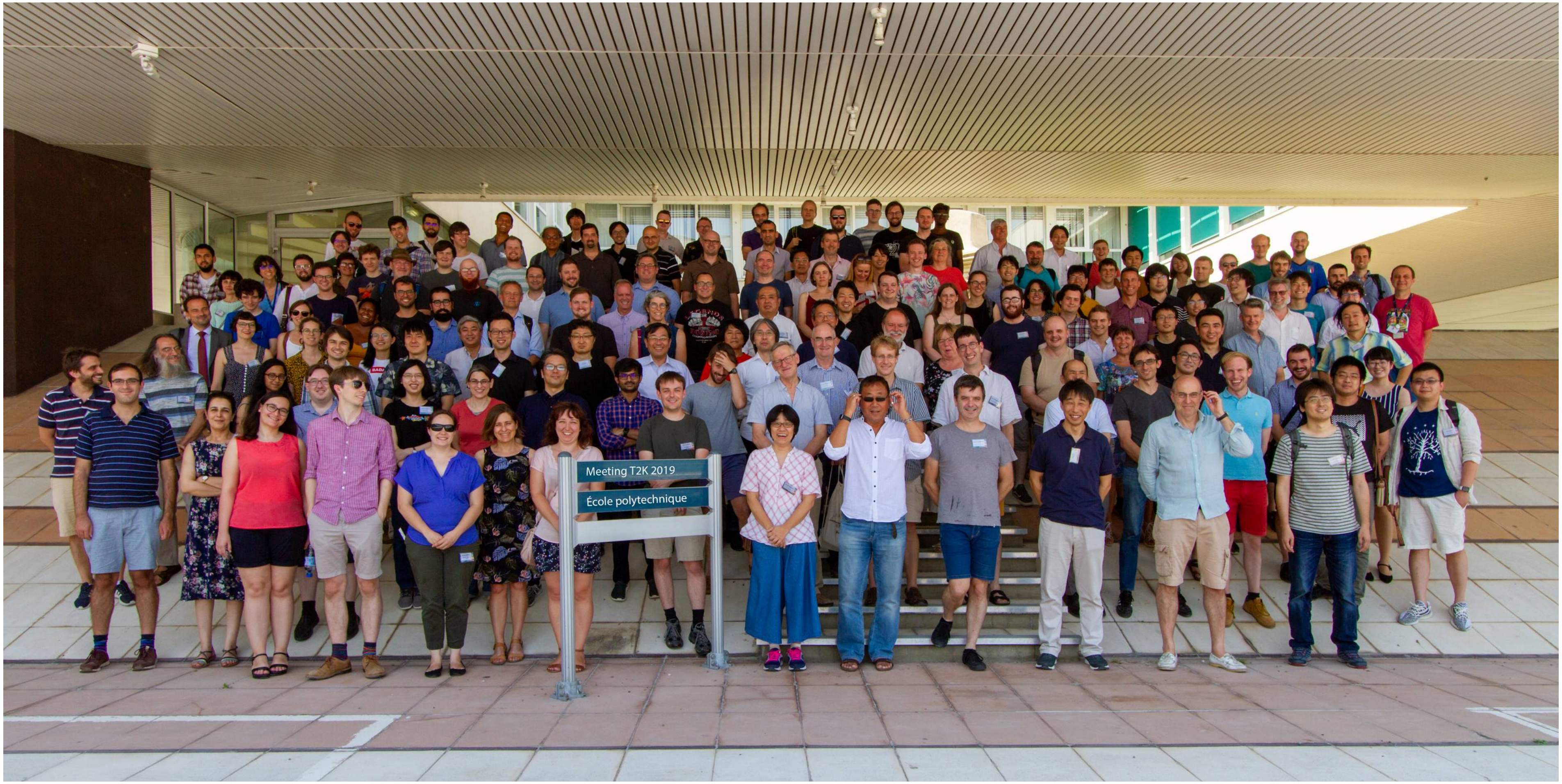
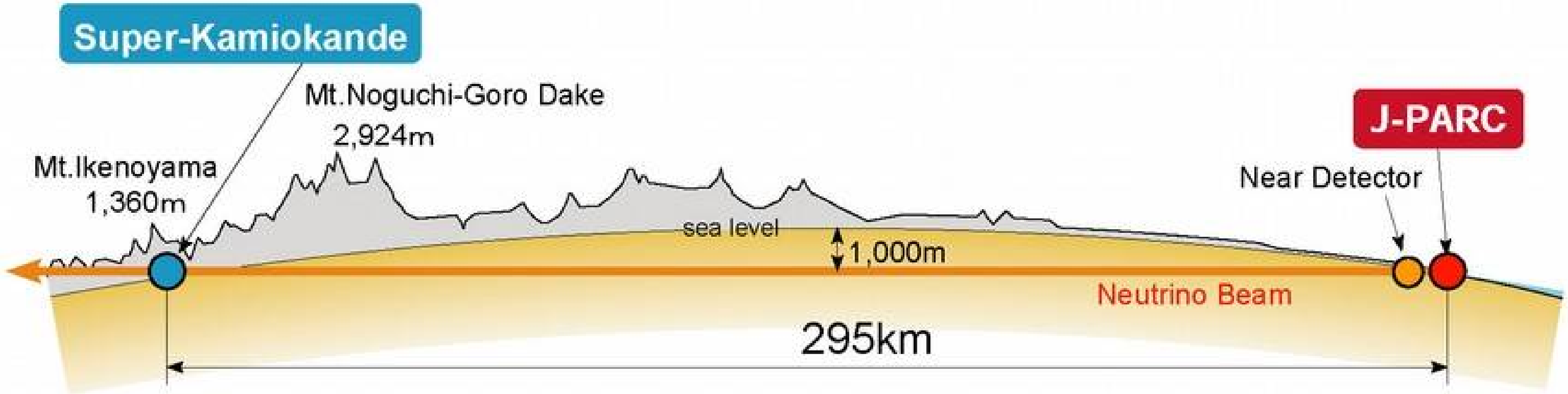
Results from the T2K experiment

KITP
28th March 2022
Callum Wilkinson

T2K collaboration

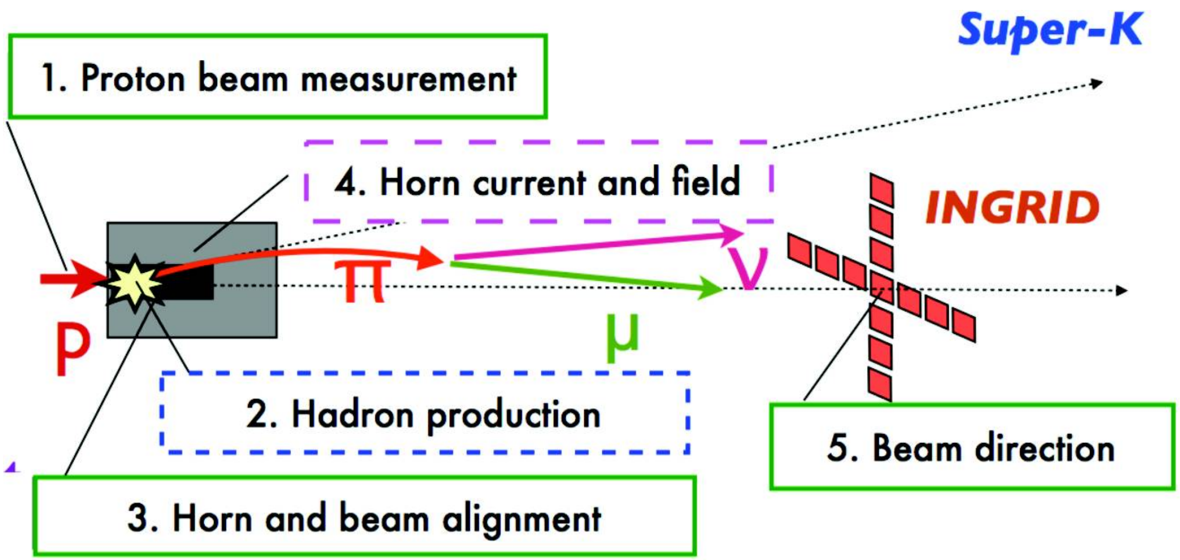
~500 members, 76 institutes, 13 countries (+CERN)

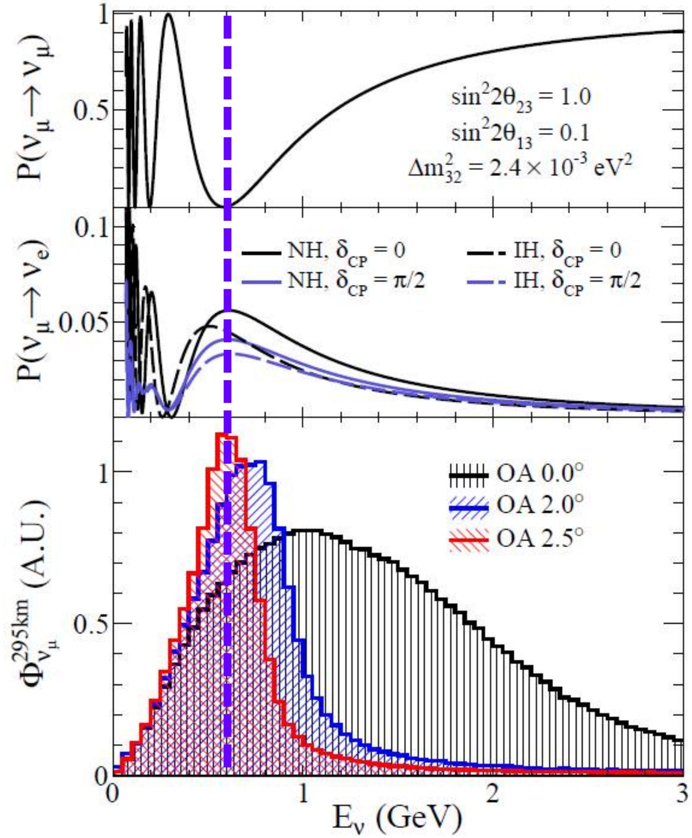


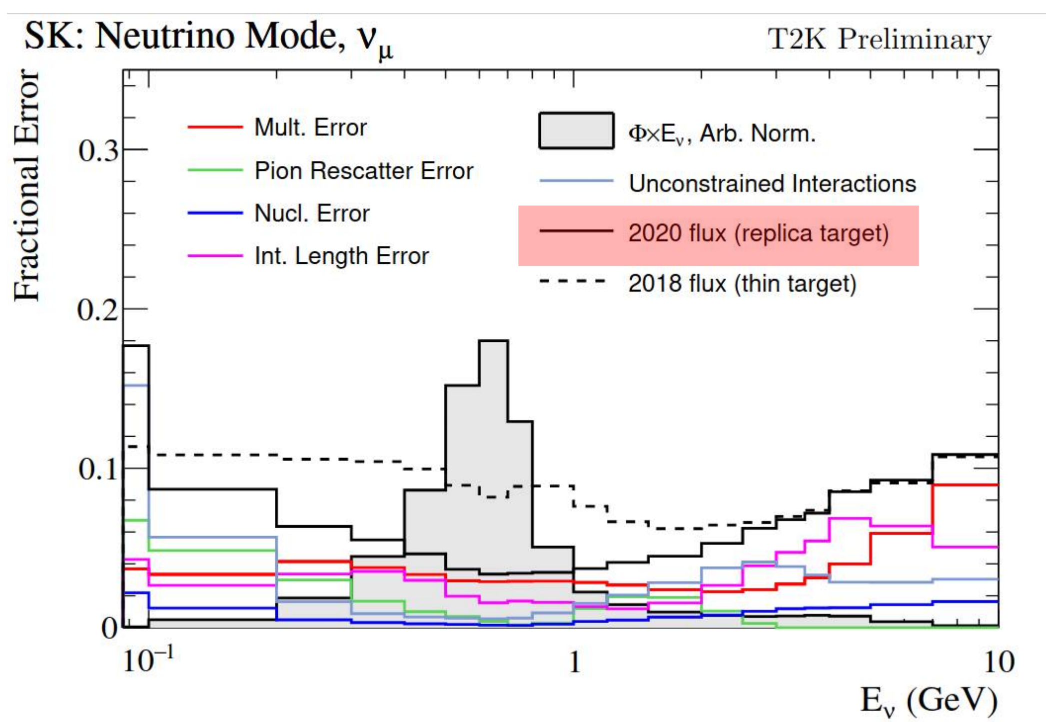


- Anatomy of the experiment
- Recent oscillation results
- Cross-section measurements
- Future plans

Neutrino beam

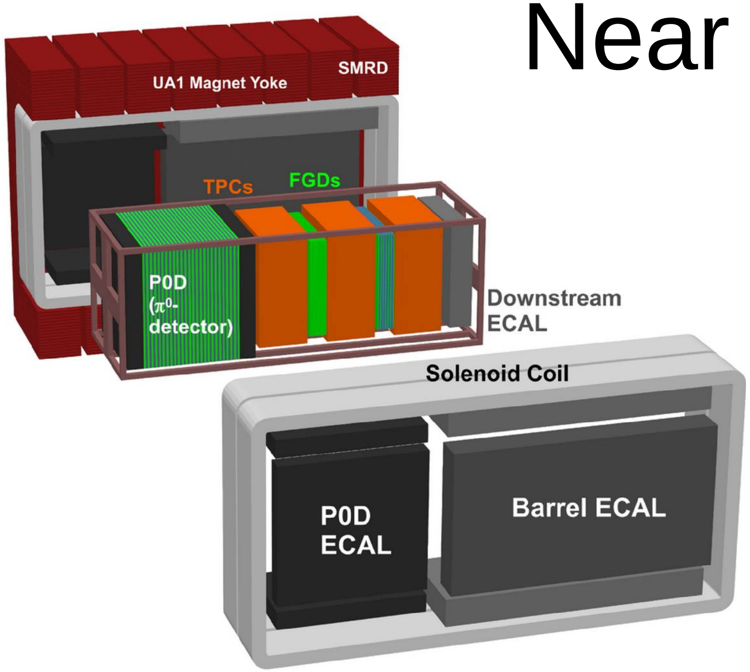




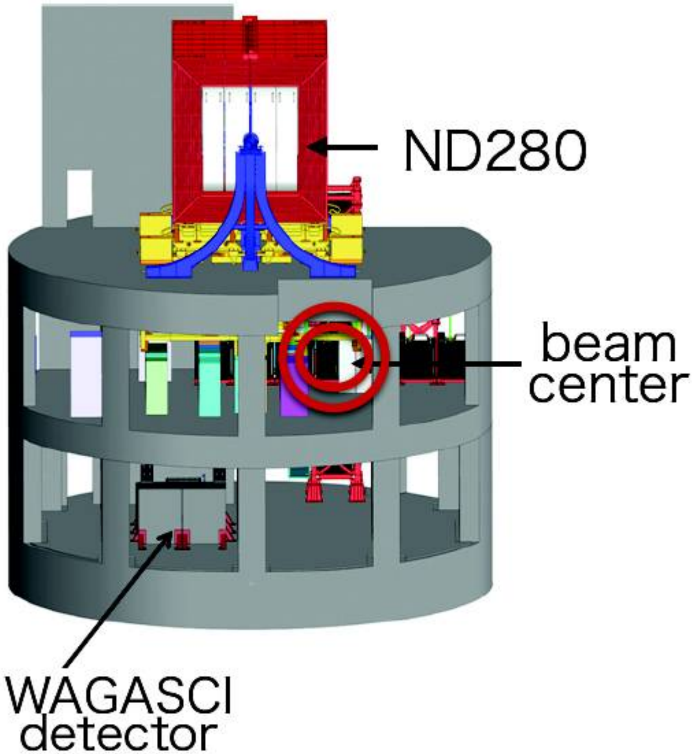


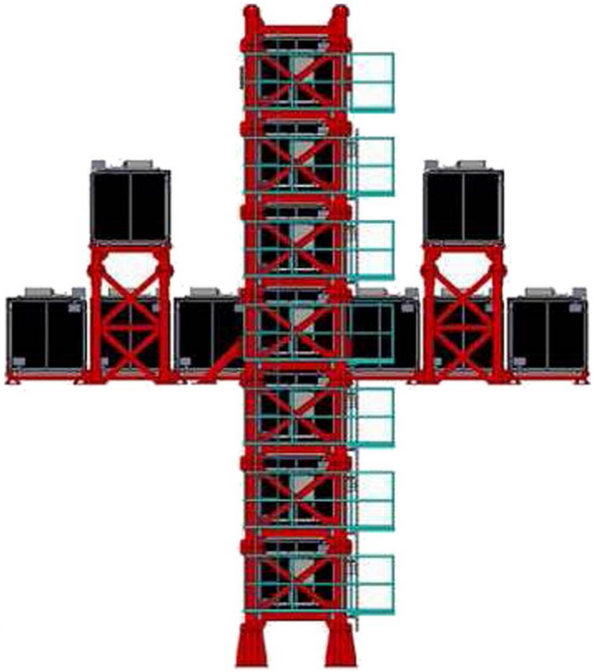
New in this analysis!

