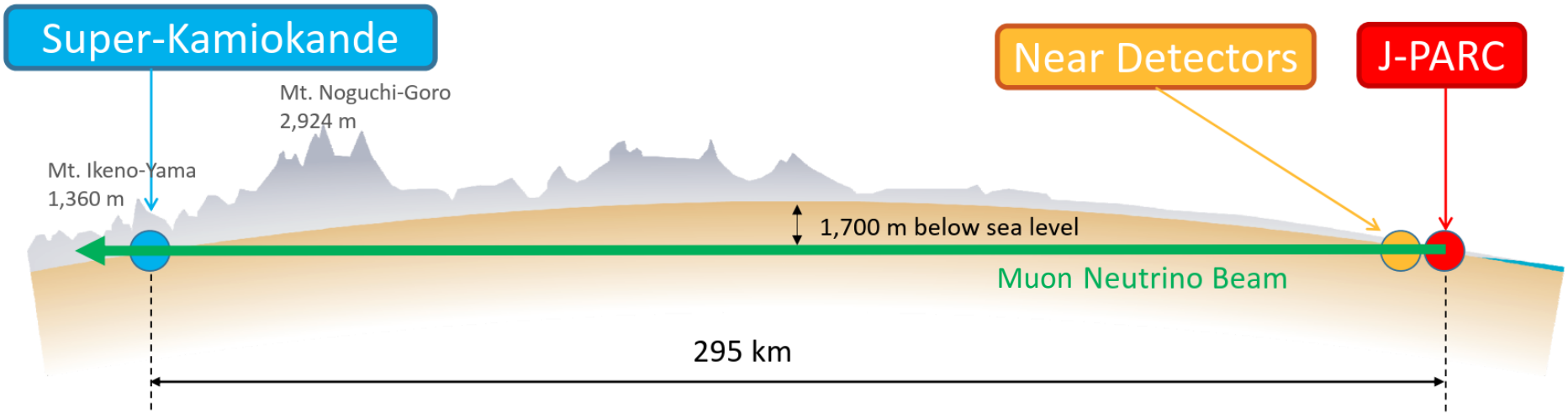
Status of T2K Oscillation Physics

Stephen Dolan
for the T2K Collaboration

stephen.joseph.dolan@cern.ch

The T2K Experiment

The T2K Experiment



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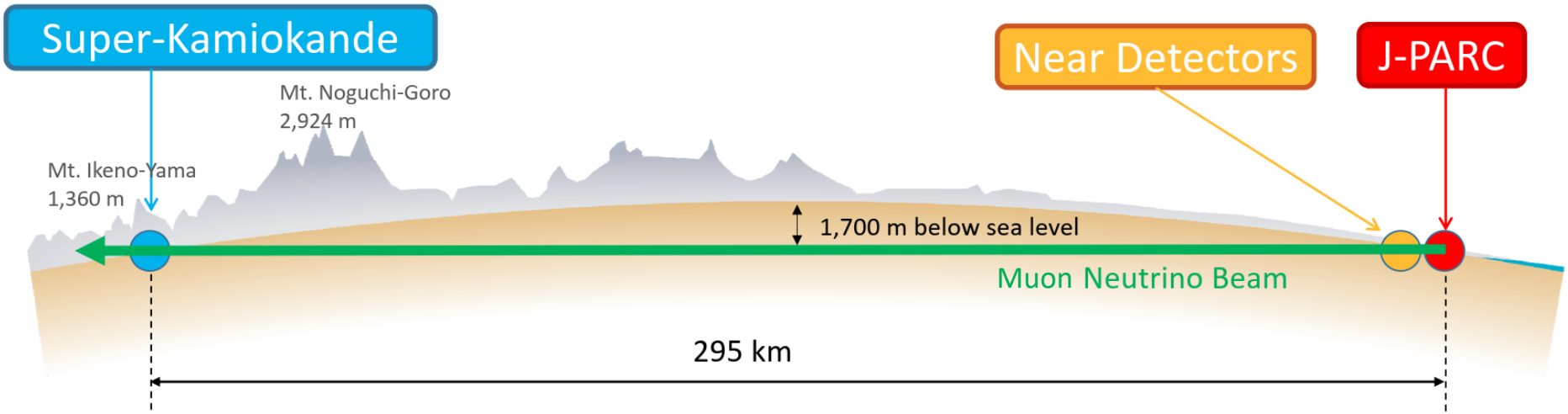

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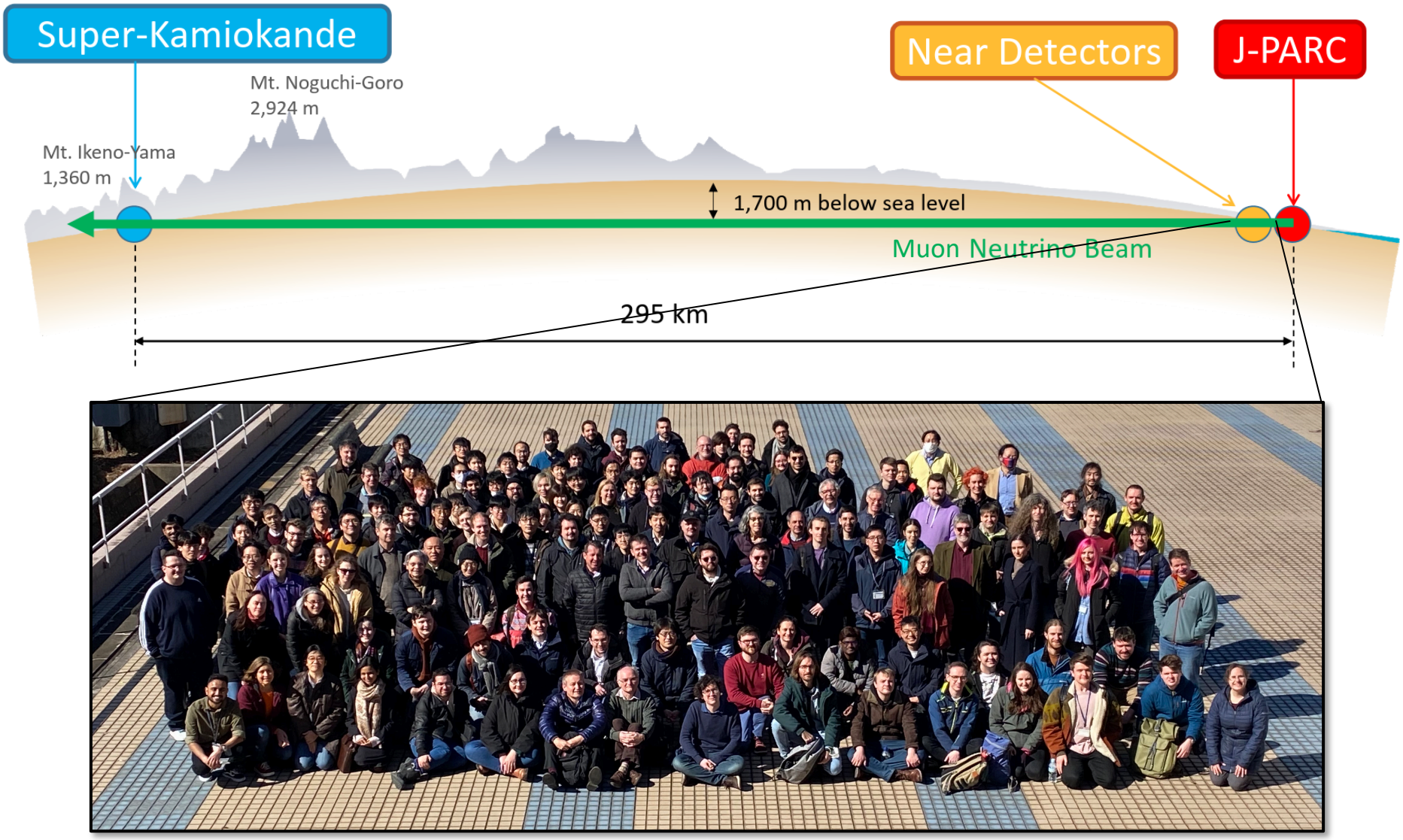
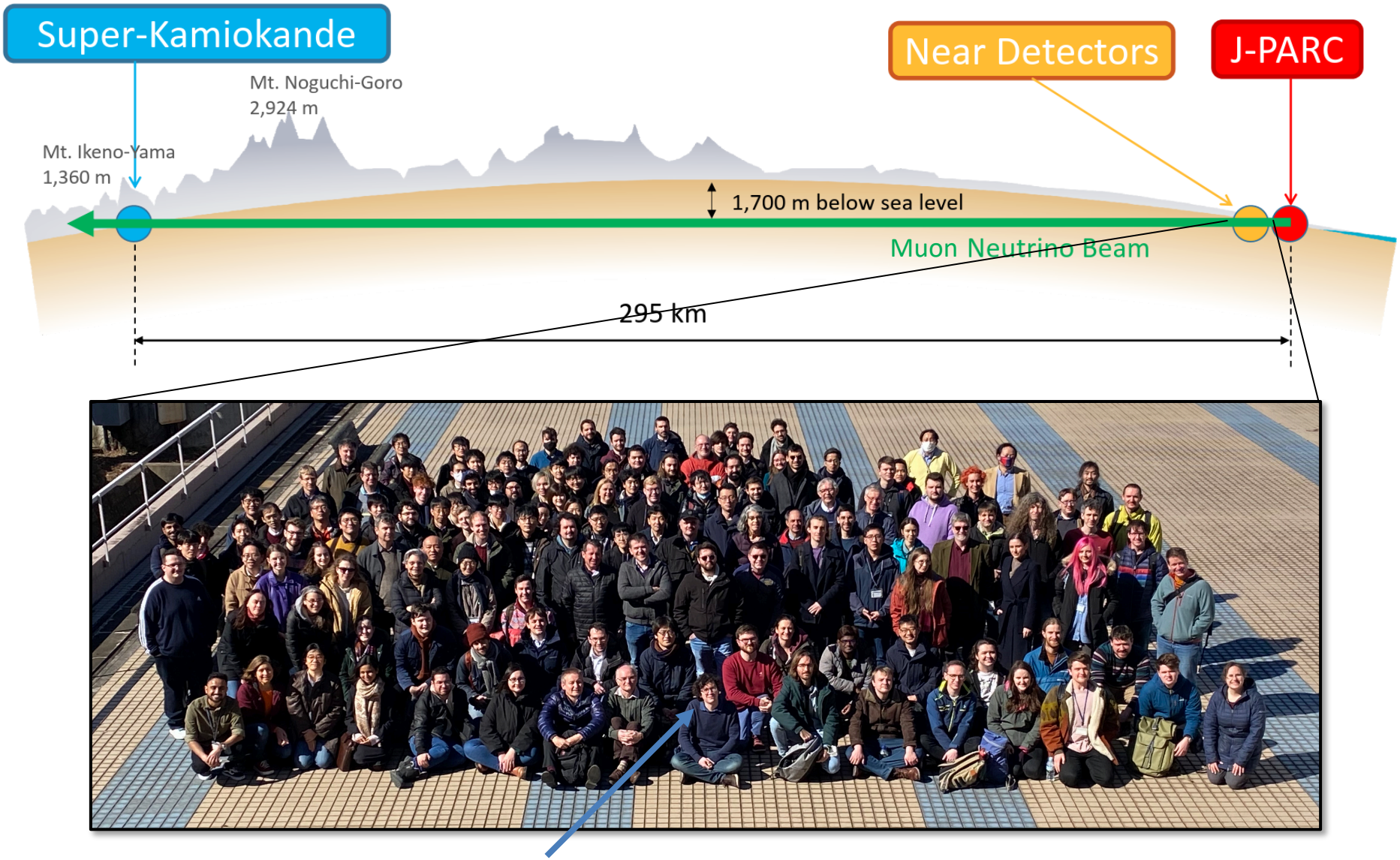
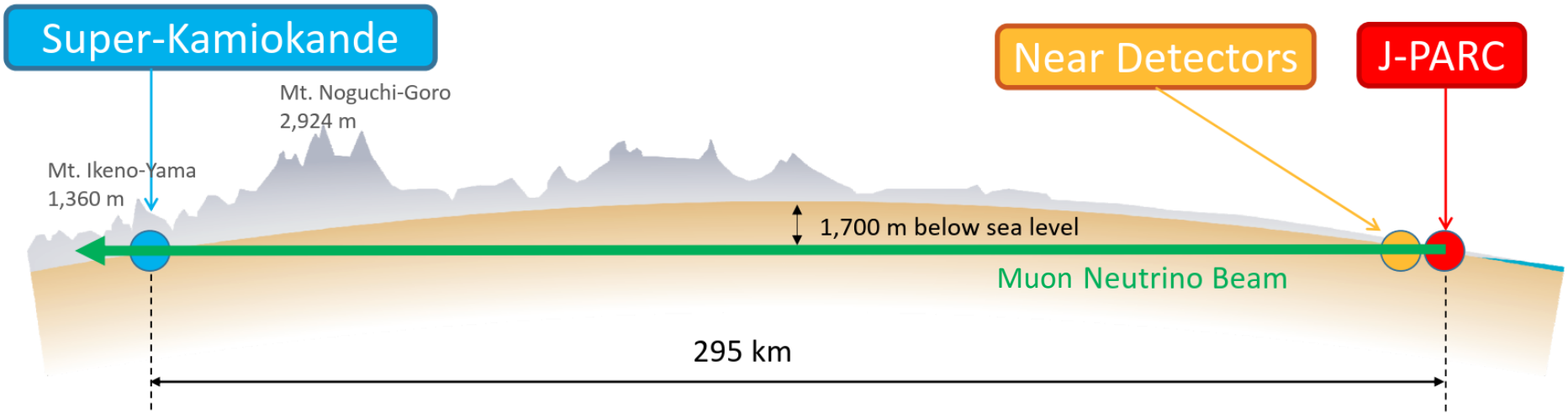
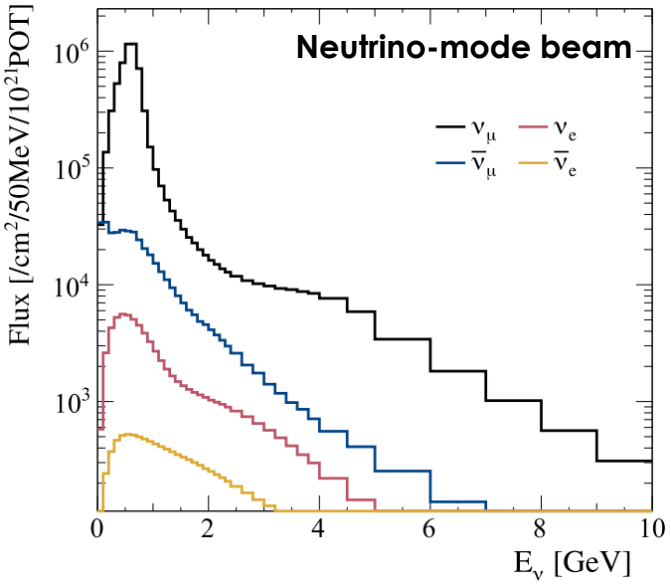


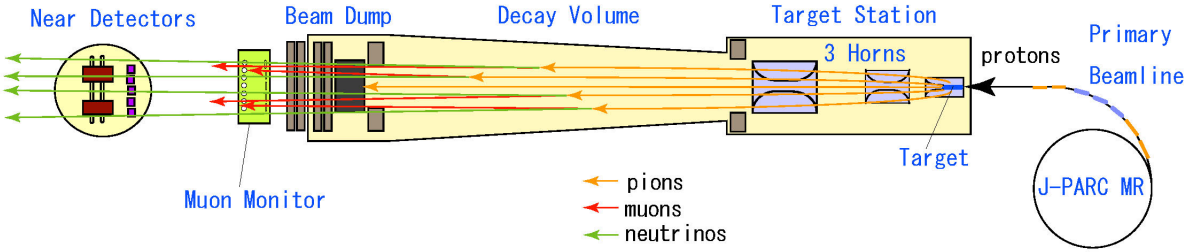
The T2K Collaboration



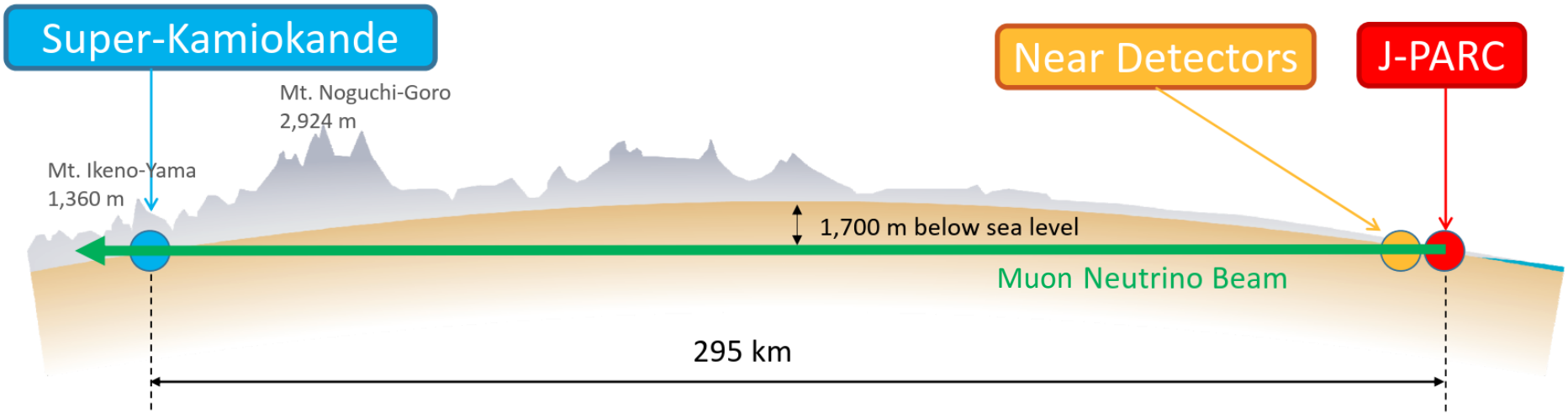
The T2K Beam


Super-Kamiokande
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
Near Detectors
J-PARC
1,700 m below sea level
Muon Neutrino Beam
295 km


Neutrino-mode beam
ν_μ
ν_e
$\bar{\nu}_\mu$
$\bar{\nu}_e$
Flux [/cm^2/50MeV/10^{21}POT]
10^6
10^5
10^4
10^3
0
2
4
6
8
10
E_ν [GeV]


Near Detectors
Beam Dump
Decay Volume
Target Station
3 Horns
protons
Primary
Beamline
Target
Muon Monitor
J-PARC MR
pions
muons
neutrinos

