MINOS Oscillation Results

16th Lomonosov Conference
Moscow, Russia
August 22, 2013

Stanley Wojcicki
Stanford University
on behalf of MINOS Collaboration

Bruno Pontecorvo (1913-1993)

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The current neutrino program is very much based on Pontecorvo's seminal ideas

Some Key Ideas

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  $^{37}Cl\ (\nu,e^-)\ ^{37}Ar$

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- Different ν flavors, 1957
  Neutrino oscillations

The current neutrino program is very much based on Pontecorvo's seminal ideas

Bruno Pontecorvo (1913-1993)

Some Key Ideas

- Solar neutrinos, 1948
  $^{37}Cl\ (\nu, e^-)\ ^{37}Ar$
- Different ν flavors, 1957
  Neutrino oscillations
- Accelerator produced ν beams, 1959
  $\pi \rightarrow \mu + \nu,\ K \rightarrow \mu + \nu$

The current neutrino program is very much based on Pontecorvo's seminal ideas

Topics Covered

- Few Experimental Details
- History
- Results from Initial Analyses
  - ν_μ and $\overline{\nu}_\mu$ disappearance
  - ν_e appearance
- New Analyses
  - Neutral Currents (4ν, sterile ν)
  - Combined 3-flavor Analysis
- Other Physics Topics (briefly)
- Future Plans

MINOS Geography

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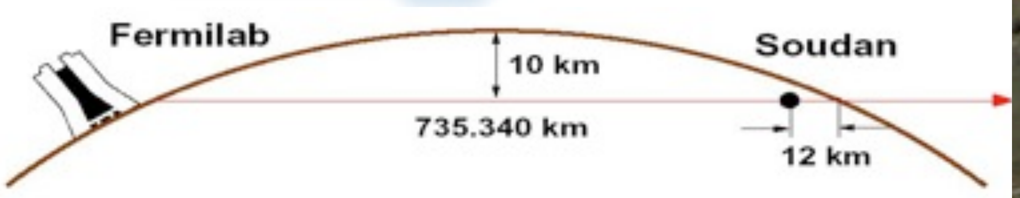

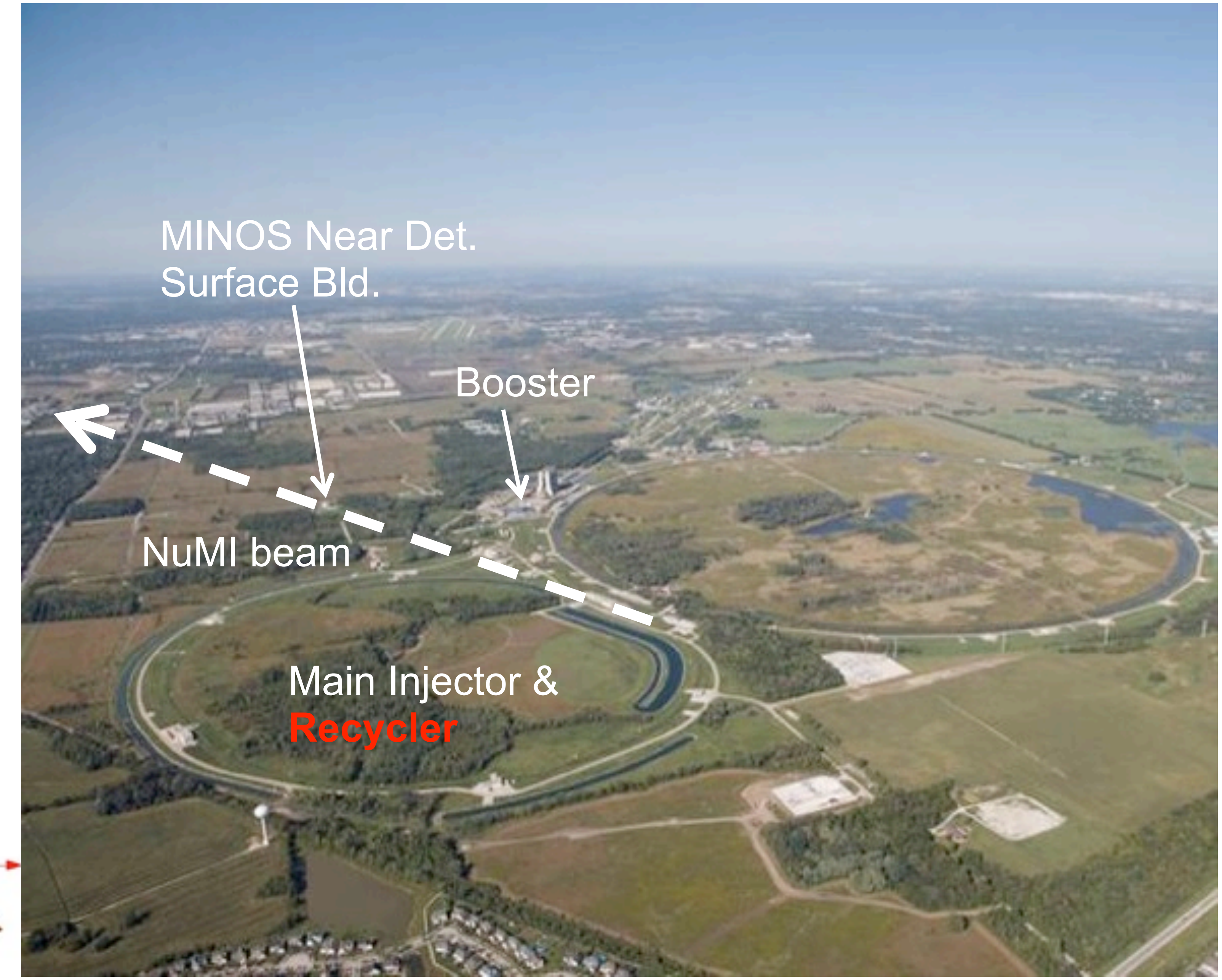

NuMI Beam

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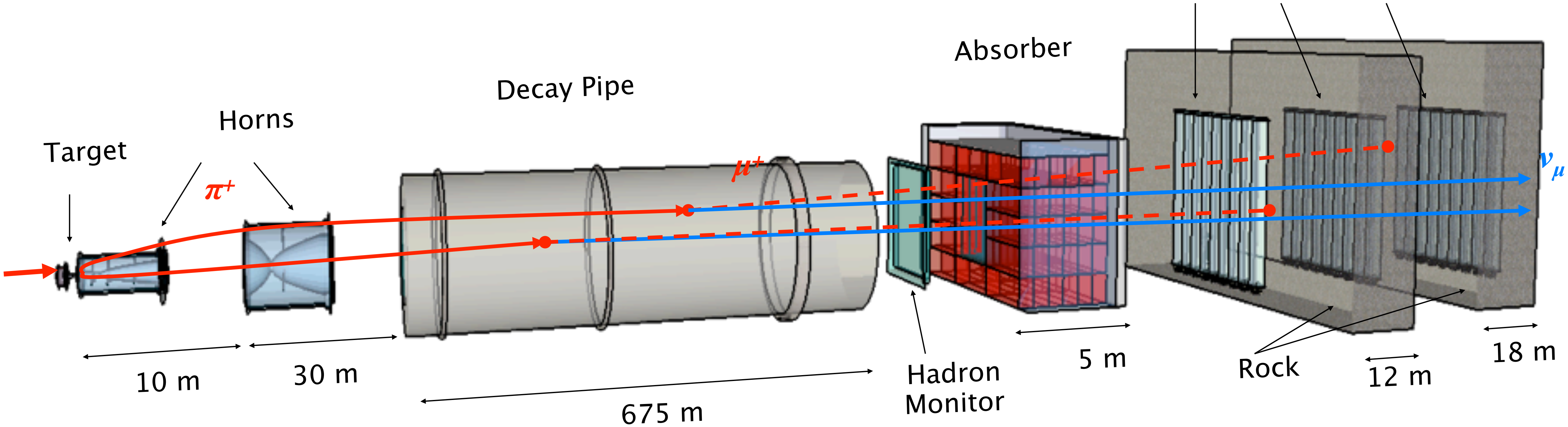
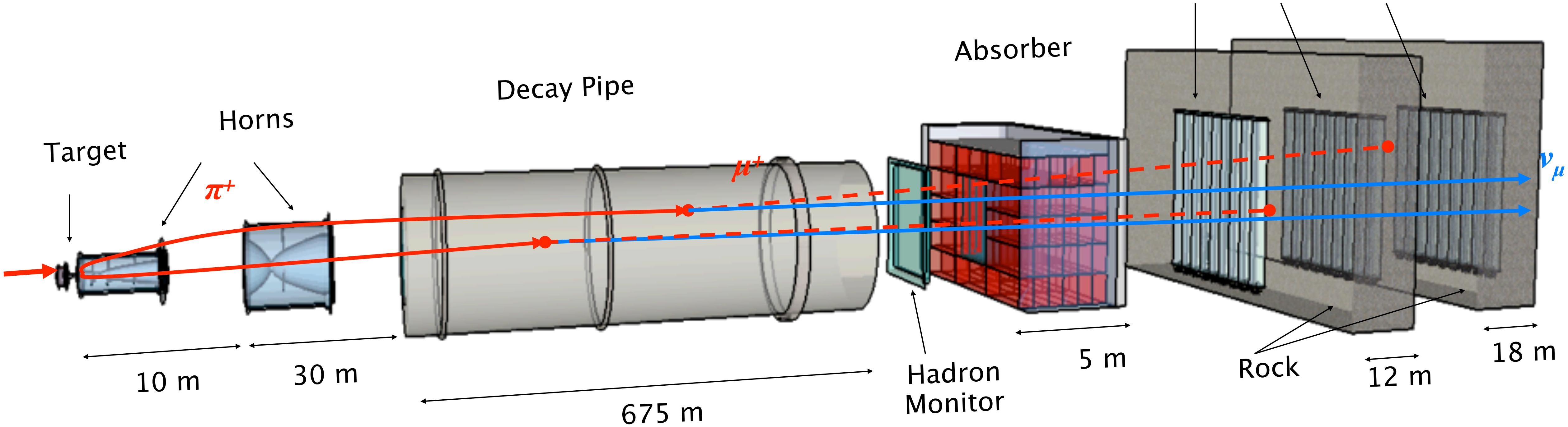


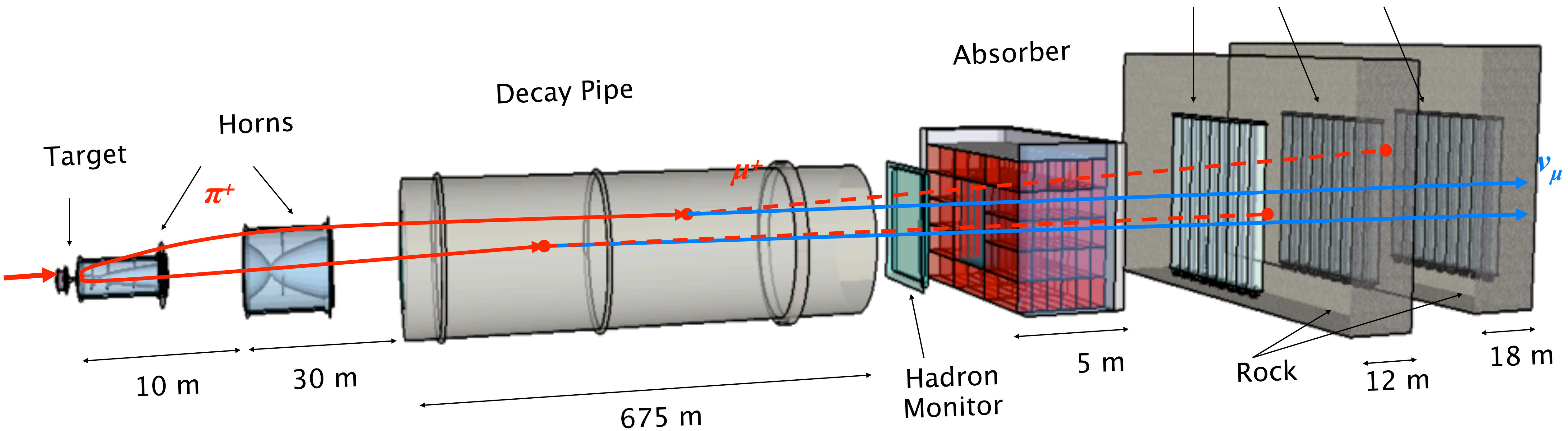
Target
Horns
π^+
Decay Pipe
μ^+
Absorber
ν_μ
10 m
30 m
675 m
Hadron
Monitor
5 m
Rock
12 m
18 m

NuMI Beam



Proton Source:
Fermilab Main Injector, 120 GeV p's
2.2s rep rate
10μs pulse length
up to 320 kW delivered on target

NuMI Beam



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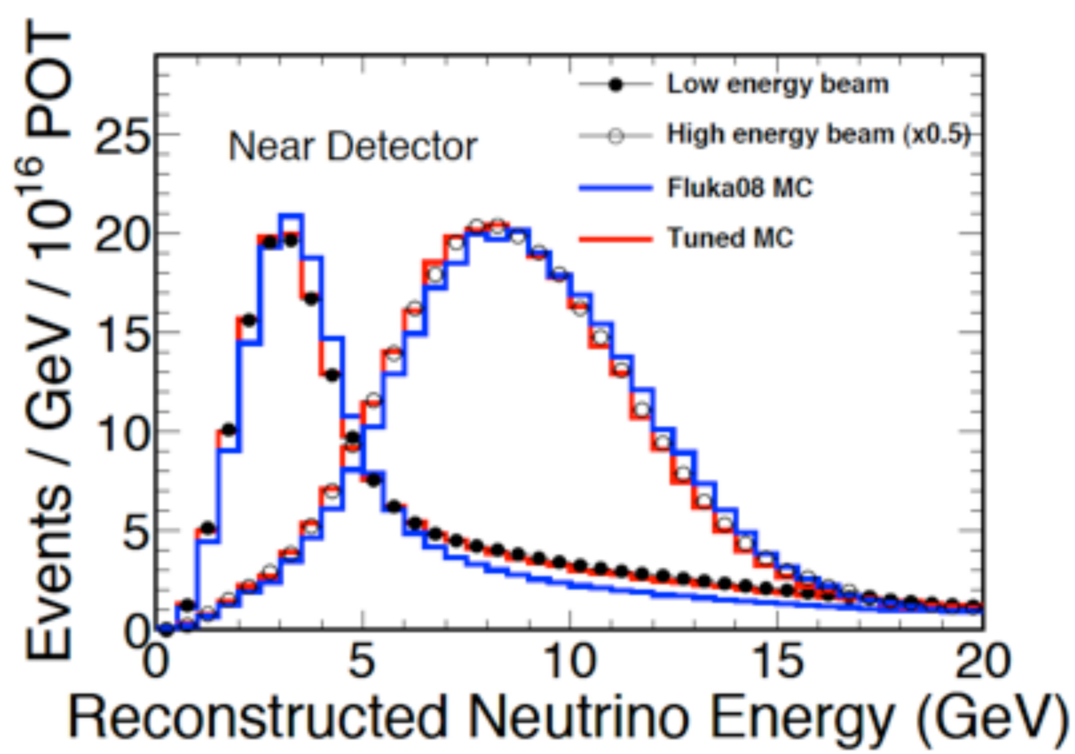
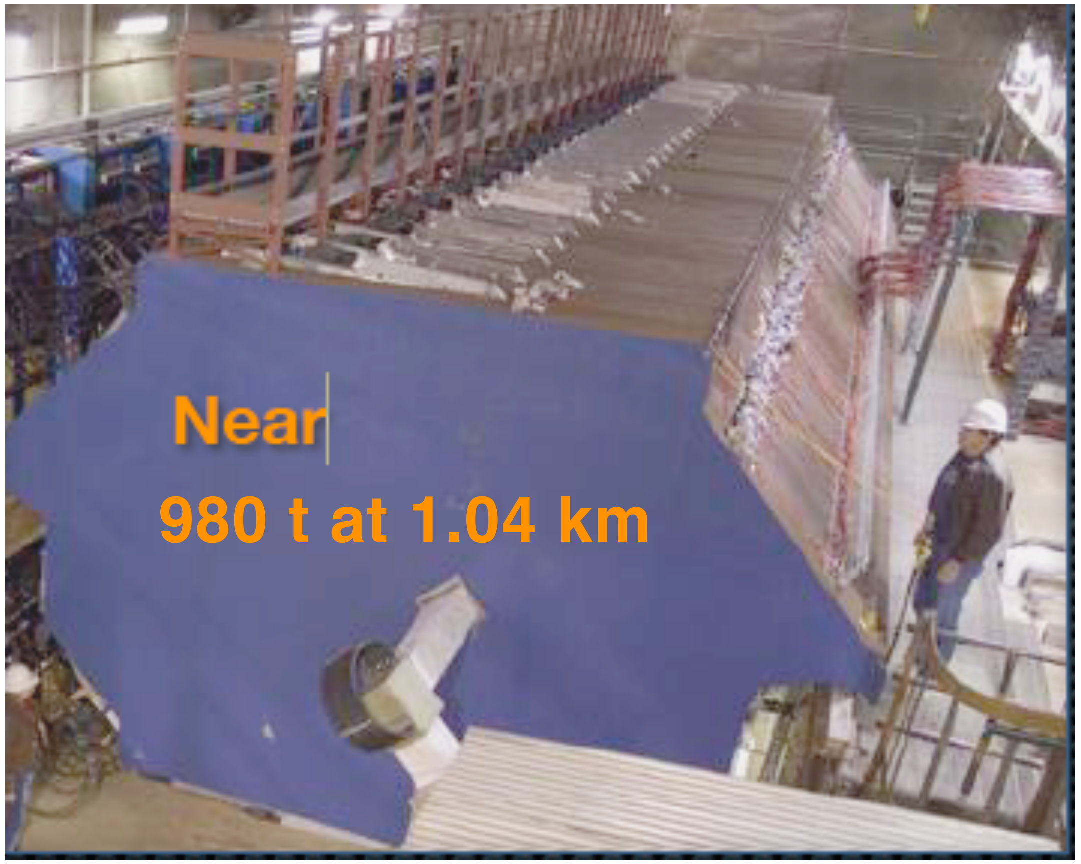
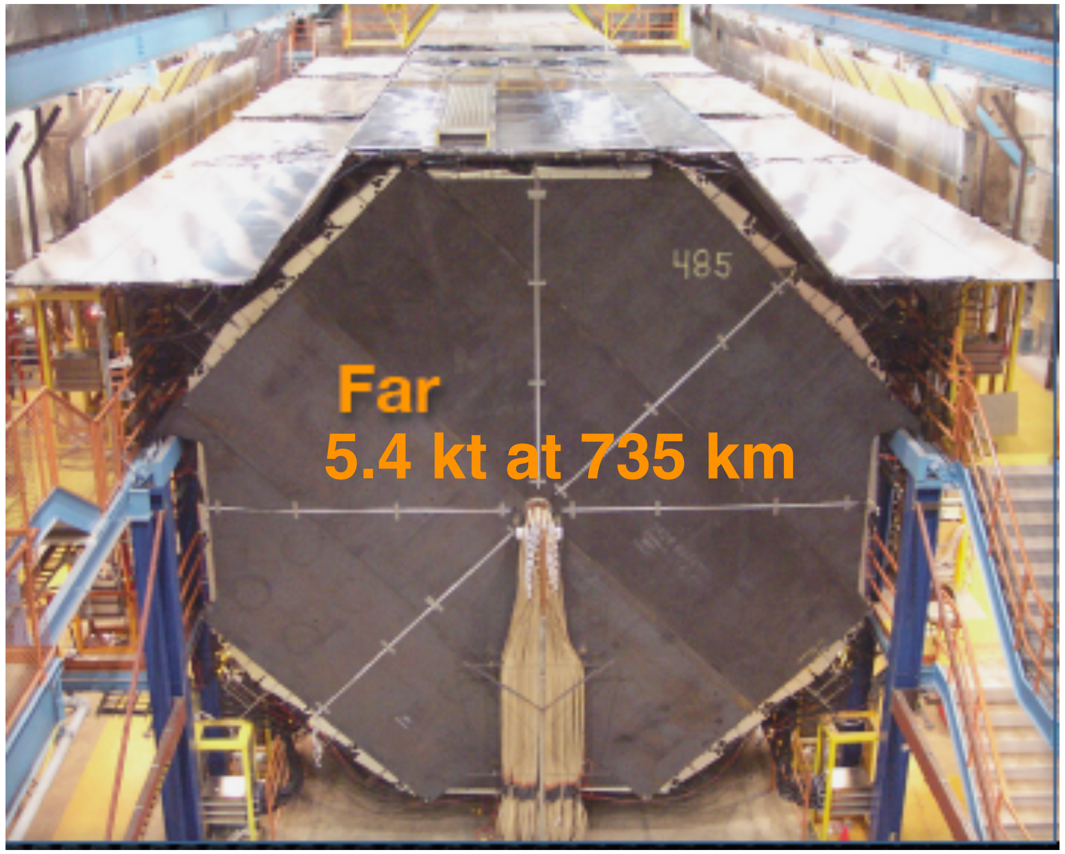


Target to first horn separation is variable
Allows different ν spectra
Allows tuning of hadron production spectra

MINOS Detectors

MINOS Detectors





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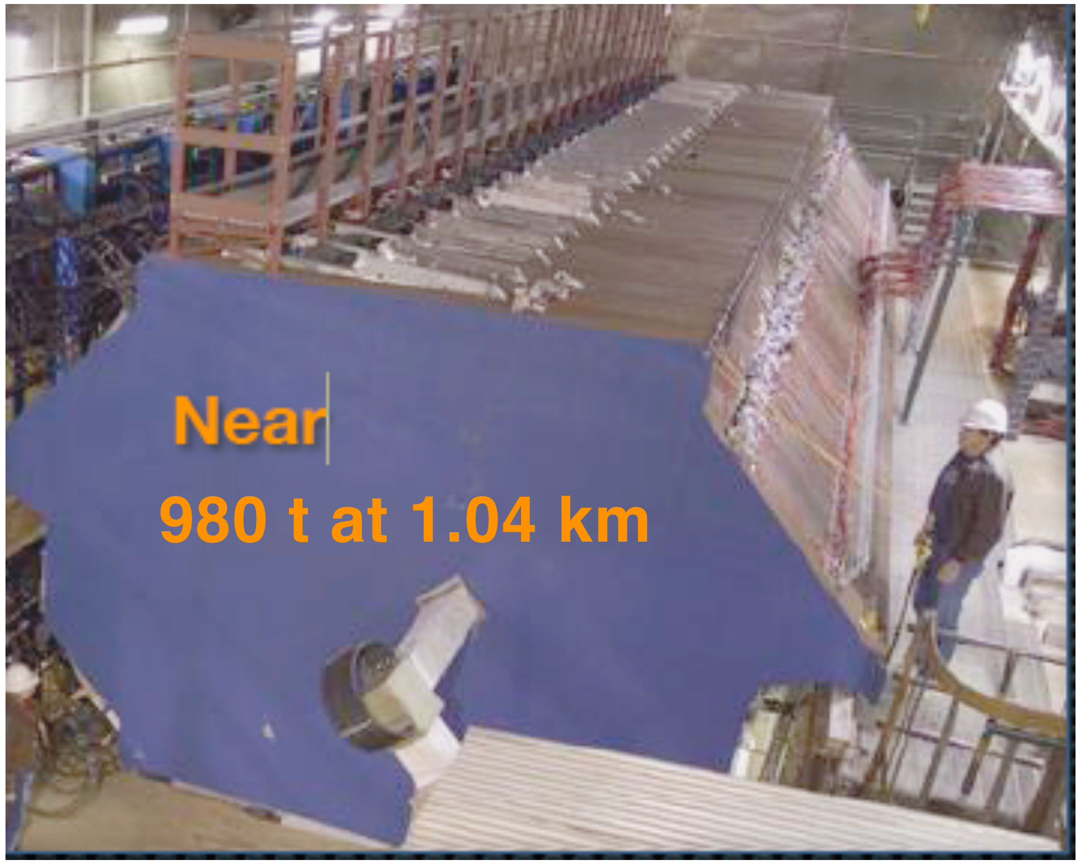

