New Results from MINOS and First Results from MINOS+

Leigh Whitehead

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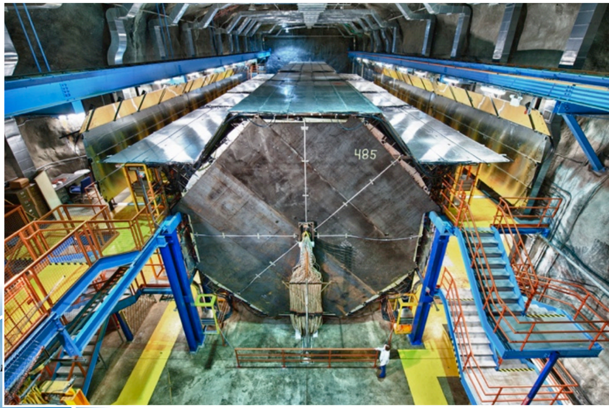
PANIC 2014 Hamburg

Outline

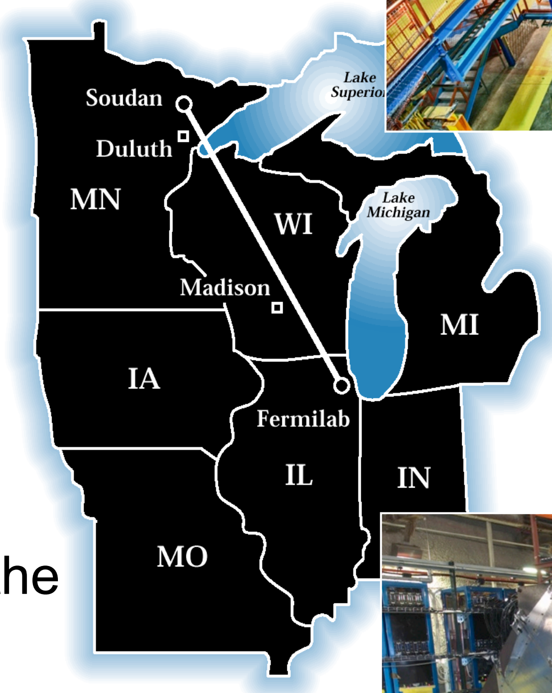
- Introduction to MINOS+
- MINOS Sterile Neutrino Analysis
- MINOS/MINOS+ Three Flavour Update
- MINOS+ Prospects

The MINOS+ Experiment

- MINOS+ is a long-baseline neutrino oscillation experiment
  - Continuation of MINOS in the NOvA era
- Exposed by the NuMI beam from Fermilab
- Two detectors: Near and Far
  - Detectors are both magnetised steel / scintillator sampling calorimeters
- Compare event spectra between the two detectors to study neutrino oscillations
- Can run in neutrino or anti-neutrino modes



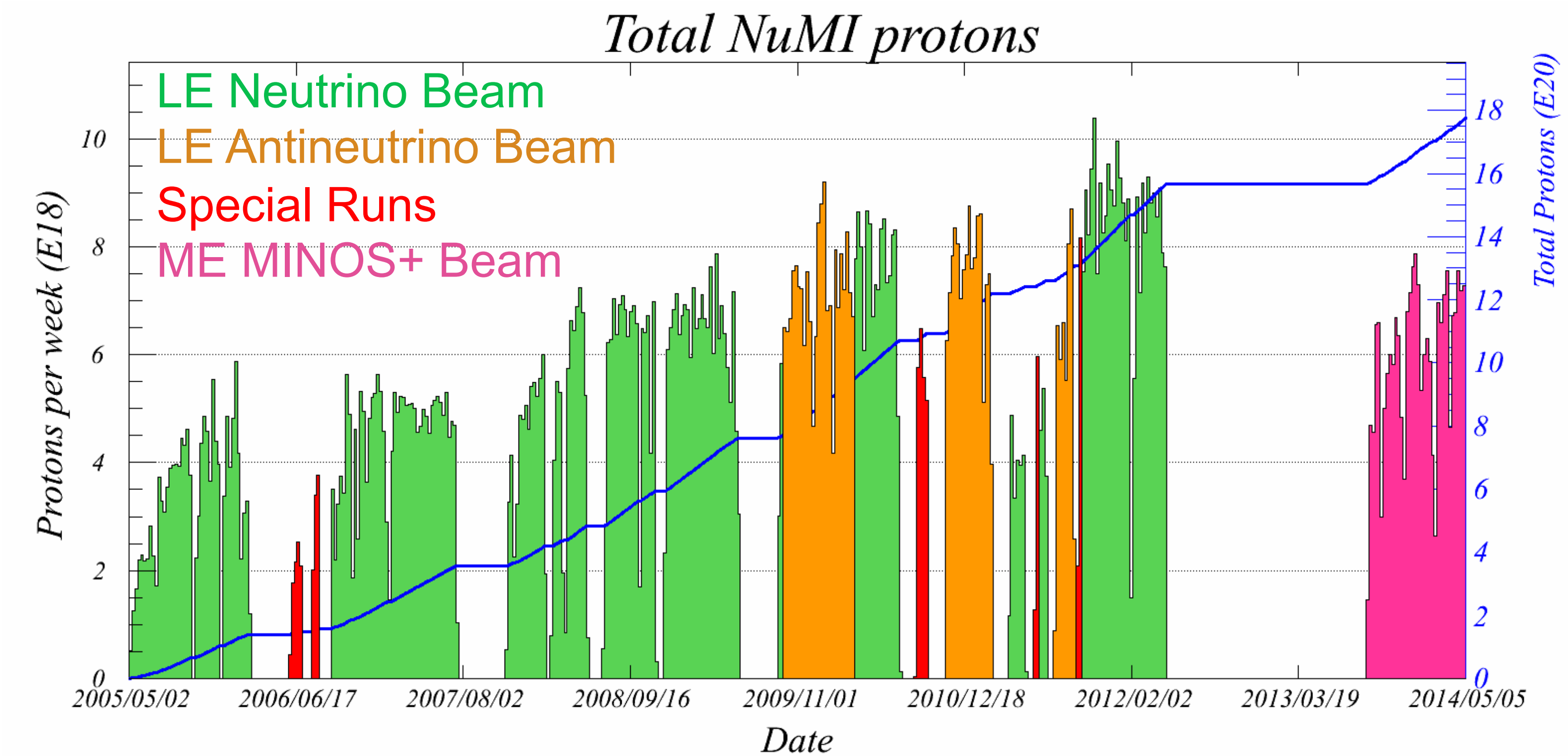
Far Detector (FD)
735km from source
5.4kt



Near Detector (ND)
1km from source
1kt

NuMI Beam Performance

- Upgraded NuMI beam started up September 4th 2013
  - Higher energy, increased intensity, rep rate and hence power

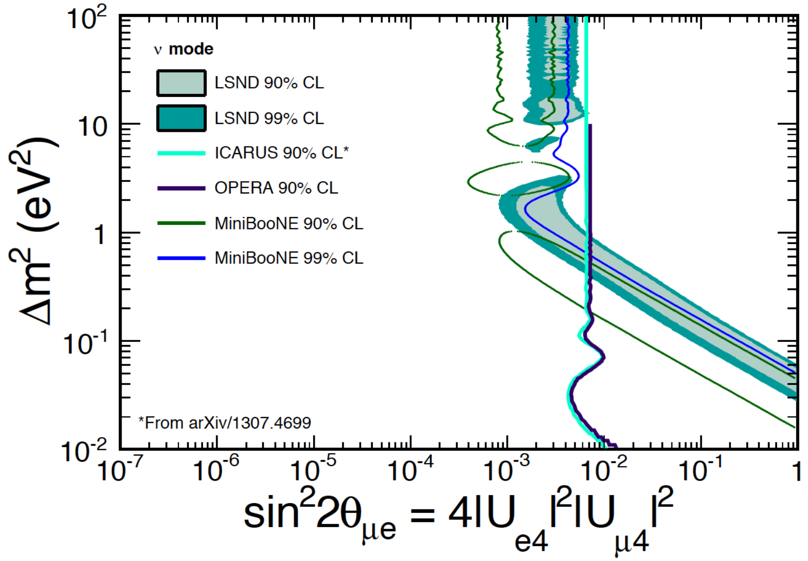


	Intensity (Protons/Pulse)	Power (kW)	Rep. Rate (s)
Current	2.4×10^{13}	280	1.7
Design	5.0×10^{13}	700	1.33

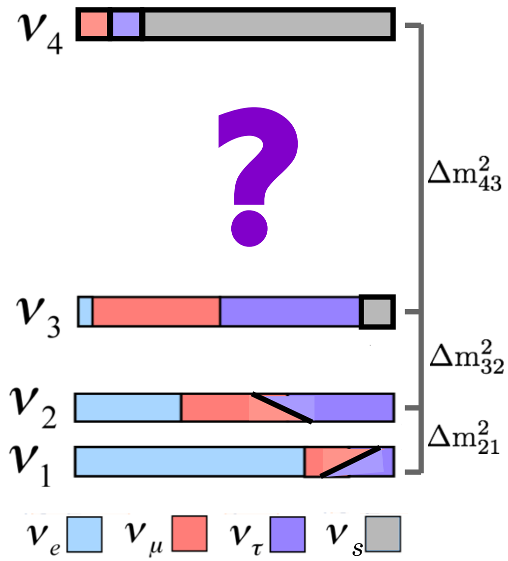
MINOS Sterile Neutrino Analysis

Sterile Neutrinos

- There have been anomalous results in various low energy short baseline appearance and reactor experiments
  - Look with long-baseline: Higher energy and different systematics
- Oscillations to a 4th light neutrino could explain results
- A sterile neutrino would be seen in MINOS as an energy dependent reduction in event rate
  - In both neutral-current (NC) and charged-current (CC) channels
- MINOS mostly sensitive to Δm^2_{43} and θ_{24}, but also to θ_{34}

