21st International Workshop on Neutrinos from Accelerators – Daegu, South Korea

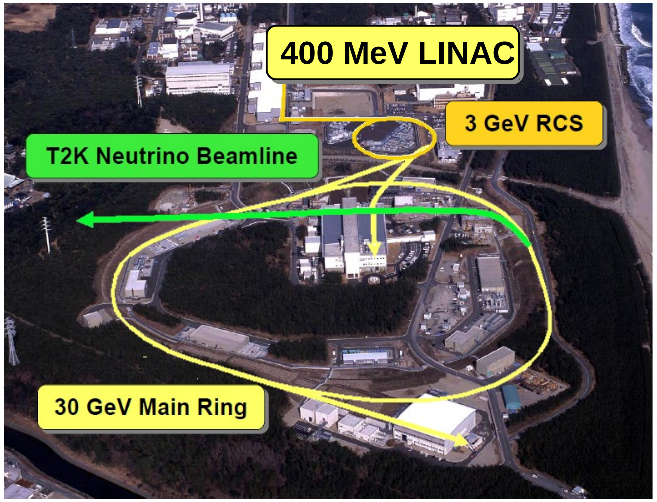
Details of T2K oscillation analysis

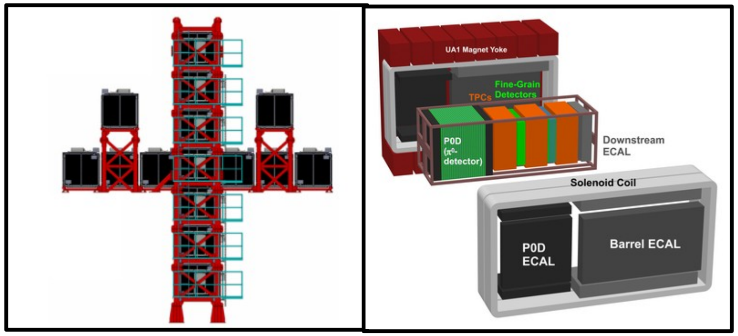
Super-Kamiokande
(ICRR, Univ. Tokyo)

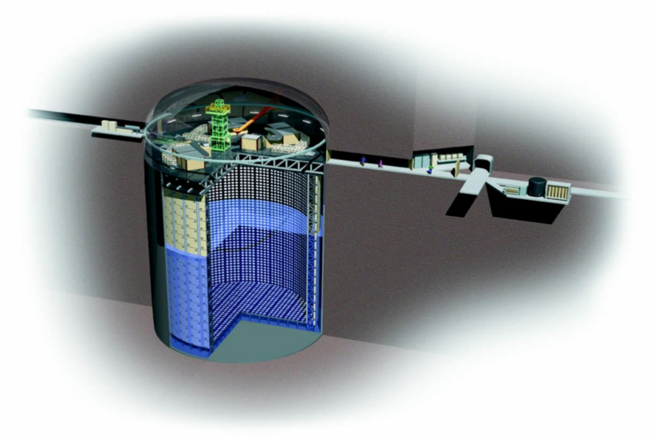
J-PARC Main Ring
(KEK-JAEA, Tokai)

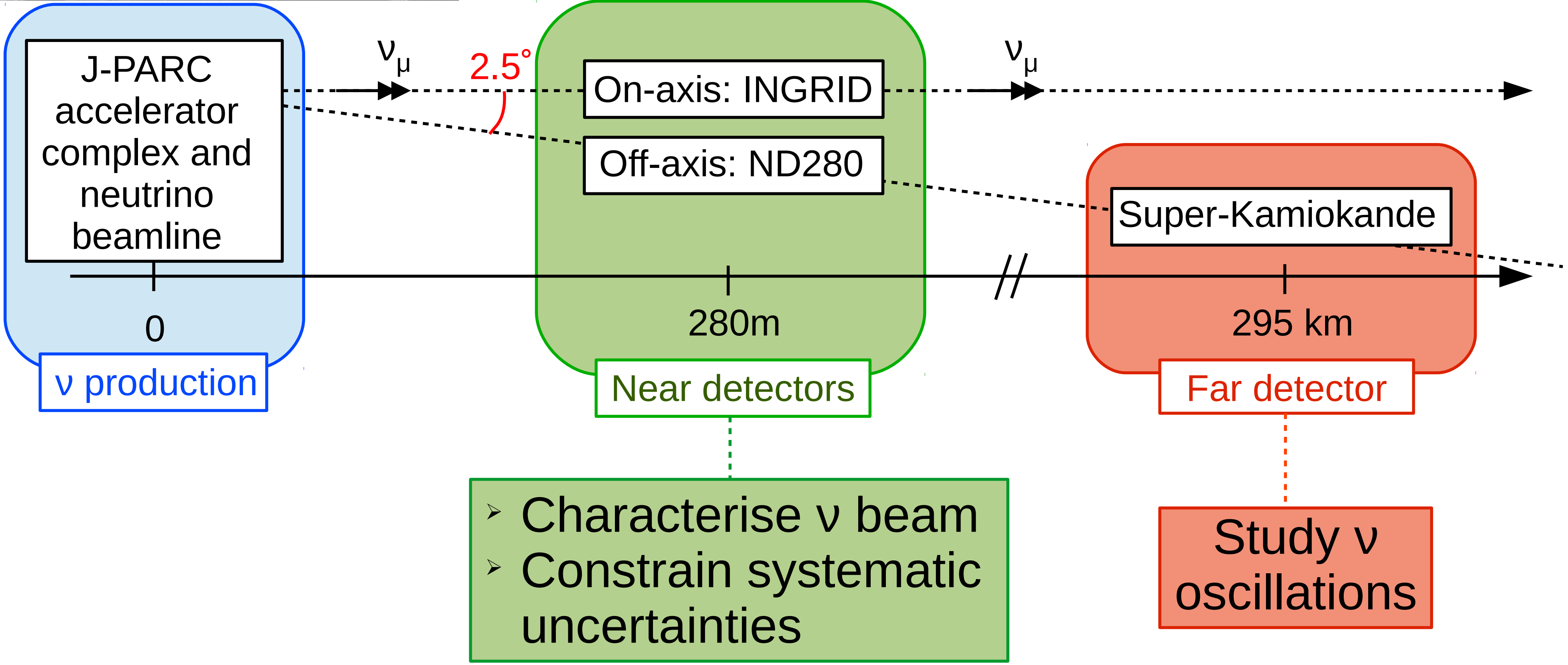
C. Bronner on behalf of the T2K collaboration
August 29th, 2019

The T2K experiment









J-PARC accelerator complex and neutrino beamline

ν_μ

2.5°

On-axis: INGRID

Off-axis: ND280

ν_μ

Super-Kamiokande

0

280m

295 km

ν production

Near detectors

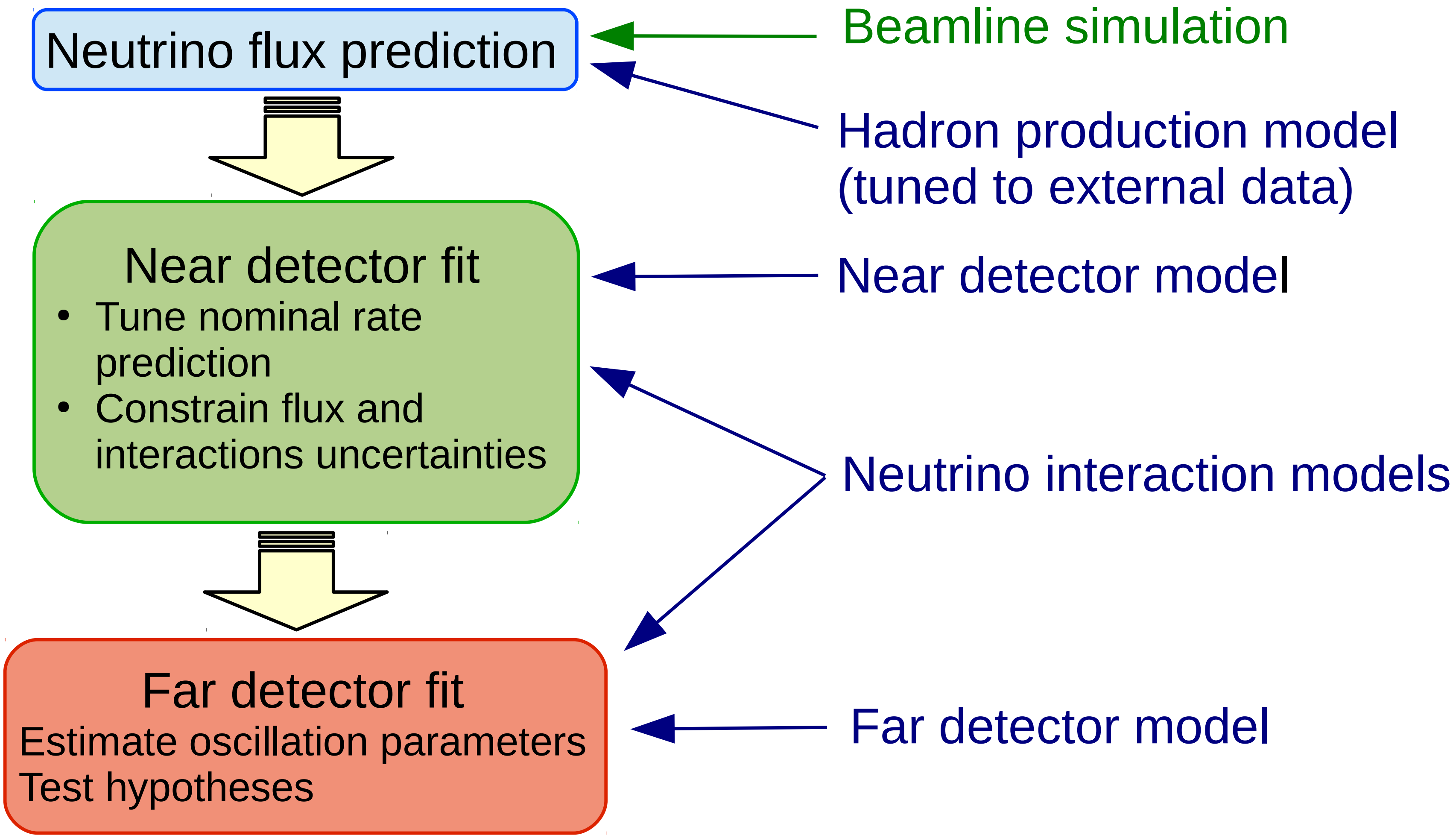
Far detector

- Characterise ν beam
- Constrain systematic uncertainties

Study ν oscillations

T2K Oscillation Analysis Overview

Likelihood analysis: compare observed data at the far detector to predictions based on a model of the experiment to make measurements



Neutrino flux prediction

Beamline simulation

Hadron production model
(tuned to external data)

Near detector fit
- Tune nominal rate prediction
- Constrain flux and interactions uncertainties

Near detector model

Neutrino interaction models

Far detector fit
Estimate oscillation parameters
Test hypotheses

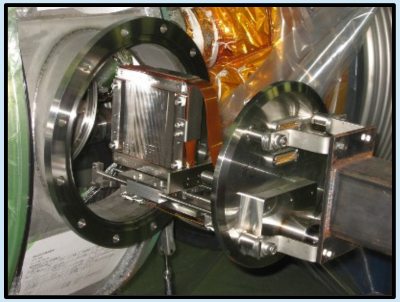
Far detector model

(Near and far detector fits can be done sequentially or simultaneously)

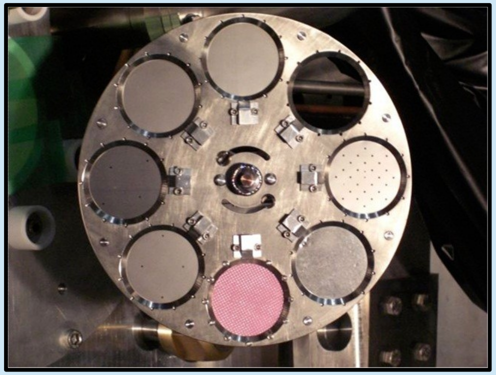
T2K Oscillation Analysis
Neutrino flux prediction

Neutrino flux predicted using a series of simulations

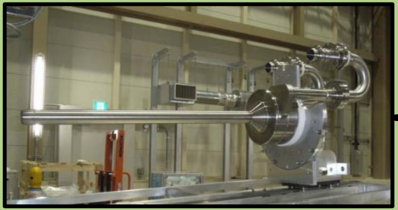
Proton beam properties



Measured by beam monitors

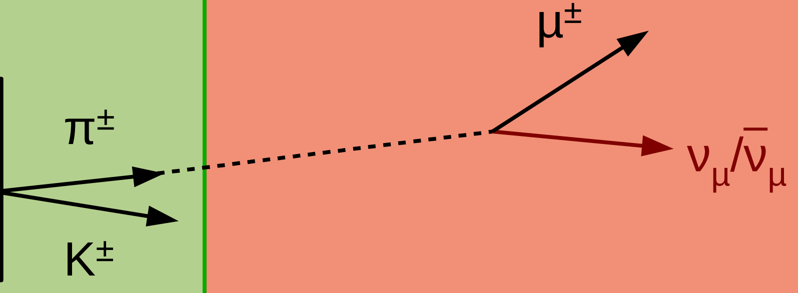


Hadron production in target



FLUKA 2011
Tuned to external data
(NA61/Shine @ CERN)

Propagation and decay of hadrons in secondary beamline



GEANT3 simulation
GCALOR package

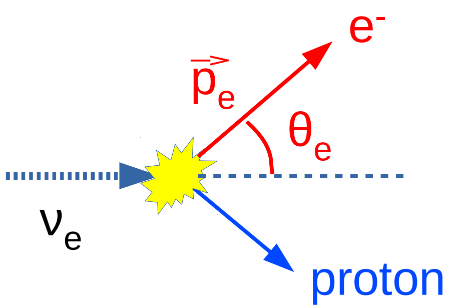
Uncertainty on flux prediction varies between 8 and 12%, depending on neutrino flavor and energy