The T2K Beam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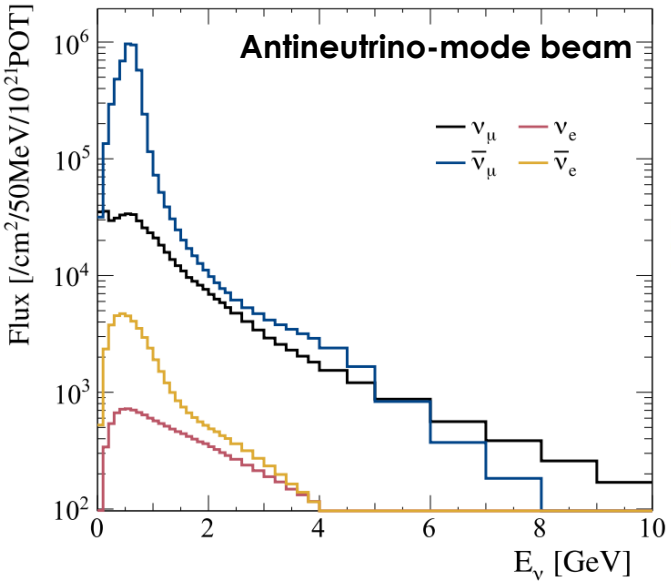
Antineutrino-mode beam
ν_μ
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Flux [/cm^2/50MeV/10^{21}POT]
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10^3
10^2
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4
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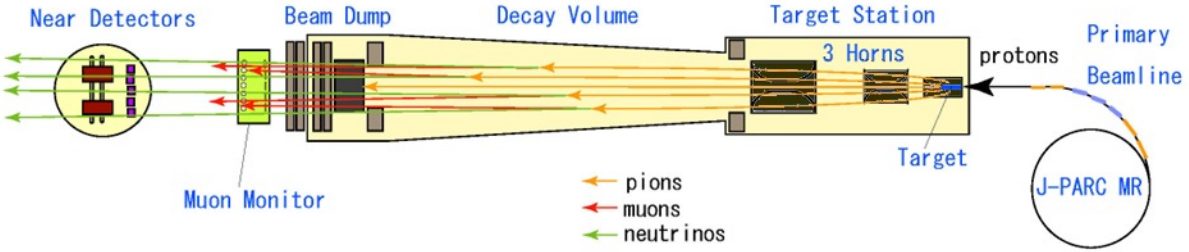
8
10
E_ν [GeV]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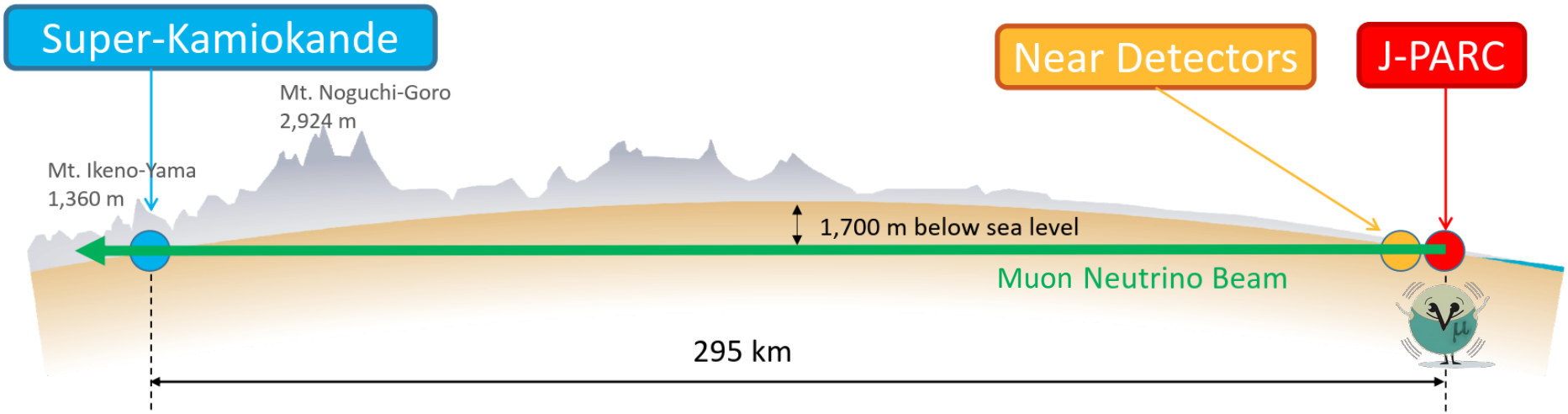
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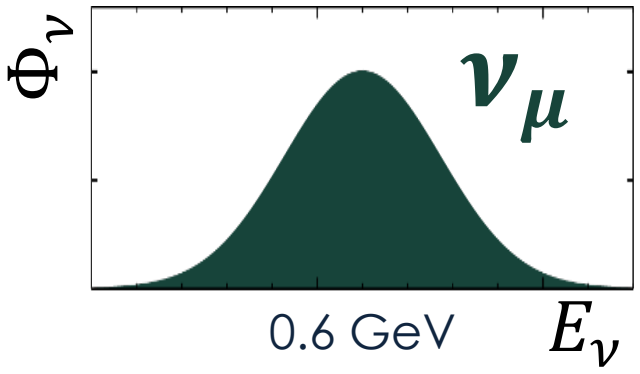
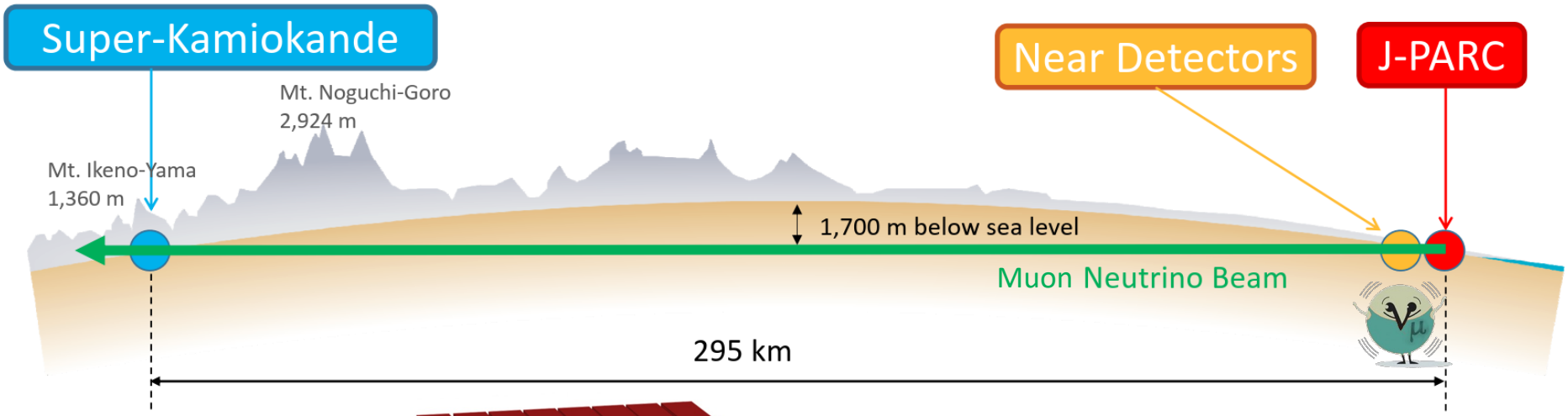
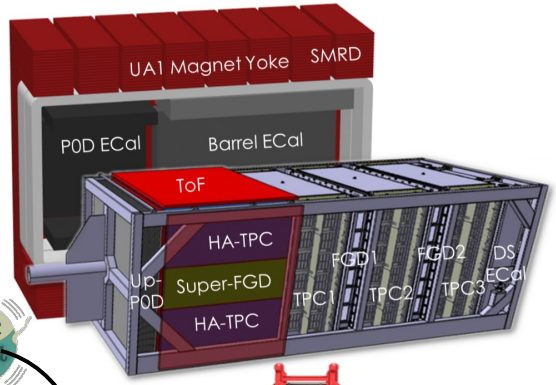
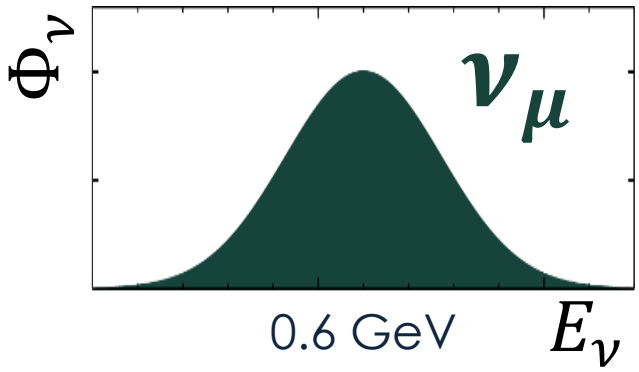
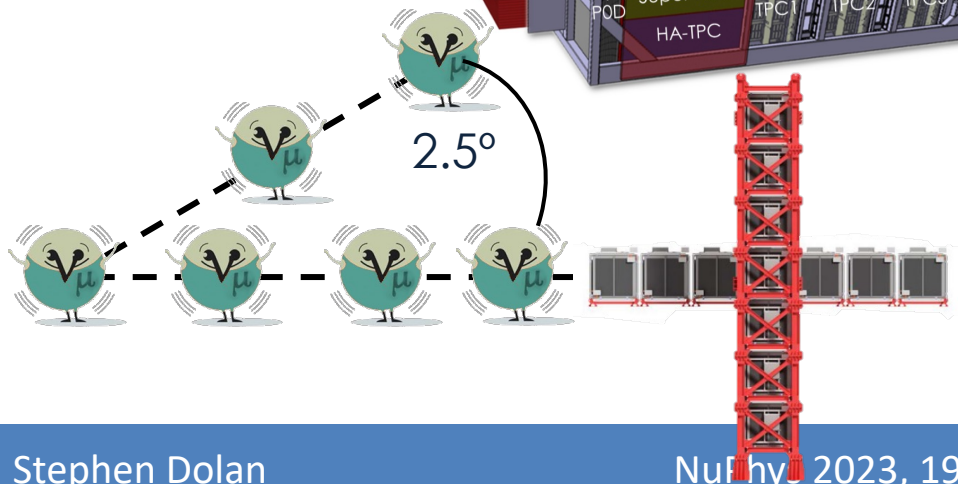

Φ_ν
ν_μ
0.6 GeV
E_ν

The T2K Near Detectors

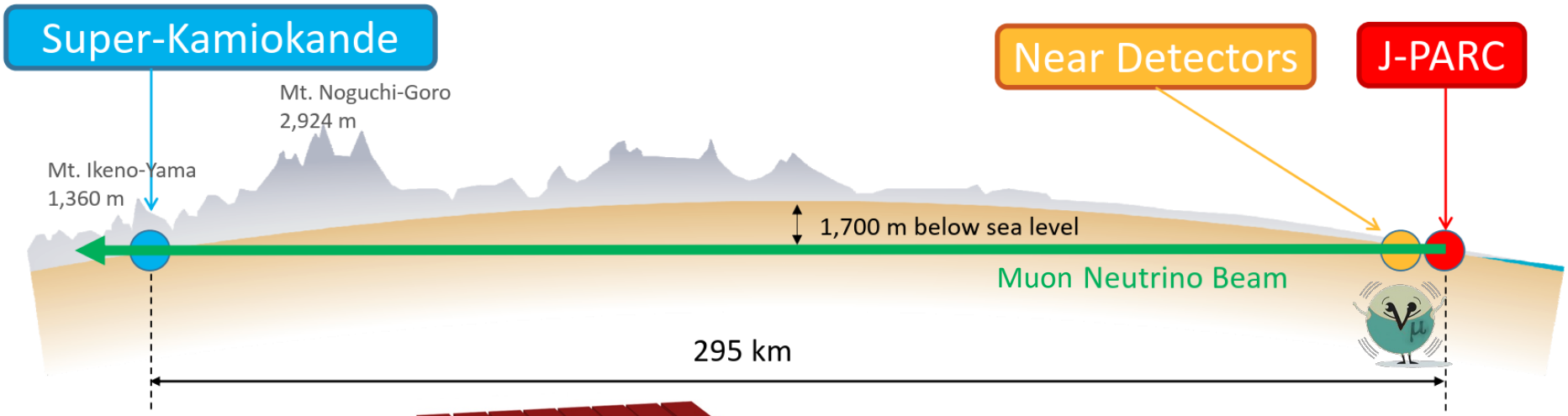


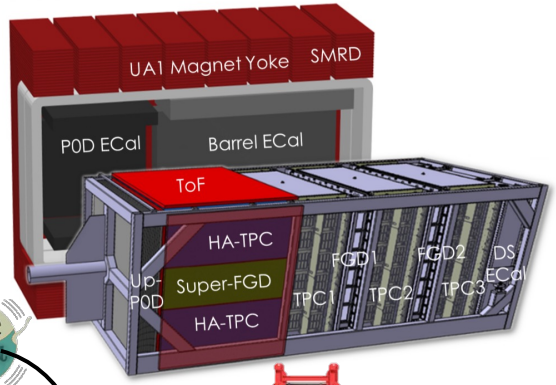


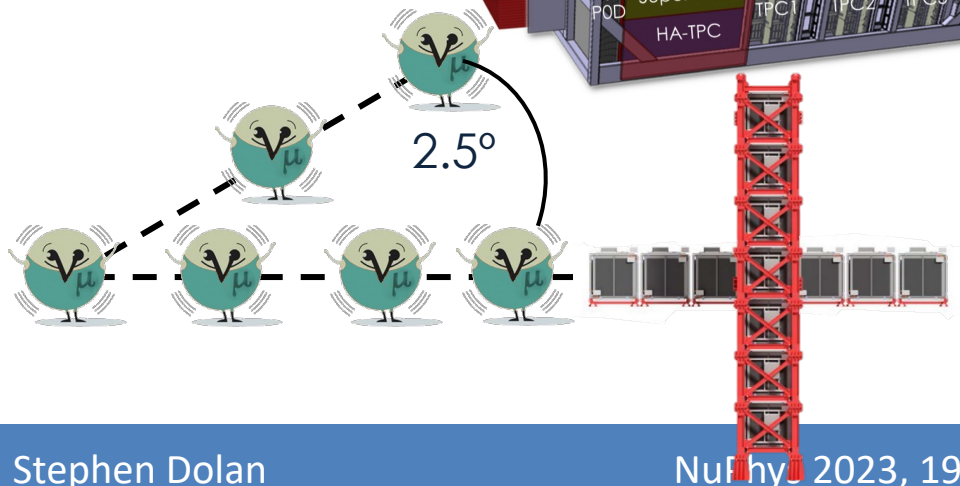


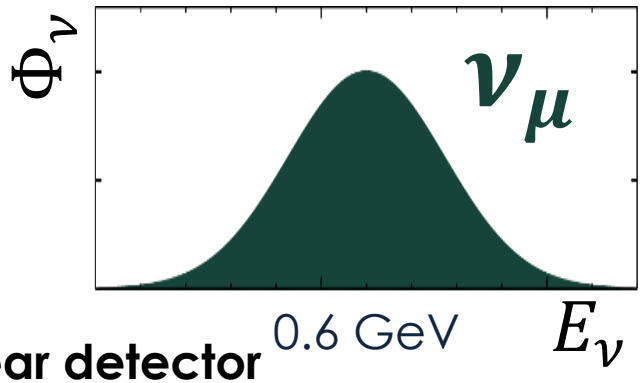


The T2K Near Detectors







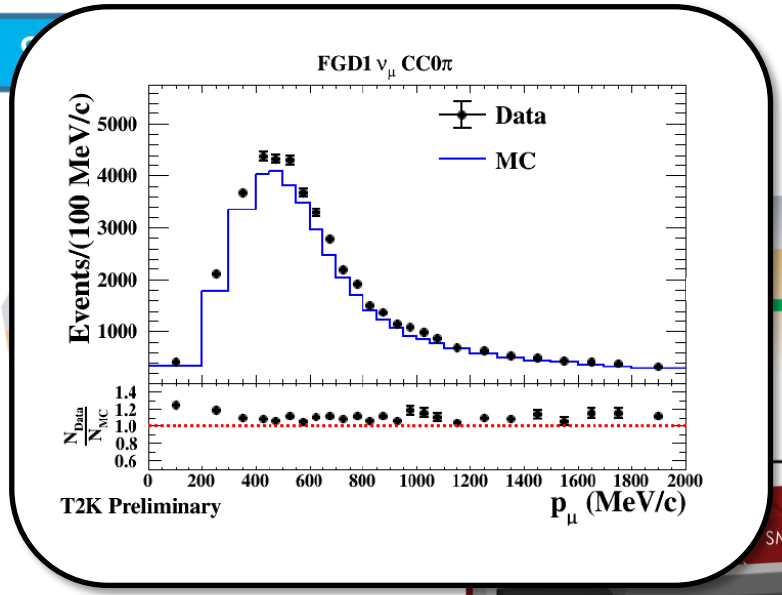


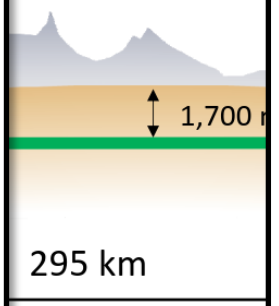
At the near detector

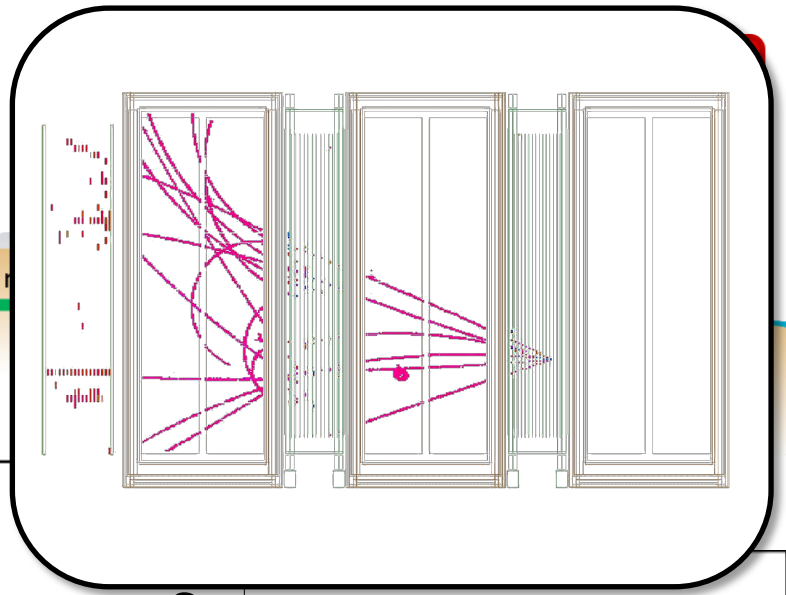
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

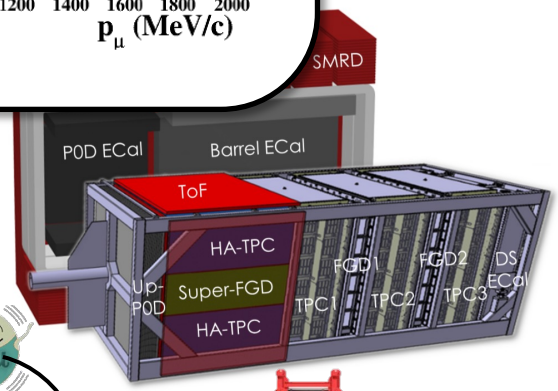
- Interaction cross section
- Neutrino flux
- Detector effects

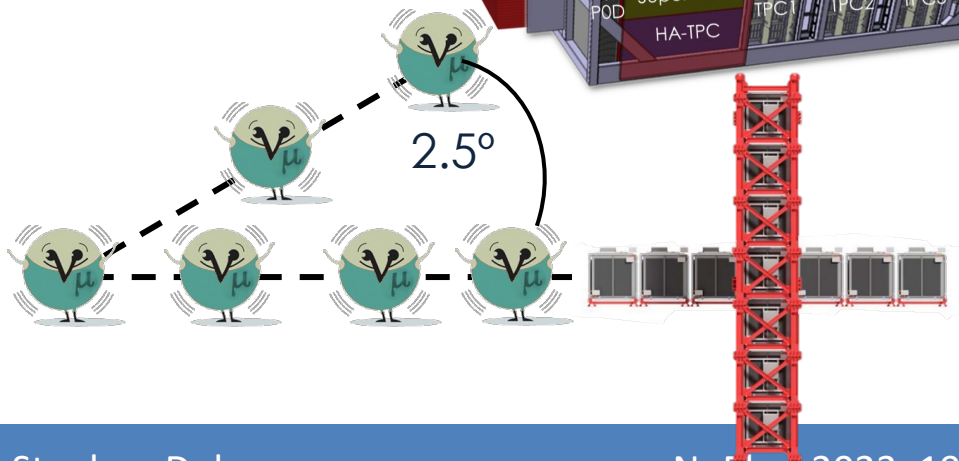
The T2K Near Detectors











At the near detector

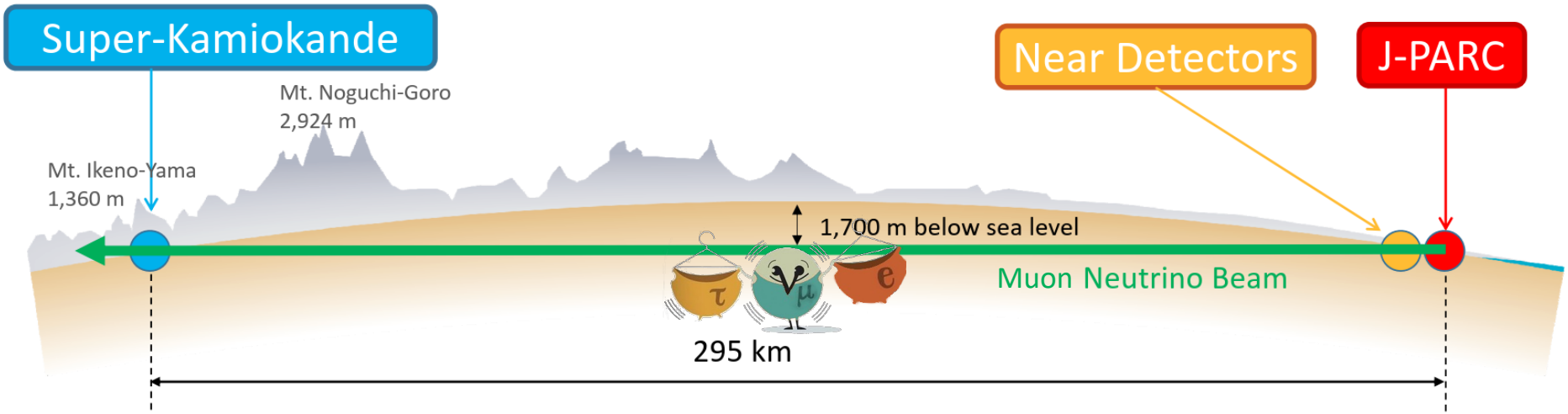
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

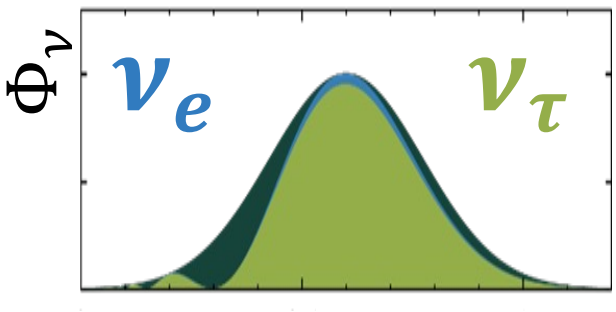
Interaction cross section

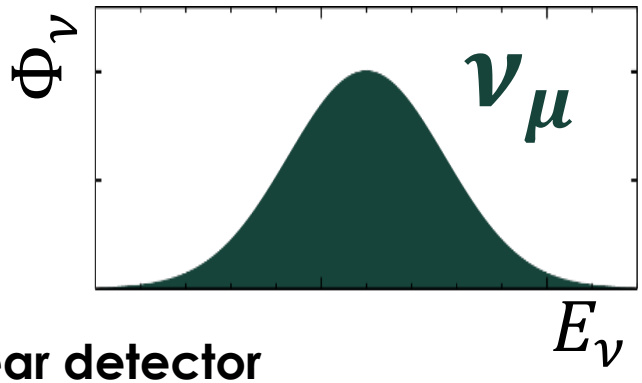
Neutrino flux

Detector effects

Oscillations at T2K







At the near detector

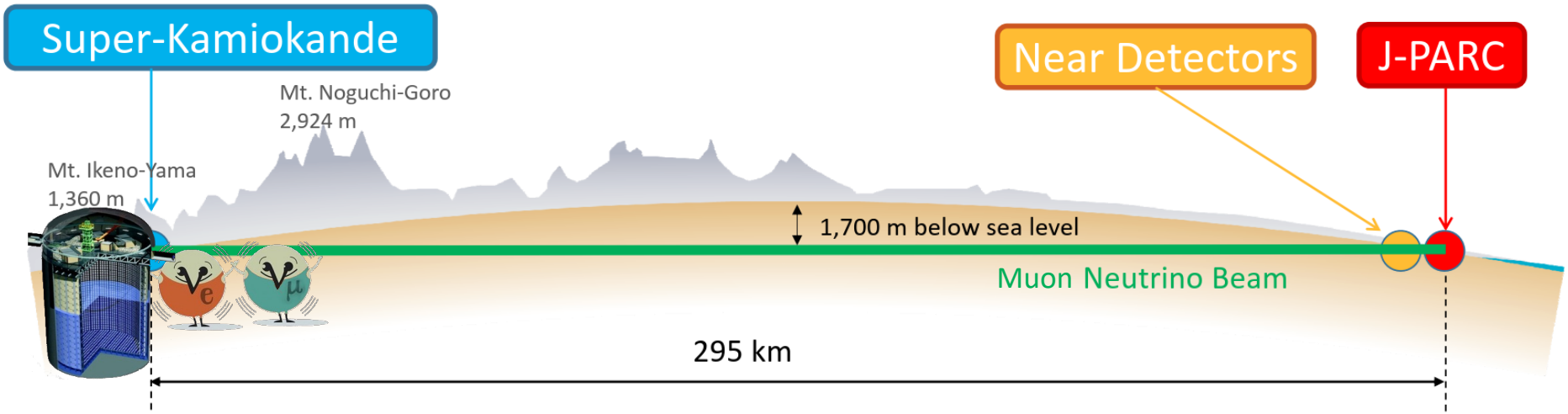
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

