Long baseline neutrino experiments
(accelerator LBL & reactor)

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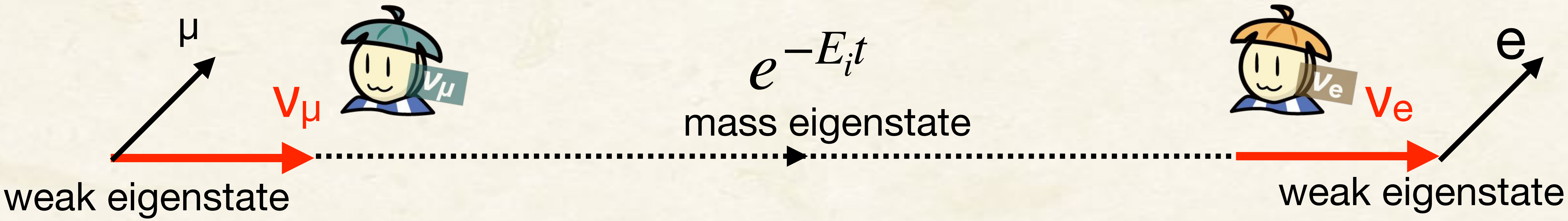
ICHEP2018, Seoul
July 9, 2018

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i} |\nu_i\rangle$$

Weak eigenstates — Mass eigenstates



Production — Propagation — Detection

Flavor change during flight

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$ (for 2 flavor)

Δm^2: mass-squared difference

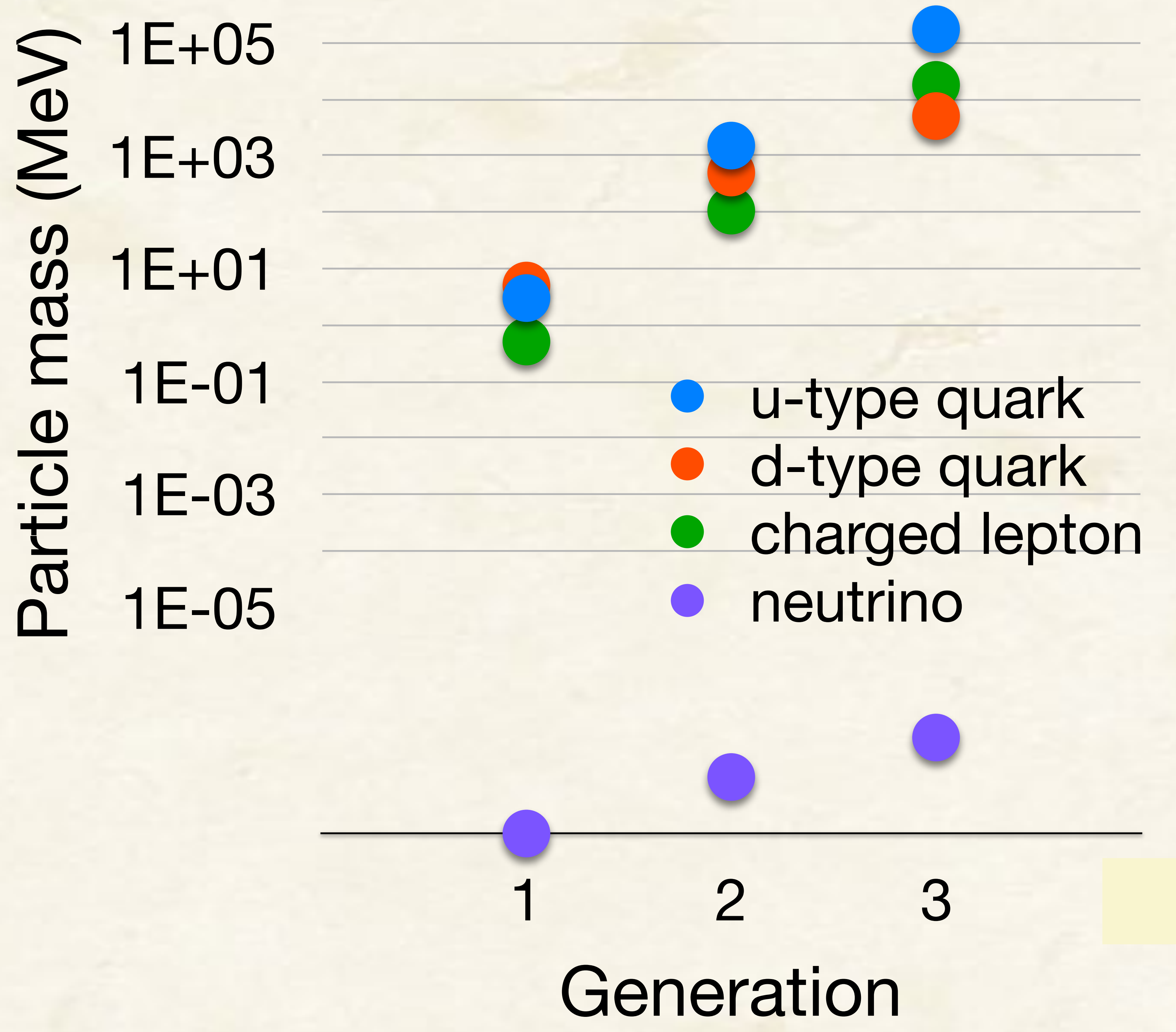
θ: mixing angle

Quantum effect over very macroscopic length!

20 years since its discovery…

We learned a lot about neutrinos through **neutrino oscillation**, but many questions emerged and remains

- Origin of **tiny mass**
  - Why mass is much smaller than other fermions?
- **Large mixing** parameters
  - Why so different from quarks?
  - Symmetry behind the pattern?
- **Mass hierarchy (ordering)**
  - Which is the heaviest?
- **CP** violation
  - Is it violated just as in quarks?
- Extra neutrino **families**?



Properties of neutrino are considered to be connected with fundamental questions

- Source of baryon asymmetry of Universe?
- Very high scale physics? (seesaw?)
- Origin of generations?

Oscillation parameter status

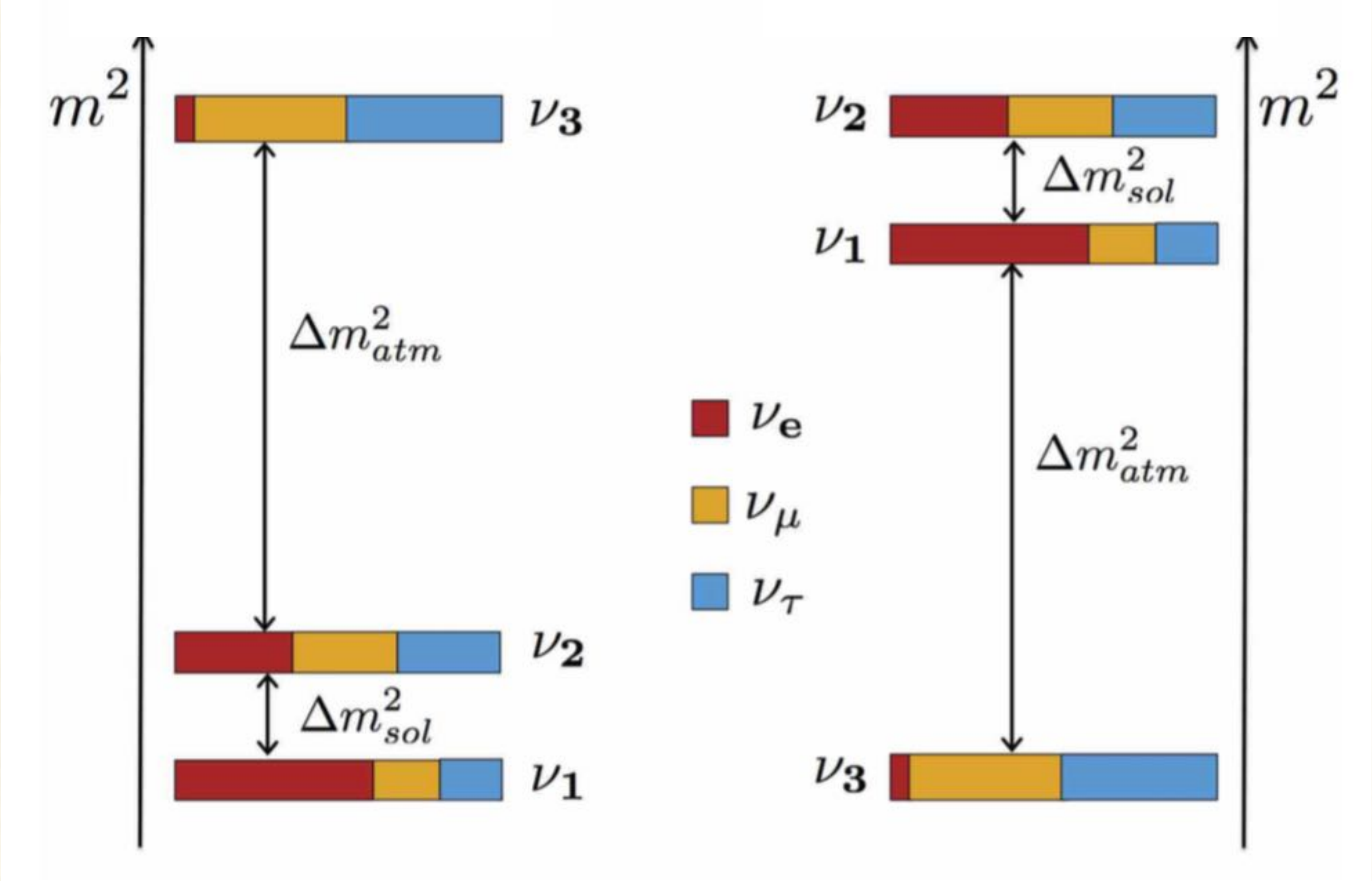
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

M. Tórtola @ NEUTRINO2018

https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50±0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)



Current major targets

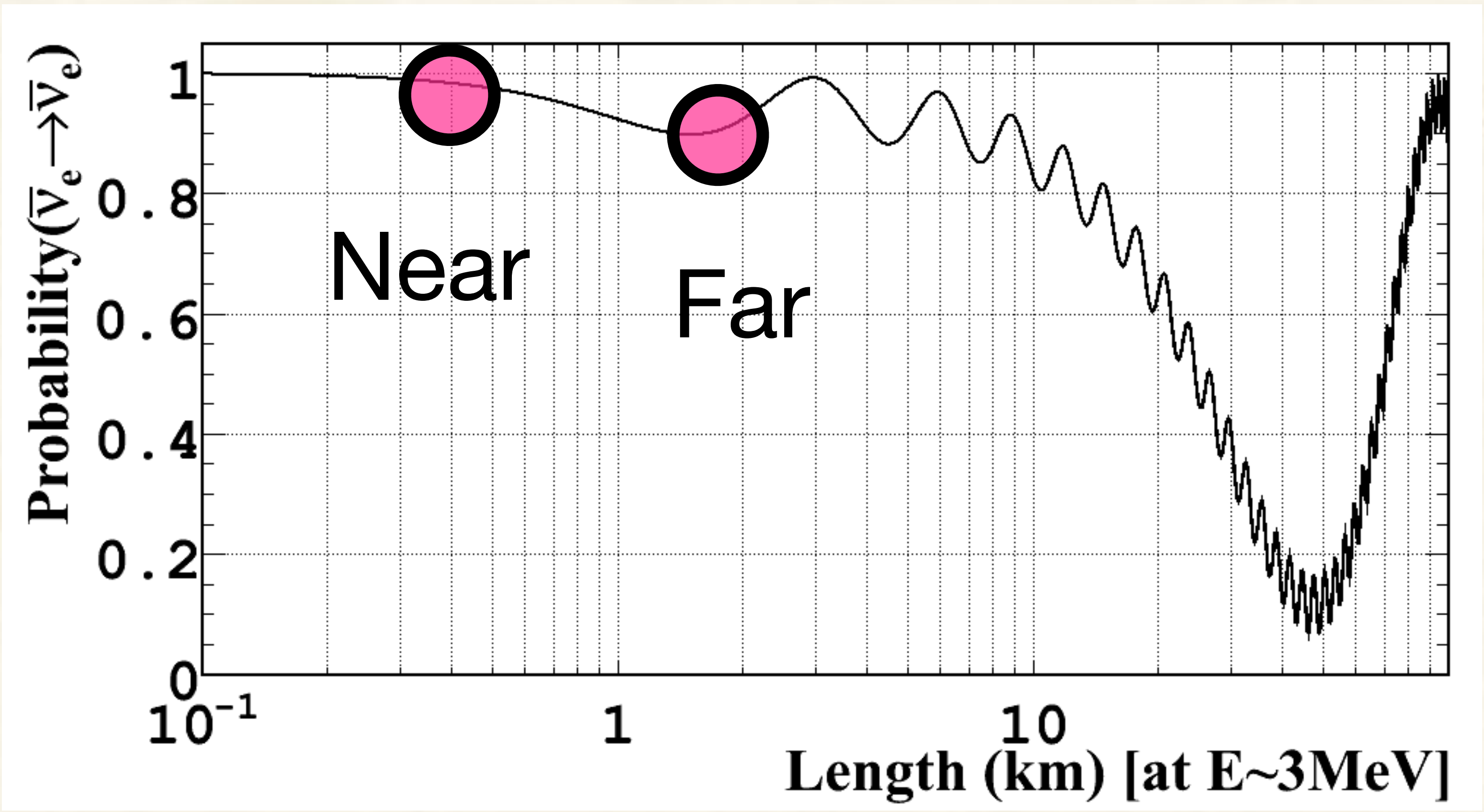
- More precision measurements
- CP violation
- Mass hierarchy
- θ_{23} octant (<=>45°?)

Reactor θ_{13} measurement

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m^2_{ee} L}{4E}\right] - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left[\frac{\Delta m^2_{21} L}{4E}\right]$$

negligible at ~1km

At ~km with reactor ν_e energy, almost pure **$\sin^2 2\theta_{13}$** measurement



Inverse beta decay for detection (delayed coincidence)

$\nu_e + p \to e^+ + n$

captured on Gd after thermalization

prompt signal

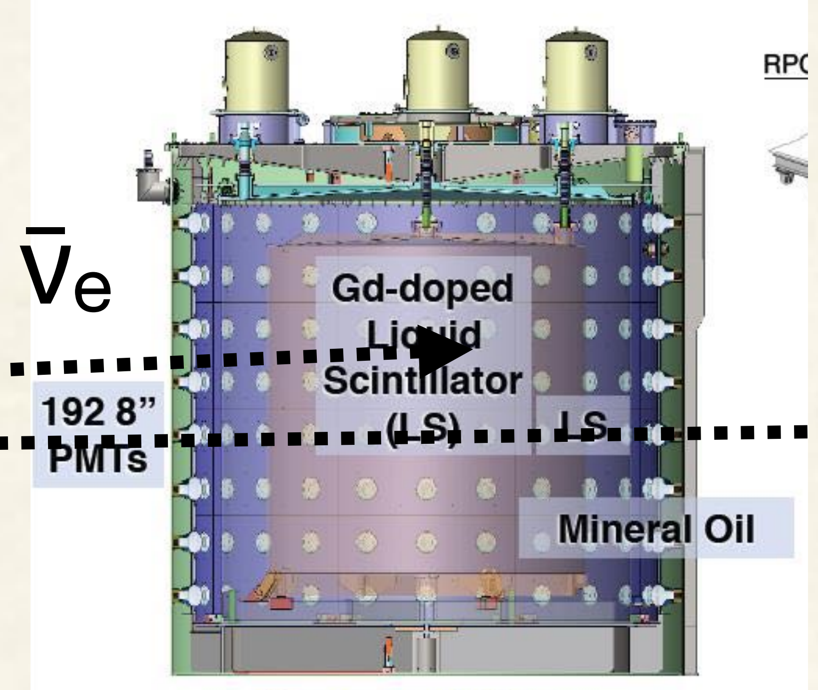
delayed signal

6×10^{20} $\bar{\nu}_e$/s/3GW$_{th}$

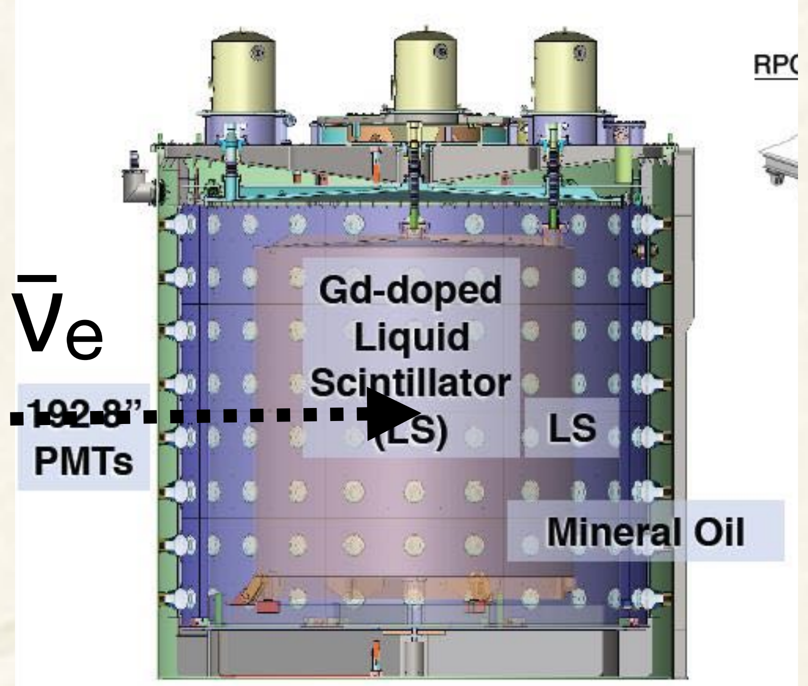
$\bar{\nu}_e$ $\bar{\nu}_e$ $\bar{\nu}_e$ $\bar{\nu}_e$

reactor

Near detector

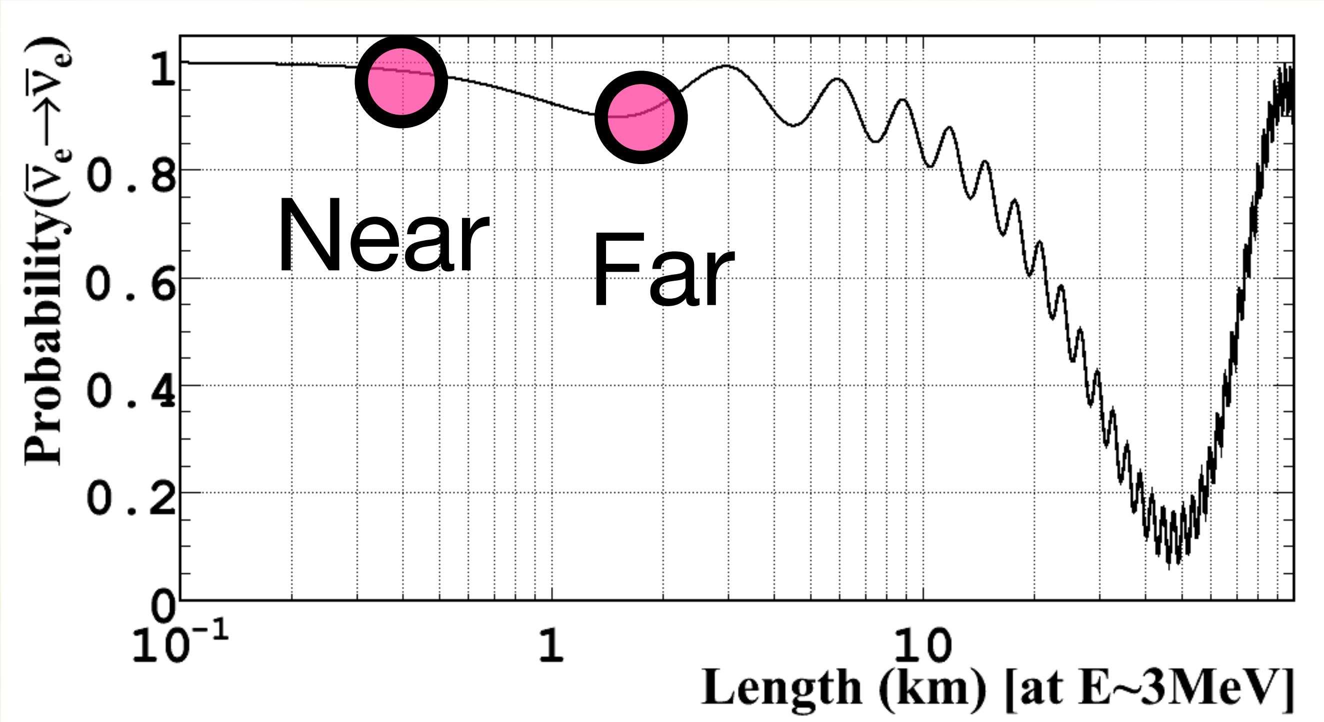


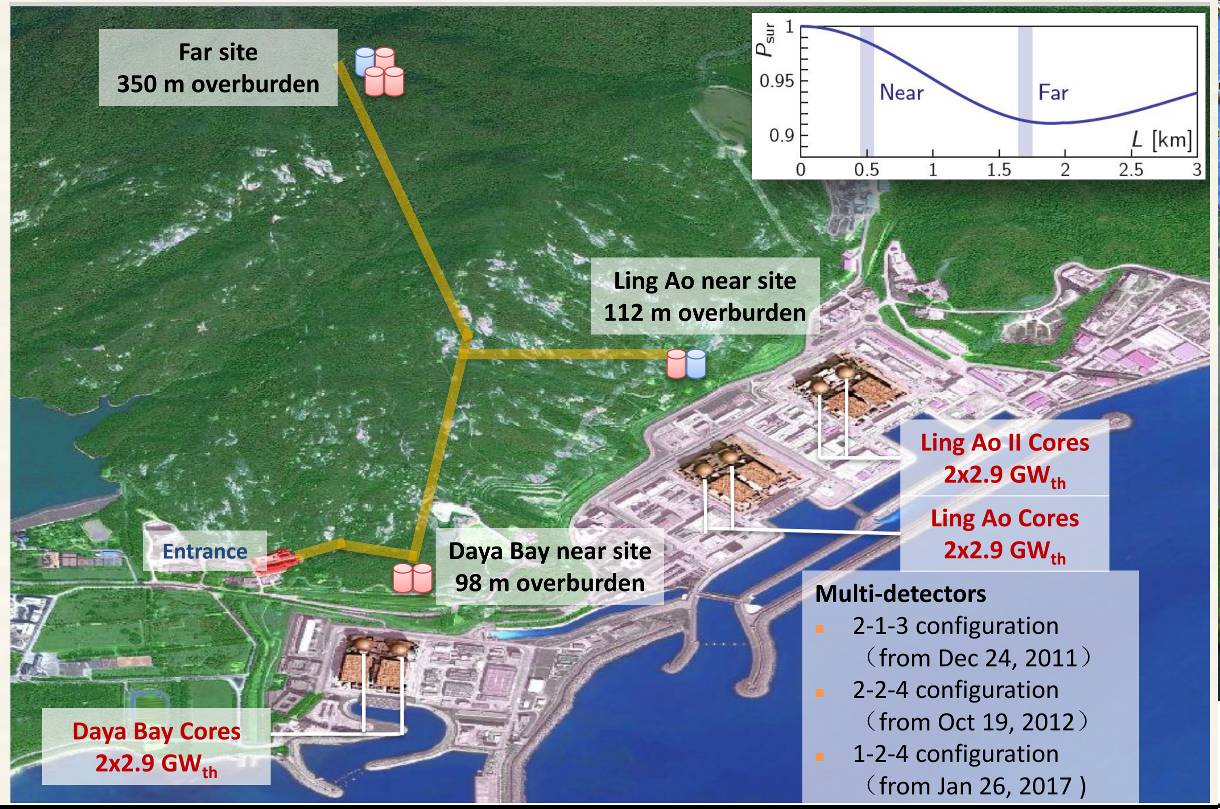
Far detector

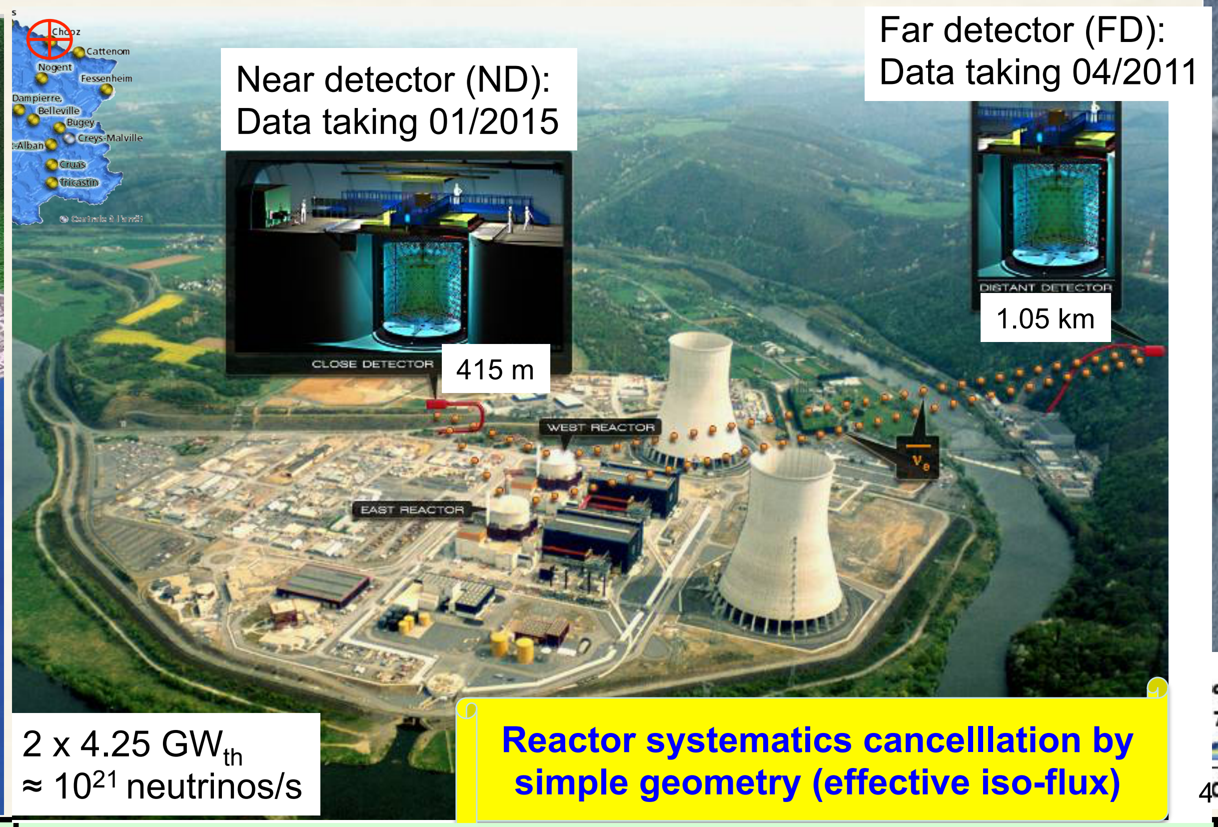


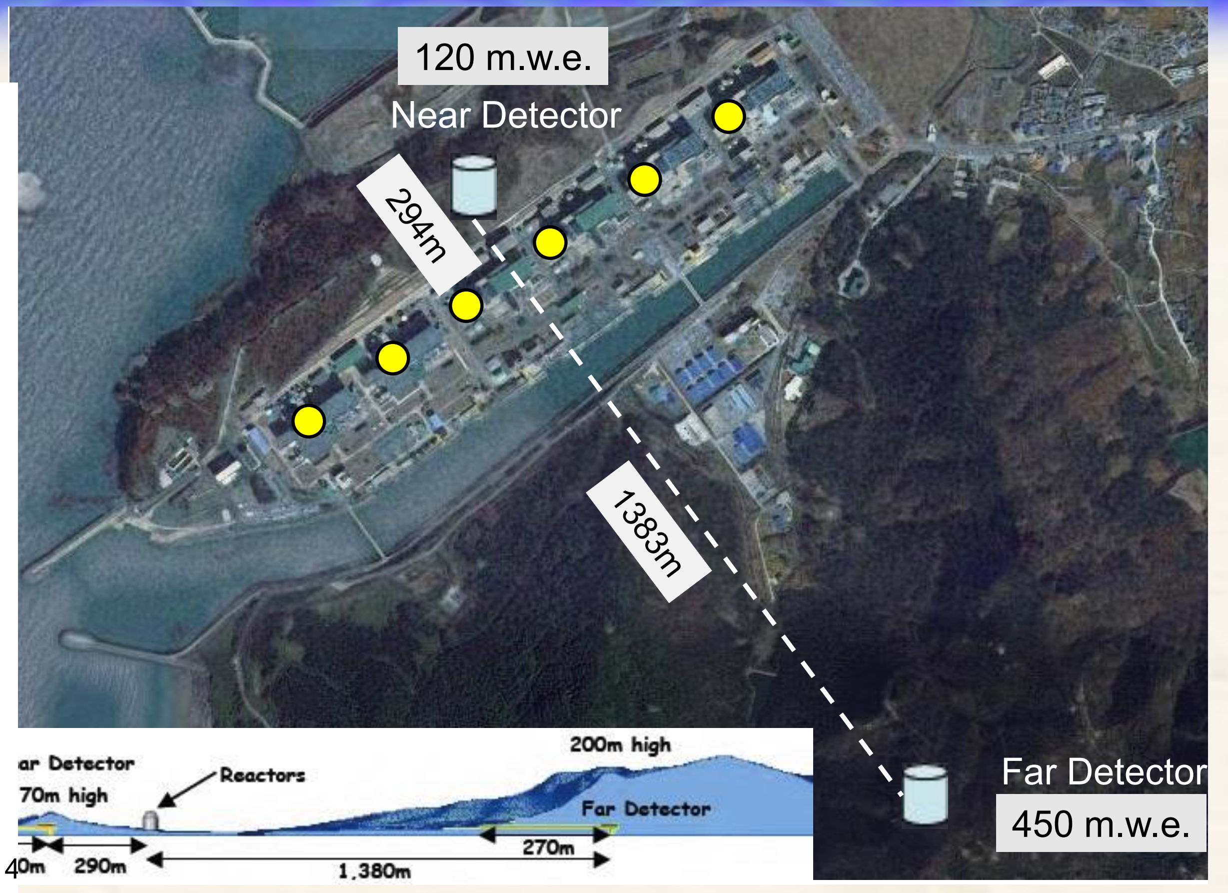
Control systematics by two detector configuration

Reactor θ$_{13}$ experiments





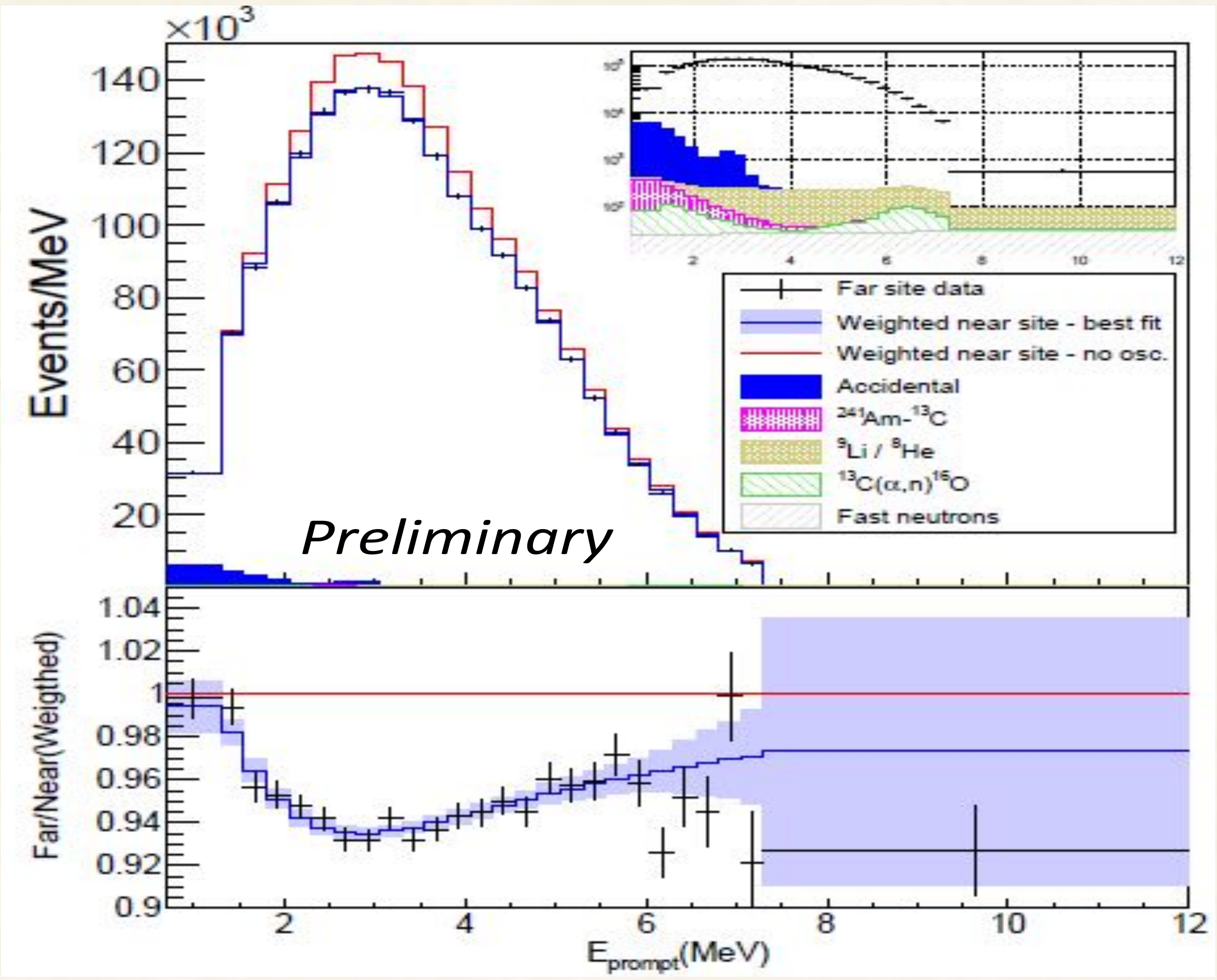




	Daya Bay (China)	Double Chooz (France)	RENO (South Korea)
Reactor power (GW$_{th}$)	17.4	8.5	16.8
Baseline	470/576/1650	400/1050	409/1444
Overburden near/far (m.w.e.)	250/265/860	80/300	120/450
Gd target mass for far detectors (tons)	80	8.3	16.5

