NEUTRINO OSCILLATIONS AND WHAT THEY HAVE TO OFFER IN THE NEAR FUTURE

CP violation and Mass Hierarchy reach, sooner and later

Jenny Thomas, Tau2016, Beijing

PLAN FOR THE DISCOVERY OF THE MASS HIERARCHY AND CP VIOLATION IN THE NEUTRINO SECTOR

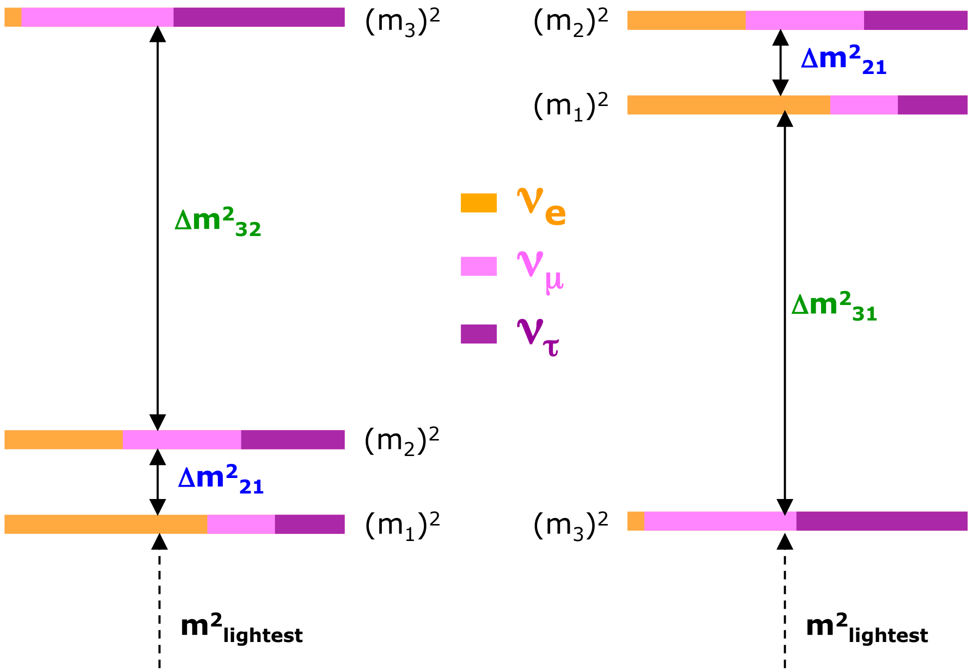
- The Present Knowledge
  - Post Neutrino 2016
- The Near Future
  - T2K, NOνA
- The Further Future
  - JUNO
- The Far Future
  - PINGU, DUNE

Shamelessly showing slides from neutrino 2016: P.Vahle(NOνA), A.Marrone(global fits), G.Ranucci(JUNO), J.Koskinen(PINGU) and ICHEP 2016:K.Iwamoto(T2K) also D.Cowen(PINGU), V.Paolone(DUNE), A.Cabrera (Double Chooz)

REMINDER OF THE QUESTIONS

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Normal hierarchy



- Three light neutrinos
- Mixing probability modified by mass squared differences
- δ_{CP} and the mass ordering are still unknown but within reach
- s_{23} now limiting next steps

REMINDER OF THE ANSWERS SO FAR….

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

Known

(pre-ν2016)

δm^2	2.4%
Δm^2	1.8%
$\sin^2\theta_{12}$	5.8%
$\sin^2\theta_{13}$	4.7%
$\sin^2\theta_{23}$	$\sim 9\%$

Unknown

CP-violating phase δ

Octant of θ_{23}

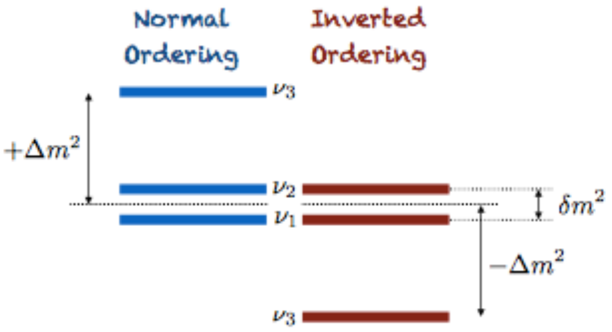
Mass Ordering → $\mathrm{sign}(\Delta m^2)$

[Dirac/Majorana neutrinos, Majorana phases, absolute mass scale]

In this talk

$$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$$

Mass Ordering = sign of Δm^2



REMINDER OF THE APPROACH

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Looking at disappearance of ν_μ (or ν_e disappearance)

$$1 - P(\nu_\mu \to \nu_\mu) = (C_{13}^4 \sin^2 2\theta_{23} + S_{23}^2 \sin^2 2\theta_{13}) \sin^2 \Phi_{32}$$

- First term depends on $\sin^2 2\theta_{23}$
- Second term depends on θ_{13} but also $\sin^2\theta_{23}$
- This means there is information in here about the octant of θ_{23} but its weak

REMINDER OF THE APPROACH

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Searching for electron neutrino **appearance** tells us about $\sin^2\theta_{13}$, mass hierarchy and δ_{CP}

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

$$\cancel{+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta_{CP} - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}}$$

CPV →

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta_{CP} \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

$$\cancel{+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta_{CP}) \sin^2 \Phi_{21}}$$

$$\cancel{-8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31}},$$

- Running with anti-neutrinos changes sign of CPV term

REMINDER OF THE APPROACH

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\boxed{e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}\boxed{e^{-i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Leading term now relies on **$\sin^2\theta_{23}$**, and **a**, related to density of electrons in the earth, leads to dependence on sign of Δm^2_{31}

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

~~$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta_{CP} - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$~~

CPV

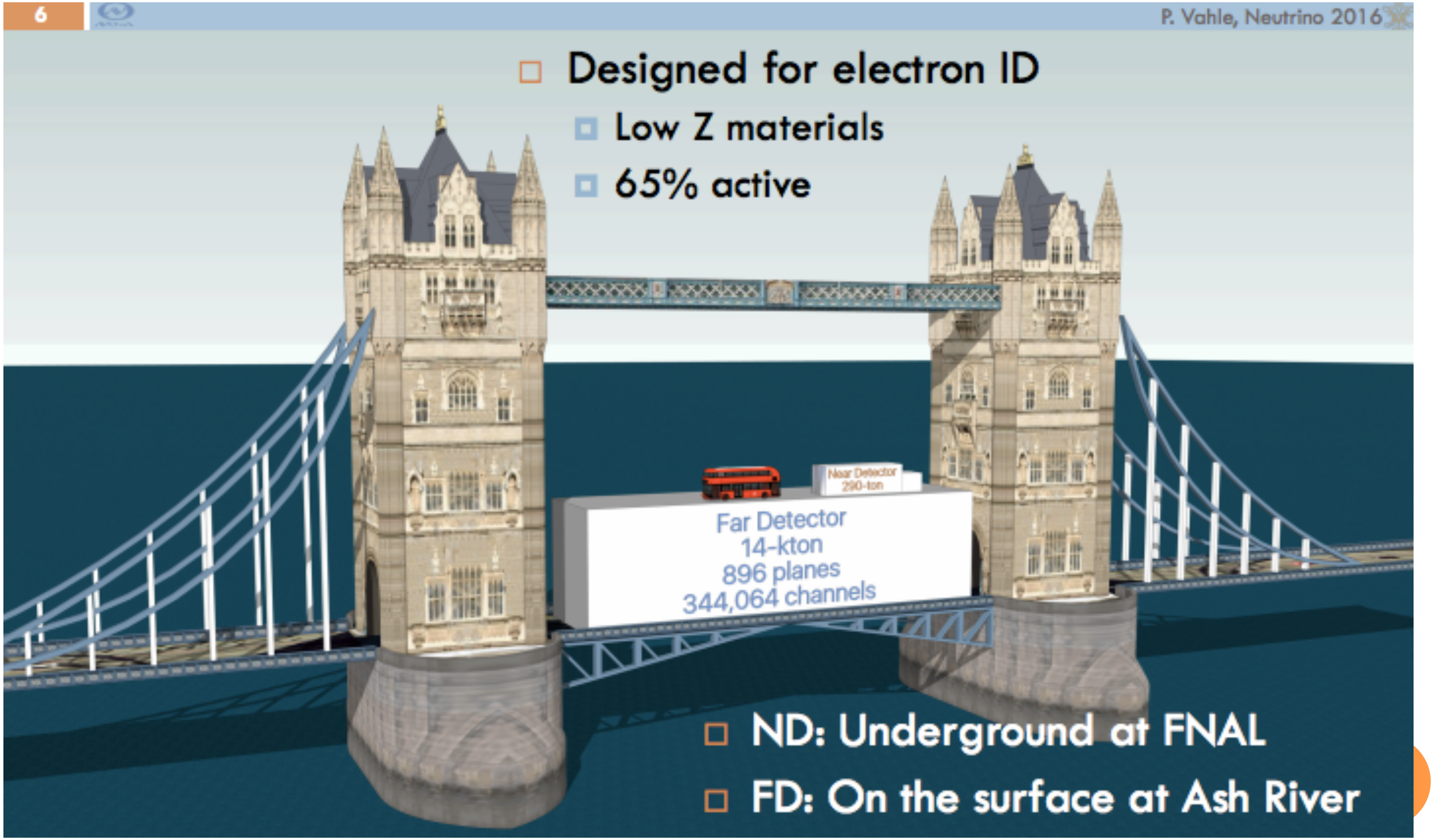
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} \boxed{S_{23}} \sin\delta_{CP} \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

~~$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta_{CP}) \sin^2\Phi_{21}$~~

~~$-8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31}$~~,

- Combining appearance and disappearance measurements tells us about the octant

AT NEUTRINO 2016, LONDON
NOvA



- Designed for electron ID
  - Low Z materials
  - 65% active

- ND: Underground at FNAL
- FD: On the surface at Ash River

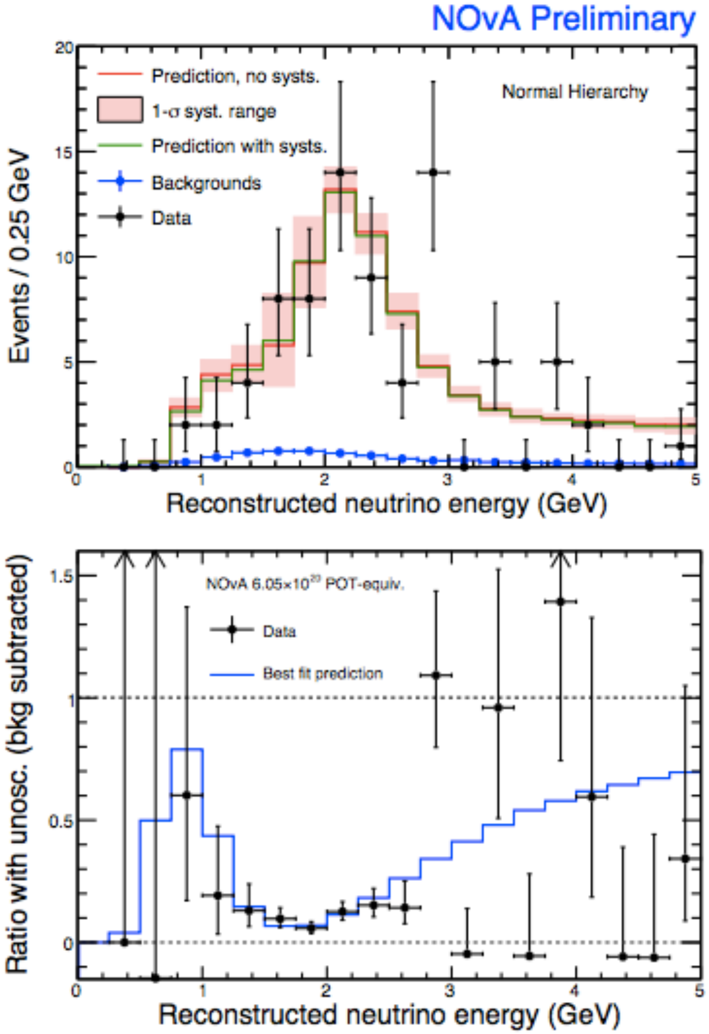
New kid on the block, first appearance at a Neutrino conference with data!

