Supported by U.S. DOE: Award DE-SC0015903

Results from NOvA and T2K

Luke Pickering for the T2K Collaboration

FPCP 2020

2020-06-10

MICHIGAN STATE UNIVERSITY

Neutrino Oscillations

Big Picture Neutrino Oscillation Questions

What is the mass ordering of the neutrino mass states?

Is there significant CP violation in the neutrino sector?

What are the precise values of the remaining neutrino oscillation parameters?

Could neutrino sector CP violation explain the matter/anti-matter asymmetry?

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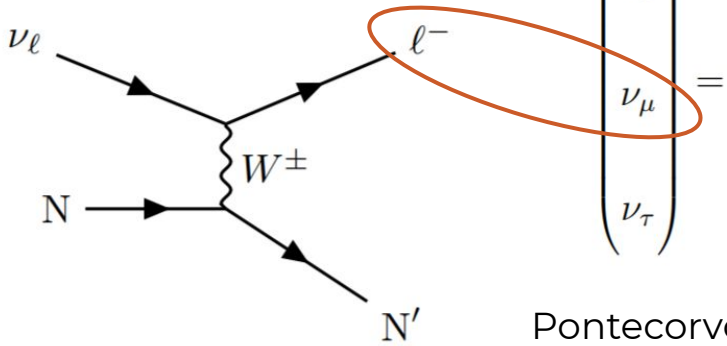
Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\mathbf{M}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

Neutrino Oscillation: PMNS

Journal of Physics G: Nuclear and Particle Physics. 43. 10.1088/0954-3899/43/8/084001

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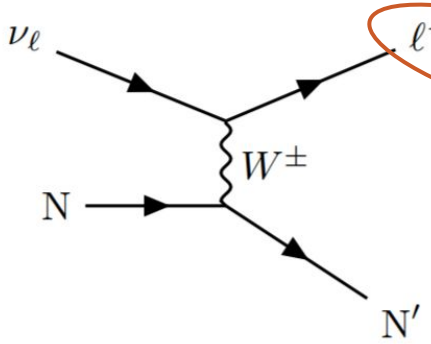

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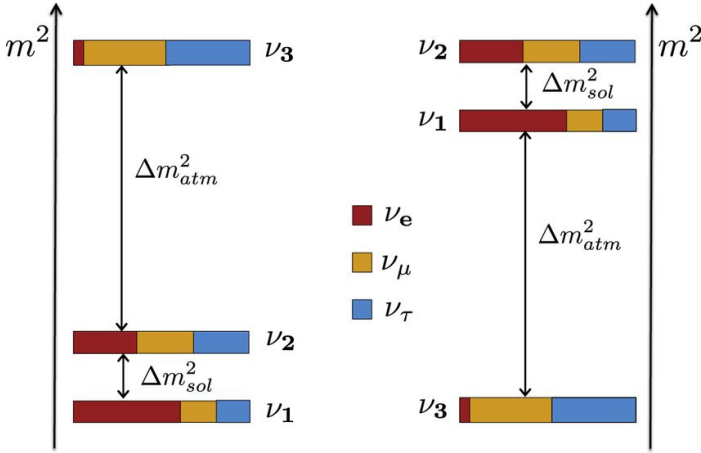
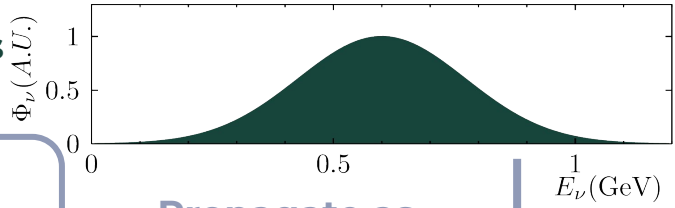


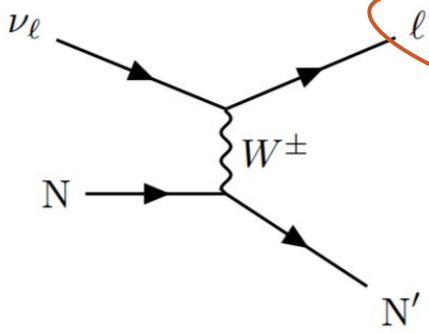
Which mass ordering?

Neutrino Oscillation: PMNS

e.g. created as muon neutrinos



Interaction with matter in flavor eigenstate defined by charged lepton.



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Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

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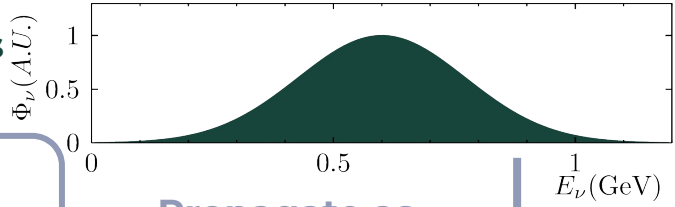

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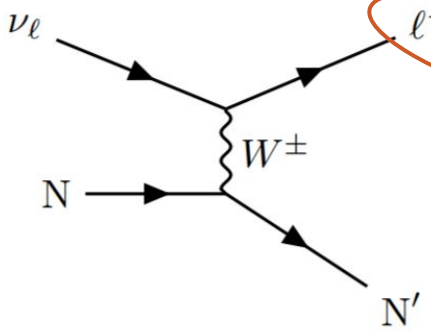

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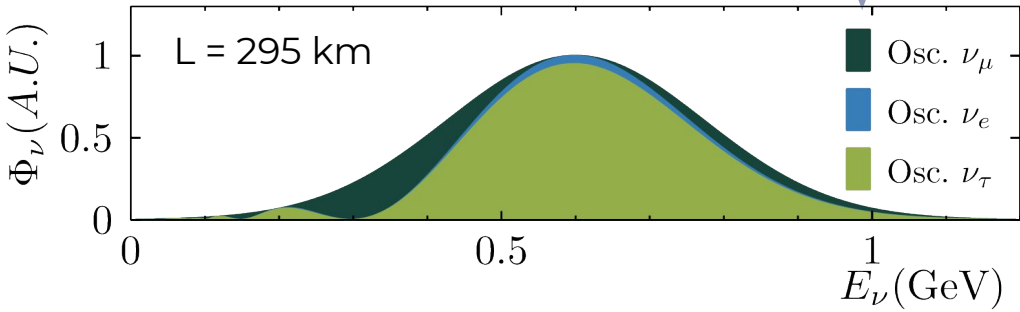
Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

Projecting back to flavor eigenstates reveals a different flavor mixture.
(if $|\Delta m^2_{ij}| \neq 0$)



Re-parameterizing the PMNS

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric /Accelerator}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

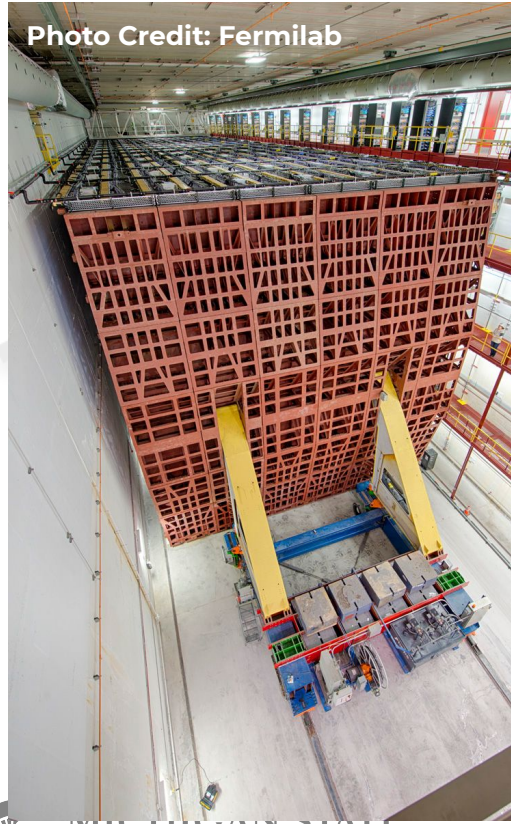
- Unitarity lets us re-parameterize PMNS matrix in terms of:
  - Three mixing angles: $C_{ij} = \cos(\theta_{ij})$
  - CP violating phase: $0<\delta_{CP}<2\pi$ or $-\pi<\delta_{CP}<\pi$

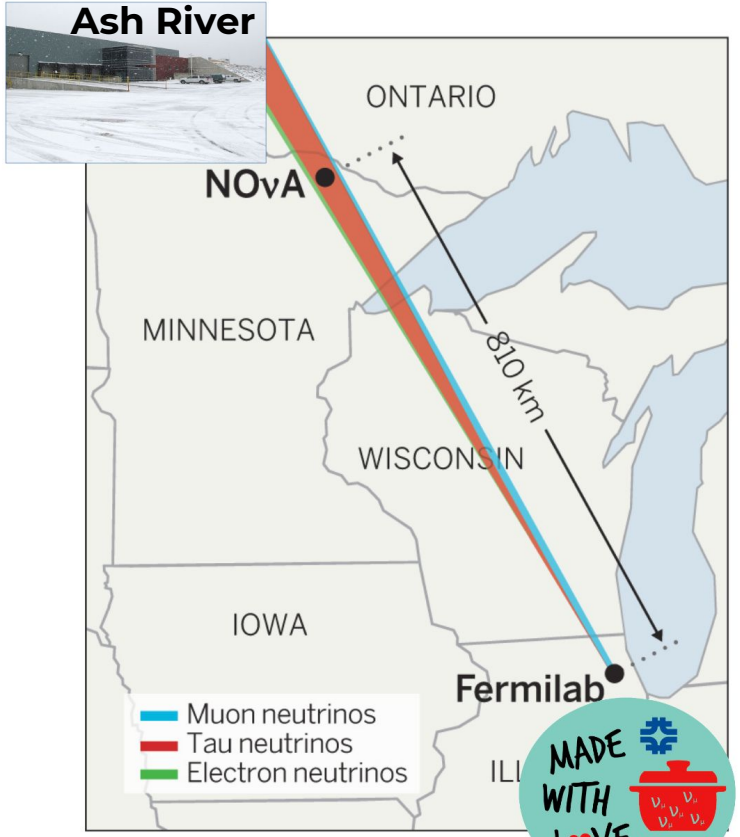
The Experiments

The NOvA Collaboration

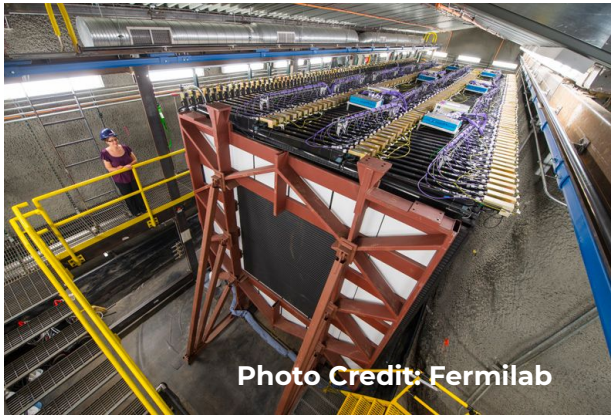

Photo Credit: NOvA Collaboration

The NOvA Experiment

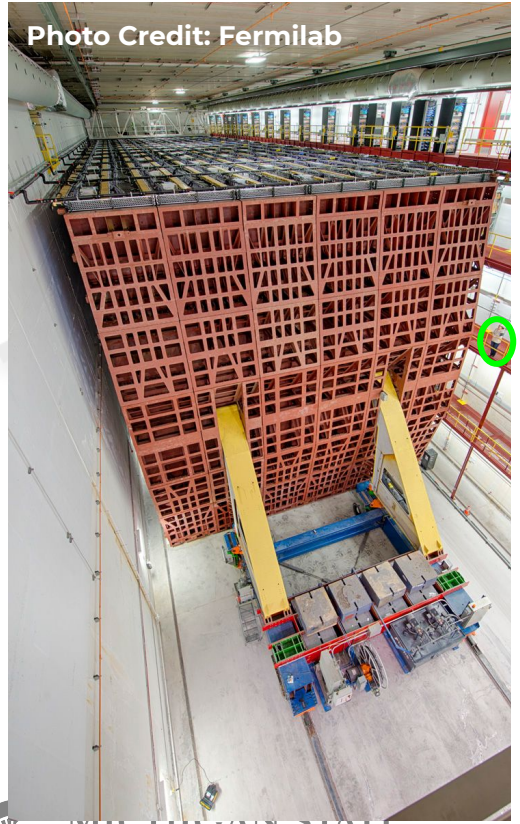


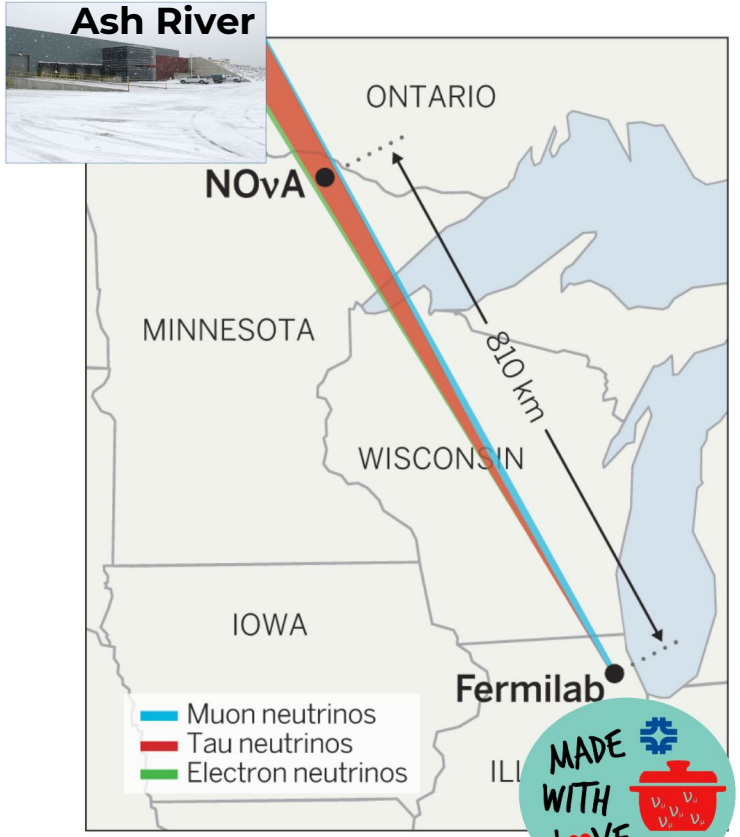


K. ENGMAN/*SCIENCE 345, 6204*



The NOvA Experiment





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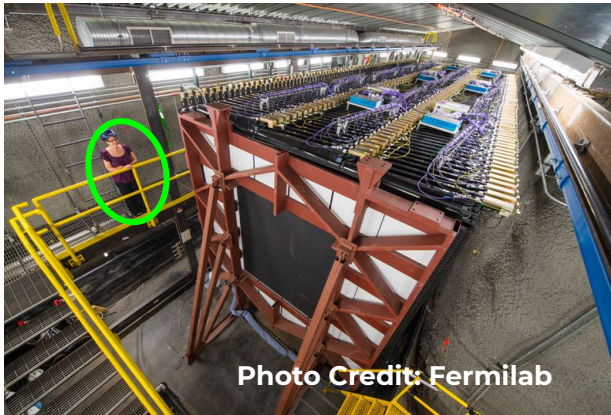
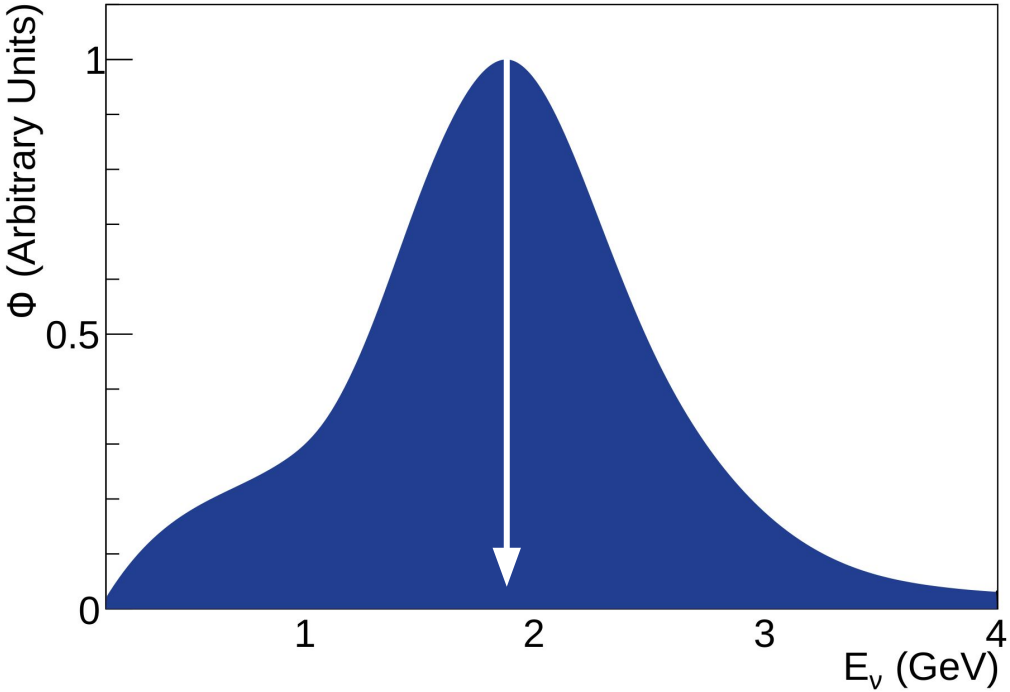


The NOvA Neutrino Flux

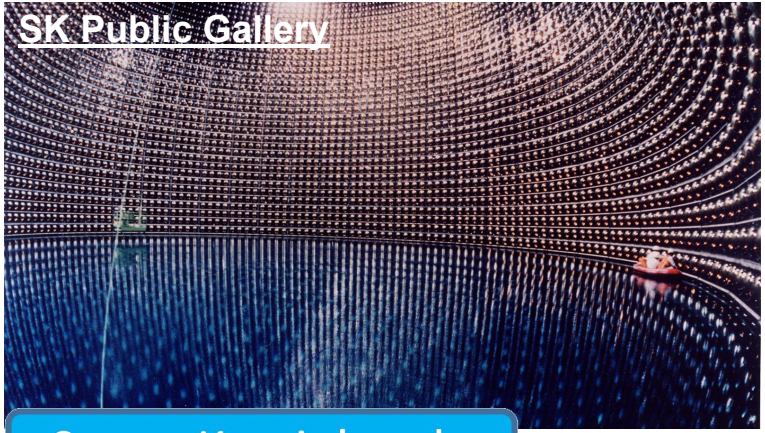
Fiducial Mass:	14 kT
Material:	Liquid scintillator
Detection technique:	Scintillation
Baseline:	810 km
Peak neutrino energy:	1.9 GeV
Location:	Ash River, MN

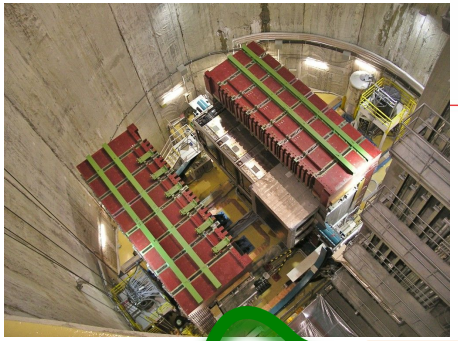


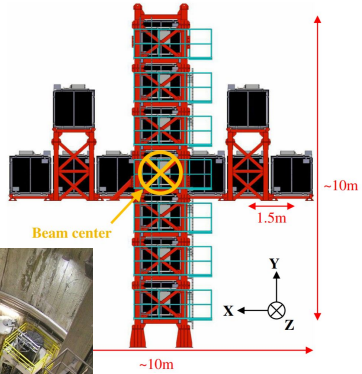
The T2K Collaboration

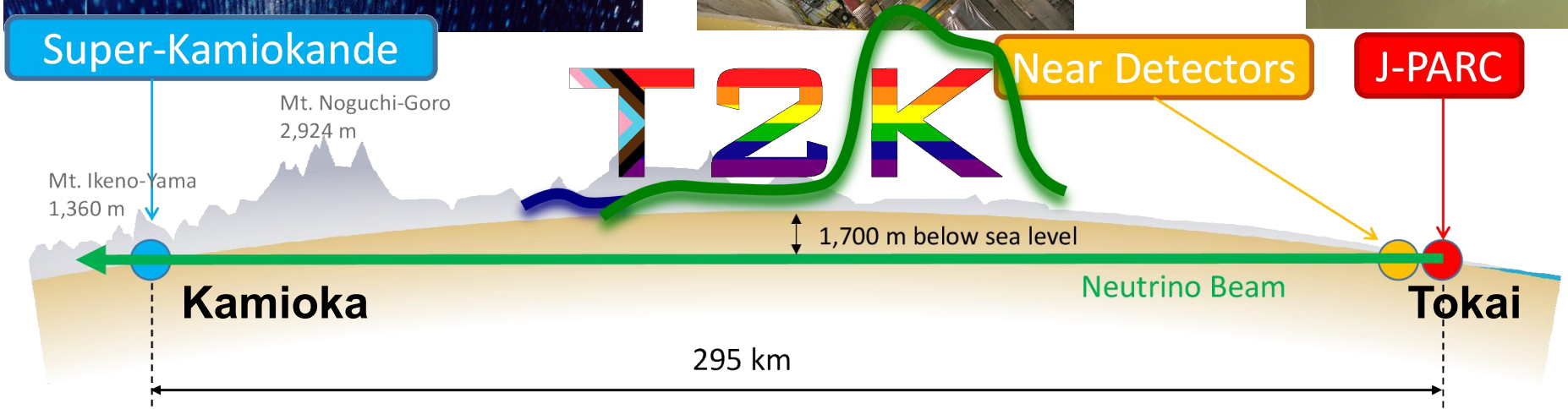
The T2K Collaboration

Tokai To Kamioka









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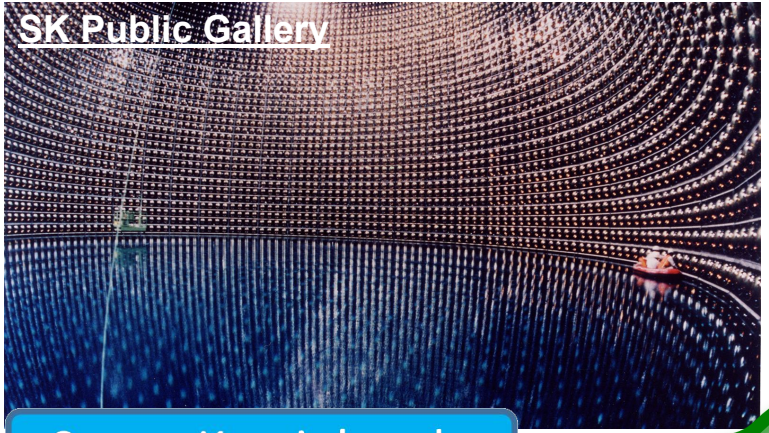

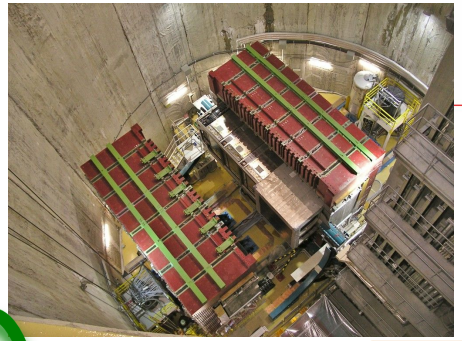

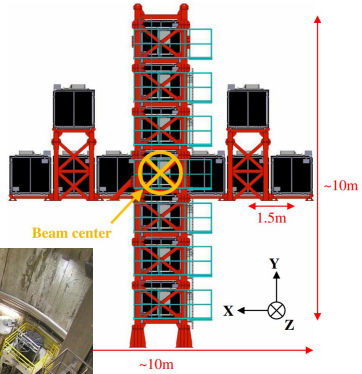

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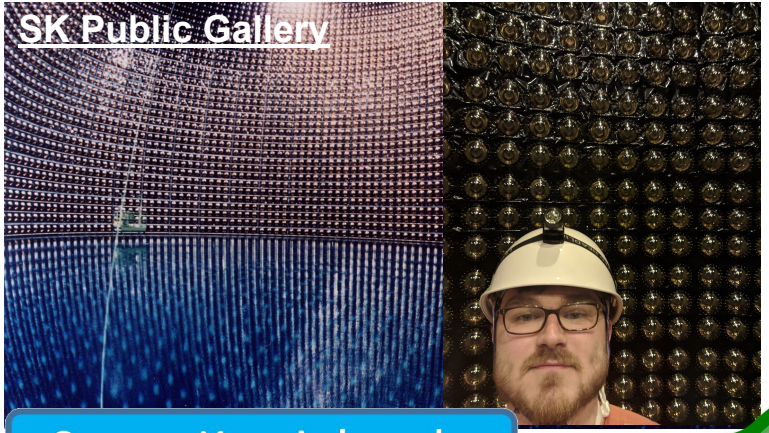
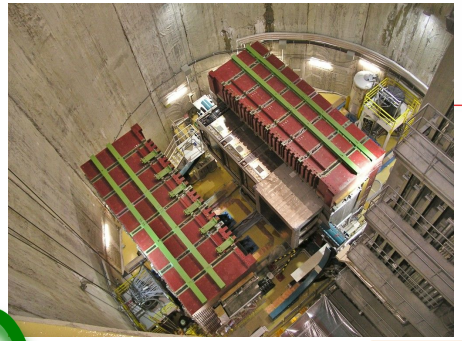
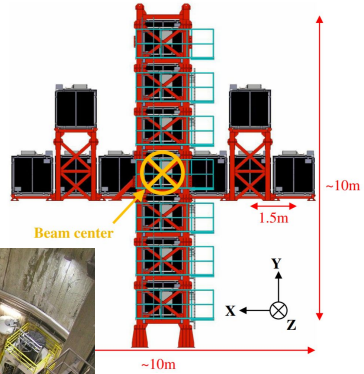


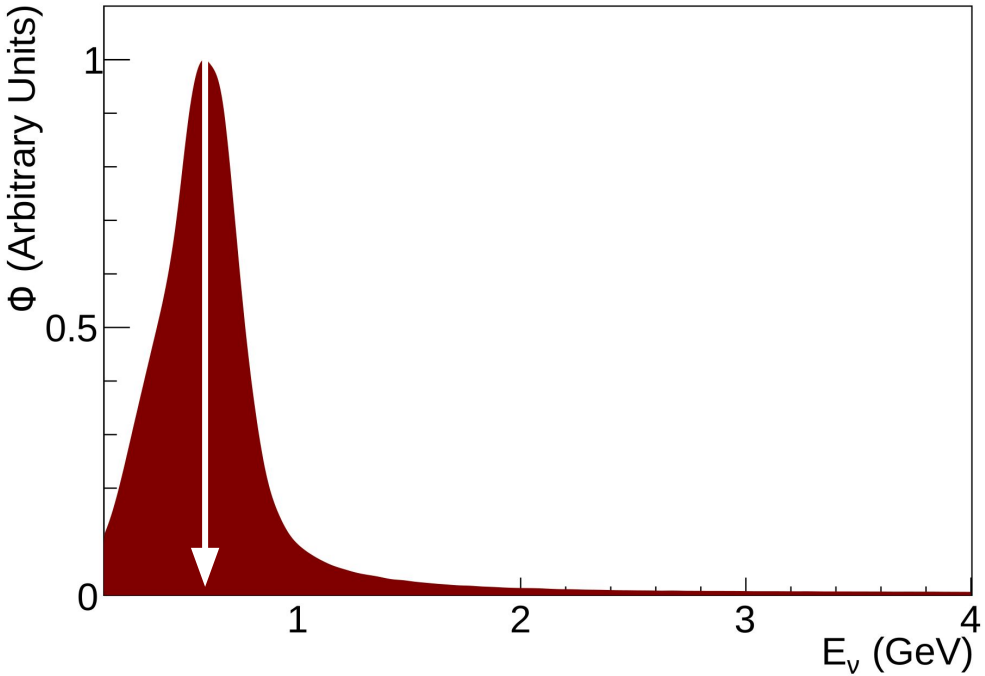




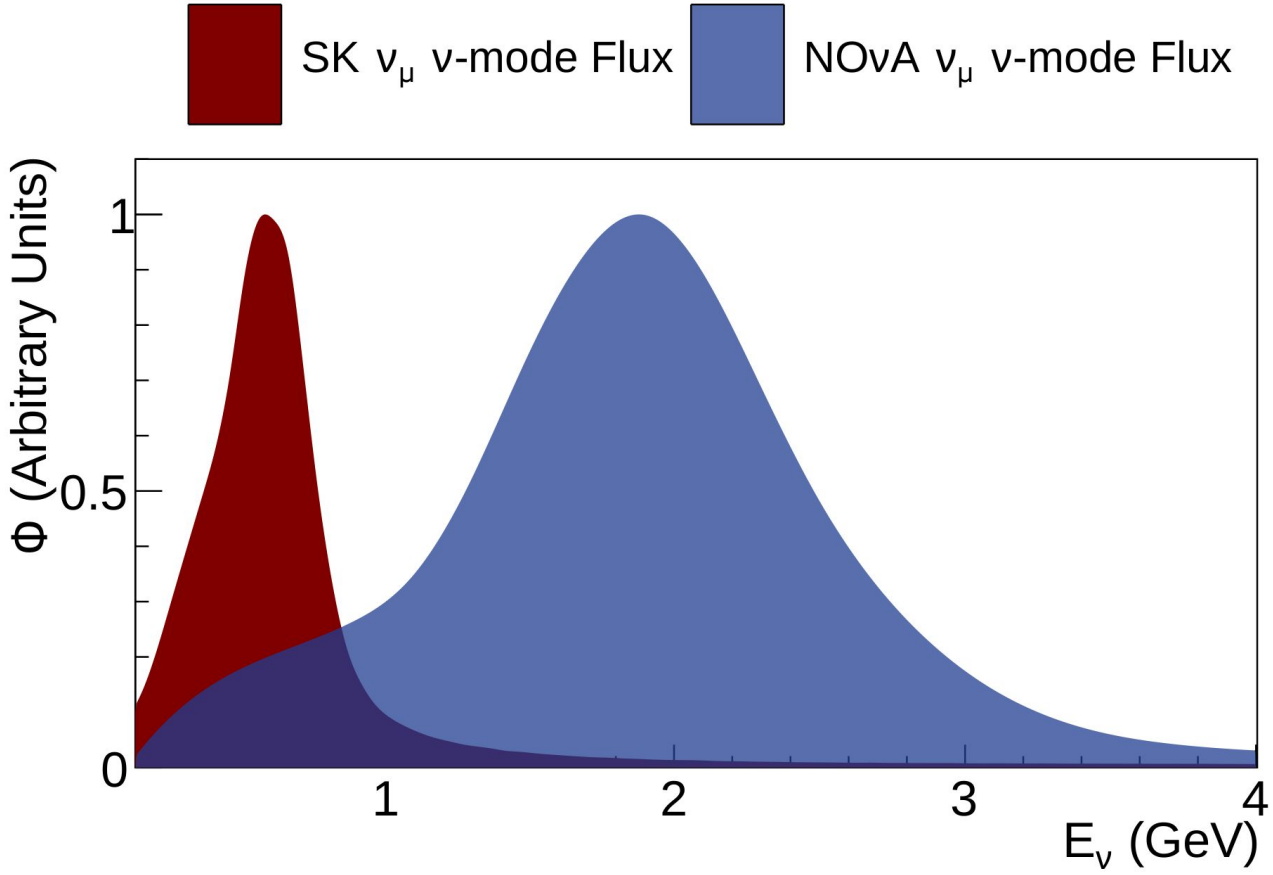
The TSK Neutrino Flux

Fiducial mass:	~22.5 kT
Material:	Ultrapure Water
Detection technique:	Cherenkov
Baseline:	295 km
Peak neutrino energy:	0.6 GeV
Location:	Mozumi Mine, Gifu, Japan

Expected Unoscillated T2K ν_μ Far Flux



T2K and NOvA Fluxes

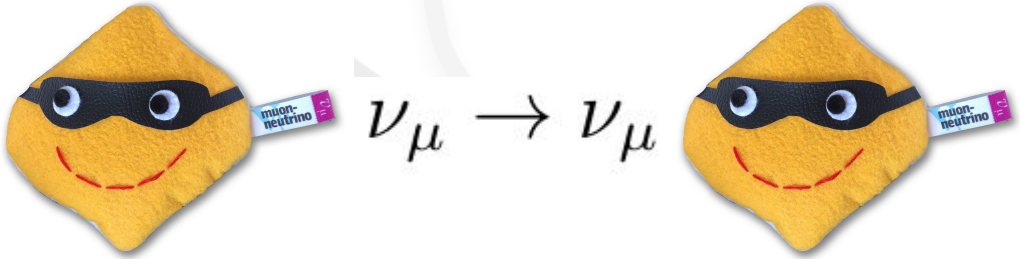


Measuring Oscillations

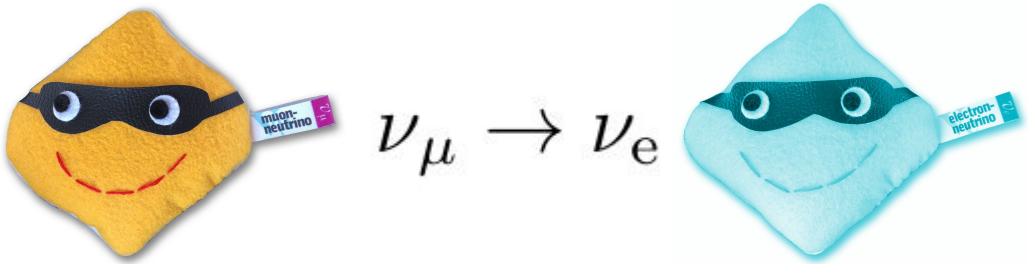
Measuring Oscillations

- Long baseline experiments study two oscillation channels:

Muon neutrino disappearance



Electron neutrino appearance



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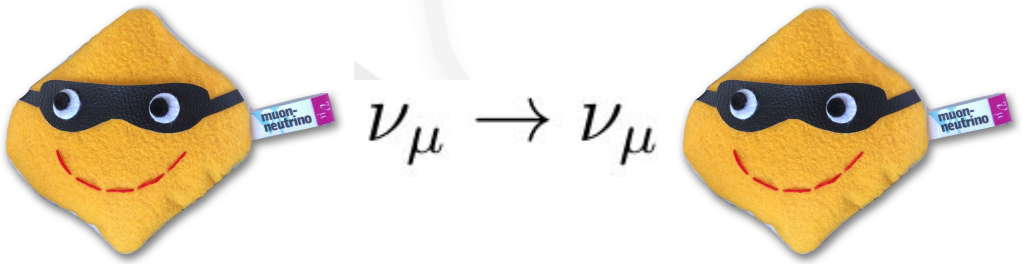

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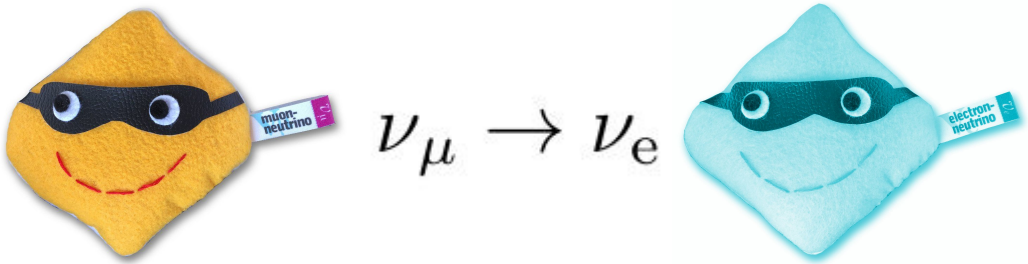

Muon Neutrino Disappearance Probability

- To leading order, muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E} + (\text{solar, matter effect terms})$$

