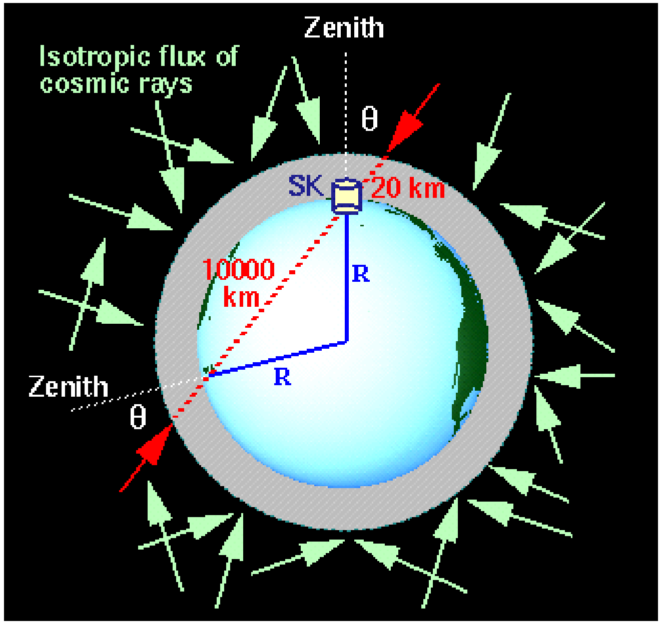
2nd Workshop for Atmospheric Neutrino Production in the MeV to PeV range

Joint analysis of T2K and Super-K atmospheric data



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C. Bronner
January 12th, 2021

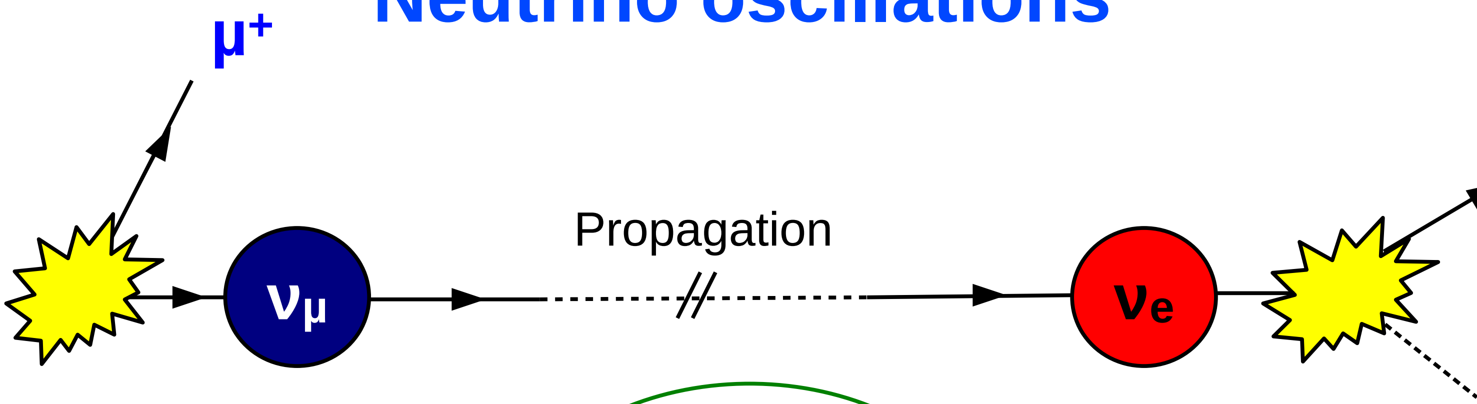
Introduction

- T2K and Super-K signed during the summer 2019 a MOU for a joint analysis of “T2K beam neutrino data and Super-Kamiokande atmospheric neutrino data for the purpose of studying oscillations within the PMNS framework”

- No material available for public presentations yet, but will discuss motivations and importance of atmospheric flux uncertainties based on available material from both experiments

- Outline:
  - Physics motivations
  - Super-Kamiokande and T2K experiments
  - Interest of a joint analysis
  - Flux uncertainties in each analysis
  - Impact of atmospheric flux uncertainties on Super-K
  - A few thoughts on correlated systematics between beam and atmospheric flux

Neutrino oscillations



Flavor eigenstates (interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates (propagation)

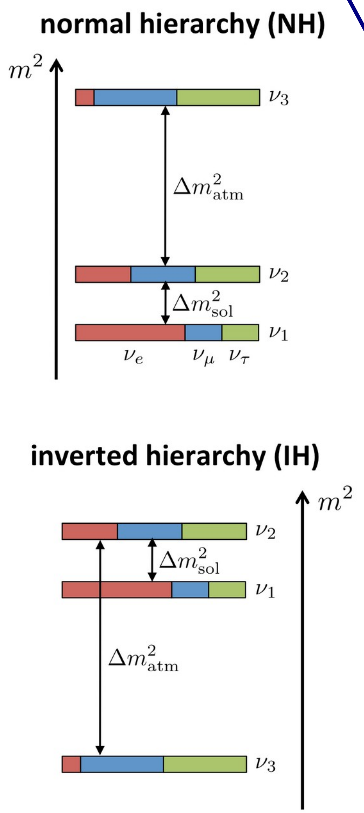
Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino with periodicity $\mathbf{\Delta m^2_{ij} L/E}$

$(\Delta m^2_{ij} = m^2_i - m^2_j)$

Neutrino oscillation
Main current physics goals

Mass hierarchy:
$m_3 > m_2, m_1$?



PDG 2016 summary table

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

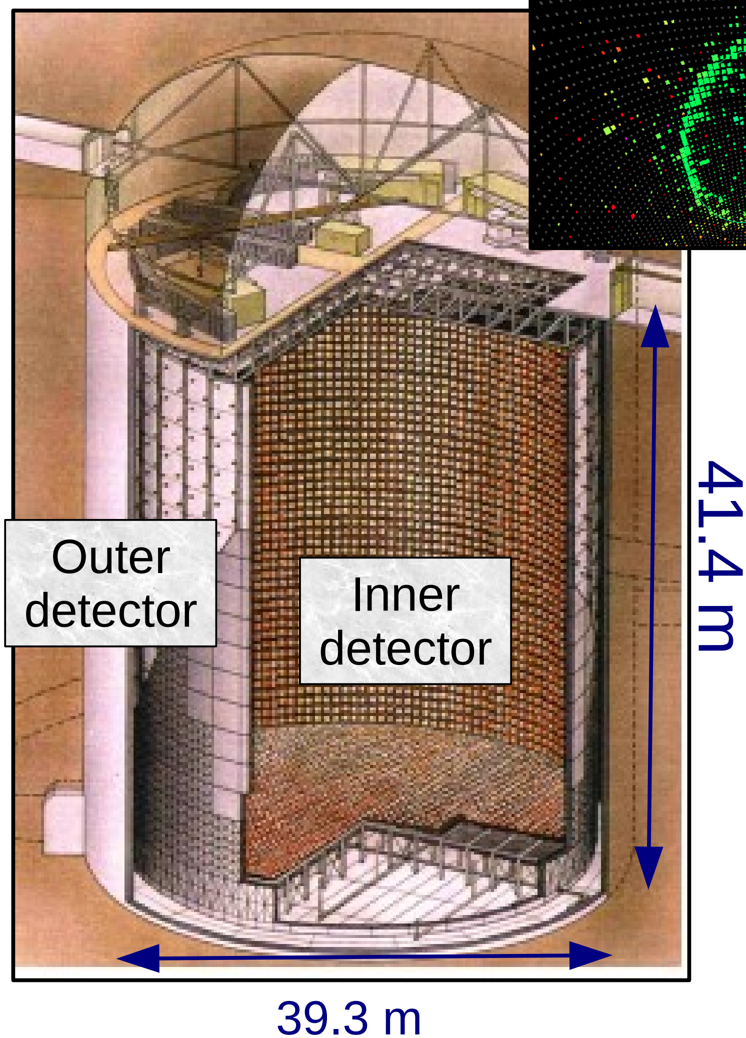
Octant of θ_{23}:
$\theta_{23} > \pi/4$?
$\theta_{23} < \pi/4$?

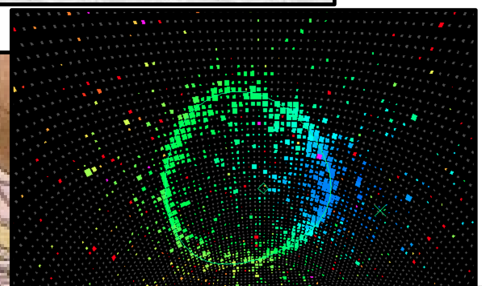
Difference between oscillations of ν and $\bar{\nu}$?

Degeneracies between those 3 questions

Super-Kamiokande experiment

- 50 kt (22.5 kt fiducial) water Cherenkov detector
- 1000m overburden
- Operational since 1996