T2K Oscillation Analysis
Neutrino interaction model

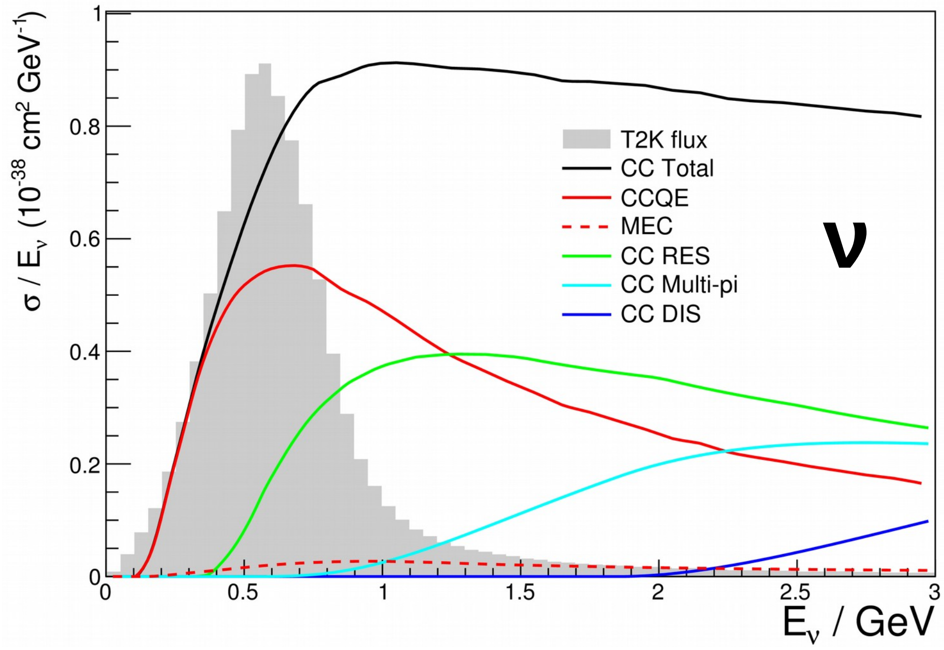
- Dominant interaction mode is CCQE

$\nu + n \rightarrow p + l^-$

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



- Other interactions can populate region of interest



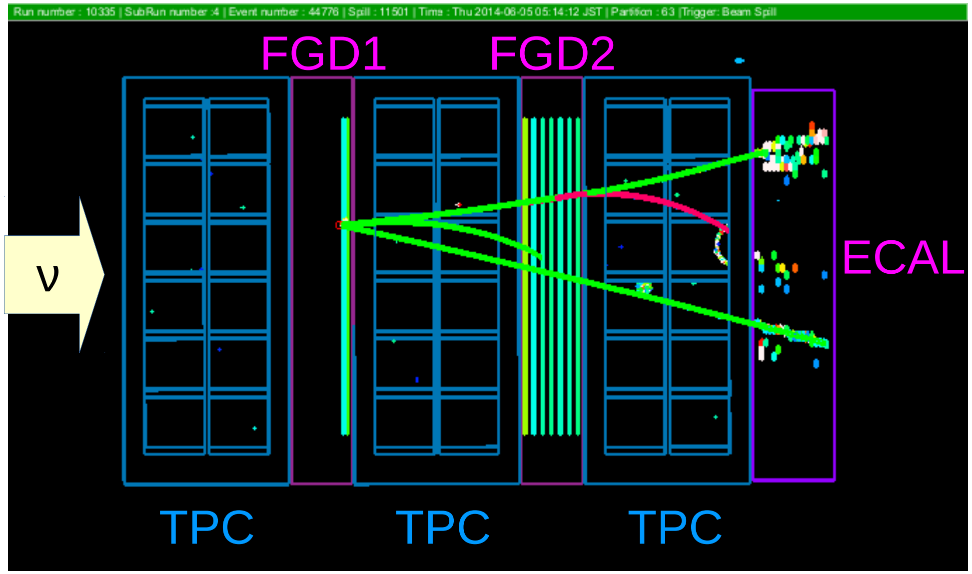
- Select interaction models using external data
- Nominal predictions from NEUT 5.3.2

- Uncertainties on model parameters (M_A, pF,…)
- Additional uncertainties for certain modes (shape, normalization)
- “Simulated Data Studies” (SDS) for alternative models and uncertainties that could not be implemented

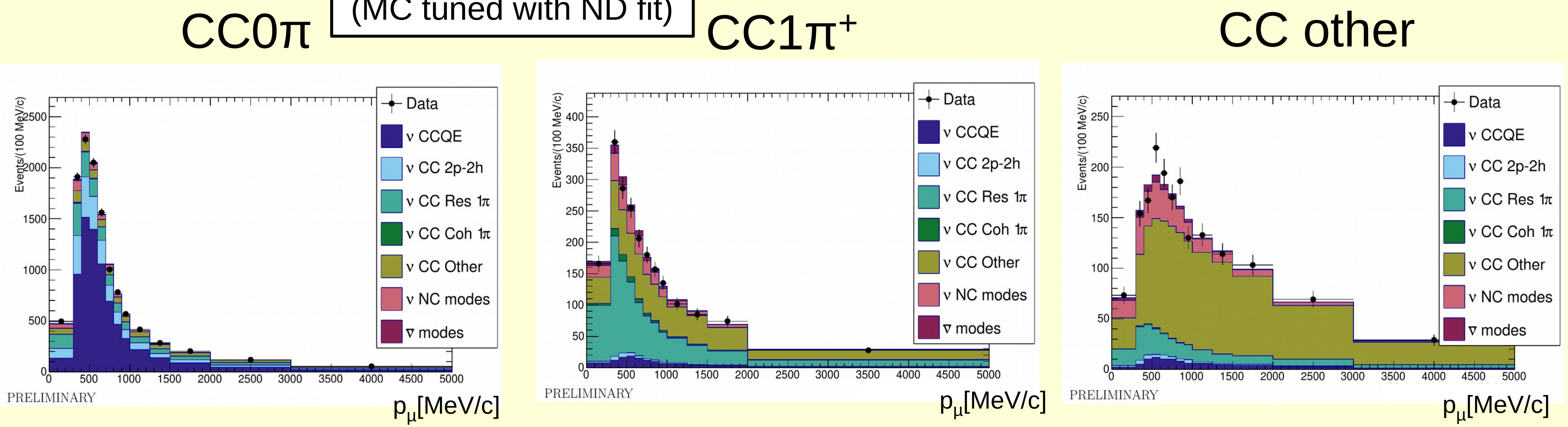
Near detector analysis
Event selection

Select CC ν_μ interactions, separate in samples

- Enriched in different type of interactions
- Interactions on different targets (FGD1: CH target, FGD2: 42% water)
- additional samples for wrong sign background in ν-mode



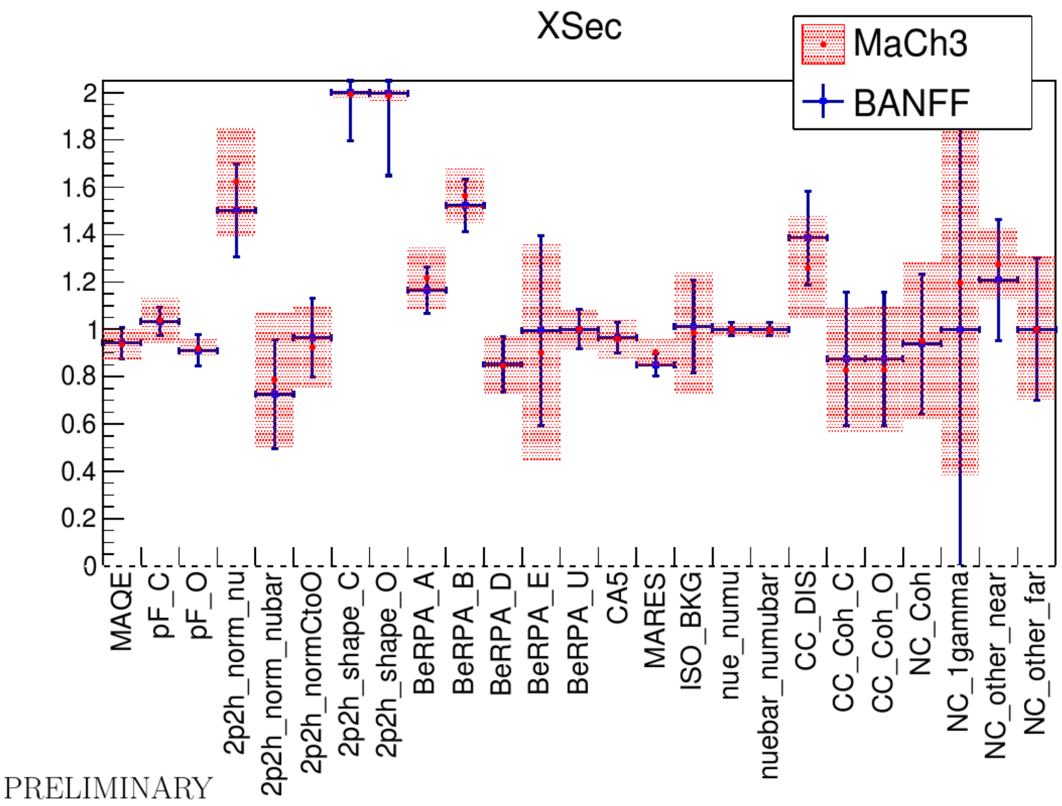
FGD1 samples
(MC tuned with ND fit)

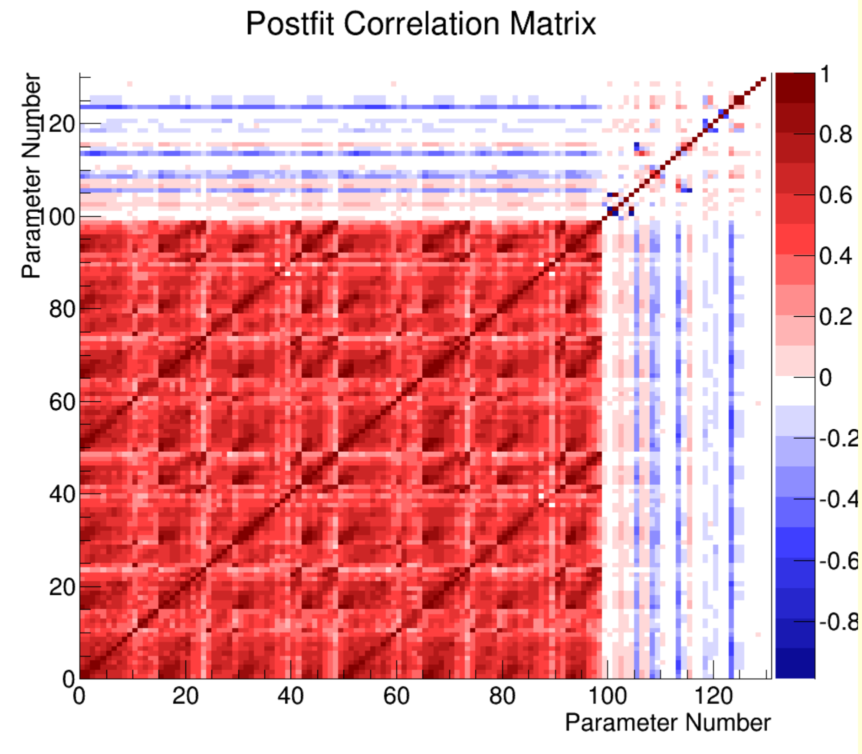


Near detector analysis
Fits

2 different fitters giving consistent results:

- “Mach3”: MCMC based marginalization to obtain posterior probabilities
- “BANFF”: gradient descent



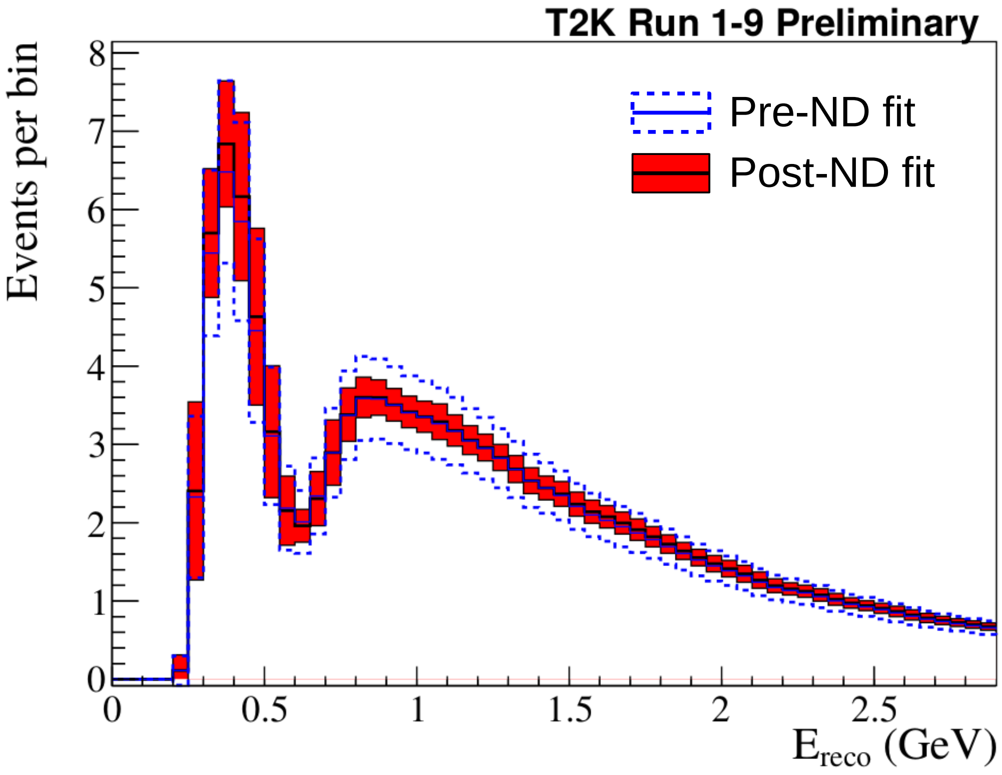


Anti-correlations between postfit flux and interaction uncertainties

Near detector analysis
Reduction of uncertainties

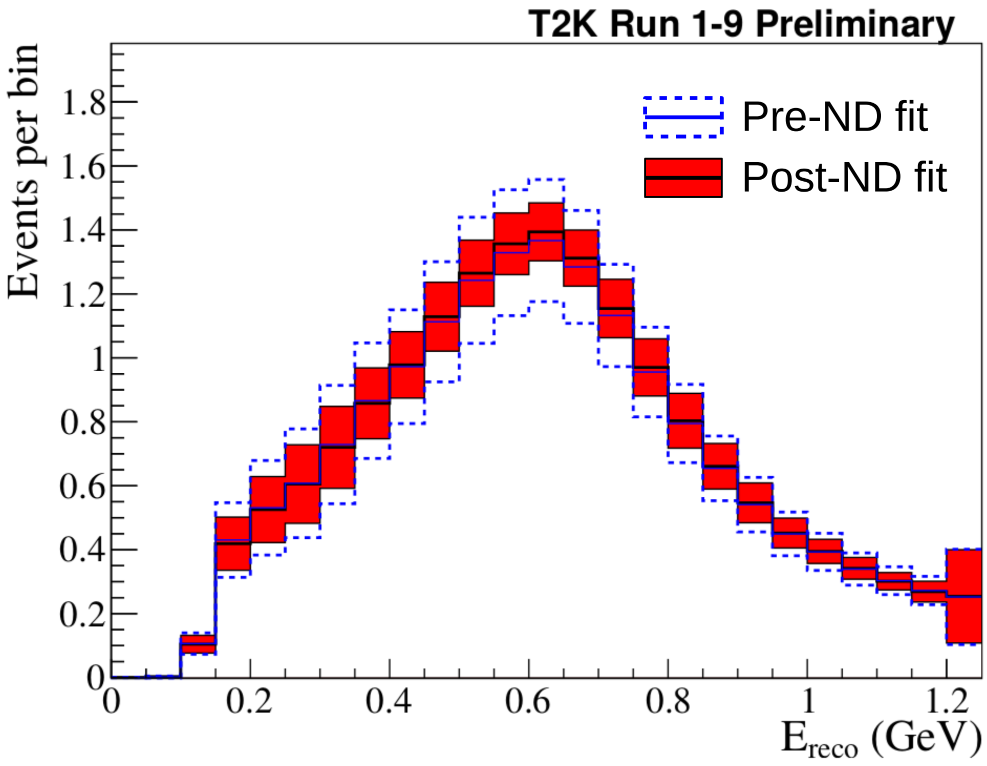
Near detector fit shifts the nominal predictions at the far detector, and reduces the flux and cross-section uncertainties