Muon Neutrino Disappearance Probability

- To leading order, muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.
- Choose L/E for maximum effect:

$$\sin^2 \frac{\Delta m^2_{32} L}{4E} \simeq 1$$

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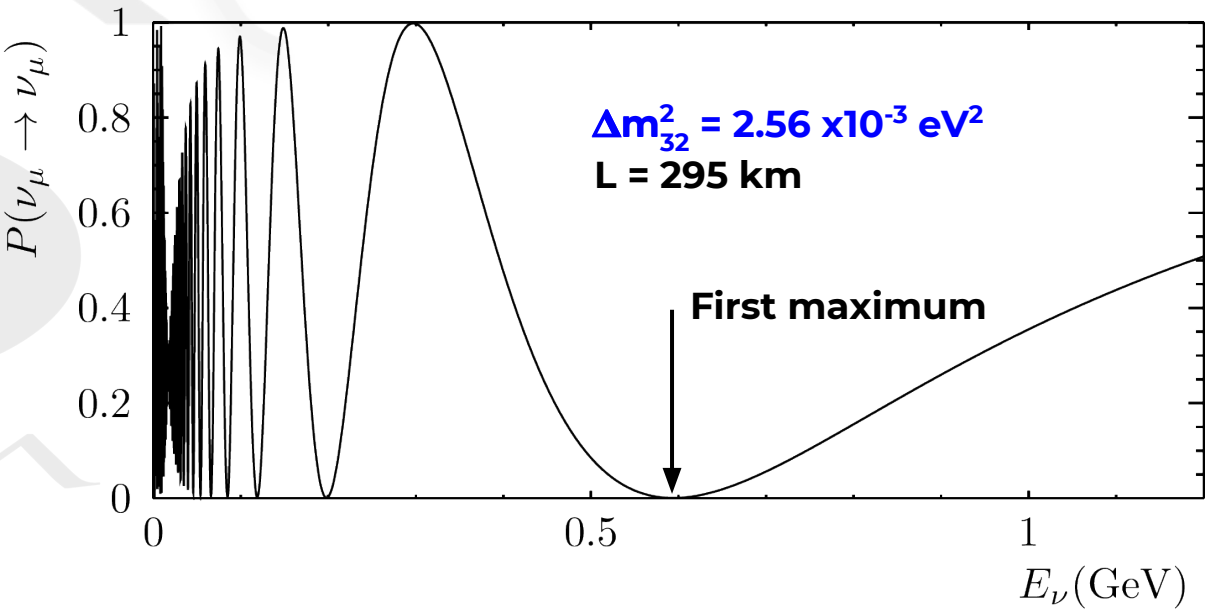
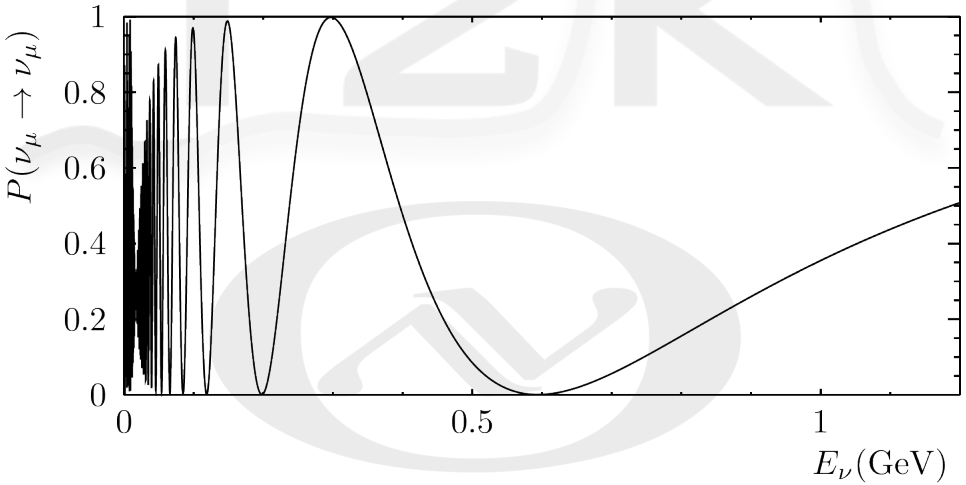
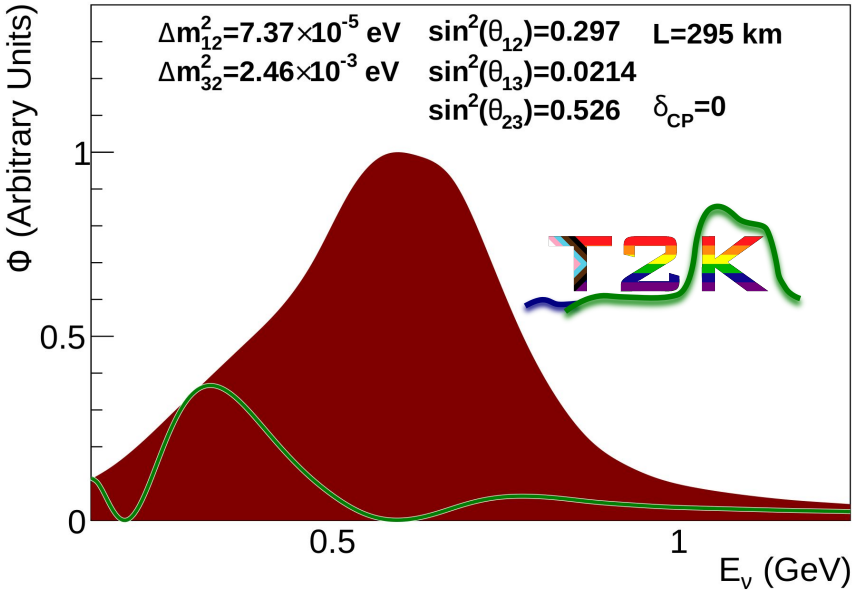


Observing Disappearance

Oscillation probability



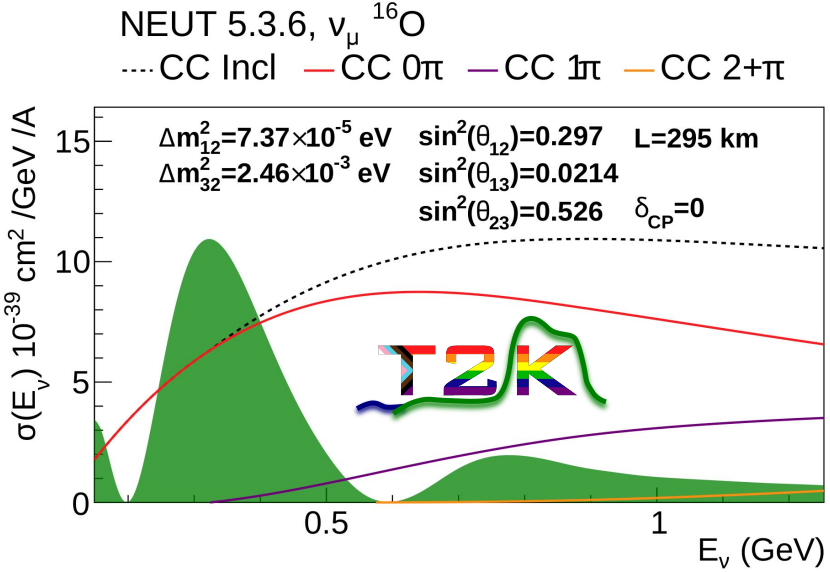
Flux • **Oscillation probability**



Number of neutrinos = **Flux** • **Oscillation probability**

Observing Disappearance

Flux · **Oscillation probability** **Cross section**

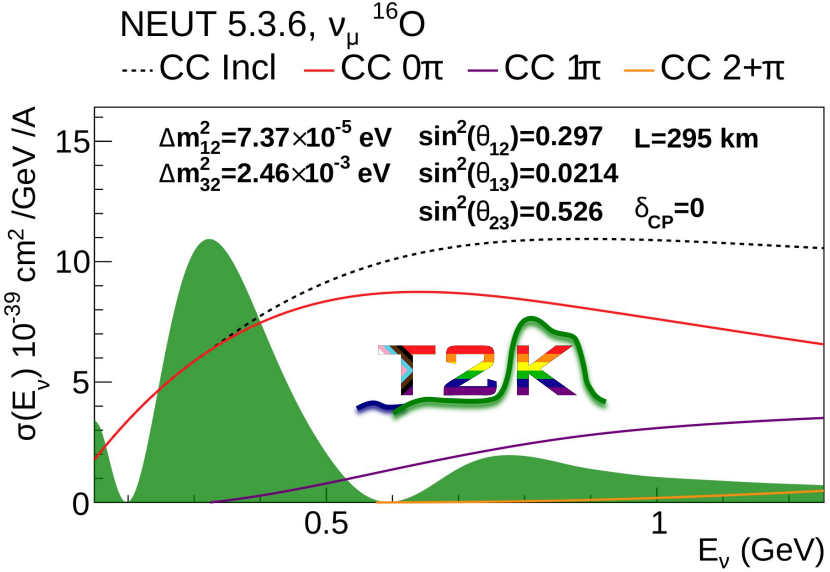


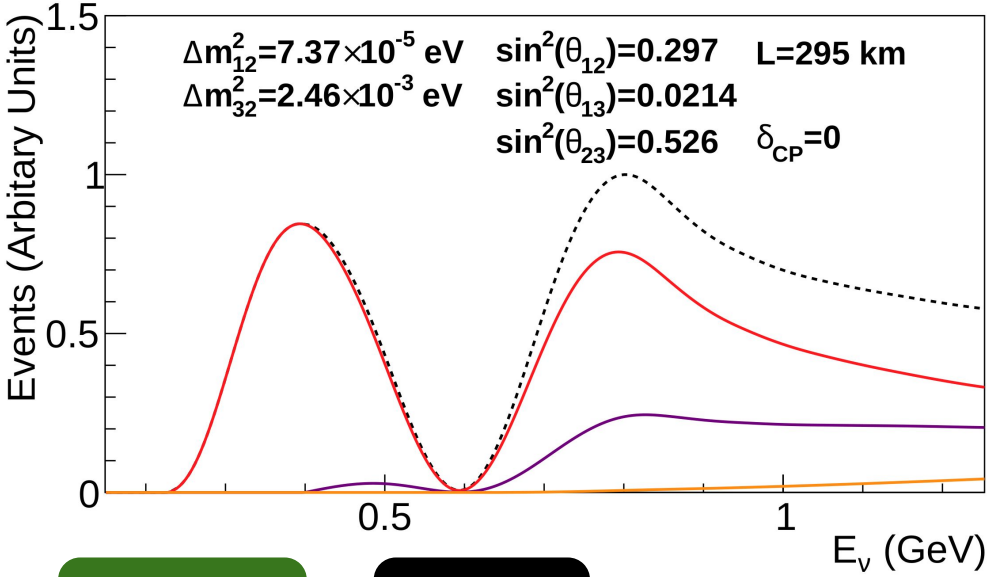
Number of events = **Flux** · **Oscillation probability** · **Cross section**

Observing Disappearance

Flux · **Oscillation probability** **Cross section**

Number of events

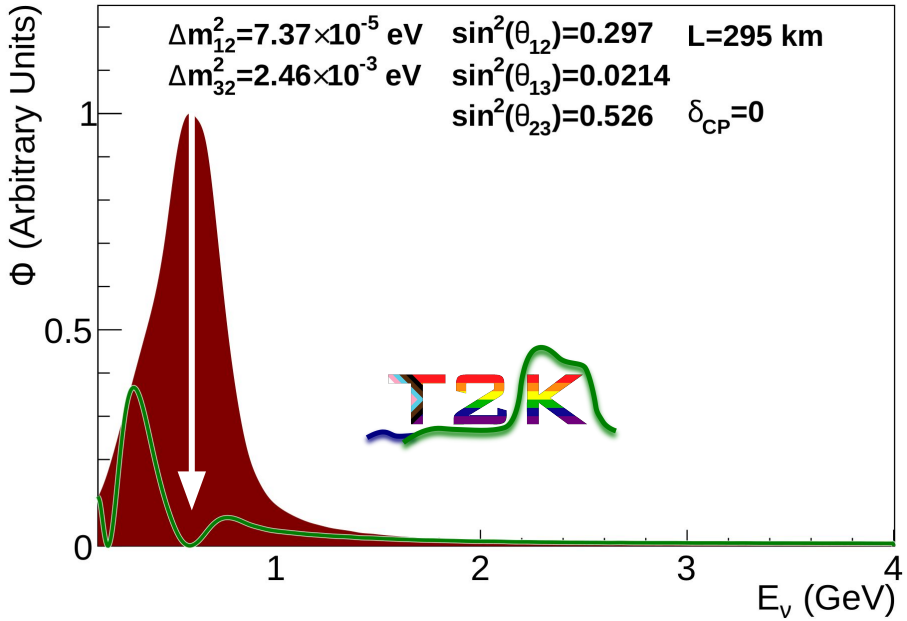


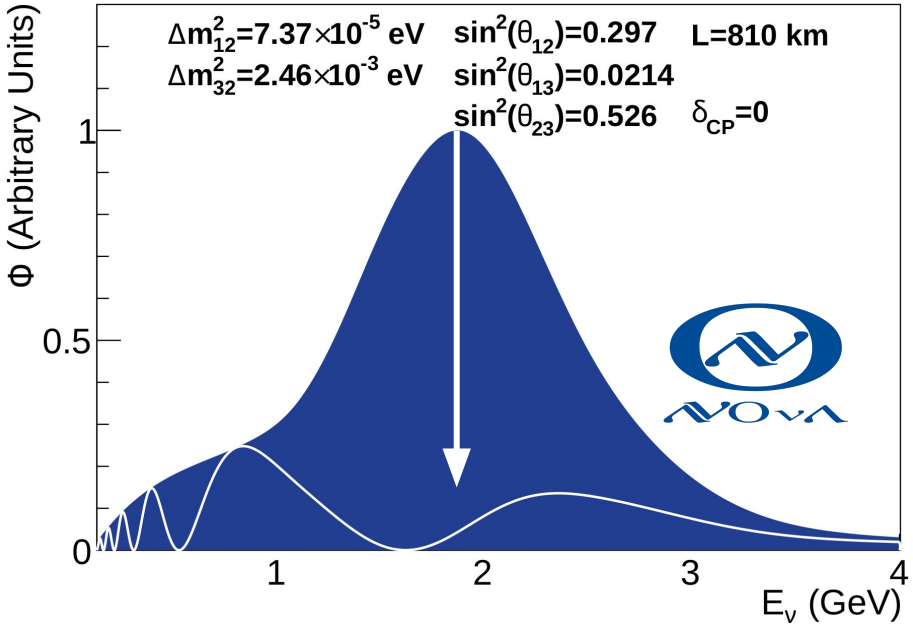


Number of events = **Flux** · **Oscillation probability** · **Cross section**

Disappearance on T2K and NOvA

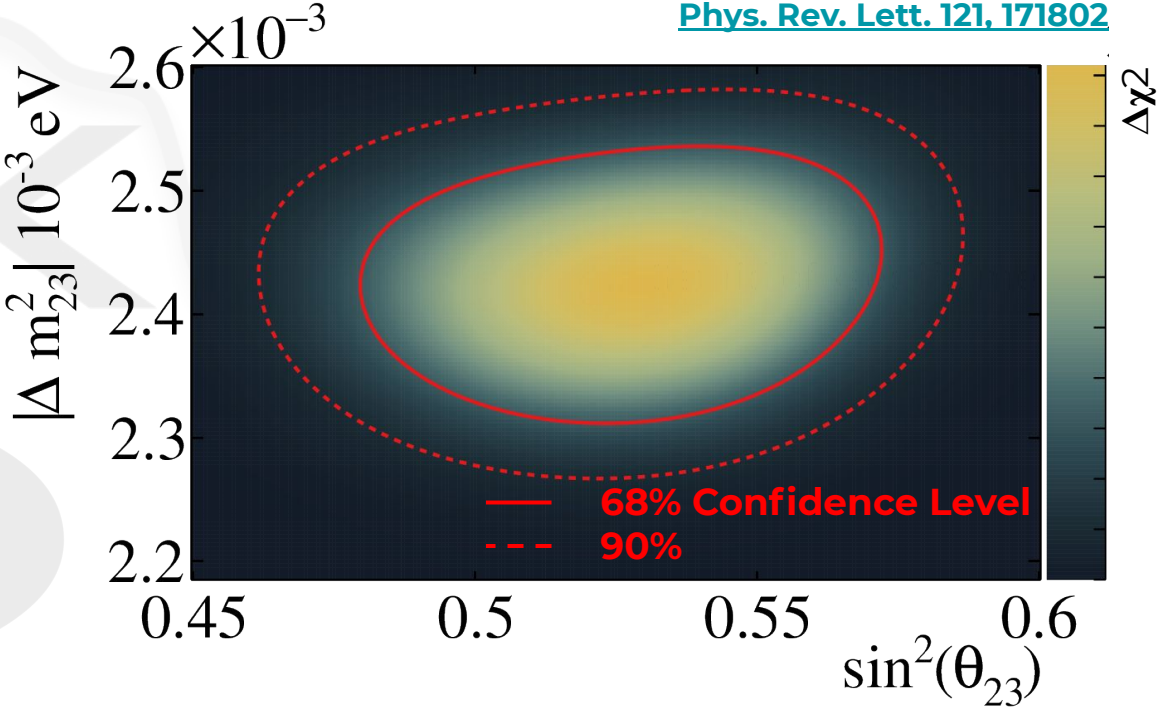
Number of neutrinos = Flux · Oscillation probability





Measuring Disappearance

Phys. Rev. Lett. 121, 171802



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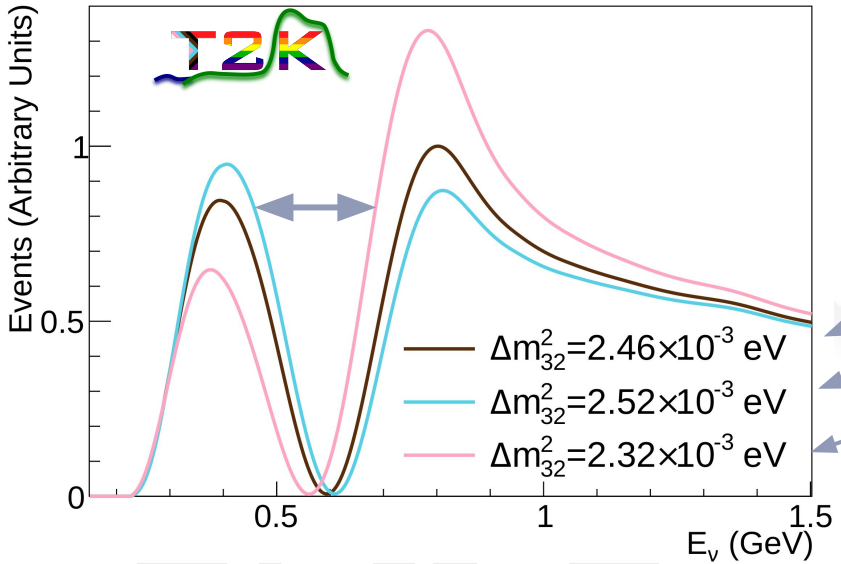
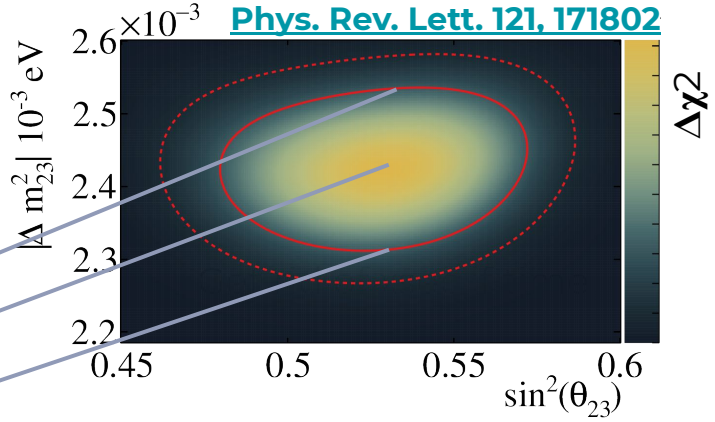
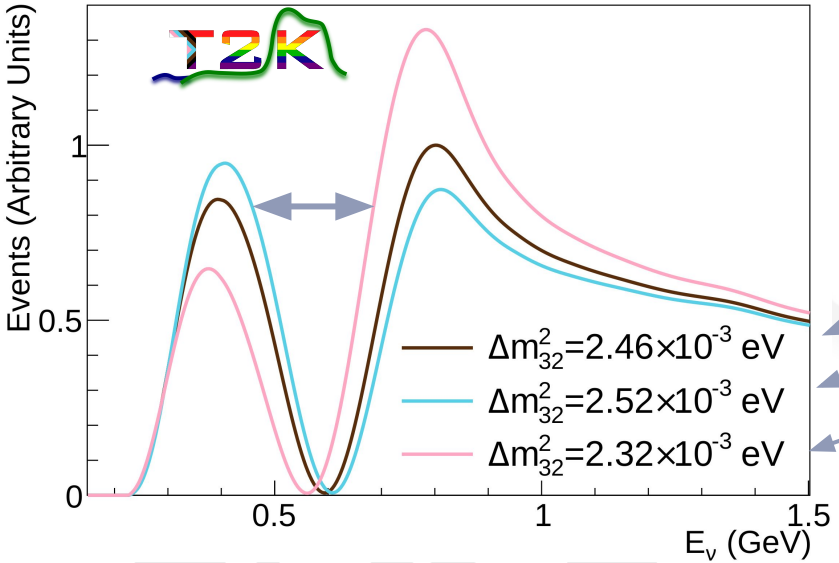


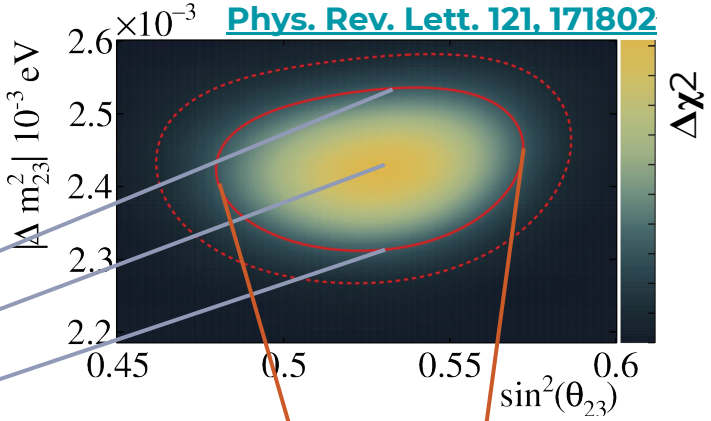


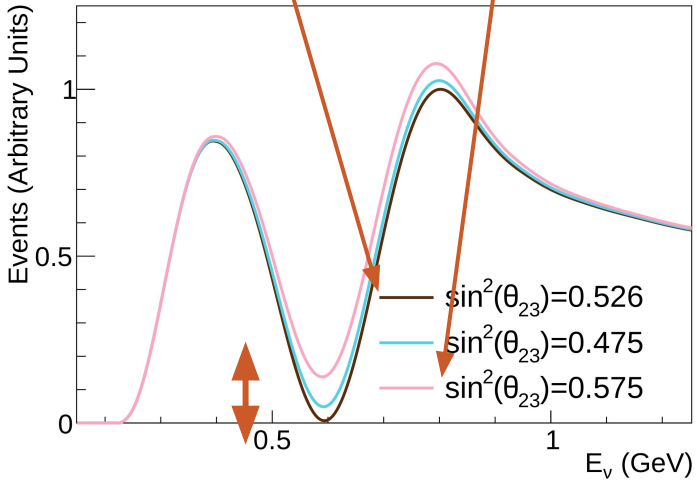
- Mass-squared splitting shifts the ‘dip’

Measuring Disappearance

68% Confidence Level
90%







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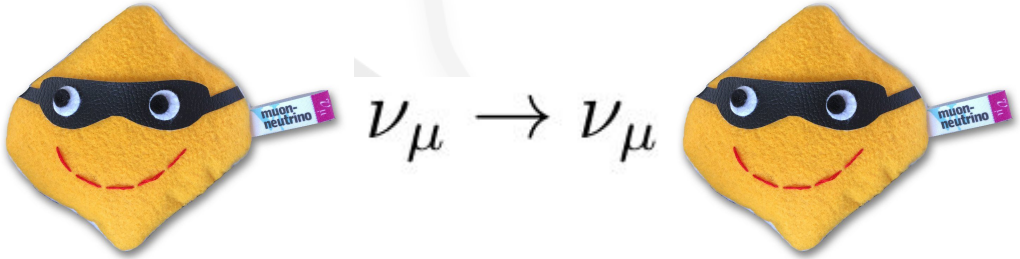
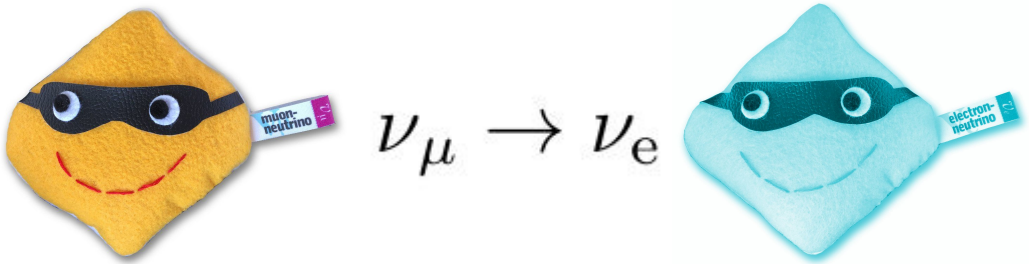


Electron neutrino appearance



Electron Neutrino Appearance

- Electron neutrino appearance probability has '**CP odd**' term.
  - Sign flip between matter and antimatter.

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$
$$+\,(\text{CP-even, solar, matter effect terms})$$

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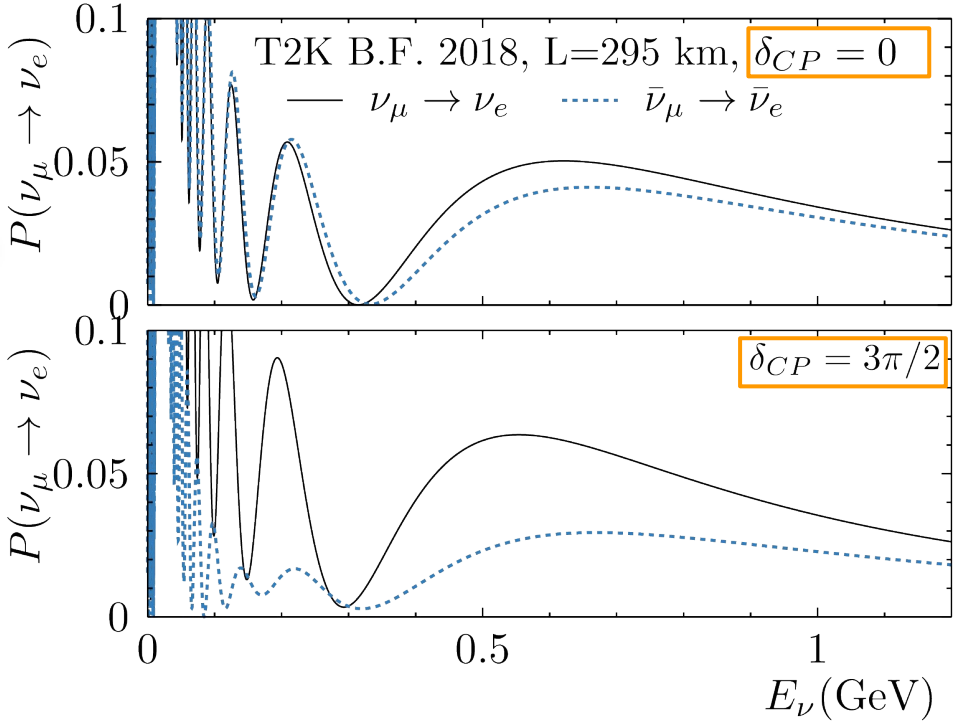

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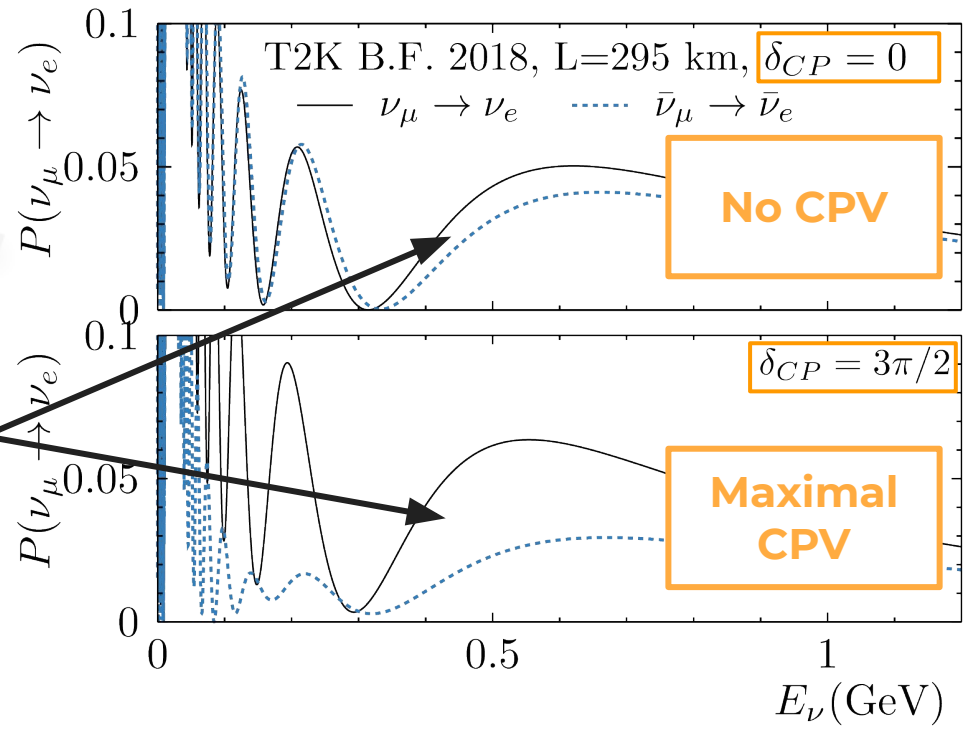
What is the value of δ_{CP}?



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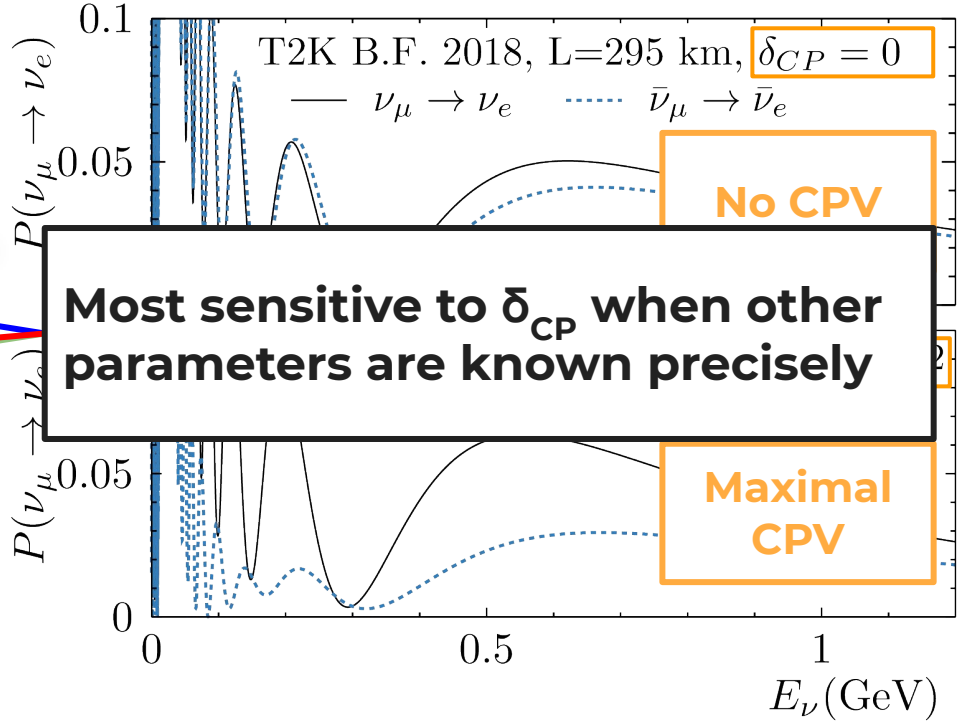
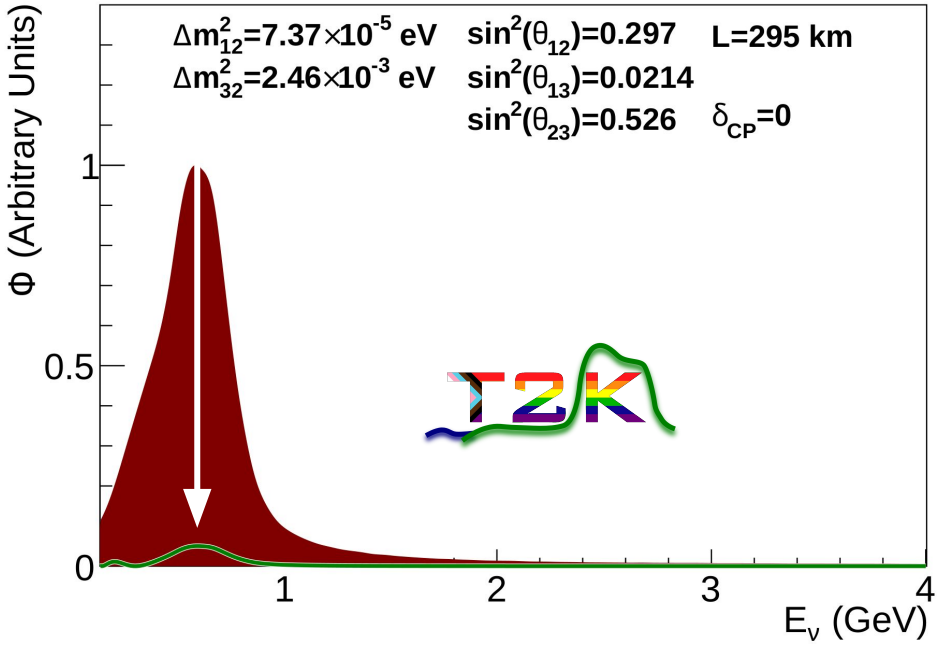
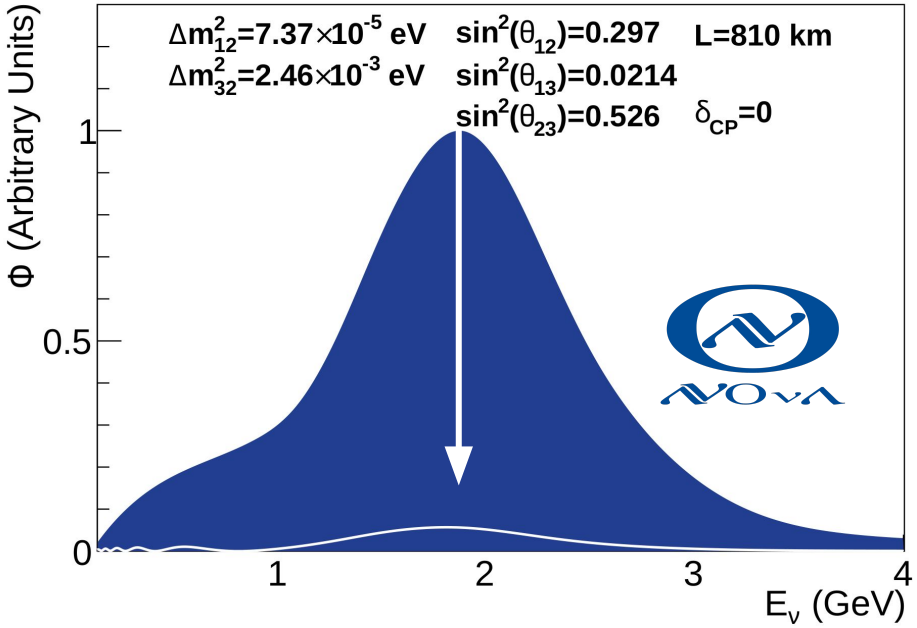


