2012 Neutrino Oscillation Landscape and Near Term Future Experiments

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Future long-baseline neutrino experiments

IoP ½-day Meeting at QMUL, 7th November 2012

Introduction

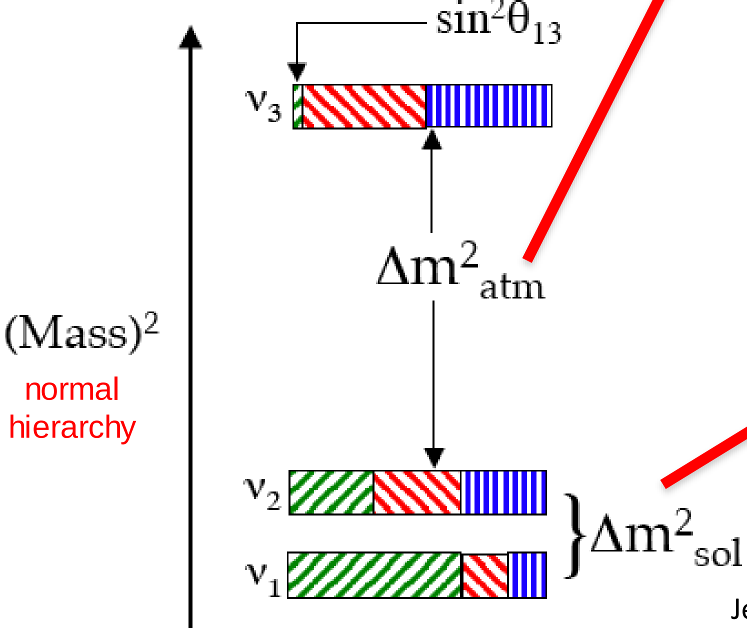
- Theory Overview
- Where we stand with the measurements
- Results: selected highlights
- Future sensitivities

Theory Overview

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Subdominant term



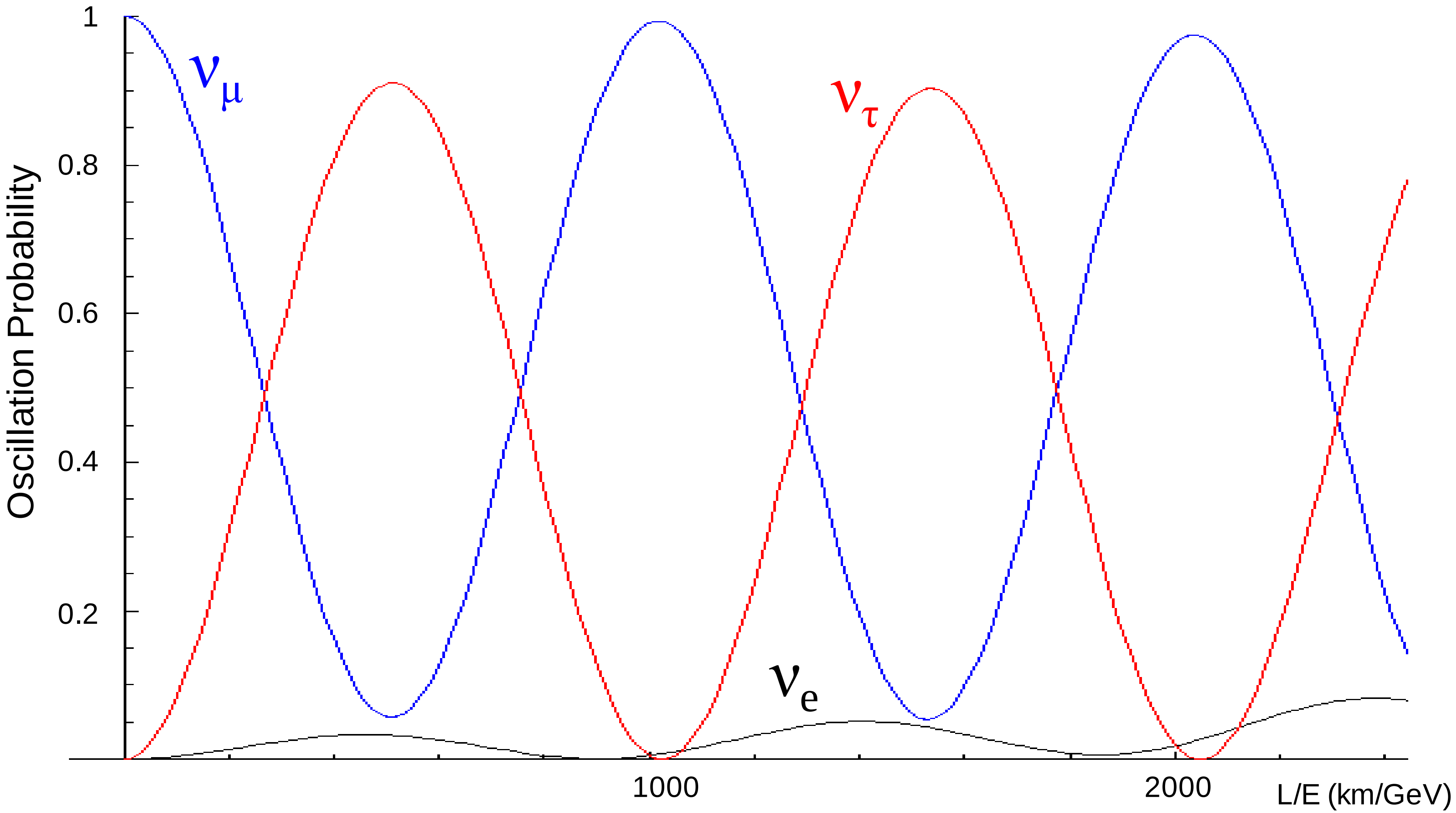
$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

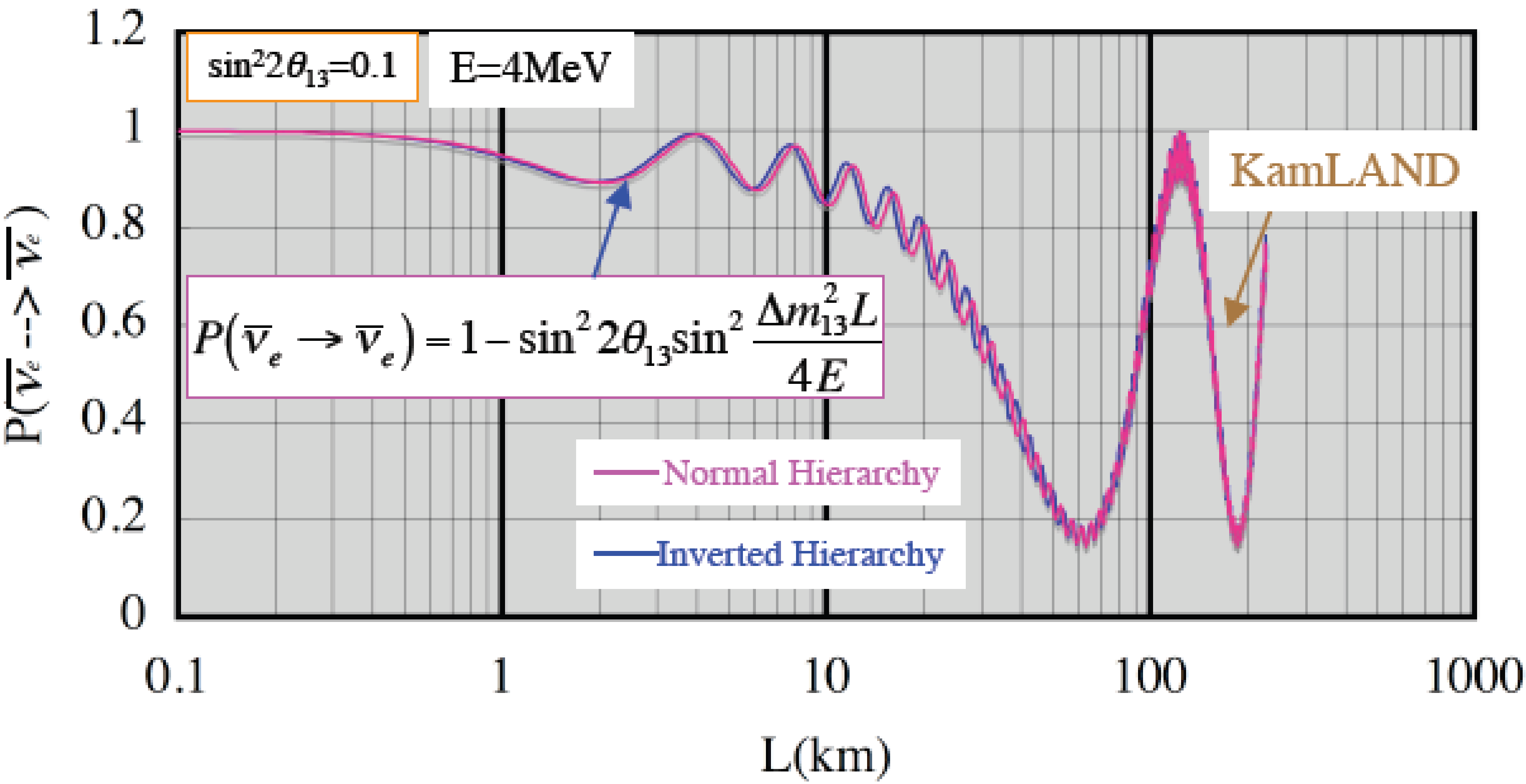
(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

Starting with ν_μ



Starting with ν_e



It’s hard to overstate…

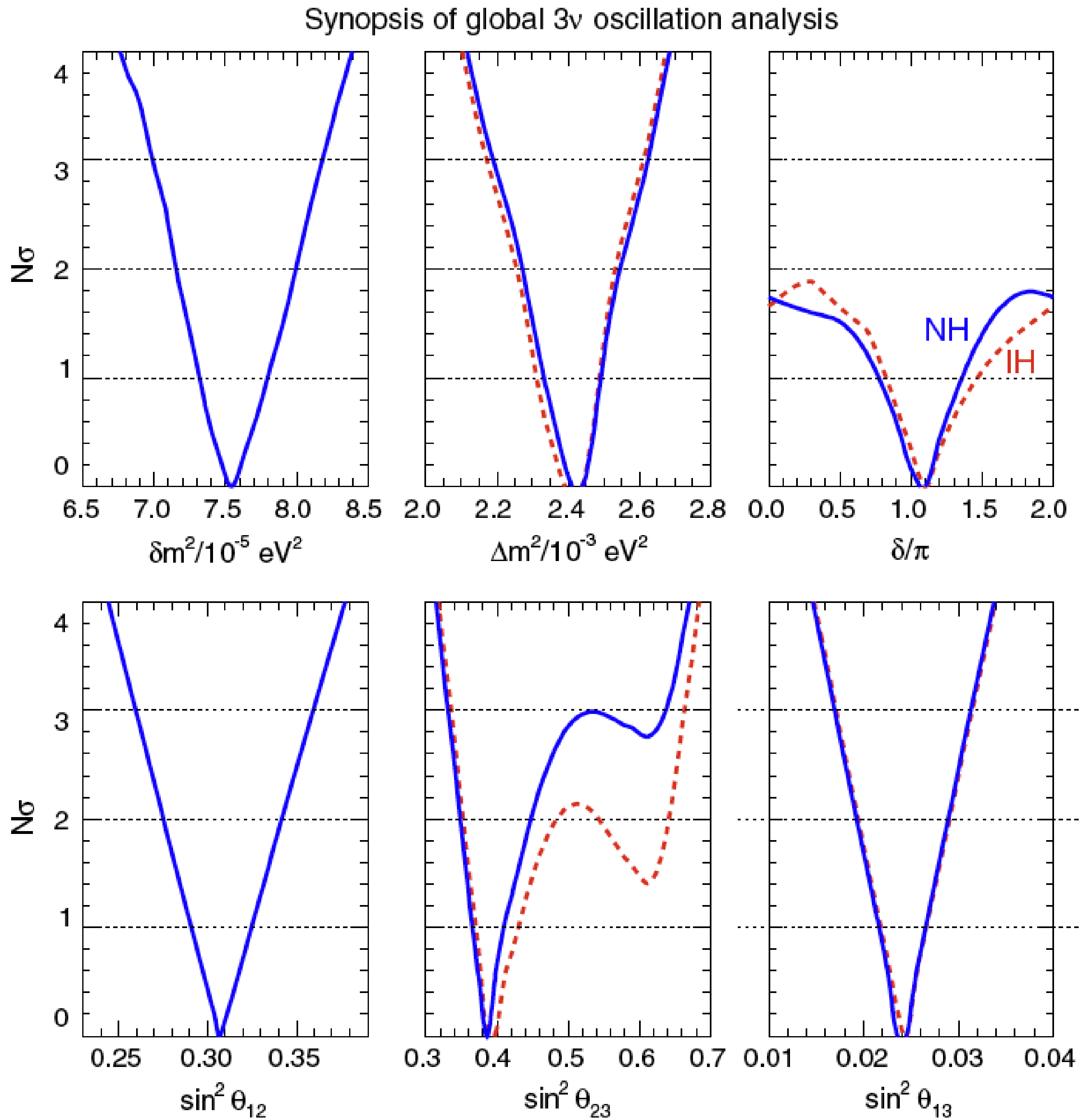
- The past ~year has seen a major breakthrough in neutrino physics
  - Our measurement of θ_{13} has gone from just an upper limit to better than θ_{23}
  - … and within 2-3 years it could be the best measured oscillation parameter!
- A new door has been opened to probing CP violation…