AT NEUTRINO 2016, LONDON
NOVA

ν_μ disappearance

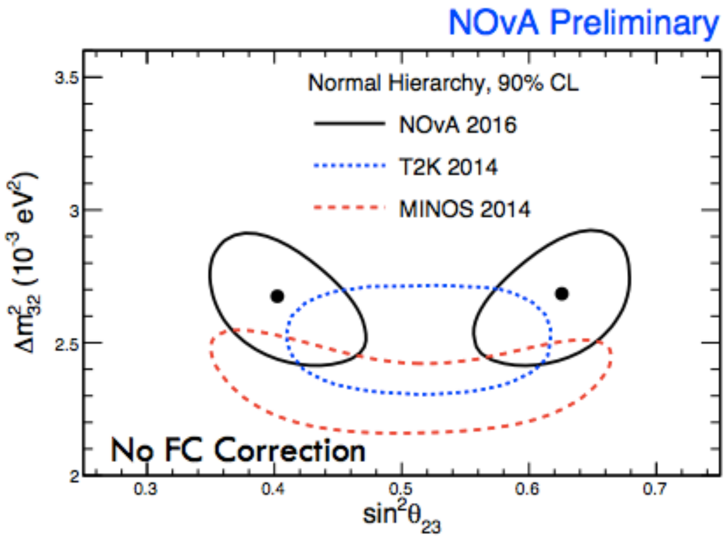
- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

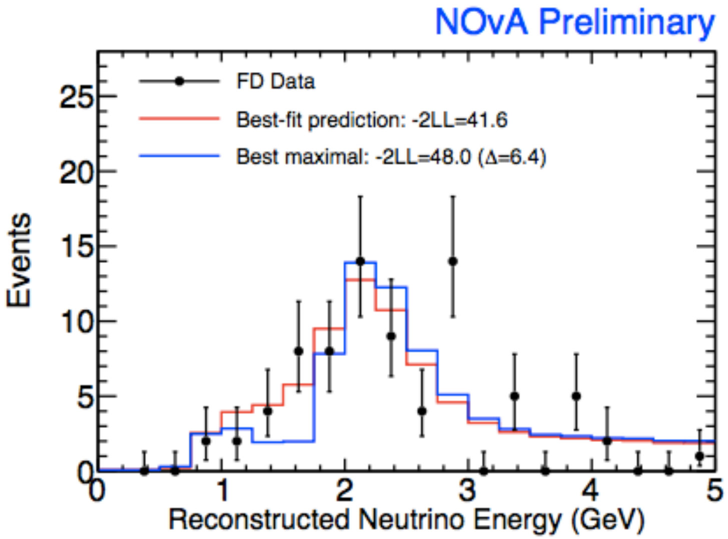
χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



AT NEUTRINO 2016, LONDON
NOVA

- Only looking at disappearance of $\nu_{\mu,}$ its not maximal at 2.5σ ! octant is degenerate…more about that later





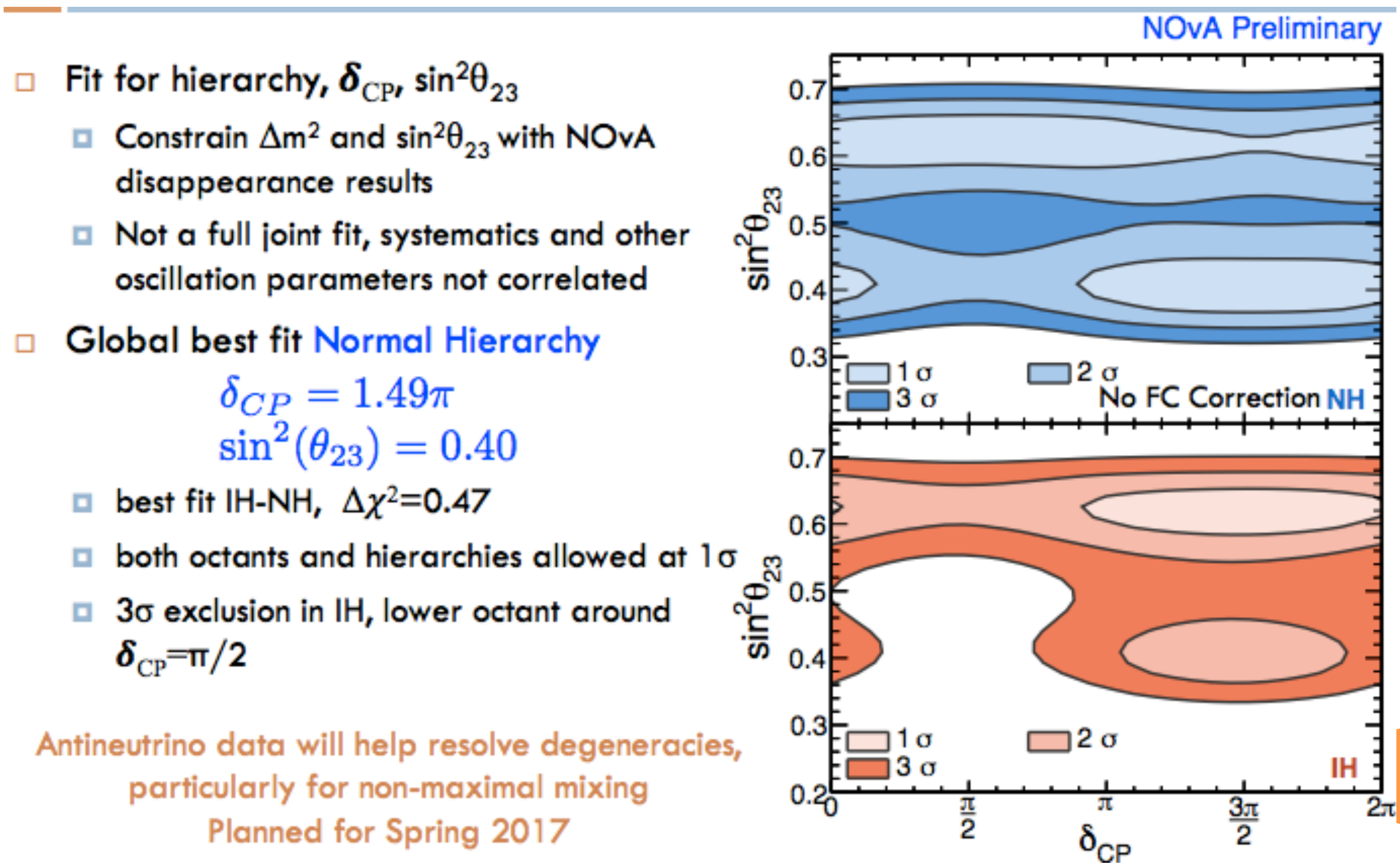
Best Fit (in NH):

$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

AT NEUTRINO 2016, LONDON
NOVA



- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

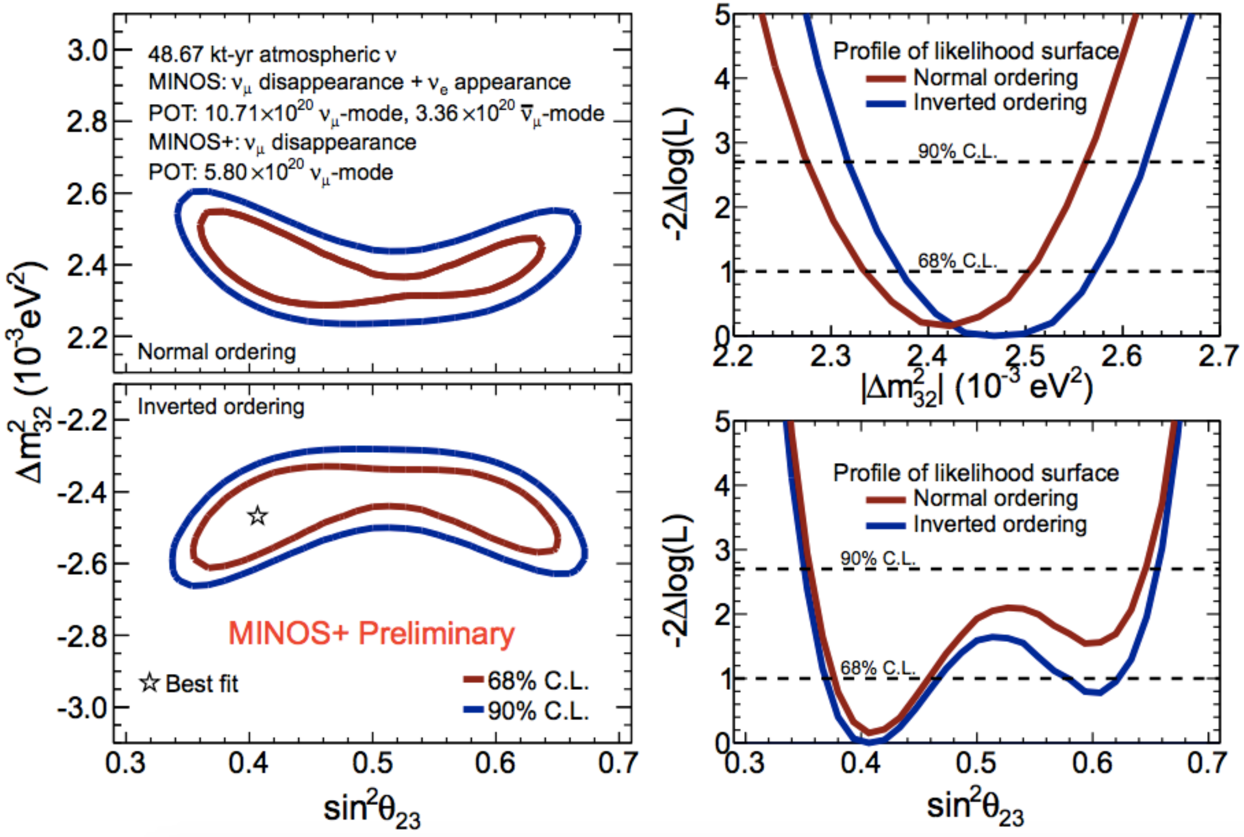
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around δ_{CP}=π/2

Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017

AT NEUTRINO 2016, LONDON
MINOS/MINOS+

- Combination of disappearance and appearance, slightly disfavours higher octant



$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted} \end{cases}$$

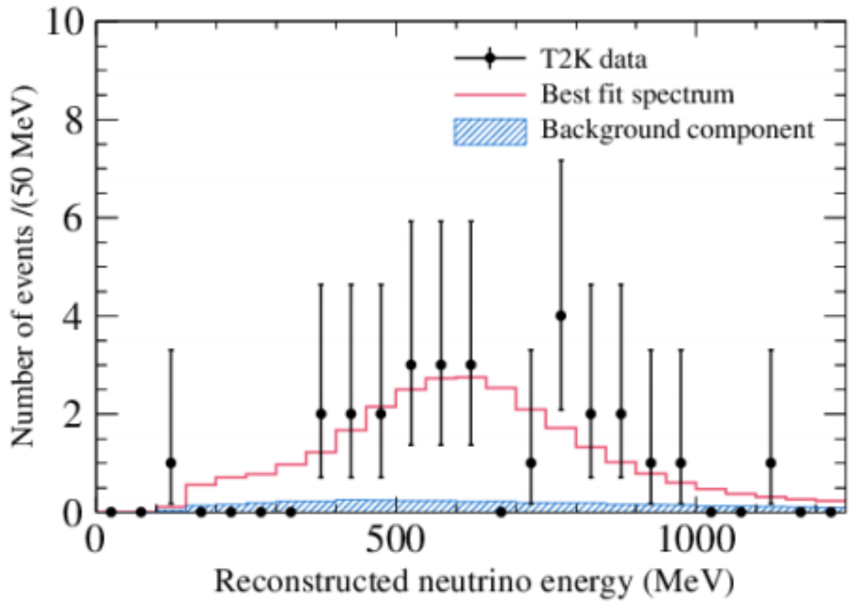
$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\,(90\%\ \text{C.L.}) & \text{Normal} \\ 0.35\text{–}0.66\,(90\%\ \text{C.L.}) & \text{Inverted} \end{cases}$$

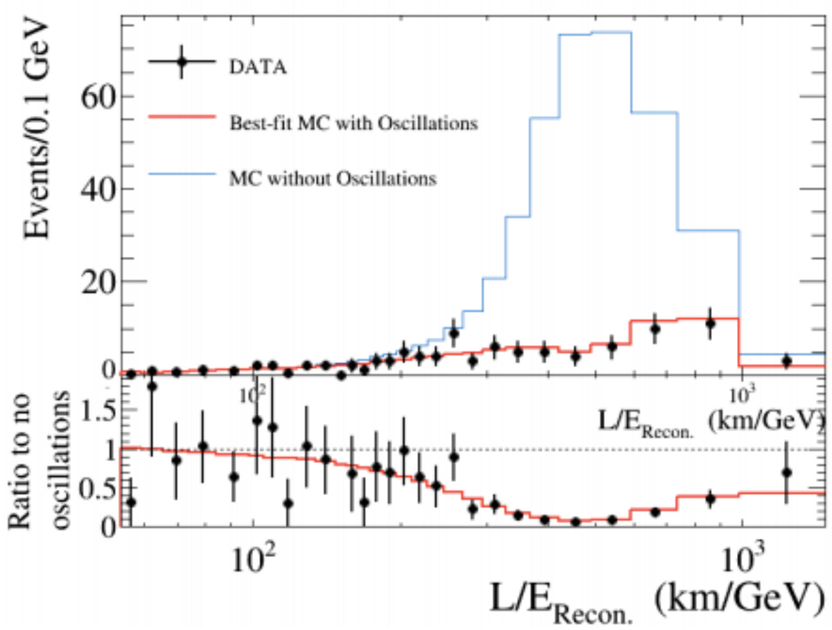
WHICH OCTANT? THE NEW PARAMETER OF INTEREST!

- Up until now, all data consistent with maximal mixing
  - Octant doesn’t matter!
- NOνA (and MINOS/MINOS+) show non-maximal mixing evidence
- MINOS/MINOS+ has a very slight preference for lower octant
- So what does T2K say?

AT NEUTRINO 2016, LONDON
T2K

- Mixing is maximal at T2K





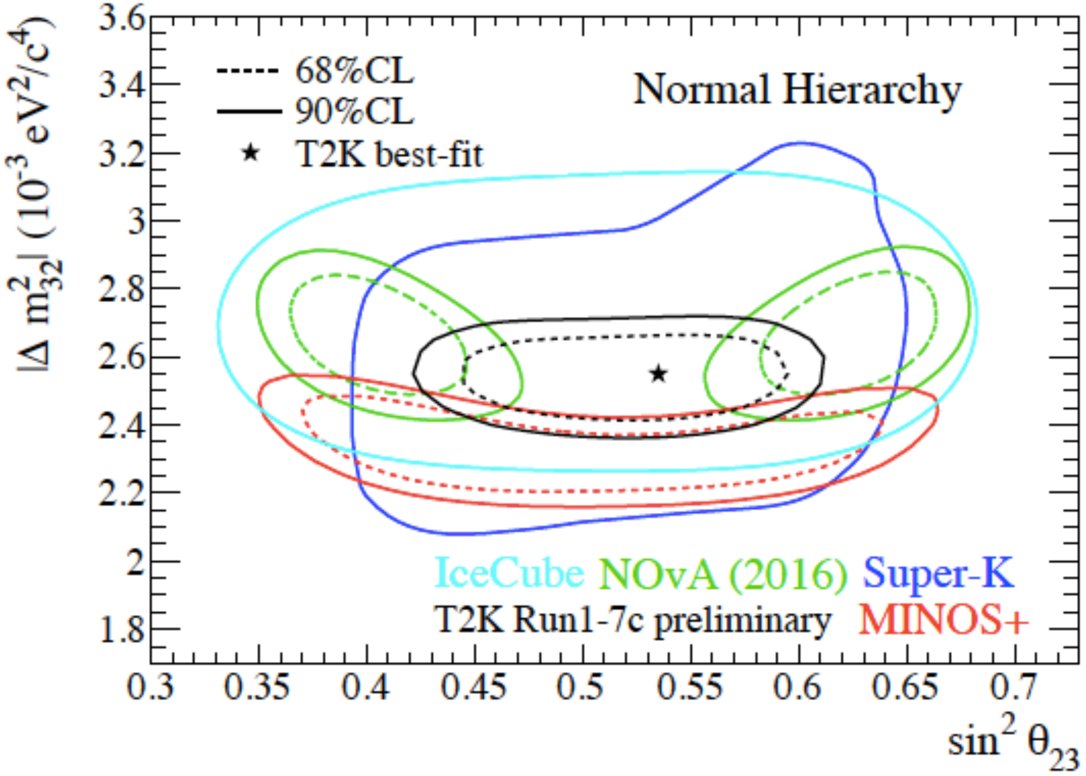
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

$$|\Delta m^2_{32}| = (2.51 \pm 0.11) \times 10^{-3} \mathrm{eV}^2/c^4$$

AT ICHEP 2016, CHICAGO

- T2K with anti-neutrinos, the tension mounts!

- Consistent with maximal mixing

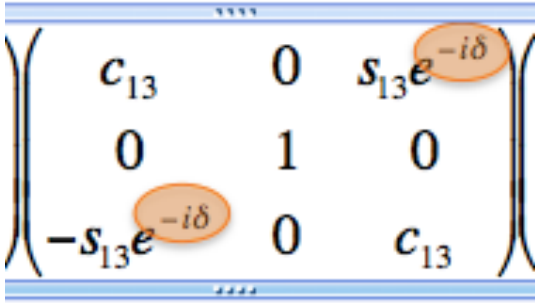


Daya Bay:
$|\Delta m^2_{ee}| = (2.45 \pm 0.08)\times 10^{-3} eV^2$
90% CL (NH)

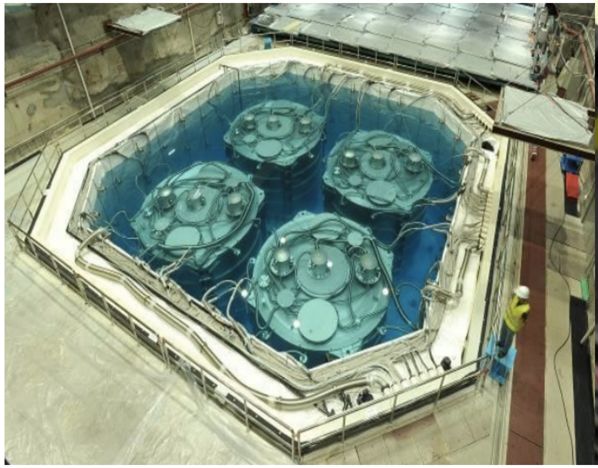
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\|\Delta m^2_{32}\|[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

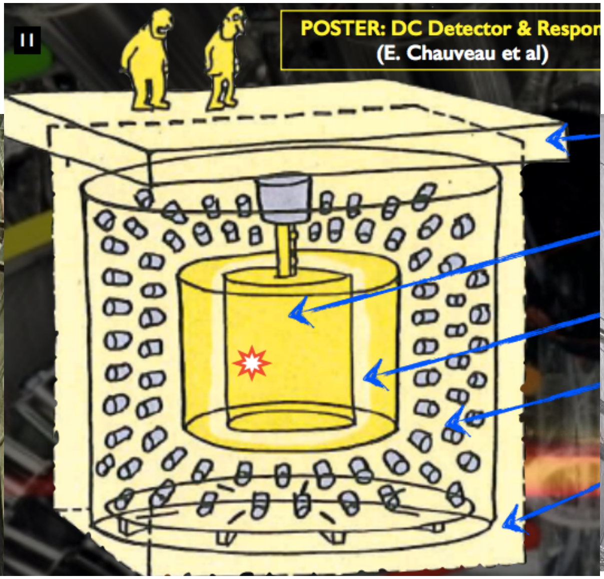
AT NEUTRINO 2016, LONDON REACTOR VALUES

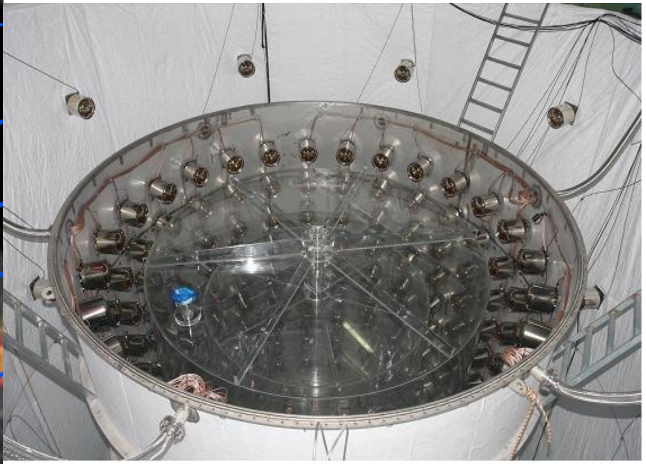
- Double Chooz : $\sin^2 2\theta_{13}$=0.111±0.018
- Daya Bay : $\sin^2 2\theta_{13}$=0.0841±0.0027±0.0019
- Reno : $\sin^2 2\theta_{13}$=0.082±0.009±0.006



