Combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance in MINOS using accelerator and atmospheric neutrinos

Phys. Rev. Lett. 112, 191801 (2014)

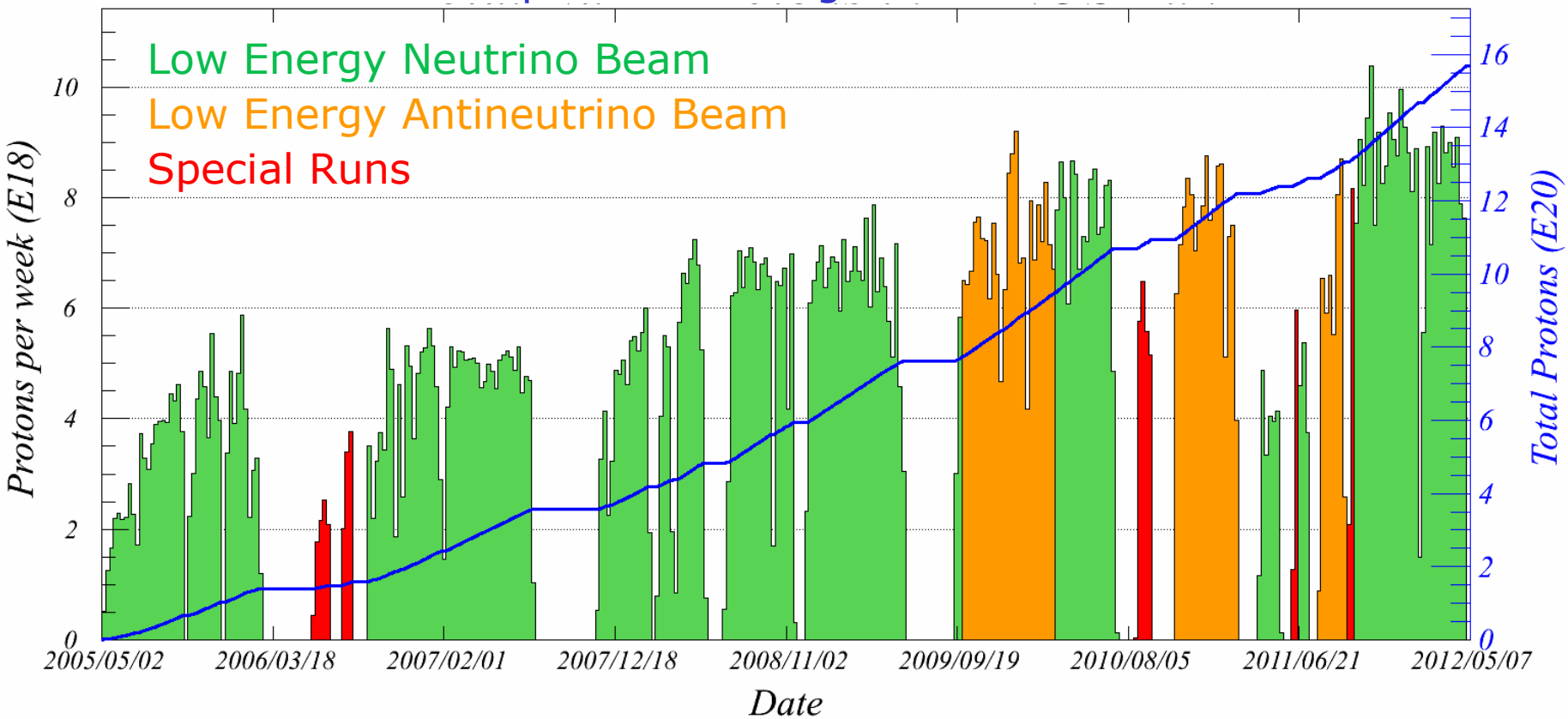
[arXiv:hep-ex/1403.0867]

MINOS three-flavour oscillation results

- Oscillation results are based on the complete set of accelerator and atmospheric neutrino data from MINOS.
- Building on two previous MINOS results:
  - Two-flavour ν_μ disappearance – PRL 110, 251801 (2013)
  - Three-flavour $\nu_\mu \rightarrow \nu_e$ appearance – PRL 110, 171801 (2013)
- The data are now combined using full three-flavour formalism. Represents the first combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance by a long-baseline neutrino experiment.
- In three-flavour formalism, the combined MINOS data provide precision measurements of Δm^2_{32} and $\sin^2\theta_{23}$ parameters.
- Combined analysis also improves previous constraints on δ_{CP}, mass hierarchy and θ_{23} octant degeneracy.
  - In particular, accelerator ν_e data and atmospheric data provide complementary probes of mass hierarchy and θ_{23} octant.