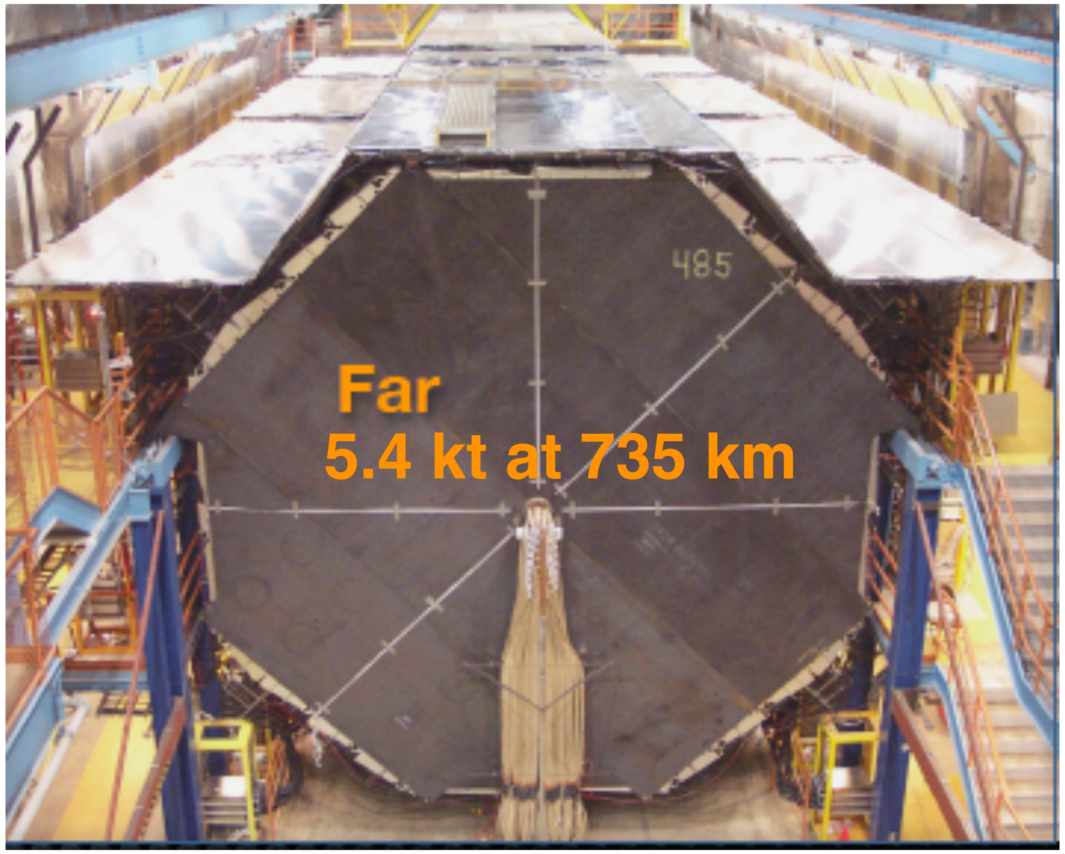

- As similar as possible functionally
- Alternating layers of steel (2.5 cm thick) and scintillator
- Alternating scintillator planes at 90 deg, 4.1 cm strips
- Light collection by wavelength shifting fibers
- Readout by 64 ch(ND) or 16 ch(FD) multi-anode PMT's
- Magnetized, average B field 1.3 T

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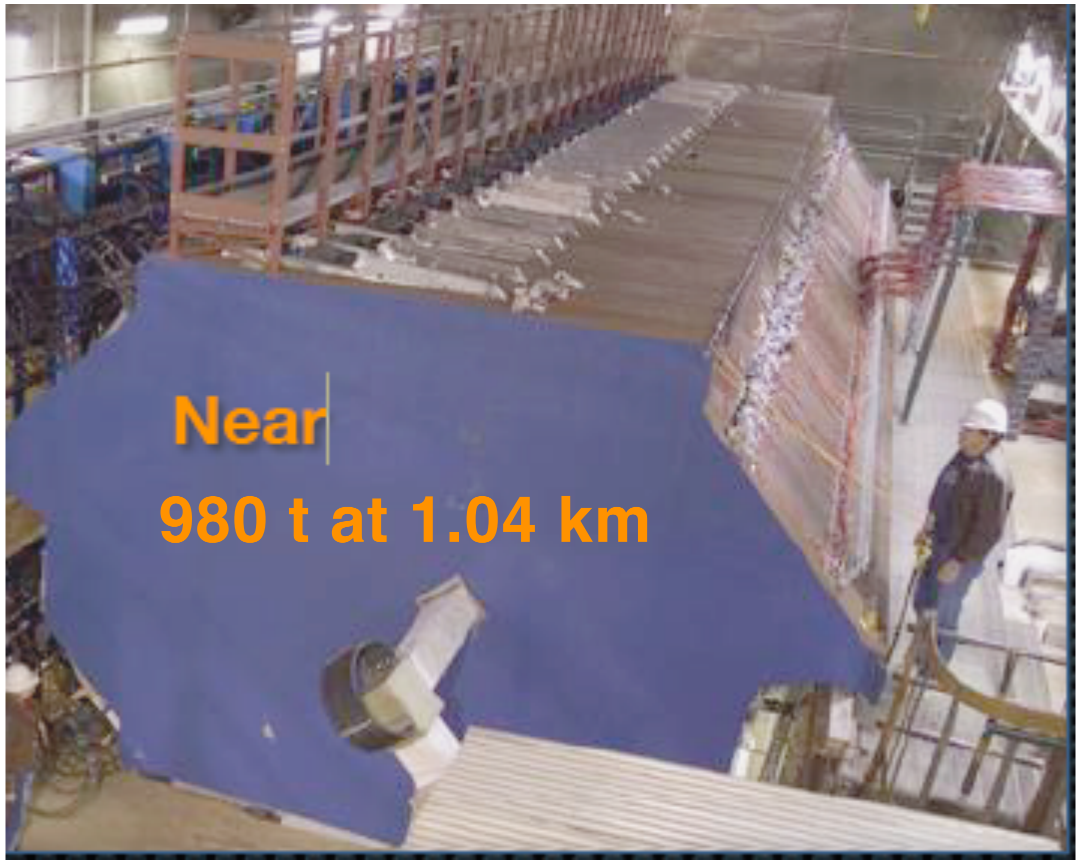

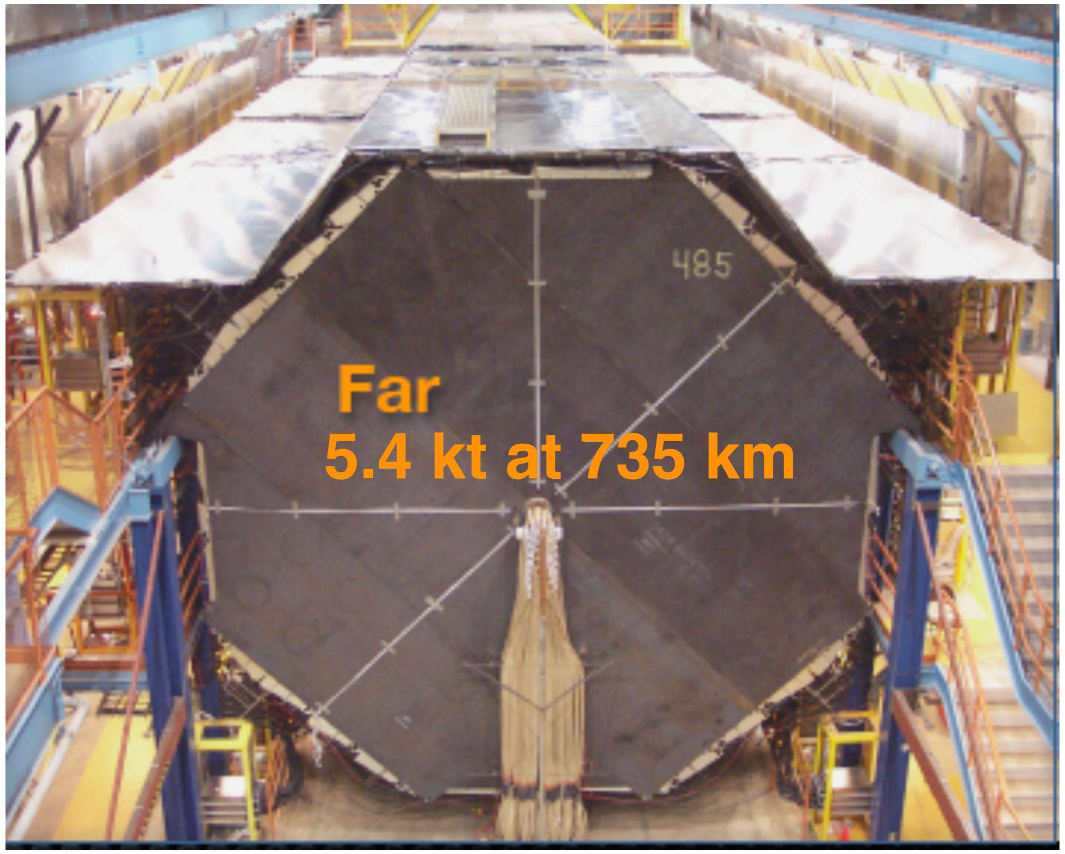

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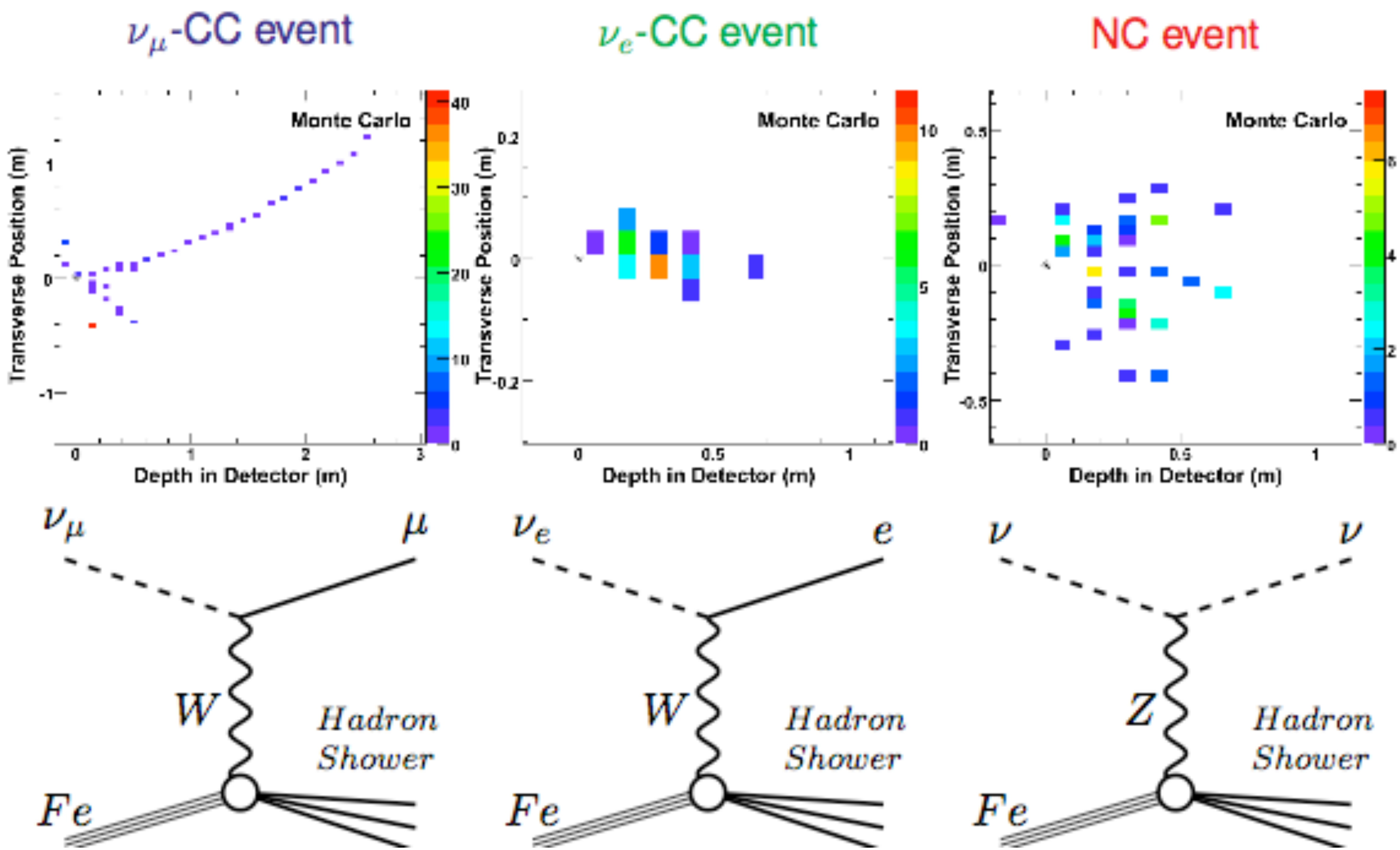
Measurements in ND are used to predict flux in FD

Event Topologies



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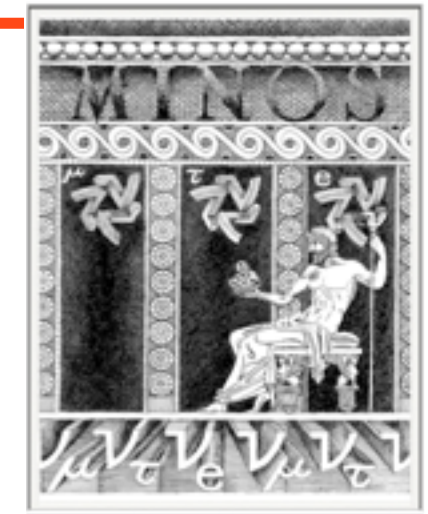

Neutrino '98, Takayama June/1998

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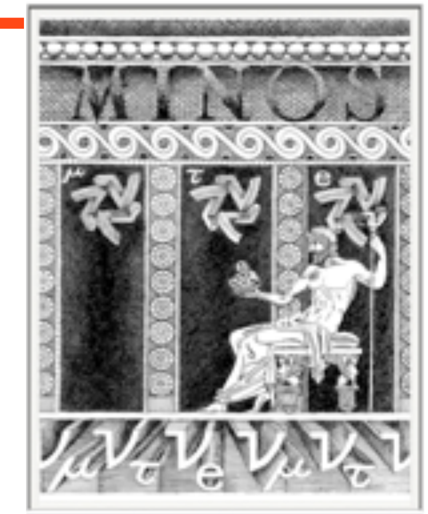

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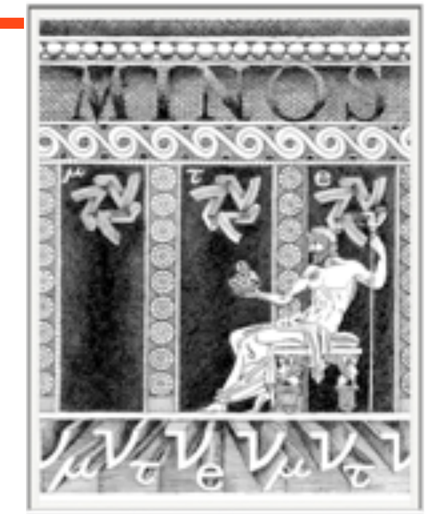

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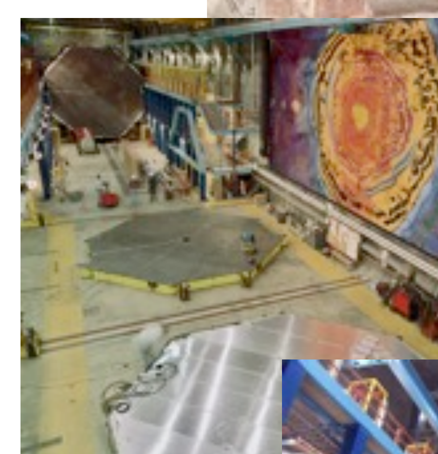

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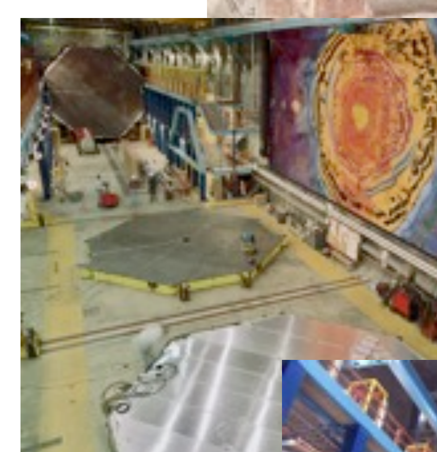

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- End of Data Taking — June/2012

Data Taking History

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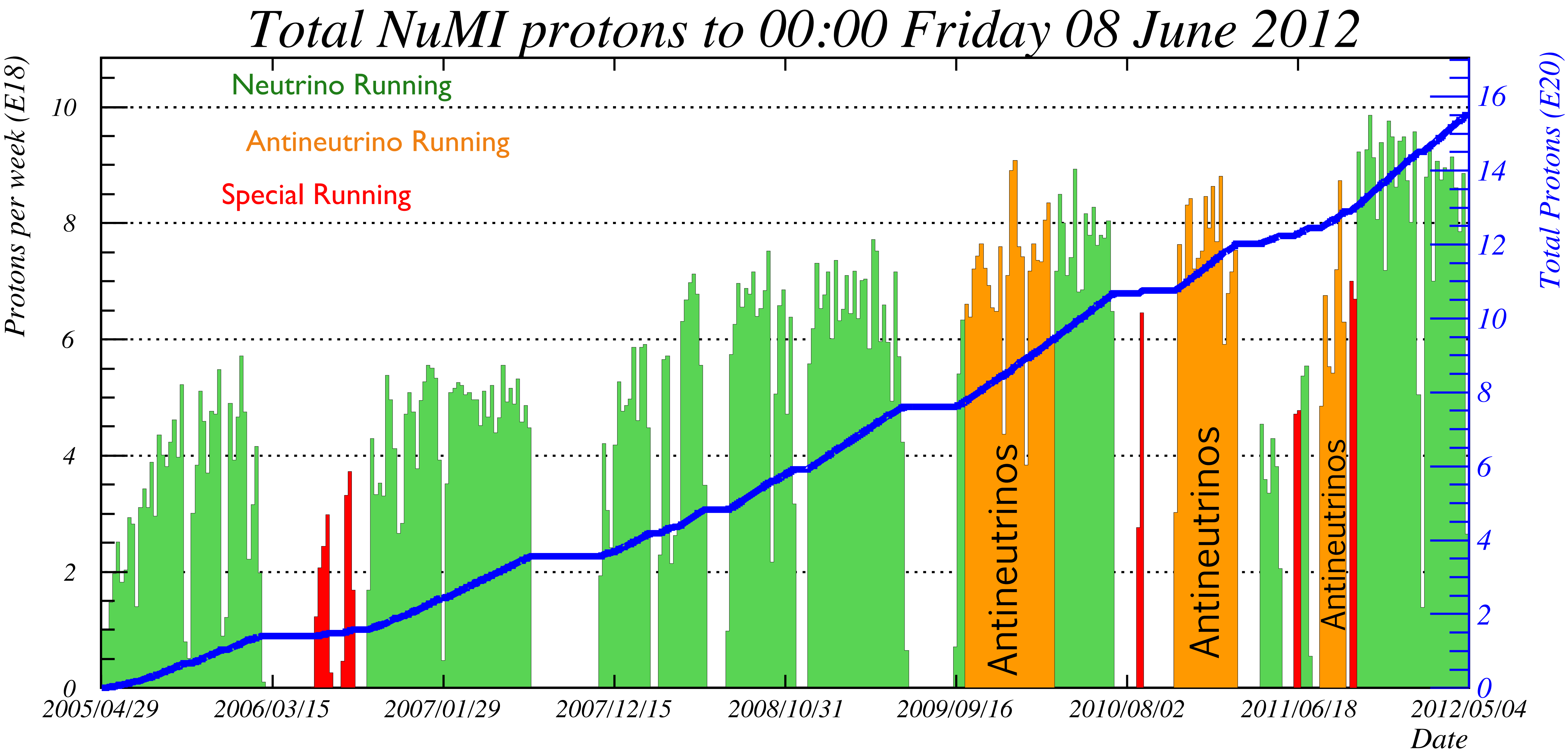

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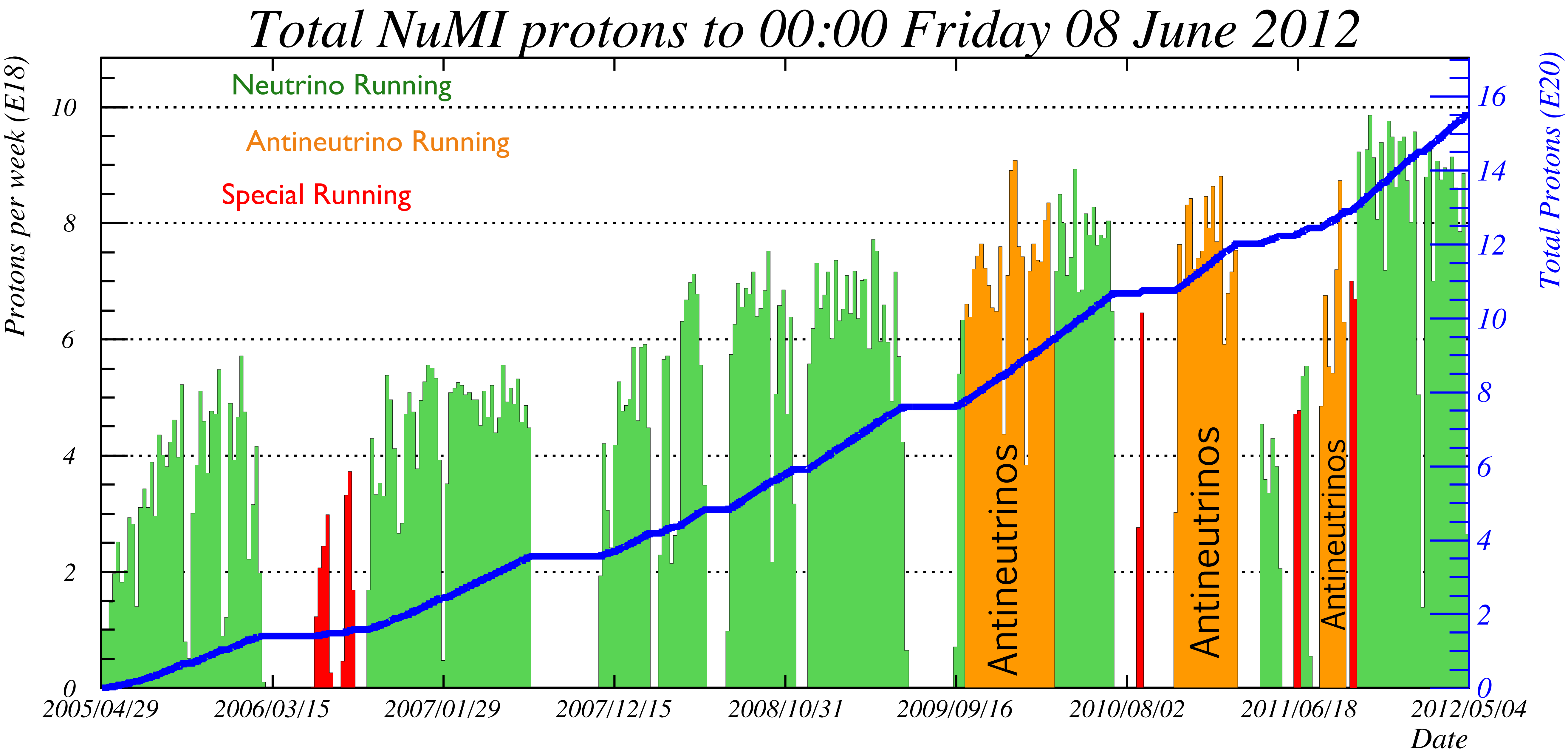
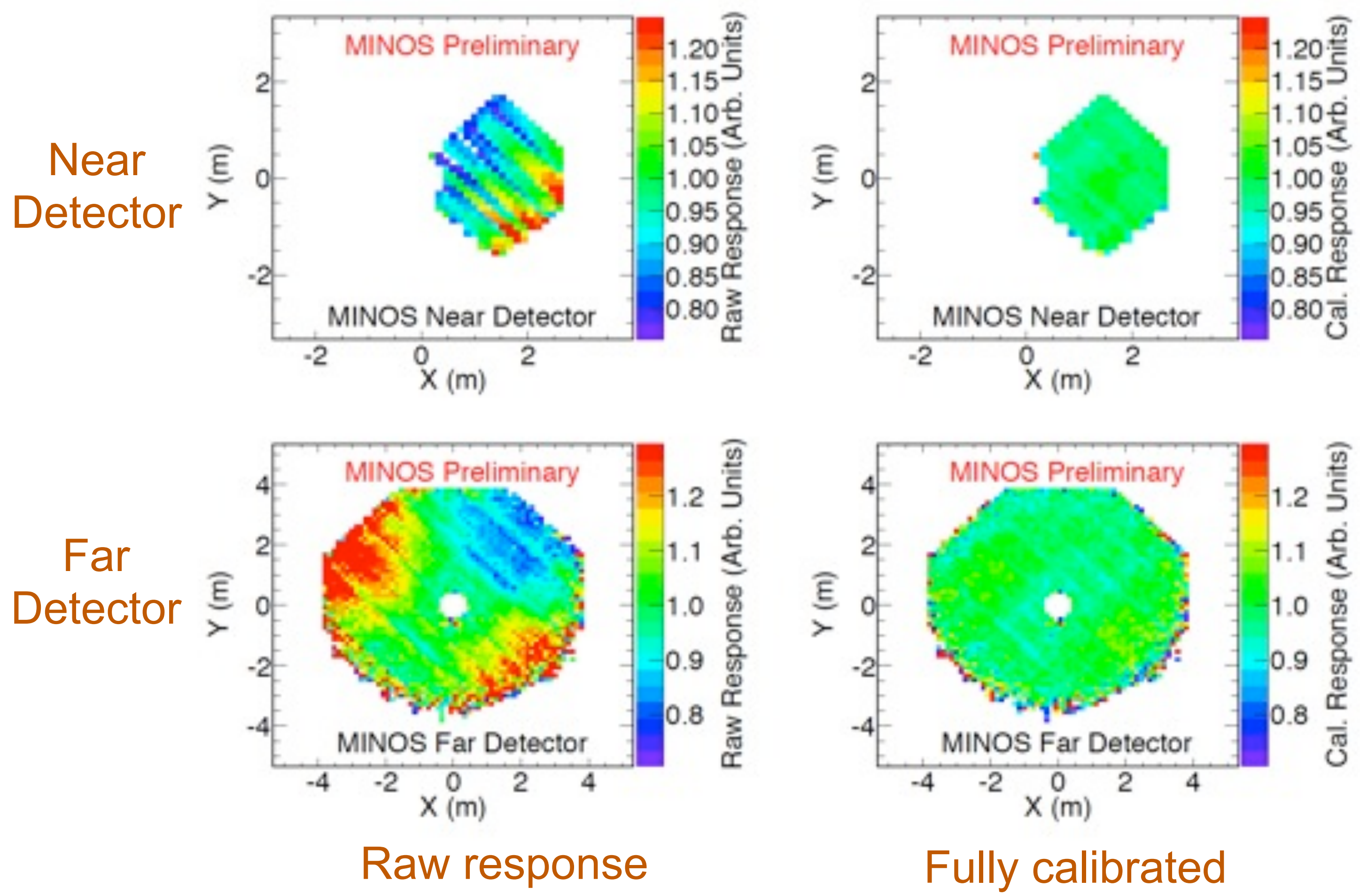


