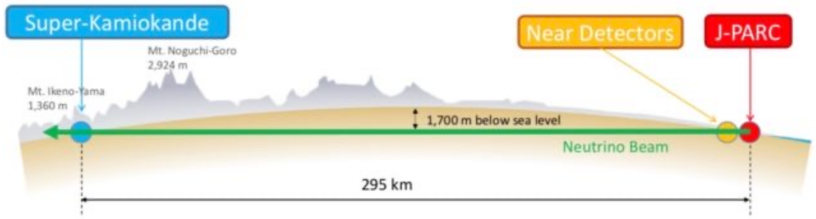
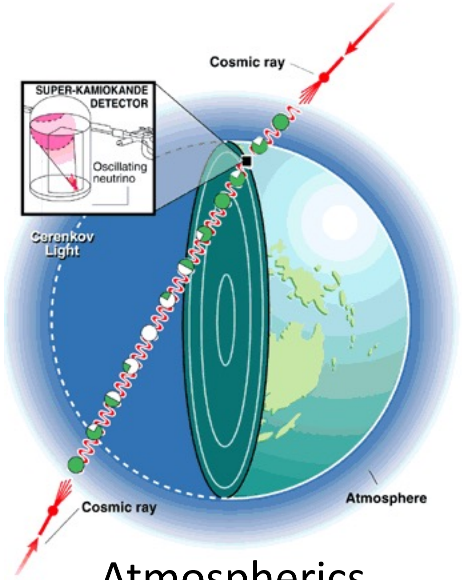
T2K+SK Joint Beam and Atmospheric Fit



Beam

+



Atmospherics

Dan Barrow

daniel.barrow@physics.ox.ac.uk

10/11/2021

Introduction

This analysis uses SK-IV period only

Aim: Produce a joint oscillation analysis of the T2K beam and the SK-IV atmospheric samples, using the analysis inputs and systematic errors already generated by the two experiments.

- MoU signed between T2K and SK June 2019

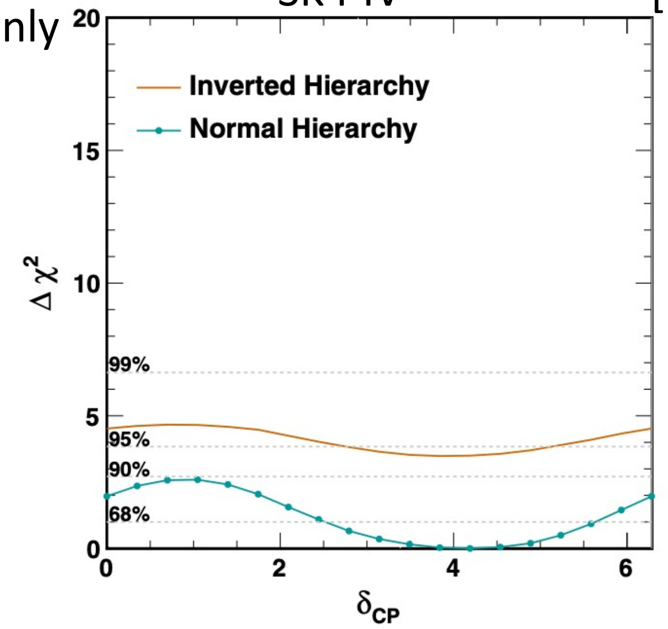
Expect sensitivity increase due to statistics increase and resolving oscillation effects from simultaneous constraint of parameters, e.g.:

- Sensitivity to Mass ordering dependent on size of matter resonance which depends on θ_{23} and δ_{cp} which are well constrained by T2K experiment

Analysis still preliminary - focus on some methodology and developments which have been made for the joint fit:

- Implementation of oscillation calculation
- Correlated detector response between beam and atmospheric samples

SK I-IV [1]



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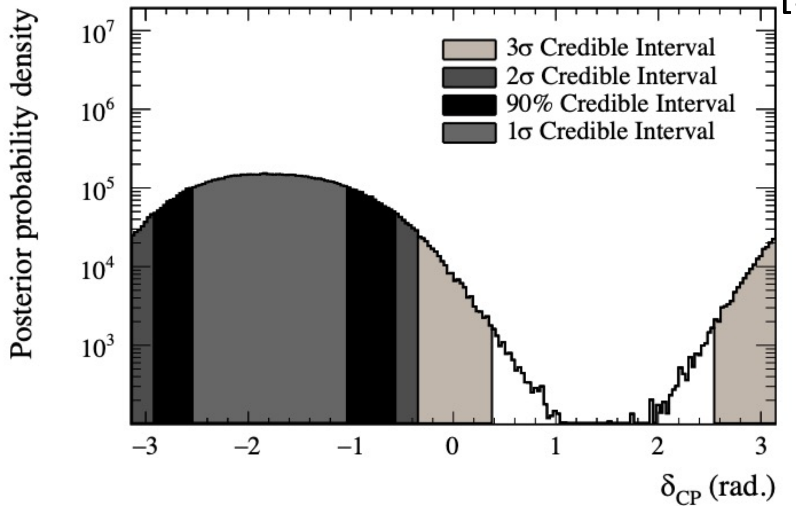
T2K Run 1-10 Preliminary [2]



T2K Analysis

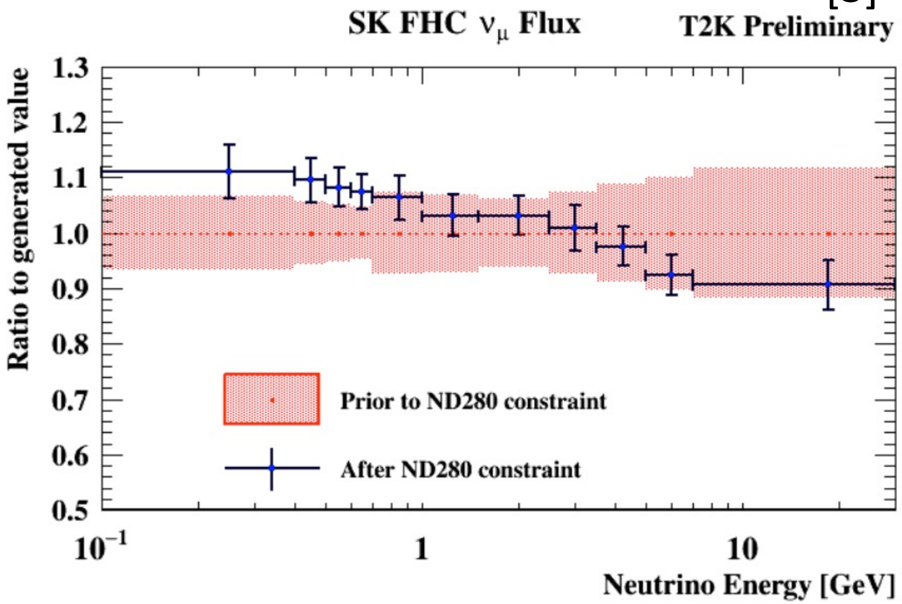
Neutrinos generated from interactions of proton beam on target

- Observed by suite of near detectors at 280m baseline
- Selections depend on subdetector, neutrino beam mode and pion information
- Similar neutrino energy and interactions as beam and atmospheric samples

Used to constrain beam flux and cross section model which is extrapolated to samples at SK

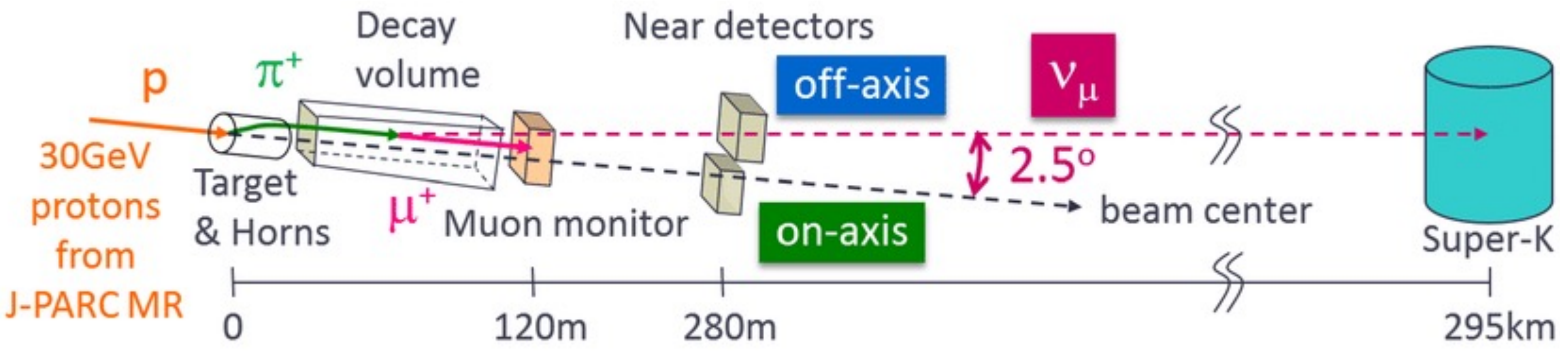
- Approx 40 cross section, 50 far detector flux parameters constrained

[3]

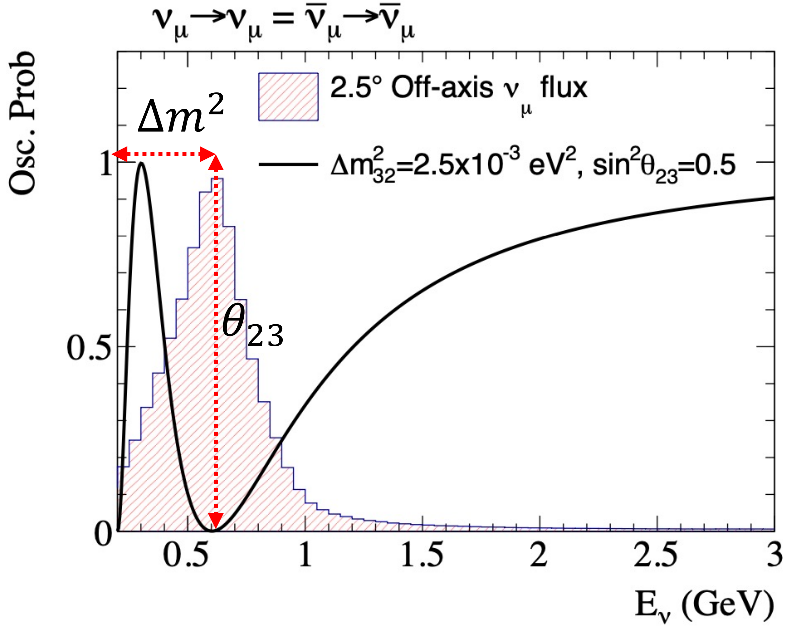


Detectors are situated off-axis with respect to beam direction:

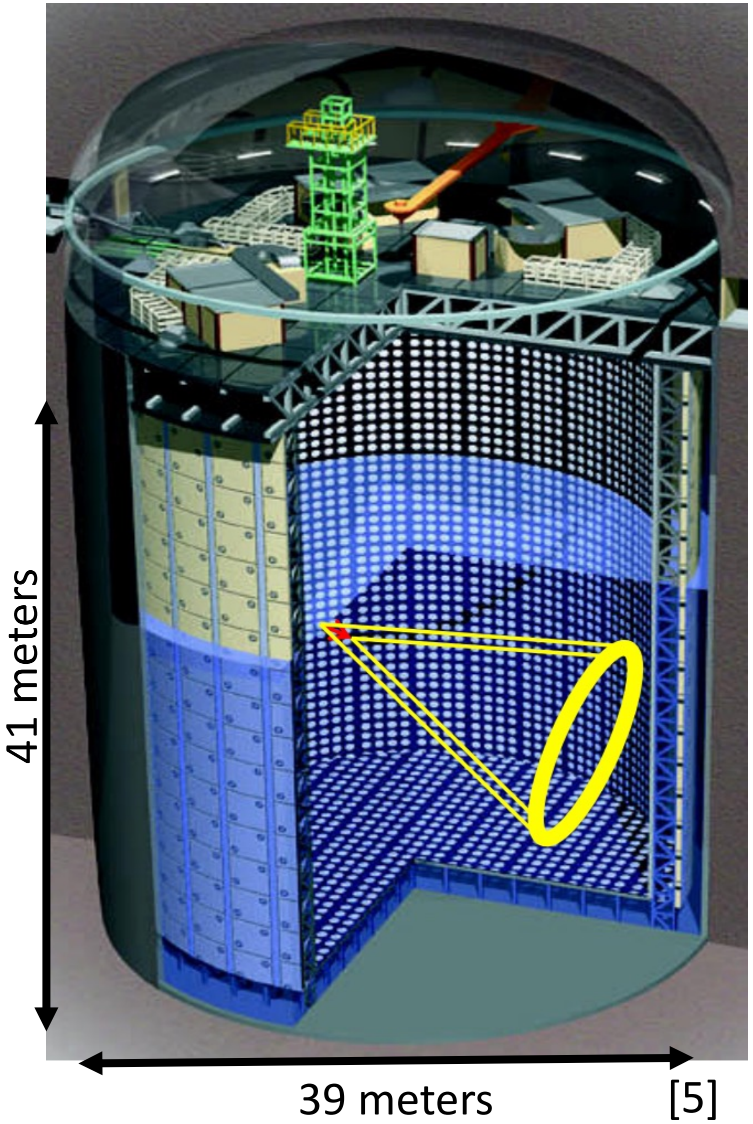
- Generates peaked flux around first oscillation dip