1 ring μ-like ($\bar{\nu}$-mode)



$\Delta N_{SK}/N_{SK}$: 12.5% → 4.4%

1 ring e-like ($\bar{\nu}$-mode)



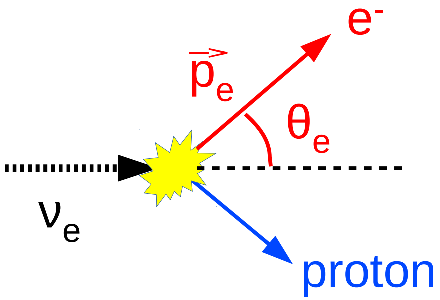
$\Delta N_{SK}/N_{SK}$: 14.4% → 7.1%

Far detector analysis
Energy reconstruction

Water Cherenkov detector:
- Only sees charged particles
- Has a momentum threshold

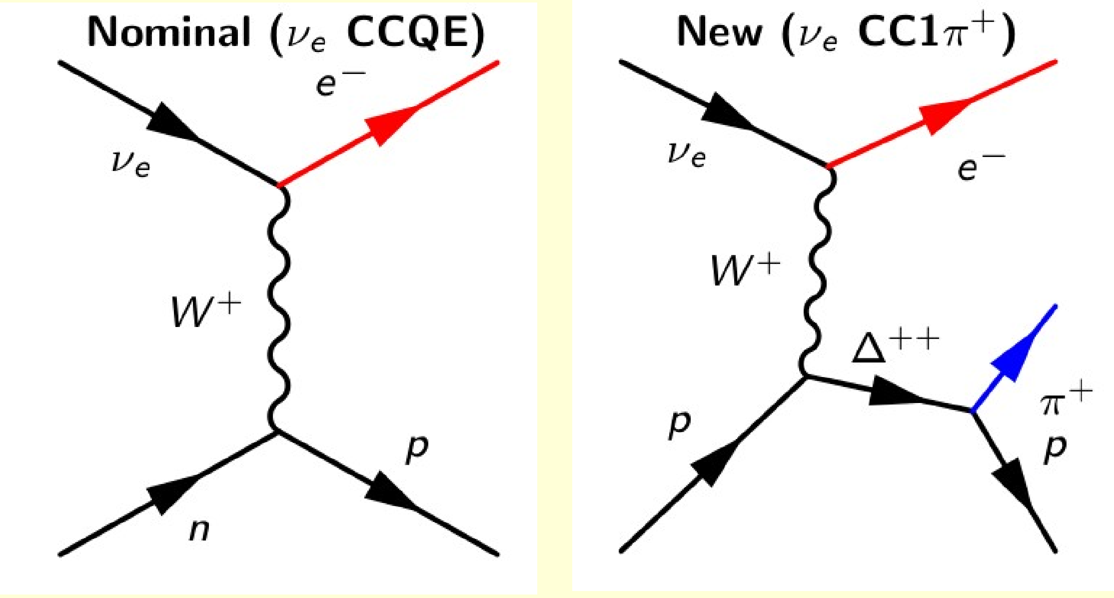
CCQE interactions

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



Knowing ν direction, can reconstruct E_ν from lepton (p,θ)

Can use similar approach for resonant pion production with $p \rightarrow \Delta^{++}$



Build samples enriched in CCQE (or CC1π) interactions

Oscillation fits
Overview

- Marginalize (integrate) over the nuisance parameters
- Bayesian, frequentist and pseudo-frequentist (fixed Δχ² intervals) results

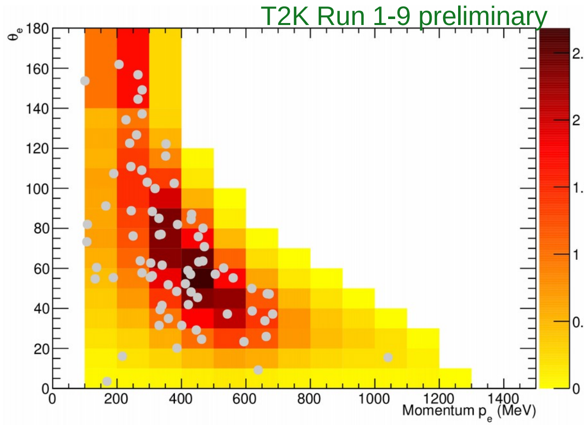
3 different analyses giving consistent results

Different use of near detector data:
- 1 joint near/far analysis
- 2 use result of ND fit as input

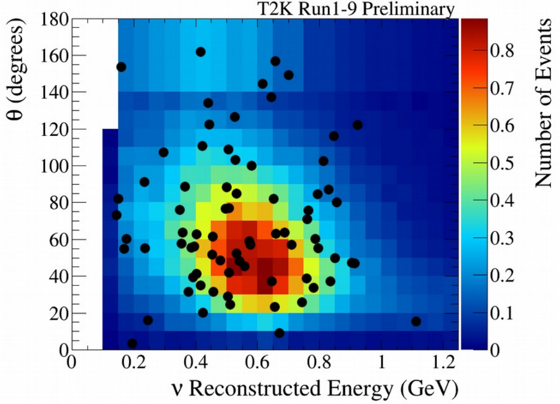
Different fitting methods:
- 2 "grid searches"
- 1 uses Markov Chain MC

Different 'shape' information for e-like samples

Lepton (p,θ)



ν E_{rec} + lepton θ

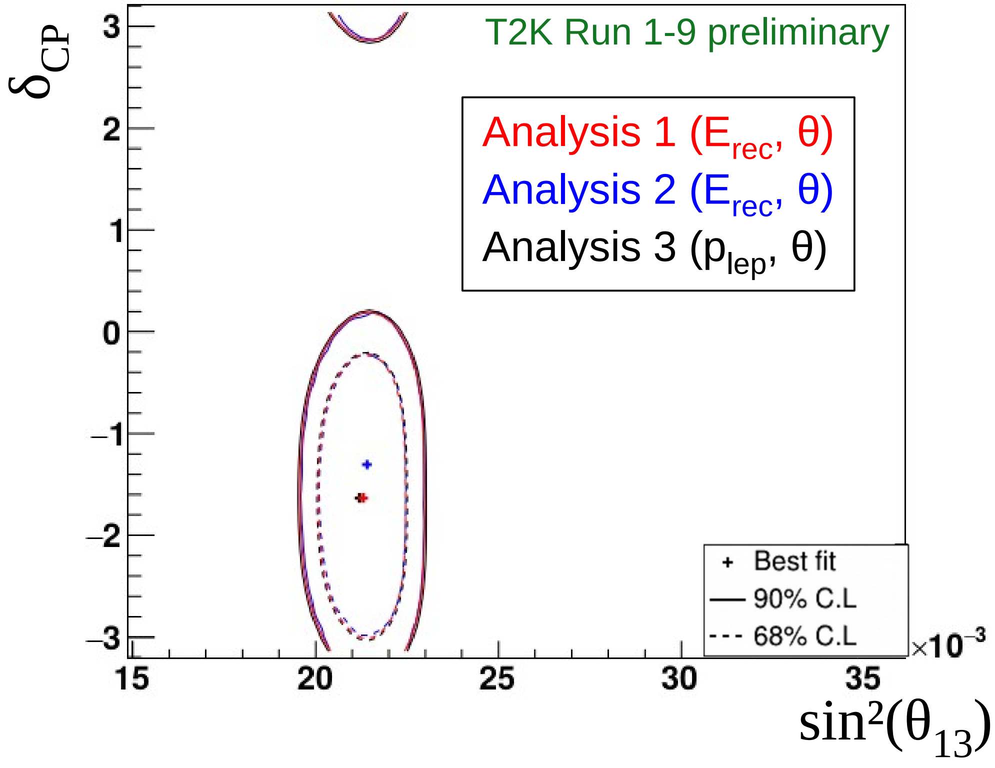


Used for results shown in plenary

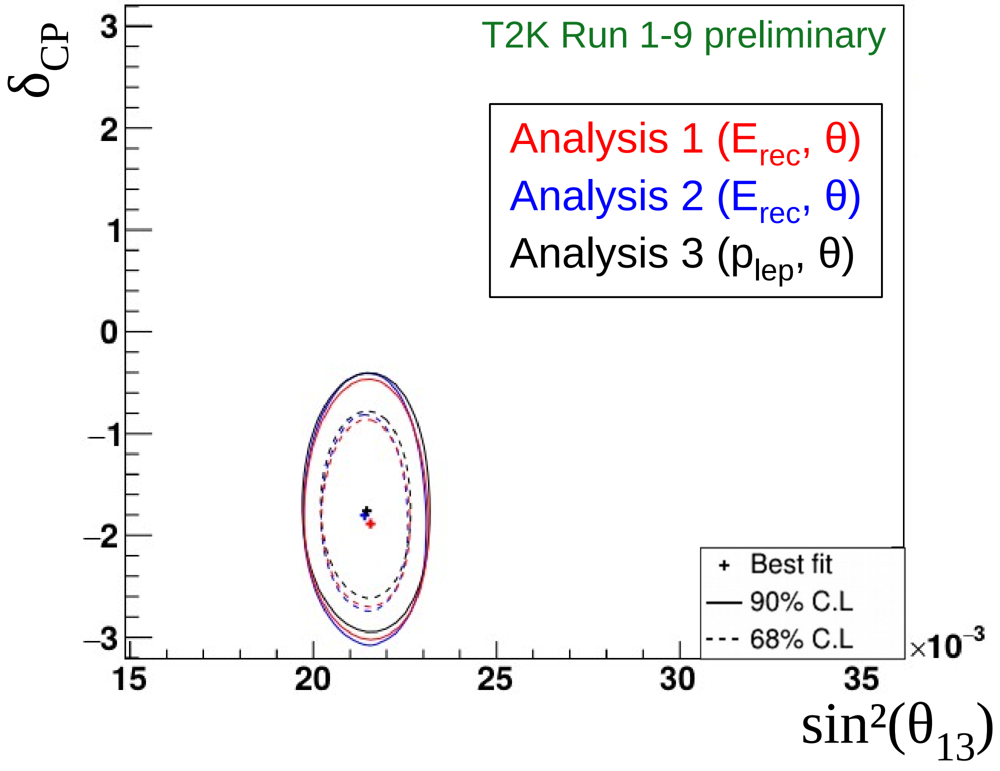
Oscillation fits
Analysis comparisons

- Despite their differences, the 3 fitters give consistent results for sensitivity
- Small differences in the results of data fits, found to be coming from the use of (p_{lep}, θ) or (E_{rec}, θ) shape information for appearance samples

Sensitivity



Data fit



Sensitivity assumes true NH, $\sin^2(2\theta_{13})=0.083$, $\delta=-1.601$, $\sin^2(\theta_{23})=0.528$, $\Delta m^2=2.509\text{e-}3$

Results of reactor experiments used to constrain $\sin^2(2\theta_{13})$

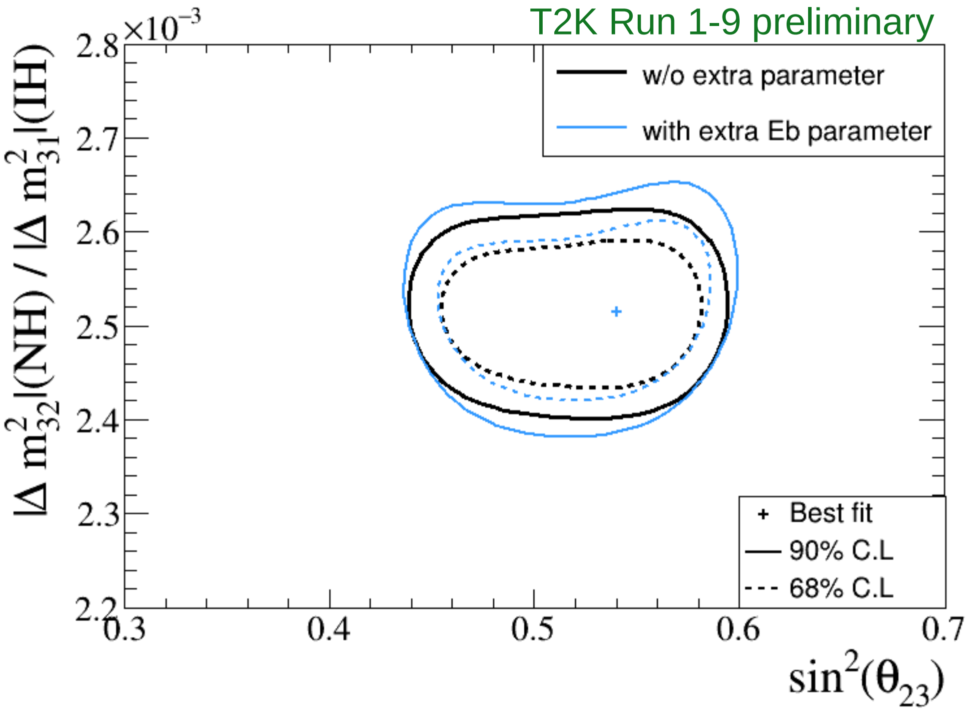
T2K Oscillation Analysis
Simulated data studies

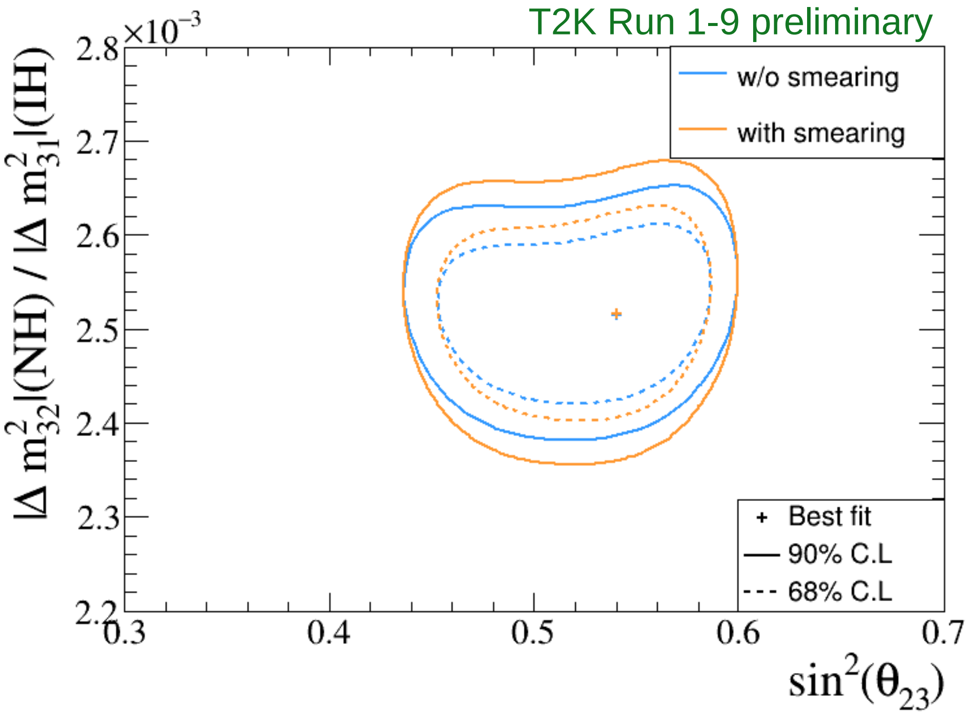
Look for possible biases by comparing sensitivities obtained when fitting our model to data generated with nominal and modified interaction models:

- Data driven (assign ND data/MC difference to 1 mode)
- Alternative models (form factors, 2p2h, nuclear model, ...)