In addition MINOS has obtained 37.88 kt yrs of atmospheric ν data

Detector performance, stability

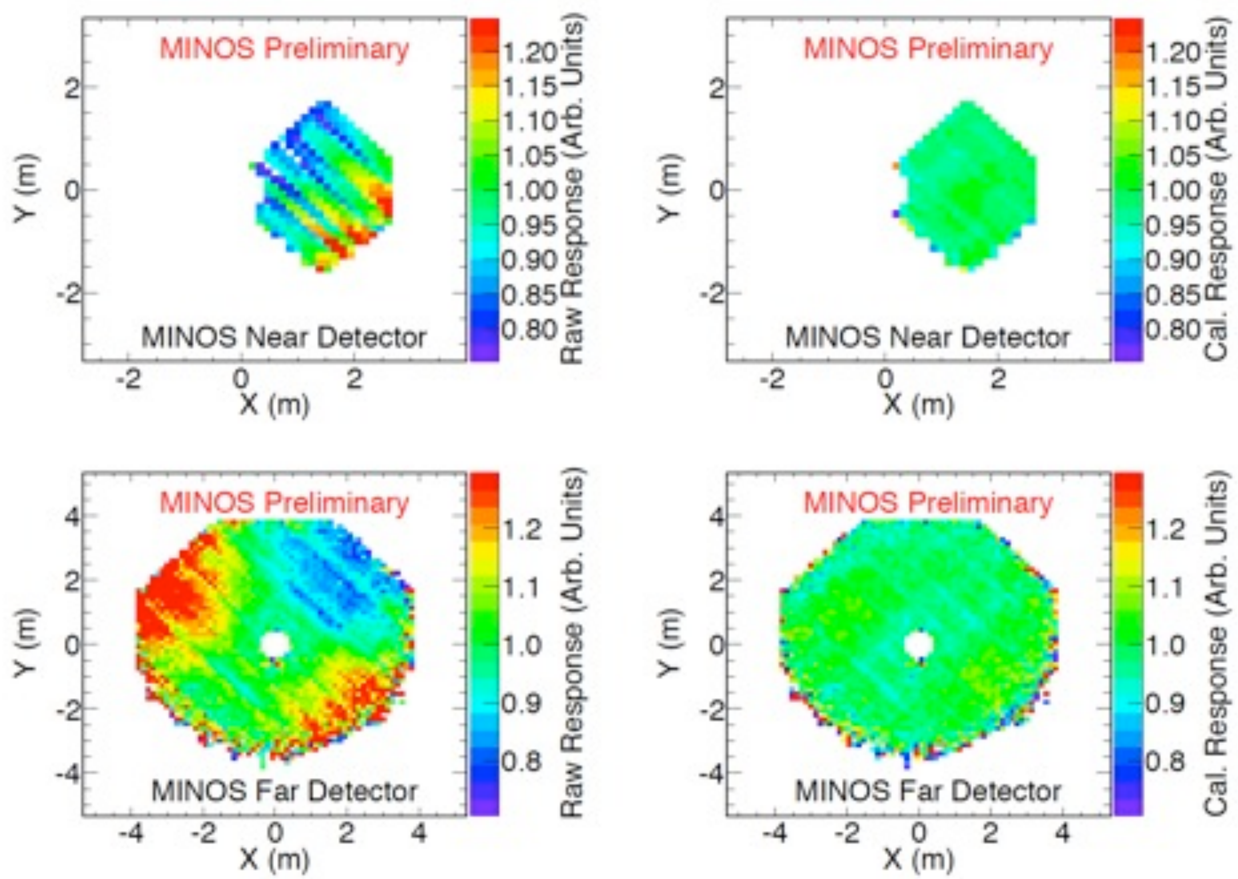
Detector performance, stability



Detector performance, stability

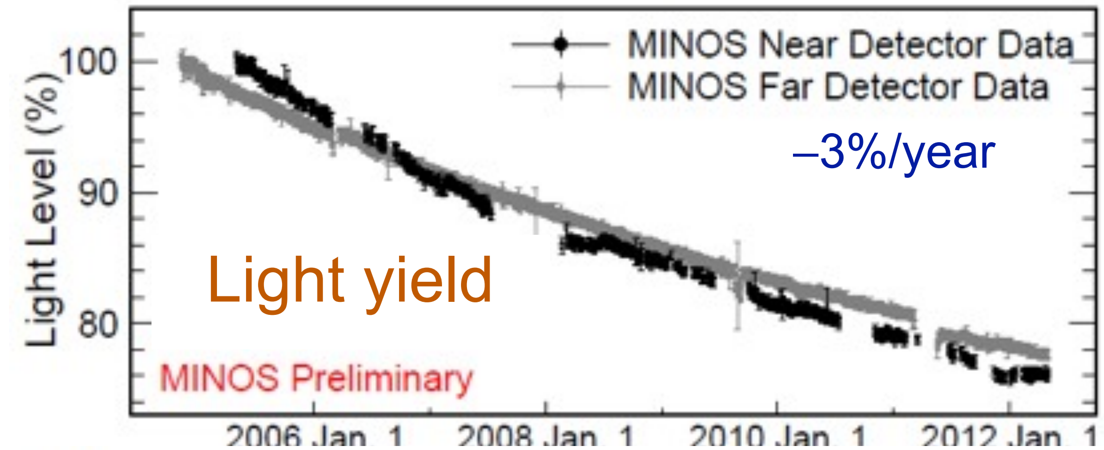
Near Detector

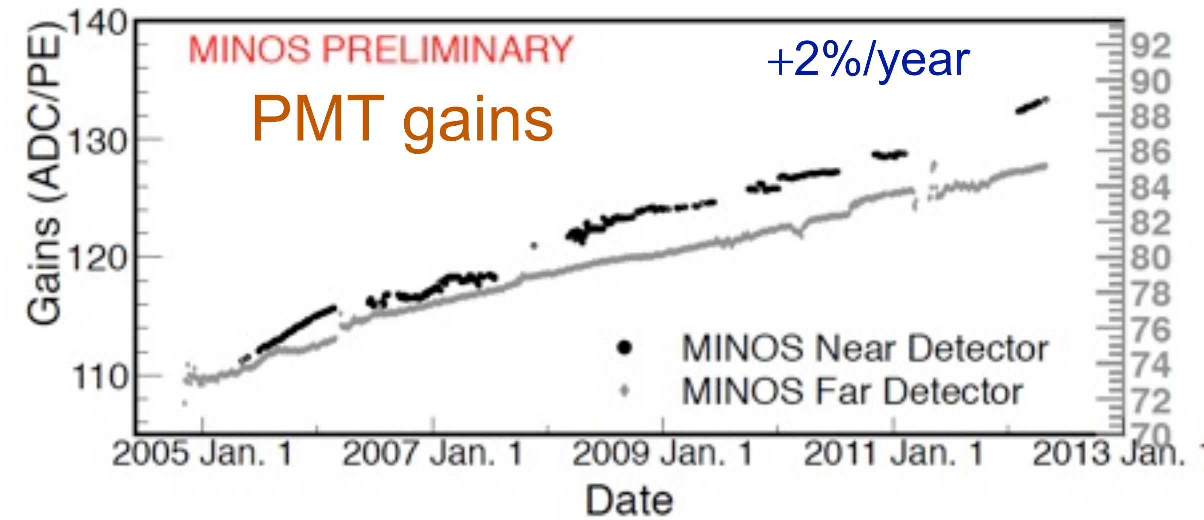
Far Detector



Raw response

Fully calibrated





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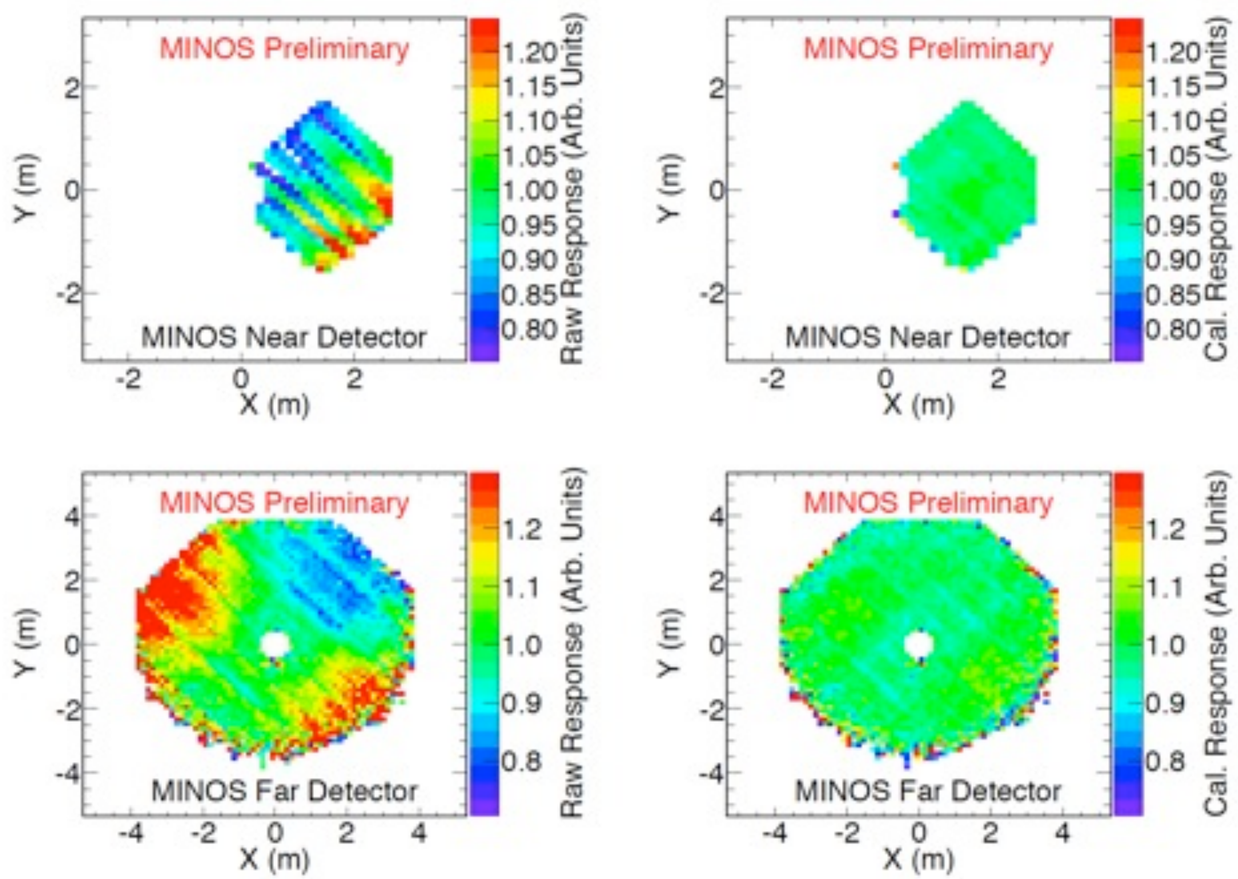

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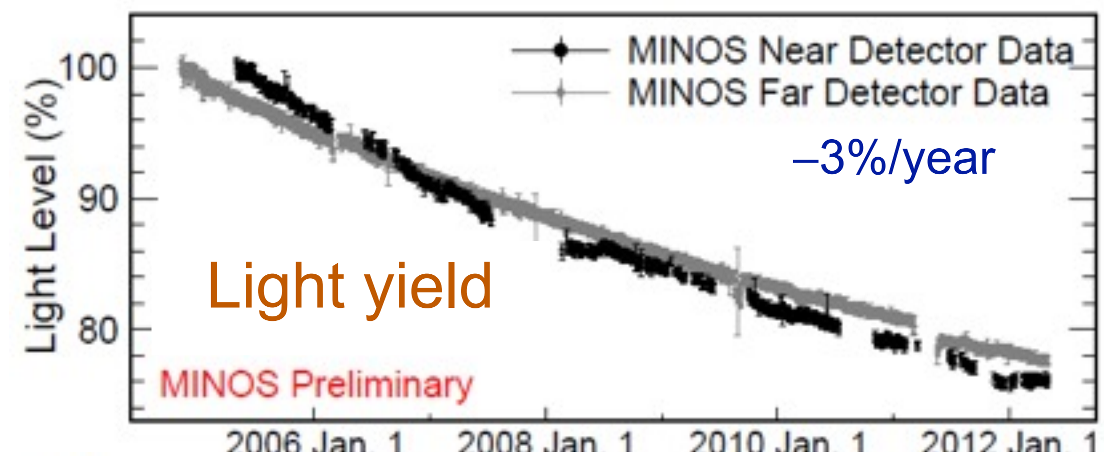

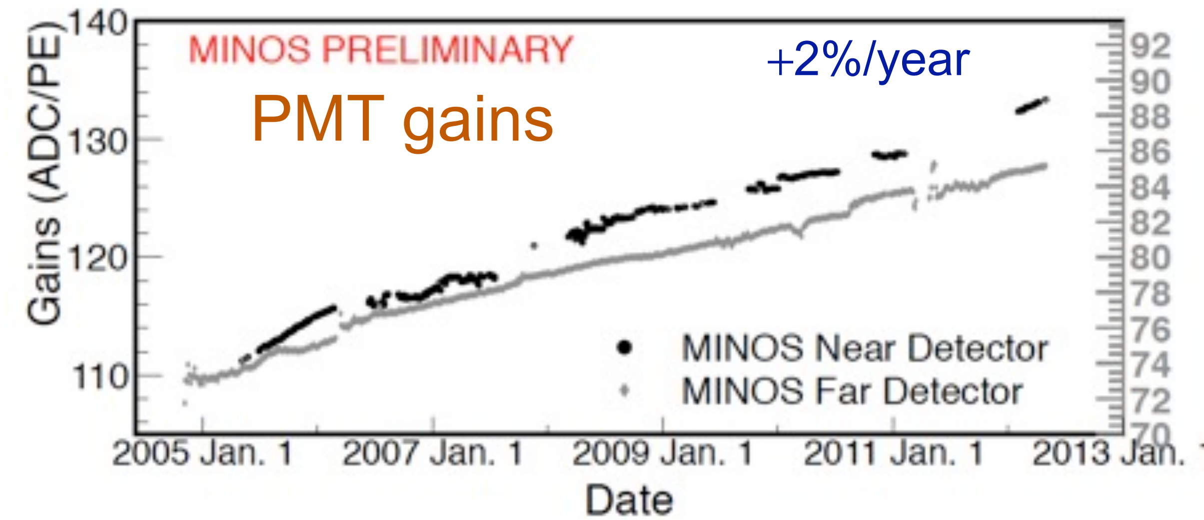

Use light injection, through-going muons and stopping muons for calibration and monitoring

What can MINOS do?

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

$\alpha = (e, \mu, \tau)$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Δm^2_{31} Δm^2_{21} Irrelevant here

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Disappearance experiment: $\nu_\mu \rightarrow \nu_x$

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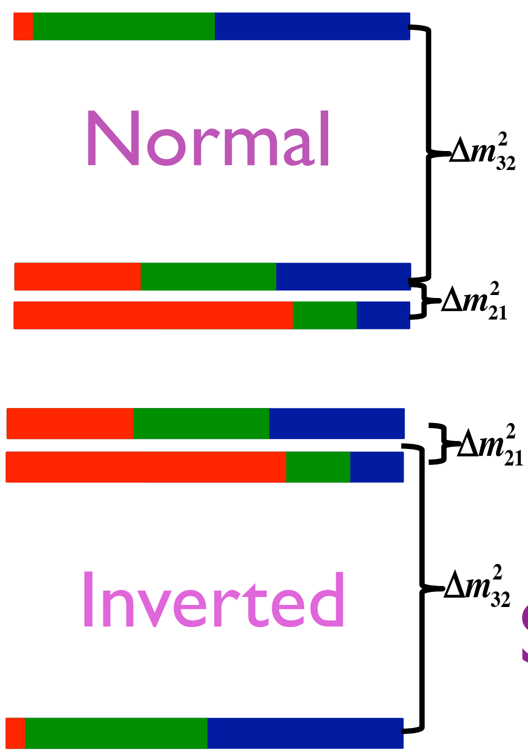

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And atmospheric ν's give information on mass hierarchy

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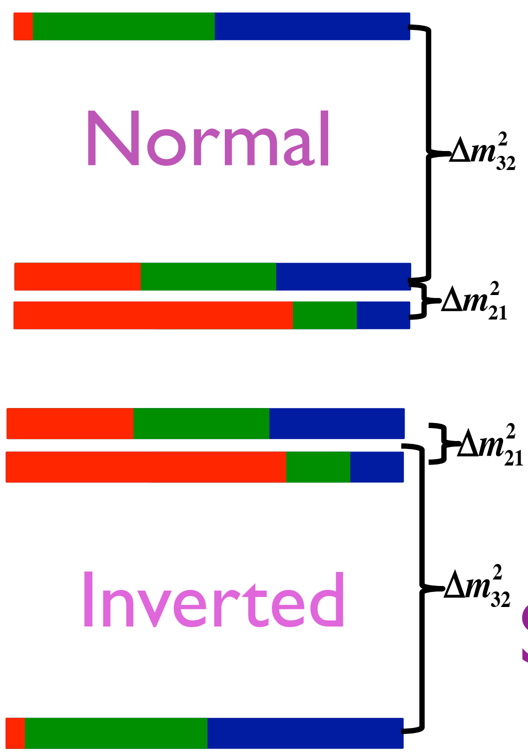

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} Discuss these first (2-flavor)

And atmospheric ν's give information on mass hierarchy

Combined Atmospheric and Beam Disappearance Analysis

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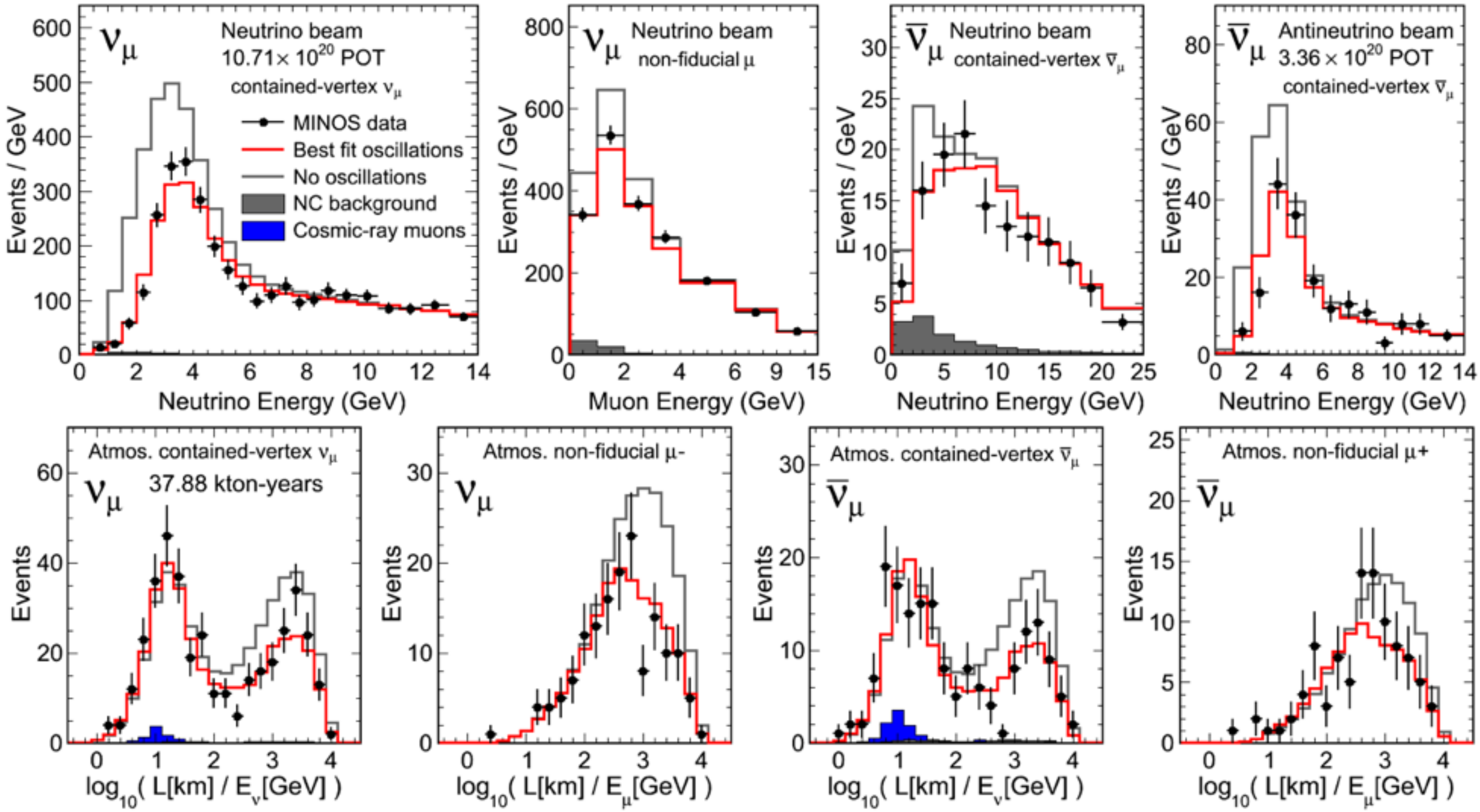

ν_μ, $\bar{\nu}_\mu$ Comparison

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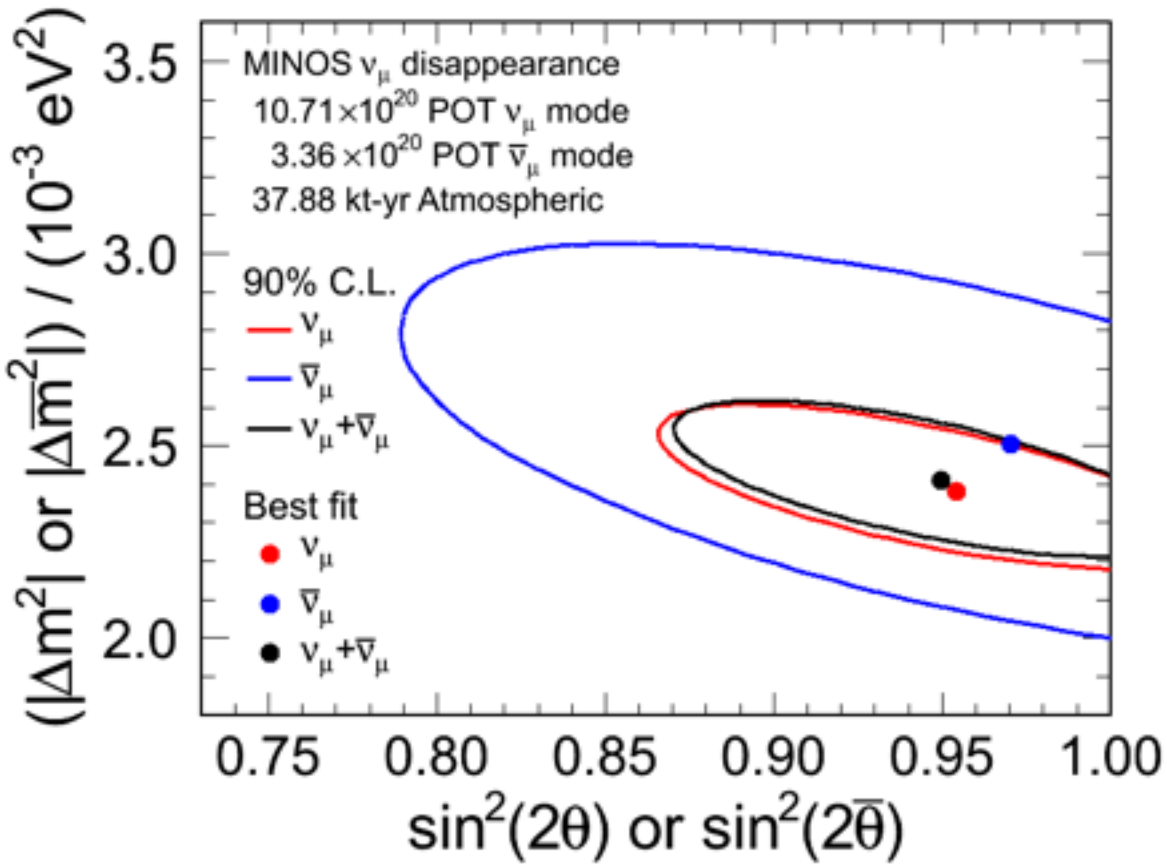