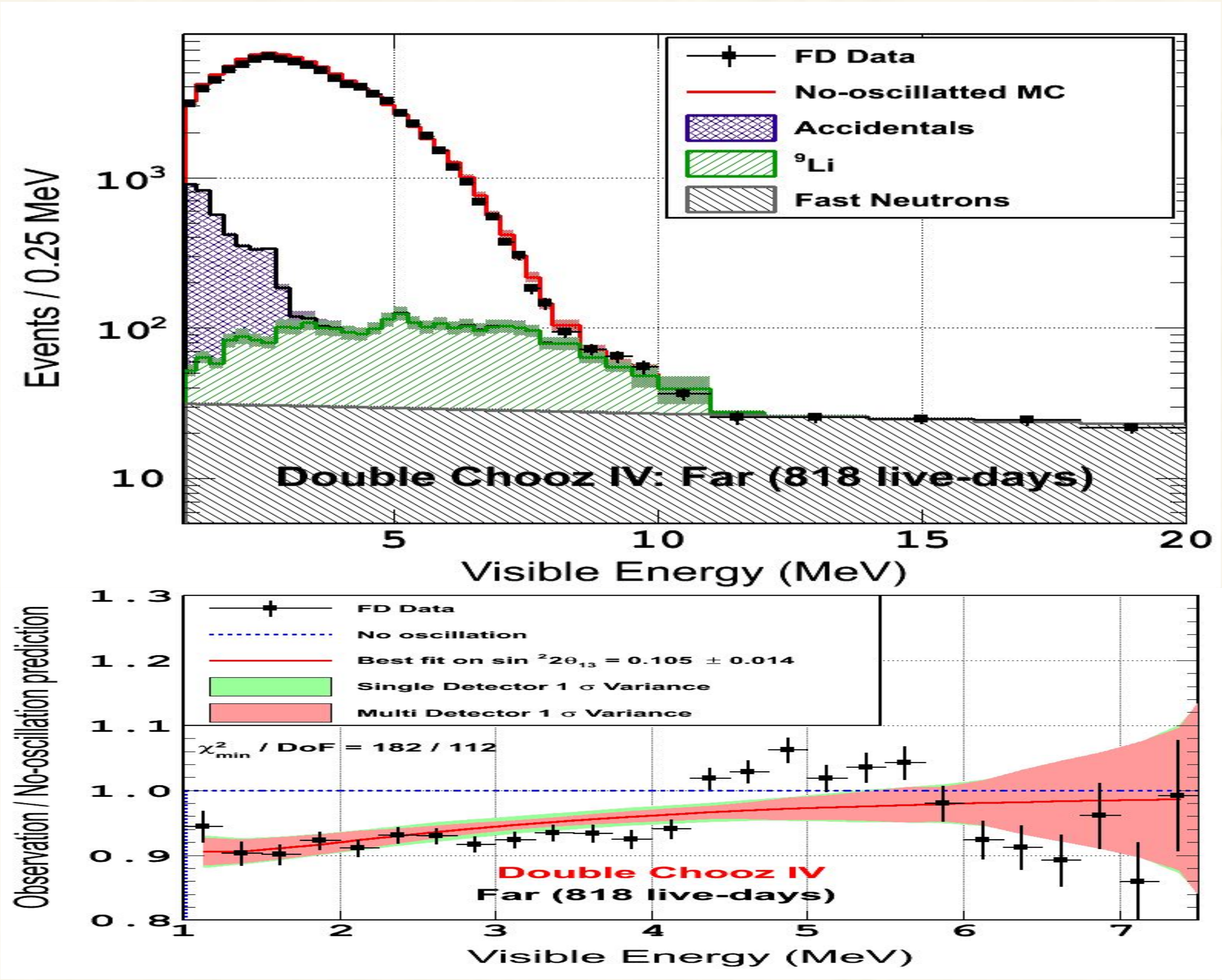
Parallel talks by H,Seo, L.Zhan, A.Stahl, B.Z.Hu, M.C.Chu

Reactor θ13: latest results

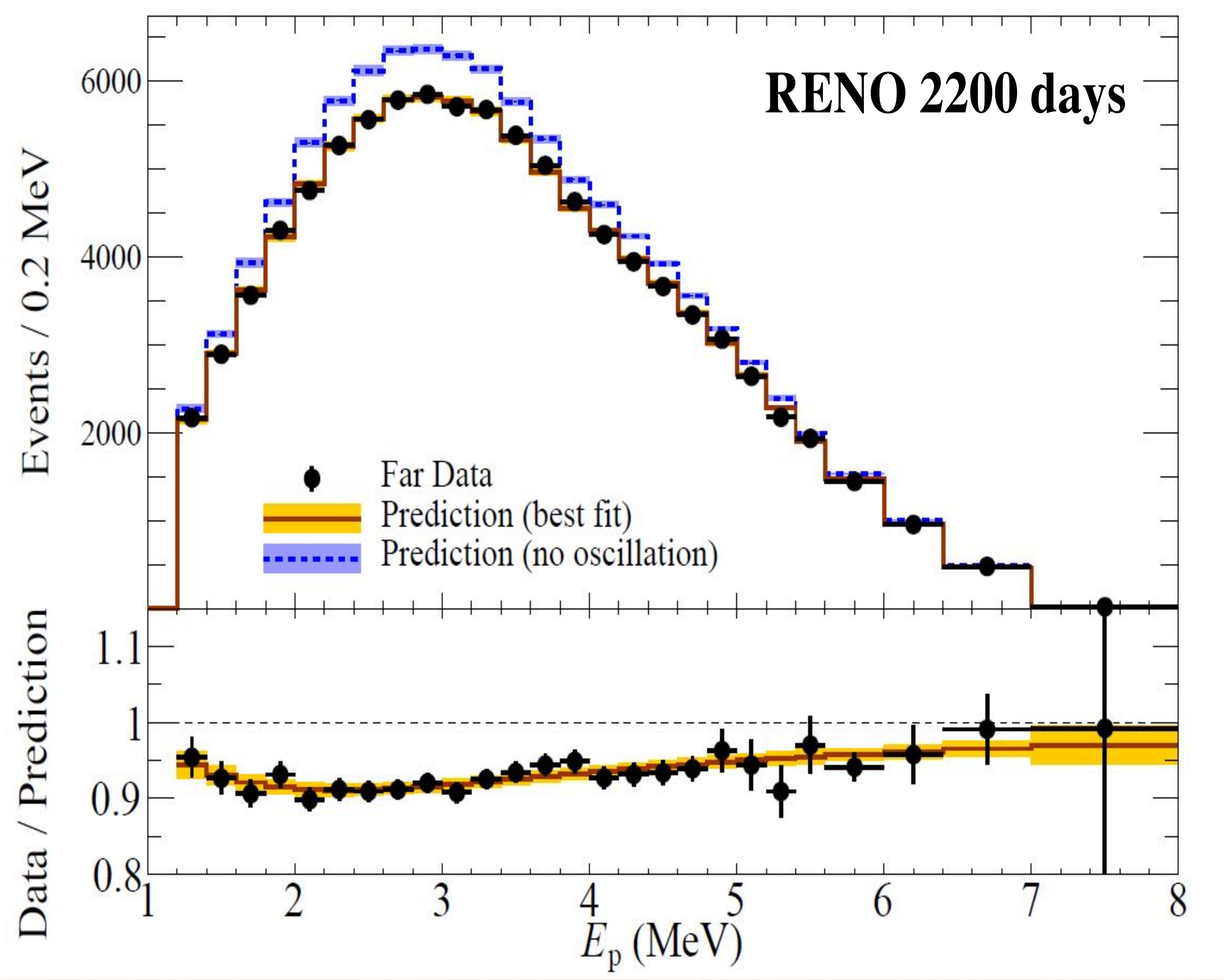


$$\sin^2 2\theta_{13} = 0.0856 \pm 0.00429$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} eV^2$$



$$\sin^2 2\theta_{13} = 0.105 \pm 0.014$$



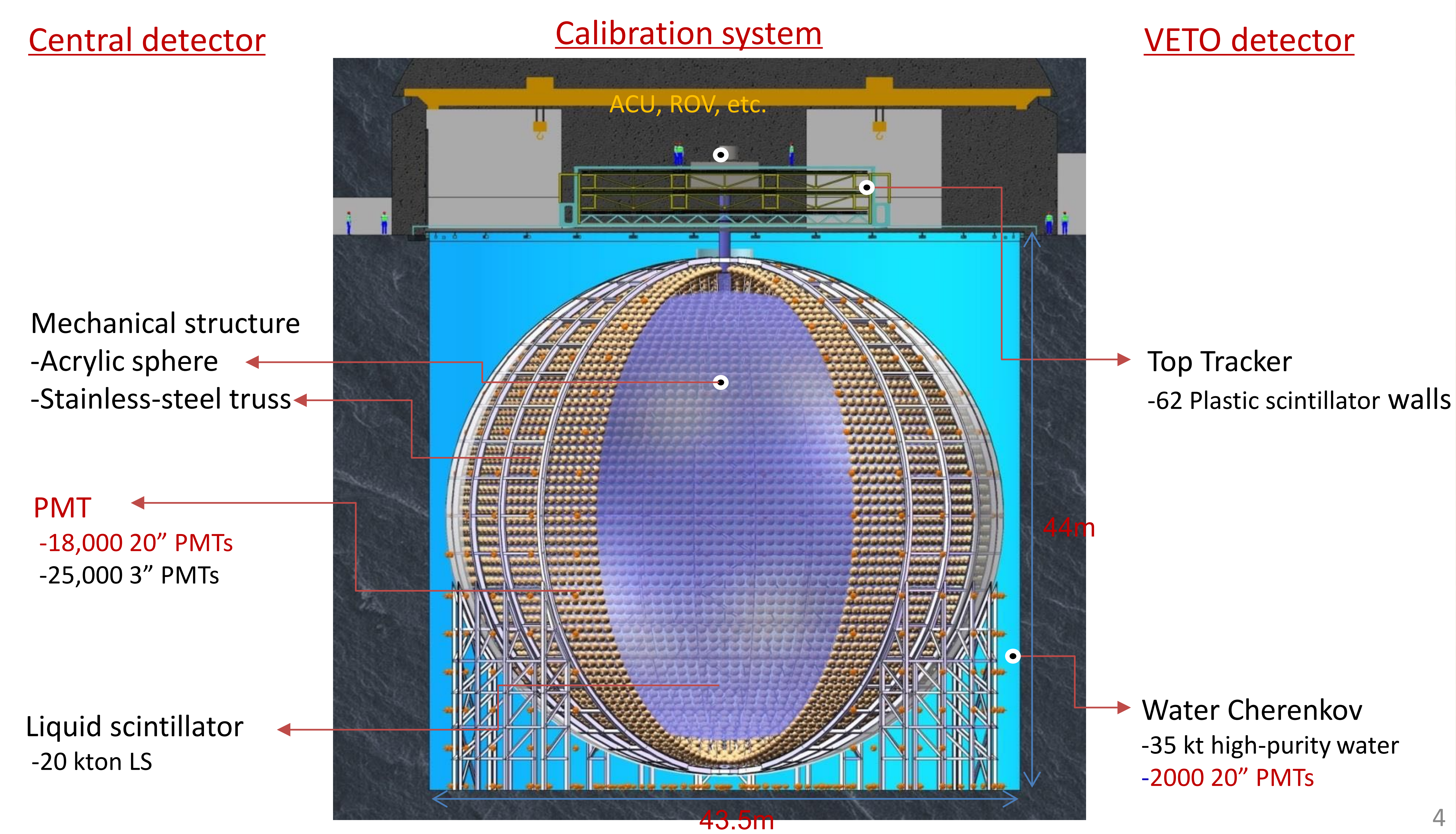
$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048 \pm 0.0047$$

$$|\Delta m^2_{ee}| = (2.68 \pm 0.12 \pm 0.07) \times 10^{-3} eV^2$$

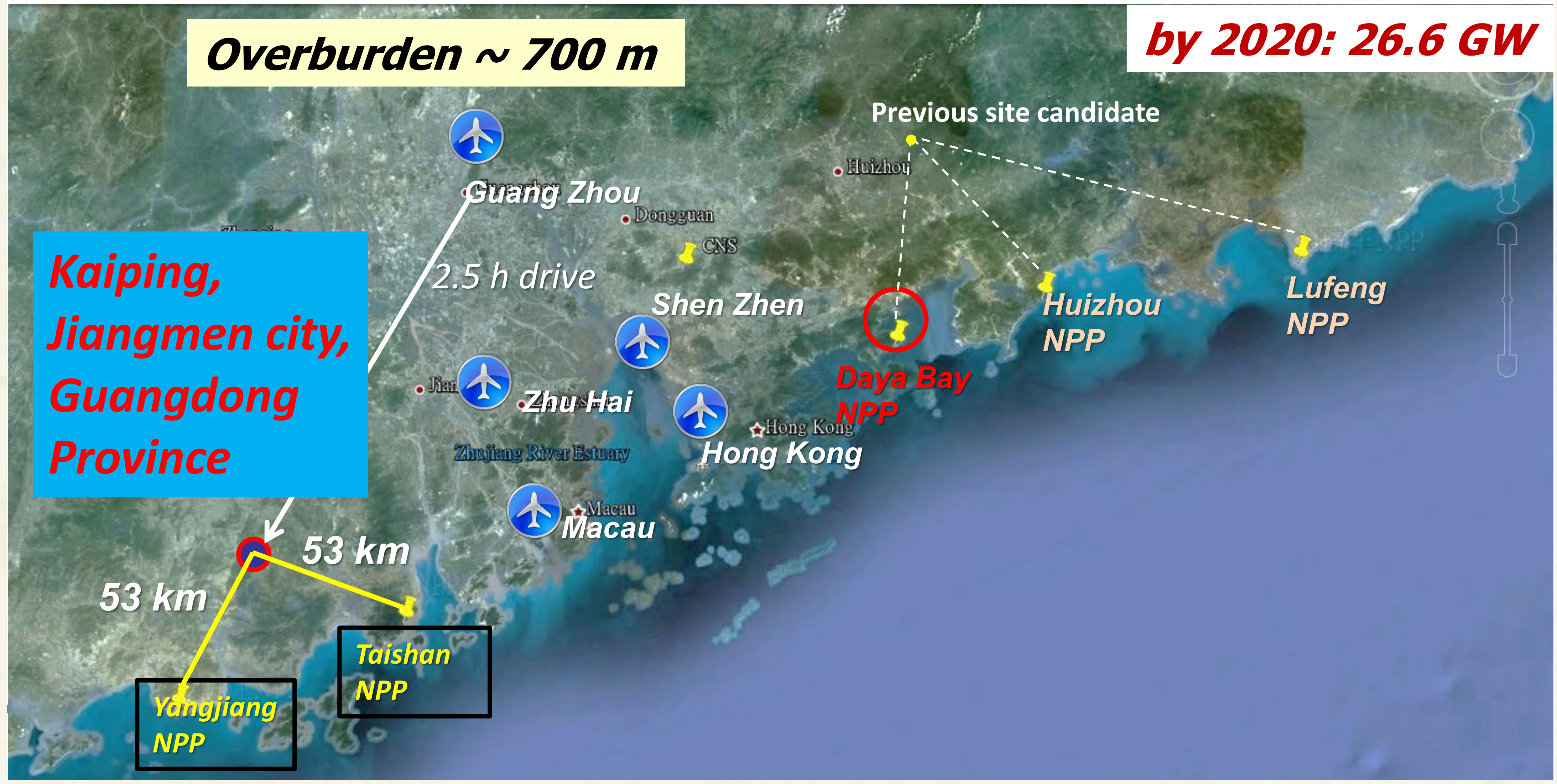
- Precision measurements of $\sin^2 2\theta_{13}$ (~5%) and also Δm^2 (~3%)
- Many other measurements are also reported (see later talk)
- Further improvement expected from all experiments in near future

JUNO

- **20kton** liquid scintillator detector at 53km from reactors
- Mass hierarchy determination
- Precision measurements (<1%) of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{ee}|$
- Other rich physics potentials



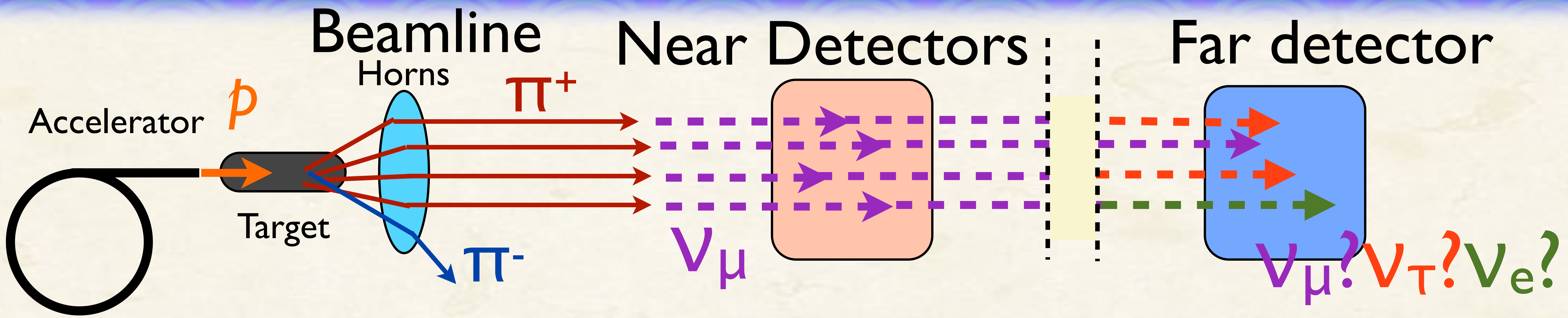
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



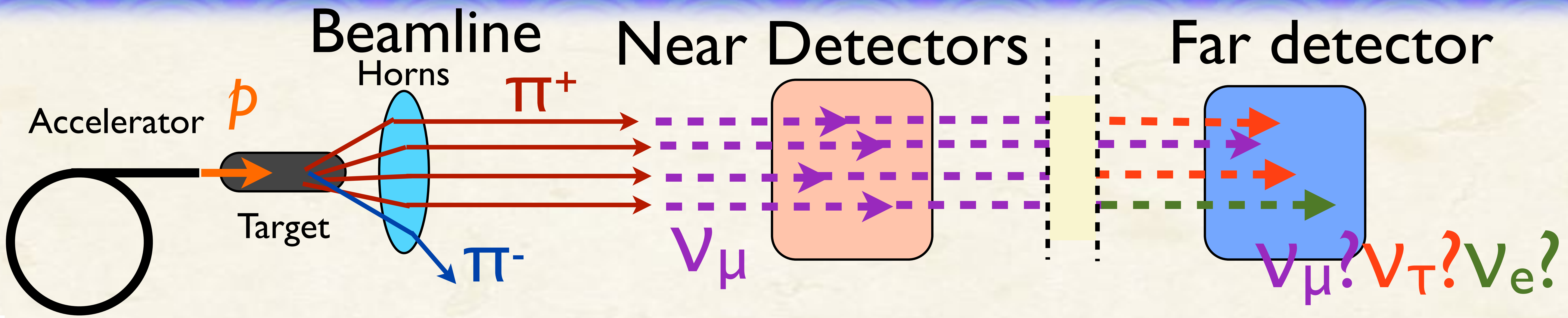
- Civil construction ongoing
- Detector R&D and fabrication are progressing
- Aim to start data-taking in 2021

Parallel talks by Q.Zhang, L.Wen, Z.Qin,

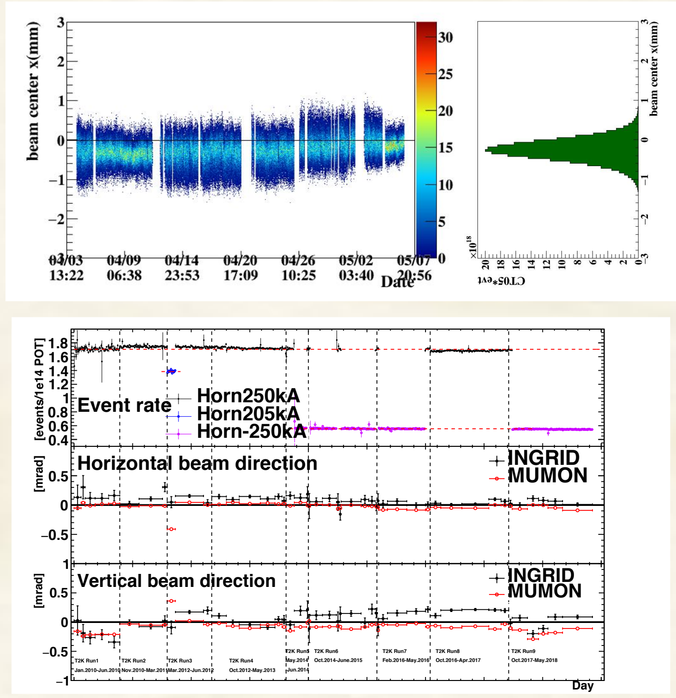
Accelerator-Based long baseline experiments



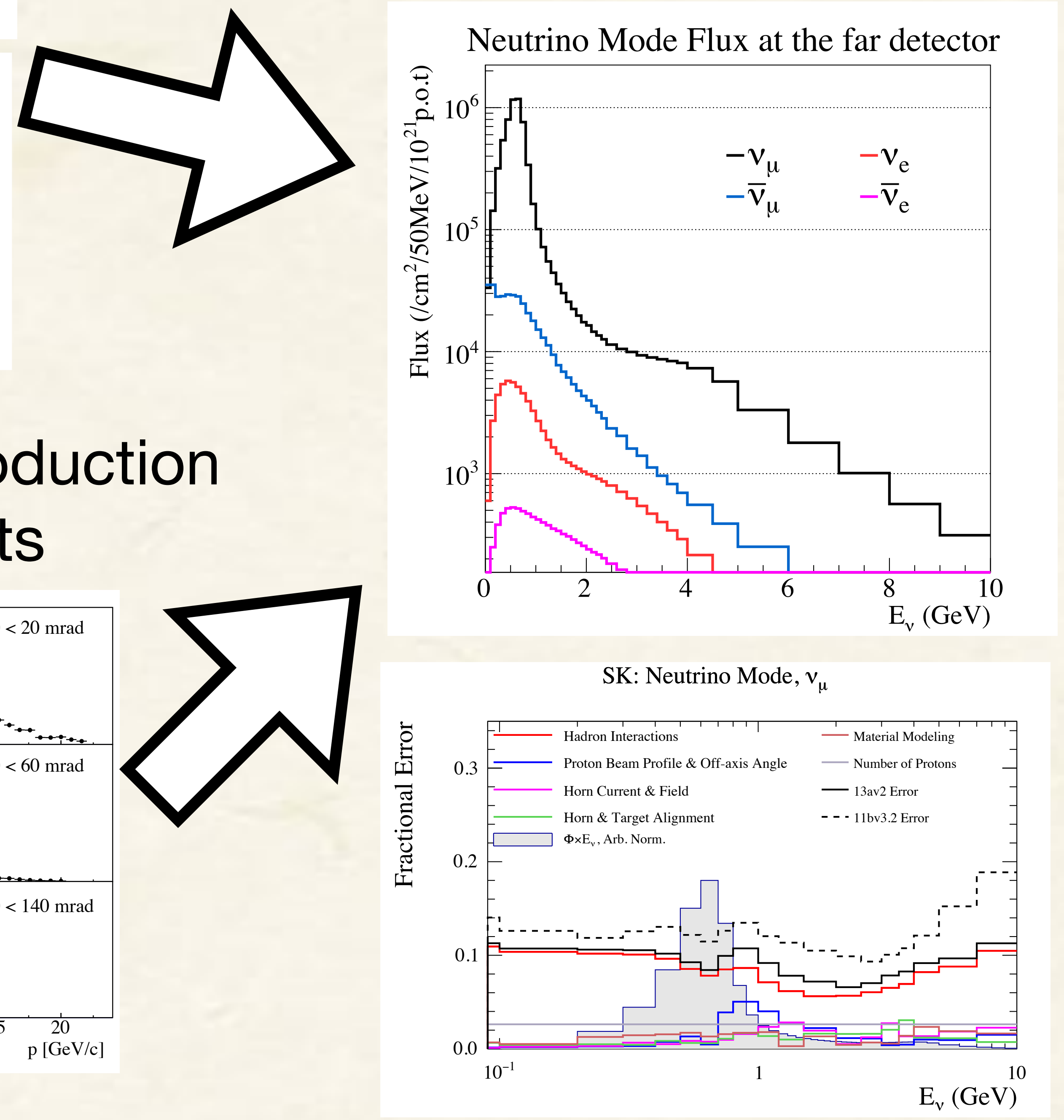
Accelerator-Based long baseline experiments



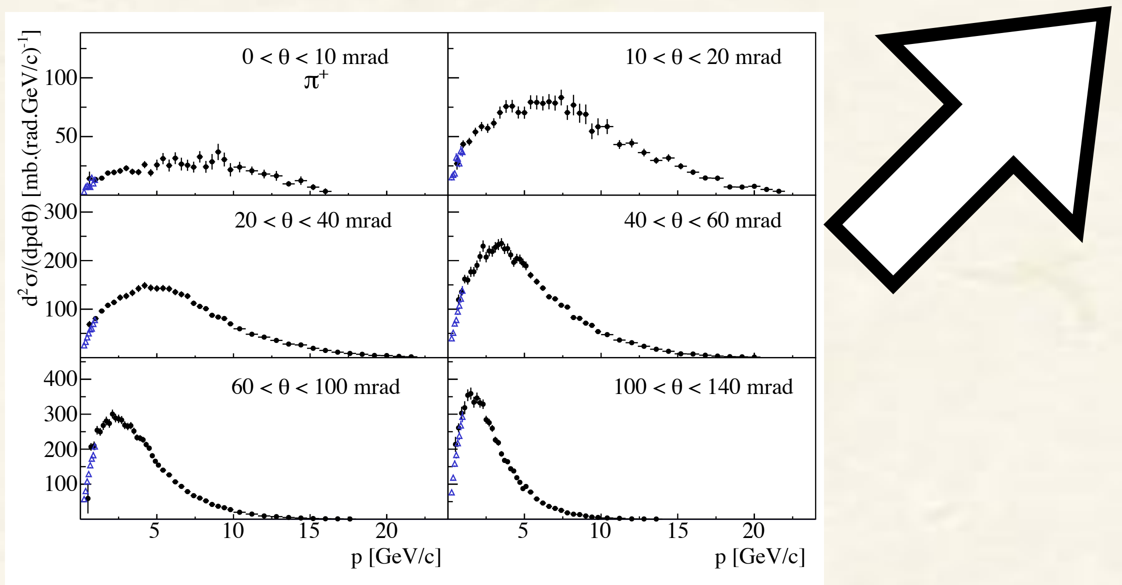
In-situ beam measurements



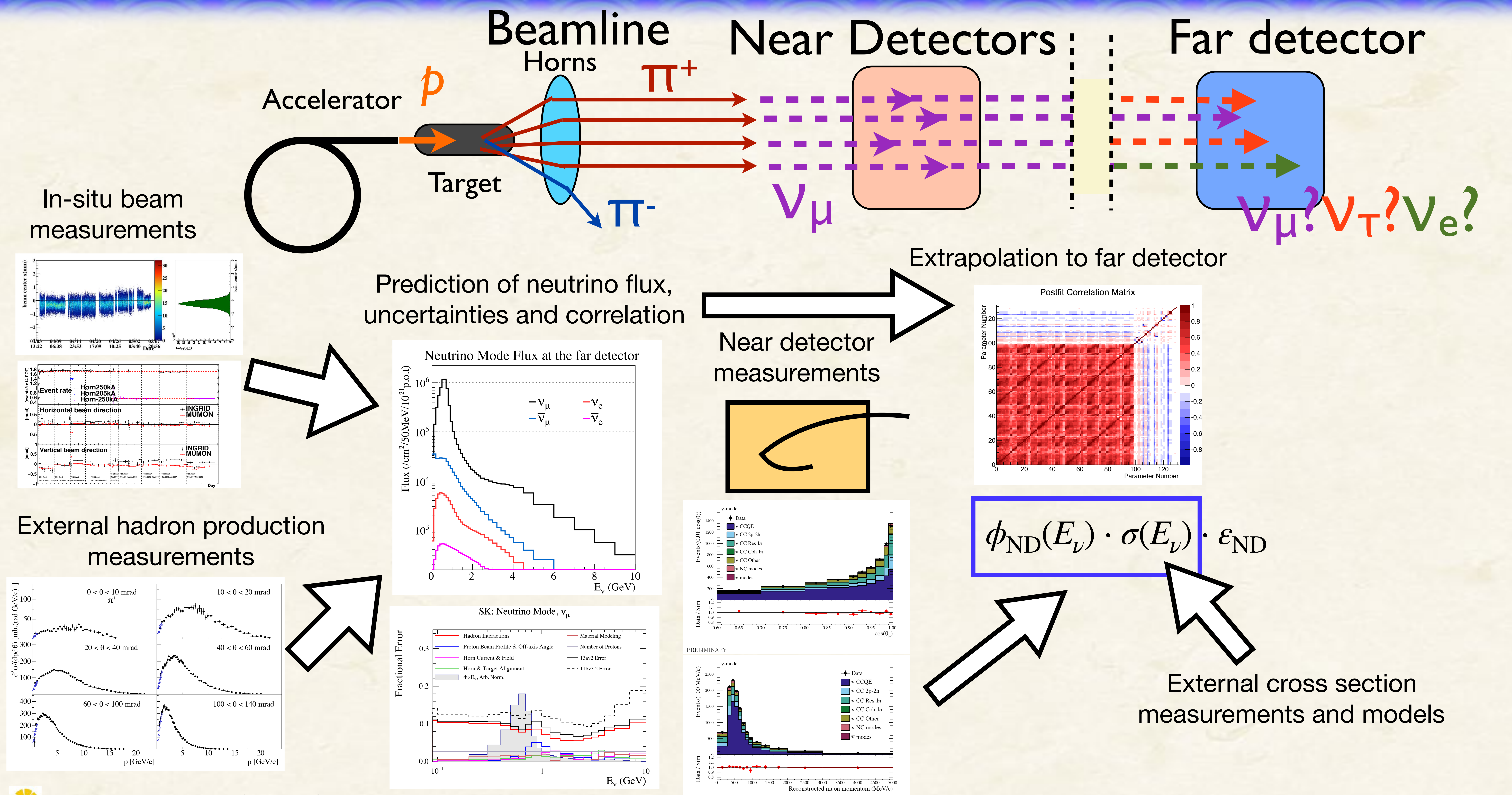
Prediction of neutrino flux, uncertainties and correlation



External hadron production measurements



Accelerator-Based long baseline experiments



Accelerator-Based long baseline experiments

Accelerator-Based long baseline experiments

Oscillations in accelerator LBL experiments

ν_μ "disappearance"

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

$\sin^2 2\theta_{23}$ from the leading term

ν_e "appearance"

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} \ll 1 \quad \Delta = \frac{\Delta m^2_{32}L}{4E} \quad A = 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

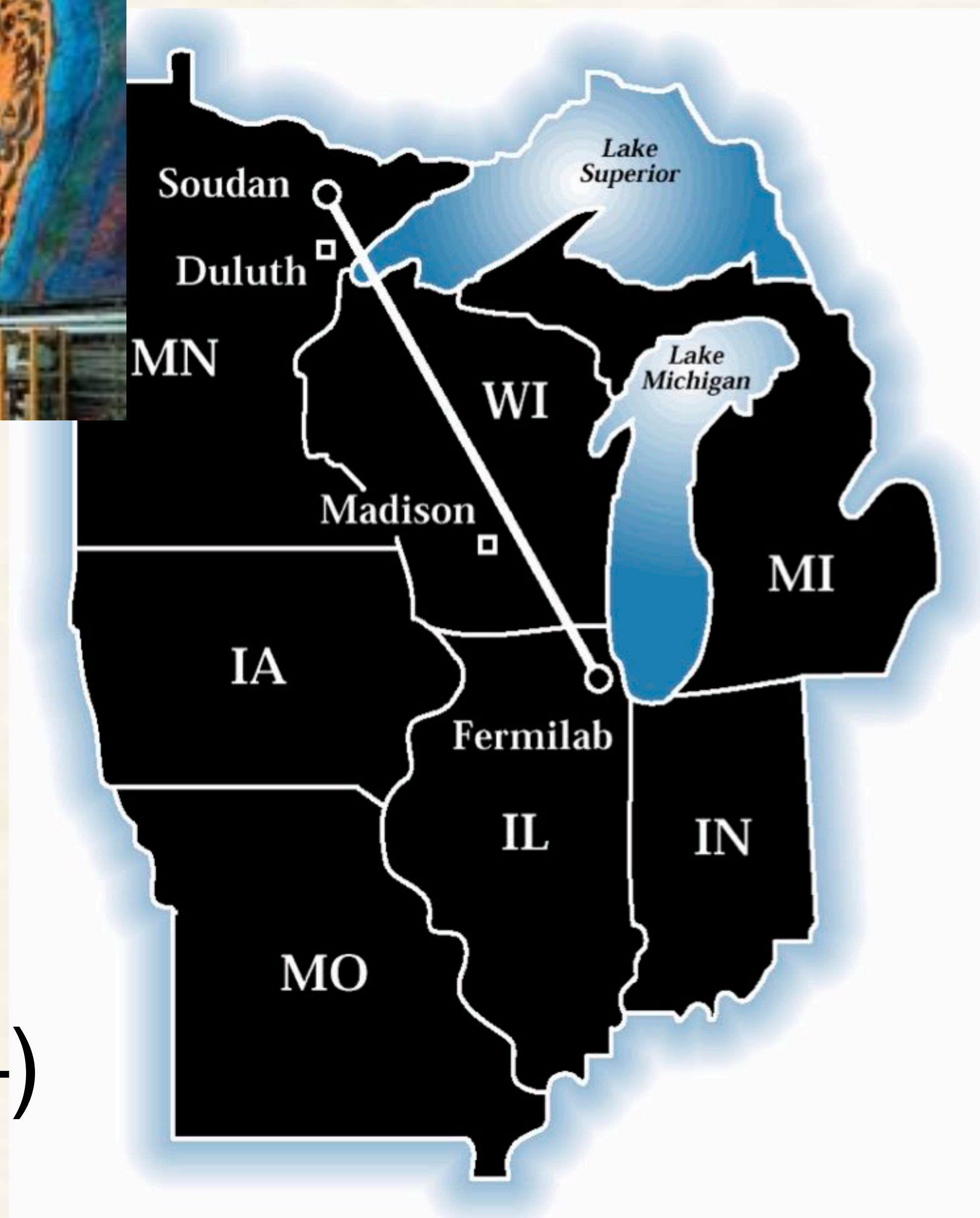
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$
$$\mp \alpha\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta_{CP}\sin\Delta\frac{\sin A\Delta}{A}\frac{\sin[(1-A)\Delta]}{1-A}$$
$$+\alpha\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\delta_{CP}\cos\Delta\frac{\sin A\Delta}{A}\frac{\sin[(1-A)\Delta]}{1-A} + O(\alpha^2)$$

M.Freund, Phys.Rev. D64 (2001) 053003

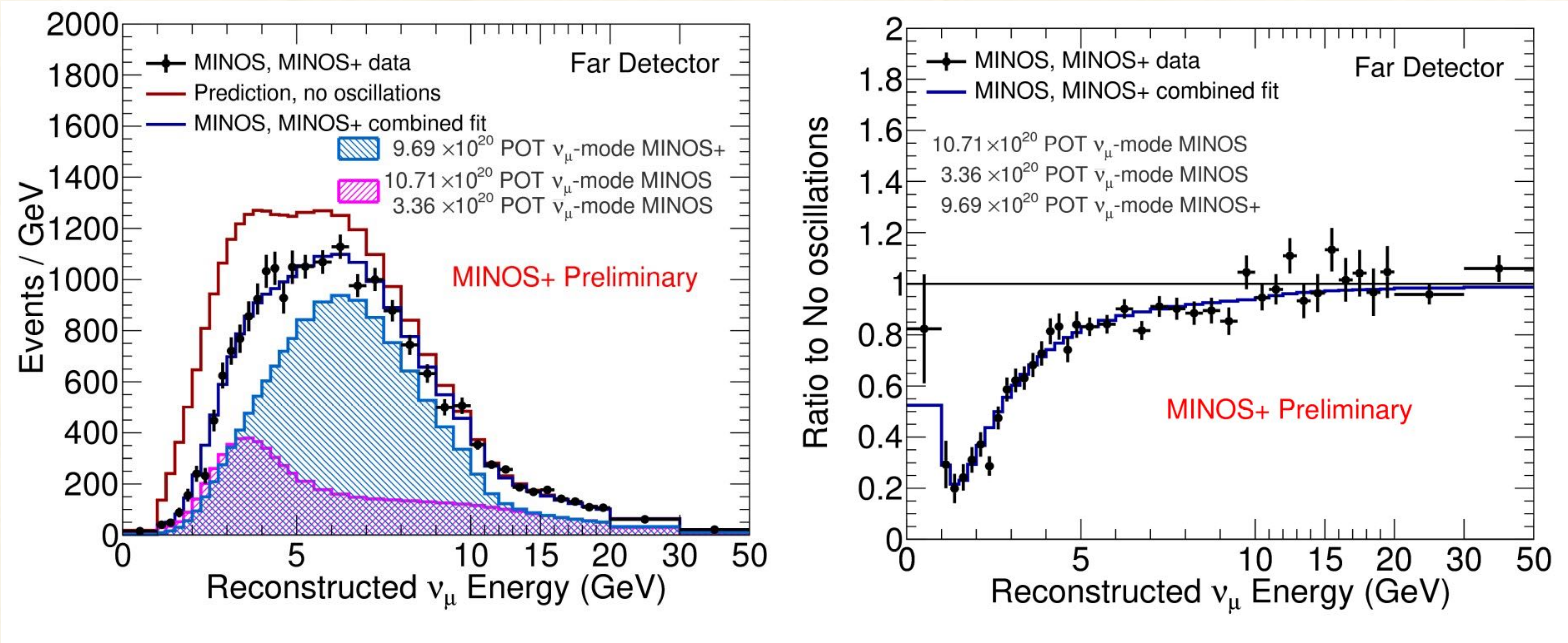
The leading term dependent on $\sin^2 2\theta_{13}$, δ_{CP} and **mass hierarchy** from sub-leading terms