Additional systematic parameter from binding energy SDS

Smearing of the contours in Δm²





Significant effect on sensitivity, in particular for Δm²

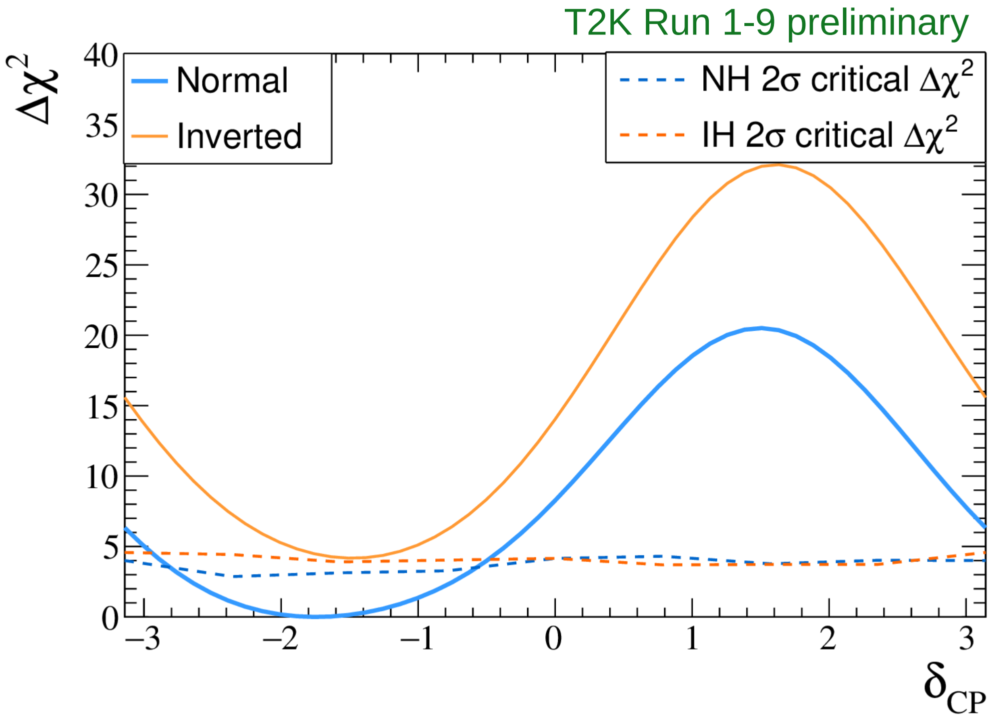
T2K Oscillation Analysis
Current results

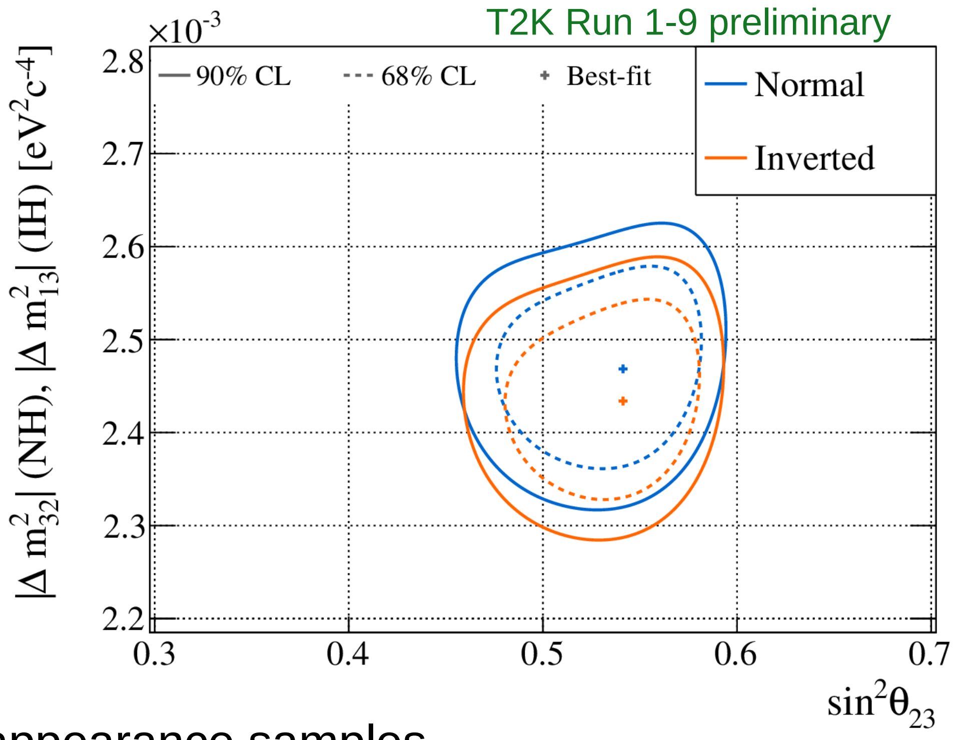
Run 1-9 results:

- 1.49e21 (ν-mode) POT + 1.63e21 ($\bar{\nu}$-mode) POT
- Conservation of CP symmetry excluded at 2σ
- Compatible with maximal mixing
- Preference for normal hierarchy and second octant

Posterior probabilities

	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	Sum
IH	0.017	0.071	0.089
NH	0.177	0.733	0.911
Sum	0.195	0.805	1





From analysis using (p_{lep}, θ) shape information for appearance samples

Reactor constraint: $\sin^2(2\theta_{13})=0.083\pm0.0031$ (PDG2018)

Run 1-9 data
Observed number of events

Observed in the run 1-9 data:

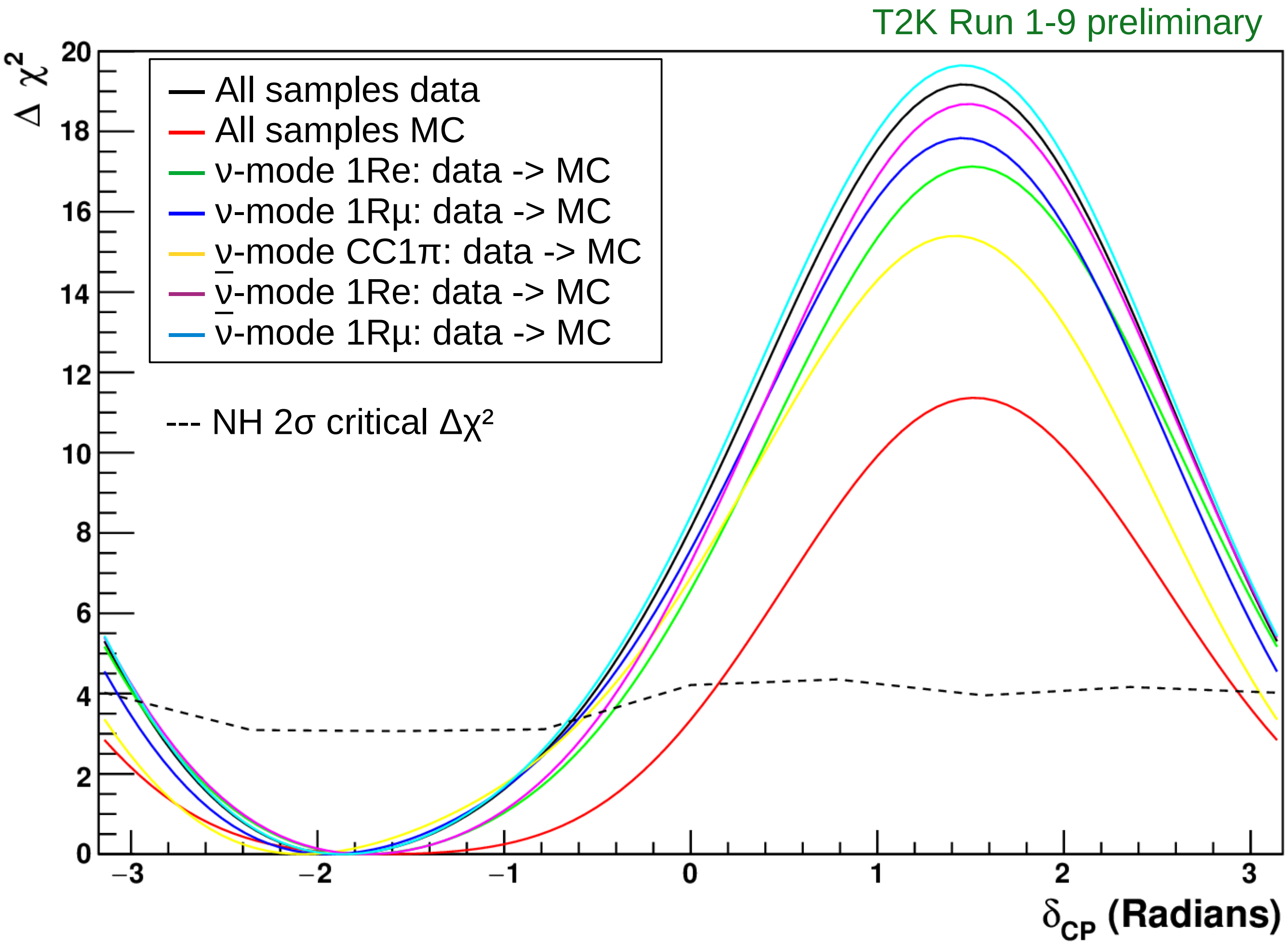
- excess of events in the neutrino mode sample targeting CC1π events
- Small deficit in the neutrino mode 1-ring muon-like sample

Sample	δ=-π/2 MC	δ=0 MC	δ=π/2 MC	δ=π MC	Observed
ν-mode 1Re	74.46	62.26	50.59	62.78	**75**
ν-mode 1Rμ	272.34	271.97	272.30	272.74	**243**
$\bar{\nu}$-mode 1Re	17.15	19.57	21.75	19.33	**15**
$\bar{\nu}$-mode 1Rμ	139.47	139.12	139.47	139.82	**140**
ν-mode e-like CC1π	7.02	6.10	4.94	5.87	**15**

MC with $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509*10^{-3}$ eV^{2}c^{-4}, **$\sin^2(\theta_{13})=0.0219$**, Normal hierarchy

Observed number of events
Impact on δ_{CP}

Can see the impact of those differences with predictions by redoing the fit for δ_{CP} replacing every time the data from one sample by MC predictions

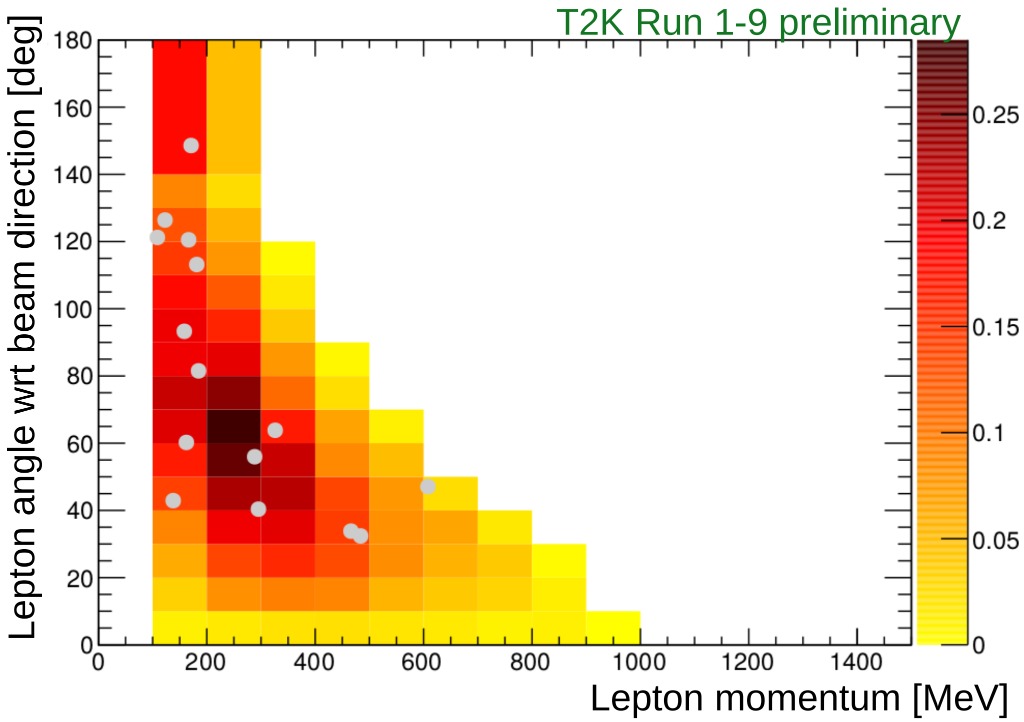


MC with $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509*10^{-3}$ eV^{2}c^{-4}, **$\sin^2(\theta_{13})=0.0212$**, Normal hierarchy
Reactor constraint: $\sin^2(2\theta_{13})=0.083\pm0.0031$ (PDG2018)

Observed number of events
Likelihood of excess seen in CC1π sample

- Kinematic distribution of the events in the e-like CC1π sample agree with MC expectations

- P-values to observe such an excess in the sample are low, but p-values to see such an excess in at least one of the 5 samples are reasonable



Probability to observe similar or larger excess in CC1π sample for different true values of the oscillation parameters

	T2K only best fit	T2K + reactor best fit
e-like CC1π sample only	2.49 %	1.34 %
With trial factor	11.3 %	5.8 %

Mass hierarchy
Significance of the results

- Significance of MH results not easy to determine (Wilks theorem does not apply, potential issues with p-values)
- T2K reports Bayesian results assuming equal prior probabilities for both hierarchies
- Data results also found to be slightly different depending on shape information used for the appearance samples

