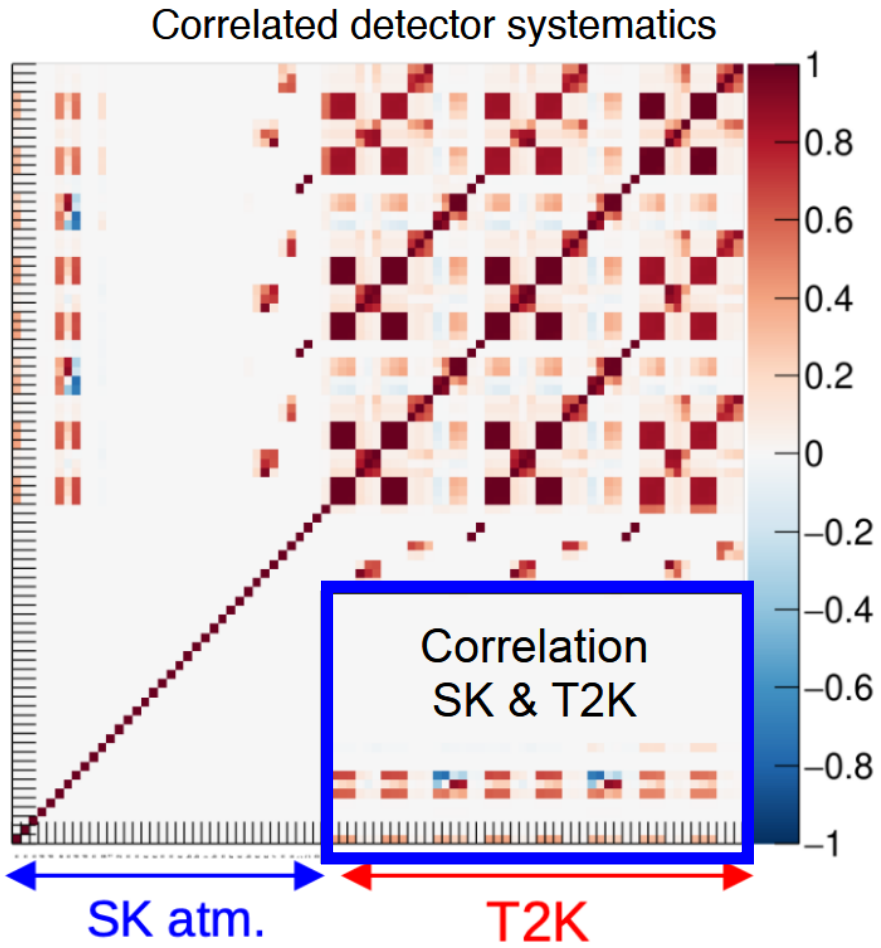


T2K interaction models:
- Very well-constrained by ND
- Robust only in 0 – 2 GeV region

SK interaction models:
- Up to 10 TeV for atmospherics!

Correlate only T2K and Sub-GeV atmospherics (with ND constraint)

Number of neutrino events = Neutrino flux (ν flux model) ⊗ Neutrino oscillation (PMNS model) ⊗ Neutrino interactions (ν cross-section models) ⊗ Neutrino detection (SK detector model)



