Future Sensitivity of the T2K Experiment

For the RCCN Workshop

Megan Friend

KEK

March 15, 2013

Outline

The T2K Experiment – Physics Goals

The physics goals of the first phase of T2K are (from LOI):

1. "... a factor of 20 more sensitive search for $\nu_\mu \to \nu_e$ appearance: $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$ ..."
2. "... an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillation measurement: $\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$ ..."
3. "... a confirmation of the $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events ..."

- Requested: 750 kW $\times$ 5e7 s (115 days $\times$ 5 years) at 30 GeV = 7.80×10^{21} POT

The T2K Experiment – Physics Goals

The physics goals of the first phase of T2K are (from LOI):

1. "... a factor of 20 more sensitive search for $\nu_\mu \to \nu_e$ appearance: $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$ ..."
2. "... an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillation measurement: $\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$ ..."
3. "... a confirmation of the $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events ..."

- Requested: 750 kW $\times$ 5e7 s (115 days $\times$ 5 years) at 30 GeV = 7.80×10^{21} POT

$\to$ Must update the T2K experimental goals following:

- Indication of ν_e appearance by T2K
- Discovery of an unexpectedly large θ_{13}
- Precise measurement of $\sin^2 2\theta_{13}$ by reactor experiments

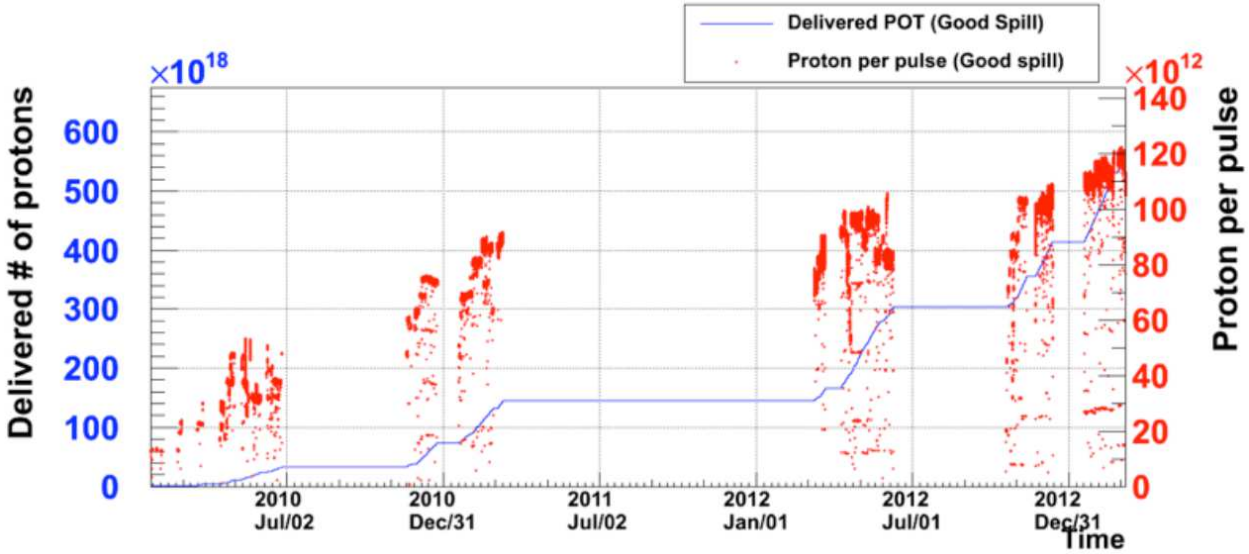
The T2K Collaboration

$\sim$500 members from 56 institutes in 11 countries

The T2K Experiment Long Baseline Neutrino Oscillation Experiment

- Primarily ν_μ, 2.5° off axis neutrino beam produced at J-PARC
- ND280 Near Detector – 280 m from ν source
  - Constrains systematic errors
  - Measures ν cross sections and beam backgrounds
- $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ events detected at the Super-Kamiokande (SK) far detector 295 km away
  - 22.5 kT fiducial volume water Cherenkov detector
  - Good performance of ν_e/ν_μ particle ID for sub-GeV energy ν's

The T2K Experiment – Current Status

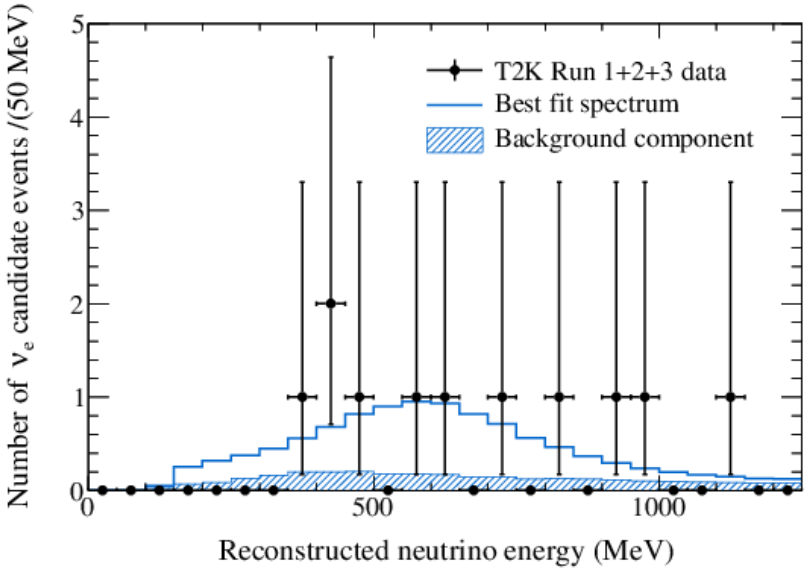


- Current total integrated POT: $\sim 5.63 \times 10^{20}$
  $\rightarrow$ Now stably running at 230 kW!
  $\rightarrow$ Currently at $\sim$7% of T2K full statistics
- Recently released appearance and disappearance results at 3.01×10^{20} POT ($\sim$4% of T2K full statistics)
- Expect 7.5-8$\times 10^{20}$ POT by August – hoping for a 5σ ν_e appearance observation
- Plan to update results this summer

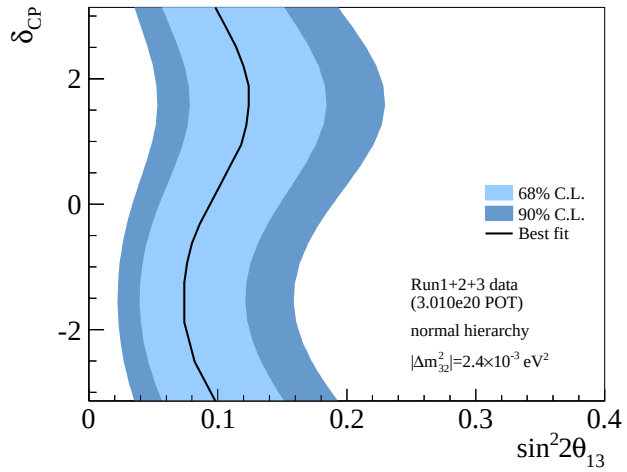
The T2K Experiment – Recent $\nu_\mu \to \nu_e$ Appearance Results

First evidence of ν_e appearance! – released at ICHEP last year

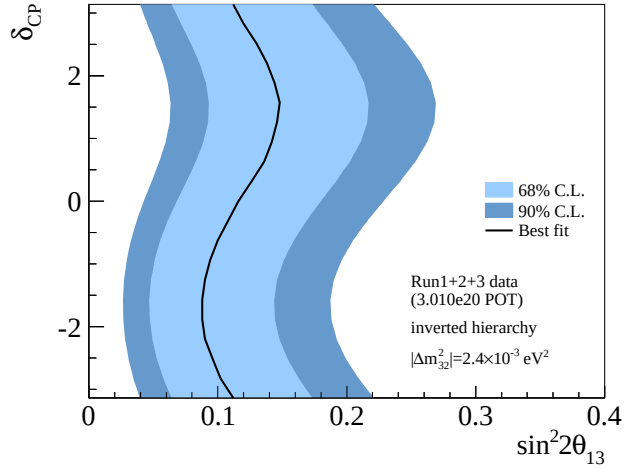
- Observed 11 ν_e candidate events for 3.01×10^{20} POT in 2012
  - Expect 3.28 events if no $\nu_\mu \to \nu_e$ oscillation – 3.2σ!
- Hope to reach 5σ this summer