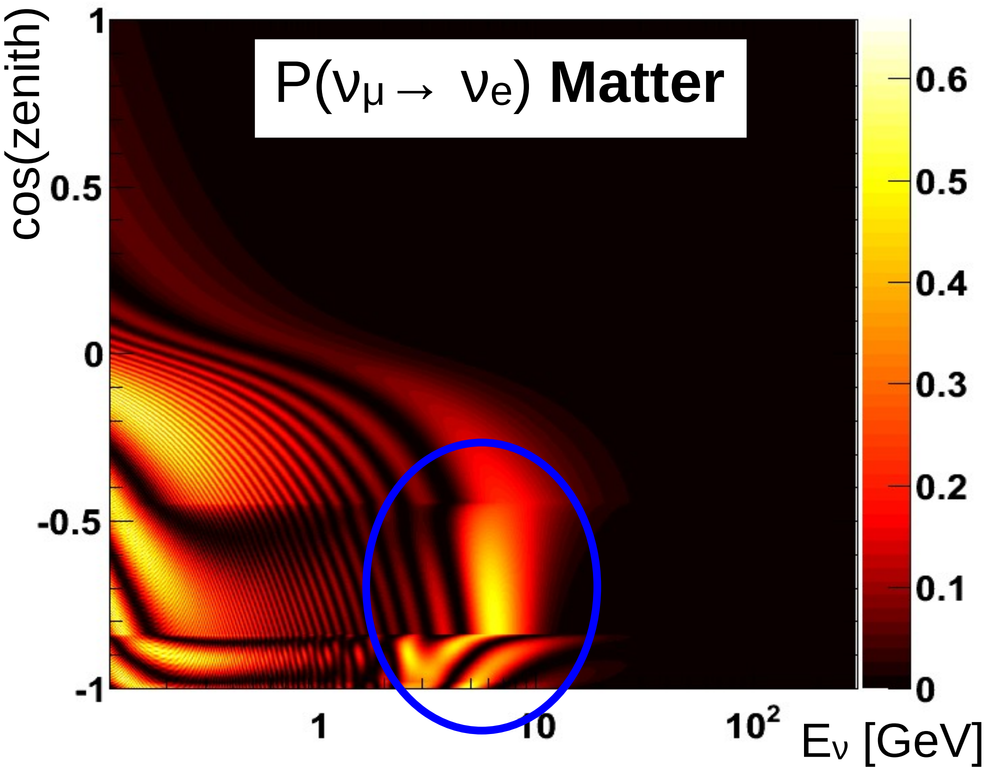


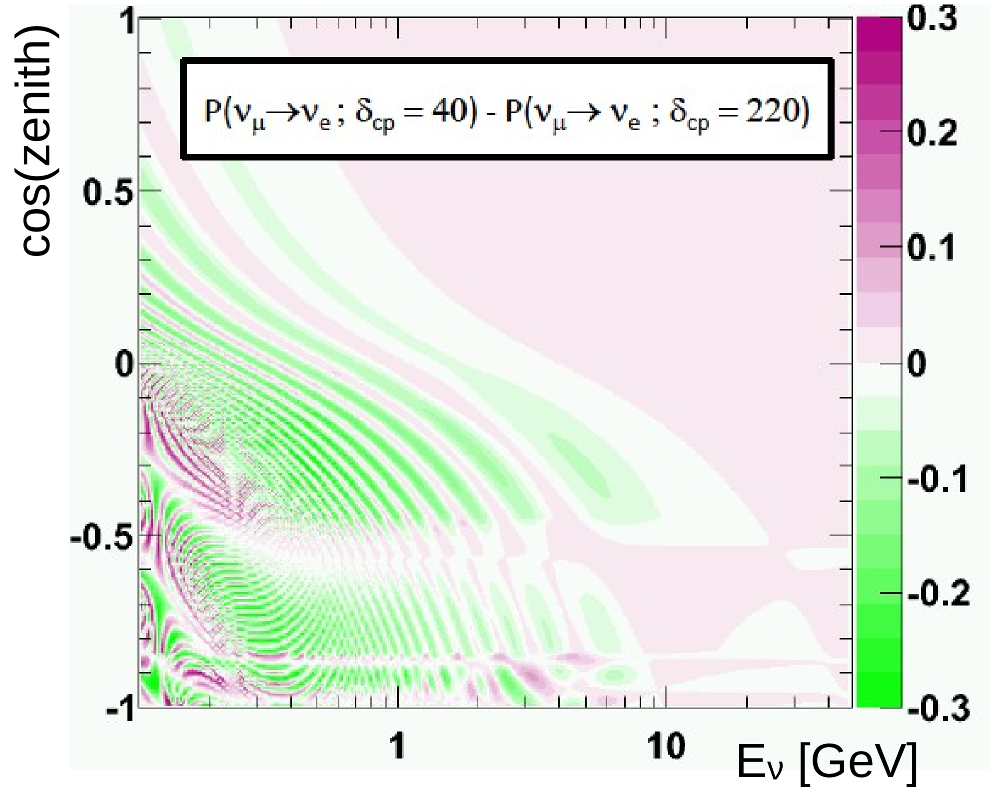
Wide physics program:
- ✓ **Atmospheric neutrinos**
- ✓ Solar neutrinos
- ✓ Supernova neutrinos
- ✓ Proton decay
- ✓ Dark matter indirect detection

- Good separation between $\mu^{\pm}$ and $e^{\pm}$ (**separate ν_{μ} and ν_{e} CC interactions**)
  → Less than 1% mis-PID at 1 GeV
- No magnetic field: **cannot separate ν and $\bar{\nu}$ on an event by event basis**
- **Only detects charged particles above Cerenkov threshold and photons**
  → limitation for energy and directional reconstruction

Atmospheric neutrinos
Interest for oscillation measurements

Ability to study the open questions comes mainly from appearance channels $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





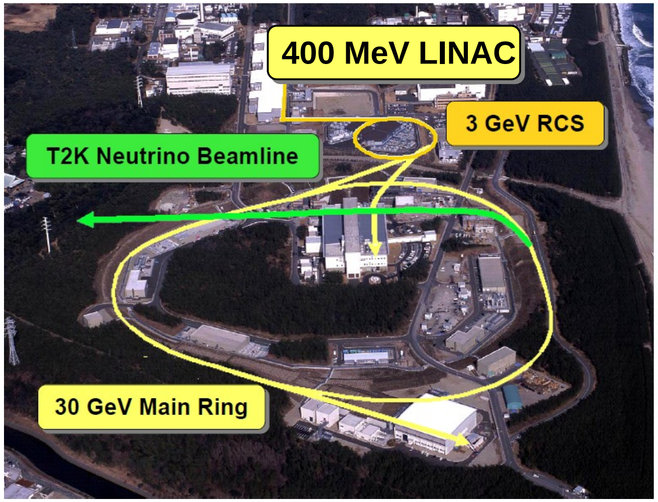
Resonance from matter effects

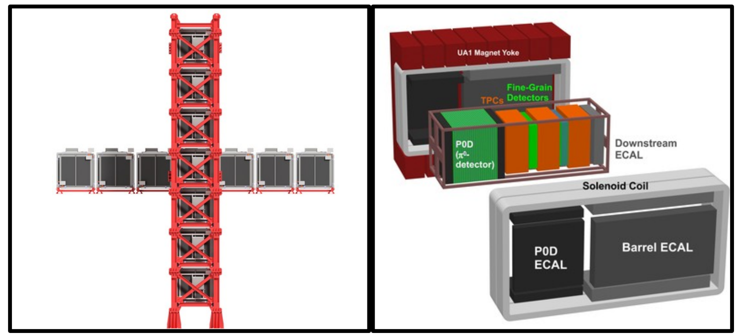
- Only for ν in NH and $\bar{\nu}$ in IH → **sensitive to the mass hierarchy**
- Size of the effect depends on $\sin^2(\theta_{23})$ → **sensitive to θ_{23} octant**

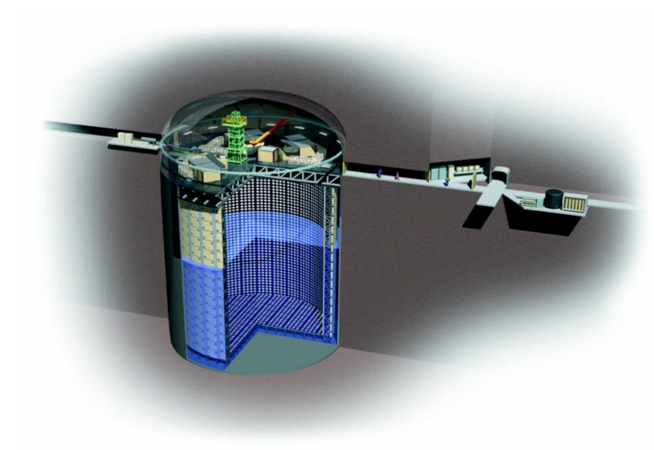
δ_{CP} modifies the oscillation patterns

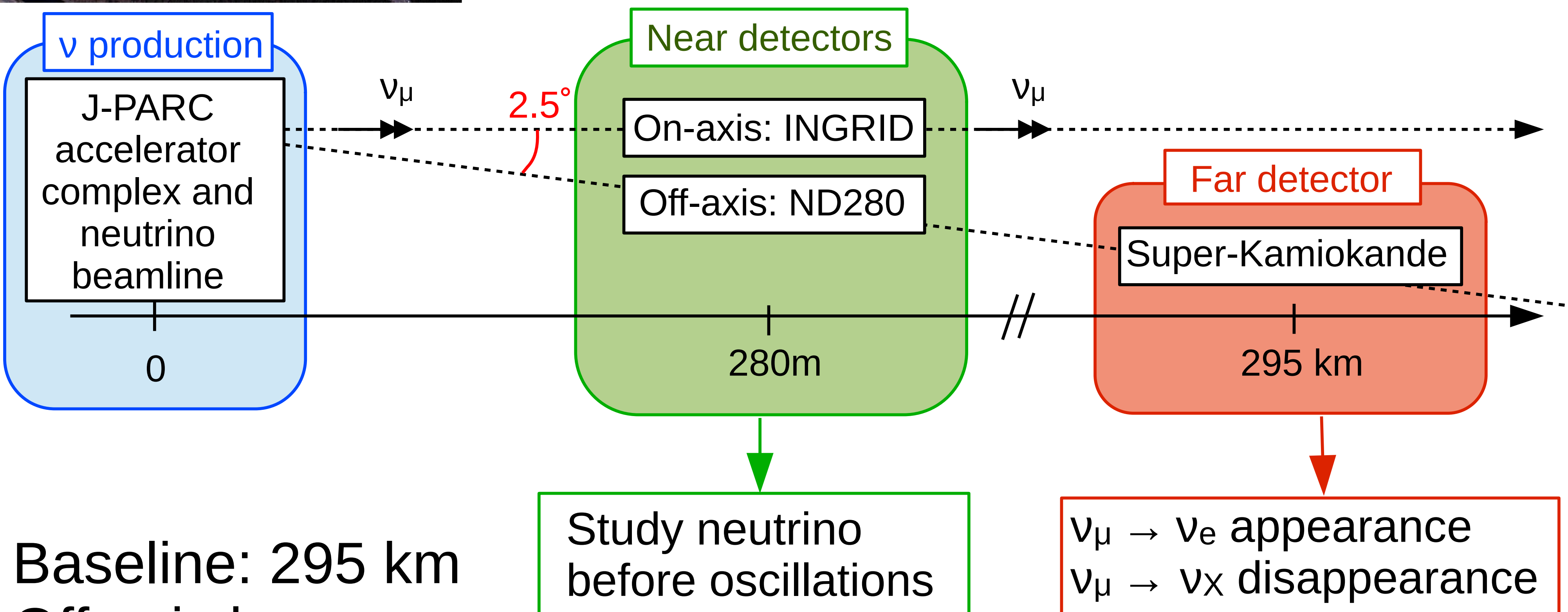
- Sensitivity from number of sub-GeV ν_e events
- More ν_e appearance events for δ~220-240º, and less for δ~40-45º

The T2K experiment Overview







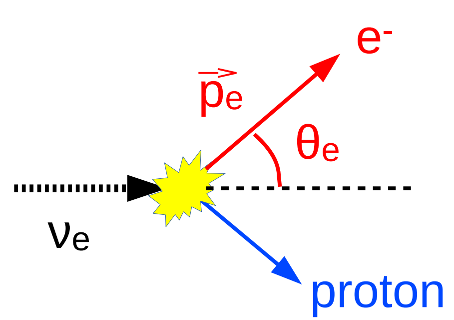


- Baseline: 295 km
- Off-axis beam

The T2K experiment
Interest for oscillation measurements

- Neutrino direction known: can reconstruct energy for CCQE events

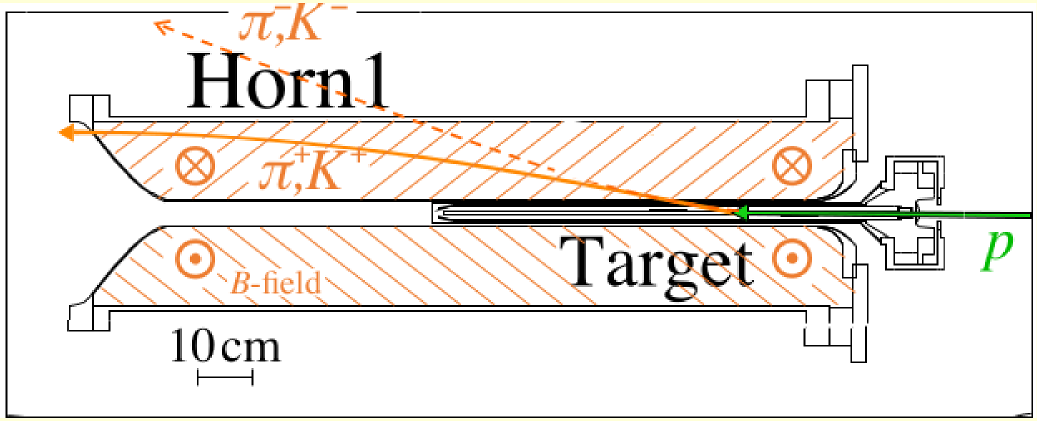
$\nu + n \rightarrow p + l^-$
$\bar{\nu} + p \rightarrow n + l^+$



- Distance traveled by neutrino known

Good L/E resolution

Neutrino beam from decay of hadrons focused by electromagnetic horns



- Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam (<1% $\bar{\nu}_e/\nu_e$ at peak)
- Can switch from mainly ν_μ to mainly $\bar{\nu}_\mu$ beam

