T2K: Status and Prospects

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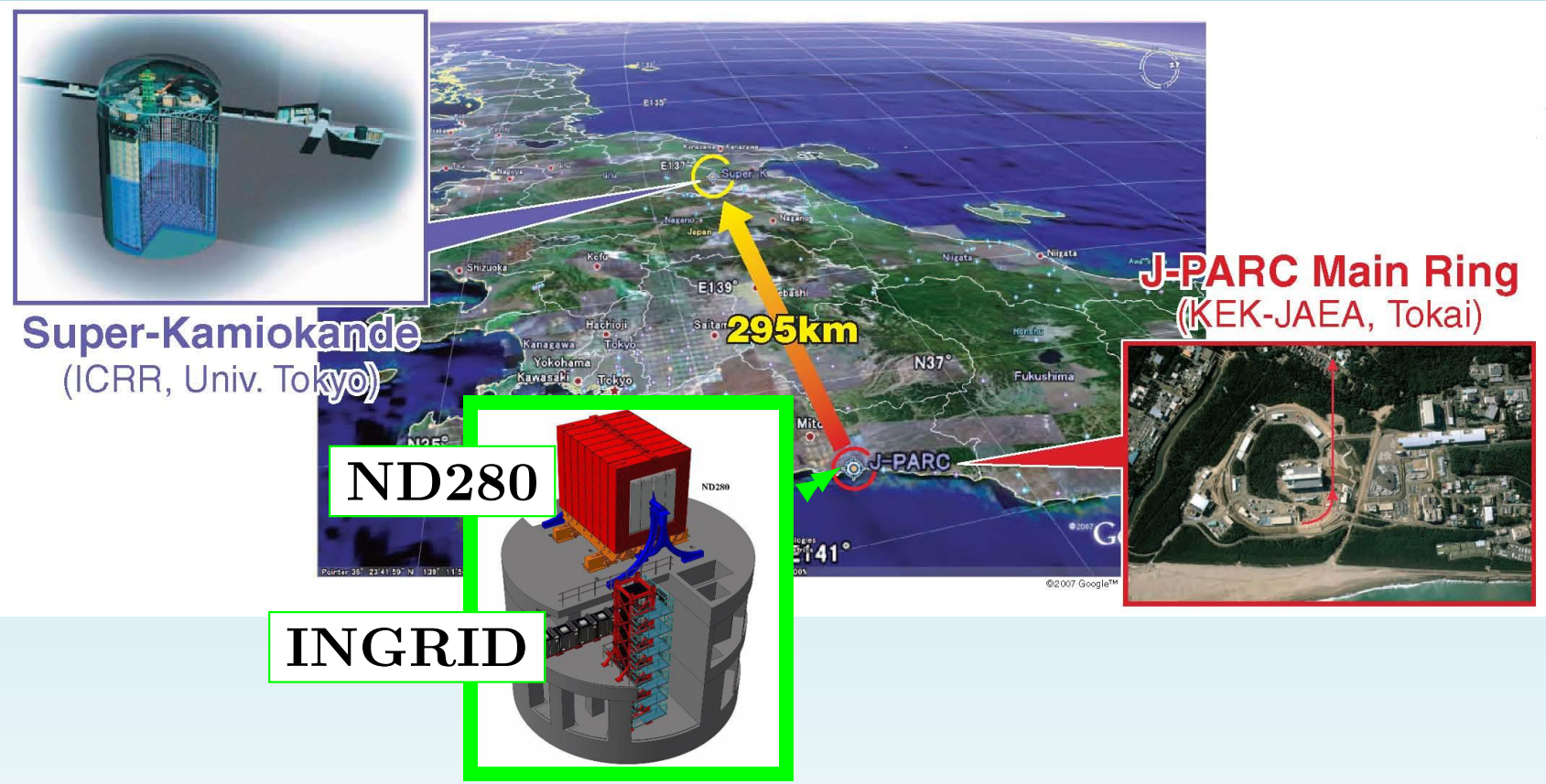
(on behalf of **T2K Collaboration**)

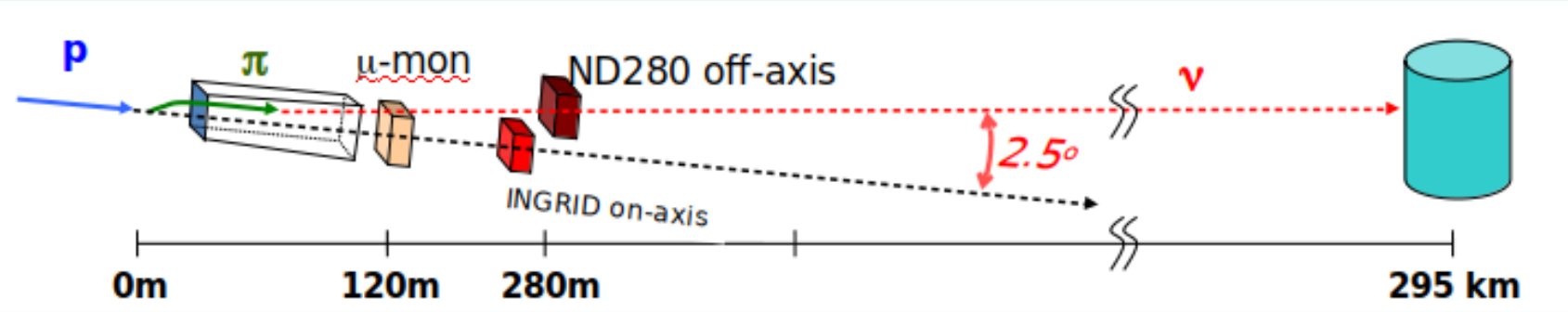
Kyoto University

Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2019

14 June, 2019

The T2K Experiment:





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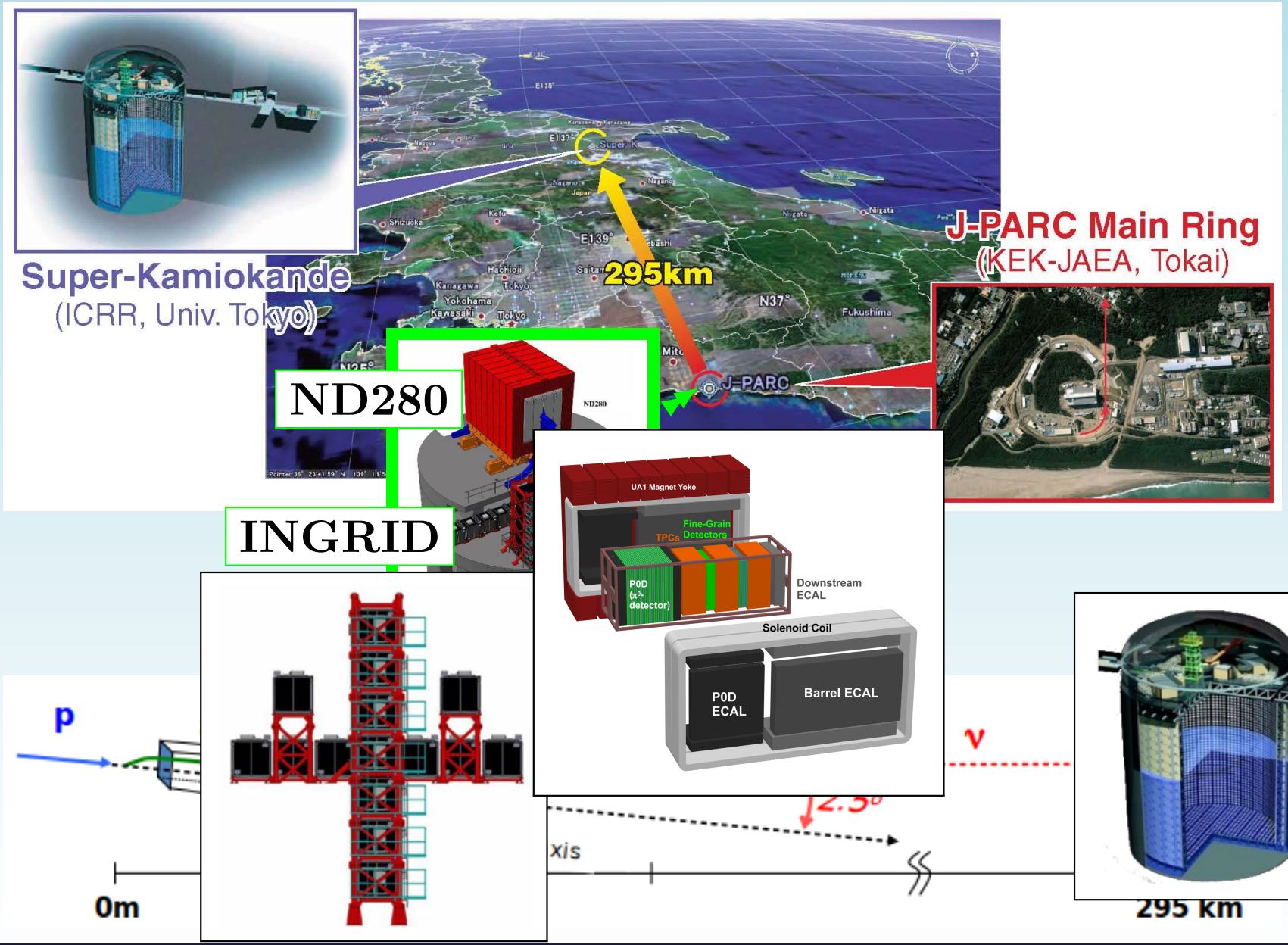
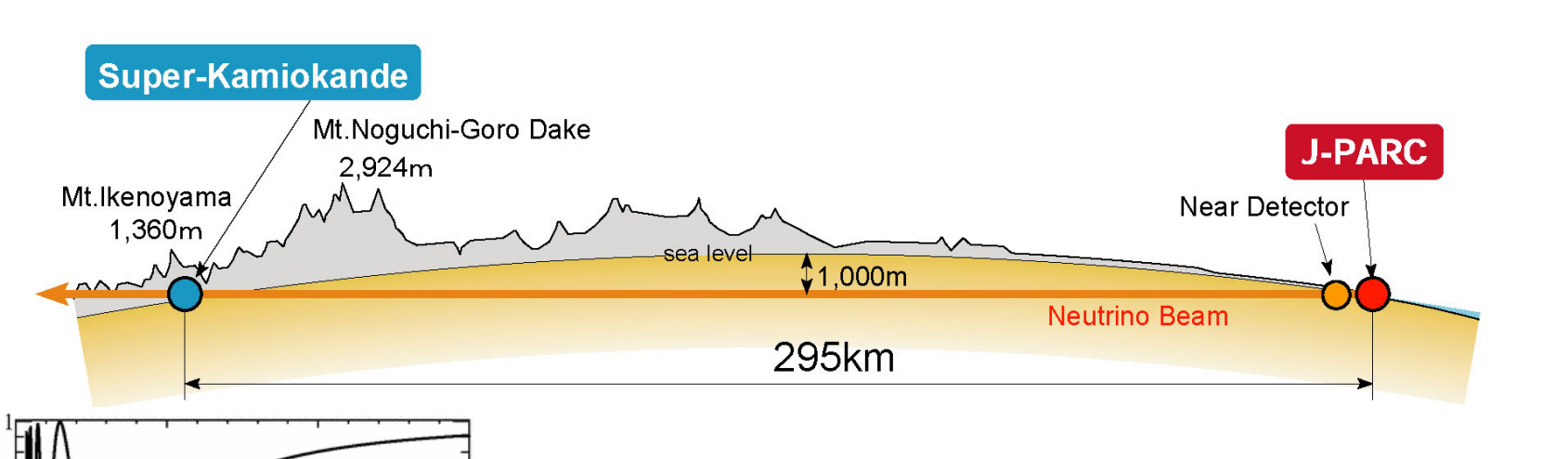
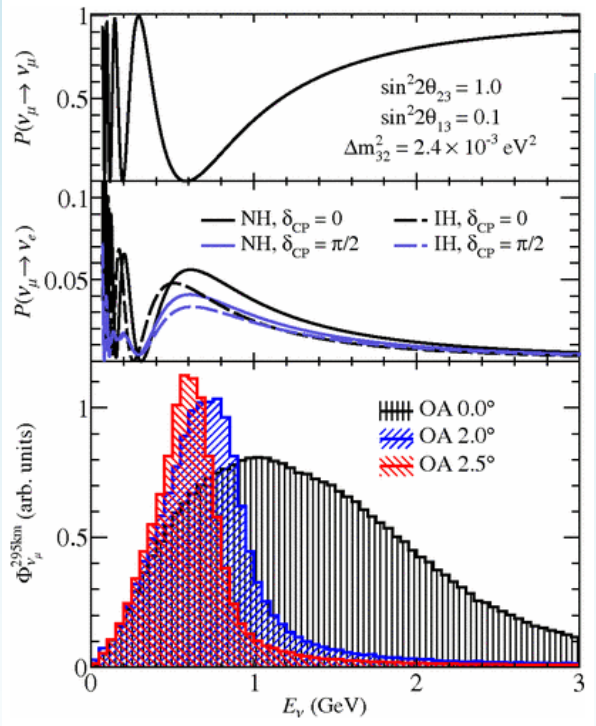