MINOS combined analysis

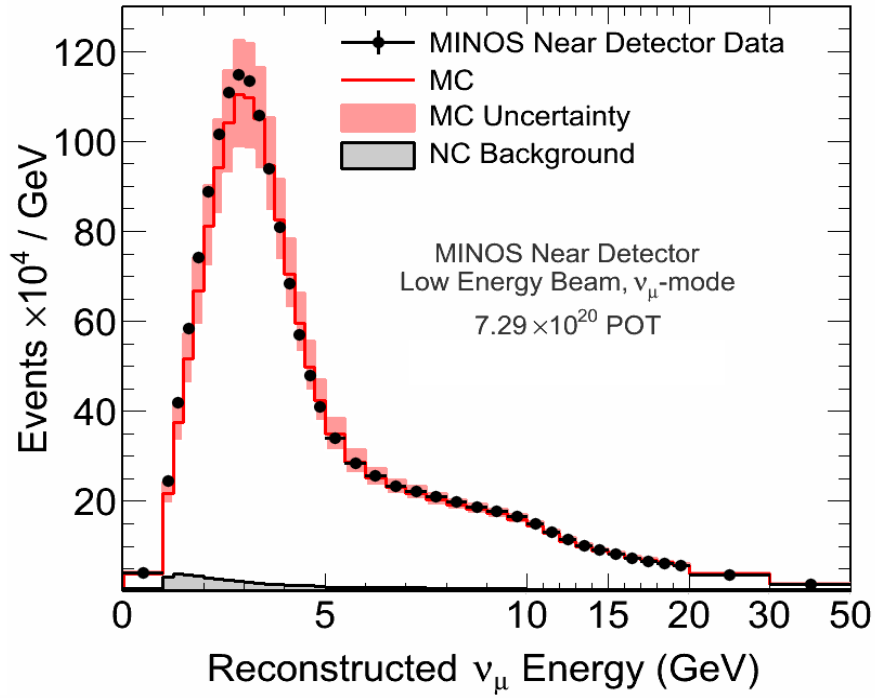
Total protons on target in NuMI beam

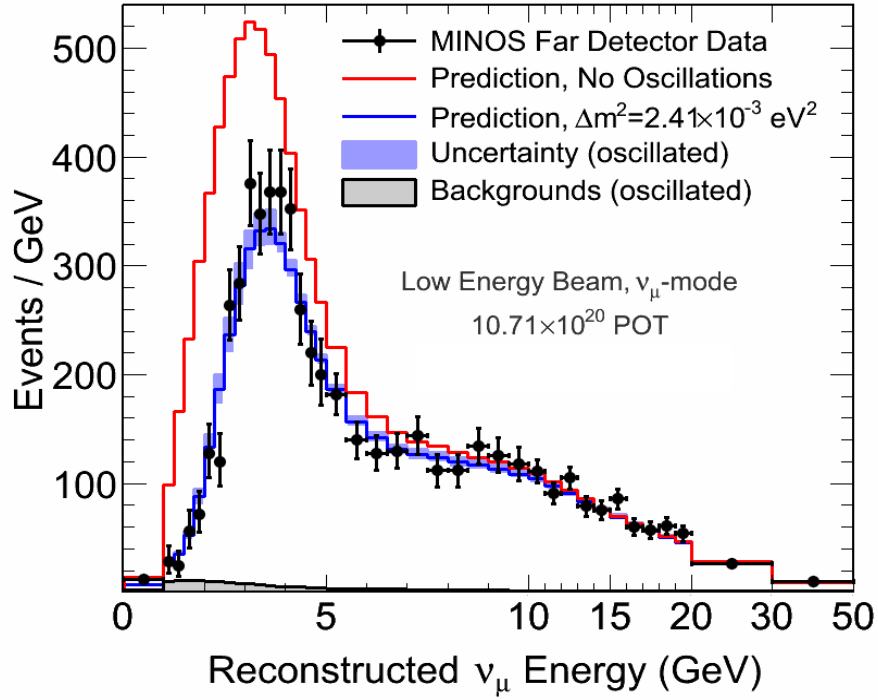


- **Accelerator and atmospheric neutrino data from MINOS:**
  - NuMI beam, neutrino mode (10.71 x 10^{20} protons-on-target)
  - NuMI beam, antineutrino mode (3.36 x 10^{20} protons-on-target)
  - Atmospheric neutrinos (37.9 kt-yrs in MINOS Far Detector)

