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

Status of T2K

Luke Pickering for the T2K Collaboration
NNN2019, Medellín, Columbia
2019-11-8

MICHIGAN STATE
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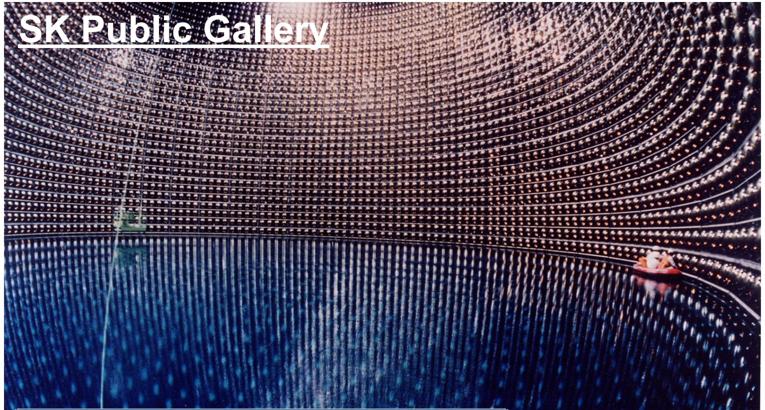
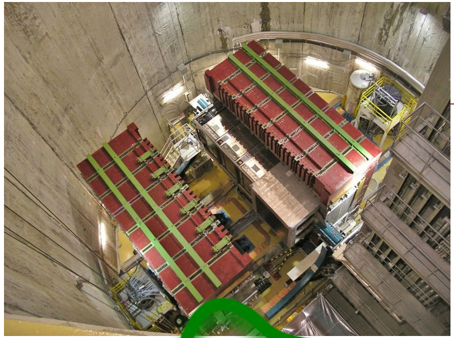
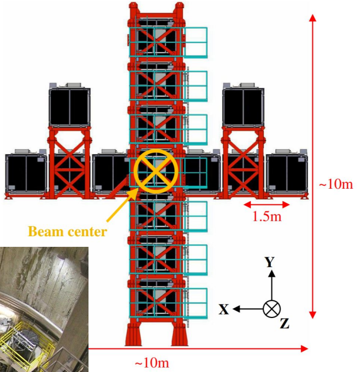
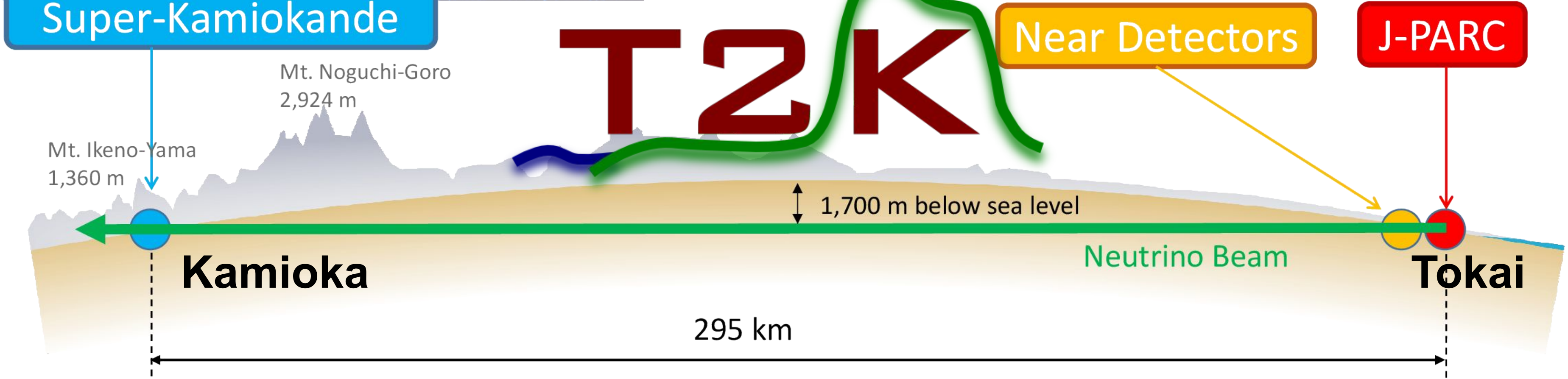
T2K

Tokai To Kamioka


SK Public Gallery



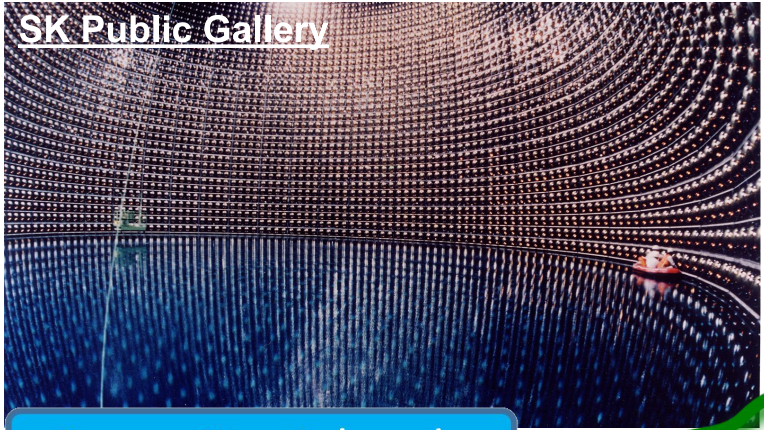



Super-Kamiokande

Near Detectors

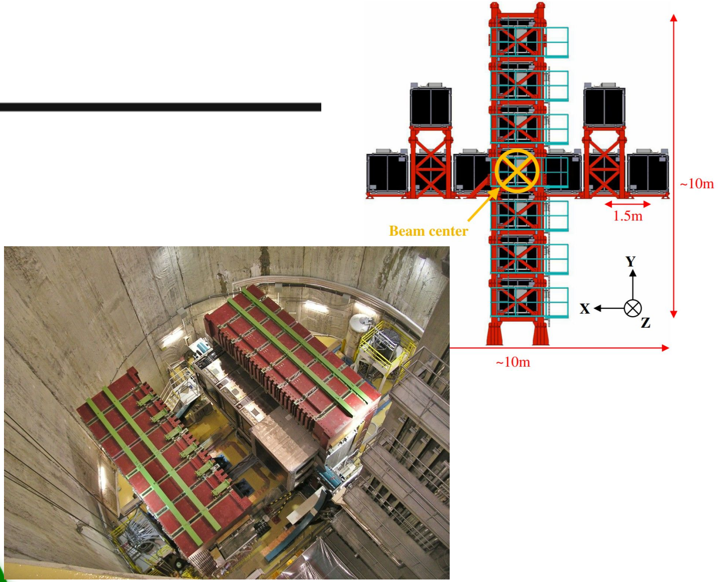
J-PARC

Tokai To Kamioka



SK Public Gallery

Super-Kamiokande



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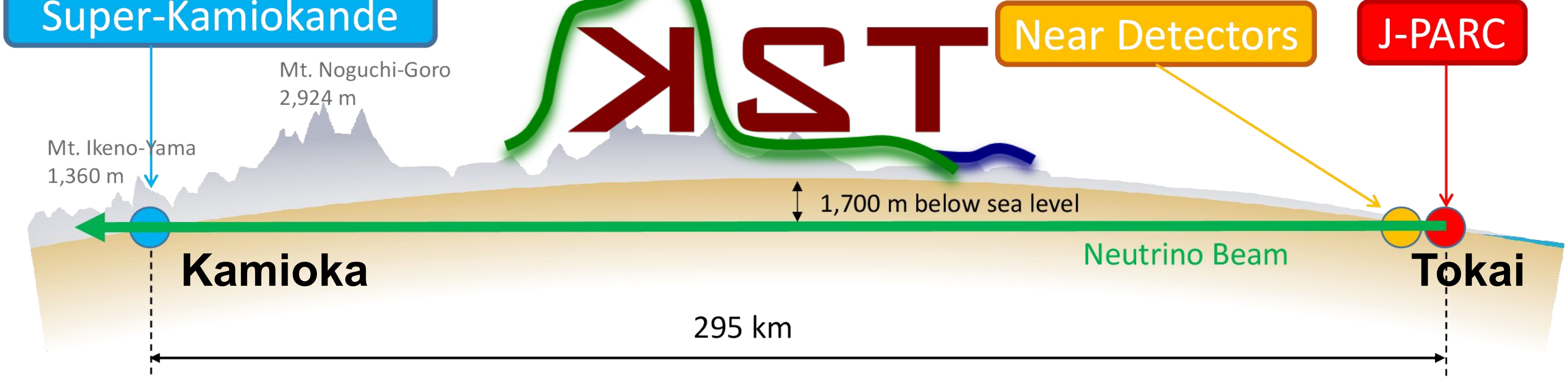
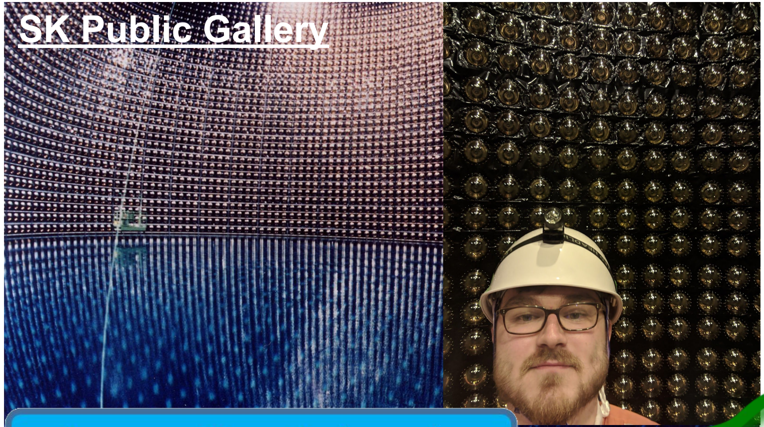


Tokai To Kamioka



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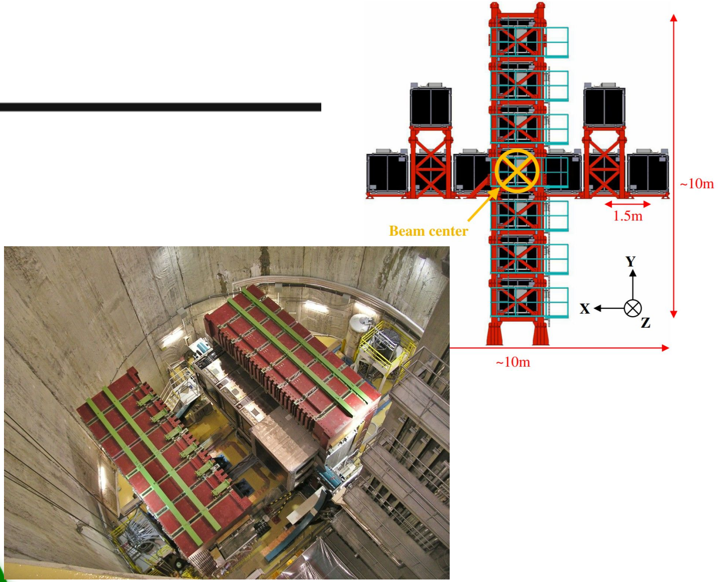

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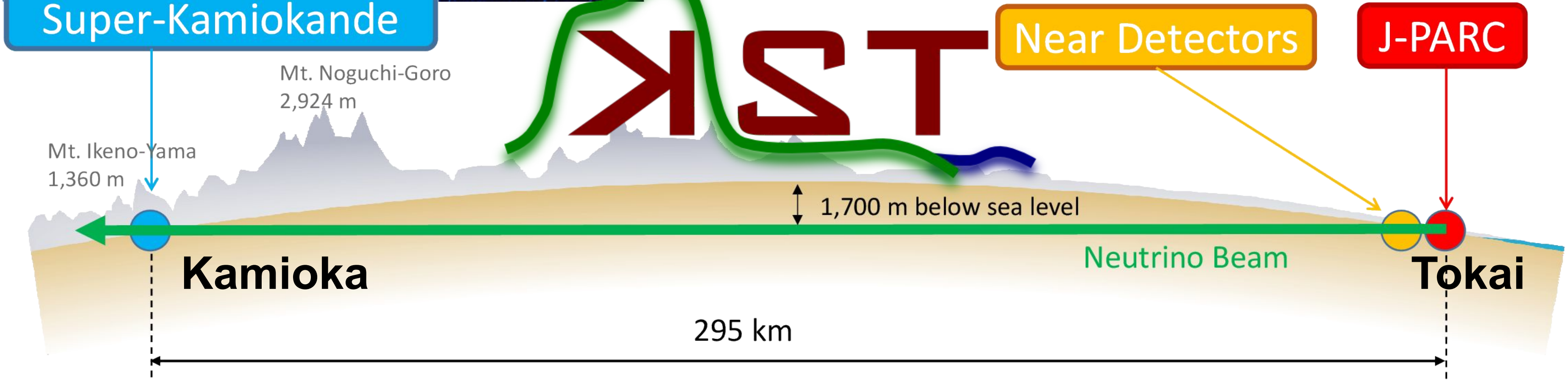


T2K At a glance

- 350 members
- 12 Countries

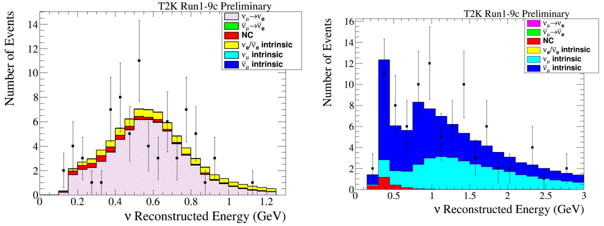
- World leading atmospheric mixing parameters
- Sensitivity to neutrino mass ordering and CP violation

- Rich interaction physics program
- Ongoing upgrades

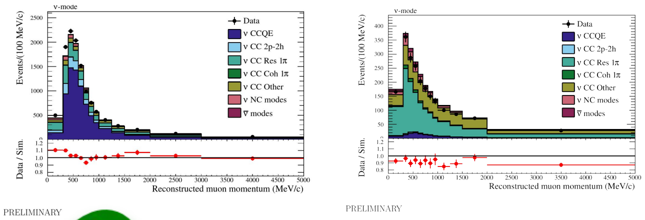
Oscillations

Anatomy of an Oscillation Analysis

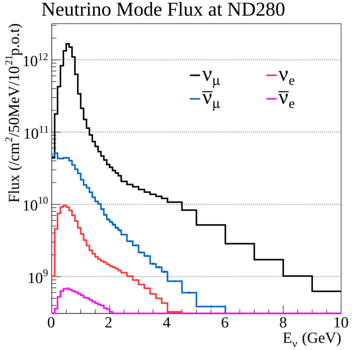
- Sample oscillated beam
- Infer oscillation probabilities

