T2K 2020 Oscillation Analysis

Results and Methodology

- Goals of T2K
- The T2K experiment
- Analysis Procedures
- Robustness Studies
- Future Analyses

Joe Walsh

On behalf of the T2K Collaboration

XIX International Workshop on
Neutrino Telescopes

Goals of the T2K Experiment

The Tokai to Kamioka experiment is a long baseline neutrino experiment looking for ν_μ disappearance and ν_e appearance in a ν_μ beam

T2K has three main aims:

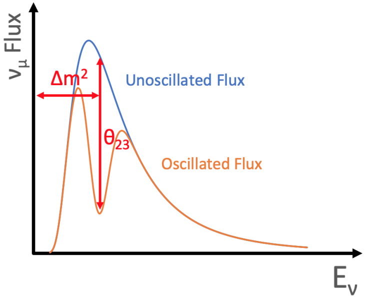
- Measure $\theta_{13}, \theta_{23}, \Delta m^2_{32}$
- Identify the Neutrino Mass ordering
- Constrain δ_{CP}

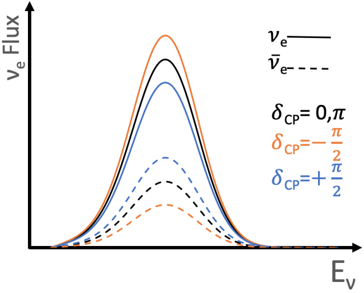
Assuming 3 flavour PMNS mixing in a pure ν_μ beam with fixed baseline L

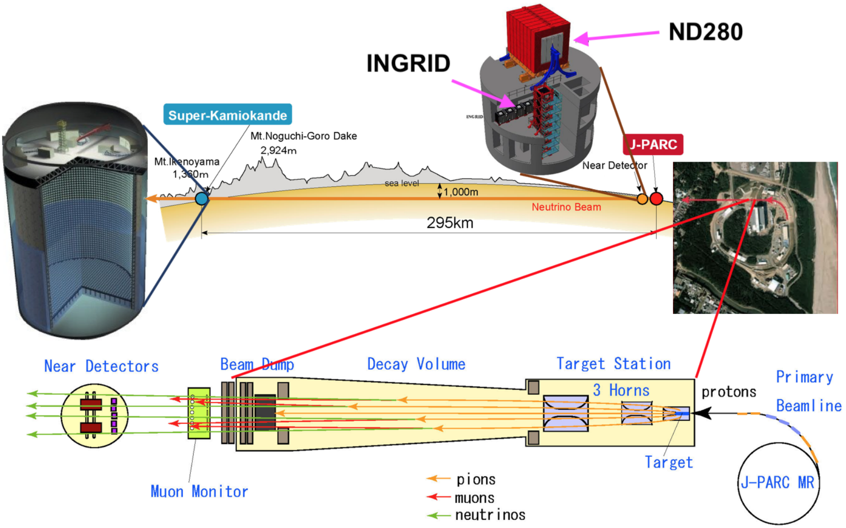
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4(\theta_{13})\sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

$$\mp 1.27\Delta m^2_{32}\frac{L}{E_\nu}8J_{CP}\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$