Where we stand experimentally

	bf ± 1σ	acc.@3σ	
Δm^2_{21}	$(7.5 \pm 0.2)\ 10^{-5}$ eV^2	(8%)	KamLAND
$\sin^2\theta_{12}$	0.31 ± 0.015	(17%)	SNO
$\|\Delta m^2_{32}\|$	$(2.4 \pm 0.1)\ 10^{-3}$ eV^2	(10%)	MINOS
$\sin^2\theta_{23}$	0.39 ± 0.03	(33%)	SK atm+LBL
$\sin^2\theta_{13}$	0.024 ± 0.003	(30%)	Reactor Ex.

δ_{CP}, θ_{23} octant, mass hierarchy (?)

[Fogli et al., arXiv:1205.5254]



Fogli et al.
arXiv:1205.5254

(Note: includes latest Neutrino 2012 results)

Synergy with 0ν2β

If LBL expts show the mass hierarchy is inverted

AND

0ν2β expts don't see a signal for m_ν ~30 meV

We know neutrinos are Dirac not Majorana
(assuming no exotic new physics)

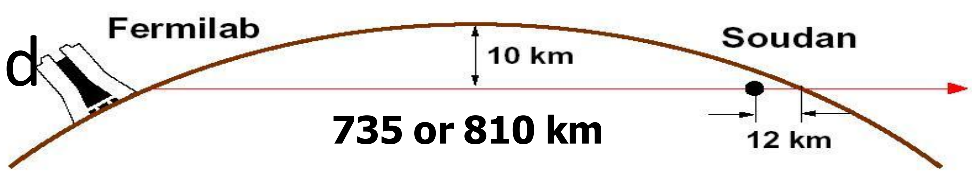
Long-Baseline Overview

- K2K, MINOS(+), T2K and NOvA
- "Conventional" beam

- Two-detector experiments:

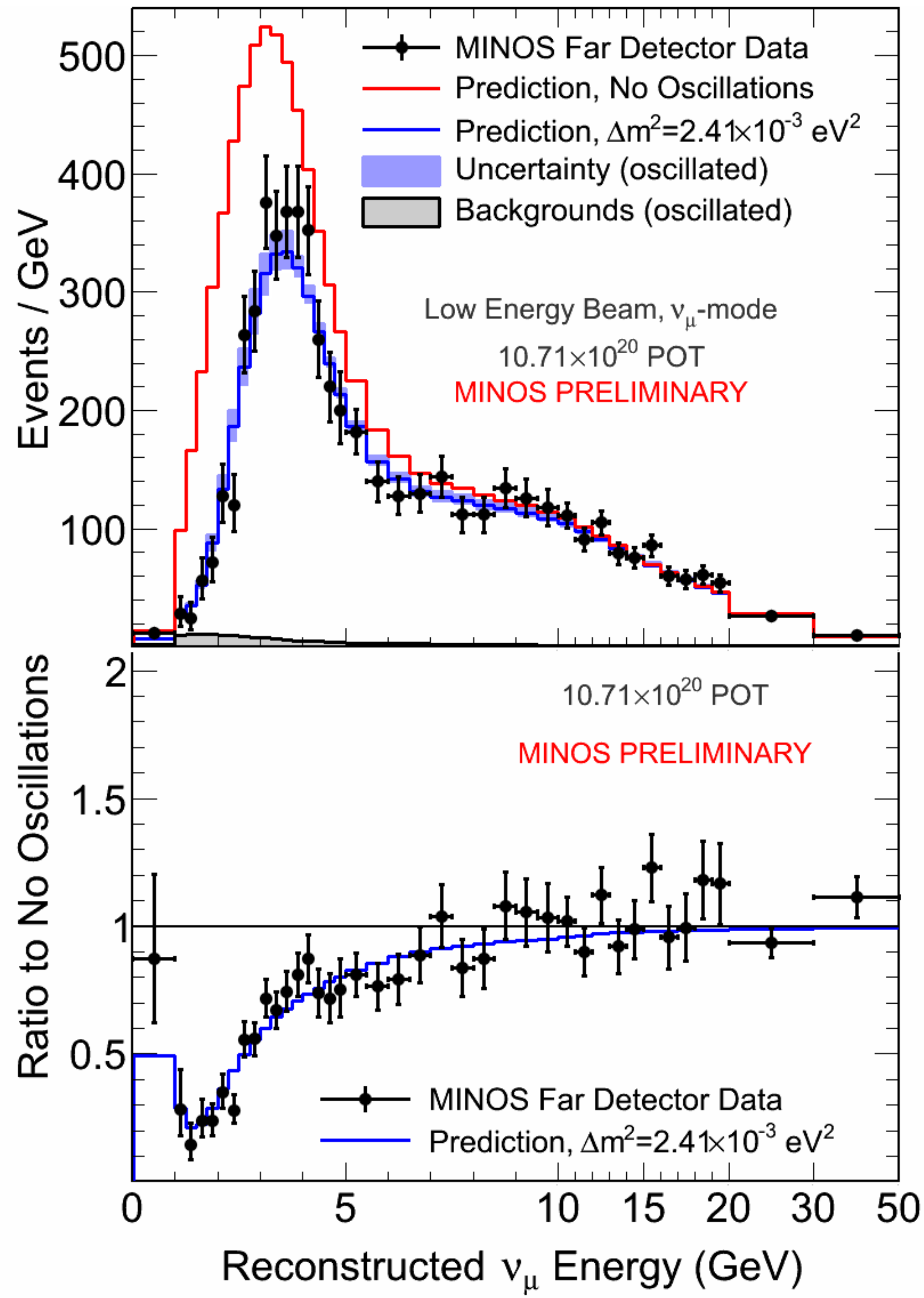
- Near detector
  - measure beam composition
  - energy spectrum

- Far detector
  - measure oscillations and search for new physics

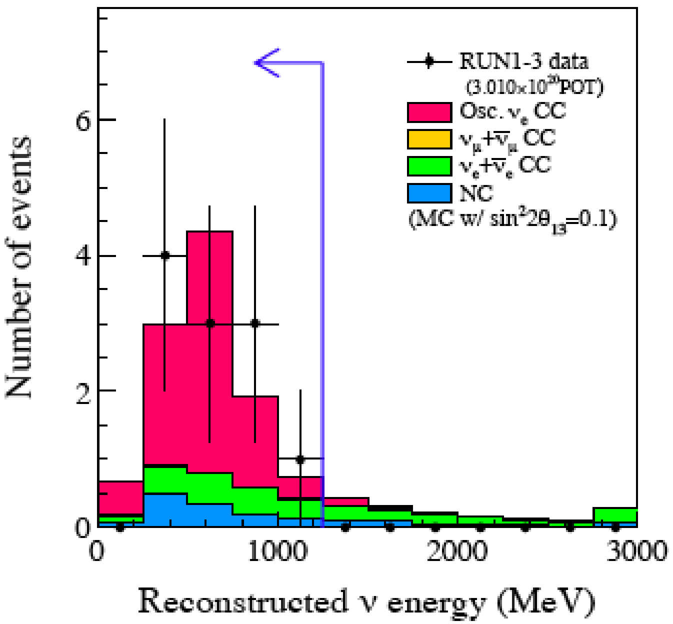


Selected Highlights

MINOS ν_μ Disappearance



T2K ν_e Appearance



11 candidate events are observed

N_{exp}=3.22±0.43 for $\sin^2 2\theta_{13}=0$

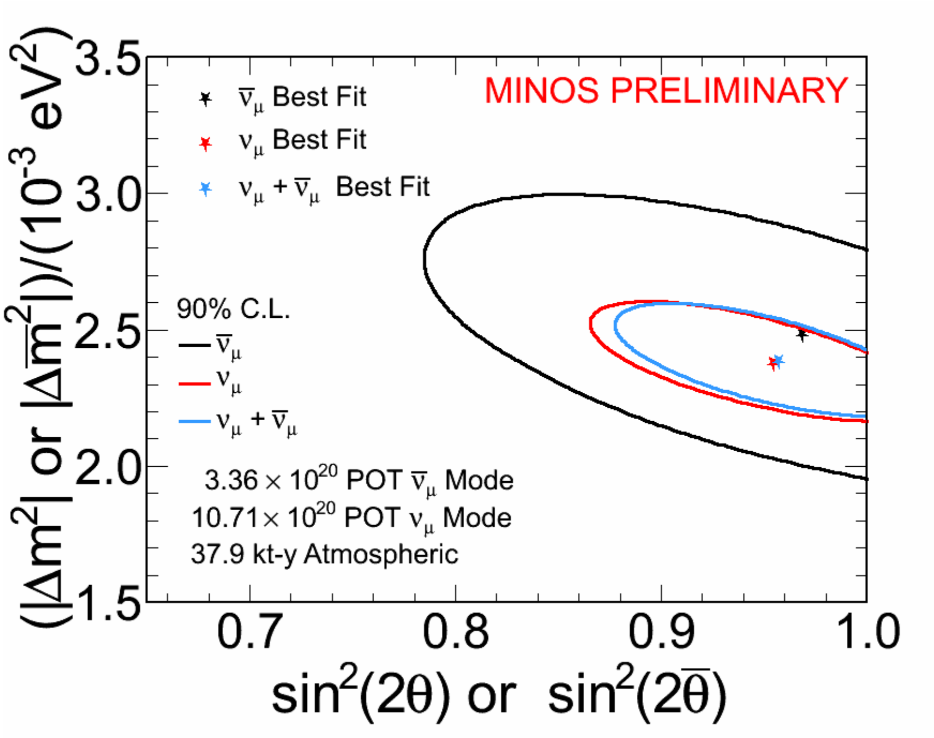
The probability (p-value) to observe 11 or more events with $\theta_{13}=0$ is 0.08% (3.2σ)

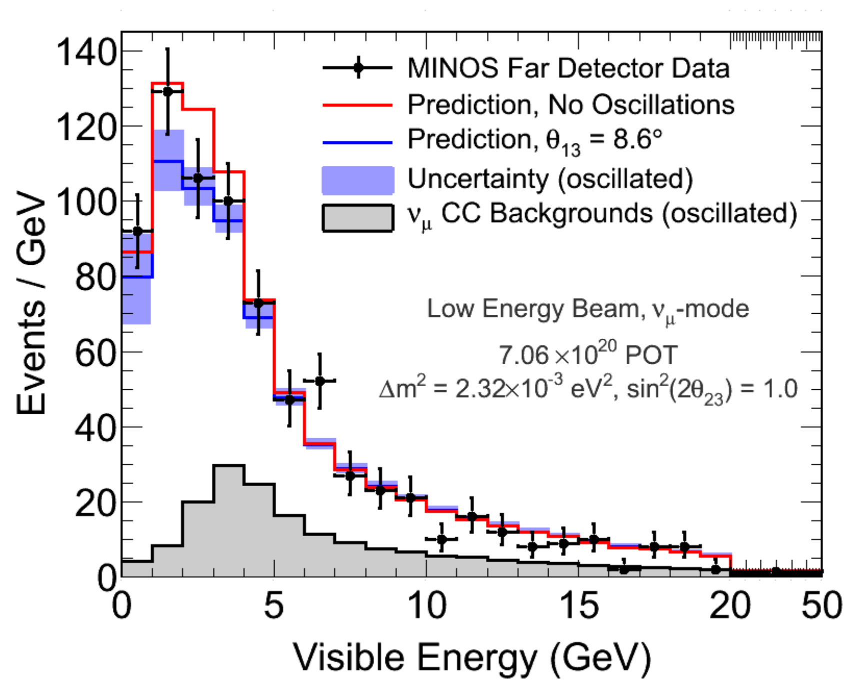
Evidence of ν_e appearance

[Sakashita, ICHEP 2012]

Probing for new physics

Do neutrinos and antineutrinos disappear in the same way?





