MINOS+

Update & Plans

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FERMILAB PAC MEETING
JANUARY 20, 2016

MINOS

Topics

1. MINOS+ Goals (reminder)
2. MINOS+ Collaboration
3. Operations
4. Analyses
   - Standard oscillations
   - Evaluating slip-stacking impact
   - Search for sterile neutrinos
   - Searches for "exotics"
5. Conclusions and plans

The charge

◆ This presentation is aimed to help PAC address the charge:

5. NOvA, MicroBooNE, and MINOS+

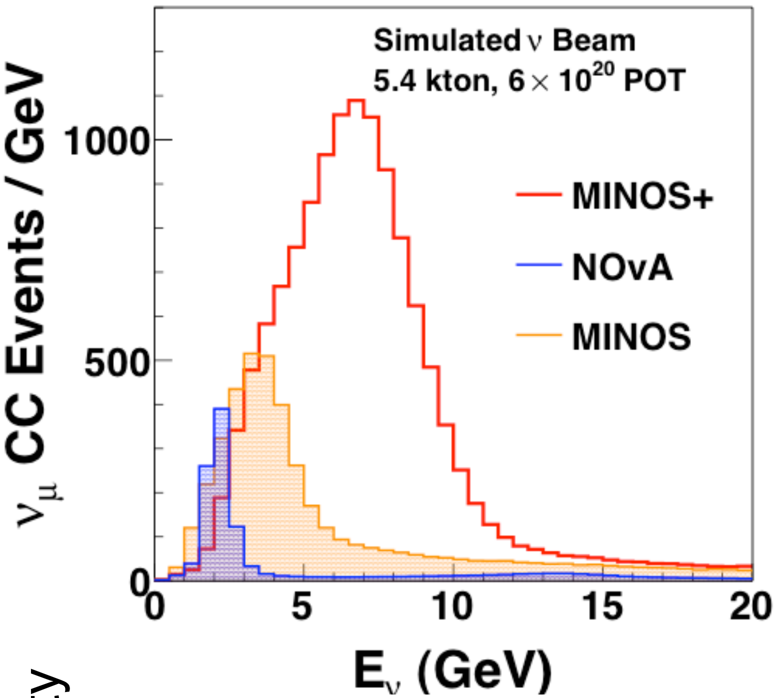
i) We ask the PAC to comment, for all three experiments, on the current situation and on the progress being made.

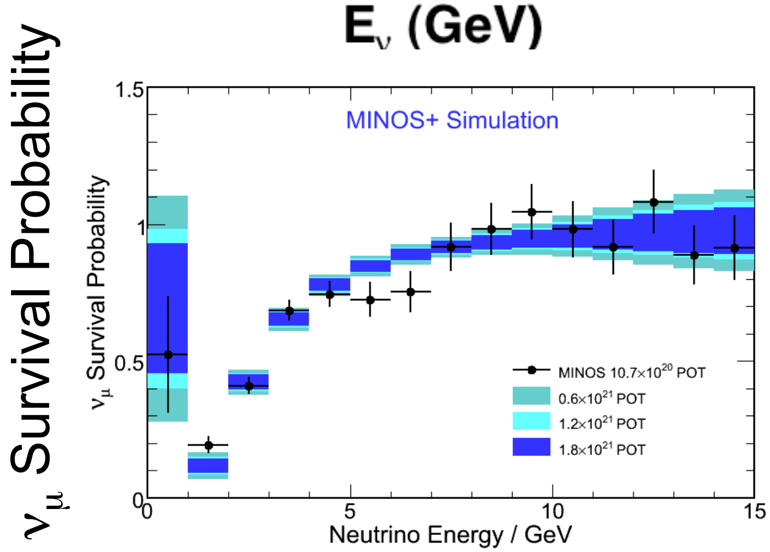
ii) The timing of the switch from neutrino to antineutrino running affects all of the NuMI experiments. We ask the PAC to comment on the strategy NOvA is proposing to determine when this switch will be made.

iii) MINOS+ is in its final year of data taking. We ask the PAC to comment on whether the experiment is likely to deliver on its basic physics goals given a realistic estimate of the final integrated POT.

iv) We ask the committee to comment on progress in MicroBooNE, the initial running of the experiment, and plans for the first physics results from the experiment.

1. MINOS+ (main) goals (a reminder)





- MINOS+ (E-1016, proposed in 2012) for continued exploitation of the NuMI beam and MINOS detectors (MINOS (E-875), proposed in 1995)
  1. Improve measurements of "atmospheric" oscillations (by probing the multi-GeV region)
  2. Search for new physics in the oscillation region
     - i. search for light sterile neutrinos
     - ii. search for NSI and other "exotic" transitions (e.g., large extra dimensions)
     - iii. continue cosmic rays data acquisition & analysis

- Requested in the proposal:
  - ✓ 3 years of running (2013-2016)
  - ✓ 18 x 10^{20} POT
  - ✓ Collect ~3000 ν_μ CC events/year