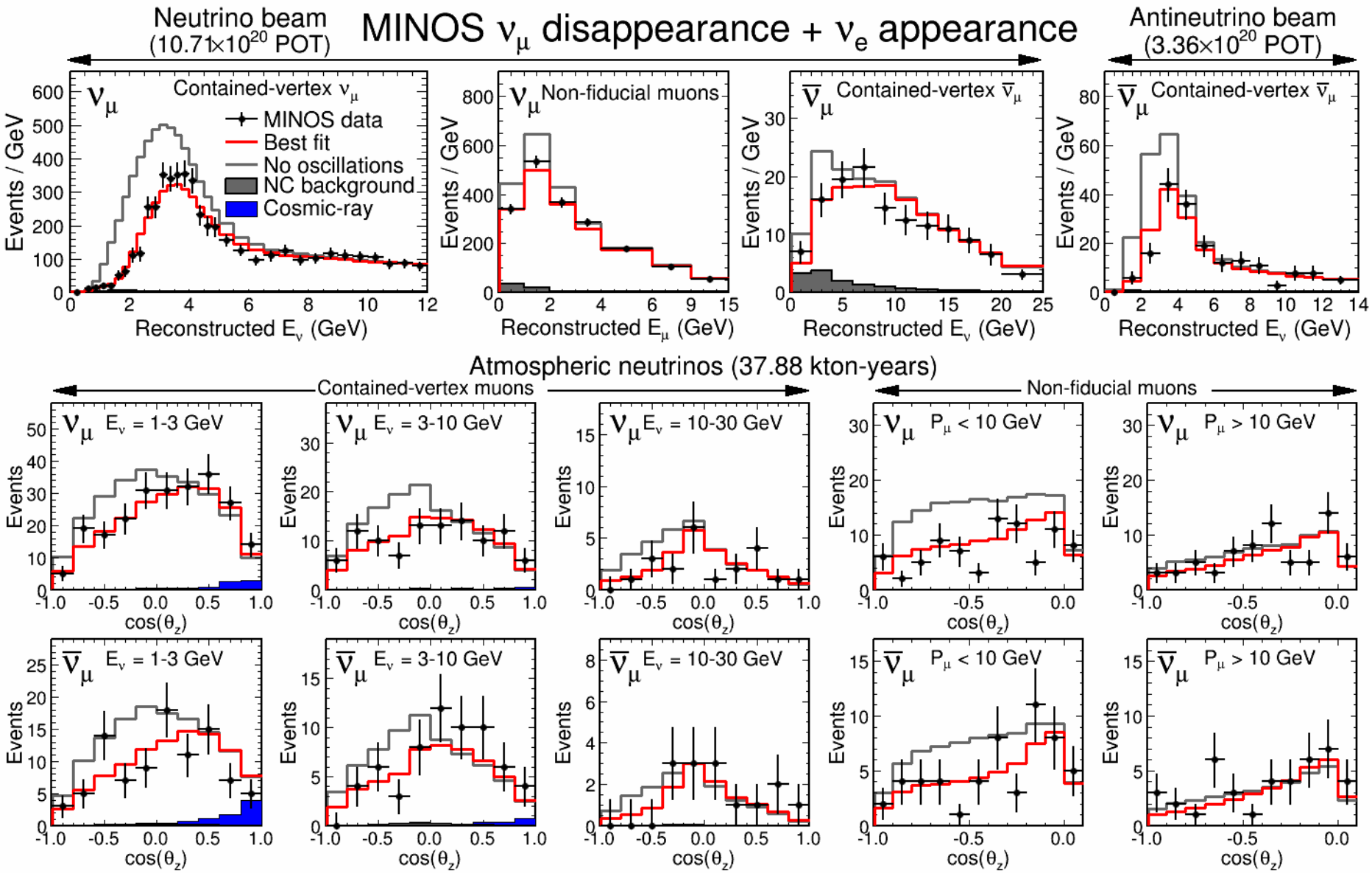
MINOS ν_μ and anti-ν_μ disappearance data

- Accelerator neutrino ν_μ and anti-ν_μ charged-current (CC) interactions are separated from the neutral-current (NC) background using a multivariate selection that identifies muon tracks.
- The MINOS detectors are magnetised, enabling separation of ν_μ and anti-ν_μ CC interactions from muon curvature.
- The neutrino energy is reconstructed by summing the muon momentum and hadronic shower energy.
- The unoscillated energy spectrum at the Far Detector is derived from the observed Near Detector data.
- Atmospheric neutrino interactions are separated from the cosmic-ray muon background by associating events with data from a scintillator veto shield constructed above the Far Detector.