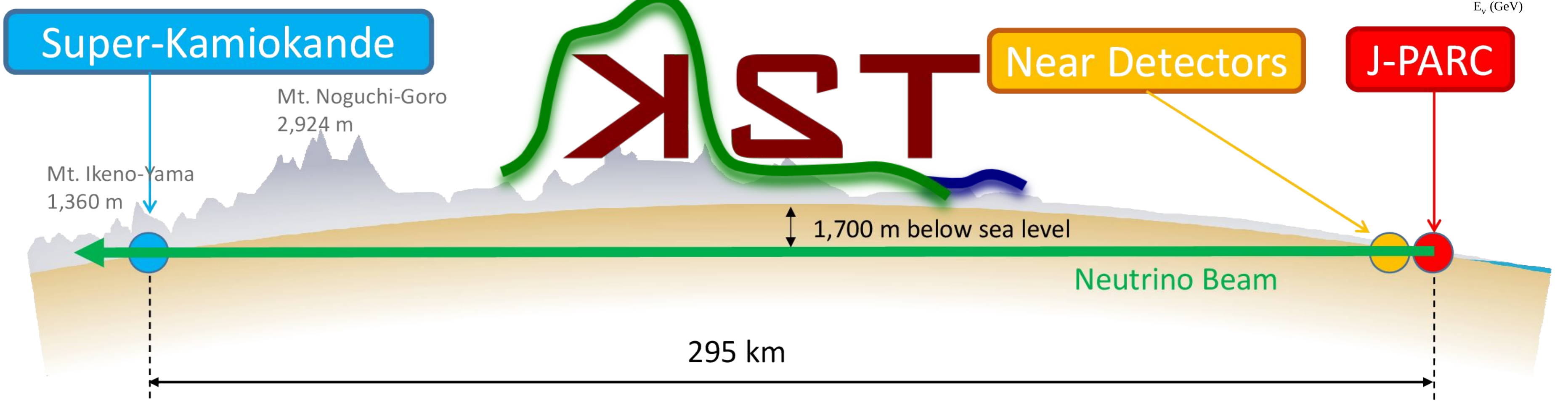


- Sample un-oscillated beam
- Study interaction physics



Produce neutrino beam

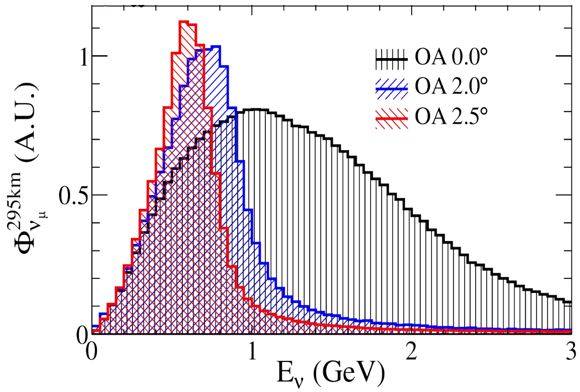



Super-Kamiokande

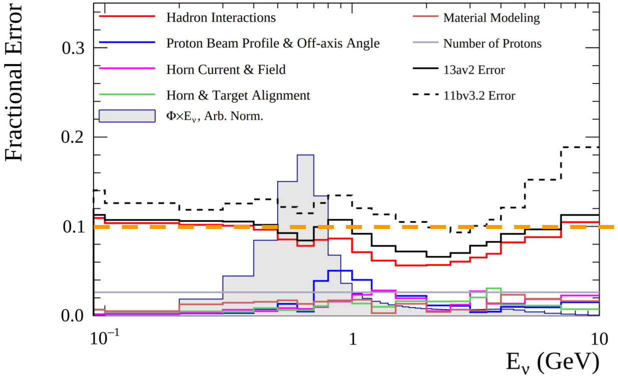
Near Detectors

J-PARC

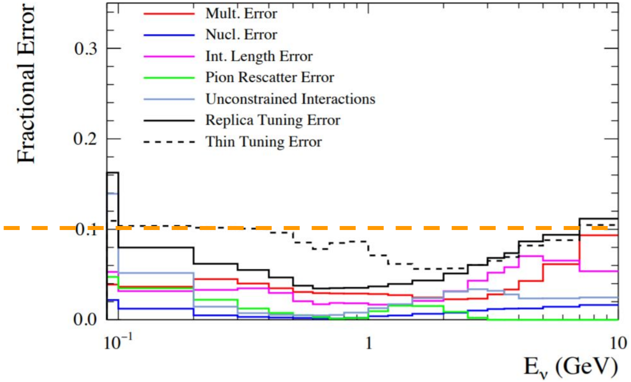
J-PARC Neutrino Beam



Thin target flux uncertainties



Replica target flux uncertainties



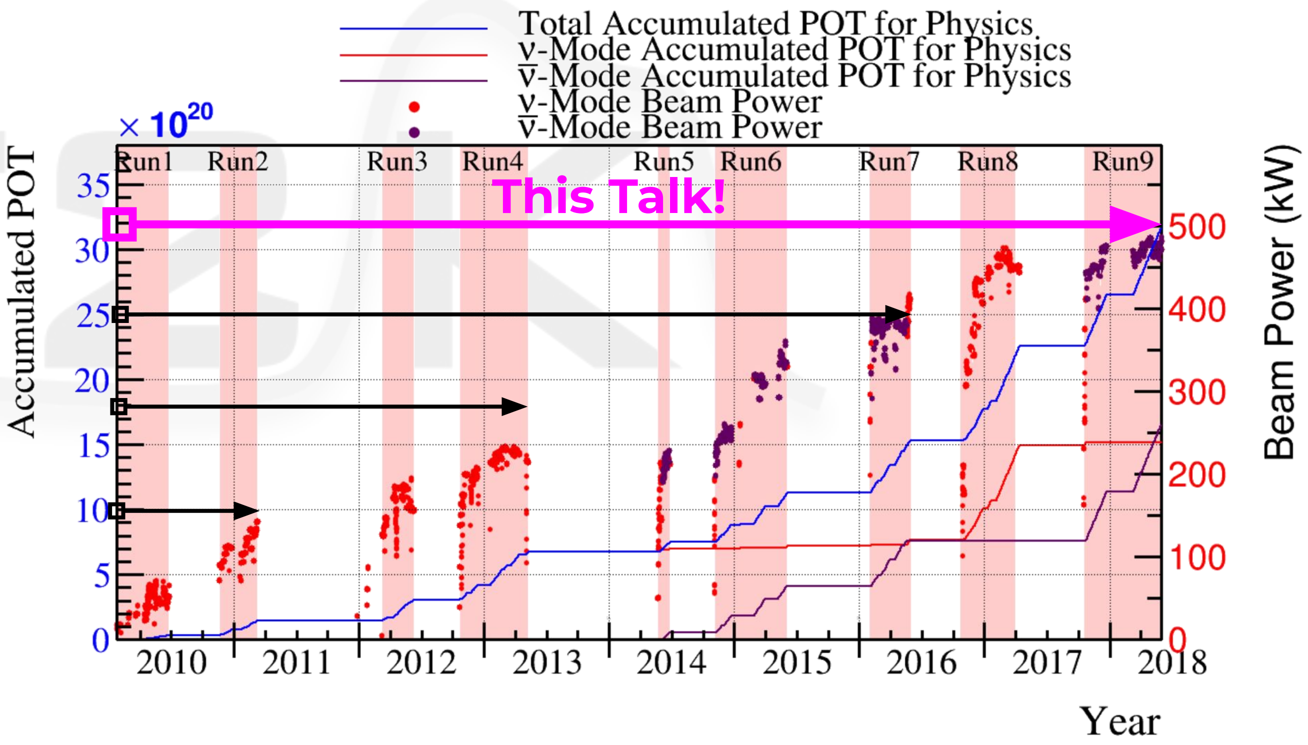
- Main T2K detectors **2.5° off-axis** with respect to the beam:
    - Kinematics of boosted pion decays result in a finer beam width
    - 0.6 GeV peak energy gives maximum oscillation signal @ 295 km
- Uncertainties dominated by **hadron-production**:
    - Simulation tuned to NA61/SHINE hadron-production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

Delivered Protons On Target

Search for CPV
[Phys. Rev. Lett. 121,171802](#)

Observation
[Phys. Rev. Lett. 112, 061802](#)

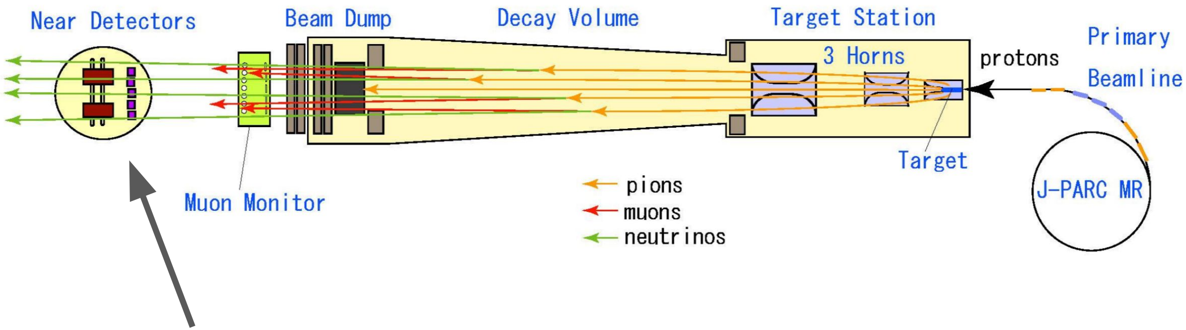
Indication
[Phys. Rev. Lett. 107, 041801](#)



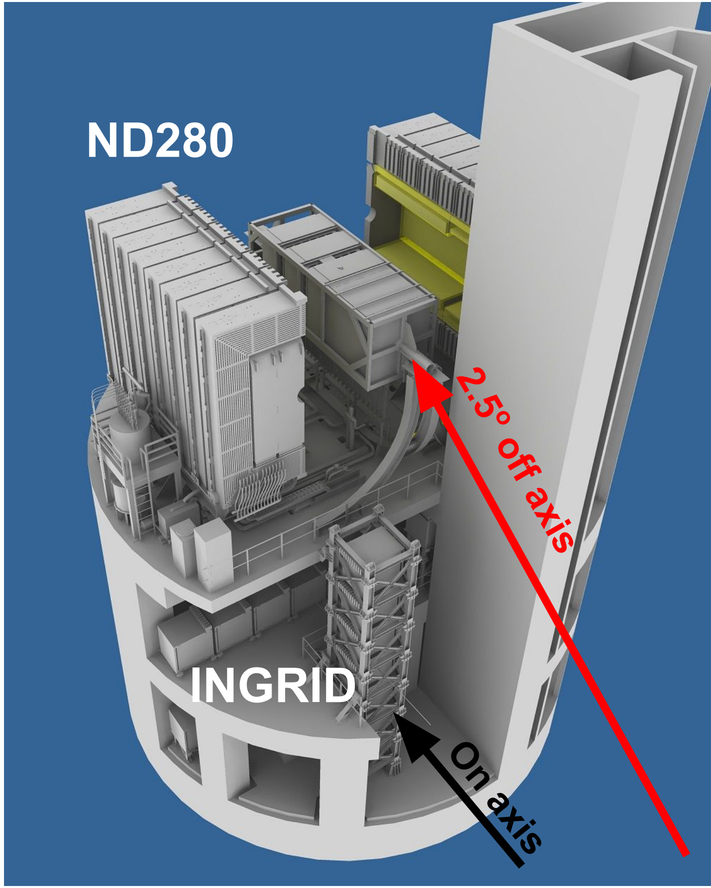
23 Jan. 2010 – 31 May 2018
POT total: 3.16×10^{21}

ν-mode 1.51×10^{21} (47.83%)
$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

Near Detector Complex

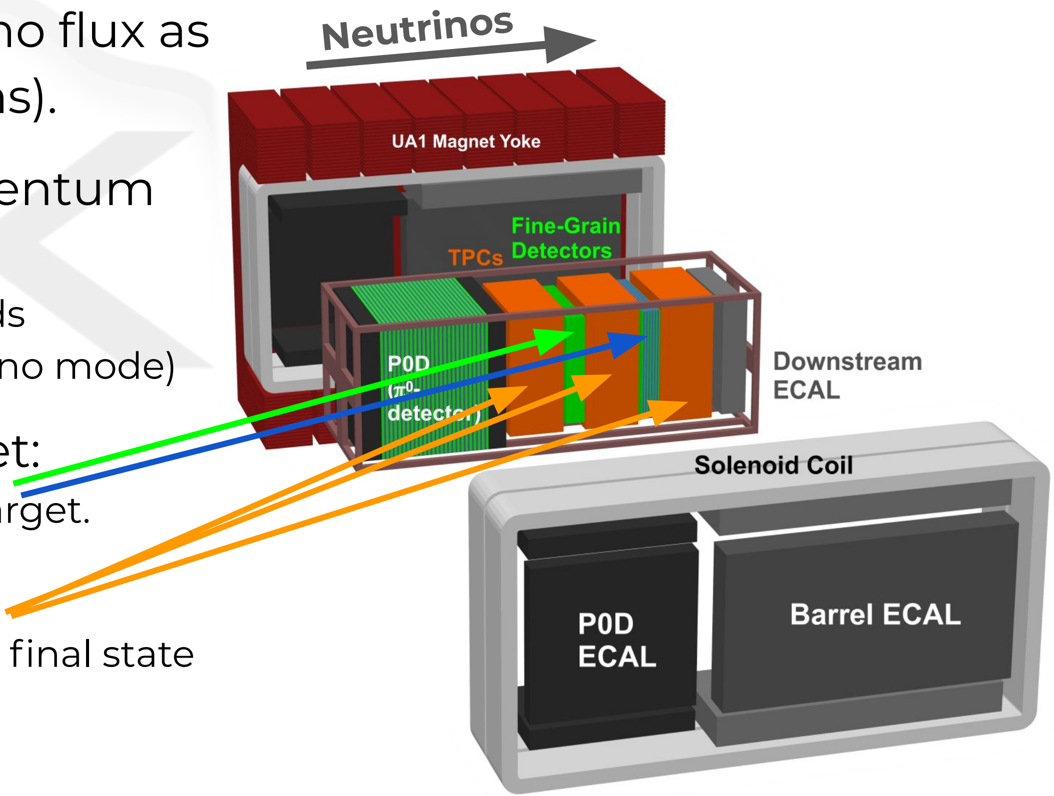


- Located 280 m downstream of proton target station.
- Houses a number of detectors in the J-PARC neutrino beam.
- Two used by T2K Oscillation analyses:
  - **INGRID**: On-axis, ensures beam alignment
  - **ND280**: Off-axis near detector



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.



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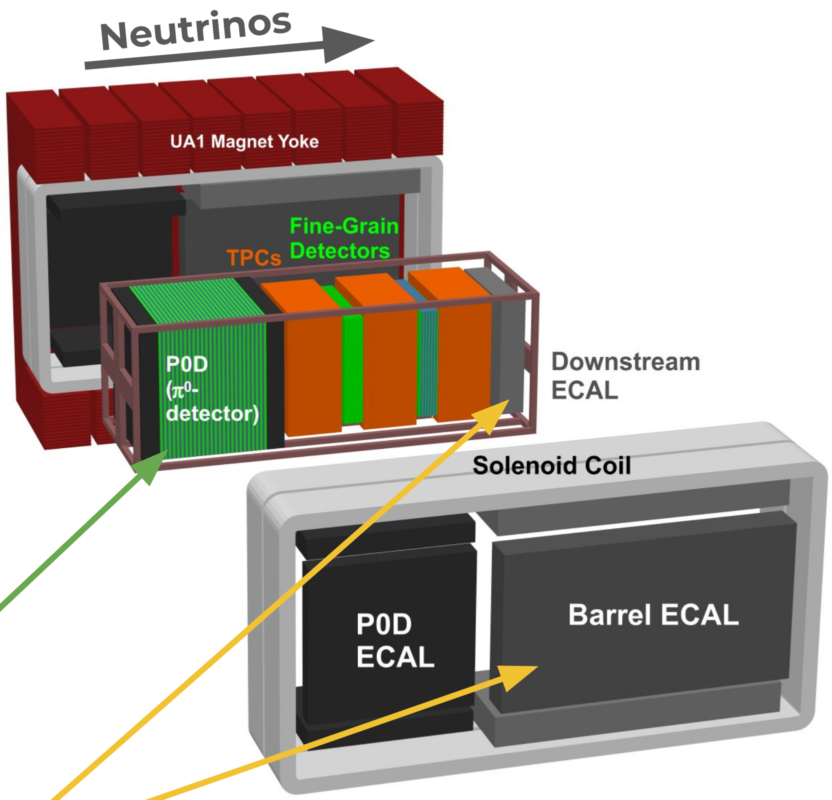
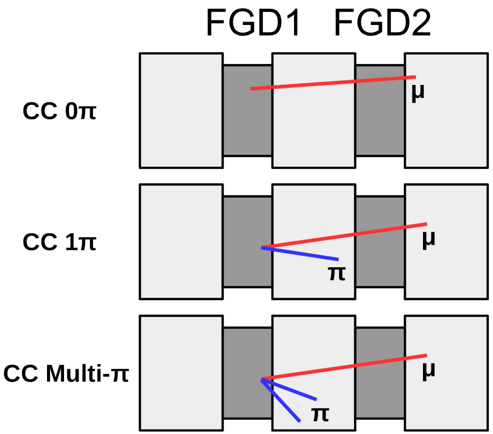
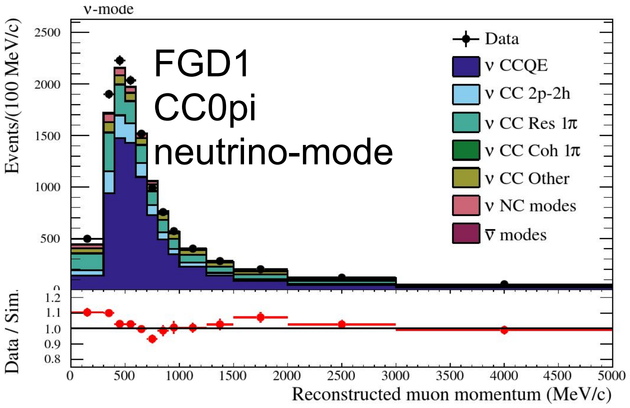
- FGD used as the neutrino target:
    - Active **CH** target + passive **water** target.
- Time Projection Chambers:
    - Good momentum/PID for charged final state particles.
- **P0D**: Specialized π^0 detector
- **ECal**: PID & escaping energy sampling

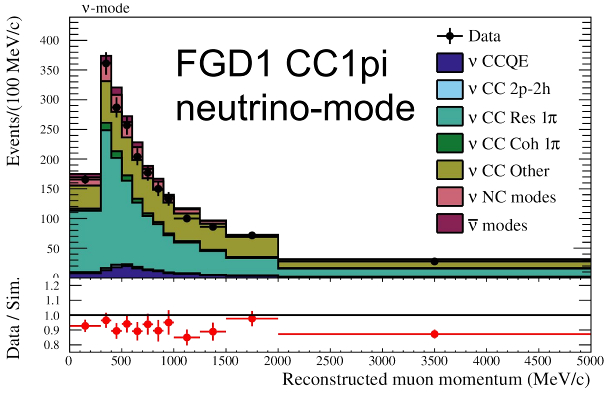


Near Detector Samples

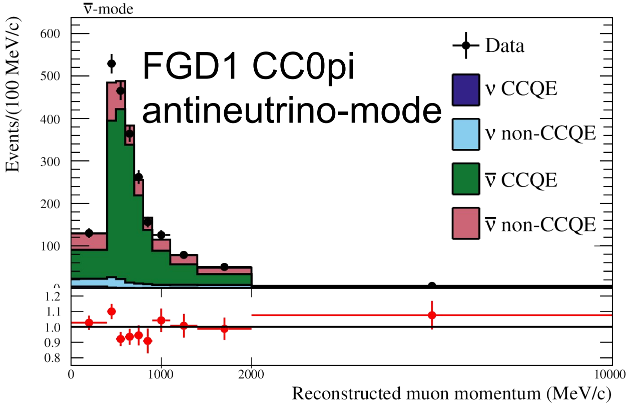




PRELIMINARY



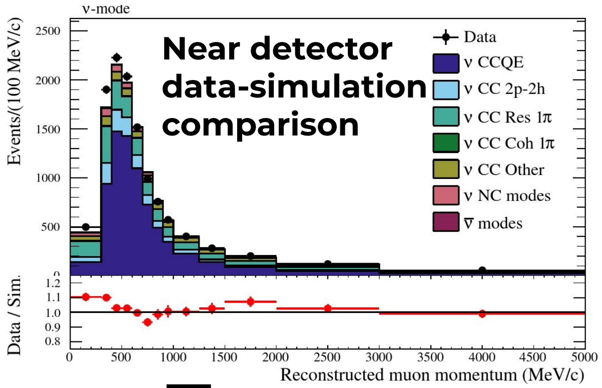
PRELIMINARY



PRELIMINARY

- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1
  - Target detector: FGD1 (CH) or FGD2 (CH+H2O)
- Binned in **observed lepton kinematics** only.
- Both neutrino and antineutrino beam modes:
  - Antineutrino separated into 1-track and N-track
  - Dedicated **ν** in anti-neutrino mode sample

