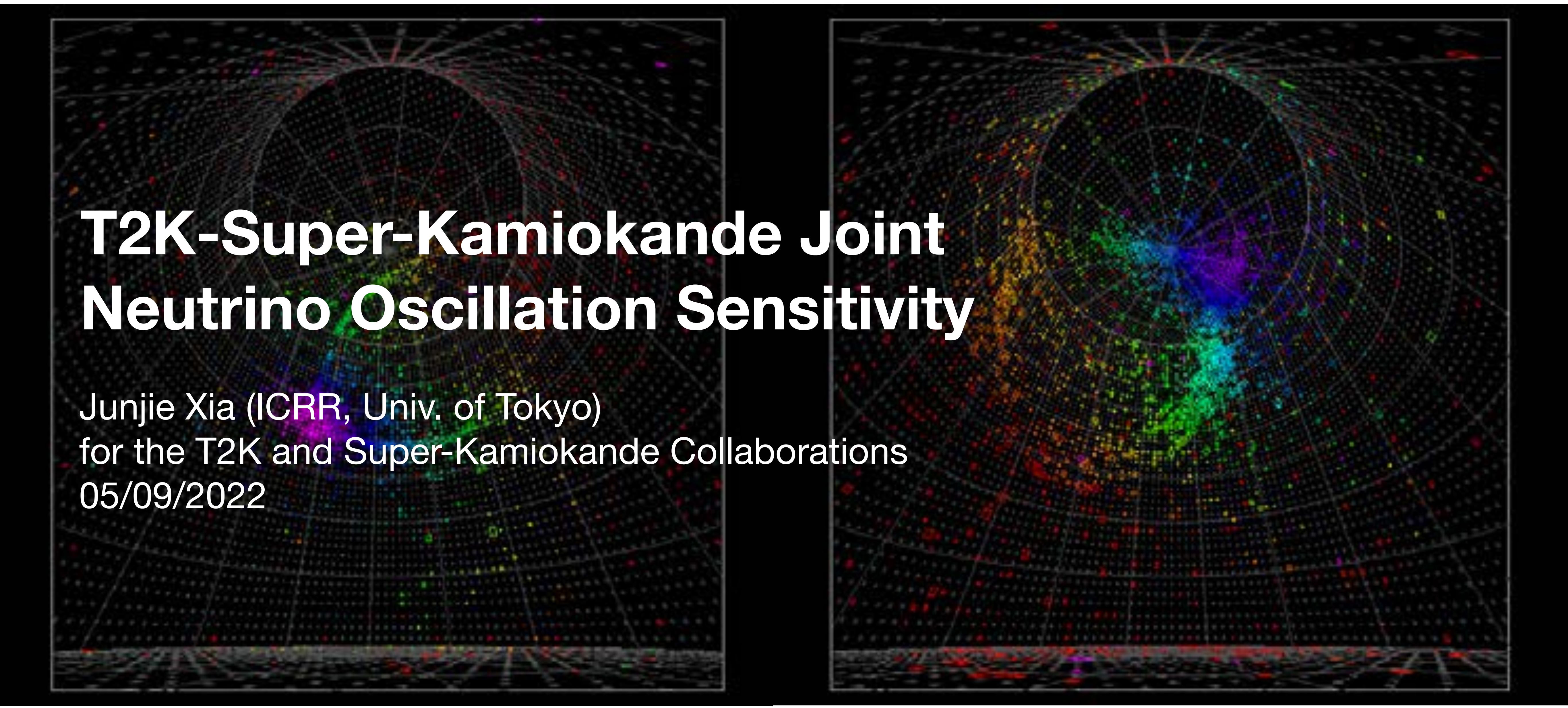
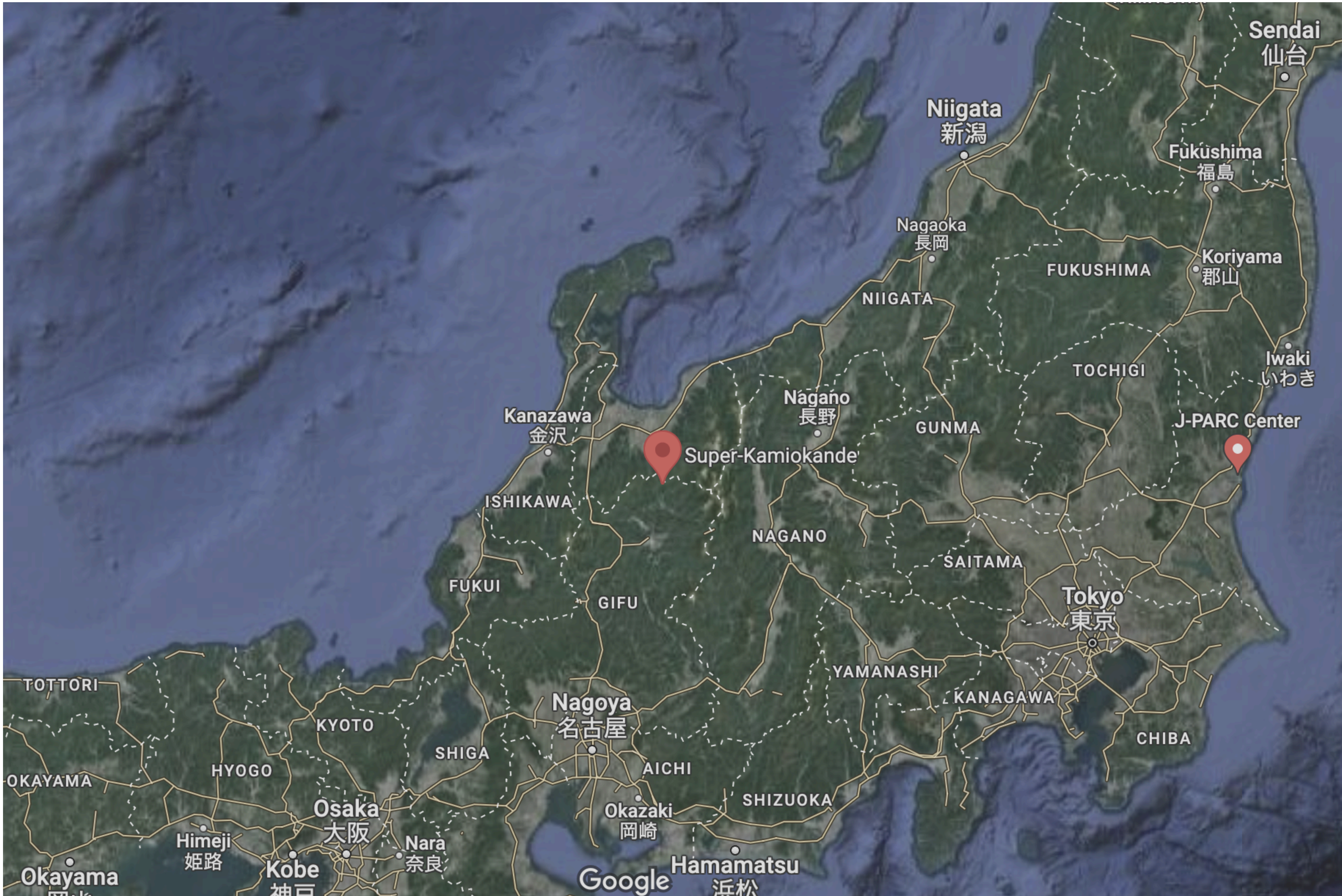


T2K-Super-Kamiokande Joint Neutrino Oscillation Sensitivity

Junjie Xia (ICRR, Univ. of Tokyo)
for the T2K and Super-Kamiokande Collaborations
05/09/2022

T2K and Super-Kamiokande (SK)



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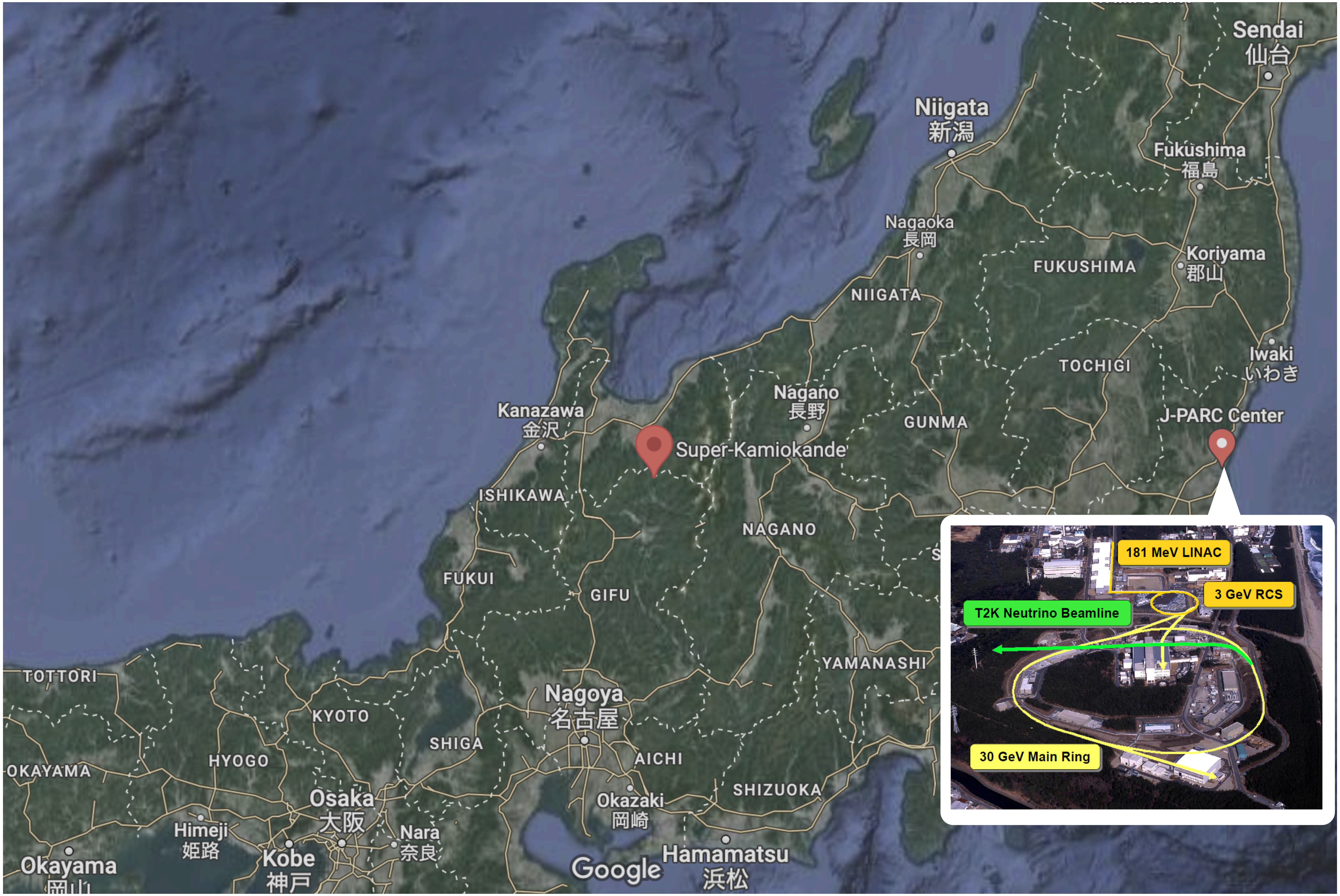

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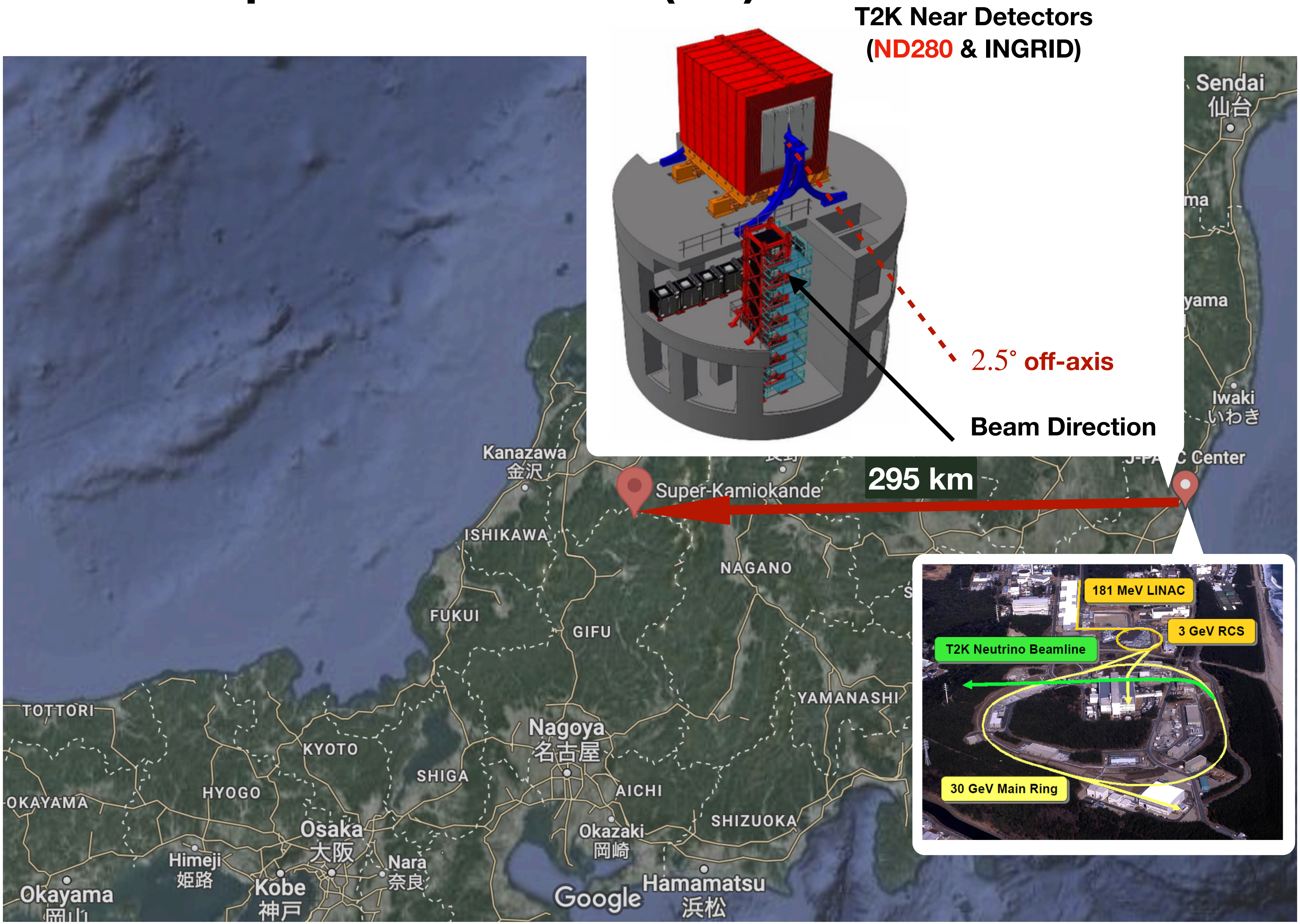

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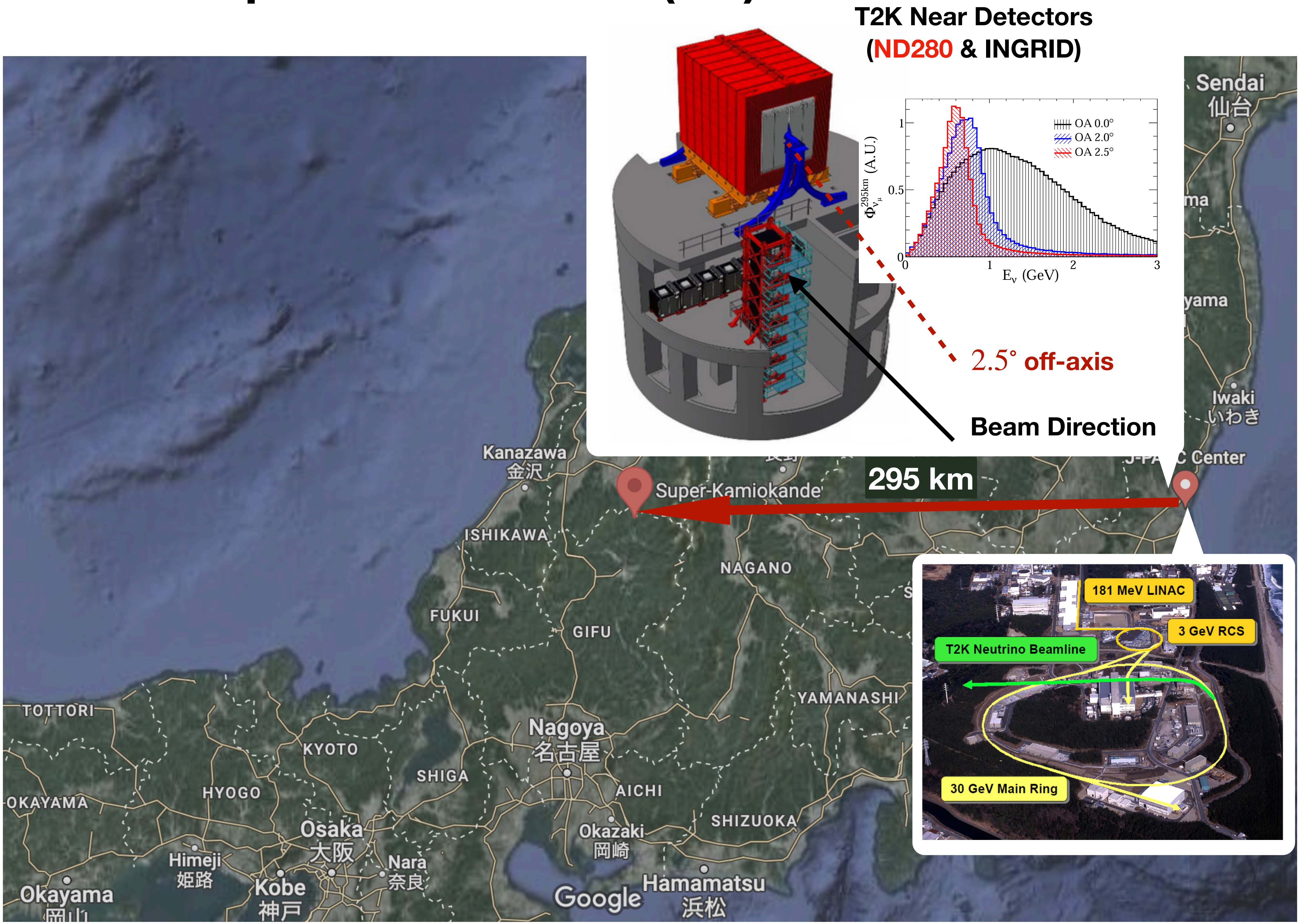

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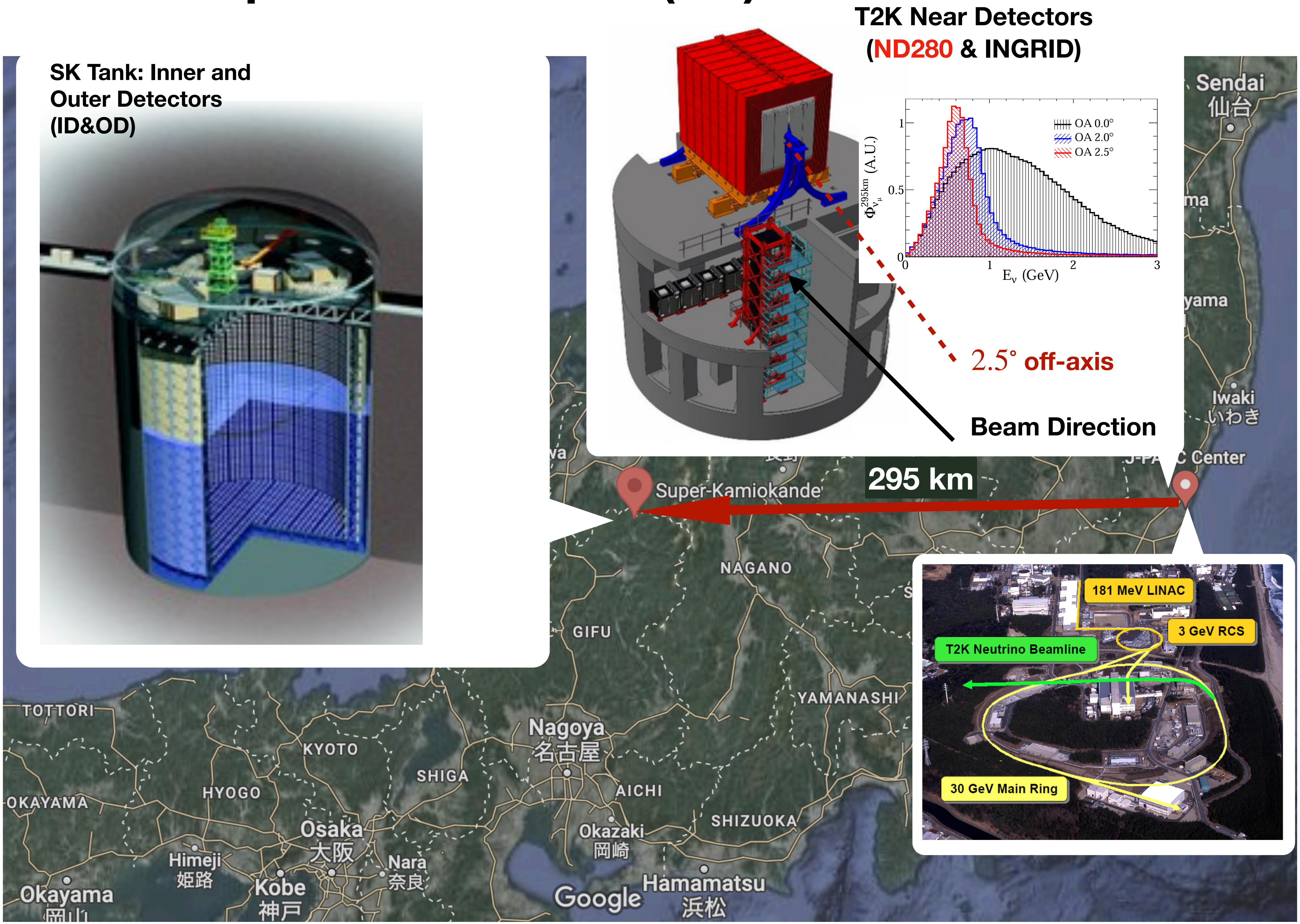
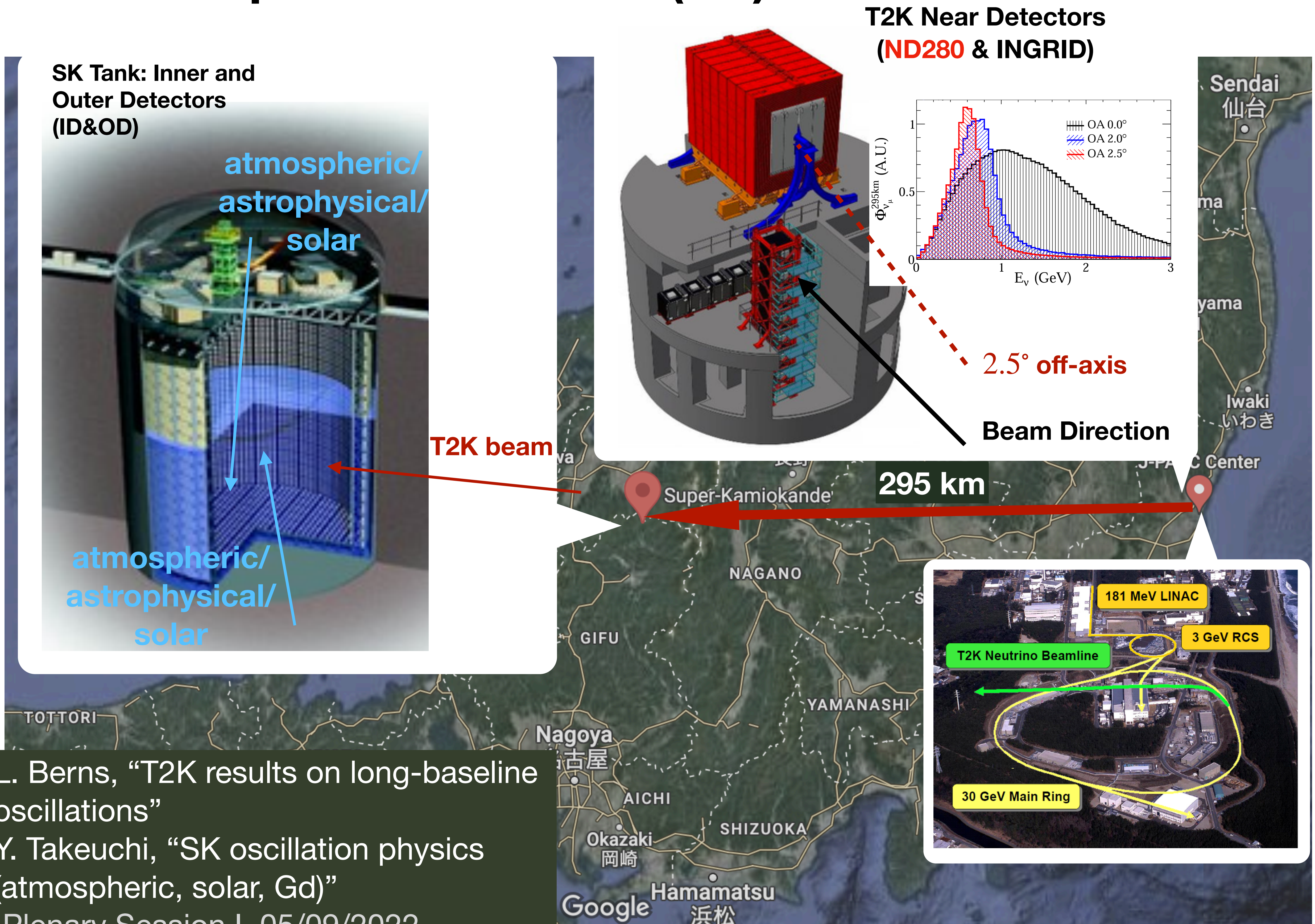


T2K and Super-Kamiokande (SK)



- L. Berns, “T2K results on long-baseline oscillations”
- Y. Takeuchi, “SK oscillation physics (atmospheric, solar, Gd)”

@ Plenary Session I, 05/09/2022

Overview of the Joint Analysis

The neutrino oscillation parameters are correlated, causing **degenerate measurements**. For example, δ_{CP} and mass ordering (MO) have similar effects to the observable in T2K.

The *a priori* assumptions in the input models may cause **biases**.

Always good to have **more statistics** for better sensitivity.

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The analysis strategies, established this year, were presented with the sensitivity results @ NEUTRINO 2022:

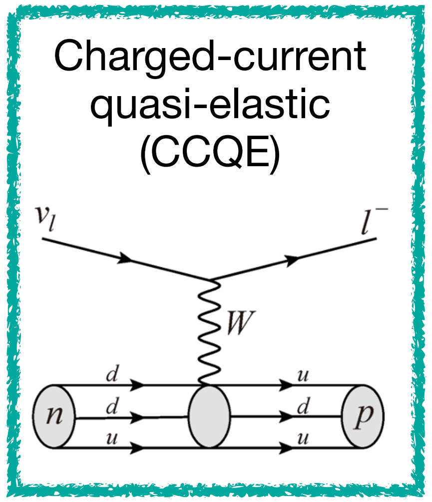
1. Oscillation Probability Calculation
2. Interaction Model and Detector Systematics
3. Sensitivity Results

Neutrino Samples in T2K Run 1-10 and SK-IV

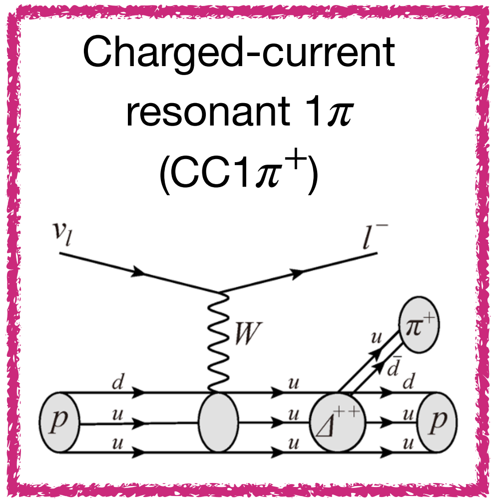
T2K Run 1-10 (2020 analysis)

- 3.6×10^{21} protons on target (POT)
- All fully contained (FC) within the SK ID
- Sub-GeV single-ring “e-like”/“μ-like”
- Separation of ν and $\bar{\nu}$ by beam modes
- 5 samples used in this joint fit:

4 “CCQE-like” samples



1 “CC1π-like” sample



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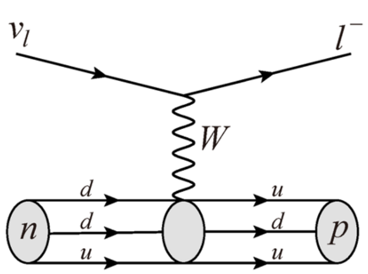
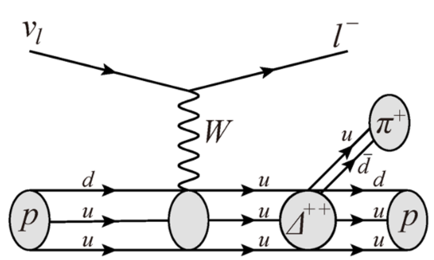
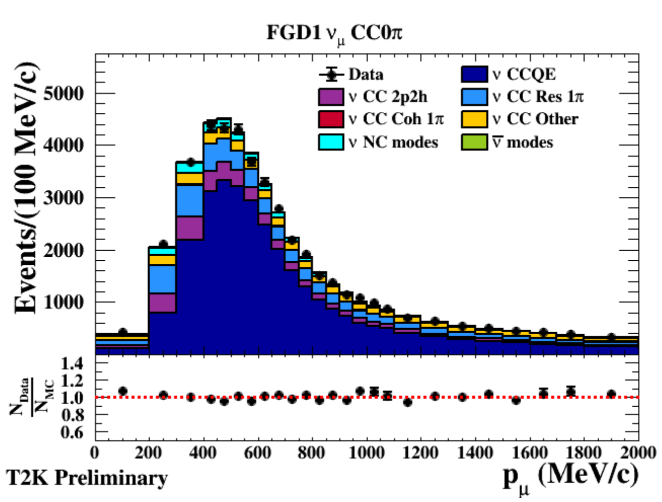


1 "CC1π-like" sample

Charged-current resonant 1π (CC1π^+)





Data fit of un-oscillated ν_μ or $\bar{\nu}_\mu$ in the ND to constrain the **neutrino flux** and **cross section uncertainties**.