Near detector complex

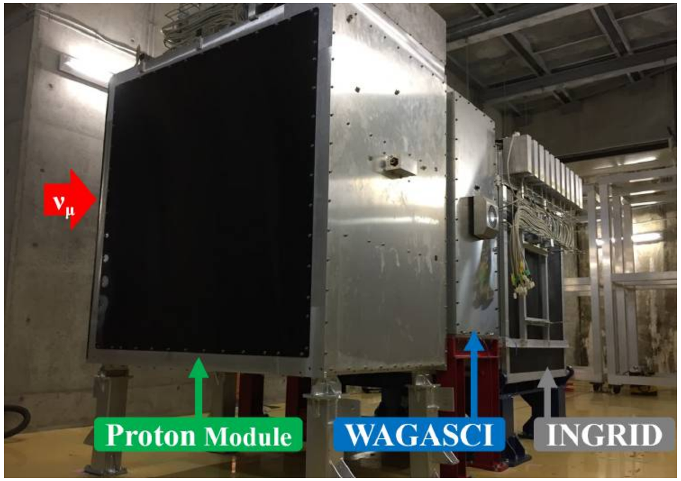


ND280 (2.5º)



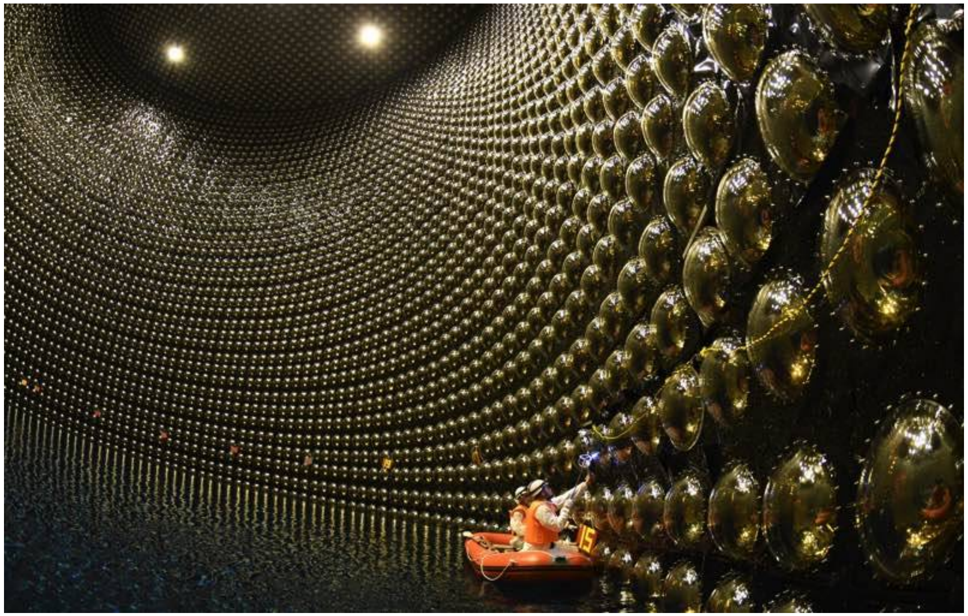


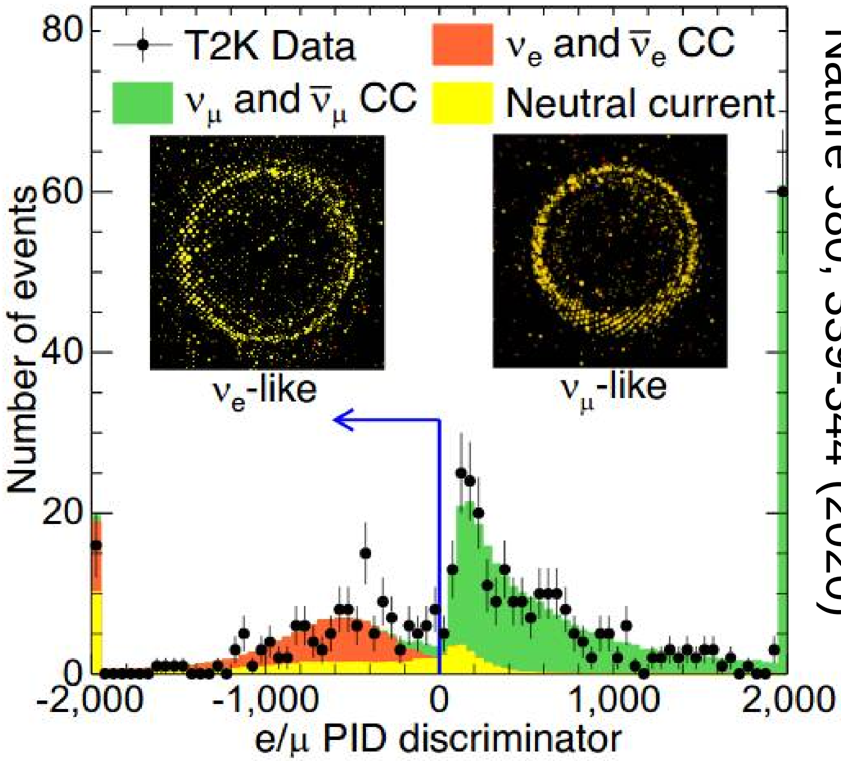
INGRID (0º)



WAGASCI (1.5º)

Far detector: Super-Kamiokande





Nature 580, 339-344 (2020)

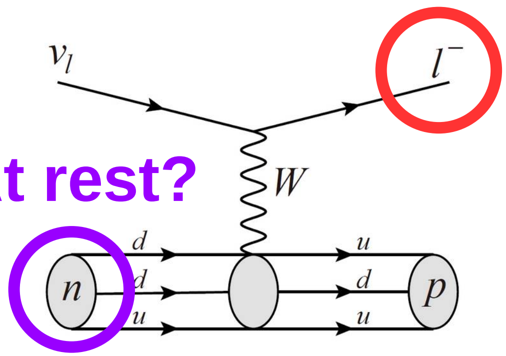
- 50 kt (27.2 kt FV) water-Cherenkov detector
- Very low background deep underground (2300 MWE)
- 40% photocathode coverage of PMTs in inner detector
- Detects particles through Cherenkov rings

SK E_ν reconstruction

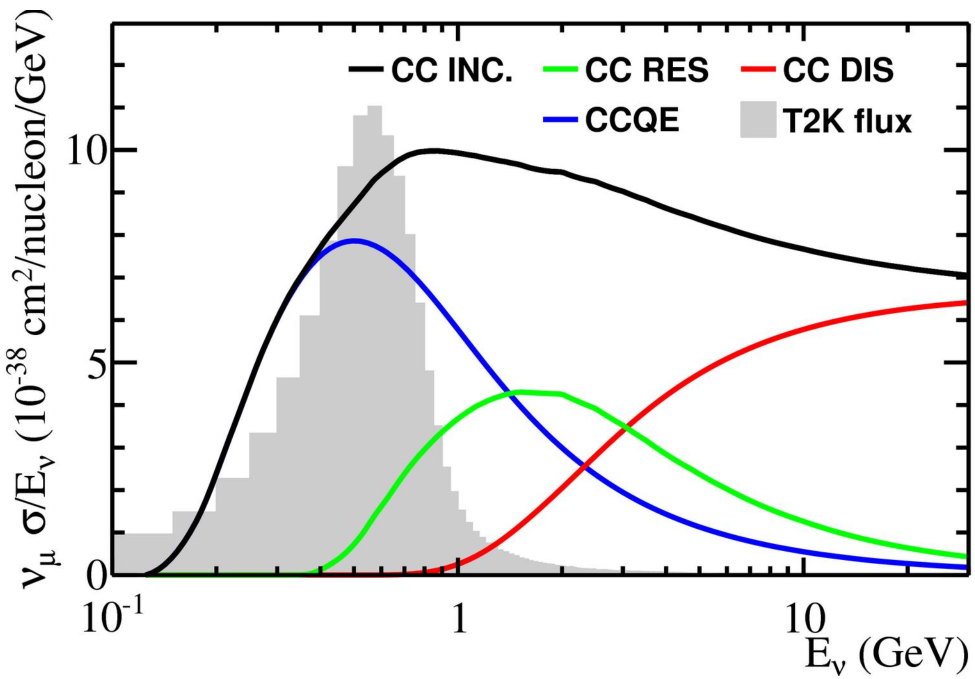
E_ν from **leptonic** variables:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

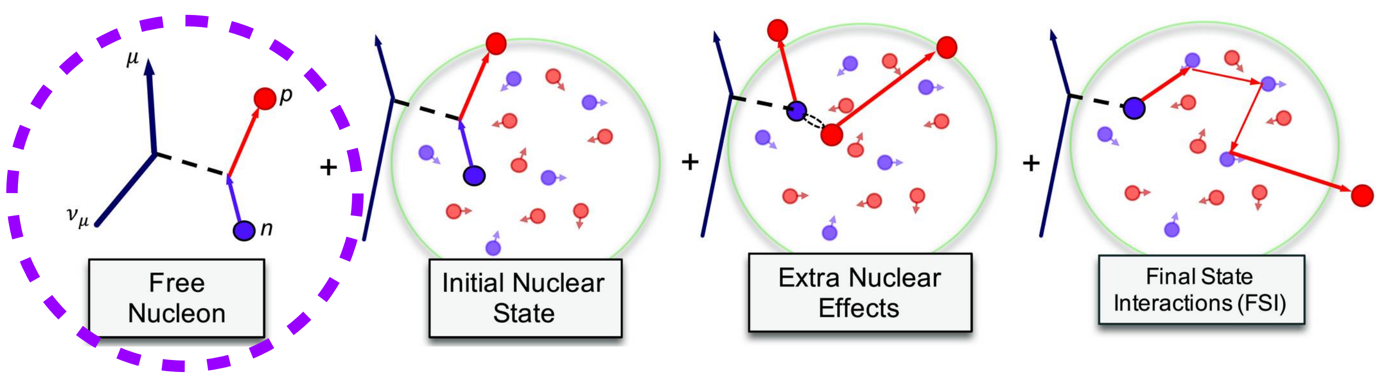
At rest?



Two-body?



CCQE



= CC0π

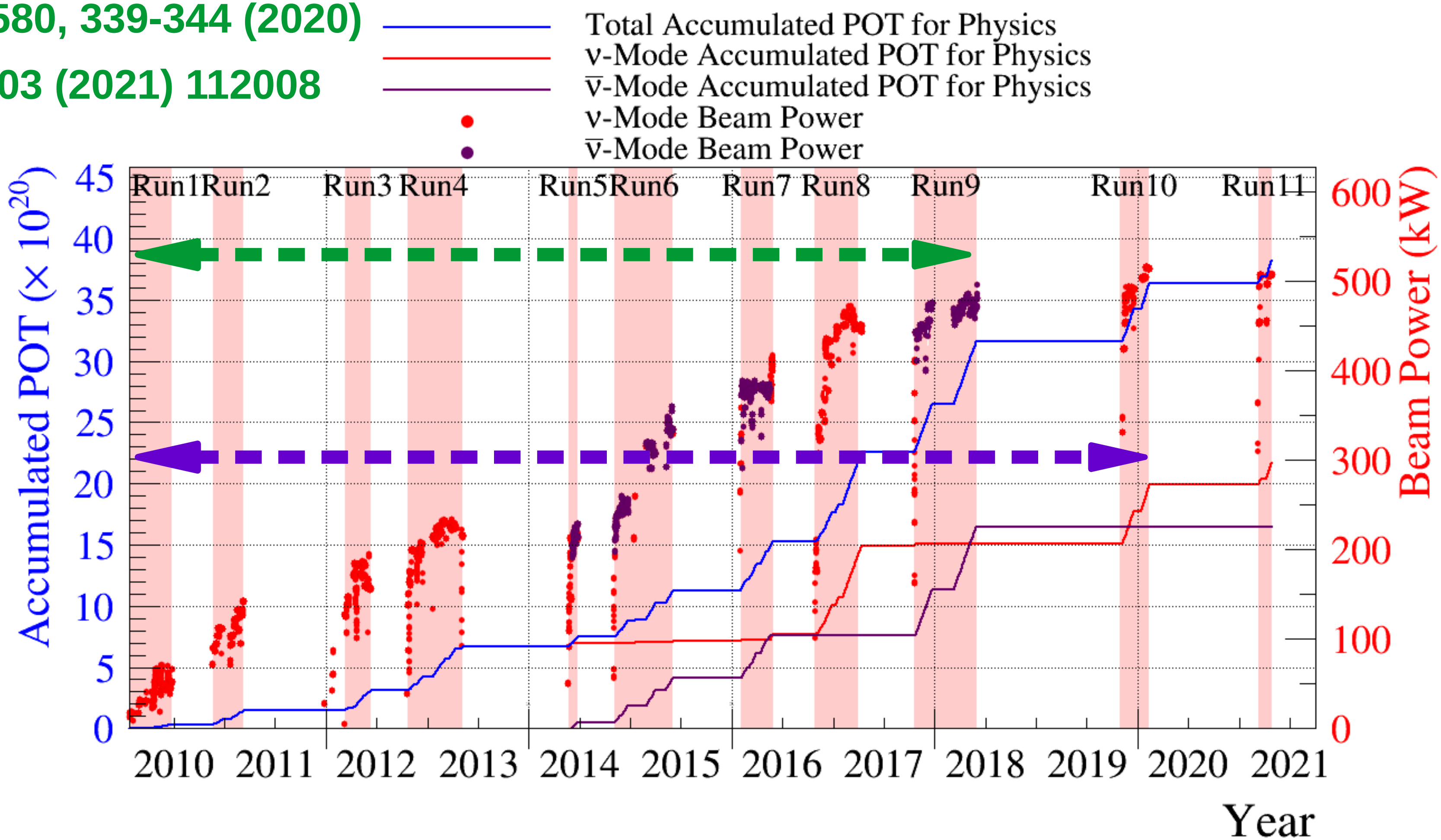
CC0π = 1p1h + 2p2h + 1π(+abs) + ...