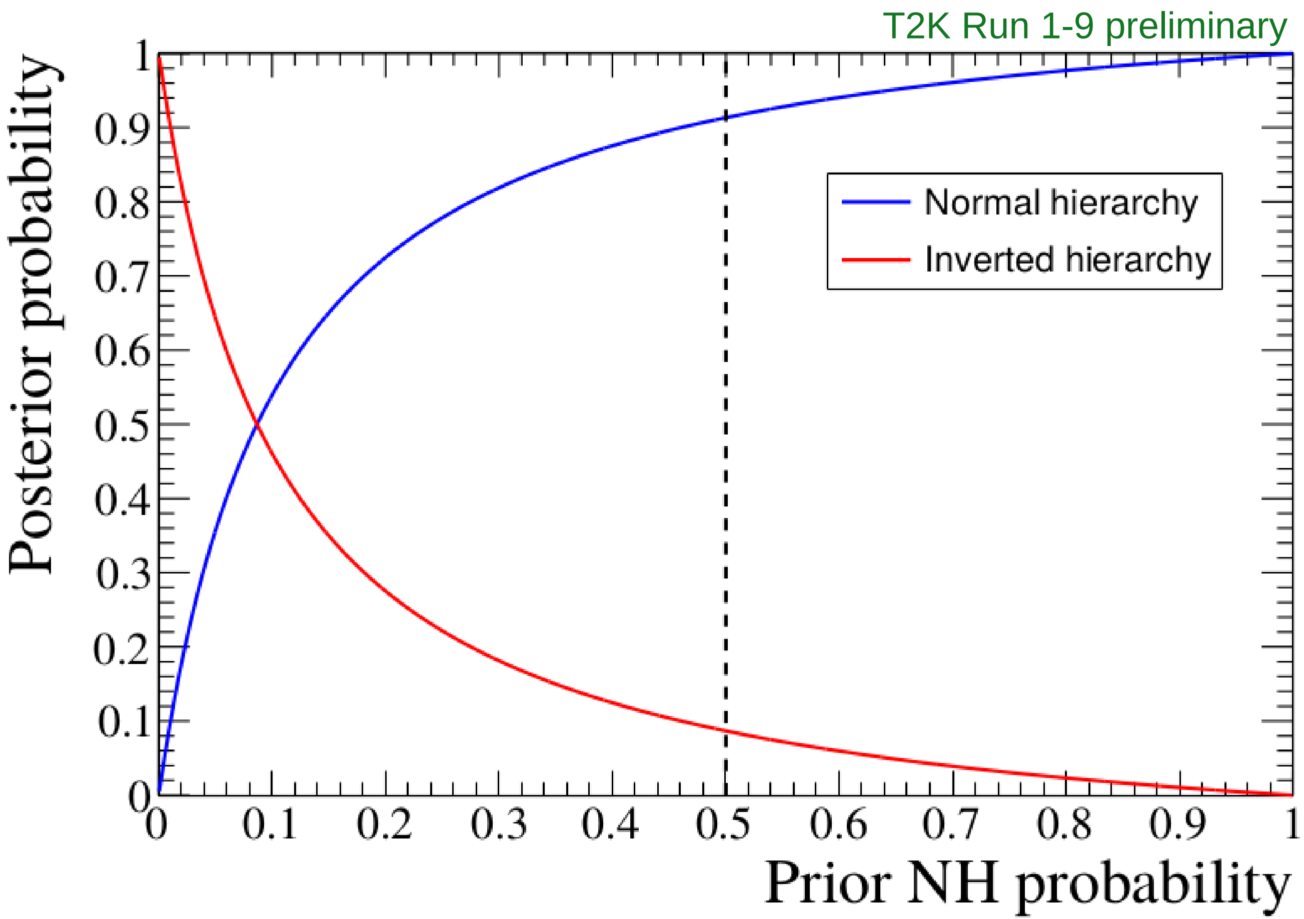
Result shown in plenary talk

	Analysis 1 (E_{rec}, θ)	Analysis 2 (E_{rec}, θ)	Analysis 3 (p_{lep}, θ)
Posterior probability for NH	0.877	0.889	0.911
Bayes factor P(NH)/P(IH)	7.13	8.00	10.23 T2K Run 1-9 preliminary

Jeffrey's scale: preference substantial (analysis 1 & 2) or strong (analysis 3) for the normal hierarchy

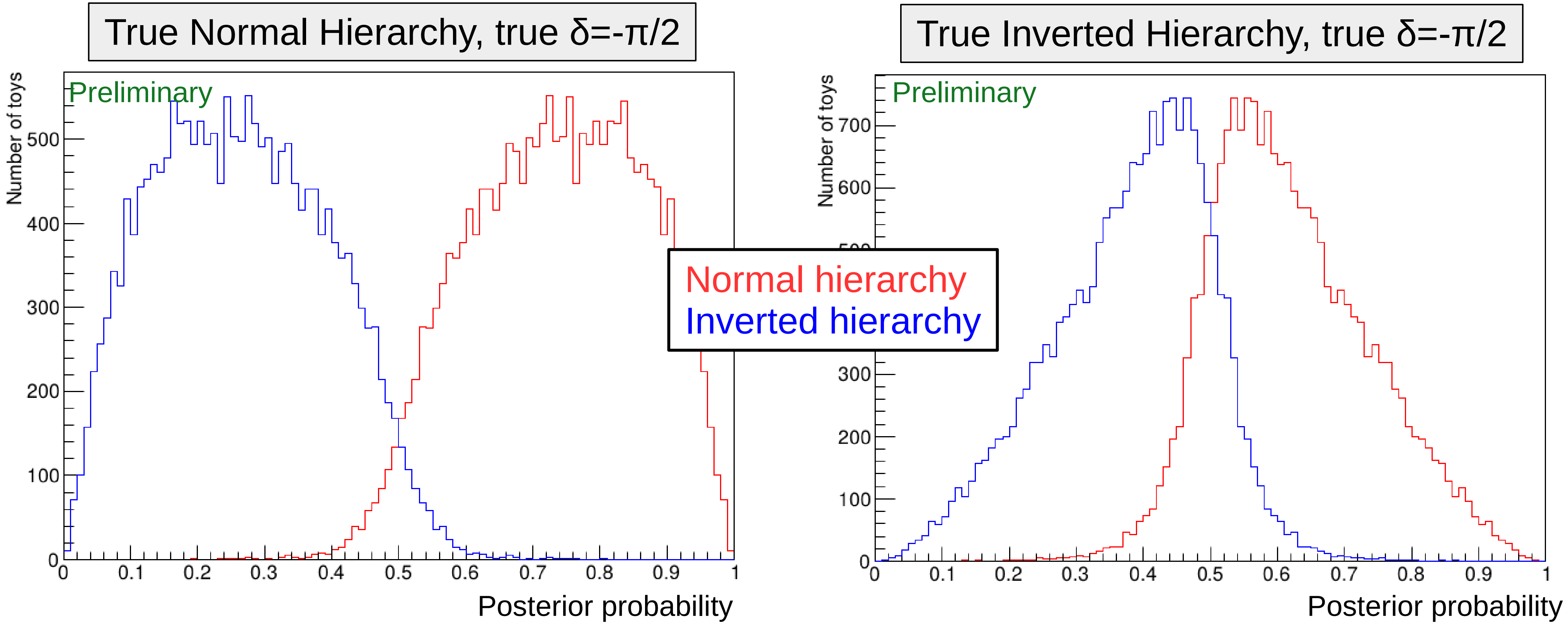
Mass hierarchy
Effect of prior probabilities

- In Bayesian hypothesis testing, prior probabilities have a large impact on the result
- Checked how the posterior probabilities obtained in T2K data fit using reactor constraint varied with prior probabilities



Mass hierarchy
Frequentist properties

- Check how often we reject the true and false MH from the other ordering having posterior probability ≥ 95%
- Found to be highly dependent on true value of δ assumed. Only for true δ around -π/2 can we expect to have an ordering with posterior probability ≥ 95%



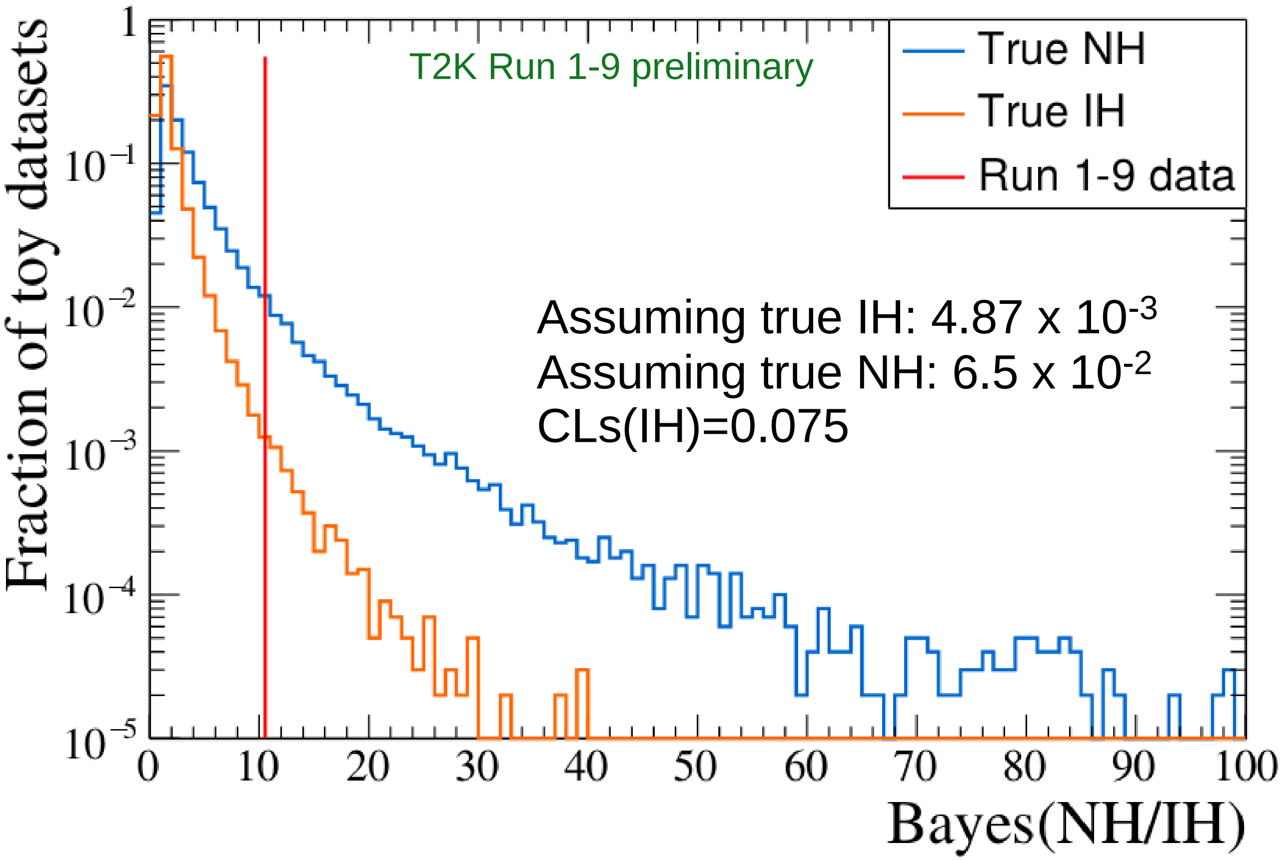
True Normal Hierarchy, true δ=-π/2

True Inverted Hierarchy, true δ=-π/2

Reject true hypothesis ~ 6% of the times we reject the false hypothesis (~ 0.2%/2.8%). Broadly consistent with our interpretation of posterior probability

Mass hierarchy
Frequentist version

Look at the fraction of the time we expect to have a Bayes factor more NH-like (=bigger) than in the data for the 2 mass hierarchy hypotheses

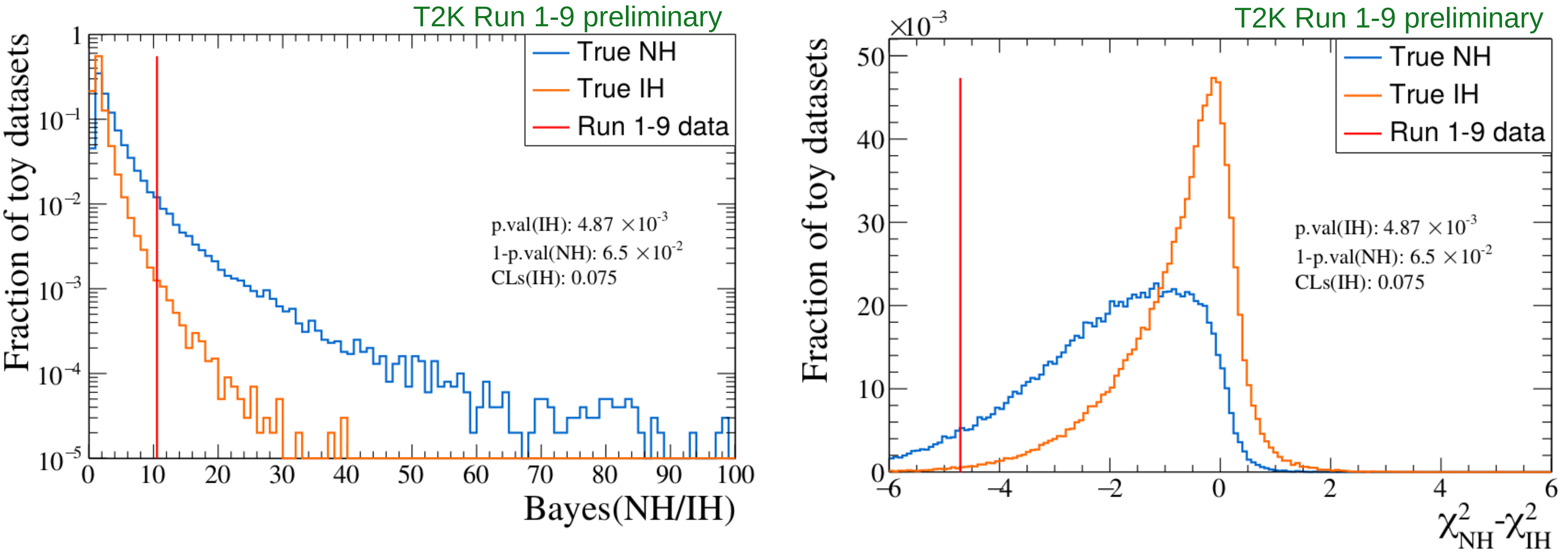


Assuming true IH: 4.87 x 10^{-3}
Assuming true NH: 6.5 x 10^{-2}
CLs(IH)=0.075

Both p-values are low
=> Misleading to claim exclusion of IH based only on the IH p-value

Mass hierarchy
Relationship with standard test statistics

- With equal prior probabilities $\Delta\chi^2=\chi^2_{NH}-\chi^2_{IH}=-2\log(\text{Bayes Factor})$
- The two test statistics give the same frequentist results