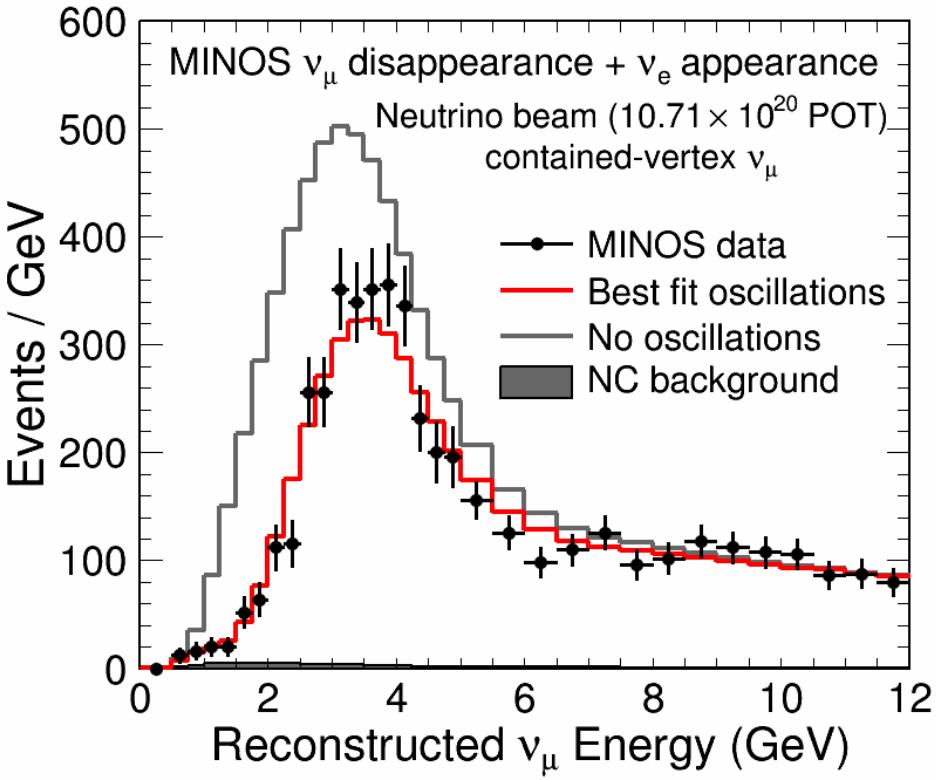


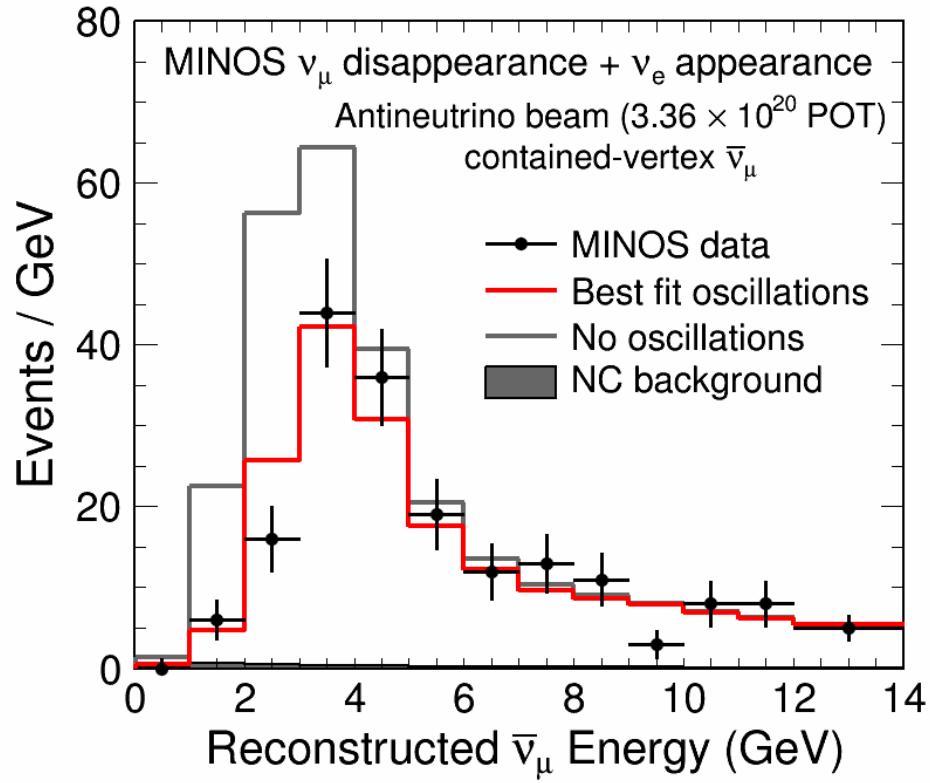


Combined accelerator and atmospheric neutrinos in MINOS Far Detector



Accelerator ν_μ and anti-ν_μ neutrinos in MINOS Far Detector

