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

Most Recent Results from T2K: Is the Mirror Cracking?

Les Rencontres de Physique de la Vallée d'Aoste

2021-03-12

Luke Pickering for the T2K Collaboration

Pronouns: He/Him/His

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Big Picture Neutrino Oscillation Questions

What is the mass ordering of the neutrino mass states?

What are the precise values of the neutrino oscillation parameters?

Is there significant CP violation in the neutrino sector?

Could neutrino sector CP violation explain the matter/antimatter asymmetry?

Big Picture Neutrino Oscillation Questions

What is the mass ordering of the neutrino mass states?

What are the precise values of the neutrino oscillation parameters?

Experiment

Is there significant CP violation in the neutrino sector?

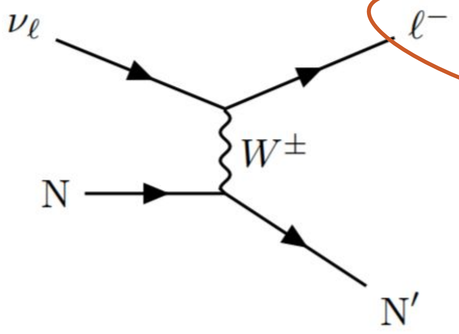
Could neutrino sector CP violation explain the matter/antimatter asymmetry?

Theory

Neutrino Oscillations: A Brief Introduction

Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.



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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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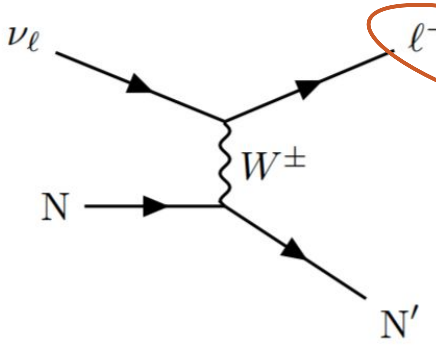

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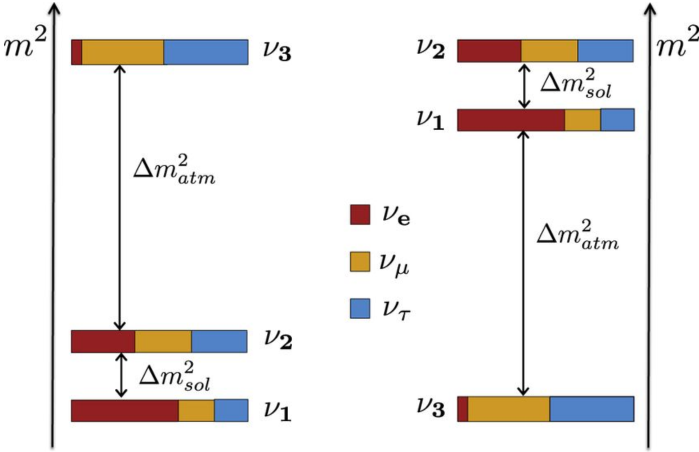

Which mass ordering?

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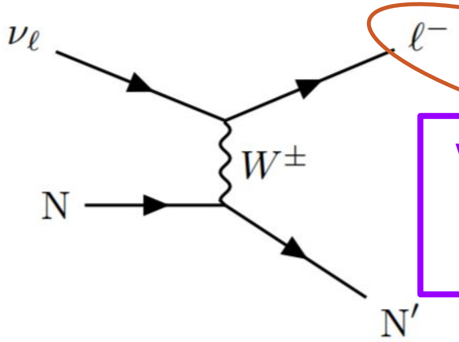

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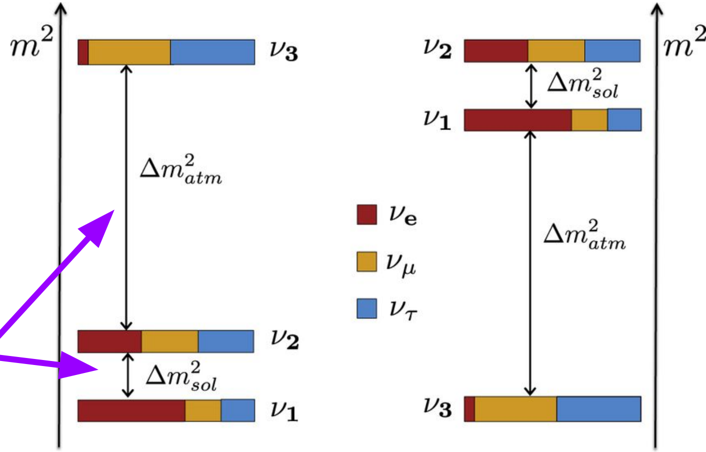
What are the precise values of the neutrino oscillation parameters?

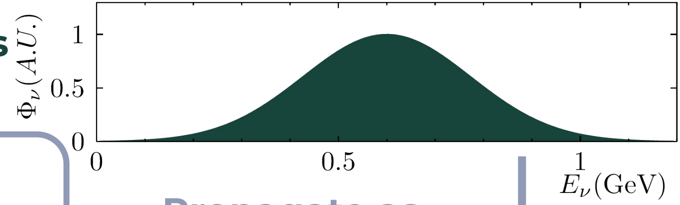
Pontecorvo–Maki–Nakagawa–Sakata



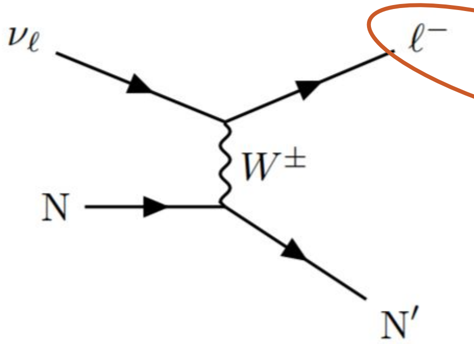
Which mass ordering?

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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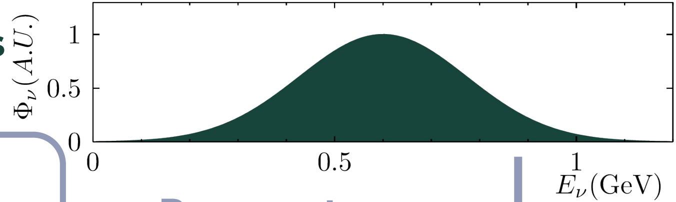

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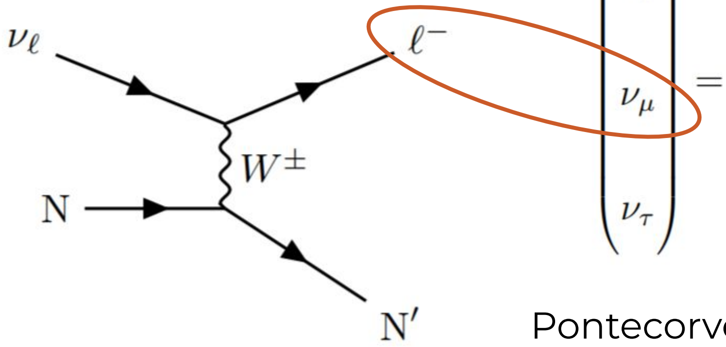

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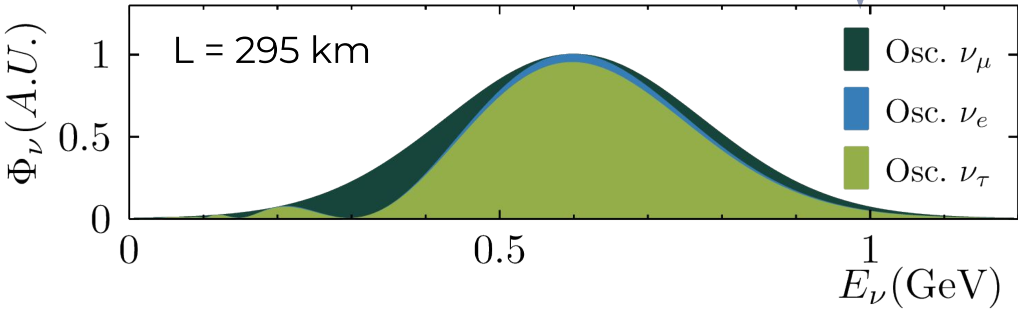
Pontecorvo–Maki–Nakagawa–Sakata

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

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Atmospheric /Accelerator **Reactor** **Solar**

- 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 $-\pi<\delta_{CP}<\pi$

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What are the precise values of the neutrino oscillation parameters?

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Measuring Oscillations

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- Long baseline experiments study two oscillation channels:

Muon neutrino disappearance

$$\nu_\mu \rightarrow \nu_\mu$$

Electron neutrino appearance

$$\nu_\mu \rightarrow \nu_\mathrm{e}$$

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Muon Neutrino Disappearance

- 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

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- Choose L/E for maximum effect:

$$\sin^2\left(\Delta m^2_{23} L/4E\right) \simeq 1$$

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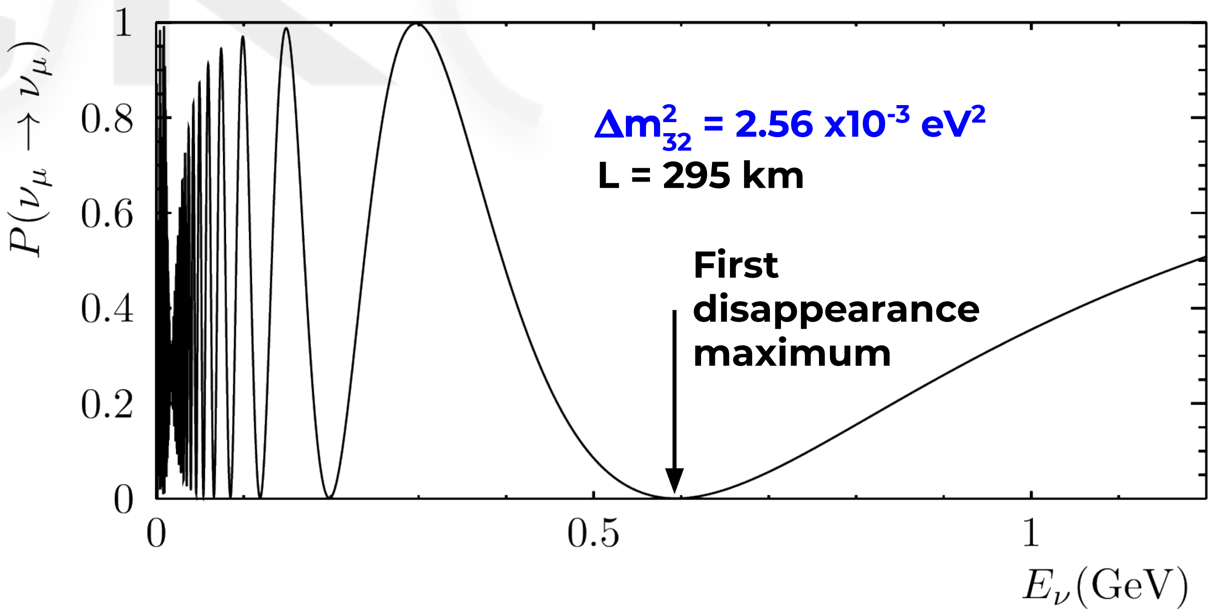
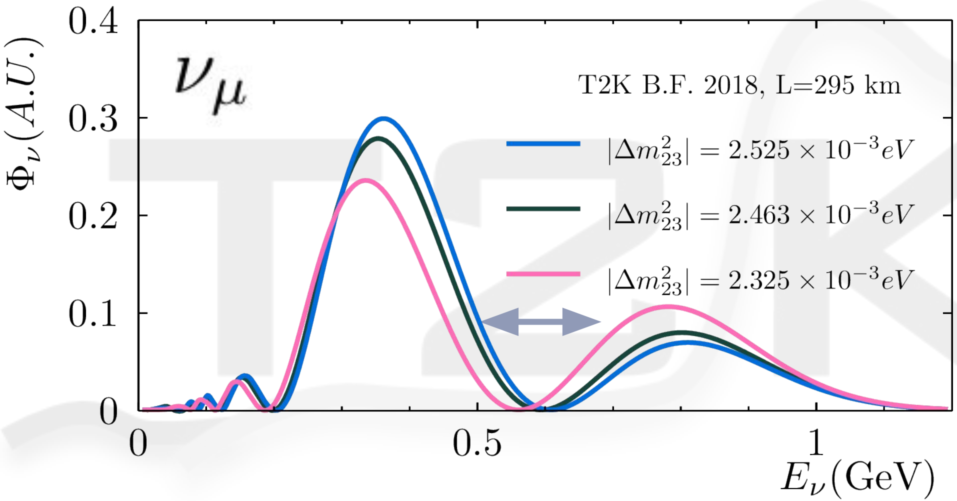
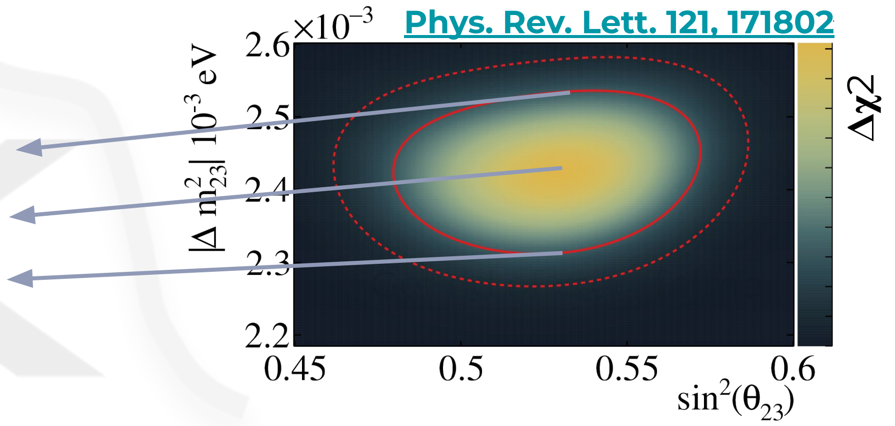


Disappearance Sensitivity

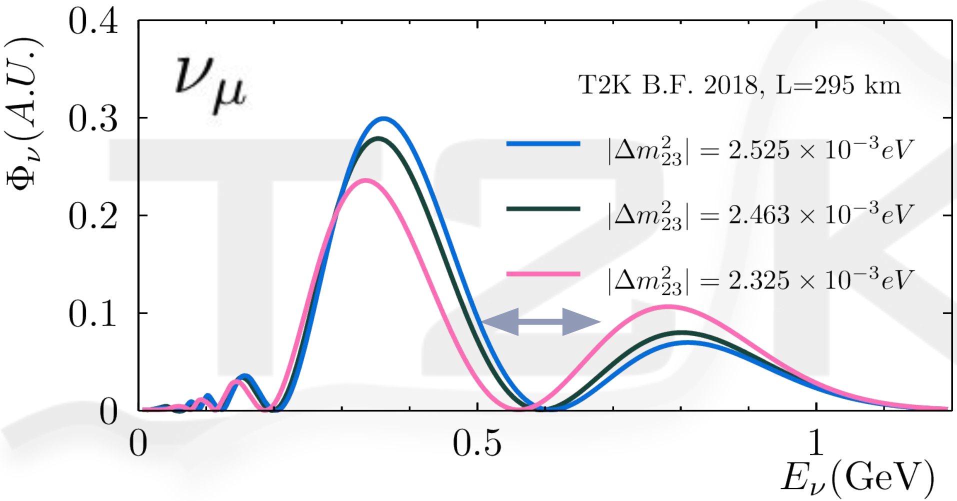


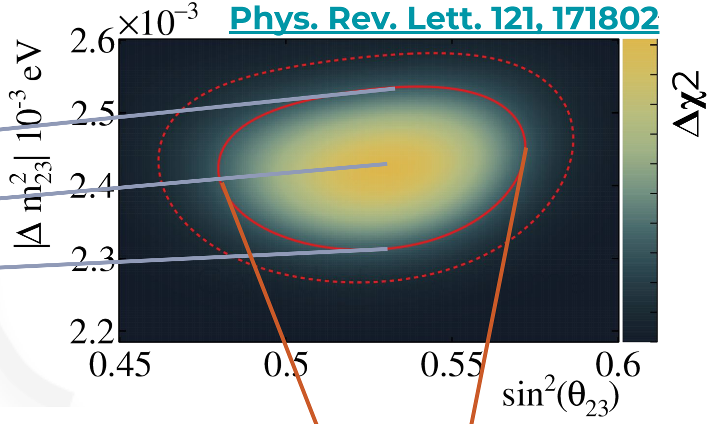


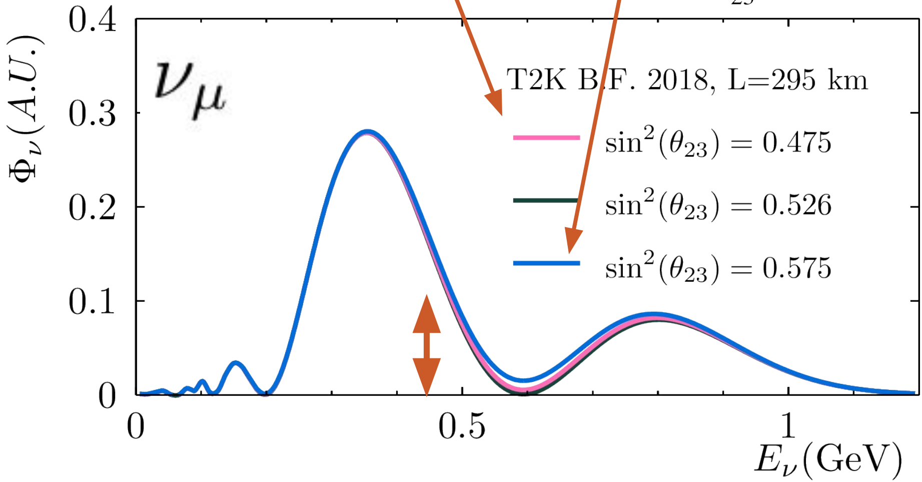
- Mass-squared splitting shifts the valley

Disappearance Sensitivity

68% Confidence Level
90%







- Mass-squared splitting shifts the valley
- Mixing angle determines the peak/valley ratio

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Muon neutrino disappearance

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Electron neutrino appearance

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Electron Neutrino Appearance

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

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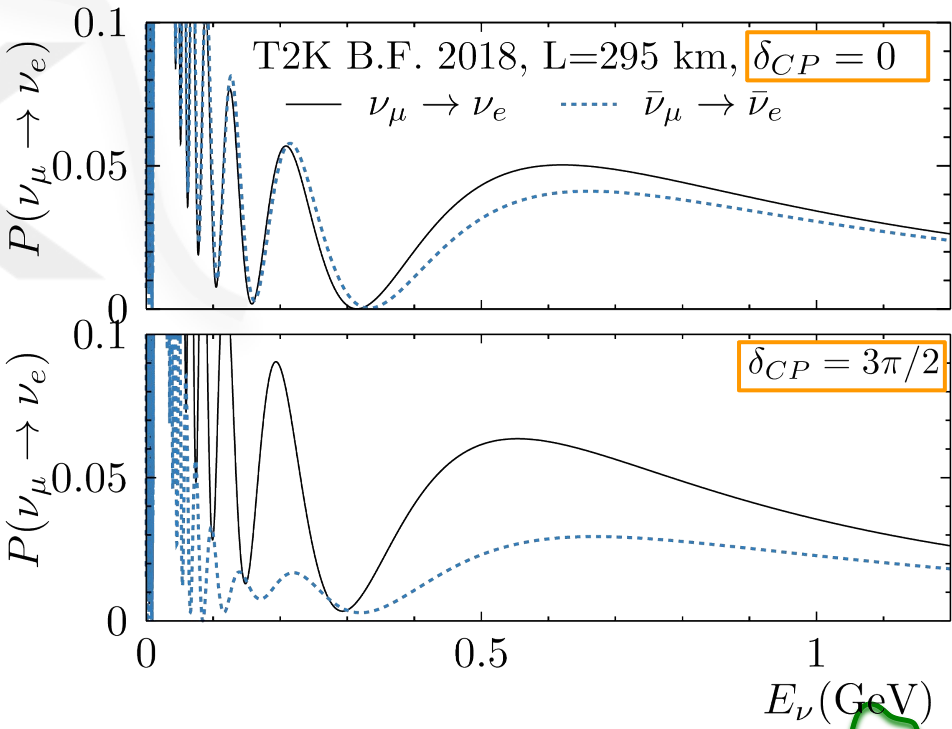

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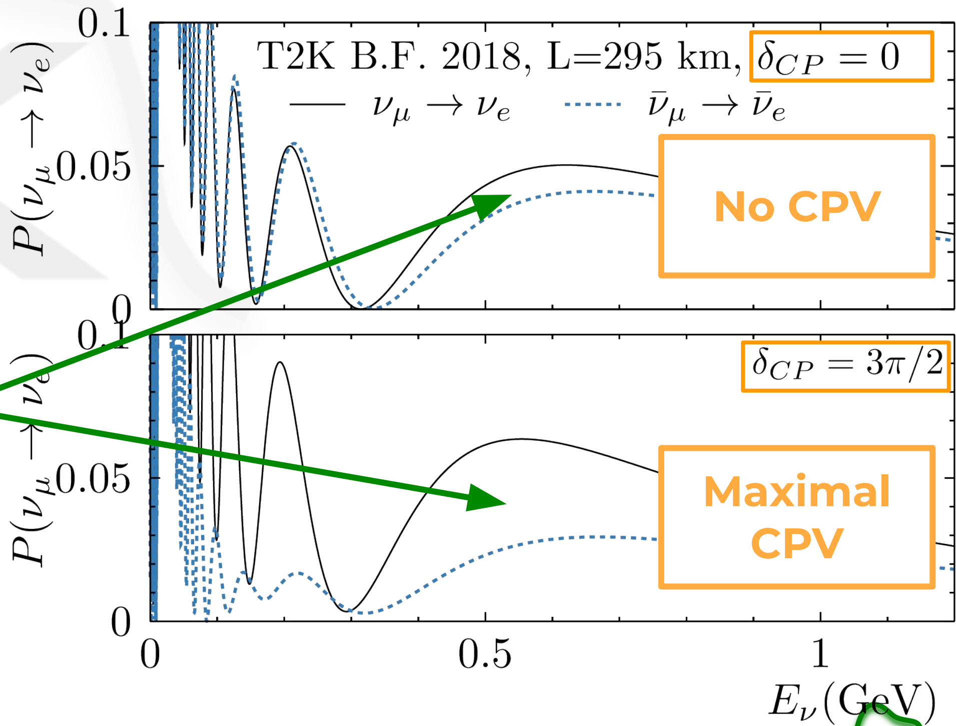
$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$ ...

Is there significant CP violation in the neutrino sector?

+ (CP-even, solar, matter effect terms)



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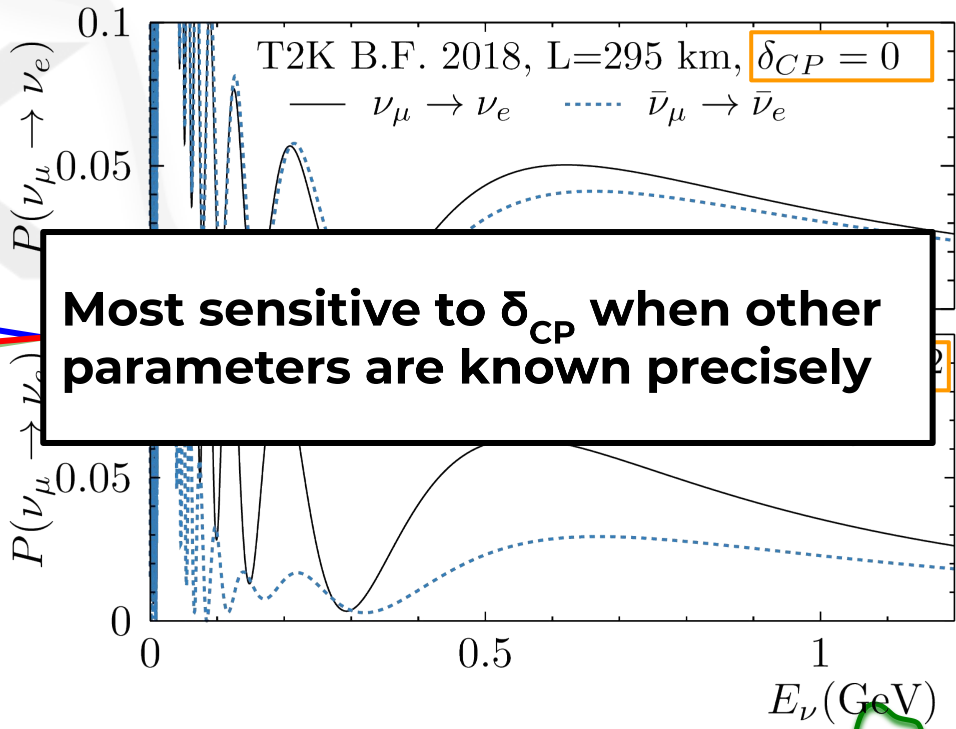
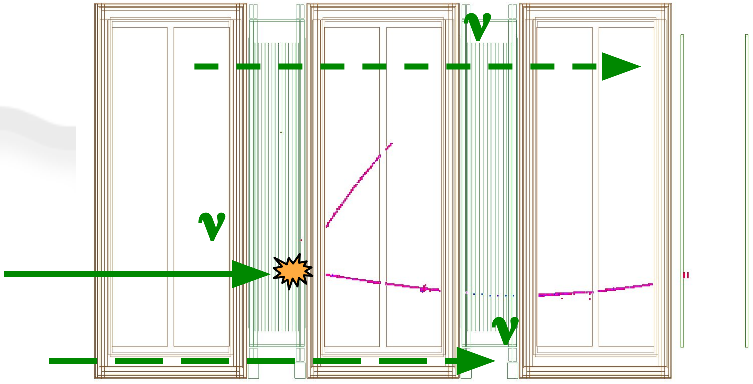


Most sensitive to δ_{CP} when other parameters are known precisely

Measuring Oscillation

- Measuring oscillation is hard because:
  - Do not know incoming particle energy (neutrino beams are broad)
  - Cannot predict where in the detector they will interact



Number of events = Flux · Cross section

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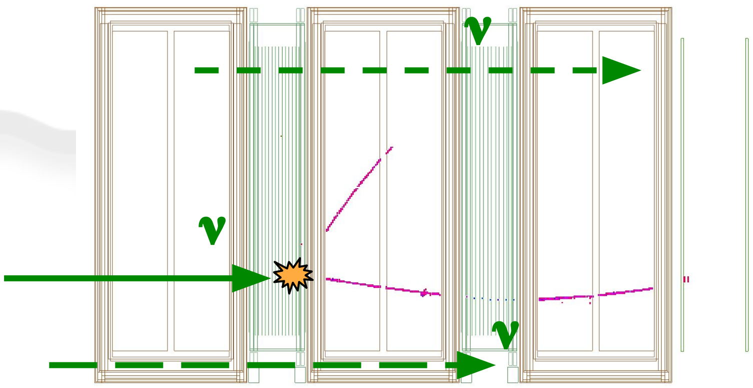

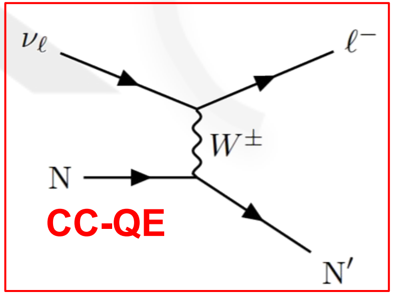

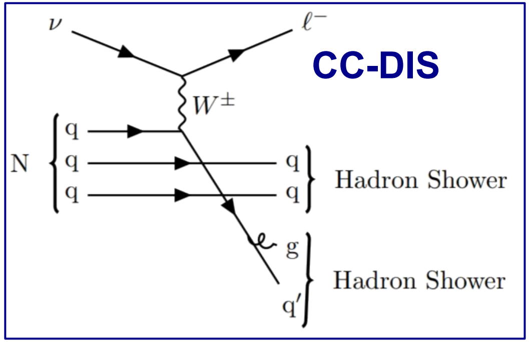

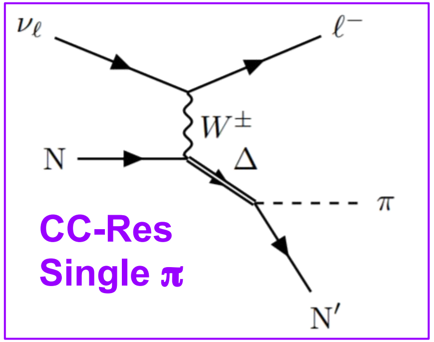

Measuring Oscillation

- Cross sections only known a priori to ~10%
  - Evolution with energy not well known

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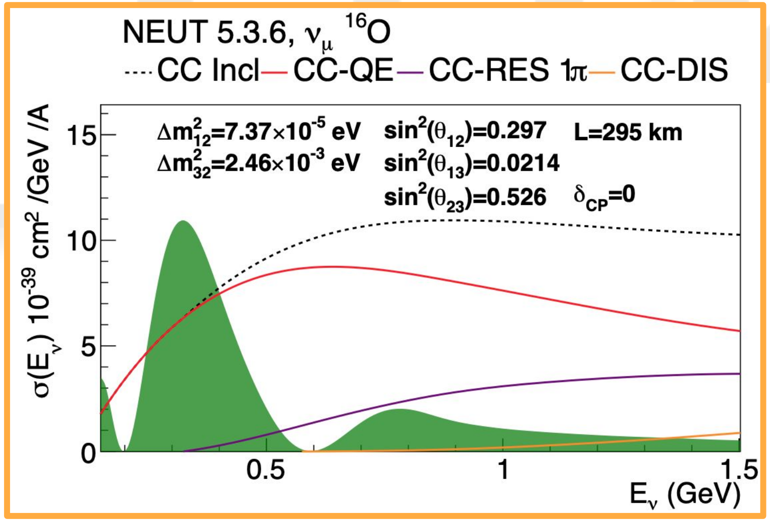

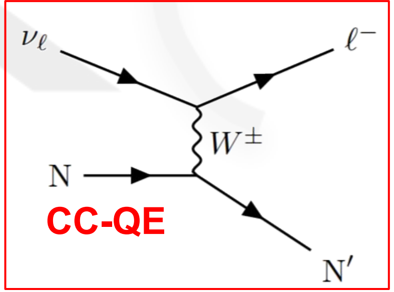

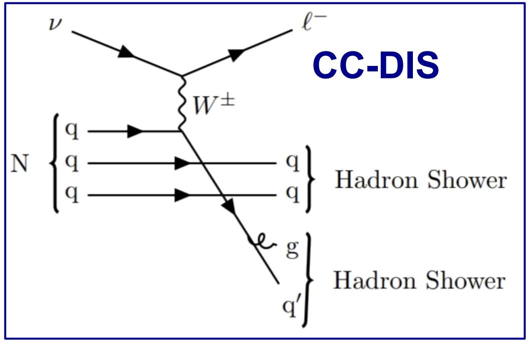

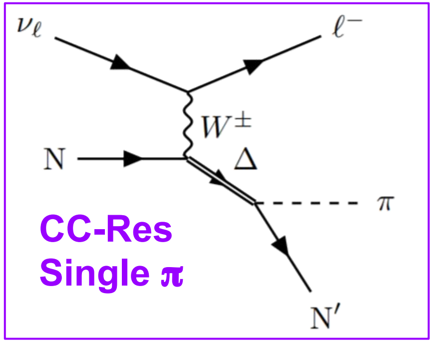

Number of events = **Flux** · **Cross section**

Measuring Oscillation

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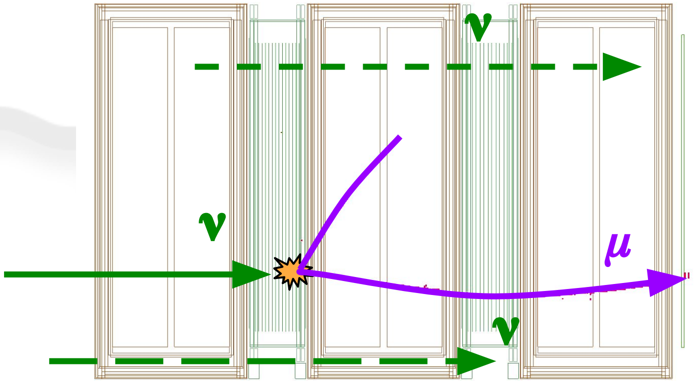
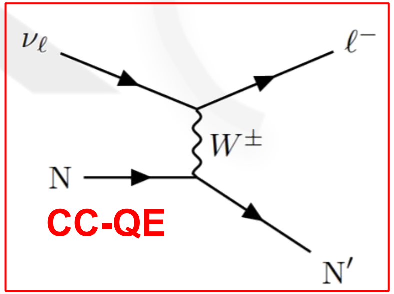
- Reconstruct neutrino energy from visible final state particles