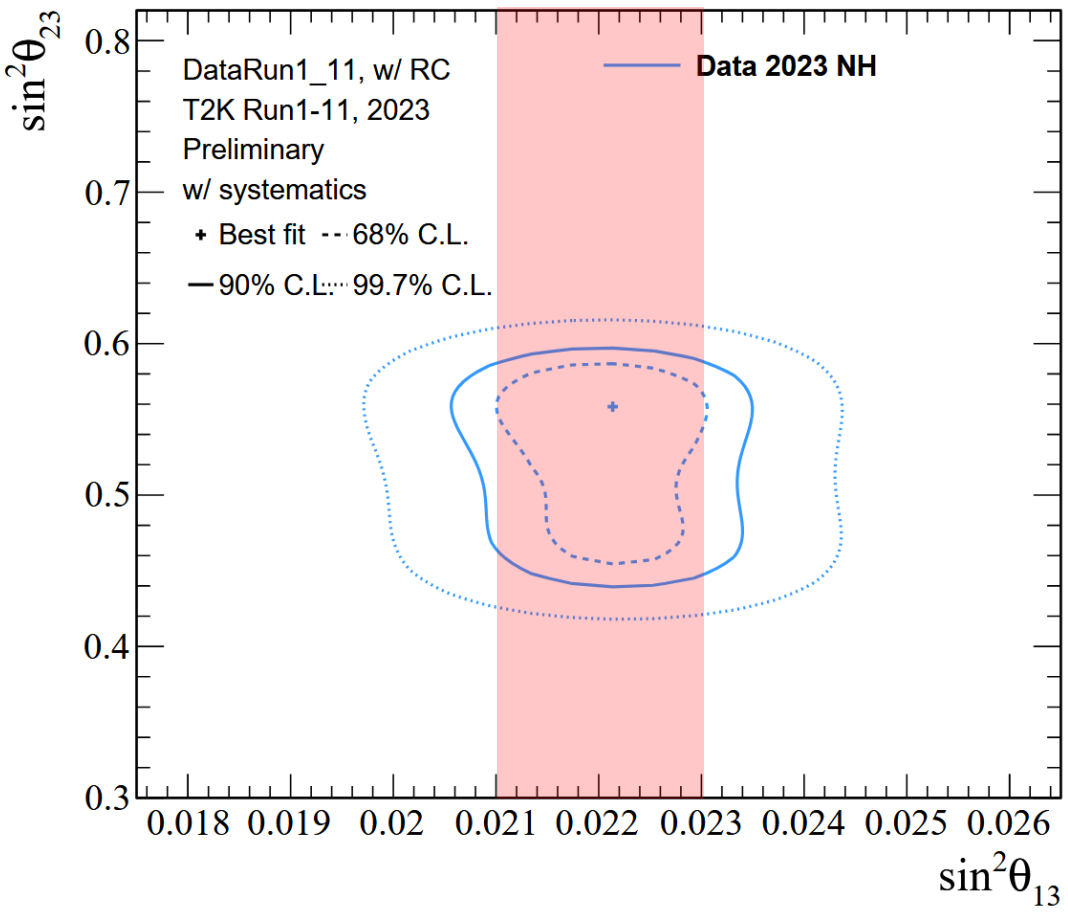
Neutrino detection models

(at Super-Kamiokande)

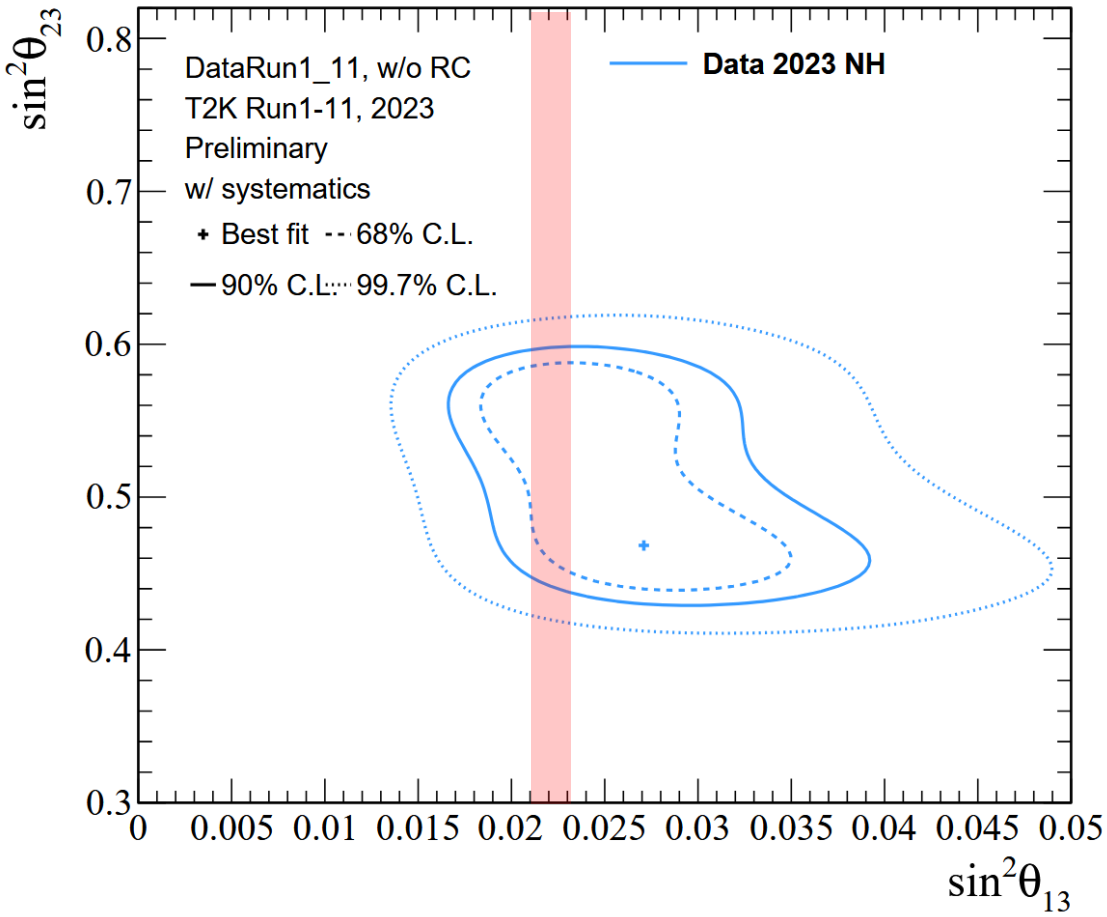
Error estimation rely on SK atmospherics
Then propagated to T2K samples

