26/07/21

T2K Status and Plans

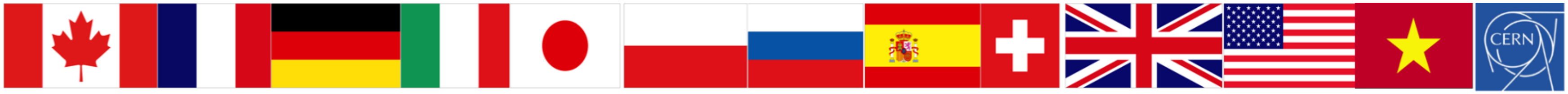
Oscillations, Interactions and the search for CP-Violation

Stephen Dolan

for the T2K Collaboration

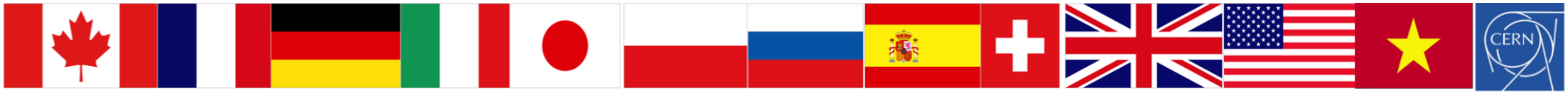
stephen.joseph.dolan@cern.ch

The T2K Collaboration



~500 members, 69 Institutes, 12 countries

The T2K Collaboration



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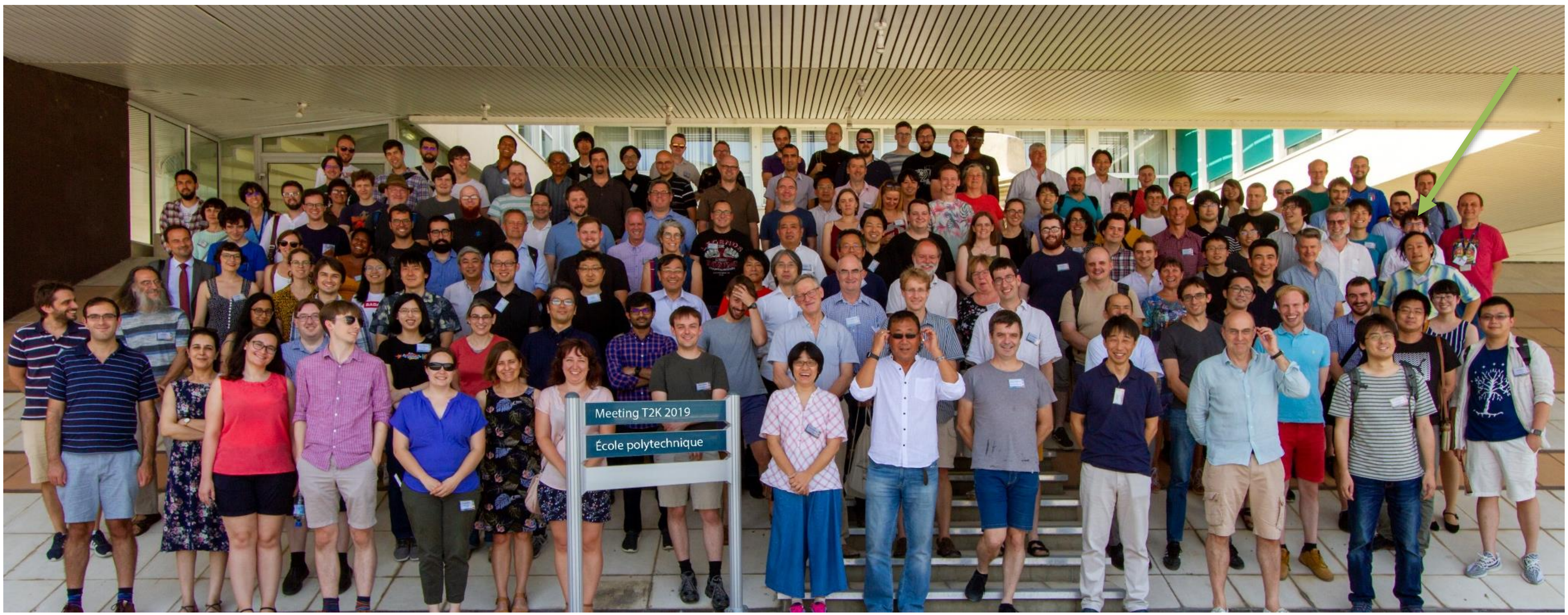
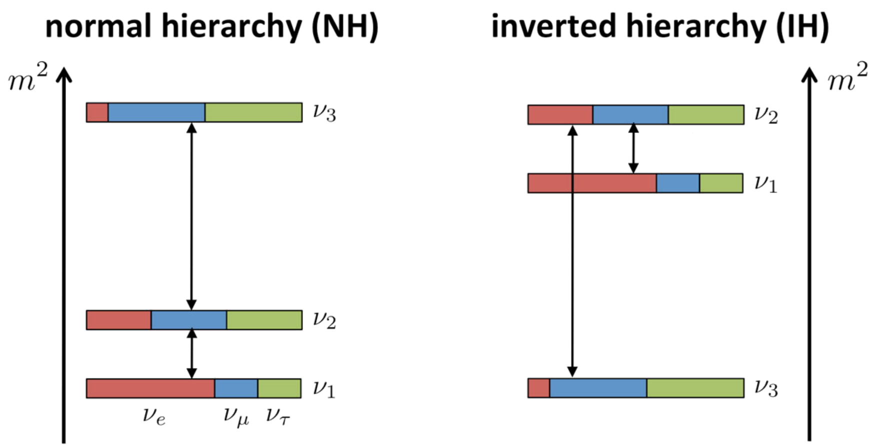
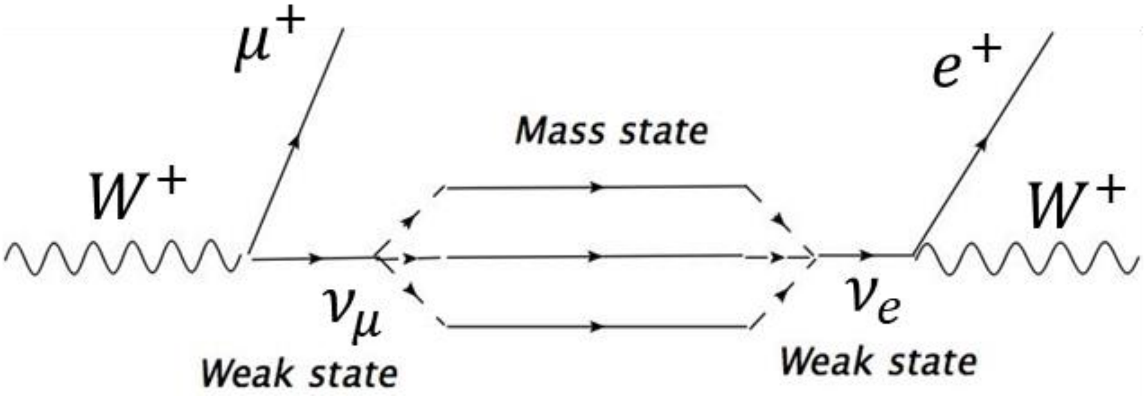


Neutrino Oscillations

- Oscillation probabilities depends on:
  - The neutrino energy
  - The travelled distance ("baseline")
  - *The difference in masses of* ν_1, ν_2, ν_3
  - *The PMNS mixing parameters*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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

$s_{ij} = \sin \theta_{ij}$
$c_{ij} = \cos \theta_{ij}$

- Three mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- One CP-Violating phase: δ_{CP}

From reactor experiments (e.g. Daya Bay) and from measuring $P(\nu_\mu \to \nu_e)$

Measuring $P(\nu_\mu \to \nu_\mu)$

Neutrino Oscillations

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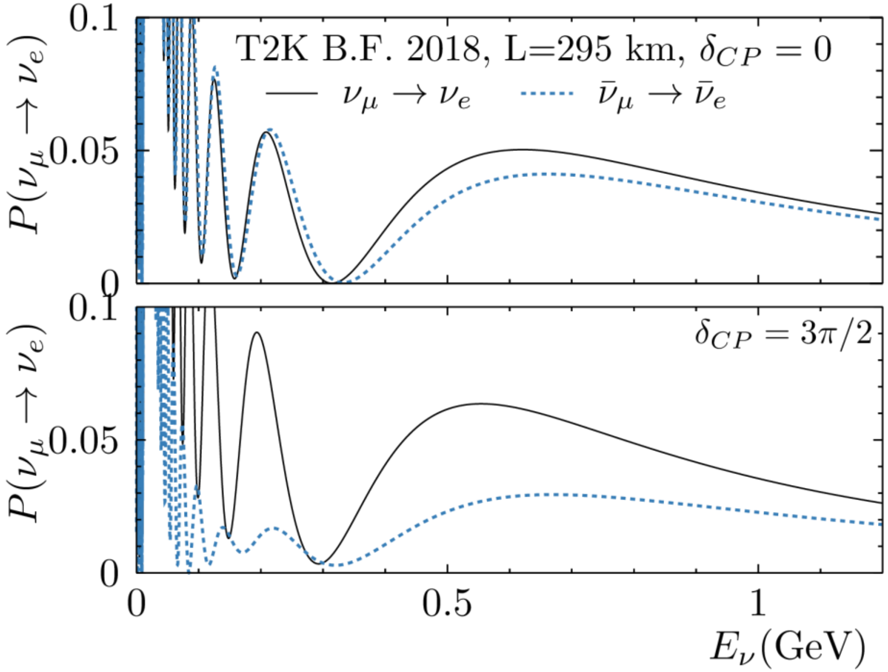

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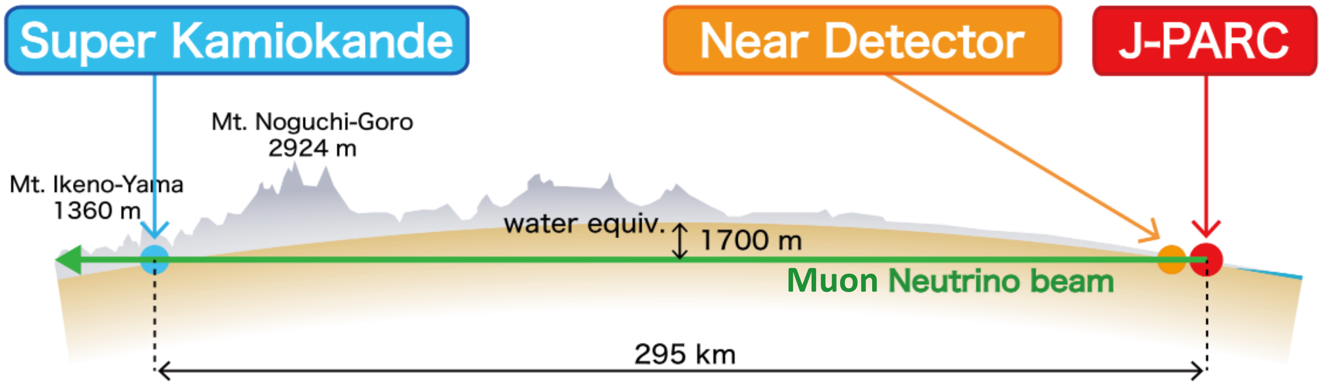
Measuring $P(\nu_\mu \to \nu_\mu)$

Required to have an imbalance between neutrino and anti-neutrino vacuum oscillations

The T2K Experiment



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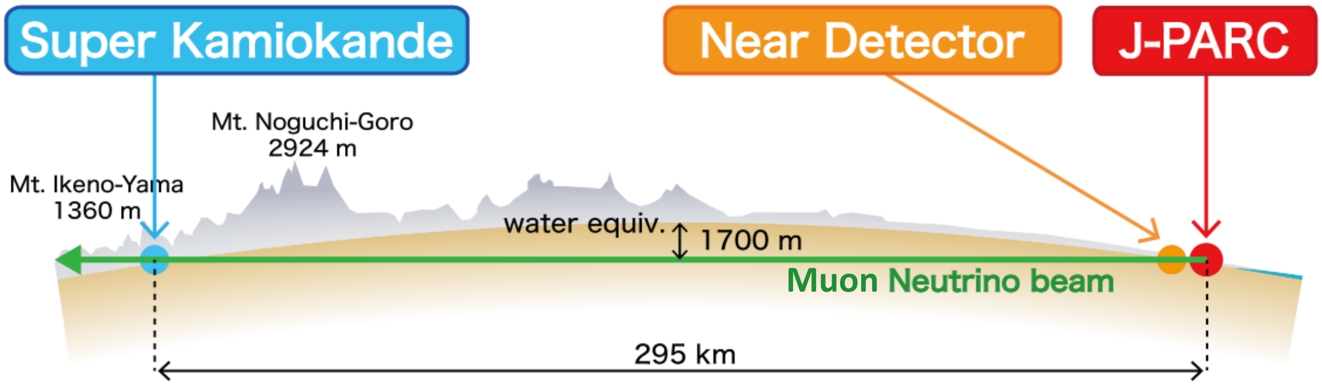

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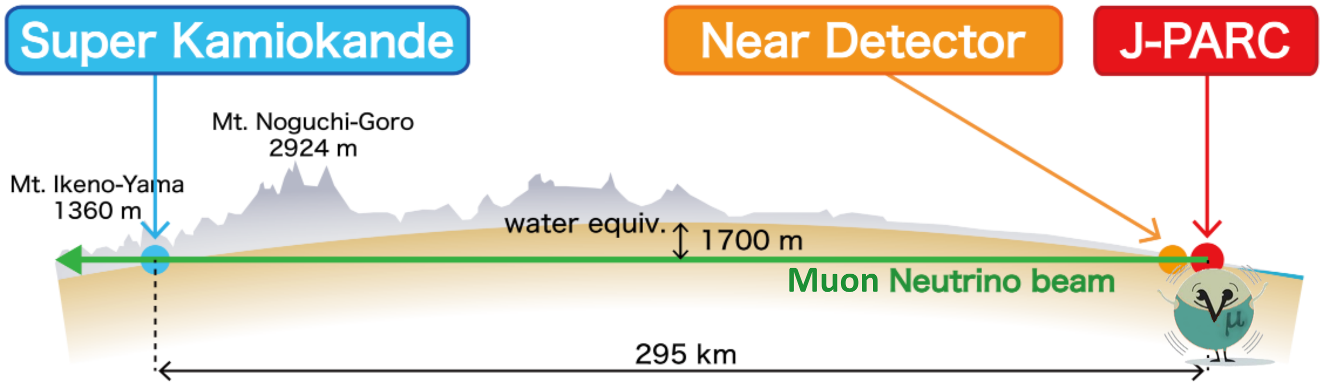
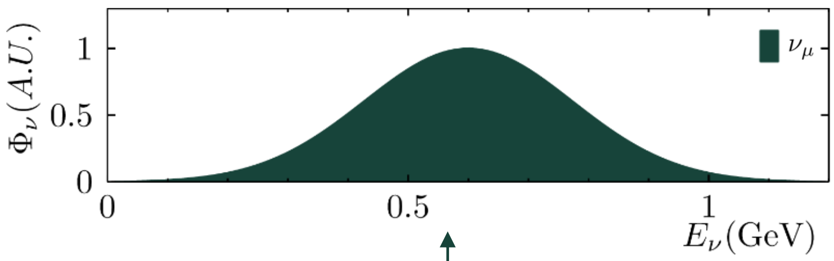
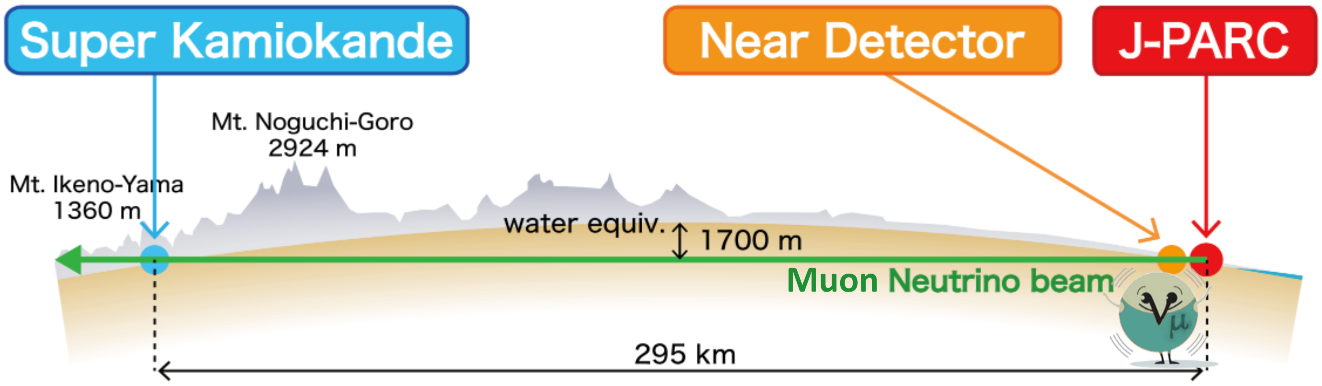
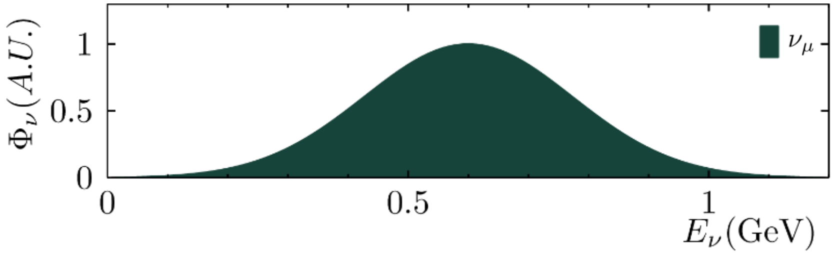




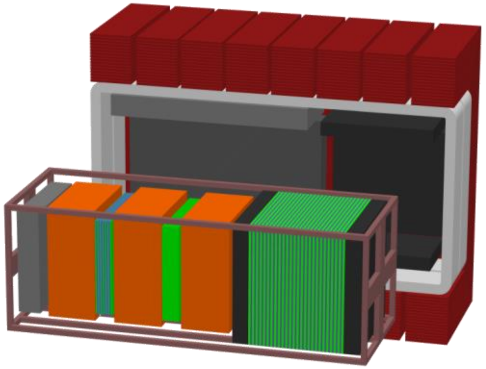
Produce predominantly ν_μ neutrino *or anti-neutrino* beam

The T2K Experiment





Near Detector
ND280



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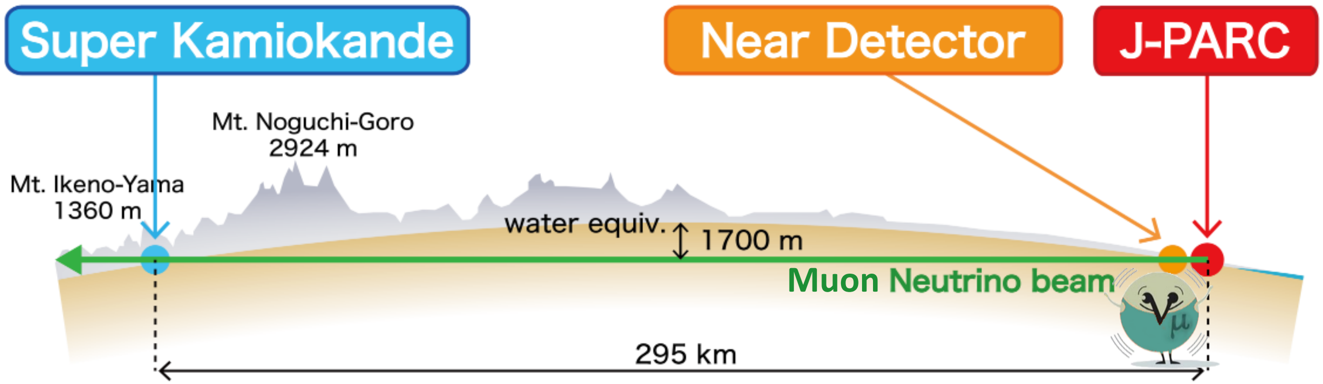
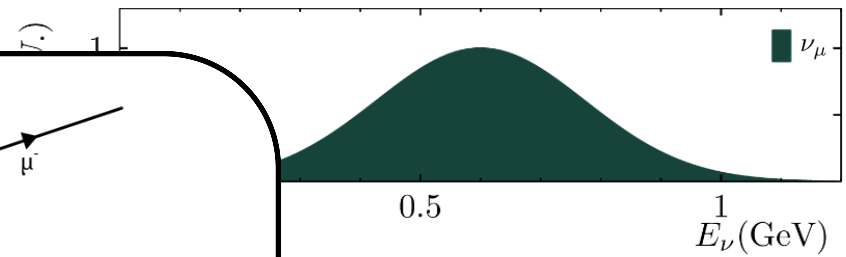
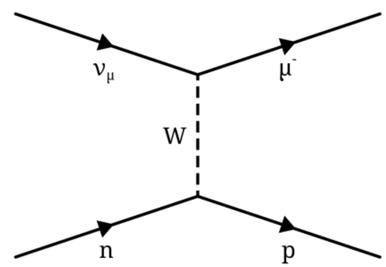






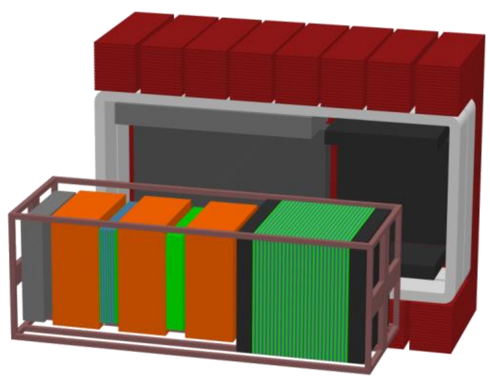
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

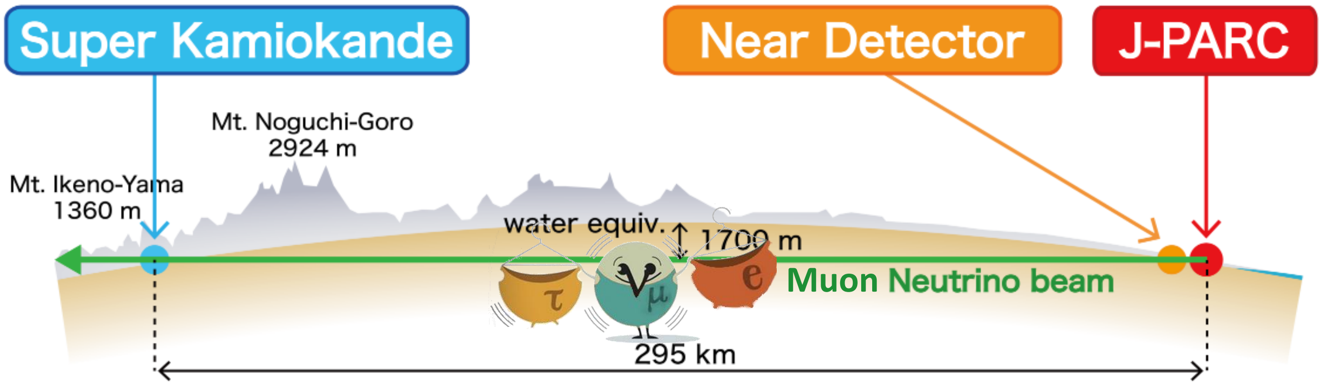
Neutrino flux

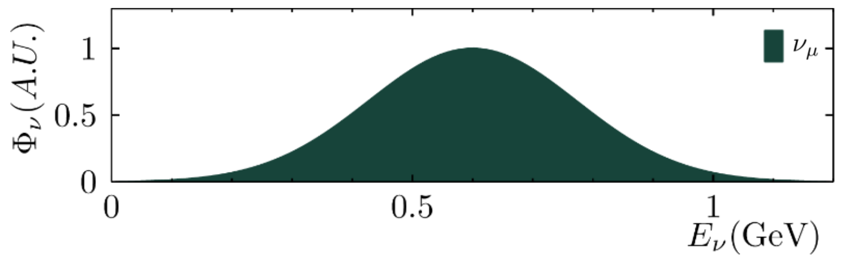
Detector effects

Near Detector
ND280

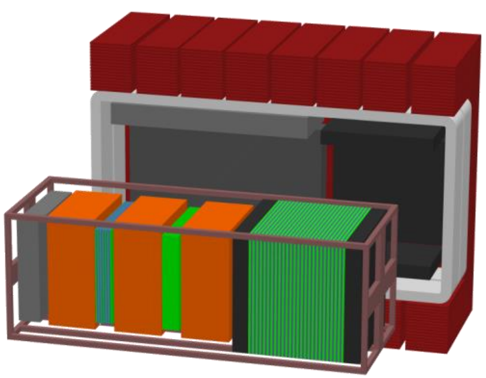


The T2K Experiment

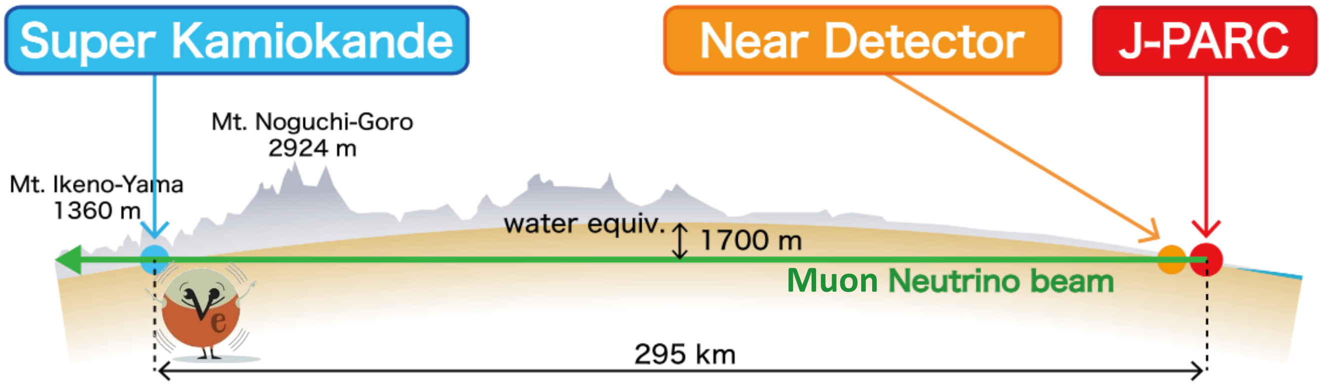


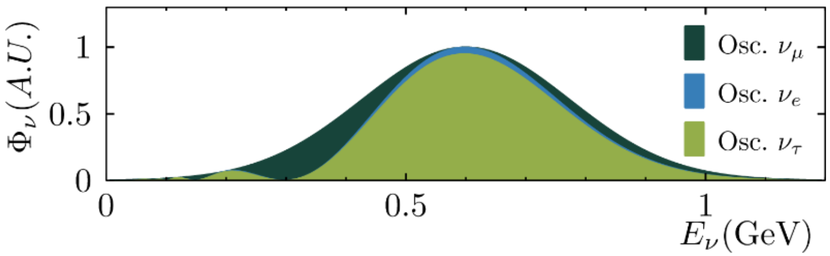


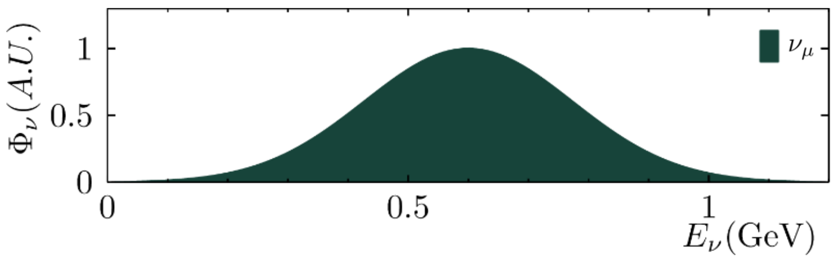
Near Detector
ND280



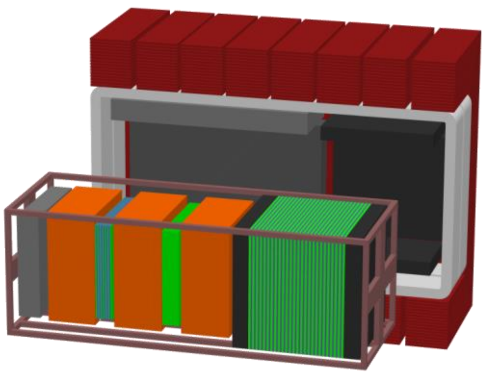
The T2K Experiment







Near Detector
ND280



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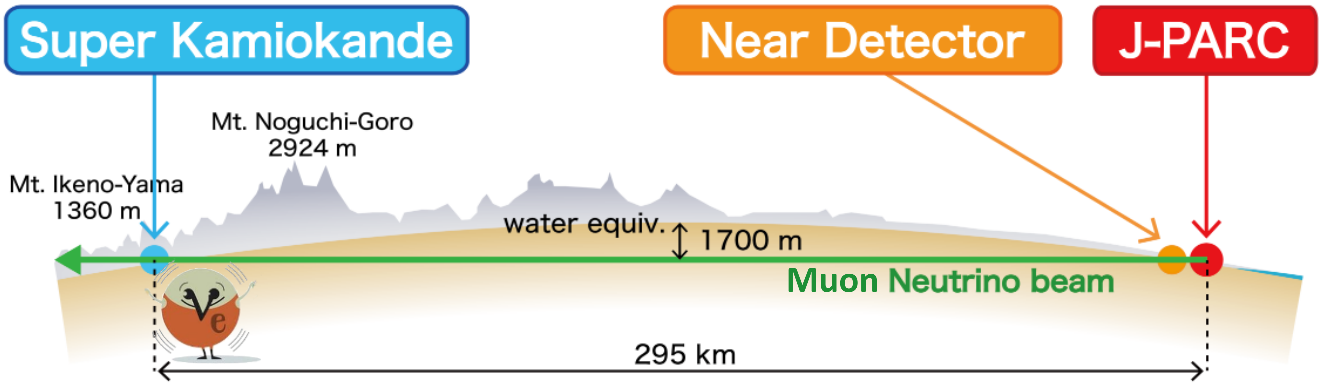
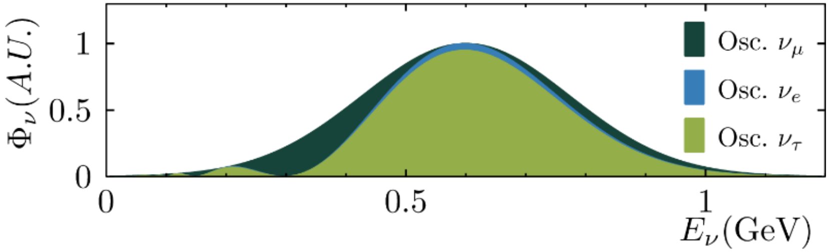
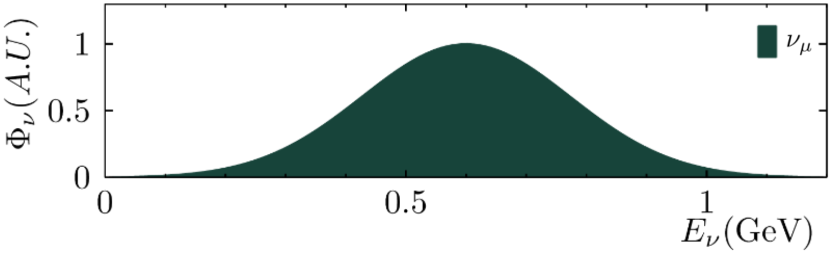
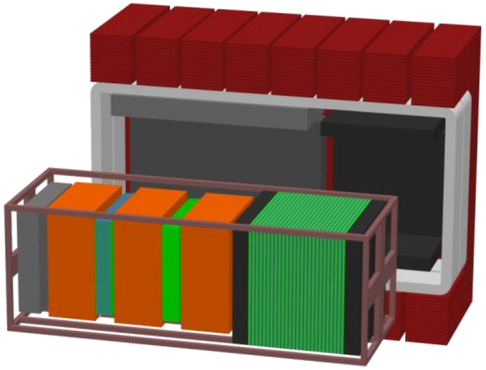






Far Detector
Super-Kamiokande

Near Detector
ND280



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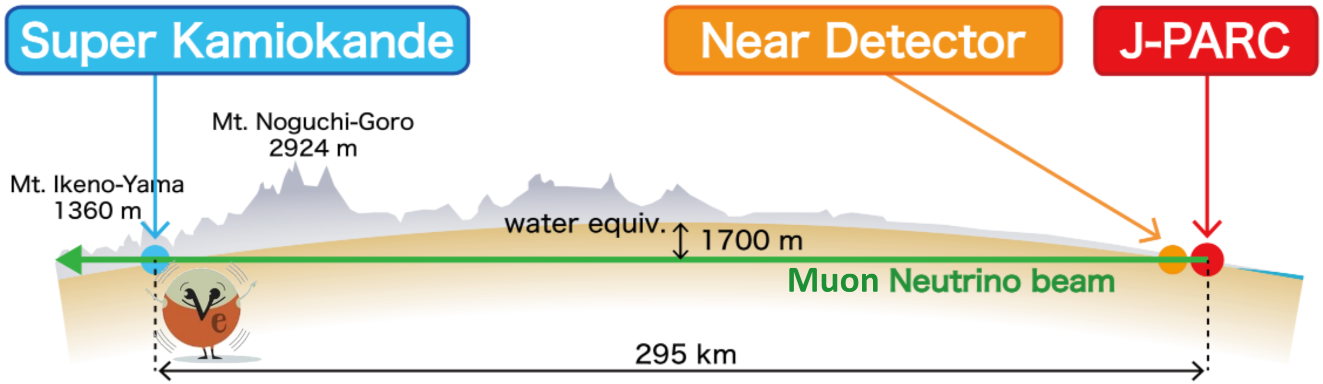