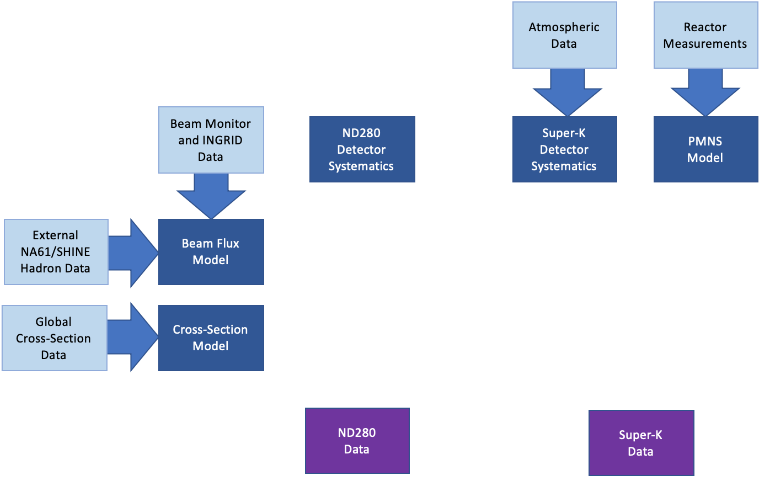




See Mathieu Guigue's talk for more details

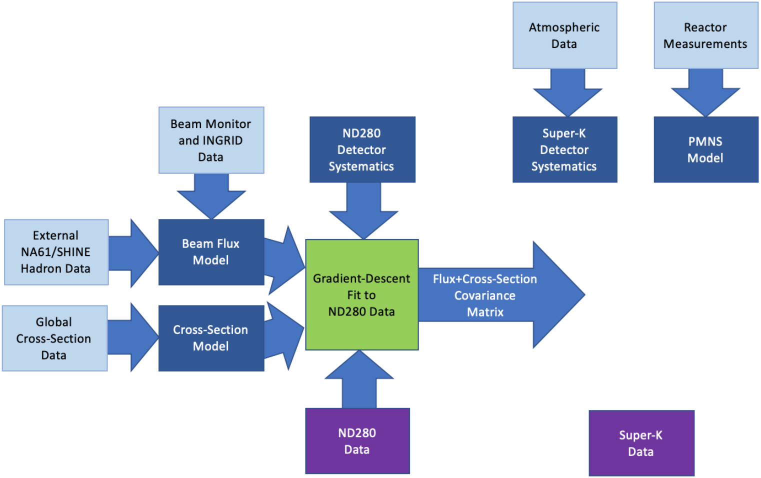
Analysis Procedure

Sequential Fit



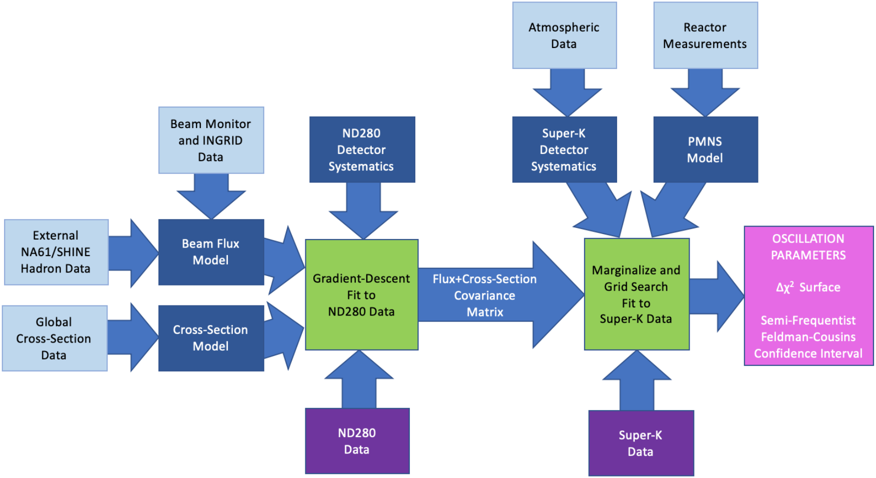
Analysis Procedure

Sequential Fit



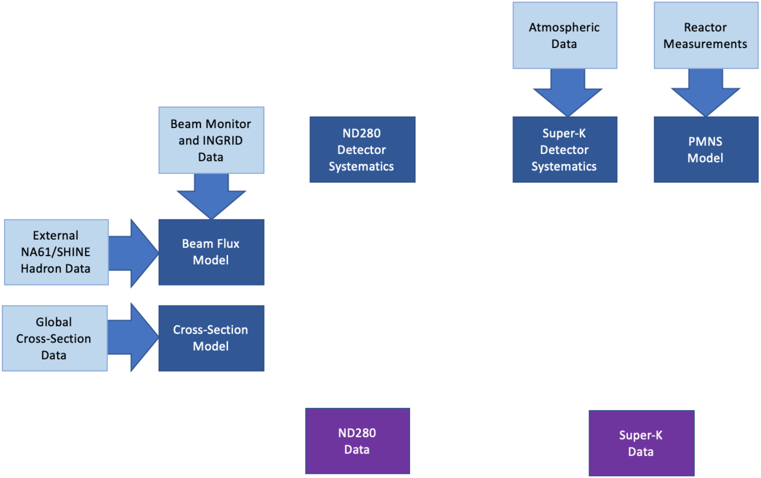
Analysis Procedure

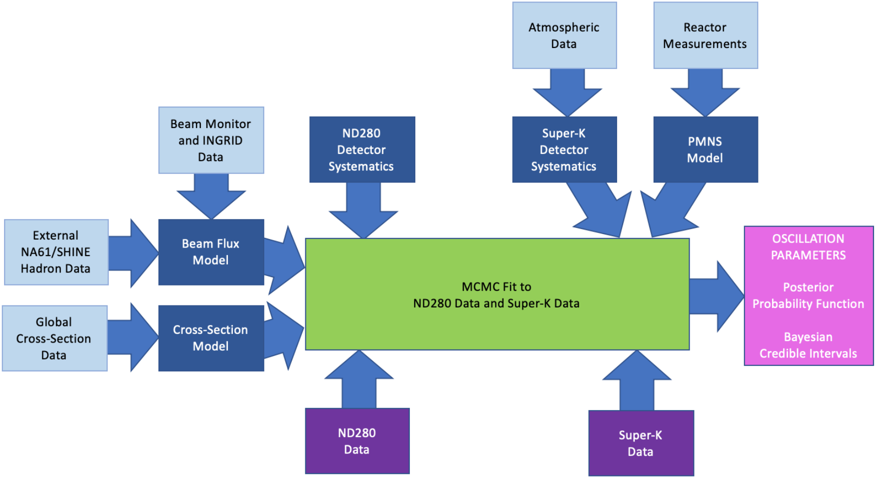
Sequential Fit



Analysis Procedure

Simultaneous Fit





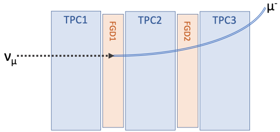
Atmospheric Data
Reactor Measurements
Beam Monitor and INGRID Data
ND280 Detector Systematics
Super-K Detector Systematics
PMNS Model
External NA61/SHINE Hadron Data
Beam Flux Model
MCMC Fit to ND280 Data and Super-K Data
OSCILLATION PARAMETERS
Posterior Probability Function
Bayesian Credible Intervals
Global Cross-Section Data
Cross-Section Model
ND280 Data
Super-K Data

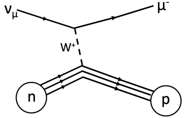
ND280 Data Samples

Samples split by $\nu/\bar{\nu}$ beam mode, target subdetector FGD1/FGD2 (hydrocarbon/hydrocarbon+water), and reconstructed pion topology.

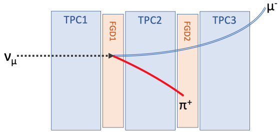
Dedicated ν_μ background in $\bar{\nu}$-beam samples

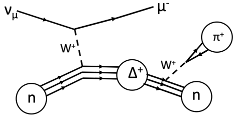
CC0π:
No pions in final state
Mostly CCQE



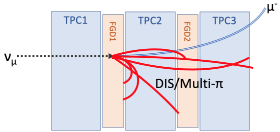


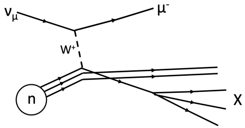
CC1π:
One pion in final state
Mostly CC-Res





CC-Other:
Any other number of mesons in final state
Multi-π/DIS



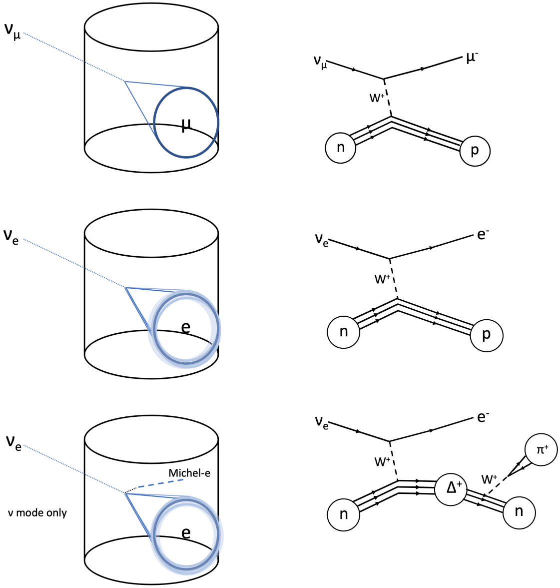


Super-K Data Samples

1Rμ:
ν or $\bar{\nu}$ mode samples
Single μ-like ring
CCQE like

1Re:
ν or $\bar{\nu}$ mode samples
Single e-like ring
CCQE like

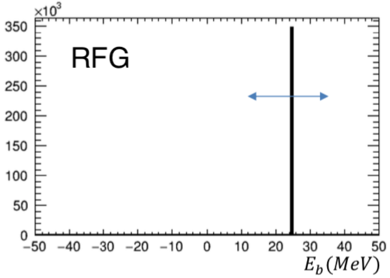
1Re1d.e.:
ν mode sample only
Second e-like ring
Trying to tag π decay
$\pi \to \mu \to e$

