THE SEARCH FOR NEW PHYSICS AT MINOS IN THE NUMI-NOνA BEAM

Or MINOS+

+ : higher energy

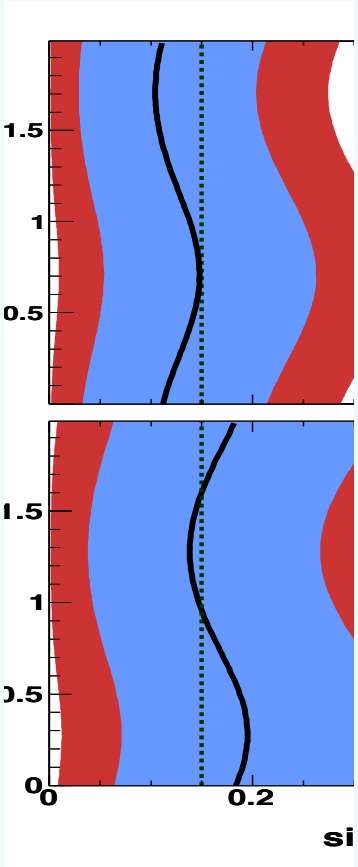
+ : higher precision

+ : higher excitement level

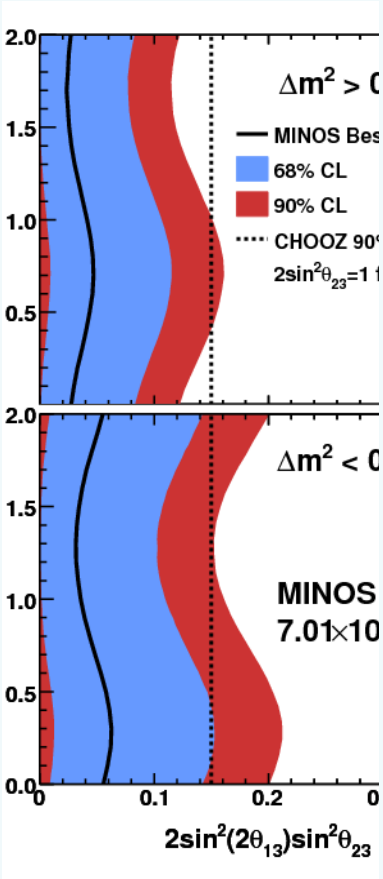
INTRODUCTION

- Neutrino Oscillations have been discovered
  - Change of CC event rate with L/E, L and E
- Precision measurement of oscillation parameters has been made by MINOS/SK/T2K
  - 5-10% errors on parameters of the model
  - Anti-neutrinos, Sterile search, limits on θ_{13} and x-sec
- Next generation LB experiments focus on two last parameters of this matrix: θ_{13} and δ_{cp}
  - Using off-axis beams and reactors
- What can MINOS contribute to world knowledge during the coming few years?

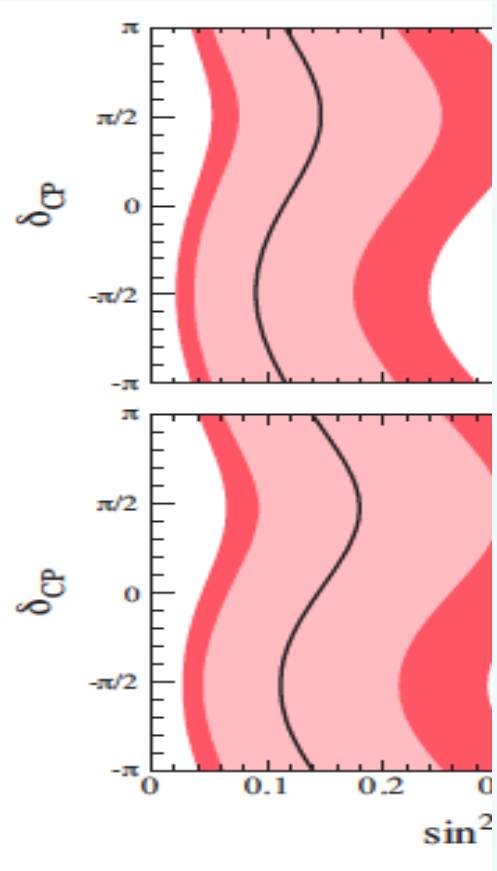
MINOS 2009



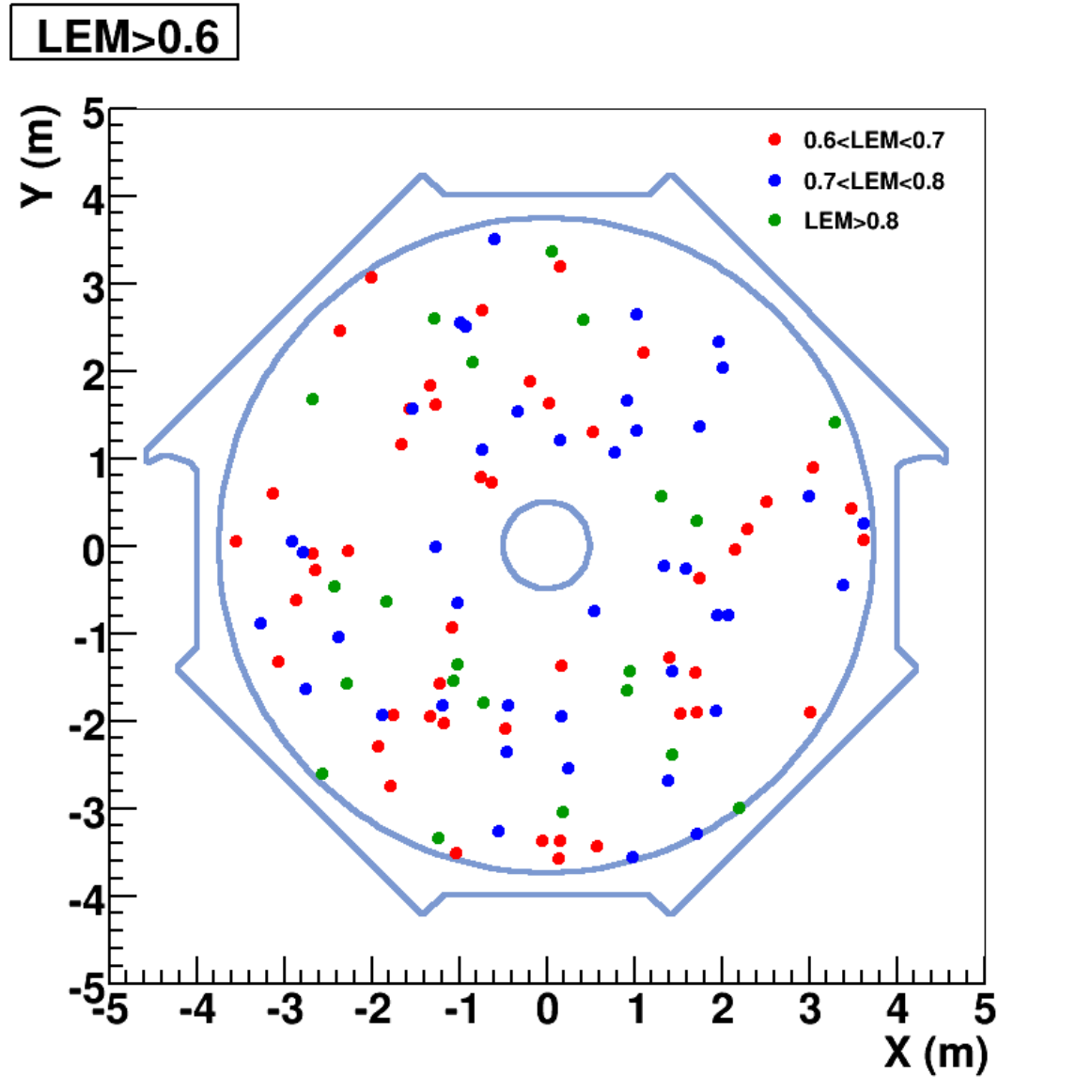
MINOS 2010



T2K 2011



HERE ARE ALL OUR EVENTS



INTRODUCTION

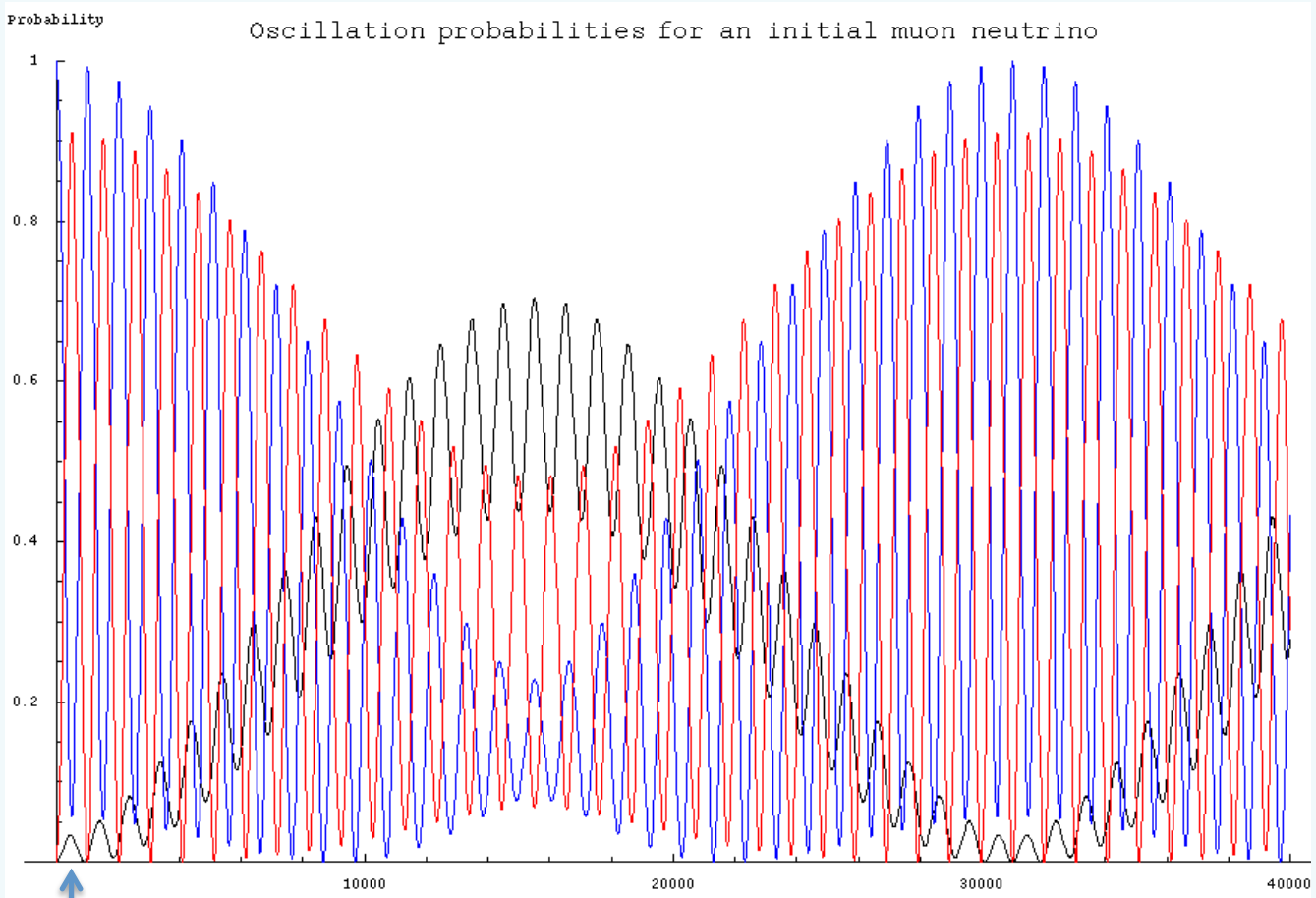
- FNAL expects shutdown to start early 2012 with high power beam starting end 2012
  - Medium Energy optimized for NOνA off-axis
- MINOS+ is a three year proposal to collect both neutrinos and anti-neutrinos with MINOS Far Detector during the initial NOνA period
- Its mission is to search for new physics
  - and do some old physics too!

OSCILLATION THEORY

Very brief summary

IN A SNAPSHOT:
WHAT ITS LIKE TO BE A MUON NEUTRINO

ν_e ν_μ ν_τ



L/E (km/GeV)

MINOS

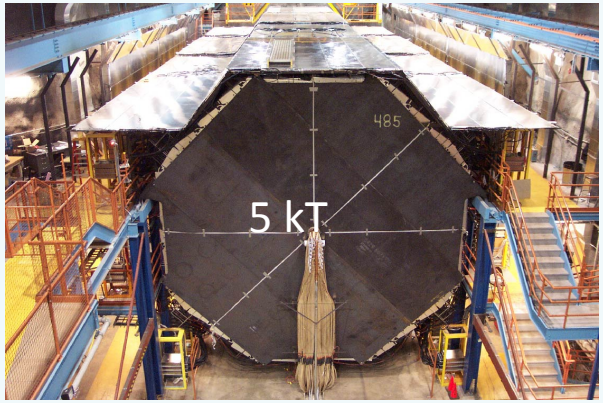
SIMPLE 2-FLAVOUR EXPRESSION

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L / E)$$

(Average L/E is about 150-200 km/GeV for MINOS FD)

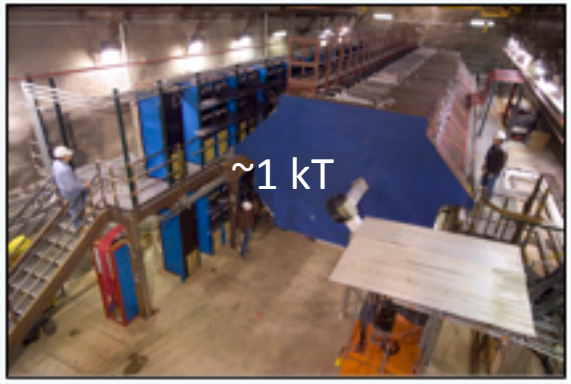
(Average L/E is about 0.2-0.3 km/GeV for MINOS ND)