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

Number of observed events = **Flux** · **Cross section** · **Detector effects**

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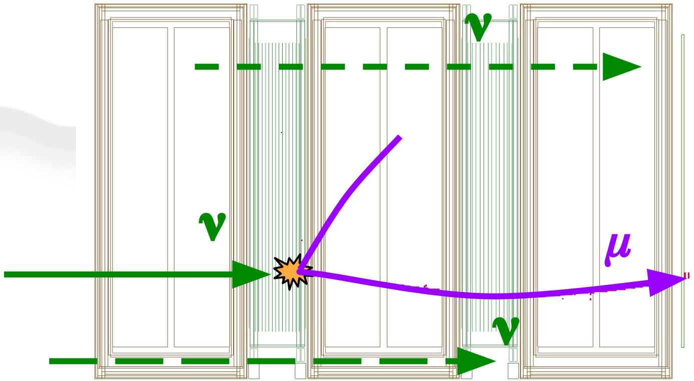

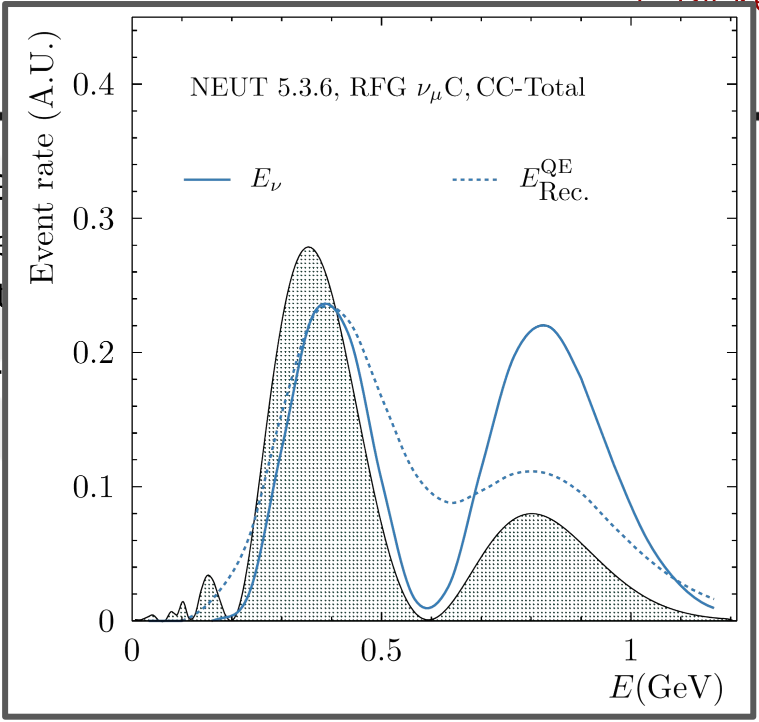

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The T2K Collaboration

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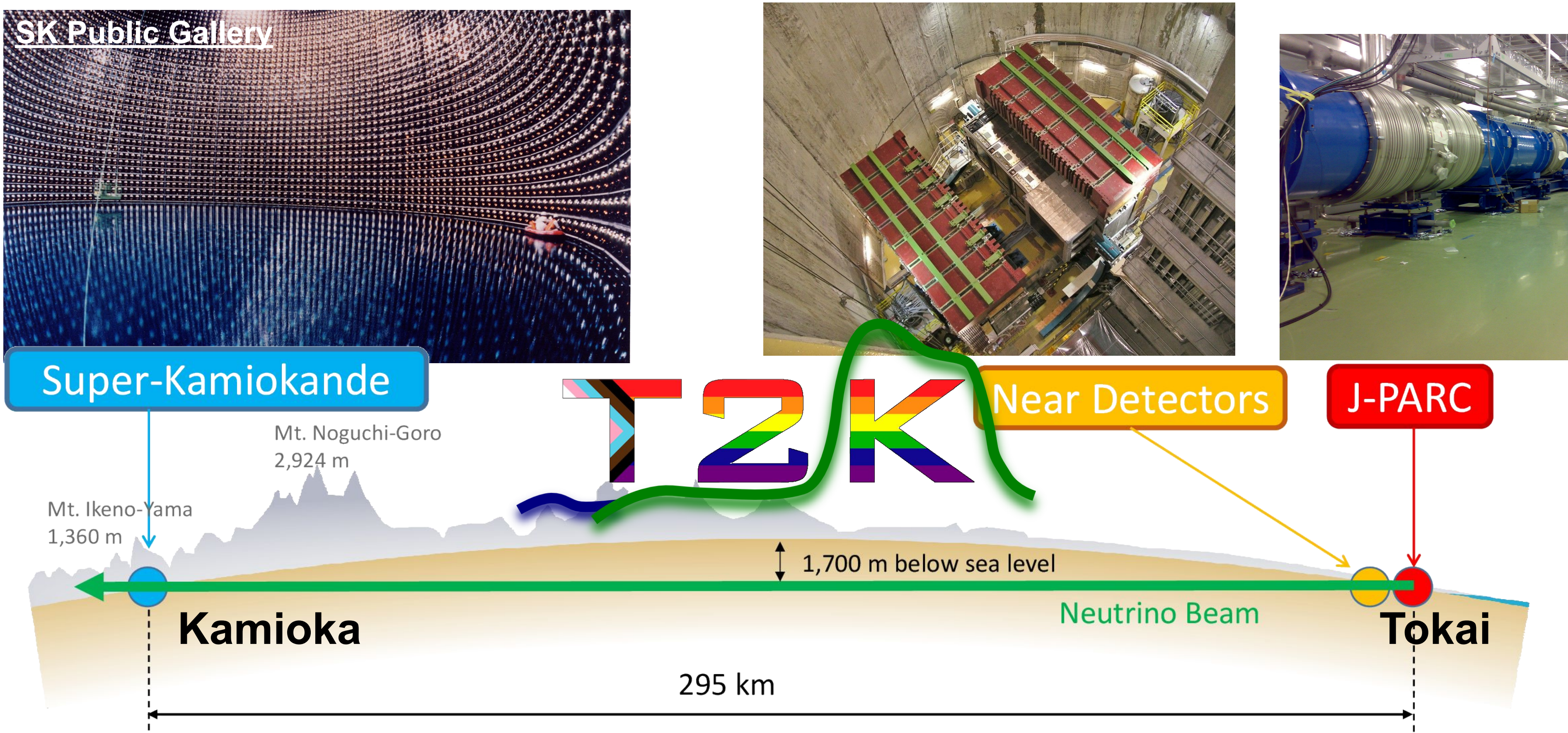
Tokai To Kamioka



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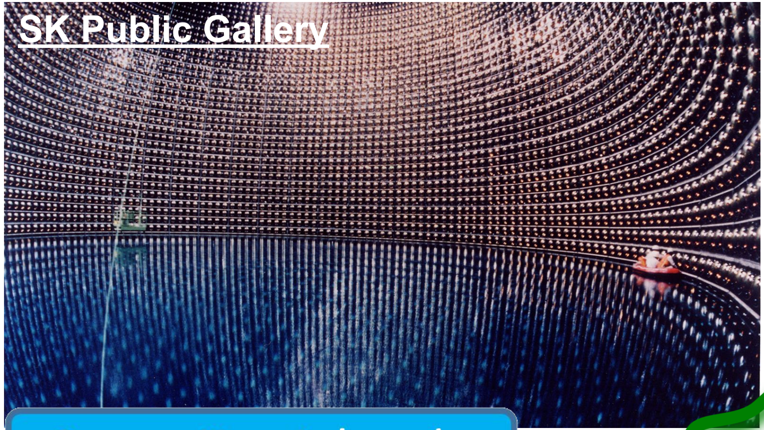

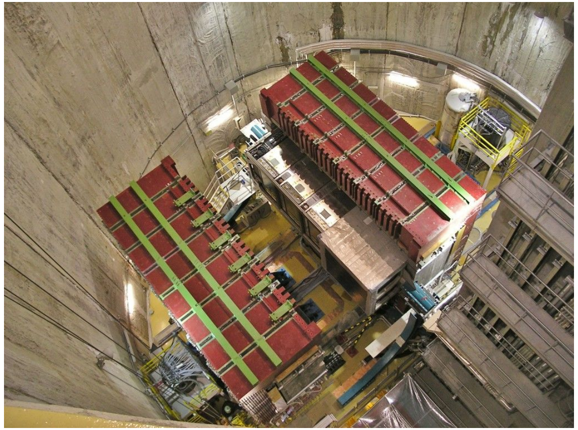

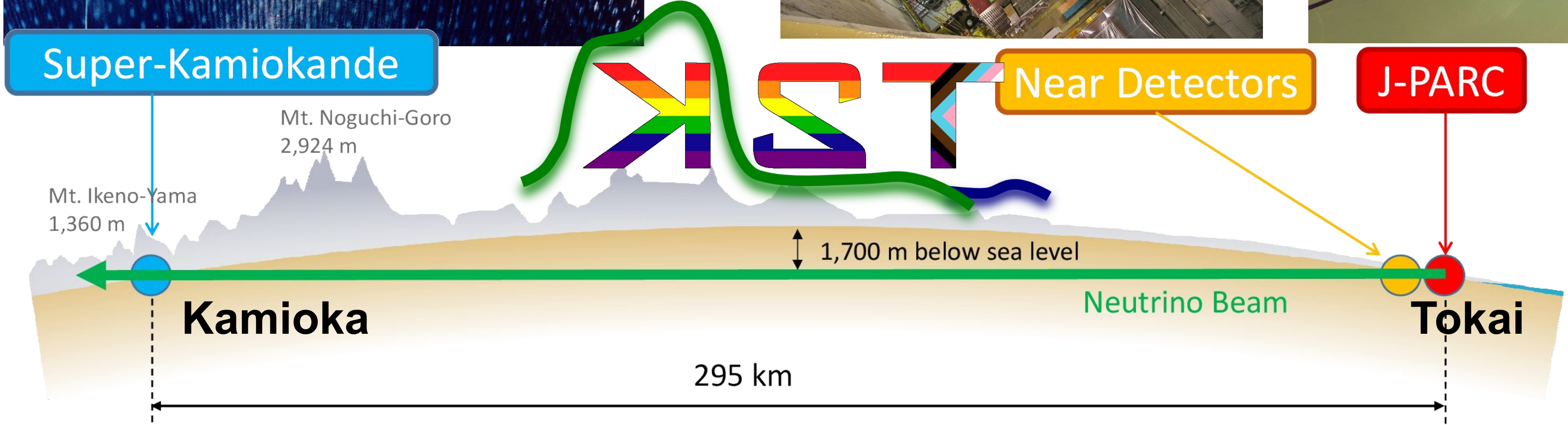

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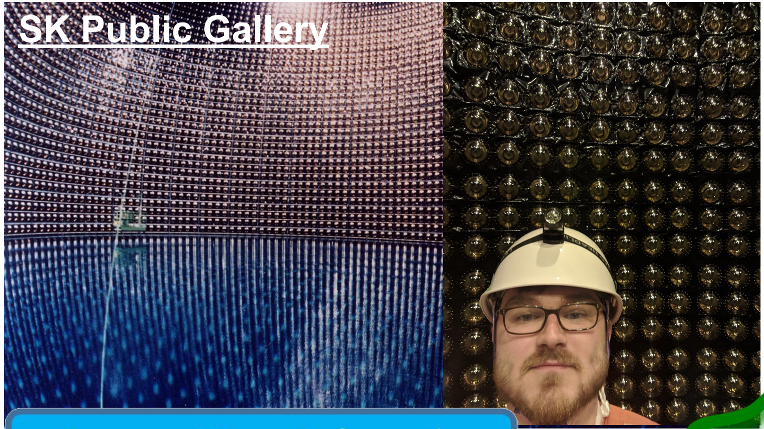

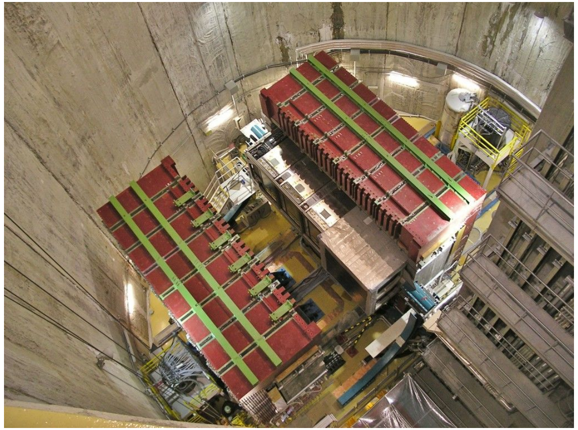

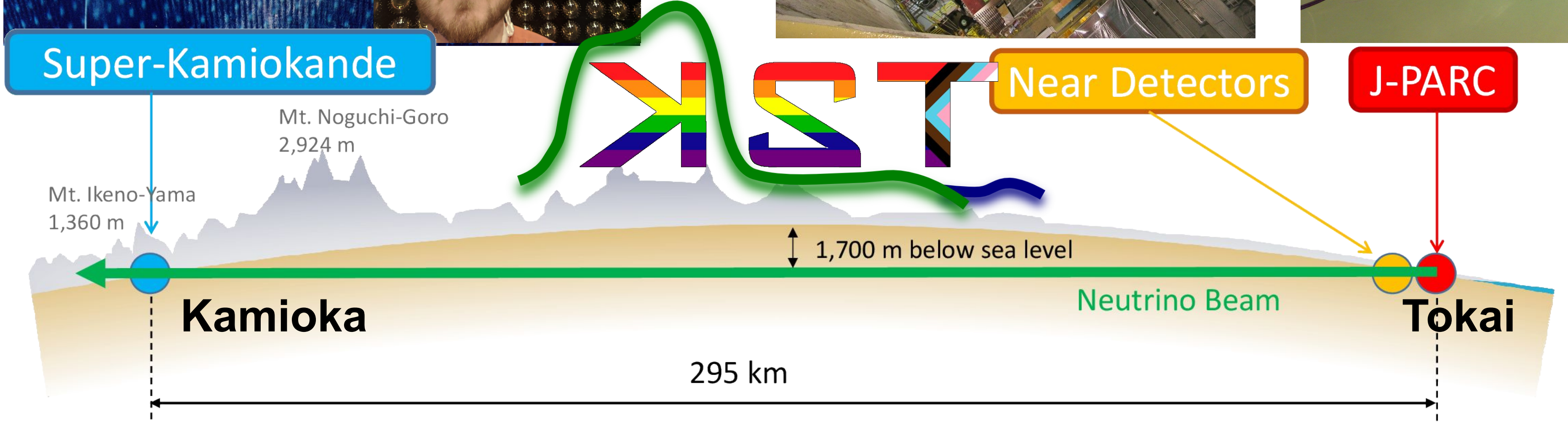

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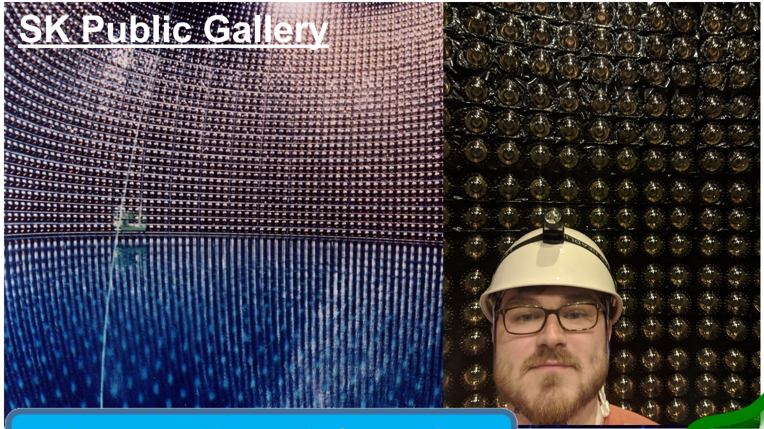
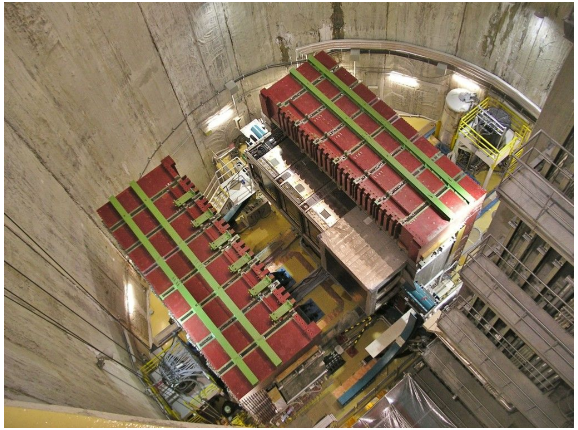
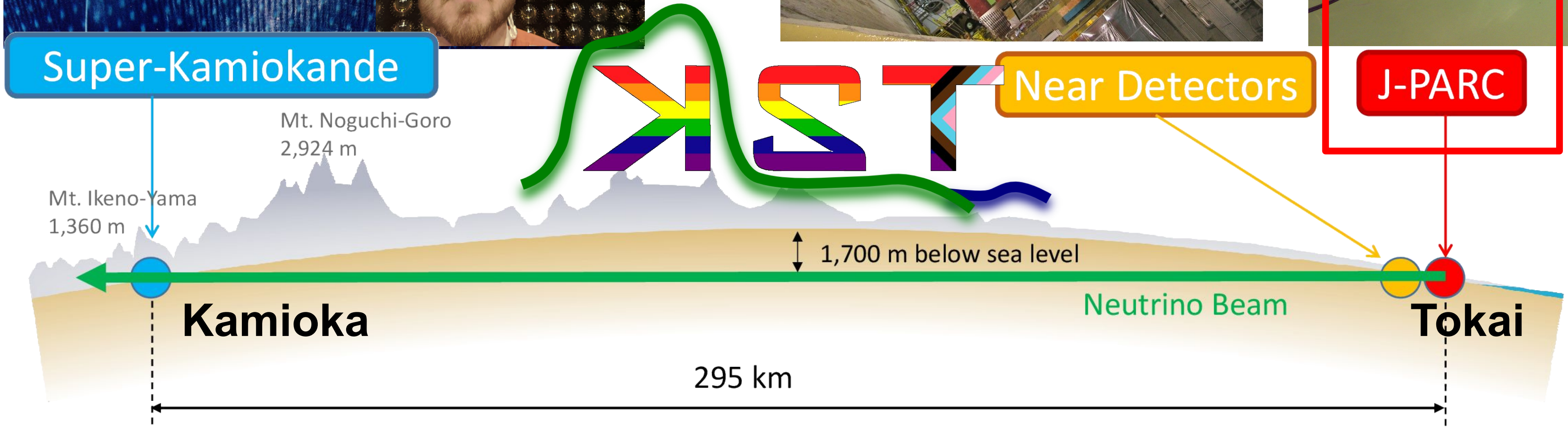
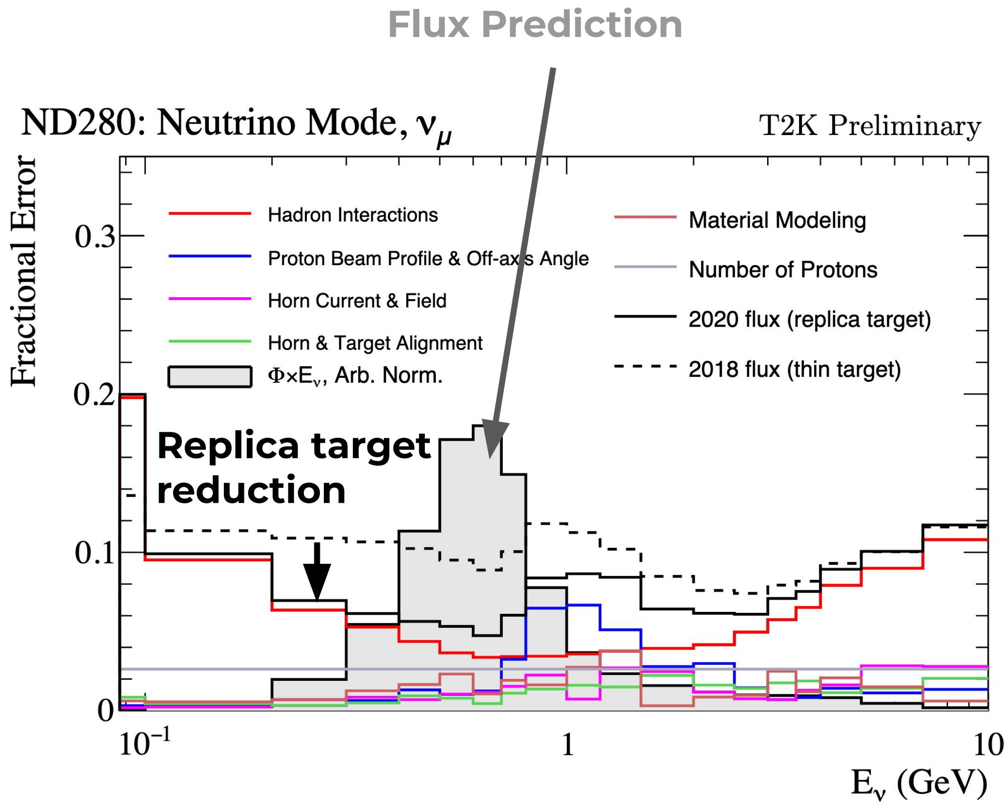




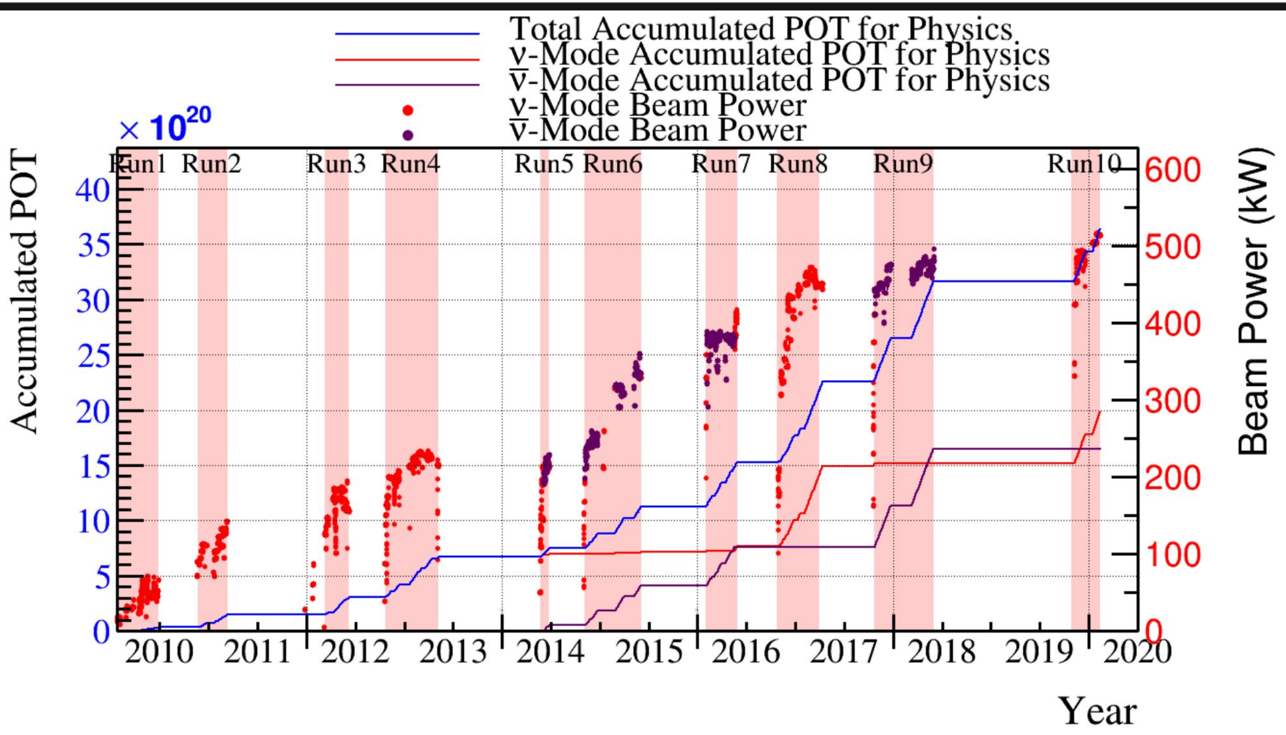


J-PARC Beam: Uncertainties

- Can run the beam in neutrino mode or antineutrino mode.
- Flux uncertainties dominated by **hadron-production**:
  - Simulation tuned to NA61/SHINE hadron-production data.
  - Incorporation of NA61/SHINE data taken with a **replica** T2K target reduced uncertainties by factor ~2.



T2K Exposure



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%)

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T2K Exposure

2020 Result

Constraint

Nature 580 7803 p339-344

Search for CPV

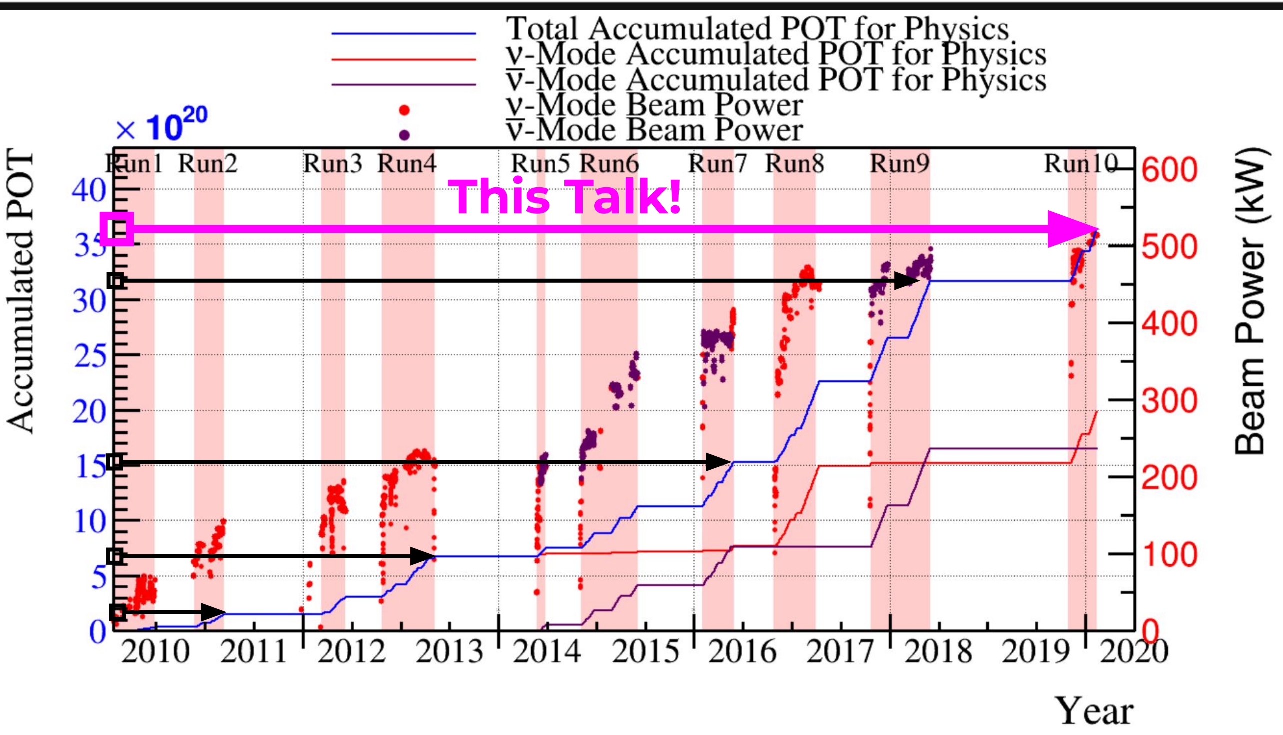
Phys. Rev. Lett. 121,171802

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)

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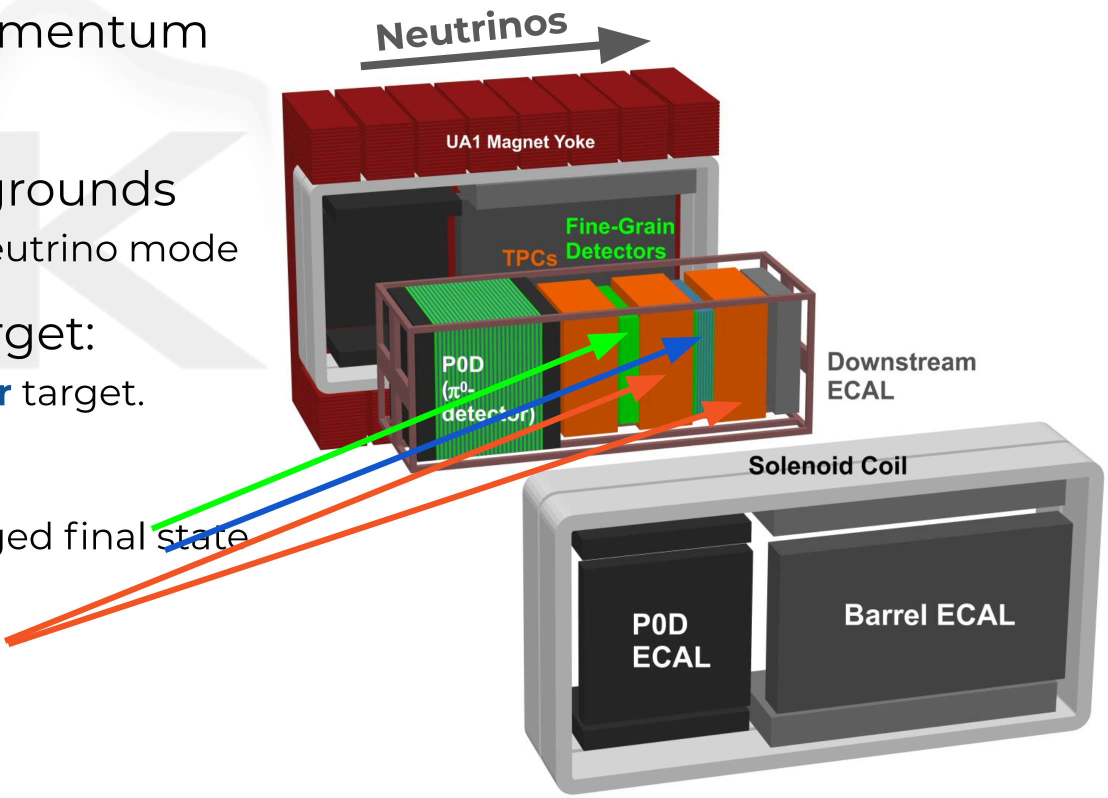
$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)

Tokai To Kamioka

T2K Near Detector

- Magnetized: Charge and momentum measurements
- Constrain 'wrong sign' backgrounds
    - μ^+ in neutrino mode, μ^- 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.