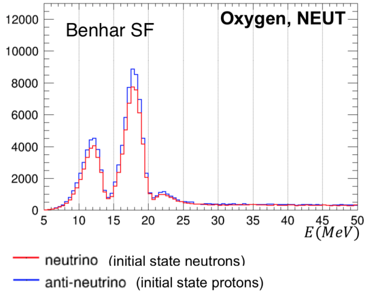


Nucleon Removal Energy

CCQE nuclear base model no longer Relativistic Fermi Gas model but Benhar Spectral Function informed by external electron scattering data.

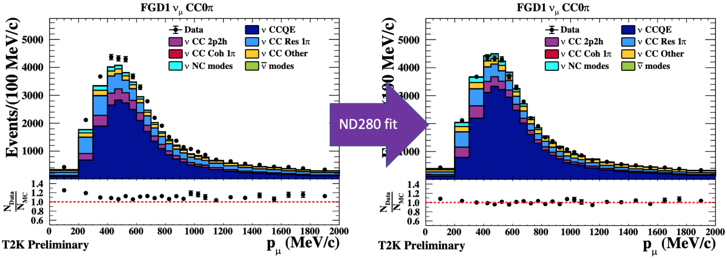
More sophisticated treatment of nuclear binding energy in the fit, implemented as a kinematic shift not an event weight.





Shift impacts lepton kinematics and E_ν^{rec} which we fit in

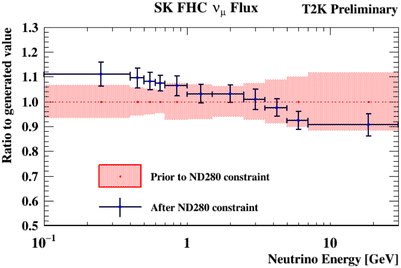
Fit enhances CCQE component of sample. Prefering high Q^2 and low E_ν.



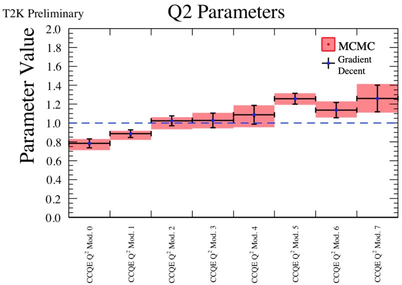
Significant reduction in parameter uncertainties.

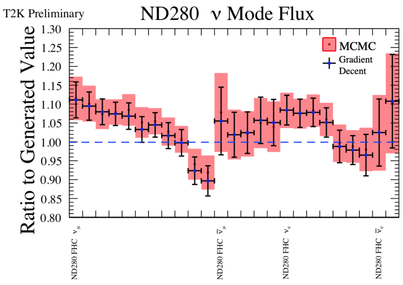
Calculate a p-value of $p = 0.74$

ND280 Data is very consistent with our model



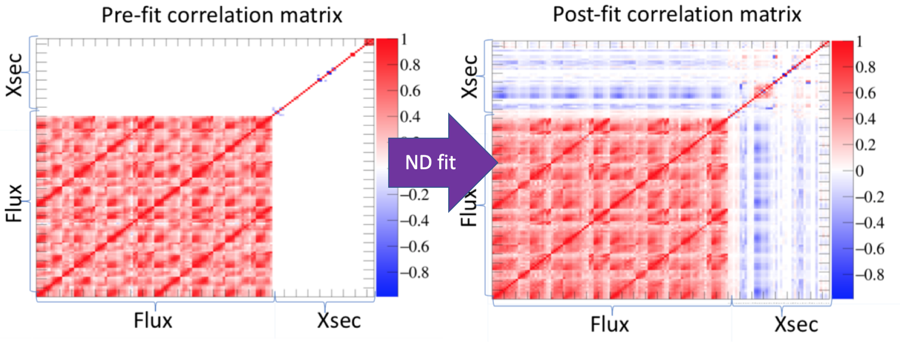
We can do comparisons of sequential and simultaneous fit methods at ND280. Very consistent results despite fundamentally different approaches.





Near Detector Correlations

Strong anticorrelations introduced between Flux and XSec parameters.

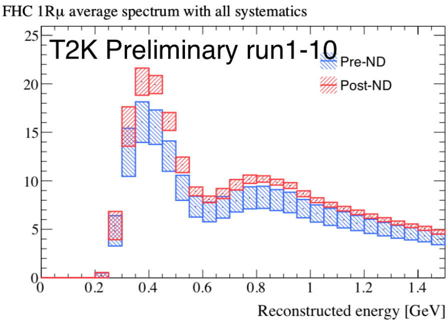


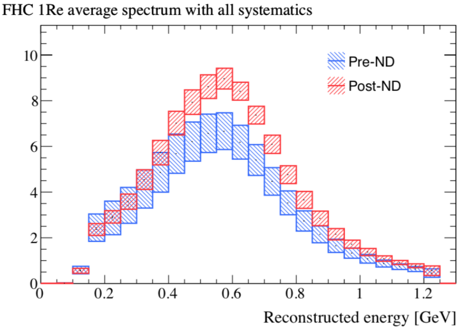
T2K Run 1-10 Preliminary

T2K Run 1-10 Preliminary

This is where the power of the ND280 fit factors into our analysis!

