T2K latest oscillation results

+ combined SK+T2K data fit results!

Adrien Blanchet

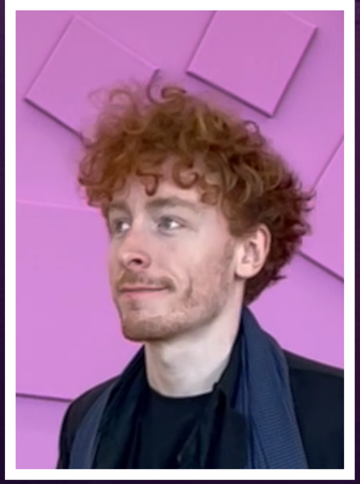
For the T2K collaboration

XXth International Workshop on Neutrino Telescopes (2023)
2023-10-25 - Venezia / Italy

Super-Kamiokande

Probably Tokyo..?

Mount Fuji !

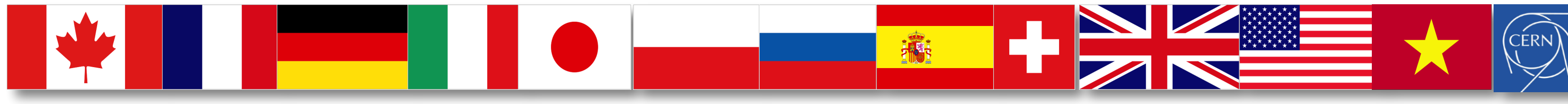


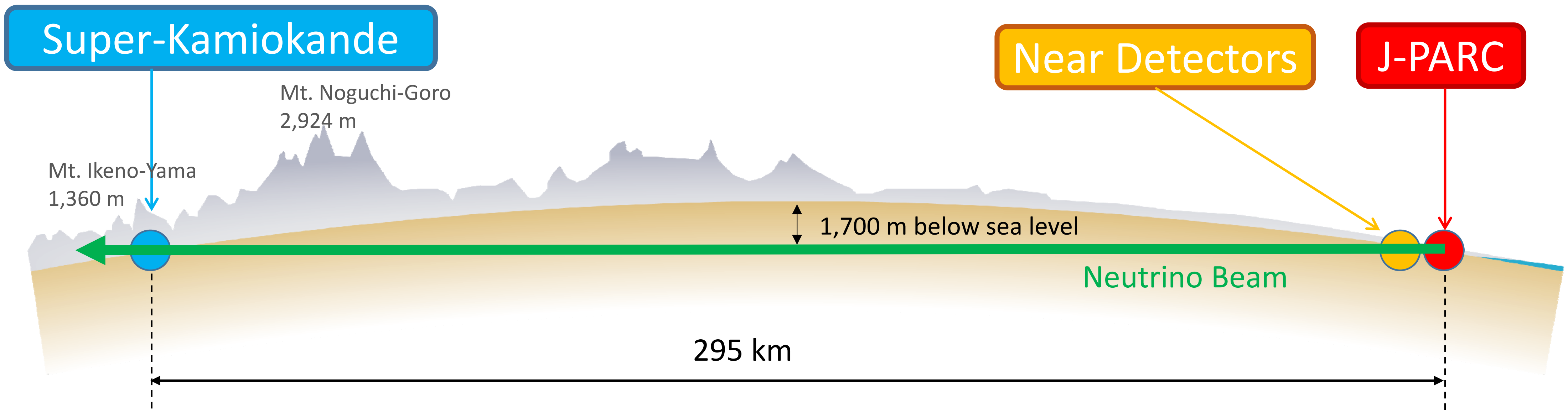
A flight to Japan in June 2023

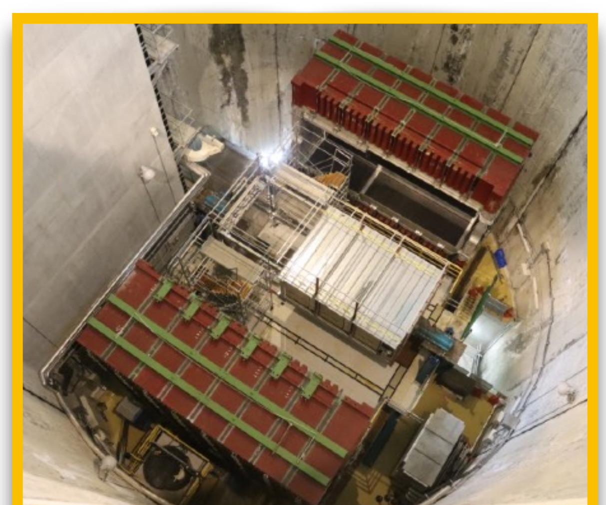
The T2K experiment

See **Thomas Holvey** talk for the global summary!

~500 collaborators across 14 countries and 75 institutes



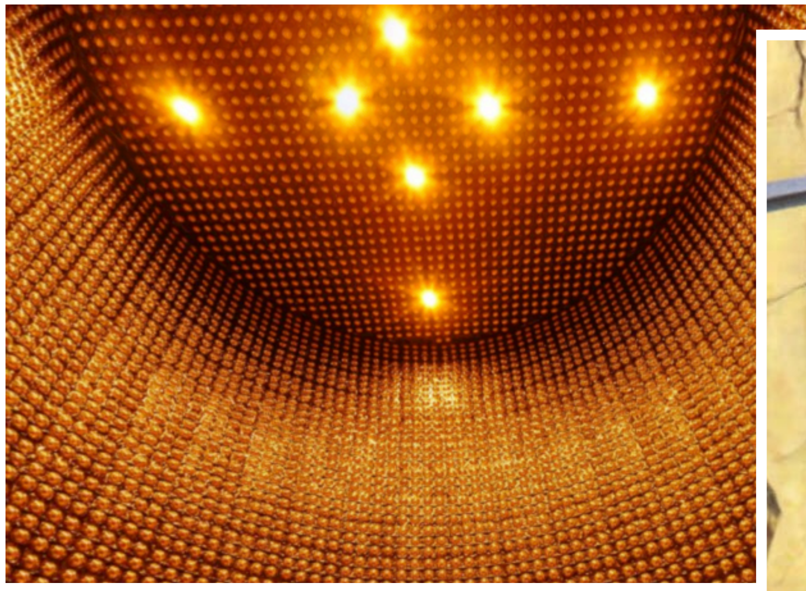


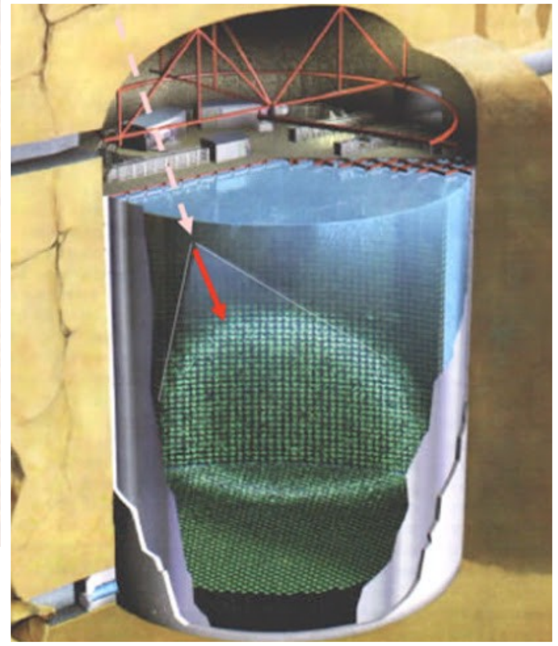


$\nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_\mu, \nu_\mu \longleftarrow \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

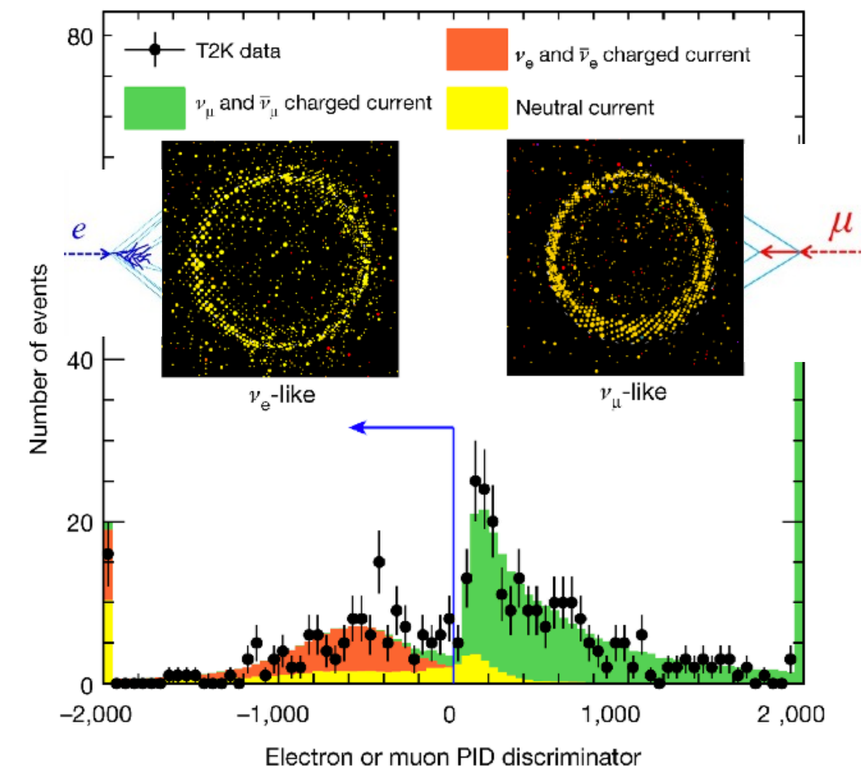
- Measure oscillation parameters with accelerator neutrinos
- Understand better neutrino interactions with matter

Highlighting Super-Kamiokande and ND280



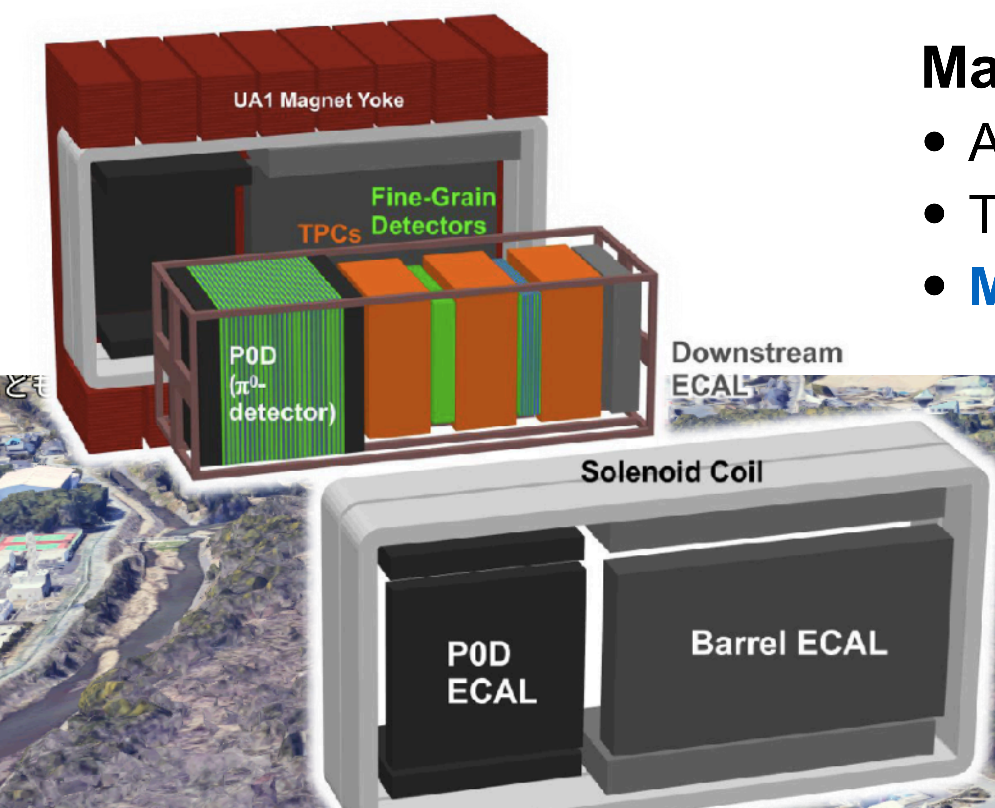


Nature 580, 339–344 (2020)



Super-Kamiokande

- Good particle identification using the ring shape and sharpness
- Neutrino energy reconstruction from lepton momentum and angle wrt beam direction
- **Not magnetised:** need near detector constraints for wrong-sign backgrounds



Main near detector: ND280

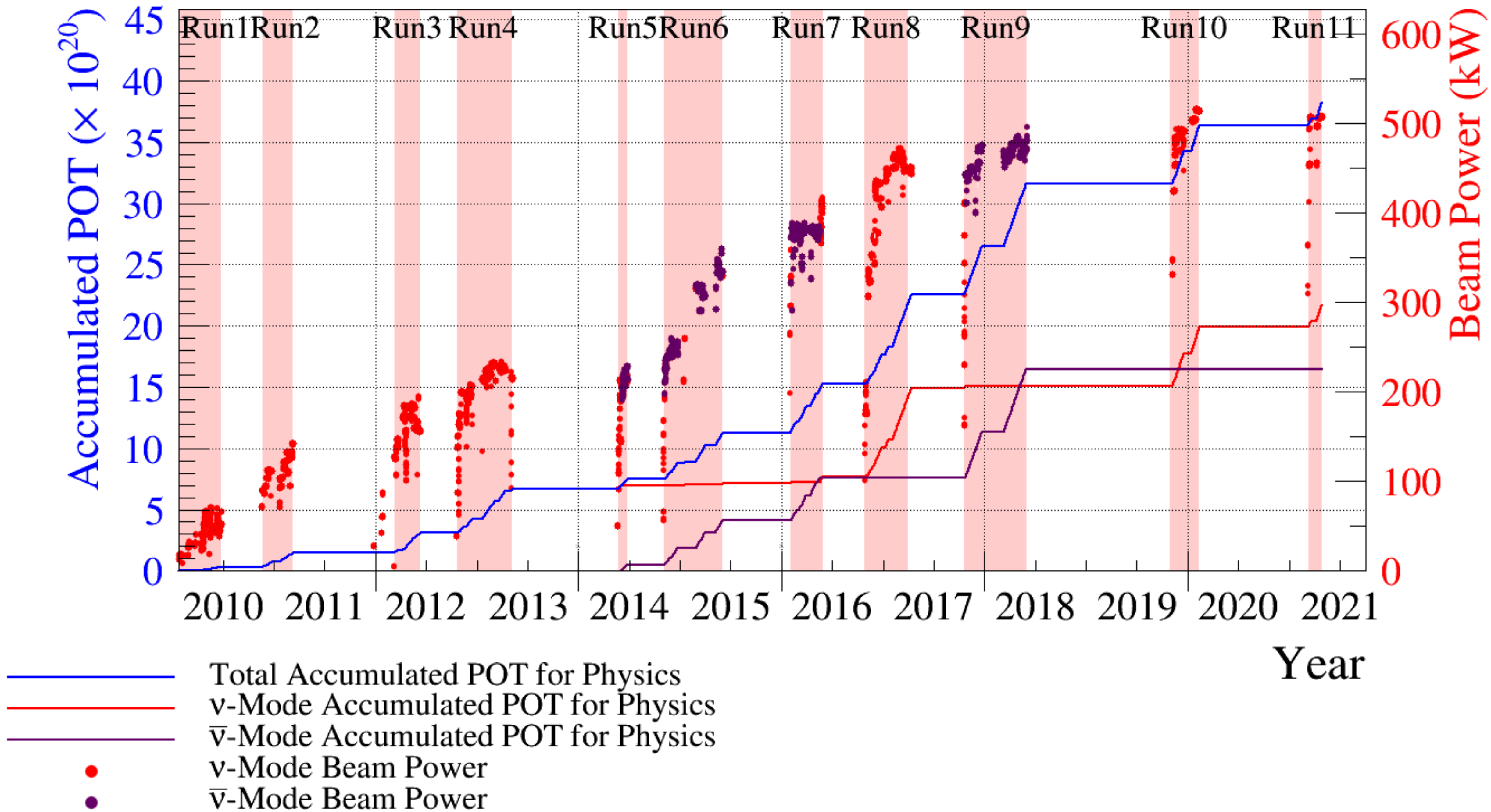
- Active scintillator (C) and passive water (O) neutrino targets
- Tracking particles with time projection chambers
- **Magnetised:** for charge and momentum reconstruction

Oscillation analysis with 2022 data release

This talk — new samples (stat. increase) — presented at Neutrino 2022

Presented at Neutrino 2020, paper published in EPJC

Nature (early 2020) — short paper **580, 339–344 (2020)**
Phys. Rev. D — long paper Phys.Rev.D 103, 112008

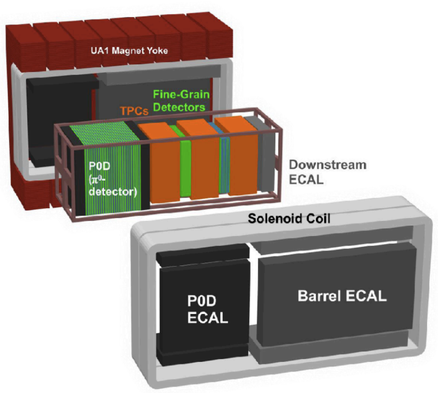


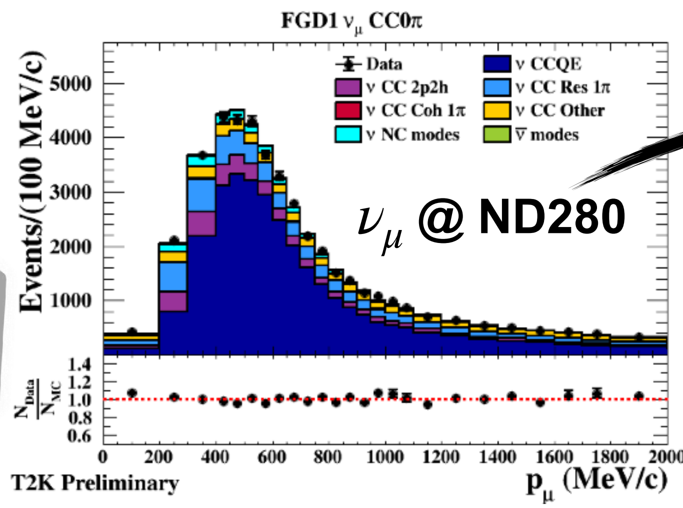
Overview and highlights of this analysis

{ Observed event rate @ SK } = { ν Flux models } × { ν cross-section models } × { SK detector model } × { oscillation parameters }

Constrained by ND280 (applies to the flux and cross-section models)

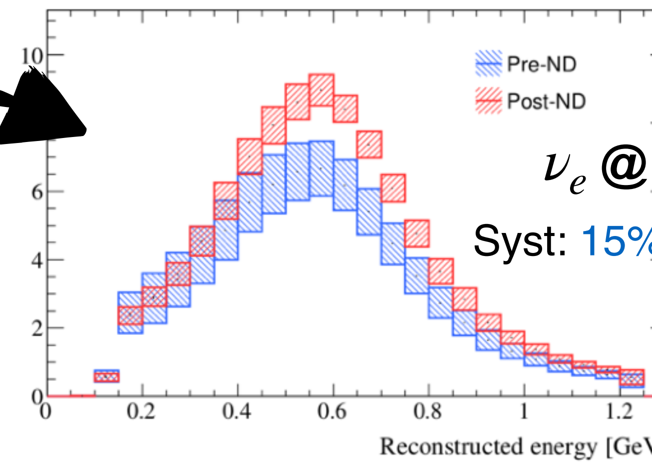
What we seek (applies to the oscillation parameters)





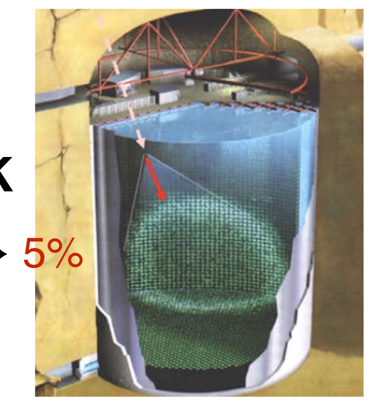
ν_μ @ ND280

Constrains and corrects *flux & cross-section systematics*



ν_e @ SK

Syst: 15% → 5%



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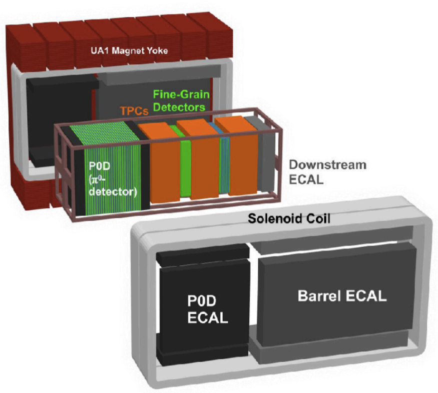

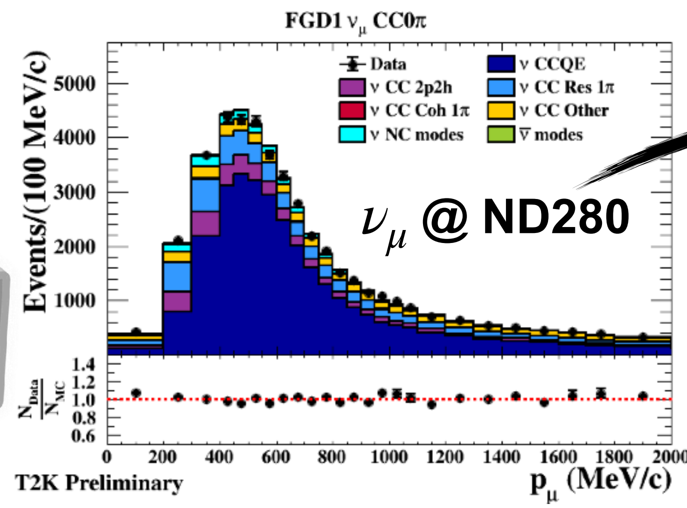

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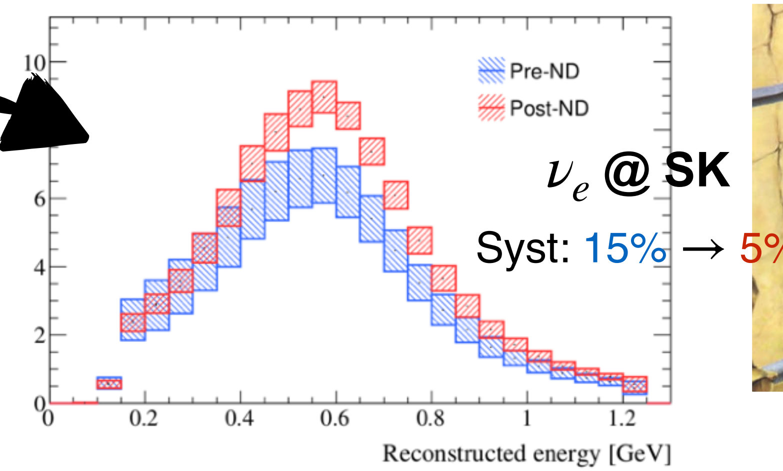