Normal Hierarchy

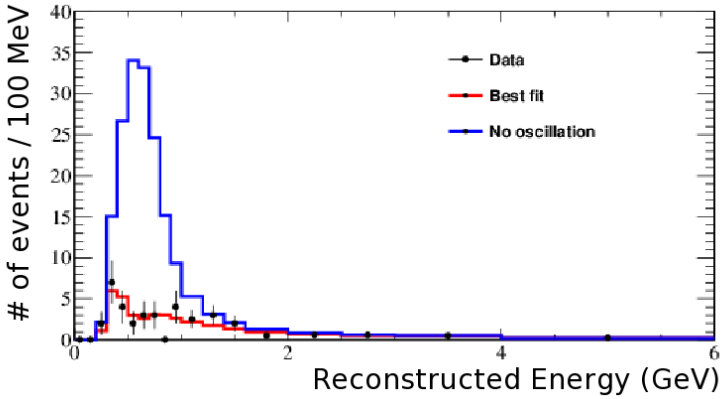


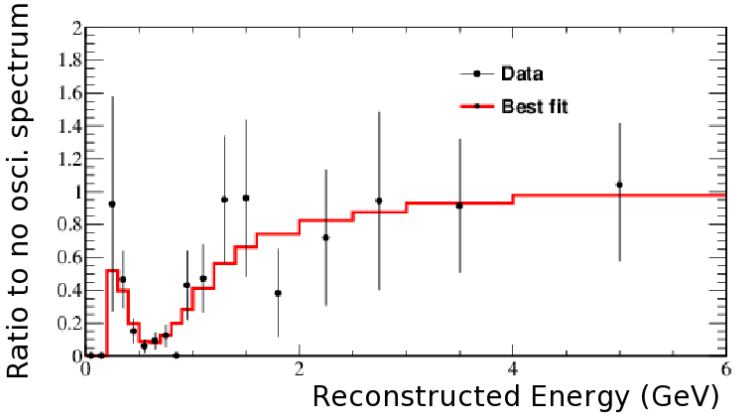
Inverted Hierarchy

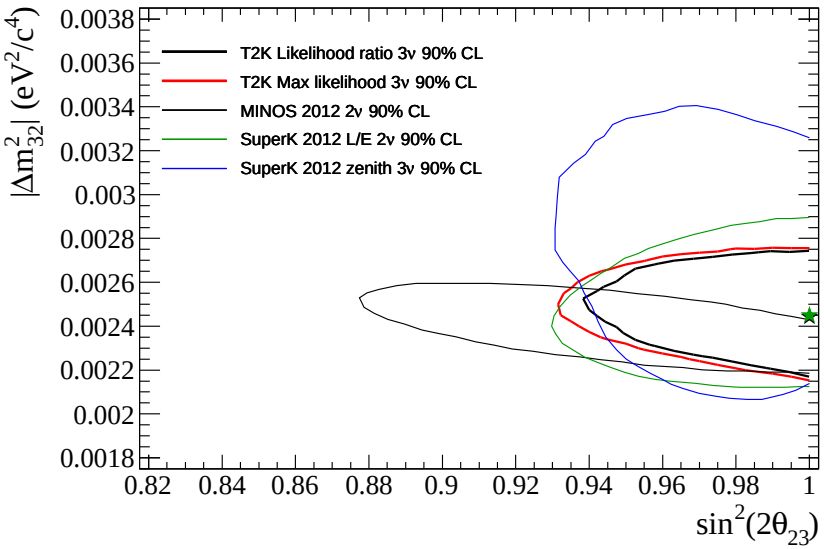


The T2K Experiment – Recent $\nu_\mu \to \nu_\mu$ Disappearance Results

New results released this year with 3.01×10^{20} POT







- World's most precise measurement of $\sin^2 2\theta_{23}$!
- T2K result consistent with maximal mixing
  $\to$ Best fit values:
  - $\sin^2 2\theta_{23} = 1.00$
  - $|\Delta m^2_{32}| = 2.45 \times 10^{-3}$ eV^2

$\nu_\mu \to \nu_e$ Oscillation Probability

Precise measurement of $\sin^2 2\theta_{13}$ enhances the T2K sensitivity to δ_{CP} and the θ_{23} octant:

(ν_μ disappearance measures $\sin^2 2\theta_{23}$ and cannot distinguish the octant alone)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin_{31} \sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} \quad \to \text{Matter effect}$$

($C_{ij} = \cos\theta_{ij}$, $S_{ij} = \sin\theta_{ij}$, $\Phi_{ij} = \Delta m_{ij}^2 L/4E$)

- δ_{CP} completely unknown
- MH completely unknown
- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.) – is θ_{23} maximal?
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ – from reactor

T2K Future Sensitivity Study

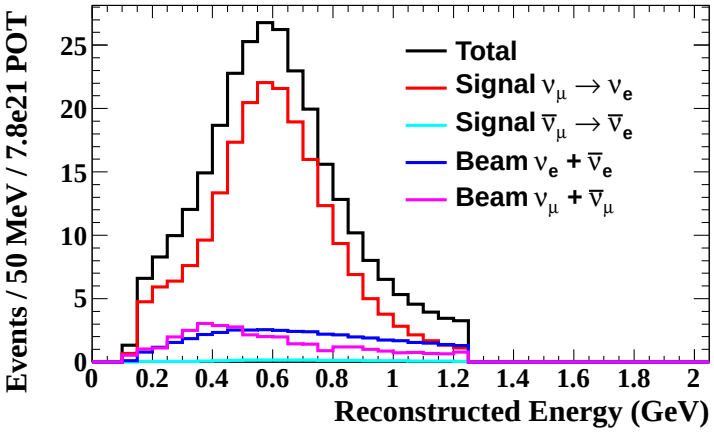
- T2K combined 3 flavor appearance + disappearance fits
  - Simultaneously fit MC SK reconstructed energy spectra for ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$
  - Maximum likelihood fit
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2 \theta_{23}$, and Δm^2_{32} are considered in plots shown
  - Results shown assume $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$ unless otherwise stated
  - NH assumed
- Systematic errors shown are current T2K systematic errors
  - $\sim$10% for ν_e, $\sim$13% for ν_μ
  - $\bar{\nu}$ errors estimated as equal to ν errors with an additional 10% normalization uncertainty
- Fits shown are done with and without a reactor constraint based on the expected ultimate precision of Daya Bay + RENO + Double Chooz on $\sin^2 2\theta_{13}$ ($= 0.1 \pm 0.005$)
- All studies shown are a work in progress

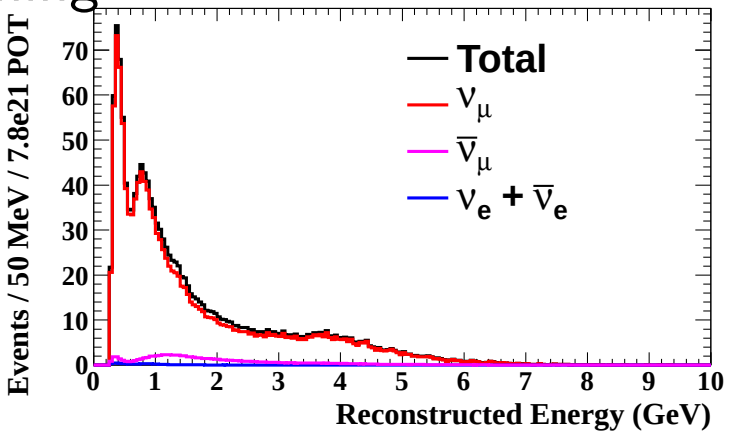
SK Reconstructed Energy Spectra at T2K Full POT