T2K Near Detector Measurement Programme

Charged-Current 0 Pions

- ν_μ CCQE C^{12} (2014)
- ν_μ CC0π $C^{12}H$ (2016)
- ν_μ CC0π H_2O^{16} (2017)
- ν_μ CC0π $C^{12}H$ (2018)
- NC 1γ $C^{12}H$ (2019)
- $\bar{\nu}_\mu$ CC0π H_2O^{16} (2019)
- $\nu_\mu/\bar{\nu}_\mu$ CC0π $C^{12}H$ (2020)
- ν_μ CC0π $C^{12}H/H_2O^{16}$ (2020)

Charged-Current 1 Pion

- ν_μ CC1π H_2O^{16} (2016)
- ν_μ CC1π $C^{12}H$ (2019)
- CC1π Transverse Imbalance (2021)

New since La Thuile 2019

Other Cross-sections

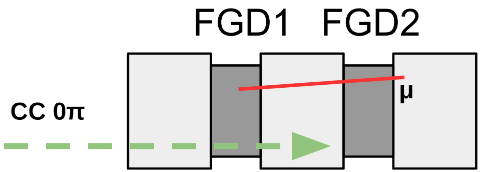
- ν_μ CCInc C^{12} (2013)
- ν NCQE O^{16} (2014)
- ν_e CCInc C^{12} (2014)
- ν_μ CC Coherent 1π C^{12} (2017)
- ν_μ CCInc C^{12} (2018)
- ν_μ CCInc P0D (2018)
- $\nu_e/\bar{\nu}_e$ CCInc C^{12} (2020)

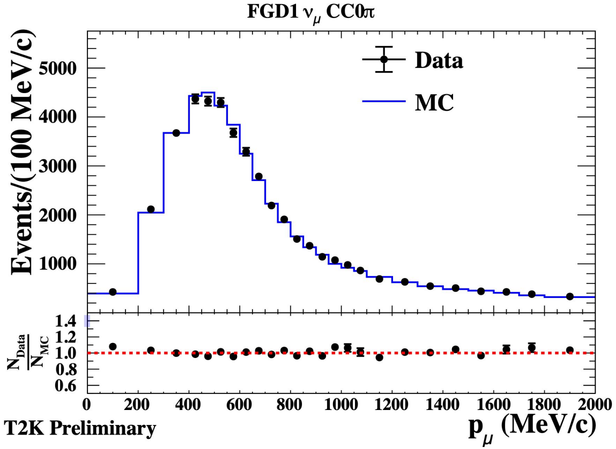
Exotic/BSM

- Search for Heavy Neutrinos (2019)

Click links to go to publication/preprints

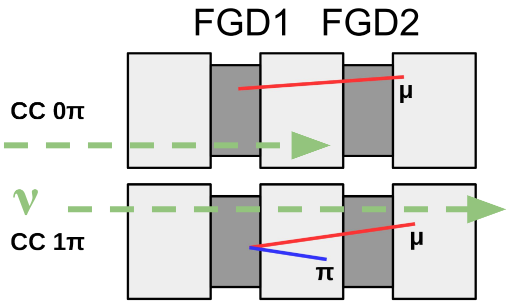
Near Detector Samples

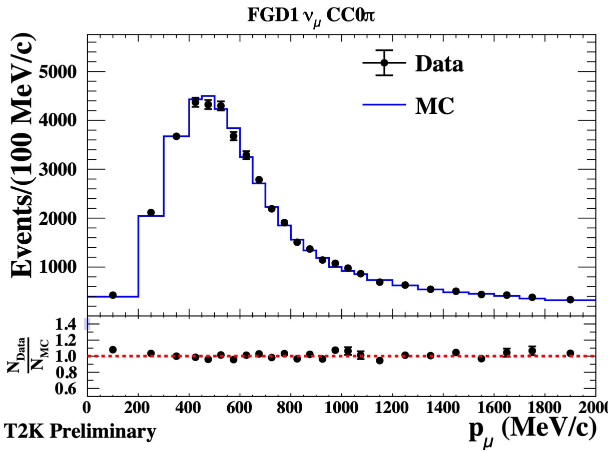


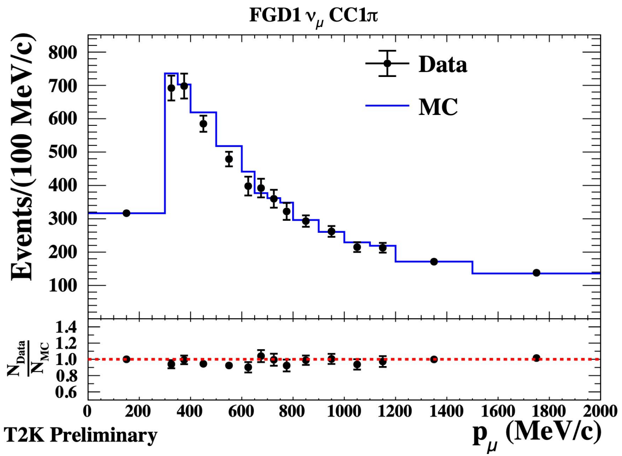


- Near detector samples separated by:
    - Reconstructed pion multiplicity: N=0

Near Detector Samples

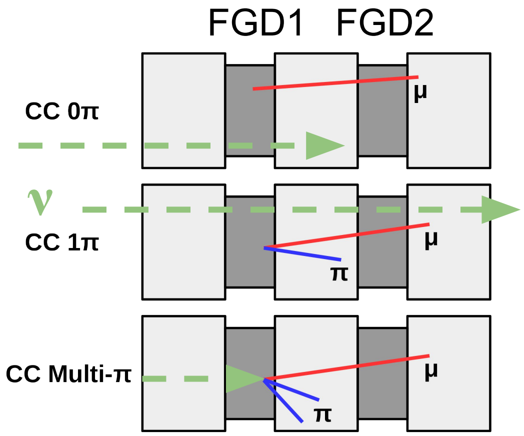


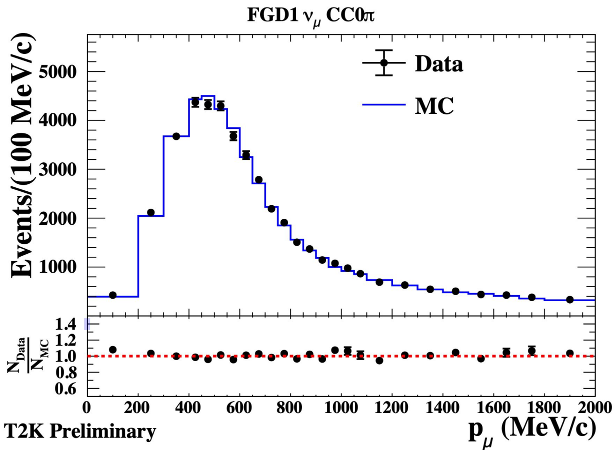


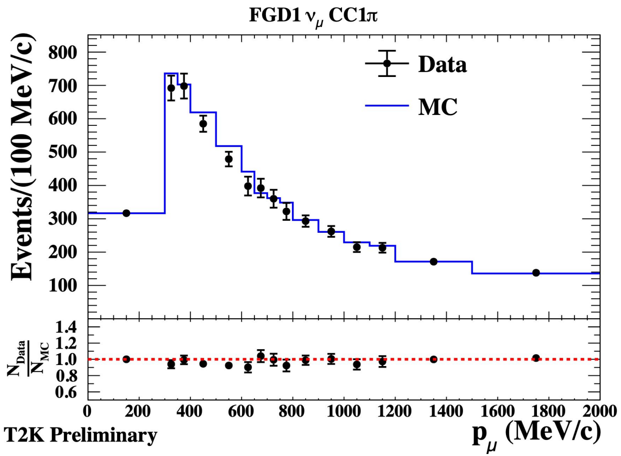


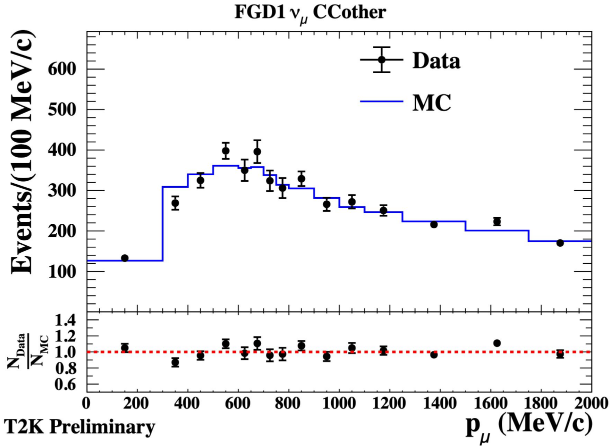
- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1

Near Detector Samples



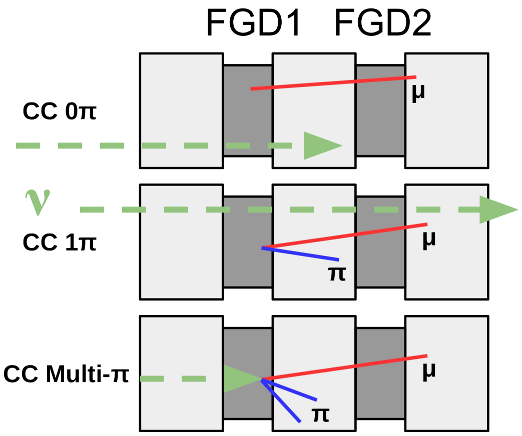


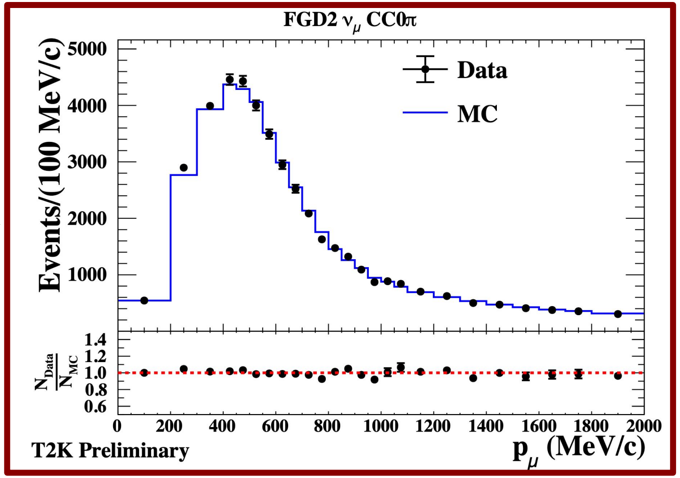




- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1

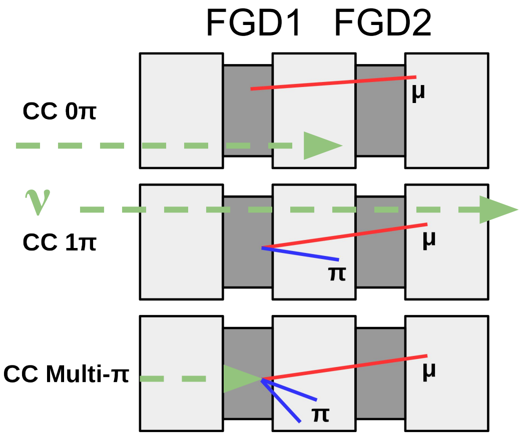
Near Detector Samples

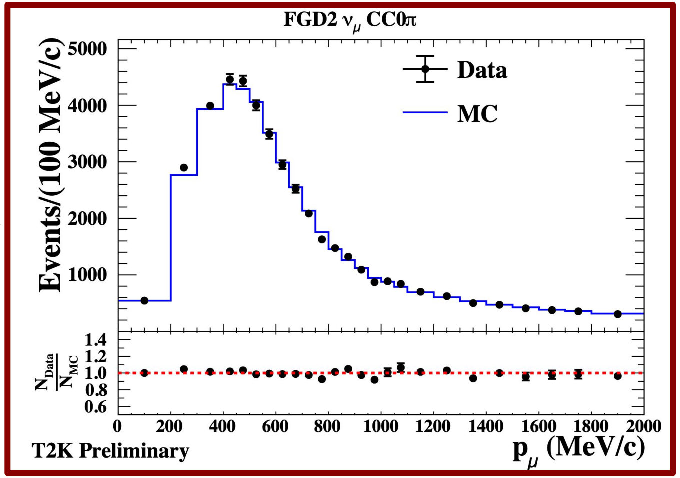


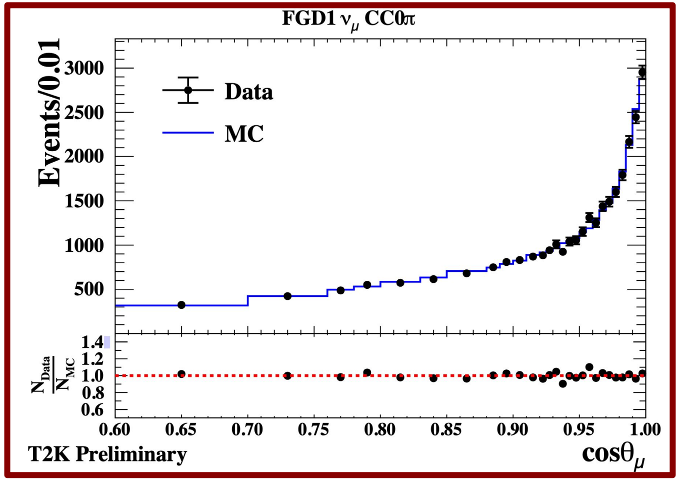


- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1
  - Detector material: CH (FGD) or CH+H_2O (FGD2)

Near Detector Samples



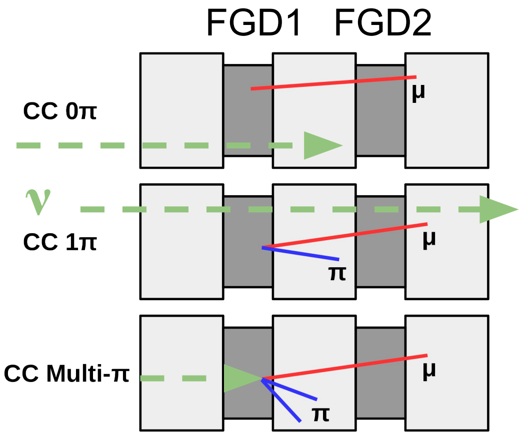


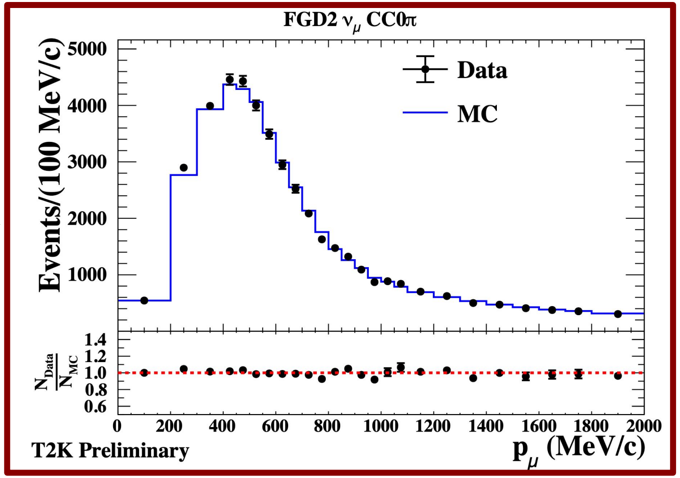


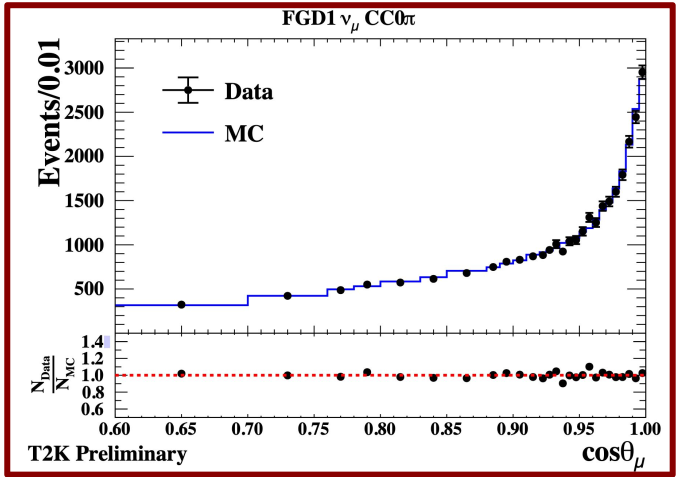
- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1
  - Detector material: CH (FGD) or CH+H2O (FGD2)

- Binned in **observed lepton kinematics** only.

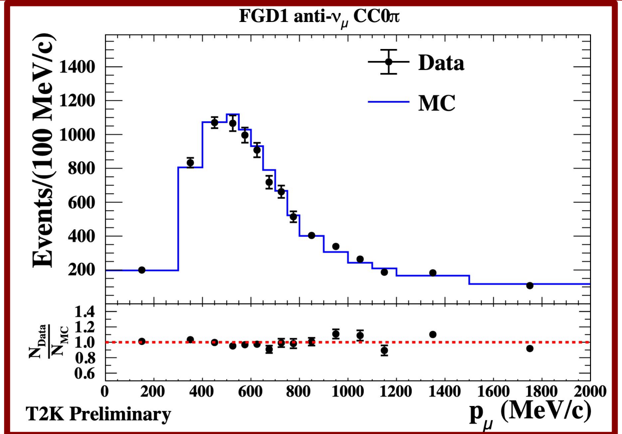
Near Detector Samples



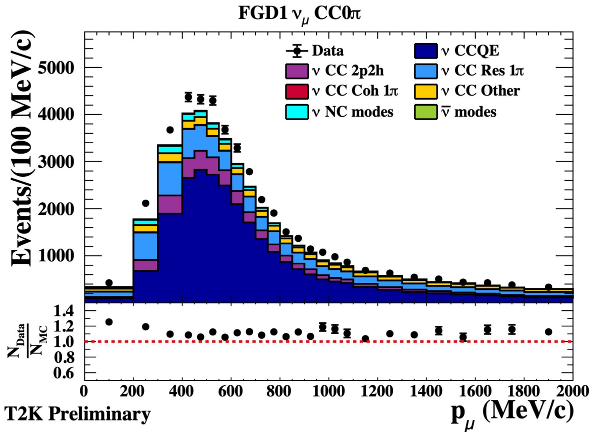




- Near detector samples separated by:
  - Reconstructed pion multiplicity: N=0, 1, >1
  - Detector material: CH (FGD) or CH+H2O (FGD2)
- Binned in **observed lepton kinematics** only.
- Both neutrino and antineutrino beam modes.

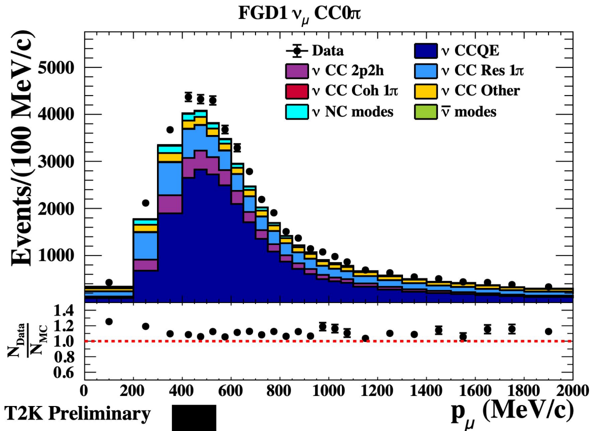


Near Detector Fit

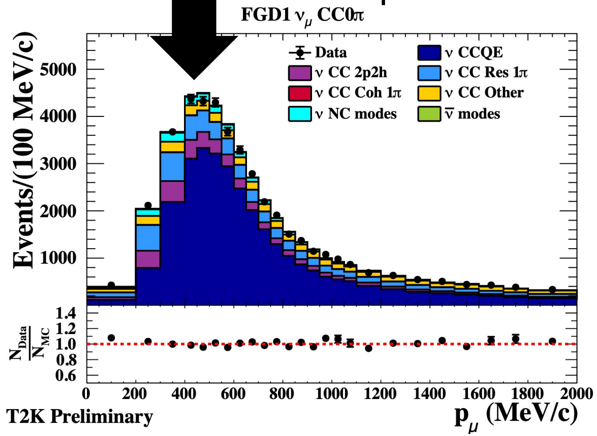


- 18 Near detector samples:

Near Detector Fit

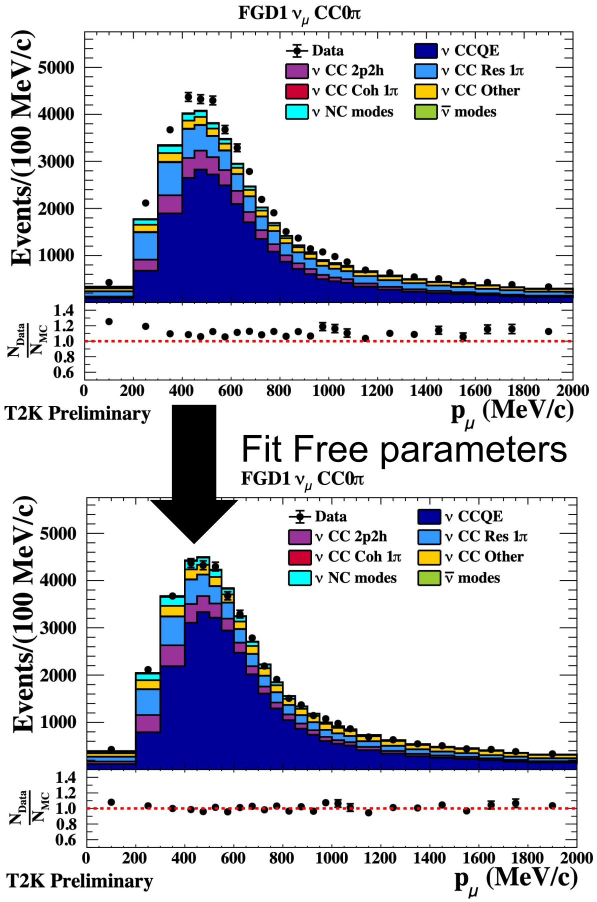


Fit Free parameters



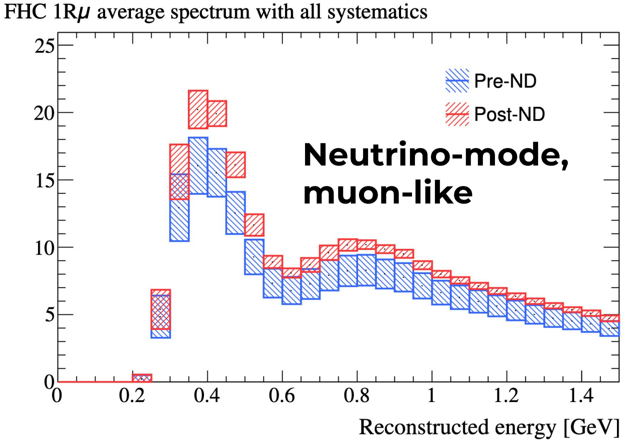
- 18 Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction

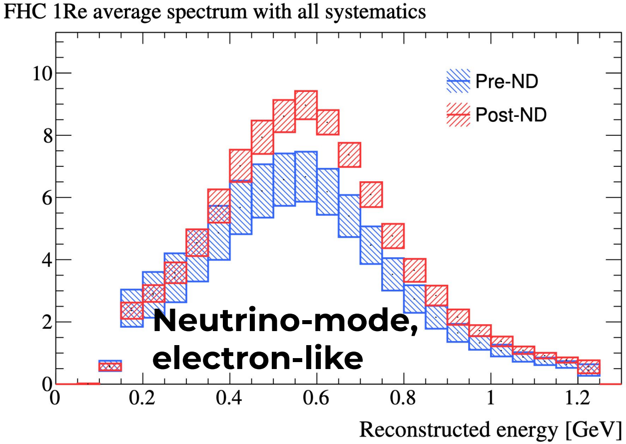
Near Detector Fit



- 18 Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction
- Tuned model constrains event rate (non-oscillation) uncertainties for Far detector

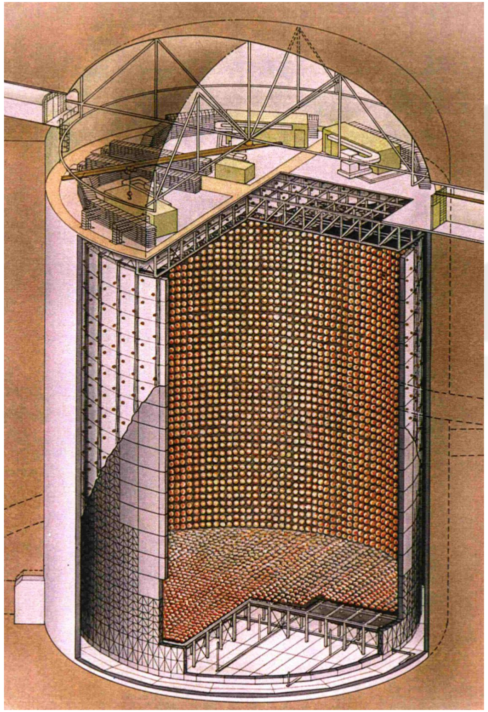
Far detector predicted event rates with oscillations





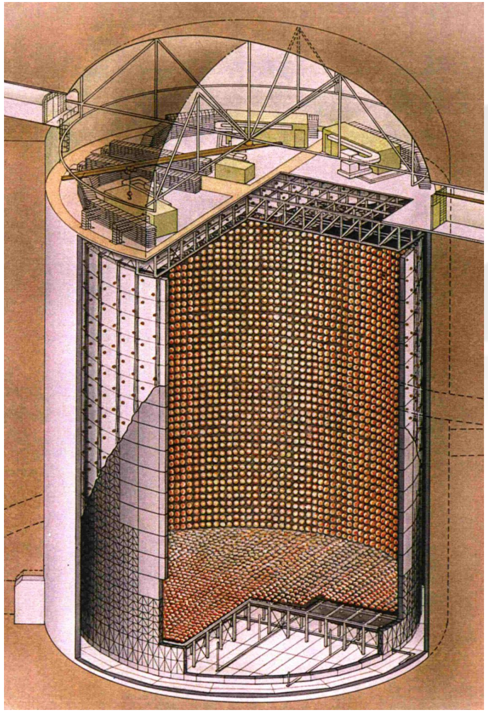
Tokai To Kamioka

Super-Kamiokande

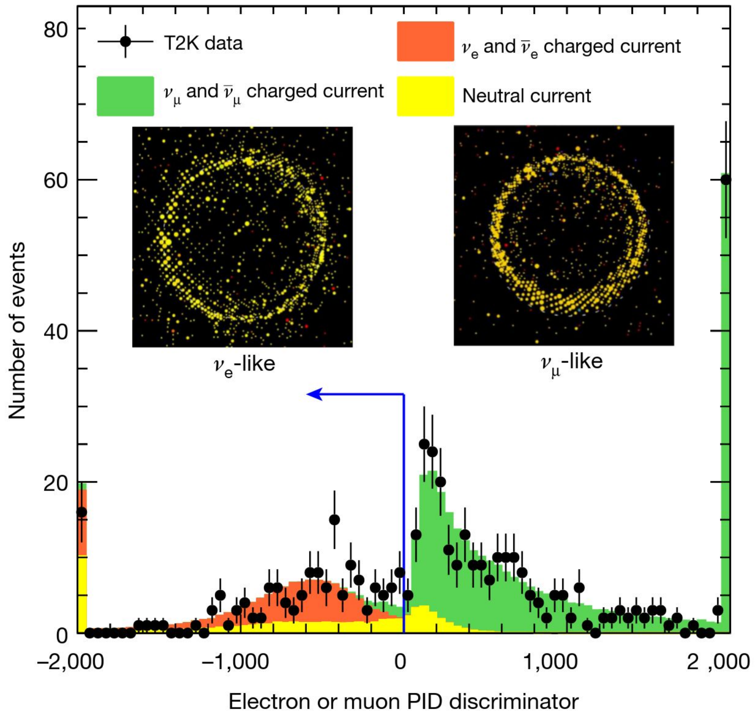


Material:	Ultrapure Water
Total Water Mass:	50 kT
Detection technique:	Cherenkov
Baseline:	295 km
Peak neutrino energy:	0.6 GeV
Location:	Mozumi Mine, Gifu, Japan

Super-Kamiokande



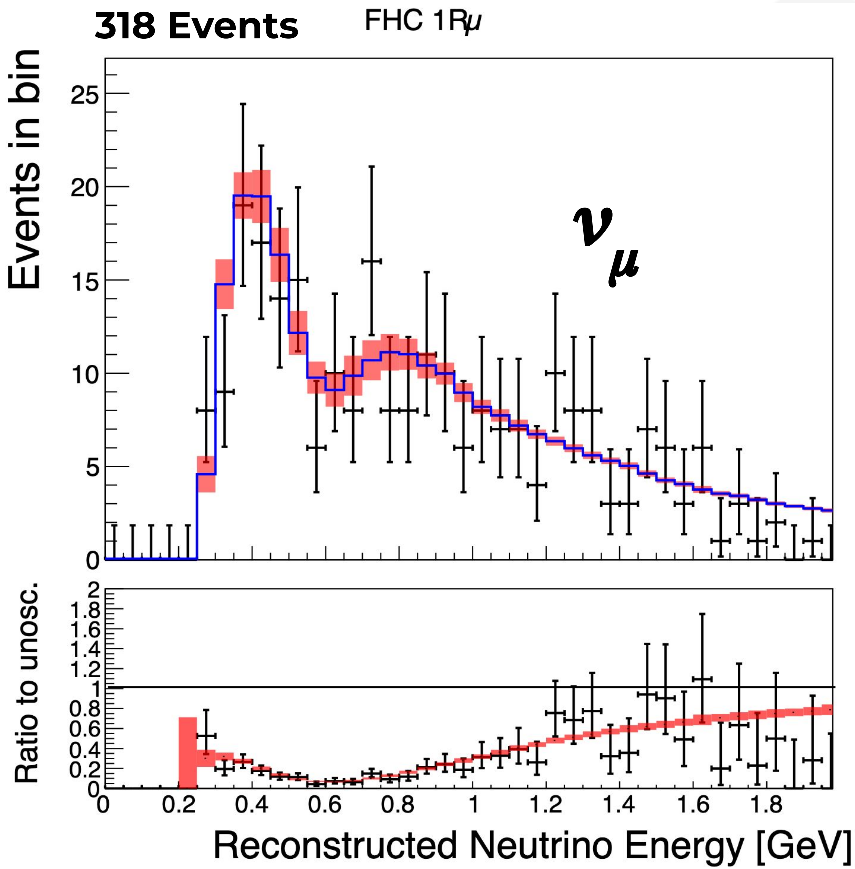
Nature 580 7803 p339-344



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

Oscillation Results

Muon-like samples

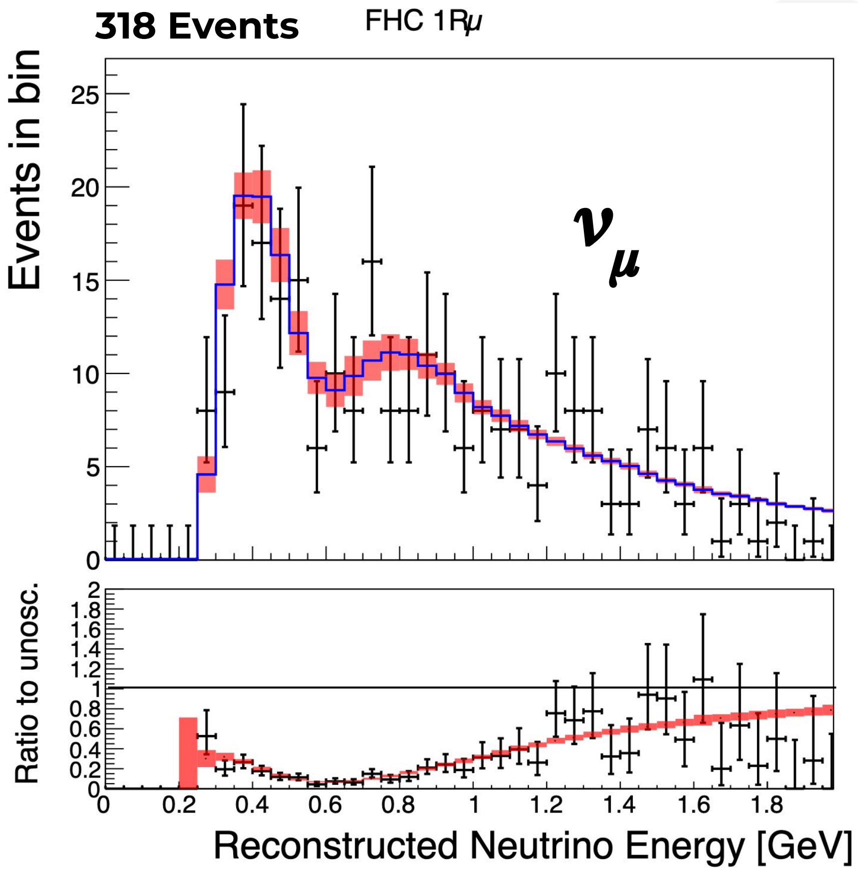


- Posterior predictive error on measured spectra. Shows remaining post-fit uncertainty in:
  - Neutrino flux prediction
  - Neutrino interaction modelling
  - Oscillation parameters