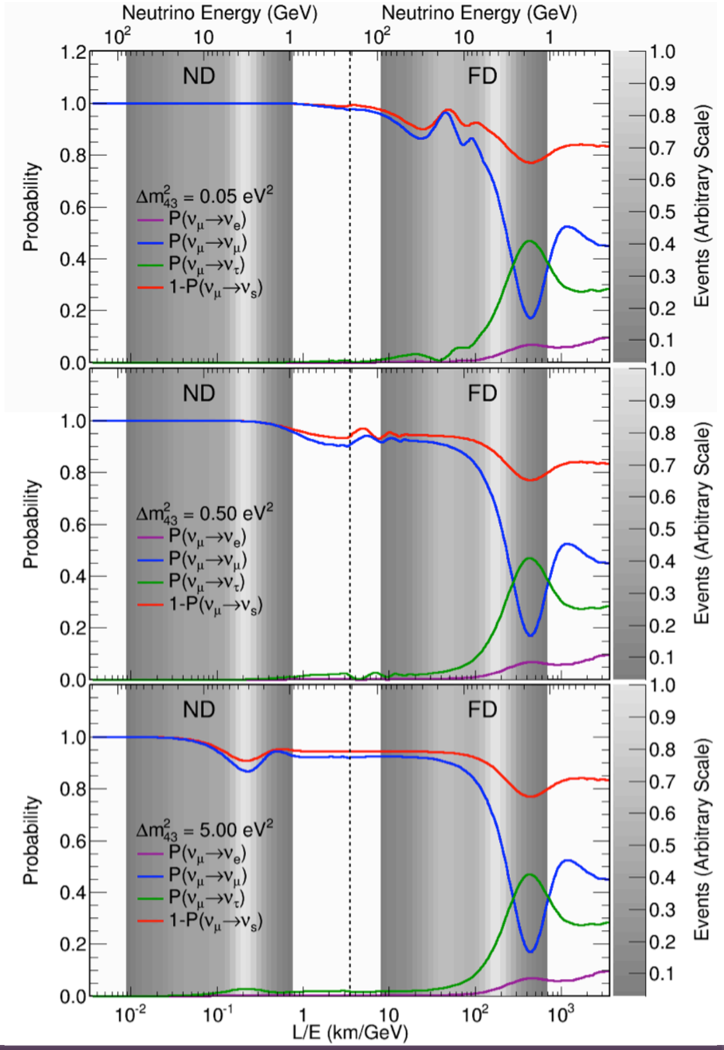


MiniBooNE, PRL 110, 161801(2013)



Sterile Neutrinos in MINOS

- Useful to think of potential oscillations in three categories:
- Small Δm^2_{43}
  - Expect spectral distortions in the FD in the high energy tail
  - No ND effects
- Medium Δm^2_{43}
  - Rapid oscillations in the FD average out
  - No ND effects
  - Counting experiment
- Large Δm^2_{43}
  - Rapid oscillations in the FD average out
  - Spectral distortions in the ND
  - Simple extrapolation no longer works



Sterile Neutrinos in MINOS

- Perform combined fit of the NC and CC samples
  - 2721 ν_μ-CC-like events in FD
  - 1221 NC-like events in FD

- For NC selection, define test statistic

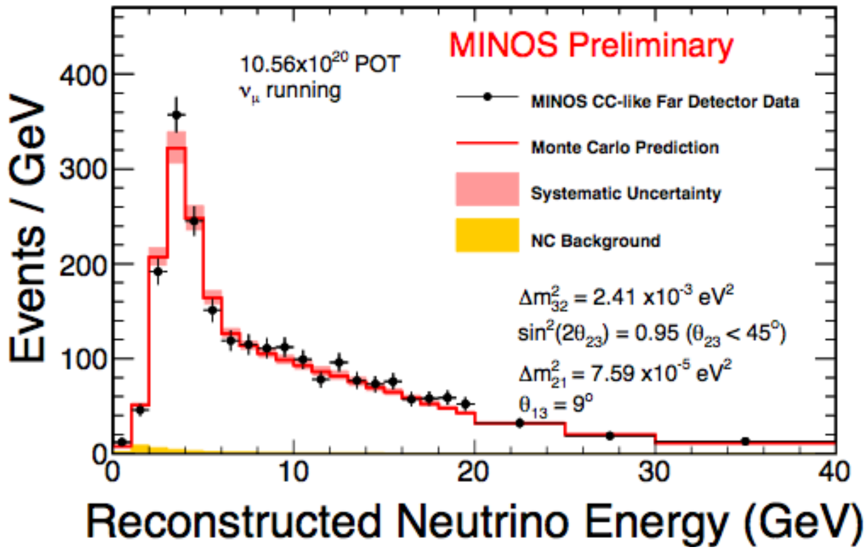
Predicted Background

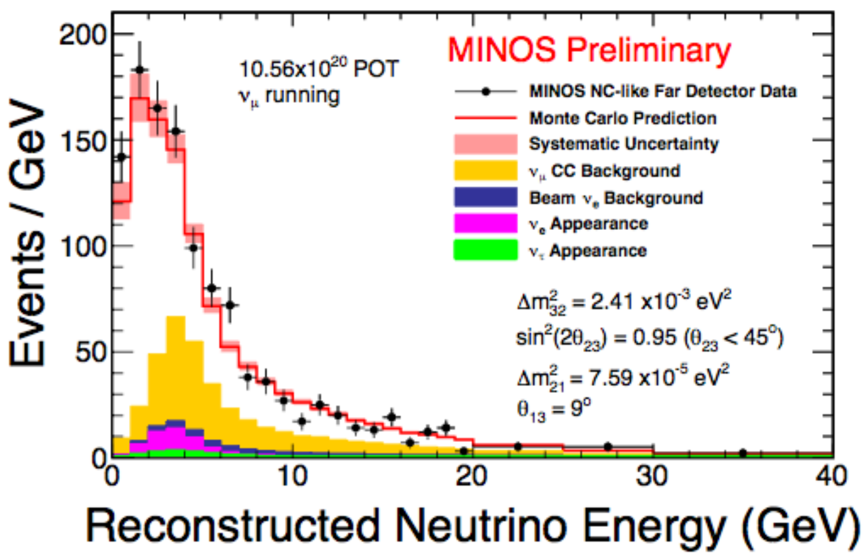
$$R = \frac{N_{data} - N_{bkg}}{S_{NC}}$$

Predicted Signal

  - 0 – 200 GeV: $R = 1.049 \pm 0.076$
  - 0 – 3 GeV $R = 1.093 \pm 0.097$

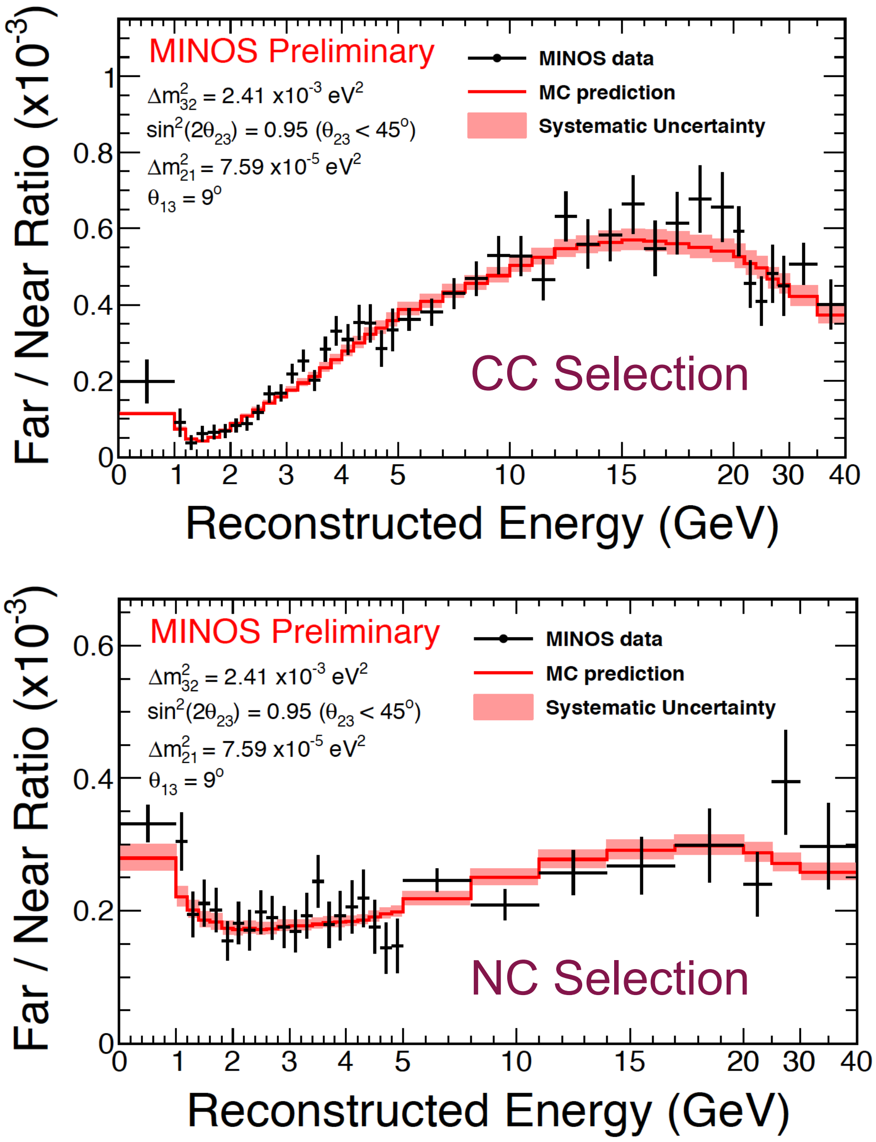
- No evidence for a sterile neutrino at $\Delta m^2_{43} \approx 0.5$ eV^2