ν_e Appearance

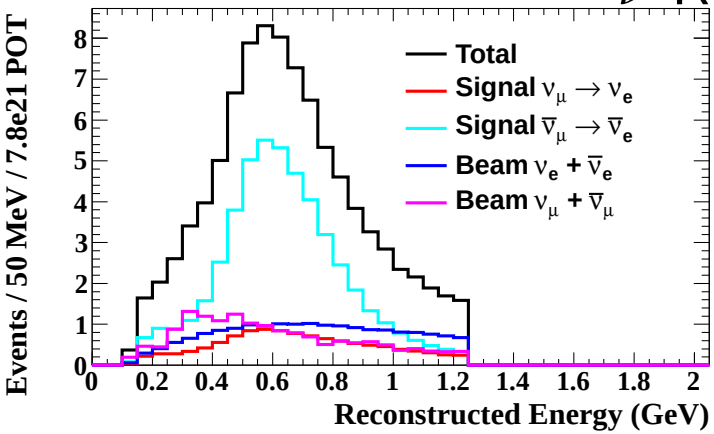
ν_μ Disappearance

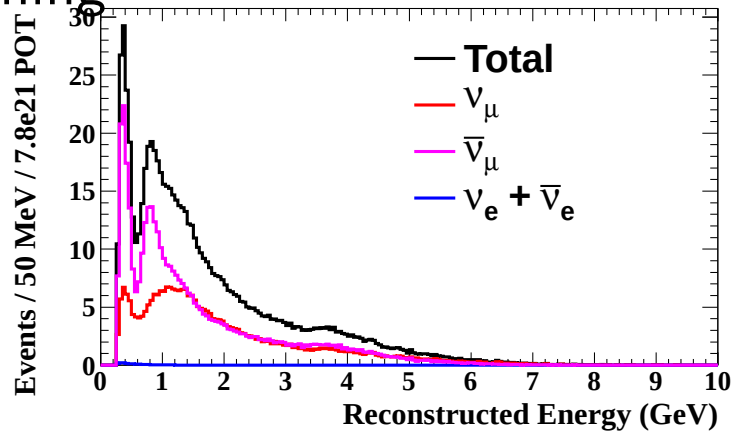
ν-Running





$\bar{\nu}$-Running

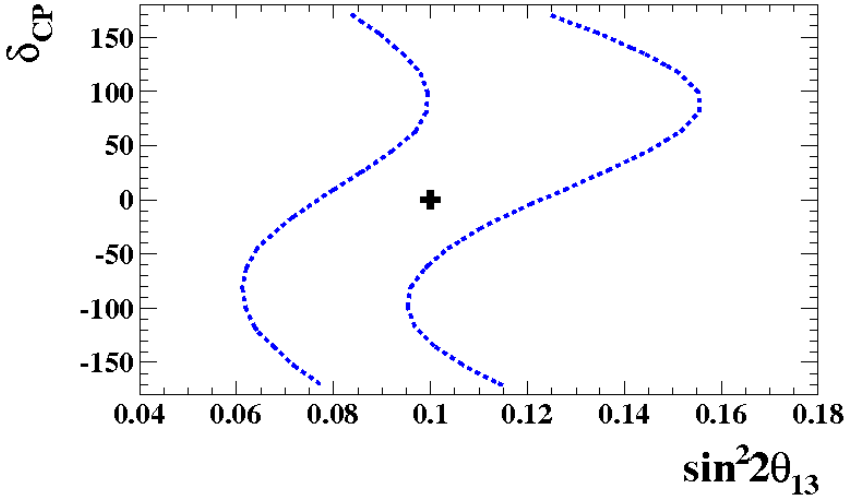




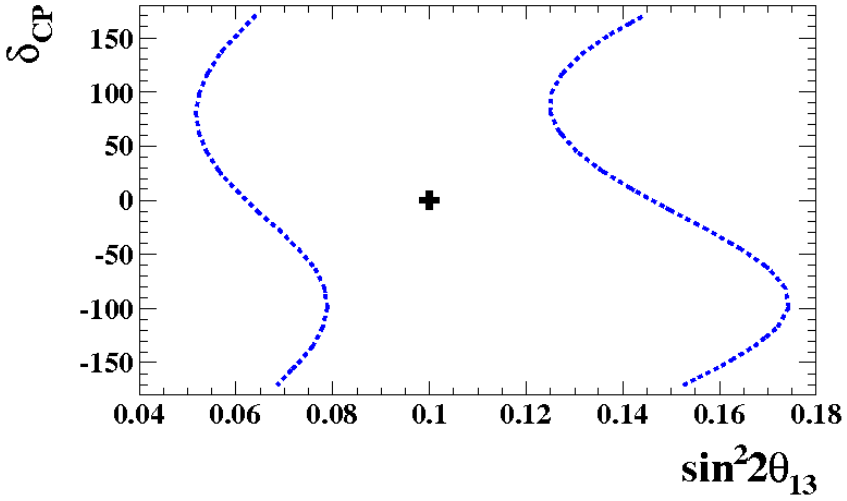
ν vs. $\bar{\nu}$ Running, Ultimate T2K 90% Allowed Region

$\bar{\nu}$ data can give us additional information (about δ_{CP}, etc.) although it comes at the cost of lower statistics
$\rightarrow$ Must optimize the ν-$\bar{\nu}$ running ratio

100% ν



100% $\bar{\nu}$

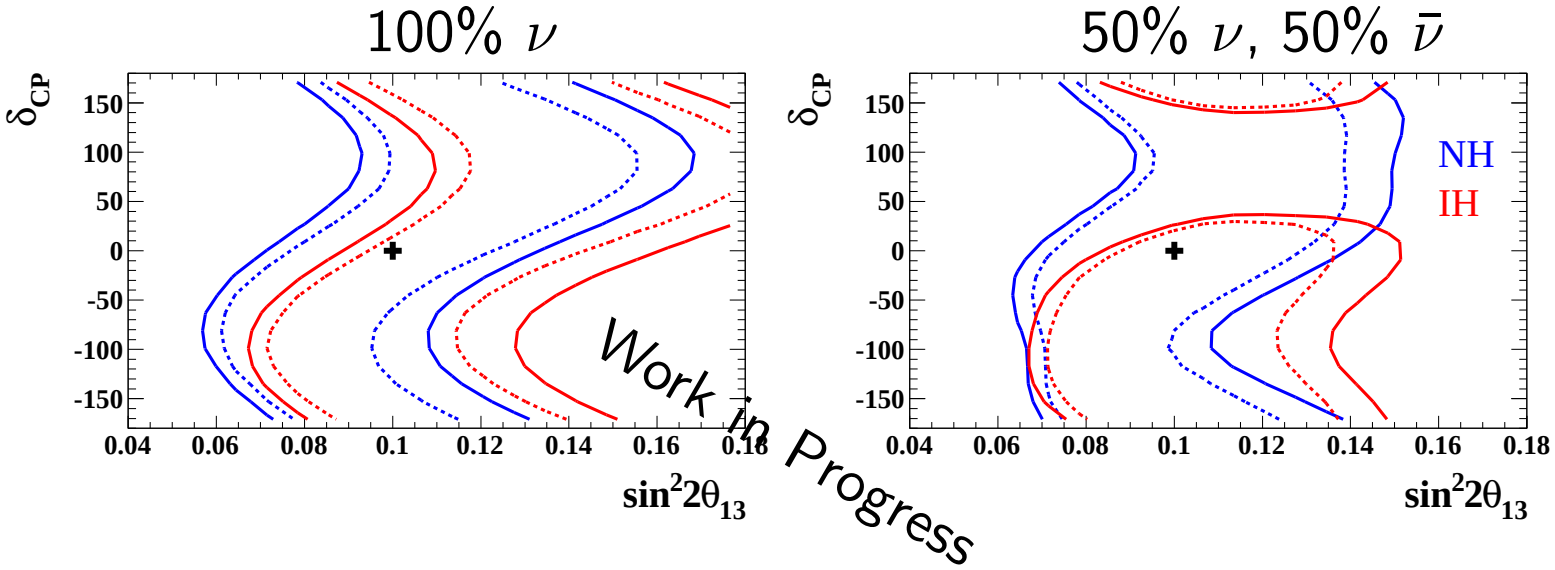


No sys. err.

T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\delta_{CP} = 0$

Dashed: no sys. err., Solid: with current sys. err.