ν-Physics @ Far and Near Detectors:



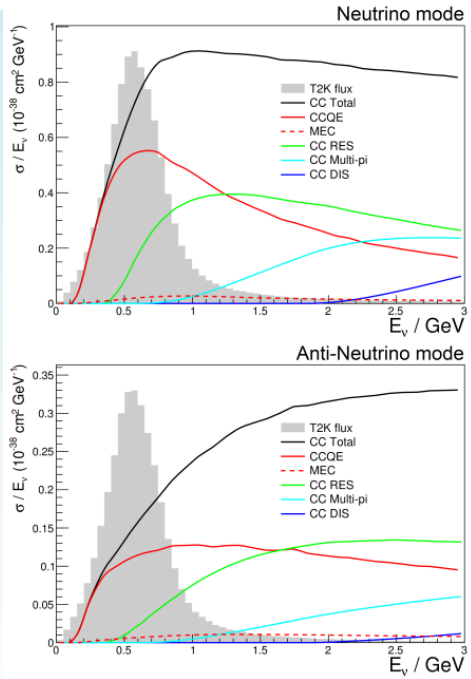


Phys. Rev. D 88, 032002

Far Detector:
ν-Oscillation parameters

Near Detectors: Pre-Osc.Flux-measurement, ν-Interaction/Cross-section measurement

$$\frac{N^{far}}{N^{near}} \sim f(\sigma, \Phi, Det)$$



Measuring neutrino Cross Sections

$$\mathbf{N}(\vec{x}) = \boxed{\boxed{\Phi(E_\nu)\cdot\sigma(E_\nu,\vec{x})\cdot\epsilon(E_\nu)}\cdot P_{ab}(E_\nu,\Delta m^2_{ij},\theta_{ij})}$$

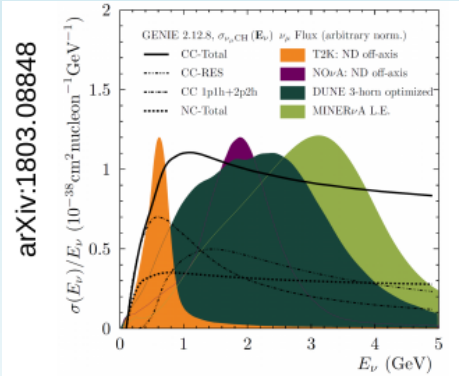
- Systematic uncertainty important for precision in oscillation results.
- **Events** ratios at **Near** and **Far** detectors do not cancel systematics: owing to different Flux, Cross-sections, Detector-smearing, and Osc. Probability.
- $\sigma(E_\nu,\vec{x})$ relate E_ν with observables

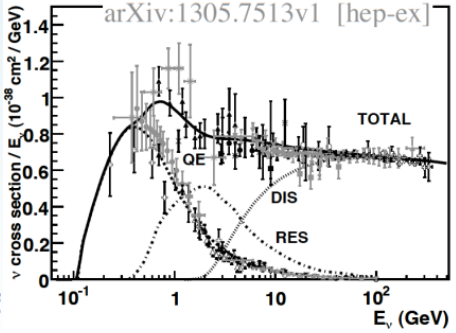
✠ Measurement of σ with minimal uncertainty