ND280 Fit Predictions at Super-K





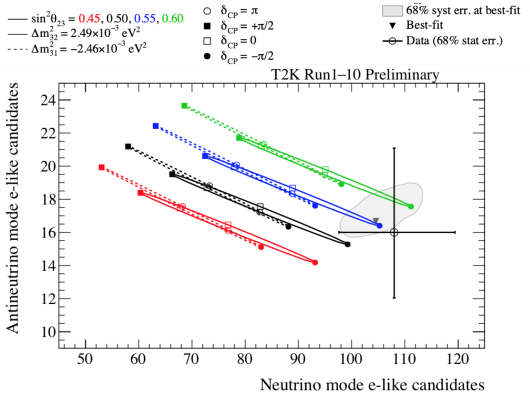
Includes Super-K detector systematic uncertainty

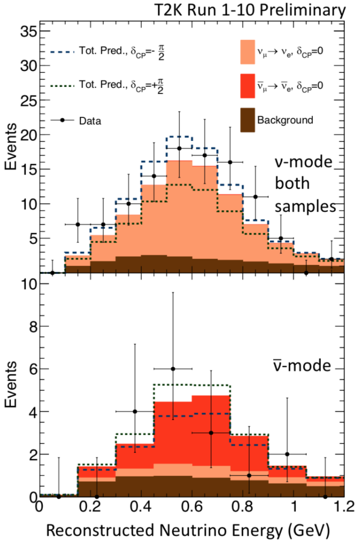
Super-K Sample	pre-ND fit error	post-ND fit error
ν_μ 1Rμ	11.1%	3.0%
$\bar{\nu}_\mu$ 1Rμ	11.3%	4.0%
ν_e 1Re	13.0%	4.7 %
$\bar{\nu}_e$ 1Re	12.1%	5.9%
ν_e 1Re1d.e.	18.7%	14.3%

Super-K Data and PMNS Predictions

We see an **excess of electron neutrinos** when compared to CP conserving case.

Suggests preference for $\delta_{CP} = -\frac{\pi}{2}$ and **Normal Ordered** masses





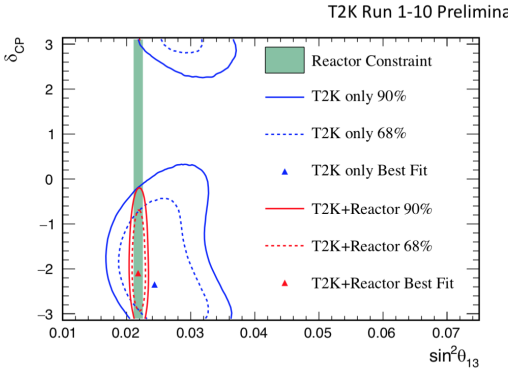
T2K vs T2K+Reactor

δ_{CP} and $sin^2\theta_{13}$

T2K produces results with T2K-only data and with the global reactor constraint on θ_{13}.

T2K-only result is consistent with reactor constraint to 1σ.

Results from here onward are **with reactor constraint applied**

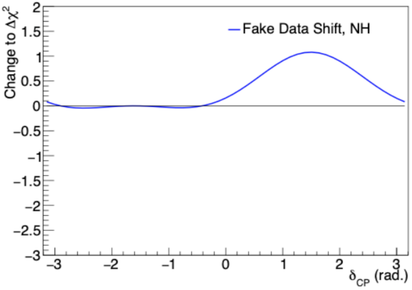


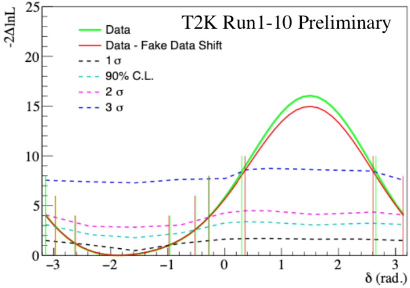
PDG 2019 reactor constraint:
https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf

We test our model uncertainty by fitting alternative models.

For δ_{CP} we assess the impact on $\Delta\chi^2$ and subtract it.

See how this change affects contours/intervals





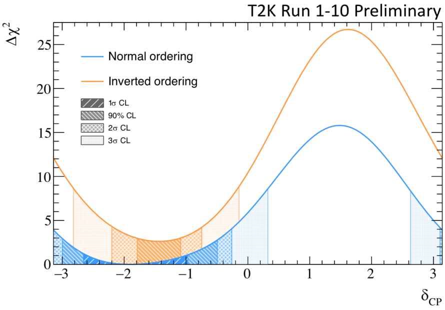
δ_{CP} Constraints

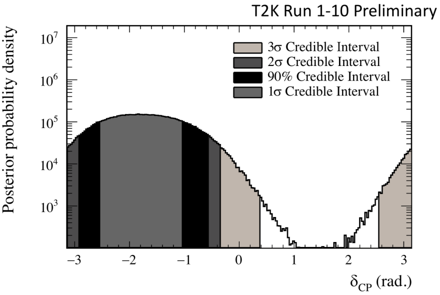
Frequentist $\Delta\chi^2$

Feldman-Cousins corrected

Bayesian posterior probability density

Marginalized over mass hierarchies.





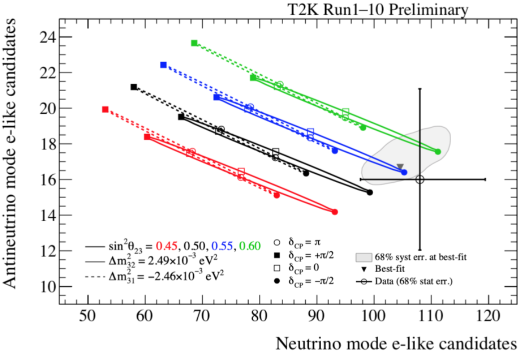
CP conserving values $(0,\pi)$ excluded at 90% but π not quite at 2σ

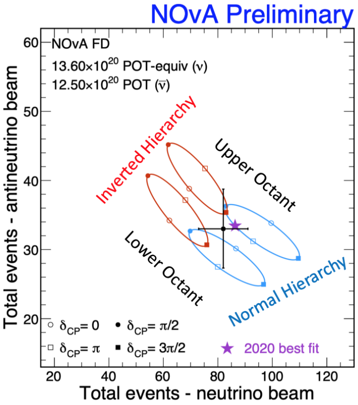
35% of all values excluded at 3σ when marginalised over both hierarchies

Alternative model robustness studies show largest $\Delta\chi^2$ change would cause left (right) edge of 90% interval to move by 0.073 (0.080)

Agreements signed with NOvA and Super-K collaborations and work on joint fits have begun.

Very different sensitivities, may break apart degeneracies.