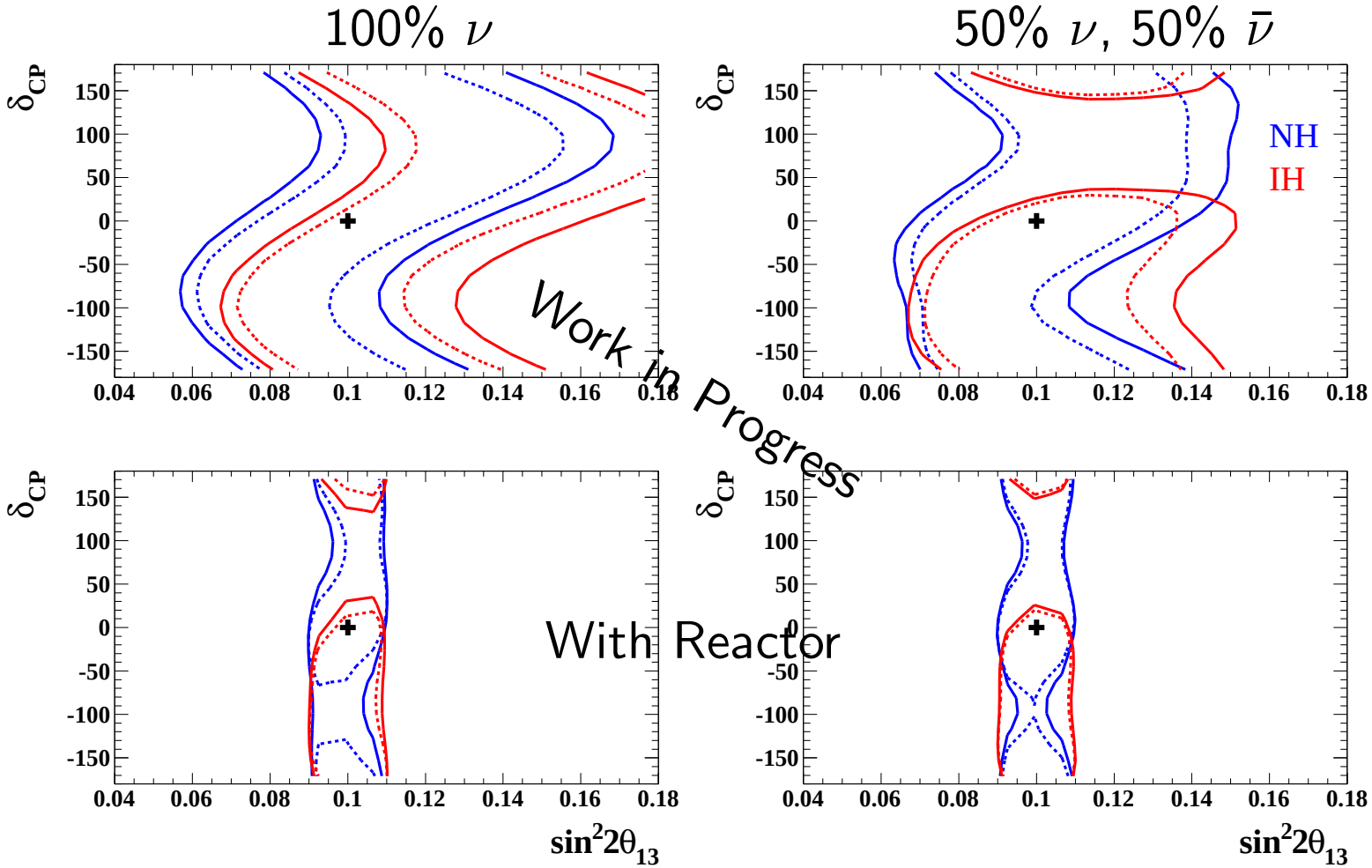
True MH is NH; contours drawn for two MH assumptions



T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\delta_{CP} = 0$

Dashed: no sys. err., Solid: with current sys. err.

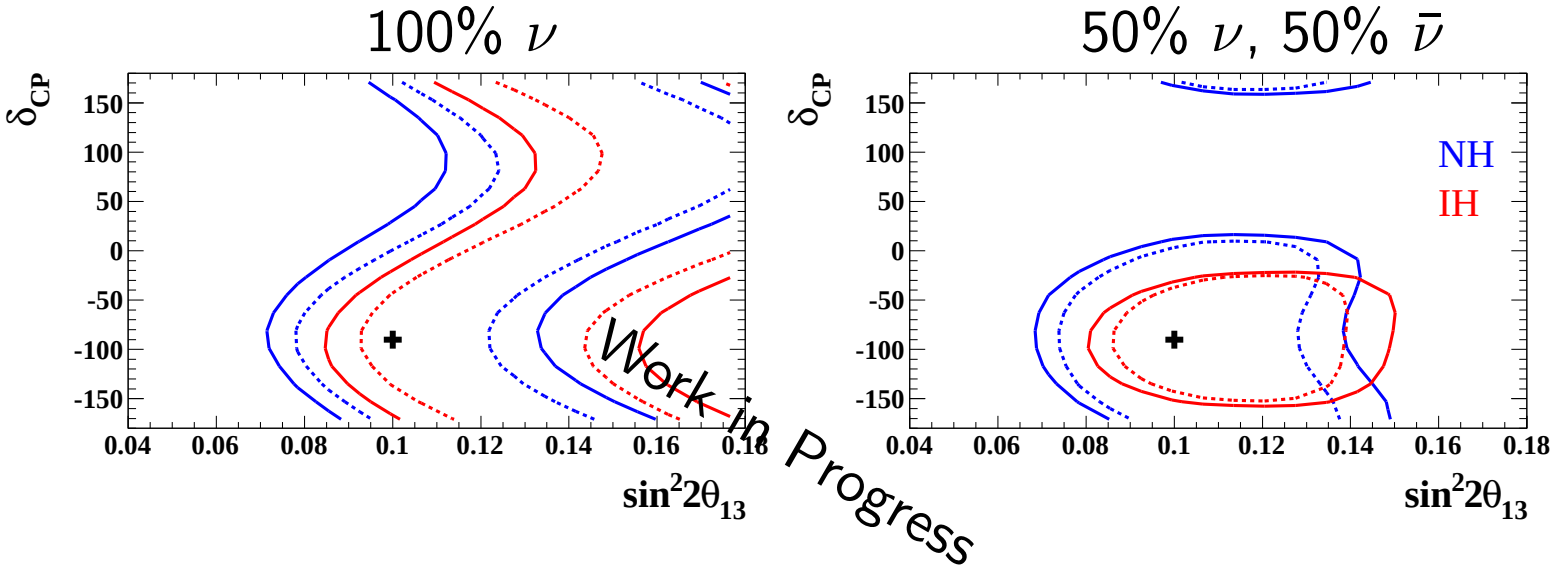
True MH is NH; contours drawn for two MH assumptions



T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\delta_{CP} = -90$

Dashed: no sys. err., Solid: with current sys. err.

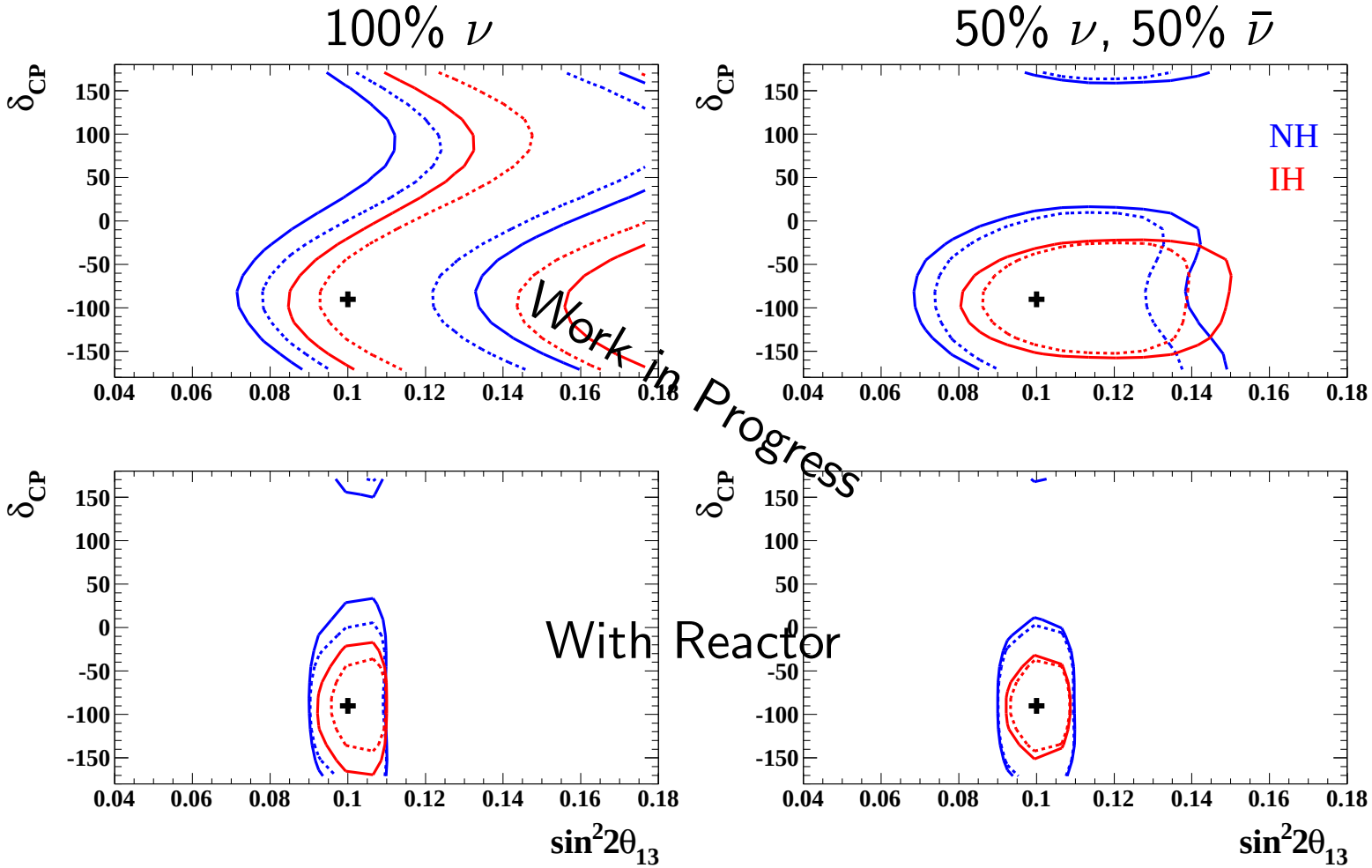
True MH is NH; contours drawn for two MH assumptions