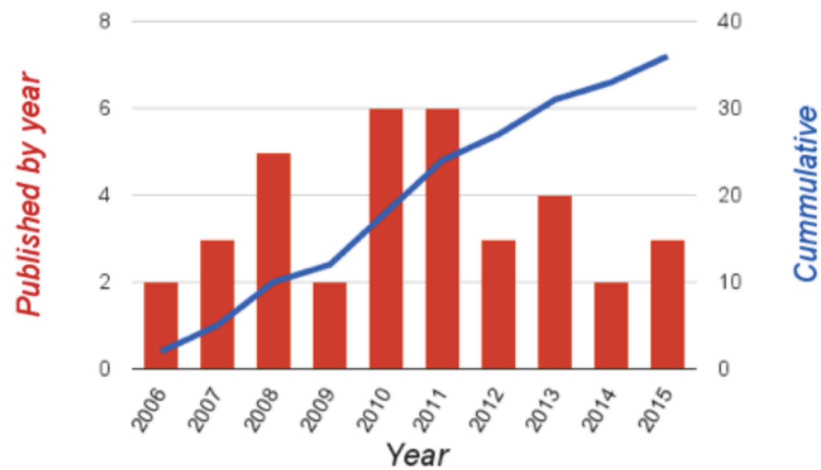
- New collaboration (but largely based on the MINOS Collaboration)
  - ✓ about 70 members (then)

2. MINOS+ Collaboration (summer survey)

- Jenny Thomas reelected Co-Spokesperson for a 3-year period
- July 2015 MINOS+ Collaboration survey (requested by DOE)

MINOS+ Collaboration (summary of a collaboration poll, July 2015)	FY16	FY17	FY18
Total US participants	31	24	22
Total foreign participants	19	14	11
Total MINOS+ participants	50	38	33
Total US FTE	12.73	9.55	9.05
Total foreign FTE	7.40	5.20	3.25
Total MINOS+ FTE	20.13	14.75	12.30

- Published two MINOS papers since June 2015
  - ⇨ "Precision measurement of the speed of propagation of neutrinos using the MINOS detectors"
    P. Adamson et al.
    (MINOS Collaboration, NIST, and USNO)
    Phys. Rev. D 92, 052005
    Published 17 September 2015
  - ⇨ "The NuMI neutrino beam"
    P. Adamson et al.
    (MINOS Collaboration)
    Nucl. Instrum. Meth.
    Volume 806, 11 January 2016,



2: Long coming MINOS (legacy) papers …

- TOF paper results: the most stringent and 2-detector accelerator-based constraints:
  - With NIST, Time and Frequency Division, Boulder
  - With US Naval Observatory , Washington, DC
  - Near Detector – to – Far Detector measurement

$$\delta t \;=\; 2.4 \;\pm\; 0.1_{stat} \;\pm\; 2.6_{sys} \;[ns]$$

$$\frac{v}{c} - 1 = (1.0 \pm 1.1) \times 10^{-6}$$

TABLE I: Dominant systematic uncertainties ($\pm 1\sigma$)

Systematic Uncertainty	Value
Inertial survey of the FD location	2.3 ns
Relative ND-FD latency	1.0 ns
FD TWTT between surface and underground	0.6 ns
GPS time-transfer accuracy	0.5 ns

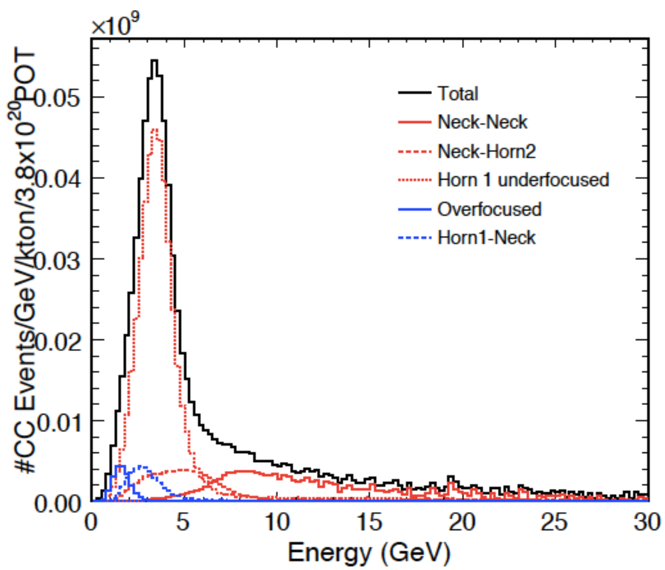
Borexino $\delta t = 0.8 \pm 0.7_{stat} \pm 2.9_{sys} \; [ns]$

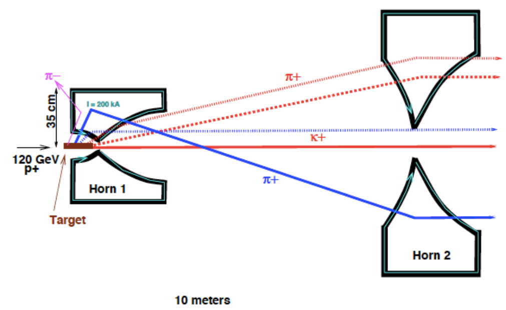
ICARUS $\delta t = 0.1 \pm 0.67_{stat} \pm 2.39_{sys} \; [ns]$

