T2K 2013 Neutrino Oscillation Results and Expected Sensitivity at the T2K Proposed POT

For NuFact2013

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for the T2K Collaboration

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Outline

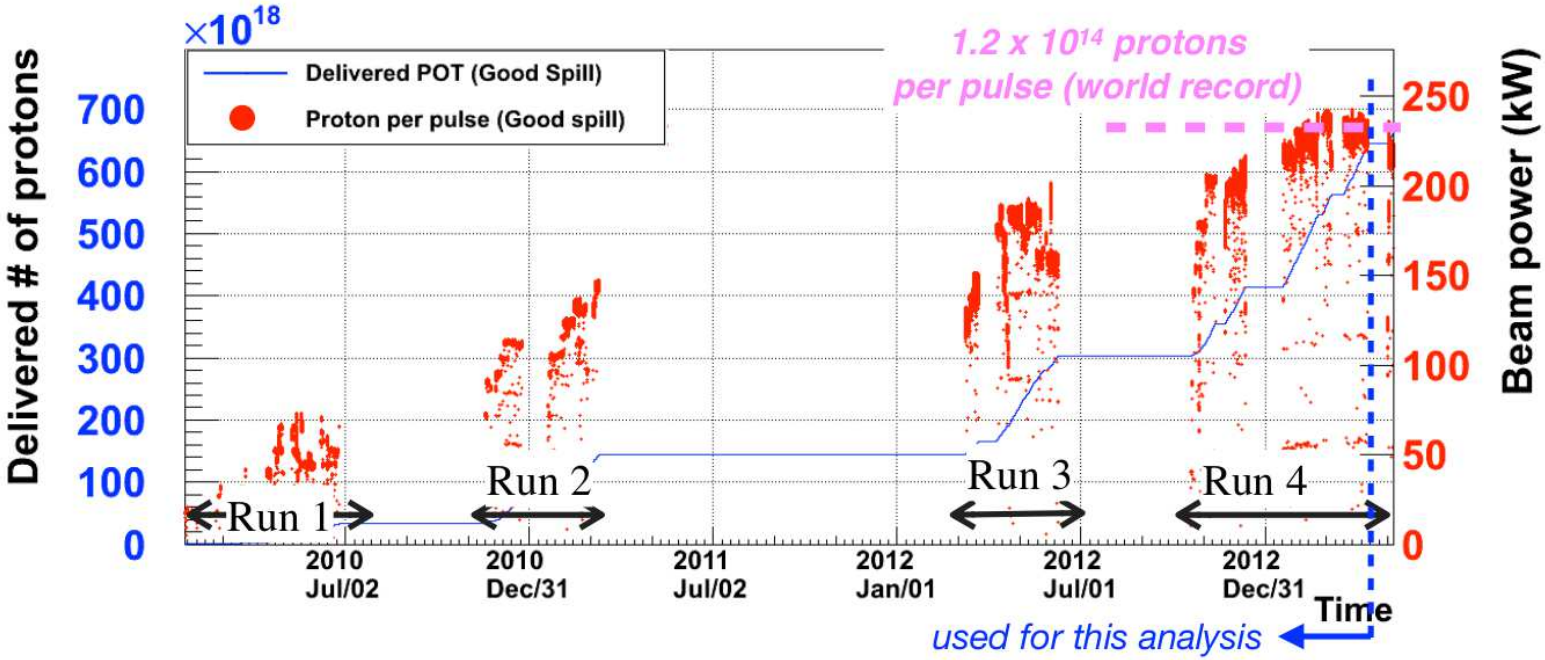
The T2K Collaboration

~500 members from 59 institutes in 11 countries

The T2K Experiment (Tokai to Kamioka Long Baseline Neutrino 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
- Neutrino interactions detected at the Super-Kamiokande (SK) far detector – 295 km from ν source
  - 22.5 kT fiducial volume water Cherenkov detector
  - Good performance of ν_e/ν_μ particle ID for sub-GeV energy ν's
  - ν_e appearance and ν_μ disappearance ν oscillation information

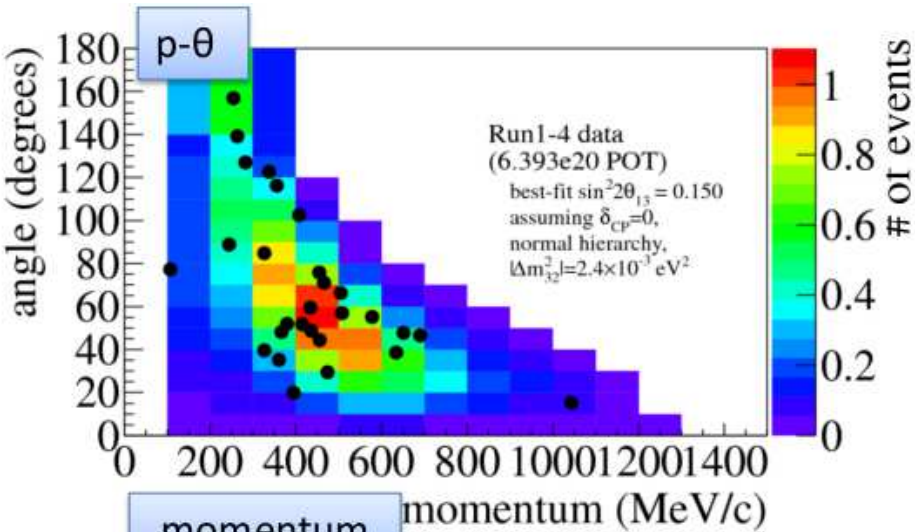
The T2K Experiment – Current Status

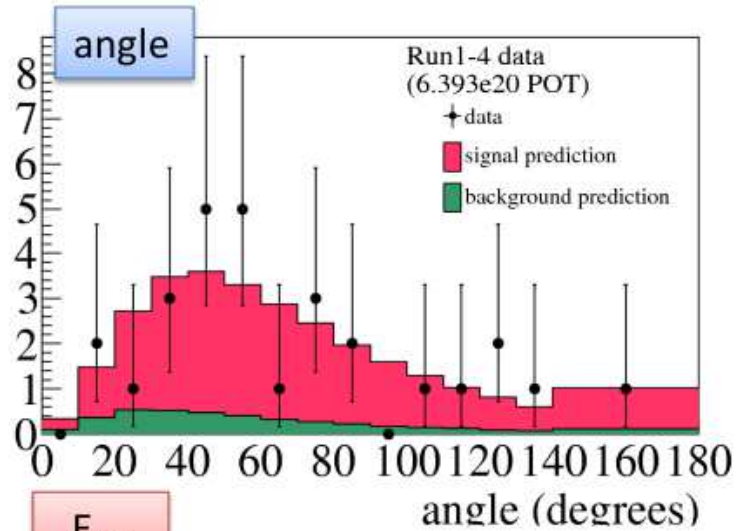


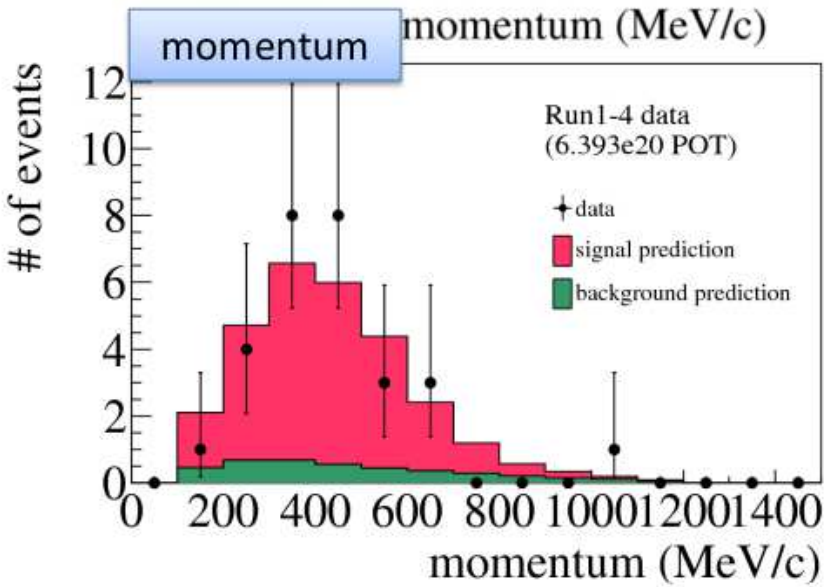
- Current total integrated POT: $\sim 6.63 \times 10^{20}$
  $\rightarrow$ $\sim$8.5% of T2K approved full statistics (7.8×10^{21} POT)
- Integrated POT analyzed for 2013 ν_e appearance results:
  6.39×10^{20}
- Integrated POT analyzed for 2013 ν_μ disappearance results:
  3.01×10^{20}

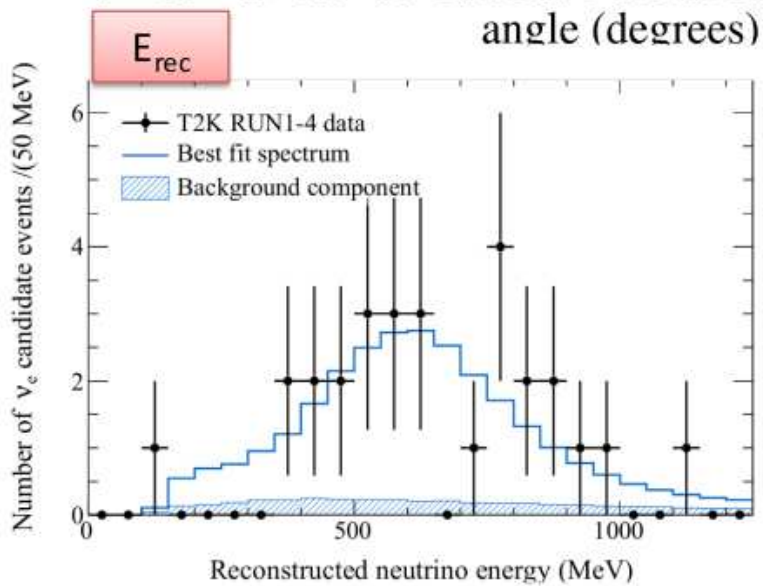
2013 $\nu_\mu \rightarrow \nu_e$ Appearance Fit Results