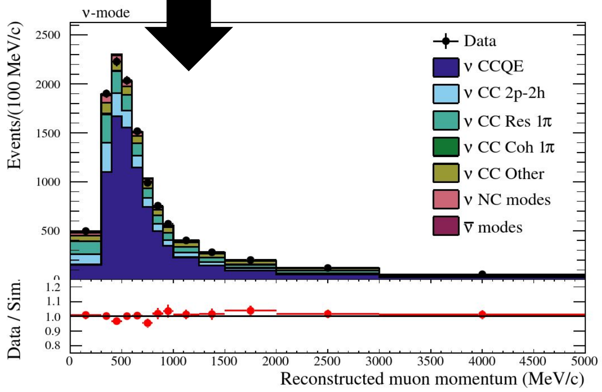
Near Detector Fit



Near detector data-simulation comparison

PRELIMINARY

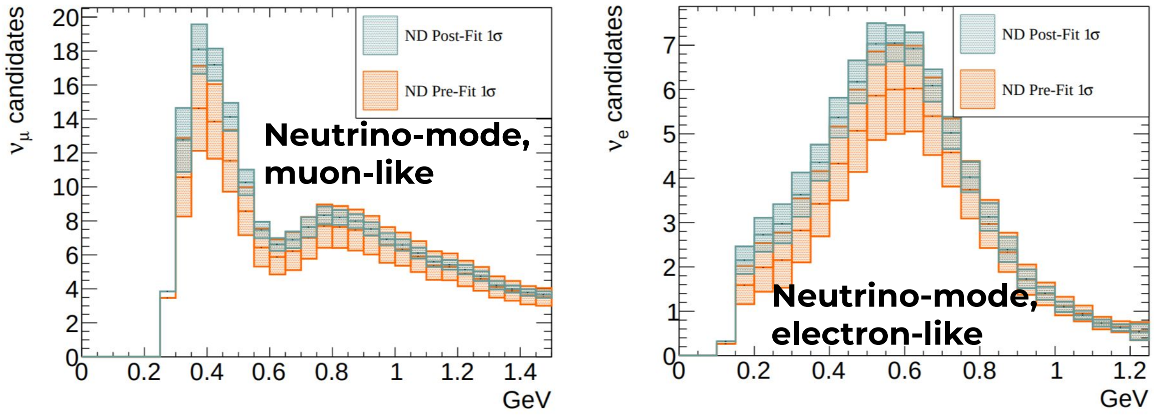
Fit Free parameters



PRELIMINARY

- ND samples used in analysis to:
  - Tune interaction model
  - Tune flux prediction
  - Correlate flux and interaction uncertainties
- ND samples either:
  - Fit simultaneously with far detector data
  - ND-tuned model propagated to far detector analysis

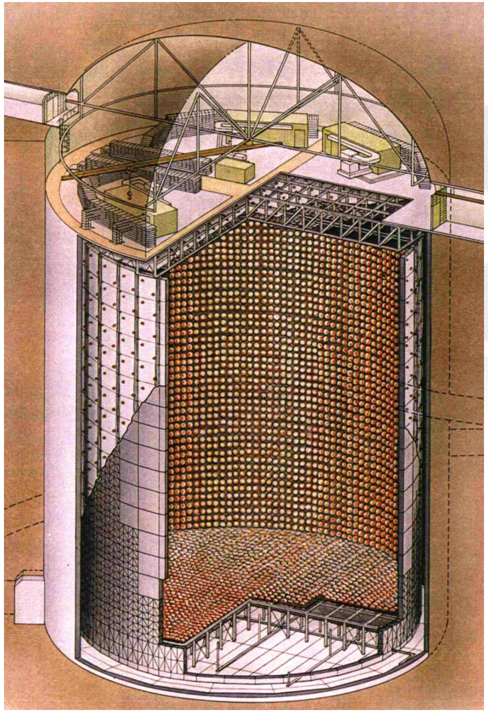
Far detector predicted event rates with oscillations

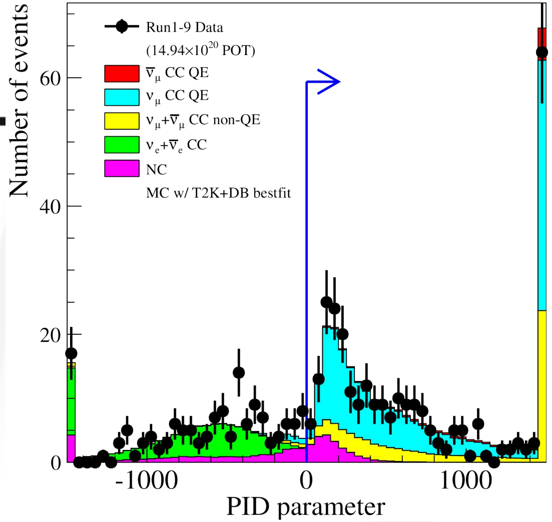


Neutrino-mode, muon-like

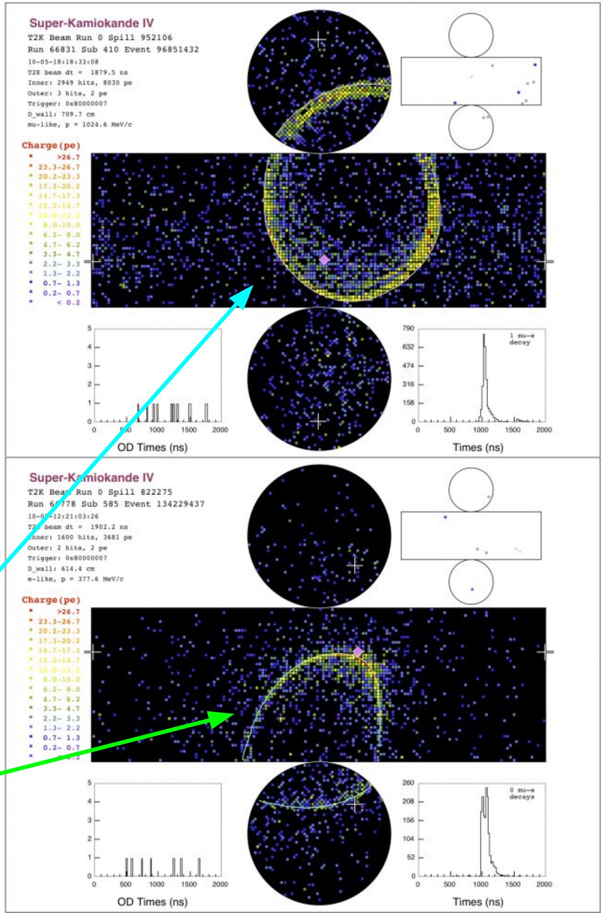
Neutrino-mode, electron-like

The Far Detector





- Water Cherenkov detector.
- Sensitive to:
  - Electrons, muons, pions, (very energetic protons)
- Can discriminate Cherenkov rings from:
  - **muon** ('sharp')
  - **electron** ('fuzzy')



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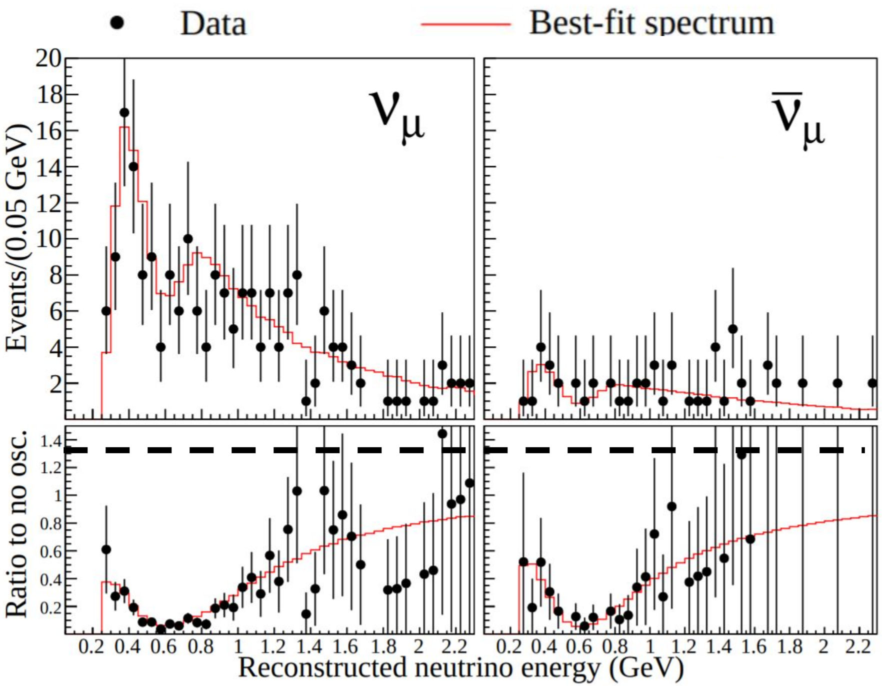
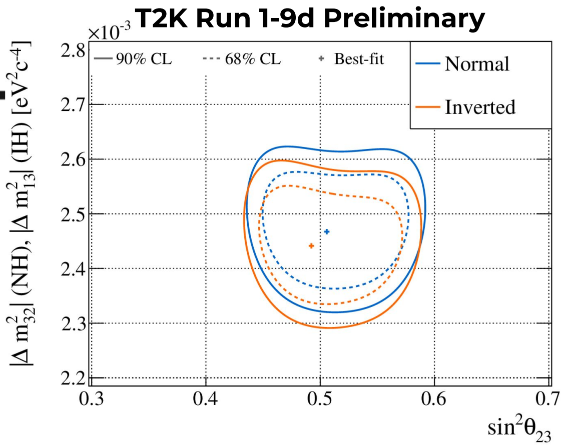
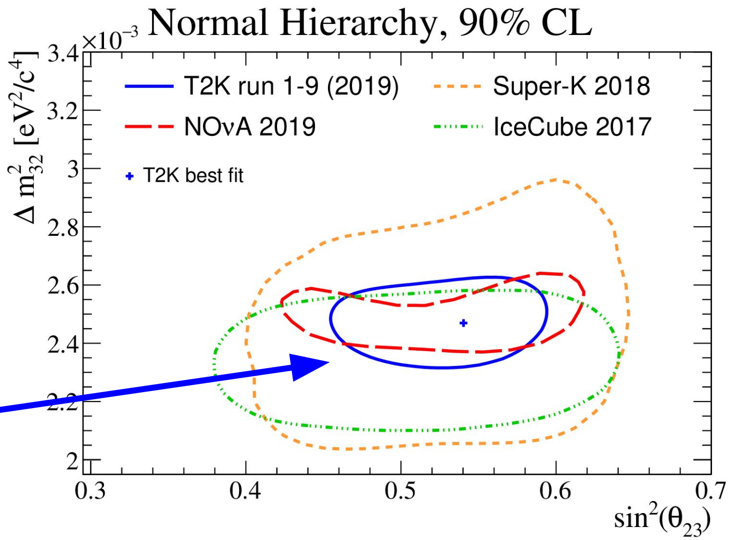
Disappearance Samples/Parameters

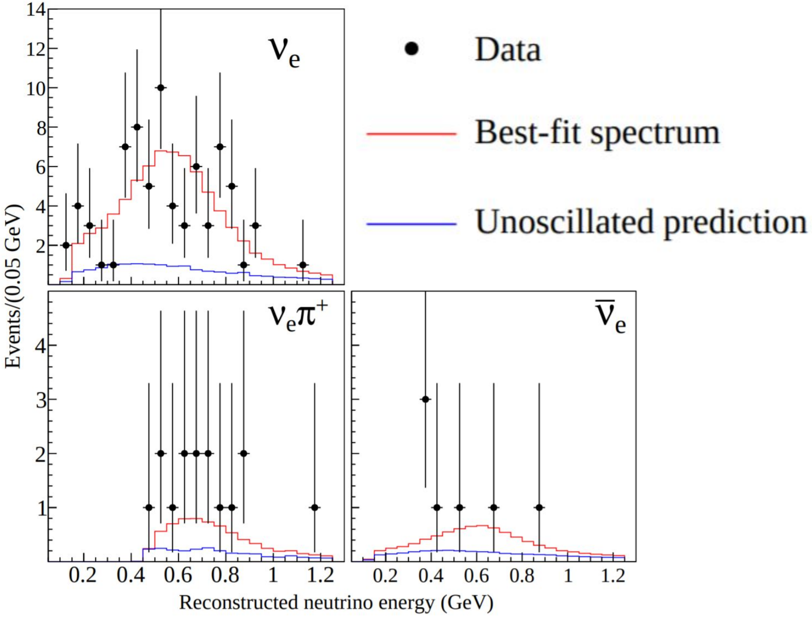


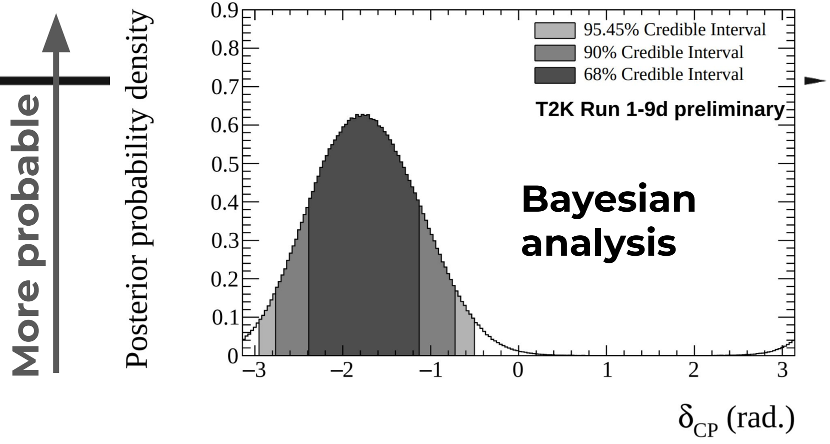


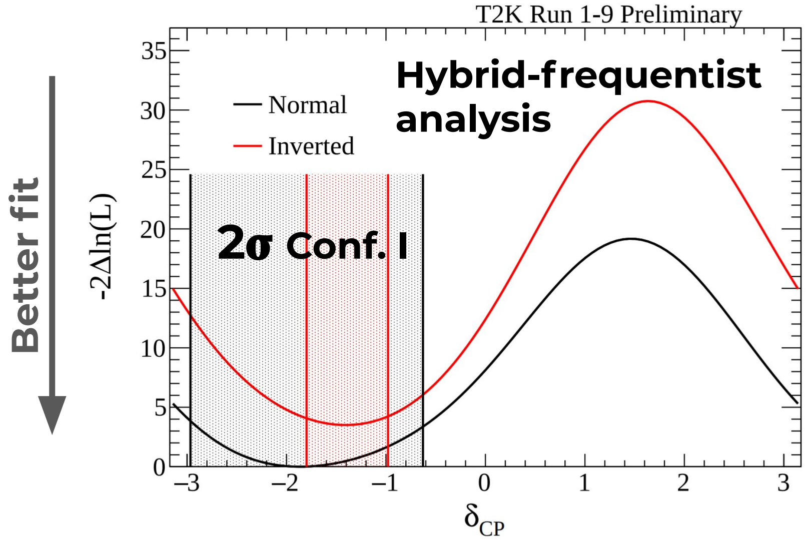


- World-leading constraint on atmospheric mixing angle.
  - Consistent with maximal mixing

Appearance



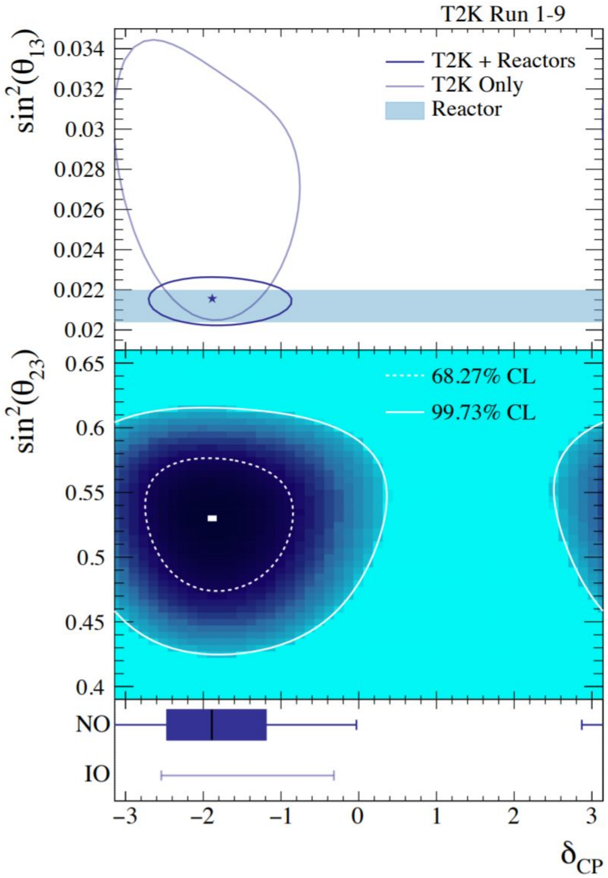




- CP conserving values lie outside the 2σ contour for both **bayesian** and **hybrid-frequentist** analyses.

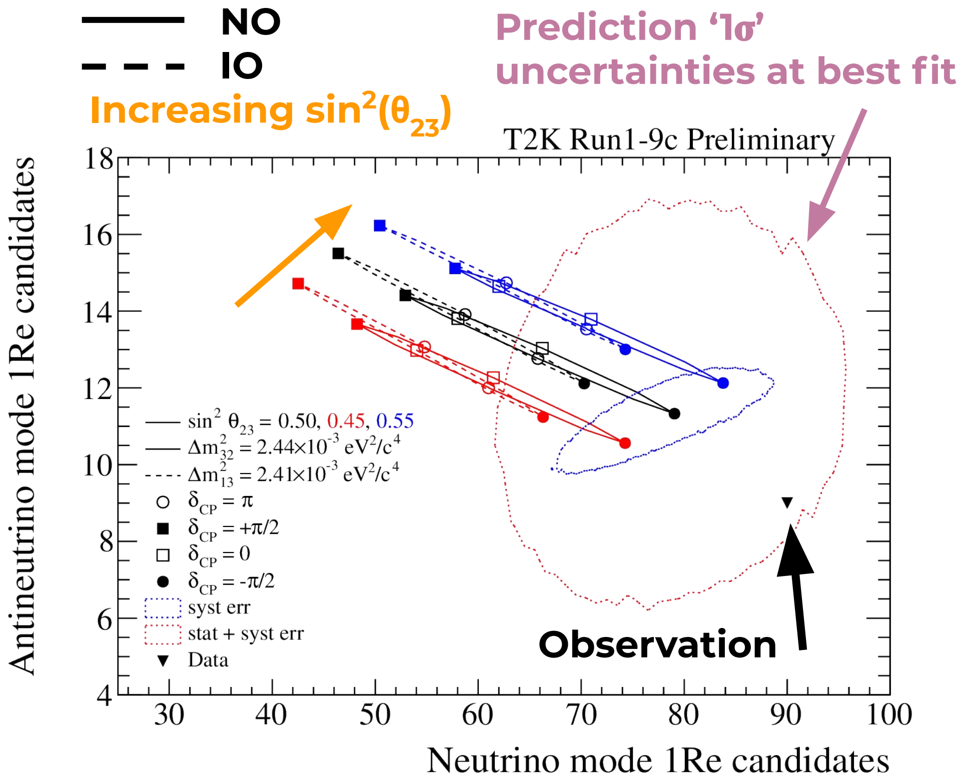
δ_{CP}: 3σ Exclusion

- Latest analysis extended to '3σ' intervals.
    - See '3σ' exclusion of CP-conserving values in inverted ordering.
    - See '1σ' exclusion of all values of δ_{CP} in inverted ordering.
- Results under peer review:
    - Pre-print available: [1910.03887 [hep-ex]](1910.03887 [hep-ex])
    - Watch for publication soon!