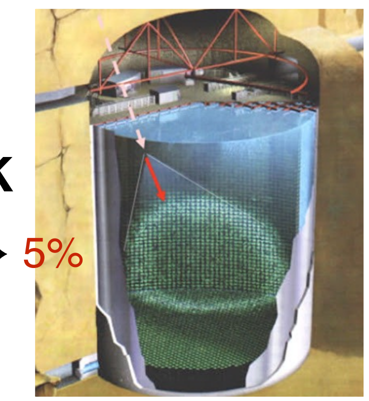

Improved flux model

- More realistic beam line modelling + use of beam monitor data
- Using high-statistics NA61 2010 kaon dataset

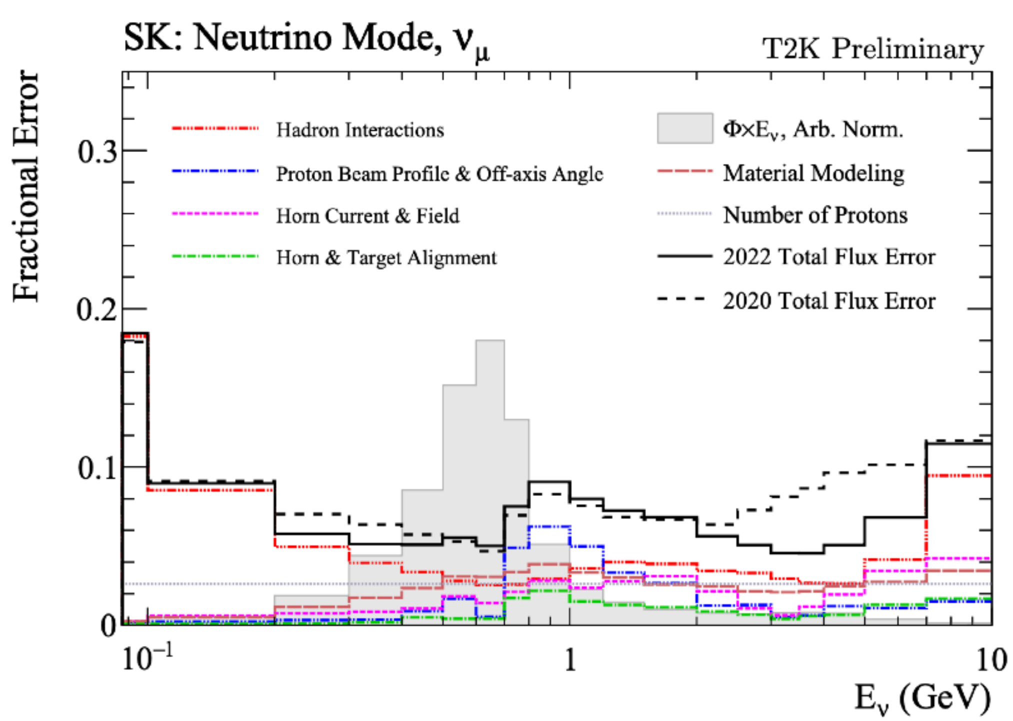

Photo from this summer
(by Eric D. Zimmerman, NA61/SHINE)

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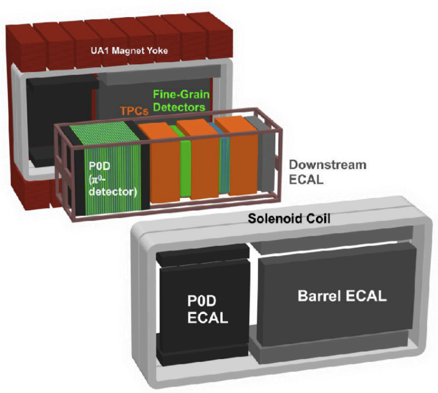
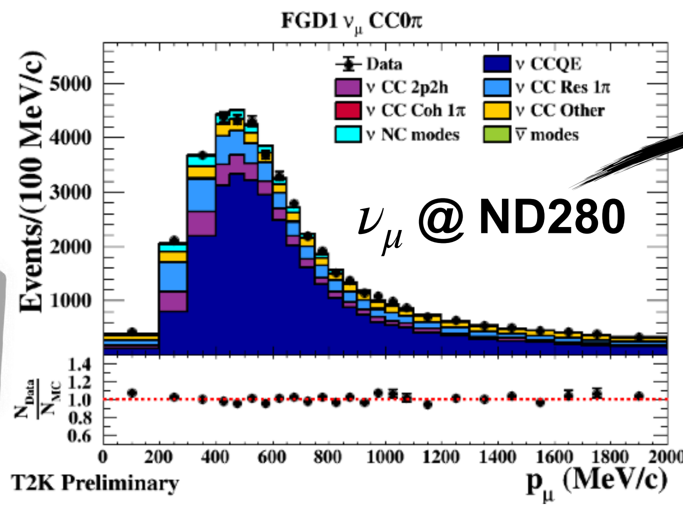
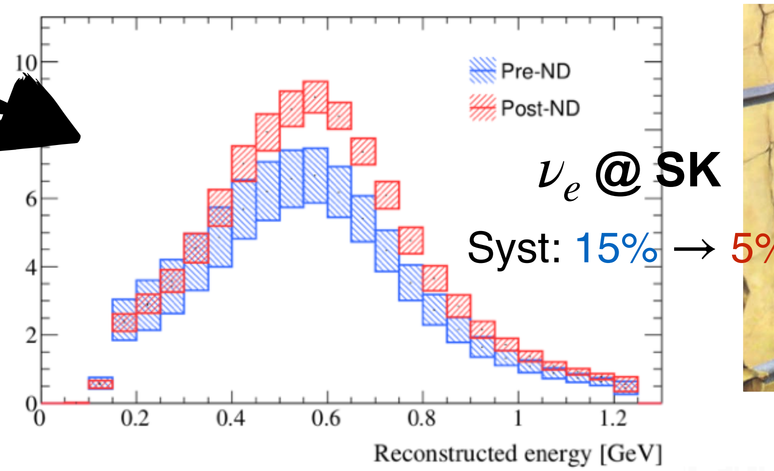
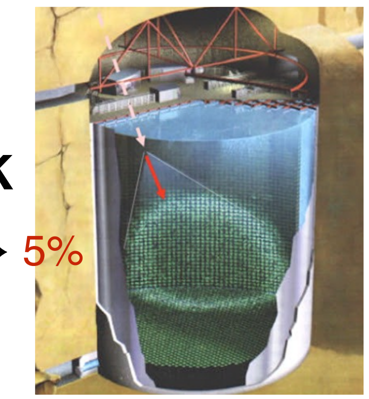
Constrained by ND280 | What we seek





Constrains and corrects *flux & cross-section systematics*



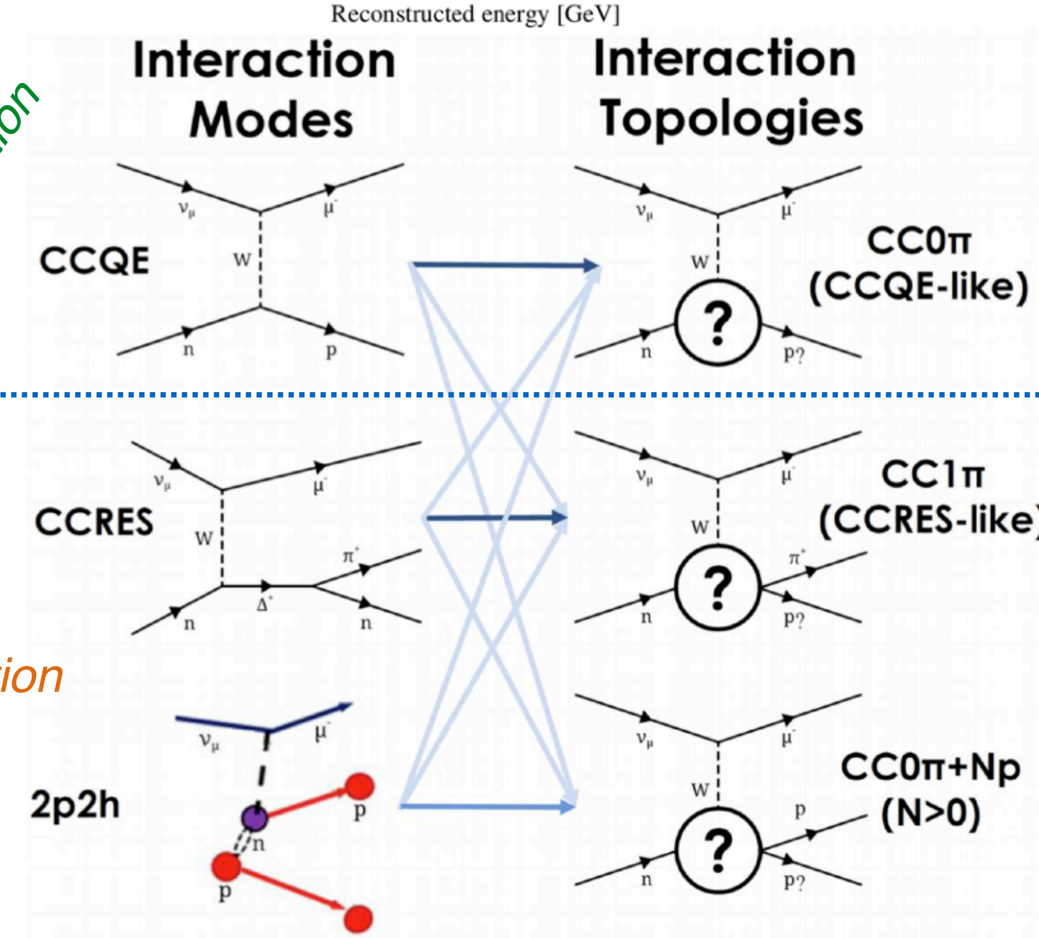


Updates to our interaction models

- Improved CCQE based on **Spectral Function model**
  - *uncertainties on nucl. shell structure*
  - *Improved momentum transfert modelling: optical potential, Pauli blocking…*
- Uncertainties for tagging protons:
  - *2p2h separation in pp and pn*
  - *nucleon FSI*
- Resonant pion production mode
  - *new uncertainties including effective binding energies*

Good E_ν reconstruction

Mis-reconstruction of E_ν



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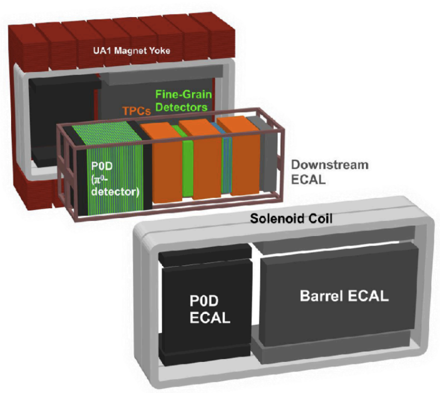
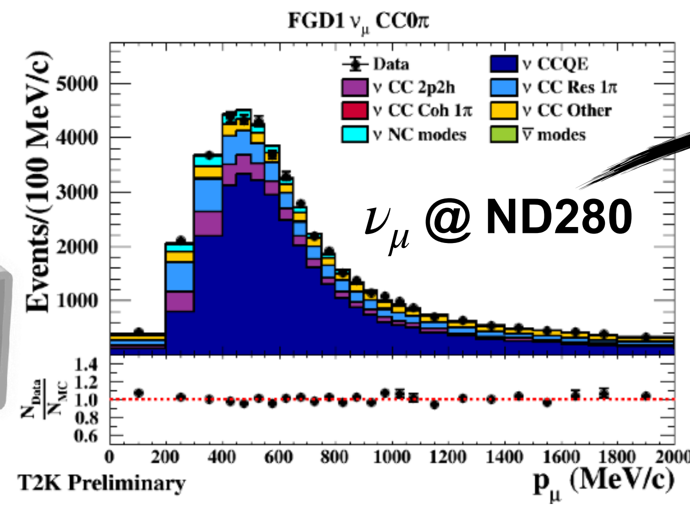
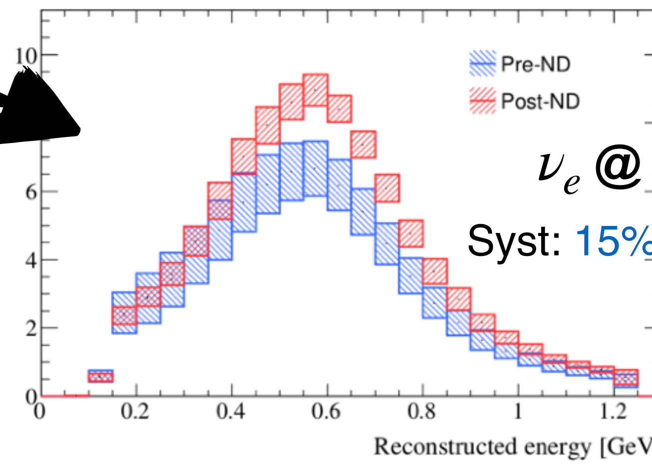
Constrained by ND280 | What we seek





***Constrains and corrects** flux & cross-section systematics*



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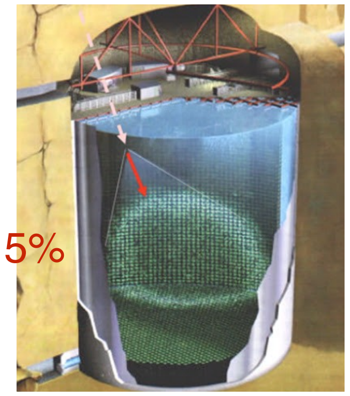
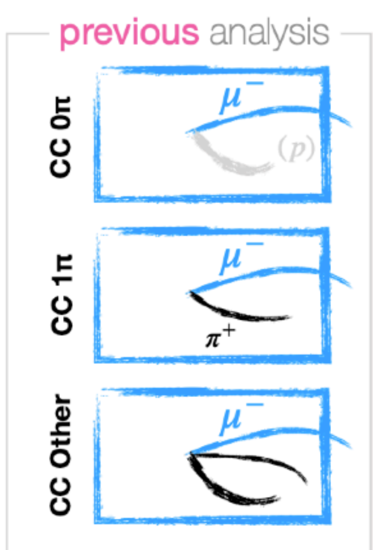
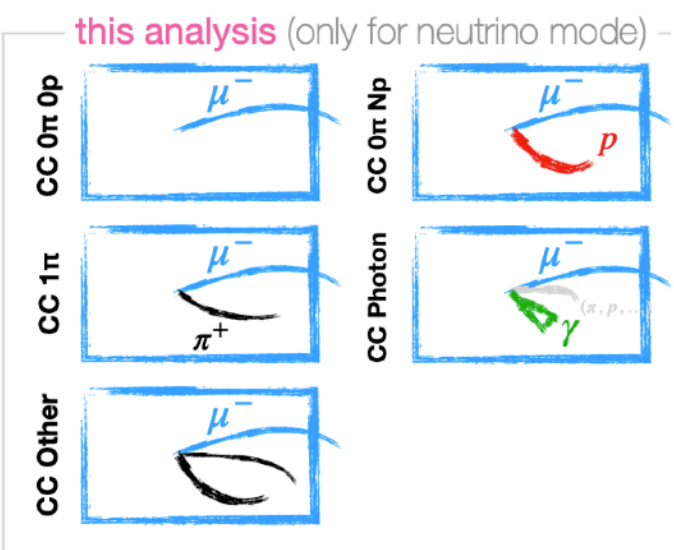
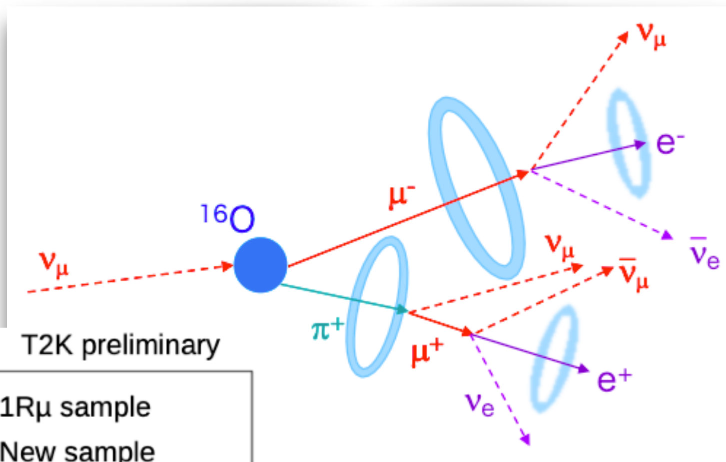


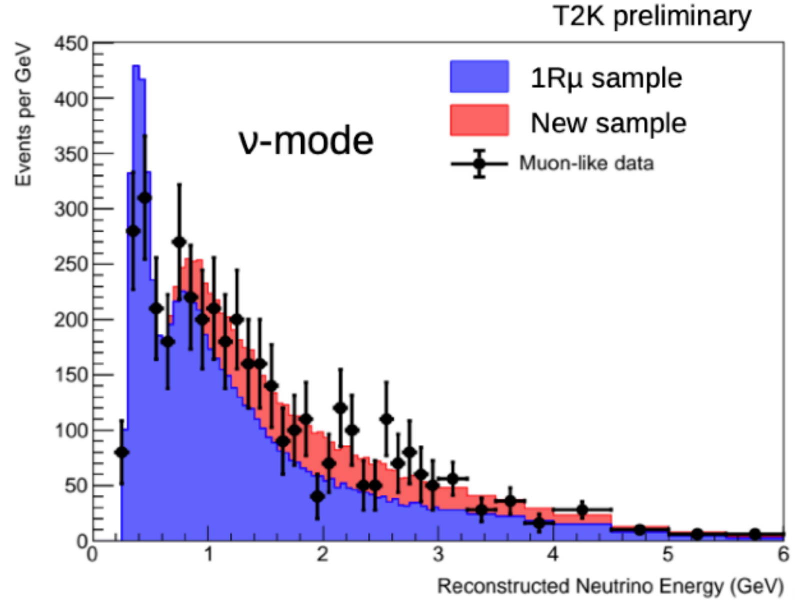
New samples

- 22 samples in ND280 now also separated by p, γ presence
- 1 numuCC1Pi sample in SK + adding multiring events





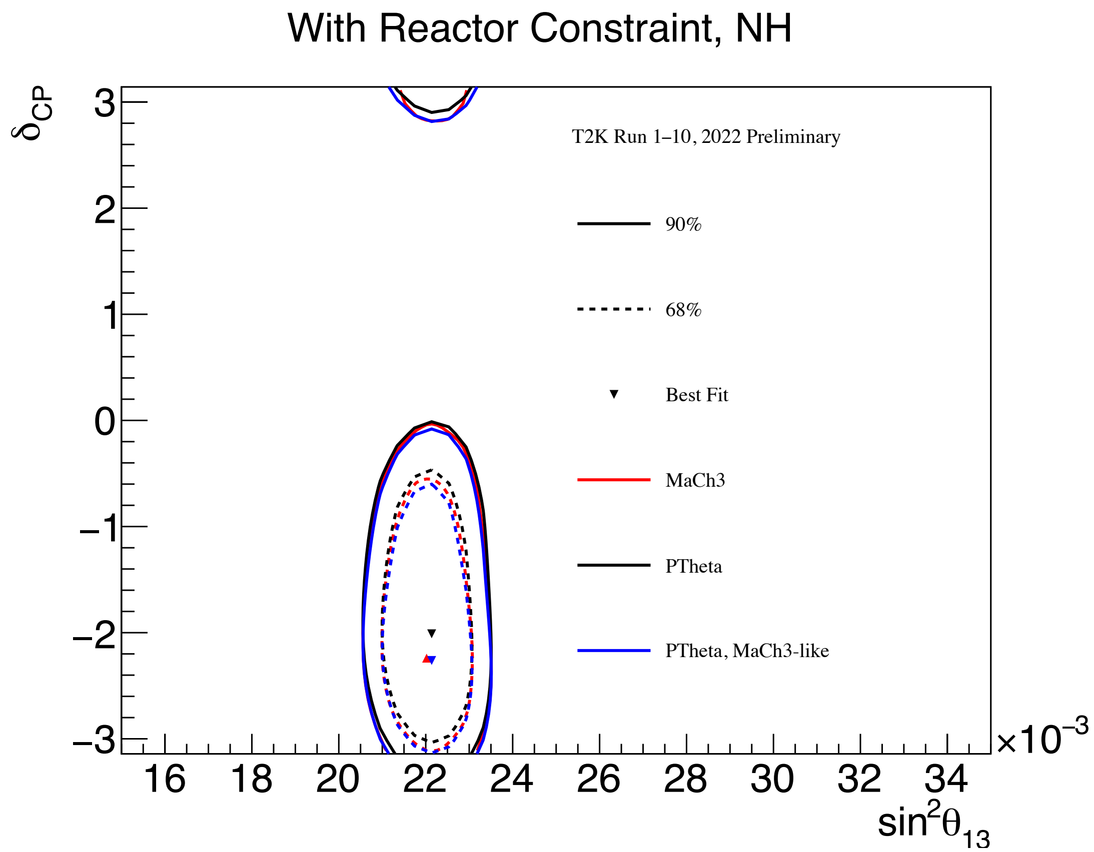




Robustness studies

Complementary fitting approaches

- (Semi-)Frequentist approach: (**P-Theta software**)
  - Using FD data only + constraints from ND as prior
  - Feldman-Cousins approach for estimating C.L.
- Bayesian credible intervals: (**MaCh3 software**)
  - Metropolis-Hastings MCMC algorithm
  - Joint ND + FD
- Very **similar results** in both approaches!