- Expected 20.4 ± 1.8 signal events and 4.6 ± 0.5 background events $\rightarrow 5.5\sigma$ sensitivity
- Observed 28 ν_e candidate events





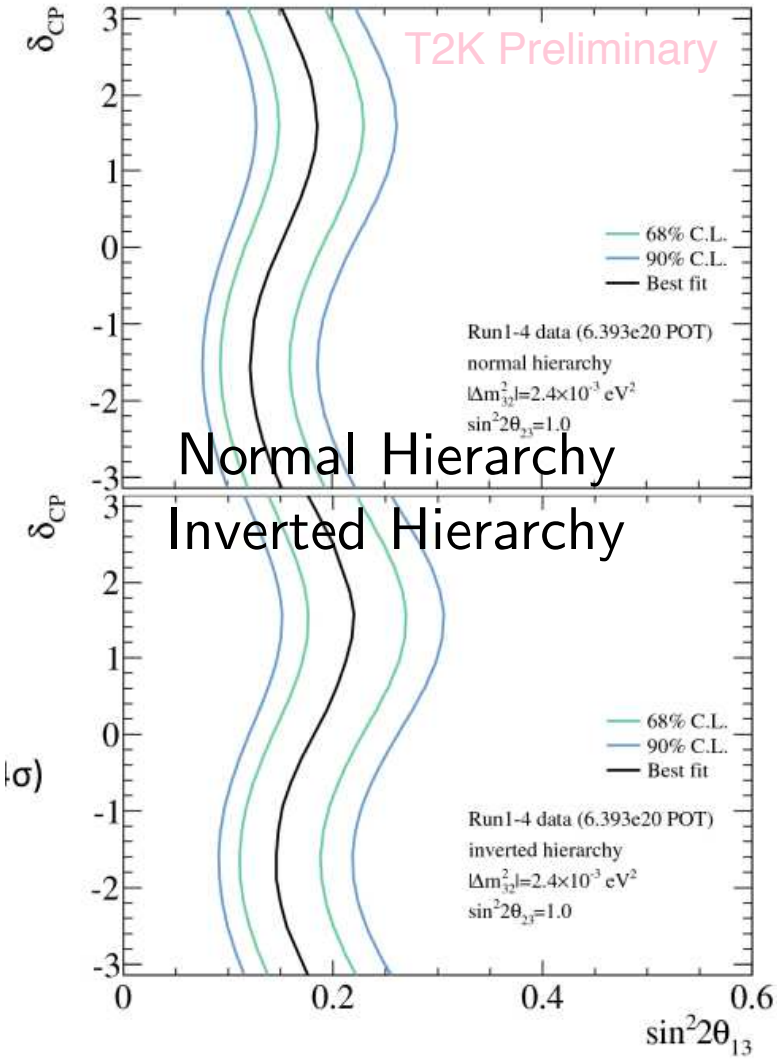




2013 $\nu_\mu \rightarrow \nu_e$ Appearance Results

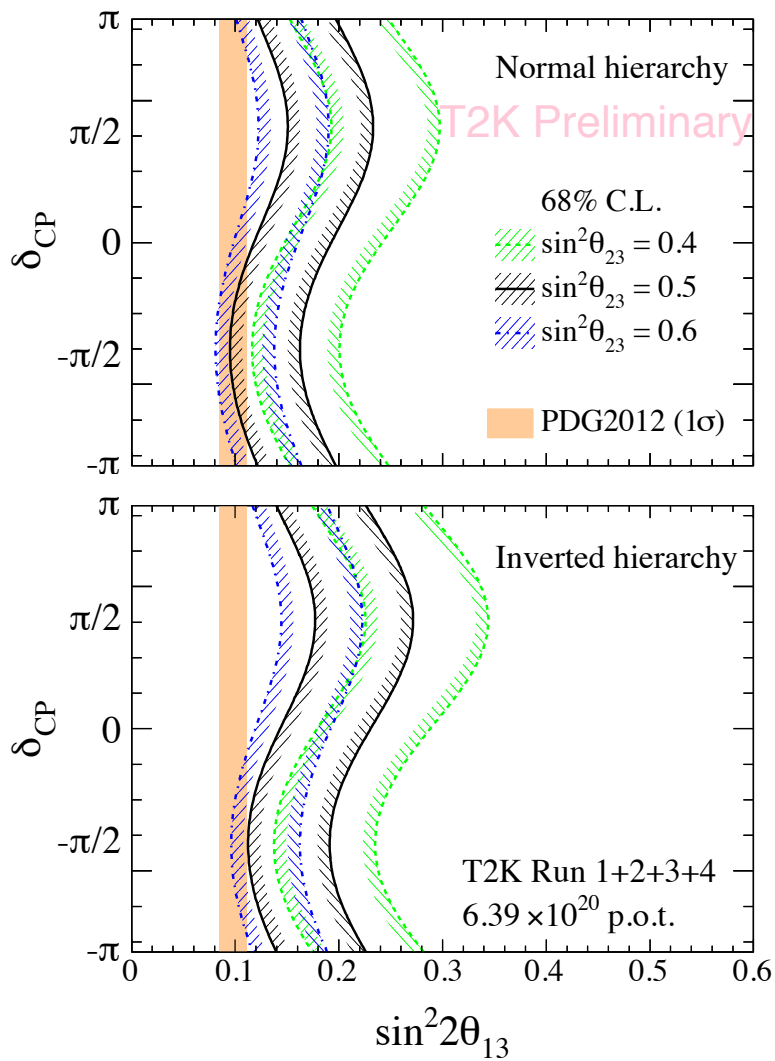
Observation of ν_e appearance
Released at EPS-HEP last month

- Observed 28 ν_e candidate events for 6.39×10^{20} POT
  - Expect 4.6 events if no $\nu_\mu \rightarrow \nu_e$ oscillation $\rightarrow$ 7.5σ observation
  - Background rejection has improved following implementation of a new SK reconstruction algorithm
    - 6.4 $\rightarrow$ 4.6 background events expected
- NOTE: δ_{CP} values are fixed when generating these plots, they are not 2D contours



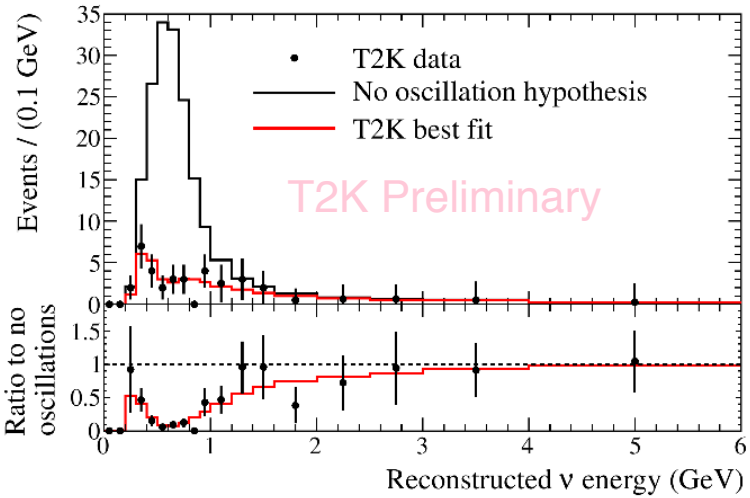
Dependence of ν_e Appearance Results on Uncertainty in $\sin^2 2\theta_{23}$

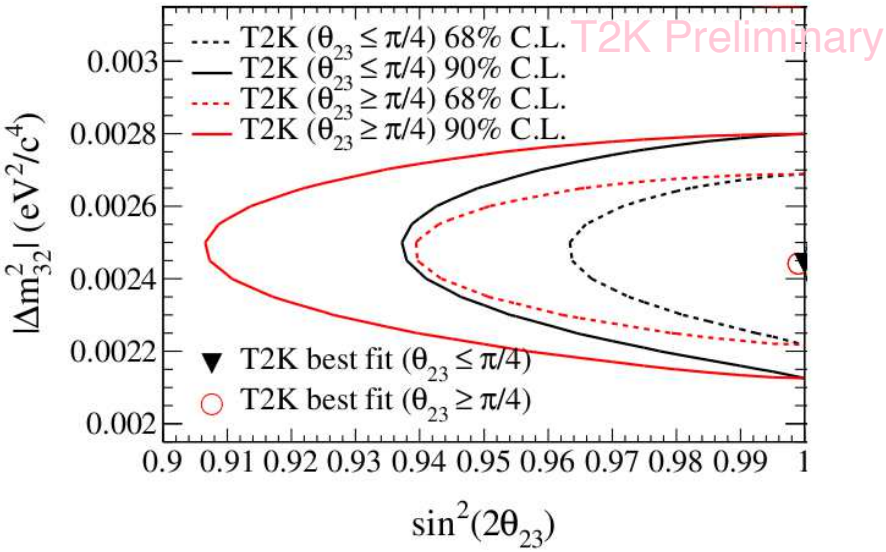
- 2013 T2K appearance results assume $\sin^2\theta_{23} = 0.5$
- However, the $\nu_\mu \rightarrow \nu_e$ appearance sensitivity depends on the true value of $\sin^2\theta_{23}$
- Precision measurement of $\sin^2\theta_{23}$ will be important for future $\nu_\mu \rightarrow \nu_e$ results
  - Particularly for possible δ_{CP} measurement
- NOTE: δ_{CP} values are fixed when generating these plots, they are not 2D contours