Do we see 100% of the NC events?

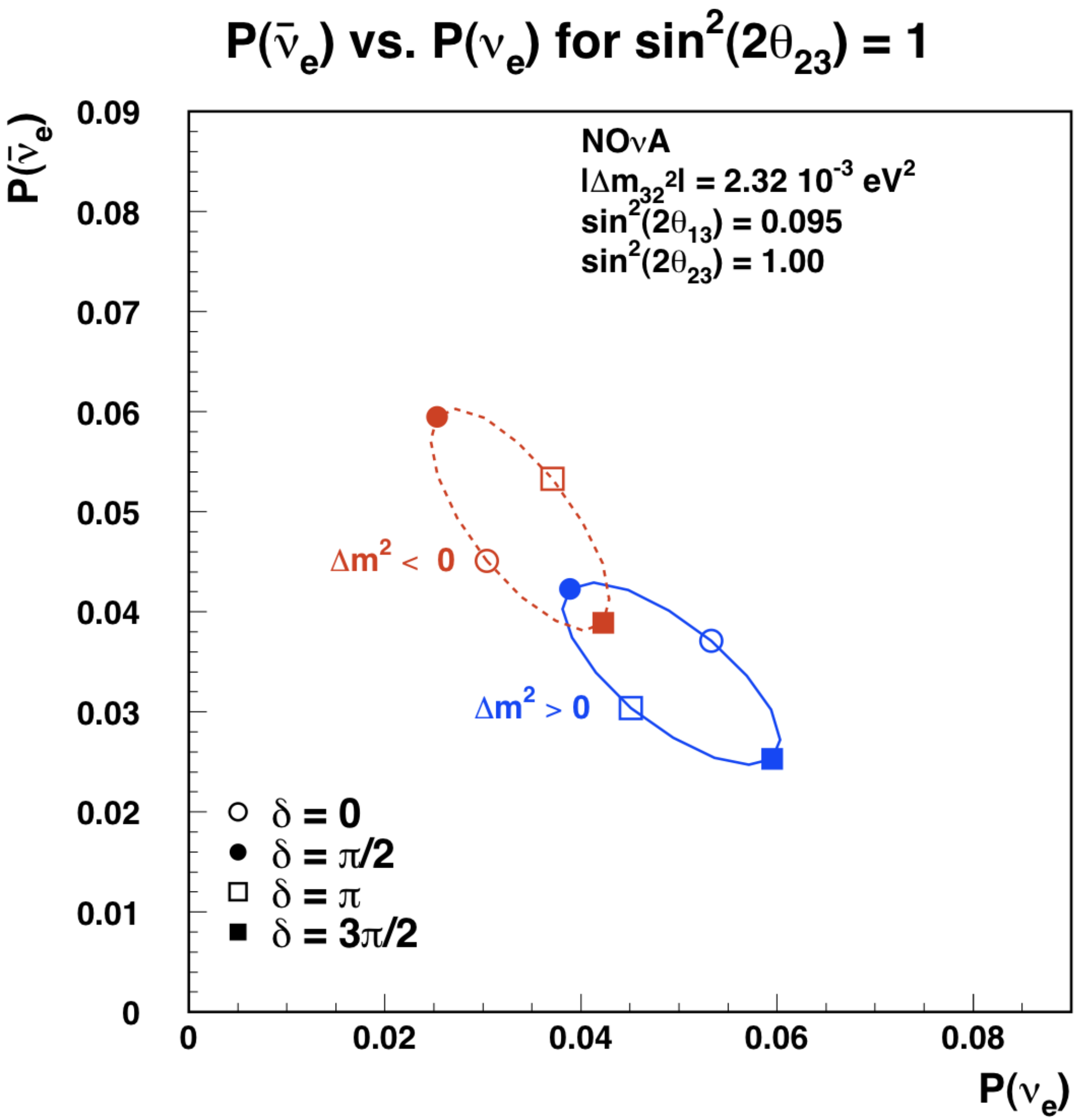
Future Sensitivities

Extrapolating T2K results

T2K Run Plan:
The J-PARC neutrino facility will provide an integrated number of protons on target of 7.5×10^{21} (equivalent to 750 kW $\times 5 \times 10^{7}$s).

Very cool time lapse video: http://www.youtube.com/watch?v=gFpK00WJl90&sns=tw

NOvA

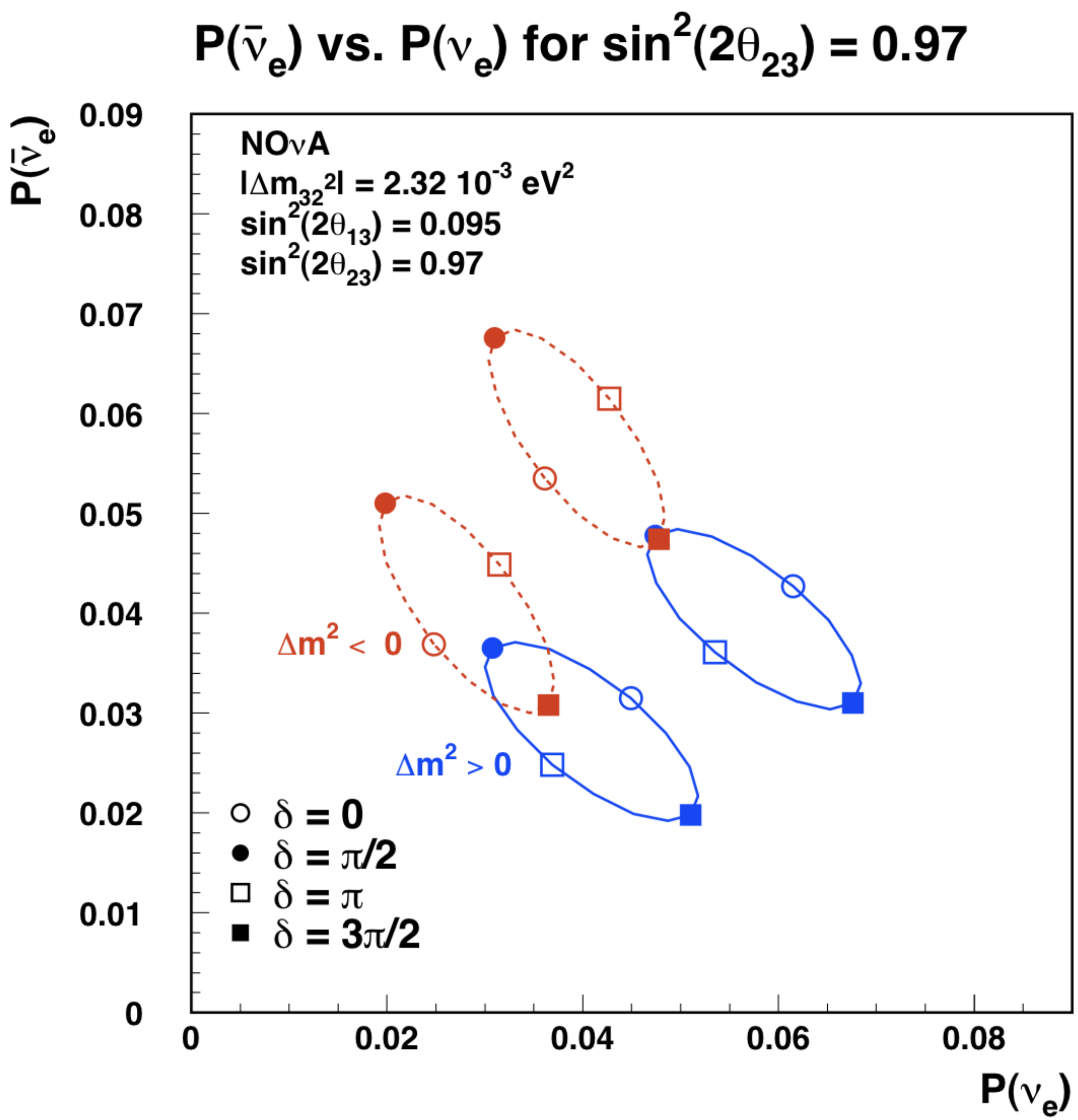


3 yr + 3 yr

beam = ν		$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \to \nu_e$	68	32

Optimised for $\sin^2(2\theta_{13})$=0.095.
45% efficiency

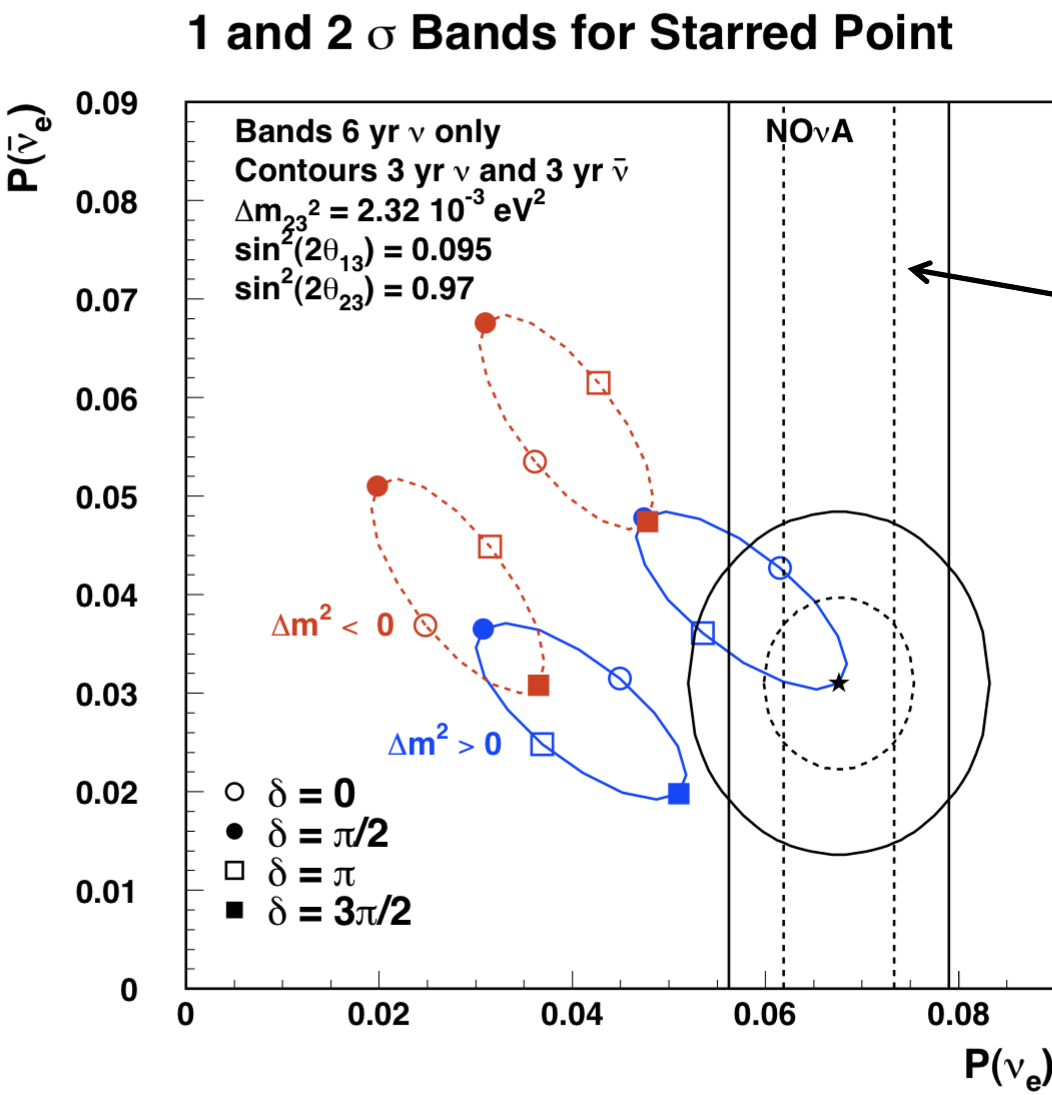
θ_{23} Octant Sensitivity



$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ *θ_{23} octant sensitivity*