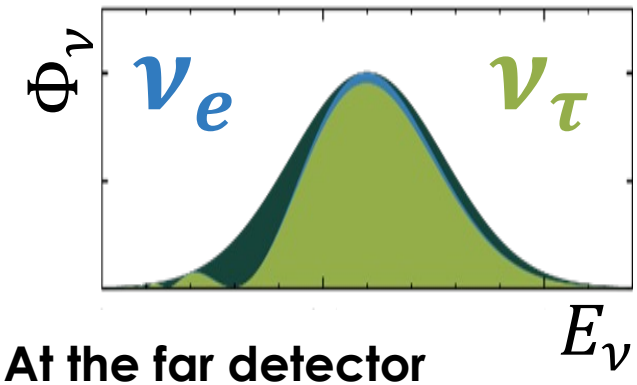
Interaction cross section

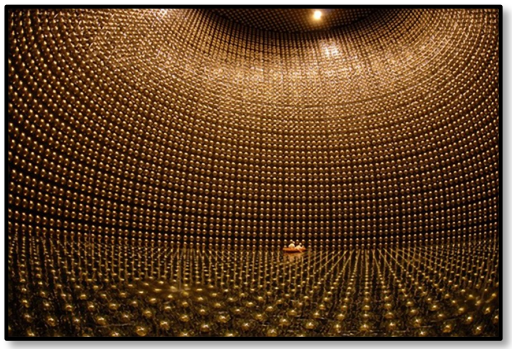
Neutrino flux

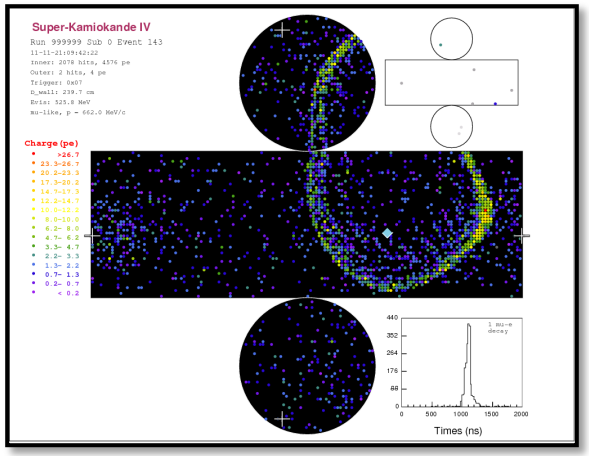
Detector effects

The T2K Far Detector









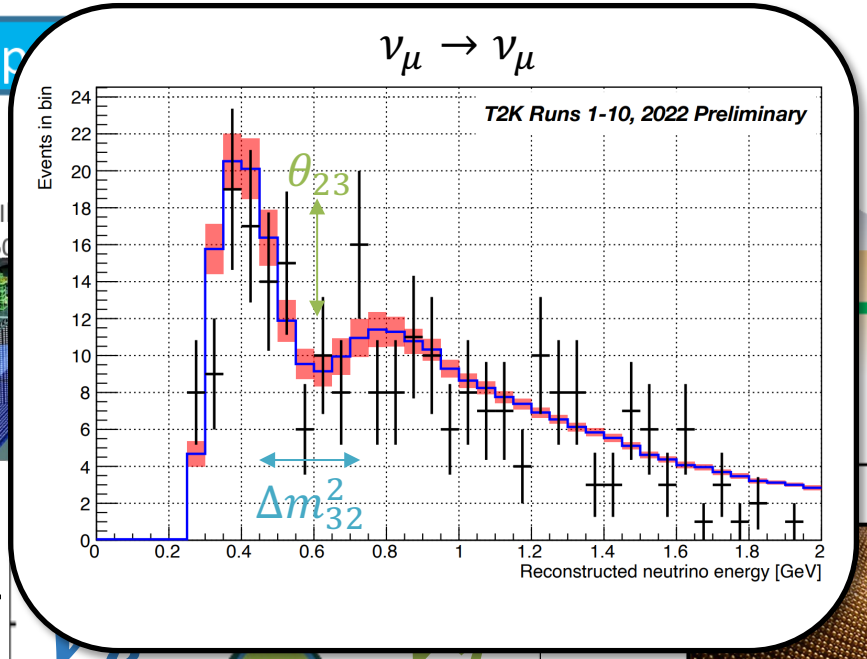
At the far detector

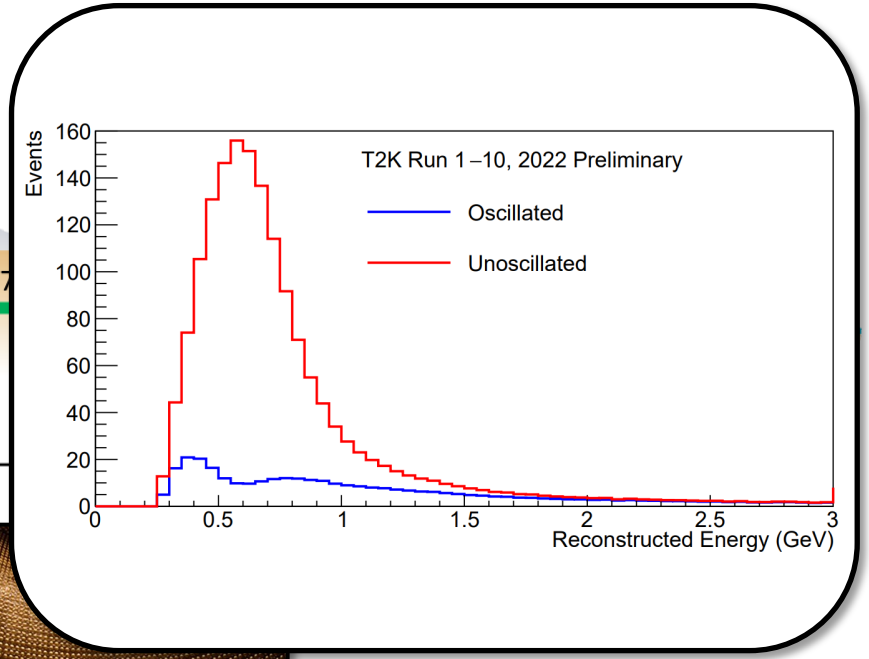
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

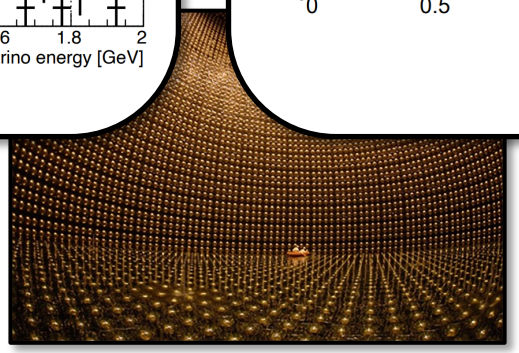
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

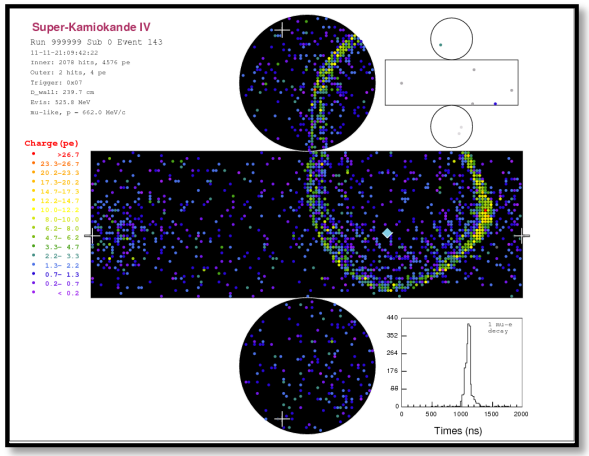
Oscillation probability

The T2K Far Detector









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Oscillation probability

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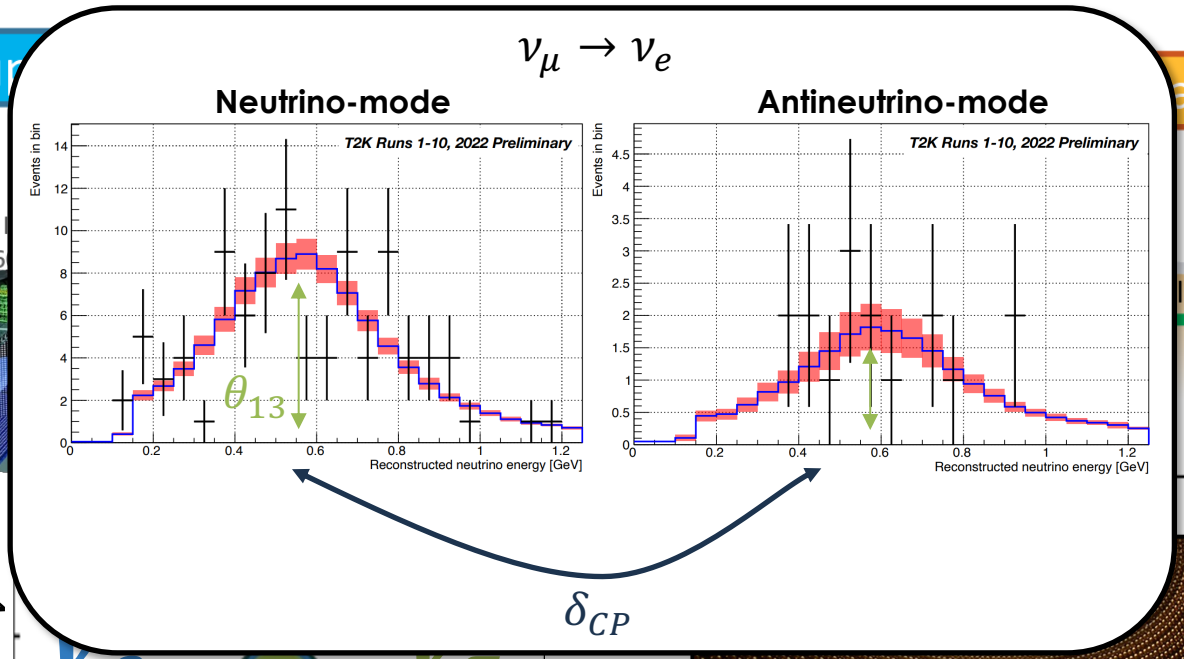

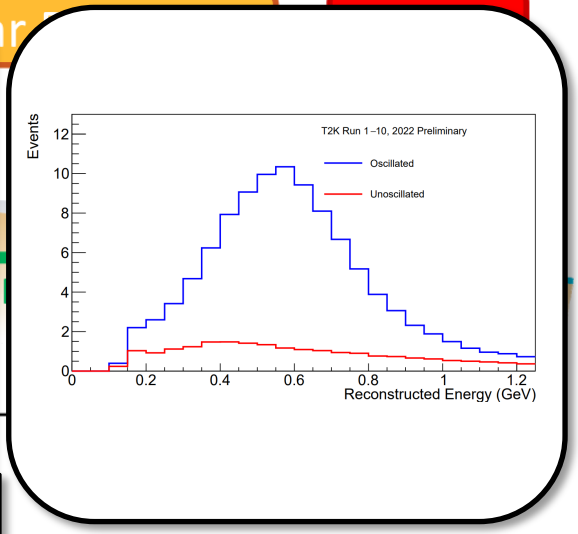

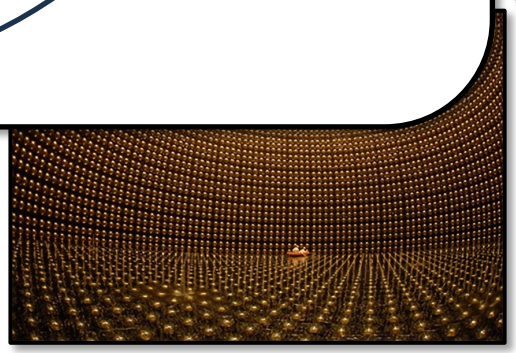

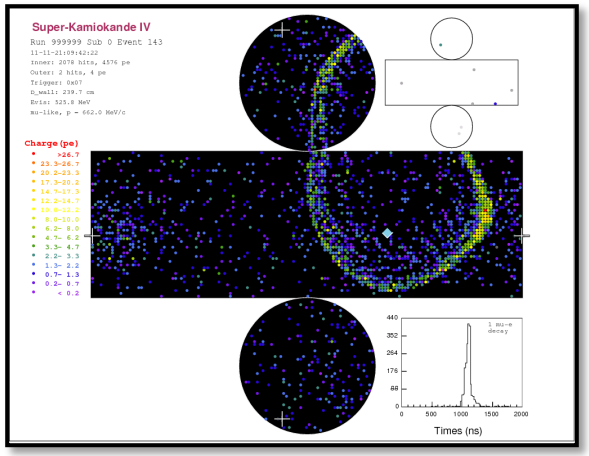

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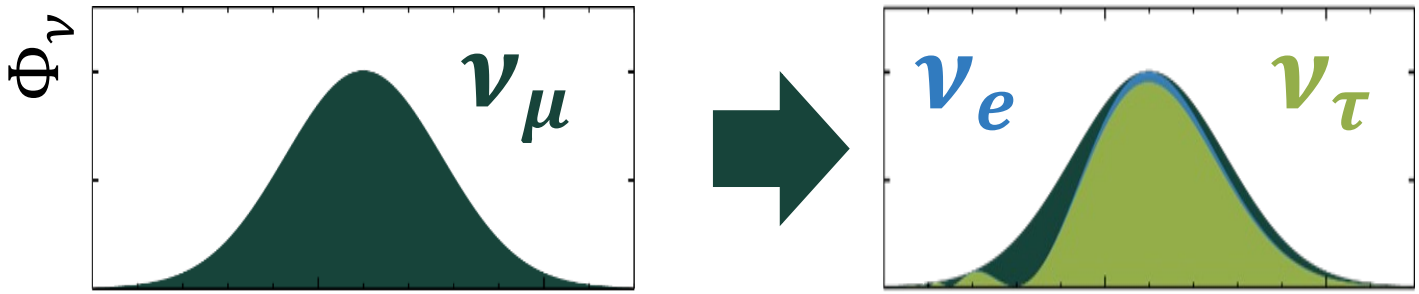
Oscillation probability

Our latest oscillation results

Updated with respect to our latest publication
(Eur. Phys. J. C (2023) **83**: 782)

First presented at Neutrino 2022

Analysis Strategy in a nutshell



At the near detector

$$N_\mu^{ND}(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

ND Detector effects

At the far detector

$$N_\mu^{FD}(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

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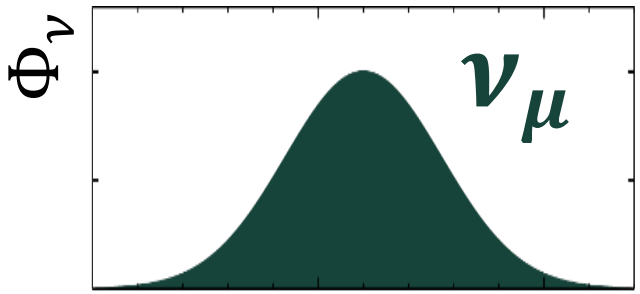
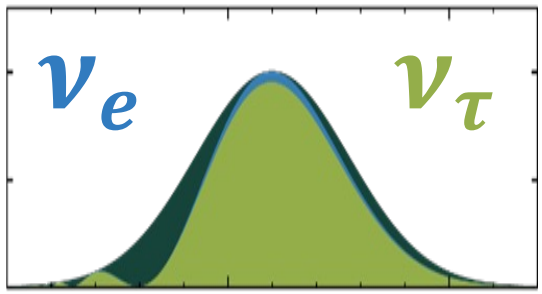
Oscillation probability

FD Detector effects

Analysis Strategy in a nutshell





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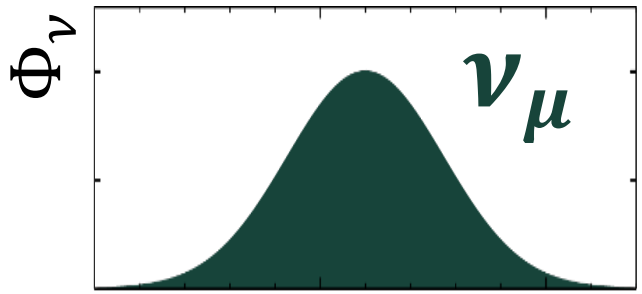
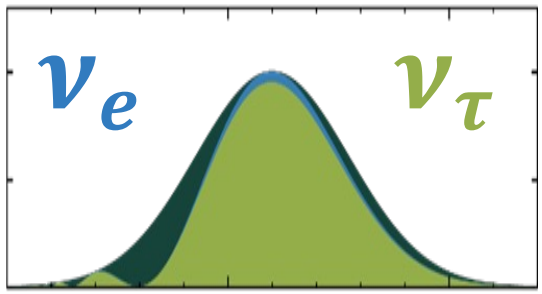
Oscillation probability

FD Detector effects

1. Parametrise a model for **these**, fit to N_μ^{ND} to constrain them

Analysis Strategy in a nutshell





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Interaction cross section

Neutrino flux

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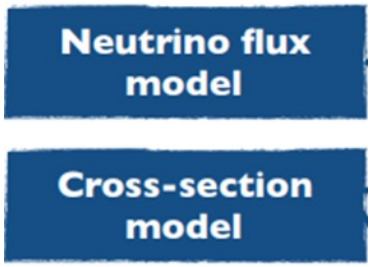
Oscillation probability

FD Detector effects

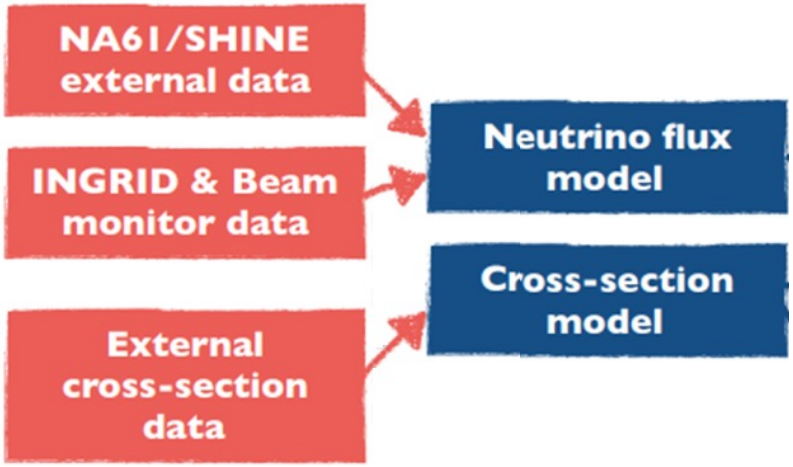
1. Parametrise a model for **these**, fit to N_μ^{ND} to constrain them

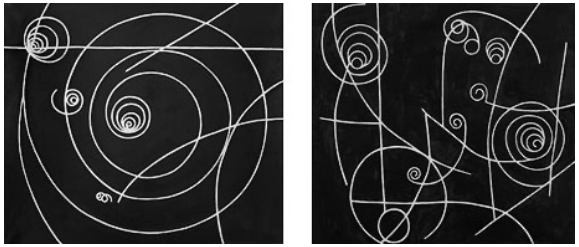
2. Fit **PMNS parameters** to N_μ^{FD} and N_e^{FD} alongside constrained model parameters from 1