Most sensitive to δ_{CP} when other parameters are known precisely

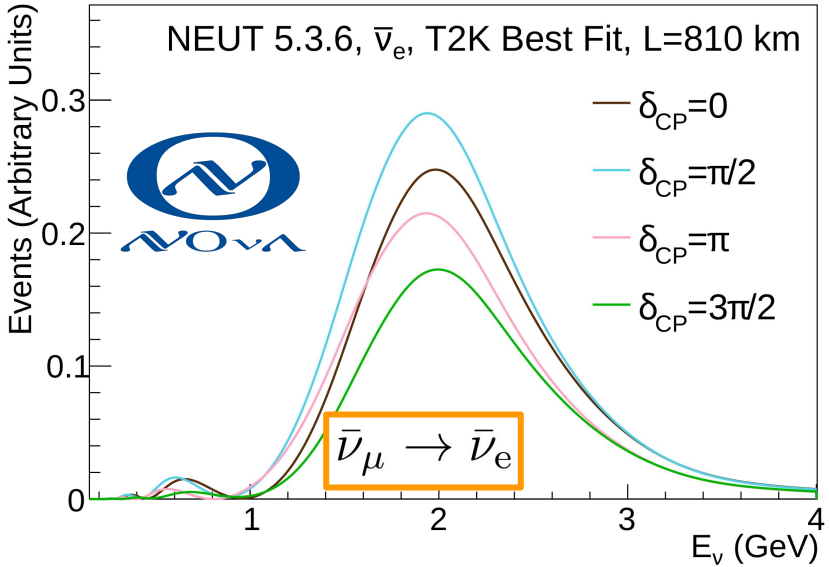
Appearance on T2K and NOvA

Number of neutrinos = Flux · Oscillation probability





Neutrino and Antineutrino Appearance



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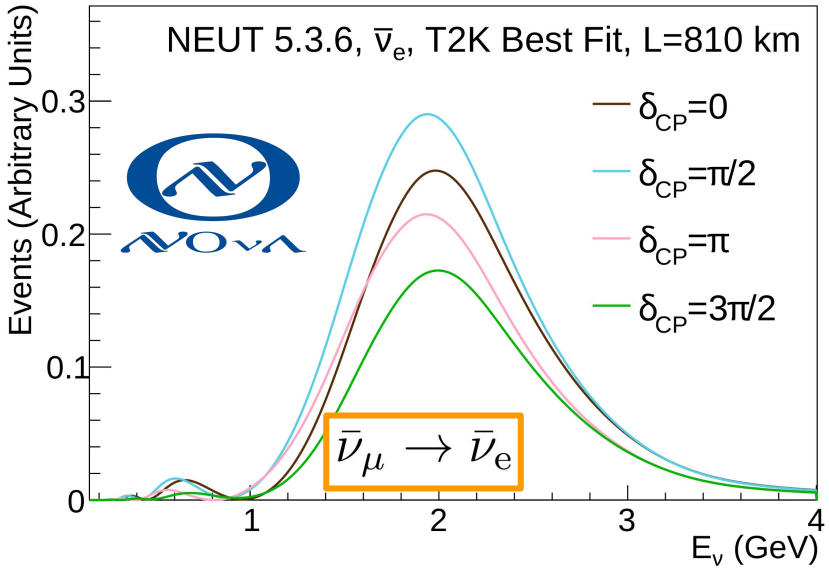
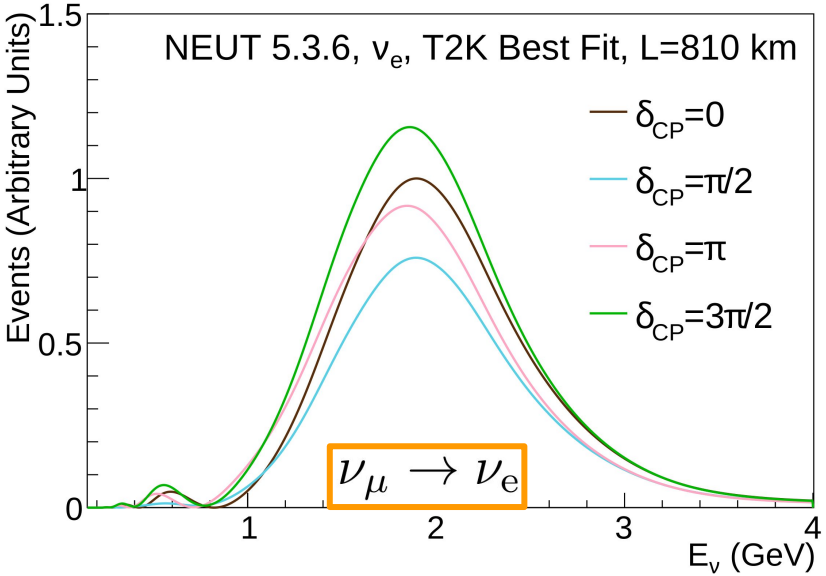
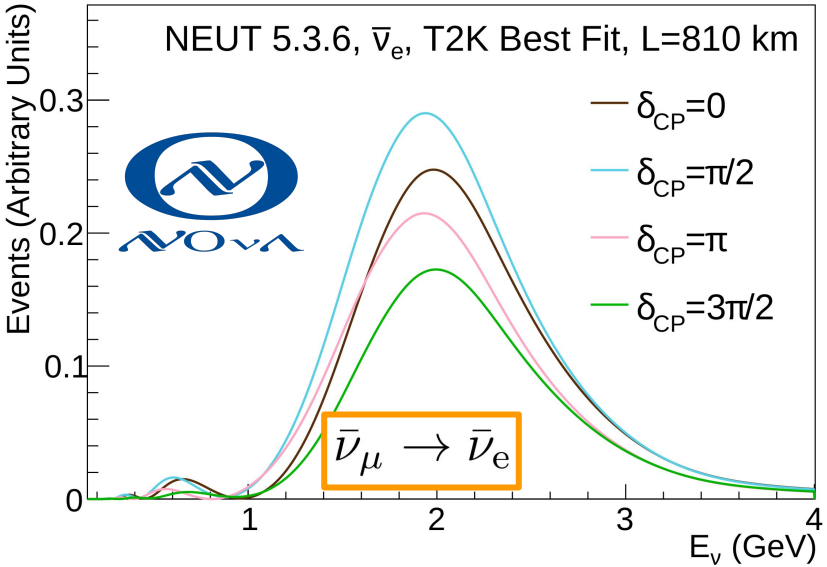
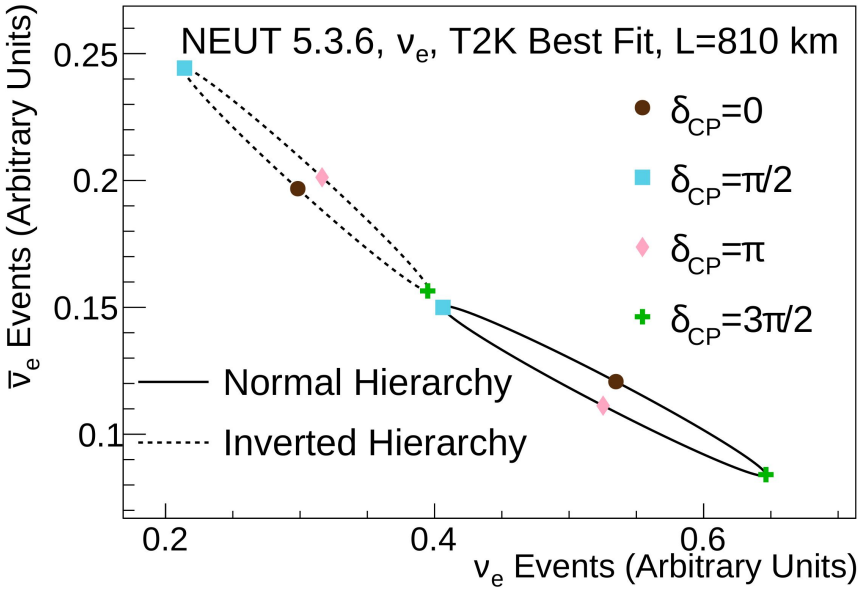
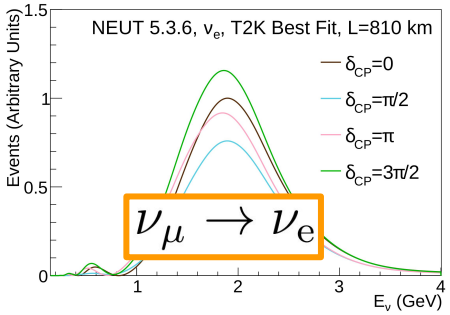




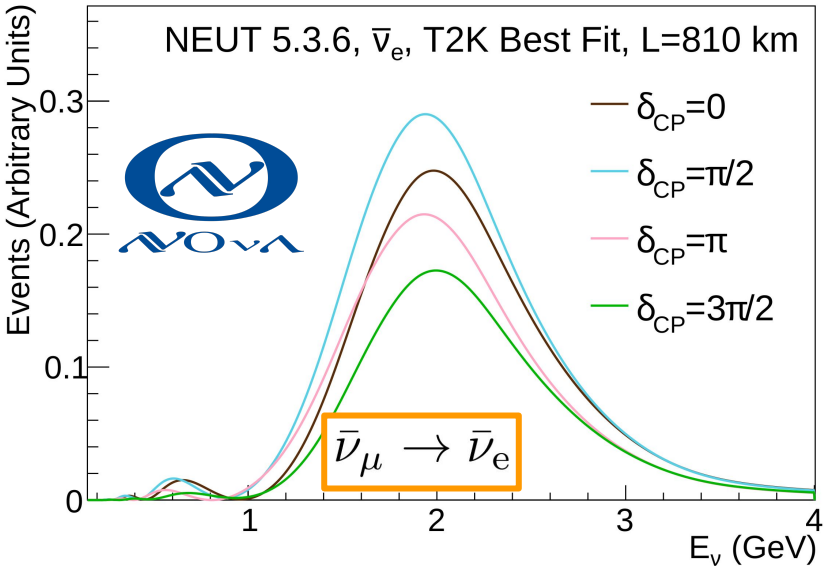
Neutrino and Antineutrino Appearance

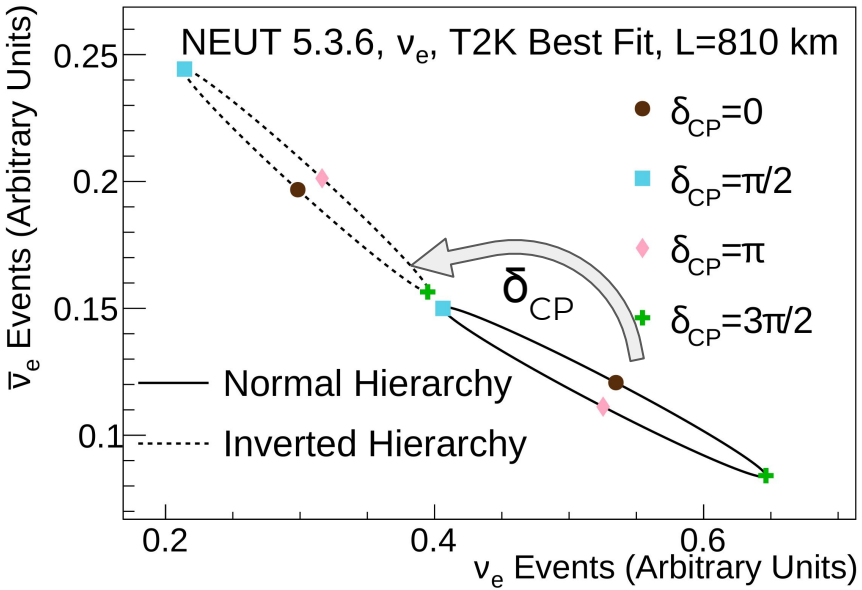


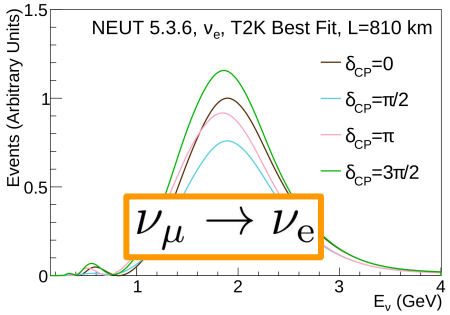




Neutrino and Antineutrino Appearance







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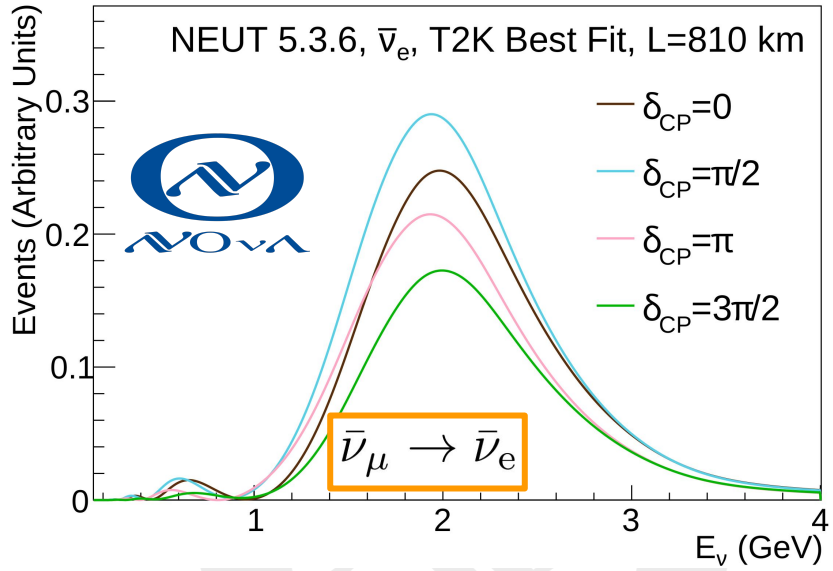
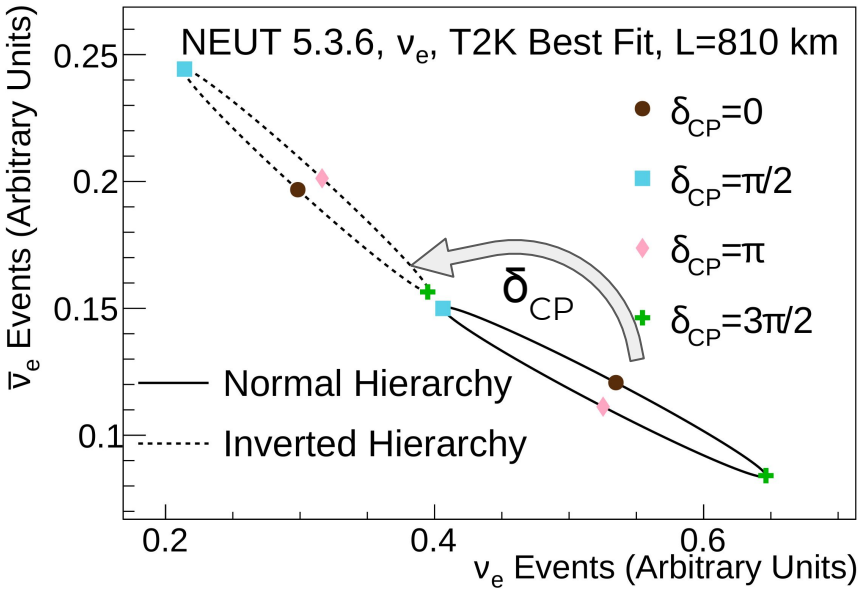
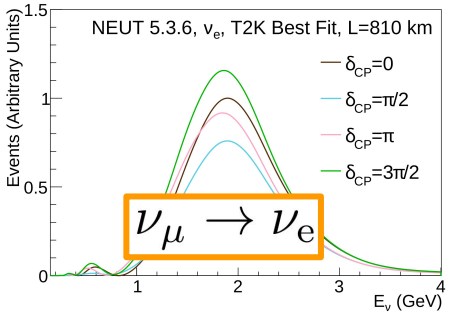
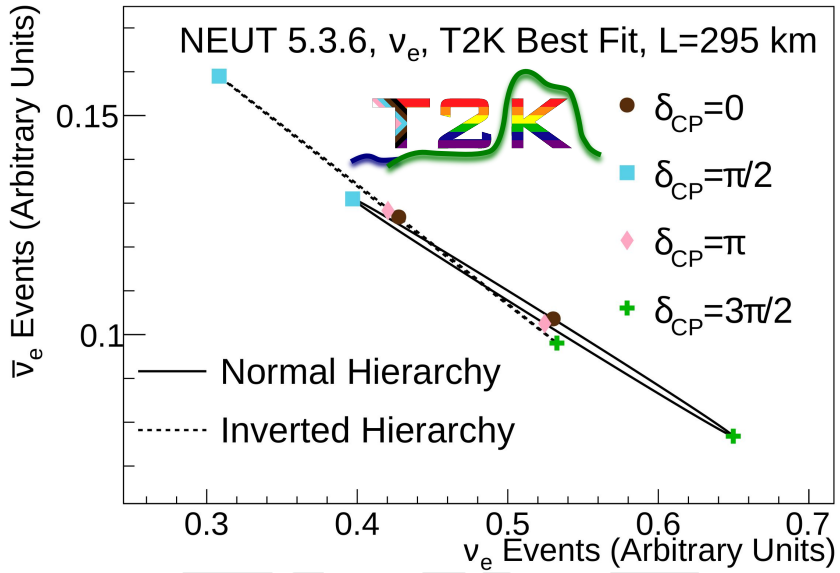


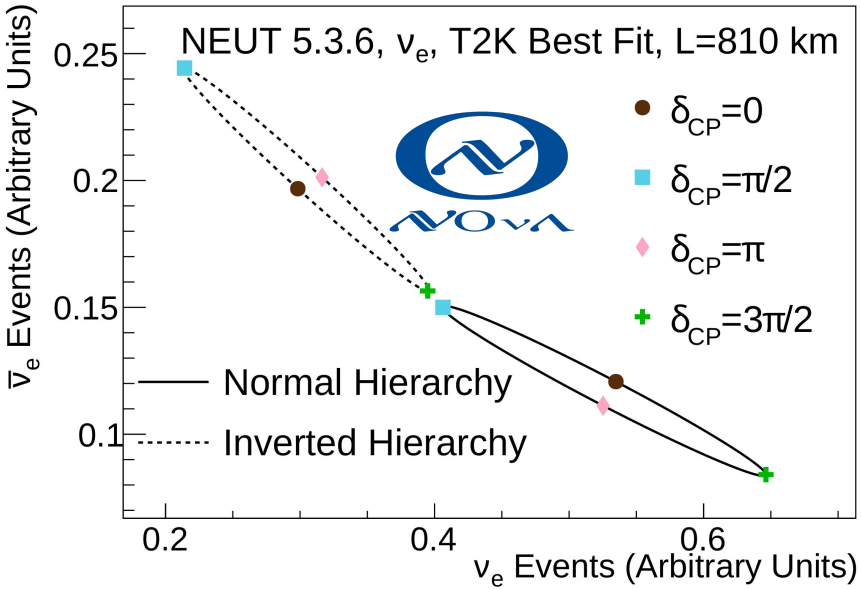


- Most sensitive to δ_{CP} if:
  - Know hierarchy
  - Know disappearance parameters well
  - Measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



T2K and NOvA Appearance Sensitivity





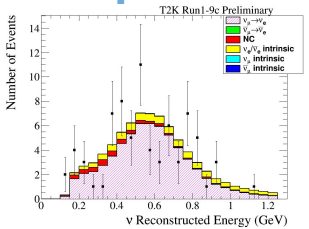
- Different characteristics due to strength of matter effect at T2K and NOvA energies.

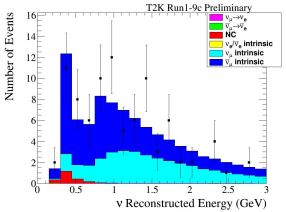
Oscillation Physics Programs


T2K

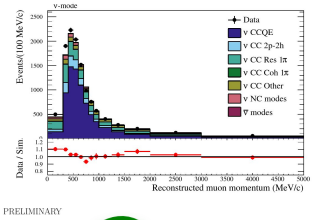
Anatomy of an Oscillation Analysis

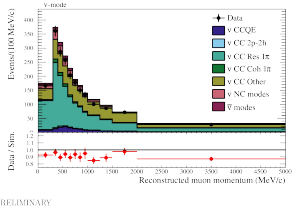
- Sample oscillated beam
- Infer oscillation probabilities



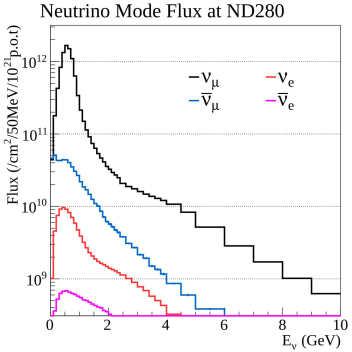


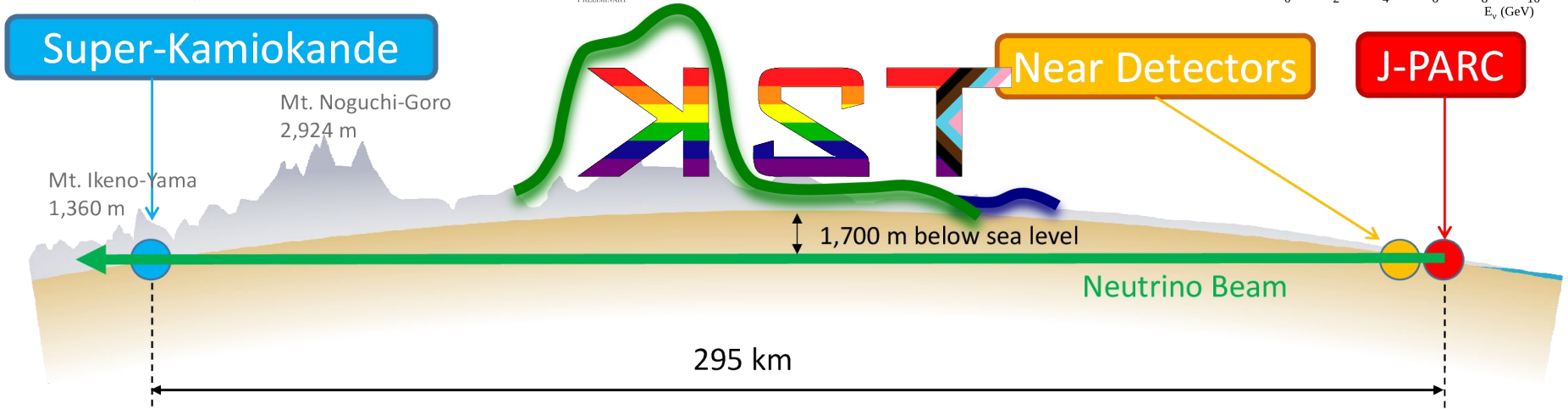
- Sample un-oscillated beam
- Study neutrino interaction physics



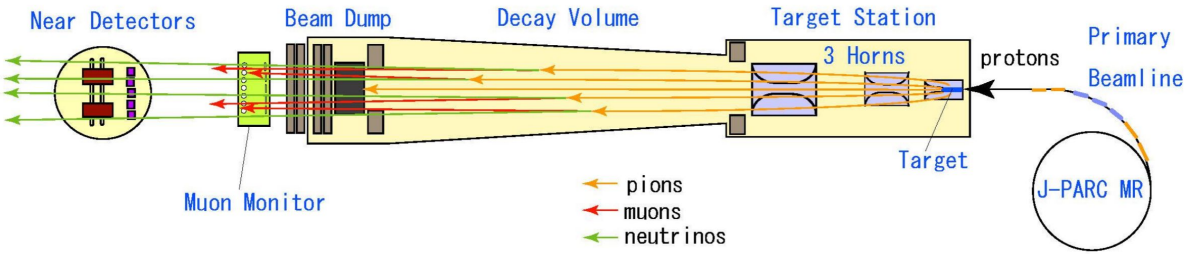


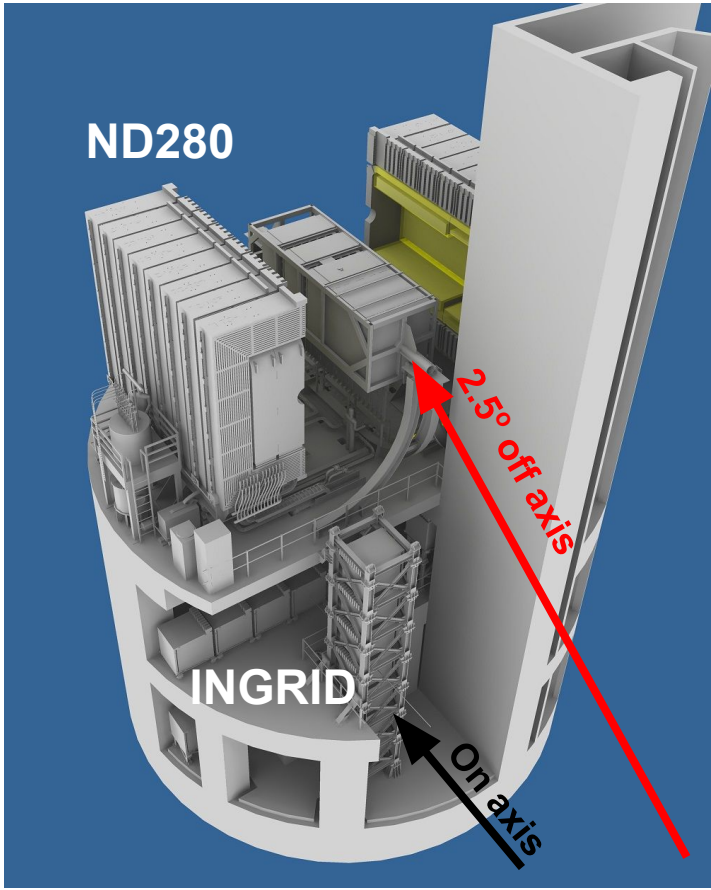
Produce neutrino beam





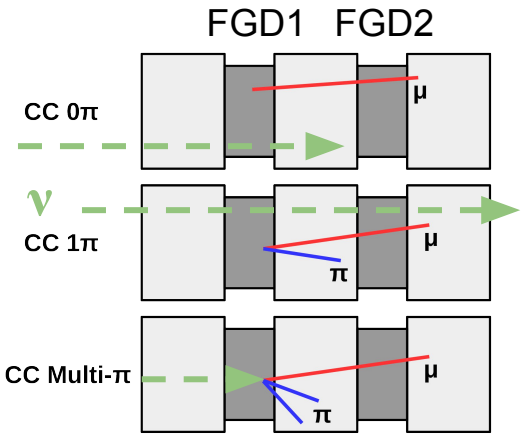
Near Detectors

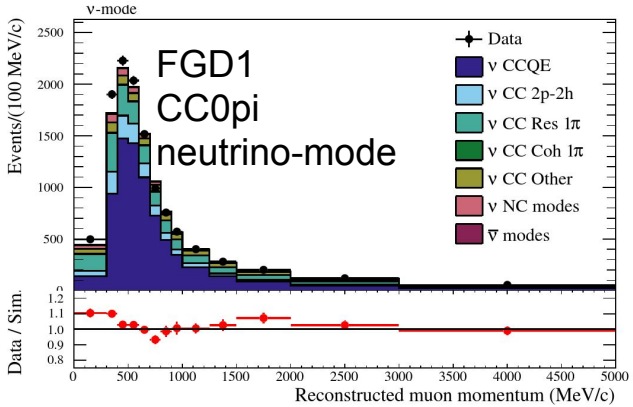




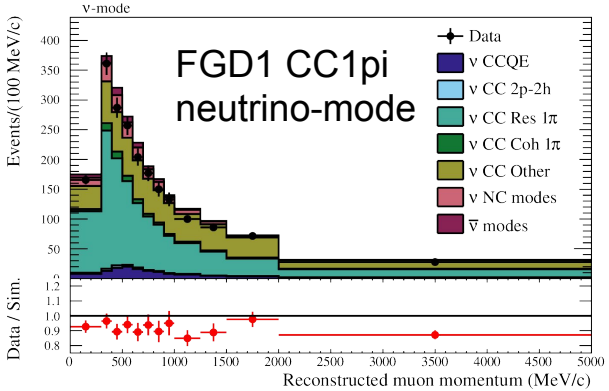
- T2K Oscillation analysis: Near Detectors
  - **INGRID**: On-axis, ensures beam alignment
  - **ND280**: Off-axis near detector
- ND280
  - Magnetized: Charge and momentum measurements
    - Constrain ‘wrong sign’ backgrounds

Near Detector Samples





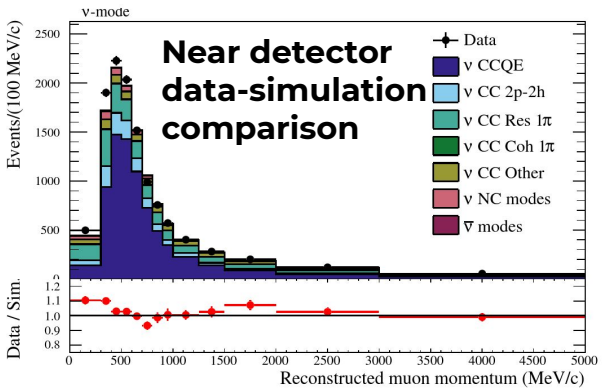
PRELIMINARY



PRELIMINARY

- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1
  - Detector material: CH (FGD) or CH+H2O (FGD2)
- Binned in **observed lepton kinematics** only.
- Both neutrino and antineutrino beam modes.

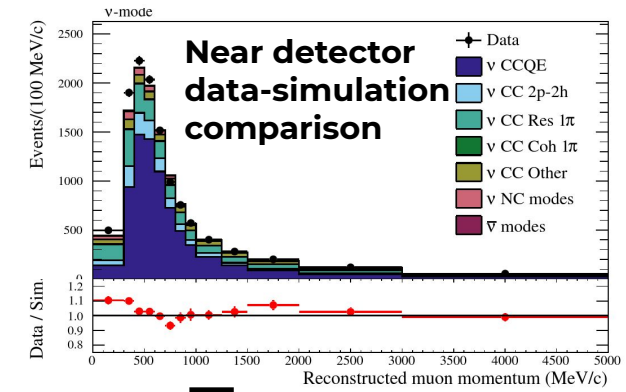
Near Detector Fit



PRELIMINARY

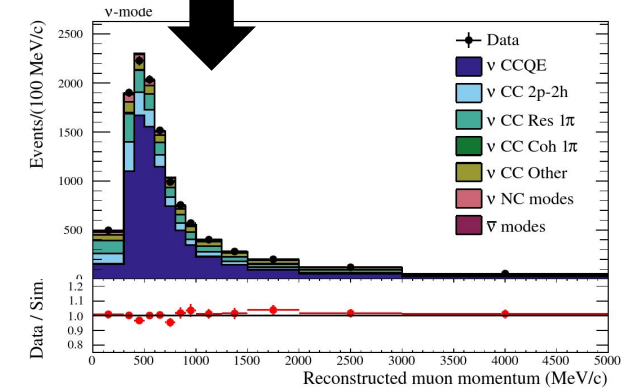
- Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction

Near Detector Fit



PRELIMINARY

Fit Free parameters



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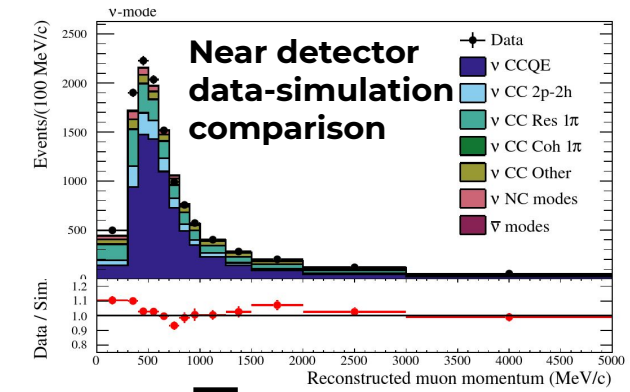

PRELIMINARY

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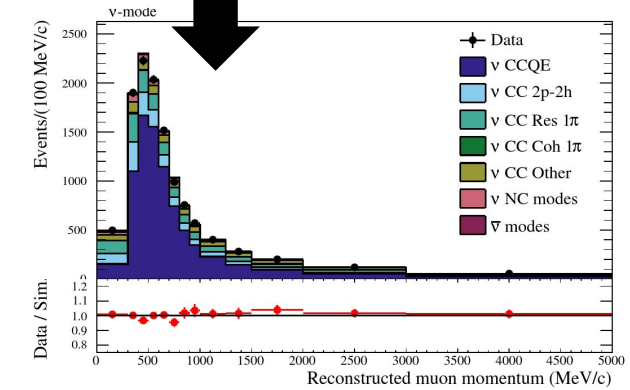
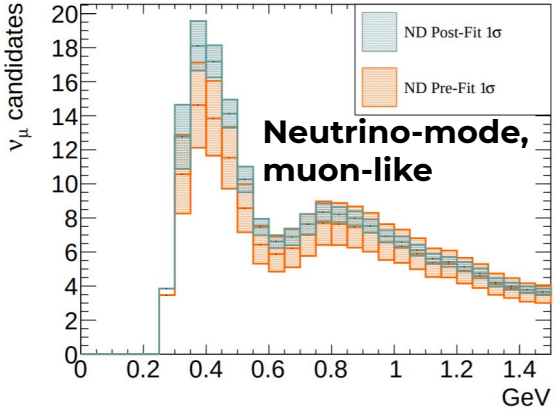
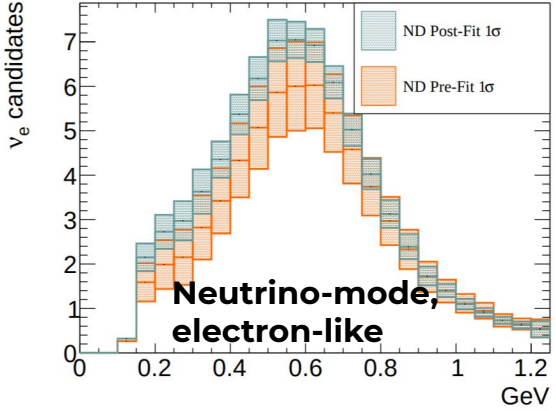


PRELIMINARY

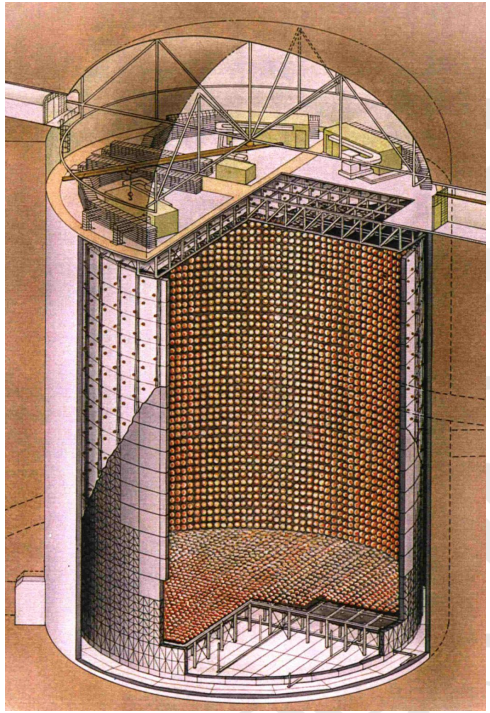
- Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction
- Constrain event rate uncertainties for Far detector