2013 $\nu_\mu \to \nu_\mu$ Disappearance Results

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



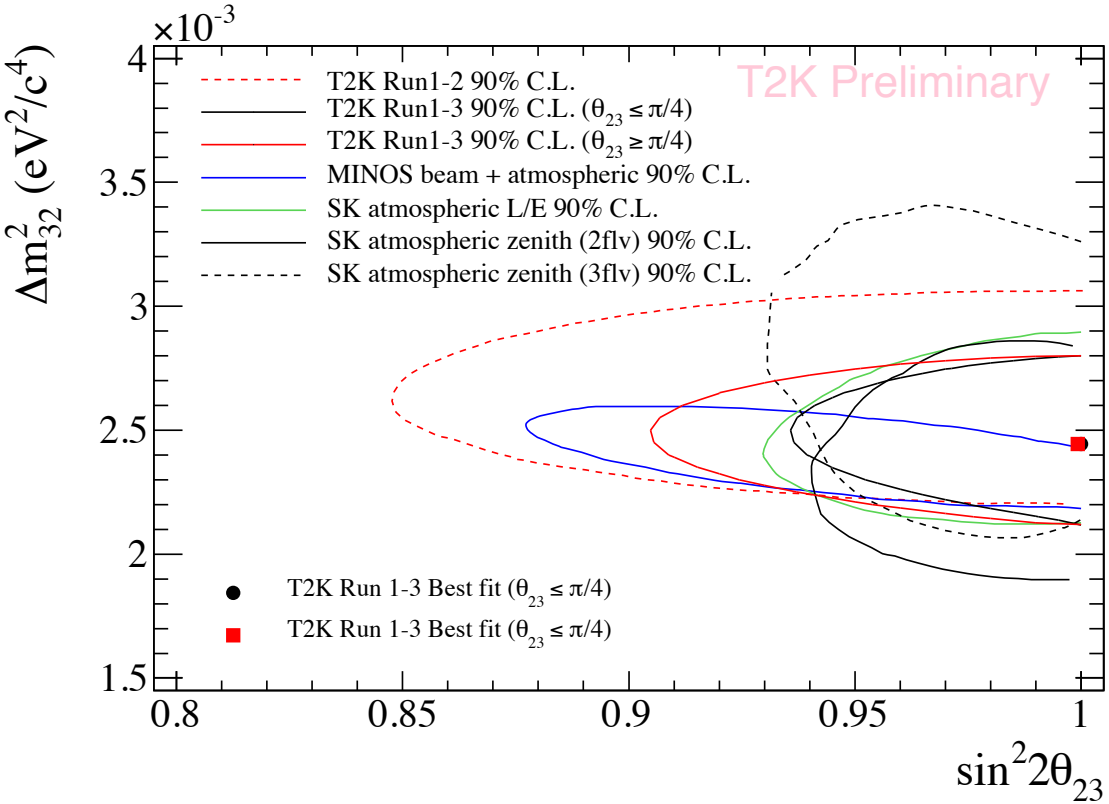


$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\underbrace{\cos^4\theta_{13}\sin^2 2\theta_{23}}_{\text{Leading Term}} + \underbrace{\sin^2 2\theta_{13}\sin^2\theta_{23}}_{\text{Next-to-Leading}})\sin^2\frac{\Delta m^2_{31} L}{4E}$$

- Newly released results showing the sensitivity assuming $\sin^2 2\theta_{13} \neq 0$ for both θ_{23} octants
- C.L. contours highly dependent on θ_{23} octant
- Best fit points are independent of octant:

$$\sin^2 2\theta_{23} = 1.00 \qquad \Delta m^2_{32} = 2.44 \times 10^{-3}\ \text{eV}^2$$

$\nu_\mu \rightarrow \nu_\mu$ World Disappearance Results



Including new T2K results released this year

- Solid red line for T2K $\theta_{23} > \pi/4$
- Solid black line for T2K $\theta_{23} < \pi/4$
- Future T2K results may be plotted in $\sin^2\theta_{23}$ instead of $\sin^2 2\theta_{23}$

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 $\times$ 5 $\times 10^7$ s (115 days $\times$ 5 years) at 30 GeV $= 7.80 \times 10^{21}$ POT

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$\to$ Can now update the T2K experimental goals following the 7.5σ observation of ν_e appearance by T2K and the precise measurement of $\sin^2 2\theta_{13}$ by reactor experiments:

- Precisely measure θ_{23} and Δm^2_{32}
- Obtain hints about δ_{CP}, θ_{23} Octant, Mass Hierarchy

$\nu_\mu \to \nu_e$ 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 $\sin^2 2\theta_{23}$ to first order and cannot distinguish the octant alone

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

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

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

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

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

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

- 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 Expected Sensitivity Analysis Method

Unlike official analysis method:

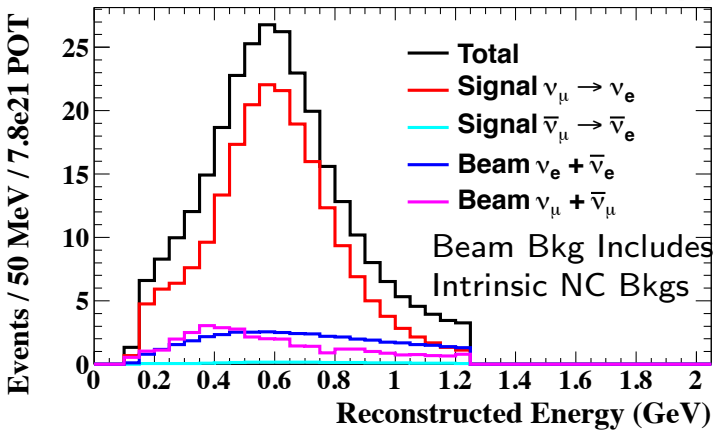
- Use both $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance MC information simultaneously
- Include possible $\bar{\nu}$-mode running information
  - Assuming full T2K statistics – 7.8×10^{21} POT
  - Simultaneously use far detector reconstructed energy spectra information for ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$ data
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2 \theta_{23}$, and Δm^2_{32} are all considered (all 4 parameters are fit simultaneously)
- Current T2K systematic errors are used
  - $\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; fully correlated with ν errors
- With and without a reactor constraint based on the expected ultimate precision of Daya Bay + RENO + Double Chooz on $\sin^2 2\theta_{13}$: $\delta(\sin^2 2\theta_{13}) = 0.005$

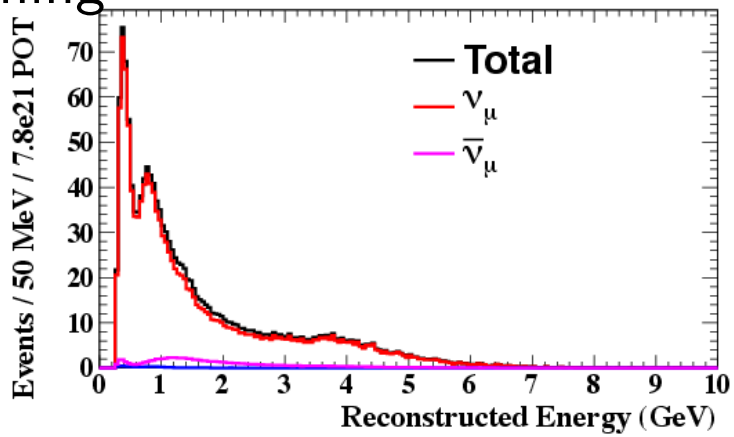
Far Detector Reconstructed Energy Spectra at Full Statistics (7.8×10^{21} POT)