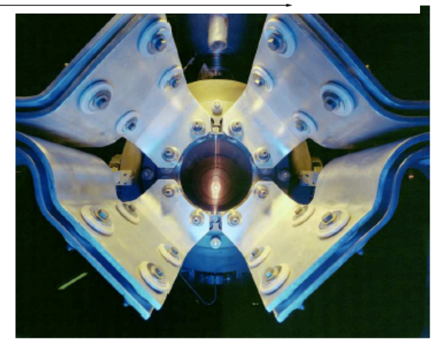
LVD $\delta t = 0.9 \pm 0.6_{stat} \pm 3.2_{sys} \; [ns]$

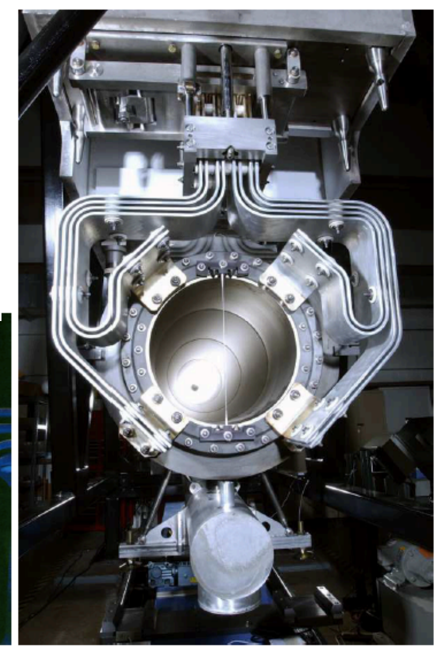
OPERA $\delta t = 1.7 \pm 1.4_{stat} \pm 3.1_{sys} \; [ns]$

