

Why theory is important to the neutrino oscillation program

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Disclaimers

I am an experimentalist on T2K and DUNE. Please interrupt if I need to clarify any terminology.

The following is my personal view— not the views of either collaboration.

The examples are insightful snapshots and are not a comprehensive review of a vibrant field. My intent is to illustrate what has been successful or difficult over the last decade.

Current:

Atmospheric: Super-Kamiokande, IceCube

Accelerator: T2K, NOvA,
Short-Baseline Neutrino
Program (SBN)

Future:

Accelerator/Atmospheric:
Hyper-Kamiokande, Deep
Underground Neutrino
Experiment

Current program is broad.

Neutrino oscillation, exotica (e.g. sterile neutrino, dark matter searches), proton decay

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions for **atmospheric and accelerator based programs**

Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|, \Delta m^2_{21}$
- CP violating phase (CPV)

Neutrino oscillation open questions

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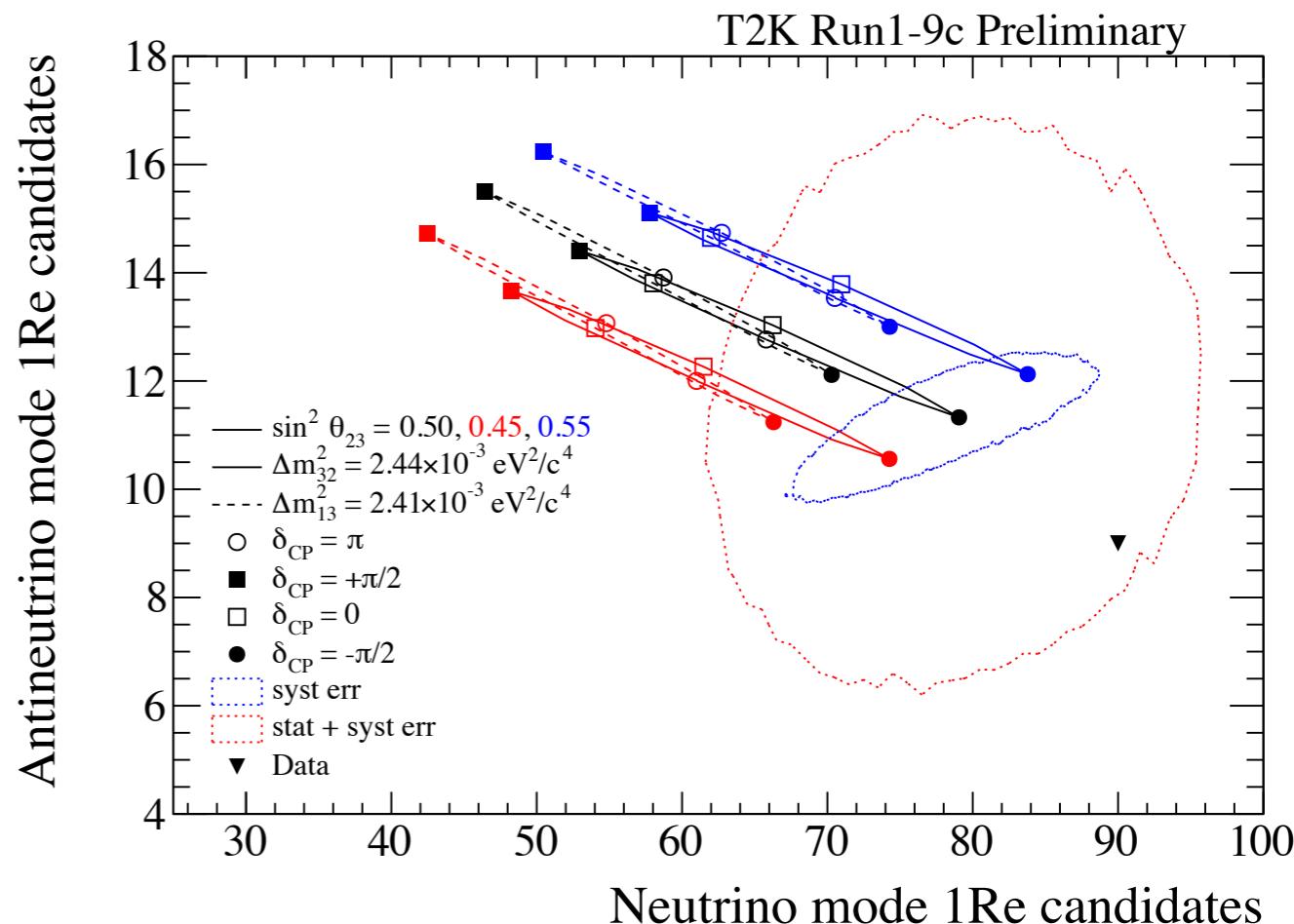
- Amplitude determined by mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$ *Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)*
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|, \Delta m^2_{21}$ *What is the ordering of the masses ($\Delta m^2_{32/31} > 0$)*
- CP violating phase (CPV) *Is there CPV in neutrinos?*

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ν_e and $\bar{\nu}_e$ appearance channel



SAMPLE	PREDICTED			
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$
ν_e appearance	73.8	61.6	50.0	62.2
$\bar{\nu}_e$ appearance	11.8	13.4	14.9	13.2

T2K Run 1-9c
preliminary

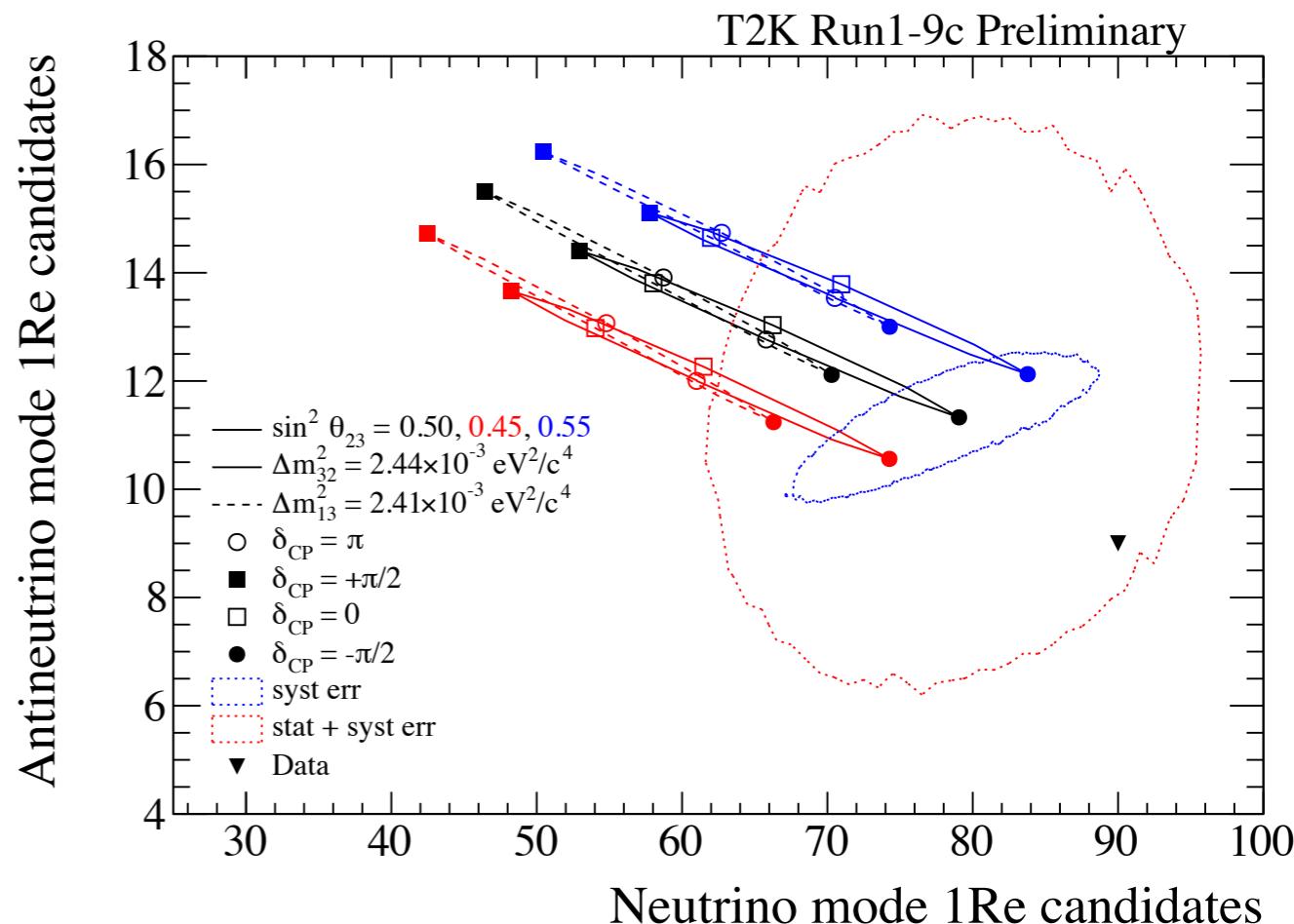
Changing δ_{CP} increases ν_e and decreases $\bar{\nu}_e$ appearance rates

Neutrino oscillation open questions

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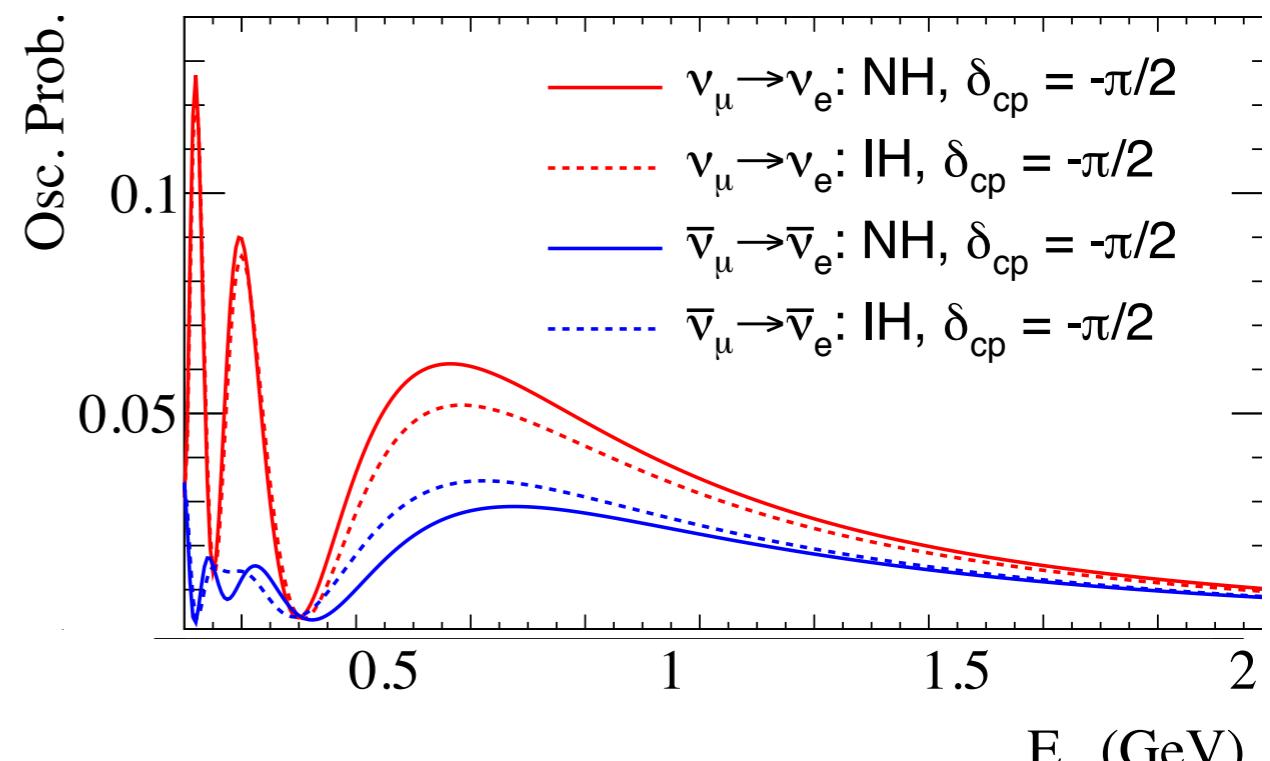
For increasing θ_{23} enhance both ν_e and $\bar{\nu}_e$ appearance

Neutrino oscillation open questions

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Normal to inverted hierarchy suppresses ν_e appearance, enhances $\bar{\nu}_e$ appearance

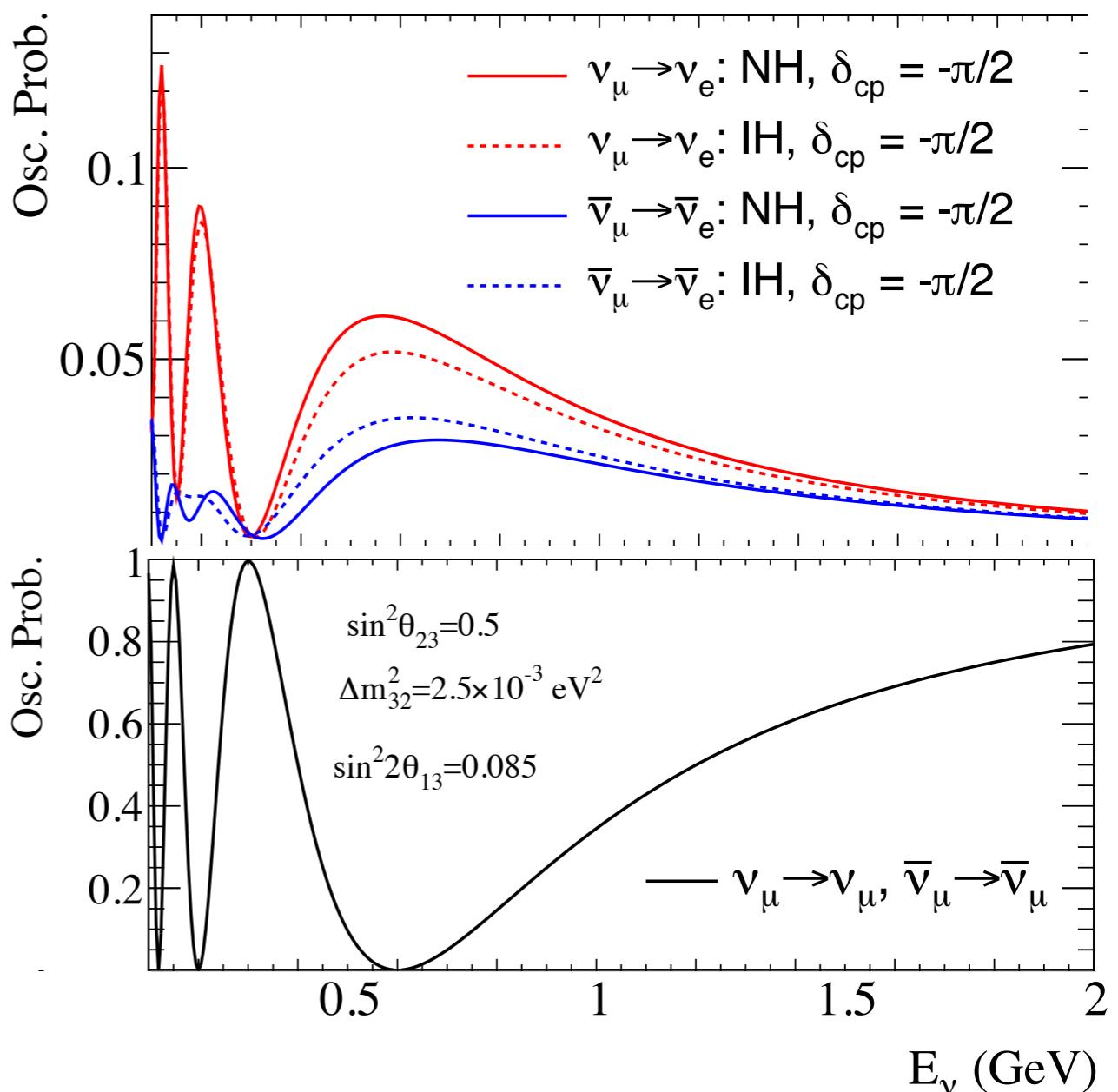
Neutrino oscillation open questions

Oscillation depends on:

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Largely independent of δ_{CP} effects

ν_μ and $\bar{\nu}_\mu$ disappearance channel



Differences between ν_μ and $\bar{\nu}_\mu$ disappearance would indicate CPT violation

Neutrino oscillation open questions

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$$N_{FD}^{\alpha \rightarrow \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Event rate used to infer oscillation physics

Oscillation analysis depends on interaction model

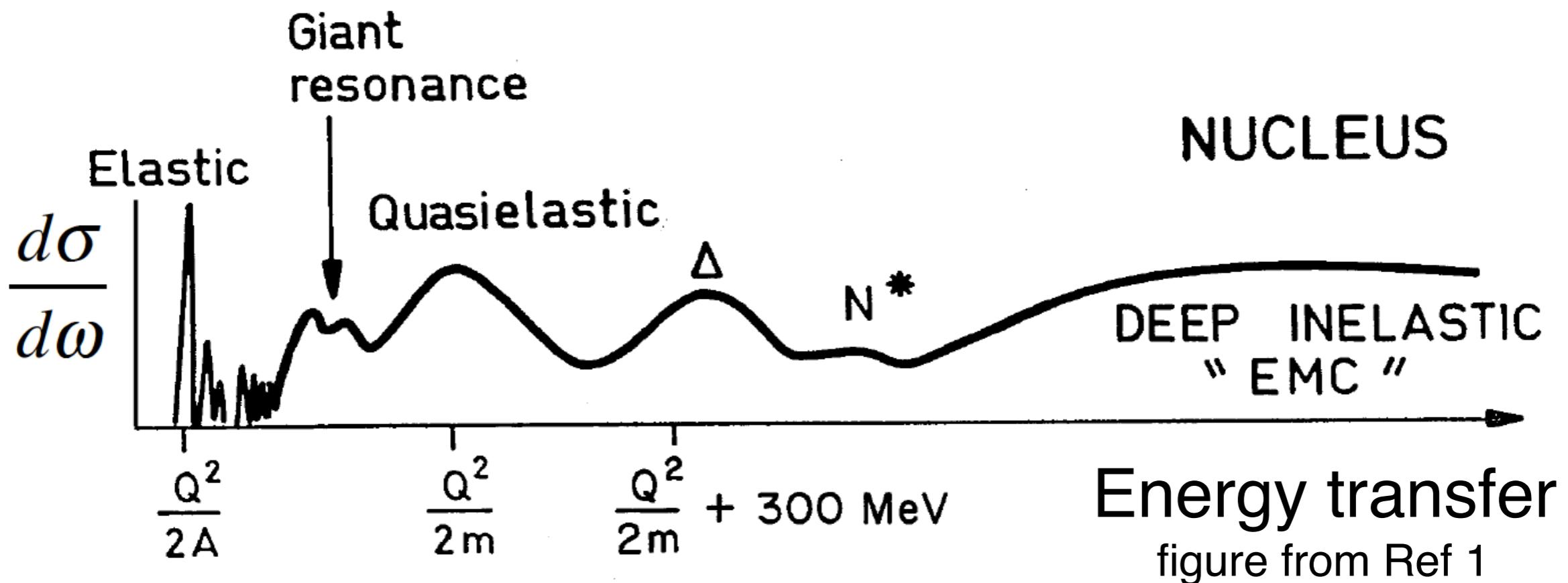
Cross section (true kinematics)

Efficiency (true kinematics)

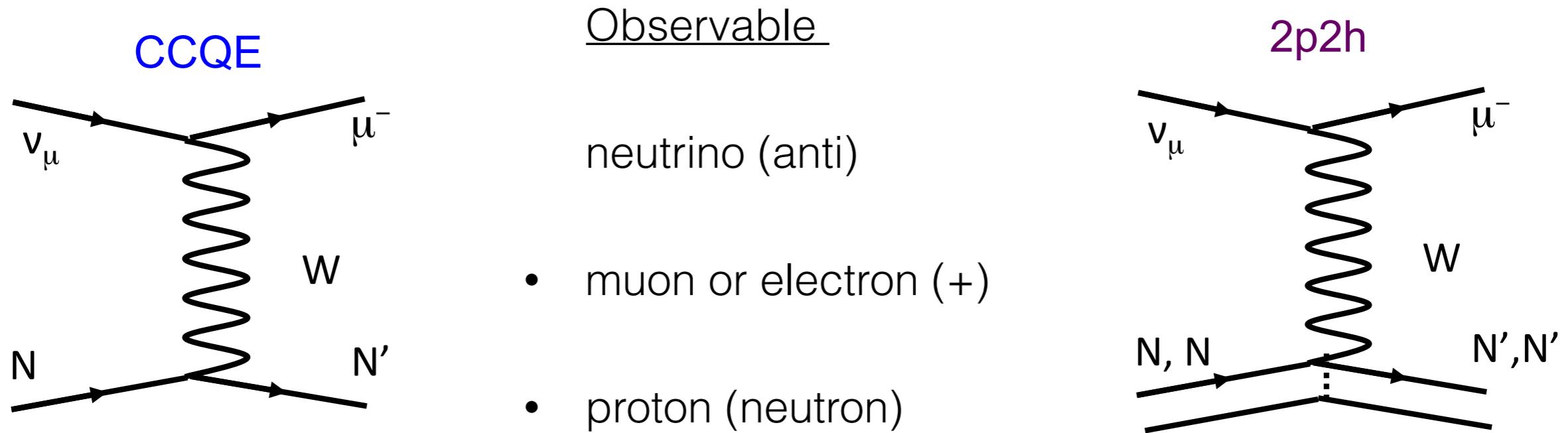
Relationship between true and reconstructed kinematics)

$$N_{FD}^{\alpha \rightarrow \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

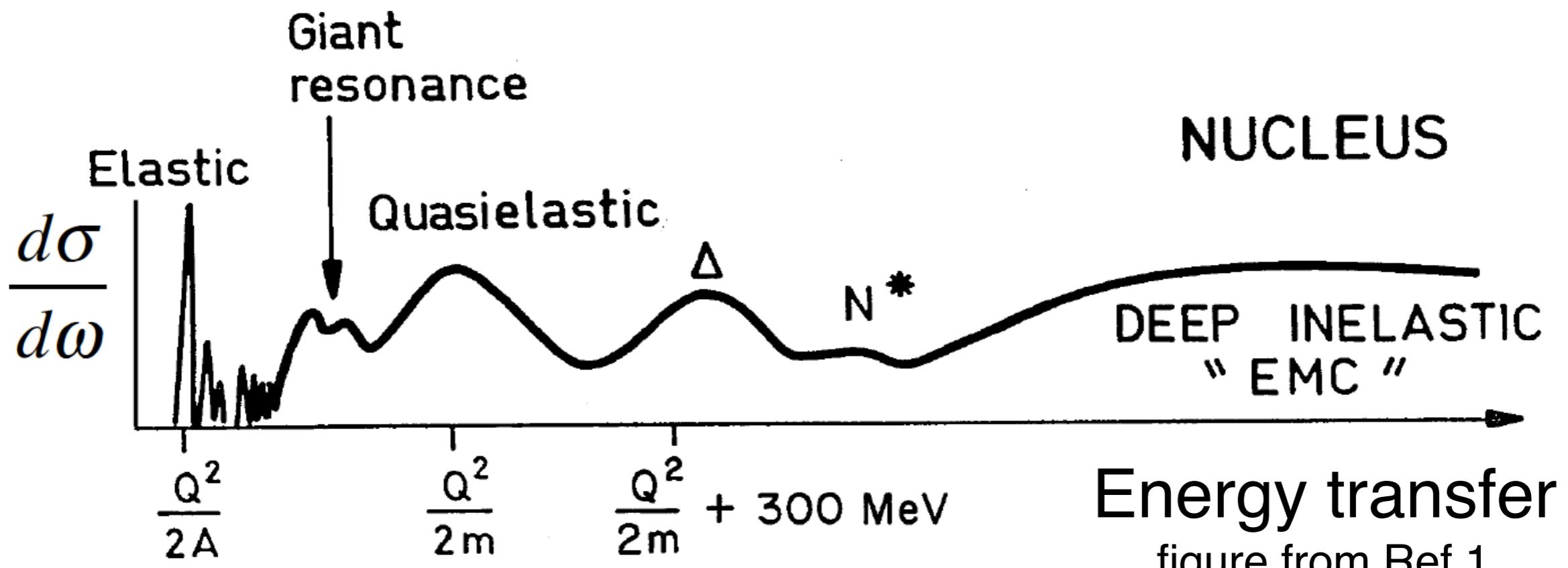
Processes in Neutrino Scattering



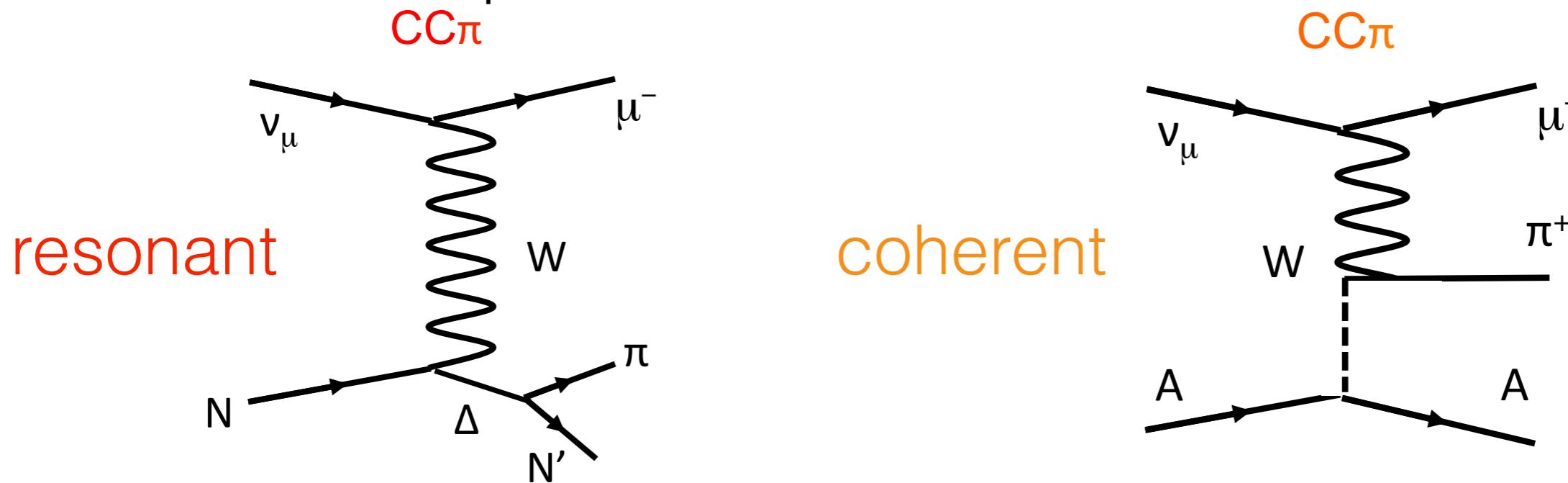
- Charged Current Quasi Elastic (CCQE) and multinucleon processes (2p2h)