[4]



Super Kamiokande Detector



[5]

50 kton water Cherenkov detector located in Kamioka observatory

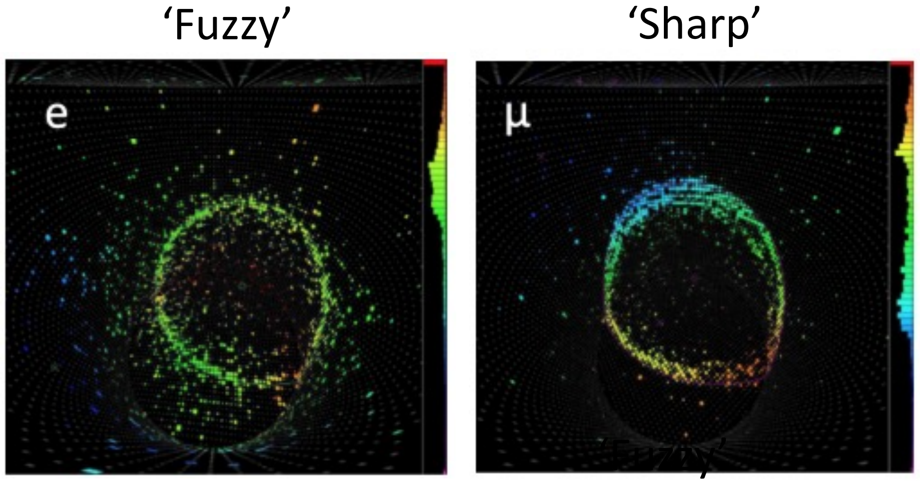
- >11,000 PMTs in inner detector

Wide array of neutrino physics across broad energy spectrum:

- Reactor neutrinos
- Solar neutrinos
- Accelerator neutrinos
- Atmospheric neutrinos

MeV → GeV

Detection technique has no information on sign of charge deposited
→ neutrino/antineutrino separation not possible event by event



Lepton separation dependent on Cherenkov ring

Neutrino Flux

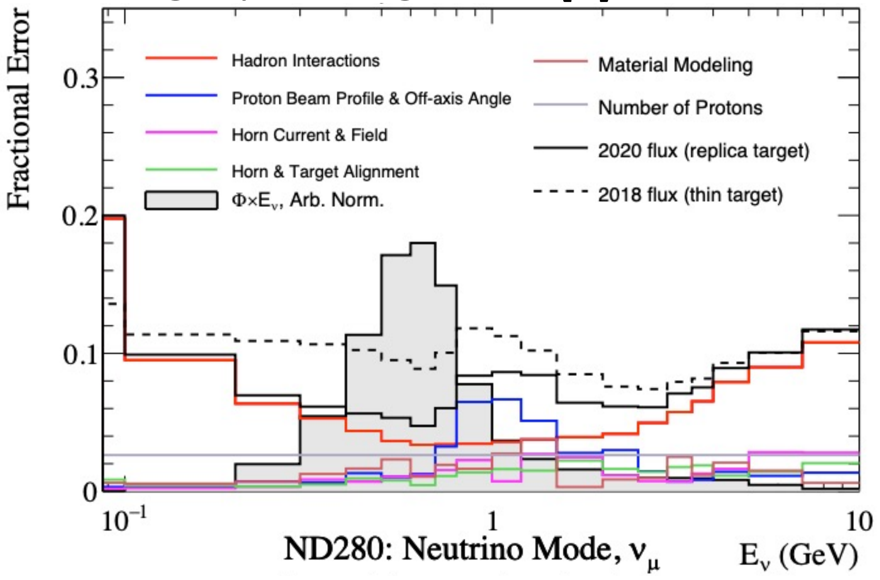
No clear method to correlate atmospheric and beam flux systematics

- Sufficient differences in energy, flux inputs and model, data constraints, target material, density, etc.
- Plan to use flux systematic models available from both experiments

Updates to neutrino flux models:

- Atmospheric neutrino flux (see L. Cook talk on Bartol model)
- Reduction in beam flux uncertainties using replica target
- Long term goal: Correlation of hadron production systematics between beam and atmospheric flux

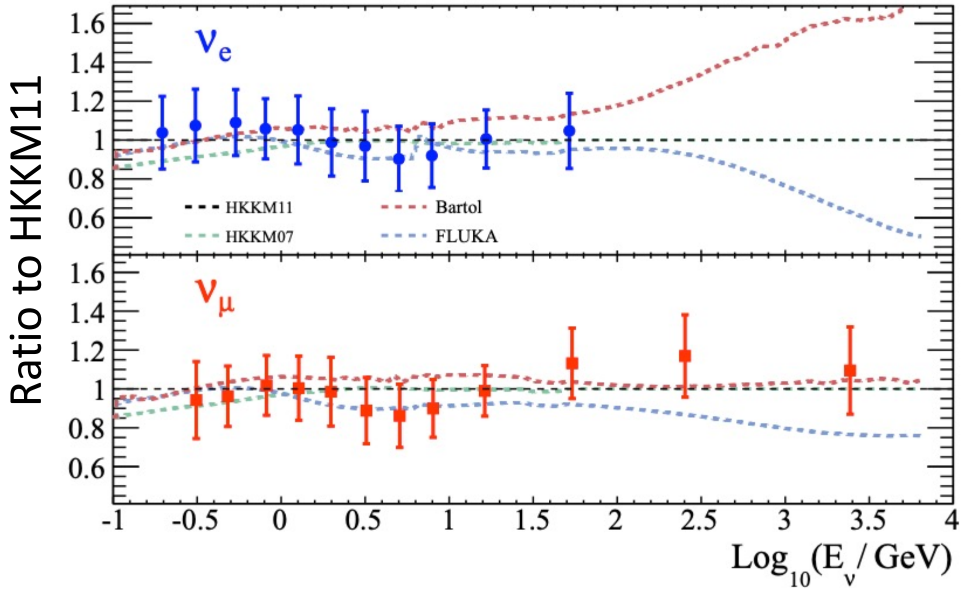
Recent analysis decreased the uncertainty of flux estimates using replica target data [2]



T2K

Flavor ratio flux systematics used in analysis are taken from ratio of models

SK



[6]

Atmospheric Neutrinos at SK

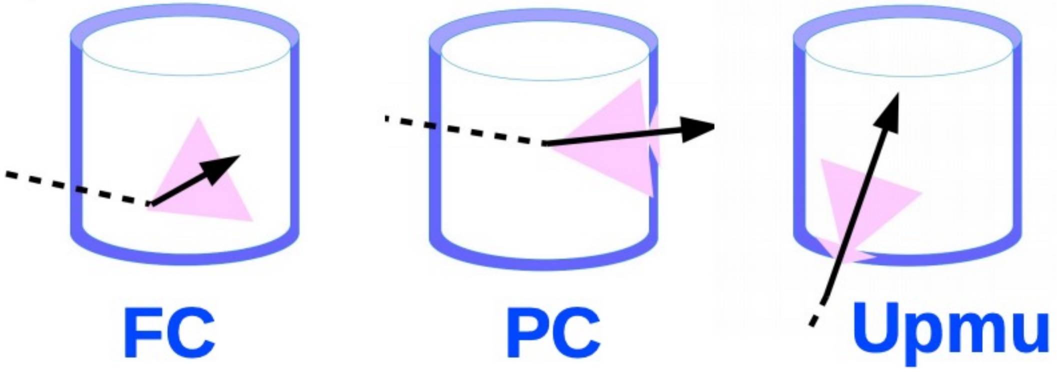
Fully Contained events separated into 13 samples depending on Energy, number of rings, PID and number of decay electrons

- Sub-GeV(Multi-GeV) events defined to have visible energy less(more) than 1.33GeV

Partially Contained events categorized by outer detector activity

Upward going Muon events split by outer detector activity and electromagnetic components

Atmospheric Sample Topologies:

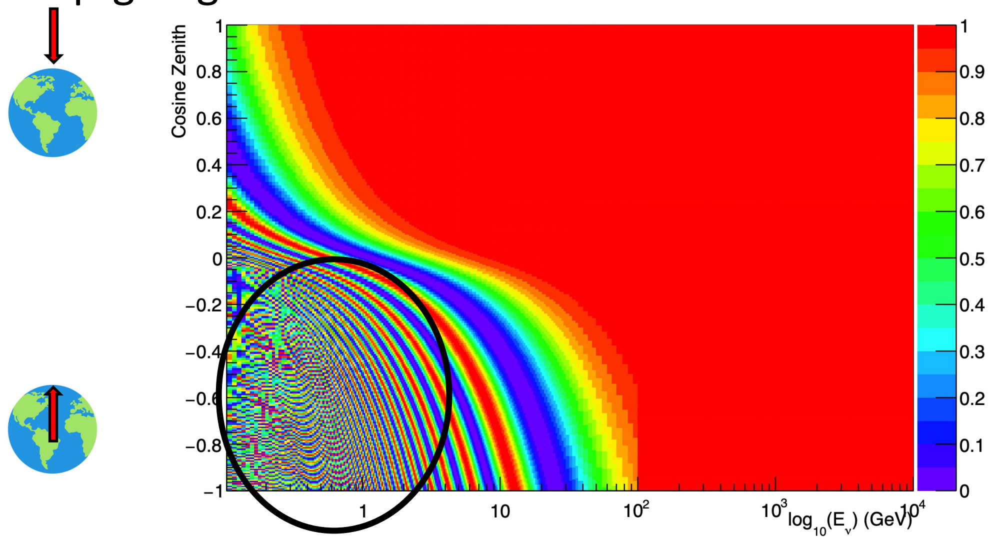


[7]

Event rate (per day):

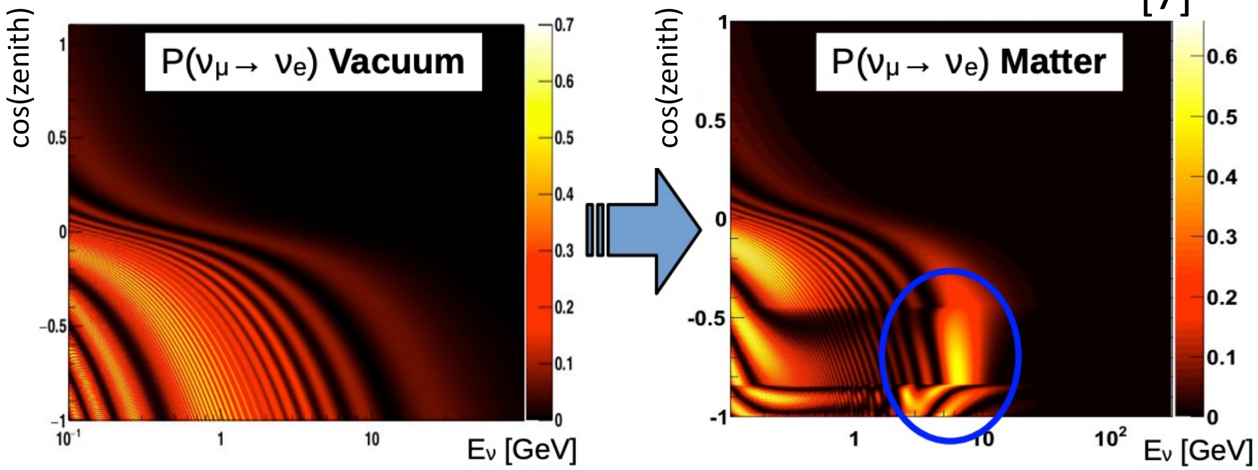
FC	PC	Upmu
8.3	0.7	1.5

Sensitivity to δ_{cp} comes from overall normalization of up-going events



Sensitivity to mass hierarchy comes from matter induced resonance

[7]

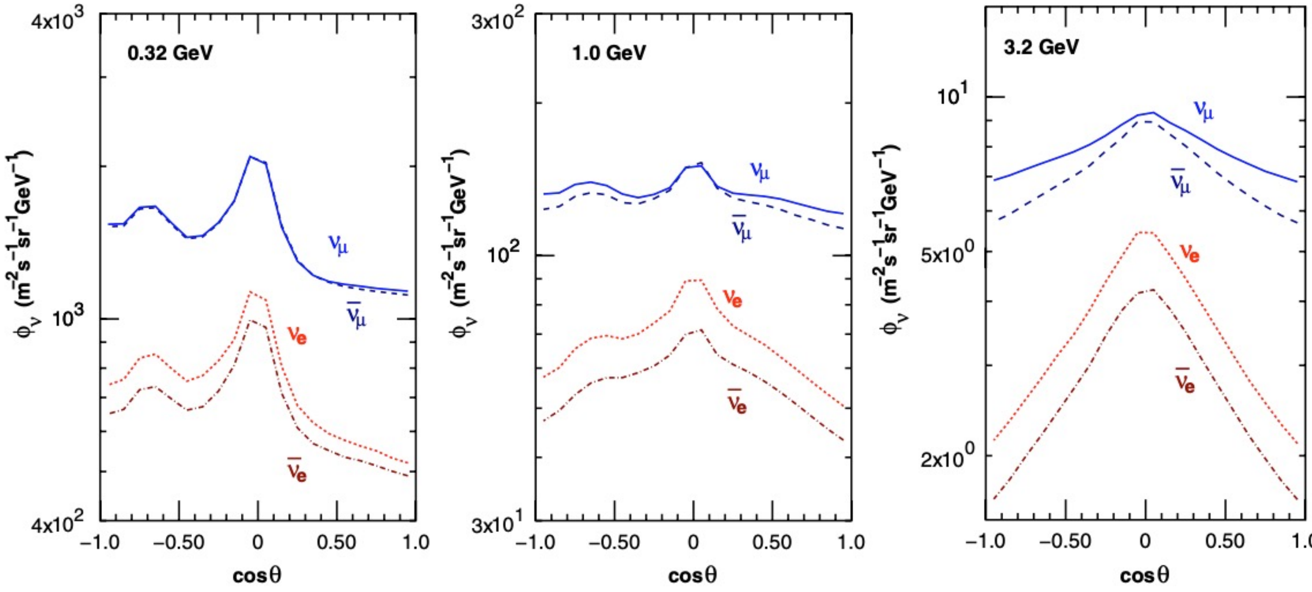


ν in normal MO, $\bar{\nu}$ in inverted MO, amplitude $\alpha\ \theta_{23}$

Atmospheric Neutrinos at SK

Bin events in momentum (related to neutrino energy) and cosine of zenith angle with respect to detector (related to propagation length):