Final results from MINOS/MINOS+

2005-2016



Baseline:
730km
Peak energy:
~3GeV (MINOS)
~7GeV (MINOS+)
+atmospheric ν

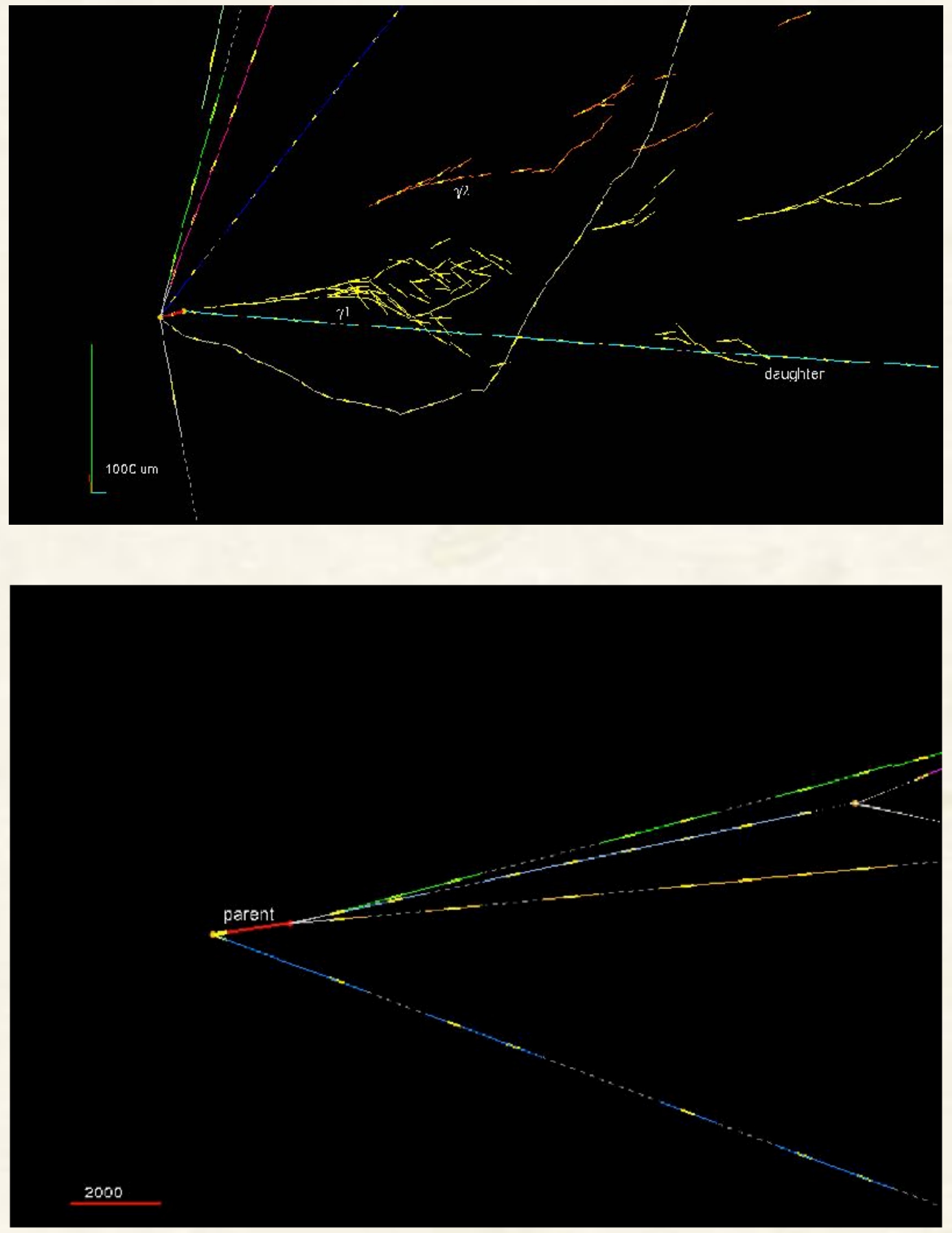


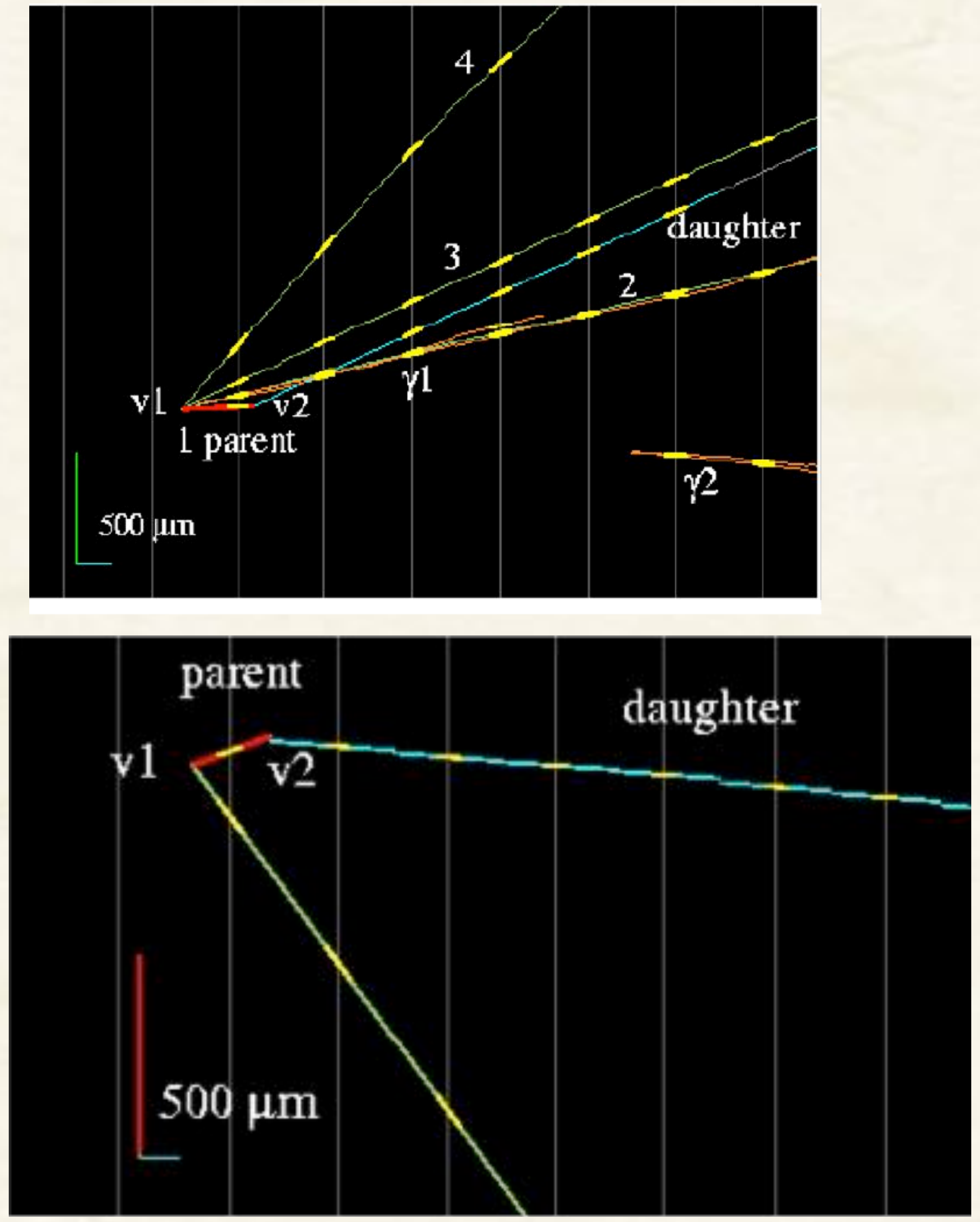
$|\Delta m^2_{32}|$ (2.28-2.55) × 10^{-3} eV^2 (NH) $\sin^2\theta_{23}$ 0.36-0.65
(2.33-2.60) × 10^{-3} eV^2 (IH)
(90%CL)

- Precise measurements of θ_{23} and Δm^2_{32}
- Consistency with three flavor prediction tightly constrains alternate oscillations hypotheses

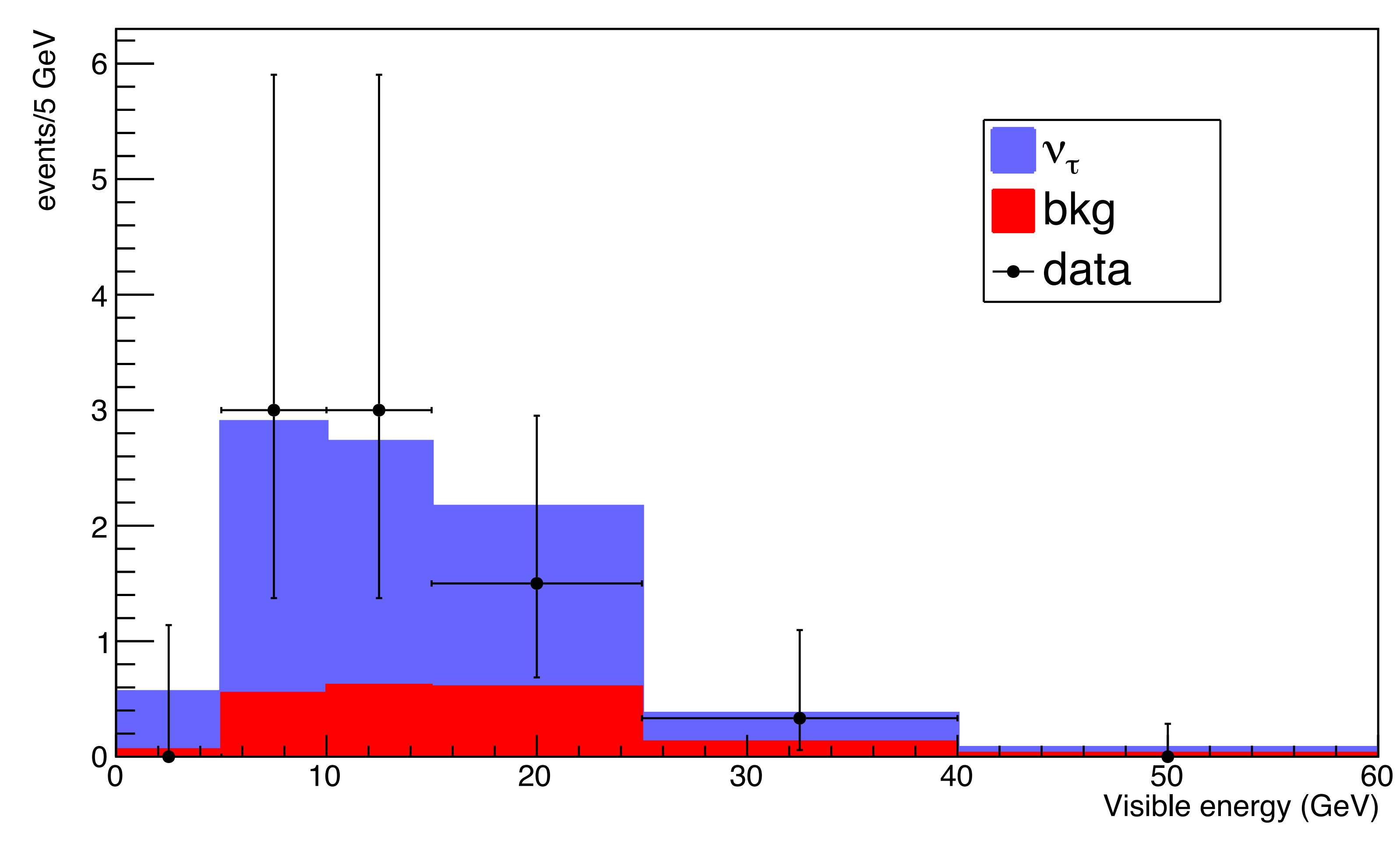
Final ν_τ results from OPERA

2008-2012





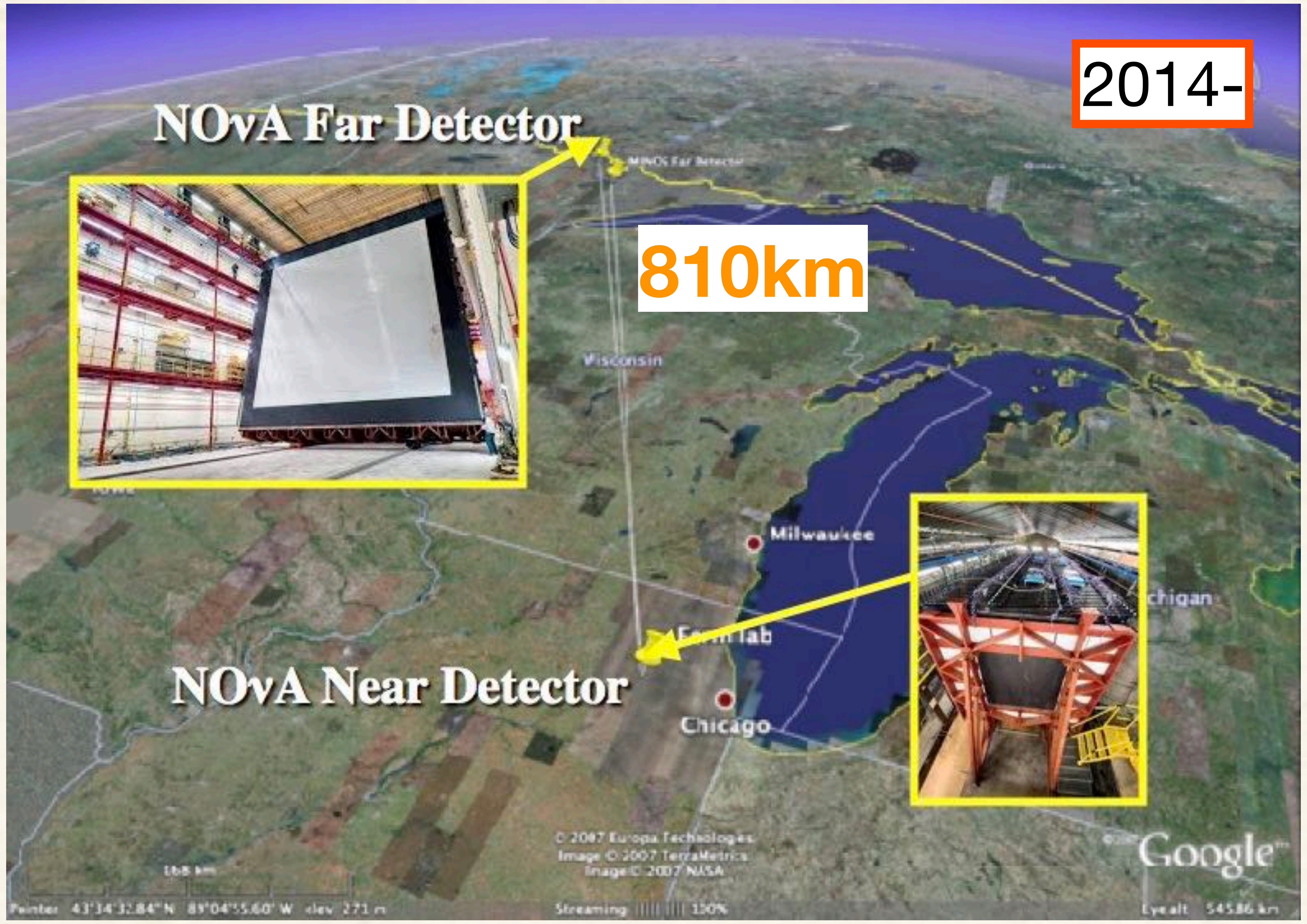
PRL **120** (2018) 211801



Δm² consistent with disappearance measurements

- Observation of ν_τ interaction using a huge emulsion-based detector
- **10** ν_τ candidates observed
  - 2.0±0.4 BG expected
  - 6.1σ significance of ν_τ appearance

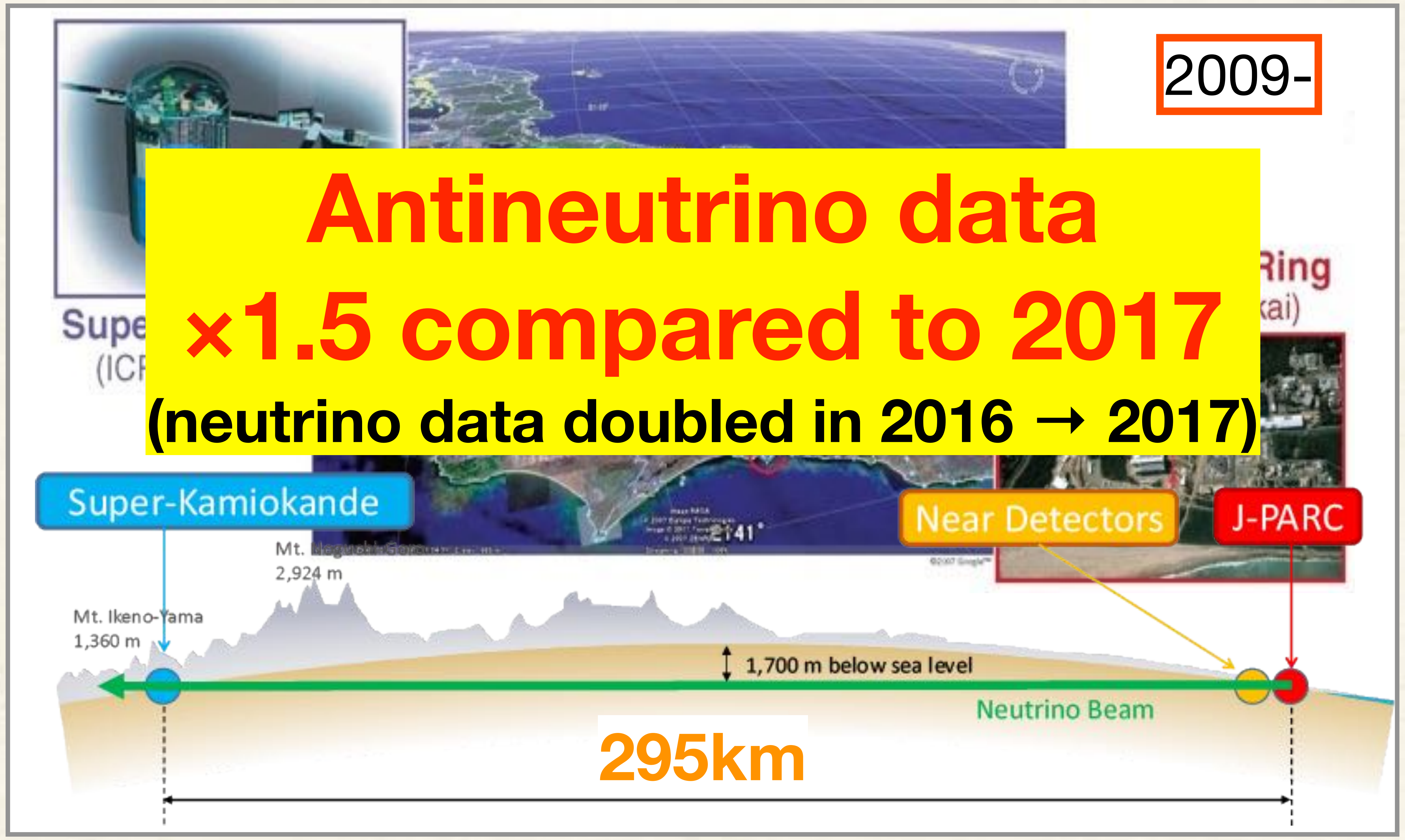
T2K and NOvA

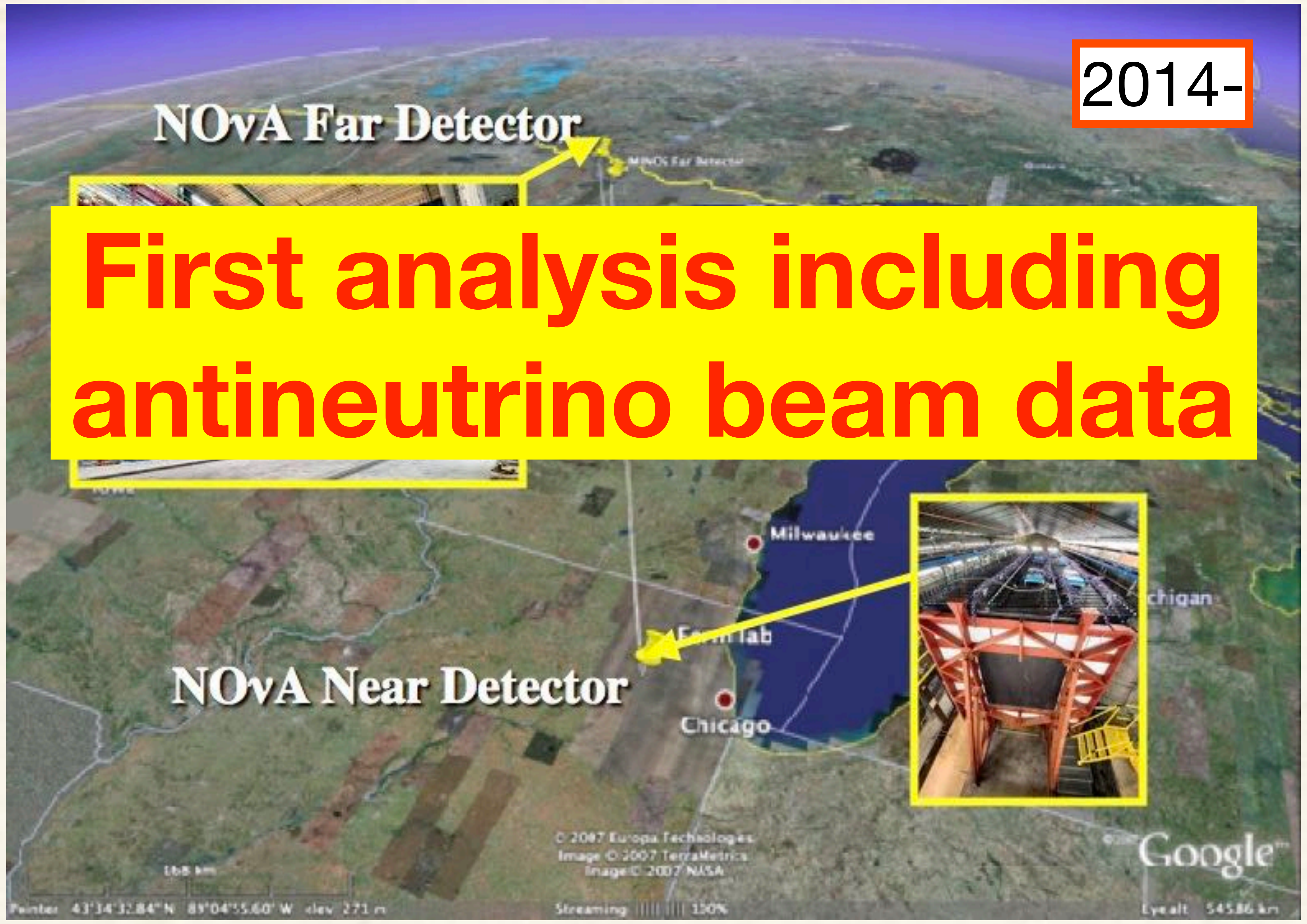


- Different baselines — different effect from matter effect (and possibly others not dependent on L/E)
  - T2K has a shorter baseline, purer effect of CPV
  - NOvA has a longer baseline, more matter effect and sensitivity to mass hierarchy
- Can provide complementary information

Parallel talks by P.Litchfield and J.Bian

T2K and NOvA





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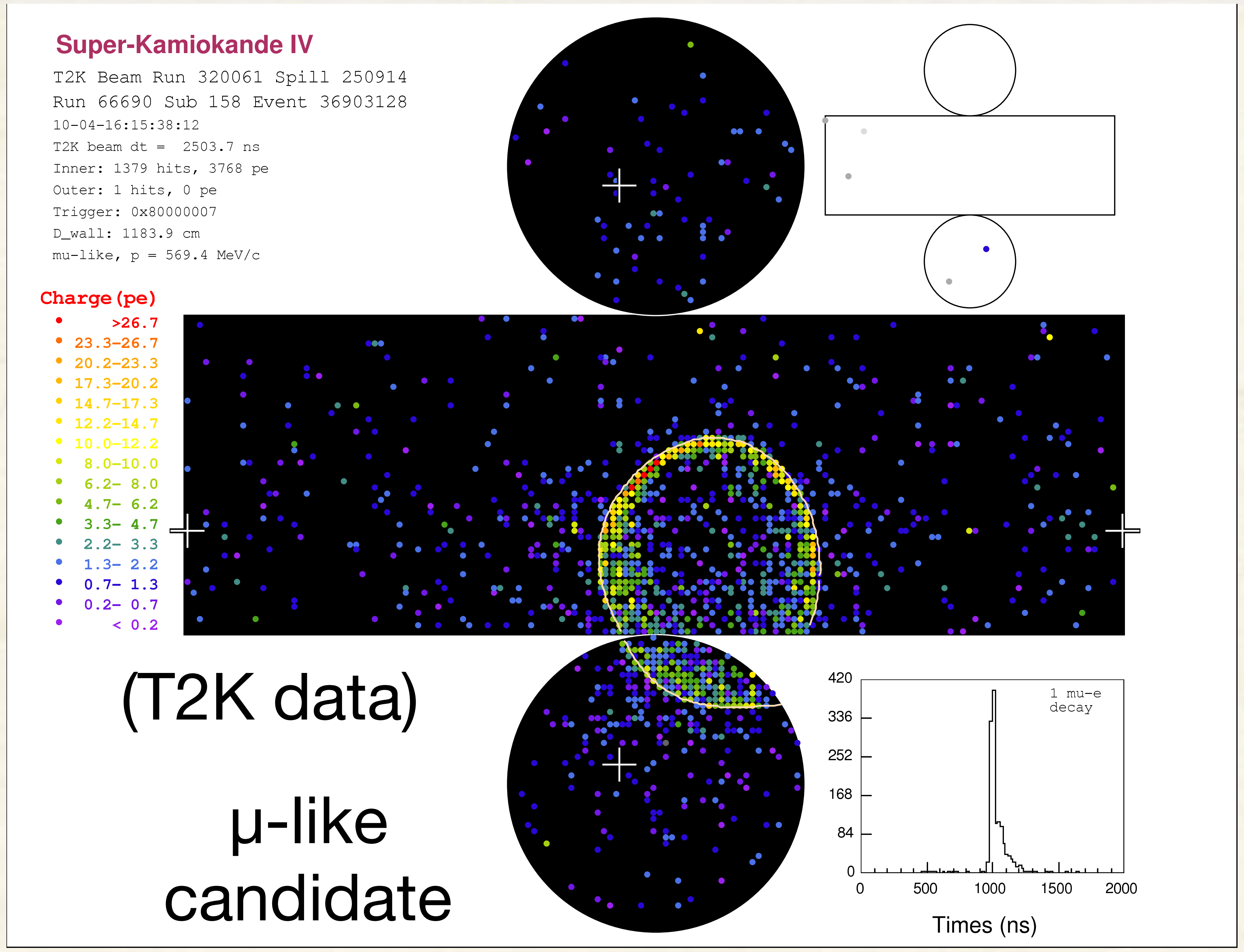
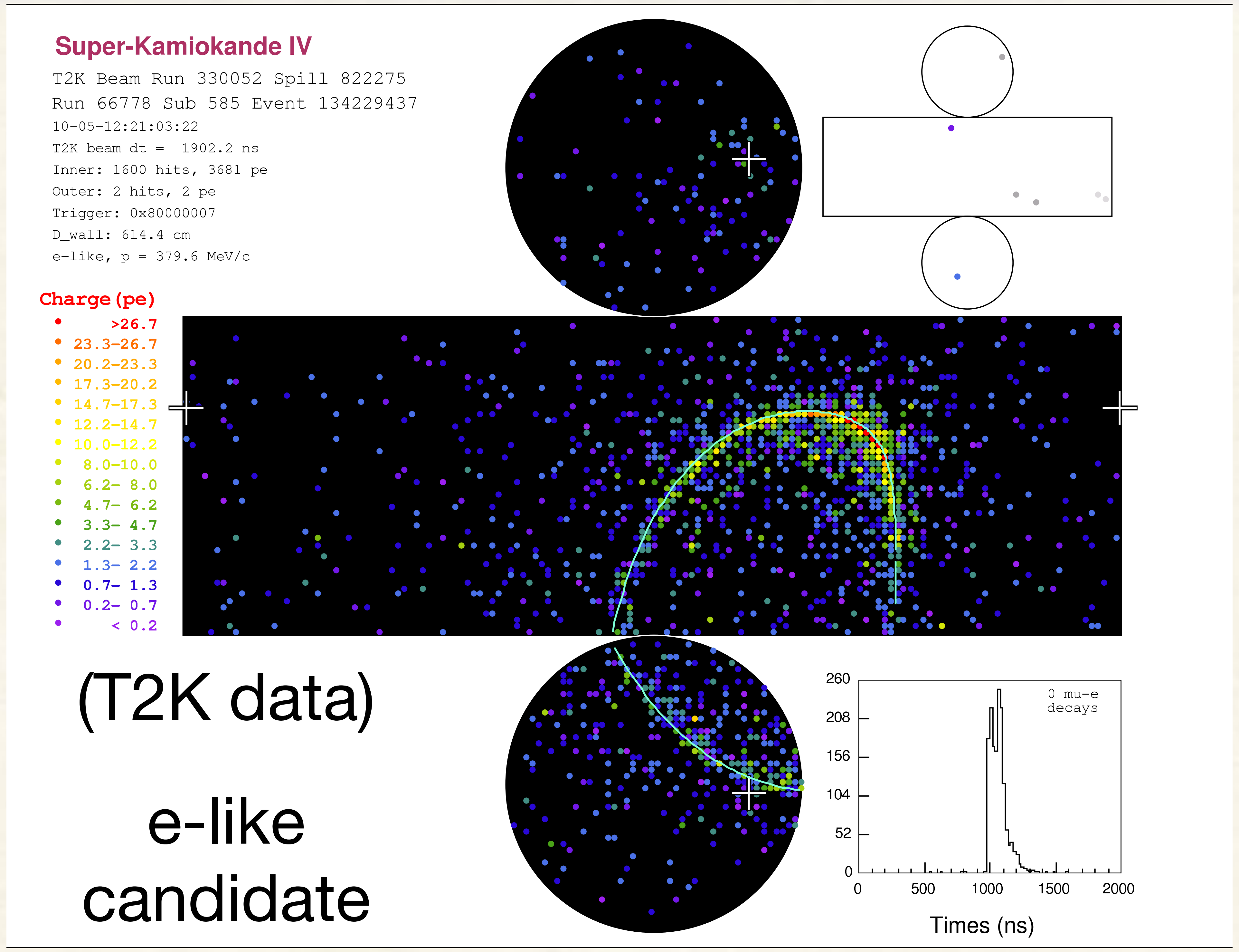
T2K: reconstruction and analysis