Oscillation Fit: Bi-event rate

- Appearance analysis is statistically limited:
    - Minimal spectral information
    - 'Bi-event' plot depicts preference for NH, $\delta_{cp}=-\pi/2$
- 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…?



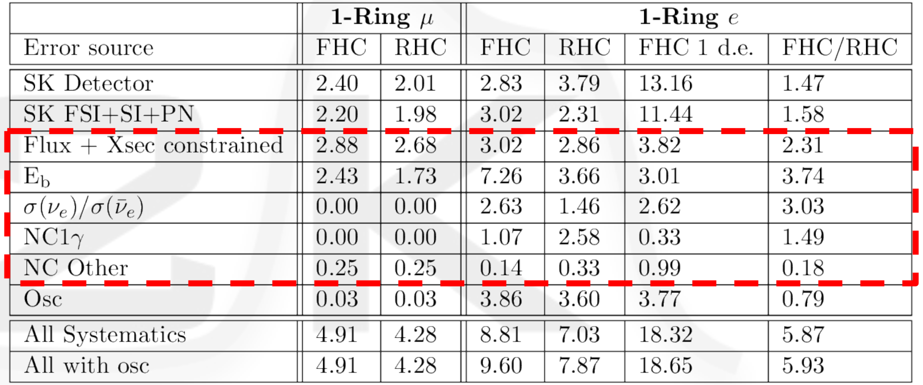
Prediction '1σ' uncertainties at best fit

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

Observation

Oscillation Fit: Sources of Error

Percentage predicted event rate uncertainty

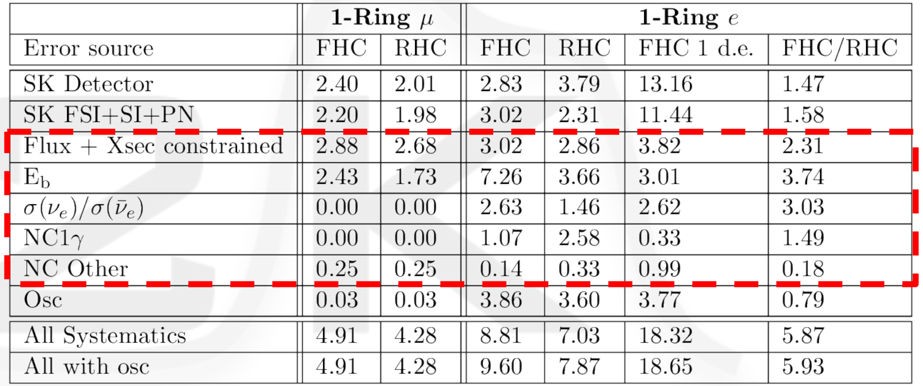


	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	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

- Cross-section × flux is the largest uncertainty:
  - **Power of ND**: Only slightly larger than SK detector uncertainties
  - Flux errors will be reduced by future hadron-production data.
  - Reducing cross-section error is a global effort:
    - T2K Near Detector measurements
    - External measurements (esp. MINERvA)
    - Theory development

Oscillation Fit: Sources of Error

Percentage predicted event rate uncertainty



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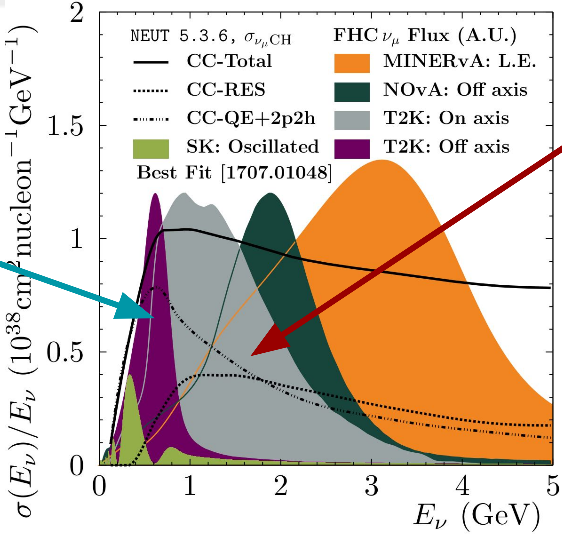
Cross Sections

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

T2K Cross-section Results

Links for your convenience

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- ν NCQE O^{16} (2014)
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- ν_μ CCInc $Fe^{56}/C^{12}H$ (2014)
- ν_μ CCQE C^{12} (2014)
- ν_μ CCQE C^{12} (2015)
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- ν_μ CC1π H_2O^{16} (2016)
- ν_μ CC Coherent 1π C^{12} (2017)
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- 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)
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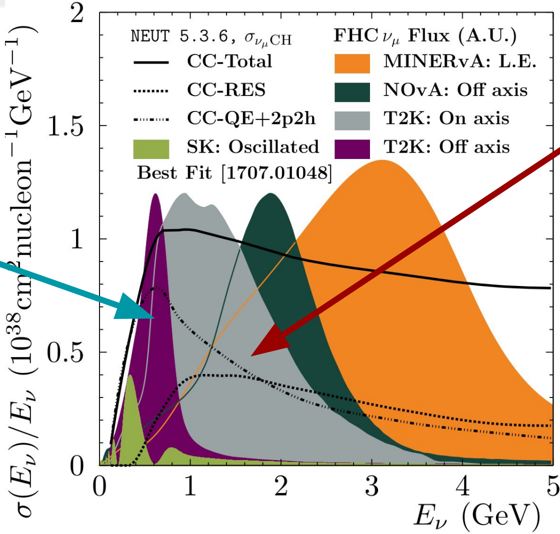
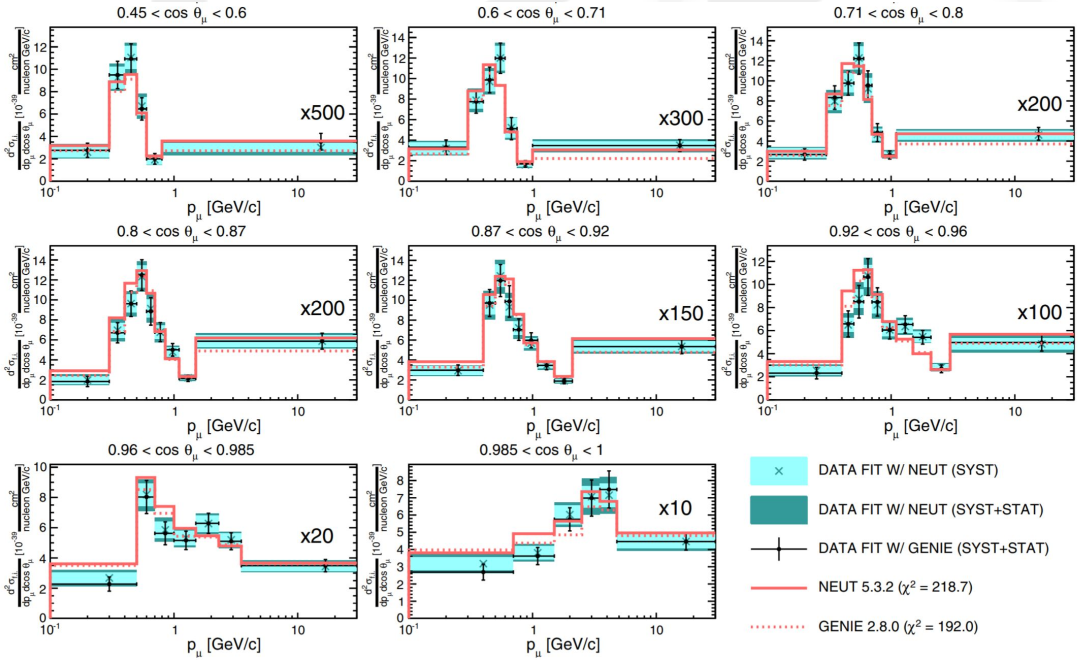


ND280 Analyses

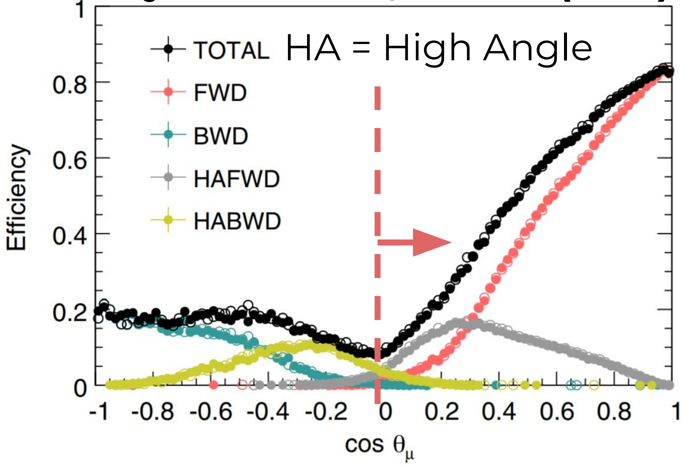
INGRID Analyses

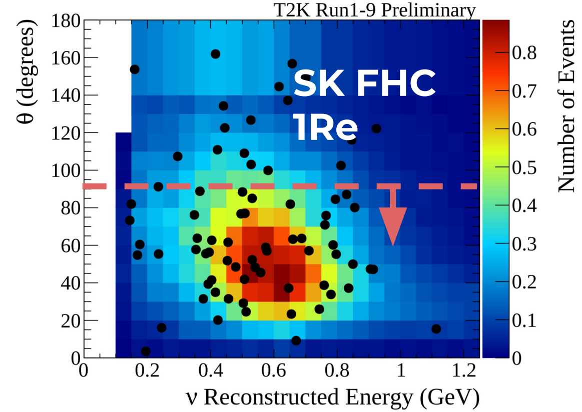
Focus 1: CCInc Expanded Phase Space

- 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)

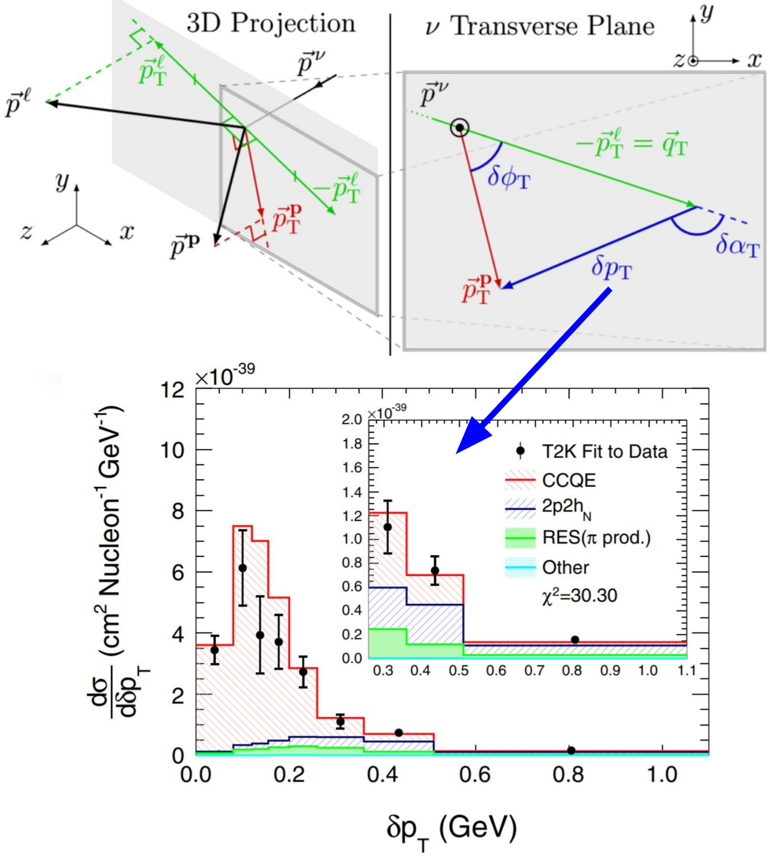




Focus 2: CC0π Transverse Variables

- 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.

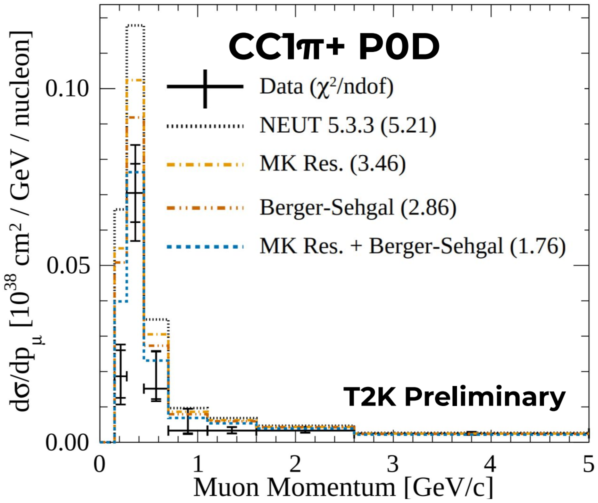
Phys. Rev. D 98, 032003 (2018)



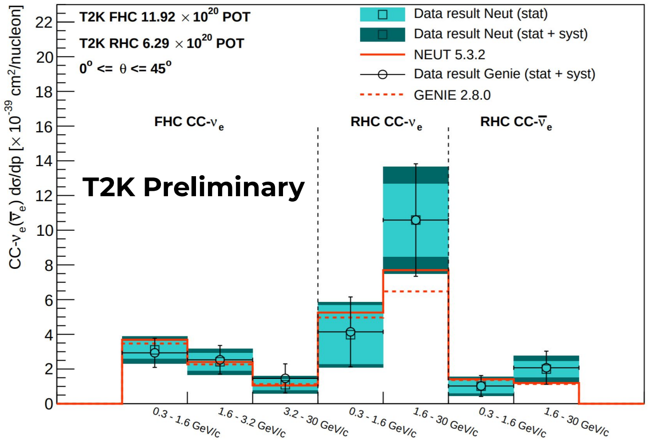
New And Future

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

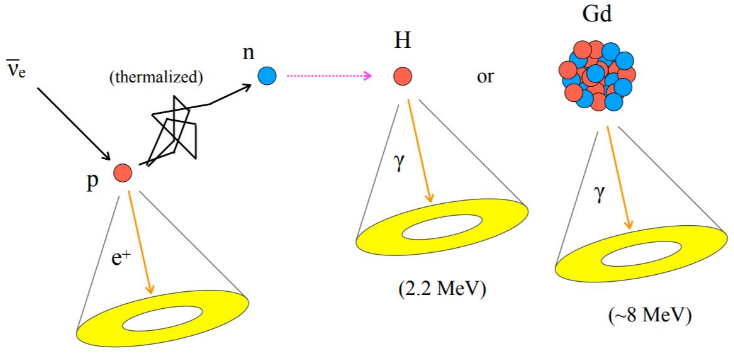


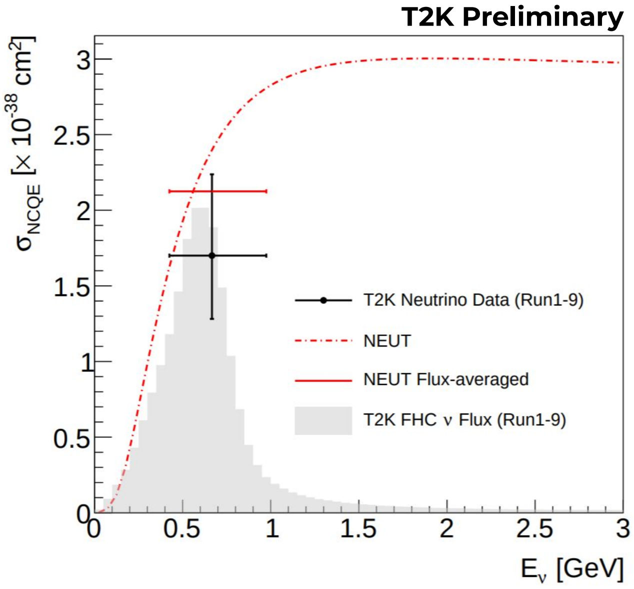
CC-ν_e and CC-$\bar{\nu}_e$ Cross-Section



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.