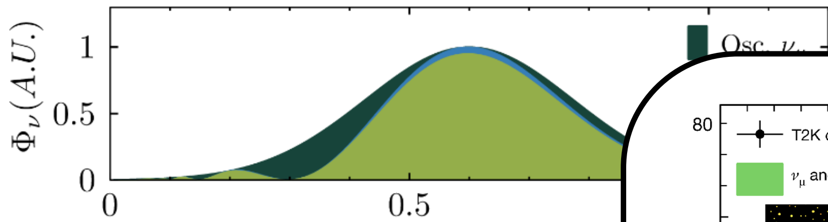

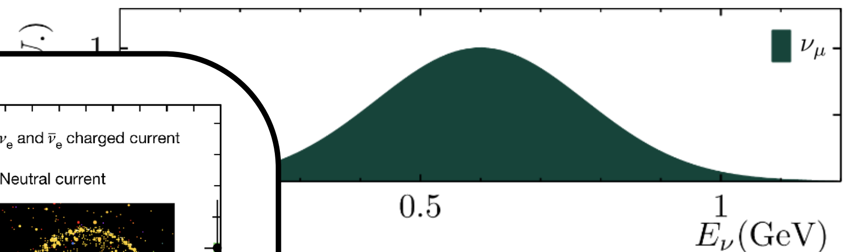

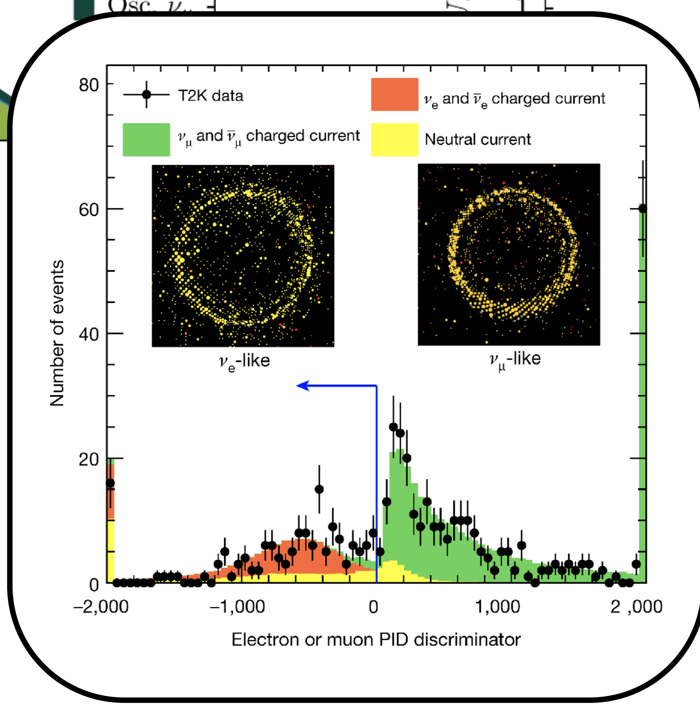

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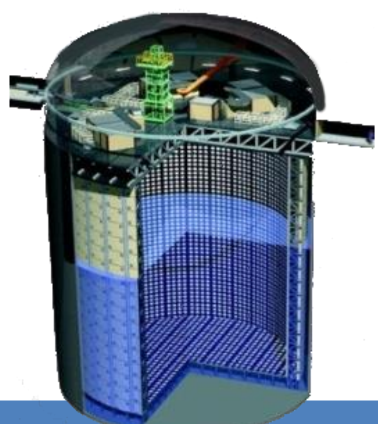
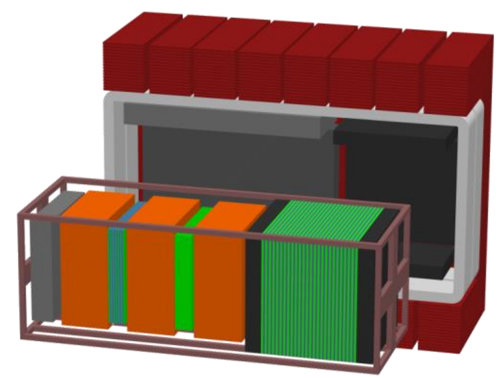


Near Detector
ND280



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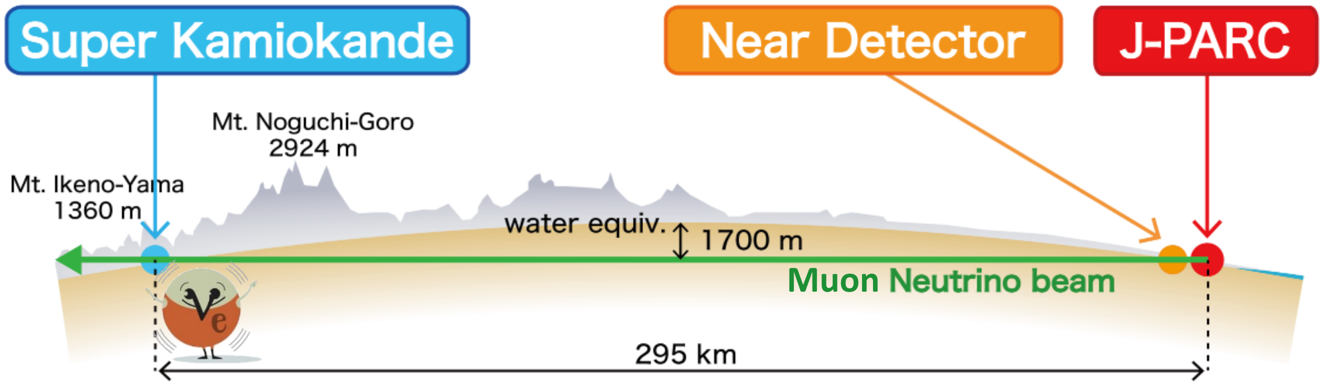

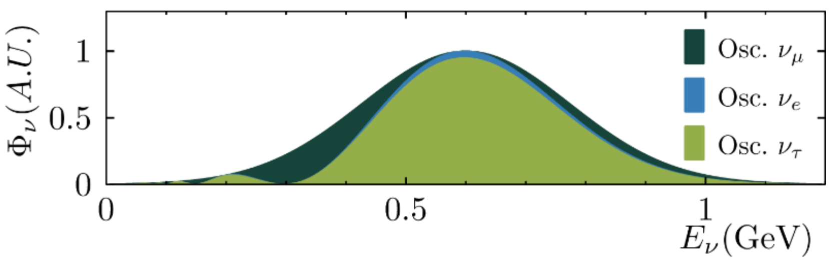

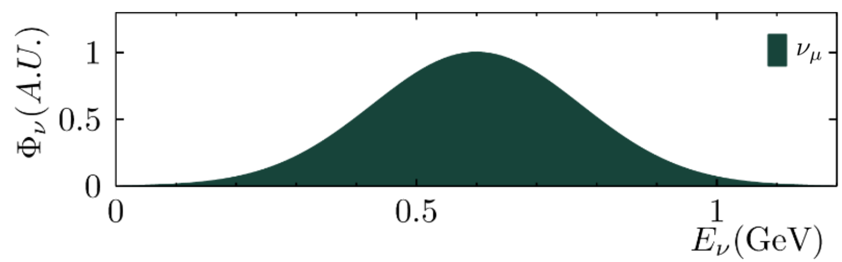

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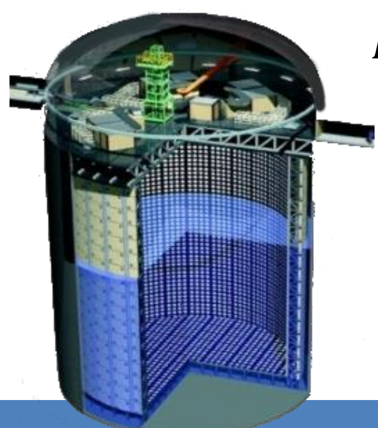


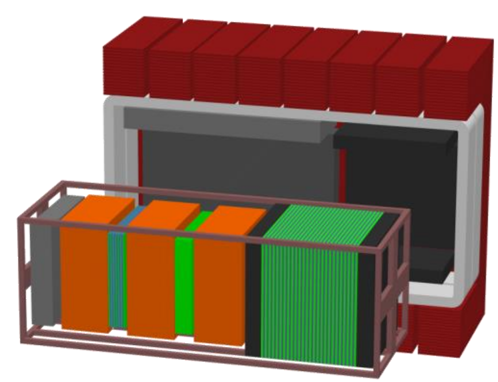
$$N_\mu(E_\nu) = P(\nu_\mu \rightarrow \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

PMNS Mixing
δ_{CP} θ_{13}
Δm^2_{32} θ_{23}

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

Near Detector
ND280



Neutrino Interactions

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

$N_\ell(\mathrm{E}_\nu)$ = Event rate
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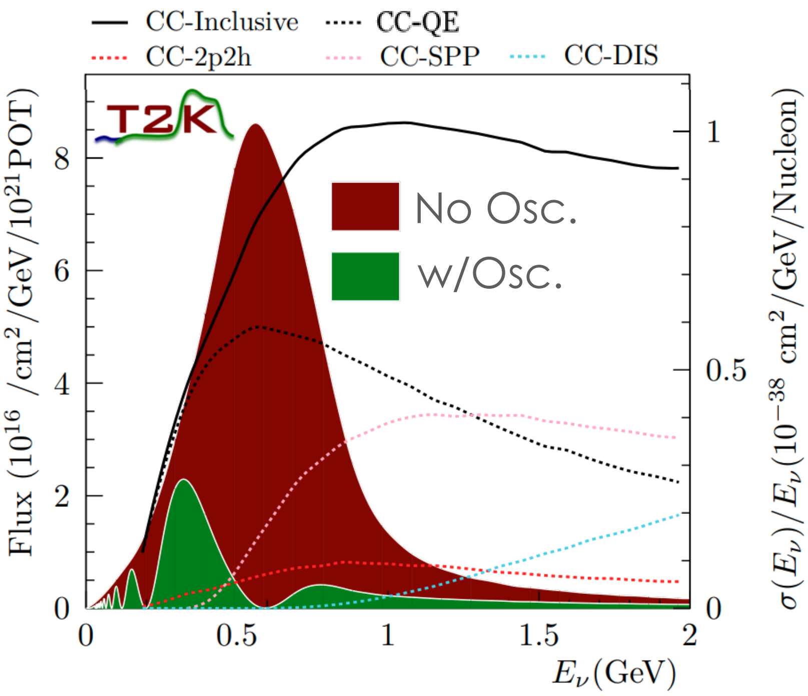
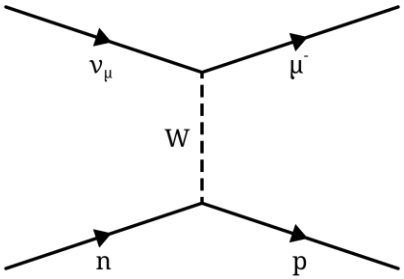
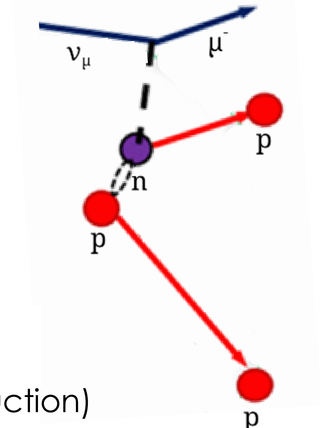
$\Phi_\nu(\mathrm{E}_\nu)$ = Neutrino flux
$\epsilon(E_\nu)$ = Detector efficiency
$\sigma_\ell(E_\nu)$ = Interaction cross section



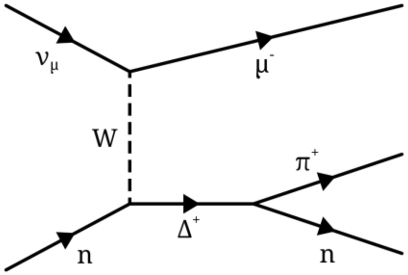
CC-QE
(Charged-Current Quasi-Elastic)



CC-2p2h
(2 particle, 2 hole)



CC-SPP
(Single Pion Production)



Neutrino Interactions

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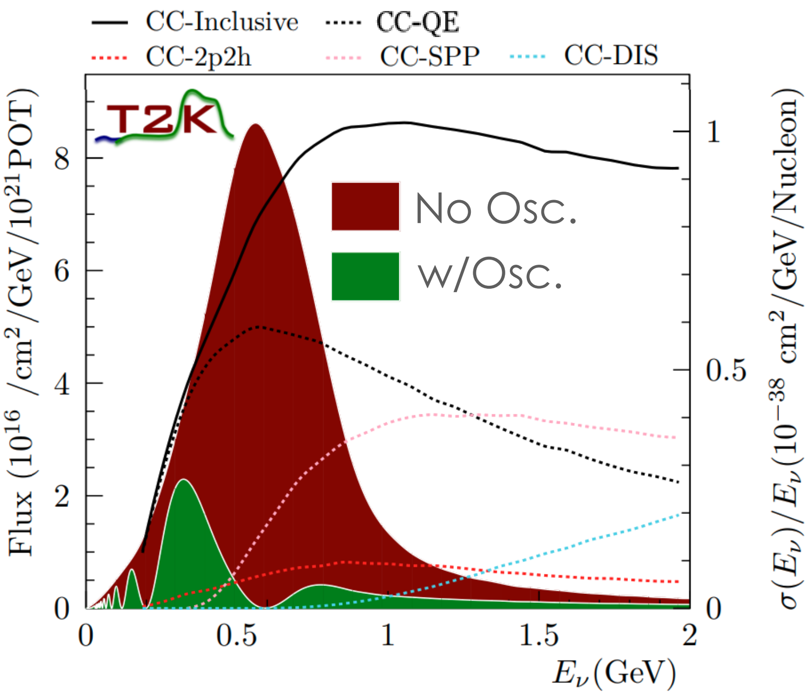

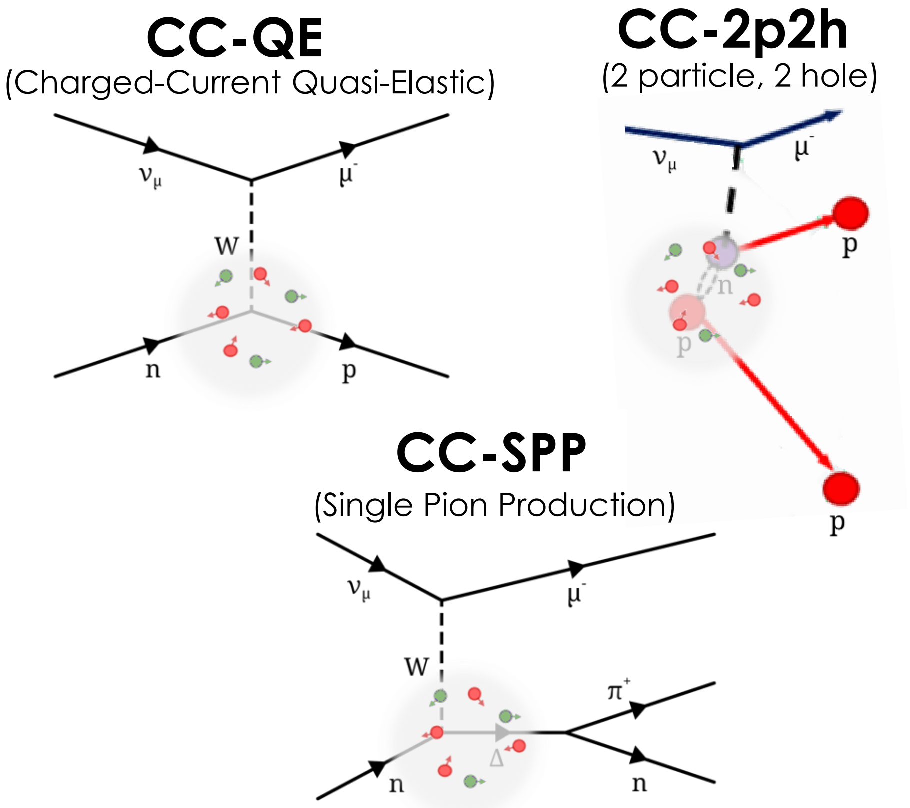

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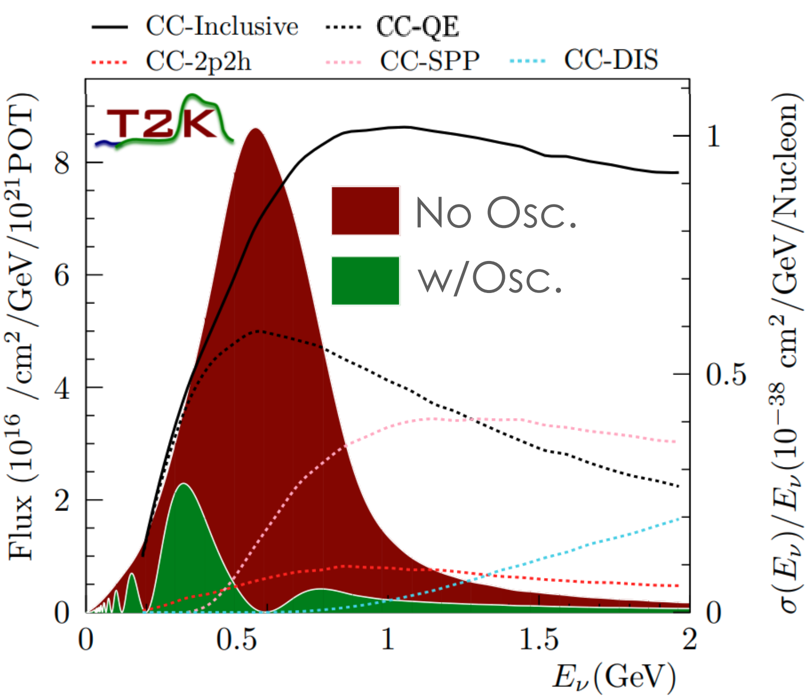

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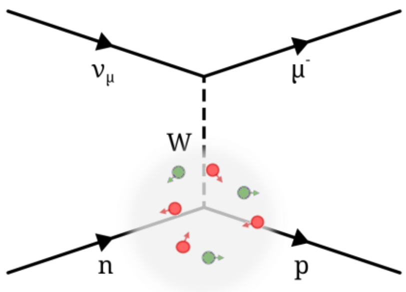

CC-2p2h
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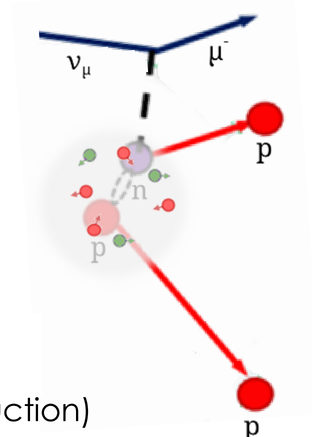
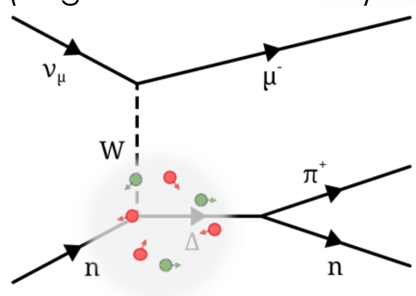


CC-SPP
(Single Pion Production)



Neutrino Interactions

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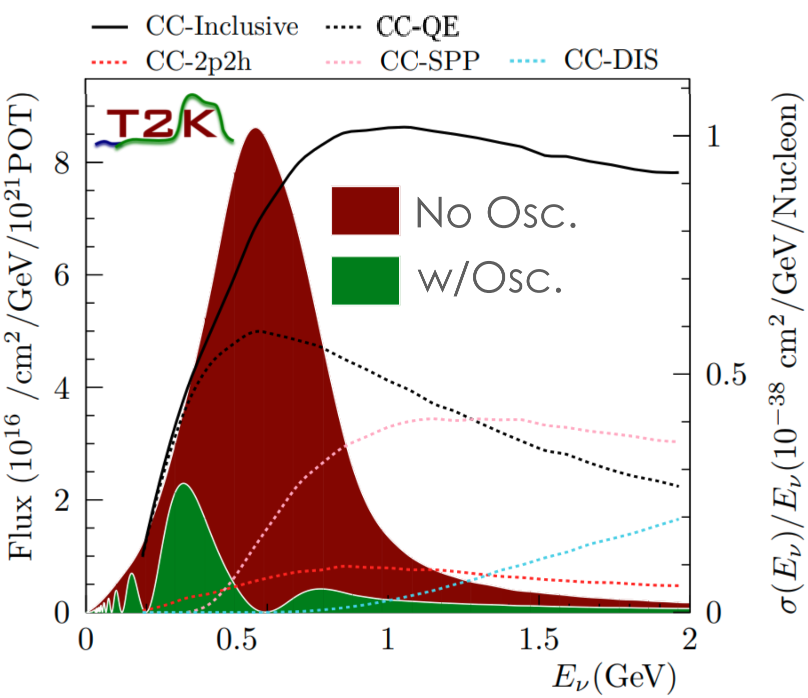

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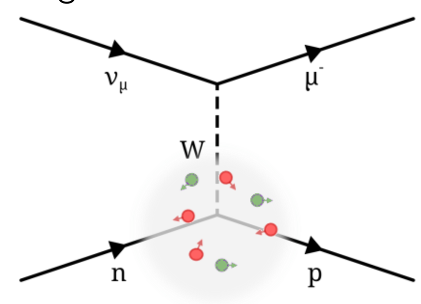

Assuming **CCQE scattering** off a **stationary nucleon**, reconstruct E_ν from the observed lepton:

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Isolate CCQE events by looking for meson-less interactions (“CC0π”)

Neutrino Interactions

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

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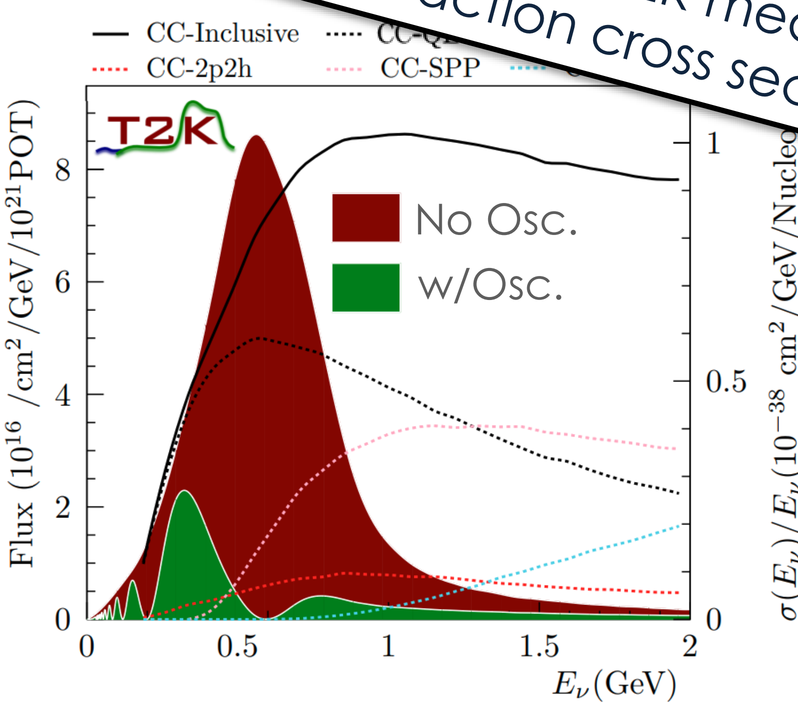
$\Phi_\nu(\mathrm{E}_\nu)$ = Neutrino flux
$\epsilon(E_\nu)$ = Detector efficiency
$\sigma_\ell(E_\nu)$ = Interaction cross section

See the latest T2K measurements of neutrino-nucleus interaction cross sections at 10:30 CET on Friday



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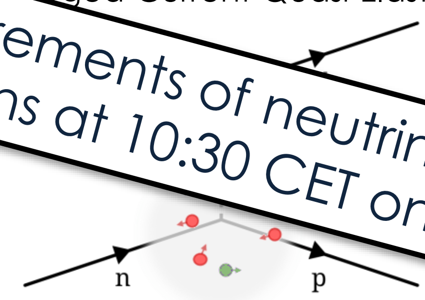


Assuming **CCQE scattering** off a ... **ary nucleon**, ... E_ν from ... ed lepton:

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

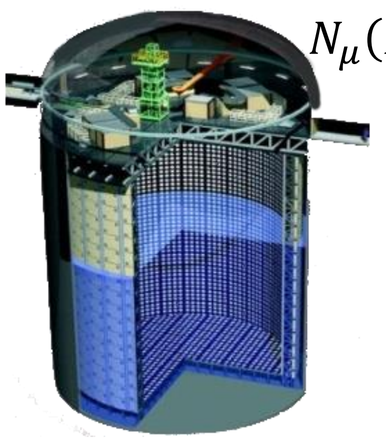
Isolate CCQE events by looking for meson-less interactions (“CC0π”)

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

Far Detector
Super-Kamiokande



Detector effects

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

Neutrino flux

Oscillation probability

Interaction cross section

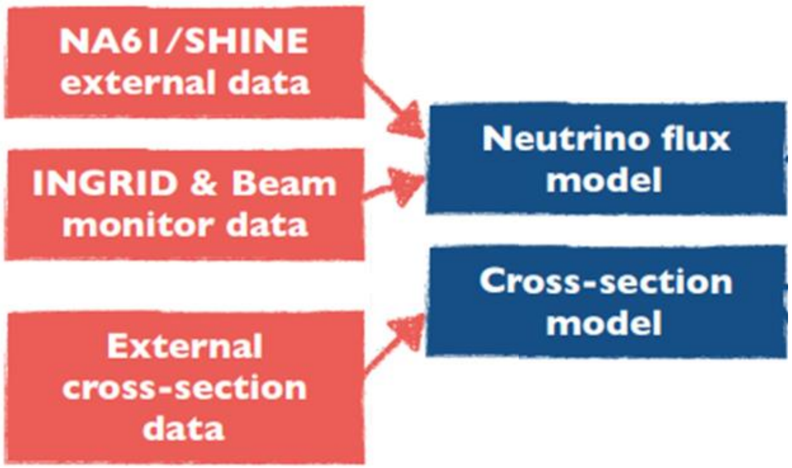
Using data taken up to spring 2020
More has already been taken for our next analysis!

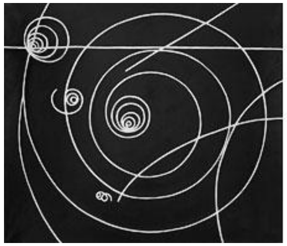
Analysis Strategy

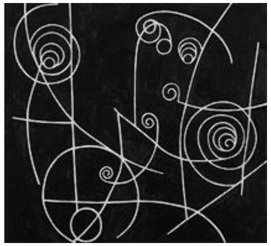
Neutrino flux model

Cross-section model

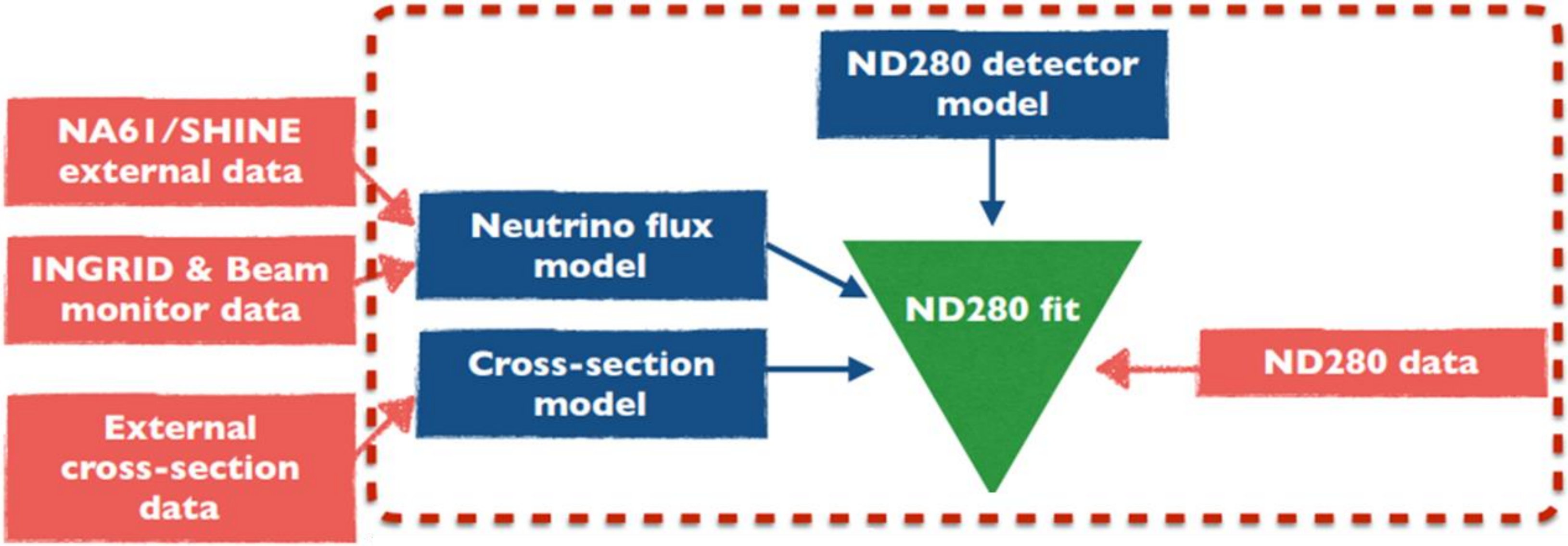
Analysis Strategy





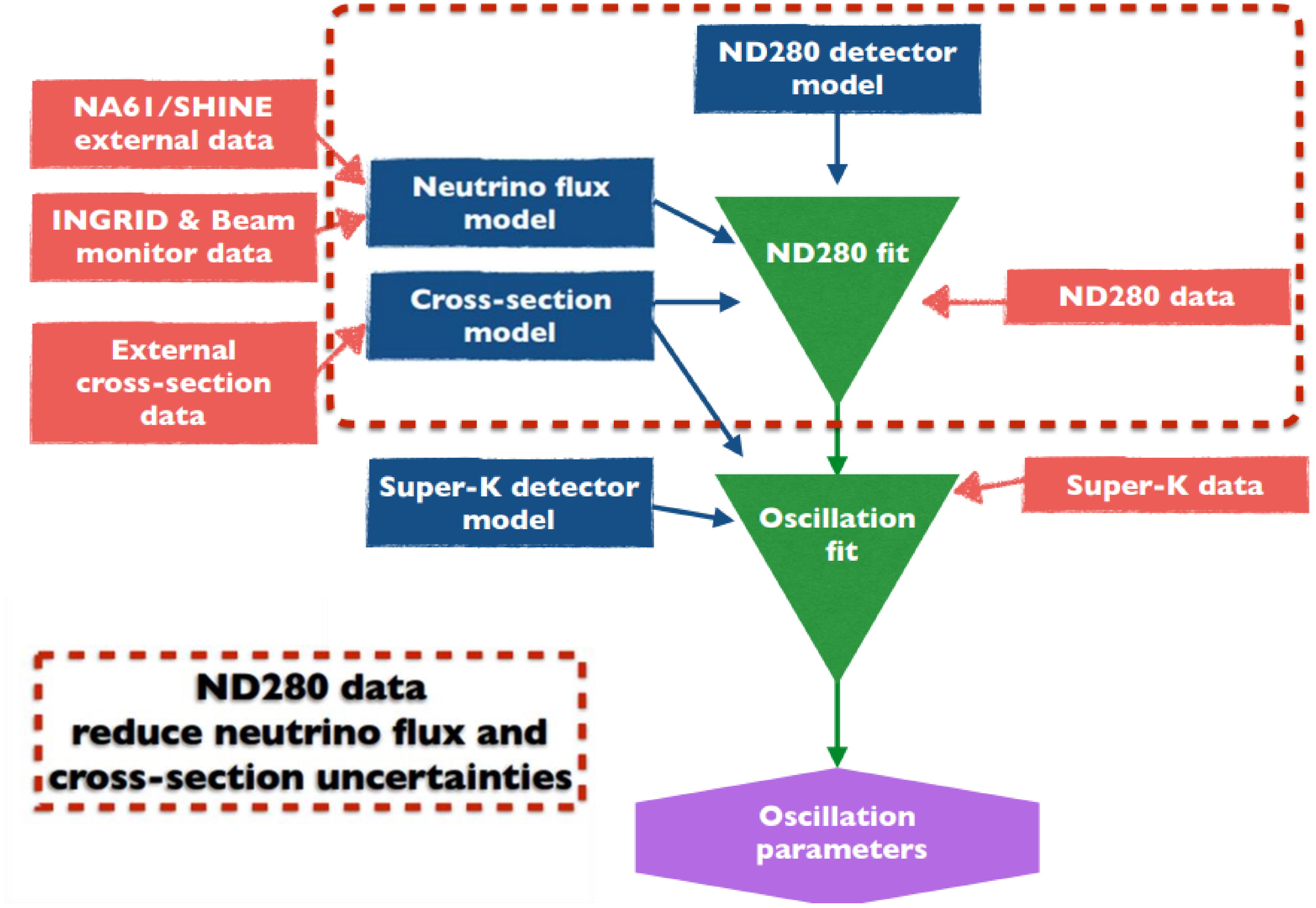


Analysis Strategy



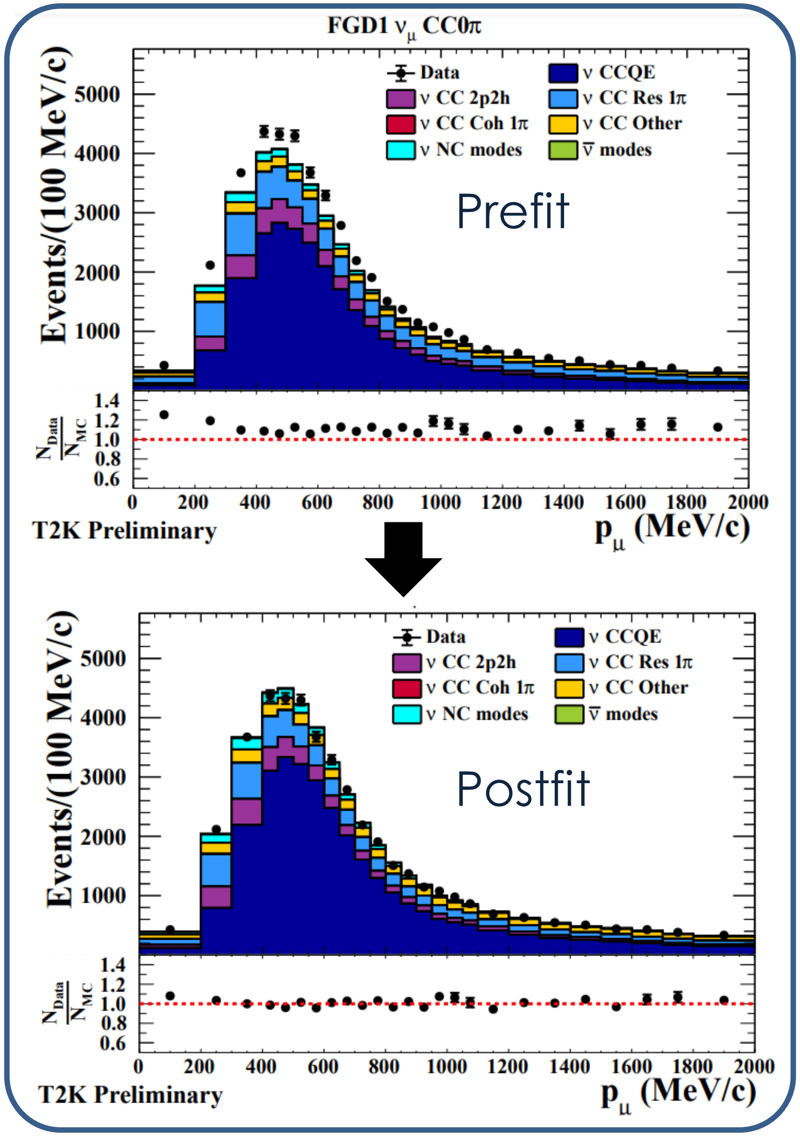
ND280 data reduce neutrino flux and cross-section uncertainties

Analysis Strategy

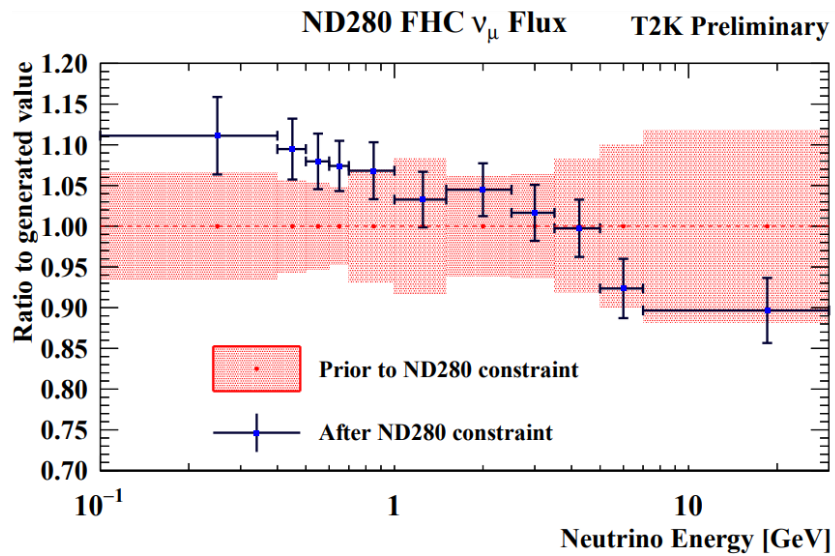


ND280 Fit

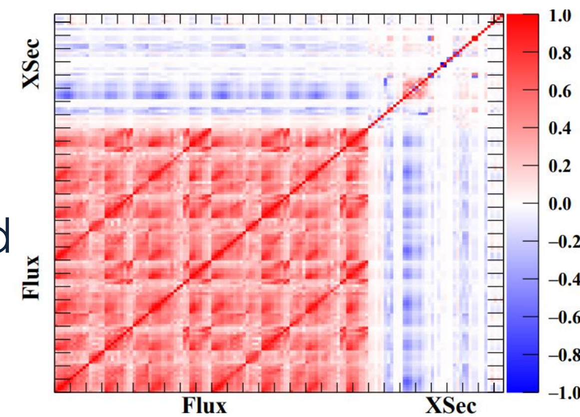
More details are provided in the backup slides



- Fit flux, cross-section, detector model parameters to 18 ND280 samples.