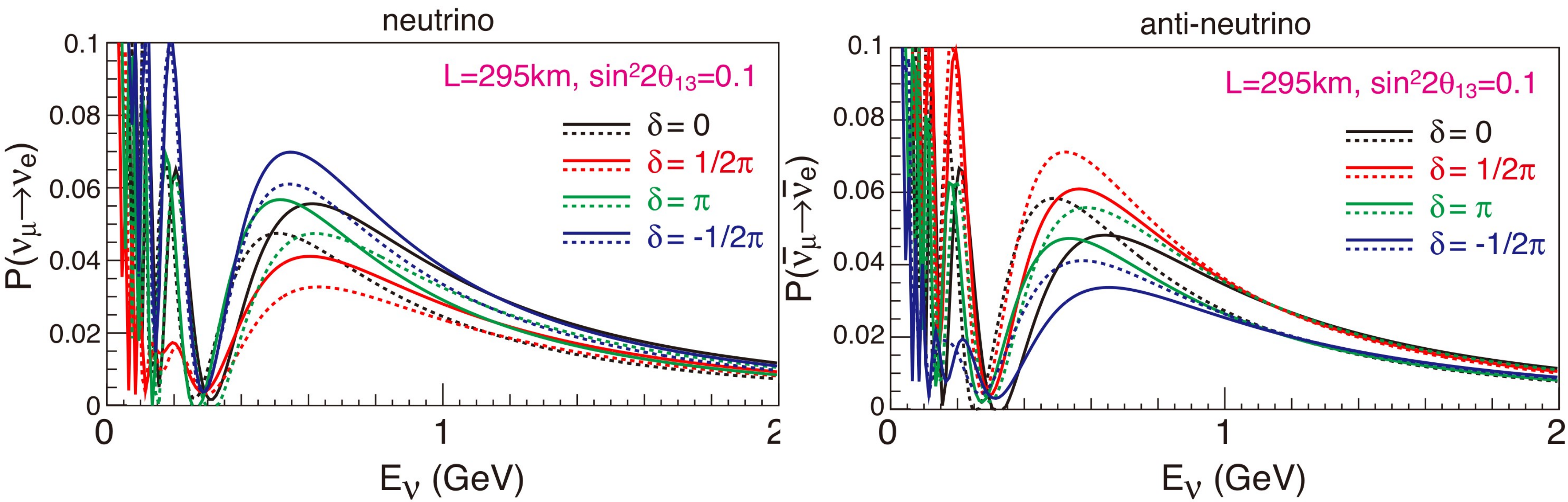
Clean samples to study $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ from lepton flavor and horns polarity

- $\nu_\mu \rightarrow \nu_\mu$ samples: good sensitivity to $\sin^2(\mathbf{2}\theta_{23})$ and $|\Delta m^2_{32}|$
- $\nu_\mu \rightarrow \nu_e$ samples: sensitivity to the 3 open questions (CP symmetry, mass hierarchy and octant of θ_{23})

The T2K experiment
Interest for oscillation measurements

Comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ allows to study CP violation and the mass hierarchy

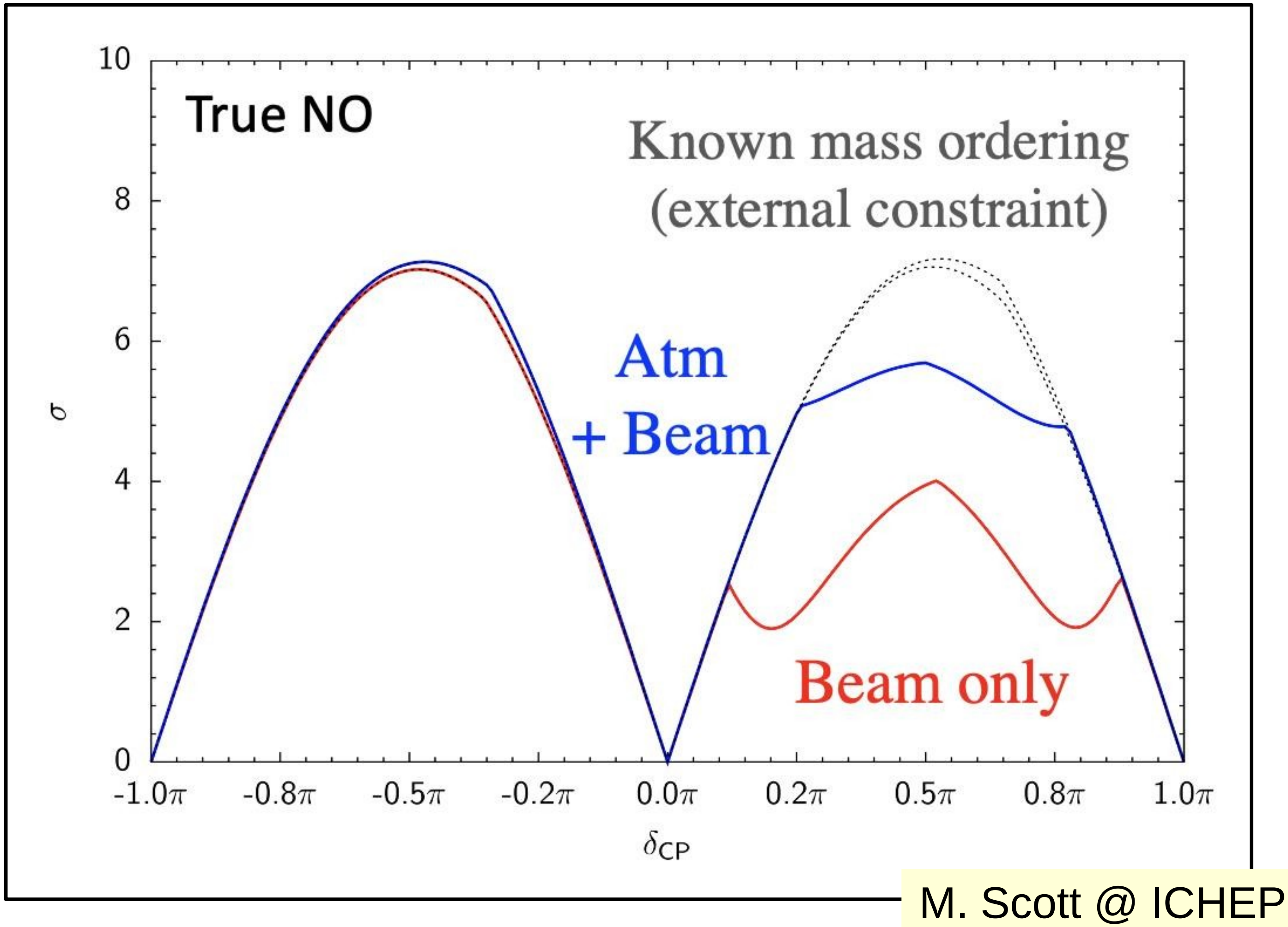
Channel	sin(δ) > 0	sin(δ) < 0	Normal hierarchy	Inverted hierarchy
$\nu_\mu \rightarrow \nu_e$	Suppressed	Enhanced	Enhanced	Suppressed
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Enhanced	Suppressed	Suppressed	Enhanced



- Degeneracies between the effect of δ and the mass hierarchy
- T2K baseline “not very long”: effect of δ dominates (~<27% vs ~10%)

Interest of combined analysis
Breaking degeneracies

- Combining atmospheric and beam data can help solve this degeneracy
- Was studied for Hyper-Kamiokande, using (simpler) combination of analyses, for the ability to exclude conservation of CP symmetry as a function of true value of δ_{CP}

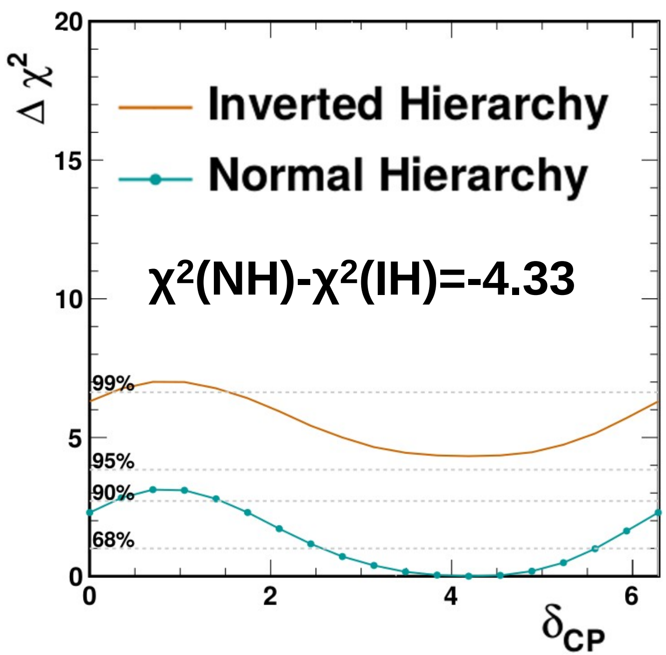


M. Scott @ ICHEP2020

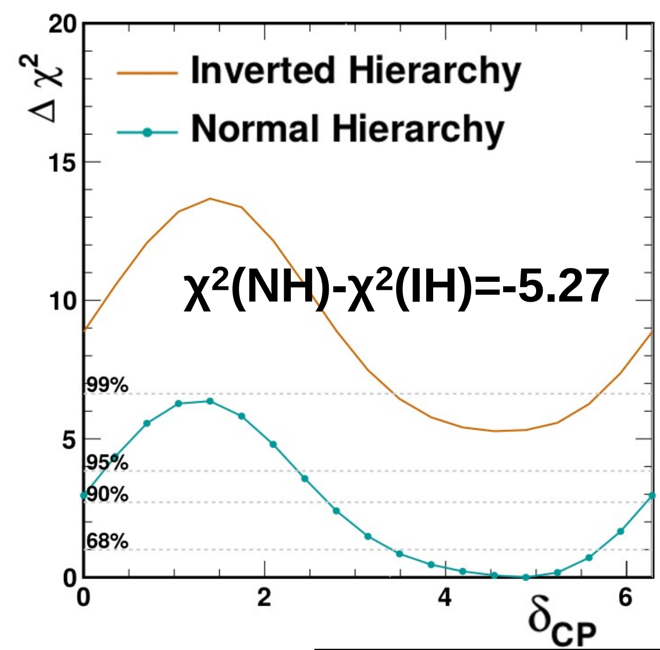
Interest of combined analysis
Increased sensitivity

- If both experiments have sensitivity to a question, combined analysis allows to add those sensitivities with proper statistical treatment
- Can also further increase sensitivity: for example, uncertainty on θ_{23} and δ limit SK sensitivity to the mass hierarchy, and (current) T2K can constrain those parameters
- Increased precision could be seen on Super-K analysis with "external constraints" (NOT a real joint fit between 2 experiments: uses a model of T2K)

Super-K atmospheric only



Super-K + external constraints



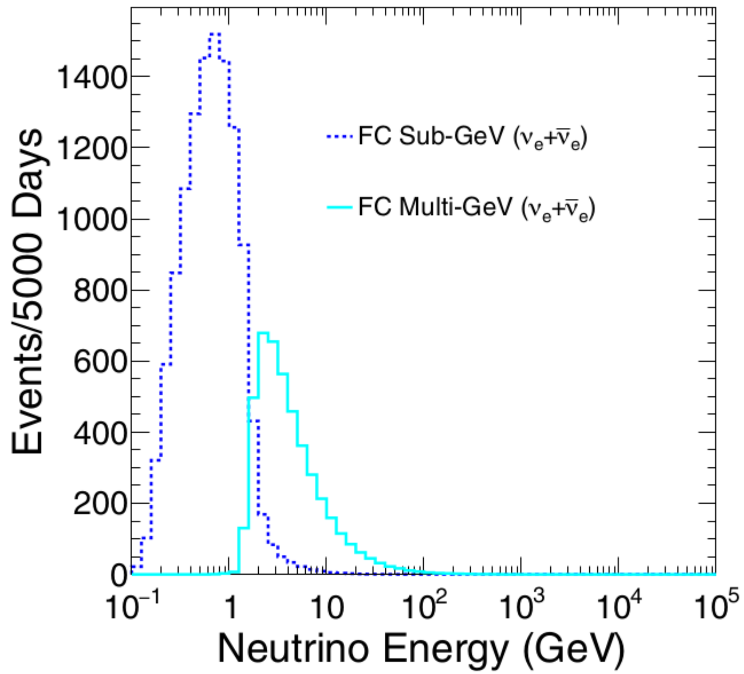
PRD 97, 072001 (2018)

Note: T2K model is based on an **old T2K analysis**. T2K current constraint on δ_{CP} much stronger (and stronger than Super-K one)