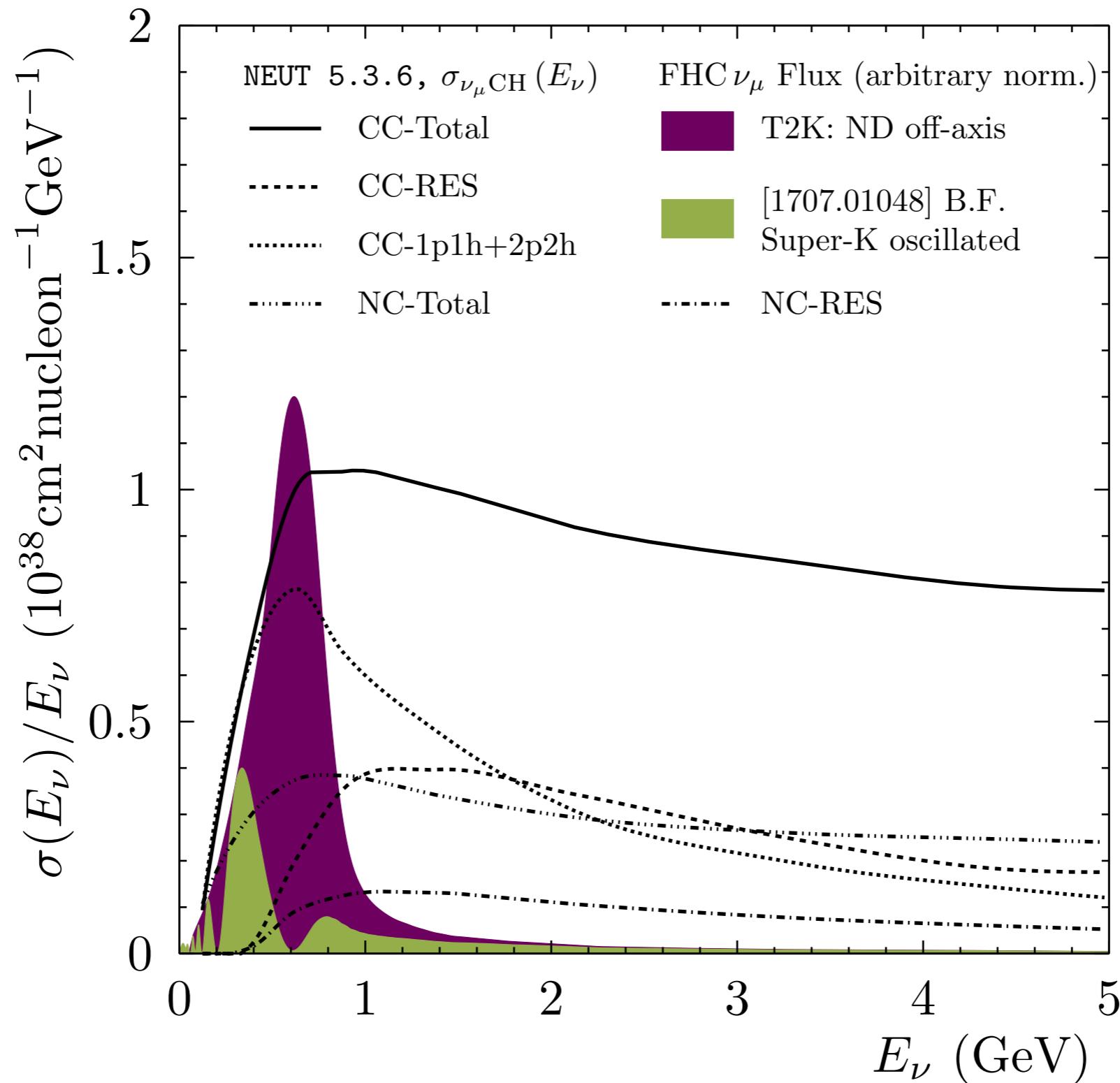
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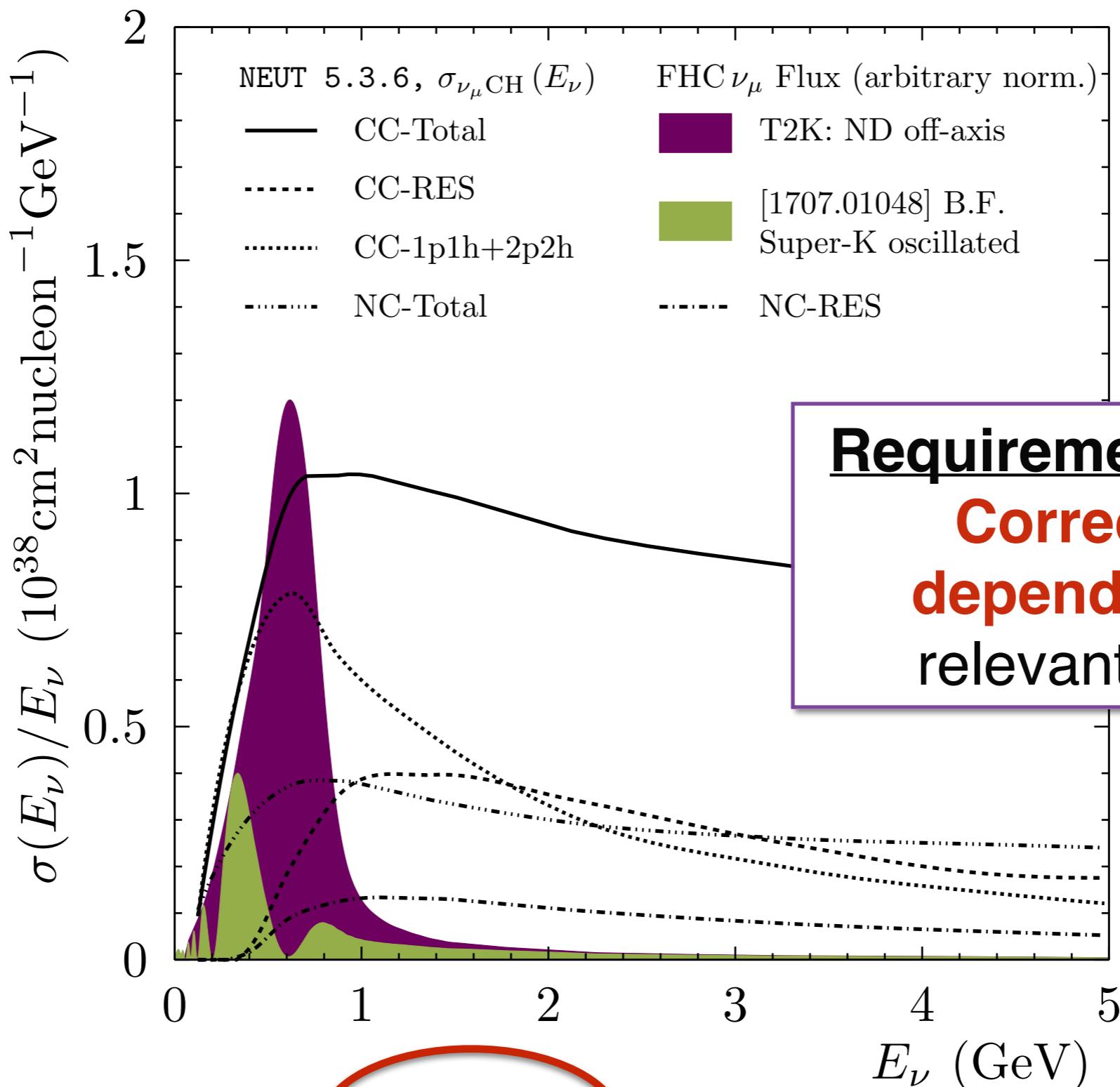
- Production of pions, CC1 $\pi^{+/0/-}$ and NC1 $\pi^{+/0/-}$



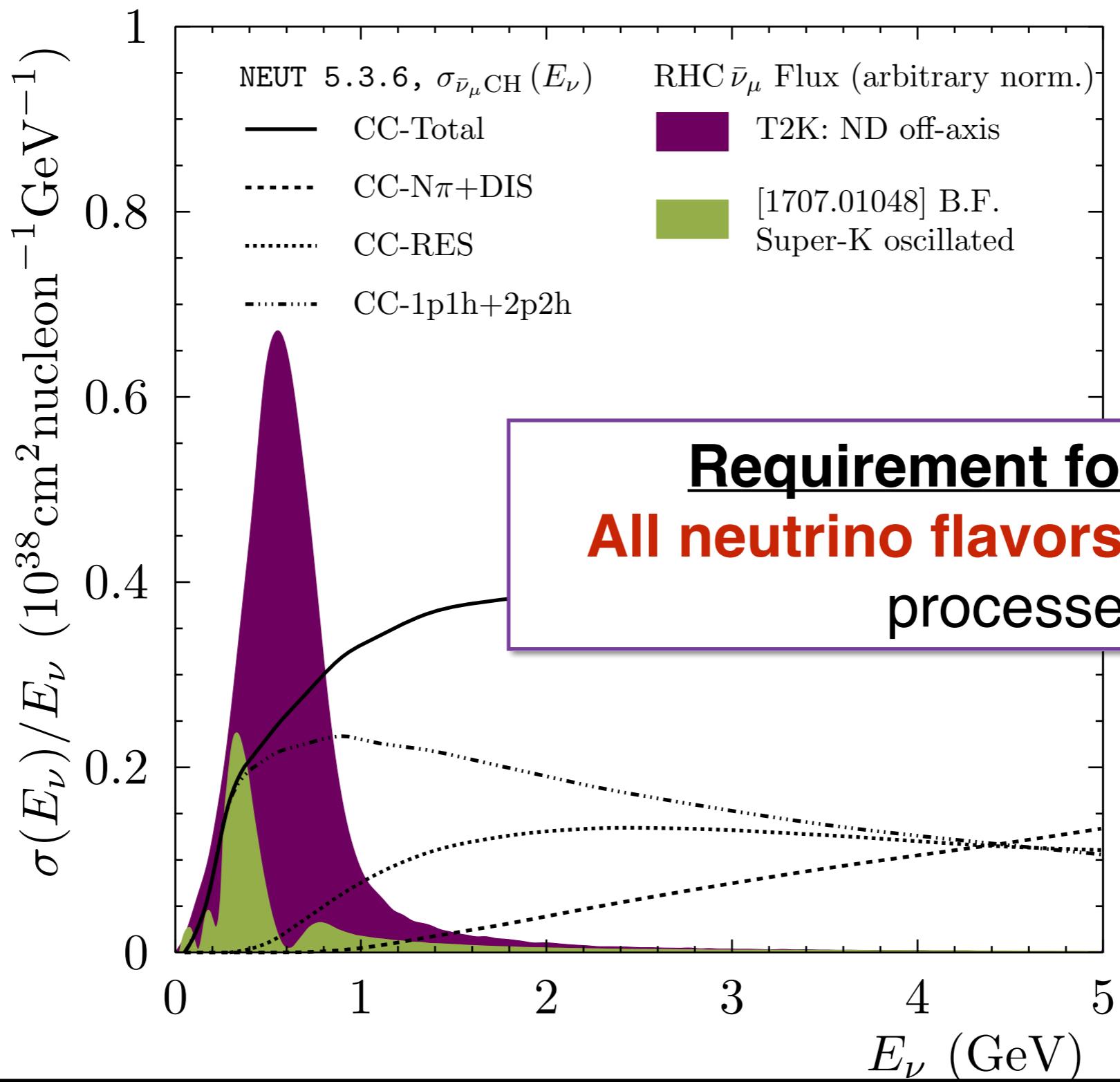
Can't isolate single processes: “wide beams”



Incident energy is not known. Spread of beam is larger than nuclear effects.

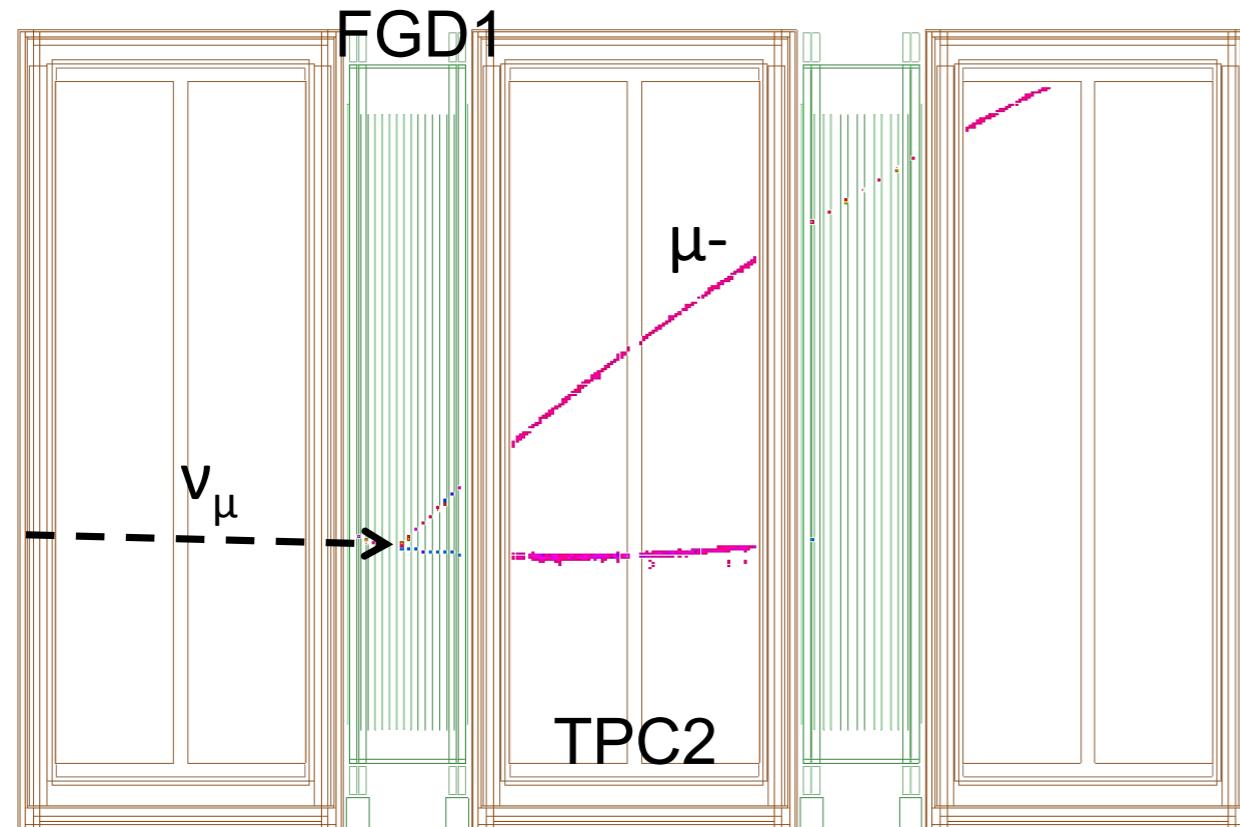


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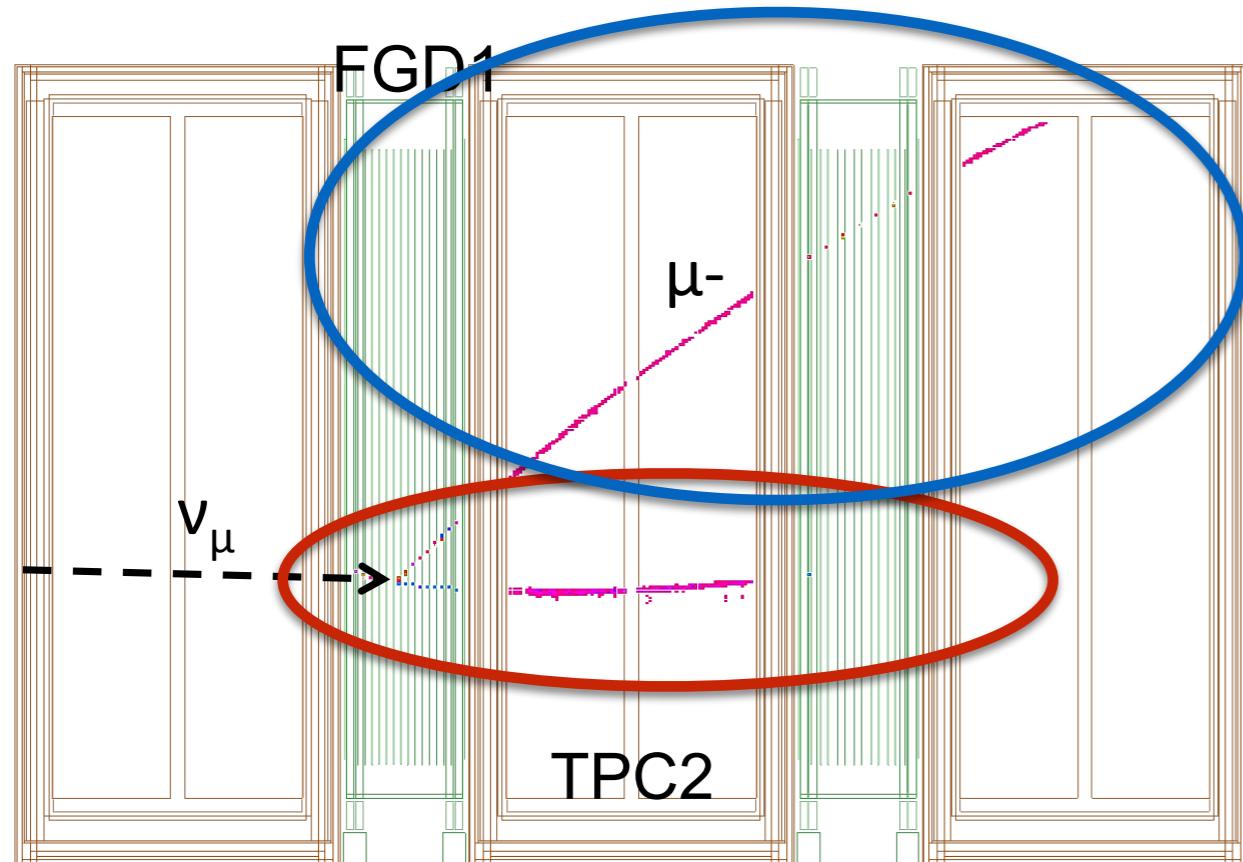
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Need: hadronic state description



- T2K event display
- CC0 π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1 π (pion absorbed in nucleus)

Needs: semi to exclusive final states



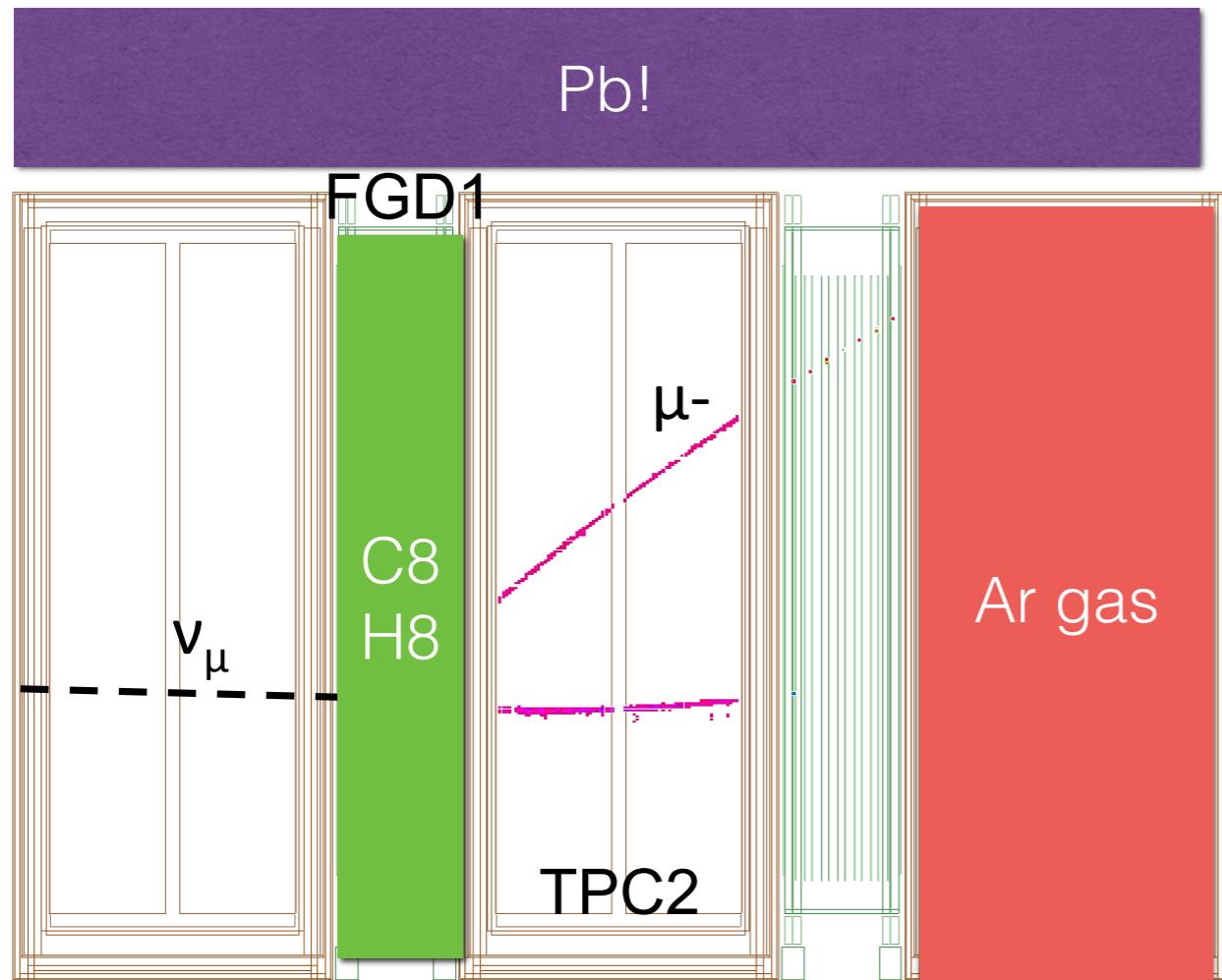
- T2K event display
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Requirement for model:

- All visible particles for efficiency (background) and energy estimates

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Needs: target material



Target materials:

- T2K: H₂O
- NOvA: CH+Cl
- SBN, DUNE: Ar

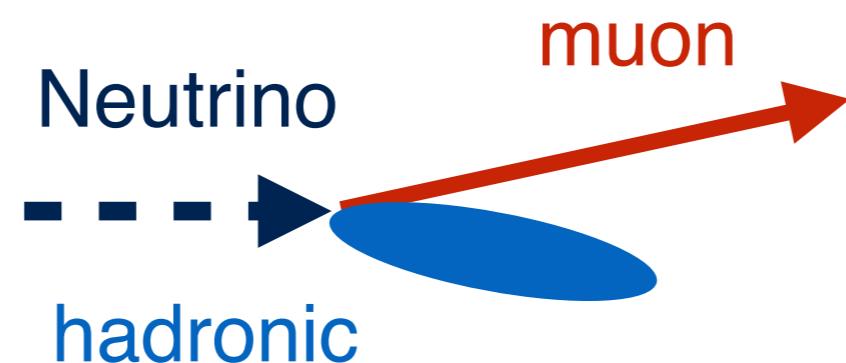
Requirement for model:

- Most nuclear targets, esp C, O, Ar

Needs: Energy estimation

- Oscillation depends on energy
 - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - m'_n{}^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos \theta_\mu)}$$
$$E_\nu = E_\mu + \sum E_{hadronic}$$