T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\delta_{CP} = -90$

Dashed: no sys. err., Solid: with current sys. err.

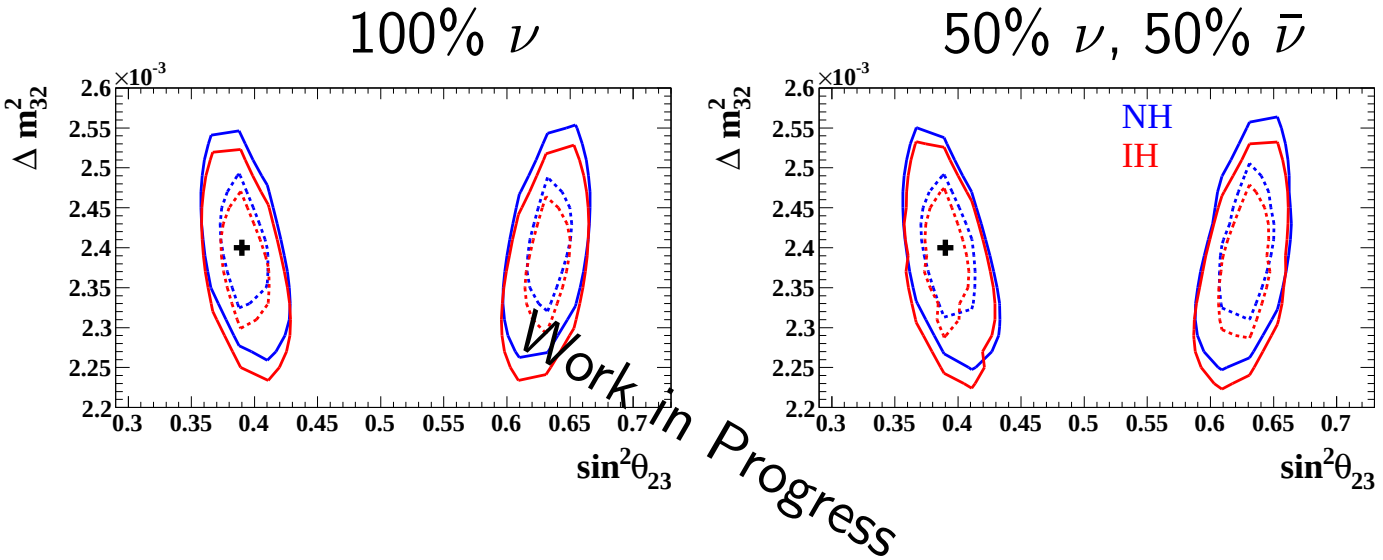
True MH is NH; contours drawn for two MH assumptions



T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\sin^2\theta_{23} = 0.39$

Dashed: no sys. err., Solid: with current sys. err.

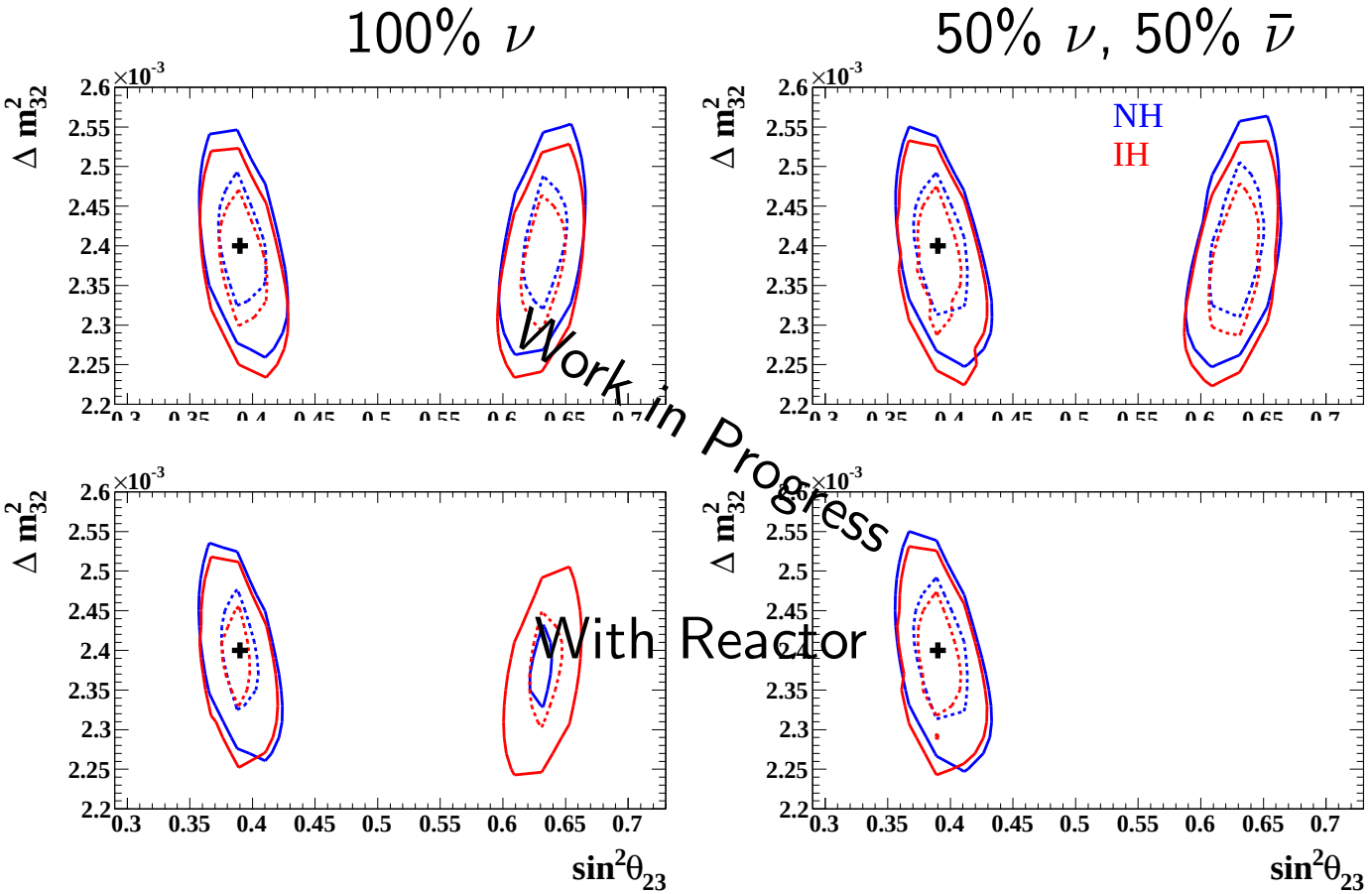
True MH is NH; contours drawn for two MH assumptions



T2K in the Post θ_{13} Era – Ultimate T2K 90% Allowed Region if $\sin^2\theta_{23} = 0.39$

Dashed: no sys. err., Solid: with current sys. err.