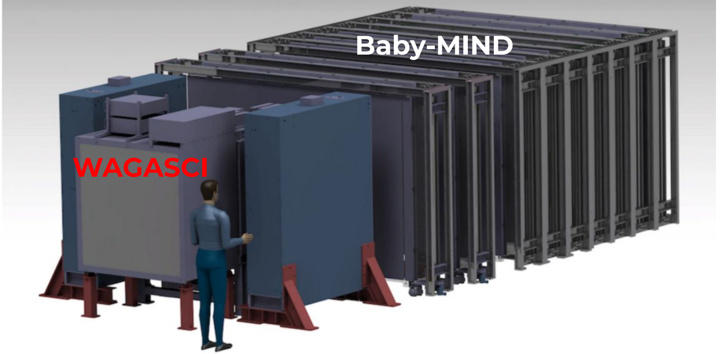


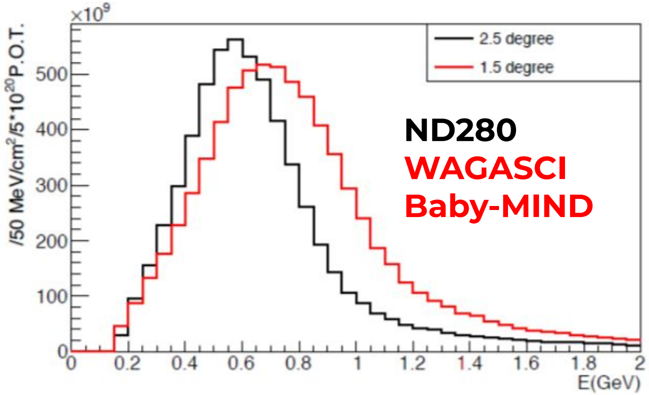


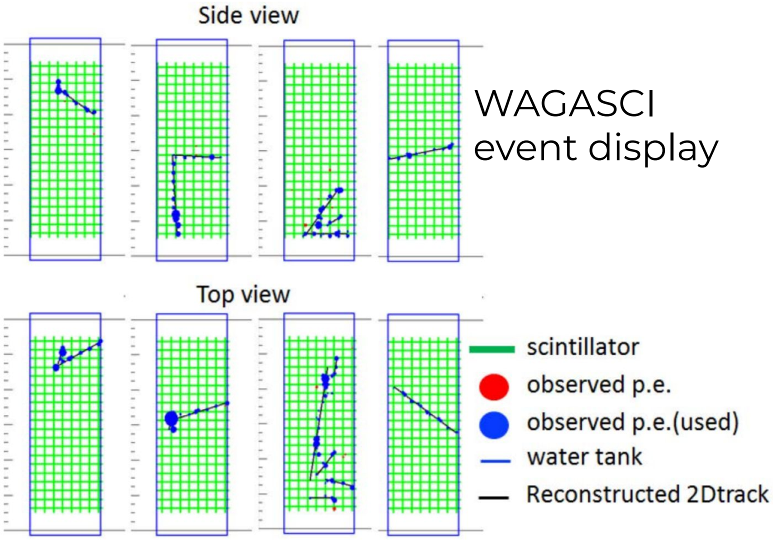
WAGASCI and Baby-MIND

- **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



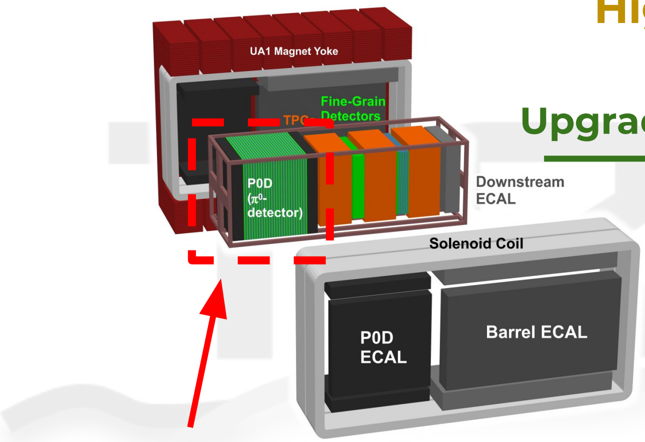




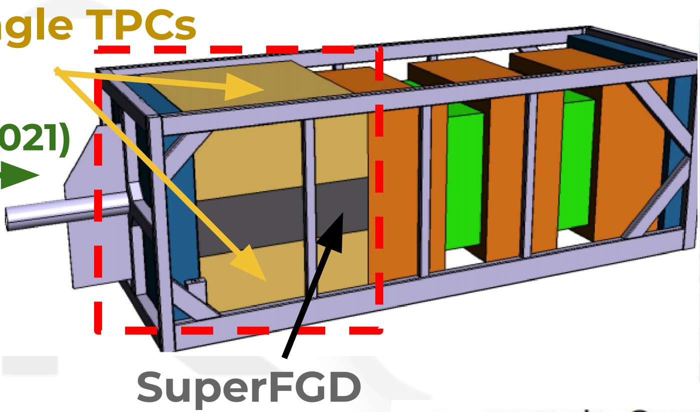
WAGASCI event display

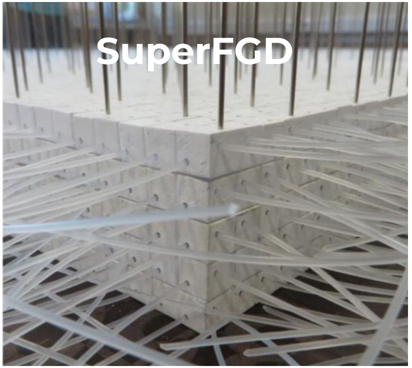
ND280 Upgrade

See Sergey's talk yesterday for more details

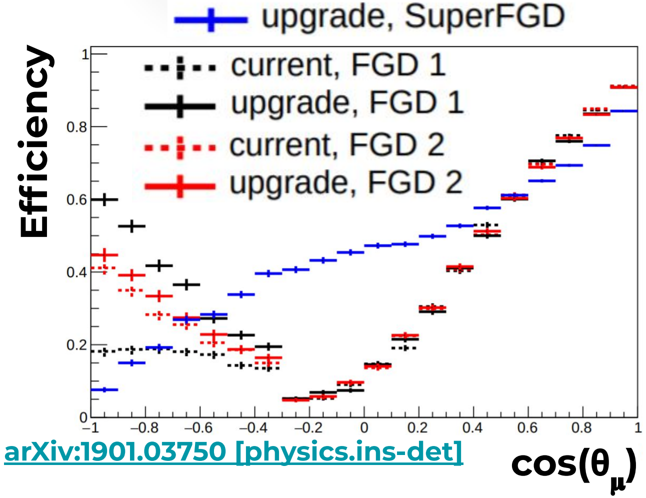


Upgrade! (~2021)





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

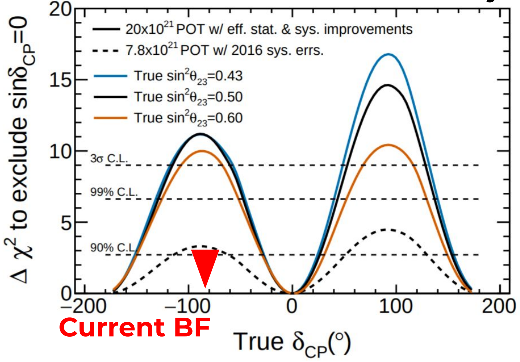


arXiv:1901.03750 [physics.ins-det]

T2K-II and J-PARC Beam upgrade

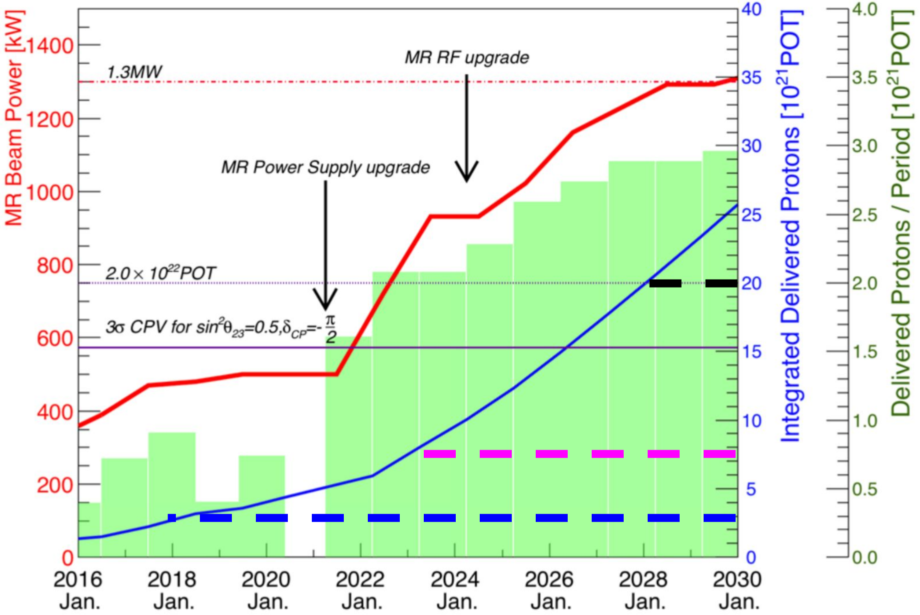
- T2K has recorded **3.16×10^{21} POT**
  - T2K original POT quota: **7.8×10^{21}**
- T2K-II to take: **20×10^{21}**
- Continued rich physics program and improved oscillation sensitivity until Hyper-K

arXiv:1609.04111v1 **CP cons. rej.**



Current BF

T2K-II Target POT (Protons-On-Target)

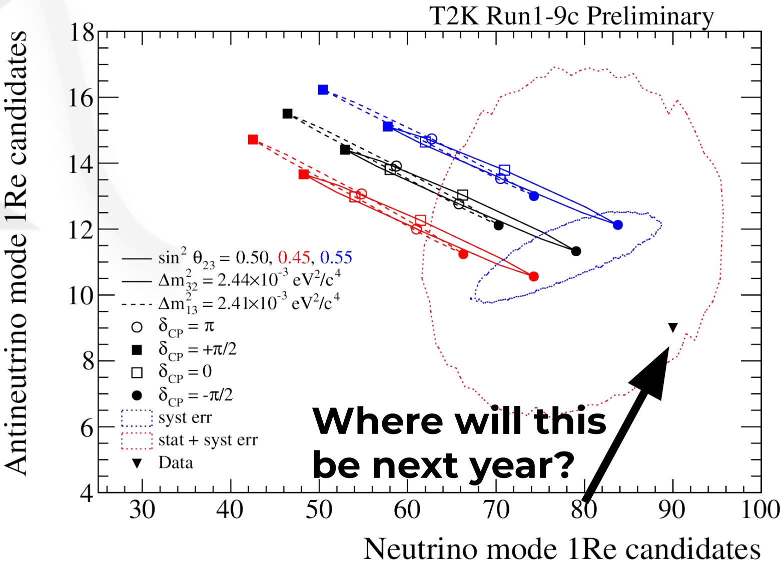


T2K-NOvA

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

Summary

- It’s an exciting time in long baseline neutrino physics!
- World-leading measurements of mixing parameters.
- Beginning to see sensitivity to lepton-sector CPV.
- Important and interesting problems to tackle in interaction physics.



Where will this be next year?