ν_e Appearance

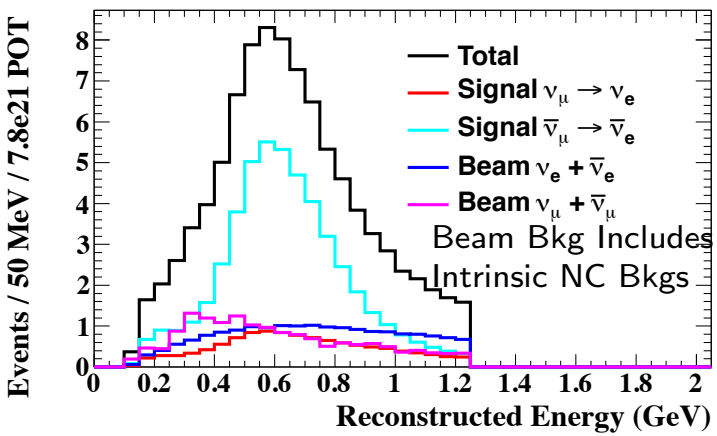
ν_μ Disappearance

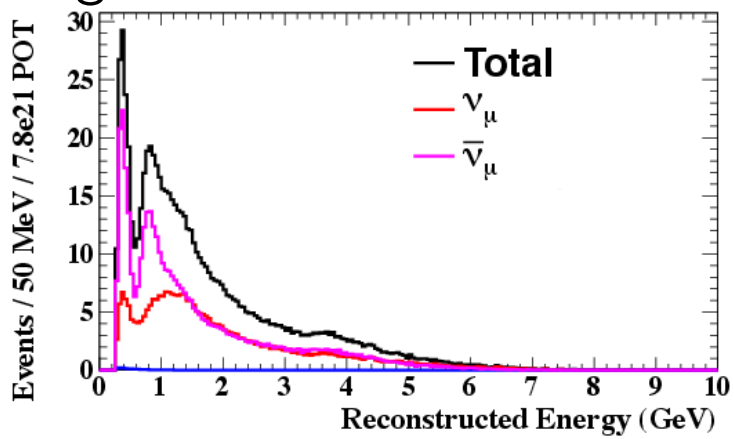
ν-Running





$\bar{\nu}$-Running





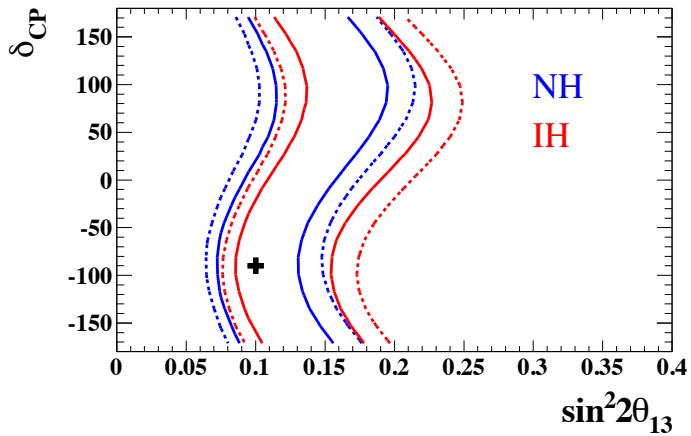
NOTE: must always choose set of "true" oscillation parameters:
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Impact of ν- vs. $\bar{\nu}$-Mode Running

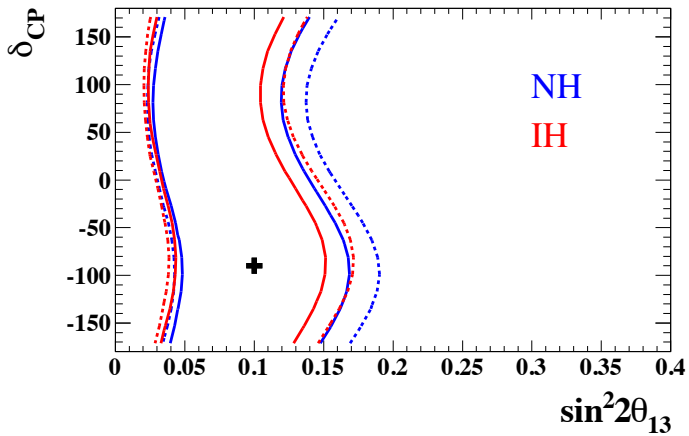
90% C.L. Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions

3.9×10^{21} POT ν



3.9×10^{21} POT $\bar{\nu}$



$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90°$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

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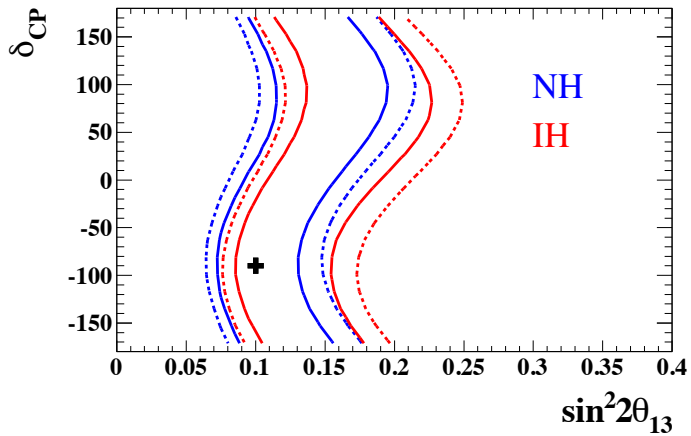
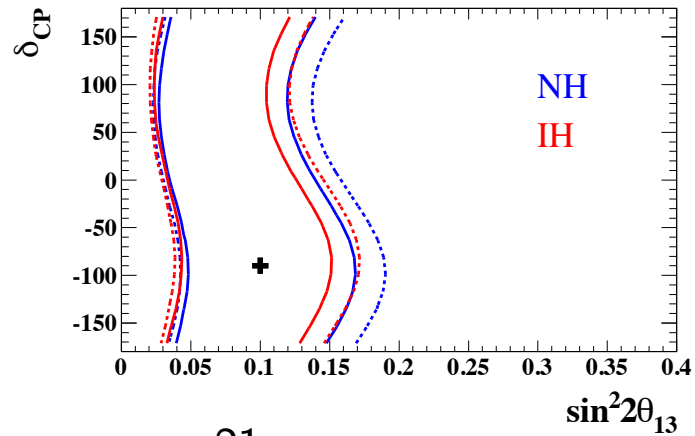


+

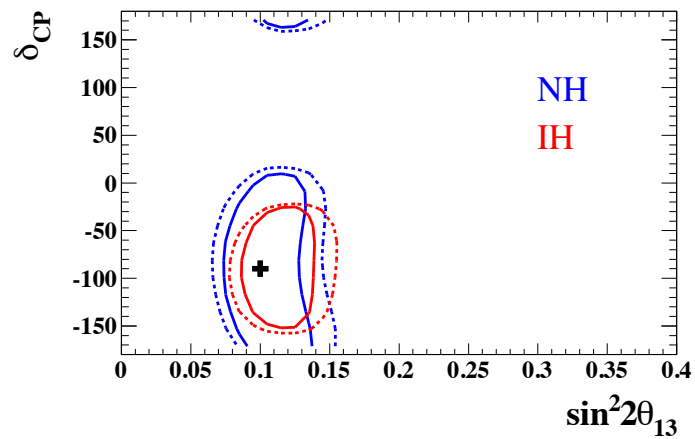
3.9×10^{21} POT $\bar{\nu}$



Difference in sensitivity to δ_{CP} for ν- vs. $\bar{\nu}$-mode beam means that δ_{CP} can be constrained with combined $\nu+\bar{\nu}$ data

$\rightarrow$

3.9×10^{21} POT both $\nu + \bar{\nu}$



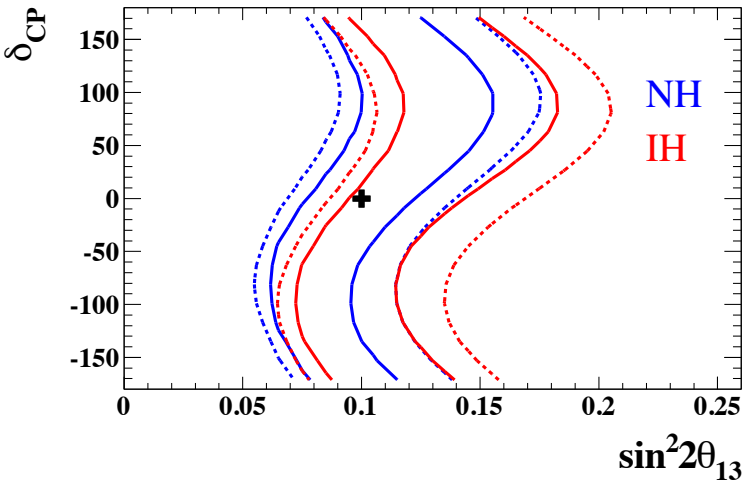
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90°$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Appearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\delta_{CP} = 0^\circ$

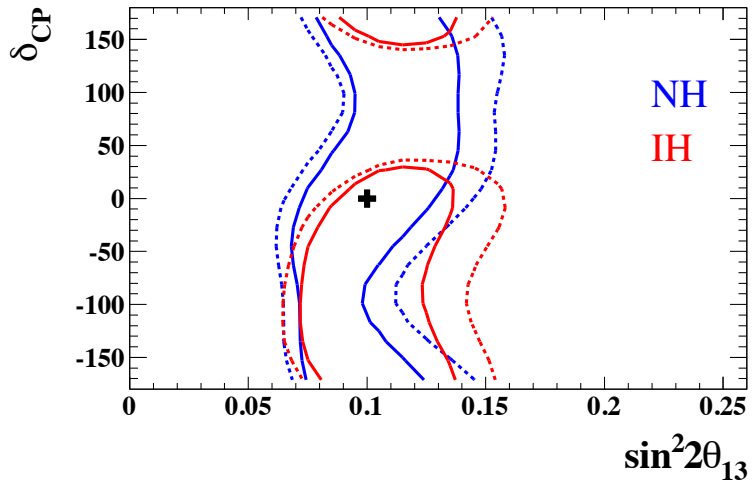
Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν



50% POT ν + 50% POT $\bar{\nu}$



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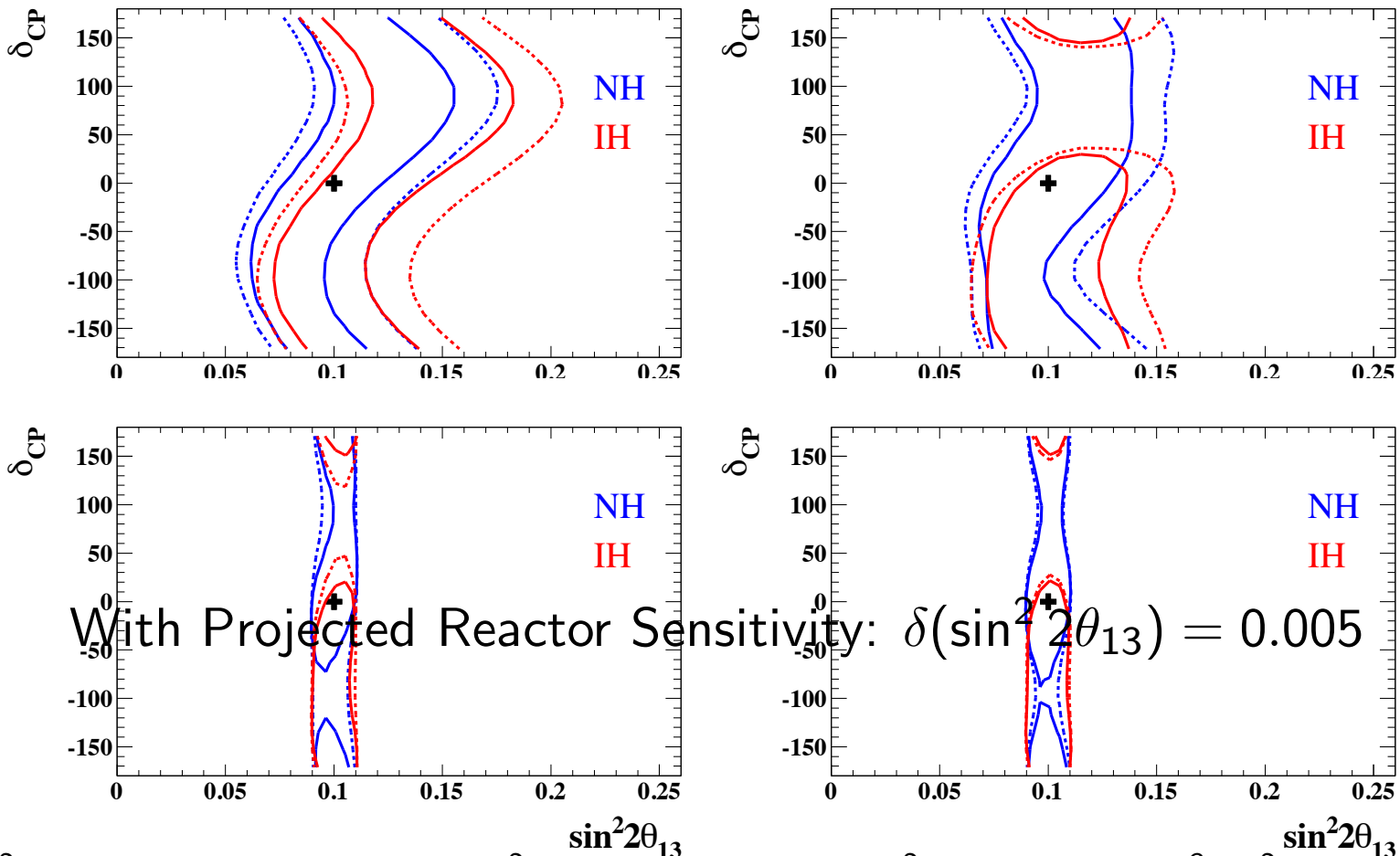
100% POT ν | 50% POT ν + 50% POT $\bar{\nu}$



With Projected Reactor Sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0^\circ$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

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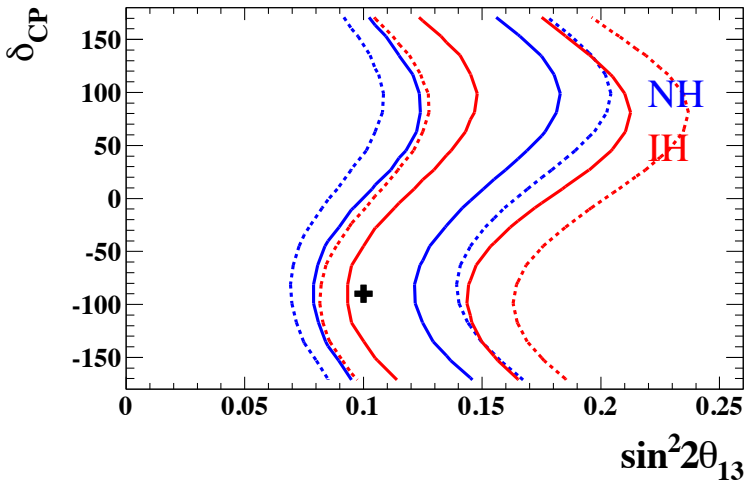
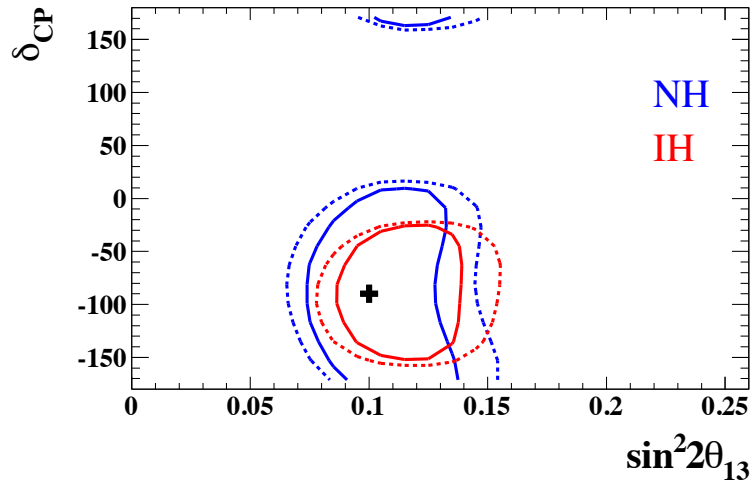


50% POT ν + 50% POT $\bar{\nu}$



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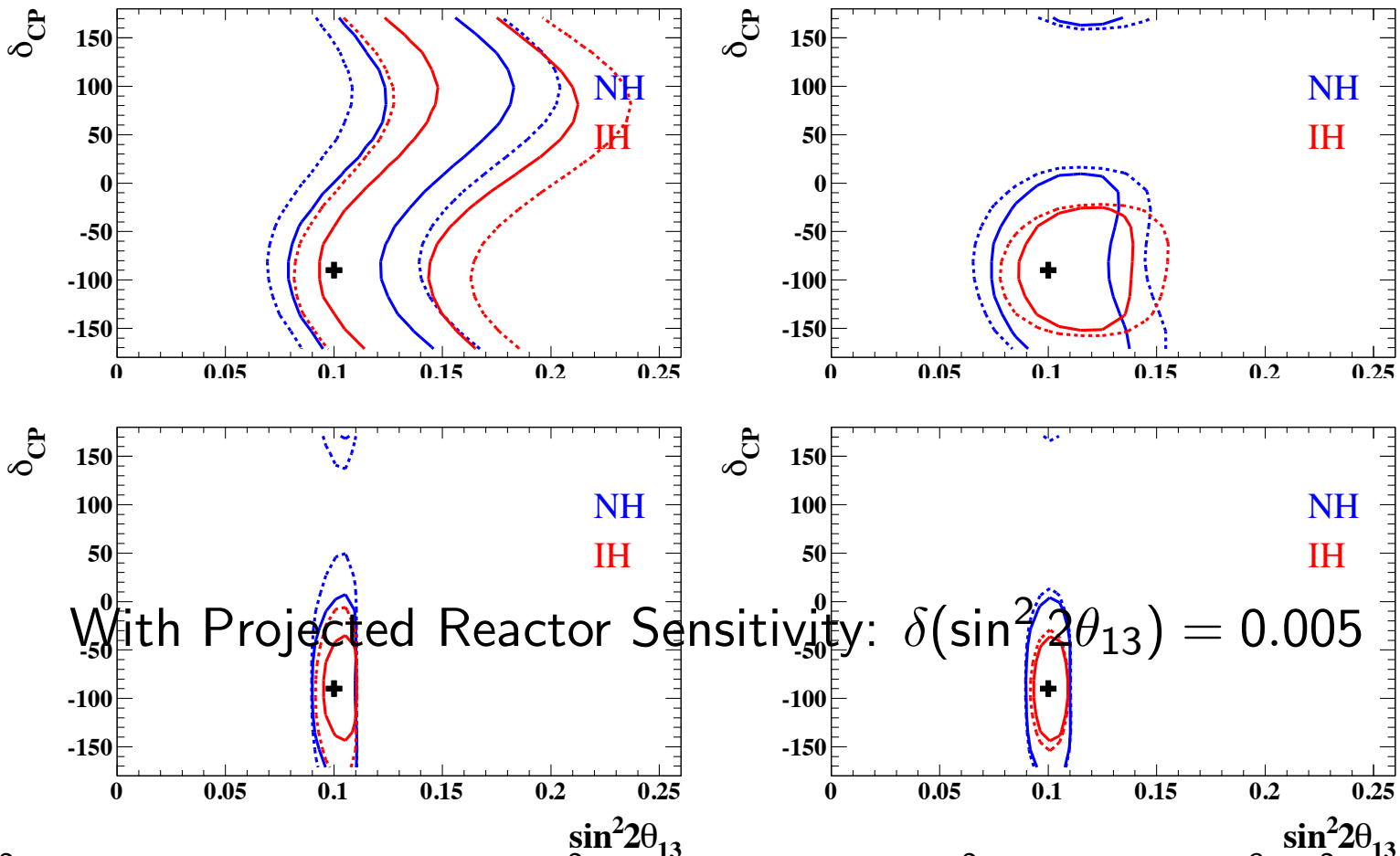