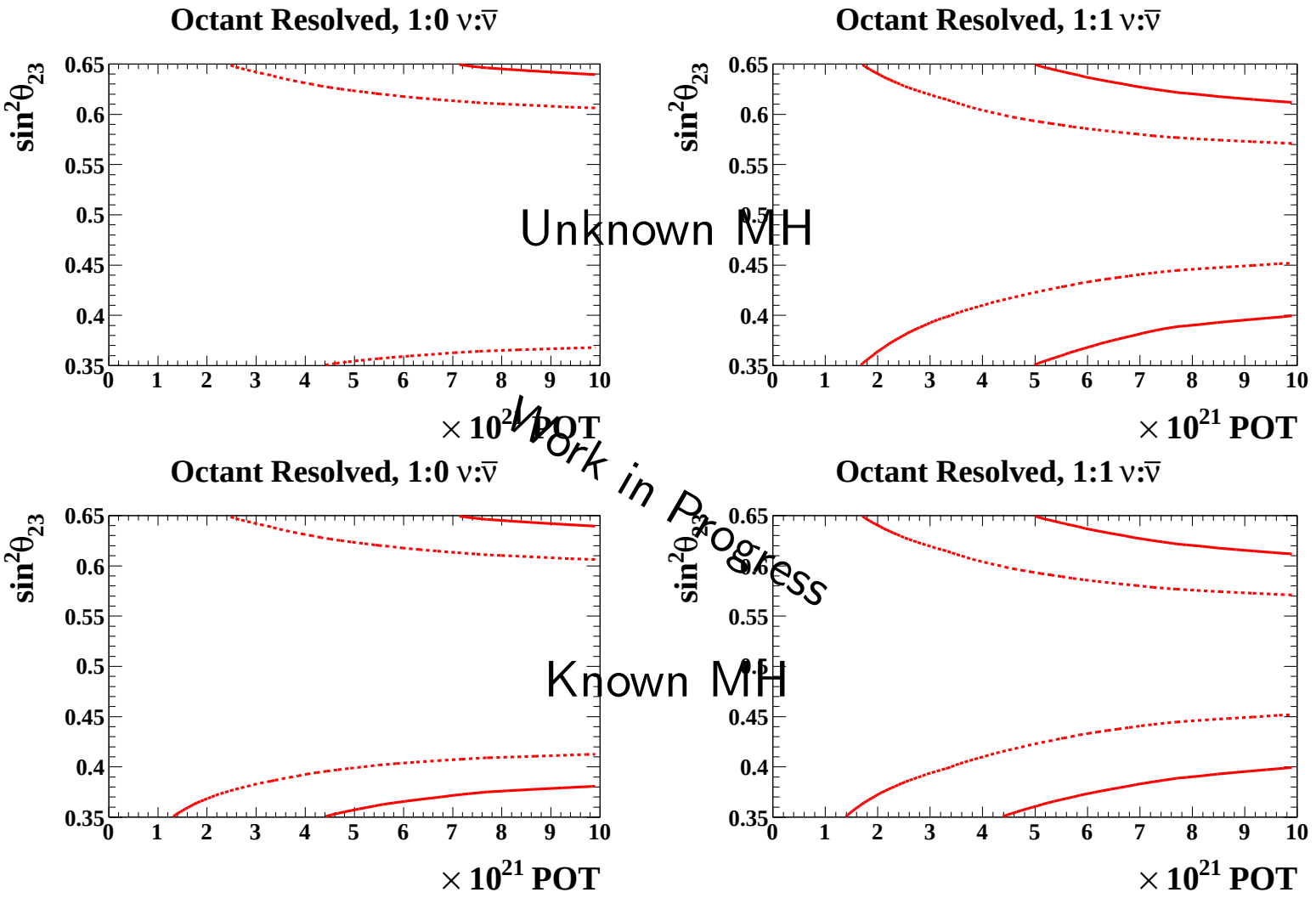
True MH is NH; contours drawn for two MH assumptions



$\sin^2\theta_{23}$ octant determination!

$\sin^2\theta_{23}$ Octant Discrimination vs. POT

Dashed: 90%, Solid: 3σ, no sys. error



Stat. error only; constrained by the ultimate reactor sensitivity

Fits to T2K + NOνA Combined

The NOνA experiment:

- Plans to start taking data this May with a partial detector
- Expected POT is 3.6×10^{21} POT in 6 years
- Baseline length: 810 km (295 km for T2K) – more sensitive to matter effects than T2K
  - Different baselines means different sensitivities!
- Detector mass: 15 kT (22.5 kT for T2K)

The combined fit:

- GLoBES (General Long Baseline Experiment Simulator) used in combined fits
- A constraint based on the ultimate reactor precision is used
- No systematic error used in this comparison/combination

δ_{CP} and MH 90% Sensitivity – T2K Only

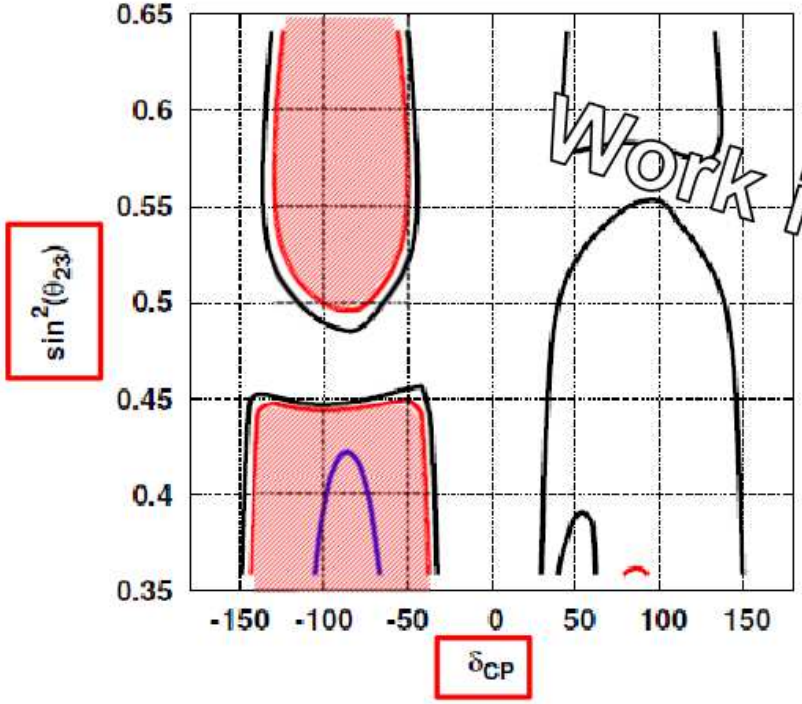
Running fraction ν mode:anti-ν mode = 100%:0%