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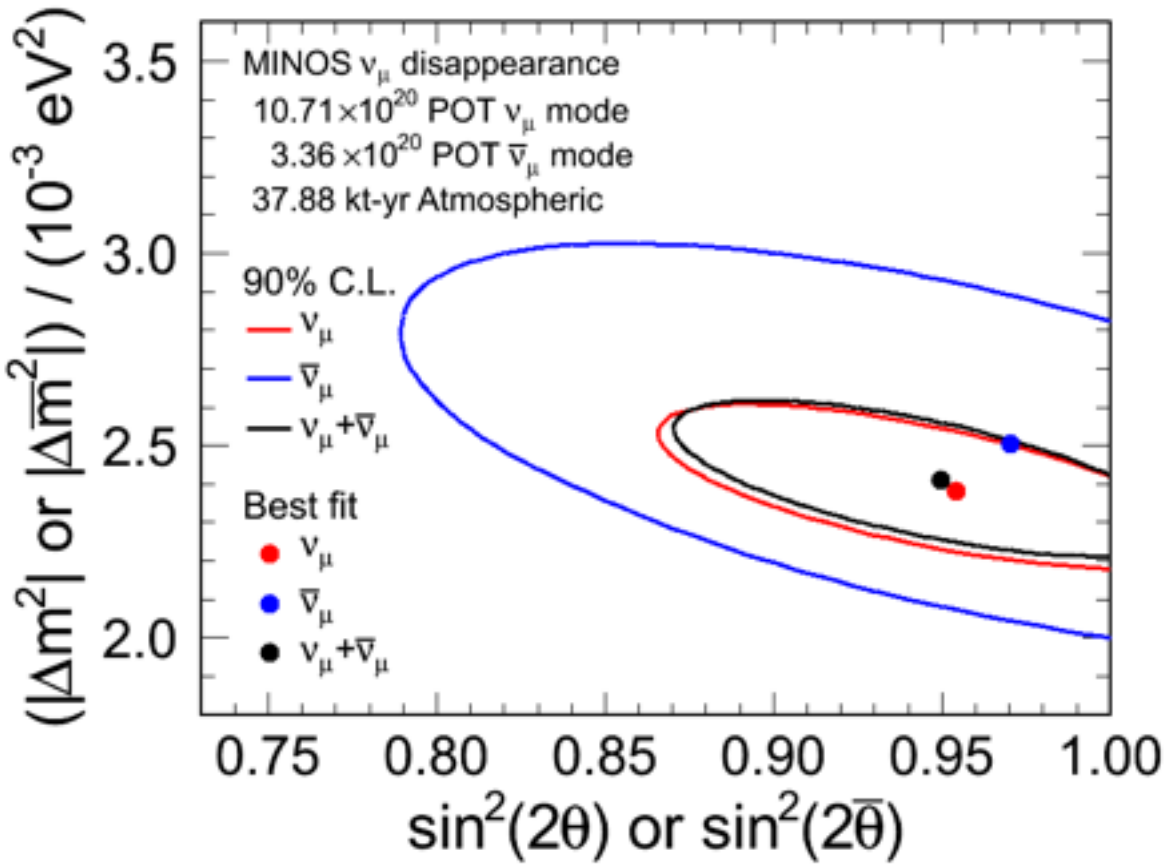

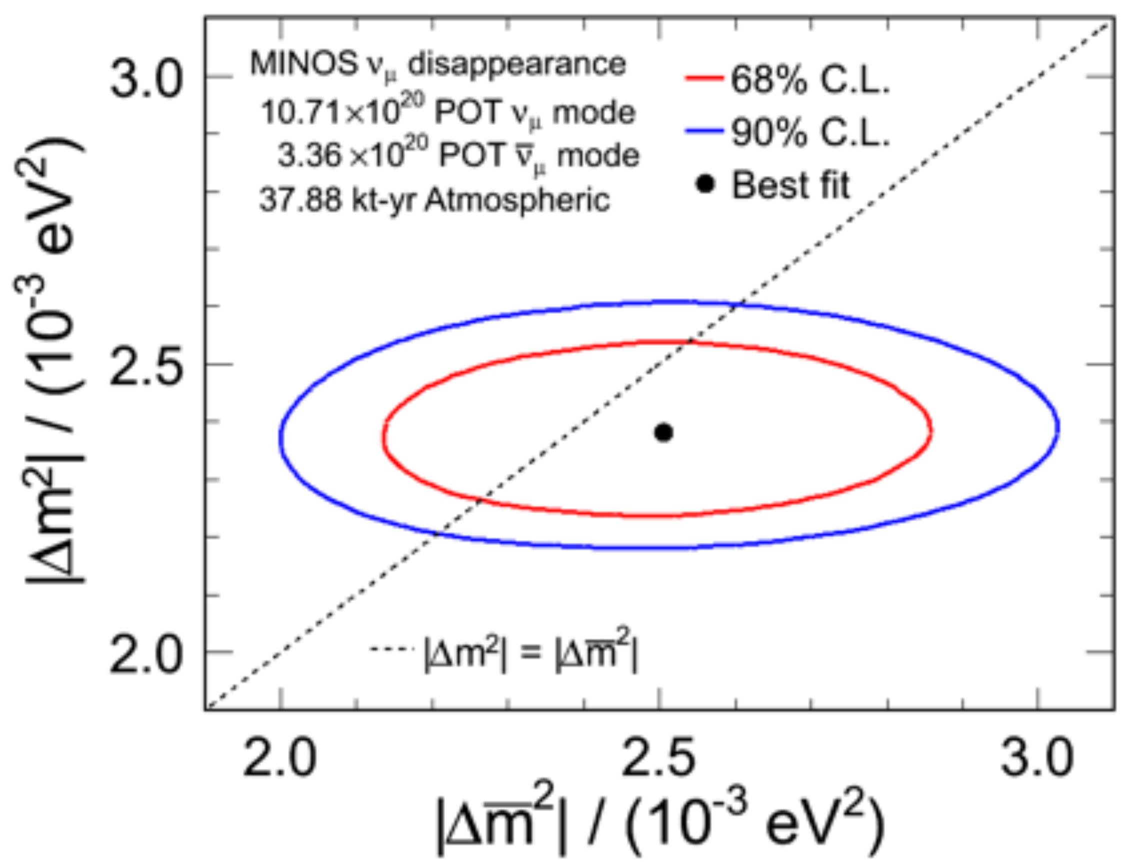

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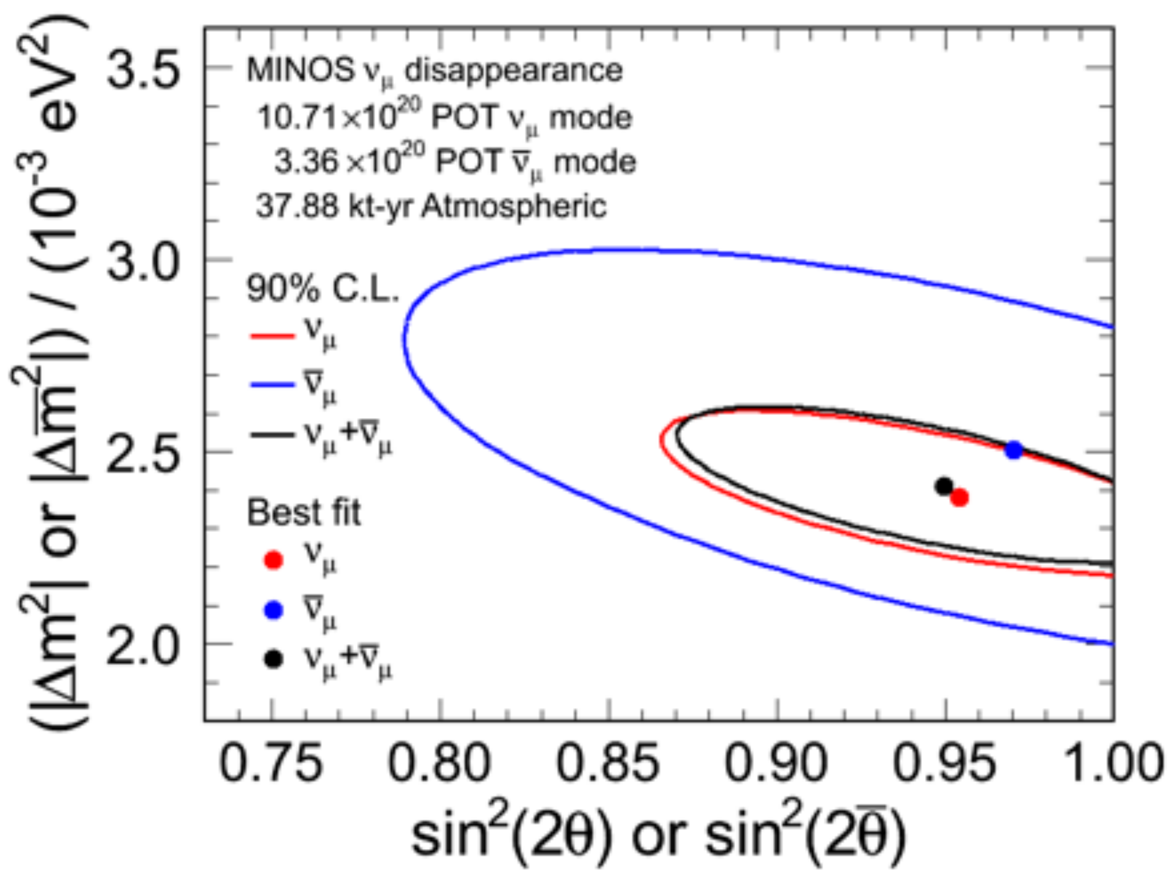
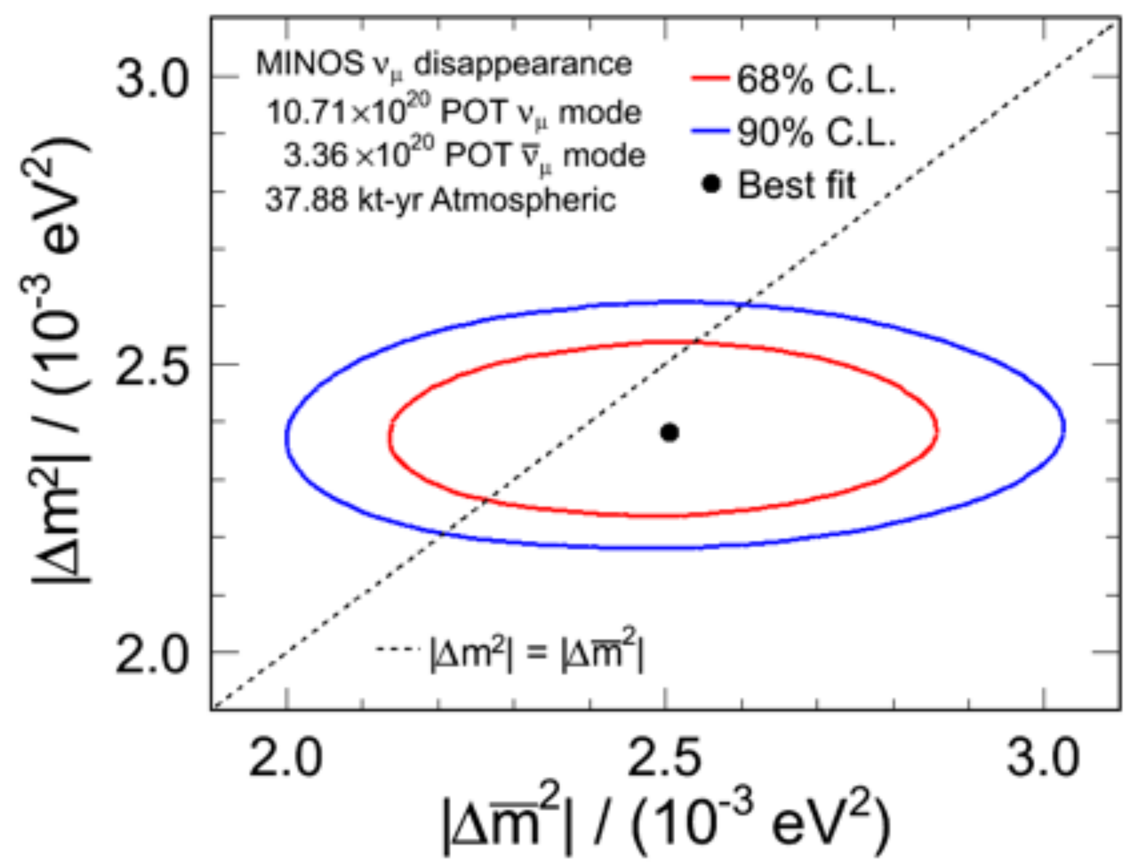




$\overline{\nu}$ oscillation parameters

$$\sin^2(2\overline{\theta}) = 0.97^{+0.03}_{-0.08}$$

$$\Delta\overline{m}^2 = 2.50^{+0.23}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2(2\overline{\theta}) > 0.83\ (90\% C.L.)$$

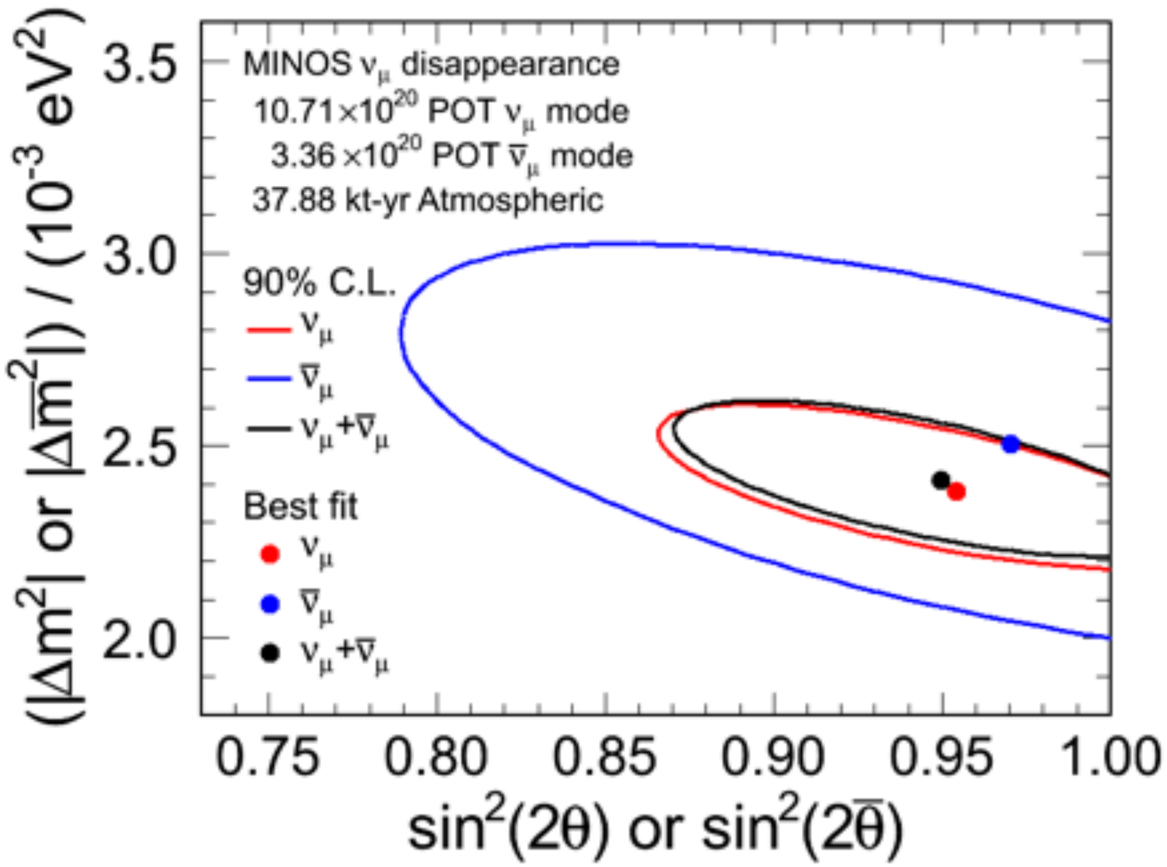
ν oscillation parameters

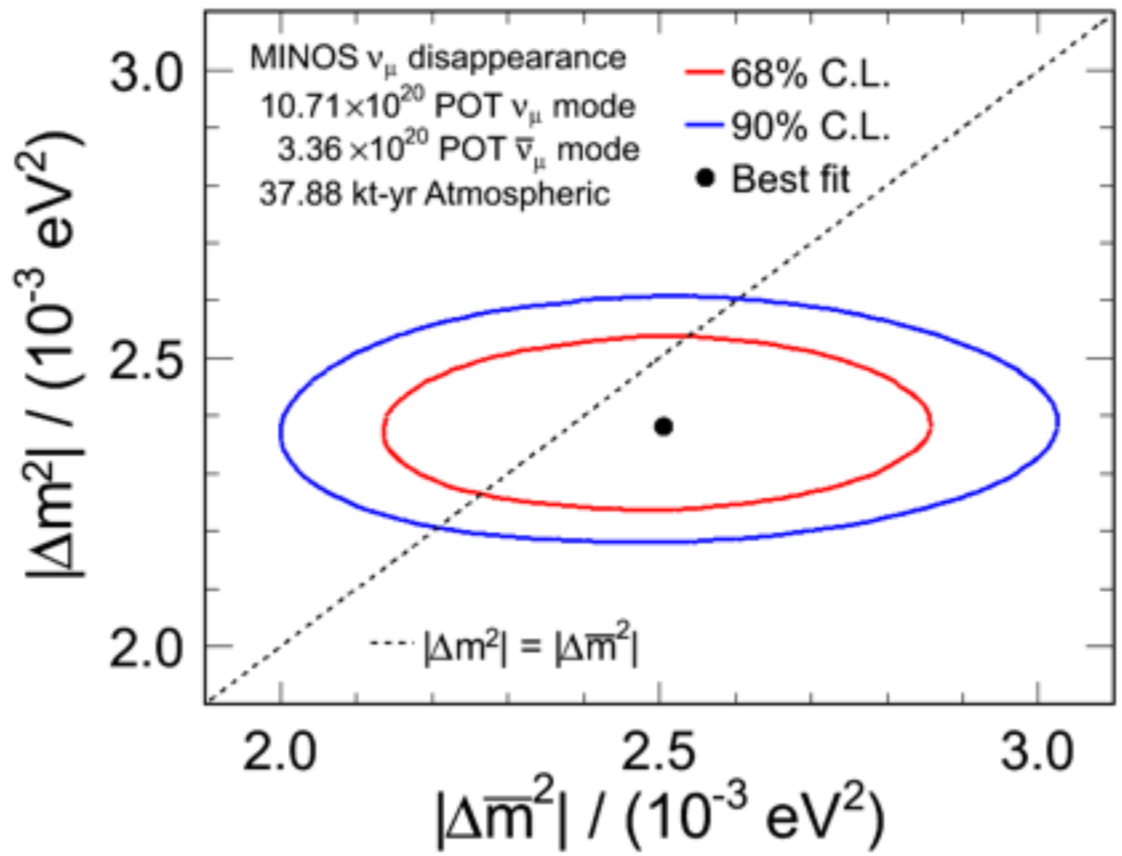
$$\sin^2(2\theta) = 0.95^{+0.035}_{-0.036}$$

$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) > 0.89\ (90\% C.L.)$$

ν_μ, $\bar{\nu}_\mu$ Comparison





$\bar{\nu}$ oscillation parameters

$$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08}$$

$$\Delta\bar{m}^2 = 2.50^{+0.23}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \ (90\% C.L.)$$

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Clearly there is good agreement in oscillation parameters

Results from Combined 2-flavor Analysis

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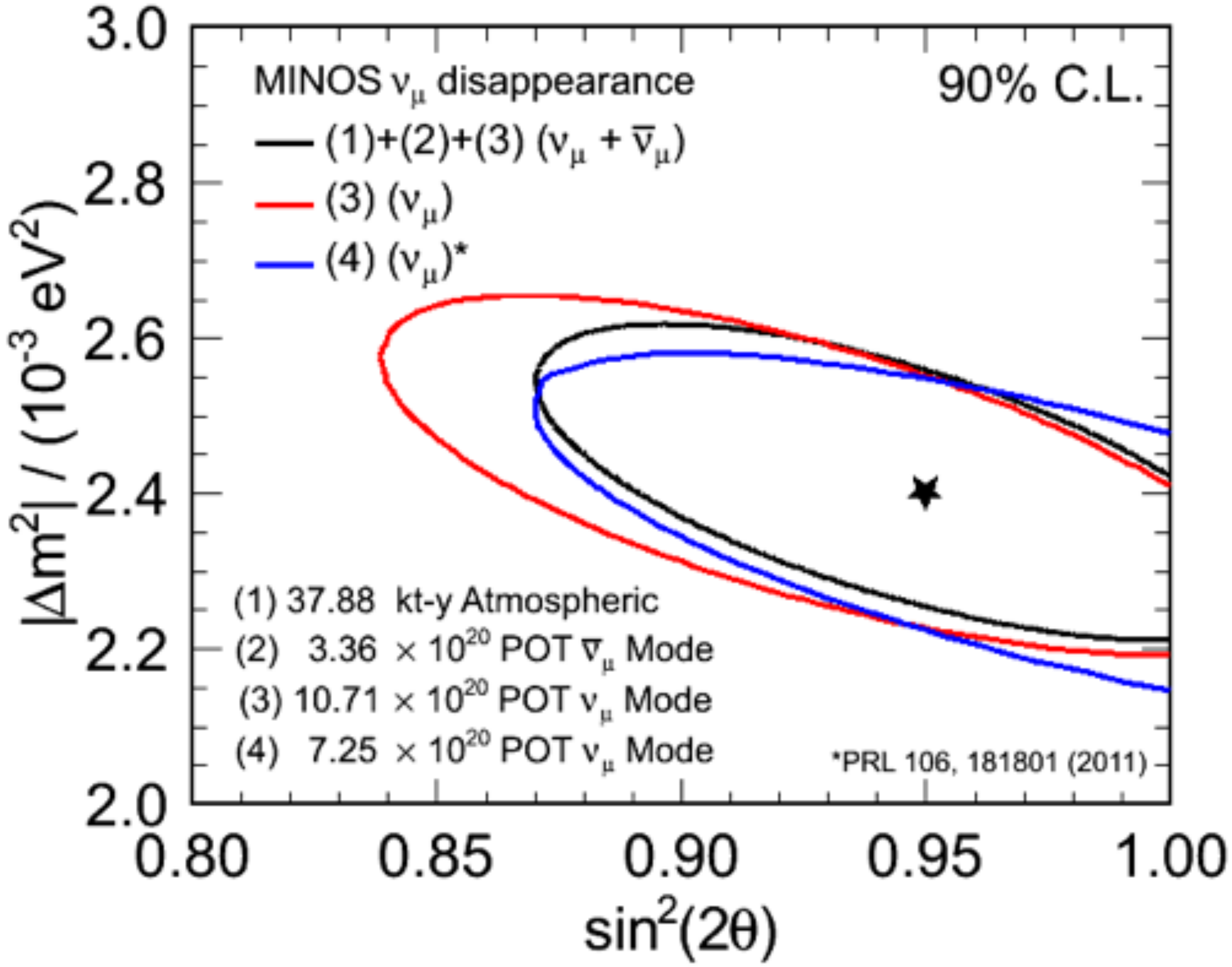