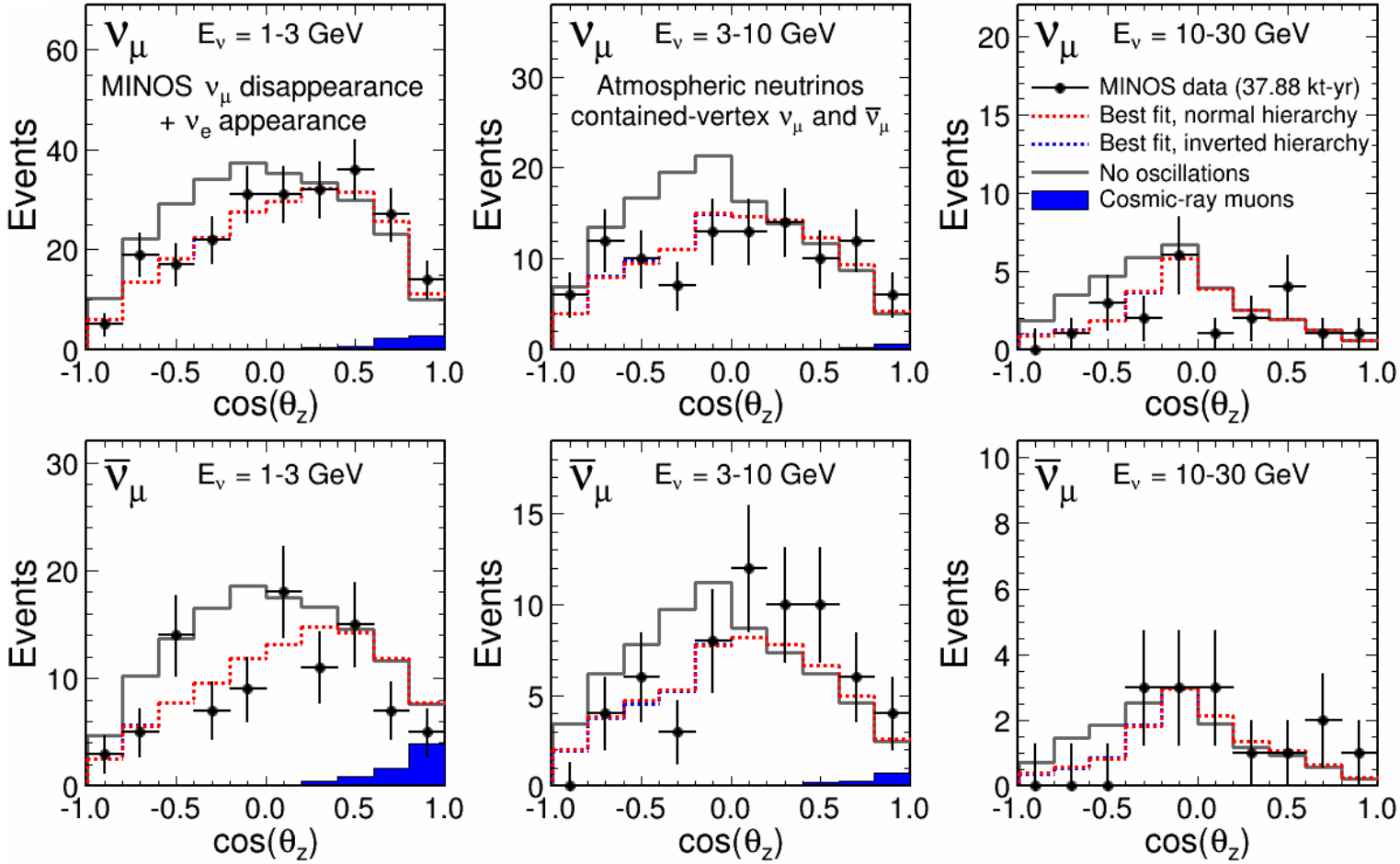




ν_μ CC events (neutrino mode)	
No oscillations	3201
Best fit oscillations	2549
Observed data	2579

anti-ν_μ CC events (antineutrino mode)	
No oscillations	313
Best fit oscillations	228
Observed data	226