Far detector predicted event rates with oscillations

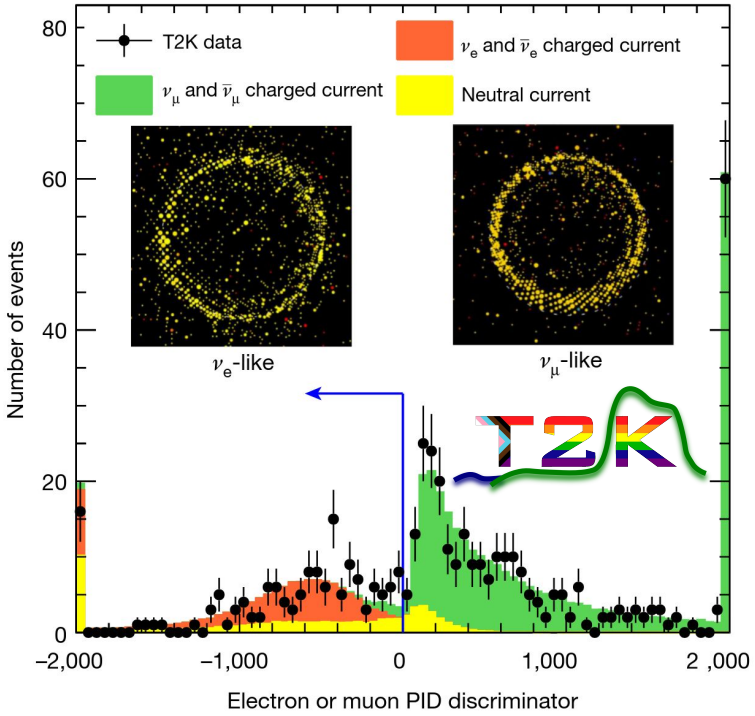




Super-Kamiokande



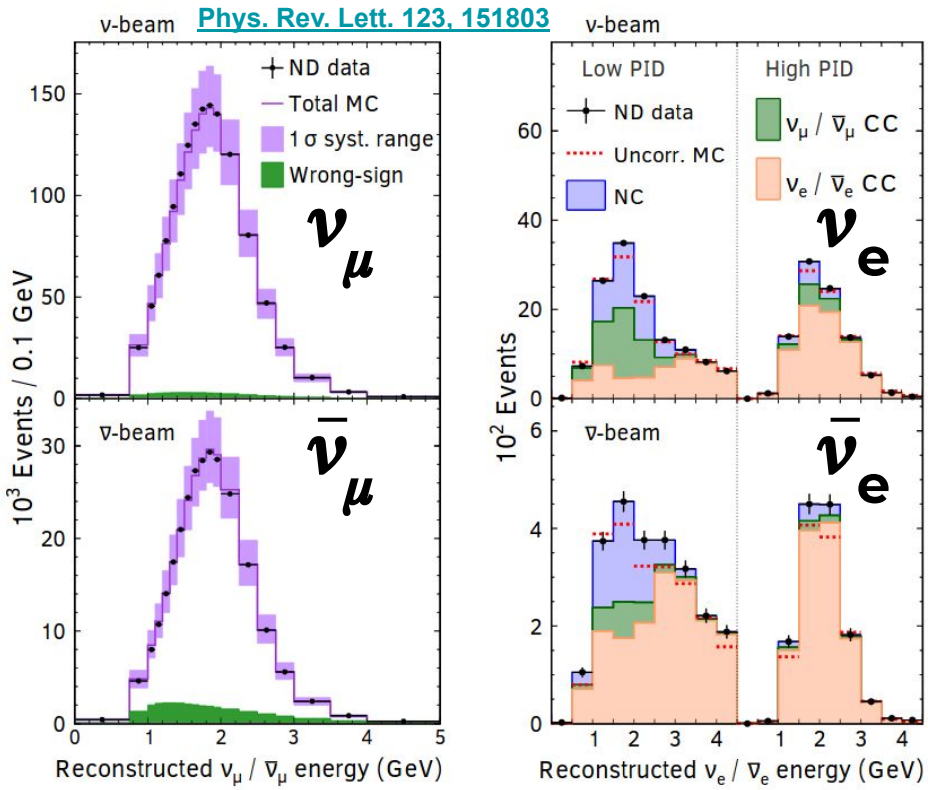
Nature 580 7803 p339-344



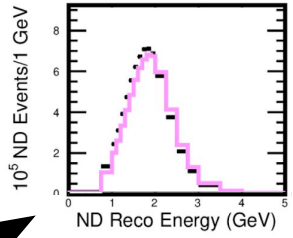
- Water Cherenkov detector.
- Sensitive to:
  - Electrons, muons, pions
- Can discriminate Cherenkov rings from:
  - **electrons** ('fuzzy')
  - **muons** ('sharp')

Near Detector Samples

- Fully active calorimeter detector:
  - Functionally identical to Far detector
- Select contained muon-like and electron-like samples:
  - Both neutrino and antineutrino beam modes
- Separated into sub samples based on reconstructed elasticity: EHadronic/ETotal
  - Improved sensitivity to interaction-mismodelling
  - Isolating higher resolution sub-samples (less EHadronic) → more disappearance shape sensitivity



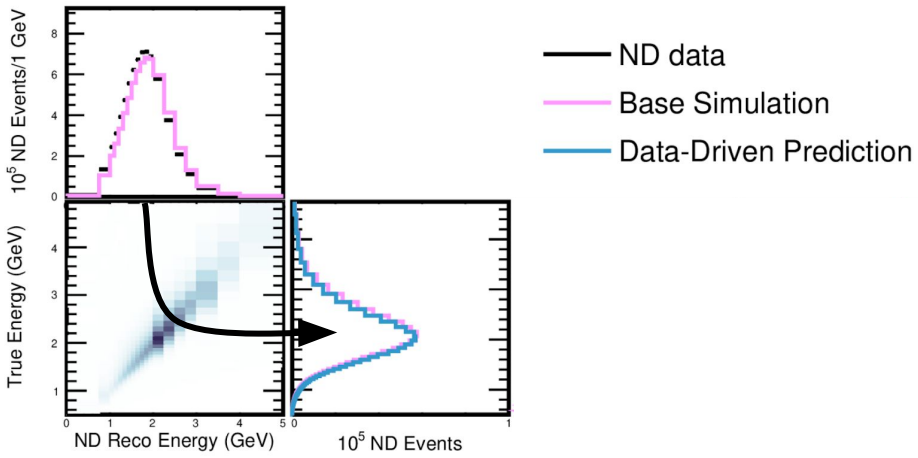
Near to Far Extrapolation



ND data
Base Simulation

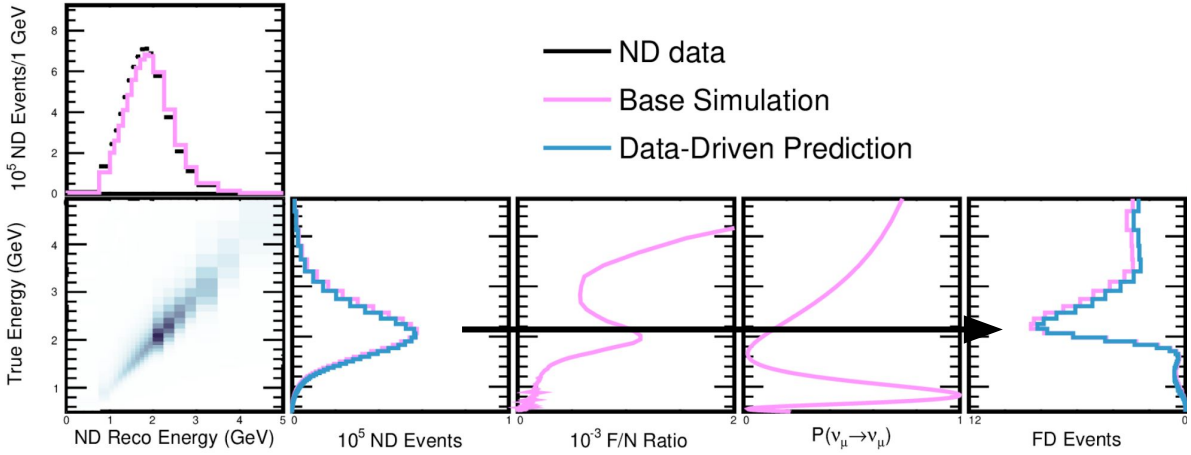
1. **Sample near detector events**

Near to Far Extrapolation



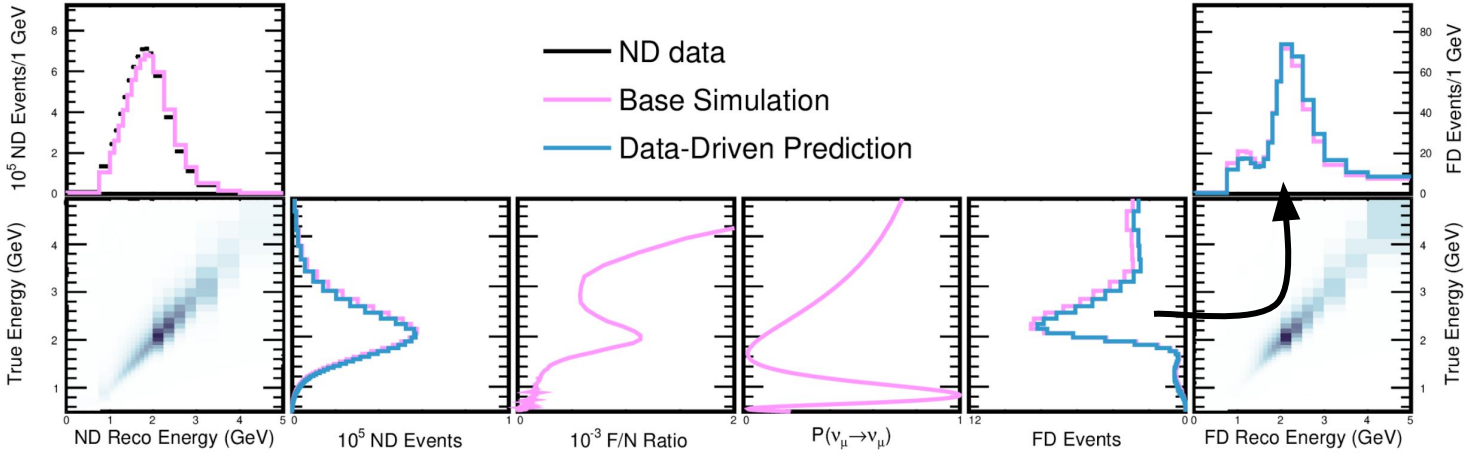
1. Sample near detector events
2. **Estimate true neutrino energy spectrum with interaction model**

Near to Far Extrapolation



1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model
3. **Account for far/near differences and oscillate true spectrum**

Near to Far Extrapolation

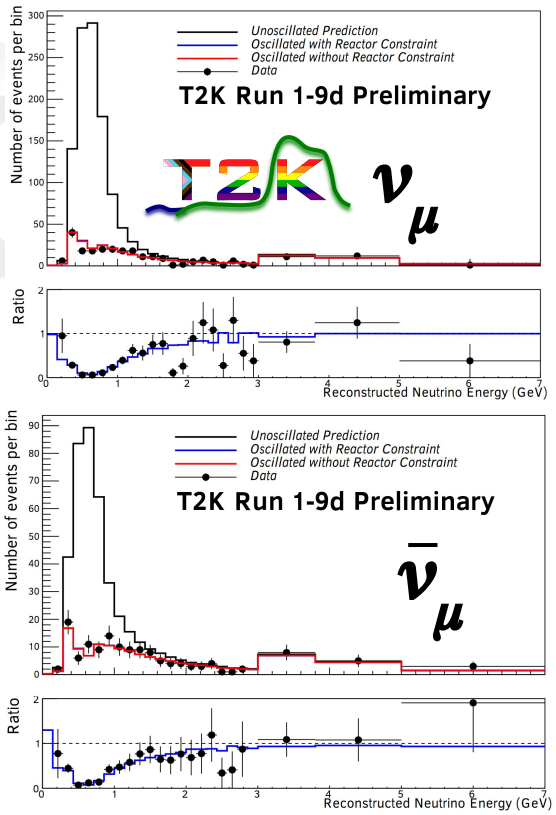


1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model
3. Account for far/near differences and oscillate true spectrum
4. **Predict observed oscillated spectrum and compare for goodness of fit.**

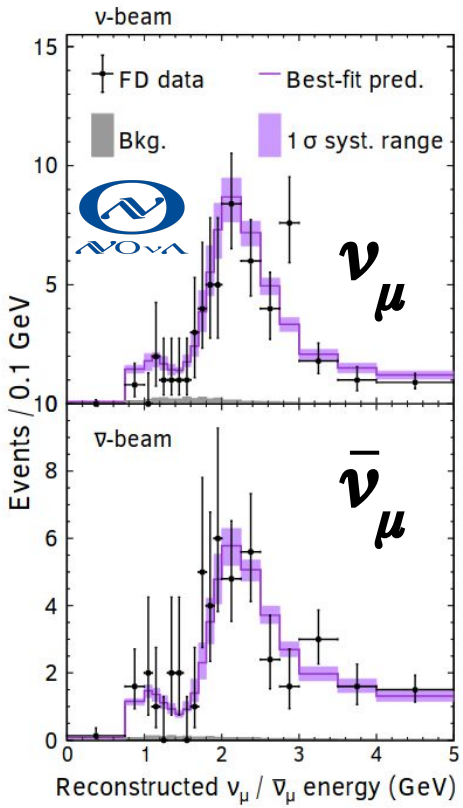
Oscillation Physics Results

Muon-like samples

- Both analysis simultaneously fit:
  - Both beam modes
  - Mu-like and e-like
- Clear oscillation shape in muon-like samples.



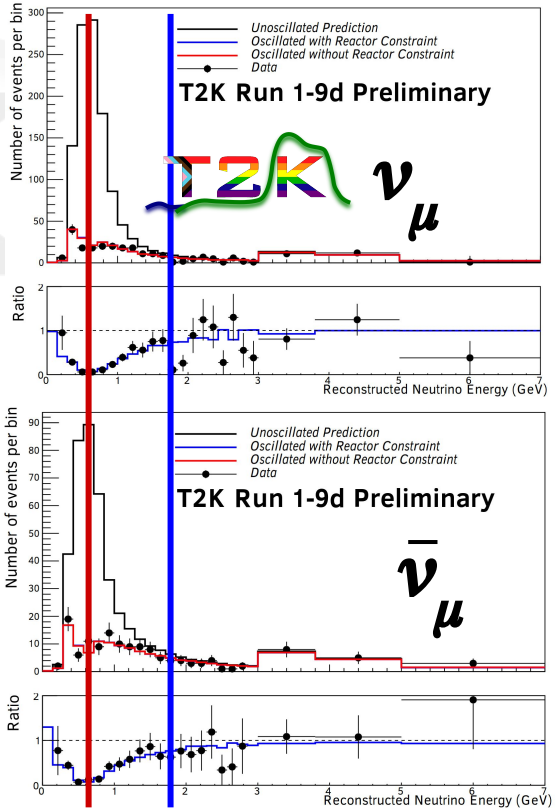
Phys. Rev. Lett. 123, 151803



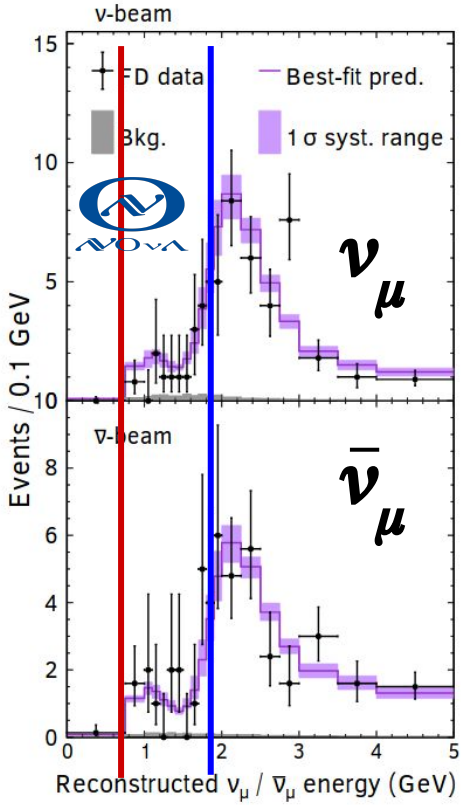
Muon-like samples

- Both analysis simultaneously fit:
  - Both beam modes
  - Mu-like and e-like
- Clear oscillation shape in muon-like samples.
- Different baselines, energies:
  - Complementary sensitivity

Peak Energy



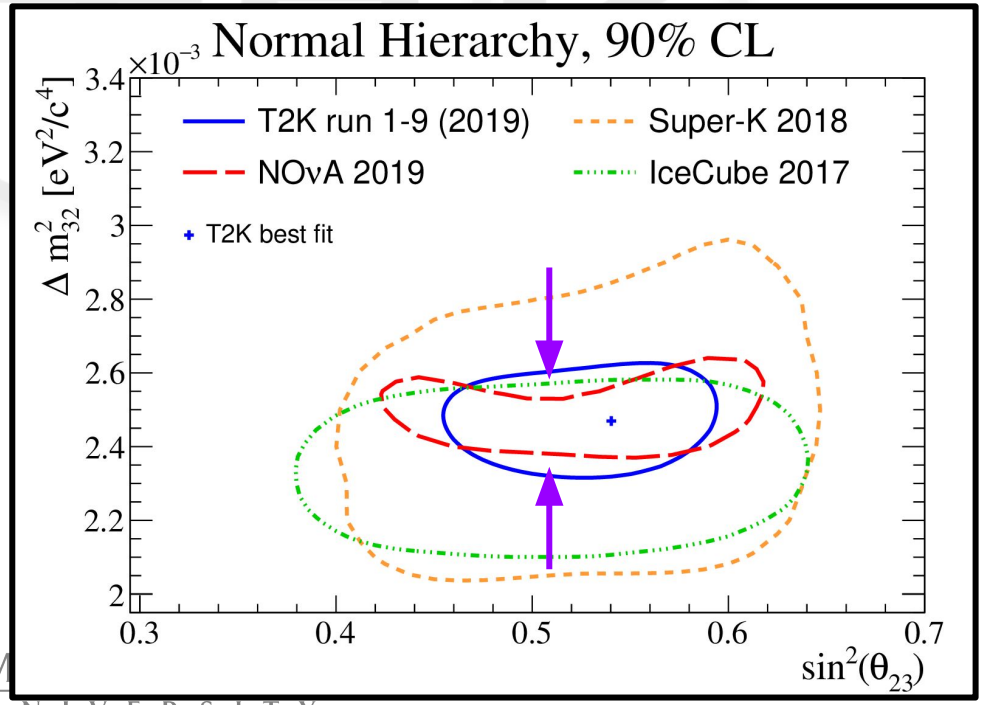
Phys. Rev. Lett. 123, 151803

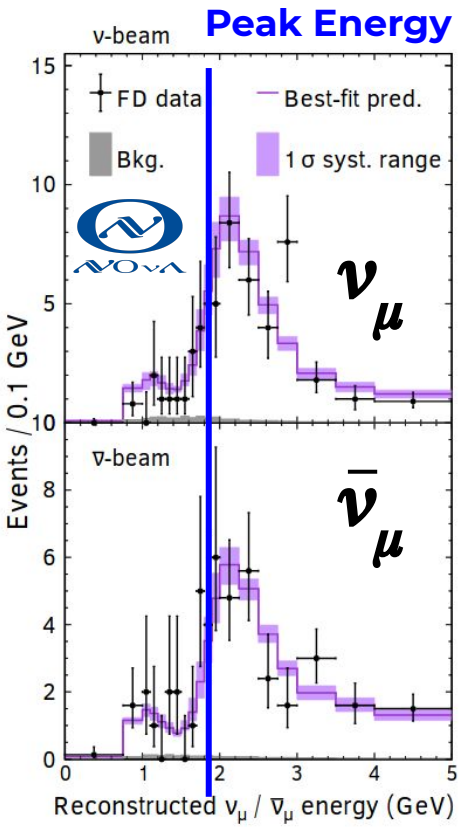


Disappearance Constraints

Phys. Rev. Lett. 123, 151803

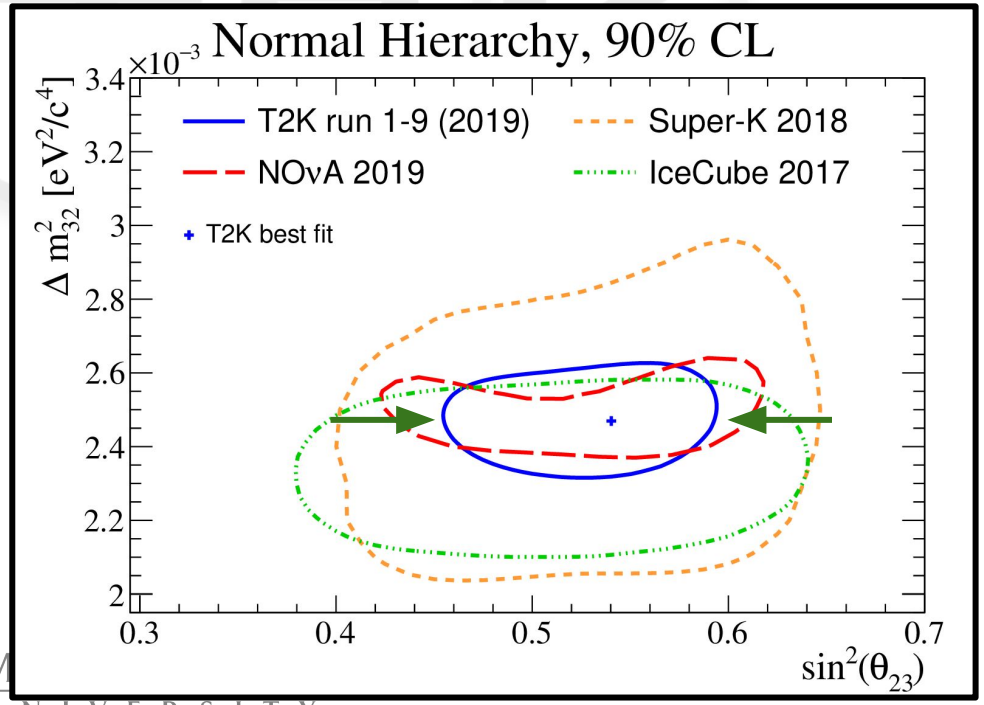
- NOvA provides slightly tighter constraint of mass-squared splitting

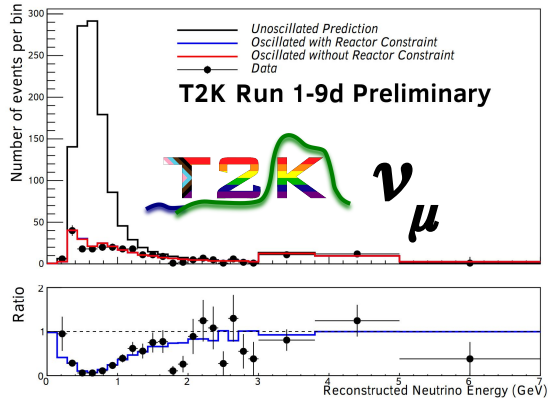


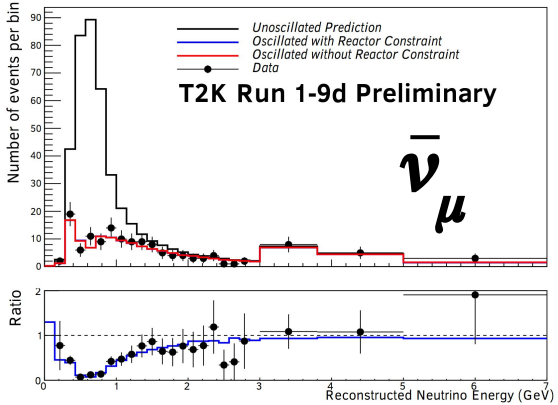


Disappearance Constraints

- T2K provides slightly tighter constraint ofthe mixing angle





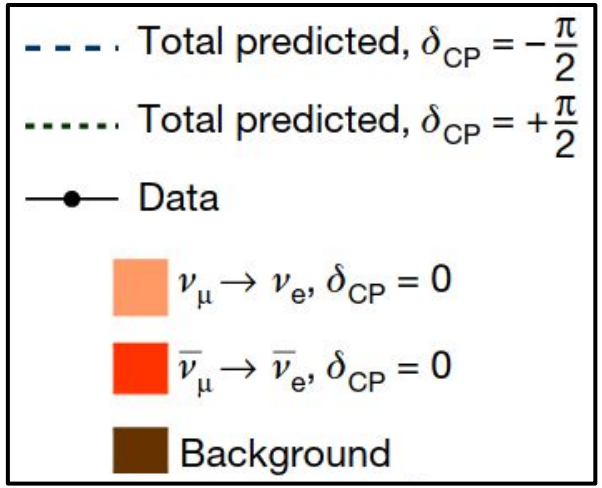


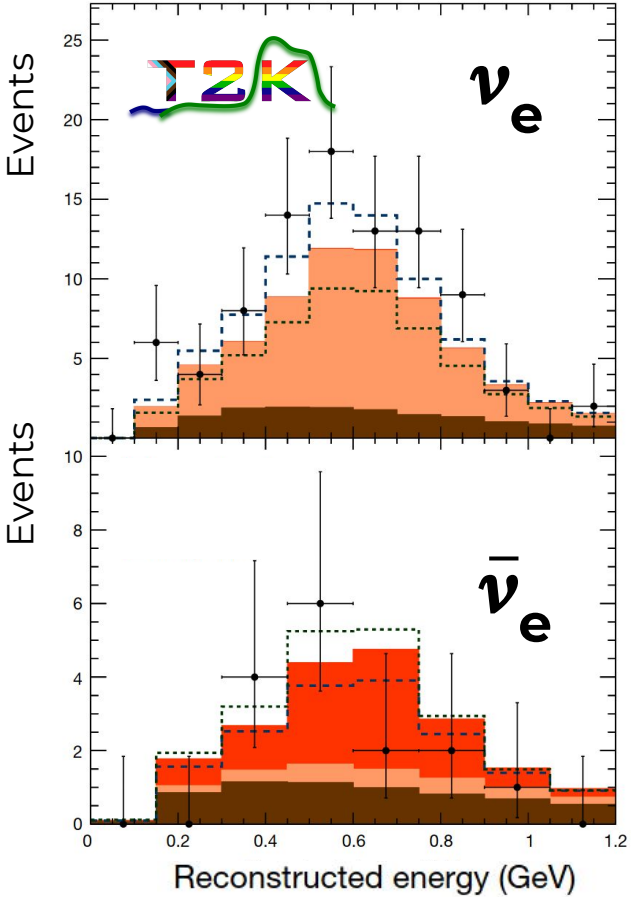
Electron-like samples

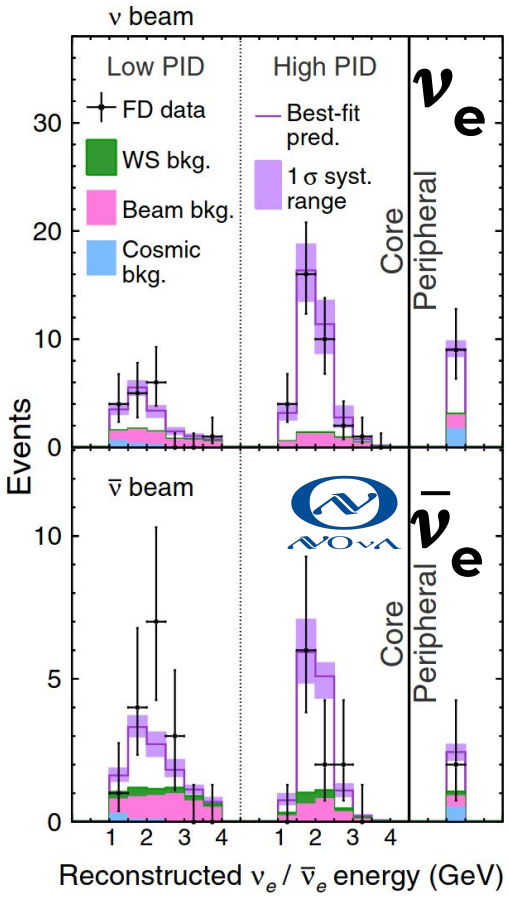
Nature 580 7803 p339-344

Phys. Rev. Lett. 123, 151803

- Both experiments:
  - See significant electron appearance above background
  - In both neutrino and antineutrino beam modes







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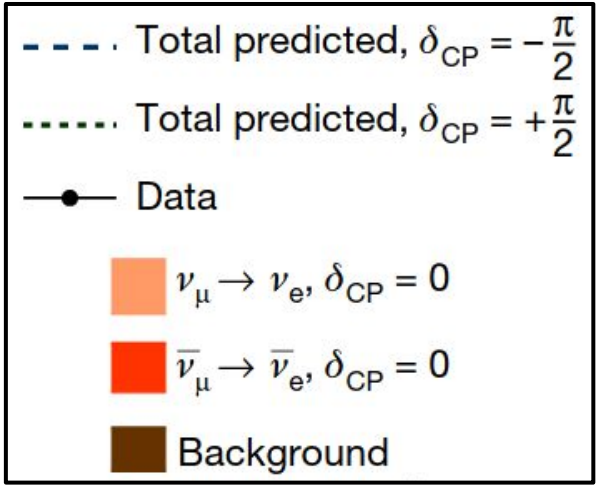
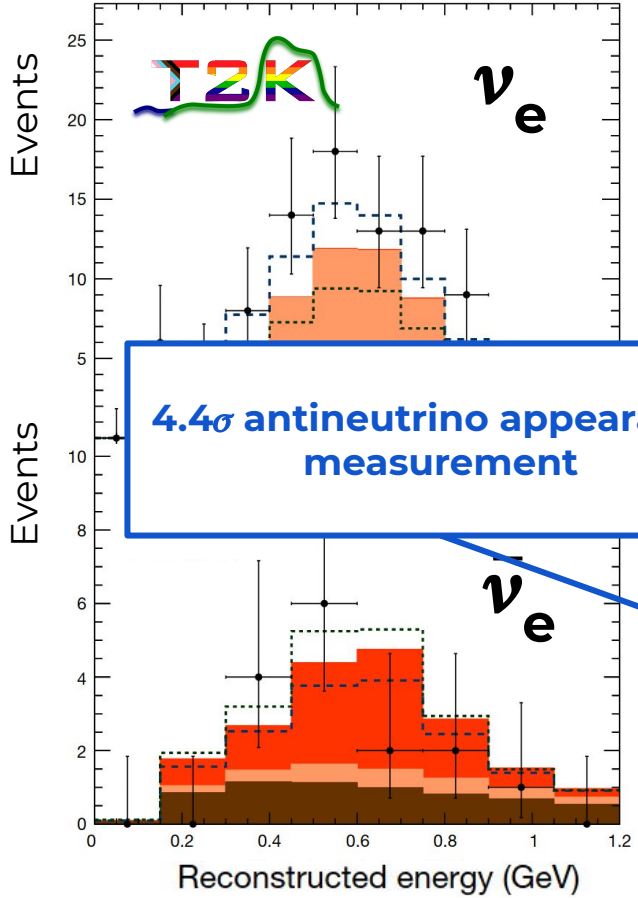
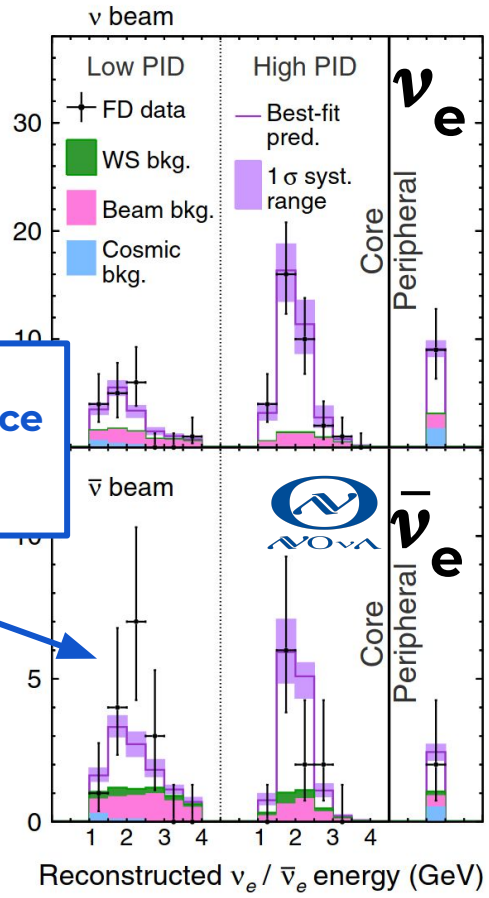




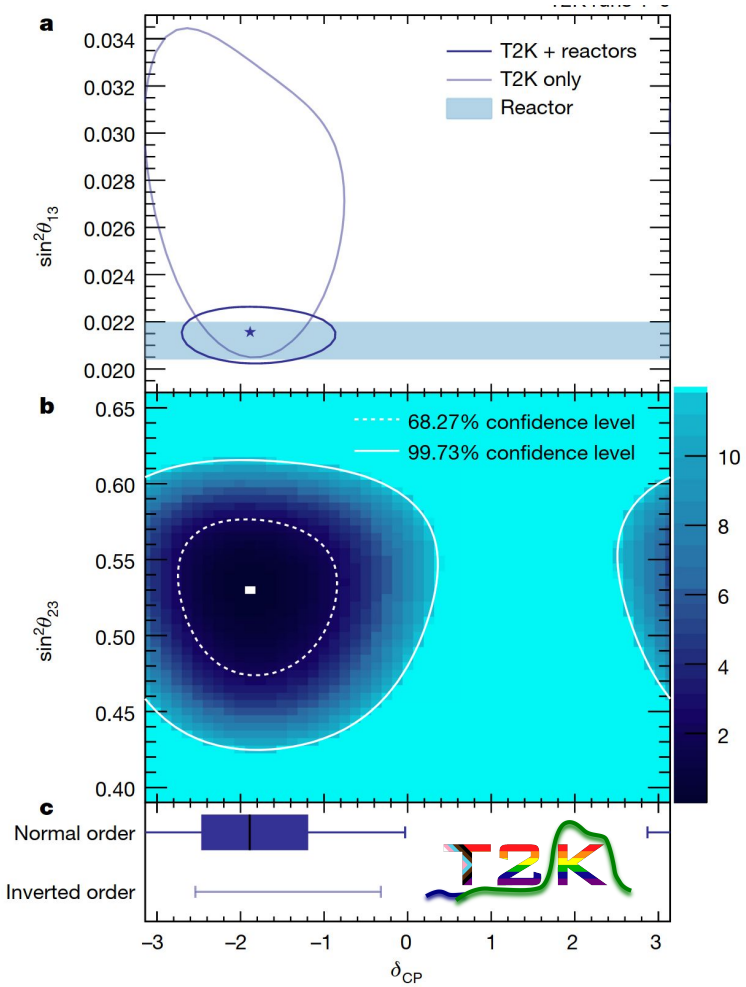


4.4σ antineutrino appearance measurement

Appearance Constraints

- Both analyses include θ_{13} constraint from reactor data.