Dataset

~3.6 x 10^{21} POT
ν:$\bar{\nu}$ ~6:5
+33% ν-mode POT

Nature 580, 339-344 (2020)

PRD103 (2021) 112008



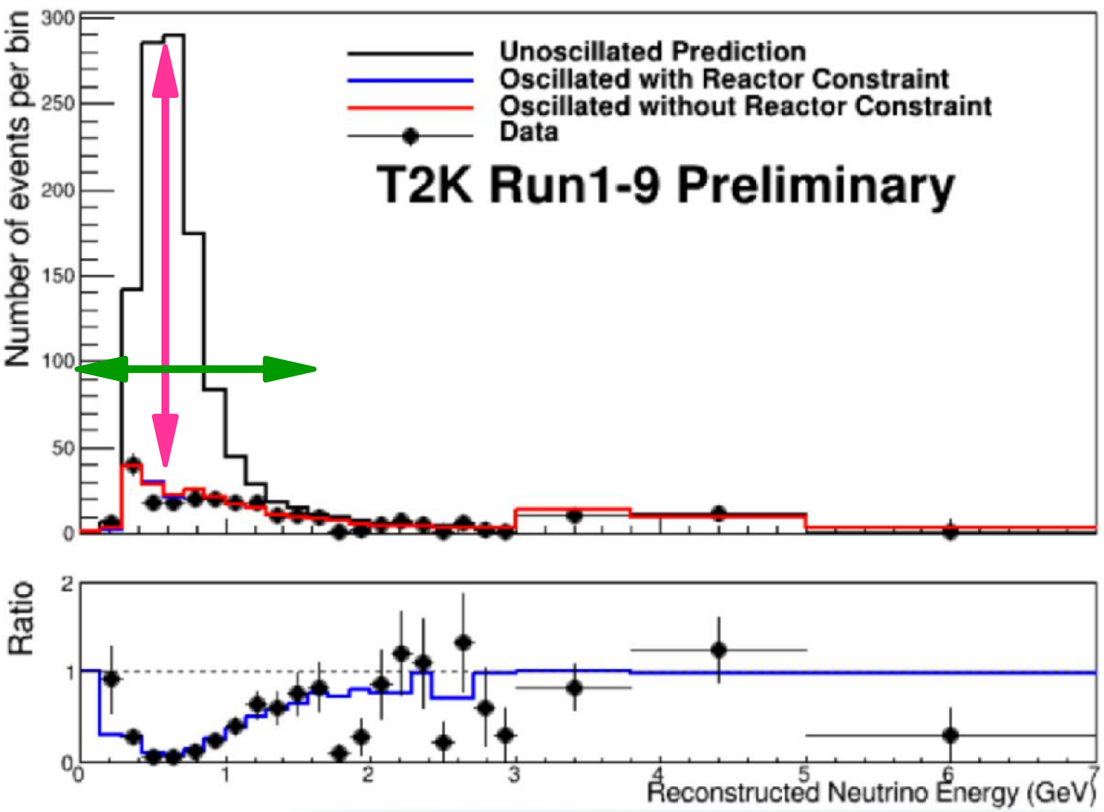
Oscillation analysis

Muon (anti)neutrino disappearance

Same probability for ν_μ and $\bar{\nu}_\mu$

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) = 1 - \underbrace{\left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)}_{}\underbrace{\sin^2\Phi_{32}}_{} + \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$



Infer parameters from the **depth** and **position** of the oscillation "dip"

Electron (anti)neutrino appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Phi_{31}$$

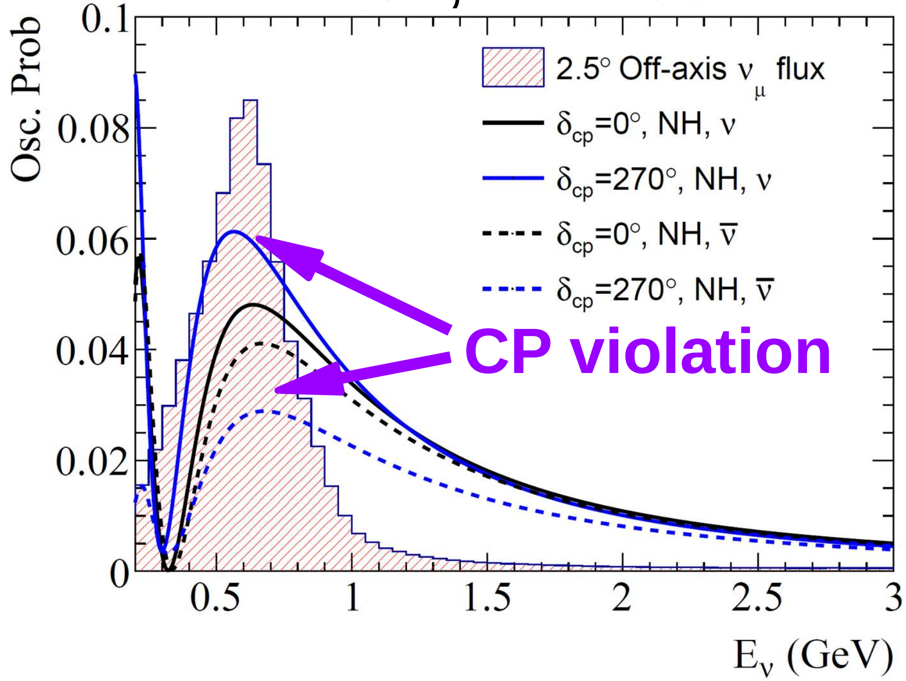
Sign change for ν_e and $\bar{\nu}_e$

$$\pm \sin\delta_{\mathrm{CP}} \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13}\sin\Phi_{21}\sin^2\Phi_{31}$$

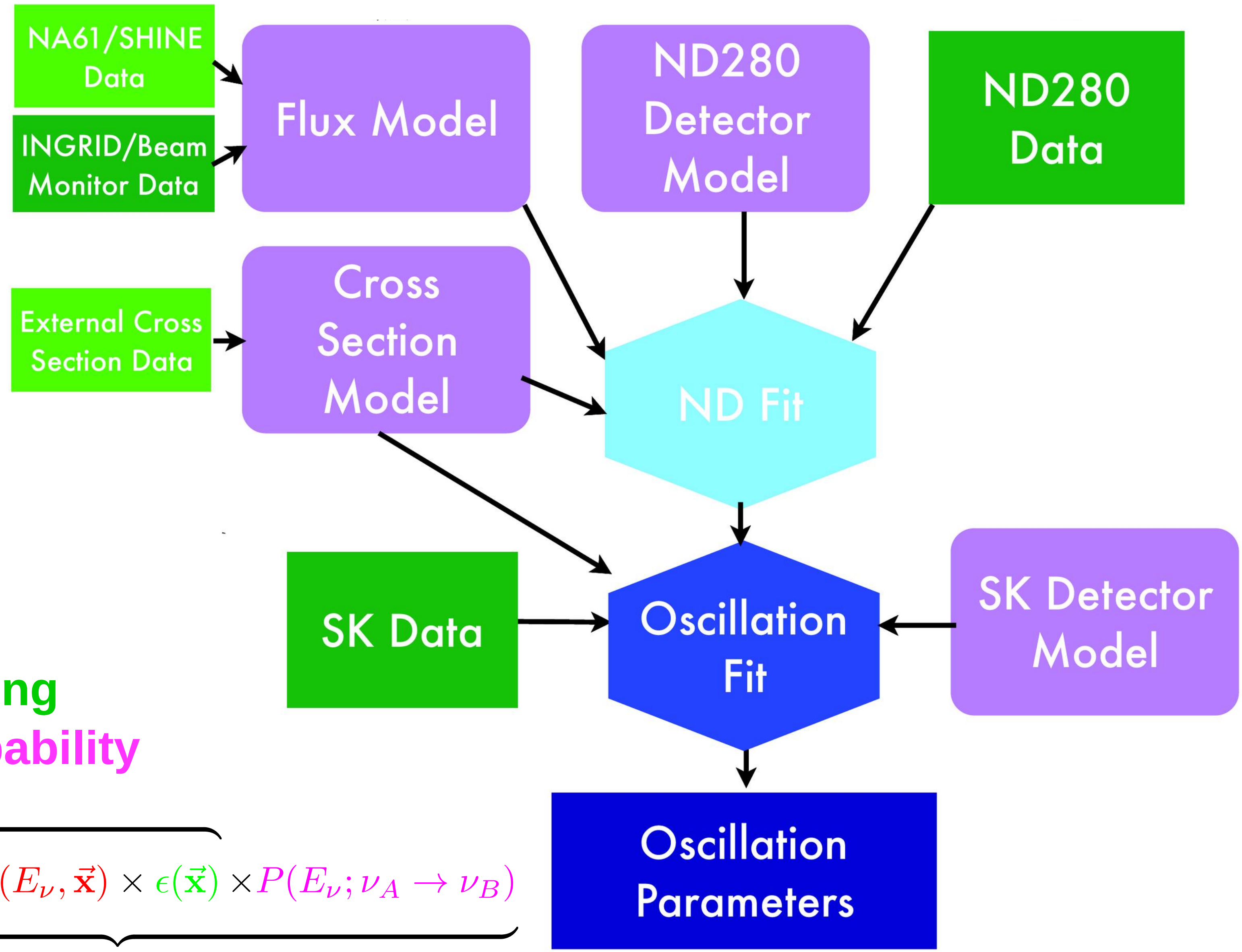
$$+ \dots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$

T2K flux, L = 295 km

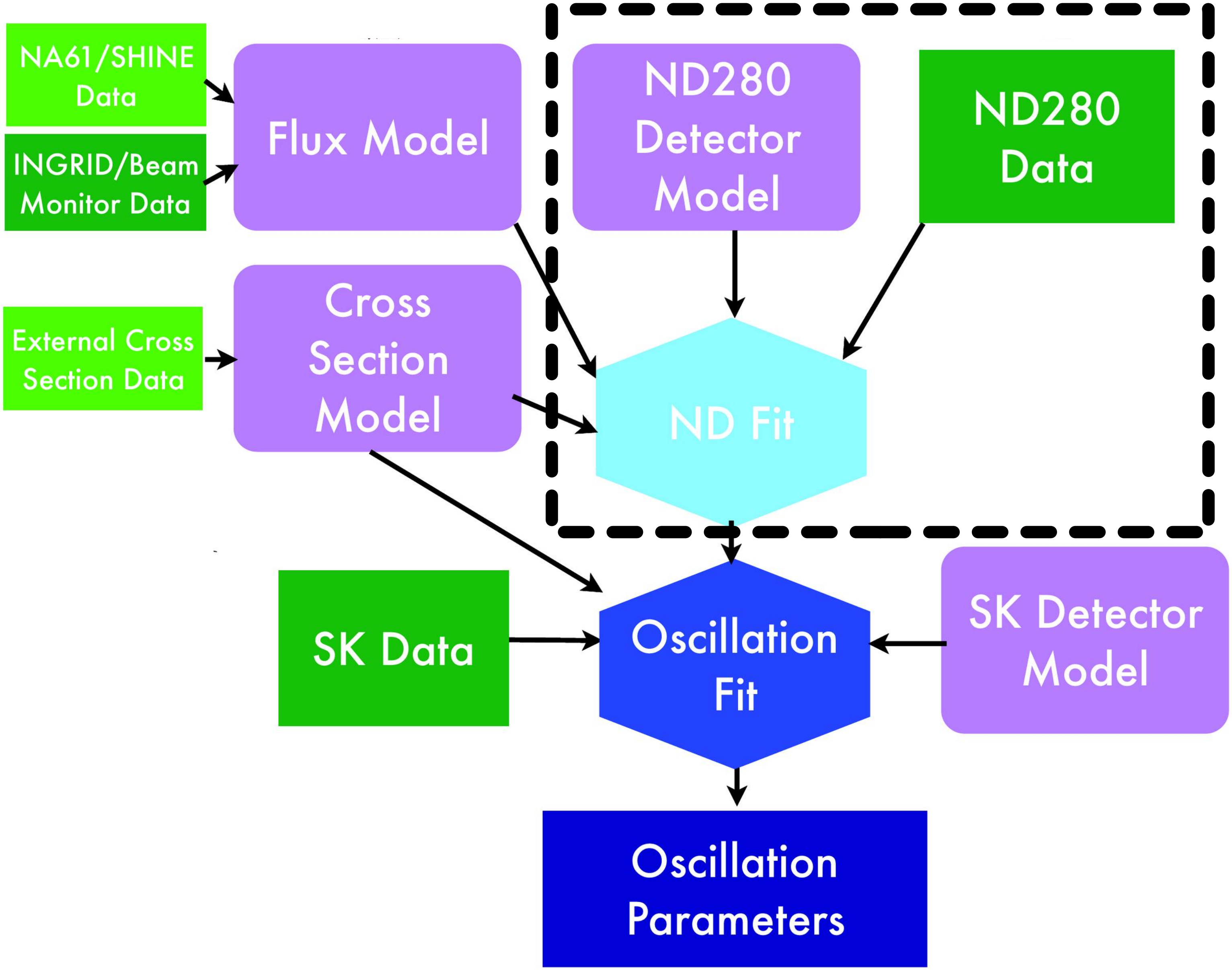


T2K analysis in one slide



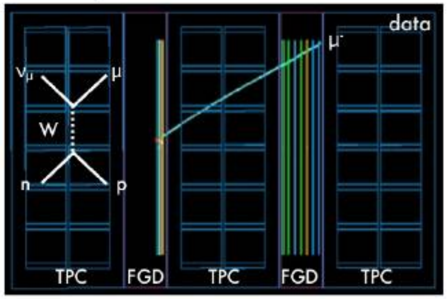
Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$

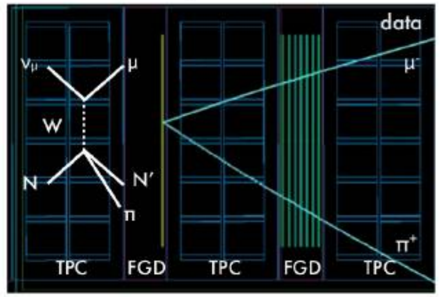

NA61/SHINE Data
INGRID/Beam Monitor Data
Flux Model
External Cross Section Data
Cross Section Model
ND280 Detector Model
ND280 Data
ND Fit
SK Data
Oscillation Fit
SK Detector Model
Oscillation Parameters