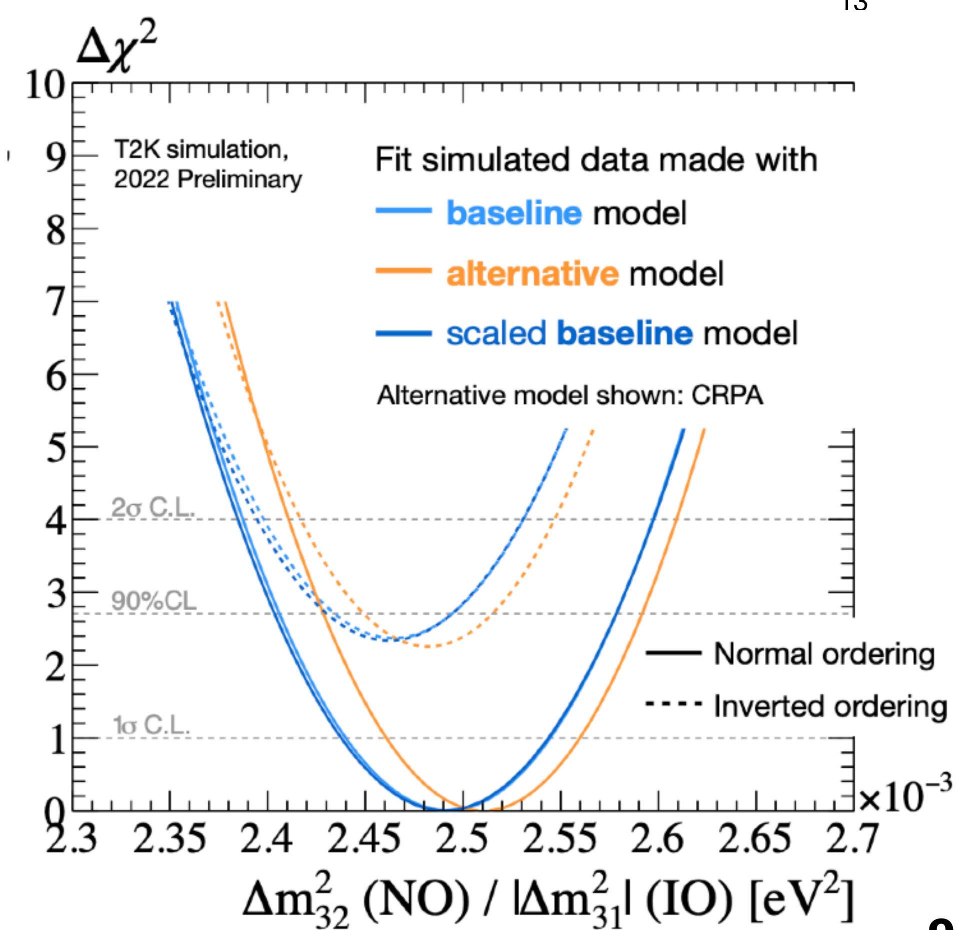


Alternative model studies

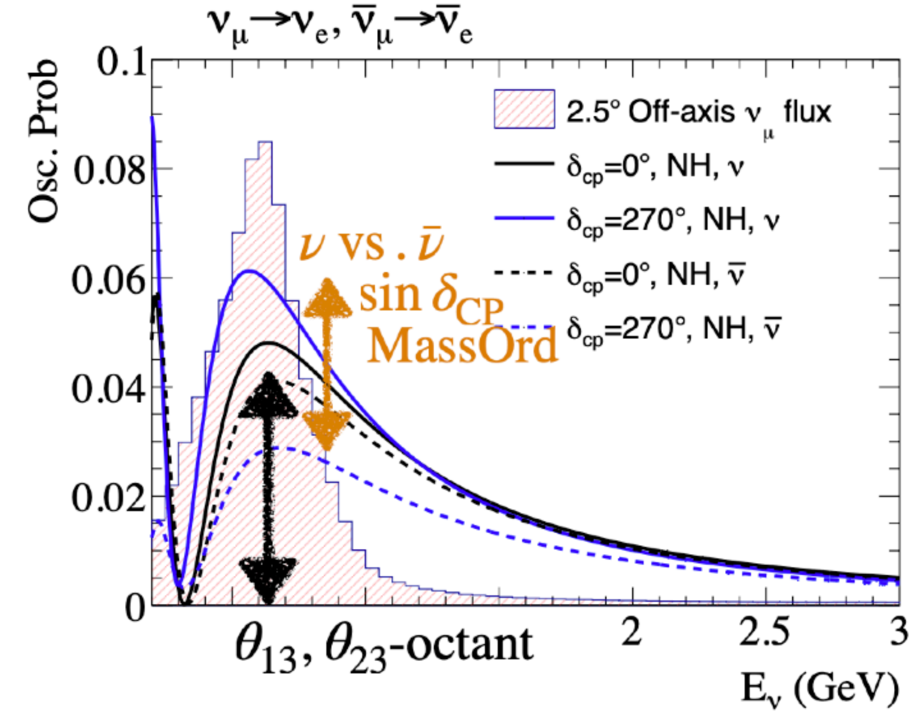
- Test how our parametrisation of the systematics is able to absorb mismodeling of interaction channels
- Using fits to "simulated data" from theory or data-driven **alternative interaction models, pion production, nuclear models…**
- Quantify biases induced on oscillation parameters

- No bias observed for θ_{23}
- Small effect on δ_{CP} but no change of the main conclusions
- **Small bias observed for Δm^2_{32}**
  - Additional gaussian uncertainty added to compensate:

$$\pm 2.7 \times 10^{-5} \mathrm{eV}^2$$



2022 (latest) oscillation results — δ_{CP}

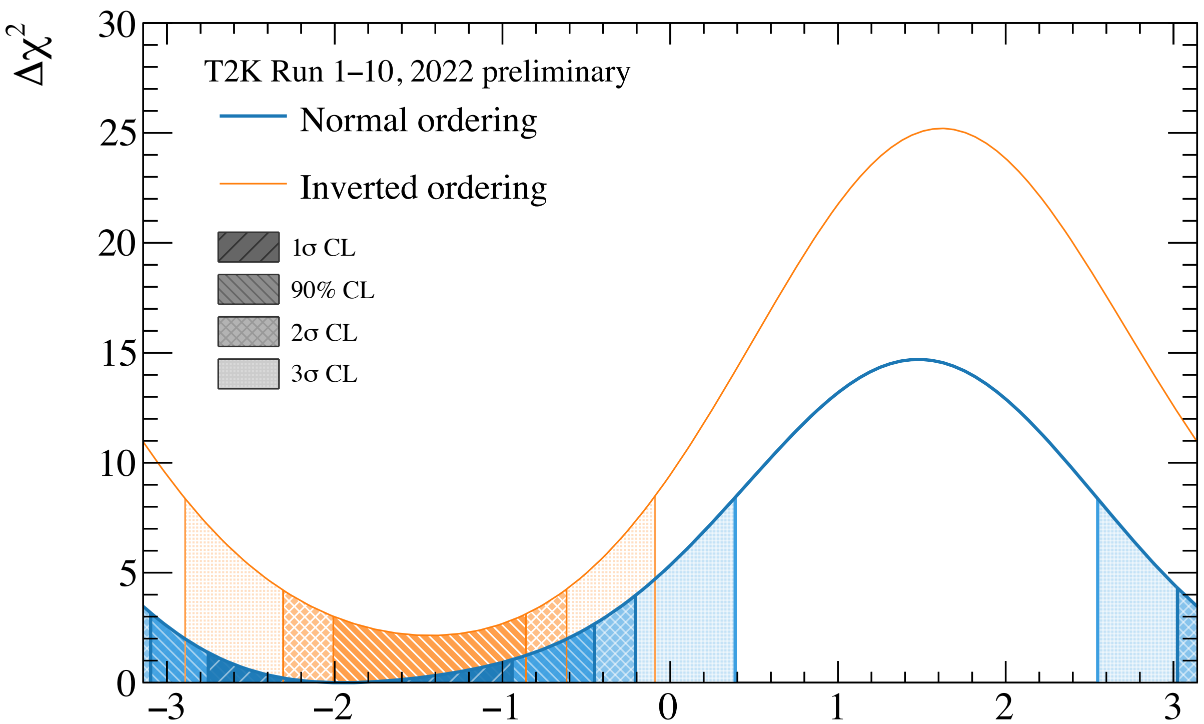


Adding reactor oscillation angle as an external constraint

- θ_{13} constraints of T2K are consistent with reactor antineutrino experiments (PDG value)

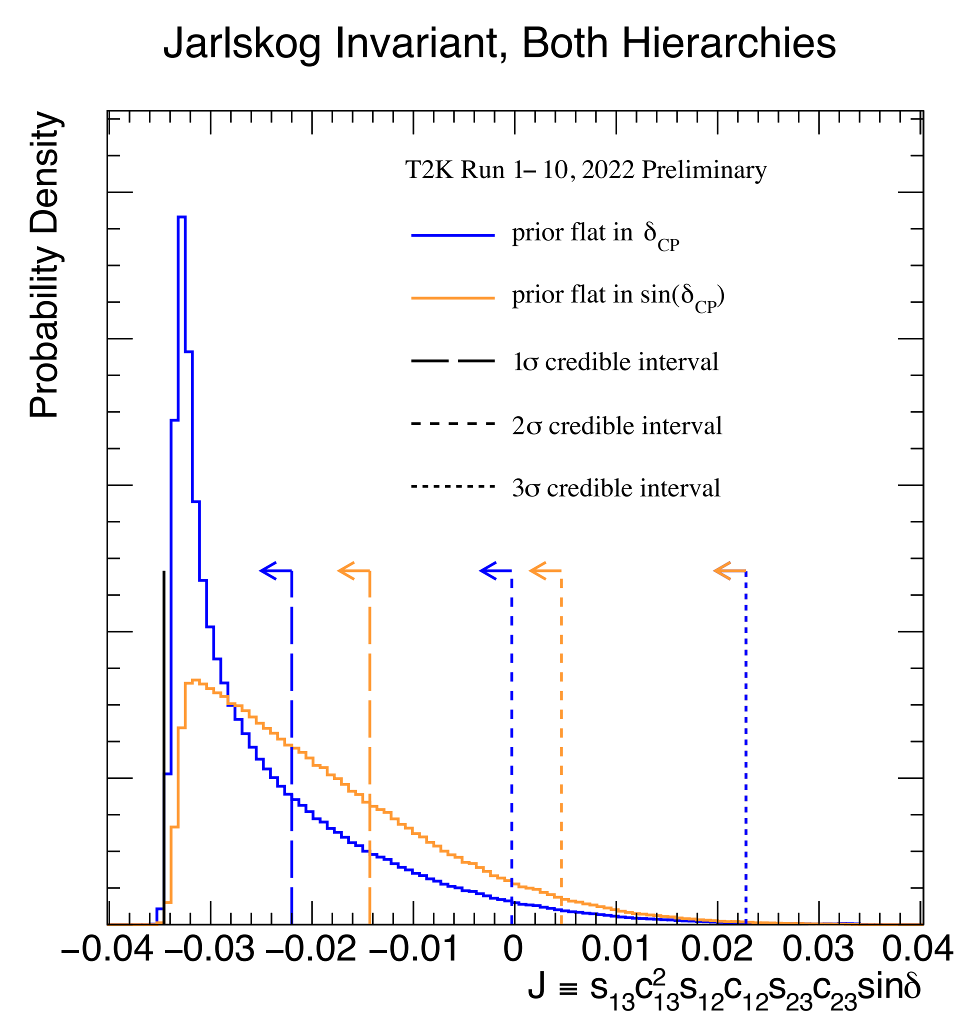
Results on the CP phase measurement

- Large region **excluded at 3σ**
- CP-conservation values ($\sin\delta_{CP} = 0$) **excluded at 90% C.L.**
- Weak preference of **normal ordering**



Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.75, -0.94]$	
90%	$[-3.10, -0.45]$	$[-2.01, -0.86]$
2σ	$[-\pi, -0.21] \cup [3.02, \pi]$	$[-2.31, -0.62]$
3σ	$[-\pi, 0.39] \cup [2.55, \pi]$	$[-2.89, -0.09]$

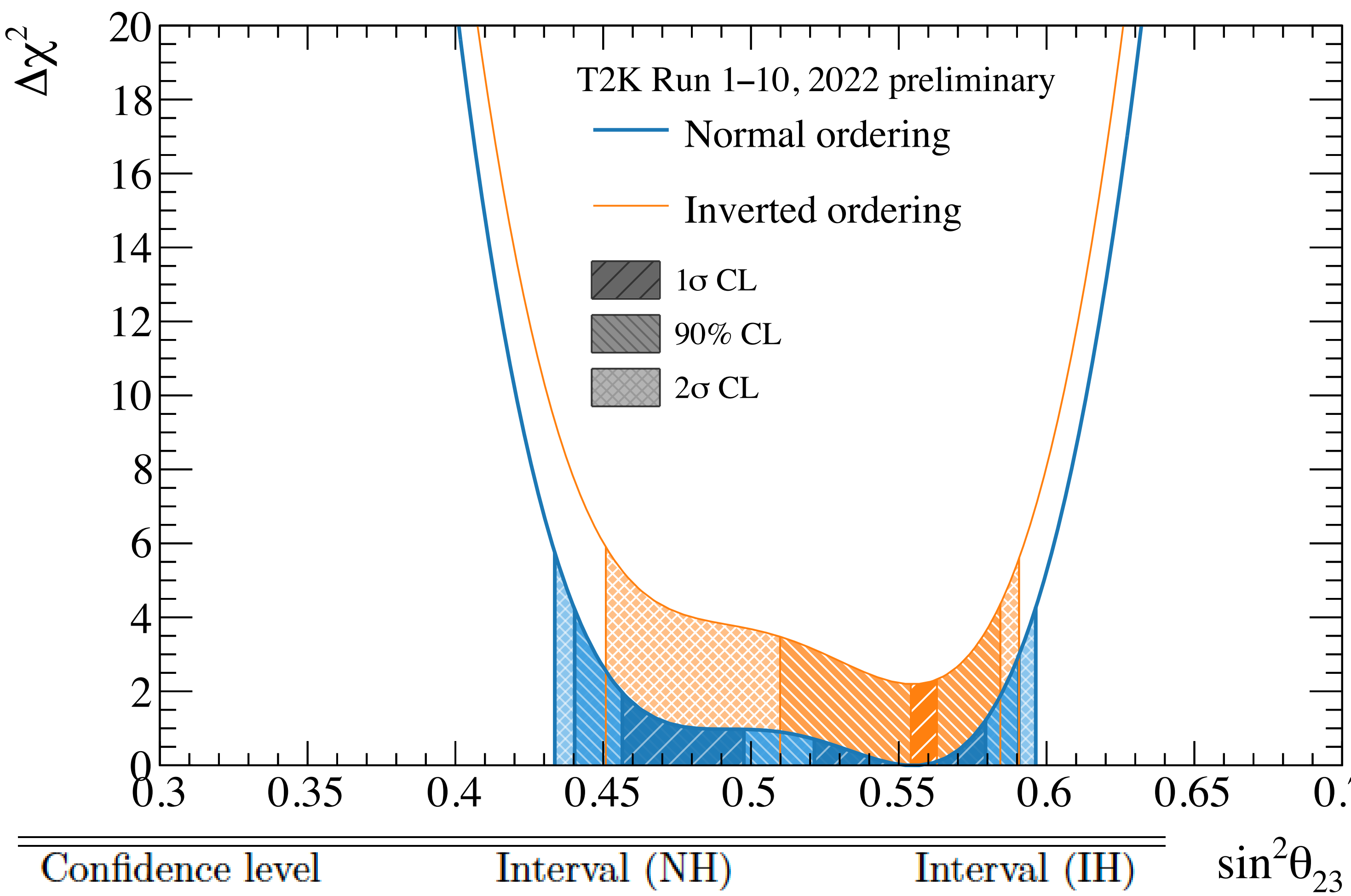
T2K Run 1-10, preliminary



2022 (latest) oscillation results – $\Delta m^2_{32}, \theta_{23}$

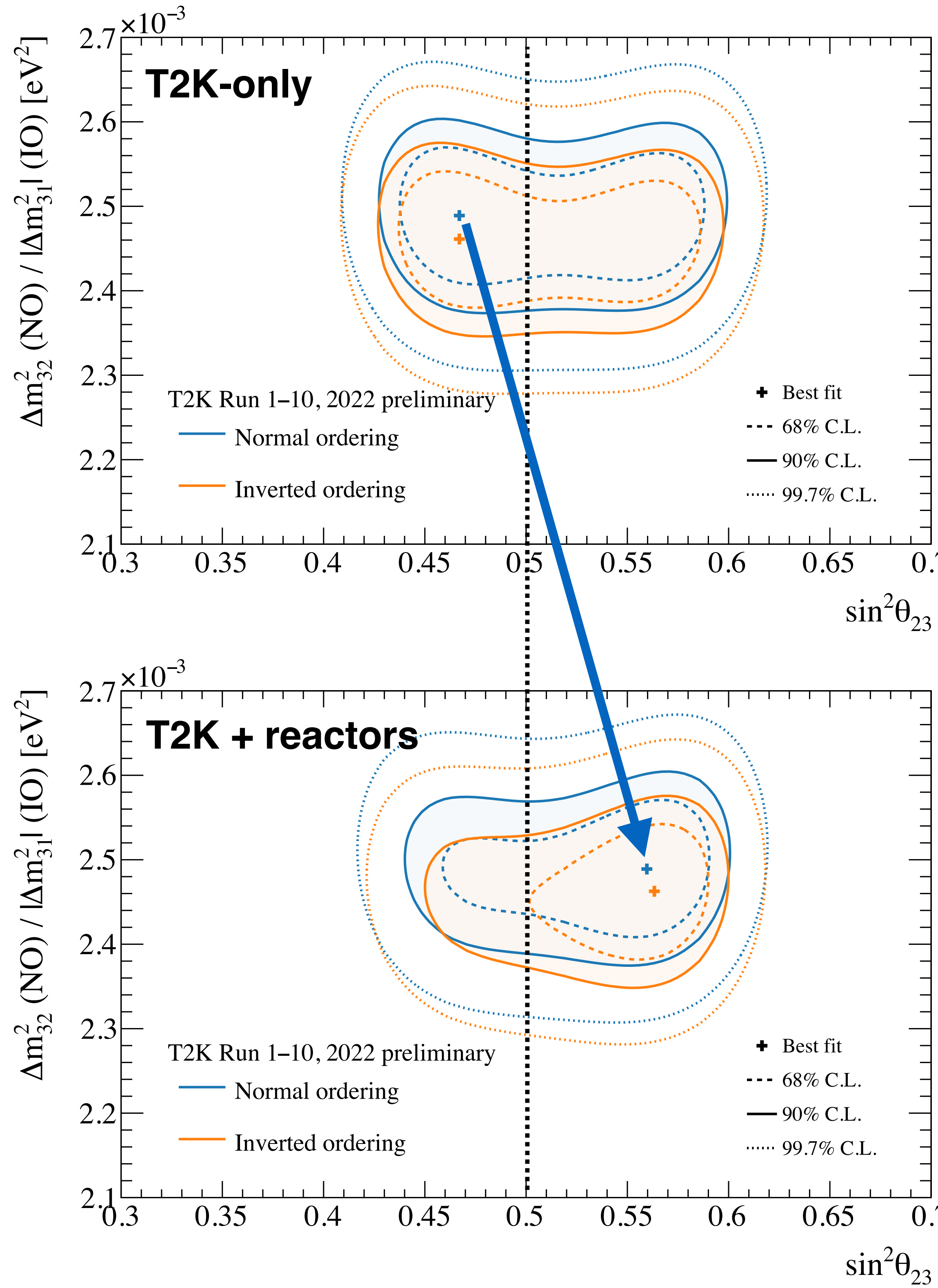
World-leading measurement of atmospheric params

- Sensitivity mainly from $\nu_\mu/\bar{\nu}_\mu$ disappearance samples
- Very weak **preference for the upper octant**
- Multiring events addition allows constraining in a more robust way the CC1pi part of the model



Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.456, 0.498] \cup [0.521, 0.579]$	$[0.554, 0.563]$
90%	$[0.440, 0.591]$	$[0.510, 0.584]$
2σ	$[0.434, 0.596]$	$[0.451, 0.591]$

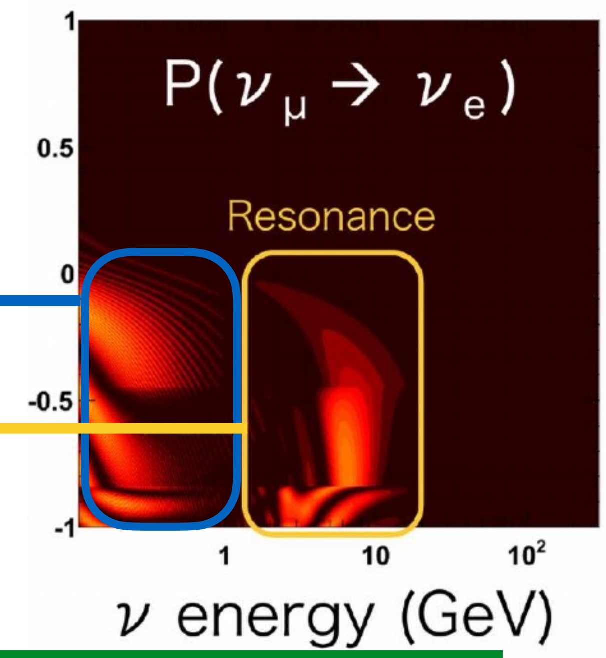
T2K Run 1-10, preliminary



Super-K (atmospheric - ν) + T2K (accelerator - ν)

Motivation for joint fit: example with SK atmospheric neutrinos

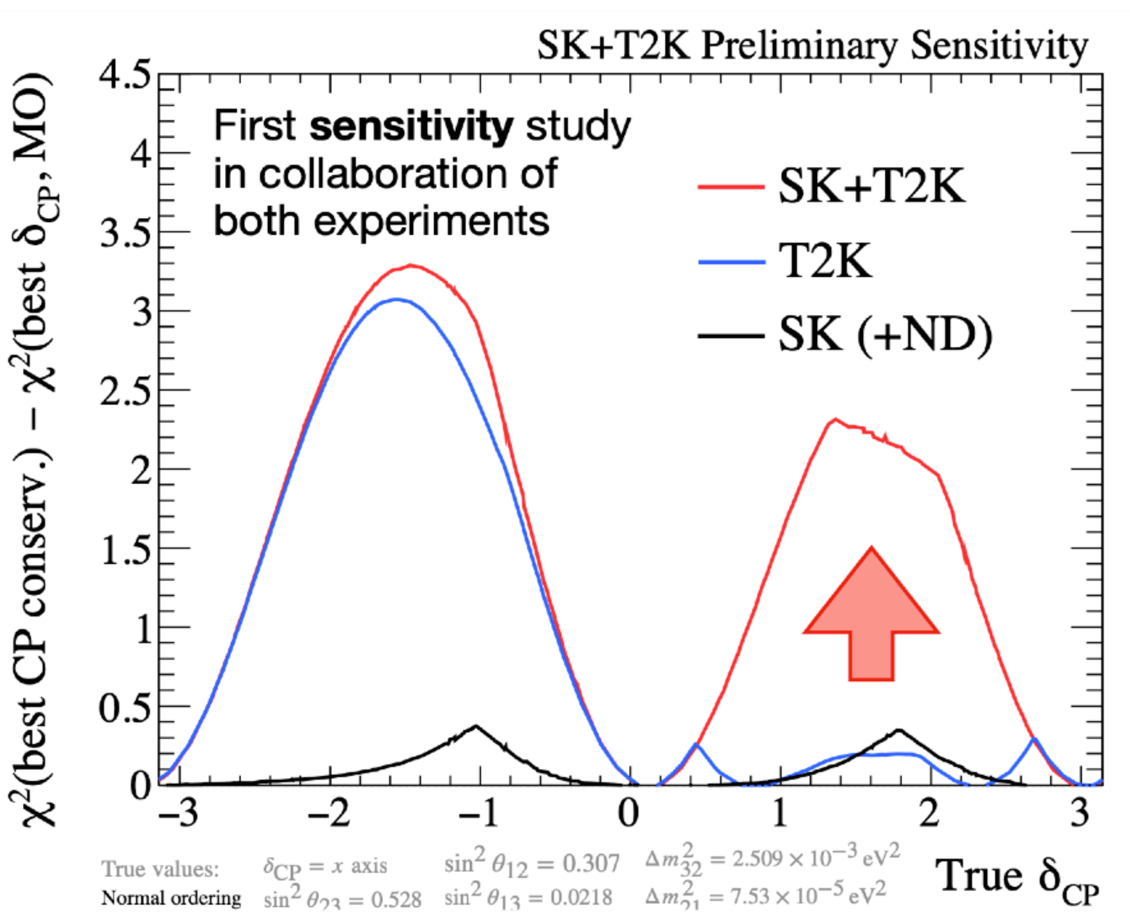
- Use sub-GeV + multi-GeV atmospheric neutrino sample
- Great decoupling between δ_{CP} and Mass Ordering (MO)
- However: **MO highly dependent on $\sin^2(2\theta_{atm})$…**
- … for which the world leading measurement is carried by T2K!