NOvA results presented by by Alex Himmel at Neutrino 2020

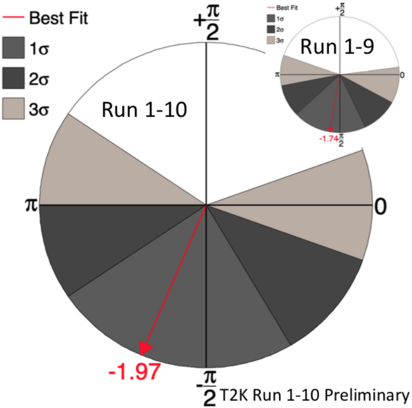
ND280 data is very compatible with our model. $p = 0.74$

Significant reduction in Super-K prediction uncertainty from ND280 fit

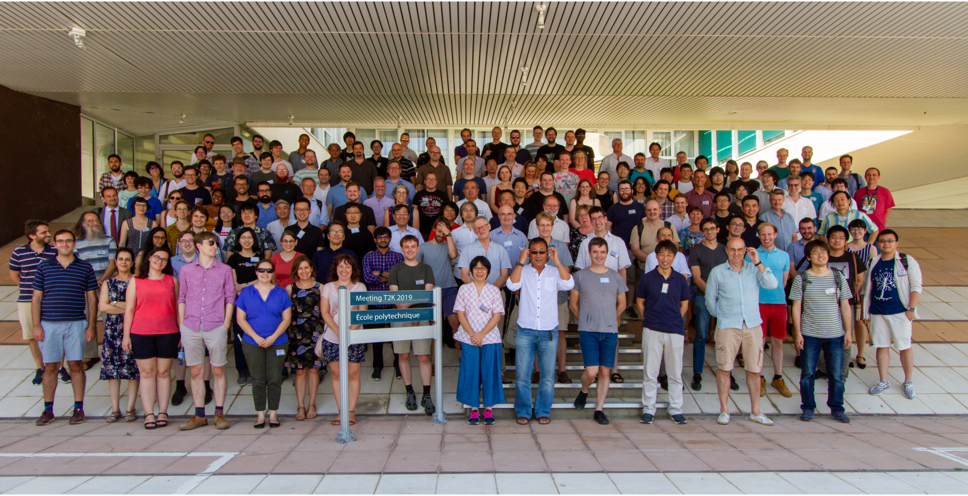
Very different fitting approaches, but very consistent results.

We exclude CP conservation at 90% and a large range of values around $+\frac{\pi}{2}$ at 3σ

Consistent with previous result



Thank You



Please see other T2K talks

Plenary Talk:
"The T2K Experiment: Status, Results and Prospects"
Mathieu Guigue Monday 2:00pm

Parallel Talks:
-"Probing nuclear effects in neutrino CC1 interactions with transverse kinematic imbalance measurement in T2K" **Ka Ming Tsui** Fri 19 10:20am
-"Towards the cross-section measurement of the CC single -production in the T2K near detector" **Grzegorz Żarnecki** Fri 19 11:35am
-"Characterizing 2p2h interactions using low momentum protons" **Joanna Zalipska Fri** 19 11:45am
-"Future neutrino physics using the upgraded ND280 detector of the T2K experiment" **César Jesús-Valls** Wed 24 11:00am
-"Using proton information to constrain T2K fit"**Kamil Skwarczyński** Wed 24 12:20pm
-"T2K latest results on muon neutrino and antineutrino disappearance" **Siva Prasad Kasetti** Wed 24 6:10pm **After this talk!!**
-"Ageing of the scintillator detectors of the T2K off-axis and on-axis near detectors, ND280 and INGRID" **Maria Antonova** Thu 25 12:10pm

BACKUP

Details of T2K analyses

	Analysis 1	Analysis 2	Analysis 3
Kinematic variables for 1Re sample at SK	Erec-θ	p_e-θ	Erec-θ
Likelihood	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio
Likelihood Optimization	Markov Chain Monte Carlo	Gradient descent and grid scan	Gradient descent and grid scan
Contours/limits produced	Bayesian Credible Intervals	Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)	Frequentist Confidence Intervals with Feldman-Cousins
Mass Hierarchy Analysis	Bayes factor from fraction of MCMC points in each	Bayes factor from likelihood integration	Frequentist p-value from generated PDF
Near Detector Information	Simultaneous joint fit	Constraint Matrix	Constraint Matrix
Systematics Handling	Simultaneous fit then marginalization	Marginalization during fit	Marginalization during fit

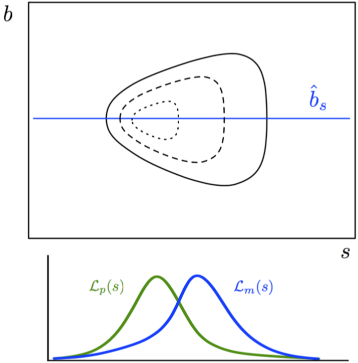
Nuisance parameters

High demensional fit can be difficult to compute best fit point.
Usually only interested in a small number (1 or 2).

Two possible approaches:

- Profile: Picks values of nuisance parameters which maximise parameter of interest
- Marginalize: Integrate over nuisance parameters

T2K uses marginalization to better handle non-Gaussian parameters

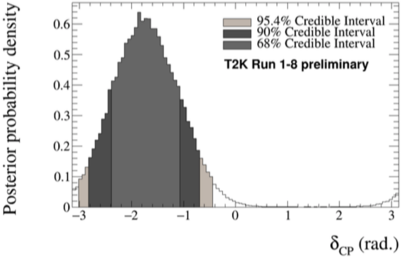


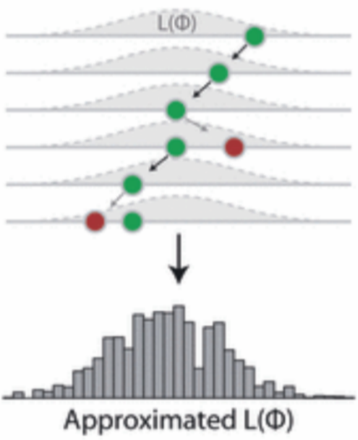
MCMC Method

Sample likelihood space with Markov Chain Monte Carlo

Stepping through parameter space according to marginalised posterior probability

Large enough number of steps gives posterior probability density



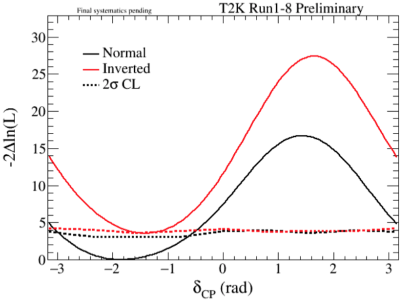


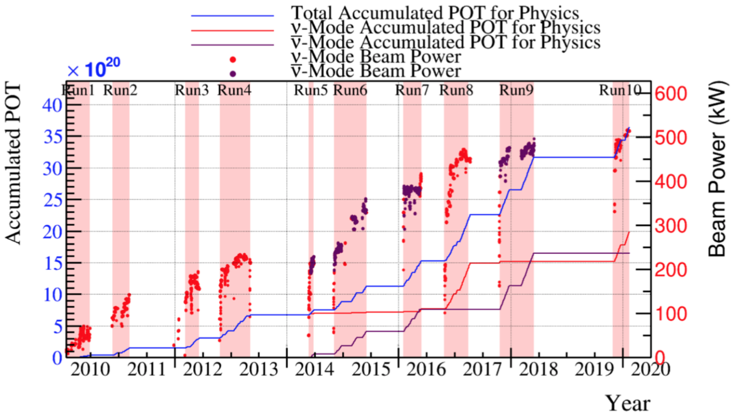
Throw toys of nuisance parameters according to covariance