Analysis Strategy

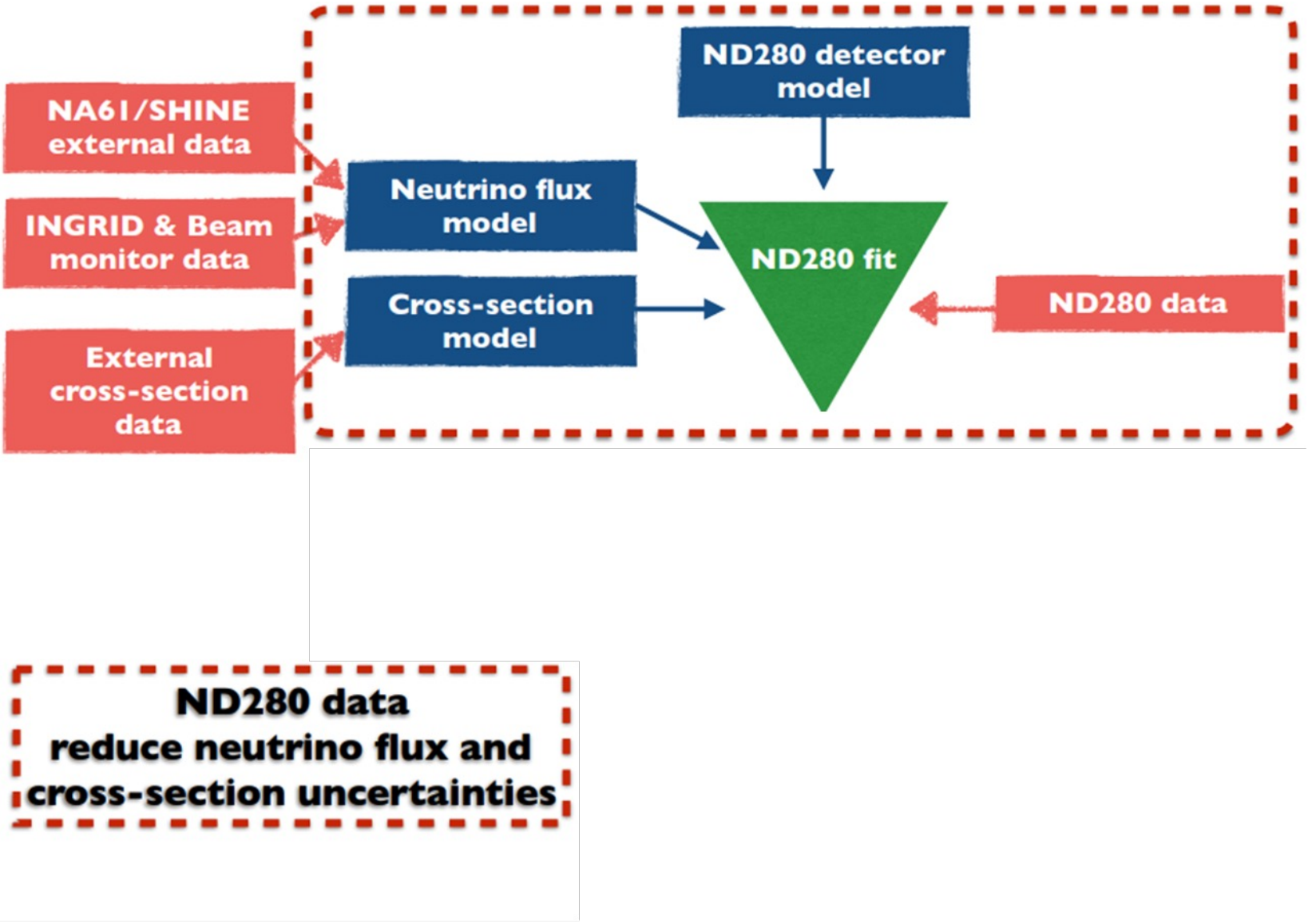


Analysis Strategy

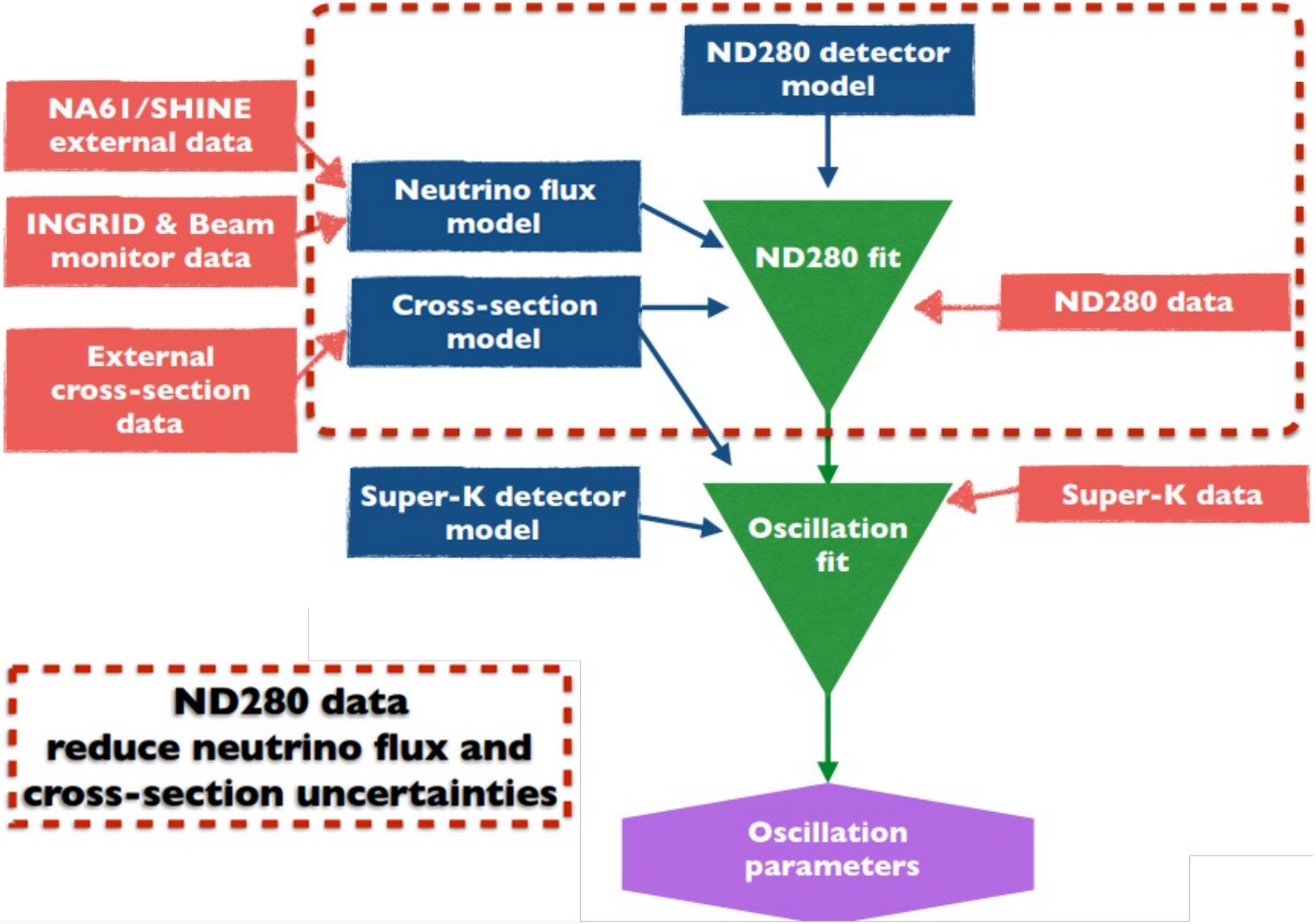




Analysis Strategy

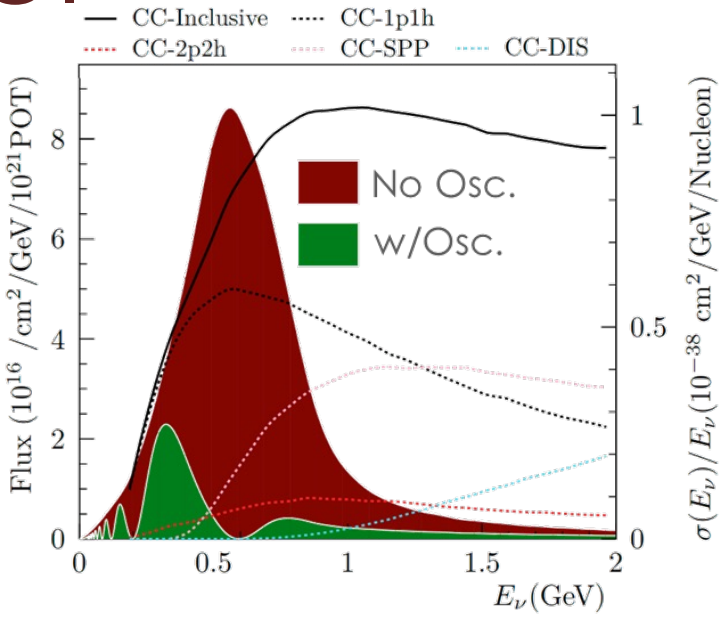


Analysis Strategy

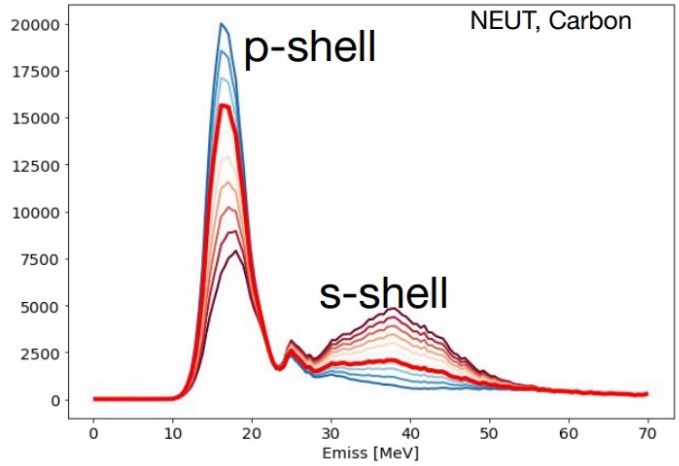


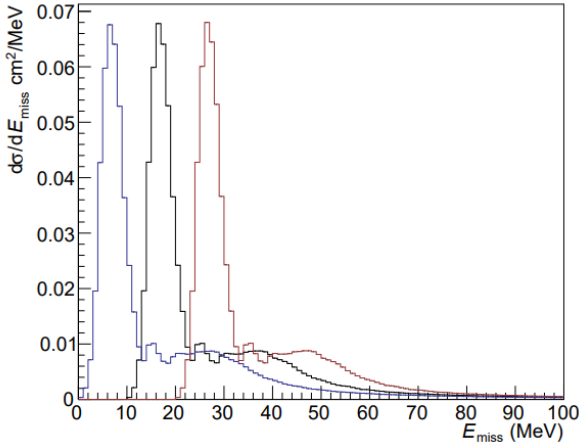
ν-interaction model

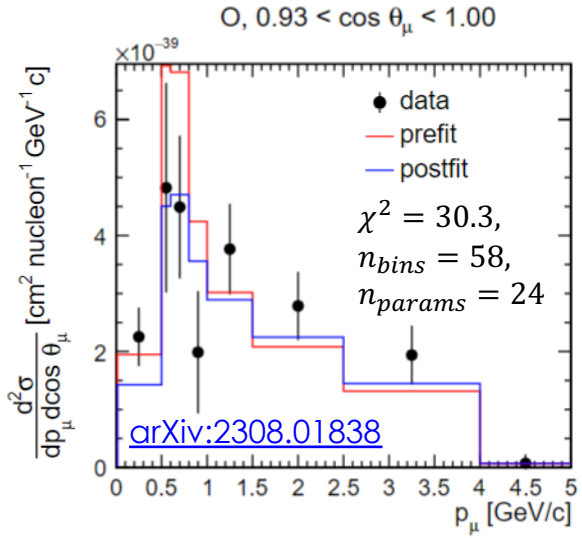
- 74 parameters covering the physics most relevant at T2K's energies. E.g.:
  - New parameterisation of the Spectral function nuclear ground state model
  - Updated treatment of nucleon correlations and FSI
- Benchmarked and validated against cross-section measurements



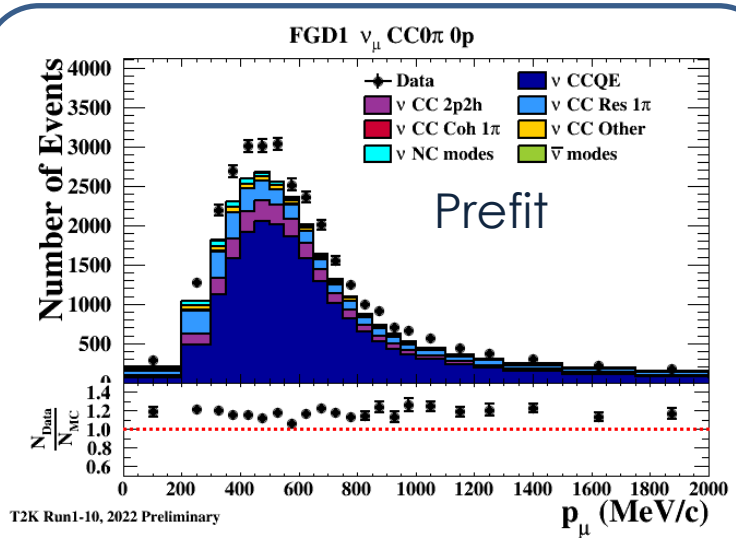
[See T2K's talk at NuINT 2022]



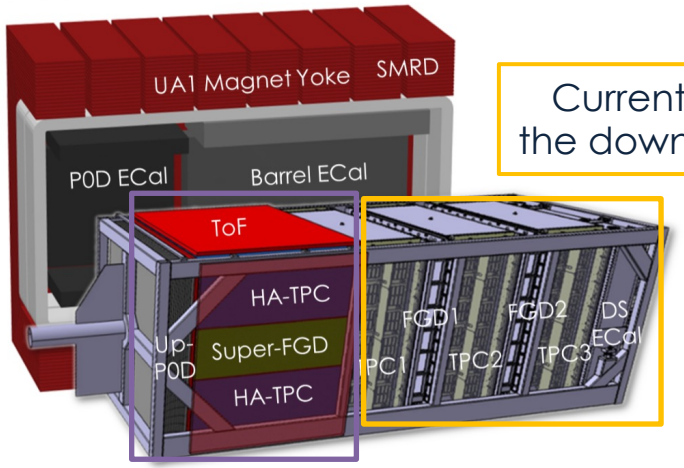




Near Detector Fit

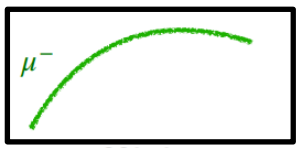


- Fit flux, cross-section, detector model parameters to 22 ND280 samples.

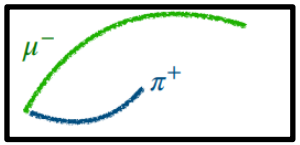


Current analysis uses the downstream tracker

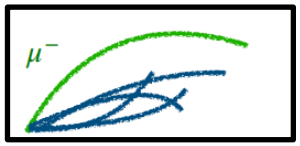
First data from the upstream upgrade detectors is being taken now!



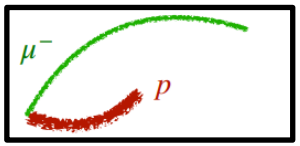
CC0π 0p



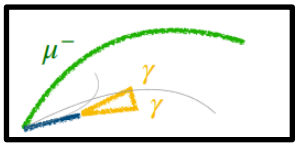
CC1π



CCOther

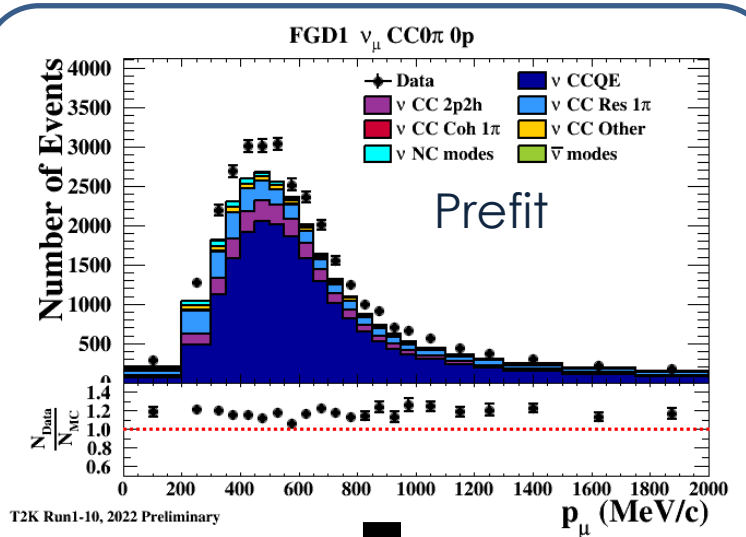


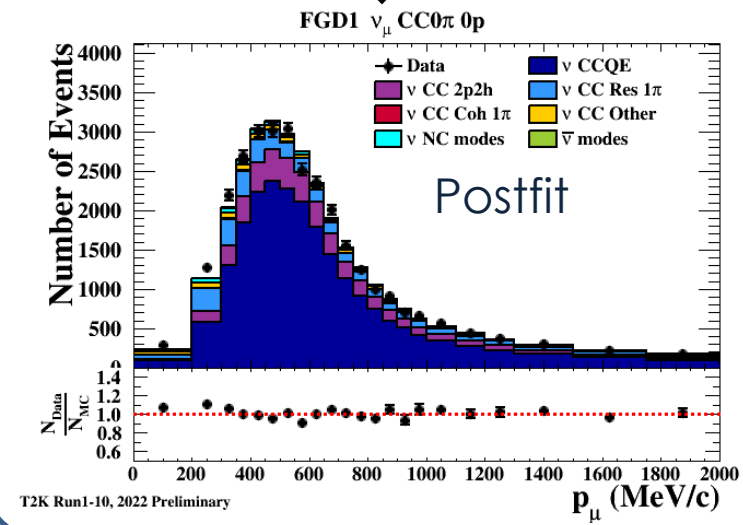
CC0π Np



CCPhoton

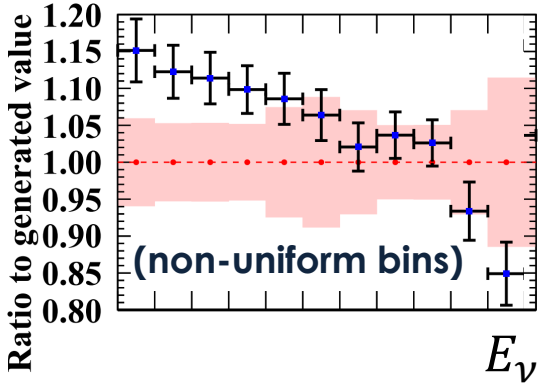
Near Detector Fit



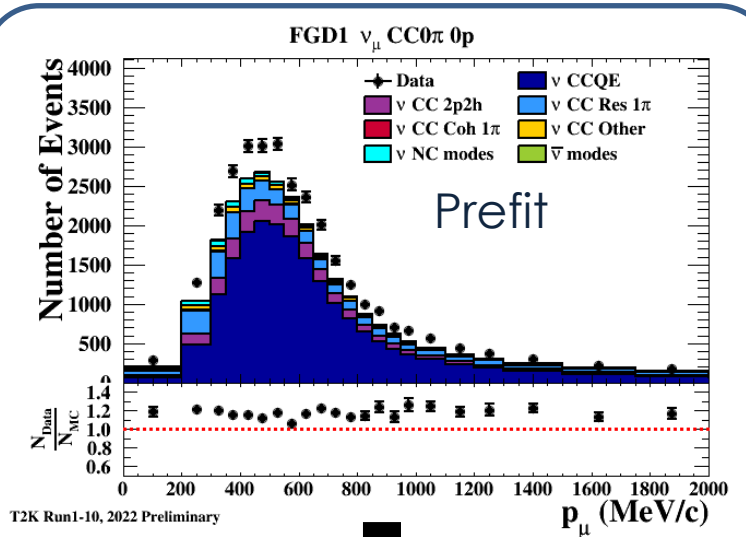


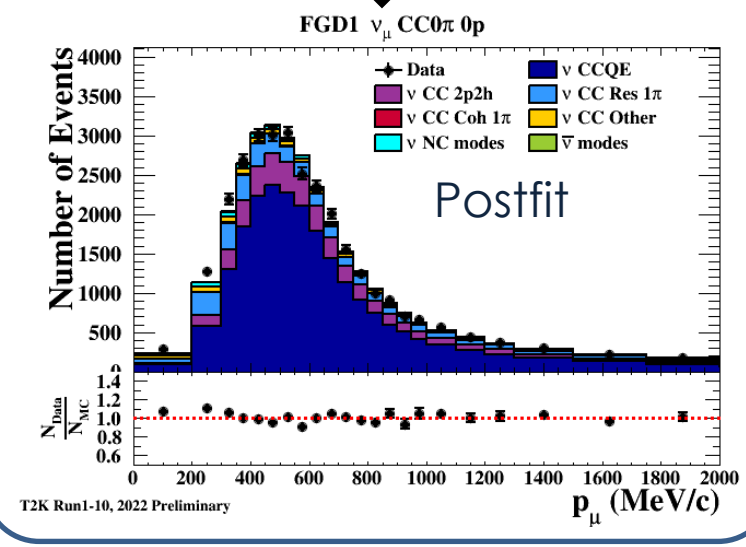
- Fit flux, cross-section, detector model parameters to 22 ND280 samples.