Sub-GeV Neutrino
Better sensitivity in δ_{CP}

Multi-GeV Neutrino
Better sensitivity in MO

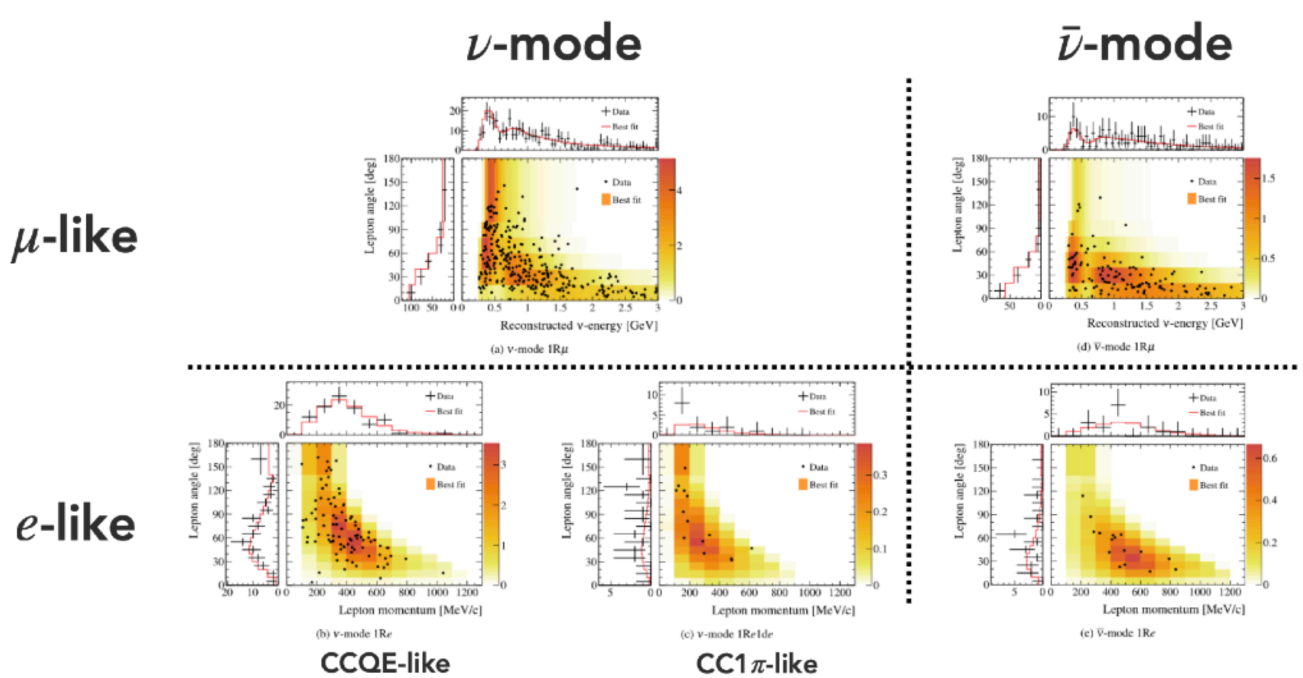
T2K constraint on θ_{23} → **Improves** → **SK constraint on MO** → **Breaks degeneracy** → **T2K constraint on δ_{CP}**



SUPER K + T2K Dataset, samples and systematics

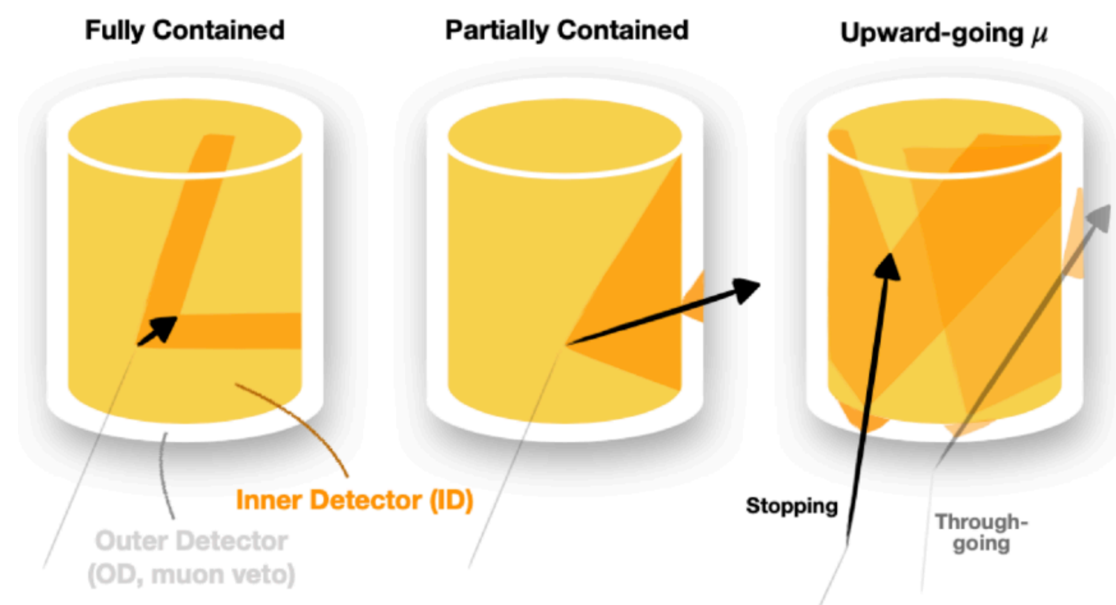
T2K Run 1-10
(from the previous analysis [EPJC])

5 beam samples



SK IV atmospherics
(from [PTEP 2019 (2019) 5, 053F01])

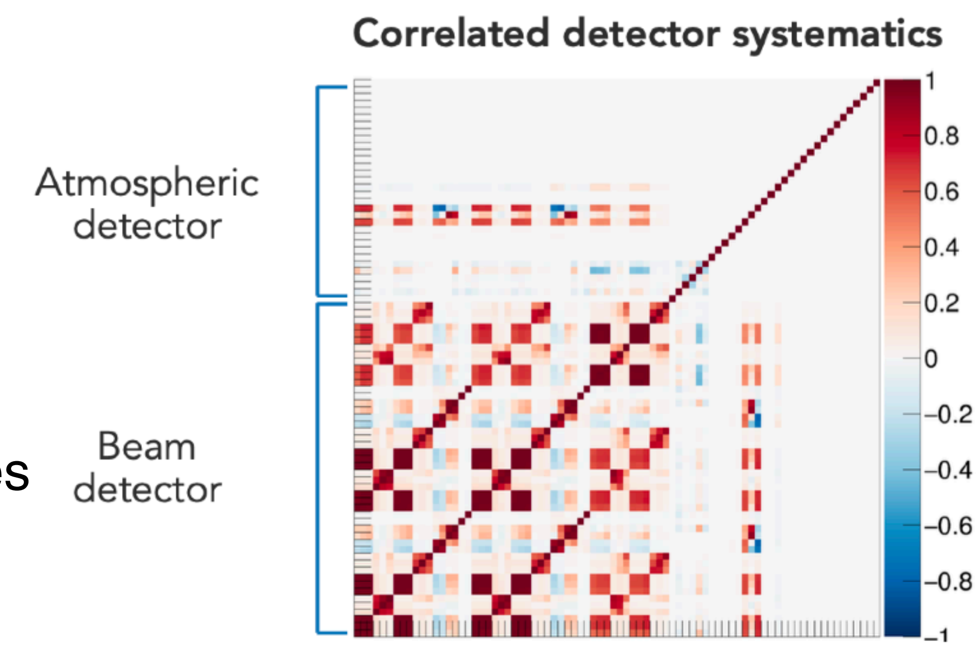
18 atmospheric samples



Systematics treatment: *paving the way for future HK analyses*

- **Flux** model taken from each experiment separately
- **Detector**: same simulation + reconstruction tools used
  - Correlation of systematics fully treated
- **Cross-section**: use different models for low and high energy samples
  - Low energy (sub-GeV): Shared model at + ND280 constraints [ref]
  - High energy (multi-GeV): Use modified SK model [ref] with additional syst.

Correlated detector systematics

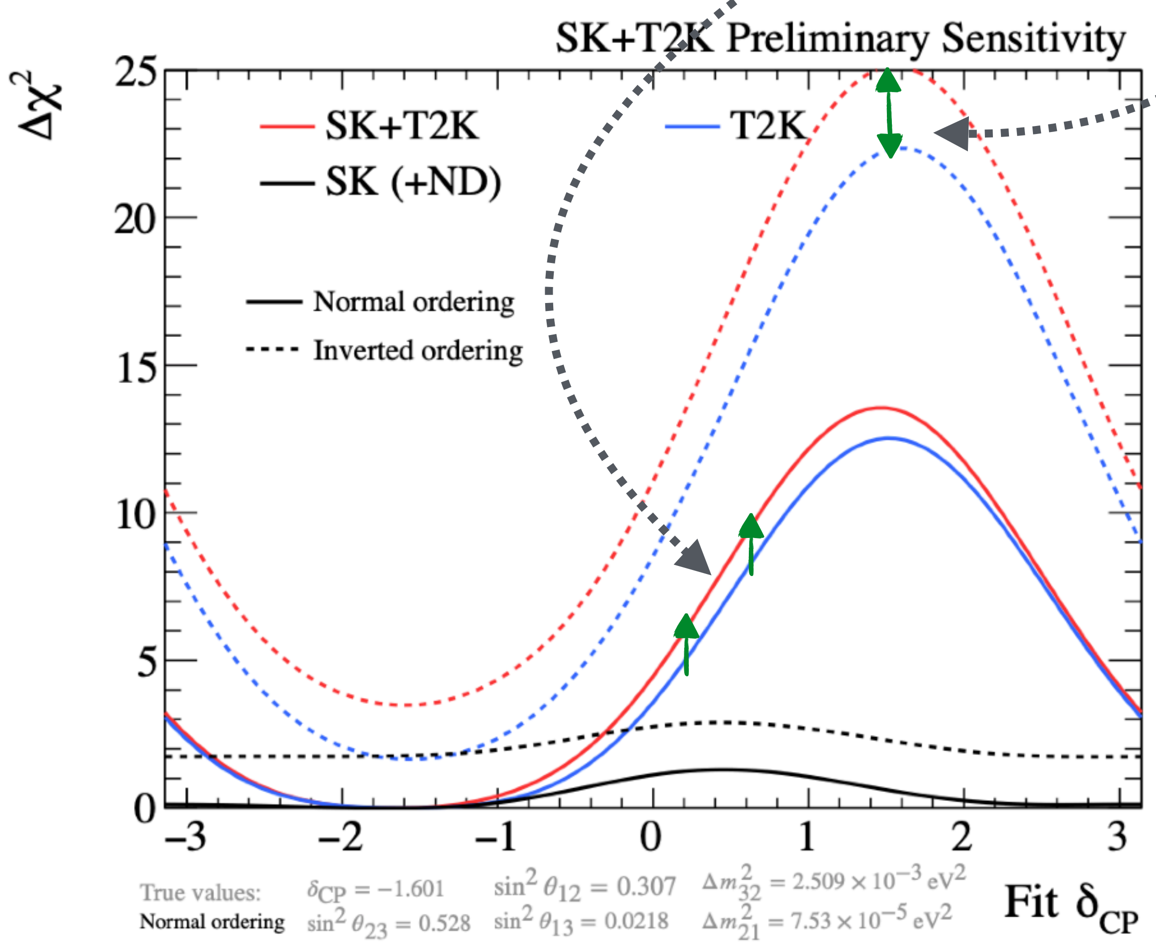


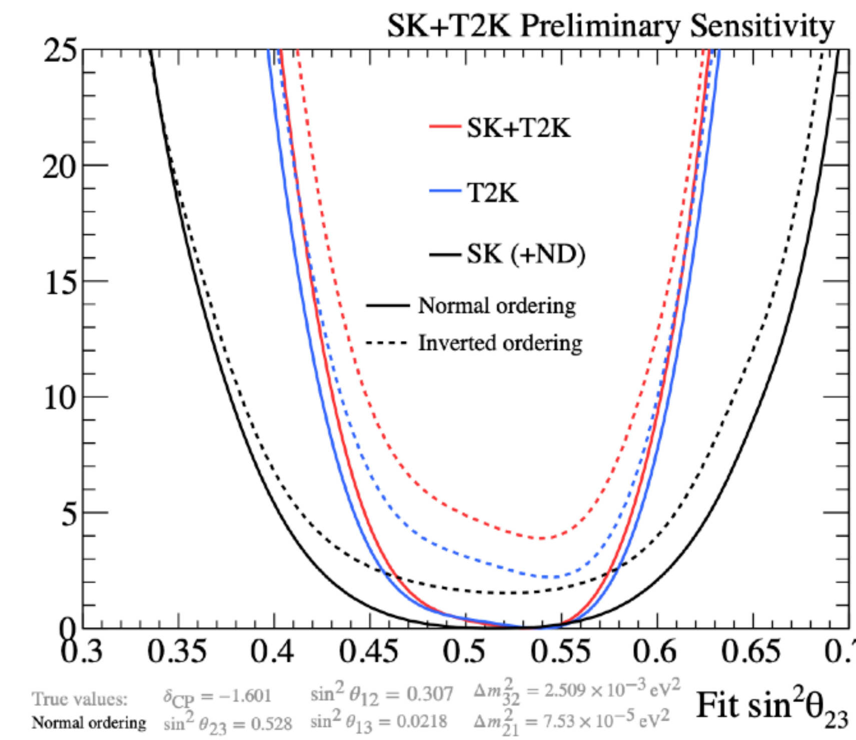
SK + T2K What do we expect?

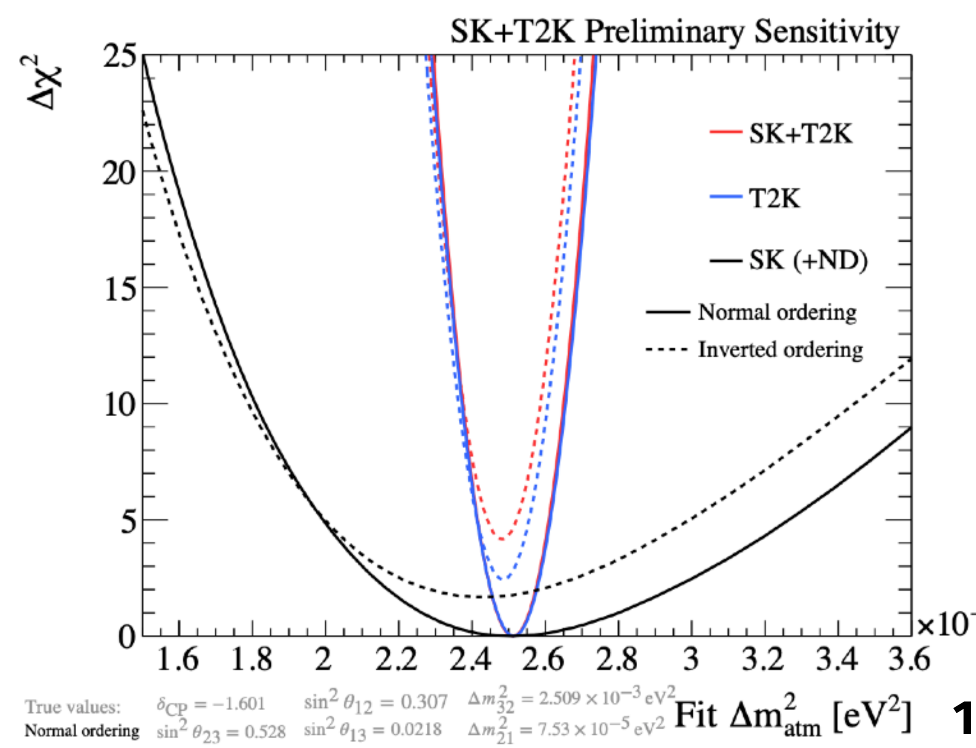
Preliminary sensitivity results

- Asimov sensitivities at true $\sin^2\theta_{23} = 0.528$, $\delta_{CP} = -1.601$, Normal Ordering
- Δm^2_{32} & θ_{23} constraint is dominated by T2K
- Main benefit of joint fit is that **both experiments are sensitive to MO**
- Noticeable **sensitivity boost for δ_{CP} in the ~0 region**

PoS NOW2022 (2023) 008







Data fit results (Bayesian analysis)

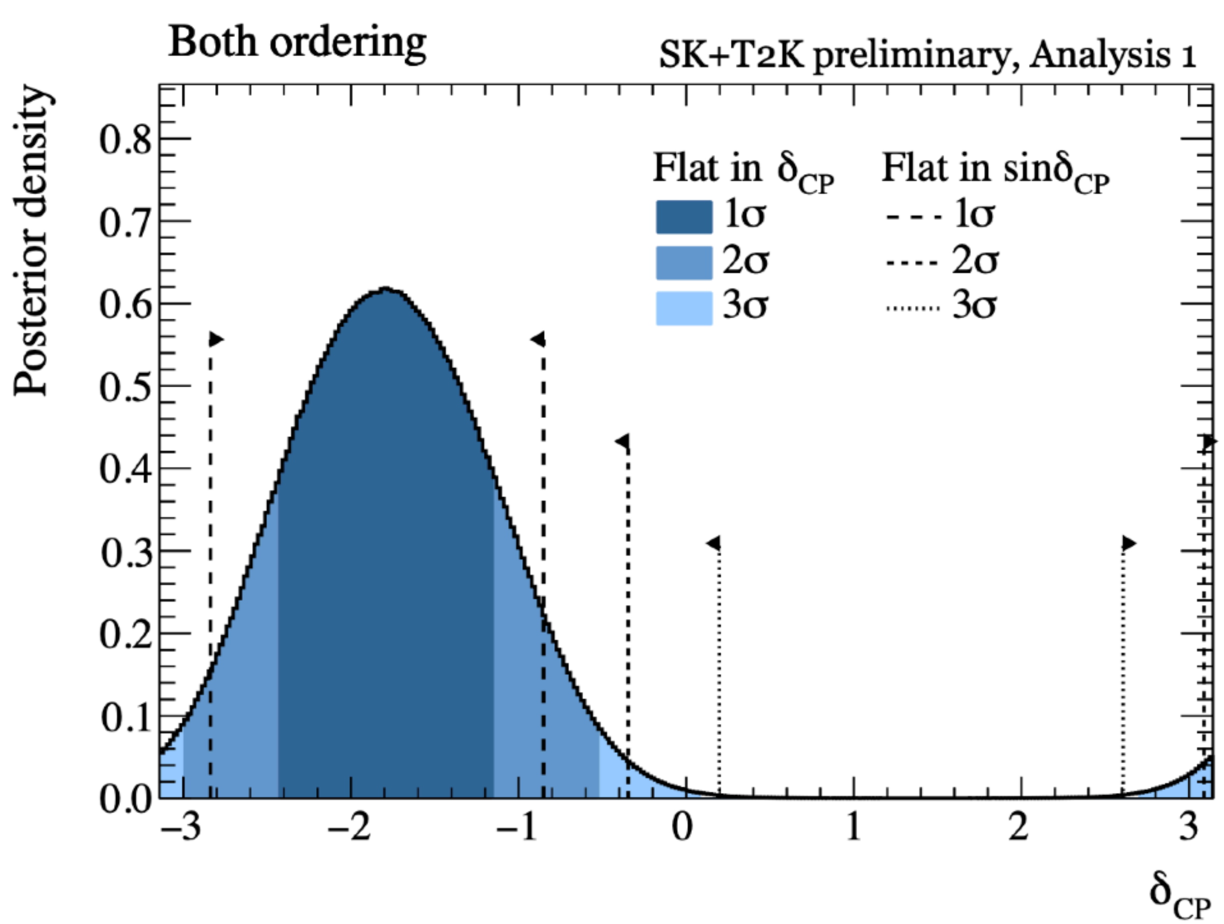
Improved δ_{CP} constraints

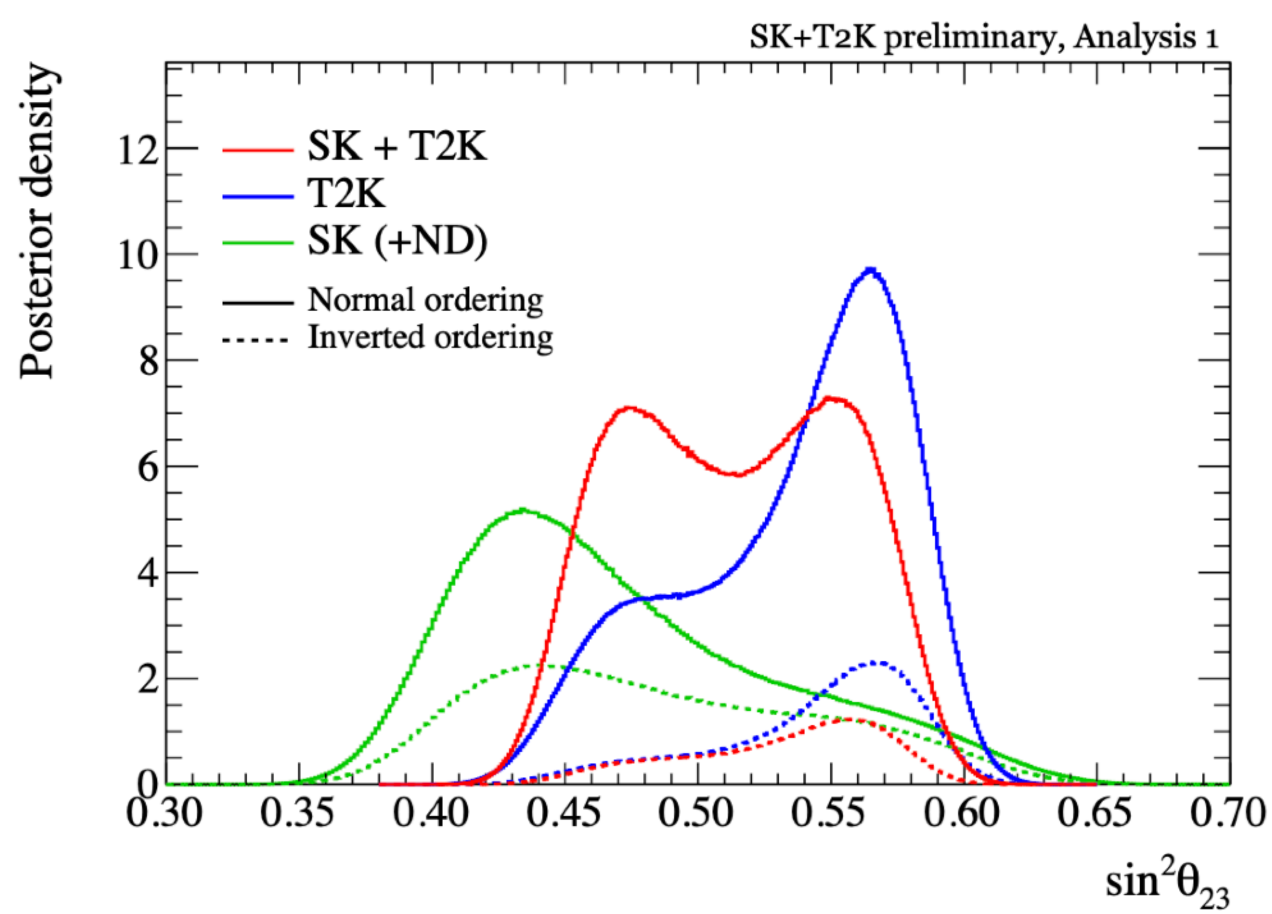
- CP conservation ($\sin\delta_{CP} = 0$) is **excluded around 2σ** with the reactor constraints applied

Slight preference for the normal mass ordering

- With the Bias factor ~9.0 (ie. 1.64σ deviation in a Gaussian assuming equal prior probabilities)
- Better constraint than T2K-only or SK-only fits

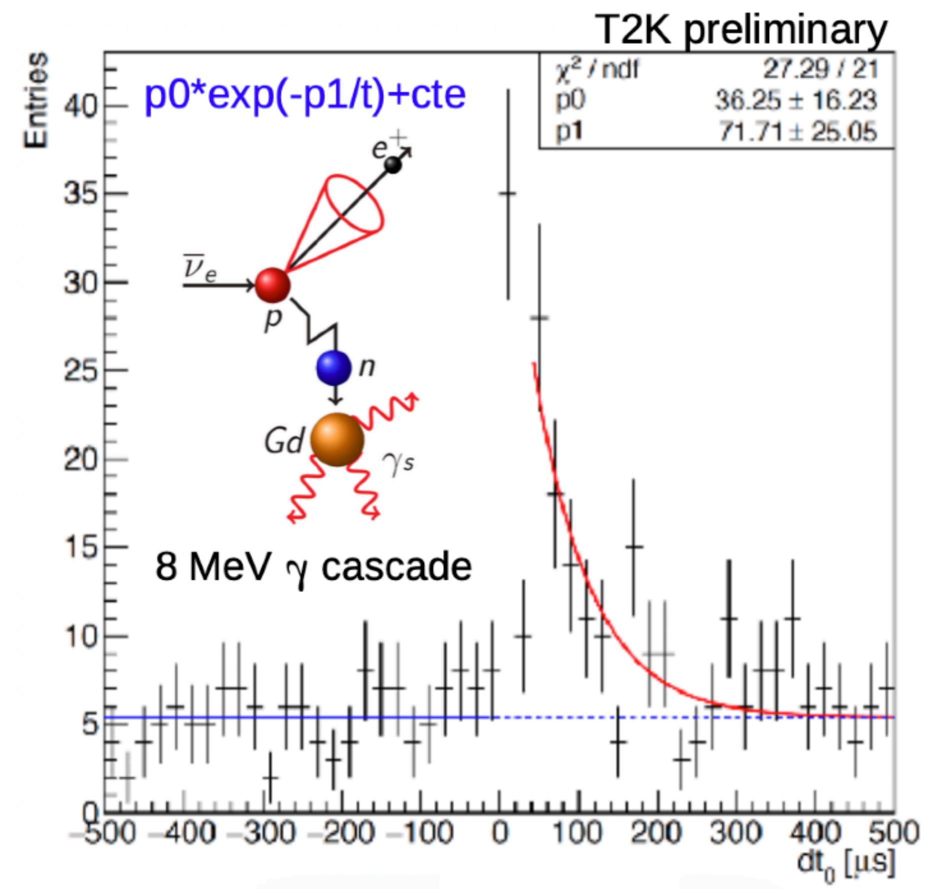
Almost equal preference to the upper and lower octant





Frequentist analysis will be reported in the near future. Stay tuned!