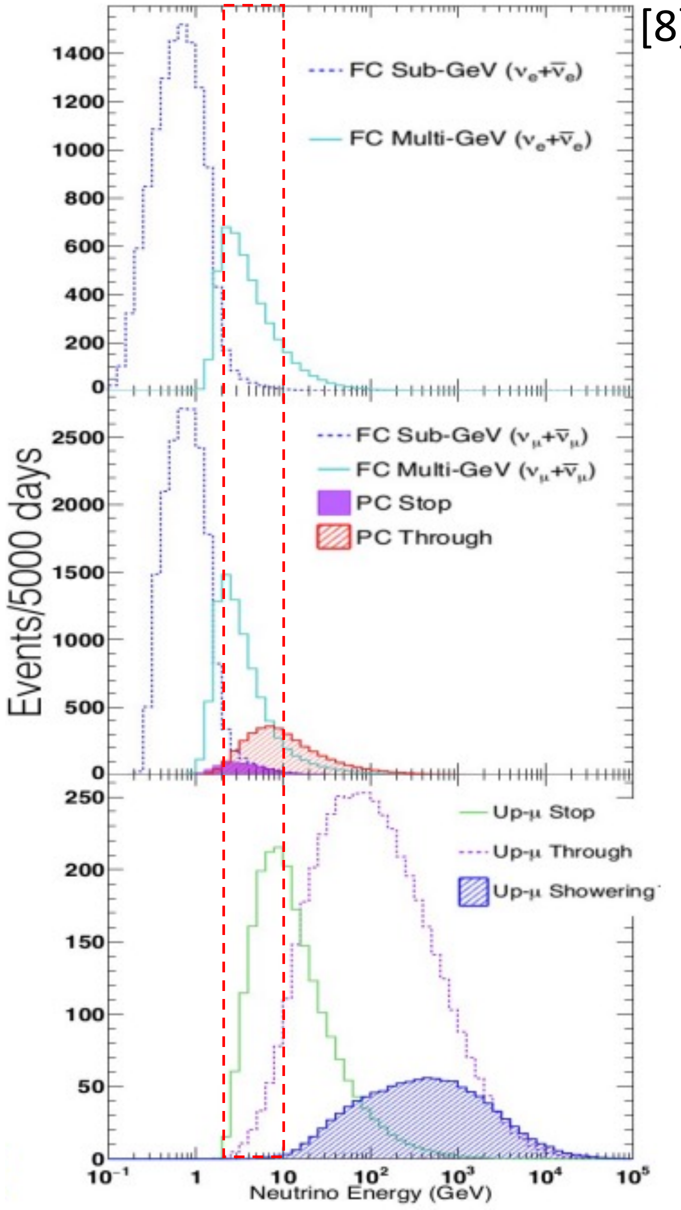
- Single-ring events use lepton candidate information
- Multi-ring events sum the momenta of each ring and use total momentum and direction



[9]

Flux is roughly up/down symmetric at high energy:

- Symmetric cosine zenith binning for systematic cancellation in this region



[8]

Mass resonance in 2 → 10 GeV region

Atmospheric Neutrinos at SK

From the T2K perspective, including atmospheric samples is challenging due to 2D oscillation probability

- Smearing of the fast oscillation wavelength → Avoid biases from MC statistical fluctuations
- Production height averaging → Include systematic on height of interaction (Methodology under review)

Recent SK analysis pre-calculates oscillation probabilities on grid of oscillation parameters

→ T2K analysis uses continuous oscillation parameters → oscillation probabilities have to be calculated 'on the fly'

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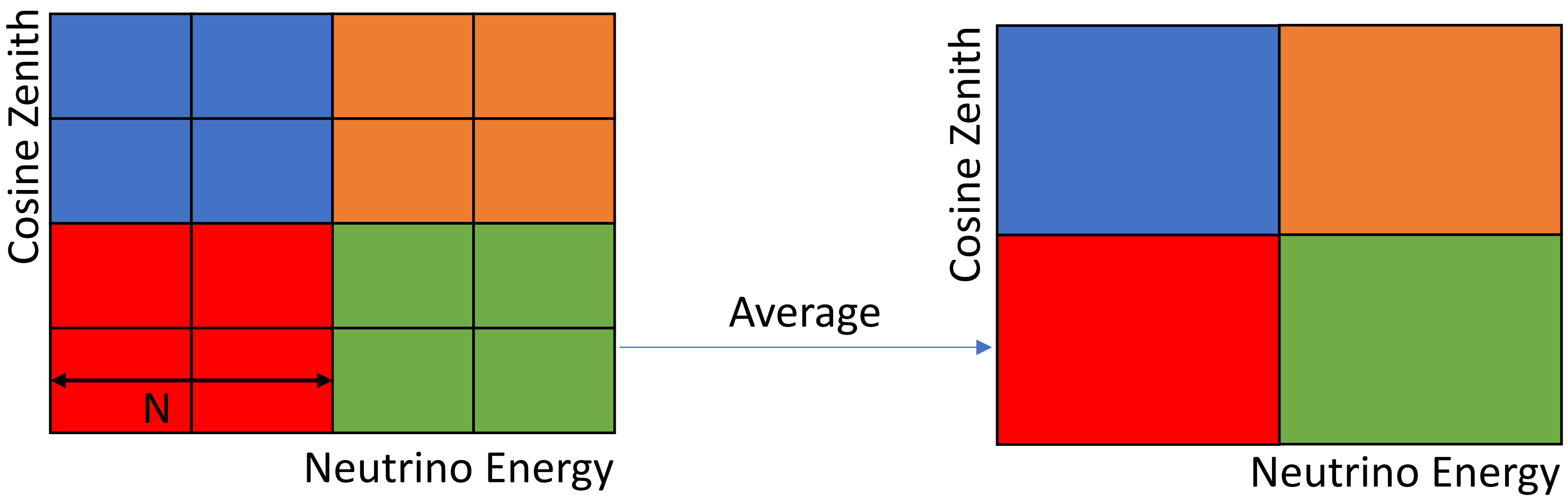
Considering binned sub-sample approach to average the oscillation probability structure:

Fine Oscillogram:

Calculate oscillation probabilities at center of bins in this sketch



Coarse Oscillogram:

Sample oscillation probabilities for event reweighting with points in this sketch

N sub-divisions per coarse oscillogram bin

Atmospheric Neutrinos at SK

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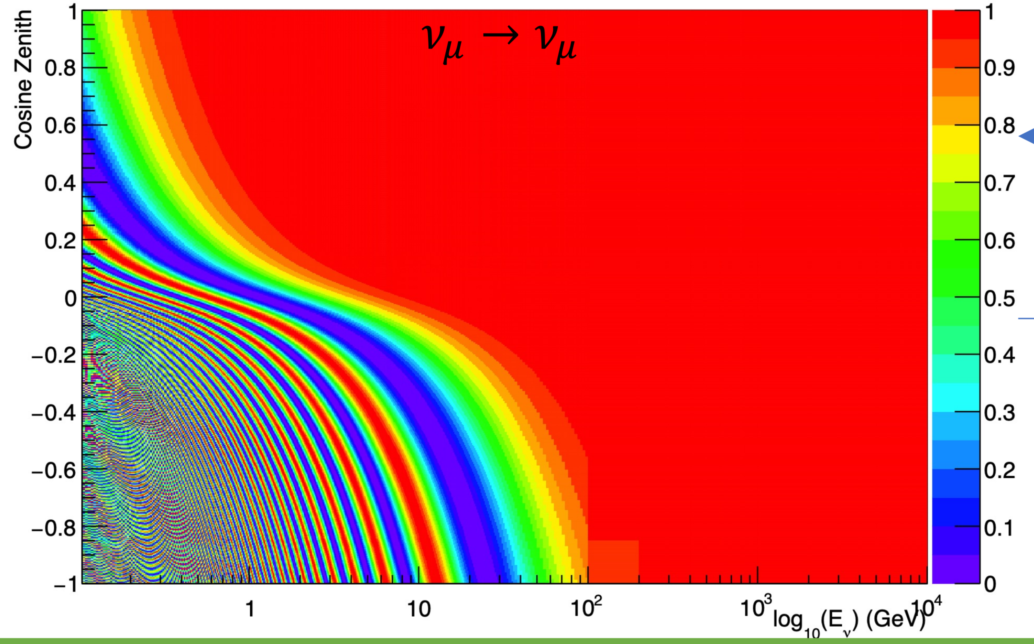
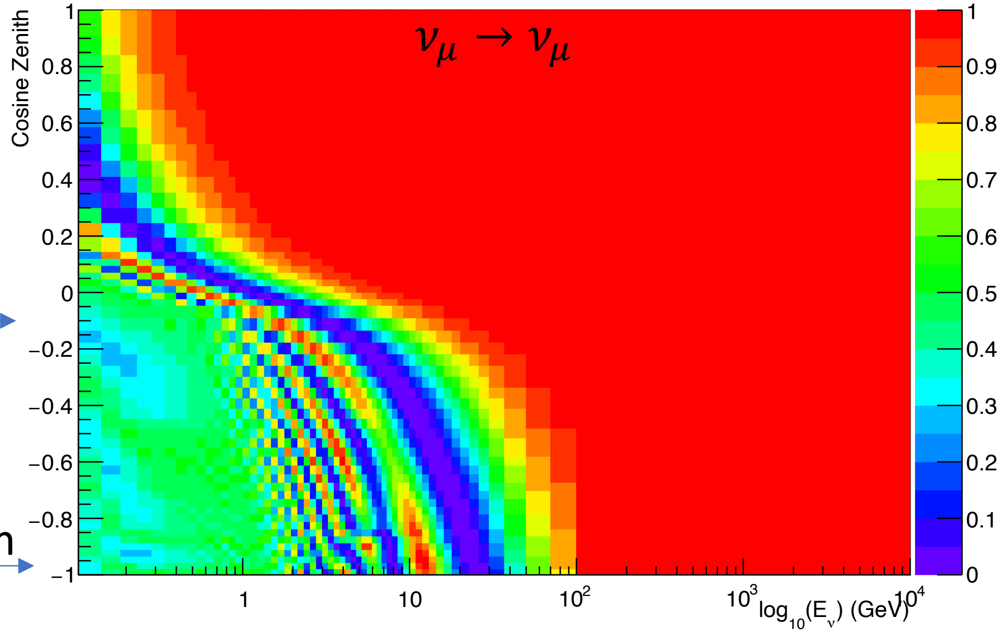


Fine oscillogram

Averaging Technique

Coarse oscillogram



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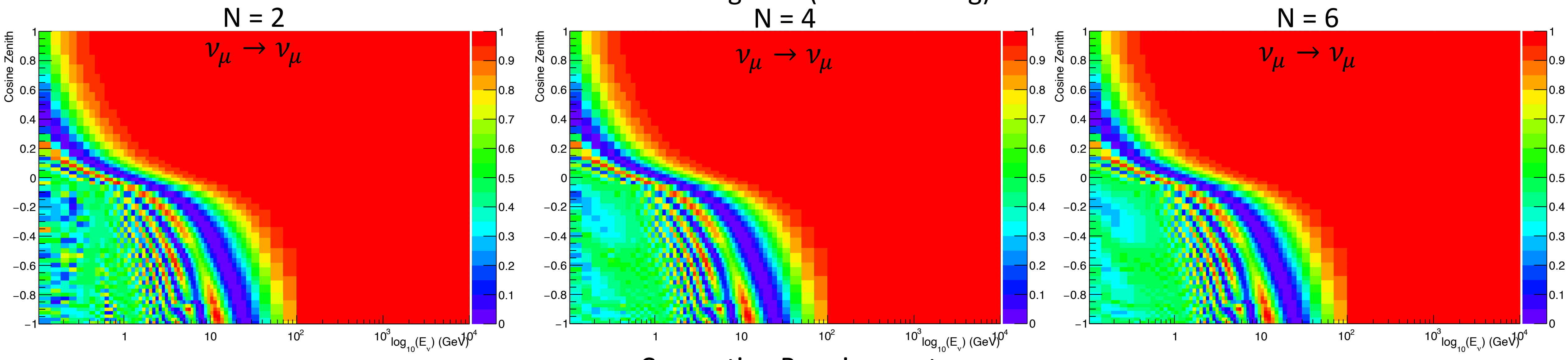
Coarse Oscillograms (Same binning):