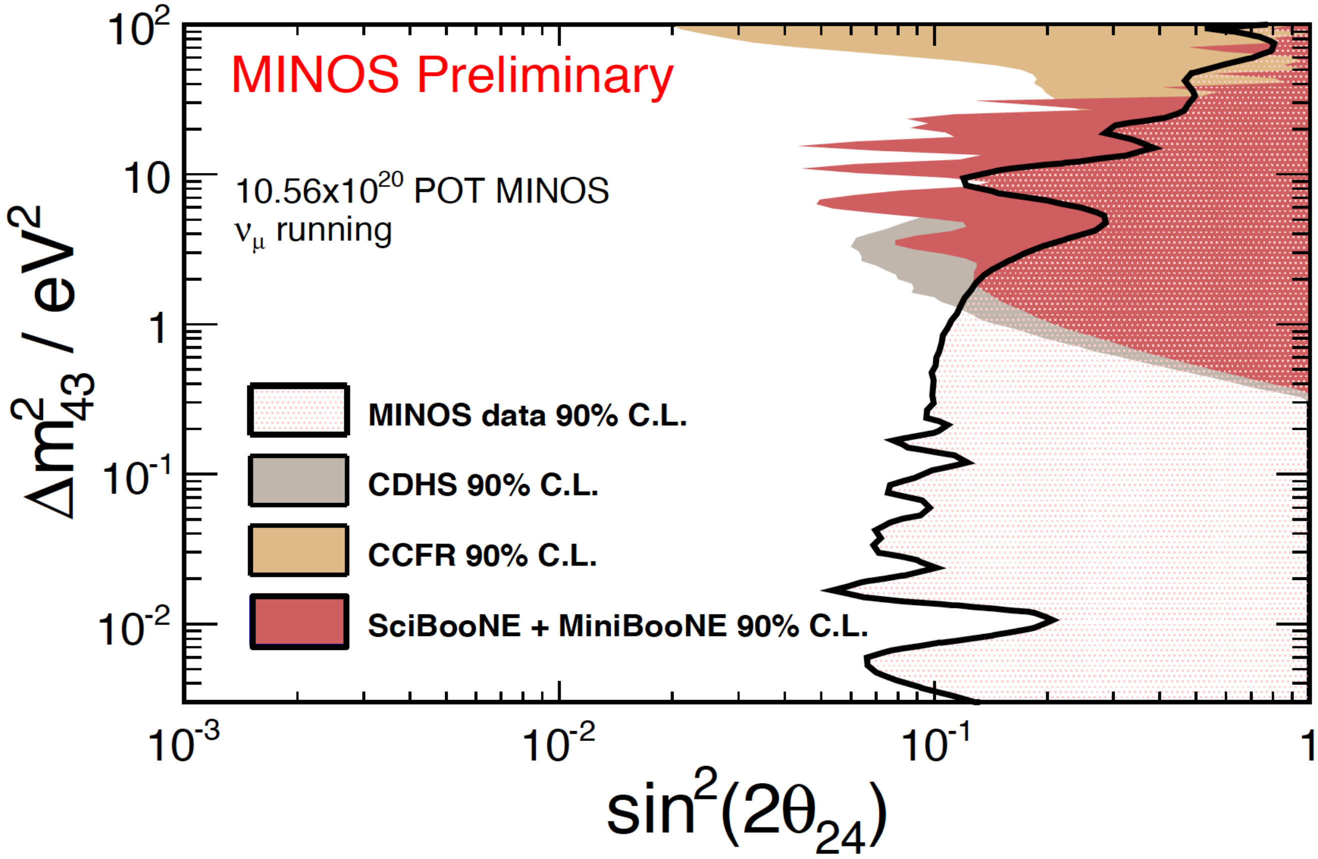
Full Four Flavour Fit

- Assume 3+1 scenario
  - Apply oscillations for ND and FD
  - Account for meson decay position
  - Fit for $|\Delta m^2_{32}|$, θ_{23}, $|\Delta m^2_{43}|$, θ_{24}, θ_{34}
- Due to potential ND oscillations, fit expected F/N ratio to data F/N ratio
  - Standard extrapolation technique not applicable in this case
  - Additional constraint on ND rate
- Use Feldman-Cousins method to obtain the confidence limits
- Careful study of systematics in the high energy tail



MINOS Sterile Neutrino Results

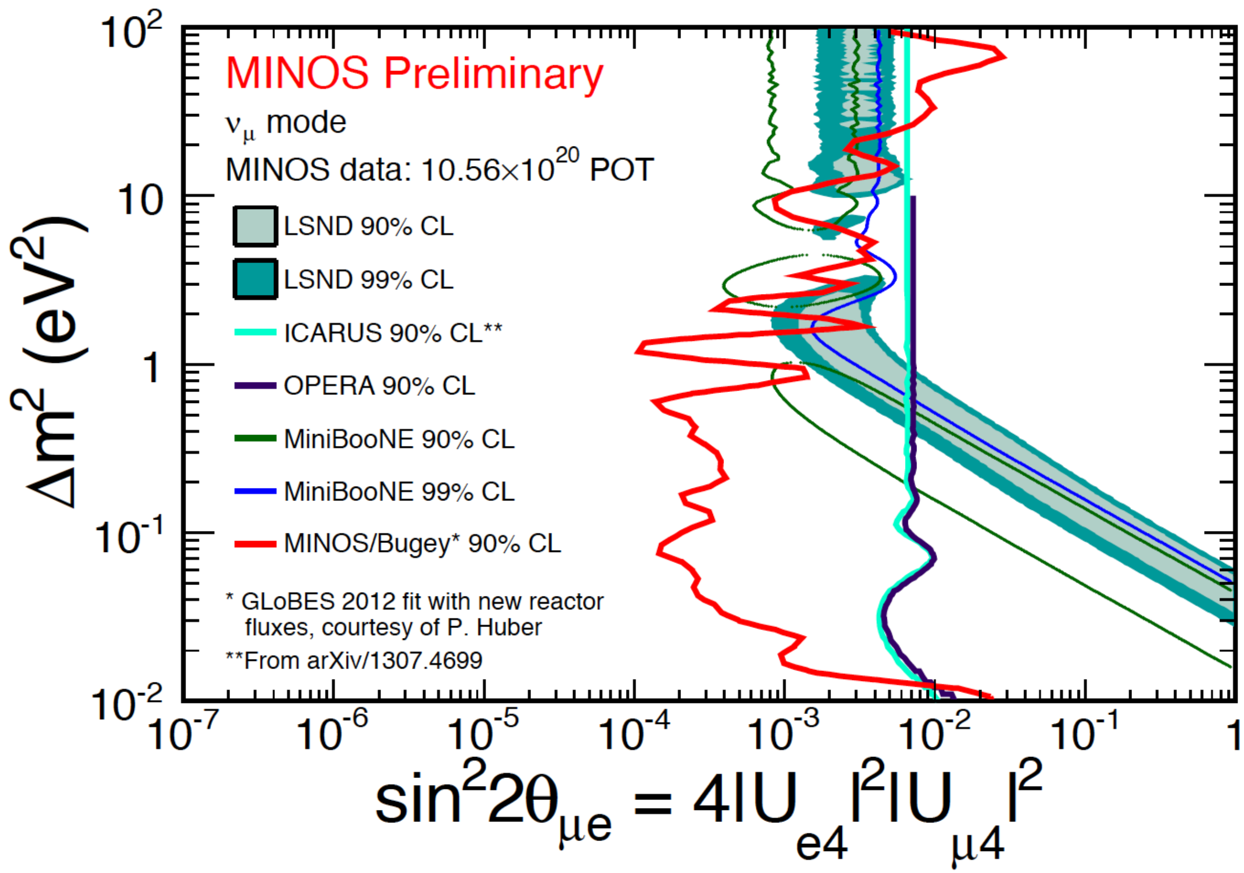
- Compare with disappearance searches in $|\Delta m^2_{43}|$, θ_{24}



- MINOS limit stretches over 4 orders of magnitude in $|\Delta m^2_{43}|$
  - For values $|\Delta m^2_{43}| < 1.0\text{eV}^2$, strongest limit on ν_μ to ν_s disappearance

Comparison with SBL Appearance

- Appearance experiments measure $\sin^2 2\theta_{\mu e} \sim \sin^2 2\theta_{14} \sin^2 \theta_{24}$
  - Combine with Bugey since MINOS not sensitive to θ_{14}



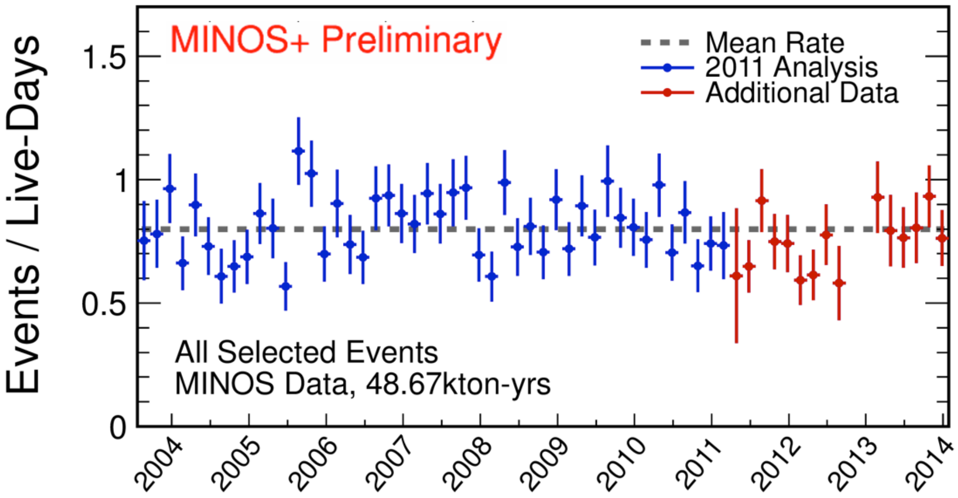
- Strong limit for values of $\Delta m^2_{43} < 1.0$ eV^2