Upcoming analyses



Finalising run 11 analysis: first data with SK-Gd!

- 9% more exposure in neutrino-mode samples
- SK-Gd 0.01% (now moving 0.03% for better neutron tagging)
- Measurement of neutrino int. with neutrons (NCQE, 2p2h,…)
- Retuning of selection + Improved evaluation of uncertainties on detector modelling and reconstruction

NOνA + T2K joint fit

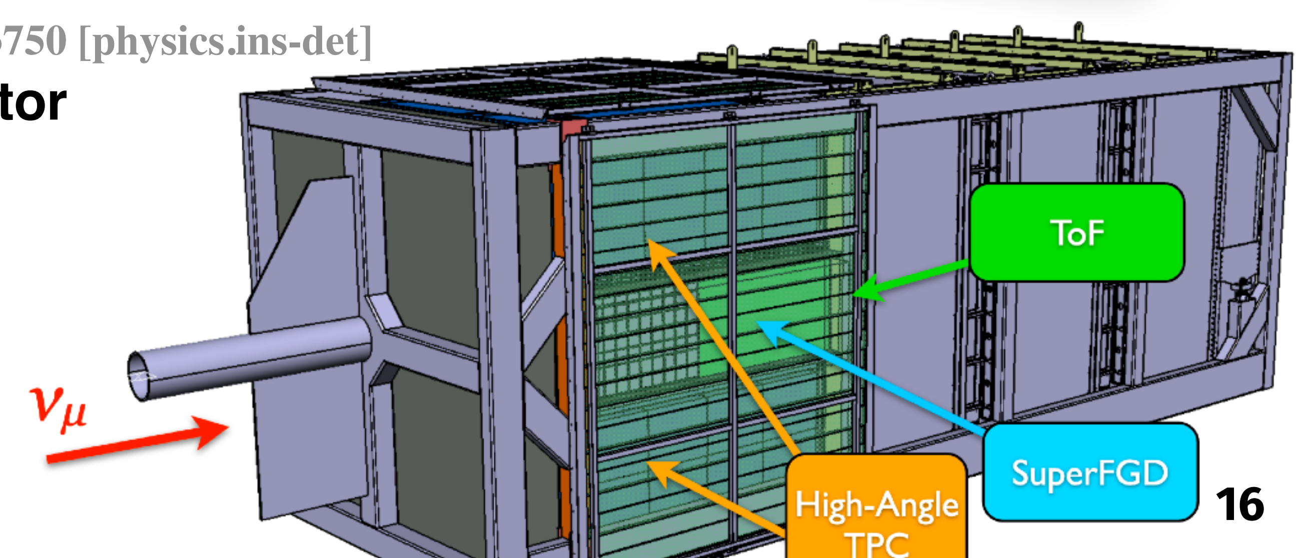
- Different oscillation **baselines, energies and detector** tech.
- Important to understand systematic correlations

T2K extended runs

- Upgraded beamline TDR: arXiv:1908.05141 [physics.ins-det]
  - Increase **beam power from ~500 kW to 1.3 MW** via upgrades to main ring power supply and RF (mostly increased rep rate)
  - Increase **horn current 250 kA → 320 kA** for ~10% more neutrinos/beam-power and reduced wrong-sign background

See **Weijun Li** and **Lorenzo Giannessi** talks!

- Upgrading ND280 with new detectors: TDR: arXiv:1901.03750 [physics.ins-det]
  - A new neutrino target: **Super-Fine Grained Detector**
  - Two new trackers: **High-Angle TPCs**
  - **Time of Flight detector planes**

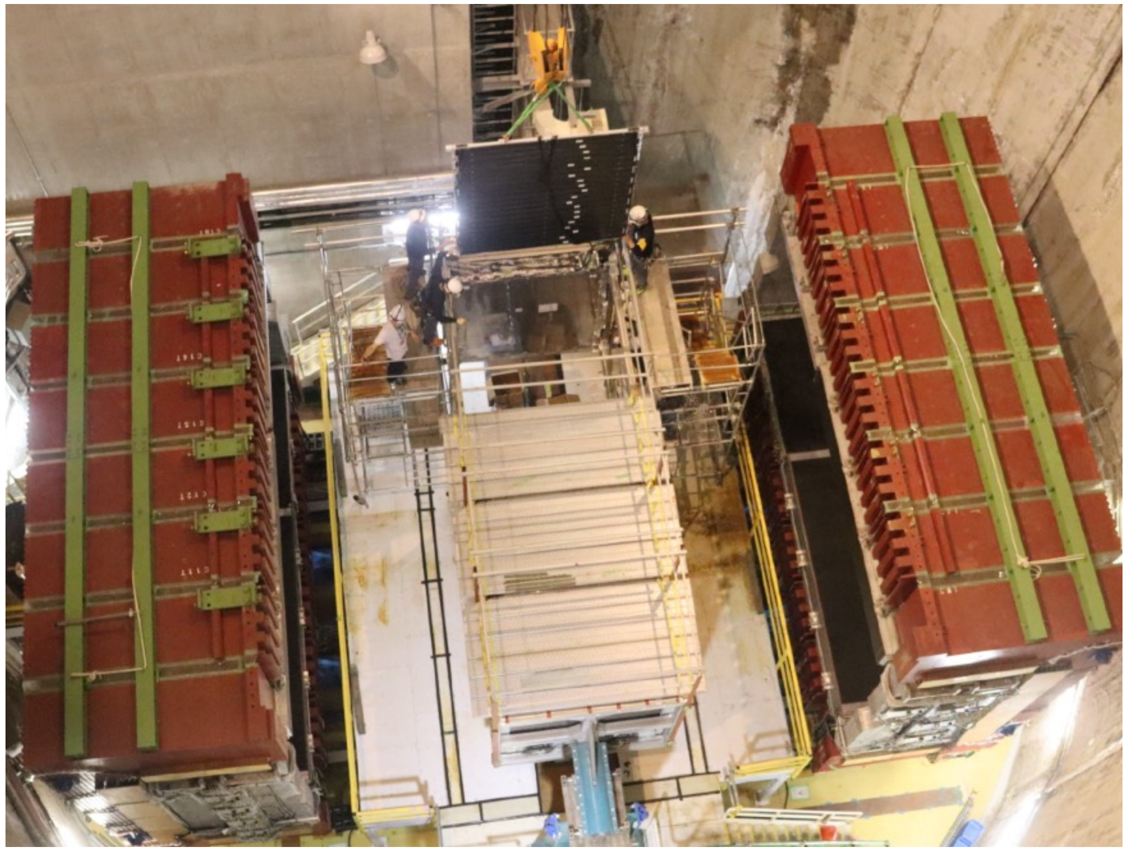


- *Will allow to probe unreached phase-space*
- *Reduce xsec systematics and better understanding of nuclear effects*

It's happening!!

5th of July 2023

installation of the first ToF planes!

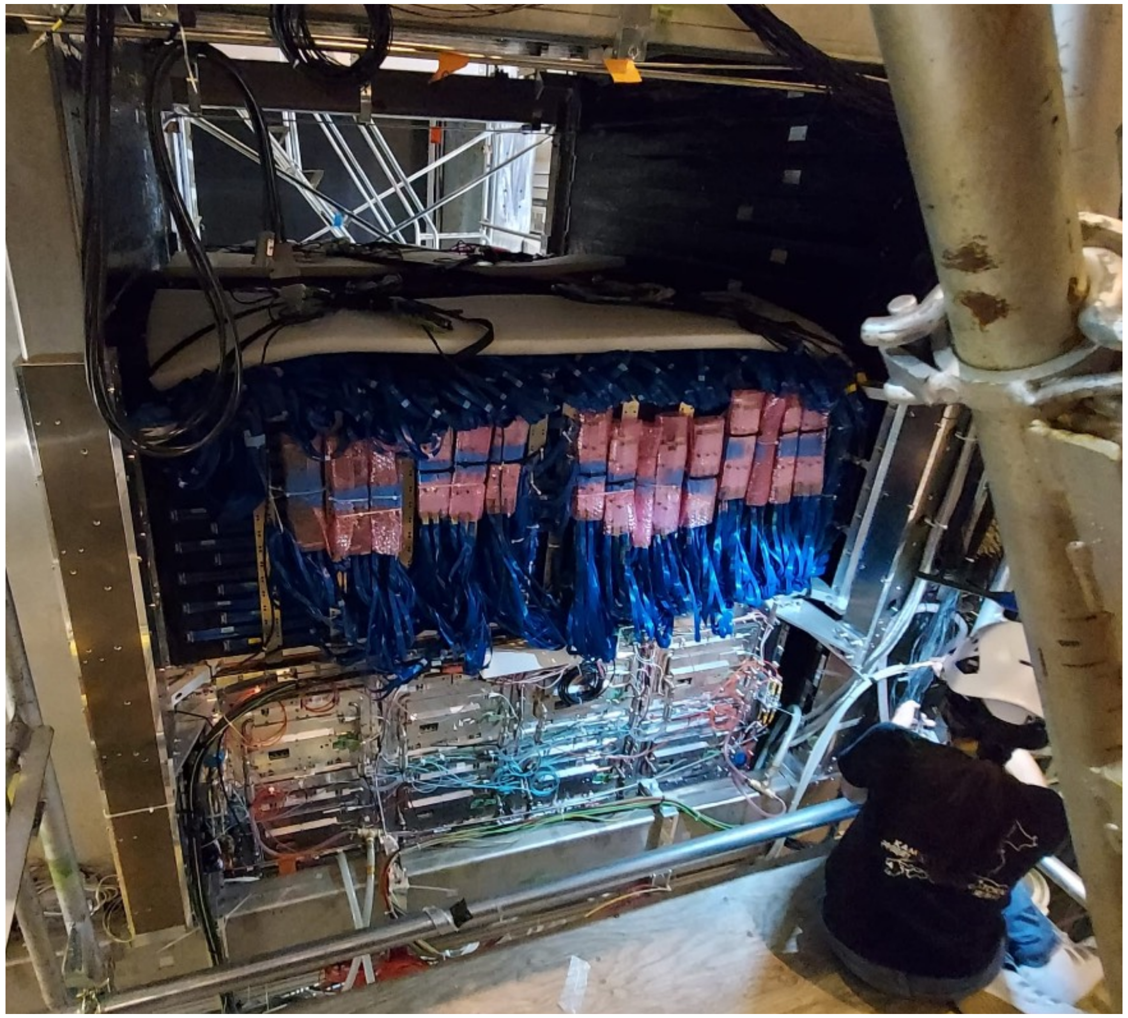


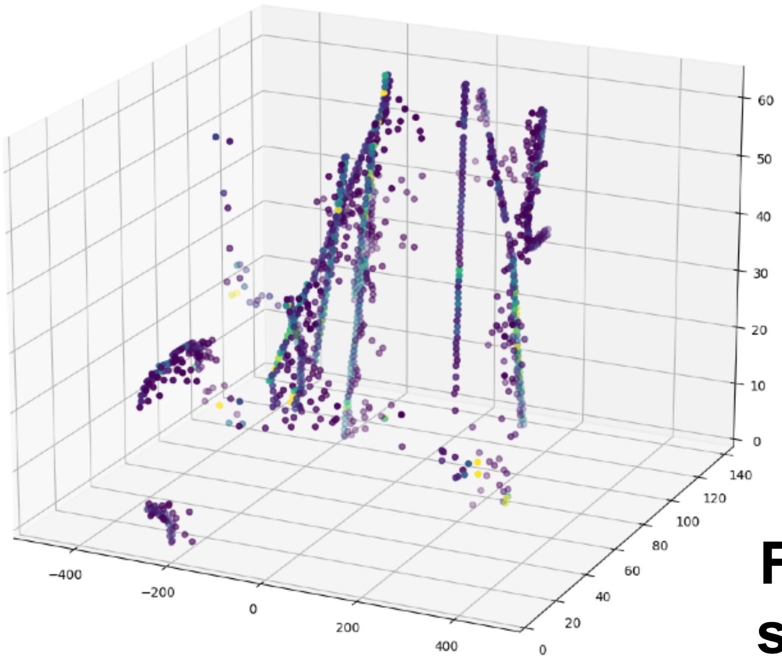
mid October 2023

SFGD installed

Bottom HATPC installed

4 / 6 ToF planes ready



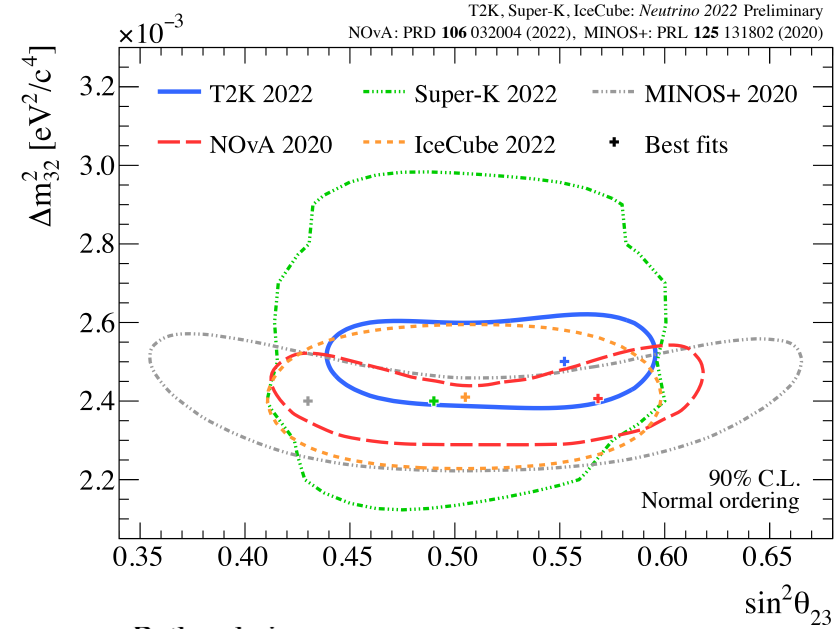


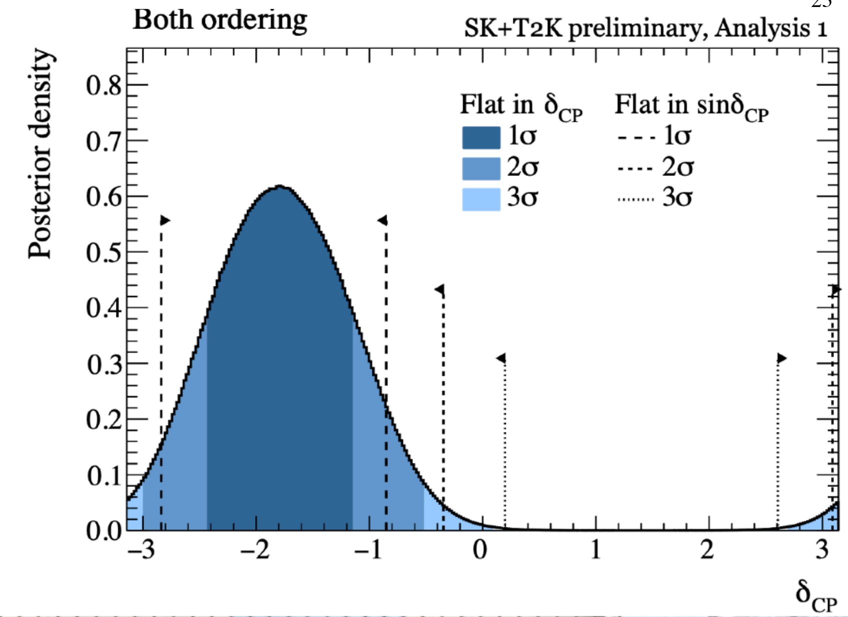
First cosmic tracks seen in the HATPC! (ToF trigger)

First beam data taking should start at the end of November!

Summary

- Latest T2K neutrino oscillation results using 3.6×10^{20} protons on target
- **2022 oscillation analysis of T2K**
  - **Many improvements** at each level of analysis
  - CP conserving values of δ_{CP} **excluded at 90% C.L.**
  - Weak preference for **normal ordering** and **upper octant**
- **First SK+T2K combined analysis reported**
  - CP conservation $(\sin \delta_{CP} = 0)$ is **excluded around 2σ C.L.**
  - Improved constraints in **favour of normal ordering**
  - Almost equal preference to the upper and lower octant
- **Exciting perspectives for the future with T2K extended runs**





Backup

Conclusion on CP symmetry

The table below summarizes the conclusion on CP symmetry from different analyses

- Based on this, we concluded that CP conservation ($\delta_{CP} = \{0,\pi\}, J_{CP} = 0$) is excluded around when the reactor constraint is applied.

SK+T2K preliminary

Analysis	Prior	CP conserving value	1σ	90%	2σ	3σ
Analysis 1	Flat in δ_{CP}	$\delta_{\mathrm{CP}} = 0, \pi$	✓	✓	✓	×
		$J_{\mathrm{CP}} = 0$	✓	✓	✓	×
	Flat in $\sin\delta_{\mathrm{CP}}$	$\delta_{\mathrm{CP}} = 0, \pi$	✓	✓	×	×
		$J_{\mathrm{CP}} = 0$	✓	✓	✓	×
Analysis 2	Flat in δ_{CP}	$\delta_{\mathrm{CP}} = 0, \pi$	✓	✓	✓	×
		$J_{\mathrm{CP}} = 0$	✓	✓	✓	×
	Flat in $\sin\delta_{\mathrm{CP}}$	$\delta_{\mathrm{CP}} = 0, \pi$	✓	✓	×	×
		$J_{\mathrm{CP}} = 0$	✓	✓	✓(×)	×

✓: excluded ×: not excluded ✓(×): excluded but may not be robust against the possible bias from an out-of-model effect

Two Bayesian analyses

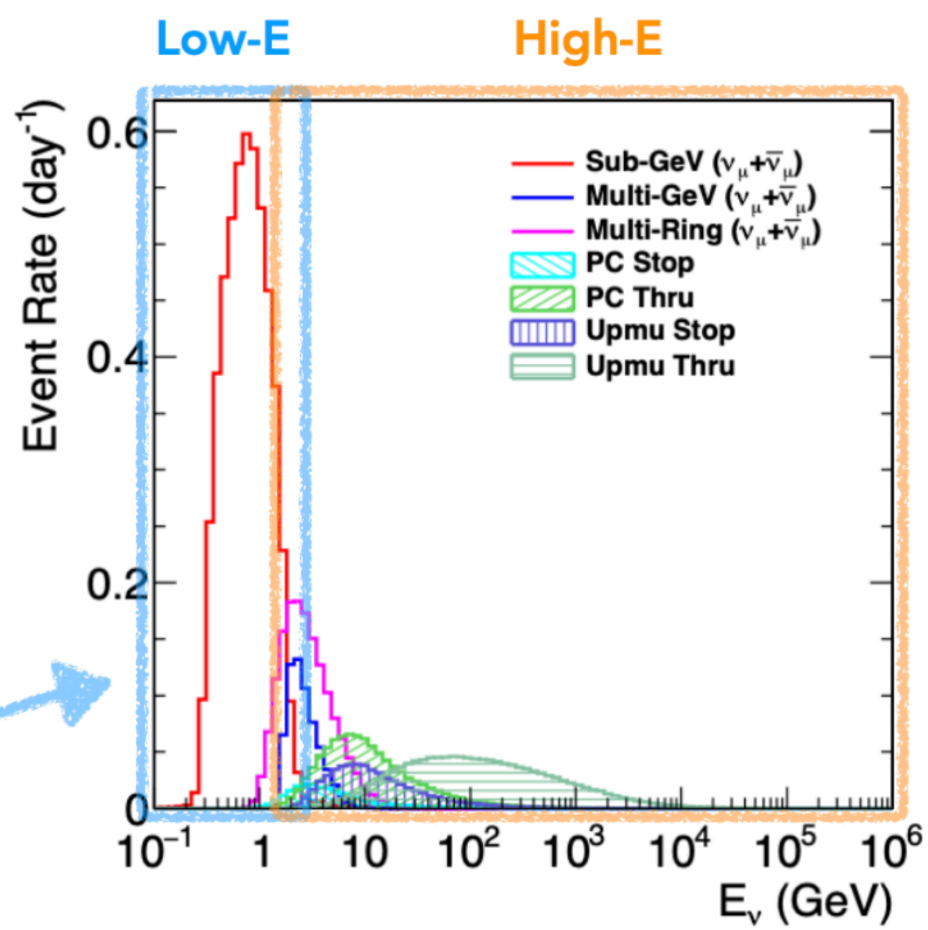
We check the validity of the results by performing multiple analyses.

- Four analysis methods have been prepared for this joint analysis.
- All of them use the **same analysis model** but use **different implementations** and **fitting methods**.