$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$

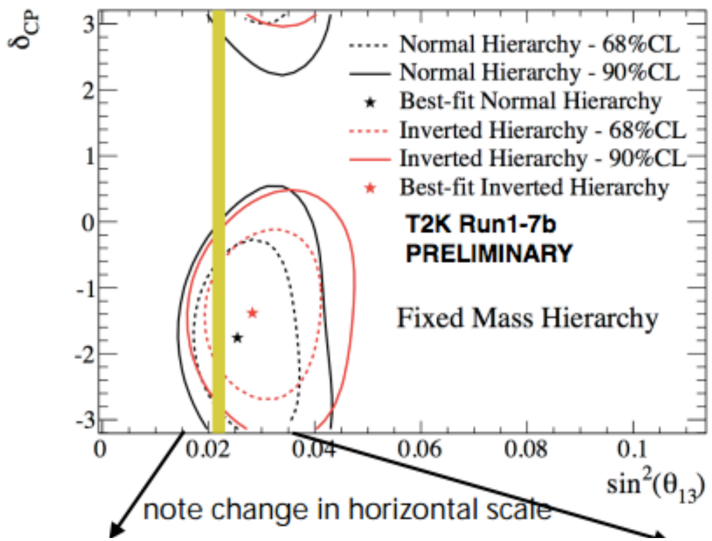






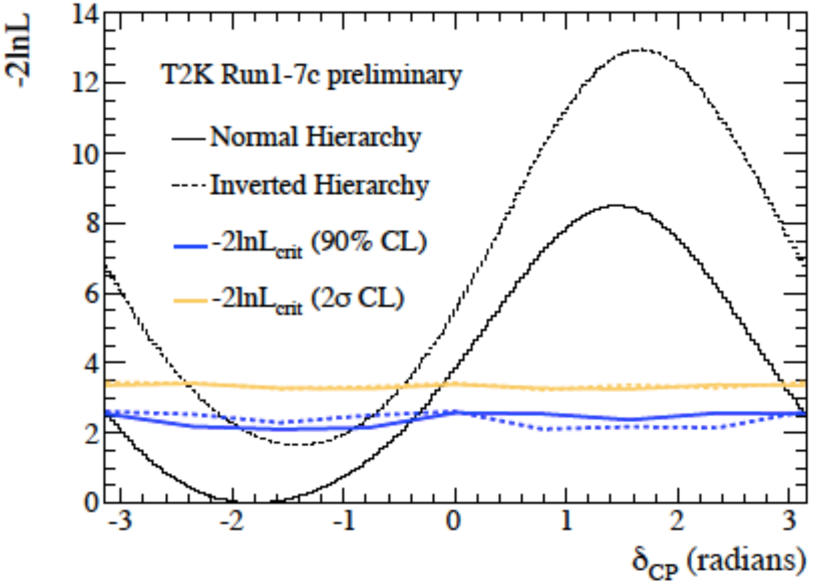
θ_{13} is the key to the Jaguar!!

MAXIMAL OR NON-MAXIMAL: A VERY BIG QUESTION : BACK TO T2K



note change in horizontal scale

Measurement (Data)



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

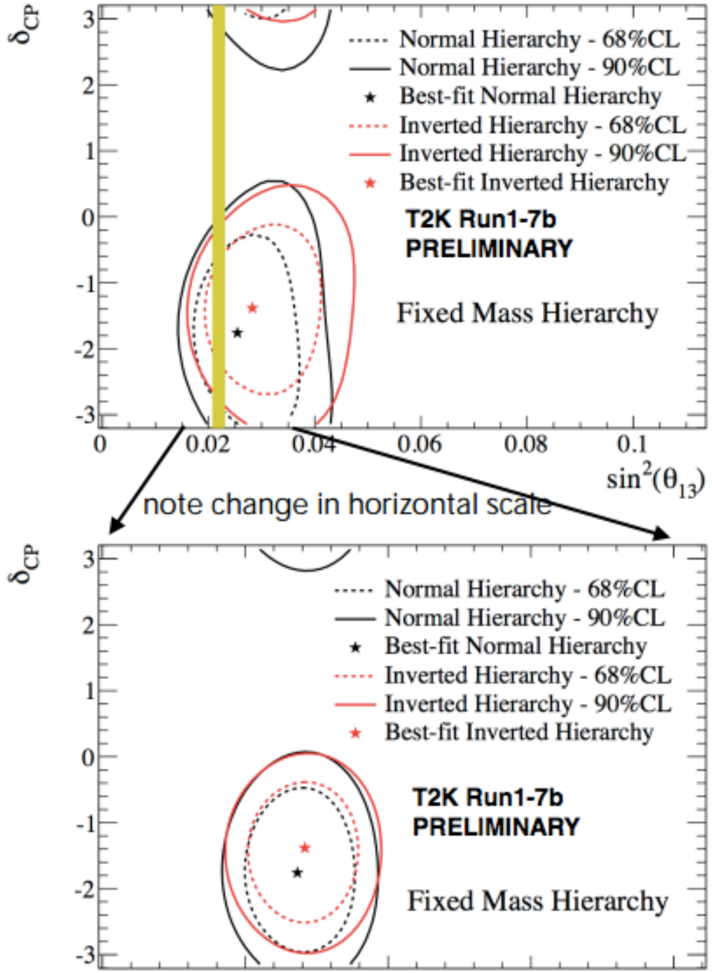
$$\cancel{+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}}$$

CPV →

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta_{CP} \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

MAXIMAL OR NON-MAXIMAL: A VERY BIG QUESTION : BACK TO T2K



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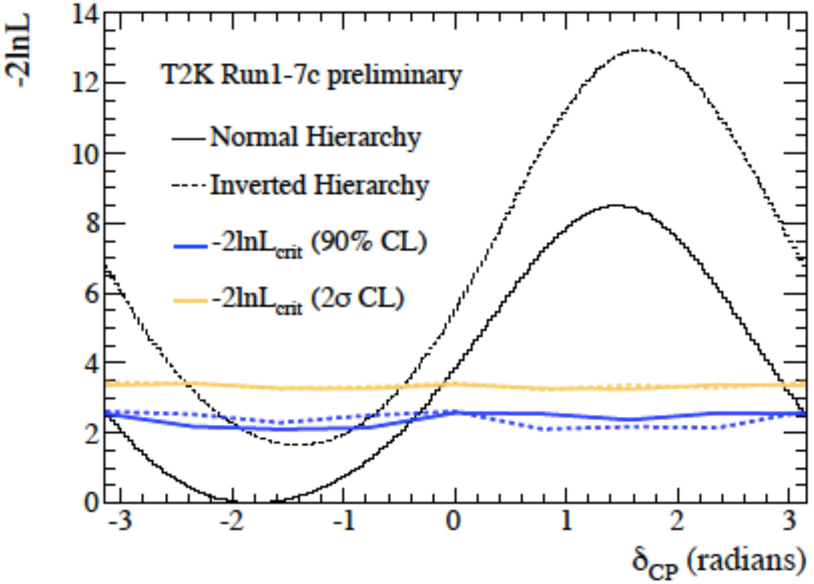
Measurement (Data)

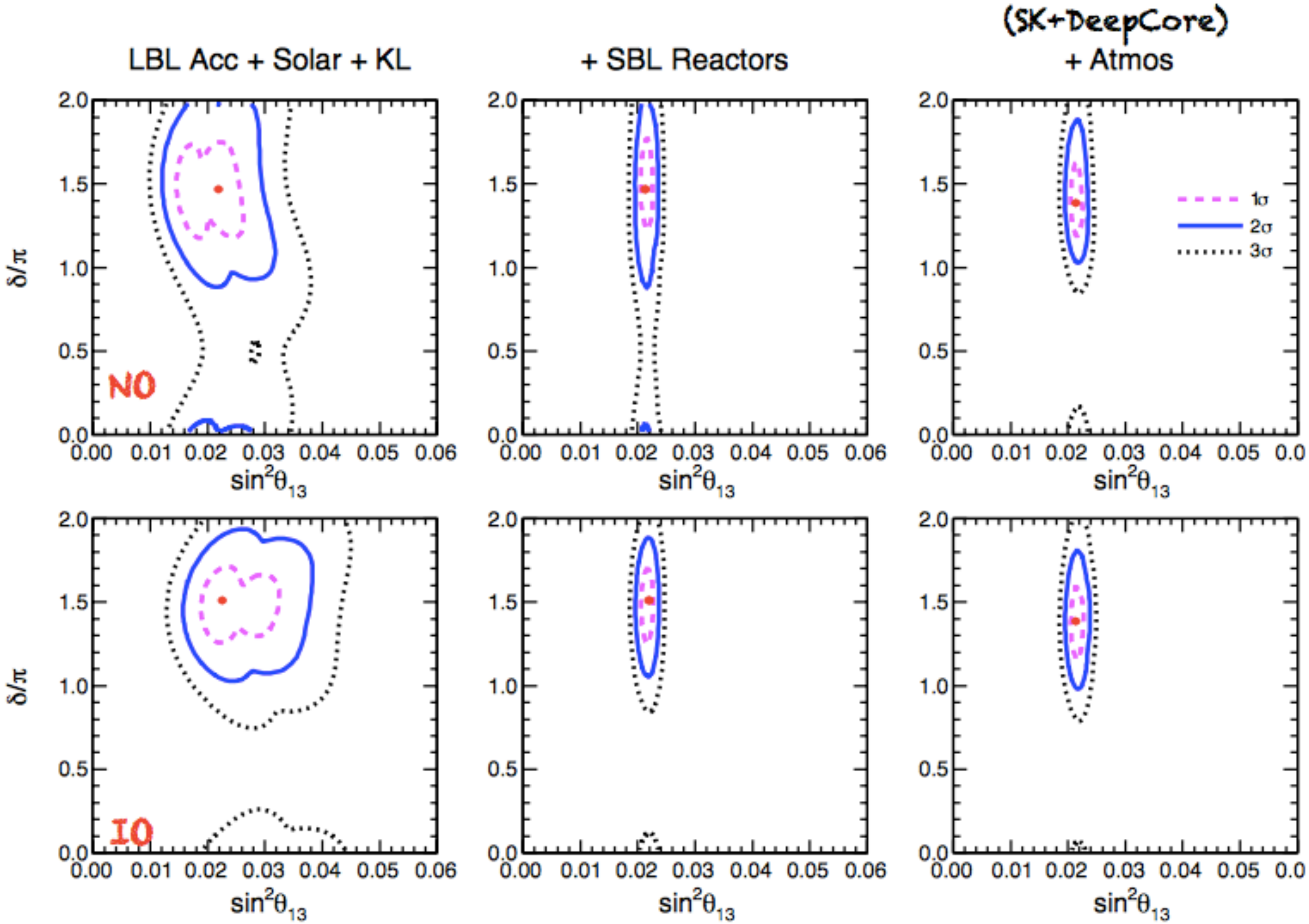


- T2K uncertainty on s^2_{23} is **very small** because its maximal
- This leads to significant reduction in δ_{cp} parameter space space