- NuMI beam "hardware" paper

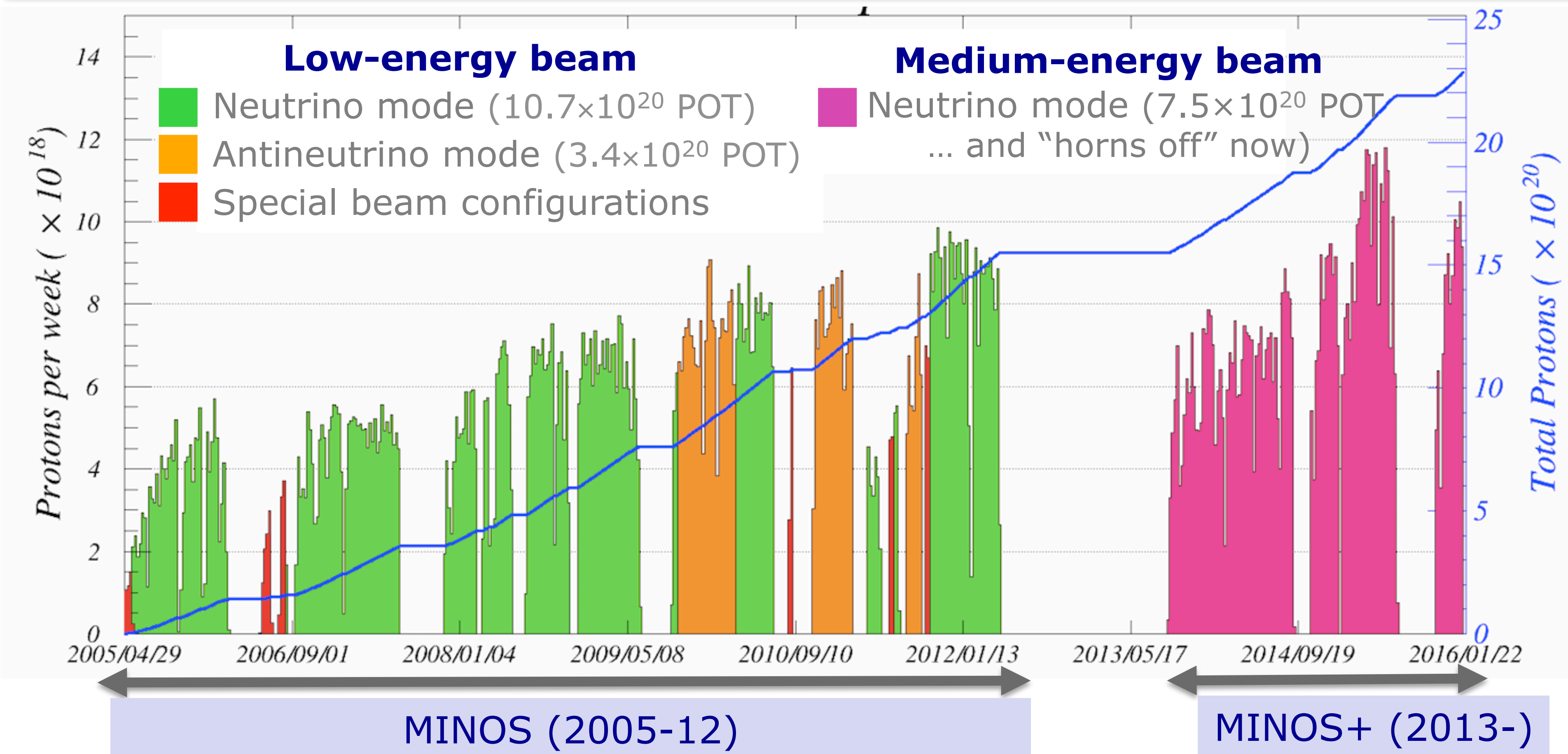






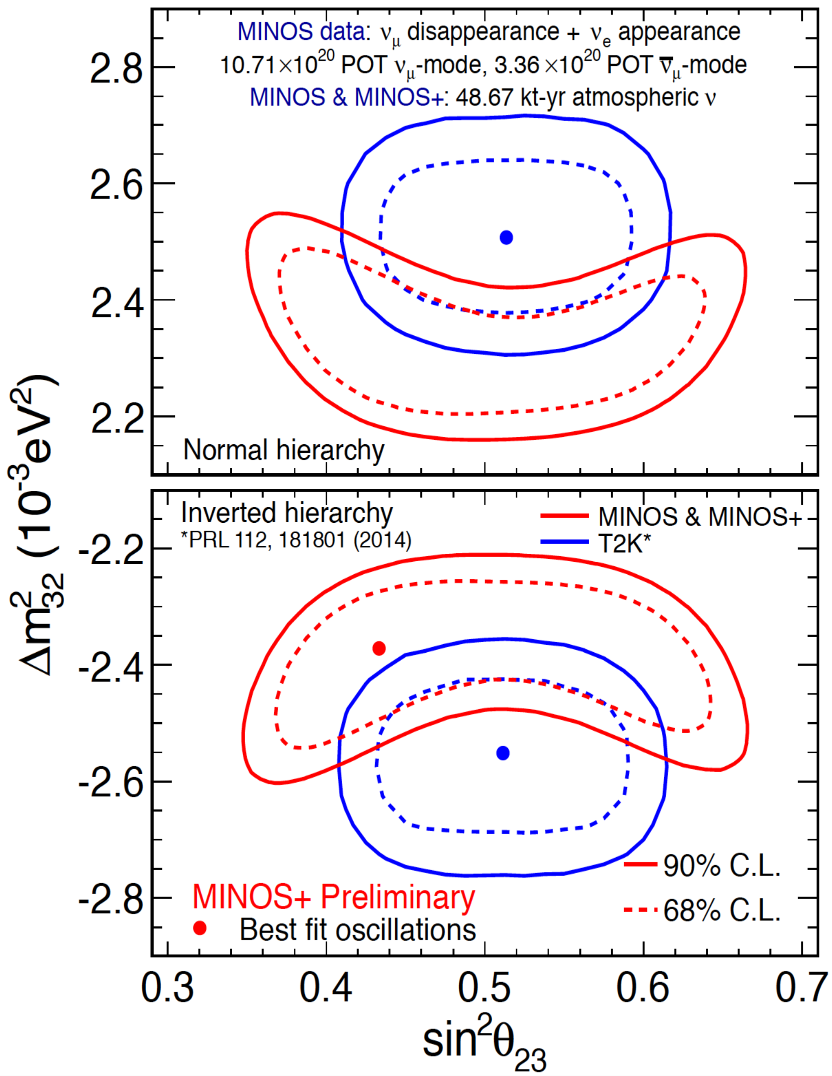


3. MINOS+ operations: POT history



- Both detectors continue to collect data with > 98% up-time
- Far Detector has collected > 50 kt-yr atmospheric neutrino data
- We project that we will accumulate about (9.5 – 11.1) x 10^{20} POT by end of FY16
  - ✓ Unfortunately this is much less than the originally requested 18 x 10^{20} POT

P. Adamson et al. [MINOS Collaboration]
Phys. Rev. Lett. 112 (2014) 191801



MINOS all data
&
MINOS+ addition:
10.79 kt*yrs of atmospheric data

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$$
$$0.36 < \sin^2\theta_{23} < 0.65 \text{ (90\% C.L.)}$$

Normal Hierarchy

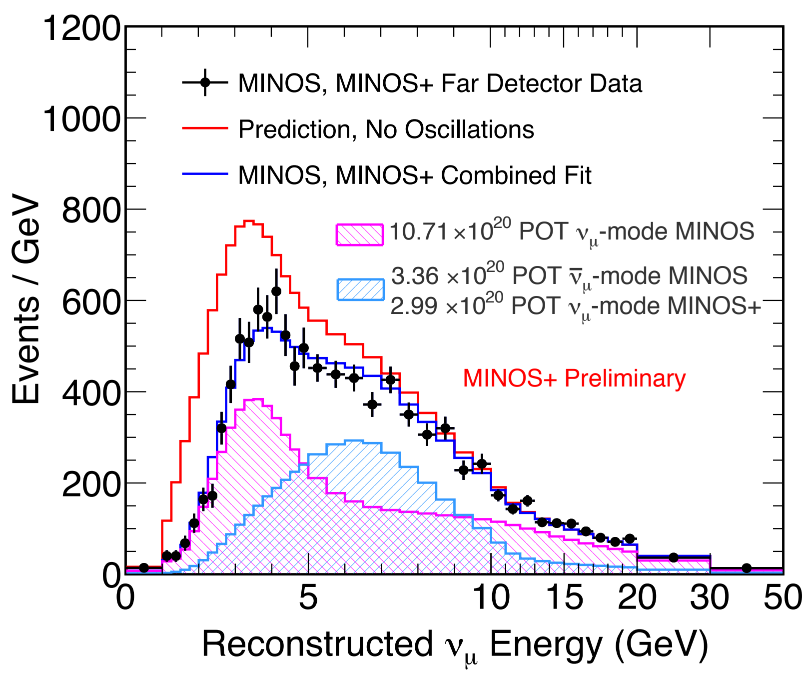
$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$
$$0.37 < \sin^2\theta_{23} < 0.64 \text{ (90\% C.L.)}$$