w/ reactor results
w/o sys. errors

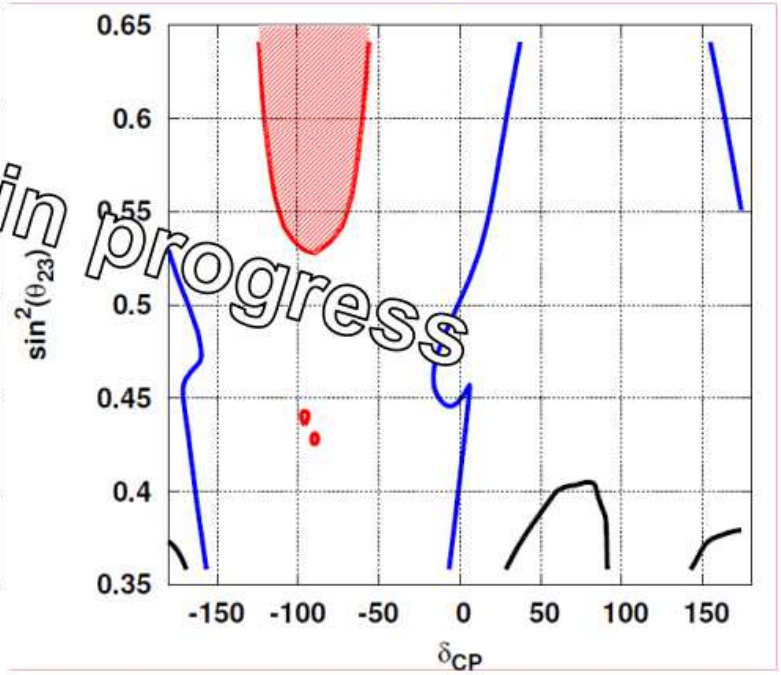
Red: T2K
Blue: NOvA
Black: T2K+NOvA

T2K sensitive region

CP violation



Mass Hierarchy discrimination



Work in progress

δ_{CP} and MH 90% Sensitivity – NOνA Only

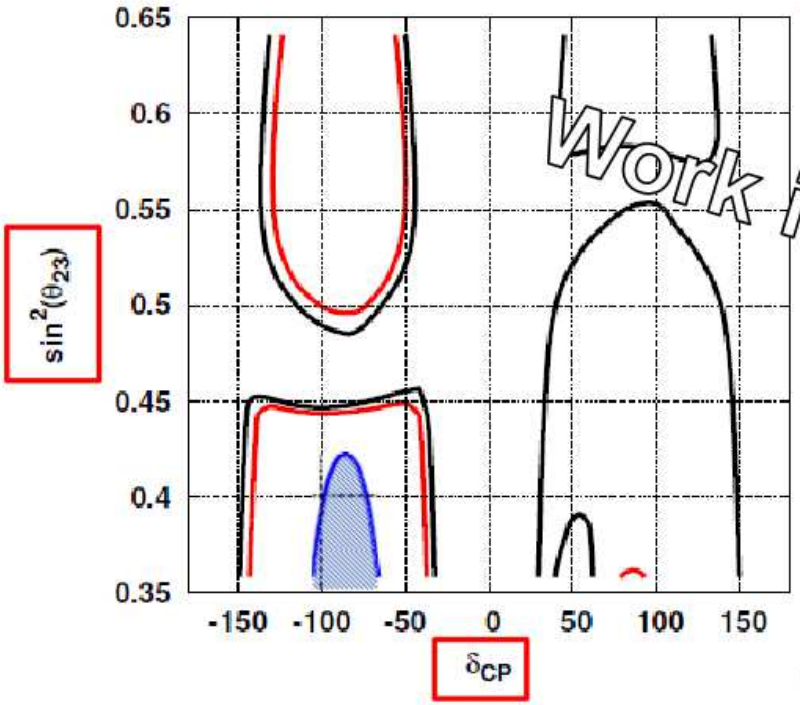
Running fraction ν mode:anti-ν mode = 100%:0%

w/ reactor results
w/o sys. errors

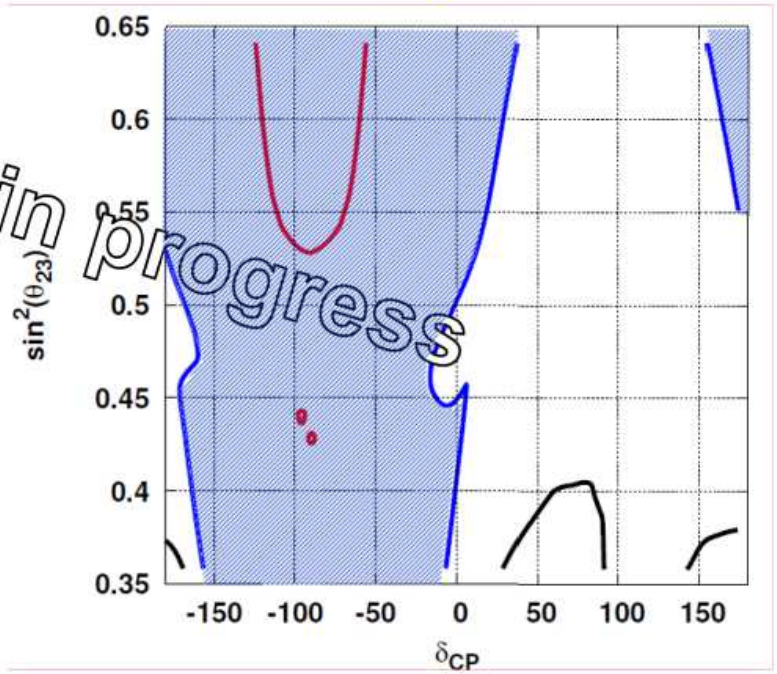
Red: T2K
Blue: NOvA
Black: T2K+NOvA

NOvA sensitive region

CP violation



Mass Hierarchy discrimination



* NOvA sensitivity may be much better for IH

δ_{CP} and MH 90% Sensitivity – T2K + NOνA Combined

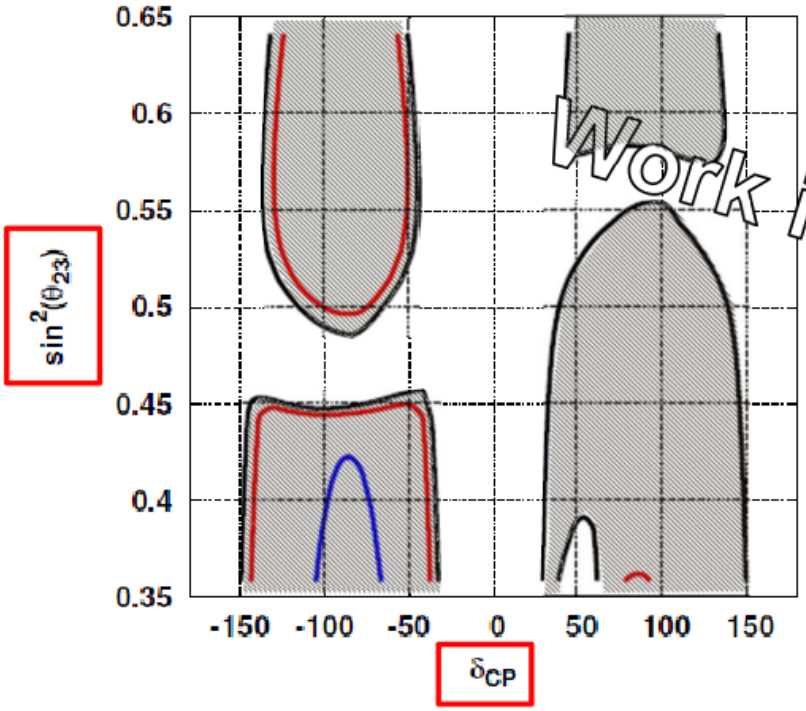
Running fraction ν mode:anti-ν mode = 100%:0%