$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

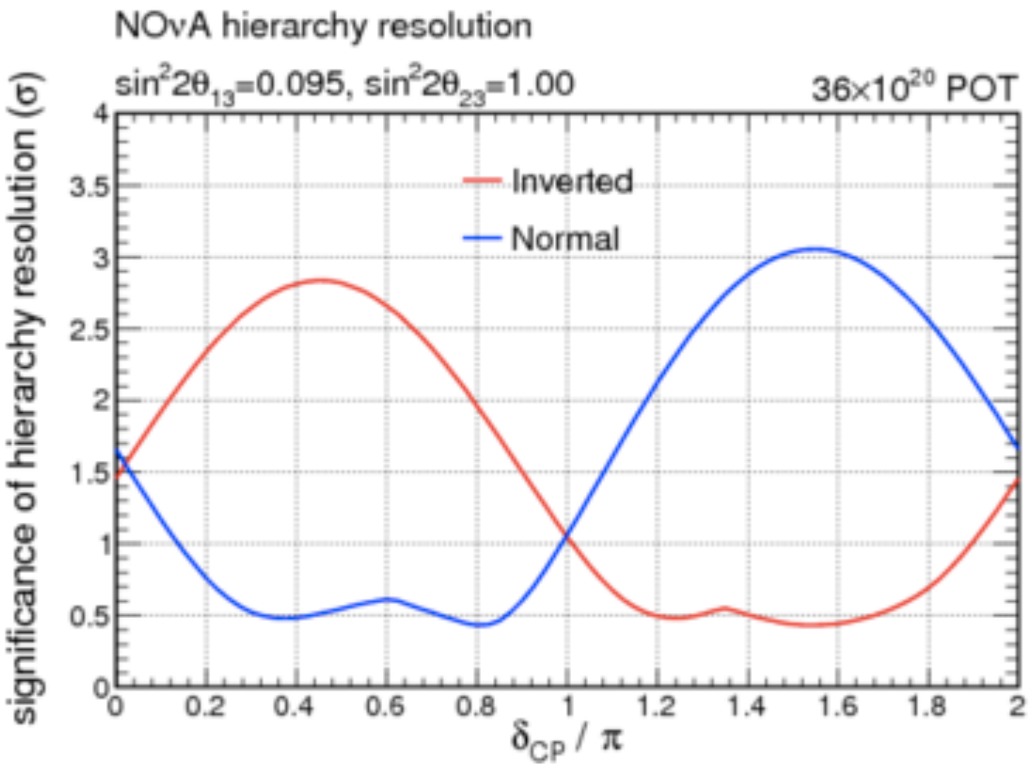
PRELIMINARY JOINT FIT IN REAL TIME! (A.MARRONNE ET AL.)

- Do we already know that δ_{cp} is not zero?



PROGNOSIS FOR MASS HIERARCHY AND CPV

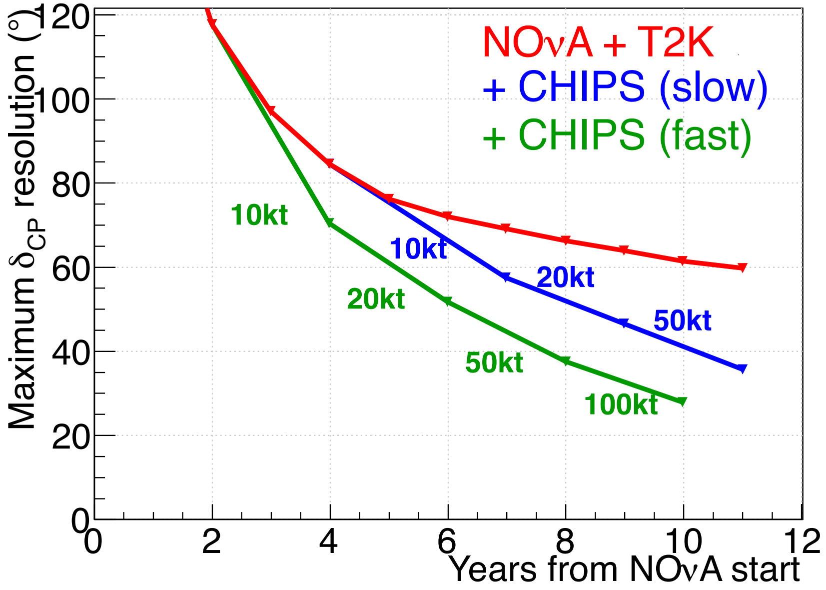
- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant (run until 2025)

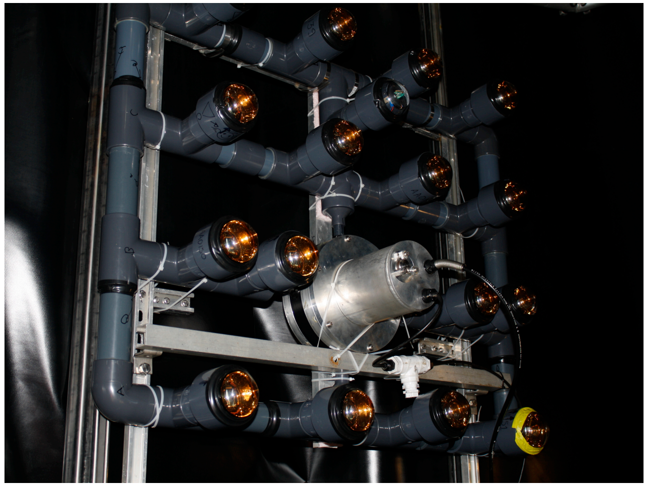


- NH, $\delta_{cp}>1$ is so far preferred
- MH could be determined to 3σ by 2022 by NOνA even if θ_{23} not maximal
- Sensitivities already somewhat overtaken by events

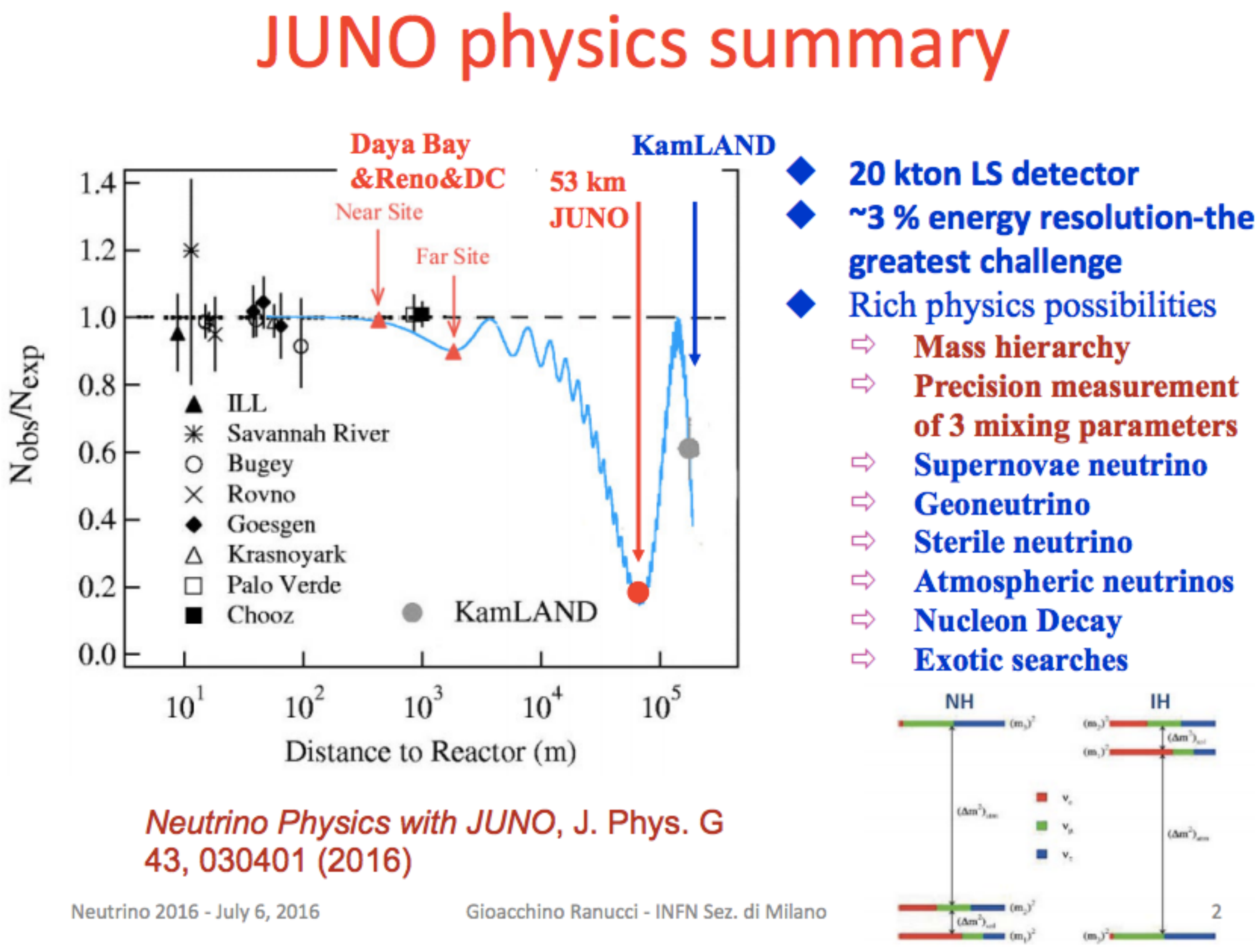
CHIPS

- 5-10kt WC detector will be deployed in NuMI beam (in N.Minnesota mine pit) in summer 2018
- Funded by ERC grant to UCL and Nikhef, and U.Wisconsin, Madison
- 7mrad off axis, will contribute to combined knowledge before 2022
- Innovative design allows detector to grow as more instrumentation becomes available
- Could point the way to affordable Mton in the future