T2K
Super-Kamiokande

SBN
DUNE

NOvA

Needs: Energy estimation

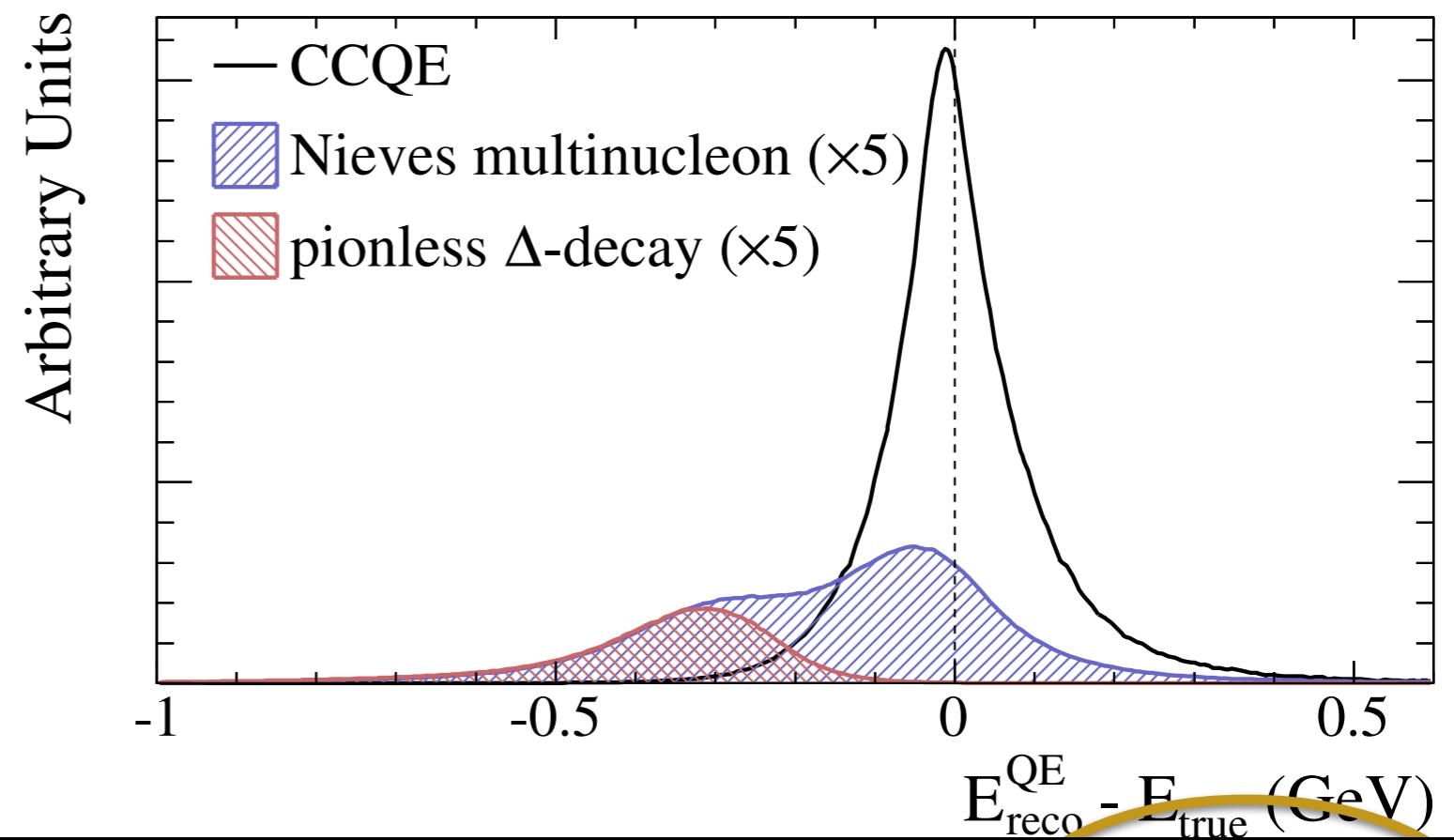
- Nuclear effects bias true and estimated neutrino energy

$$E_\nu^{QE} = \frac{m_p^2 - m'_n{}^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos \theta_\mu)}$$

T2K, PRL 112, 181801 (2014)

Requirement for model:

- Correct mix of processes per topology
- true - reconstructed kinematic relationship



$$N_{FD}^{\alpha \rightarrow \beta}(E_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{true}}) \times \sigma_\beta^i(E_{\text{true}}) \times P_{\alpha\beta}(E_{\text{true}}) \times \epsilon_\beta(E_{\text{true}}) \times R_i(E_{\text{true}}; E_{\text{reco}})$$

Experimental solutions

$$N_{FD}^{\alpha \rightarrow \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

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- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
 - Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
 - Example in-situ information: beam line monitors

Experimental solutions

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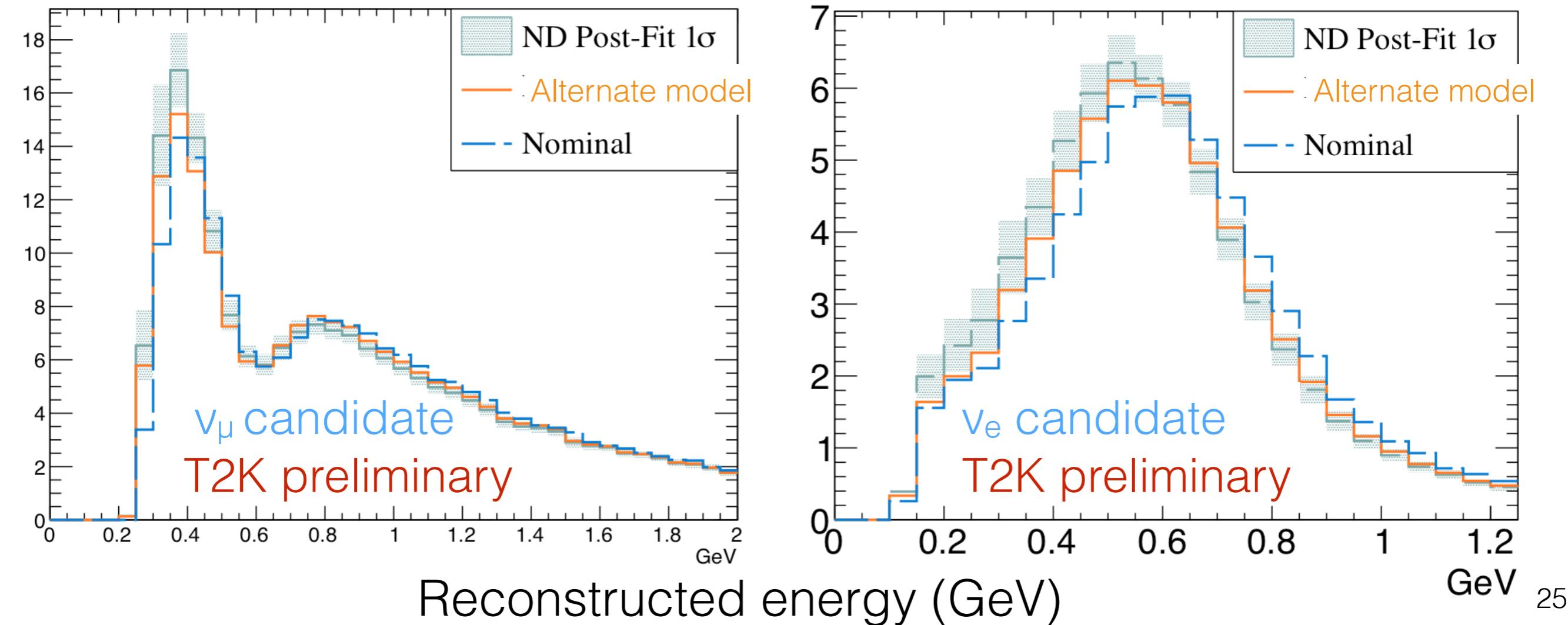
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 - Example in-situ information: beam line monitors
- External experiments:
 - Example: electron scattering experiments

“Fake data studies”

- Sometimes, it is not possible to incorporate into the analysis a new interaction model quickly. And, existing uncertainties may already cover the effect.
- To test the robustness of our oscillation analysis, we do “fake data studies” where:
 - Prepare an alternate model, and include it in the analysis as if it were data
 - Run entire T2K oscillation analysis chain (fit near detector with nominal cross section uncertainties and propagate) to evaluate effect on oscillation parameters
 - If we see a measurable effect in the analysis, update systematic uncertainty.

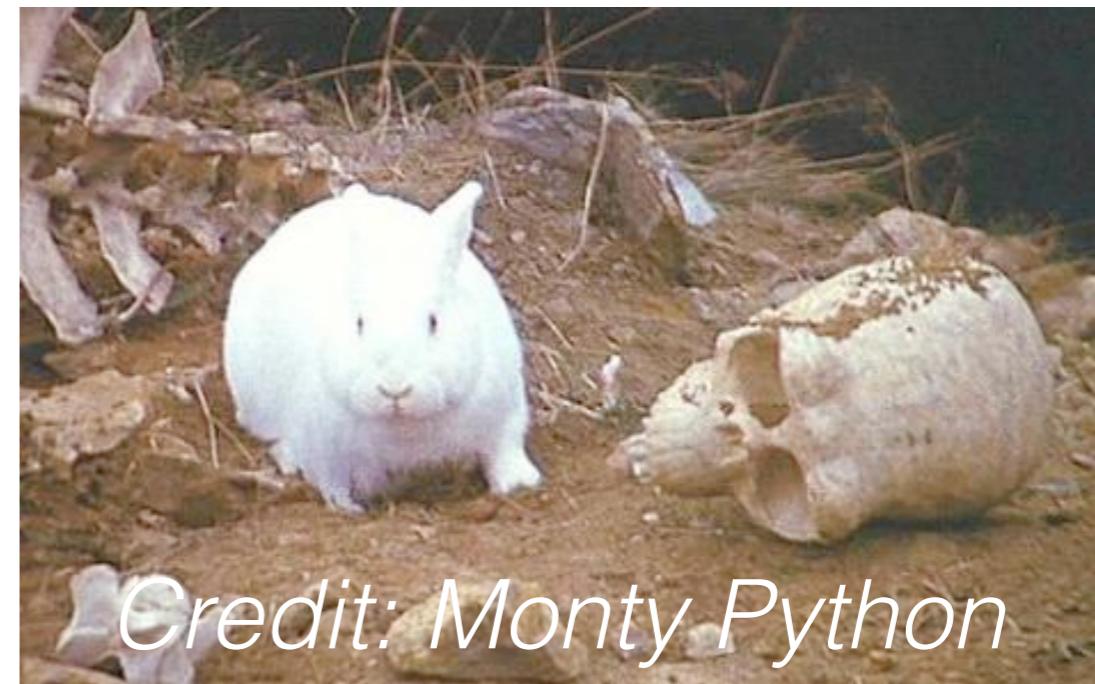
An example “fake data study”

- Create a “data” set corresponding to an alternate QE model
- Run entire T2K oscillation analysis chain (fit near detector with nominal cross section uncertainties and propagate) to evaluate effect on oscillation parameters

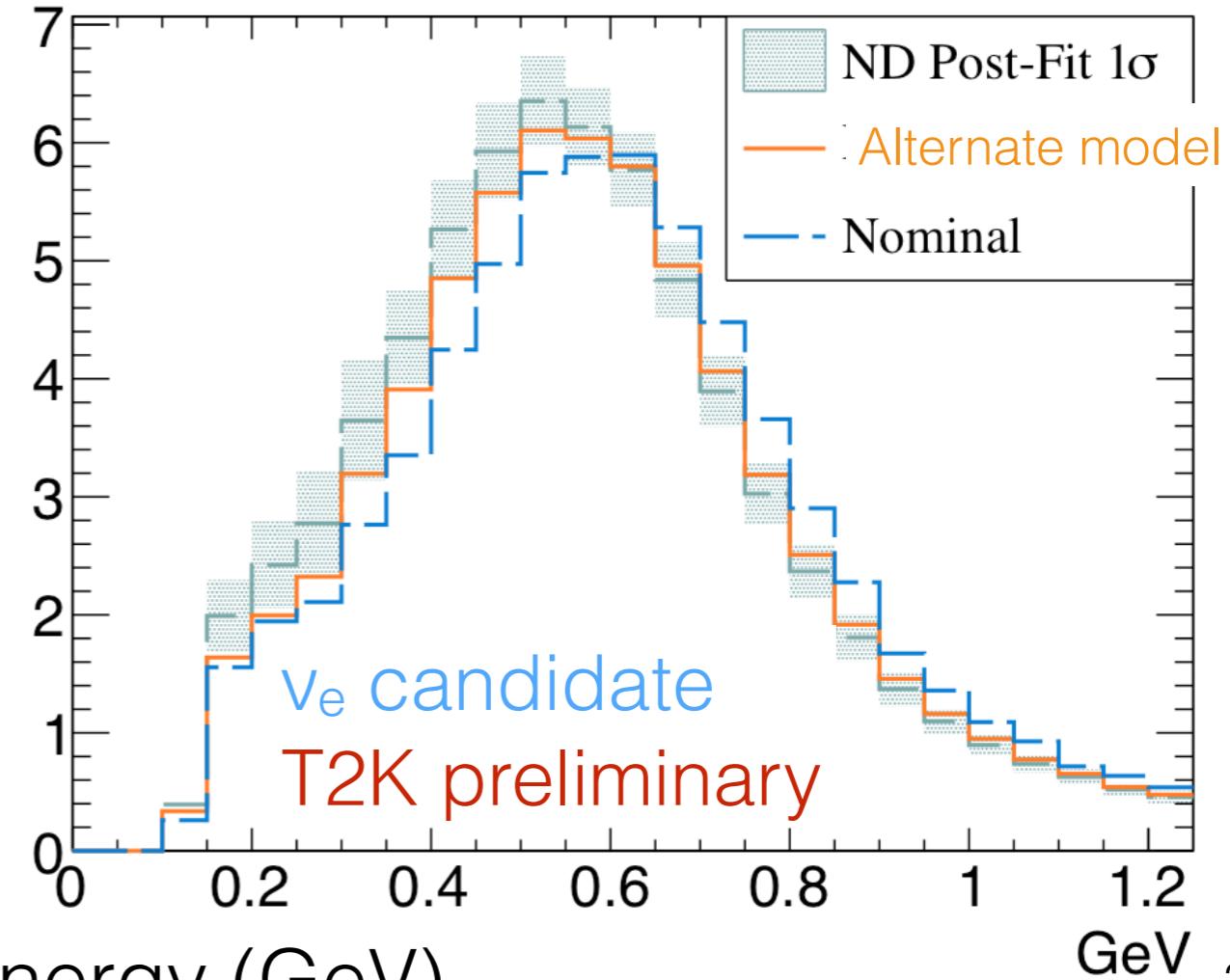
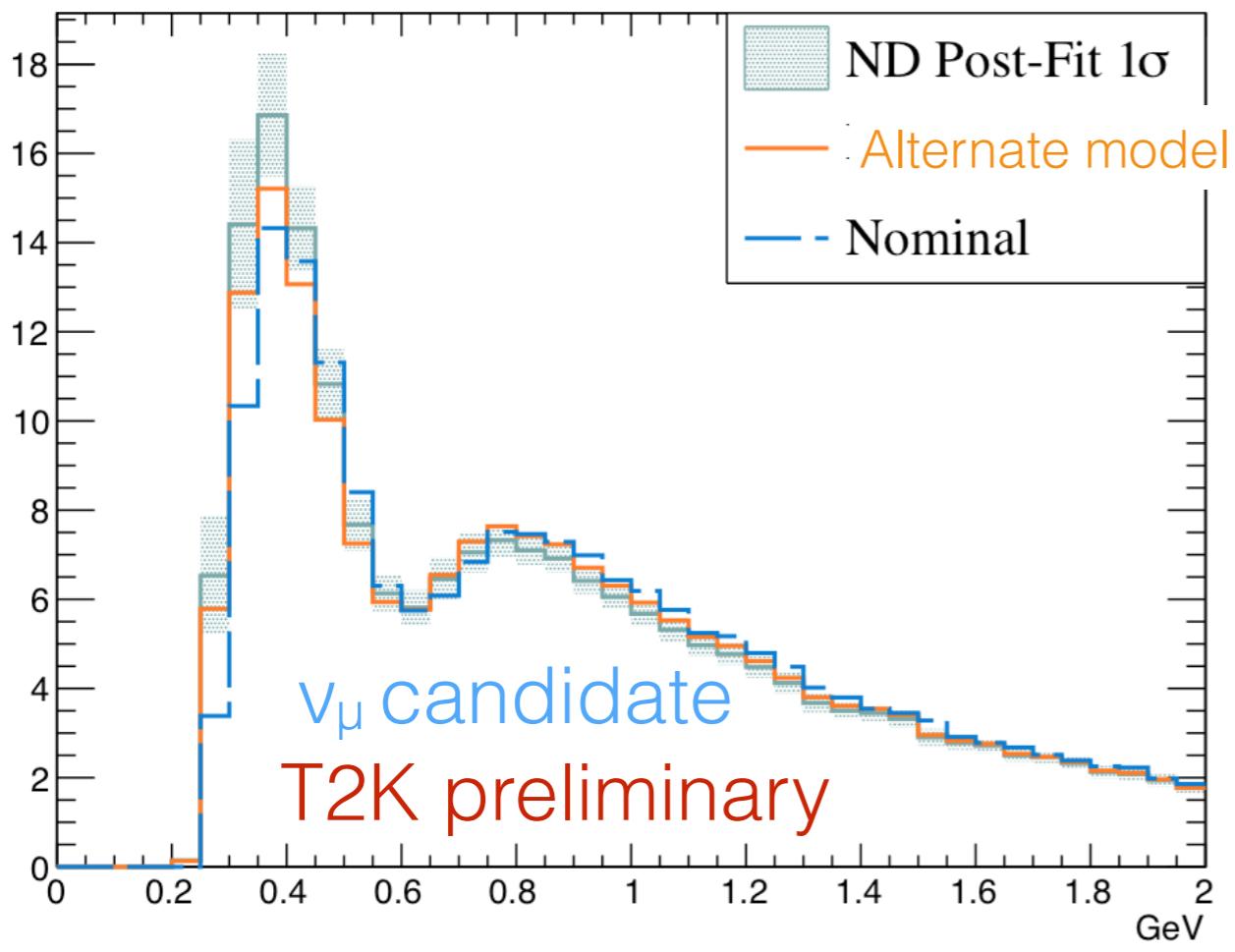


An example “fake data study”

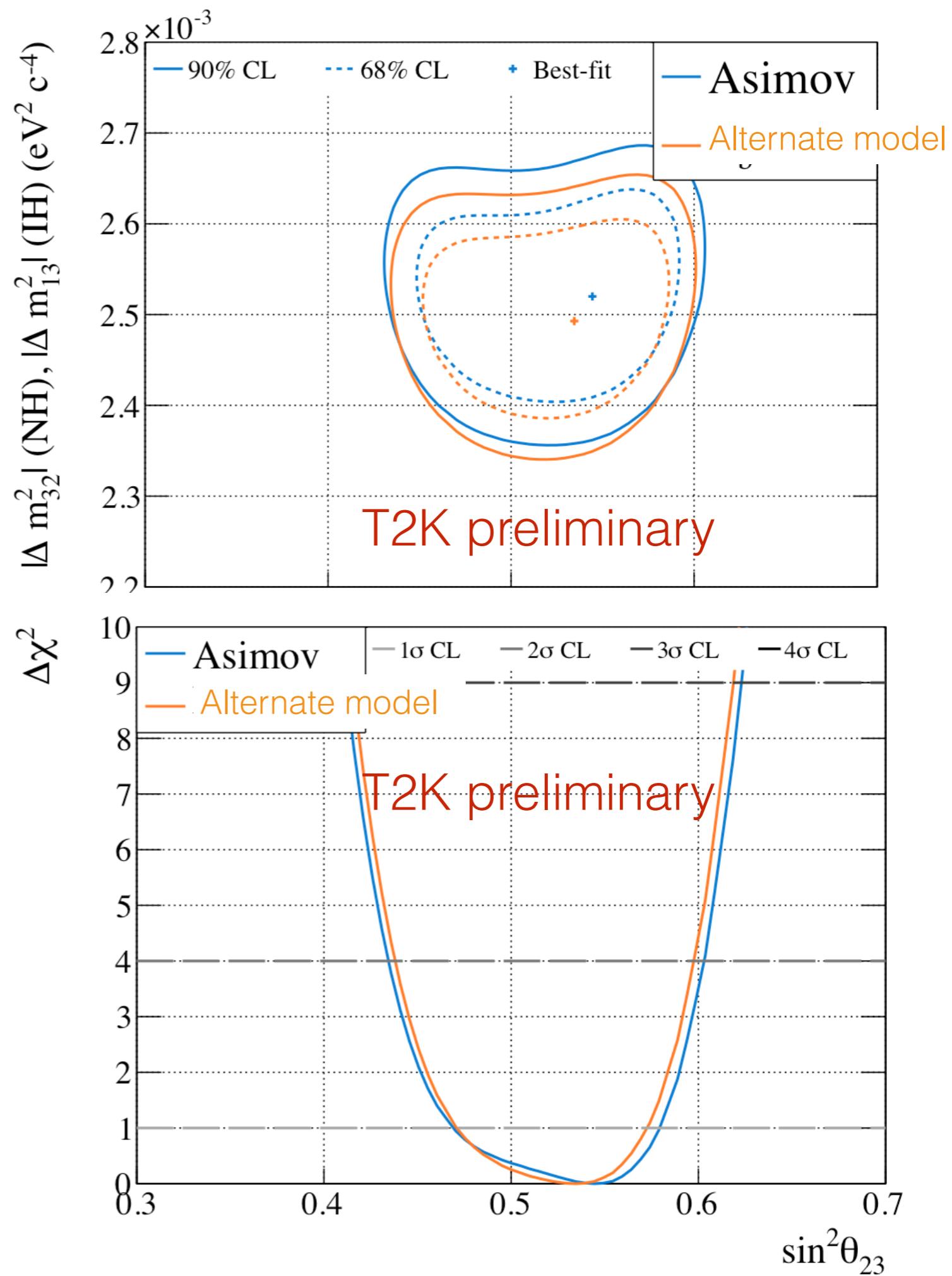
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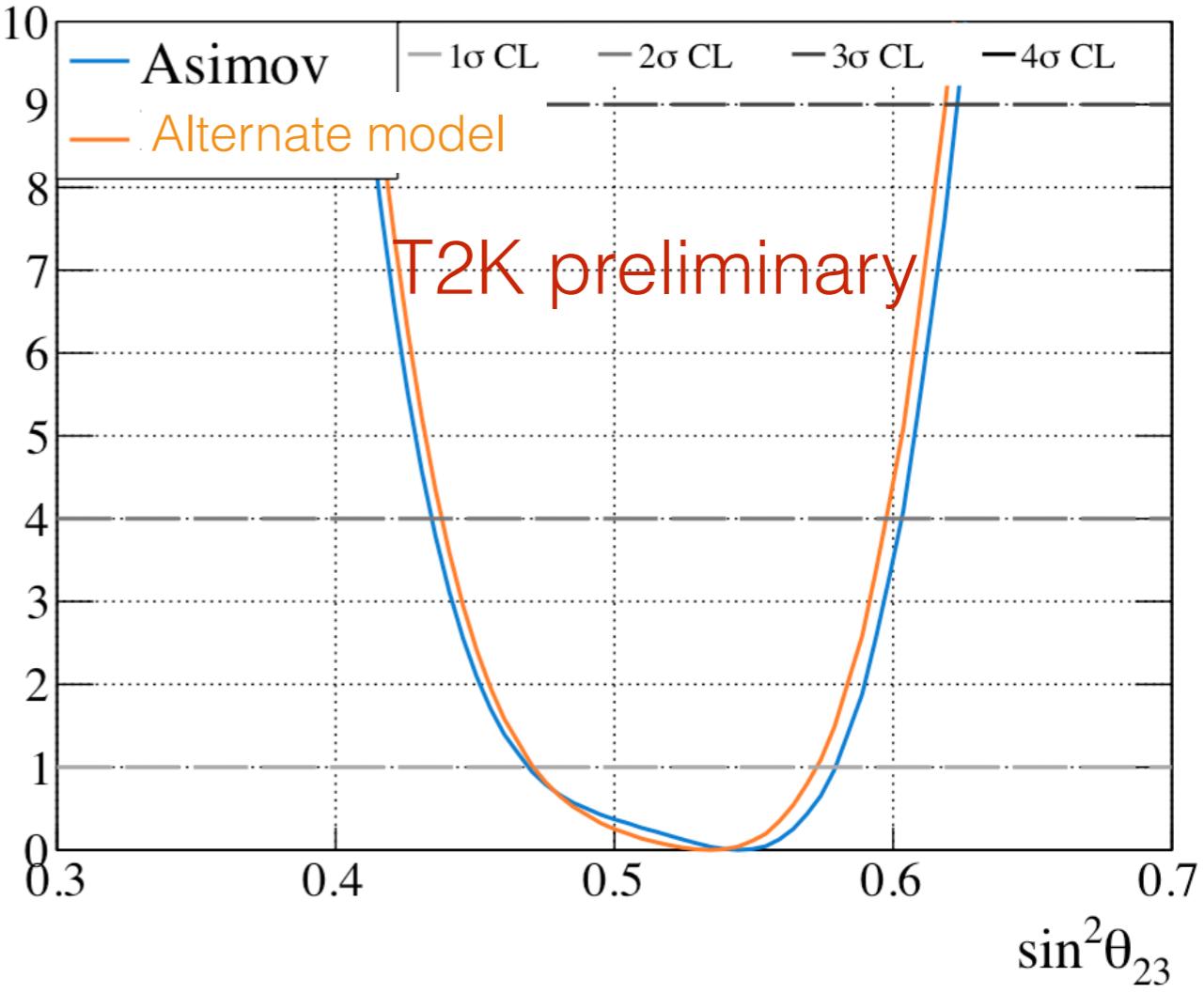
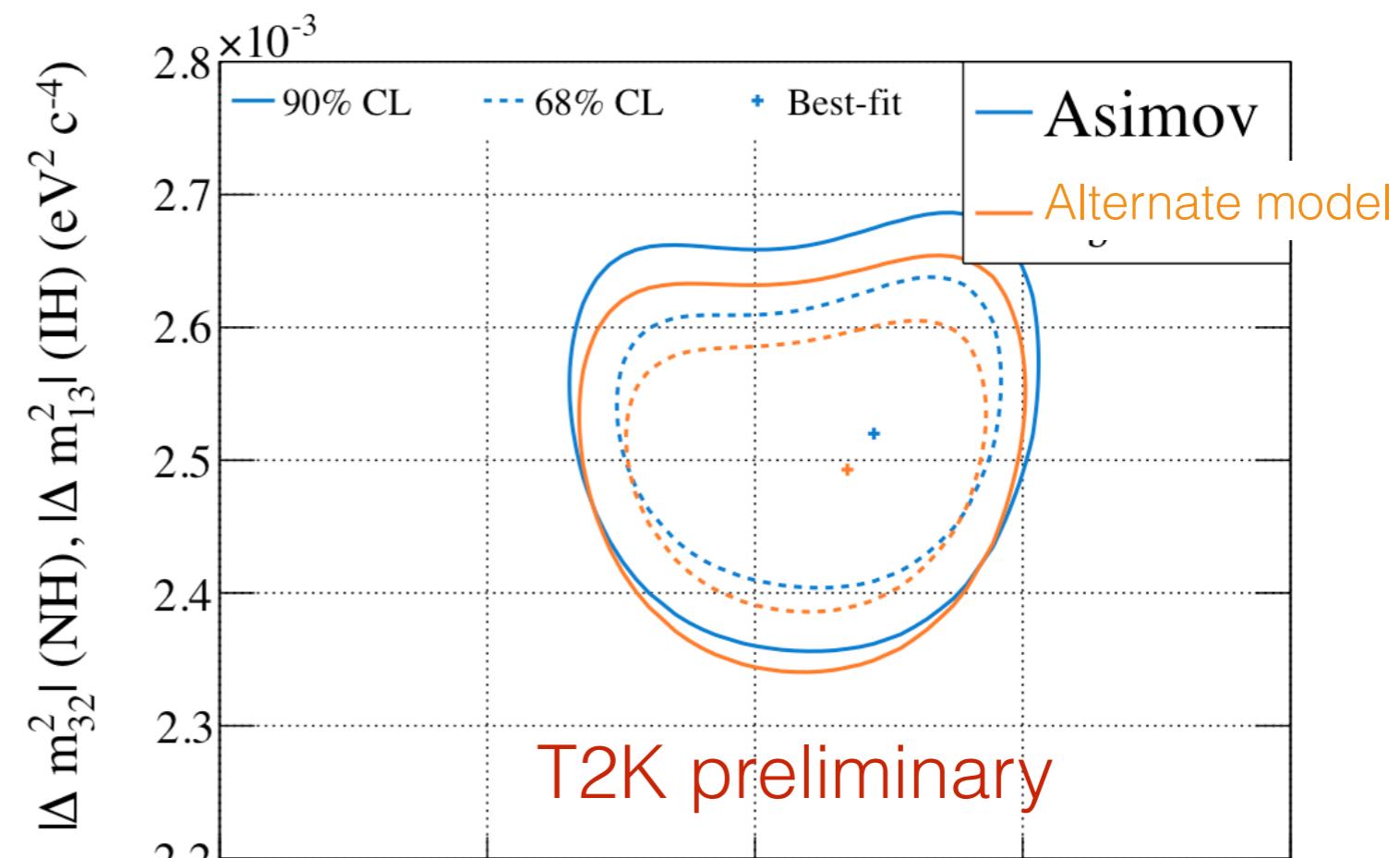
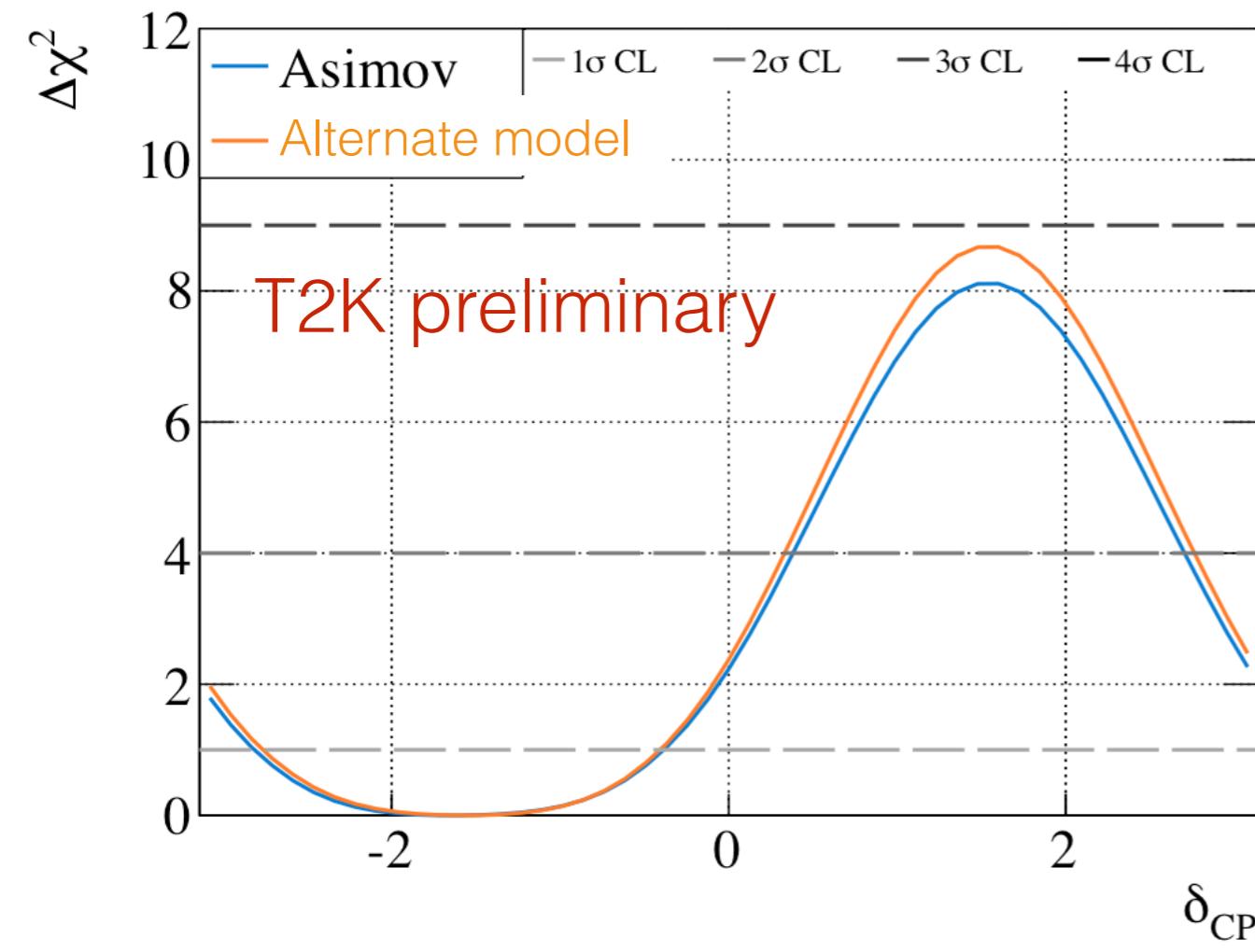
Credit: Monty Python