MINOS/MINOS+ Three Flavour Update

Data Samples

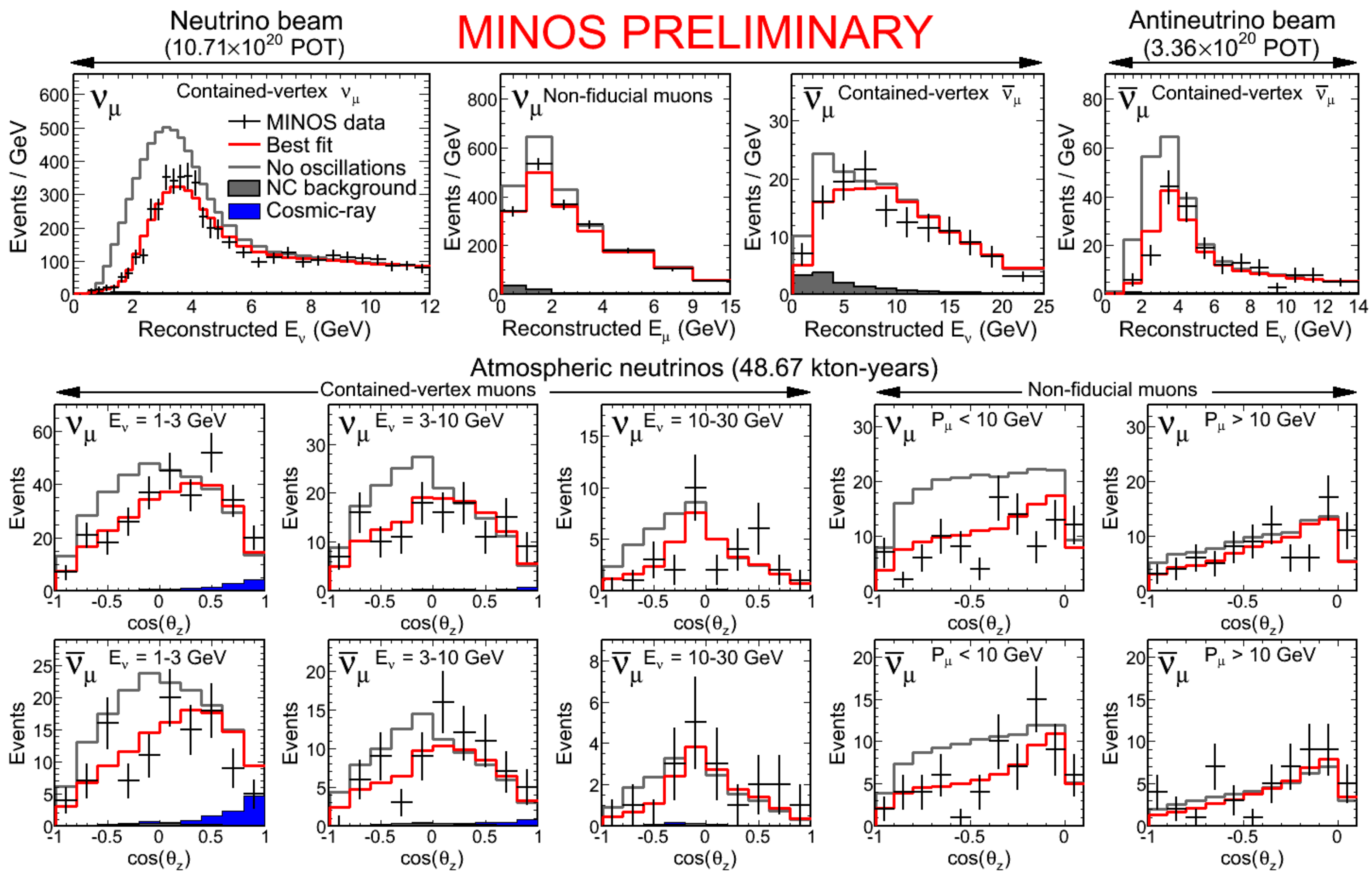
- Update to the result published MINOS combined three flavour analysis
  - PRL 112, 191801 (2014)
  - Full MINOS appearance and disappearance samples
    - 10.71×10^{20} POT neutrino mode
    - 3.36×10^{20} POT antineutrino mode
    - 37.88 kton-years FD atmospheric neutrinos

- Added additional 10.8 kton-years (28%) MINOS+ atmospherics



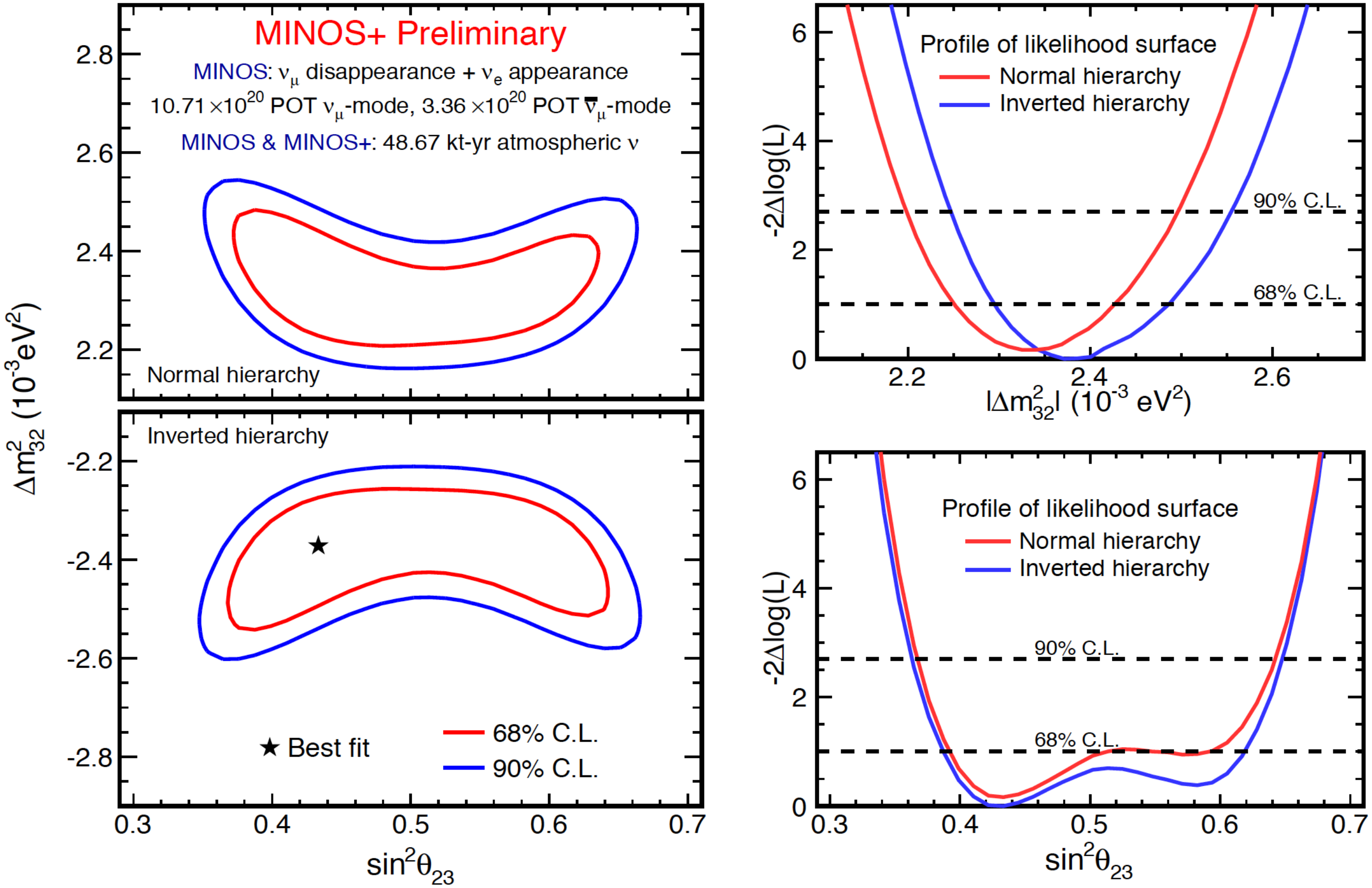
Data Samples

- Disappearance sample spectra



Combined Fit Results

- In the fit, $|\Delta m^2_{32}|$, θ_{23} and δ_{CP} unconstrained
  - θ_{13} constrained by reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$
  - Solar parameters fixed: $\Delta m^2_{21} = 7.54\times10^{-5}\ \text{eV}^2$ and $\sin^2\theta_{12} = 0.307$ †



† Fogli et al. Phys. Rev. D 86, 013012 (2012)