Computing Requirement

Atmospheric Neutrinos at SK

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Recent SK analysis pre-calculates oscillation probabilities on grid of oscillation parameters

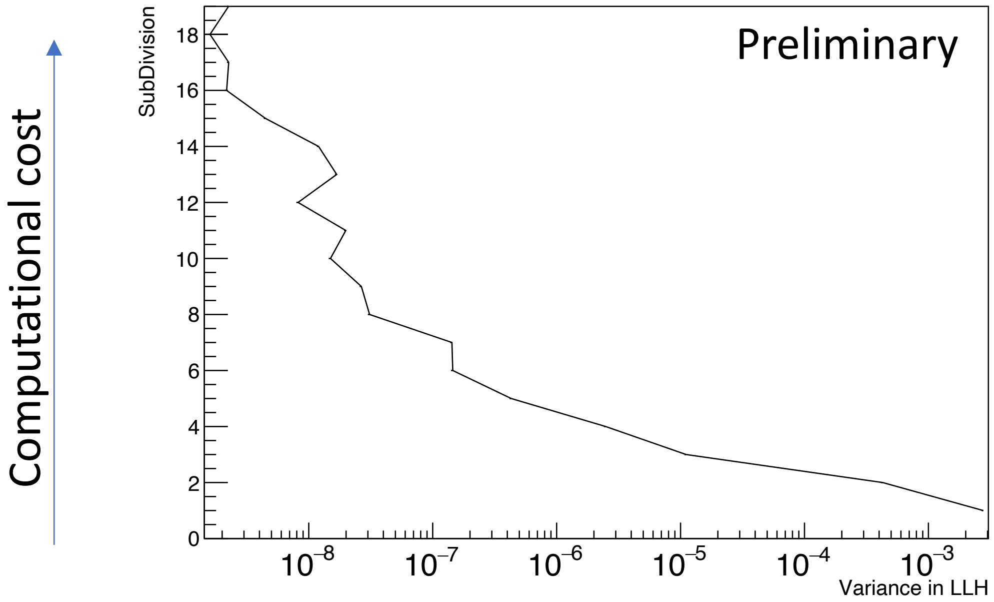
→ T2K analysis uses continuous oscillation parameters → oscillation probabilities have to be calculated 'on the fly'

Justify the choice of binning based on variance of likelihood to an Asimov

- Reweight sample at different number of sub divisions
- Calculated over many oscillation parameter throws

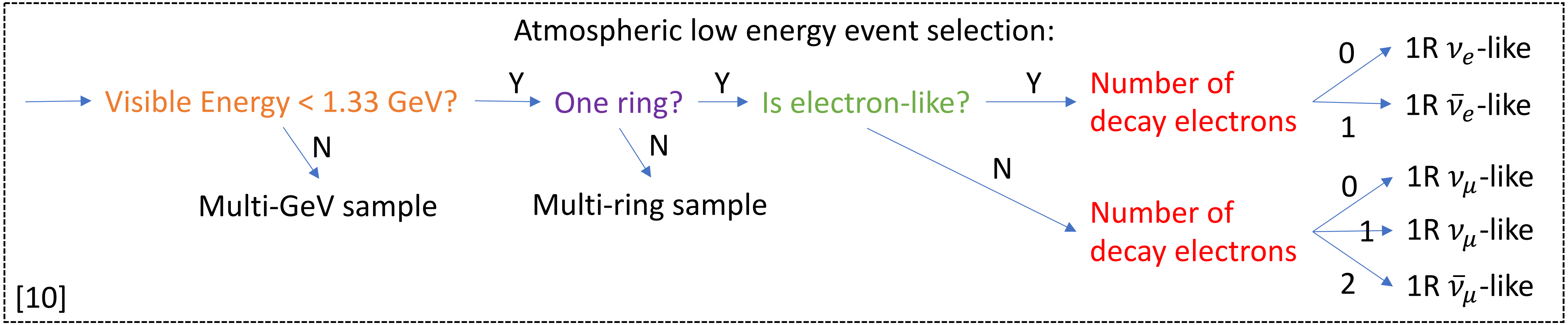
Trade off between smaller variance (High computational cost) and larger variance (Low computational cost)

- Both memory and time per calculation



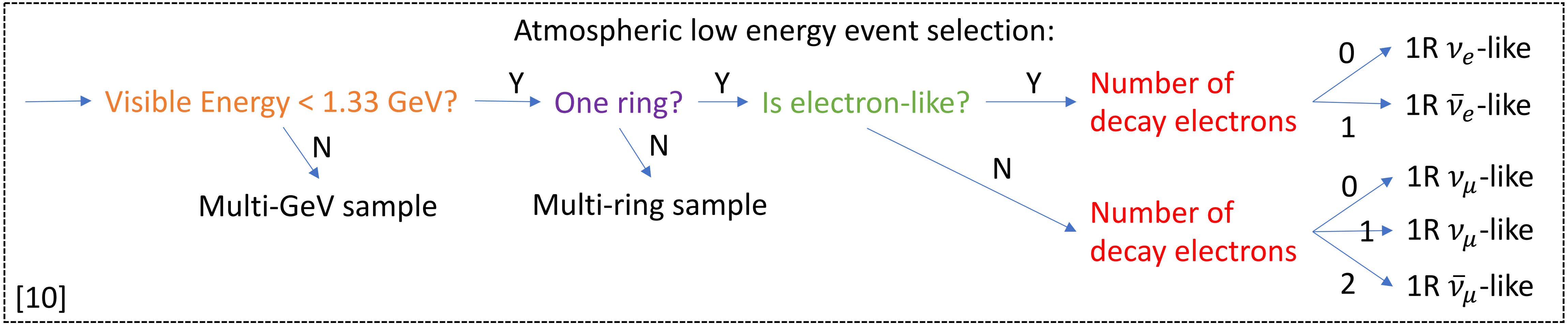
Event Selection for Neutrinos at SK

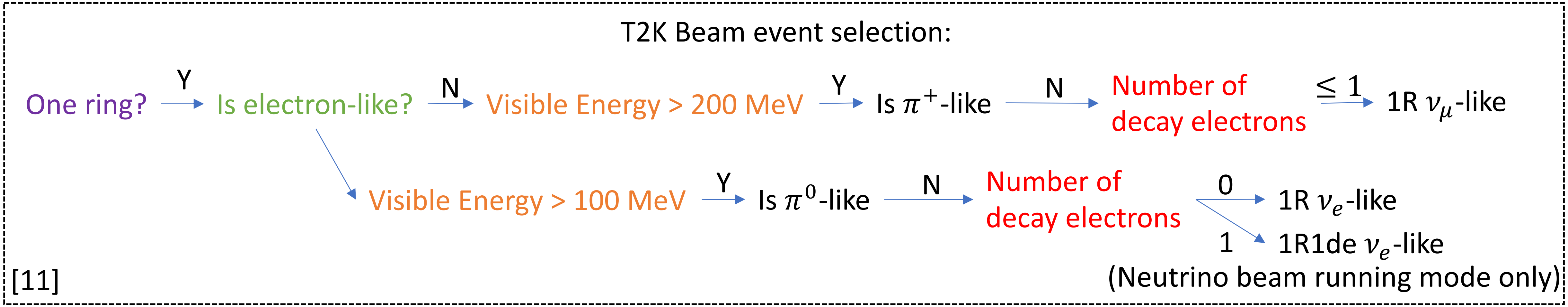
For events which are fully contained:



Event Selection for Neutrinos at SK

For events which are fully contained (And in expected beam window):





Detector Systematics

One proposed method: Can use fact that similar cuts are applied in low energy atmospheric and beam samples to devise correlated detector systematics model response

- Another alternative is to use the official systematics from each experiment → no correlation

Method: Fit shift/smear parameters which modify PID distributions inducing event migration simultaneously with oscillation parameters:

- Detector systematics for T2K estimated prior to the oscillation parameter fit using similar technique
- Allows correlations between detector systematics to other systematics

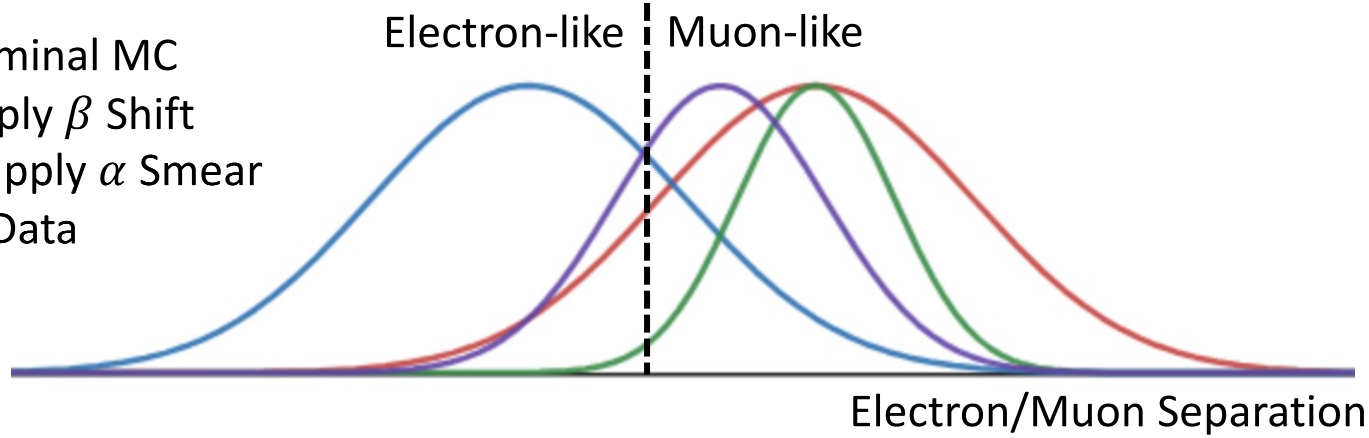
When performing oscillation parameter fit, include likelihood term between detector PID distribution for Data and MC

Variations of α's/β's alters the PID distribution, changing which events would have been selected as electron-like or muon-like

$$L^i_{jk} \rightarrow \alpha^i_{jk} L^i_{jk} + \beta^i_{jk}$$

i = PID parameter to shift
j = True Visible Topology Bin
k = Visible Energy bin

Red: Nominal MC
Blue: apply β Shift
Green: apply α Smear
Purple: Data



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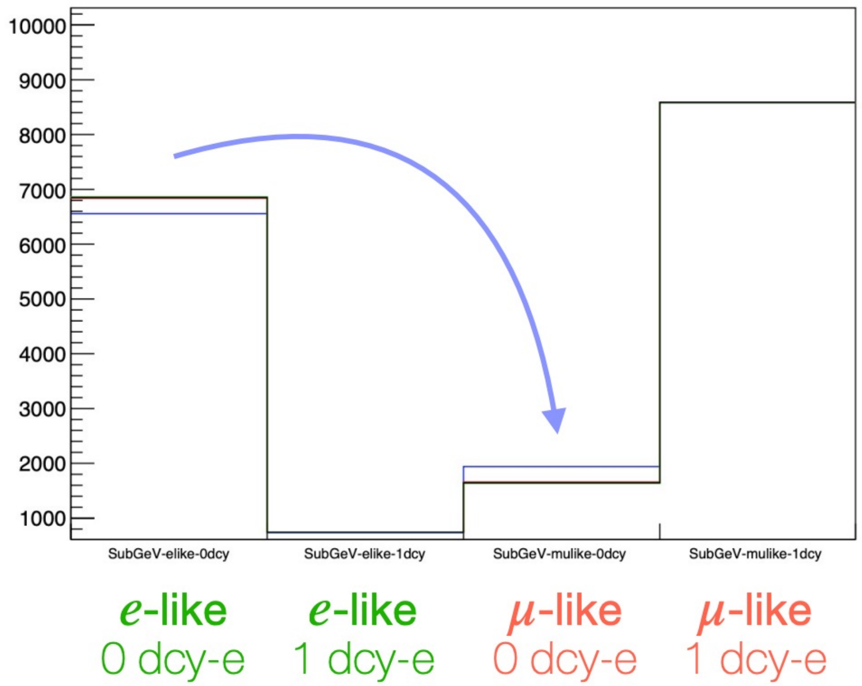