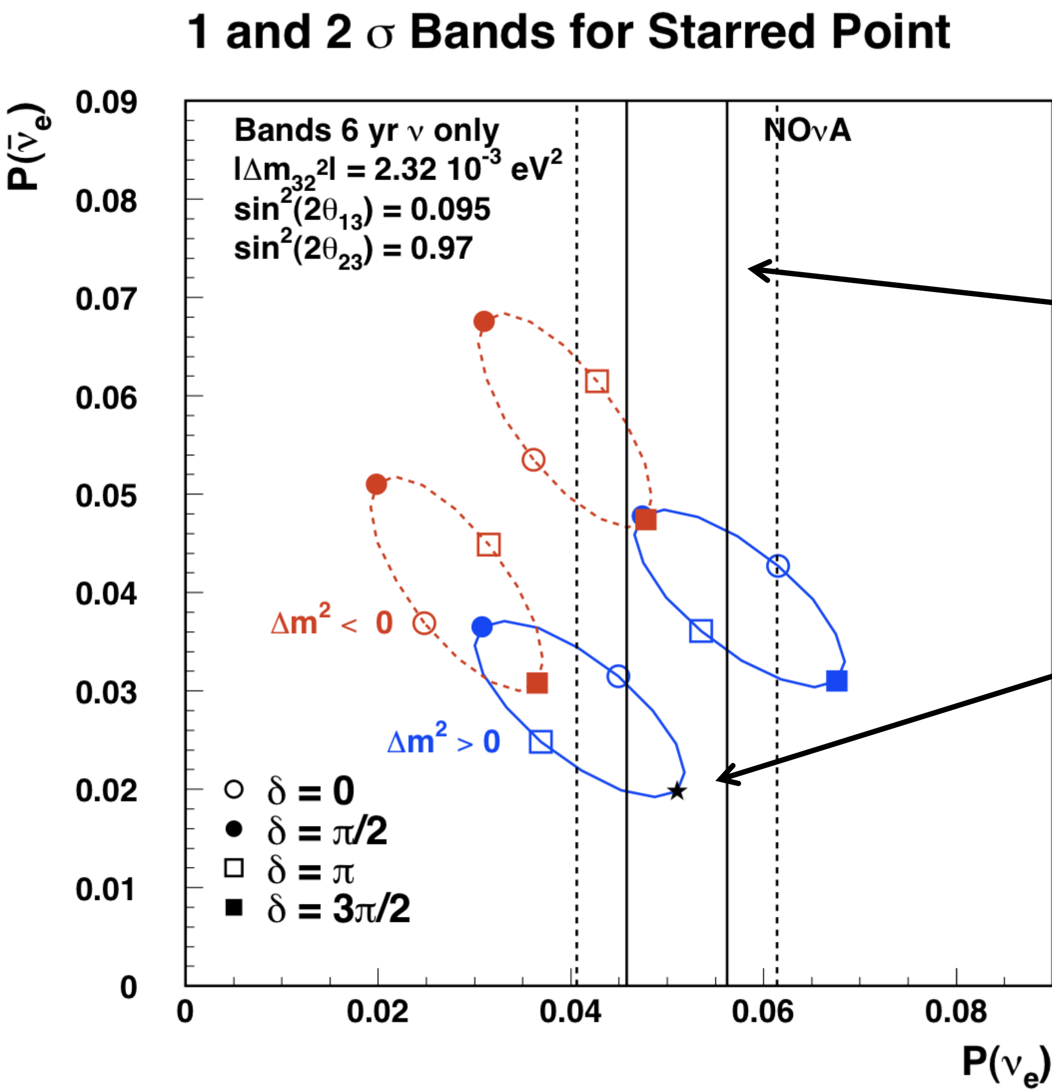
NOvA Sensitivity for starred point



Run neutrinos only (vertical lines)

Run neutrinos AND antineutrinos (black circles)

A different starred point



Run neutrinos only (vertical lines)

For this starred point you want a mixture of neutrinos and antineutrinos

This is most often the case

3 sensitivity plots

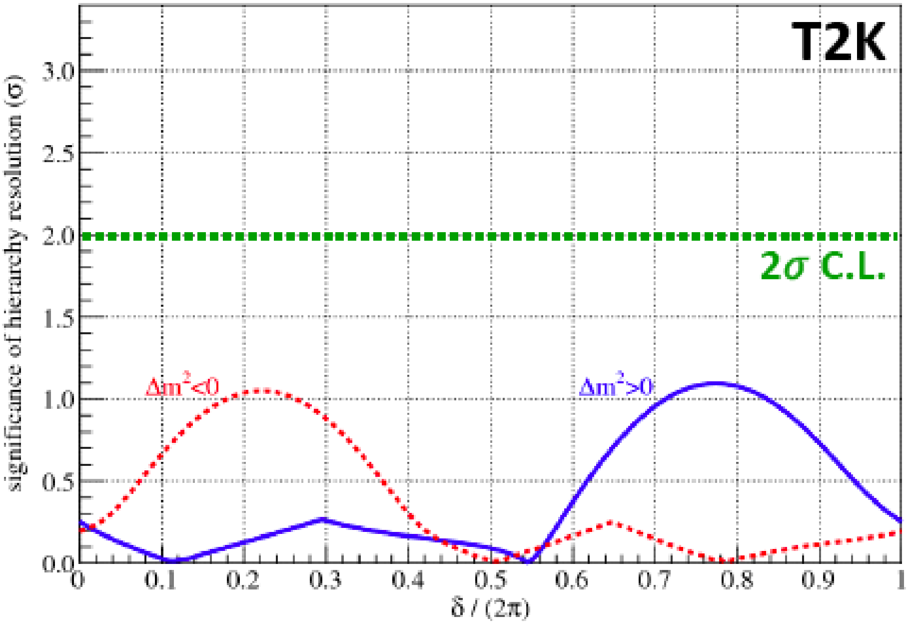
-- hierarchy
-- CPv
-- θ_{23} octant

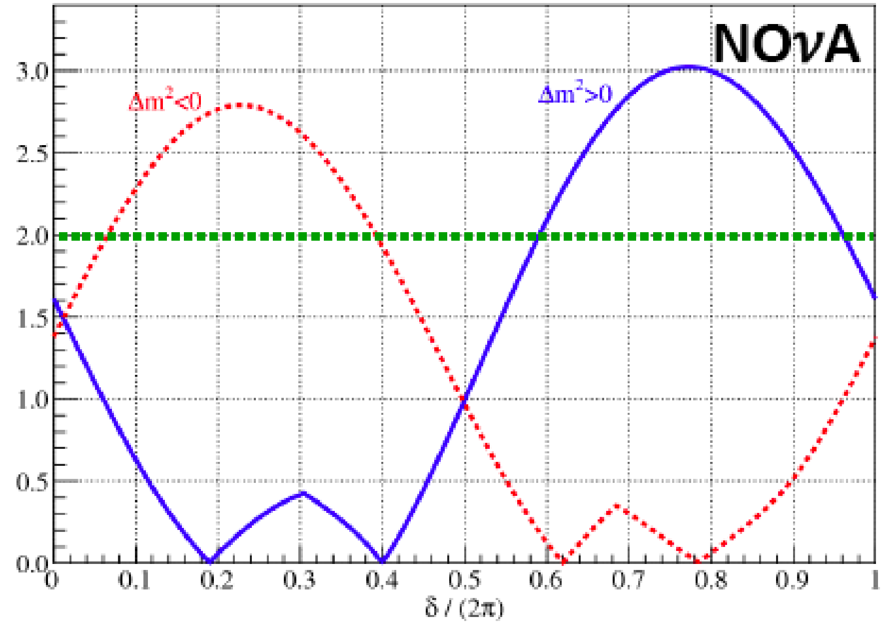
T2K, NOvA and combination

[Thanks to Ryan Patterson for the slides (at NuFact 2012)]

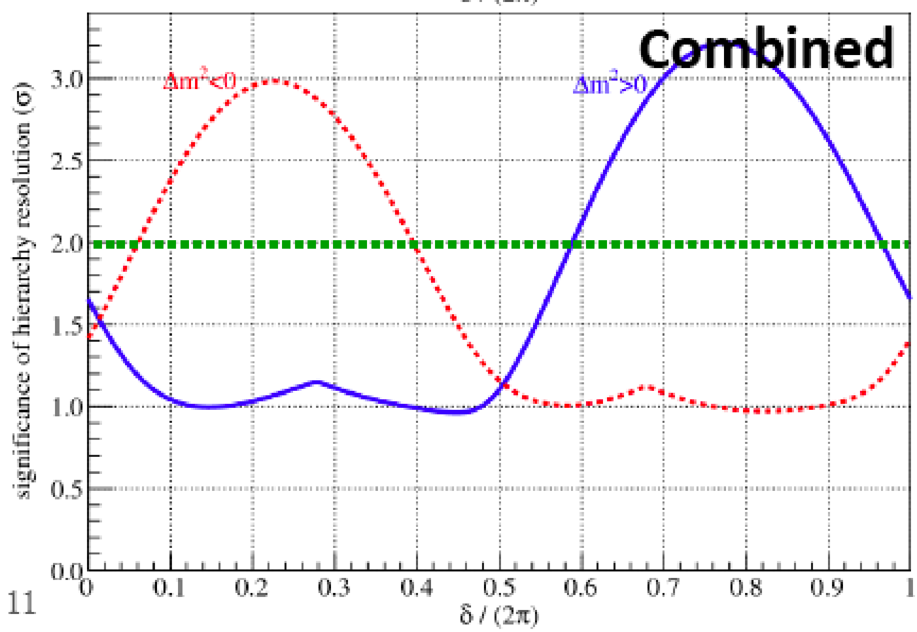
Hierarchy resolution at the end of 2019. Even split of ν and $\overline{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$





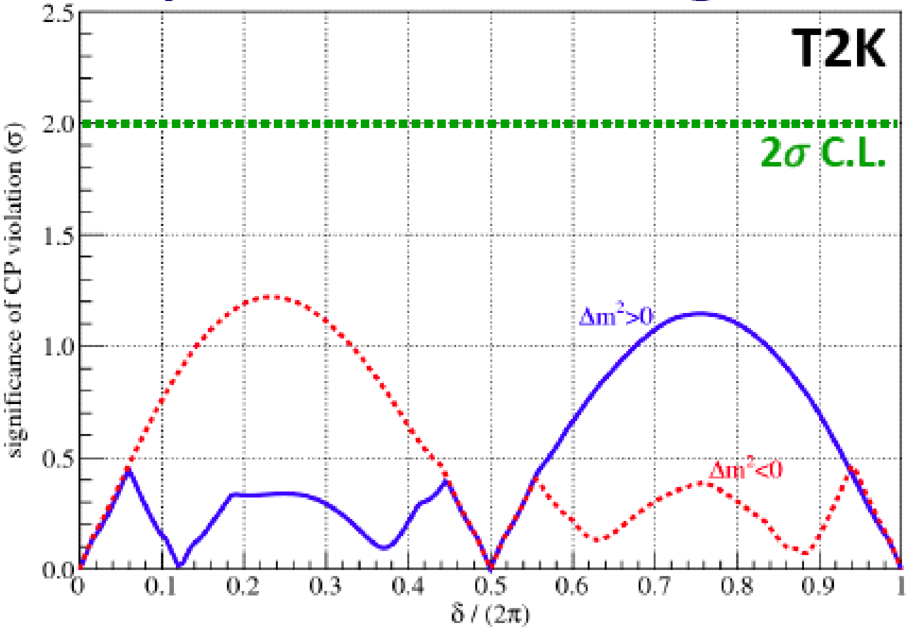
- **2σ C.L. (~95% C.L.) marked in green**
- **T2K baseline** too short for hierarchy
- **<u>NOνA alone:</u>** 37% of δ range covered
- **<u>NOνA+T2K:</u>** 38% of δ range covered
- *But:* note that **the combination is greater than the sum of its parts** in the "degenerate" region (reaching a modest 1σ everywhere)