Combined Fit Results

- Inverted Hierarchy

$$\left|\Delta m_{32}^{2}\right| = 2.37_{-0.07}^{+0.11} \times 10^{-3} eV^{2}$$

$$\sin^{2}\theta_{23} = 0.43_{-0.05}^{+0.19}$$

$$0.36 < \sin^{2}\theta_{23} < 0.65 \ (90\% \ C.L.)$$

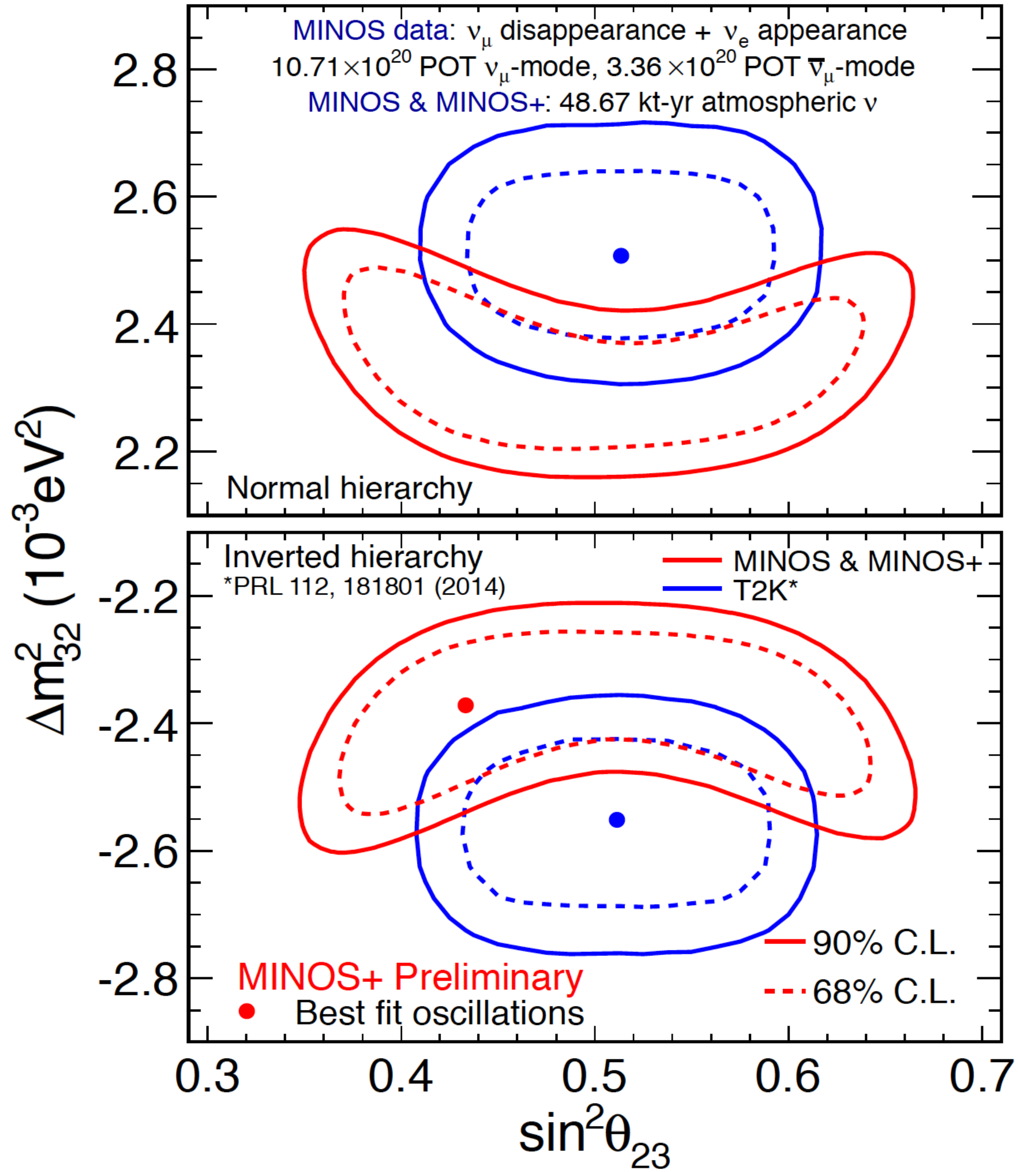
- Normal Hierarchy

$$\left|\Delta m_{32}^{2}\right| = 2.34_{-0.09}^{+0.09} \times 10^{-3} eV^{2}$$

$$\sin^{2}\theta_{23} = 0.43_{-0.04}^{+0.16}$$

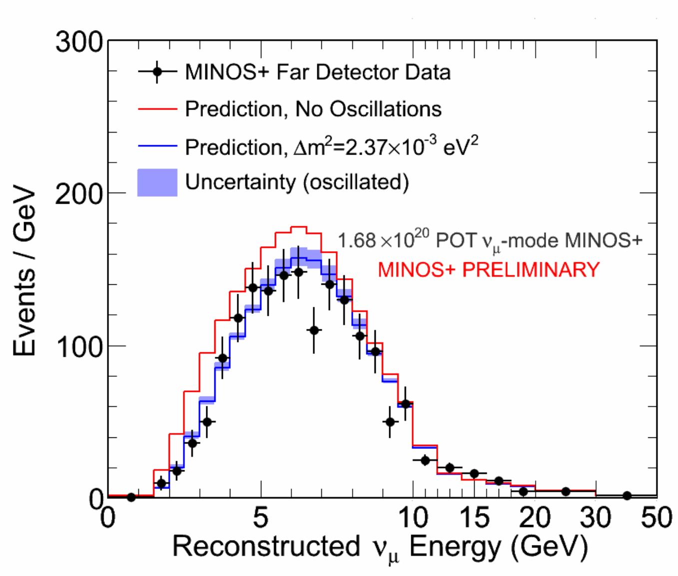
$$0.37 < \sin^{2}\theta_{23} < 0.64 \ (90\% \ C.L.)$$

- Inverted Hierarchy favoured by only -2Δlog(L) = 0.16
- Most precise measurement of $|\Delta m^2_{32}|$ to date.



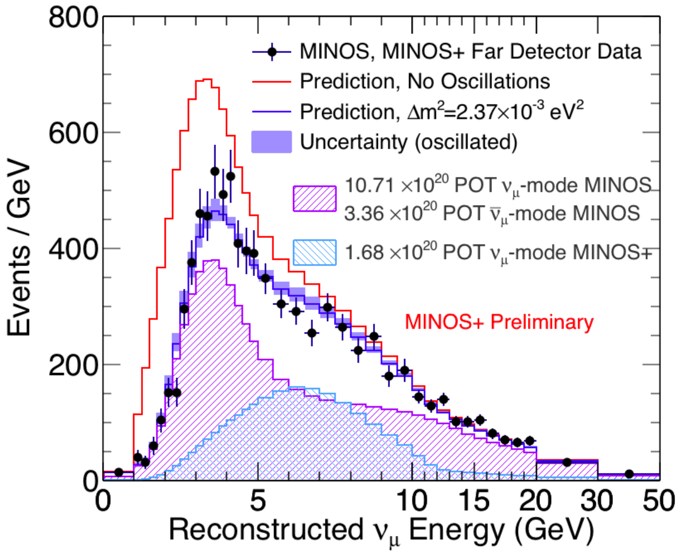
MINOS+ Beam Data

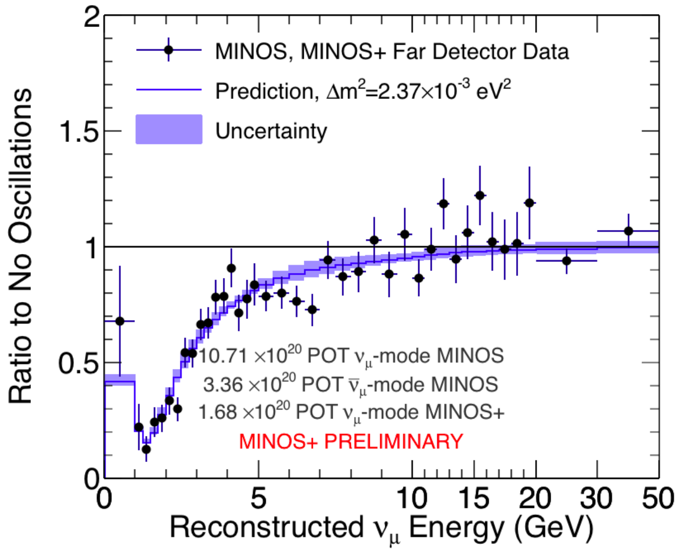
- MINOS+ data consistent with oscillations measured by MINOS



- MINOS+ will collect 3.5×10^{20} POT by the shutdown in September 2014

- Expect to see the first MINOS/MINOS+ combined beam fit soon

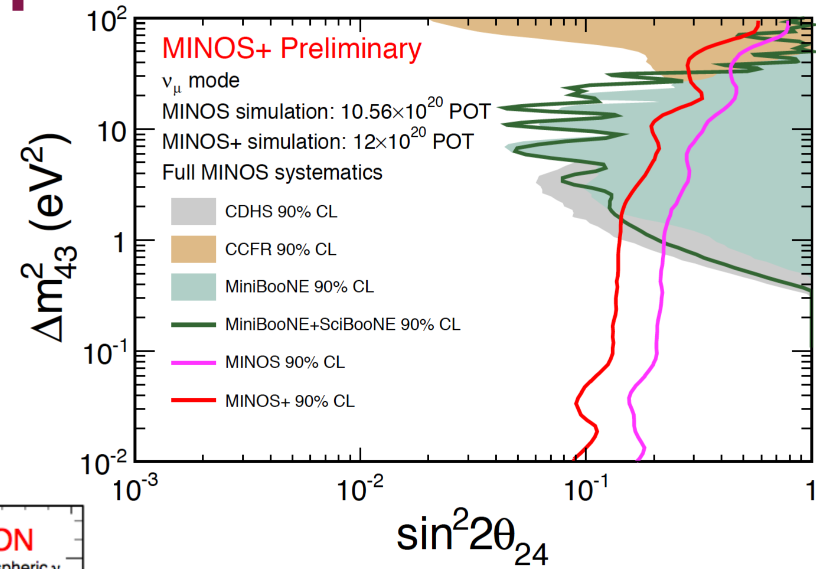


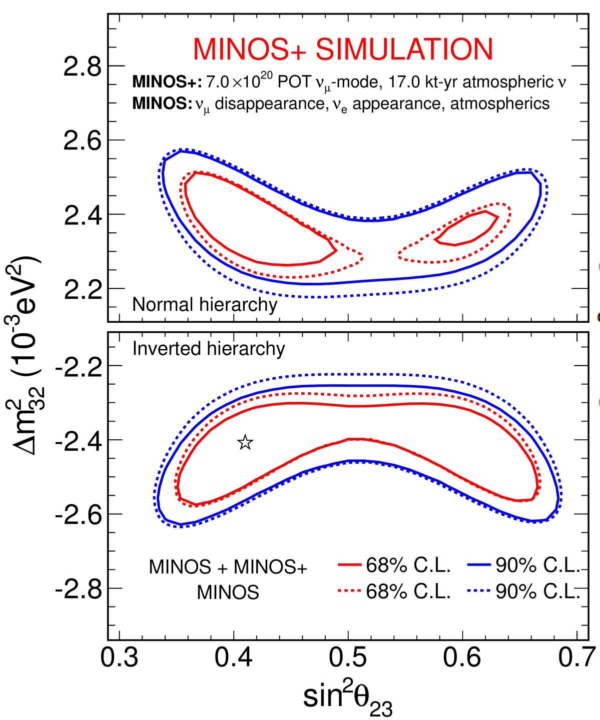


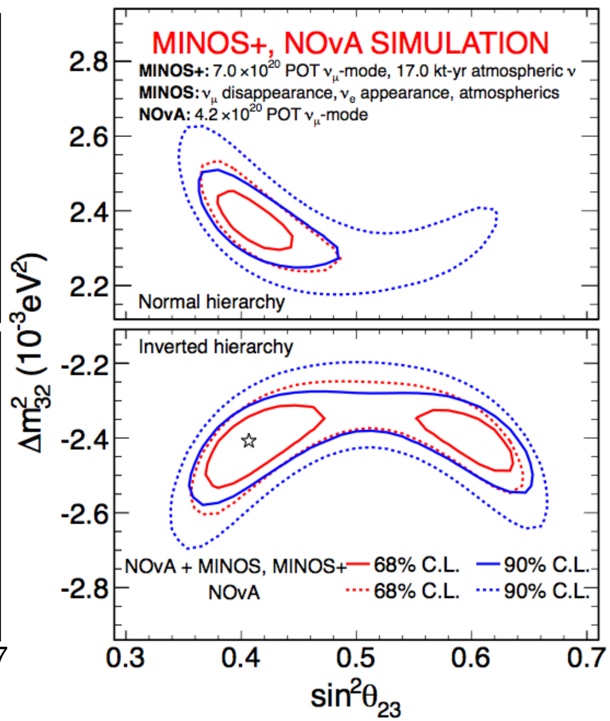
MINOS+ Prospects

MINOS+ Prospects

- MINOS+ will continue to probe sterile neutrinos
  - Expected sensitivity by 2016 shown compared to MINOS and SBL disappearance experiments







- Expected three flavour sensitivity by 2015
- Assuming best fit from previous analysis *PRL **112**, 191801 (2014)*
- Can combine with NOvA

Summary

- MINOS found no evidence of a sterile neutrino
  - Strong limits set across over 4 orders of magnitude in $|\Delta m^2_{43}|$
- Improved three flavour oscillations result with the inclusion of MINOS+ atmospheric neutrino data
  - World leading measurement of $|\Delta m^2_{32}|$
- MINOS+ is continuing to take data
  - Will provide precision test of oscillations away from the maximum
  - Expect MINOS/MINOS+ combined beam fit soon
- MINOS+ has lots of prospects I could not mention here:
  - Large extra dimensions
  - Non-standard interactions
  - Anomalous ν_e appearance at high energy