Marginalize nuisance parameters to produce 1D or 2D $\Delta\chi^2$ surface

Grid search in this $\Delta\chi^2$ for best fit point

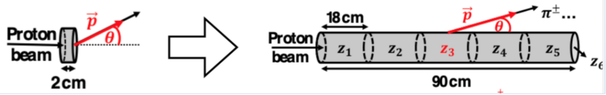
Use toys to calculate $\Delta\chi^2_{crit}$ and construct Felman Cousins intervals

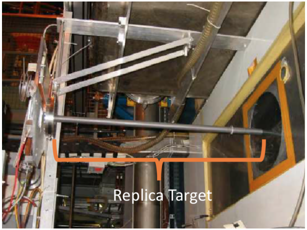


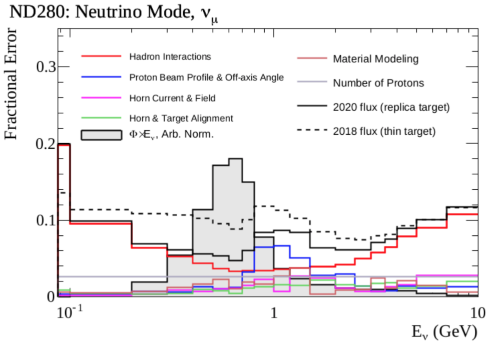


*POT = Protons On Target

33% increase in ν-mode POT at Super-K and double the POT at ND280
ν-mode POT of 1.97×10^{21} and $\bar{\nu}$-mode POT of 1.63×10^{21}.







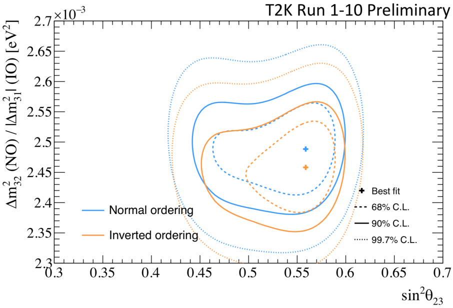
In order to constrain beam flux model we use external hadron production data from NA61/SHINE

Previously thin target data
Now T2K replica target data

Reduces error in flux peak from 8% to 5%.

Vladisavljevic T. (2020) `https://arxiv.org/abs/1207.2114`

Atmospheric parameters

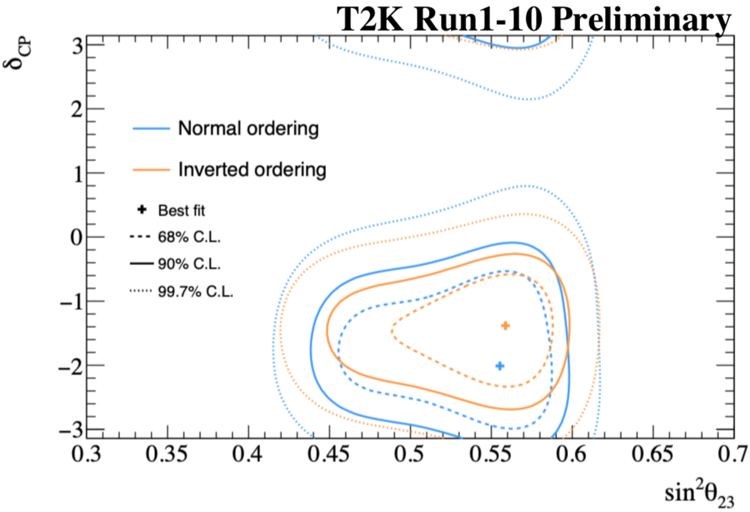


Preference for upper octant of θ_{23} and normal ordered neutrino masses.

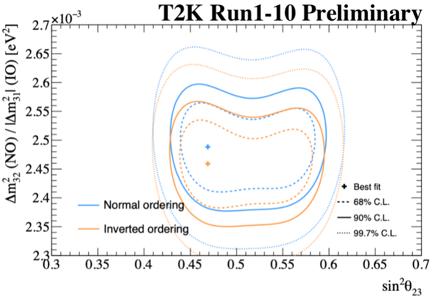
Slight preference for non-maximal $\sin^2\theta_{23}$

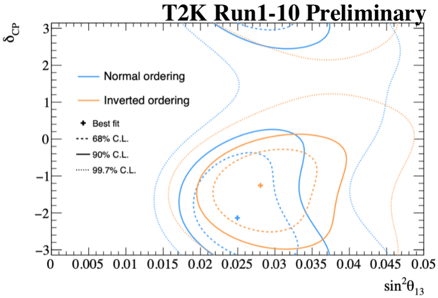
Posterior Probabilities

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	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

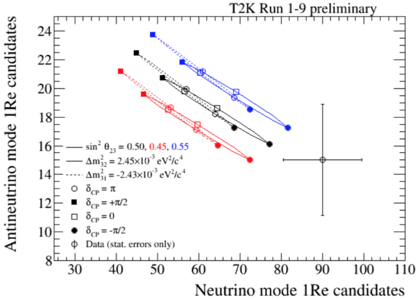

T2K Run1-10 Preliminary
δ_{CP}
Normal ordering
Inverted ordering
Best fit
68% C.L.
90% C.L.
99.7% C.L.
3
2
1
0
−1
−2
−3
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
$\sin^2\theta_{23}$

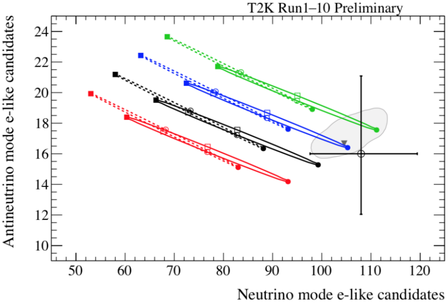
Contours without reactor constraint





Previous result was far more non-PMNS like due to excess of neutrinos. This excess has reduced with addition of statistics.