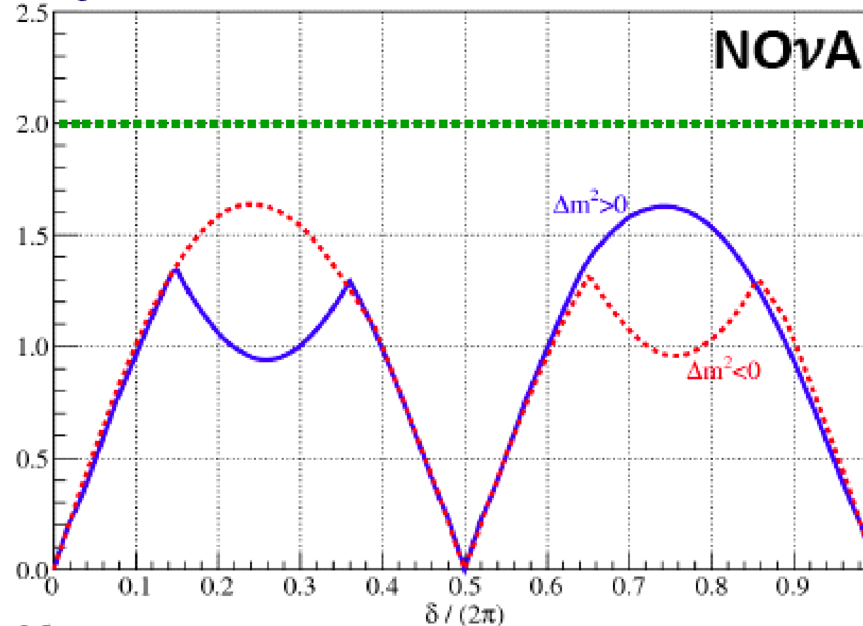


Ryan Patterson, Caltech 11

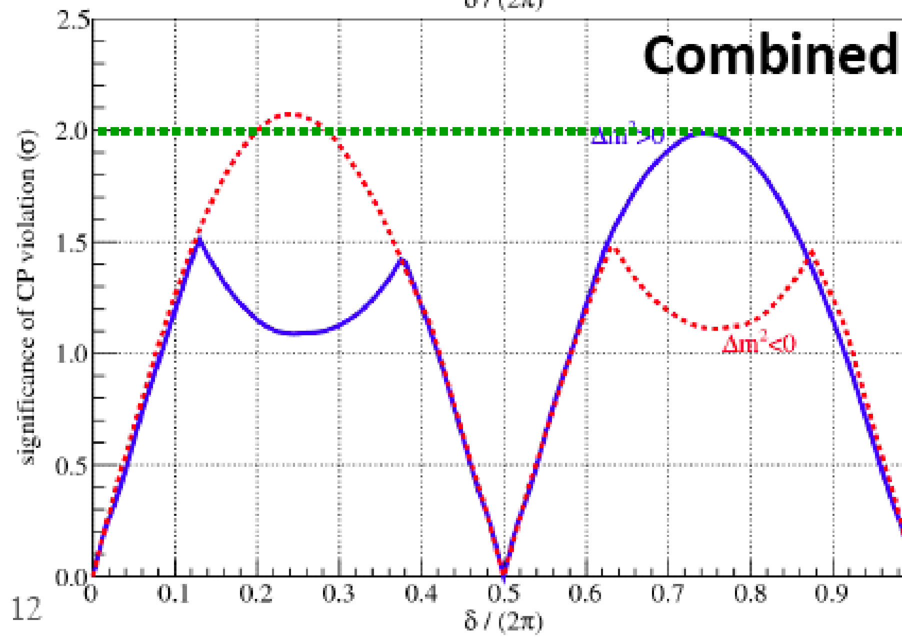
CP violation determination at the end of 2019. Even split of ν and $\bar{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$





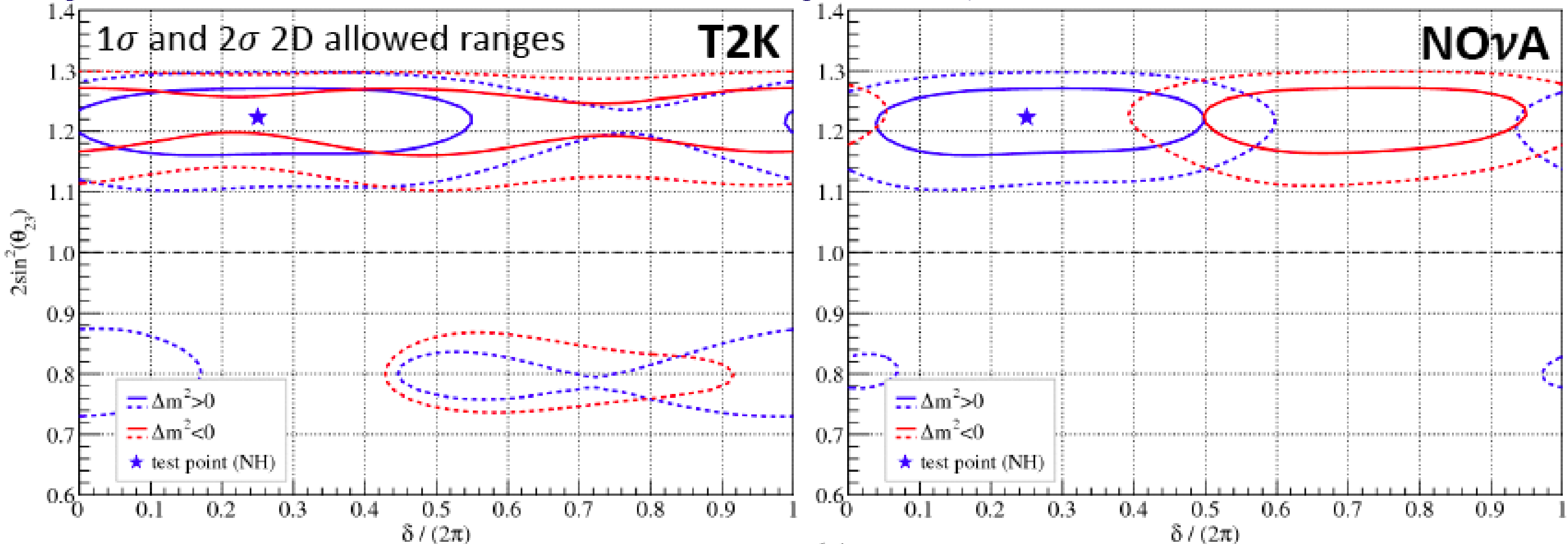
- **CPv tough all around!**
- Essentially **no coverage at 2σ**, but a good start over much of δ
- <u>Note:</u> unlike the hierarchy reach, this **can be arbitrarily hard**, depending on the true answer



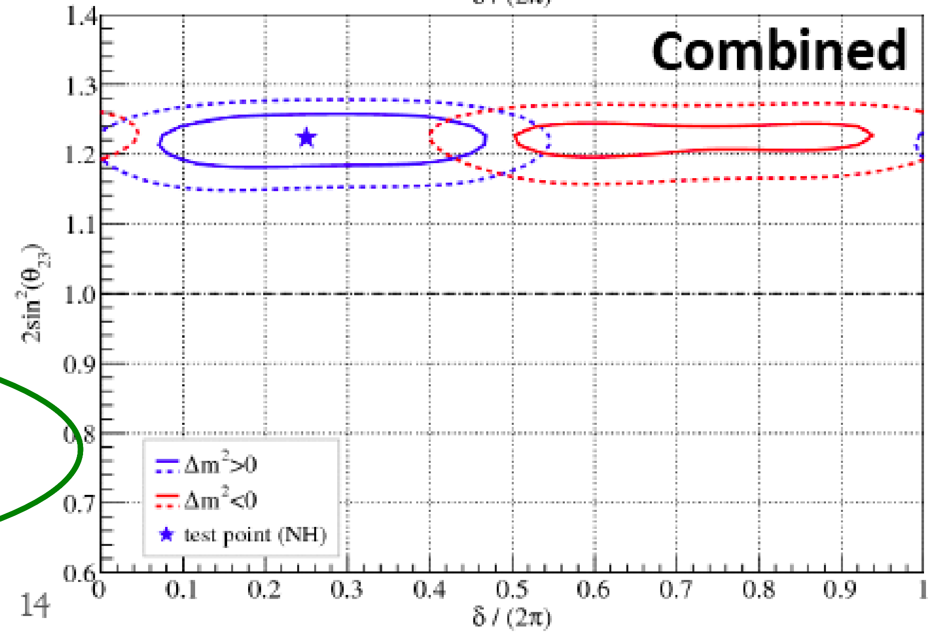
Ryan Patterson, Caltech 12

Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\overline{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})=0.095$



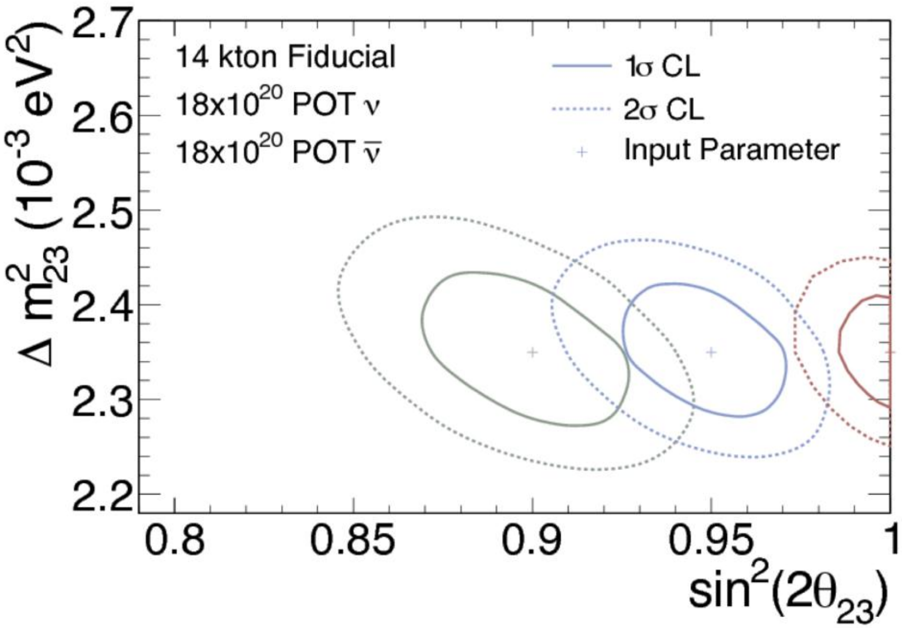
- **Non-maximal mixing scenario:** $\sin^2(2\theta_{23})=0.95$, $\theta_{23}>\pi/4$
- **…with unfavorable δ this time**
- **Octant still resolved at >2σ, despite "degeneracy"**
- ***This is a general point:*** *octant determination is largely insensitive to hierarchy and δ*



Ryan Patterson, Caltech 14

Future of ν_μ disappearance

- As well as ν_e app…
- Use the traditional measurement of θ_{23} to attack the question of whether non-maximal
- T2K, NOvA comparable
- Statistical precision to 1% in $\sin^2(2\theta_{23})$
  - Aim for similar systematics



Upgrades??