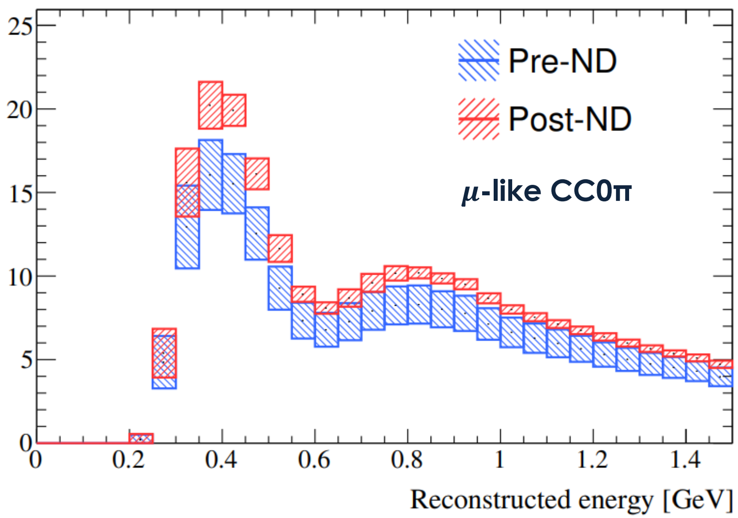
- Final output is parameter uncertainties and correlations



ND280 Fit

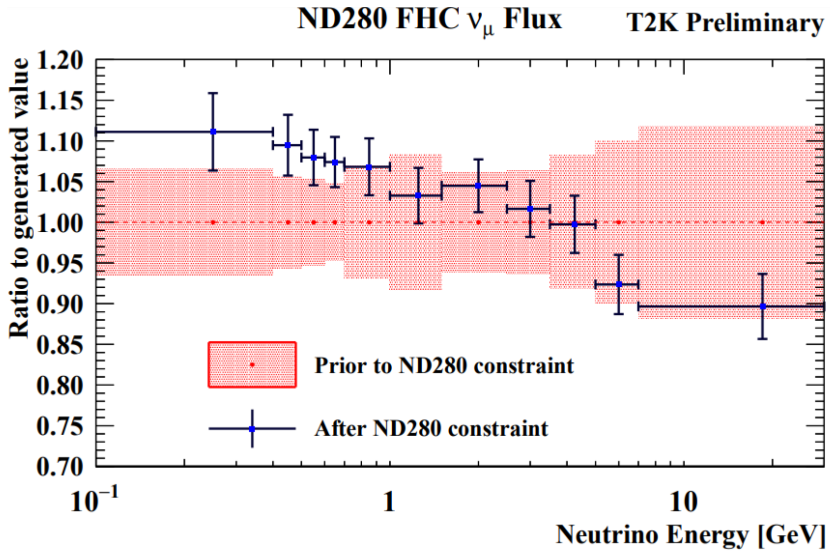
More details are provided in the backup slides

The constrained model can then be used to predict what we expect to see at Super K

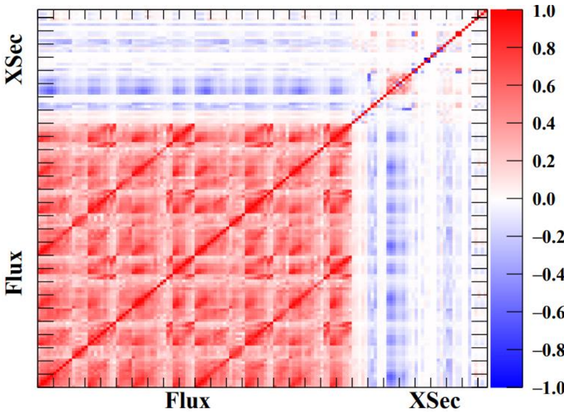


This is the input to the Far detector fit where we extract the oscillation parameters

- Fit flux, cross-section, detector model parameters to 18 ND280 samples.



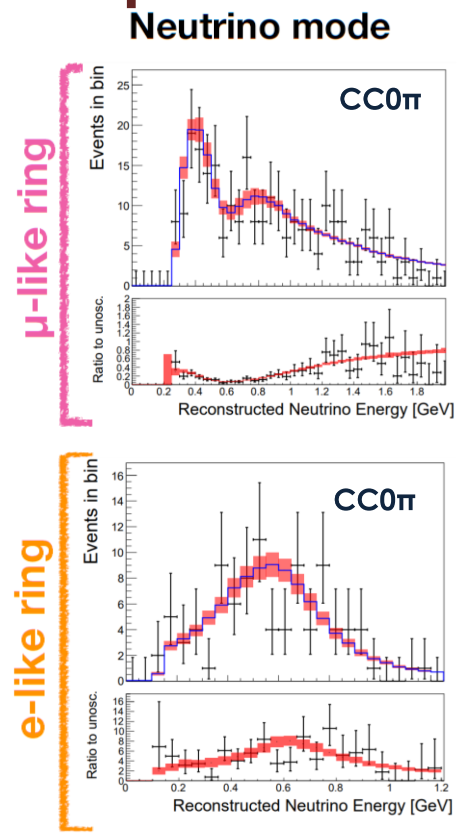
- Final output is parameter uncertainties and correlations



Oscillation Fit Samples

Analyse outgoing lepton kinematics from 5 **different samples**:

- CC0π: majority of CC events, best understood, best E_ν reconstruction



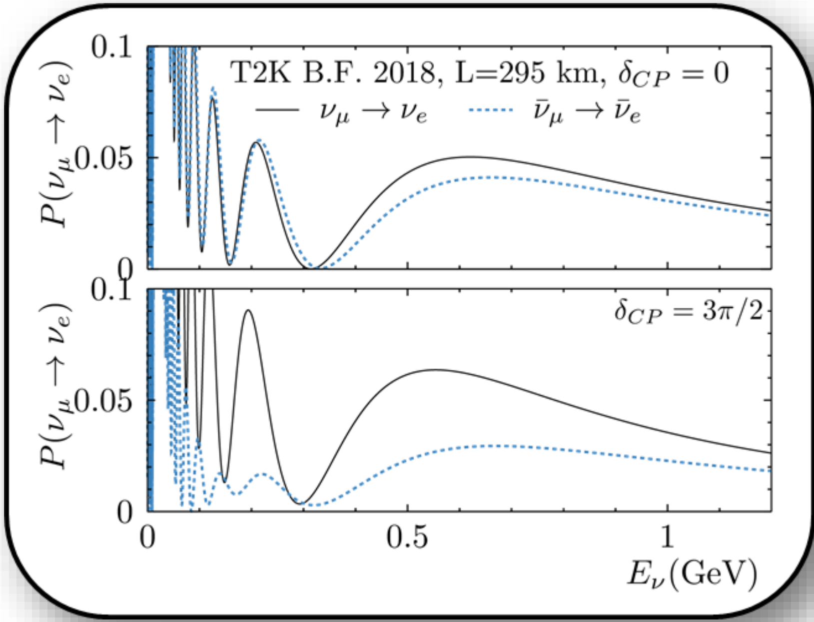
Probes $P(\nu_\mu \to \nu_\mu)(E_\nu)$: sensitive to $\Delta m^2_{3\ell}$ and θ_{23}

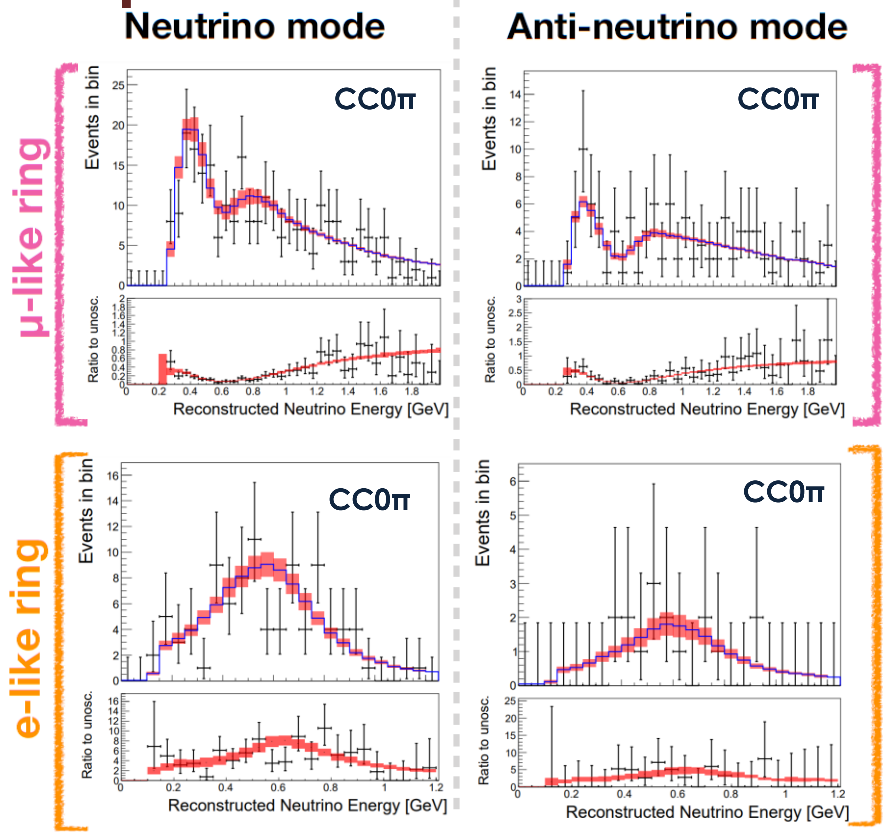
Probes $P(\nu_\mu \to \nu_e)(E_\nu)$: sensitive to θ_{13} and δ_{CP}

Oscillation Fit Samples

Analyse outgoing lepton kinematics from 5 **different samples**:

- CC0π: majority of CC events, best understood, best E_ν reconstruction
- Include anti-neutrino and neutrino samples: additional sensitivity to δ_{CP}

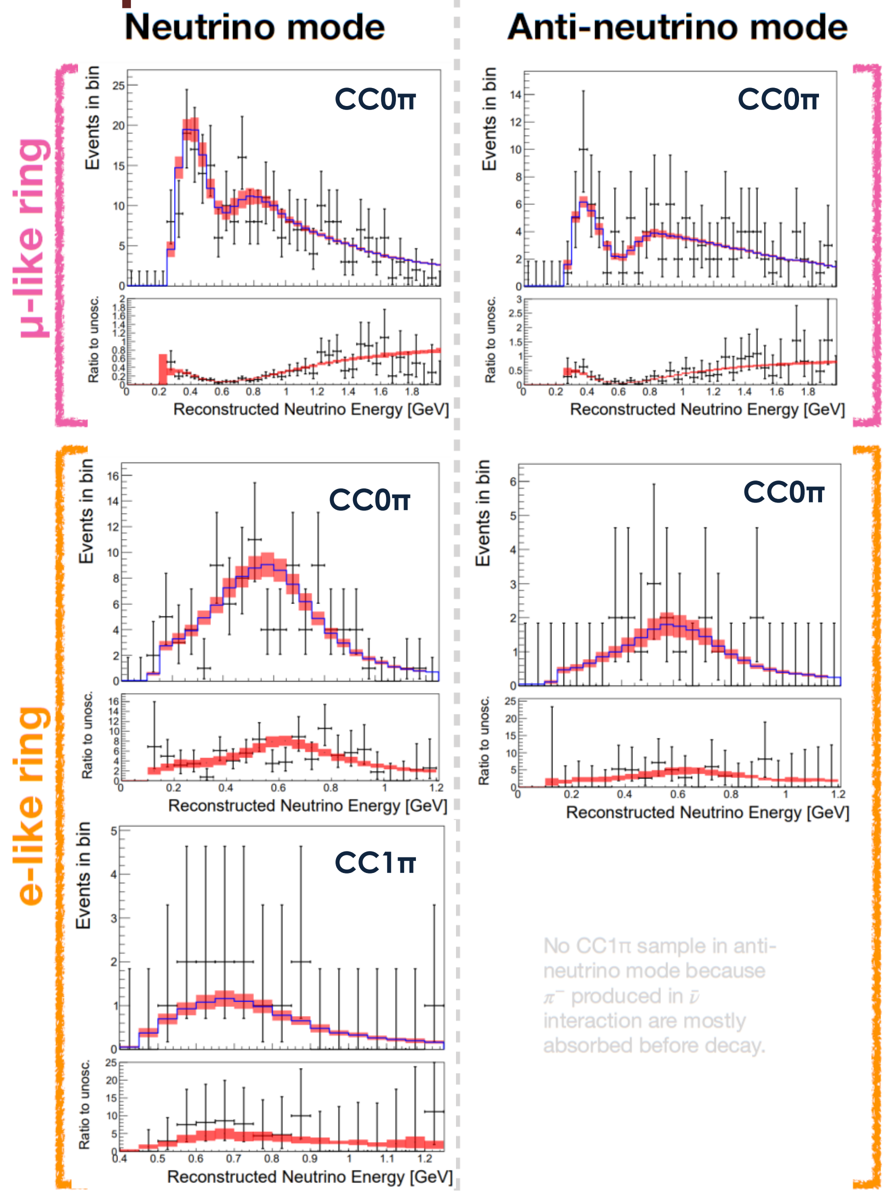




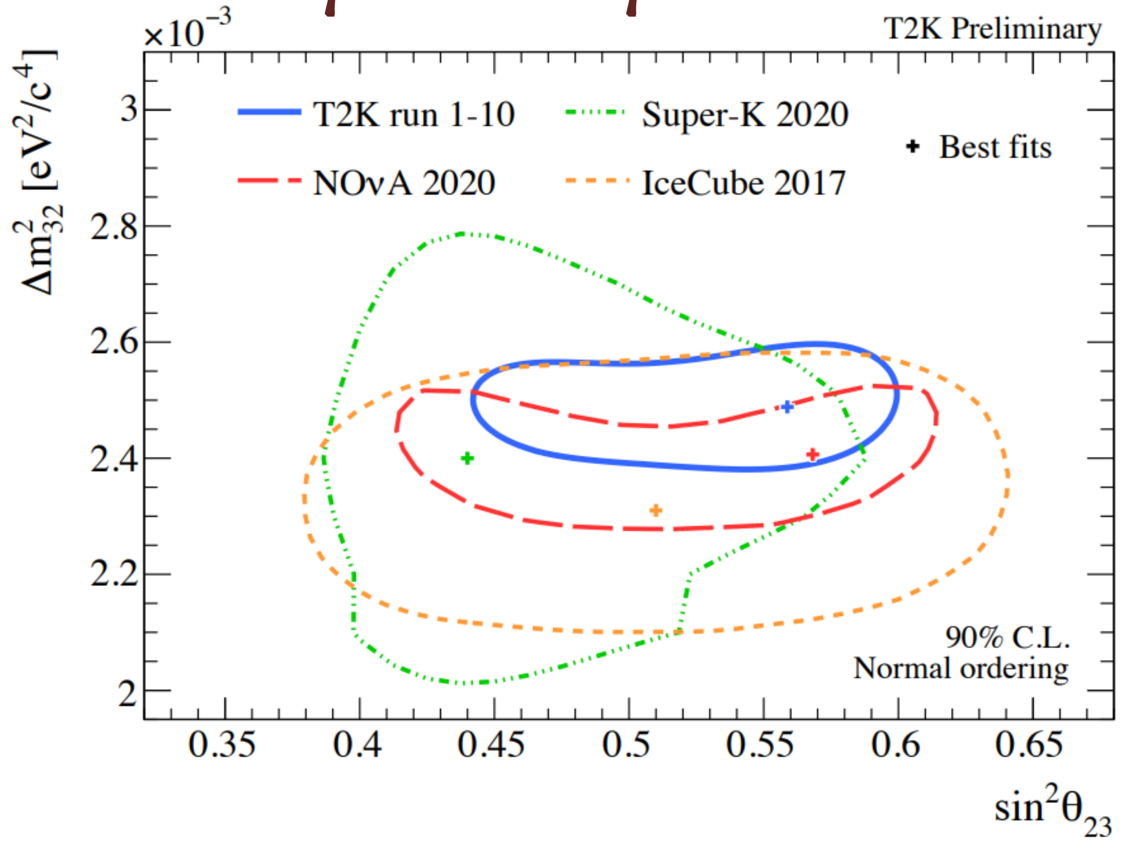
Oscillation Fit Samples

Analyse outgoing lepton kinematics from 5 **different samples**:

- CC0π: majority of CC events, best understood, best E_ν reconstruction
- Include anti-neutrino and neutrino samples: additional sensitivity to δ_{CP}
- Additional CC1π sample for ν_e appearance
  - Lower statistics, less accurate E_ν, but useful to supplement CC0π samples

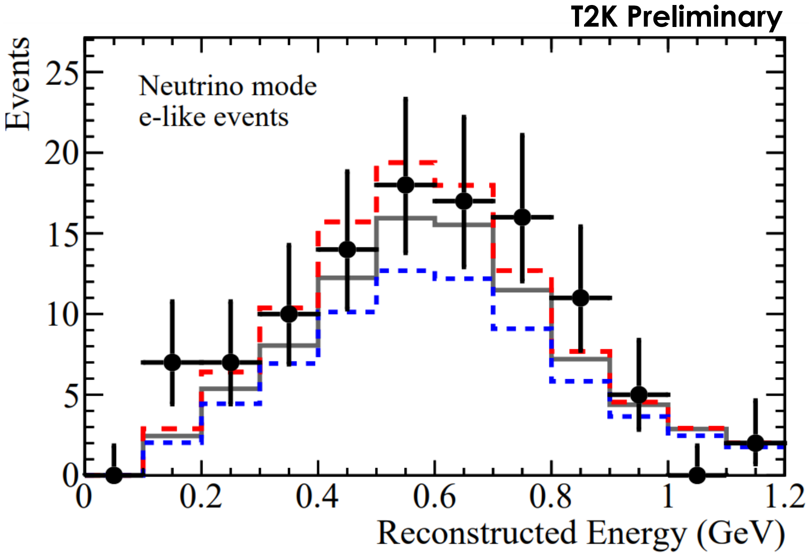


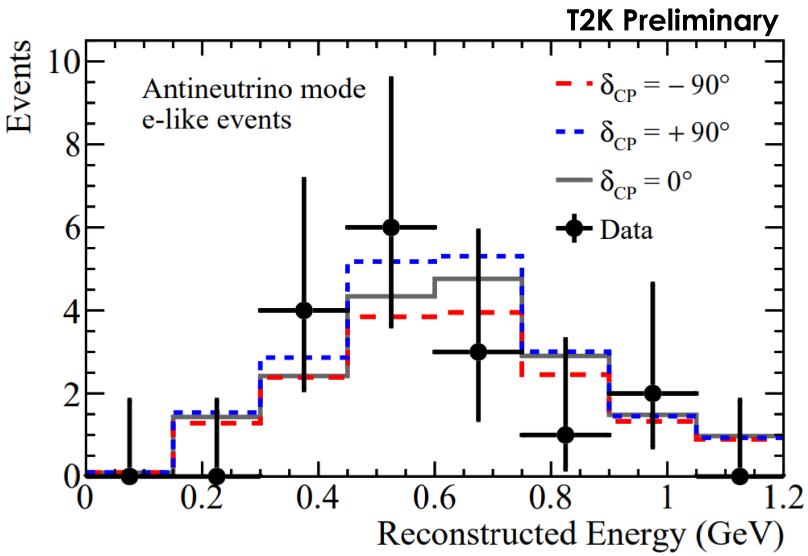
Fit results ($\nu_\mu \to \nu_\mu$)



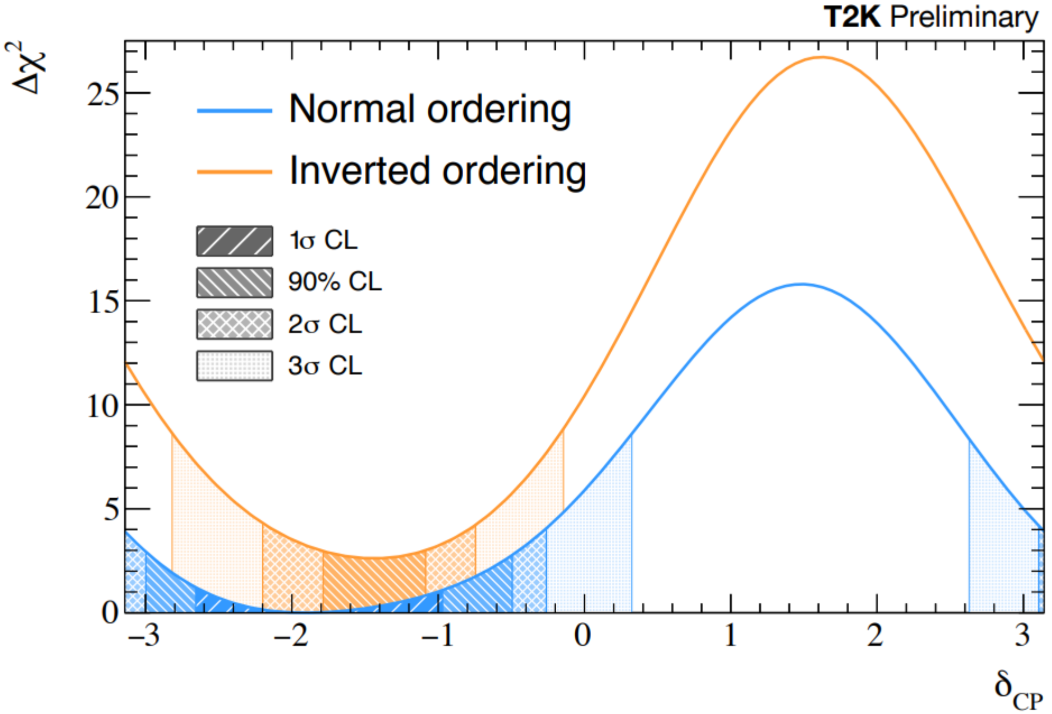
- World leading constraint on $\sin^2\theta_{23}$
- Compatible with maximal mixing ($\sin^2\theta_{23} = 0.5$)

Fit results (δ_{CP})

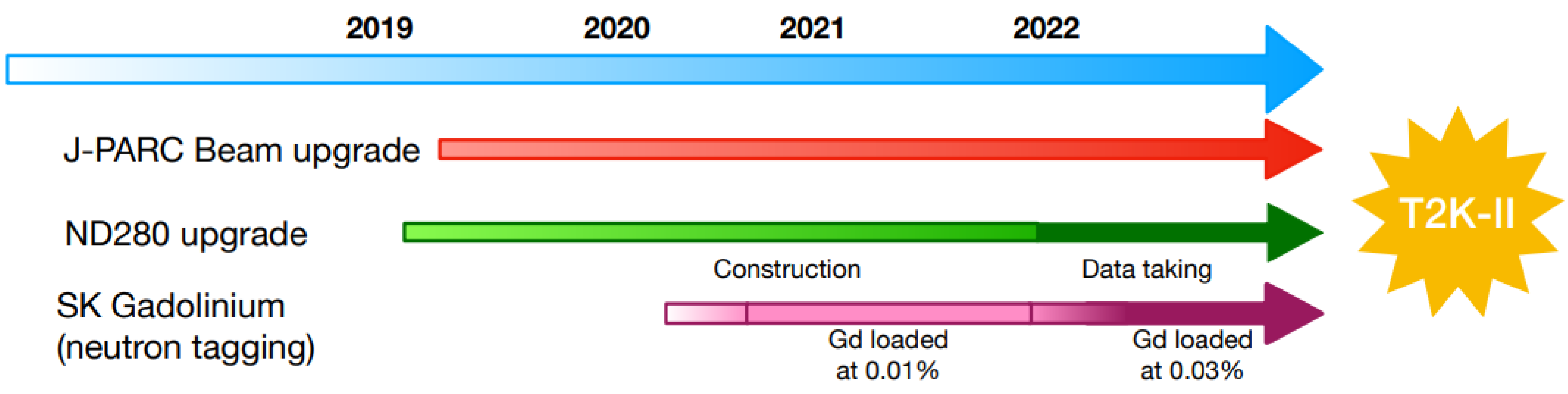




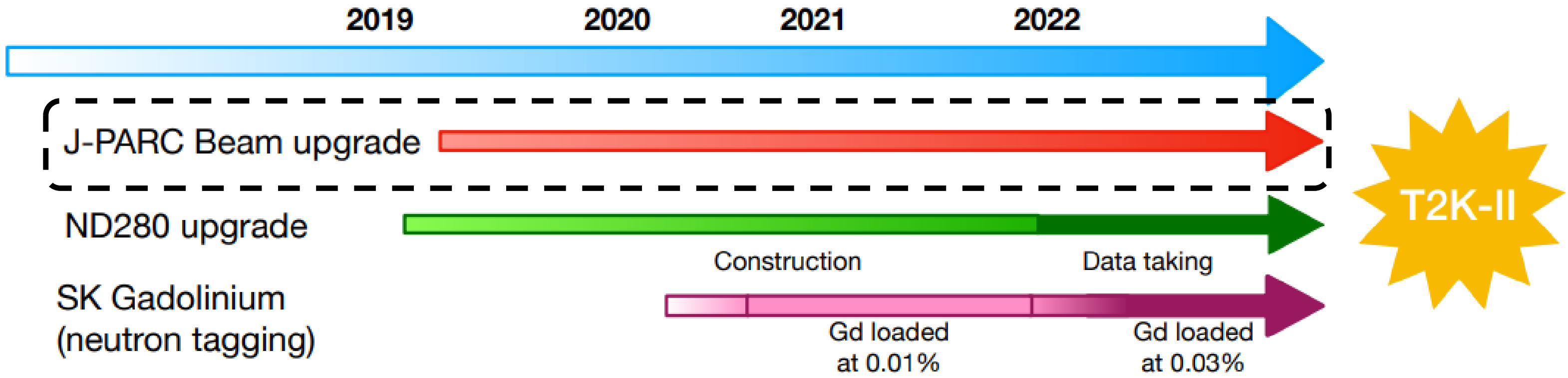
- Large region excluded at 3σ
- CP-conservation (0,±) excluded at 90%
- Weak preference for normal mass ordering



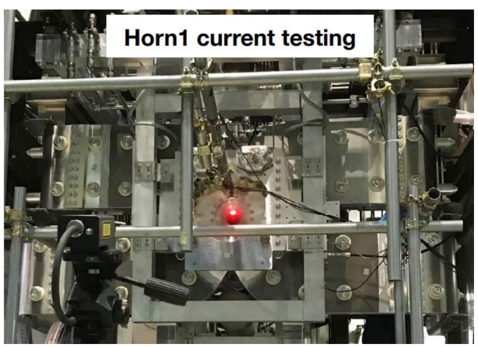
T2K-II: a bright future



T2K-II: a bright future



More power, more statistics



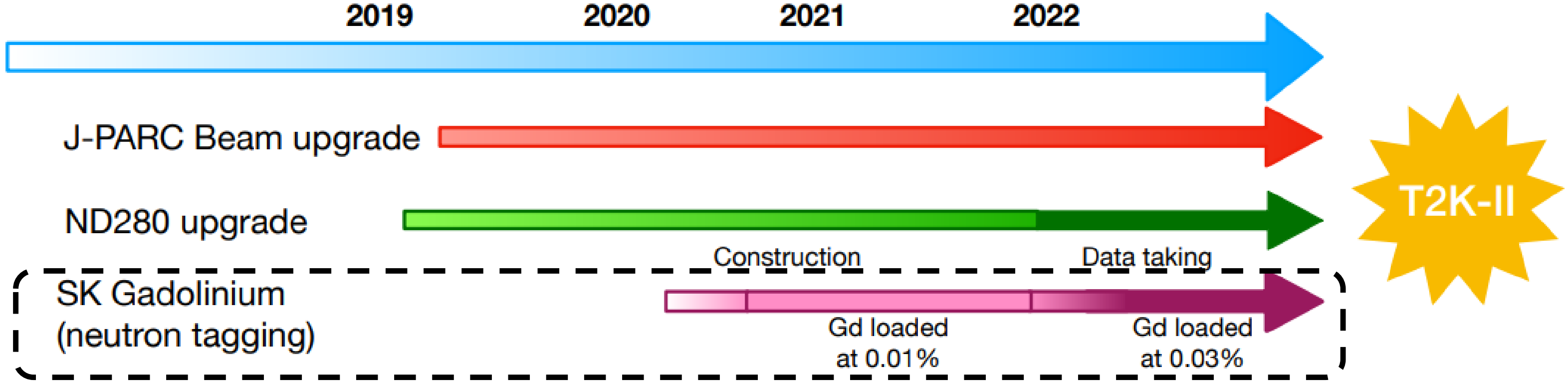
Beam power

$$500\ kW \rightarrow \sim 900\ kW \rightarrow \sim 1.3\ MW$$

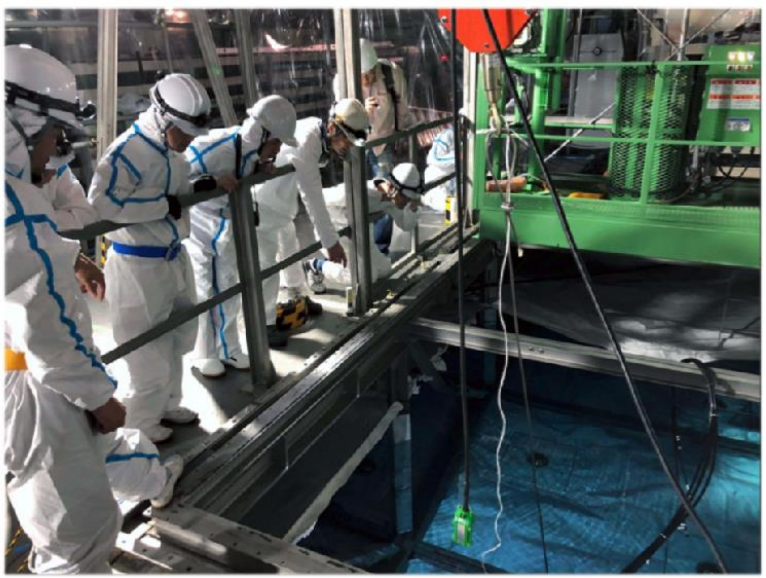
Today ***~2024*** ***~2028***

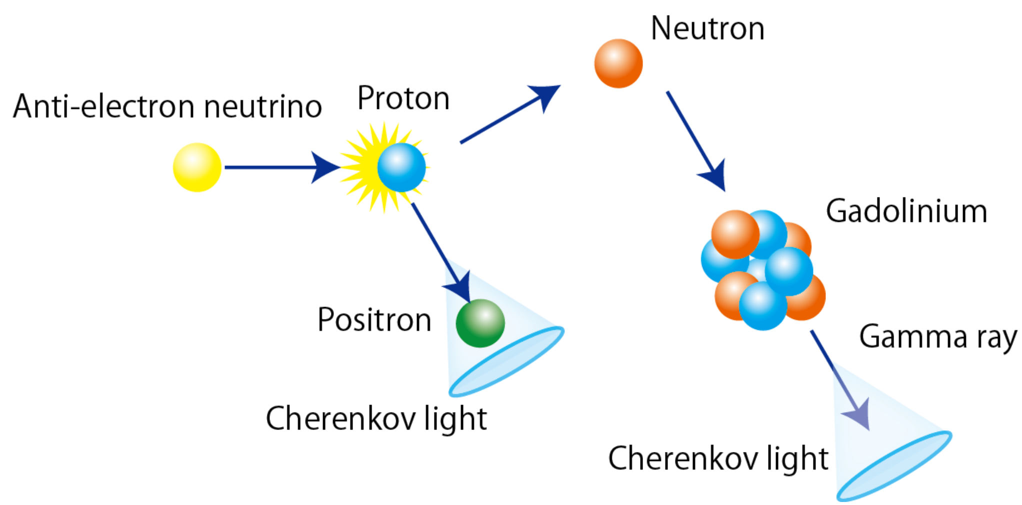
- Replacing two of the beam's magnetic focussing horns
- Upgrading horn power supply to enable faster beam repetition rate
- Improving the beam target cooling capability