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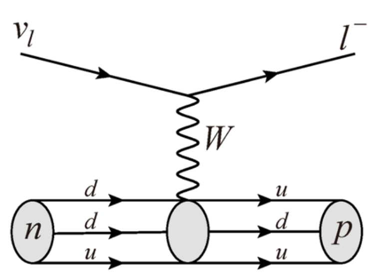

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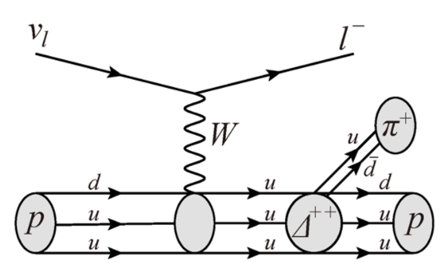

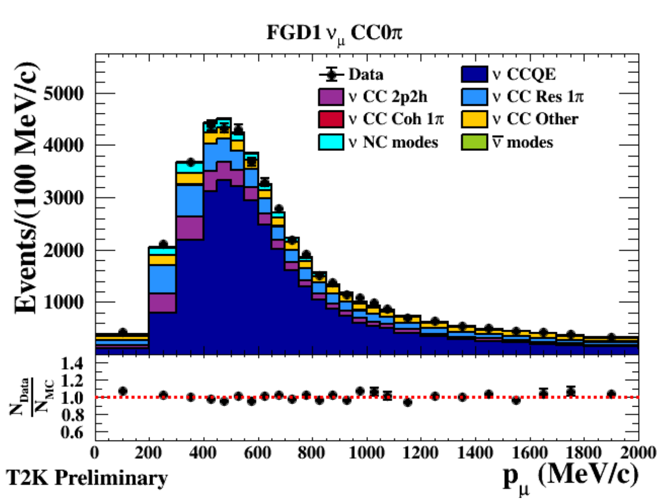

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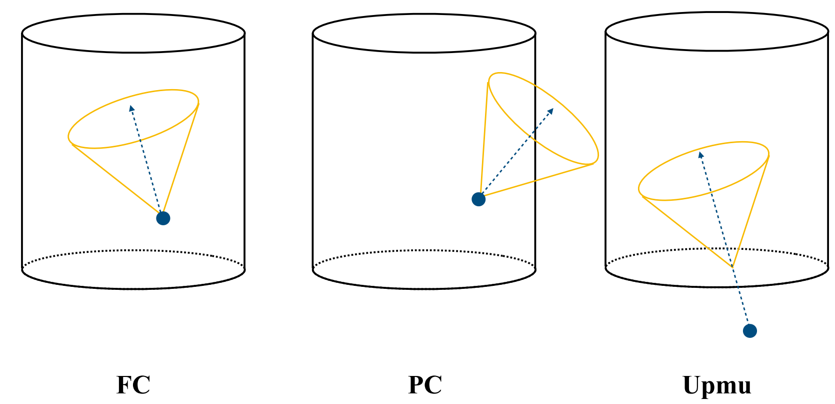
SK-IV Atmospheric

Fully contained, partially contained (PC), and up-going muon (Upmu)



- 3244.4 days of data taking
- Sub&multi-GeV, single&multi-ring, "e-like"/"π^0-like"/"μ-like", stopping&thru-going, showering&non-showering
- 18 samples used in this joint fit with the same selection as in arXiv:1901.03230

Neutrino Samples in T2K Run 1-10 and SK-IV

T2K Run 1-10 (2020 analysis)

- 3.6×10^{21} protons on target (POT)
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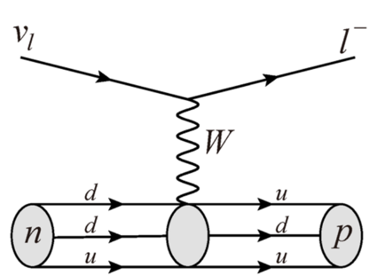

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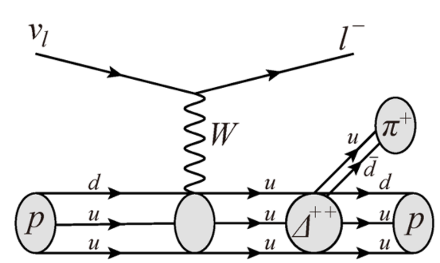

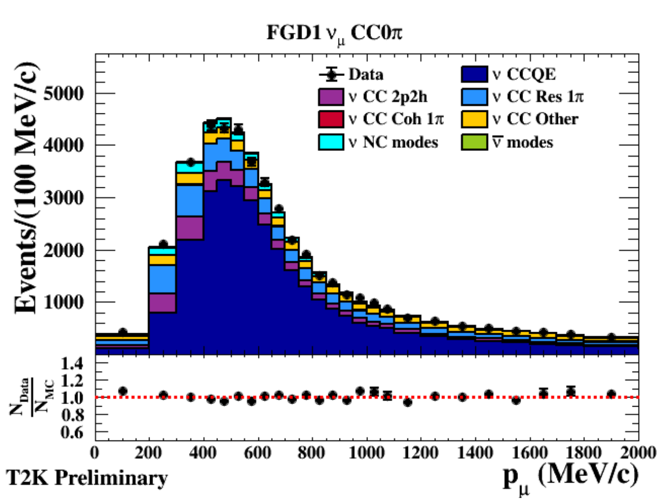

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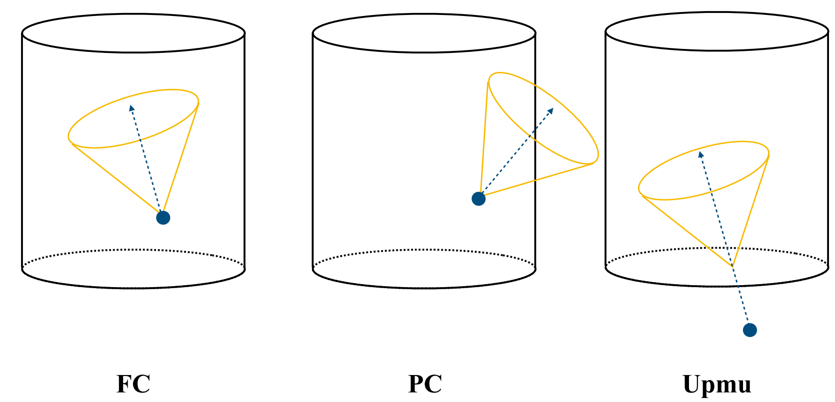
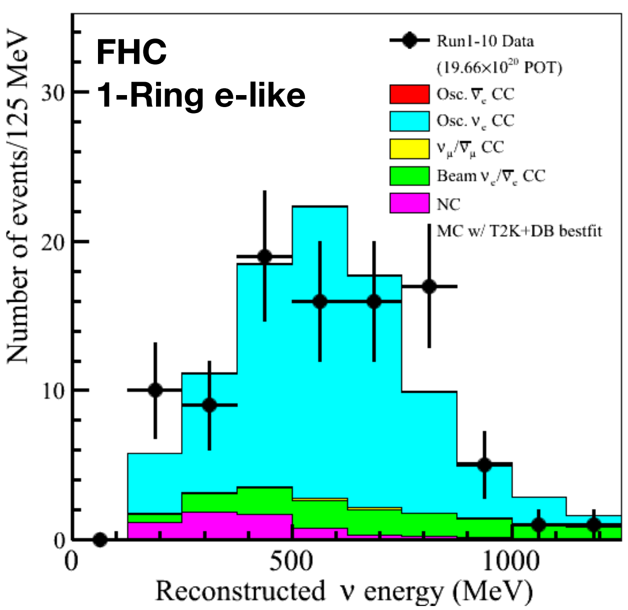


- 3244.4 days of data taking
- Sub&multi-GeV, single&multi-ring, "e-like"/"π^0-like"/"μ-like", stopping&thru-going, showering&non-showering
- Selections for the sub-GeV single-ring samples are **very similar but not identical** with the T2K samples — this difference has **no impact** to the oscillation sensitivity with the systematic uncertainties in this joint fit.

Neutrino Samples in T2K Run 1-10 and SK-IV

T2K Run 1-10

T2K Preliminary



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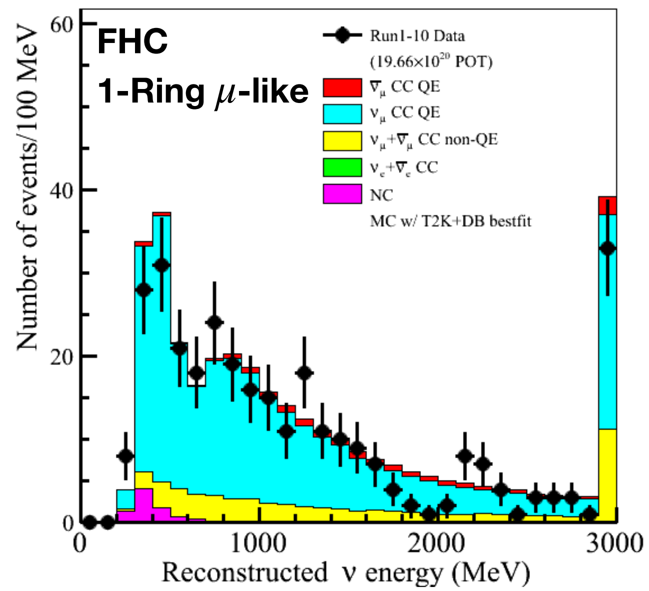
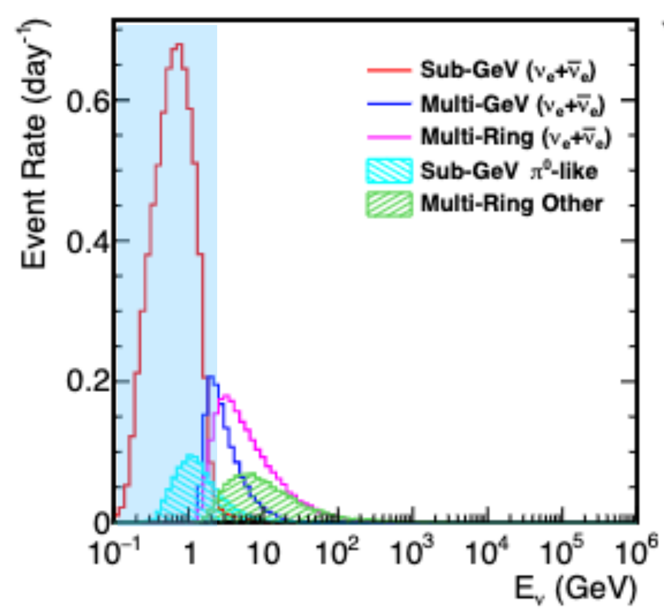
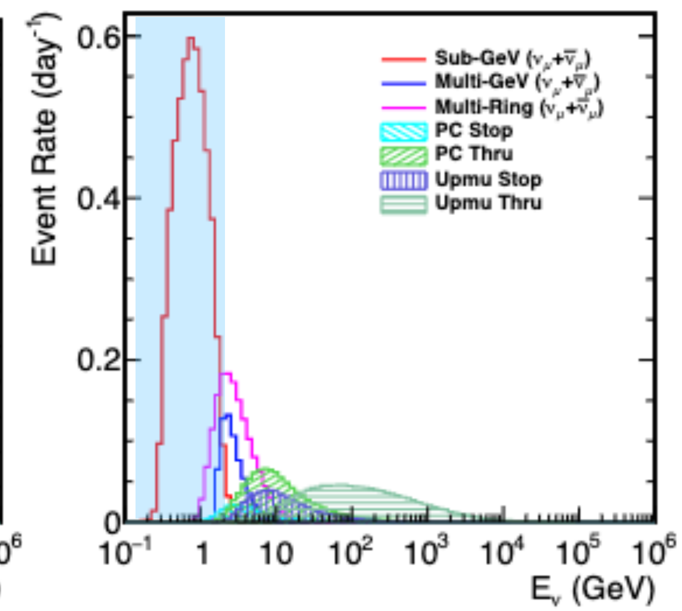


SK-IV Atmospheric

e-like & π^0-like



μ-like, PC, & Upmu



Neutrino Samples in T2K Run 1-10 and SK-IV

T2K Run 1-10

SK-IV Atmospheric

T2K Preliminary

T2K Preliminary

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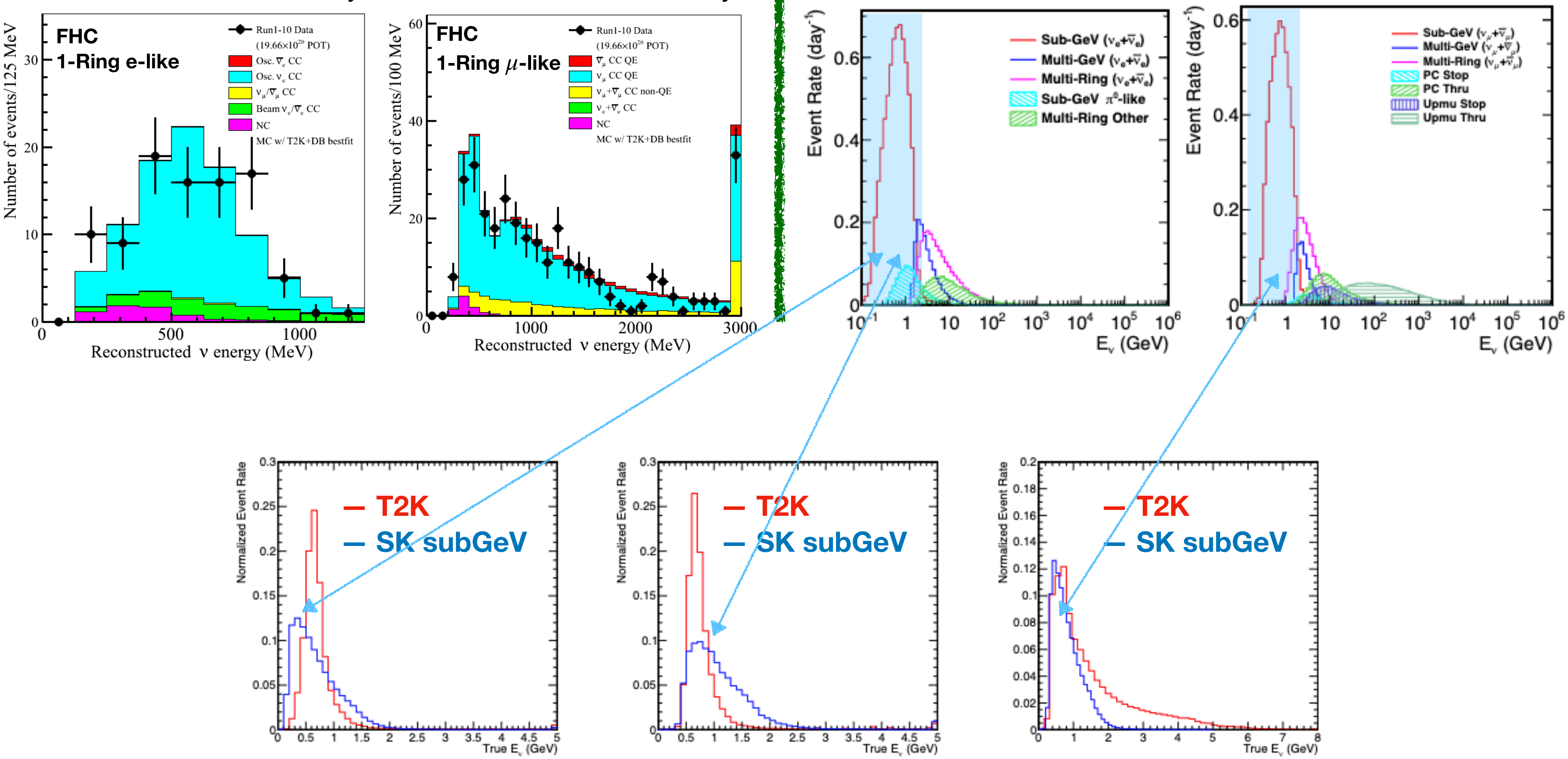


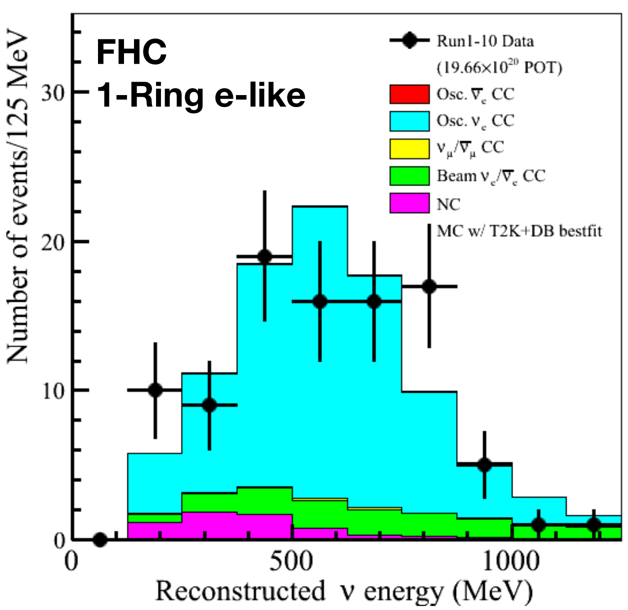
(A) *e*-like CCQE

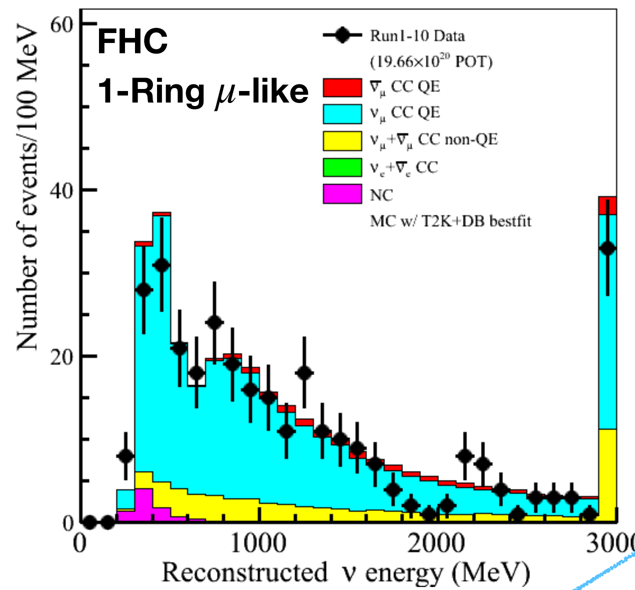
(B) *e*-like CC1π^+

(C) μ-like CCQE

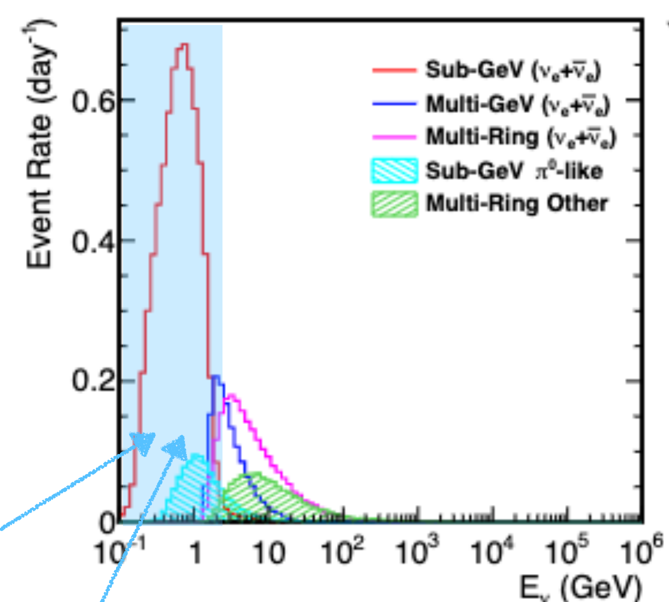
Neutrino Samples in T2K Run 1-10 and SK-IV

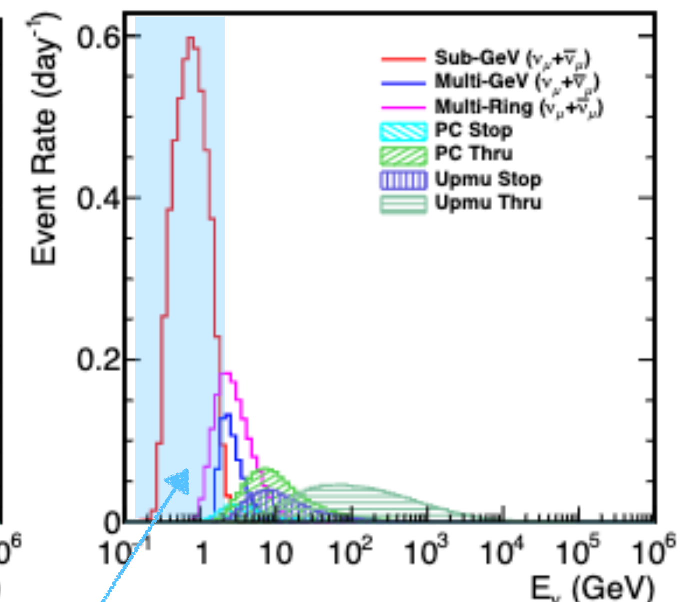
T2K Run 1-10



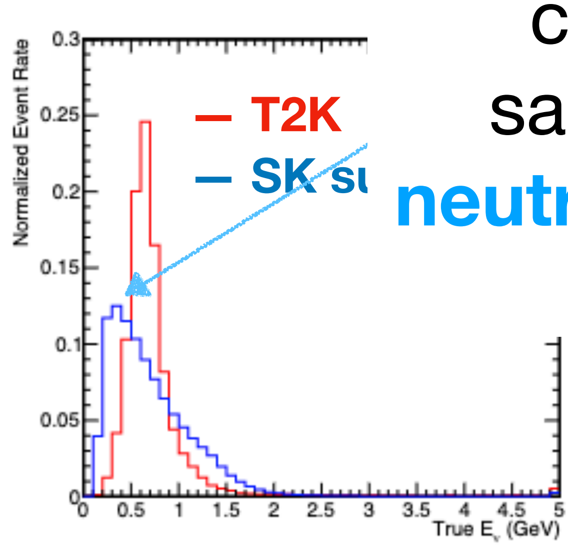


SK-IV Atmospheric

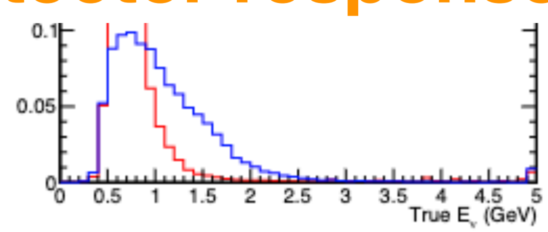




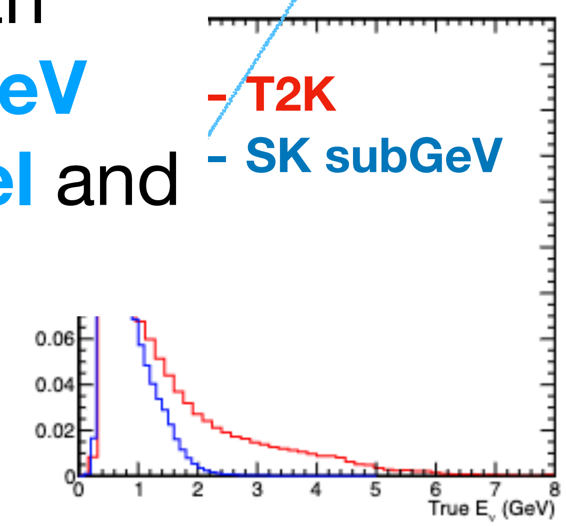
Same systematic uncertainties could be applied to both samples, e.g. the **sub-GeV neutrino interaction model** and **detector responses.**



(A) *e*-like CCQE



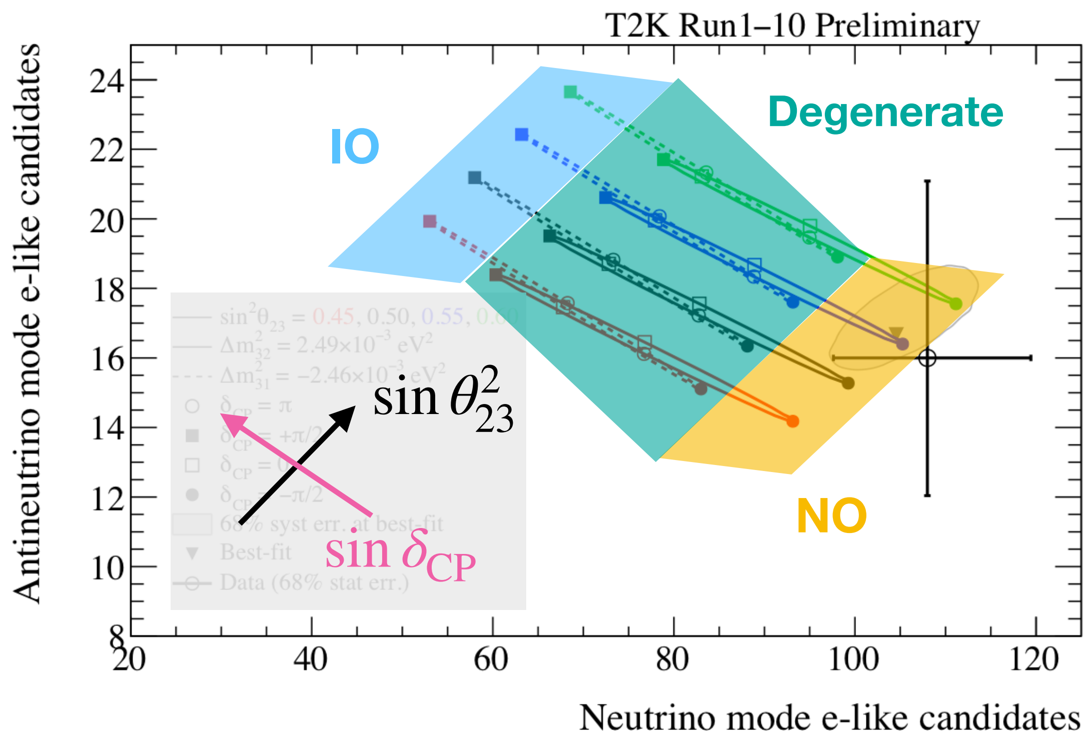
(B) *e*-like CC1π^+



(C) μ-like CCQE

Sensitivity to the Oscillation Parameters

T2K

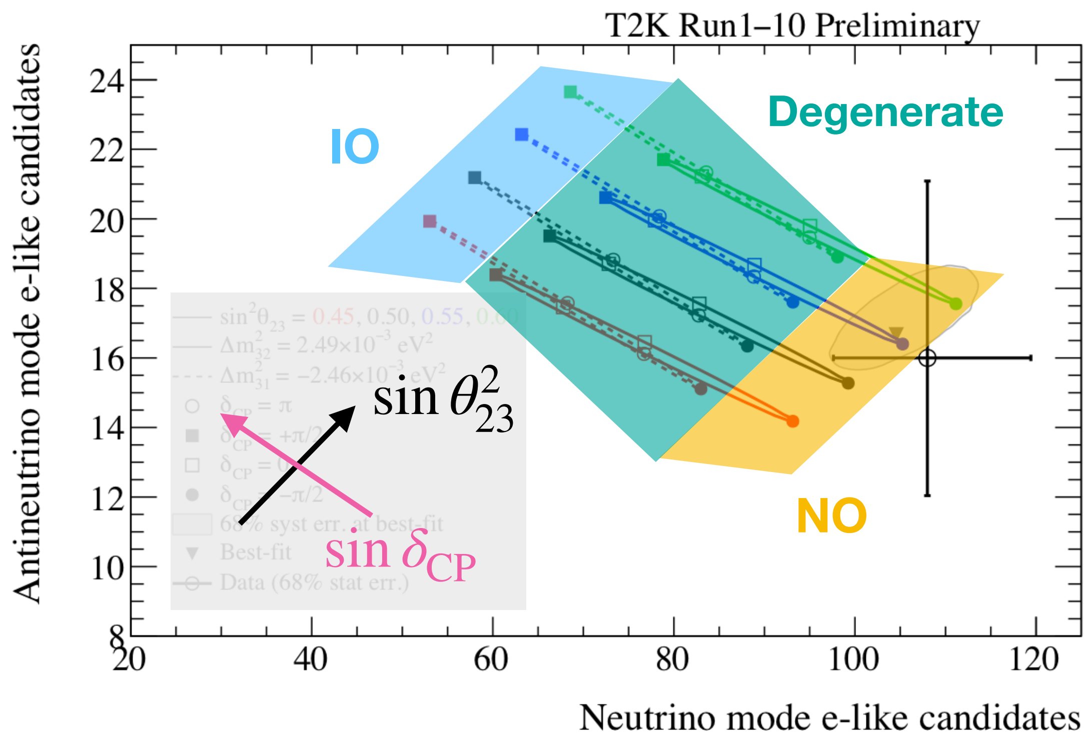


Simultaneous fit of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ constrains $\sin\delta_{\text{CP}}$.

The effect to ν_e and $\bar{\nu}_e$ event rates is degenerate between δ_{CP} and mass ordering (MO), the latter of which T2K has a limited sensitivity to.

Sensitivity to the Oscillation Parameters

T2K



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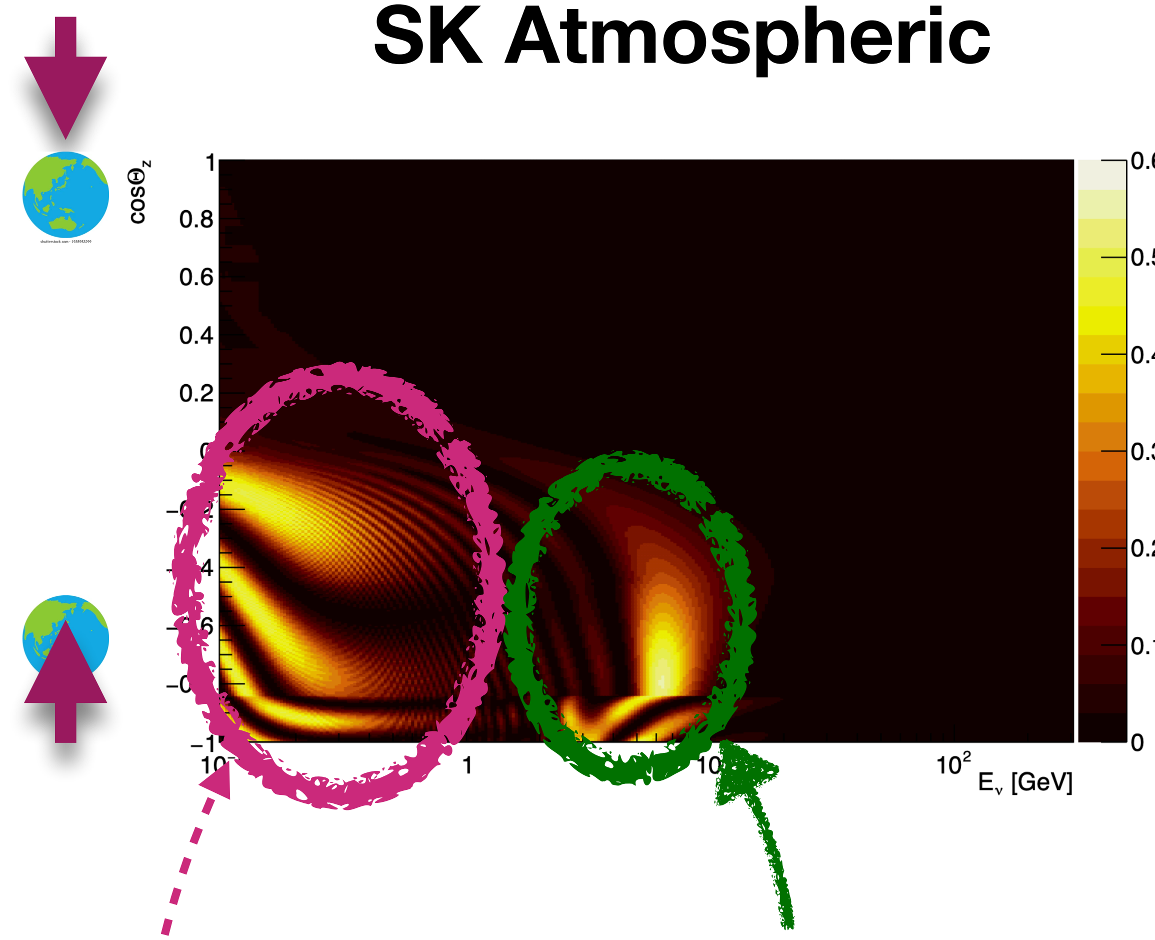
SK Atmospheric

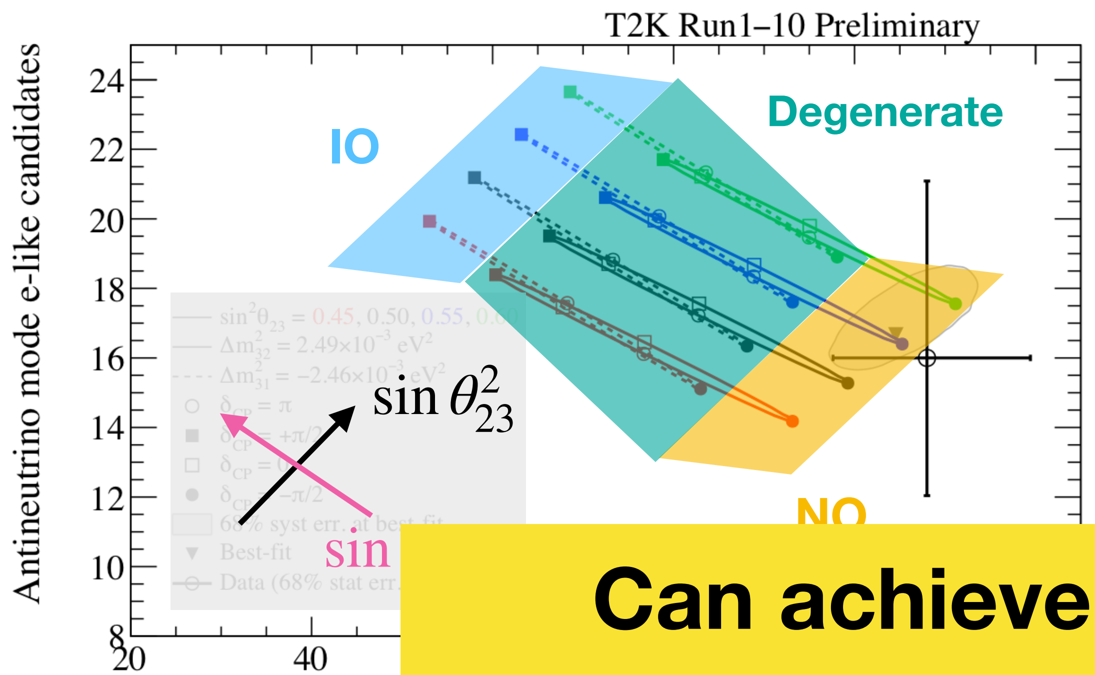


Oscillation resonance of few GeV neutrinos in the earth core and mantle provides sensitivity to MO: resonance in $\nu_\mu \rightarrow \nu_e$ if normal ordering (NO) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ if inverted (IO).