- Alternate models may create biases for current analysis; T2K adds additional uncertainty
- We mustn't run away!



- Alternate models may create biases for current analysis; T2K adds additional uncertainty
- Effect depends on model (here, not much impact on δ_{CP})



List of alternate model tests

QE+2p2h

- Benhar et al QE (SF)
- Martini et al 2p2h
- Alternate form factors (2 studies)
- Binding energy

Data-driven

- Differences in pion kinematics at ND280
- Attribute data/model differences muon kinematics to 1p1h or 2p2h and propagate (ND280, MINERvA inspired: 2 studies)

Resonance

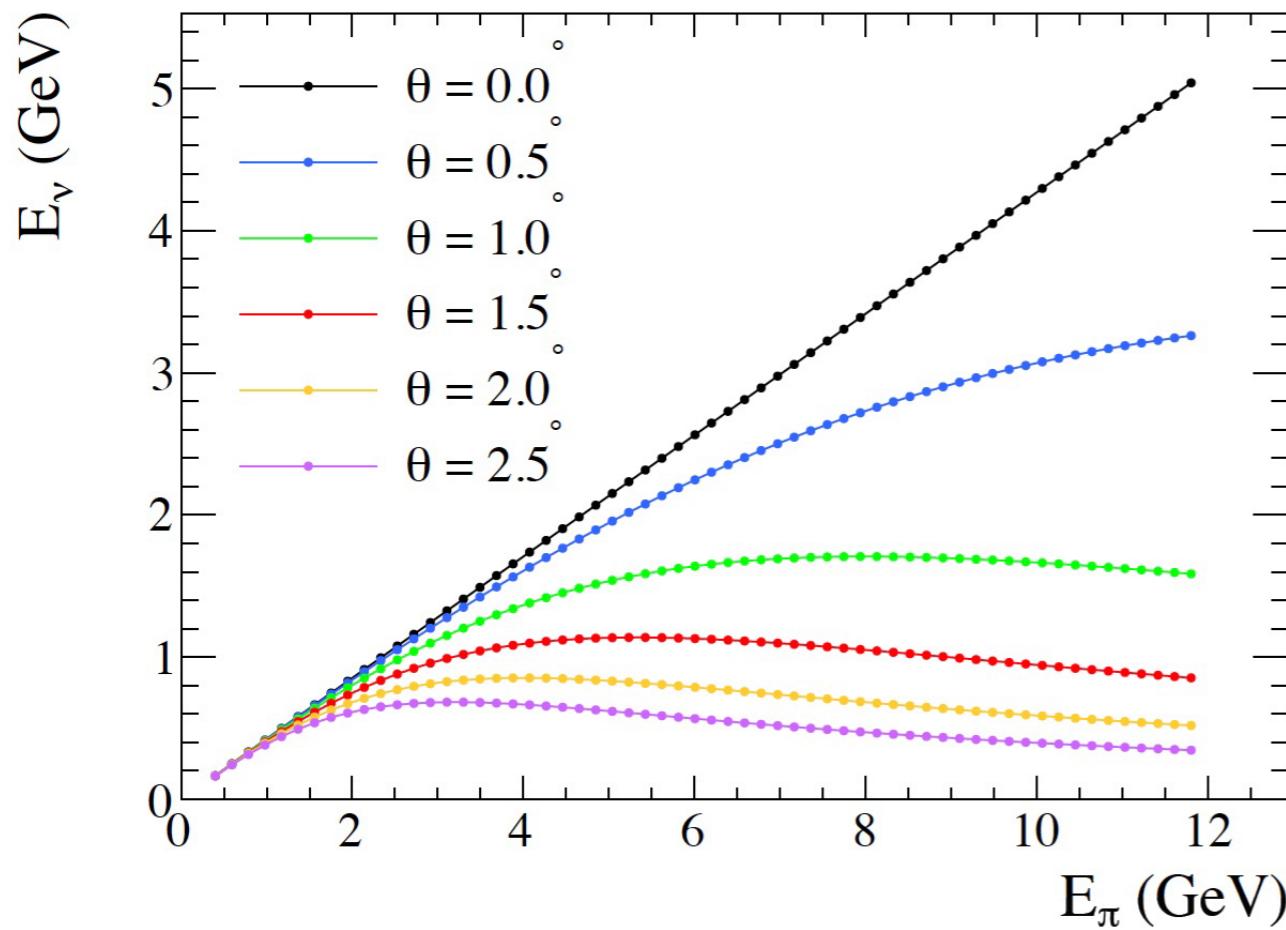
- MK model + NEUT bug fix
- Multipion production multiplicity improvement

Many of the alternate model tests showed an impact on the atmospheric parameters and uncertainties were increased

Challenge for current statistical uncertainty

One new approach: ν PRISM

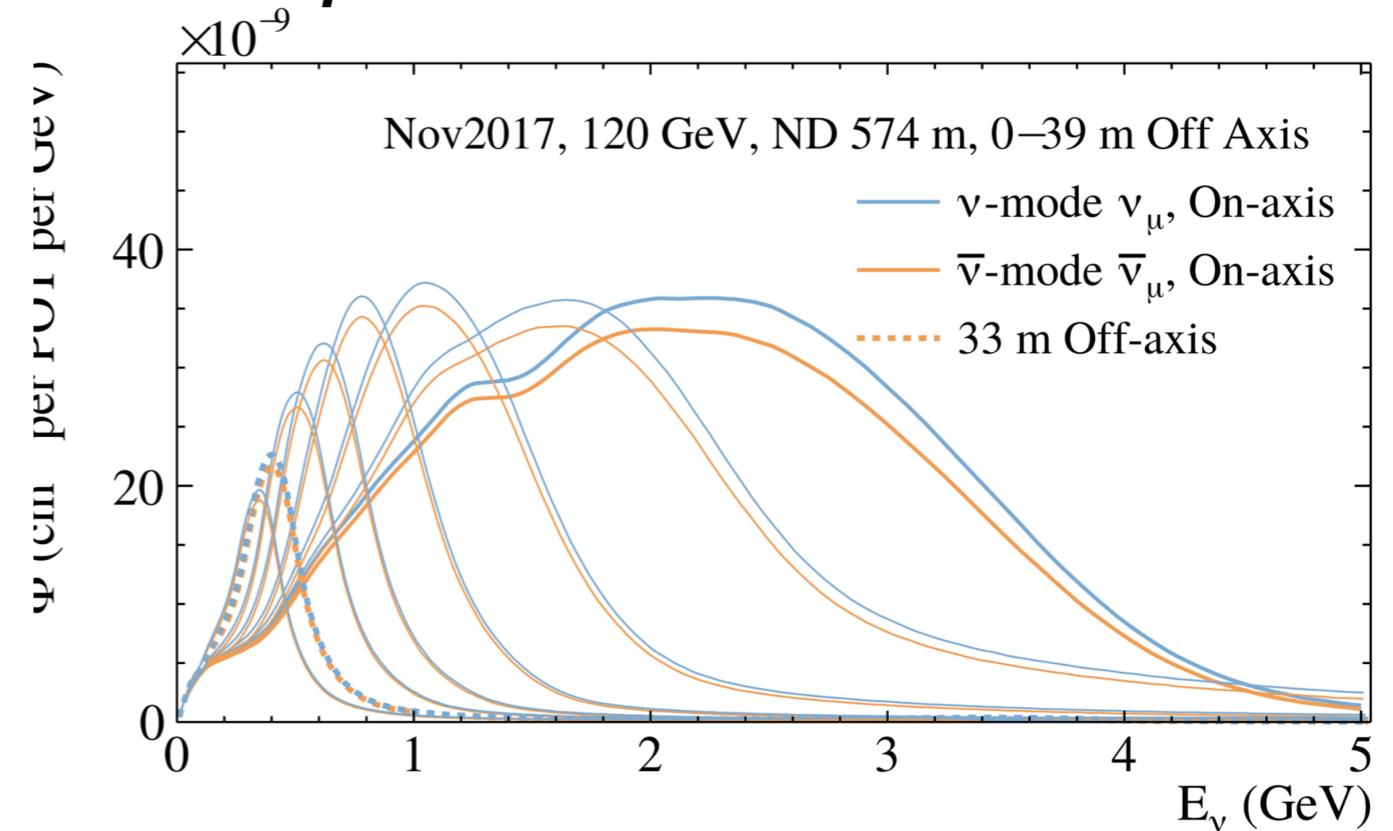
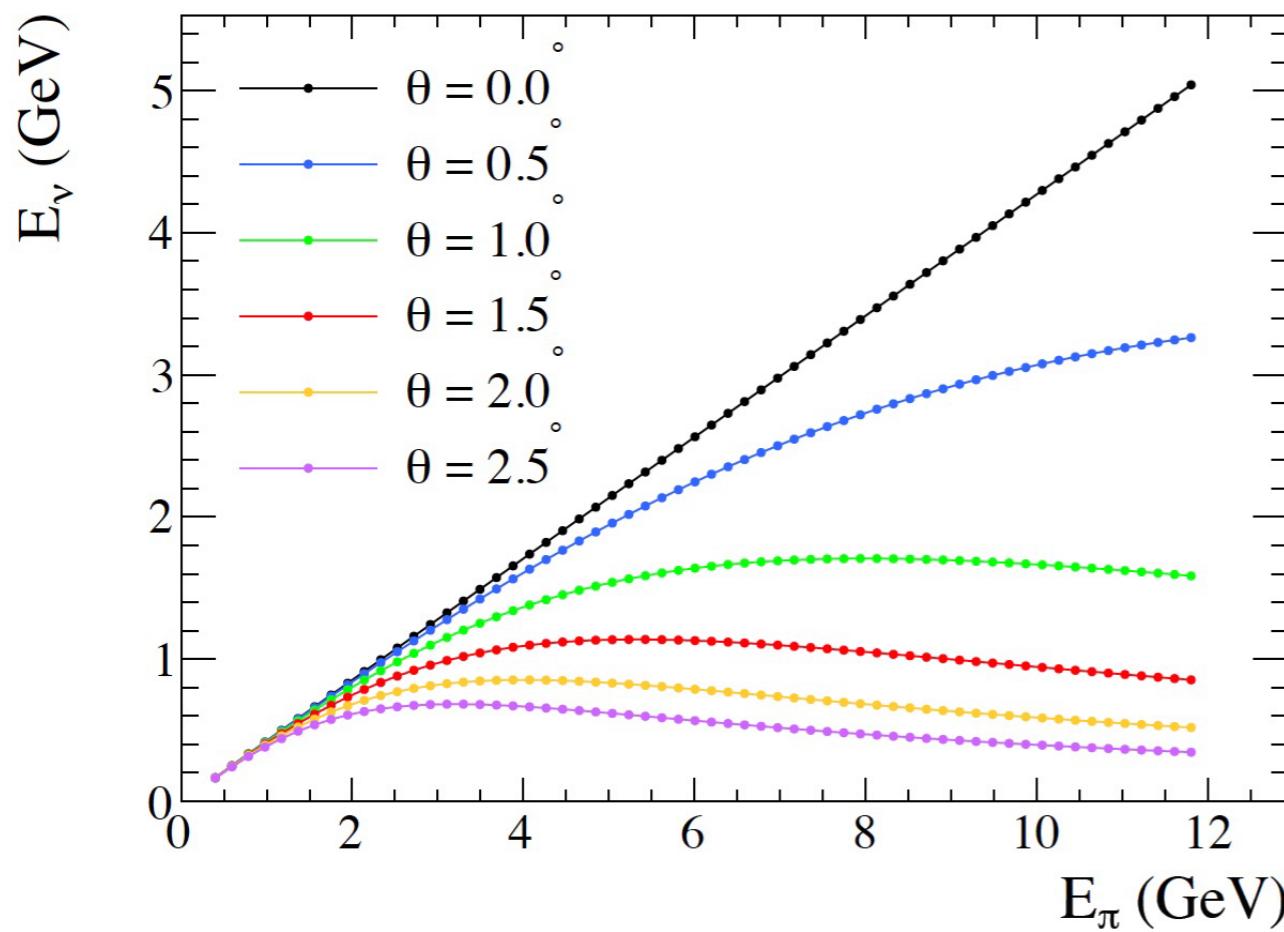
Precision Reaction Independant Spectrum Measurement



Neutrino energy spectrum
changes in transverse
direction to (proton) beam

One new approach: vPRISM

Precision Reaction Independant Spectrum Measurement

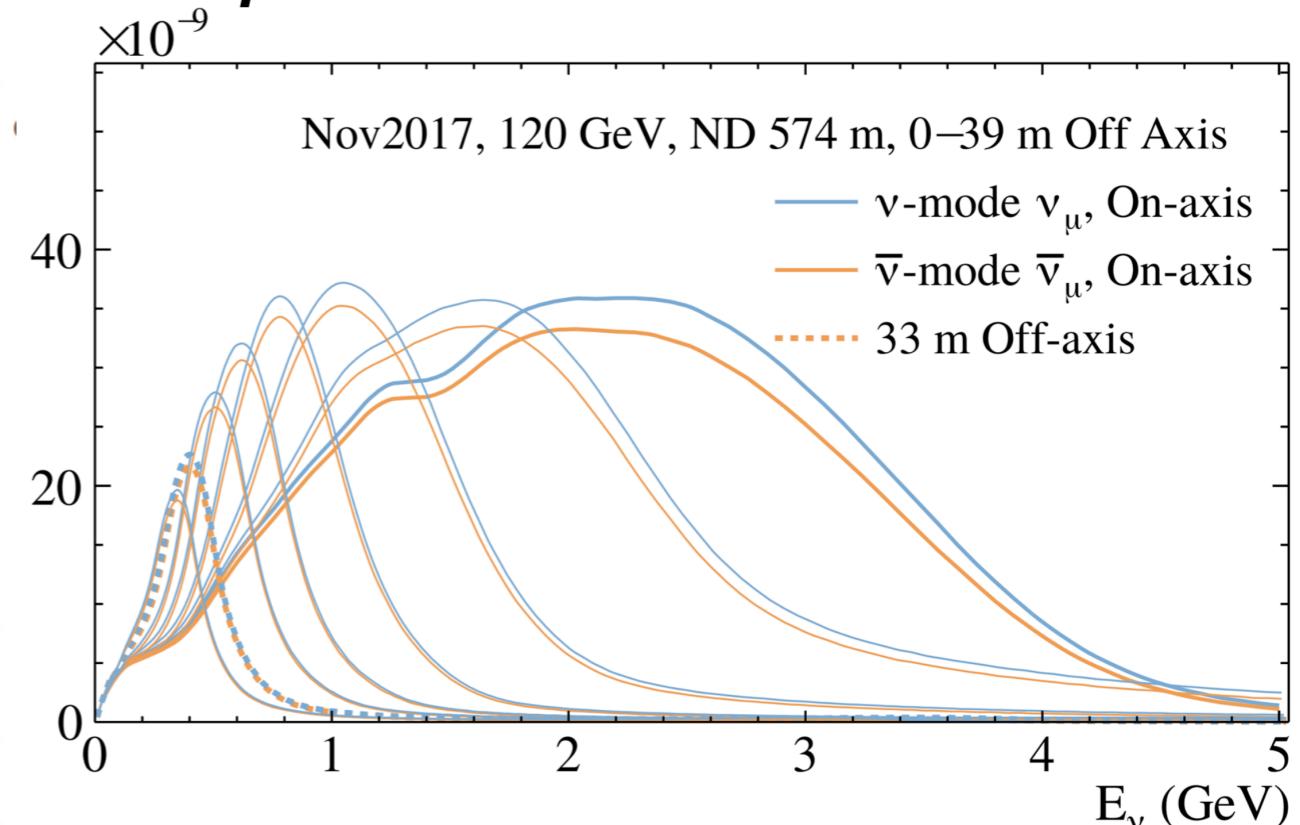
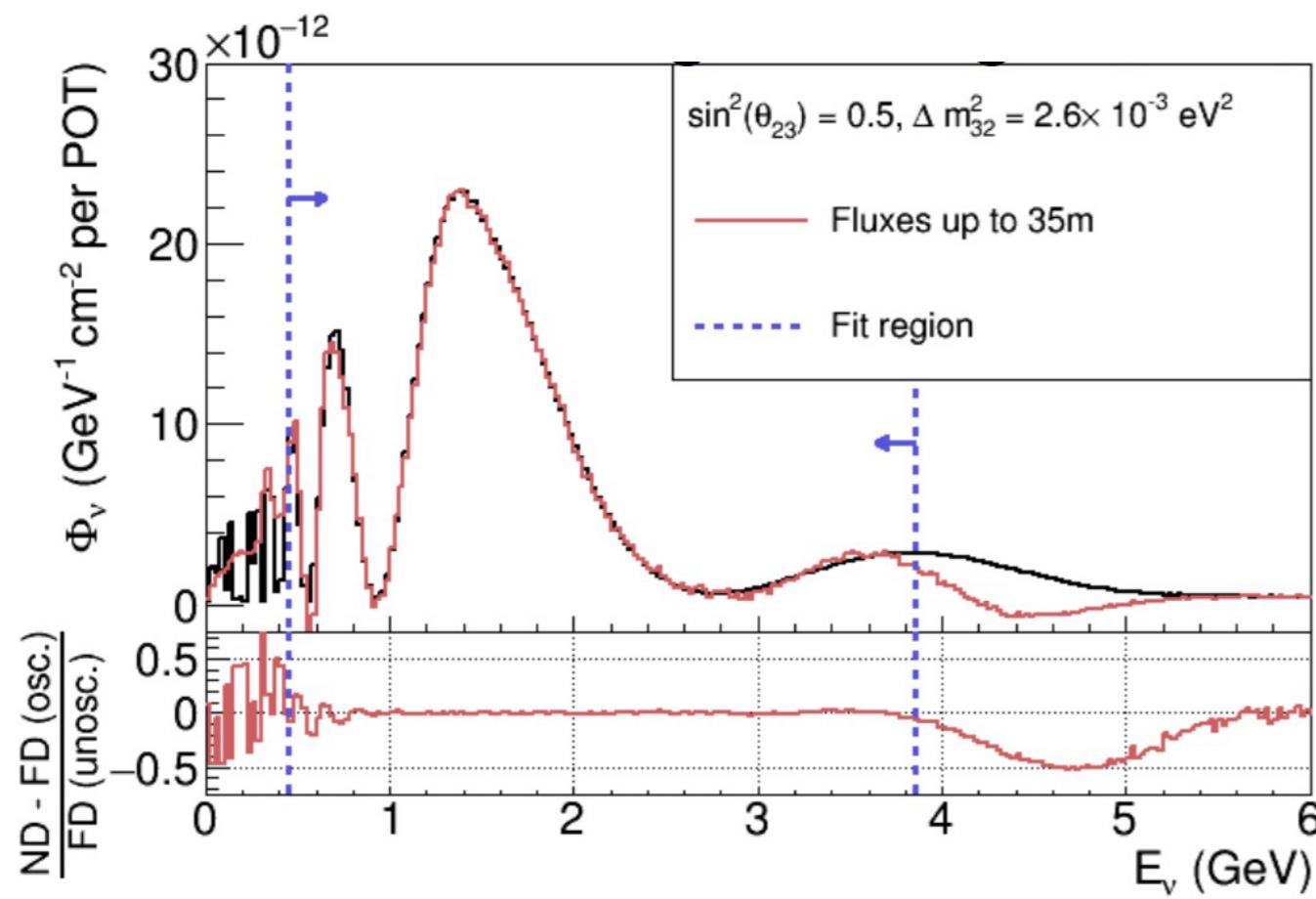


DUNE Preliminary

Peak shifts down, spectrum narrows

One new approach: vPRISM

Precision Reaction Independant Spectrum Measurement



DUNE Preliminary

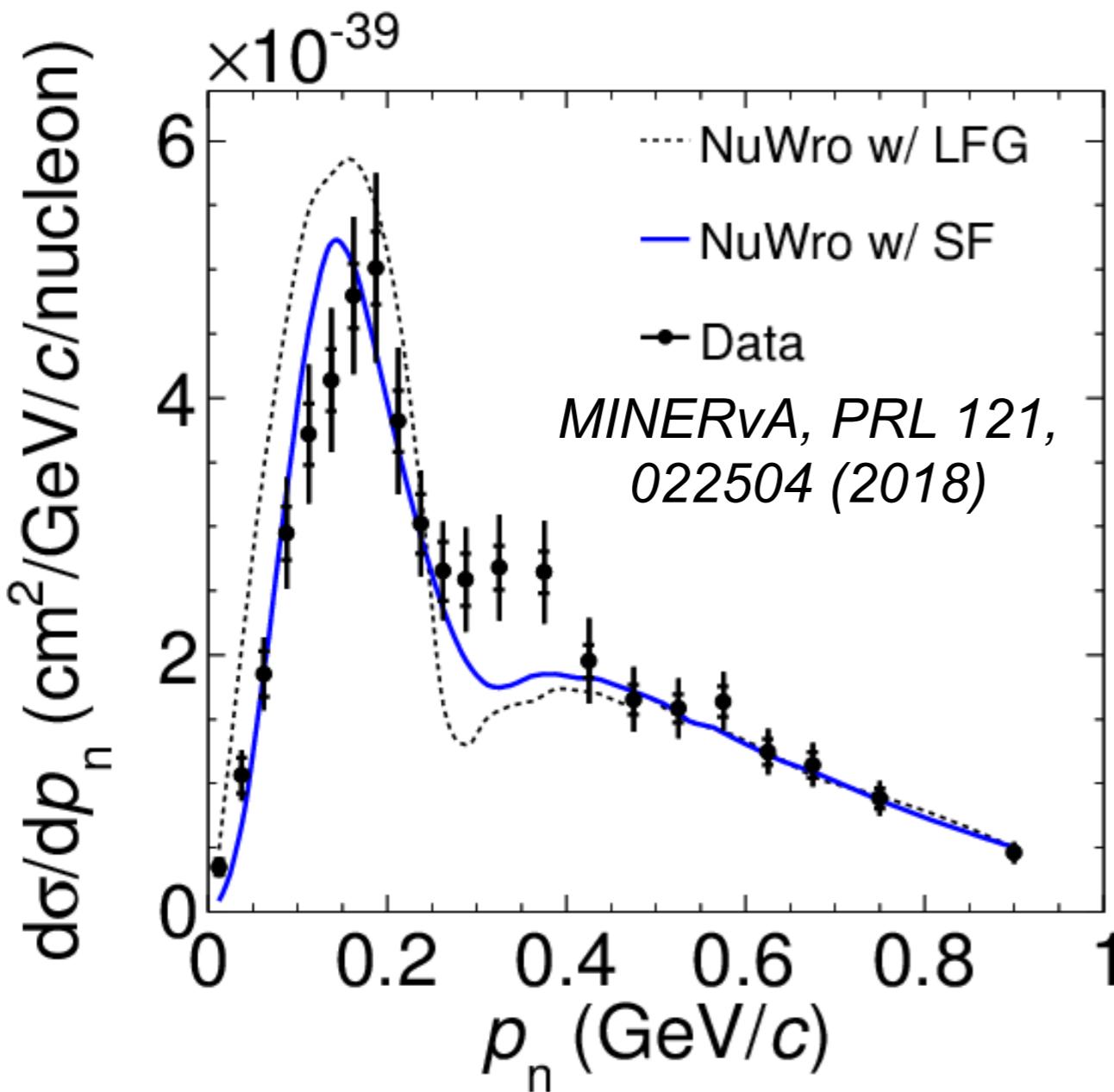
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Many near detectors can approximate far detector oscillated flux! Changing beam line optics can help, too.