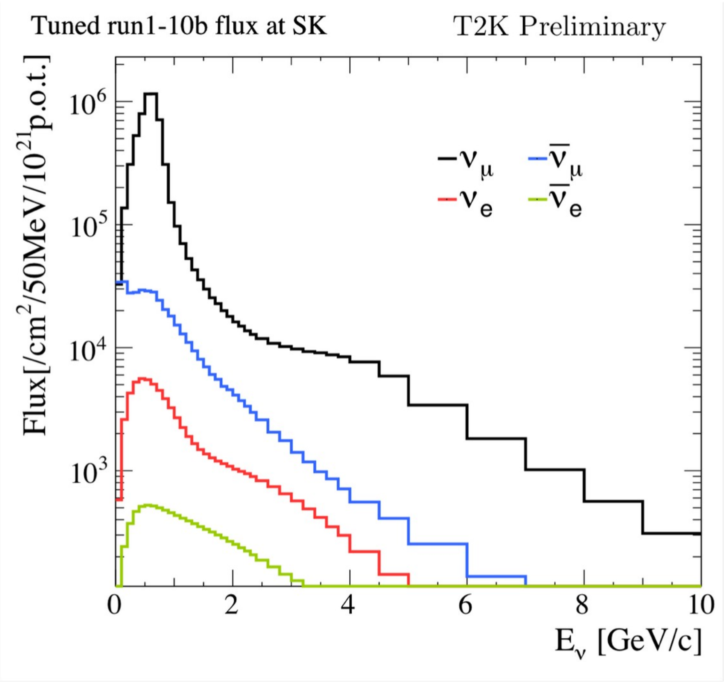
Systematic uncertainties

- Joint analysis needs to take into account correlations between systematic uncertainties for the 2 experiments where needed
- Particularly relevant between SK Sub-GeV and T2K samples: similar energies and event selections in the same detector
- Will focus on flux uncertainties here, but also have to consider neutrino interaction and detector systematics

Unoscillated predictions for SK atmospheric



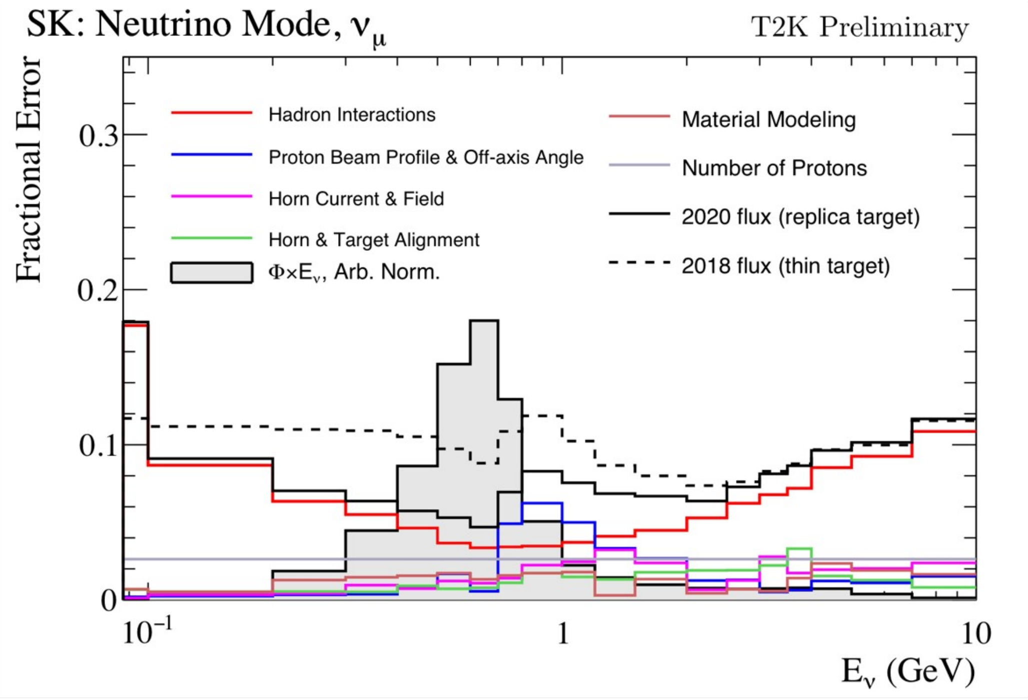
T2K flux prediction

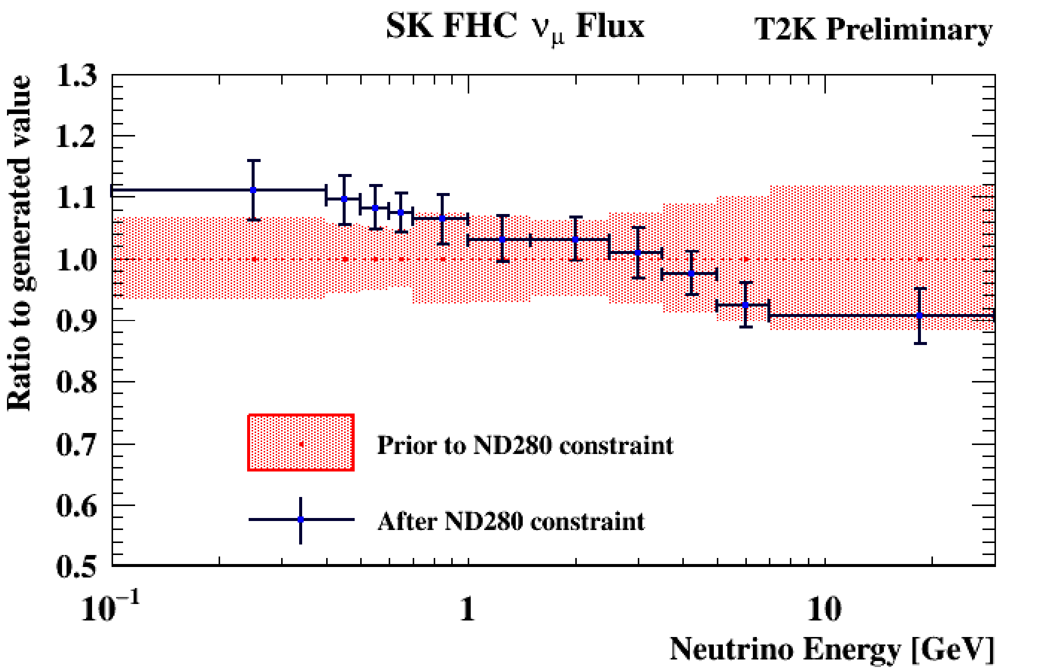


Initial idea:
- Start with the models from each experiment (without correlations)
- Add correlations when updates for Honda and Bartol models become available

Flux uncertainties
T2K

- Uncertainty parameterized as a function of energy for the different flavors of neutrino
- Different contributions, hadron interaction uncertainties dominant at most energies
- Use NA61/Shine data to tune prediction and reduce uncertainties
  Use of replica target data allowed to significantly reduce uncertainty in new analysis
- Near detector allows to further tune predictions and reduce uncertainties on flux at SK

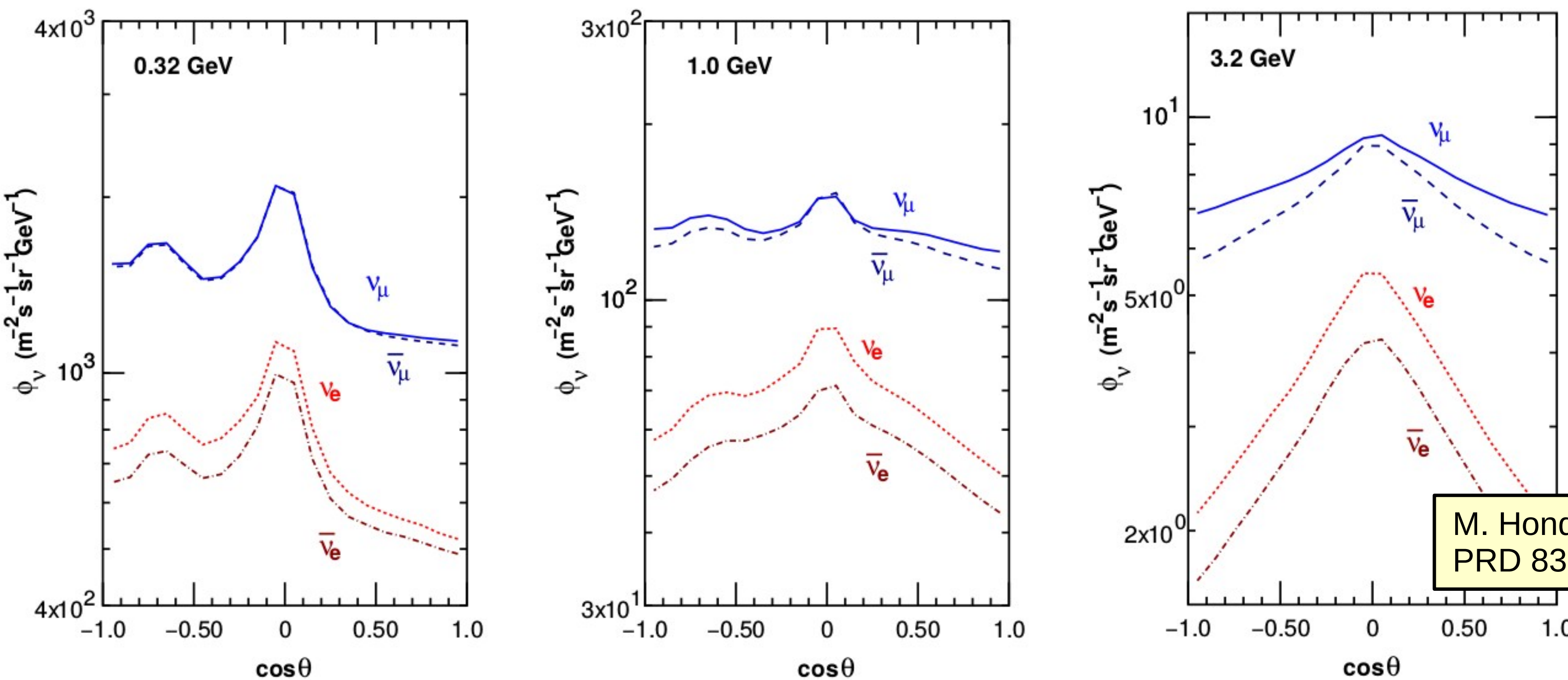




Systematic uncertainties Super-Kamiokande

SK atmospheric: no near detector, but can use up/down symmetry at high energy (MH):
- flux is approximately up/down symmetric at high energy
- Down-going high energy neutrinos did not have time to oscillate

=> main concern becomes up/down asymmetric effects



M. Honda et al. PRD 83 (2011)

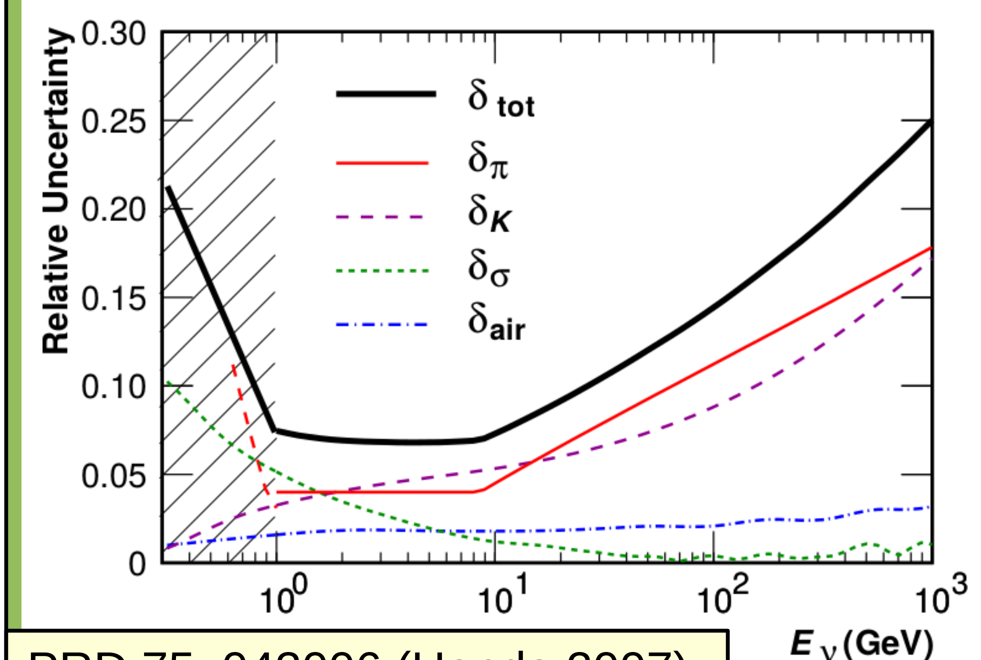
Not expected to work as well for sub-GeV events (sensitive to δ_{CP})
=> extra constraint on systematic uncertainties potentially interesting