⇒ Reduced Systematics in Osc. analysis @FD

⇒ Better goals-designing of future OA experiments

⇒ Several measurements needed to constrain and develop ν-interaction models

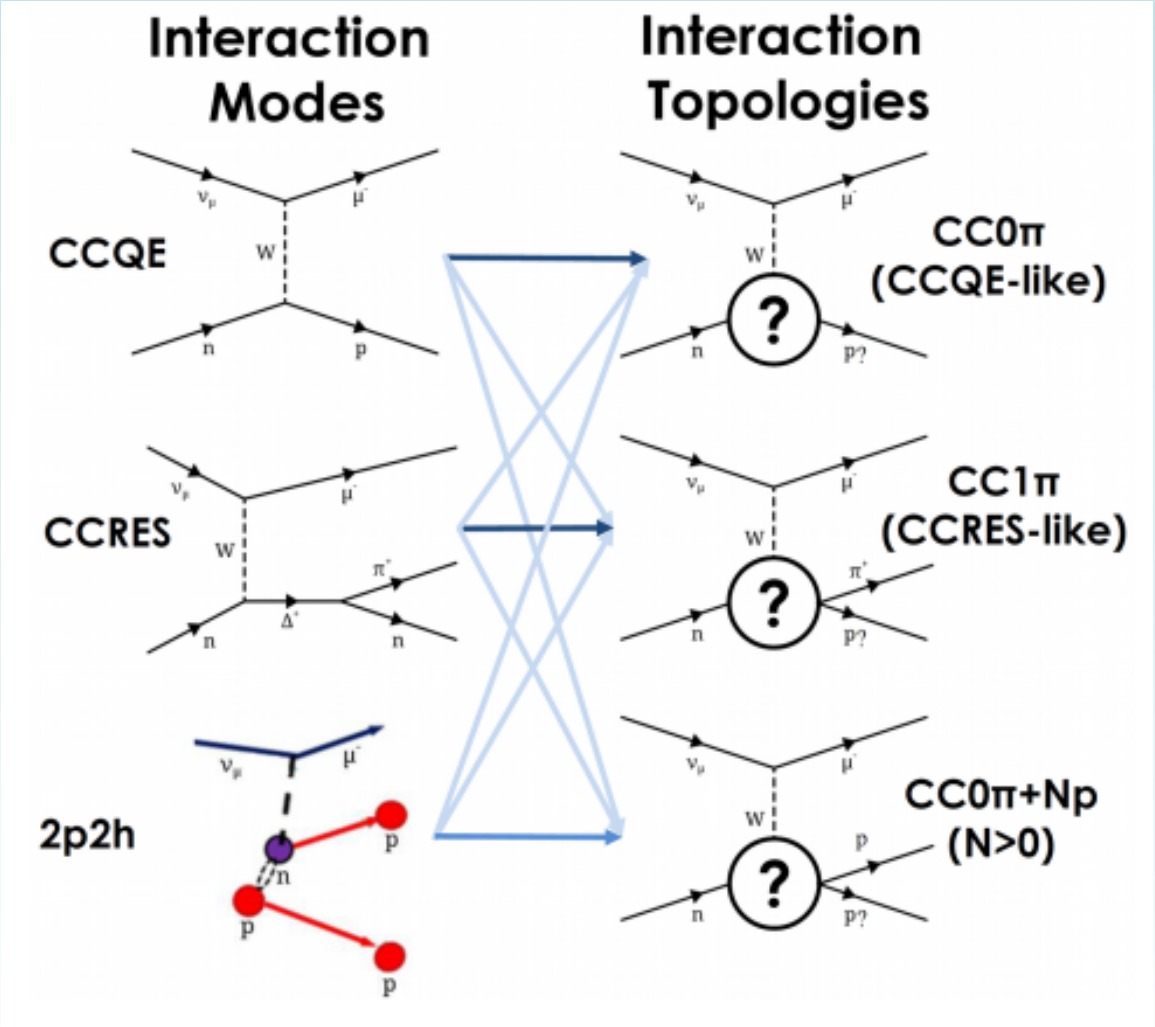


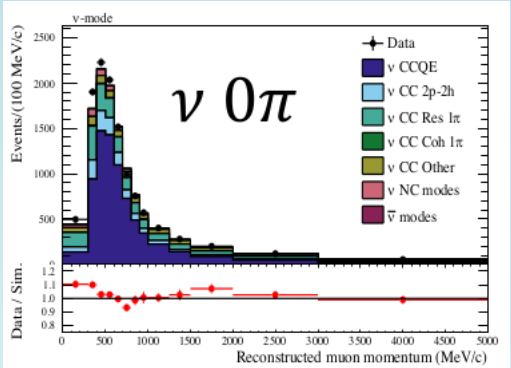


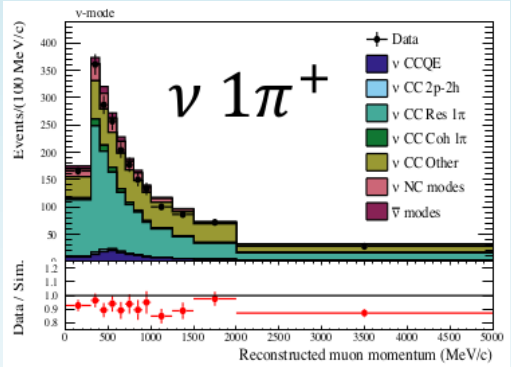
Flux-U.Details @poster: Lukas

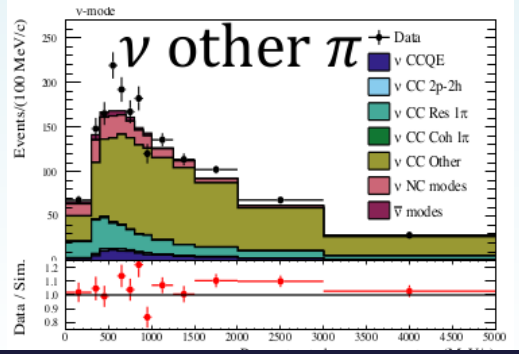
The Cross-section Strategy:

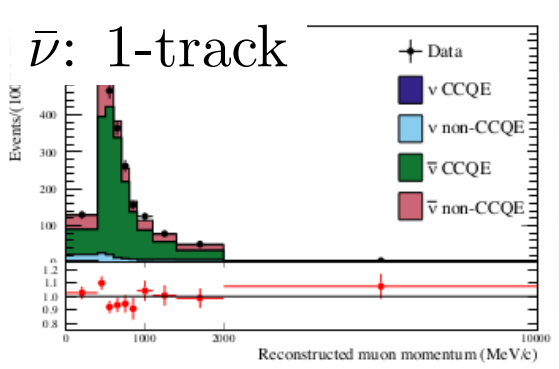
- Nuclear & Detector effects obscure true interaction mode
- Sample w.r.t visible outgoing hadron (π) content

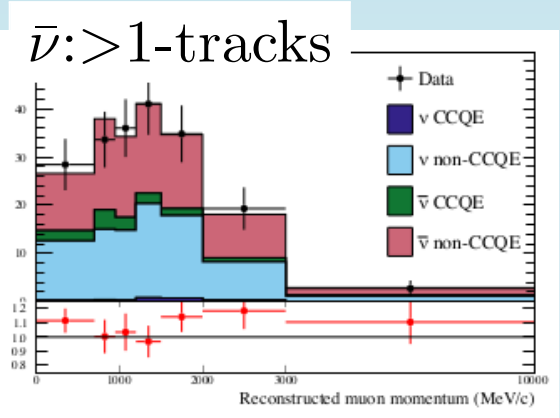




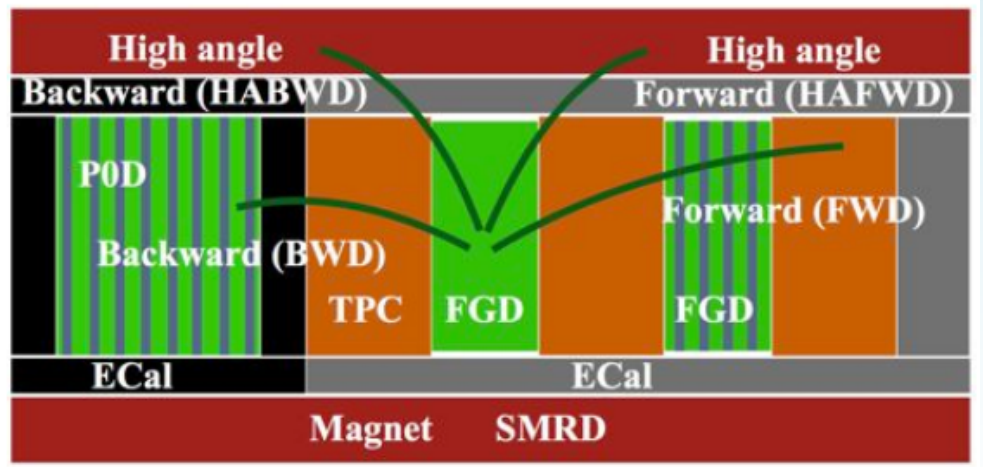


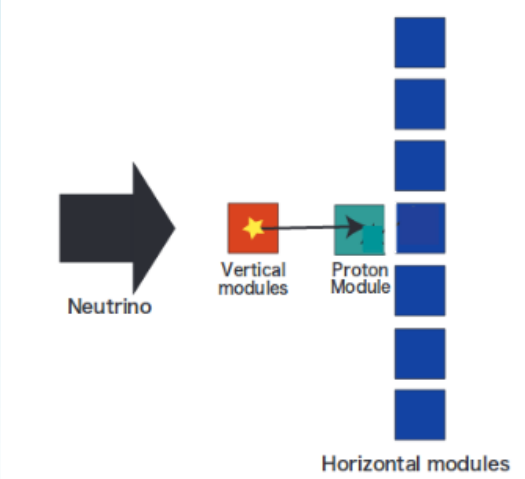






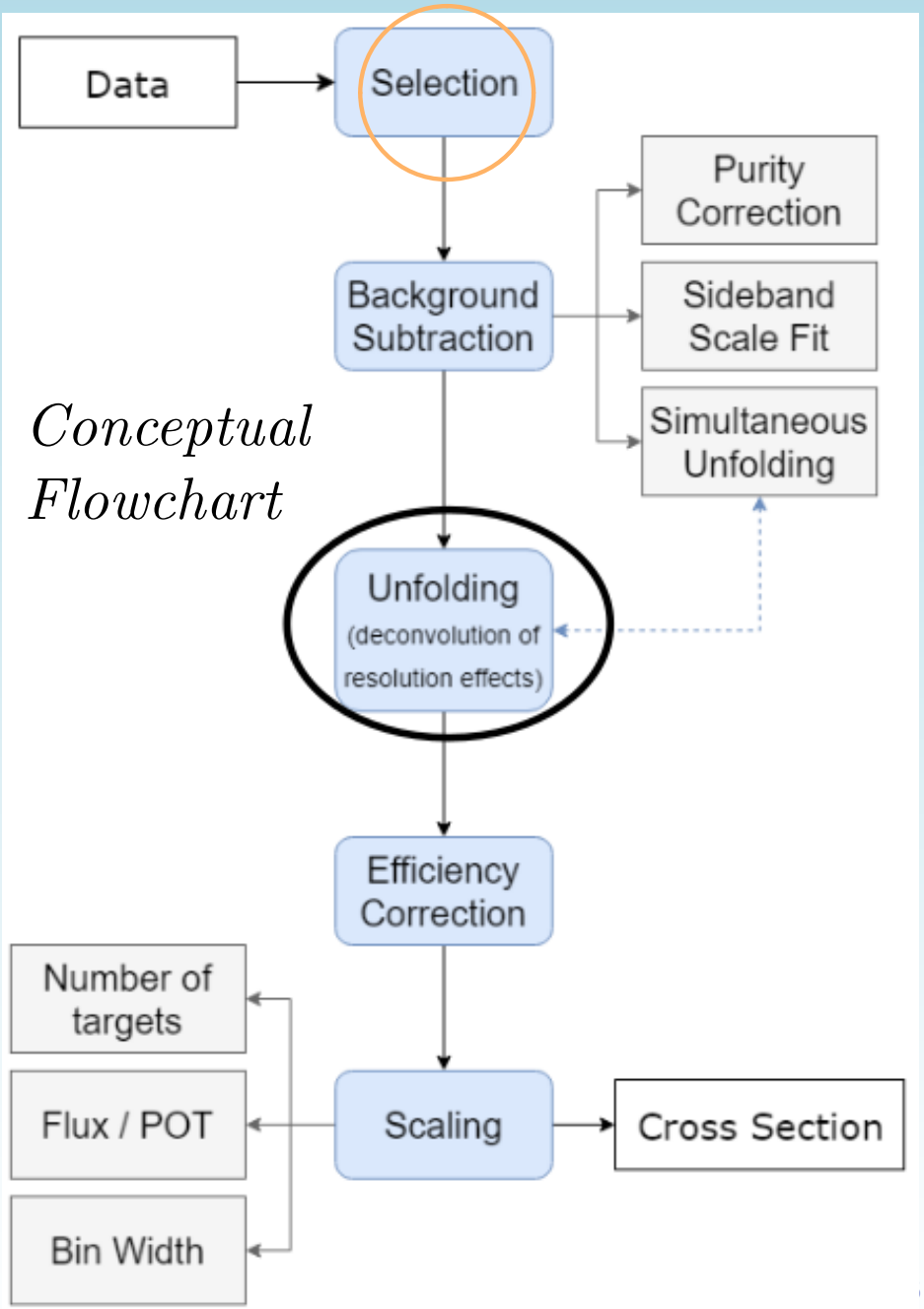
- Sample w.r.t. to #reconstructed tracks
- Measure in: Reconstructed muon momentum and direction.
- Multi-targets: CH and CH+H2O separately, Fe, H2O
- Multi-beam energy peaks: Off-axis: 2.5° ~0.6 GeV; On-axis:0° ~1 GeV
- Phase space coverage: fwd, bwd, 4π.