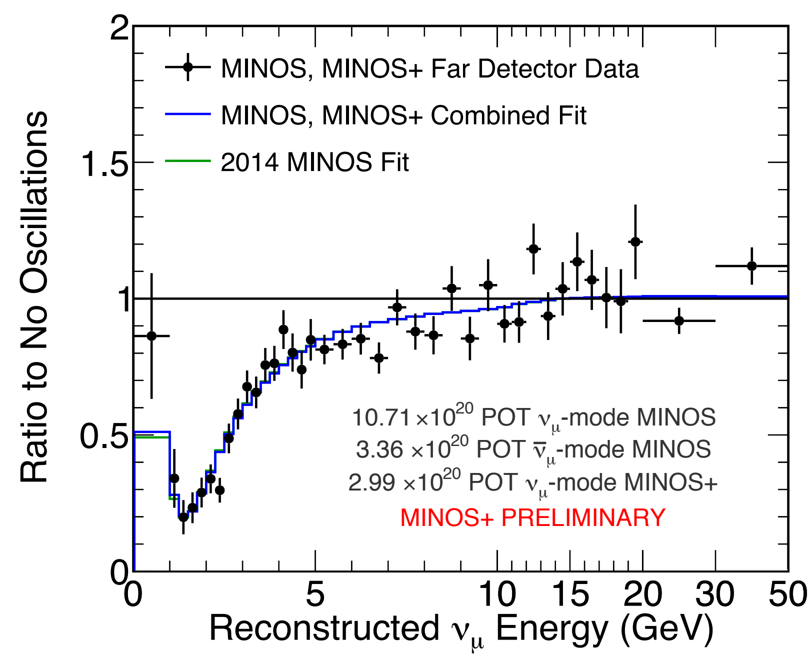
4. Analyses: standard oscillations: MINOS & MINOS+

- Combined spectrum of MINOS and MINOS+ disappearance data
- Can test the rising "edge" of the spectral ratio (survival probability)
- Will later perform a combined fit of both
- MINOS+ now is expecting the total ME exposure (9.5 – 11.1) x 10^{20} POT (out of 18 proposed), ~3x more than below

  "baseline" "design"

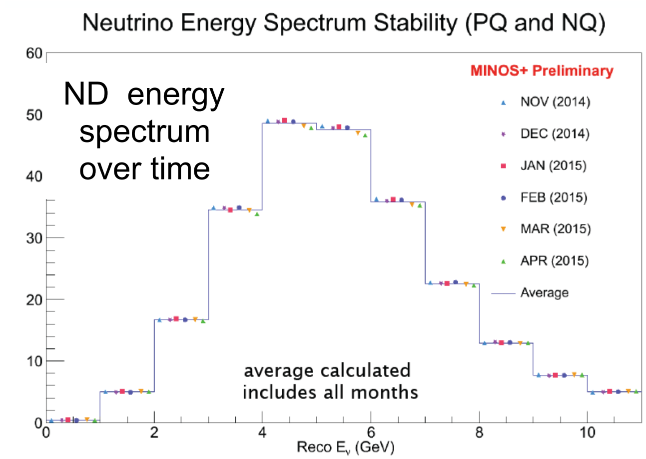
  (assuming 3.8 and 5.4, respectively, for FY16)