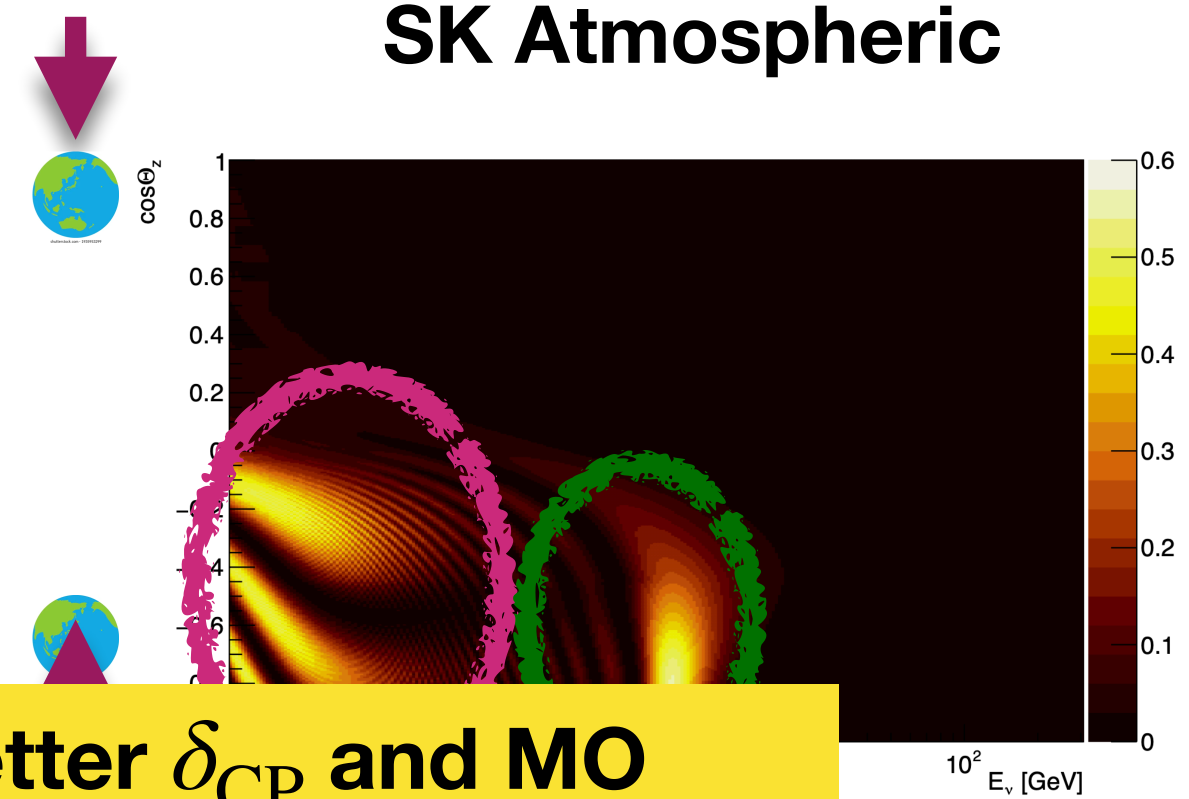
The normalization of sub-GeV e-like samples is weakly sensitive to $\delta_{\rm CP}$.

Sensitivity to the Oscillation Parameters

T2K



SK Atmospheric



Can achieve better δ_{CP} and MO sensitivities by combining the two.

But how to apply the systematic uncertainty models from the two experiments?

Simultaneou…

$\bar{\nu}_\mu \to \bar{\nu}_e$ co…

The effect t…

degenerate between δ_{CP} and mass ordering (MO), the latter of which T2K has a limited sensitivity to.

…f few GeV

…ore and mantle

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…dering (NO)

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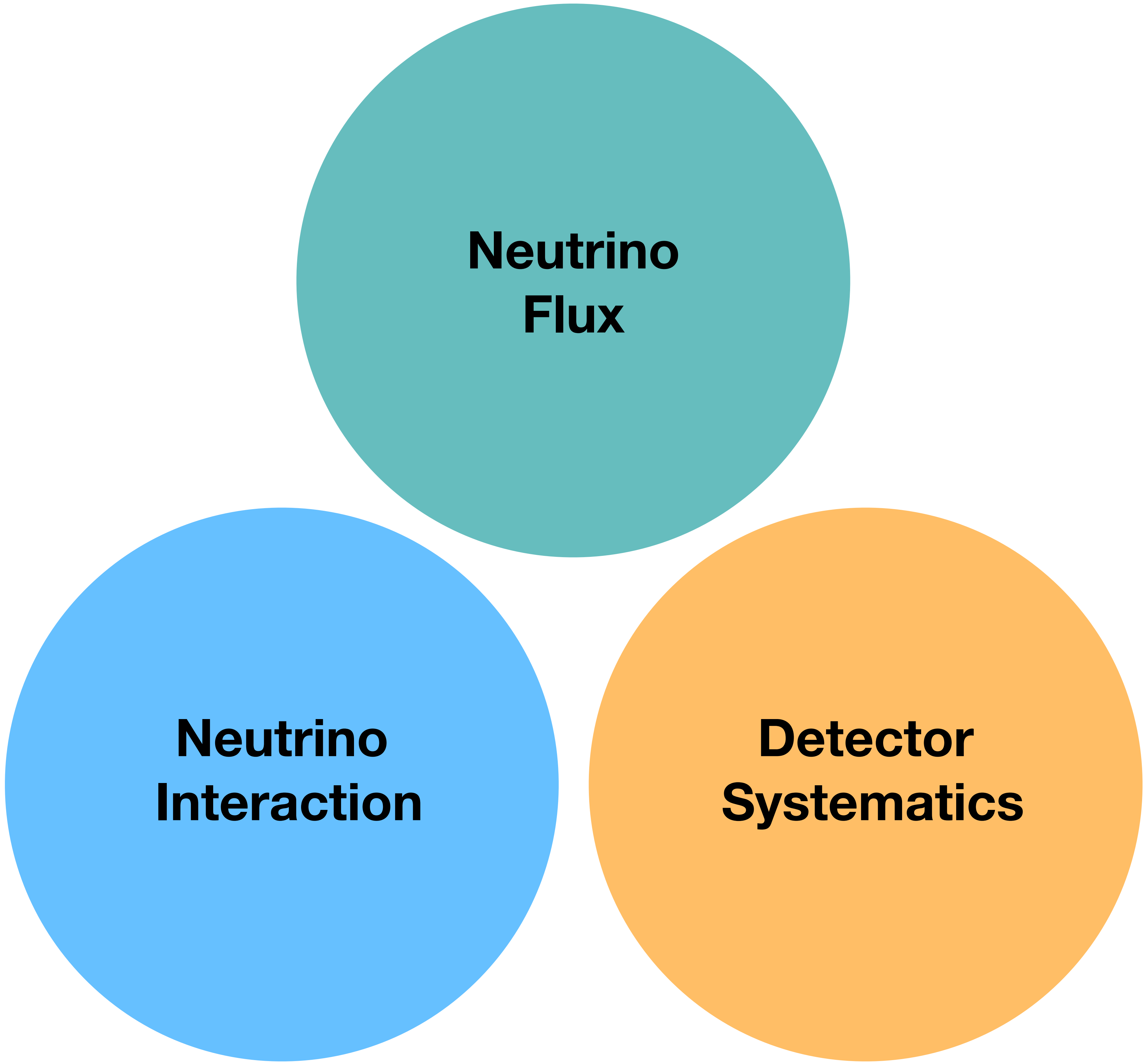
Input Models to the T2K-SK Joint Oscillation Analysis



Input Models to the T2K-SK Joint Oscillation Analysis

T2K Beam Flux

Based on J-PARC beam simulation and NA61/SHINE results

~5% uncertainty around the flux peak

Neutrino Flux

How to correlate?

SK Atm Flux

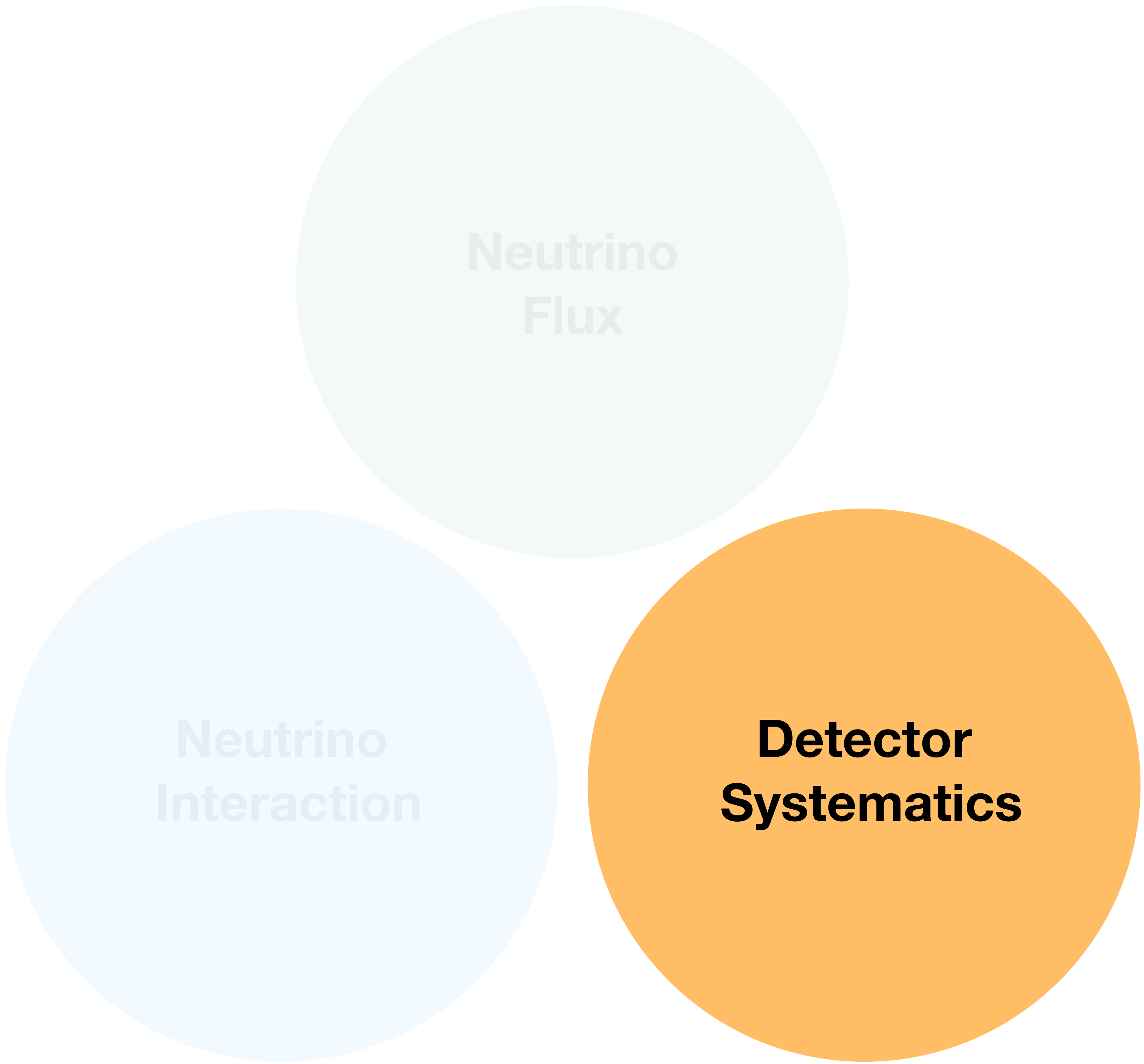
Based on 2011 Honda flux model

5~10% uncertainty in FC&PC, 10~20% in Upmu

In this joint analysis the two flux models are implemented as they are in each reference experiment **without** correlation.

Ongoing work to update the SK atmospheric flux model. Then correlations may be applied due to similar hadro-production measurement inputs.

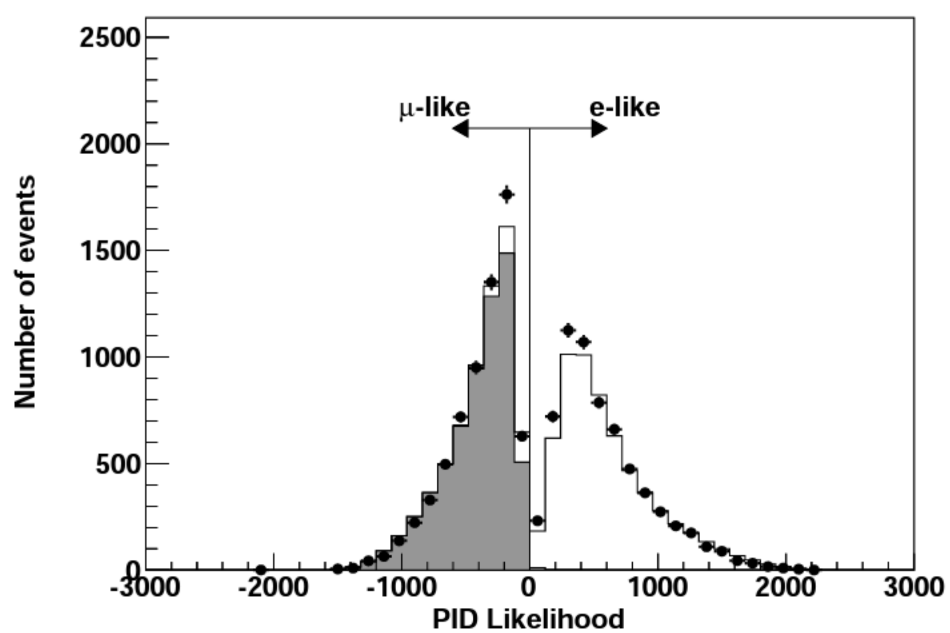
Input Models to the T2K-SK Joint Oscillation Analysis



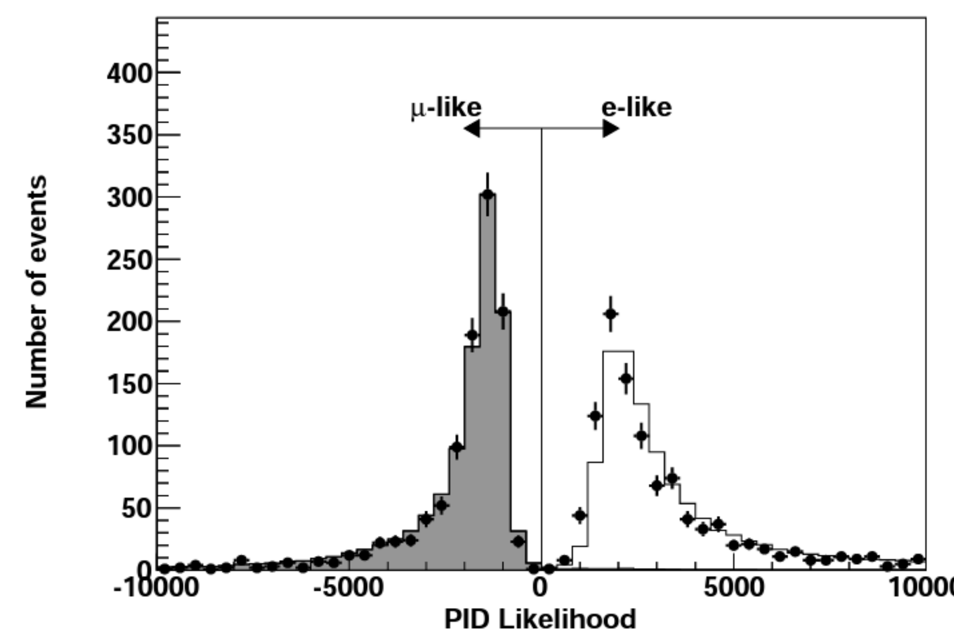
Input Models to the T2K-SK Joint Oscillation Analysis

One example of detector systematic uncertainties: e/mu PID

Separation by the likelihoods of reconstructed particle hypotheses, which depend on the reconstructed particle kinematics and detector responses



(a) Sub-GeV events



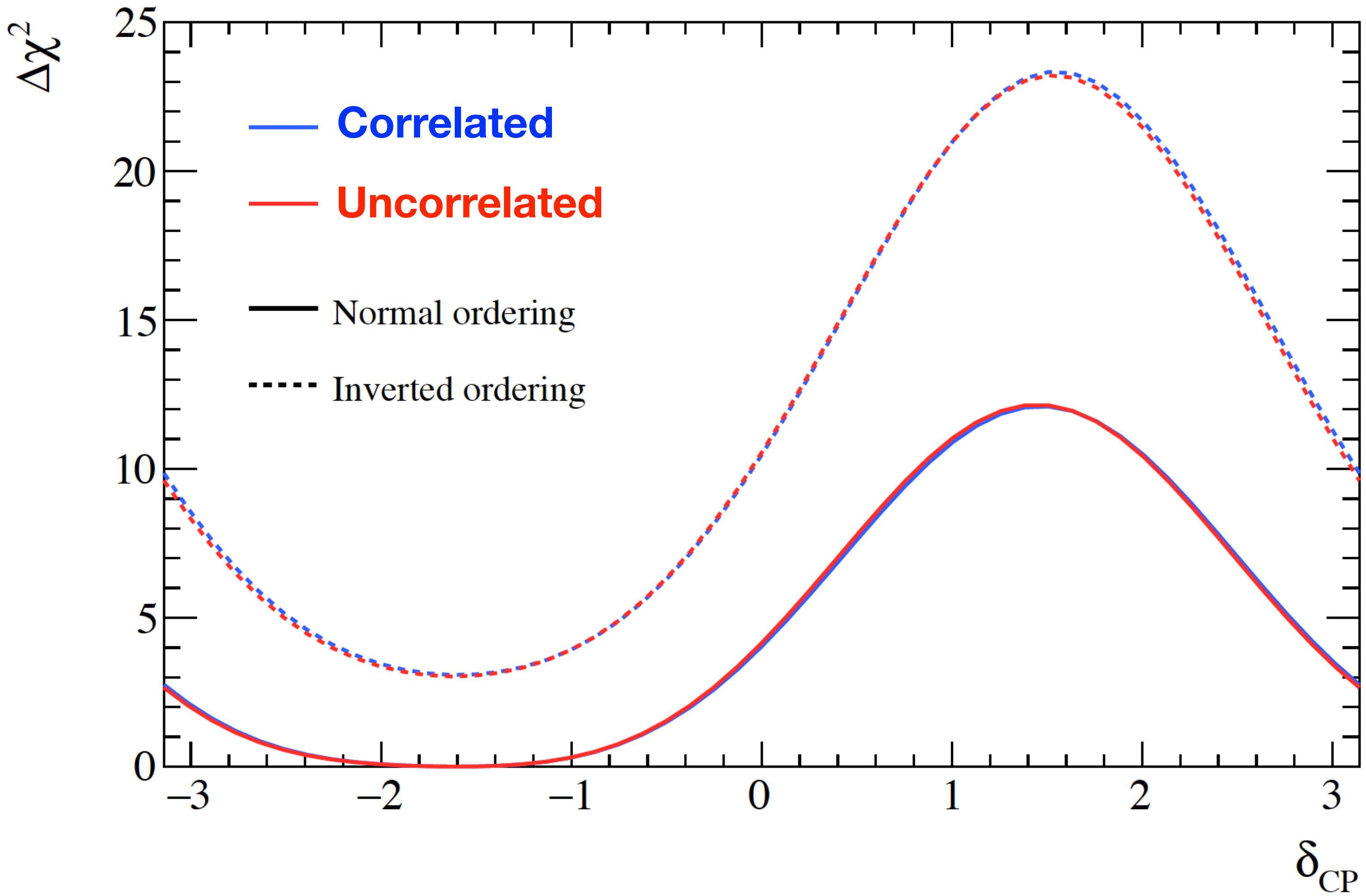
(b) Multi-GeV events

M. Jiang et al., 2019

- **The same detector (SK) is used for the T2K and SK neutrino samples**
- **The same reconstruction tool is used for both samples in this joint analysis**

Input Models to the T2K-SK Joint Oscillation Analysis

Attempted to correlate the existing detector systematic uncertainties from T2K and SK but found negligible impact to sensitivities:



$\Delta m^2_{21} = 7.53 \times 10^{-5}\text{eV}^2, |\Delta m^2_{32,31}| = 2.509 \times 10^{-3}\text{eV}^2,$
$\sin^2\theta_{23} = 0.528, \sin^2\theta_{12} = 0.307, \sin^2\theta_{13} = 0.0218,$
$\delta_{CP} = -1.601, \text{MO} = \text{NO},$

*PDG 2019 reactor neutrino constraint on θ_{13} always applied

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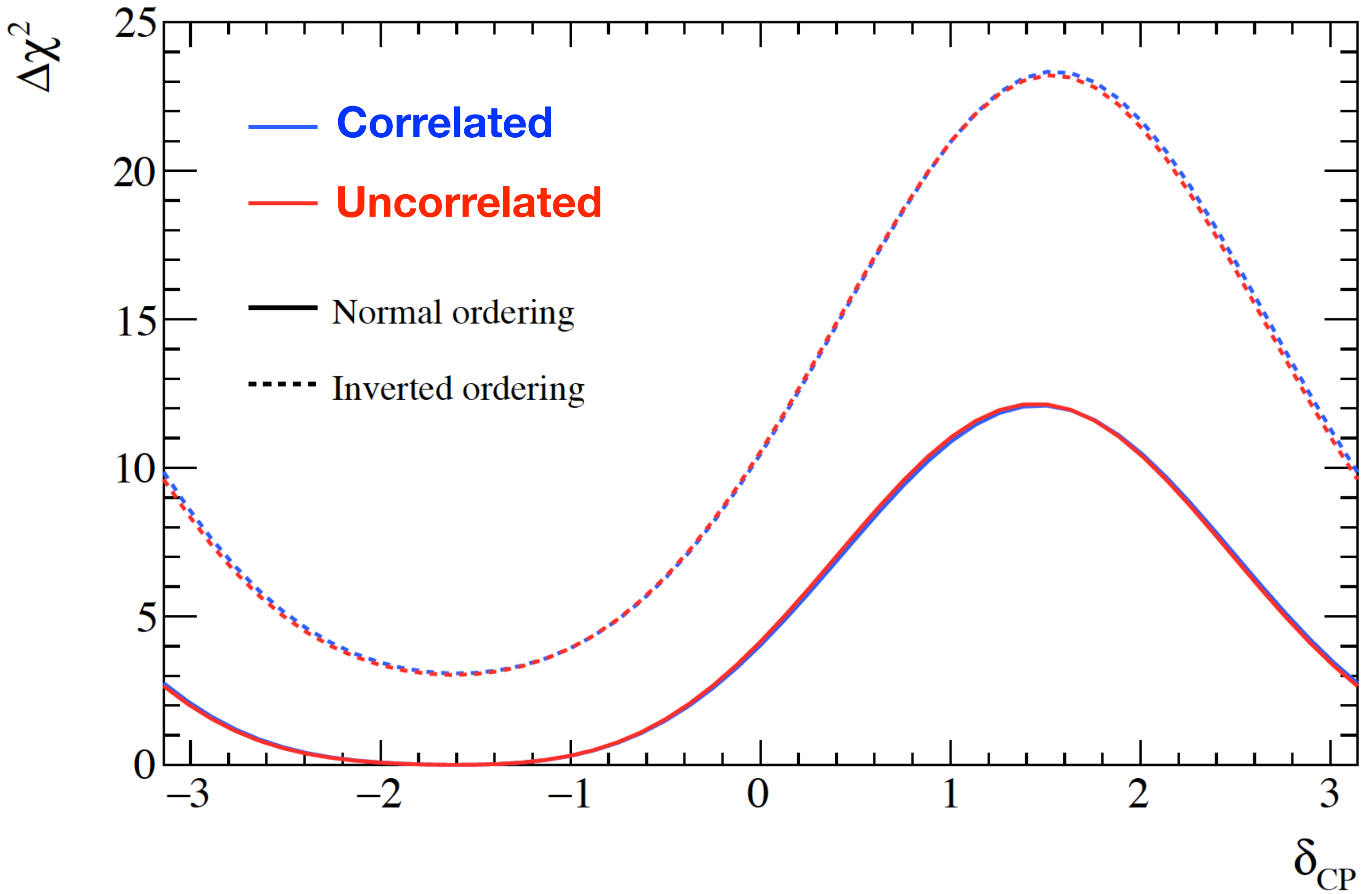

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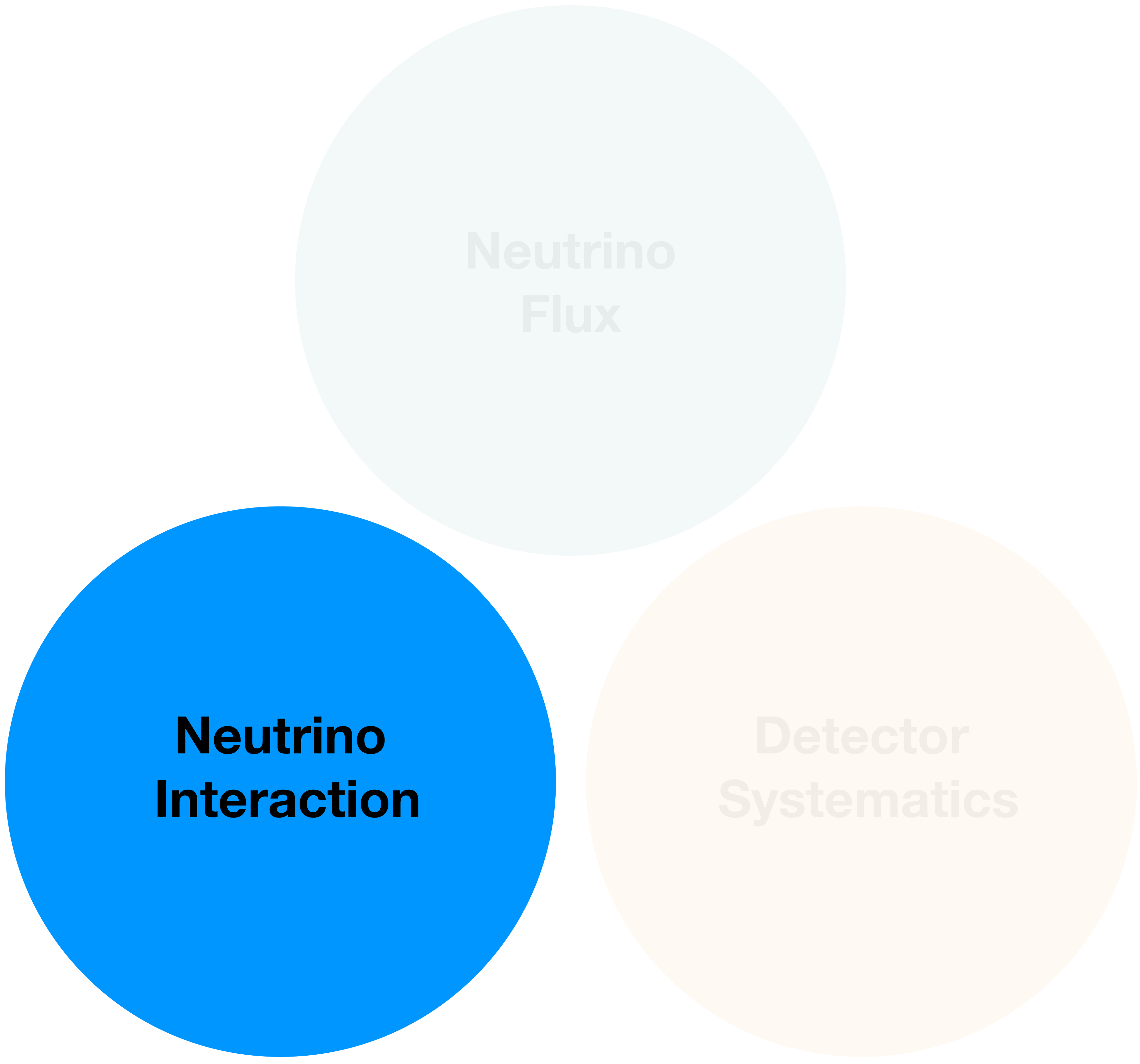
Correlation of existing models **NOT** included this time.

Ongoing work for constraints of the common detector systematic parameters when fitting the oscillation and systematic parameters simultaneously.

*PDG 2019 reactor neutrino constraint on θ_{13} always applied

Input Models to the T2K-SK Joint Oscillation Analysis



Input Models to the T2K-SK Joint Oscillation Analysis

SK Model

- CCQE parameterization developed for local Fermi gas model (PhysRevC.83.045501)

T2K Model

- CCQE developed for spectral function (SF) model (Nuc. Phys. A 579, 493)

- Strong constraints along with the flux model by the ND data fit

Neutrino Flux

Neutrino Interaction

Detector Systematics

Input Models to the T2K-SK Joint Oscillation Analysis

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T2K Model

- CCQE developed for spectral function (SF) model (Nuc. Phys. A 579, 493)
- Strong constraints along with the flux model by the ND data fit

Unified to SF as the baseline nuclear model for CCQE

Applying **T2K ND constraints** (2020 analysis) of neutrino interaction parameters **on the SK low energy samples and** most of the **CCQE** interaction **in the high energy**

Applying modified SK model to the high energy samples.

For more details on the T2K ND data-driven constraints of flux&interaction models:
L. Berns, "T2K results on long-baseline oscillations" @ Plenary Session I, 05/09/2022

Input Models to the T2K-SK Joint Oscillation Analysis

SK Model

- CCQE parameterization developed for local Fermi gas model (PhysRevC.83.045501)

T2K Model

- CCQE developed for spectral function (SF) model (Nuc. Phys. A 579, 493)
- Strong constraints along with the flux model by the ND data fit

Unified to SF as the baseline nuclear model for CCQE

Applying **T2K ND constraints** (2020 analysis) of neutrino interaction parameters **on the SK low energy samples and** most of the **CCQE** interaction **in the high energy**

Applying modified SK model to the high energy samples.

Is the T2K ND data-driven model sufficient?

Are the T2K and SK samples compatible with the ND constraints?