Nature 580 7803 p339-344



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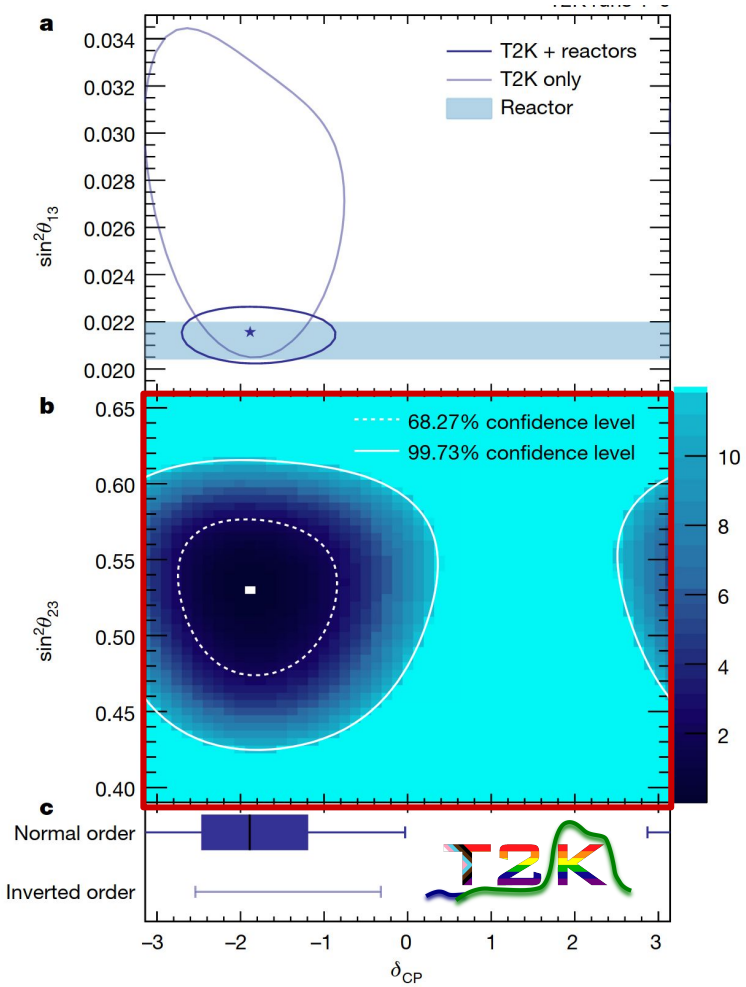

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Phys. Rev. Lett. 123, 151803

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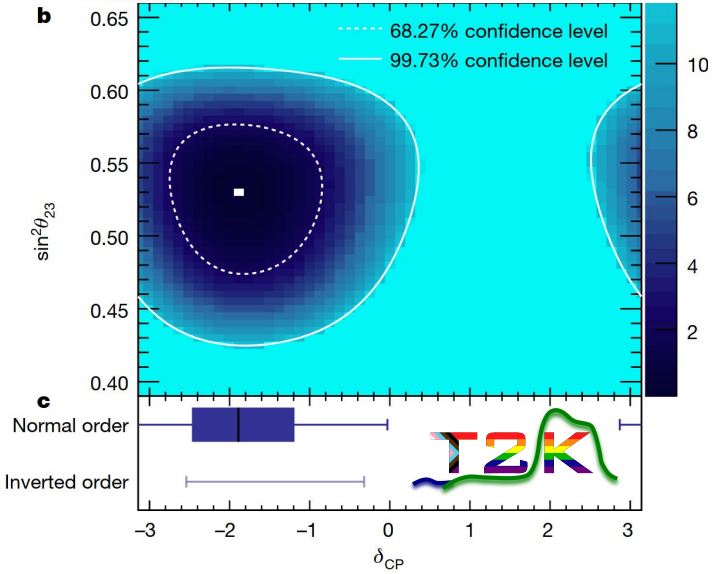

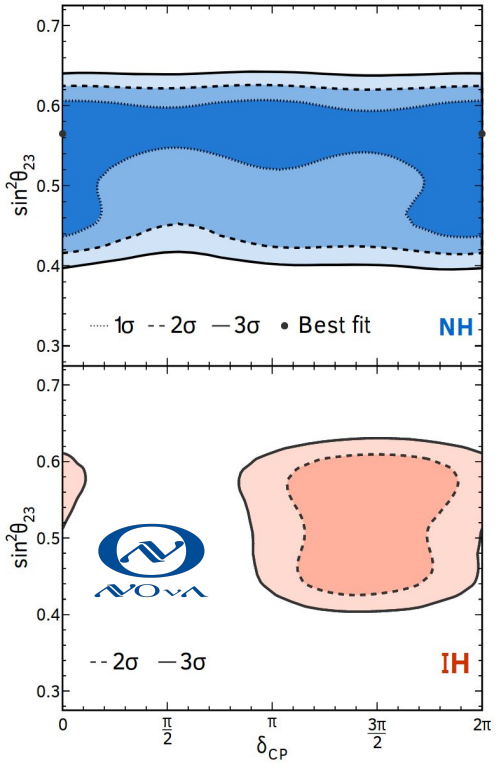

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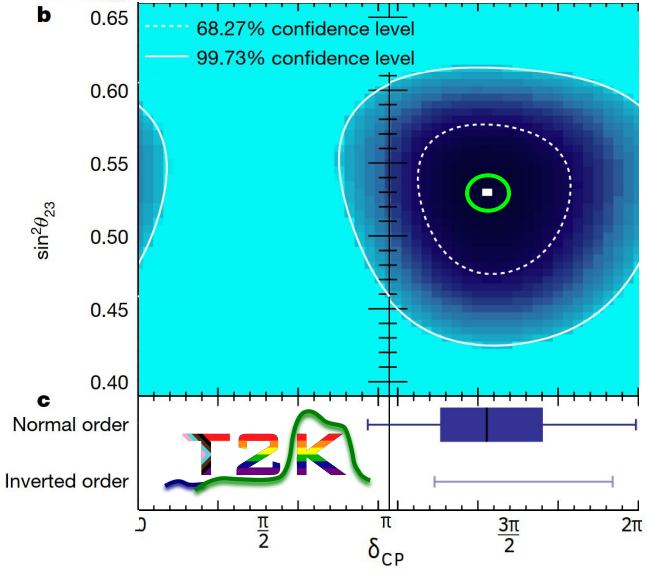
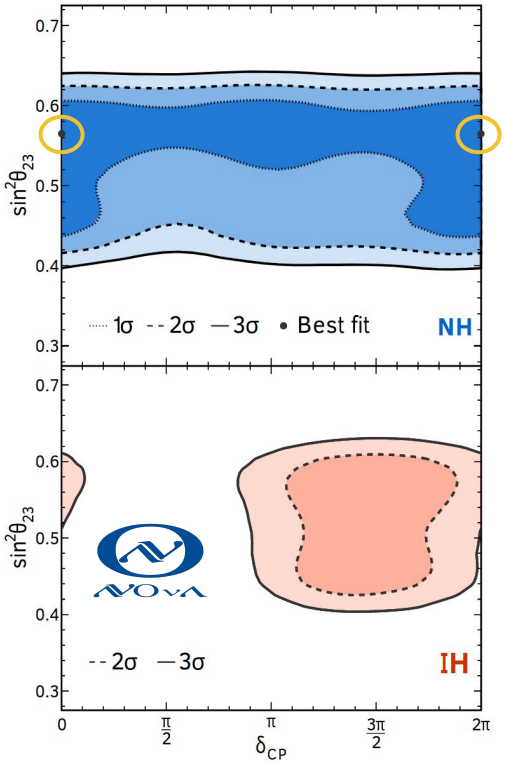
Nature 580 7803 p339-344





Appearance Constraints

Phys. Rev. Lett. 123, 151803

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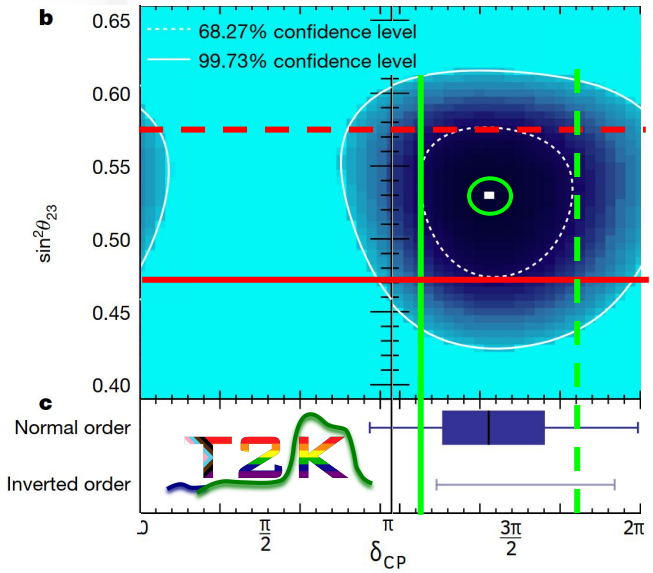
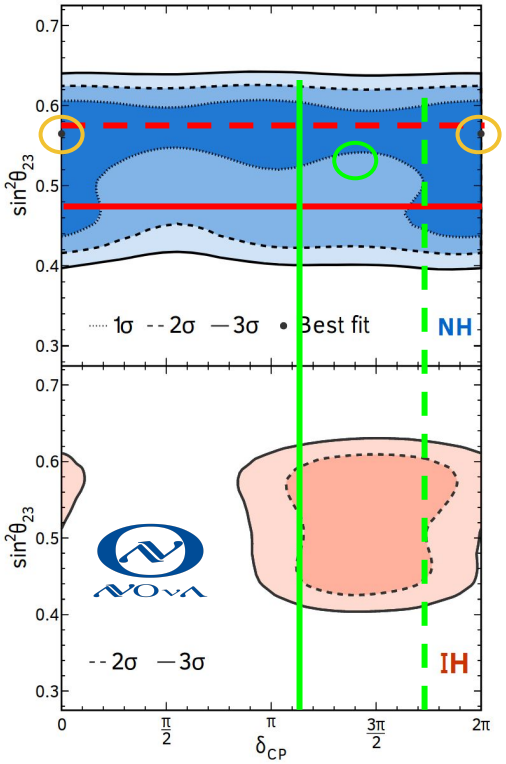
Nature 580 7803 p339-344





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Phys. Rev. Lett. 123, 151803

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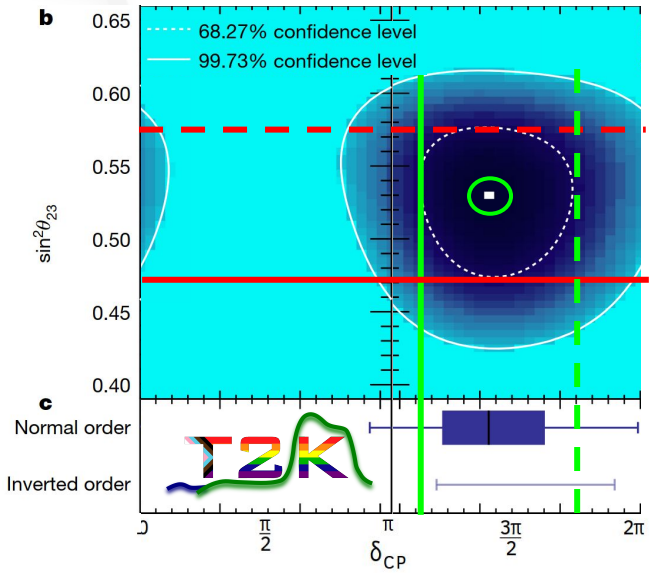
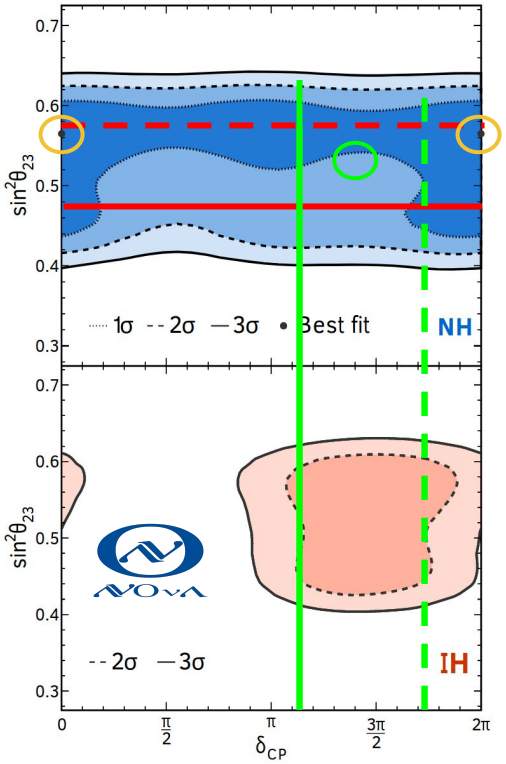
Nature 580 7803 p339-344



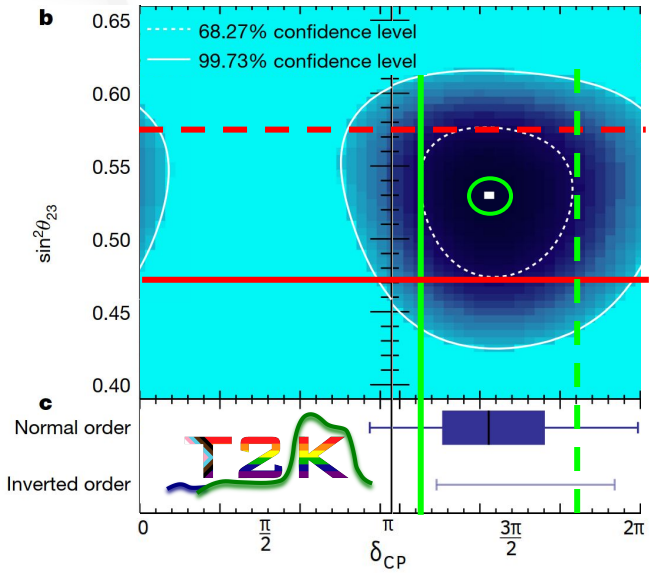


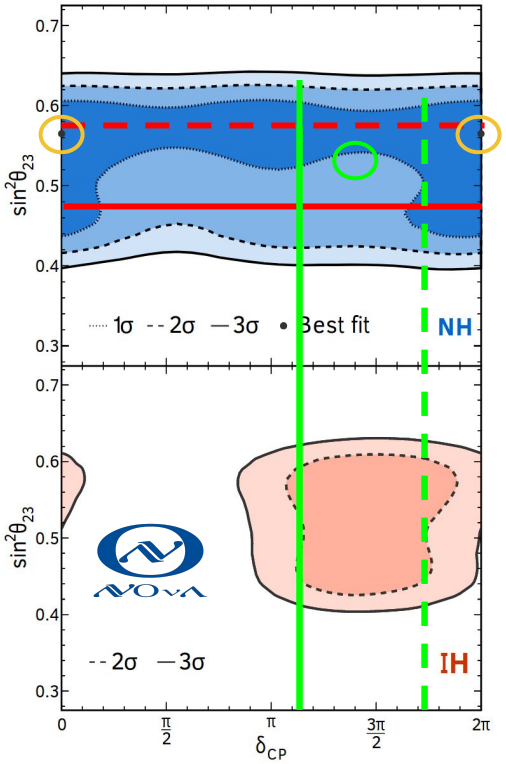
Appearance Constraints

Phys. Rev. Lett. 123, 151803

- Overlapping 1σ regions.
- Both analyses disfavor the inverted mass hierarchy.
- Latest T2K: First result favoring values at 3σ.
  - **Disfavors CP conservation at 2σ**

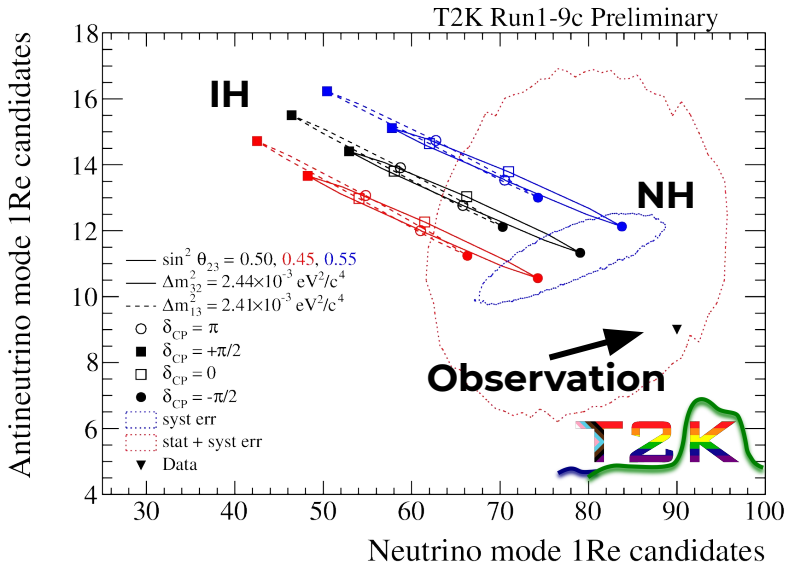
Nature 580 7803 p339-344





Matter vs. Antimatter rates

J. Wolcott, FNAL UM2019



- Compare expected and observed ν_e and $\bar{\nu}_e$ rates:
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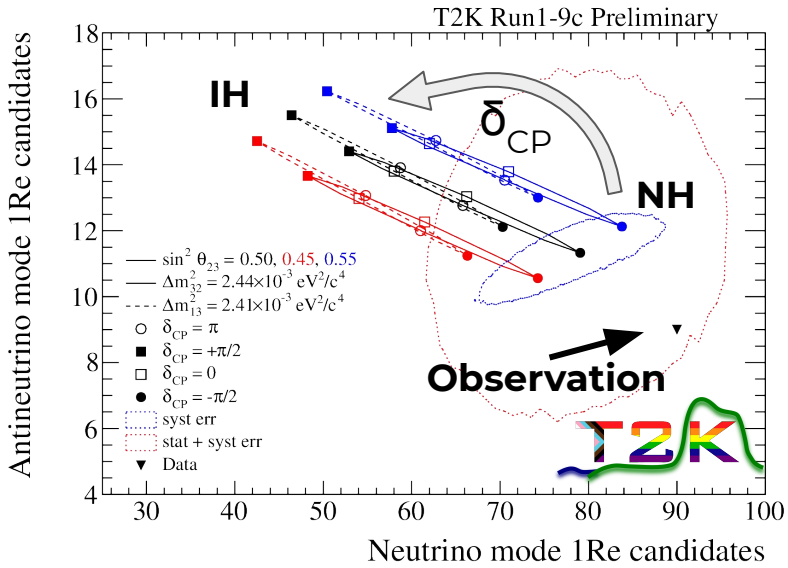

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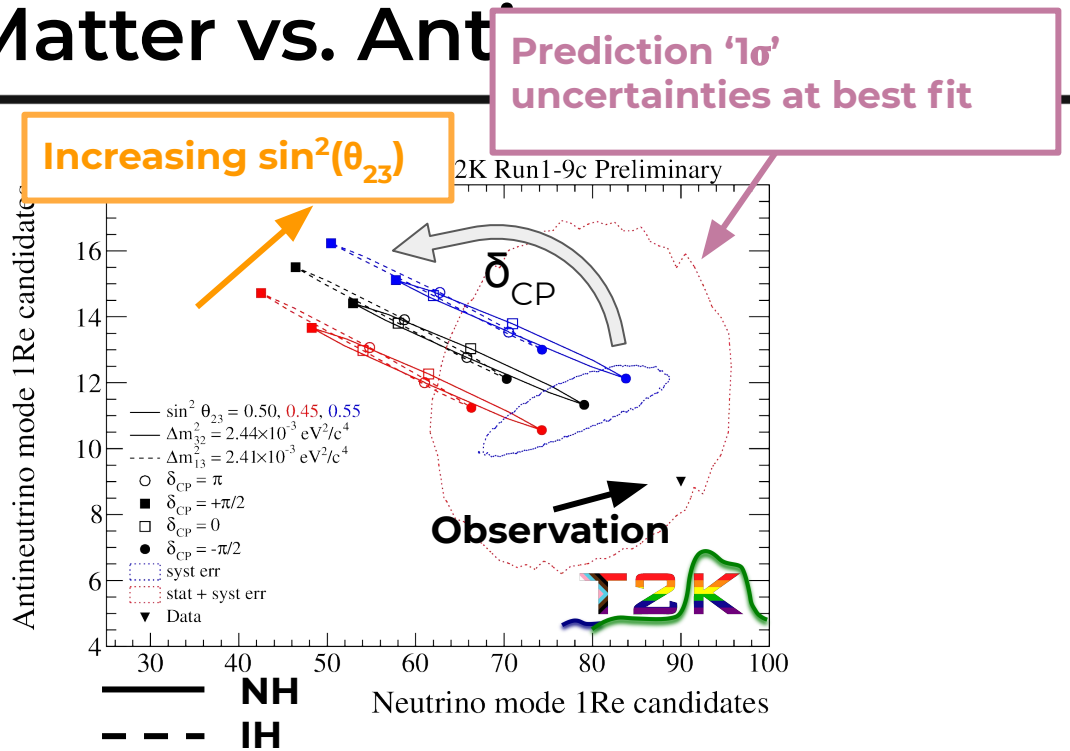

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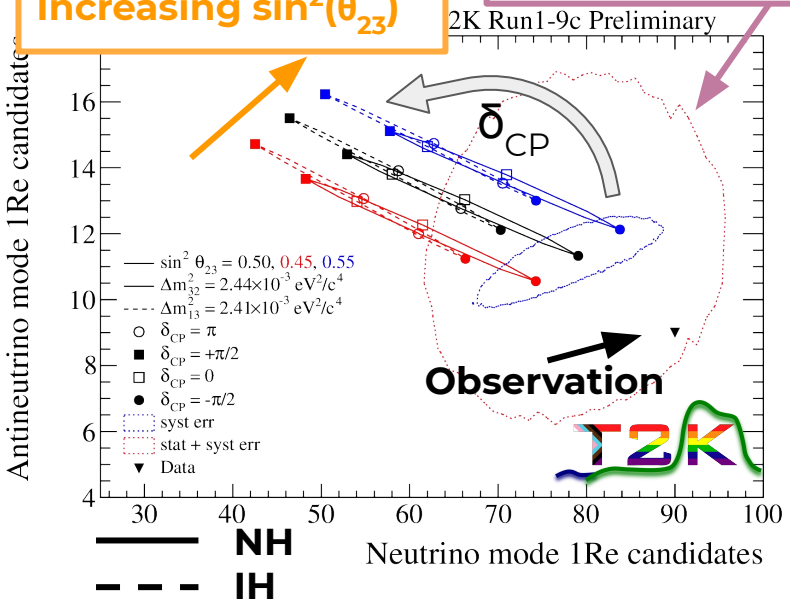
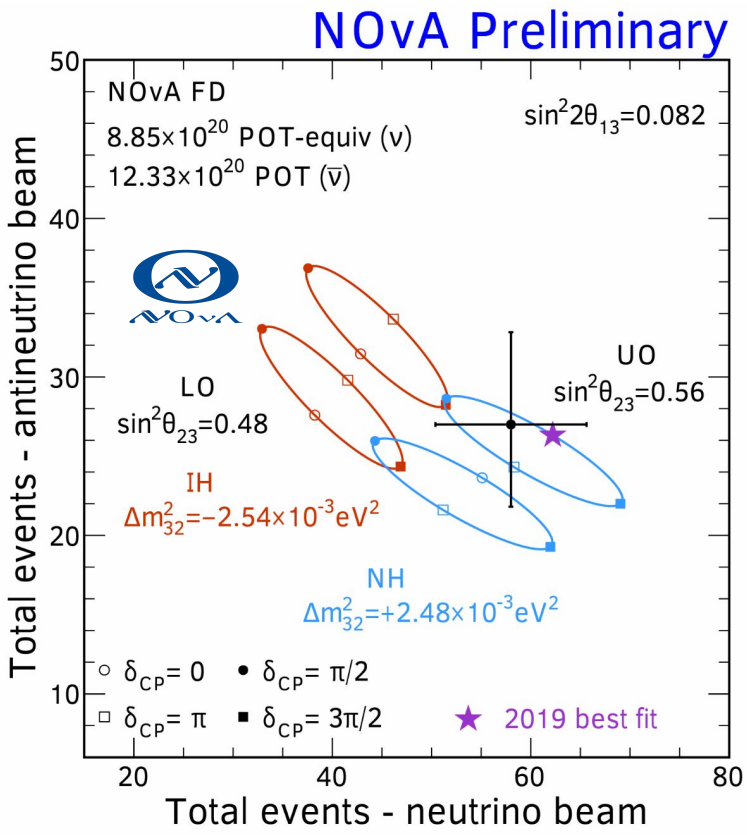
Matter vs. Anti

J. Wolcott, FNAL UM2019

Prediction '1σ' uncertainties at best fit

Increasing $\sin^2(\theta_{23})$





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T2K-NOvA Complementarity

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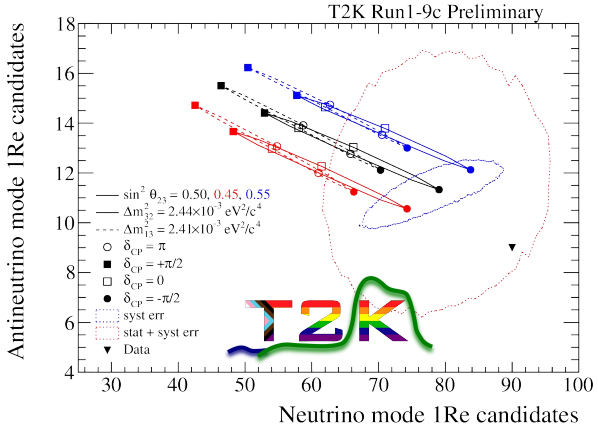
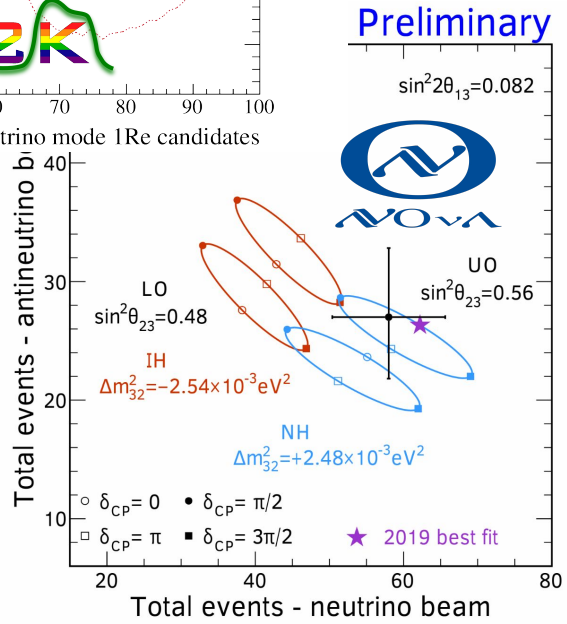
- Complementary sensitivities:
  - Degenerate dcp/hierarchy values for one baseline not for the other.





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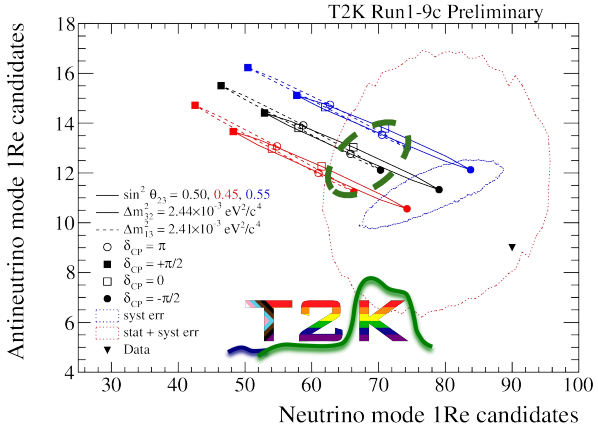
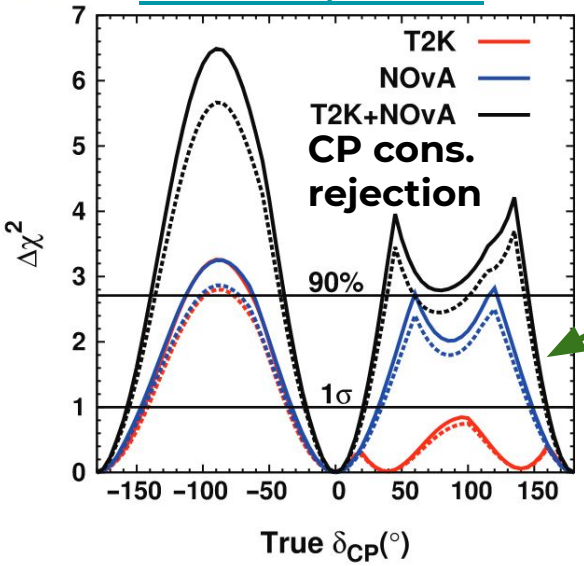
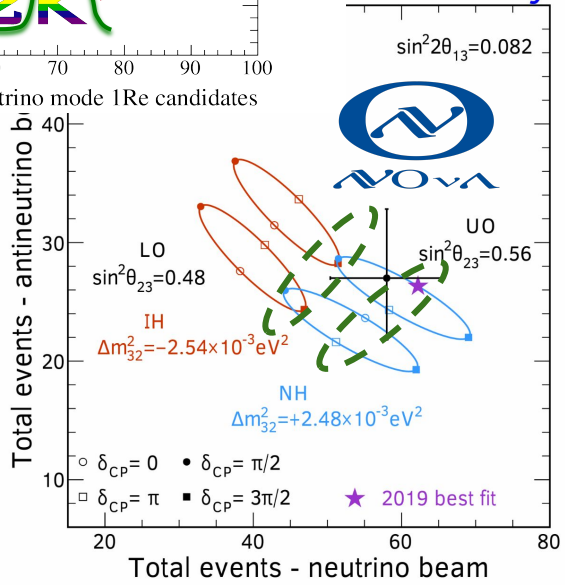


(b) PTEP2015, 043C01



Degenerate for T2K but not NOvA

Preliminary



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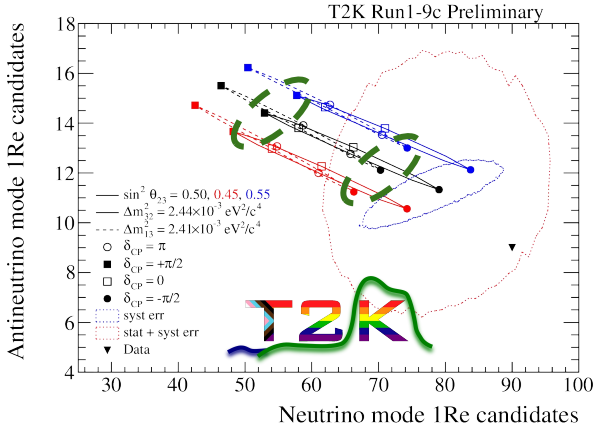
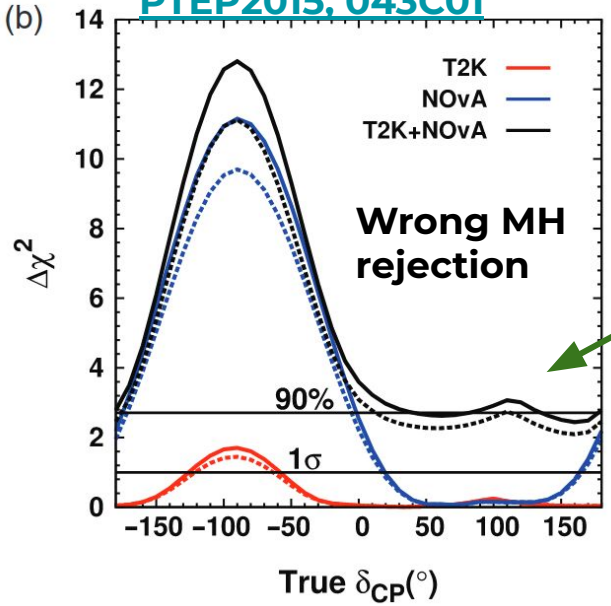
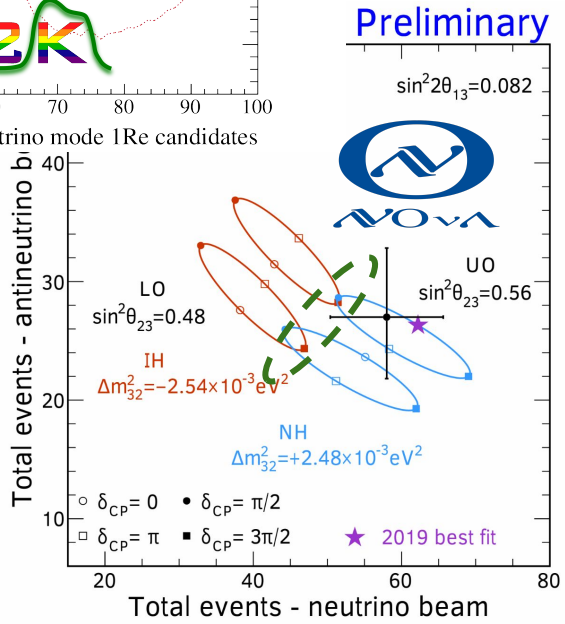


PTEP2015, 043C01



Degenerate for NOvA but not T2K+NOvA



Joint Fit

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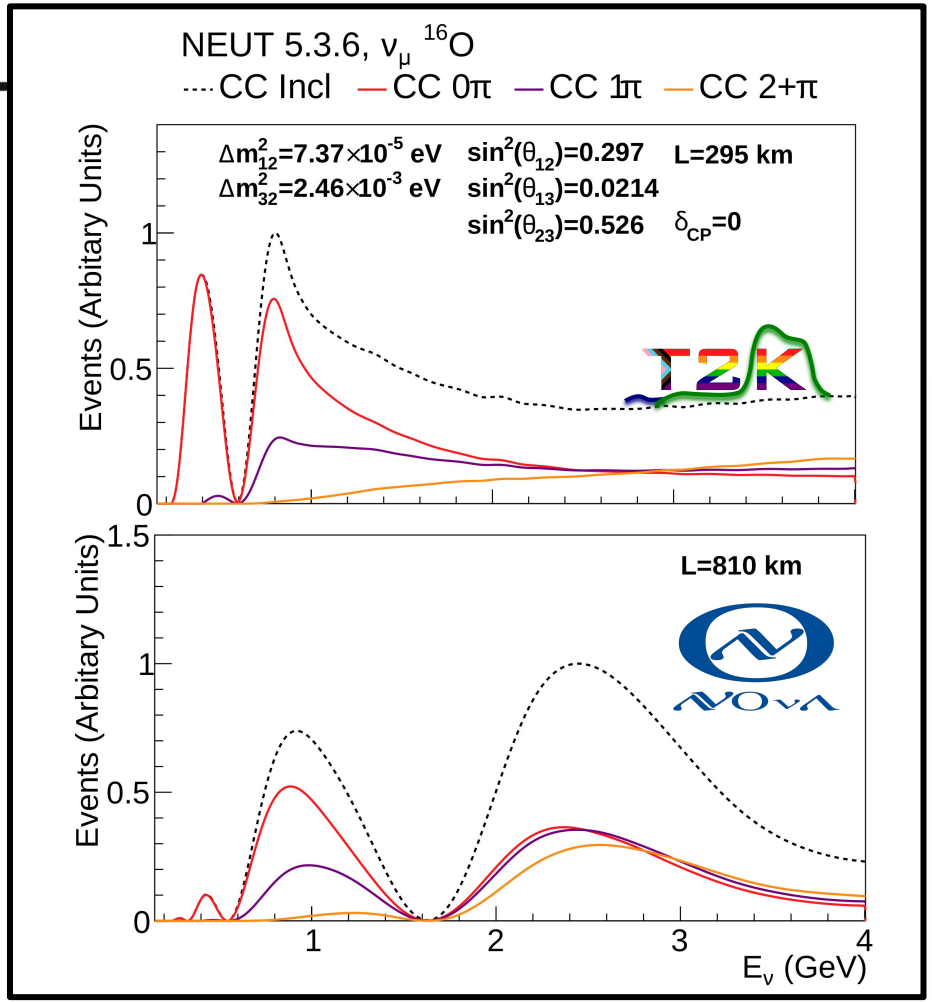

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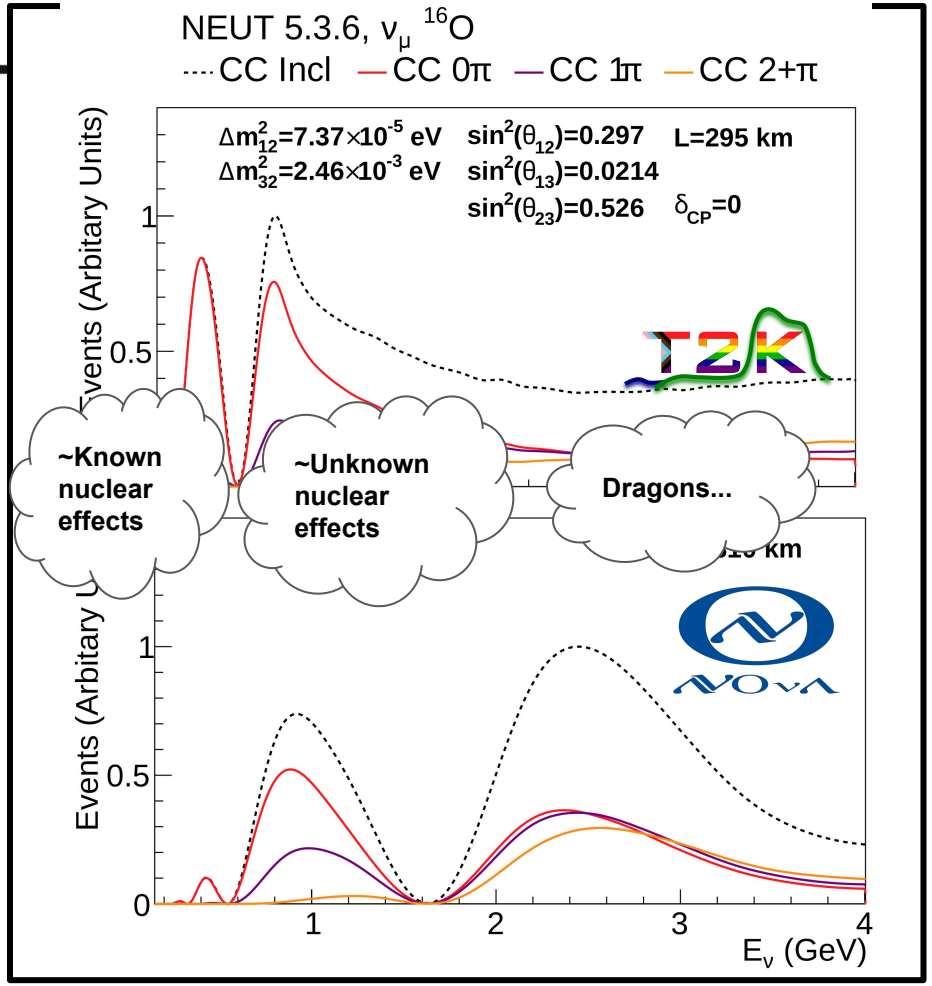
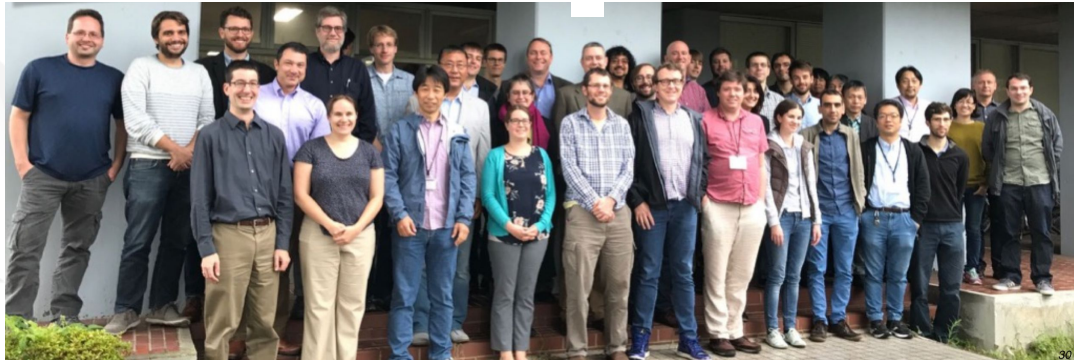


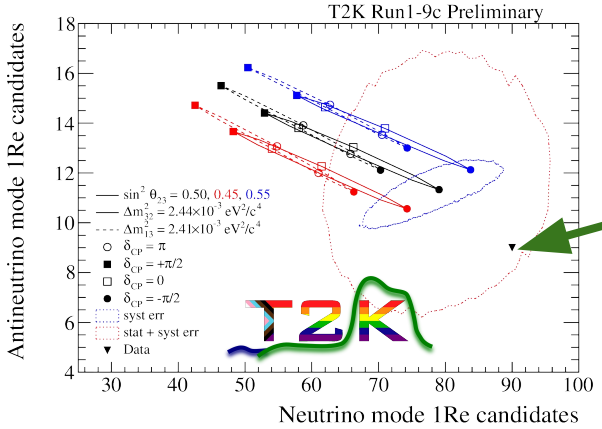
T2K-NOvA

- Joint analysis workshops on-going:
  - Four successful meetings since 2017 J-PARC and FNAL
  - Strong US-Japan support!
- Challenging joint analysis:
  - Different experimental setups
  - Different peak energy
  - Different analysis methodology
- But T2K-NOvA sensitivity is worth the challenge!