Workflow

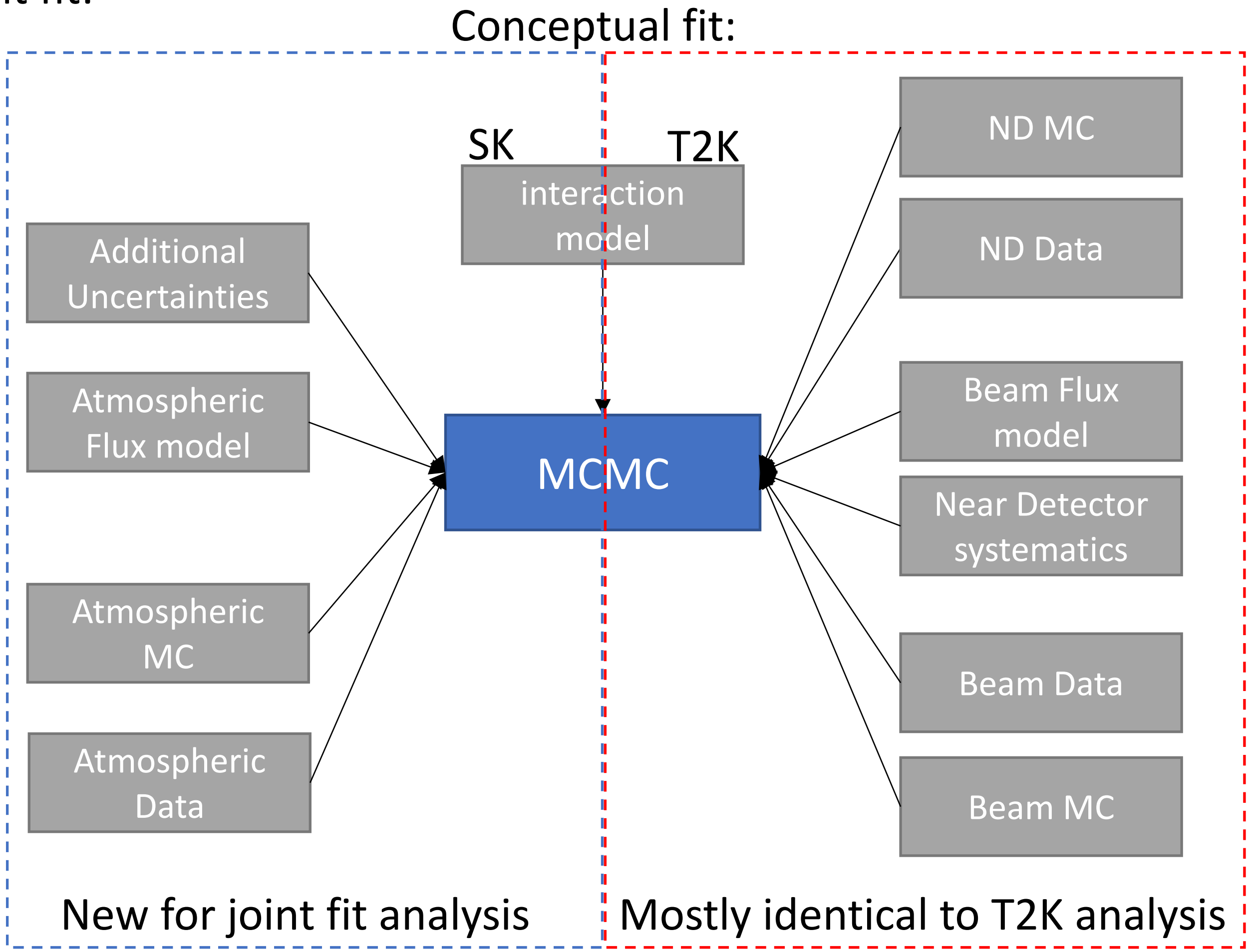
Workflow for joint oscillation fit (Simultaneous near detector, beam and atmospheric fit) used in one of the T2K fitters (MaCh3) undertaking the joint fit:

SK:

High energy Xsec Model

Systematics from calibration sources

Flux model from recent SK analysis



T2K:

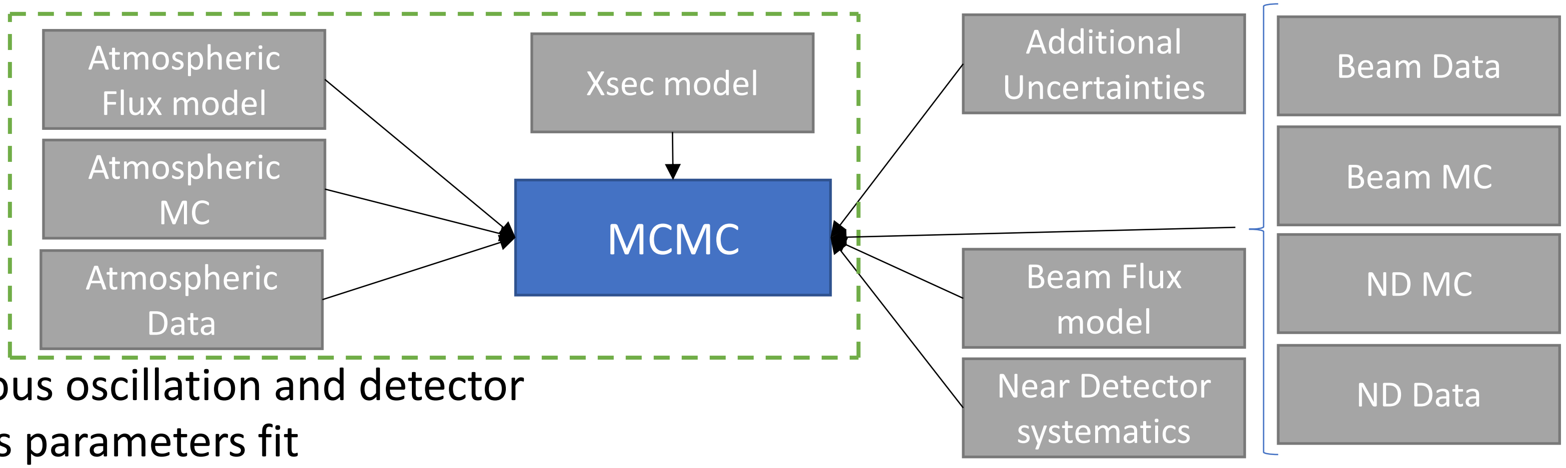
2020 Analysis Xsec Model

Pion tagged samples selected in near detector (ND)

NA61/SHINE data constraint on replica target

Detector Systematics for T2K?

Workflow for joint oscillation fit (Simultaneous near detector, beam and atmospheric fit)



Simultaneous oscillation and detector systematics parameters fit

Detector Systematics for T2K?

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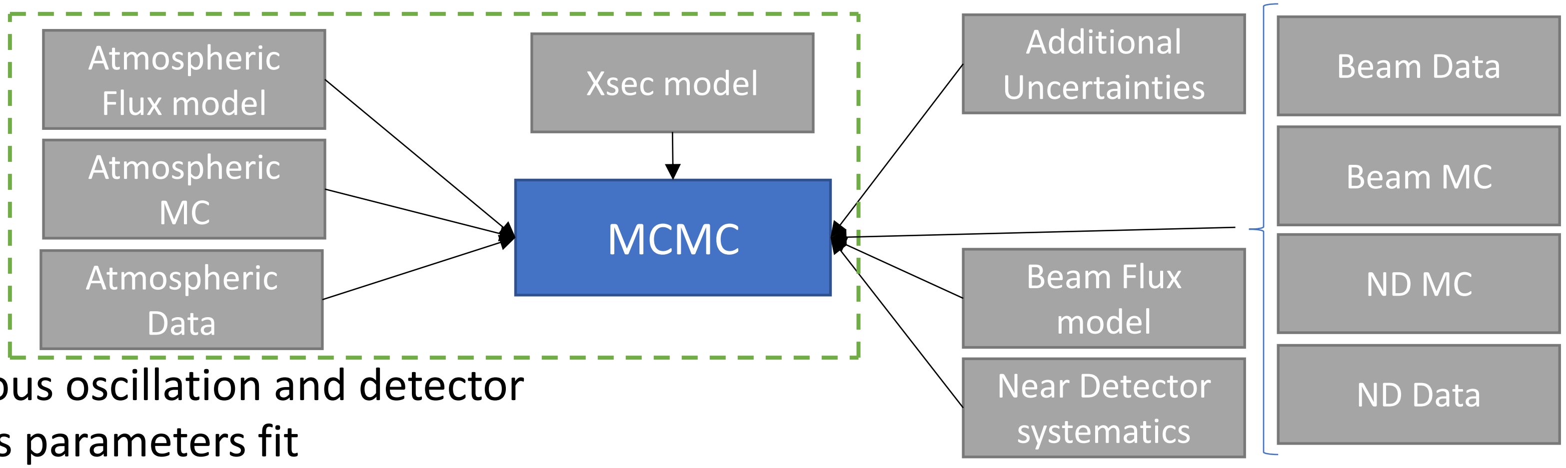
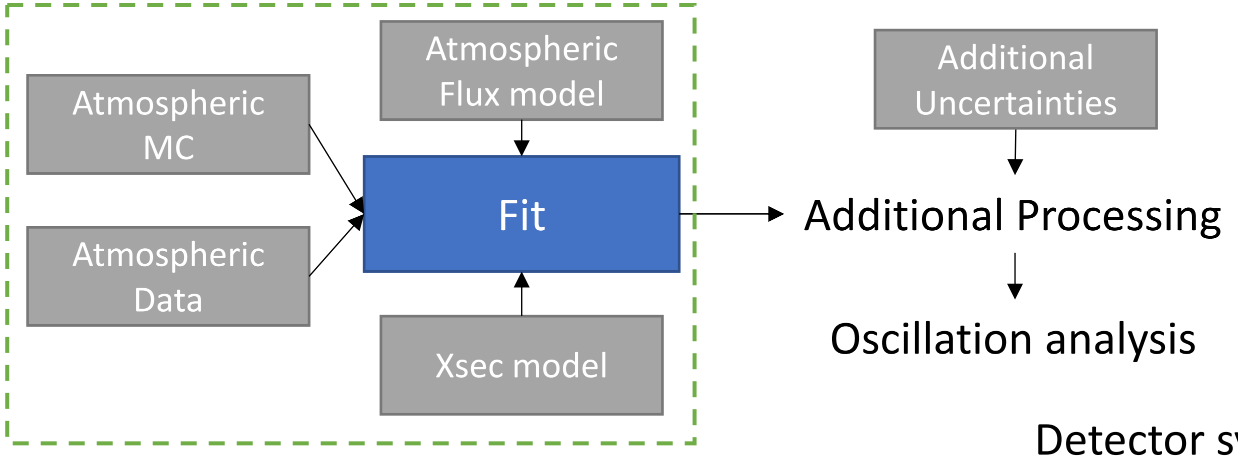


Simultaneous oscillation and detector systematics parameters fit

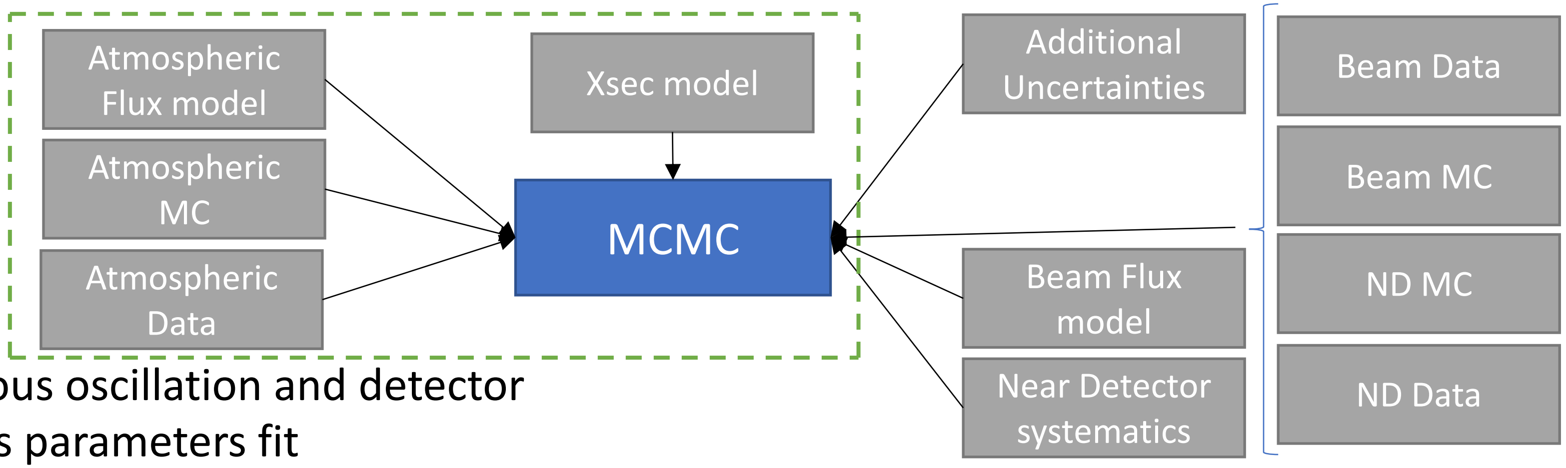
Conceptual workflow for T2K far detector systematics



Detector systematic parameters fit

Detector Systematics for T2K?