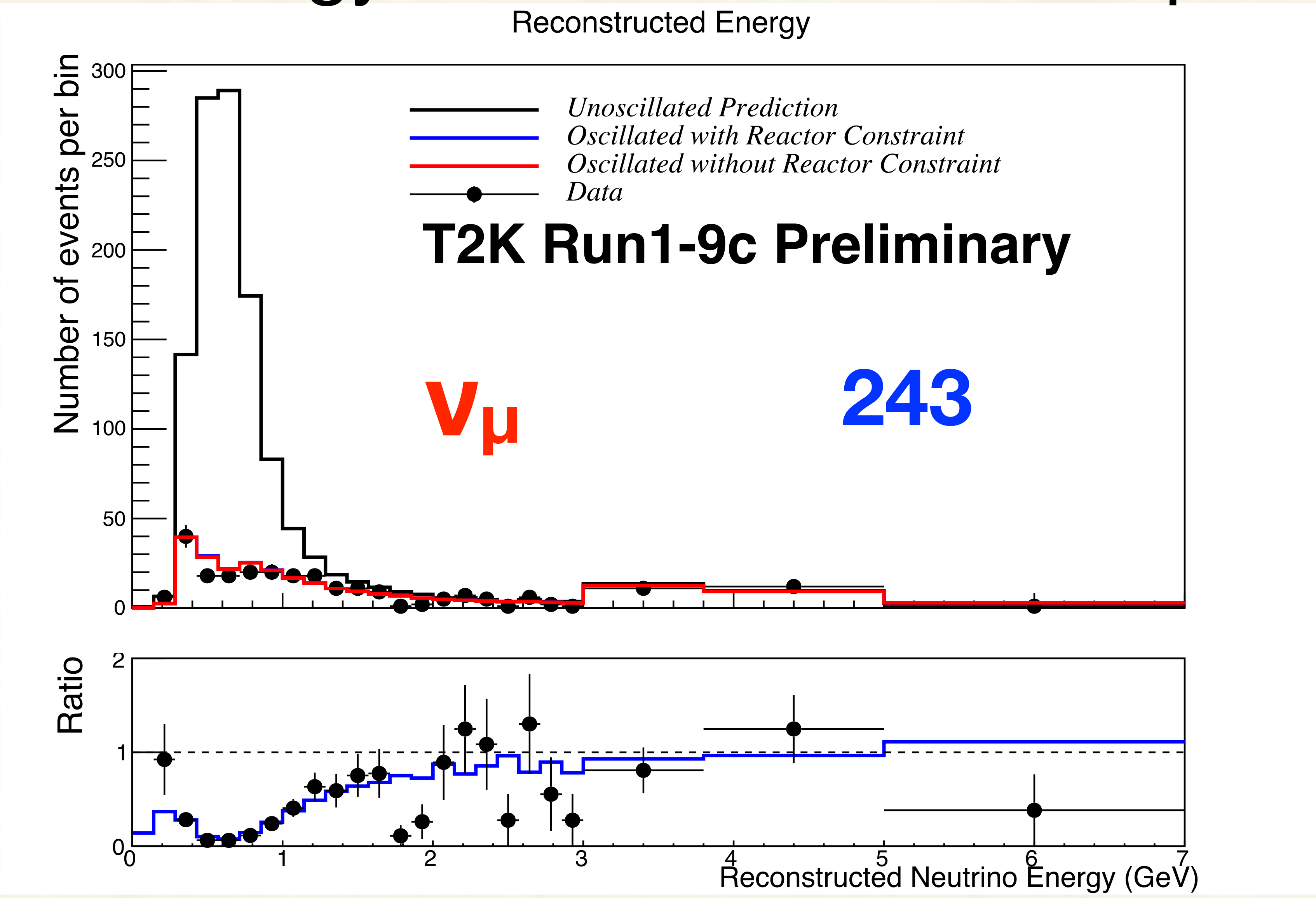


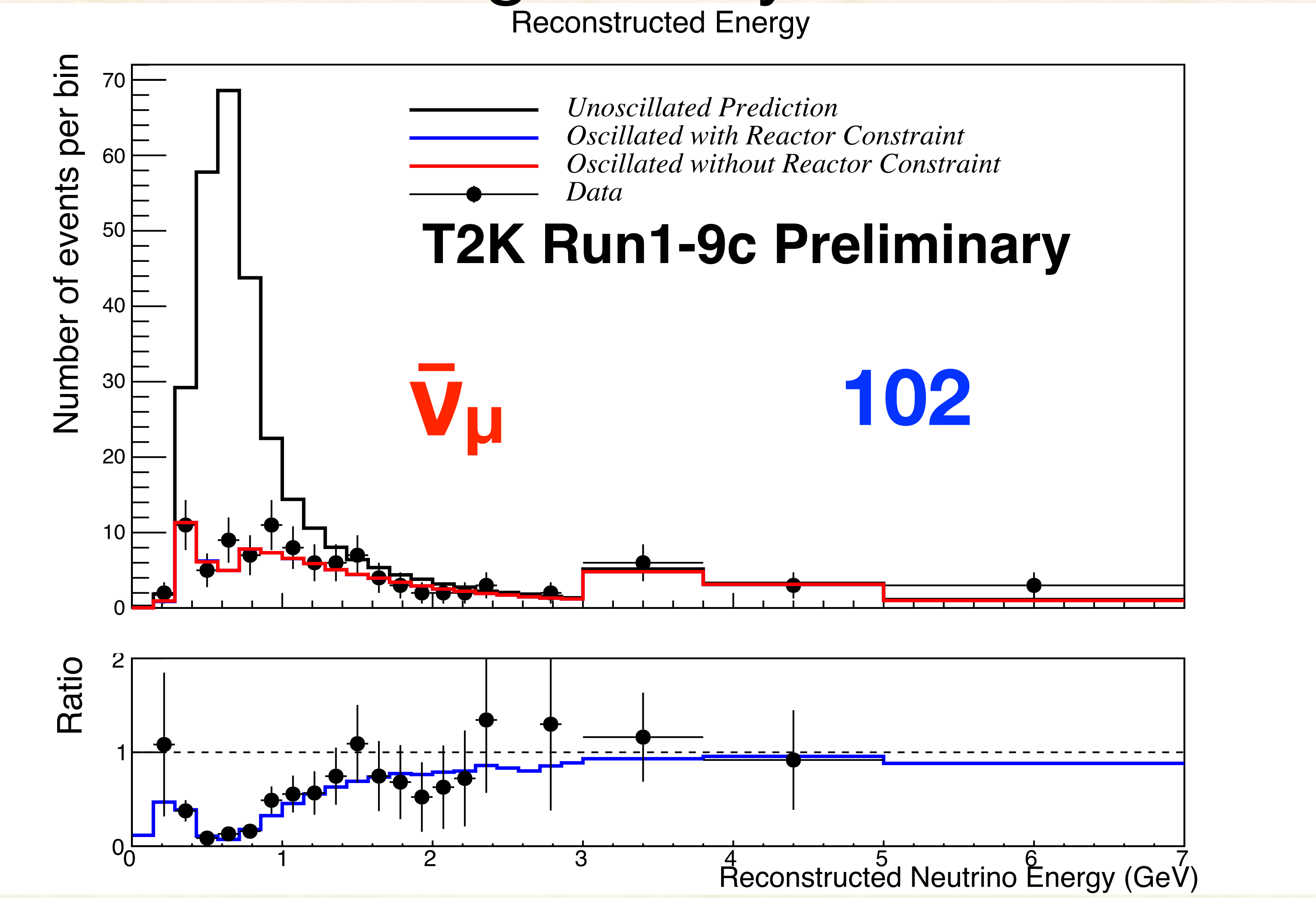


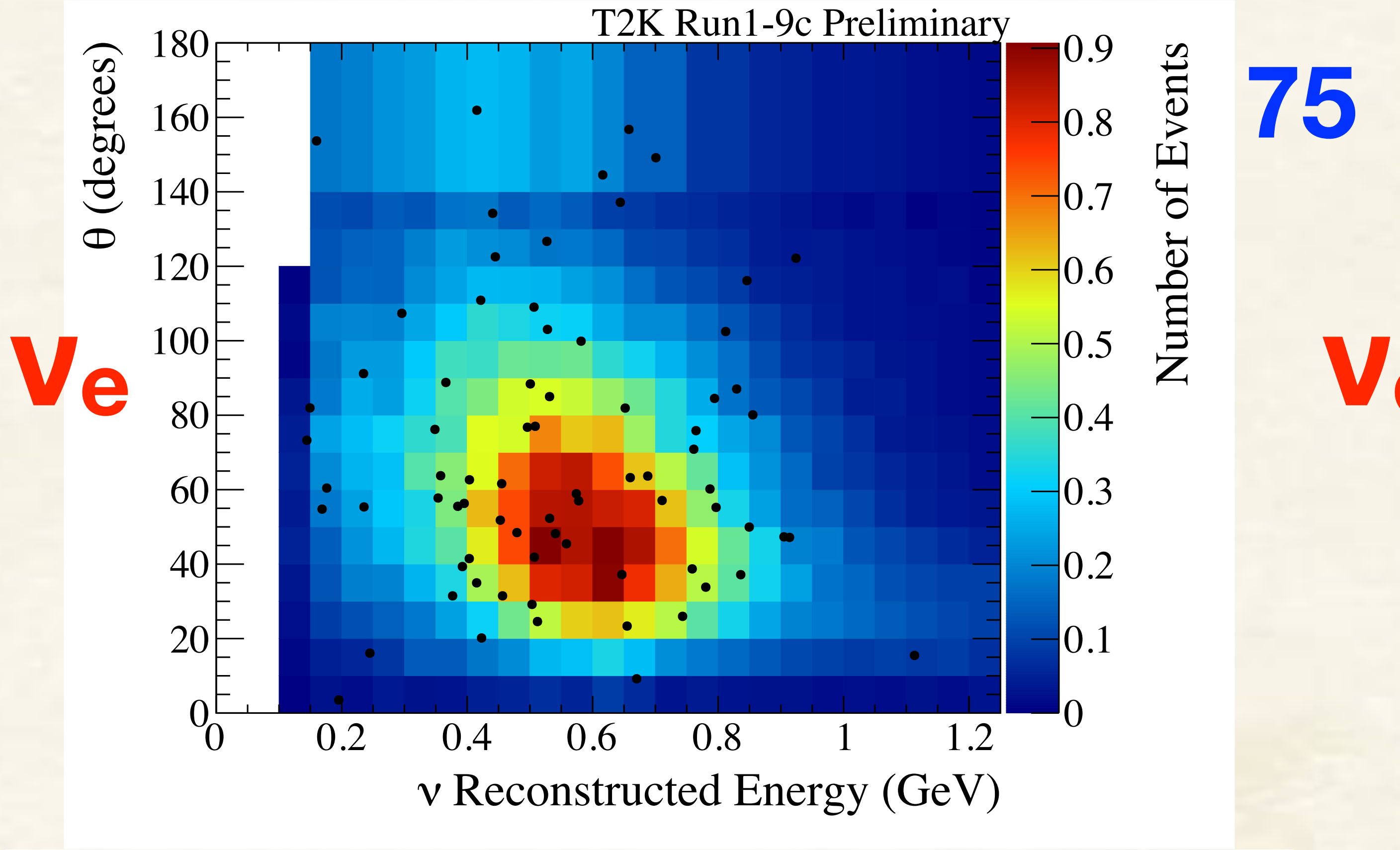
- **Improved reconstruction algorithm applied since 2017**
  - Maximize likelihood based on charge and time from all PMTs
  - Improved signal efficiency and purity
  - Optimized fiducial selection to increase statistics (+~20%)
- Improvements in cross section modeling

T2K: far detector (SK) data

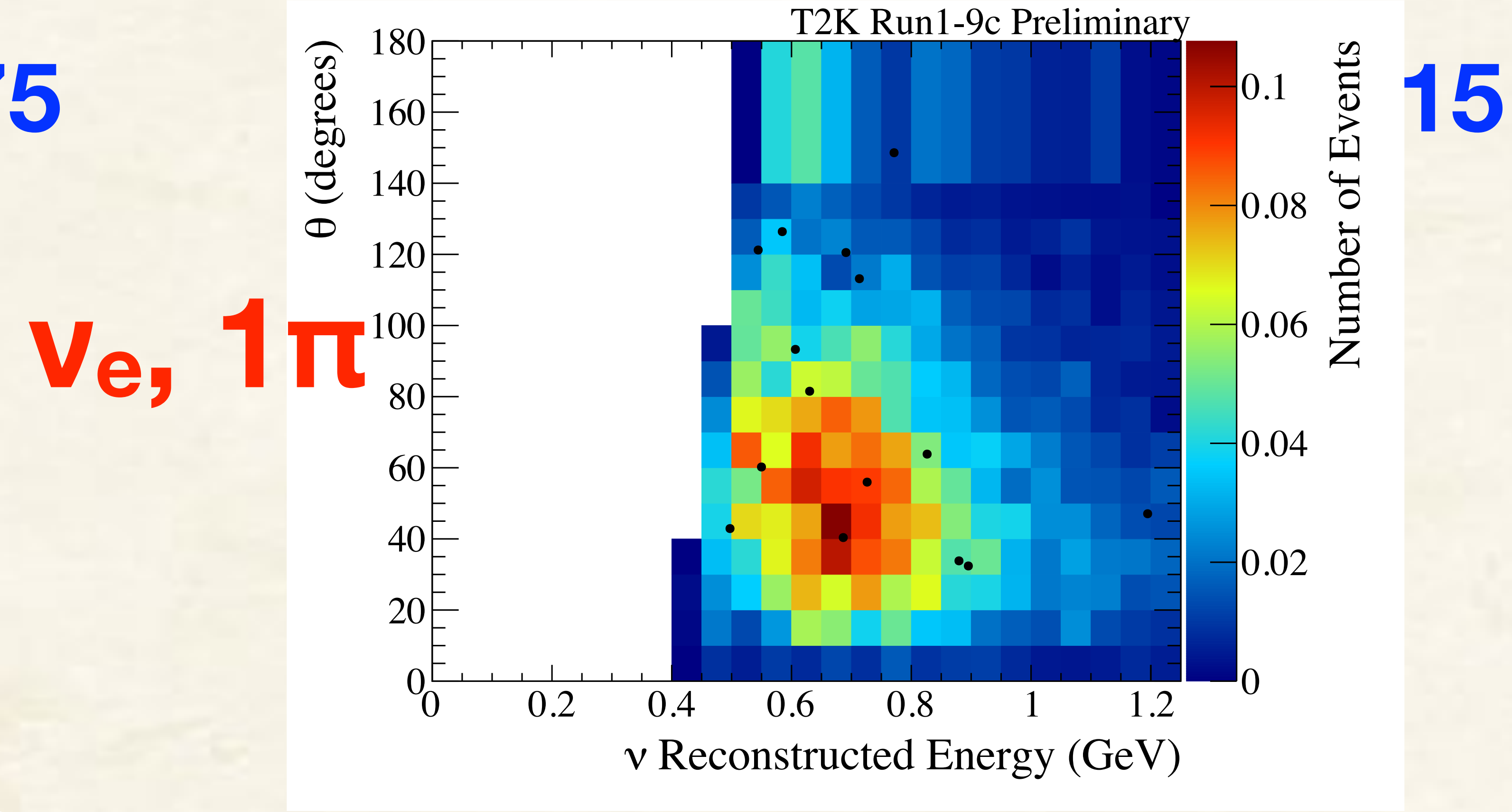
Energy reconstructed from lepton kinematics assuming 2 body interaction



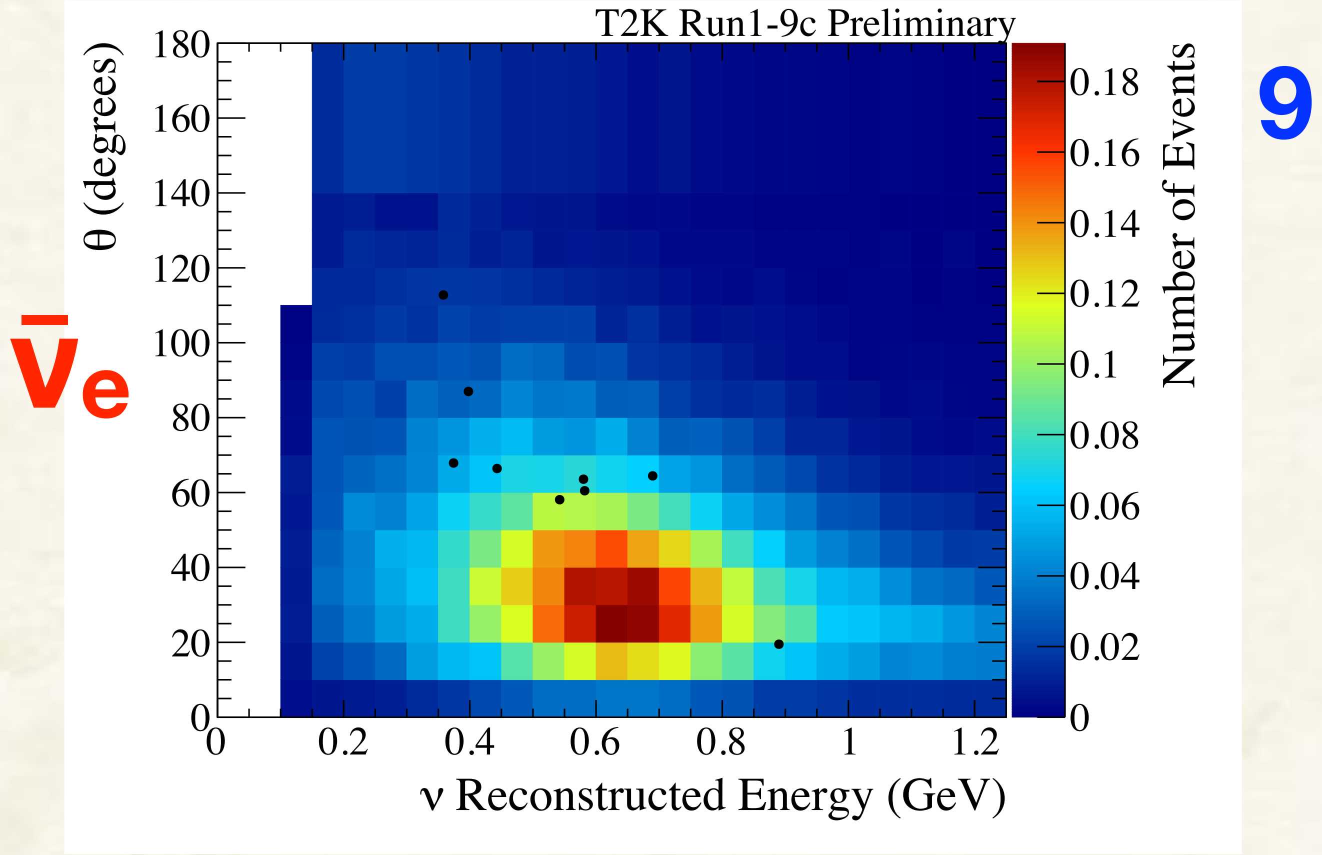




ν beam, 1 ring e, no decay-e

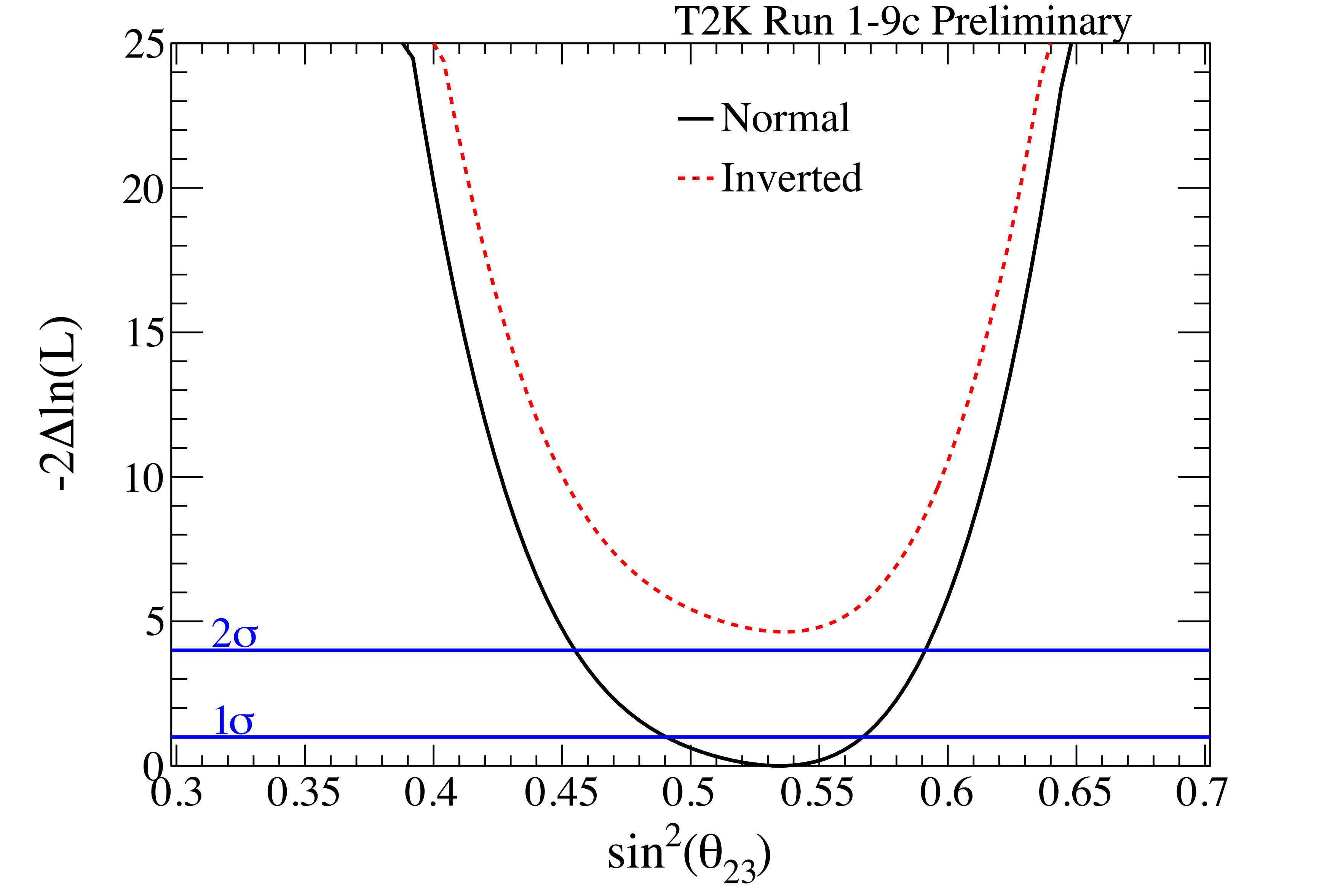


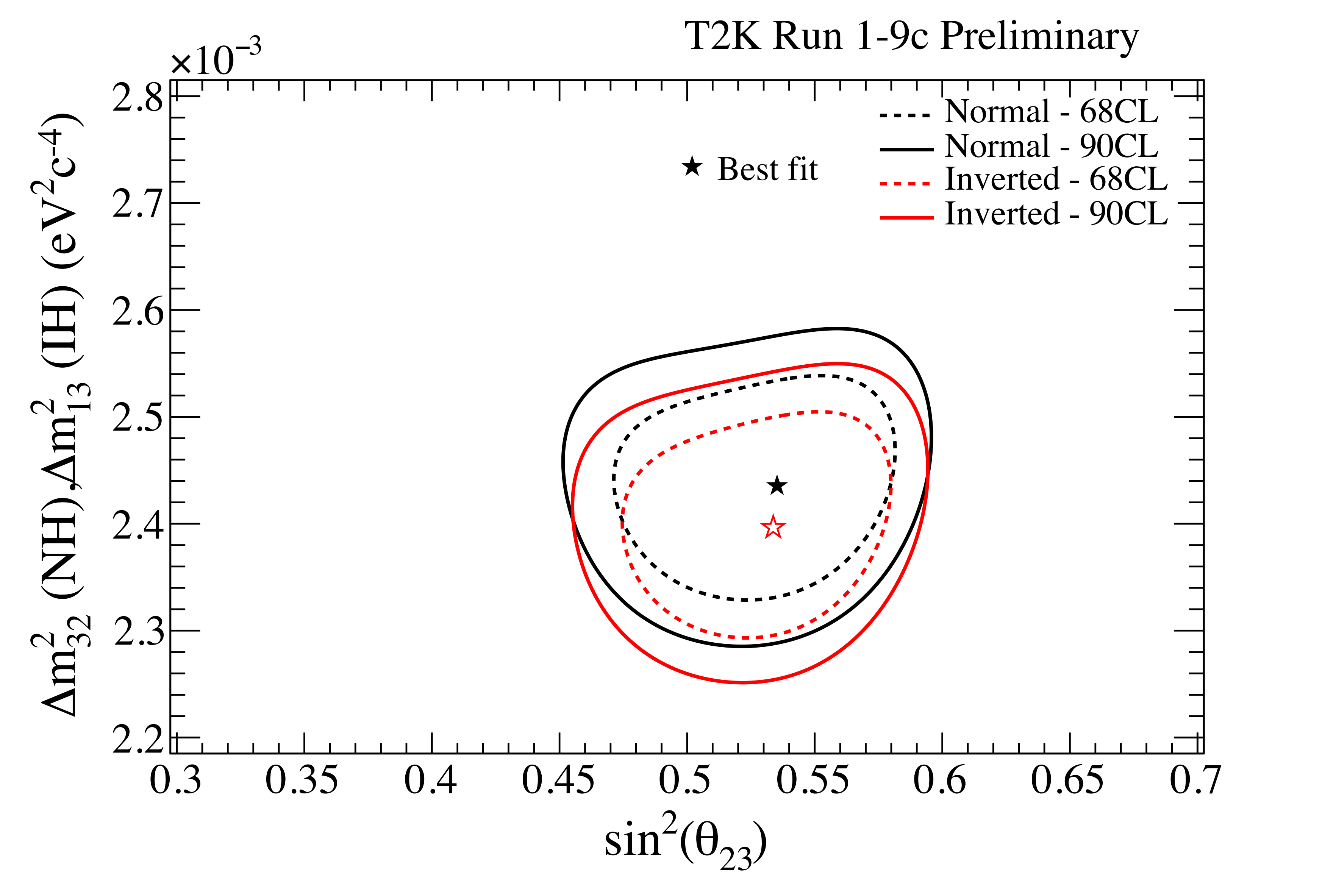
ν beam, 1 ring e, 1 decay-e



ν̄ beam, 1 ring e, no decay-e

T2K: Δm^2_{32} and θ_{23}





Joint fit of all samples

Normal hierarchy:

$$\sin^2\theta_{23} = 0.536^{+0.031}_{-0.046}$$

$$\Delta m^2_{32} = (2.434 \pm 0.064) \times 10^{-3}\mathrm{eV}^2$$

Inverted hierarchy:

$$\sin^2\theta_{23} = 0.536^{+0.031}_{-0.041}$$

$$\Delta m^2_{13} = (2.410^{+0.062}_{-0.063}) \times 10^{-3}\mathrm{eV}^2$$

Posterior probabilities based on a Bayesian analysis

	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	Sum
NH	0.204	0.684	0.888
IH	0.023	0.089	0.112
Sum	0.227	0.773	1

Bayes factor NH/IH = 7.9

$\bar{\nu}_e$ appearance search in T2K

- Dedicated searches performed by hypothesis testing:

  PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0)

Expected events:	11.8 for β=1
	6.5 for β=0
Observed:	9 events

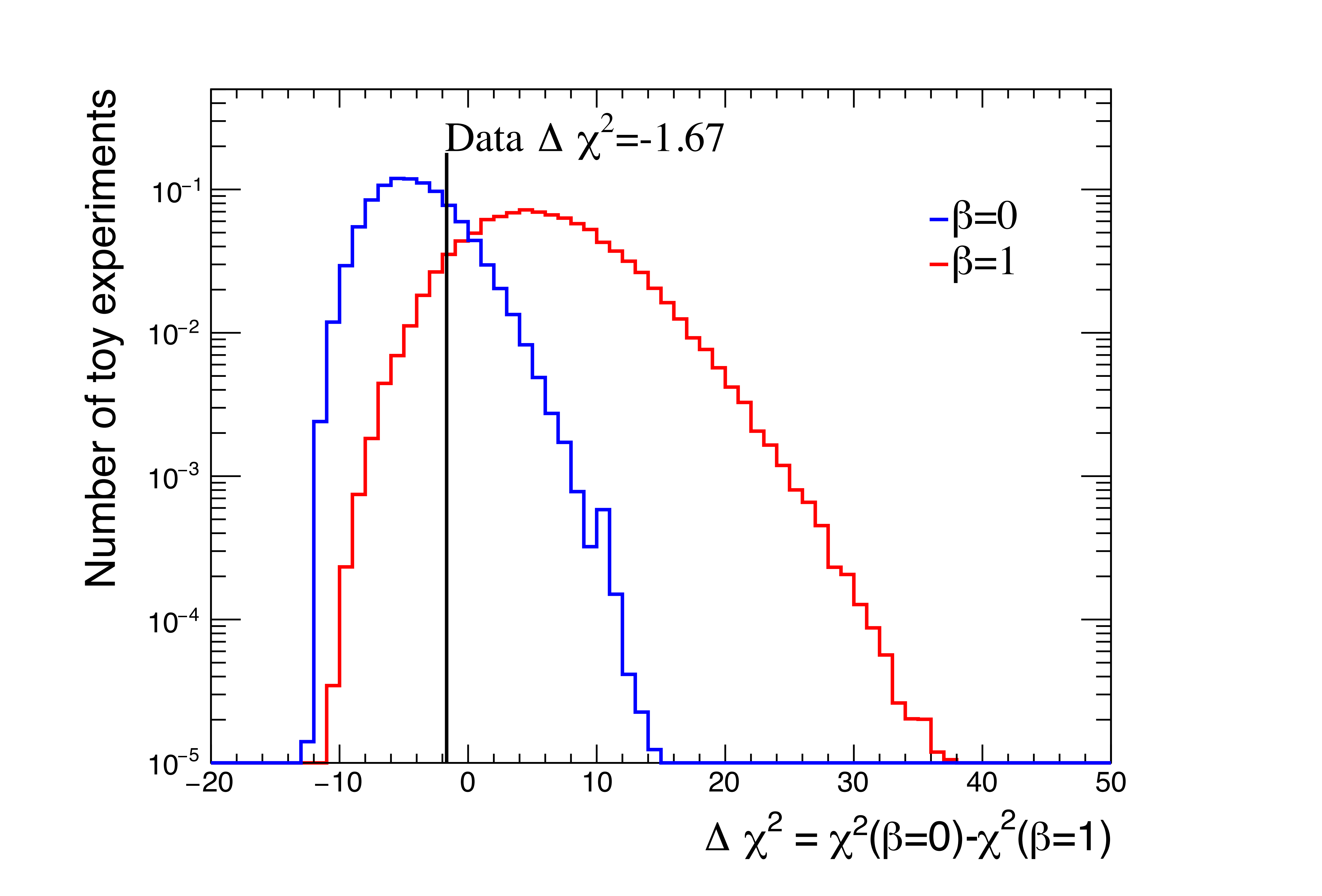
Construct $\Delta\chi^2$ with rate+shape (p, θ)

other oscillation parameters constrained from T2K data other than $\bar{\nu}_e$ sample

Obtained p-values:

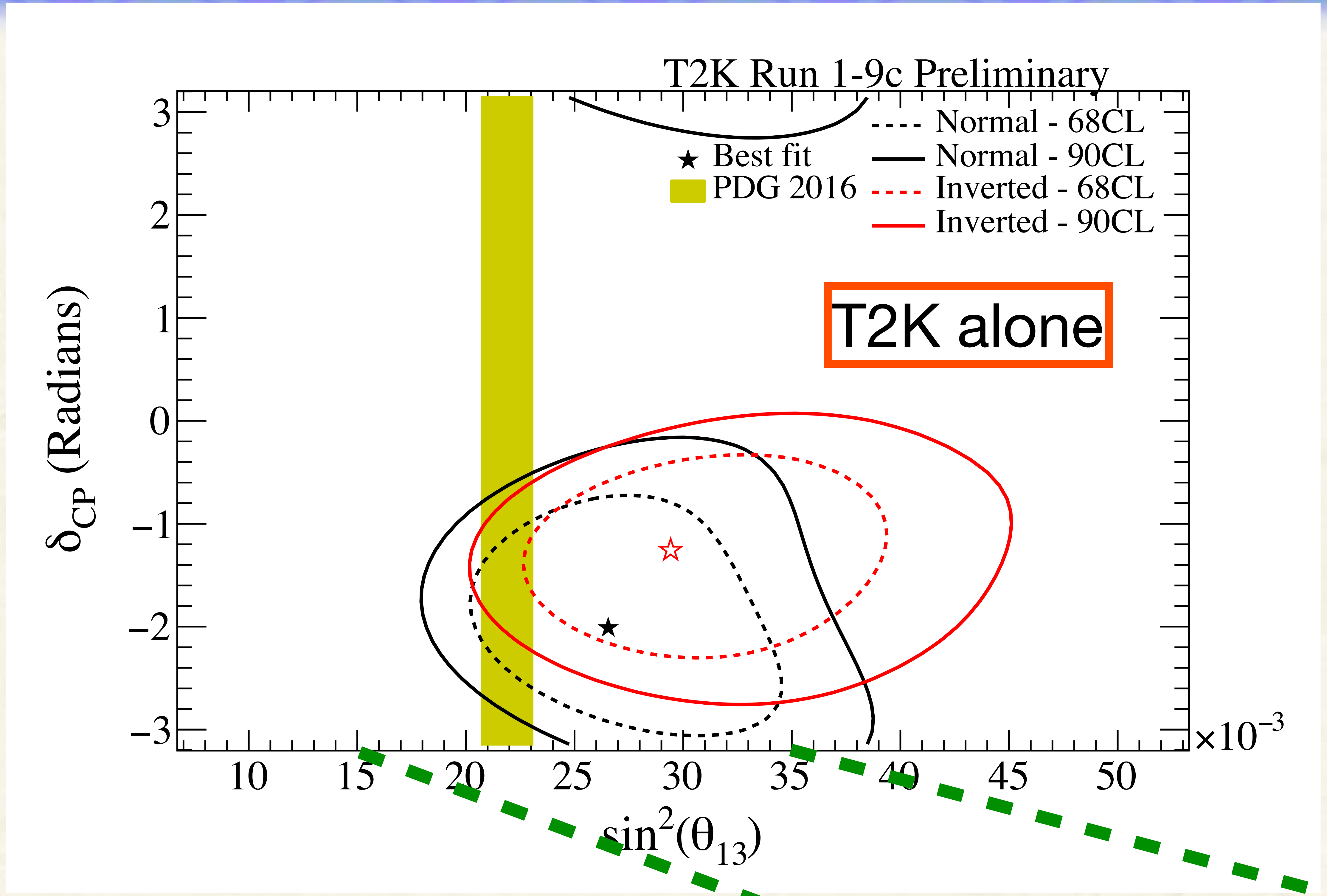
PMNS appearance (β=1): p=0.0867

No appearance (β=0): p=0.233

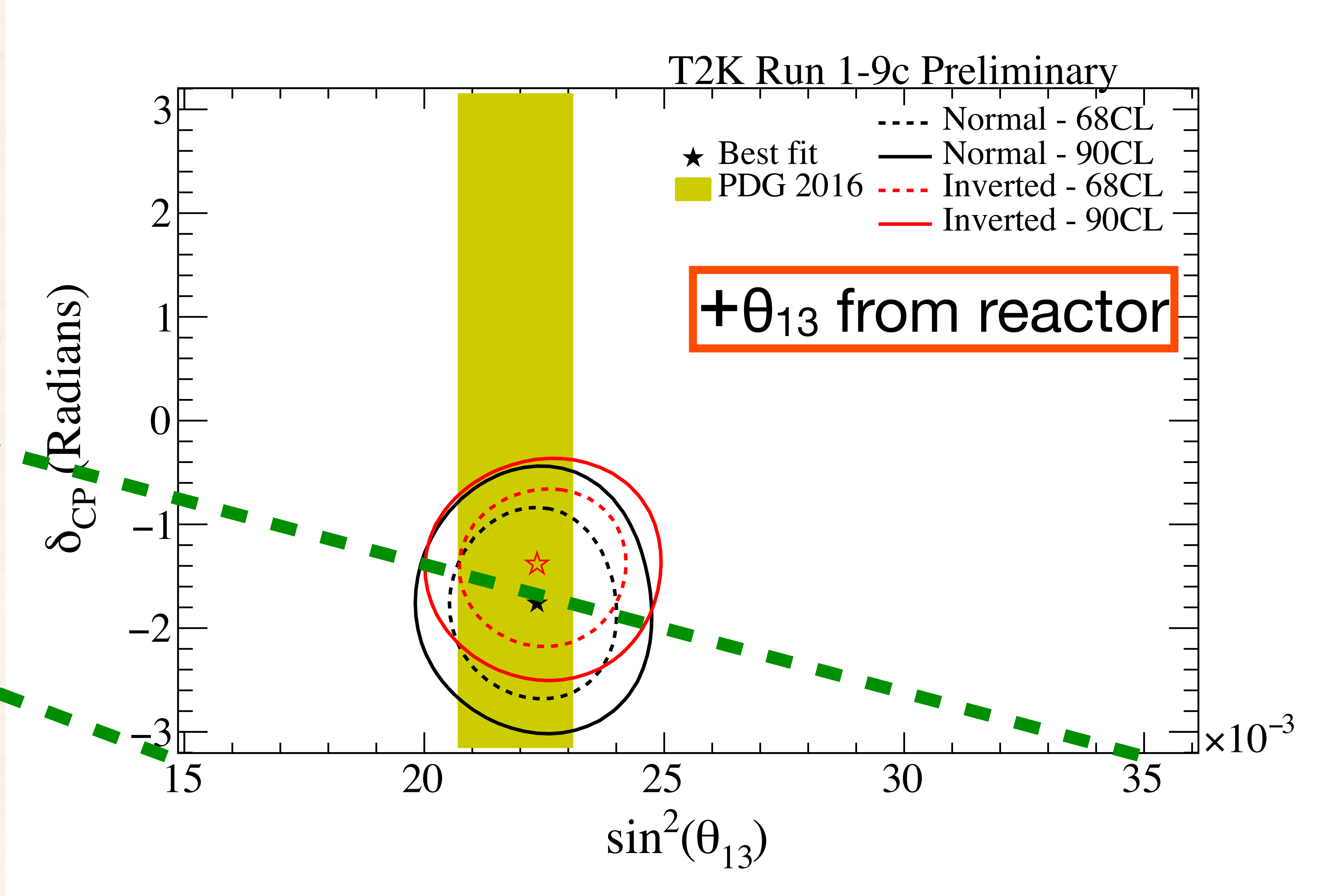


No strong statistical conclusion from T2K data yet

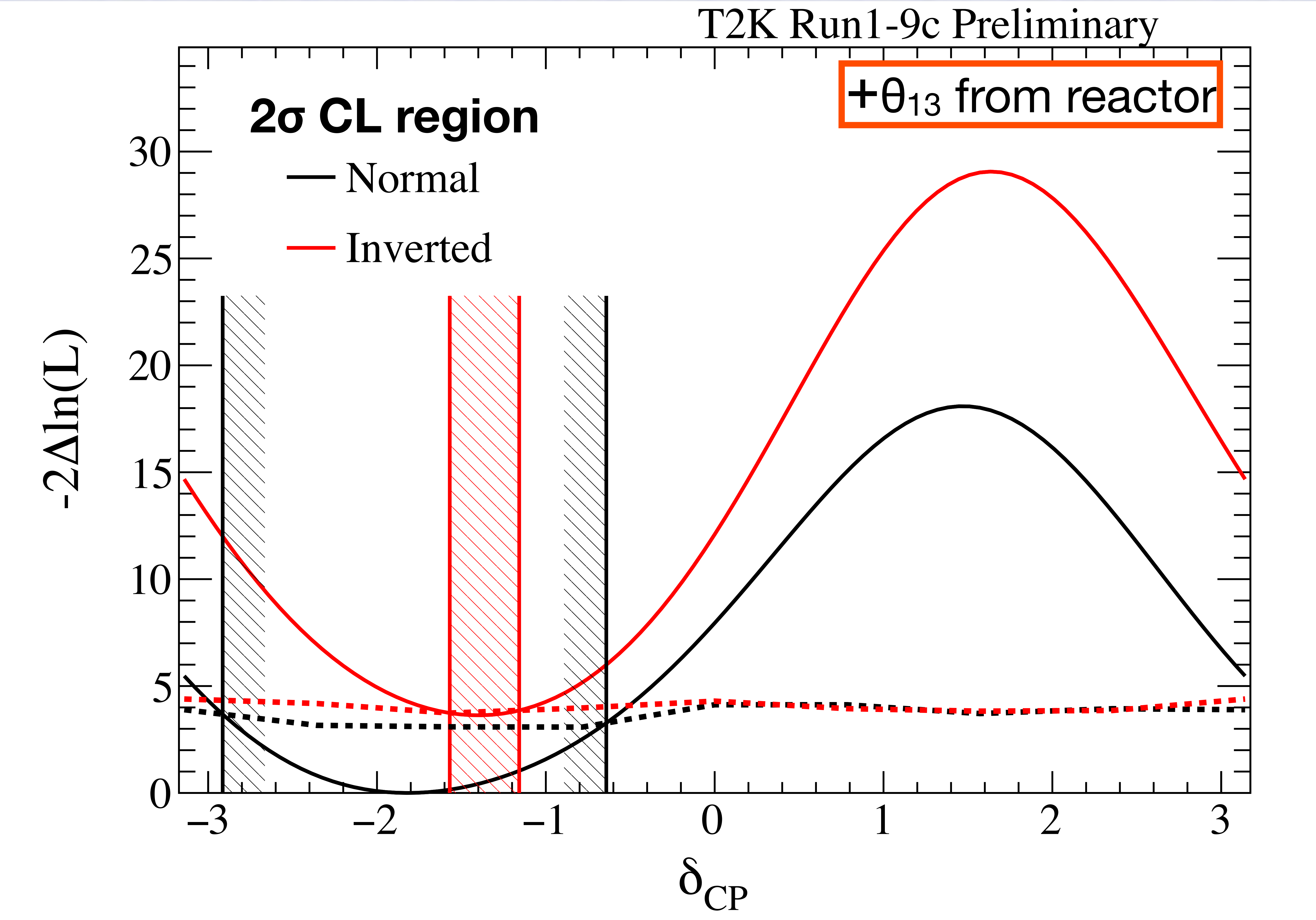
T2K: θ_{13} and δ_{CP}



- **Constraint on δ_{CP} with T2K data alone**
- Tighter constraint with θ_{13} value from reactor