ND280 data

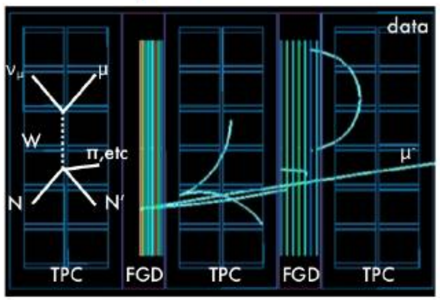
ν_μ CC0π



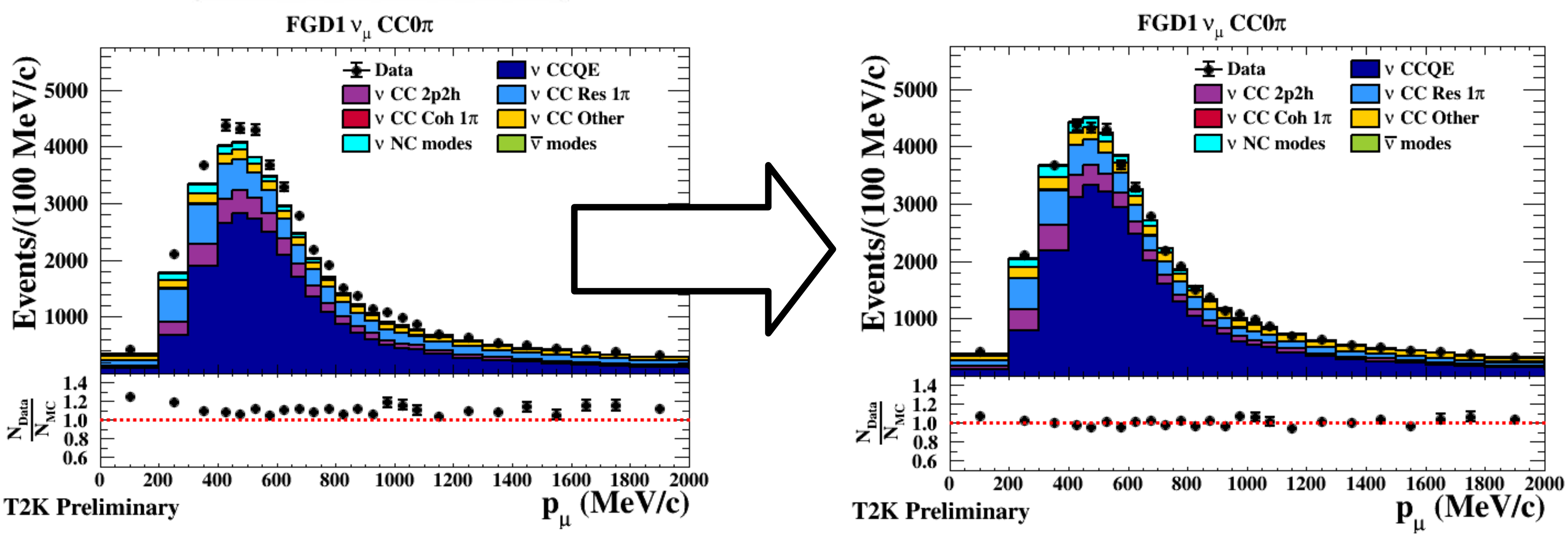
ν_μ CC1π^+



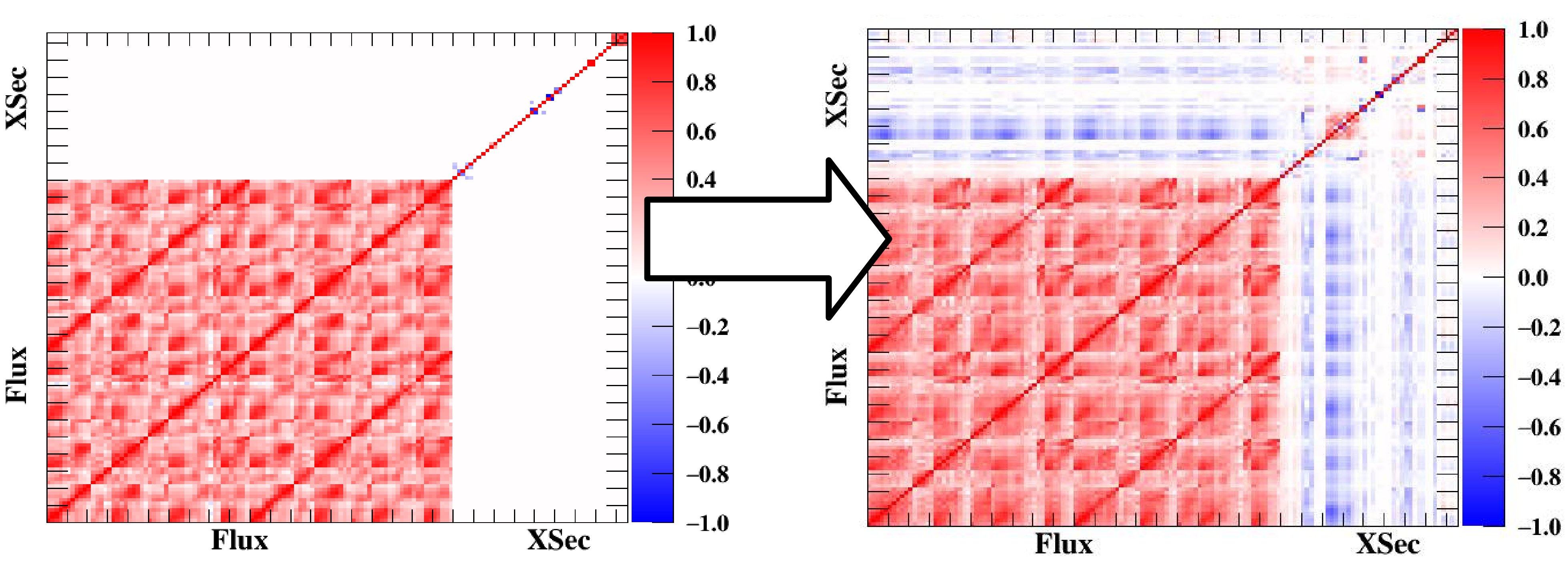
ν_μ CC other



- Subdivide data based on number of final state pions
- ν and $\bar{\nu}$-modes (split into μ^+/μ^-)
- Samples on plastic and water/plastic mixed targets
- Fit detector, XSEC and flux parameters

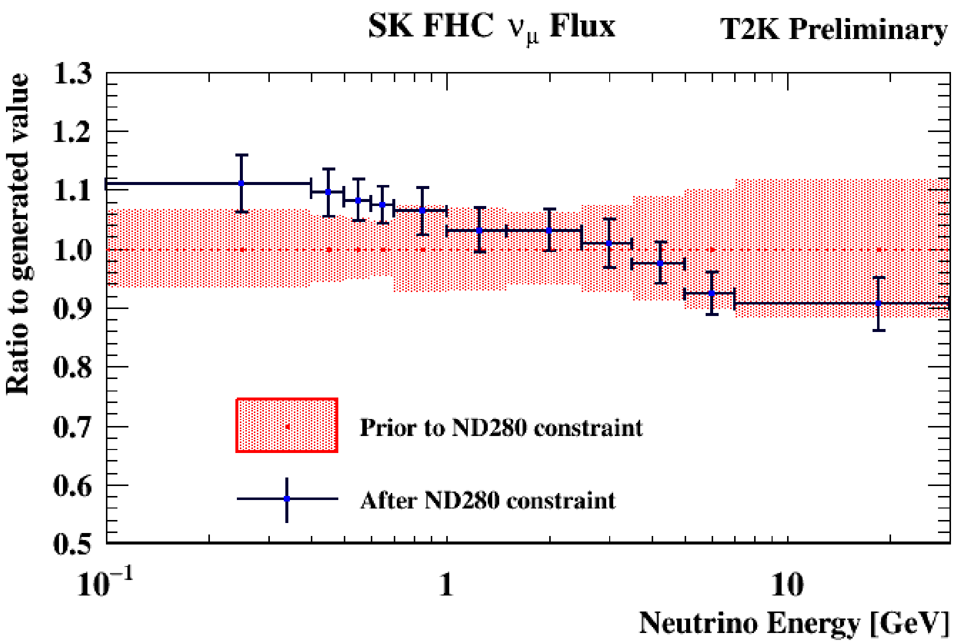


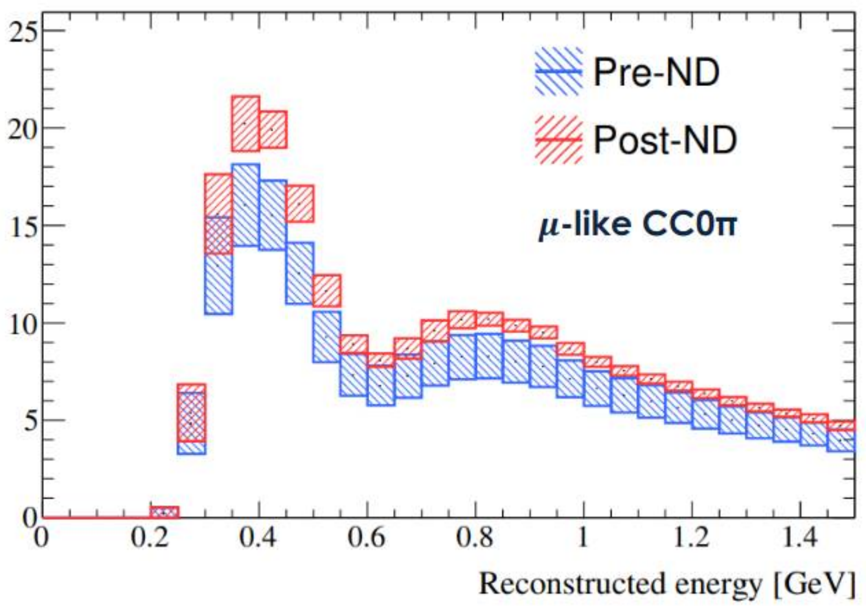
ND280 constraint



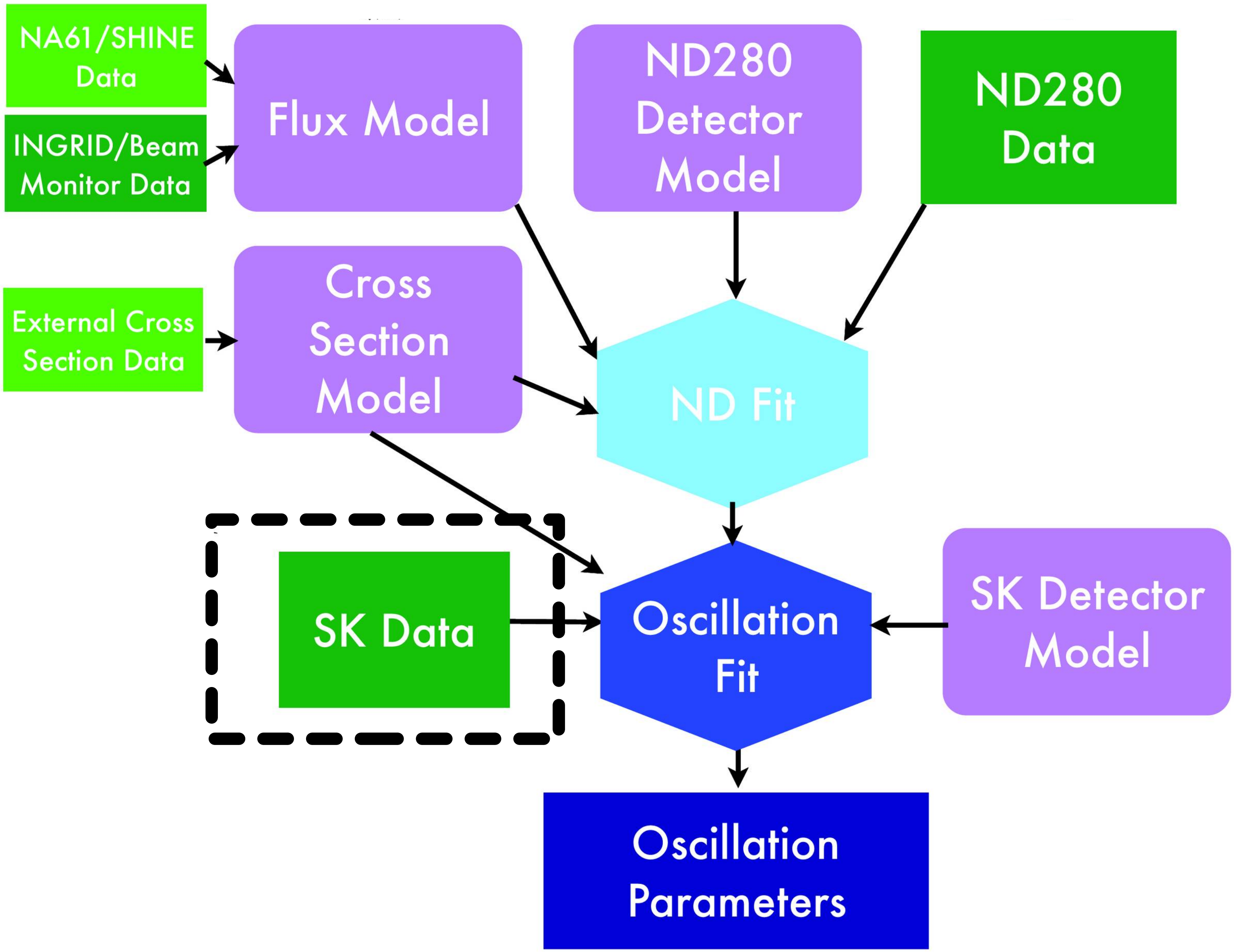
- Central values and uncertainties of systematics change as data updates model assumptions
- Strong *rate* constraint introduces anticorrelation between flux and XSEC

Constraining the SK prediction





- SK prediction is updated ND-constrained model
- Fitted flux parameters mostly agree within 1 sigma prior uncertainty → reassuring!
- Uncertainty on flux+XSEC reduced to be less than the SK detector uncertainty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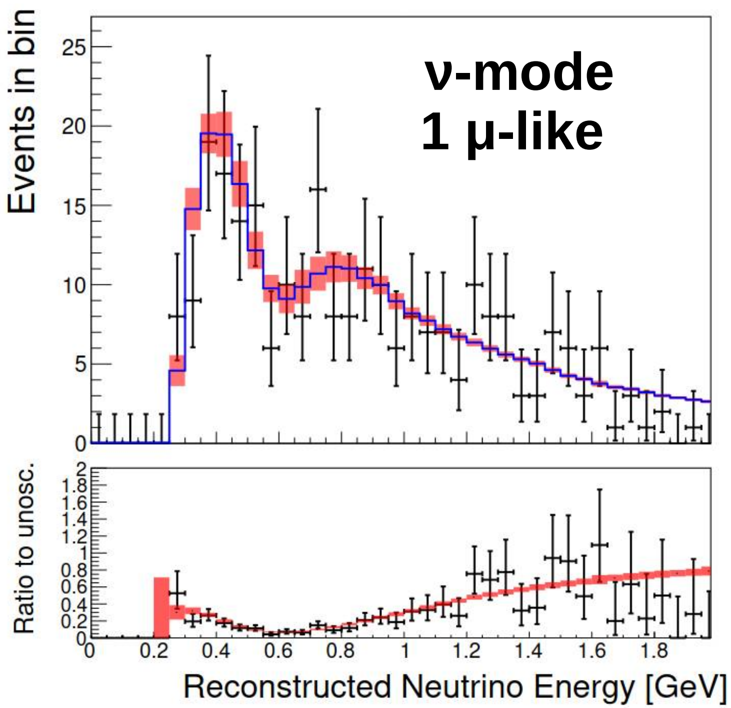
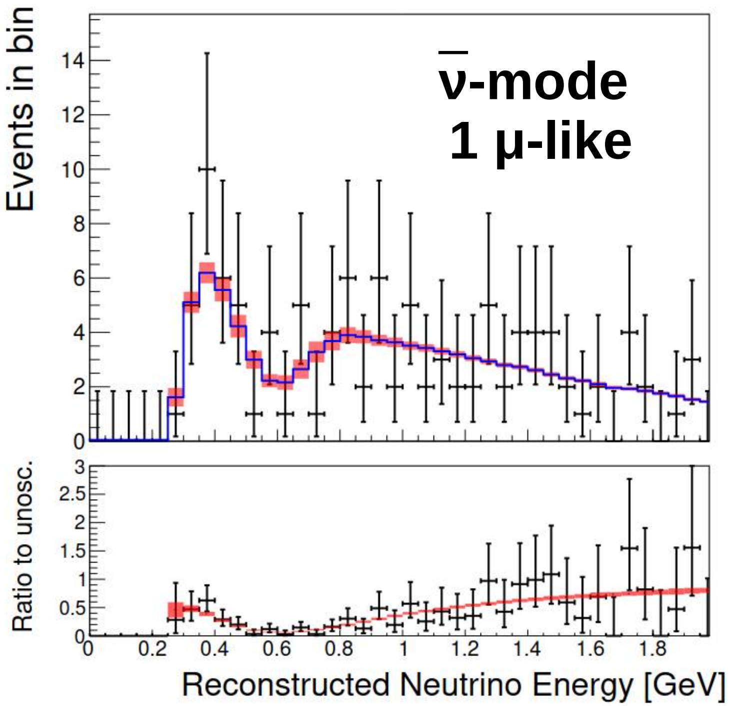
T2K dataset at SK





- 1 μ-like ring
- ≤ 1 decay electron
- All samples binned in E_{rec},θ_l

$$\nu_\mu(\bar{\nu}_\mu) + N \to \mu^-(\mu^+) + X$$

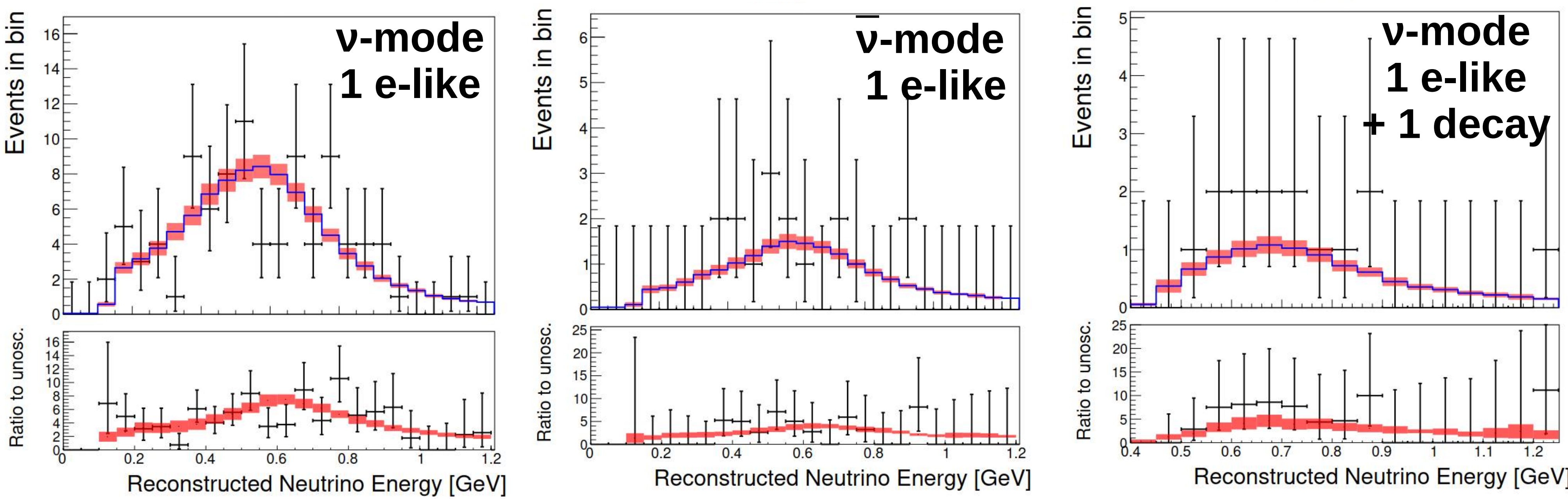
$$\downarrow$$

$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

◌ = *detected particles*

$$E_{\mathrm{rec}} = \frac{m_p^2 - m_n'^2 - m_{\mathrm{lep}}^2 + 2m_n' E_{\mathrm{lep}}}{2(m_n' - E_{\mathrm{lep}} + p_{\mathrm{lep}} \cos\theta_{\mathrm{lep}})}$$