Results presented in this talk are from two analyses that can produce Bayesian results:

	Analysis 1	**Analysis 2**
Oscillation probability Systematic response	Binned	Event by event / Binned
T2K sample binning	$(E_{\mathrm{rec}}, \theta)$ for μ-like samples (p, θ) for e-like samples	(E_{rec}) for μ-like samples $(E_{\mathrm{rec}}, \theta)$ for e-like samples
T2K near detector constraint	Gaussian approximation (Sequential fit)	Full likelihood (Simultaneous fit)
Fast oscillation smearing	Semi-analytic averaging	Down-sampling finer to coarser grid
Earth density	Average density + deviations	Average density

Cross-section models



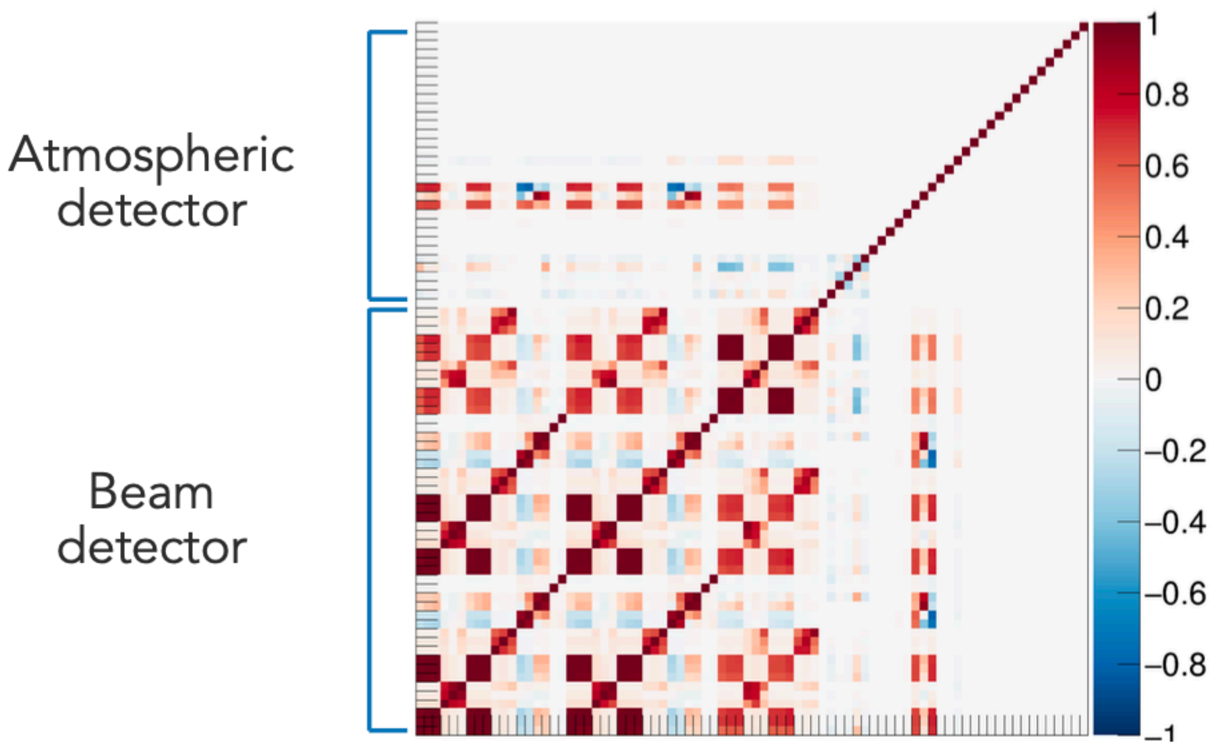
Use a common cross-section model with T2K

	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

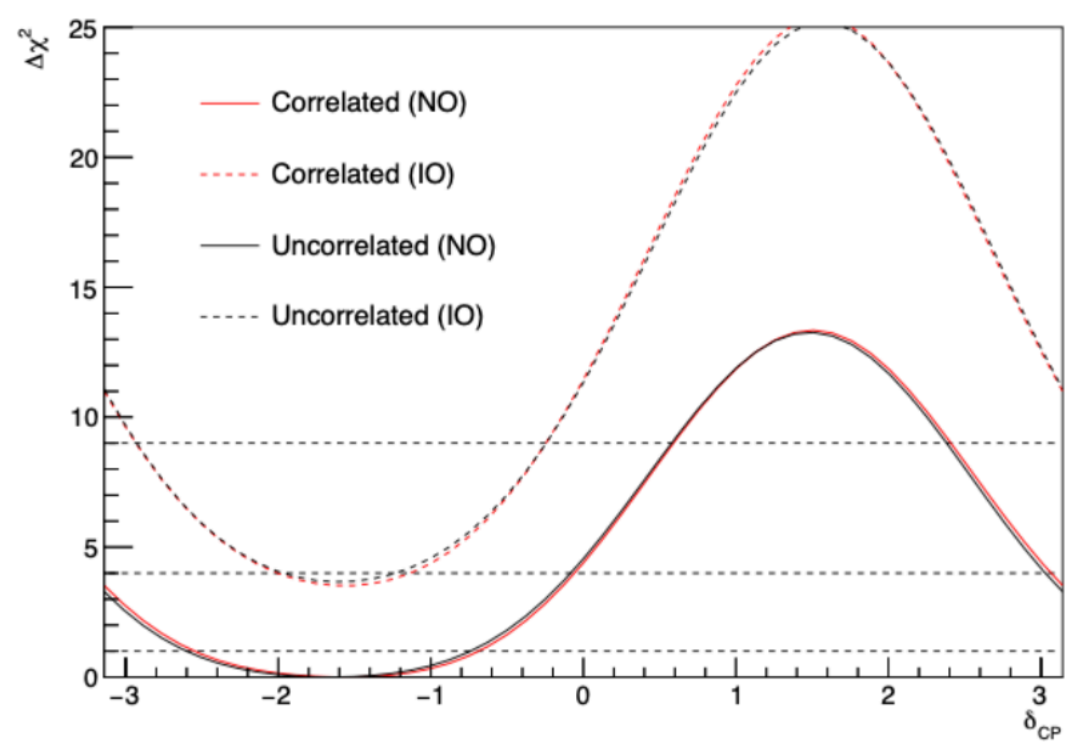
Detector systematics

- **Correlations between T2K and SK detector systematics are taken into account** by reevaluating the T2K detector systematics using the atmospheric MC (reweighted to the T2K flux and the T2K selection is applied).
- Including the correlations makes the analysis more robust but has a limited impact at current statistics.

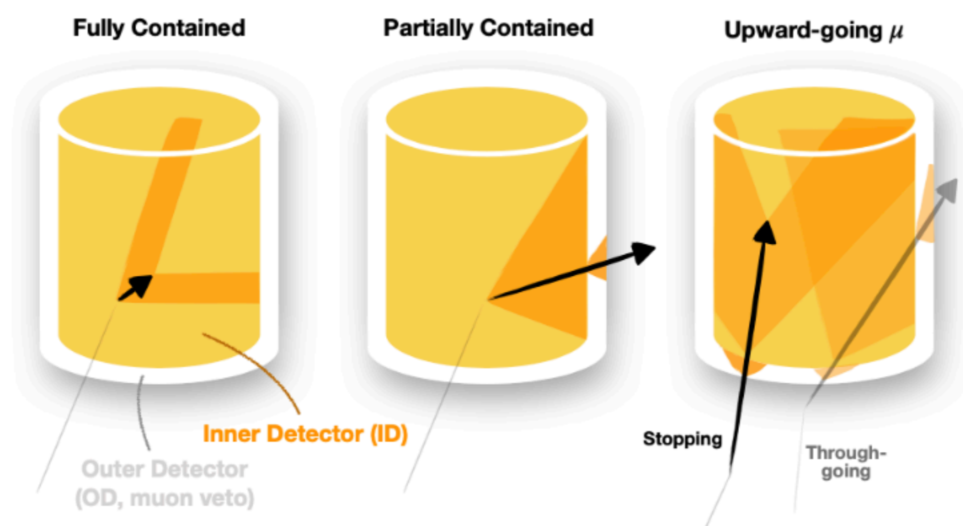
Correlated detector systematics



Effect of the correlation on the sensitivity



Atmospheric samples



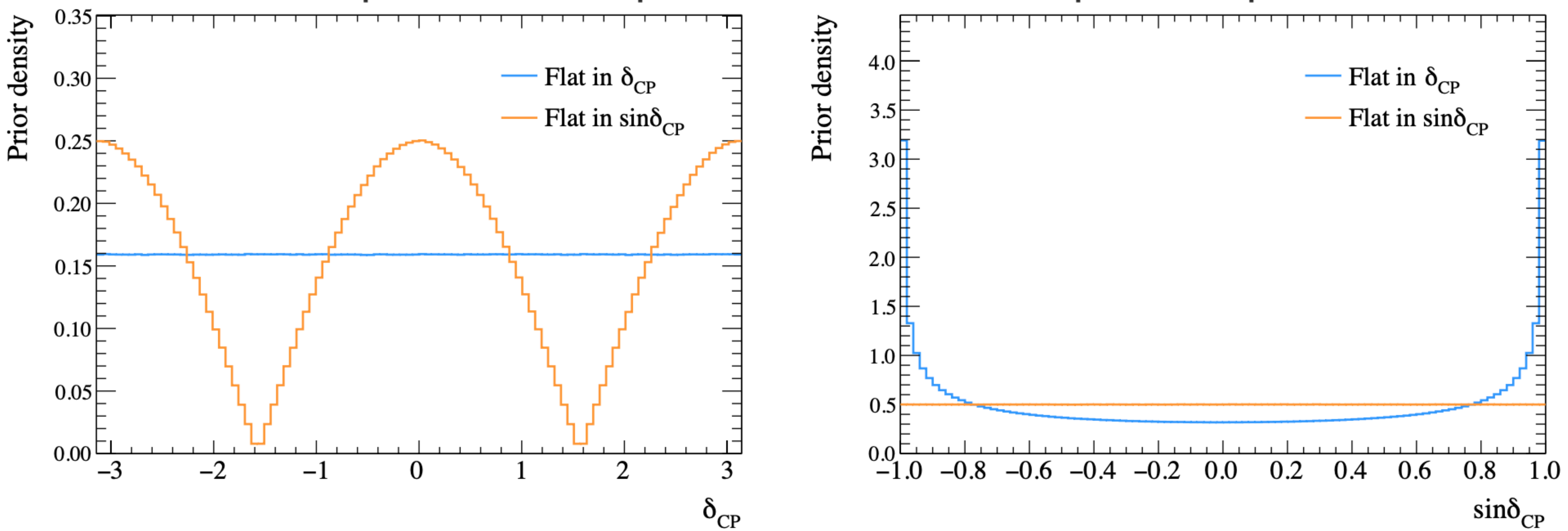
Sample Name	Category	Selection			
SubGeV elike 0dcy	Fully Contained (FC)	Sub-GeV	Single-ring	e-like	0 decay-e
SubGeV elike 1dcy					1 decay-e
SubGeV mulike 0dcy				μ-like	0 decay-e
SubGeV mulike 1dcy					1 decay-e
SubGeV mulike 2dcy					≤ 2 decay-e
SubGeV pi0like			Multi-ring	Two e-like rings	
MultiGeV elike nue		Multi-GeV	Single-ring	e-like	≤ 1 decay-e
MultiGeV elike nuebar					0 decay-e
MultiGeV mulike				μ-like	
MultiRing elike nue			Multi-ring	e-like	ν_e-like
MultiRing elike nuebar					$\bar{\nu}_e$-like
MultiRing mulike					other
MultiRingOther 1				μ-like	
PCStop	Partially Contained (PC)	No charge deposition in OD			
PCThru		Charge deposition in OD			
UpStop mu	Up-going Muon (UpMu)	Stopping			
UpThruNonShower mu		Through-going Non-showering			
UpThruShower mu		Through-going Showering			

Bayesian prior choices

Two widely accepted non-informative priors were tested in our analysis of CP violation.

- Uniform δ_{CP}: closer to Jensen's prior for Haar measure.
- Uniform $\sin\delta_{CP}$: closer to Jeffrey's prior for this analysis ($\propto \sqrt{\det(I_{\text{Fisher}})}$).

Comparison of the two prior distributions in different parameter spaces



Model robustness studies

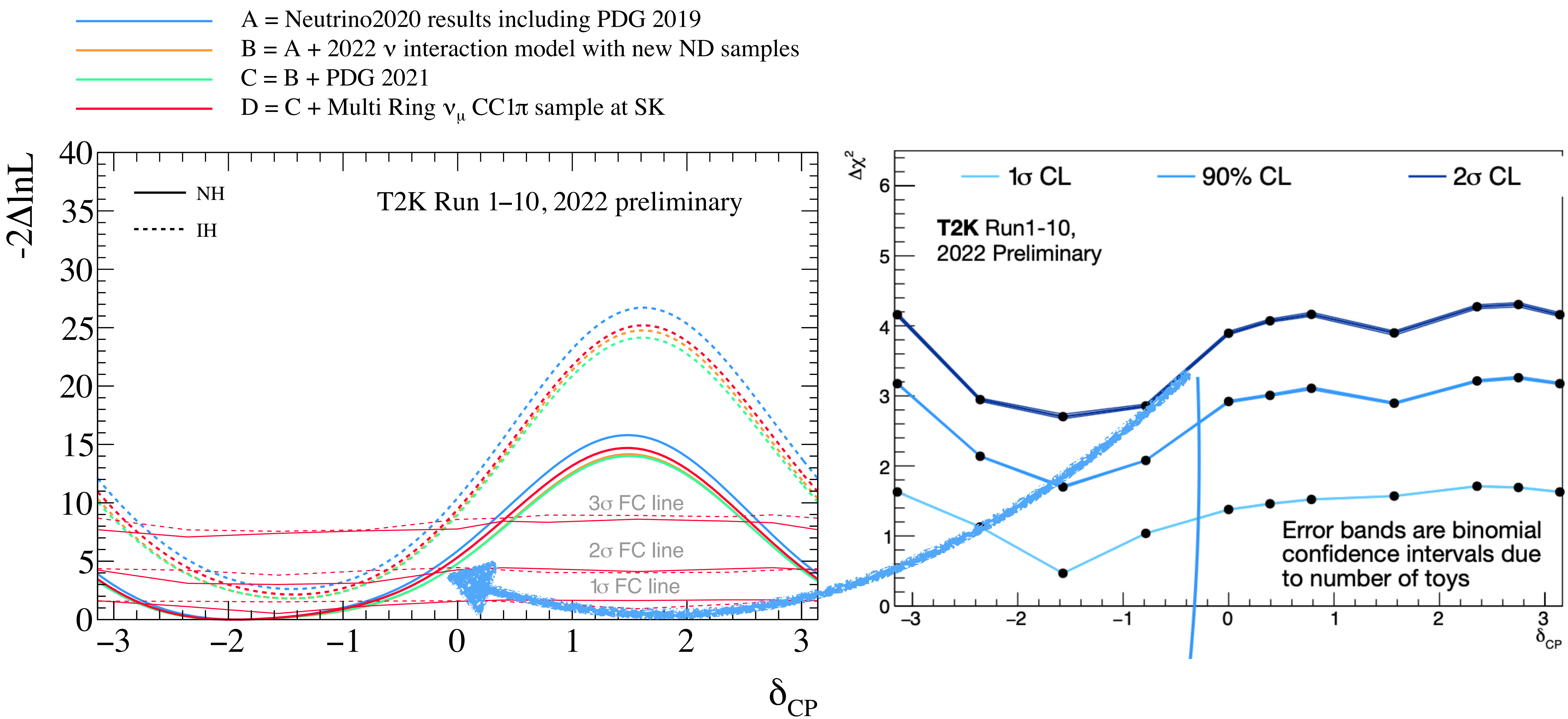
How good our systematic parametrisation is at absorbing alternative models

- Performing “fake data sensitivity studies”, by trying to fit an alternative Asimov model
- Report possible observed biases on oscillation parameters

14 simulated data studies have been performed to test a possible bias in the analysis

	Model component
Martini 2p2h	2p2h
ND280 data-driven pion kinematics	CC1π
CC0π non-QE alteration	CC0π
Removal energy	Nuclear Model
Axial form factors	CCQE
Pion SI bug fix	CC1π, CC$n\pi$
LFG	Nuclear model
CRPA	Nuclear model
Pion multiplicity	CC$n\pi$
Energy-dependent $\sigma_{\nu_e}/\sigma_{\nu_\mu}$	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$
Xsec-only fit	Fit
Atmospheric down-going CC1π	CC1π
Atmospheric full-zenith CC1π	CC1π
No-migration energy scale fit	Fit

Coverage Studies using Feldman-Cousins Method



- 50k toy experiments for a couple of δ_{CP}/MO values, randomly sampling θ_{13} (reactor prior) and atmospheric samples from the Asimov contour set at current data-BF point
- Map the critical values of $\Delta\chi^2$ for each C.L.
- Linear interpolation for reporting CPV contours

Systematics budget

Pre-ND fit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

T2K Run 1-10, preliminary

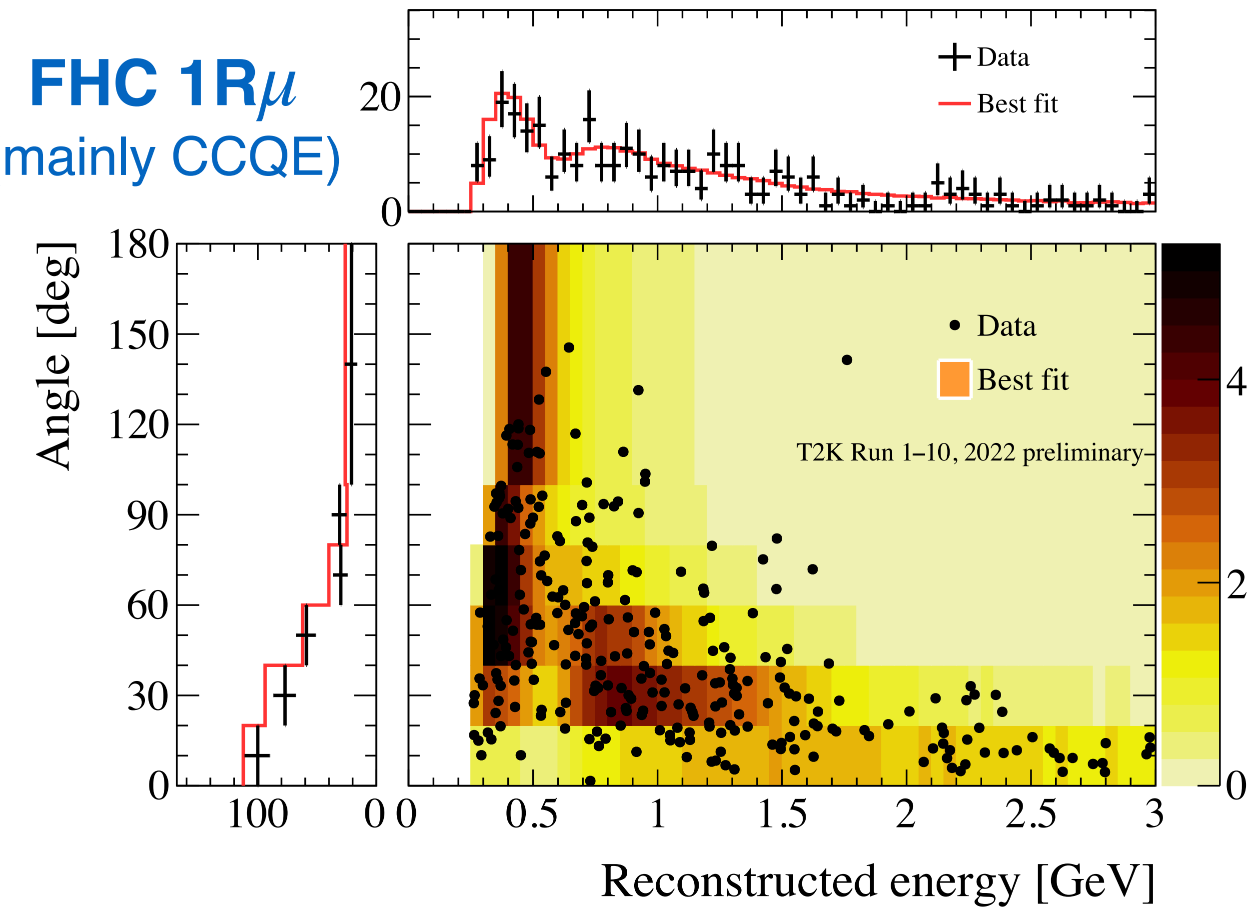
Post-ND fit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