T2K: constraint on δ_{CP}

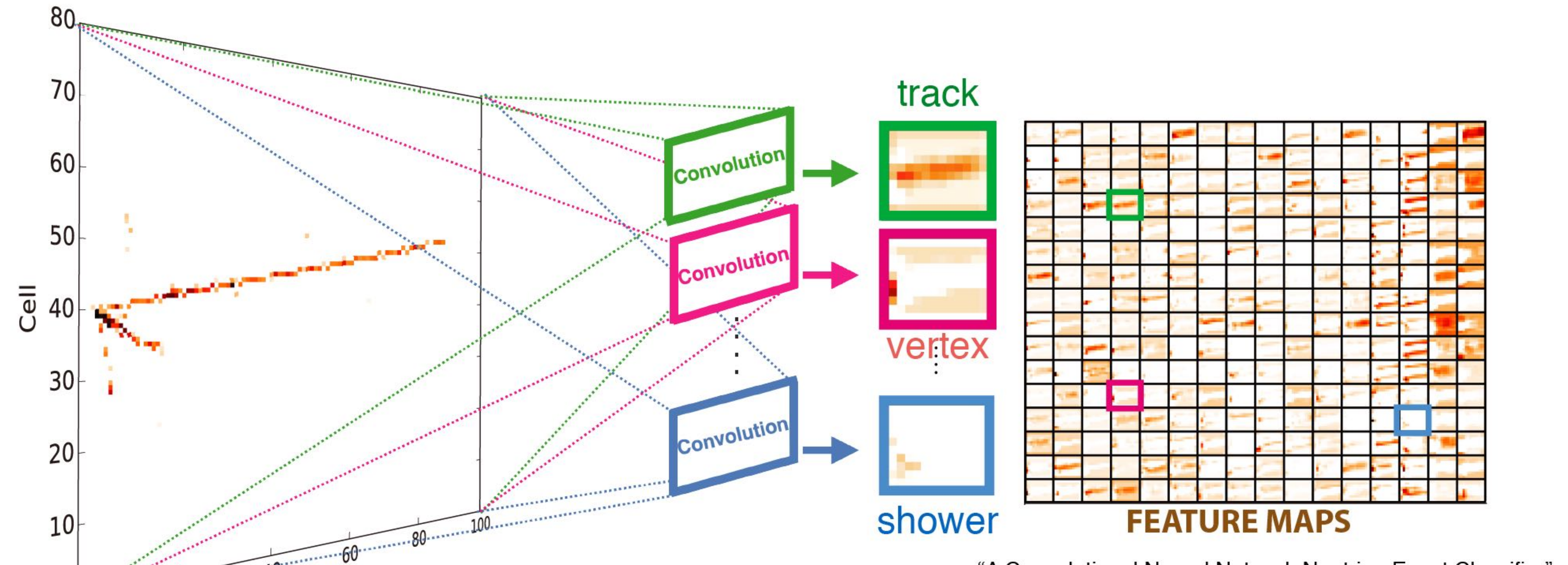


$\sin\delta_{CP}$=0 (δ=0, π) outside of 2σ CL region

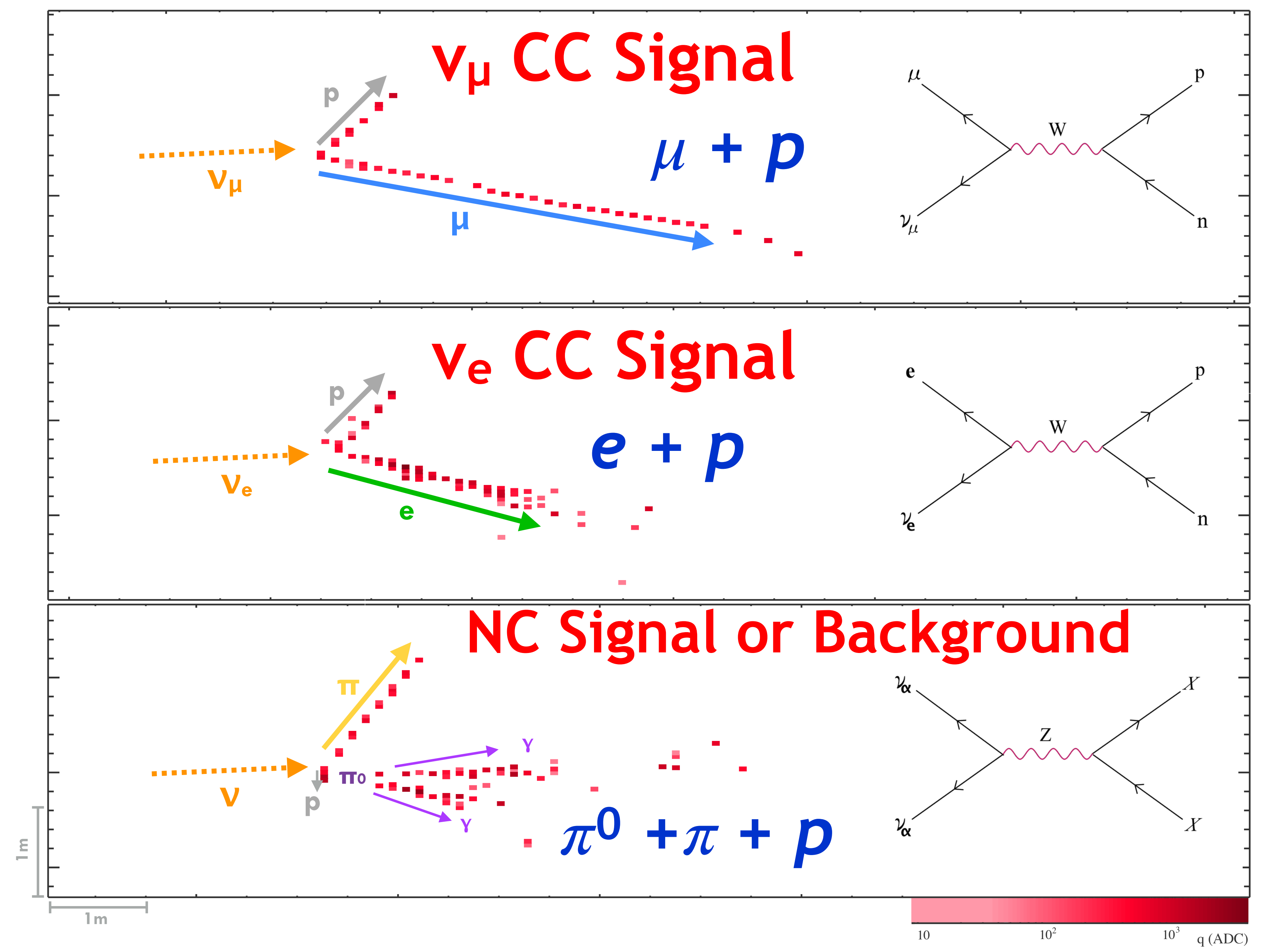
First hint of CP violation in the lepton sector!

NOvA event classification

- Pioneering the use of **Convolutional Neural Networks** in neutrino experiment
- Treating cells as pixels and charge as color, extract features from data
- Improved classifier used for 2018 analysis
  - with separate training for the neutrino and antineutrino beams

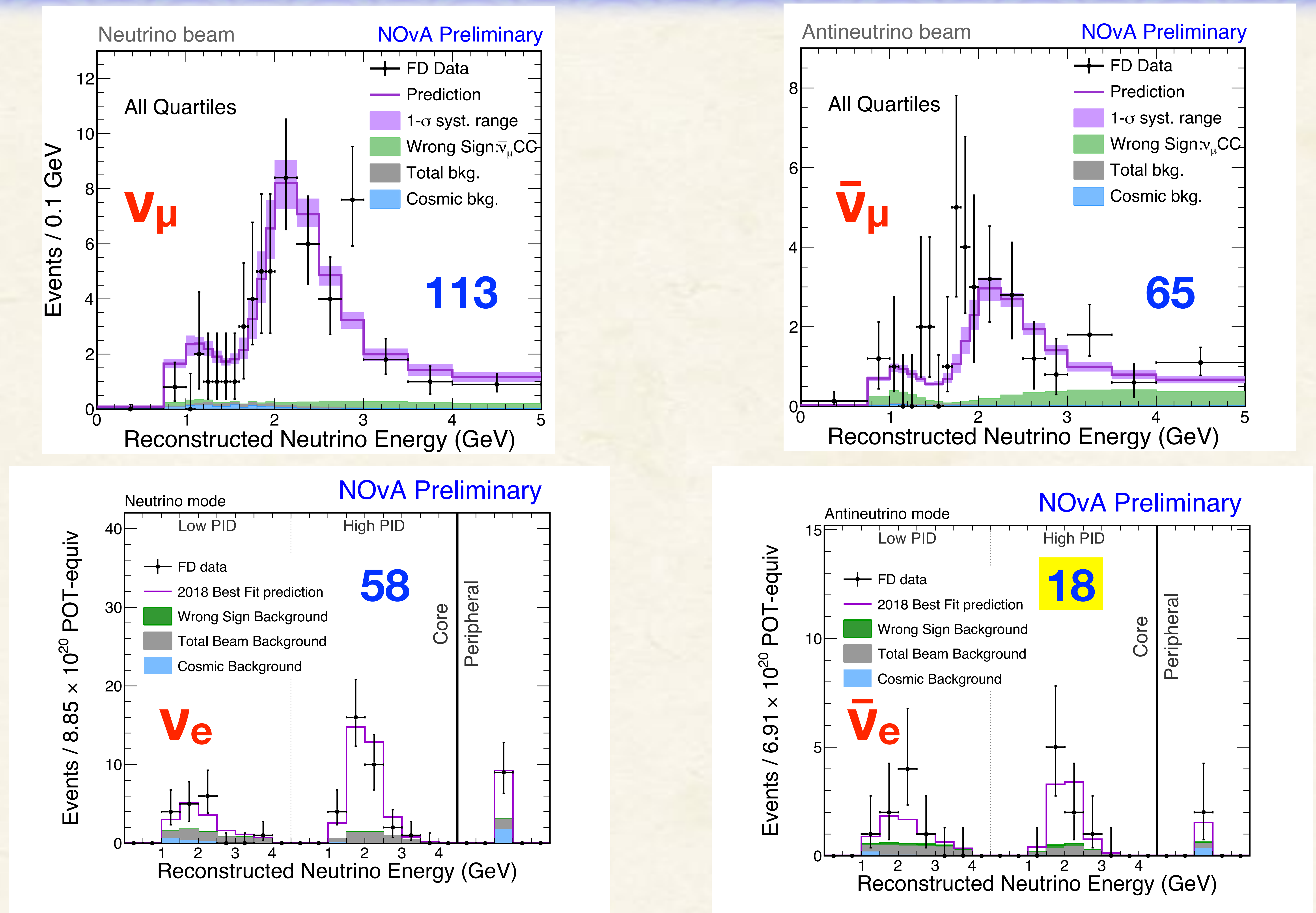


"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016



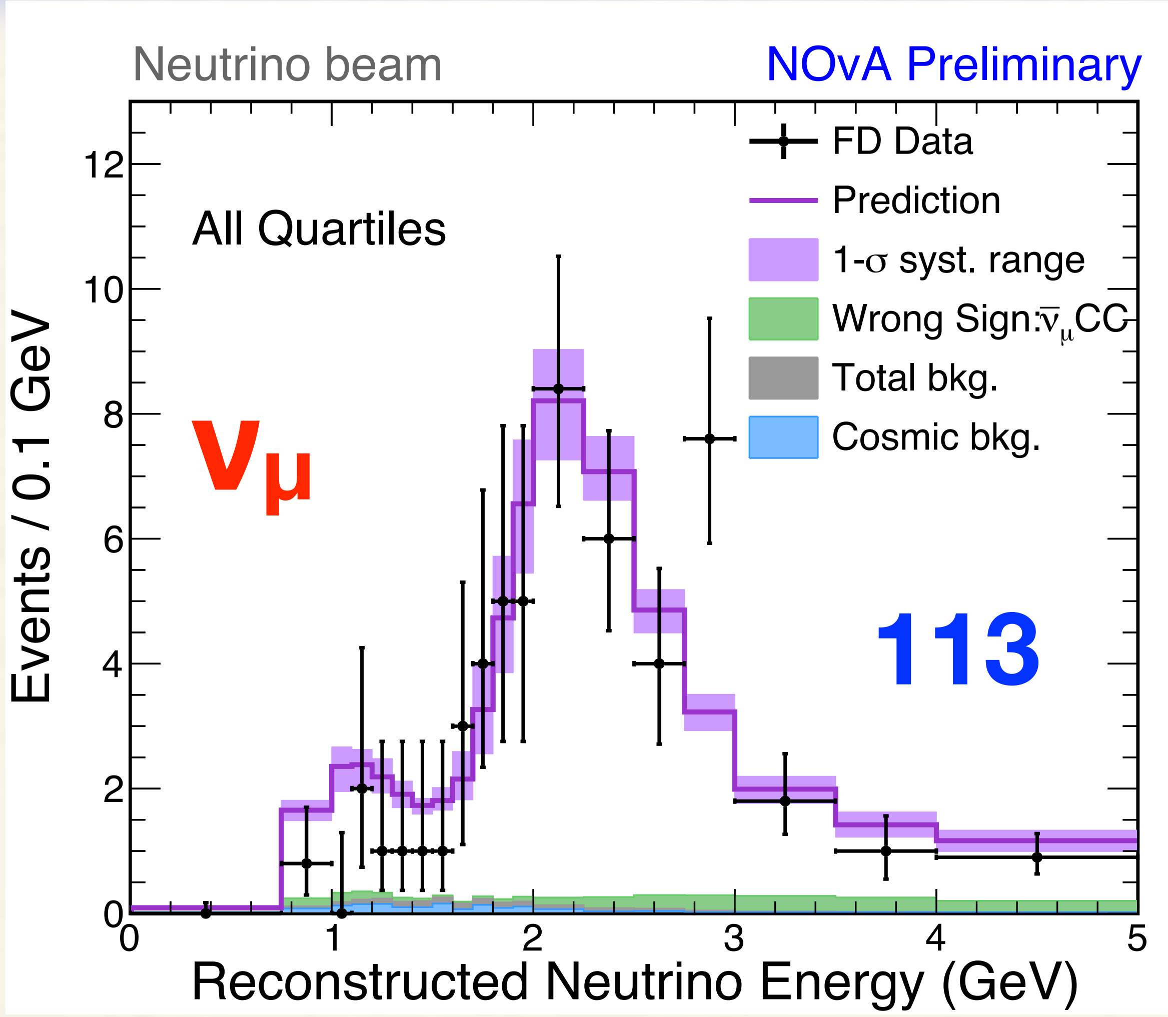
- Neutrino energy reconstruction from E_l (range[μ]/calorimetric[e])+ E_{had} (calorimetric)

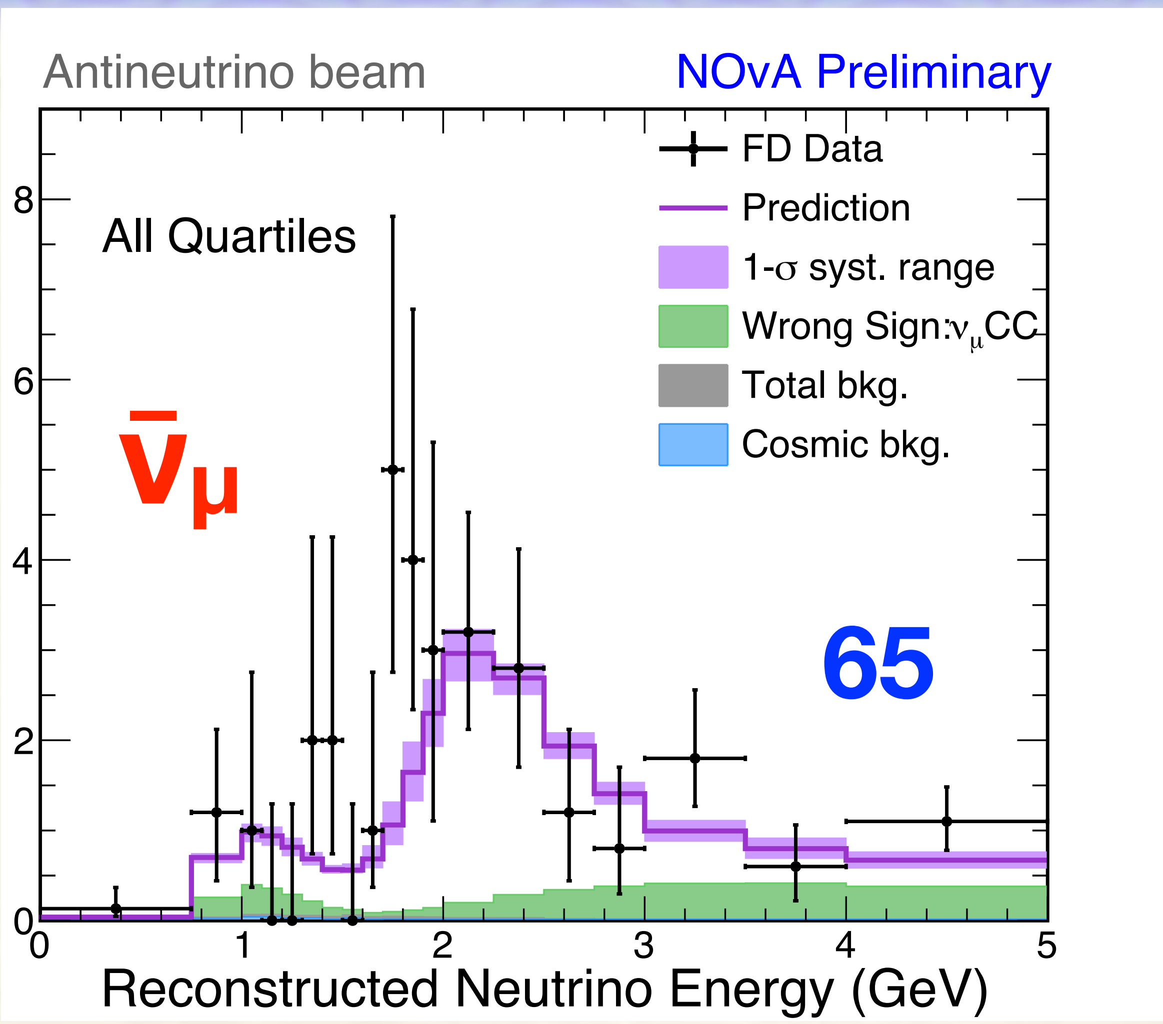
NOvA FD data

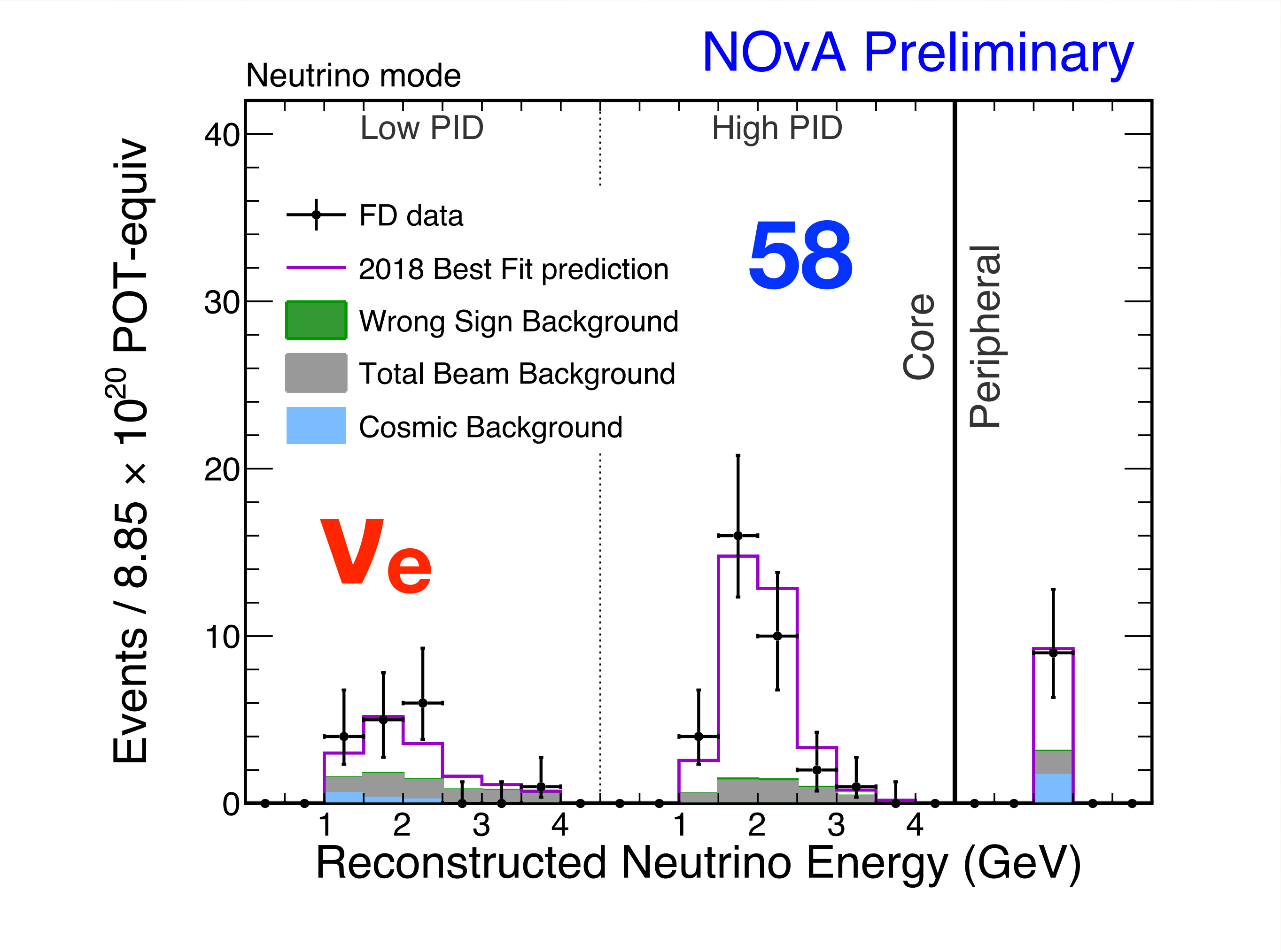


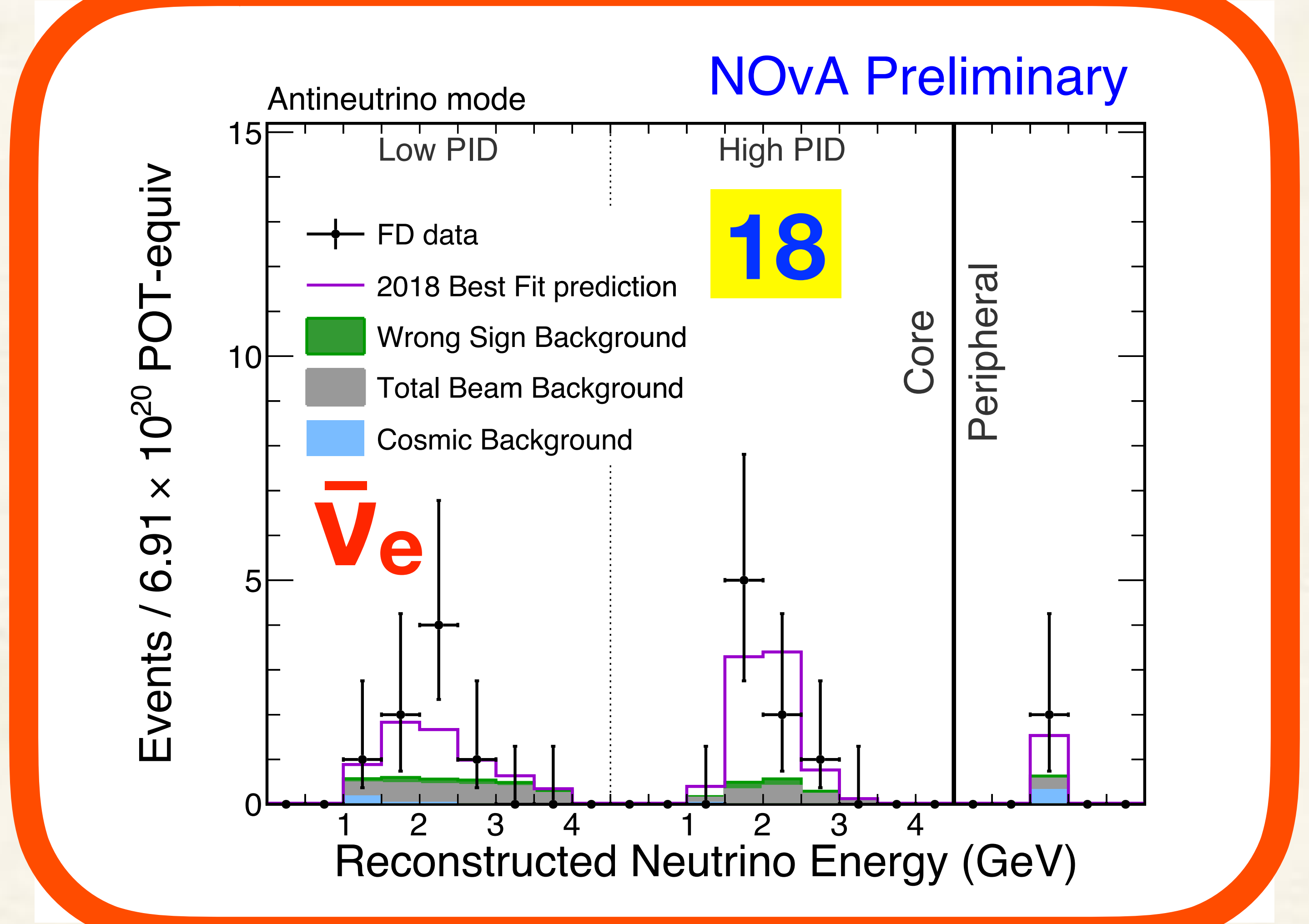
Neutrino beam
NOvA Preliminary
All Quartiles
FD Data
Prediction
1-σ syst. range
Wrong Sign: $\bar{\nu}_\mu$ CC
Total bkg.
Cosmic bkg.
ν_μ
113
Events / 0.1 GeV
Reconstructed Neutrino Energy (GeV)
Antineutrino beam
NOvA Preliminary
All Quartiles
FD Data
Prediction
1-σ syst. range
Wrong Sign: ν_μ CC
Total bkg.
Cosmic bkg.
$\bar{\nu}_\mu$
65
Reconstructed Neutrino Energy (GeV)
Neutrino mode
NOvA Preliminary
Low PID
High PID
FD data
2018 Best Fit prediction
Wrong Sign Background
Total Beam Background
Cosmic Background
58
Core
Peripheral
ν_e
Events / 8.85 × 10^{20} POT-equiv
Reconstructed Neutrino Energy (GeV)
Antineutrino mode
NOvA Preliminary
Low PID
High PID
FD data
2018 Best Fit prediction
Wrong Sign Background
Total Beam Background
Cosmic Background
18
Core
Peripheral
$\bar{\nu}_e$
Events / 6.91 × 10^{20} POT-equiv
Reconstructed Neutrino Energy (GeV)

NOvA FD data



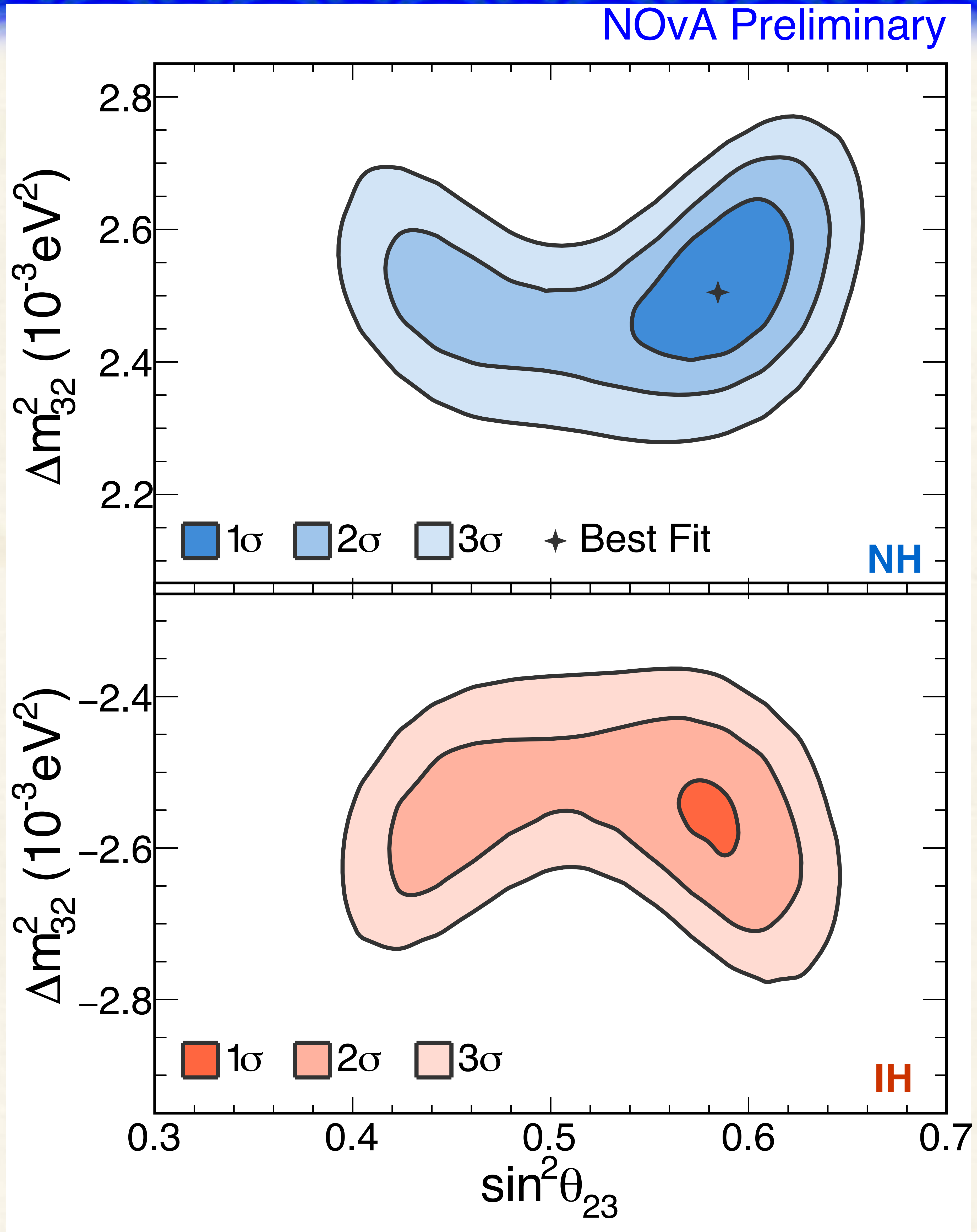






>4σ evidence of $\bar{\nu}_e$ appearance!