Flux uncertainties
Super-Kamiokande

Combination of
- Overall normalization systematics
- Ratio systematics for flux contents ($(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$, $\bar{\nu}_e/\nu_e$, $\bar{\nu}_\mu/\nu_\mu$) and directions (up/down, horizontal/verical).
- Additional systematics for K/π parents, solar activity and production height

Normalization systematics

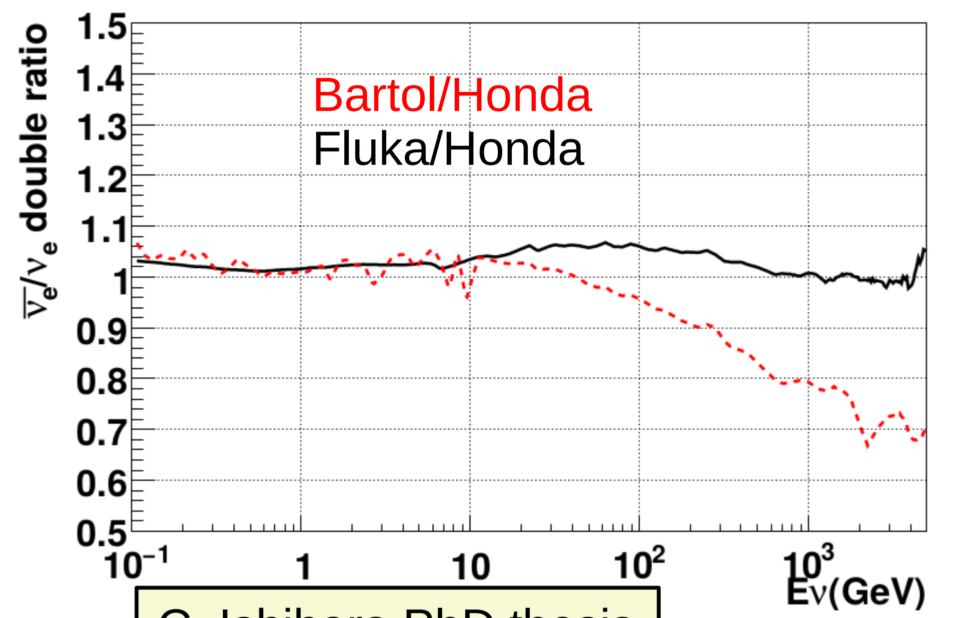
Based on δ_π and δ_σ from Honda 2007



PRD 75, 043006 (Honda 2007)

Ratio systematics

Comparison with Bartol (PRD70, 0423006 (2004)) and Fluka (Astropart. Phys 19 269 (2003)) models



C. Ishihara PhD thesis

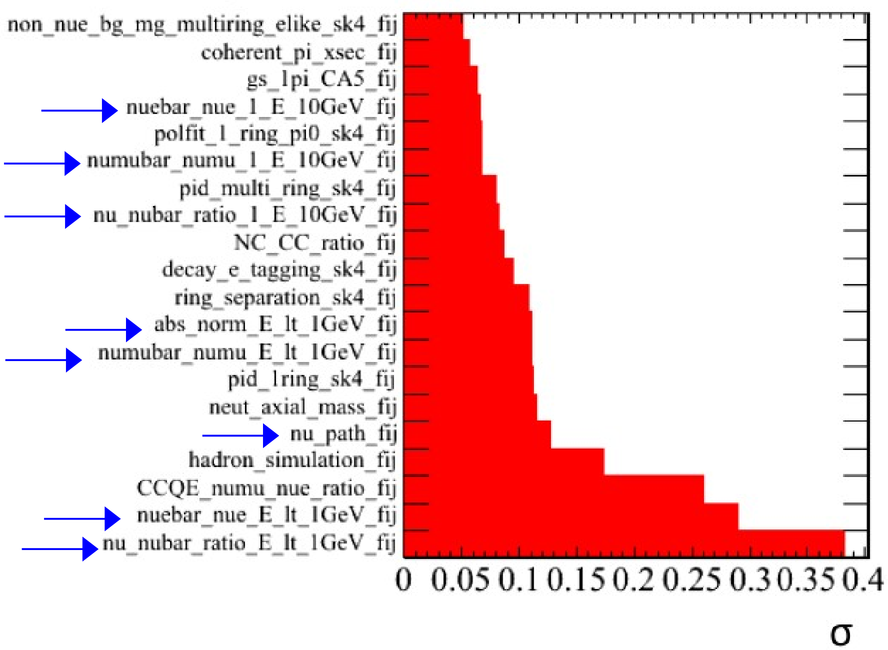
Effect of atmospheric flux uncertainties CP symmetry (SK atmospheric only)

- Effect of the different systematic uncertainties was studied a few years ago, for current SK and high statistics case (scaled to 10 year Hyper-K)
- For CP violation, sensitivity comes from comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ via number of up-going e-like events in sub-GeV region
- Uncertainties on muon to electron flavor ratio, and ν_e to $\bar{\nu}_e$ ratio particularly relevant

Ability to reject δ_{CP}=0 if true δ_{CP}=-π/2

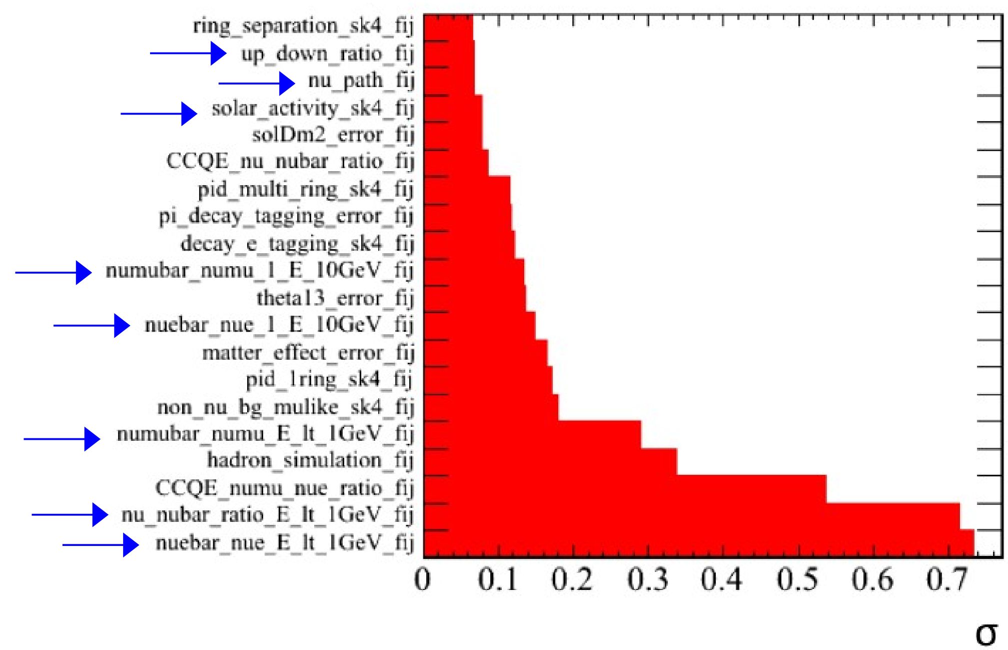
Super-Kamiokande

Effect of removing individual syst. on $\Delta\chi^2$



Scaled to 10 years HK

Effect of removing individual syst. on $\Delta\chi^2$



nuebar_nue_E_lt_1GeV ≡ $\bar{\nu}_e/\nu_e$ ratio for $E_\nu \leq$1GeV

nu_nubar_ratio_E_lt_1GeV ≡ $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ ratio for $E_\nu \leq$1GeV

→ : Flux uncertainty

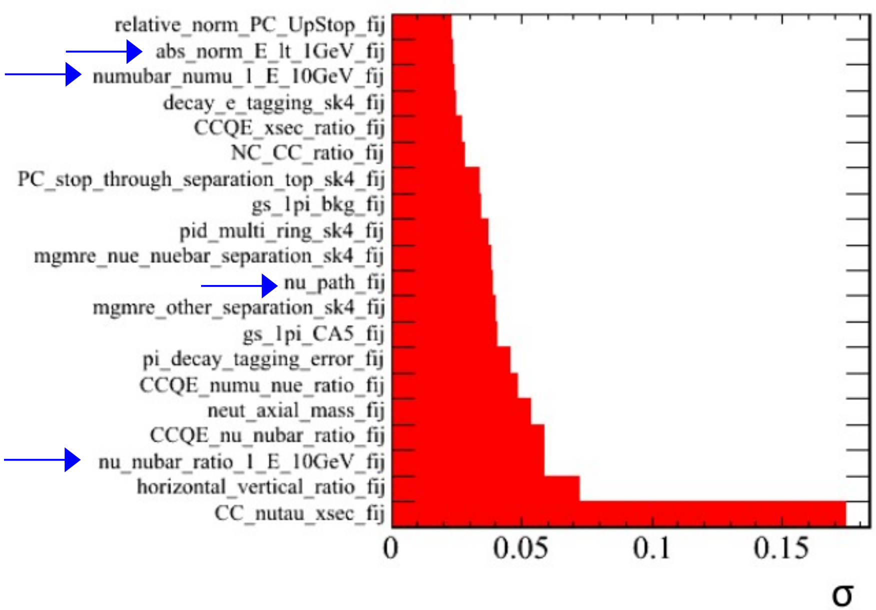
Effect of atmospheric flux uncertainties Mass hierarchy (SK atmospheric only)

- For MH, important uncertainties are currently normalization of up/down asymmetric effects (ν_τ) and size of the resonance (θ_{13}, matter effects) at higher statistics
- Surprisingly, uncertainty of flux up/down ratio does not appear. Constrained by low energy events?
- Overall flux uncertainties less important for MH than for CP symmetry

Ability to reject IH if true NH

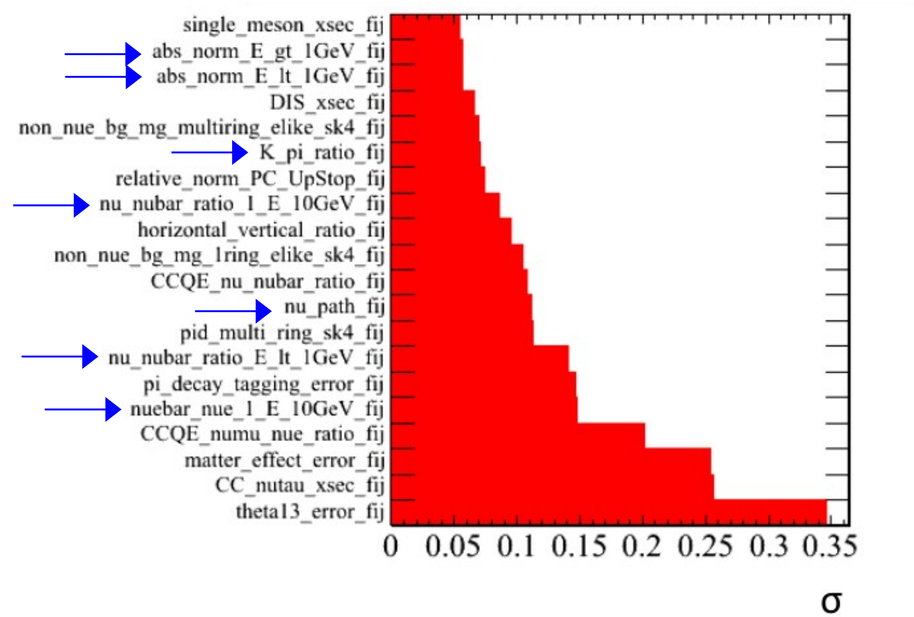
<u>Super-Kamiokande</u>

Effect of removing individual syst. on $\Delta\chi^2$



<u>Scaled to 10 years HK</u>

Effect of removing individual syst. on $\Delta\chi^2$



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nu_nubar_ratio_1_E_10GeV ≡ $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ ratio for $1 \le E_\nu \le 10$GeV