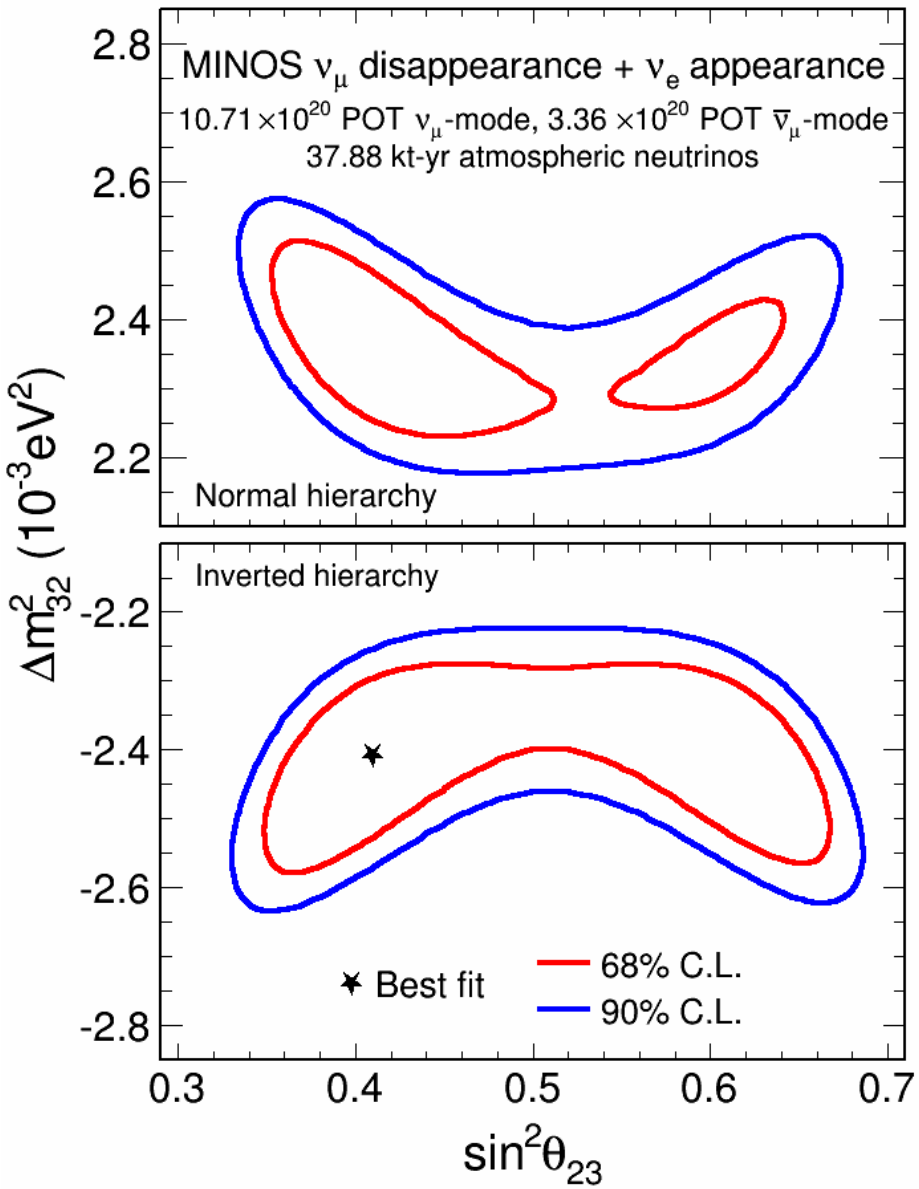
Atmospheric ν_μ and anti-ν_μ neutrinos in MINOS Far Detector



- In this analysis, atmospheric neutrino data are binned as a function of energy and angle.
- Provides limited sensitivity to mass hierarchy in MSW resonance region.

contained-vertex ν_μ and anti-ν_μ	
No oscillations	1100
Best fit oscillations	878
Observed data	905