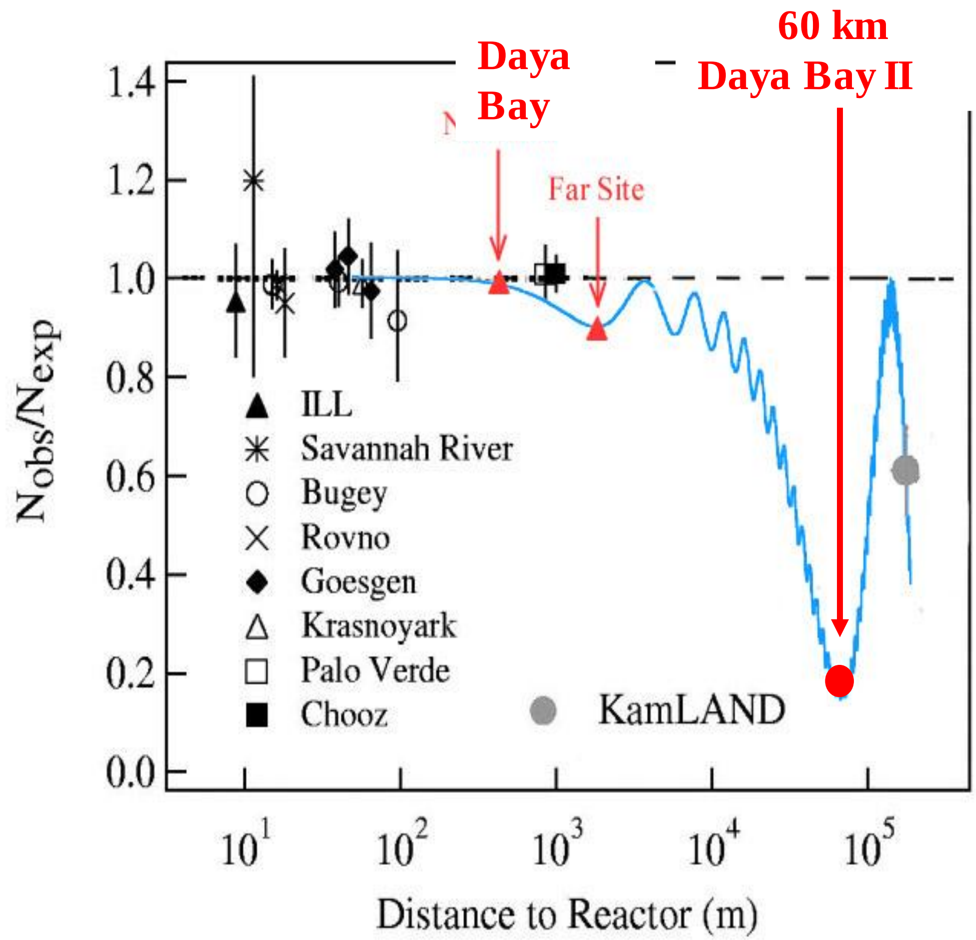
- NOvA:
  - 14 kt → 18 kt
  - 6 year run → 10 year run
  - Combined gives a factor of 2 in exposure
- T2K/Japan Future
  - see Tsuyoshi Nakaya's talk

MINOS+

(see talk by Justin Evans)

Daya Bay II

- 60km-baseline reactor experiment
- Very interesting and challenging proposal
- Default parameters:
  - Detector size: 20kt
  - Energy resolution: 3%
  - Thermal power: 36 GW
  - Baseline 58 km
- Mass hierarchy & precision meas.



[Jun Cao, Shenzhen Conf.]

High Energy Physics – Experiment

A Review of Long-baseline Neutrino Oscillation Experiments

G. J. Feldman, J. Hartnell, T. Kobayashi

(Submitted on 5 Oct 2012)

A review of accelerator long-baseline neutrino oscillation experiments is provided, including all experiments performed to date and the projected sensitivity of those currently in progress. Accelerator experiments have played a crucial role in the confirmation of the neutrino oscillation phenomenon and in precision measurements of the parameters. With a fixed baseline and detectors providing good energy resolution, precise measurements of the ratio of distance/energy (L/E) on the scale of individual events have been made and the expected oscillatory pattern resolved. Evidence for electron neutrino appearance has recently been obtained, opening a door for determining the CP violating phase as well as resolving the mass hierarchy and the octant of theta23: some of the last unknown parameters of the standard model extended to include neutrino mass.

Comments:	43 pages, 36 figures. Invited review for the special issue on neutrinos of Advances in High Energy Physics
Subjects:	**High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
Cite as:	arXiv:1210.1778 **[hep-ex]**
	(or arXiv:1210.1778v1 **[hep-ex]** for this version)

Submission history

From: Jeffrey Hartnell [view email]

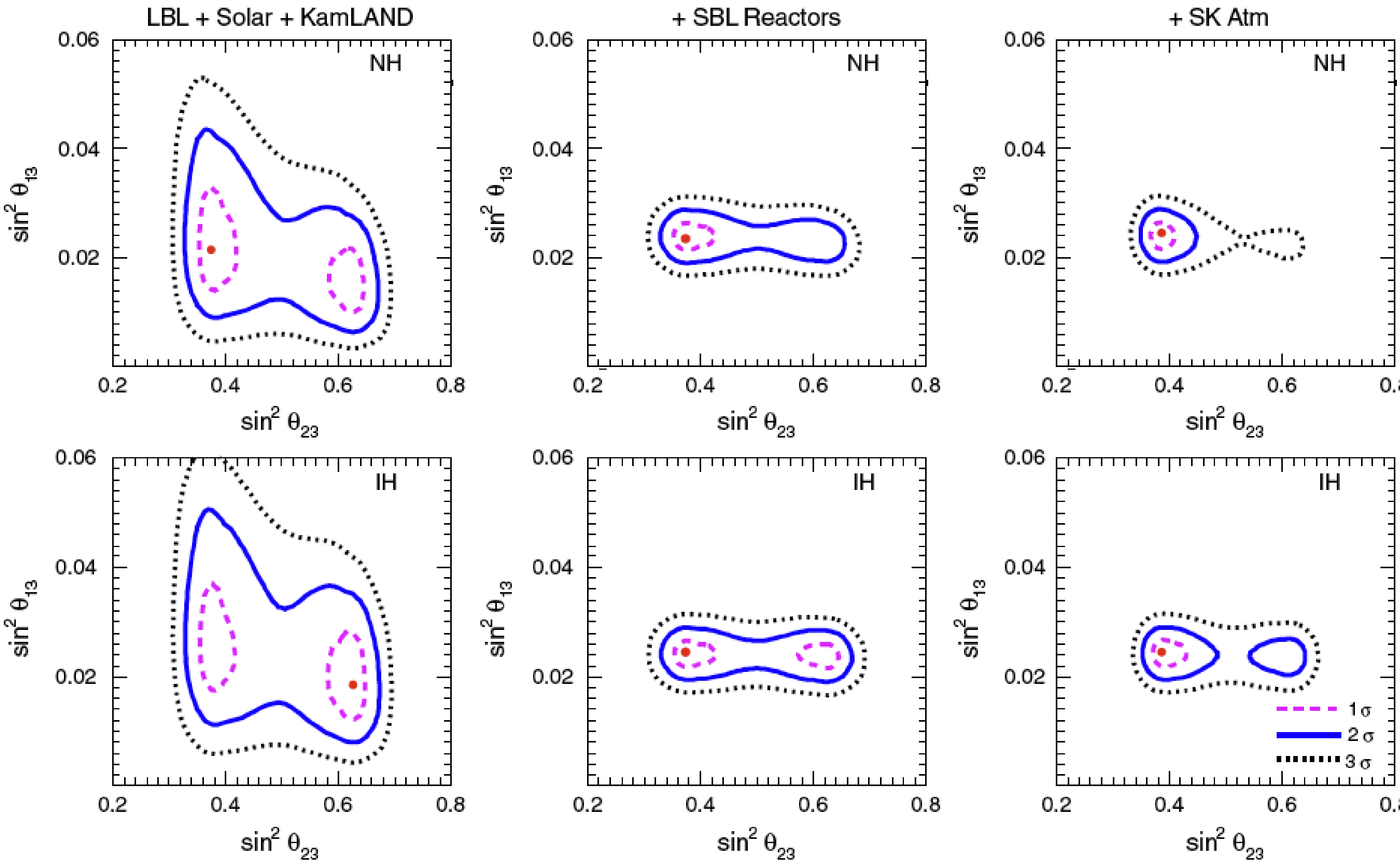
[v1] Fri, 5 Oct 2012 14:59:38 GMT (3853kb,D)

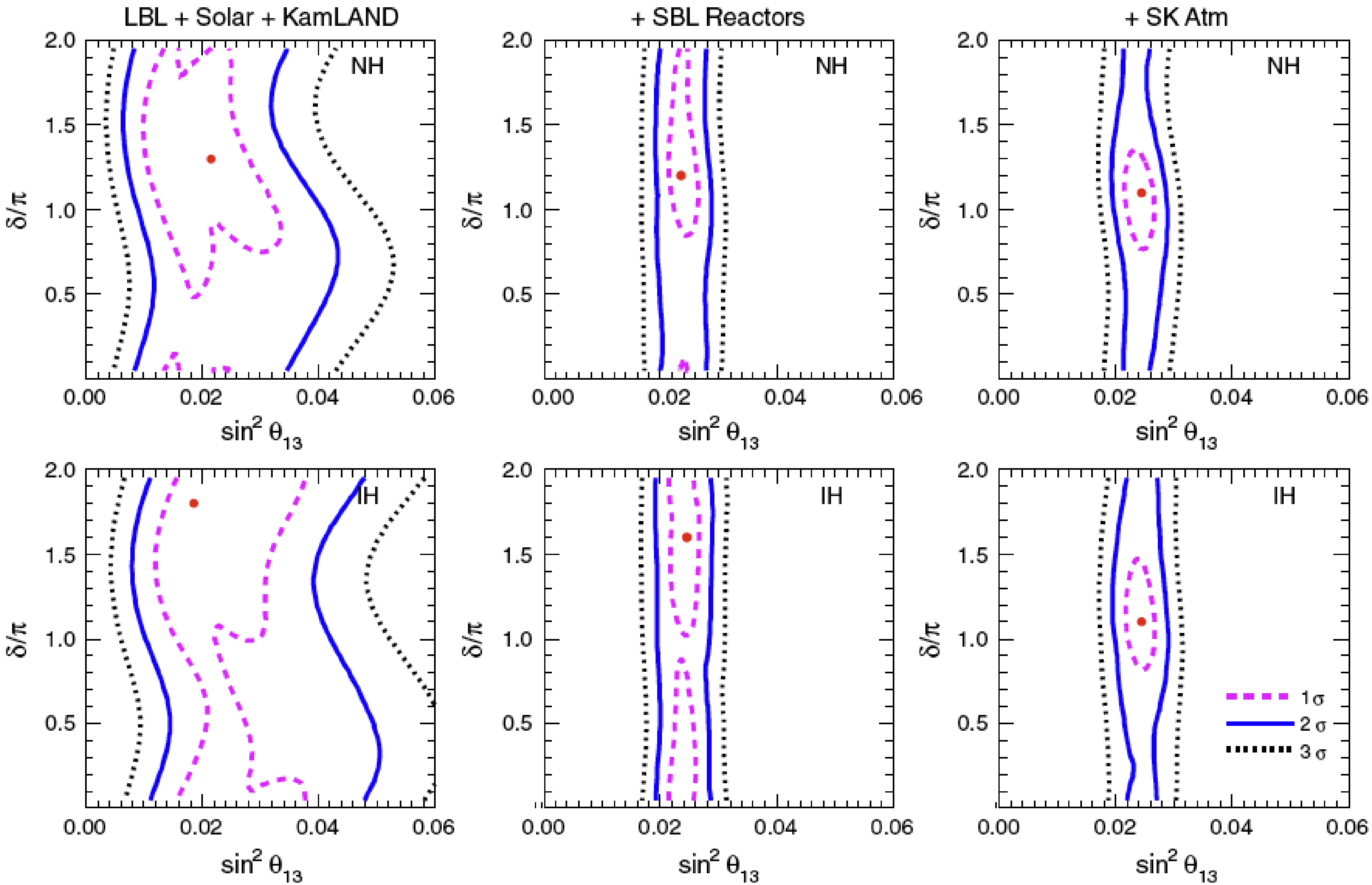
Conclusions

- The recent discovery of non-zero θ_{13} has opened the door to a 2nd golden age of neutrino physics
- May gain critical information on mass hierarchy and θ_{23}-octant in the next decade
  - Hierarchy at >95% CL for 38% of δ
  - Octant at >95% CL for $\sin^2(2\theta_{23})=0.95$
- CPv is tough!
  - Combined fits will be important
- Very exciting past 18 months
  - new results just around the corner

Backup slides

Contributions to θ_{23}




LBL + Solar + KamLAND
+ SBL Reactors
+ SK Atm
NH
IH
δ/π
sin² θ13
2.0
1.5
1.0
0.5
0.00
0.02
0.04
0.06
1σ
2σ
3σ

- **The scenario**
  - NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)
  - T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)
  - NOνA achieves a further 20% sensitivity gain through analysis improvements
  - T2K achieves a further 10% sensitivity gain through analysis improvements

Note: different vertical scale than before.