→ : Flux uncertainty

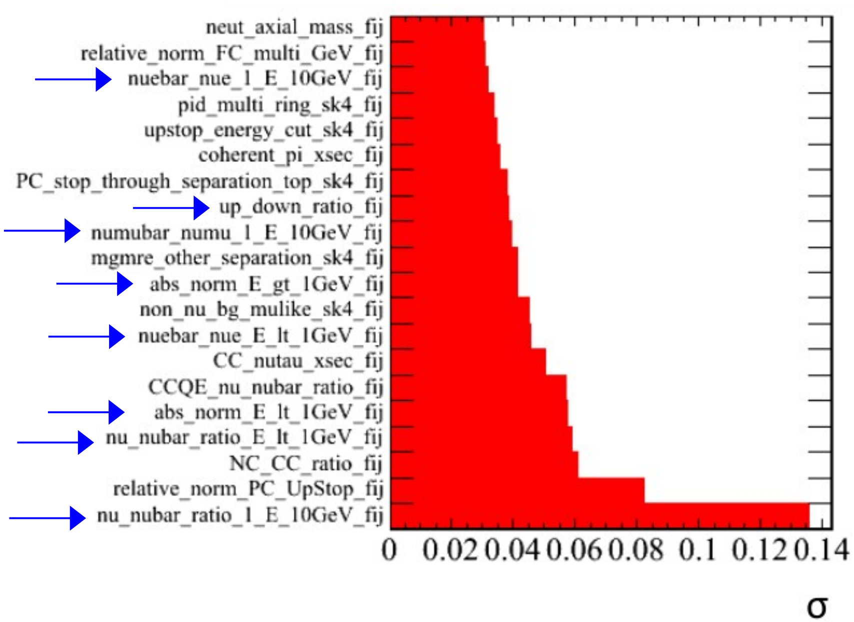
Effect of atmospheric flux uncertainties θ_{23} octant (SK atmospheric only)

- Sensitivity to octant comes mostly from resonance due to matter effect.
  Impact on number of e-like (through $\nu_\mu \rightarrow \nu_e$) and μ-like ($\nu_\mu \rightarrow \nu_X$) multi-GeV events
- Some small additional contribution in the sub-GeV region
- Uncertainty on flavor ratio in multi-GeV region has a significant impact

Ability to reject $\sin^2(\theta_{23})>0.5$ if true $\sin^2(\theta_{23})=0.45$

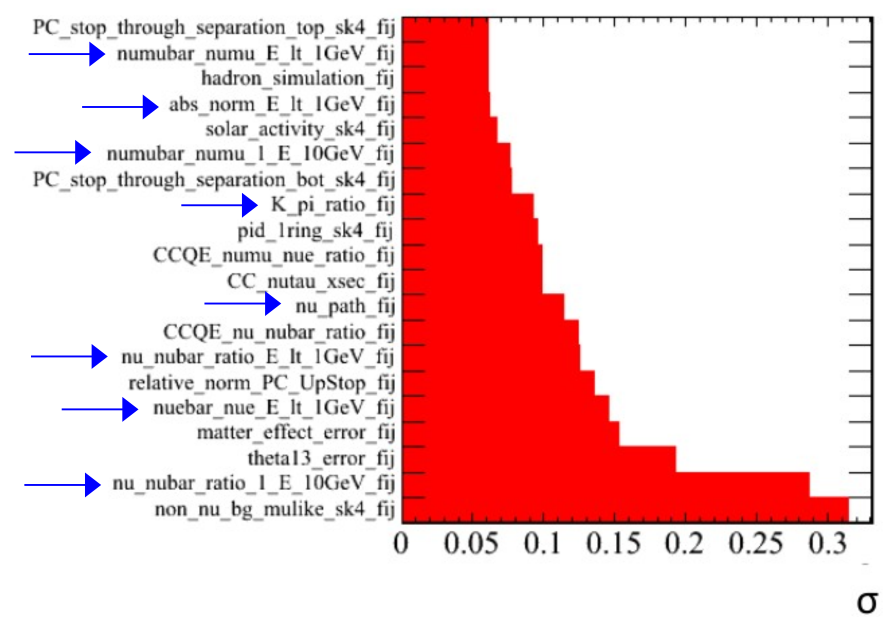
<u>Super-Kamiokande</u>

Effect of removing individual syst. on $\Delta\chi^2$



<u>Scaled to 10 years HK</u>

Effect of removing individual syst. on $\Delta\chi^2$



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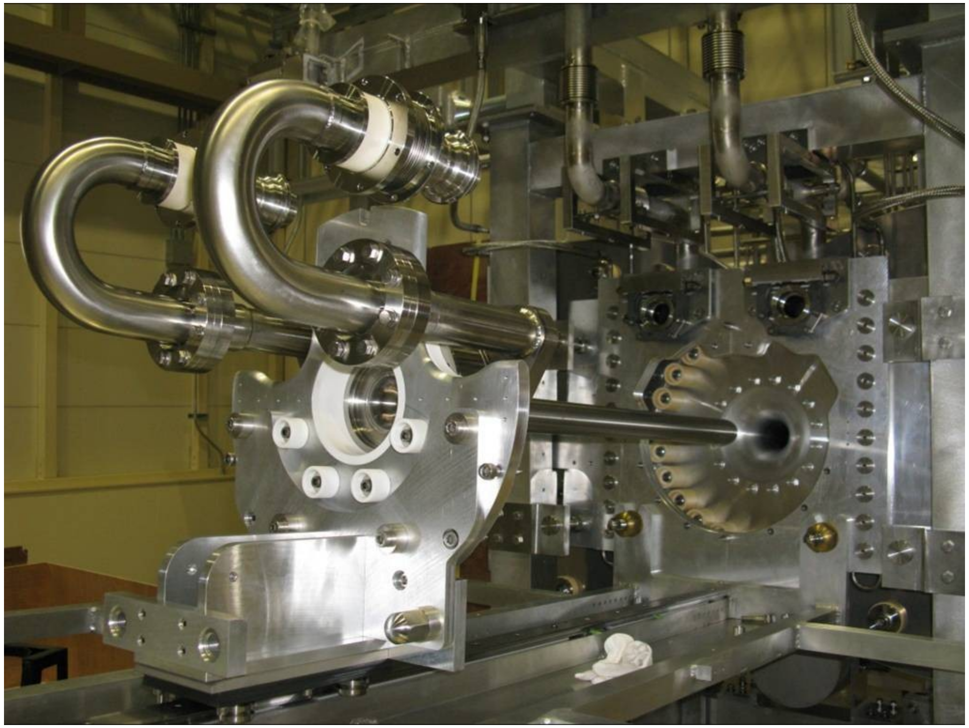
nu_nubar_ratio_1_E_10GeV ≡ $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ ratio for $1 \leq E_\nu \leq 10$GeV

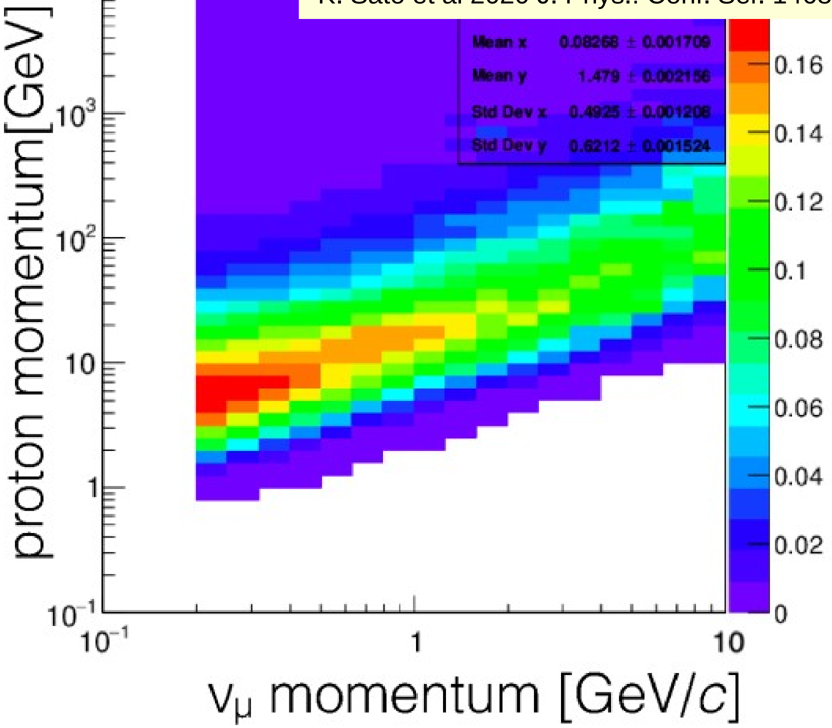
→ : Flux uncertainty

Correlated flux systematics
Thoughts/questions

- Question of correlation between atmospheric flux clearly relevant for this joint fit
- Component for which we expect correlations is hadron production
- Both T2K and updates on atmospheric models tuned to hadron production experiments, but:
  - T2K has re-interaction in large target and is tuned on replica target data
  - Range of energies contributing different



K. Sato et al 2020 J. Phys.: Conf. Ser. 1468 012194

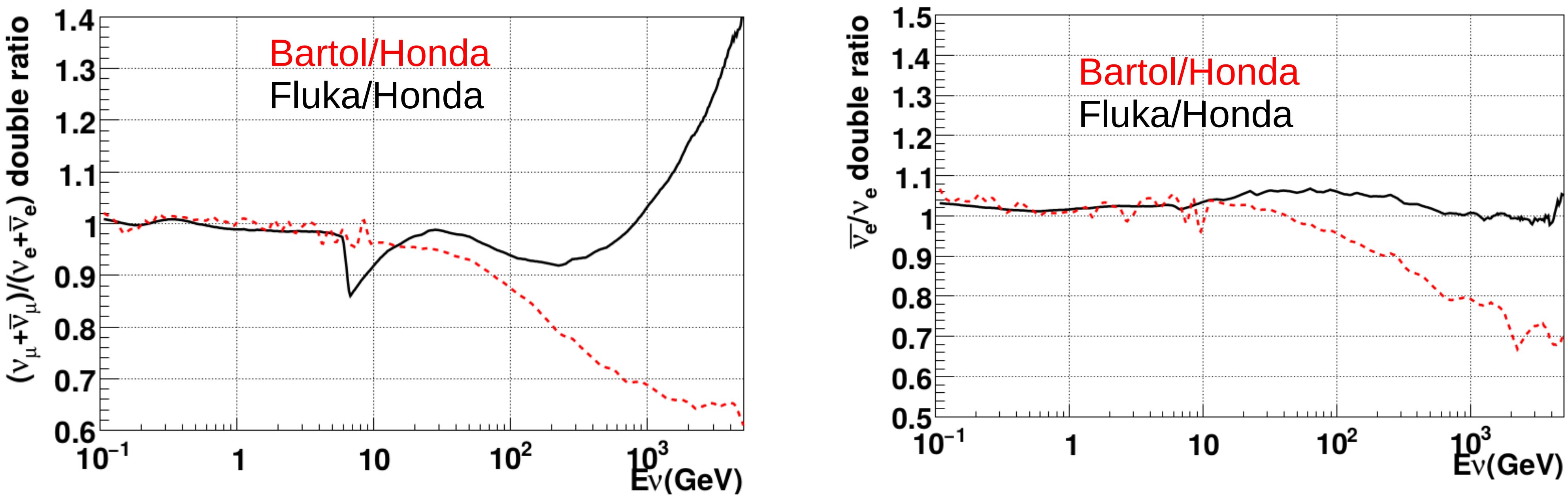


Can we have a common model or correlations between models for hadronic interaction part?