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Extra Systematic Parameters beyond the ND Constraints

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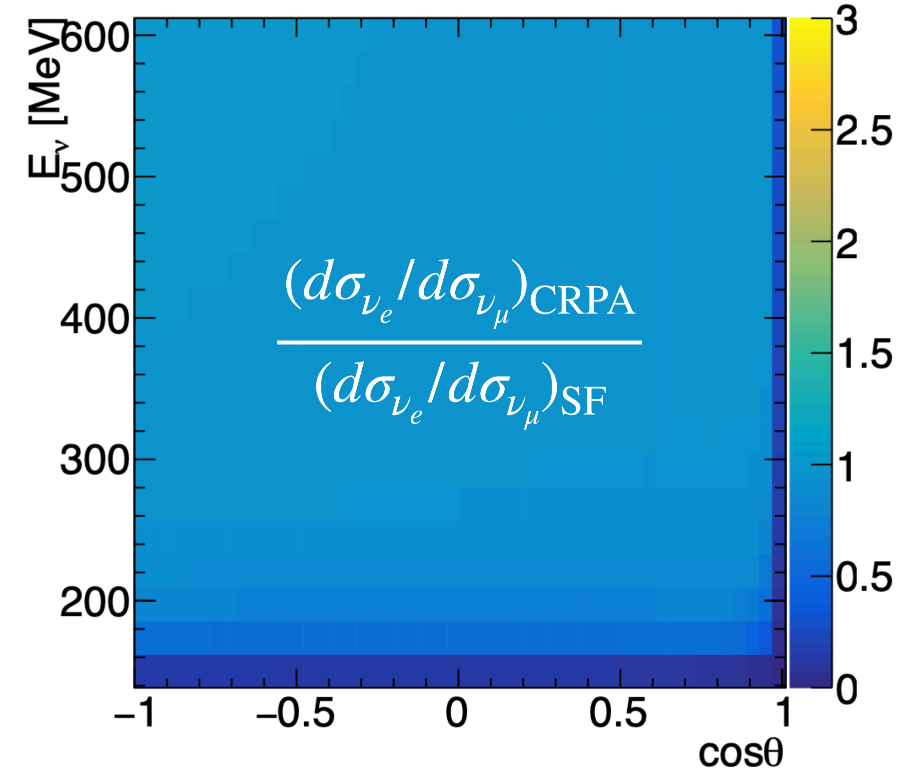
T2K ND data-driven constraint is not effective for the ν_e and $\bar{\nu}_e$ cross section uncertainties, which is critical for δ_{CP}.

Introduced energy and lepton scattering angle dependent parameters based on difference of SF and CRPA (Phys. Rev. C, 65, 025501) nuclear models for ^{16}O.



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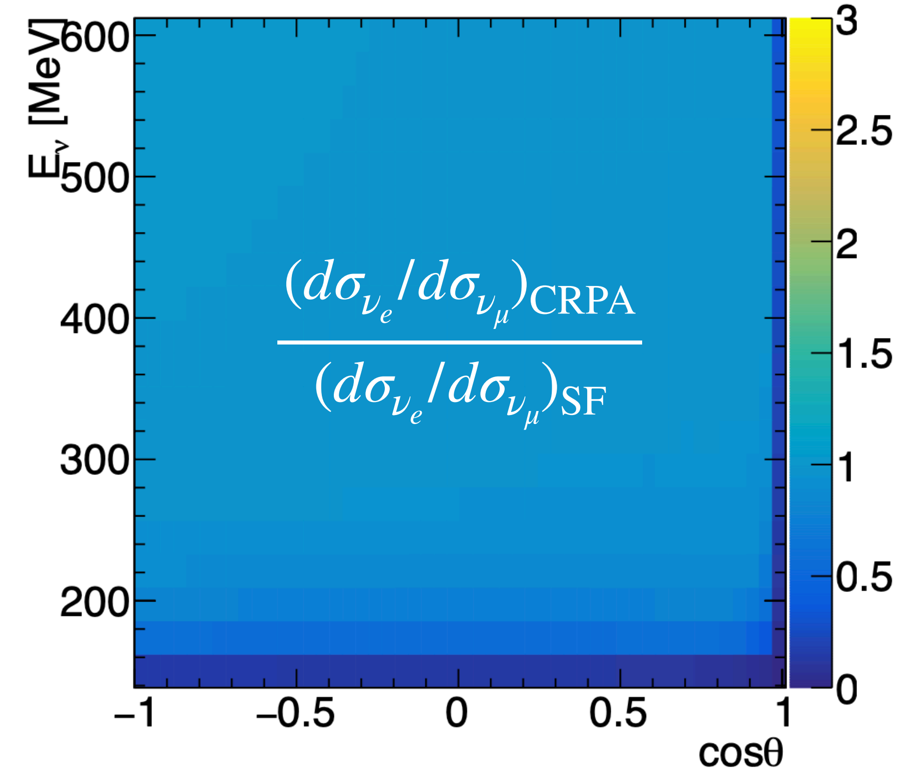

NC1π^0:

- T2K NC1π^0 model is insufficient for SK atmospheric samples.
- two uncertainties on the NC resonant and coherent 1π^0 interactions, estimated using MiniBooNE data (Phys. Rev. D, 81:013005).

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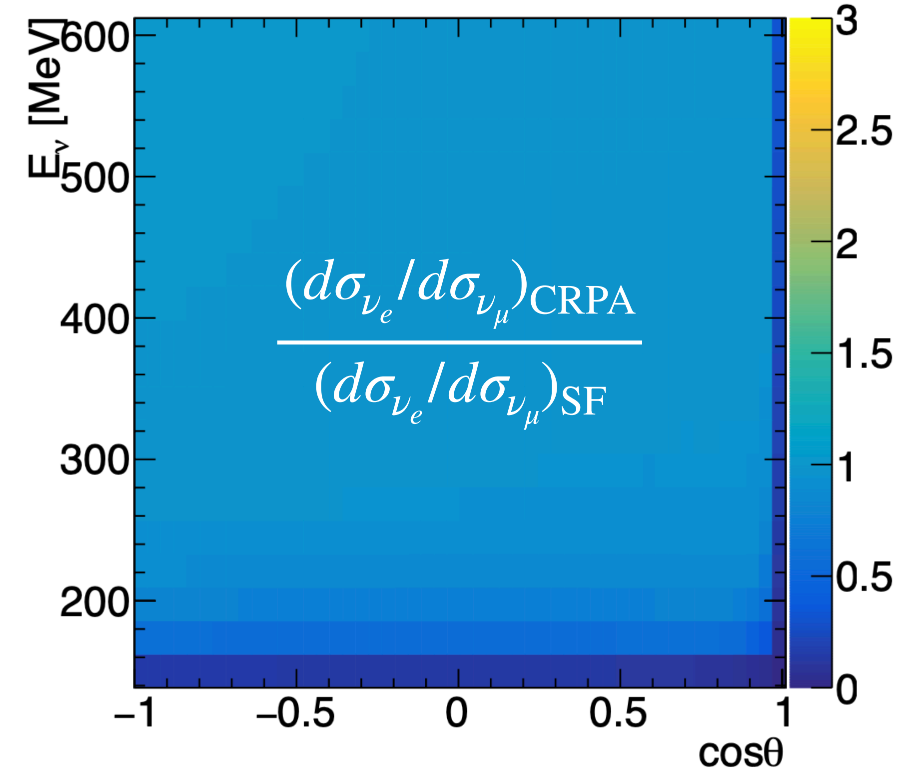

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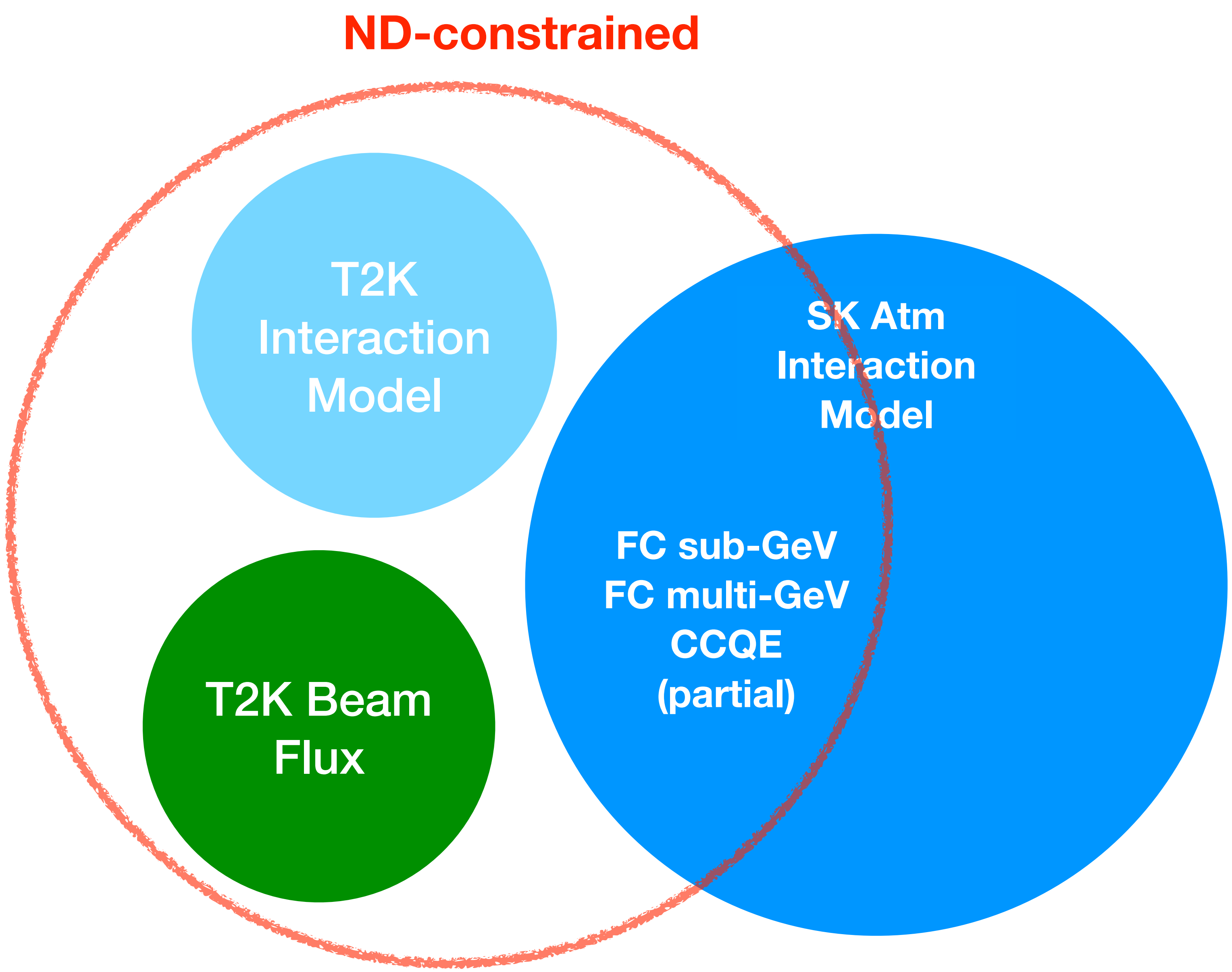
CC1$\pi^\pm$:

- Observed a difference in the prediction of "CC1π-like" sample event rate between SK and T2K ND.
- An *ad hoc* parameter tuning pion momentum distribution to improve the compatibility is implemented.
- A few other approaches are also being developed.

Quick Summary of the Joint Analysis Input Models



SI: Secondary Interaction
FC: Fully Contained
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Upmu: Up-going Muon

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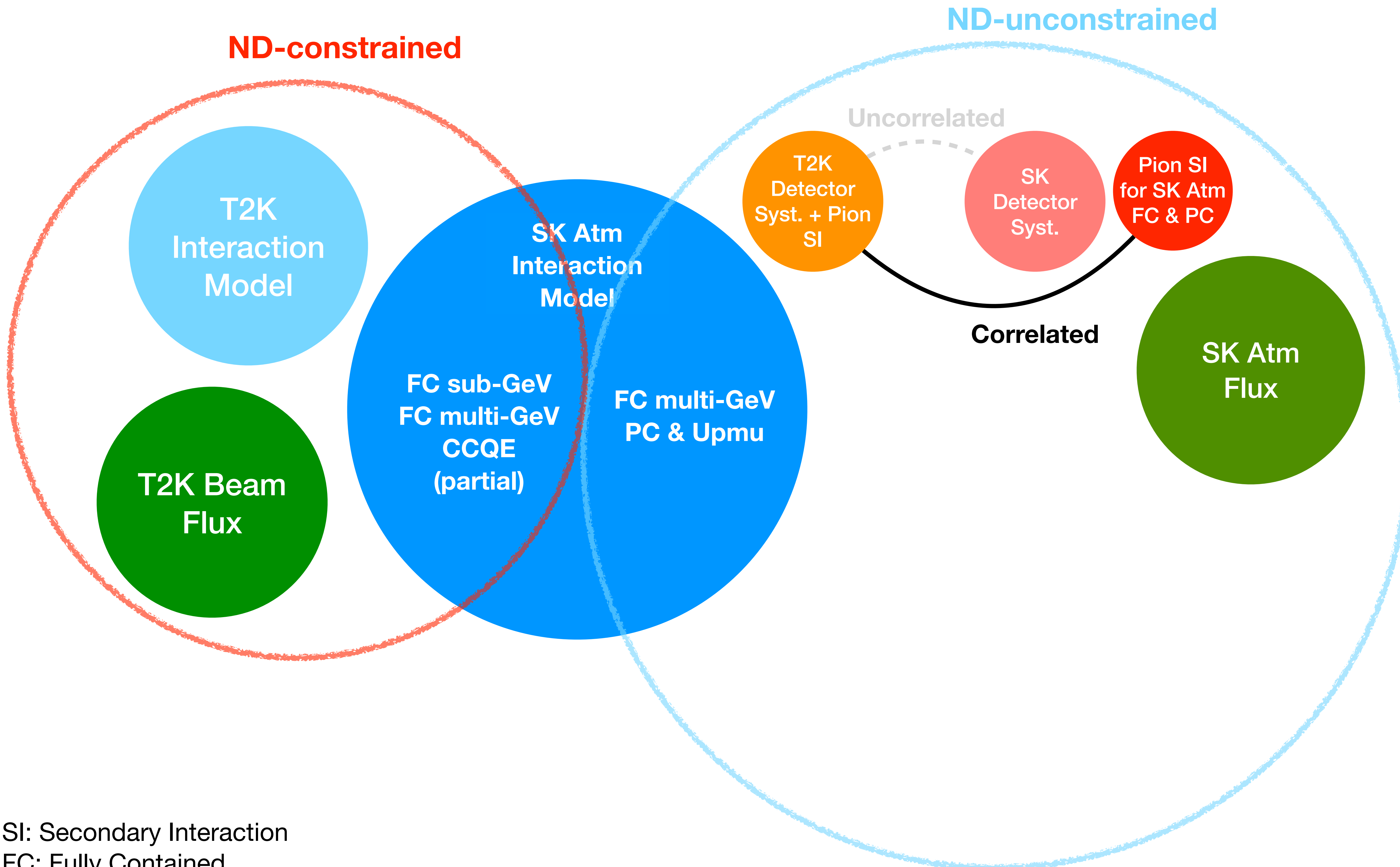

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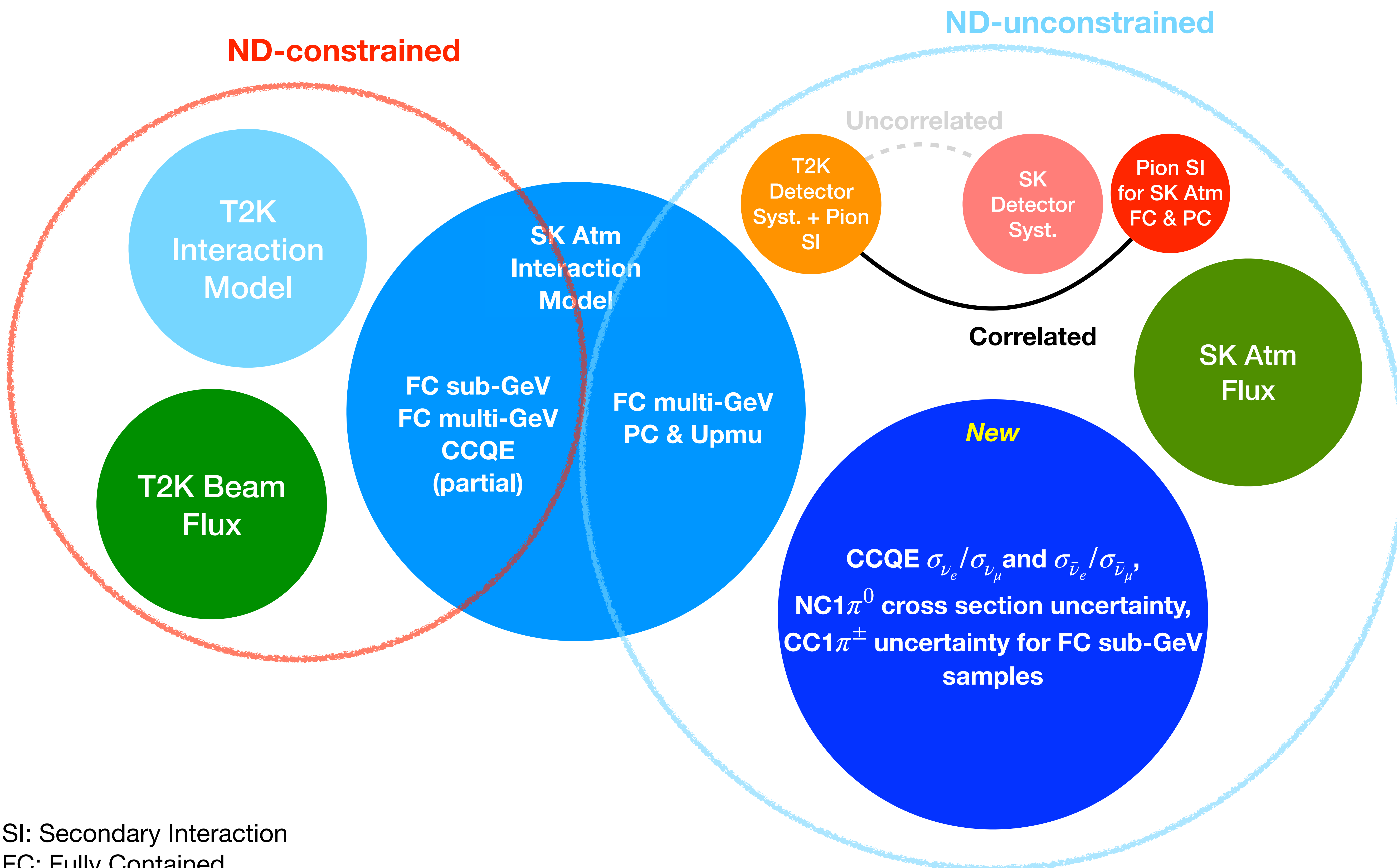

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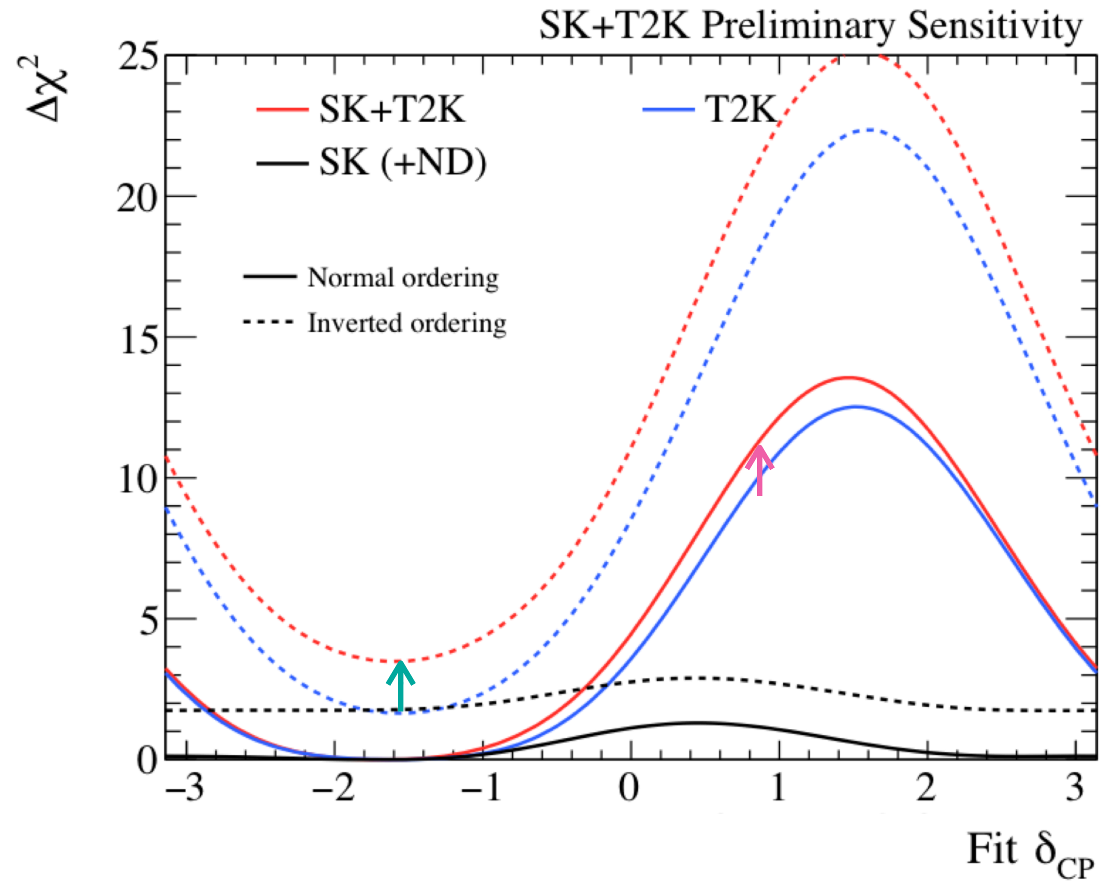
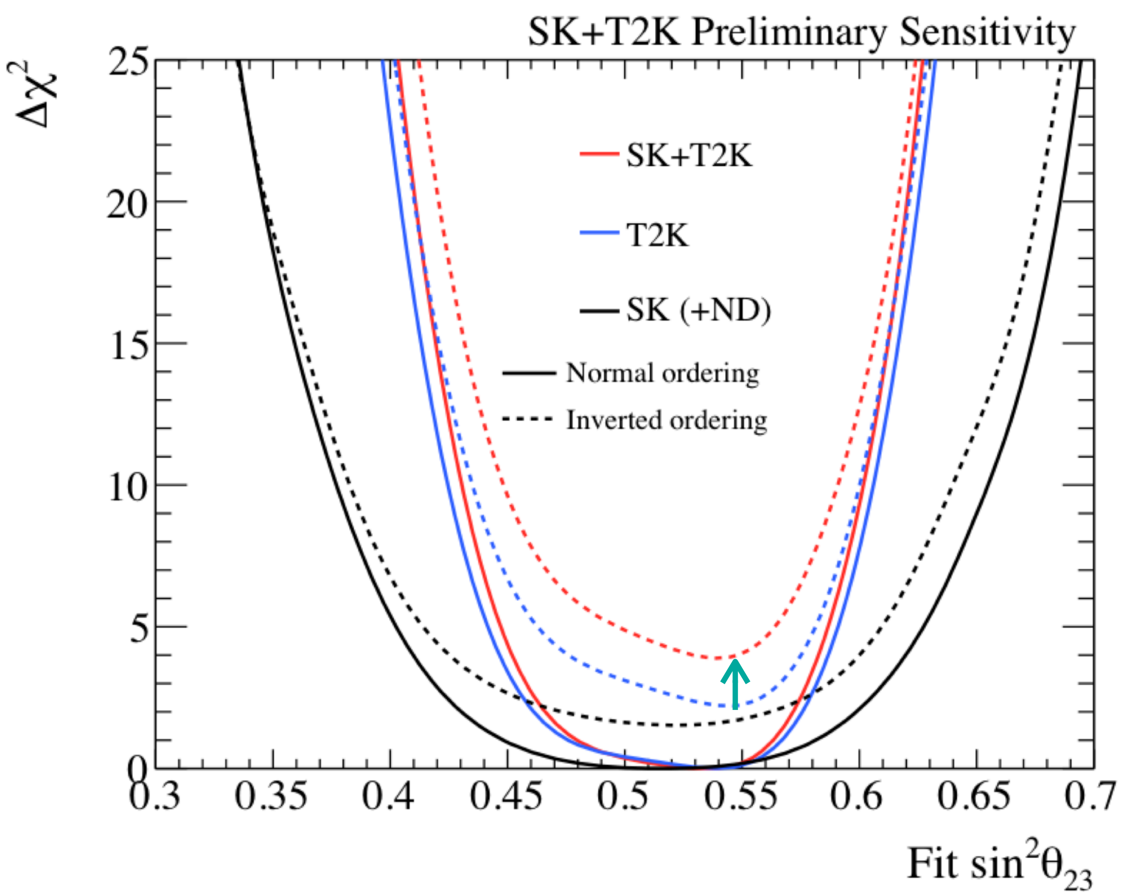
Expected Sensitivity of δ_{CP}, Δm^2_{32}, $\sin^2\theta_{23}$ and MO

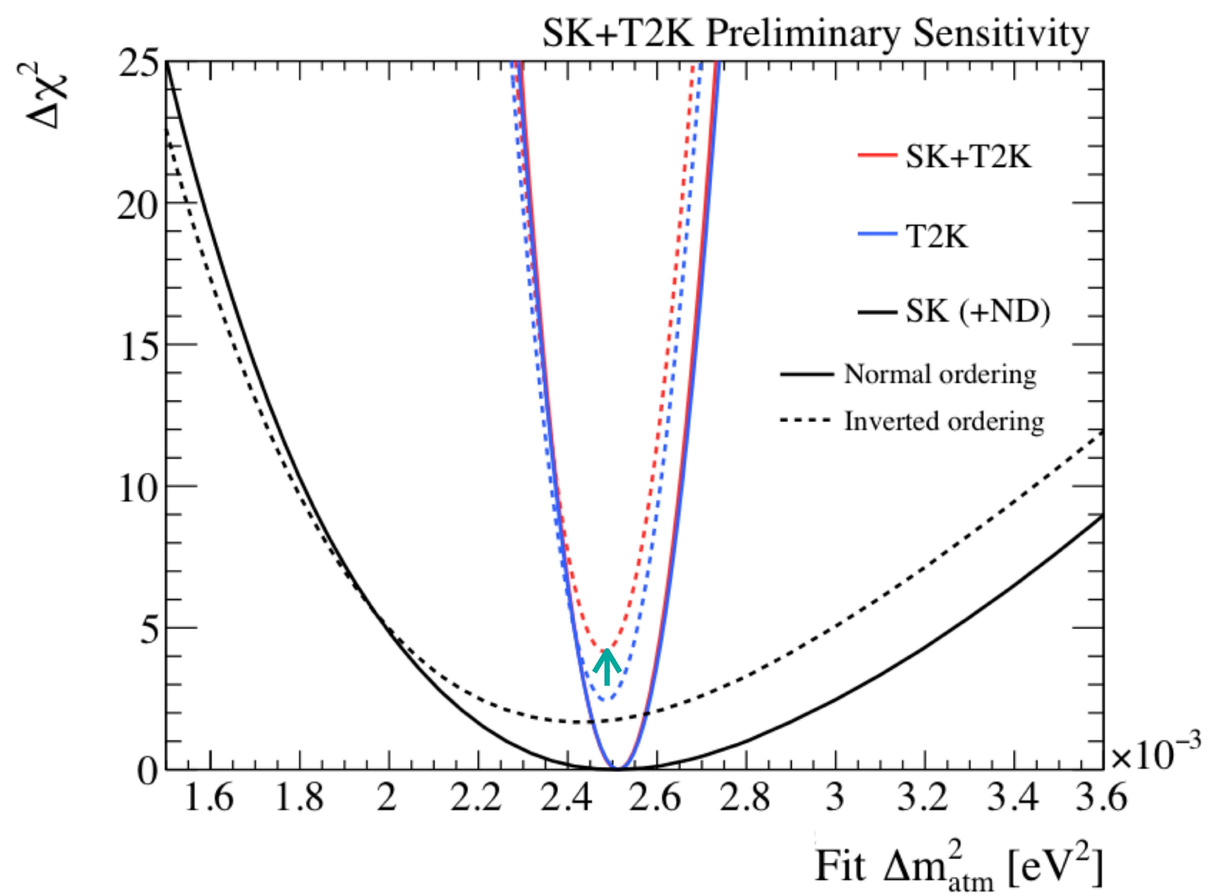
1D fits by **maximum-likelihood method** with the "other" oscillation parameters marginalized, for example in the fit of δ_{CP} all the other parameters including $\sin^2\theta_{23}$ and Δm^2_{32} are marginalized.