Correlations are introduced between SK and T2K detector systematics

Impact of Reactor Constraint

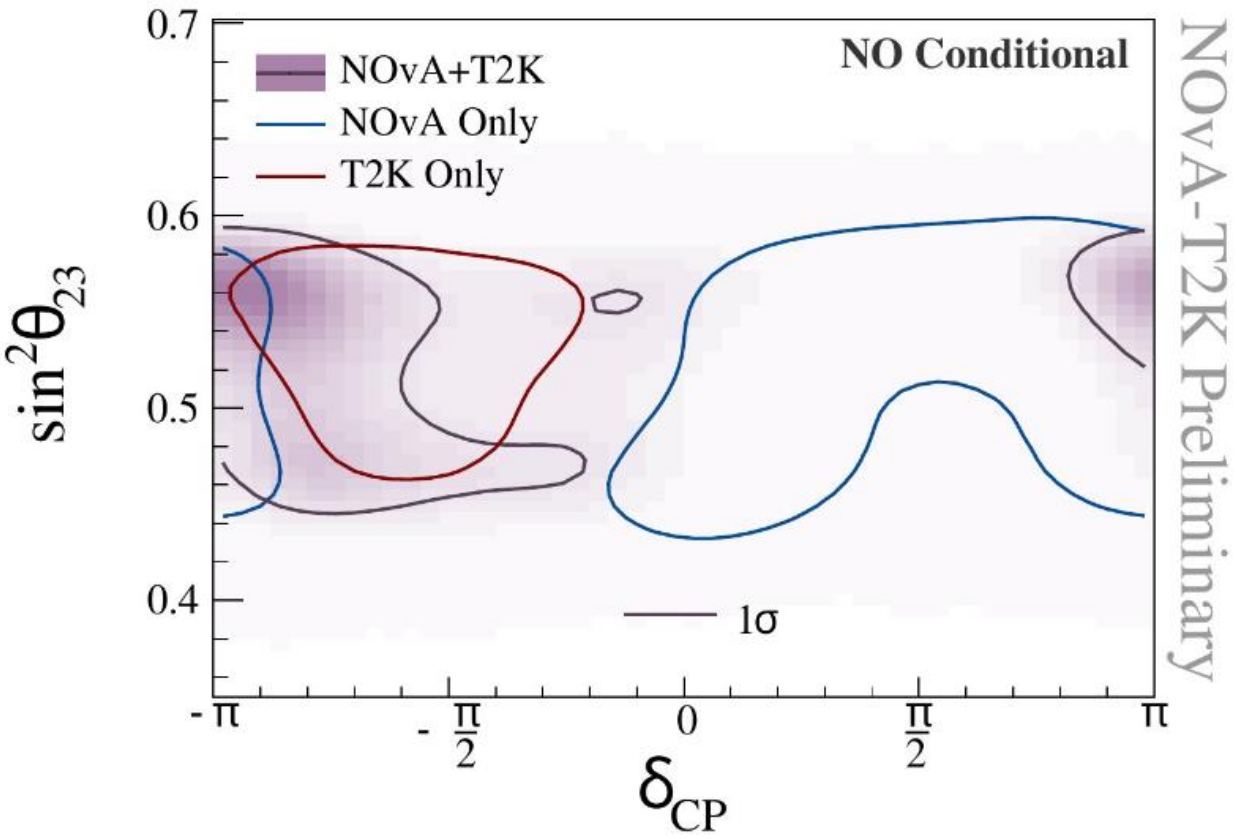