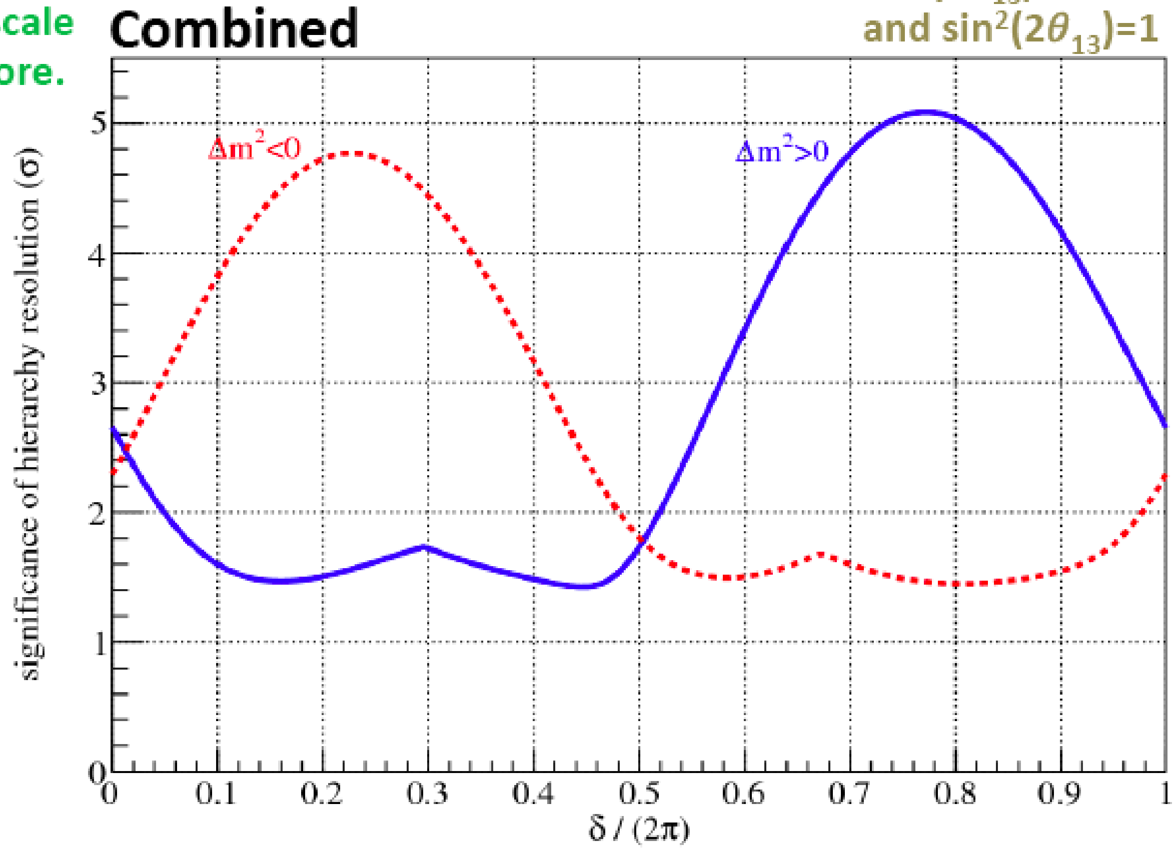
For $\sin^2(2\theta_{13})=0.095$ and $\sin^2(2\theta_{13})=1$

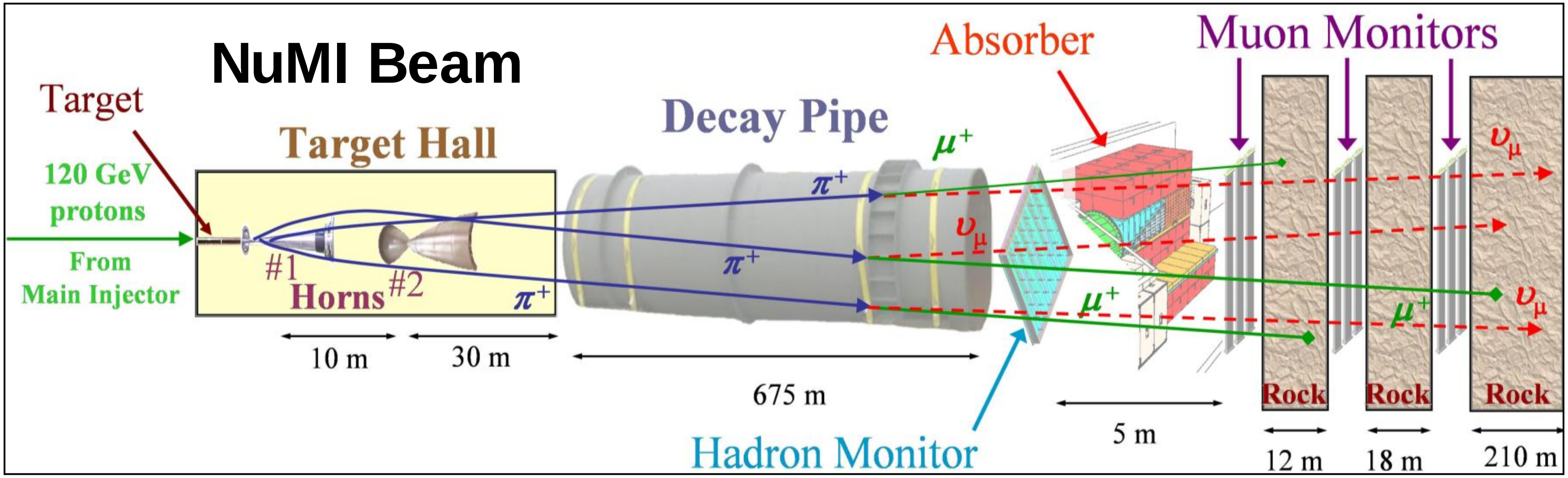
Raw hierarchy sensitivity
maximal mixing scenario

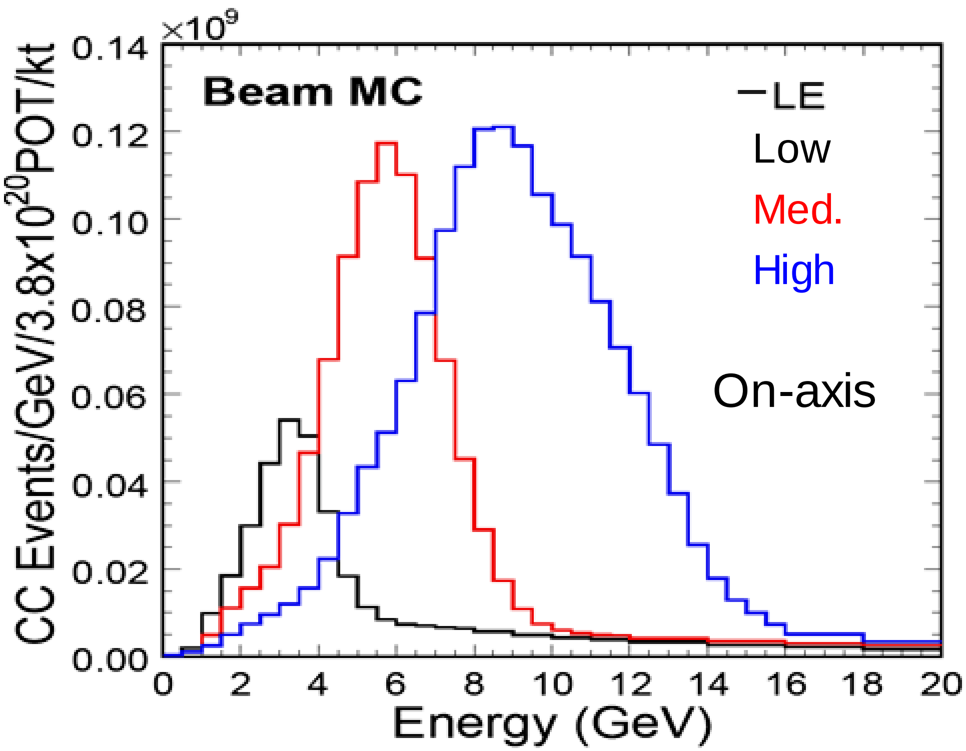
Best: 5.1σ

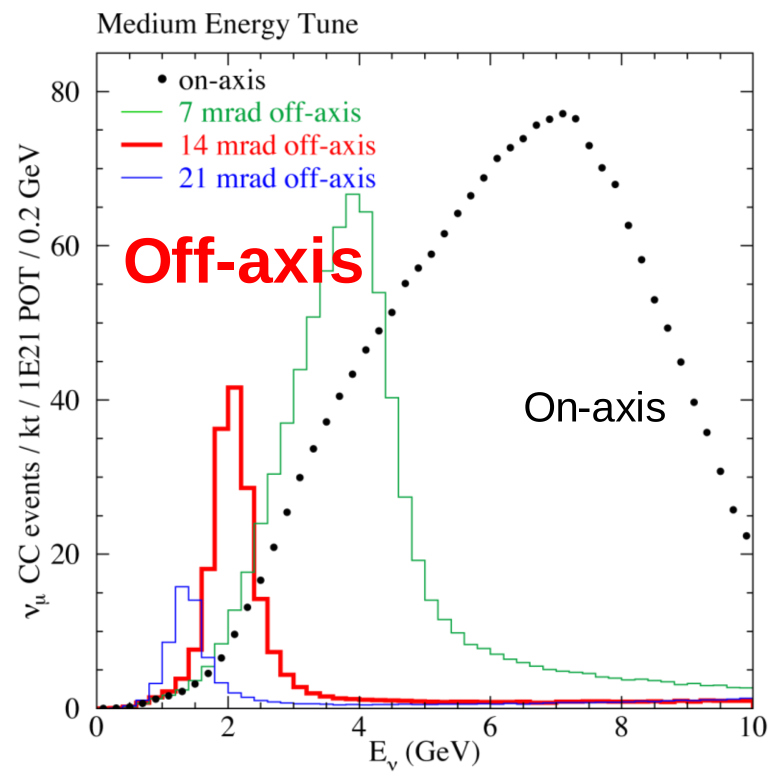
53% of δ range: >2σ
40% of δ range: >3σ

Everything >1.4σ: a good start.