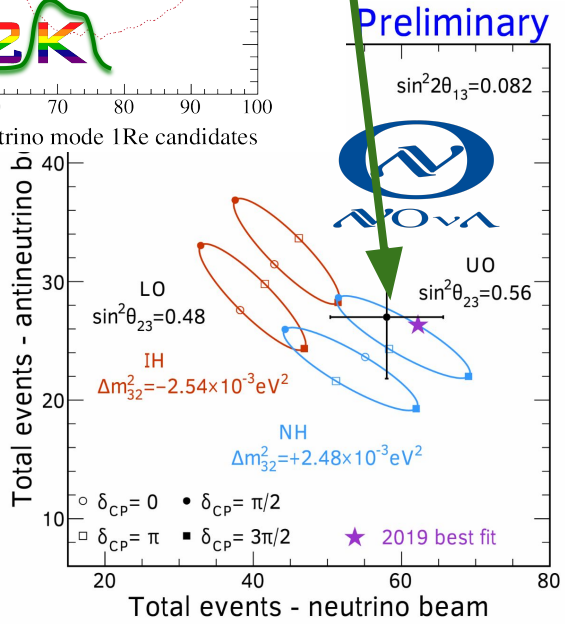


Summary

- It's an exciting time in long baseline neutrino physics!
- Precision measurements of neutrino mixing parameters.
- Seeing sensitivity to lepton-sector CPV.
- Exciting prospect for joint analysis exploiting rich NOvA-T2K complementarity for CPV sensitivity.



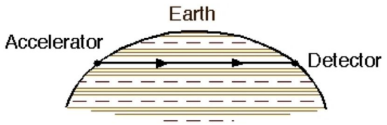
Where will these be next year?



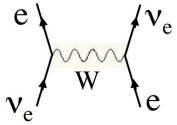

Dawn from the summit of Fuji-san
Thanks for listening
MICHIGAN STATE
UNIVERSITY

Slides from B. Kaser (INSS 2015 Neutrino Osc)

Neutrino Flavor Change In Matter



involves



or

Coherent forward scattering via this W-exchange interaction leads to an extra interaction potential energy —

$$V_W = \begin{cases} +\sqrt{2}G_F N_e, & \nu_e \\ -\sqrt{2}G_F N_e, & \bar{\nu}_e \end{cases}$$

Fermi constant — Electron density

This raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

18

The fractional importance of matter effects on an oscillation involving a vacuum splitting Δm^2 is —

$$\underbrace{[\sqrt{2}G_F N_e]}_{\text{Interaction energy}} \,/\, \underbrace{[\Delta m^2/2E]}_{\text{Vacuum energy}} \equiv x \,.$$

The matter effect —

— Grows with neutrino energy E

— Is sensitive to Sign(Δm^2)

— Reverses when ν is replaced by $\bar{\nu}$

This last is a "fake CP violation" that has to be taken into account in searches for genuine CP violation.

19

Oscillation Results Backup

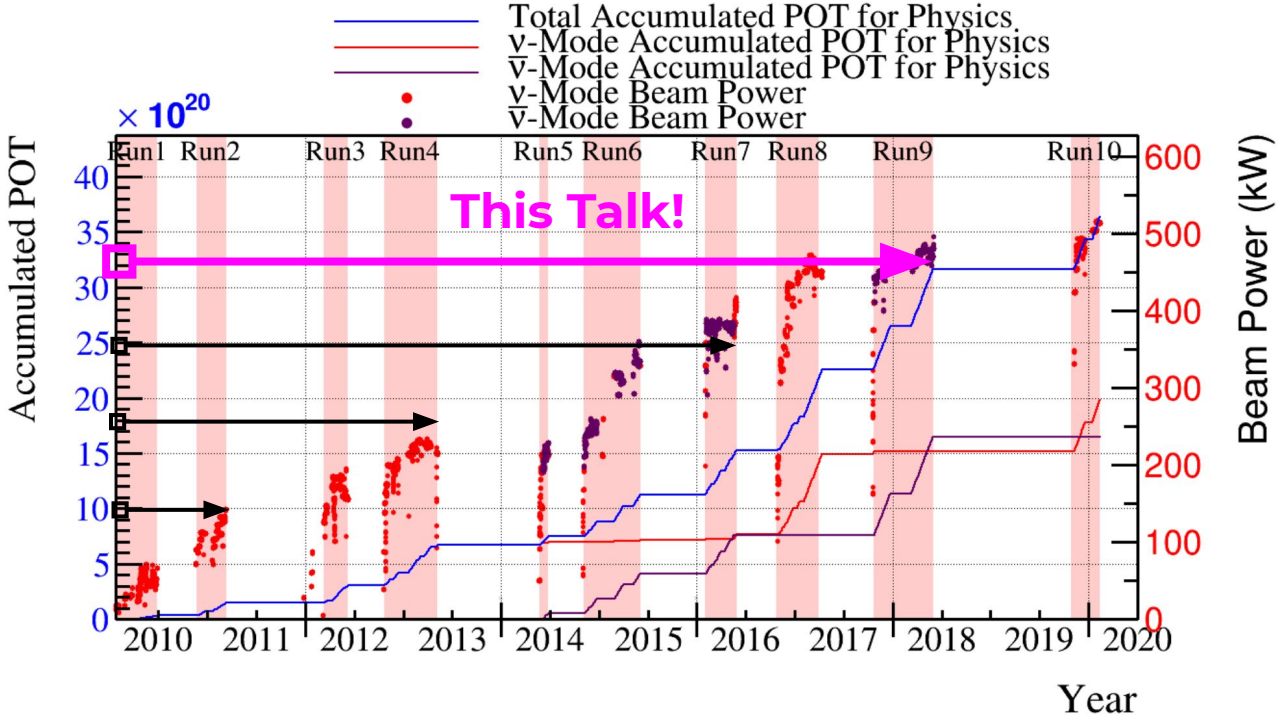
T2K Exposure

Constraint
Nature 580 7803 p339-344

Search for CPV
Phys. Rev. Lett. 121,171802

Observation
Phys. Rev. Lett. 112, 061802

Indication
Phys. Rev. Lett. 107, 041801



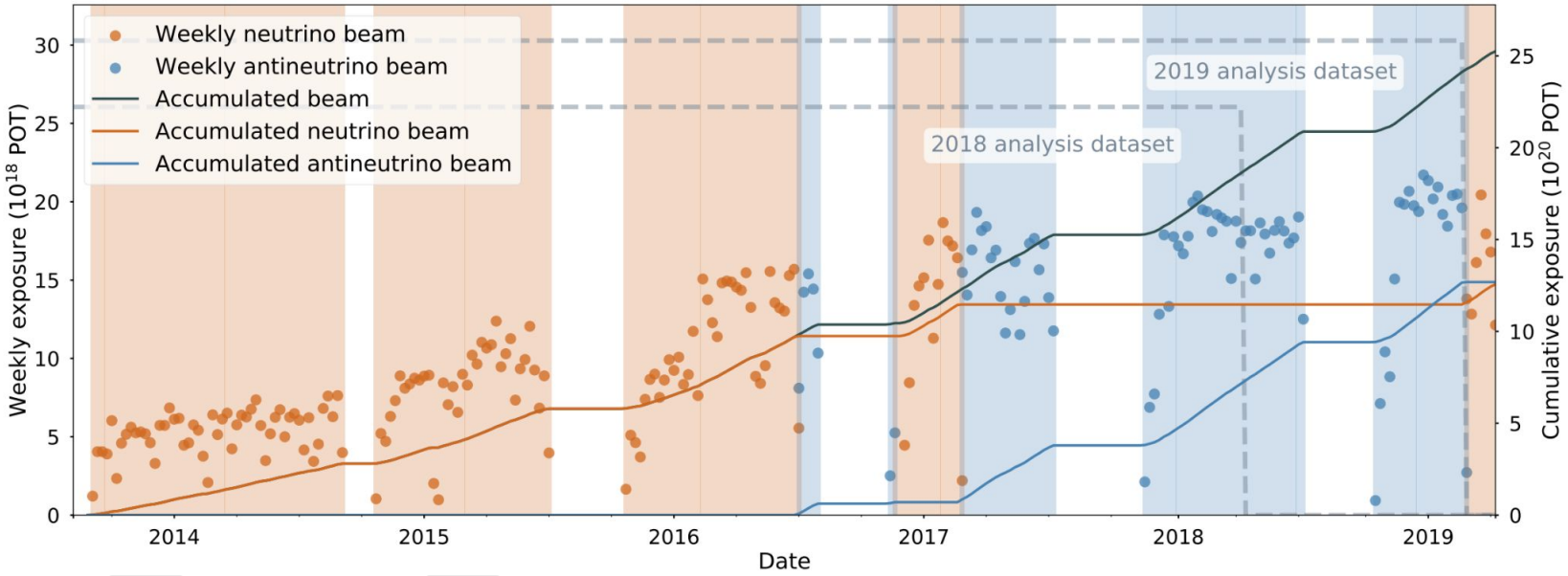
23 Jan 2010 - 12 Feb 2020

POT Total : 3.64059×10^{21}
(maximum power 522.627 kW)

ν mode : 1.99006×10^{21} (54.7%)

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

NOvA Exposure

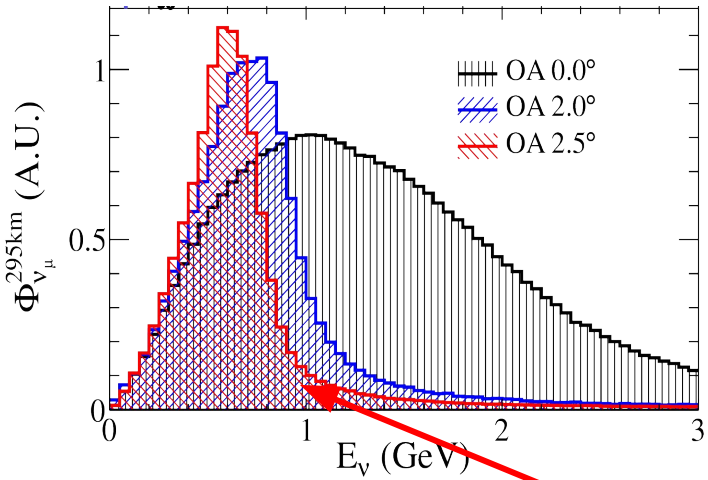


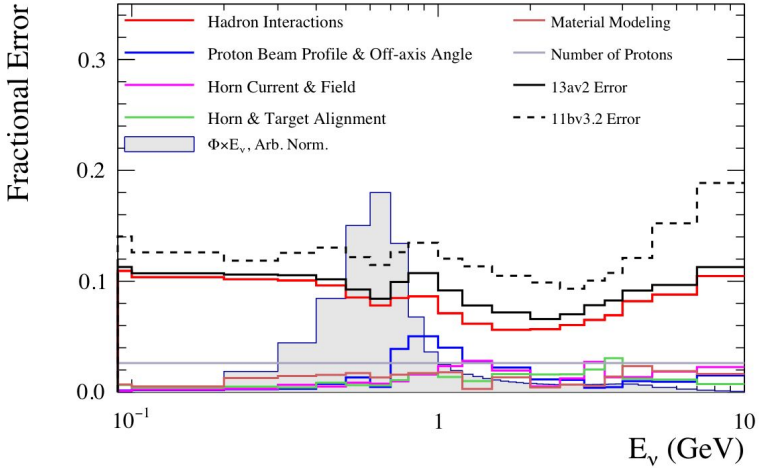
J. Wolcott, FNAL UM2019

758 kW peak hourly avg:

currently highest in the world

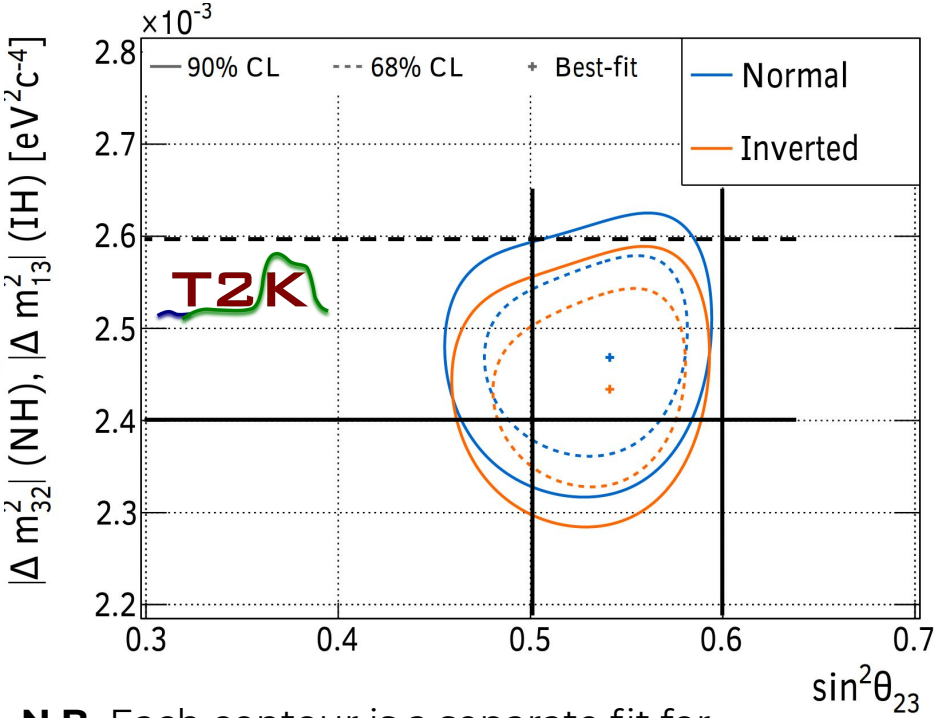
J-PARC Neutrino Beam

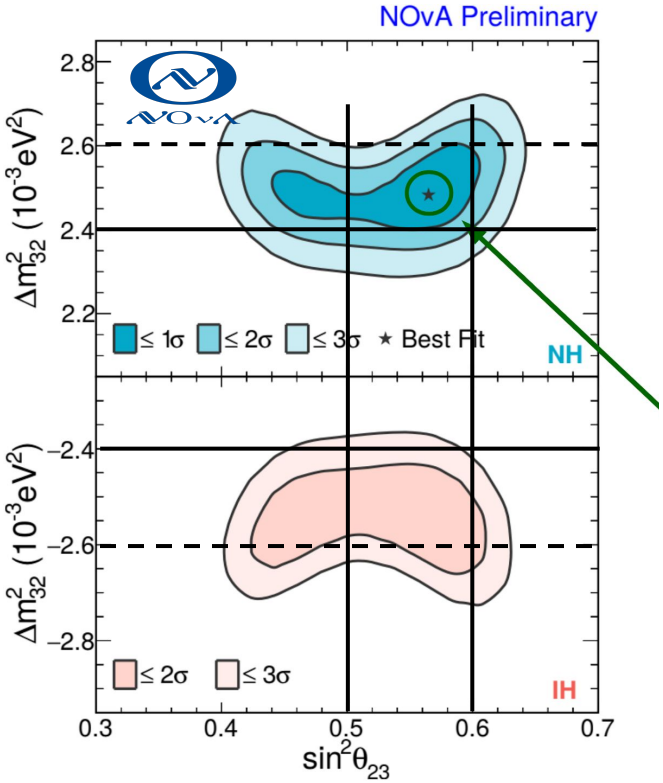




- Main T2K detectors **2.5° off-axis** with respect to the beam:
  - Kinematics of boosted pion decays result in a finer beam width, peaked around ideal L/E.
- Uncertainties dominated by **hadron-production**:
  - Simulation tuned to NA61/SHINE hadron-production data.
  - Currently ~10% uncertainty in the beam peak.

Disappearance Results (w/IH)





N.B. Each contour is a separate fit for T2K: (global fit disfavors IH to 1σ)

Oscillation Results: Sources of Error

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others	+1.6/-1.6	+1.5/-1.5	+1.4/-1.2	+1.0/-1.0
Total	+7.4/-8.5	+5.6/-6.2	+5.8/-6.4	+6.3/-4.9

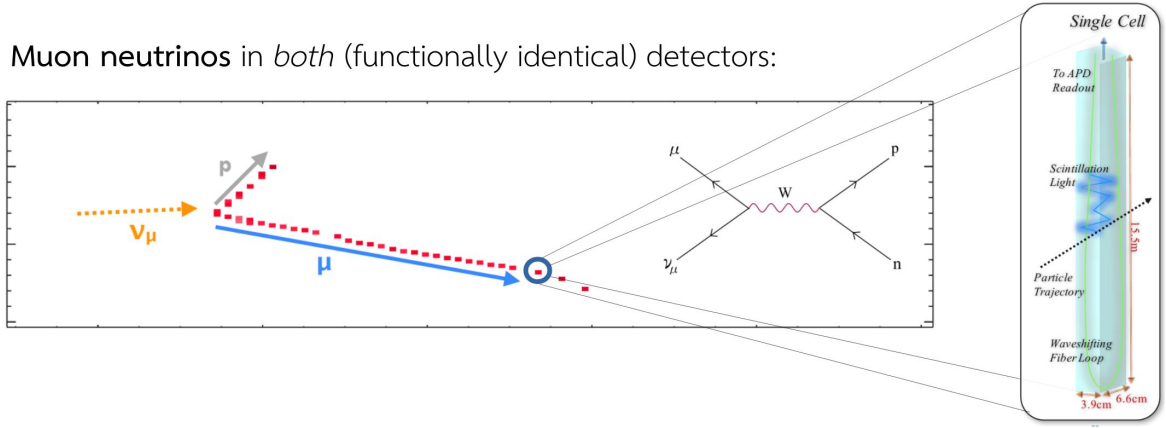
- Neutrino interaction uncertainties large for both experiments

NOvA Oscillation Details

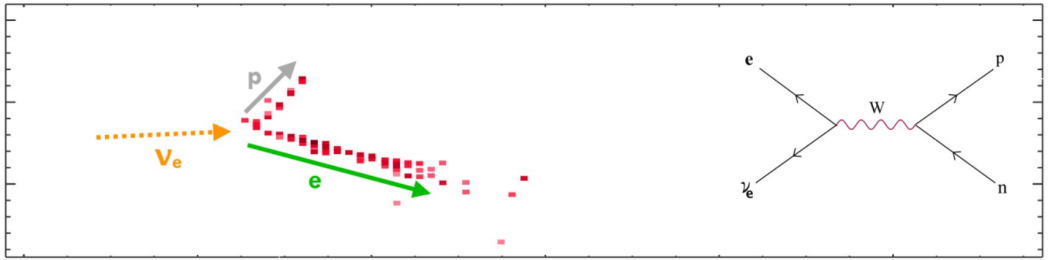
Event Displays

J. Wolcott, FNAL UM2019

Muon neutrinos in *both* (functionally identical) detectors:



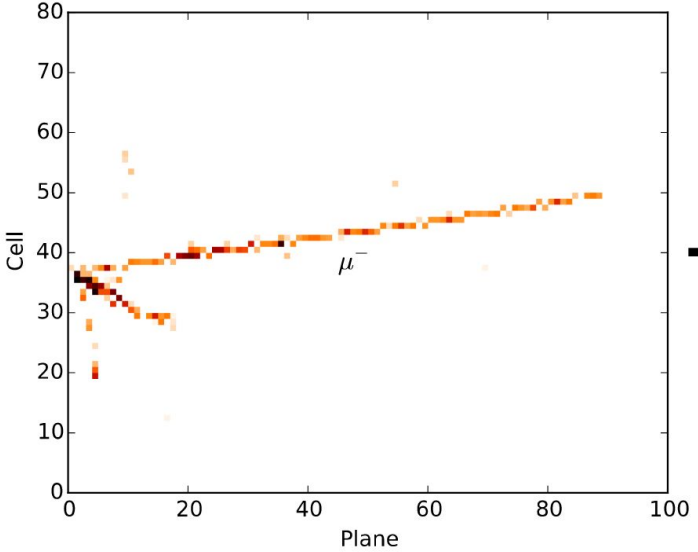
Electron neutrinos in *both* (functionally identical) detectors:



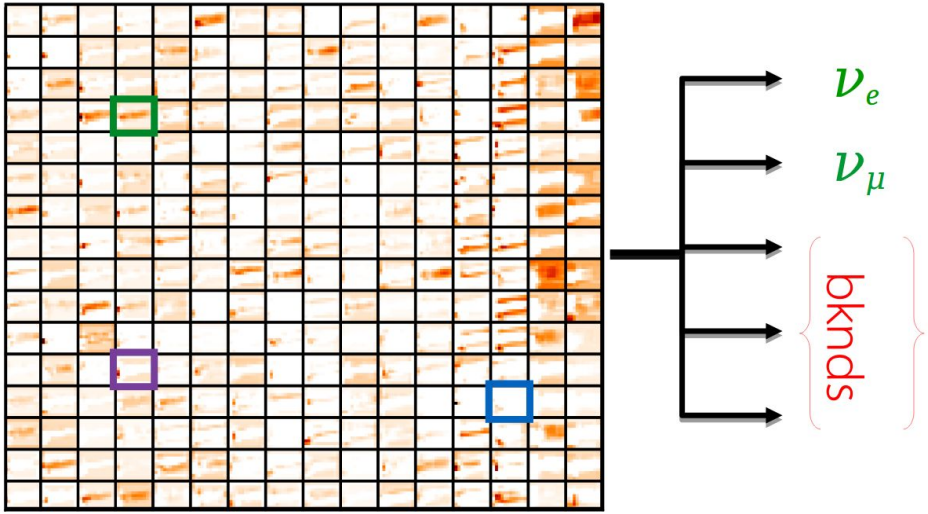
Selection

J. Wolcott, FNAL UM2019

Input Image



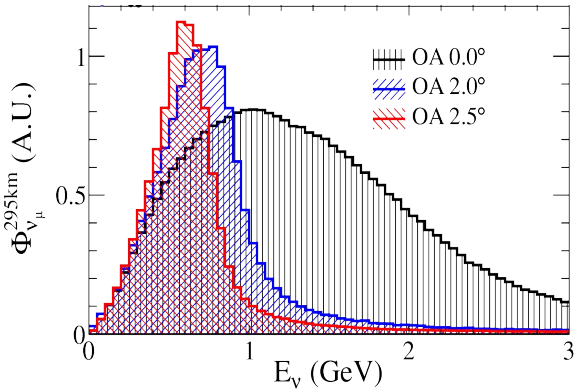
Learned variations on the original image



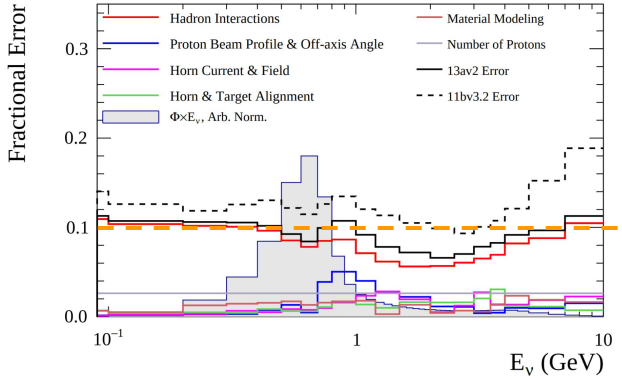
T2K Oscillation Details

J-PARC Neutrino Beam

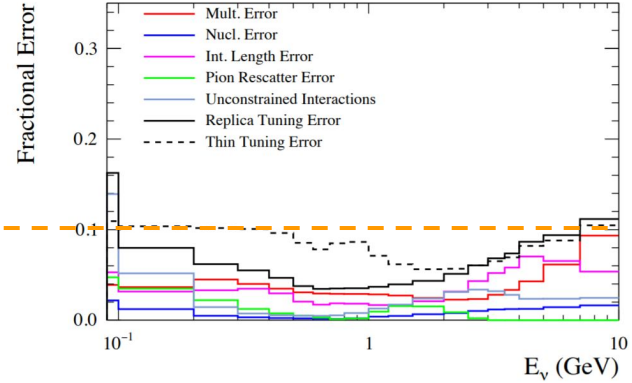
L. Pickering



Thin target flux uncertainties



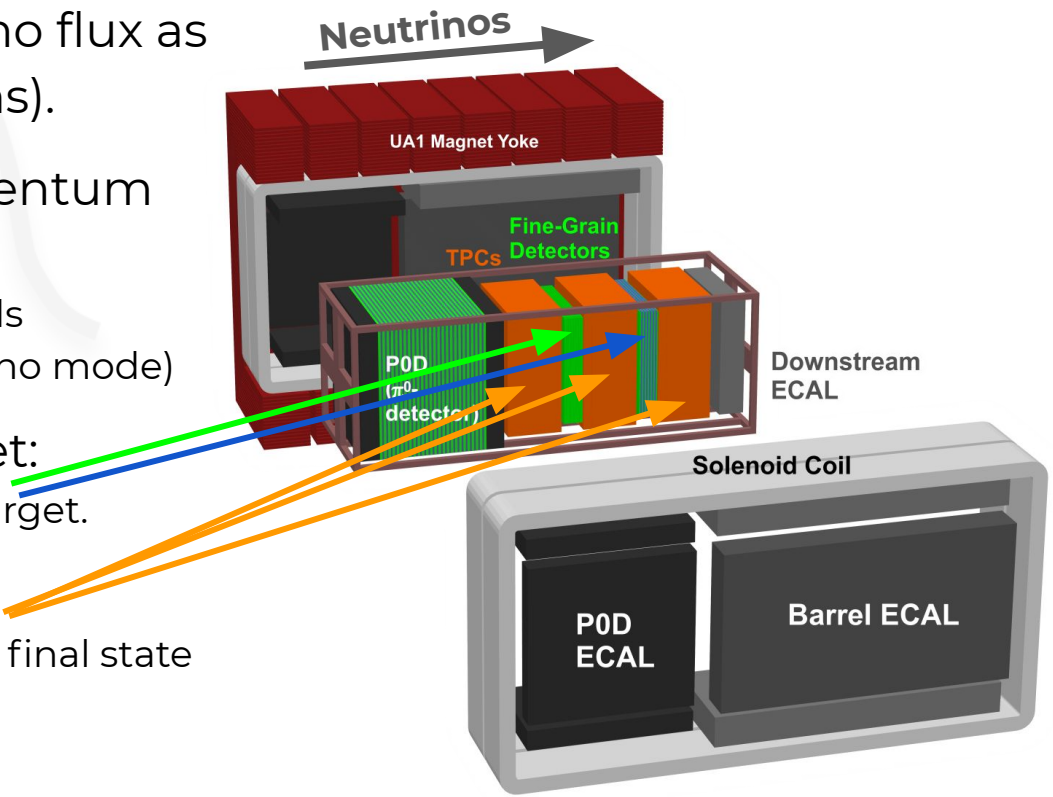
Replica target flux uncertainties



- Main T2K detectors **2.5° off-axis** with respect to the beam:
  - Kinematics of boosted pion decays result in a finer beam width
  - 0.6 GeV peak energy gives maximum oscillation signal @ 295 km
- Uncertainties dominated by **hadron-production**:
  - Simulation tuned to NA61/SHINE hadron-production data.
  - Current: Latest `thin target' analysis: ~10% uncertainty at peak energy
  - **New**: 'replica target' tune to reduce uncertainty by a factor of 2.

ND280

- 2.5° off axis: Sees similar neutrino flux as far detector (without oscillations).
- Magnetized: Charge and momentum measurements
  - Constrain 'wrong sign' backgrounds ($\bar{\nu}$ in neutrino mode, ν in antineutrino mode)
- FGD used as the neutrino target:
  - Active **CH** target + passive **water** target.
- Time Projection Chambers:
  - Good momentum/PID for charged final state particles.