T2K dataset at SK



- $\nu/\bar{\nu}$-mode: 1 e-like ring, 0 decay electrons

$$\nu_e(\bar{\nu}_e)+N\to e^-(e^+)+X$$

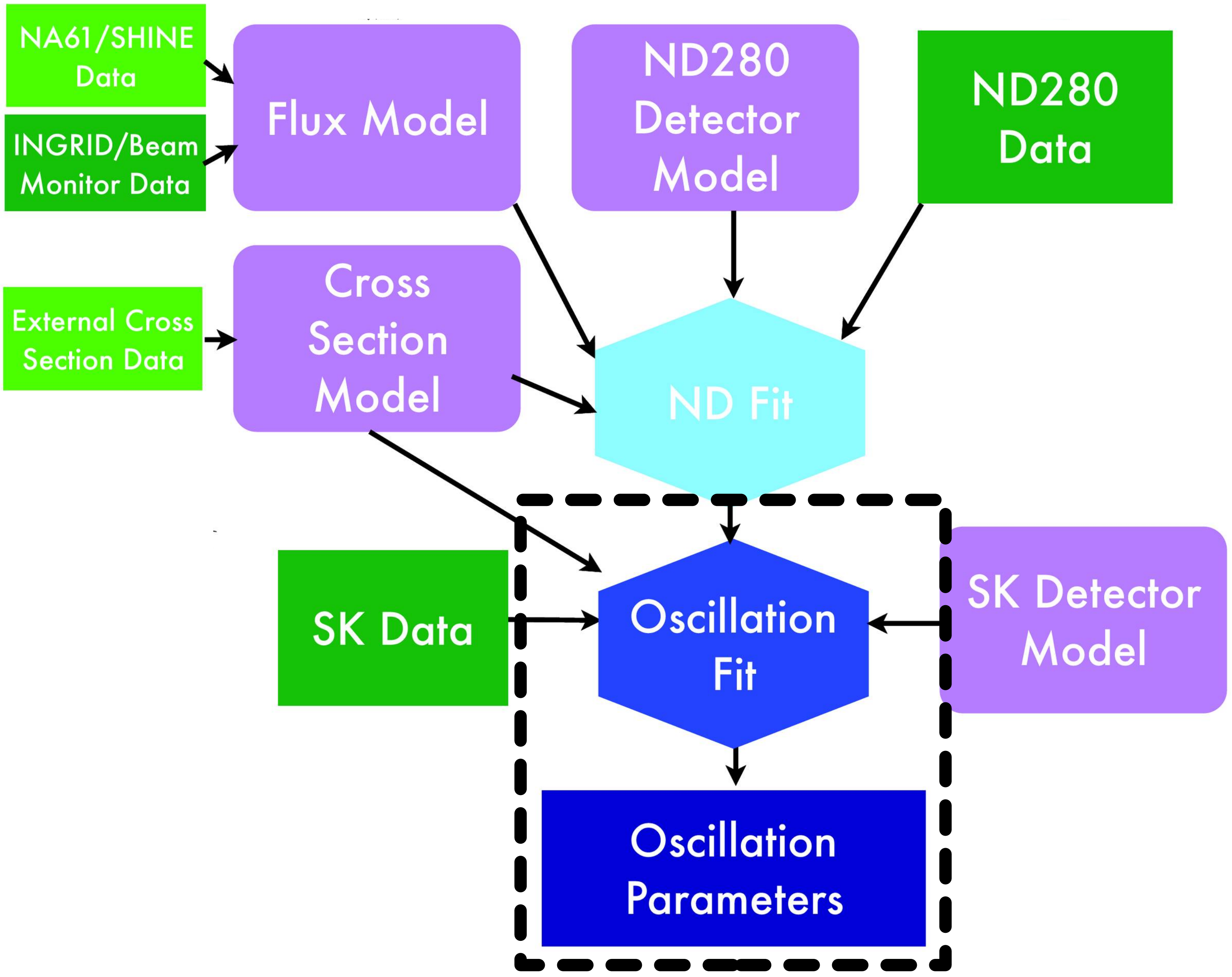
- ν-mode: 1 e-like ring, 1 decay electron

$$\nu_e+N\to e^-+\pi^++X$$
$$\downarrow$$
$$\mu^++\nu_\mu$$
$$\downarrow$$
$$e^++\nu_e+\bar{\nu}_\mu$$

= *detected particles*

- $E^{\Delta}_{\mathrm{rec}}$ used for 1 e-like + 1 decay electron sample

$$E^{\Delta}_{\mathrm{rec}}=\frac{m_{\Delta}^2-m_n'^2-m_e^2+2m_n'E_e}{2(m_n'-E_e+p_e\cos\theta_e)}$$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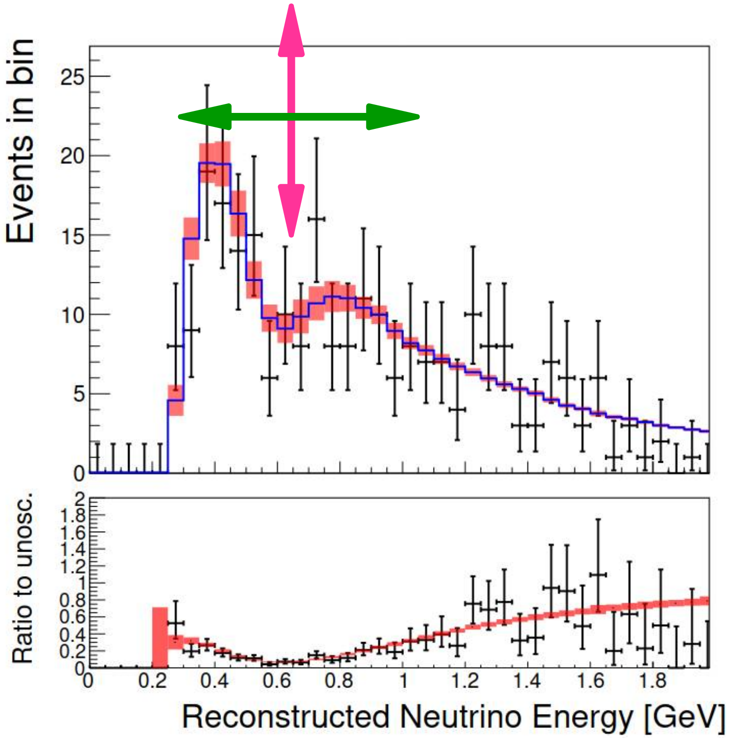
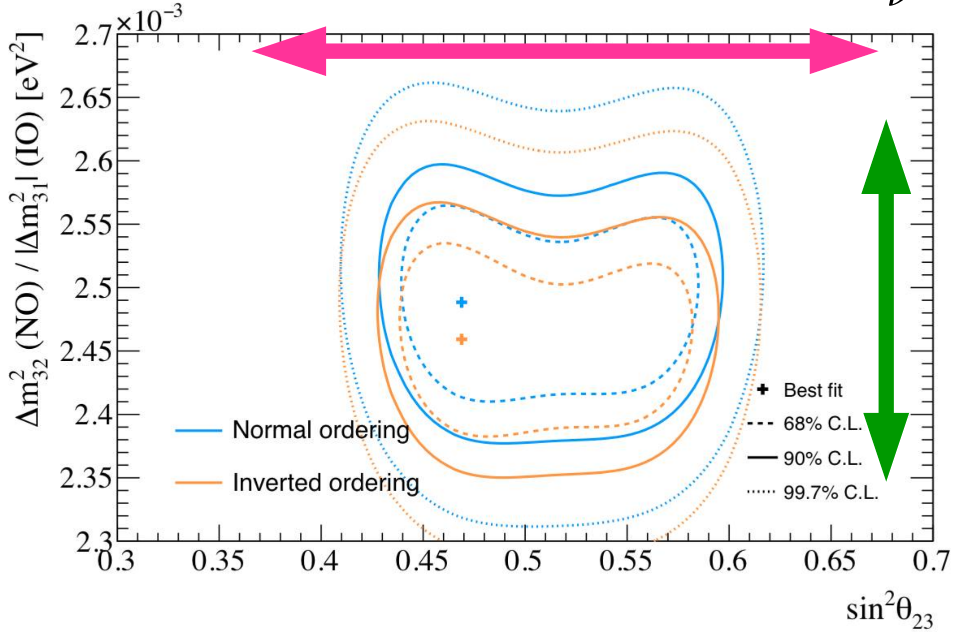
T2K ν_μ-disappearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) = 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Phi_{32} + \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji}L}{E_\nu}$$





- Fit normal and inverted hierarchies separately
- *$\sin^2\theta_{23}$ by convention* (leading order appearance probability)

T2K ν_e-appearance

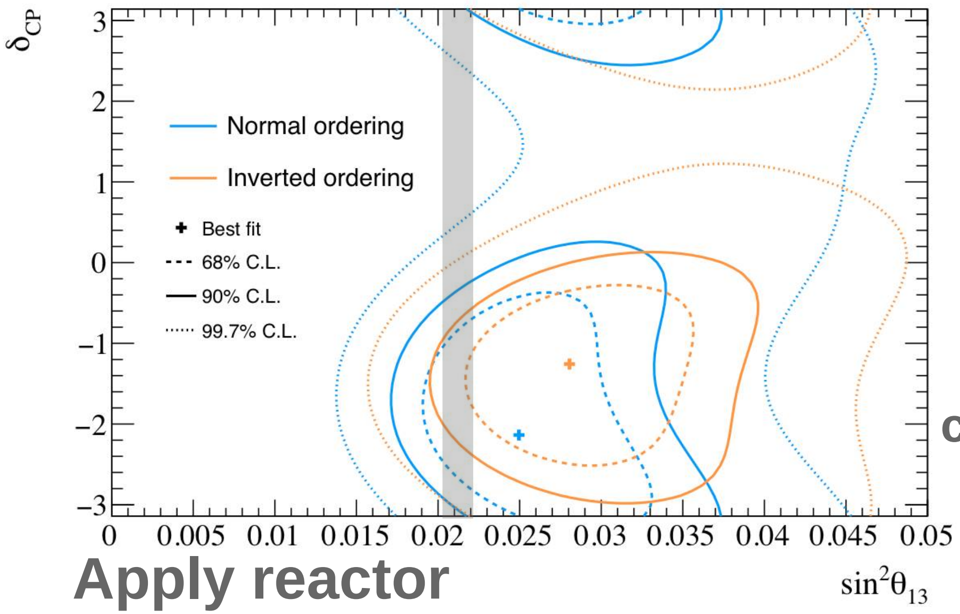
- Best fit $\sin^2\theta_{13}$ consistent with **PDG value**:

  T2K: $\sin^2\theta_{13} = 0.028^{+0.0028}_{-0.0065}$

  PDG: $\sin^2\theta_{13} = 0.0212 \pm 0.0008$

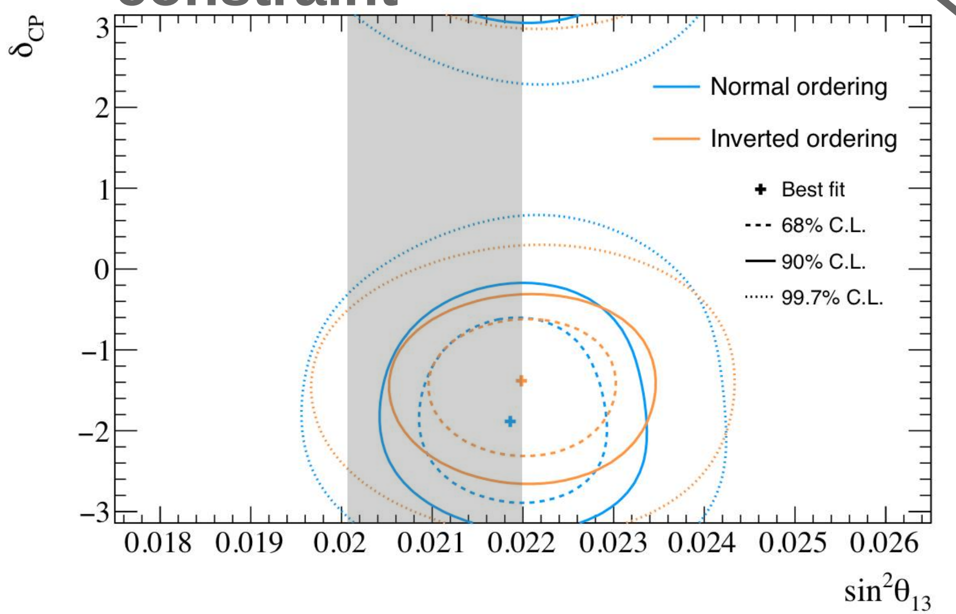
- Closed 90% contours with and without reactor constraint on θ_{13}