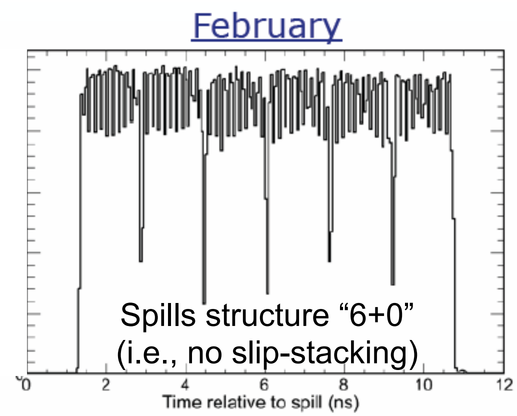


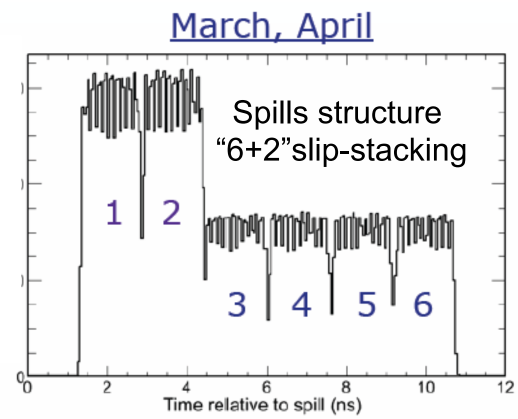


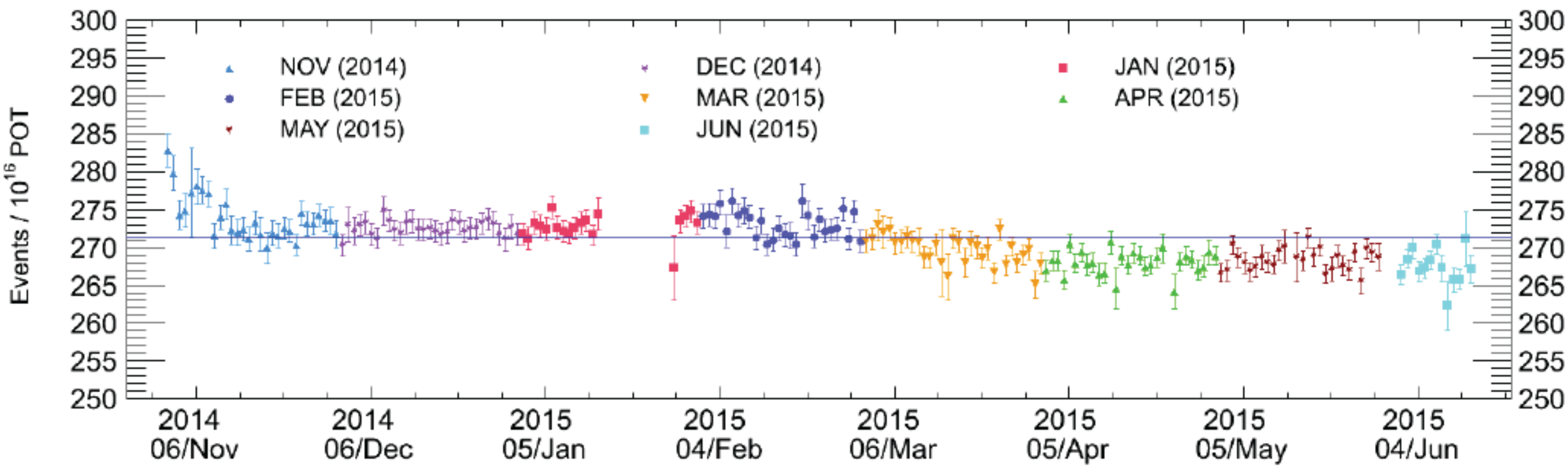
4. Analyses: a slip-stacking issue …

- While monitoring the beam (early 2015) …
- Intense effort since June (needed MC with several occupancy levels)