THE FURTHER FUTURE, JUNO, 2022

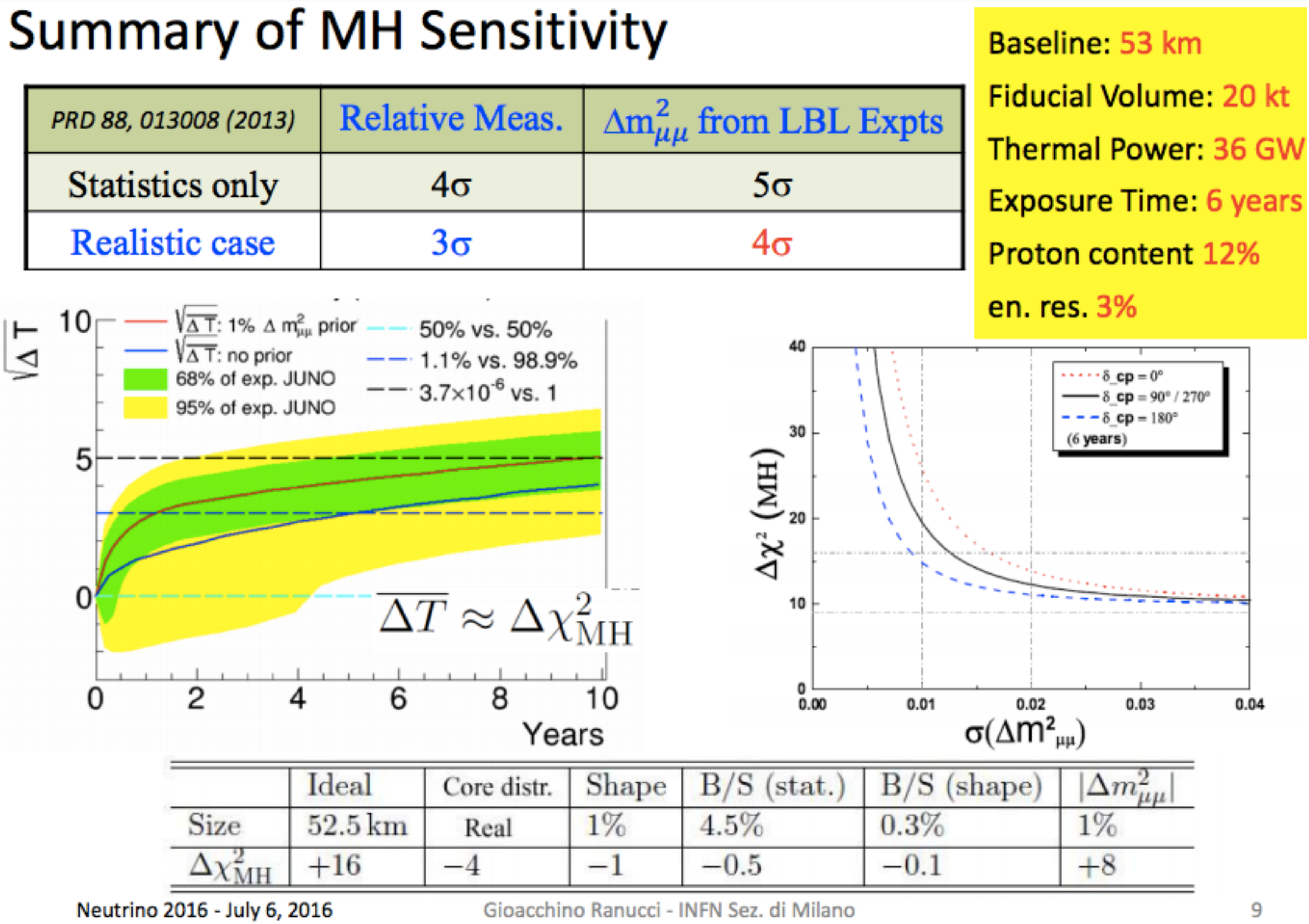


JUNO physics summary

- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

THE FURTHER FUTURE, JUNO, 2022



Summary of MH Sensitivity

PRD 88, 013008 (2013)	Relative Meas.	$\Delta m^2_{\mu\mu}$ from LBL Expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

Baseline: 53 km

Fiducial Volume: 20 kt

Thermal Power: 36 GW

Exposure Time: 6 years

Proton content 12%

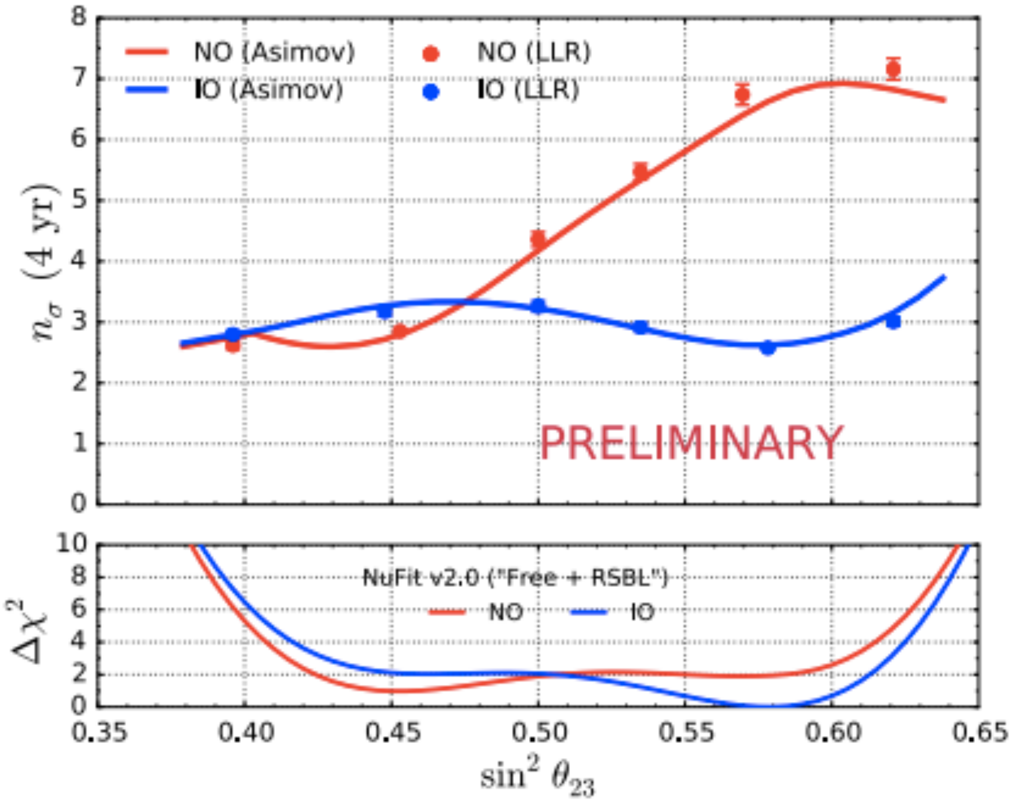
en. res. 3%

	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\mathrm{MH}}$	+16	−4	−1	−0.5	−0.1	+8

Could be fast: depends on error on $\Delta m_{\mu\mu}$!

PINGU

- Independent measurement 5 years from start date, 2017-2022?
- 3σ in 4 years, or 3 years with external prior



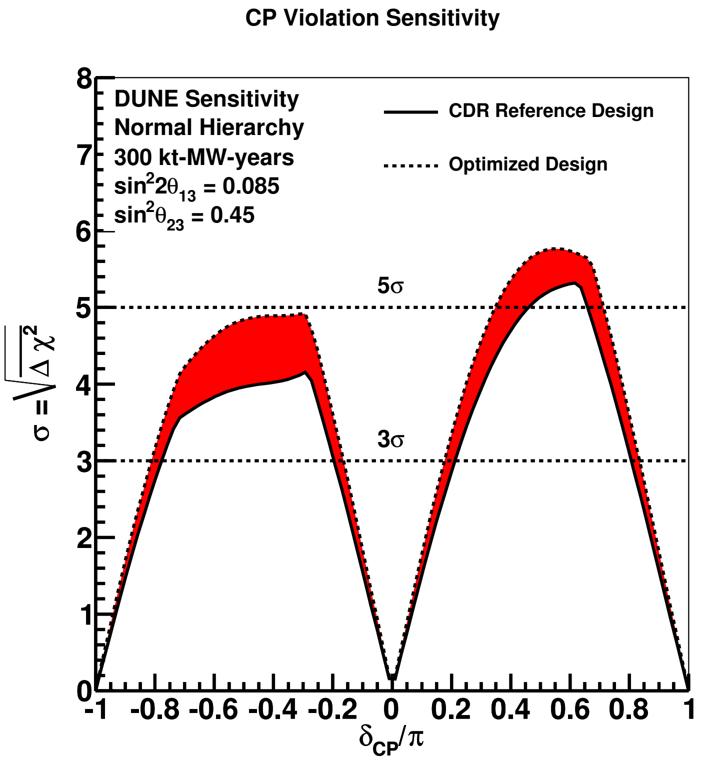
Fully deployed PINGU data only. Addition of partial deployment PINGU data and multi-year DeepCore data will improve sensitivity

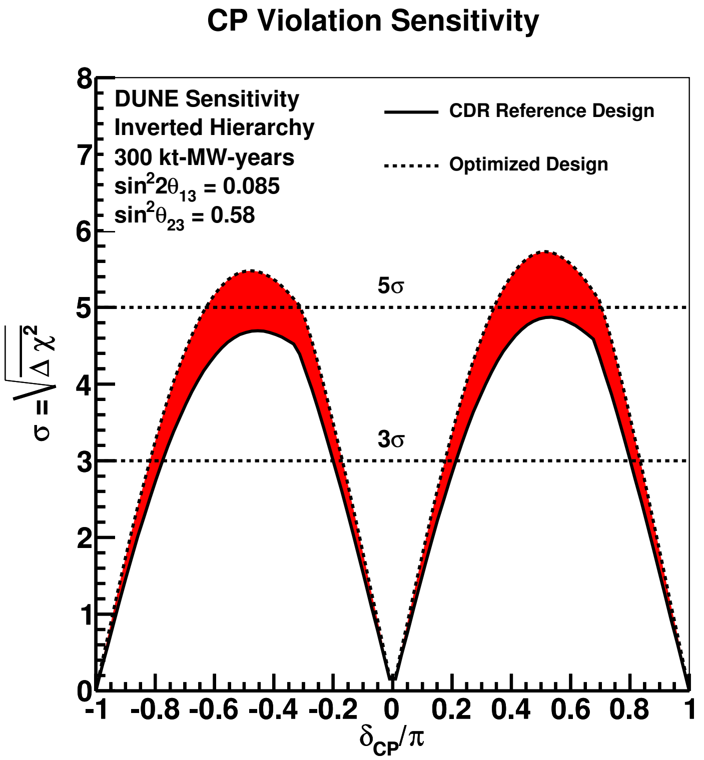
- Combination of signal in track and cascade channel
- Sensitivity from pseudo-data set based log-likelihood ratio (LLR) and Asimov analysis methods are in good agreement

DUNE Physics:
CP Violation Sensitivity

Sensitivity to CP Violation, after 300 kt-MW-yrs
(3.5+3.5 yrs x 40kt @ 1.07 MW)

(Bands represent range of beam configurations)