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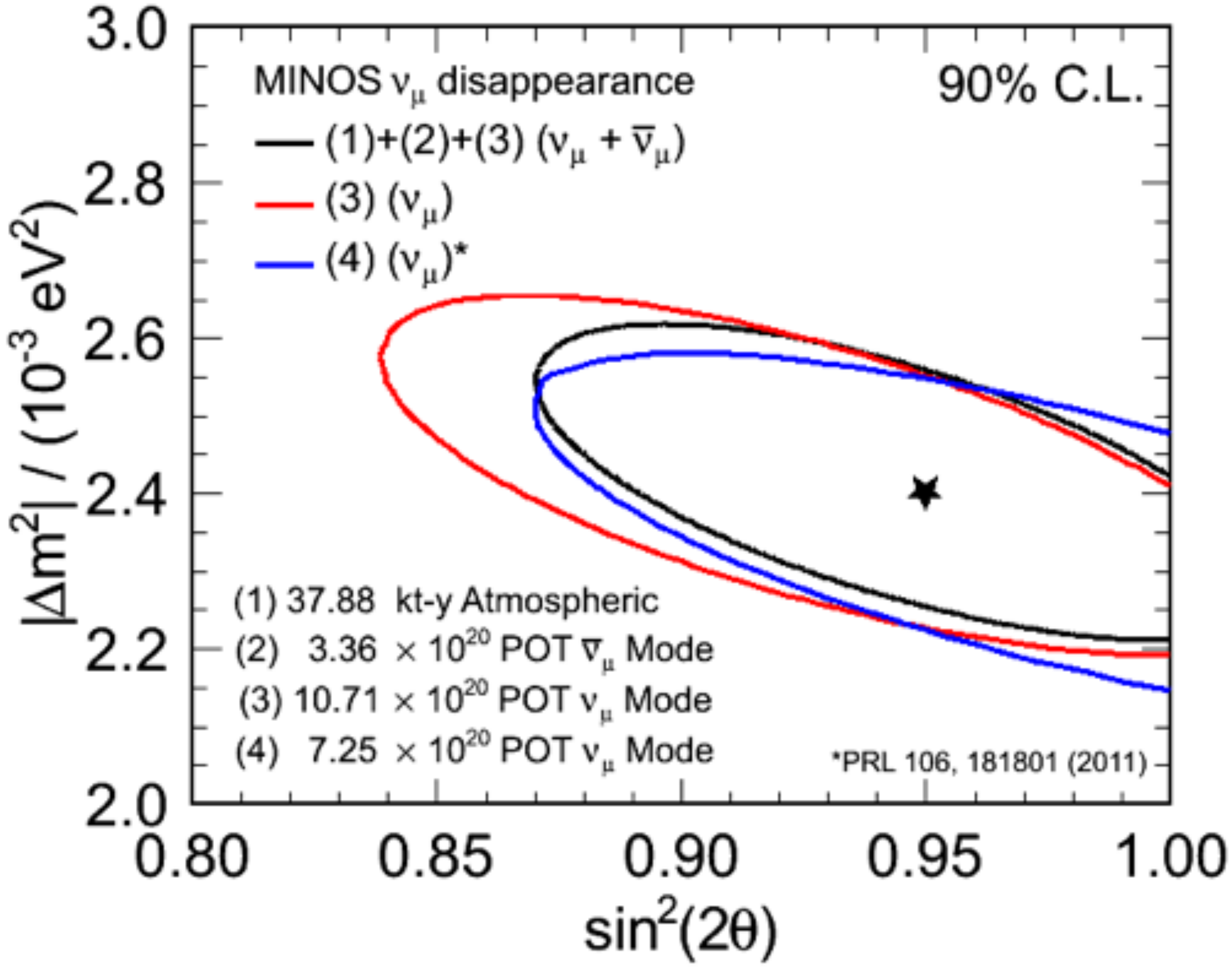

MINOS Final 2 flavor Results

$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} \mathrm{eV}^2$$
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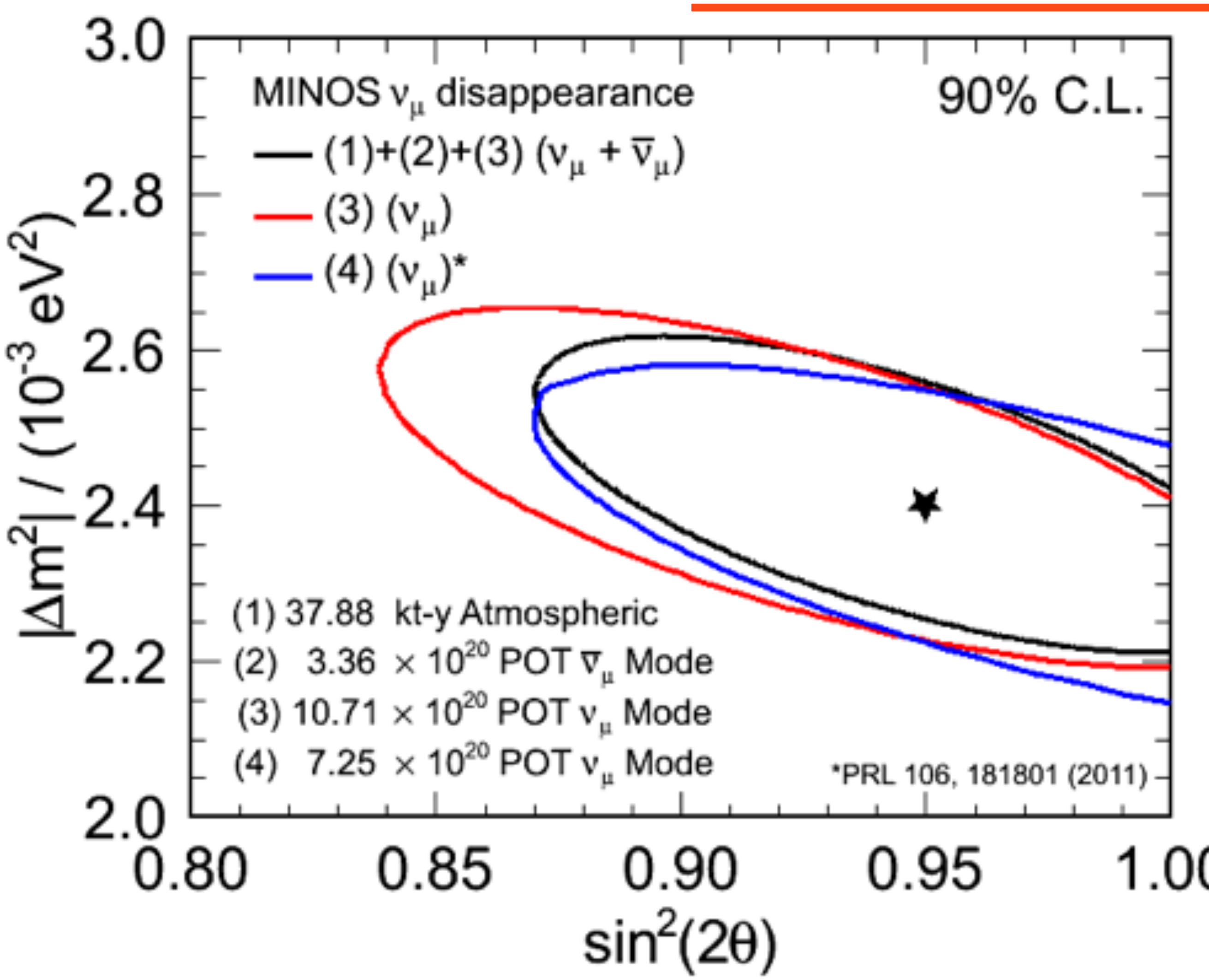

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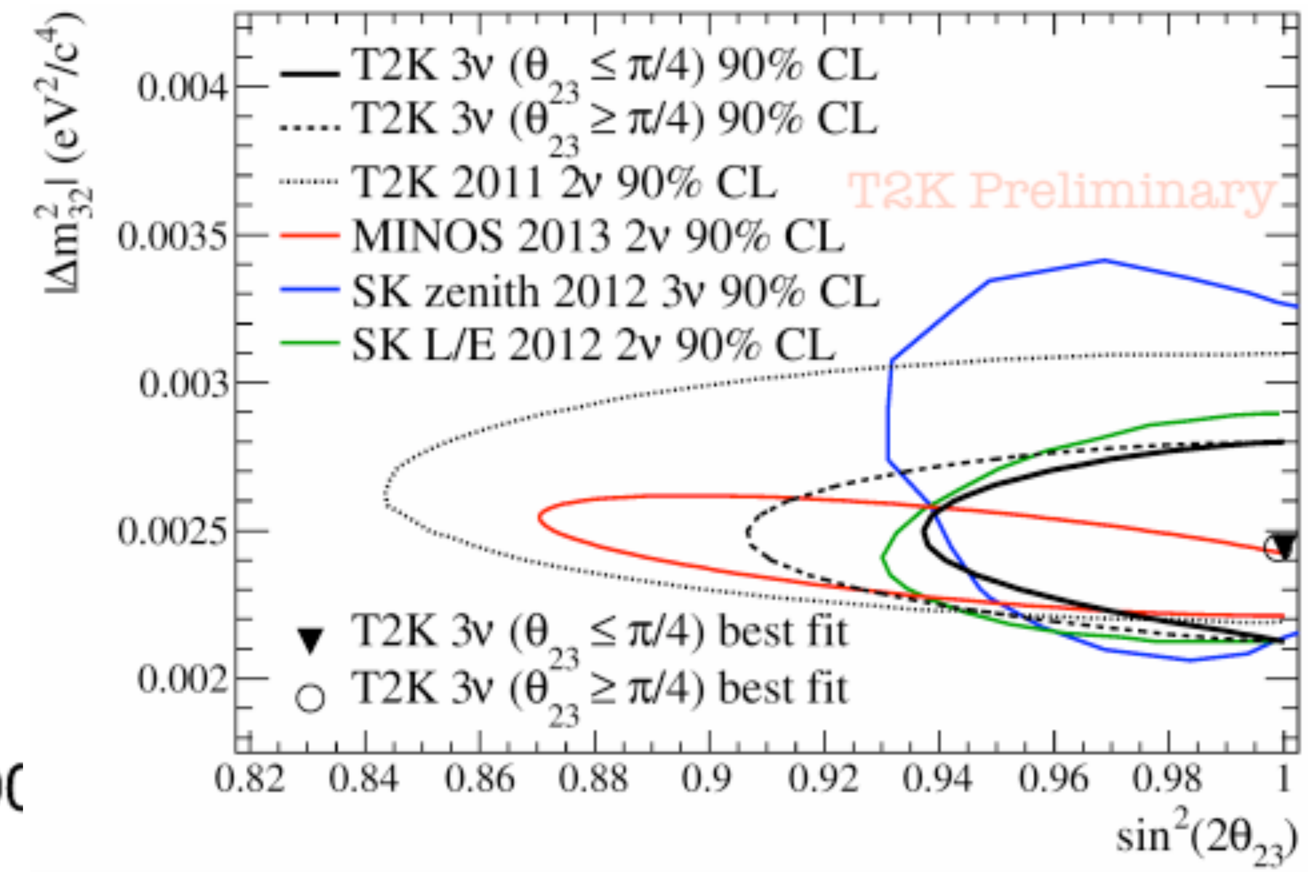

MINOS, SuperK and T2K contours superimposed

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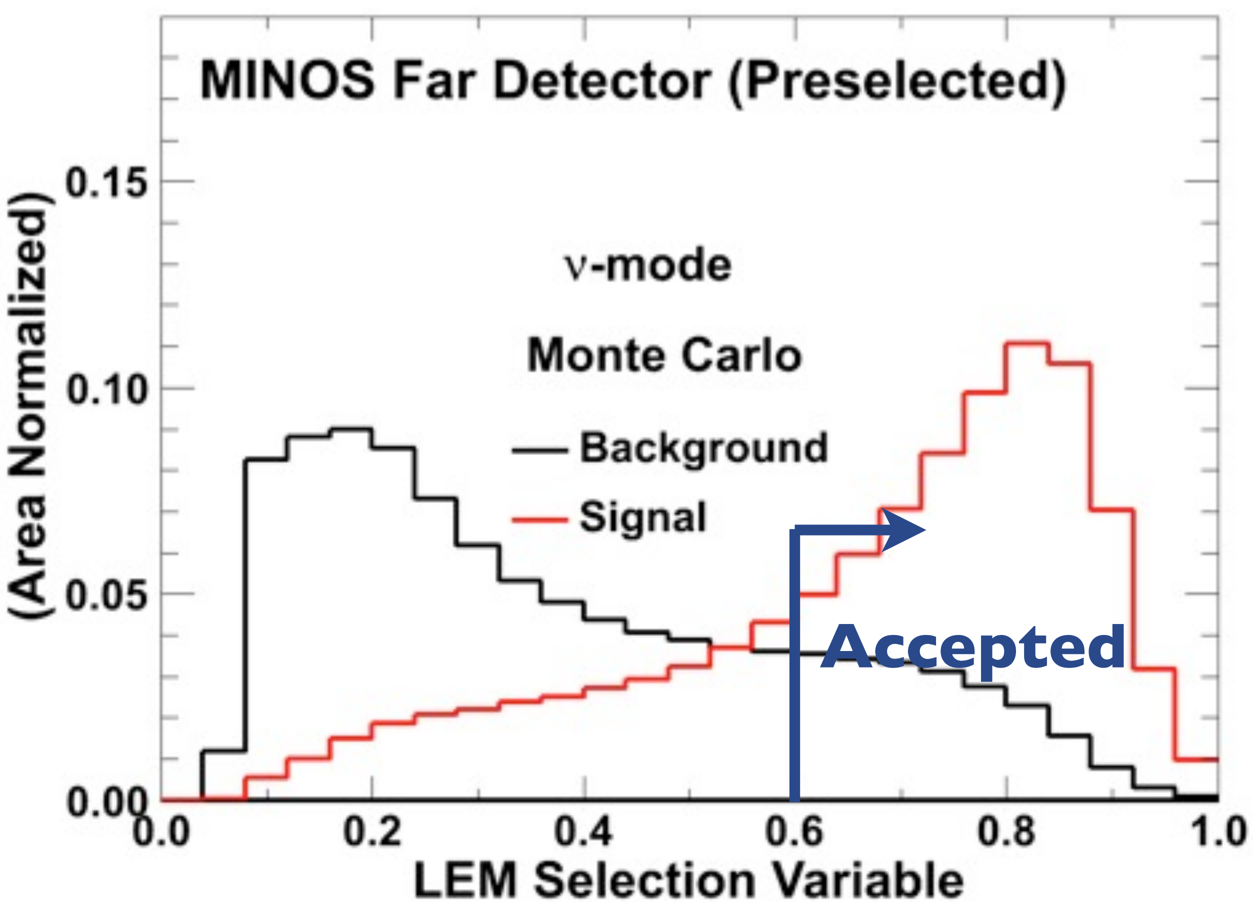

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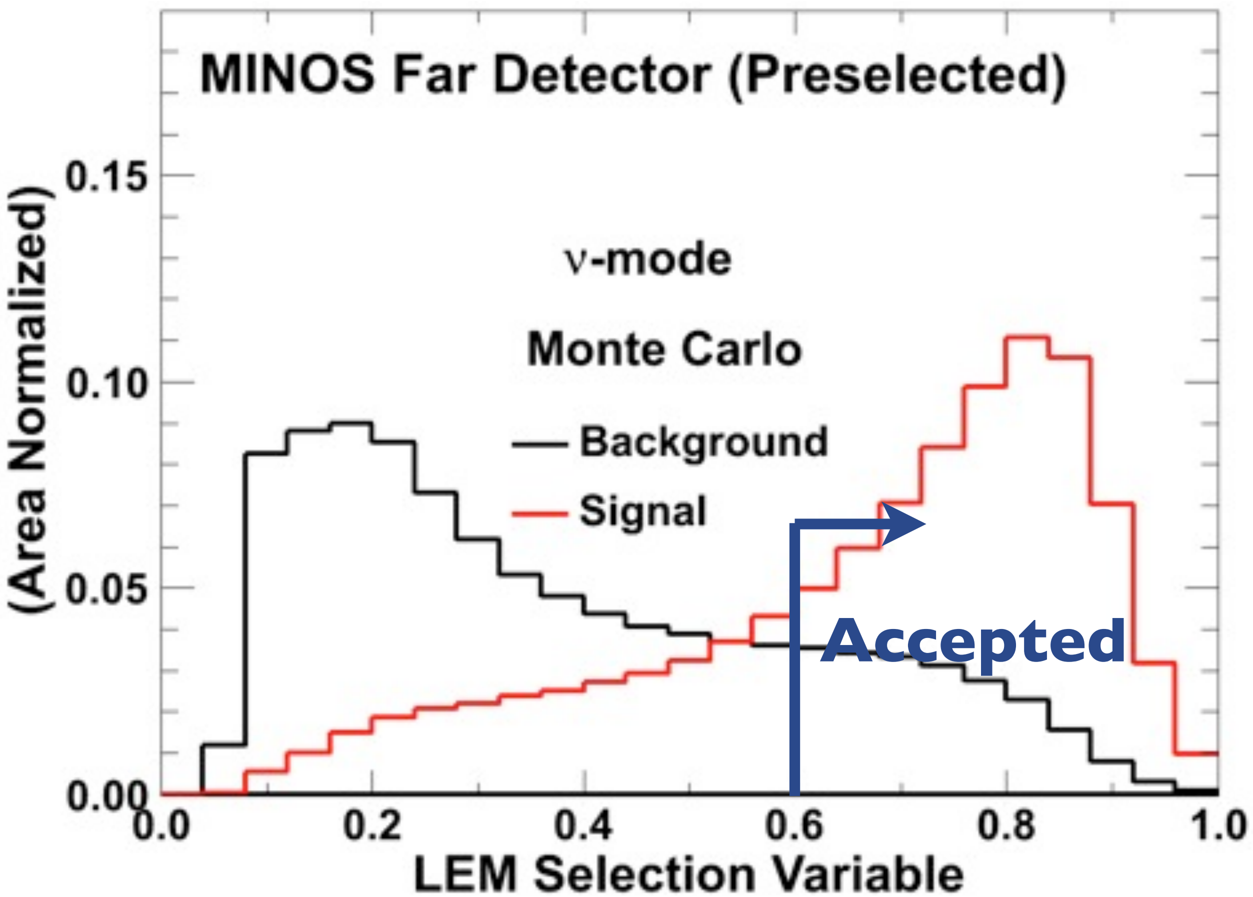

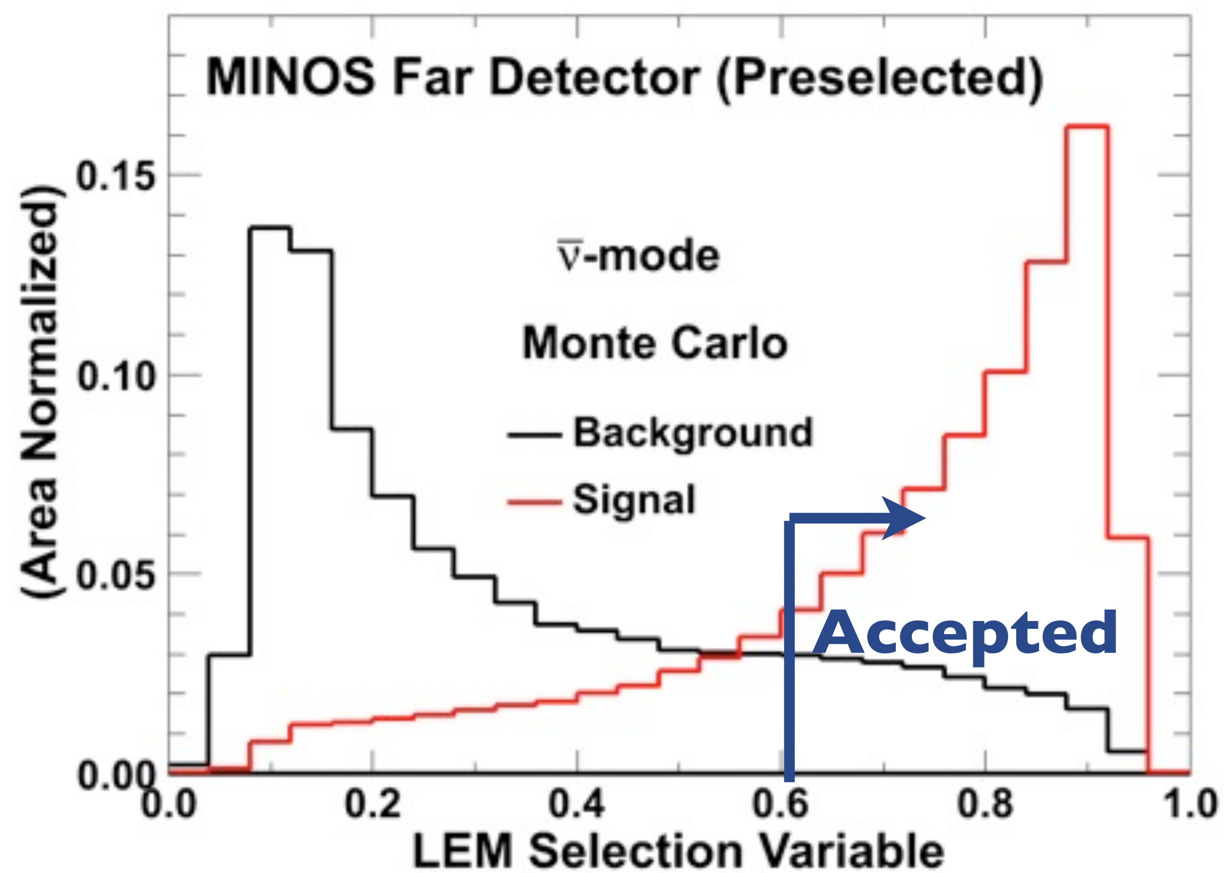

ν_e Contour Plots

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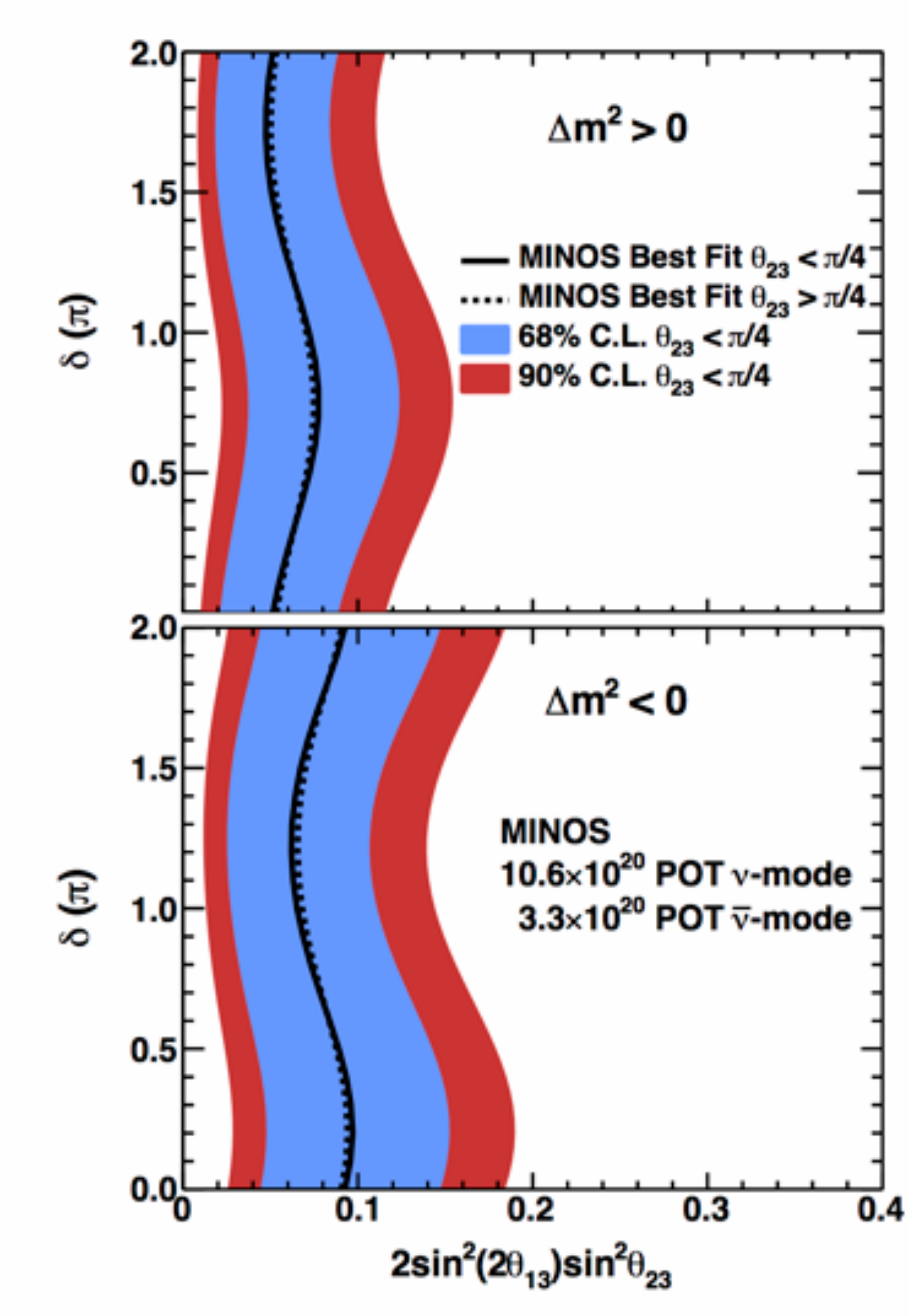

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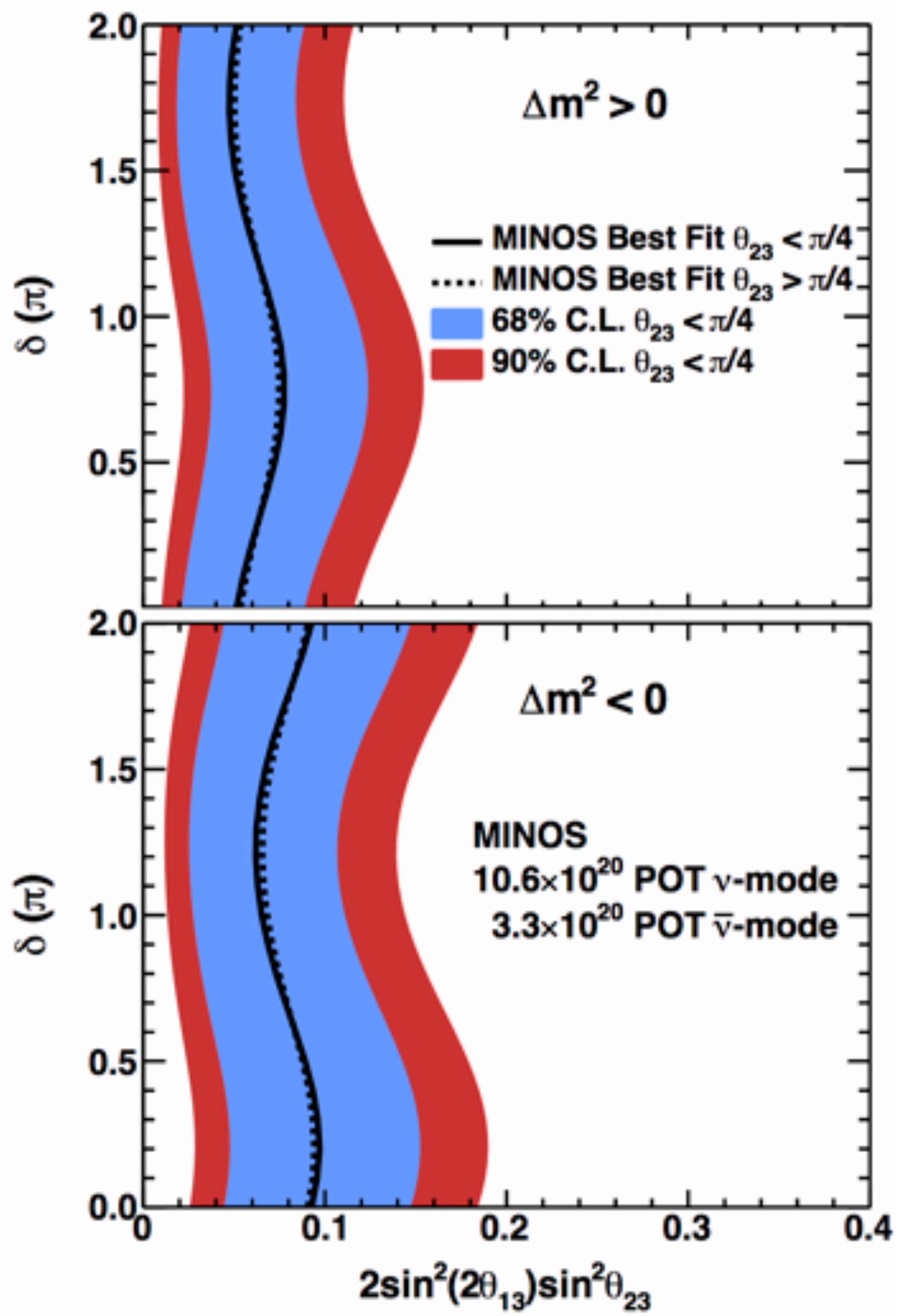

ν_e and $\bar{\nu}_e$ combined

At $\delta_{CP} = 0$ and $\theta_{23} < \pi/4$,

- Assuming normal hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$

$$0.01 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.12 \text{ (90\% C.L.)}$$

- Assuming inverted hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$

$$0.03 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.18 \text{ (90\% C.L.)}$$

NEW Analyses

4ν? Sterile Neutrinos?