- Preference for δ_{CP} ~ $-\pi/2$

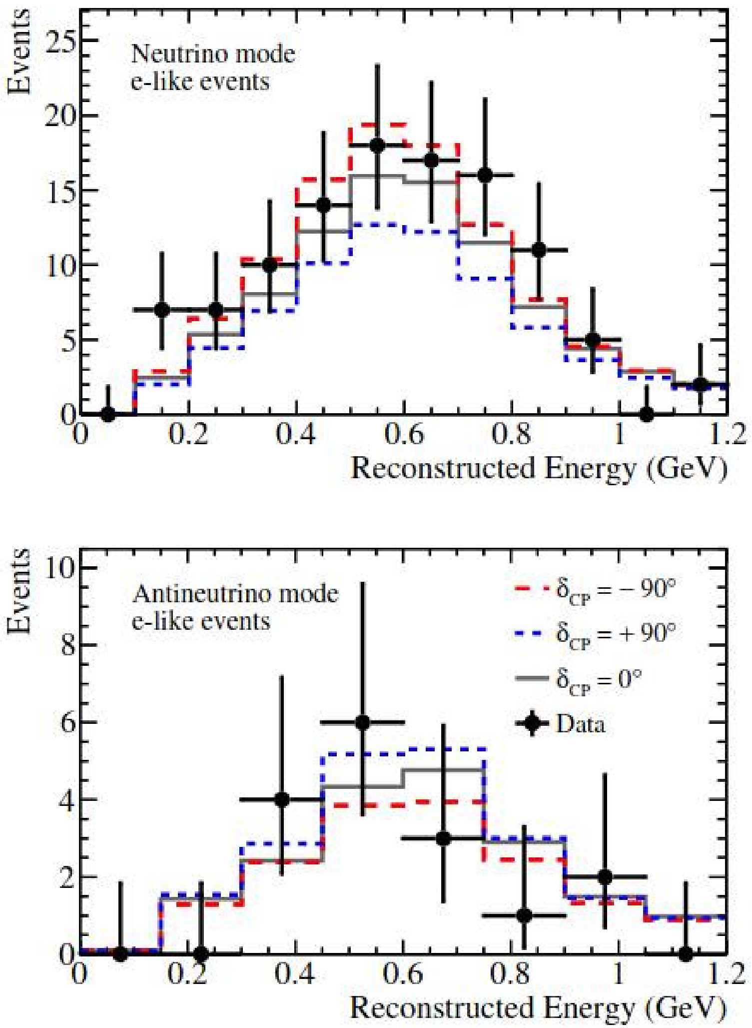


Apply reactor constraint

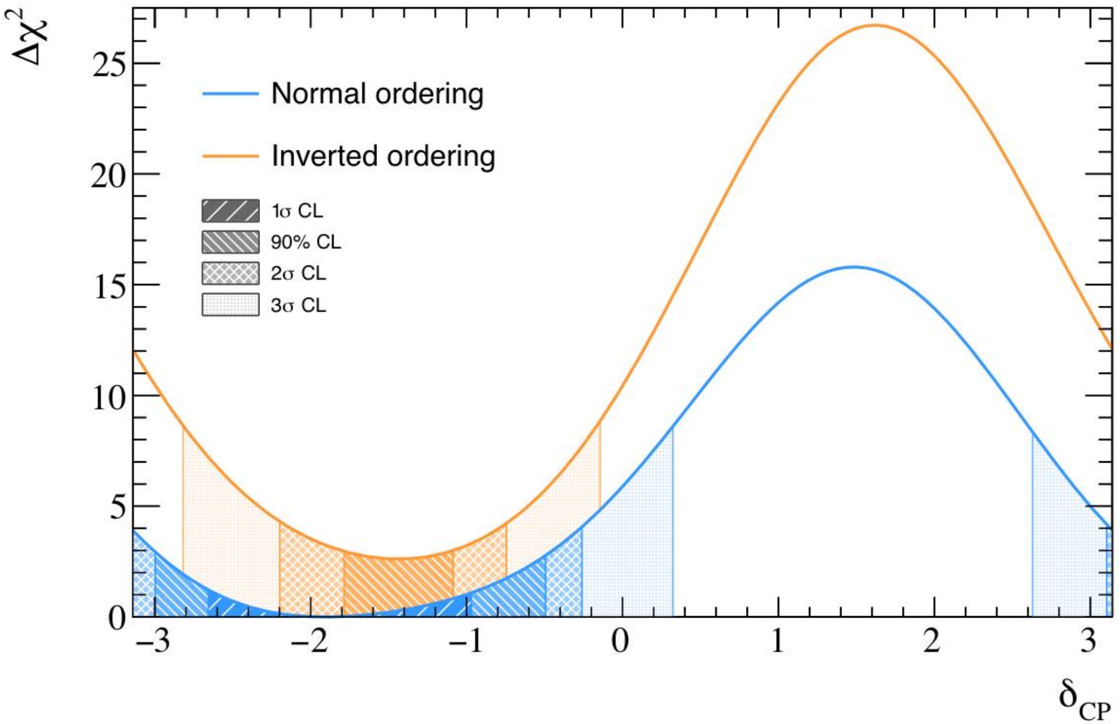
Scale change



T2K ν_e-appearance



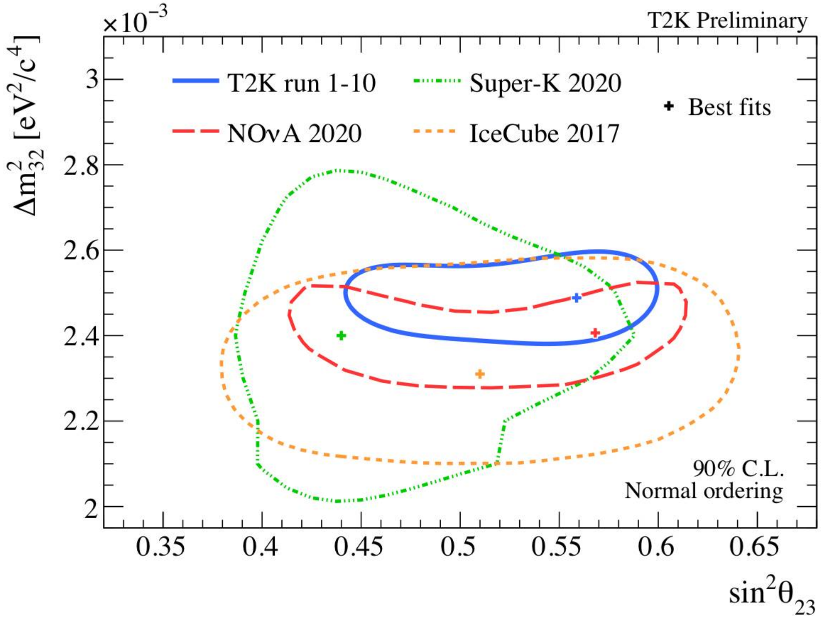
FC-corrected



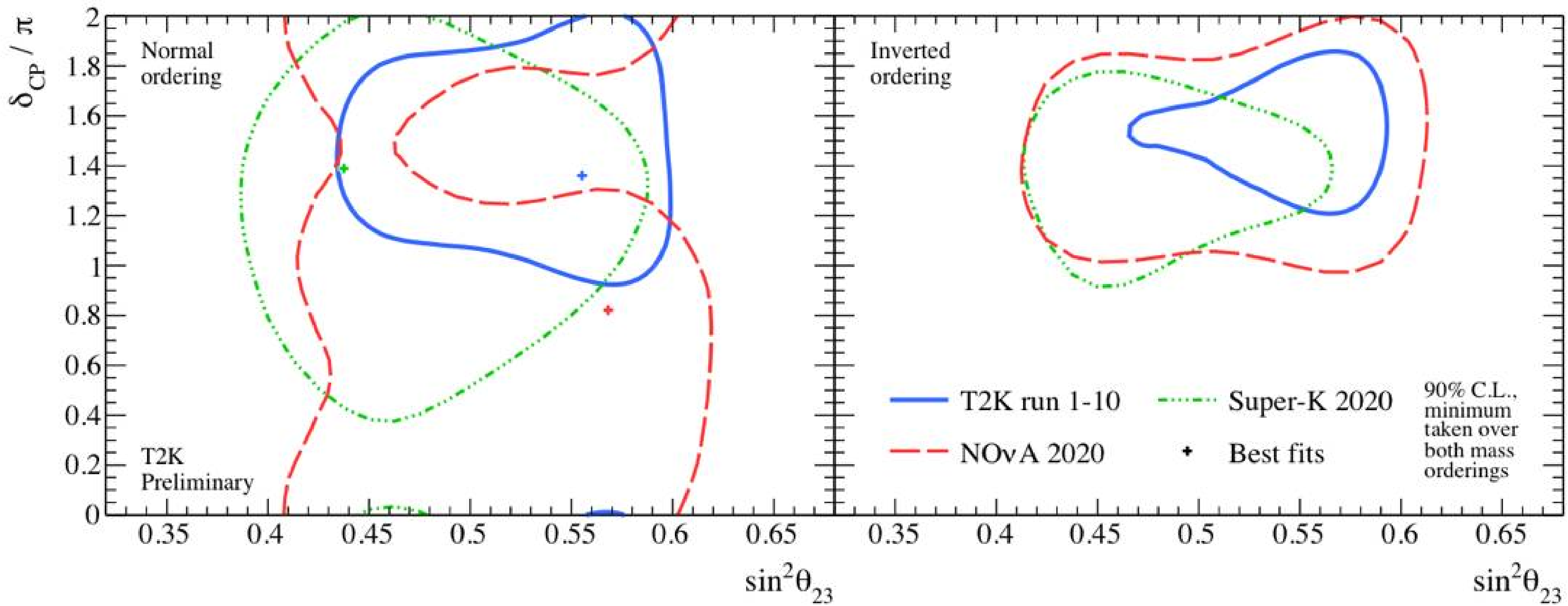
δ_{CP} = [0, ±π] excluded at ~2σ

Mild preference for normal ordering

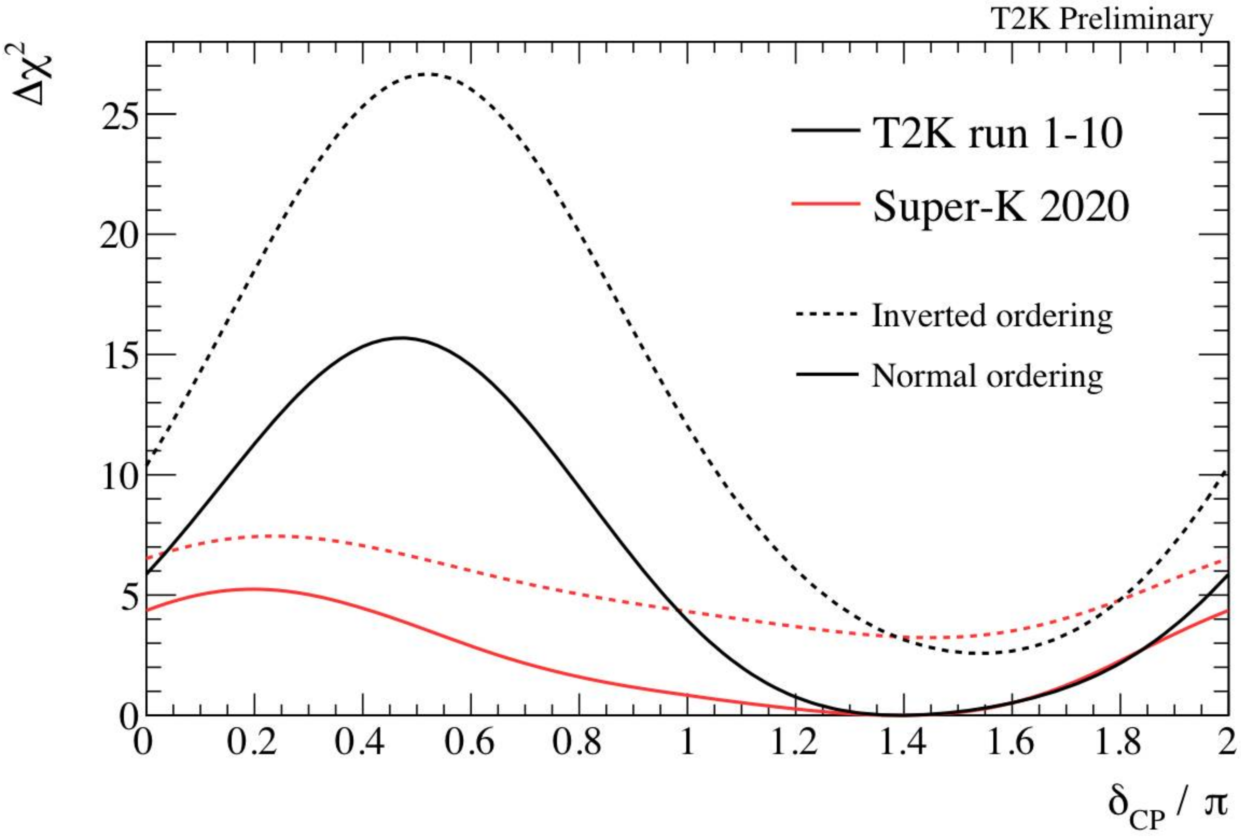
Comparison with other experiments



- T2K has world leading Δm^2-$\sin^2\theta_{23}$ constraint
- World leading δ_{CP} constraint
- Prefer different δ_{CP} value to NOvA, too soon to talk about tension



Joint fits



- Additional benefits from combining T2K with other data
- T2K+NOvA and T2K+SK (atmospheric) analyses are ongoing

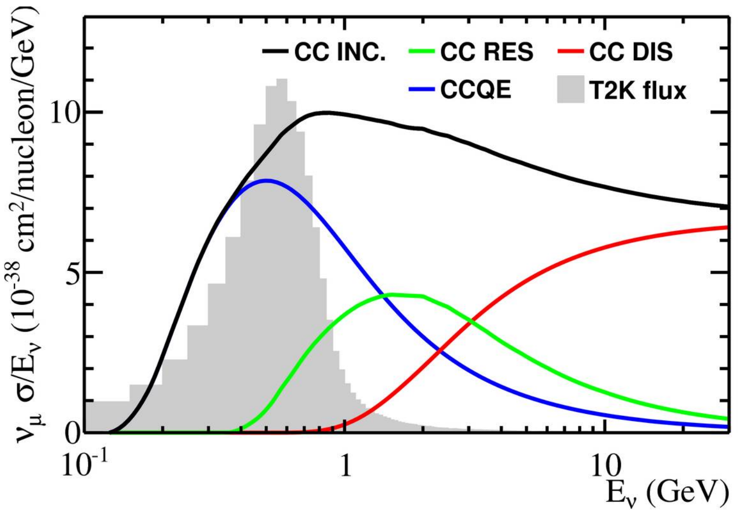
Neutrino cross-section measurements

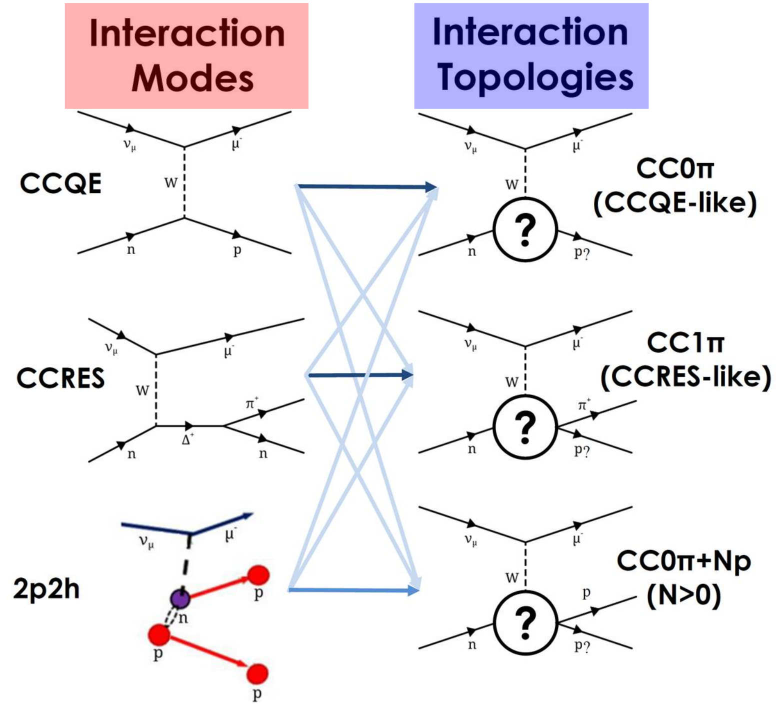
What can we measure?

$$R(\vec{\mathbf{x}}) = \overbrace{\underbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}_{} \times P(E_\nu; \nu_A \to \nu_B)}^{}$$

Near

Far



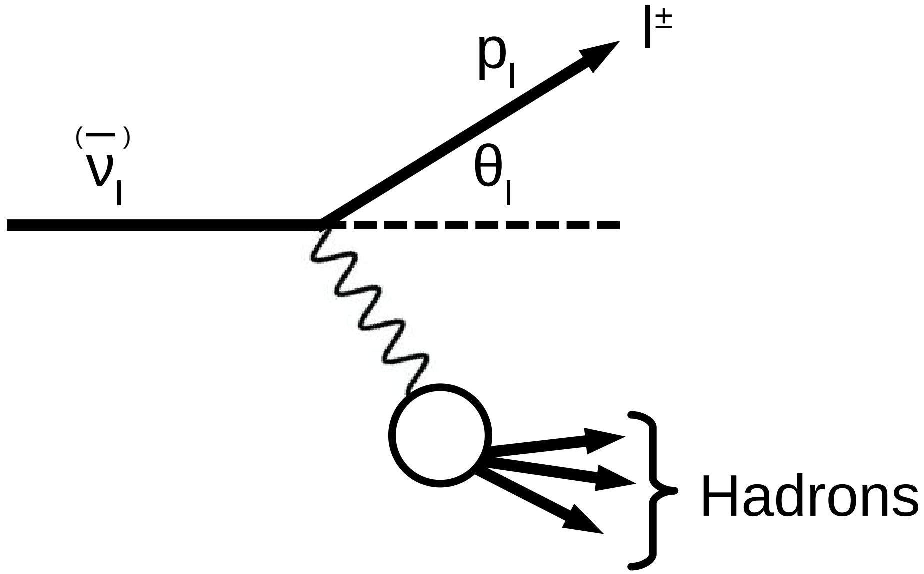


$$\boxed{\widetilde{\sigma}_k(\vec{\mathbf{y}})} = \sum_i \int_{E_{\min}}^{E_{\max}} \boxed{\sigma_i(E_\nu, \vec{\mathbf{x}})} \times \mathrm{FSI}(\vec{\mathbf{x}}, \vec{\mathbf{y}}) dE_\nu$$

T2K cross-section strategy

Build selections of ***interaction topologies*** by adding restrictions on **outgoing hadrons:**

- No model-dependent corrections
- Increasing $N_\pi \approx$ increasing energy transfer