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

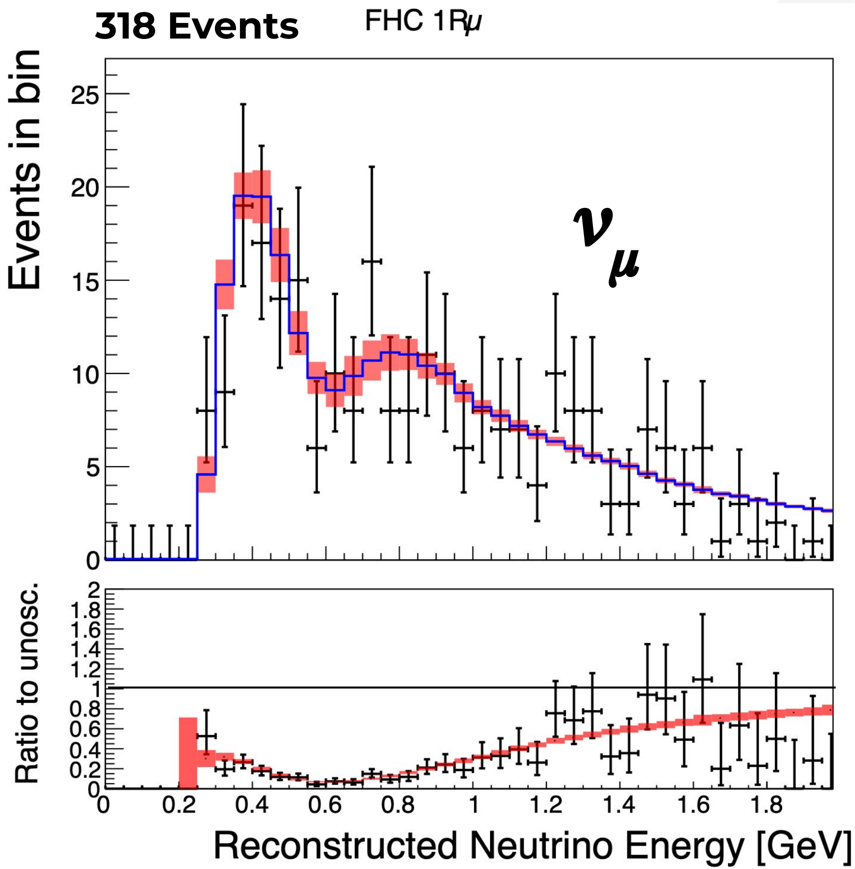
Muon-like samples

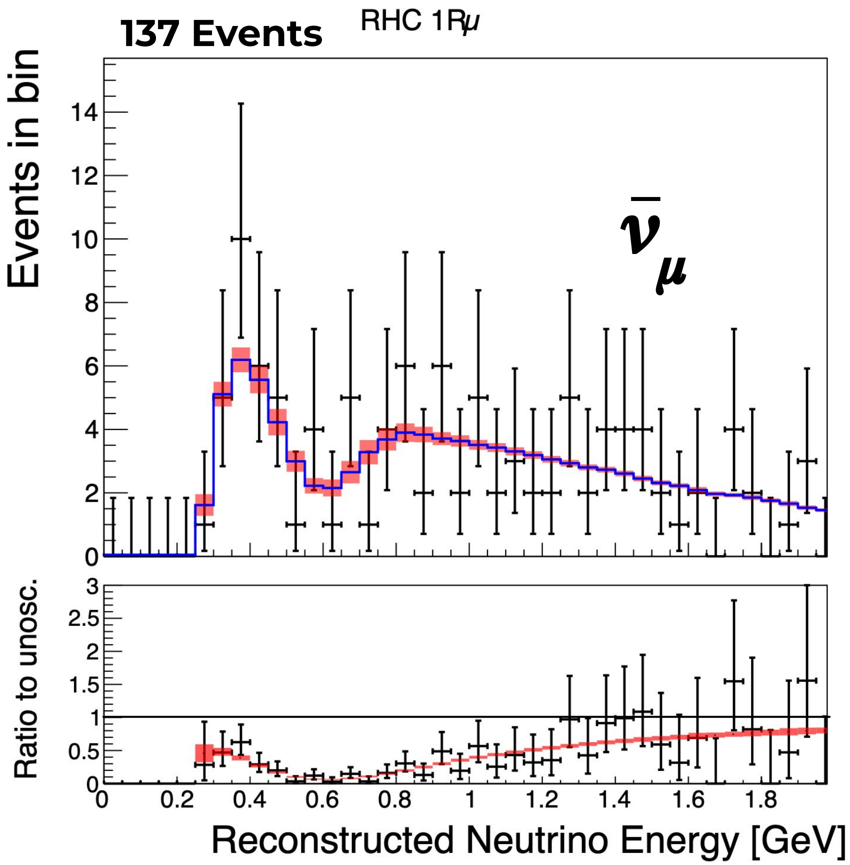
318 Events



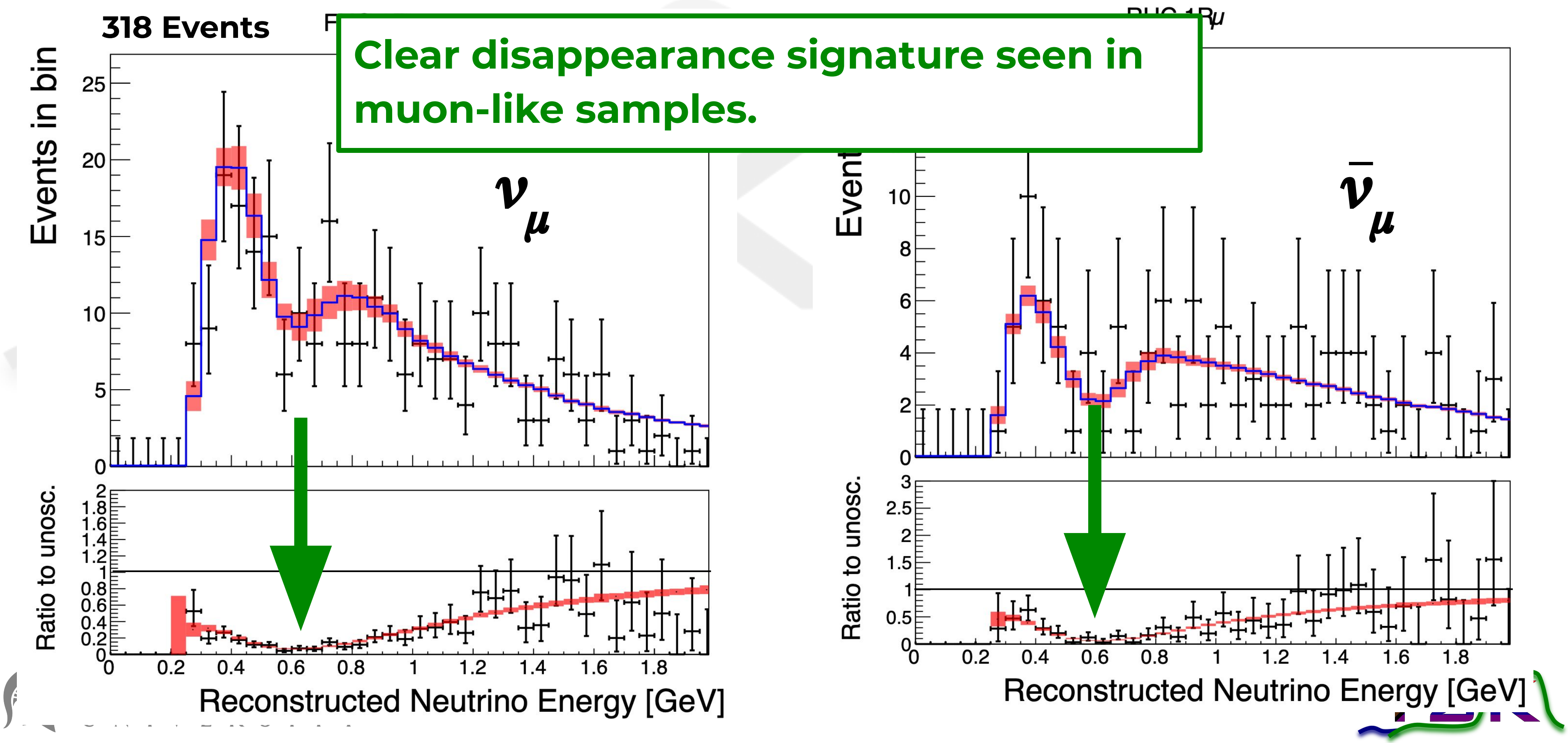
- Posterior predictive error on measured spectra. Shows remaining post-fit uncertainty in:
  - Neutrino flux prediction
  - Neutrino interaction modelling
  - Oscillation parameters
- Simultaneous fit to five samples:
  - muon-like and electron-like samples
  - neutrino-mode and anti-neutrino mode samples

Muon-like samples



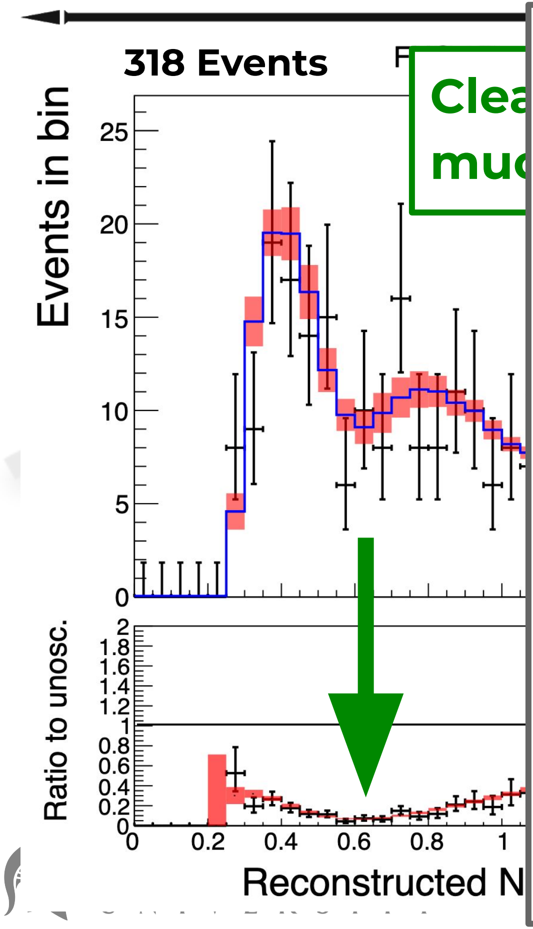


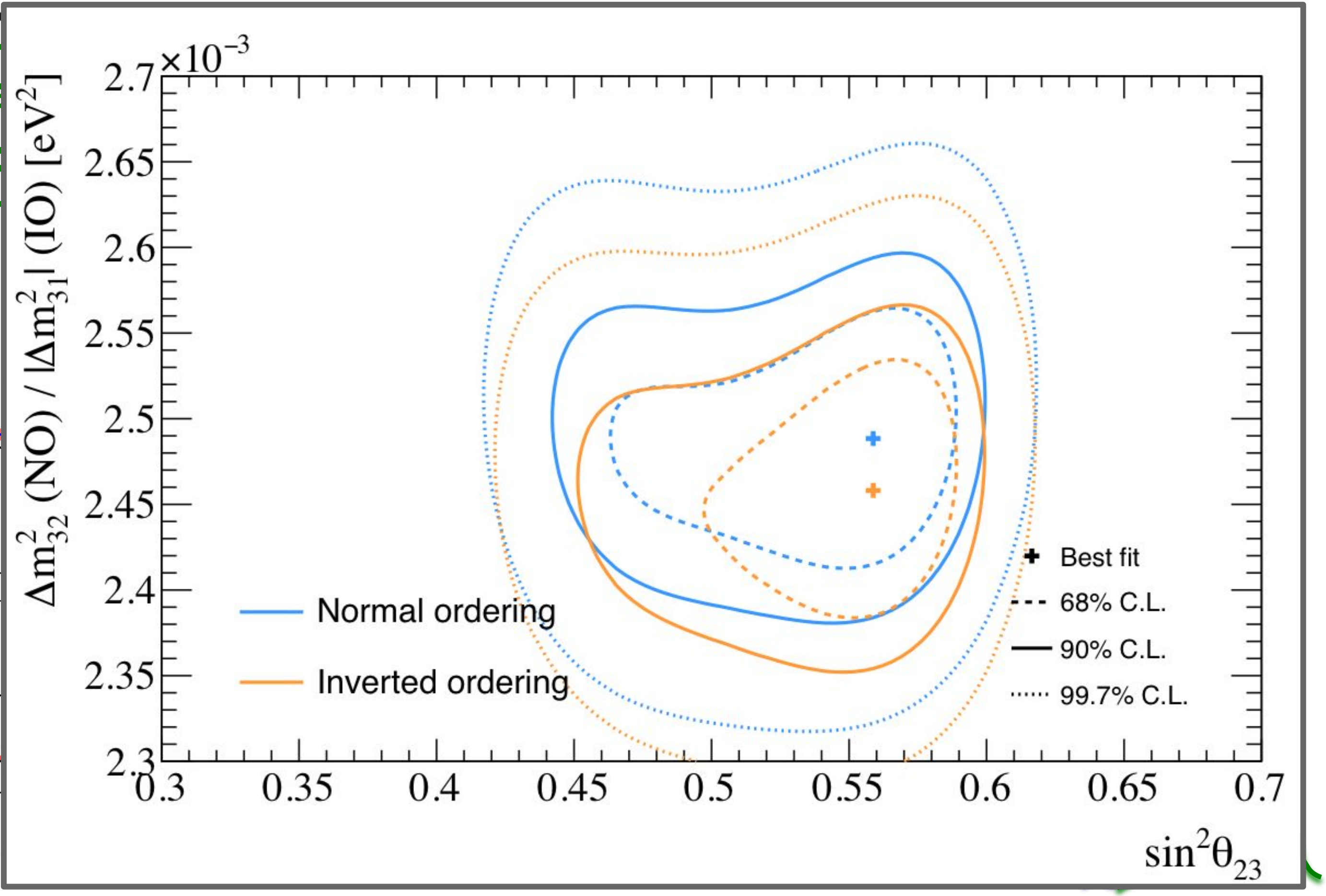
Muon-like samples



Clear disappearance signature seen in muon-like samples.

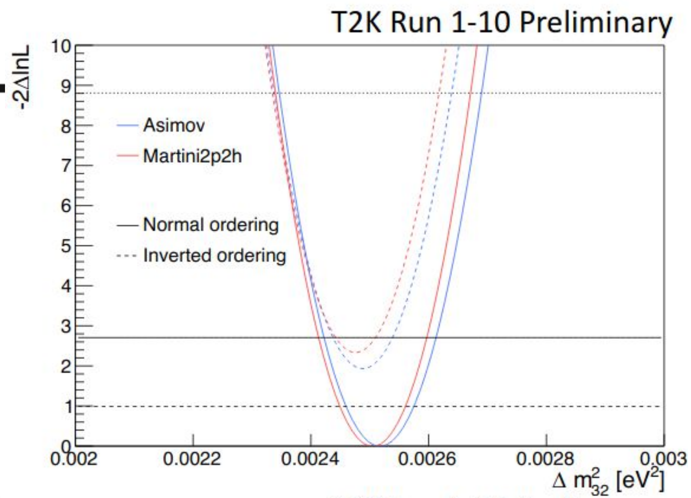
Muon-like samples

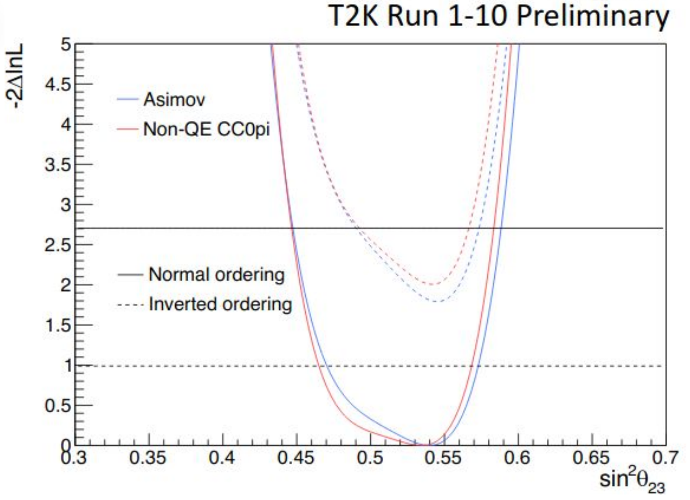




Robustness Studies

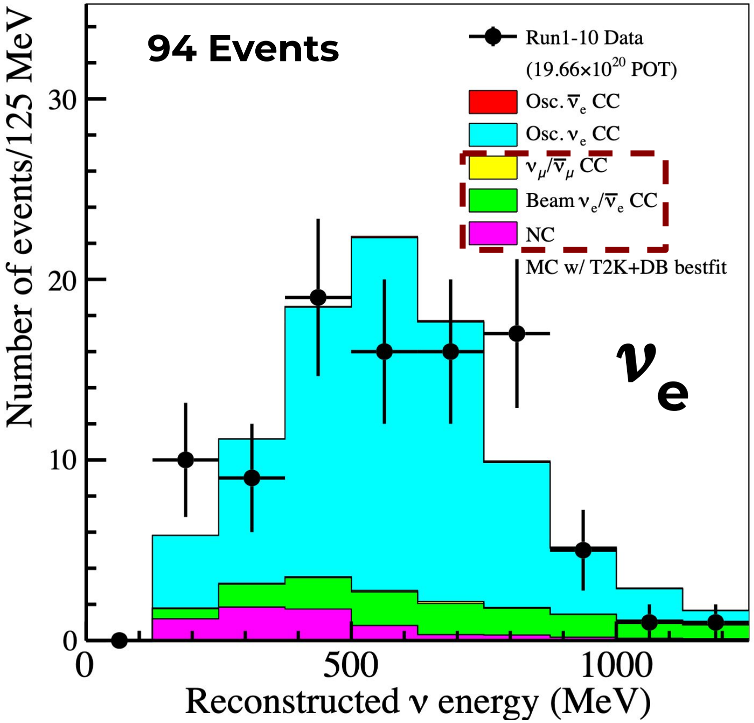
- Systematic uncertainty in neutrino interaction models are large.
- Full simulation of multiple different models is computationally infeasible.
- Develop reweighting schemes to make 'mock data' predictions from various alternate models.
  - Test if analysis is robust to such variations and inflate uncertainties as necessary.
- No significant bias seen on δ_{CP}, θ_{23}, or θ_{13} from any alternate model study:
  - Small bias on Δm^2_{32} accounted for by inflating error by 1.4×10^{-5} eV^2

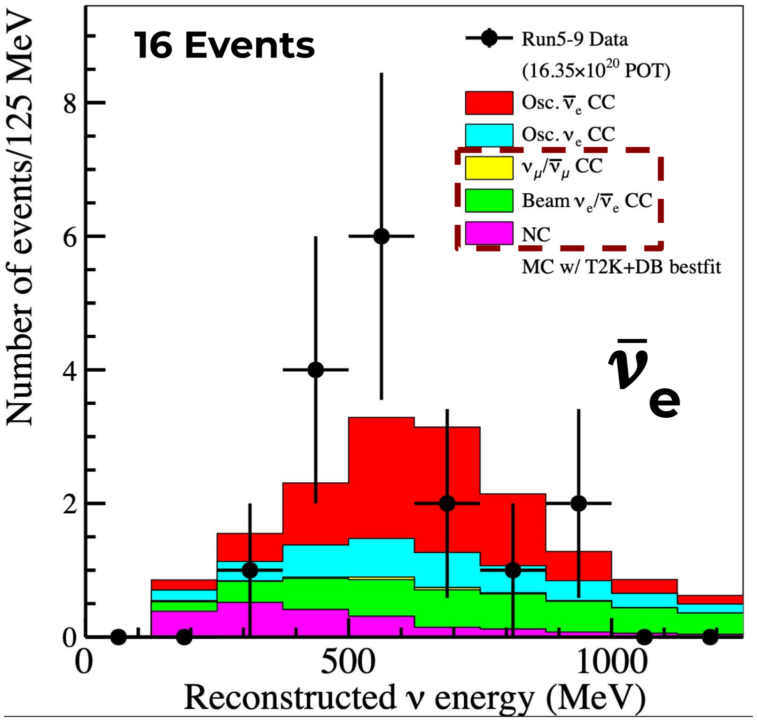




Electron-like samples

- **Significant electron appearance seen above predicted backgrounds**

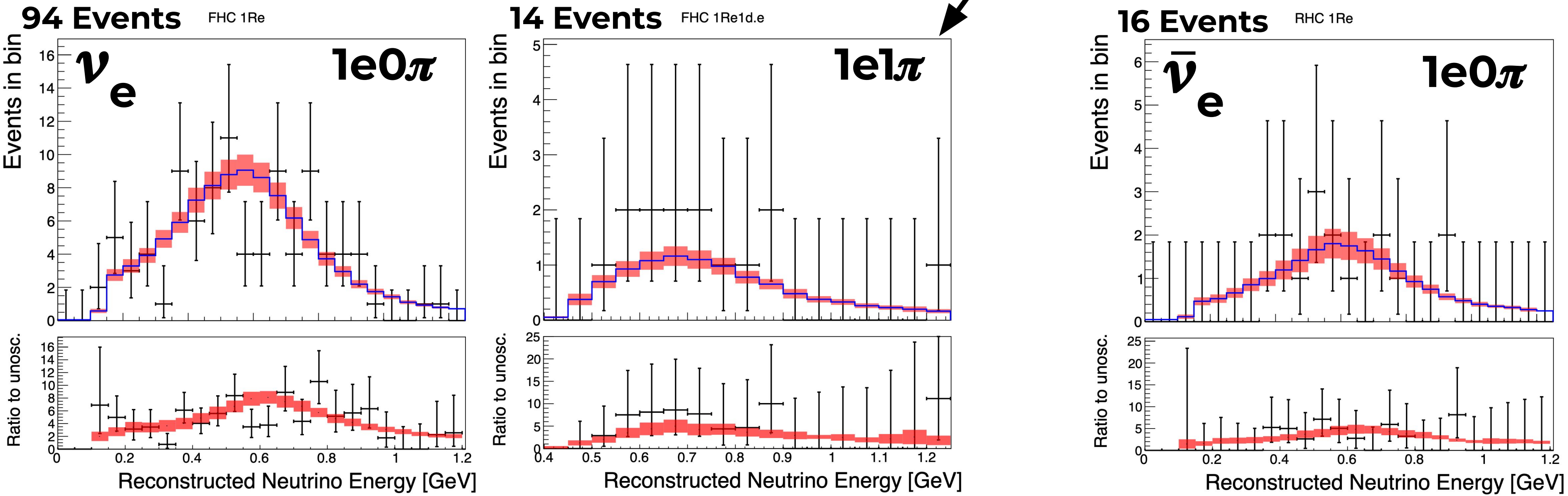




Electron-like samples

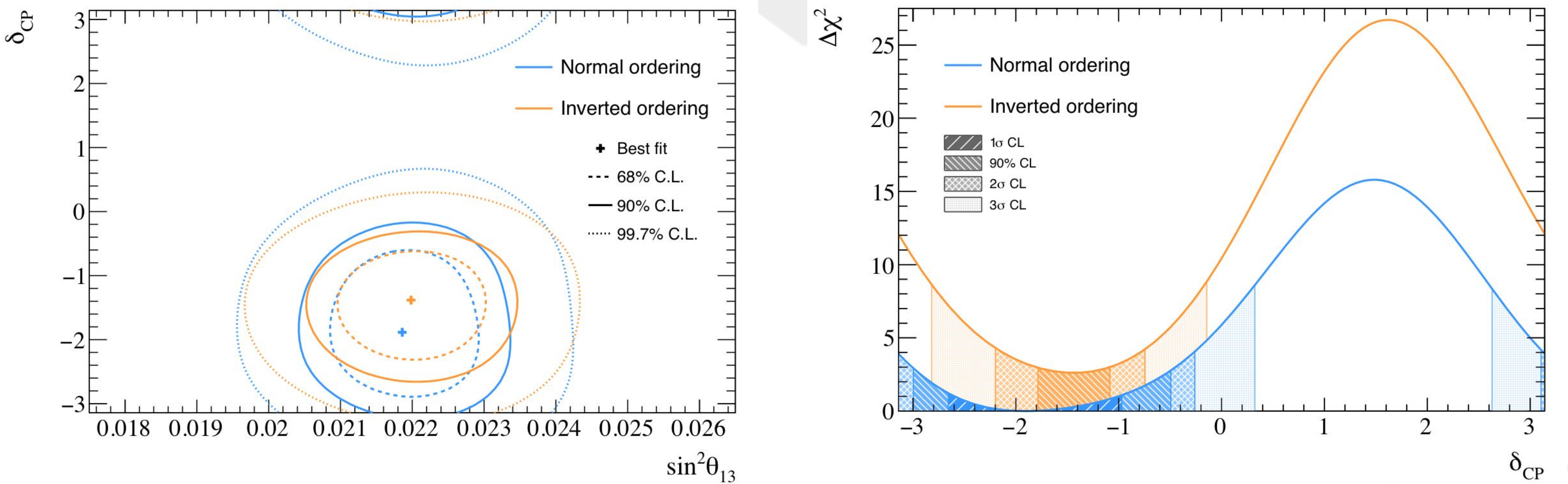
- Significant electron appearance seen:
  - Both neutrino and antineutrino beam modes

Select electron-neutrino single-pion events by tagging delayed michel electron from pion decay



Appearance Constraints

- Includes PDG constraint on θ_{13} from reactor neutrino measurements.
- Disfavor CP conservation (δ_{CP}=0,±π) at 90%
- Bayesian analysis favors Normal mass ordering at 80% confidence.
    - Largest bias seen in robustness studies moves edge of 90% contour by **0.08**.

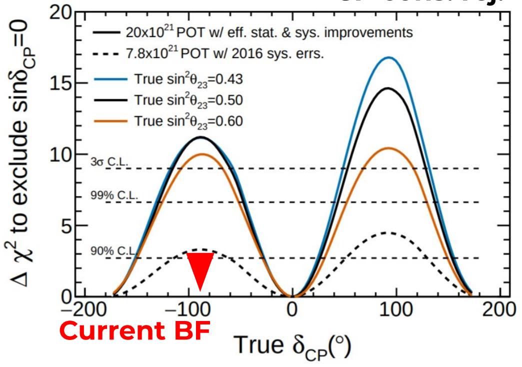


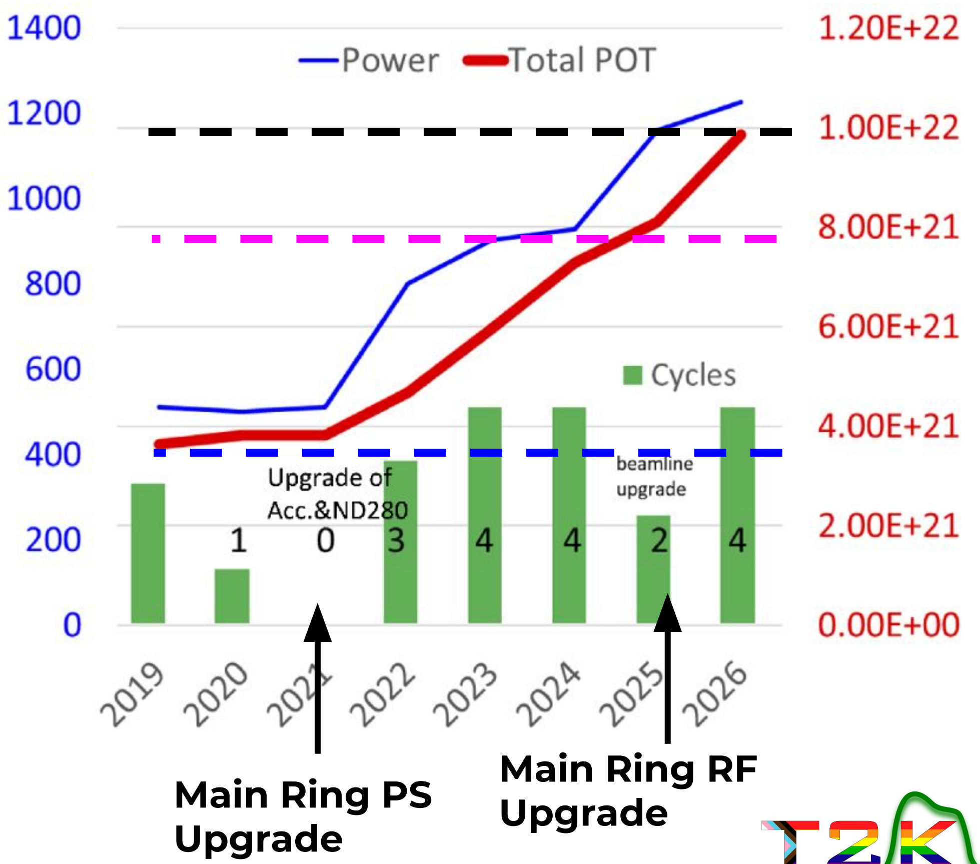
The Future

T2K Extension and J-PARC Beam Upgrade

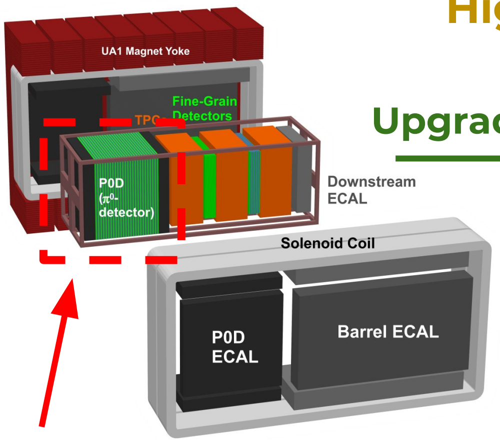
- T2K has recorded **3.64x10²¹ POT**
- KEK now budget for: **10x10²¹**
- Continued rich physics program and improved oscillation sensitivity until Hyper-K

arXiv:1609.04111v1

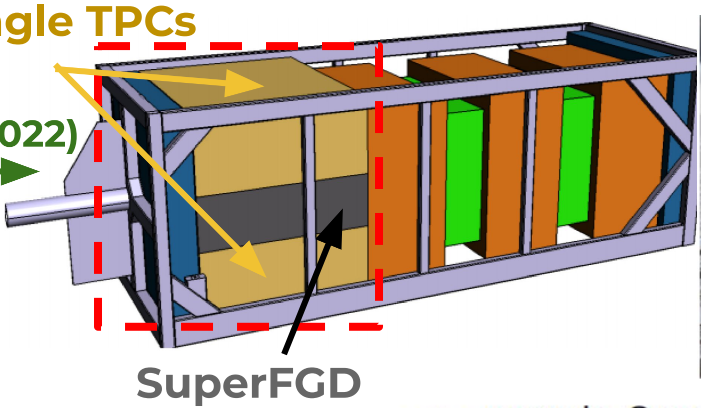


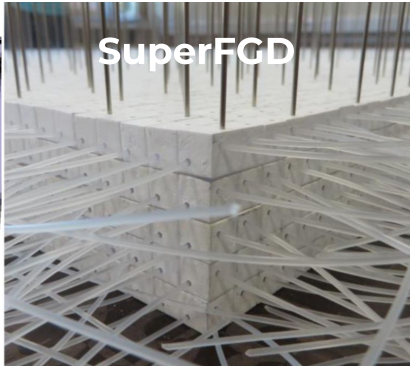


ND280 Upgrade

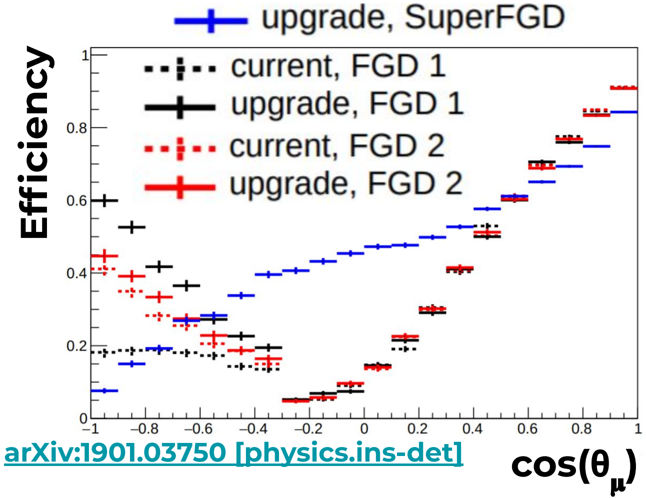


Upgrade! (~2022)





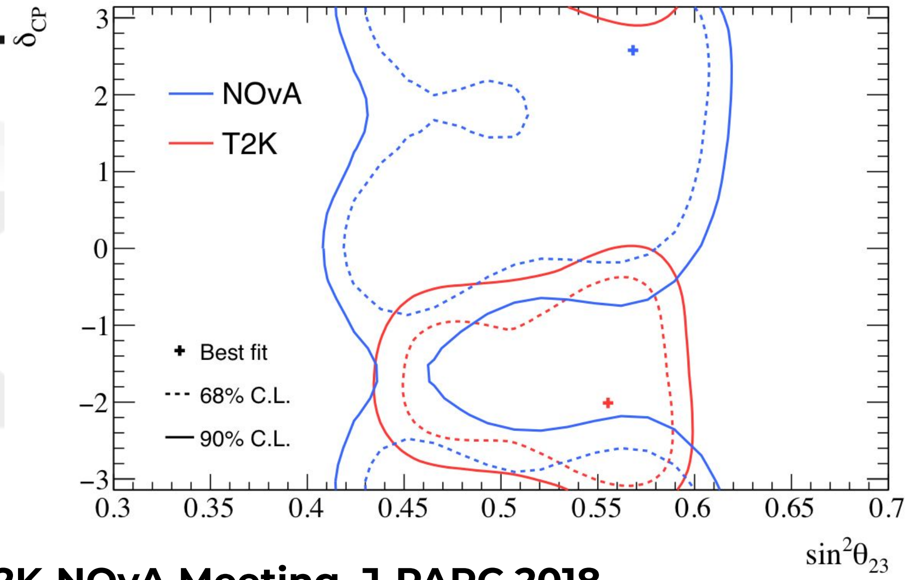
- **P0D** will be replaced for ND280 upgrade
- New 3D scintillator detector + horizontal TPCs:
  - **Improved acceptance**
    - **High angle**
    - Low momentum (esp. protons)



arXiv:1901.03750 [physics.ins-det]

- Ongoing joint oscillation fit effort with the NOvA collaboration.
- Probe the same oscillation physics (Same L/E)
  - Different L
    - T2K: 295 km
    - NOvA: 810 km
  - Different <E>
    - T2K: 0.6 GeV
    - NOvA: 2.3 GeV
  - Different dominant systematic uncertainties
- Complementary constraints!