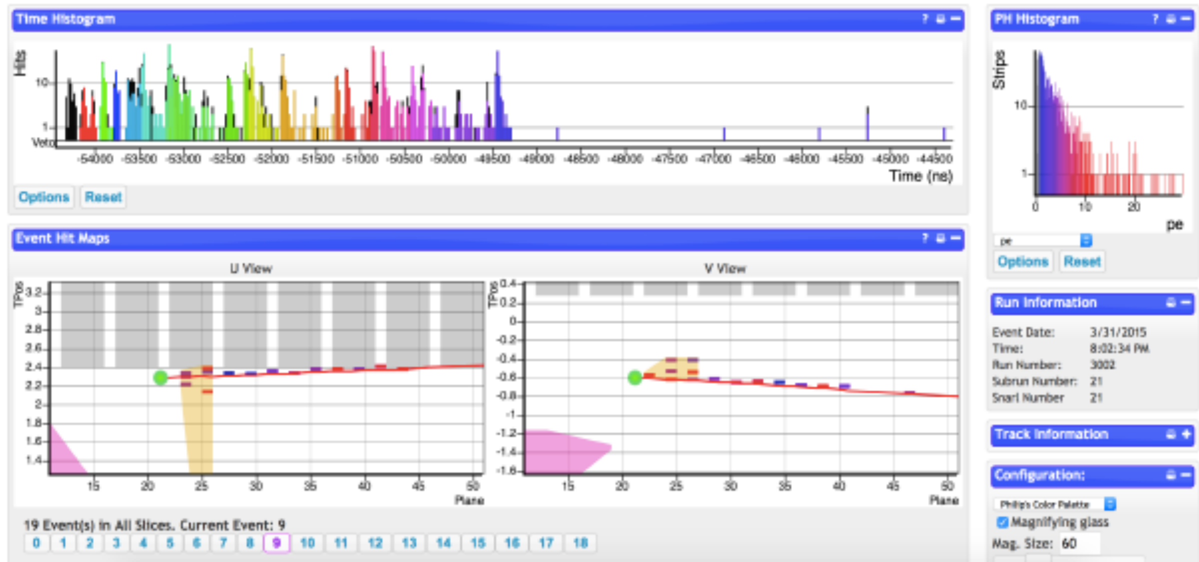


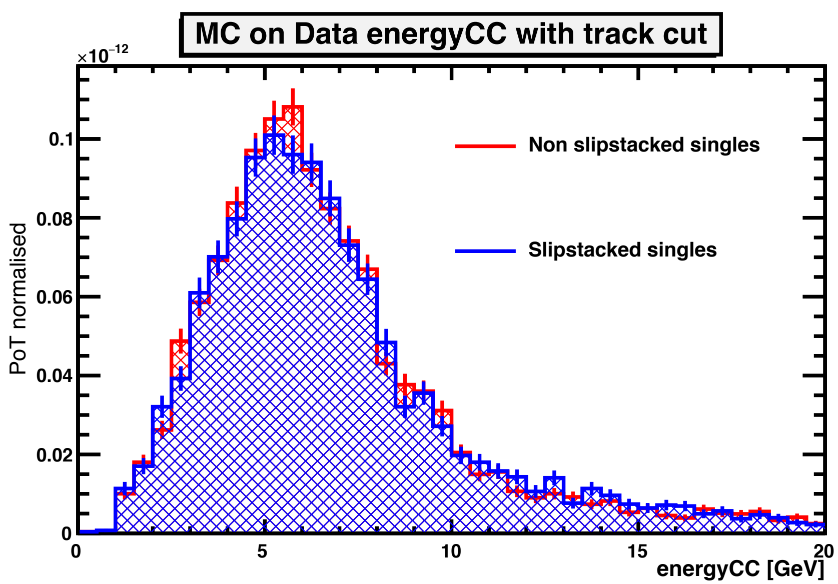


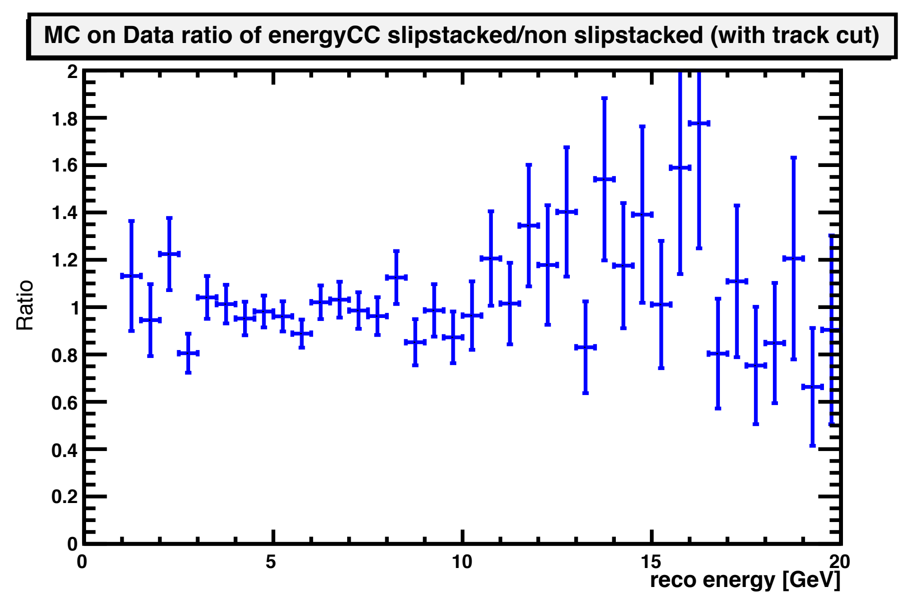


4. Analyses: MC on data overlay and reconstruction

- New tool: overlay MC singles on real data
- Look for the MC event and reconstruct it
- PID not finalized yet due to technical reasons