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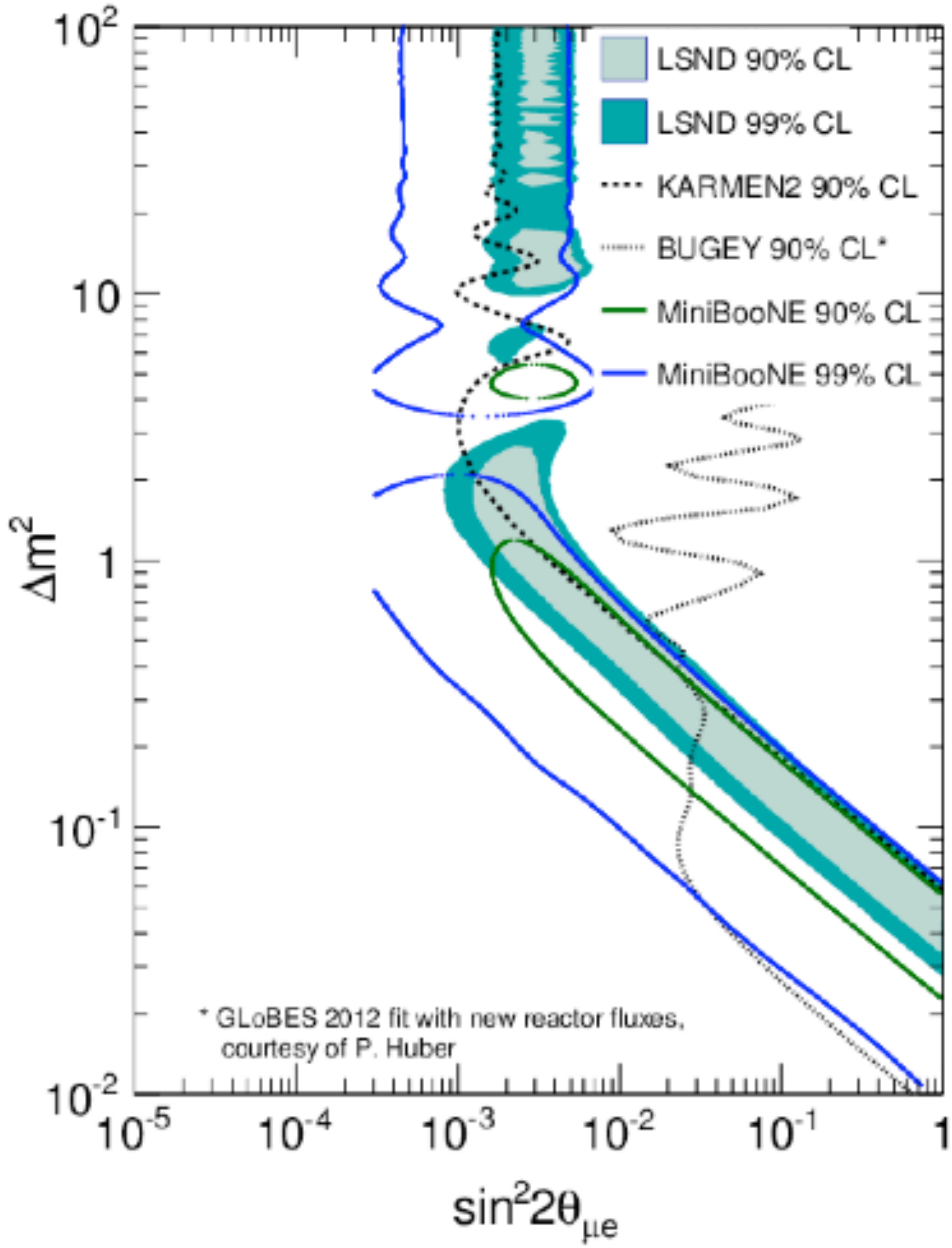

Sterile Neutrinos

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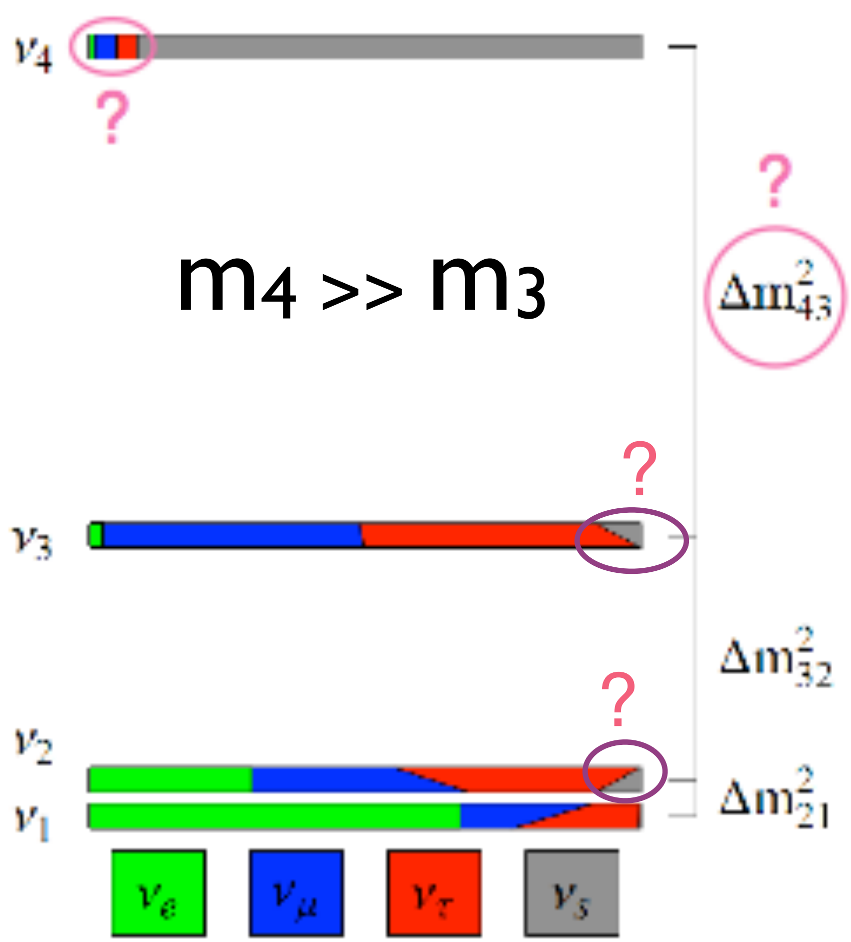

One possible 4ν model (3+1)

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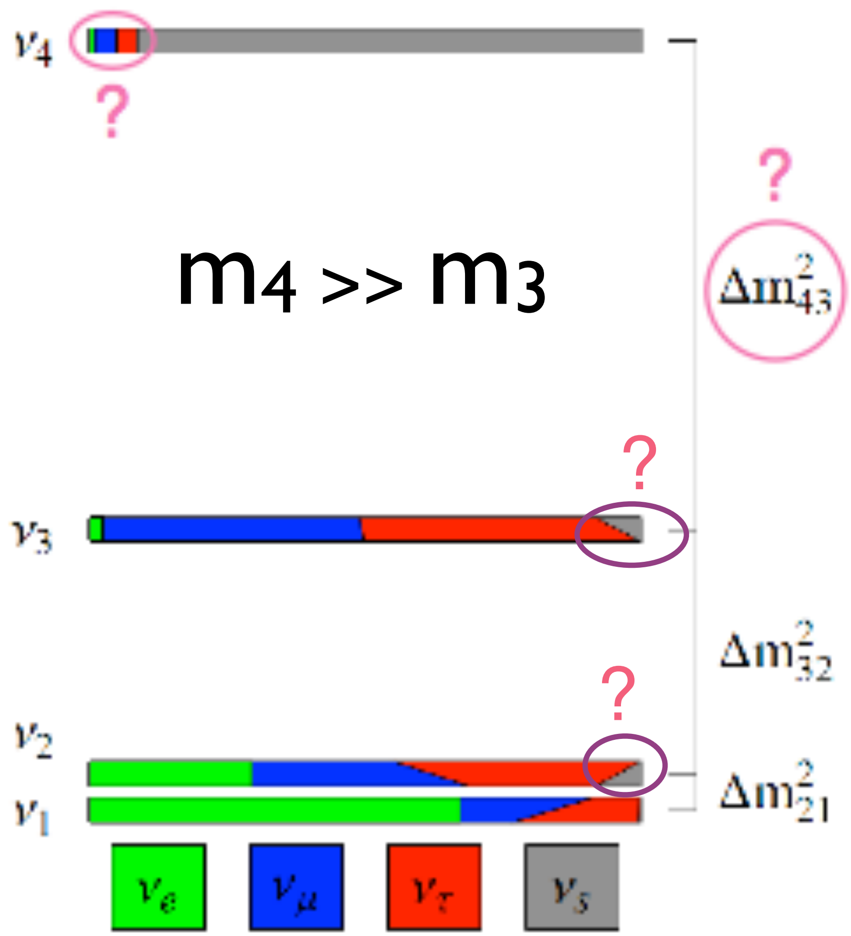

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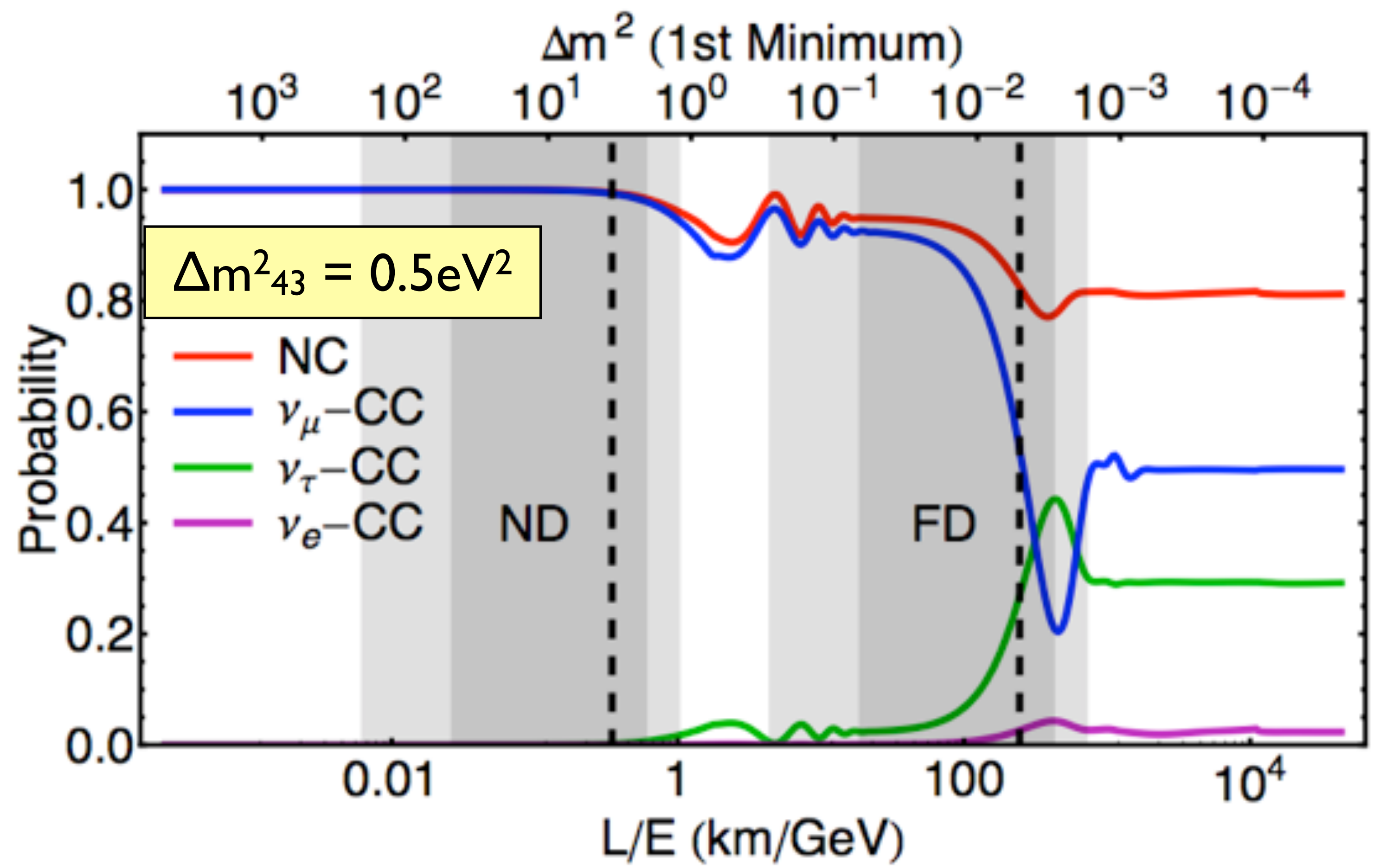
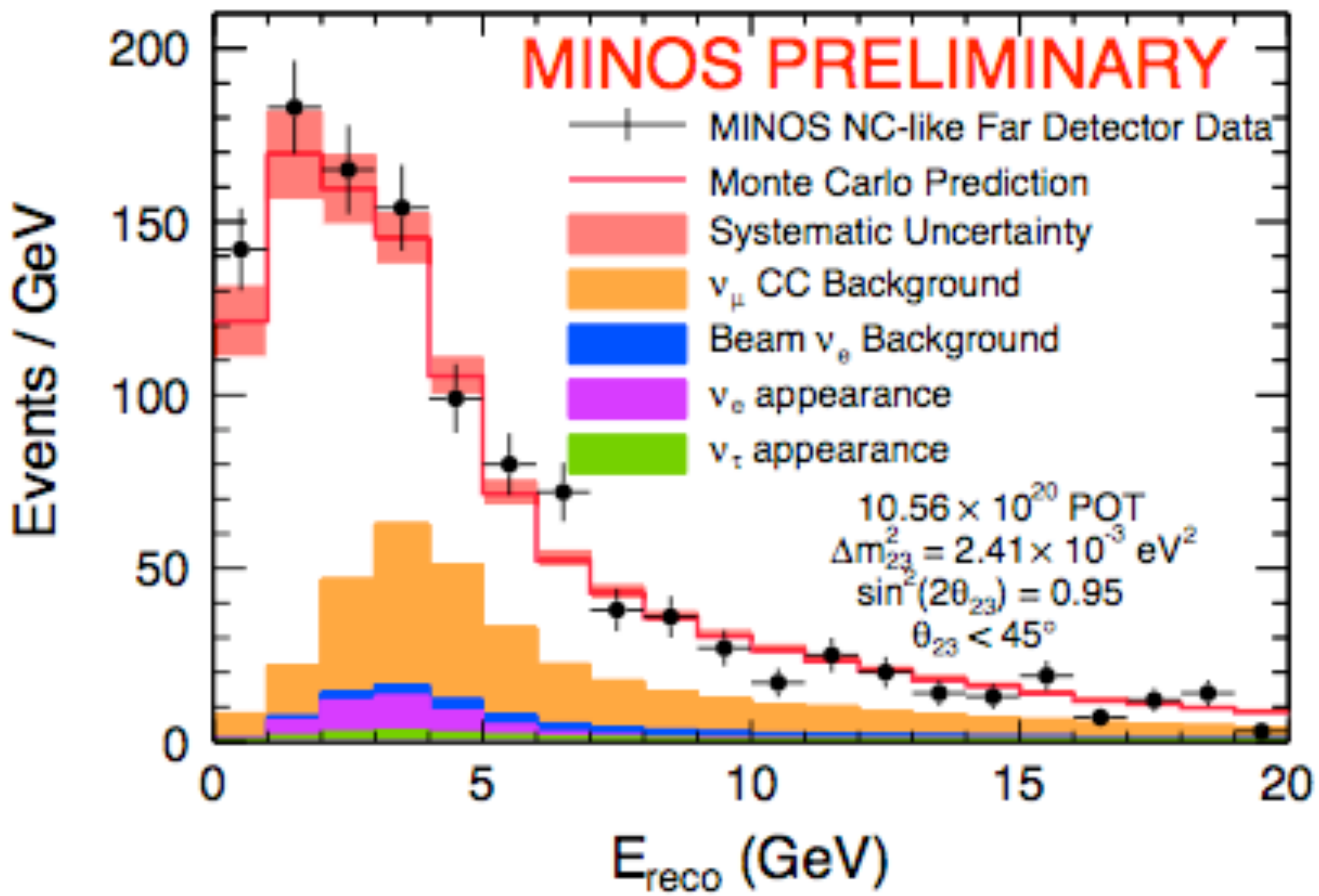


Potential behavior of different channels for a 4ν model similar to the one on the left

Sterile Neutrino Results

Sterile Neutrino Results

Comparison with standard 3-flavor prediction
(Model independent)



$$R = \frac{Data - CC_{Bkgd}}{NC_{Pred}}$$

0-200 GeV: $R = 1.049 \pm 0.076$

0-3 GeV: $R = 1.093 \pm 0.097$

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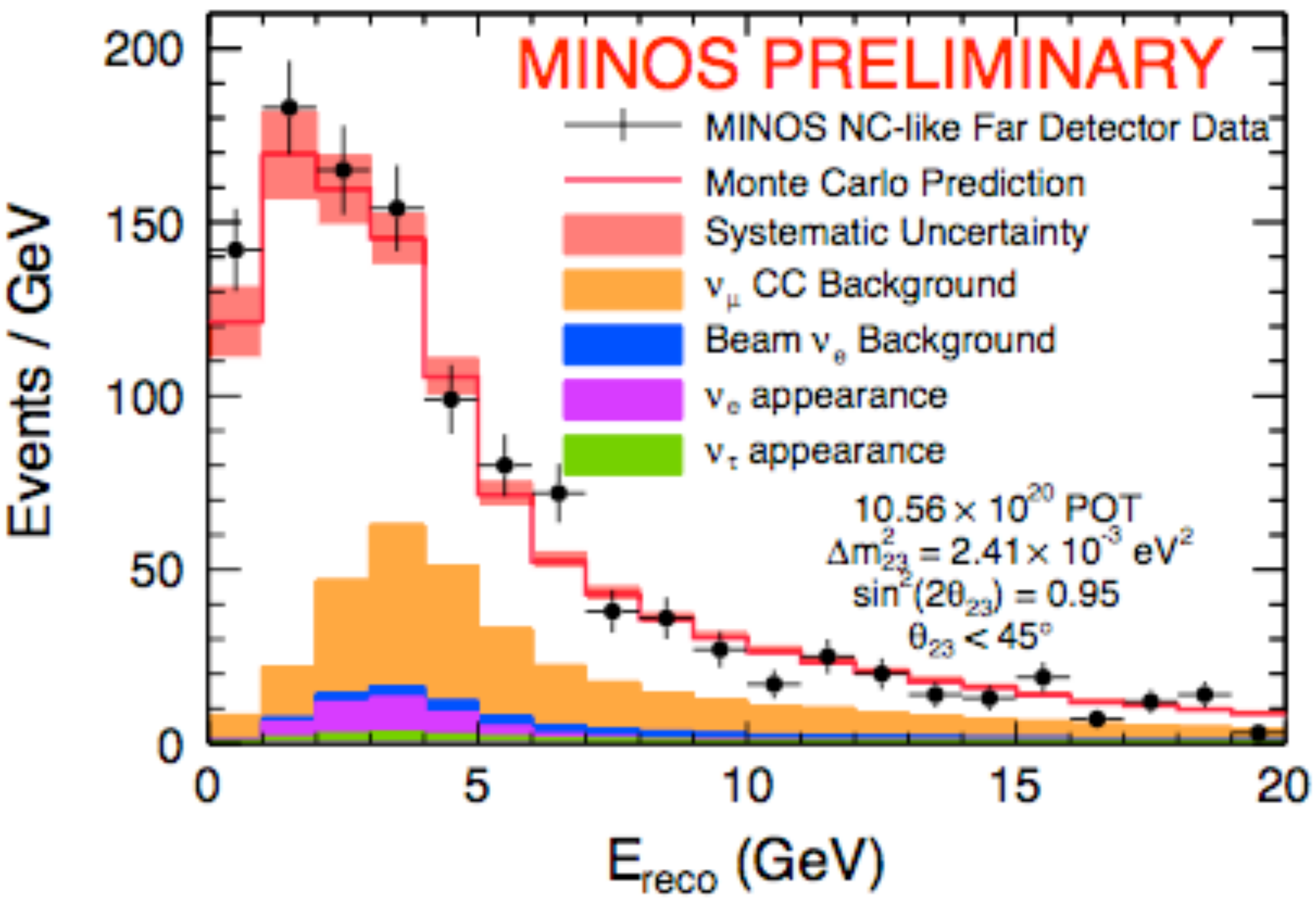

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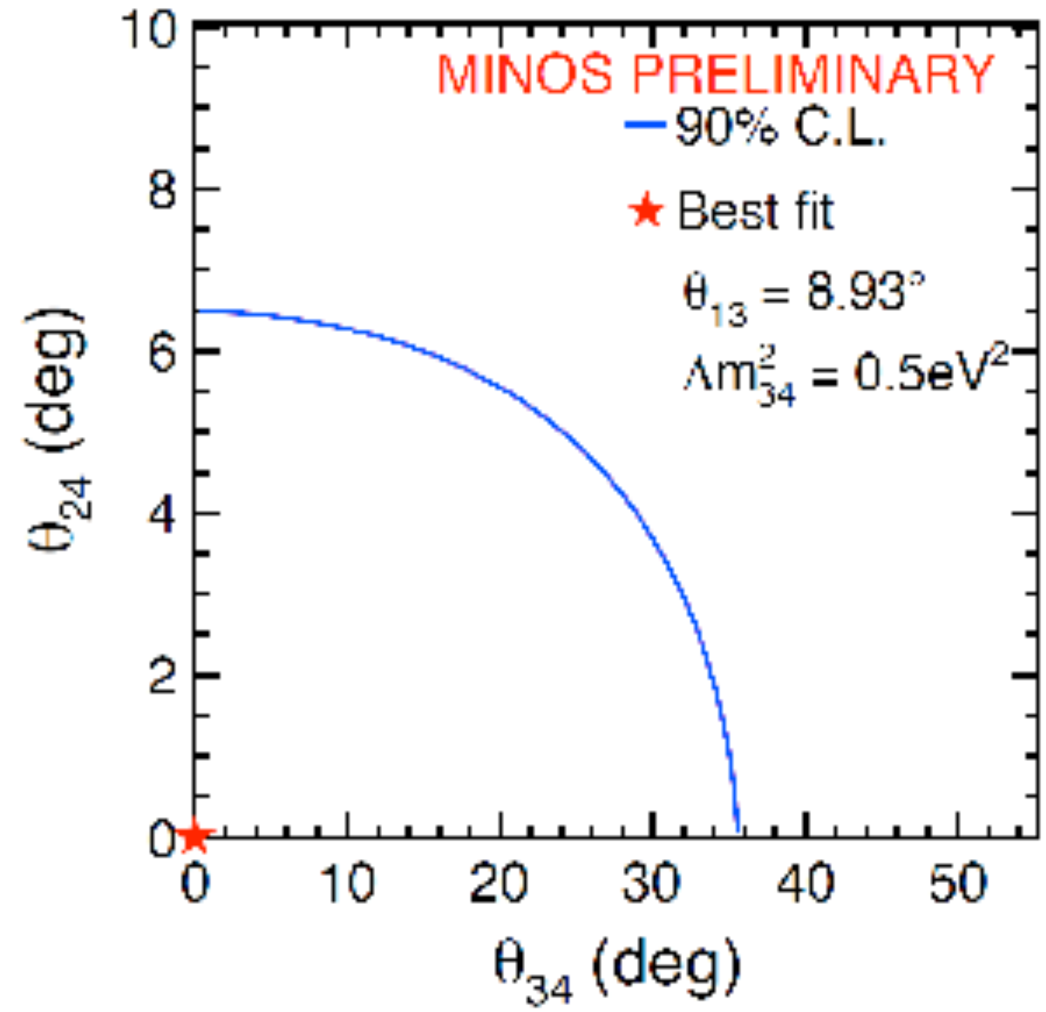

$\sin^2\theta_{24} < 0.0073$ at 90% C.L.