Improved sensitivity of δ_{CP} and MO by this joint analysis

$\Delta m^2_{21} = 7.53 \times 10^{-5}\mathrm{eV}^2, |\Delta m^2_{32,31}| = 2.509 \times 10^{-3}\mathrm{eV}^2,$
$\sin^2\theta_{23} = 0.528, \sin^2\theta_{12} = 0.307, \sin^2\theta_{13} = 0.0218,$
$\delta_{CP} = -1.601, \mathrm{MO} = \mathrm{NO},$

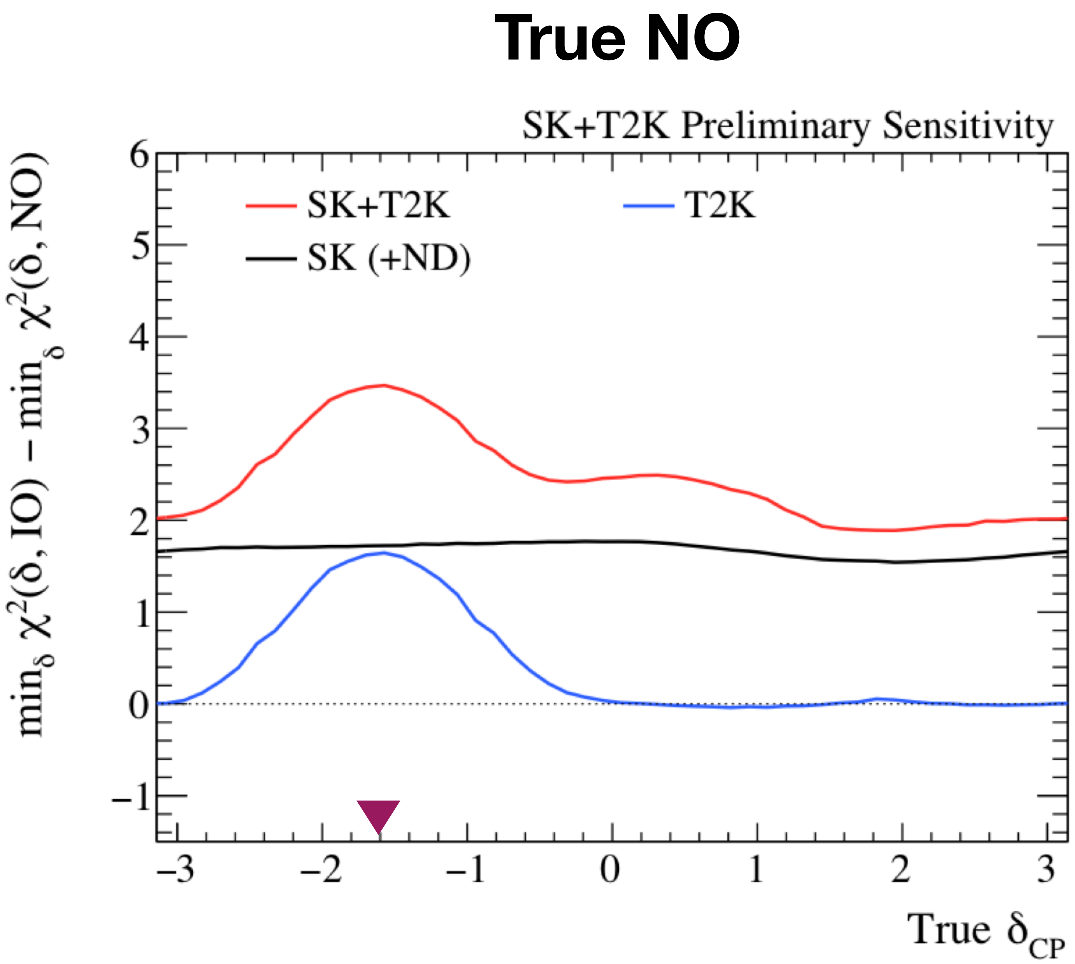


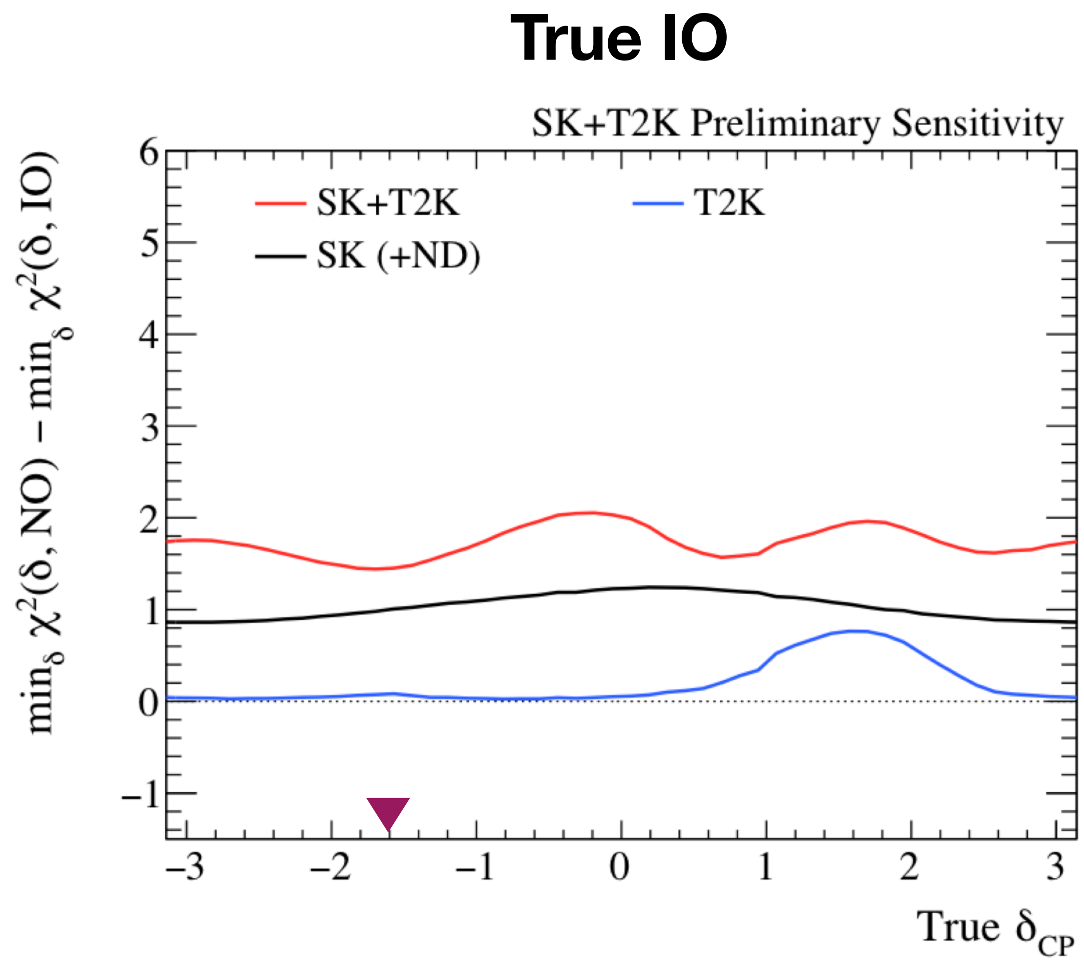




*PDG 2019 reactor neutrino constraint on θ_{13} always applied

Expected Sensitivity of MO as a Function of δ_{CP}



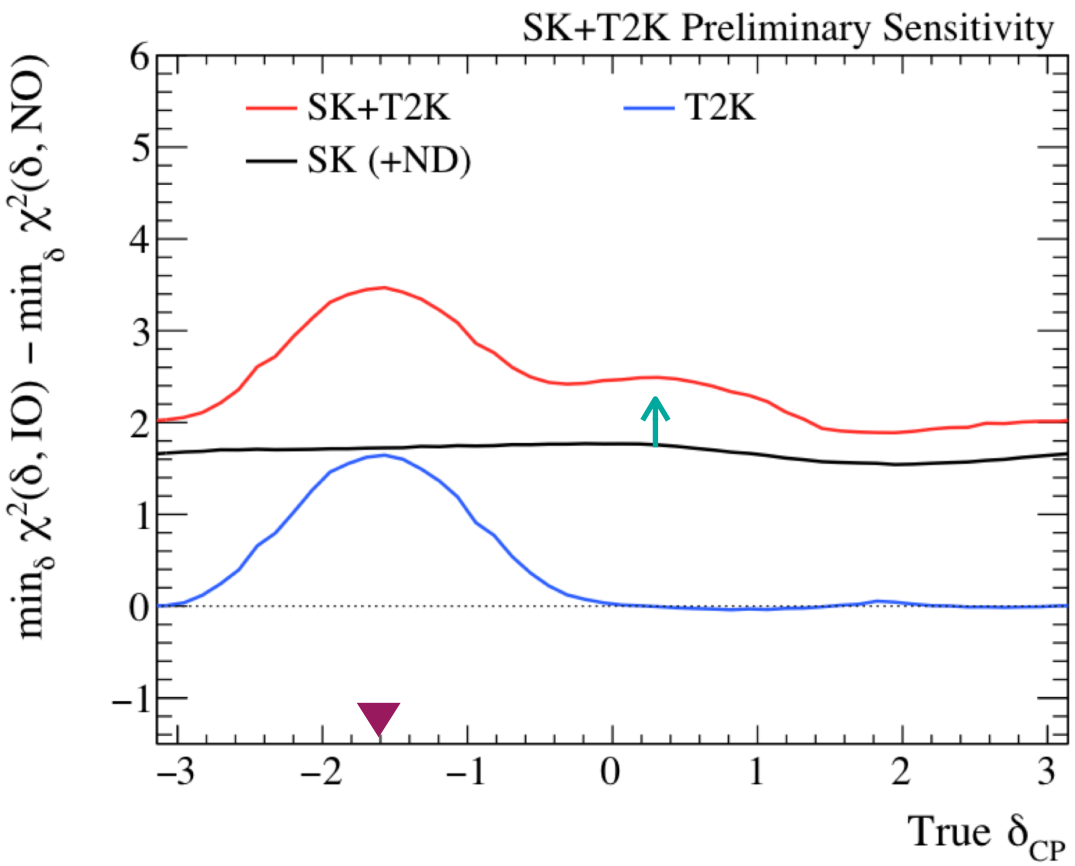


Sensitivity for rejecting the wrong MO at different true δ_{CP} values, with other oscillation parameters marginalized.

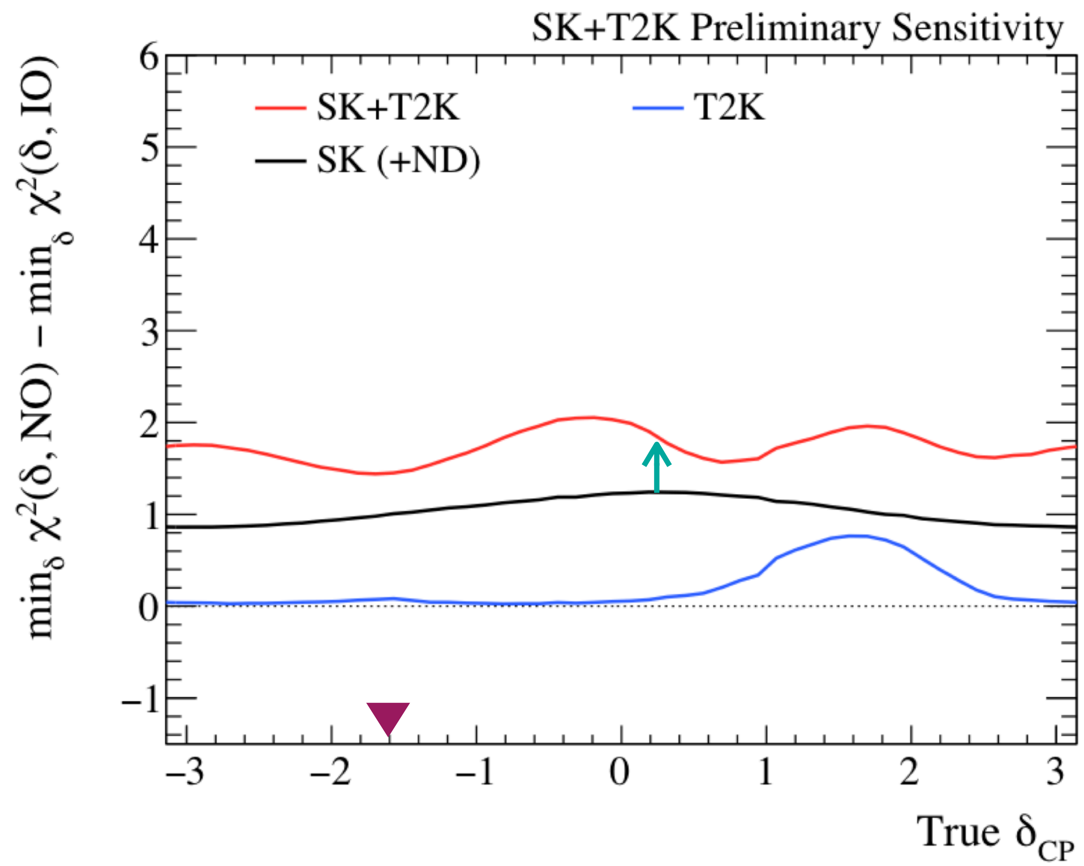
*PDG 2019 reactor neutrino constraint on θ_{13} always applied

Expected Sensitivity of MO as a Function of δ_{CP}

True NO



True IO



Sensitivity for rejecting the wrong MO at different true δ_{CP} values, with other oscillation parameters marginalized.

T2K's sensitivity to MO strongly depends on δ_{CP}, while SK has a flat distribution that is overall more sensitive.

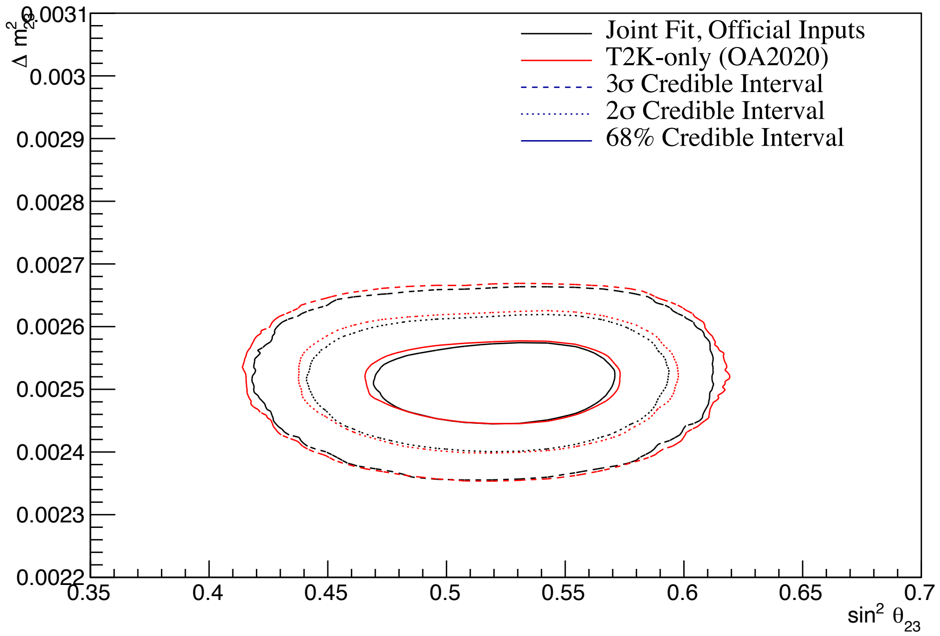
In both MO, the joint analysis has achieved better sensitivity of MO compared to either T2K-only or SK-only.

*PDG 2019 reactor neutrino constraint on θ_{13} always applied

Simultaneous Fit of δ_{CP}, Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, and MO

Posterior probability density distributions from a Bayesian analysis

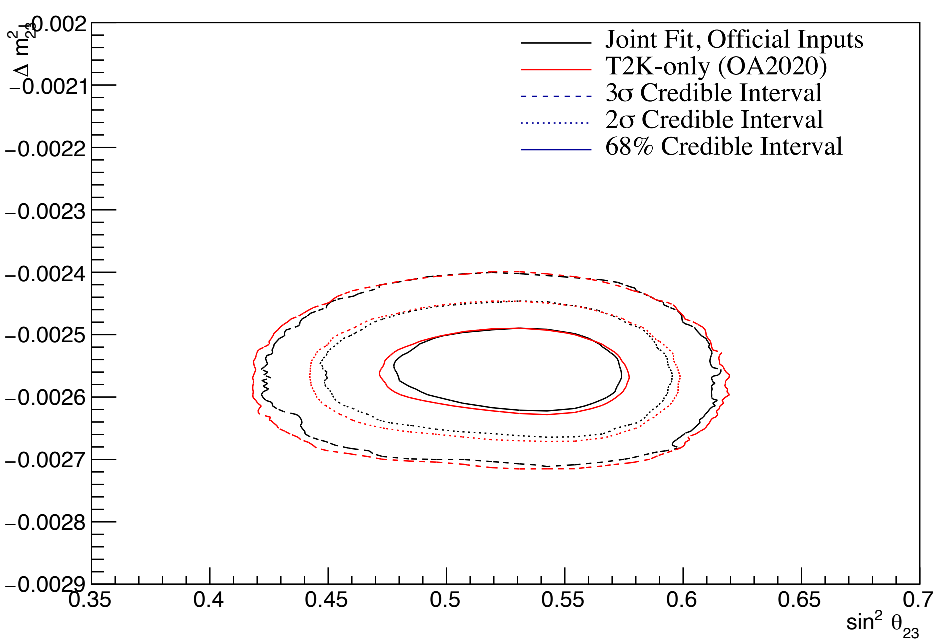
True NO



Red: T2K only

Black: This joint analysis

True IO



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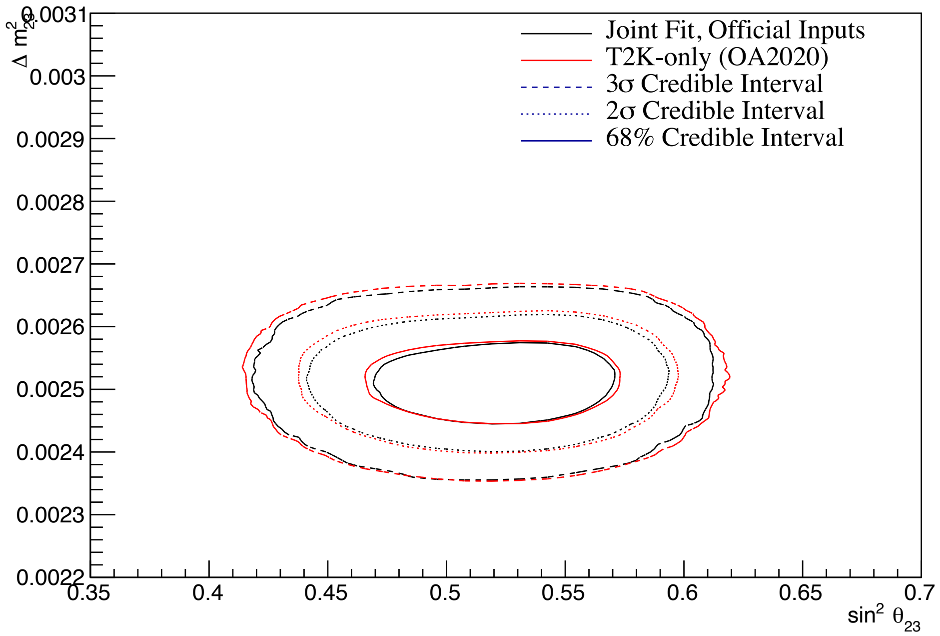

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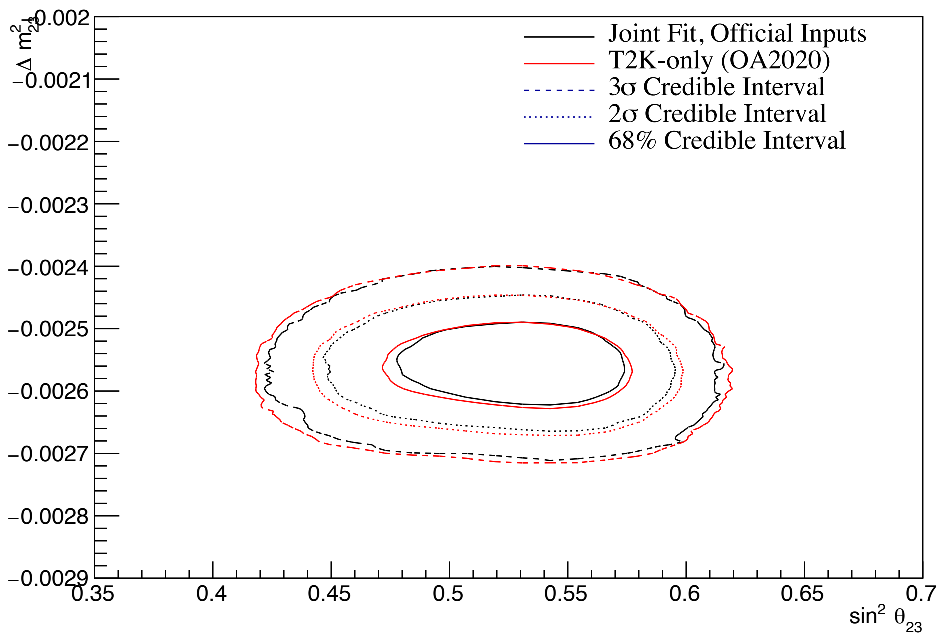

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Sensitivities of $\sin^2\theta_{23}$ and Δm^2_{32} by this joint analysis are similar to the T2K-only case, though minor improvements are visible.

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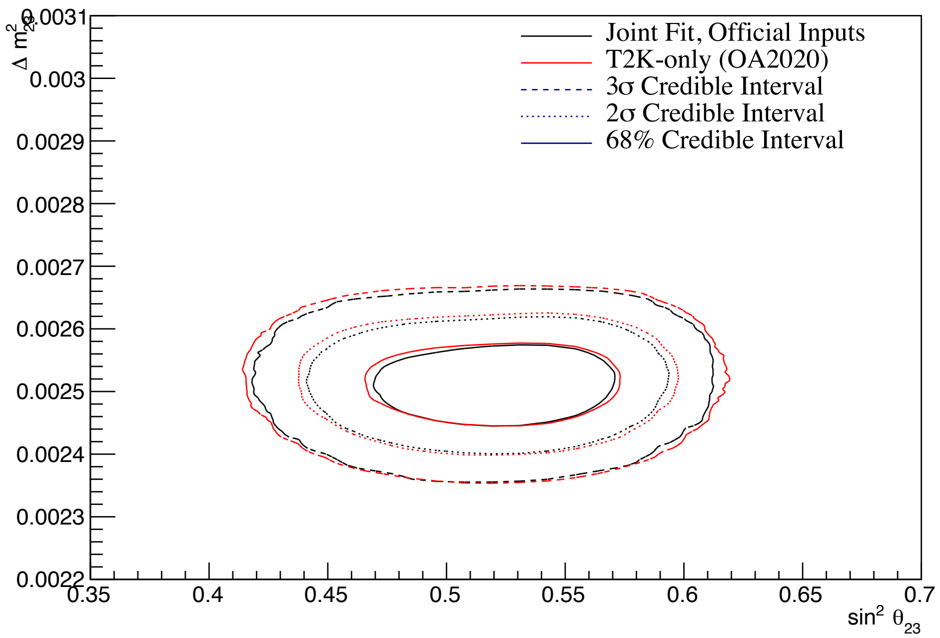

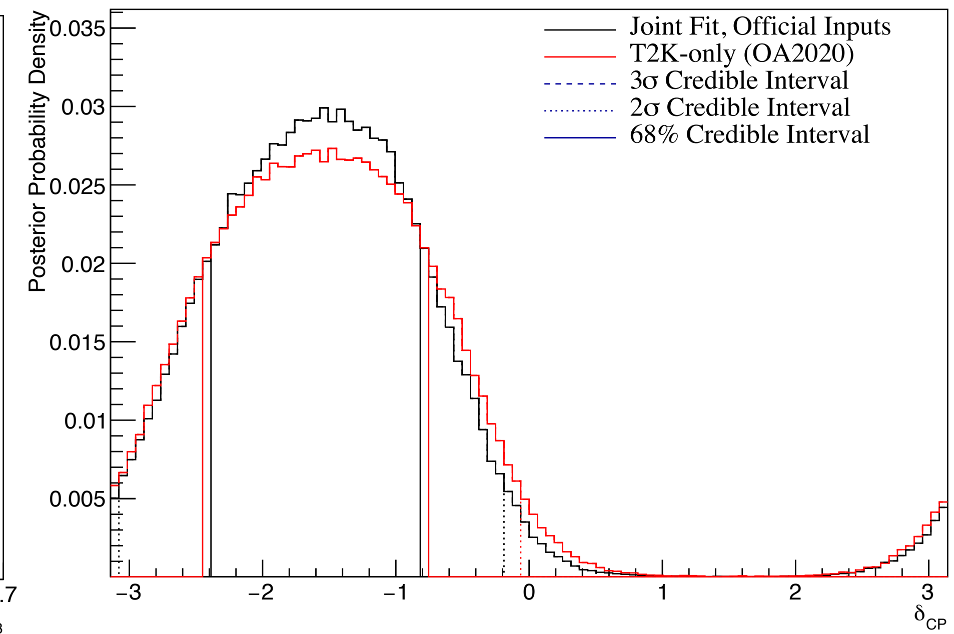

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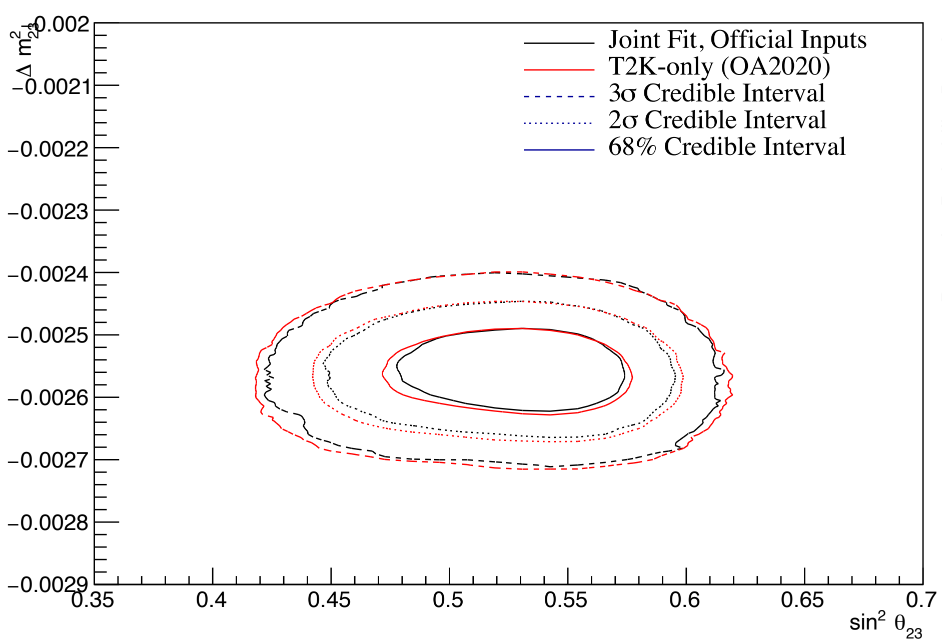
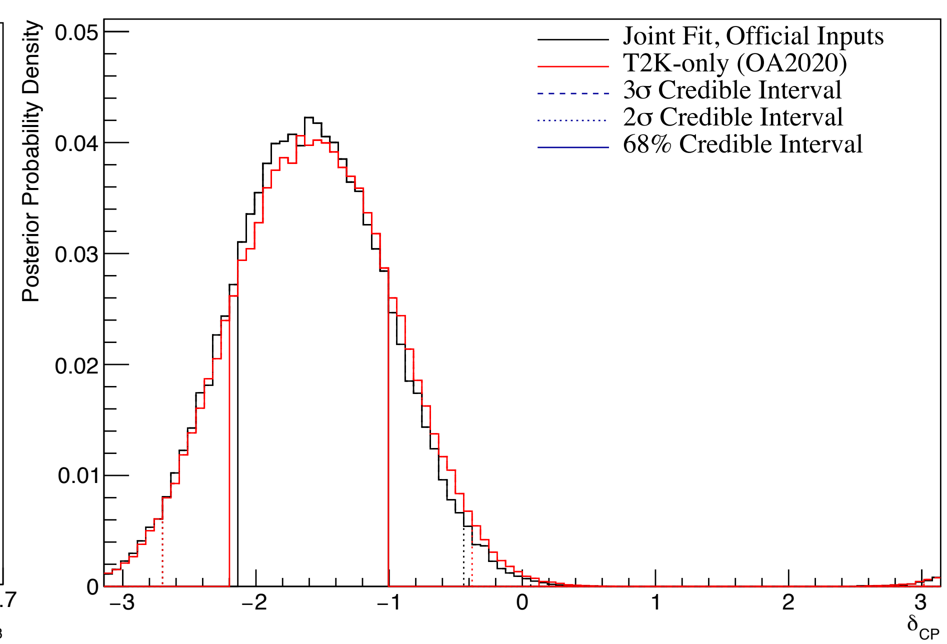
Sensitivities of $\sin^2\theta_{23}$ and Δm^2_{32} by this joint analysis are similar to the T2K-only case, though minor improvements are visible.

Improved sensitivity of δ_{CP} in both MO, with larger improvement in the NO.

True IO





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*PDG 2019 reactor neutrino constraint on θ_{13} always applied

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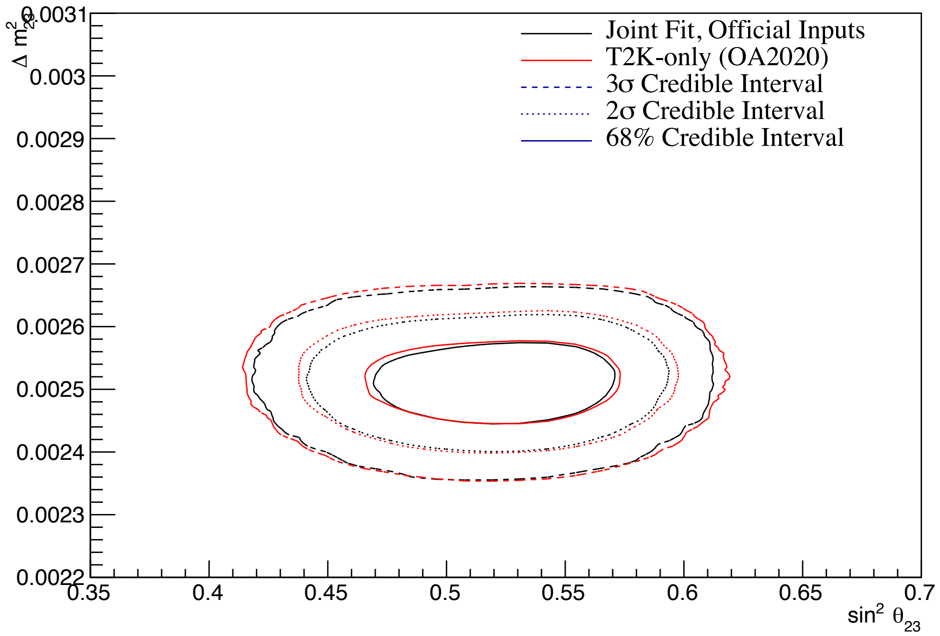

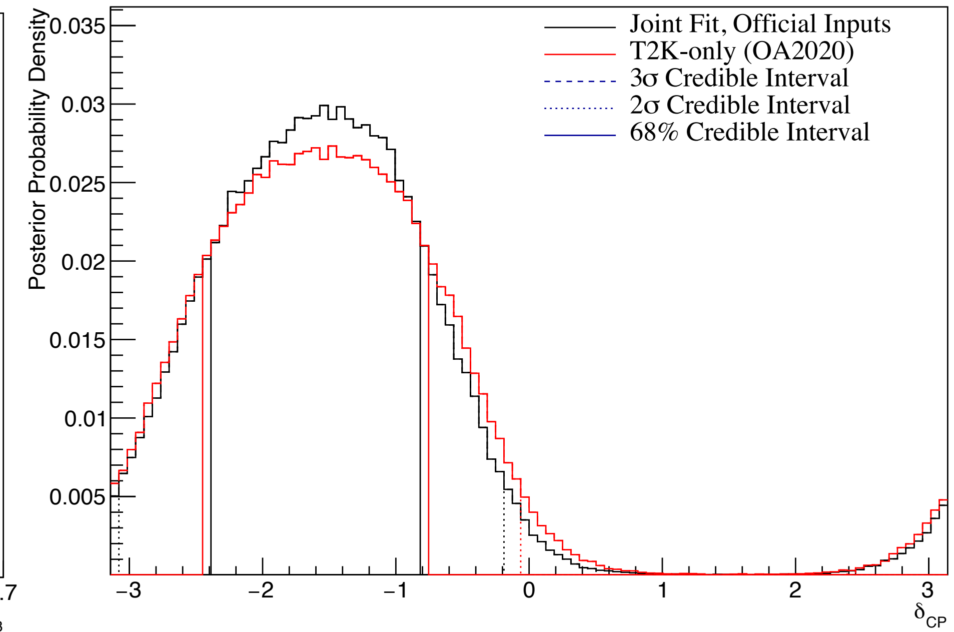

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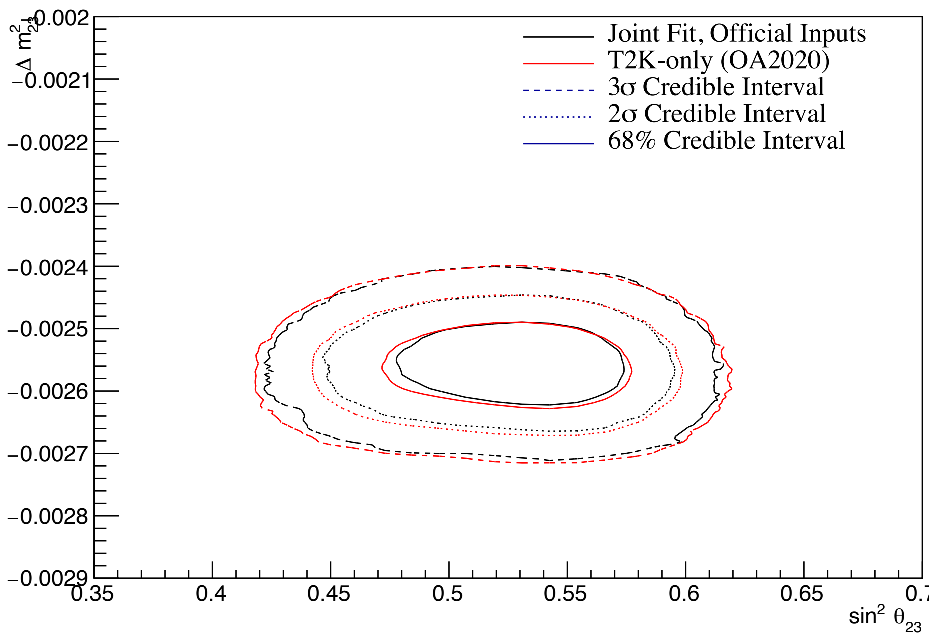

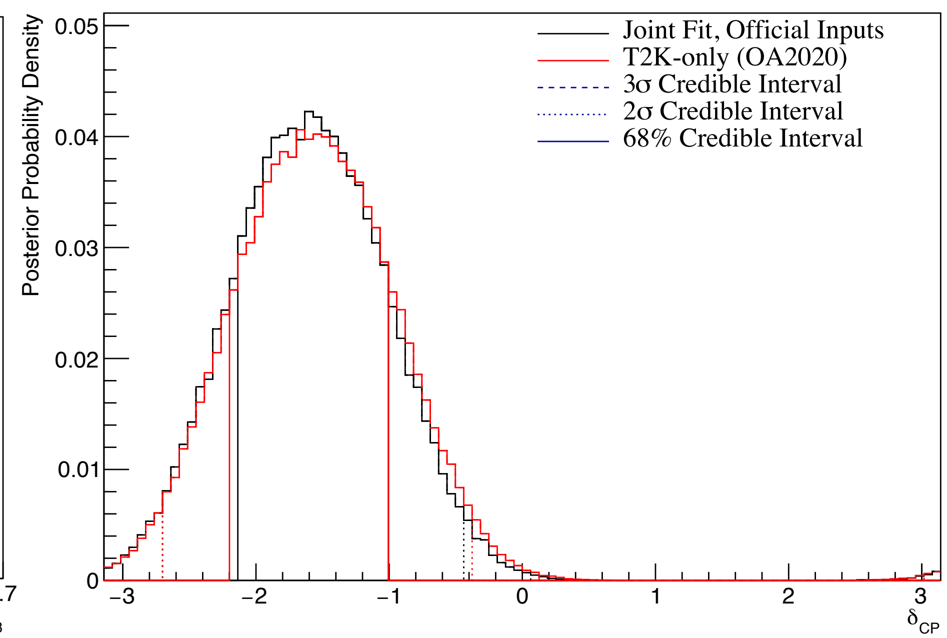

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Improved sensitivity of $\delta_{\rm CP}$ in both MO, with larger improvement in the NO.