NOvA: Δm^2_{32} and θ_{23}

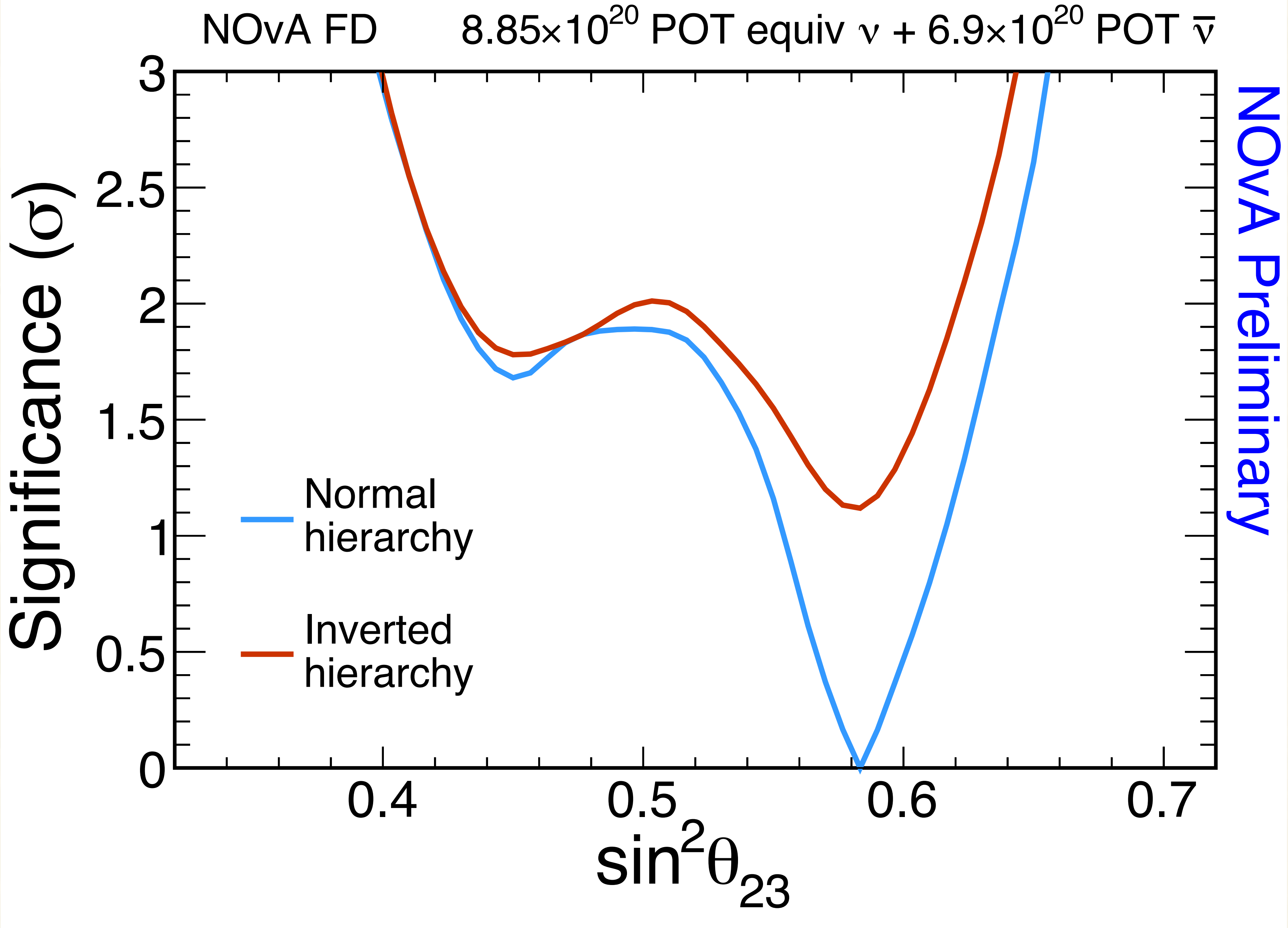


- Results from joint fit of ν_μ and ν_e

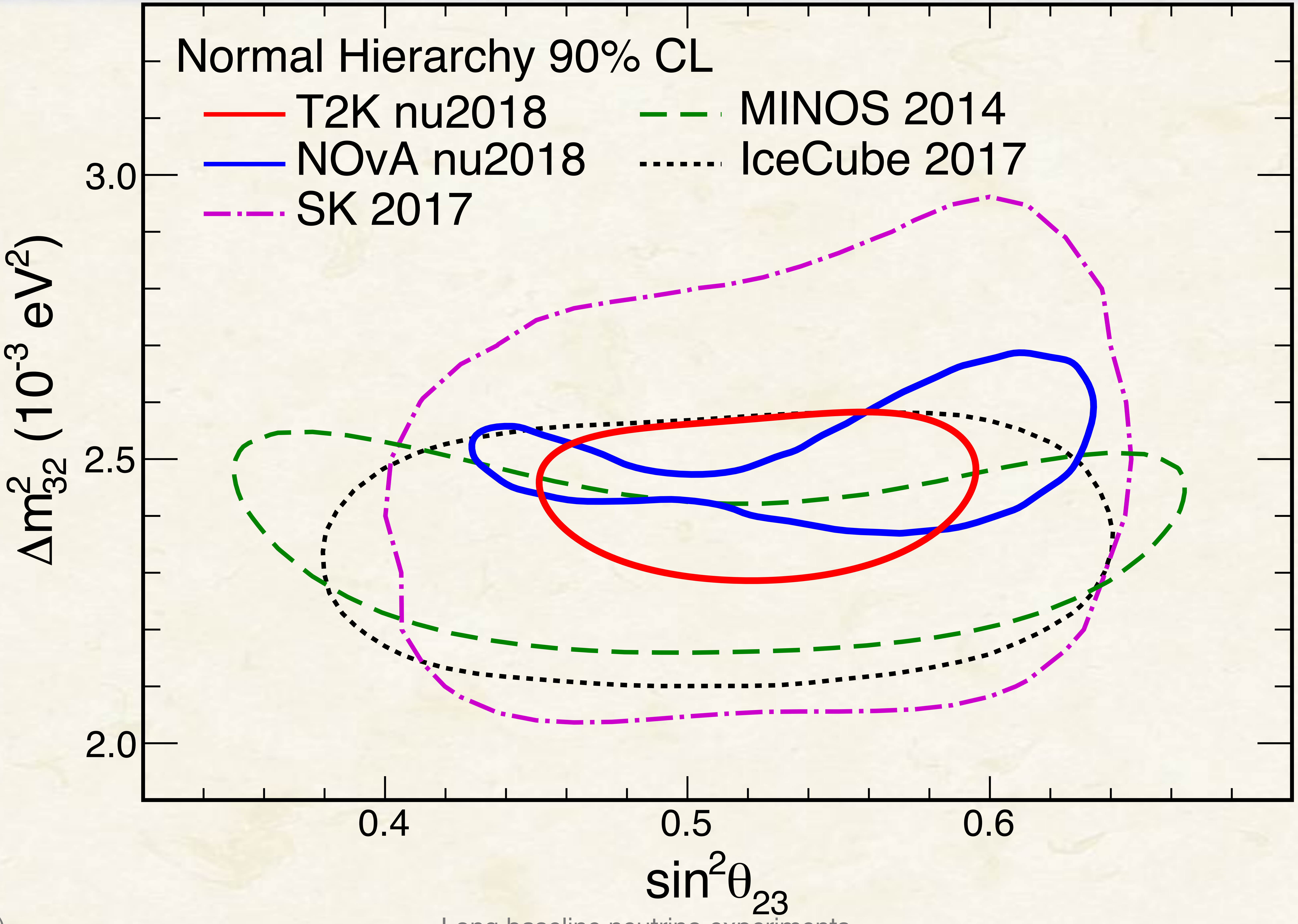
$$\sin^2\theta_{23} = 0.58 \pm 0.03$$

$$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}\mathrm{eV}^2$$

Prefer non-maximal at 1.8σ
Exclude lower octant at similar level



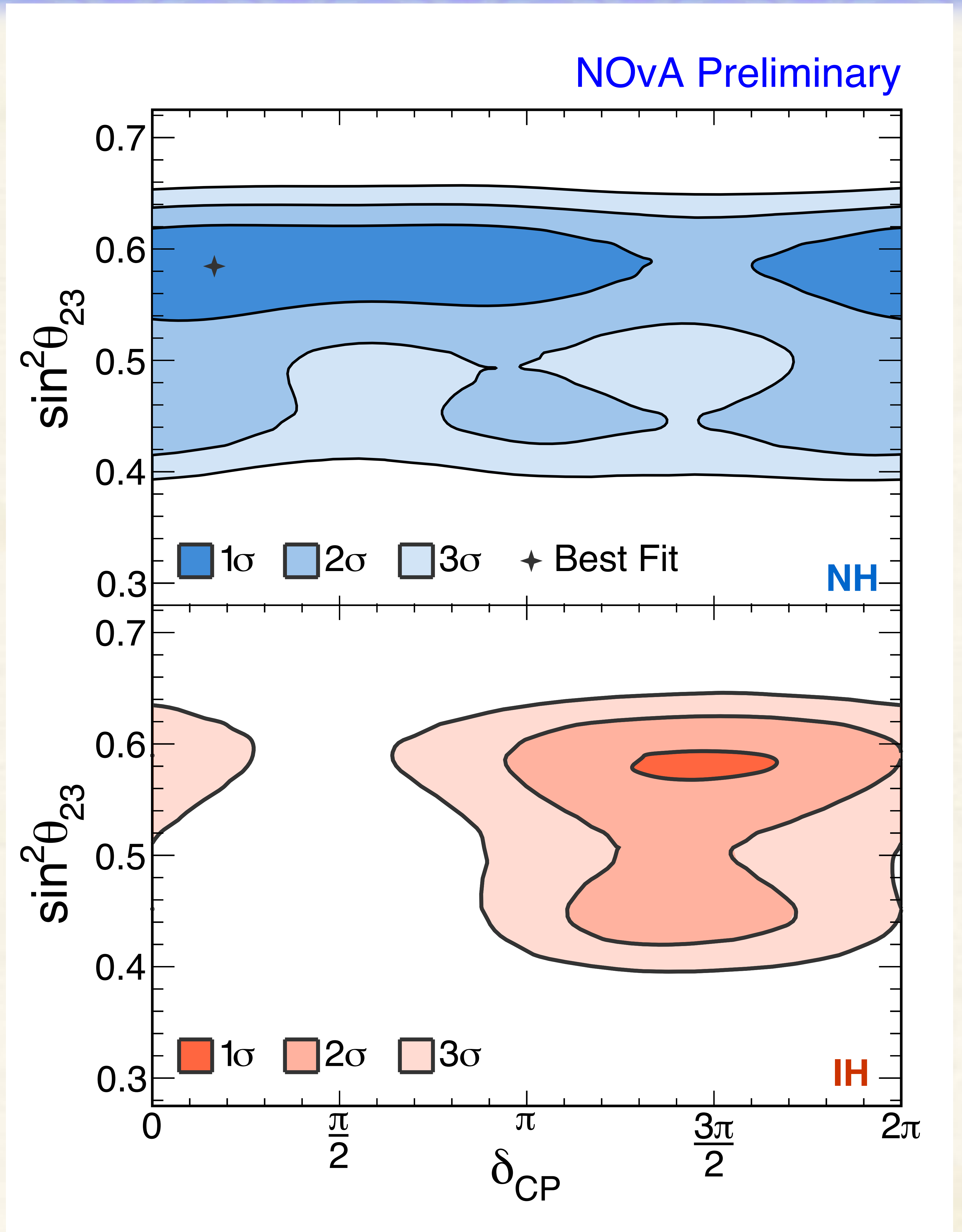
Comparison: Δm^2_{32} — θ_{23}

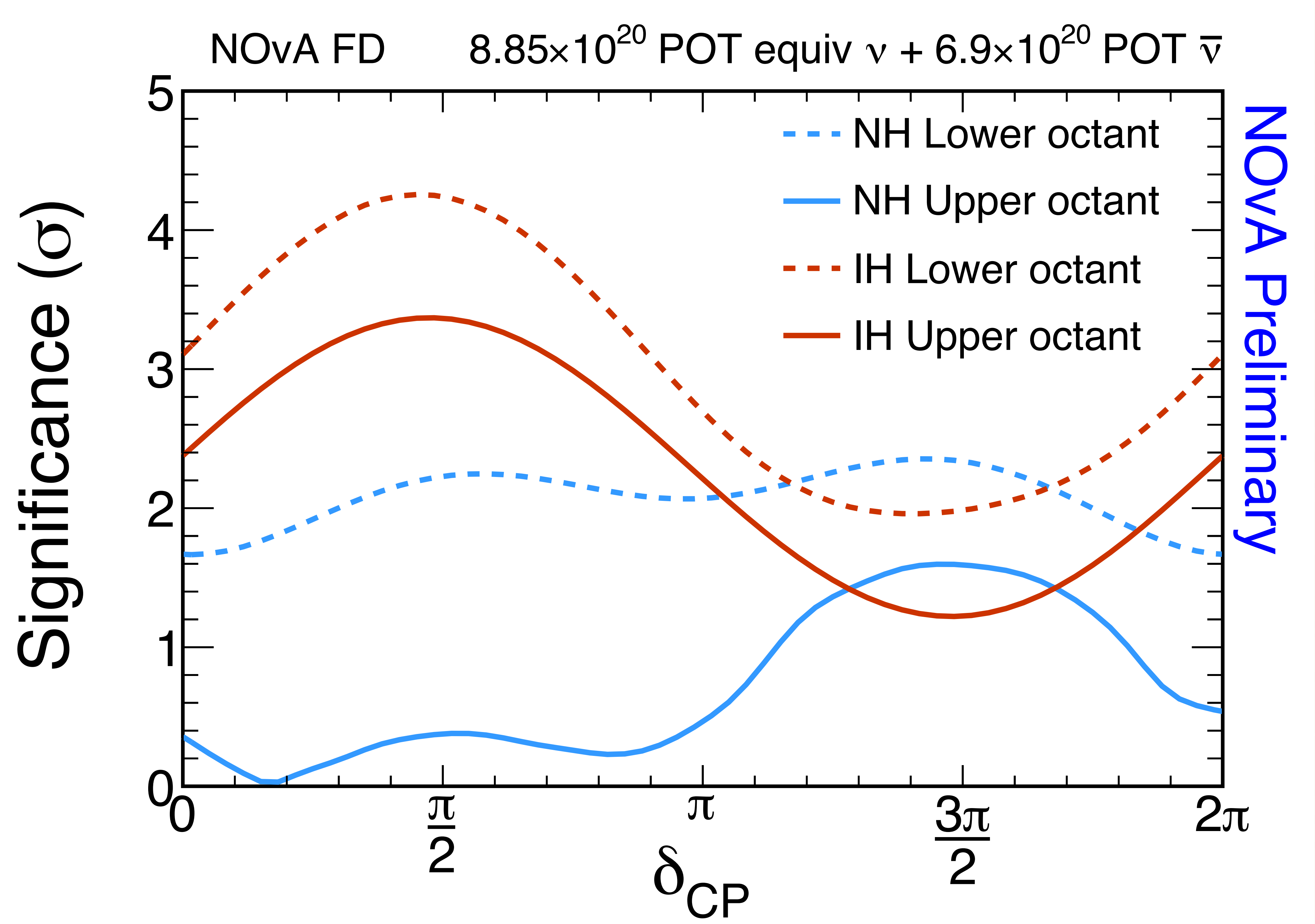


$\sin^2\theta_{23}$: <10%
$|\Delta m^2|$: 3-4%

NH preferred by T2K, NOvA, SK

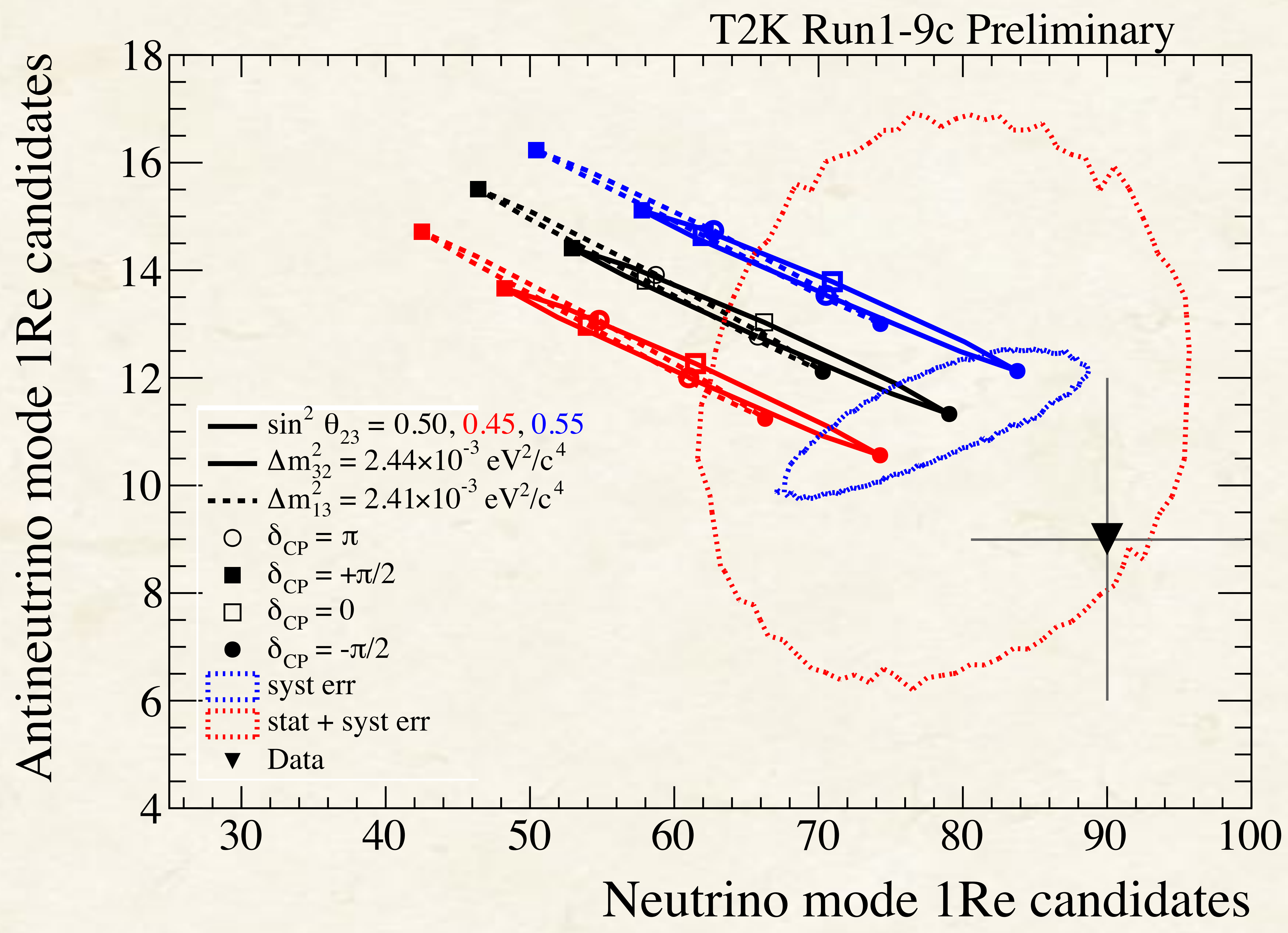
NOvA: δ_{CP} and mass hierarchy

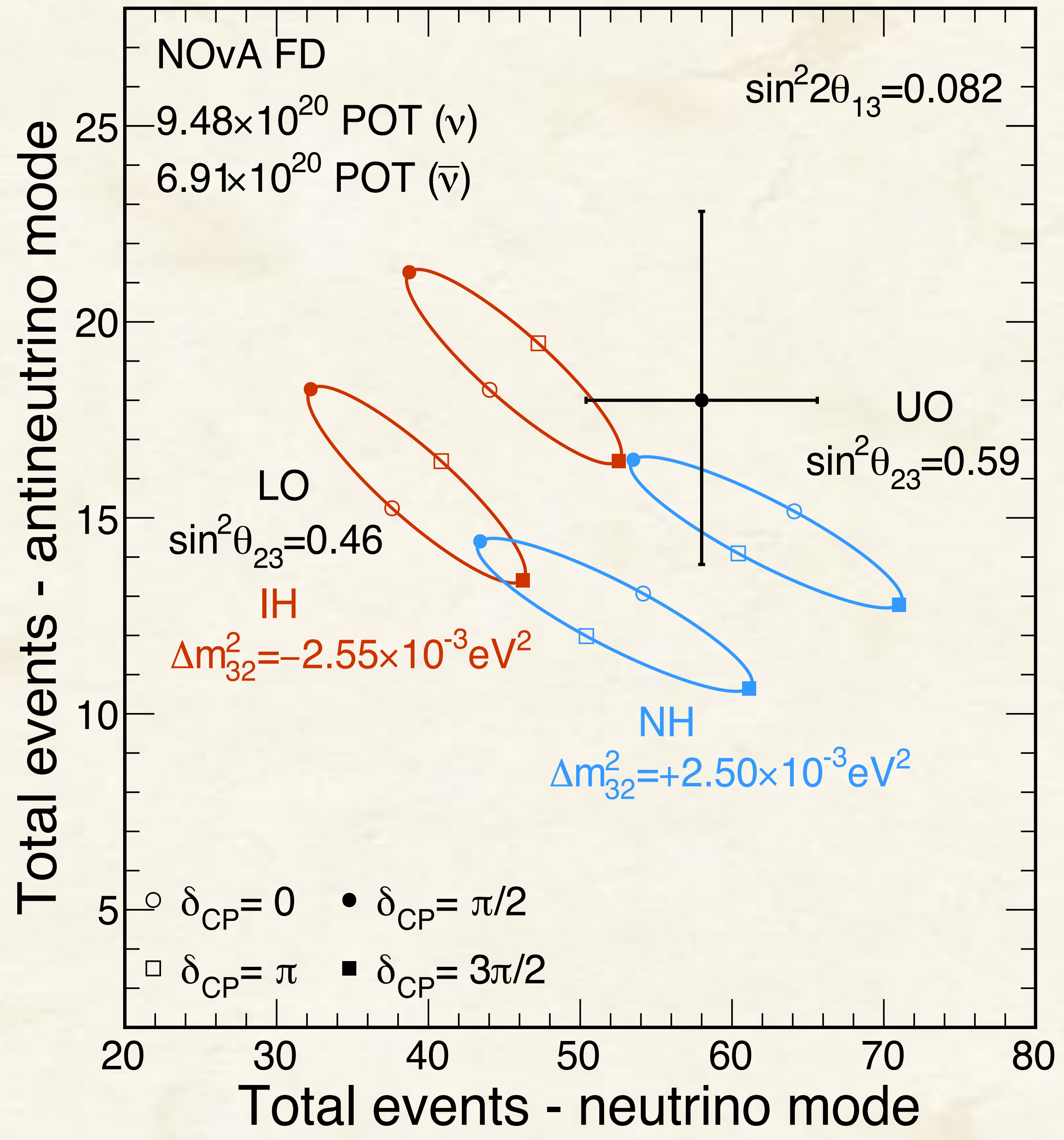




- Best fit: Normal Hierarchy, δ_{CP} = 0.17π

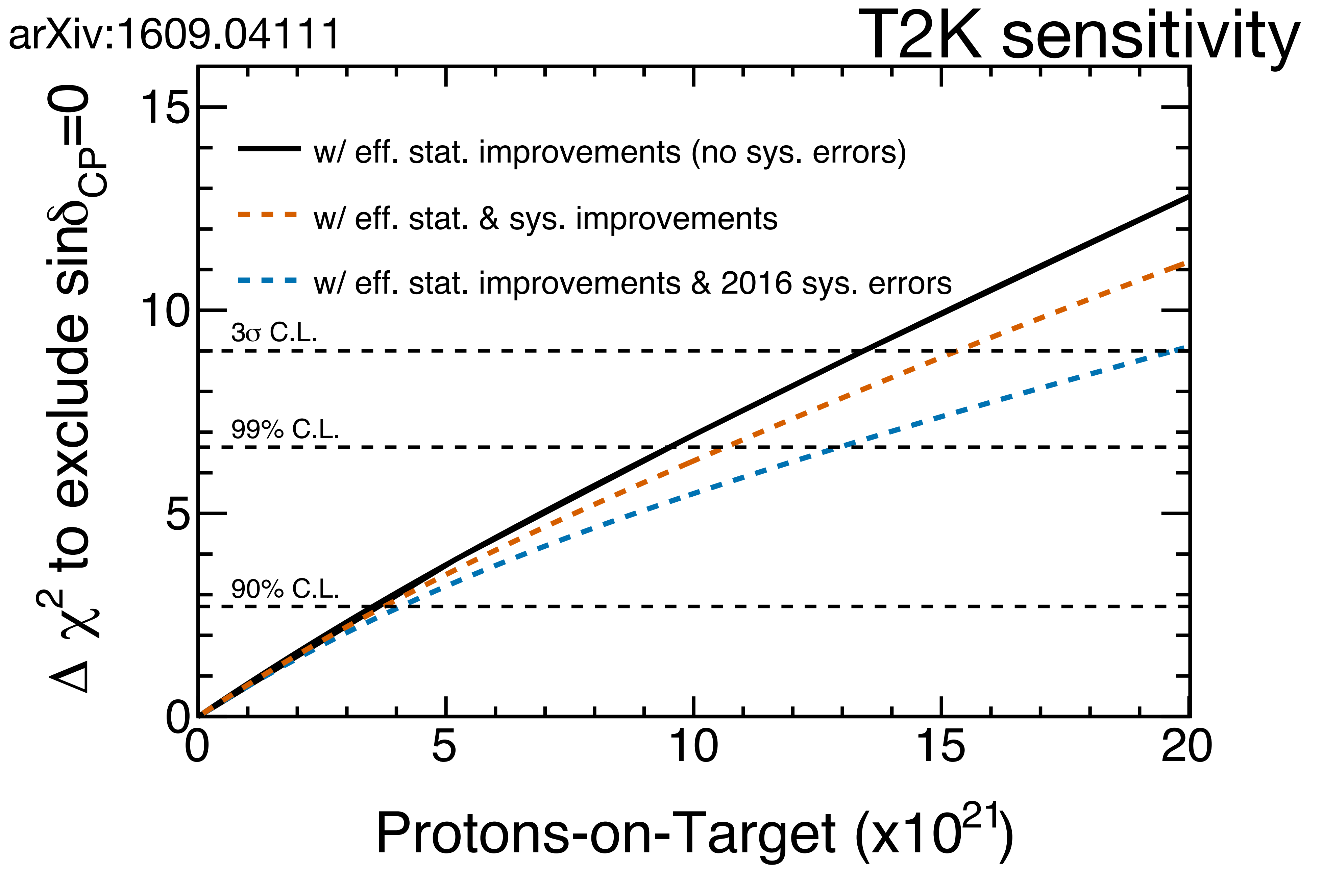
Prefer NH by 1.8σ
Exclude δ_{CP}=π/2 in the IH at >3σ

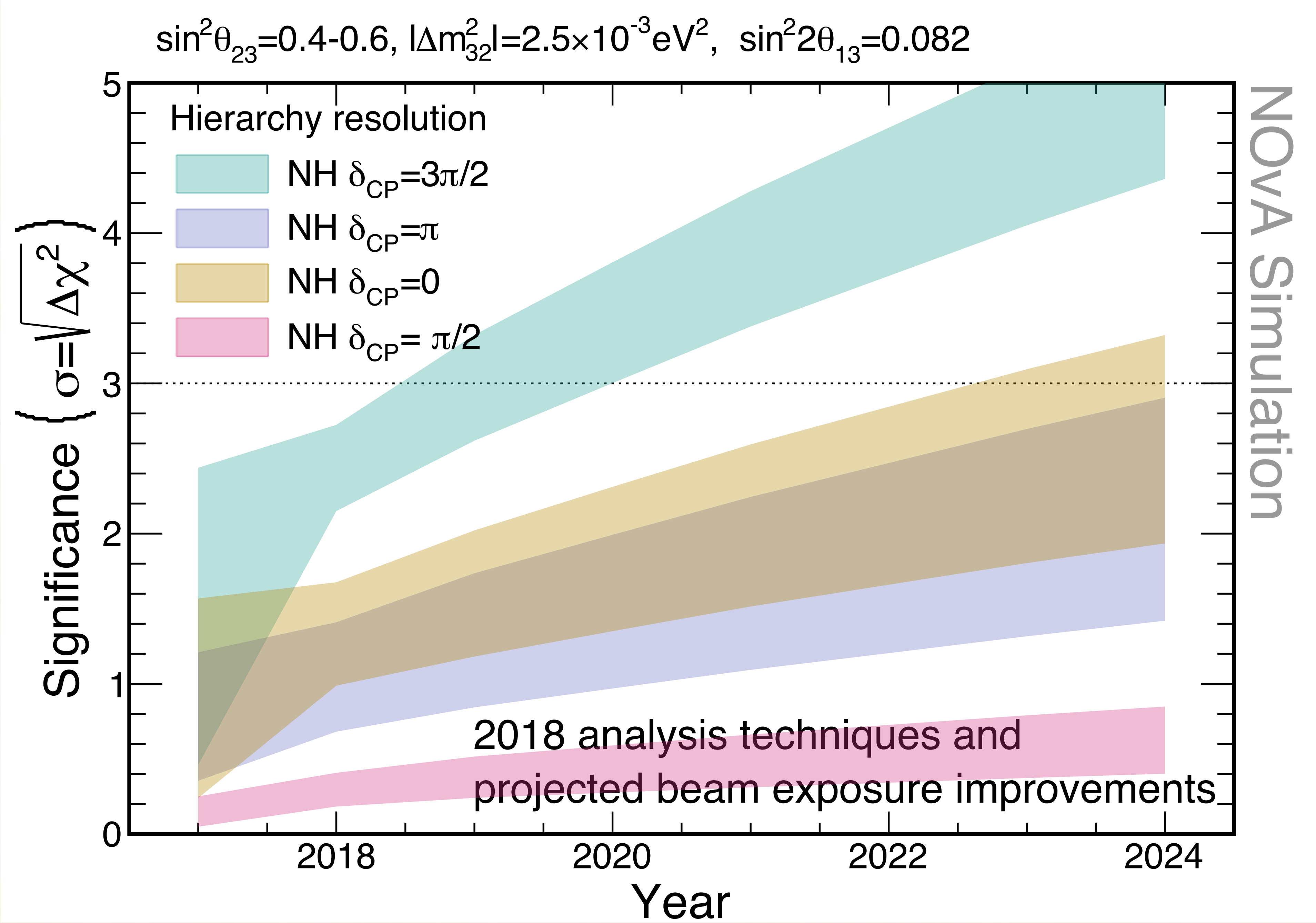




Beginning of lepton CPV era!

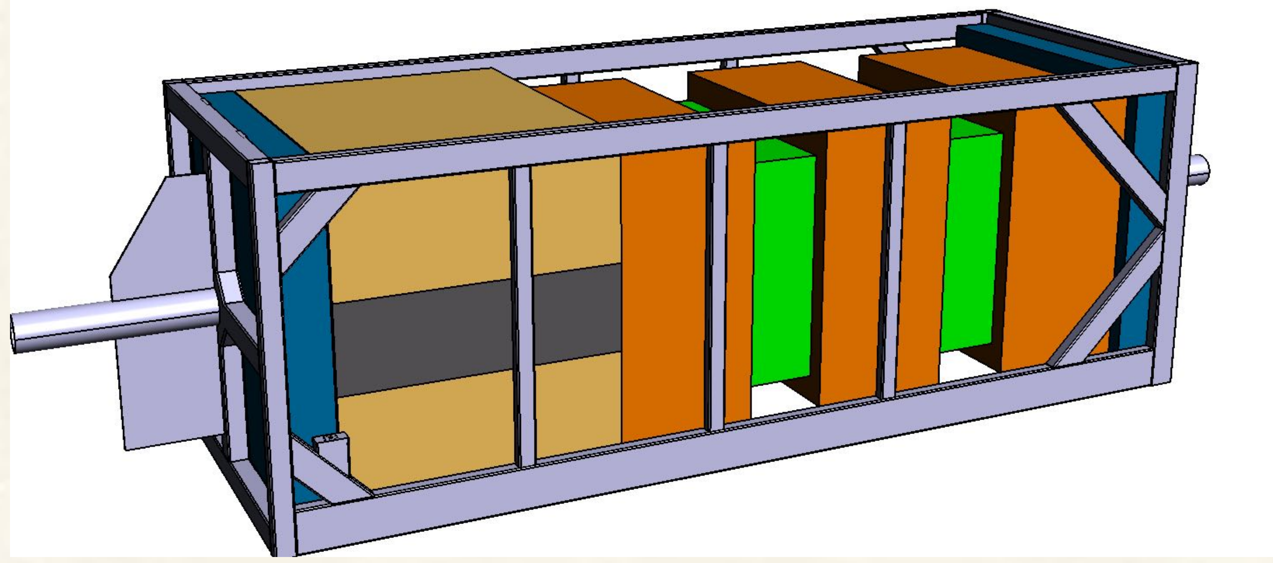
The excitement continues…





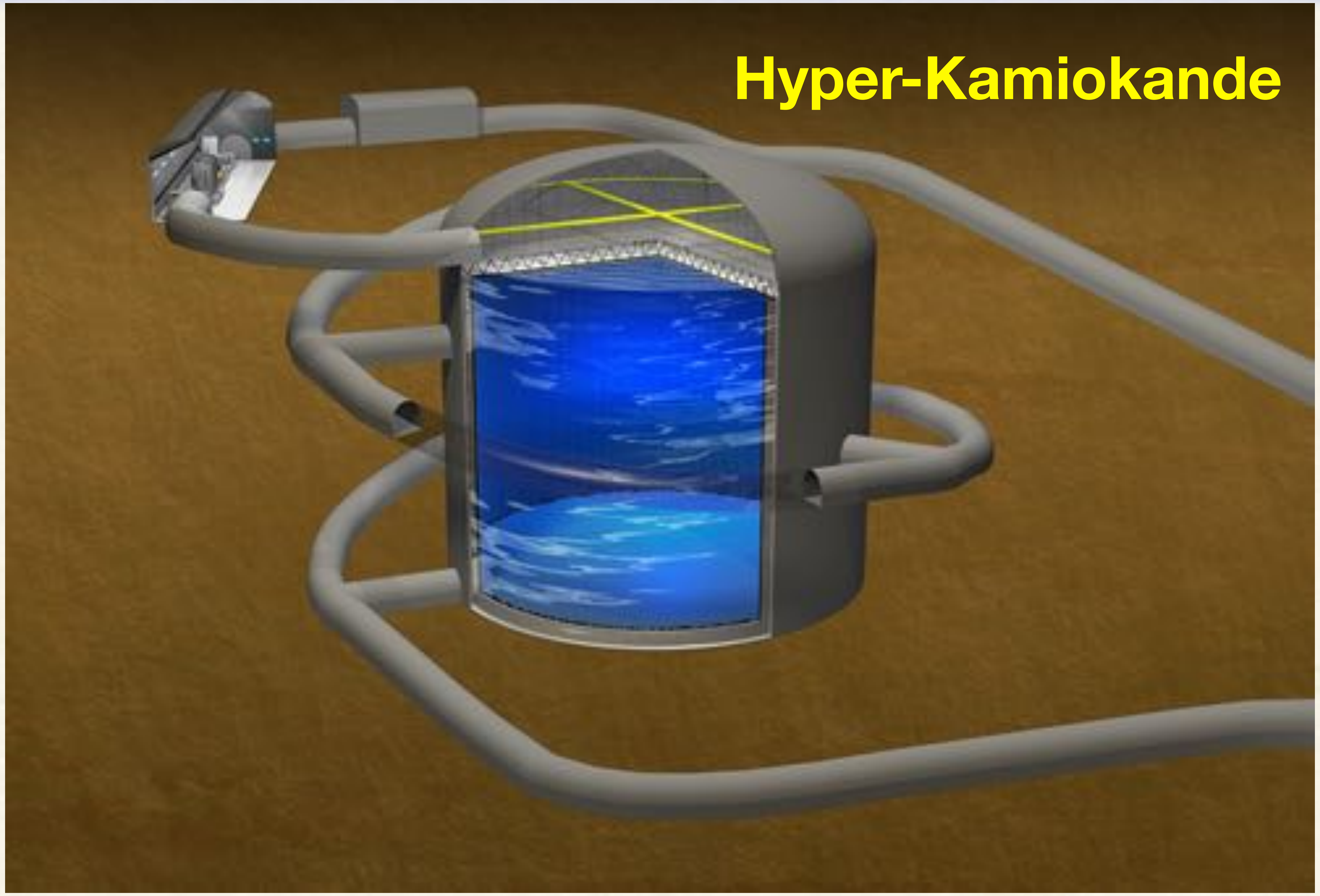
- Both experiments envision to further enhance their capabilities
  - T2K: beam power increase (1.3MW) and ND280 upgrade
  - NOvA: accelerator improvement (0.9MW) and test beam
  - Analysis improvements
- Good prospects for mass hierarchy, CP violation, …