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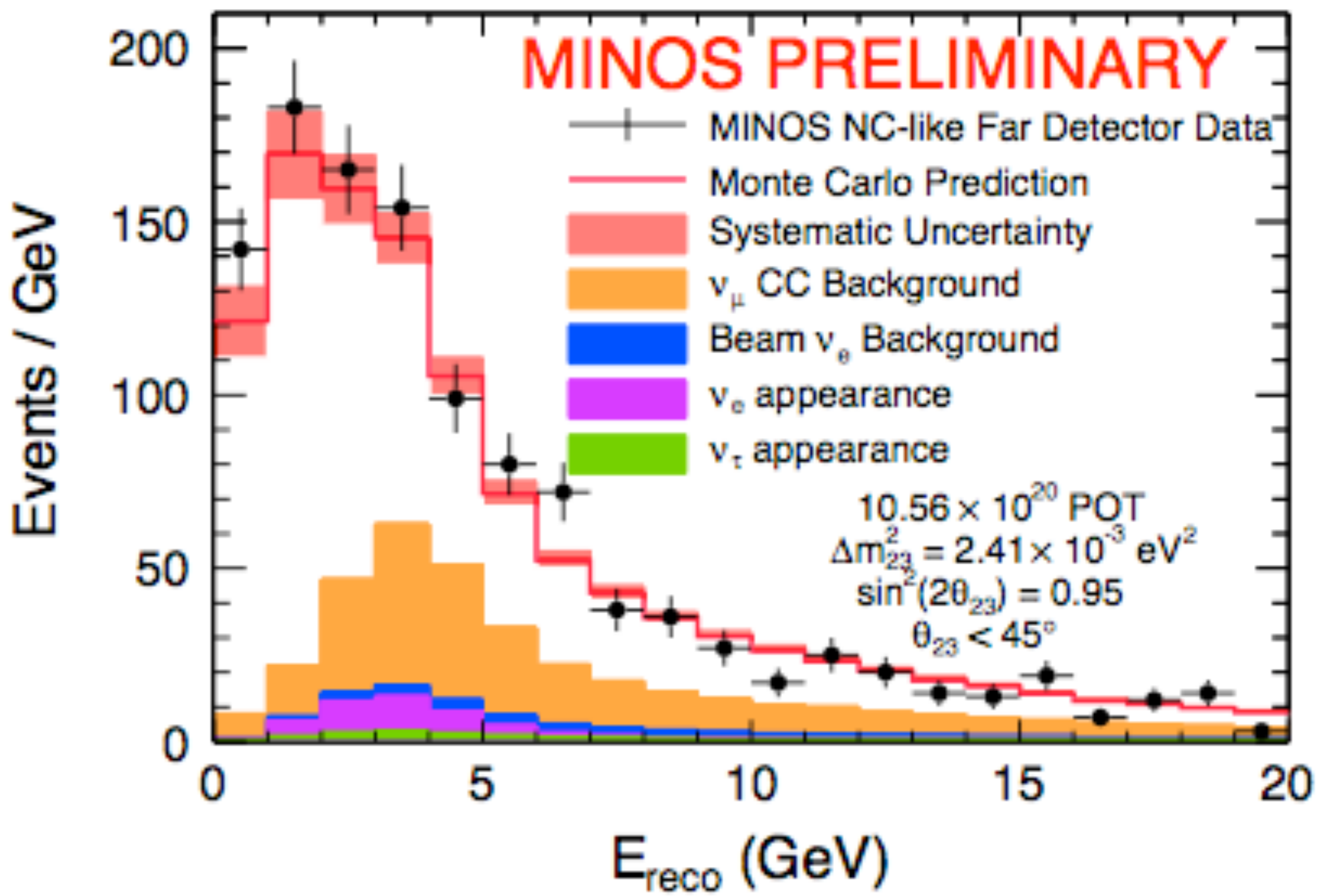

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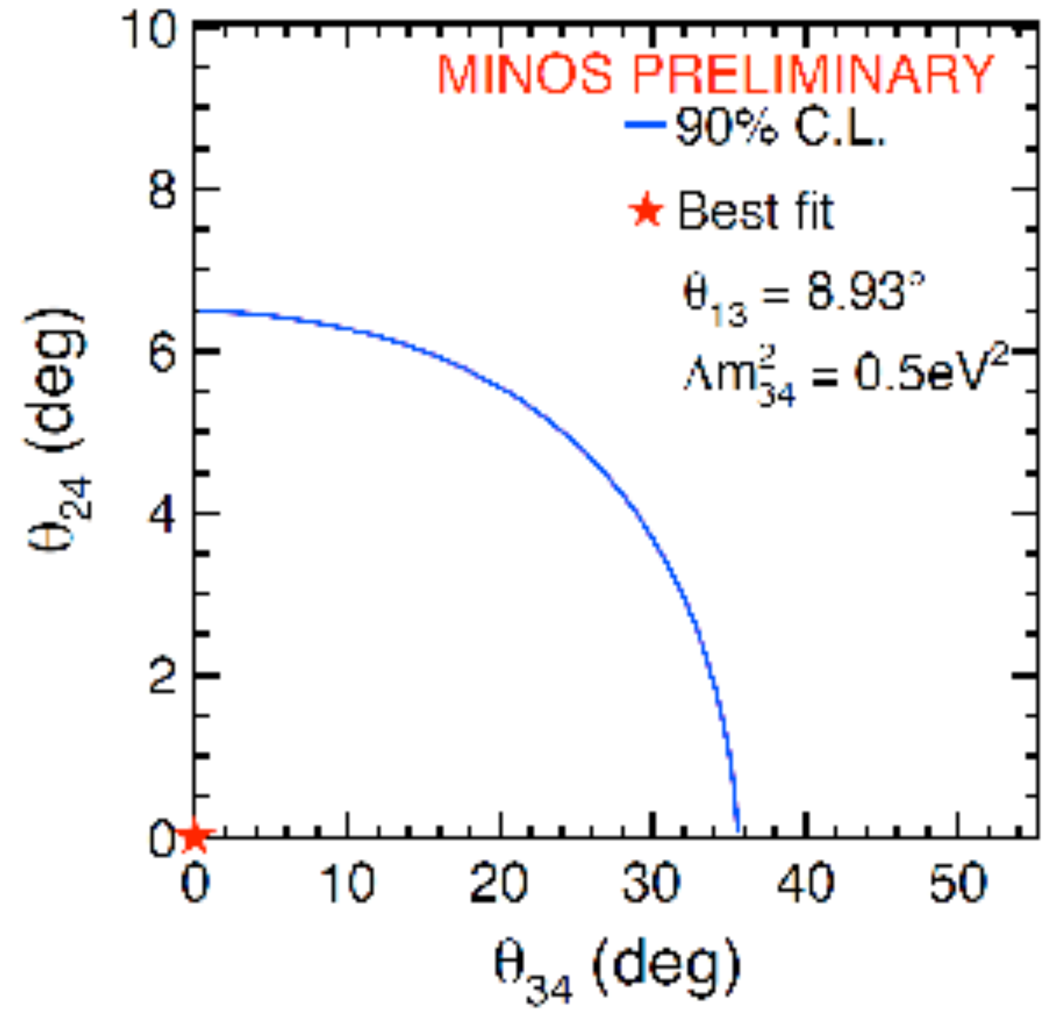

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Further exploration of dependence on Δm^2_{43} is yet to come

Compare with Current Status

(Within the framework of the 3+1model)

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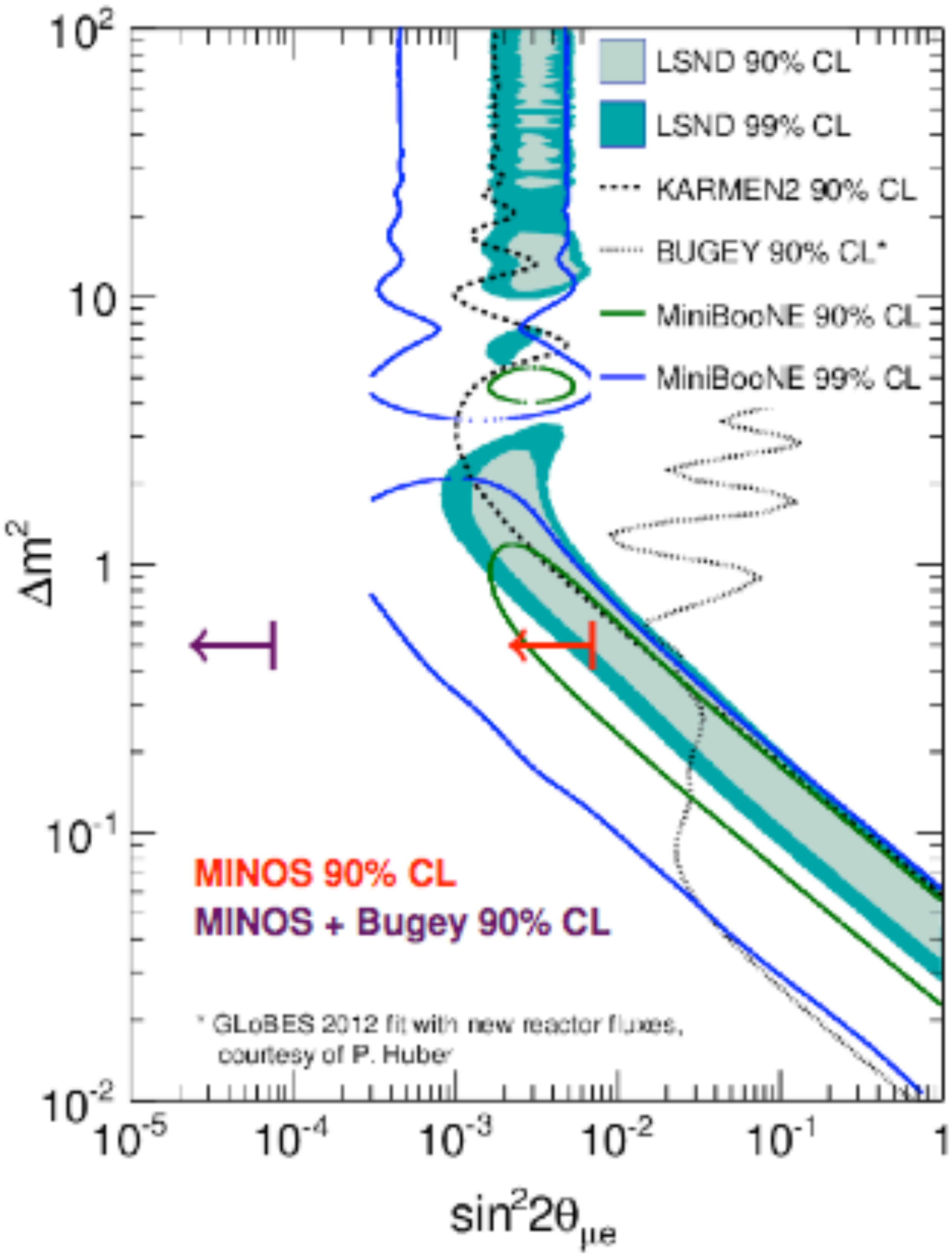

- Due to a small overall excess observed in data, we obtain stronger limits than our sensitivity
- At $\Delta m^2_{43} = 0.5$ eV^2:
- MINOS only: $\sin^2(2\theta^{\oslash}_{\mu e}) < 7.1 \times 10^{-3}$ at 90% C.L.
- MINOS + Bugey: $\sin^2(2\theta^{\oslash}_{\mu e}) < 7.7 \times 10^{-5}$ at 90% C.L.

The full relevant phase space for $\Delta m^2{}_{43}$ is currently being explored

Slide from J.L.B.Coelho

Combined 3-flavor Analysis

(Disappearance and Appearance)

- Data used
  - ★ 10.71×10^{21} POT ν_μ mode
  - ★ 3.36×10^{21} POT $\overline{\nu_\mu}$ mode
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- Method employed (4 parameters)
  - ★ 3 free parameters (no constraint): $\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}
  - ★ External constraint on $\sin^2\theta_{13} = 0.0242 \pm 0.0025$, from reactor experiments
  - ★ Fogli et al. global analysis, arXiv:1205.5254, used for fixed $\Delta m^2_{21} = 7.54 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.307$
  - ★ Maximum likelihood surface (4D) obtained for each mass hierarchy

1D and 2D Profiles

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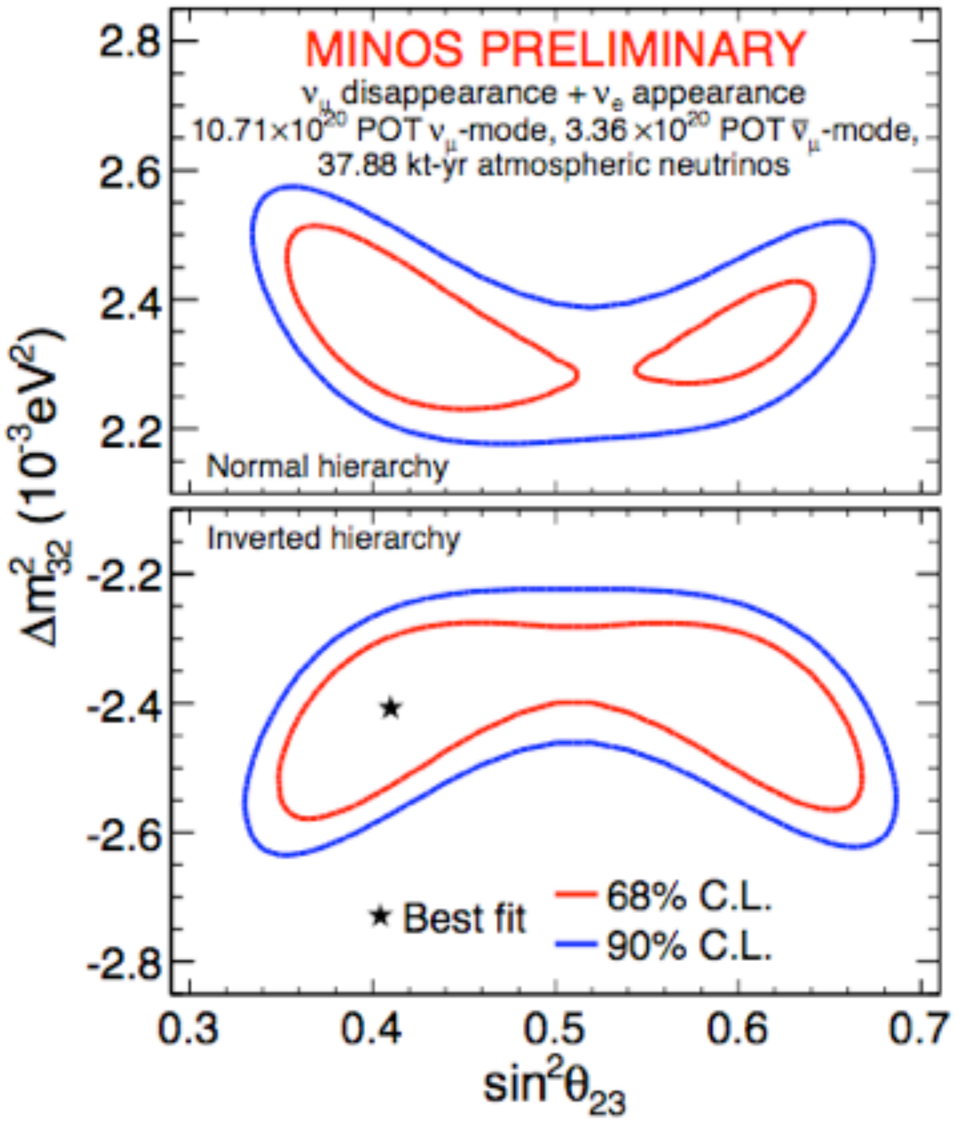

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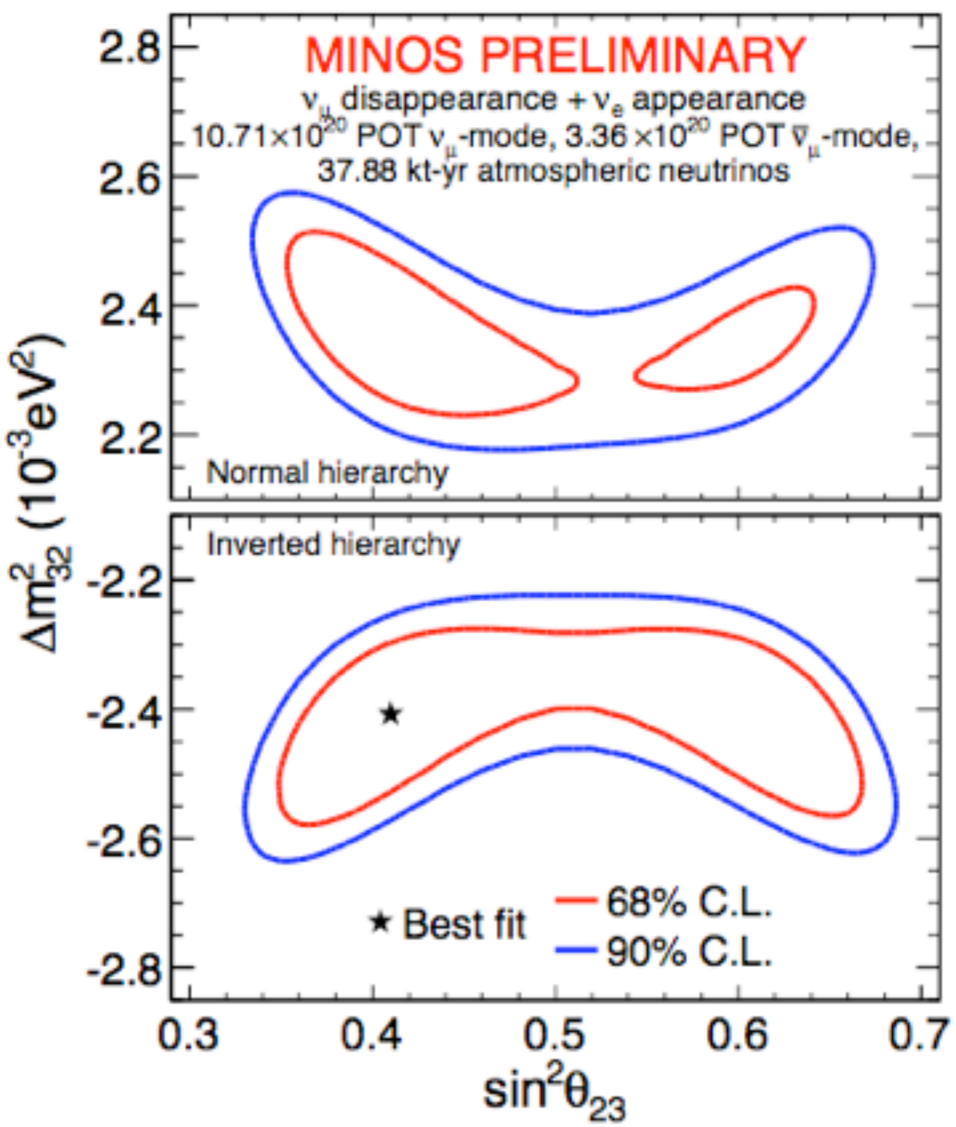

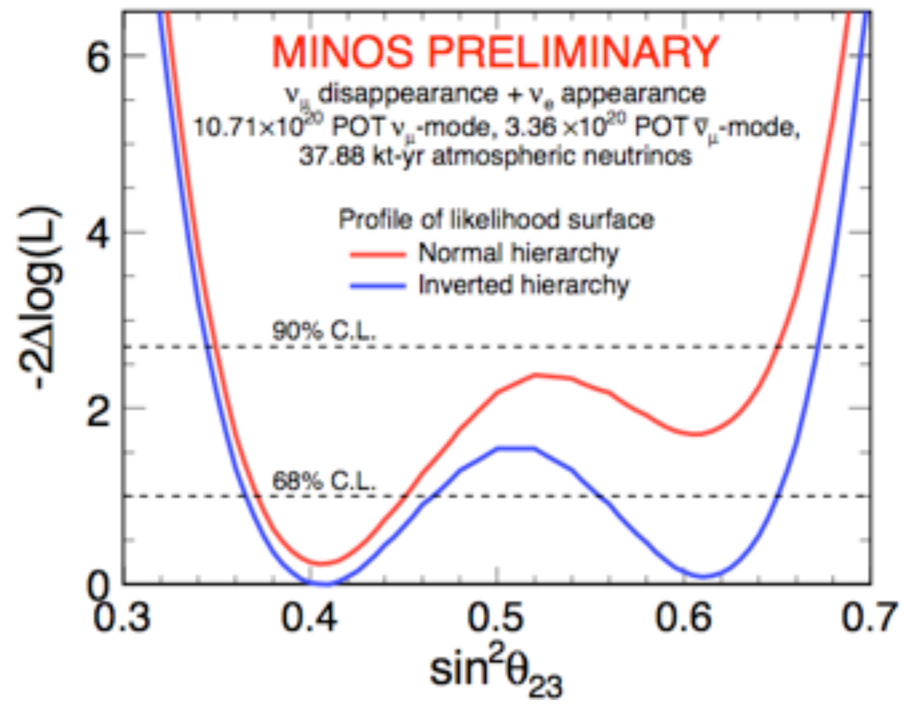

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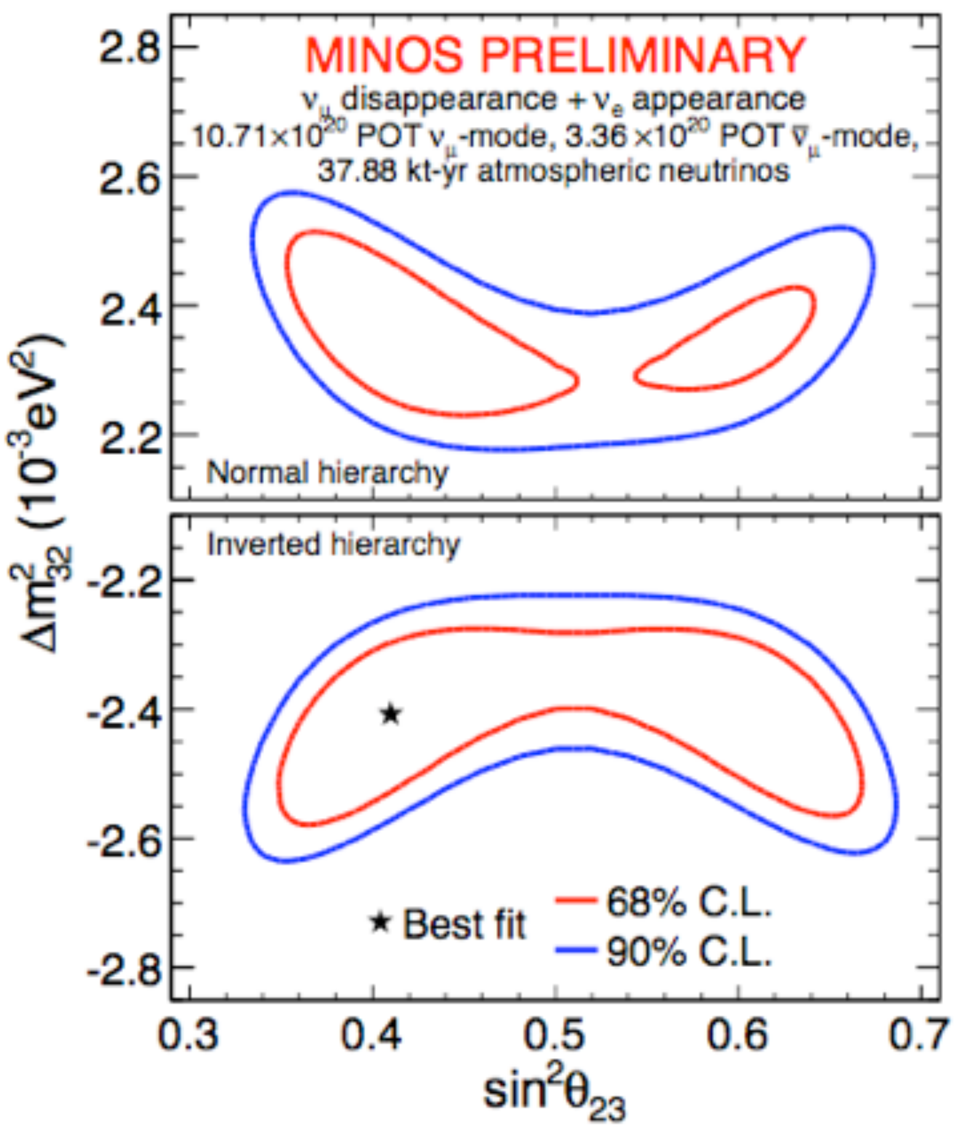