ND280

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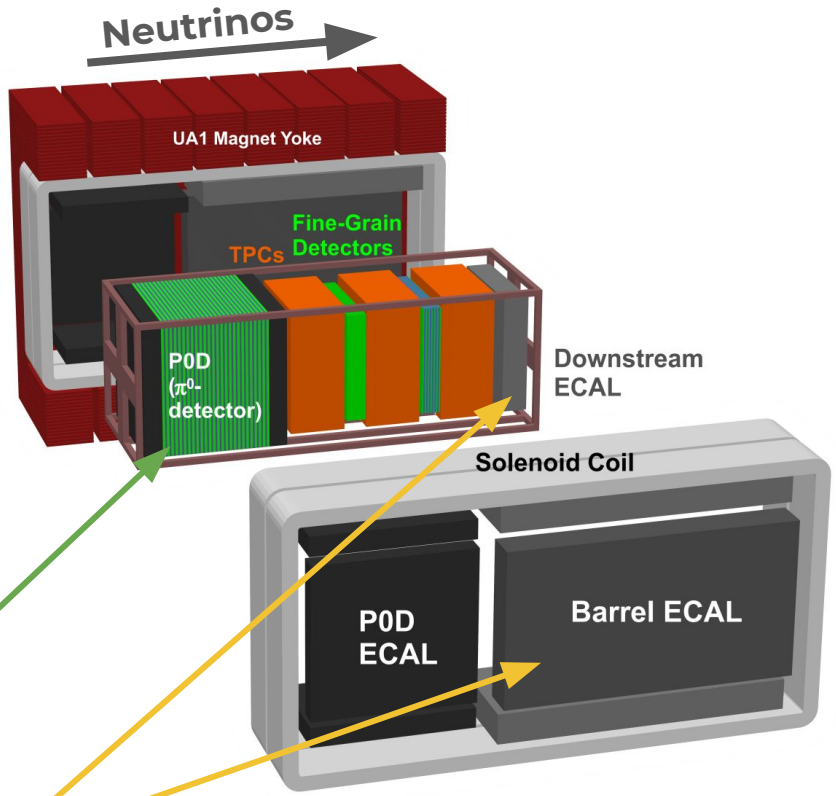
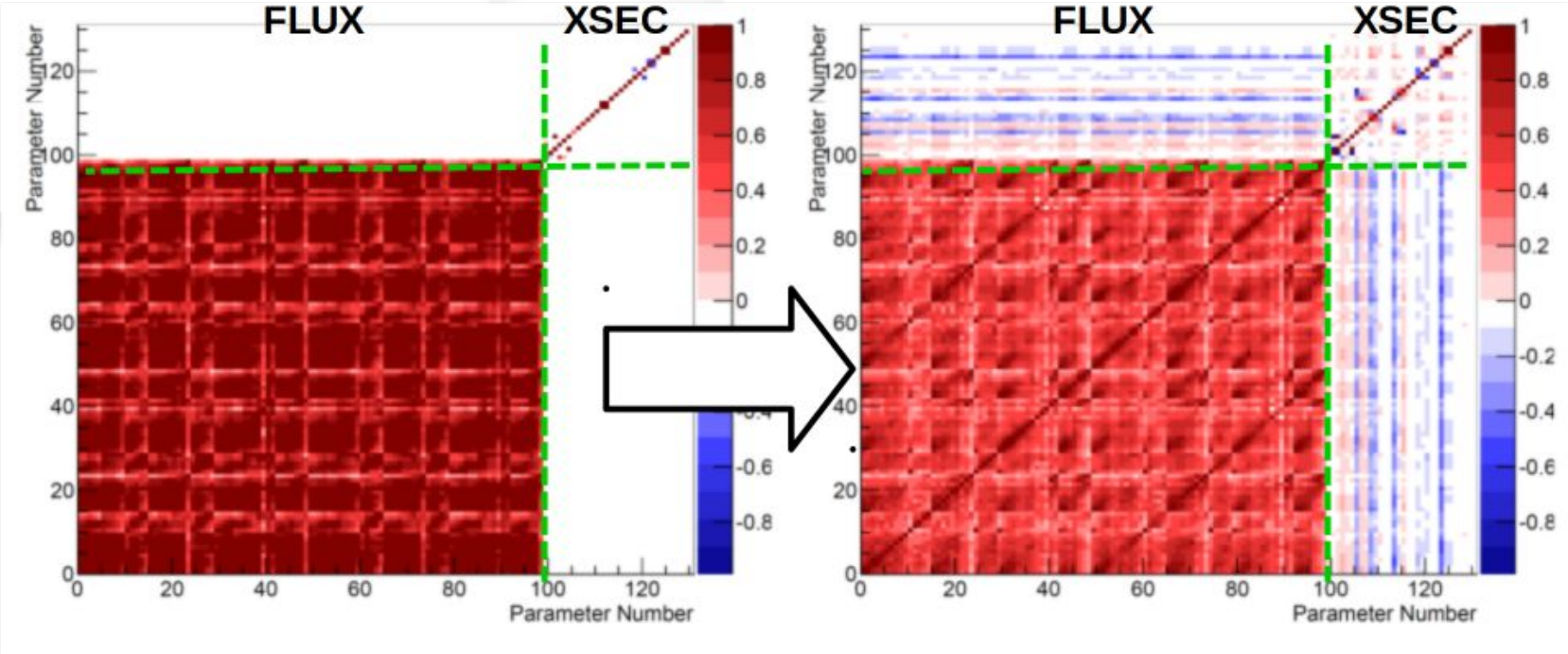
- FGD used as the neutrino target:
  - Active **CH** target + passive **water** target.
- Time Projection Chambers:
  - Good momentum/PID for charged final state particles.
- **P0D**: Specialized π^0 detector
- **ECal**: PID & escaping energy sampling



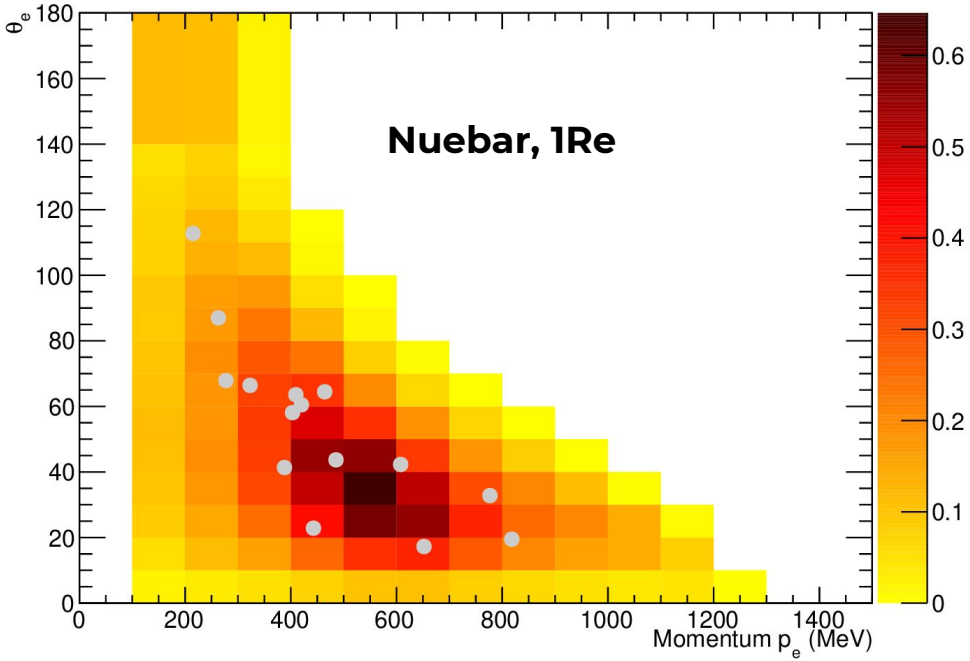
Near detector Flux/XSec Correlations

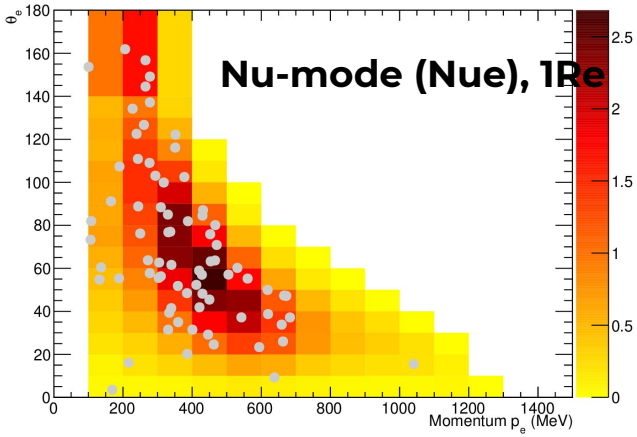
ND280 constraint

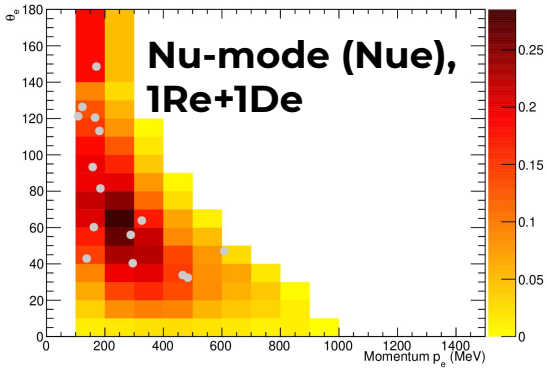


Predicted Event Rates p/theta

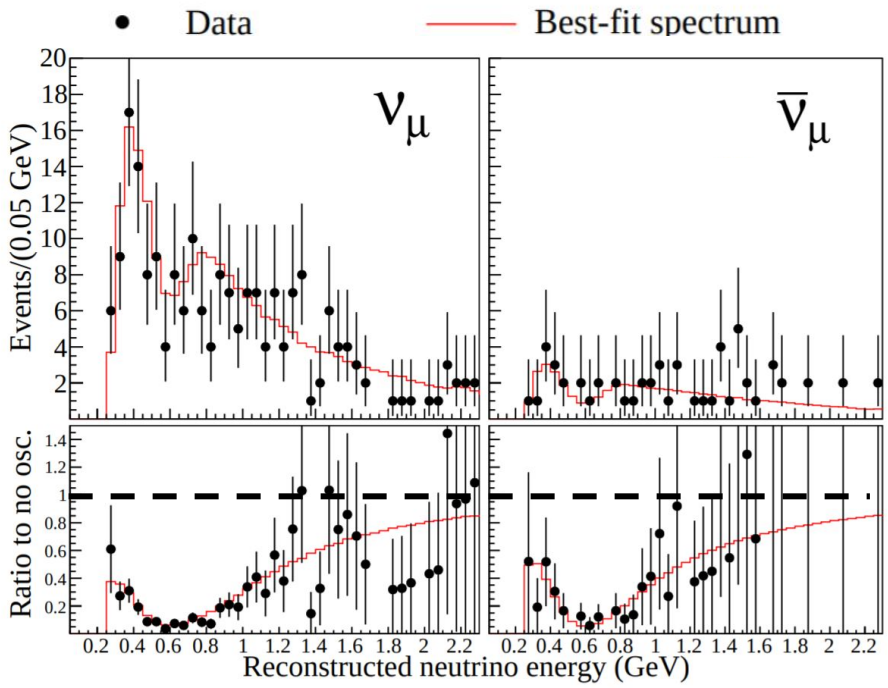
L. Pickering

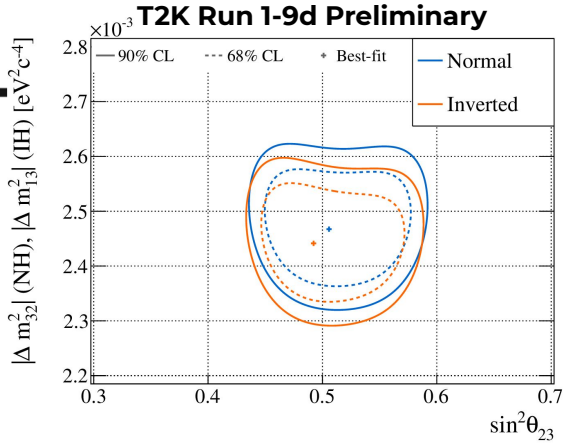


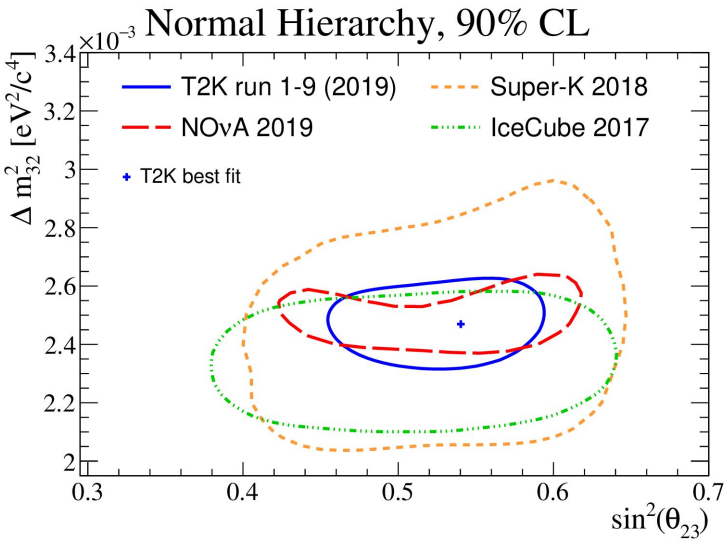




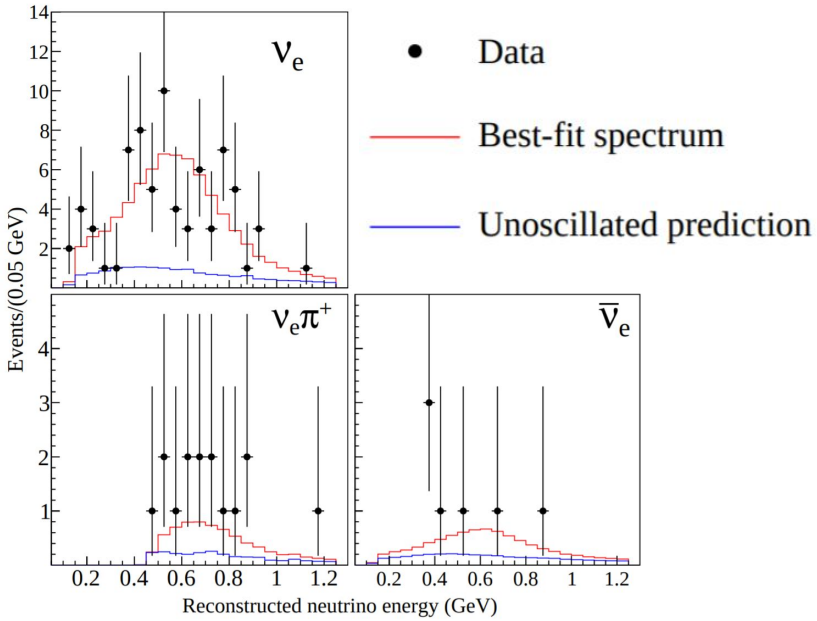
Disappearance Samples/Parameters



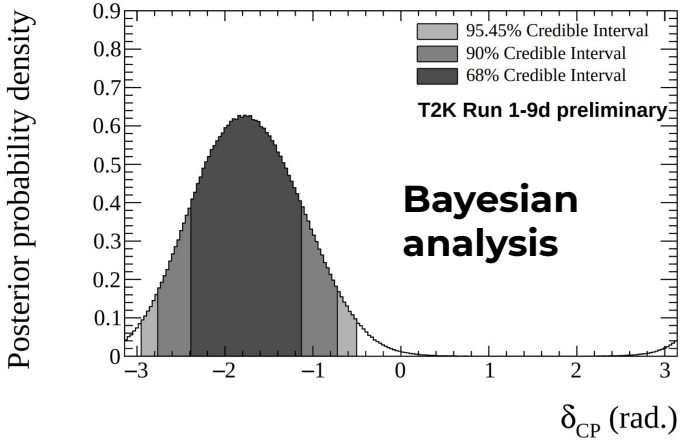




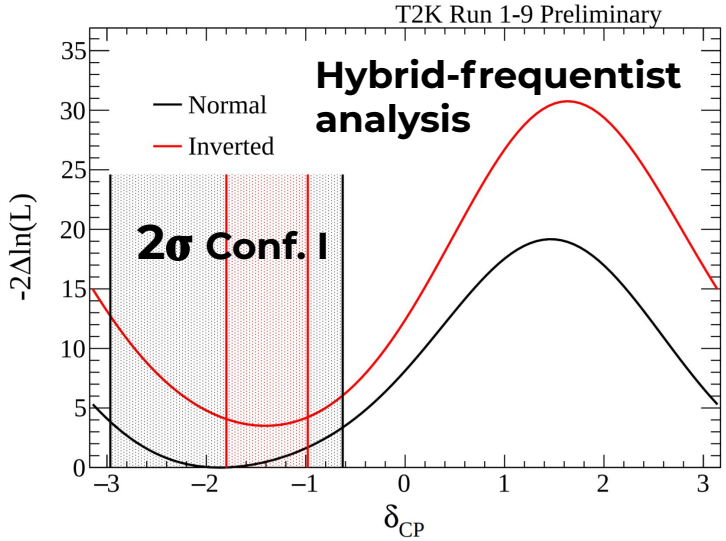
Electron-like samples



More probable

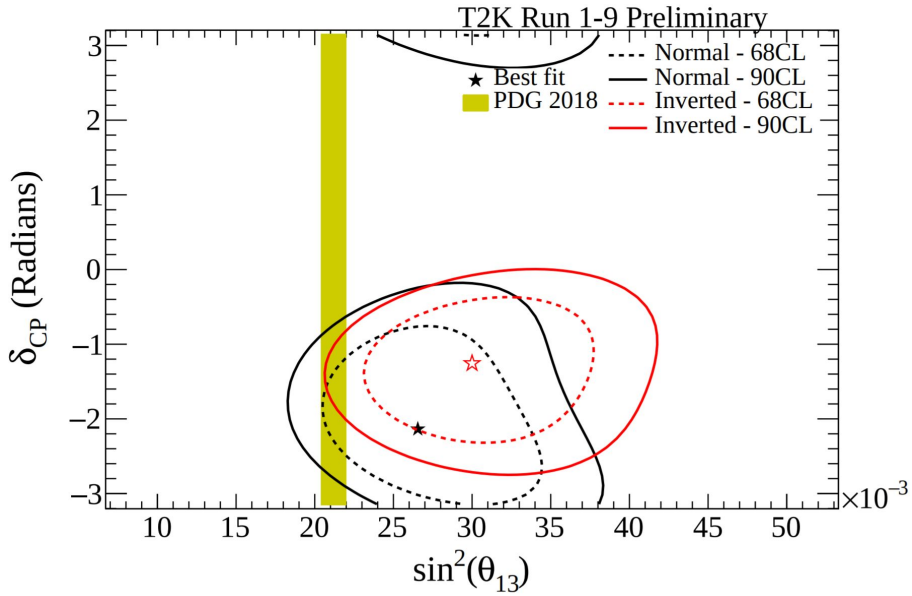


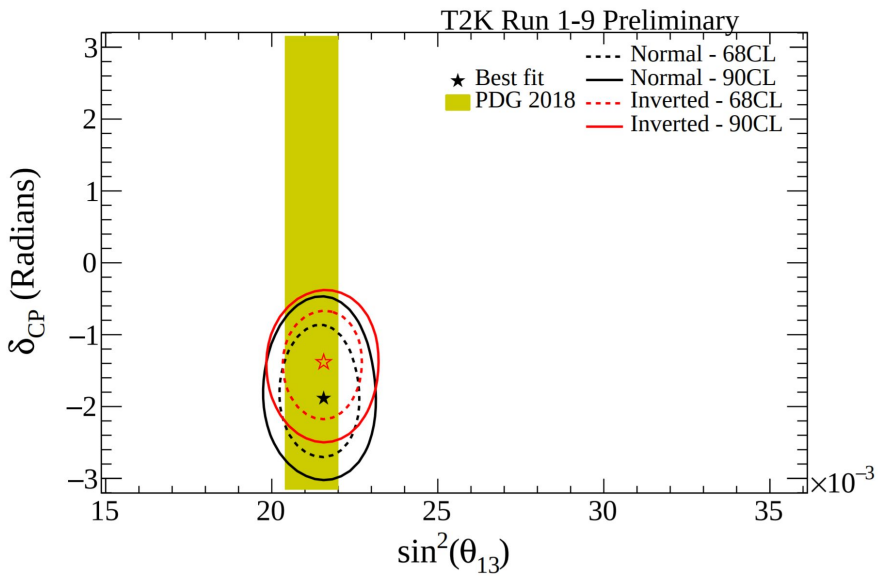
Better fit



- CP conserving values lie outside the 2σ contour for both **bayesian** and **hybrid-frequentist** analyses.

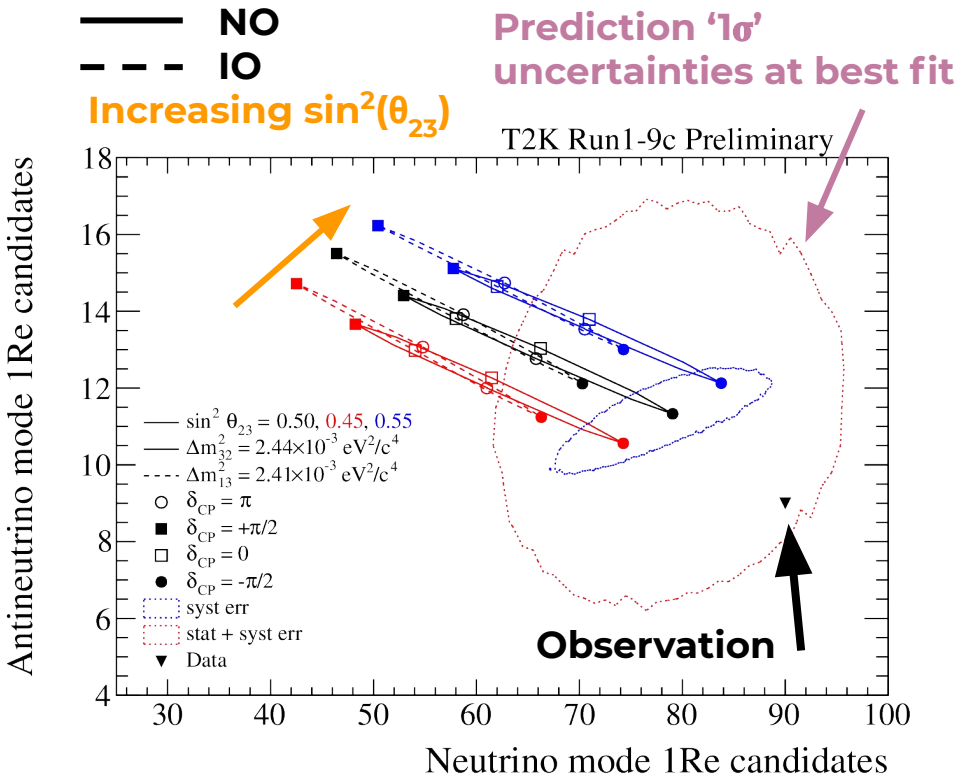
dcp/th13 contours





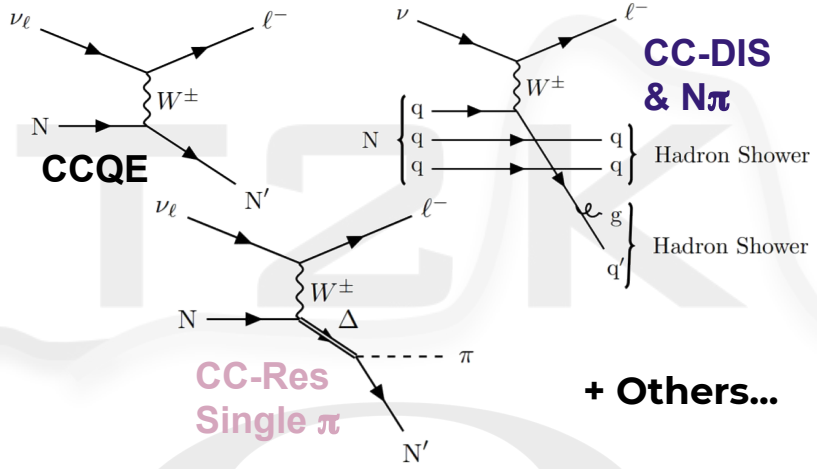
Oscillation Fit: Bi-event rate

- Appearance analysis is statistically limited:
  - Minimal spectral information
  - 'Bi-event' plot depicts preference for NH, δ_{cp}=-π/2
- Observed $\bar{\nu}_e/\nu_e$ near edge of expected region given disappearance fit and PMNS oscillations.
- Excited to see more data:
  - Statistical fluctuation?
  - Modelling problem?
  - Something more exotic…?

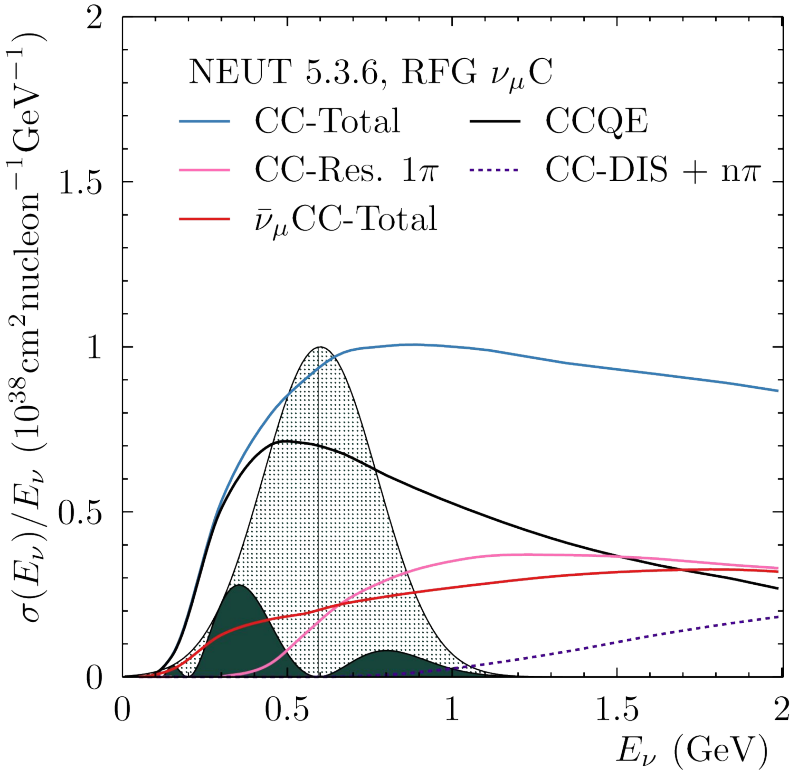


Neutrino–Matter Interactions

Measuring Oscillations: Interactions



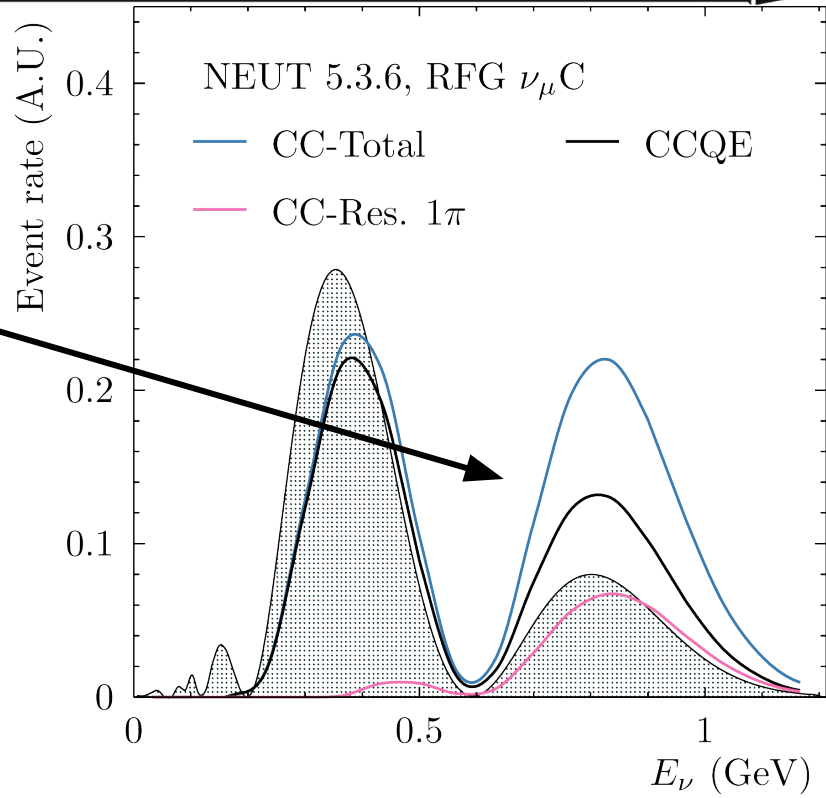
NEUT: Acta Phys.Polon. B40 (2009) 2477-2489



- **But**, don't observe the flux: see final states of neutrino--matter interactions.
- Problematic energy range required by L/E.
- **Antineutrino** cross-section ~⅓ neutrino.

Measuring Oscillations: Events

- Cross-section is non-linear near process 'turn on':
  - Event spectrum shape differs from flux shape in a non-trivial way.
- E_ν spectrum of interacting neutrinos still has characteristic oscillation shape:
  - If flux and cross-sections are well understood we can infer oscillation probabilities.

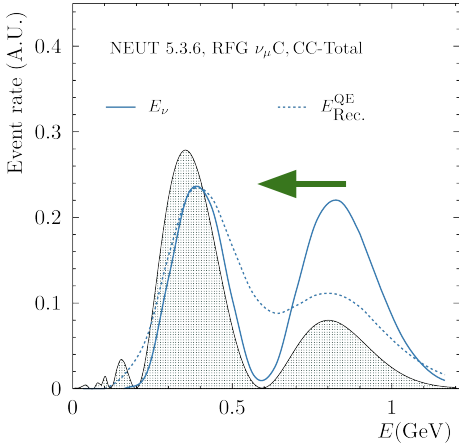


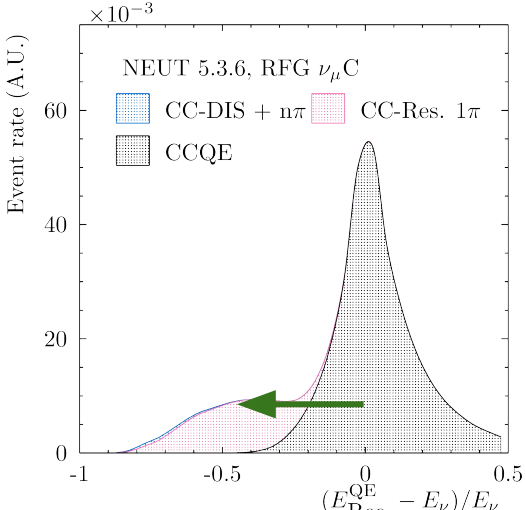
Measuring Oscillations: Observables

- **But**, don't observe E_ν ...
- Reconstruct from observables:
  - Can look for oscillation signature in any observable, but some Erec is most intuitive
  - *e.g.*

$$E_{\text{rec}}^{\text{QE}} = \frac{2M_{\text{N}}E_\ell - M_\ell^2 + M_{\text{N}'}^2 - M_{\text{N}}^2}{2\left(M_{\text{N}} - E_\ell + |\vec{p}_\ell|\cos\left(\theta_\ell\right)\right)}$$

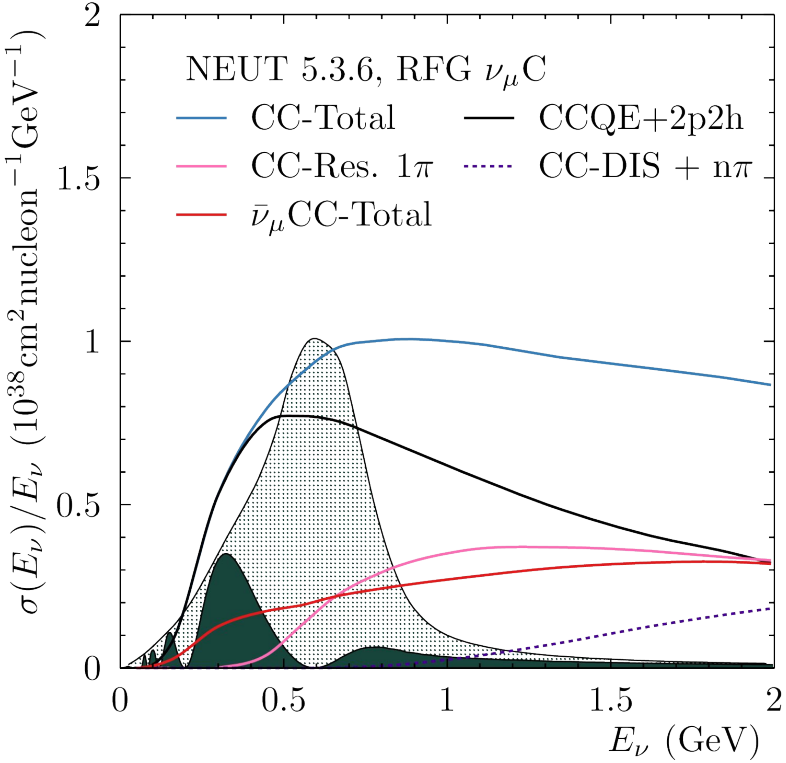
  - Unbiased energy reconstruction from just charged lepton for **true CCQE** events only:
  - Any **non-CCQE** get significant ERec. bias.
- Can only infer oscillation probabilities correctly if '**feed down**' is well modelled.



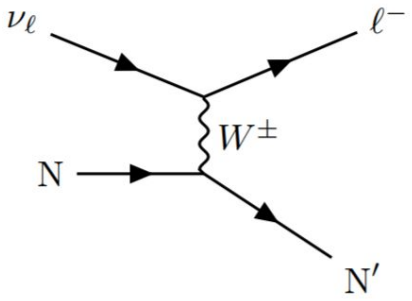


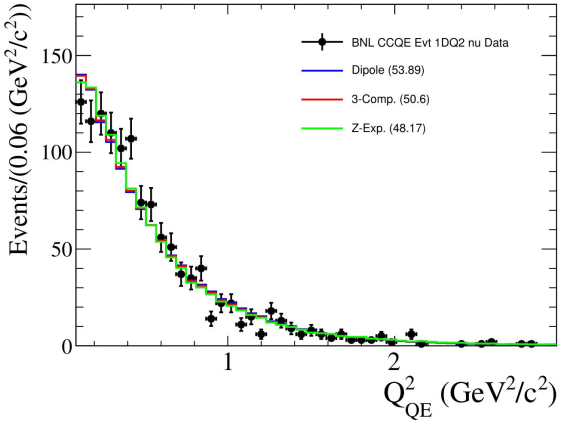
What's Important for T2K

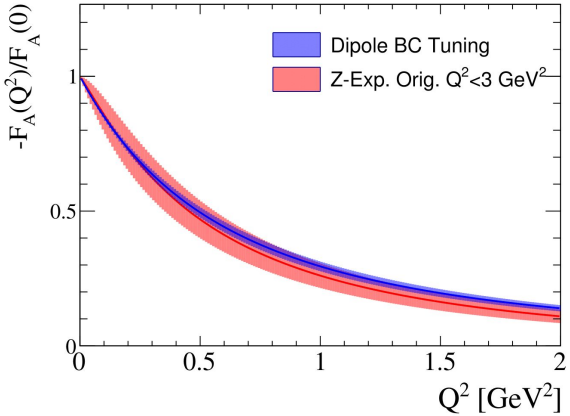
- Analyses rely strongly on the modelling of $E_\nu \leftrightarrow E_{Rec.}$
- Turns out nuclear physics is hard:
  - CCQE Axial form-factor
  - W-propagator screening
  - Multi-nucleon processes (2p2h)
  - Final state interactions (e.g. π absorption)
  - Nuclear potential
- On T2K: Focus on modelling 0π final states:
  - Mostly from CCQE+2p2h and 1π production with 'stuck' pion.



CCQE Axial form factor



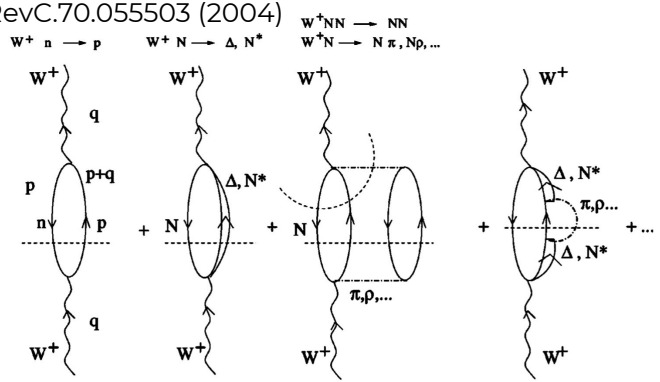


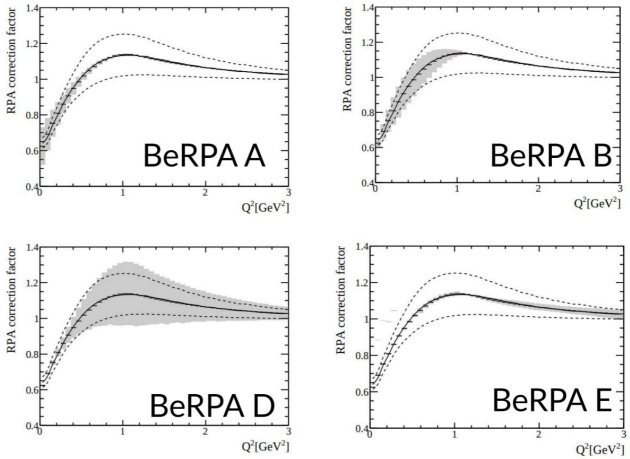


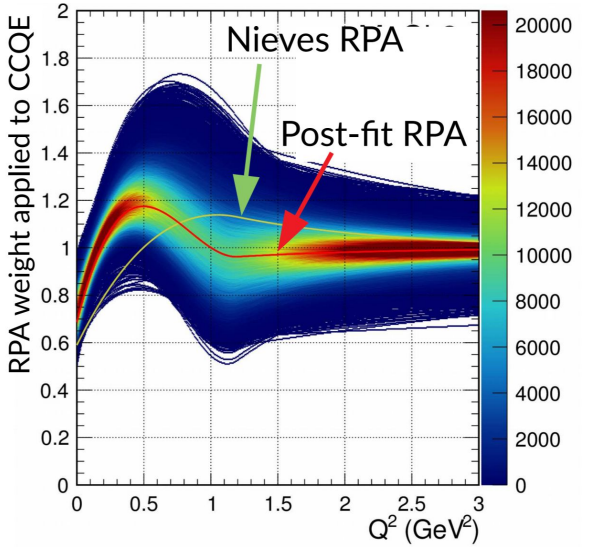
- Fit nucleon-level processes to historic bubble chamber data
  - ~ Free from nuclear effects.
- Dipole form is often used for the Axial form factor, $F_A\left(Q^2\right) = F_A\left(0\right) / \left(1 + Q^2/M_A^2\right)^2$
  - Single free parameter M_A: Strong constraint at low Q^2 causes over constraint at high Q^2.
- Model-independent parameterizations allow better description of the uncertainty: Phys. Rev. D **84**, 073006 (2011)
  - Aim to include in T2K OA 2019.