Persistent challenges: *we need theory*

- **Robust implementation**

- Simulations are using inclusive calculations (quasielastic plus 2p2h plus pion production) with a fragmentation model, plus an FSI cascade or transport.
- Example: Disagreements in semi-inclusive data



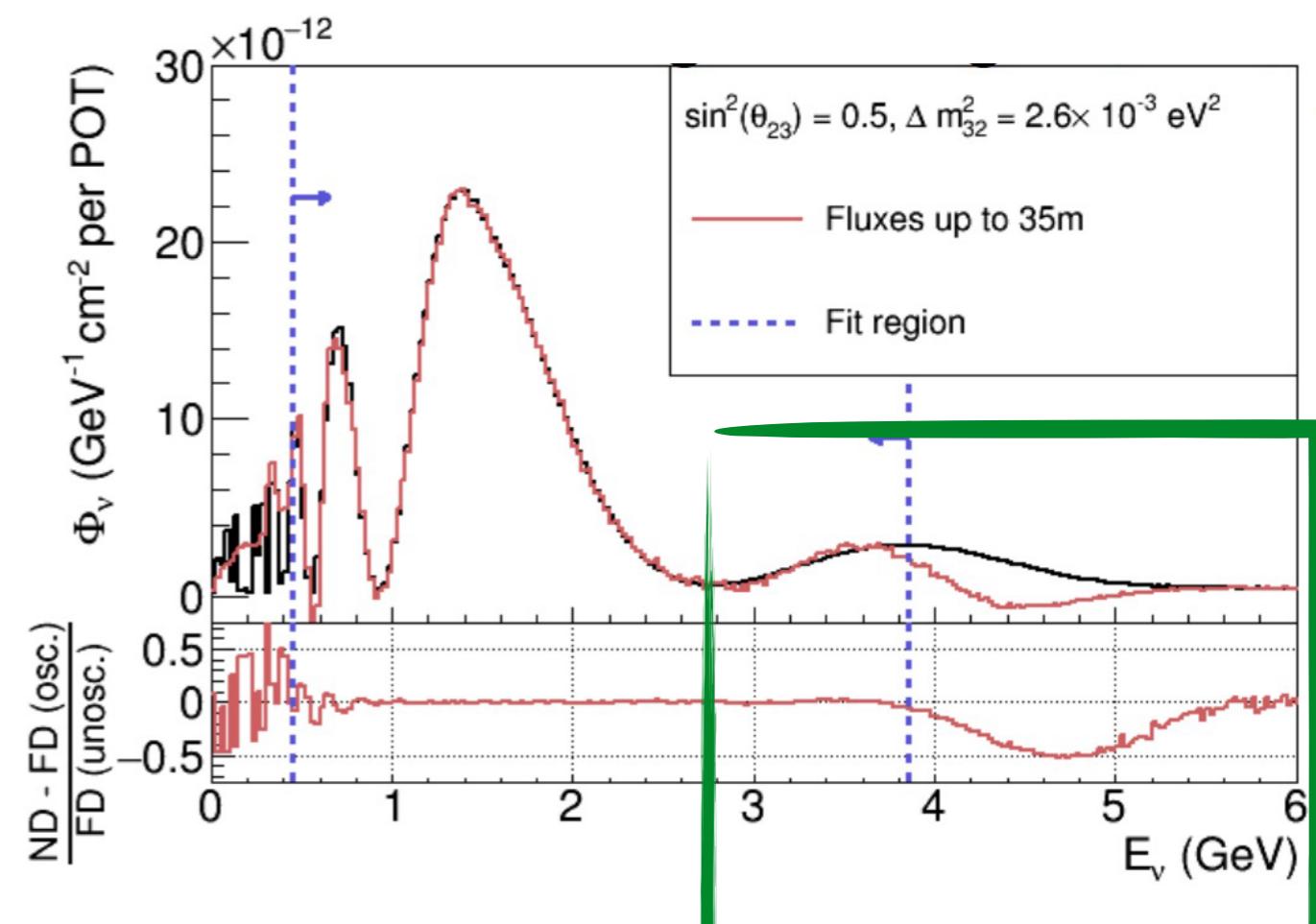
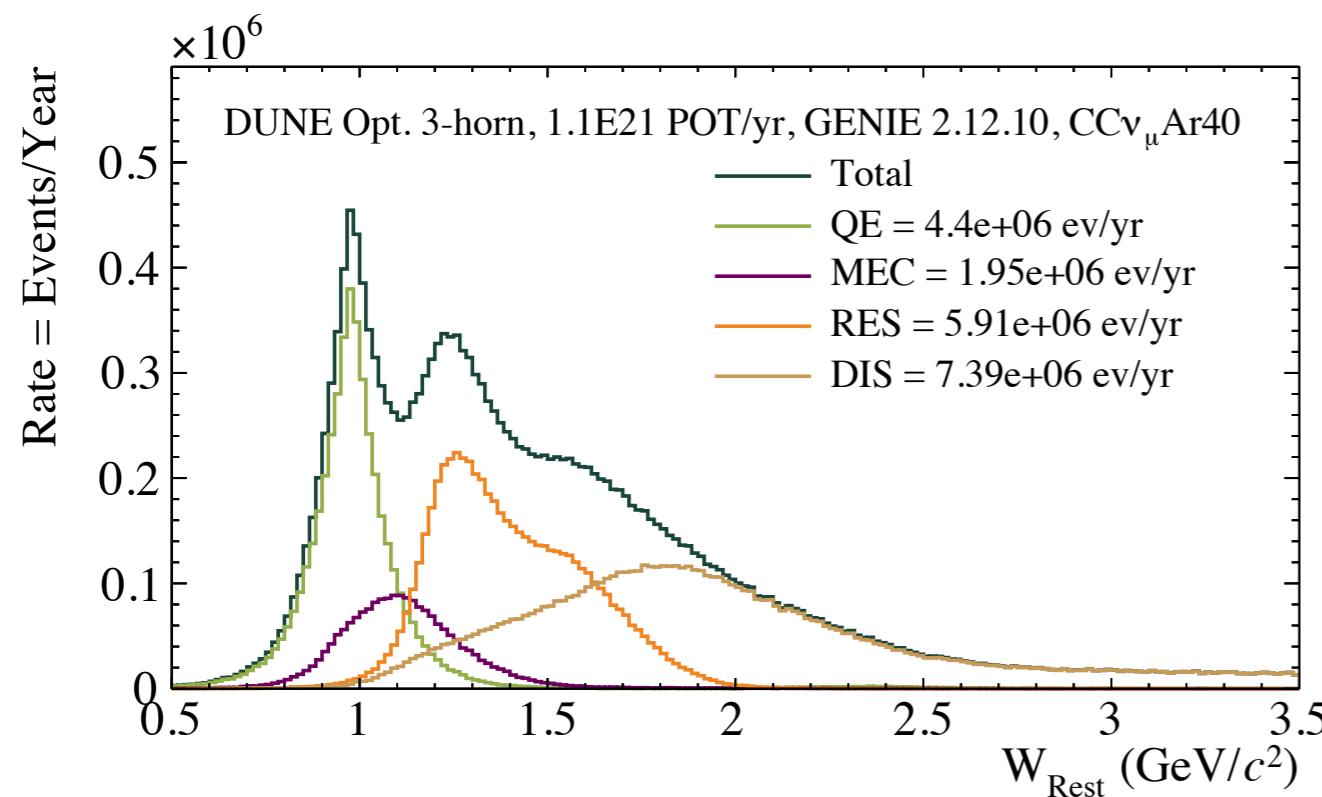
- OK, so this model doesn't agree... well none of them do!
- We need **real semi-inclusive** theory for the hadronic state (NOvA, SBN DUNE... and T2K's neutron tagging...)
- We need to question simplifications/approximations/extrapolations

Persistent challenges: *we need theory*

- Robust implementation
- **Processes with small rates at near detectors**
 - Limited near detector information
 - NC single photon production, NC diffractive production
 - Electron (anti)neutrinos cross sections
 - Related: Radiative corrections to exclusive processes on nuclei

Persistent challenges: we need theory

- Robust implementation
- Processes with small rates at near detectors
- **Transition region** // Shallow Inelastic // Deep Inelastic Scattering
 - Little/no single nucleon data to start from
 - How do we handle double counting? Extrapolations/approximations?



Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- **Continued work on QE/multinucleon/resonant processes**
 - 5+ year effort to implement new QE, 2p2h models has produced a much easier interface for theory groups within generators and has been remarkably successful at predicting the lepton.
 - Everyone: Expand into resonance!
 - Nuclear theory: semi-inclusive! Heavier targets!
 - Lattice QCD: axial FF at 10% level

Key feature: close collaboration between theory and experimental groups

Persistent challenges: *we need theory*

- Robust implementation
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**Key feature: close
collaboration between theory
and experimental groups**

*We need to support people to start and finish the
work on both experimental and theory side*

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- Continued work on QE/multinucleon/resonant processes
- **Uncertainty estimation and treatment**
 - Are there other processes missing?
 - Is our propagation of an uncertainty correct (within a model?) What alternate choices may be considered which are valid/reasonable?
 - Models may be limited in regions of validity (e.g. 2p2h status). We must push past incomplete models with some sensible uncertainty.
 - Crucial help in electron scattering data interpretation for neutrino experiments.

Key feature: confront and discuss issues together

Summary

- Neutrino oscillation experiments are a key window on outstanding questions of fundamental physics parameters
- A robust interaction model is critical to current and future neutrino oscillation (and other) experiments
 - We have seen cases where our model assumptions or approximations in implementation matter

Summary

- Neutrino oscillation experiments are a key window on outstanding questions of fundamental physics parameters
- A robust interaction model is critical to current and future neutrino oscillation (and other) experiments
 - We have seen cases where our model assumptions or approximations in implementation matter
 - Support needed! And what do you need to set targets?
 - Identifying weaknesses in implementation, testing impact in analysis
 - Uncertainty quantification (and parameterization choice) for QE, multinucleon, resonance processes
 - Semi-inclusive modelling

Backup

What the community is worried about

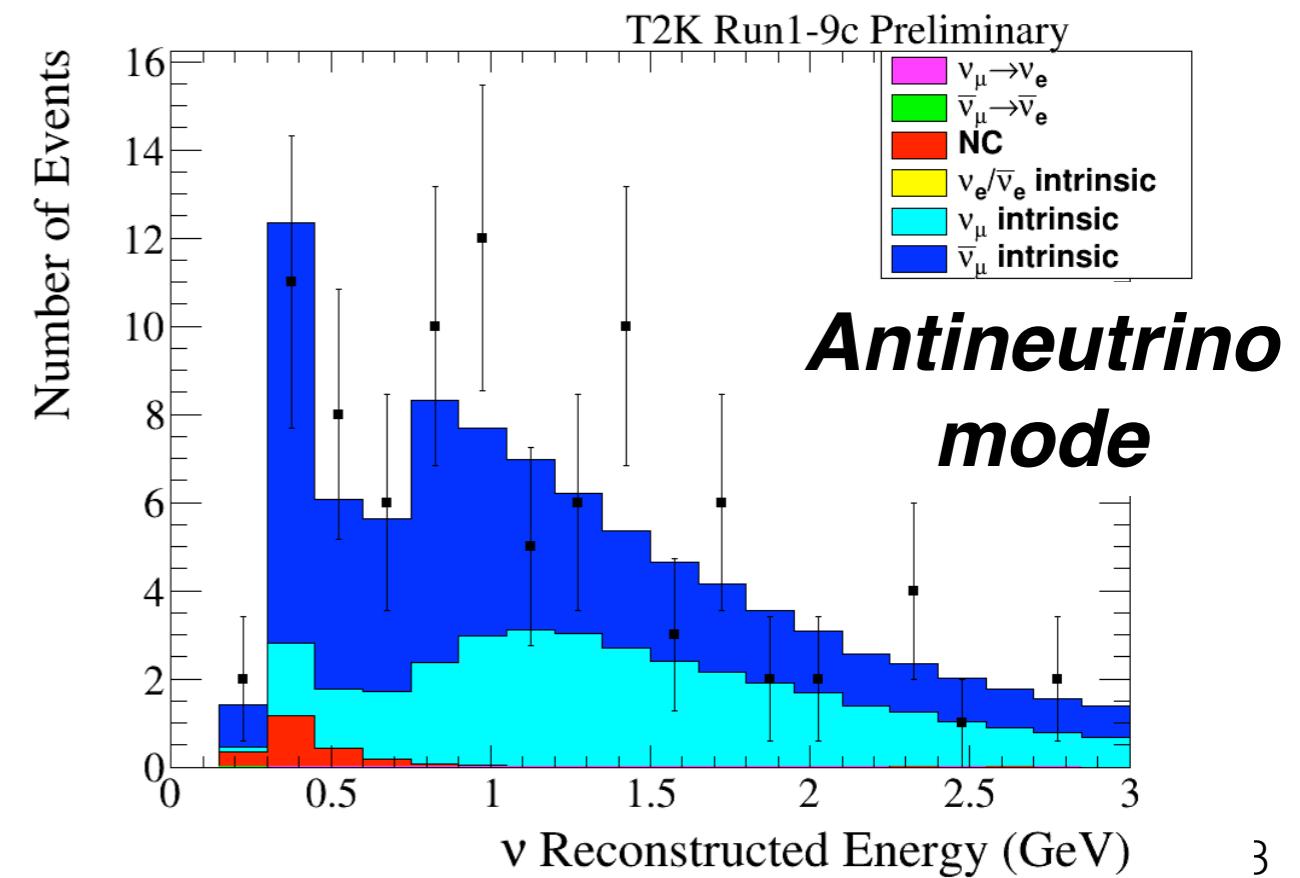
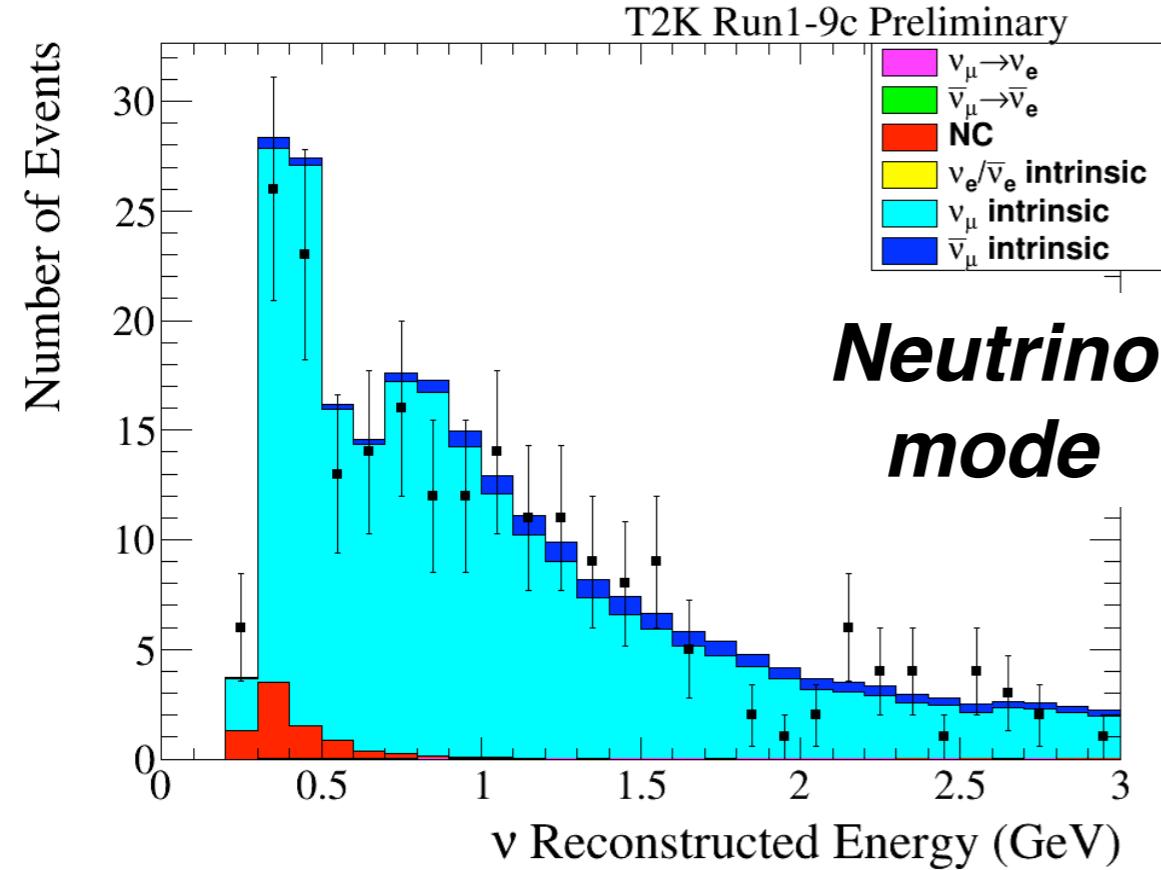
From Nu-Print workshop: <https://indico.fnal.gov/event/15849/timetable/#20180312>

- What are the uncertainties needed for the 2p2h?
 - Large uncertainties on leptonic side (across q0-q3?). Differences between nu and nubar in overall strength.
 - What should be the hadronic final state association? And how much energy into (which) outgoing particles?
- Insufficiency of current resonance model to describe pion kinematics, low Q2 discrepancies.
 - 2p2h-like processes in resonance production?
 - Need NC for significant backgrounds (or exotic signals)
- Transition region! Incomplete experimental and theoretical footing
- Need heavier targets (Ar!) model efforts
- nue/numu uncertainties
- *Kendall adds: NC diffractive processes not explicitly assessed*