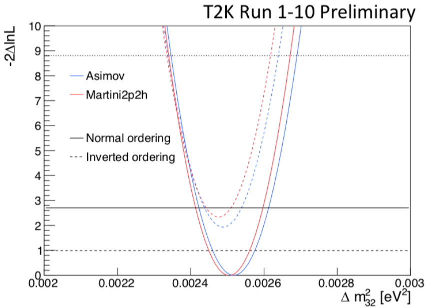
Robustness Studies

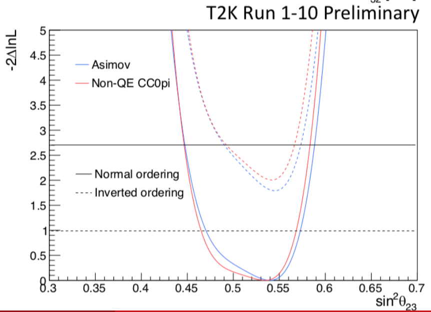
We assess the robustness of our model by fitting it to alternative models, seeing the impacts on our uncertainty contours and parameters.

No significant biases seen in θ_{13}, θ_{23} or δ_{CP}

Small bias seen in Δm^2_{32}.
We account for this with an additional uncertainty of 1.4×10^{-5}

Significant reduction in previous Δm^2_{32} bias due to more physical parametrisation of nuclear removal energy



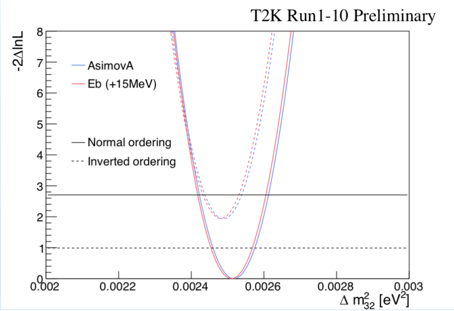


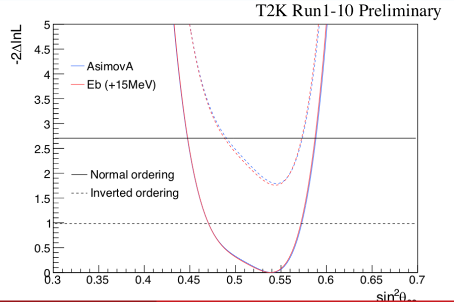
Nuclear removal energy was previously a dominant source of bias on Δm^2_{32} contours.

This was accounted for with large heuristic uncertainty.

Removal energy now applied as kinematic shift which moves events around fitted space

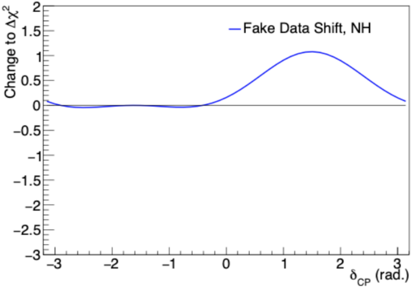
Much smaller bias seen in new result due to better nuclear model and removal energy uncertainty treatment.

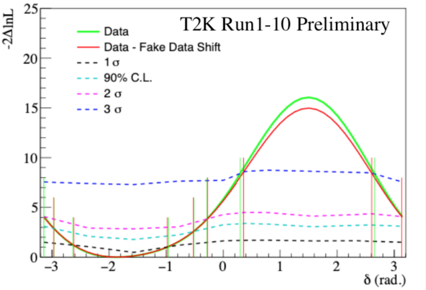




Test impact of alternate model on δ_{CP} result by subtracting change in $\Delta\chi^2$ seen in alternate model study from data $\Delta\chi^2$ distribution

We report the largest shift in either direction on both left and right edges of 90% interval





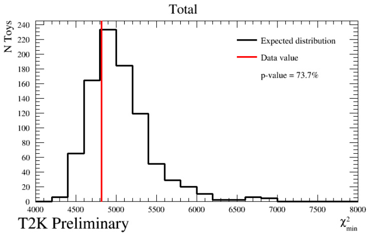
P-value

By calculating a p-value for our near detector best fit, we can test the ability of our model to cover the region of phase space which best describes our data.

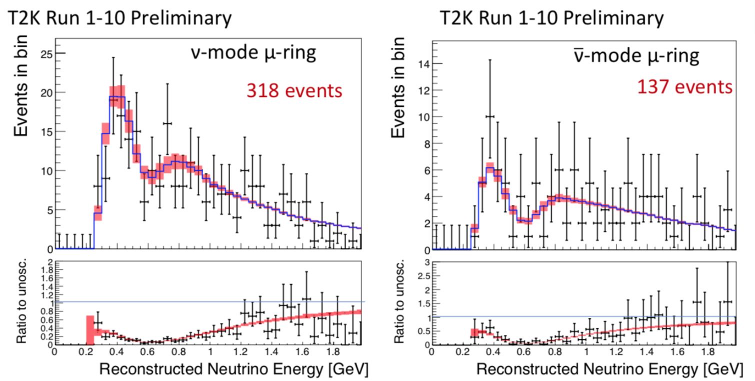
"Toy" data sets are thrown from prior covariance and the nominal model is fit to each toy.

The fraction of fits with a χ^2_{min} greater than that of the data, and therefor less likely than the data given our model, is the p-value.

From this we calculate $p = 74\%$ which is an improvement on previous value (2018) $p = 50\%$



Events with single muon like ring in ν and $\bar{\nu}$ beam modea. Systematic uncertainty (red band) on rate is 3.0 (4.0)% in ν -mode ($\bar{\nu}$-mode)



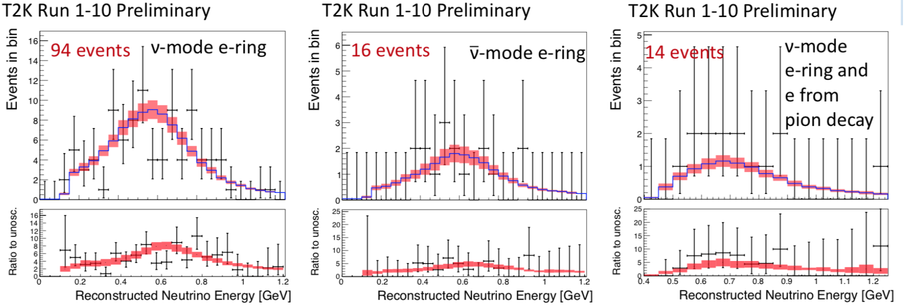
Position and size of dip can be seen in ratio to unoscillated case.