Also achieved stronger sensitivity of NO with Bayes factor ($P_{\rm NO}/P_{\rm IO}$) increased from 4.2 (T2K-only) to 7.9 (this joint analysis).

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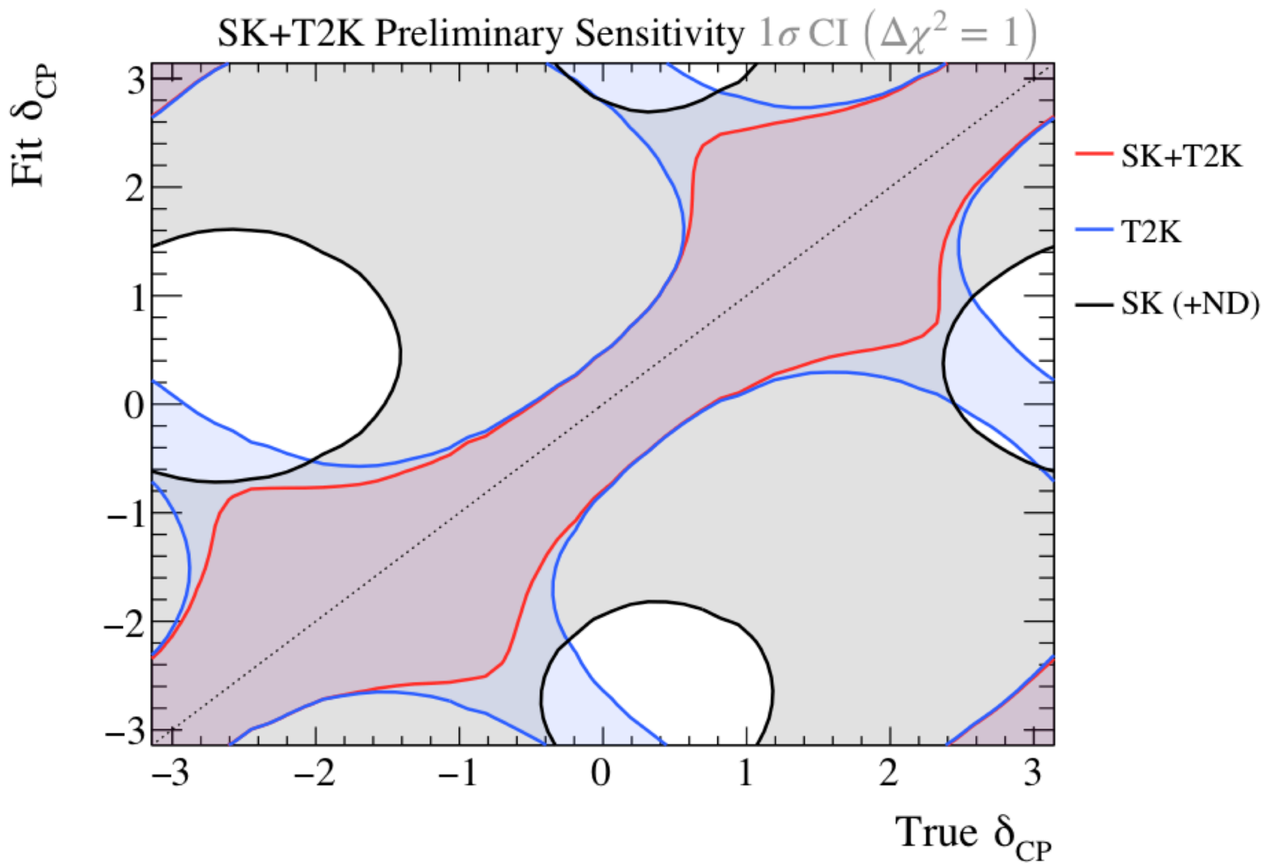
*PDG 2019 reactor neutrino constraint on θ_{13} always applied

Joint Fit Solving Degeneracy of δ_{CP} and MO (True NO)



Shaded areas represent the 1σ confidence intervals (estimated by $\chi^2_{\text{true}\delta} - \chi^2_{\text{best}} \leq 1$)

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True IO in the backup.

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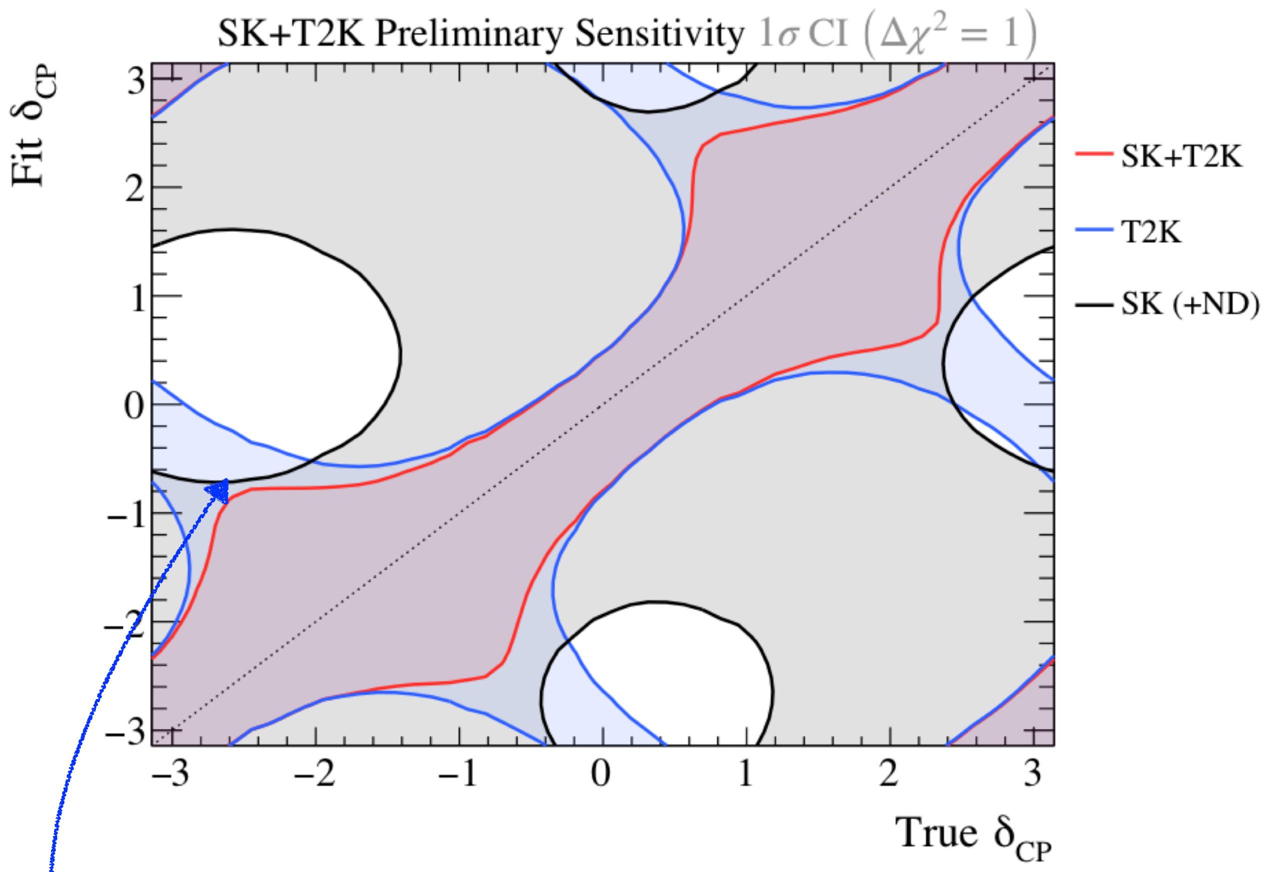

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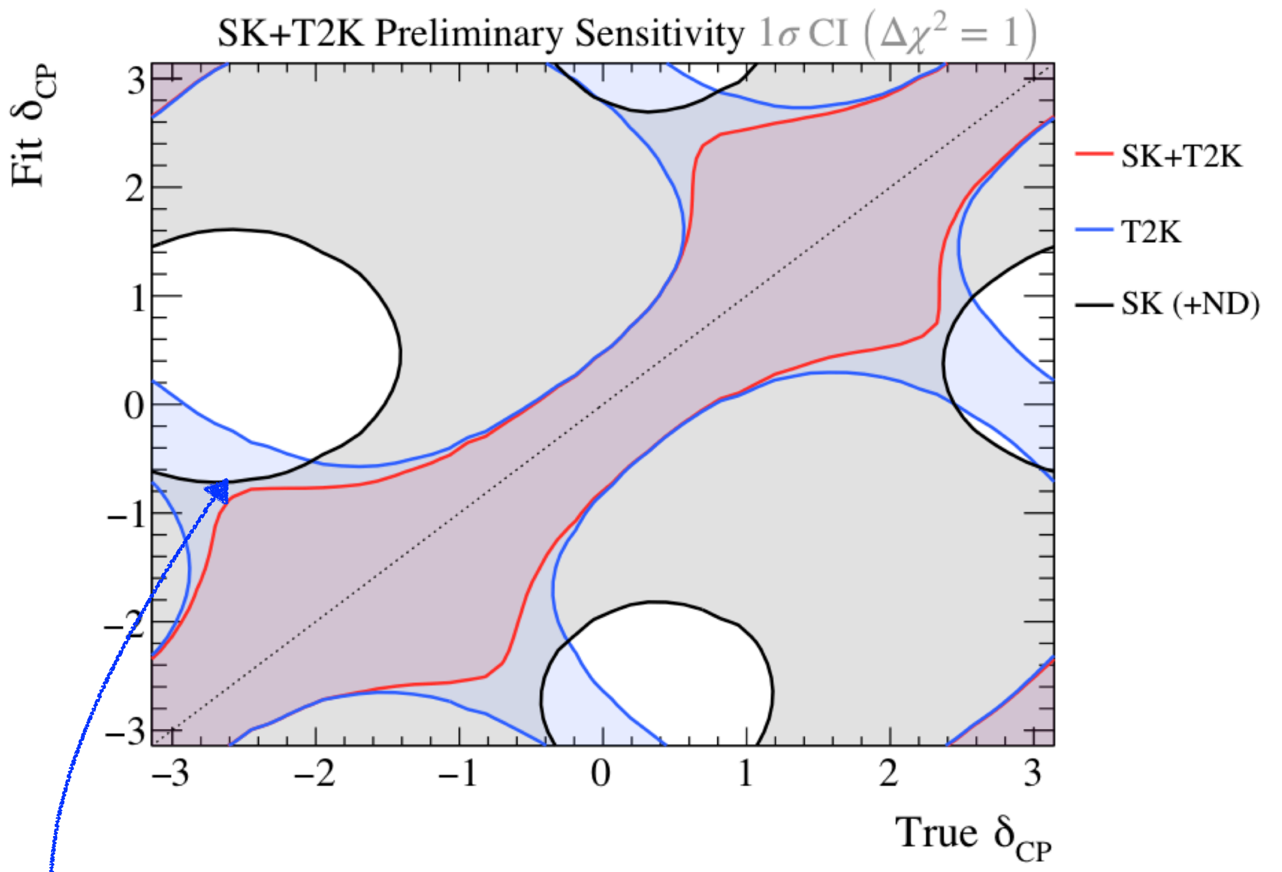

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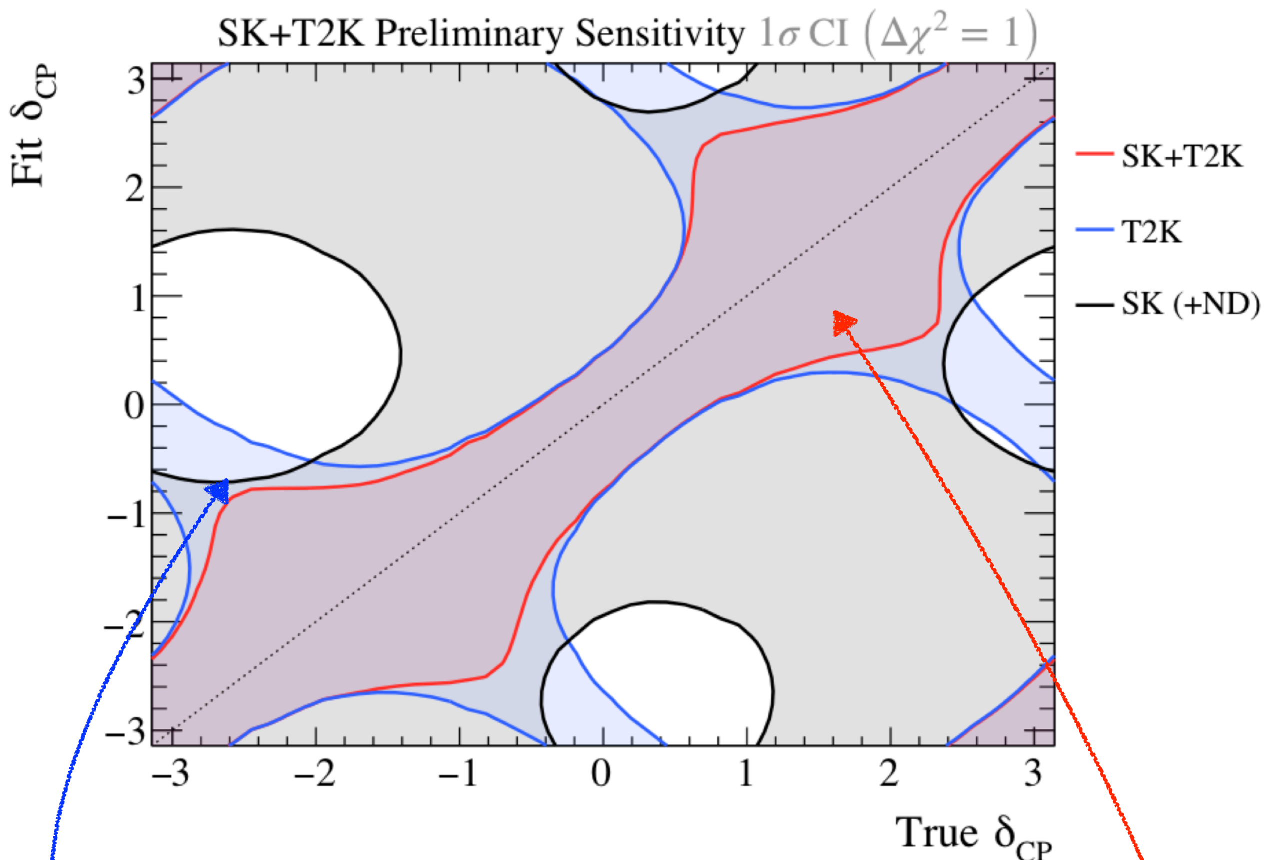

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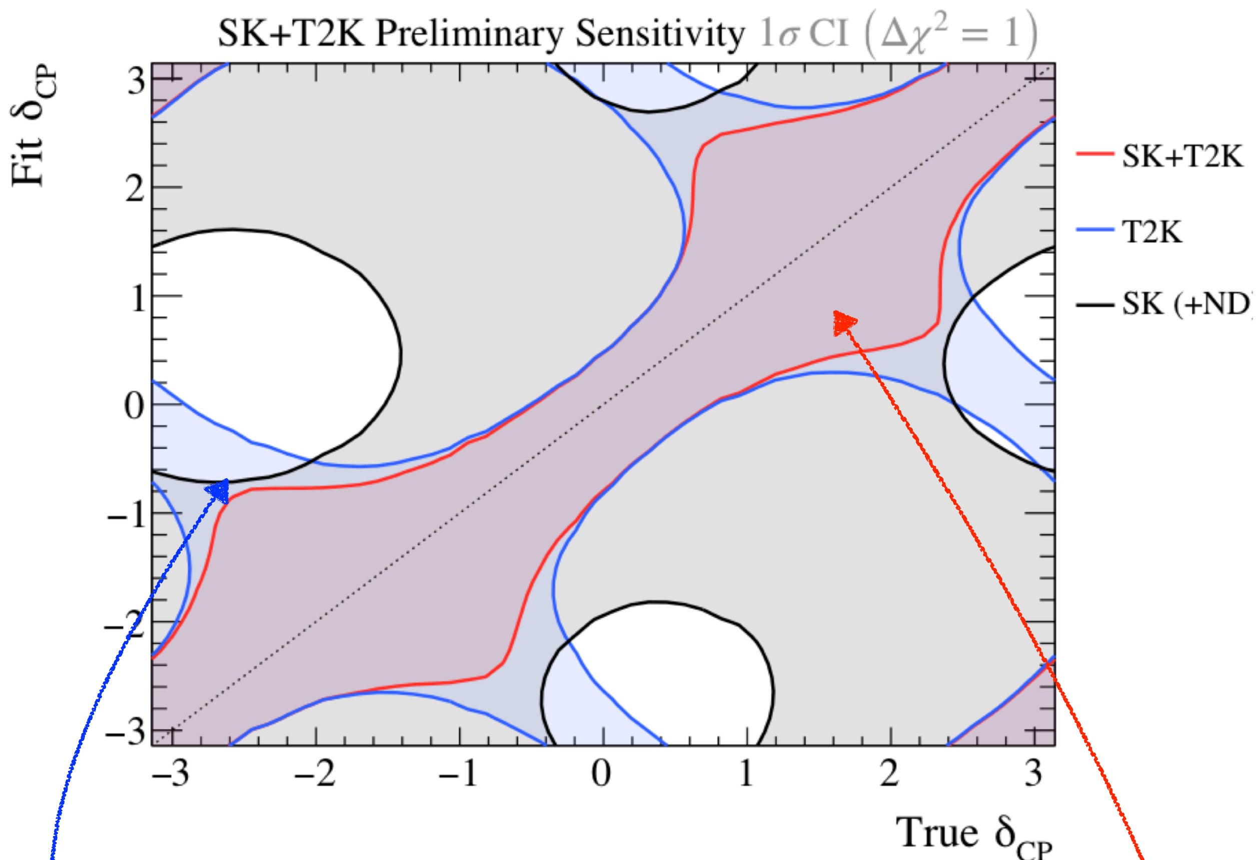

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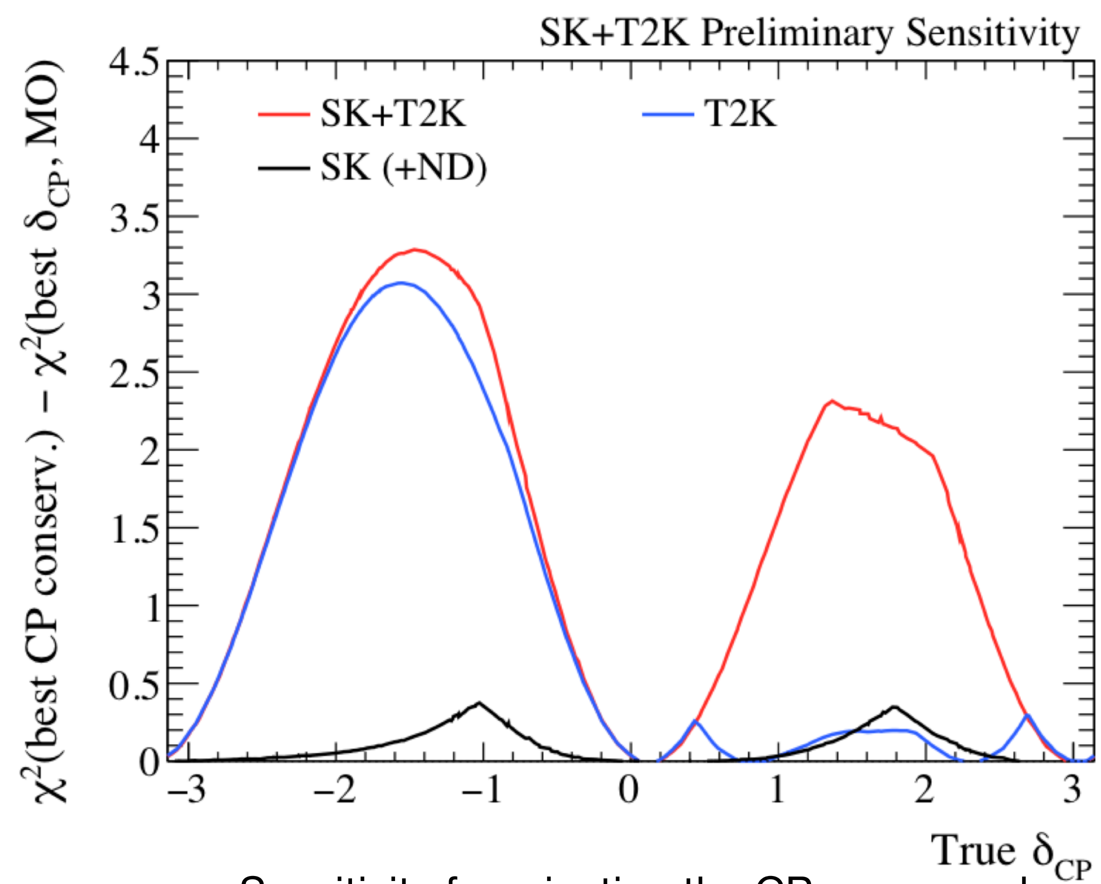

Sensitivity for rejecting the CP-conserved hypothesis at different true δ_{CP} values

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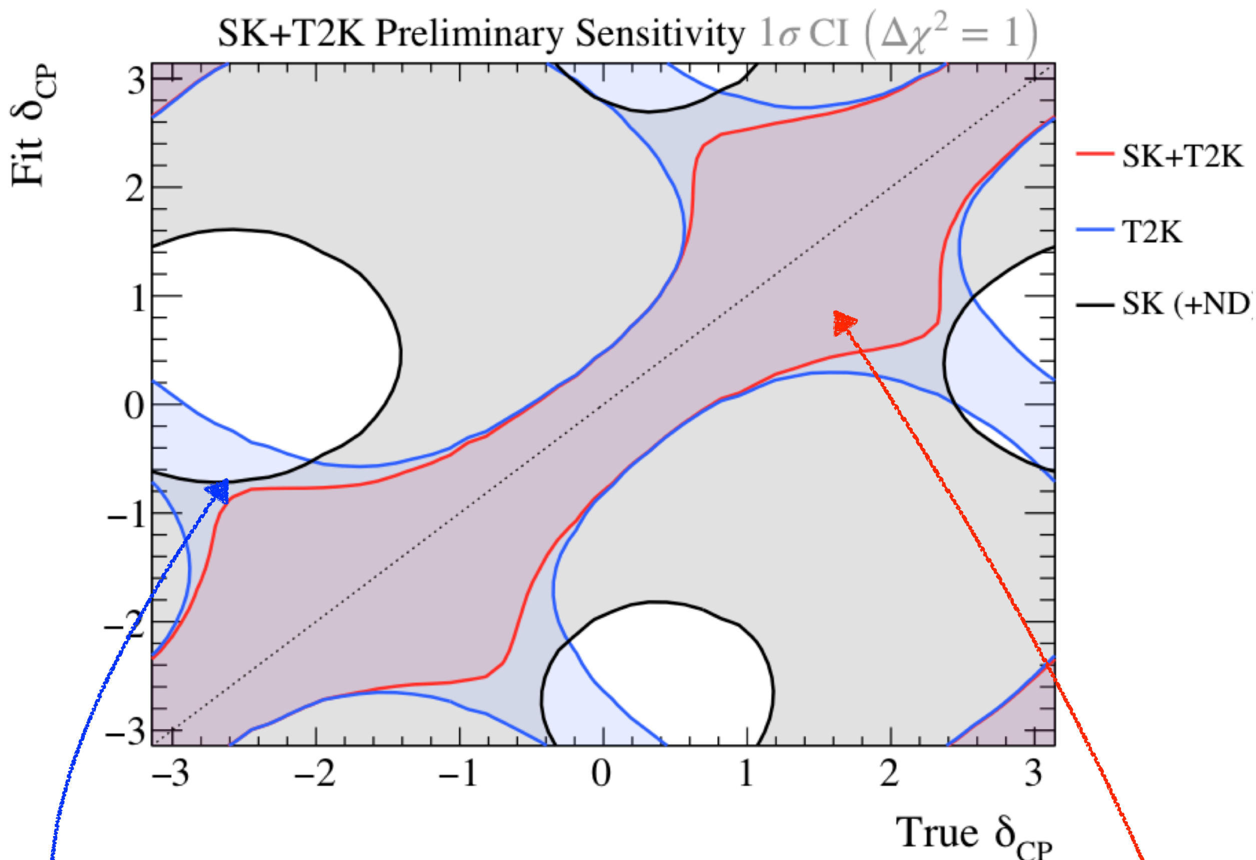

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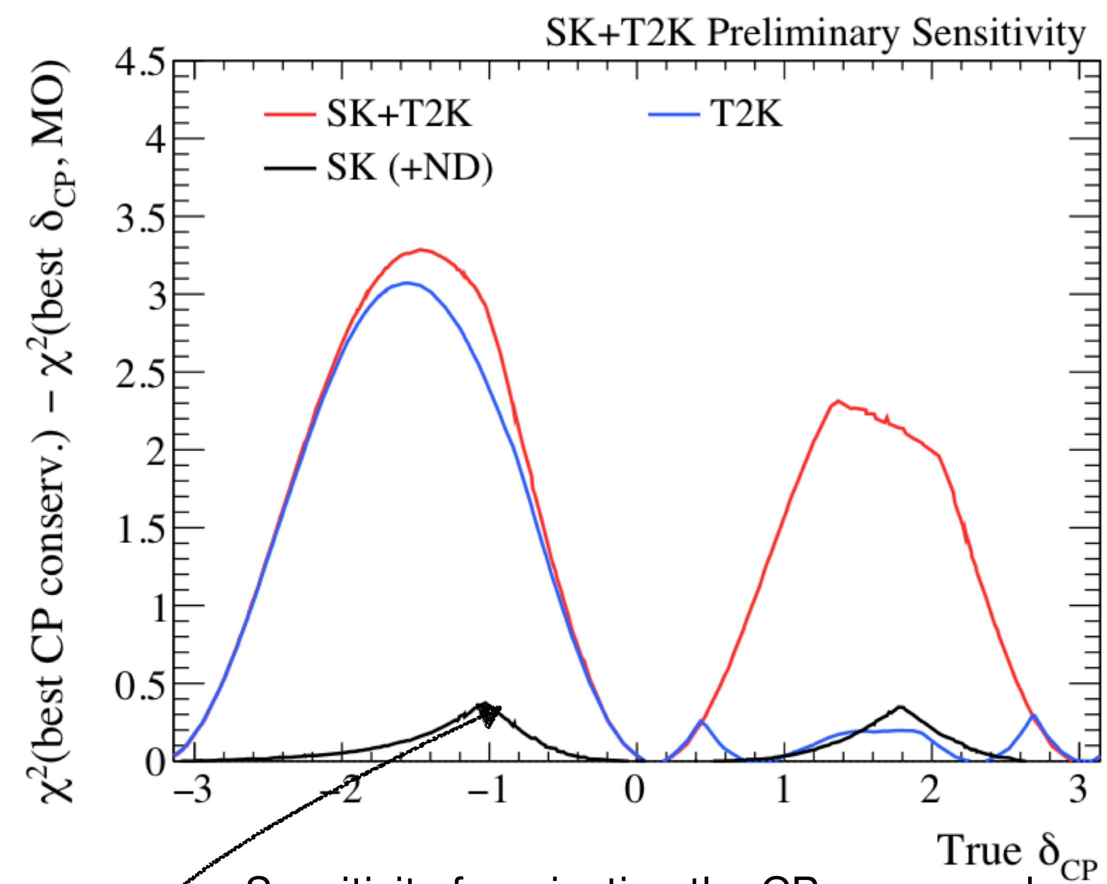

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Atm samples are sensitive to $\sin\delta_{CP}$ and $\cos\delta_{CP}$, though the overall sensitivity is weaker.

Combining the two helps resolving the degeneracy in the constraint of δ_{CP}.

The δ_{CP} sensitivity from SK atmospheric samples are generally weaker than the T2K samples.

*PDG 2019 reactor neutrino constraint on θ_{13} always applied
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Truth: $\Delta m^2_{21} = 7.53 \times 10^{-5}\text{eV}^2, |\Delta m^2_{32,31}| = 2.509 \times 10^{-3}\text{eV}^2,$
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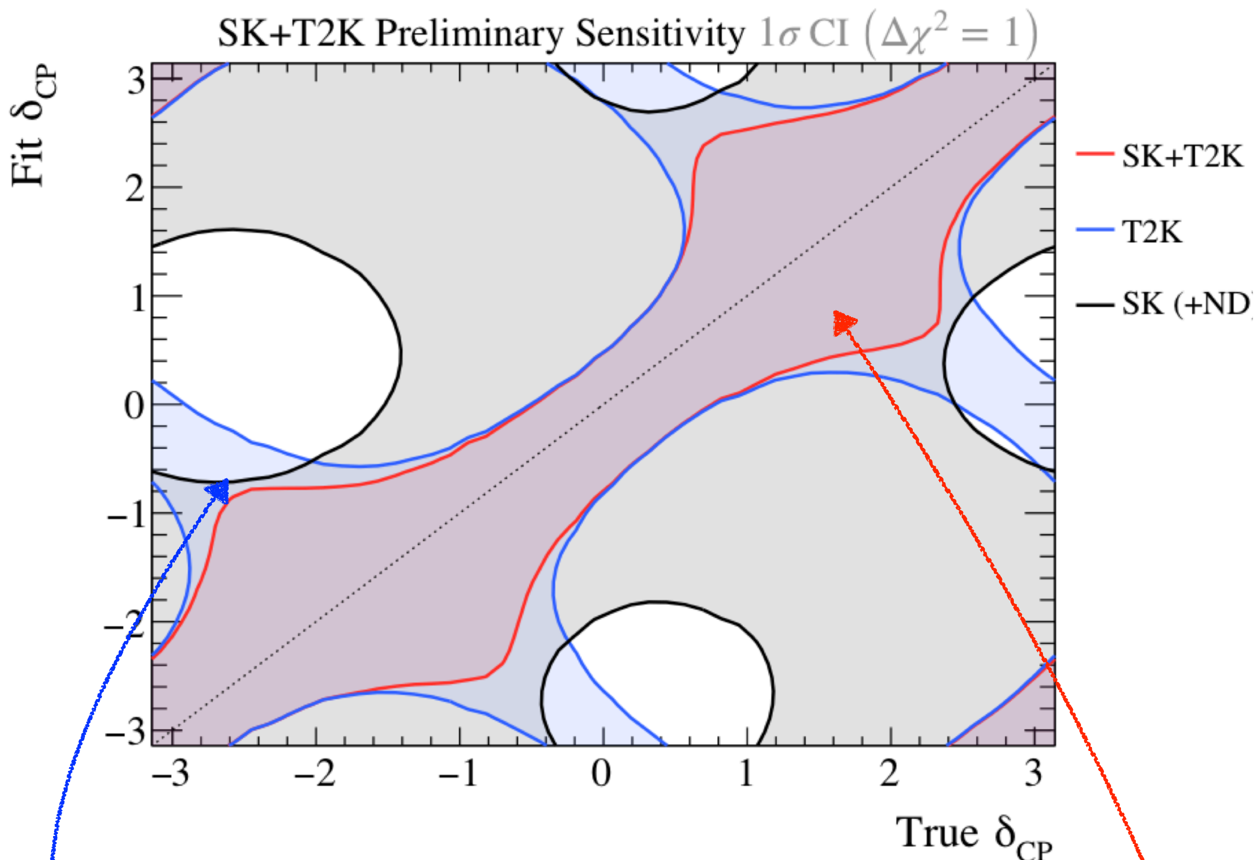
True IO in the backup.