T2K: Precision era of $\Delta m_{23}^{31/32}$, θ_{23}

Data through Run 9c:
 2.62×10^{21}
Neutrino 2018 results

ν_μ and $\bar{\nu}_\mu$ candidates

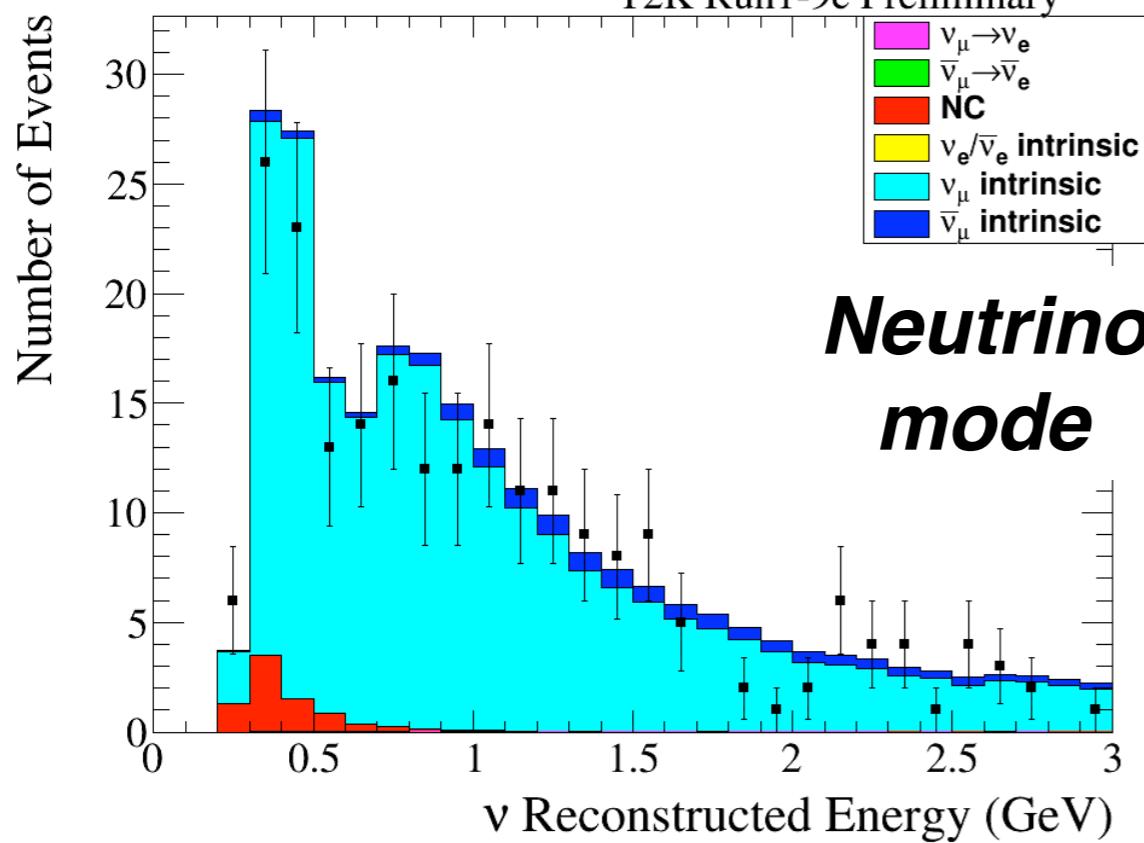


T2K: Precision era of $\Delta m_{31/32}$, θ_{23}

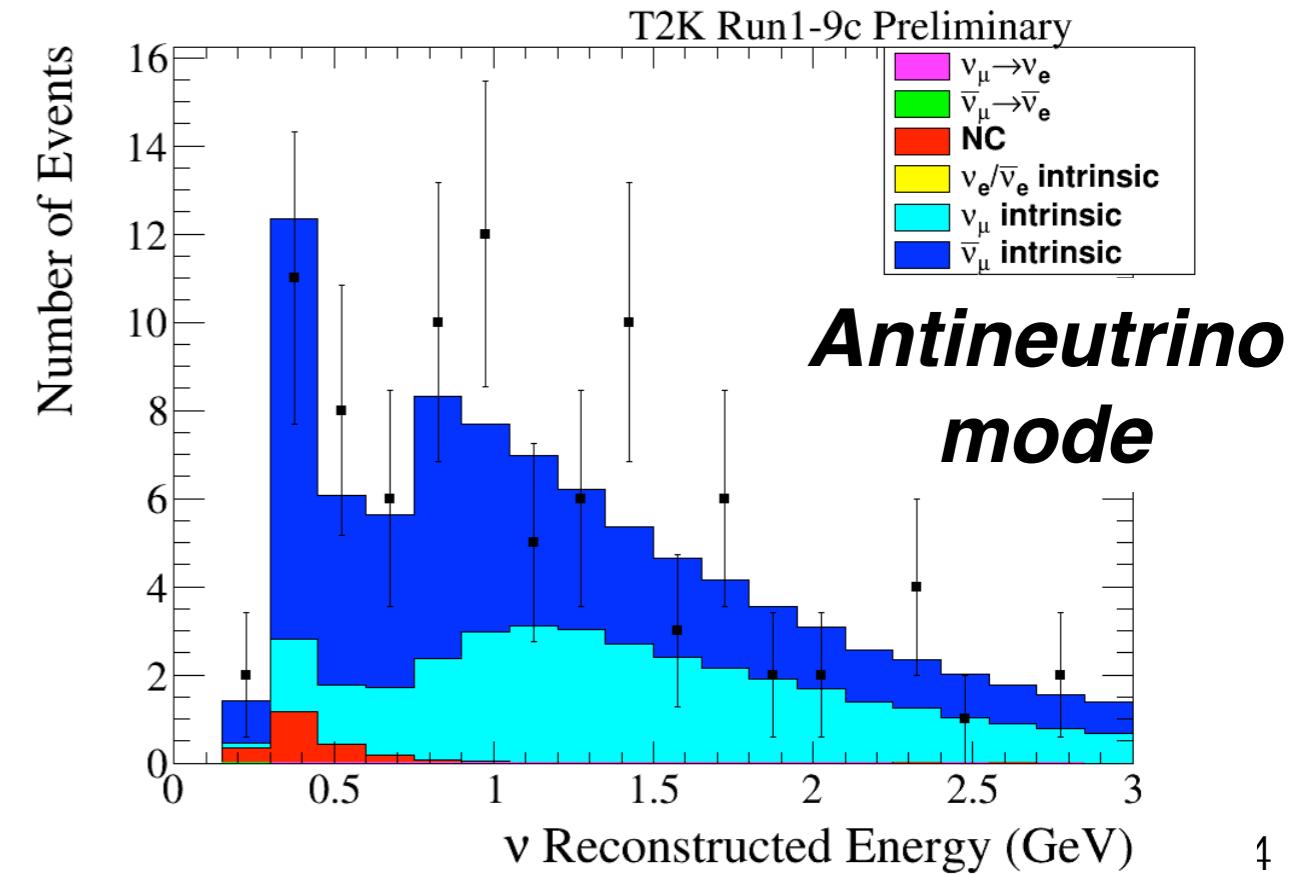
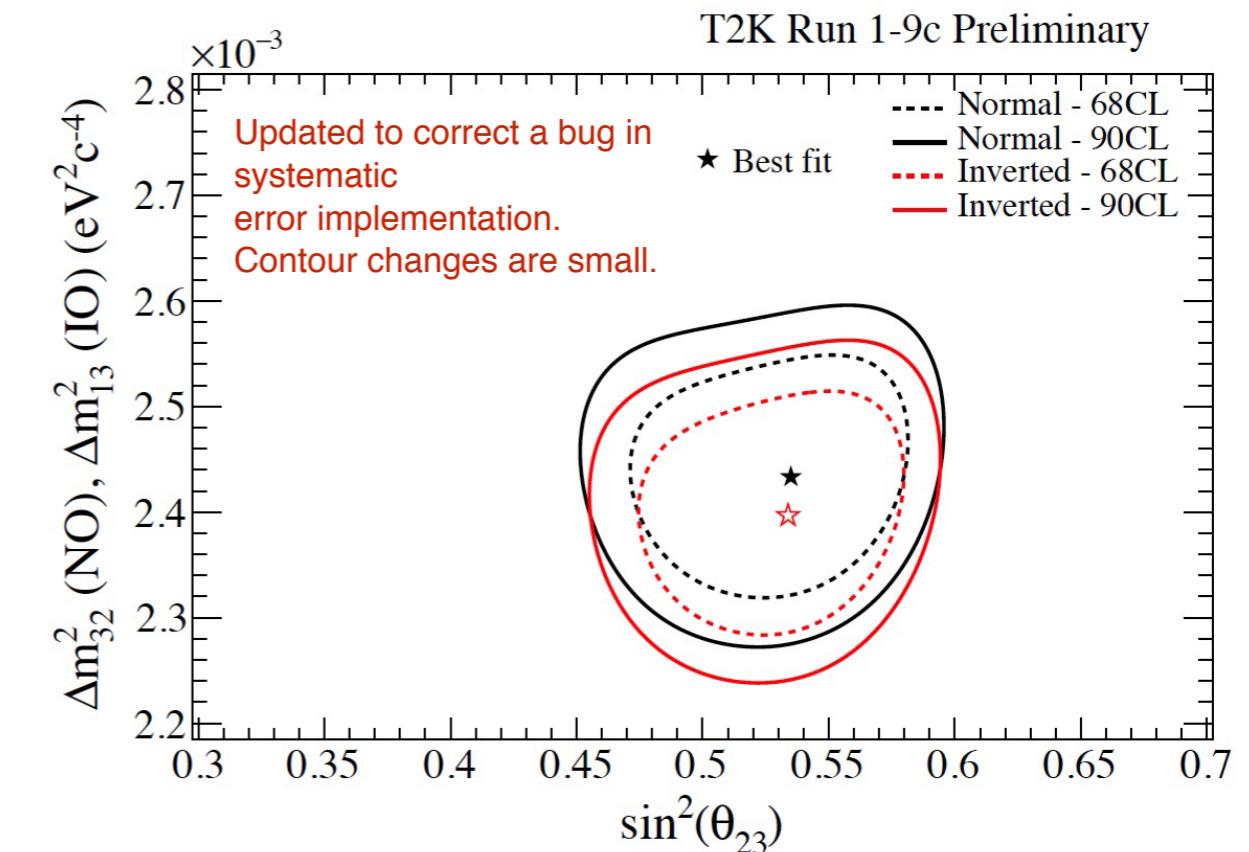
- T2K continues to favor maximal mixing ($\theta_{23}=45\text{deg}$)

Data through Run 9c:
 2.62×10^{21}
Neutrino 2018 results

ν_μ and $\bar{\nu}_\mu$ candidates



Neutrino mode

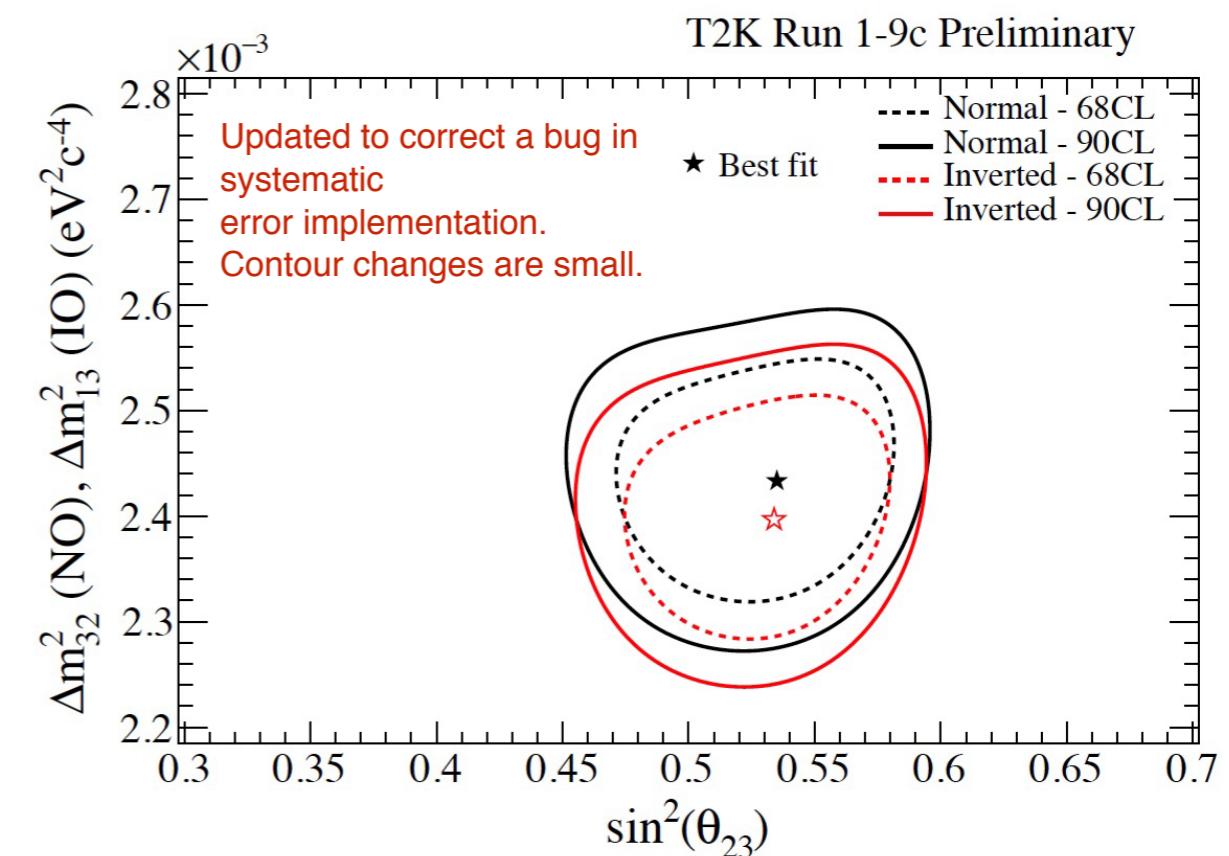
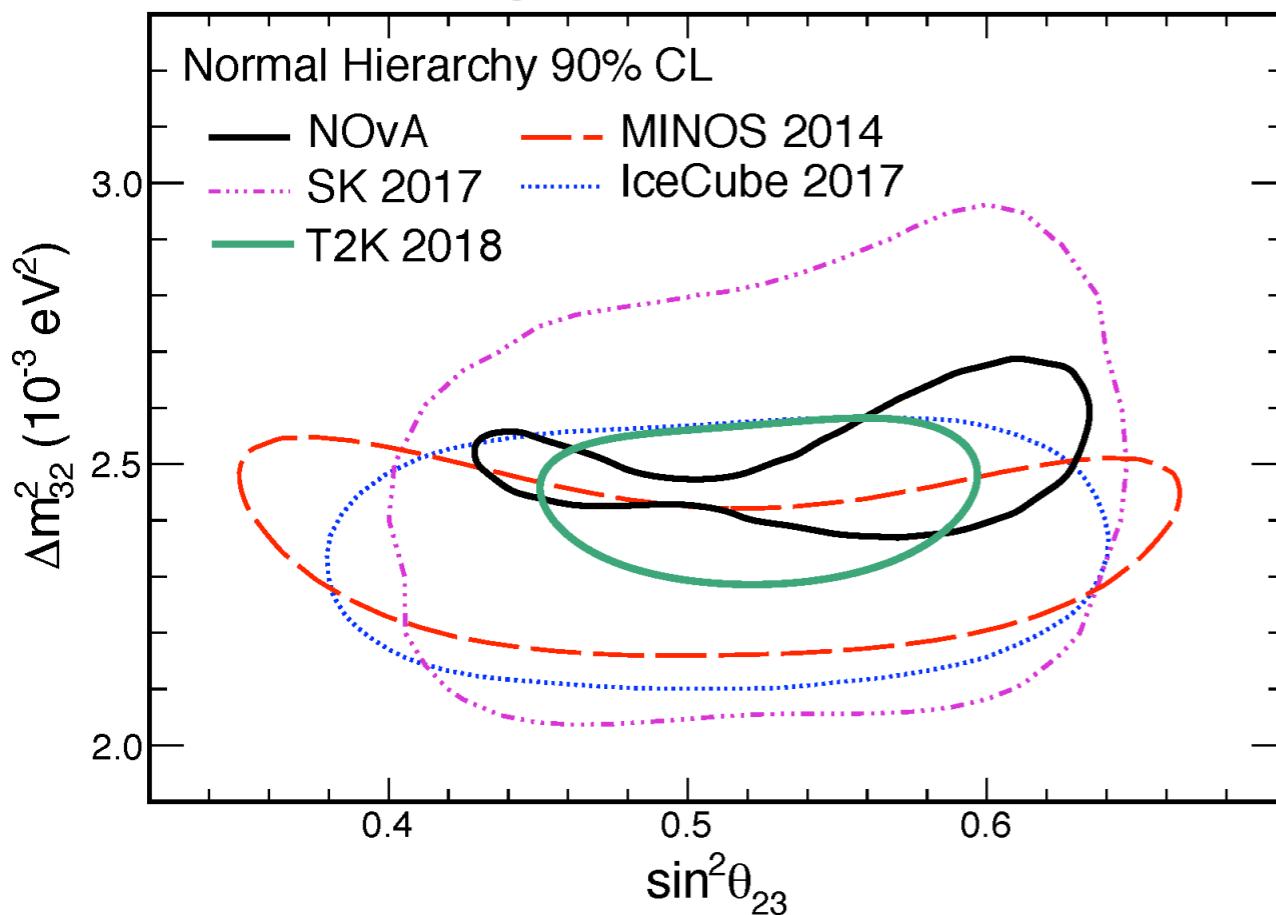


Antineutrino mode

T2K: Precision era of $\Delta m_{31/32}$, θ_{23}

- T2K continues to favor maximal mixing ($\theta_{23}=45\text{deg}$)
- Global picture rapidly changing

NOvA @ Neutrino 2018

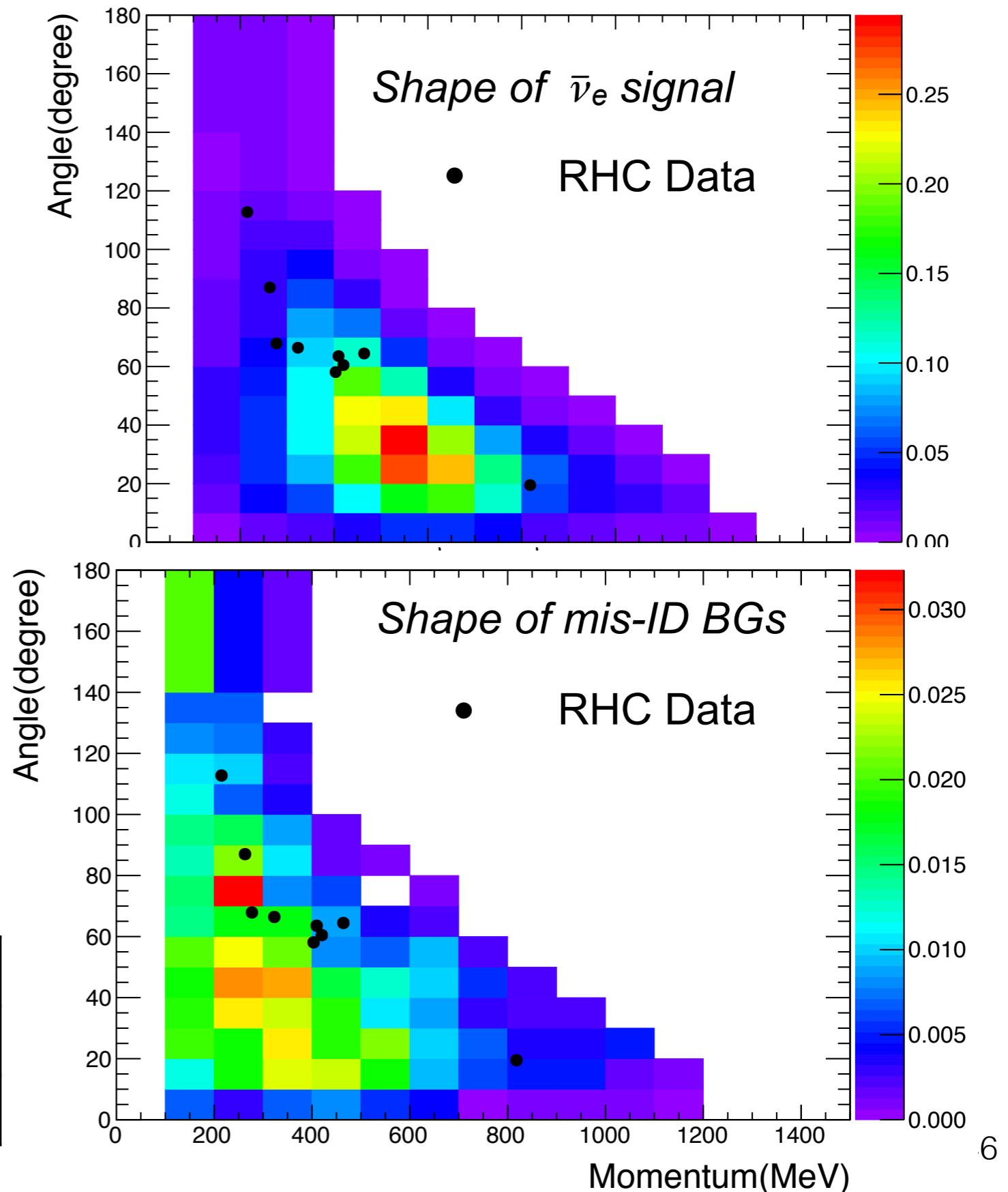


T2K: Is there $\bar{\nu}_e$ appearance?

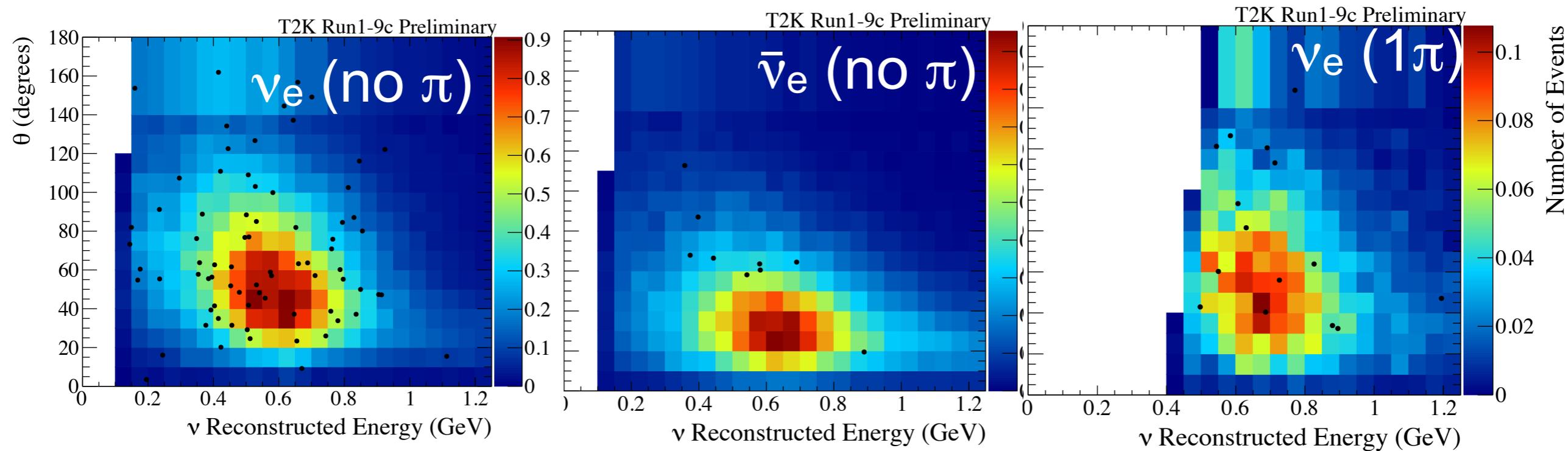
Data through Run 9c:
 2.62×10^{21}
Neutrino 2018 results

- Test hypothesis of appearance (expect 11.8 events) and no appearance (expect 6.5 events)
- Observe 9 events
- No strong statistical statement yet

HYPOTHESIS	P-VALUE
NO appearance	p=0.233
PMNS appearance	p=0.0867

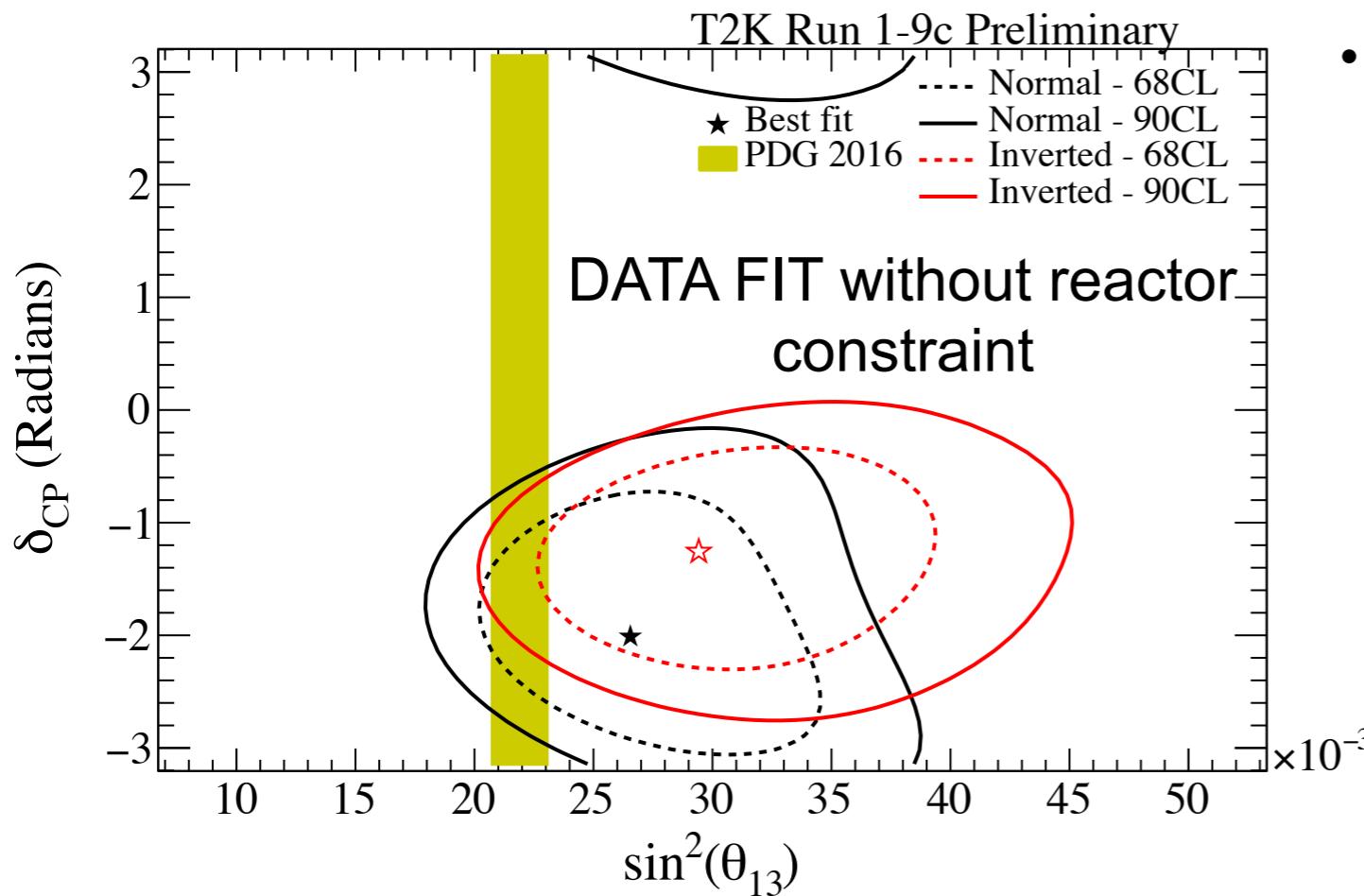


T2K: Window on CPV



SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	
ν mode: ν_e (no pion)	73.8	61.6	50.0	62.2	75
ν mode: ν_e (1 pion)	6.9	6.0	4.9	5.8	15
$\bar{\nu}$ mode: $\bar{\nu}_e$ (no pion)	11.8	13.4	14.9	13.2	9