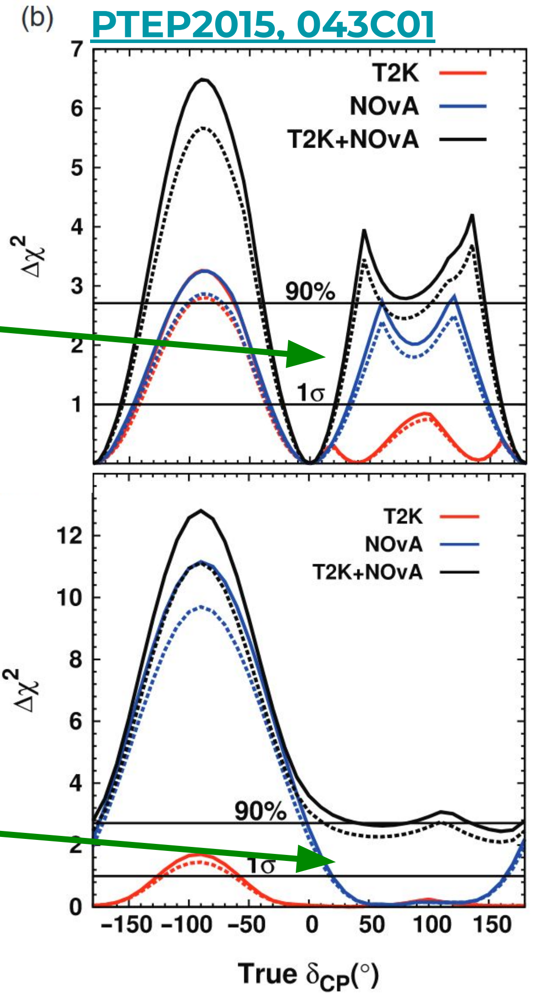
Latest results from each experiment



Joint T2K-NOvA Meeting, J-PARC 2018

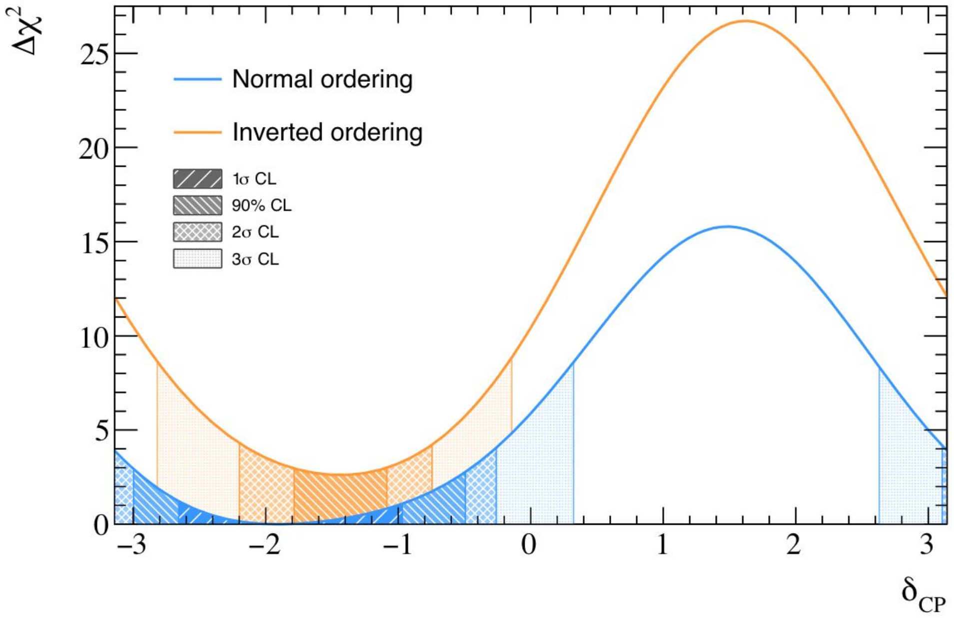
CP conservation rejection:
Degenerate for T2K but not T2K+NOvA

Wrong mass ordering rejection:
Degenerate for T2K, NOvA but not T2K+NOvA



Summary

- It's an exciting time in long baseline neutrino physics!
- World-leading measurements of neutrino mixing parameters.
- Seeing sensitivity to lepton-sector CPV.
- Future joint fit with NOvA expected to increase sensitivity to CPV!



Dawn from the summit of Fuji-san

Thanks for listening

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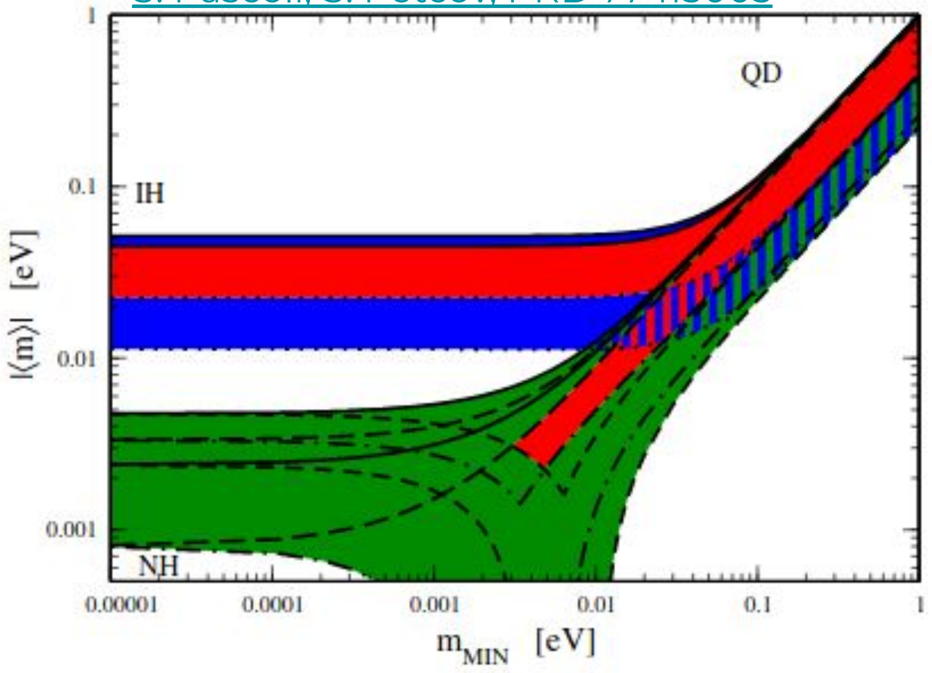
Impact of Mass Ordering

- If inverted ordering, why?
  - Would break a structure seen in other areas of the standard model.
- If inverted ordering (IH), then there is a lower limit on required sensitivity for neutrinoless double beta decay searches for Majorana nature of the neutrino.

S. Pascoli, S. Petcov, PRD 77 113003

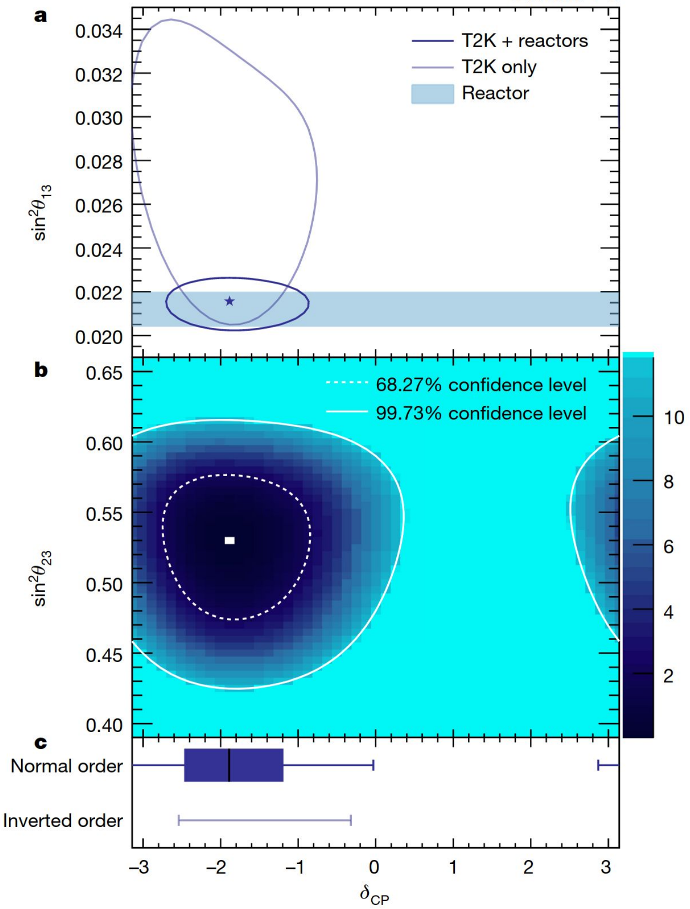


What Changed Since 2019?


The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos

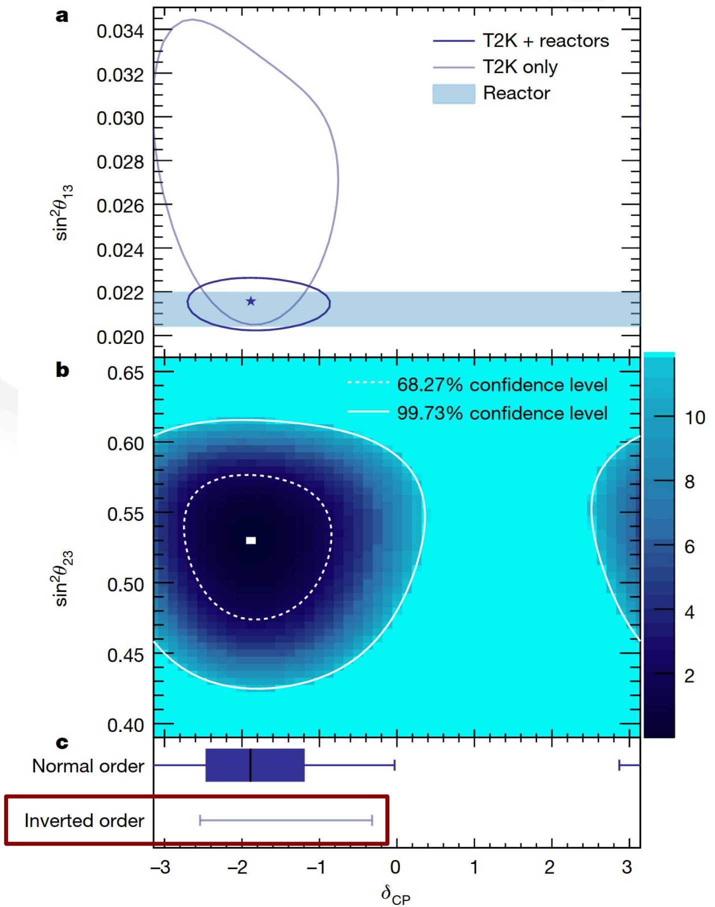
Appearance Constraints

- 2019 Analysis (Nature 580 7803)



Appearance Constraints

- 2019 Analysis (Nature 580 7803)
  - Disfavored inverted ordering at 1 sigma
  - Disfavored δ_{CP} = 0 at 3 sigma



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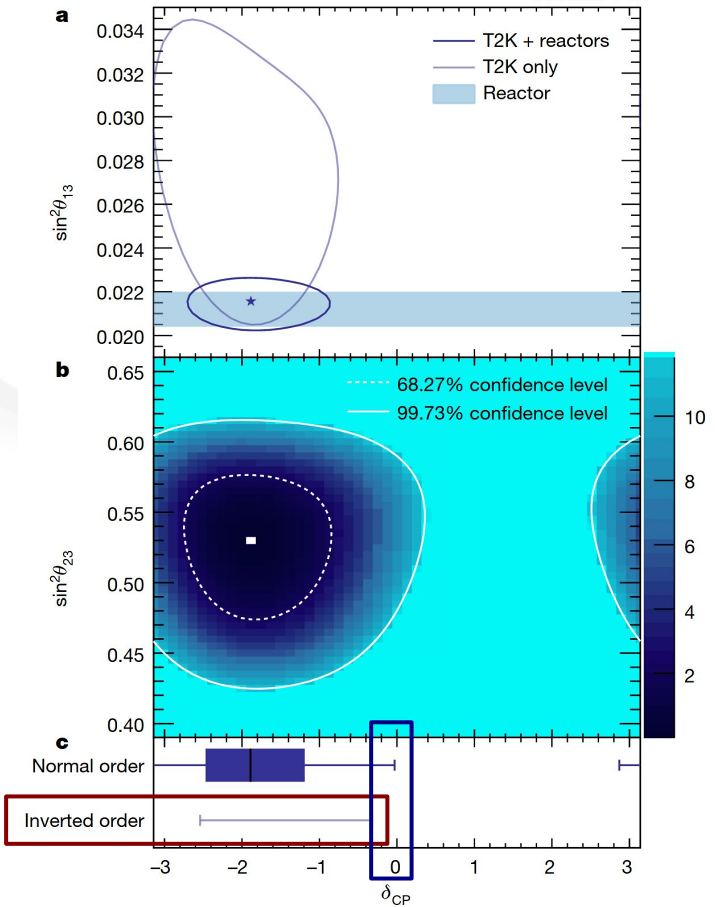

Appearance Constraints

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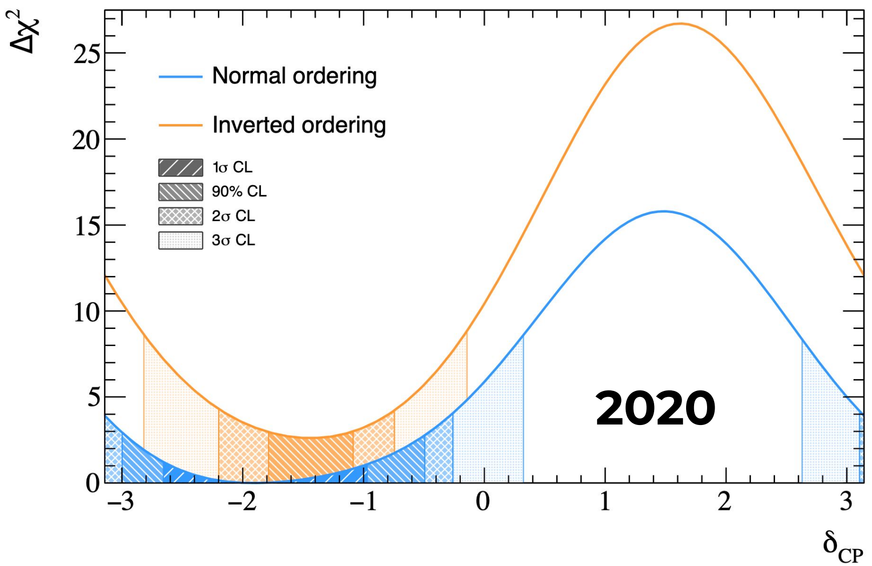

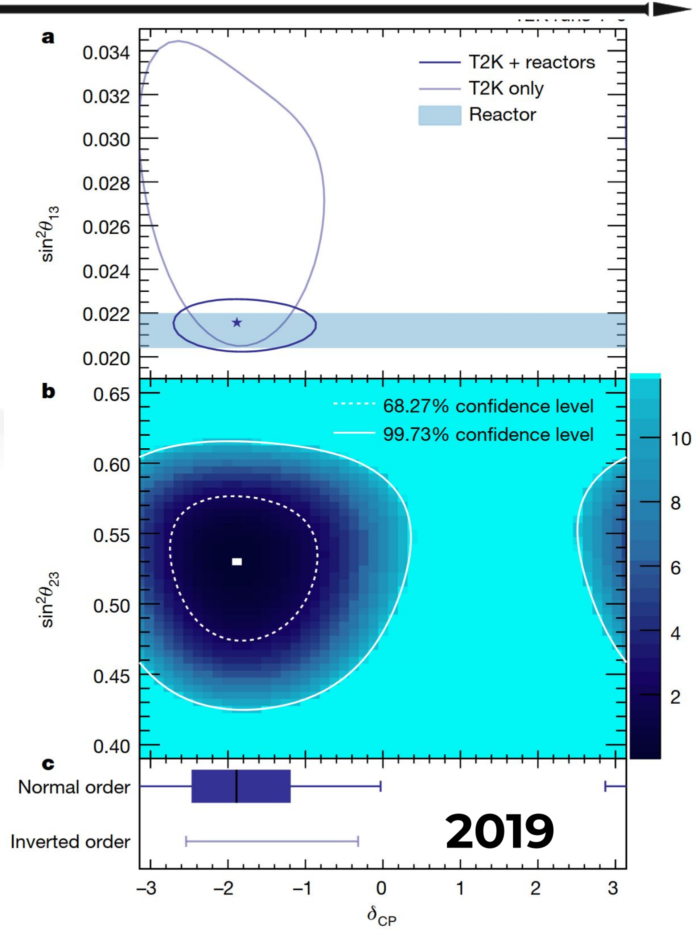

Appearance Constraints

- 2019 Analysis ([Nature 580 7803](#))
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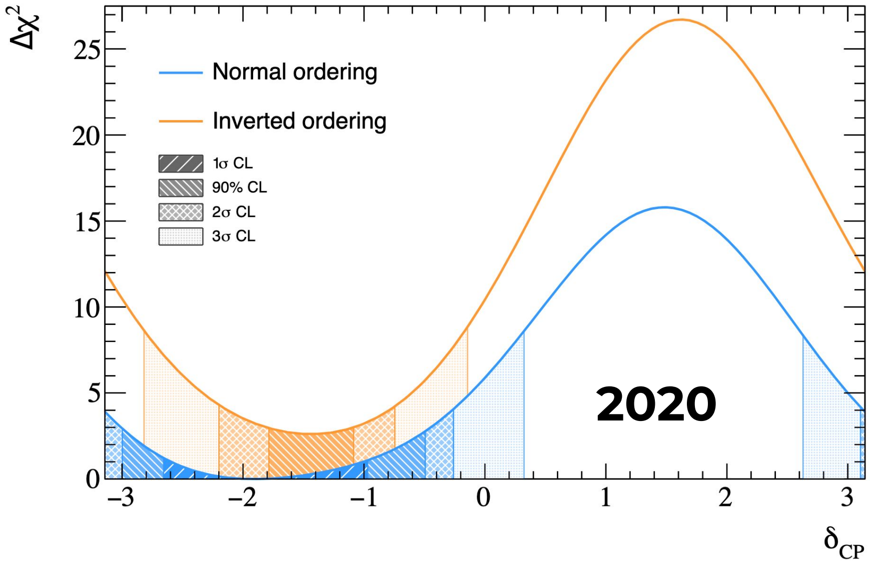
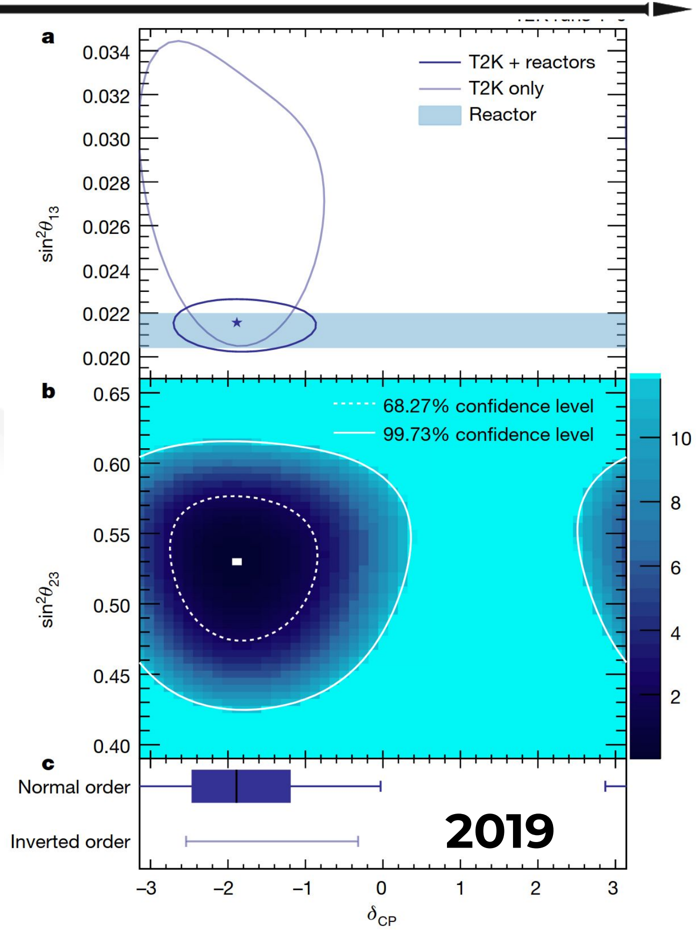
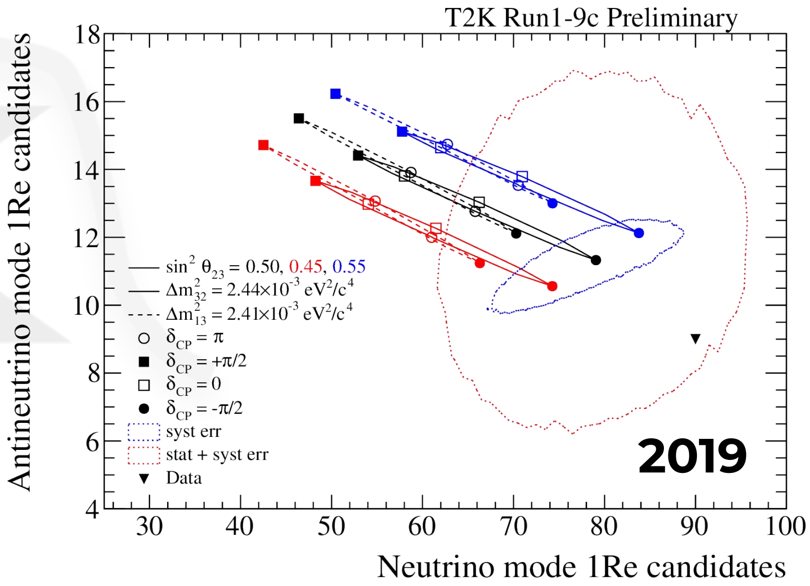
  - Disfavored δ_{CP}= 0 at 3 sigma
- 2020 Analysis presents slightly looser constraint. **Why?**





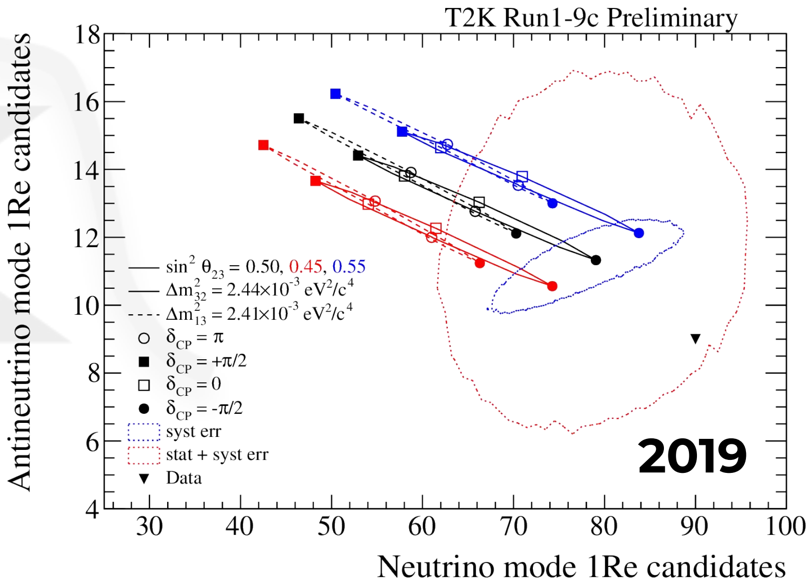
What Changed?

- Previous result exceeded projected CPV sensitivity through 1-sigma tension with PNMS prediction.

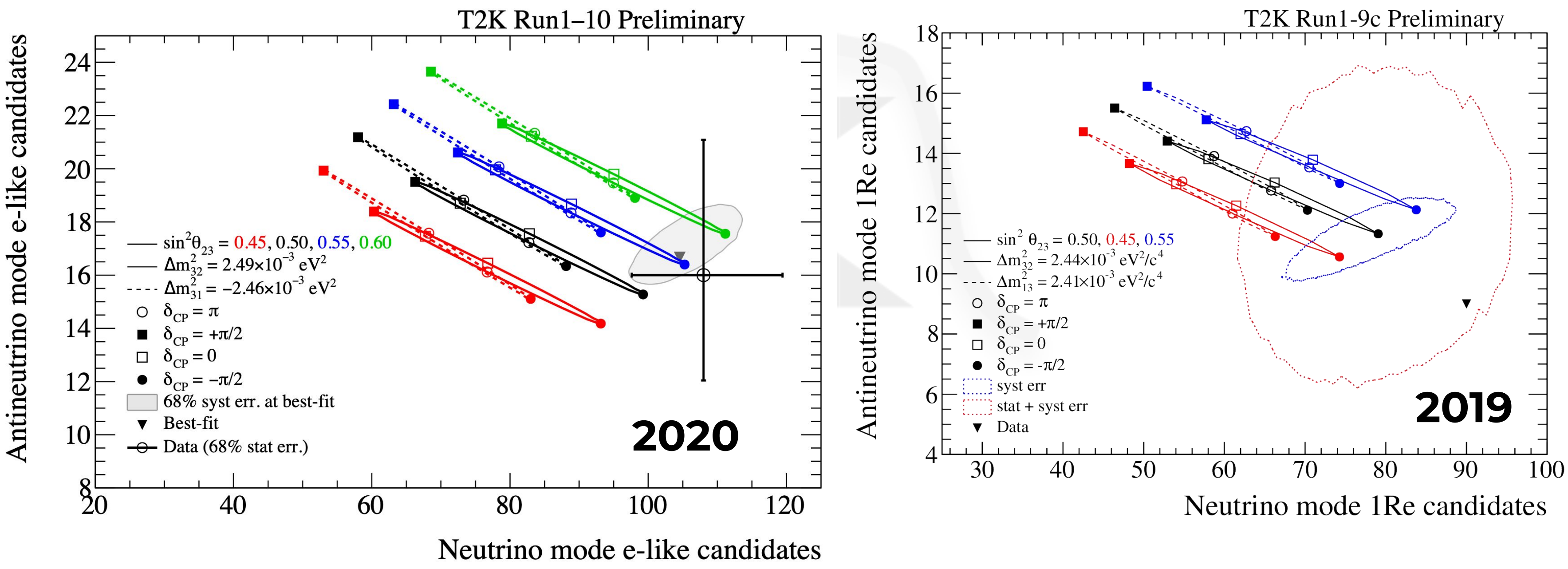


What Changed?

- Previous result exceeded projected CPV sensitivity through 1-sigma tension with PNMS prediction.
    - Expected at the time to be a statistical fluctuation
    - 'Too many' neutrinos and 'too few' anti-neutrinos.



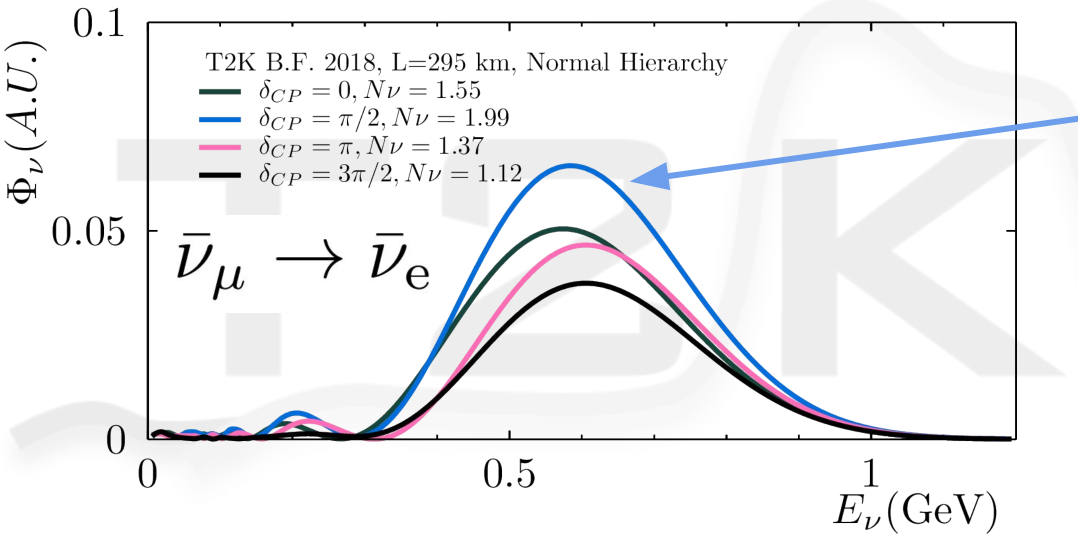
What Changed?

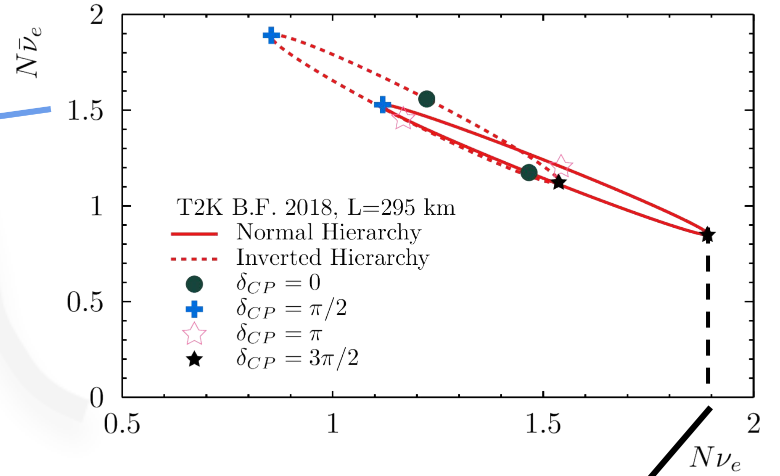


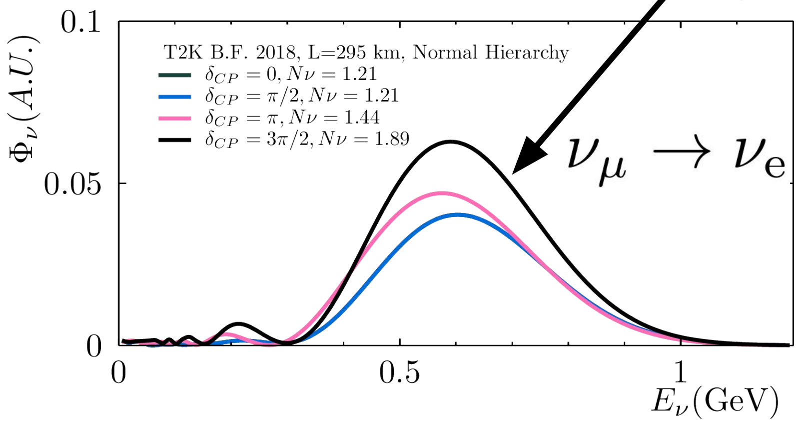
2020 result is 'more consistent' with PMNS predictions, more inline with projected sensitivity.