T2K-II: a bright future

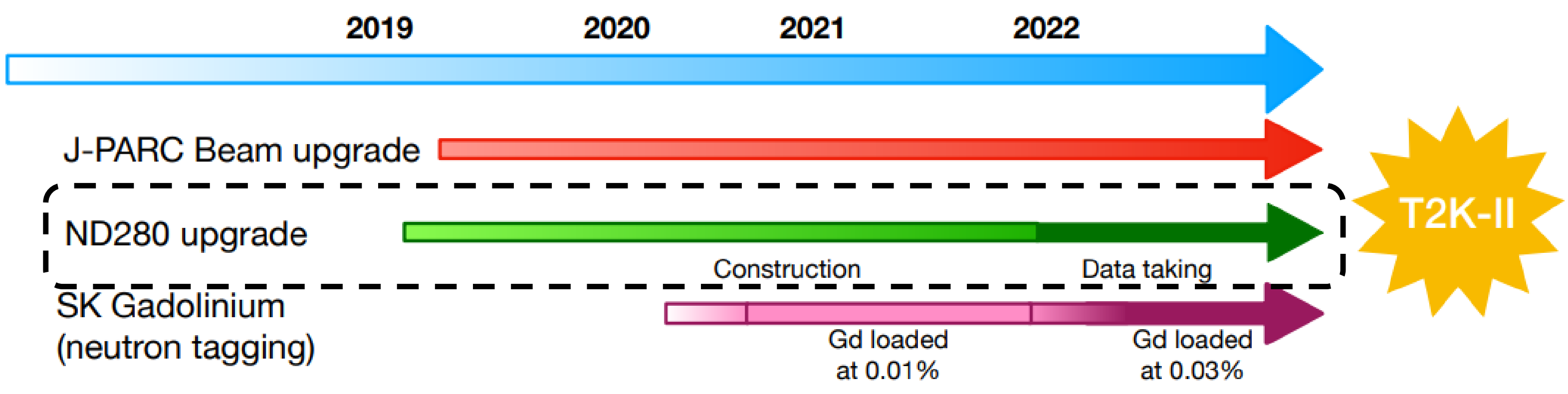


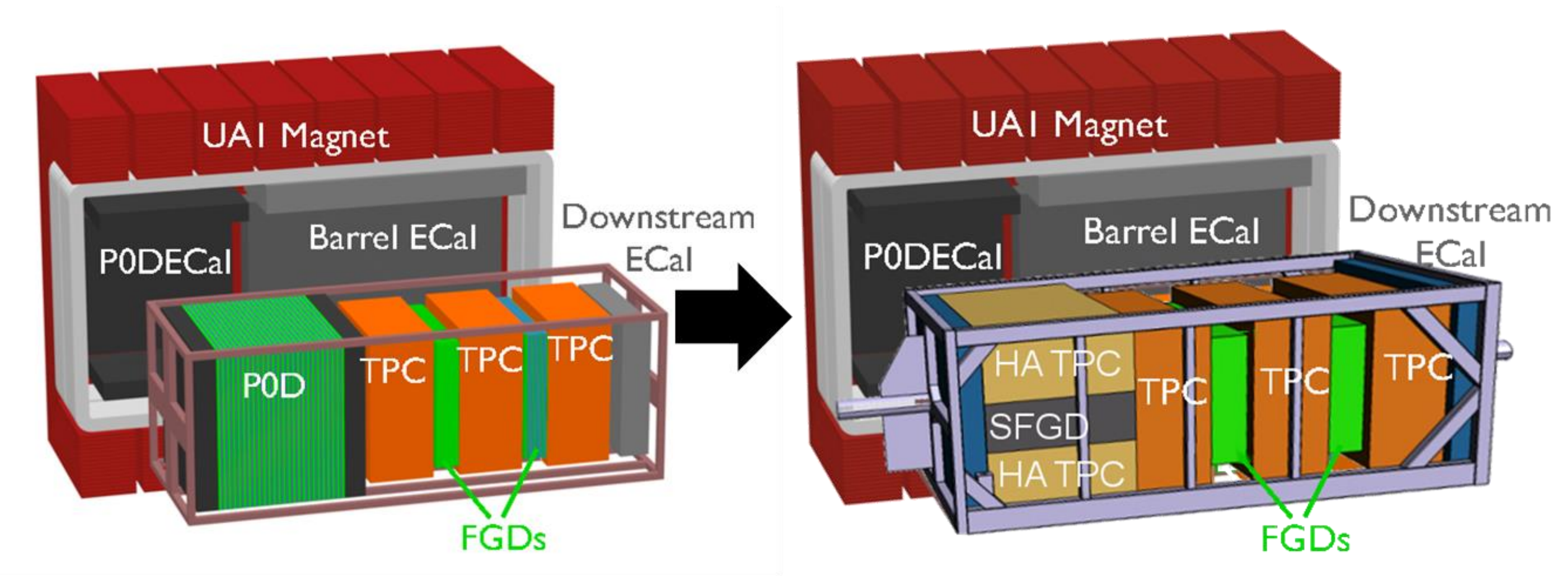
Neutron tagging at SK



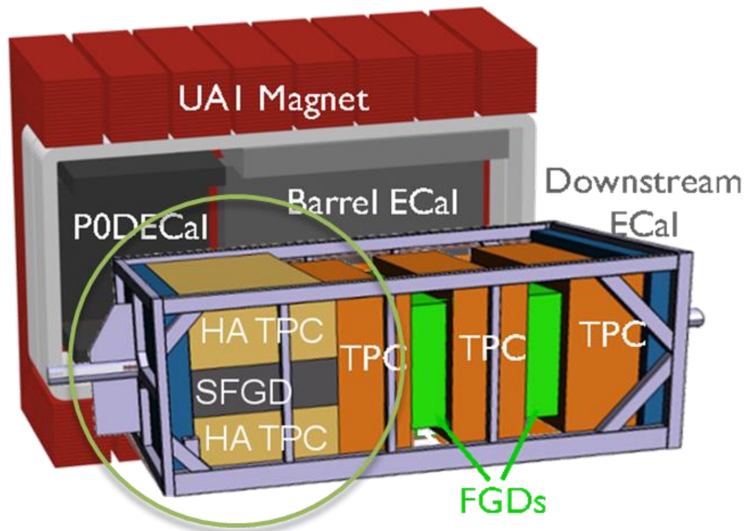


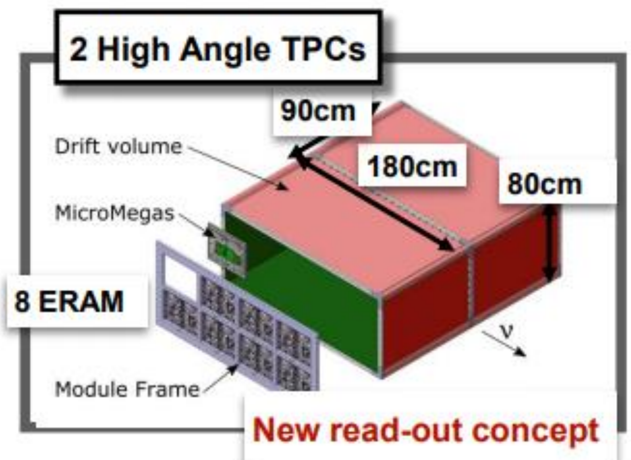
T2K-II: a bright future



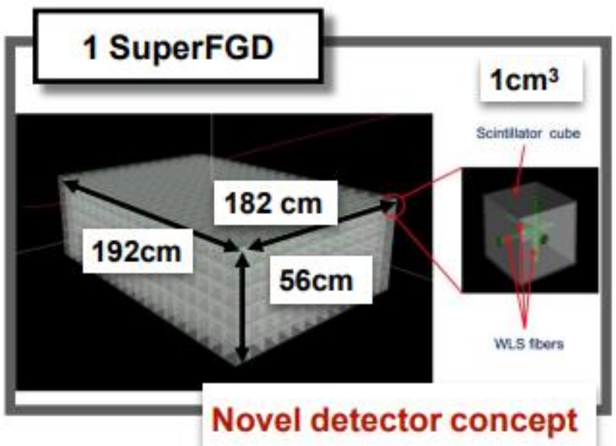


ND280 Upgrade

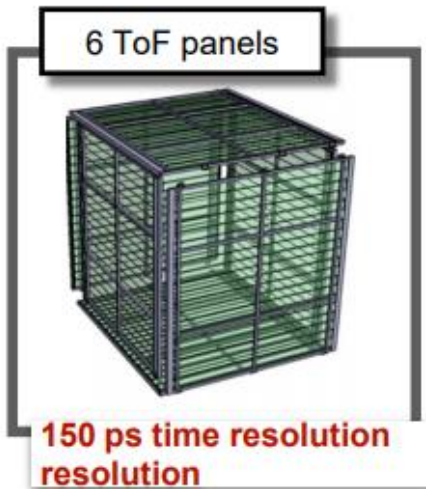




NIM A 957 163286 (2020)

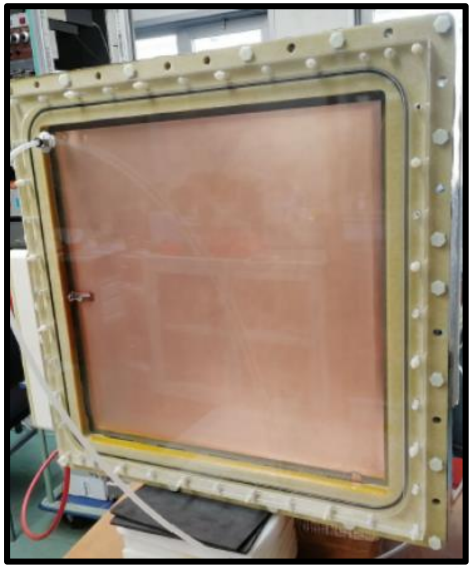


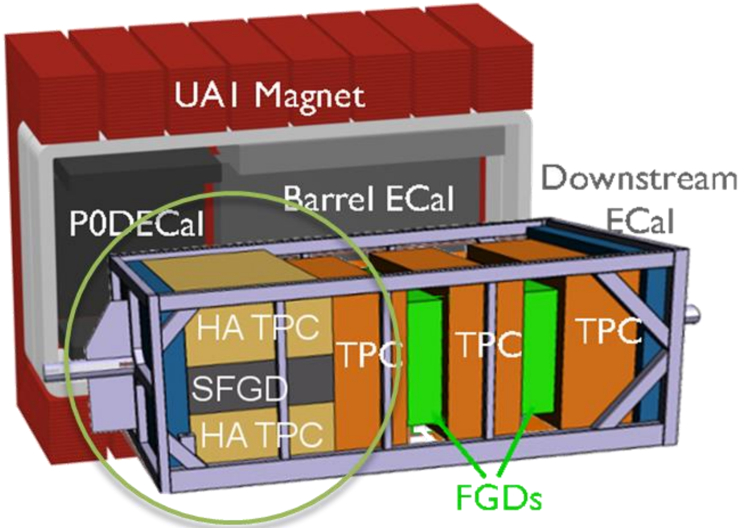
JINST 13, P02006 (2018)
JINST 15 P12003 (2020)

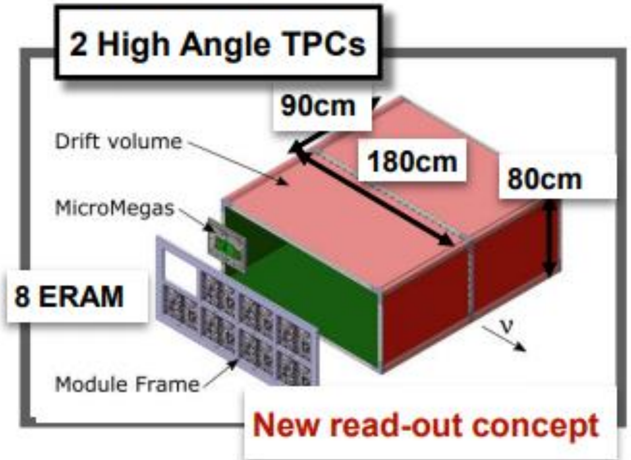


JPS Conf. Proc. 27, 011005 (2019)

ND280 Upgrade







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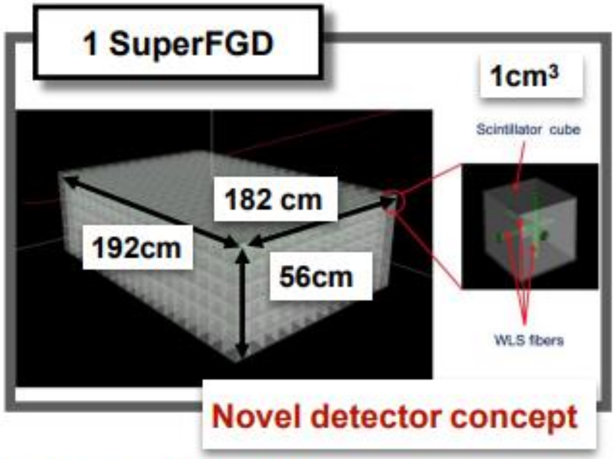
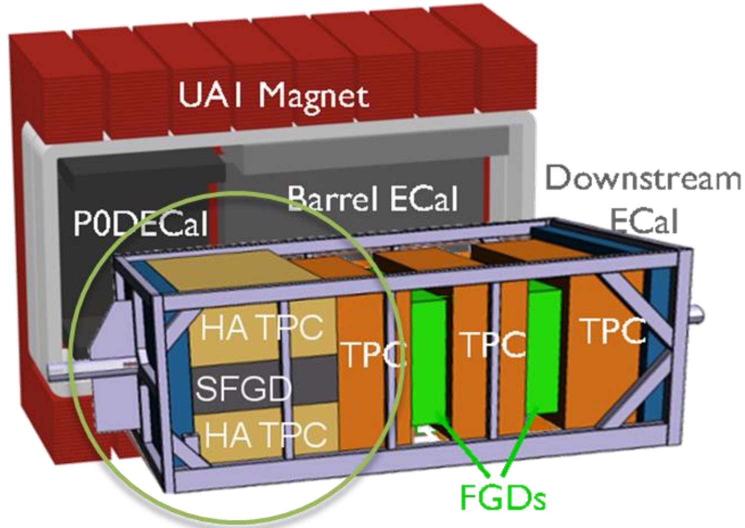
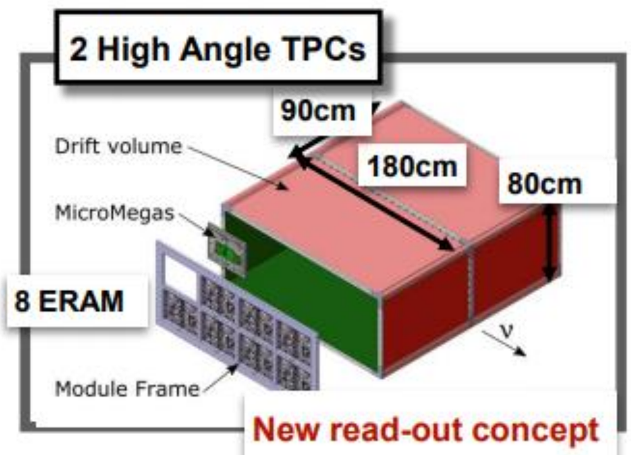


JINST 13, P02006 (2018)
JINST 15 P12003 (2020)

JPS Conf. Proc. 27, 011005 (2019)

ND280 Upgrade





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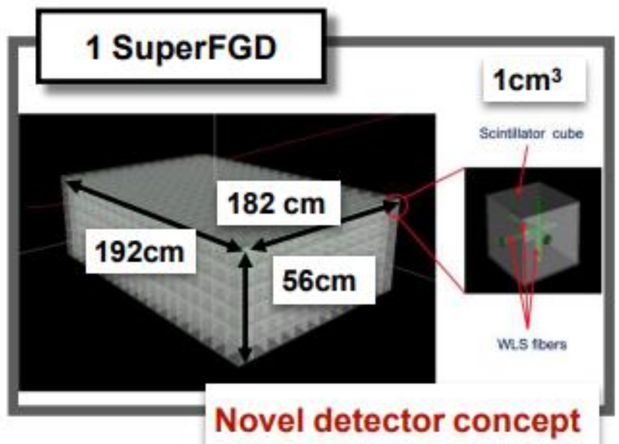

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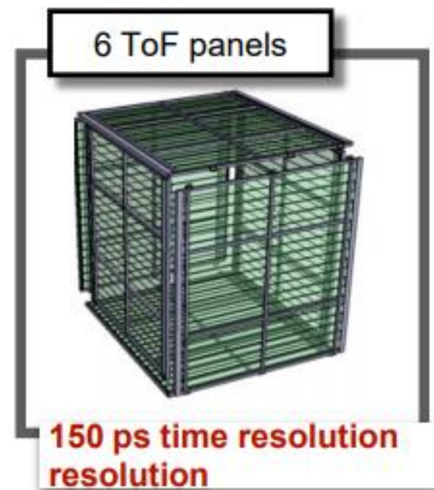

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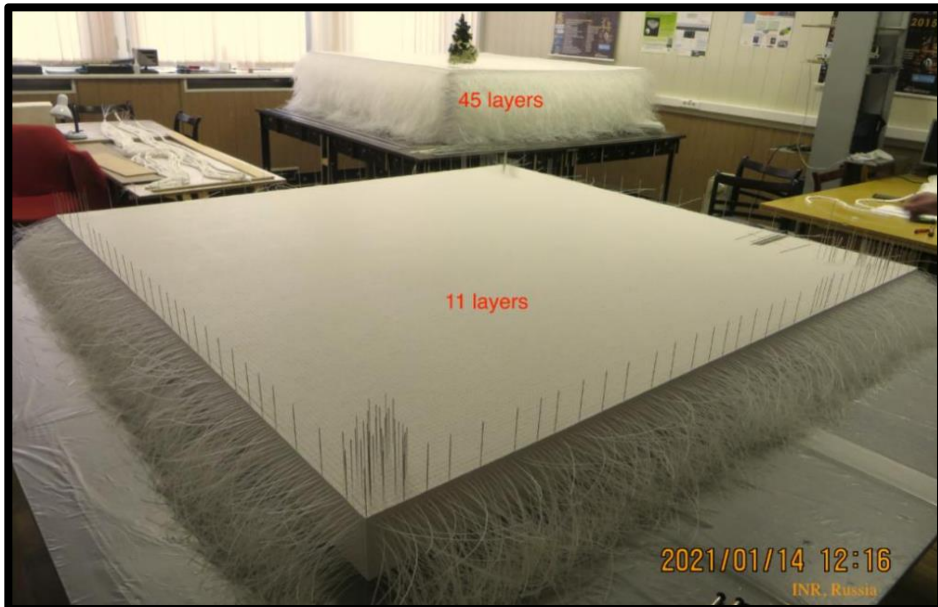
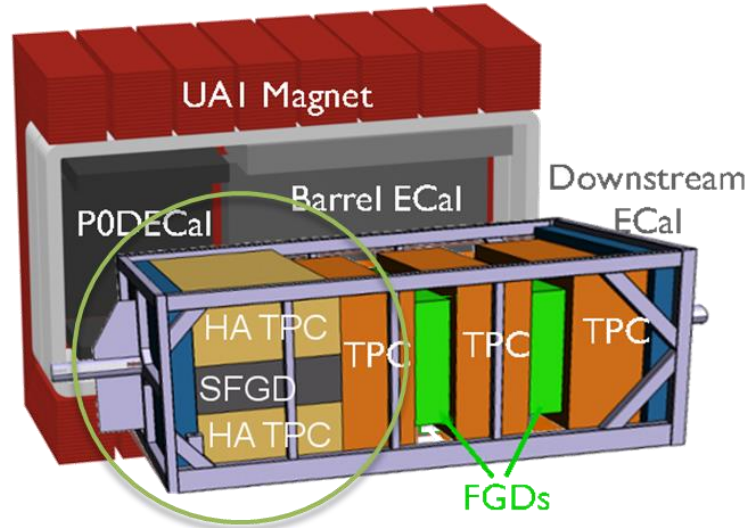
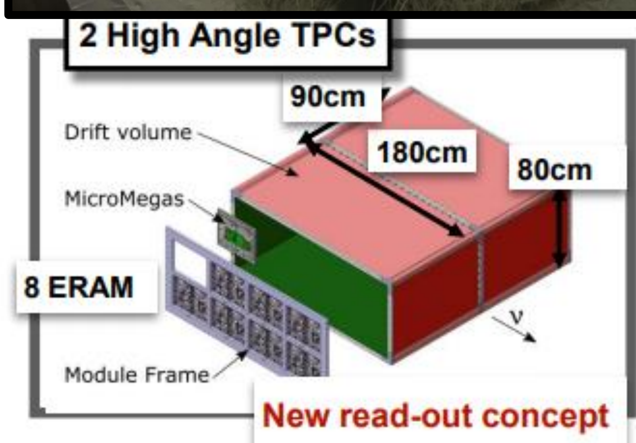
ND280 Upgrade







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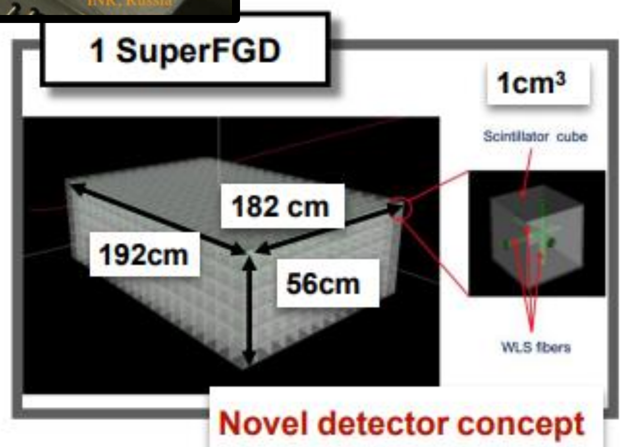

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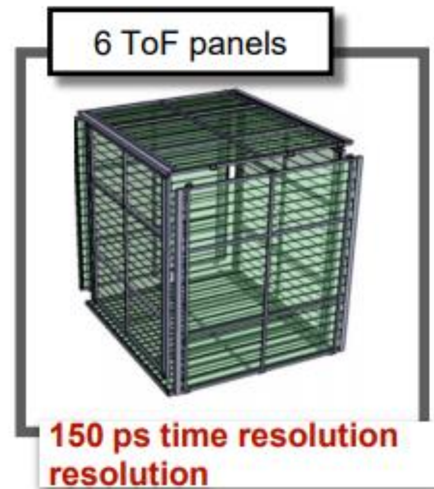
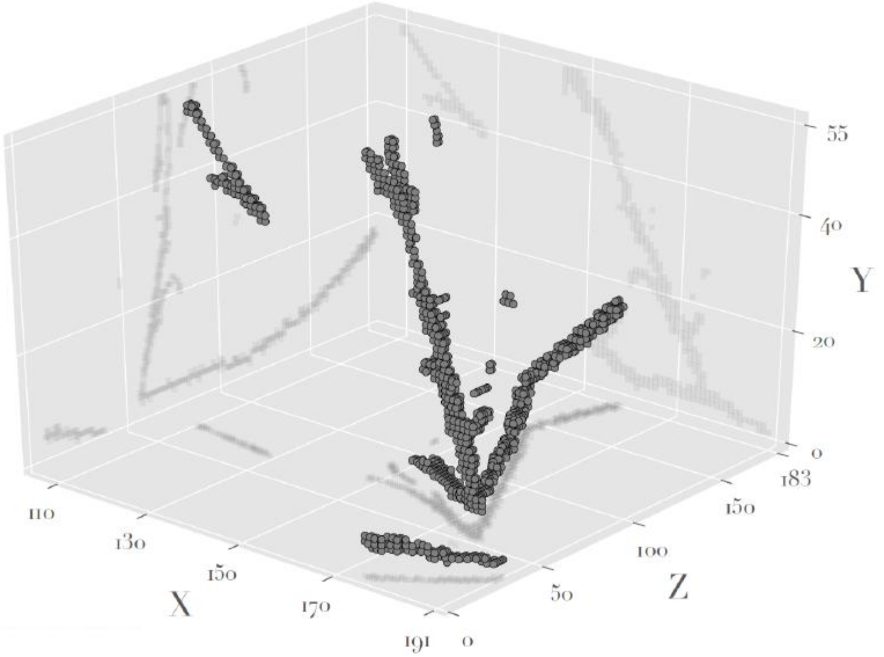


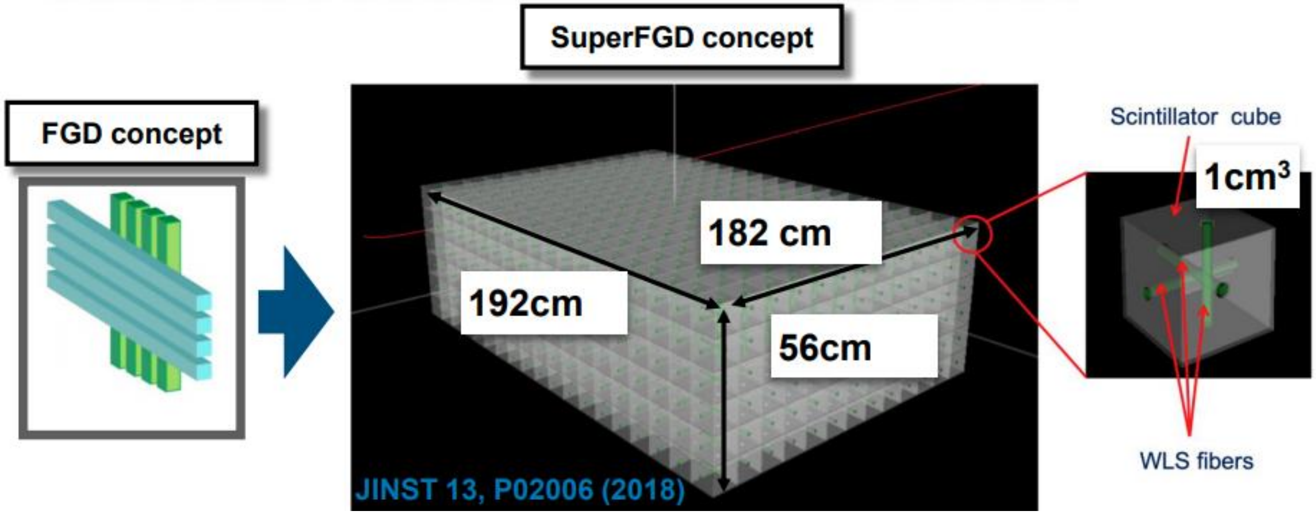
JPS Conf. Proc. 27, 011005 (2019)

The Super FGD (SFGD)

The SFGD:

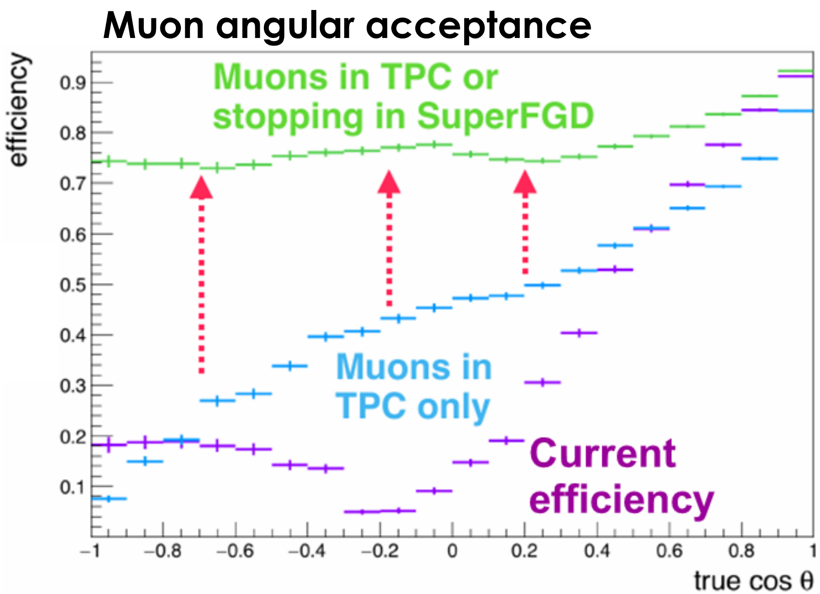
- 2 million scintillator cubes
- 58,000 channels
- 2.1 tons target mass





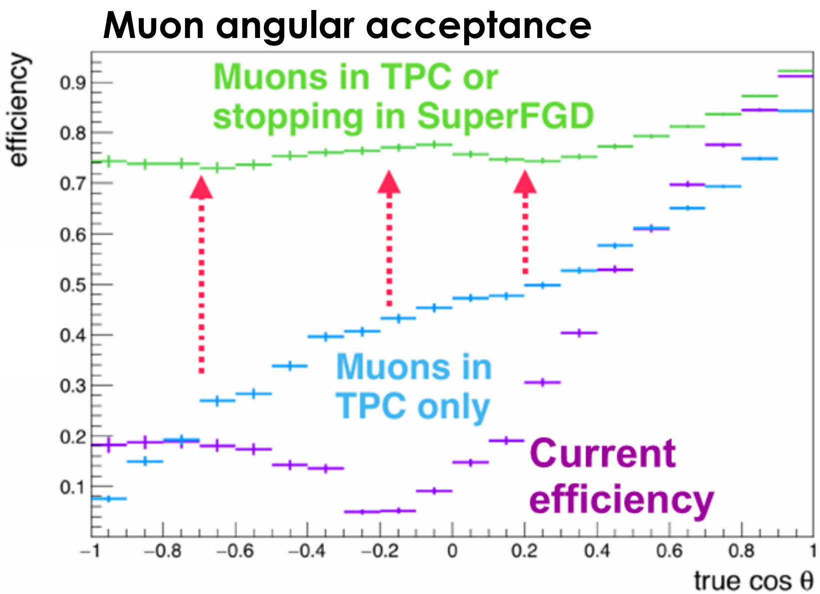
Detector Performance

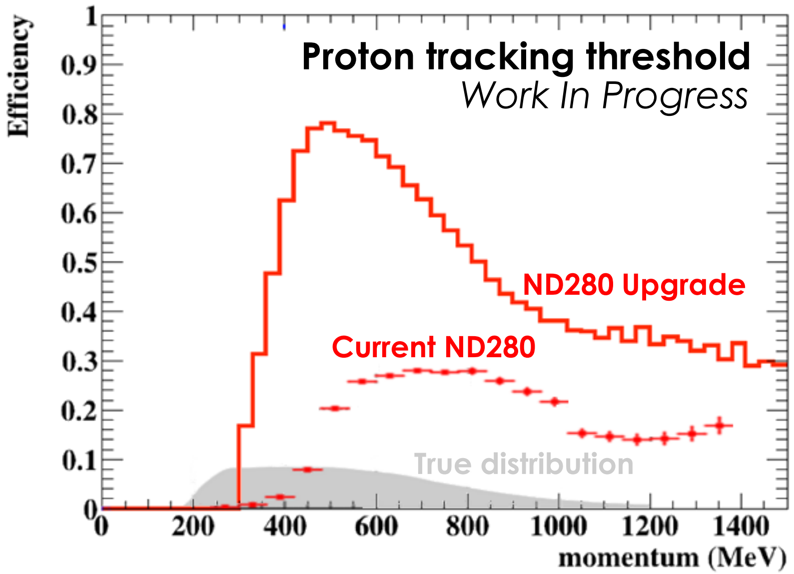
- Dramatically improved angular acceptance



Detector Performance

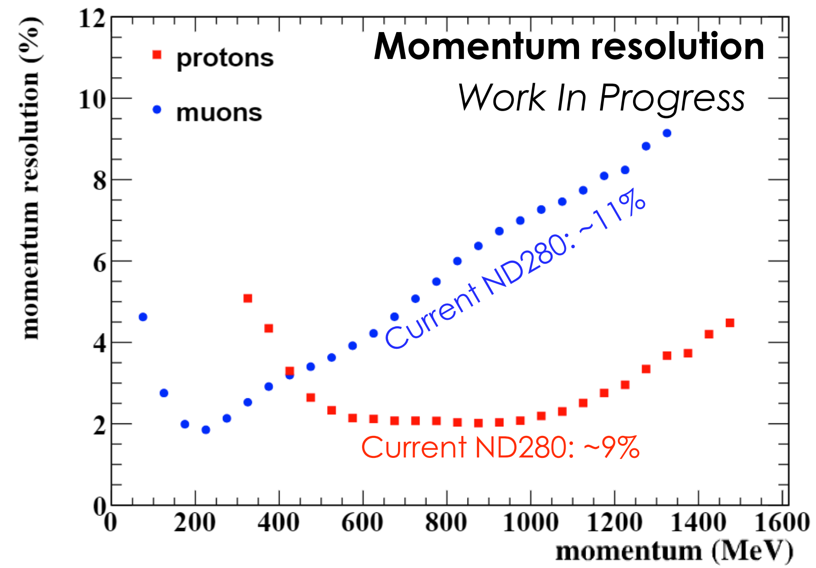
- Dramatically improved angular acceptance
- Much lower tracking thresholds

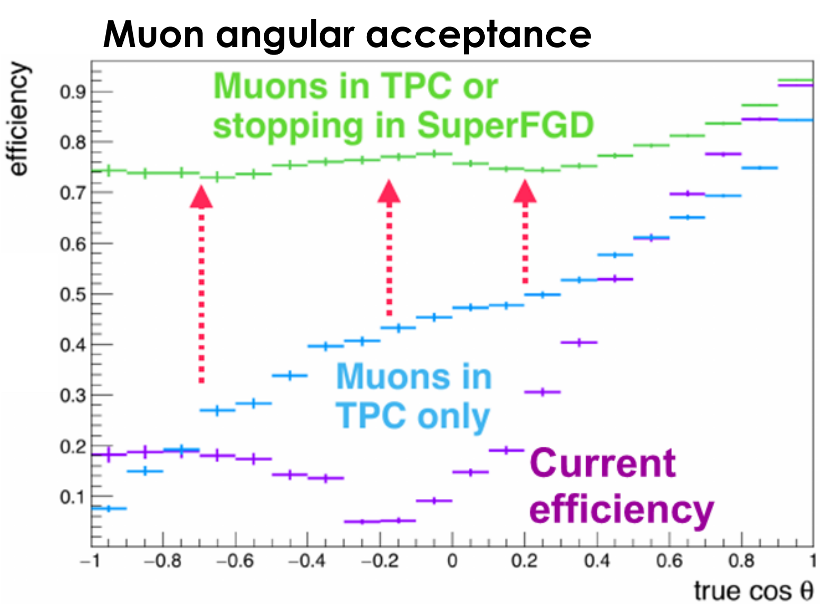


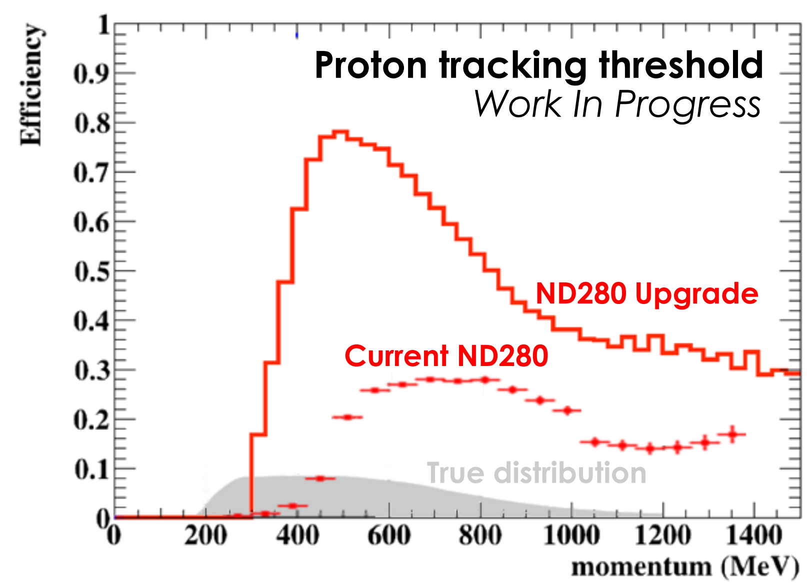


Detector Performance

- Dramatically improved angular acceptance
- Much lower tracking thresholds
- Substantially improved resolutions