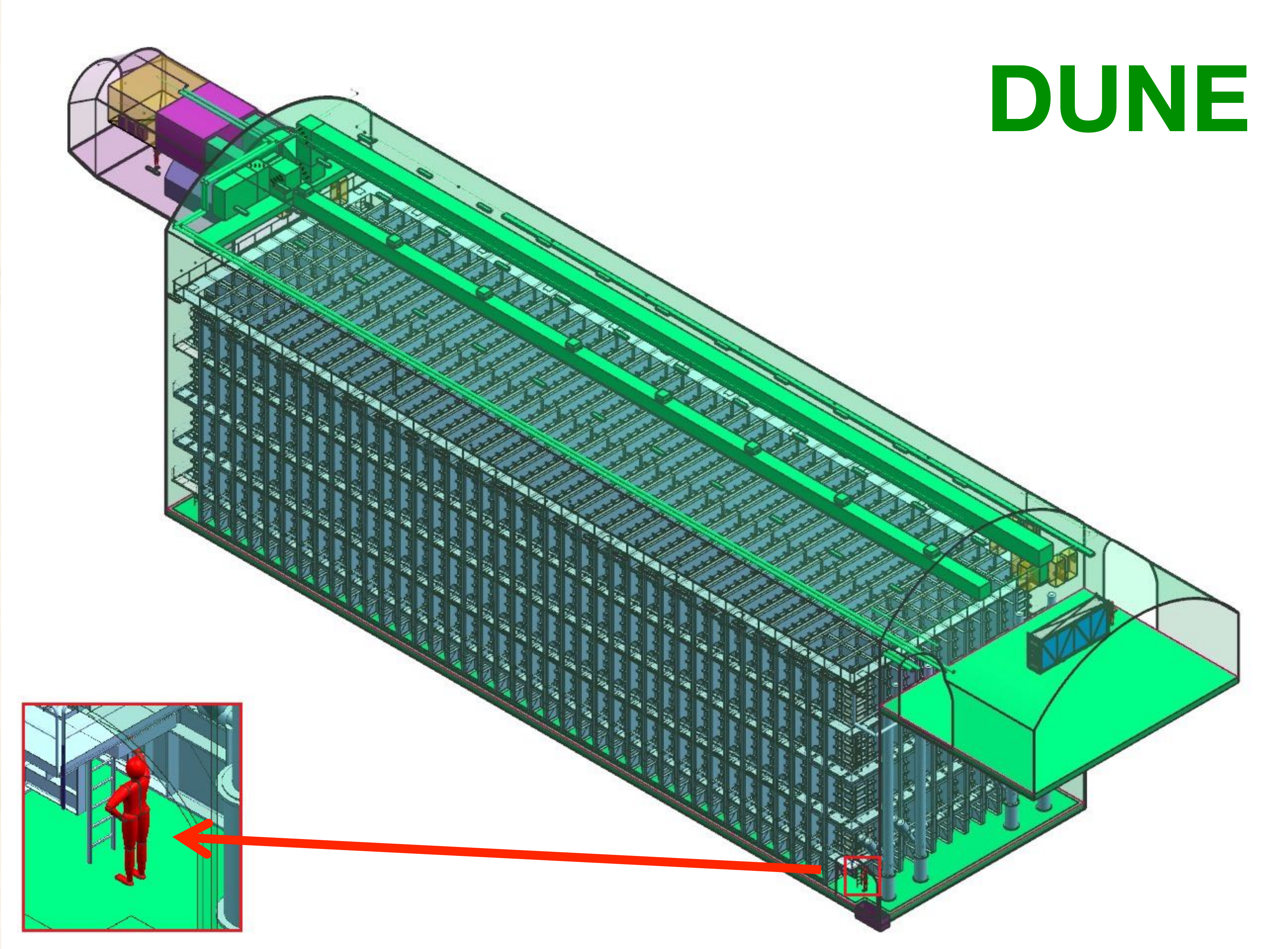
Upgraded T2K ND280

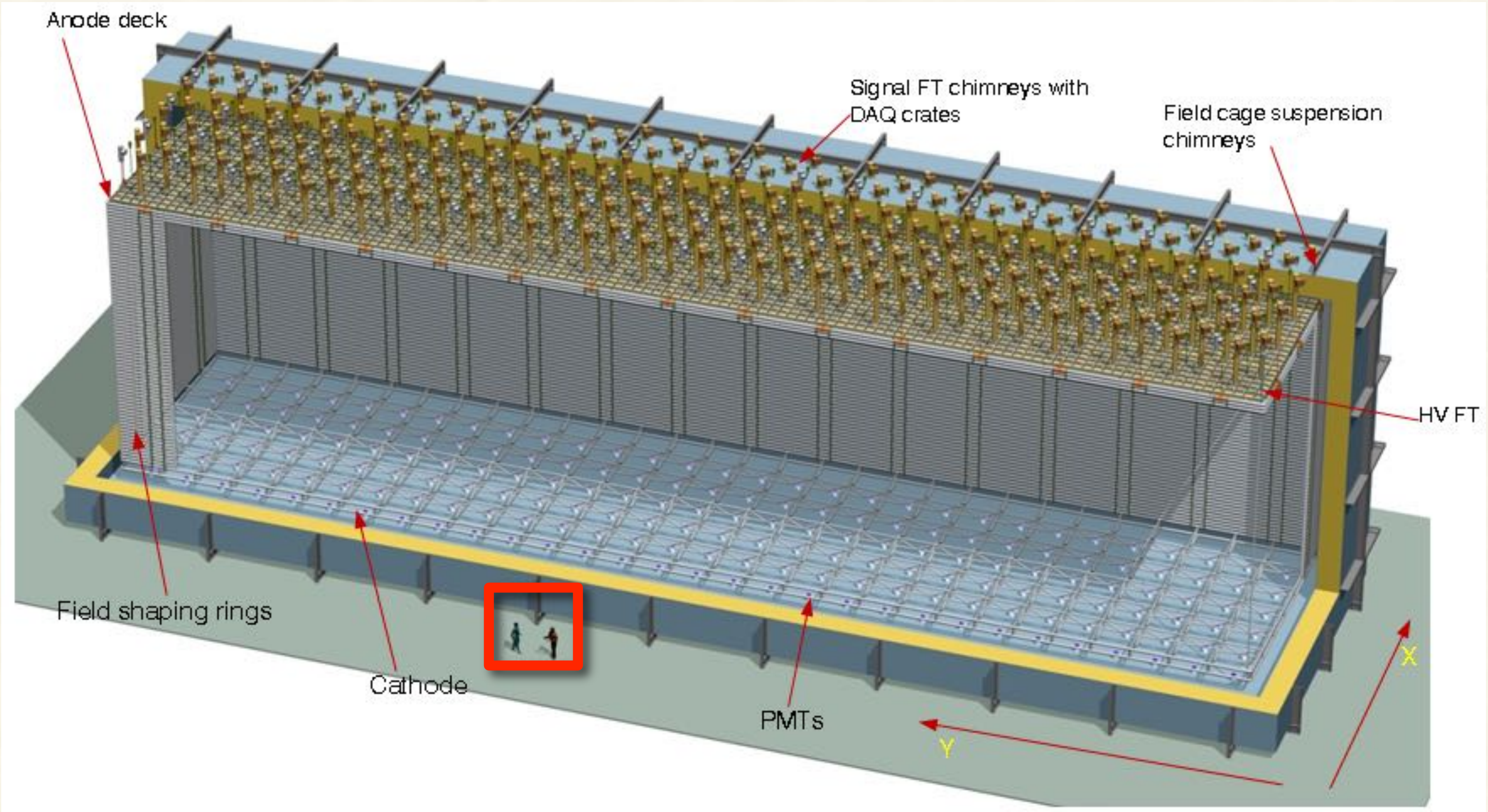


Parallel talk by K.Iwamoto

...to the next generation!







- See later talk by Prof. Jae Yu

Conclusions

- Rapid and steady progress in neutrino oscillation physics
- **MINOS/MINOS+** and **OPERA** final results strongly support the three flavor scenario
- **Daya Bay/Double Chooz/RENO** continue to improve precision of θ_{13}, **JUNO** is coming
- **T2K** and **NOvA** explore CP and mass hierarchy with neutrino and antineutrino beams
- Excitement will continue and grow. Stay tuned for more results!

Additional material

JUNO

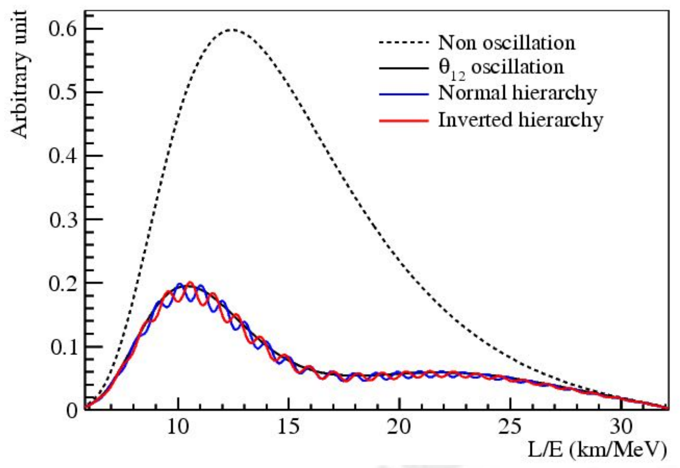
3.1 Mass Hierarchy

- Oscillation probability is independent of CP phase and θ_{23} (Reactor neutrinos)

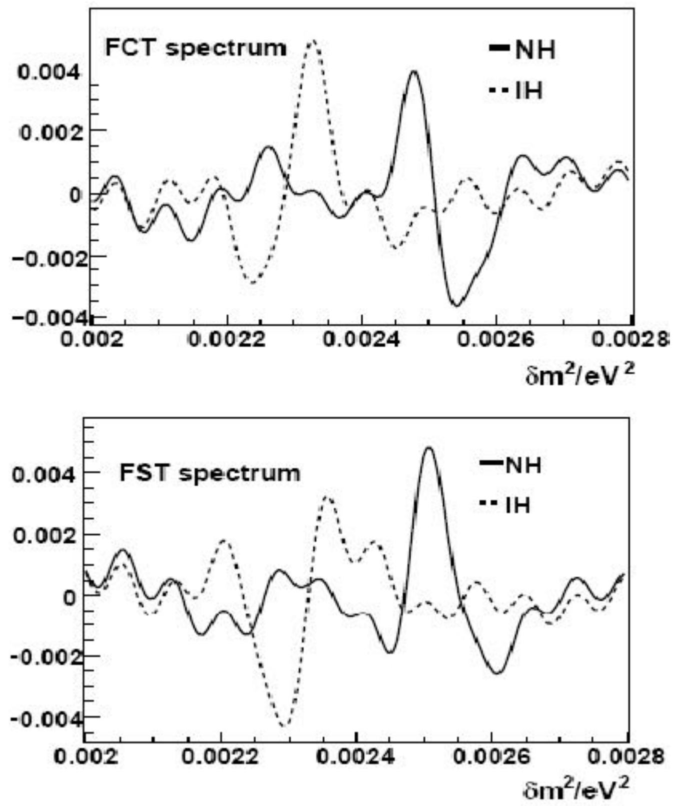
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

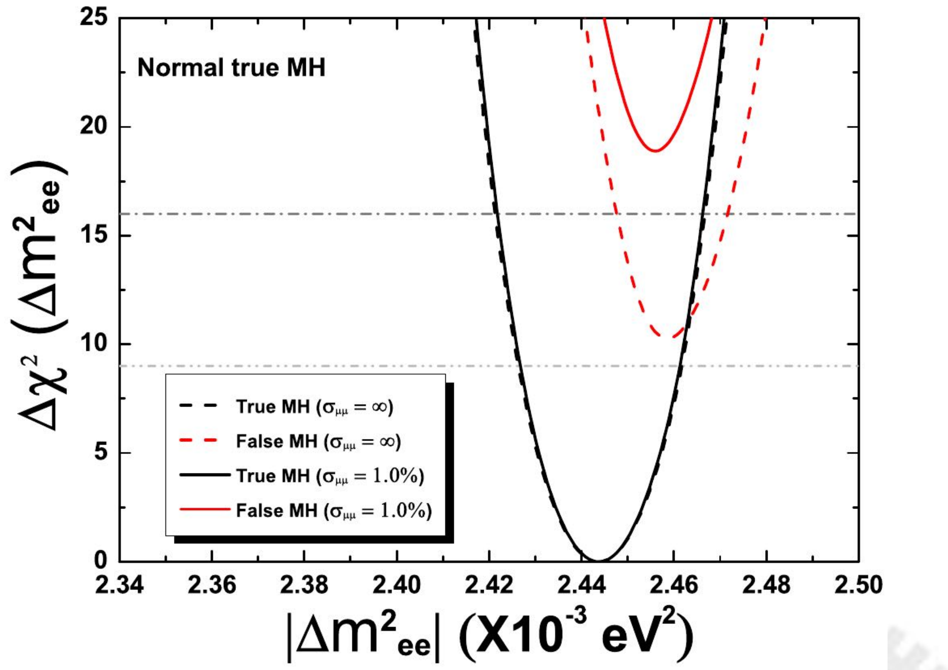
+ NH
- IH



- *The big suppression is the "solar" oscillation (Δm^2_{12}, $\sin^2\theta_{12}$)*
- *"Large" value of θ_{13} is crucial*



- No pre-condition of Δm^2_{32}
- Only depends on shape but not absolute peak position



- Sensitivity with 100k events (~6 yrs)

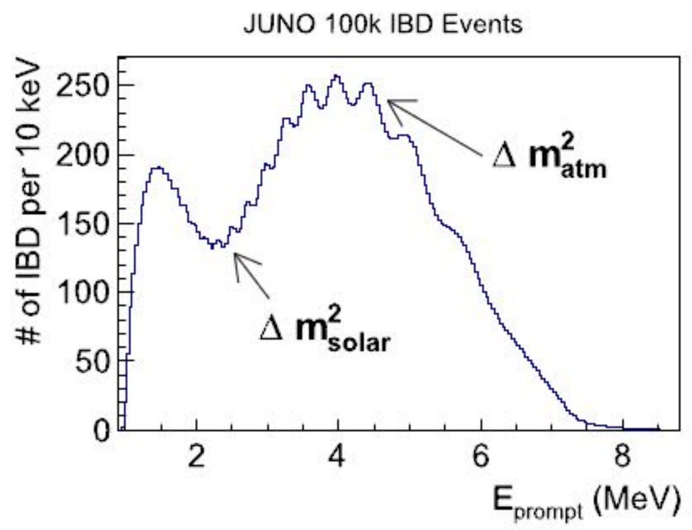
✓ No constraint: $\overline{\Delta\chi^2} > 9$

✓ With 1% constraint: $\overline{\Delta\chi^2} > 16$

3.2 Measurement of Oscillation Parameters

Due to good energy resolution and proper baseline, JUNO can help to:

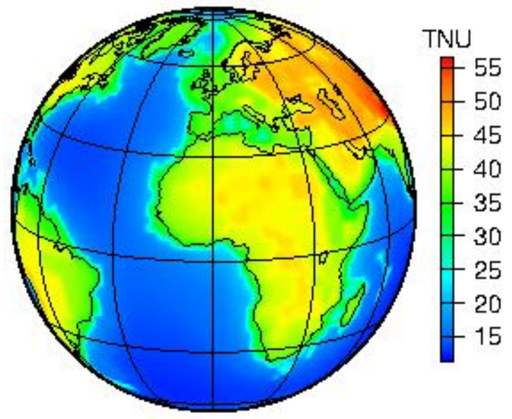
- **Improve precisions of three parameters (Δm^2_{21}, Δm^2_{ee} and $\sin^2\theta_{12}$) to sub-percent level, several times improvement compared with current precision.**
- **Probe the unitarity of U_{PMNS} to ~1% level**



	Nominal	+B2B (1%)	+BG	+EL (1%)	+NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

3.3 Neutrino Astrophysics and Others

- Neutrinos from the Earth escape freely and bring the information about U, Th and K abundances and their distributions
- Due to its largest LS size, the expected geo-neutrino rate in JUNO is ~1.1/day.
- Within the 1st year, JUNO will record more geo-neutrino events than all other detectors



➢ ***JUNO will be the most precise experiment for geo-neutrino study. In the meanwhile, JUNO is also attractive for other neutrino astrophysics, such as supernova neutrinos, diffuse supernova neutrinos, solar neutrinos and atmospheric neutrinos.***

Beside these, additional physics is also rich in JUNO

- Sterile neutrinos
- Dark matter searches
- Proton decay
- Other exotic searches

Neutrino beams and long baseline experiments

Accelerator	Experiment	Baseline	Beam power	Years
KEK-PS (KEK)	K2K	250km	5kW	1999-2004
Main Injector (Fermilab)	MINOS(+)	730km	400kW+	2005-2016
SPS (CERN)	OPERA / ICARUS	730km	510kW	2008-2012
J-PARC MR (J-PARC/KEK)	T2K	295km	500kW (design:750kW)	2009-
Main Injector (Fermilab)	NOvA	810km	700kW	2014-

T2K: data and predictions

Sample	Predicted ($\sin^2\theta_{23}=0.528$)				Observed
	$\delta=0$	$\delta=+\pi/2$	$\delta=\pi$	$\delta=-\pi/2$	
ν beam, 1Rμ	268.2	268.5	268.9	268.5	**243**
ν̄ beam, 1Rμ	95.3	95.5	95.8	95.5	**102**
ν beam, 1Re 0 decay-e	61.6	50.1	62.2	73.8	**75**
ν beam, 1Re 1 decay-e	6.0	4.9	5.8	6.9	**15**
ν̄ beam, 1Re 0 decay-e	13.4	14.9	13.3	11.8	**9**

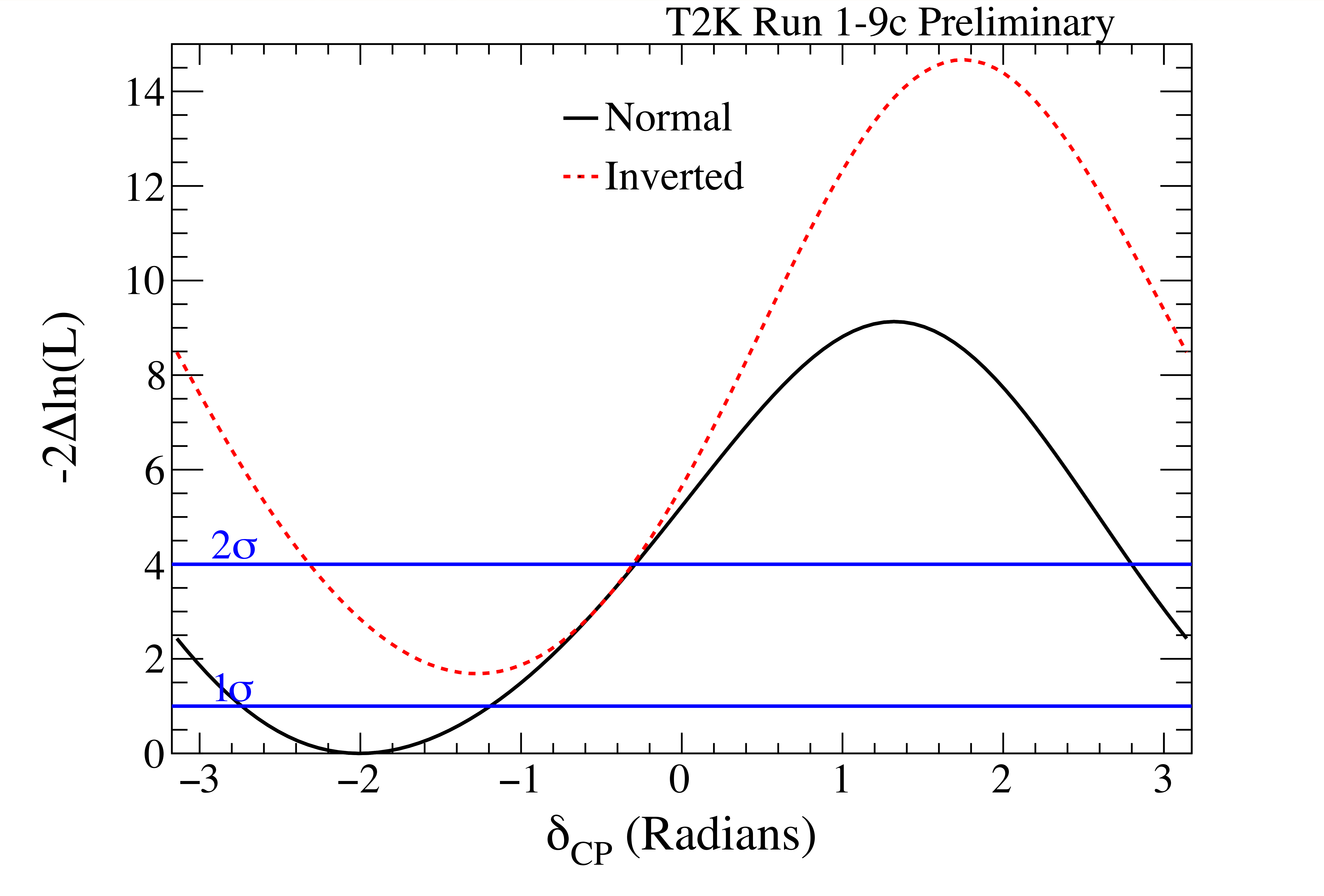
$\sin^2\theta_{23} = 0.528$
$\sin^2\theta_{13} = 0.0219$
$\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2

Consistent with maximal ν_μ disappearance
Prefer large CP violation ($\delta_{CP} \sim\pi/2$)

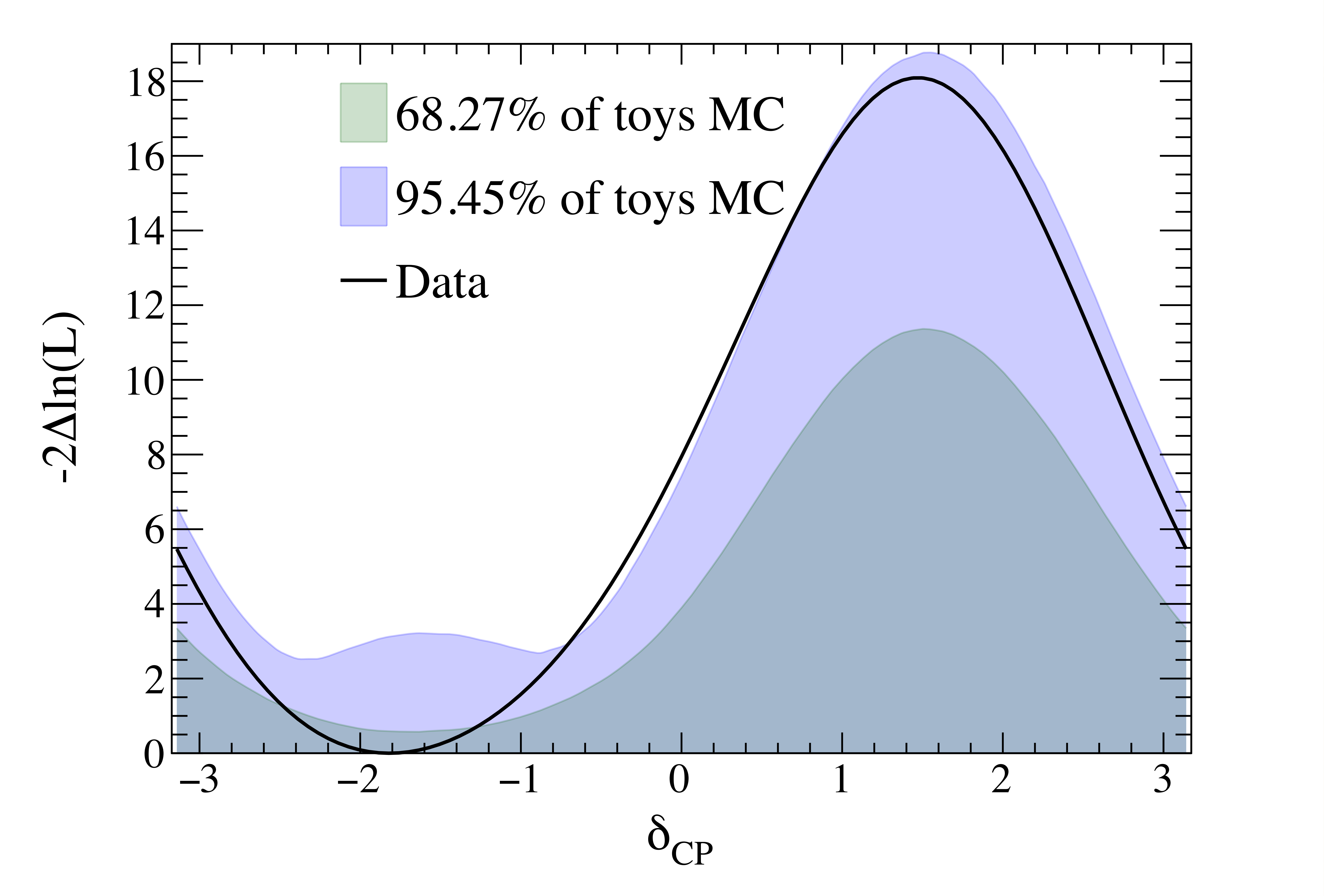
T2K systematic error

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

δ_{CP} with T2K alone



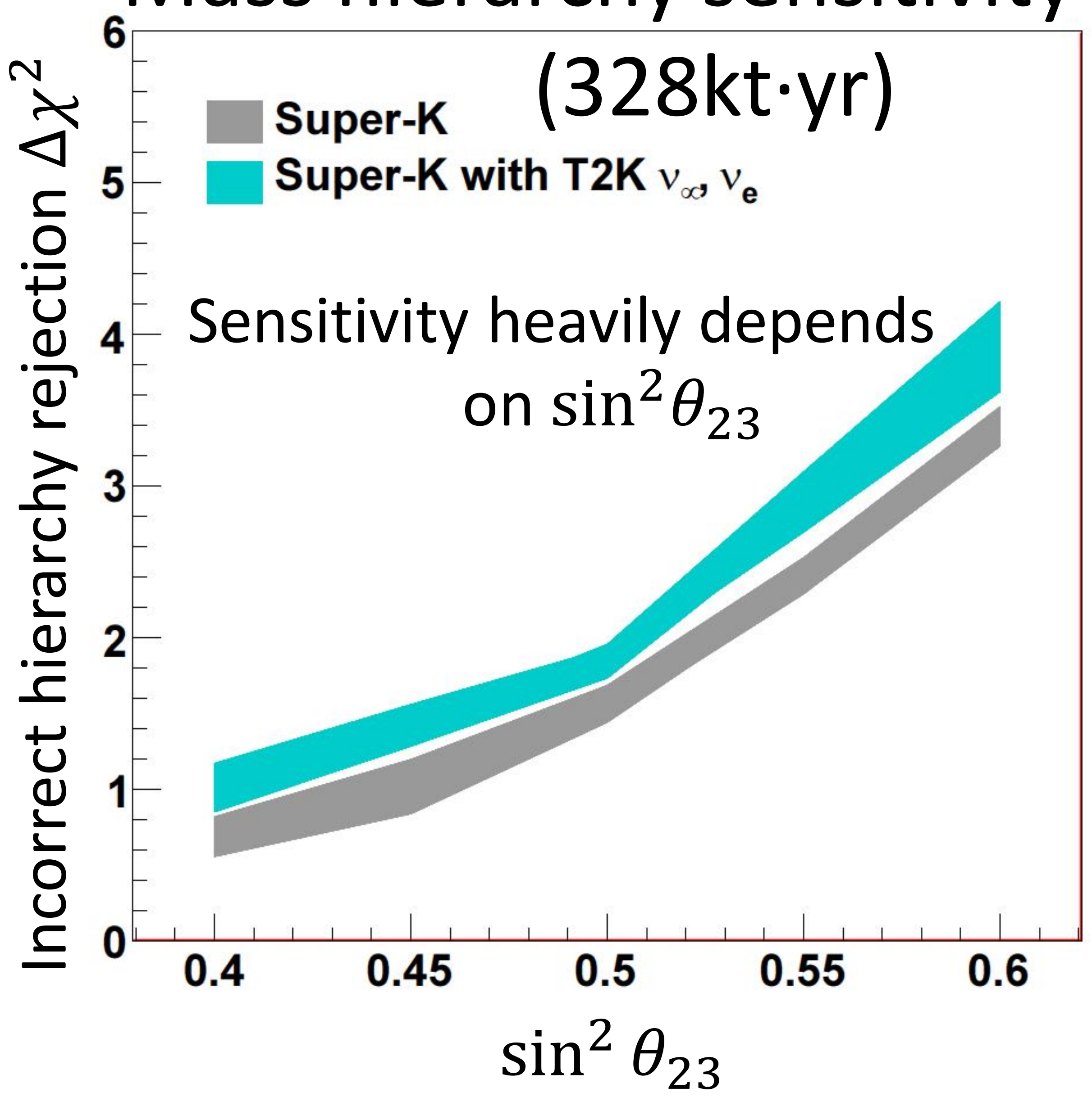
T2K sensitivity and data result



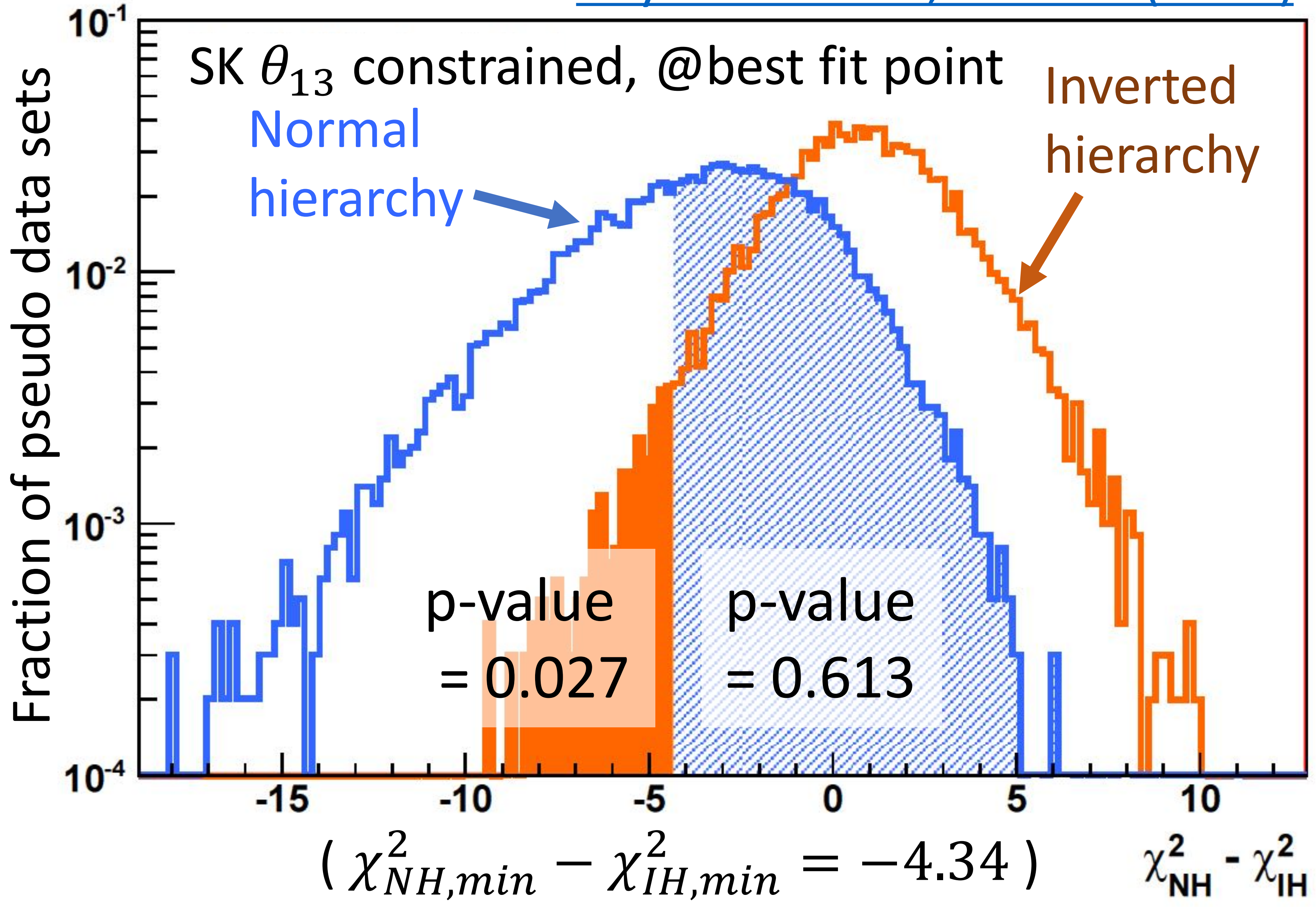
Mass hierarchy from Super-K

Determination of hierarchy determination

Mass hierarchy sensitivity



Phys. Rev. D 97, 072001 (2018)



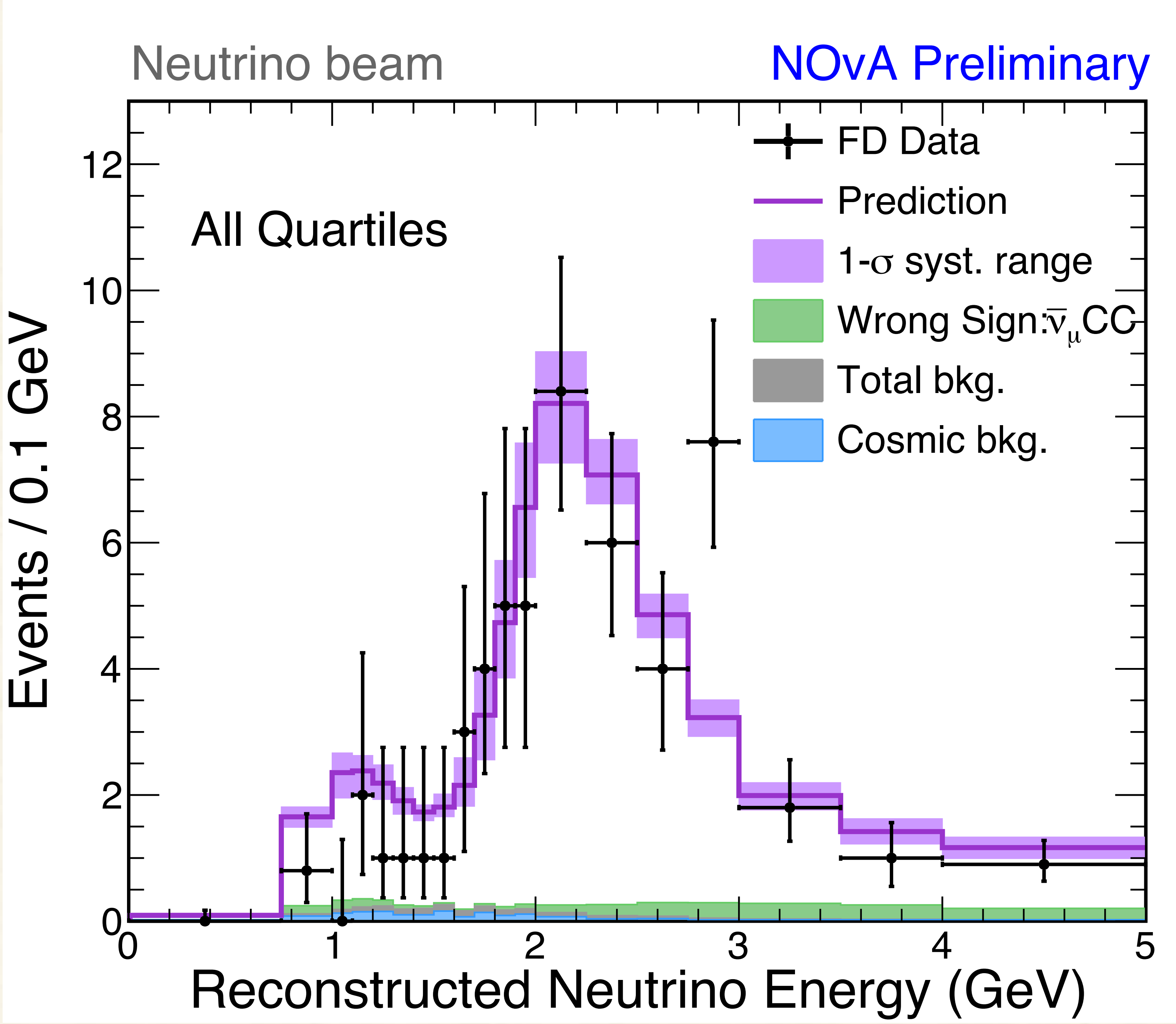
Estimate p-values using pseudo-data for the smallest and largest $\sin^2\theta_{23}$.