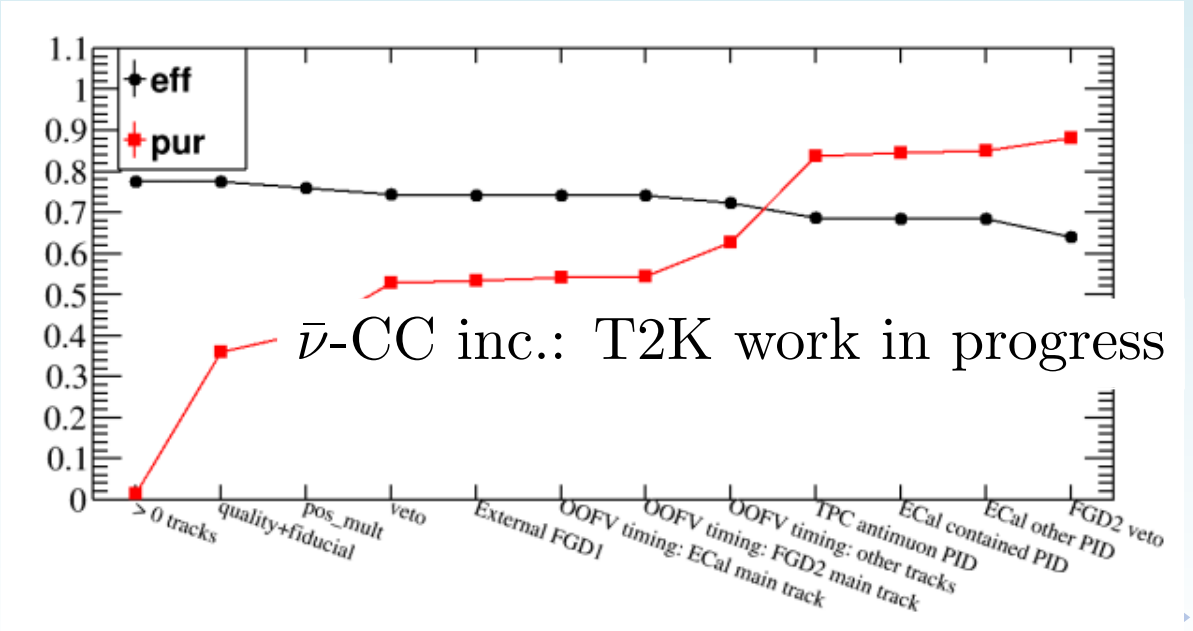
Sample Selection:

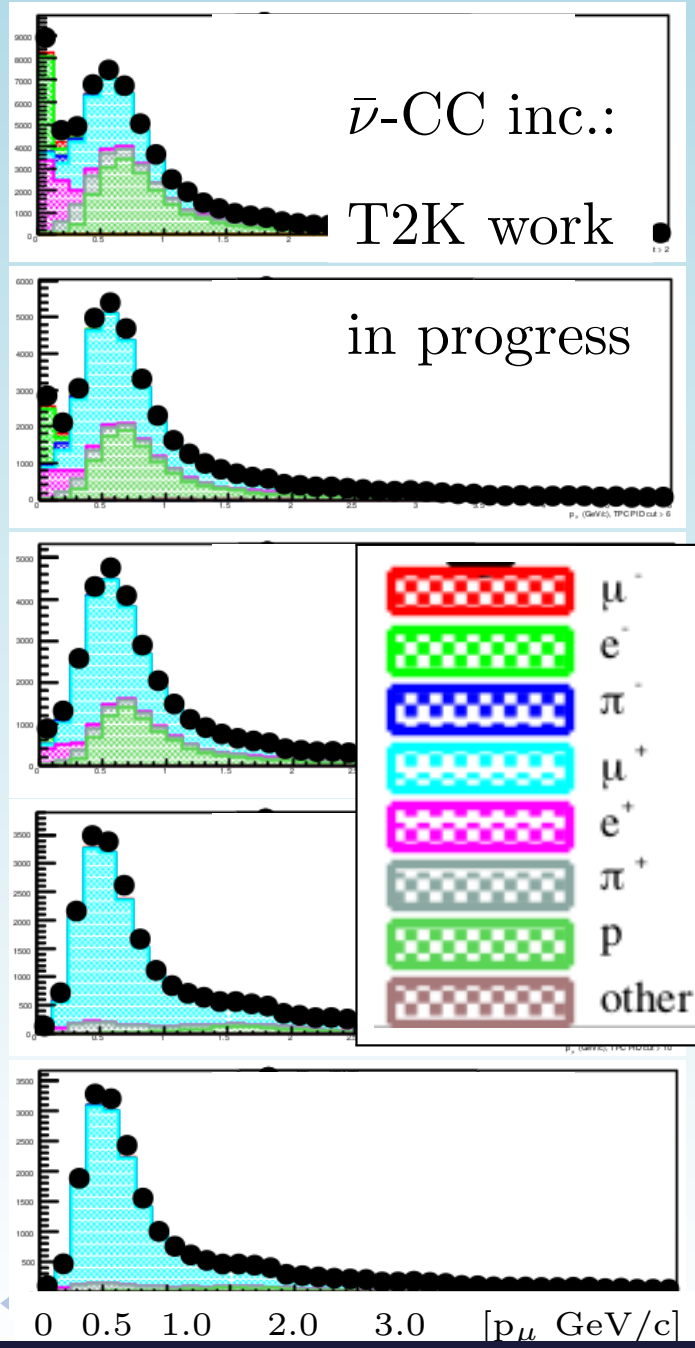
- ND280 flux favors ν-CCQE as a major fraction
- Appropriate selections to ensure high purity of an int.mode. Altered criteria enrich other modes
- Signal selection efficiency and purity ensuring crucial.
- Primarily: Event quality, Total multiplicity, Quality and fiducial origin cut, μ-CID multiplicity check etc.
- Other cuts applied depending on the considered target.



As for example in the following sample in FGD1:

- Vetoing with TPC and FGD2 applied
- Additional constraints from the ECAL improve the selection, by reducing the p-bkg.
- Max. Signal efficiency/purity in the p_μ and $\cos\theta_\mu$ ensured





Unfolding the Reconstructed Events:

- An unfolding method used aiming to remove the detector effects in the measurement
- The flux-avg./int. xsec. is calculated from the **unfolded** events N in each bin, $N_{\alpha\beta}$

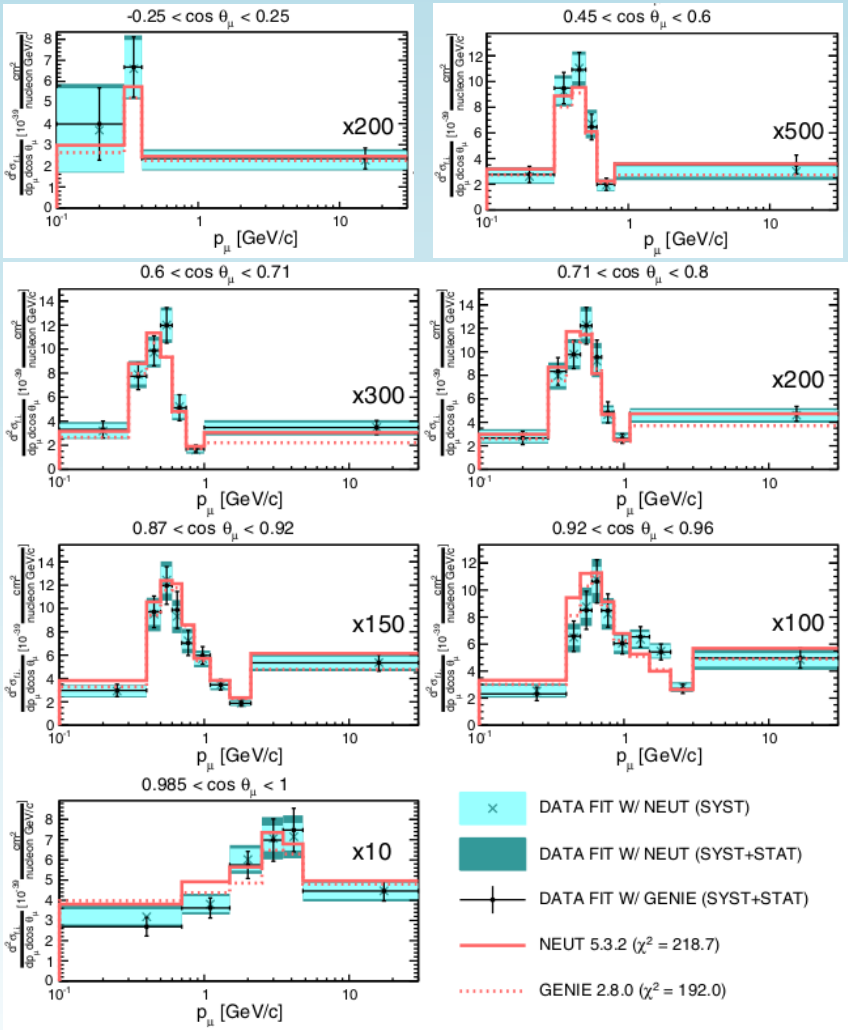
$$For\ e.g.\ ,\ \langle \frac{\delta^2\sigma}{\delta p_\mu \delta \cos\theta_\mu} \rangle_{\alpha\beta} = \frac{\hat{N}_{\alpha\beta}}{T\Phi\Delta p_{\mu,\alpha}\Delta\cos\theta_{\mu,\beta}}$$

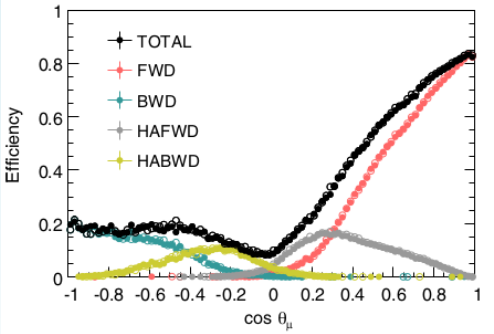
  And finally also obtain total cross section σ.
- So choice of the **Unfolding method** to be used must be checked to ensure min. MC bias, and convergence of the unfolding process.
- **Unfolding Techniques:** D'Agostini, SVD, TUnfold or binned-likelihood fit and many more available.
- Checks with lots of pseudo data sets. After lot of checks and reviews: unblind the data.
- Forward-folding techniques also used by some.