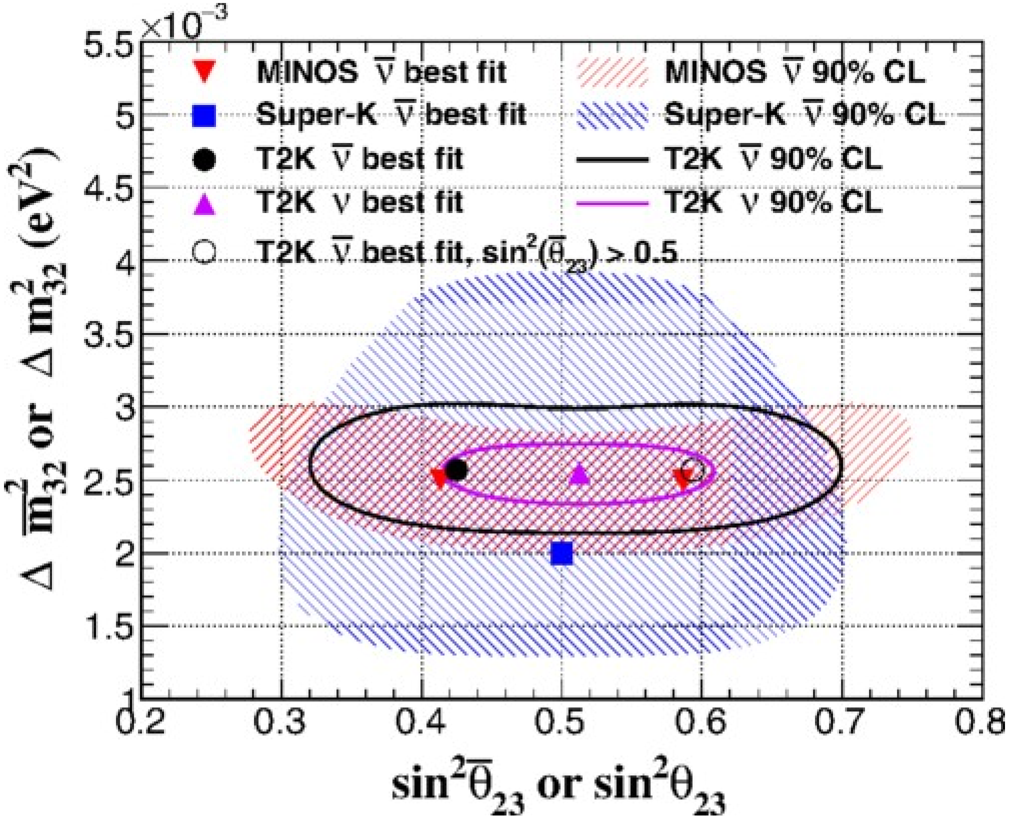
(numbers indicate the fraction of the time we obtain a result more NH-like than in the data)

Result in preparation
Comparison of ν_μ and $\bar{\nu}_\mu$ oscillations

Last published in Phys. Rev. D 96, 011102(R) 2017

Since this paper:

- doubled data set
- Improved oscillation analysis
- New reconstruction algorithm at the far detector
- Improved event selection at far detector (reduce background)



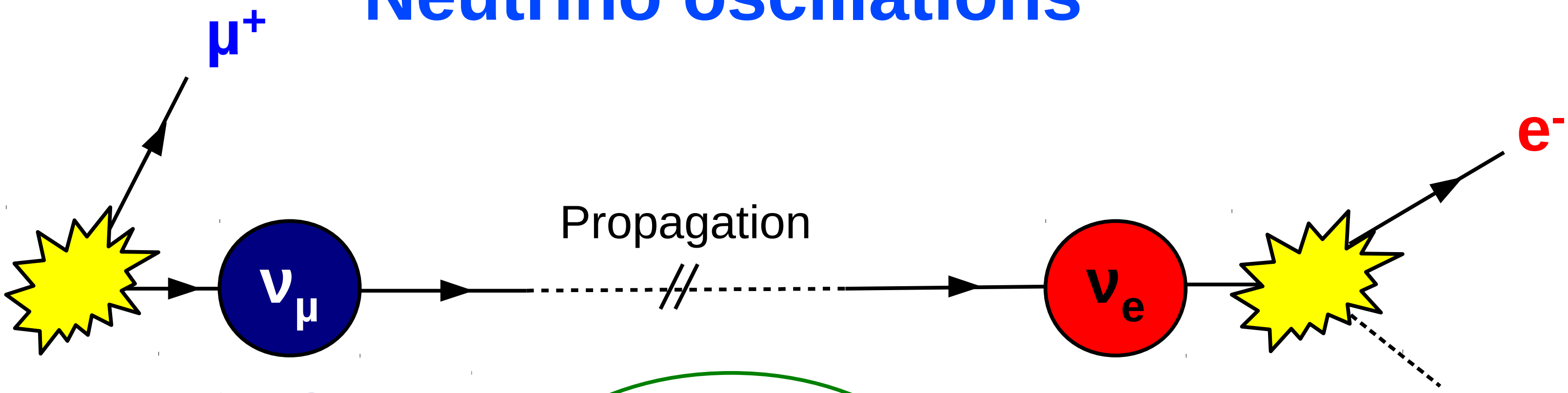
Updated result with improved sensitivity in preparation

Summary

- T2K oscillation analysis compares observation at the far detector to predictions to measure oscillation parameters and test hypothesis
- Predictions made using a model of the experiment, built from simulation and external data
- Near detector data allow to tune the predictions, and reduce the uncertainties
- Additional procedure “Simulated data studies” to take into account additional uncertainties not covered by changes of the model parameters
- Current T2K data exclude conservation of CP symmetry with 2σ significance, and a preference for normal hierarchy and the octant $\sin^2\theta_{23}>0.5$

BACKUP

Neutrino oscillations



Flavor eigenstates
(interaction)

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

Mass eigenstates
(propagation)

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

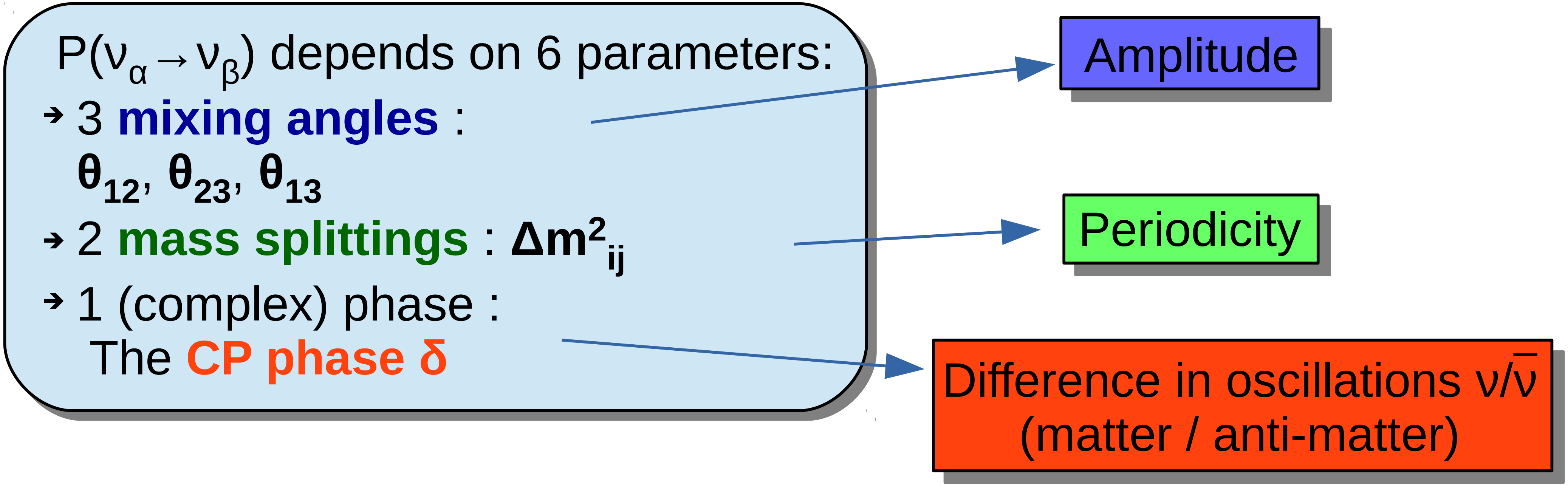
$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino with periodicity $\mathbf{\Delta m^2_{ij} L/E}$

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

Neutrino oscillations
Parameters

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

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



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

- 3 **mixing angles** : $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
- 2 **mass splittings** : $\boldsymbol{\Delta m^2_{ij}}$
- 1 (complex) phase : The **CP phase δ**

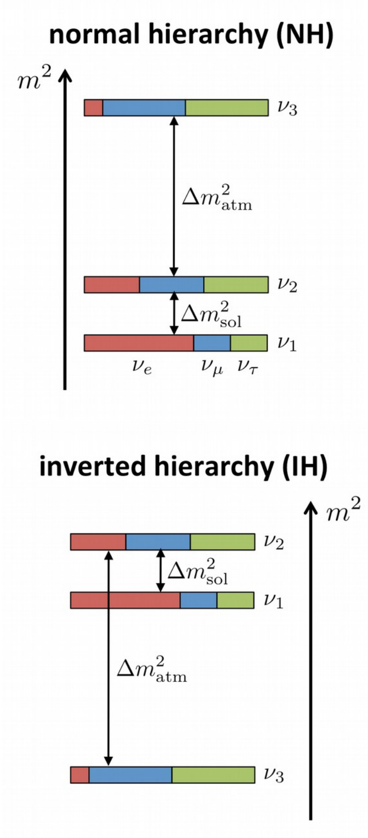
Amplitude

Periodicity

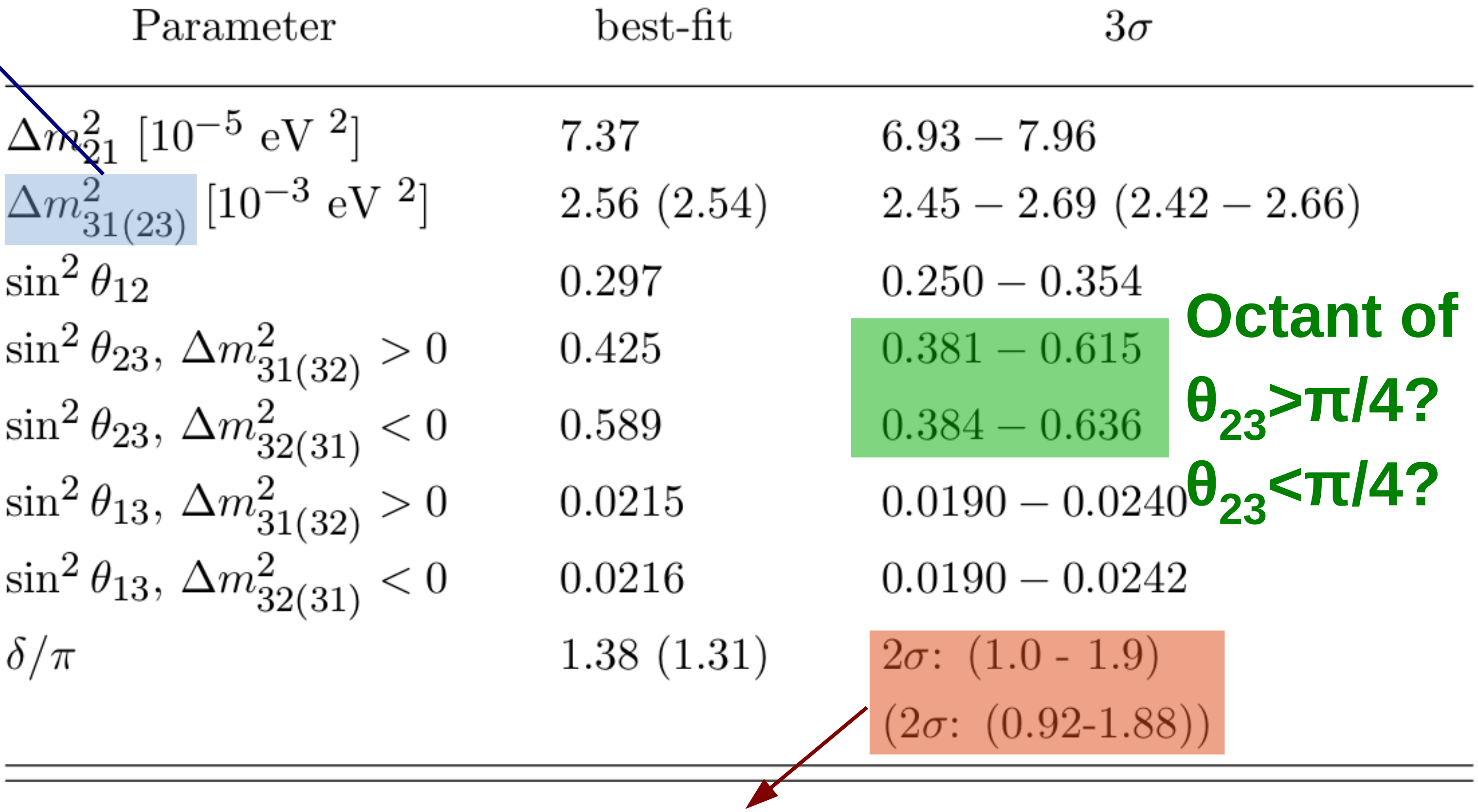
Difference in oscillations $\nu/\bar{\nu}$ (matter / anti-matter)

Neutrino oscillation
Open questions

Mass hierarchy: $m_3 > m_2, m_1$?



PDG 2017 summary table



Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Octant of θ_{23}:

$\theta_{23} > \pi/4$?

$\theta_{23} < \pi/4$?

Violation of CP symmetry in neutrino oscillations?

Long-baseline experiments
First measurements

In first approximation LBL experiments can measure some of the PMNS parameters through exclusive channels:

Far detector ν_μ events

$\nu_\mu \rightarrow \nu_X$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})} \sin^2\left(1.27 \frac{\boxed{\Delta m^2} \times L}{E}\right)$$

Precise measurement of θ_{23} and $|\Delta m^2|$

Far detector ν_e events

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \boxed{\sin^2(2\theta_{13})} \sin^2\left(1.27 \frac{\Delta m^2 \times L}{E}\right)$$

- Observation of ν_e appearance
- Measurement of θ_{13}

And similar measurements for anti-neutrinos

How can we measure δ ?