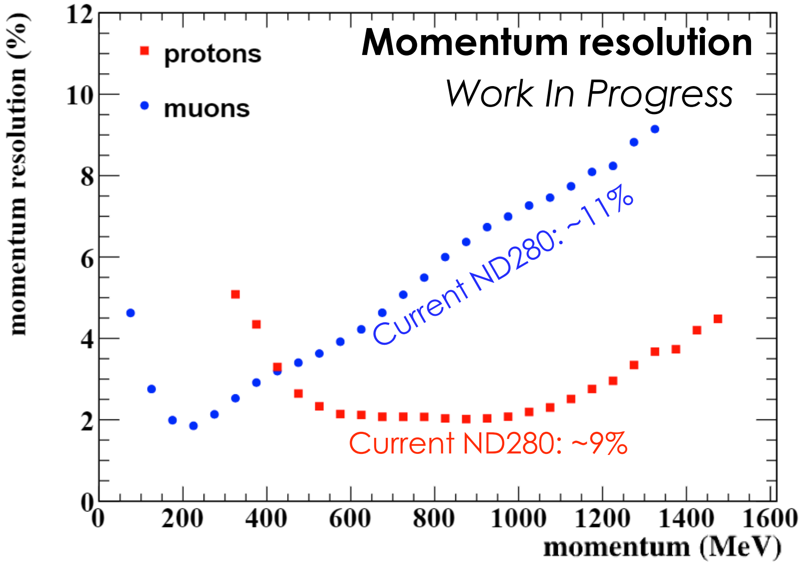


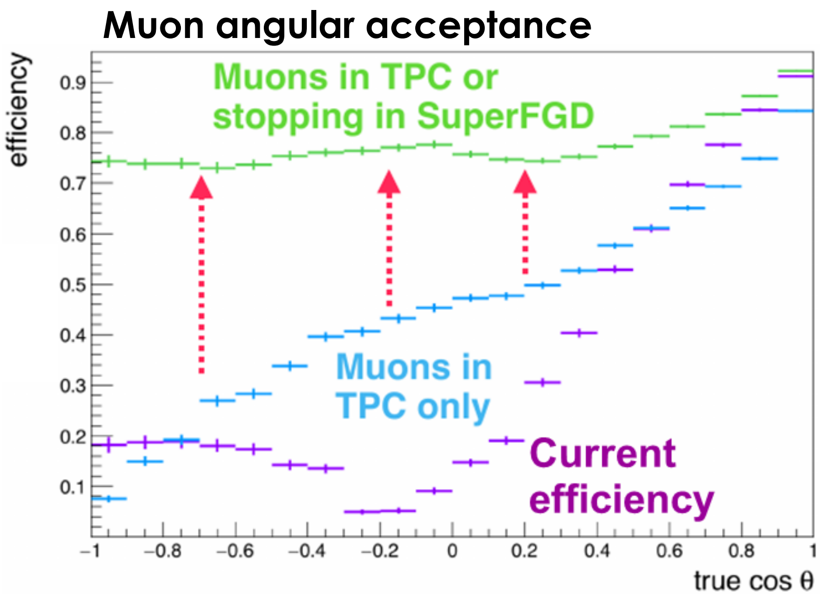


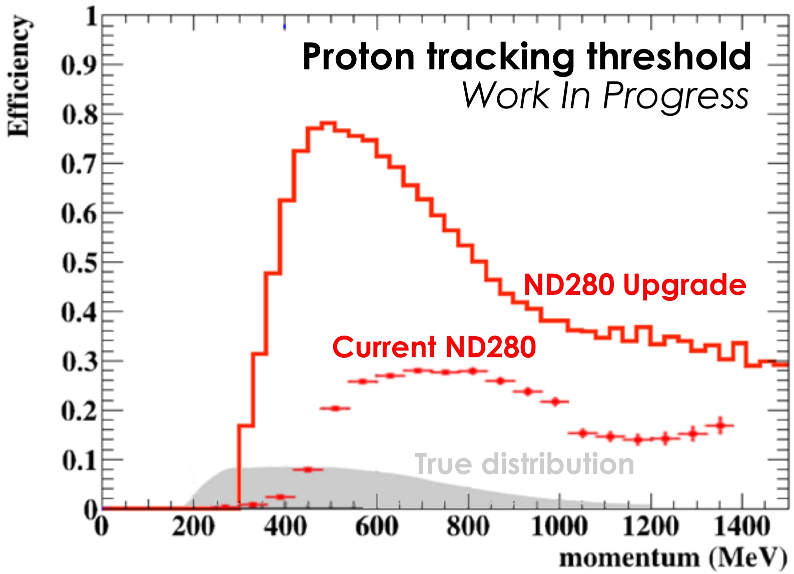


Detector Performance

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



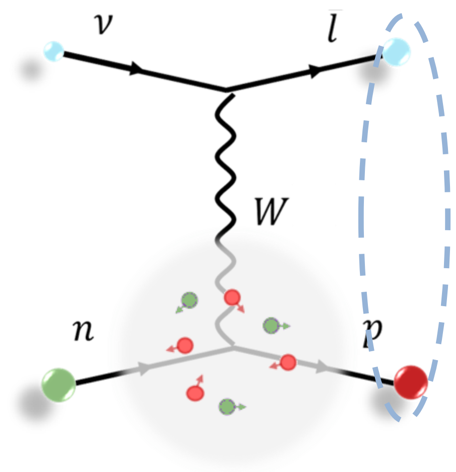


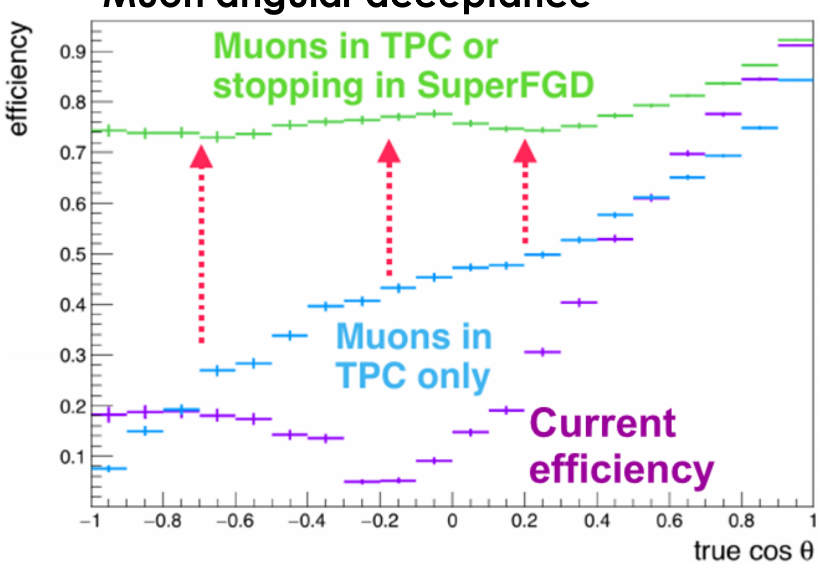


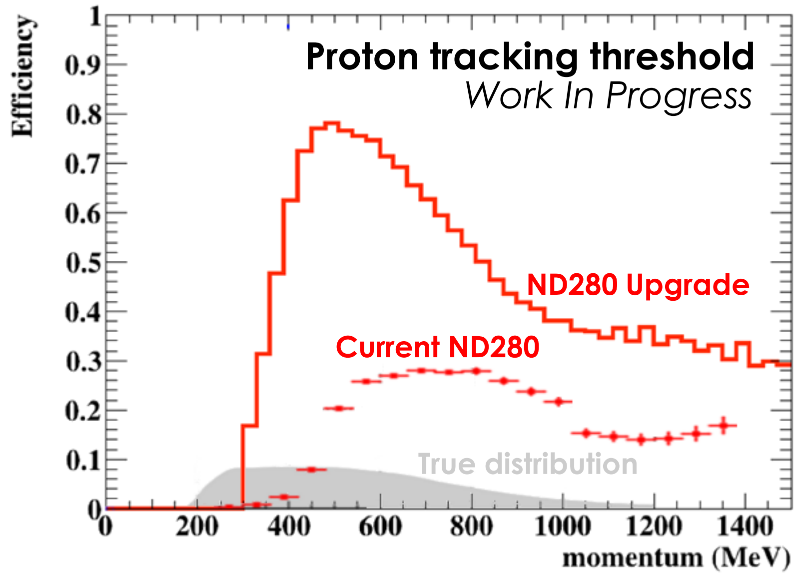
Physics Sensitivity

More details are provided in the backup slides

- Primary sources of systematic uncertainties stem from *nuclear effects* in neutrino scattering
- Very difficult to characterise with current ND280 due to *limited proton/neutron acceptance*
- The upgrade will overcome these limitations: more powerful and **less ambiguous** model constraints







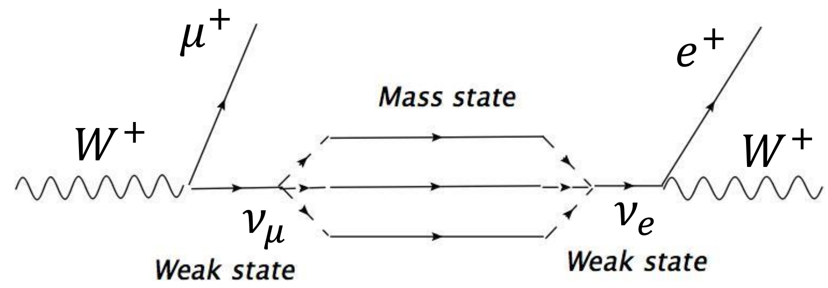
Summary

- T2K is making world-leading analyses of neutrino oscillations
- Provided first constraints on the δ_{CP} PMNS parameter, **excluding the CP conserving values at 90% CL**
- Through increased statistics and detector upgrades, T2K will continue to improve its measurements as it transitions to T2K-II
- However, to stop future measurements becoming **pre-maturely limited**, *it is essential to reduce systematic uncertainties*
- The upcoming upgrade to ND280 will allow T2K to confront the physics responsible for the most troublesome sources of such uncertainties

BACKUP

Neutrino Oscillations

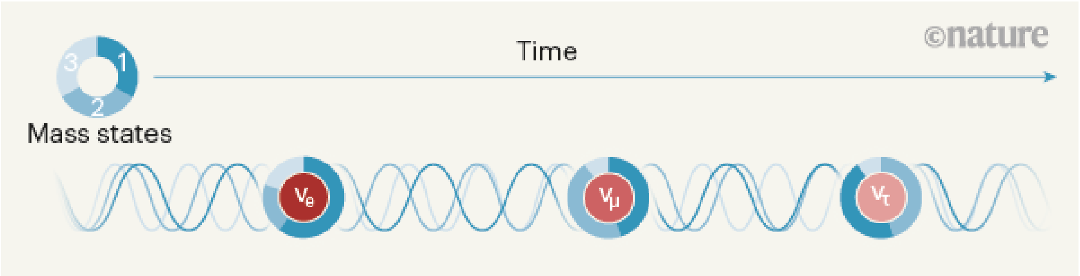
- Neutrinos are **produced** in particular weak eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$
- These are linear combinations of mass eigenstates (ν_1, ν_2, ν_3) related by a unitary matrix, U_{PMNS}
- Neutrinos **propagate** in their mass eigenstates, losing their flavour identity as they go
- When neutrinos interact, they collapses into a weak state again with a $(\nu_e, \nu_\mu, \nu_\tau)$ probability which depends on its current admixture of mass states



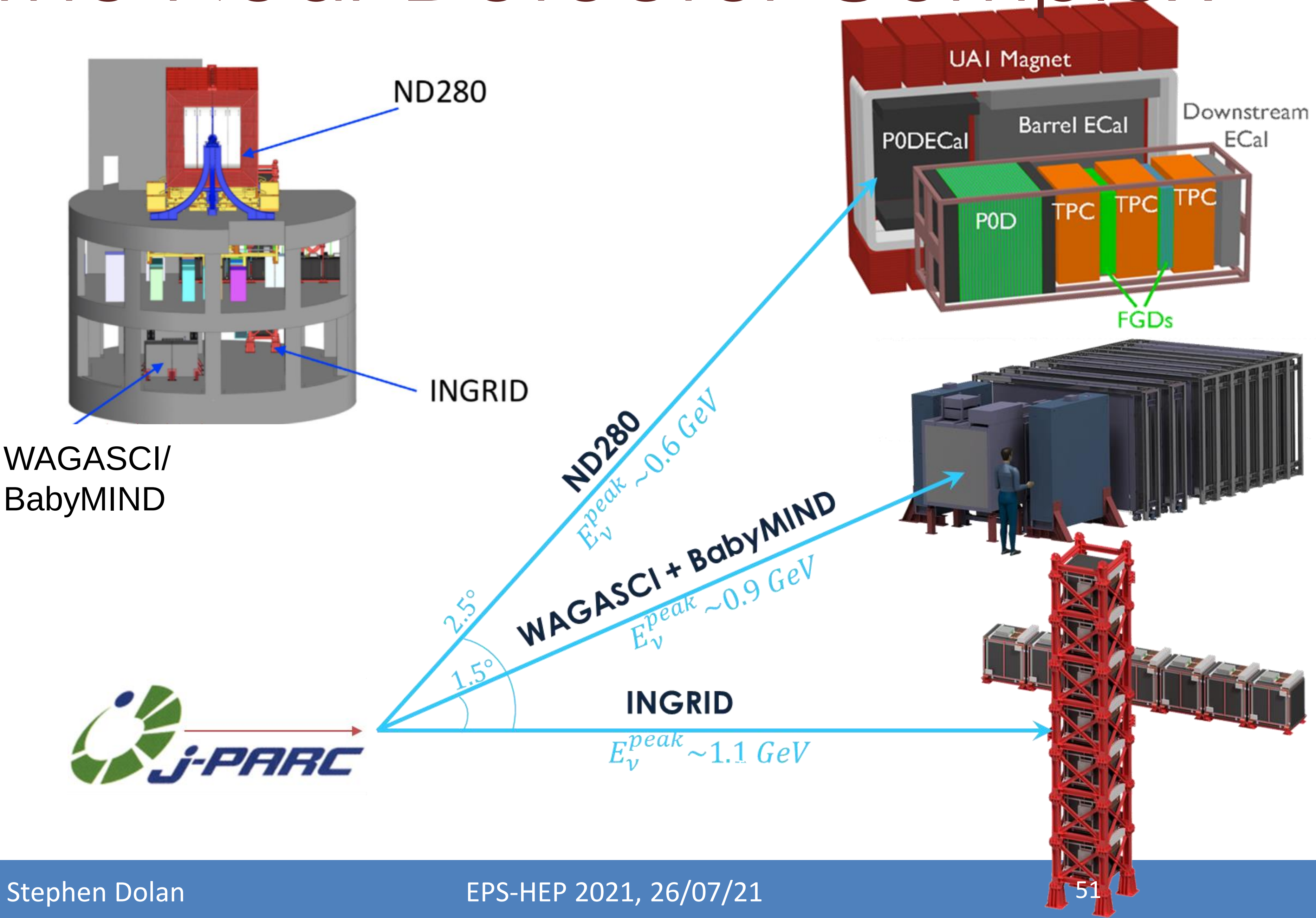
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS = **P**ontecorvo-**M**aki-**N**akagawa-**S**akata

The probability of finding a neutrino as a particular flavour "*oscillates*" as its mass states evolve



The Near Detector Complex



The Near Detector: ND280

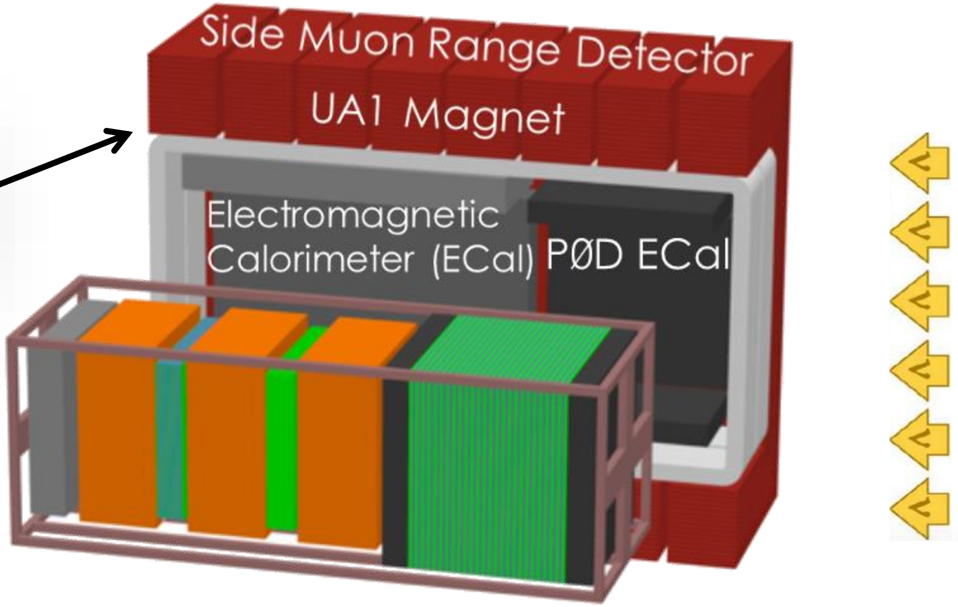
On Axis ~ 1.1 GeV

ND280

Peak E_ν

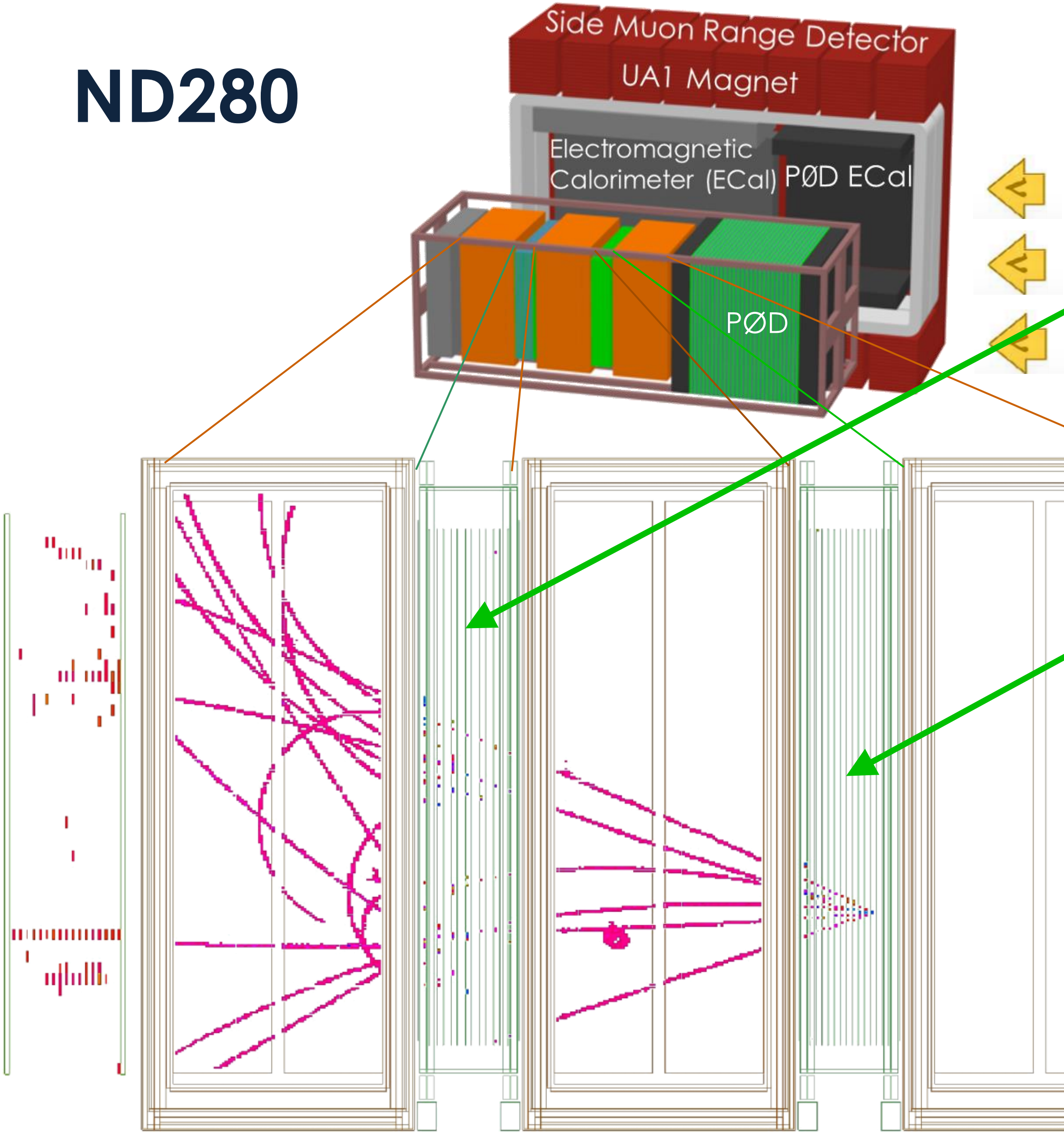
Off Axis ~ 0.6 GeV

Former UA1 Magnet:
- Provides 0.2 T field



The Near Detector: ND280

ND280



On Axis ~ 1.1 GeV

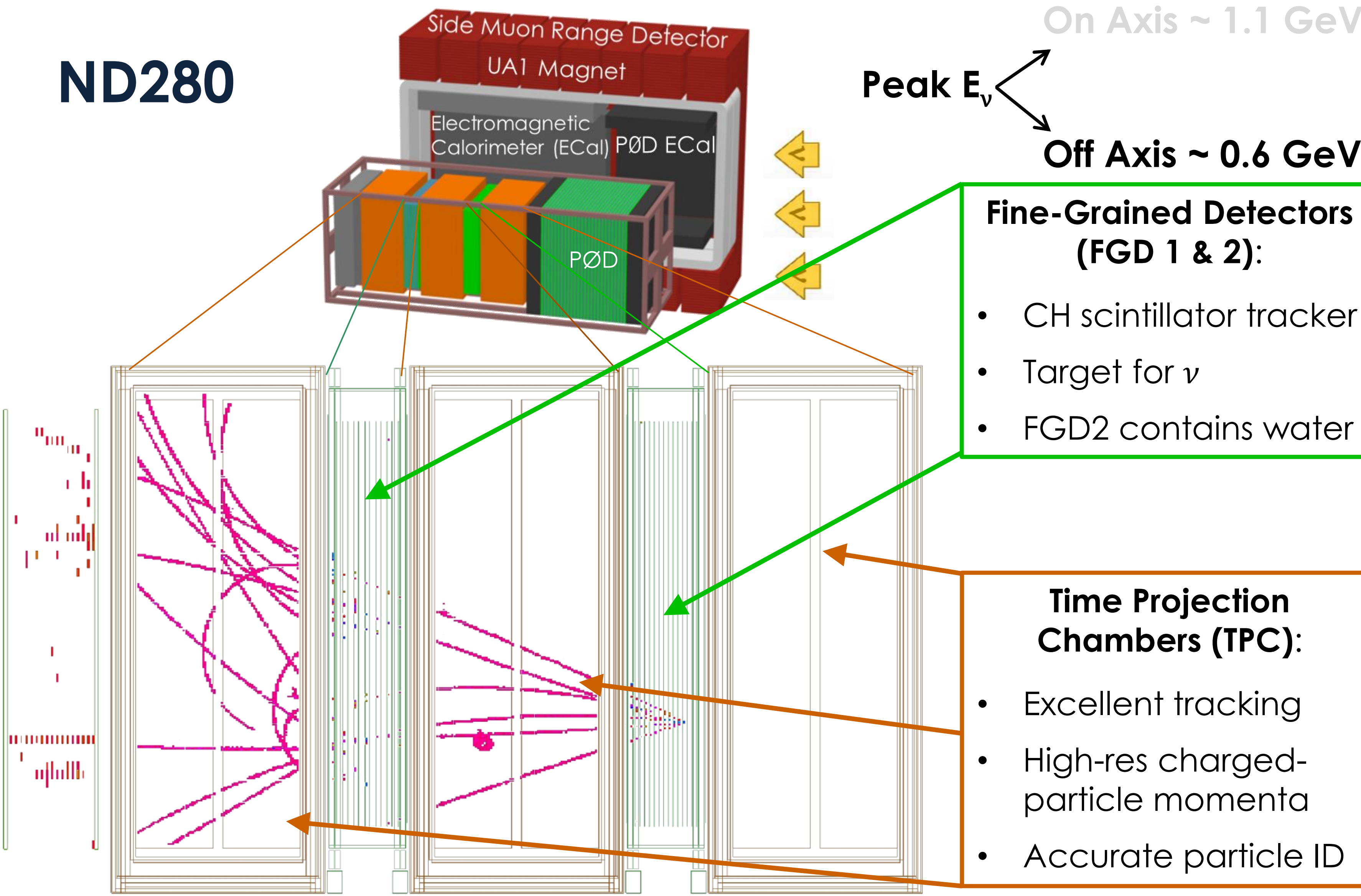
Peak E_ν

Off Axis ~ 0.6 GeV

Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

The Near Detector: ND280



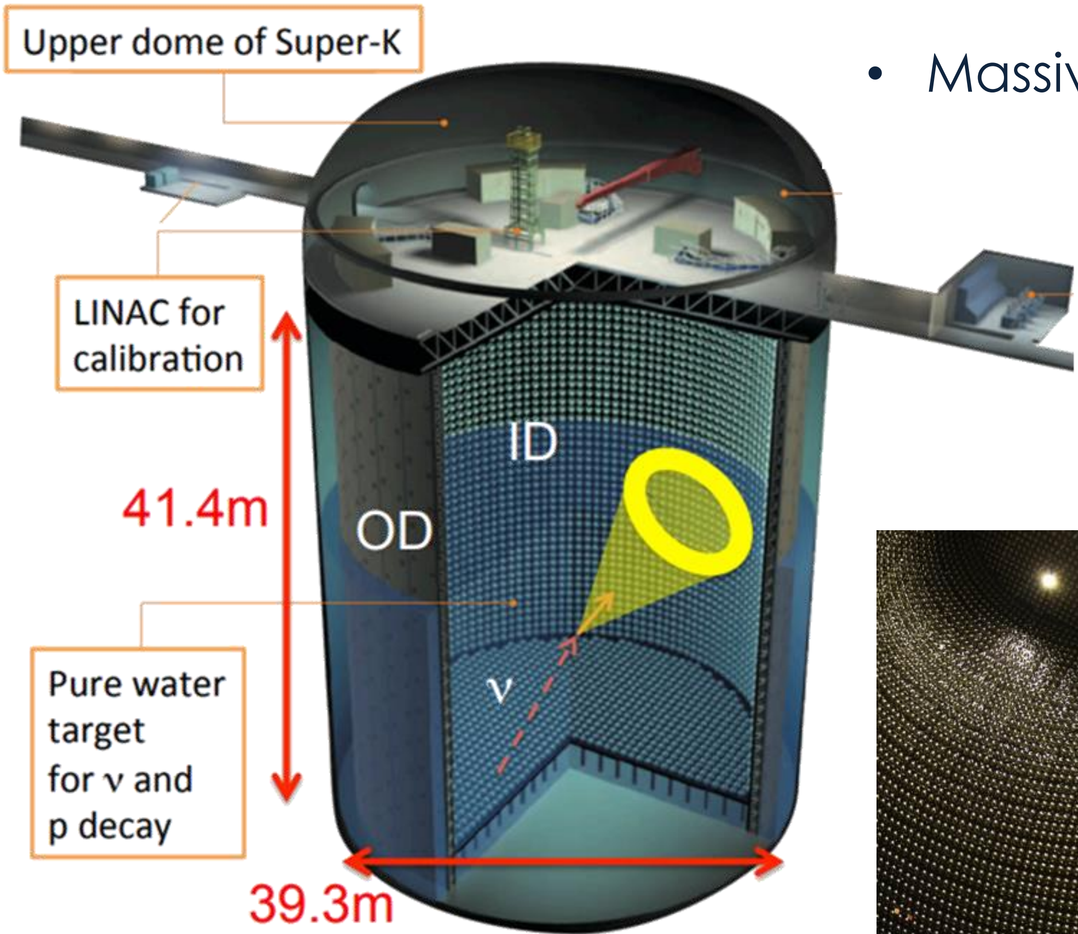
Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

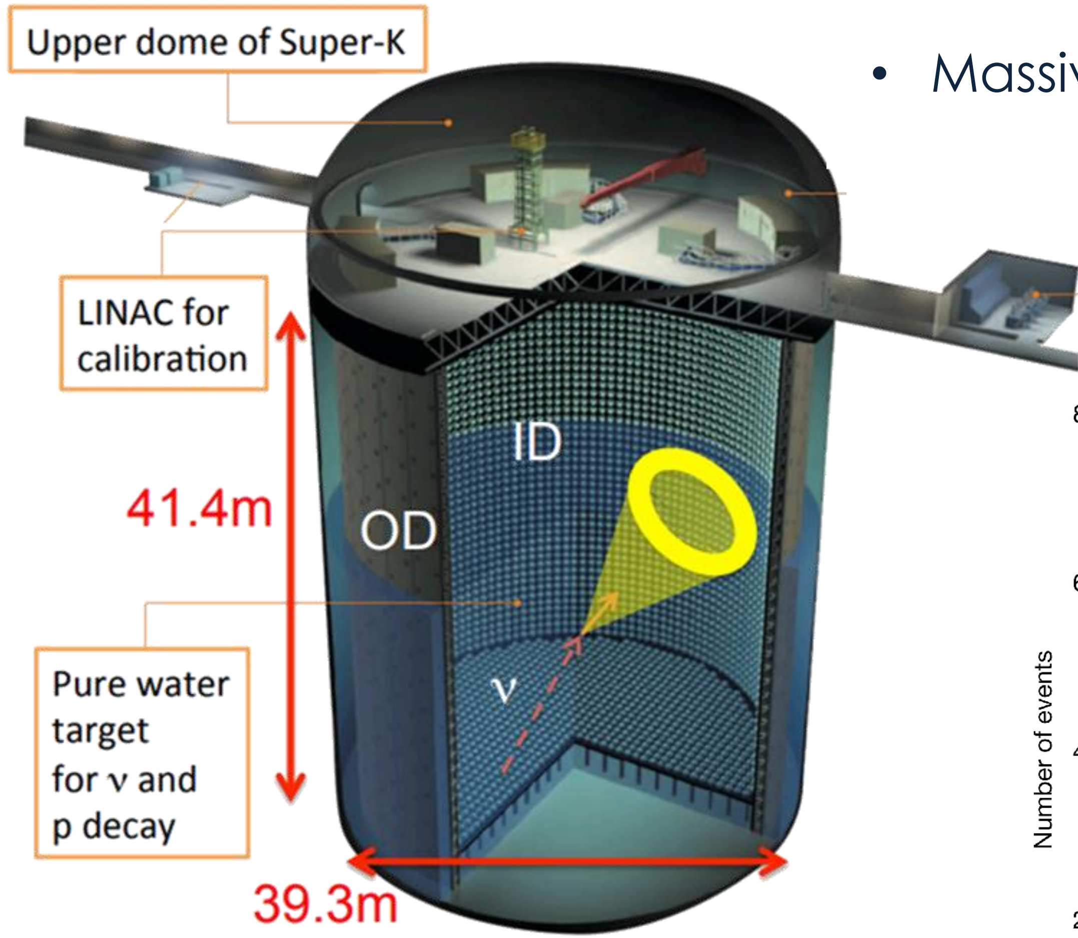
- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

The Far Detector (295 km)



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

The Far Detector (295 km)