Workflow for joint oscillation fit (Simultaneous near detector, beam and atmospheric fit)



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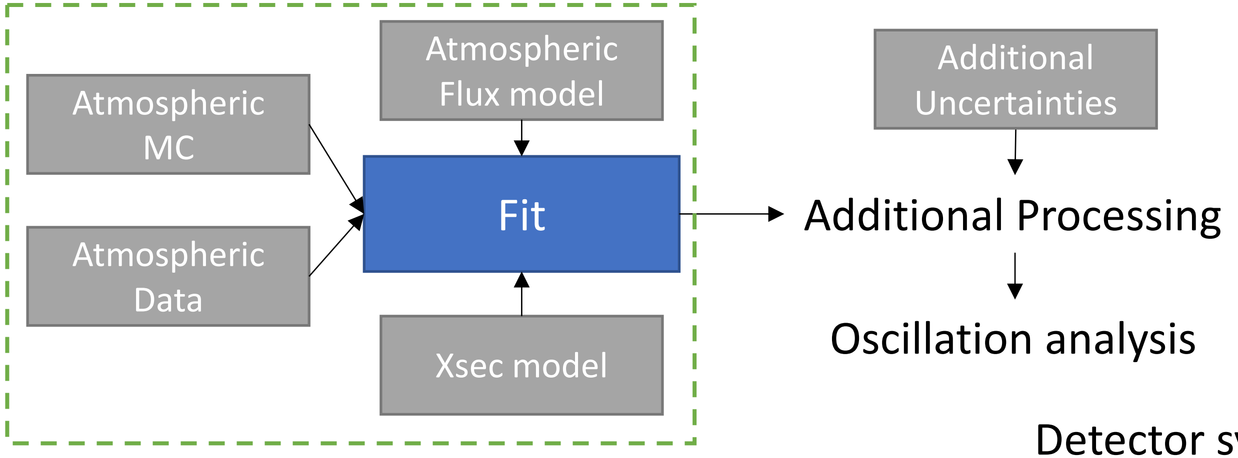

Detector systematic parameters fit

Framework created for joint oscillation fit contains similar ingredients to detector parameter fitter:

- Allows cross check of implementation

Turn oscillation parameter fitting off and have a conceptually similar fitting method

Need to incorporate additional uncertainties for consistent detector systematics used in T2K 2020 analysis:

- Code has been developed to allow this

Conclusion

Joint oscillation parameter fit of T2K beam and SK atmospheric samples ongoing, with expected improvements in δ_{cp}, mass ordering and θ_{23} octant determination due to resolved degeneracies;

- Differing choices of systematic approaches being taken by the different fitters will help to understand where and how correlations effect constrain on oscillation parameters
- Using official inputs from experiments where justifiable, developing techniques where correlations could matter

Many developments from T2K perspective incorporating ability to handle atmospheric samples (More than discussed in this talk):

- Developments to incorporate oscillation smearing; required for SK analysis to avoid parameter bias
- Considerations of run-time feasibility

Correlated detector model being developed to enable correlated response between beam and atmospheric samples:

- Estimation of the impact of correlated detector model will be evaluated by running fits with and without beam/atmospheric correlations
- Removing oscillation parameter fit allows easy comparison to T2K detector systematic estimation analysis – Cross check for both, potential for updates

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Backup Slides

Bibliography

[1] M. Jiang et al, SK collaboration, *Progress of Theoretical and Experimental Physics*, Volume 2019, Issue 5, May 2019, 053F01,

[2] P. Dunne, T2K collaboration, Latest Neutrino Oscillation Results from T2K, Neutrino 2020

[3] J. Wals, T2K Near Detector Fit, Joint APP, HEPP and NP Conference, Link

[4] M. Wascko, T2K collaboration. T2K Status, Results, and Plans, neutrino 2018

[5] Nakajima, SK collaboration, Recent results and future prospects from Super-Kamiokande

[6] E. Richard et al, SK collaboration, (Super-Kamiokande Collaboration), Phys. Rev. D 94, 052001

[7] C. Bronner, PANE2018: Link

[8] K. Abe *et al.* (Super-Kamiokande Collaboration), Phys. Rev. D 97, 072001

[9] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D 83, 123001

[10] M. Jiang, Thesis, Study of the neutrino mass hierarchy with the atmospheric neutrino data collected in Super-Kamiokande IV

[11] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 103, 112008

[12] X. Li, Thesis, A Joint Analysis of T2K Beam Neutrino and Super-Kamiokande Sub-GeV Atmospheric Neutrino Data

[13] T. Vladisavljevic, The T2K Flux Predictions , NuInt2018, Link

MoU

MEMORANDUM OF UNDERSTANDING

between

The Super-Kamiokande Collaboration, represented by its Spokesperson

on the one hand,

and

The T2K International Collaboration, represented by its Spokesperson

on the other hand,

hereafter referred to as “the Parties” or individually as “Party,” concerning the combined analysis of their data sets.

Preamble

The study of neutrino oscillations is among the goals of both the Super-Kamiokande and T2K experiments. The T2K experiment utilizes neutrinos produced by the J-PARC proton synchrotron and subsequently observed by a complex of near detectors as well as the Super-Kamiokande detector to study the oscillations of primarily 600 MeV neutrinos over a 295 km baseline. Super-Kamiokande, outside of its role in the T2K experiment, observes atmospheric neutrinos over several decades in energy and a wide variety of path lengths. As a result of these configurations the T2K and Super-Kamiokande data sets have complementary sensitivity to neutrino oscillations, which can be enhanced through combined analysis. In particular, the combined data set is expected to improve constraints on key aspects of the PMNS mixing paradigm, including the neutrino mass ordering, the value of the atmospheric mixing angle, and the CP phase.

This Memorandum of Understanding (MOU) provides a framework for collaboration on analyses making use of data sets with sensitivity to neutrino oscillations from both experiments.

Atmospheric Neutrinos at SK

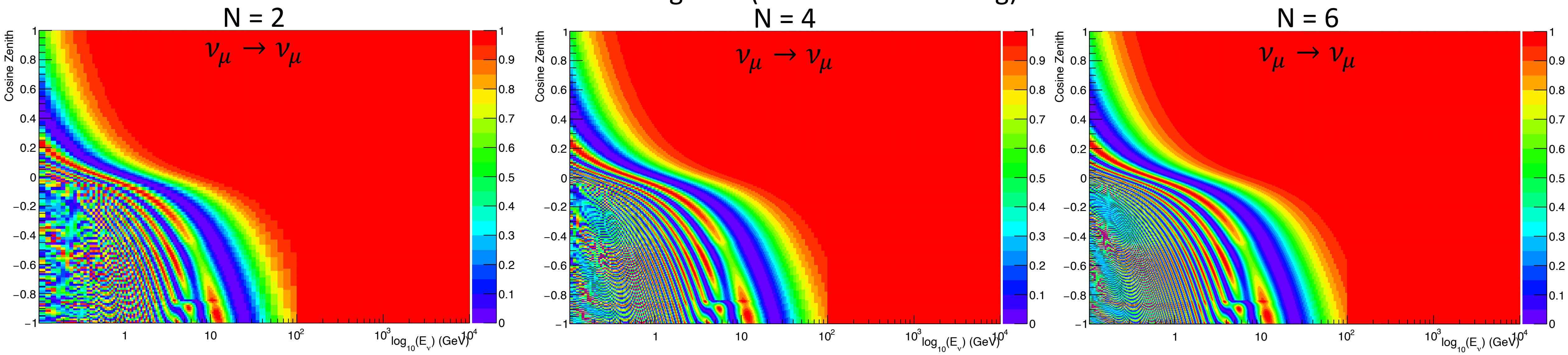
From the T2K fitter perspective, including atmospherics is challenging as 2D oscillation probability

- Smearing of the fast oscillation wavelength → Avoid biases/MC statistical fluctuations
- Production height averaging → Include systematic on height of interaction (Methodology under review)

SK analysis: pre-calculate oscillation probabilities on grid of oscillation parameters

T2K analysis: continuous oscillation parameters → oscillation probabilities have to be calculated 'on the fly'

Fine Oscillograms (Same coarse binning):



Computing Requirement

Detector Systematics

One proposed method: Can use fact that similar cuts are applied in low energy atmospheric and beam samples to devise correlated detector systematics model response

- Another alternative is to use the official systematics from each experiment → no correlation

Method: Fit shift/smear parameters which modify PID distributions inducing event migration simultaneously with oscillation parameters:

- Detector systematics for T2K estimated prior to the oscillation parameter fit use this technique
- Can instead perform simultaneous fit allowing correlations between samples and to other systematics

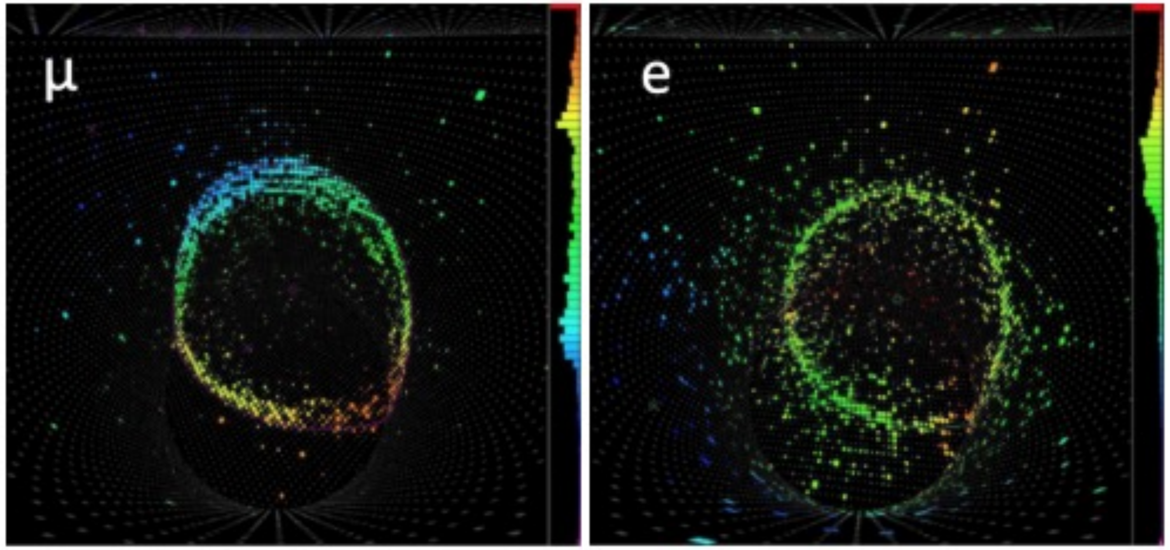
Implementation: Parameterize detector response using shift and smear distributions:

- For single ring samples: ring separation, electron-muon separation and other event selection cuts

$$L^i_{jk} \rightarrow \alpha^i_{jk} L^i_{jk} + \beta^i_{jk}$$

i = PID parameter to shift
j = True Visible Topology Bin
k = Visible Energy bin

Expect response to function of true visible topology (Single ring vs. overlapping rings) as well as energy deposition in detector



'Sharp' 'Fuzzy'

Cross Section

Similar constituent interaction modes between beam and atmospheric samples – correlated model?

SK:

[12]

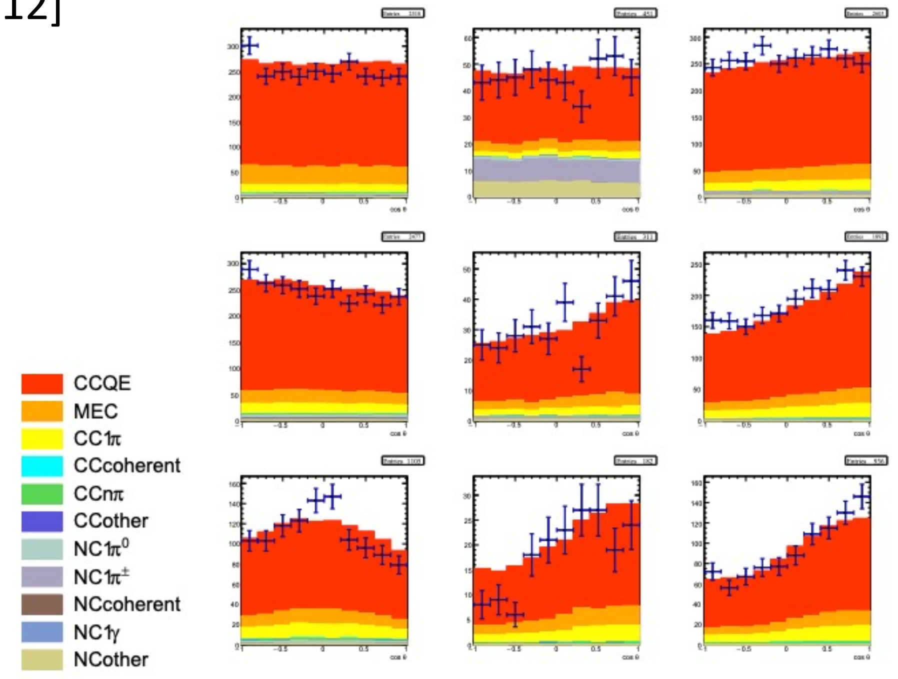
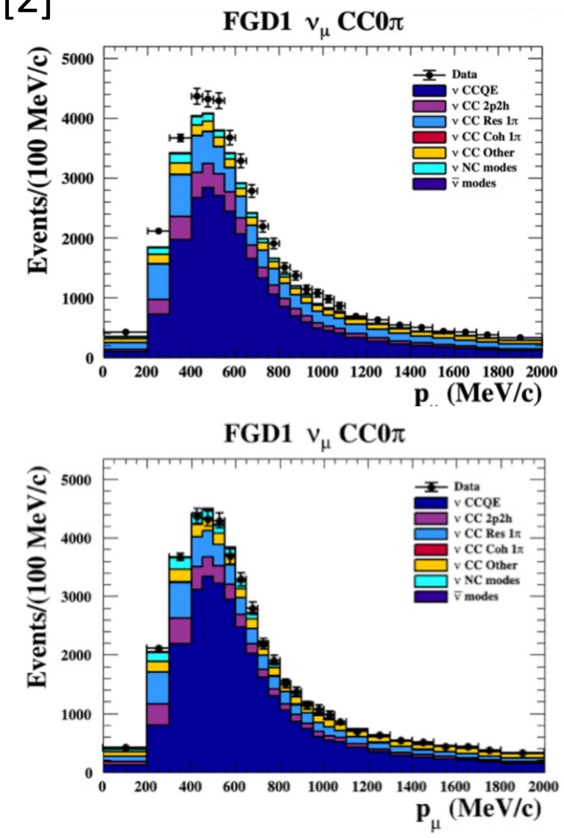


Figure 6.14: The pre-fit cosine zenith angle distributions. The samples from left to right are: 1Re 0_{dcy}, 1Rμ 0_{dcy}, 1Rμ 1_{dcy}. The energy ranges from top to bottom are: $E_{vis} < 400$ MeV, $400 < E_{vis} < 700$ MeV, $700 < E_{vis} < 1330$ MeV. Data is shown with statistical errors only. The oscillation parameters shown in Table 6.11 are used to calculate the MC predictions. 2519.89 days of SK-4 data is used, and MC is scaled to the same exposure as data. $\cos\theta = 1$ for downward going events; $\cos\theta = -1$ for upward going events.