Look for violation of CP symmetry by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Full probability in vacuum:

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
& - 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\boxed{\sin\delta}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}
\end{aligned}
$$

$\sin^2\Delta_{ij} = \sin^2(1.27\,\Delta m_{ij}^2 \times L/E)$

$\nu \rightarrow \bar{\nu}$

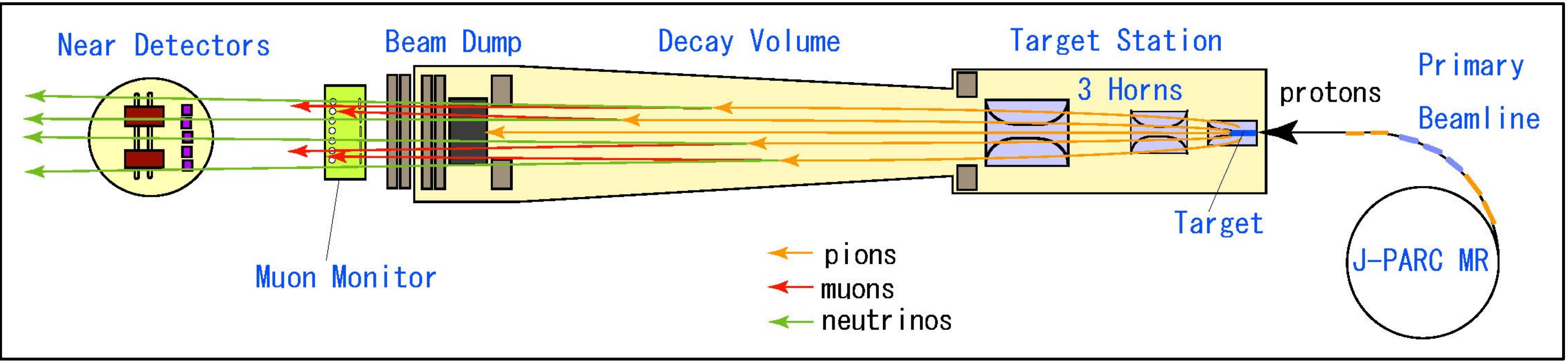
$\delta \rightarrow -\delta$

Change in expected appearance probability (at first maximum) wrt δ=0 or π (~27% effect in T2K)

Oscillation	δ > 0	δ < 0
$\nu_\mu \rightarrow \nu_e$	Suppressed	Enhanced
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Enhanced	Suppressed

The T2K experiment
Neutrino production

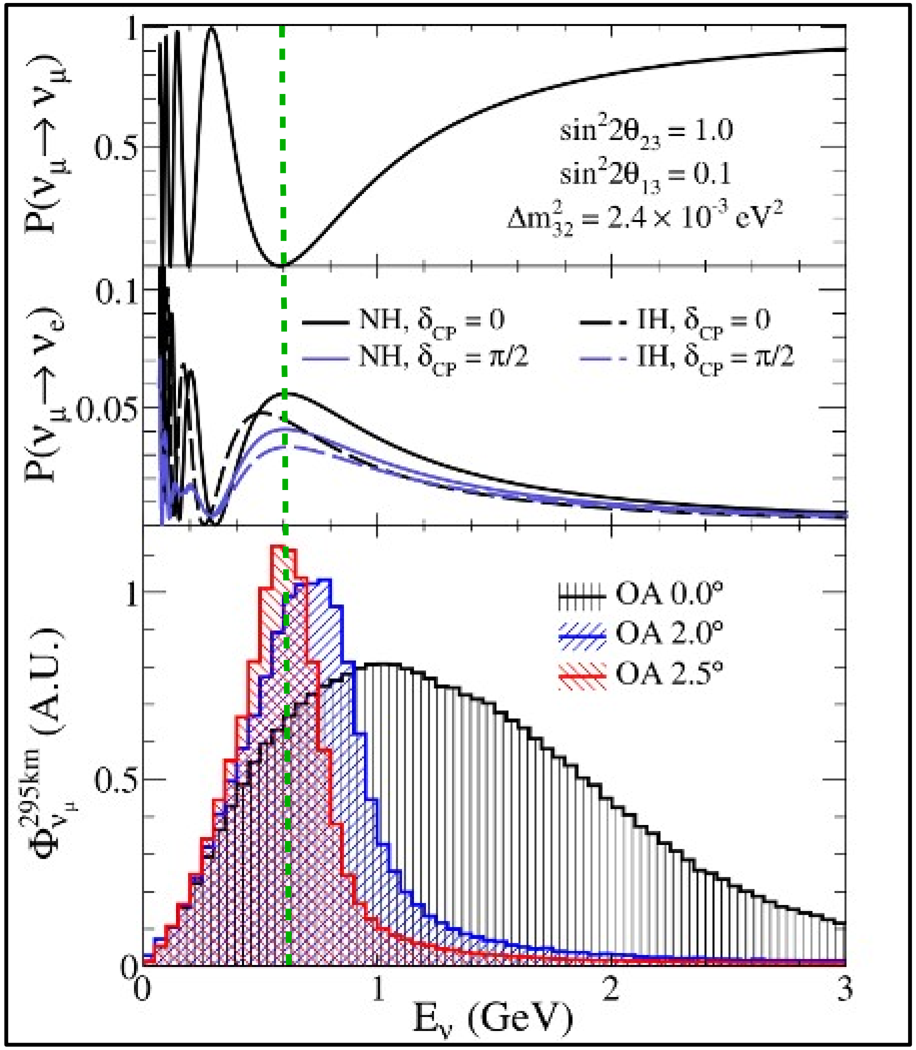
Conventional neutrino beam produced from 30 GeV protons

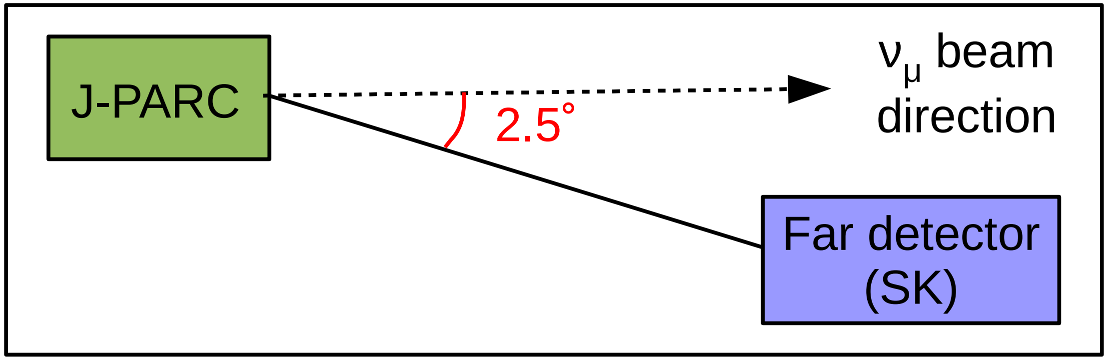


Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam, with an intrinsic $\nu_e/\bar{\nu}_e$ component (<1% at peak)

Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities

The T2K experiment
Off-axis beam





J-PARC

ν_μ beam direction

2.5°

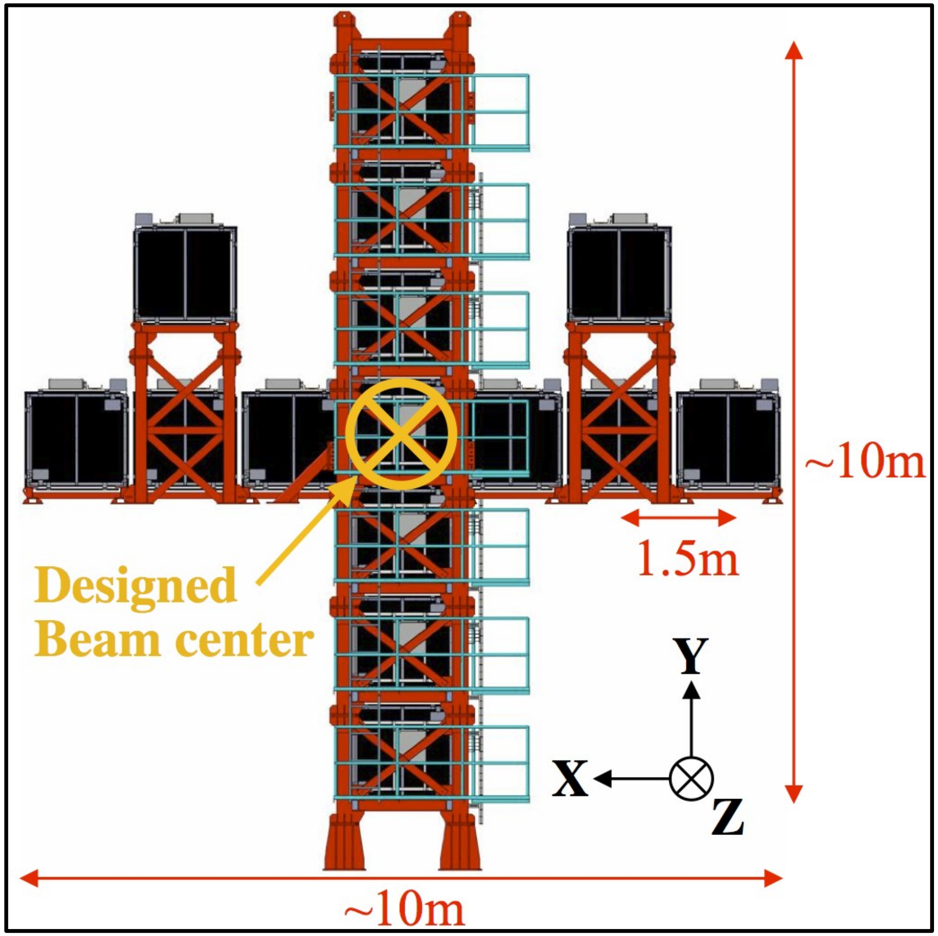
Far detector (SK)

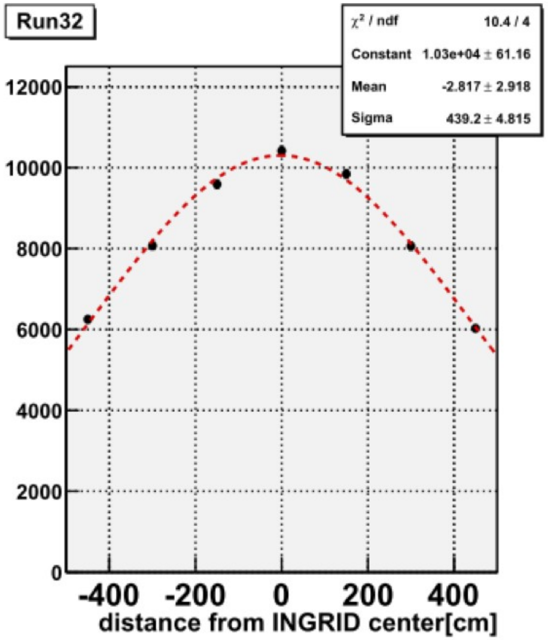
- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