- Massive water Cherenkov detector
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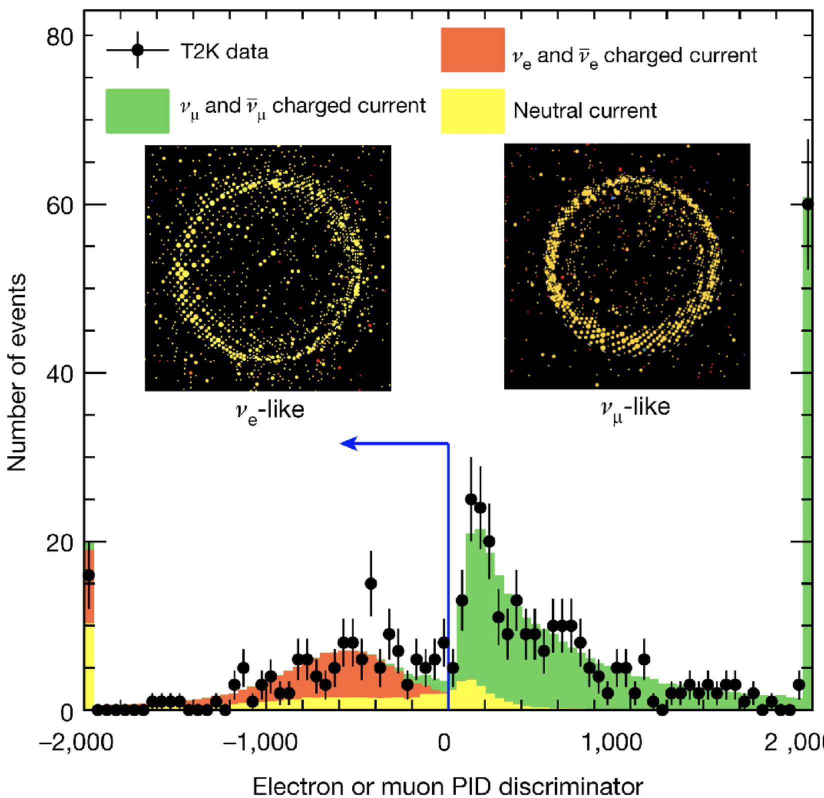
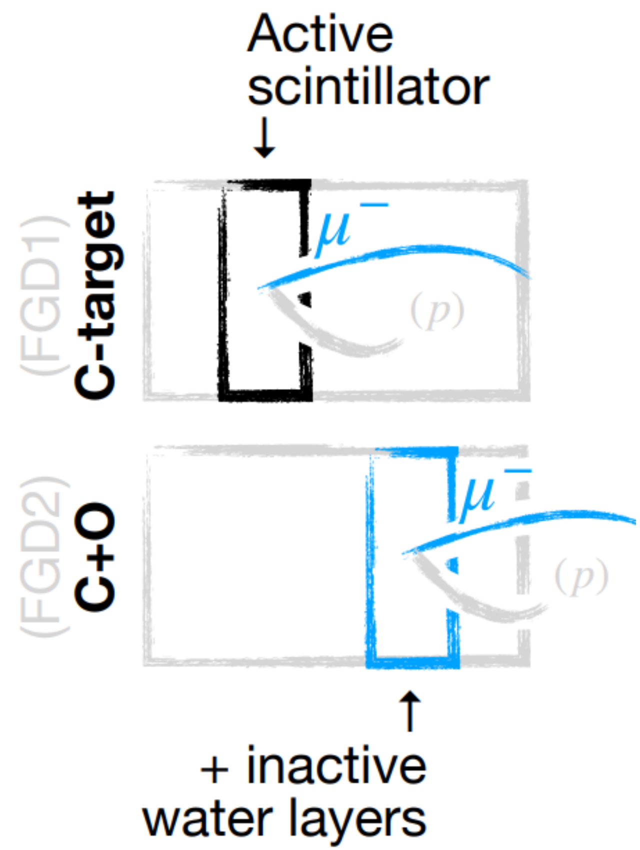


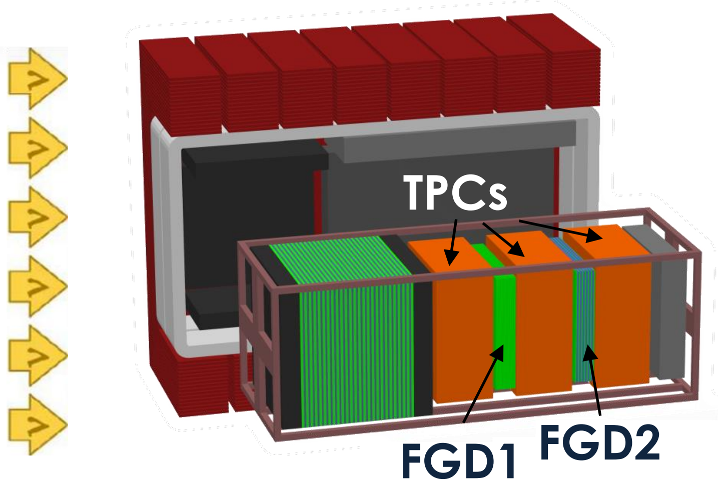
Particle identification through analysis of Cherenkov ring topology

ND280 Fit Samples

Analyse outgoing $\mu^{+/-}$ momentum and angle from **18 different samples.**
These are separated by:

1. FGD 1 / FGD 2 targets
2. Reconstructed pion multiplicity
3. neutrino / anti-neutrino beam mode
4. Charge of the reconstructed muon (for anti-neutrino beam mode only)



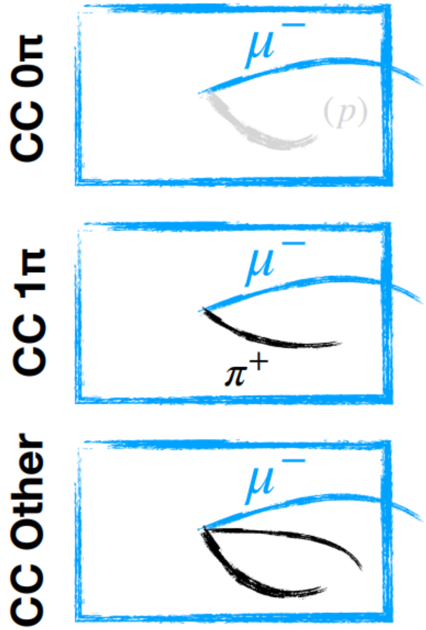


Separately constrain neutrino interactions on Carbon and Oxygen

ND280 Fit Samples

Analyse outgoing $\mu^{+/-}$ momentum and angle from **18 different samples**.
These are separated by:

1. FGD 1 / FGD 2 targets
2. Reconstructed pion multiplicity
3. neutrino / anti-neutrino beam mode
4. Charge of the reconstructed muon (for anti-neutrino beam mode only)



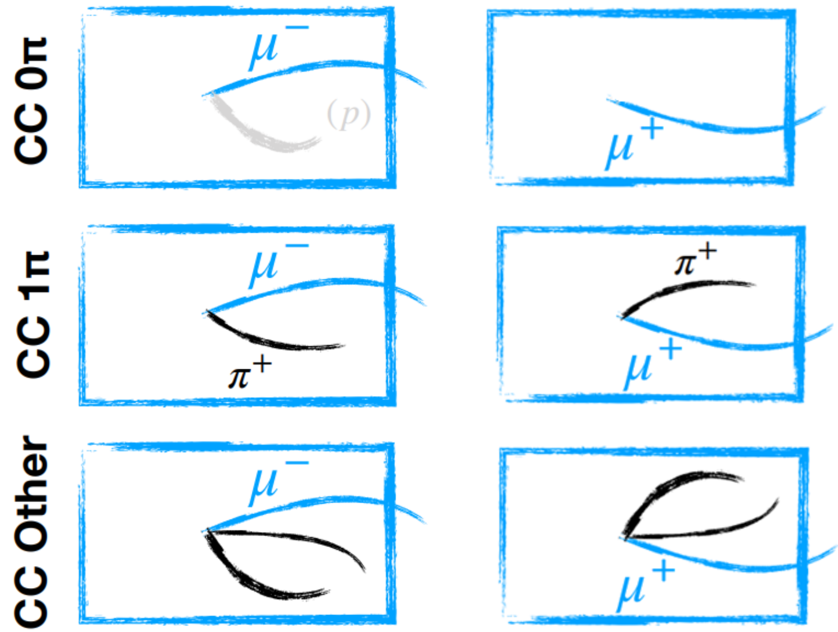
Separation of different interaction modes:

- CC0π → Mostly CCQE+2p2h
- CC1π → Mostly RES π prod.
- CCOther → Mostly DIS

ND280 Fit Samples

Analyse outgoing $\mu^{+/-}$ momentum and angle from **18 different samples.** These are separated by:

1. FGD 1 / FGD 2 targets
2. Reconstructed pion multiplicity
3. neutrino / anti-neutrino beam mode
4. Charge of the reconstructed muon (for anti-neutrino beam mode only)



Separation of different interaction modes:

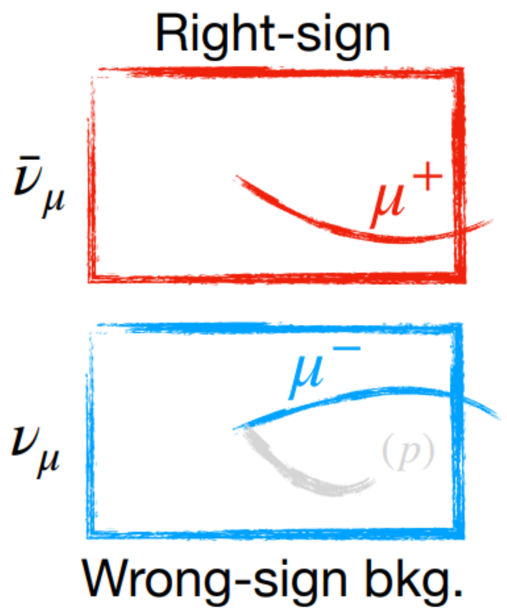
- CC0π → Mostly CCQE+2p2h
- CC1π → Mostly RES π prod.
- CCOther → Mostly DIS

Understand differences in neutrino and anti-neutrino interactions

ND280 Fit Samples

Analyse outgoing $\mu^{+/-}$ momentum and angle from **18 different samples.** These are separated by:

1. FGD 1 / FGD 2 targets
2. Reconstructed pion multiplicity
3. neutrino / anti-neutrino beam mode
4. Charge of the reconstructed muon (for anti-neutrino beam mode only*)



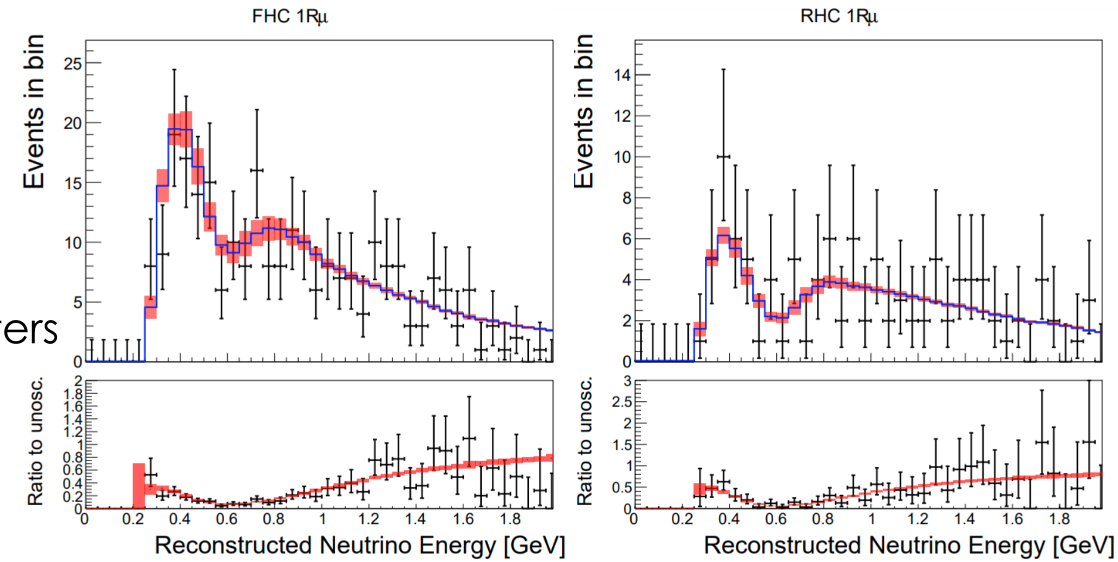
Accounts for the neutrino contamination to the anti-neutrino beam mode

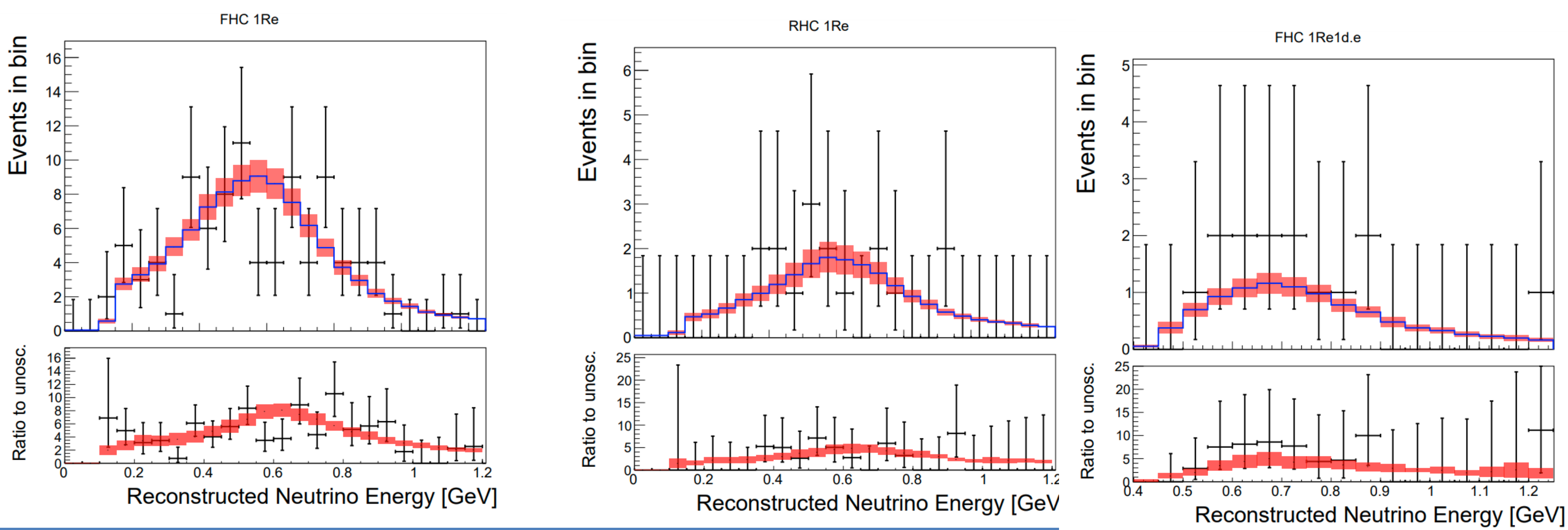
*Not needed in neutrino beam mode since the anti-neutrino contamination is very small

Oscillation Fit

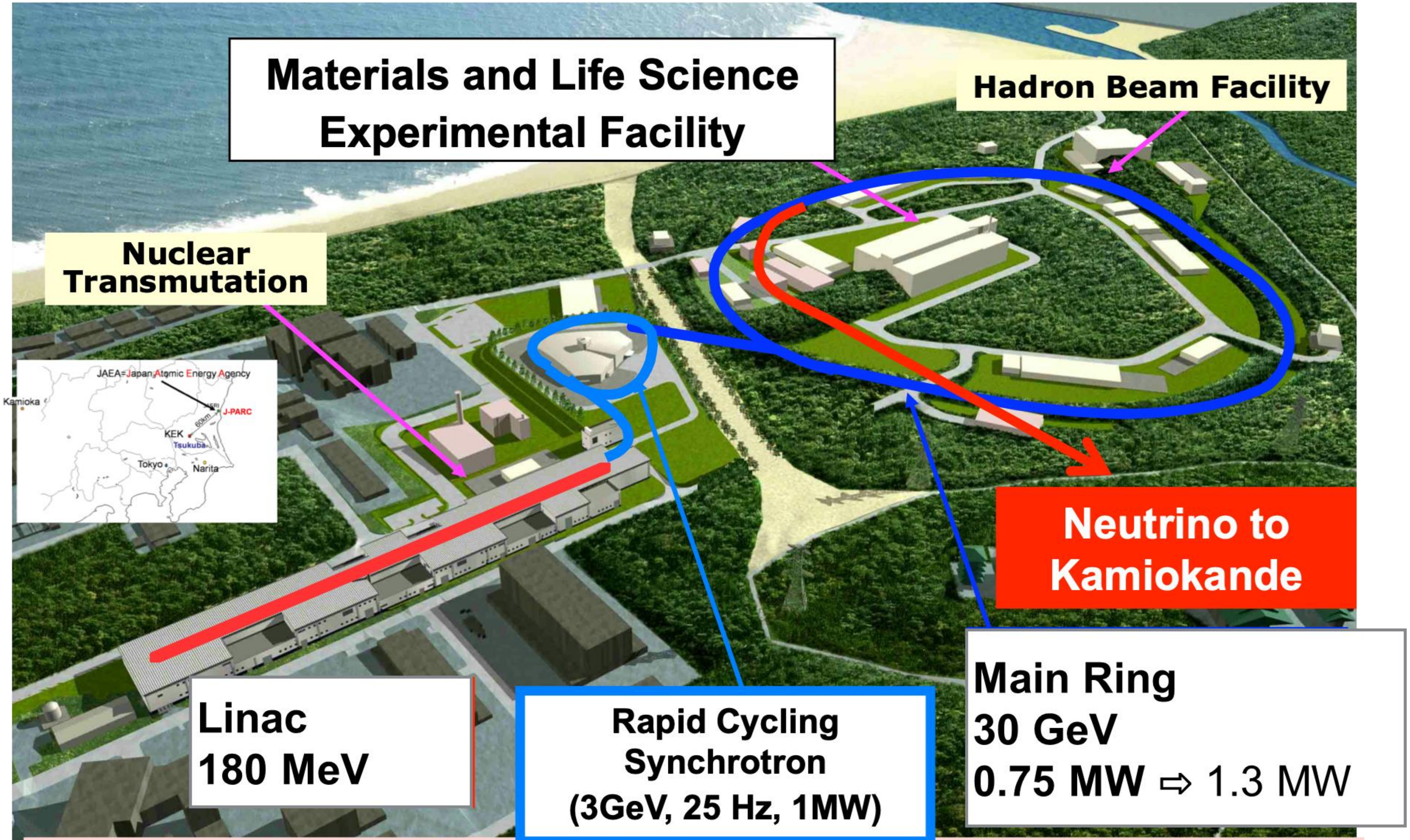
In the fit

- Oscillation parameters
- Flux + cross-section parameters (most contained by ND280 fit)
- Super-K detector model parameters
- Use measurement of θ_{13} from reactor experiments as an extra constraint





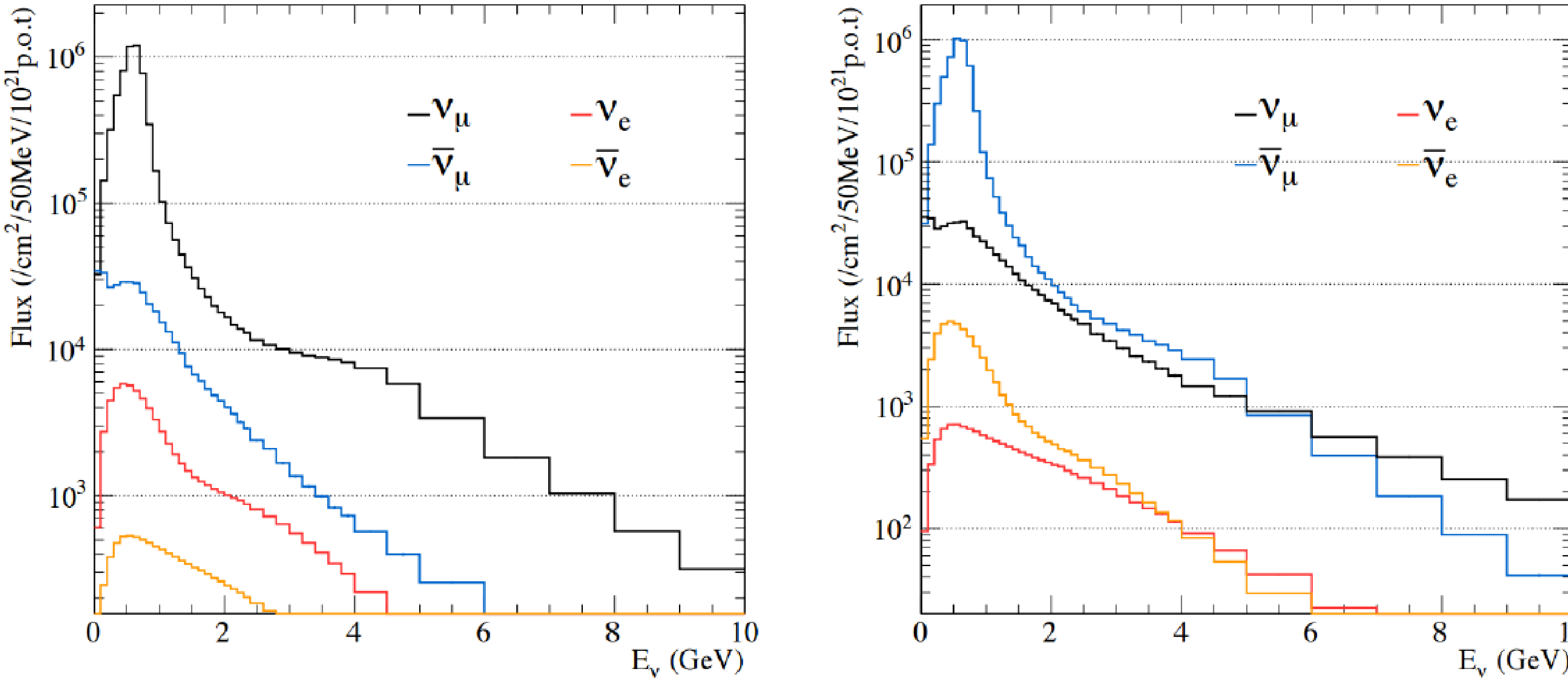
J-PARC: Proton Accelerator



J-PARC = Japan Proton Accelerator Research Complex

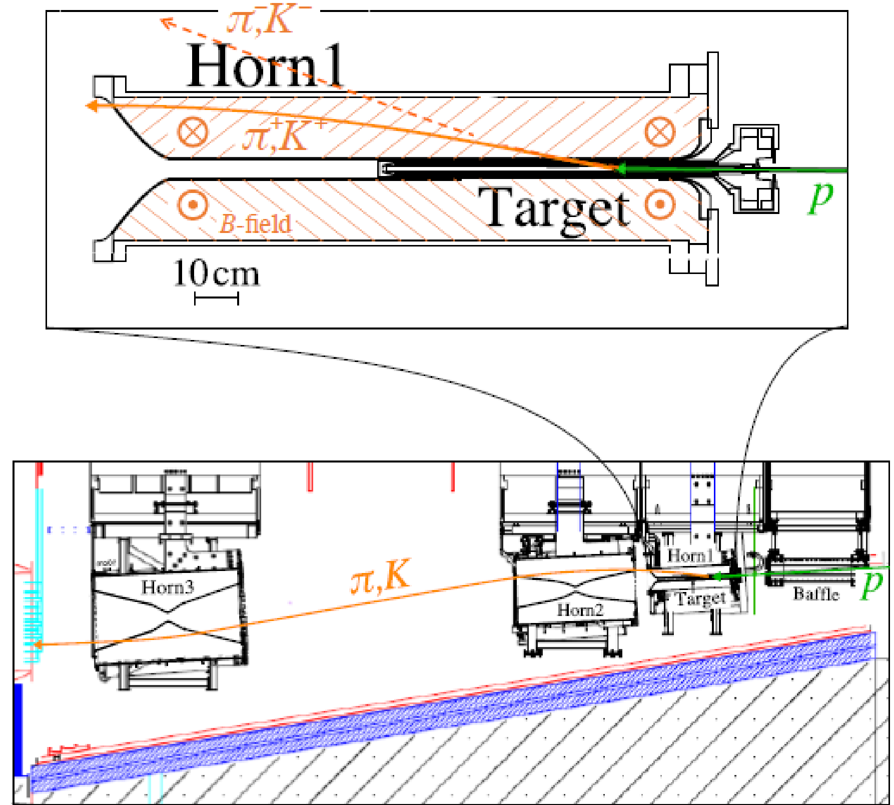
Joint Project between KEK and JAEA

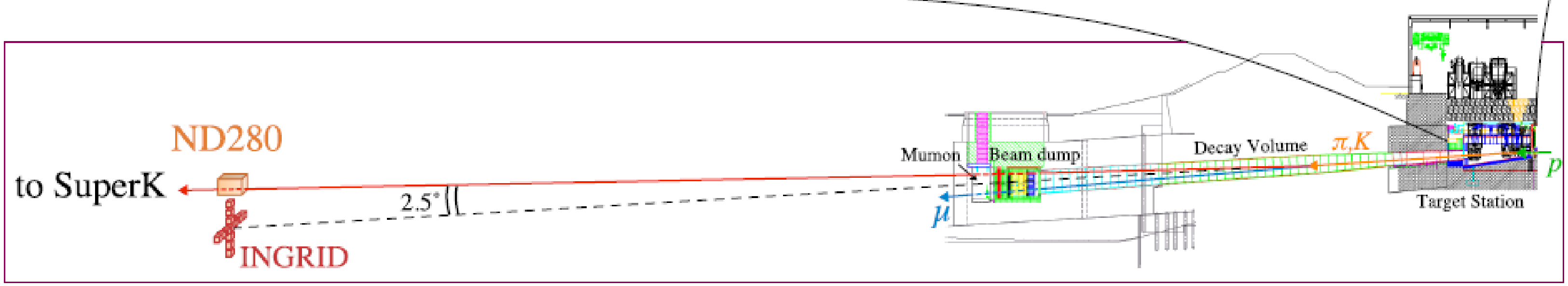
The T2K Flux Prediction



J-PARC: Neutrino Beamline

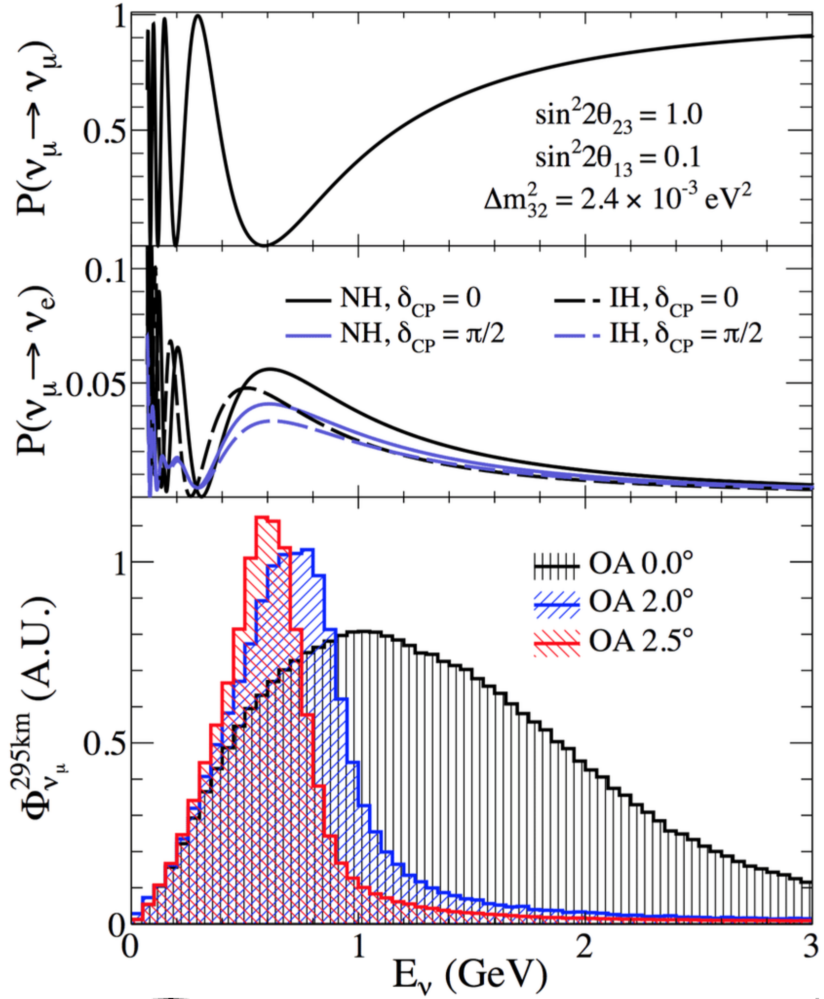
- Accelerated 30 GeV protons hit a graphite target and produce π, K
- Charged $\pi^{+(-)}$ are focussed towards SuperK using three magnetic horns
- $\pi^{+(-)}$ decay in specialised volume to $\mu^{+(-)} + \overset{(-)}{\nu}_\mu$
- Select $\nu_\mu/\bar{\nu}_\mu$ by focussing π^+/π^-

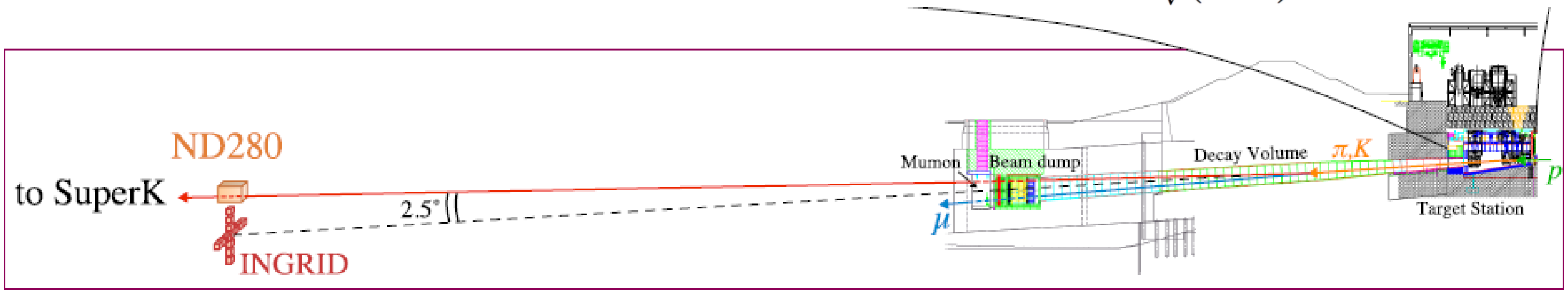




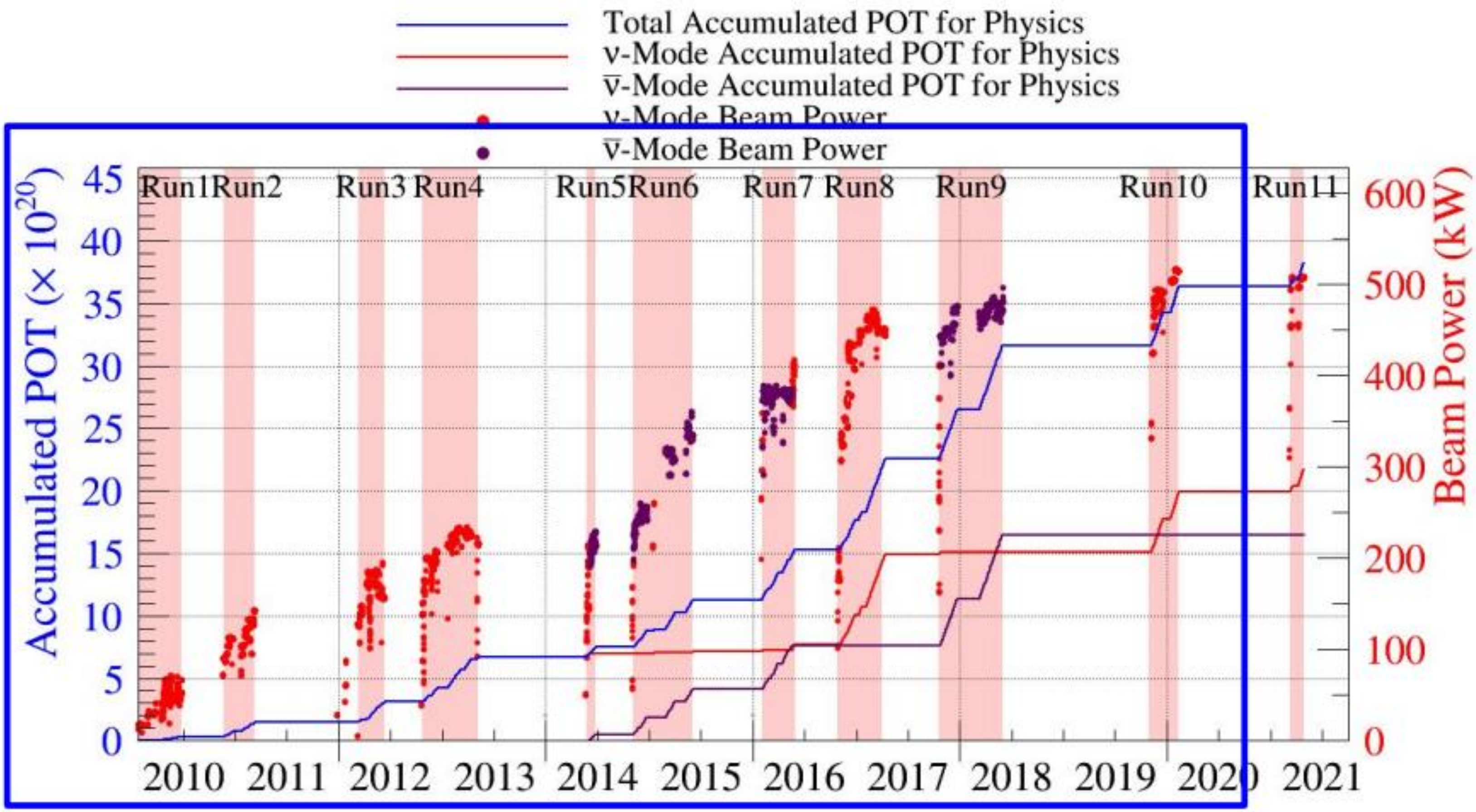
Off-Axis Beam

- Beam pointed 2.5° off-axis from Super-K
- Off-axis beam → Narrower neutrino energy spectrum
- Beam peaked at oscillation maximum
- Maximises sensitivity to oscillation parameters at the cost of a lower event rate





Data set



OA2020 results: Run 1-10

ν mode : 1.99006×10^{21} (54.7%)

$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)

Data taken with SK Gd: Run 11:

ν-mode POT (FHC) : 2.116 x 10^{21}

$\bar{\nu}$-mode (RHC) POT : 1.651 x 10^{21}

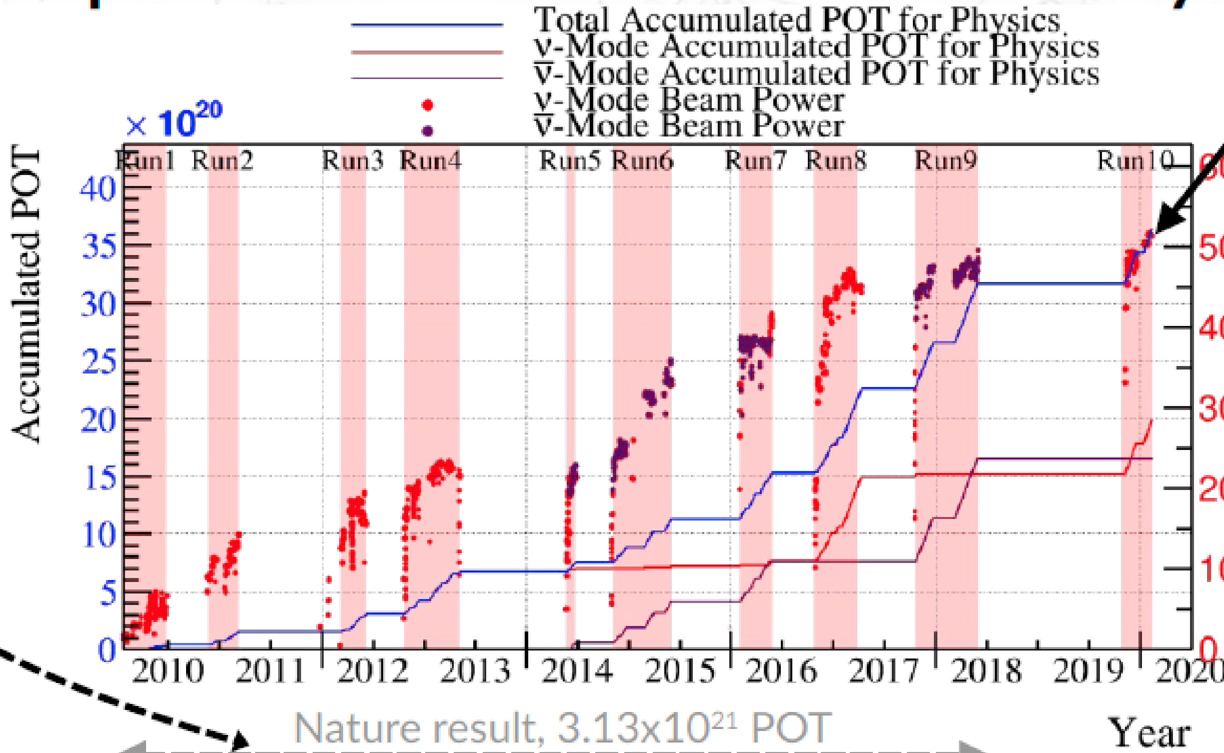
Total delivered: 3.818x10^{21}

Improvements on last analysis

Nature 580, 339-344

arXiv:2101.03779

Phys. Rev. D 103, 011101 (2021)



515 kW!