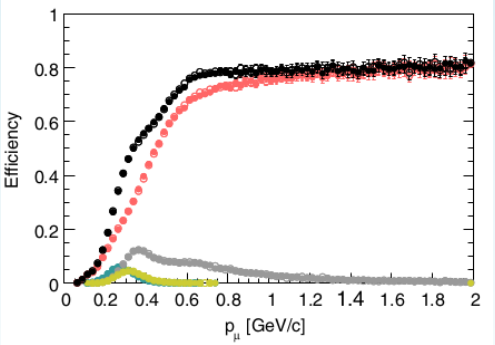
Cross Section Results from T2K:

CC Inclusive on CH (Off-axis):

- Fwd, Bwd, & High angle selections
- CCQE dominance, Flux-integrated Cross Section ($\sim$ 6.9±0.7% stat. ± 8.7% fluxU. ± 1.8% syst. $\times 10^{-39}$cm^{2}nucleon^{-1})
- Binned likelihood fit, unregularised. Fit with both NEUT and GENIE as priors.



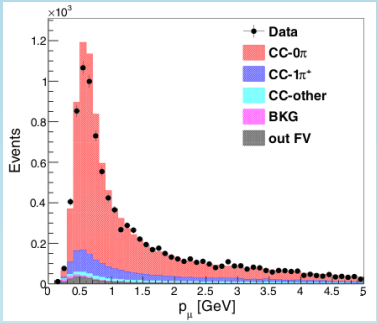


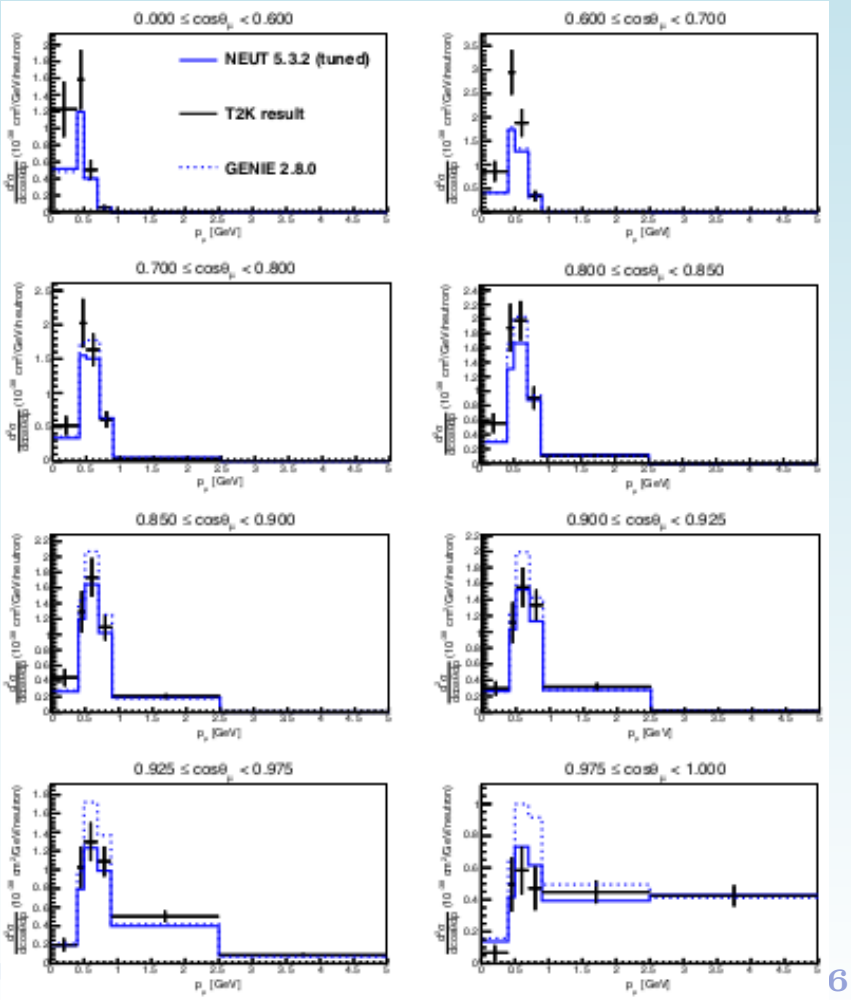


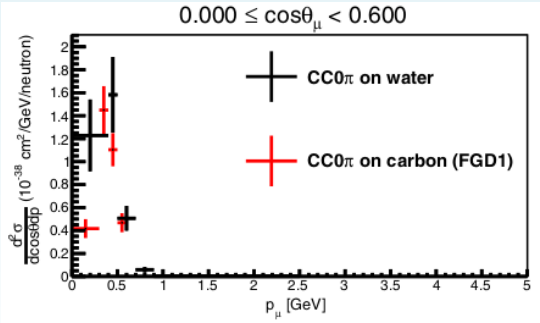
PRD 98, 012004 (2018)

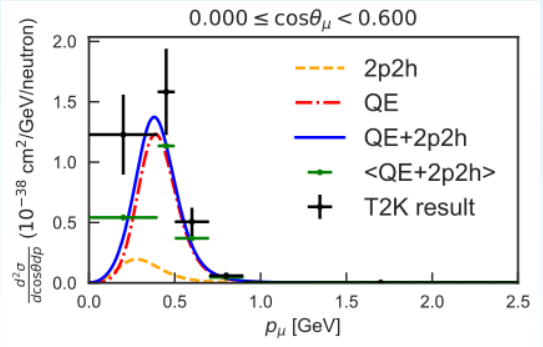
CC 0pi on CH, H2O (Off-axis):

- CC0π $\sim$ 80% CCQE + 12% 2p2h
- Measurements in P0D (2018) (1-track), Compared with FGD1(2016)
- Unfolded with D'Agostini method, MC truth used as prior
- Flux-int. $\sigma^{CC0\pi}_{\nu_\mu\ H2O}$= 0.95 $\pm$8% stat. $\pm$8% fluxU. $\pm$10% syst. $\times 10^{-38}$cm^{2}nuc^{-1}
- Compared with other models. Better if 2p2h included.





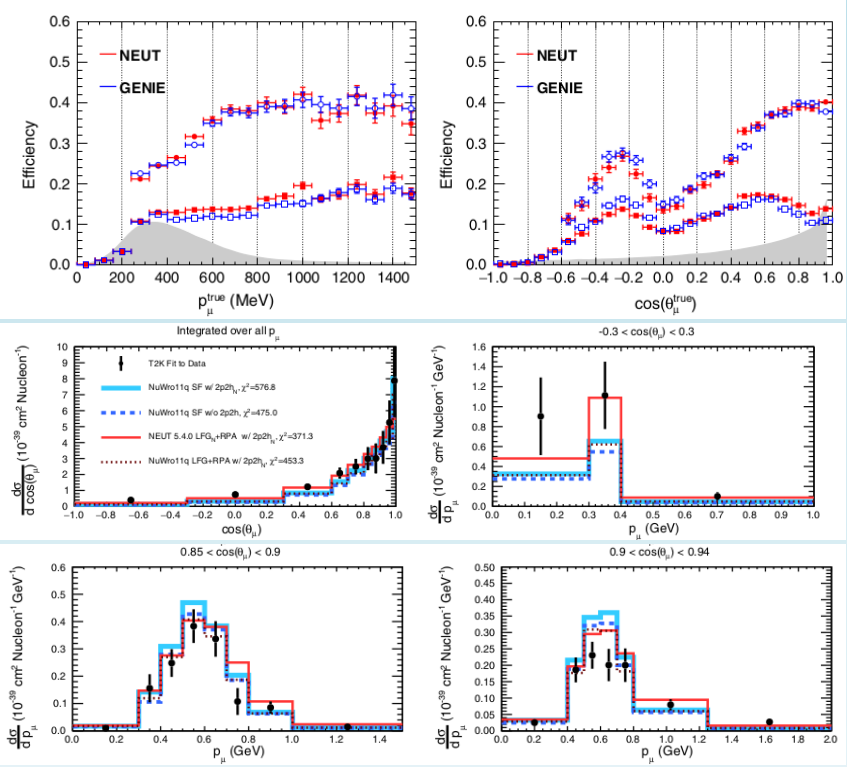




PRD 97, 012001 (2018), PRD 93, 112012 (2016)

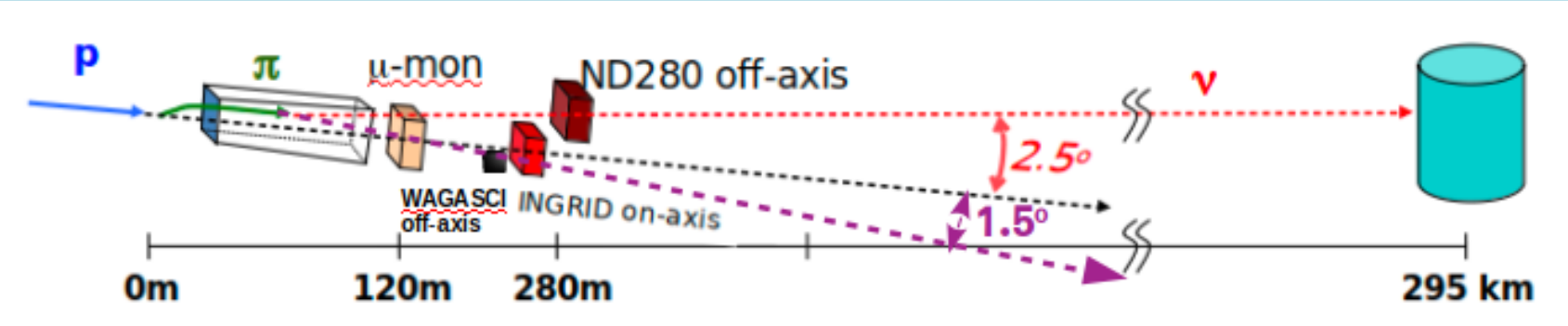
Many More Cross Section results:

- ☑ CC 0π+p on CH (Off-axis, phasespace constraints boosting the efficiency; Standard Transverse variables introduced for probing p): PRD 98, 032003 (2018)
- ☑ CC Inclusive on CH, Fe, H2O (On-axis): Paper under prep.
- ☑ CC-$1\pi^+$ on CH, H2O (Off-axis): PRD 95 (2017) 012010
- ☑ CC0π for $\bar{\nu}_\mu$ on H2O (Off-axis): Paper under prep.