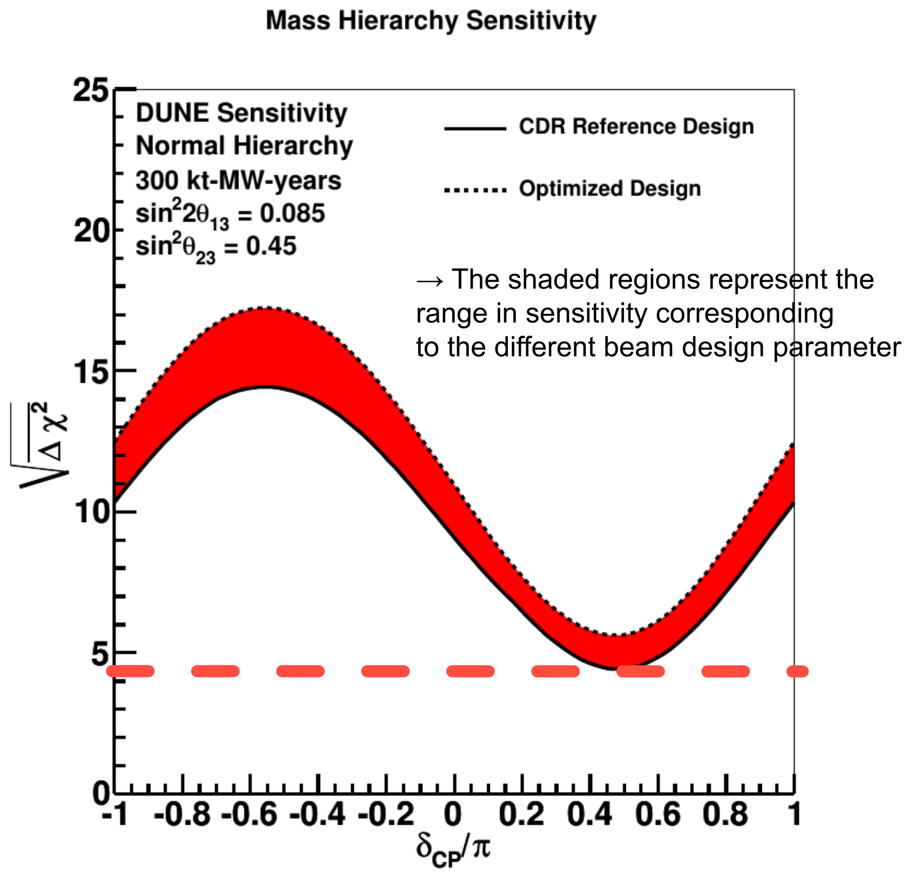

CP Violation Sensitivity


CP Violation Sensitivity

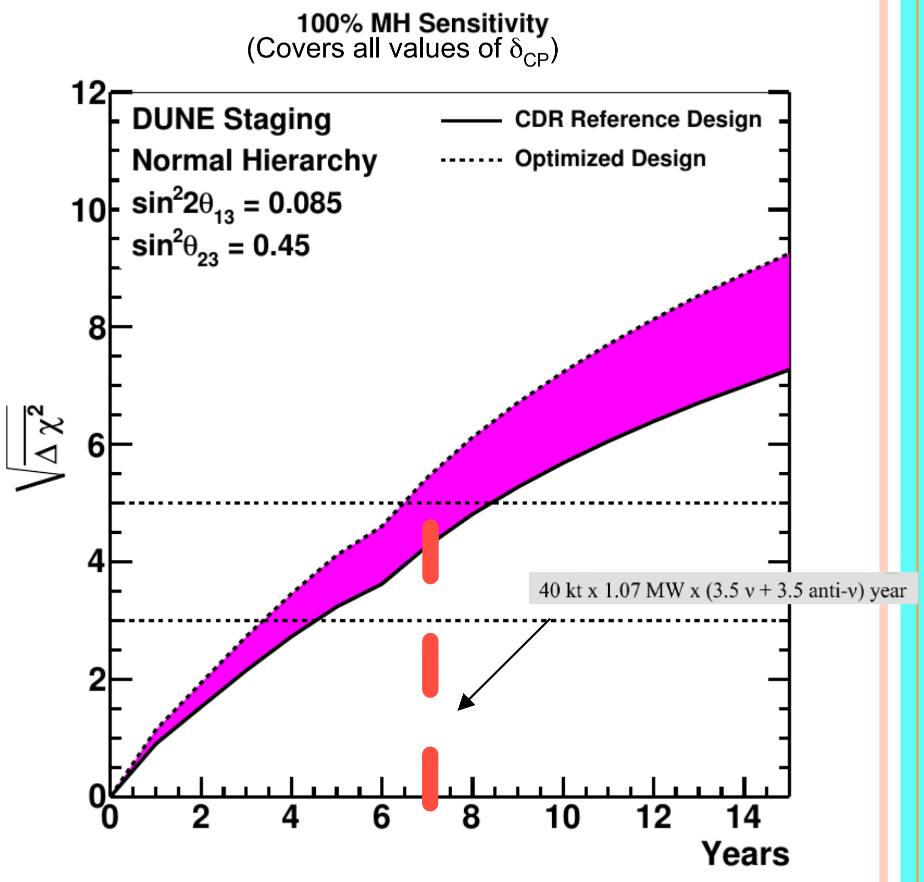
Official timeline : 2032 for this sensitivity

DUNE Physics: MH Sensitivity

Discrimination (between NH and IH) parameter as a function of the unknown δ_{CP} for an exposure of 300 kt·MW·year (40 kt·1.07 MW·7 years).


Mass Hierarchy Sensitivity

→ The shaded regions represent the range in sensitivity corresponding to the different beam design parameter


100% MH Sensitivity

(Covers all values of δ_{CP})

40 kt x 1.07 MW x (3.5 ν + 3.5 anti-ν) year

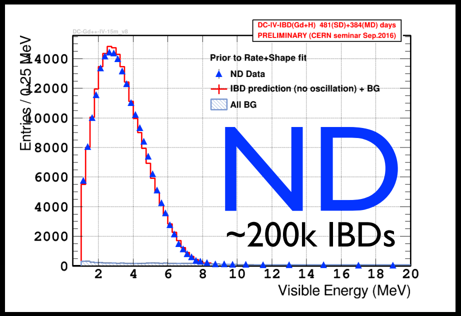
→ The minimum significance (the lowest point on the curve on the left) where the mass hierarchy can be determined any value of δ_{CP} as a function of years of running

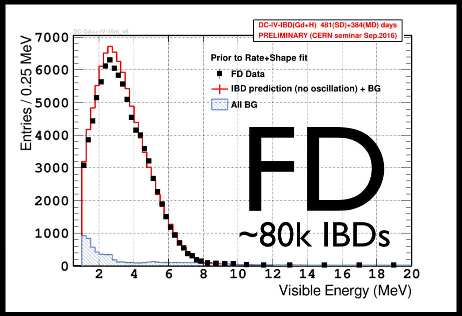
Official timeline : 2032 for this sensitivity

JUST WHEN WE THOUGHT EVERYTHING WAS SETTLED…..

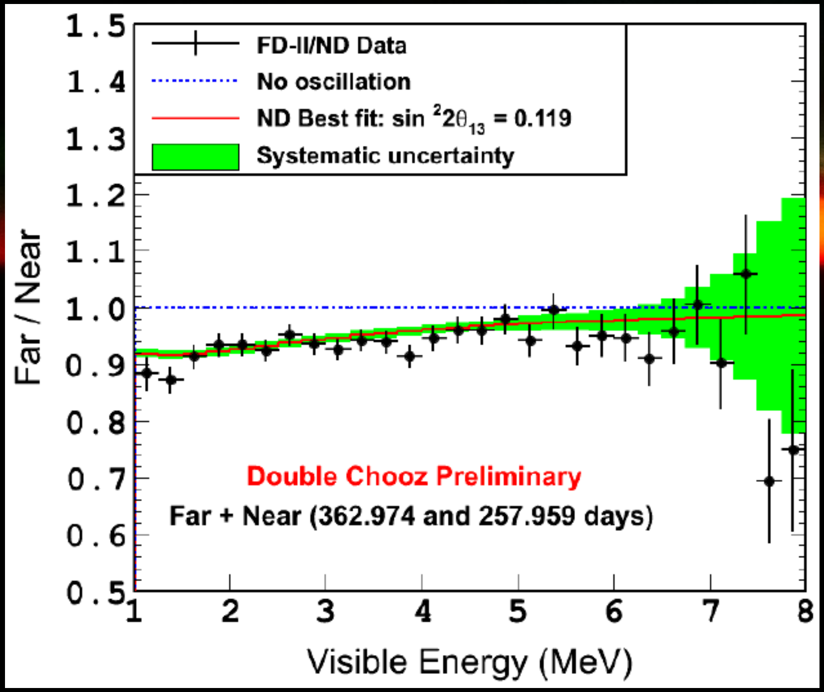
Yesterday, a new result from Double Chooz…..

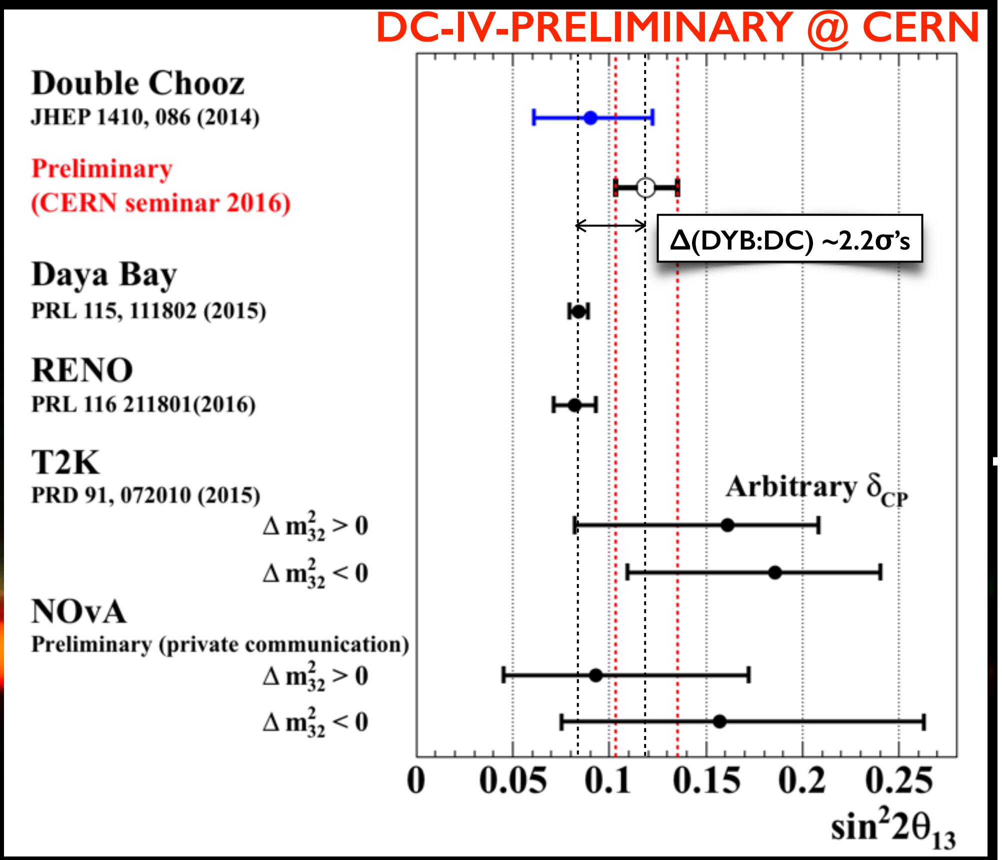
DC-IV PRELIMINARY results @CERN (Sept.2016)





3x SD-fits (MC) ⊕ MD-fit
(inter-detector correlations)





$$\sin^2(2\theta_{13})^{R+S}=(0.119\pm0.016)$$

(marginalised over $\Delta m^2=(2.44\pm0.09)eV^2$)

reactor-θ_{13} key for **CP-violation** & **mass hierarchy**→ **redundancy fundamental**

(DC pushing to resolve: improvements coming soon)