NEUTRINO 2020

Soon on arxiv!

Nature result, 3.13×10^{21} POT

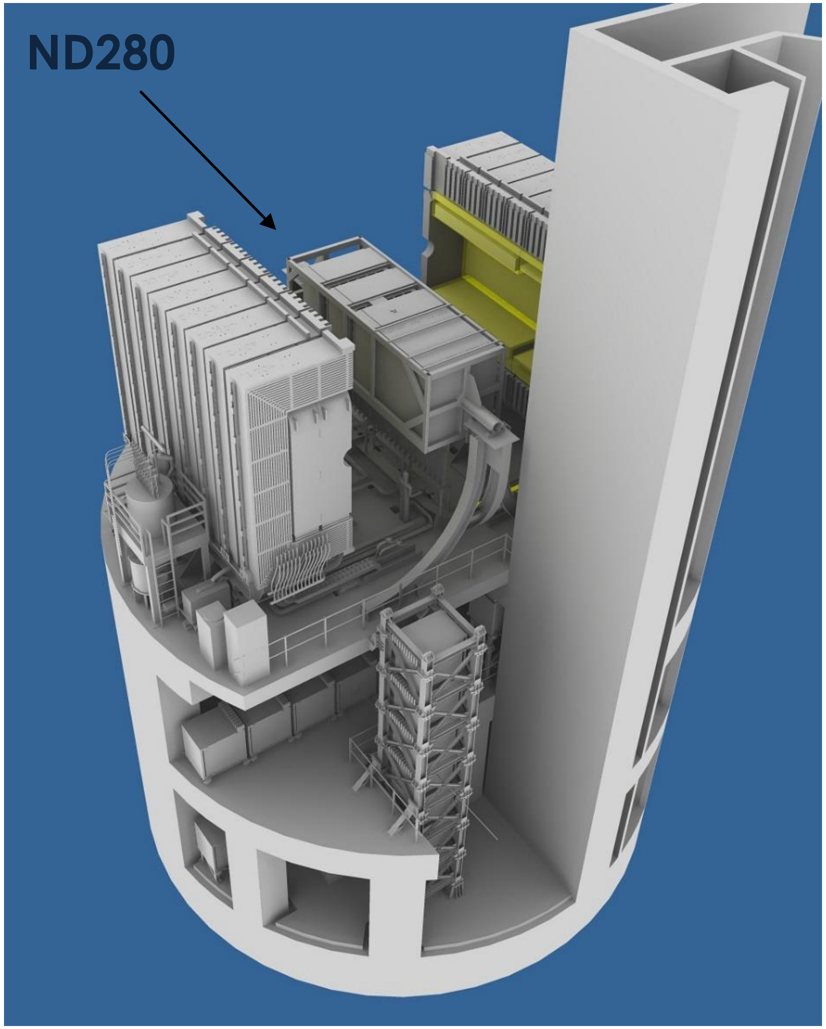
This result, 3.6×10^{21} POT

Improvements on Nature paper

- Far detector statistics: +32% ν POT, same anti-ν POT
- Near detector statistics: +98% ν POT, +116% anti-ν POT
- Improved flux constraint, using NA61/SHINE replica target data
- Overhauled interaction model, and updated ND280 selections

Clarence Wret 38

The Near Detectors (280m)

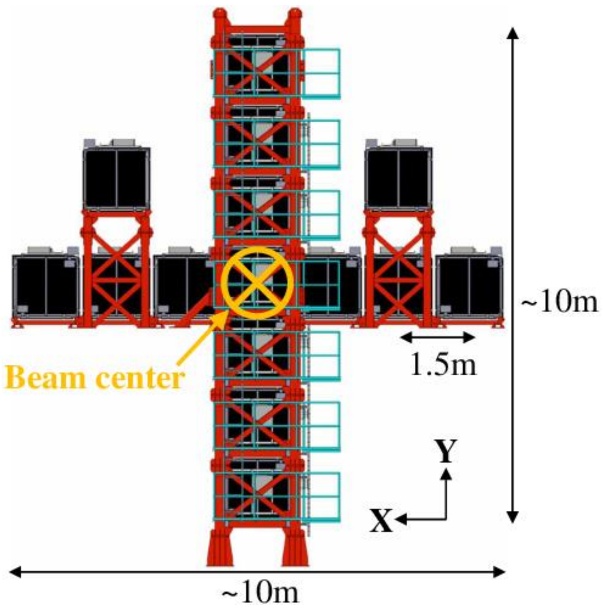


Peak E_ν

On Axis ~ 1.1 GeV

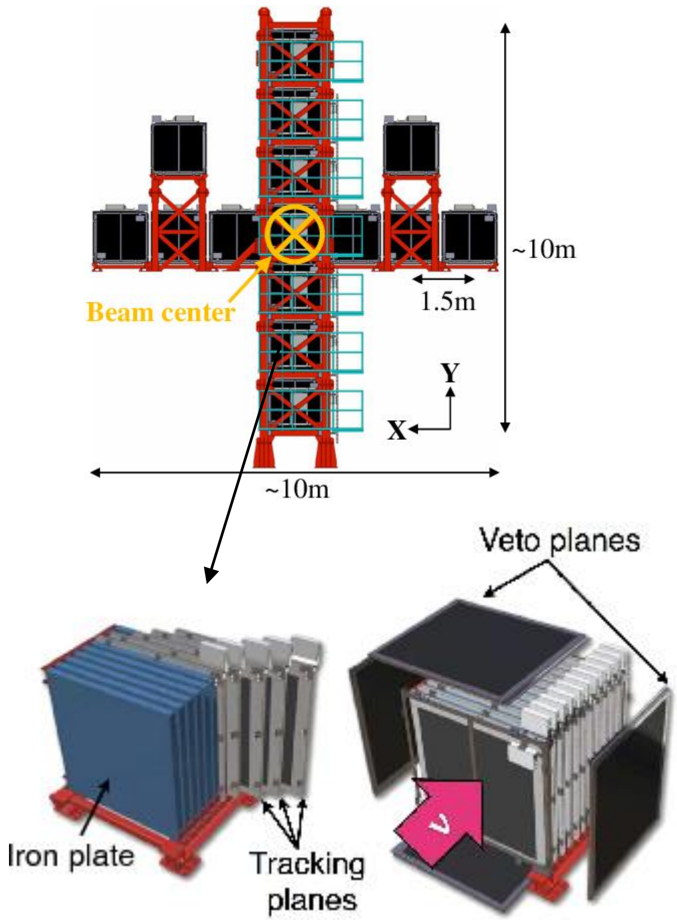
Off Axis ~ 0.6 GeV

INGRID (front View) :

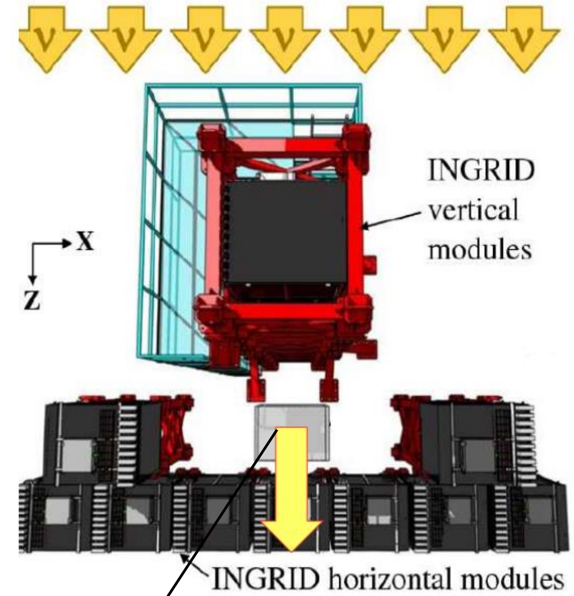


The Near Detectors (280m)

INGRID (front view) :



INGRID (top view) :



Proton Module (fully active scintillator tracker) *or* **Water Module** (interleaved layers of water)

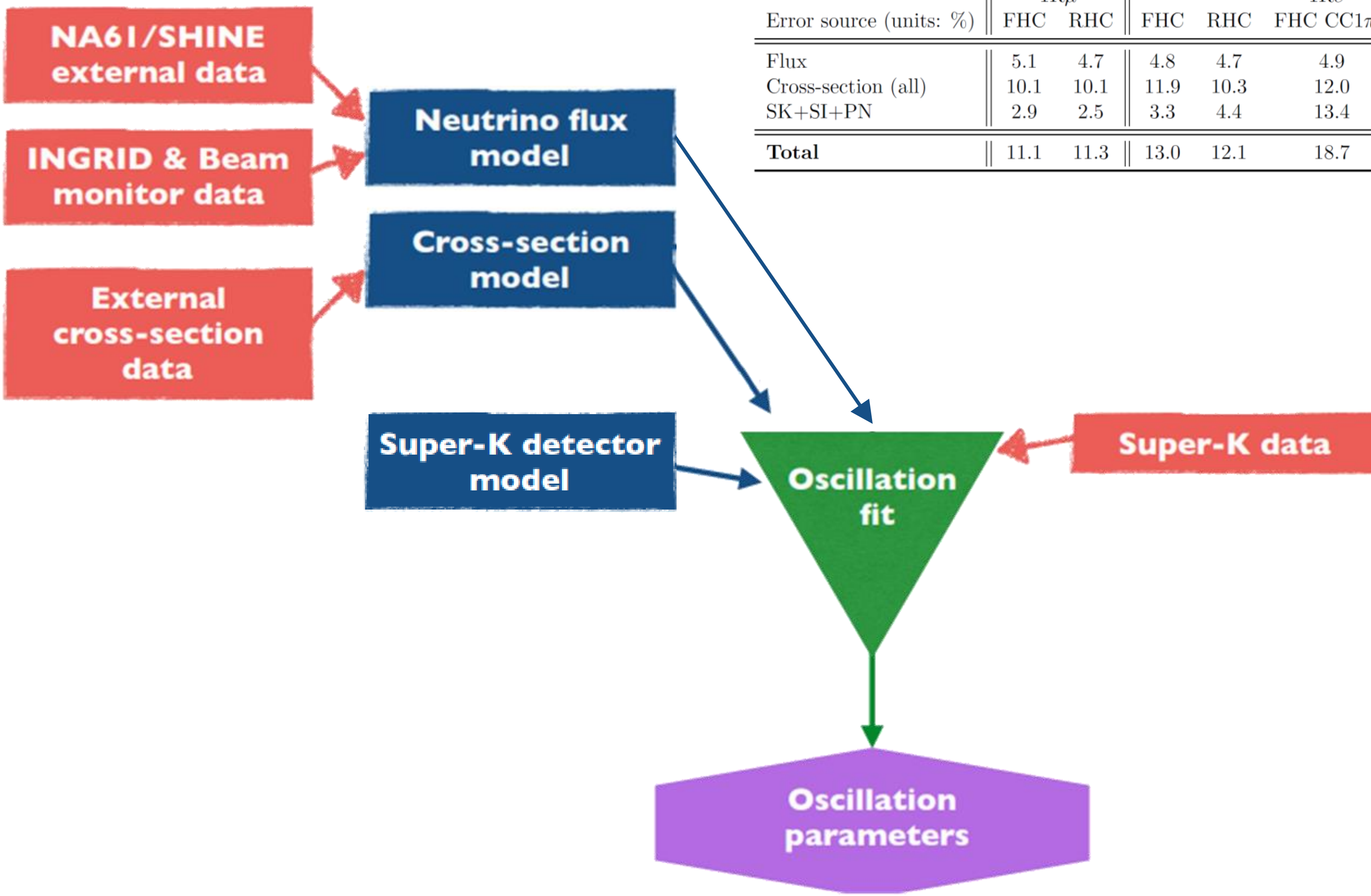
INGRID Modules: Stacks of scintillator bars interleaved with Iron sheets.

Fe, $H_2$0 and CH targets available

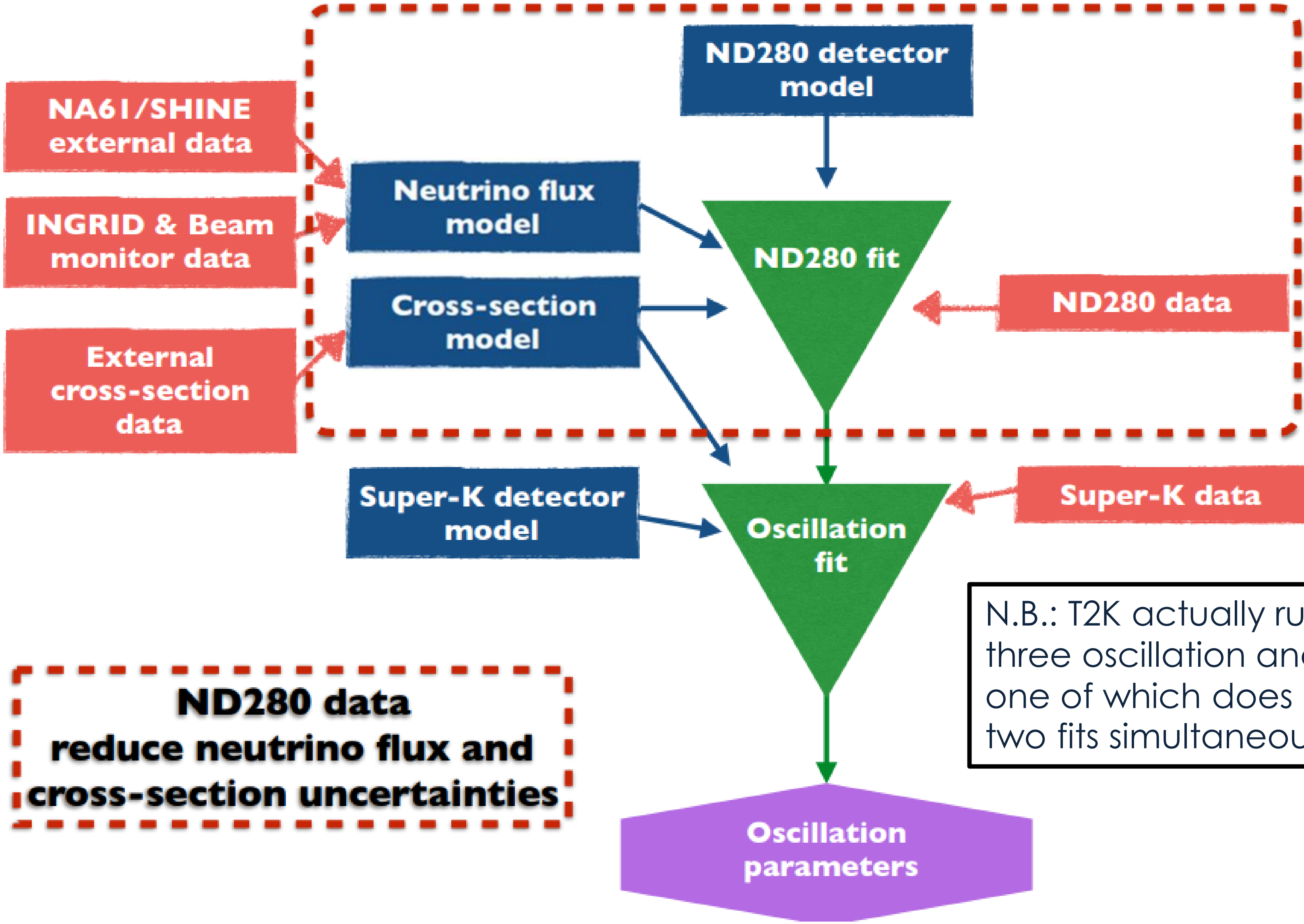
Analysis Strategy

Systematic Uncertainties

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

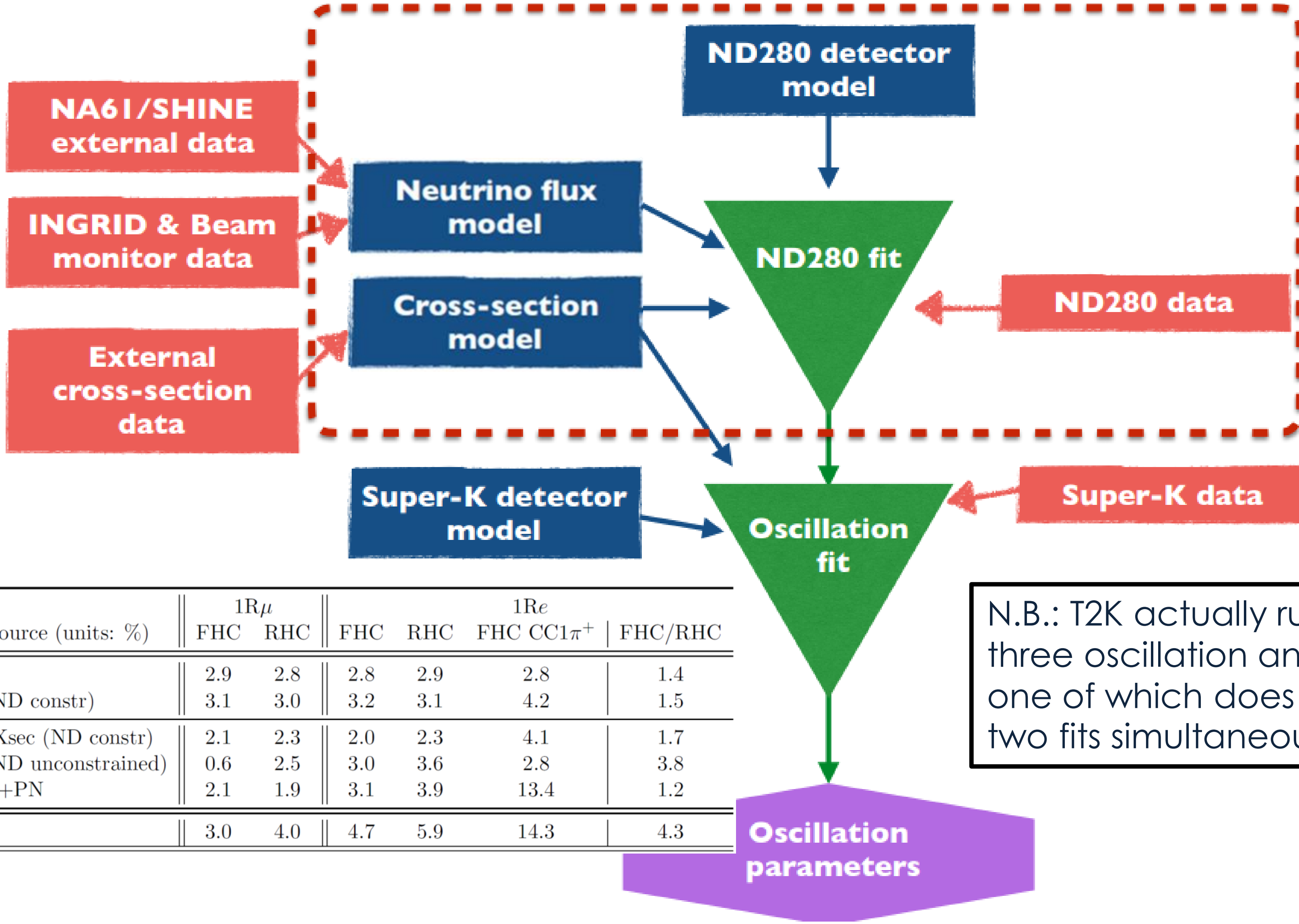


Analysis Strategy



N.B.: T2K actually runs three oscillation analyses, one of which does the two fits simultaneously.

Analysis Strategy

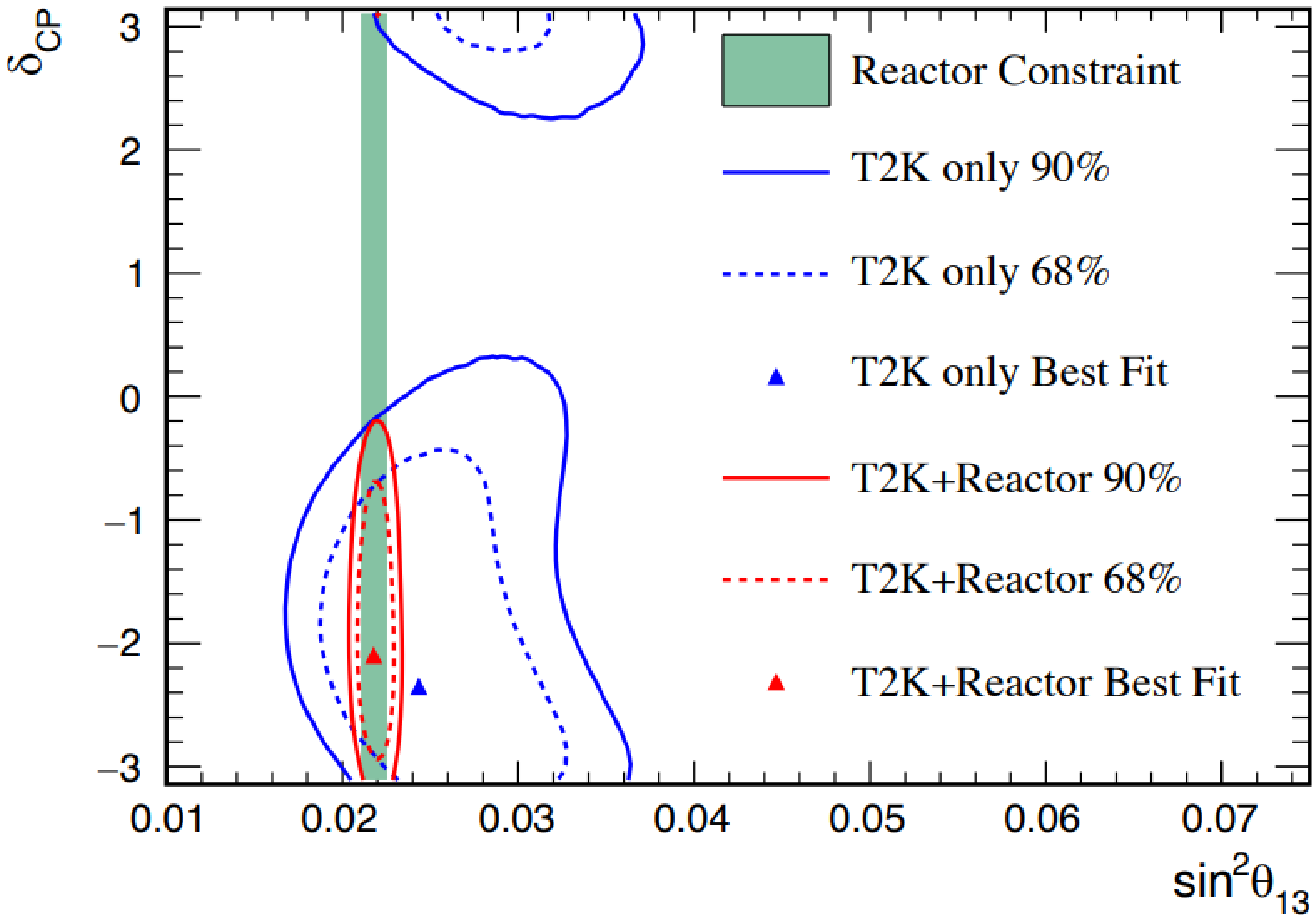


Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

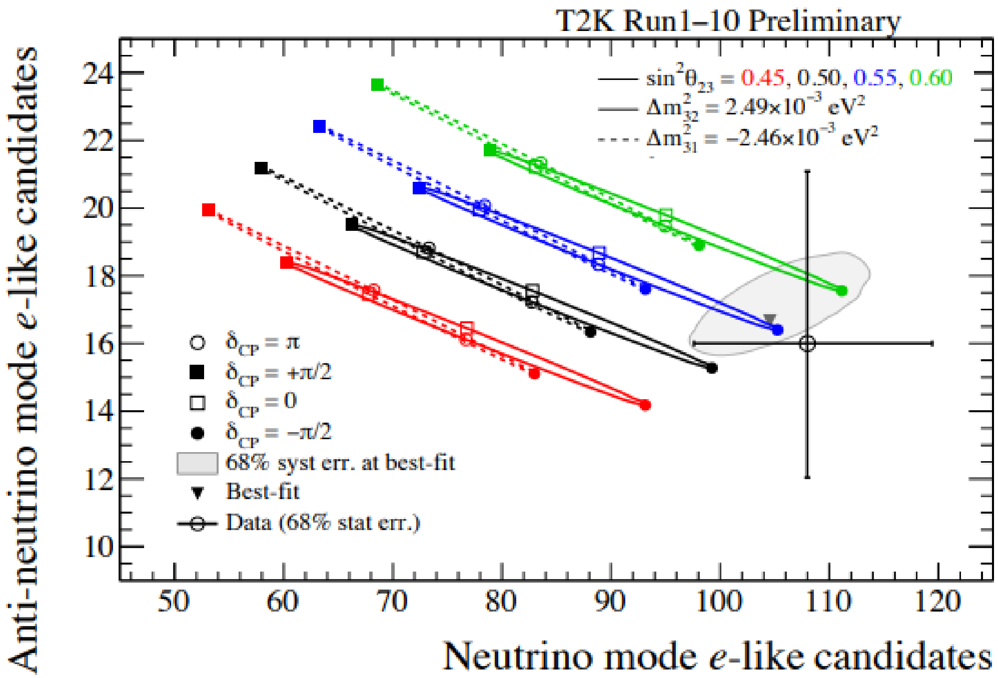
N.B.: T2K actually runs three oscillation analyses, one of which does the two fits simultaneously.

Reactor Constraint

T2K Run 1-10 Preliminary



ν_e and $\bar{\nu}_e$ appearance



Octant

Mass ordering

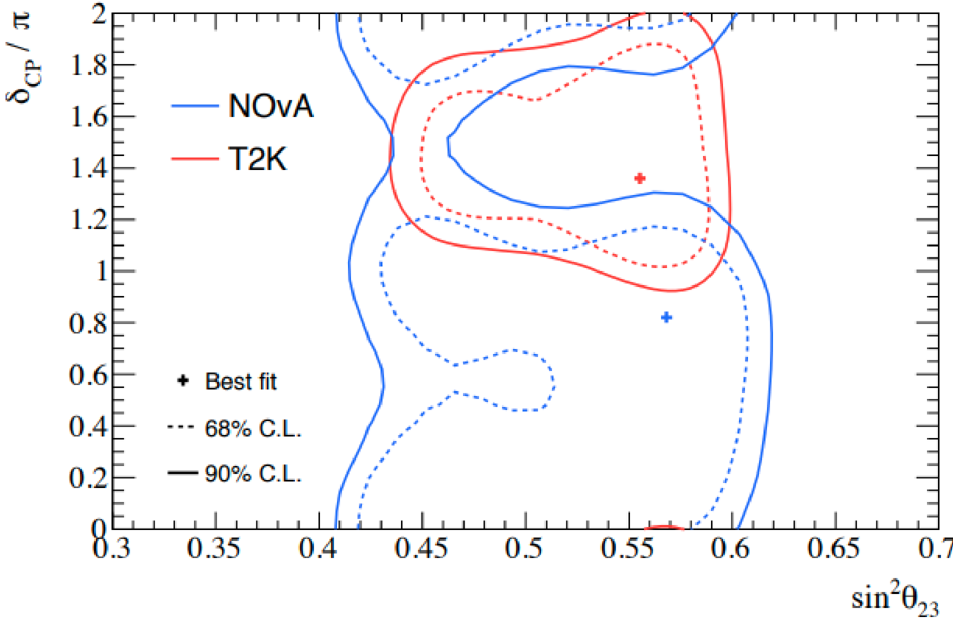
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Ongoing joint fits

NOvA + T2K

Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, T2K Preliminary

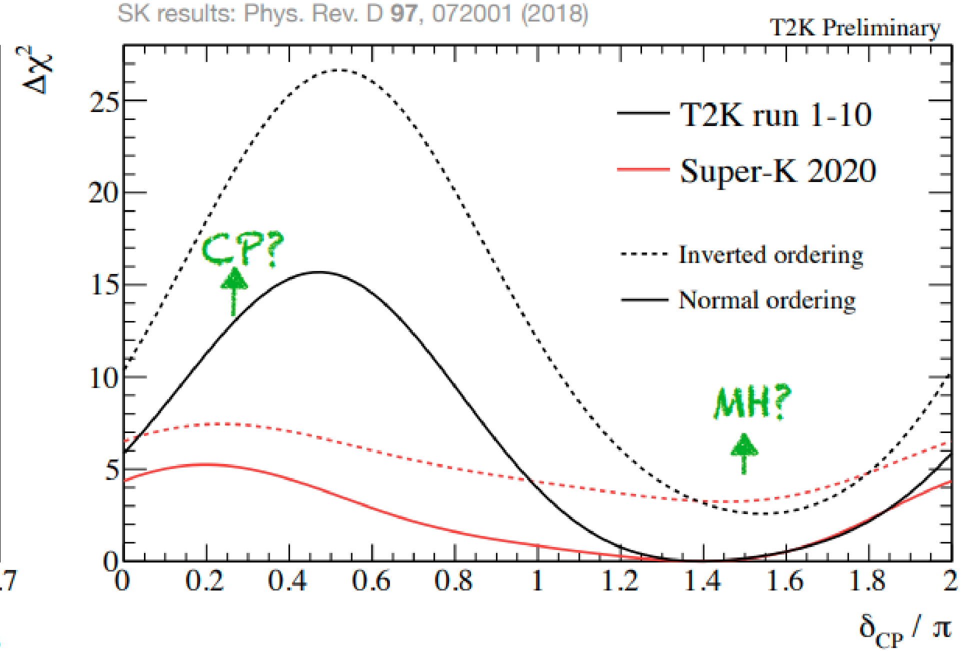


SK + T2K

atmospheric + accelerator

Comparison of released contours (not joint fit)

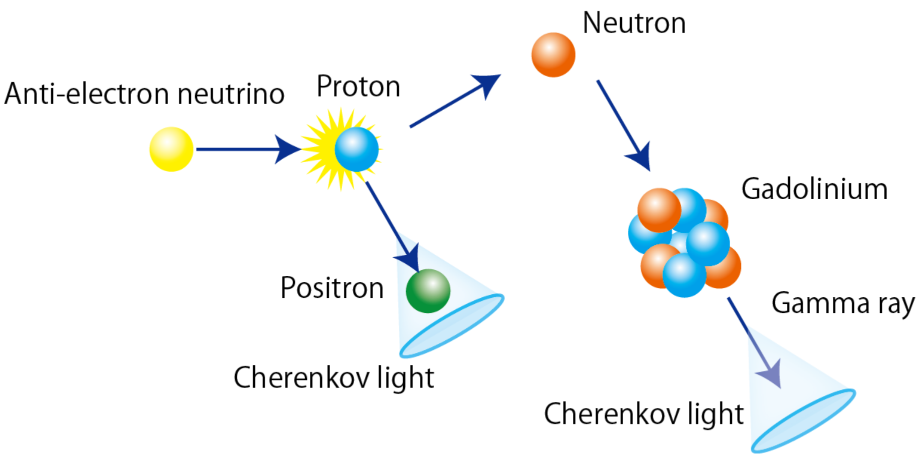
SK results: Phys. Rev. D **97**, 072001 (2018)

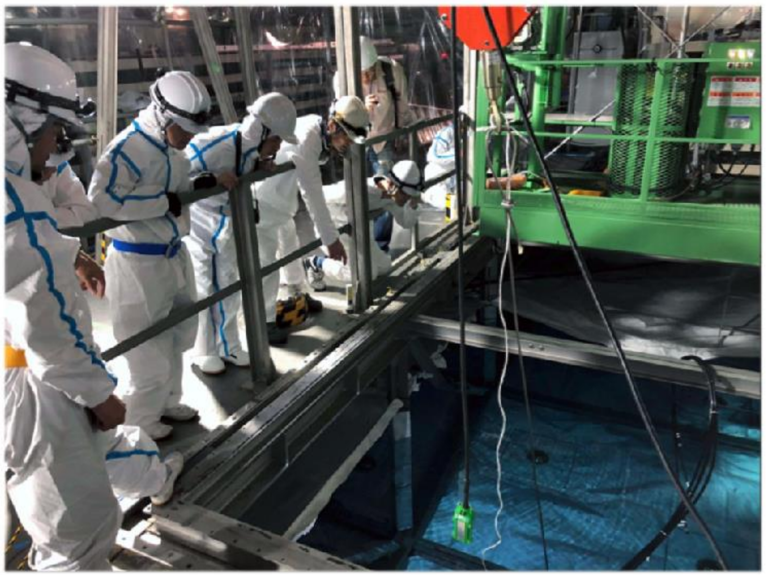


- Simultaneous analysis of experiments with different baselines/energies/detector technologies
- Expect increased sensitivity beyond the improved statistics
  - Sensitivity in one experiment can resolve parameter degeneracies in another

SK with Gadolinium

- Gd allows detection of neutrons: useful for T2K physics as well as for supernova relic neutrinos
- Plans for Gadolinium (Gd) loading at SK are proceeding well





Why do we need an Upgrade?