‘RPA’: W Propagator Screening

PhysRevC.70.055503 (2004)



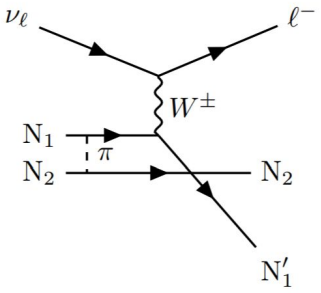




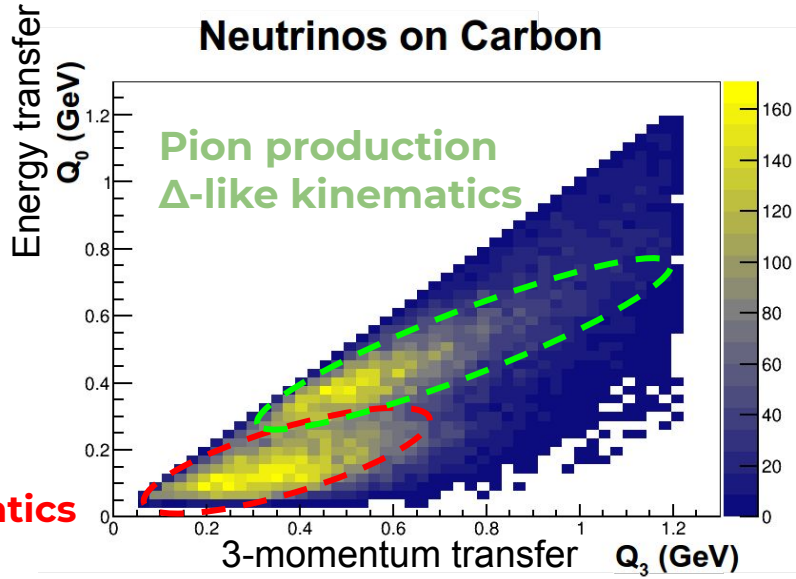
- CCQE suppression from nuclear screening of W-propagator.
- T2K parameterize uncertainty as piecewise 1D function in Q^2.
  - Post-fit shape doesn’t resemble calculation shape…
- Theoreticians not in agreement that RPA is so important with better nuclear model: *c.f.* GiBUU

Multi-nucleon Interactions

- Scattering from bound nucleon-nucleon pairs within the nucleus: **different $E_\nu \leftrightarrow E_{Rec.}$**
- Not possible to study in isolation, will always also have:
  - True CCQE
  - CC1pi with missed pion
  - Other nuclear effects
- Current multi-nucleon models improve experimental agreement, but some way still to go.

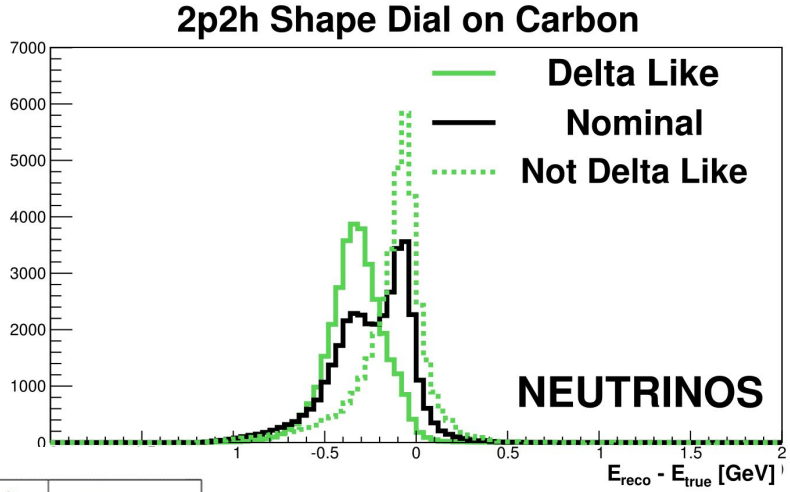


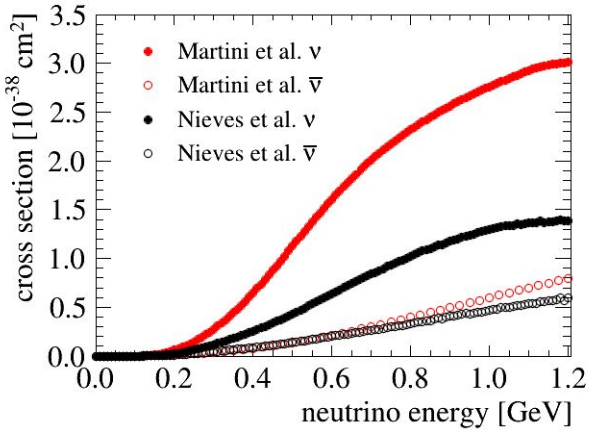
Example of Multi-nucleon interaction (2p2h/NN)

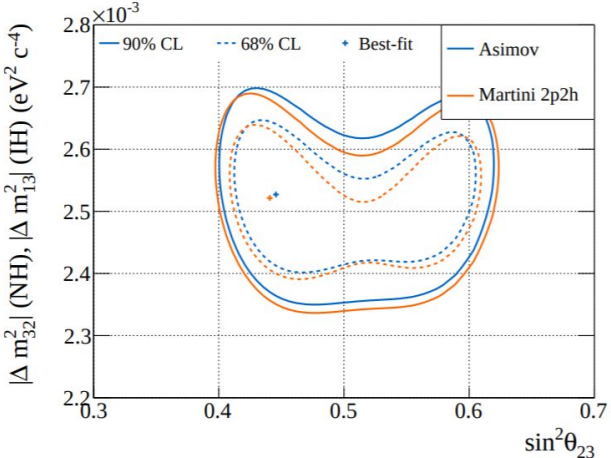


Effect on Oscillation Analysis

- Want to check how biased the results might be if the wrong multi-nucleon model was chosen:
  - Assign uncertainty to QE-like/Δ-like nature of multi-nucleon interaction.
  - Run oscillation analysis with 'fake data' generated with an alternate model.



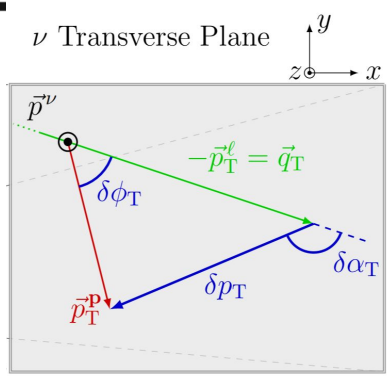




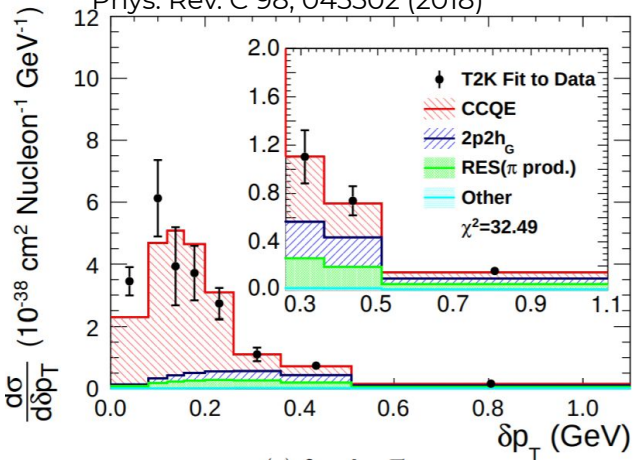
Near detector fit prefers between nominal and Δ-like

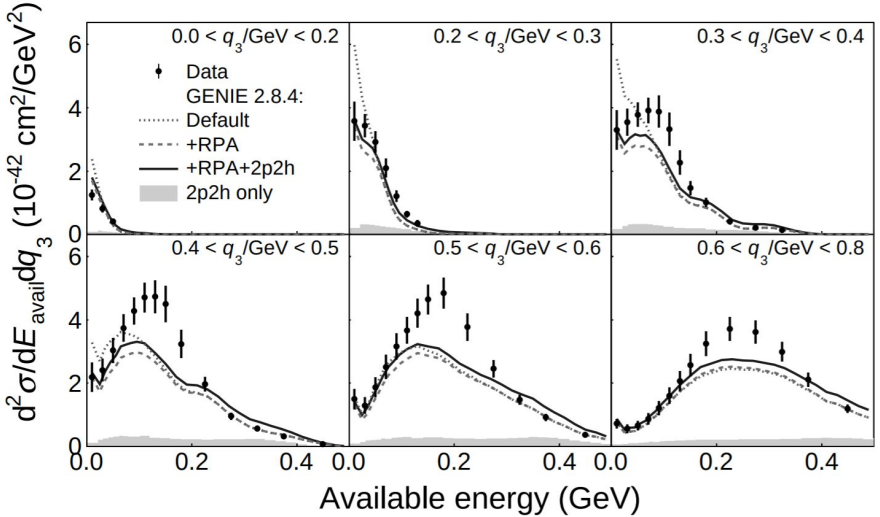
Lepton-Hadron Correlations

- Investigate lepton-hadron correlations.
- Two recent approaches:
  - Transverse imbalance
  - q0/q3 reconstruction
- Hard to use directly in OA:
  - Existing models can't be bent to fit with current freedom…
  - Build 'fake data' informed by these results and use to test OA robustness.



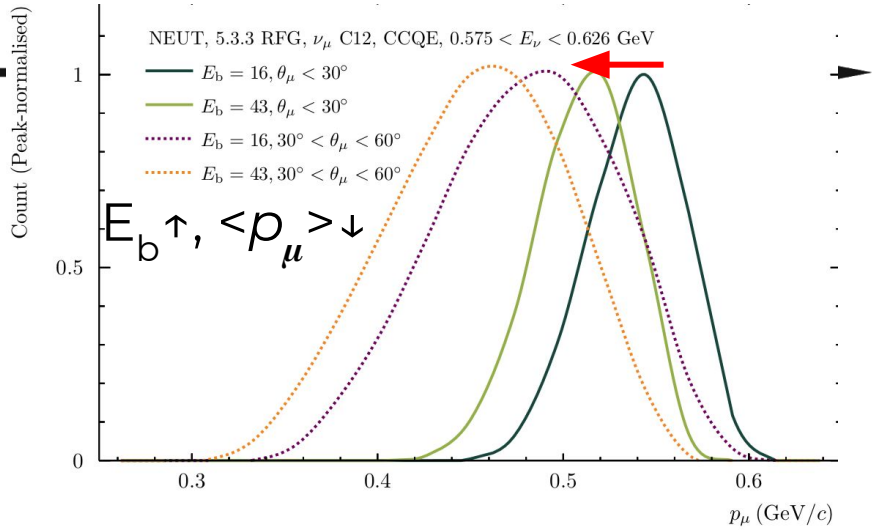
Phys. Rev. C 98, 045502 (2018)

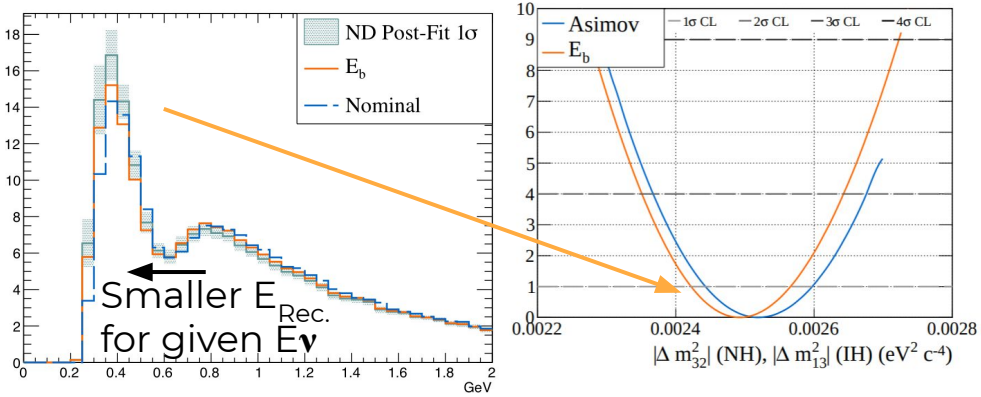




Binding Energy

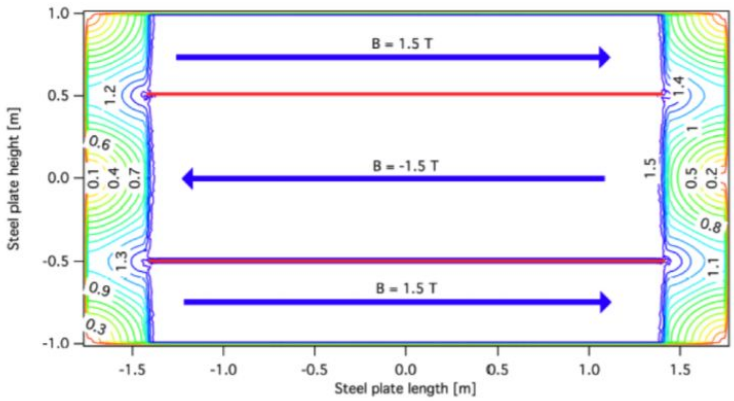
- Energy associated with liberating struck nucleon from nuclear potential
- A. Bodek's re-analysis found that the default NEUT value was poor [arXiv:1801.0797]
- For 2018 T2K OA, a fit to mock-data with a large shift in Eb was used to assess uncertainty
  - Largest single source of error.
- In the future, a smaller prior from A. Bodek's analysis will be used.

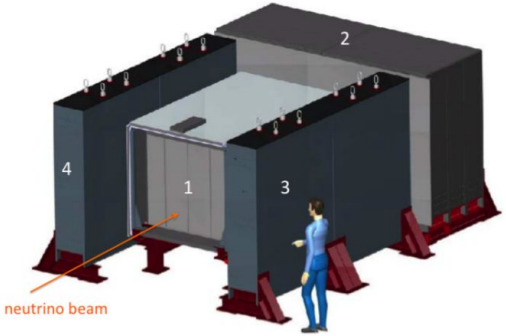


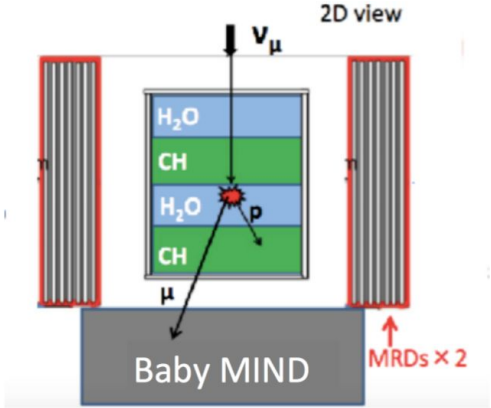


(b) Δm^2_{23} with reactor constraint

Baby-MIND


B = 1.5 T
B = -1.5 T
B = 1.5 T
Steel plate height [m]
Steel plate length [m]


2
4
1
3
neutrino beam

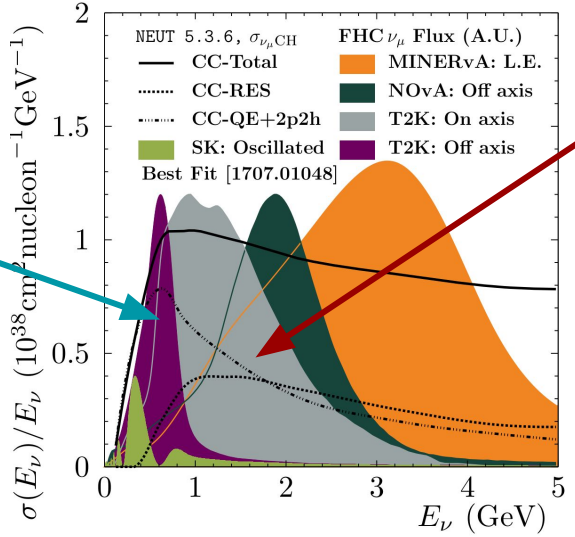

2D view
ν_μ
H_2O
CH
H_2O
CH
p
μ
Baby MIND
MRDs × 2

T2K Cross Sections

T2K Cross-section Results

Links for your convenience

- ν_μ CCInc C^{12} (2013)
- ν NCQE O^{16} (2014)
- ν_e CCInc C^{12} (2014)
- ν_μ CCInc $Fe^{56}/C^{12}H$ (2014)
- ν_μ CCQE C^{12} (2014)
- ν_μ CCQE C^{12} (2015)
- ν_μ CCInc Fe^{56} (2015)
- ν_μ CC0π $C^{12}H$ (2016)
- ν_μ CC1π H_2O^{16} (2016)
- ν_μ CC Coherent 1π C^{12} (2017)
- ν_μ CC0π H_2O^{16} (2017)
- ν_μ CC0π $C^{12}H$ (2018)
- ν_μ CCInc C^{12} (2018)
- $\nu_\mu/\bar{\nu}_\mu$ CCInc P0D (2018)
- ν_μ CCInc $C^{12}H$ O^{16} Fe^{56} (2019)
- NC 1γ $C^{12}H$ (2019)



ND280 Analyses

INGRID Analyses

MICHIGAN STATE UNIVERSITY

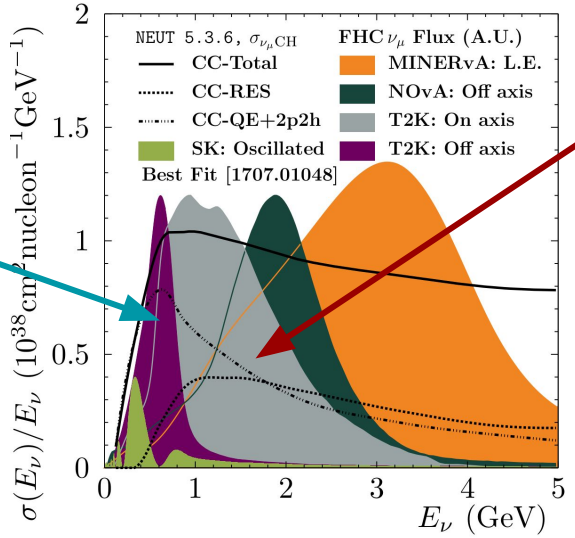
T2K Cross-section Results

Links for your convenience

- ν_μ CCInc C^{12} (2013)
- ν NCQE O^{16} (2014)
- ν_e CCInc C^{12} (2014)
- ν_μ CCInc $Fe^{56}/C^{12}H$ (2014)
- ν_μ CCQE C^{12} (2014)
- ν_μ CCQE C^{12} (2015)
- ν_μ CCInc Fe^{56} (2015)
- ν_μ CC0π $C^{12}H$ (2016)
- ν_μ CC1π H_2O^{16} (2016)
- ν_μ CC Coherent 1π C^{12} (2017)
- ν_μ CC0π H_2O^{16} (2017)
- ν_μ CC0π $C^{12}H$ (2018)
- ν_μ CCInc C^{12} (2018)
- $\nu_\mu/\bar{\nu}_\mu$ CCInc P0D (2018)
- ν_μ CCInc $C^{12}H$ O^{16} Fe^{56} (2019)
- NC 1γ $C^{12}H$ (2019)

ND280 Analyses

INGRID Analyses



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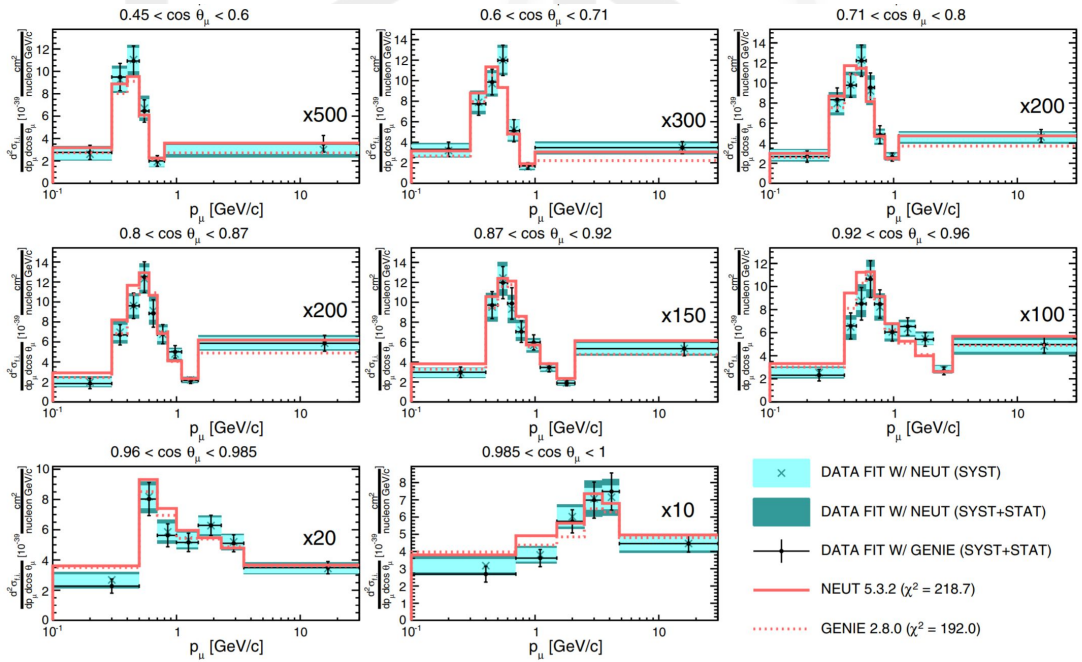
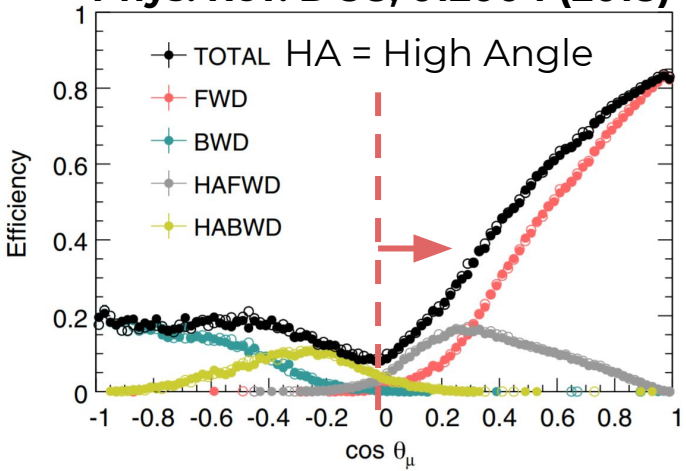
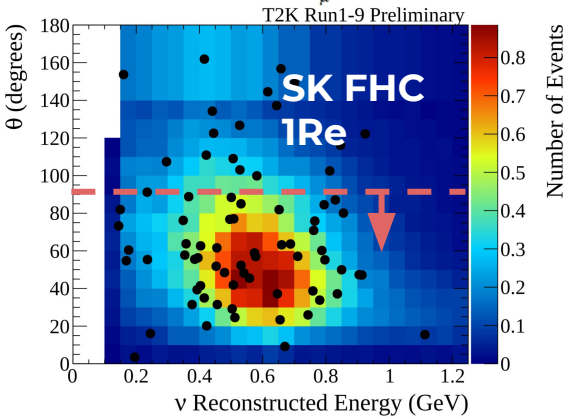
Focus 1: CCInc Expanded Phase Space

- Previous ND fit only use **Forward** sample
  - Expanded PS better matches SK 4π acceptance.
  - Cross-section work directly improved oscillation analysis sample.



Phys. Rev. D 98, 012004 (2018)

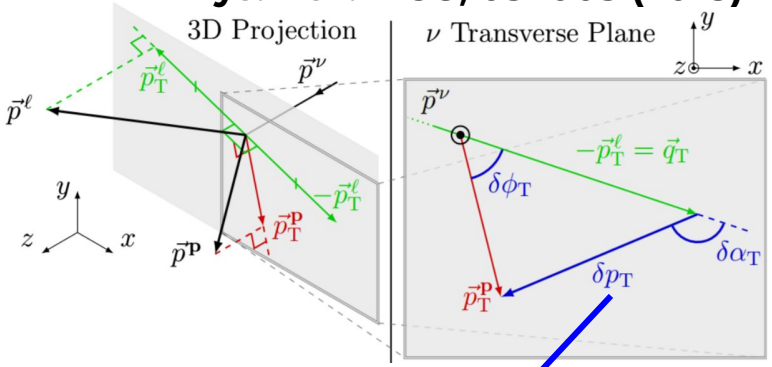


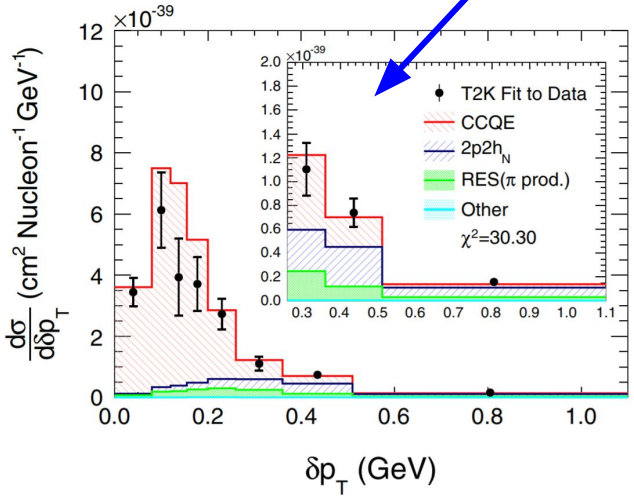


Focus 2: CC0π Transverse Variables

- CC0π: Dominant process at T2K energies:
  - Measuring lepton-hadron correlations probes relevant nuclear physics:
    - Oscillation measurements assume Observable ⇌ True energy relationship
    - Unknown nuclear effects distort this
      ⇒ biased oscillation parameters
  - Analysis careful to reduce interaction model dependence:
    - Signal defined by nuclear-leaving particles.
    - Restricted signal phase space.

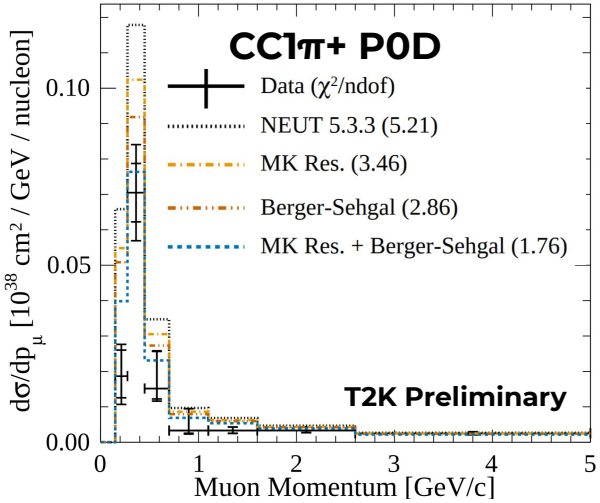
Phys. Rev. D 98, 032003 (2018)



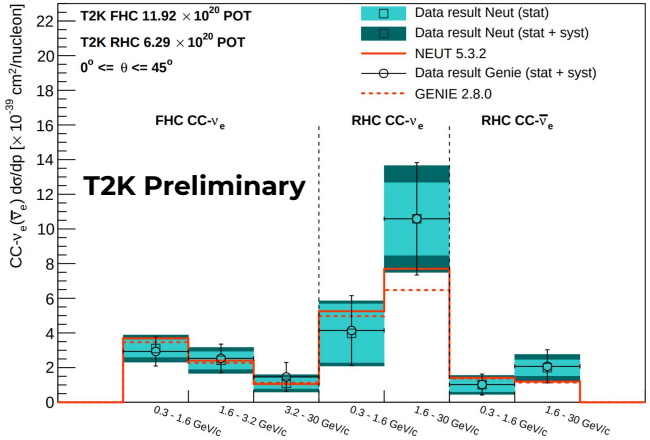


New Cross-section Results

- Newly approved results:
  - ν_μ CC1π+ CH
  - $\nu_\mu/\bar{\nu}_\mu$ CC0π CH
  - ν_μ CC1π+ P0D
  - $\nu_e/\bar{\nu}_e$ CCInc CH
    - First $\bar{\nu}_e$ since BC era!
  - ν_μ CC0π C/O
  - NCQE at SK!
- + many more in earlier stages.
- T2K analysers developing and deploying:
  - Novel analysis techniques
  - Statistically robust data publication methodologies

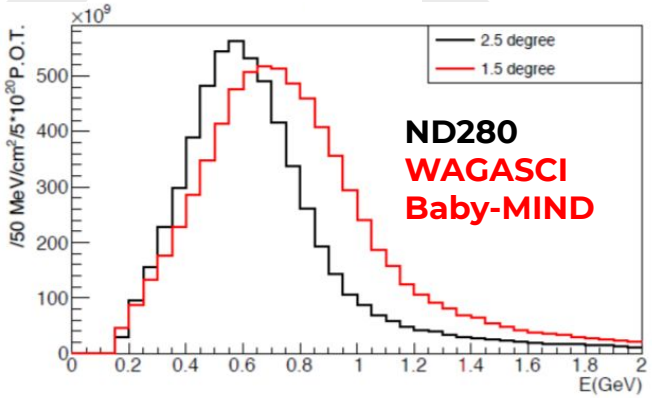


CC-ν_e and CC-$\bar{\nu}_e$ Cross-Section

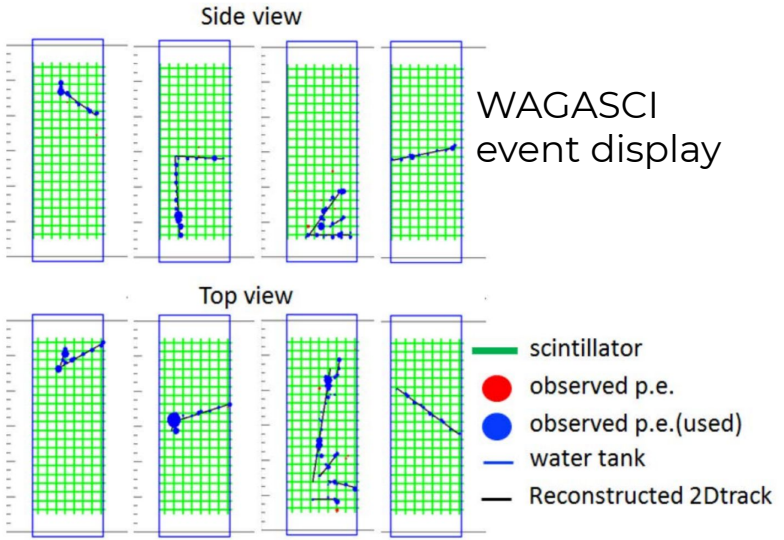


WAGASCI and Baby-MIND

- **WAGASCI**:
  - Water/Scintillator detector
  - Can run water-out for CH subtraction
  - One module on-axis and one at 1.5° off axis.
- **Baby-MIND**:
  - Compact magnetised iron plate and scintillator detector
  - ranging, charge, and momentum



J-PARC P69-2018-5



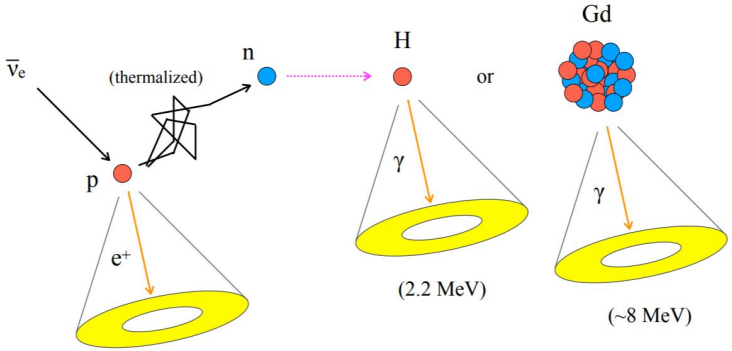
WAGASCI event display

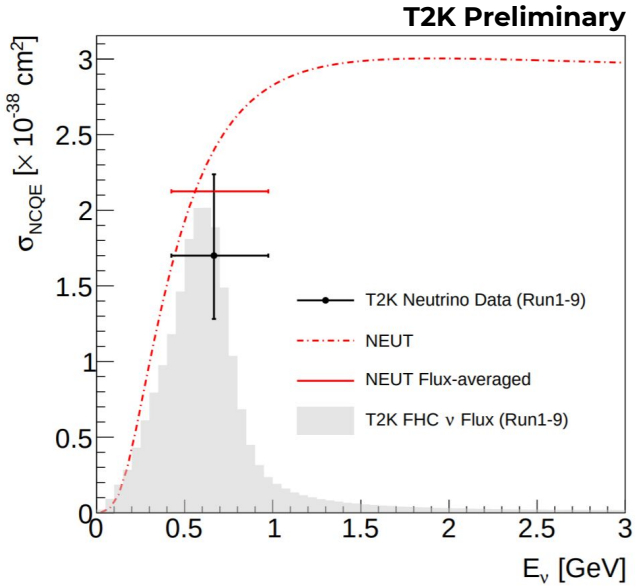
See Hiro's talk for more about the future!

New And Future

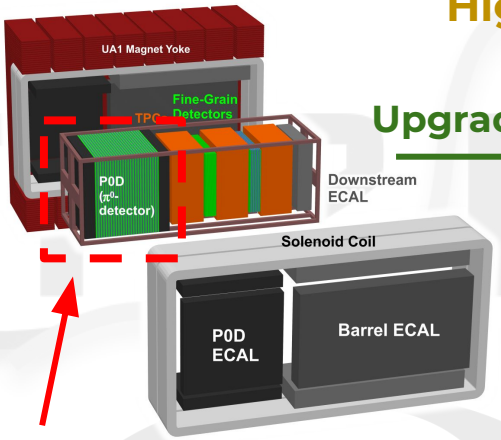
SK-Gd

- Super-K deep cleaned in preparation for Gadolinium doping.
- Much improved efficiency for neutron capture:
  - Sensitivity to supernova relic neutrinos
  - Statistical separation of neutrino/antineutrino rate
  - Many unknown interaction effects: total cross-section, FSI, ...
- **New!** T2K-SK NCQE cross-section measurement:
  - Neutron-producing background process for supernova relics and coincidence with charged current oscillation signal events.

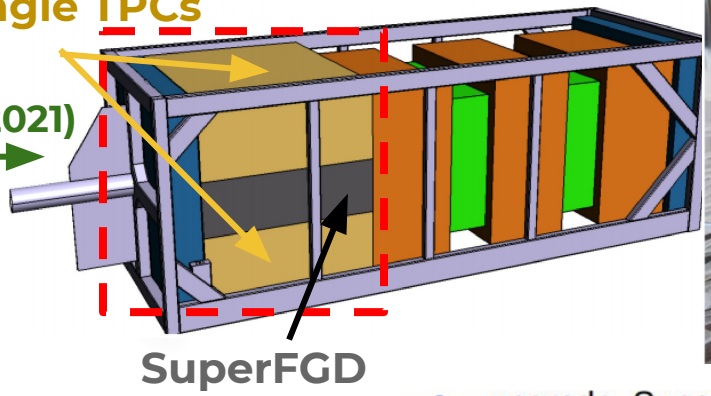


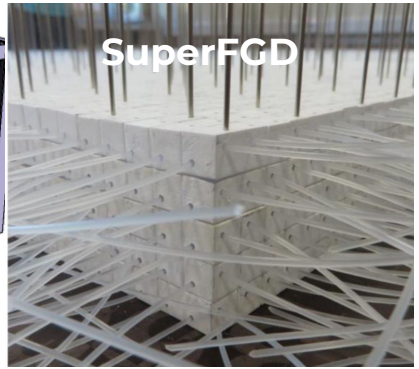


ND280 Upgrade

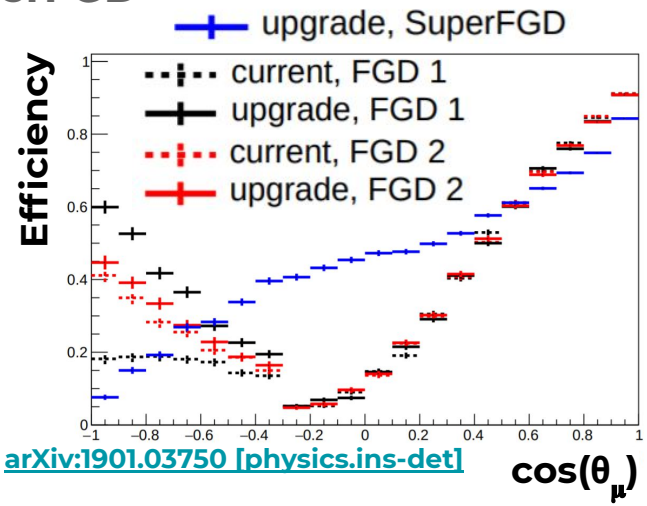


Upgrade! (~2021)





- **P0D** being replaced for T2K-II
- New 3D scintillator detector + horizontal TPCs:
  - **Improved acceptance**
    - **High angle**
    - Low momentum (esp. protons)



arXiv:1901.03750 [physics.ins-det]

T2K-II and J-PARC Beam upgrade

- T2K has recorded **3.16x10^{21} POT**
  - T2K original POT quota: **7.8x10^{21}**
- T2K-II to take: **20x10^{21}**
- Continued rich physics program and improved oscillation sensitivity until Hyper-K