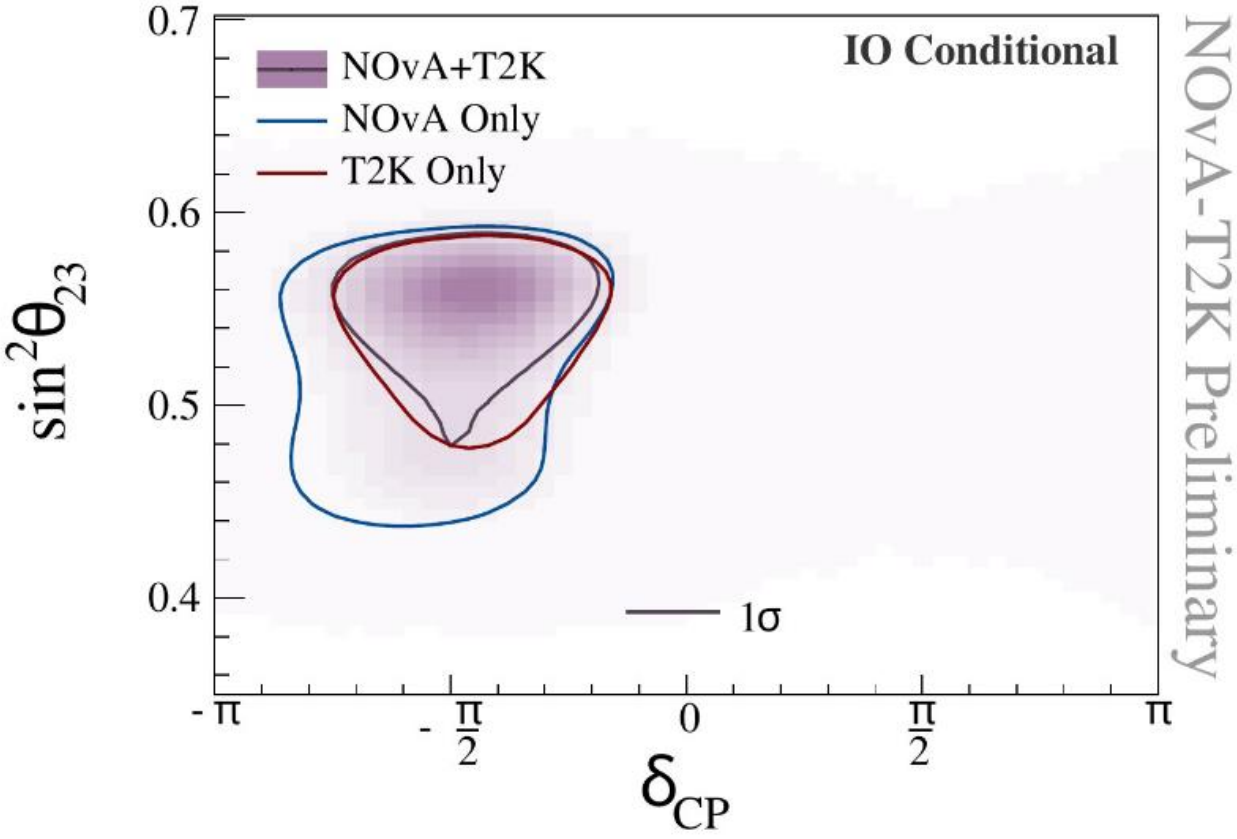
With Reactor Constraint



Without Reactor Constraint

NOvA+T2K Joint Fit results





Comparison with other experiments