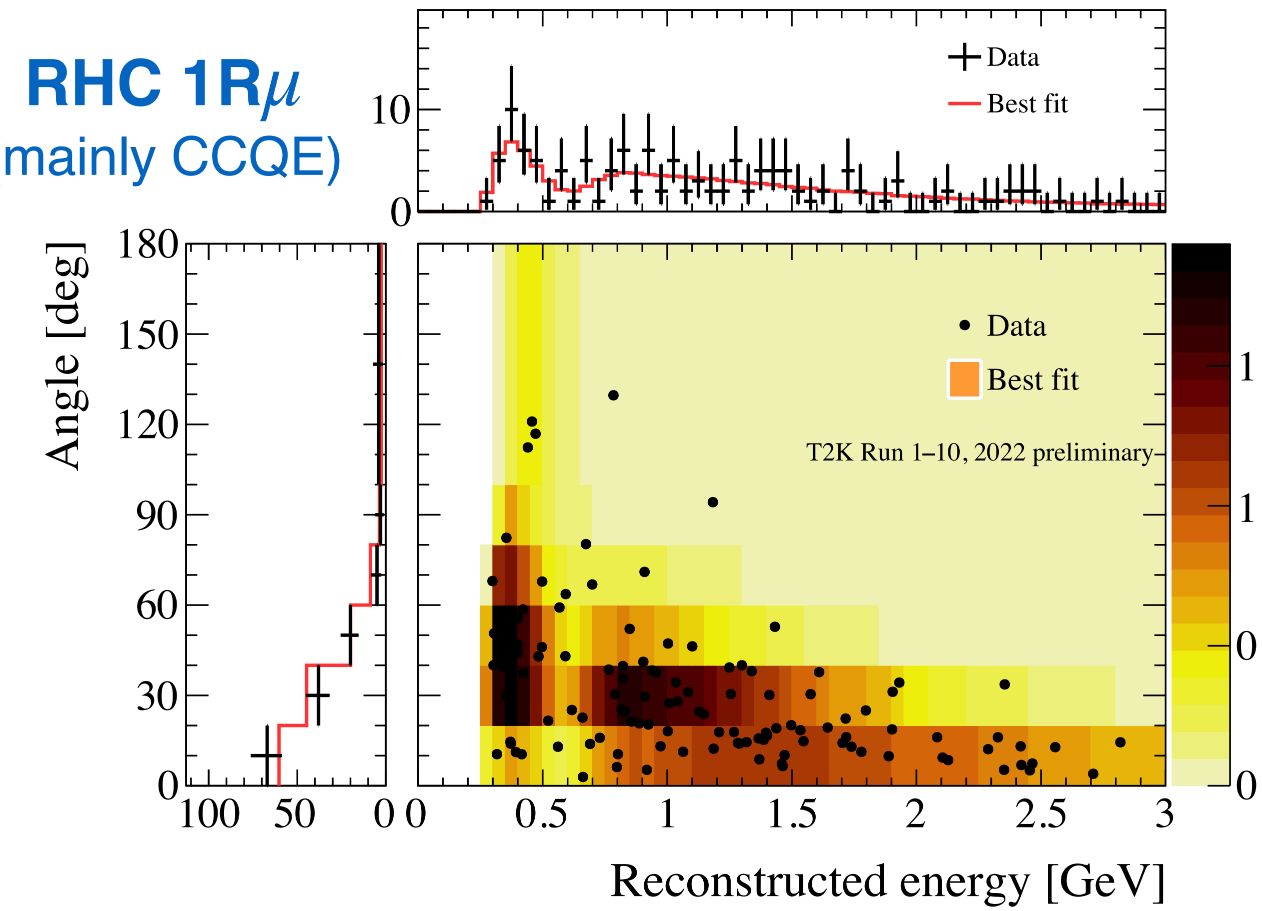
T2K Run 1-10, preliminary

2022 OA — μ-like samples

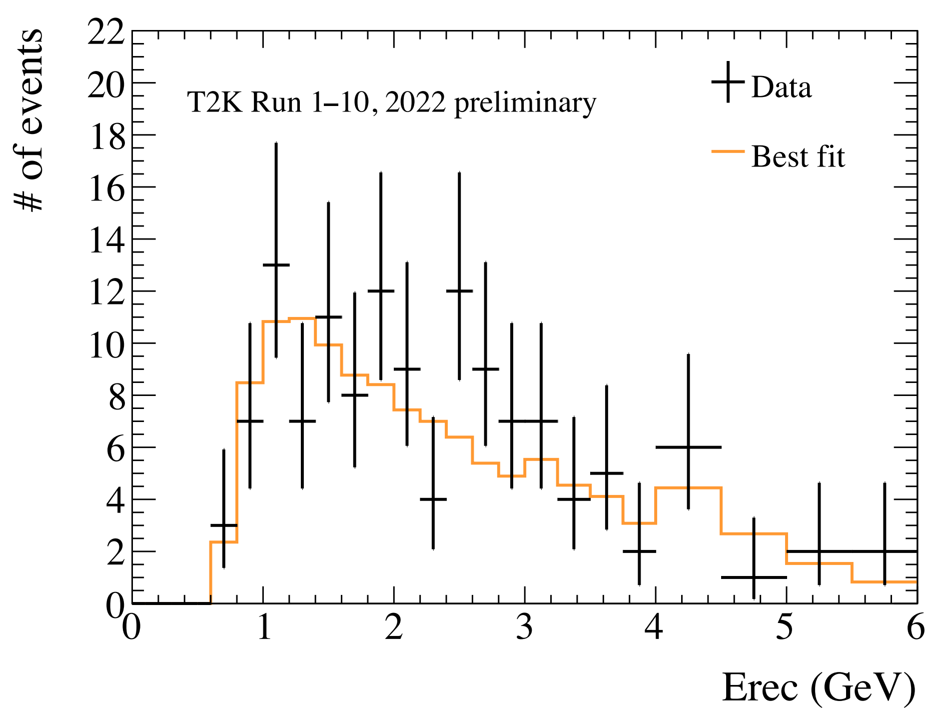
FHC 1Rμ
(mainly CCQE)



RHC 1Rμ
(mainly CCQE)



FHC 1 or 2 R $\mu + \pi$
(mainly CC1π^+)



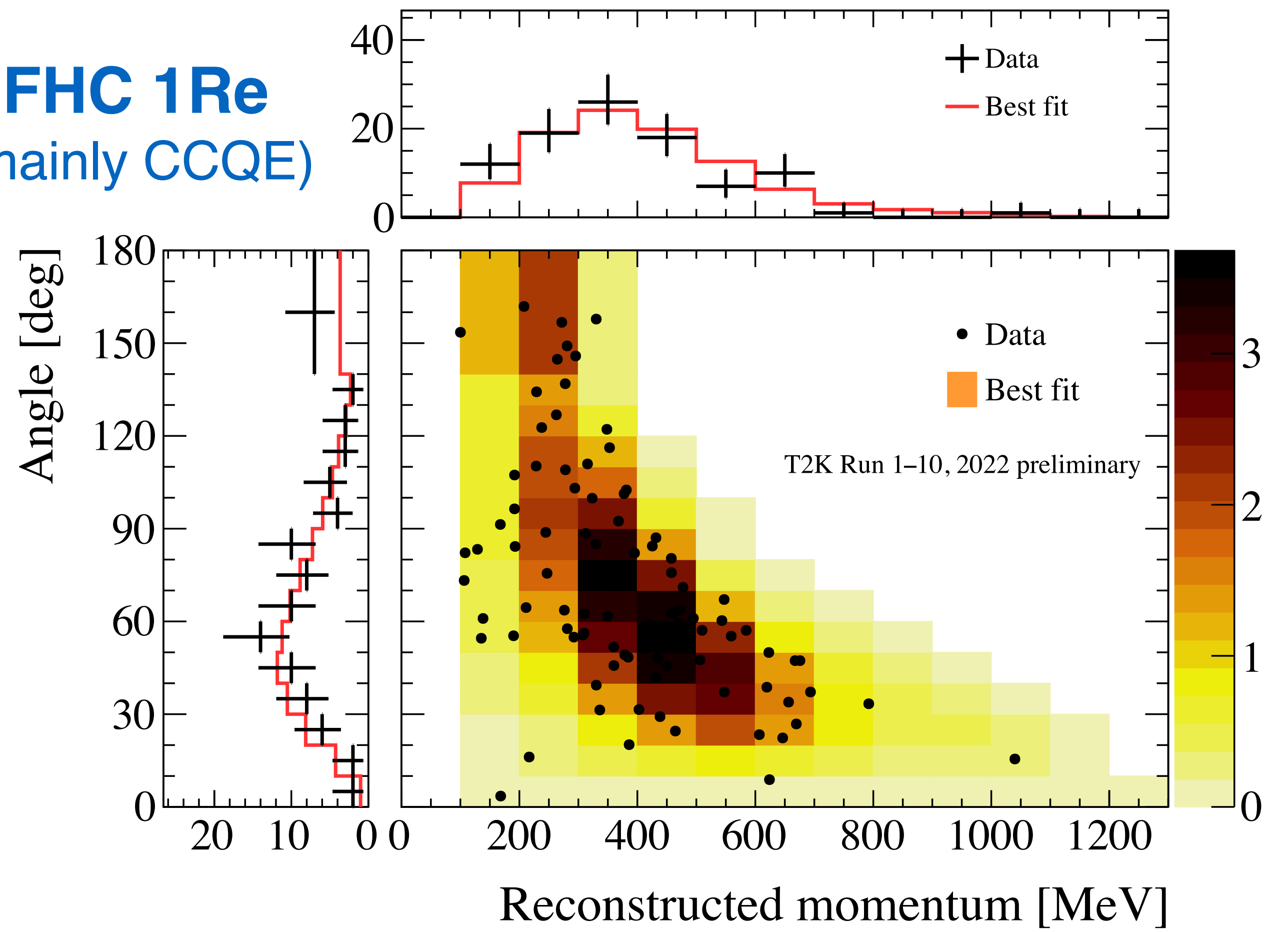
Event rates

	Data
FHC 1Rμ	318
RHC 1Rμ	137
FHC 1Re	94
RHC 1Re	16
FHC 1R ν_e CC1π^+	14
FHC MR ν_μ CC1π^+	134
FHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	191
RHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	71

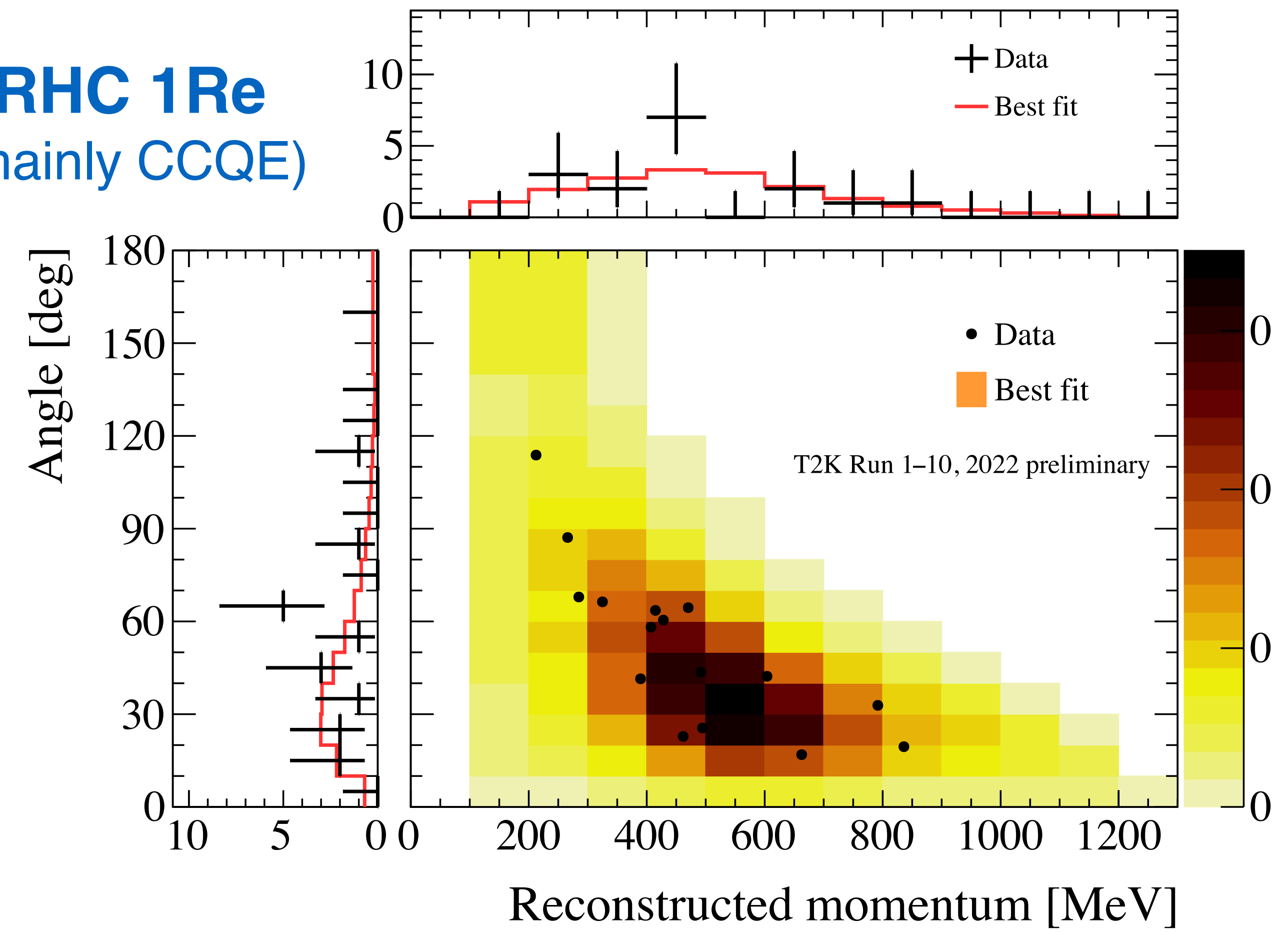
T2K Run 1-10, preliminary

2022 OA — e-like samples

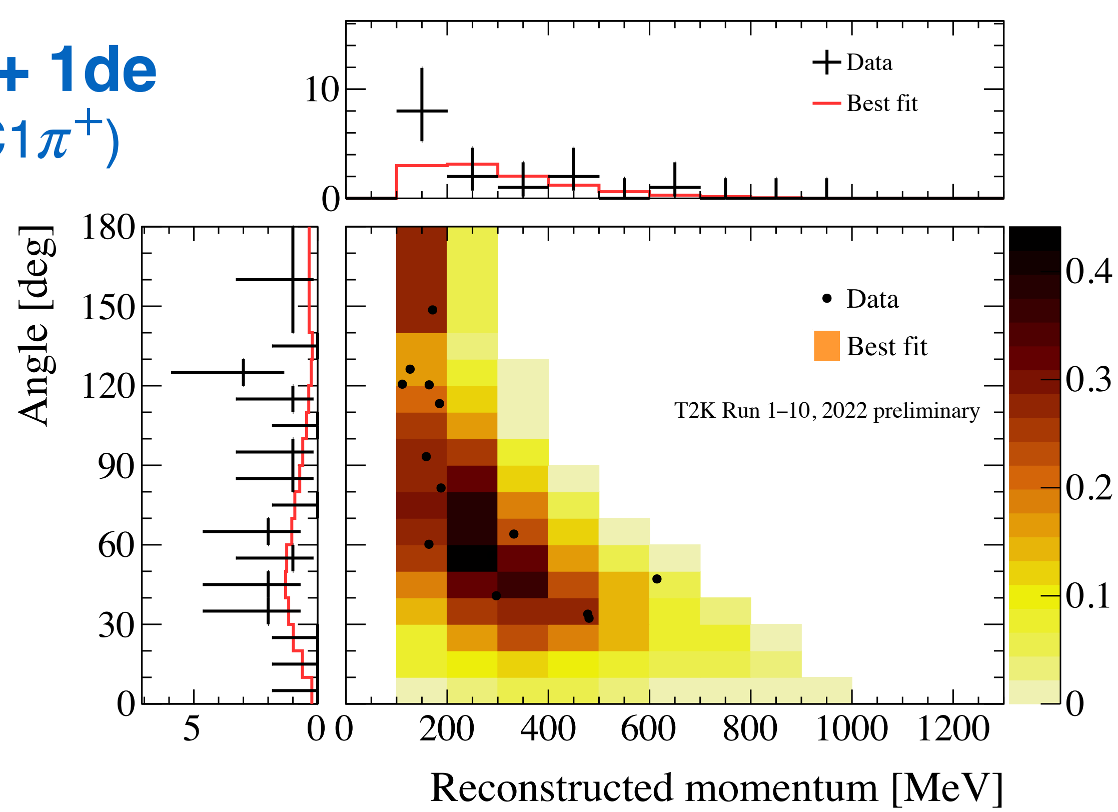
FHC 1Re
(mainly CCQE)



RHC 1Re
(mainly CCQE)



FHC 1Re + 1de
(mainly CC1π^+)

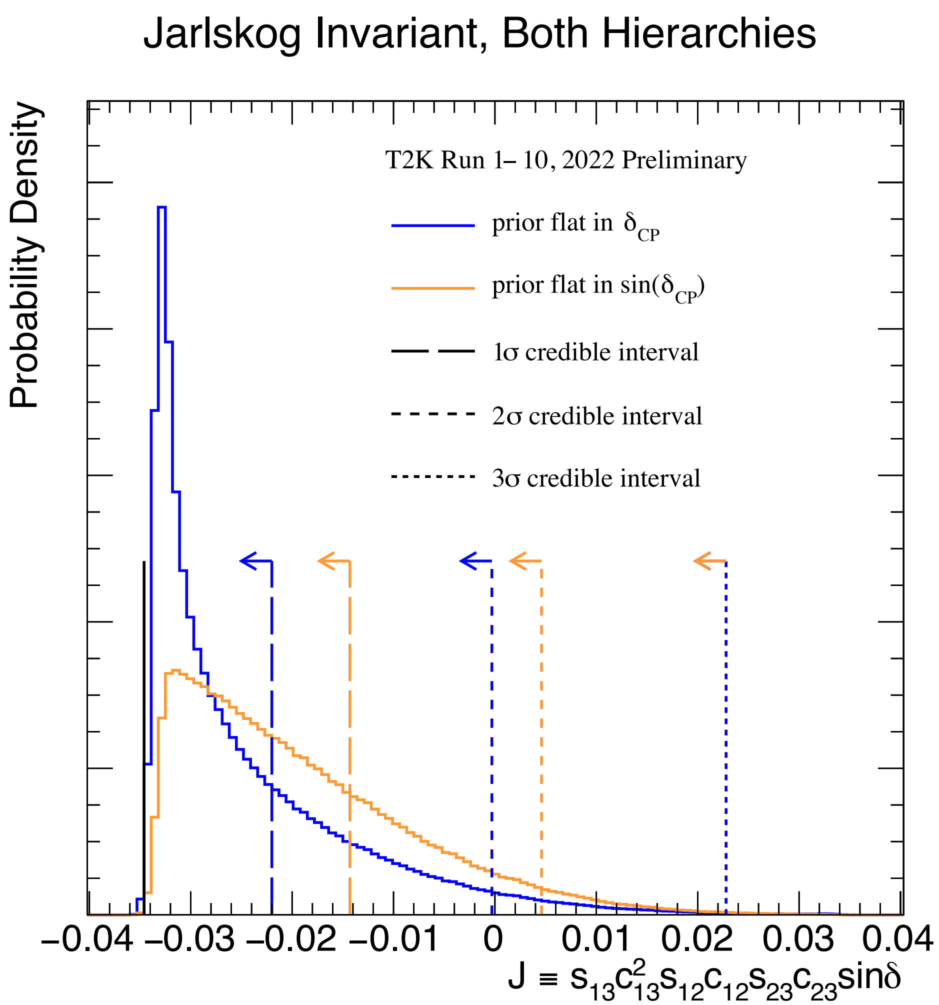


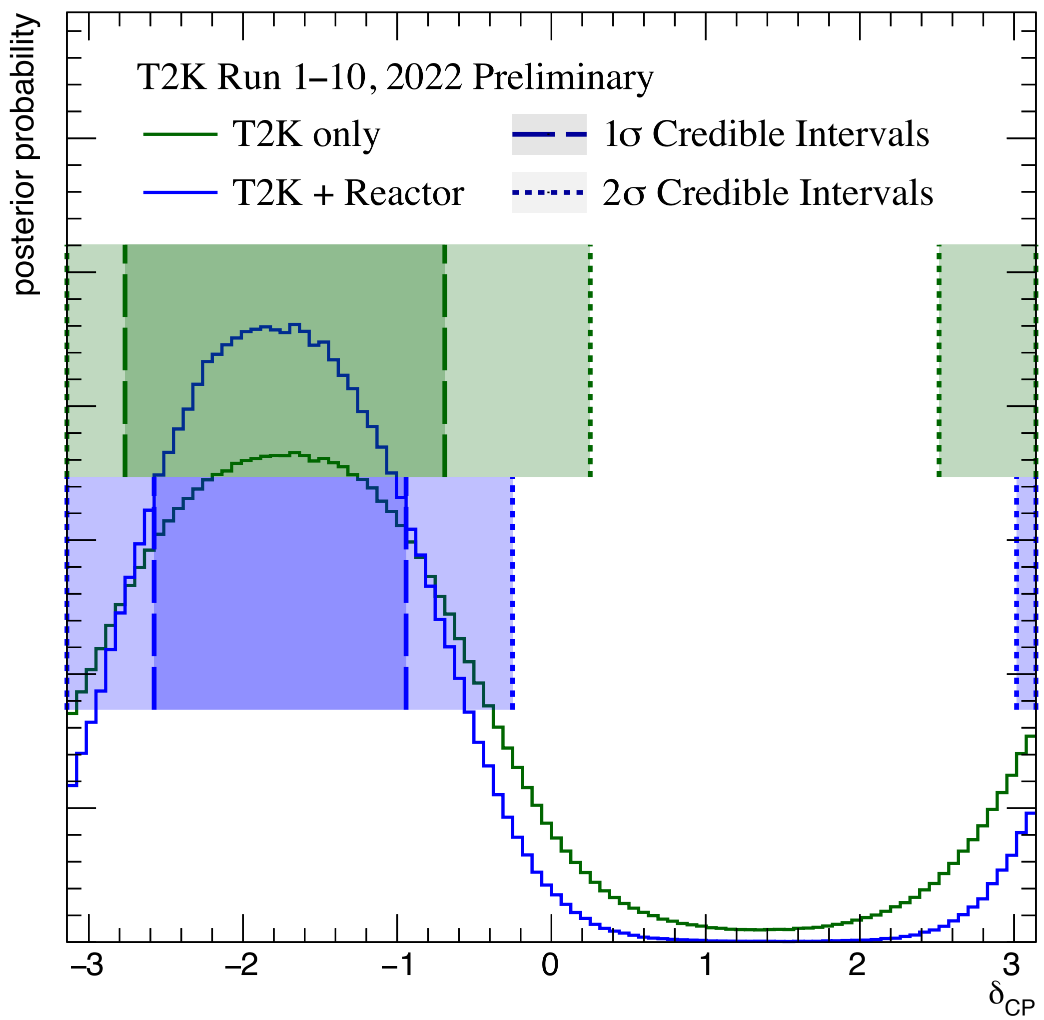
Event rates

	Data
FHC 1Rμ	318
RHC 1Rμ	137
FHC 1Re	94
RHC 1Re	16
FHC 1R ν_e CC1π^+	14
FHC MR ν_μ CC1π^+	134
FHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	191
RHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	71