- Current measurements are statistics limited, but not for long!
- Largest systematics related to **neutrino-nucleus interactions**
  - Often degenerate with oscillation parameters
  - Confuse neutrino energy reconstruction
- Essential to reduce this uncertainty for future analyses

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

$N_\ell(\mathrm{E}_\nu)$ = Event rate
$P(\nu_{\ell'} \to \nu_\ell)(E_\nu)$ = Oscillation probability
$\Phi_\nu(\mathrm{E}_\nu)$ = Neutrino flux
$\epsilon(E_\nu)$ = Detector efficiency
$\sigma_\ell(E_\nu)$ = Interaction cross section

T2K

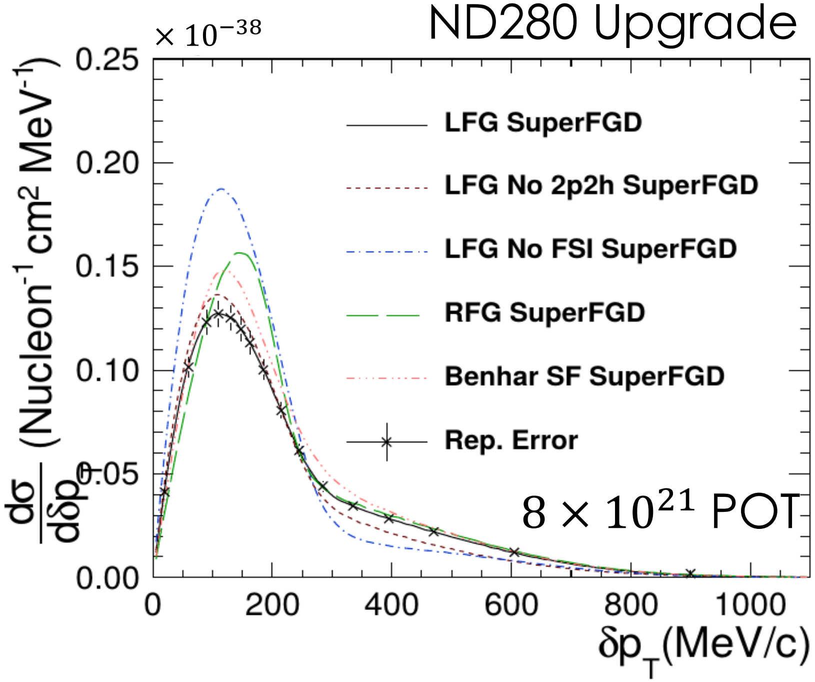
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Physics Sensitivity

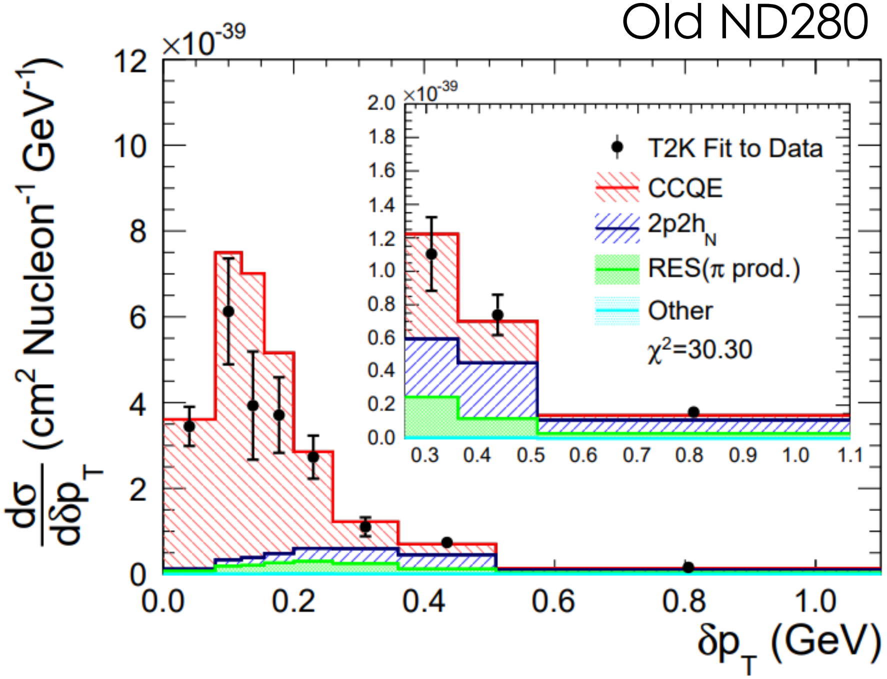
- SFGD can measure the **transverse momentum imbalance** between the outgoing muon and proton

- Sensitive to the physics which drives the main uncertainties in neutrino oscillation analyses

ND280 Upgrade

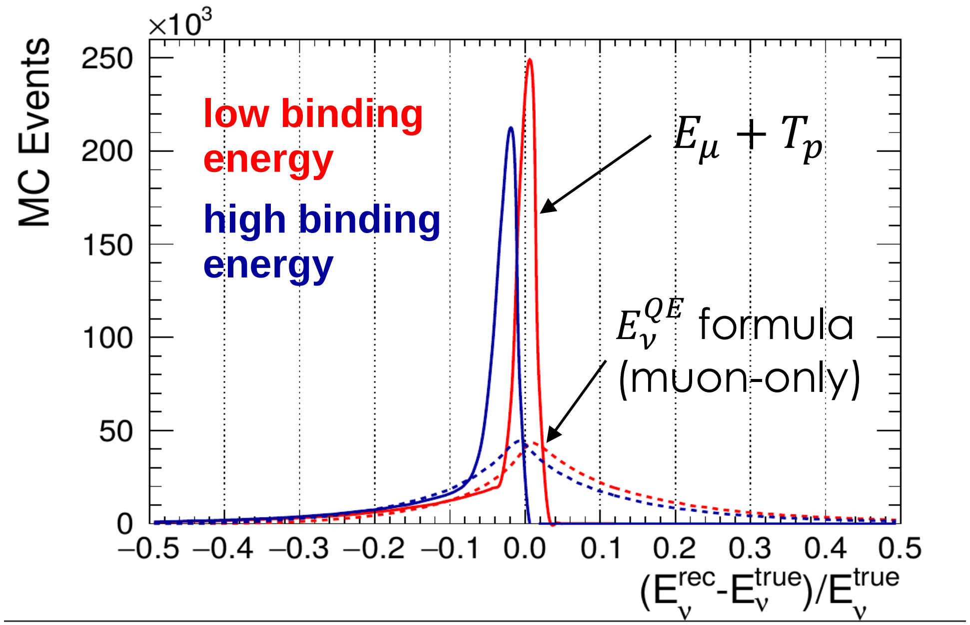


Old ND280



Physics Sensitivity

- SFGD can use alternative methods of reconstructing neutrino energy
- Uses both the outgoing muon and proton energies as an estimator

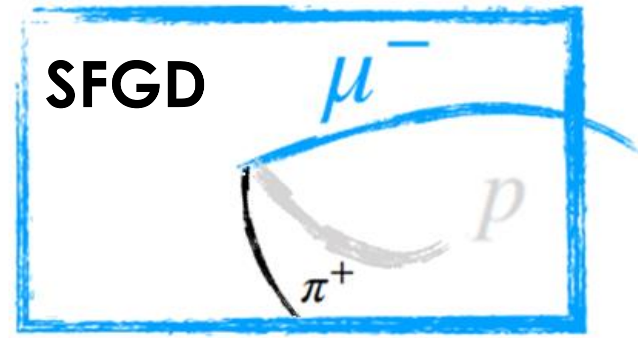


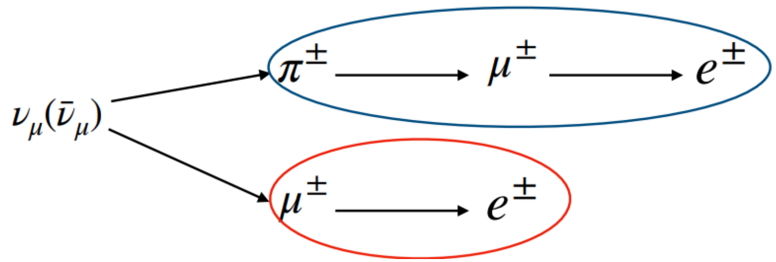
- More robust E_ν estimator: more sensitive to physics that can cause a poor reconstruction of neutrino energy

Physics Sensitivity

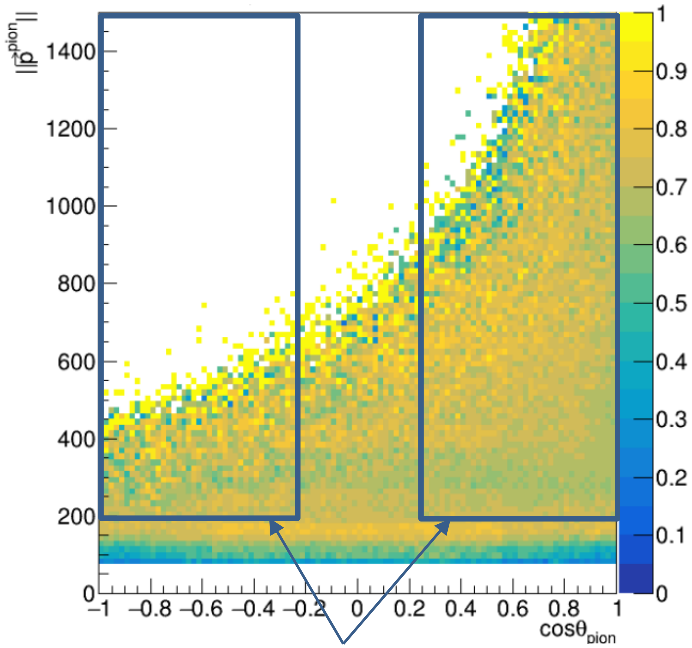
- Improved pion tracking thresholds and decay electron tagging allow access to much wider phase space than before

CC 1π





ND280 Upgrade estimated charged pion tracking efficiency (w/o decay e^- tagging)



ND280 high efficiency regions

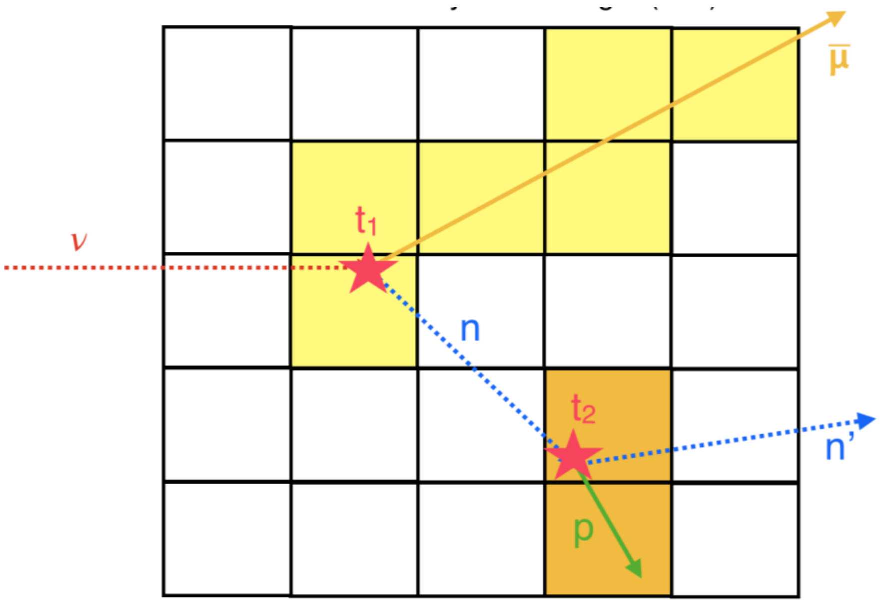
- Can measure kinematics of untracked pions using decay electron positon!

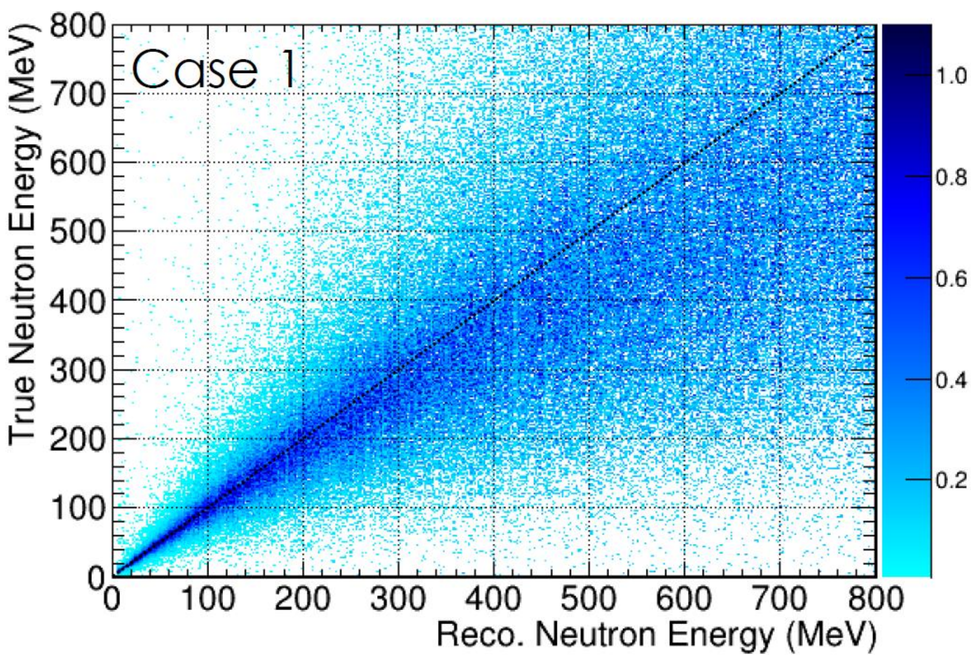
- Lower proton *and* pion tracking thresholds better permit analyses of three particle final states
  - More sensitive to key physics
  - ~5 times higher efficiency

SFGD: a neutron detector

- Can look for neutrons via their re-interaction within a detector

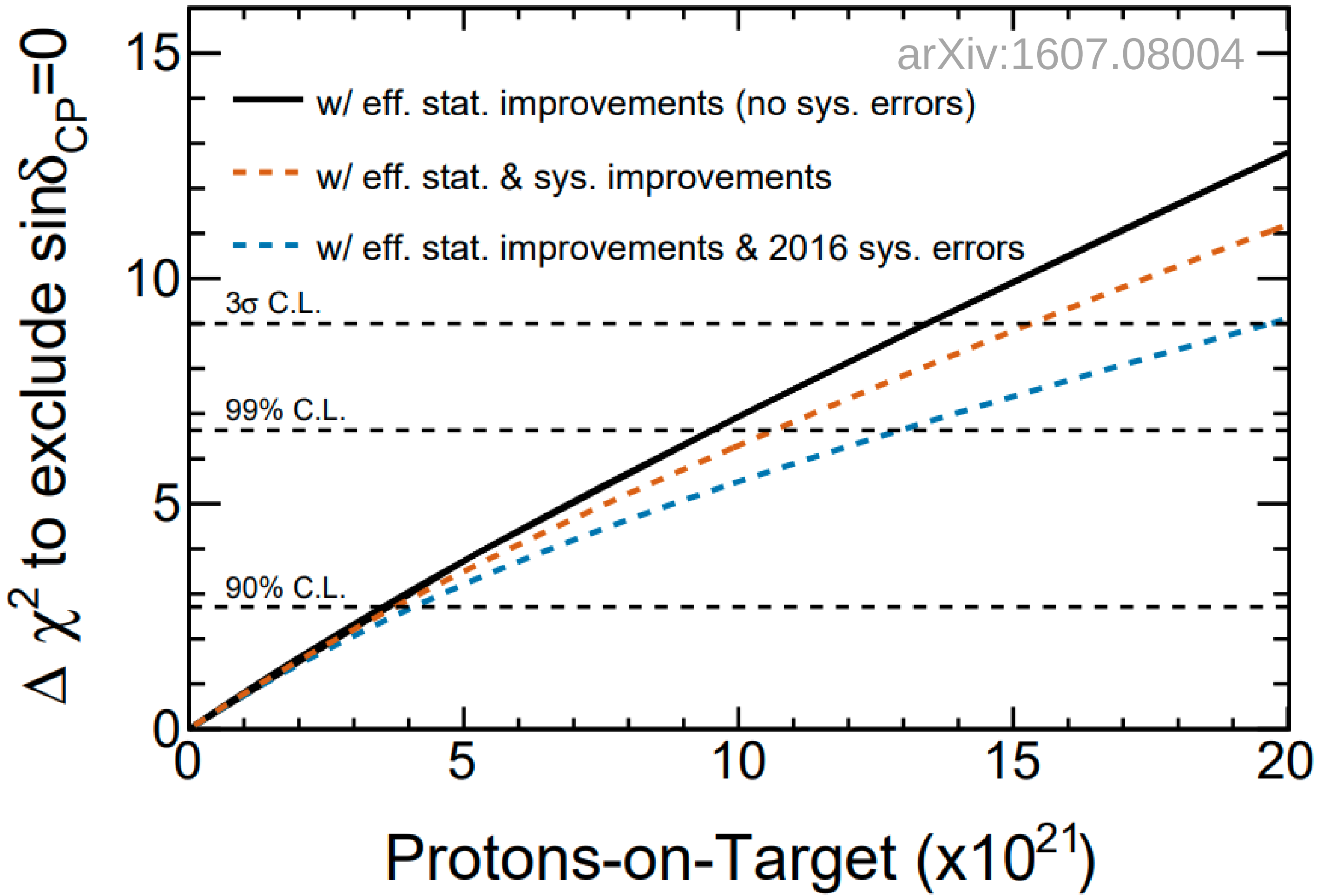
- If the path is long enough (>20 cm) neutron energy is measured using the time of flight with resolution 15-30% (for ~1 ns timing resolution)





Phys. Rev. D **101**, 092003

T2K Projected Sensitivity



ν oscillations need ν cross sections

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \boxed{\sigma(E_\nu^{true})} \boxed{P(\alpha \rightarrow \beta, E_\nu^{true})} \epsilon(E_\nu^{true}) \boxed{S(E_\nu^{true}, E_\nu^{reco})}$$

$N_{pred}(E_\nu^{reco})$	=	Expected number of events
$\Phi(E_\nu^{true})$	=	Neutrino flux
$\sigma(E_\nu^{true})$	=	Interaction cross sections
$P(\alpha \rightarrow \beta, E_\nu^{true})$	=	Oscillation probability
$\epsilon(E_\nu^{true})$	=	Selection efficiency
$S(E_\nu^{true}, E_\nu^{reco})$	=	Smearing matrix

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \rightarrow \beta)$

ν oscillations need ν cross sections

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \boxed{\sigma(E_\nu^{true})} \boxed{P(\alpha \to \beta, E_\nu^{true})} \epsilon(E_\nu^{true}) \boxed{S(E_\nu^{true}, E_\nu^{reco})}$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

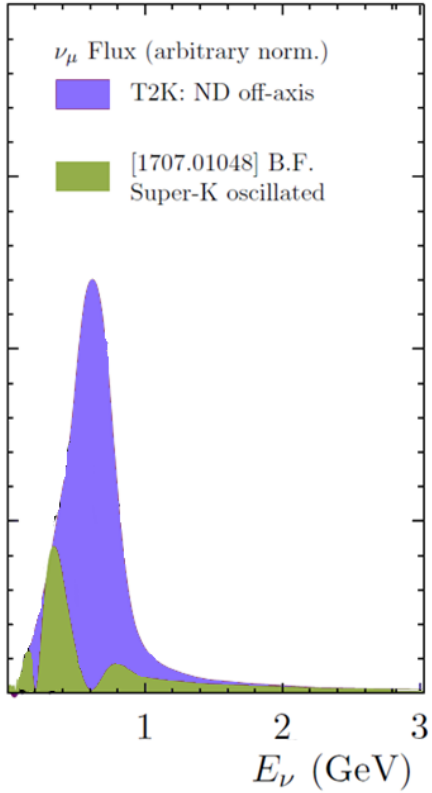
$\boxed{\sigma(E_\nu^{true}) = \text{Interaction cross sections}}$

$\boxed{P(\alpha \to \beta, E_\nu^{true}) = \text{Oscillation probability}}$

$\epsilon(E_\nu^{true})$ = Selection efficiency

$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \to \beta)$
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance



ν oscillations need ν cross sections

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\boxed{\sigma(E_\nu^{true})}\,\boxed{P(\alpha\to\beta, E_\nu^{true})}\,\epsilon(E_\nu^{true})\,\boxed{S(E_\nu^{true}, E_\nu^{reco})}$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

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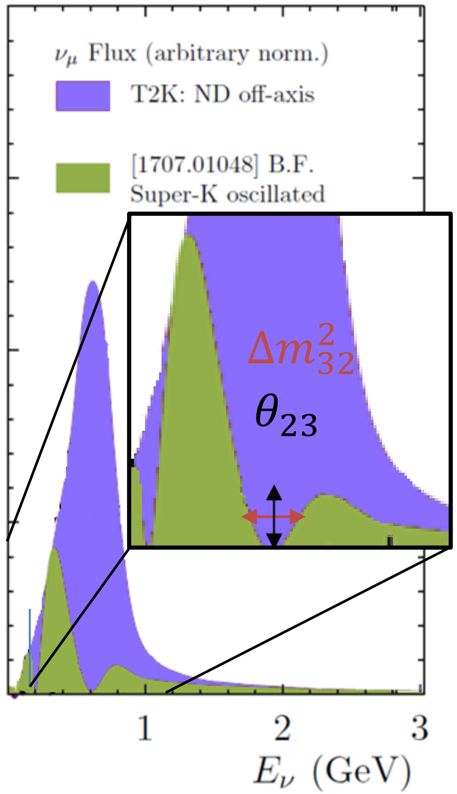
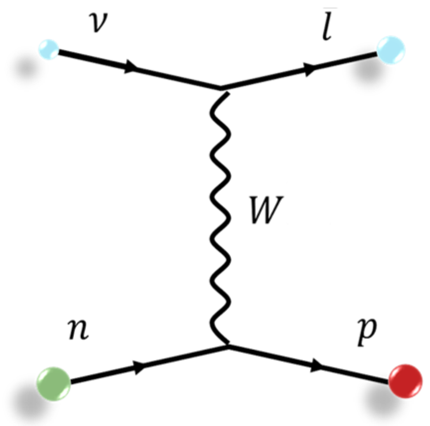
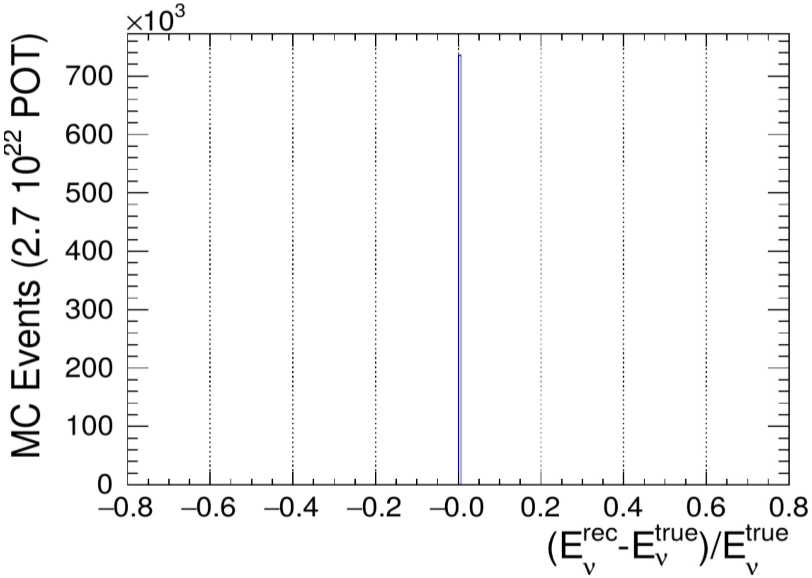
- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \to \beta)$
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}



Neutrino Interactions at T2K/HK

CCQE (1p1h)

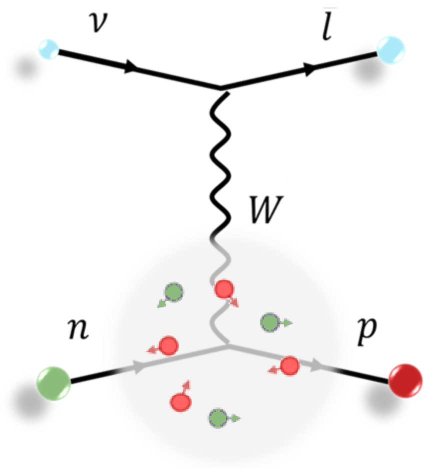


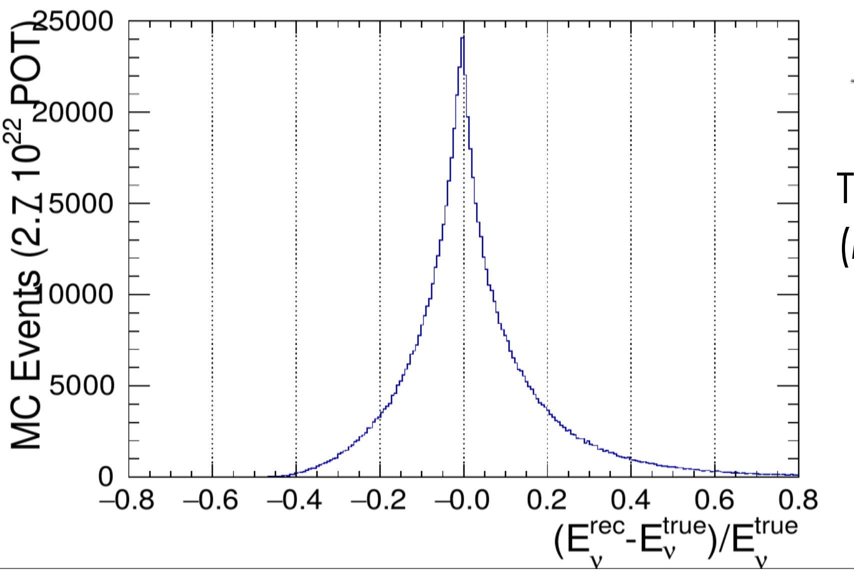


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Calculation from lepton kinematics is perfect only for **elastic scattering** off a **stationary nucleon**

Neutrino Interactions at T2K/HK

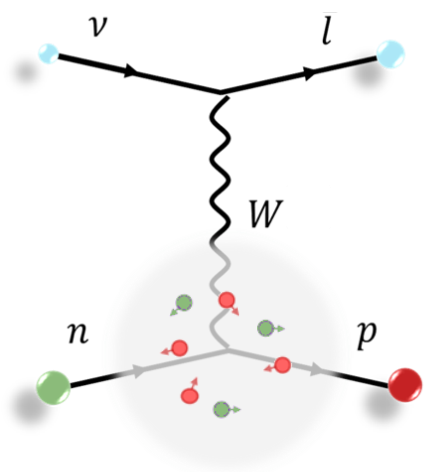


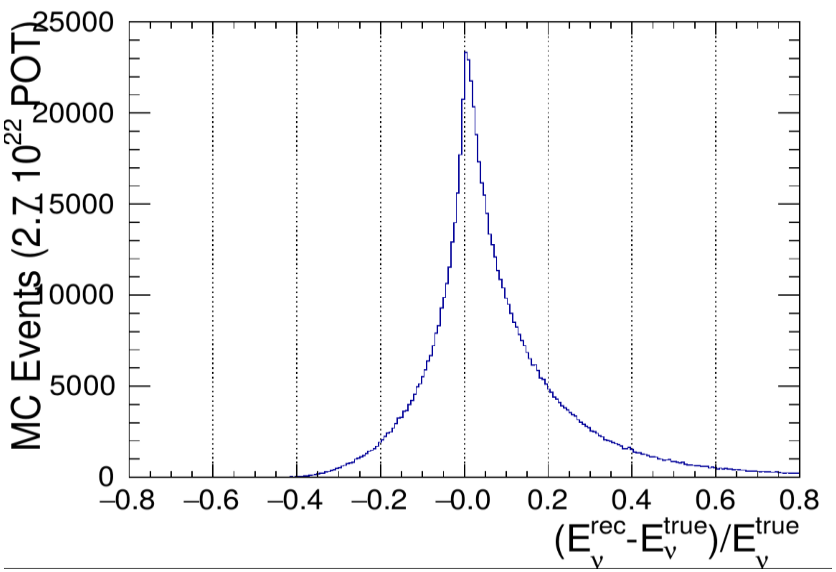


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

Neutrino Interactions at T2K/HK



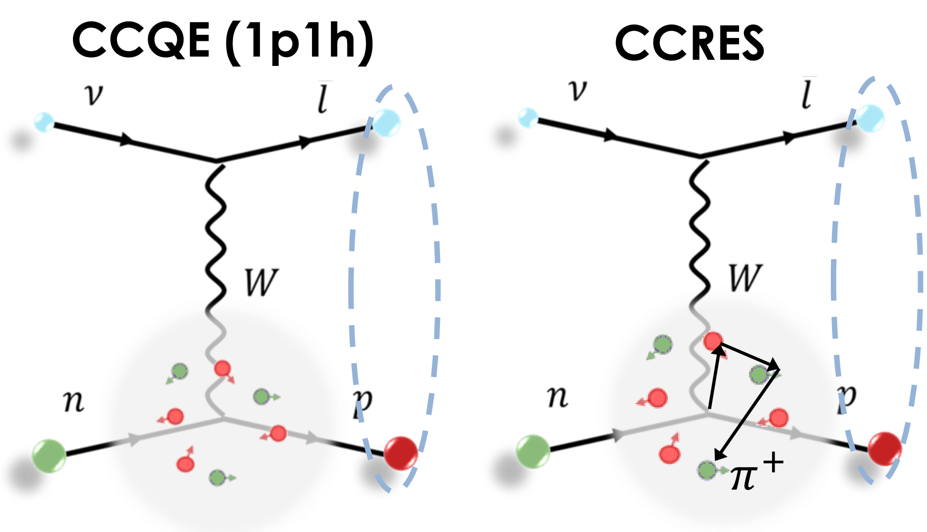


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

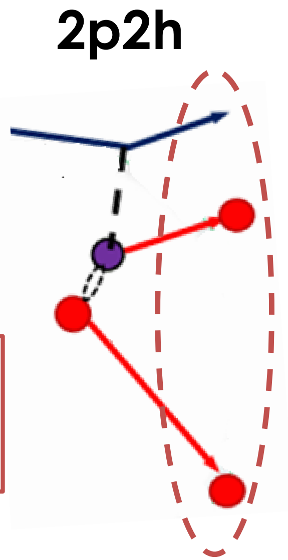
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

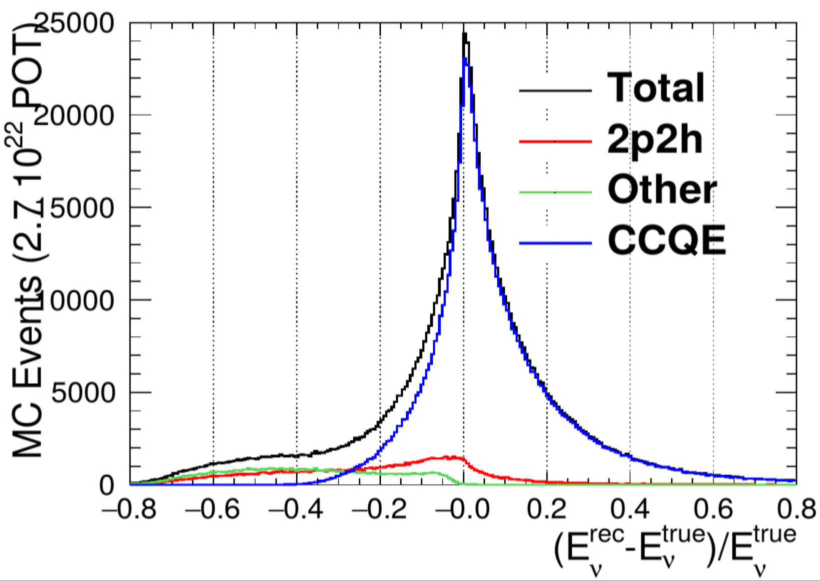
Neutrino Interactions at T2K/HK



Final state interactions (FSI) can cause different interaction modes to have the same final state



Interactions off a bound state of two nucleons can result in **2p2h** final states



$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Does not work well for non-CCQE events: 2p2h and CC1π with pion abs. FSI

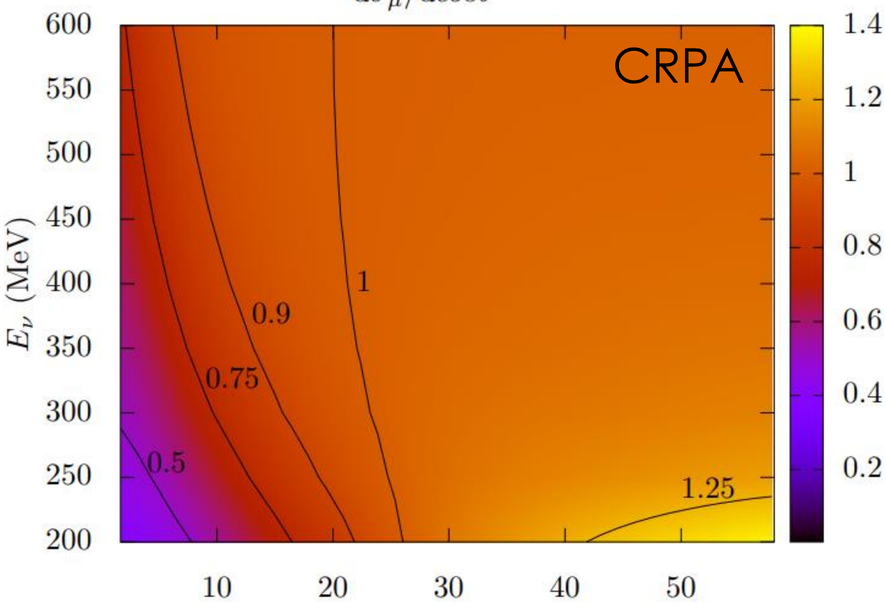
Electron vs muon neutrino cross sections

- Different models can predict quite different cross section ratios!
- Critical for the future

$$\frac{d\sigma_e/dcos\theta}{d\sigma_\mu/dcos\theta}$$

	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

Tabulated from Phys. Rev. C **96**, 035501 and the left figure



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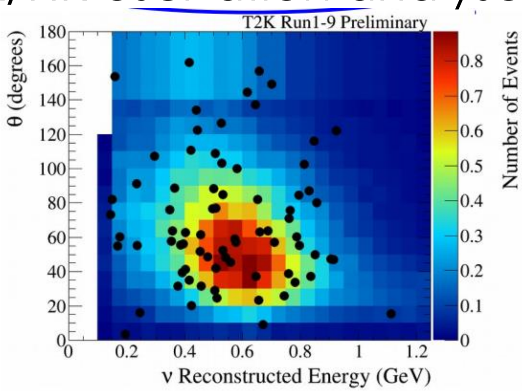
These differences are predicted in regions that are relevant to T2K/HK oscillation analyses



End