ND:

[2]



(a) FGD1 FHC ν_μ 0π

A correlated cross section model could create additional constraint on atmospheric samples

Detector Systematics

Benefits of simultaneous fitting of alpha/betas:

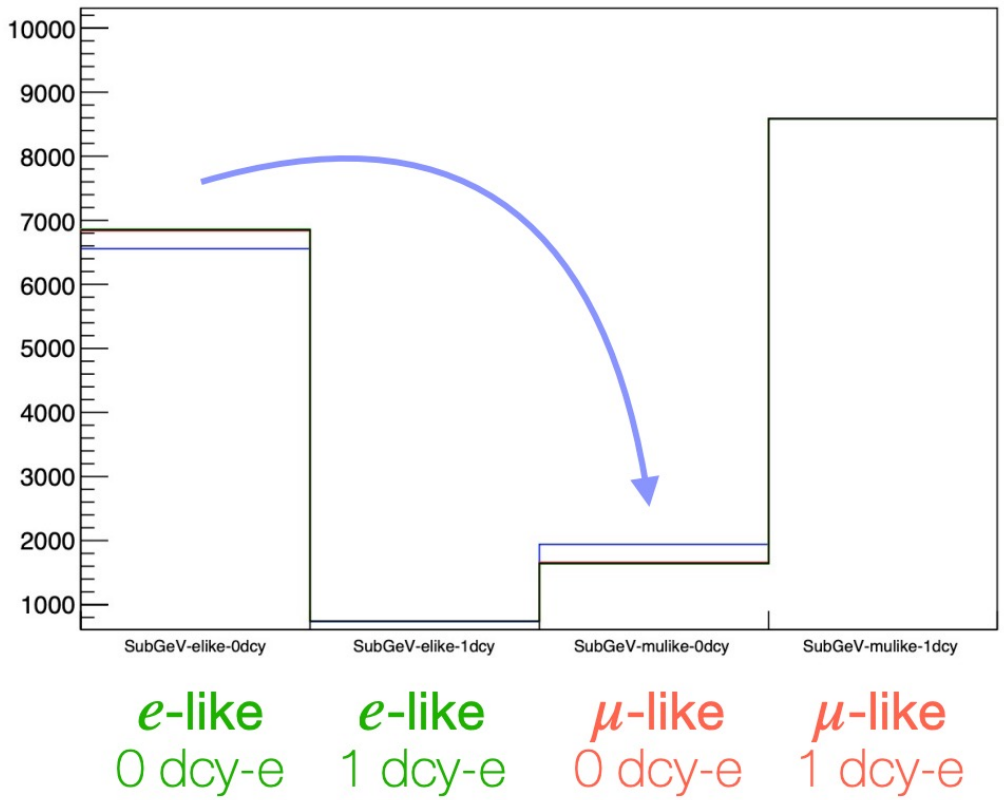
- Correlation of response in beam and atmospheric samples
- Comparison to framework which performs atmospheric neutrino fit for T2K oscillation analysis detector systematic estimation?

Negatives:

- Correlation may have no significant effect on oscillation parameters
- Technical detail: Additional systematics have to be considered to match systematics associated with official T2K results

Fitter (MaCh3) developed to add ability to simultaneously fit shift/smear parameters:

- Variations of electron/muon PID distribution systematics show conservation of event rate while moving electron-like events to be classified as muon-like



Atmospheric Neutrinos at SK

Bin events in momentum (related to neutrino energy) and cosine of zenith angle with respect to detector (related to propagation length):

- Single-ring events use lepton candidate information
- Multi-ring events sum the momenta of each ring and use total momentum and direction

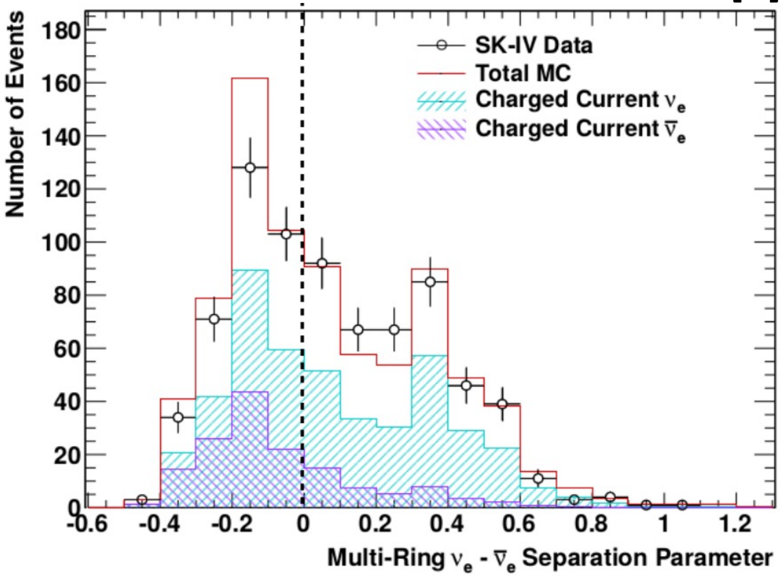
MH sensitivity depends on resolution on matter resonance effect:

- ν_e in NH, $\overline{\nu_e}$ in IH
- No magnetic field → can not distinguish $\nu/\bar{\nu}$ event-by-event

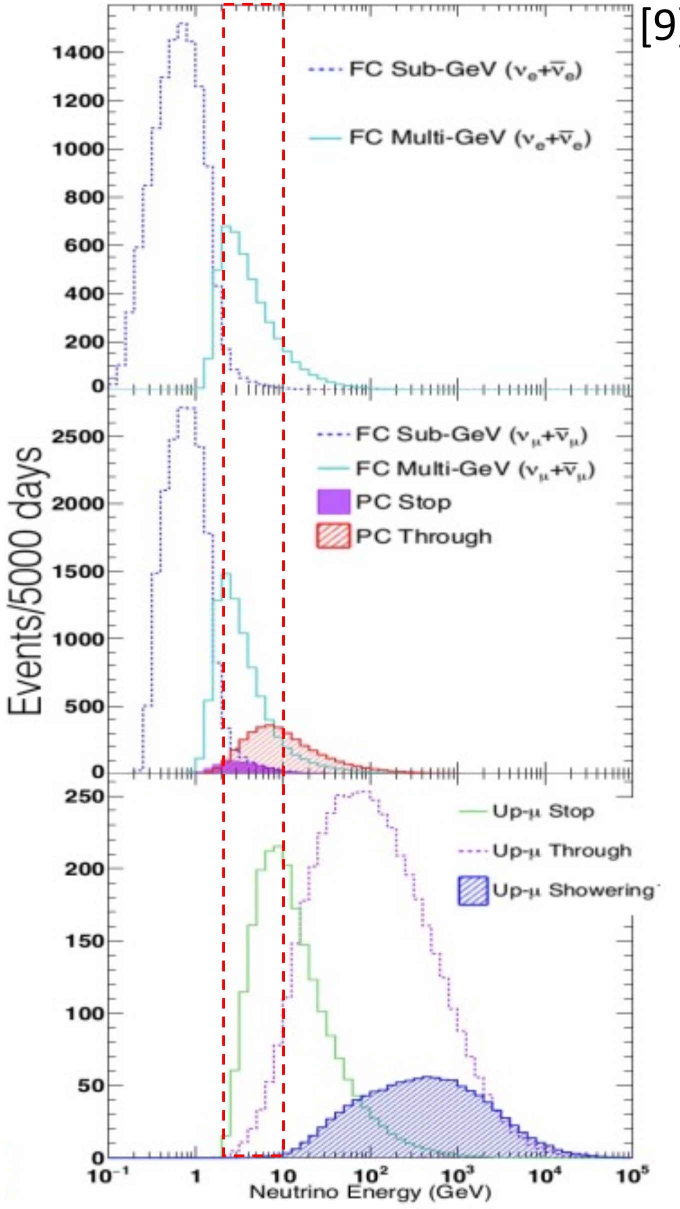
Increase sensitivity by having flavor enriched samples – Two stage selection:

- Cuts to remove ν_μ and NC background
- Likelihood based selection to separate $\nu/\bar{\nu}$ based on typical interaction kinematics

$\bar{\nu}_e$-like ν_e-like [1]



[9]

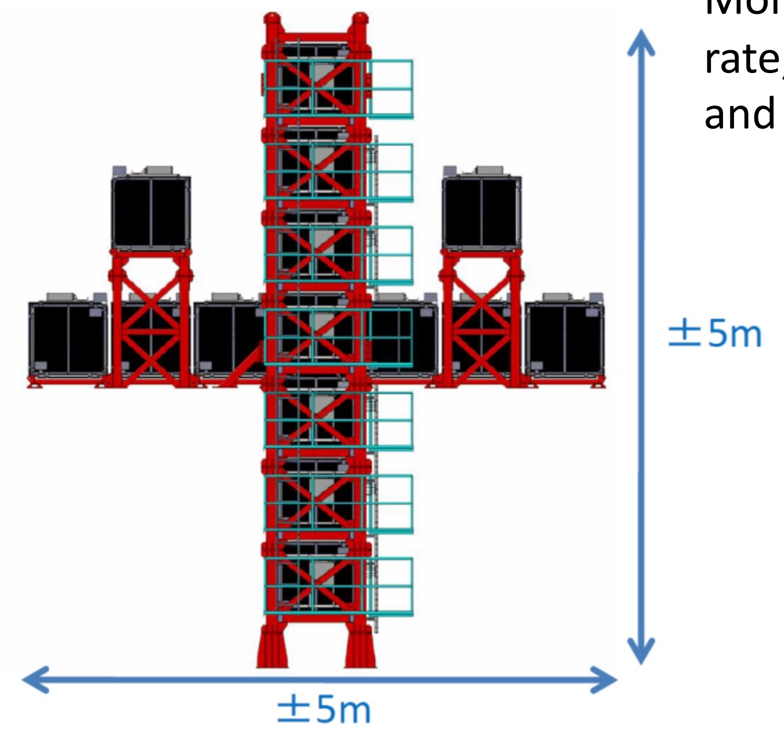


Mass resonance in 2 → 10 GeV region

Near Detector

Suite of Near Detector situated at 280m baseline

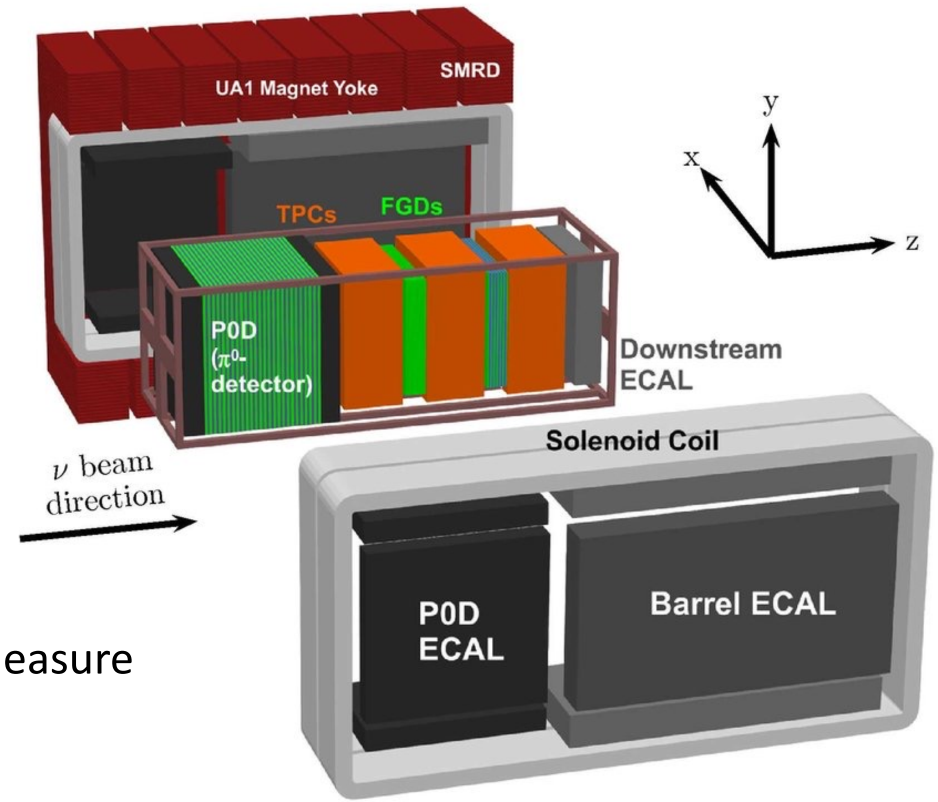
INGRID:



On-axis Detector

Monitors beam rate, direction and stability

ND280:



Off axis detector

Magnetized tracker to measure momentum and charge

Constrains cross section model and flux

Beam Flux

FLUKA modelling of interaction in graphite target:
- Input from T2K beam profile

Particle propagation handled by Geant3 and Galor:
- Horn and decay volume

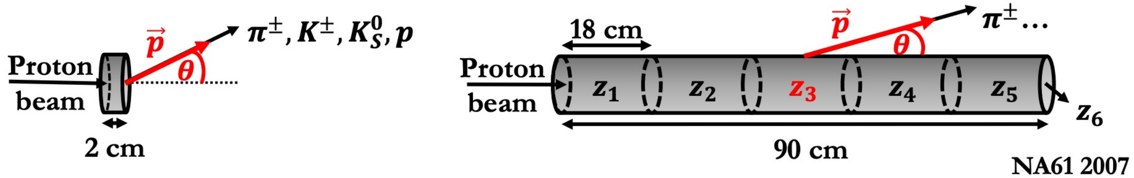
Tuning constrained by hadron production model (NA61/SHINE, HARP, etc.)