THE MINOS EXPERIMENT



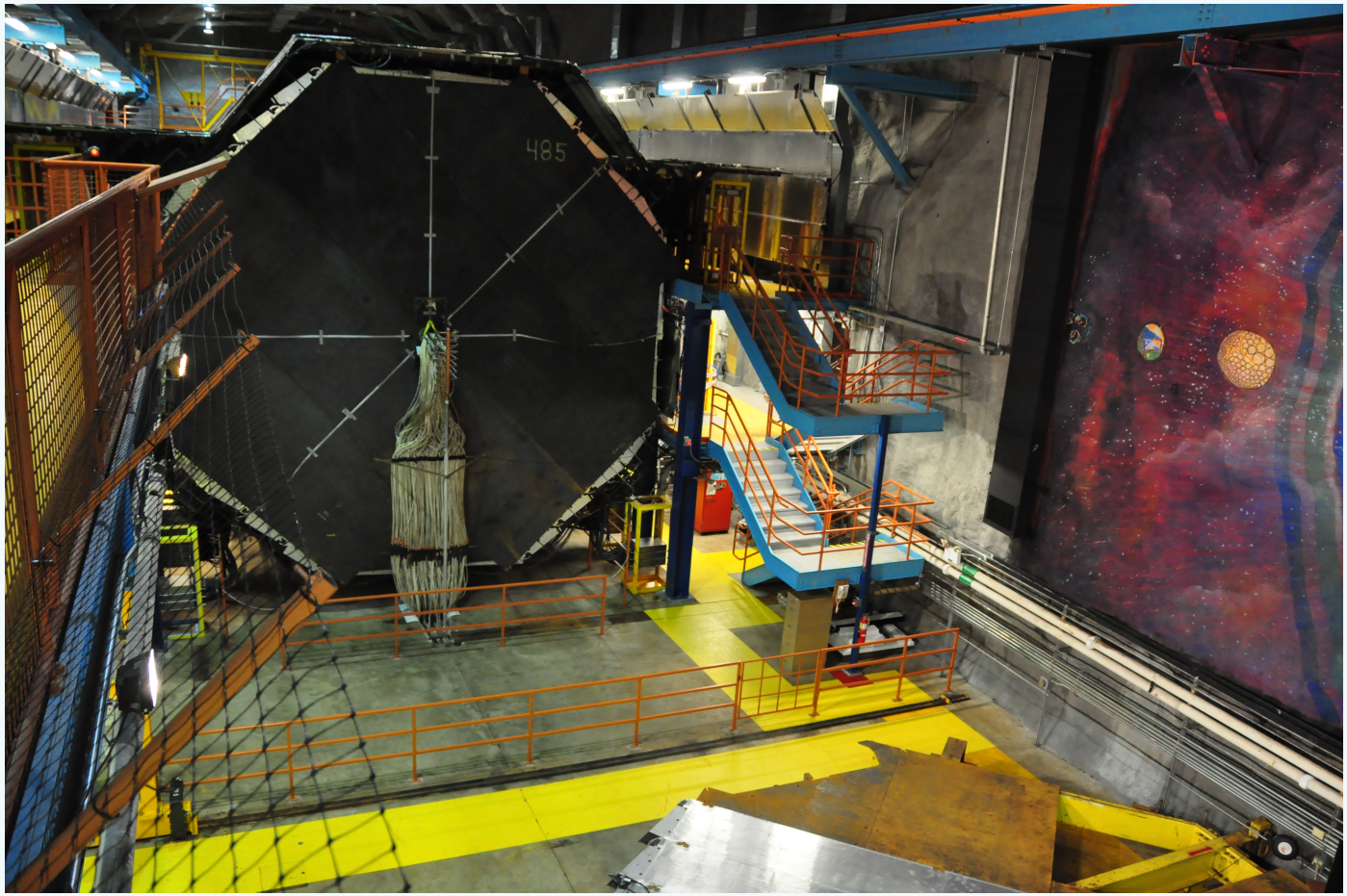
- Long baseline neutrino oscillation experiment
  - Neutrinos from NuMI
  - L=735km, E~1-5GeV
  - L/E ~150-250 km/GeV
  - Atmospheric neutrino L/E

- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties
- Magnetic field measures charge



DURING THE MINOS WASH

AFTER THE WASH

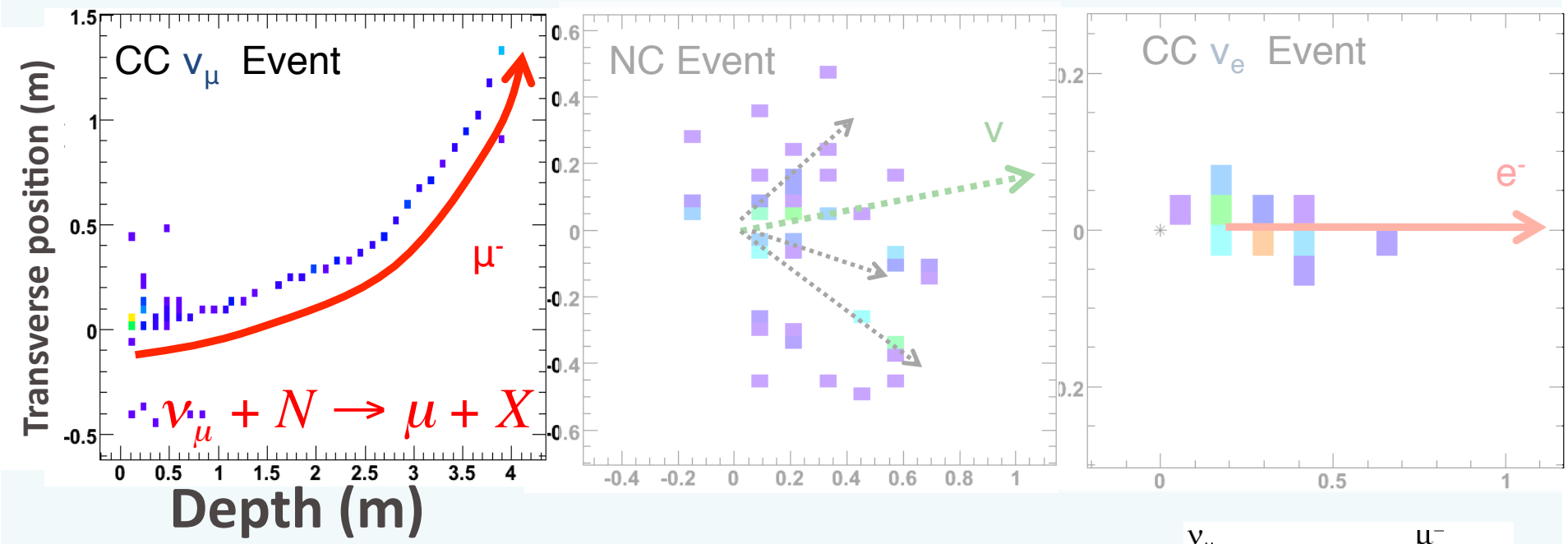


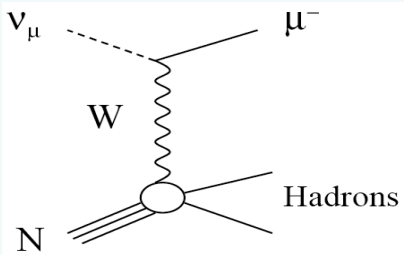
EVENTS IN THE MINOS DETECTORS

muons or no muons?

NEUTRINO EVENTS IN MINOS

Simulated Events

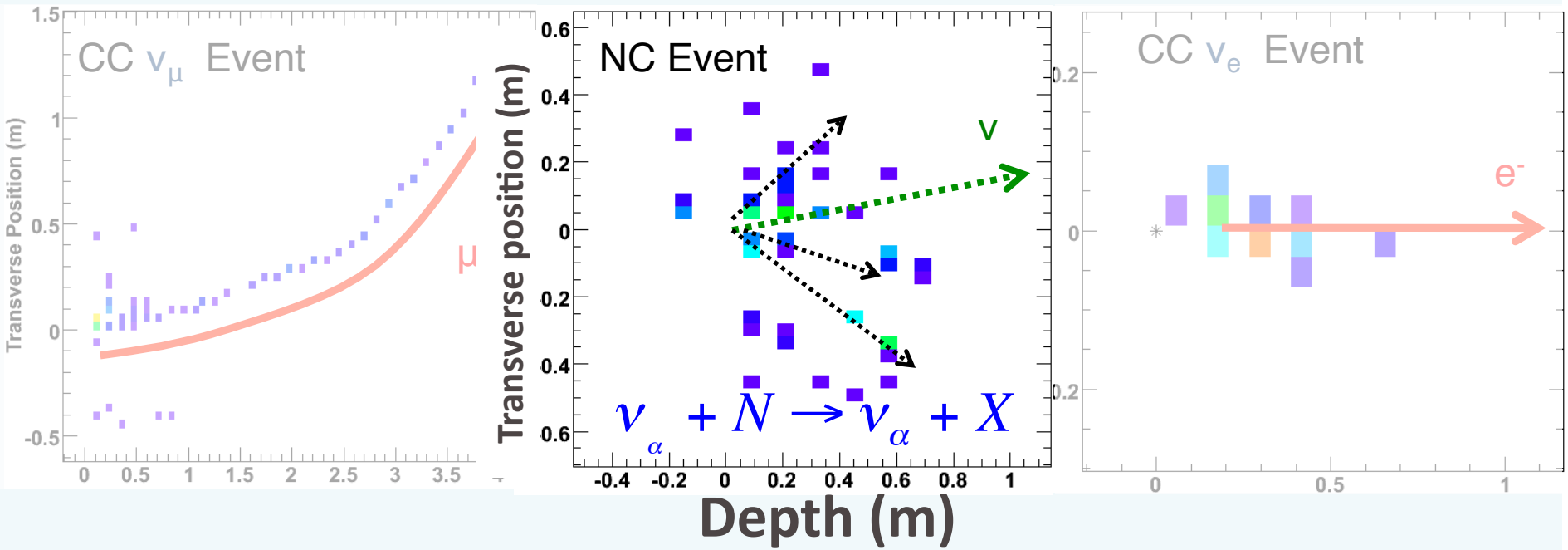




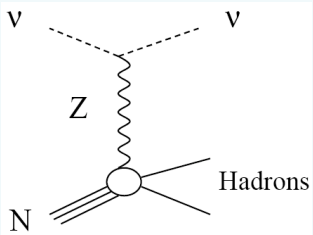
- ν_μ Charged Current events:
  - long μ track, with hadronic activity at vertex
  - neutrino energy from sum of muon energy (range or curvature) and shower energy

EVENTS IN MINOS

Simulated Events

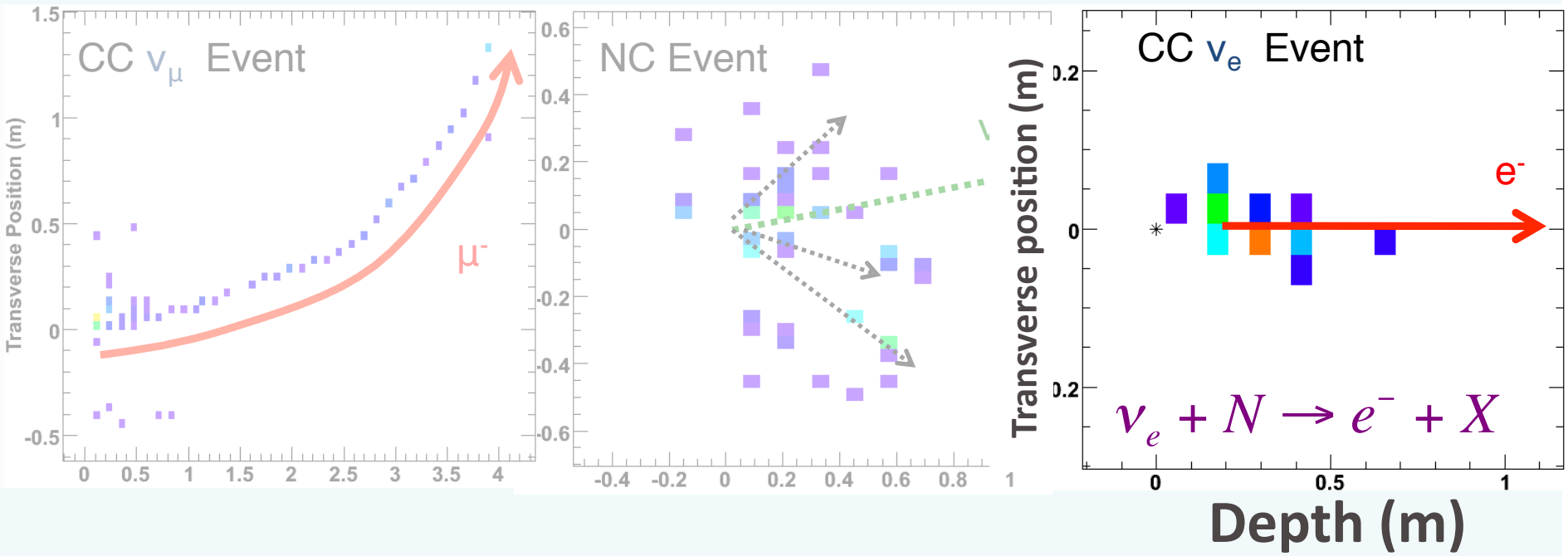


- Neutral Current events:
  - short, diffuse shower event
  - shower energy from calorimetric response

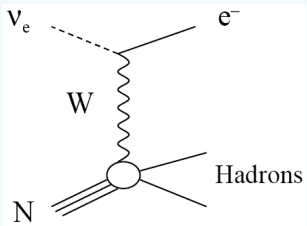


EVENTS IN MINOS

Simulated Events



- ν_e Charged Current events:
  - compact shower event with an EM core
  - neutrino energy from calorimetric response