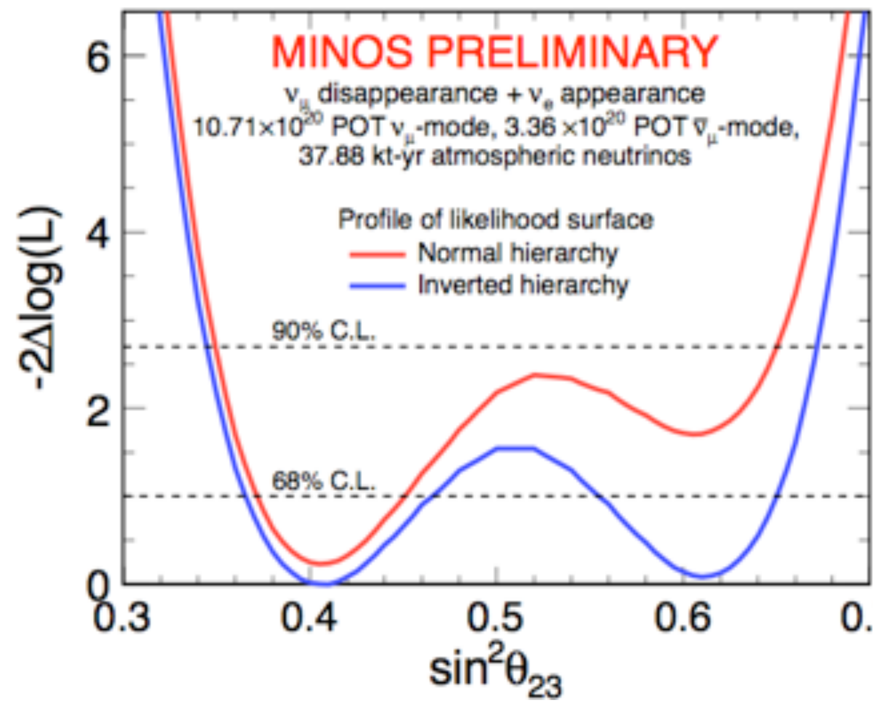

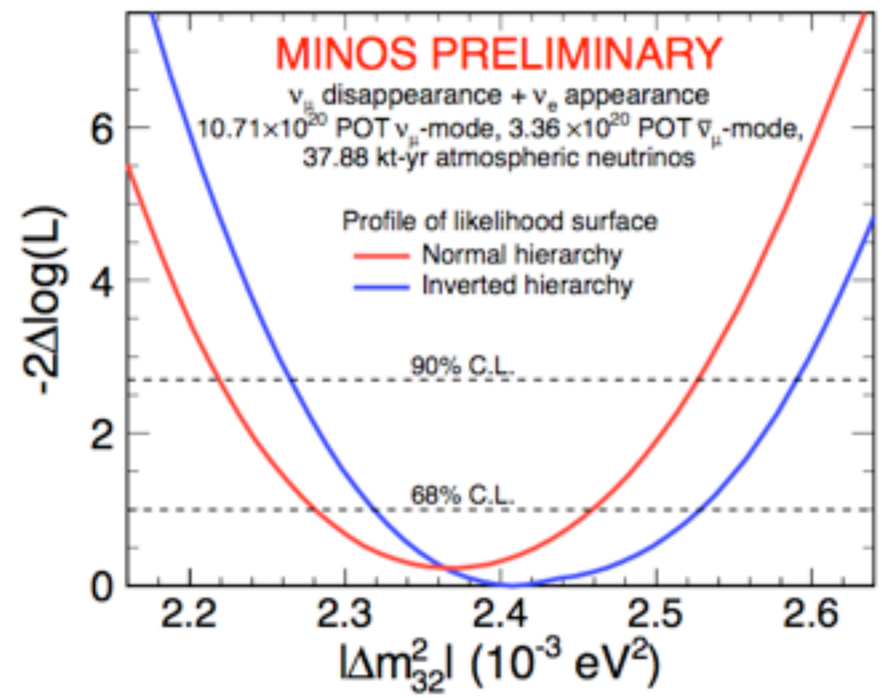

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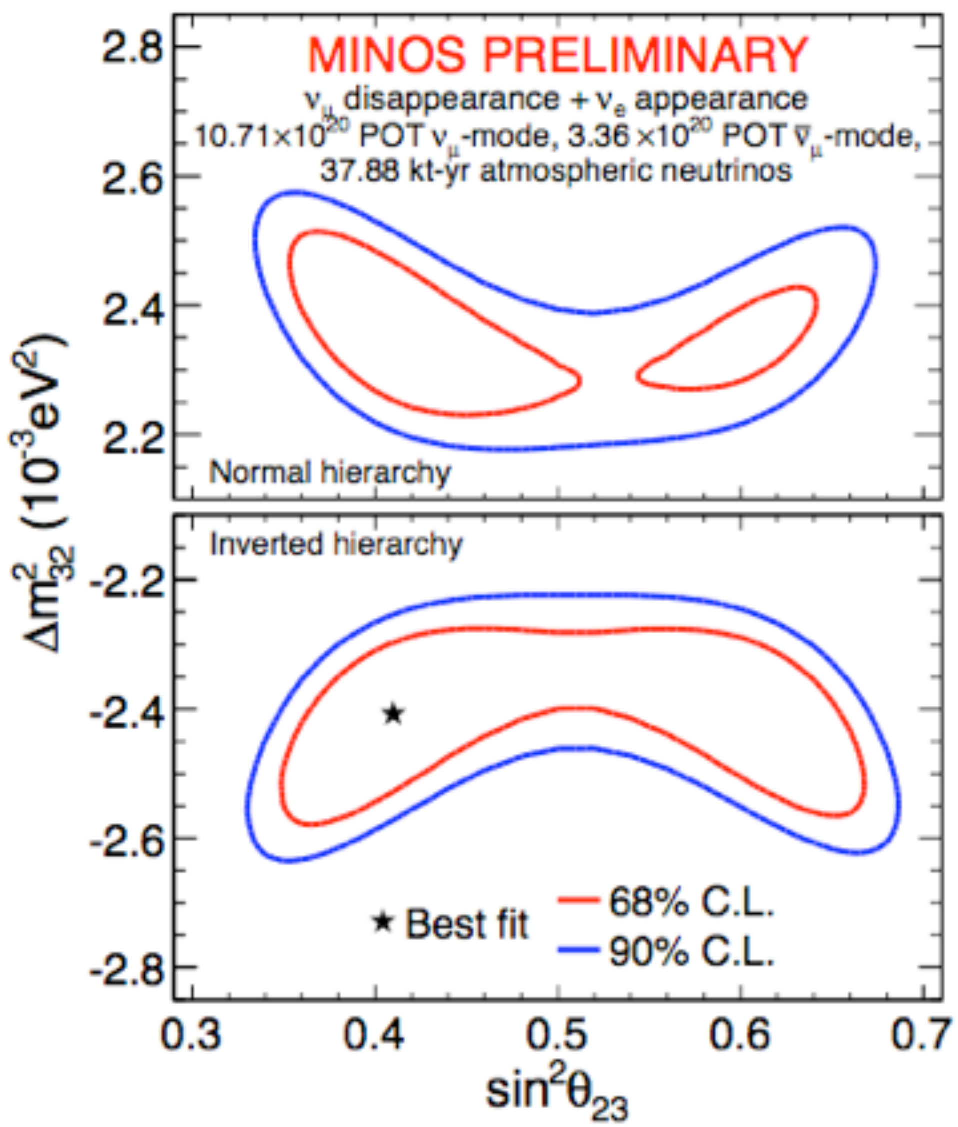
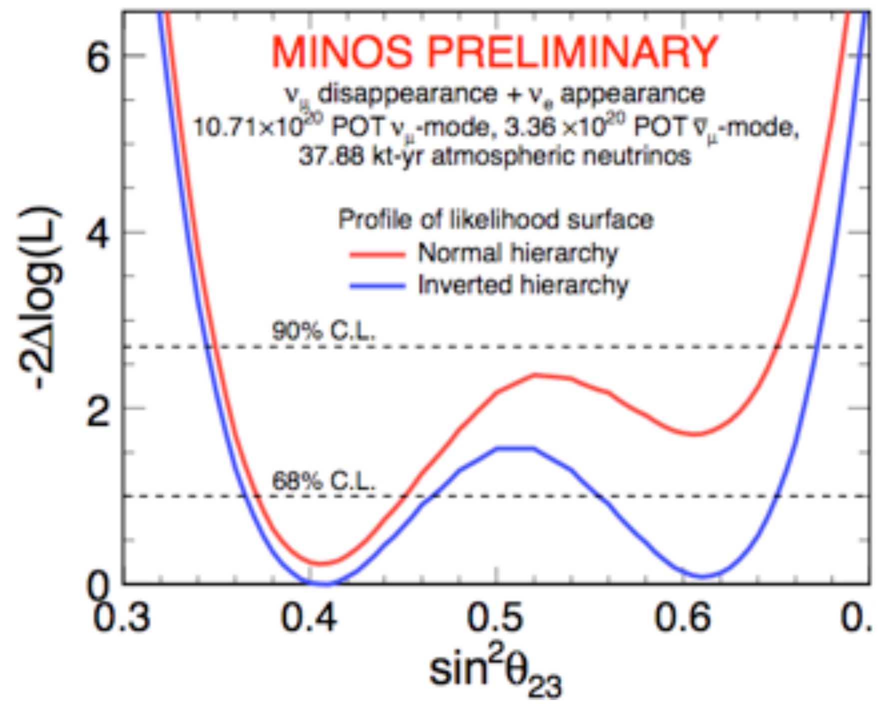
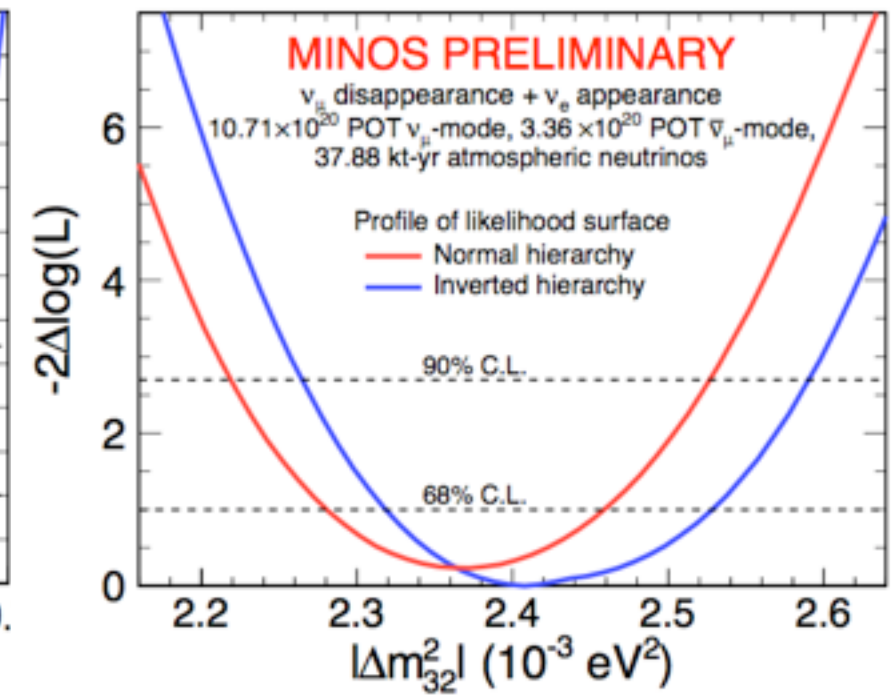






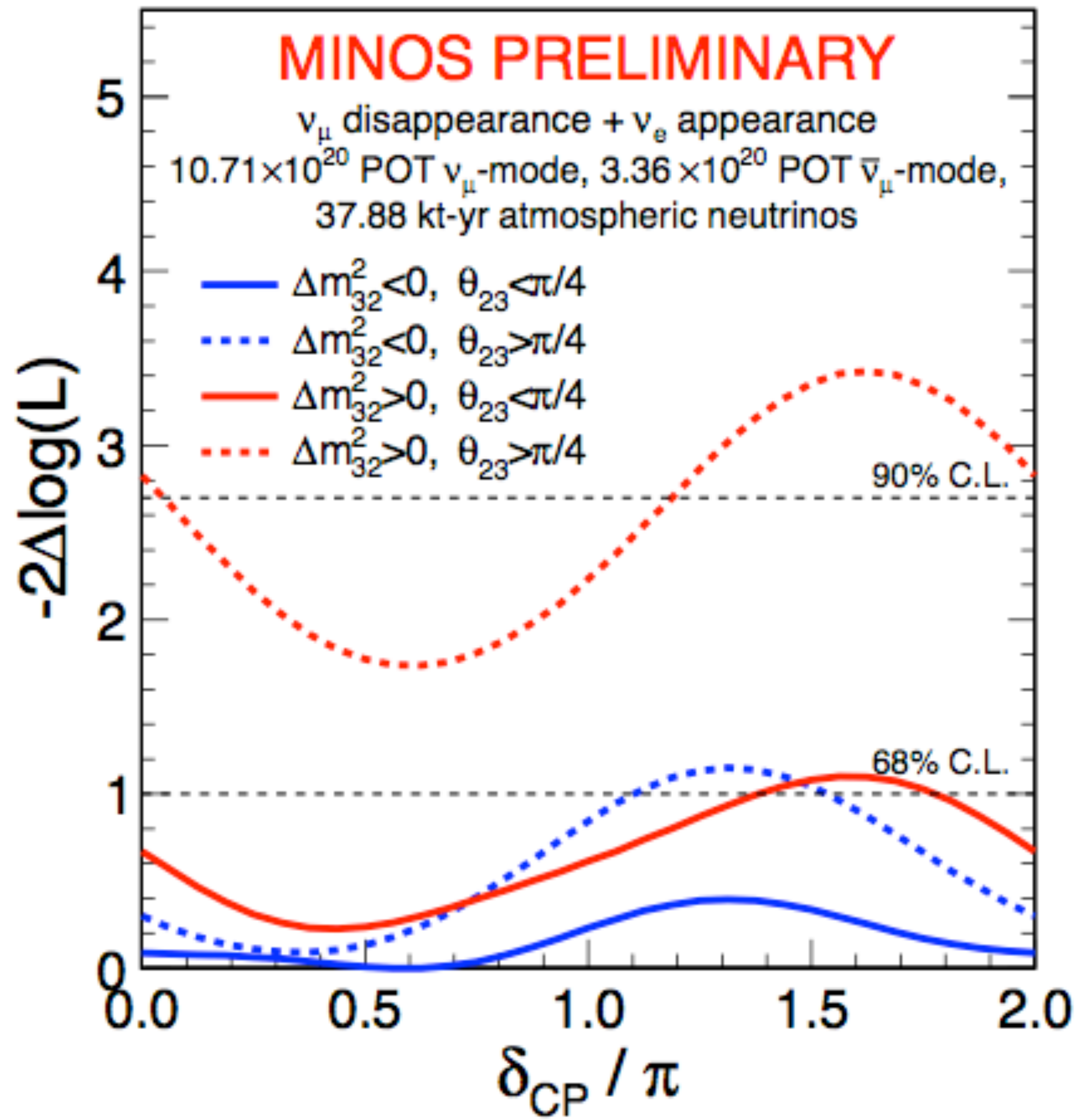
	Parameter	Best fit	Confidence limits
Normal hierarchy	$\|\Delta m^2_{32}\|/10^{-3}\text{eV}^2$	2.37	$2.28 - 2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35 - 0.65$ (90% C.L.)
Inverted hierarchy	$\|\Delta m^2_{32}\|/10^{-3}\text{eV}^2$	2.41	$2.32 - 2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34 - 0.67$ (90% C.L.)

Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

Preference for lower octant: $-2\Delta\log L = 0.09$

Preference for non-maximal mixing: $-2\Delta\log L = 1.54$ (⇒ 79% C.L.)

Profiles as function of δ_{CP}



Other Physics Topics

- Neutrino TOF

  ND - FD Baseline for v=c : 2,449,316.3±2.3 ns

  MINOS Result: =(-2.4 ± 0.1_{stat} ± 2.6_{syst}) ns
- Neutrino cross sections
- Quasielastic scattering
- Cosmic ray muon charge ratio at ~1 TeV
- Multi-muons in cosmic rays
- Muon seasonal variation
- Searches for anomalous neutrino interactions
- Tests of Lorentz invariance

What Next?

MINOS+

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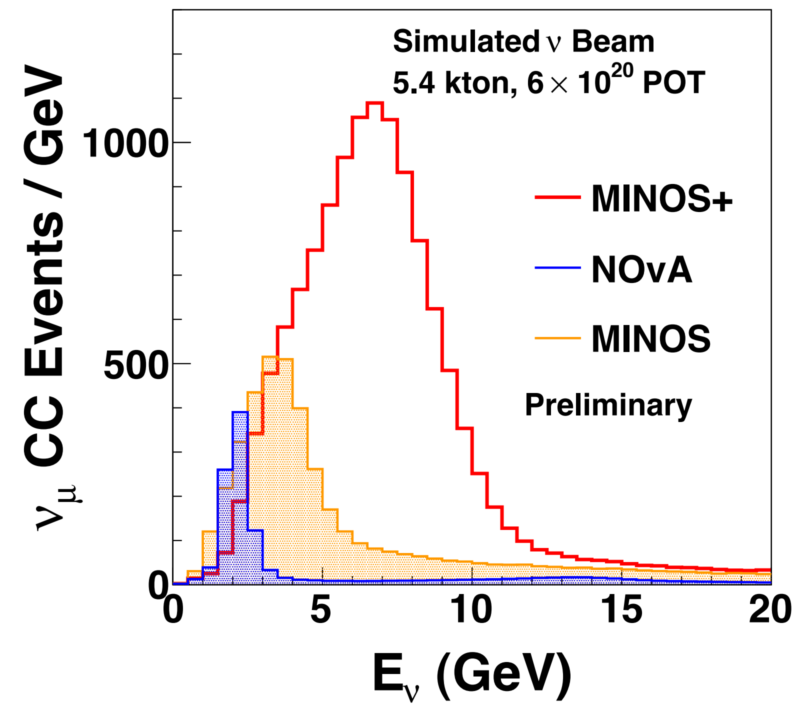
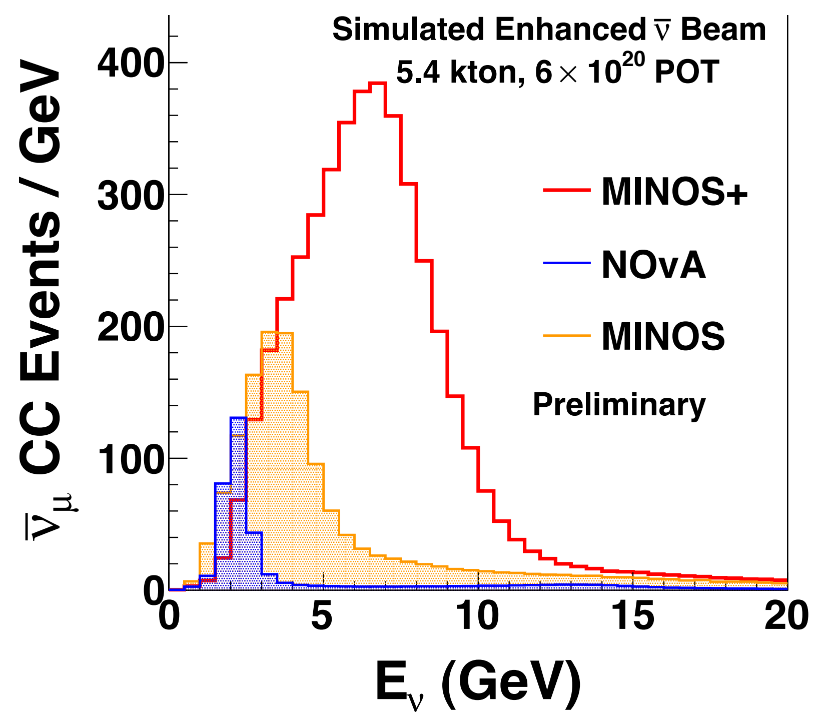
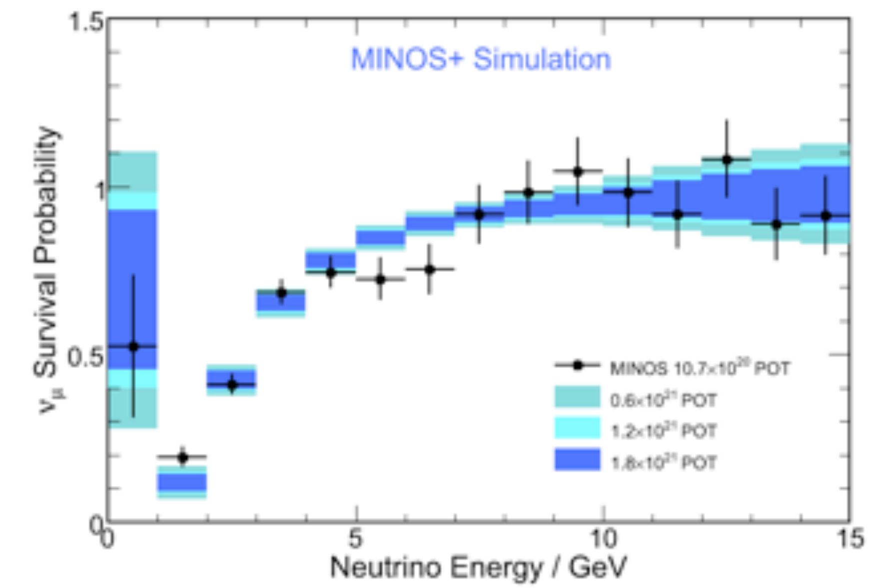
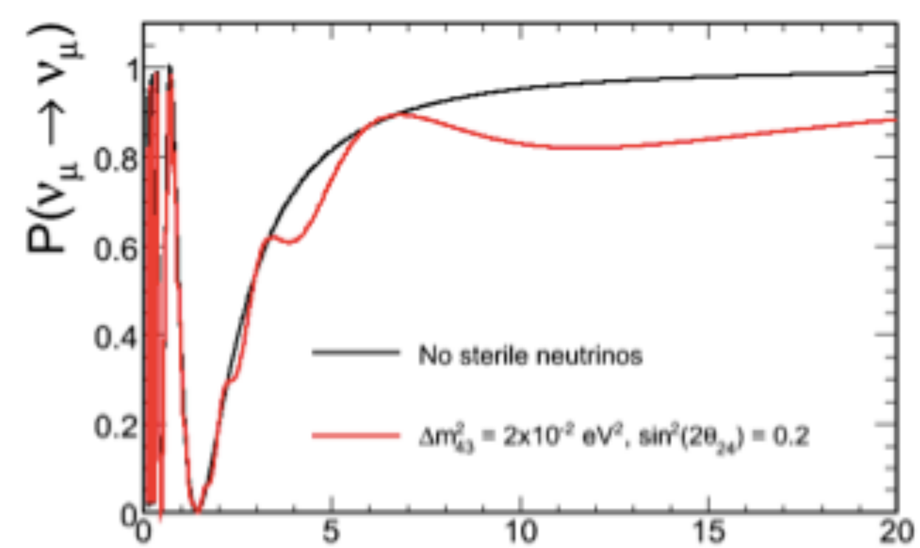




MINOS+ Physics Goals

- Parameters
  - ★ 3 years of running
  - ★ 3000 ν_μ CC events per year
- Physics Goals
  - ★ Precision measurements
  - ★ Emphasis on higher energy
  - ★ Search for sterile neutrinos
  - ★ Search for non-standard interactions





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- Let us wish them luck

With many thanks to all my MINOS collaborators
This presentation is the result of their hard work

The MINOS Collaboration