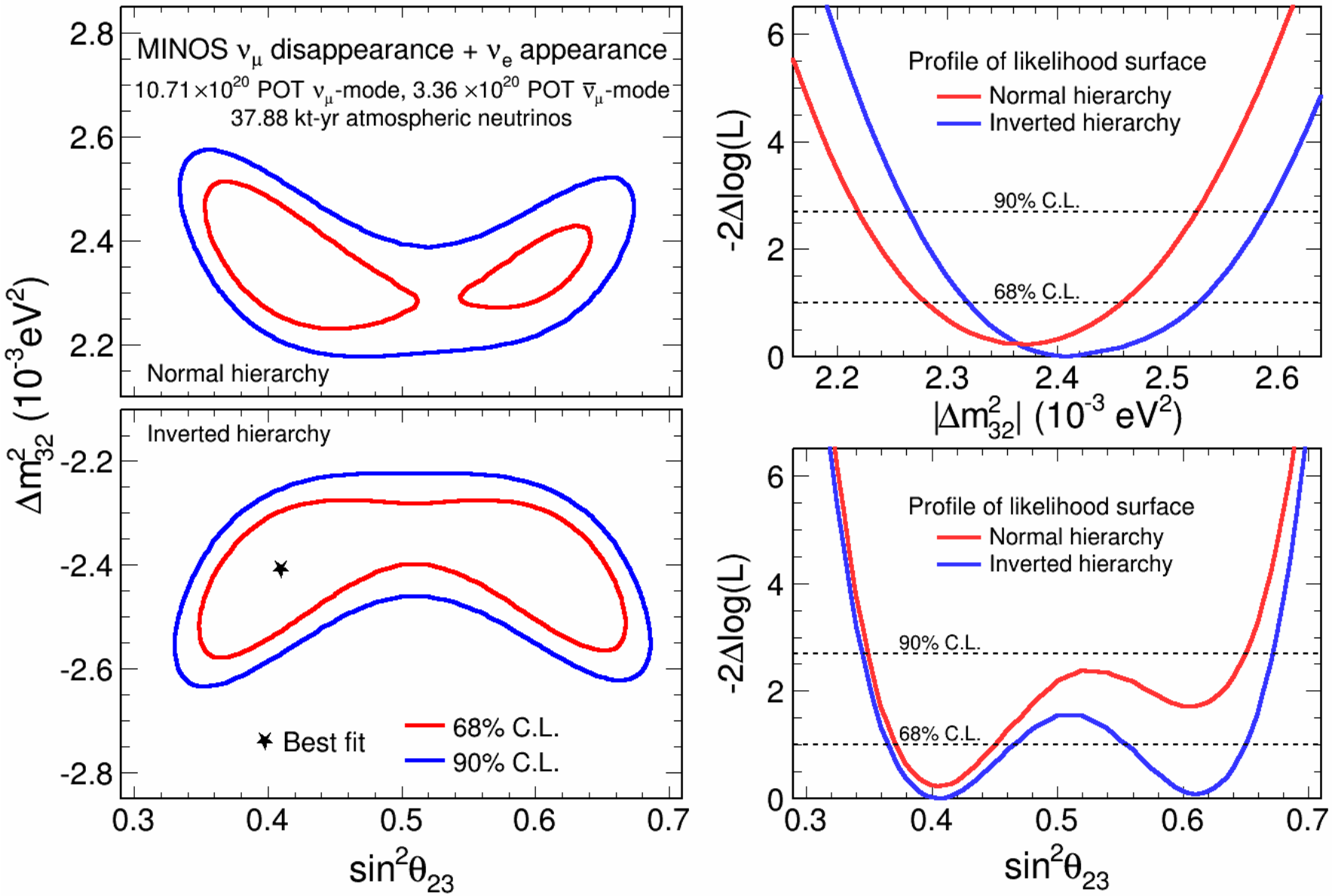
Three-flavour oscillation fit



- Fit four oscillation parameters:
  - Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP}.
- Combine 4D likelihood functions from ν_μ disappearance data and ν_e appearance data.
  - Take ν_μ and ν_e systematic parameters as uncorrelated.
- Apply external constraint on θ_{13} using average of reactor neutrino experiments:
  - $\sin^2\theta_{13}=0.0242\pm0.0025$.
- Solar oscillations parameters*:
  - $\Delta m^2_{21} = 7.54\times10^{-5}$ eV^2
  - $\sin^2\theta_{12} = 0.307$
- Obtain 4D likelihood surface for each mass hierarchy.