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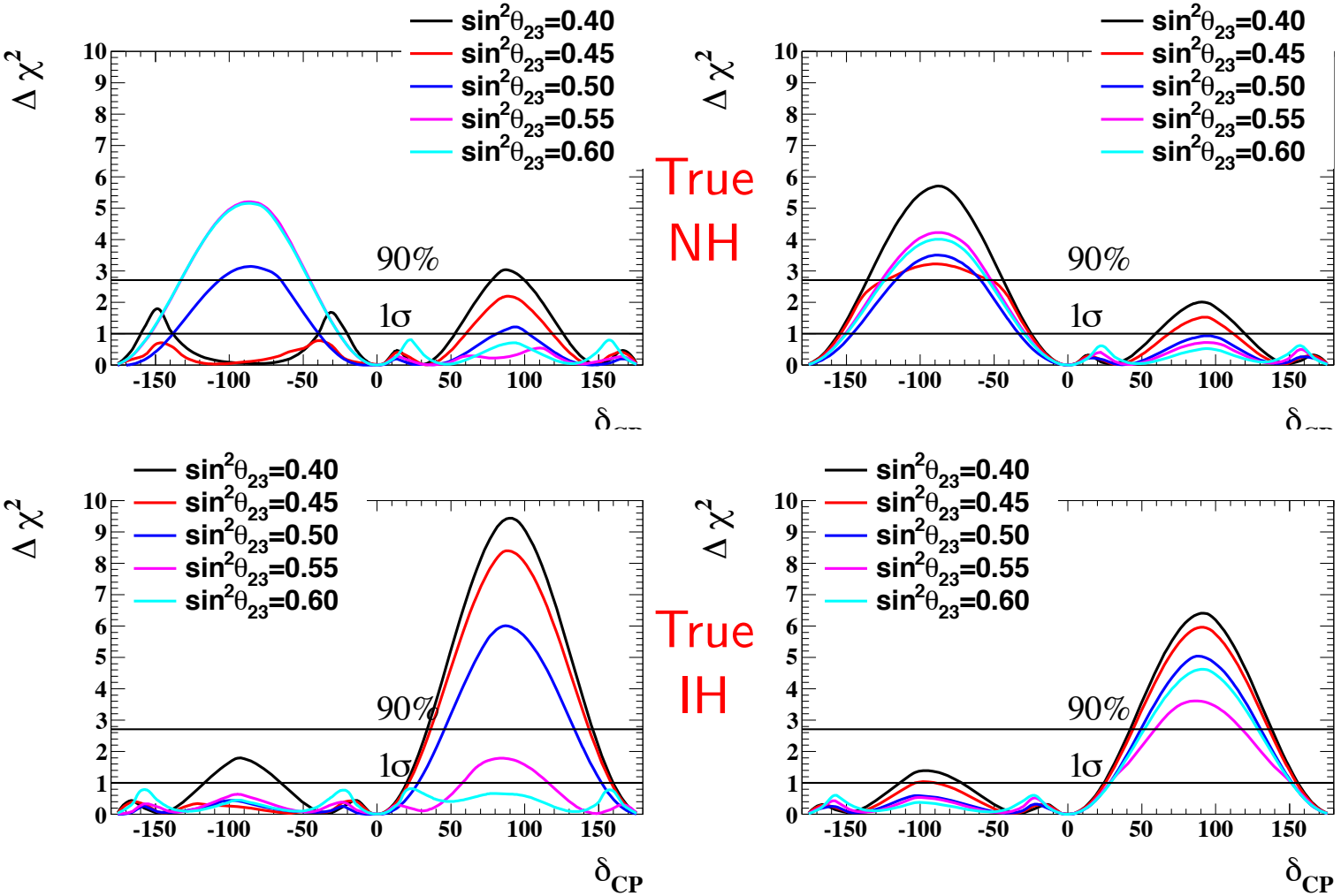
T2K Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

7.8×10^{21} POT; Without systematic error

100% POT ν | 50% POT ν + 50% POT $\bar{\nu}$



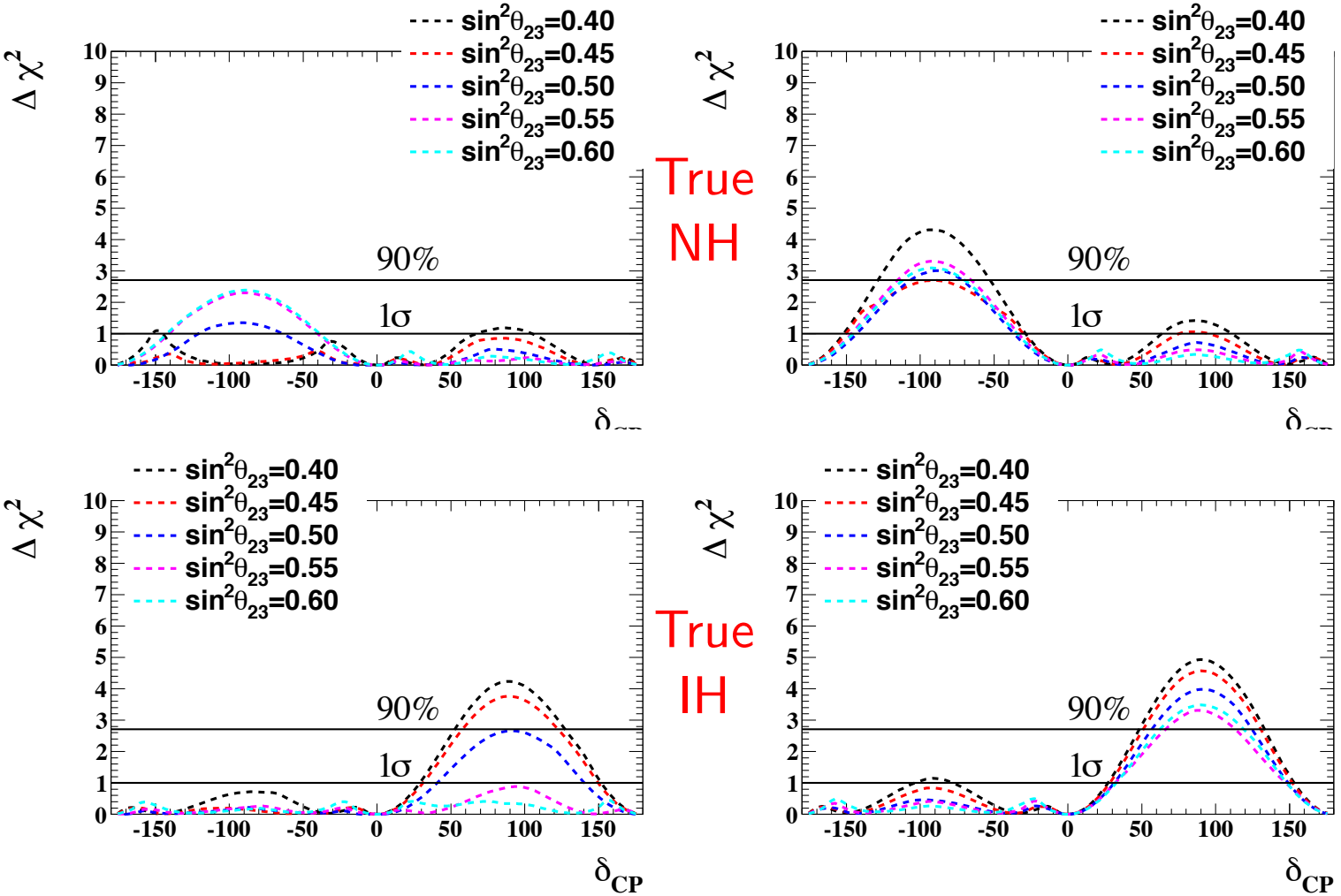
Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

7.8×10^{21} POT; With current systematic errors

100% POT ν | 50% POT ν + 50% POT $\bar{\nu}$



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θ_{13} constrained by the projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

Disappearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\sin^2\theta_{23} = 0.4$

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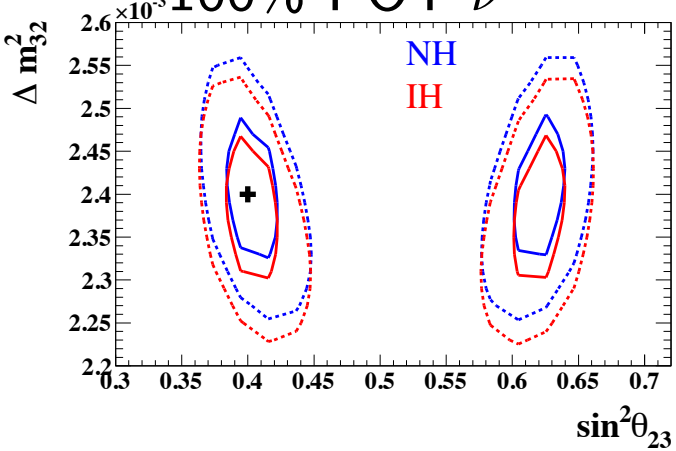
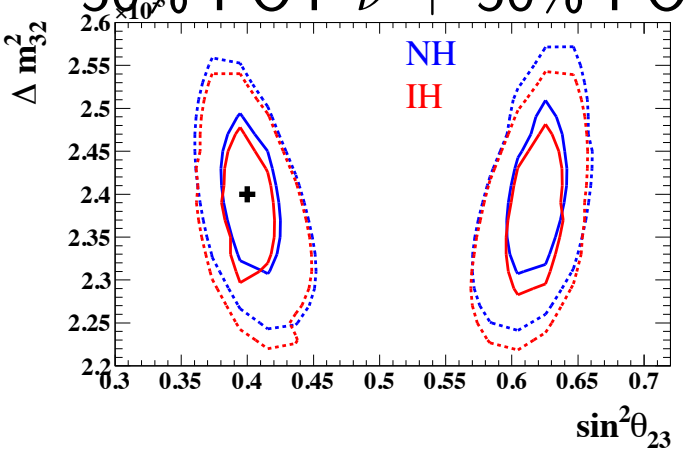
100% POT ν