Dawn from the summit of Fuji-san

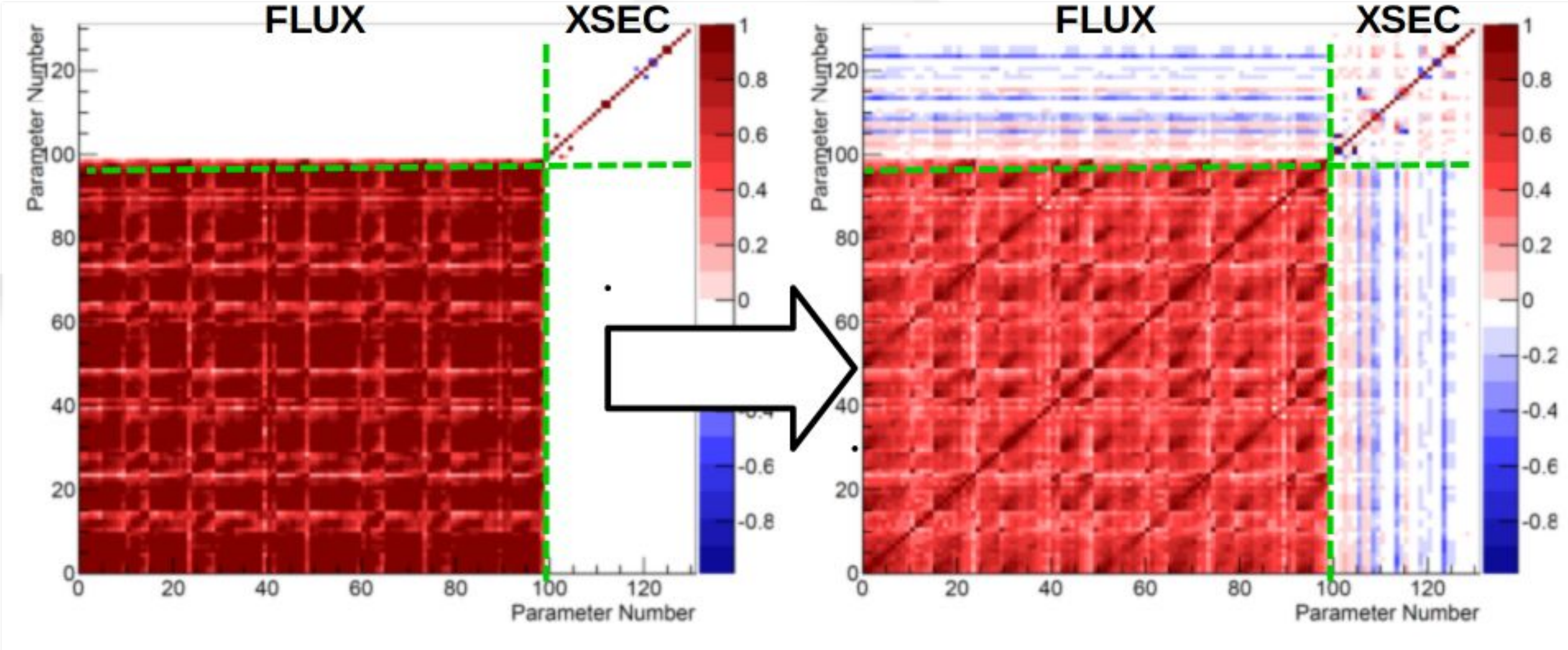
Thanks for listening

MICHIGAN STATE UNIVERSITY

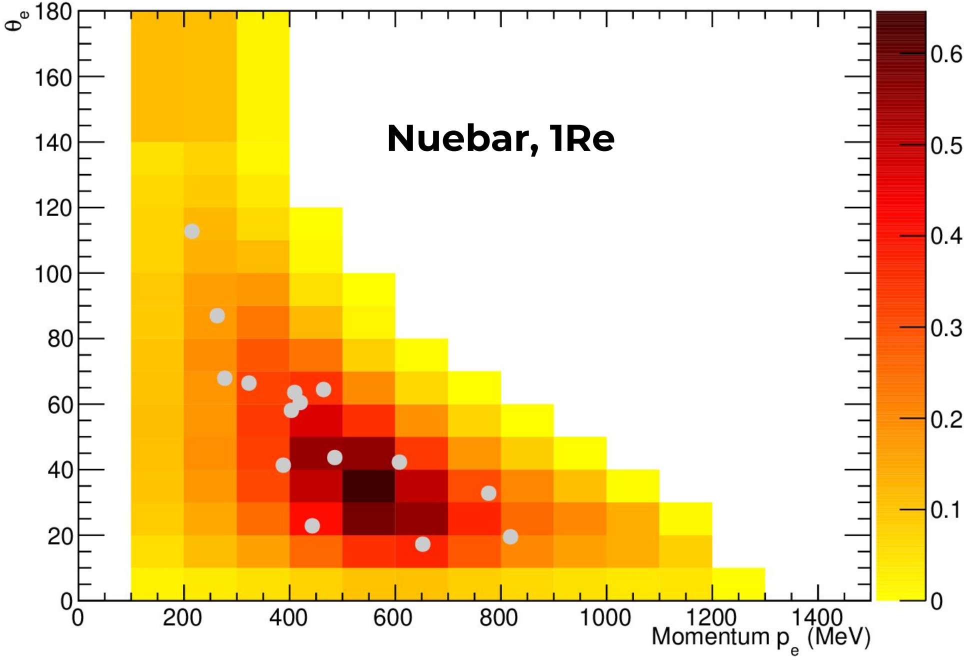
T2K

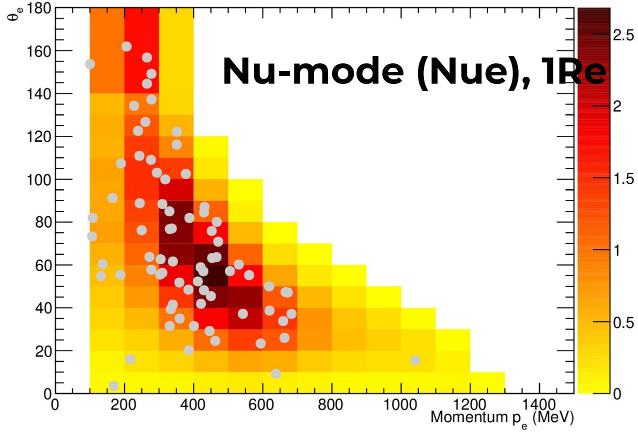
Near detector Flux/XSec Correlations

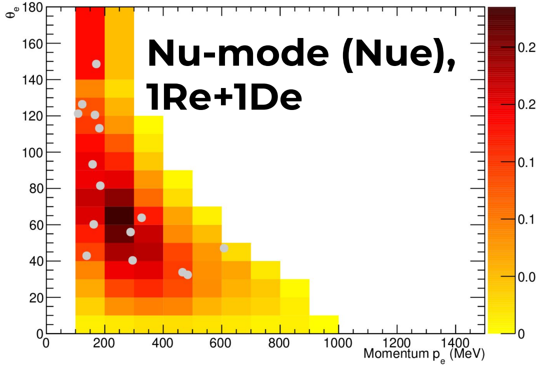
ND280 constraint



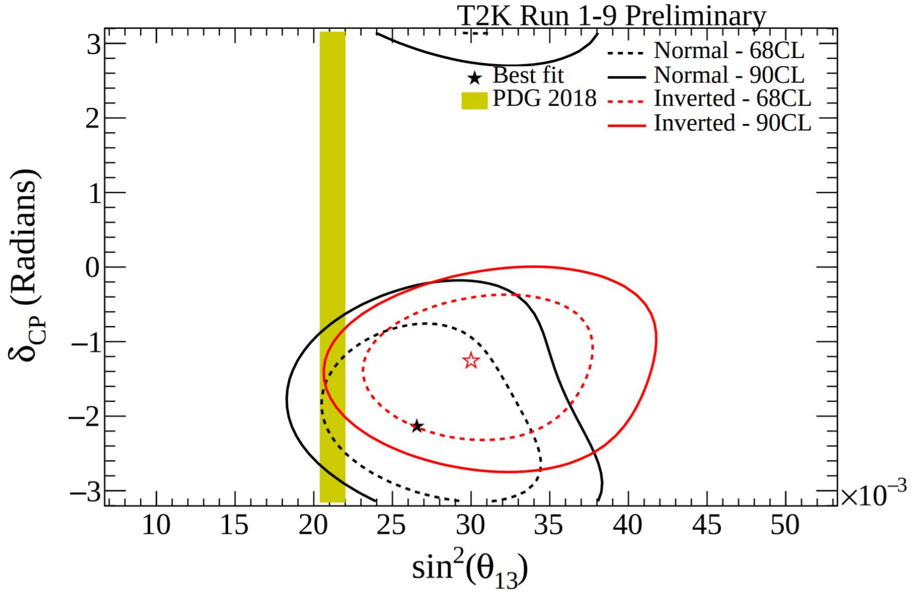
Predicted Event Rates p/theta

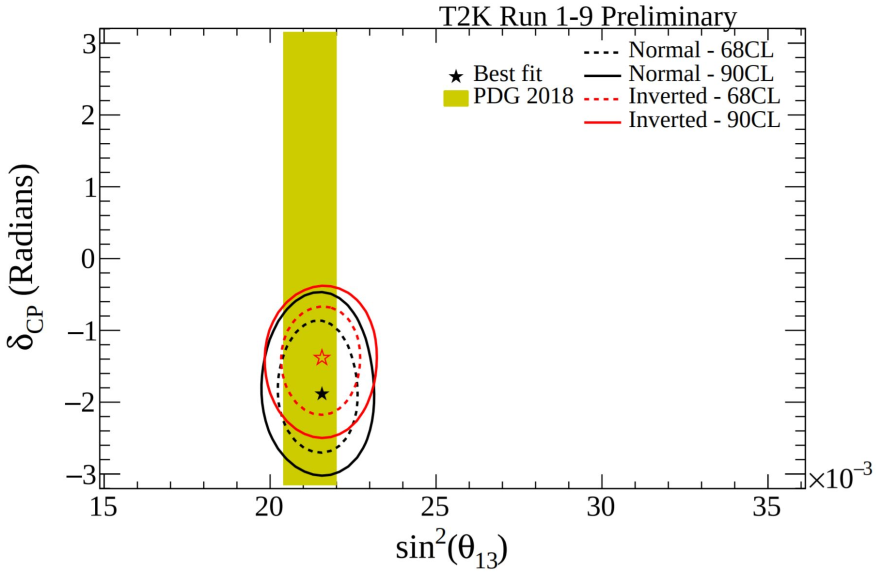






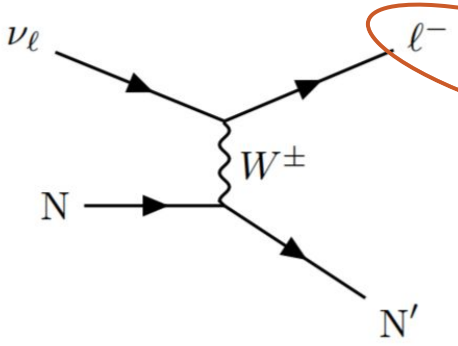
dcp/th13 contours





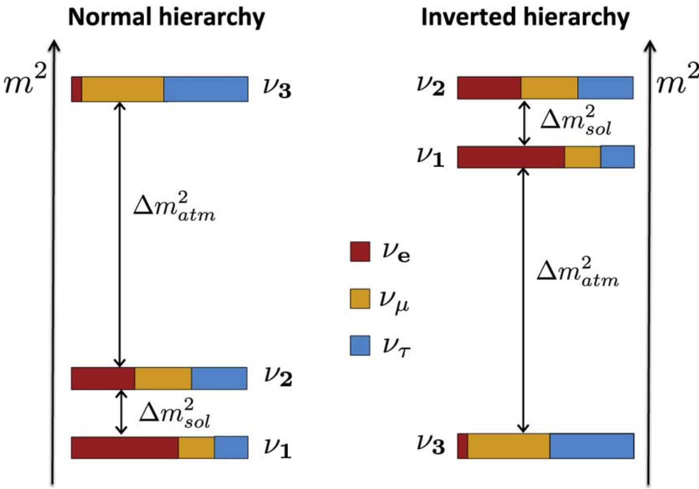
Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}}_{\mathbf{M}_{\text{PMNS}}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

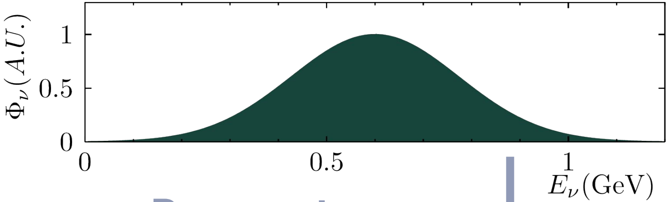
Pontecorvo–Maki–Nakagawa–Sakata



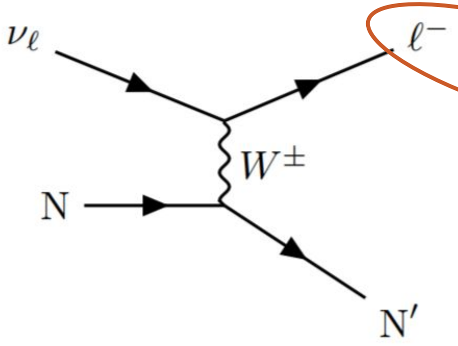
Journal of Physics G: Nuclear and Particle Physics. 43. 10.1088/0954-3899/43/8/084001

Neutrino Oscillation: PMNS

***e.g.* created as muon neutrinos**



Interaction with matter in flavor eigenstate defined by charged lepton.



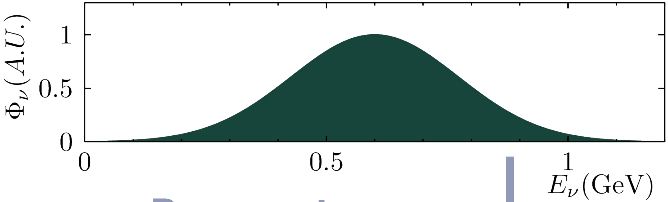
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\mathbf{M}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

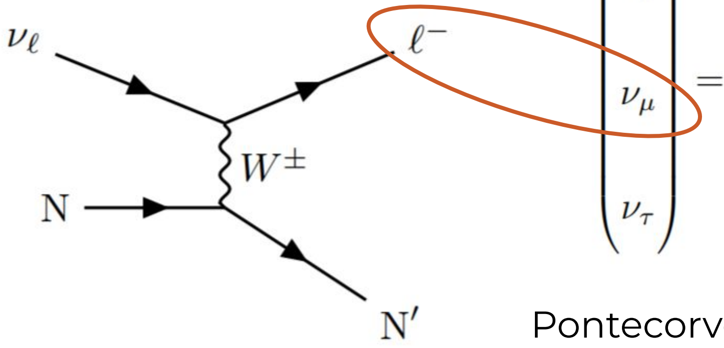
Propagate as superposition of mass/energy eigenstates.

Neutrino Oscillation: PMNS

***e.g.* created as muon neutrinos**



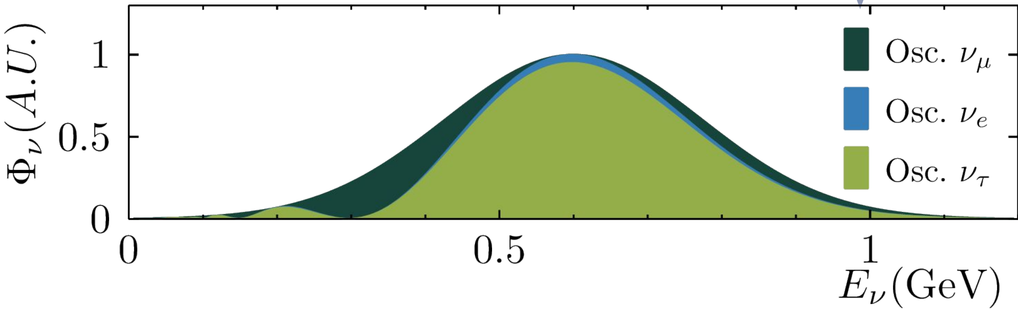
Interaction with matter in flavor eigenstate defined by charged lepton.



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}}_{\mathbf{M}_{\text{PMNS}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.



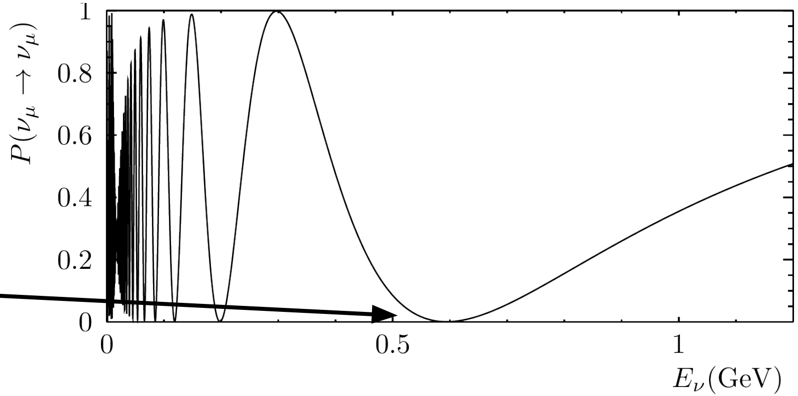
Projecting back to flavor eigenstates reveals a different flavor mixture.
(if $|\Delta m^2_{ij}| \neq 0$)

Neutrino Flavor Change: Oscillation

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

- Can re-parameterize PMNS matrix:
  - Mixing angles: $C_{ij} = \cos(\theta_{ij})$
  - CP violating phase: $0<\delta_{CP}<2\pi$
- To leading order, muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.
- Choose L/E so that for maximum effec $\sin^2\left(\Delta m^2_{23}L/4E\right) \simeq 1$

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



Neutrino Flavor Change: Oscillation

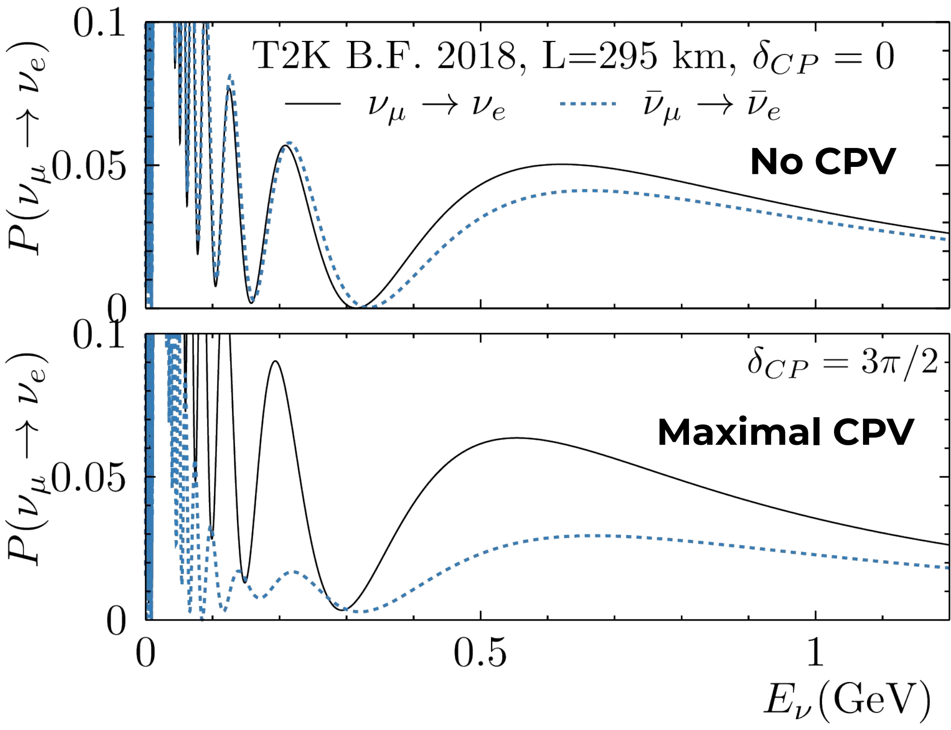
- Electron neutrino appearance probability has ‘**CP odd**’ term.
  - Sign flip between matter and antimatter.

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \boldsymbol{\sin^2\theta_{23}}\boldsymbol{\sin^2 2\theta_{13}}\sin^2\frac{\boldsymbol{\Delta m^2_{32}}L}{4E}$$

$$(+)-\Big[\sin 2\theta_{12}\boldsymbol{\sin 2\theta_{23}}\boldsymbol{\sin 2\theta_{13}\cos\theta_{13}}$$

$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\boldsymbol{\Delta m^2_{32}}L}{4E}\boldsymbol{\sin\delta_{CP}}\Big]$$

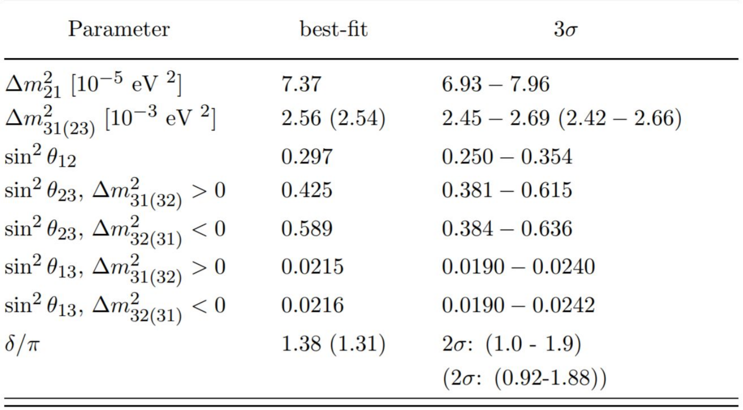
$$+\ (\text{CP-even, solar, matter effect terms})$$



Neutrino Oscillation: What Now?

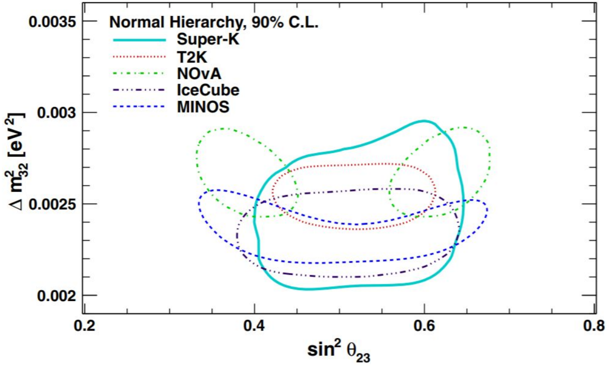
- Evidence for neutrino oscillation is overwhelming: *c.f.* 2015 Nobel Prize
- We know: all mixing angles and both mass-squared splittings ≠ 0.
- **Search for CP violation in the neutrino sector**—*i.e.* measure δ_{CP}
- Most sensitive to δ_{CP} when:
  - Mixing angles are known precisely
  - Mass ordering is known

PDG 2018:
Neutrino Masses, Mixing, and Oscillations



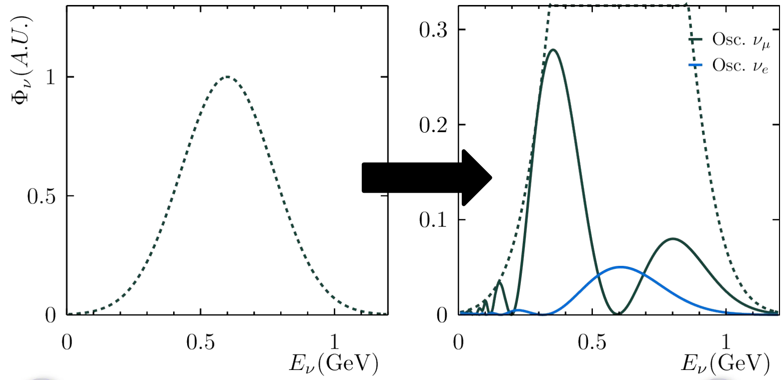
Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589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

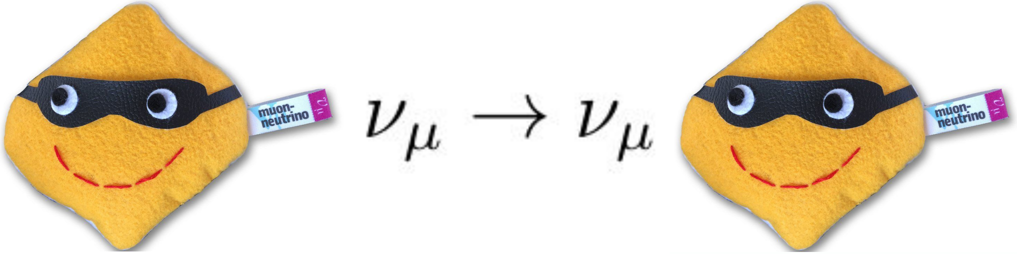
Phys. Rev. D97, 072001 (2018)

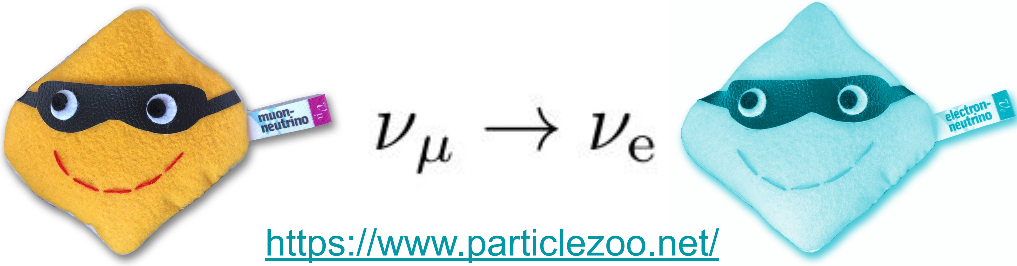


Long Baseline Oscillation: Channels

- Accelerator neutrino beams are mostly muon (anti)neutrinos.
  - Electron-flavor final states from pion decays strongly helicity suppressed.
- T2K beam is not high enough energy to produce $\tau^{\mp}$
  - ν_τ invisible
- Study two channels, each in two beam modes:
  - ν_μ disappearance
  - ν_e appearance