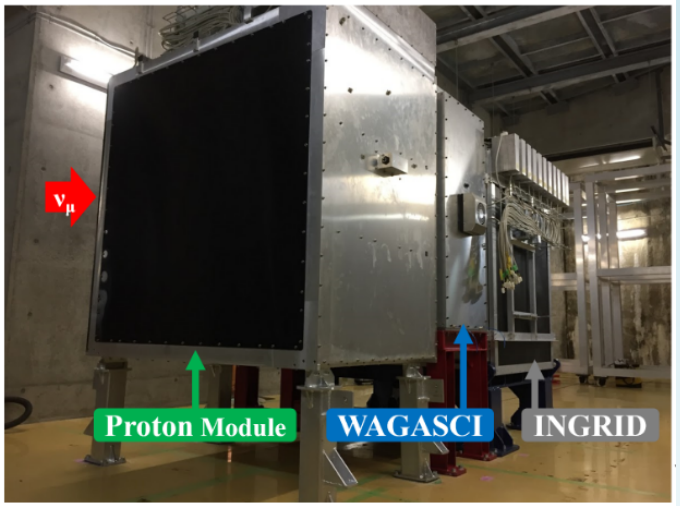


- □ NC$1\pi^\circ$ and CC$1\pi^\circ$ (rate measured: PRD 97 032002 (2018), cross section ongoing).
- □ $\nu_e/\bar{\nu}_e$ in the FHC/RHC mode: coming soon.
- □ Several more analyses ongoing: $\bar{\nu}_\mu$CC-Inc., NC1γ etc. etc.

Newer Near Detectors: (Off-Axis)

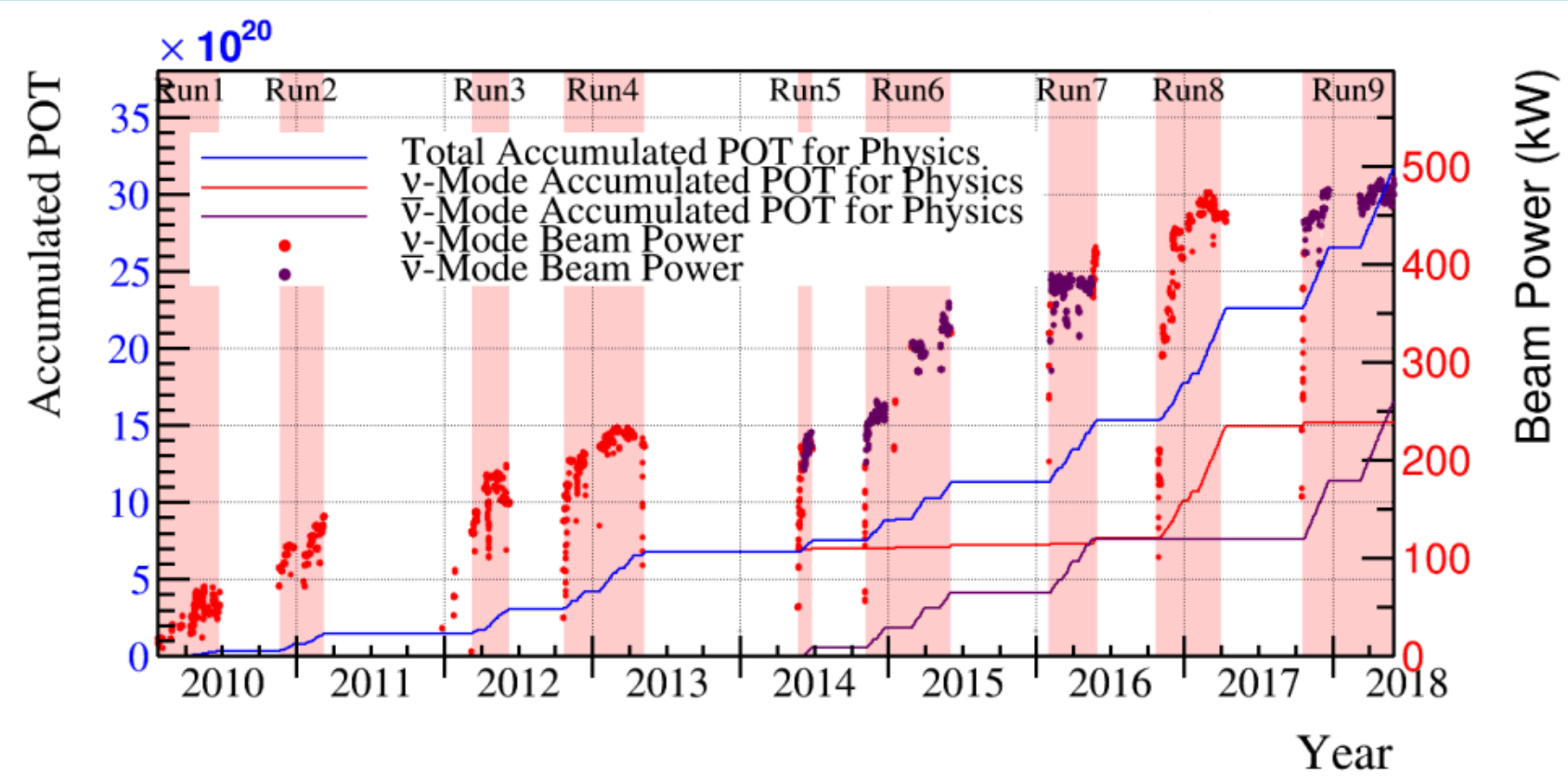


- The **WAGASCI** detector at 1.5° Off-Axis taking data since 2017
- Cross Section measured with $\bar{\nu}_\mu$ on H2O, CH.



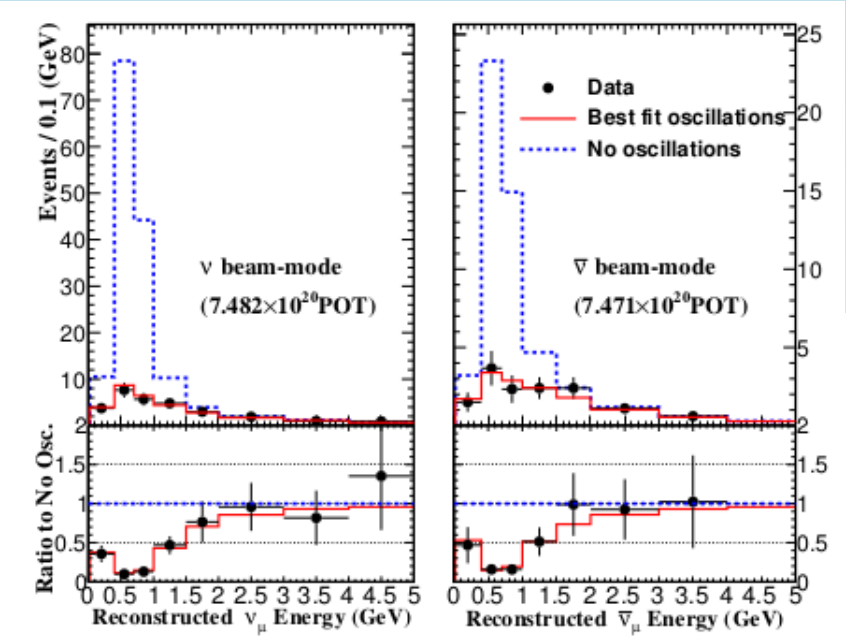
$$
\begin{aligned}
\sigma^{\bar{\nu}_\mu}_{\mathrm{H_2O}} &= \left[1.082 \pm 0.068(\mathrm{stat.})^{+0.145}_{-0.128}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \\
\sigma^{\bar{\nu}_\mu}_{\mathrm{CH}} &= \left[1.096 \pm 0.054(\mathrm{stat.})^{+0.132}_{-0.117}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \\
\sigma^{\bar{\nu}_\mu}_{\mathrm{H_2O}}/\sigma^{\bar{\nu}_\mu}_{\mathrm{CH}} &= 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.}) \\
\sigma^{\bar{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}} &= \left[1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1} \\
\sigma^{\bar{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= \left[1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1} \\
\sigma^{\bar{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}}/\sigma^{\bar{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.})
\end{aligned}
$$

Oscillation Studies at the FAR detector: T2K-SK



The Oscillation Measurements: Super-Kamiokande

(General details already covered in Roger's talk)

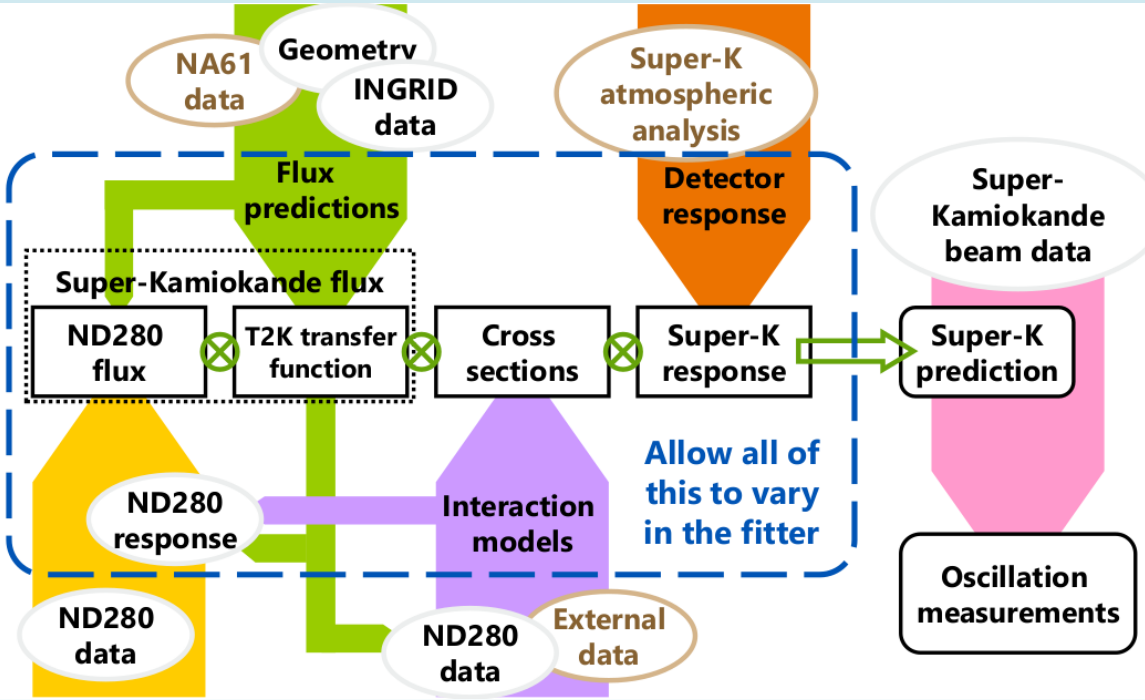


Phys. Rev. D 96, 011102

Octant degeneracy? CP violation?