Example: constraint on flux parameters



Near Detector Fit





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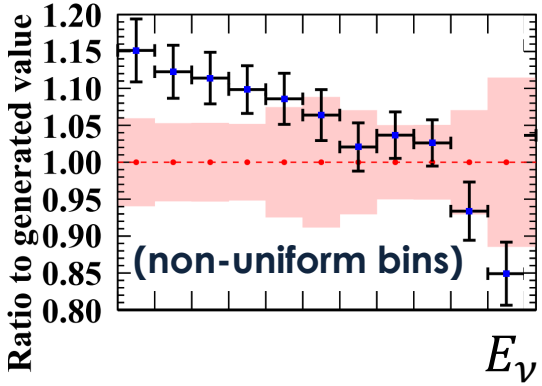
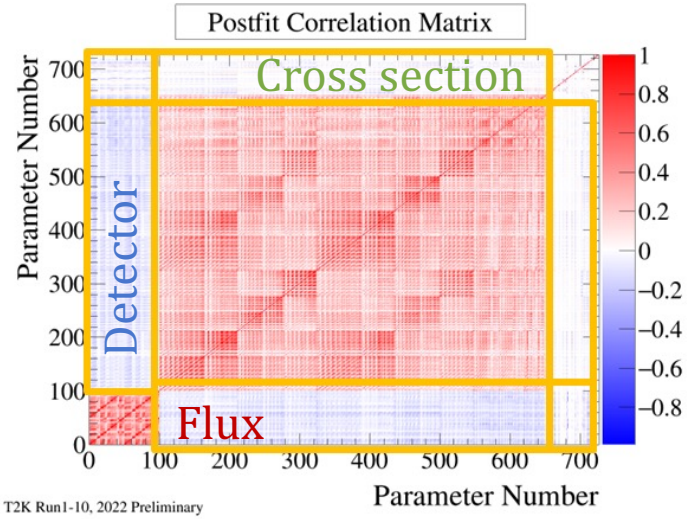
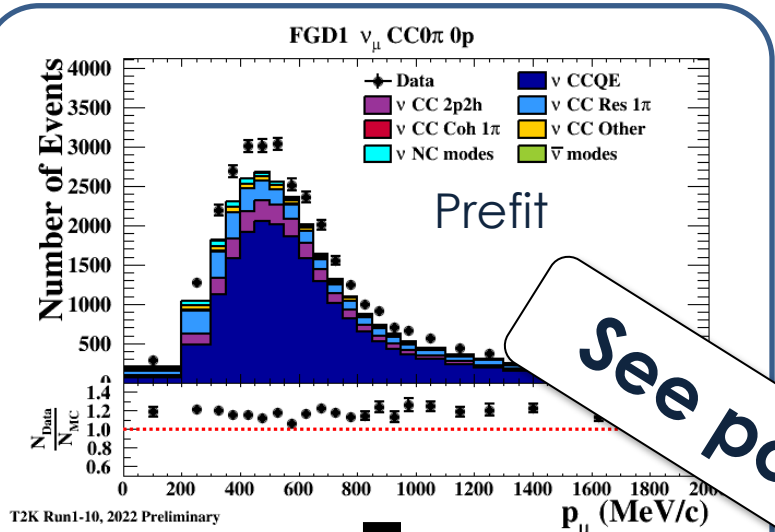


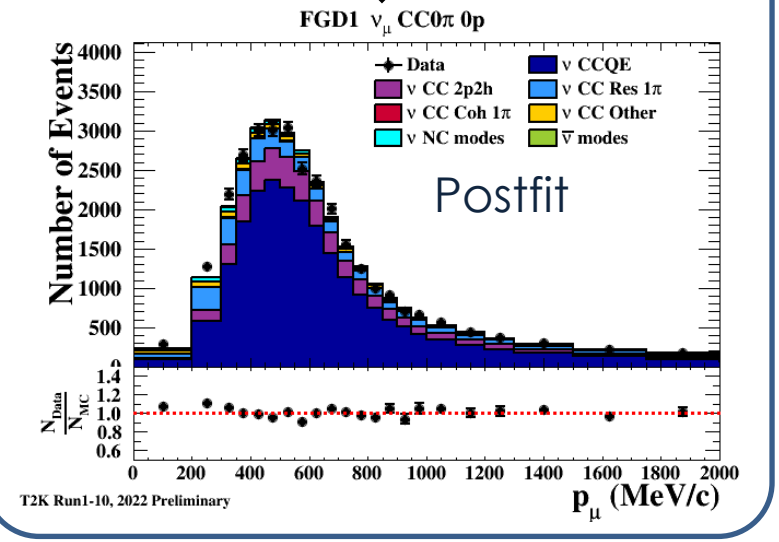
Fit provides:

- Tuned parameters
- Constrained parameters
- Correlations between them



Near Detector Fit





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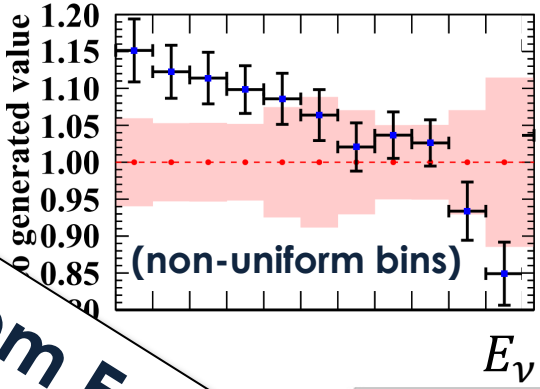

See poster from E. Miller

Fit provides:

- Tuned parameters
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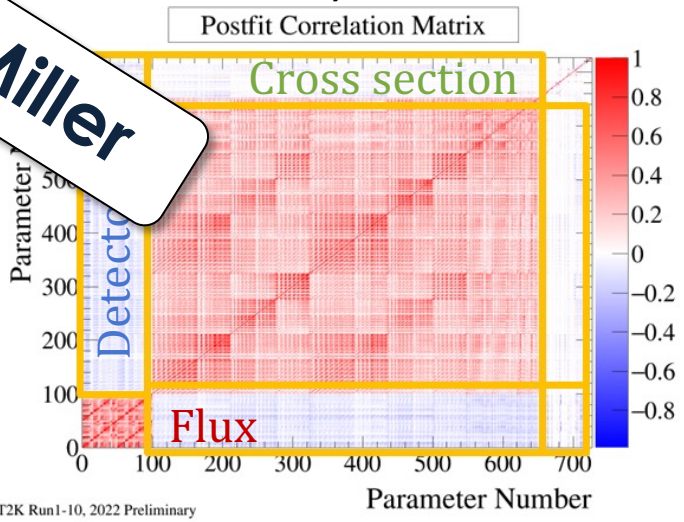
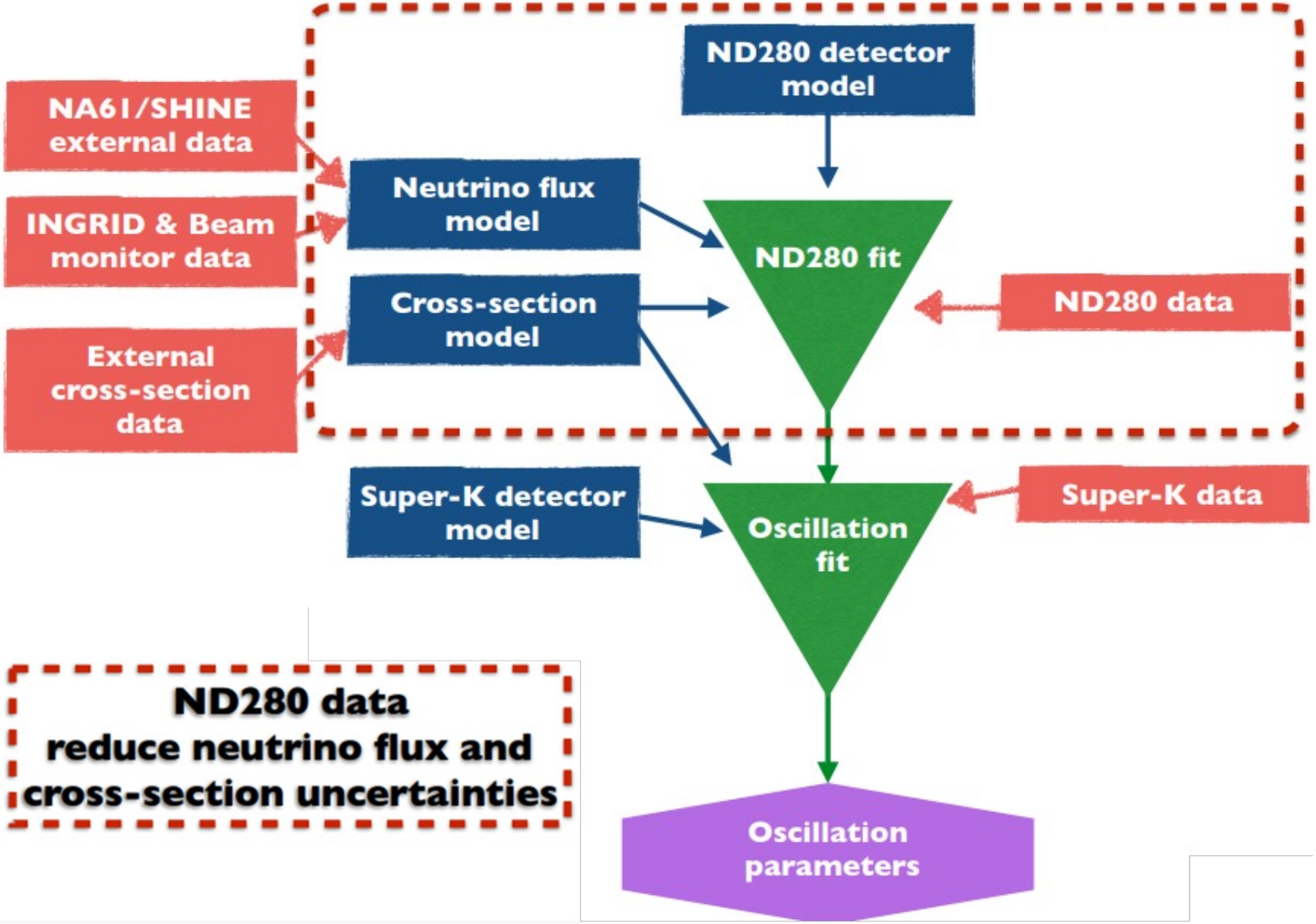
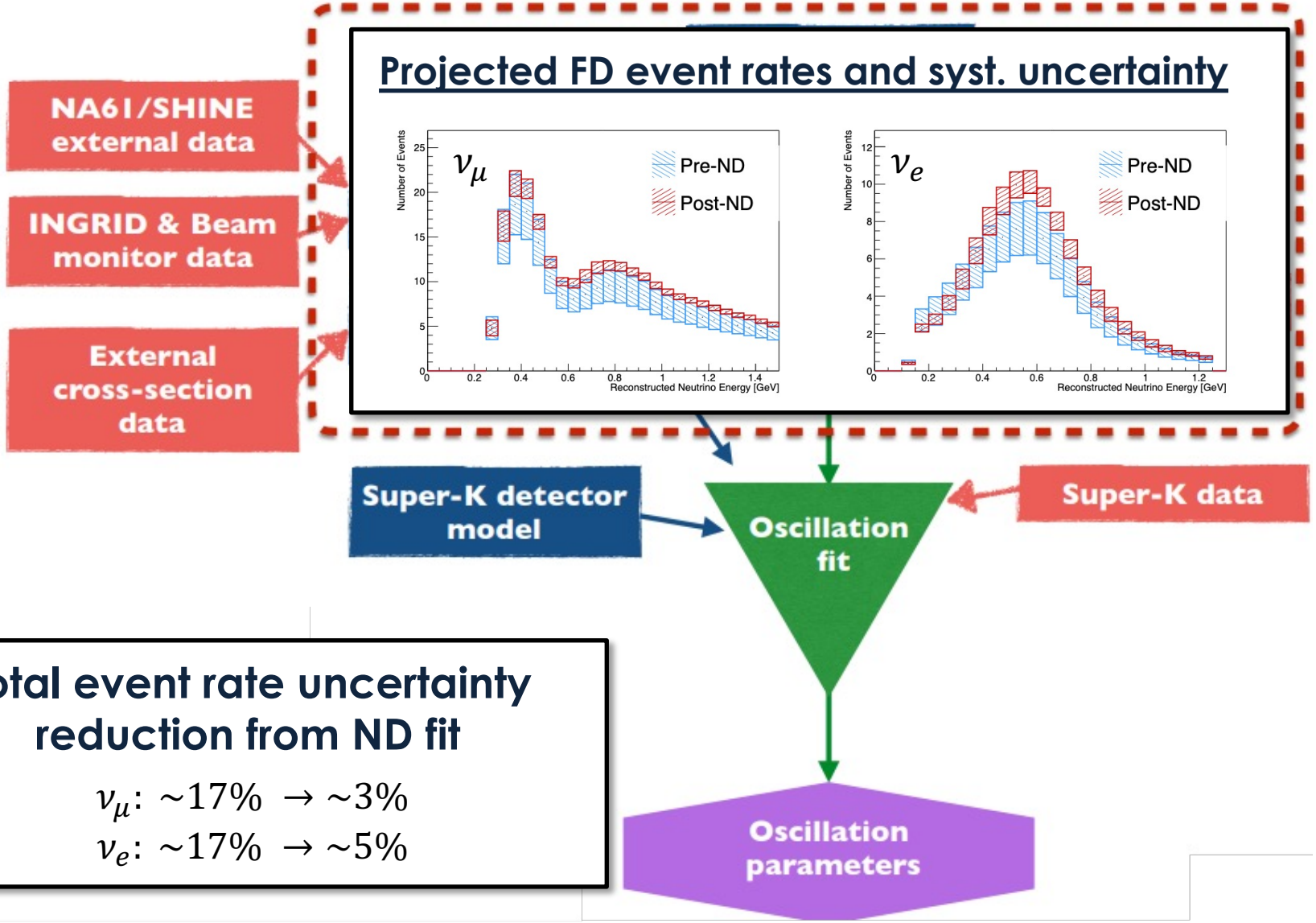


Analysis Strategy



Analysis Strategy

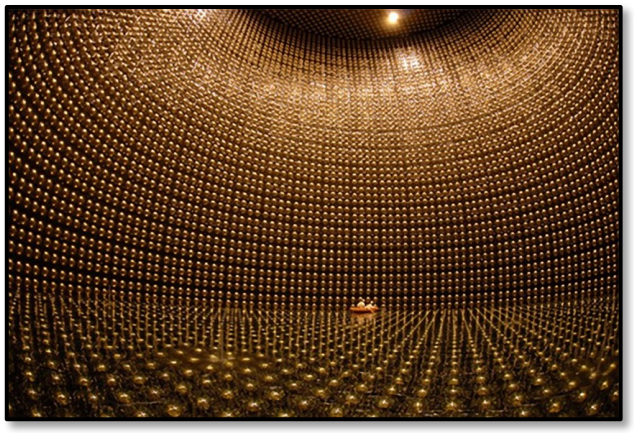


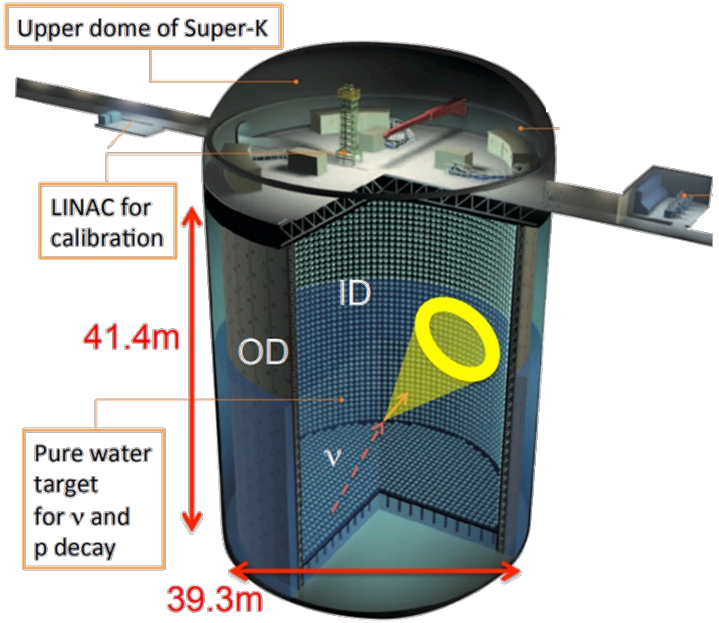
Total event rate uncertainty reduction from ND fit

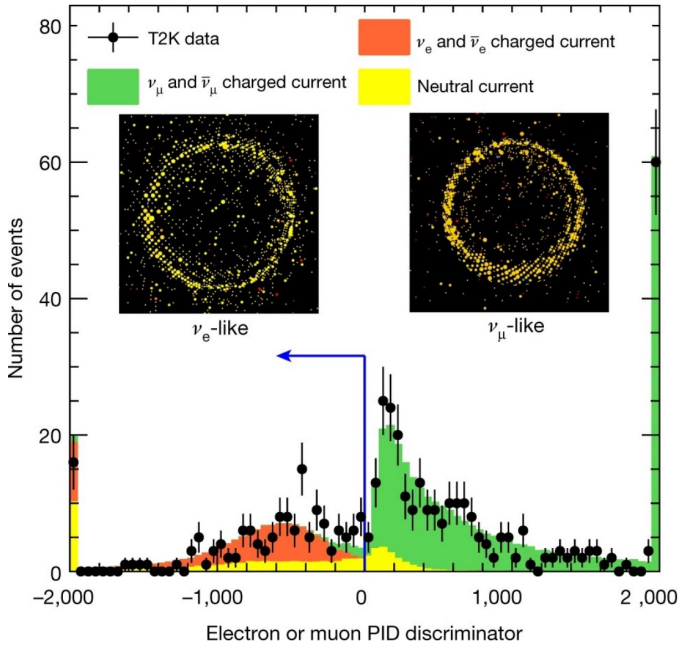
ν_μ: ~17% → ~3%

ν_e: ~17% → ~5%

Far Detector Fit



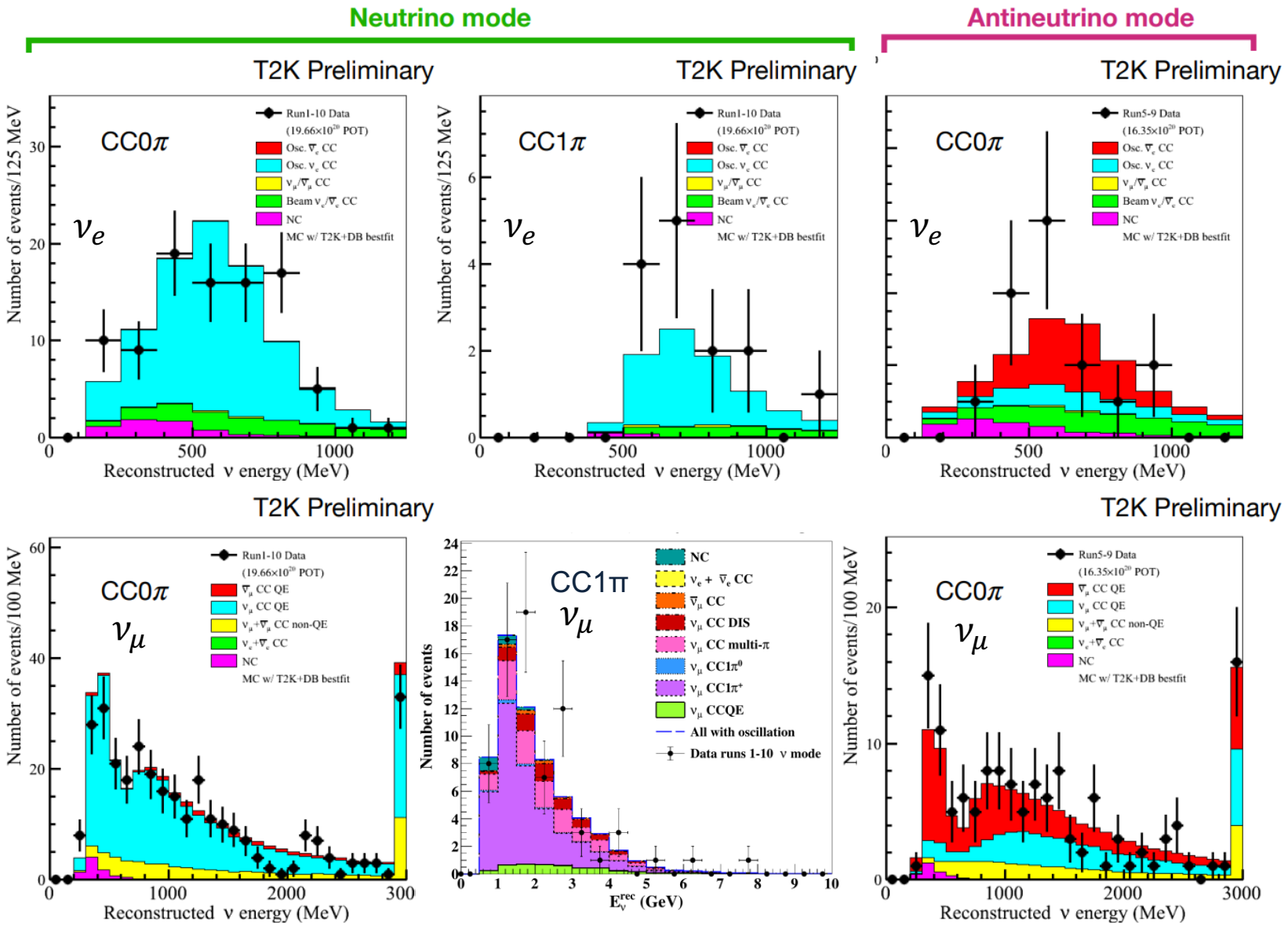




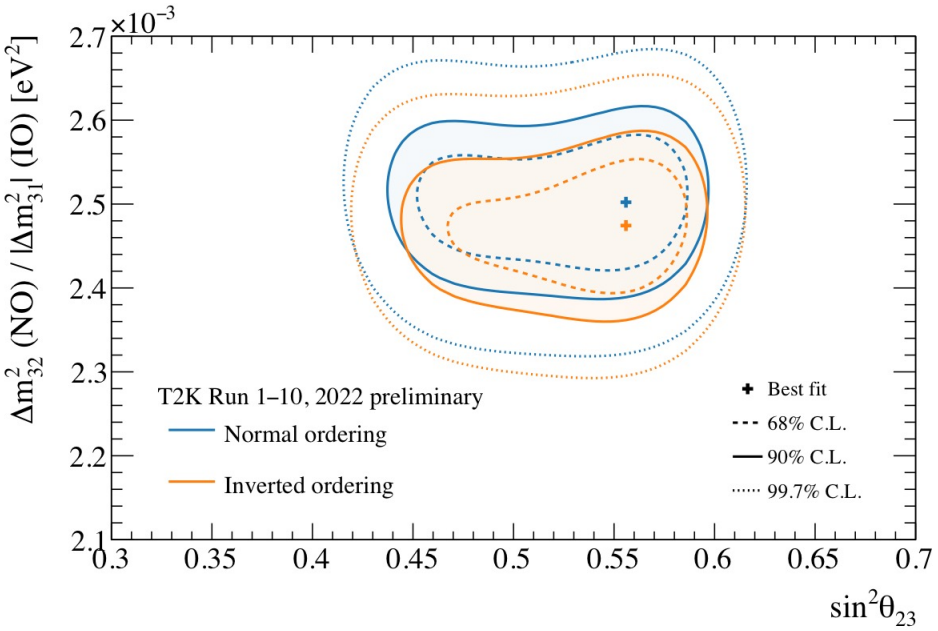
Super-K

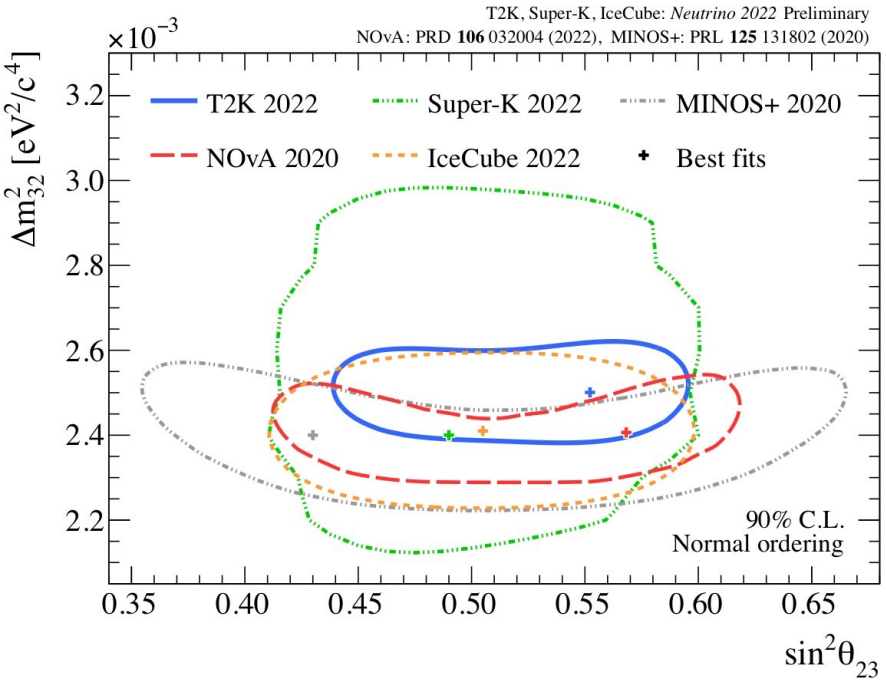
- 50 kton of ultra-pure water
- ~11,000 20” PMTs
- 1000 m under a mountain