Correlated flux systematics
Thoughts/questions

Based on SK studies, most relevant atmospheric flux systematics are about content rather than normalization, in particular $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ and $\bar{\nu}_e/\nu_e$ ratios

Currently estimated in SK using model comparisons



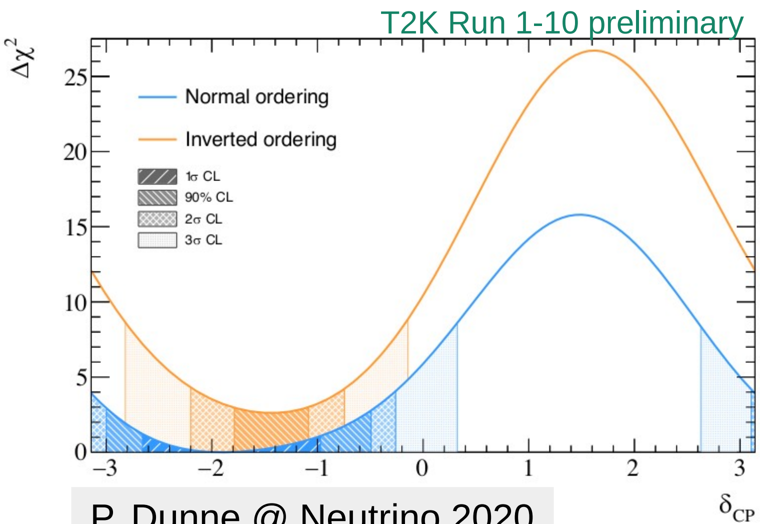
C. Ishihara PhD thesis

Not obvious how to extract a component of this systematic coming from hadronic interactions that could be correlated with beam flux hadron production uncertainties

Need new approach?

Summary

- Work started on a simultaneous analysis of T2K and Super-K atmospheric data to study neutrino oscillations with increased precision



P. Dunne @ Neutrino 2020

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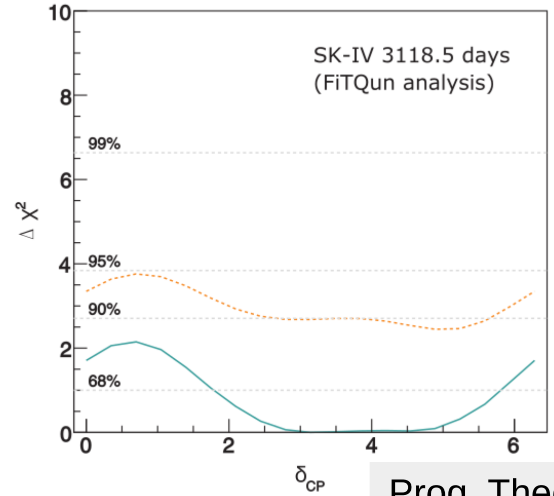


= ?

(note: different x axis conventions)

Prog. Theor. Exp. Phys. 2019, 053F01

- Initially starting studies with flux model from each experiment

- Studies in SK indicate that most relevant atmospheric flux uncertainties are muon to electron flavor ratio, and $\bar{\nu}_e/\nu_e$ ratio.
  Important for study of CP symmetry and octant of θ_{23}, less for the mass hierarchy

- In the longer term, question of a unified model for hadron interactions and correlation of flux uncertainties between beam and atmospheric neutrinos relevant
  Not clear it would be easy to directly correlate uncertainties between the models used by the 2 experiments

BACKUP

Neutrino oscillations Parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

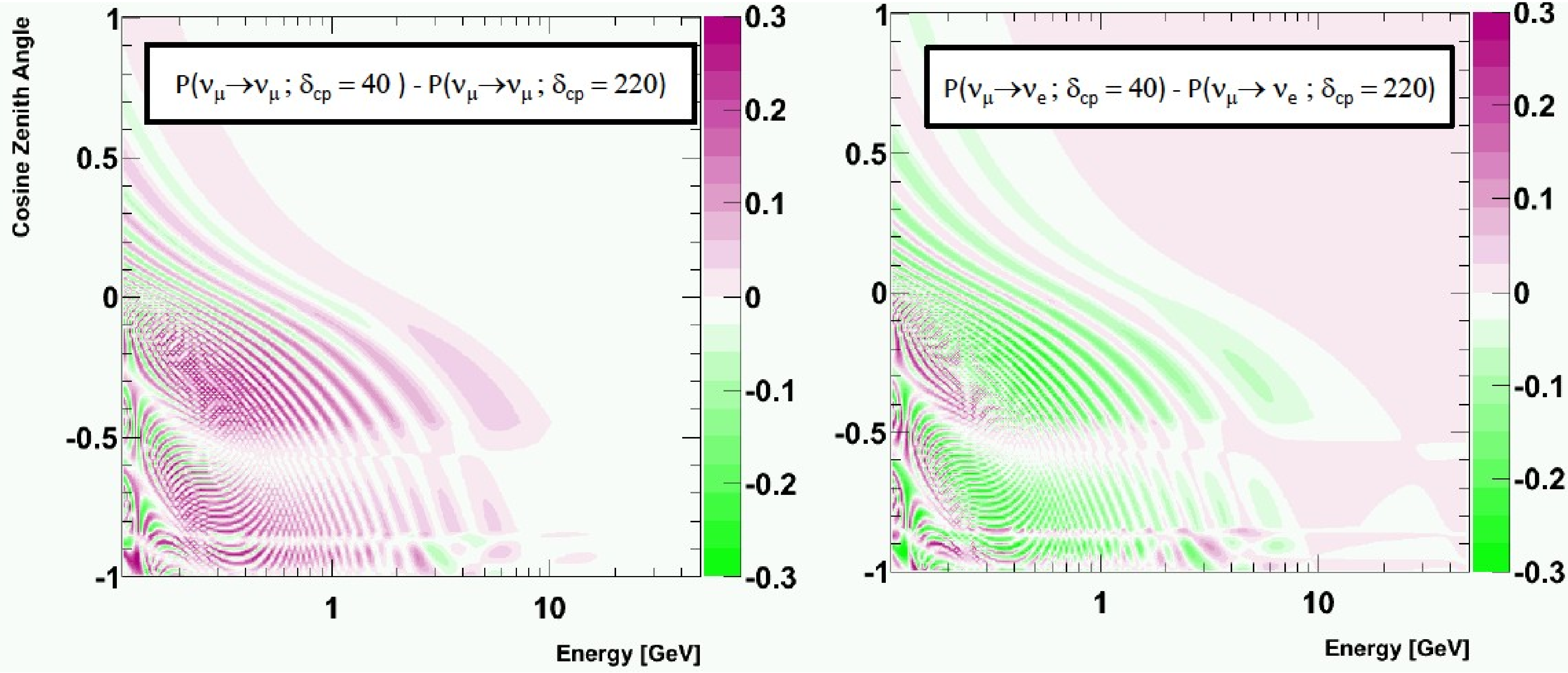
($c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$)

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : **θ_{12}, θ_{23}, θ_{13}** → Amplitude
- 2 **mass splittings** : **Δm^2_{ij}** → Periodicity
- 1 (complex) phase : The **CP phase δ** → Difference in oscillations $\nu/\bar{\nu}$

Atmospheric neutrino oscillations
Delta CP

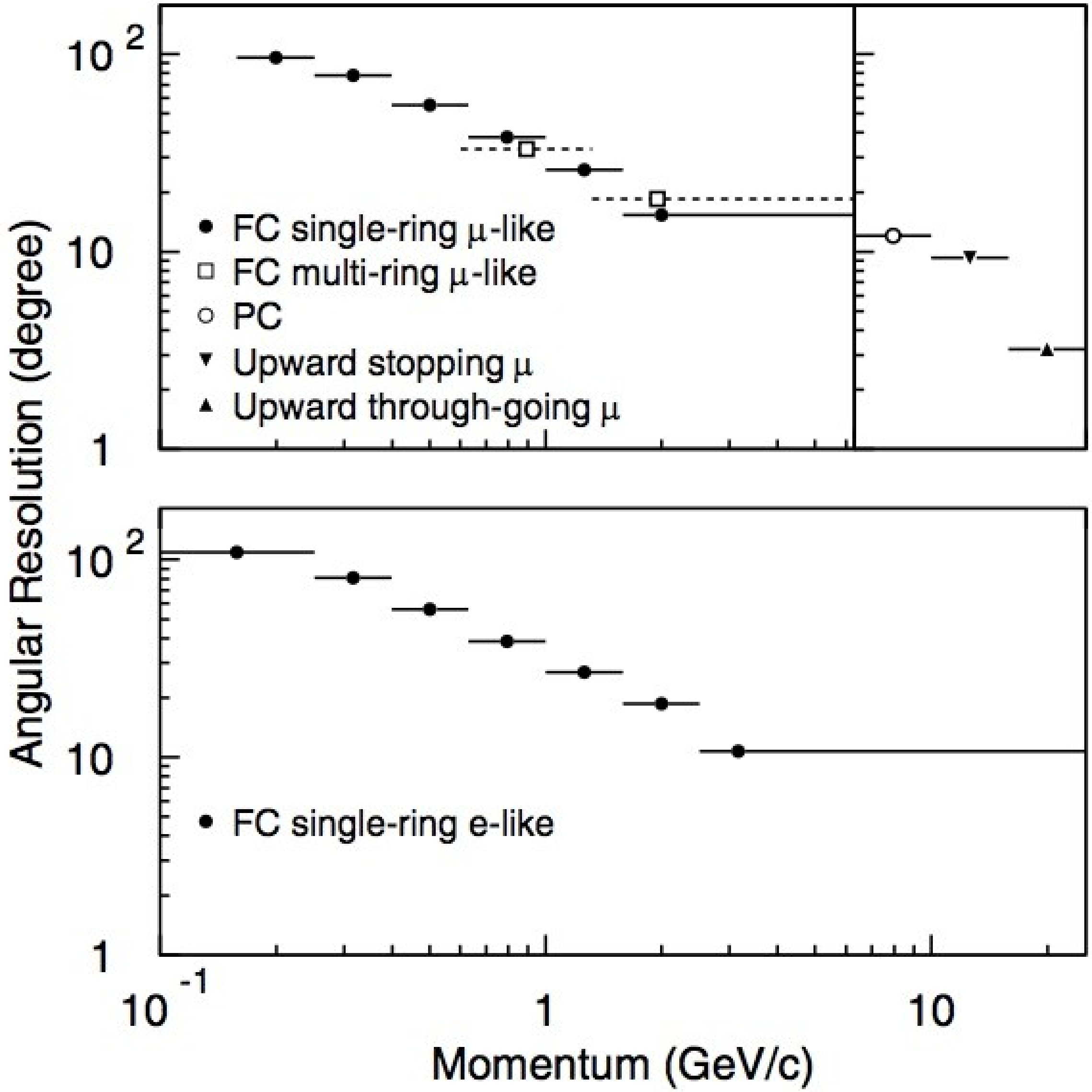
Value of δ_{CP} modifies the oscillation patterns in a complicated way