Thank You

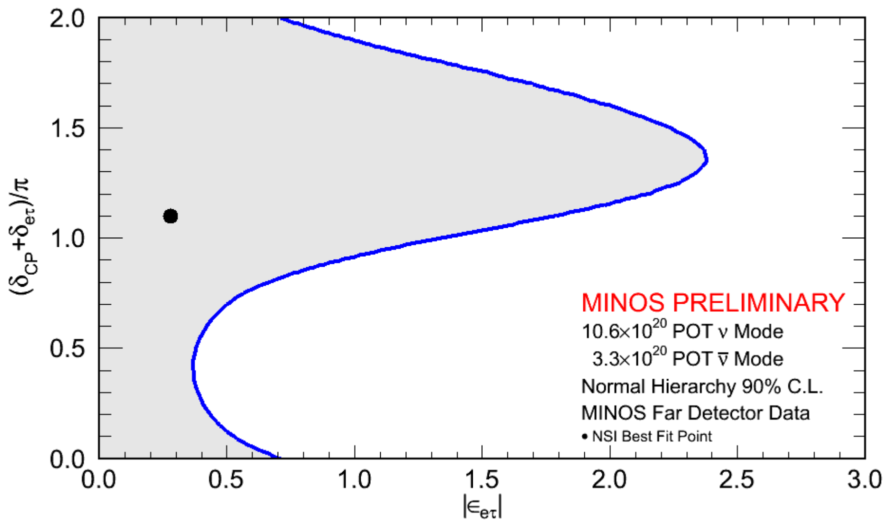
MINOS NSI Result

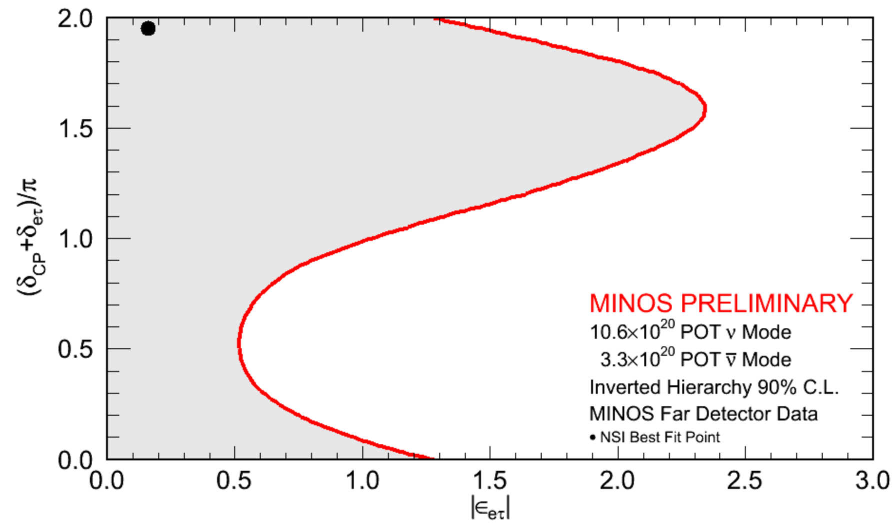
- Non-standard interactions provide a framework to accommodate deviations from standard oscillations

$$H = U_{PMNS}\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{bmatrix}U^\dagger_{PMNS} + \sqrt{2}G_F n_e\begin{bmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^\star_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{bmatrix}$$

  - MINOS sensitive to $\varepsilon_{e\tau}$ from ν_e appearance and $\varepsilon_{\mu\tau}$ from ν_μ disappearance

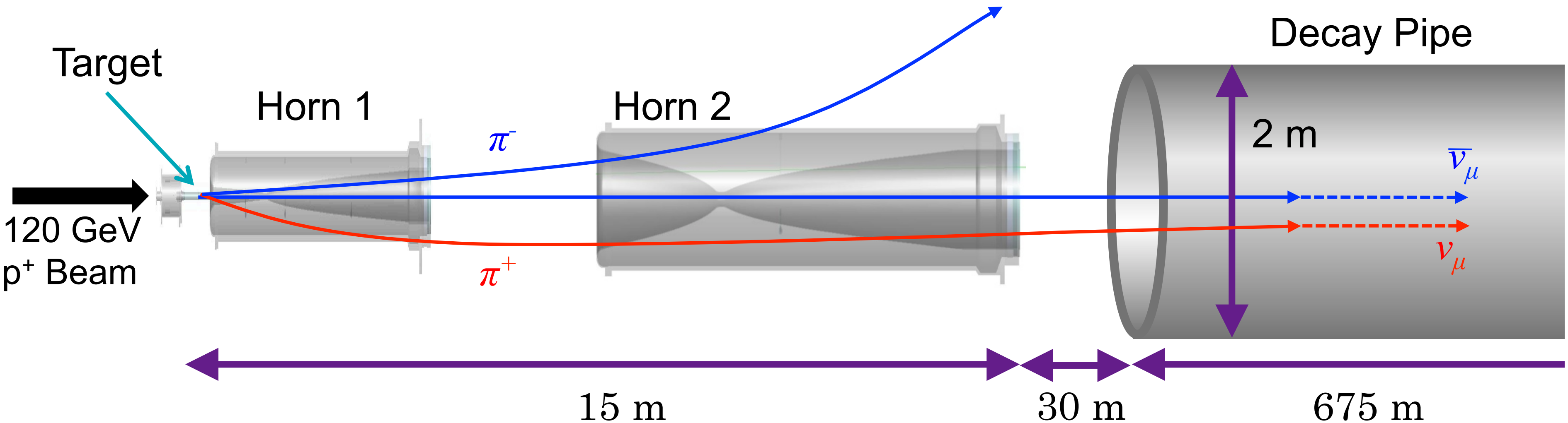
- This new $\varepsilon_{e\tau}$ analysis uses NSI formalism from: *Friedland et al. PRD **70**, 111301 (2004)* *Coelho et al. PRD **86**, 113015 (2012)*



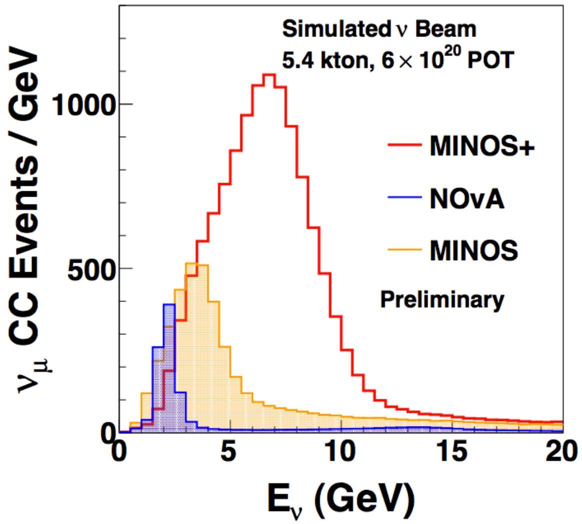


The NuMI Beam

- Beam starts with 120 GeV protons from the Main Injector.

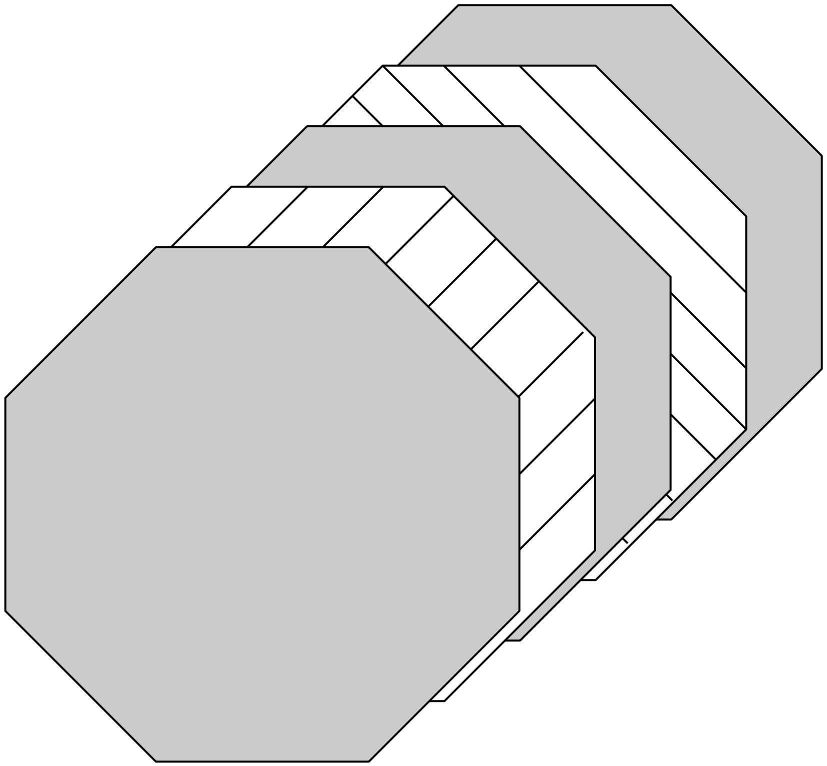


- Now runs in the medium energy mode
- New target design for the NOvA era



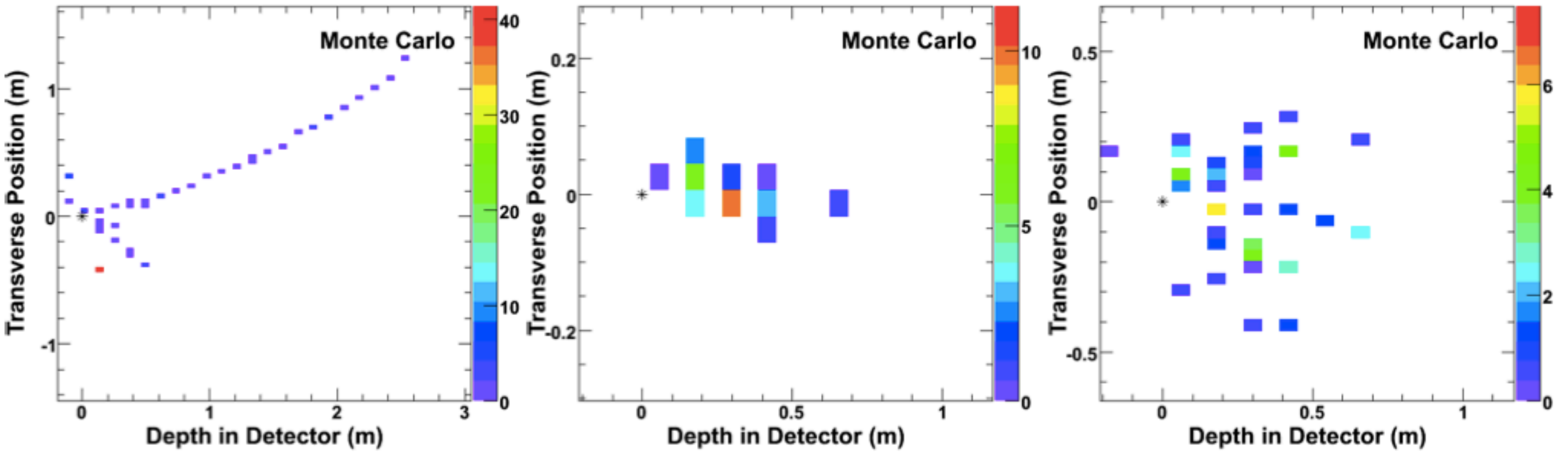
Detector Technology

- Detectors built from alternating planes:
  - 2.54cm steel absorber ~1.4 X_0
  - 1cm thick scintillator.
- Scintillator planes:
  - Made from plastic scintillator bars, each 4.1cm wide.
  - Read out by multi-anode PMTs via WLS fibres.
  - Alternating layers have bars in orthogonal directions views, U and V
- Magnetic field allows for charge separation.
  - Both detectors have average field of 1.3T



Event Topologies in MINOS

- Expect to see three classes of event.