T2K Run 1-10, preliminary

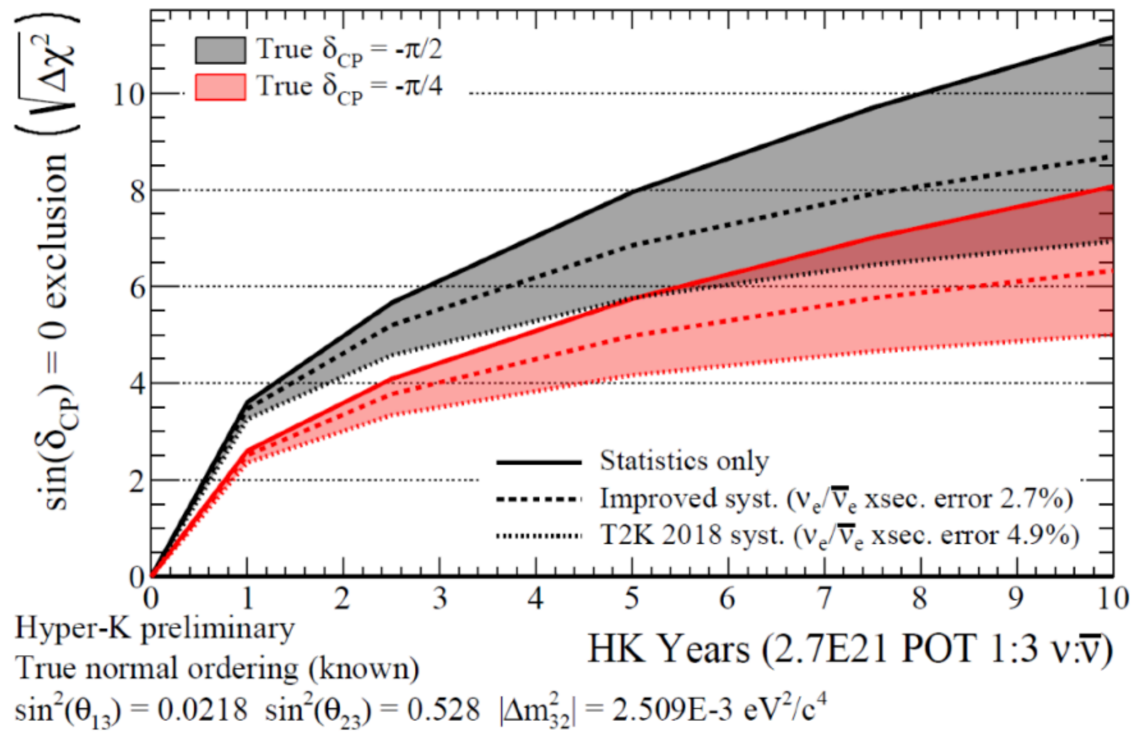
Bayesian analysis

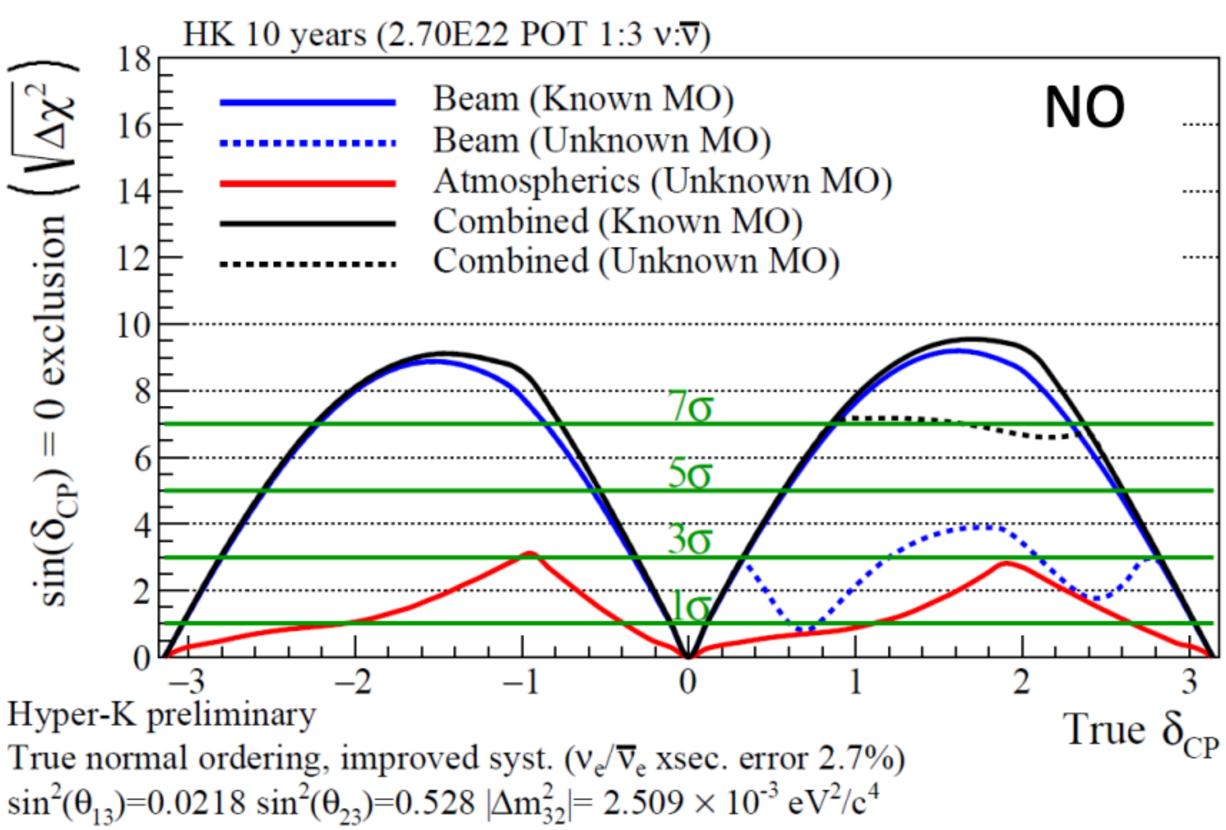


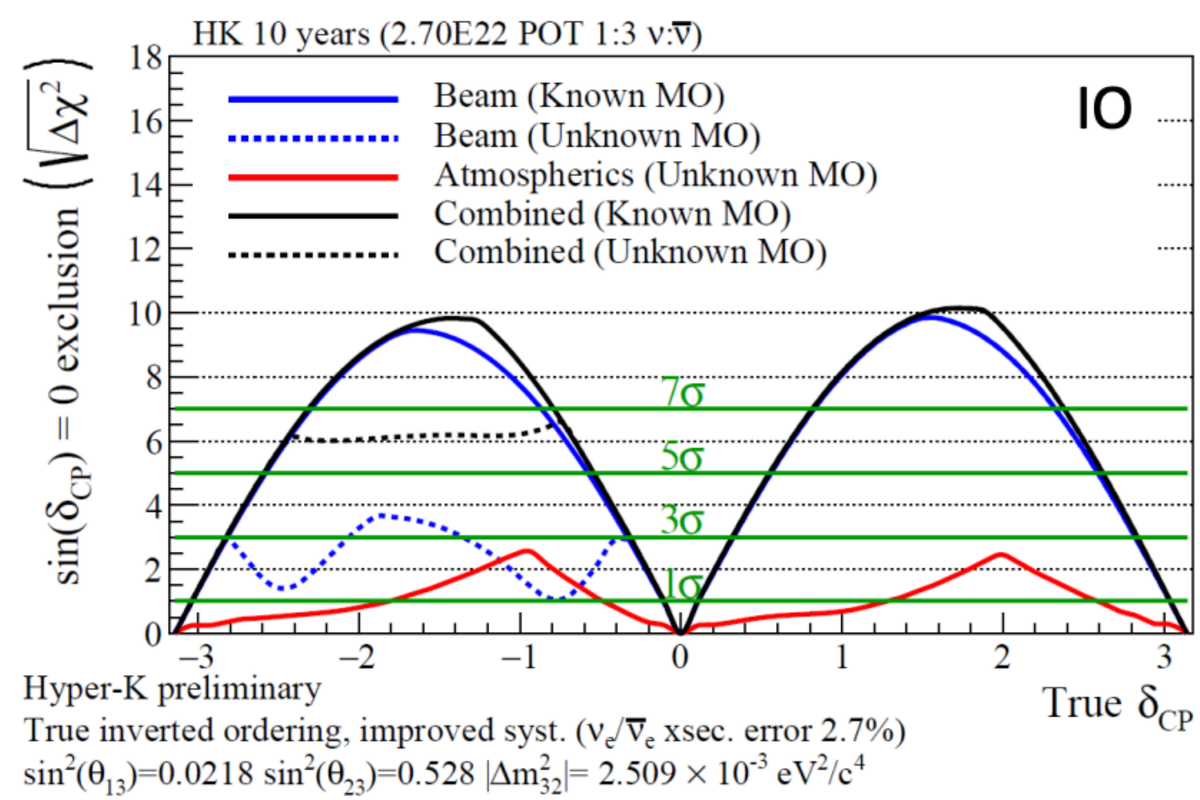


- Priors flat in plotted variables are assumed
- Top two plots marginalized over mass ordering with uniform prior
- Qualitatively similar results to frequentist fits
- Application of reactor constraint on θ_{13} results in preference of upper octant.

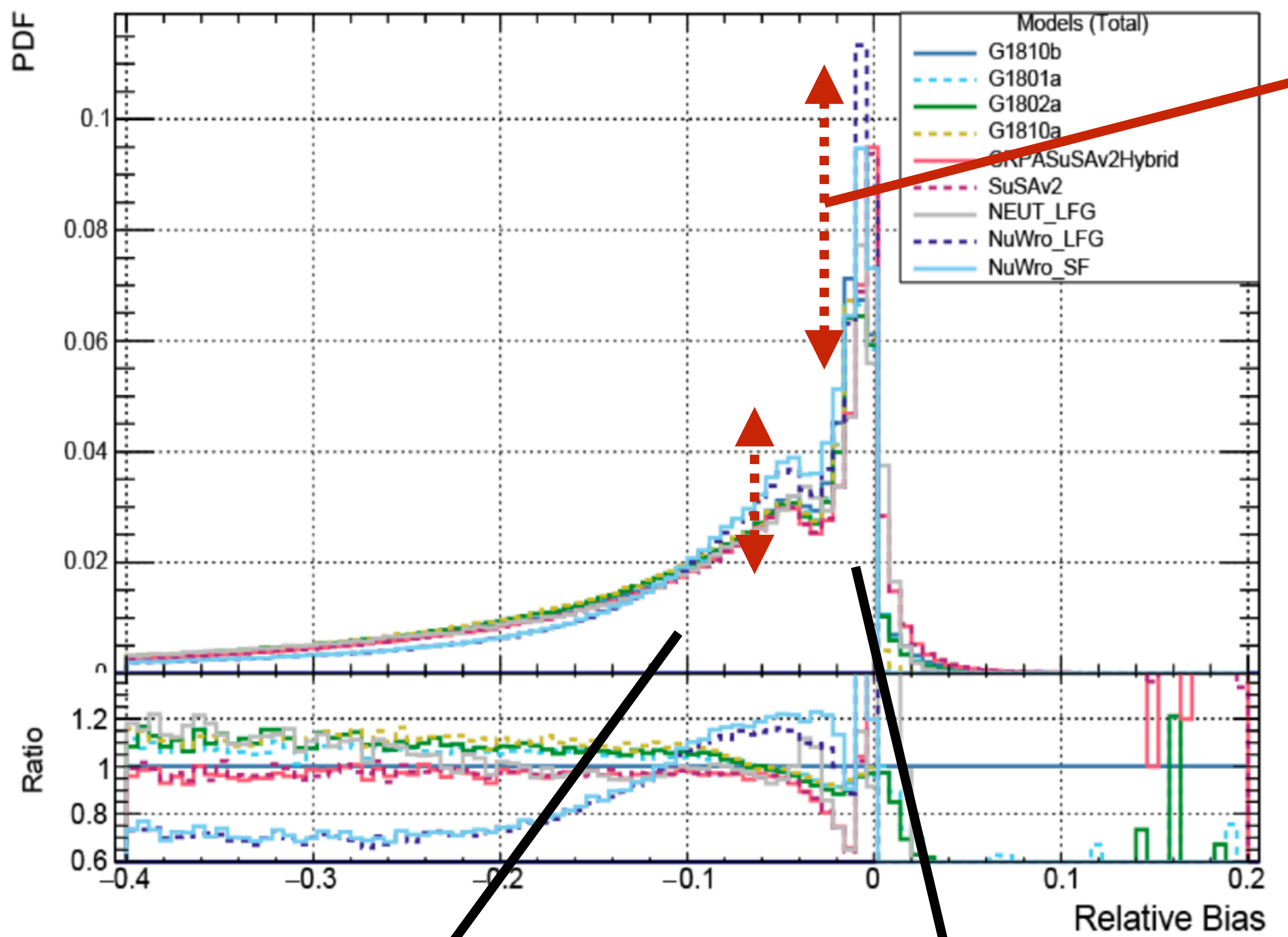
Hyper-Kamiokande era







Crucial role of improving our interaction models

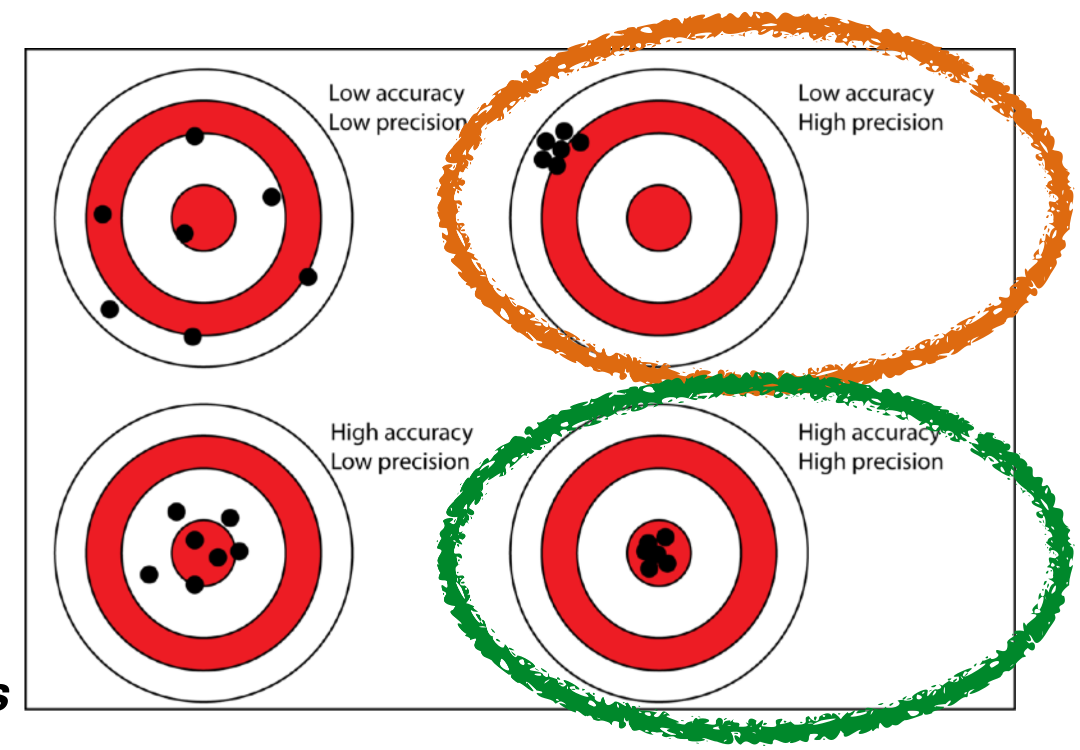


Adam Wong — Evaluating Bias Uncertainties for the DUNE Experiment

The actual tricky point!

Cross-section of every signal interaction channel have to be **very well known (alternative model studies) and parametrised (systematics)** to quantify the underlying population of reconstructed neutrinos

What we don't want!!



What we want!

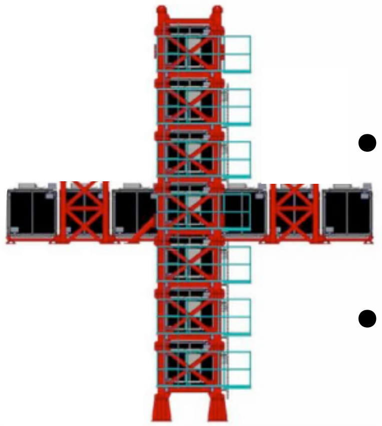
Events with mis-reconstructed E_ν

- ***NOT an issue for measuring osc!***
- *Only washing out the osc. prob signal with the proxy variable*

Good E_ν reconstruction events

- *Best proxy for probing the oscillation probability*
- *Carry most of the sensitivity*

The near detectors in Tokai

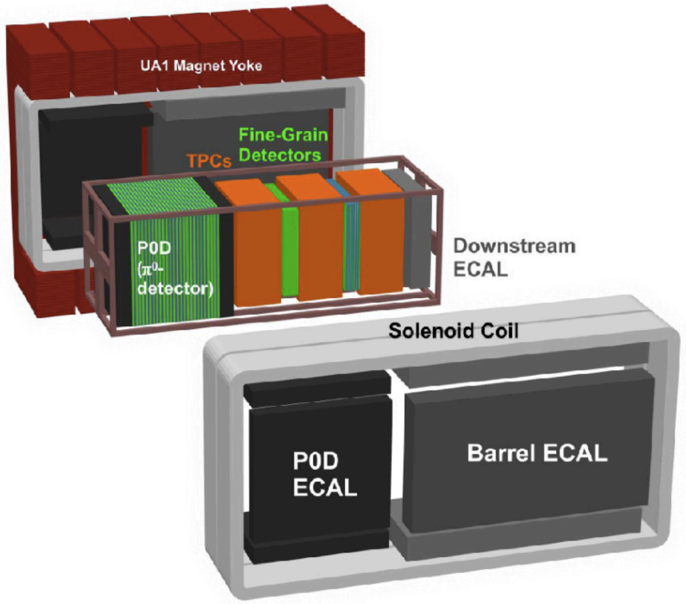


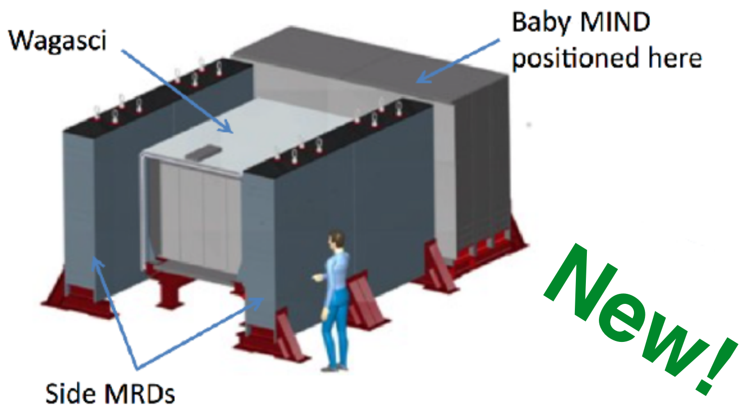
INGRID: On-axis

- Iron-scintillator sandwich detector
- Monitors the beam direction and intensity

ND280: Off-axis

- Active scintillator (C) and passive water (O) neutrino targets
- Tracking particles with time projection chambers
- **Magnetised** for charge and momentum reconstruction

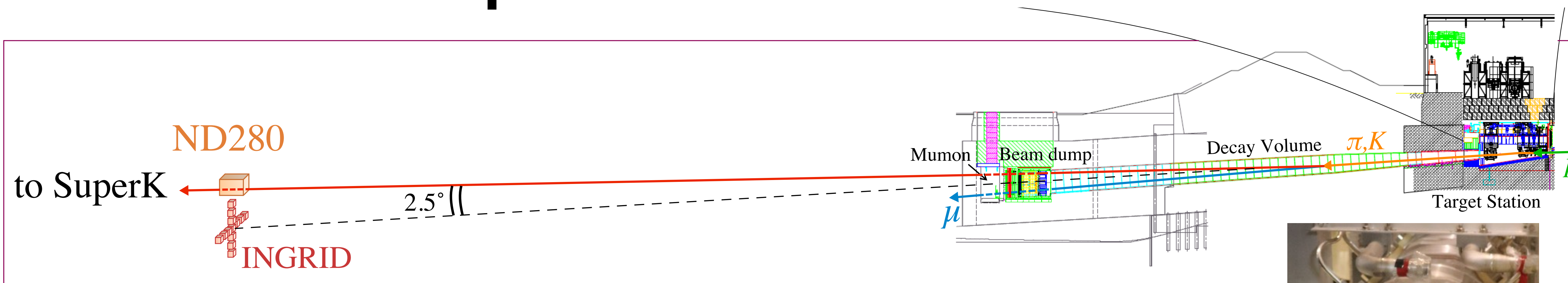


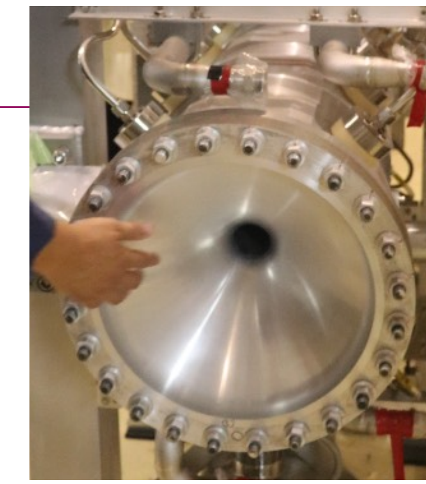


Wagasci/Baby MIND: Off-axis

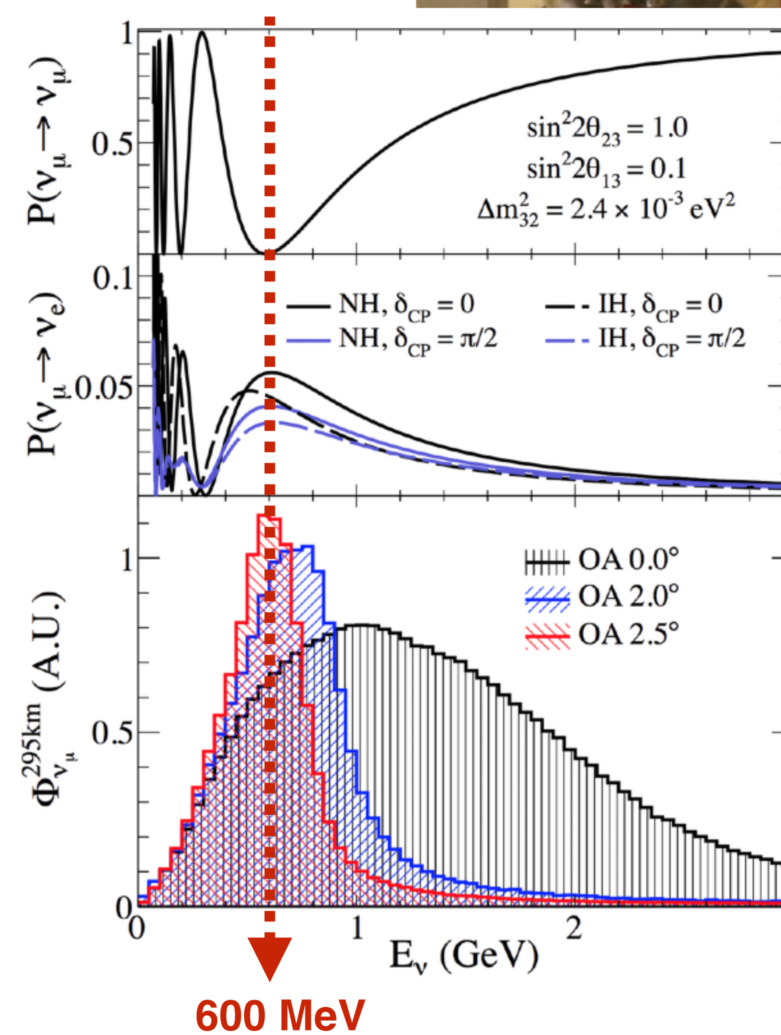
- Water target and cuboid lattice scintillators for high angle acceptance
- Compact **magnetised** iron muon range detector

Neutrino beam production





- JPARC provides accelerated protons at ~30GeV
- Protons collide with a 90cm graphite target, producing π, K
- 3 successive magnetic horns selectively focus positively or negatively charged hadrons that decay into neutrinos or antineutrinos
- **Two production modes**
  - Forward Horn Current (FHC) / Neutrino mode
  - Reverse Horn Current (RHC) / Antineutrino mode
- Off-axis technique for sending a narrow and sub-GeV energy spectrum to the far detector



Studying neutrino oscillations with T2K

ν_μ —— ν_1, ν_2, ν_3 ⟶ ν_μ? ν_e?

PRODUCTION **PROPAGATION** **DETECTION**

PMNS matrix for flavour mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 mixing angles + 1 complex phase:

$$\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{CP}$$

+ Quantum mechanics for propagation

2 additional independant parameters:

$$\Delta m^2_{31},\ \Delta m^2_{21} \quad (\Delta m^2_{ij} \doteq m_i^2 - m_j^2)$$

Open questions addressed with T2K:

- Value of the CP violating phase in the leptonic sector
- Mass ordering (MO) - sign of Δm^2_{32}
- Is θ_{23} maximal? Or which octant does it belongs? (> or < than $\pi/4$)

Benefiting from the many advantages of using accelerator neutrinos:

quasi-pure muon (anti)neutrino source, neutrino or antineutrino production, well studied flux at emission (near detectors), energy and distance selection

$\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$ $\xrightarrow[\text{Neutrino production mode}]{}$ $\nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \boxed{\nu_e, \nu_e,} \nu_\mu, \nu_\mu$

$\bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu, \bar\nu_\mu$ $\xrightarrow[\text{Antineutrino production mode}]{}$ $\bar\nu_\tau, \bar\nu_\tau, \bar\nu_\tau, \bar\nu_\tau, \boxed{\bar\nu_\tau, \bar\nu_e,} \bar\nu_\mu, \bar\nu_\mu$