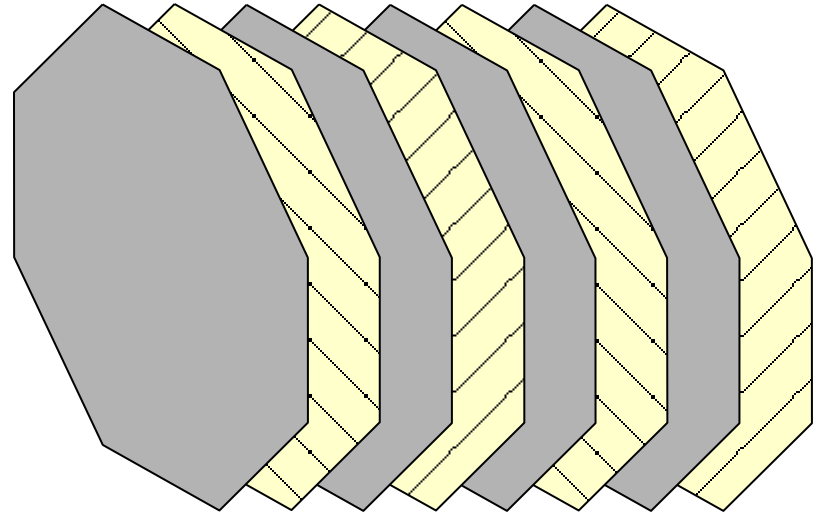



NuMI Beam
Target
Target Hall
120 GeV protons
From Main Injector
#1
Horns
#2
10 m
30 m
Decay Pipe
675 m
Absorber
Muon Monitors
Hadron Monitor
5 m
Rock
Rock
Rock
12 m
18 m
210 m

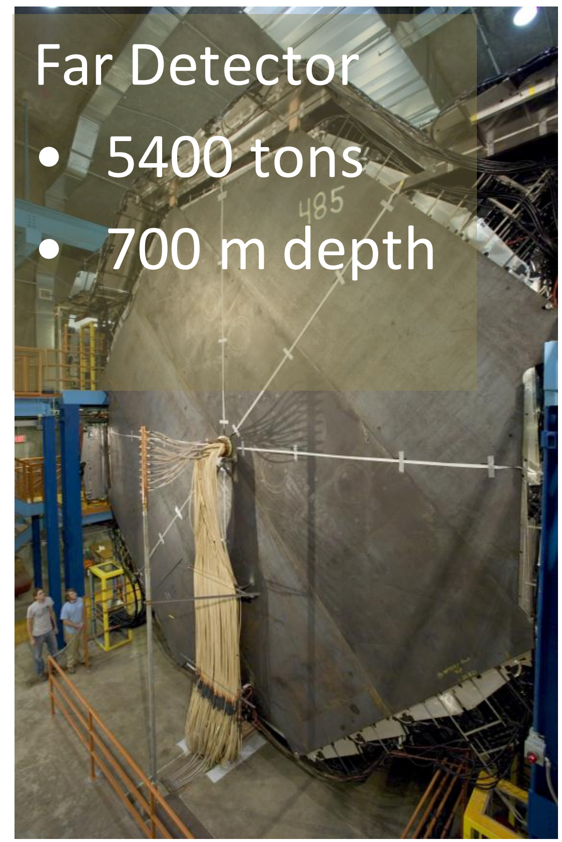

Beam MC
LE
Low
Med.
High
On-axis
CC Events/GeV/3.8x10^20POT/kt
Energy (GeV)


Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
Off-axis
On-axis
CC events / kt / 1E21 POT / 0.2 GeV
(GeV)

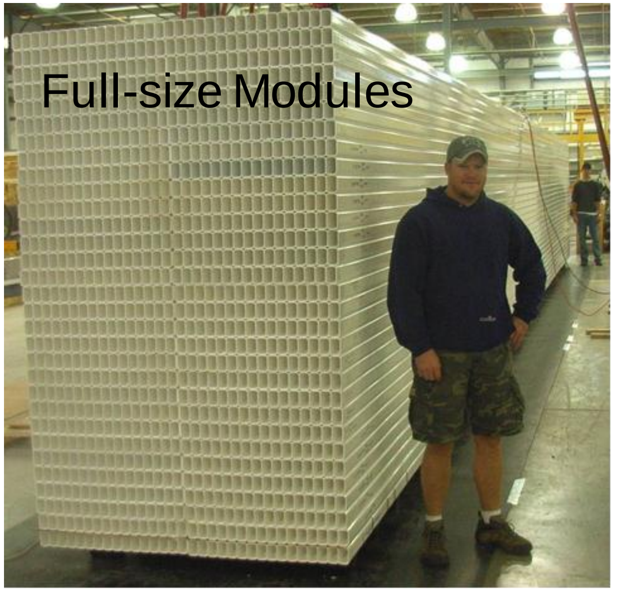
MINOS Detectors



- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick
  - scintillator strips 4.1 cm wide
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-

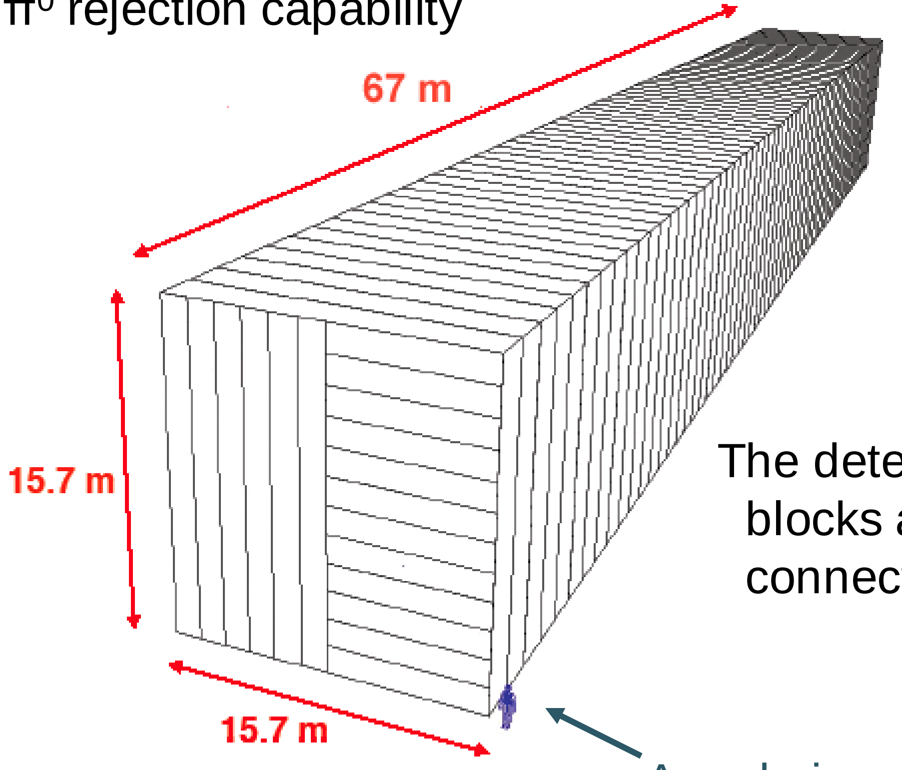


NOvA Far Detector



TASD: Totally Active Scintillator Design

Longitudinal sampling is ~0.15 X_0, which gives:
-- excellent μ-*e* separation
-- π^0 rejection capability

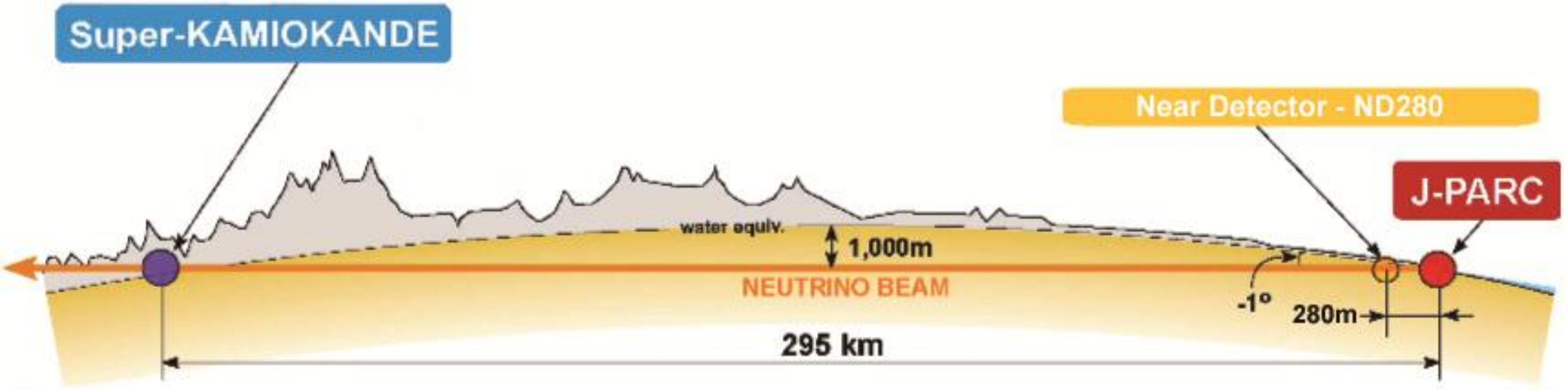


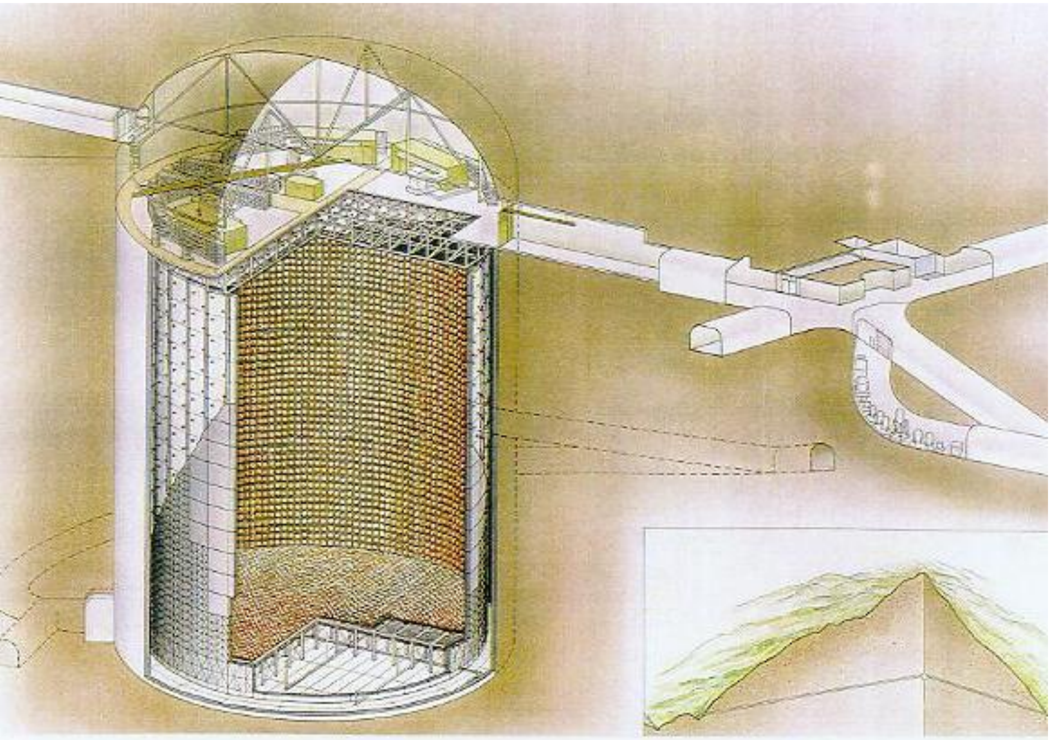
An admirer

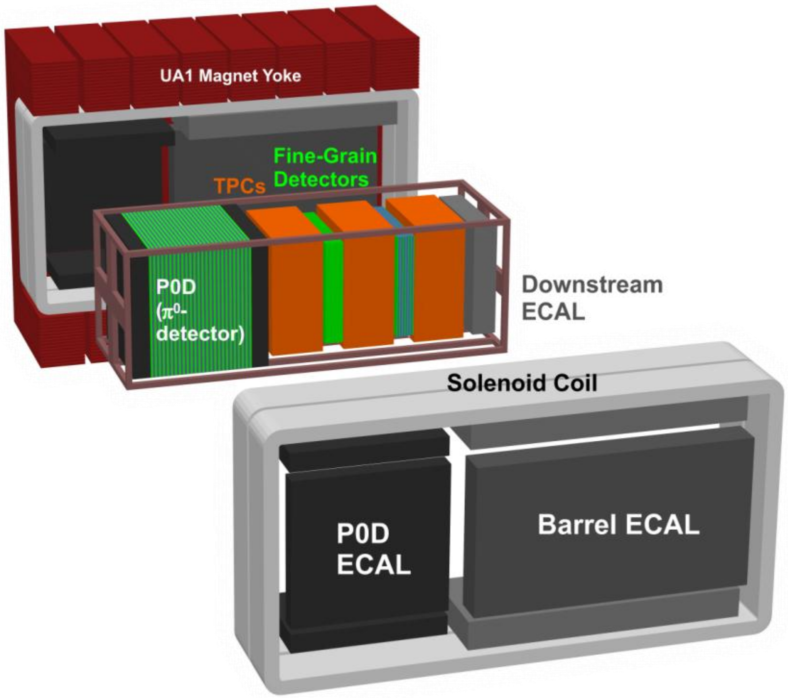
Baseline total mass of 14 kT. Enough room in the building for 18 kT

The detector can start taking data as soon as blocks are filled and the electronics connected.

T2K


Super-KAMIOKANDE
Near Detector - ND280
J-PARC
water equiv.
1,000m
NEUTRINO BEAM
-1°
280m
295 km




UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π^0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL