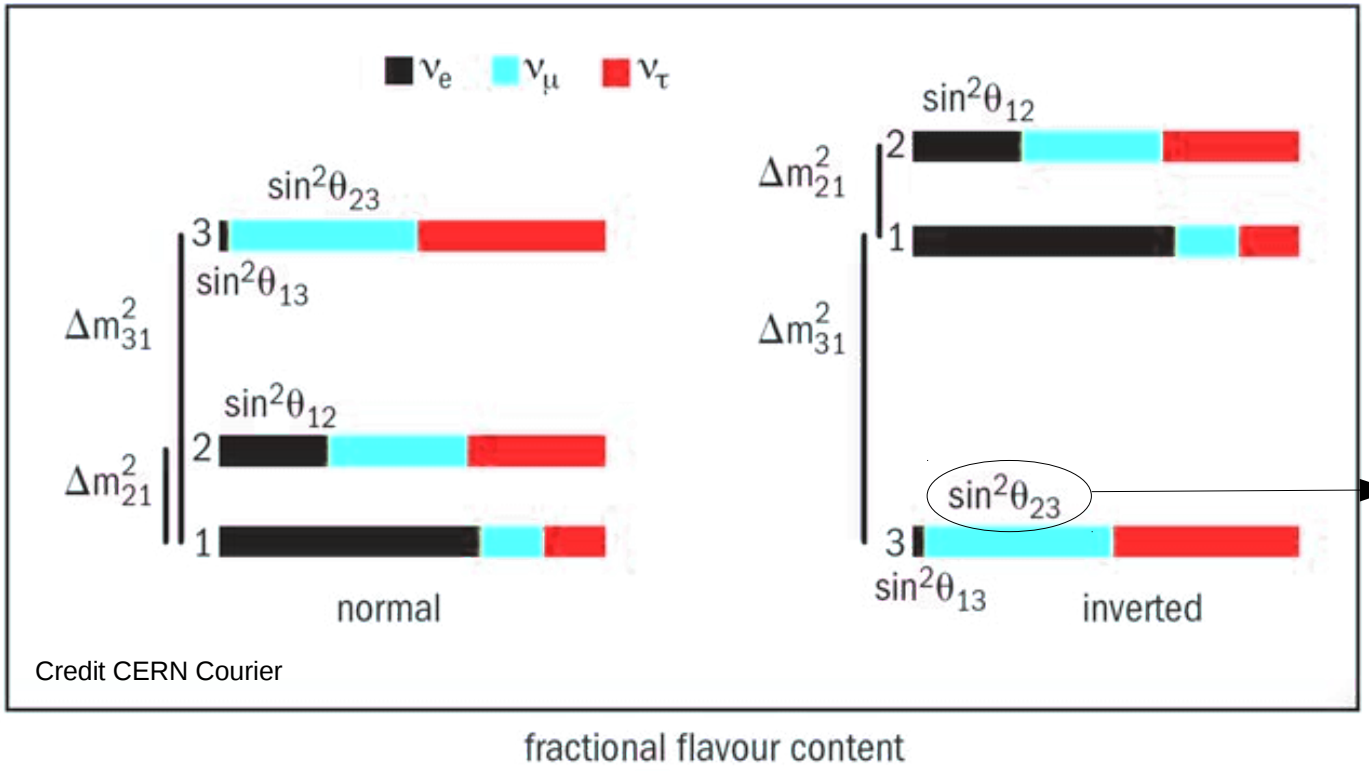
MINOS+ Disappearance Analysis

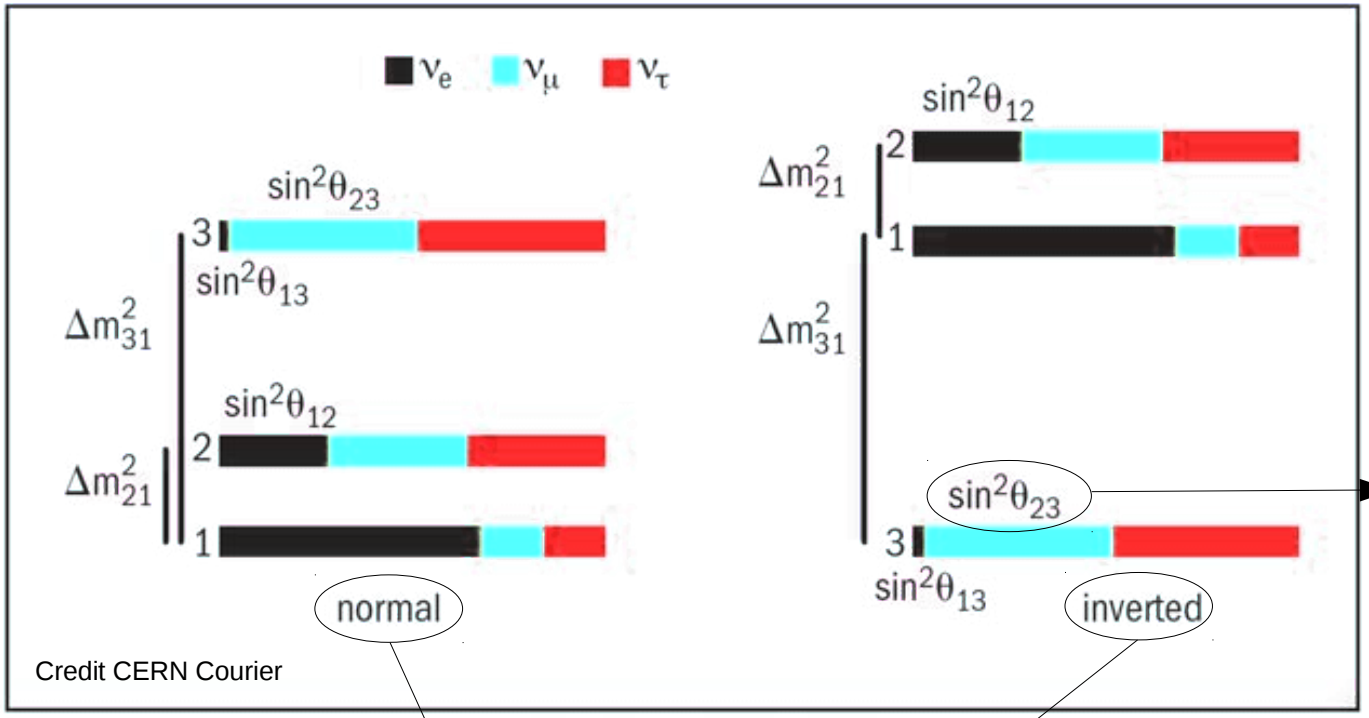
Theory: What We Don't Know



Octant of $\sin^2(\theta_{23})$

Recent results suggest θ_{23} is not maximal. If so, is it greater or less than $\pi / 4$?

Theory: What We Don't Know

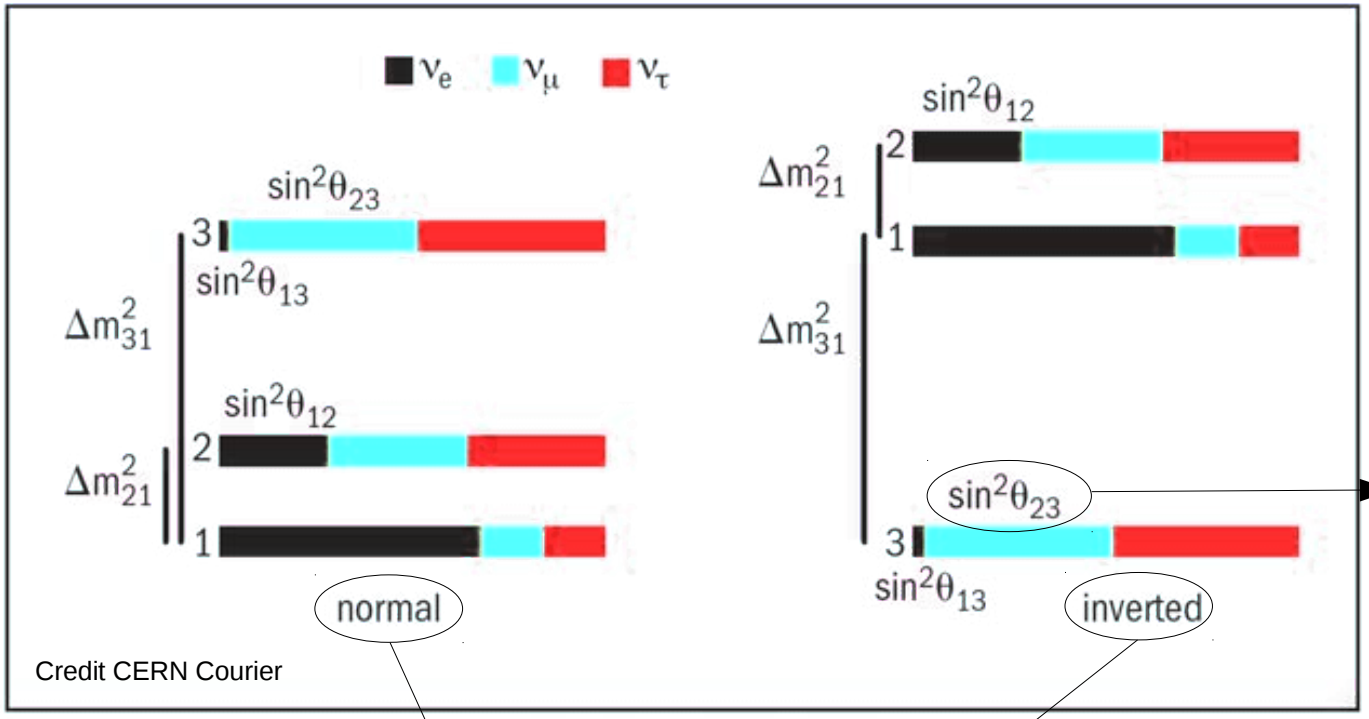


Octant of $\sin^2(\theta_{23})$

Mass hierarchy

Is ν_3 more – or less – massive than $\nu_{1,2}$?

Theory: What We Don't Know



Octant of $\sin^2(\theta_{23})$

Mass hierarchy

δ_{CP}

Do neutrino oscillations violate CP symmetry?

MINOS

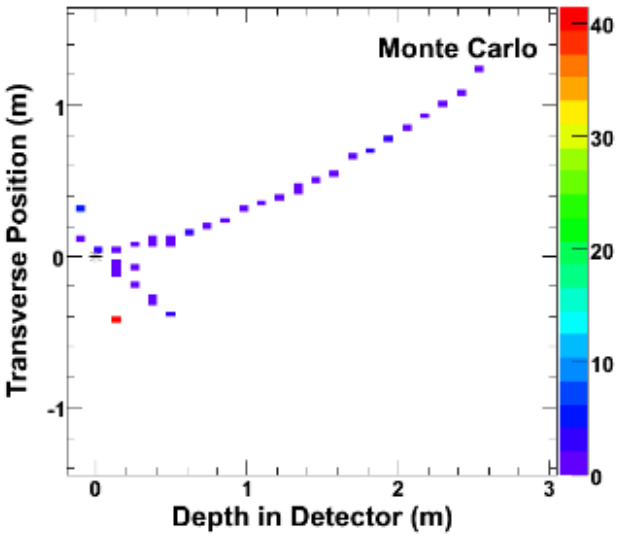
- Long-baseline two-detector neutrino disappearance experiment.
- Sits in the NuMI beam.
  - World's most intense neutrino beam.
- Two detectors:
  - Near Detector 1km from neutrino production point.
  - Far Detector 734km further.

MINOS Detectors

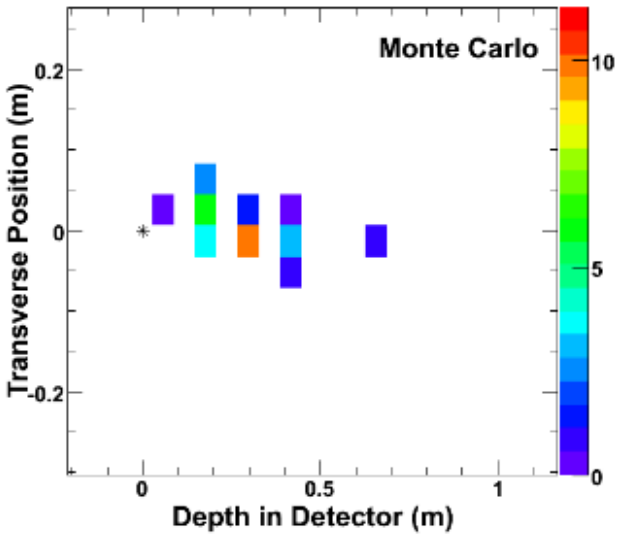
- Identical design but for size:
  - 1 kT Near Detector
  - 5.4 kT Far Detector
- Sampling, tracking calorimeter.
- Repeating planar structure:
  - Steel → Scintillator → Air
- Magnetised.
  - Allows for charge separation and energy measurement by curvature.

MINOS Event Topologies

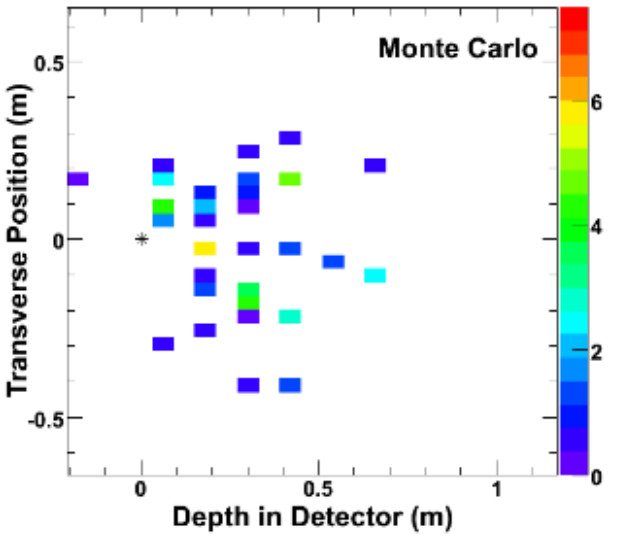
ν_μ-CC event

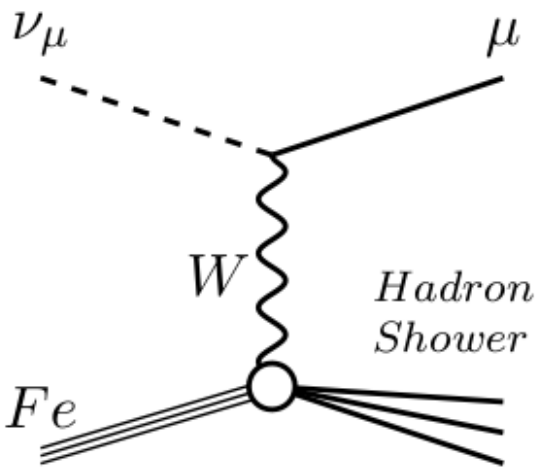


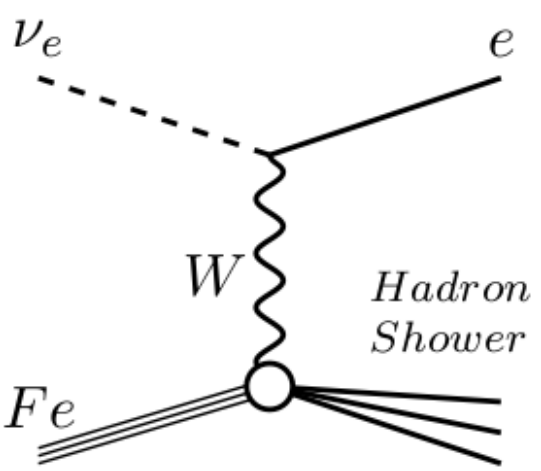
ν_e-CC event

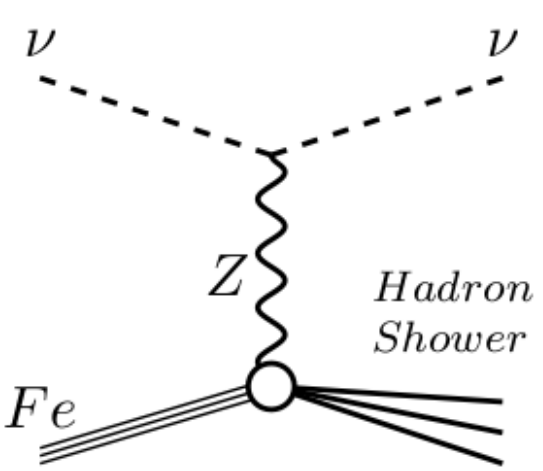


NC event

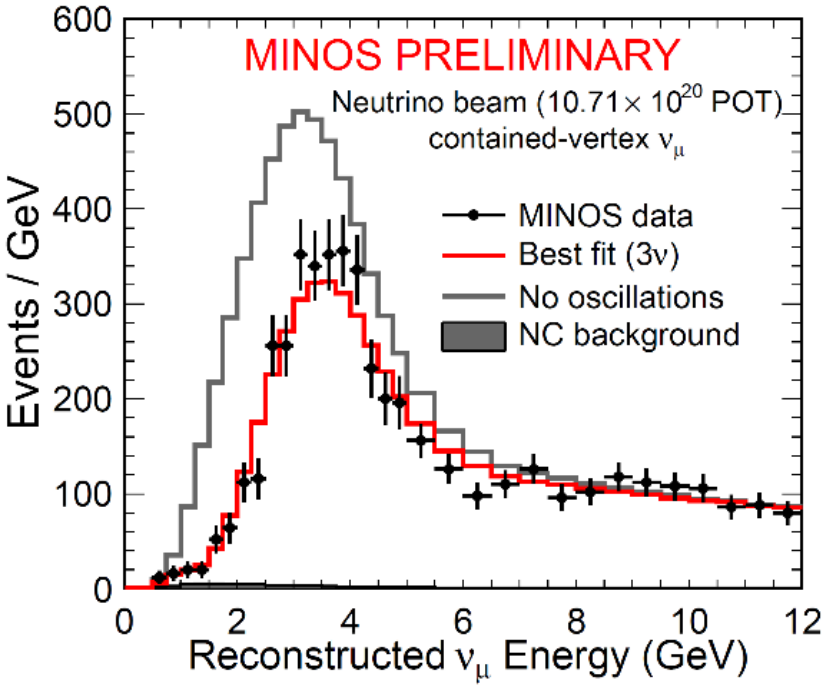


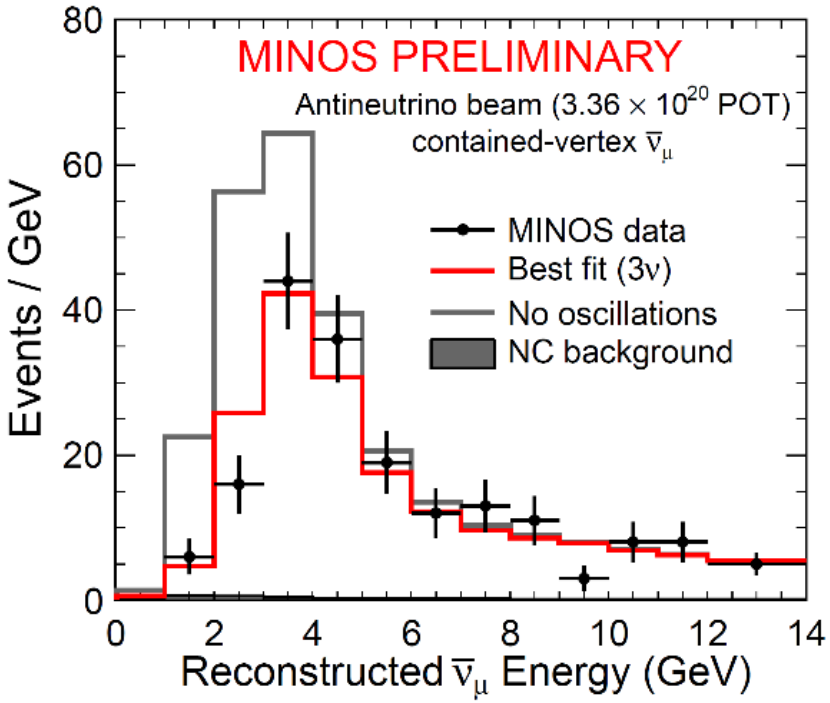






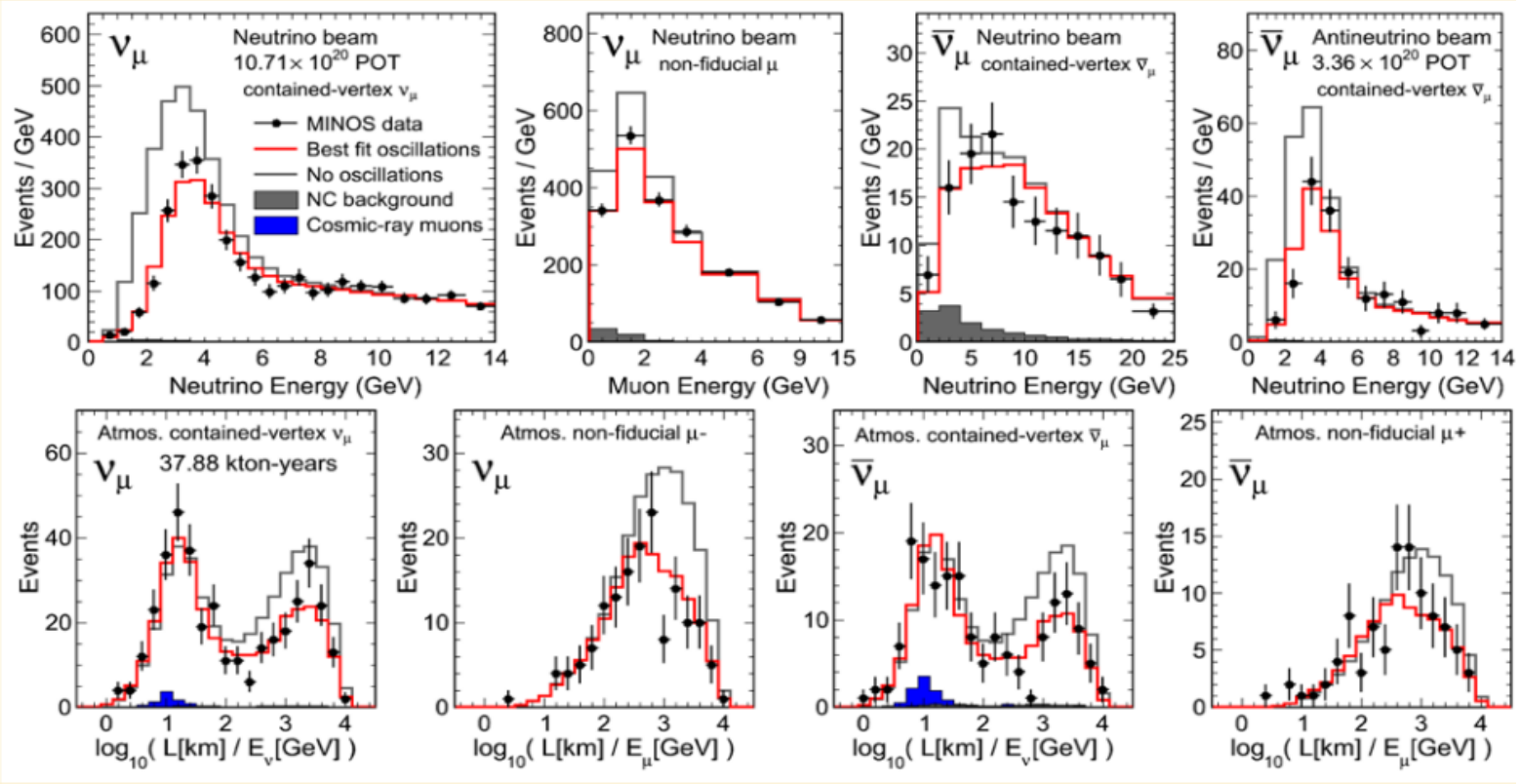
MINOS Analysis: Beam





- kNN selector based on track length, width and scintillator response.
- Far detector predictions generated by applying a set of transformations to the Near Detector data.

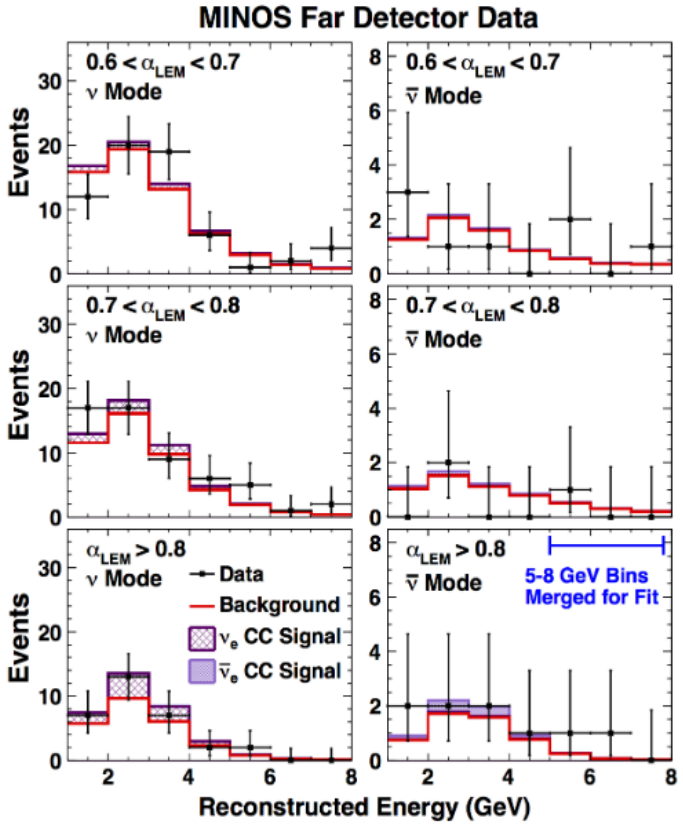
MINOS Analysis: Atmos

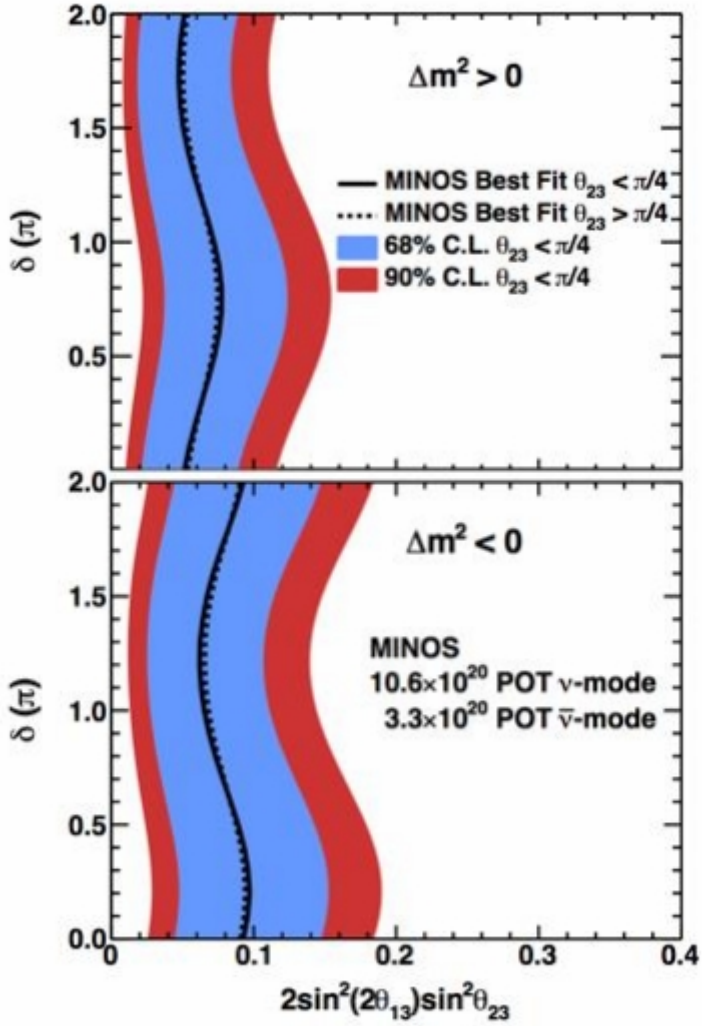


- Data are binned in L/E based on angular reconstruction.
- Matter effects lead to sensitivity to mass hierarchy and octant.

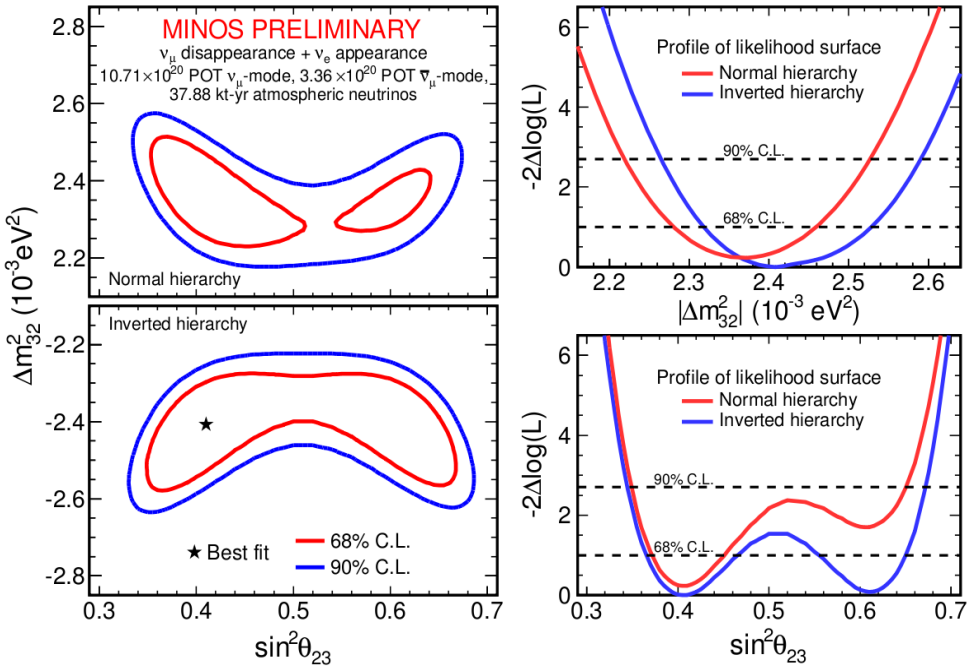
MINOS Analysis: Nue Appearance

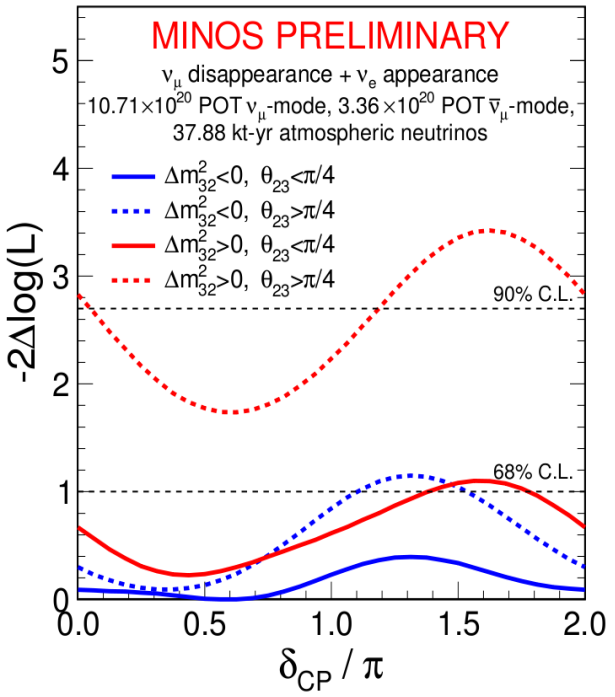
- Library event matching algorithm and ANN-based selection.





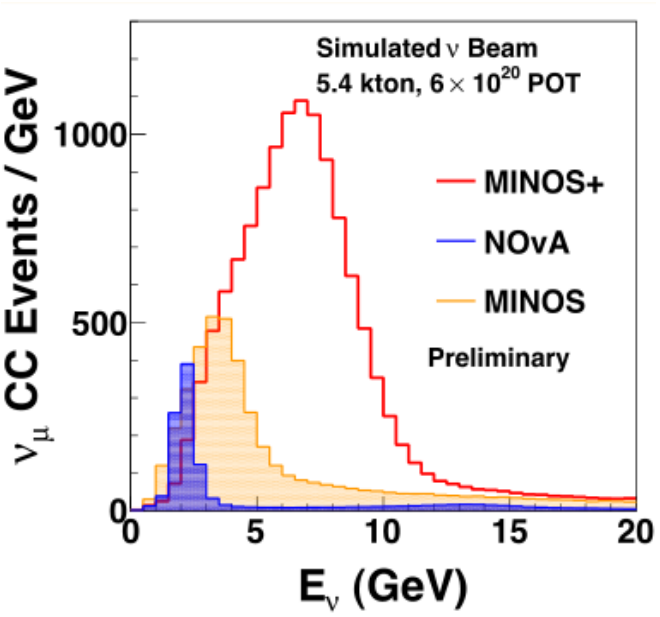
MINOS Results

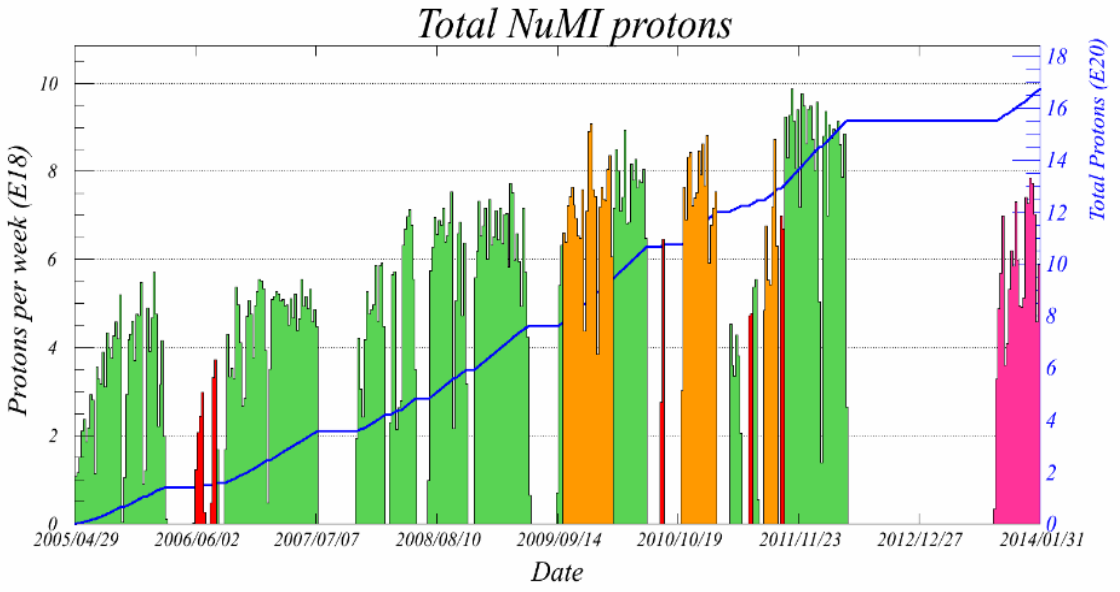




Mass hierarchy	θ_{23} octant	Δm^2_{32} / 10^{-3}eV^2	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}/π	$-2\Delta\log(\mathcal{L})$
$\Delta m^2_{32} < 0$	$\theta_{23} < \pi/4$	-2.41	0.41	0.0243	0.62	0
$\Delta m^2_{32} < 0$	$\theta_{23} > \pi/4$	-2.41	0.61	0.0241	0.37	0.09
$\Delta m^2_{32} > 0$	$\theta_{23} < \pi/4$	$+2.37$	0.41	0.0242	0.44	0.23
$\Delta m^2_{32} > 0$	$\theta_{23} > \pi/4$	$+2.35$	0.61	0.0238	0.62	1.74

MINOS+





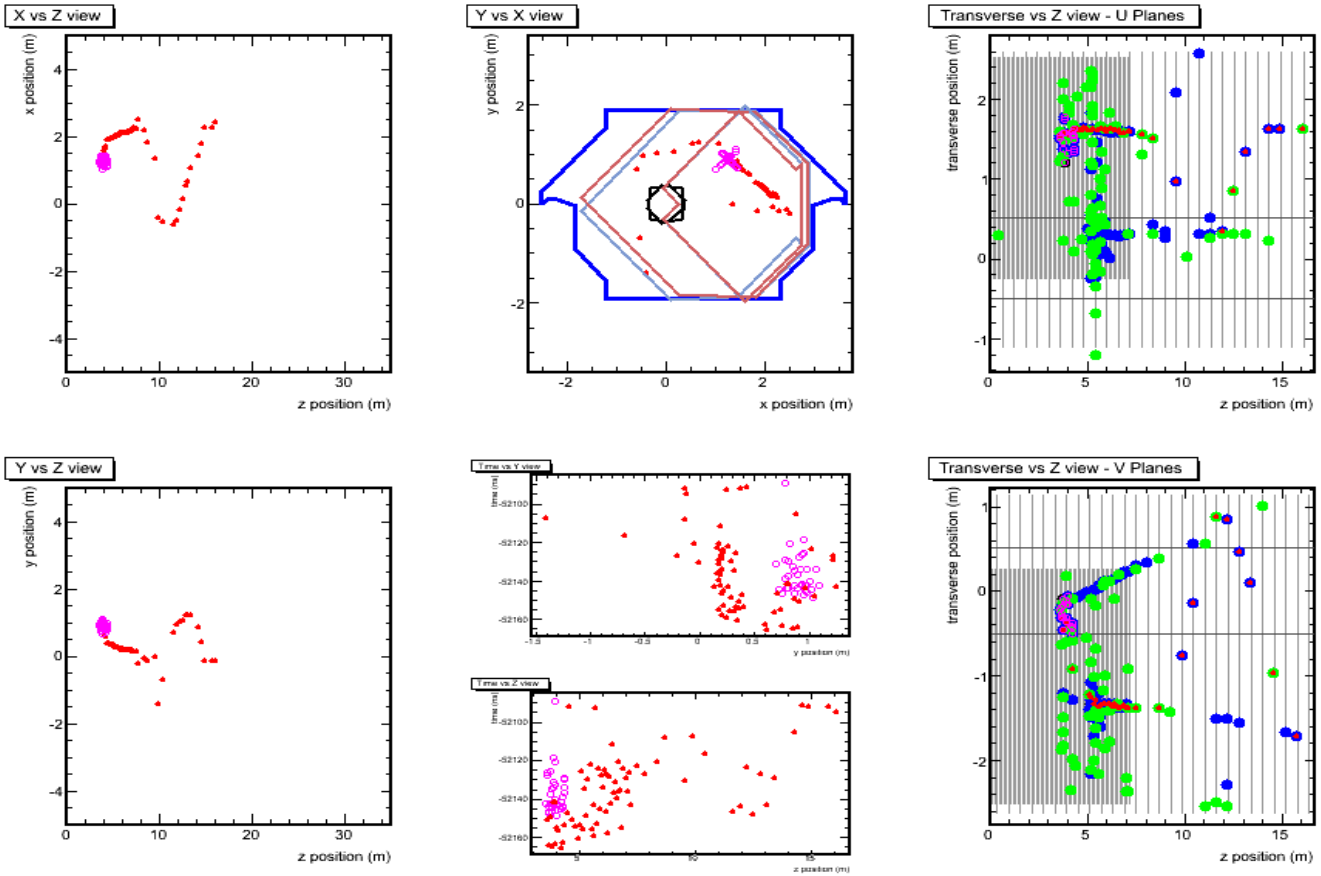
- MINOS era ended with NuMI shutdown in April 2012.
- Higher-energy beam switched on in September 2013.

MINOS+: Analysis

- 'Top-up' of the MINOS analysis.
- Beam:
  - 6 months more beam data
  - New reconstruction.
  - Retuned selection.
  - Independent beam systematics.
- Atmospheric:
  - 2 years more atmospherics.
  - No changes, simply added to MINOS atmospheric data.
- Nue appearance: MINOS only

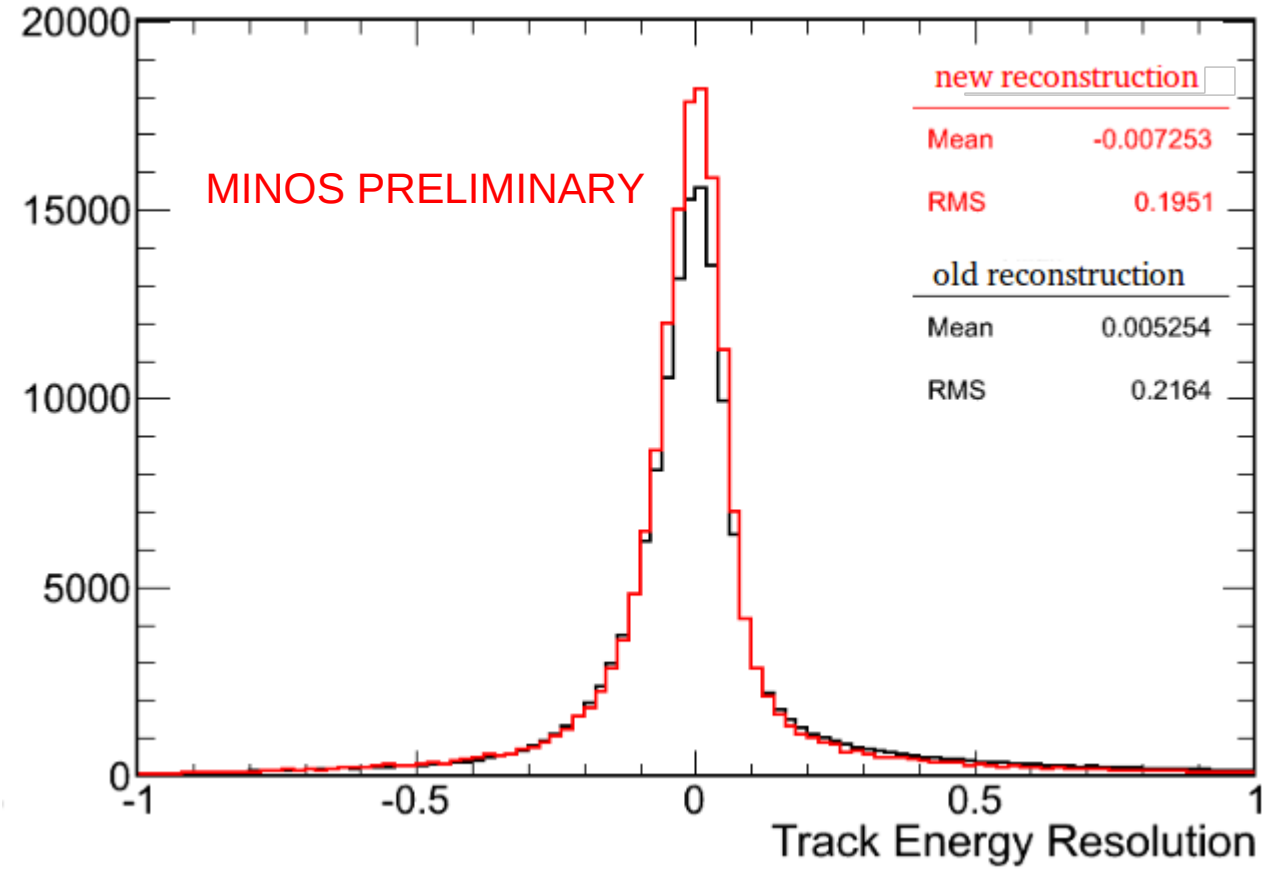
Changes For MINOS+: Reconstruction

- Higher intensity, energy → larger events, more pile-up.
- Becomes a significant problem at the Near Detector.



Changes For MINOS+: Reconstruction

- Redesign / retune of several reconstruction algorithms.



Changes For MINOS+: Selection

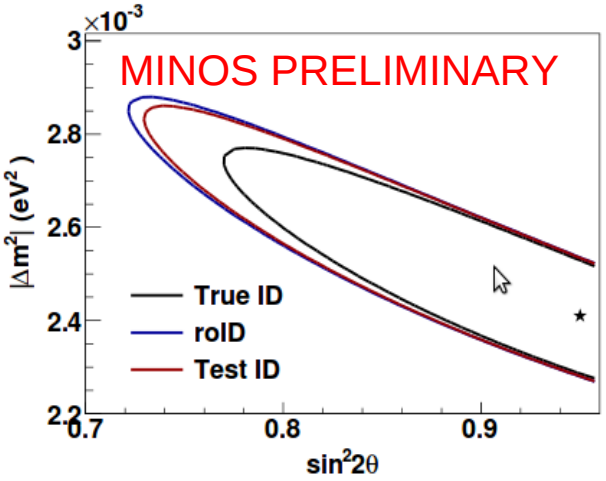
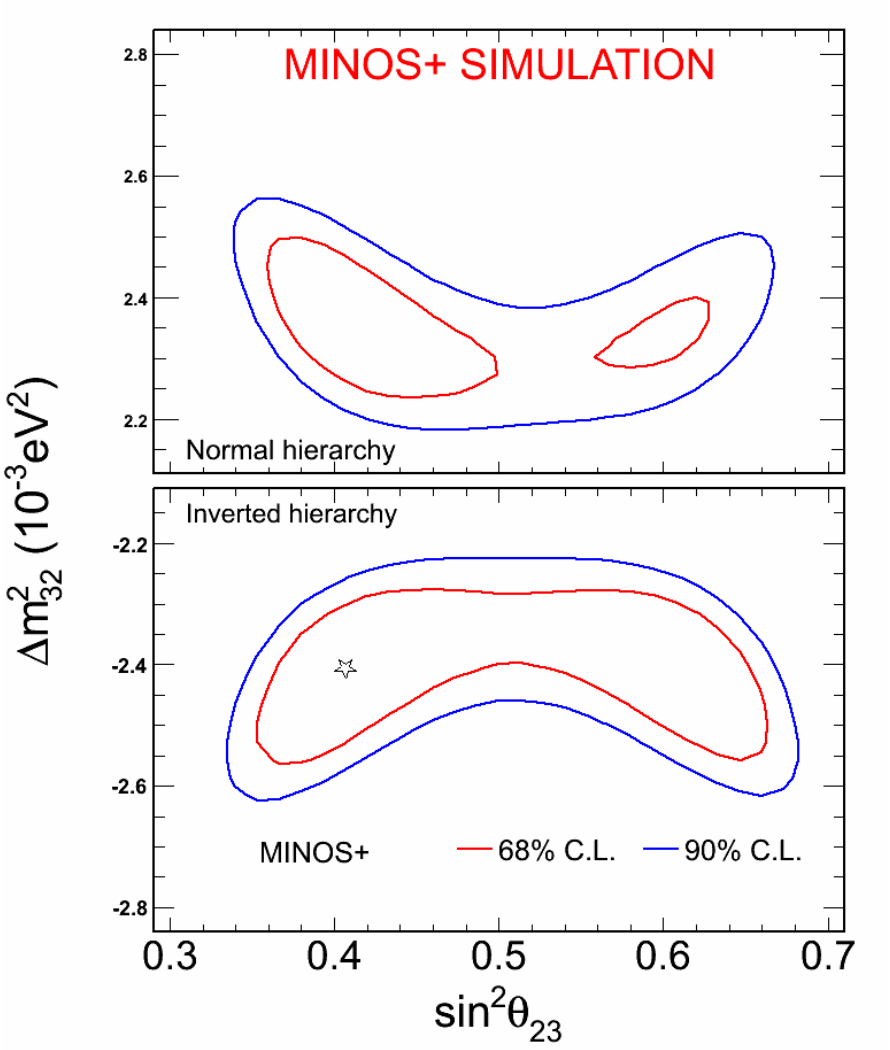


Figure 14: Sensitivity change after using MINOS+ training set (`testID`). It is better than the case with no retraining (`roID`).

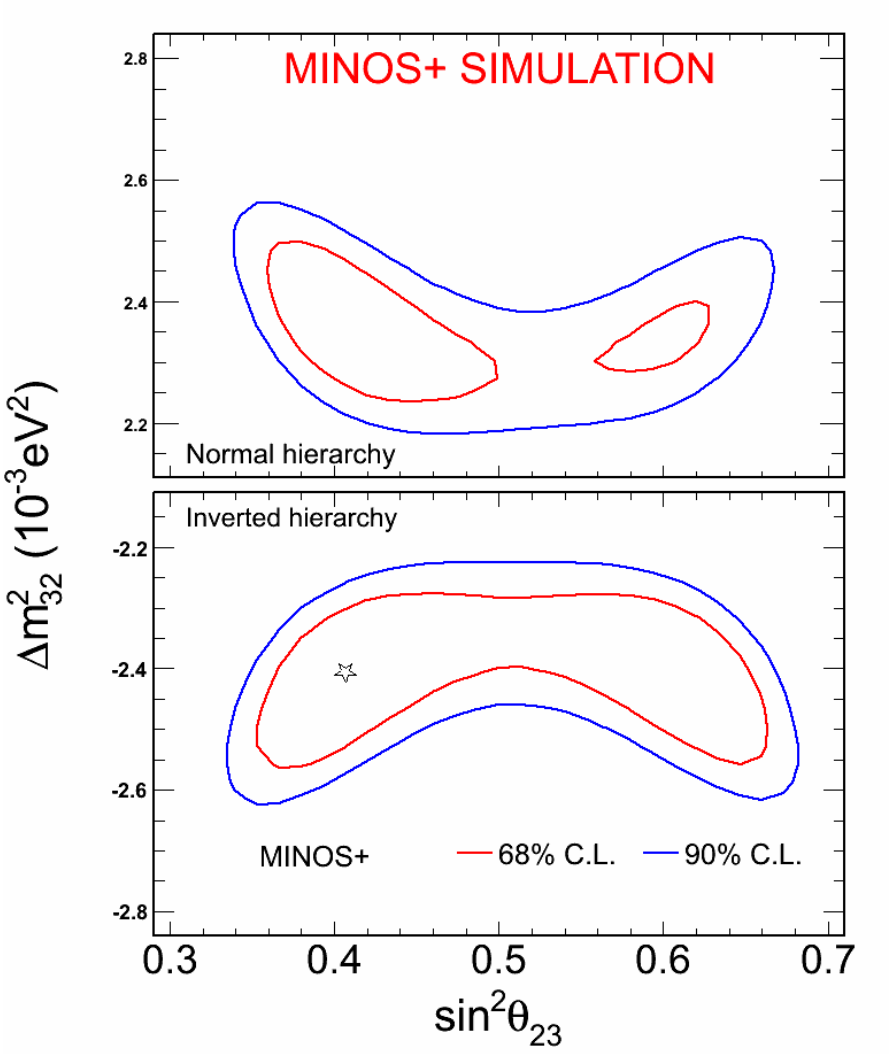
- Increase in energy → change in event topology (larger events)
- Retraining of kNN selector necessary.

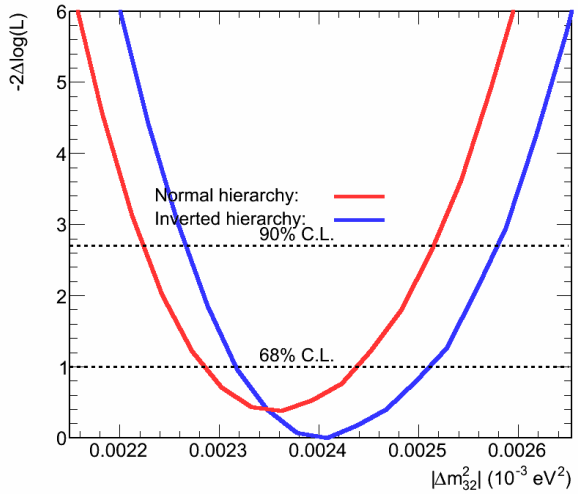
Sensitivities

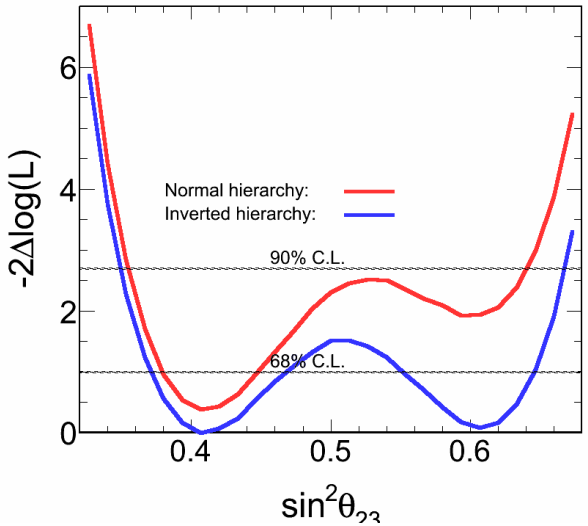


- Add MINOS+ fake data to the MINOS combined fit.
- Fake data oscillated at the MINOS best fit point:
  - $\text{Sin}^2(\theta_{23}) = 0.41$
  - $\Delta m^2 = -2.41\text{e-}3\ \text{eV}^2$
  - $\delta_{CP} = 0.62\pi$
- No systematics included in the MINOS+ sample in this plot.

Sensitivities







Outlook

- MINOS+ is continuing to make precision measurements of the atmospheric sector.
- Combination of atmospheric and appearance data on top of the beam analysis allows us to have a say on octant, hierarchy and CP violation.

Thanks