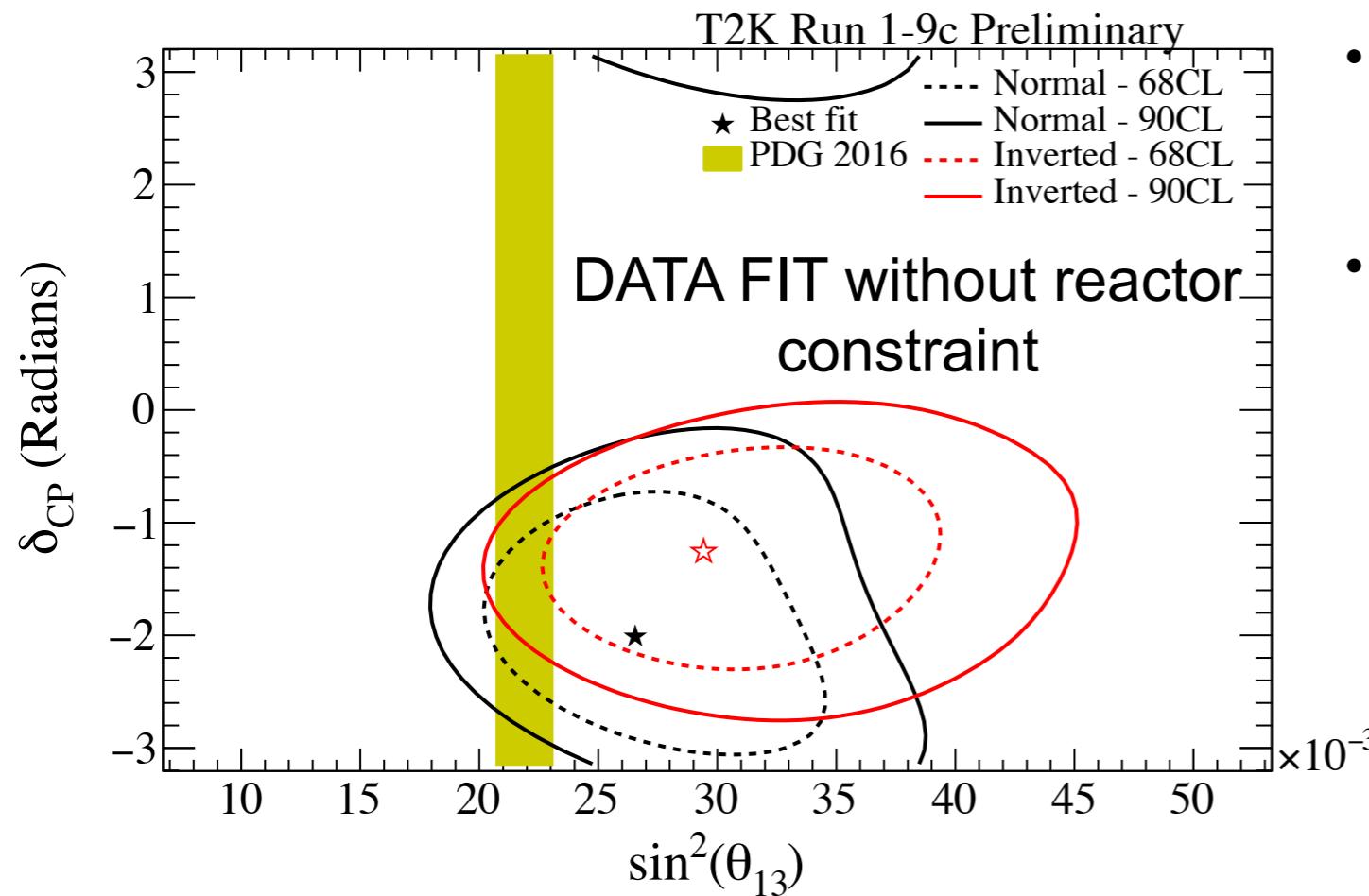
T2K: Window on CPV



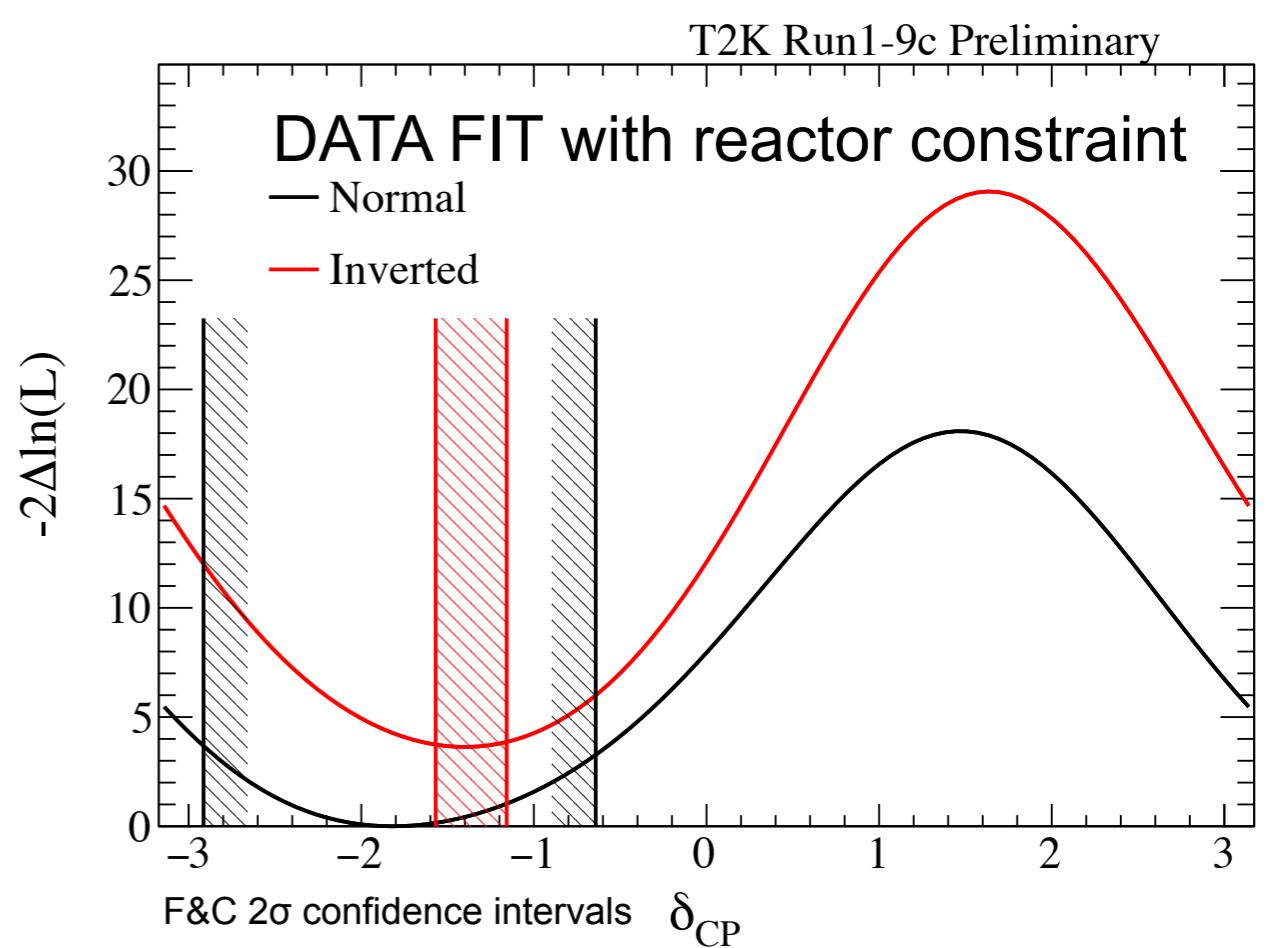
- Consistent with reactor measurements

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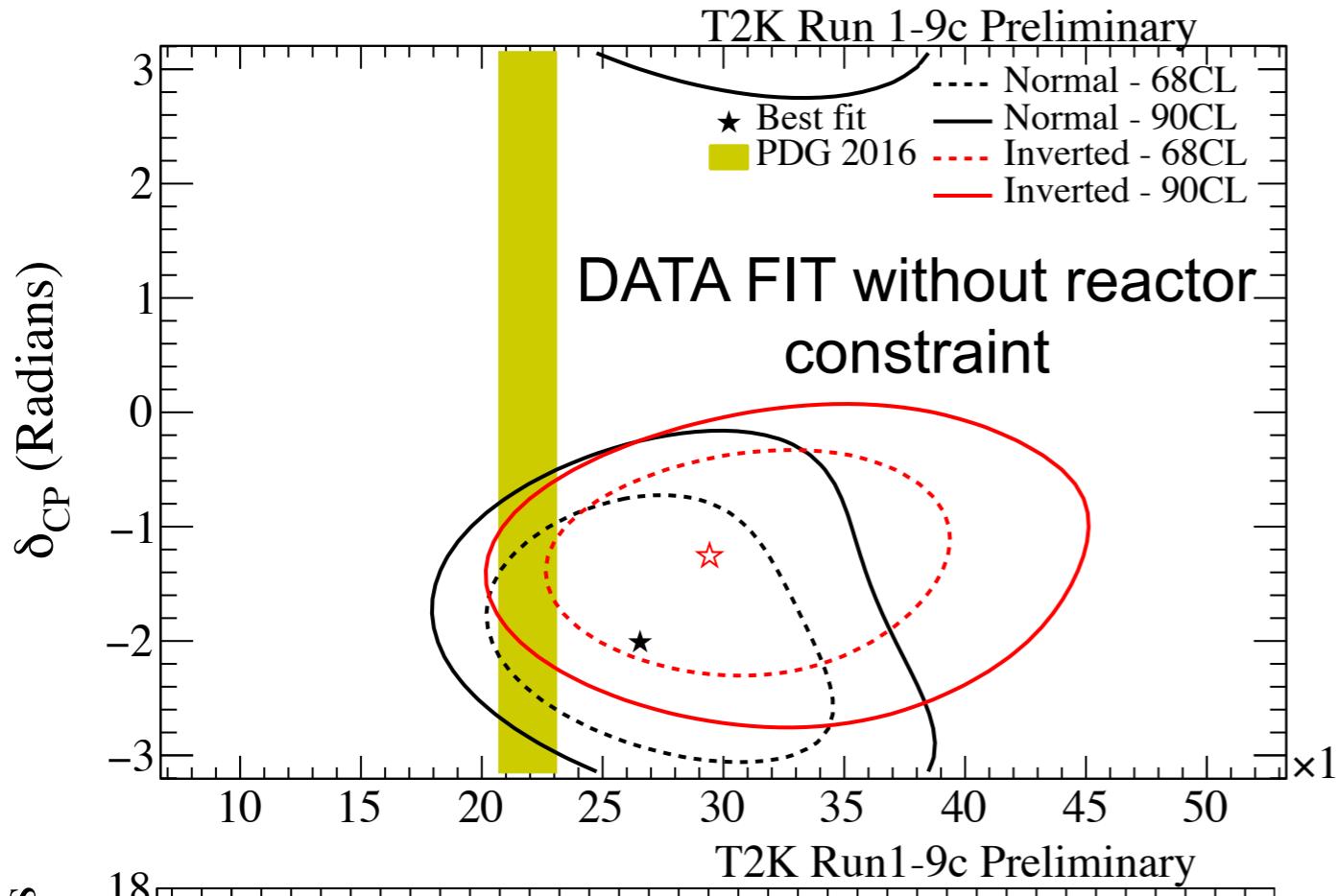
T2K: Window on CPV



- Consistent with reactor measurements
- CP conserving values outside of 2σ region for both hierarchies

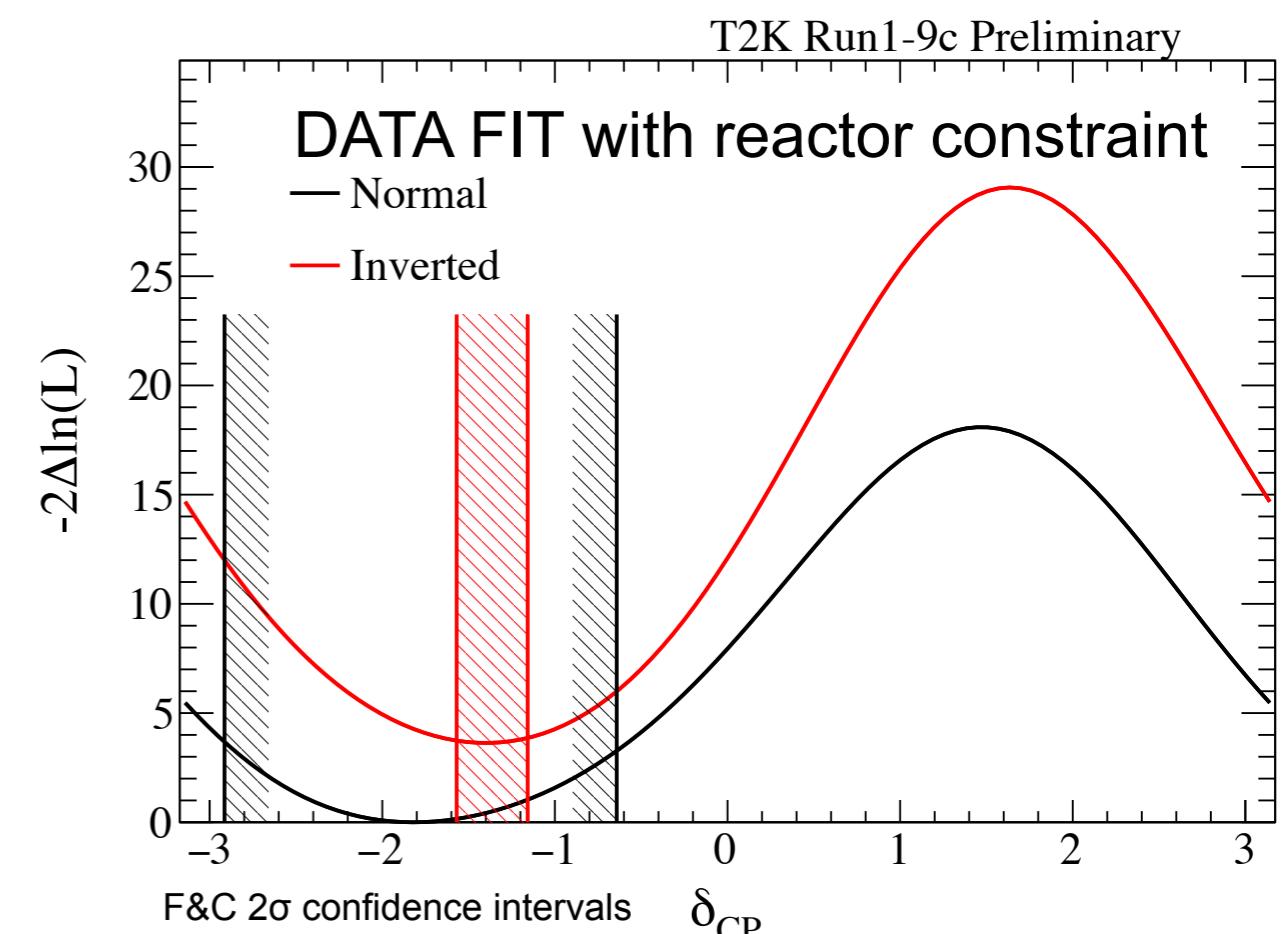
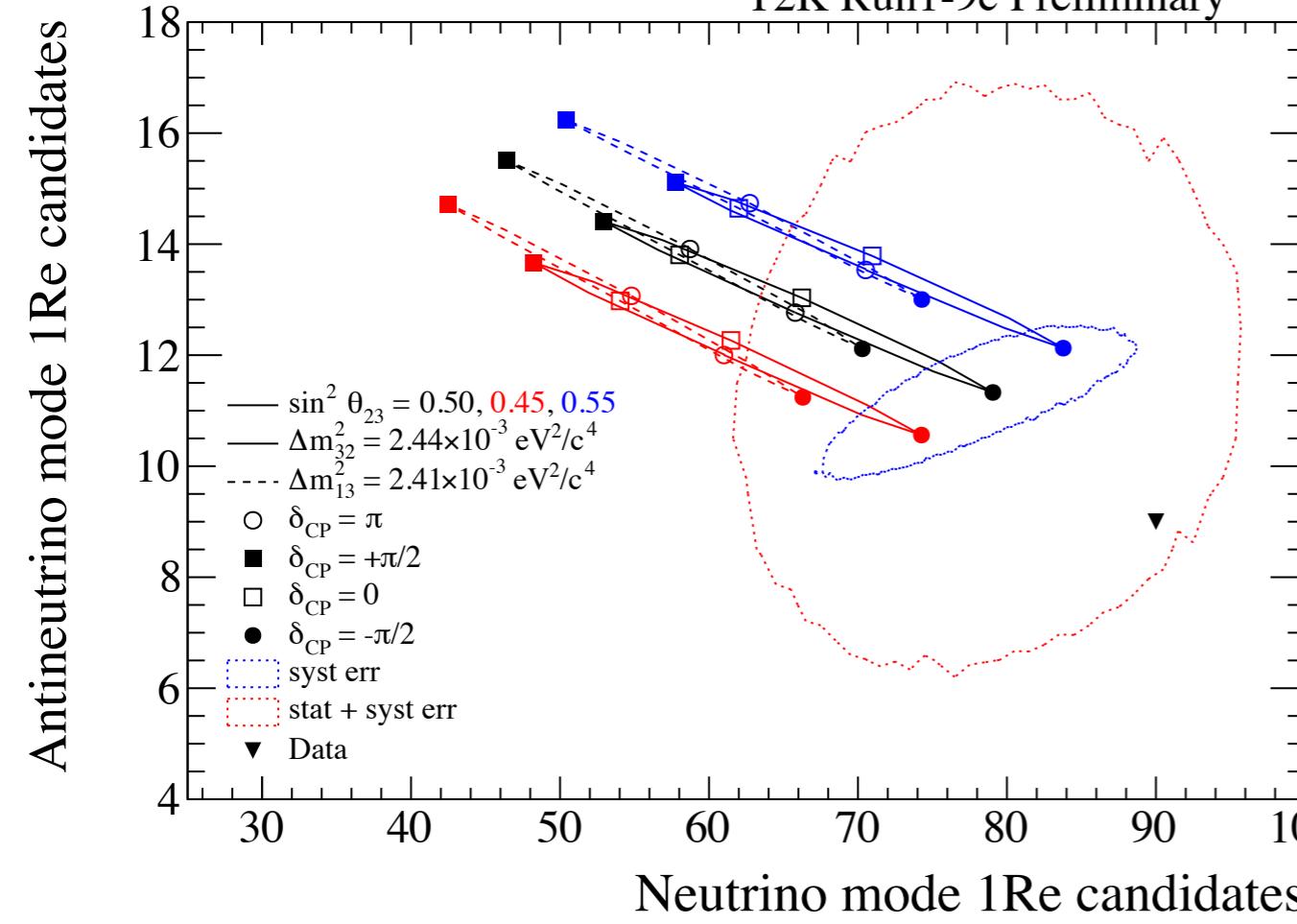


T2K: Window on CPV



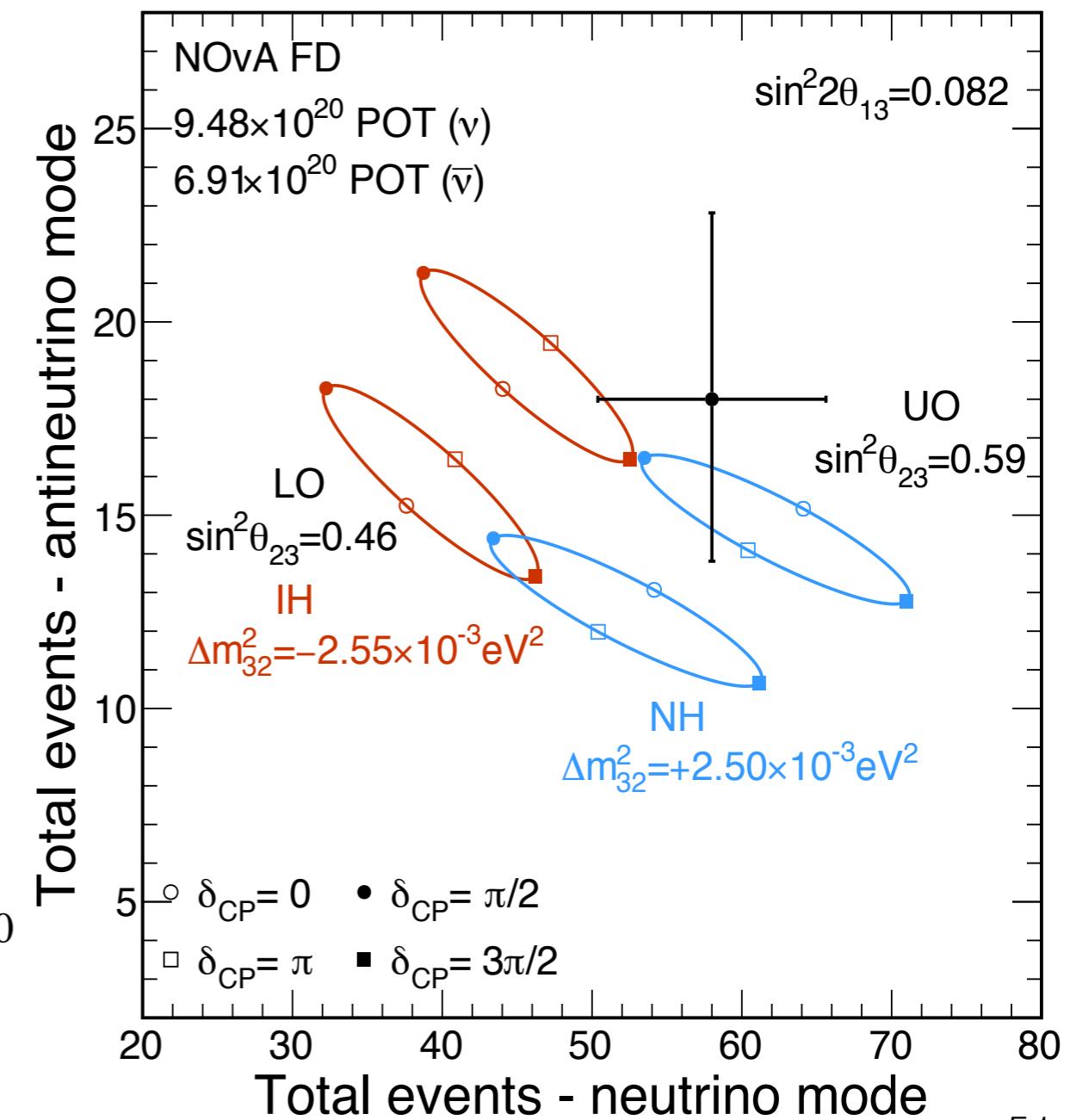
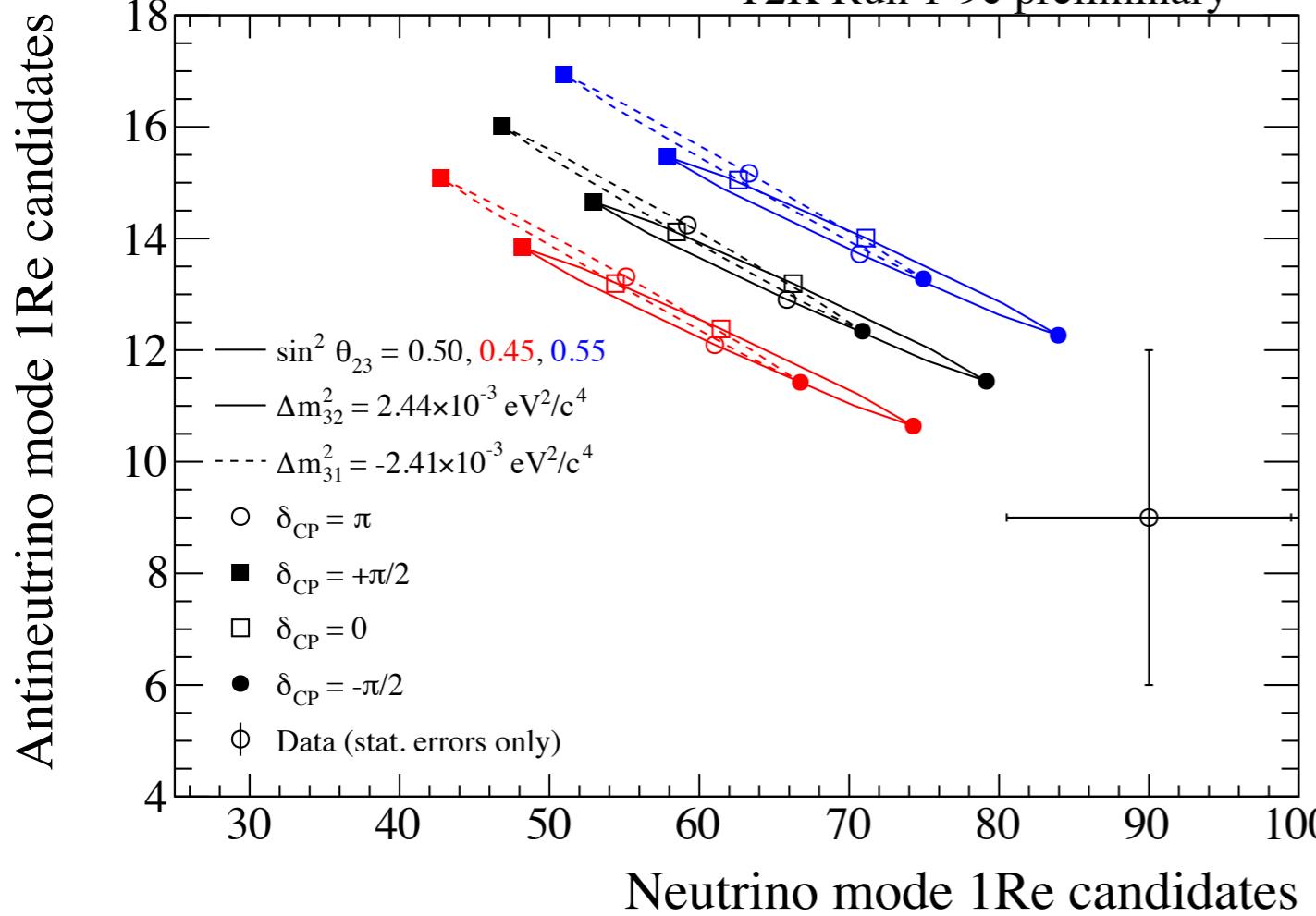
- Consistent with reactor measurements
- CP conserving values outside of 2σ region for both hierarchies

	$\sin^2\theta_{23} \leq 0.$	$\sin^2\theta_{23} > 0.$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1