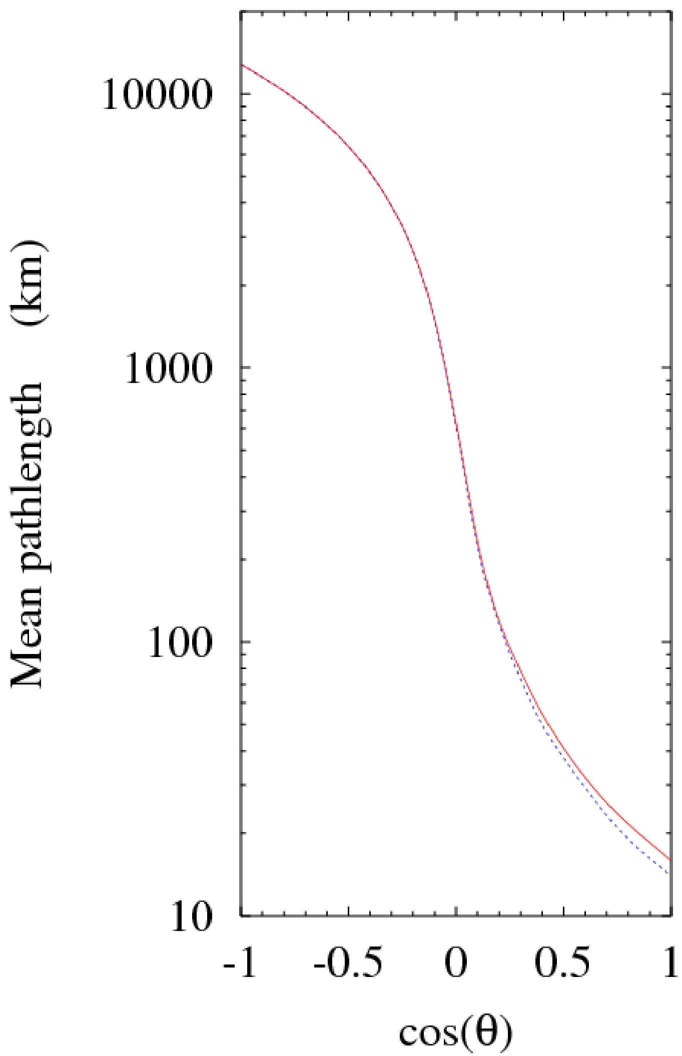
- Given neutrino flux and detector energy and angular resolution, sensitivity mainly comes from number of sub-GeV e-like events
- More ν_e appearance events for δ~220-240º, and less for δ~40-45º

Angular resolution

PRD71, 112005 (2005)



Relation between L and cos(θz)



Super-K analysis with external constraints
Model of the T2K experiment

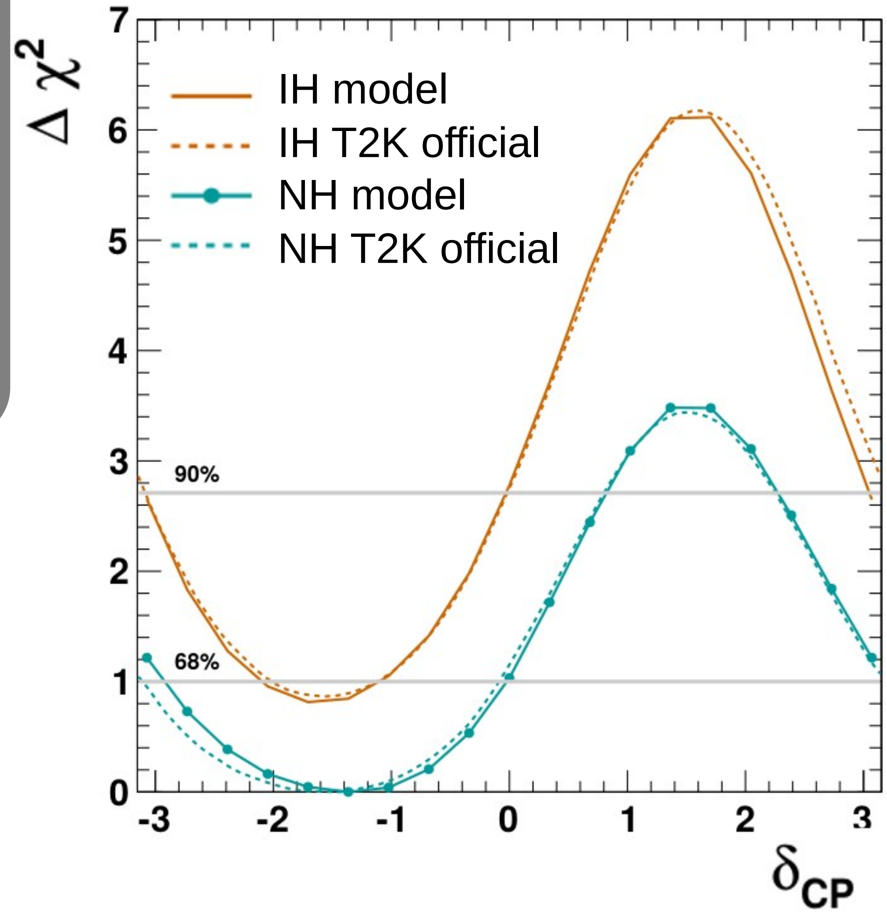
NOT a joint analysis between the 2 collaborations. Use SK tools to build a model of T2K and fit data based on publicly available information

- Neutrino interaction generator and detector simulation common between the experiments → **reweight atmospheric MC to mimic T2K flux**
- Systematic uncertainties :
  -interaction and detector fully correlated
  -flux uncorrelated
- Propagate published results of near detector fit for interaction and beam flux parameters

Uses T2K data and analysis from PRD 91, 072010 (2015) – not latest results

- 6.57e20 POT in ν-mode
- No $\bar{\nu}$-mode data
- No appearance CC1π sample
- Appearance samples binned in E_{rec}
- Not using new reconstruction and FV

Model reproduces well official results



Super-K analysis sensitivity
Mass hierarchy

- Sensitivity of the the SK atmospheric analysis to determine the mass hierarchy with 2 different reconstruction algorithm: fiTQun and APFit
- Joint fit will be based on fiTQun with expanded Fiducial Volume analysis

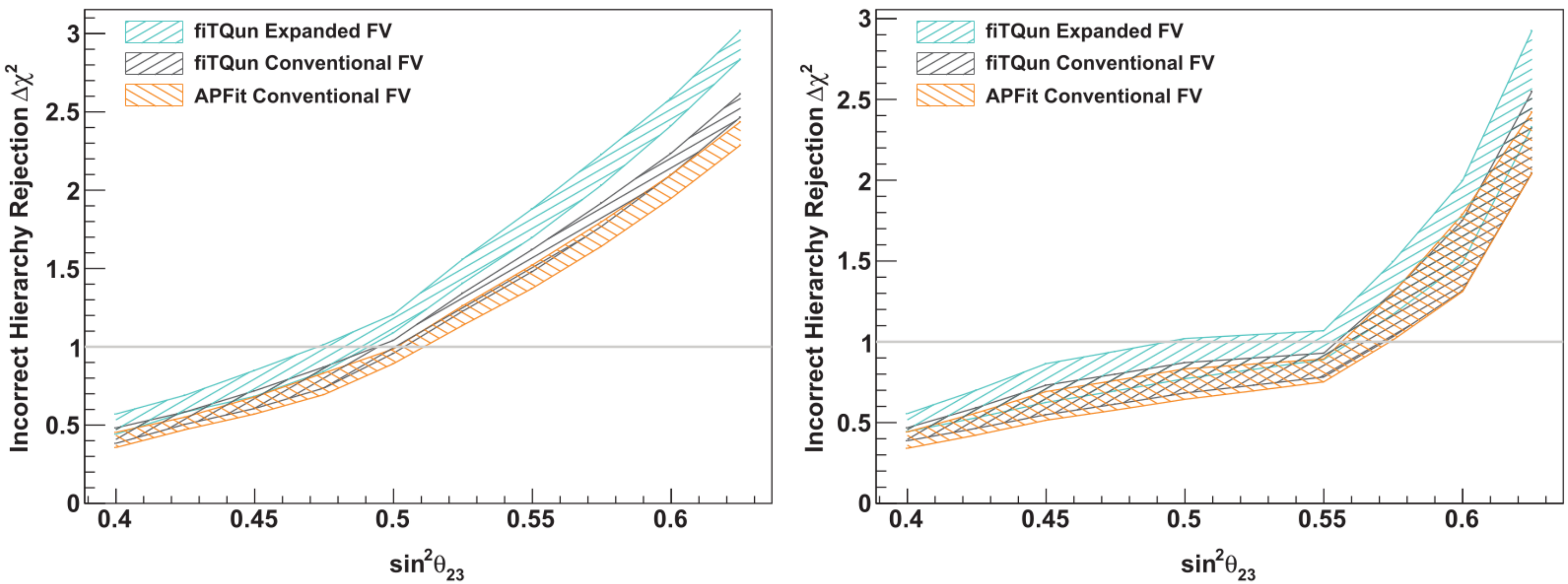


Fig. 22. Expected sensitivity to the normal mass hierarchy (left) and inverted hierarchy (right) as a function of the true value of $\sin^2\theta_{23}$. Here $\sin^2\theta_{13} = 0.0210 \pm 0.0011$ and the assumed livetime is 3118.5 days. Gray and blue bands show the sensitivity of the analysis with event samples reconstructed with fiTQun in the conventional FV and expanded FV, respectively. Orange lines denote the sensitivity when events are reconstructed using the APFit algorithm with the conventional FV. The widths of the bands correspond to the uncertainty from δ_{CP}.

M. Jiang et al, Prog. Theor. Exp. Phys. 2019, 053F01

Super-K analysis sensitivity θ_{23} octant

- Sensitivity of the the SK atmospheric analysis to determine the θ_{23} octant for 2 different reconstruction algorithms: fiTQun and APFit
- Joint fit will be based on fiTQun with expanded Fiducial Volume analysis

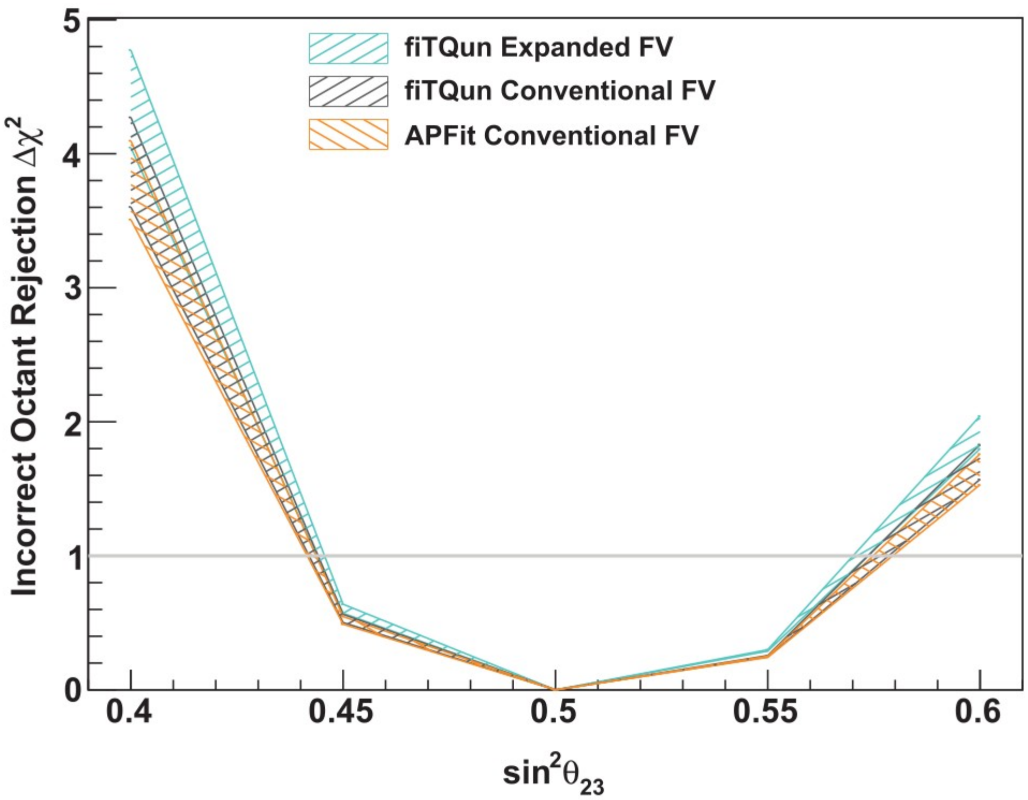


Fig. 23. Expected sensitivity to rejecting the wrong octant as a function of the true value of $\sin^2\theta_{23}$ for the true normal mass hierarchy. The other conditions are the same as in Fig. 22.

M. Jiang et al, Prog. Theor. Exp. Phys. 2019, 053F01