50% POT ν + 50% POT $\bar{\nu}$



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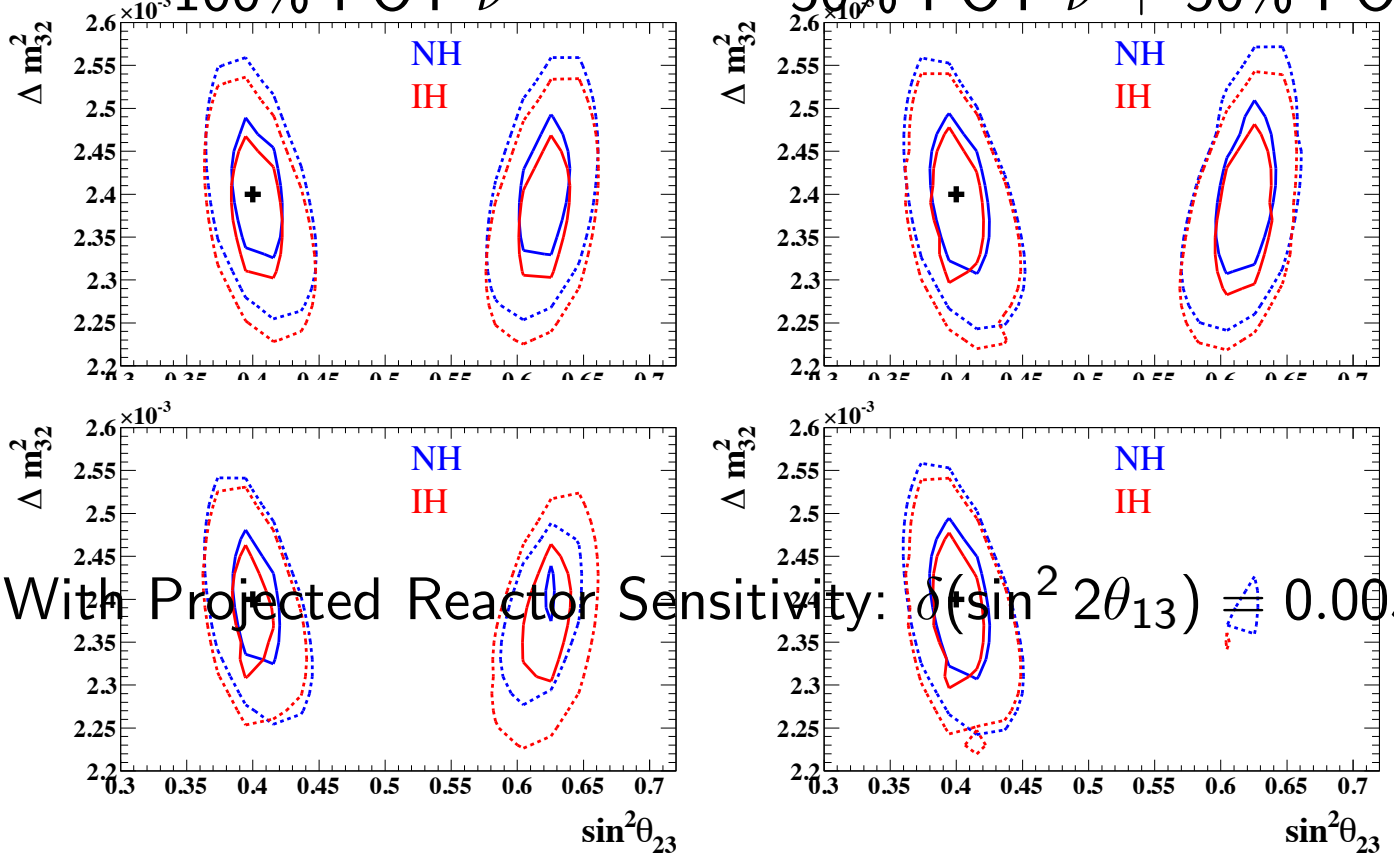


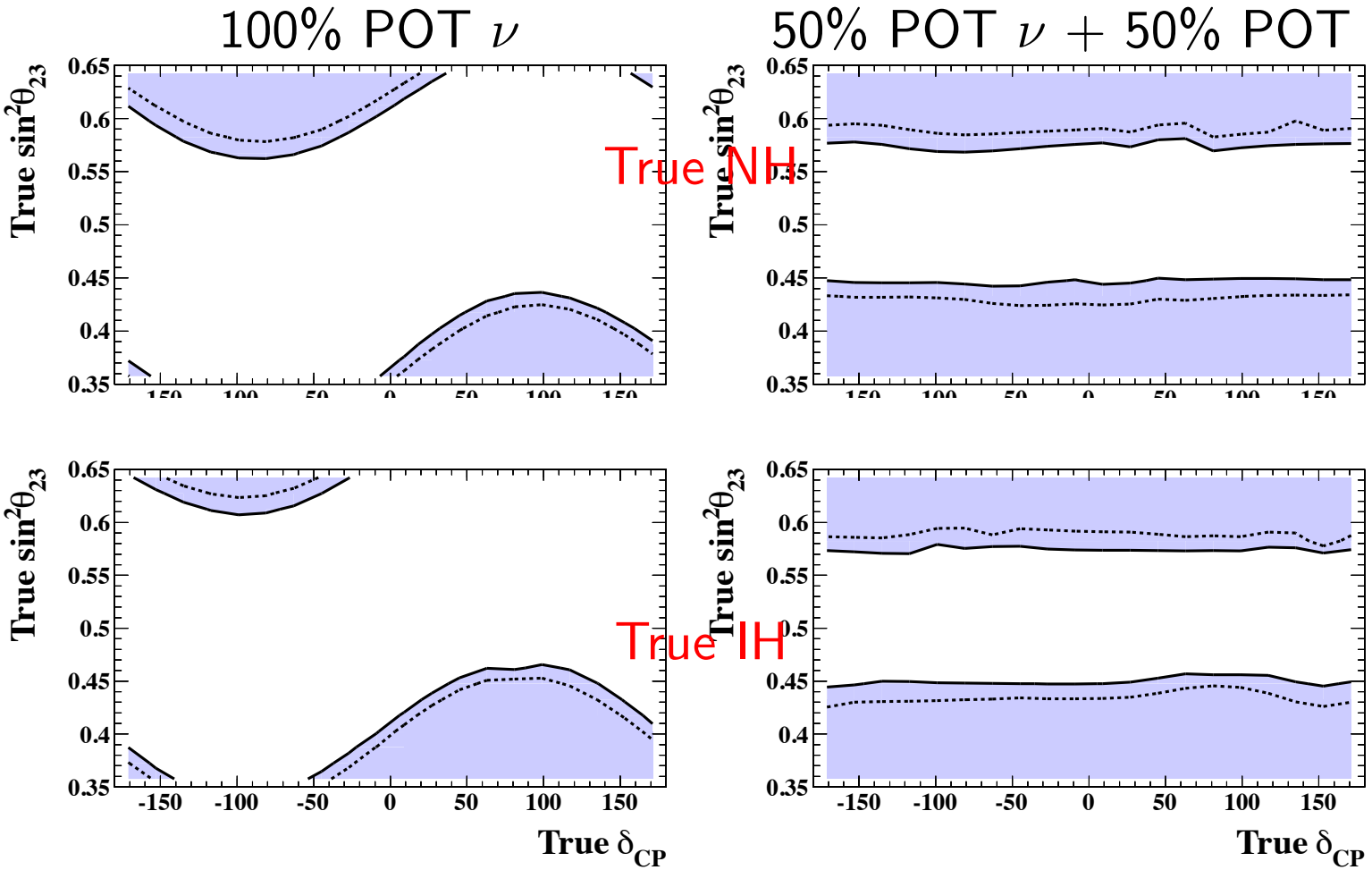
With Projected Reactor Sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

$\sin^2\theta_{23}$ octant nearly determined!