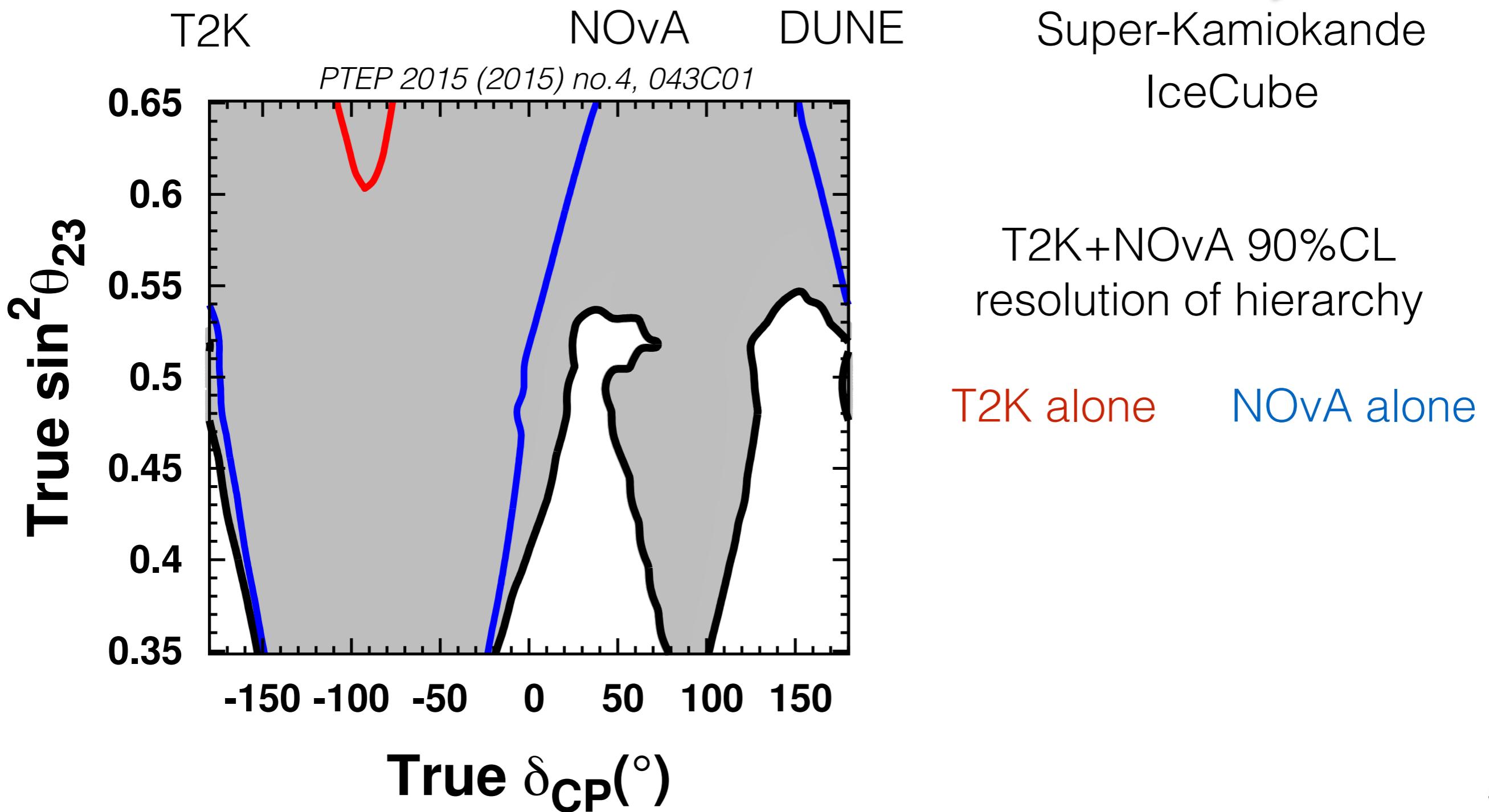
“Competition” with NOvA

- NOvA2018: prefers normal hierarchy, non-maximal θ_{23} and disfavors lower octant; exclude $\delta_{CP}=\pi/2$ in IH at $>3\sigma$
- $\bar{\nu}_e$ appearance with 18 events (5.3 background expected)



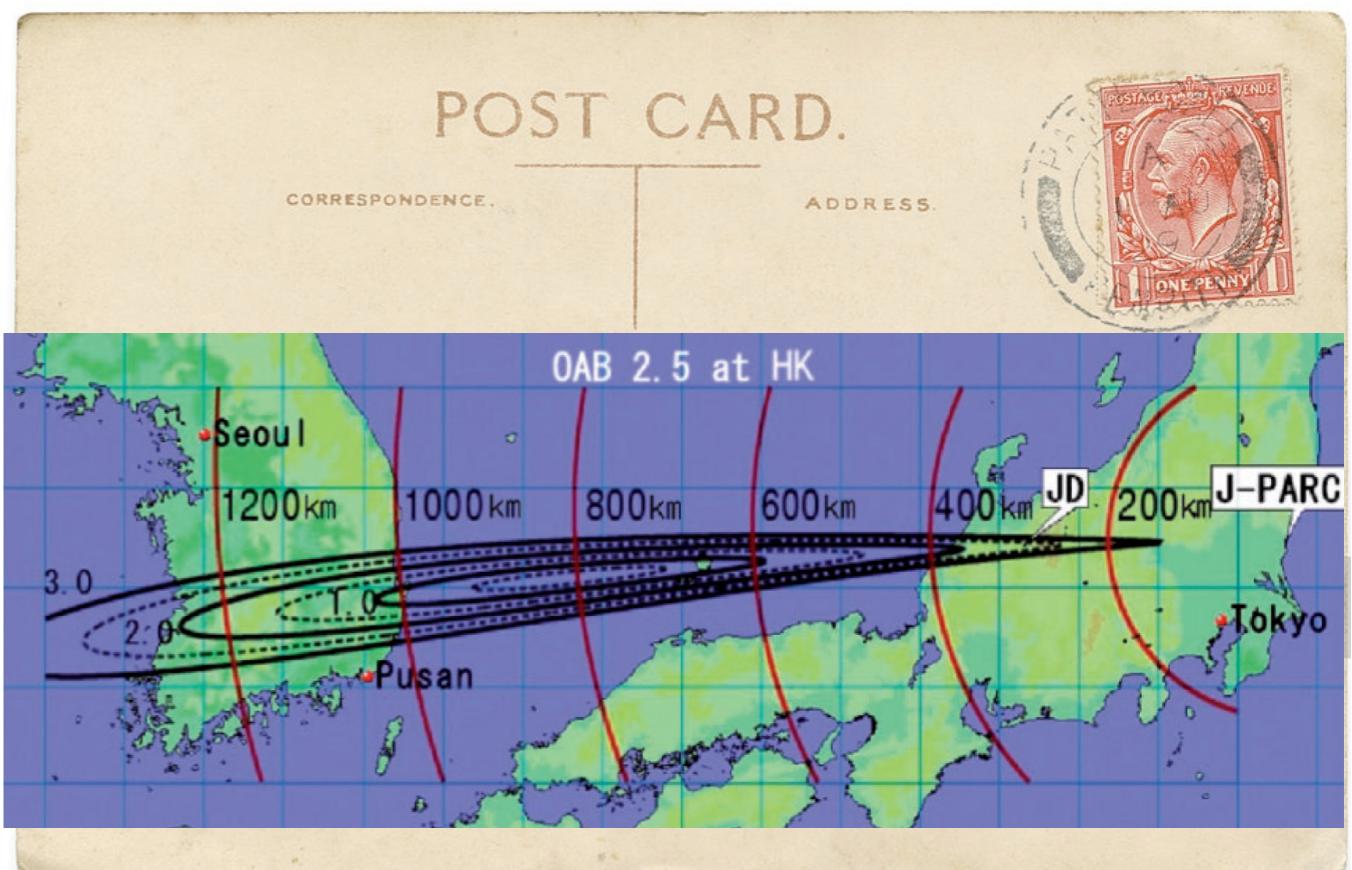
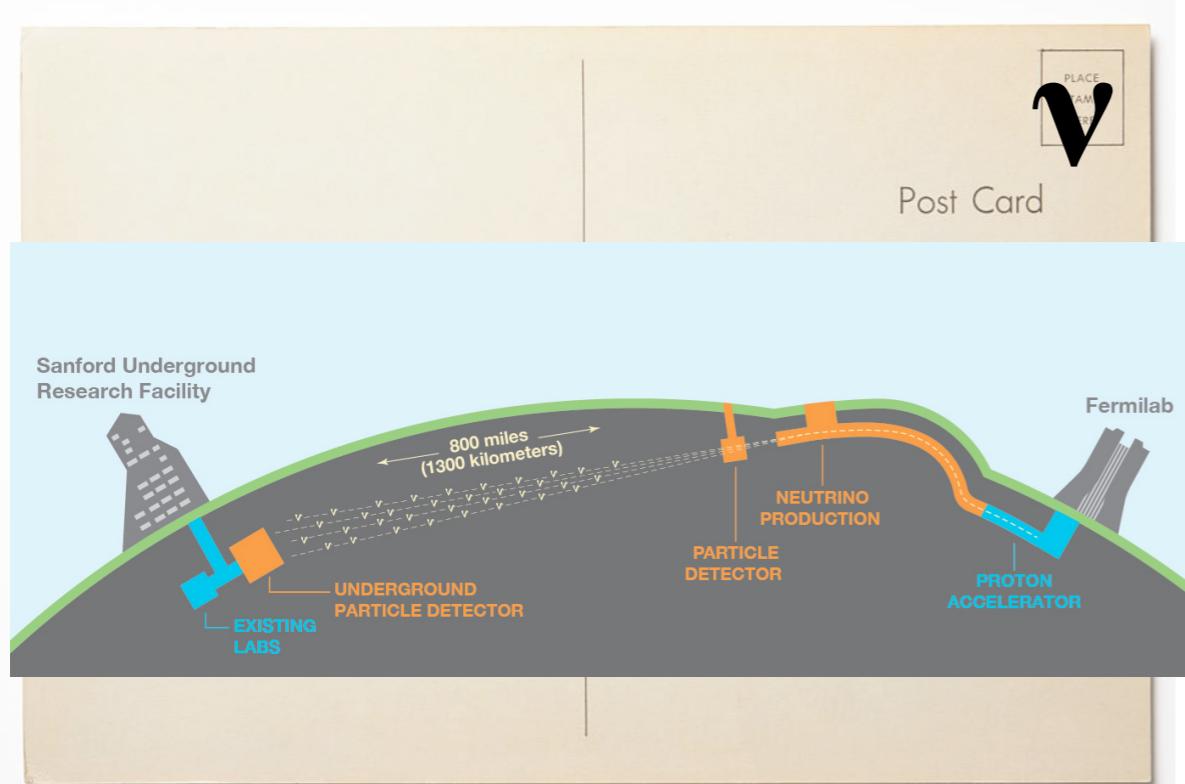
Complementary window: Matter effects

Strength of matter effect

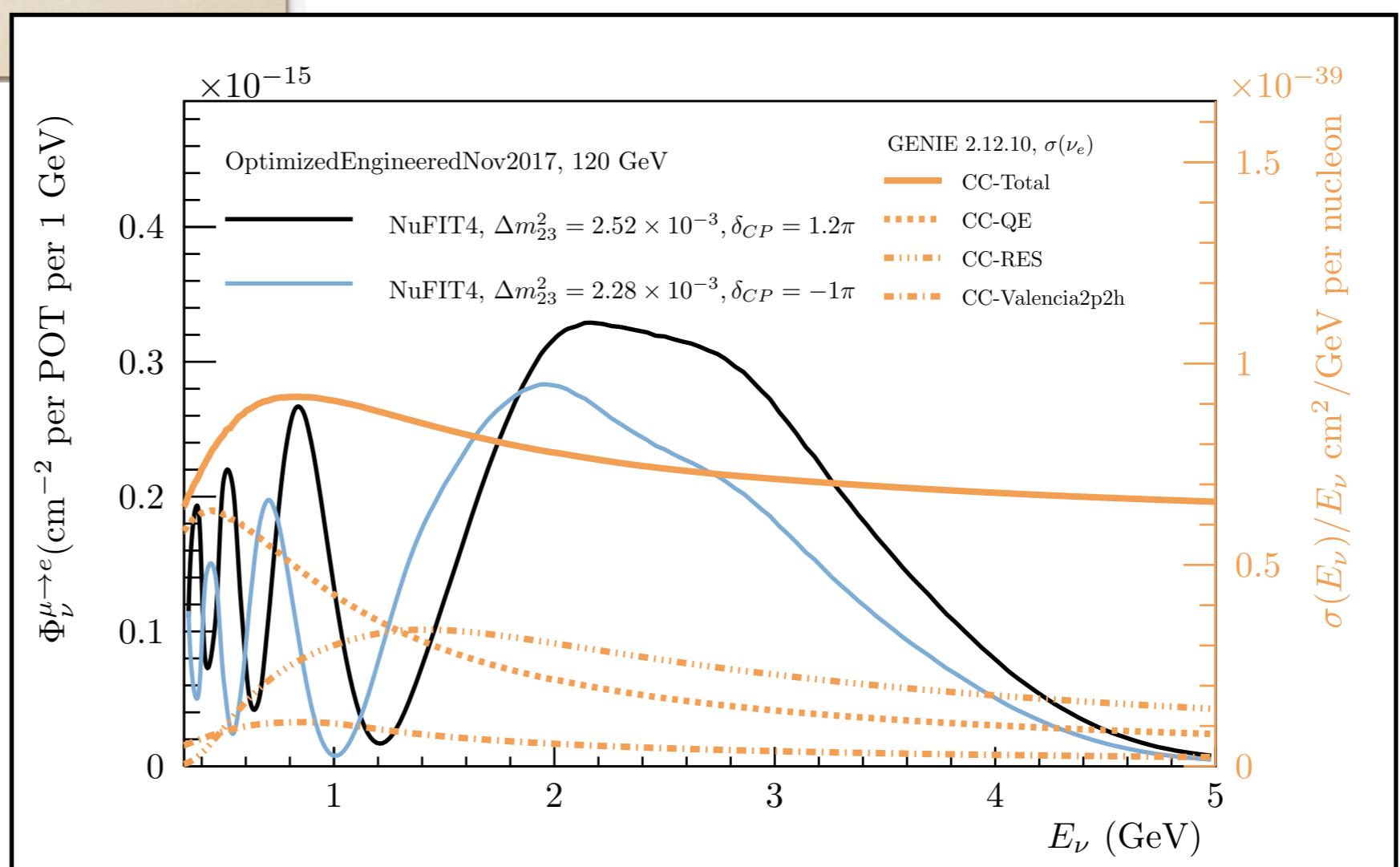
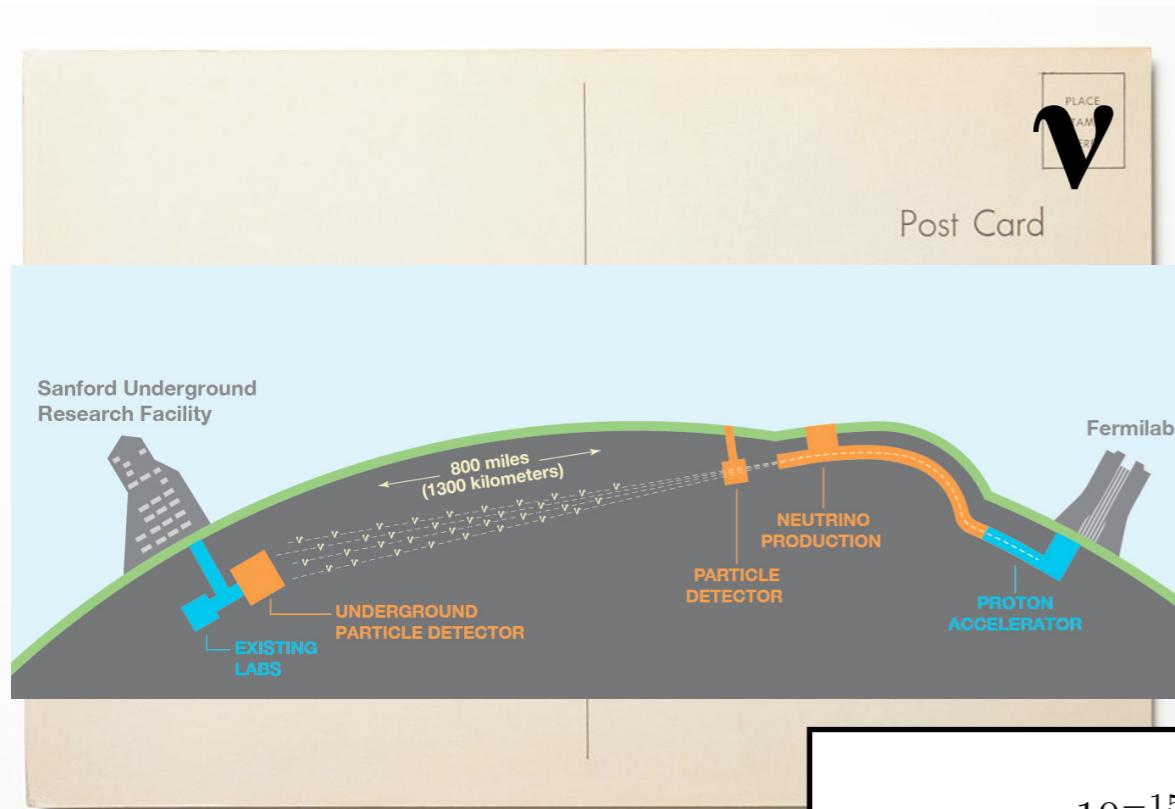


See the world! with neutrinos

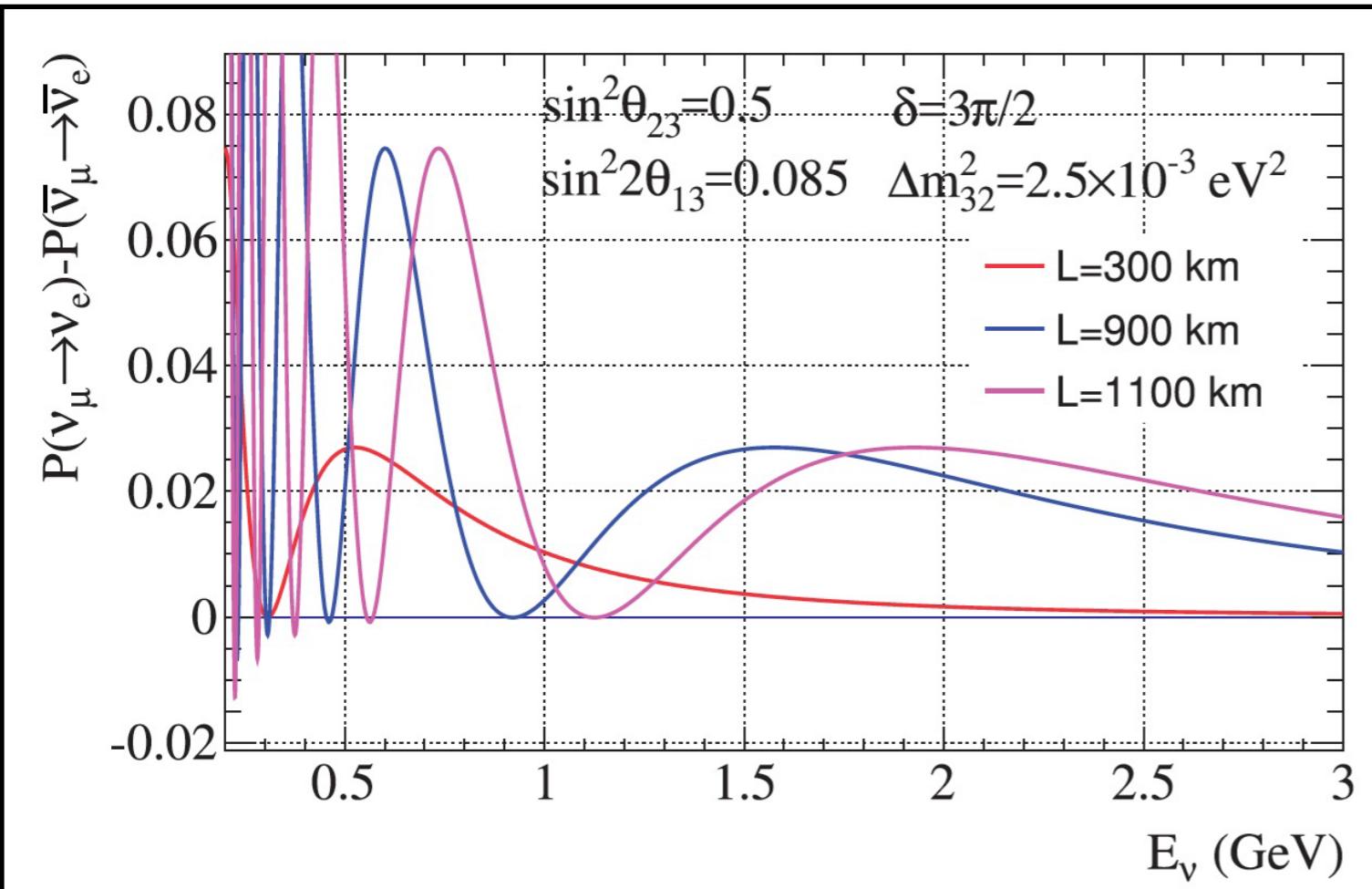
Two big projects planned



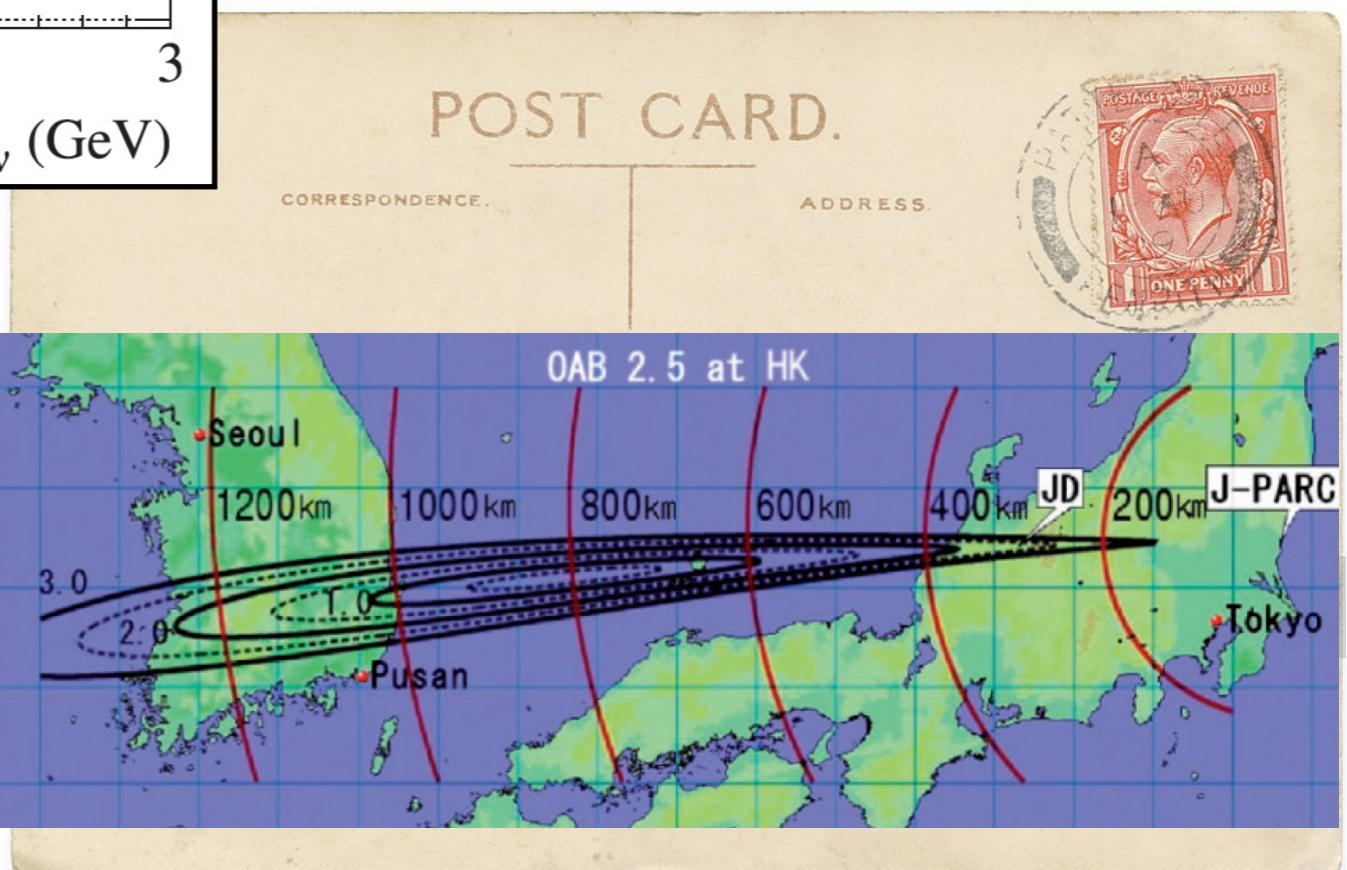
Deep Underground Neutrino Experiment (DUNE)



Tokai-to-Hyper-Kamiokande (T2HK) (T2HKK?)



Prog. Theor. Exp. Phys. 2018 , 063C01



T2K overall uncertainty budget

Error source	1-ring μ -like		1-ring e-like			
	v-mode	\bar{v} -mode	v-mode	\bar{v} -mode	v-mode CC1 π	v_e/\bar{v}_e

- **Four flavors, five samples:** predominantly neutrino beam or predominantly antineutrino. v_μ with no pion, v_e with pion and without pion
- **Primarily CCQE, 2p2h, resonant pion production processes**
 - But, NC pion production backgrounds for both v_e and v_μ ; photons mimic nue , pion may mimic v_μ

T2K overall uncertainty budget

Error source	1-ring μ -like		1-ring e-like			
	v-mode	\bar{v} -mode	v-mode	\bar{v} -mode	v-mode CC1 π	v_e/\bar{v}_e
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- Total uncertainty is about 5% - 18%, sample dependent
 - Near detector reduces uncertainty by about a factor of ~2, recall wide flux, different acceptance, and $v_\mu \rightarrow v_e$ inferences

All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
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$$N_{FD}^{\alpha \rightarrow \beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true}; \mathbf{p}_{reco})$$

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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
$\sigma(v_e)/\sigma(v_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1 γ	0	0	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

- Detector and final state interactions (pion reinteraction model)

Includes some cross section uncertainties, but this also lumps purely detector effects (e.g. secondary interactions) as both are tuned to external pion scattering data)

Also includes “photonuclear” effect

T2K overall uncertainty budget

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- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint** (limited by acceptance, different energy dependance)
 - Convolves input priors in a nontrivial way

T2K overall uncertainty budget

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- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
 - Nucleon removal energy; Large uncertainty before upcoming e,e'p constraint
 - Other uncertainties ALSO shift the true-reco response — 2p2h (in ND) and FSI (top line)

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- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
- **Differences between v_μ and v_e cross section**
 - Theoretically driven uncertainty, difficult to probe experimentally, 1 parameter

T2K overall uncertainty budget

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- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
- **Differences between v_μ and v_e cross section**
- **Single photon production** - difficult to measure at ND, small rate, large uncertainty, 1 parameter