Far Detector Fit



Far Detector Fit: ν_μ focus

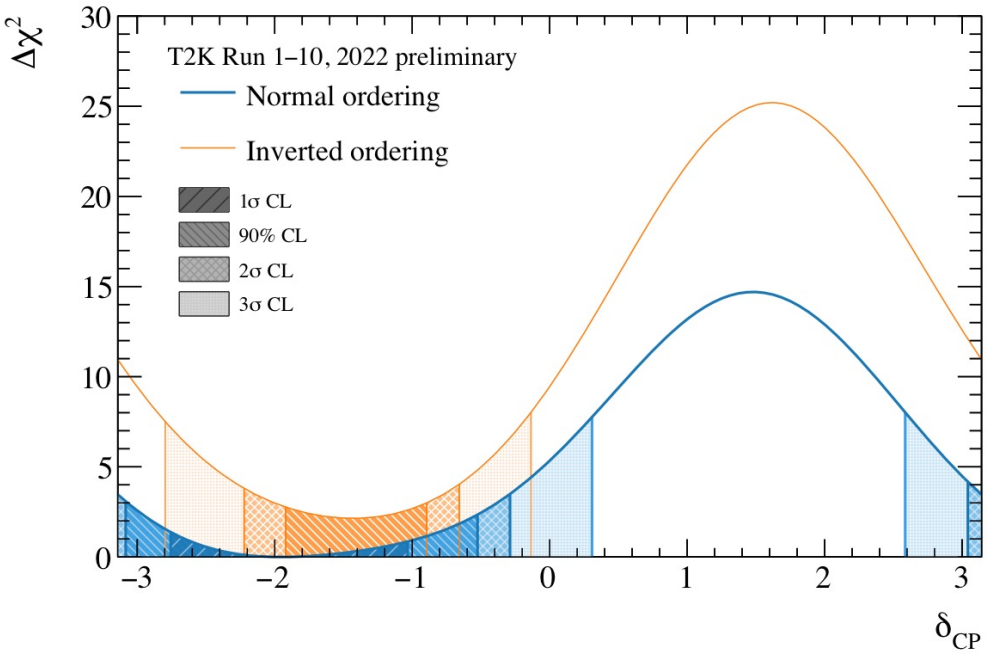


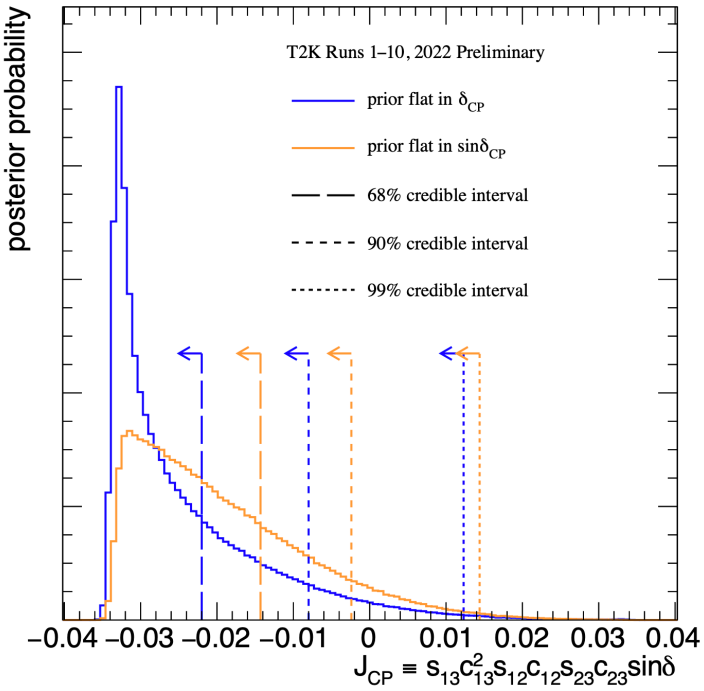


- Leading constraints on $\sin^2\theta_{23}$ and Δm^2_{32}
- Weak preference for the upper octant and normal mass ordering
  - Bayes factors of ~3 for both

Reactor neutrino constraint on θ_{13} always applied: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Far Detector Fit: ν_e focus





- Exclude CP-conserving values of δ_{CP} at between 90% and 2σ
- Exclude CP-conservation (Jarlskog invariant, J=0) at:
  - 2σ for a flat prior in δ_{CP}
  - 90% for a flat prior in $\sin\delta_{CP}$

PMNS-parameterisation independent metric for CPV

Reactor neutrino constraint on θ_{13} always applied: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Joint fit with Super-K

Atmospheric oscillations @ SUPER-K

- SK independently measures atmospheric neutrino oscillations
  - Sensitive to the mass ordering, but not to δ_{CP}

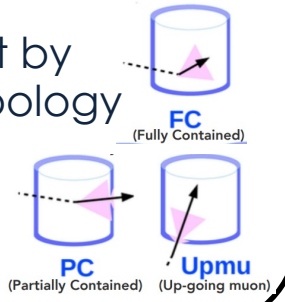
Atmospheric event samples

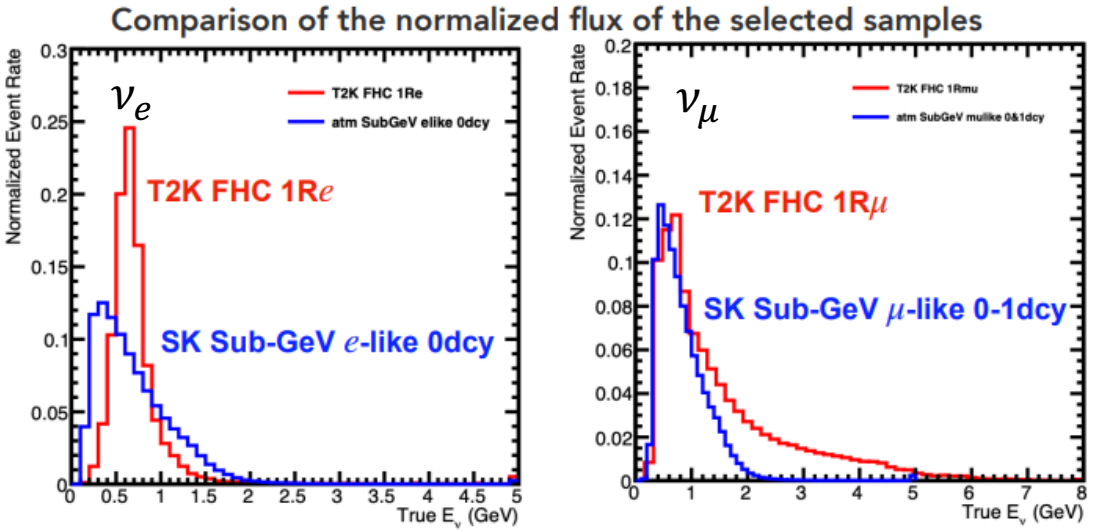
Based on [PTEP 2019 (2019) 5, 053F01]

3244 days of data taking

18 samples, split by energy and topology

Wider energy range than T2K





Atmospheric oscillations @ SUPER-K

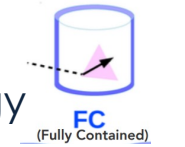
- SK independently measures atmospheric neutrino oscillations
  - Sensitive to the mass ordering, but not to δ_{CP}
- T2K's δ_{CP} constraints are **partially degenerate with the mass ordering**
  - SK inference on the mass ordering helps **lift this degeneracy**
- Systematic uncertainties can be **correlated and reduced**
  - **SK benefits from near detector** cross-section model constraints
  - Both benefit from **shared systematics** related to SK detector

Atmospheric event samples

Based on [PTEP 2019 (2019) 5, 053F01]

3244 days of data taking

18 samples, split by energy and topology



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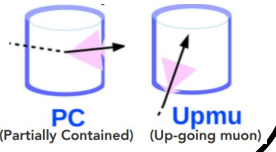
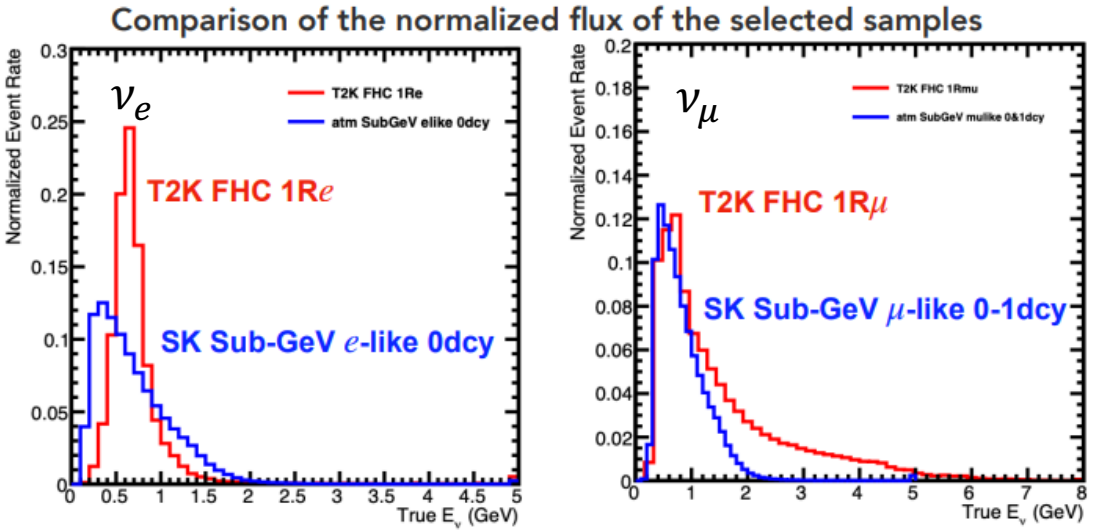
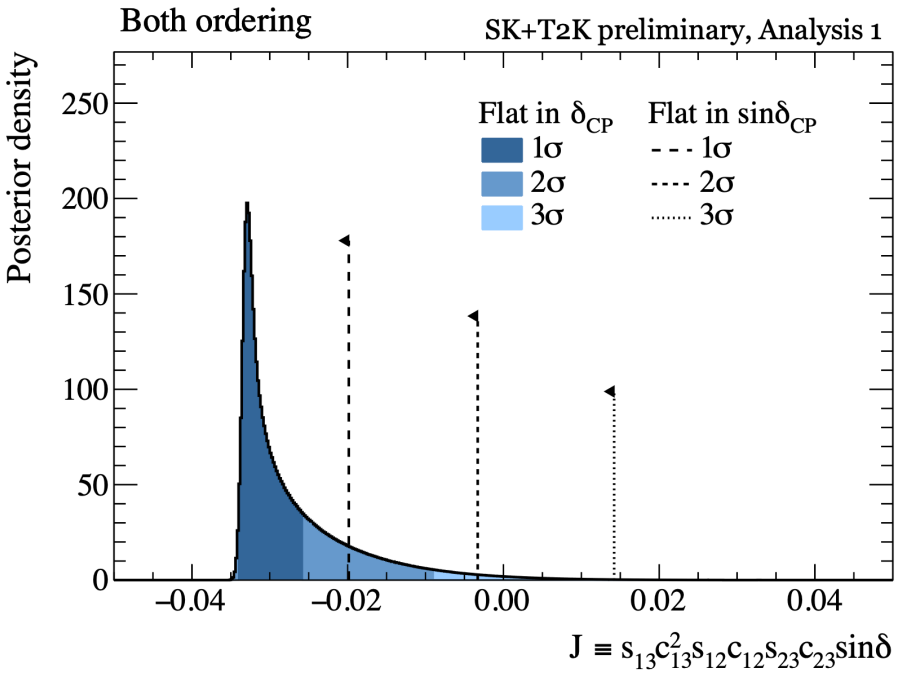
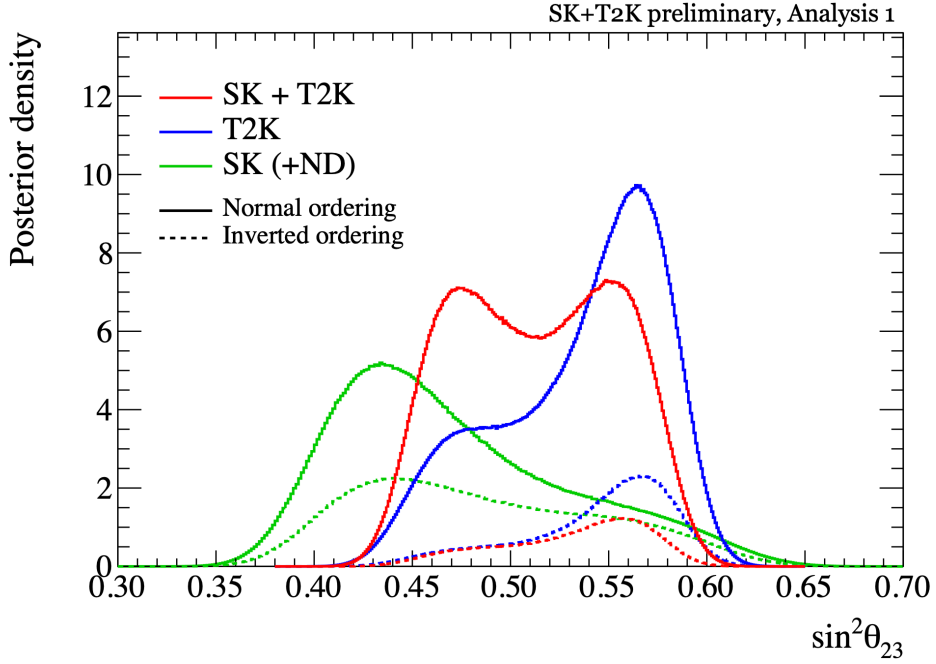




Joint fit results

- Stronger constraints on CPV compared to T2K only
  - J=0 excluded at ~2σ
- No appreciable octant preference
- Preference for normal mass ordering
  - 90% posterior probability





Prospects for precision

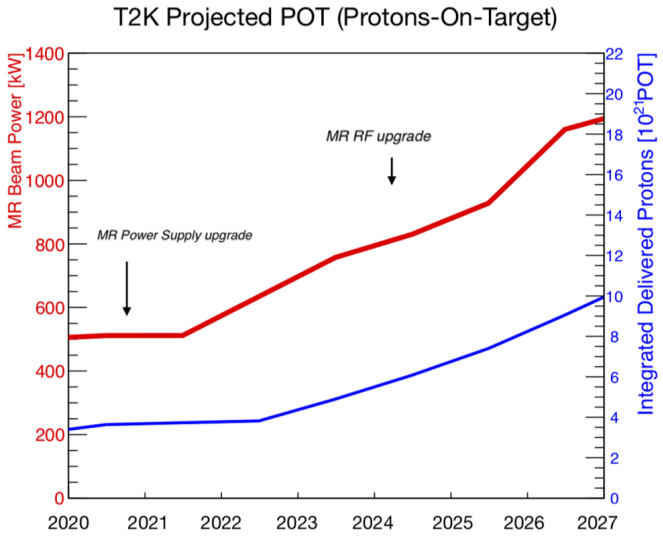
Event rates and systematics

- T2K remains largely limited by statistical uncertainties
  - First priority: more data!

Dominant SK Sample	# events	Stat. uncertainty	Total syst. uncertainty
$\nu_\mu \rightarrow \nu_\mu$	318	5.6%	3.4%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	137	8.5%	3.9%
$\nu_e \rightarrow \nu_e$	94	10%	5.2%
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	16	25%	5.8%

Event rates and systematics

- T2K remains largely limited by statistical uncertainties
  - First priority: more data!
- Recently completed beam upgrade
  - Expect accelerated data taking!
  - Beam power has been stable at >700 kW



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Dominant SK Sample	# events	Stat. uncertainty	Total syst. uncertainty	ν-int. model uncertainty
$\nu_\mu \rightarrow \nu_\mu$	318	5.6%	3.4%	3.7%*
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	137	8.5%	3.9%	3.5%
$\nu_e \rightarrow \nu_e$	94	10%	5.2%	3.8%
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	16	25%	5.8%	3.5%

*The ν-int. model uncertainty is larger than the total error due to anti-corelations with other sources

Event rates and systematics

- T2K remains largely limited by statistical uncertainties
  - First priority: more data!
- Recently completed beam upgrade
  - Expect accelerated data taking!
  - Beam power has been stable at >700 kW
- Neutrino interaction systematics are playing an increasingly large role
  - Potential biases from out-of-model alterations contribute significantly

(See backups for details)

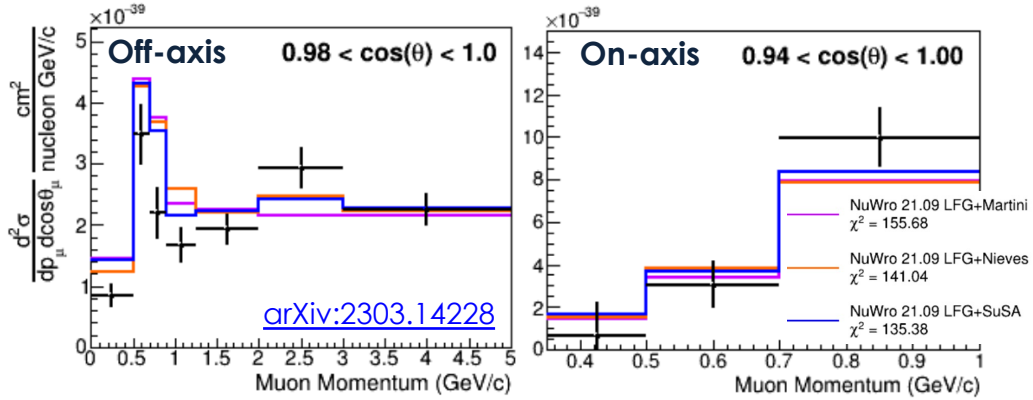
Parameter	Total uncertainty	Stat. uncertainty	Syst. uncertainty	Extra uncertainty from mock data studies
Δm^2_{32}	~2.4%	~1.9%	~0.8%	~1.2%

(Estimated from Asimov fits, not real data)

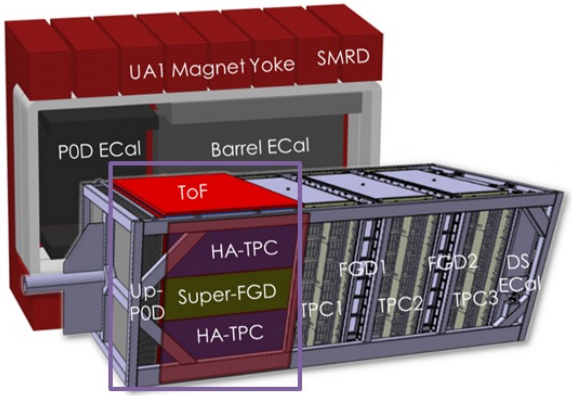
Event rates and systematics

- T2K remains largely limited by statistical uncertainties
  - First priority: more data!
- Recently completed beam upgrade
  - Expect accelerated data taking!
  - Beam power has been stable at >700 kW
- Neutrino interaction systematics are playing an increasingly large role
  - Potential biases from out-of-model alterations contribute significantly
  - Next priority: better interaction modelling and near-detector constraints