Joint Fit Solving Degeneracy of δ_{CP} and MO (True NO)



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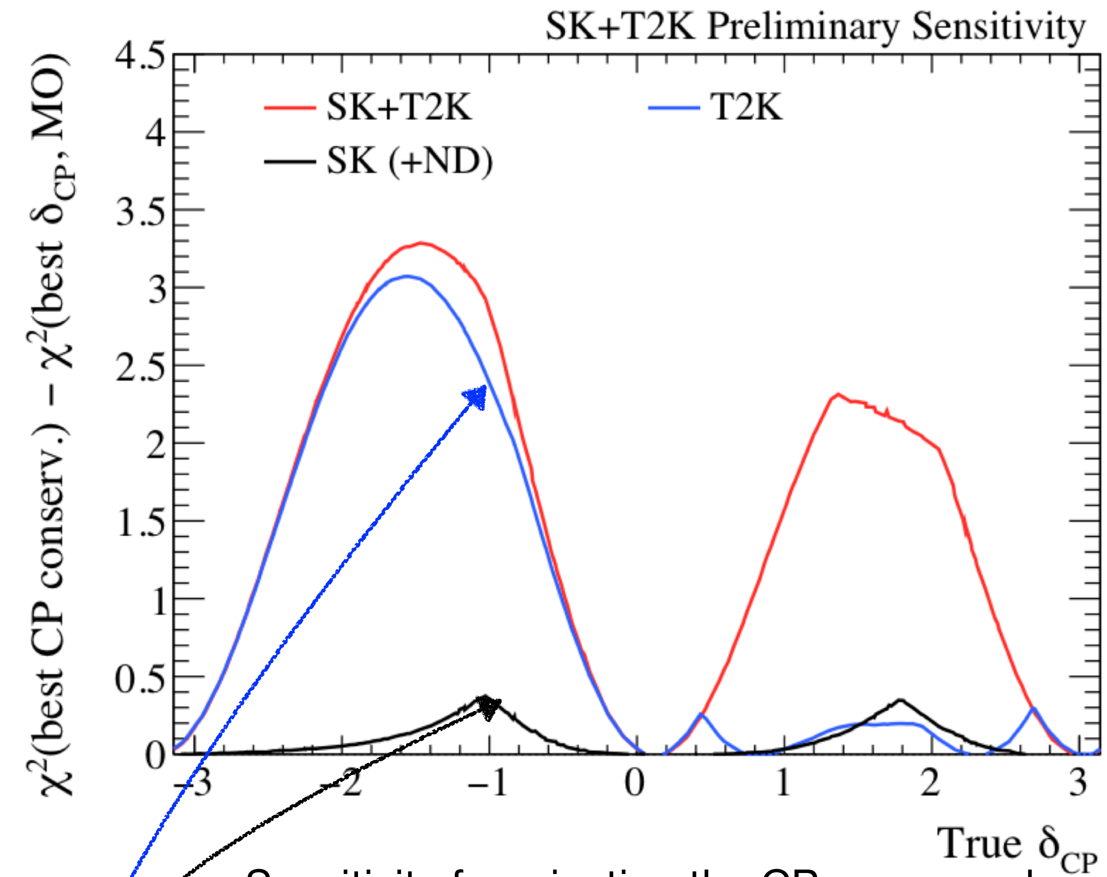

Sensitivity for rejecting the CP-conserved hypothesis at different true δ_{CP} values

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Atm samples are sensitive to $\sin\delta_{CP}$ and $\cos\delta_{CP}$, though the overall sensitivity is weaker.

Combining the two helps resolving the degeneracy in the constraint of δ_{CP}.

The δ_{CP} sensitivity from SK atmospheric samples are generally weaker than the T2K samples.

Meanwhile, the sensitivity to CP-violation from T2K samples is dependent on MO.

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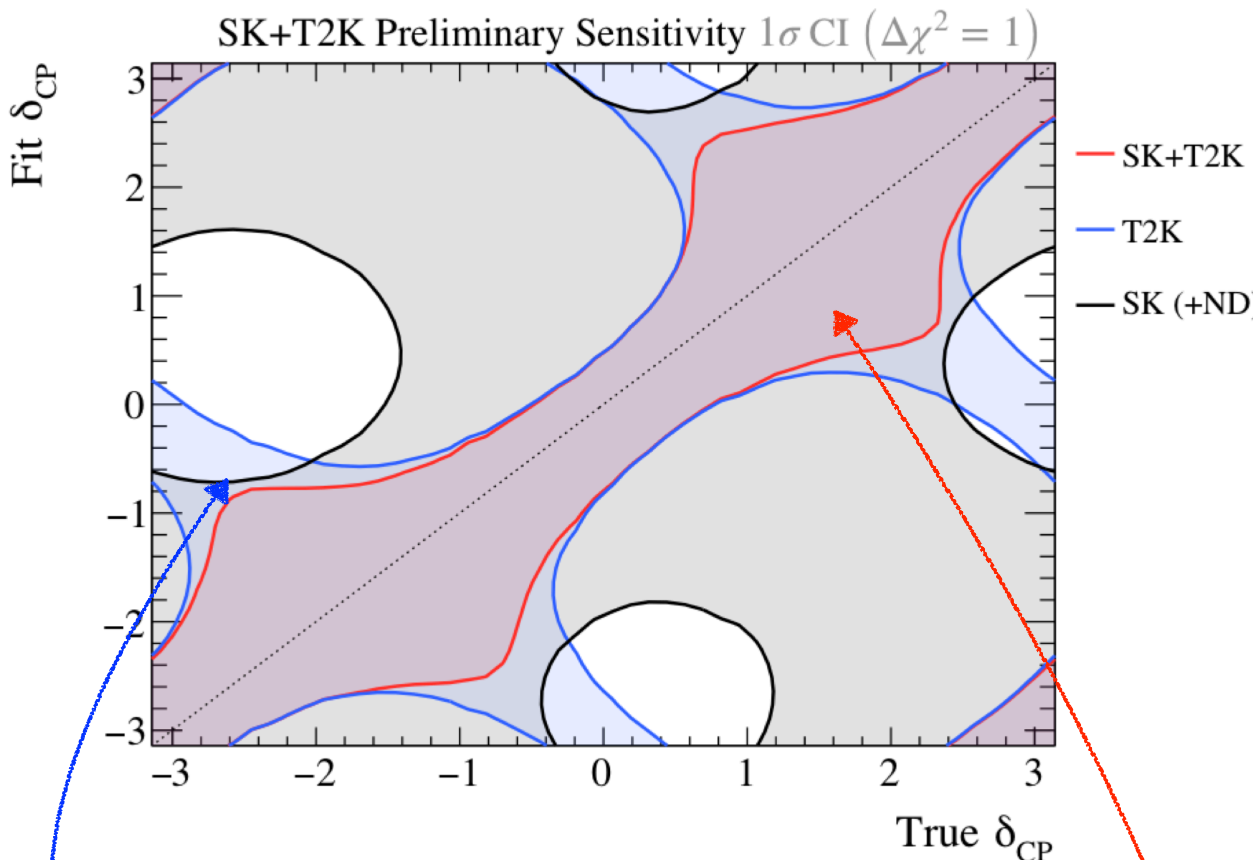
True IO in the backup.

Joint Fit Solving Degeneracy of δ_{CP} and MO (True NO)



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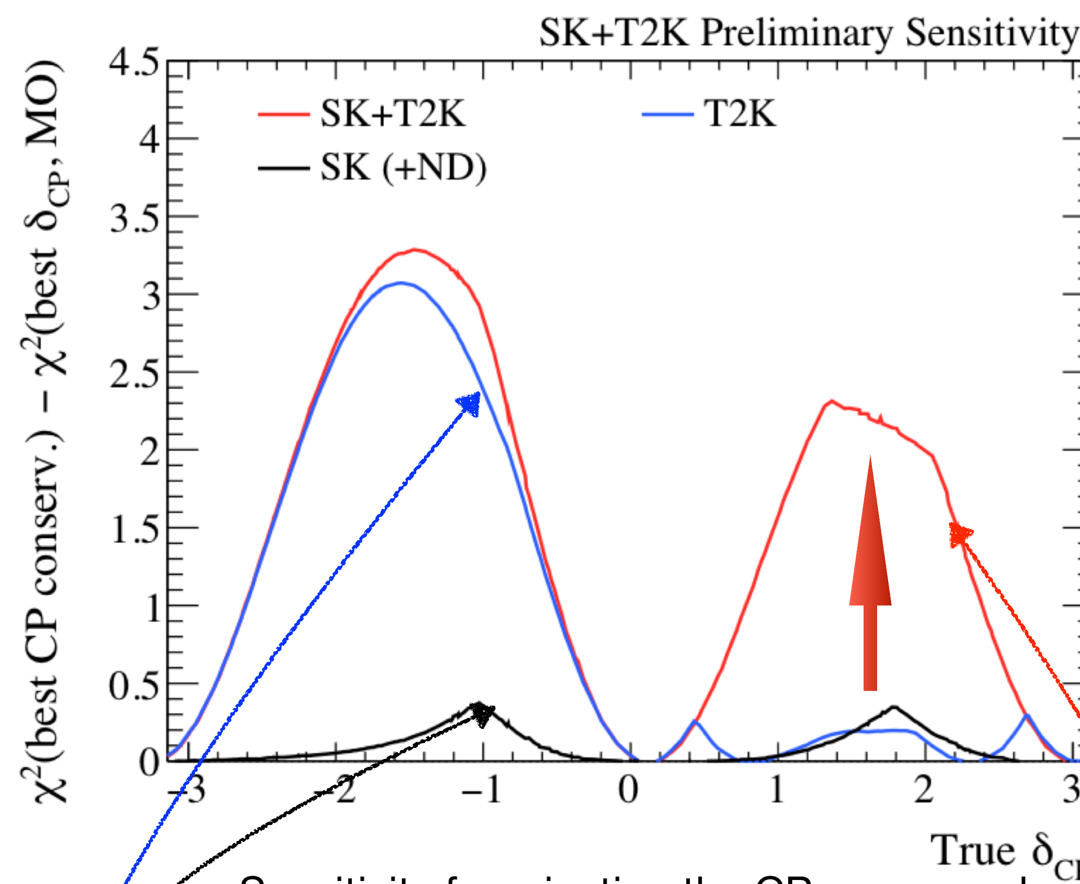

Sensitivity for rejecting the CP-conserved hypothesis at different true δ_{CP} values

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Truth: $\Delta m^2_{21} = 7.53 \times 10^{-5}\text{eV}^2, |\Delta m^2_{32,31}| = 2.509 \times 10^{-3}\text{eV}^2,$
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Summary and Outlook

The first T2K-SK joint sensitivity result of neutrino oscillation parameters is achieved by combining the T2K Run 1-10 and SK-IV neutrino samples.

The joint analysis is conducted with input models from both reference experiments, with substantial extensions and studies of the systematic uncertainties:

- **T2K ND** constraints **applied to** the neutrino interaction model of the SK **atmospheric** neutrino samples **when appropriate**;
- **Extra parameters introduced** to ensure model robustness and compatibility;
- Neutrino flux and detector systematics models **uncorrelated** in this work, with further investigation scheduled for the future analysis.

This joint analysis has **increased sensitivities to δ_{CP} and MO** by resolving the degeneracies of these two parameters.

Ongoing stress tests to verify the robustness of the present joint analysis model before unblinding data in less than 1 year.

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Stay tuned for more results in the near future!

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Backup Slides

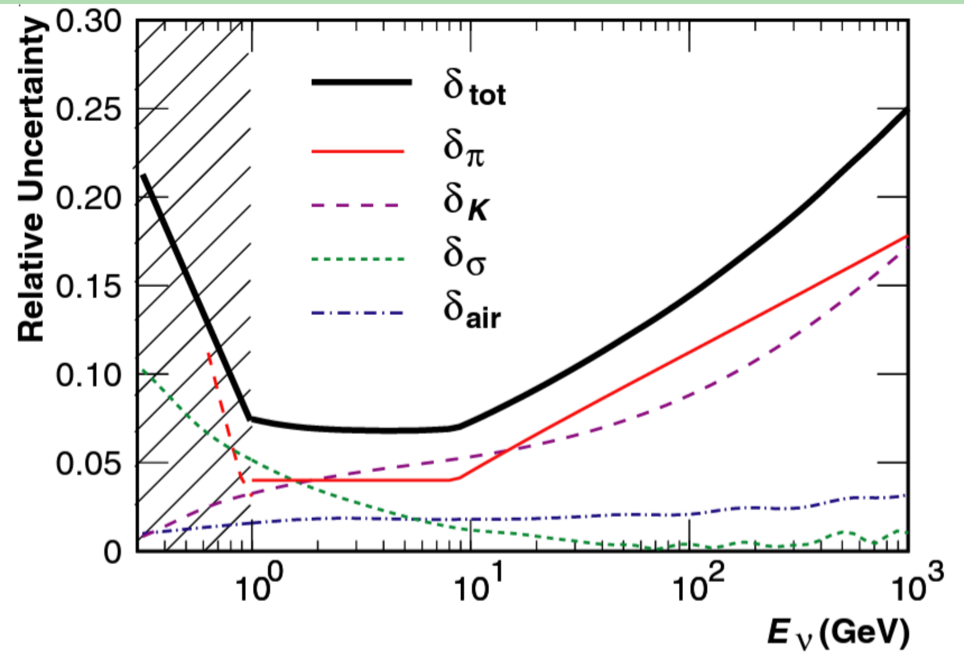
Oscillation Parameter Truth for Sensitivity Studies

Parameters	A	B	NoCPV	NoMax23	AIO
Δm^2_{21}		$7.53 \times 10^{-5}\,\text{eV}^2$			
Δm^2_{32} (NH) / $\lvert\Delta m^2_{31}\rvert$ (IH)		$2.509 \times 10^{-3}\,\text{eV}^2$			
$\sin^2\theta_{23}$	0.528	0.45	0.528	0.45	0.528
$\sin^2\theta_{12}$ ($\sin^2 2\theta_{12}$)		0.307 (0.851)			
$\sin^2\theta_{13}$ ($\sin^2 2\theta_{13}$)		0.0218 (0.0853)			
δ_{CP}	−1.601	0	0	−1.601	−1.601
Mass ordering		Normal			Inverted

Unless specially noted, the sensitivity results are achieved with Set A values assumed.

Flux Models of the T2K-SK Joint Oscillation Analysis

Atmospheric Flux

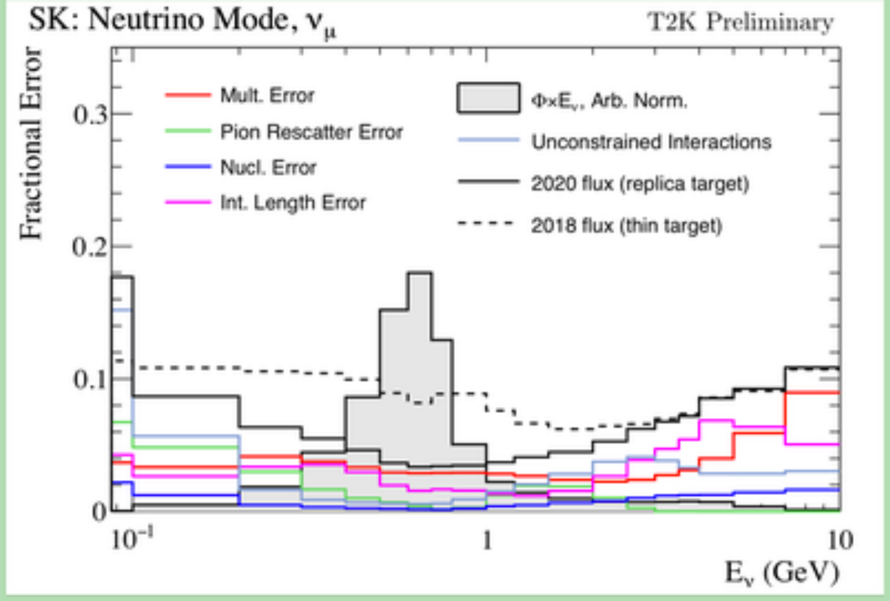


M. Honda, PHYSICAL REVIEW D 75, 043006 (2007)

Based on Honda flux model (2011), systematic uncertainties estimated by the difference among Honda, Bartol, and Fluka calculations.

Integrated flux error size of 5~10% for FC&PC samples and 10~20% for Upmu.

Beam Flux



Generated with J-PARC 30-GeV proton beam simulation and measurement of hadron production in NA61/SHINE.

Integrated error ~5% near the flux peak around 0.6 GeV and reaches ~10% at higher and lower neutrino energies.

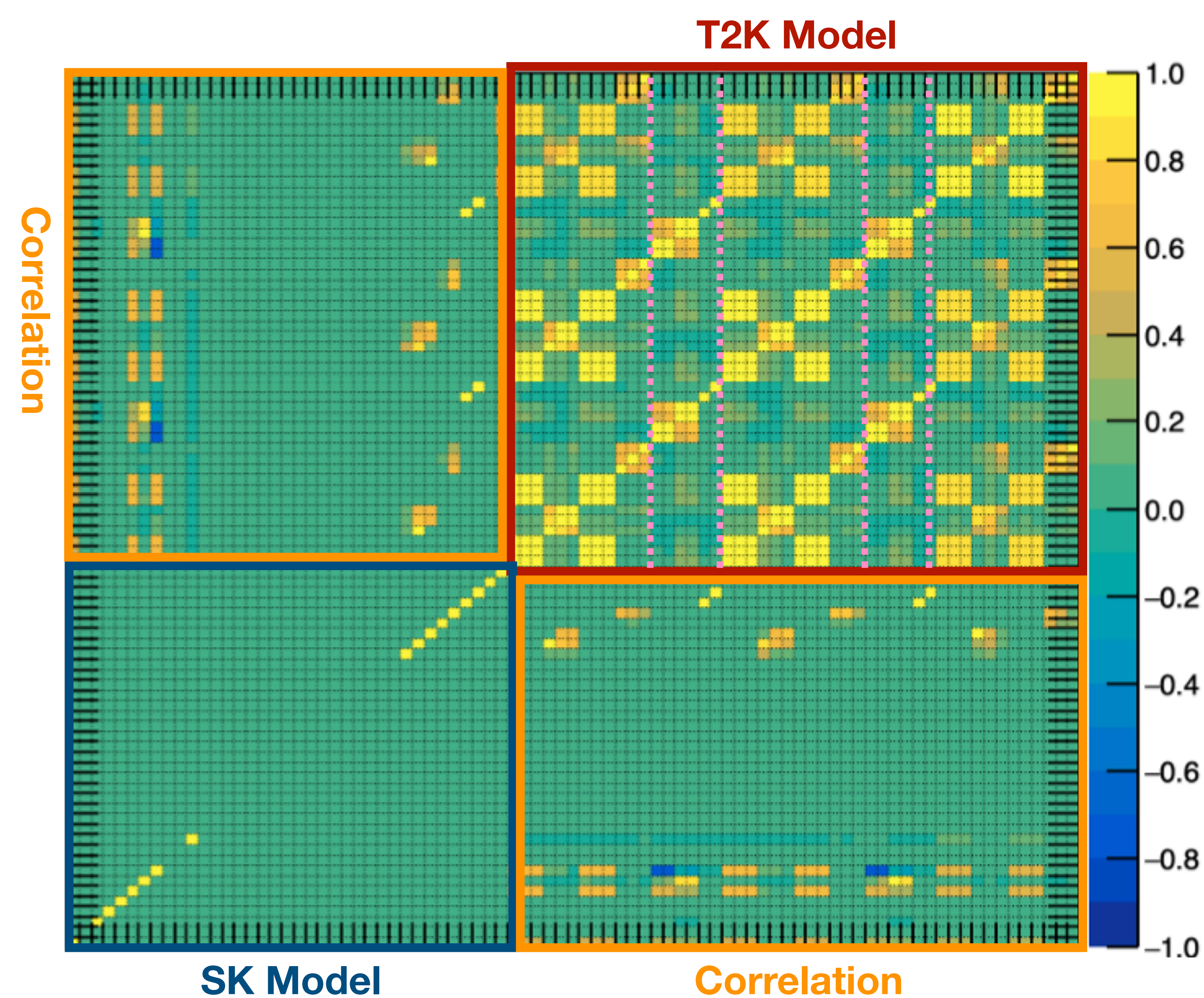
Access to ND data-driven constraints

Detector Systematic of the T2K-SK Joint Oscillation Analysis

The detector systematics for the T2K beam samples are estimated using various events in SK including the atmospheric neutrino and cosmic μ.

To understand the potential correlation of the detector systematic models from T2K and SK, compared the distortion of the T2K and SK neutrino event spectra under the effect of varying detector systematic parameters.

A covariance matrix is generated by this method with the **existing** T2K and SK detector systematic models and their possible correlation.

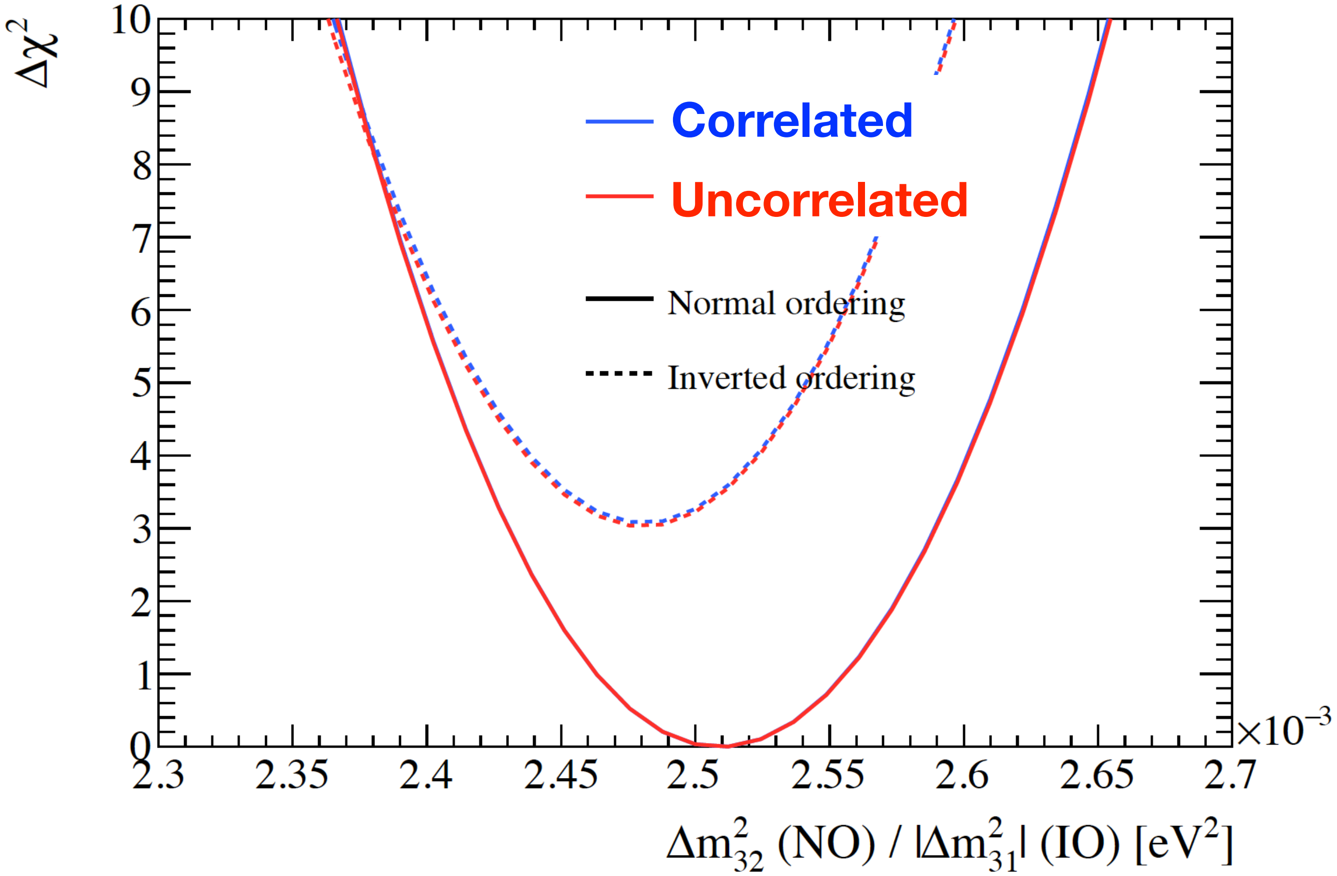


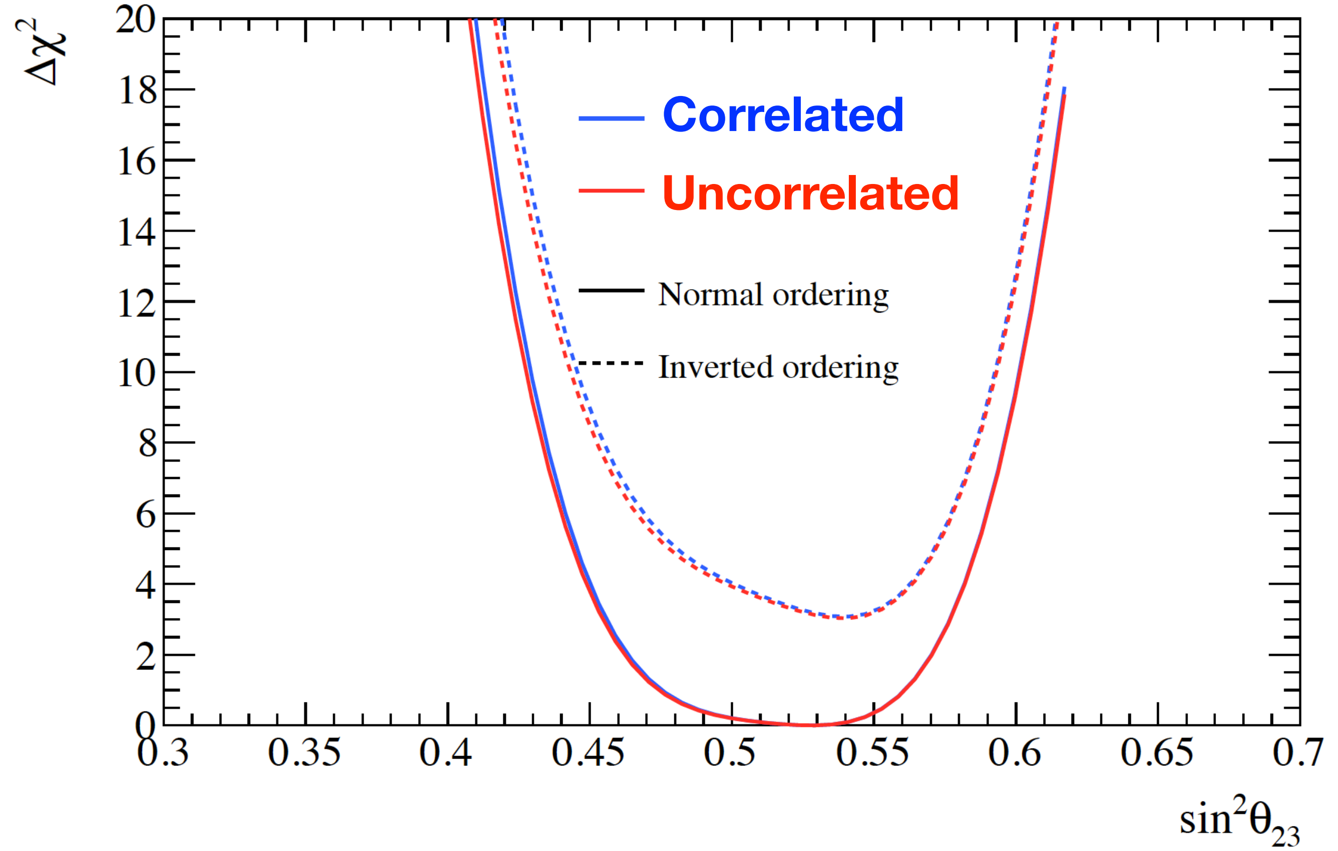
SK matrix composed of systematic parameters

T2K matrix composed of the change of sample event rate binned by lepton momentum and true CC/NC channels under the variation of systematics
From left to right:
FHC e-like (CC/NC)->RHC e-like (CC/NC)->FHC μ-like (CC/NC)->RHC μ-like (CC/NC)->FHC e-like CC1π (CC/NC)

Detector Systematics of the T2K-SK Joint Oscillation Analysis

Attempted to correlate the existing detector systematic uncertainties from T2K and SK but found negligible impact to sensitivities:





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$$\delta_{CP} = -1.601, \mathrm{MO} = \mathrm{NO},$$

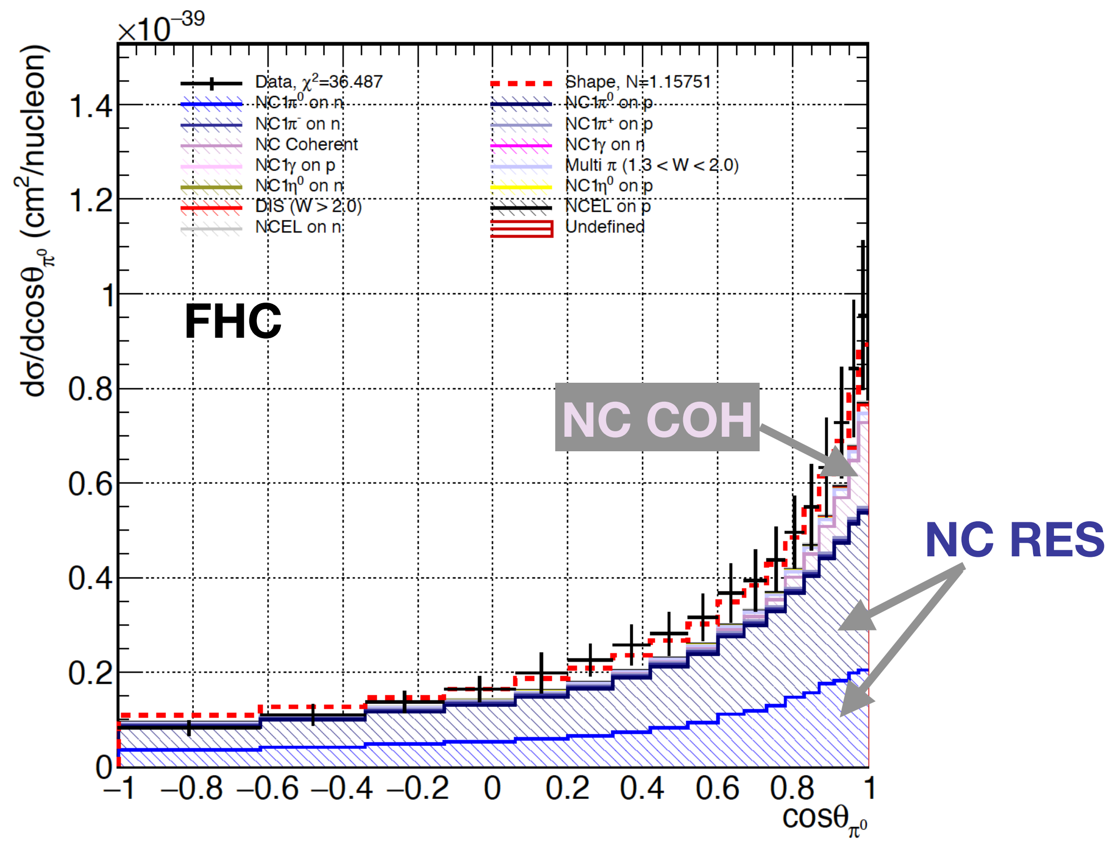
*PDG 2019 reactor neutrino constraint on θ_{13} always applied