Order of Mass Hierarchy ?

The Analysis Strategy (Conceptual):



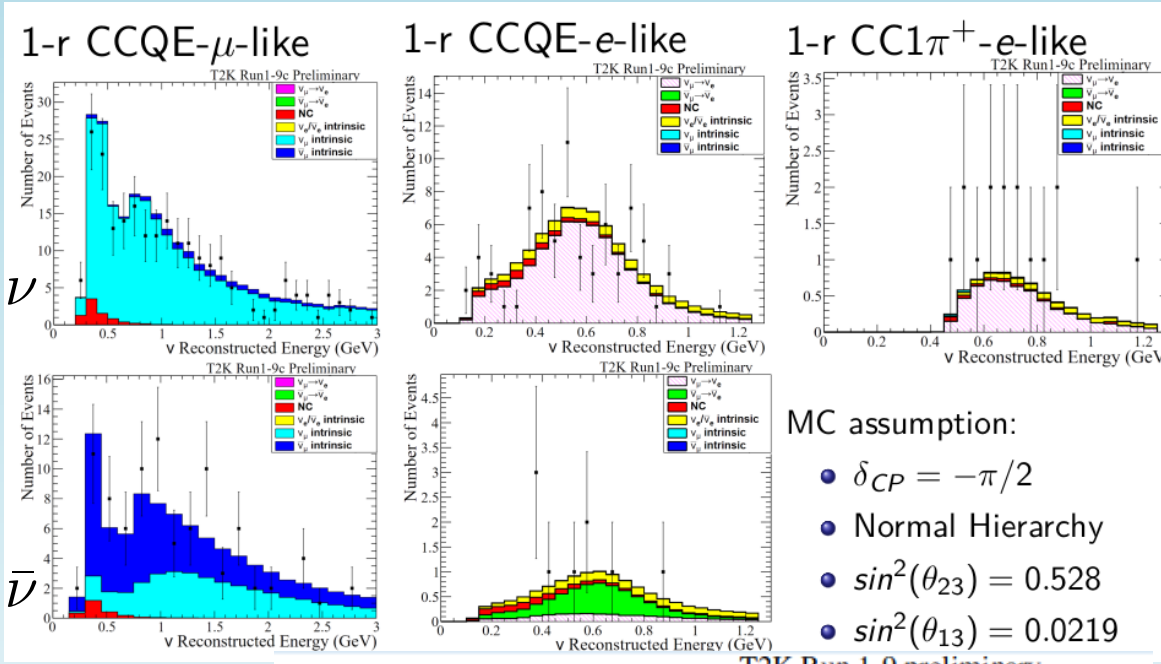
- ν_μ Disappearance: Precision measurement of θ_{23} and Δm^2_{32}
- $\nu_e/\bar{\nu}_e$ Appearance: δ_{CP}

Analyses & Results:

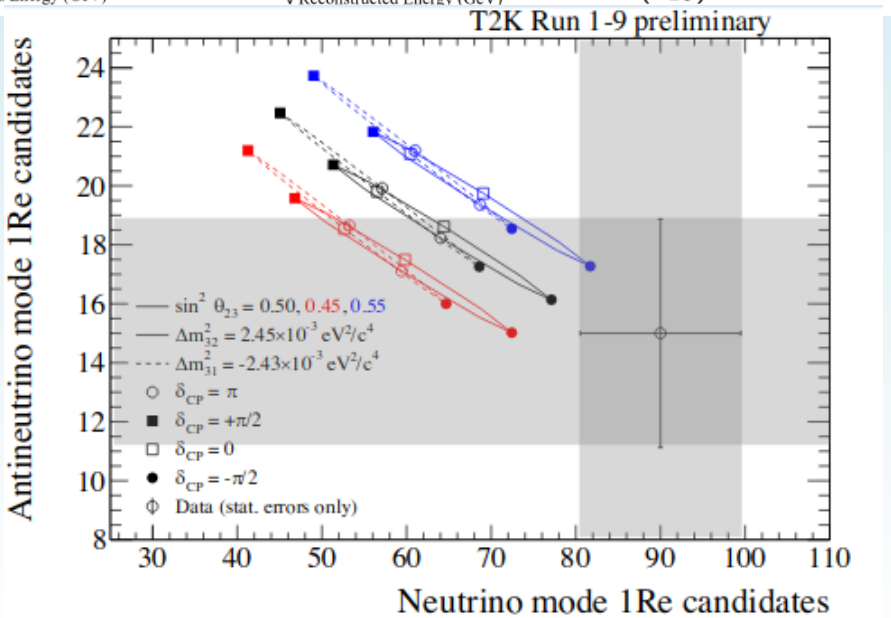
- Improved reconstruction & classifier
- Expanded Fiducial Volume
- Select events with no pions (& $\nu_e 1\pi^+$)

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

- Fit is done simultaneously to all five data samples

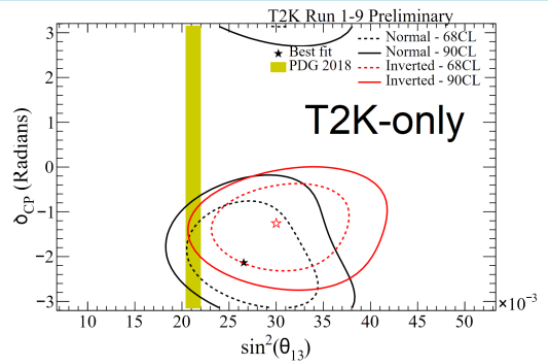


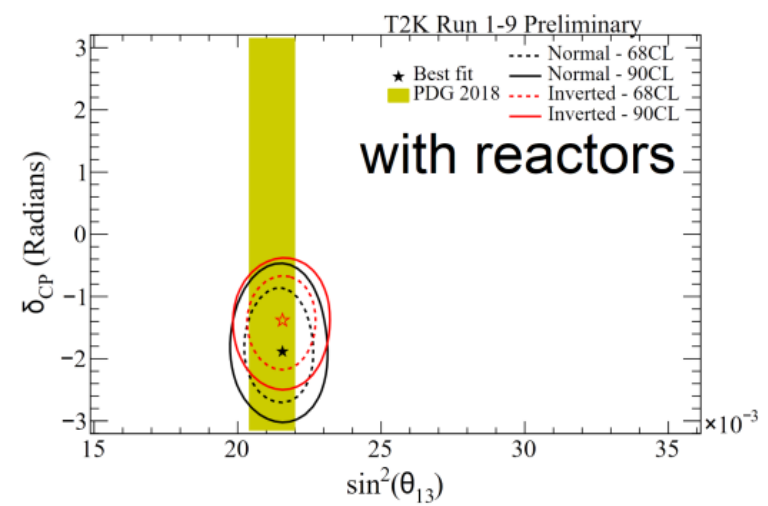
Sample	Predicted				Observed	Systematic uncertainty for prediction
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
ν̄ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
ν̄ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + 1π⁺	7.0	6.1	4.9	5.9	15	18.4%



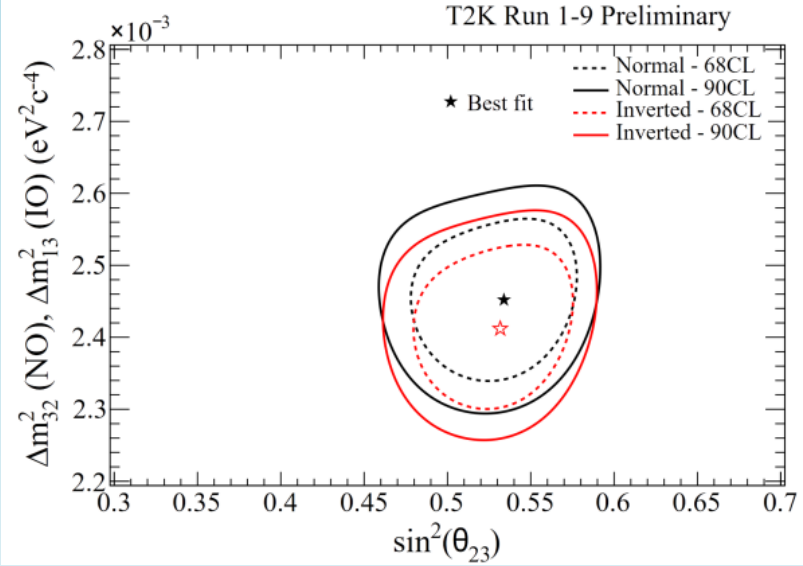
Results from T2K-SK data:

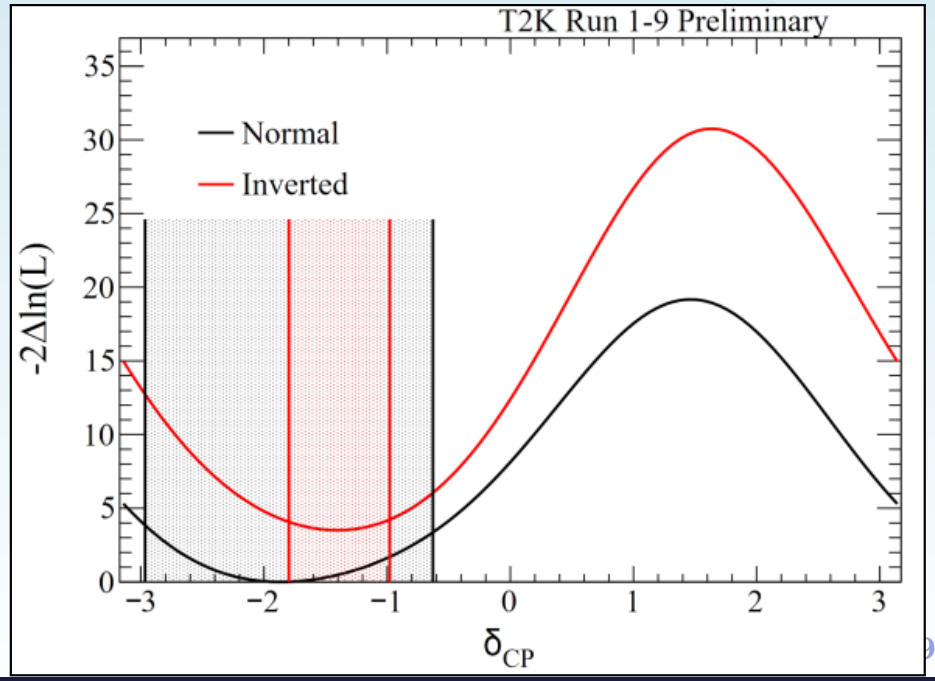
- Favoring $\delta_{CP} \sim -\pi/2$, 2σ confidence interval
- Including reactor constrain, matches PDG2018 value: $\sin^2\theta_{13} = 0.0212$





- Maximal mixing favored



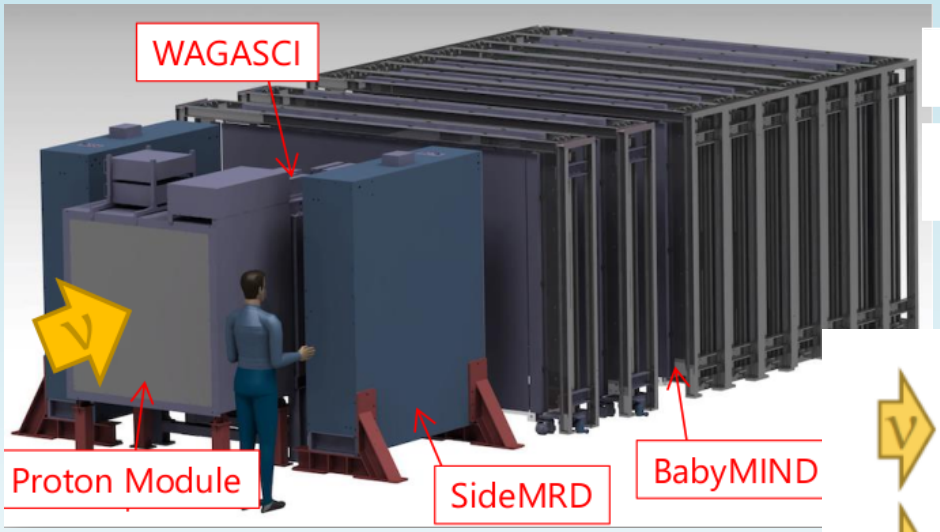


Status Summary and Prospects:

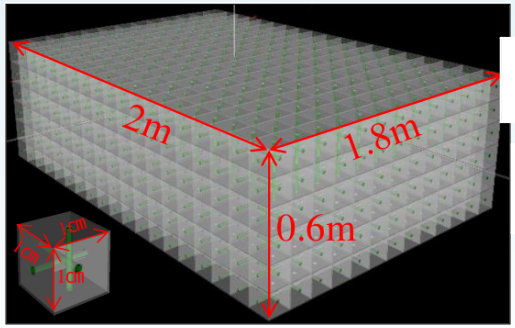
- T2K has added more new $\bar{\nu}$-data in the analyses.
- Oscillation Results updated; 2σ in deciding CP-violation
- T2K-near detectors: on-axis, off-axis: Cross sections measured for several samples, several still on-going.
- T2K near detectors (ND280/WAGASCI/BABYMIND) and beamline upgrade to allow 750 kW–1.3 MW: to set for obtaining 3σ in deciding CP-violation.

Status Summary and Prospects: (contd...)

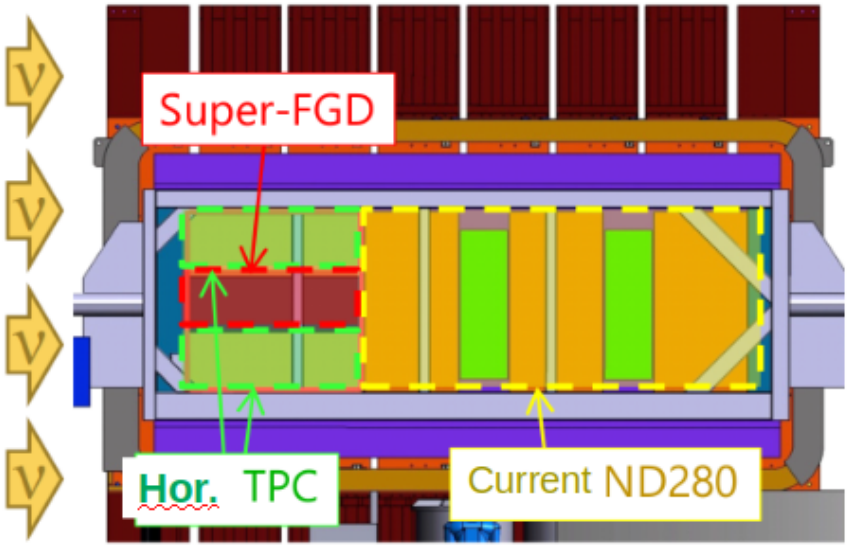
- New off-axis WAGASCI already started
- BABYMIND being integrated, to add charge id-capability to WAGASCI
- Ongoing efforts to install the ND280-Upgrade very soon



Details talked at Kenji/Giorgio posters



More@posters: Soichiro, Takuji,Yuki



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Thank you !

Back ups:

We define for every bin k:

$$\hat{N_k} = \frac{\sum_j^{n_r} U_{jk}(N_j^{sel} - B_j)}{\epsilon_k}. \tag{1}$$

- the selected events in reconstructed bin $j = 1, ..., n_r$: N_j^{sel}.
- the background events in reconstructed bin j: B_j.
- the generated events in true bin $k = 1, .., , n_t$: N_k

The smearing matrix S_{jk} = the number of events generated in the k-th bin and reconstructed in the j-th bin.

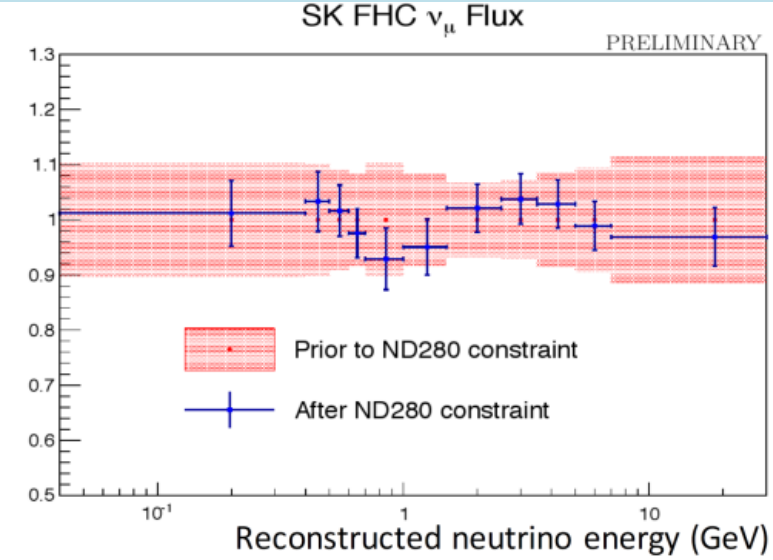
- the probability to have an event reconstructed in the bin j when it has been generated in the true bin k: $P(j|k) = \frac{S_{jk}}{N_k}$
- the probability that an event was generated in the truth bin k given that it was reconstructed in bin j: U_{jk} (unfolding matrix)

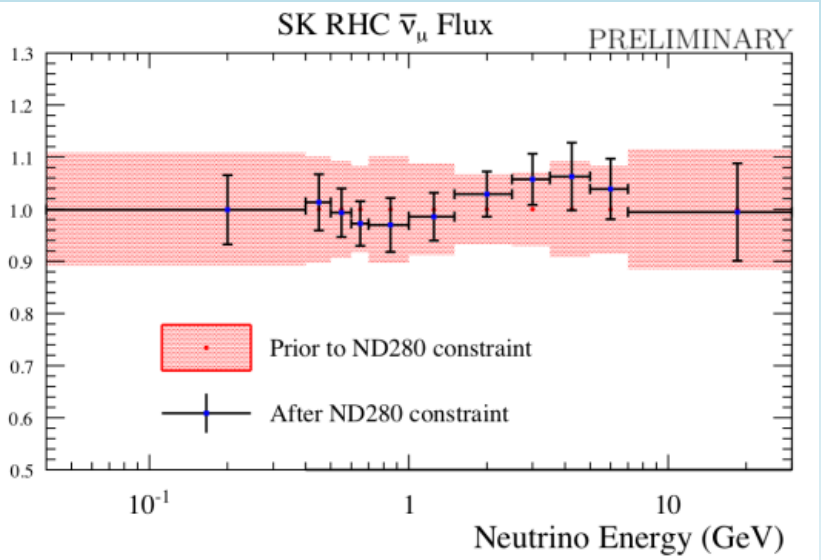
$$U_{jk} = \frac{\frac{S_{jk}}{N_k}\frac{N_k}{\sum_k N_k}}{\sum_\alpha^{n_t}(\frac{S_{j\alpha}}{N_\alpha}\frac{N_\alpha}{\sum_\alpha N_\alpha})} = \frac{S_{jk}}{\sum_\alpha^{n_t} S_{j\alpha}} \tag{2}$$

$$\epsilon_k = \frac{\sum_j^{n_r} S_{jk}}{N_k} \tag{3}$$

Back

Effect of ND280-fit on SK-analyses:





Sample	w/o ND280	w/ND280
FHC $1R_\mu$	14.6%	5.1%
RHC $1R_\mu$	12.5%	4.5%
FHC $1R_e$	16.9%	8.8%
RHC 1Re	14.4%	7.1%

The Oscillation Probability:

Appearance

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$