New cross-section measurements

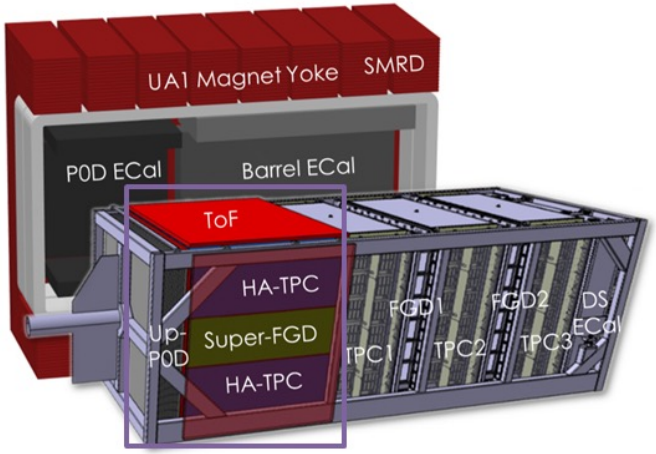


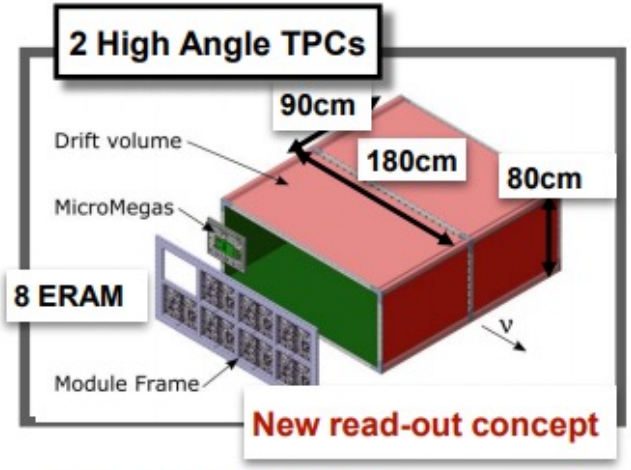
Upgraded near detector



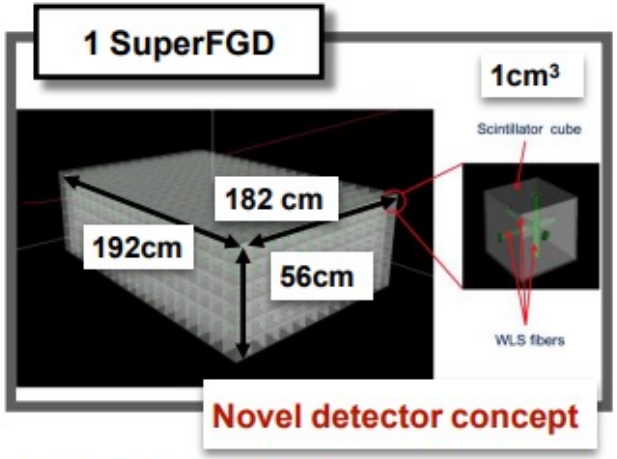
Near detector upgrade

arXiv:1901.03750

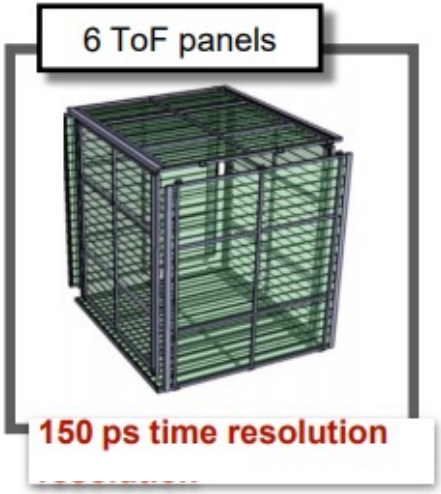




NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



JPS Conf. Proc. 27, 011005 (2019)

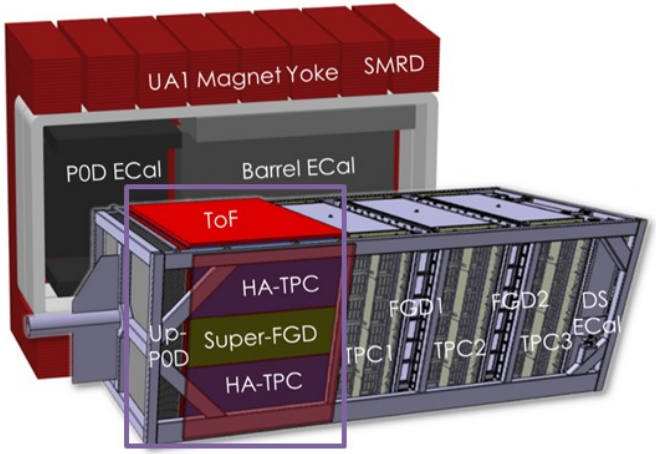
Near detector upgrade

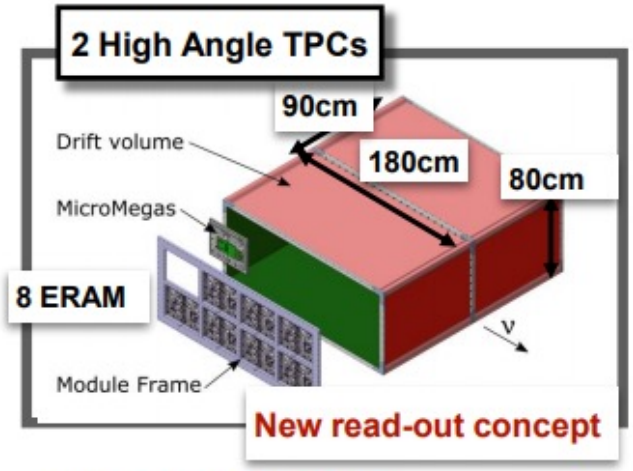
arXiv:1901.03750

- 4π angular acceptance
- Lower tracking thresholds

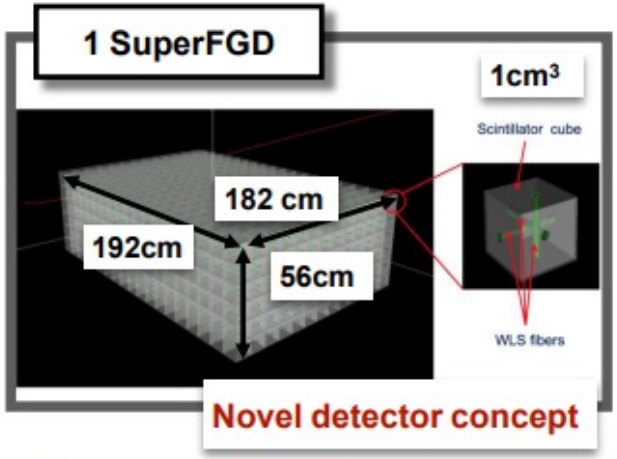
$p_p^{thresh} \sim 300\ MeV/c$

$p_\mu^{thresh} < 100\ MeV/c$

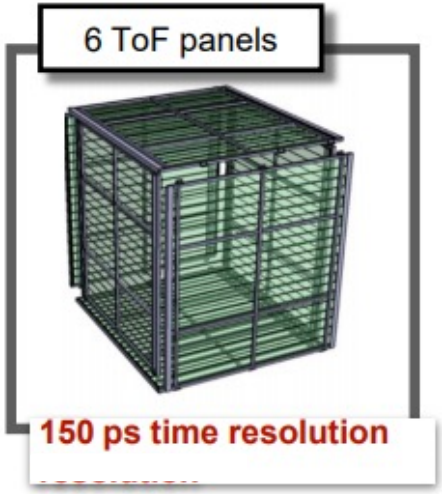




NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



JPS Conf. Proc. 27, 011005 (2019)

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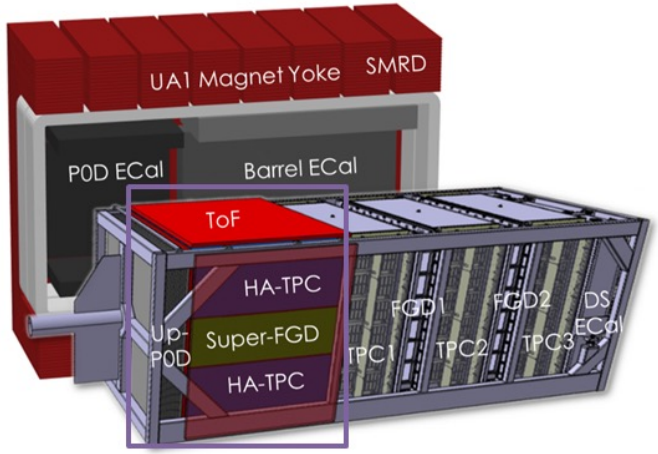
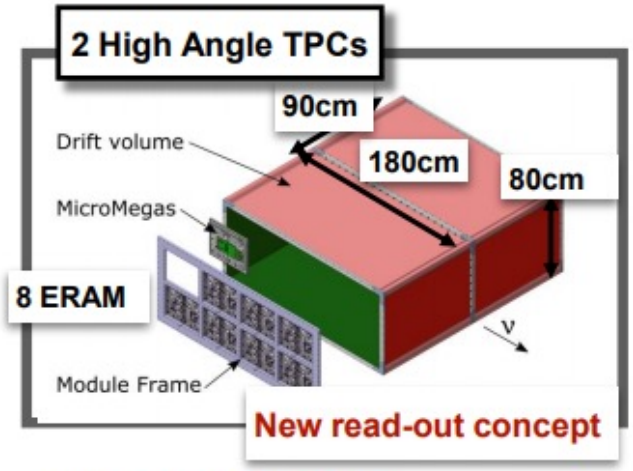
- Lower tracking thresholds $p_p^{thresh} \sim 300\ MeV/c$ $p_\mu^{thresh} < 100\ MeV/c$
- Substantially improved resolutions $\Delta p_p/p_p < 5\%$

Phys. Rev. D **105**, 032010





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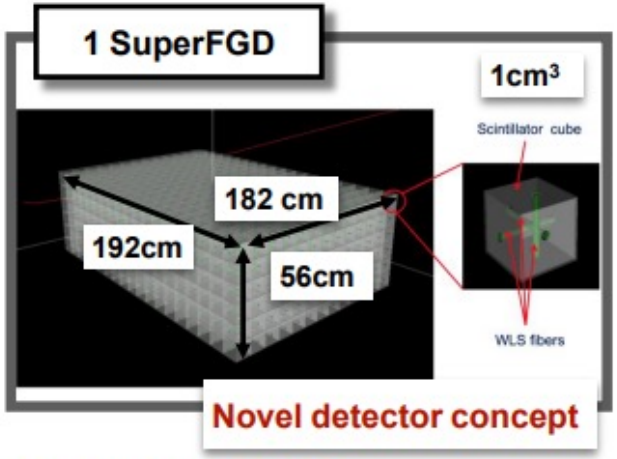

JINST 13, P02006 (2018)
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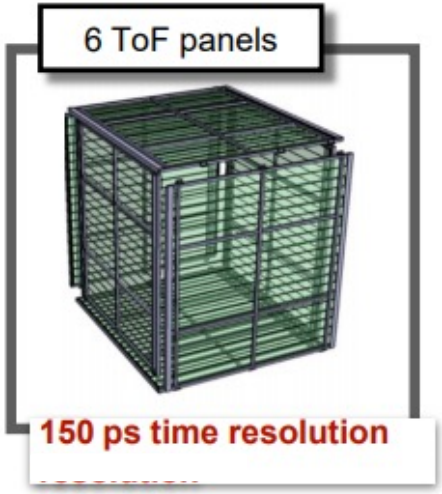


JPS Conf. Proc. 27, 011005 (2019)

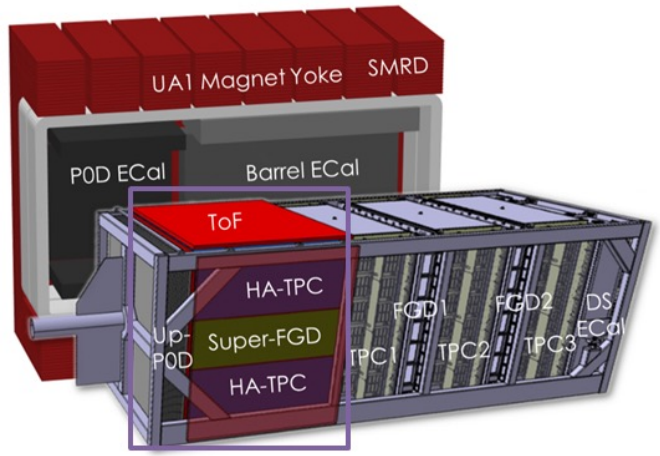
Near detector upgrade

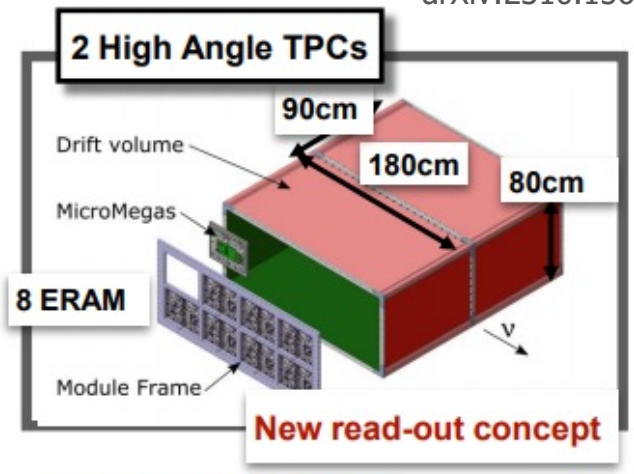
arXiv:1901.03750

- 4π angular acceptance
- Lower tracking thresholds $p_p^{thresh} \sim 300\ MeV/c$ $p_\mu^{thresh} < 100\ MeV/c$
- Substantially improved resolutions $\Delta p_p/p_p < 5\%$

  Phys. Rev. D **105**, 032010
- Better timing resolution enables neutron energy measurements! $\Delta p_n/p_n < 30\%$

  Phys. Rev. D **101**, 092003
  arXiv:2310.15633





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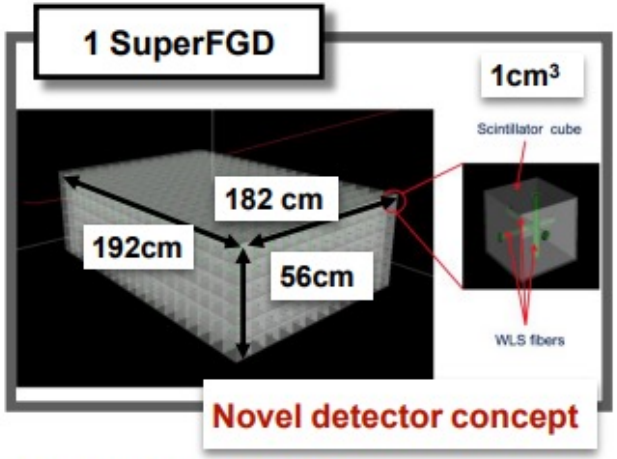

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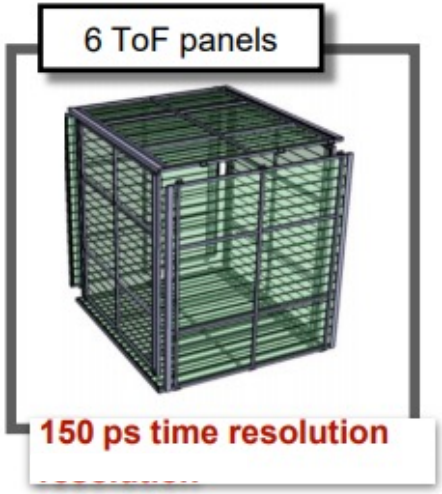
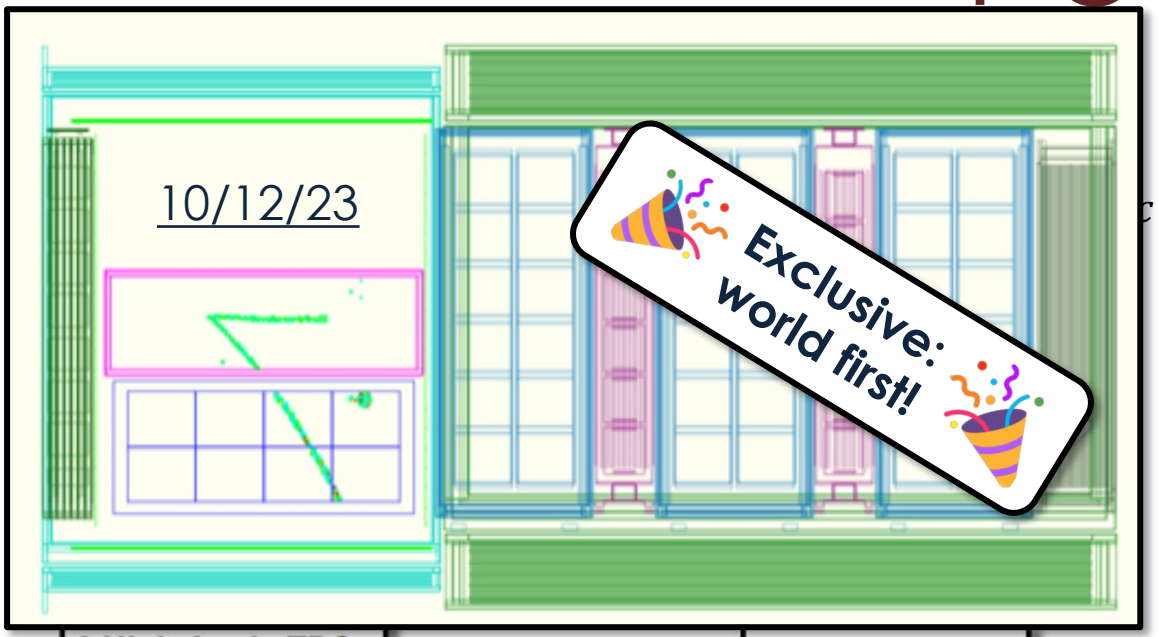
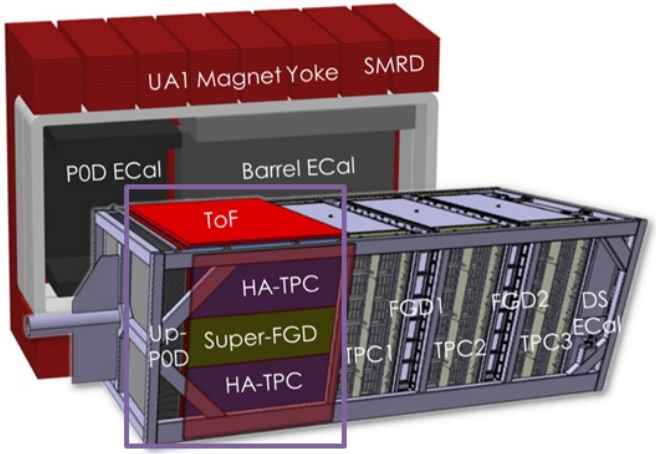


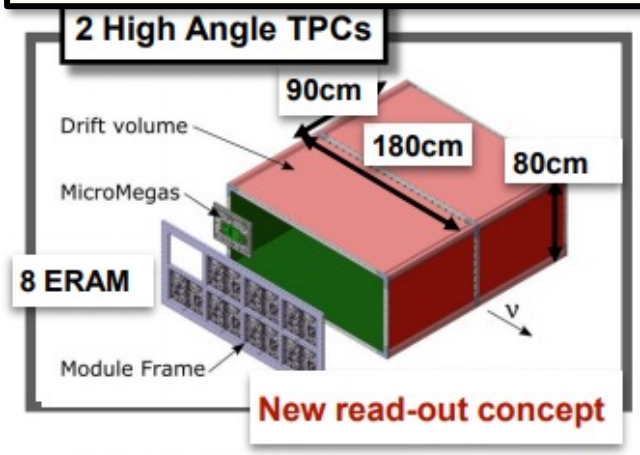
JPS Conf. Proc. 27, 011005 (2019)

Near detector upgrade

arXiv:1901.03750







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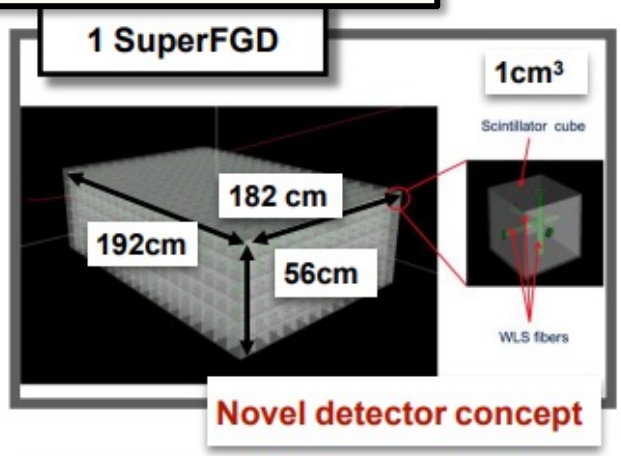

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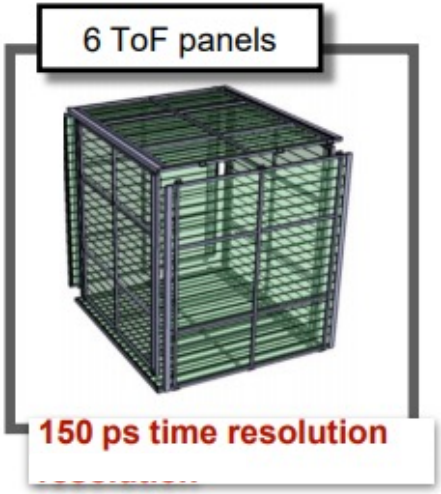