[13]

NA61/SHINE Hadron Production Datasets for T2K

SHINE NA61

- Two different graphite target configurations are used:
  - Thin-target TT (2 cm, 0.04 λ_I): directly constrains ~60% of T2K flux
  - Replica-target RT (90 cm, 1.9 λ_I): potential to directly constrain up to ~90% of T2K flux



Beam + Graphite target	Mom (GeV/c)	year	Data	POT ($\times 10^6$)
p+TT	31	2007	$\pi^{\pm}, K^+$	0.7 (pilot run)
p+TT	31	2009	$\pi^{\pm}, K^{\pm}, K^0_S, p$	5.4
p+T2K RT	31	2007	$\pi^{\pm}$	0.2 (pilot run)
p+T2K RT	31	2009	$\pi^{\pm}$	2.8
p+T2K RT	31	2010	$\pi^{\pm}, K^{\pm}, p$	10

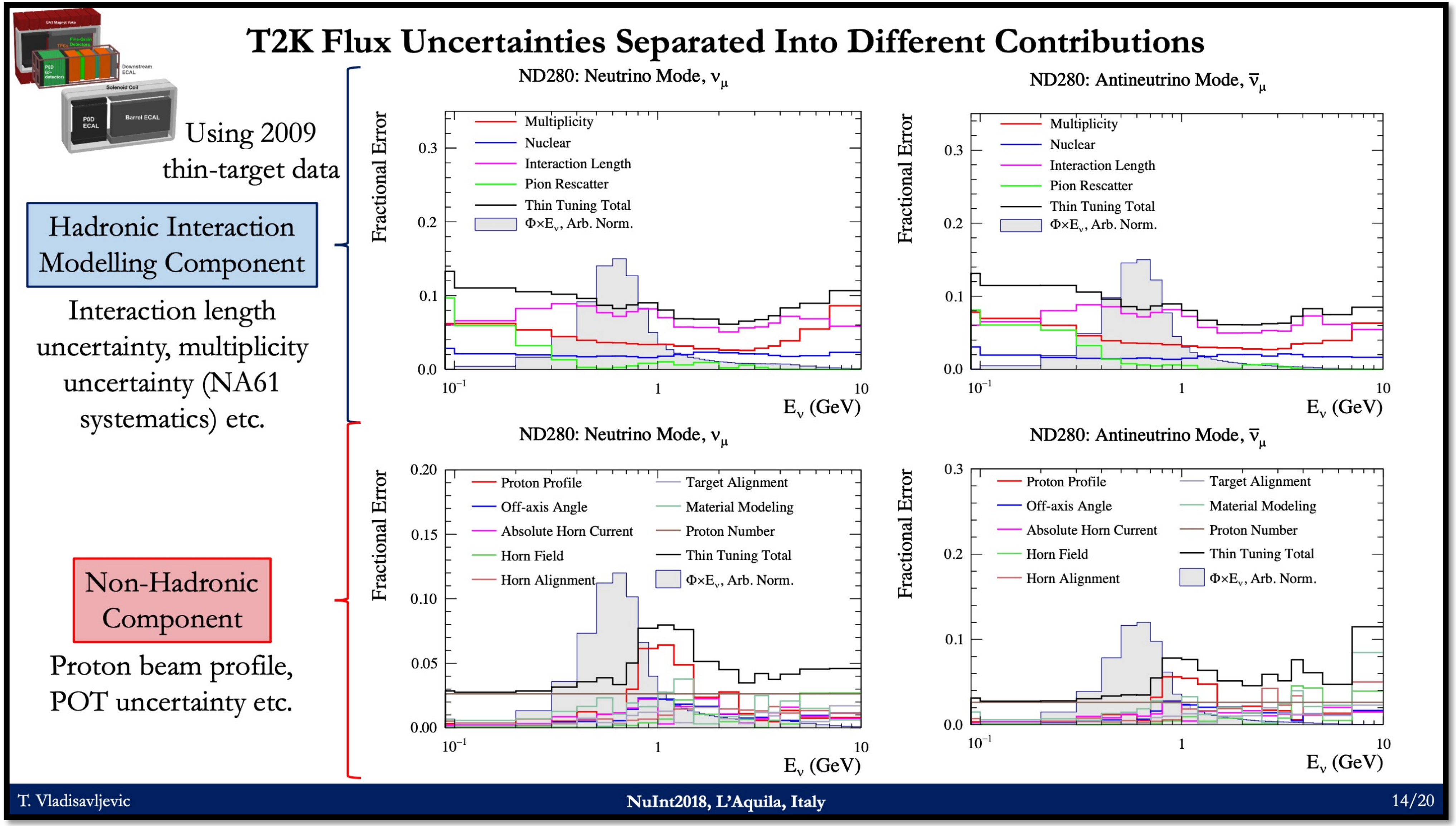
NA61 2007 thin-target dataset
10.1103/PhysRevC.84.034604
10.1103/PhysRevC.85.035210
NA61 2009 thin-target dataset
10.1140/epjc/s10052-016-3898-y
NA61 2009 replica-target dataset
10.1140/epjc/s10052-016-4440-y
NA61 2010 replica-target dataset
arXiv:1808.04927

- **Thin tuned flux**: official T2K flux prediction tuned with **NA61/SHINE 2009 thin-target data**
- **Replica tuned flux**: flux prediction using **NA61/SHINE 2009 replica-target data** to constrain pions exiting from the target. The yield of other hadrons from the target, the pion yield not covered by the replica-target dataset, as well as out-of-target interactions are still constrained with **NA61 2009 thin-target data**.

T. Vladisavljevic NuInt2018, L'Aquila, Italy 7/20

Beam Systematics

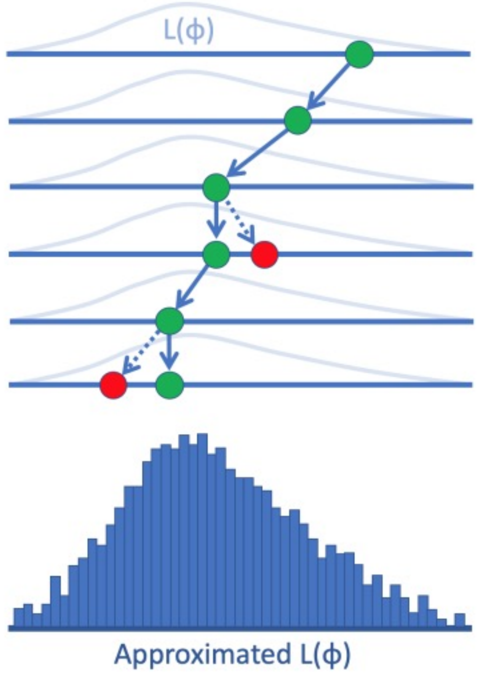
[13]



MaCh3 – Bayesian MCMC Fitter

Event-by-event handling of all samples:
- No binning artefacts
- Slower than binned approach → requires high performance

Modified to simultaneously fit atmospheric and beam samples



Markov Chain Monte Carlo method stepping through parameter space populating posterior probability density function

See Thomas Holvey's slides for more details

Workflow

Workflow for joint oscillation fit (Simultaneous near detector, beam and atmospheric fit) used in one of the T2K fitters (MaCh3) undertaking the joint fit:

Updates for atmospherics:

- More flexible sample handling to allow atmospheric samples
- Configurable application of kinematic cut variables in different parameters
- Addition of 2D atmospheric oscillation calculation
- Simultaneous fitting of oscillation and detector parameters

<u>In total:</u>

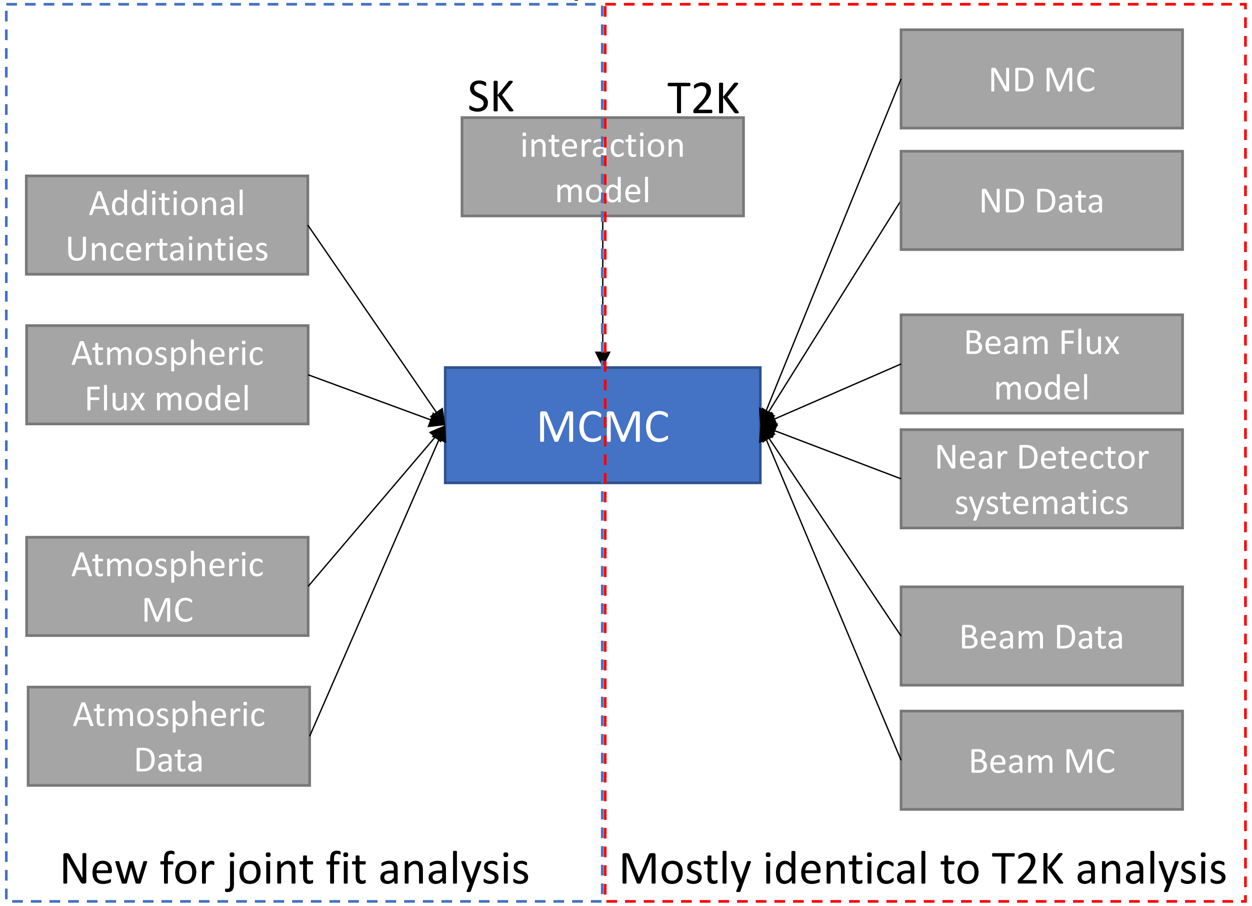
O(3 million) ND events

O(2.5 million) Beam FD events

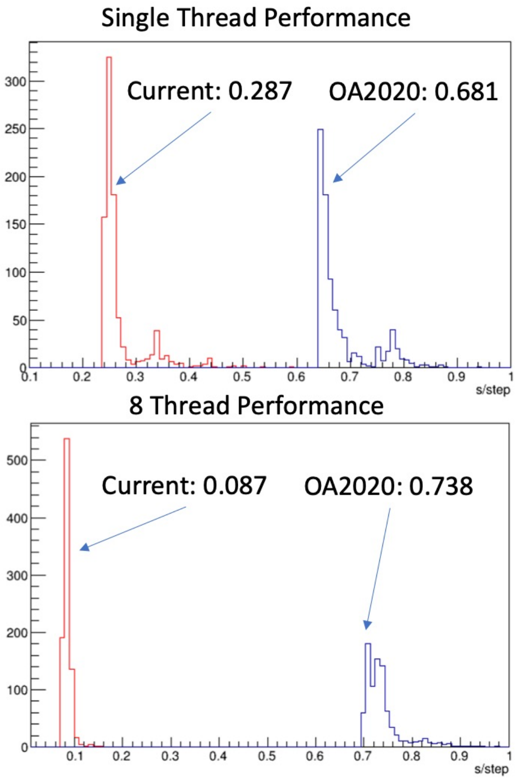
O(4 million) atmospheric events

→ Computationally challenging

Conceptual fit:



Significant performance increases:



<u>Indicative improvement</u>