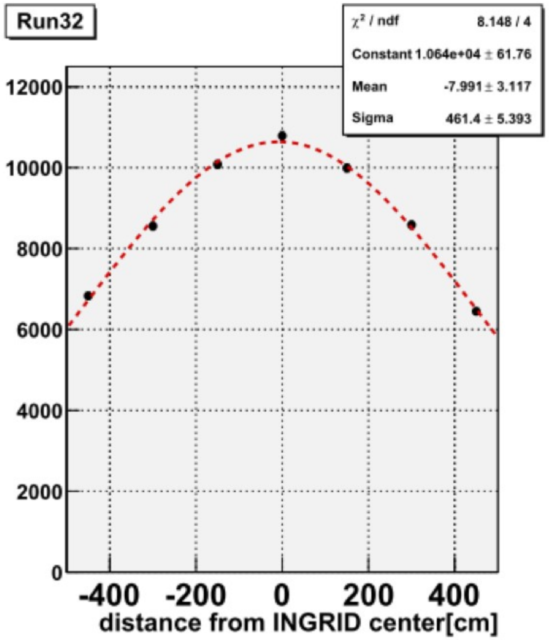
The T2K experiment
Near detectors

On-axis detector INGRID (Interactive Neutrino GRID)
Located 280m from the target

- 16 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability

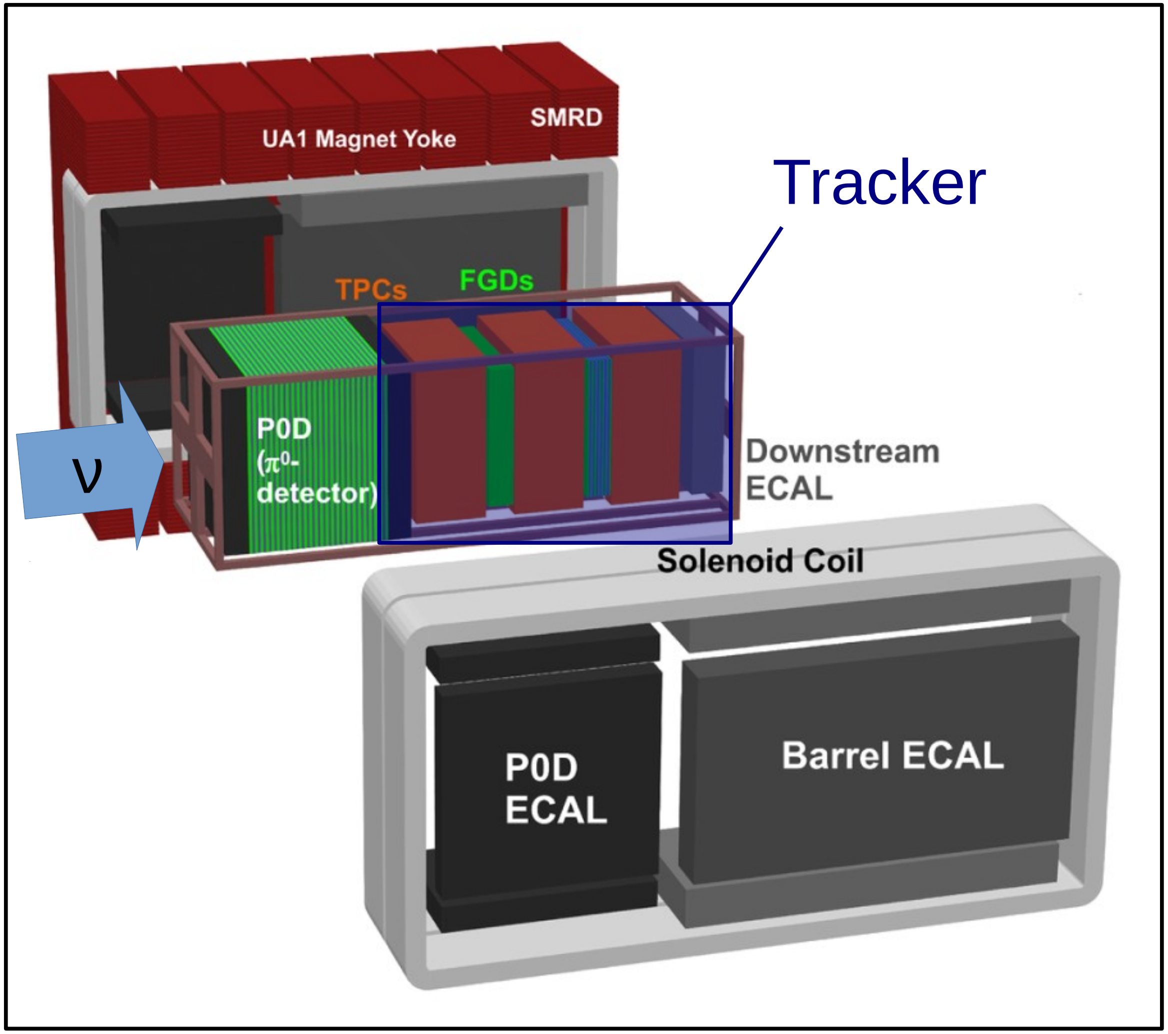




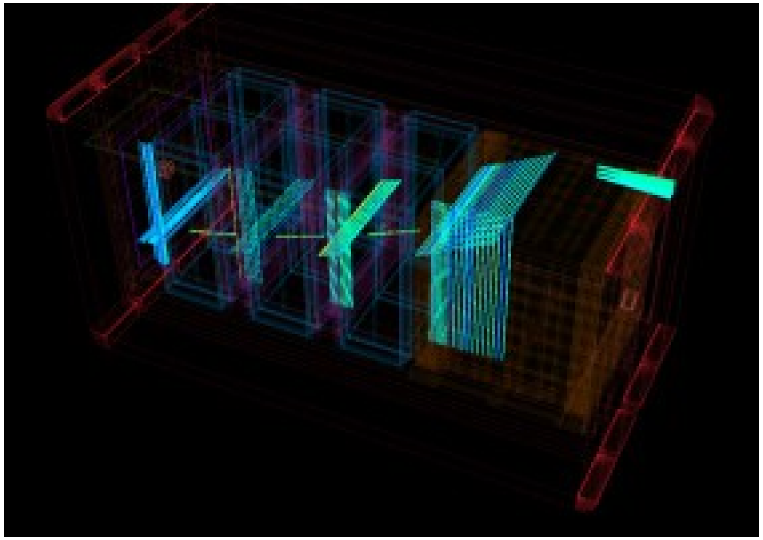


The T2K experiment
Off-axis near detectors

Off-axis near detector ND280
Located 280m from the target



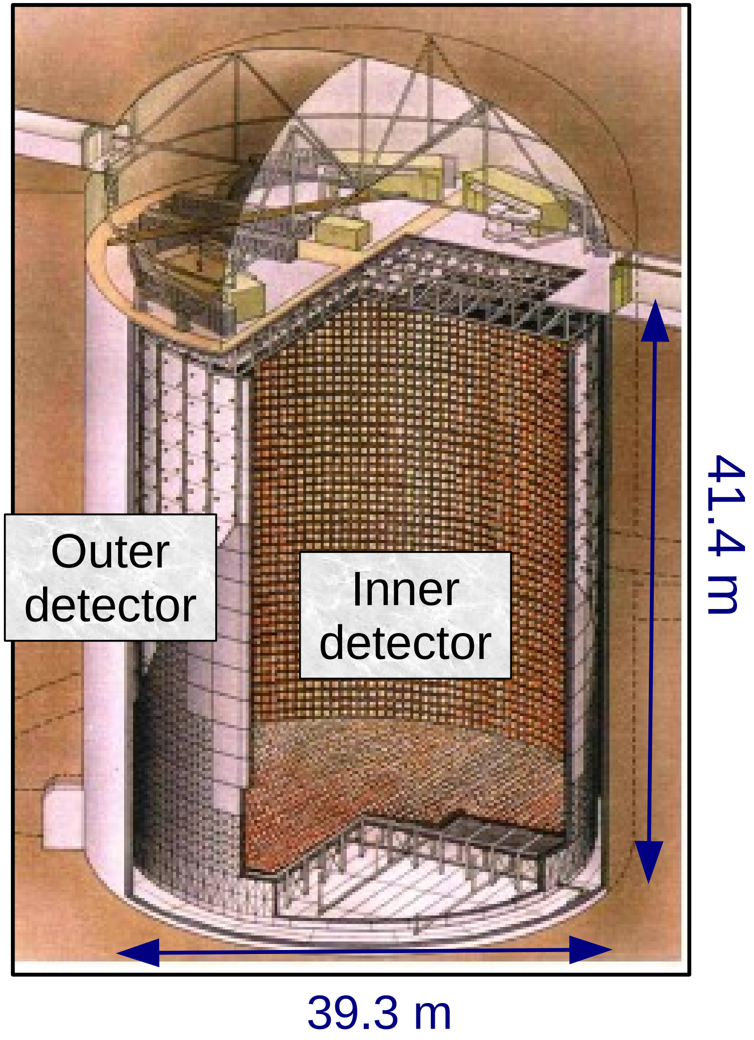
- Several detectors inside a 0.2 T magnetic field
- Good tracking capabilities
- 'Tracker' used to constrain flux and interaction uncertainties for oscillation analysis
- Rich cross-section measurement program



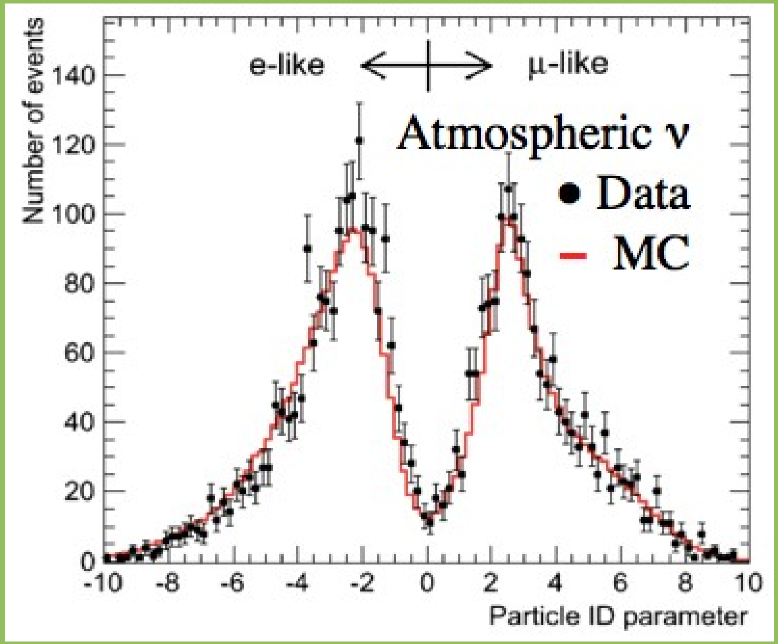
The T2K experiment
Far detector: Super-Kamiokande

Located 295 km from the target
Synchronized with beamline via GPS

- 50 kt water Cherenkov detector
- Operational since 1996



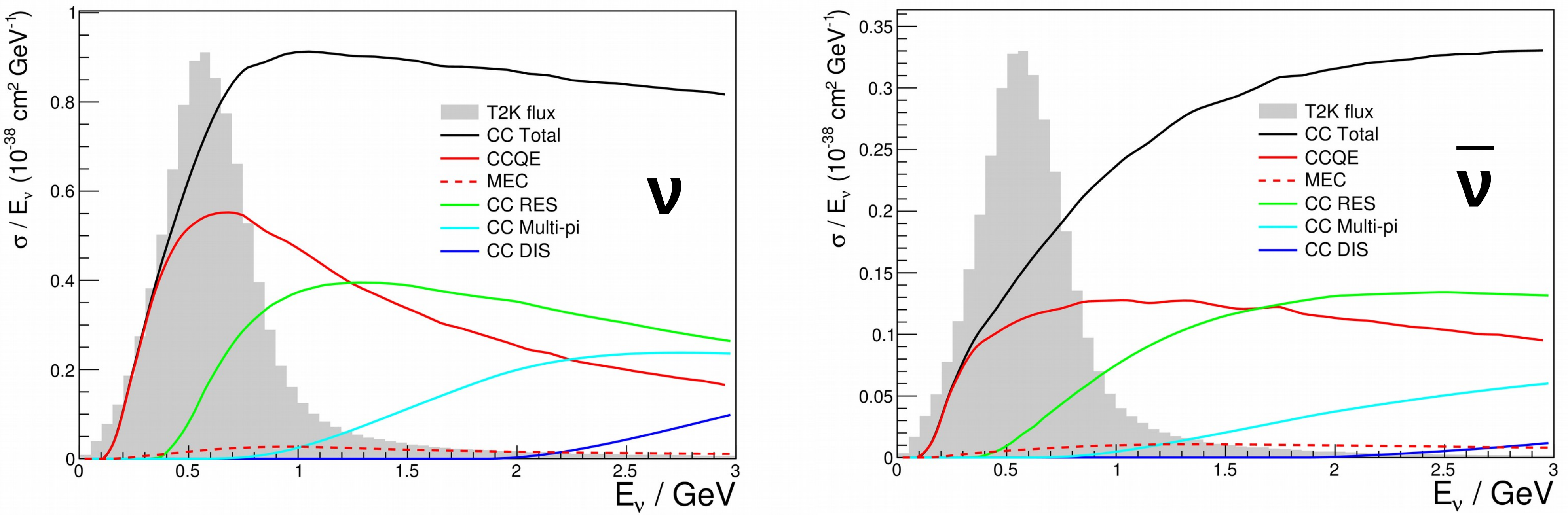
Good separation between $\mu^{\pm}$ and $e^{\pm}$ (separate ν_{μ} and ν_{e} CC interactions)



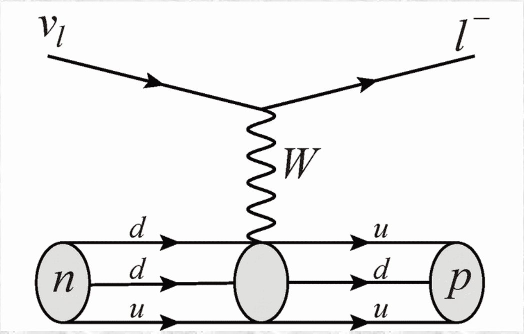
No magnetic field: cannot **separate ν and $\bar{\nu}$ on an event by event basis**

Neutrino interactions

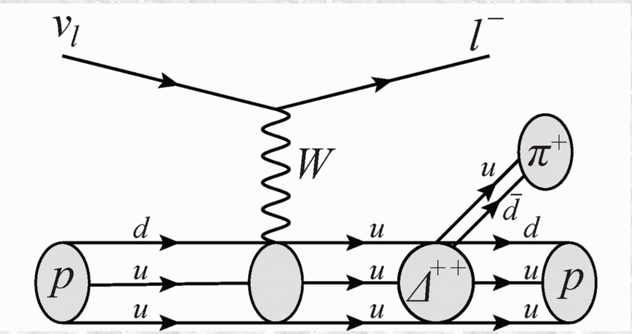
- Need to detect neutrino flavor => charged-current interactions
- At T2K energies, dominant interaction mode is charged-current quasi-elastic



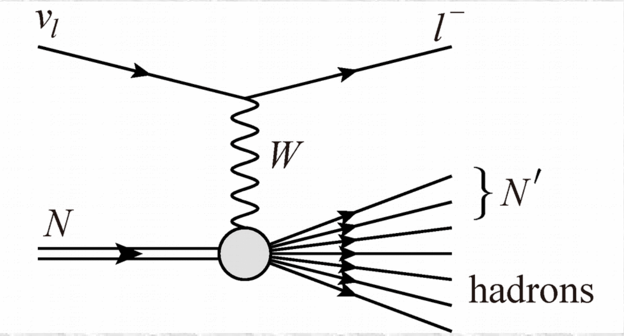
CCQE



CC RES



CC DIS/Multi-pi

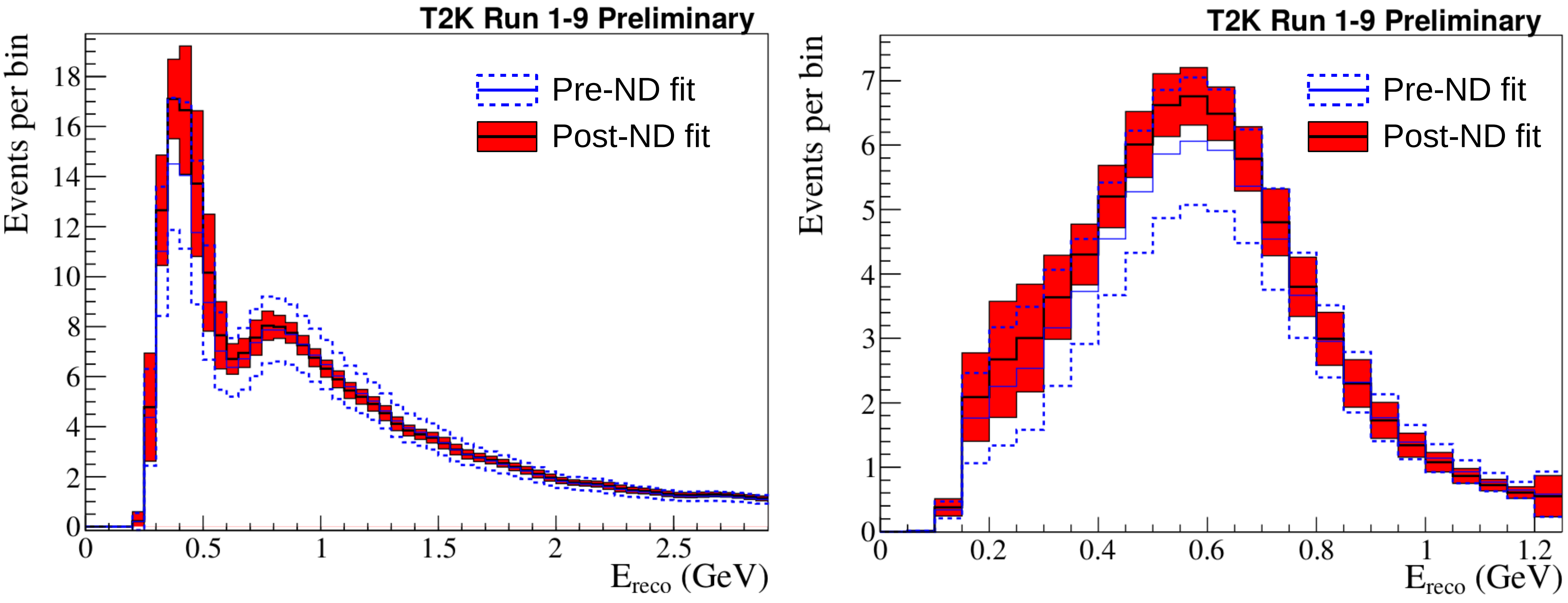


Near detector fits
Reduction of uncertainties

Near detector fit shifts the nominal predictions at the far detector, and reduces the flux and cross-section uncertainties

1 ring μ-like (ν-mode)

1 ring e-like (ν-mode)



$\Delta N_{SK}/N_{SK}$: 14.7% → 5.1%

$\Delta N_{SK}/N_{SK}$: 16.8% → 8.8%