BiProb

Neutrino and Antineutrino Appearance

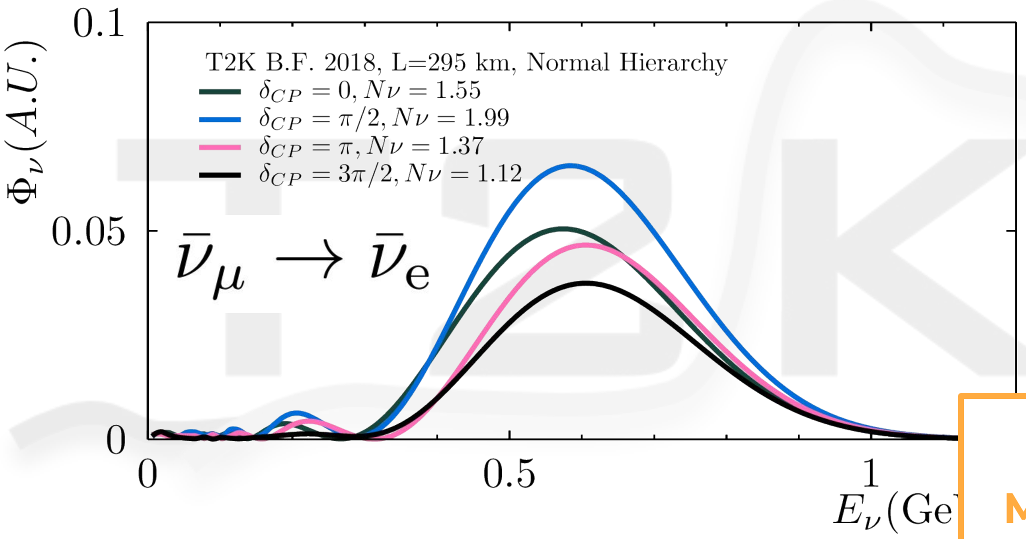


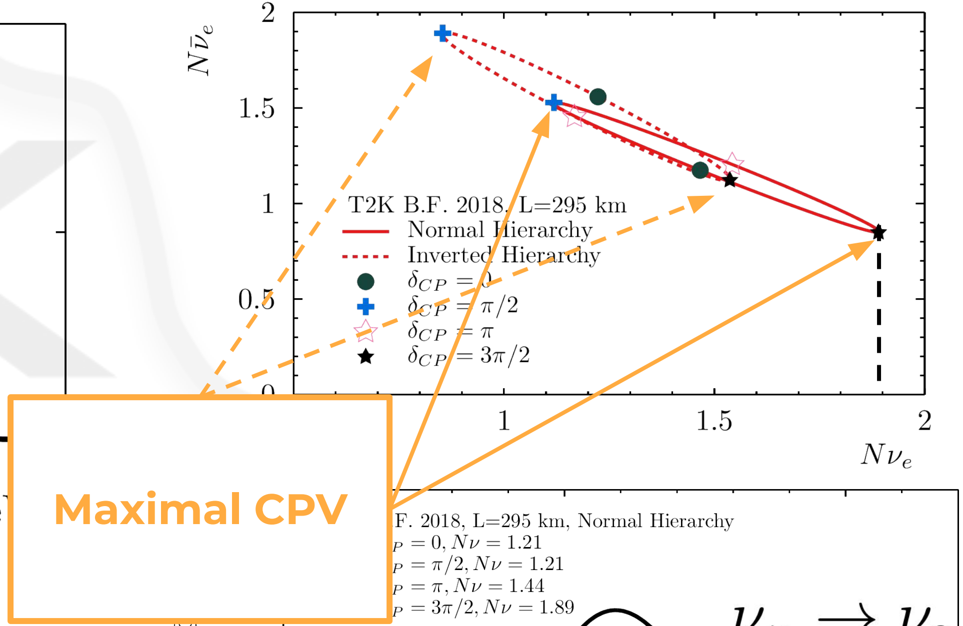


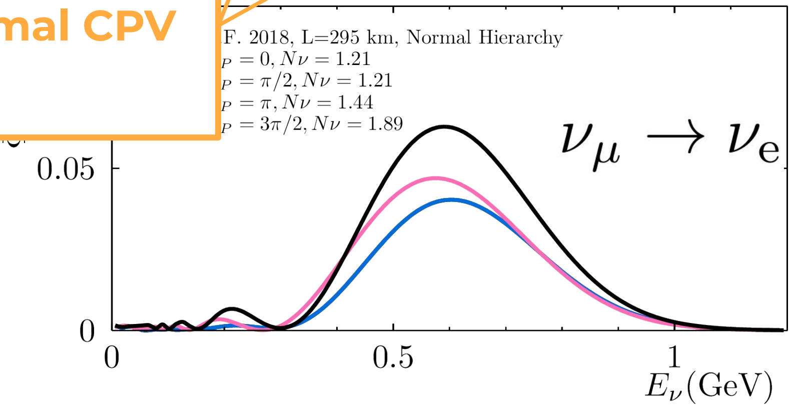


- Most sensitive to δ_{CP} if:
  - Know hierarchy
  - Know disappearance parameters well
  - Measure in both beam modes: $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Neutrino and Antineutrino Appearance







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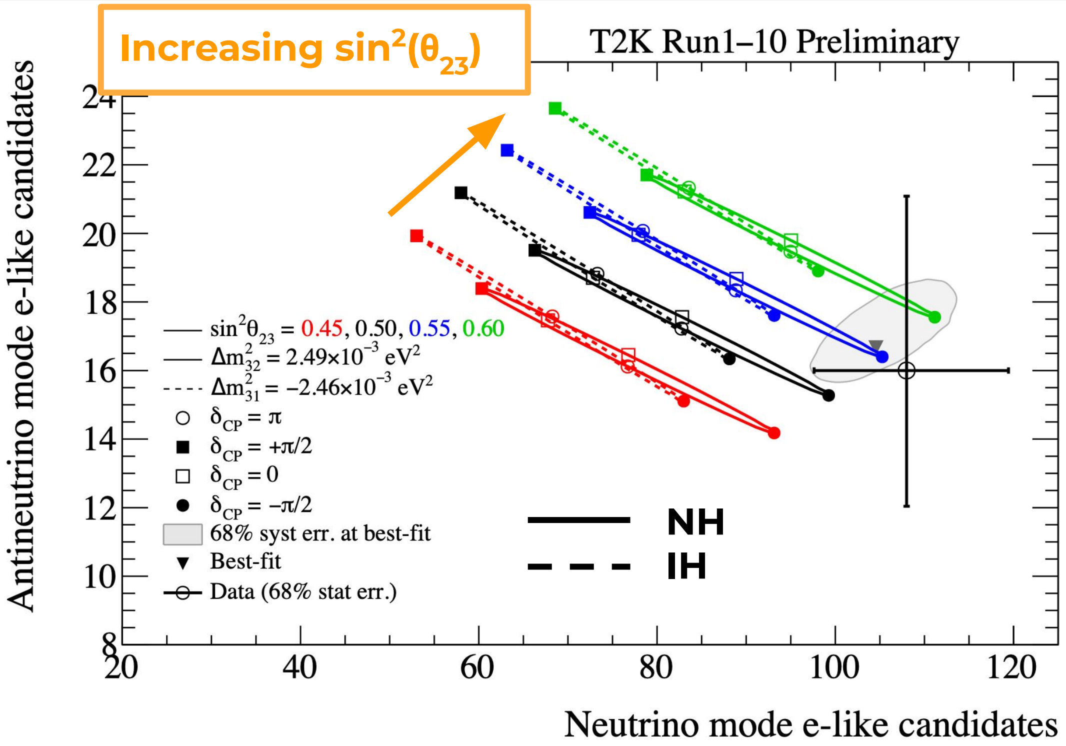
Matter vs. Antimatter rates

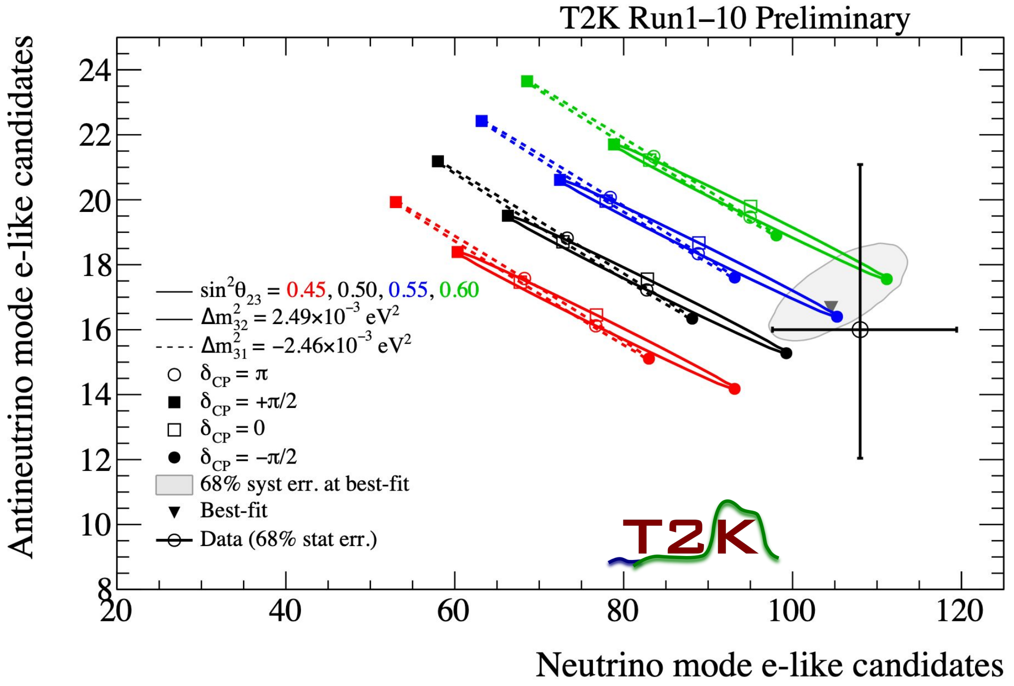


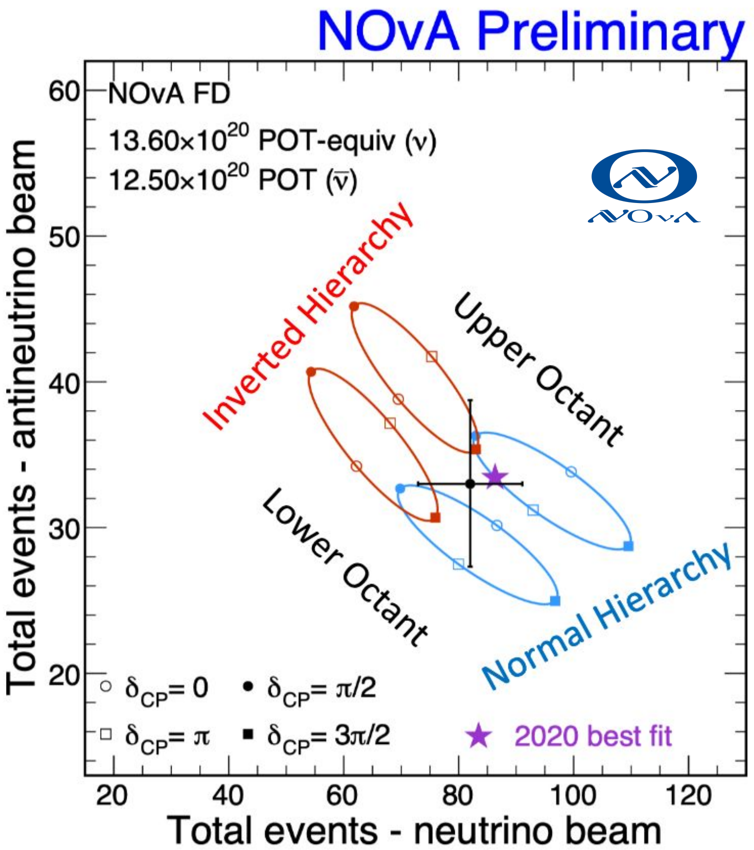
- Compare expected and observed ν_e and $\bar{\nu}_e$ rates:
  - Sensitivity to δ_{CP} and Mass hierarchy

T2K and NOvA

A. Himmel, Neutrino2020

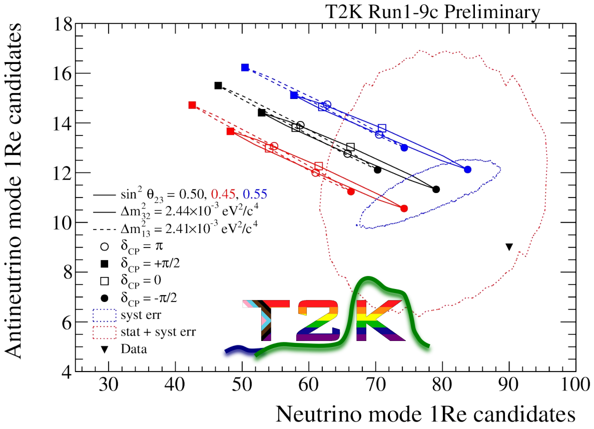
Both experiments measure the same L/E, but with different L and different <E>.

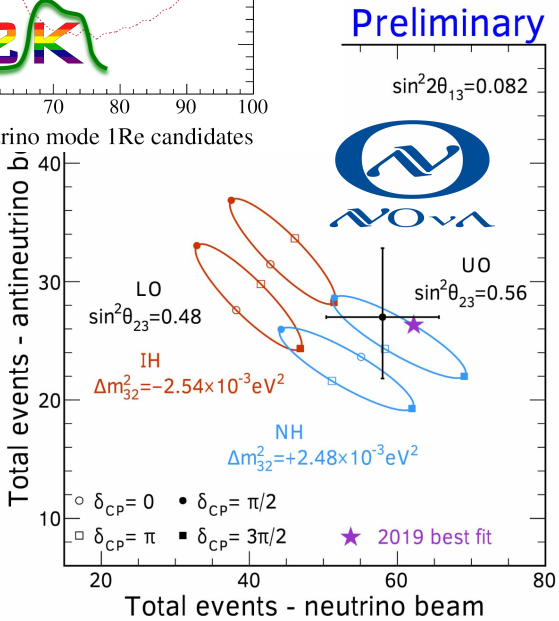




T2K-NOvA Complementarity

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





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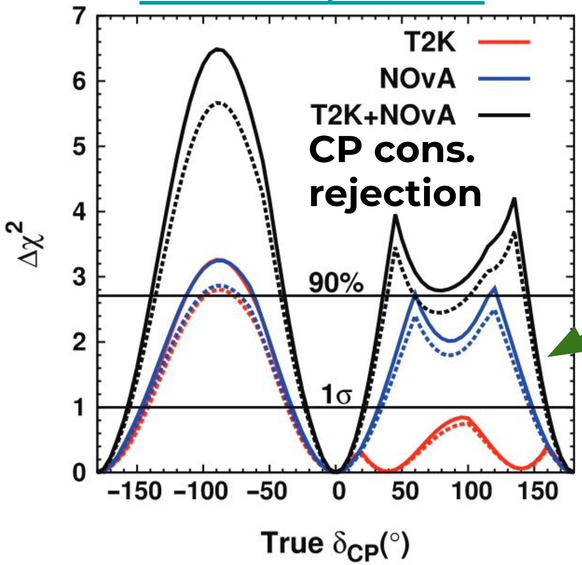
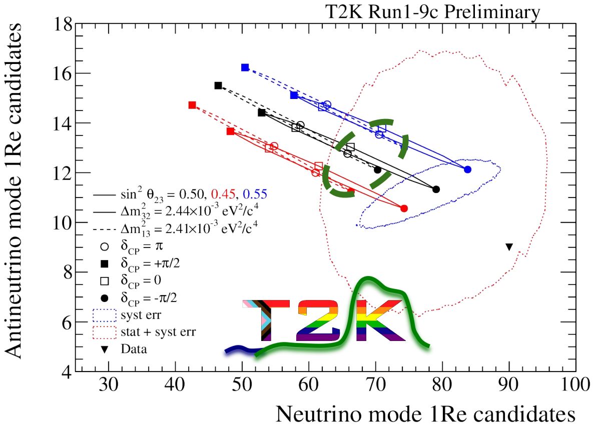
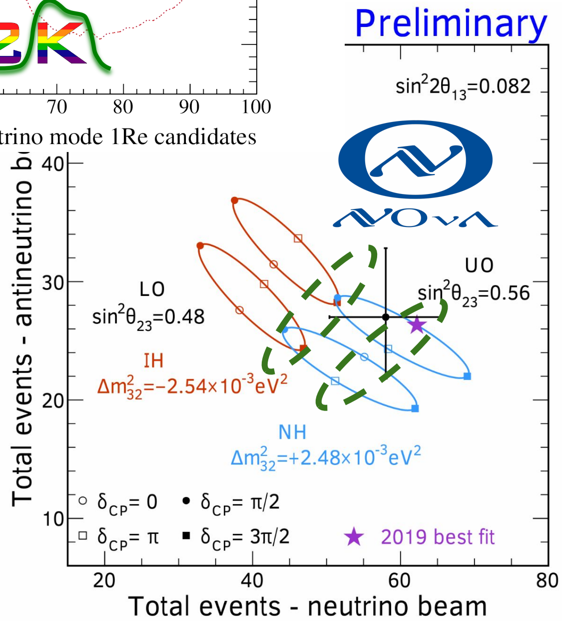
(b) PTEP2015, 043C01





Degenerate for T2K but not NOvA



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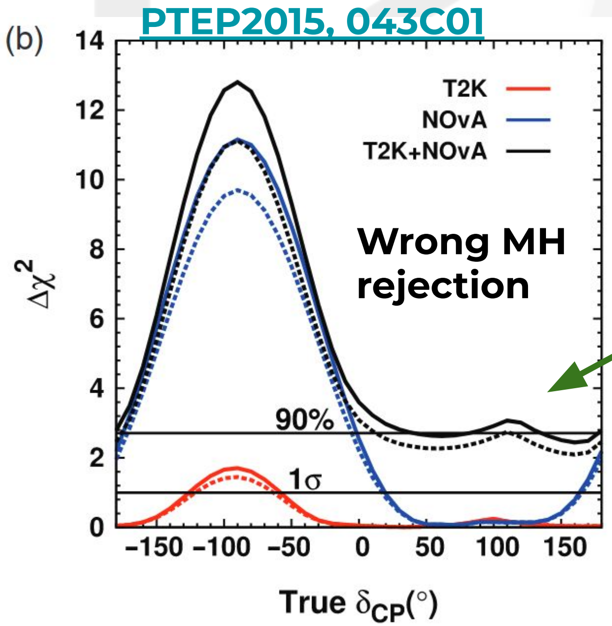
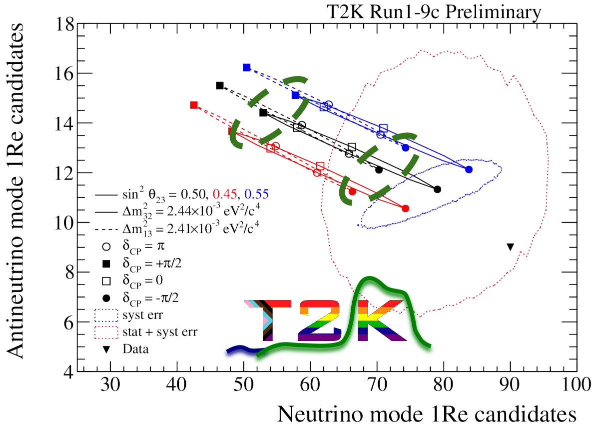
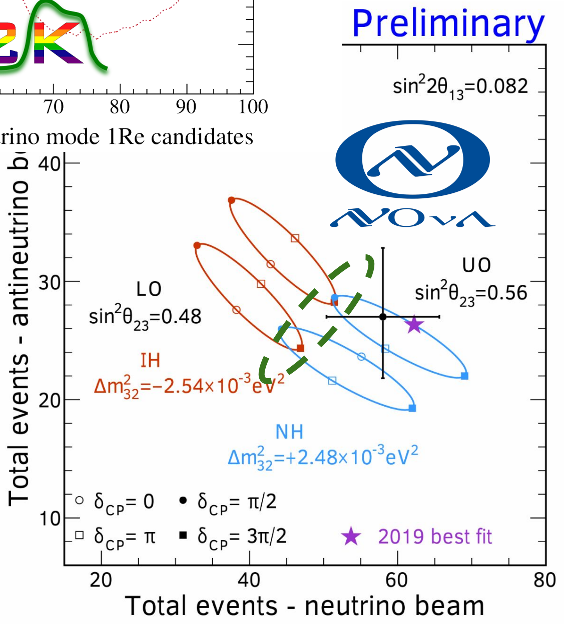




Degenerate for NOvA but not T2K+NOvA



T2K-NOvA Complementarity

A. Himmel, Neutrino2020

- Complementary sensitivities from both experiments:
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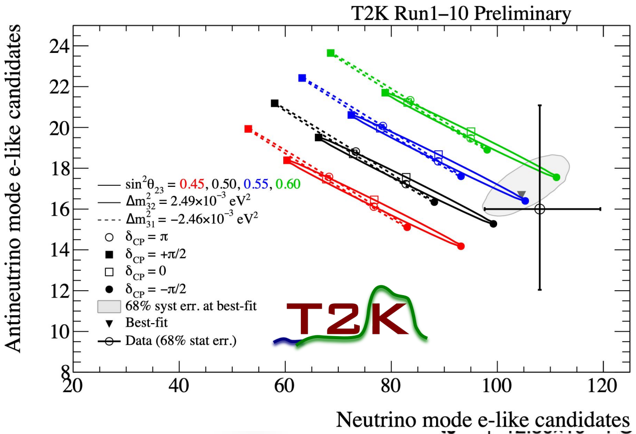

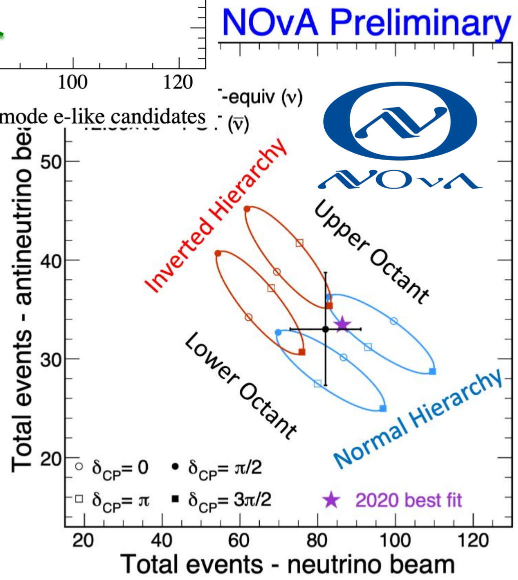

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[A. Himmel, Neutrino2020](#)

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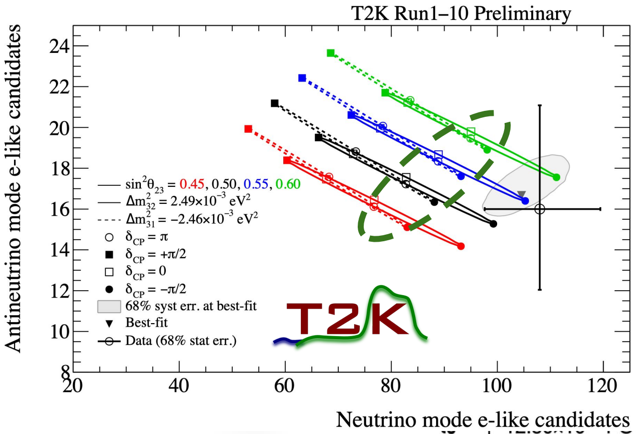
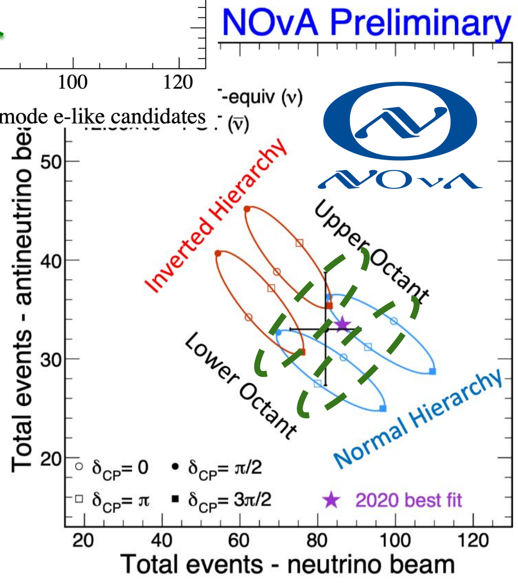


Degenerate for T2K but less for NOvA



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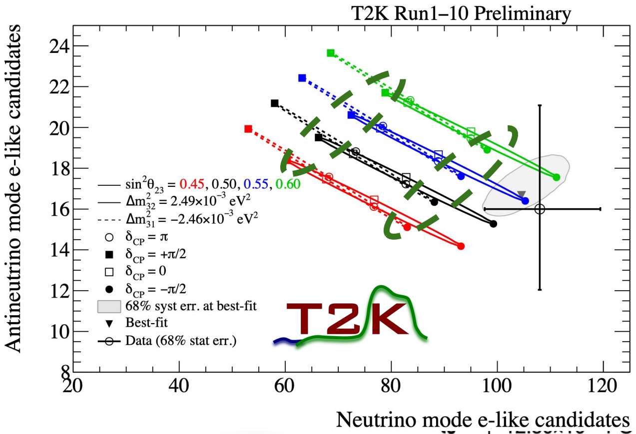

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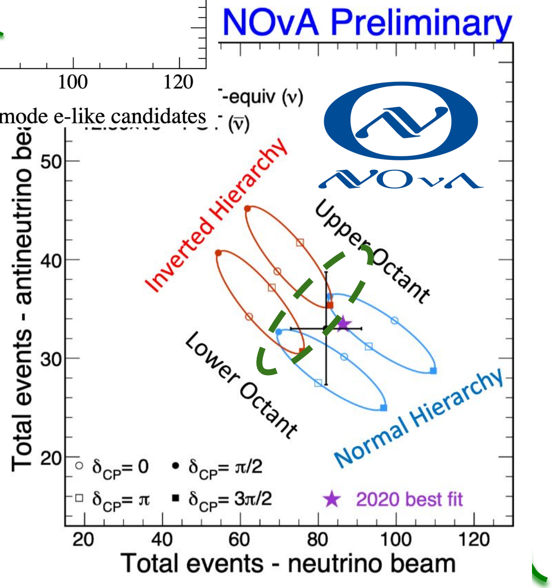

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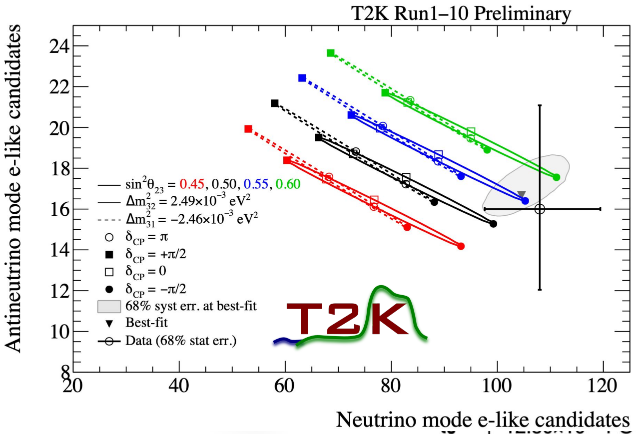
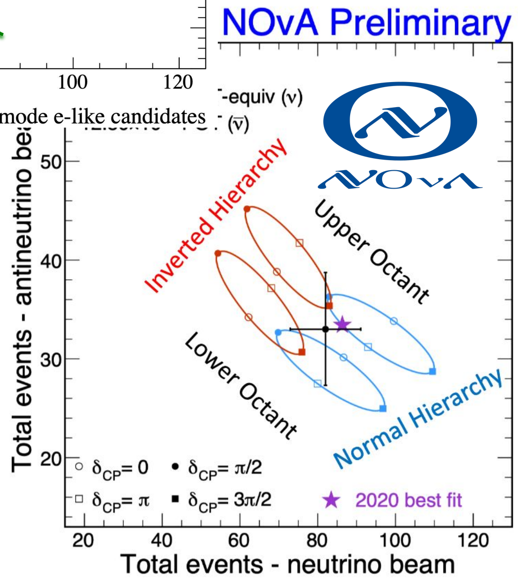
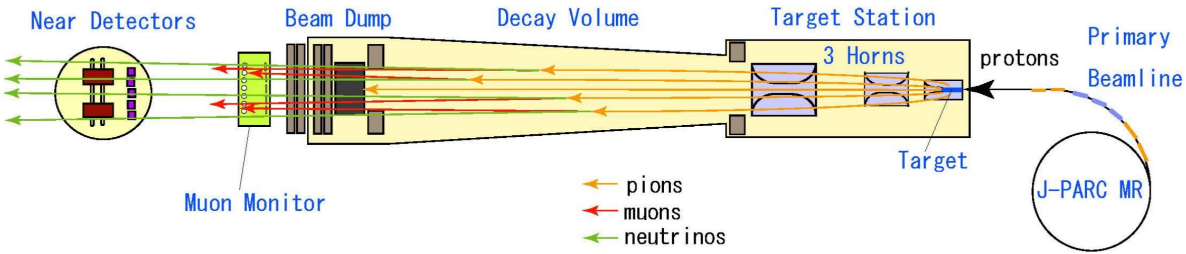
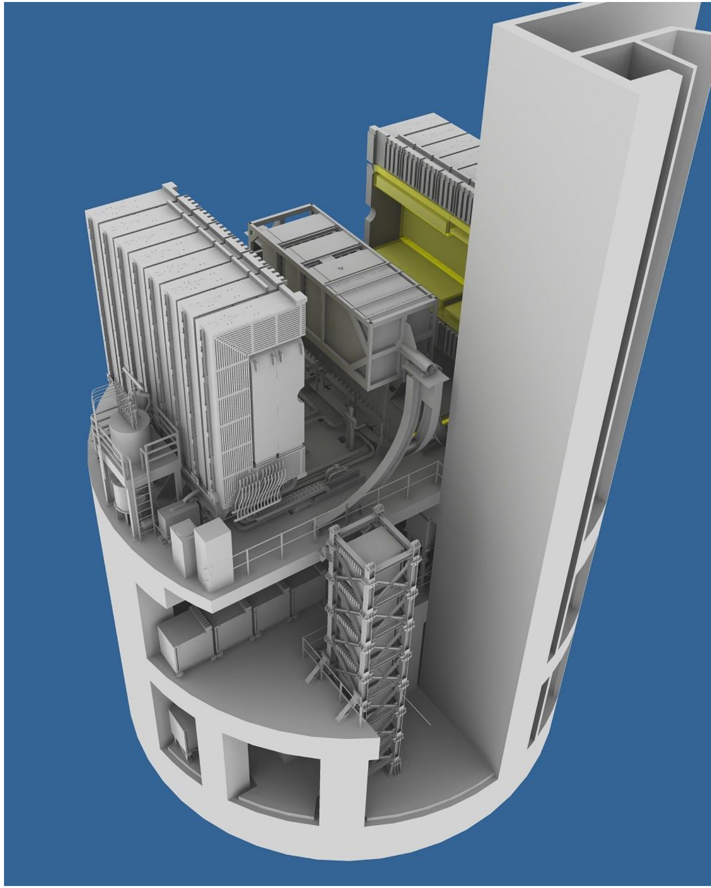




Oscillation Details

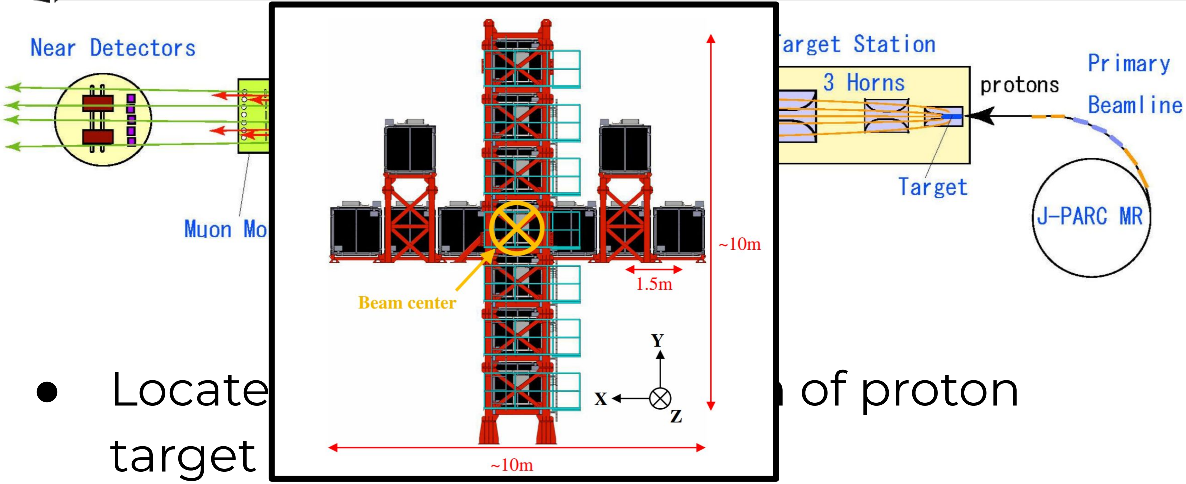
Near Detector Complex





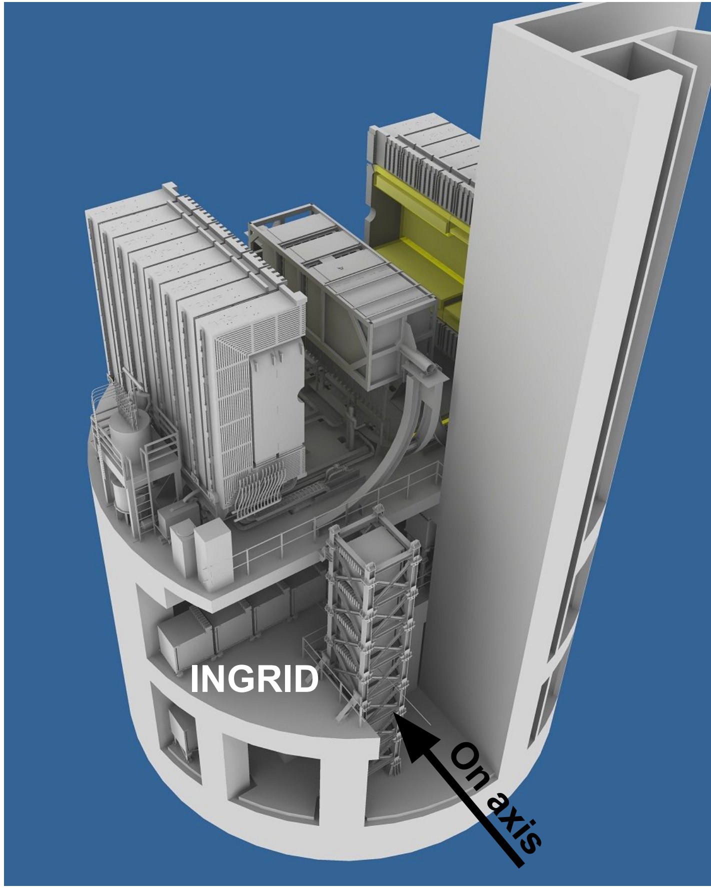
- Located 280 m downstream of proton target station.

Near Detector Complex



- Locate … of proton target

- Two used by T2K Oscillation analyses:
  - **INGRID**: On-axis, ensures beam alignment



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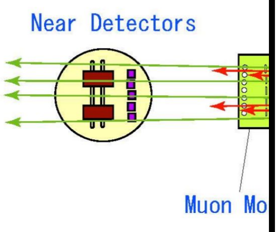

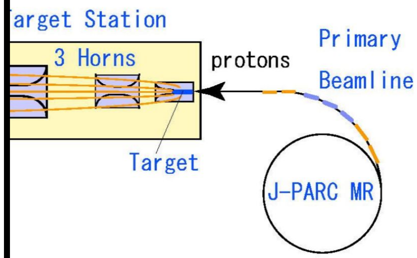

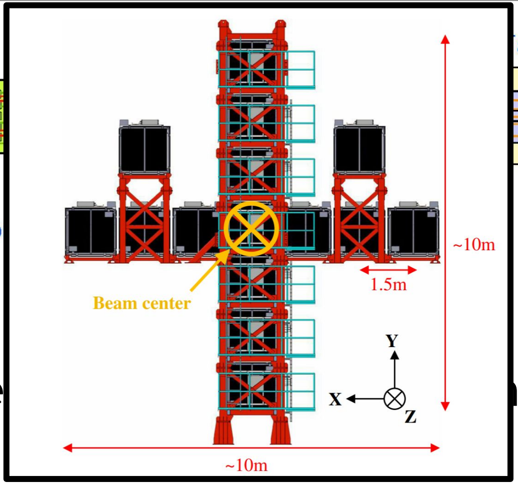

- Locate … of proton target
- Two used by T2K Oscillation analyses:
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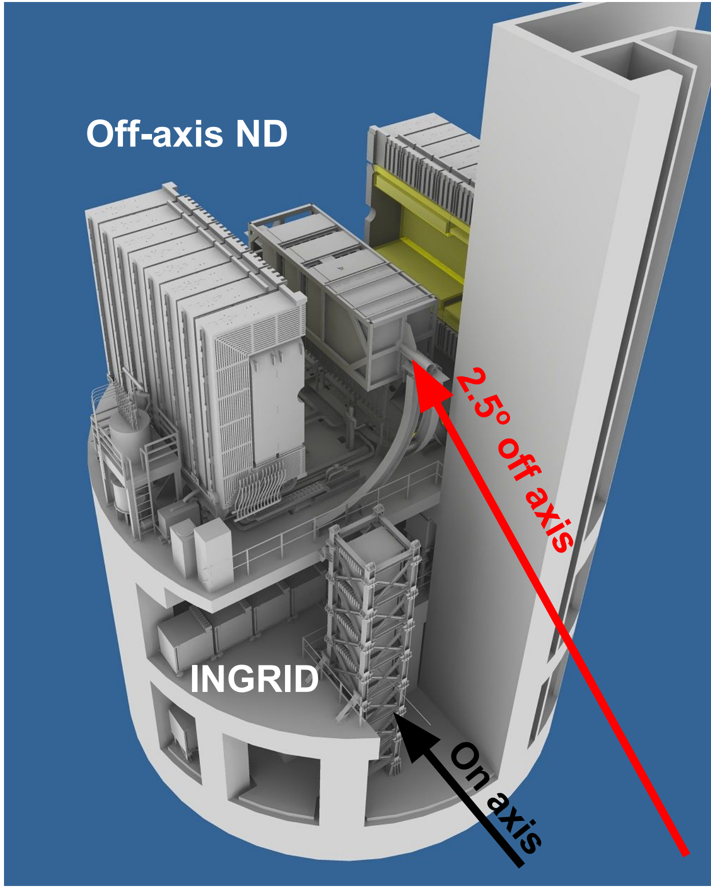
  - Off-axis near detector

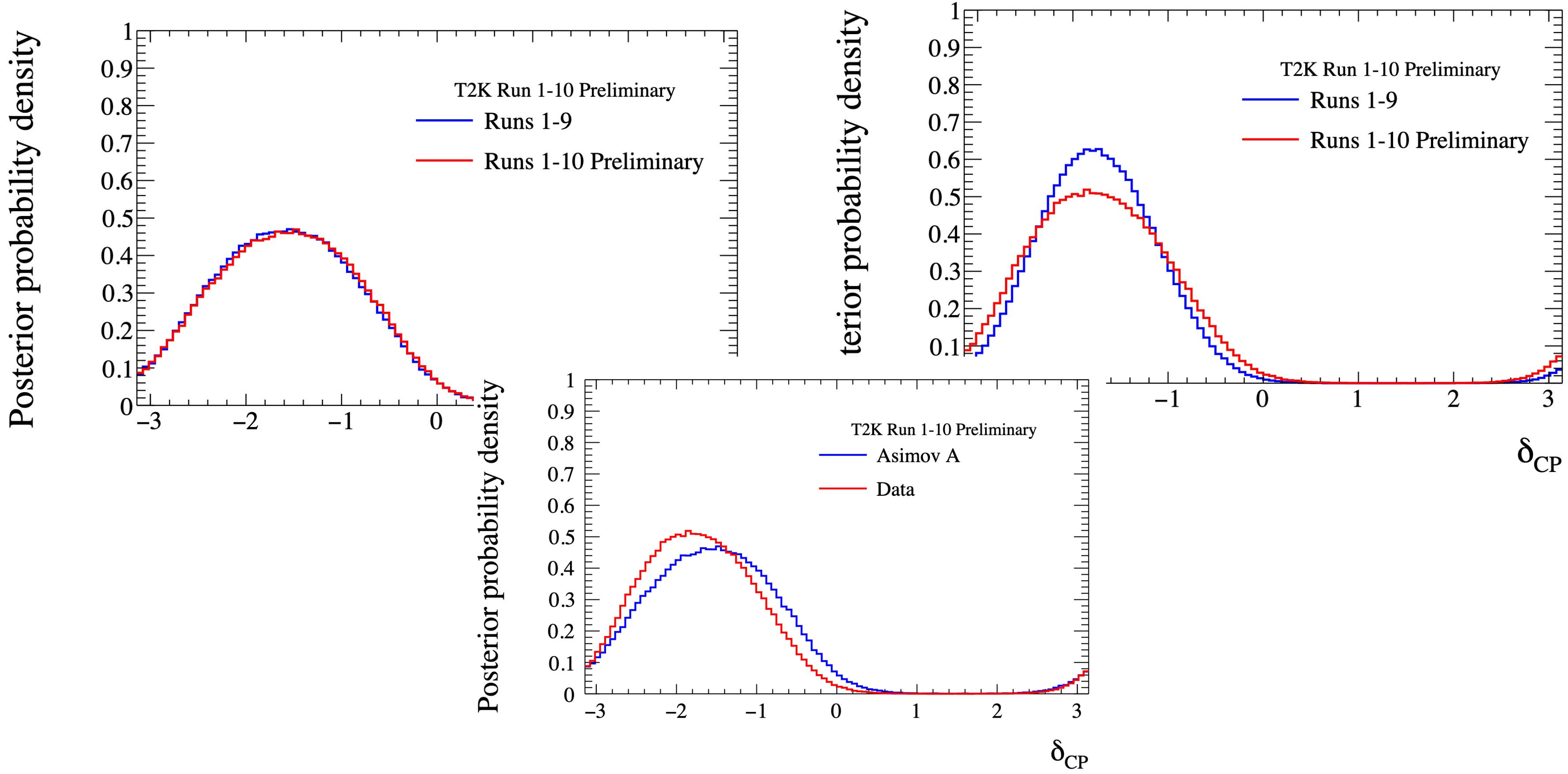


Uncerts table

Table 20: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit. To obtain error rates comparable with the "Flux+Xsec (ND constrained)" presented by MaCh3 [22], square sum the "Flux+Xsec (ND constr)", "$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$", "NC γ".

Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
$\mathrm{BG}_A^{\mathrm{RES}}$ low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Expected Sensitivity



T2K-NOvA Complementarity

- Complementary sensitivities from both experiments:
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- Joint fit with access to full likelihood allows for:
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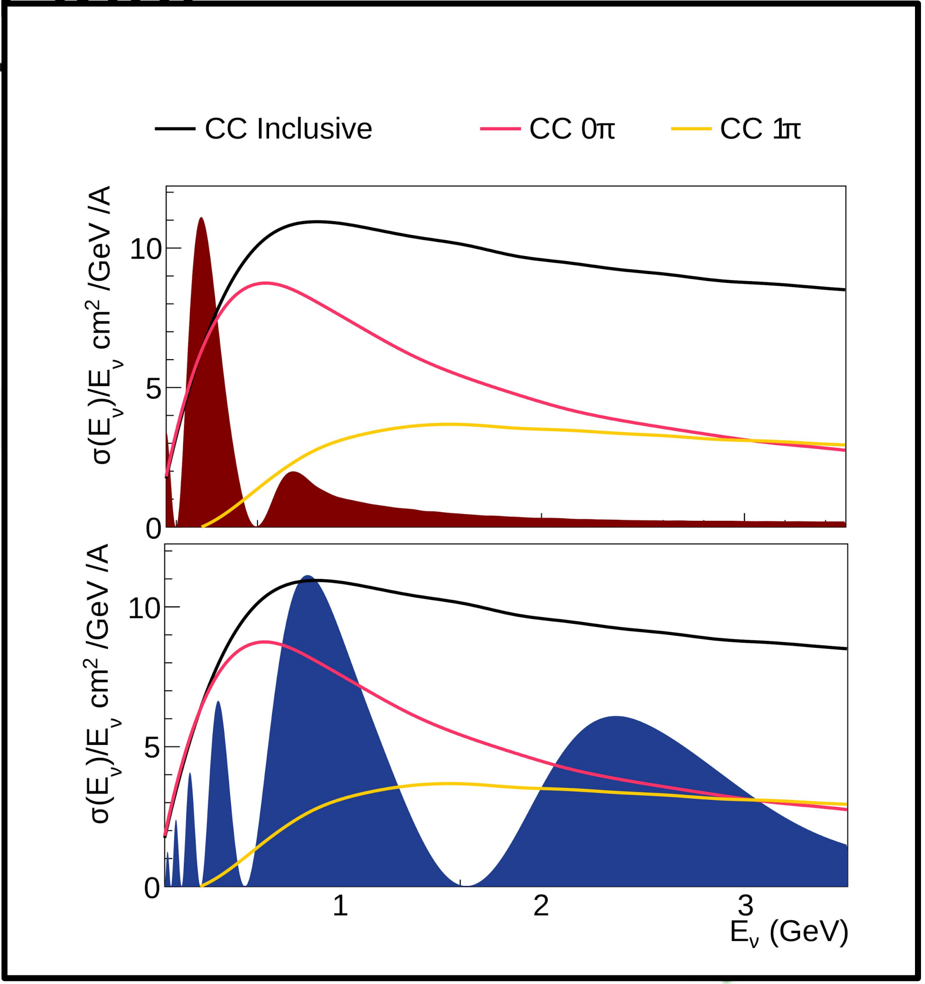
- Studies of which systematic parameters should be correlated are underway!



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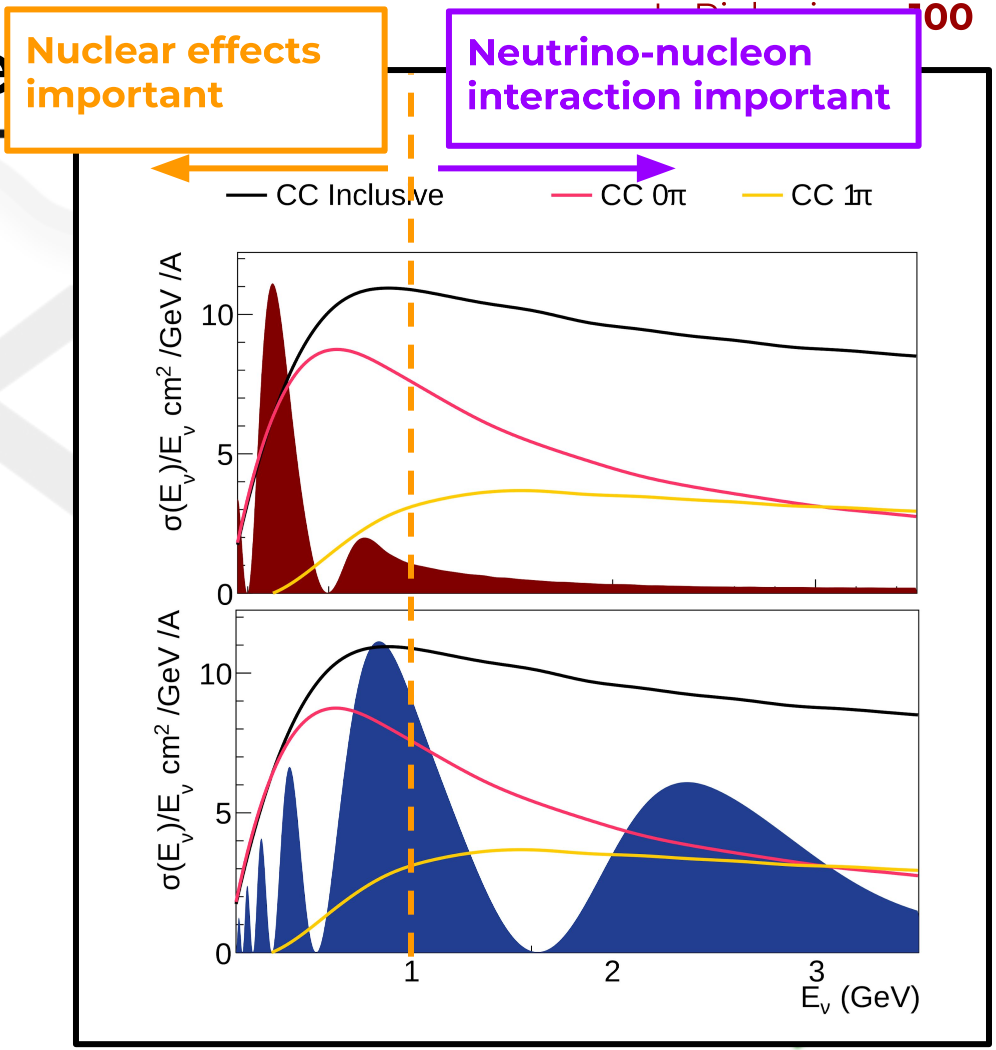


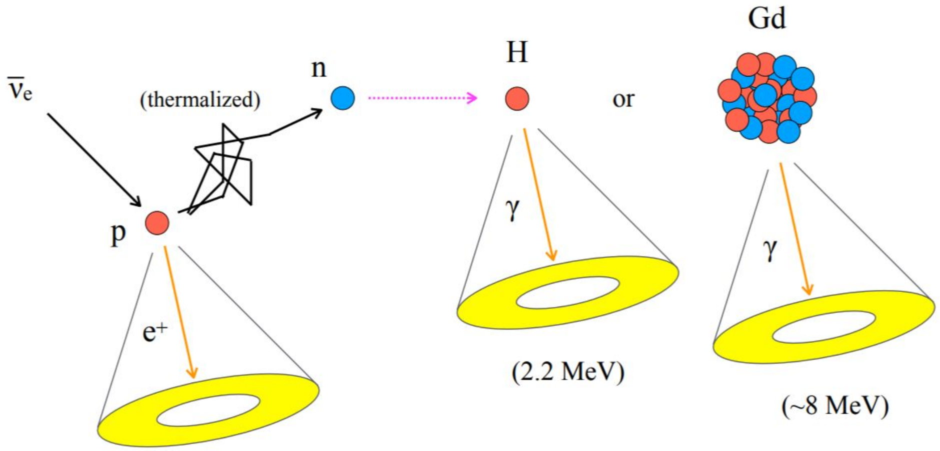
MICHIGAN STATE UNIVERSITY

T2K-NOvA

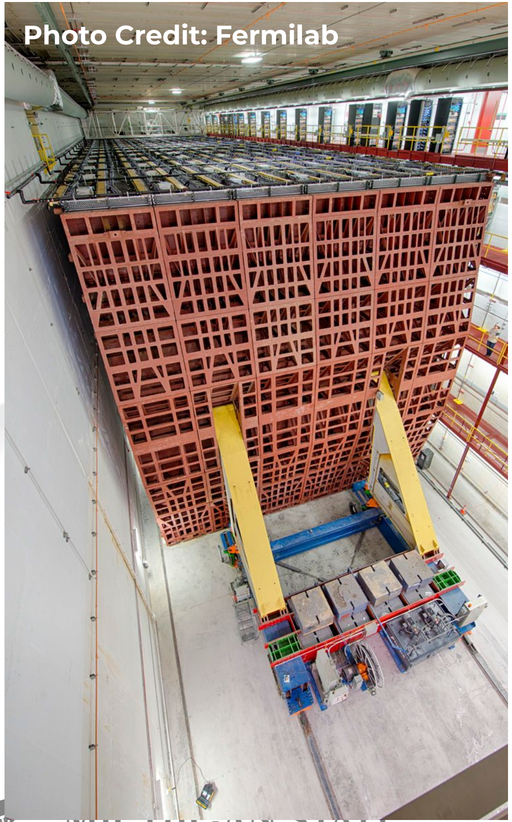
- Joint analysis workshops on-going:
  - Four successful meetings since 2017 J-PARC and FNAL
  - Strong US-Japan support!
- Challenging joint analysis:
  - Different experimental setups
  - Different peak energy
  - Different analysis methodology
- But T2K-NOvA sensitivity is worth the challenge!

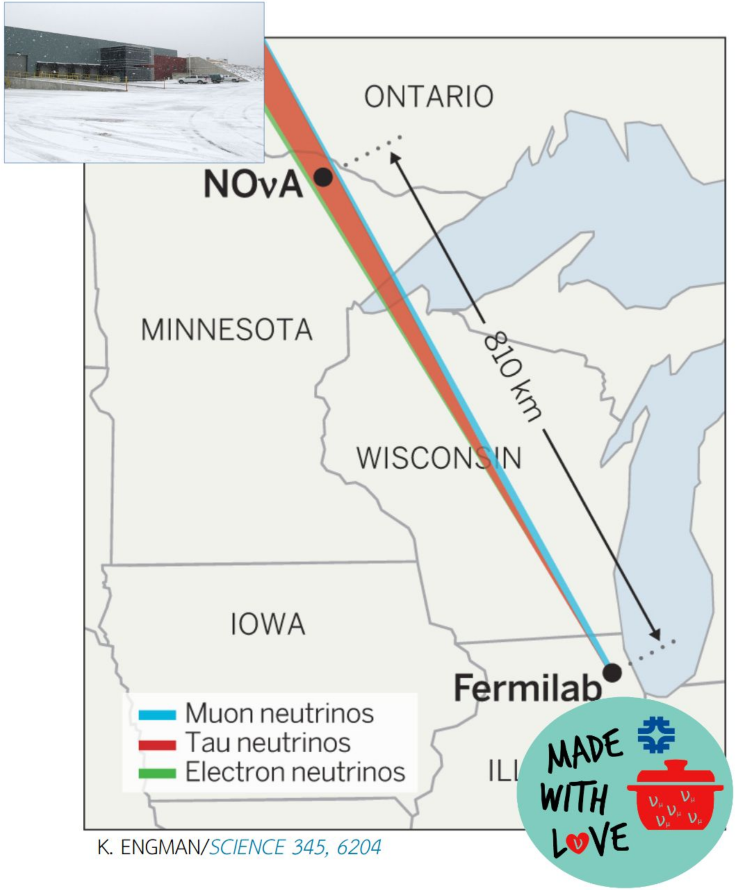
SK-Gd

- Super-K deep cleaned in preparation for Gadolinium doping.
  - Gd loading is underway!
- Much improved efficiency for neutron capture:
  - Statistical separation of neutrino/antineutrino rate
- Extra constraint on 'wrong sign' backgrounds at the far detector

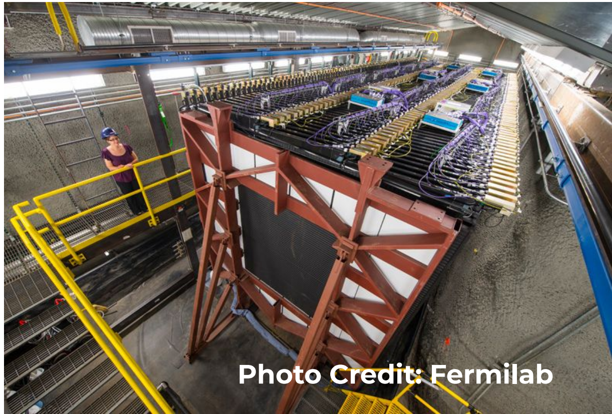


The NOvA Experiment





K. ENGMAN/*SCIENCE 345, 6204*



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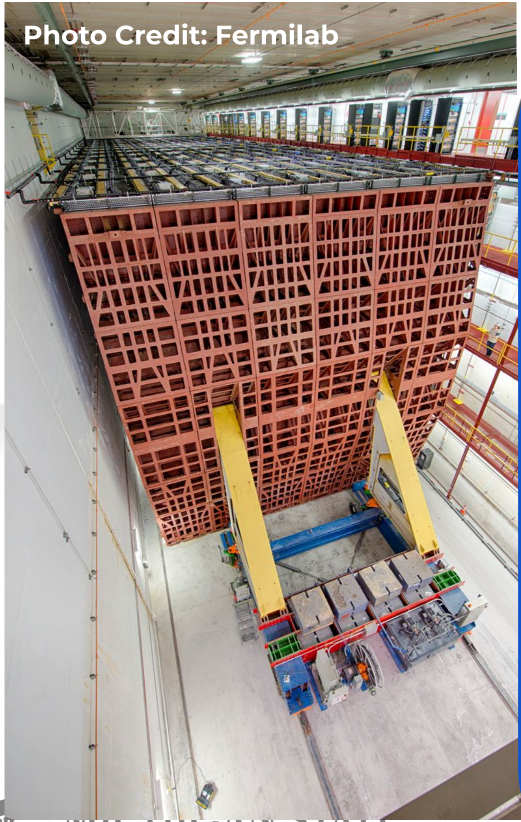
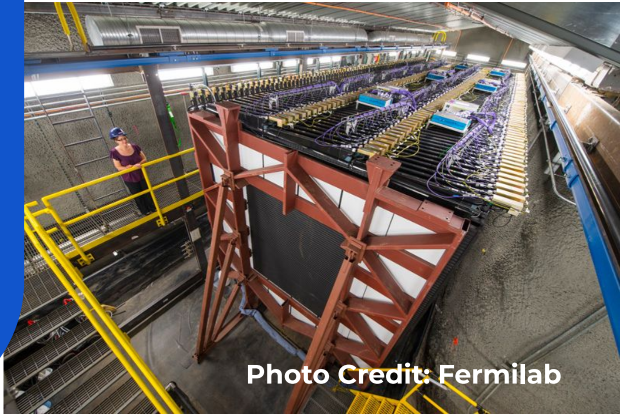


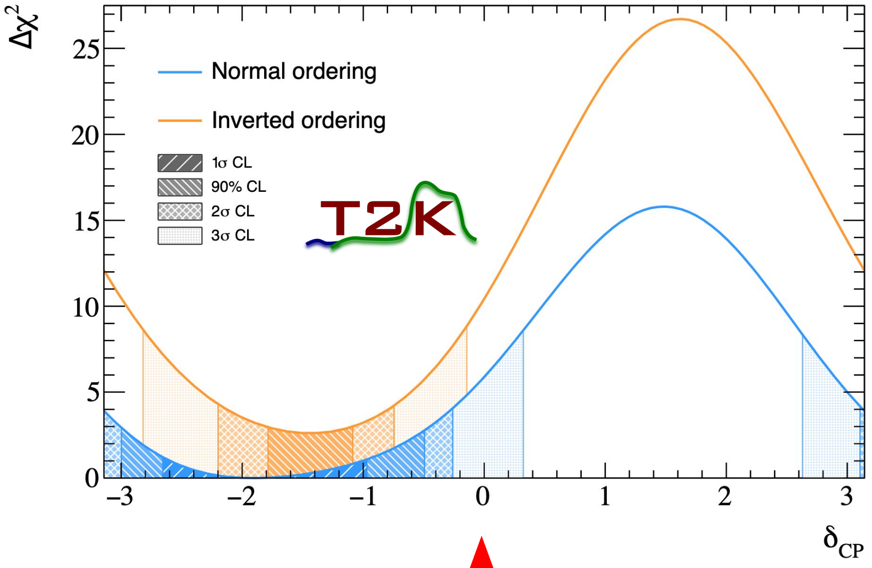
NOvA Far Detector

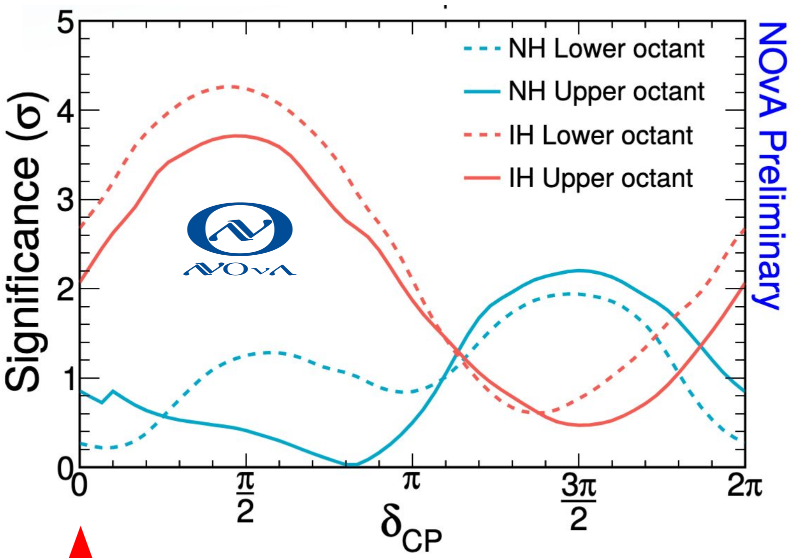
Fiducial Mass:	14 kT
Material:	Liquid scintillator
Detection technique:	Scintillation
Baseline:	810 km
Peak neutrino energy:	1.9 GeV
Location:	Ash River, MN