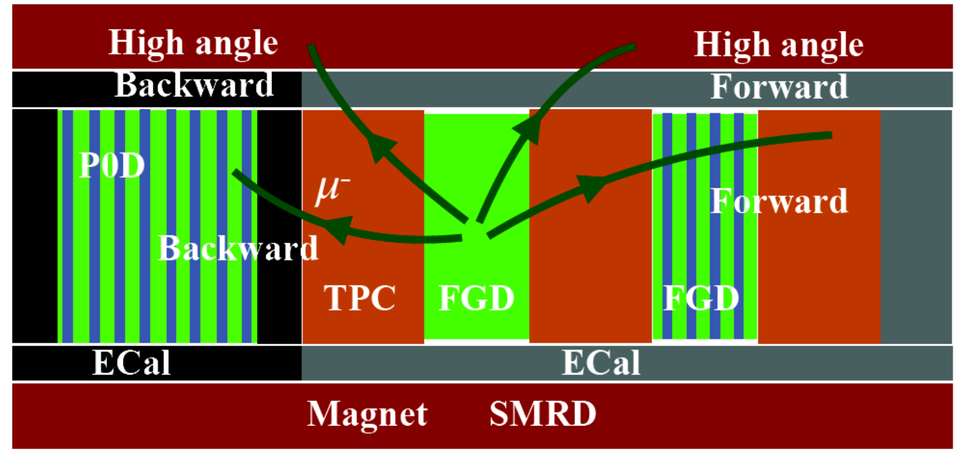
Initially measure lepton kinematics, add hadron kinematics over time

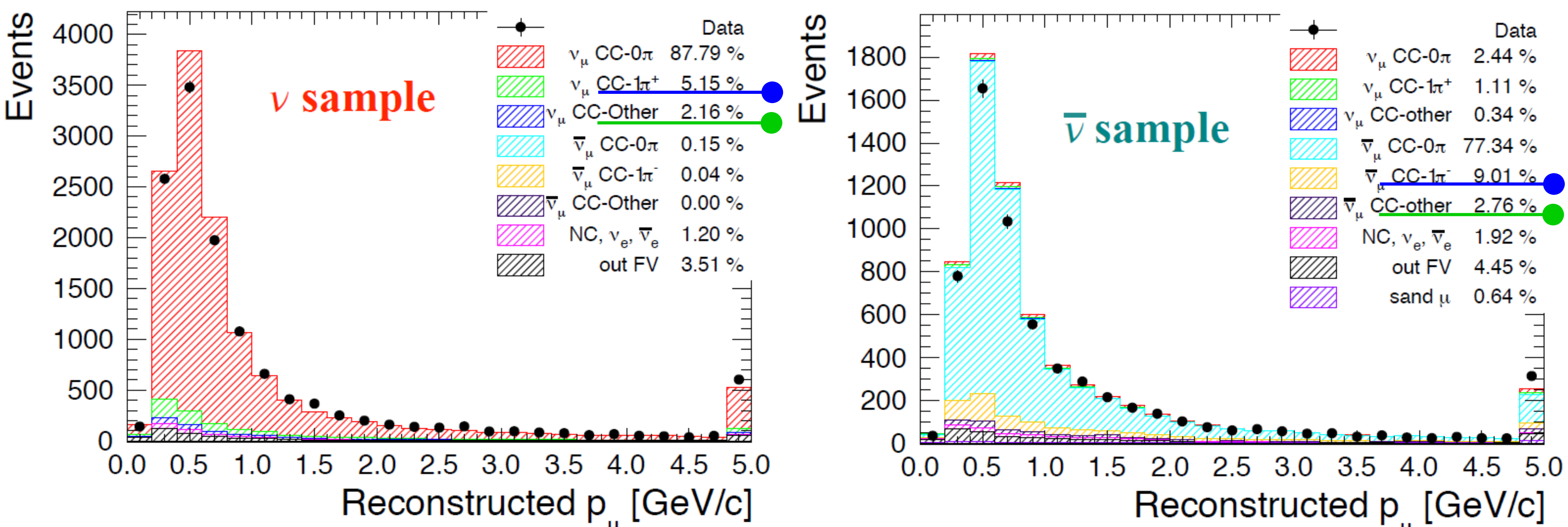
Benefit from different fluxes/targets

Avoid model dependence

ND280 CC0π $\bar{\nu}_\mu$ & ν_μ

- Measure CC0π on C_8H_8 by selecting muon, allowing protons, and vetoing pions
- Control samples for **CC1π** & **CCNπ** backgrounds

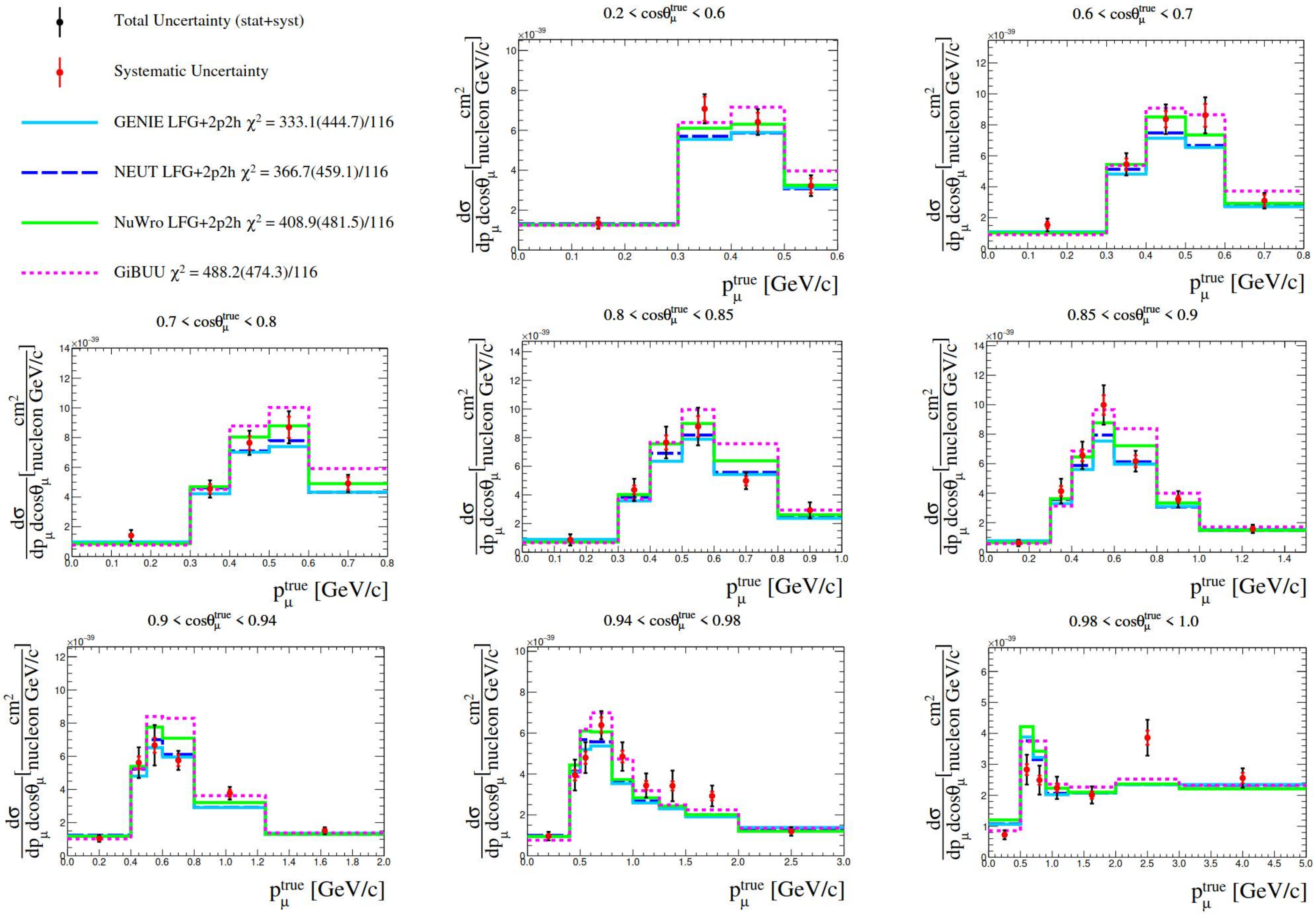




PRD 101 (2020) 112001

ND280 CC0π $\bar{\nu}_\mu$ & ν_μ

Simultaneous fit to measure cross section in 58 p_μ,cosθ_μ bins for each mode, including correlations between the samples



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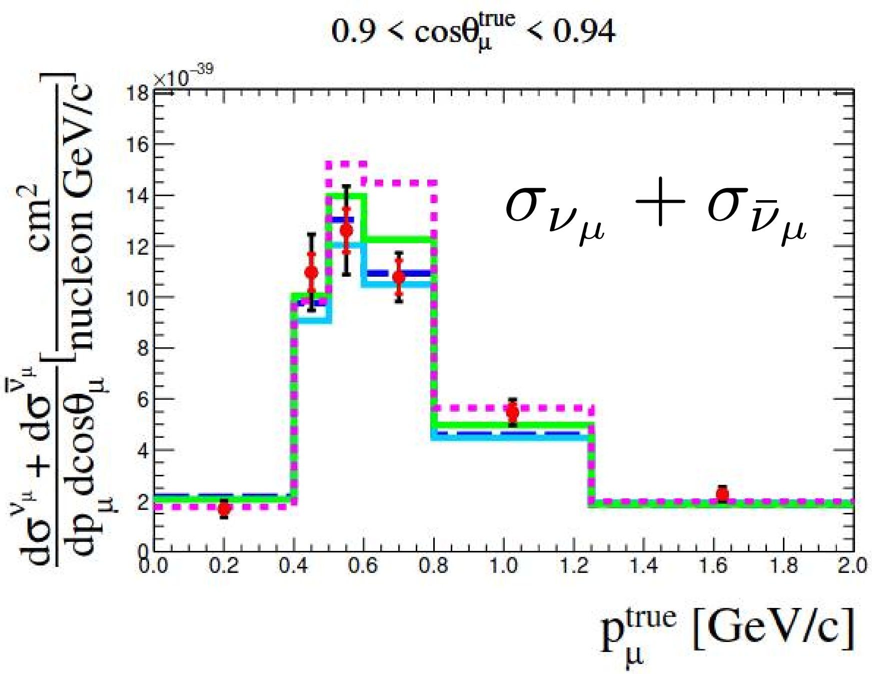
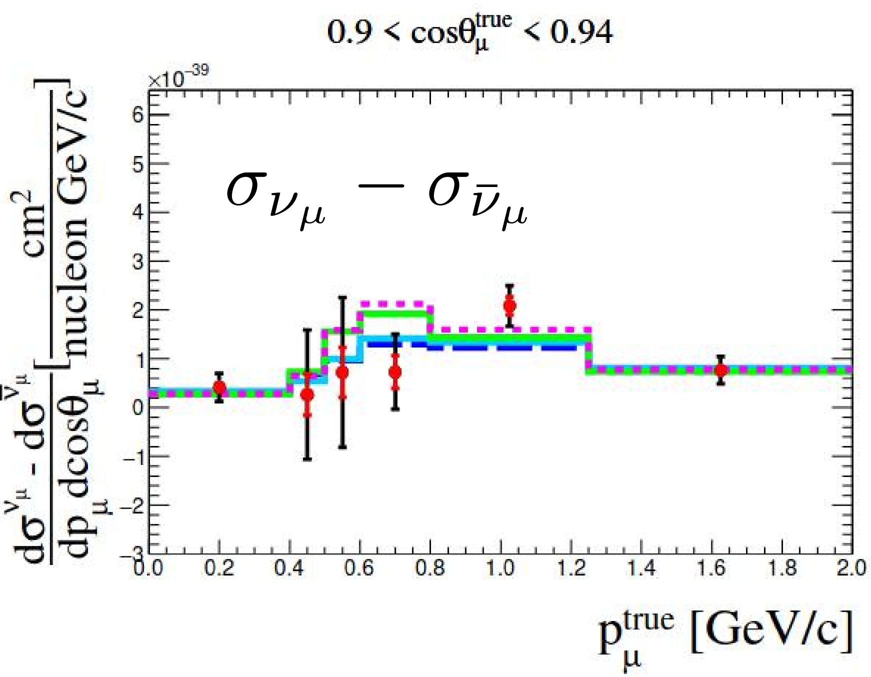
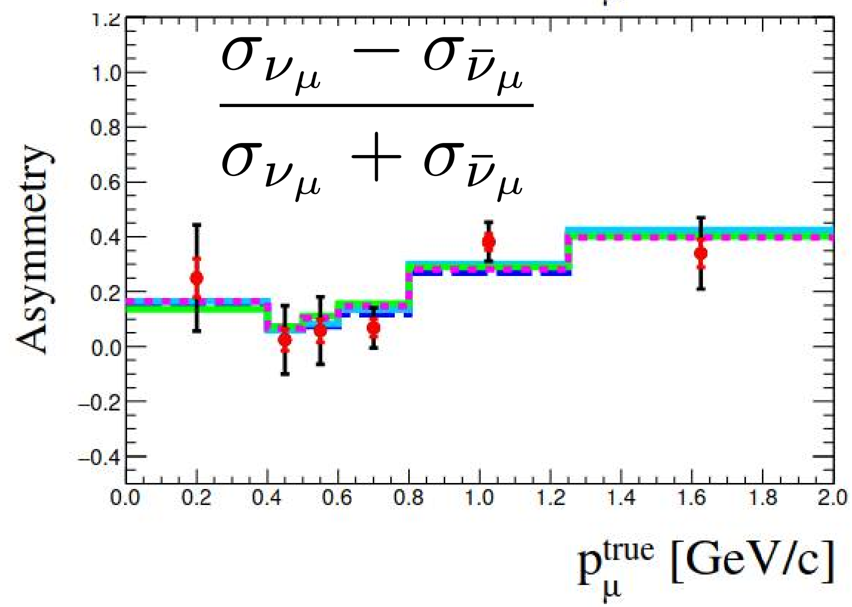
ND280 CC0π $\bar{\nu}_\mu$ & ν_μ

- Correlations between measurements can be used to uncover model differences
- Adds significantly more power for model-building







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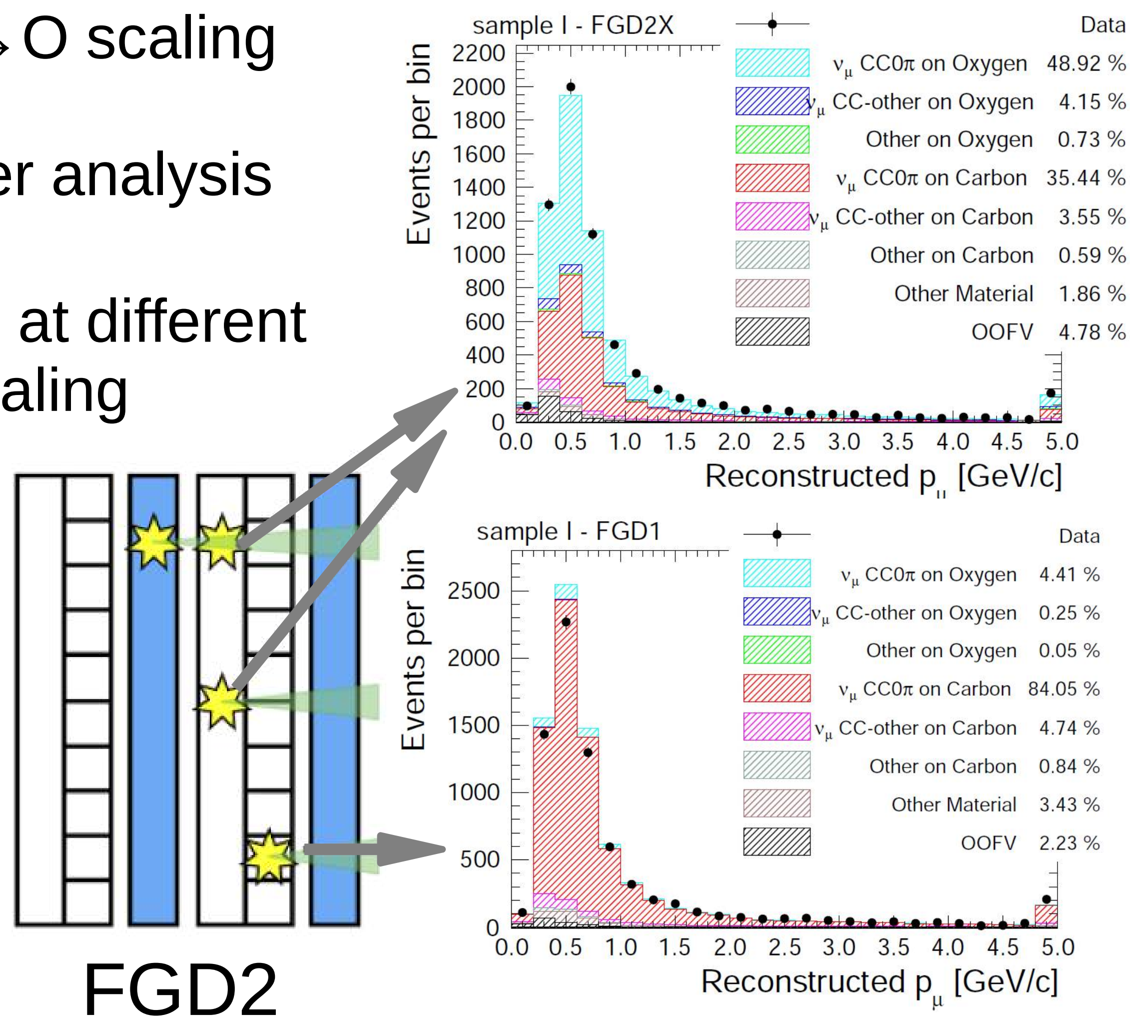
ND280 ν_μ-CC0π C_8H_8 & H_2O