*Fogli et al. (arXiv:1205.5254)

MINOS oscillation results



MINOS oscillation results

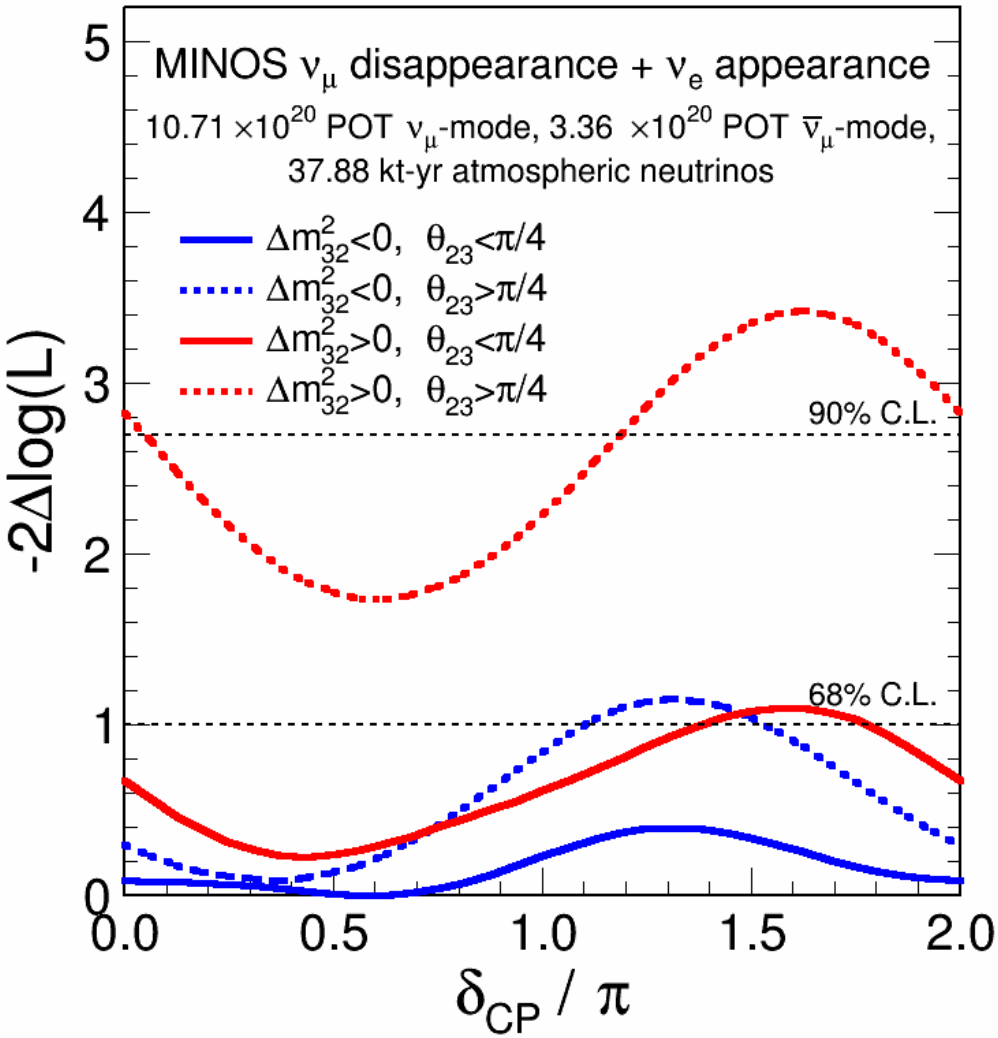
- The four local best fit points:

Hierarchy	Octant	Best fit parameters				$-2\Delta\log(L)$
		$\Delta m^2_{32}/10^{-3}eV^2$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}/π	
Inverted	Lower	-2.41	0.41	0.0243	0.62	-
Inverted	Higher	-2.41	0.61	0.0241	0.37	0.09
Normal	Lower	2.37	0.41	0.0242	0.44	0.23
Normal	Higher	2.35	0.61	0.0238	0.62	1.74

- Confidence limits (C.L.):

Hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}eV^2$	$\sin^2\theta_{23}$ (90% C.L.)
Normal	2.28 – 2.46	0.35 – 0.65
Inverted	2.29 – 2.50	0.34 – 0.67

- Confidence limits on Δm^2_{32} and $\sin^2\theta_{23}$ are dominated by ν_μ disappearance data but inclusion of accelerator ν_e appearance data improves limits on θ_{23}.
- Measurements of Δm^2_{32} are most precise that have been reported to date.
- The MINOS data disfavour maximal mixing by $-2\Delta\log(L)=1.54$.

MINOS oscillation results

- Log-likelihood profile as function of δ_{CP} is calculated for each combination of mass hierarchy and θ_{23} octant.
- The data disfavour 36% (11%) of parameter space defined by mass hierarchy, θ_{23} octant and δ_{CP} at 68% (90%) C.L.
- Combination of normal hierarchy and higher θ_{23} octant is disfavoured by $-2\Delta\log(L)=1.74$.
  - Strengthens previous constraint from accelerator ν_e appearance data.