CC ν_{μ}	CC ν_{e}	NC ν_{x}
Identify muon track and use curvature to measure the sign. Momentum comes from range or curvature (if not contained).	Compact electro-magnetic shower.	Disperse hadronic shower energy deposits.

Four Flavour Oscillations

- A fourth neutrino state adds:
  - 3 mixing angles: $\theta_{14}, \theta_{24}, \theta_{34}$
  - 3 mass splittings: $\Delta m^2_{43}, \Delta m^2_{42}, \Delta m^2_{41}$
  - 2 additional complex phases

$$U_4 = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- LSND/MiniBooNE measured $\sin^2 2\theta_{\mu e} \sim \sin^2 2\theta_{14} \sin^2 \theta_{24}$

- MINOS NC measures $\sin^2 2\theta_{\mu s} \sim \sin^2 2\theta_{24} \cos^2 \theta_{34}$

- Reactor experiments measure $\sin^2 2\theta_{ee} \sim \sin^2 2\theta_{14}$

- Therefore it makes sense to combine MINOS with a reactor experiment such as BUGEY to set a limit on $\sin^2 2\theta_{\mu e}$

Sterile Analysis - Systematics

- 26 systematic uncertainties included in the fit via a covariance matrix

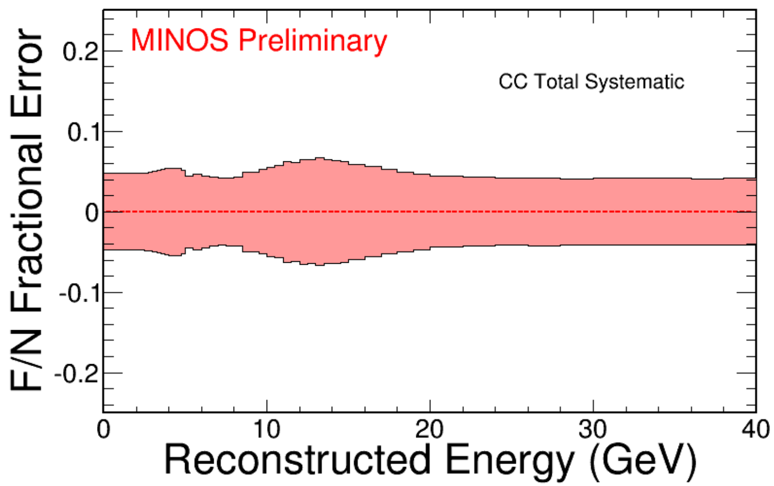
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

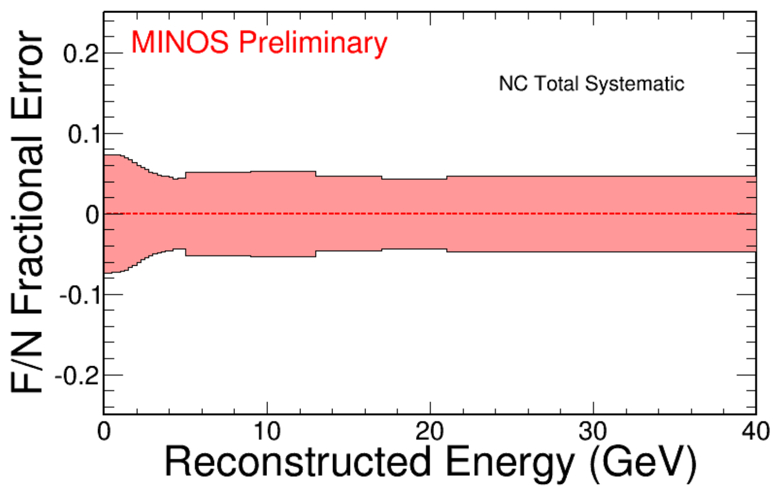
o_i : Observed events in bin i

e_i : Predicted events in bin i

V : Covariance matrix

  - Many sources: selection, energy scale cross-sections, normalistion, beam flux etc





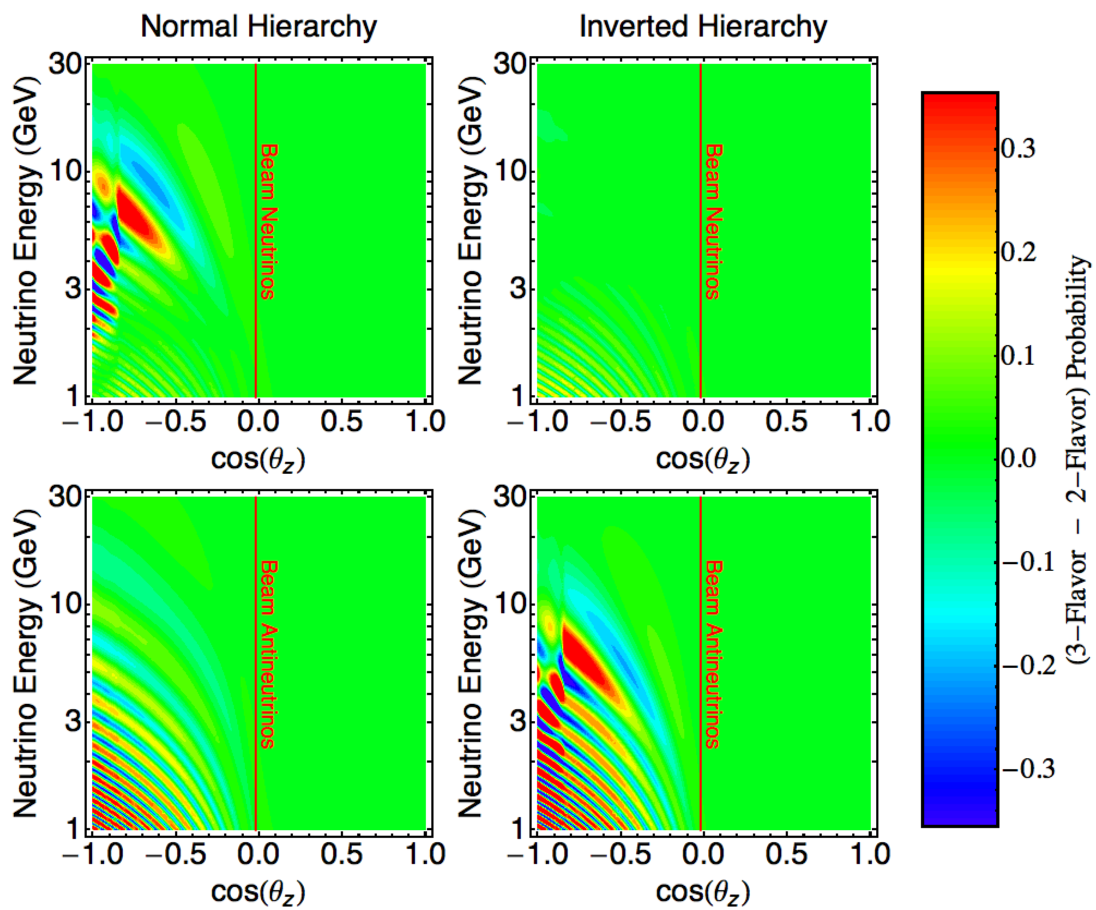
Matter Effects (MSW)

- Interactions with matter modify the standard oscillations
  - Comparing between 2 and 3 flavour oscillations, see fairly large variation for ~few GeV atmospheric neutrinos