w/ reactor results
w/o sys. errors

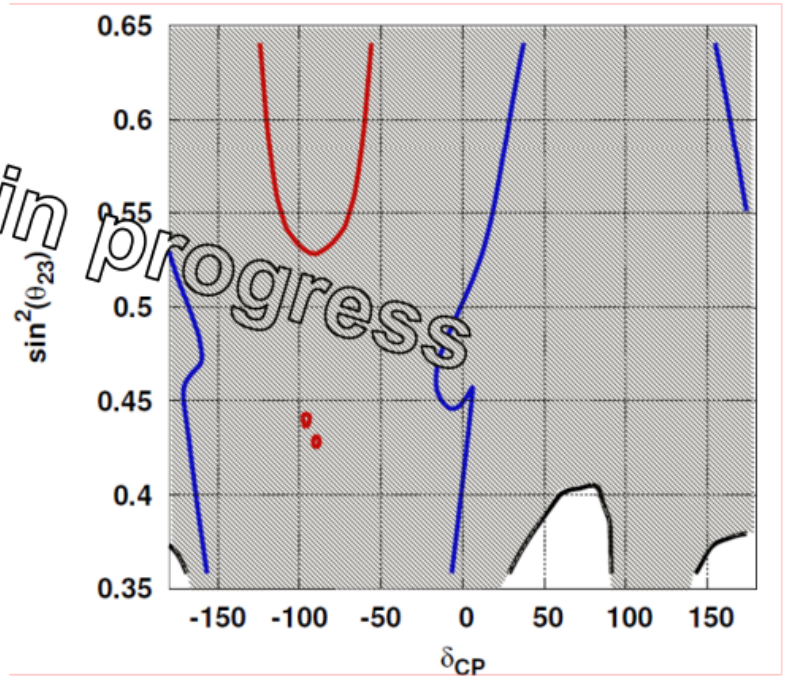
Red: T2K
Blue: NOvA
Black: T2K+NOvA

T2K+NOvA sensitive region

CP violation

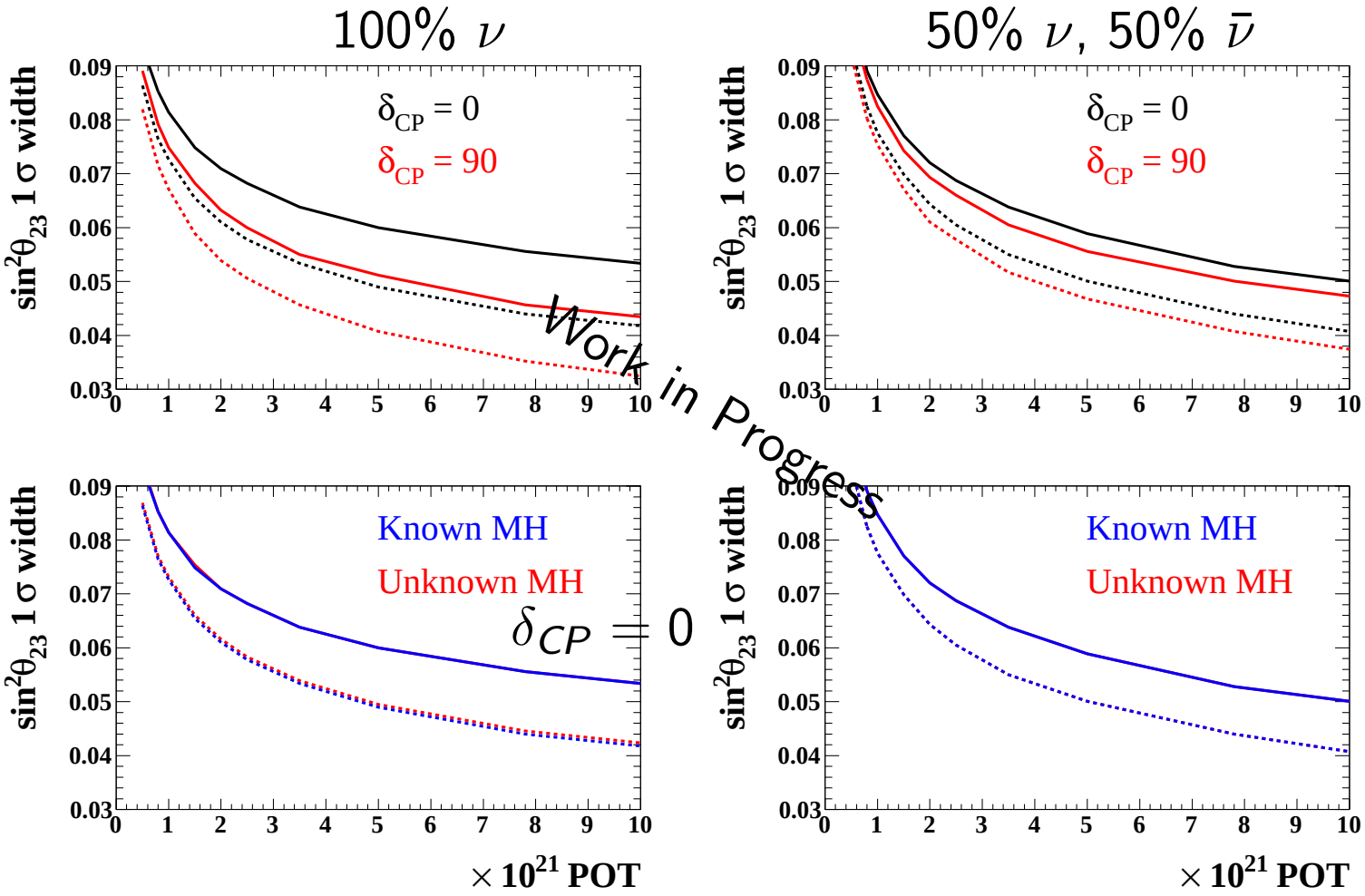


Mass Hierarchy discrimination



T2K $\sin^2\theta_{23}$ 1σ Precision vs. POT

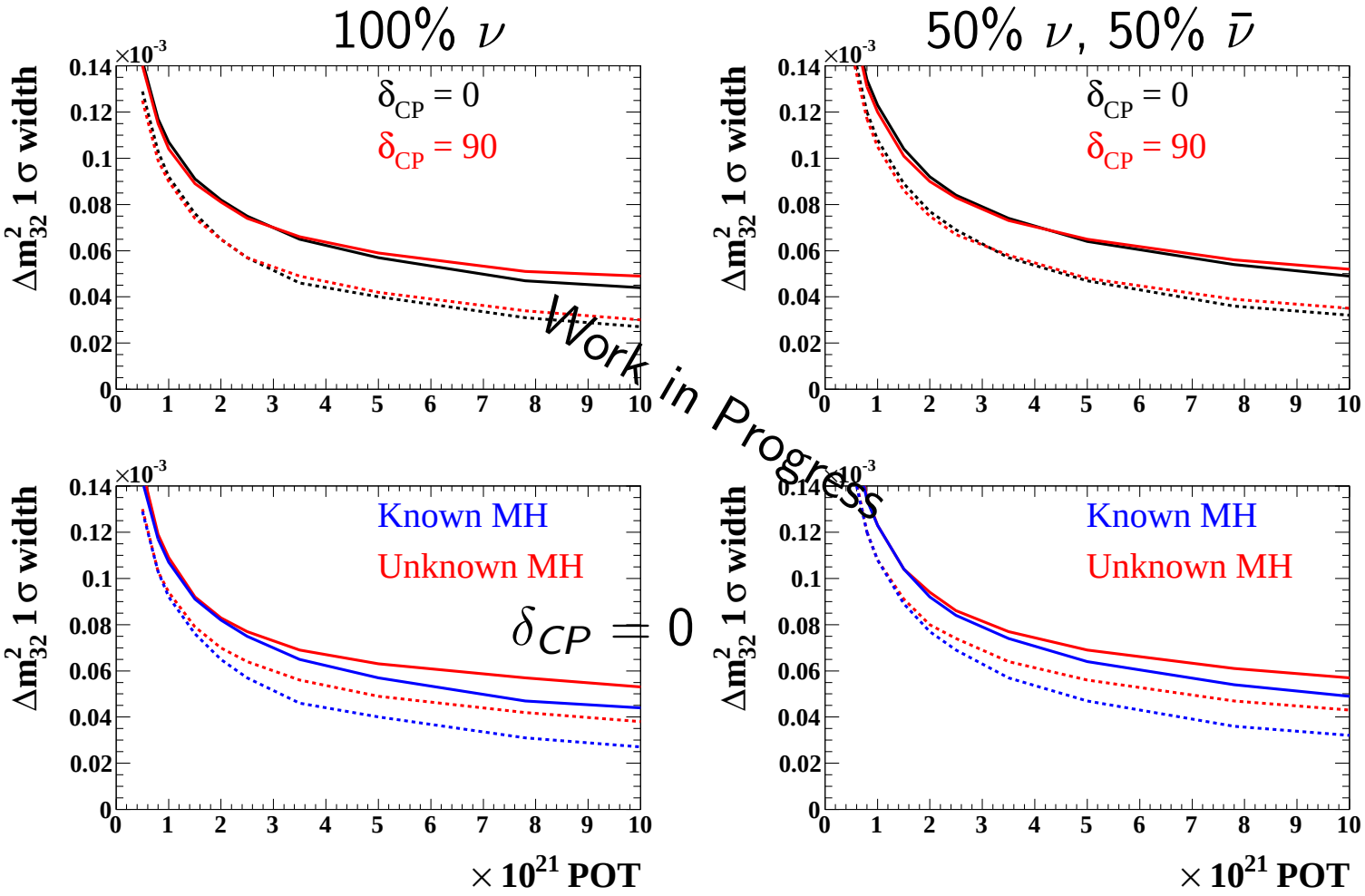
Dashed: no sys. err., Solid: with current sys. err.



Constrained by the ultimate reactor sensitivity

T2K Δm^2_{32} 1σ Precision vs. POT

Dashed: no sys. err., Solid: with current sys. err.



Constrained by the ultimate reactor sensitivity

Conclusion

T2K recent results and current status:

- 3.2σ evidence of ν_e appearance!
- World record on precision of $\sin^2 2\theta_{23}$!
  - T2K's most recent results are with 3.01×10^{20} POT
  - Currently have taken $\sim 0.54 \times 10^{21}$ POT ($\sim 7\%$ of the total approved 7.8×10^{21} POT)
- Collaboration is beginning to discuss the optimal ratio for ν:$\bar{\nu}$ running – may take $\bar{\nu}$ data this year

T2K future sensitivity:

- At the full statistics (2021), T2K has sensitivity for δ_{CP}, non-maximal θ_{23}, and θ_{23} octant
- Also has sensitivity to MH and other increased sensitivities when combined with the NOνA experiment