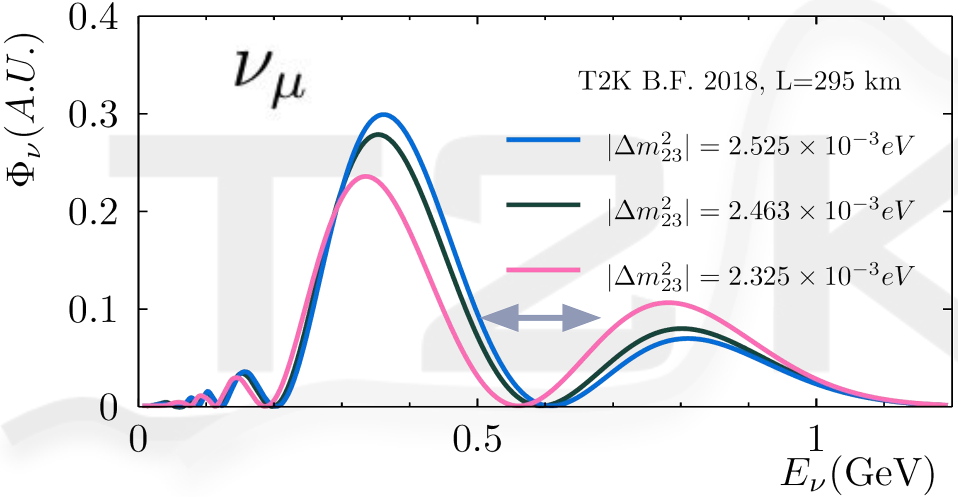


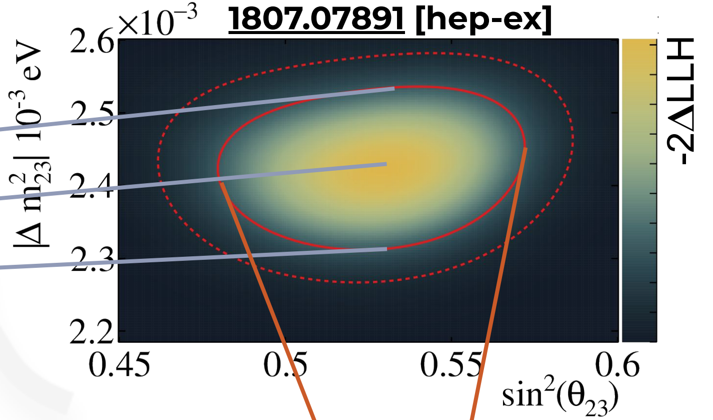


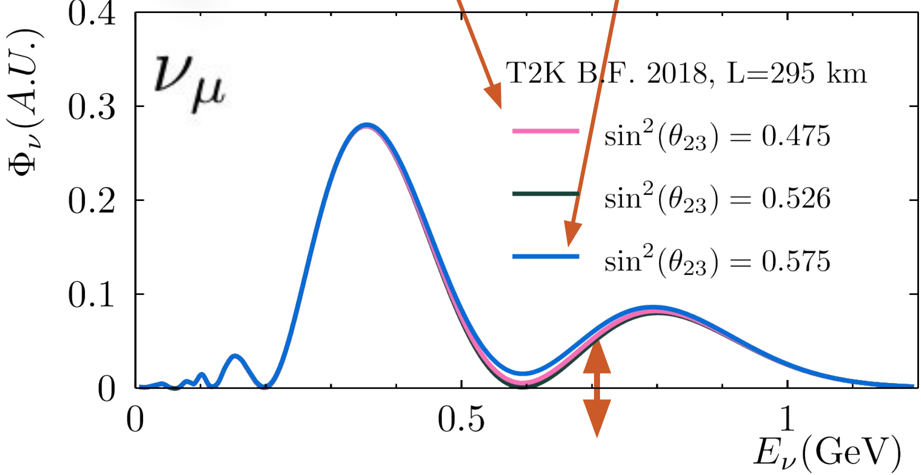


https://www.particlezoo.net/

Oscillation Channel: Disappearance

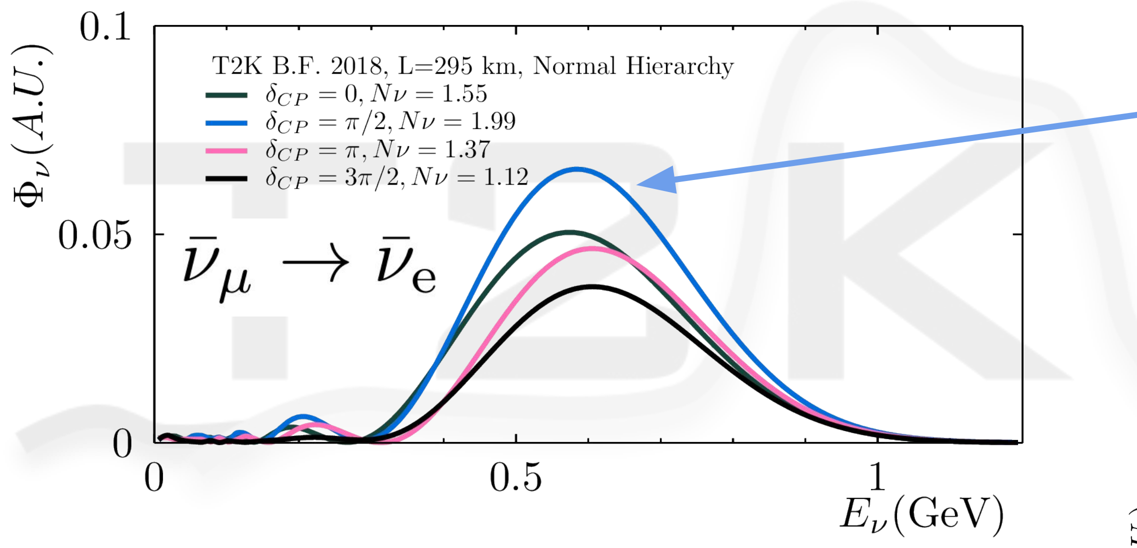


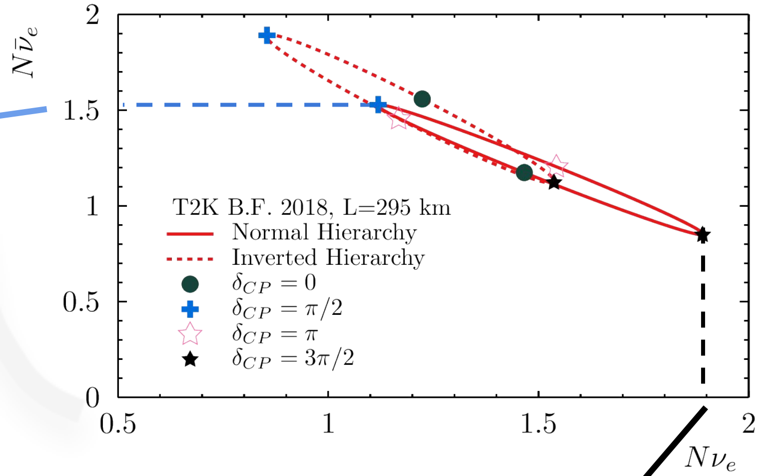


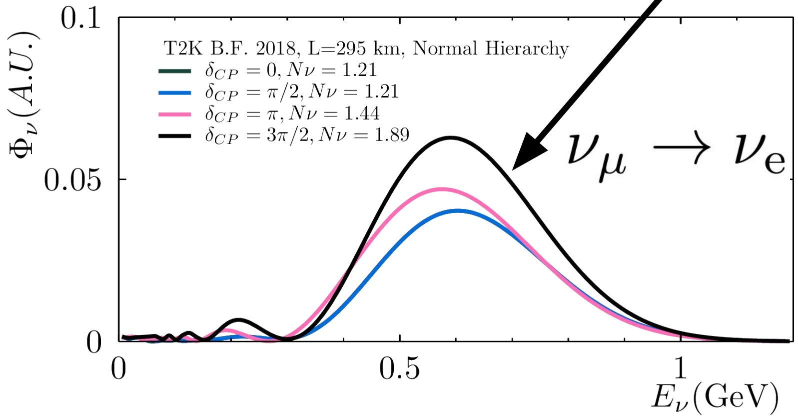


- Sensitivity to parameters comes from **position** and **depth** of first oscillation maximum.

Oscillation Channel: Appearance

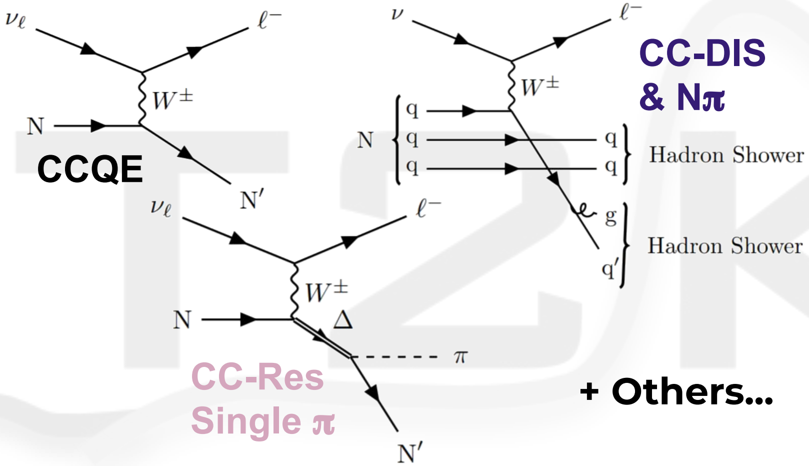






- Most sensitive to δ_{CP} if:
  - Know hierarchy
  - Know disappearance parameters well
  - Measure in both beam modes: $\nu_\mu \rightarrow \nu_e$
    $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Measuring Oscillations: Interactions



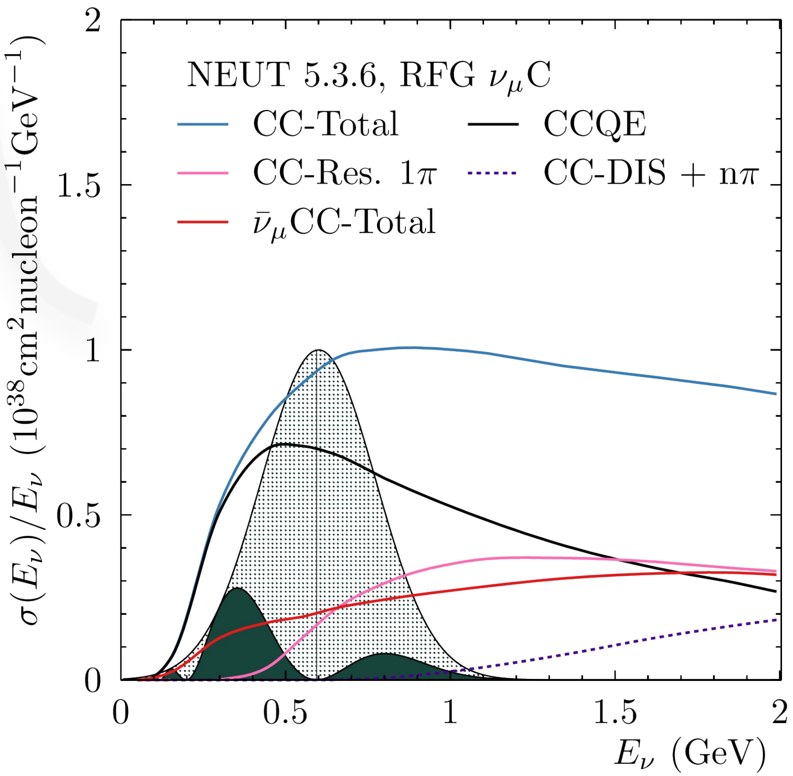
CCQE

CC-DIS & Nπ

CC-Res Single π

+ Others...

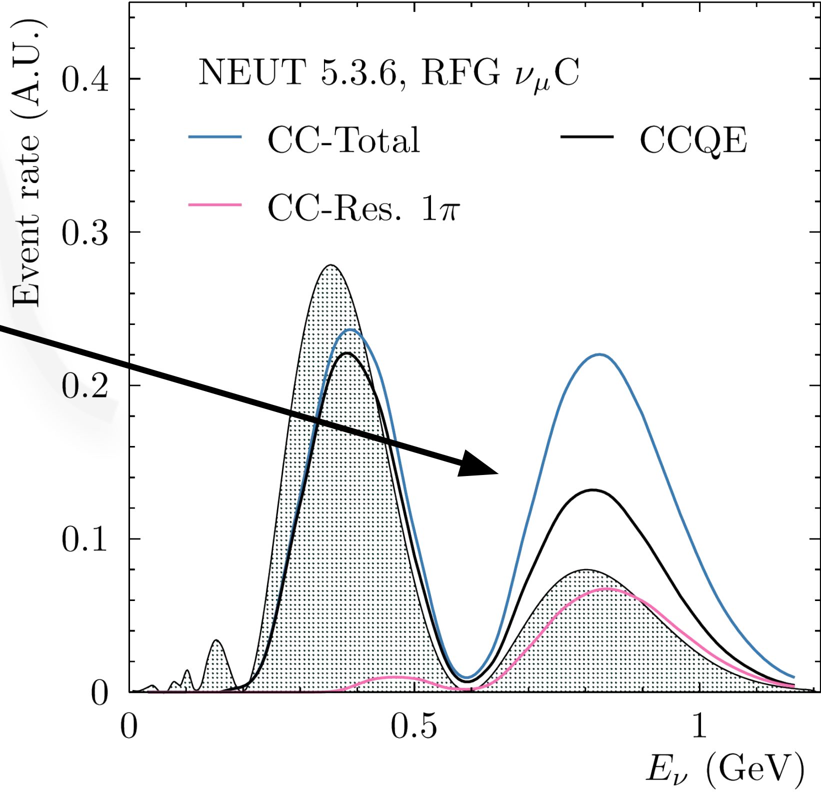
NEUT: Acta Phys.Polon. B40 (2009) 2477-2489



- **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.

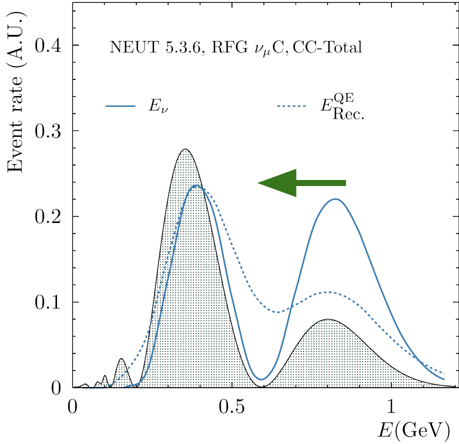


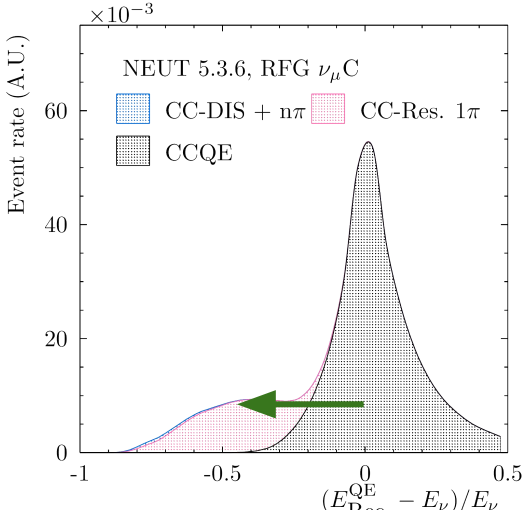
Measuring Oscillations: Observables

- **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.*

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

  - 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.

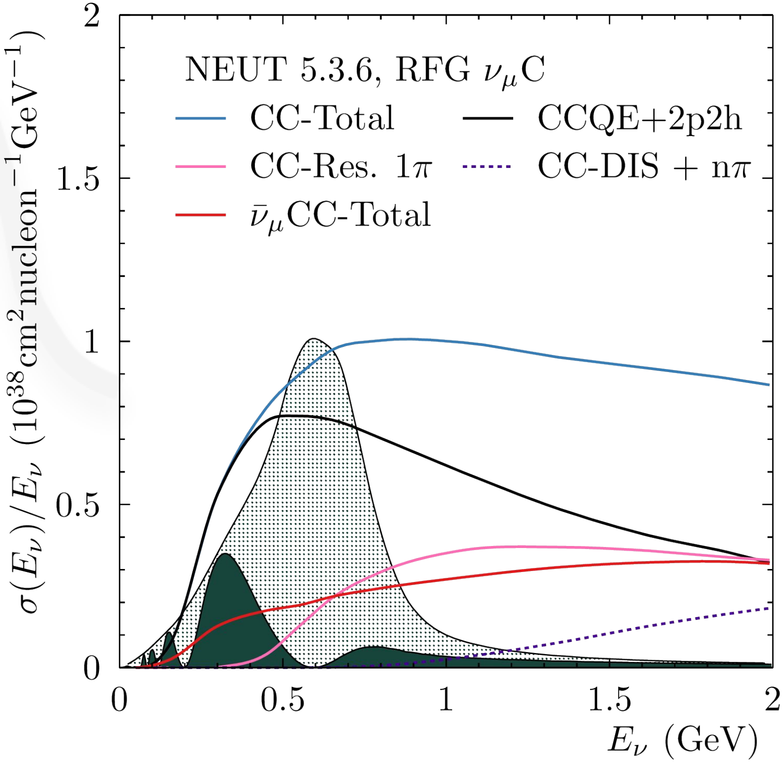




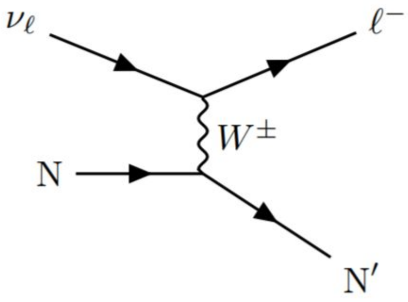
Neutrino–Matter Interactions

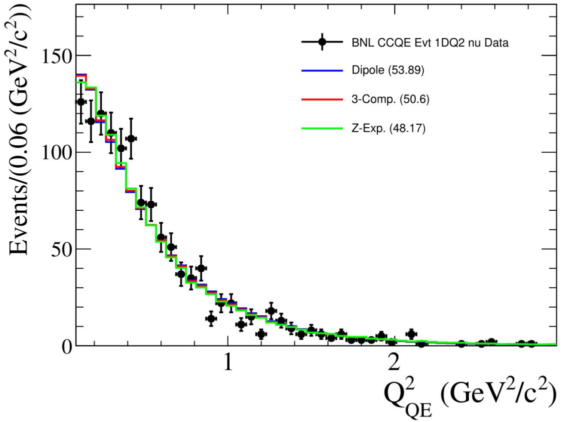
What's Important for T2K

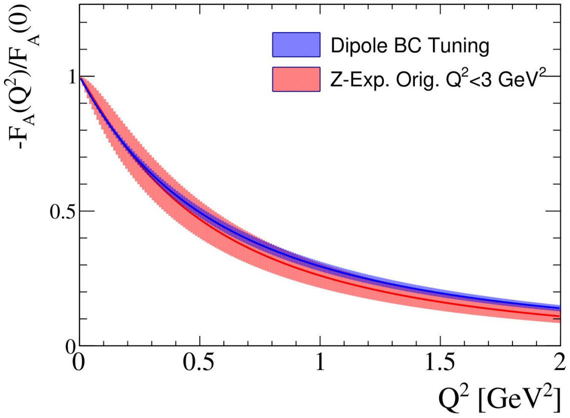
- Analyses rely strongly on the modelling of $E_\nu \leftrightarrow E_{Rec.}$
- Turns out nuclear physics is hard:
  - CCQE Axial form-factor
  - W-propagator screening
  - Multi-nucleon processes (2p2h)
  - Final state interactions (e.g. π absorption)
  - Nuclear potential
- On T2K: Focus on modelling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