JPS Conf. Proc. 27, 011005 (2019)

Summary

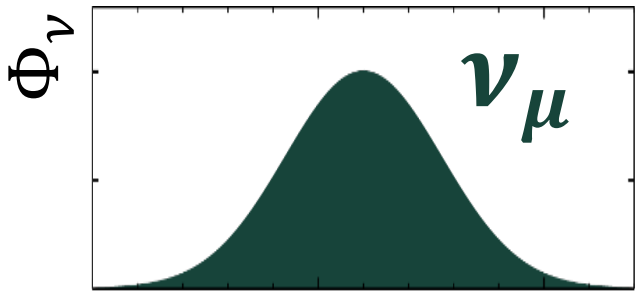
- Recent T2K and T2K+SK neutrino oscillation analyses are setting world-leading constraints on oscillation parameters
  - **CP conservation** excluded at 90% (T2K) / 2σ (T2K+SK)
  - **Normal ordering** preferred with a Bayes factor of 9 (T2K+SK)
- Both analyses **are statistics limited**, but more data in a more powerful beam is being taken right now!
- With more stats, comes a responsibility to **improve treatment of systematic uncertainties**
  - Dominant source is related to $\boldsymbol{\nu}$ **interactions**
  - **Near detector upgrade** provides powerful tools to mitigate them

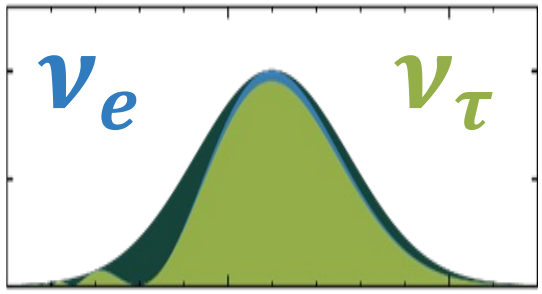
Backups

Analysis Strategy

The idea in a nutshell

- Produce beams of ν_μ and $\bar{\nu}_\mu$
- Measure $\overset{(-)}{\nu}_\mu$ (disappearance) and $\overset{(-)}{\nu}_e$ (appearance) event rate at FD
- Parametrise flux, cross-section and detector models
- Constrain the former two at the near detector
- Fit for the oscillation parameters at the far detector





At the near detector

$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

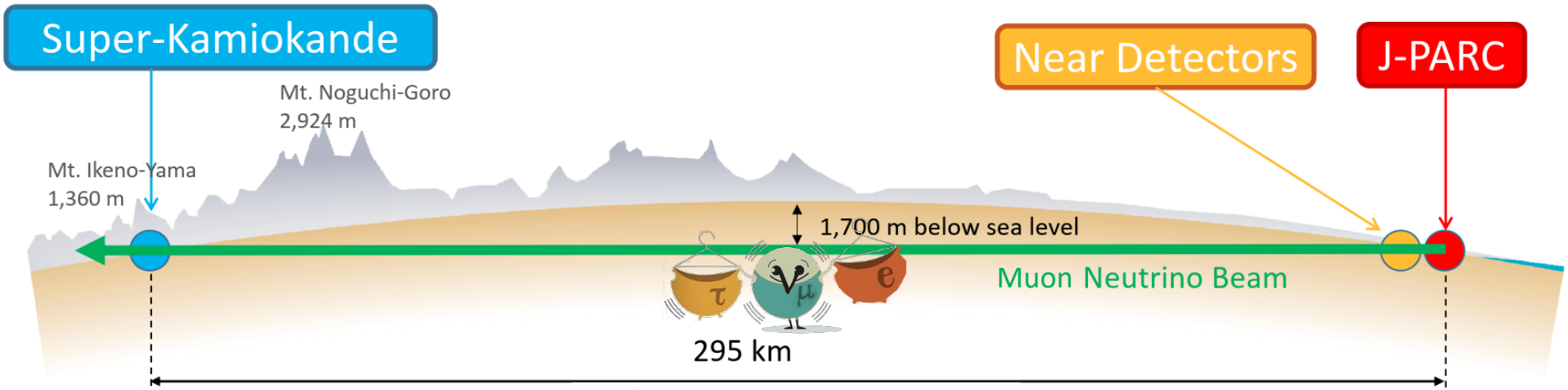
At the far detector

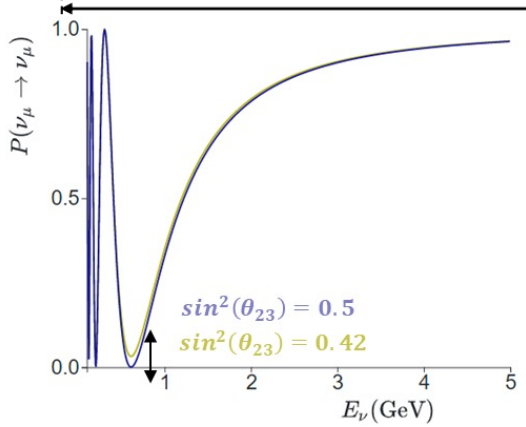
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

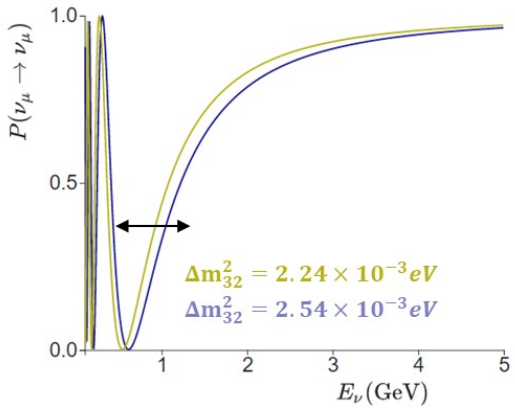
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

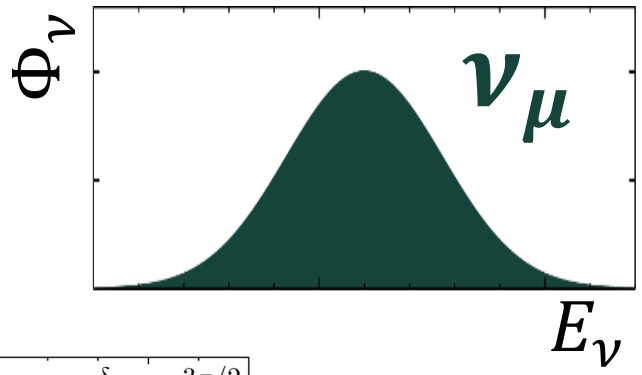
Oscillation probability

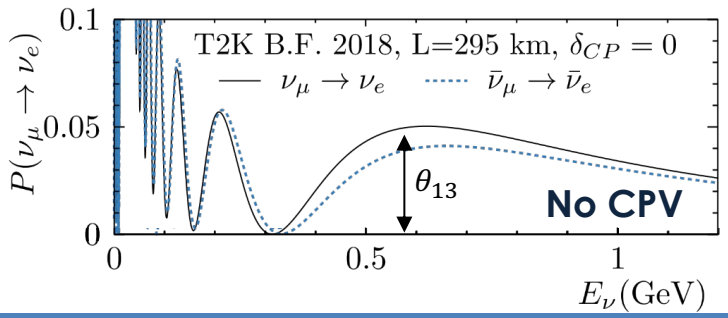
Oscillations at T2K

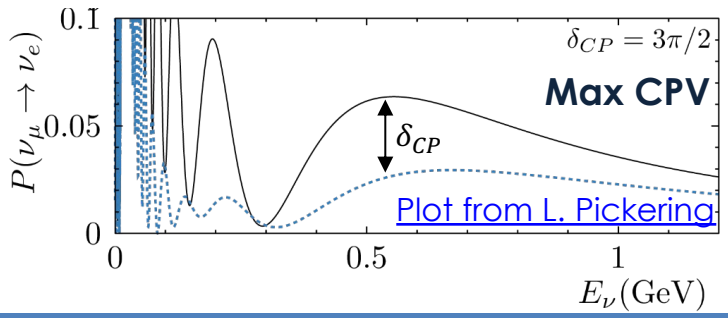












Neutrino Interactions

$$N_\ell(E_\nu) = P(\nu_\mu \to \nu_\ell)(E_\nu)\,\sigma(E_\nu)\,\Phi_\nu(E_\nu)\,\epsilon(E_\nu)$$

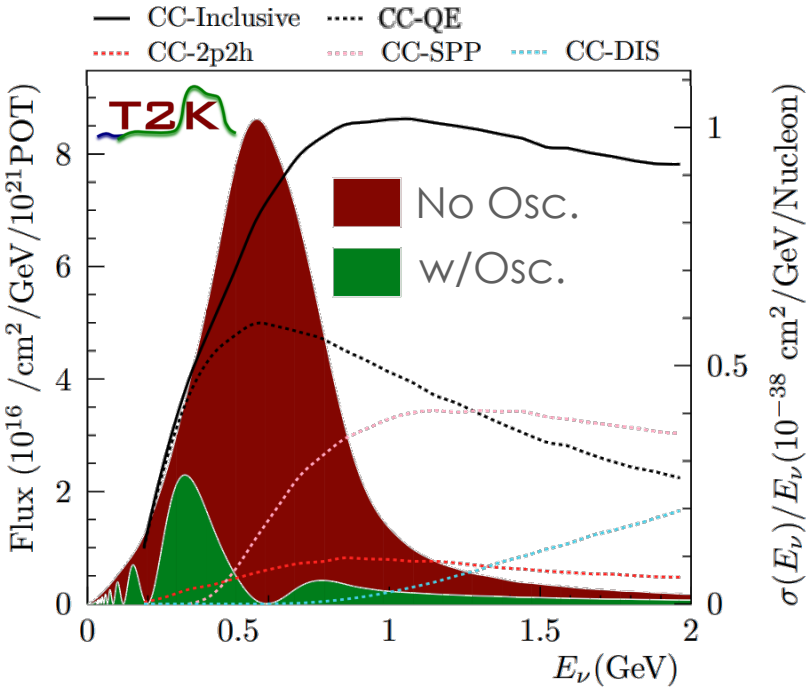
$N_\ell(E_\nu)$ = Event rate

$P(\nu_{\ell'} \to \nu_\ell)(E_\nu)$ = Oscillation probability

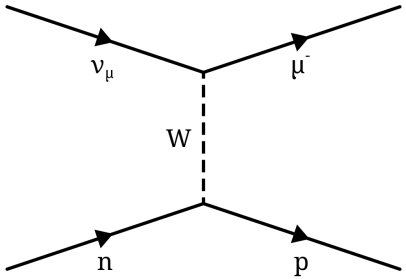
$\Phi_\nu(E_\nu)$ = Neutrino flux

$\epsilon(E_\nu)$ = Detector efficiency

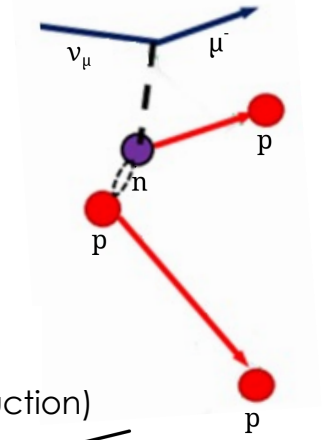
$\sigma_\ell(E_\nu)$ = Interaction cross section



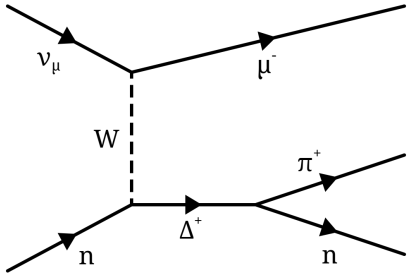
CC-QE
(Charged-Current Quasi-Elastic)



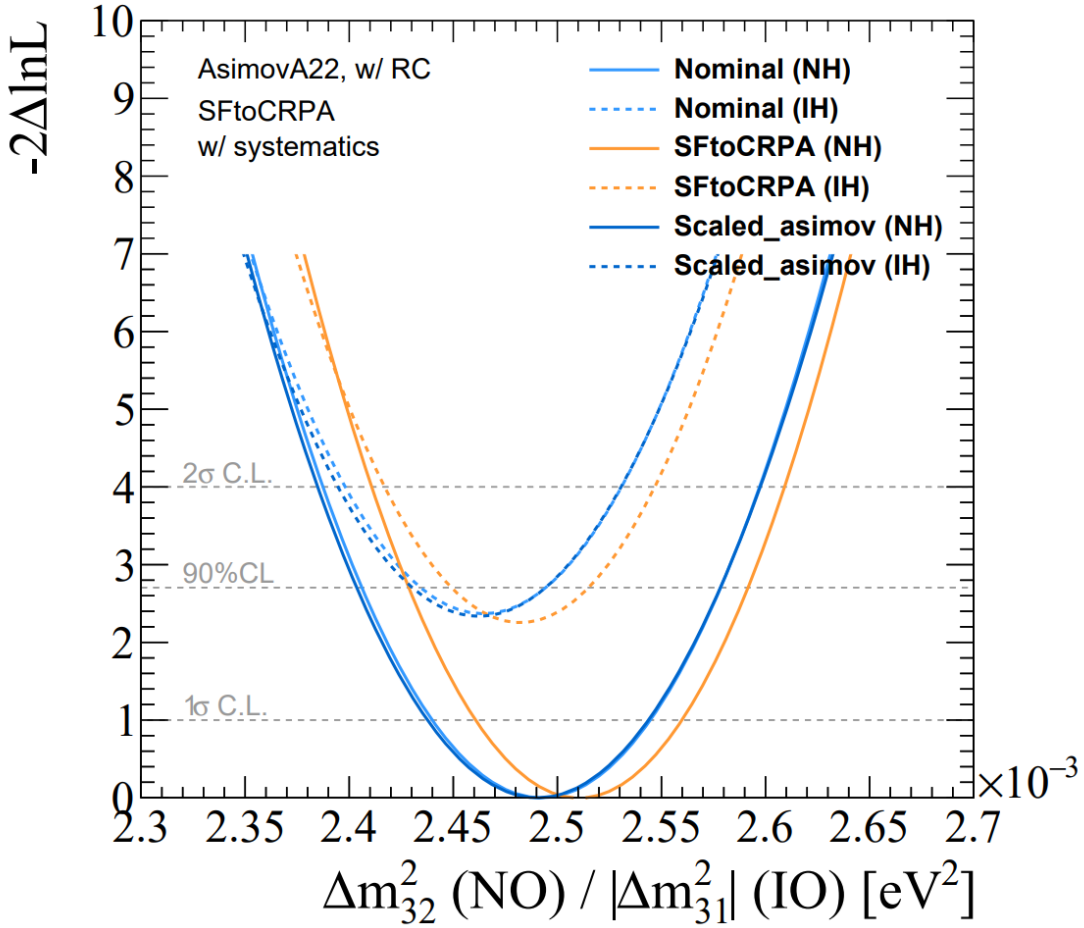
CC-2p2h
(2 particle, 2 hole)



CC-SPP
(Single Pion Production)

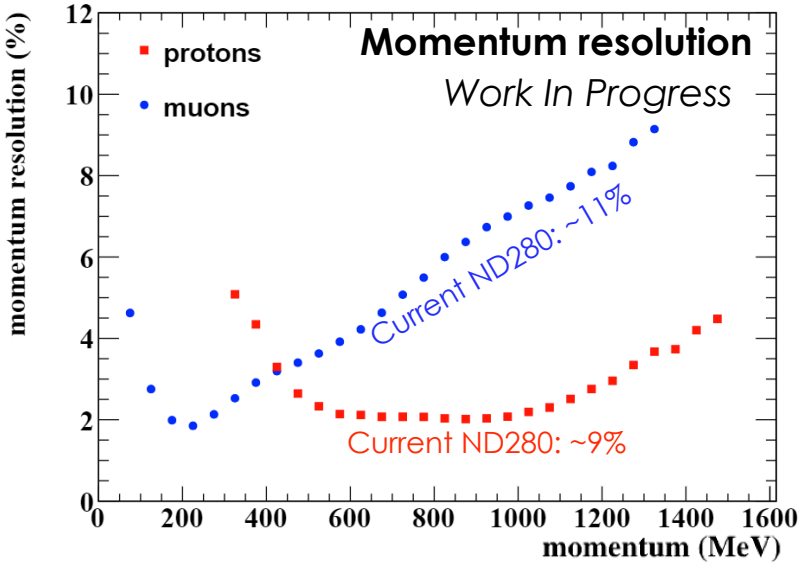


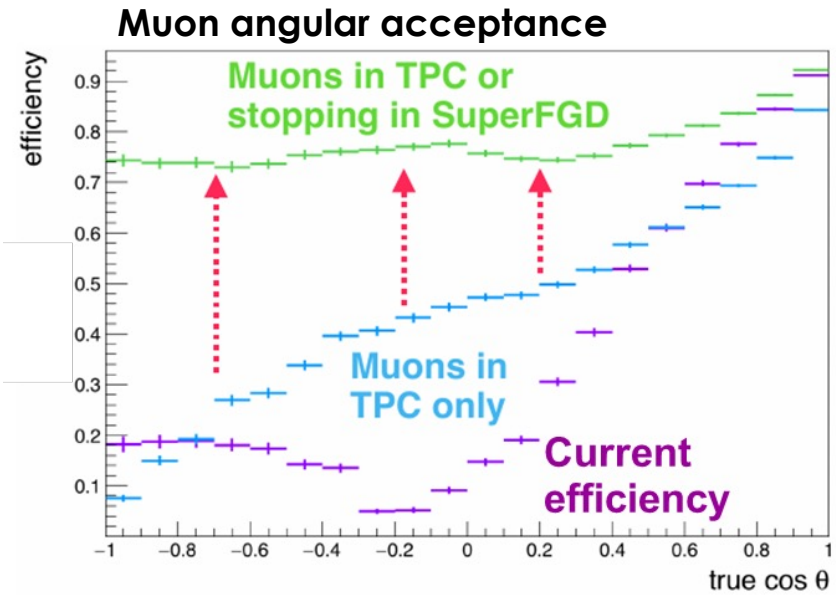
Mock data study example

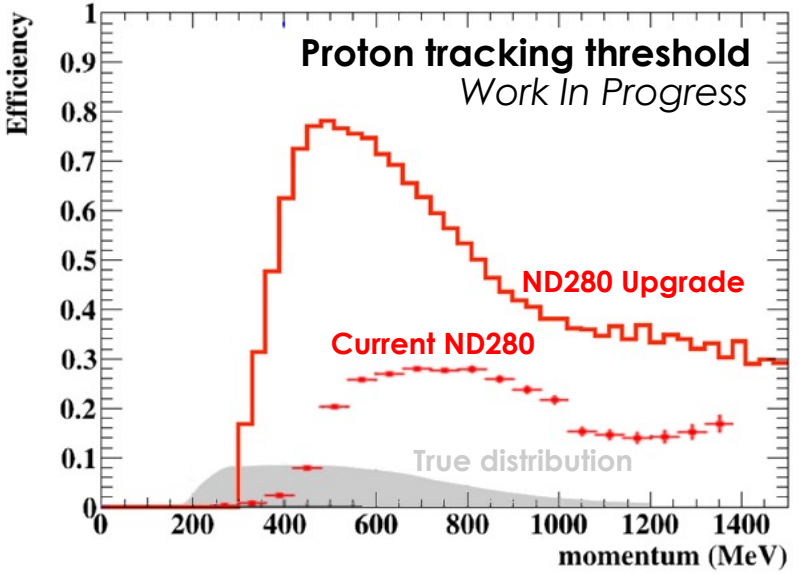


Upgrade detector performance

- Dramatically improved angular acceptance
- Much lower tracking thresholds
- Substantially improved resolutions
- Better timing resolution enables neutron energy measurements!

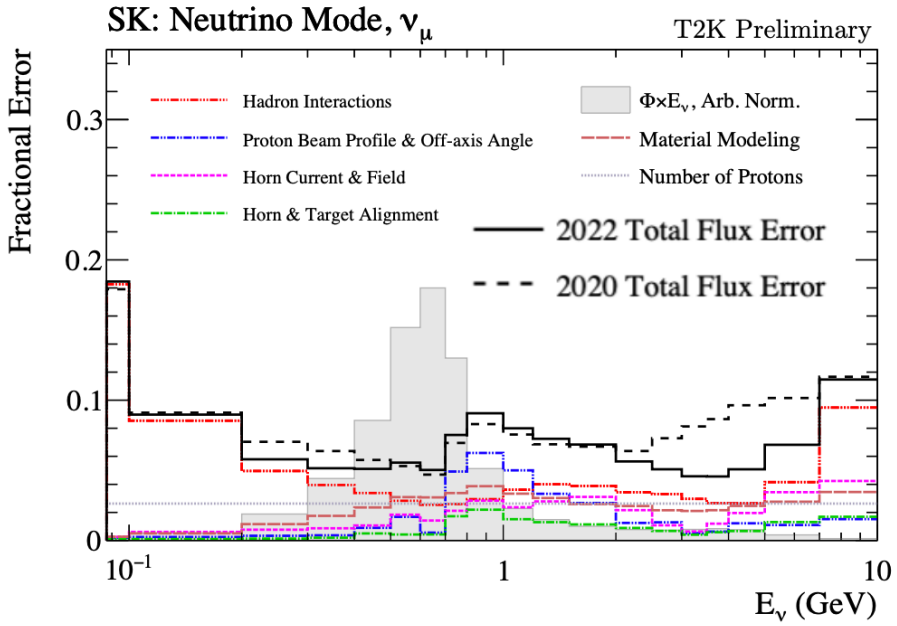






Updated flux prediction

- Uses **NA61/SHINE** 2010 T2K replica target data for hadron production
  - Adds more stat to $\pi^{\pm}$ production
  - Also adds $K^{\pm}$ and proton data
- Overall **reduction of flux error** compared to 2009 replica target data (**by ~6%**)



Accumulated data

This analysis: 3.6×10^{21} **POT**