T2K and NOvA

A. Himmel, Neutrino2020





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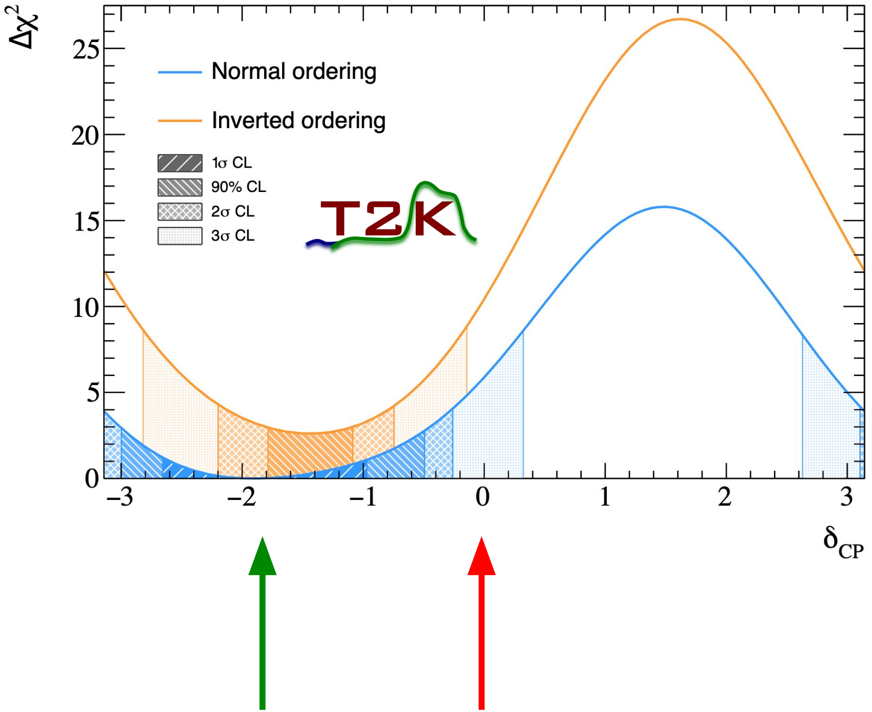
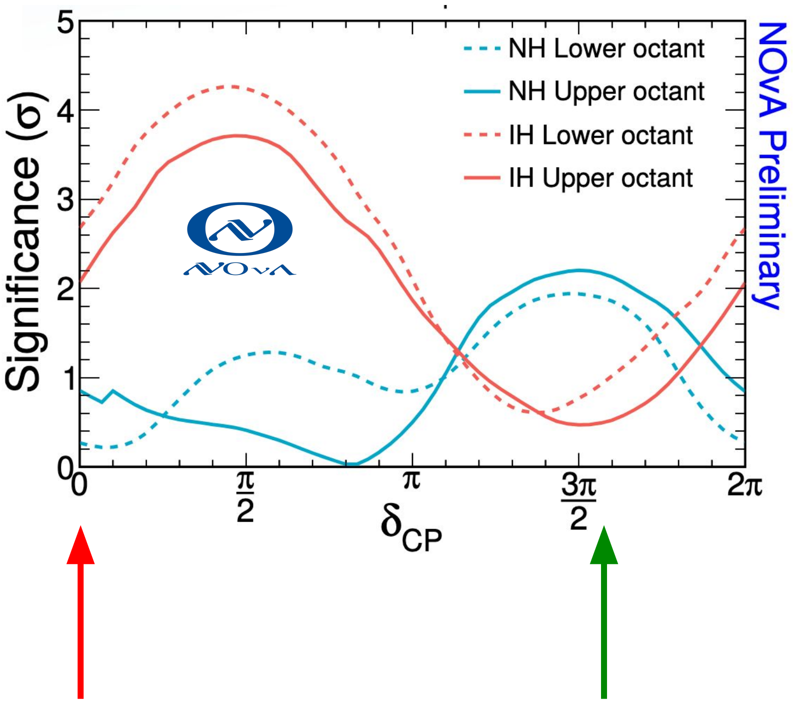
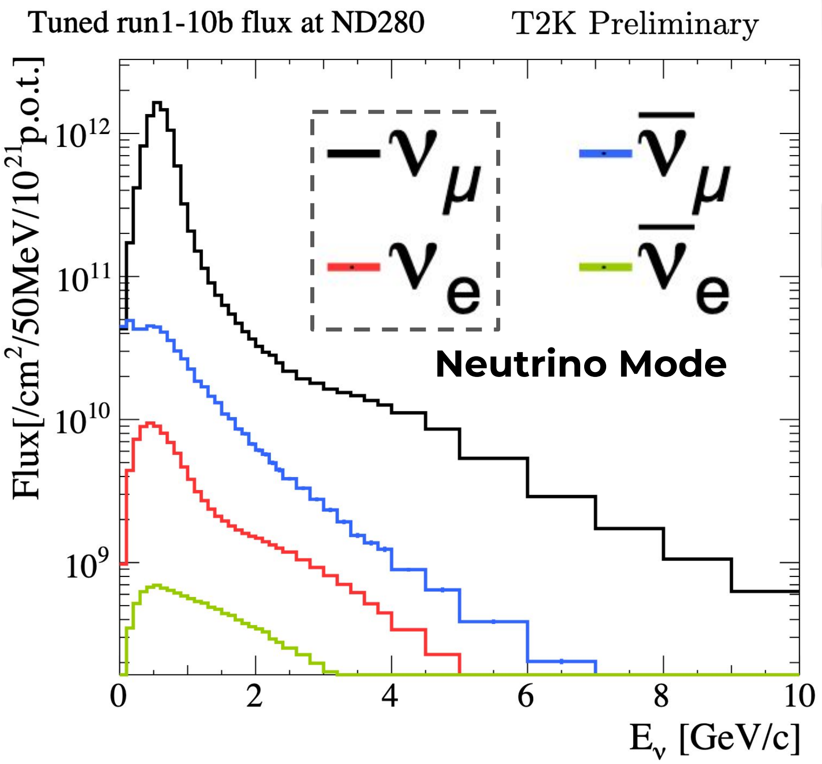
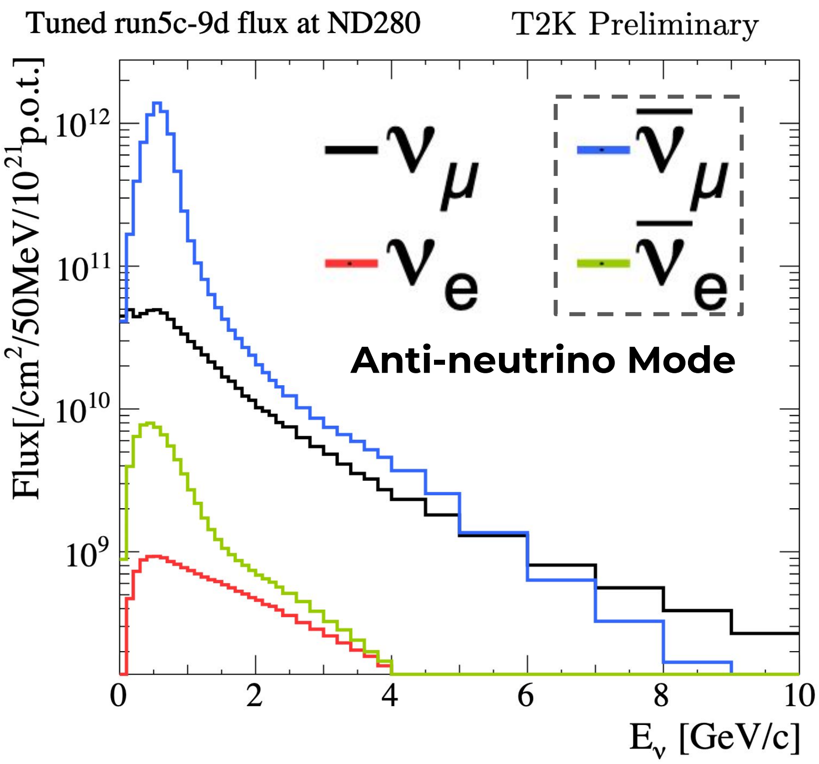




Flux Uncertainties

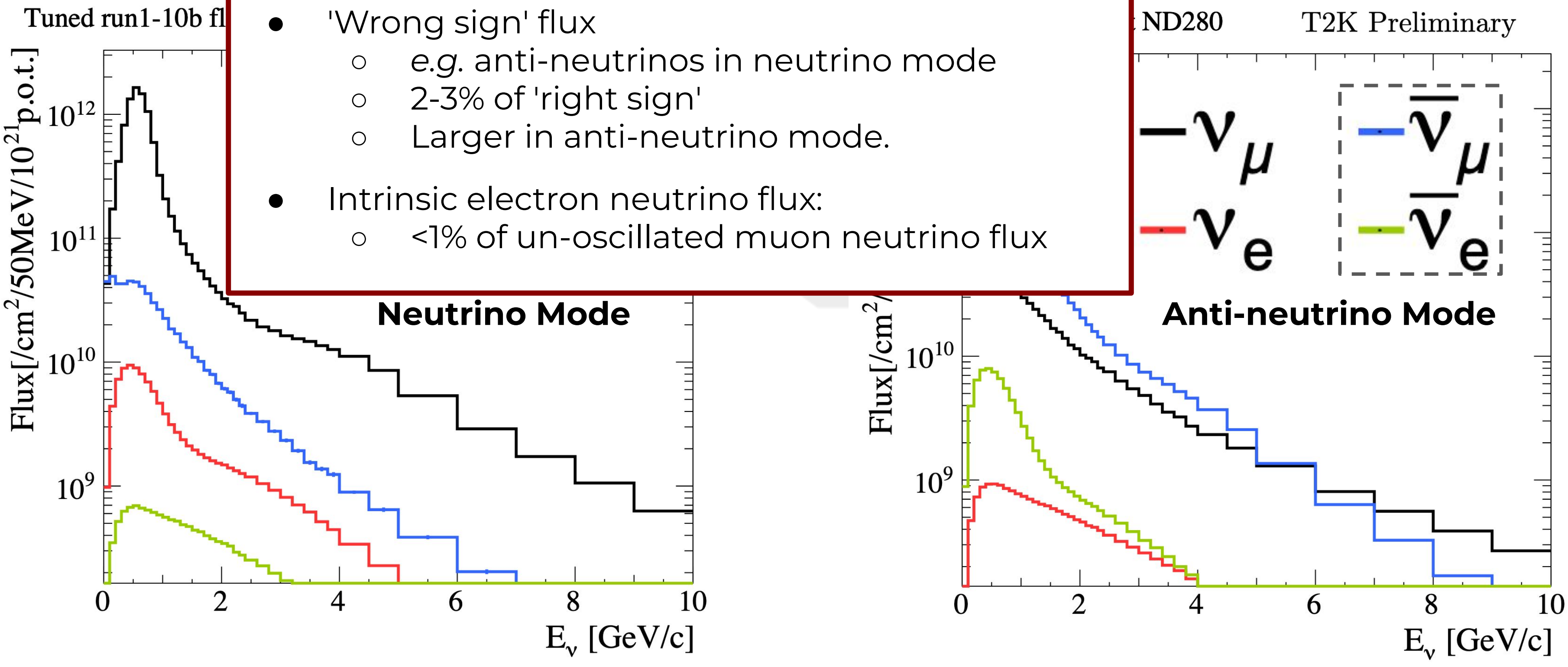
J-PARC Beam: Neutrino Species

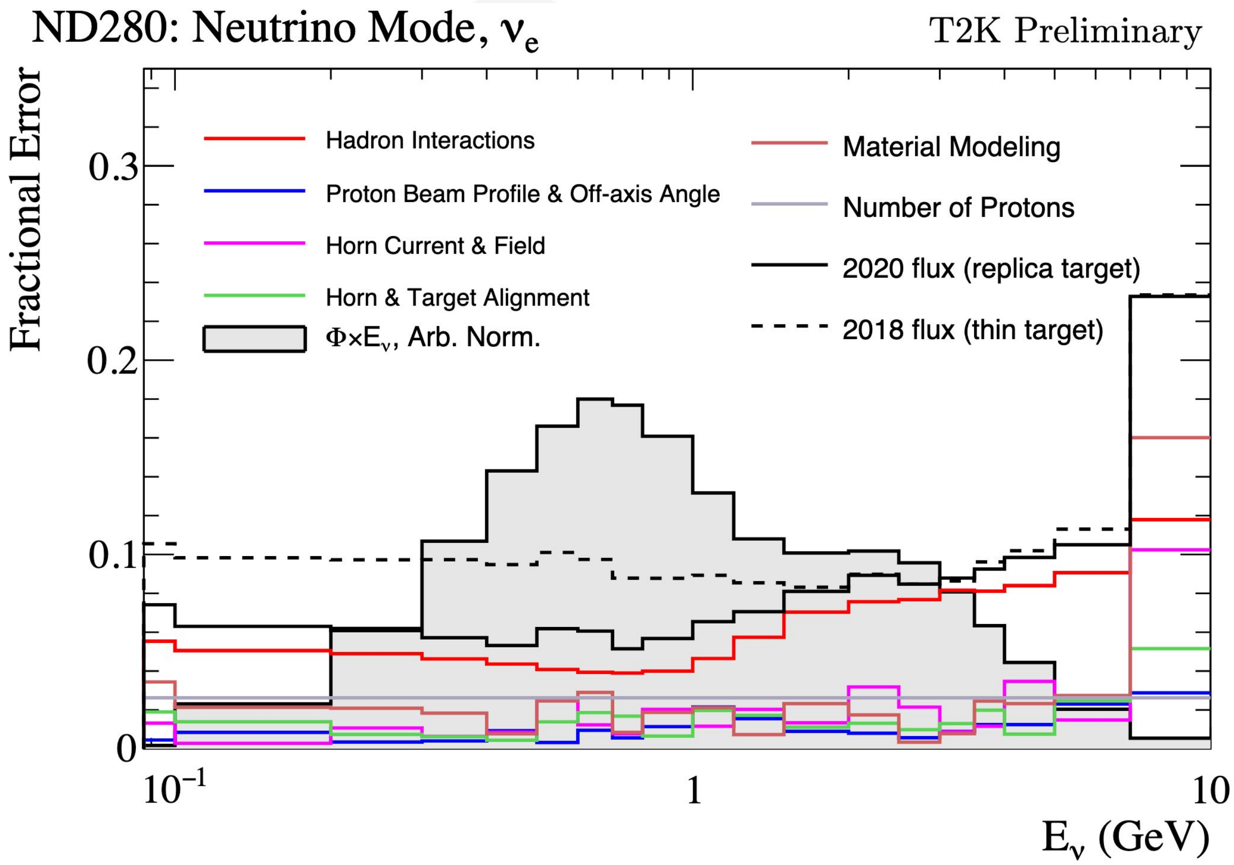


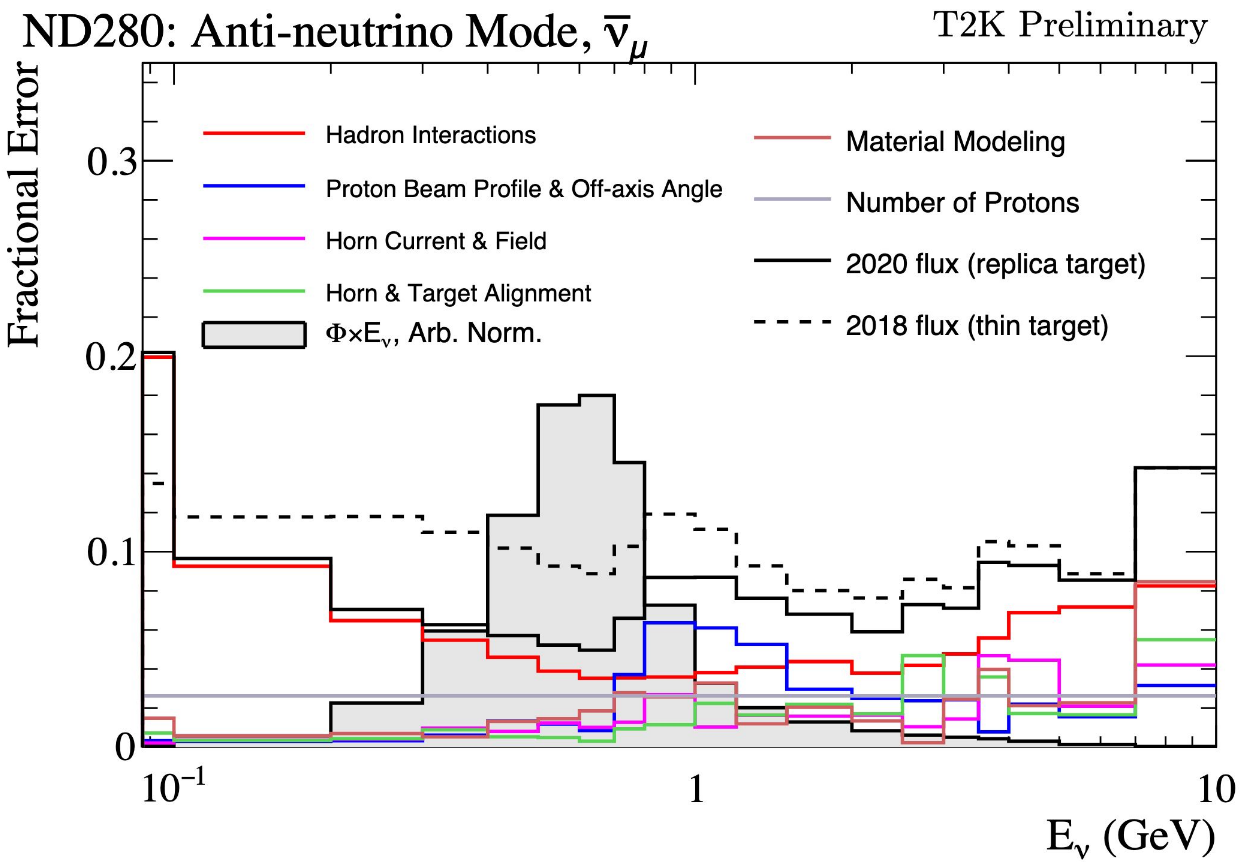


J-PARC Beam: Neutrino Species

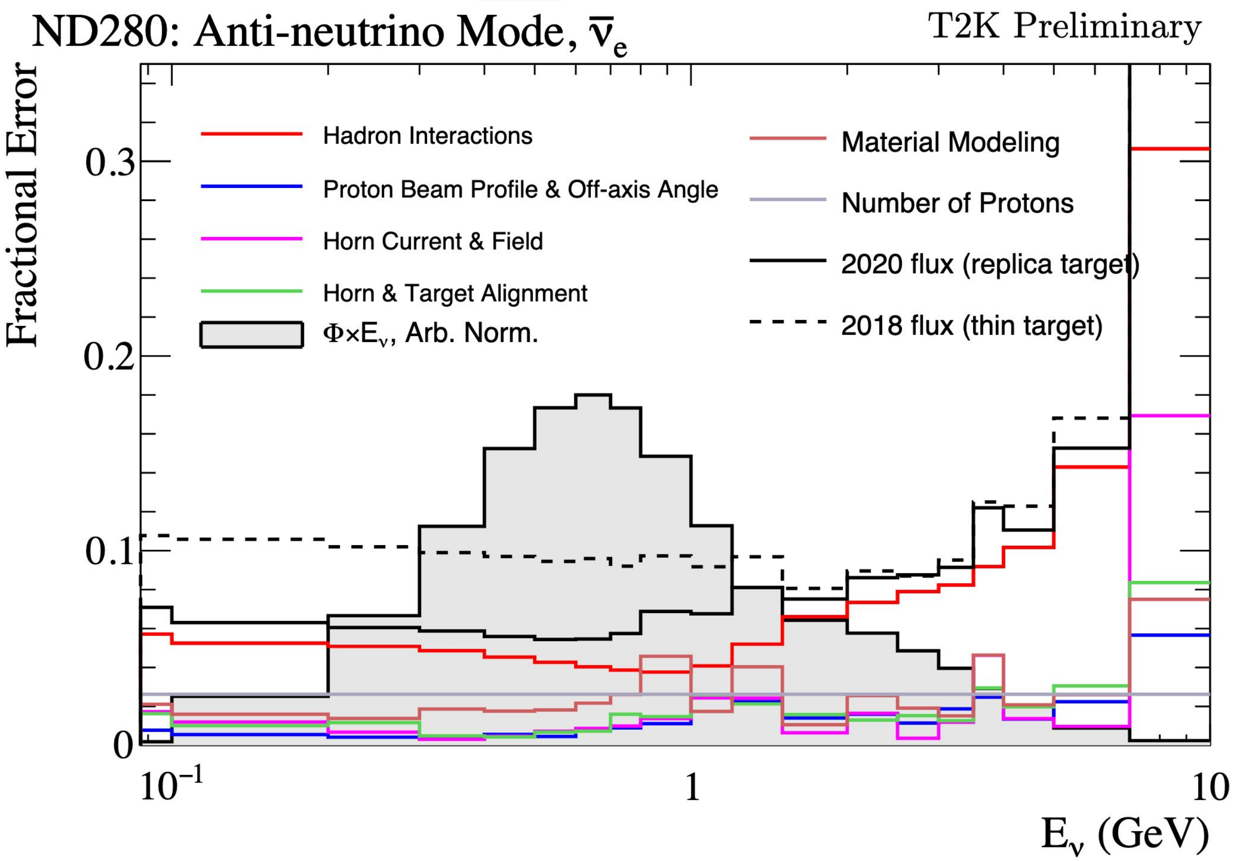
- 'Wrong sign' flux
  - *e.g.* anti-neutrinos in neutrino mode
  - 2-3% of 'right sign'
  - Larger in anti-neutrino mode.
- Intrinsic electron neutrino flux:
  - <1% of un-oscillated muon neutrino flux




ND280: Neutrino Mode, ν_e
T2K Preliminary
Fractional Error
0.3
0.2
0.1
0
Hadron Interactions
Proton Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
2020 flux (replica target)
2018 flux (thin target)
10^{-1}
1
10
E_ν (GeV)



ND280: Anti-neutrino Mode, $\bar{\nu}_\mu$
T2K Preliminary
Fractional Error
0.3
0.2
0.1
0
10^{-1}
1
10
E_ν (GeV)
Hadron Interactions
Proton Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
2020 flux (replica target)
2018 flux (thin target)



ND280: Anti-neutrino Mode, $\bar{\nu}_e$
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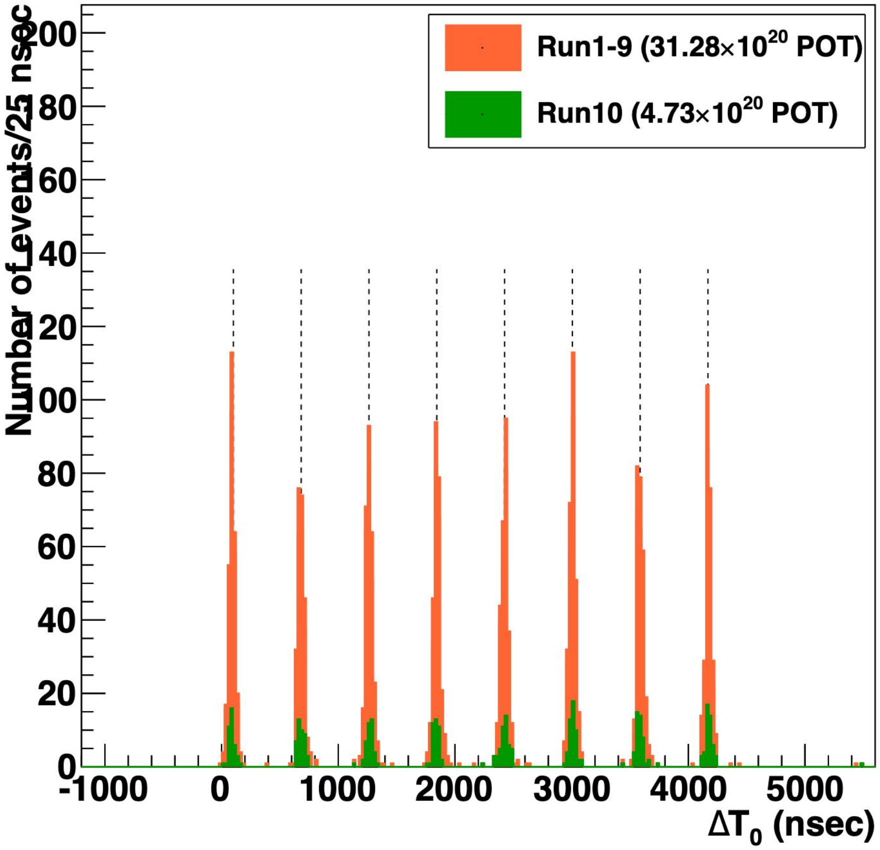
Material Modeling
Number of Protons
2020 flux (replica target)
2018 flux (thin target)
10^{-1}
1
10
E_ν (GeV)

SK Details

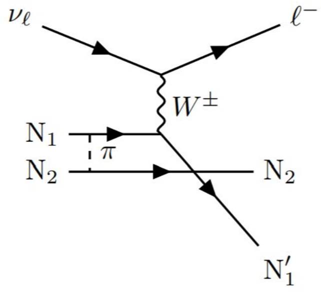
Beam Bunch Timing at SK



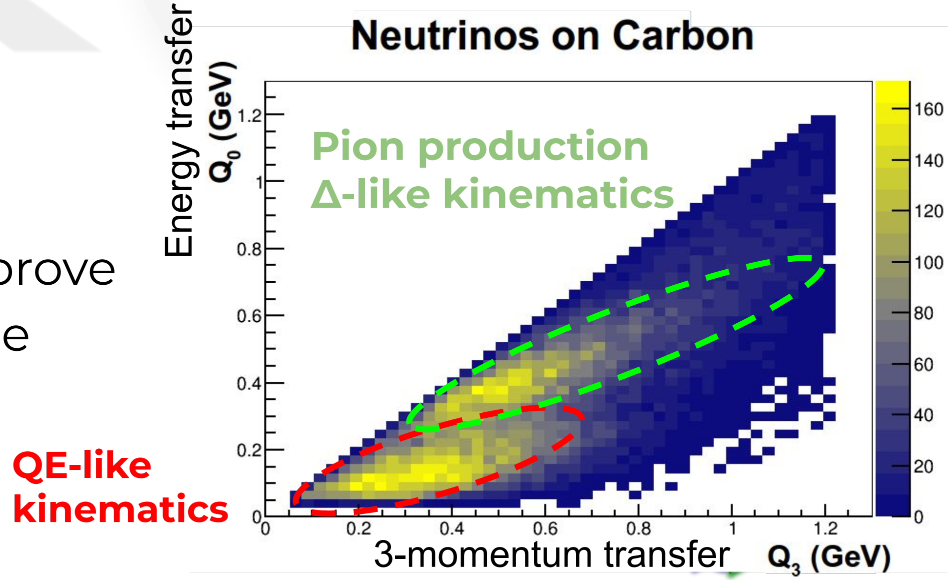
Neutrino–Matter Interactions

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.

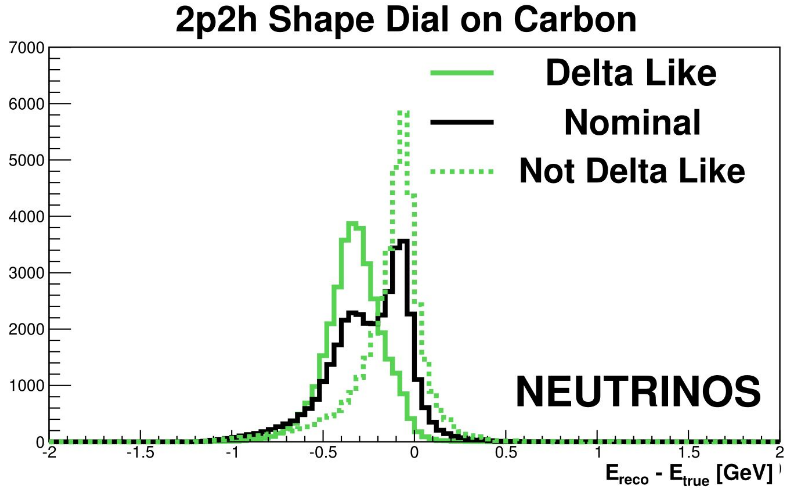


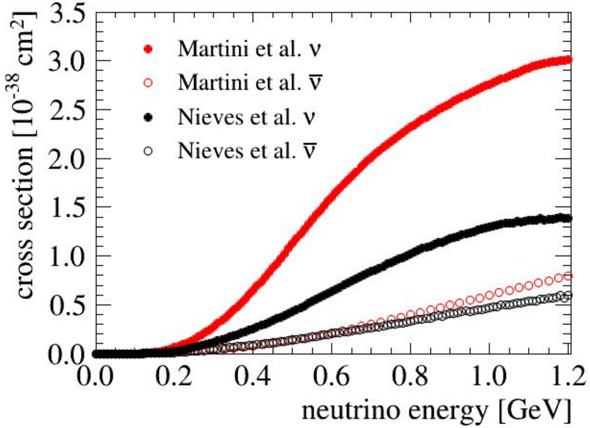
Example of Multi-nucleon interaction (2p2h/NN)



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.

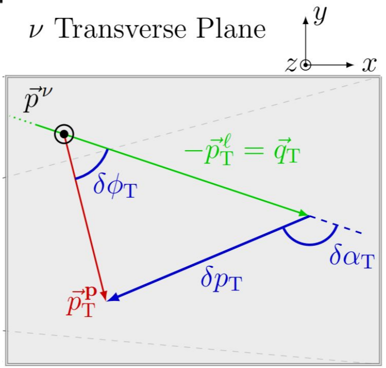




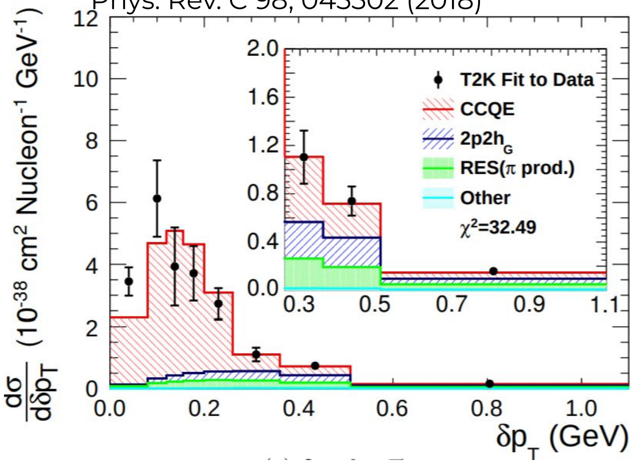
Near detector fit prefers between nominal and Δ-like

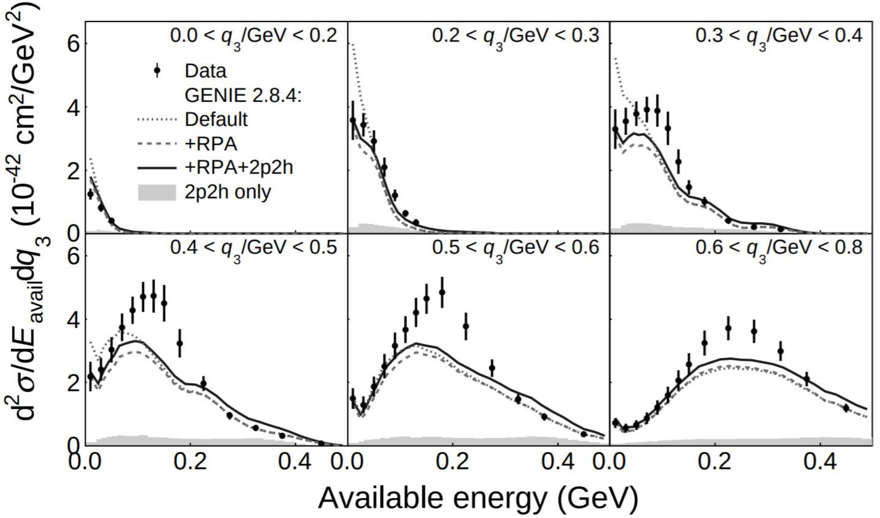
Lepton-Hadron Correlations

- 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.



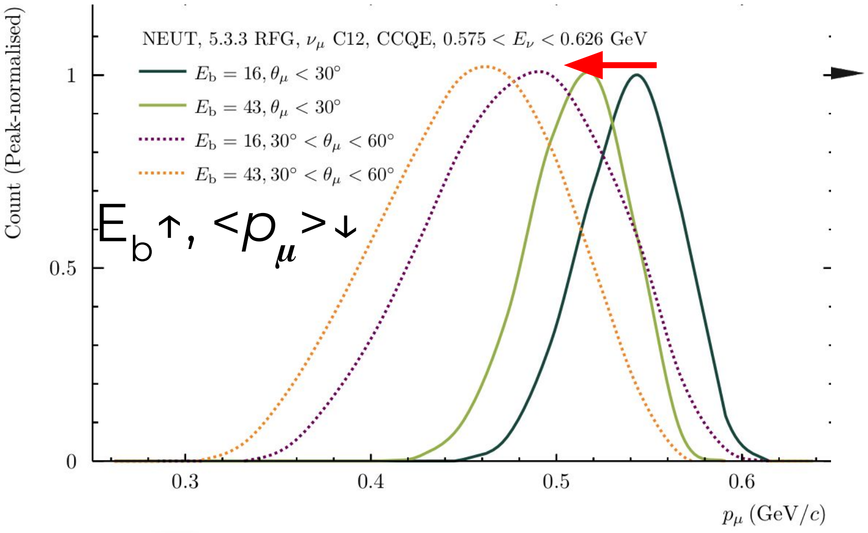
Phys. Rev. C 98, 045502 (2018)

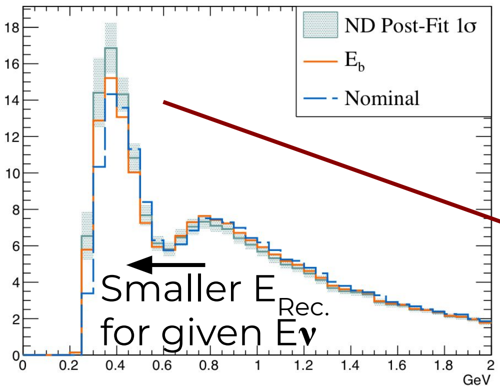


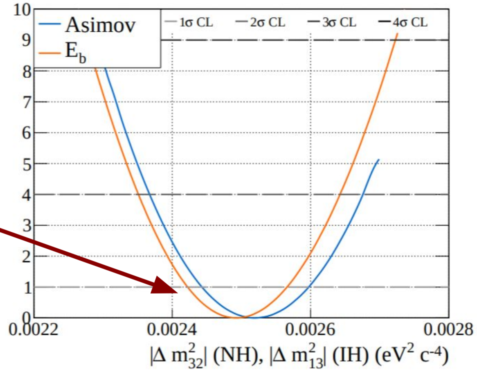


Binding Energy

- 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