- Changes the probability by up to 30%

- Gives sensitivity to the mass hierarchy

- Very small effect for the beam neutrinos



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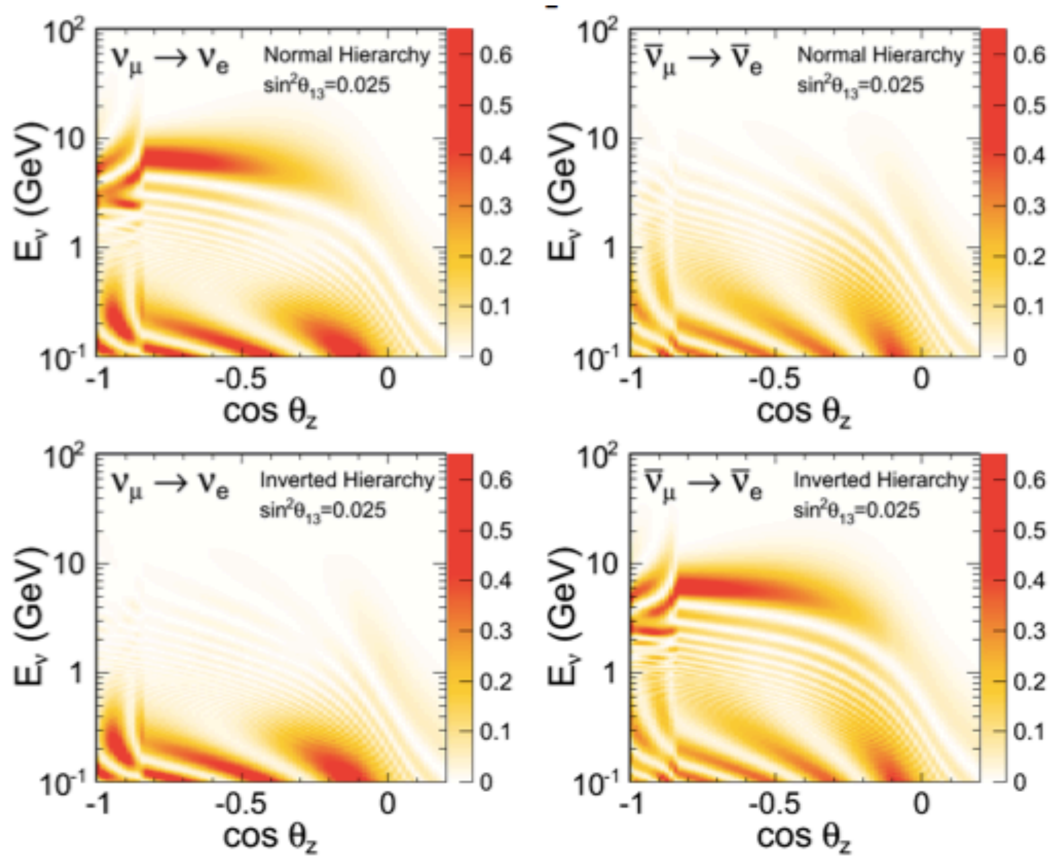
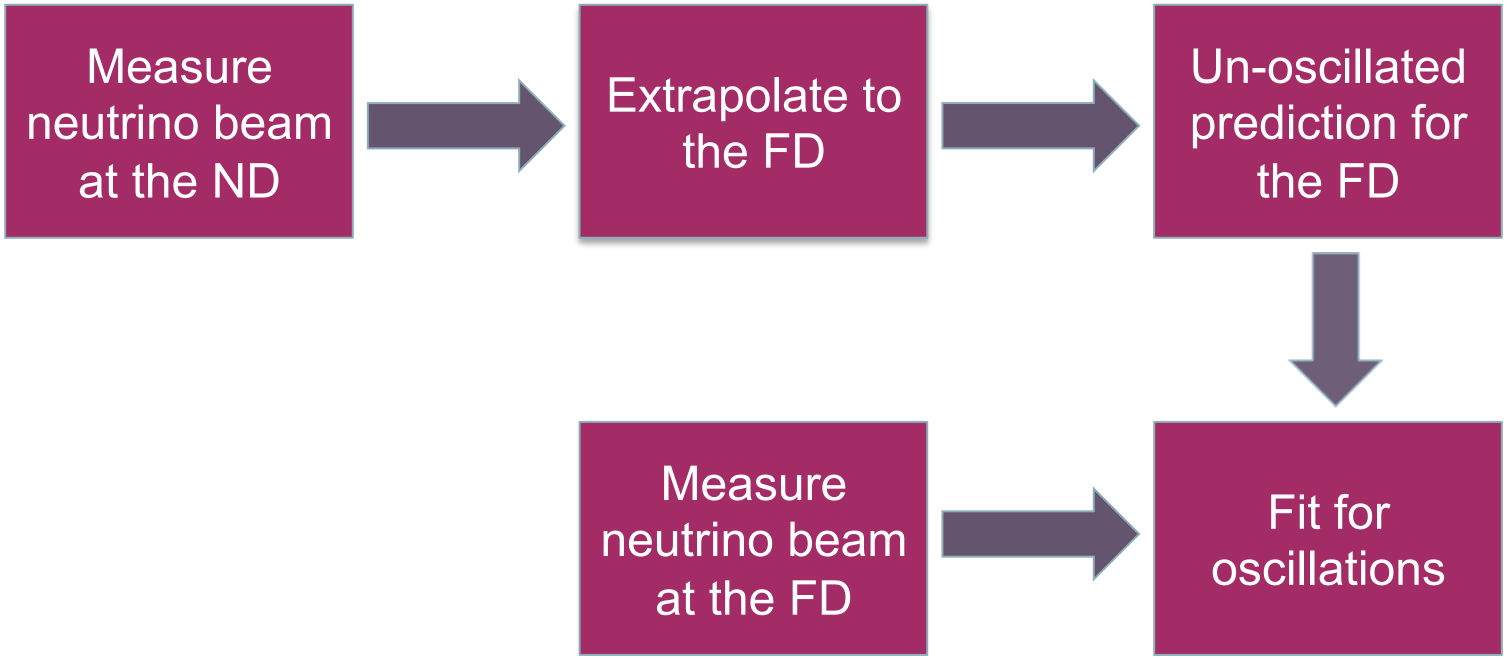


Three Flavour Analysis – Methodology I

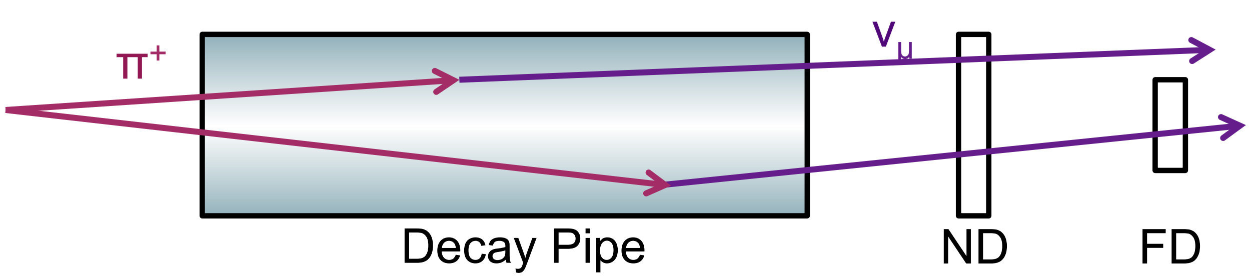
- Use the ND to predict the FD un-oscillated spectrum



- The extrapolation to the FD requires a few steps…

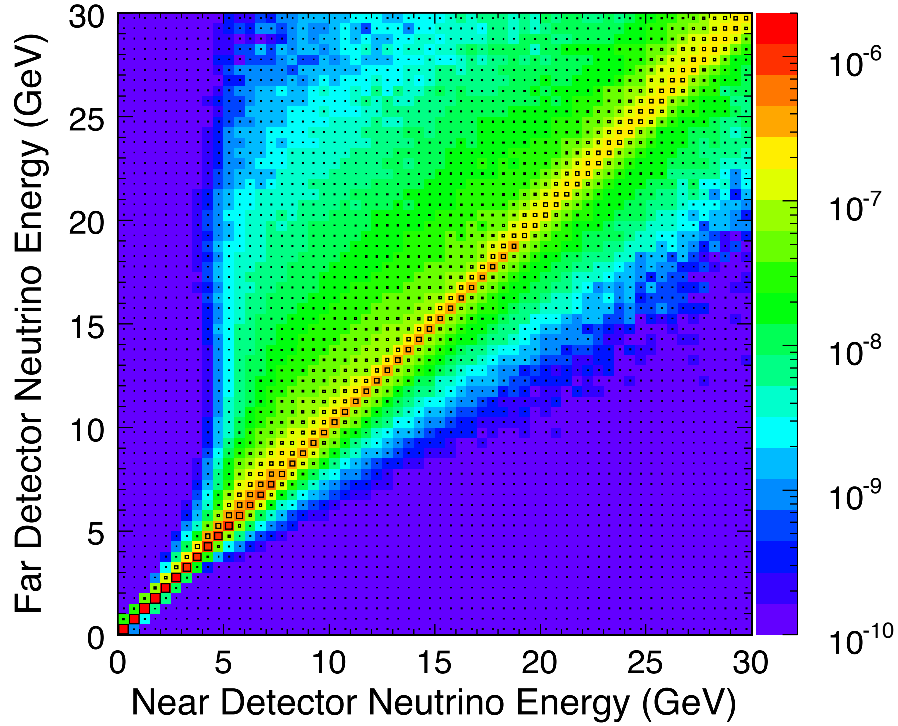
Three Flavour Analysis – Methodology II

- Starting with the ND data:
  - Correct for ND purity and efficiency and apply reco-true matrix
  - Account for cross-sections, POT and ND mass
- Need to account for beam differences now
  - The energy spectrum differs between the two detectors
    - Different angular acceptances
    - Low energy pions decay upstream in the decay pipe.
  - FD sees a point source
  - ND sees an extended source



Three Flavour Analysis – Methodology III

- Apply the beam matrix to extrapolate to the FD.



- Then apply the FD specific corrections.
  - These are the analogues to those shown previously for the ND

- Provides the un-oscillated prediction at the FD

Three Flavour Analysis - Yields

- Break down of the event yields in the three flavour analysis:

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2496	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	319	312
Non-fiducial ν from ν_μ beam	3197	2807	2911
Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$	1414	1024	1134
Atm. non-fiducial $\mu^+ + \mu^-$	732	575	590
Atm. showers	932	877	899

Three Flavour Analysis – Best Fit Results

- Atmospherics only

Hierarchy	Best fit oscillation parameters Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	-2Δlog(L)
Normal	2.03	0.50	0.0242	0	-
Inverted	2.13	0.50	0.0242	1.57	0.559

- Atmospherics + Beam Disappearance

Hierarchy	Best fit oscillation parameters Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	-2Δlog(L)
Normal	2.31	0.59	0.0243	0	0.020
Inverted	2.37	0.43	0.0243	1.57	-

- Atmospherics + Beam Disappearance + Beam Appearance

Hierarchy	Best fit oscillation parameters Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	-2Δlog(L)
Normal	2.34	0.43	0.0242	1.77	0.16
Inverted	2.37	0.43	0.0243	1.77	-

Hierarchy	Parameter	Best fit	Confidence limits
Normal	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.34	2.25 - 2.43 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.39 - 0.59 (68% C.L.) 0.37 - 0.64 (90% C.L.)
Inverted	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.37	2.30 - 2.48 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.38 - 0.62 (68% C.L.) 0.36 - 0.65 (90% C.L.)

Three Flavour Analysis - Systematics

- Systematics fitted as nuisance parameters

Systematic Parameters	Best fit
BeamNumuNorm	1.24
BeamNumuNCBkg	0.16
BeamNumuShwEn	-0.43
BeamNumuTrkEn	0.79
AtmosNormCV	0.49
AtmosNormRock	0.13
AtmosChgCV	-0.64
AtmosChgRock	1.46
AtmosNueNorm	-0.31

Systematic Parameters	Best fit
AtmosNCBkg	-0.51
AtmosSpecNumuCV	-0.62
AtmosSpecNumuBarCV	1.18
AtmosSpecNuRock	0.39
AtmosSpecNuBarRock	0.35
AtmosZenith	-0.24
AtmosNumuTrkEnExit	-0.11
AtmosNumuShwEn	0.28