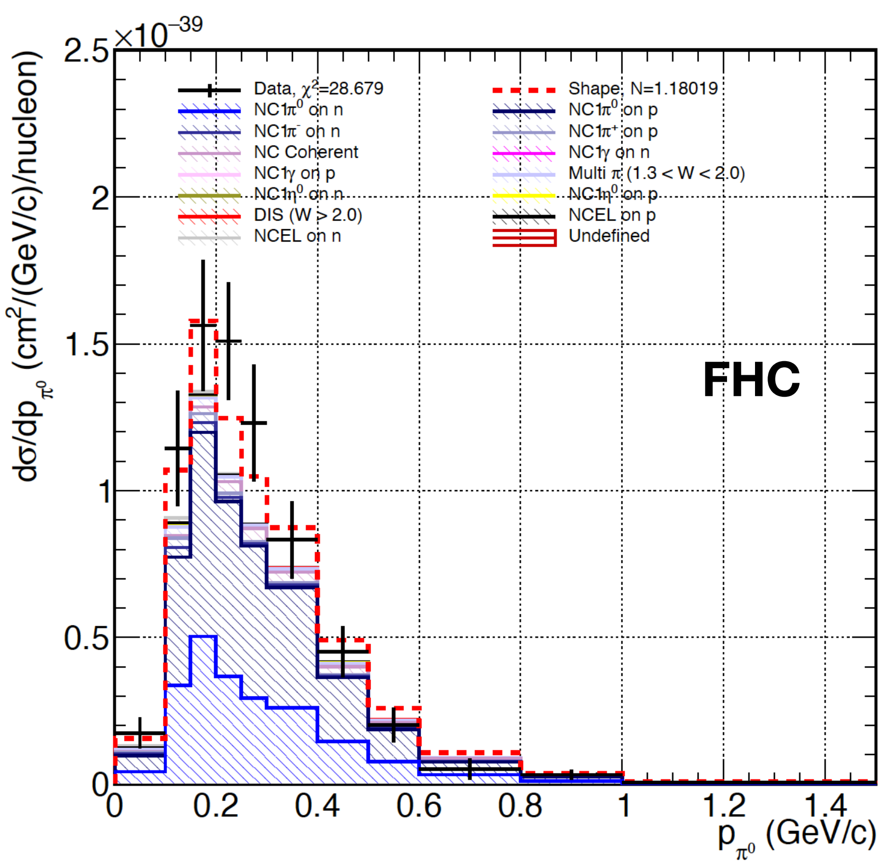
Extra Systematic Parameters beyond the ND Constraints

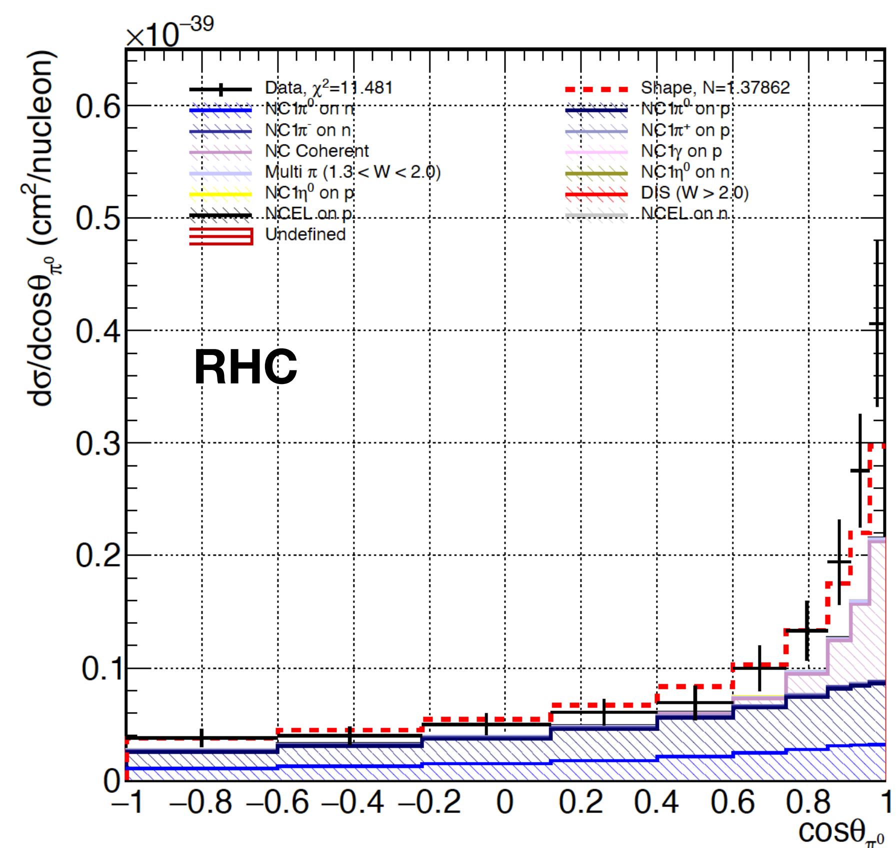
NC1π^0

The existing T2K model is not sufficient for the joint fit with a dedicated sub-GeV 2-ring π^0-like SK sample.

Estimated the error in this interaction channel with MiniBooNE data (Phys. Rev. D, 81:013005) and assigned 30% and 100% normalization error to the NC1π^0 resonant (RES) and coherent (COH) scatterings, respectively.



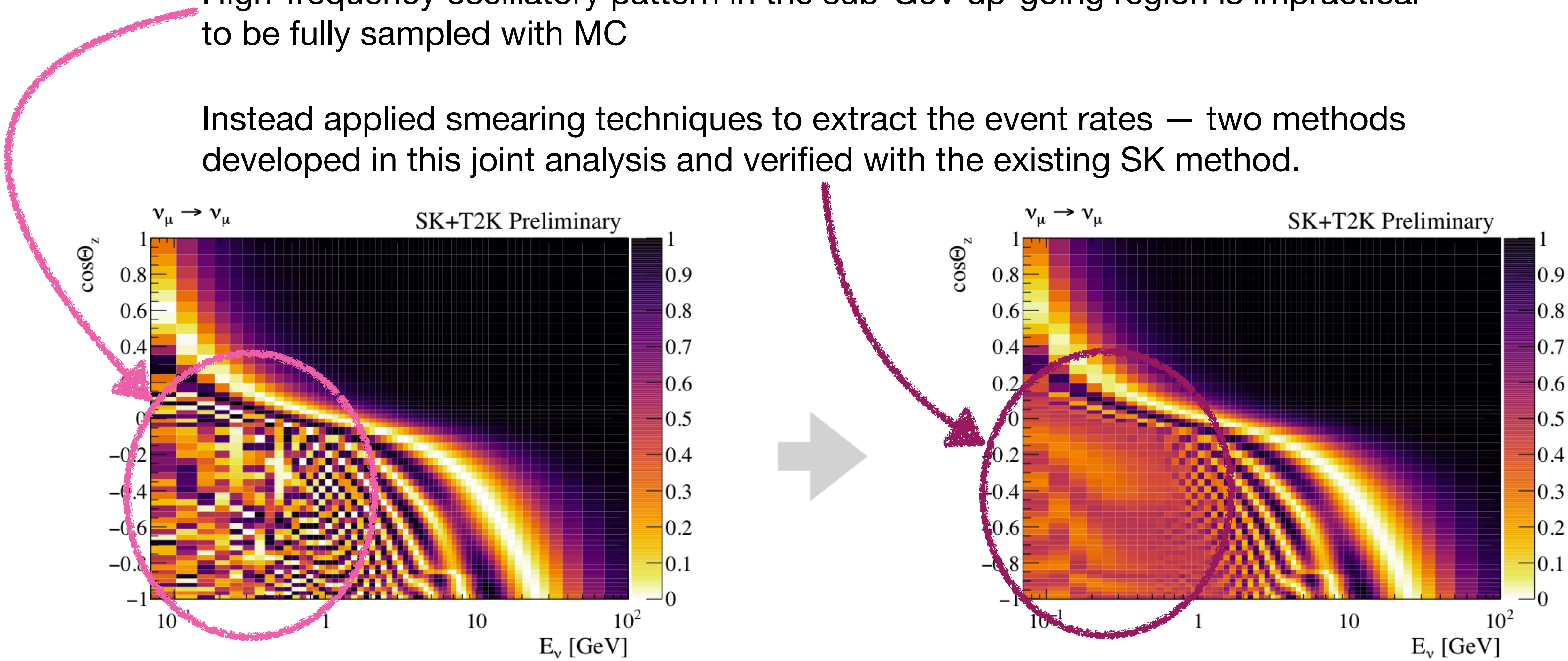




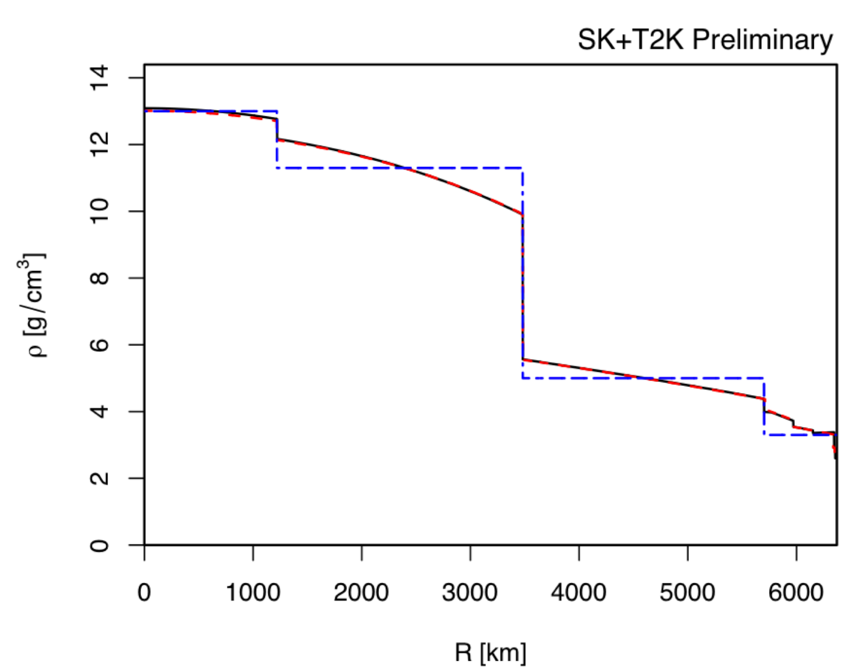
Treatment of the 3-flavor Neutrino Oscillation

High-frequency oscillatory pattern in the sub-GeV up-going region is impractical to be fully sampled with MC

Instead applied smearing techniques to extract the event rates — two methods developed in this joint analysis and verified with the existing SK method.



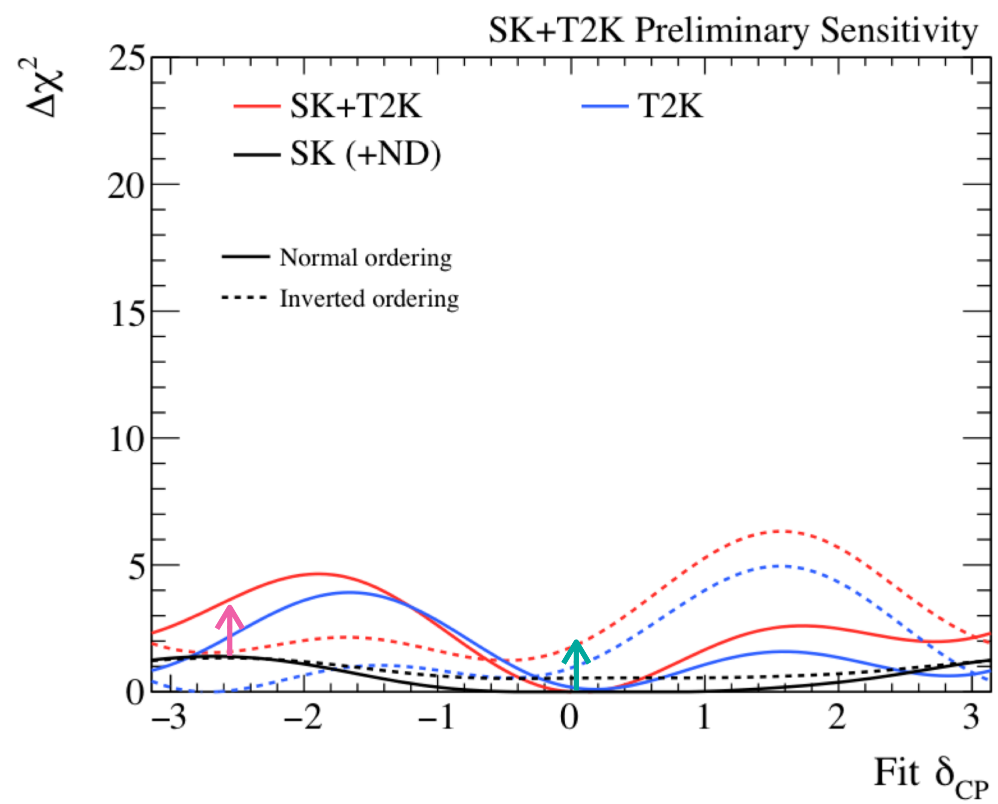
Improved sensitivity by using finer gradient earth density model for the calculation of oscillation probability instead of the simple constant density layers.

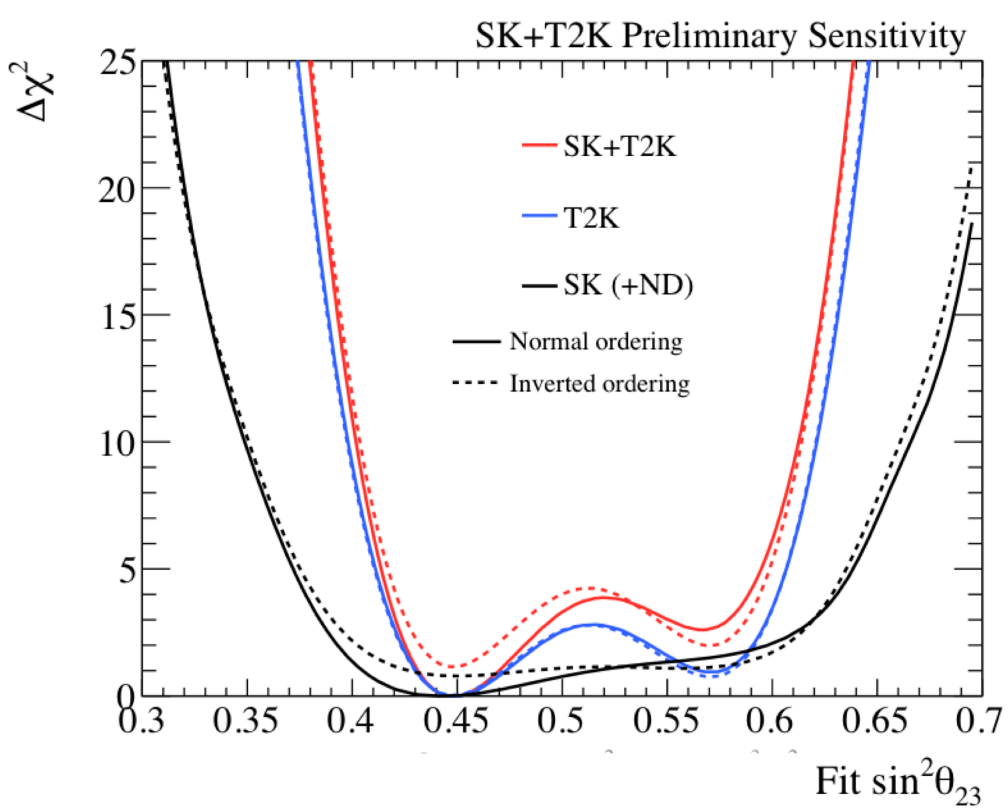


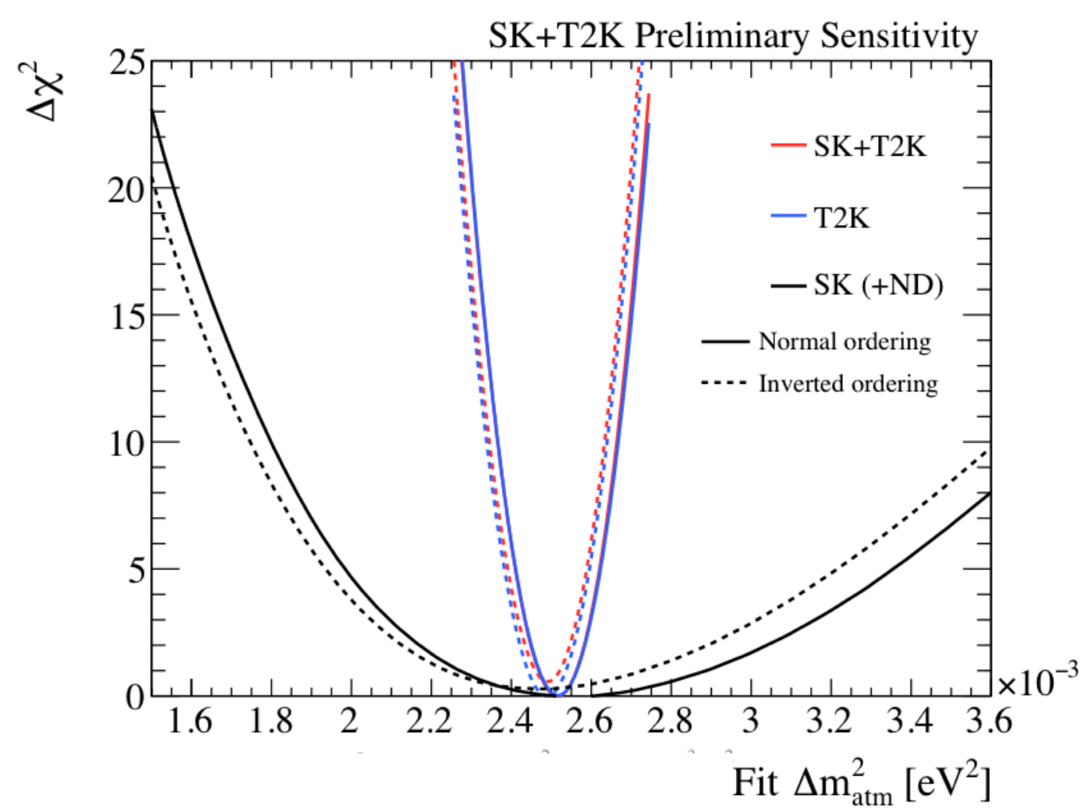
Sensitivity of δ_{CP}, Δm^2_{32}, $\sin^2\theta_{23}$ and MO (Set B)

1D fits with the “other” oscillation parameters marginalized, for example in the fit of δ_{CP} all the other parameters including $\sin^2\theta_{23}$ and Δm^2_{23} are marginalized.

Improved sensitivity of δ_{CP} and MO by this joint analysis







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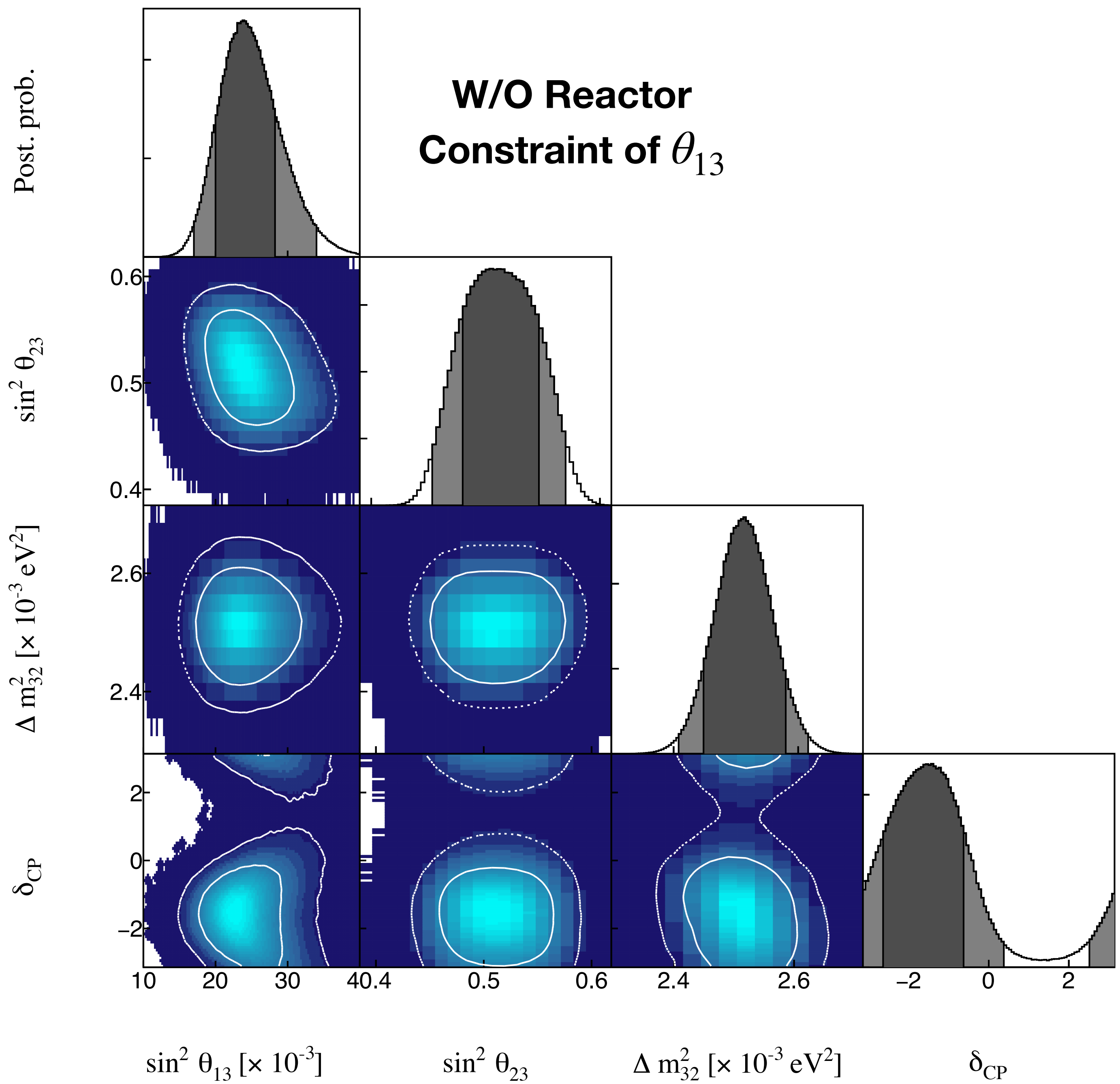
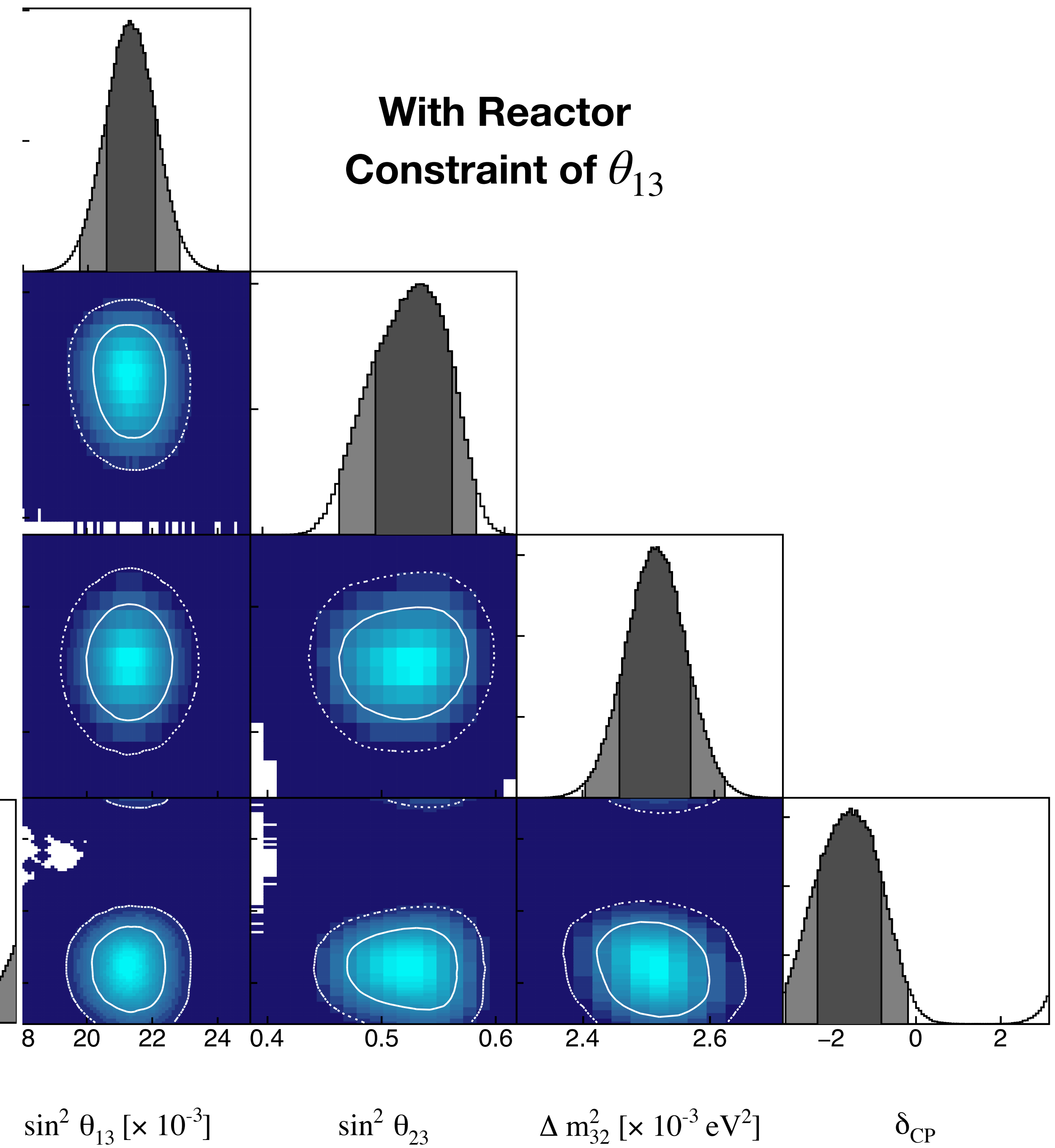
Simultaneous Fit of δ_{CP}, Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, and MO





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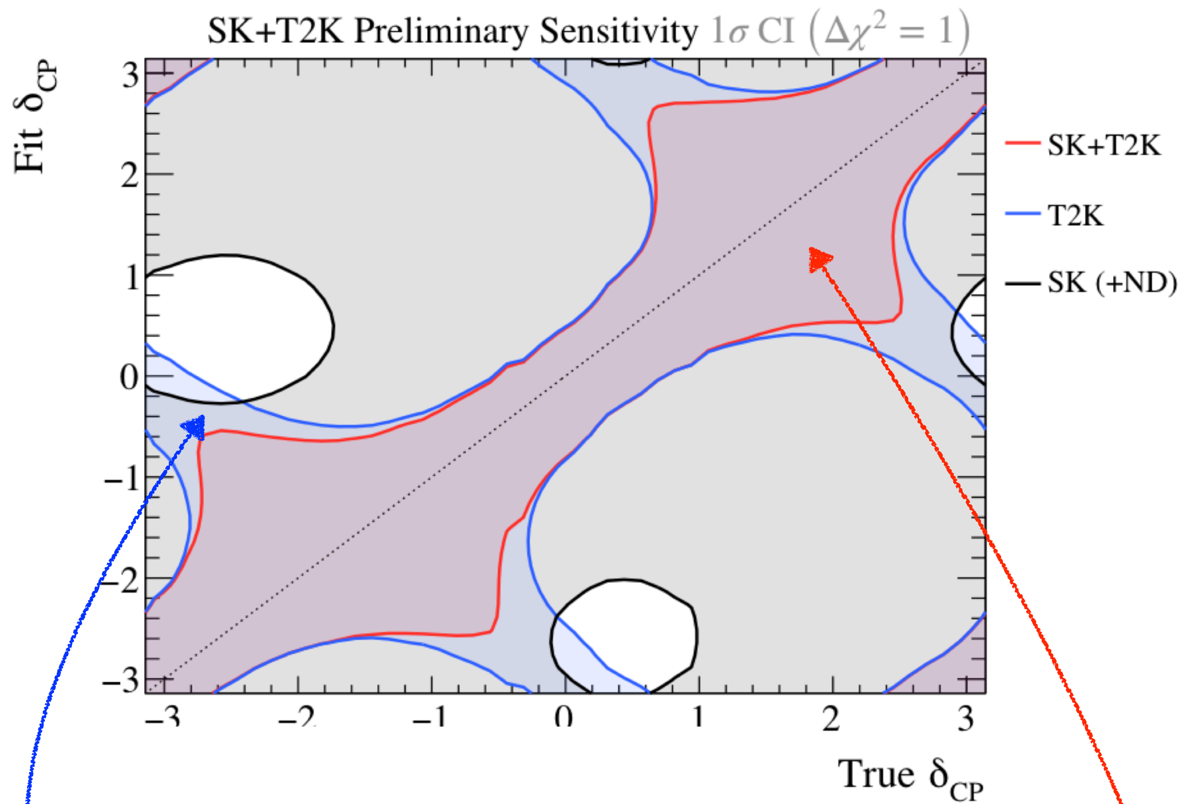
Marginalized over both MO (NO only for Δm^2_{32})

Joint Fit Solving Degeneracy of δ_{CP} and MH (True IO)



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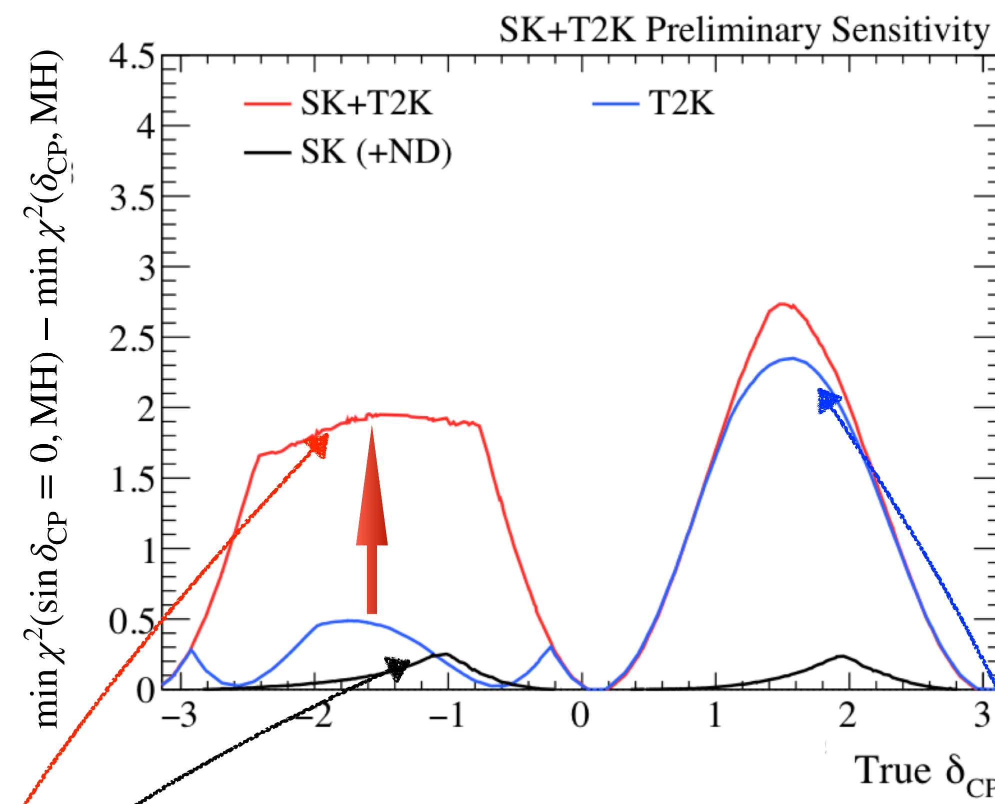

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