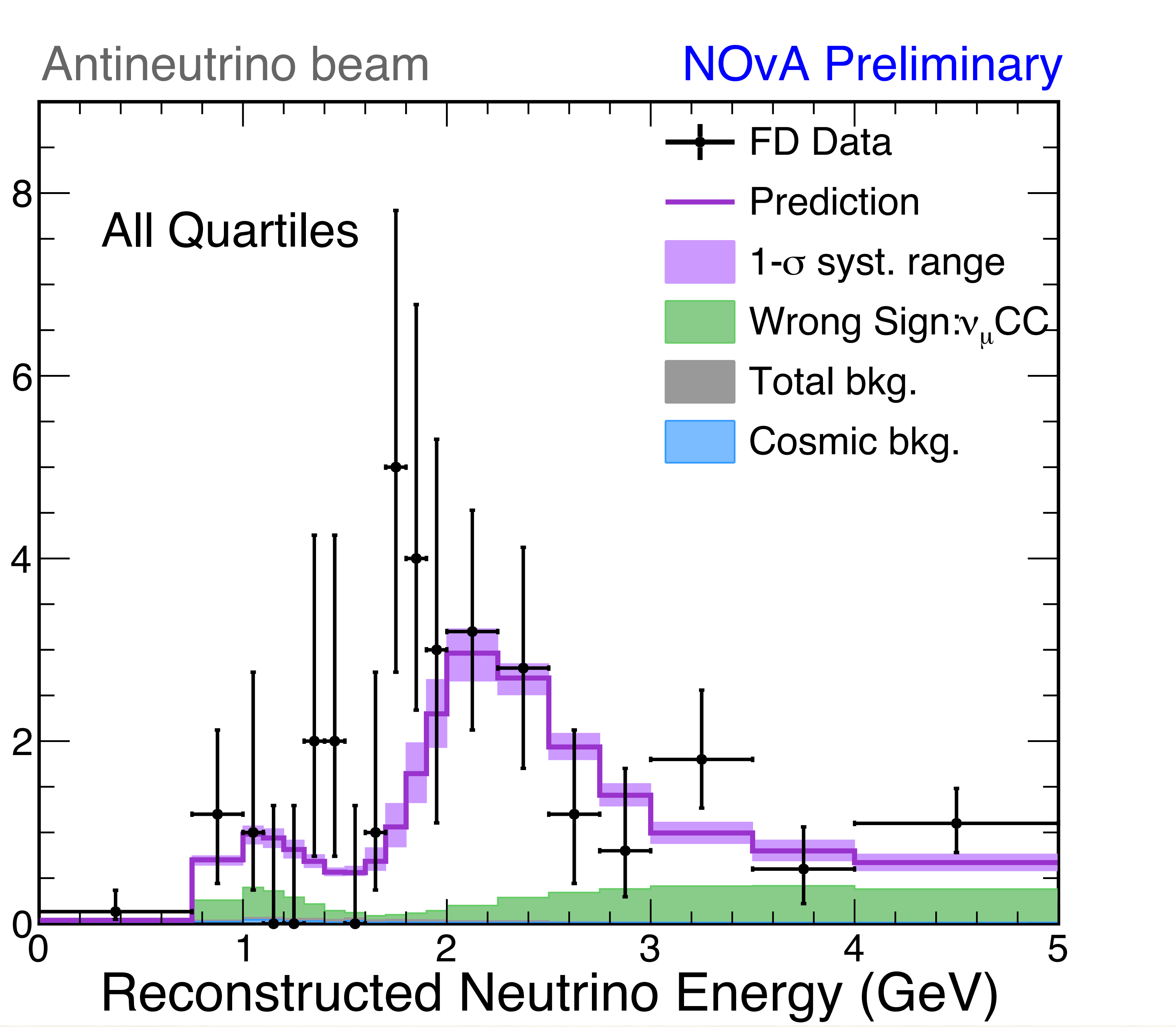
Hypothesis test ~ CL_s method : $\mathrm{CL_s}(\text{IH rejection}) \equiv \frac{p_{0(IH)}}{1-p_0(NH)}$

Normal hierarchy is favored ➡

SK only	80.6 ~ 96.7%
SK + T2Kmodel	91.5 ~ 94.5%

NOvA: ν_μ and $\bar{\nu}_\mu$ data

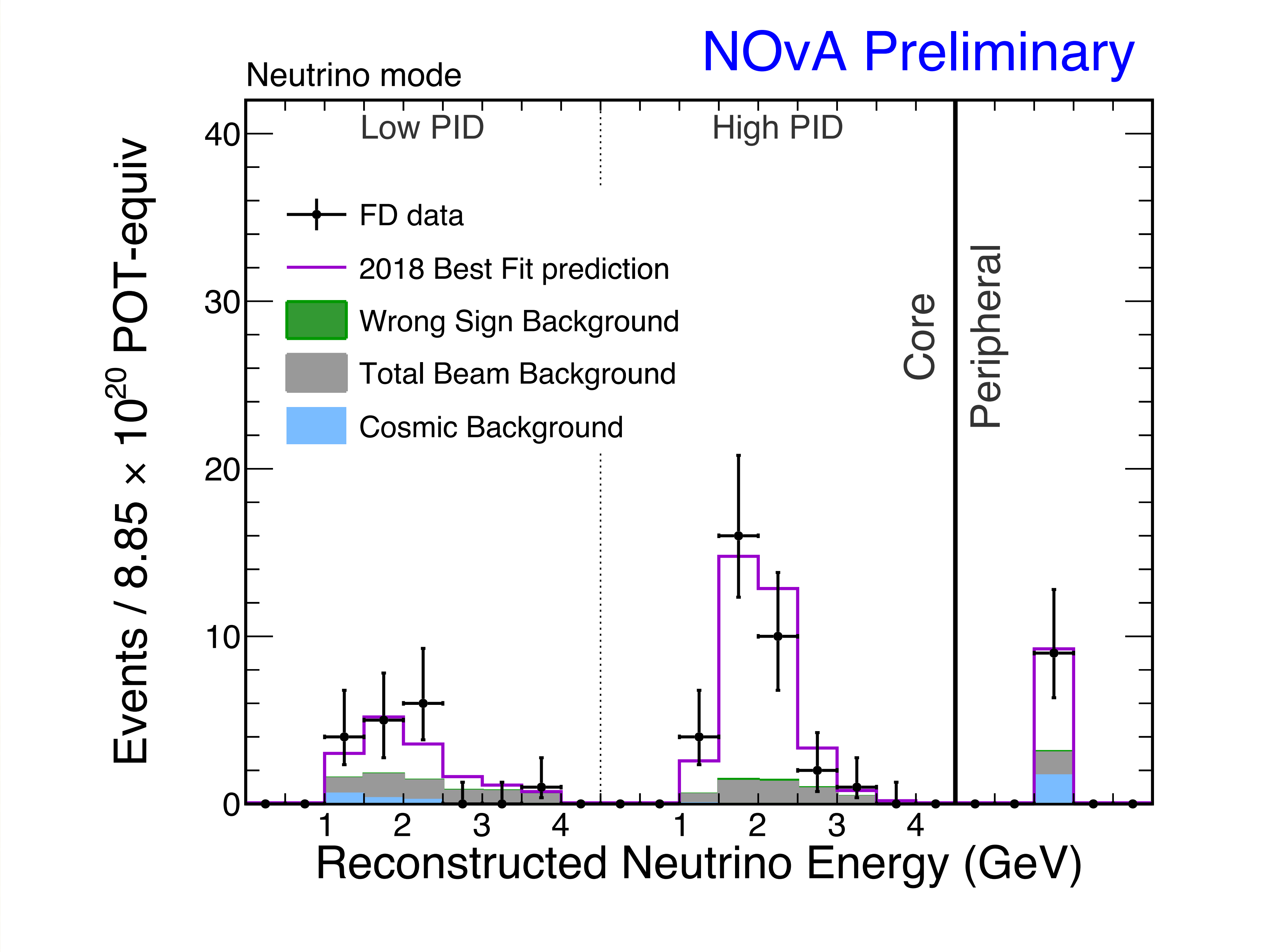


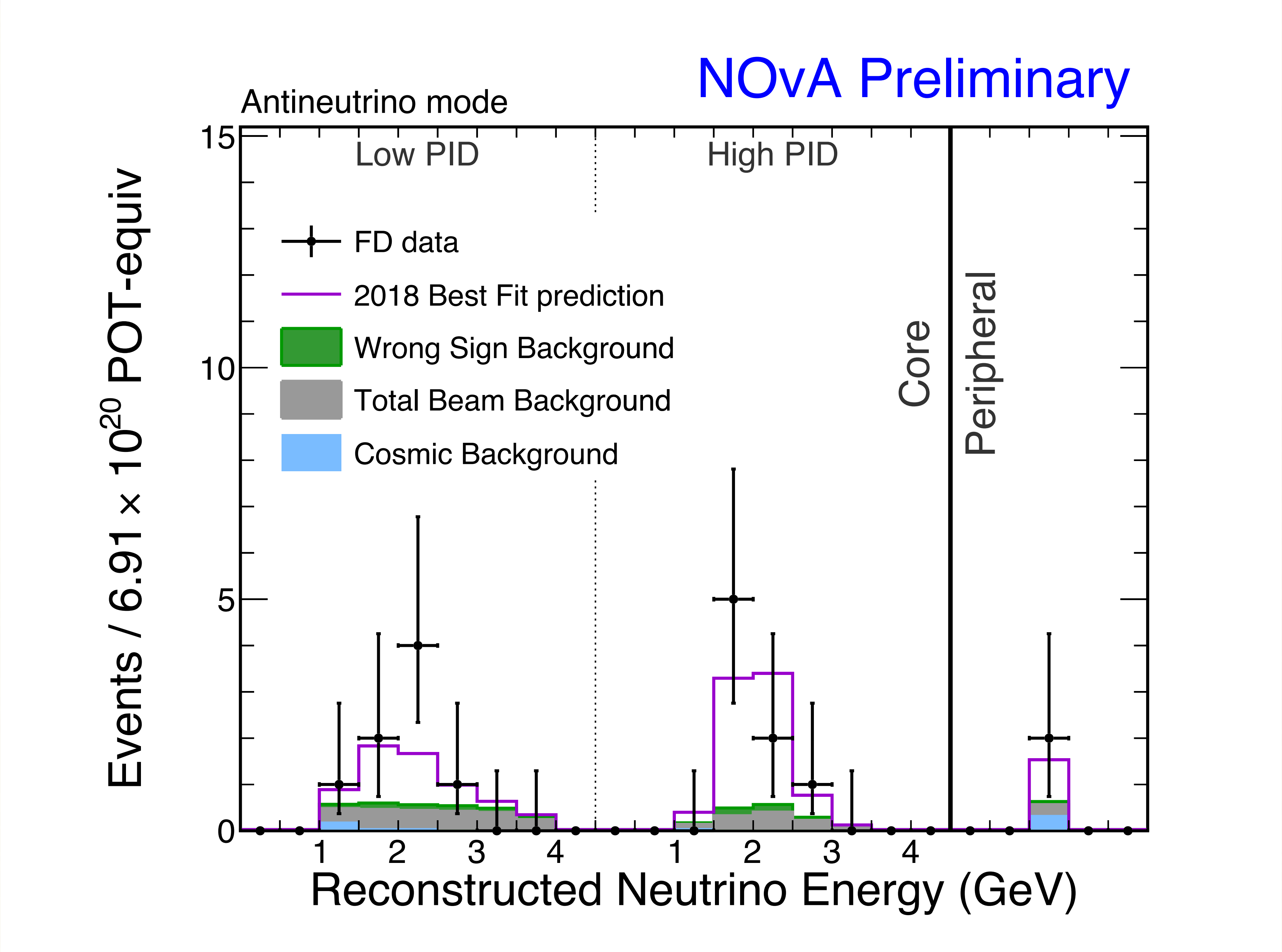


Observed	113
Best fit prediction	121
Beam BG	1.2
Cosmic BG	2.1
Unoscillated	730 +38/-49(syst)

Observed	65
Best fit prediction	50
Beam BG	0.6
Cosmic BG	0.5
Unoscillated	266 +12/-14(syst)

NOvA: ν_e and $\bar{\nu}_e$ data



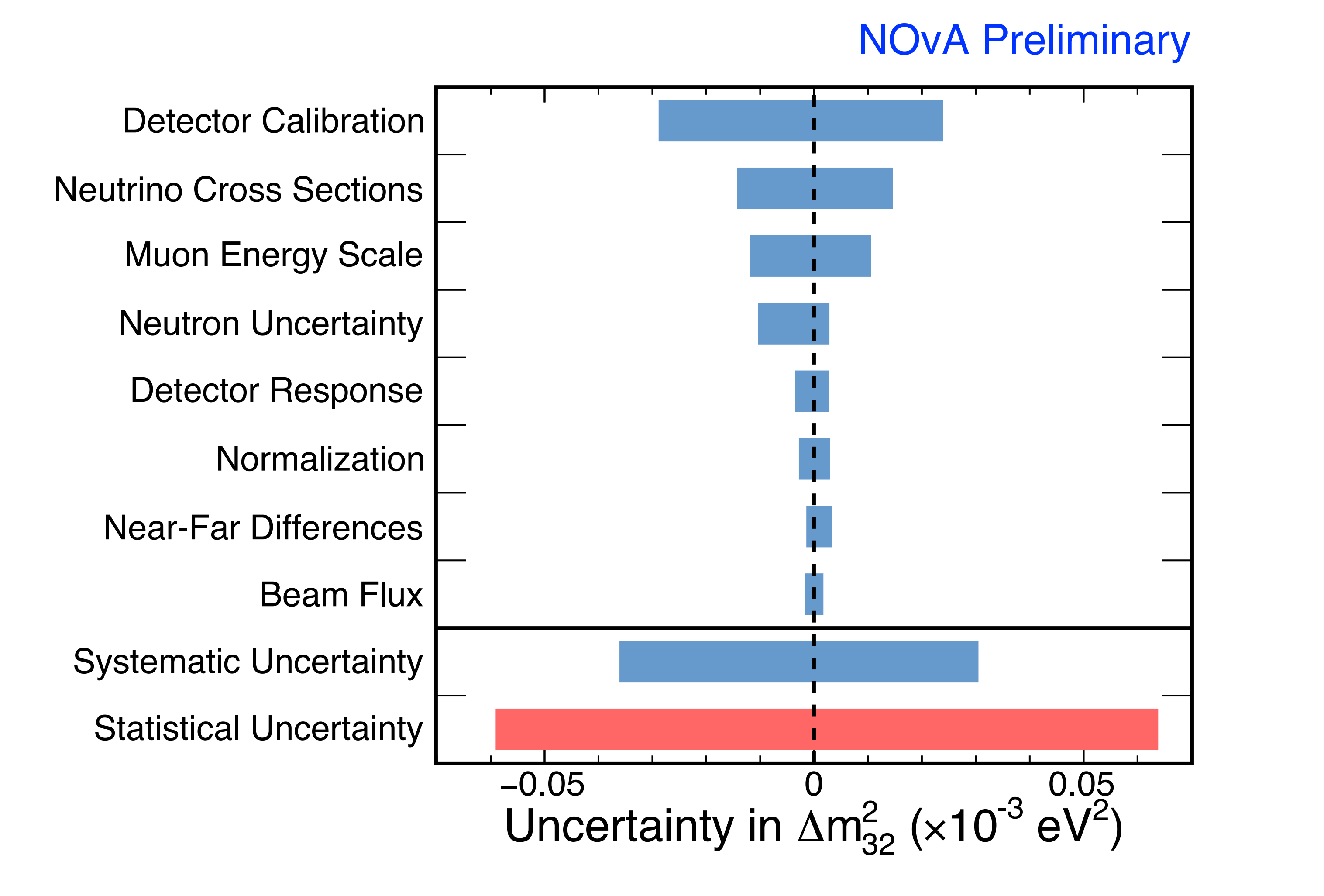


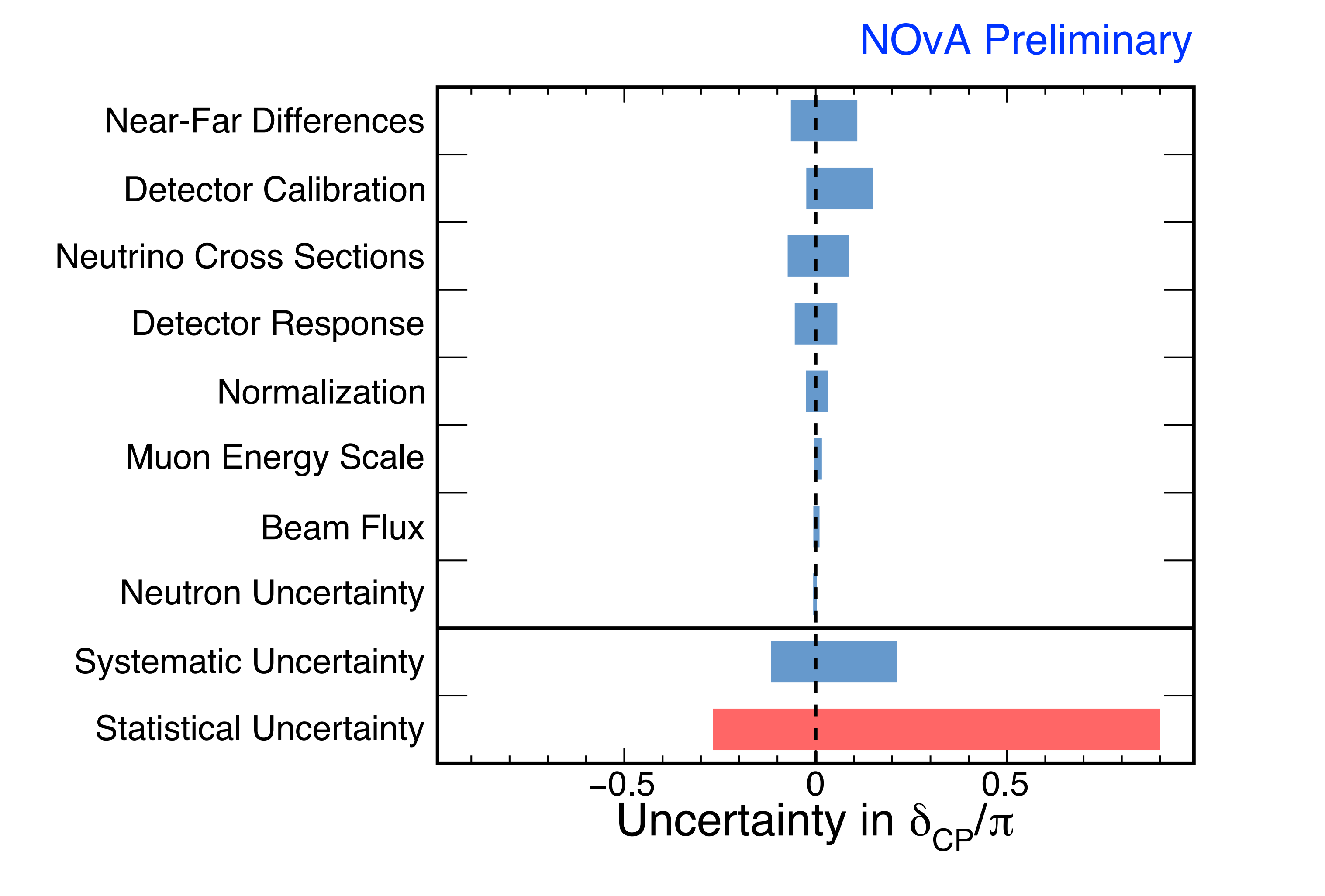
Observed	58
Prediction	30-75
Wrong-sign	0.3-1.0
Beam BG	11.1
Cosmic BG	3.3
Total BG	14.7-15.4

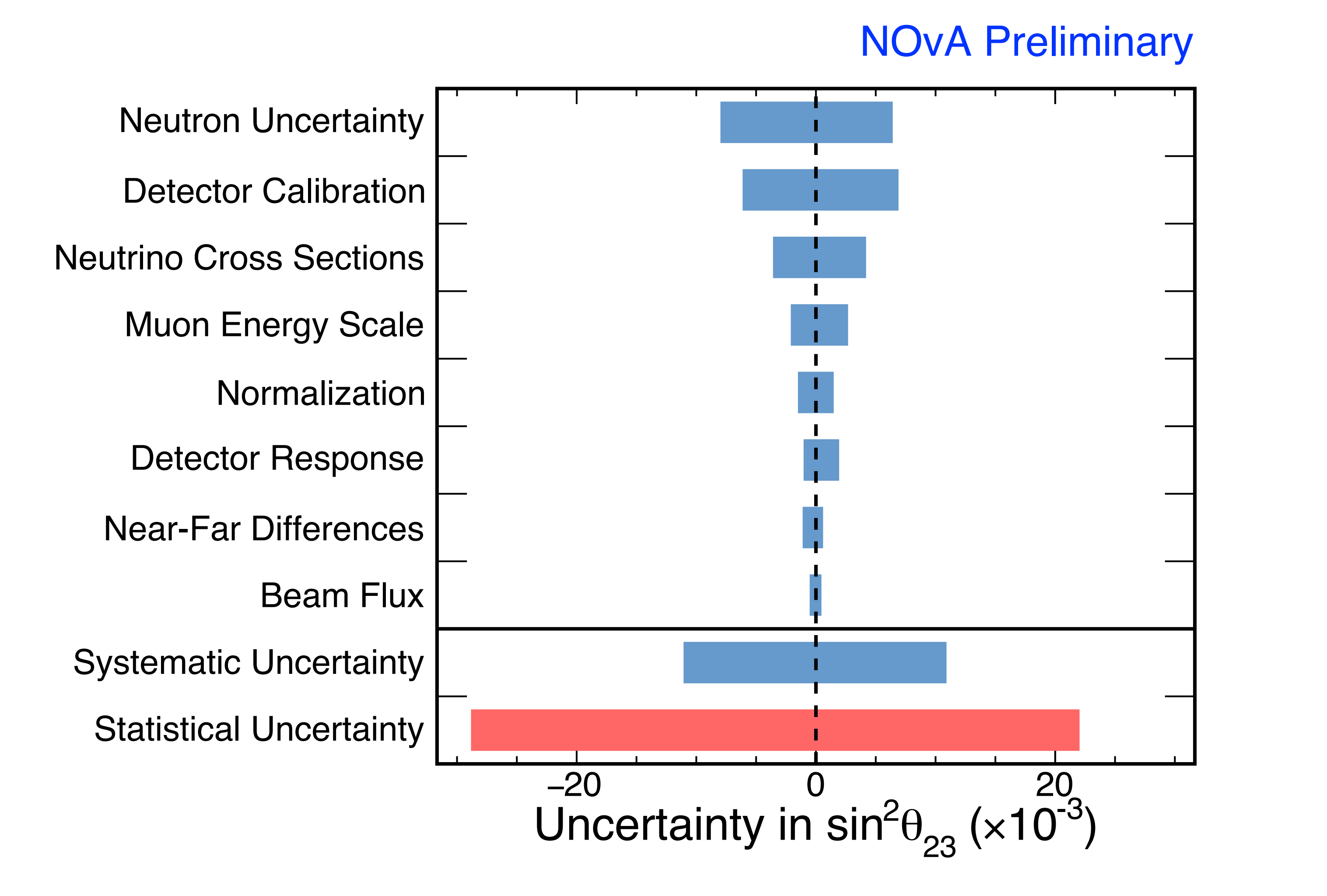
Observed	18
Prediction	10-22
Wrong-sign	0.5-1.5
Beam BG	3.5
Cosmic BG	0.7
Total BG	4.7-5.7

>4σ evidence of $\bar{\nu}_e$ appearance!

NOvA systematic uncertainties







- Improved systematic uncertainties. We are still statistics limited but calibration and cross sections are the largest uncertainties.
- Our upcoming test beam program will address the calibration and detector response uncertainties.

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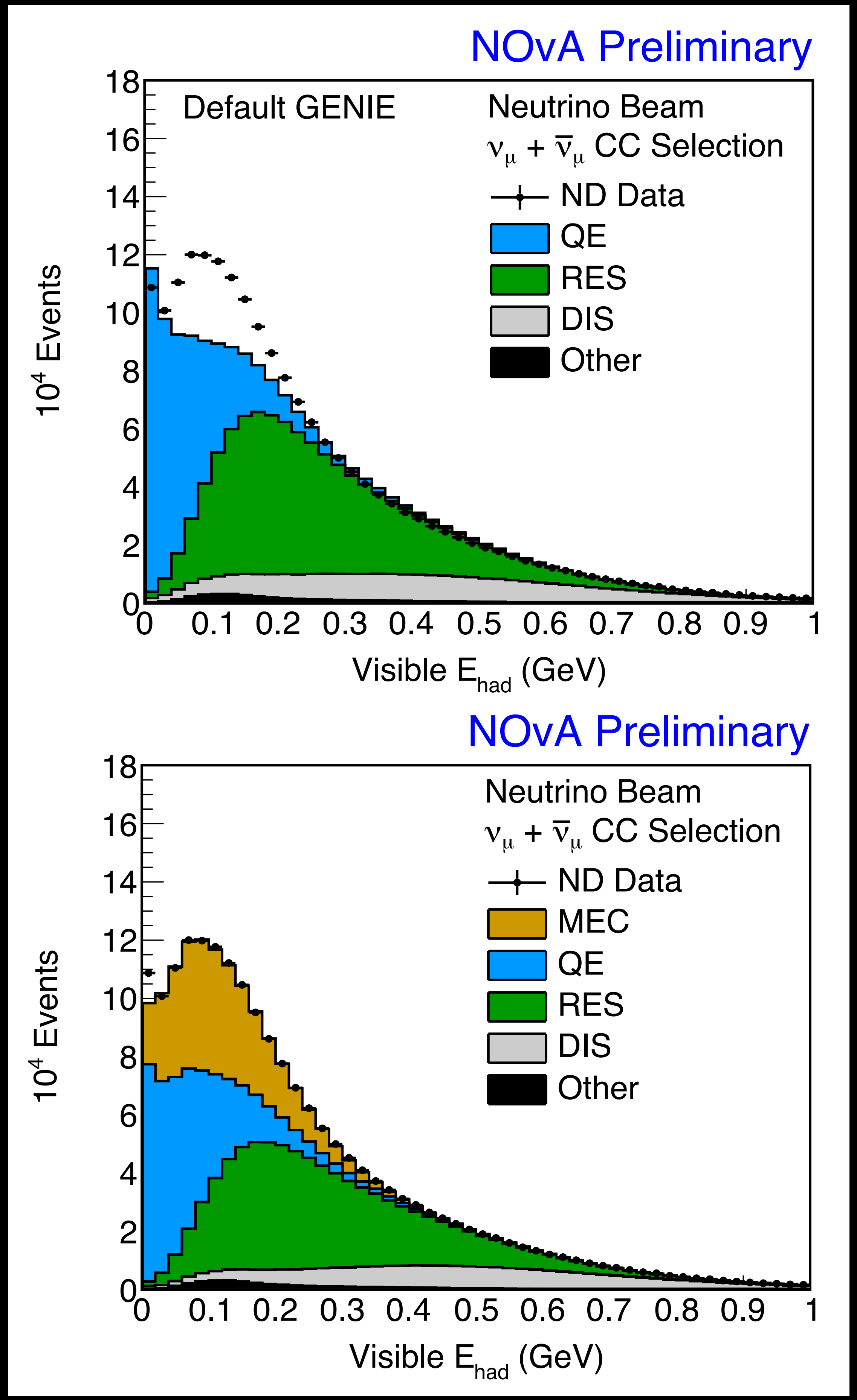
NOvA

NEUTRINO INTERACTION TUNING



- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Various corrections and tunings are applied:
  - Correct quasielastic component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
  - Apply same long-range effect as for QE to resonant baryon production as well. Nonresonant inelastic scattering (DIS) at high invariant mass (W>1.7 GeV/c^2) weighted up 10% **based on NOvA data**.
  - Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] **based on NOvA ND dat**a to account for multinucleon knockout (2p2h).

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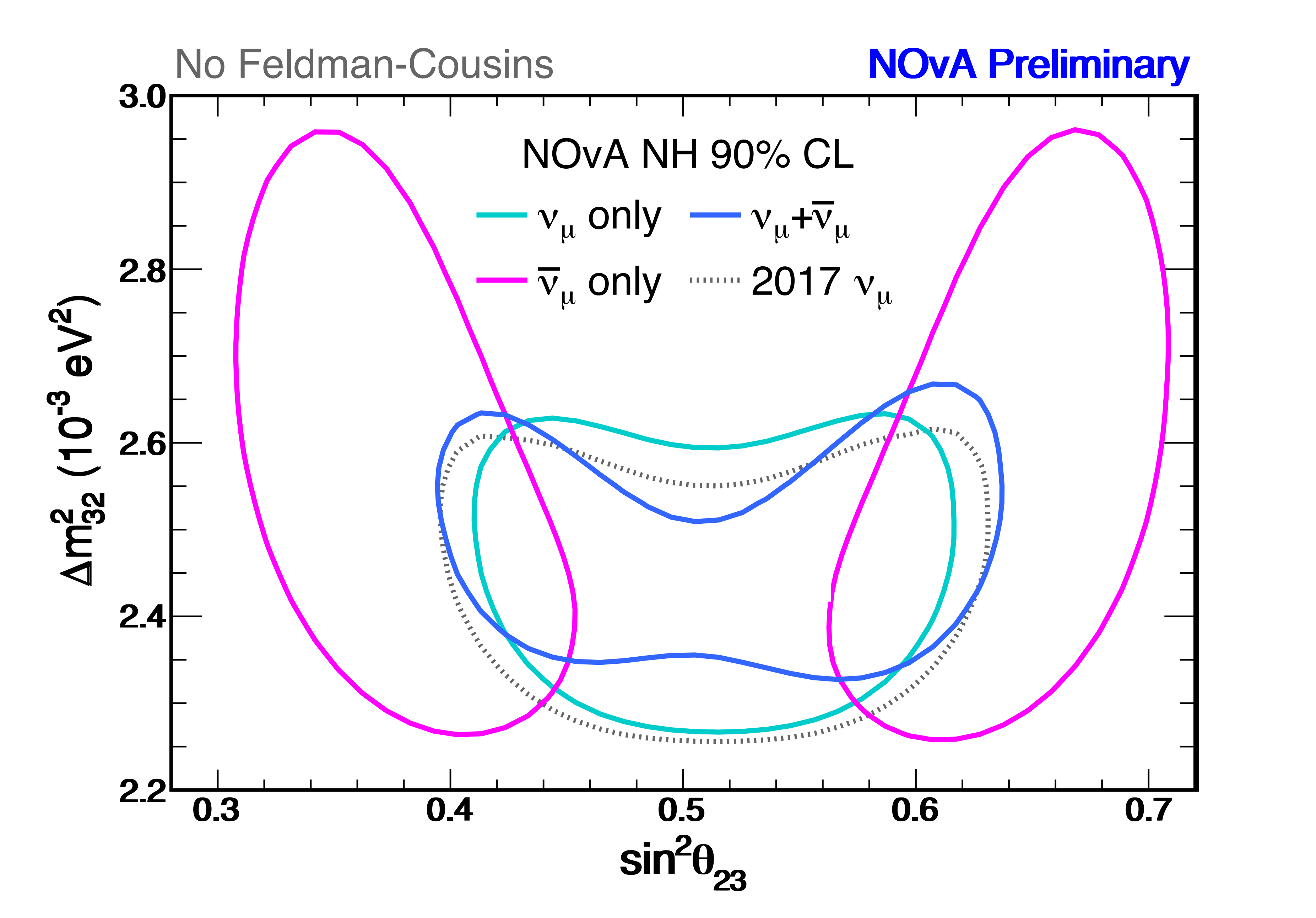
MUON NEUTRINO DISAPPEARANCE

- The combined data of neutrino and antineutrino beams are fitted assuming CPT invariance.
- We observe 113 events and expect 126 at this combined best fit for the neutrino beam mode and observe 65 events and expect 52 at the best fit in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution than the neutrino beam mode. However the χ^2s are consistent with the combined fit oscillation parameters with $p > 4\%$.



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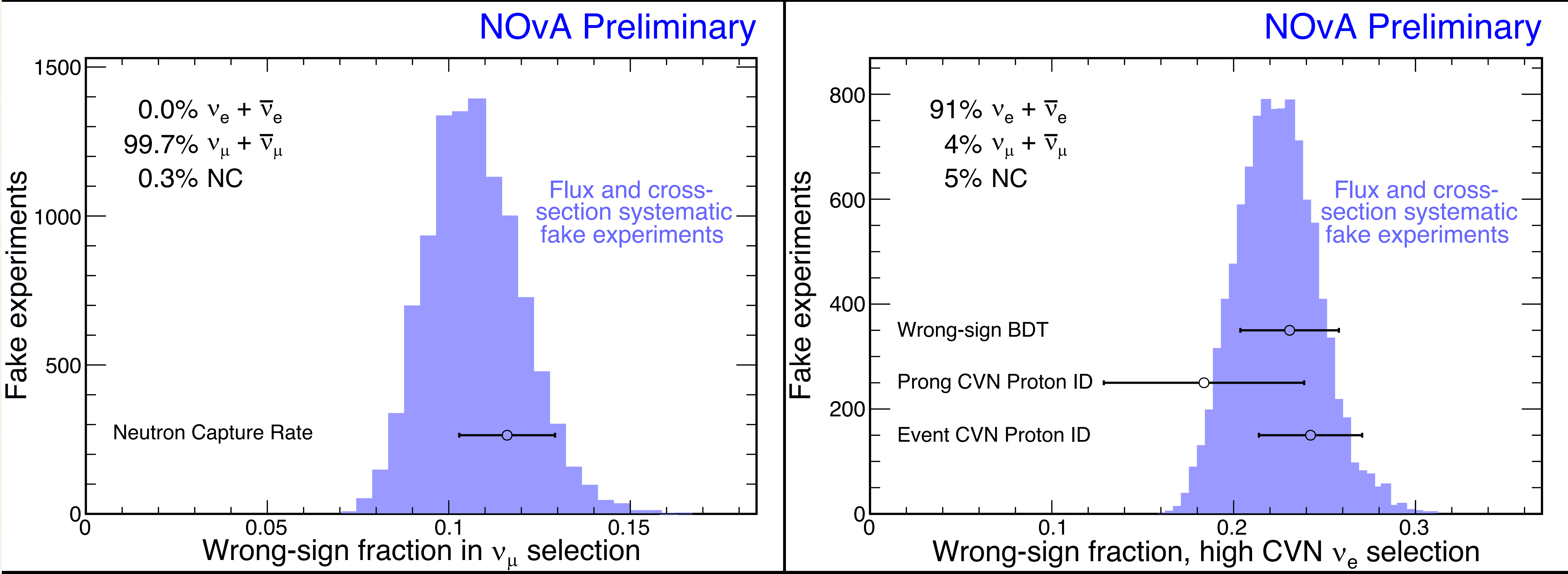
WHAT IS DIFFERENT IN ANTINEUTRINOS? WRONG-SIGN CONTAMINATION



- 11% wrong-sign in the ν_μ ND sample background
  - Consistent with data-based cross-check using neutron captures.
- 22% (32%) in the ν_e ND background in the high (low) PID bin
  - Consistent with data-based cross-checks using identified protons and event kinematics.
- •~10% systematic uncertainty from flux and cross section
- Does not include uncertainties from detector effects.

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PREDICTING THE FAR DETECTOR OBSERVATIONS

- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
  - Estimate the underlying true energy distribution of selected ND events.
- The measured spectrum is used to make a prediction of the expectation at the FD
  - Multiplying the true energy distribution by the Far/Near Ratio, applying oscillation probabilities and then converting to a predicted reconstructed energy distribution
- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.