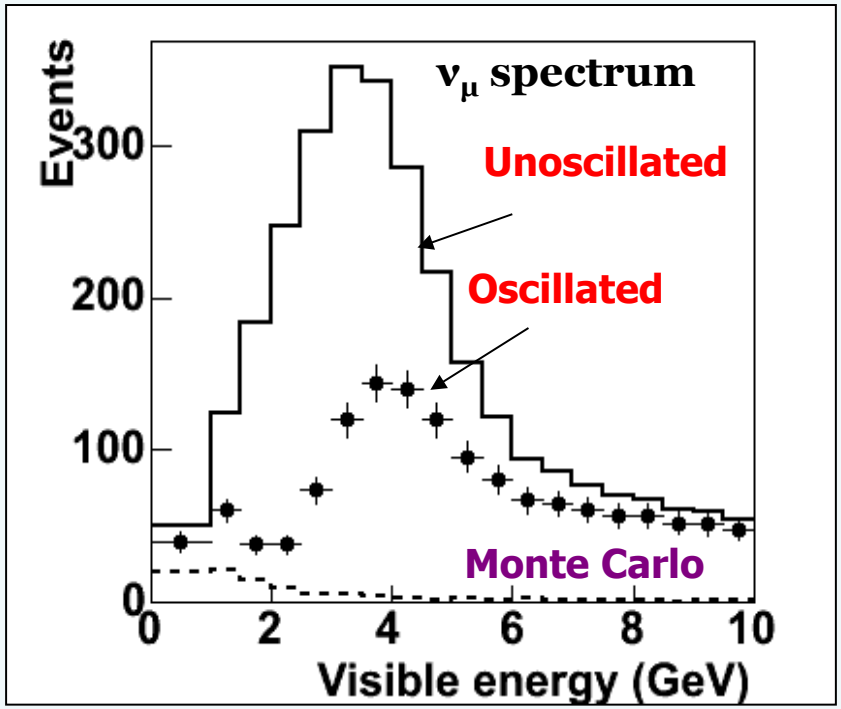
MEASURING OSCILLATIONS

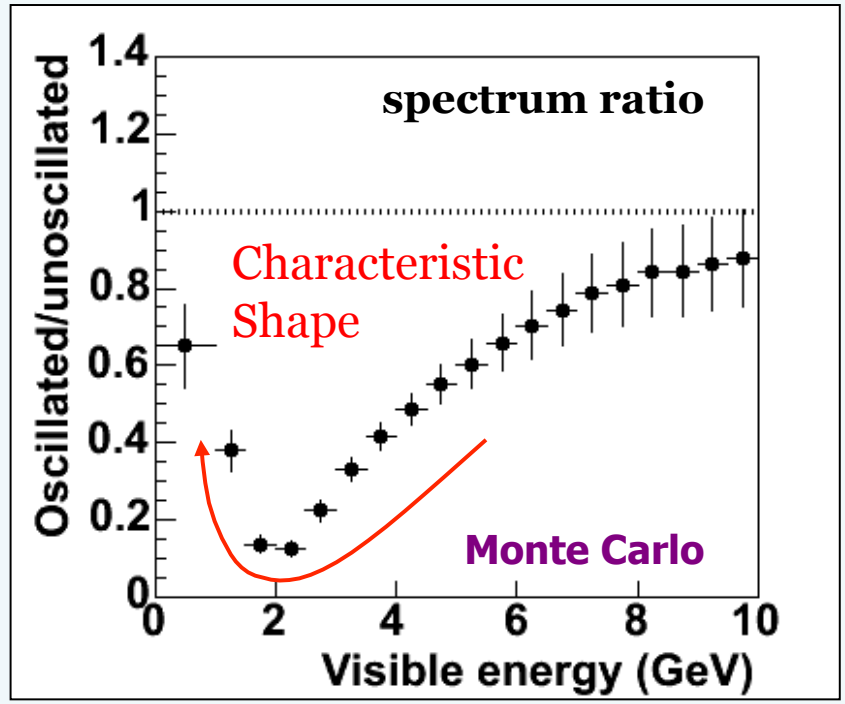
The easy way

ν_μ DISAPPEARANCE

- Look for ν_μ disappearance as a function of neutrino energy
- Use ND to predict unoscillated spectrum at Far Detector
- Compare with measured spectrum to extract oscillation parameters

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L / E)$$





(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ eV^2$ **)**

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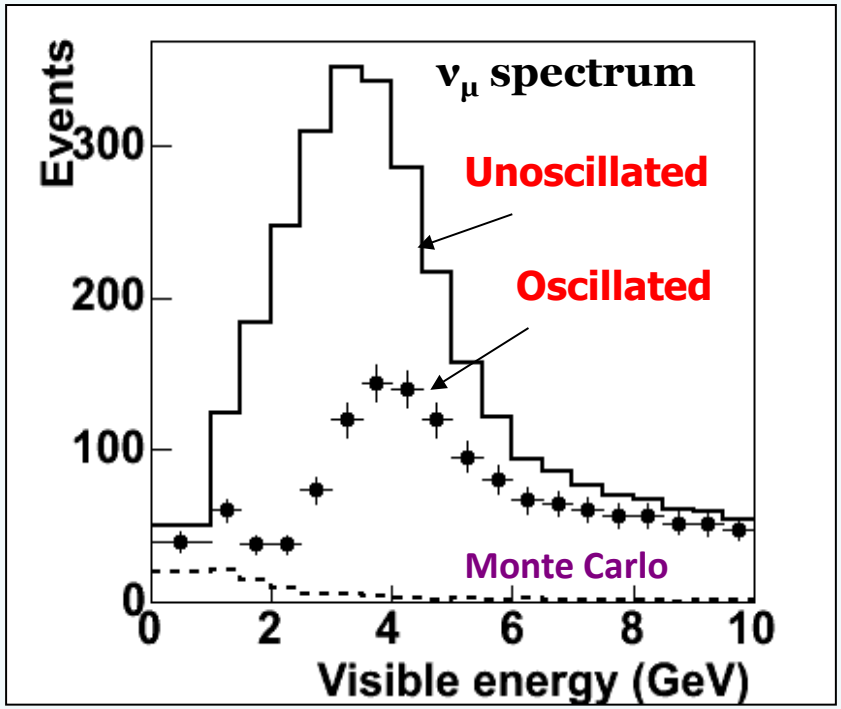

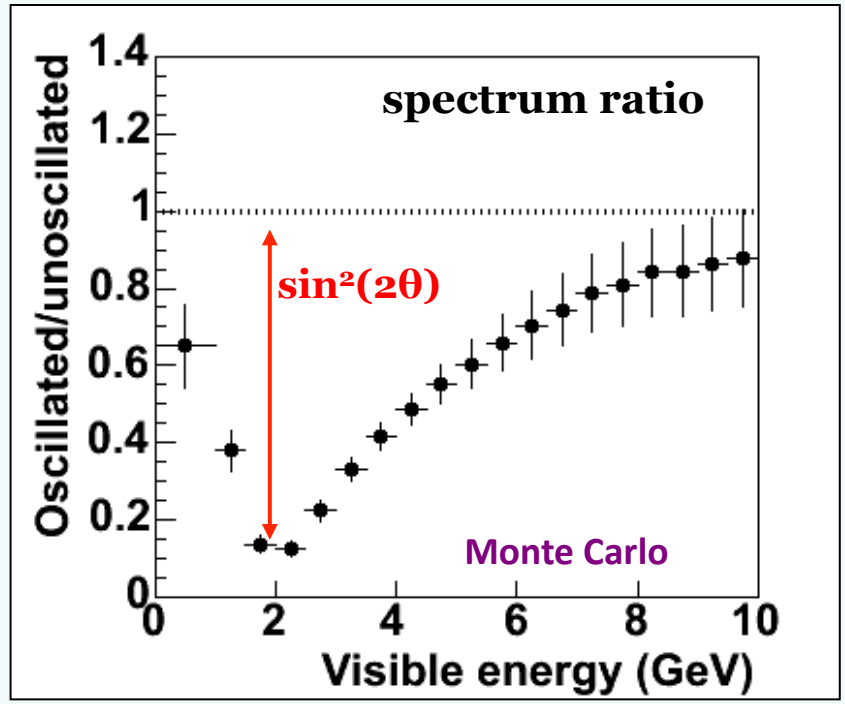

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ν_μ DISAPPEARANCE

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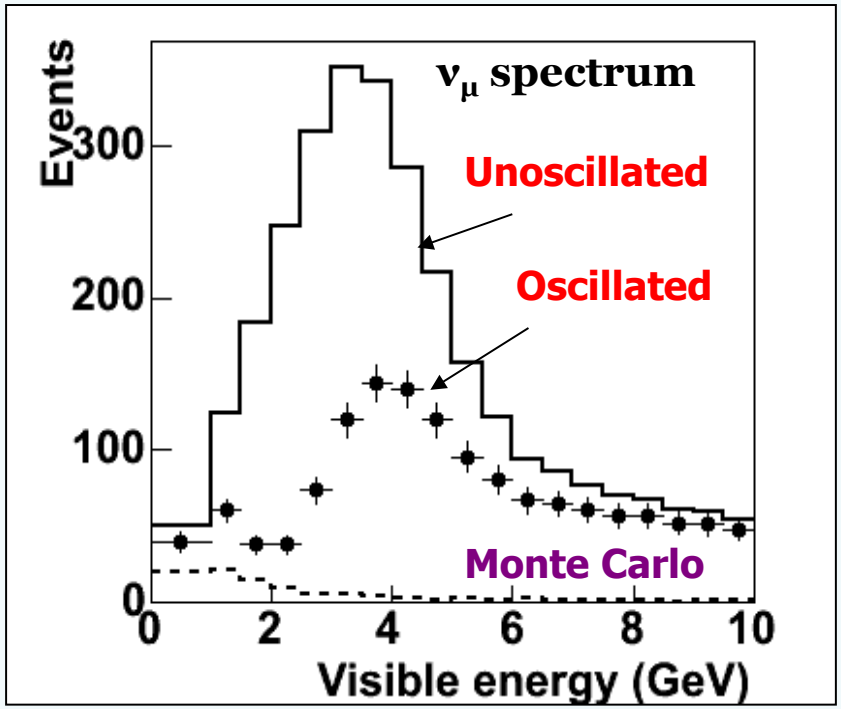

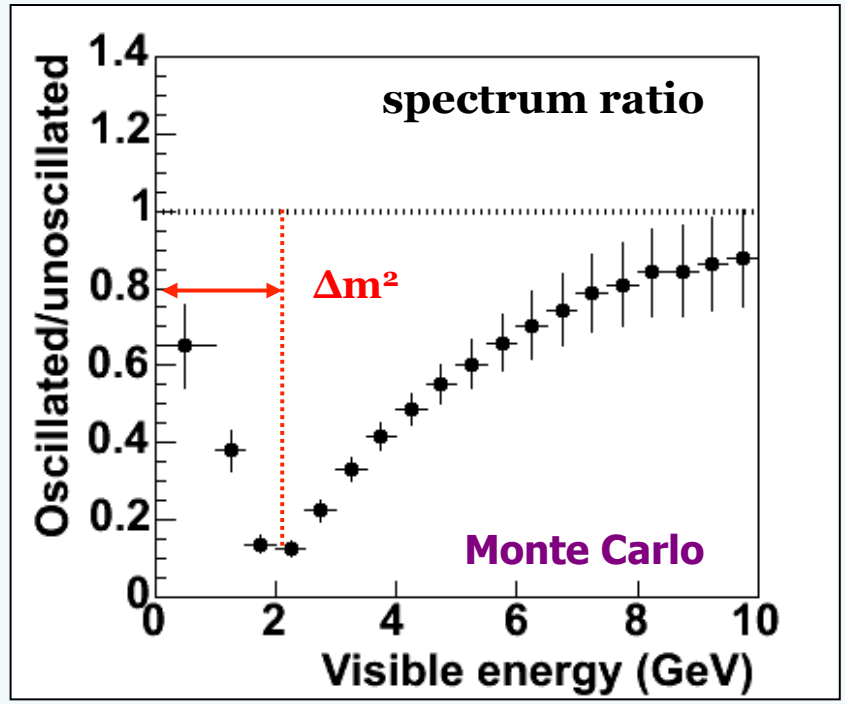

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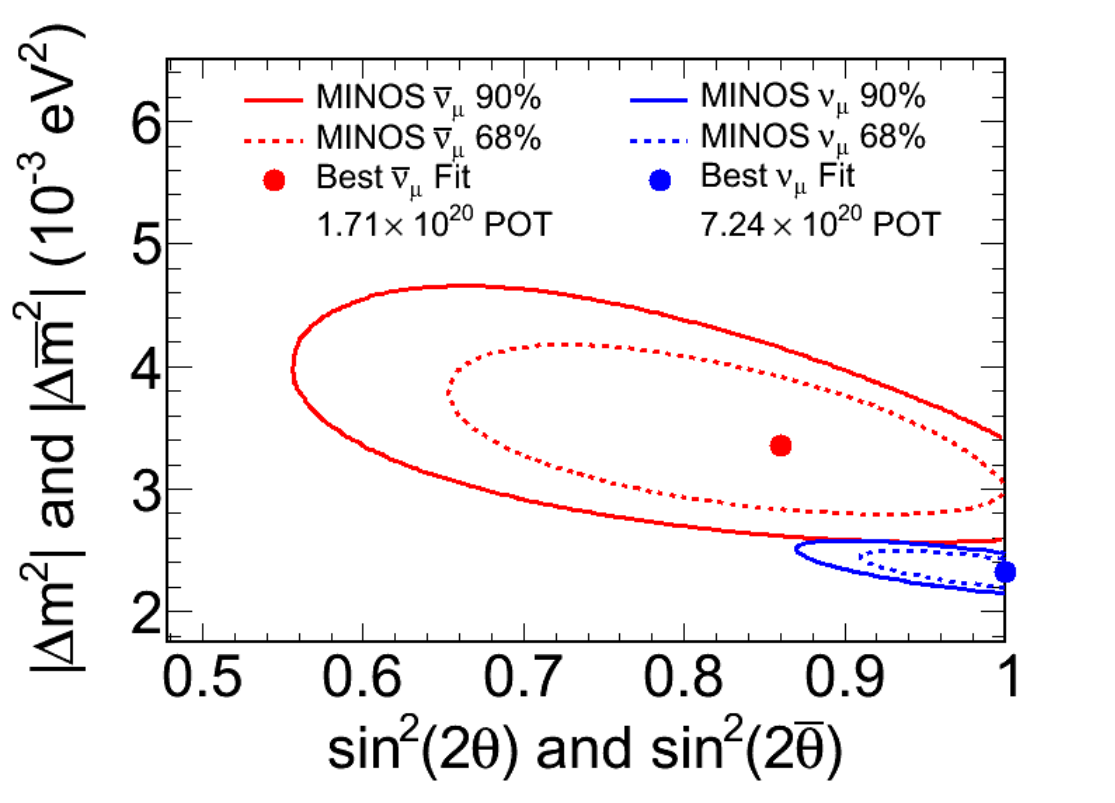
RECENT RESULTS



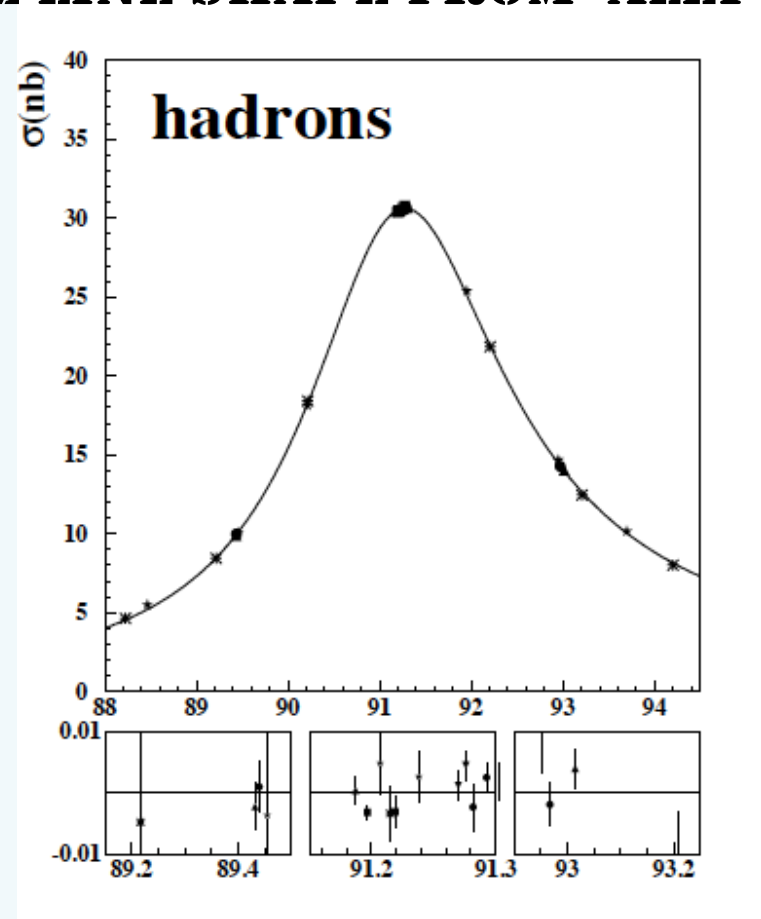
- ~2% probability of common parameters
- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy

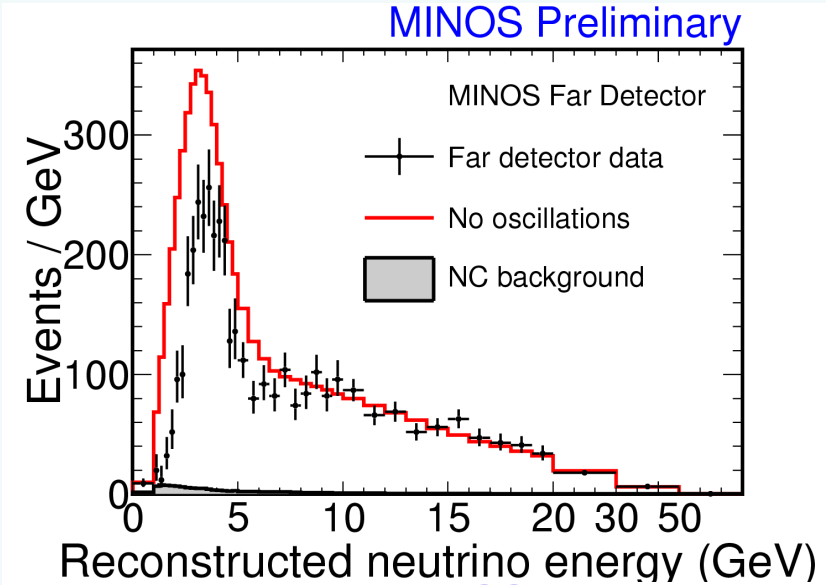
MINOS PLUS POINTS

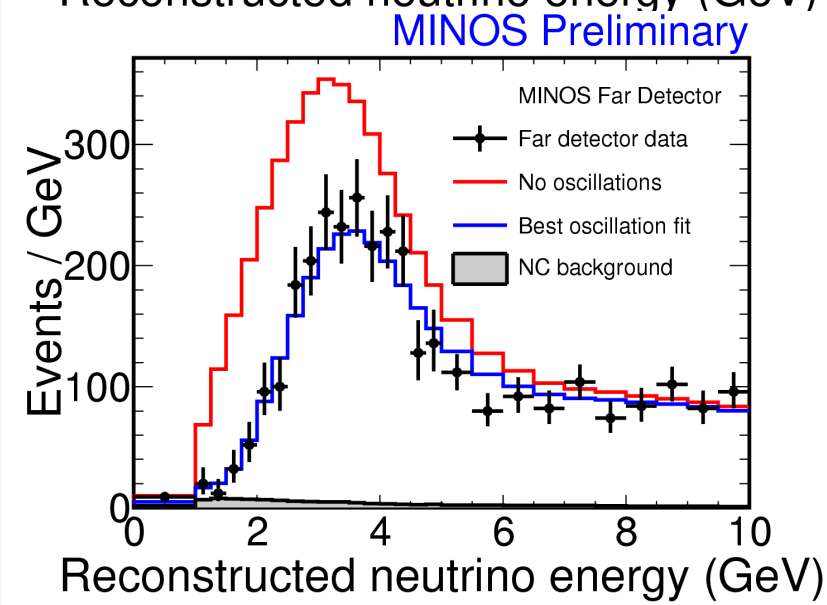
- The overarching reason to run MINOS in the NuMI-NOνA beam is to look for new physics in a previously unexplored region
- Very complementary to NOνA
  - event by event muon charge measurement
  - different energy
  - different cross section composition
  - different systematics

PRECISION MEASUREMENT?

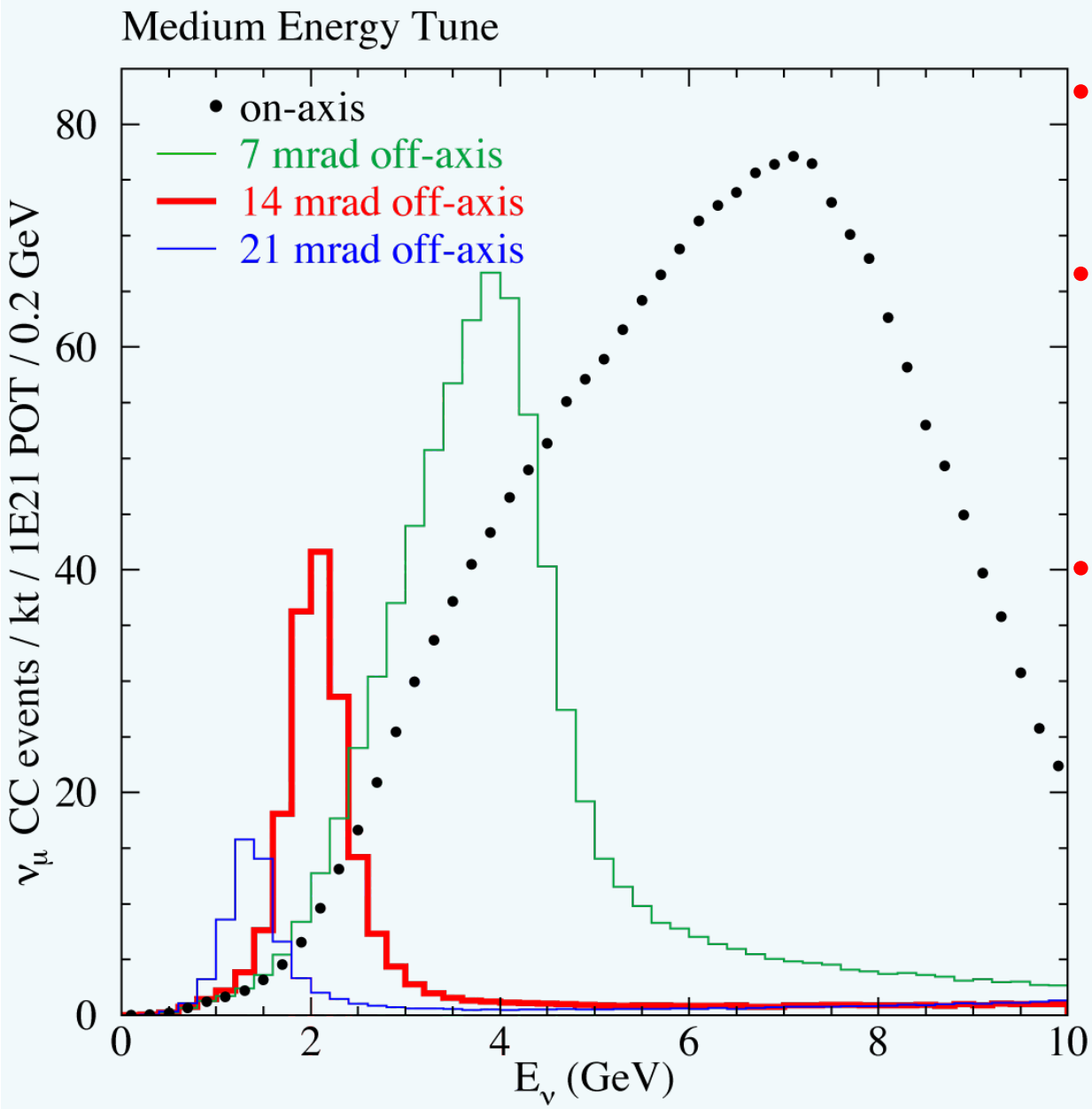
Z LINE-SHAPE FROM ALEPH







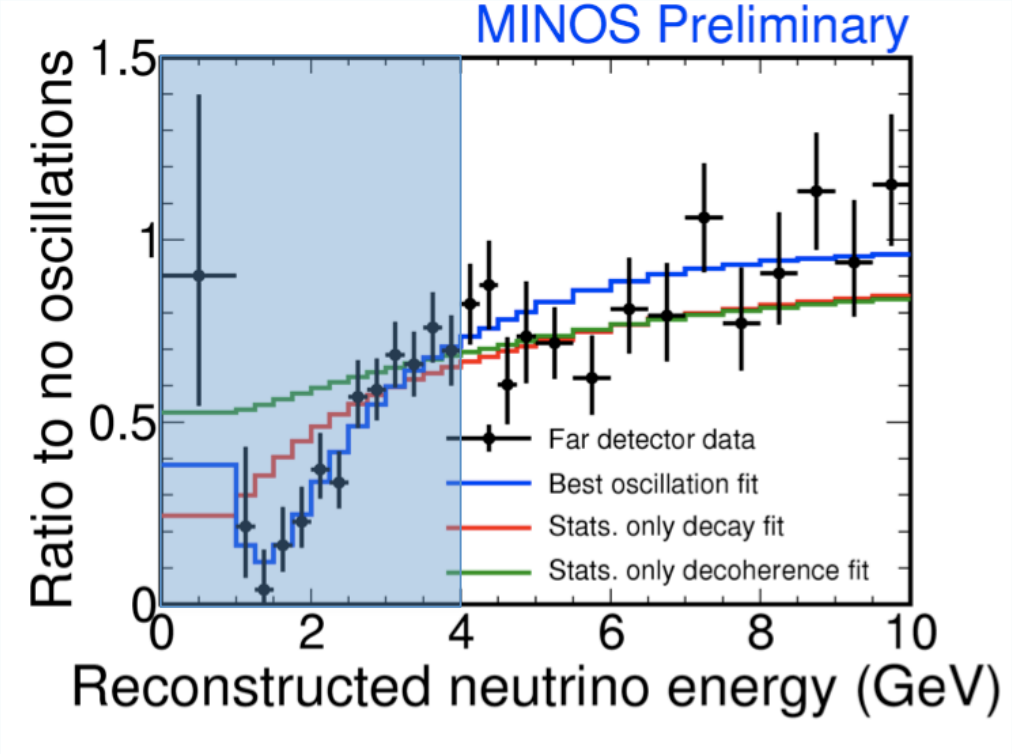
PRECISION MEASUREMENT



- If we turn MINOS off, area under the black points will be lost!
- ~3000 CC events/year between 4-10GeV (including energy resolution and efficiencies)
- Running scenario for coming studies assumes 3 years running and at least one in either neutrino or antineutrino mode

PRECISION MEASUREMENT

- MINOS+ will explore the presently very statistically limited region above 4 GeV in the oscillation plot.
- Estimates give ~3000 CC events in this region in one year of Nova running (about 2x what we have in the LE peak region after ~5 years running)
- In 4-10 GeV region, error bars go from 25%/GeV to ~5%/0.5GeV after 2 years



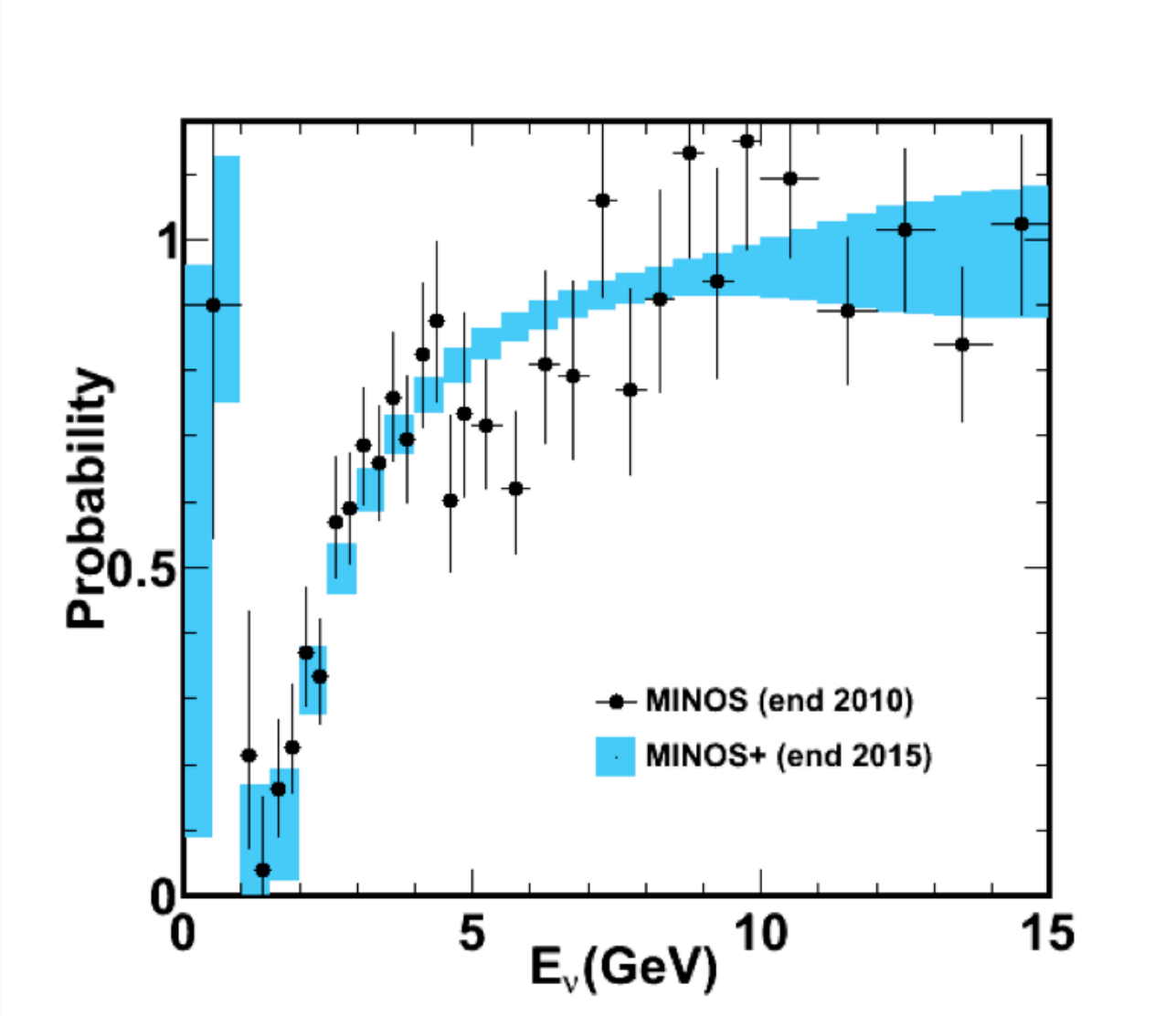
THE PHYSICS REACH OF MINOS+

From the very ordinary to the very extraordinary, in that order…

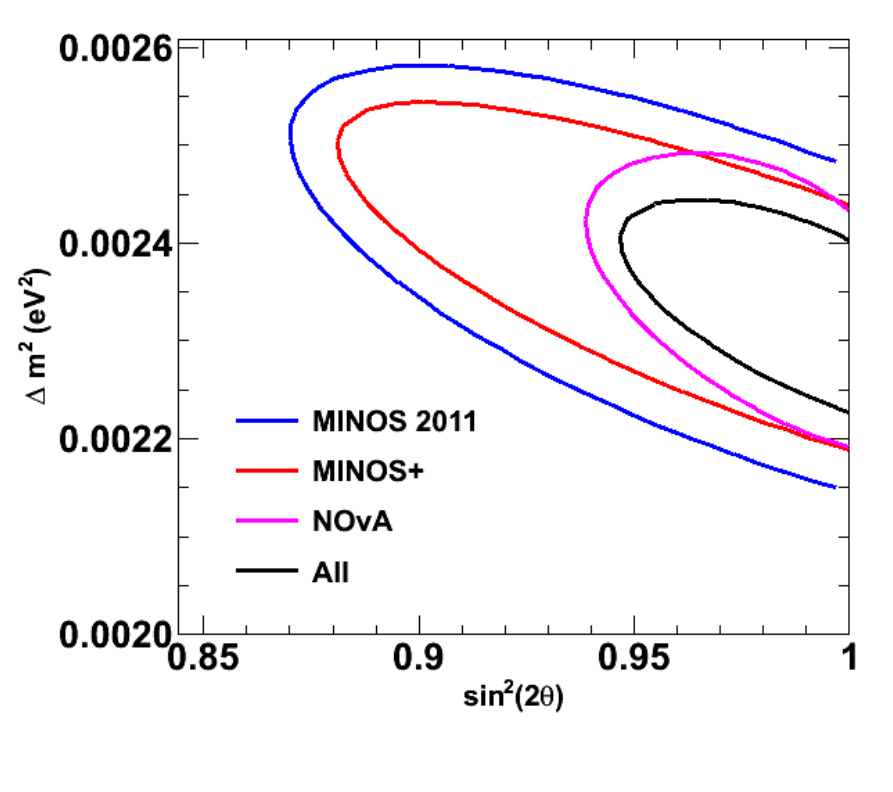
$\sin^2 2\theta$ AND ΔM^2

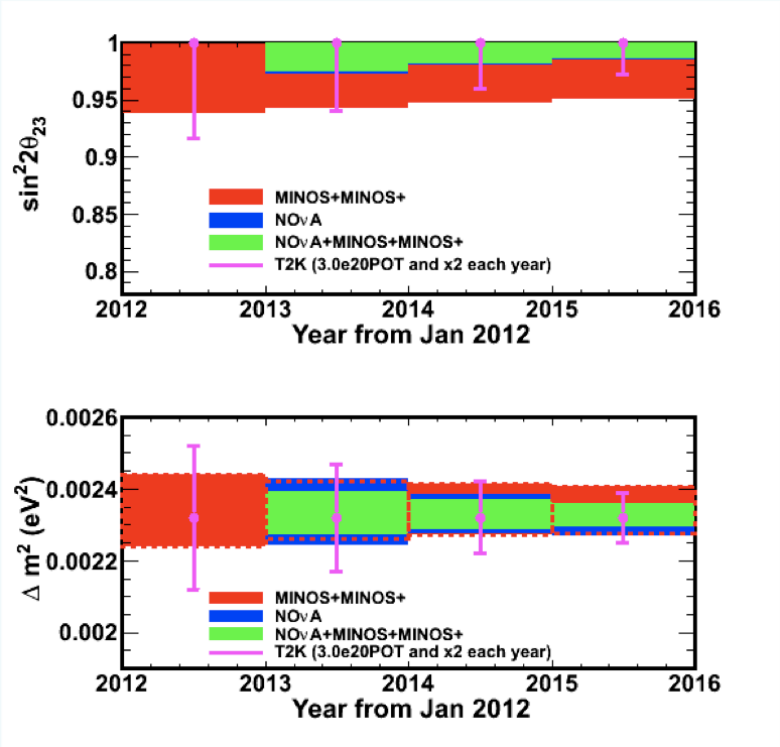
Those well known parameters

RATIO OF OSCILLATED TO NON-OSCILLATED FOR MINOS+



MINOS, MINOS+ AND NOνA





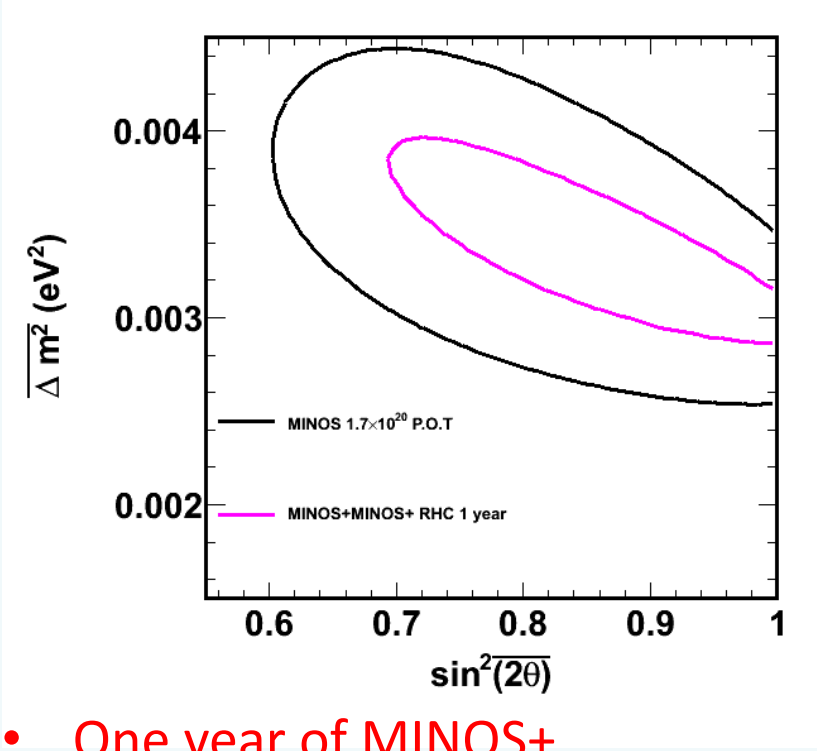
- One year of MINOS+
- MINOS continues to dominate Δm^2 measurement
- NOνA 89% complete

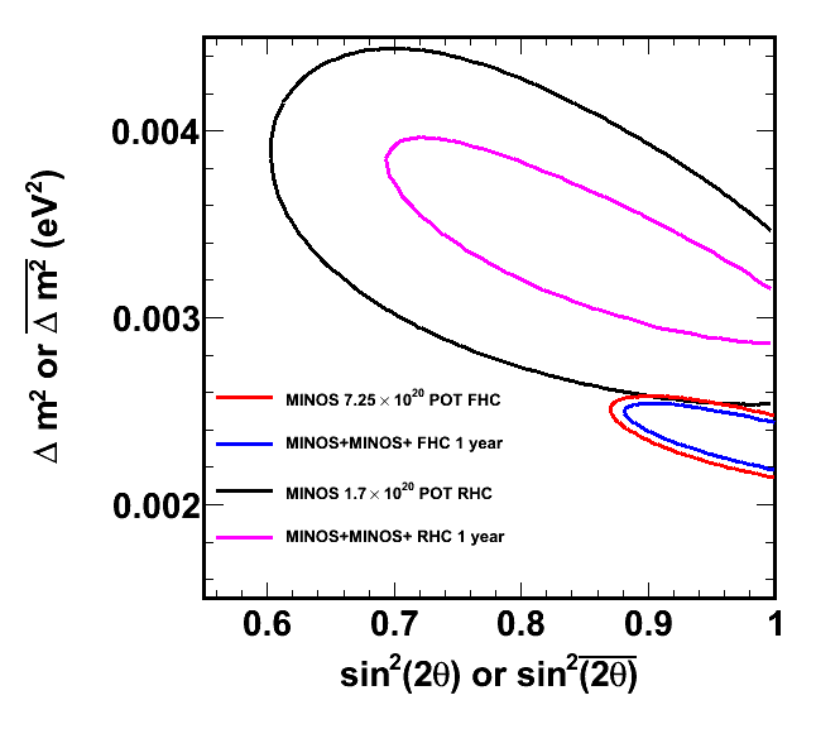
- Three years of MINOS+
- NOνA complete after first 18 months
- Significant improvements to parameters' accuracy over 3 years period due to MINOS+

$\sin^2 2\theta$ AND Δm^2

Those less well known parameters

MINOS AND MINOS+

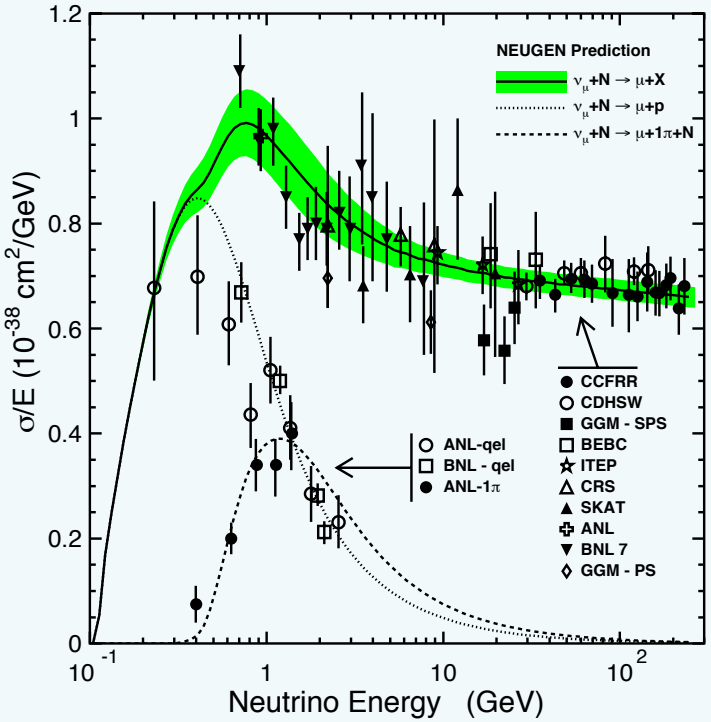


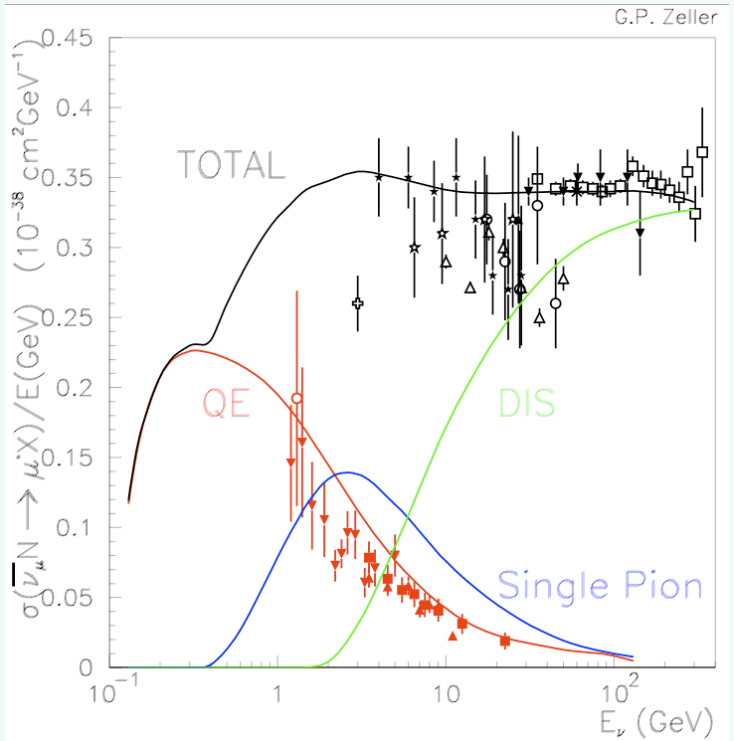


- One year of MINOS+
- MINOS continues to dominate Δm^2 bar measurement
- Combination of counting and shape different from LE beam
- If new physics here, MINOS+ will be able to unravel it with the energy spectrum giving model discrimination (hard for NOVA)

- One year of MINOS+
- Compare purple and blue contours to see measurement of different neutrino and anti-neutrino
- Assumes MINOS present anti-nu result

EXAMPLE





- It has been suggested that mis-modelling a particular type of event (eg QE) could result in a different energy scale for neutirnos and anti-neutirnos
- We are studying that presently (but it looks much too big)
- MINOS+ looks at a region where QE is ~10% of total compared to 30% now
- **DIFFERENT SYSTEMATICS!!!!!!**

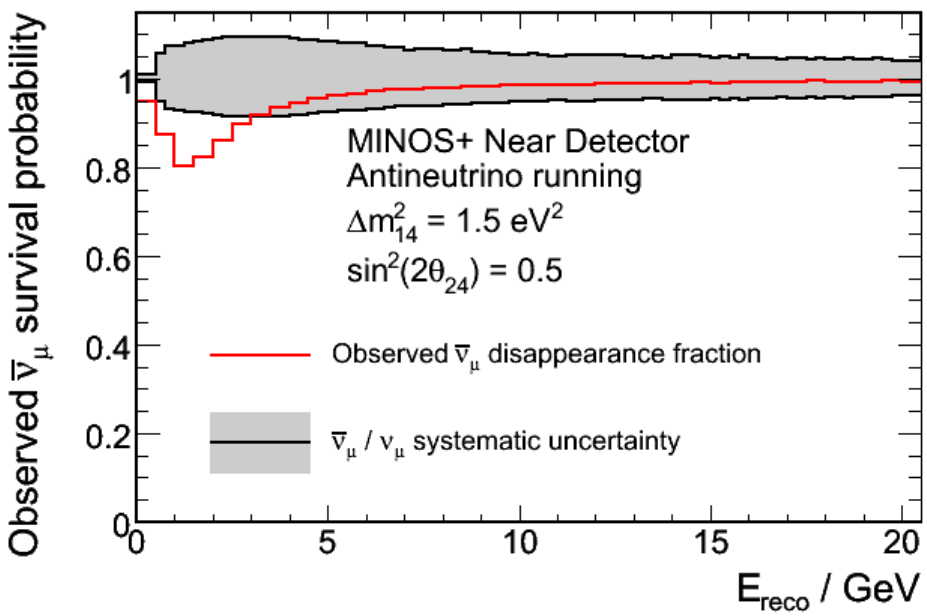
SEARCH FOR STERILE NEUTRINOS

A long baseline search

DIFFERENT EXPERIMENTS

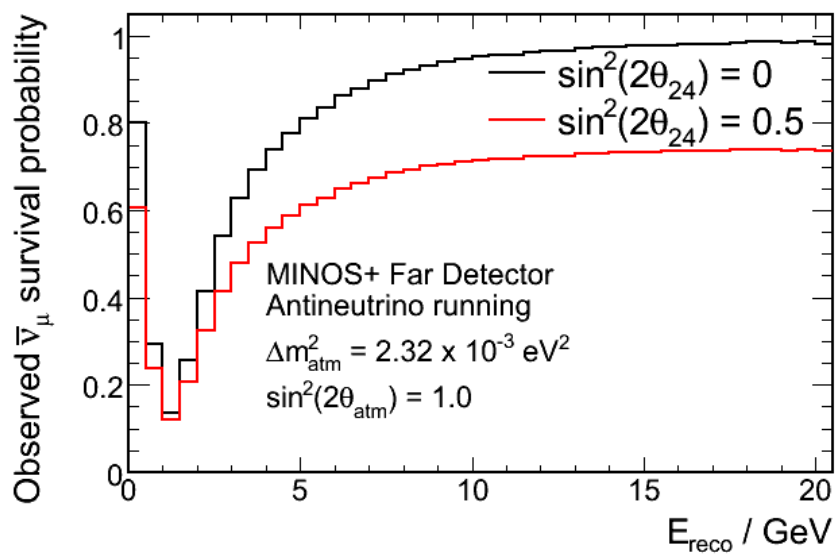
- Reactor experiments (ν_e disappearance): θ_{14}
- MiniBooNE and LSND (ν_e appearance):$\theta_{14}+\theta_{24}$
- MINOS (NC and ν_μ disappearance) $\theta_{24}+\theta_{34}$
- MiniBooNE and LSND, CDHS, CFFR (ν_μ disap):θ_{24}
- MINOS+ (ν_μ disappearance) : θ_{24}
- MINOS+ (NC disappearance) : $\theta_{24}+\theta_{34}$

AN EXAMPLE

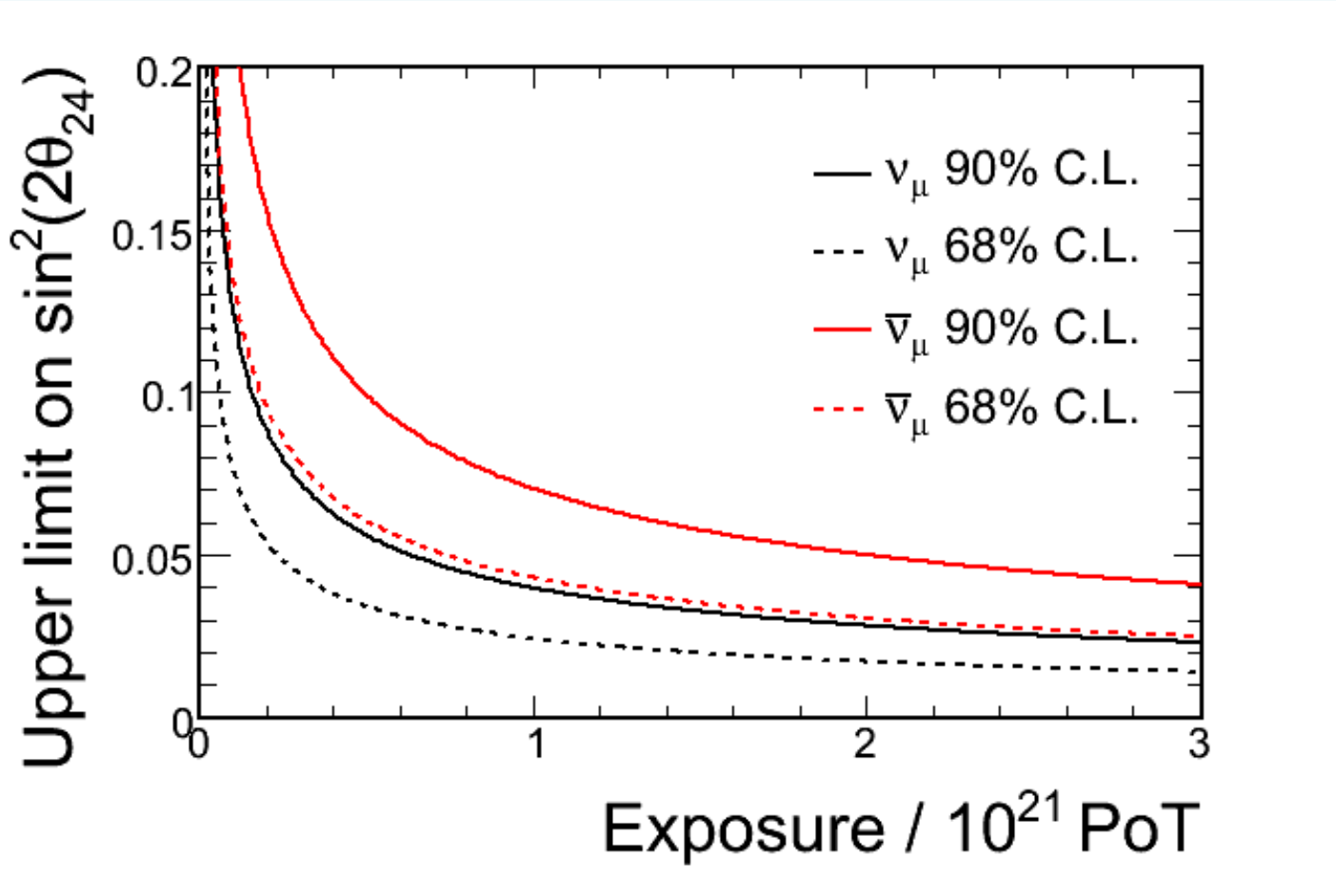


cross section uncertainties such as M_A_QE, M_A_Res, or the total CC cross section will affect numu and numubar in the same way

Systematic error is on ratio of numu to numubar

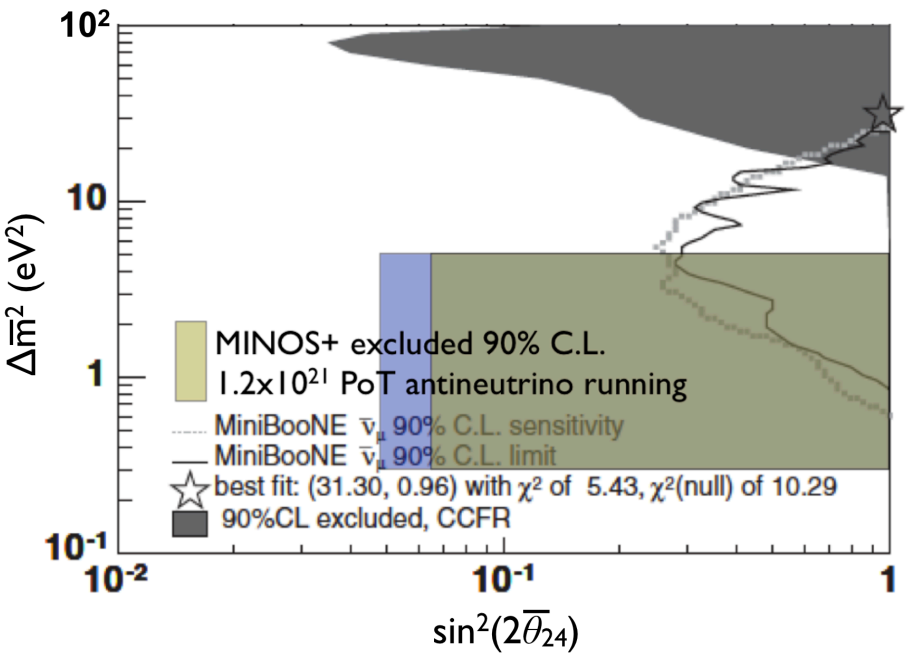


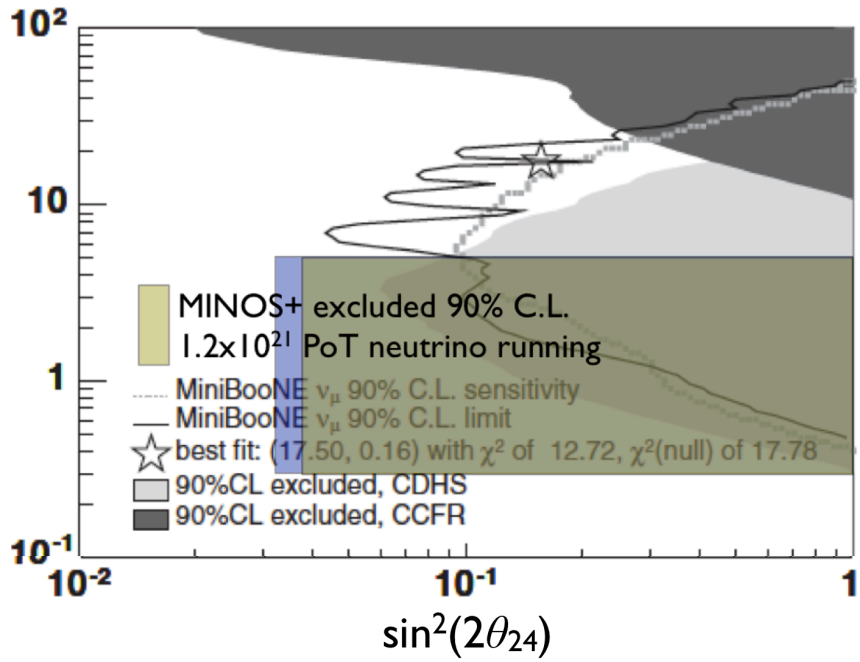
MINOS+ ν_μ DISAPPEARANCE



MINOS+ $\nu_\mu \rightarrow \nu_s$

- Muon disappearance



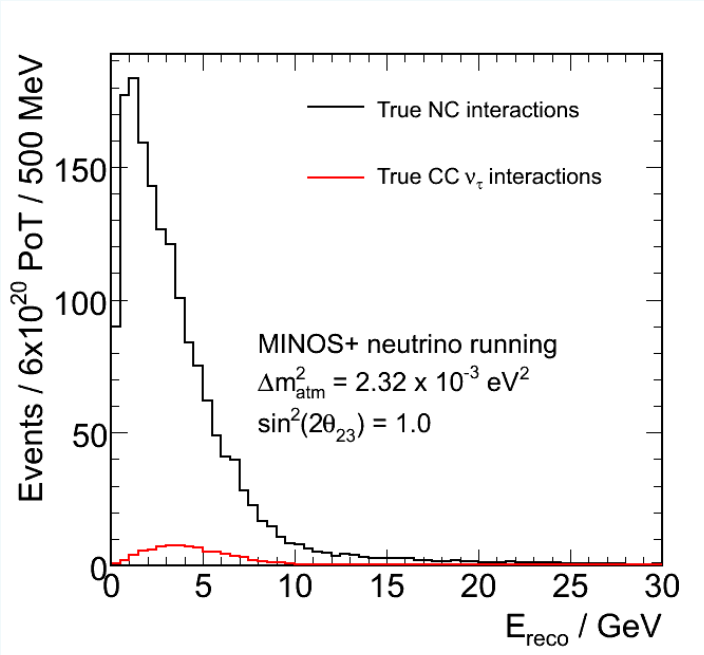


- Including NC and CC disappearance probes mixture of $\theta_{24}+\theta_{34}$

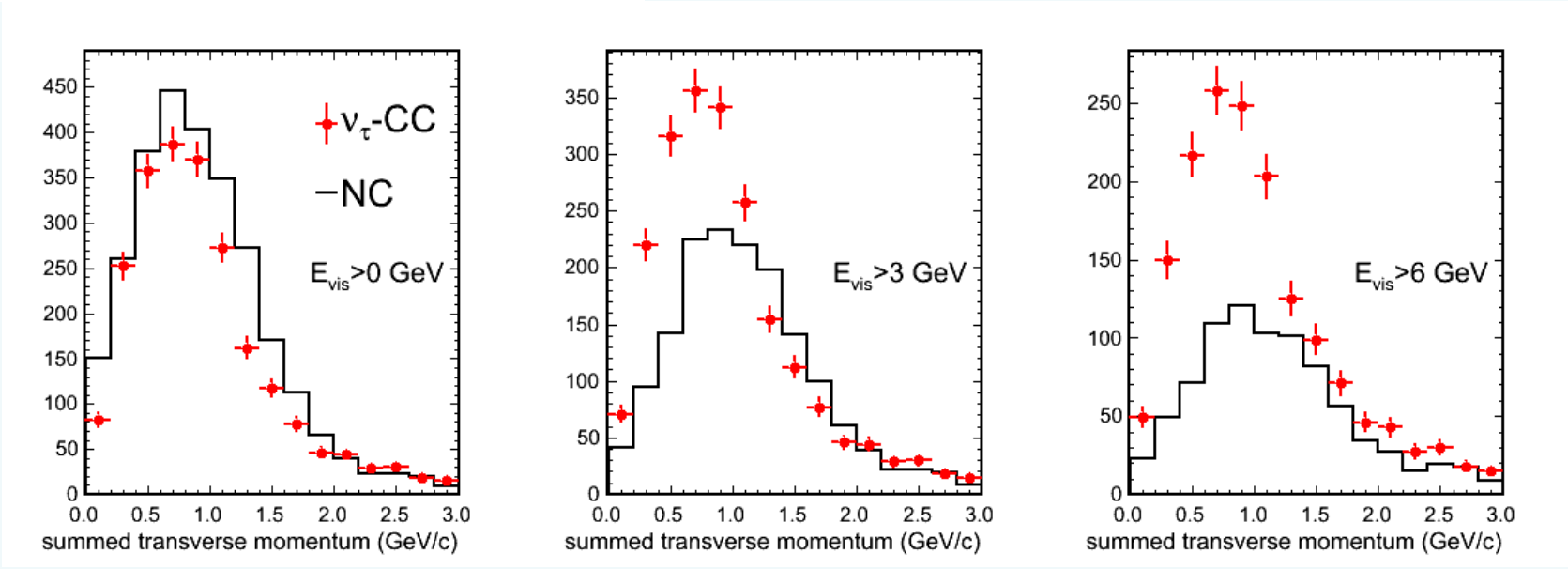
CAN WE SEE TAU NEUTRINOS?

Another needle in a haystack

TAU NEUTRINOS



- There are 80 tau events/ 1000 NC
- This is not THAT bad sig:bkg = 1:10
- With some work it *might* be possible to see a signal but its hard!
- OPERA have 1 tau event so far…

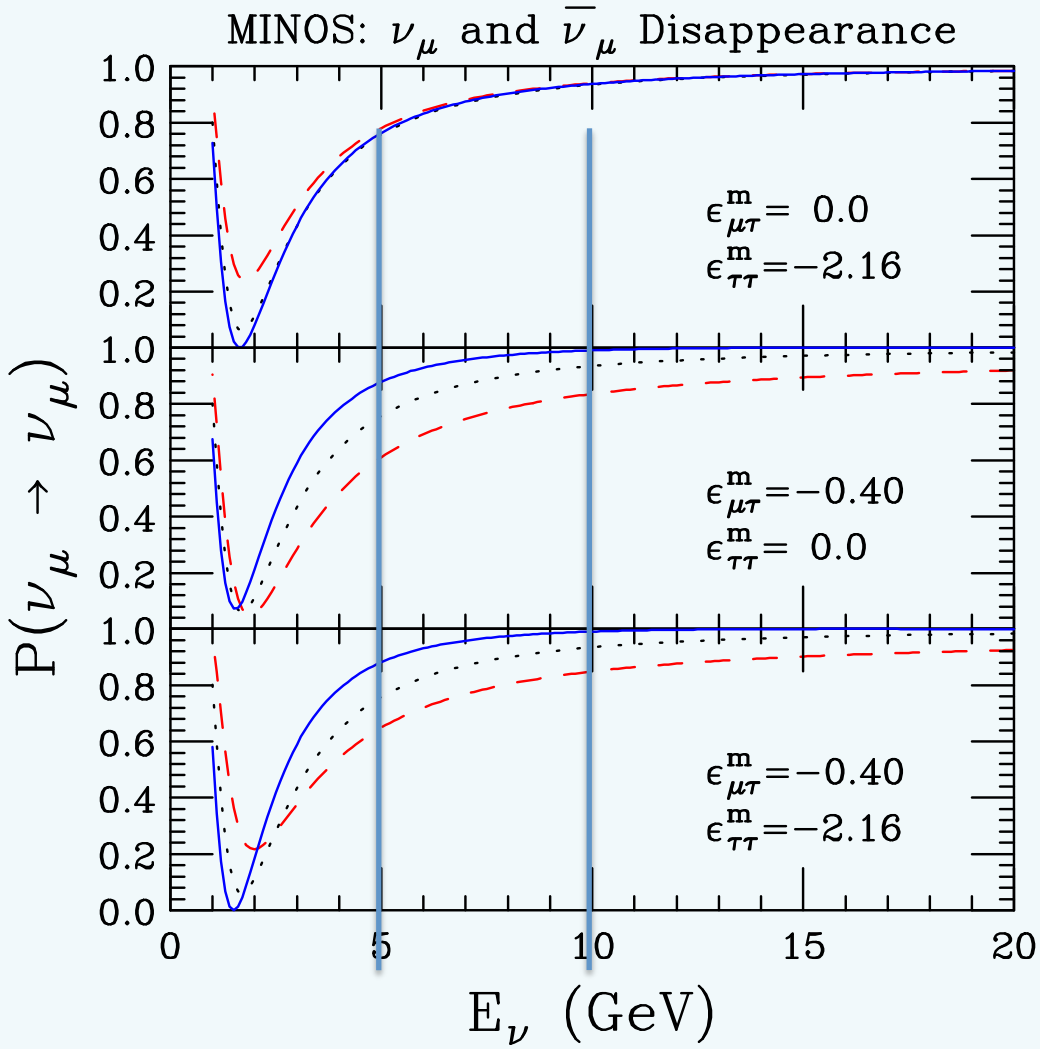


NON-STANDARD INTERACTIONS

Differences between neutrinos and anti-neutrinos due to non-standard matter effects

NON STANDARD INTERACTIONS❁

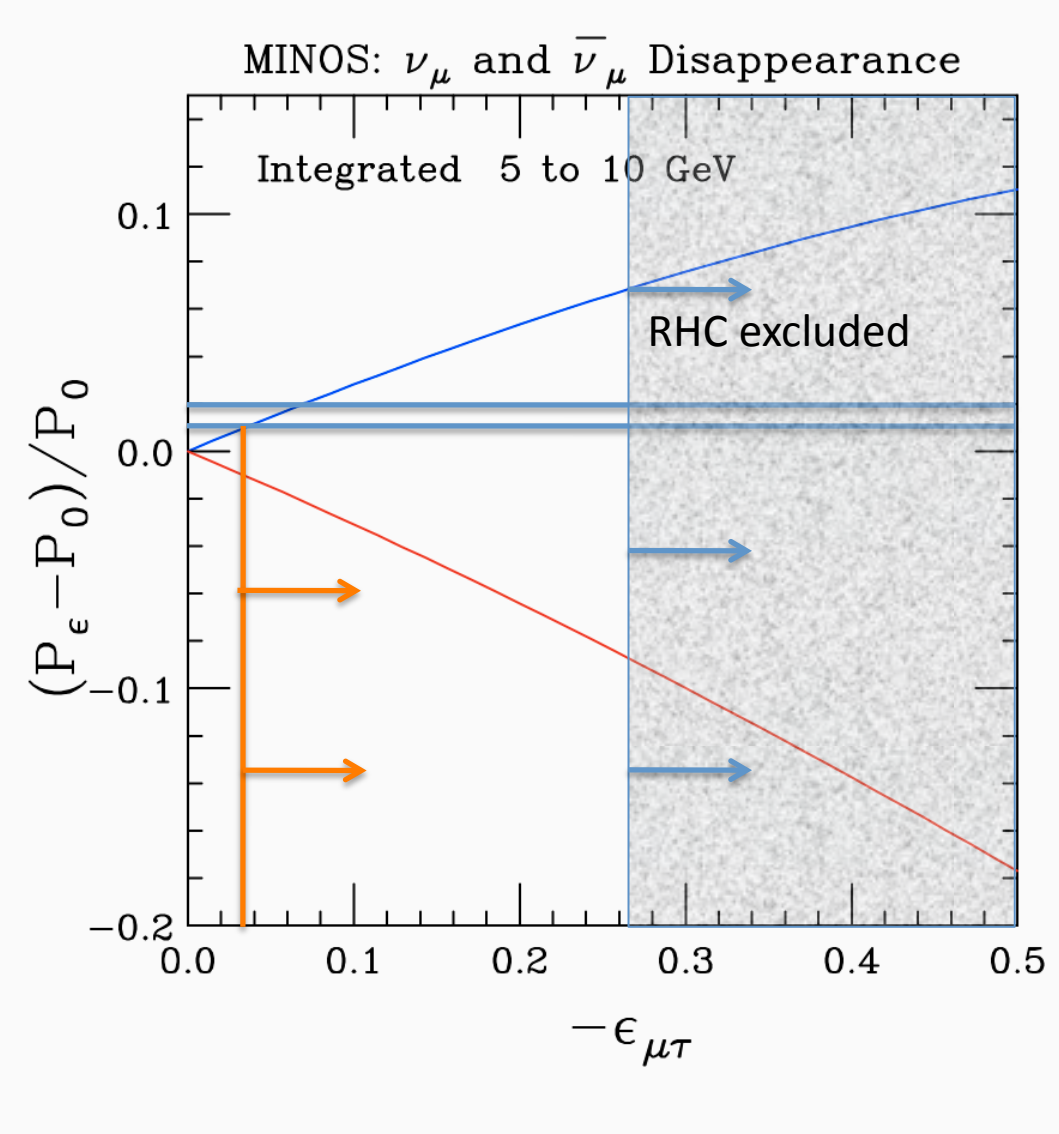
- Our anti-neutrino result has motivated some work from other theorists*
- Note the NSI has a measurable effect in neutrinos as well as antineutrinos
- Comparison of low energy to high energy behavior could disentangle this without anti-nu running



❁ Alexander Friedland , Cecilia Lunardini, Phys.Rev.D74:033012,2006.

*J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010).

NSI (STEPHEN PARKE)



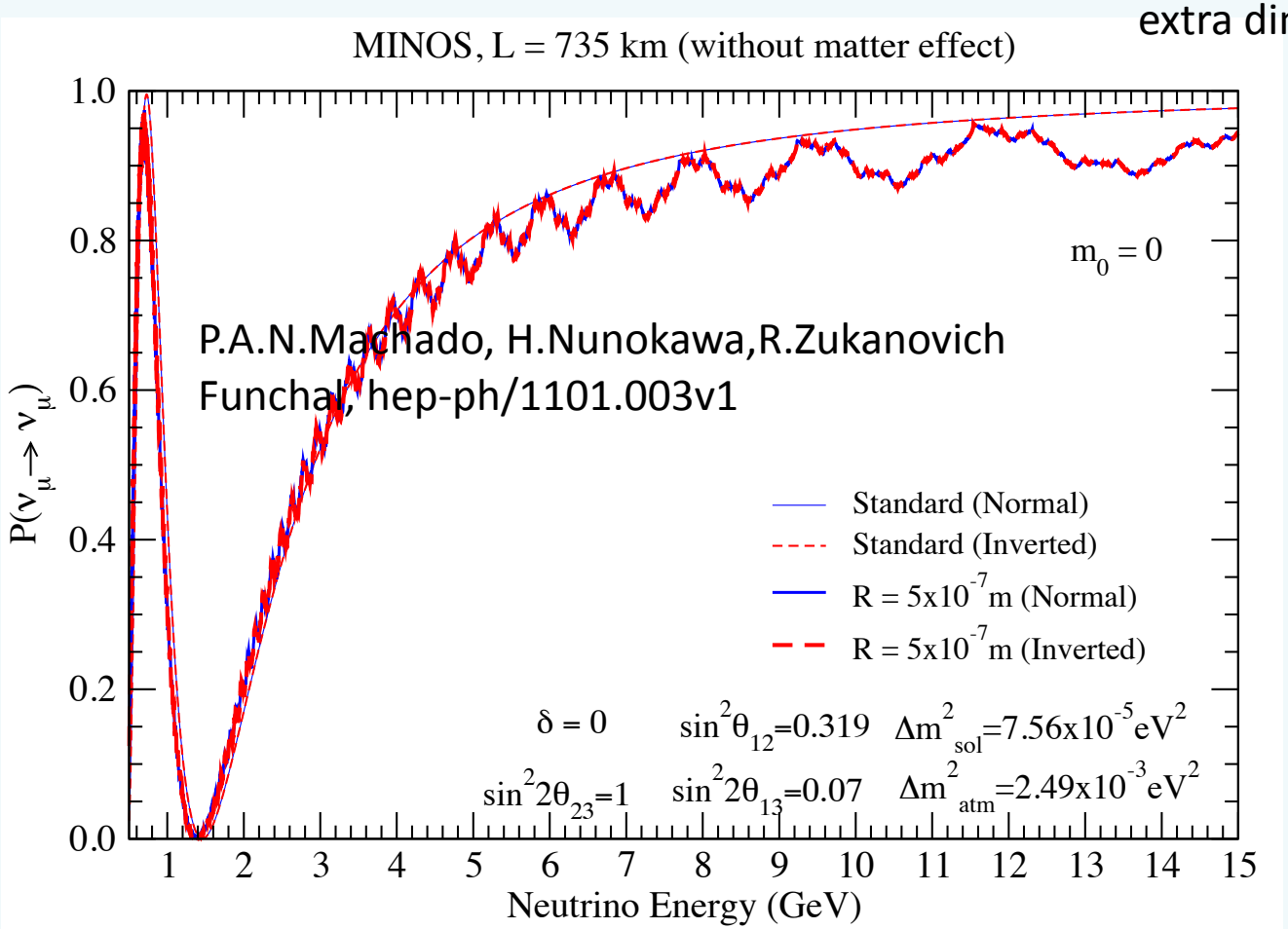
- NSI parameter $\varepsilon_{\mu\tau}$ can be significantly constrained
- ~3000 cc events/year between ~5-10GeV gives 2% on this normalization after 1 year, <1% after 2 years
- Already constrained by RHC running
- We can improve this limit with just one year in neutrino mode with MINOS+

SEARCH FOR EXTRA DIMENSIONS

And possibly world peace?

EXTRA DIMENSIONS

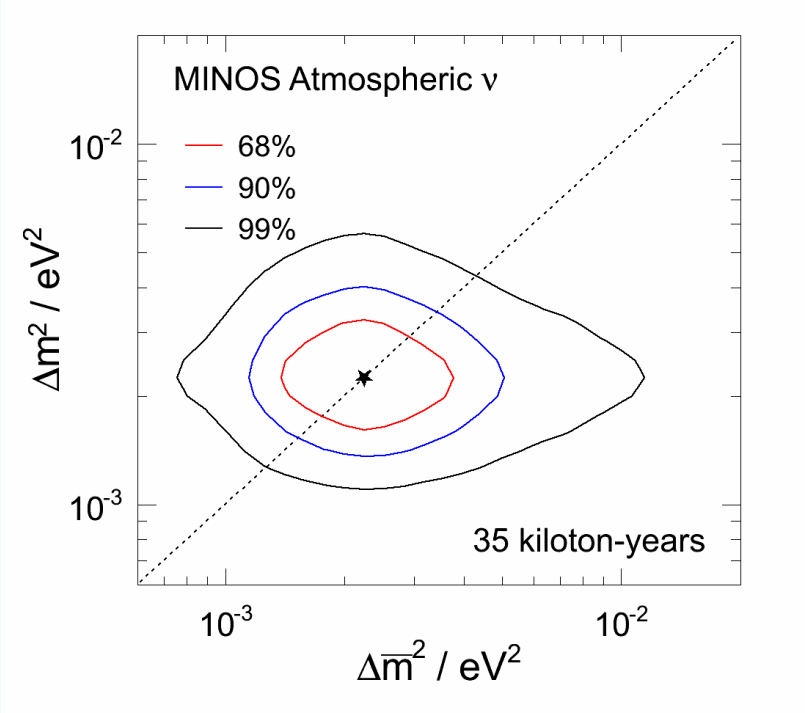
Assumes heavy RH (sterile) neutrino + extra dimensions!

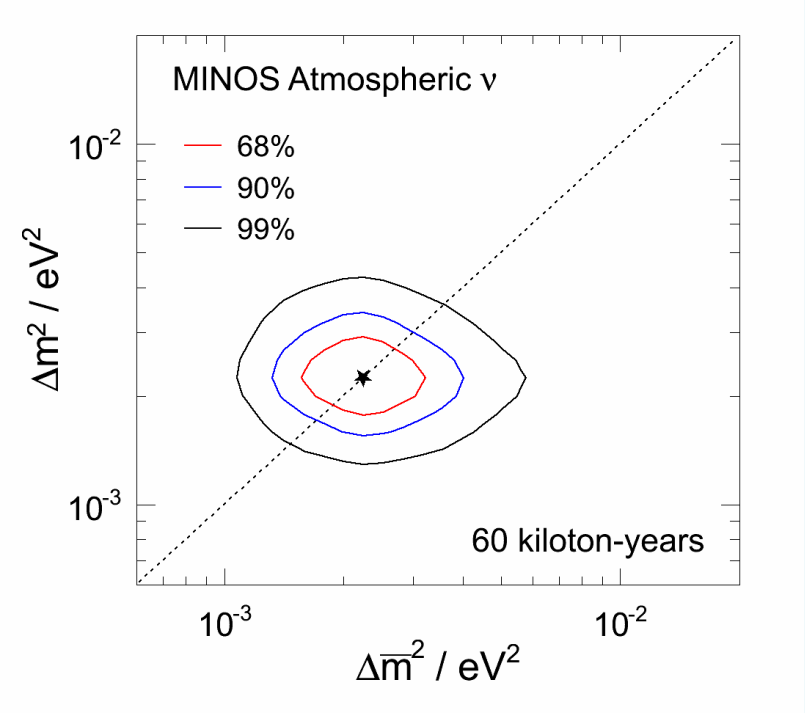


- MINOS data has already put limit on extra dimensions at about 1 micron level.
- This is just an example of the breadth of subjects which can be studied in the long baseline neutrino beam at higher energy

ATMOSPHERICS

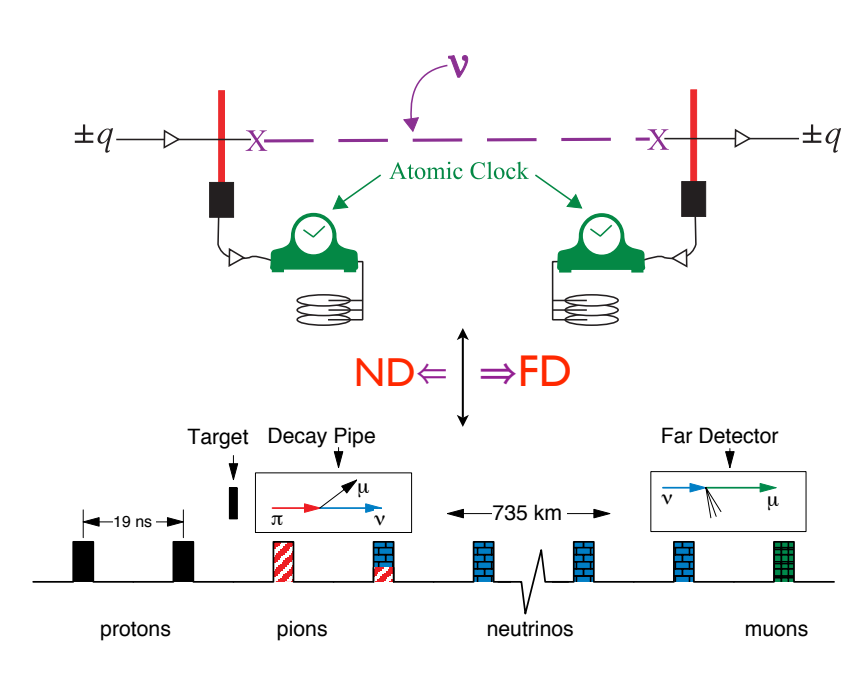
- Of course, MINOS+ will continue to amass atmospheric neutrinos, another internal consistency check





TIME OF FLIGHT

- Fundamental constant to measure
- $(1-v/c)<5 \times 10^{-7}$ s
- 2 orders improvement on previous measurement
- Cross calibrate small detectors with the FD and ND muons, use the atomic clock instead of GPC
  - 1 ns timing instead of 64ns
  - Instrinsic FD timing

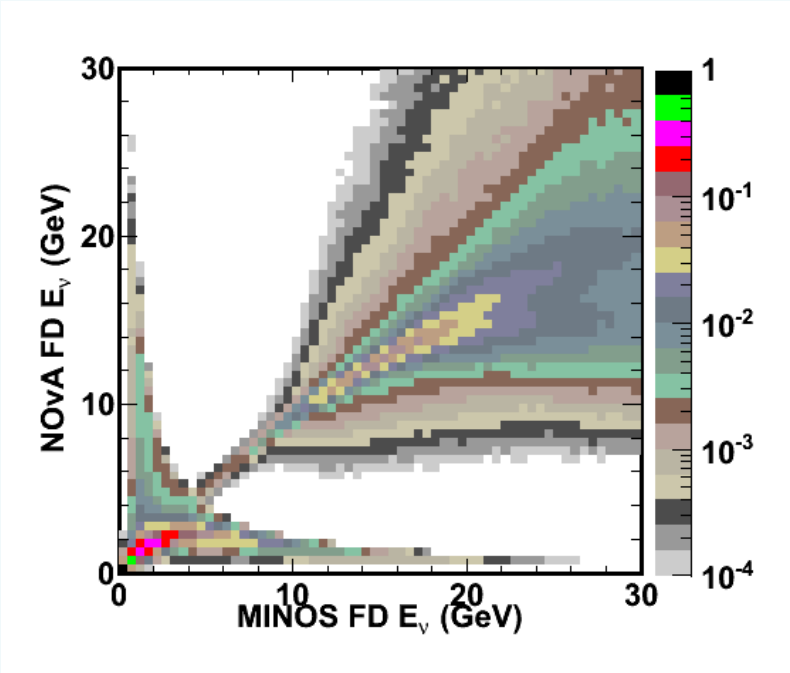


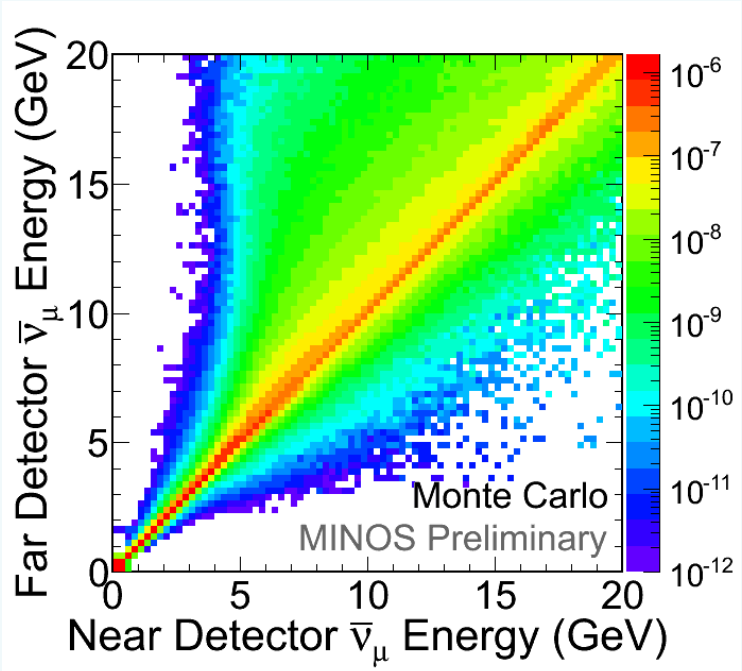
FNAL

- FNAL stands to have the most versatile neutrino facility in the world
  - MINOS FD : long-baseline monitoring for new physics
  - MINERVA : beam components, cross sections, flux
  - MINOS ND : flux, charge sign flux components
  - NOνA : first to mass heirarchy???
  - And forwards to LBNE…….

FNAL

- Same hadrons produce very different energy neutrinos in the on axis and off axis detectors
- More information can be gained for the flux constraints
- Already, MINOS has proposed an experiment-wide beam group to start working on this





ESTIMATE OF HARDWARE RESOURCE REQUIREMENTS

- NuMI beam
  - No additional requirement beyond NOvA
- Soudan Laboratory
  - Needs to operate beyond FY2013
- Hardware M&S
  - Main need is to replace obsolete DAQ processors
    - Use solution recommended by MINERvA/MINOS task force to upgrade.
  - MINERvA upgrade was estimated at ~$150 K for Near Detector
  - Scale to Far Detector – additional MINOS+ cost of $300K.
  - Exploring staging options and possible cost reductions
- Other components
  - PMT's: adequate supply of both types
  - Other components either adequate or available; detailed census ongoing.

ESTIMATE OF HUMAN RESOURCE REQUIREMENTS

- Adequate support for scientific effort essential to reverse current roll-off.
- For DOE institutions, census of collaboration
  - Peak new students and postdocs: ~10
  - Peak total DOE FTE for MINOS and MINOS+: ~17
- Estimate of total (additional*) university postdoc/student cost to U.S. agencies: ~$2M/yr.
- Changes
  - Losing Indiana, Harvard and ANL
  - Gaining Los Alamos and potential Indian Collaborators
- Maintain adequate Soudan crew
- Increase computing effort.

CONCLUSIONS

Motherhood and apple pie

NEUTRINO MASS

- It is arguable that the fact of such tiny neutrino mass does tell us that there is physics at the GUT scale
- Neutrinos are the only 'lab-based' handle on the physics at this GUT scale
- The massive RH-Majorana neutrinos which seem to be there naturally via the see-saw mechanism are the favored explanation as to why neutrino mass is so small
- Surprisingly, there are a lot of disparate effects which show up in the high energy neutrino N/F ratio, and we can look at it.
- So .... lets look at it!!!

WE SHOULD LOOK EVERYWHERE FOR EVIDENCE

BACKUP SLIDES

If you are here we have run out of time

TIME OF FLIGHT

Measuring Neutrino speed in MINOS

What: Measure ν ToF with ±1ns over *L*=735km

Motivation: A new observable for the experiment

Measure ν_μ (μ-) speed with *x80* higher precision ⇒ ***|1-v/c|<5e-7***

Search for anomalous ν_x (NC, e-/+, μ+) speed wrt ν_μ

How: Auxiliary detector `A', [2-Sci + 3-RPC's] Planes,

at Near ⇒ T1

FD synchronized to (identical) auxiliary detector 'B' ⇒ T2

Atomic clocks at Near and FD continually synchronize the Auxiliary detectors `A' & 'B' (~1ns)

Systematic Errors: $\Delta L \rightarrow 0.1m$; Clock synchronization; FD-synchronization; π-flight time; etc ⇒ ≃ 1ns achievable

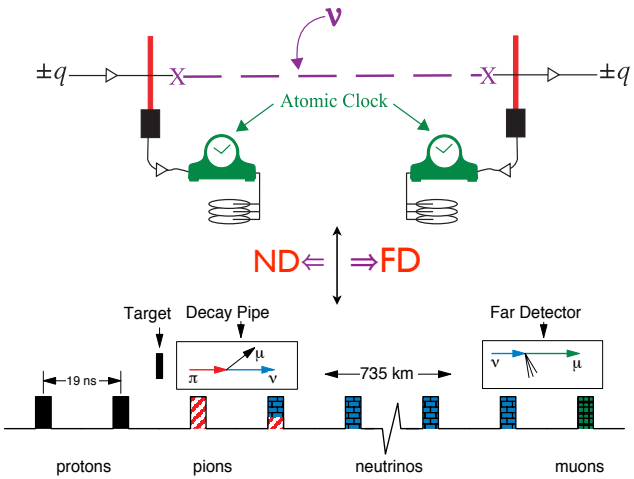
Cost: (a) Atomic clock & associated electronics: $268k
(b) Auxiliary detector at ND, FD, Spare: $ 70k
(c) Synchronization Operating expense/yr: $ 43k

How long: AC-Aquisition, electronics, auxiliary detector: 12 months

Installation, commence operation: +6 months

Who: Carolina, Austin, ... groups; FD-electronics group

⇒ *Something novel: 2-PRL's, 1-NIM, Discovery?*



Aux.Detectors time calibrate MINOS Detectors to the Atomic Clocks

GPS (~65ns) is replaced by AC-TWSTT