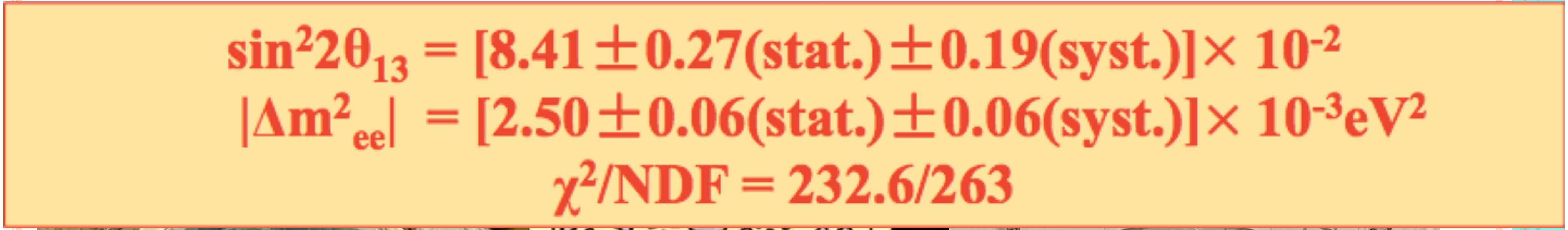
SUMMARY AND CONCLUSION

- The neutrino oscillation parameter list is being ticked off very fast!
- Each new neutrino conference leads to progress
- Up until today, it looked like things would be wrapped up very soon wrt δ_{cp}
  - Larger θ_{13} means significance of exclusion of δ_{cp} is less
  - Larger θ_{13} means reach of NOνA improved
  - Swings and roundabouts
- Personal feeling is that by 2022 we should know the MH, and we should know that $\delta_{CP} \neq 0$ at 3σ
- The following years should confirm this at 5σ

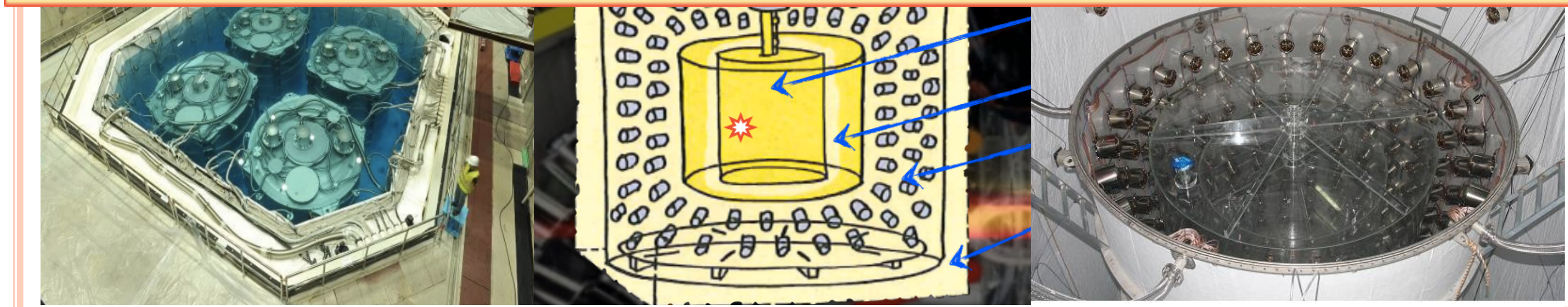
AT NEUTRINO 2016, LONDON

REACTOR VALUES

- Double Chooz : $\sin^2 2\theta_{13}=0.111\pm0.018$
- Daya Bay : $\sin^2 2\theta_{13}=0.0841\pm0.0027\pm0.0019$
- Reno : $\sin^2 2\theta_{13}=0.082\pm0.009\pm0.006$



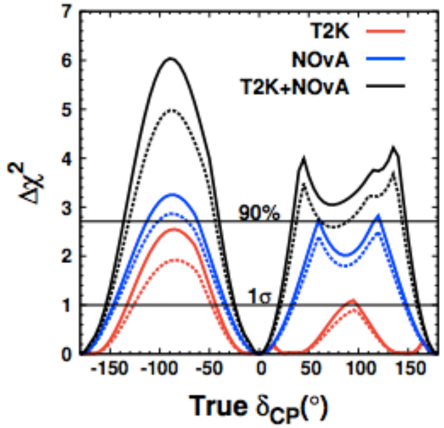
$$\sin^2 2\theta_{13} = [8.41\pm0.27(\text{stat.})\pm0.19(\text{syst.})]\times 10^{-2}$$
$$|\Delta m^2_{ee}| = [2.50\pm0.06(\text{stat.})\pm0.06(\text{syst.})]\times 10^{-3}\text{eV}^2$$
$$\chi^2/\text{NDF} = 232.6/263$$



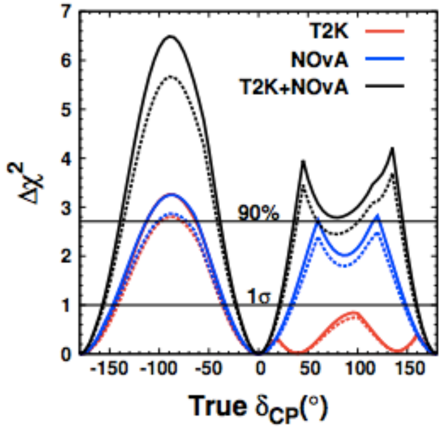
θ_{13} is the key to the Jaguar!!

PROGNOSIS

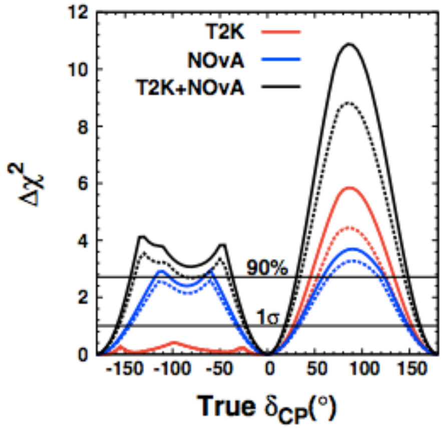
- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant



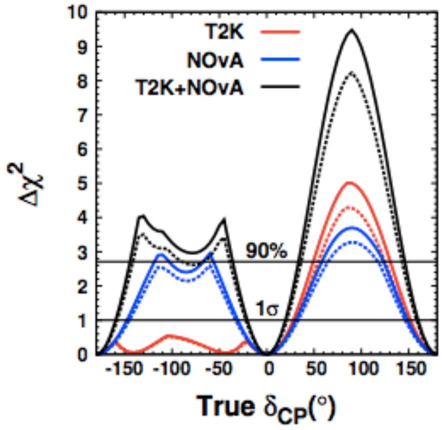
(a) 1:0 T2K, 1:1 NOνA ν:ν̄, NH



(b) 1:1 T2K, 1:1 NOνA ν:ν̄, NH



(c) 1:0 T2K, 1:1 NOνA ν:ν̄, IH

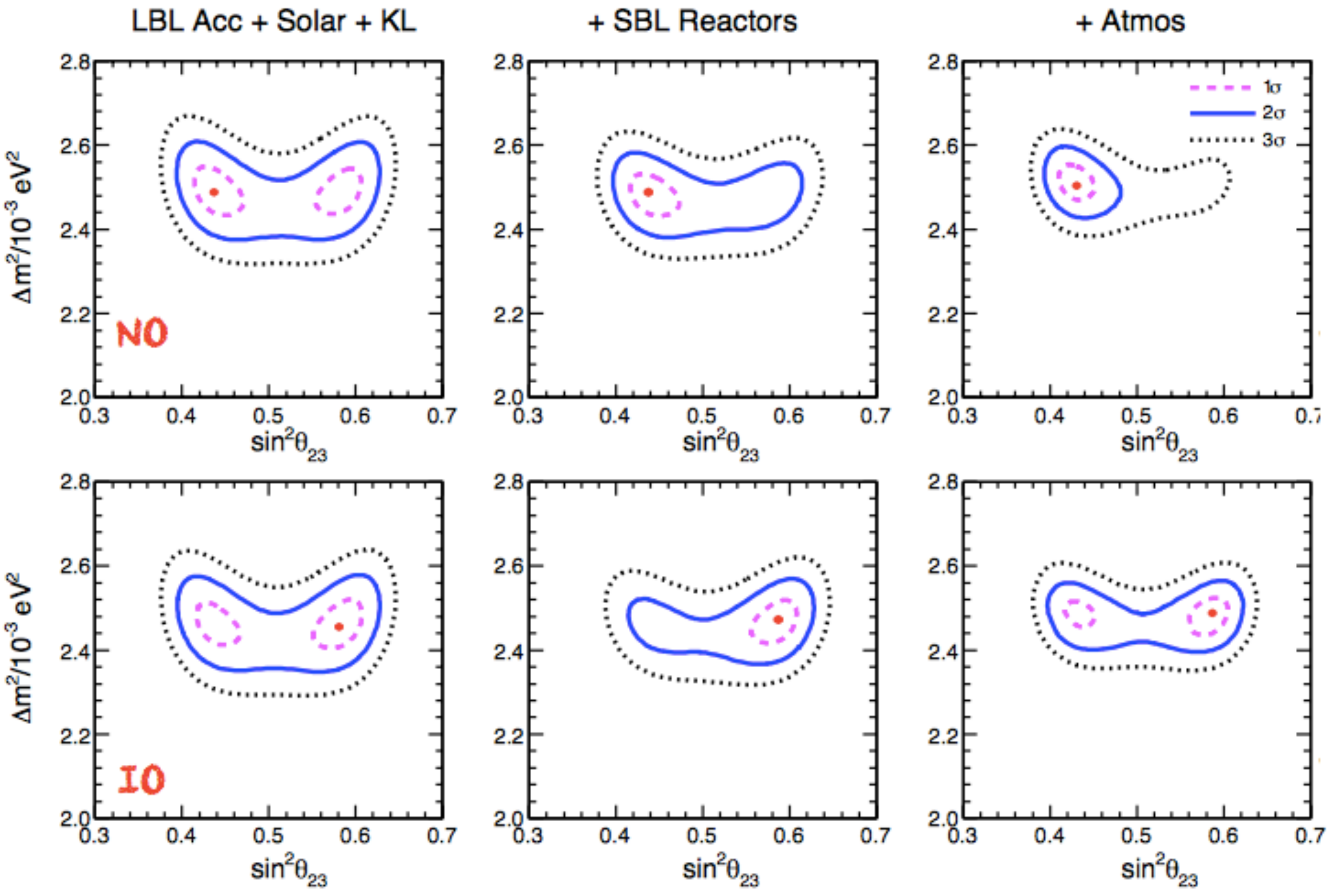


(d) 1:1 T2K, 1:1 NOνA ν:ν̄, IH

- Ultimate precisions depend on run strategy
- JPARC upgrade in 2018 is significant
- MH will likely be determined to >> 3σ by 2022 by combination

PRELIMINARY JOINT FIT IN REAL TIME! (A.MARRONNE ET AL.)

- Value of s^2_{23} still weakly constrained
- But joint fit doesn't resolve the real issue!



NOW TO THE FUTURE, 2027+7 YEARS