Super-Kamiokande samples

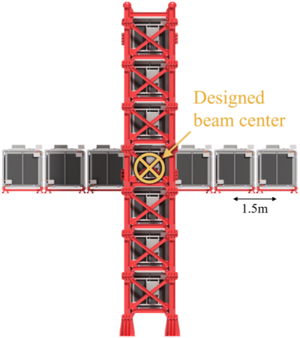
ν_e samples

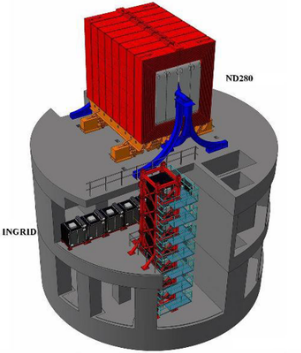
Two samples with single electron-like rings, for ν and $\bar{\nu}$ beam mode.

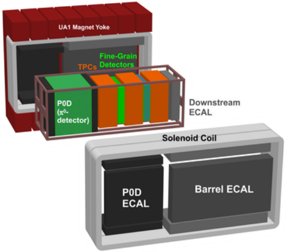
An additional sample with Michel electron from π decay to isolate CC1π events.



Two near detectors in this analysis.
280 m downstream from the target.





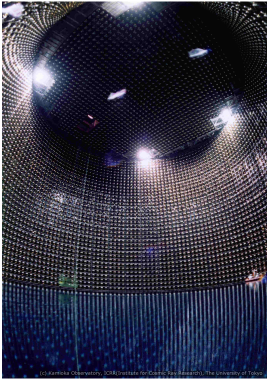


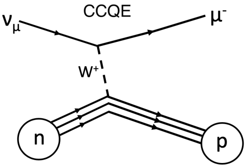
INGRID

ND280

On-axis
Iron-plastic scintillator
Measures direction
and intensity

Off-axis
Plastic Scintillator
And Water targets
Constrains models



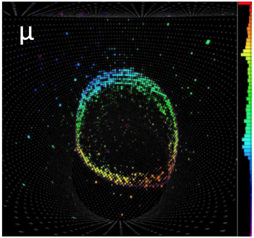


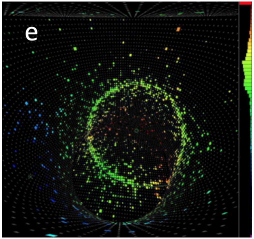
50,000 tonne water Cherenkov detector

11,000 20" inner PMTs, 2,000 8' outer PMT for cosmics/exiting particles

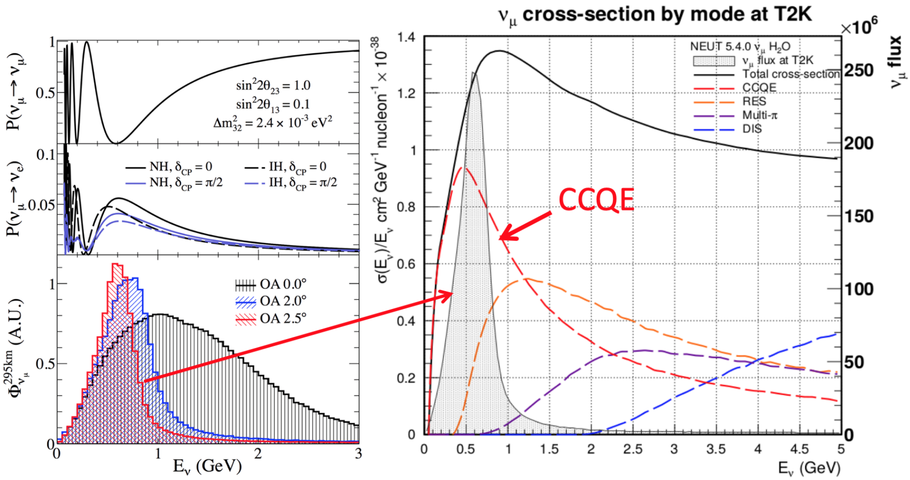
Muons have sharp well defined rings

Electrons scatter and make diffuse "fuzzy" rings

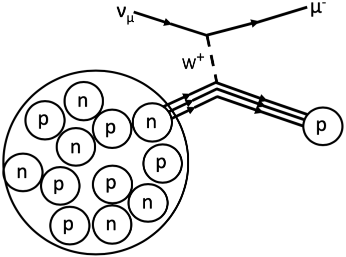




We can narrow and enhance our ν beam flux around our desired E_ν.
Super-K is at 2.5° off-axis - 600 MeV peak



Neutrino oscillations are E_ν dependent. We need an observable close to the true E_ν



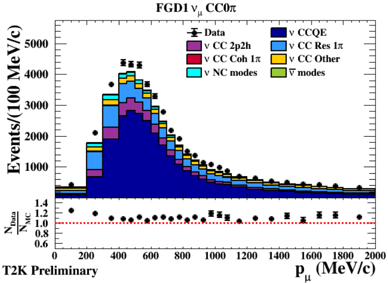
Reconstruct neutrino from final state charged lepton

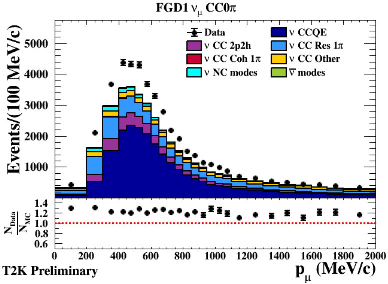
Assuming quasi-elastic scattering from single bound nucleon (CCQE)

$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_l - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

Impact of priors on prefit prediction

Effect of externally motivated priors on parameters giving Q^2 freedom to CCQE events on ND280 FGD1 CC0π sample





Bibliography

NA61/Shine Flux constraint
https://arxiv.org/abs/1207.2114
Relativistic Fermi Gas model
https://doi.org/10.1016/0370-1573(72)90010-5
(+Random phase approximation)
https://link.aps.org/doi/10.1103/PhysRevC.83.045501
Benhar SF
https://doi.org/10.1016/0375-9474(94)90920-2

Reactor Experiment Constraint
https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf
NOvA 2020 Result
https://indico.fnal.gov/event/43209/contributions/187840/attachments/130740/159597/NOvA-Oscilations-NEUTRINO2020.pdf