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0°$, $\sin^2\theta_{23} = 0.4$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

θ_{23} Octant 90% C.L. Discrimination

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



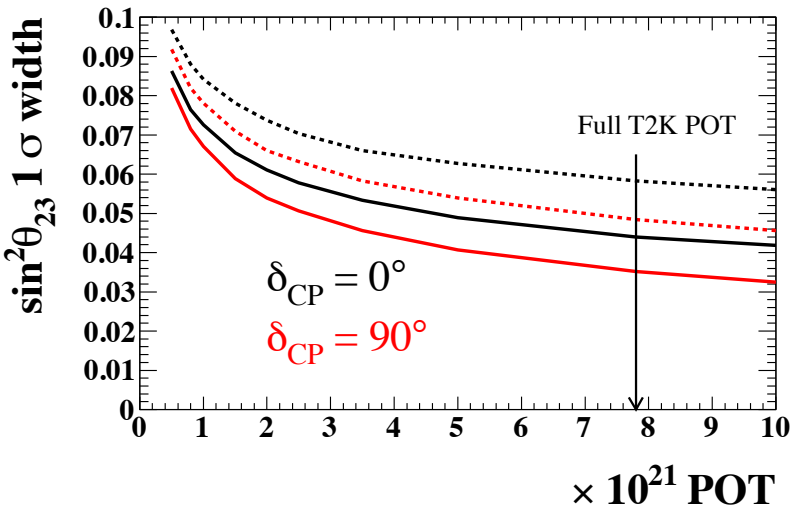
Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

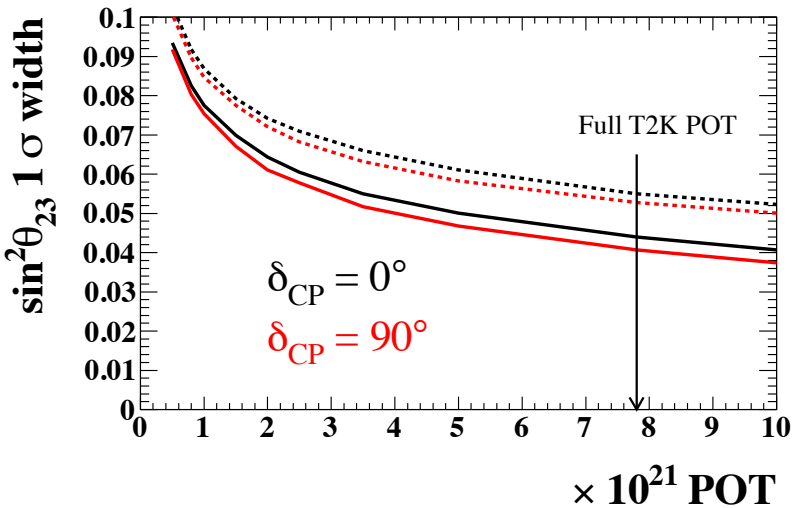
T2K $\sin^2\theta_{23}$ 1σ Precision vs. POT

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

100% POT ν



50% POT ν + 50% POT $\bar{\nu}$



- Statistical limit of 1σ precision is $\sim$0.045 at full POT
- Running with a combination of ν- and $\bar{\nu}$-mode slightly degrades sensitivity in some cases, although it also reduces the effect of systematic errors

Assuming true:

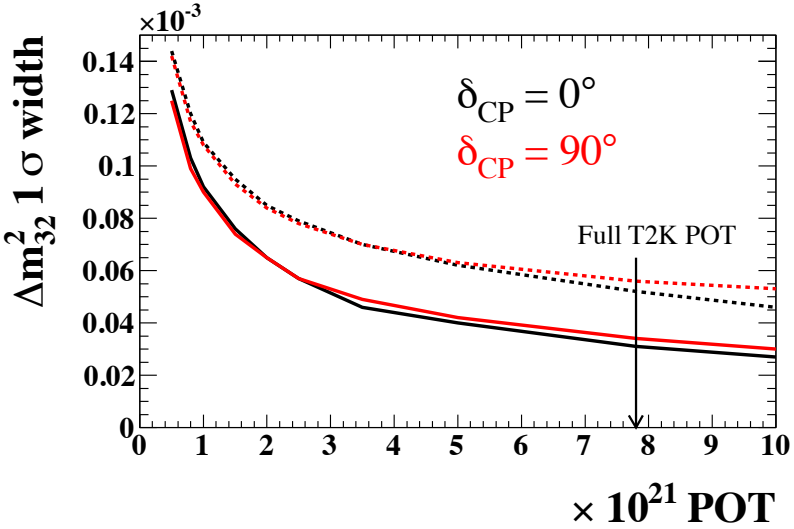
$$\sin^2 2\theta_{13} = 0.1,\ \sin^2\theta_{23} = 0.5,\ \Delta m^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2,\ \text{NH}$$

θ_{13} constrained by the projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

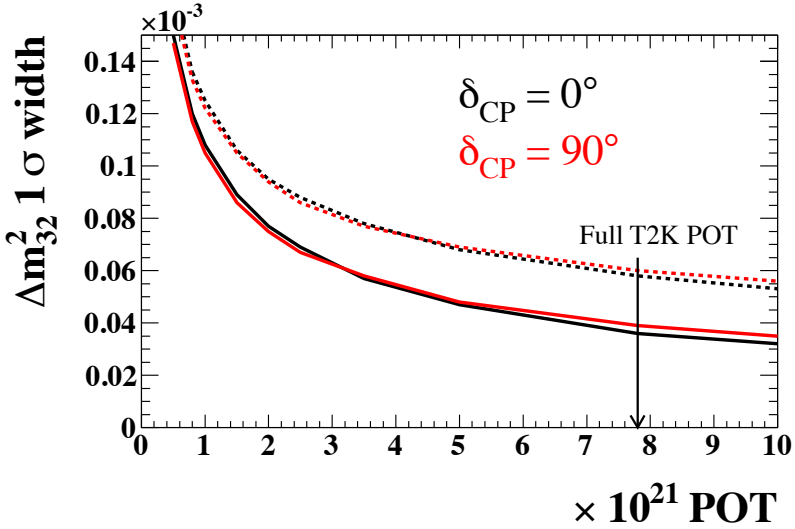
T2K Δm^2_{32} 1σ Precision vs. POT

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

100% POT ν



50% POT ν + 50% POT $\bar{\nu}$



- Statistical limit of 1σ precision is $\sim 4\times10^{-5}$ eV^2 at full POT
- Running with a combination of ν- and $\bar{\nu}$-mode very slightly degrades the Δm^2_{32} sensitivity, although sensitivity is largely independent of $\nu/\bar{\nu}$ running ratio

Assuming true:

$$\sin^2 2\theta_{13} = 0.1,\ \sin^2\theta_{23} = 0.5,\ \Delta m^2_{32} = 2.4\times10^{-3}\ \text{eV}^2,\ \text{NH}$$

θ_{13} constrained by the projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

Conclusion

T2K recent results and current status:

- 7.5σ ν_e appearance observation
- ν_μ disappearance results for both θ_{23} octants
  - Results assuming $\sin^2 2\theta_{13} \neq 0$
  - θ_{23} octant dependence of disappearance analysis results

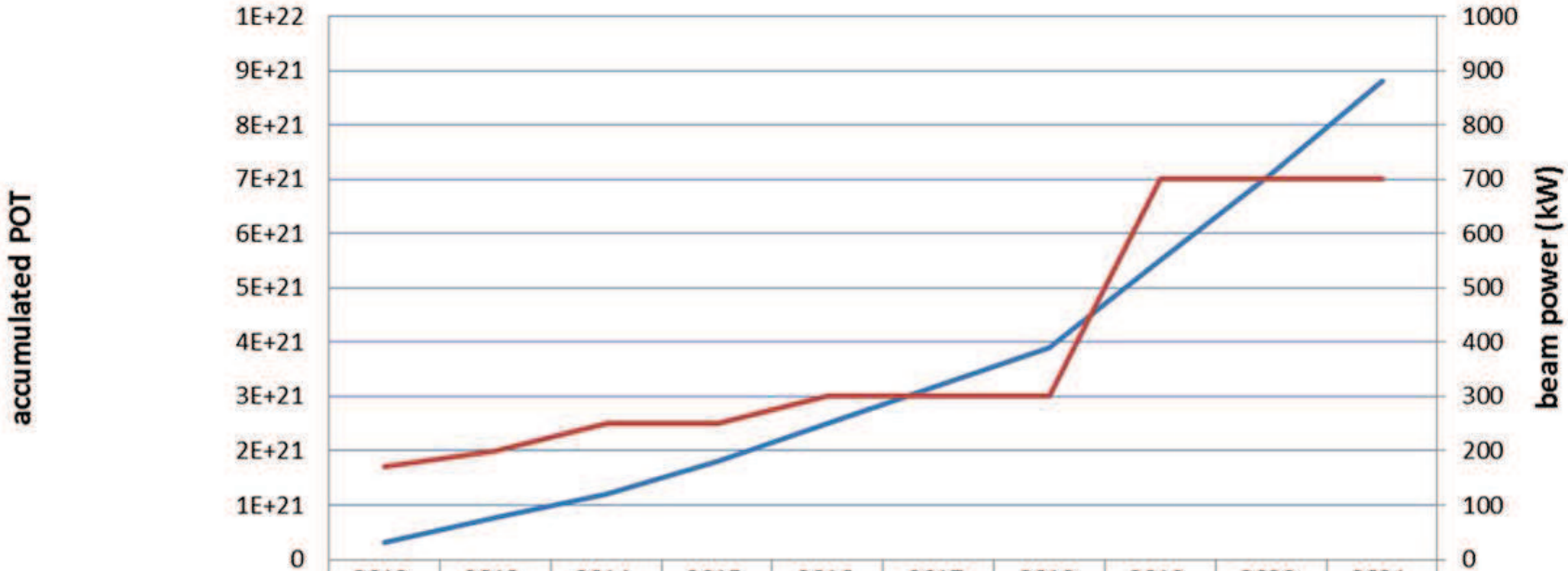
T2K expected sensitivity at 7.8×10^{21} POT:

- At the full statistics, T2K may have sensitivity to constrain δ_{CP} and determine the θ_{23} octant
- T2K strategy (ν- vs. $\bar{\nu}$-mode) is still to be decided
  - Will be decided based on input from these case studies
  - Information about accelerator status and development also needed

Backup Slides

T2K POT Accumulation Scenario

Possible scenario based on the J-PARC accelerator upgrade plan



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
accumulated POT	3.1E+20	7.8E+20	1.2E+21	1.8E+21	2.50E+21	3.20E+21	3.90E+21	5.50E+21	7.10E+21	8.80E+21
beam power	170	200	250	250	300	300	300	700	700	700