CCQE Axial form factor

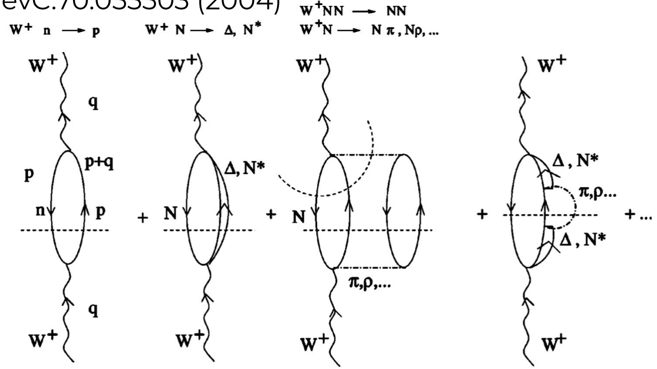




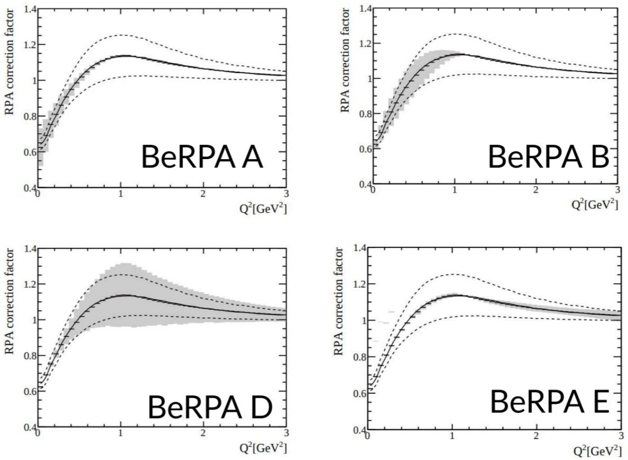


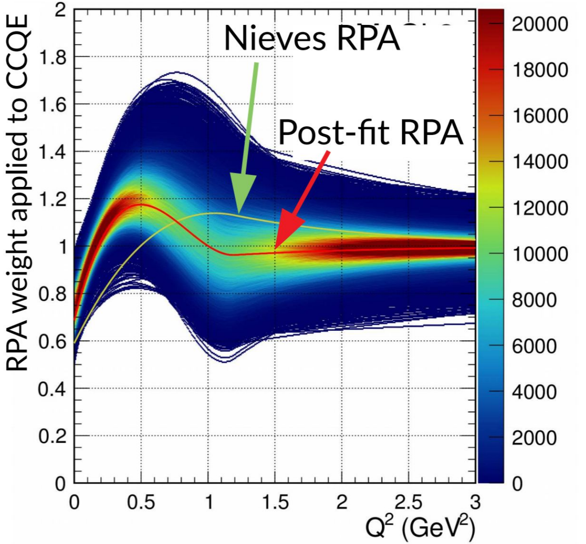
- Fit nucleon-level processes to historic bubble chamber data
  - ~ Free from nuclear effects.
- Dipole form is often used for the Axial form factor, $F_A\left(Q^2\right) = F_A\left(0\right)/\left(1+Q^2/M_A^2\right)^2$
  - Single free parameter M_A: Strong constraint at low Q^2 causes over constraint 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)

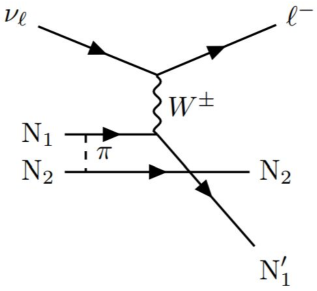




- CCQE suppression from nuclear screening of W-propagator.
- T2K parameterize uncertainty as piecewise 1D function in Q^2.
    - Post-fit shape doesn’t resemble calculation shape…
- Theoreticians not in agreement that RPA is so important with better nuclear model: *c.f.* GiBUU

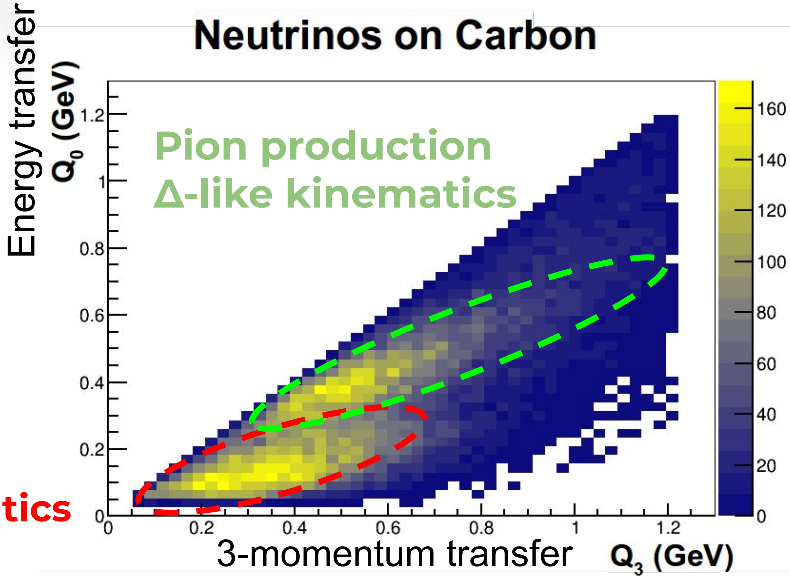
Multi-nucleon Interactions

- 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)

Neutrinos on Carbon

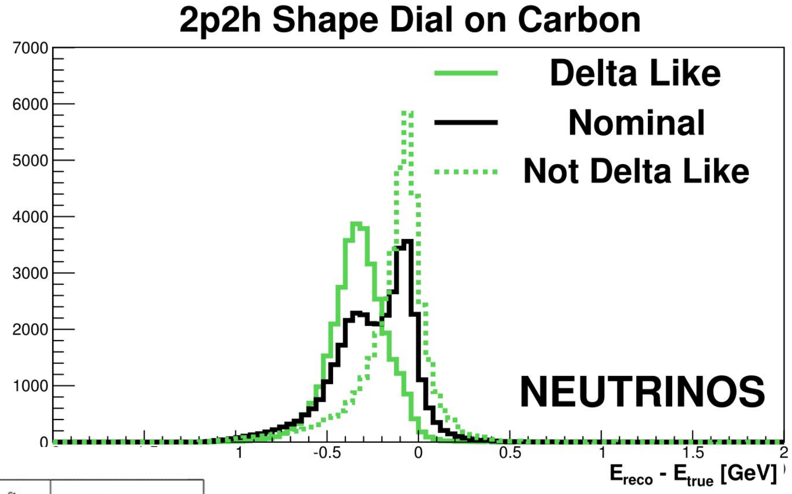


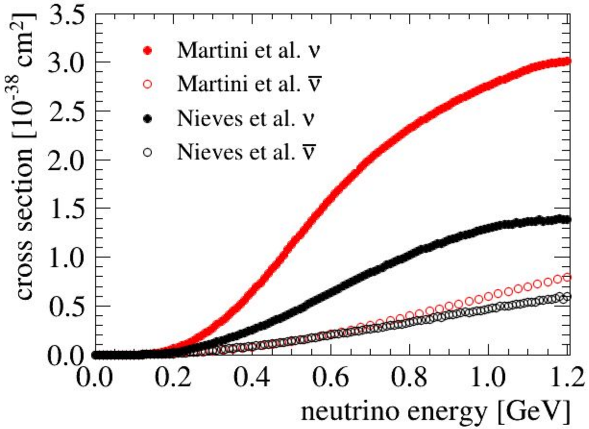
Pion production Δ-like kinematics

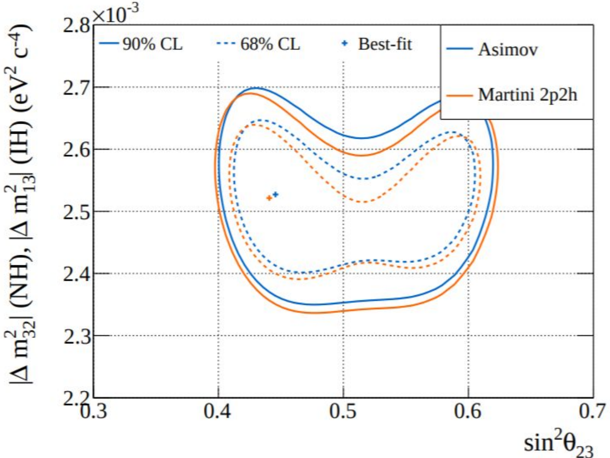
QE-like kinematics

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.



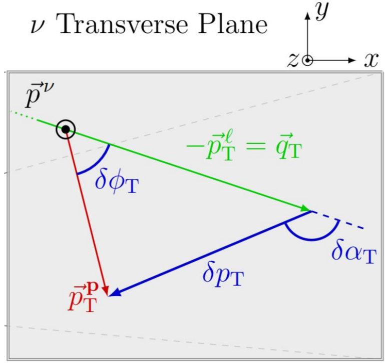




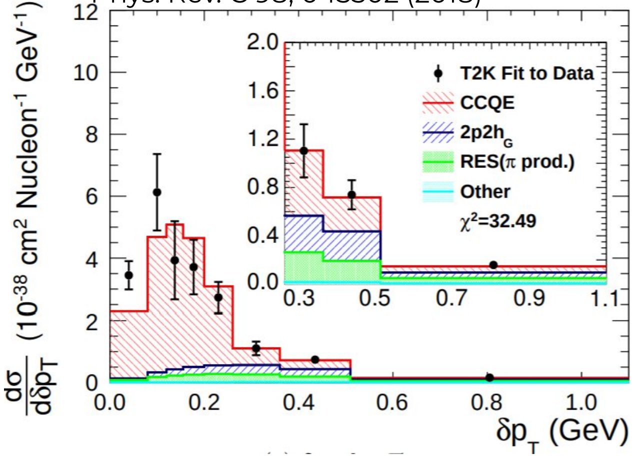
Near detector fit prefers between nominal and Δ-like

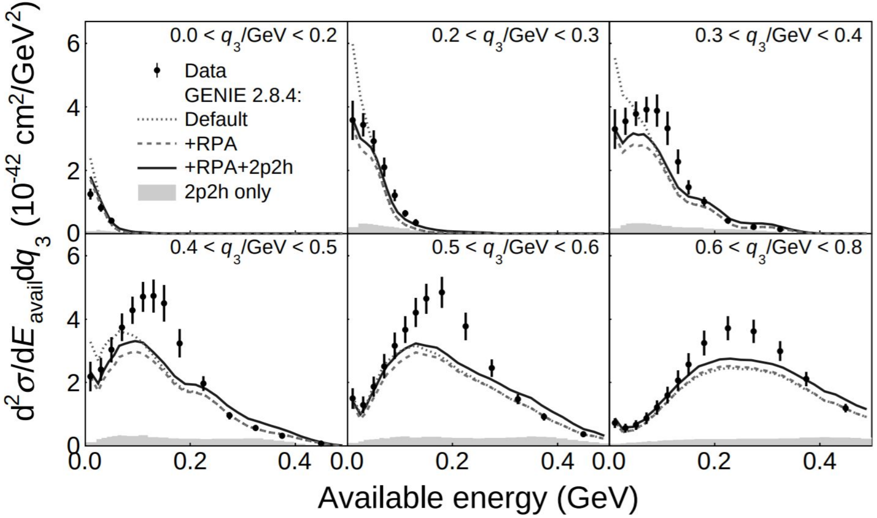
Lepton-Hadron Correlations

- 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.



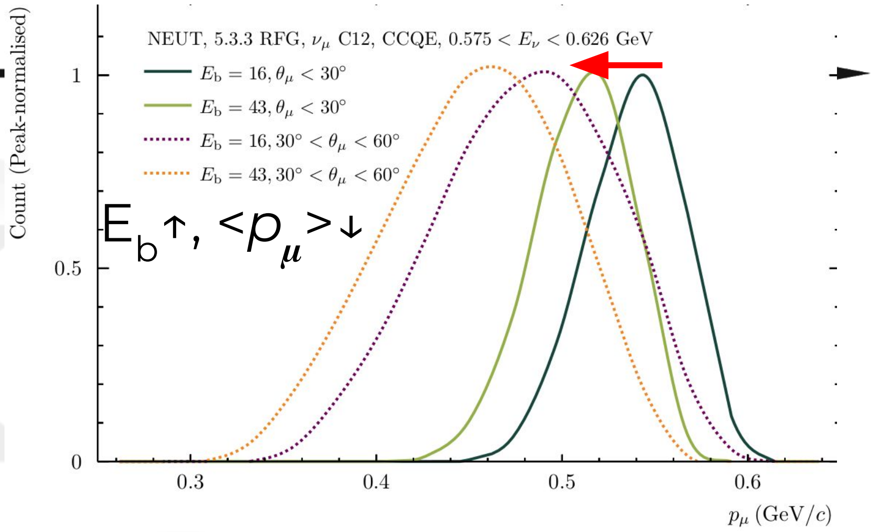
Phys. Rev. C 98, 045502 (2018)



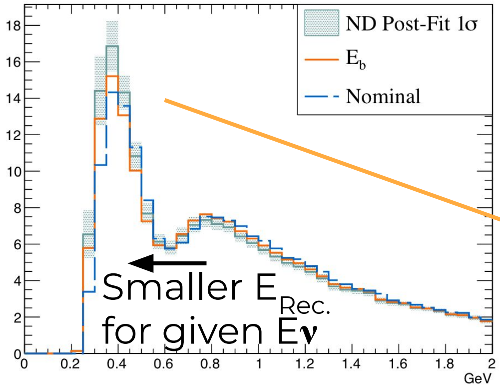


Binding Energy

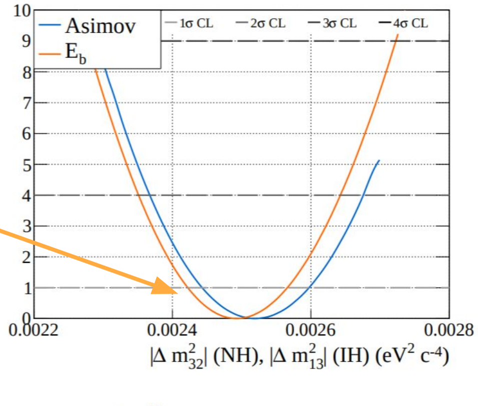
- Energy associated with liberating struck nucleon from nuclear potential
- A. Bodek's re-analysis found that the default NEUT value was poor [arXiv:1801.0797]
- For 2018 T2K OA, a fit to mock-data with a large shift in Eb was used to assess uncertainty
    - Largest single source of error.
- In the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



E_b↑, $\langle p_\mu \rangle$↓

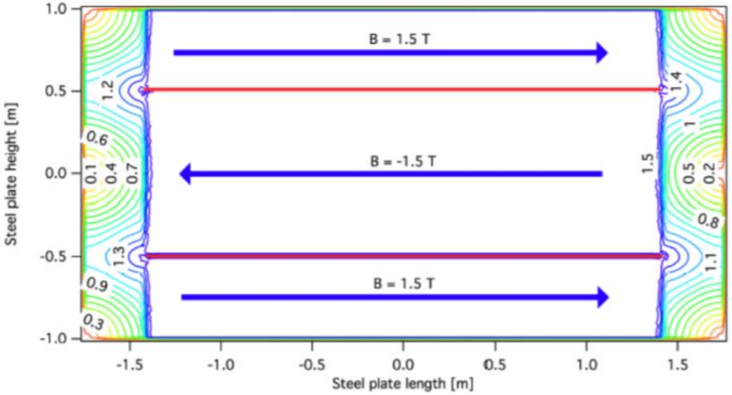


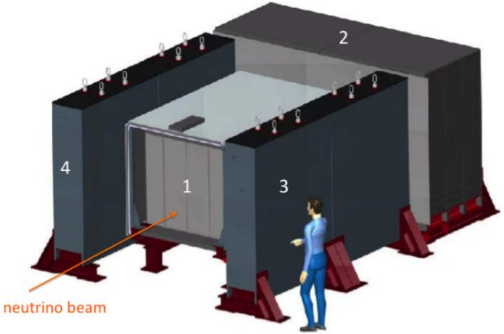
Smaller $E_{Rec.}$ for given E_ν

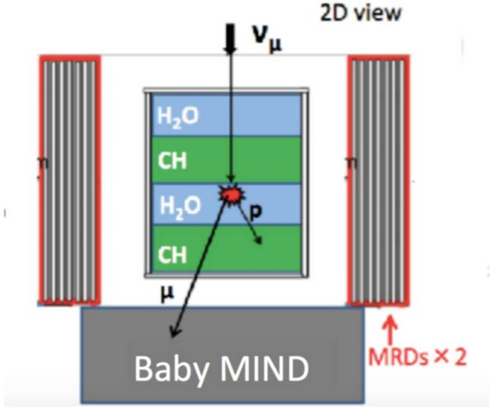


(b) Δm^2_{23} with reactor constraint

Baby-MIND


B = 1.5 T
B = -1.5 T
B = 1.5 T
Steel plate height [m]
Steel plate length [m]
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
1.2
0.6
0.1
0.4
0.7
1.3
0.9
0.3
1.4
1
1.5
0.5
0.2
0.8
1.1


2
4
1
3
neutrino beam


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