- Combined FGD1 (C_8H_8) and FGD2 (C_8H_8 + H_2O) analysis
- Starting to investigate C → O scaling
- Next: Full $\bar{\nu}_\mu/\nu_\mu$, C_8H_8/water analysis
- Future: multiple detectors at different on-axis positions → E_ν scaling
- First analysis from WAGASCI (1.5° off-axis) PTEP (2021) 043C01



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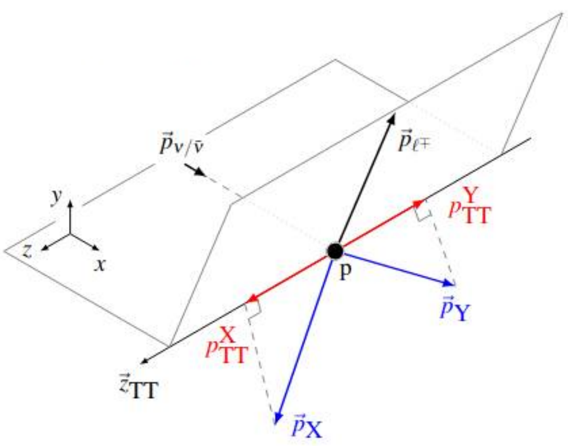
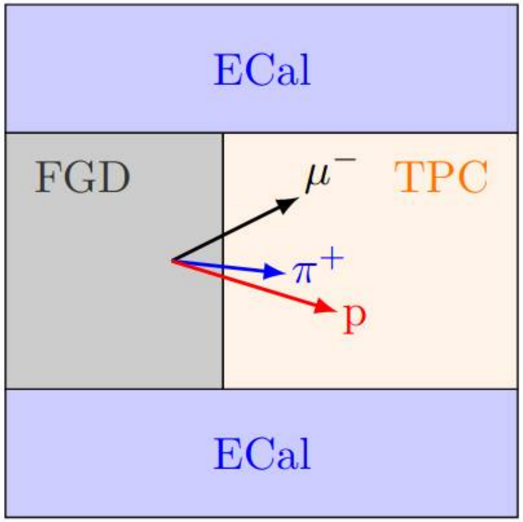
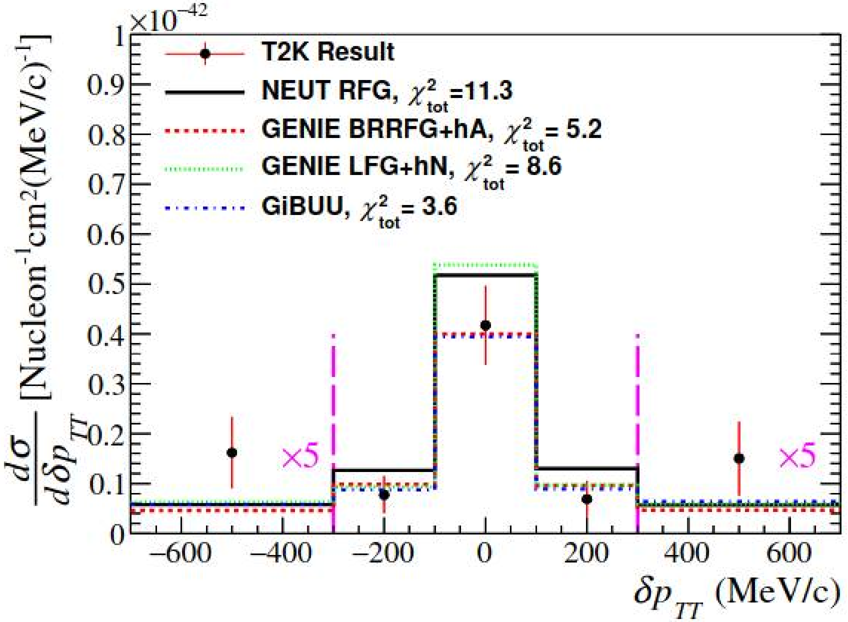
Double transverse measurement

- Example of an alternative approach: identify sensitive variables for testing models
- ν_μ-CC1π^+Np selection, form sensitive variable from the μ, π and leading proton kinematics
- Challenging systematics, but maximizes impact of low-statistics exclusive samples







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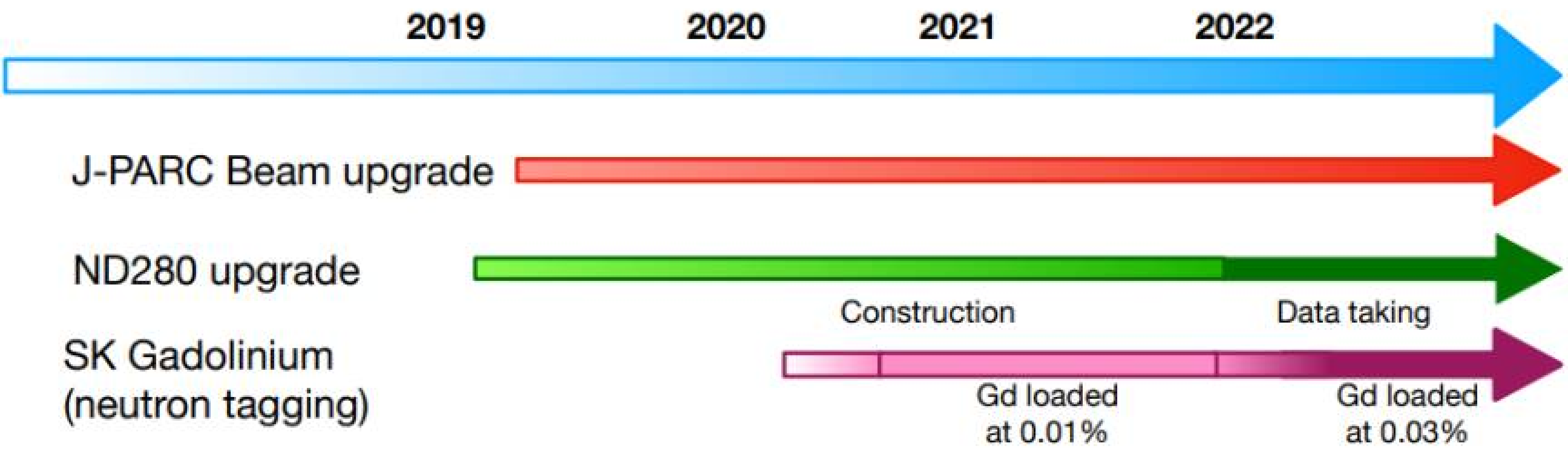
T2K future


2019
2020
2021
2022
J-PARC Beam upgrade
ND280 upgrade
Construction
Data taking
SK Gadolinium
(neutron tagging)
Gd loaded
at 0.01%
Gd loaded
at 0.03%

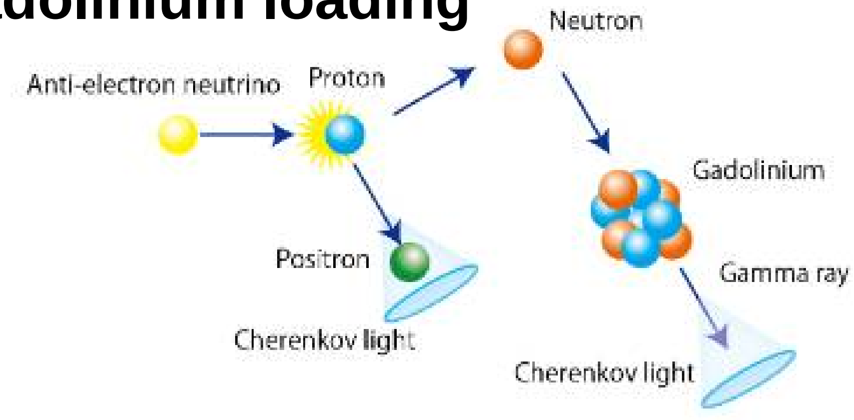
T2K future in one slide

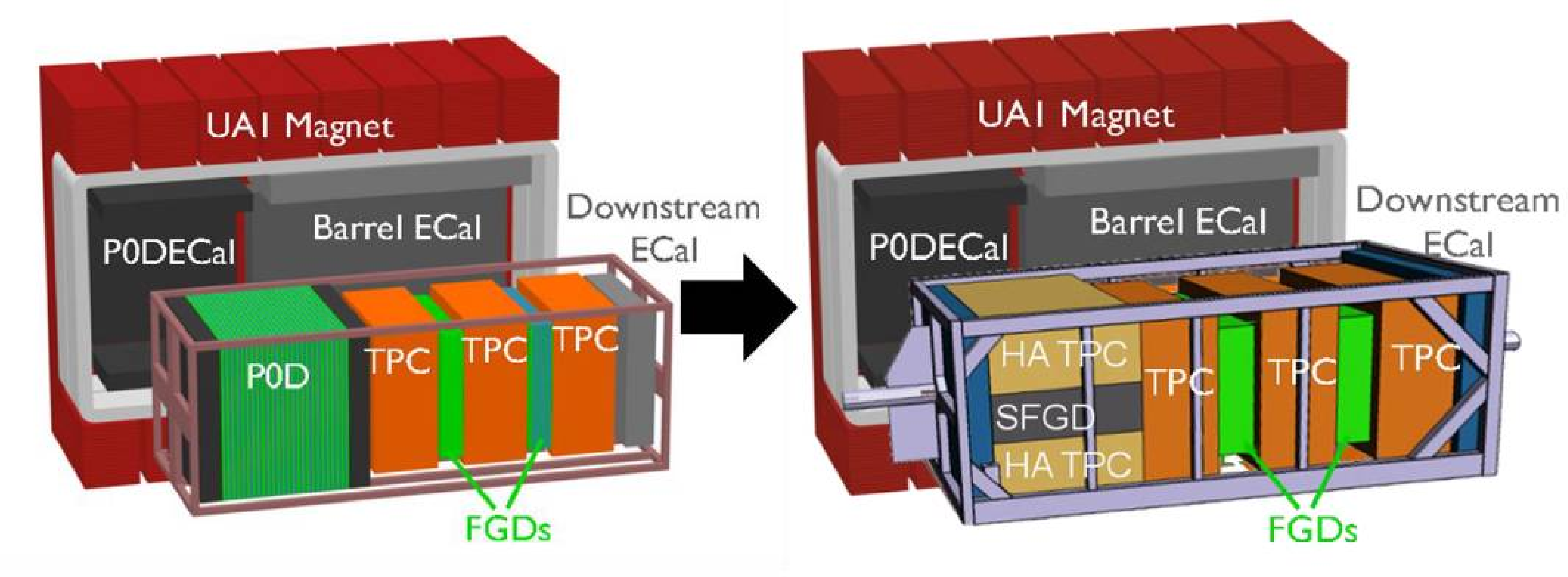
Beam power

500kW → 800 kW → 1.2 MW
Today ~2024 ~2027

- 2x horn replacements
- Horn power supply upgrades
- Improving beam target cooling

Gadolinium loading





Summary

- T2K has world-leading neutrino oscillation measurements of disappearance parameters
- Exciting oscillation results left to come, particularly in combination with other experiments!
- Cross-section measurement program continuing, strong focus on **model-independence**
- T2K upgrade program will add exciting additional capabilities!

Backup

SK sample uncertainties

Before ND fit

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	$1Re$ FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

After ND fit

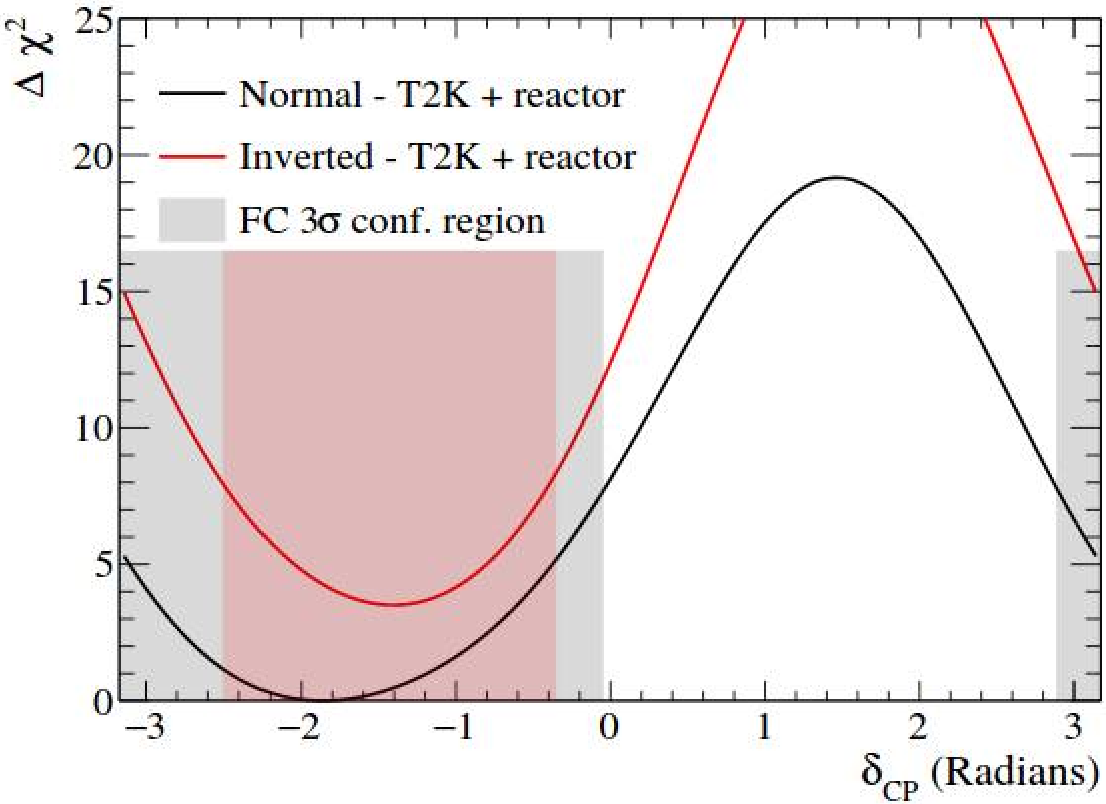
Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	$1Re$ FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Octant and hierarchy

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	0.770	1.000

- Bayesian analysis assumes equal prior probability for octant and hierarchy
- Fraction of MCMC steps in each octant/hierarchy gives the posterior probability for each
- T2K weakly prefers normal hierarchy and upper octant

2018/19 T2K ν_e-appearance



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CP-conserving values, δ_{CP} = [0, ±π] excluded at 2σ

δ_{CP} = 0 excluded at 3σ!

Cross-section extraction

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}_{ij}^{-1} \left(N_j - B_j\right)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

Cross-section model independence

The signal definition and background subtraction can be model dependent

Some unfolding methods introduce bias

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}^{-1}_{ij}(N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

Choice of variables

Efficiency corrections couple to model in complex ways