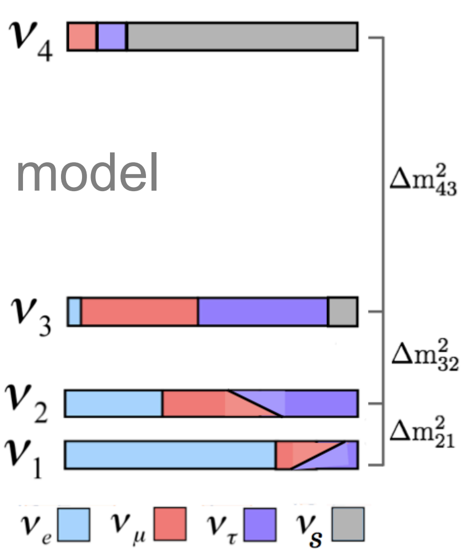


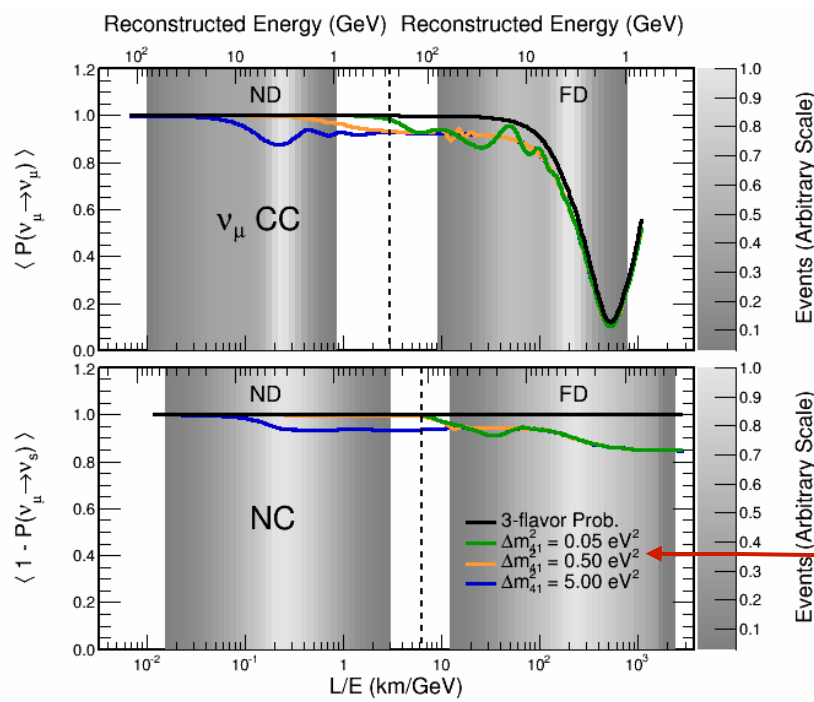


4. Analyses: search for sterile neutrinos

- Main signatures of sterile neutrino oscillations:
  - ✓ ν_μCC spectrum: deviations from std. osc. due to extra mass splitting (Δm^2_{43})
  - ✓ NC spectrum: deficit due to $\nu_\mu \rightarrow \nu_s$ disappearance.
- The two detector configuration of MINOS+ enables a search for new sterile oscillation modes at a wide range of Δm^2 values
- Can occur in both the Near and the Far Detector
- Future: The higher energy spectrum of MINOS+ enhances the sensitivity to spectral distortions beyond the standard oscillation framework

"3+1" model



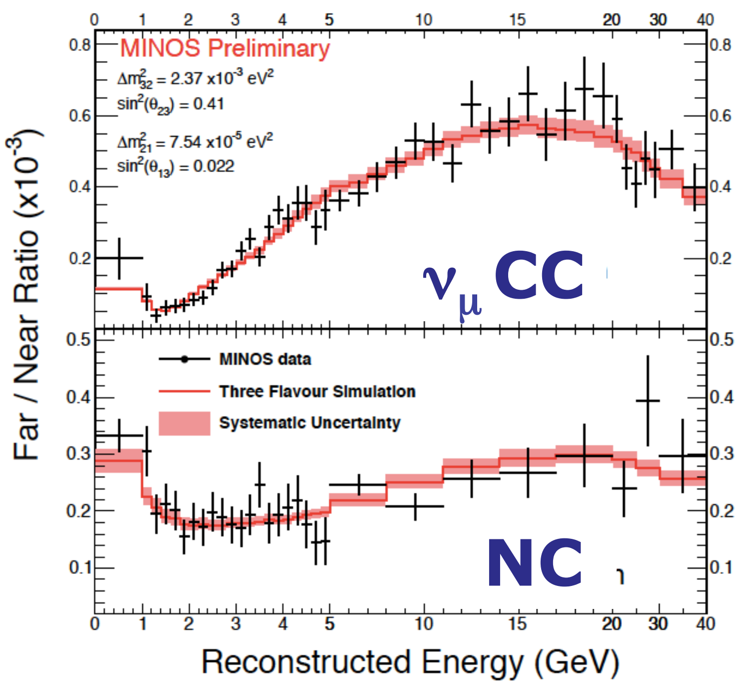


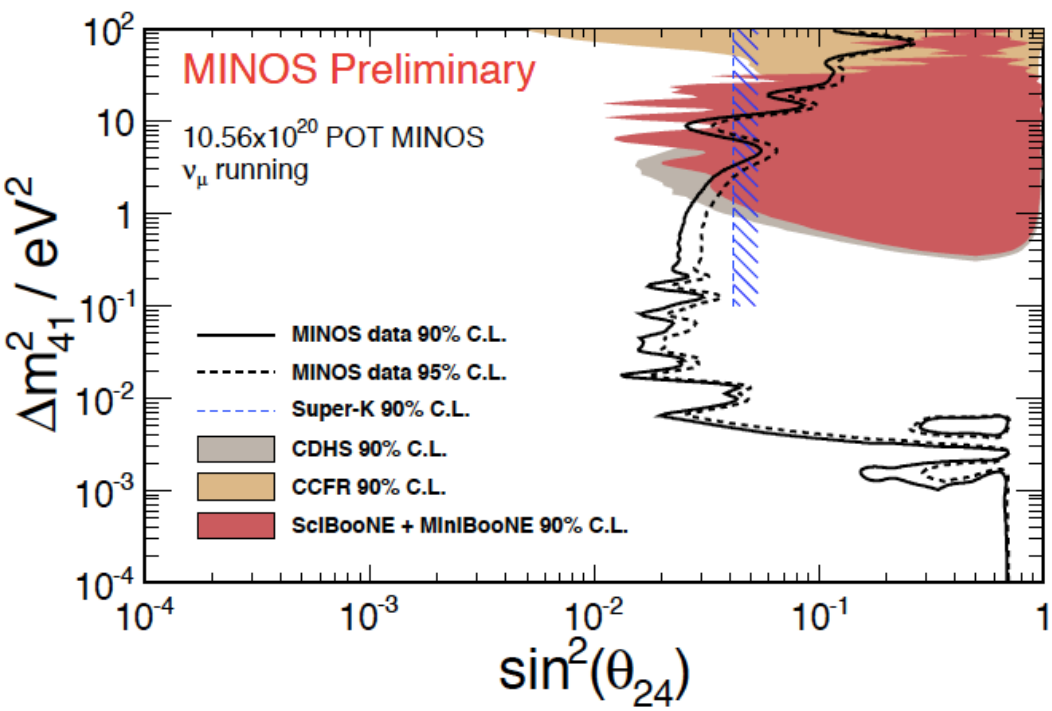
High Δm^2_{43}: oscillations in ND

Low Δm^2_{43}: oscillations in FD

4. Analyses: search for sterile neutrinos

- Possible distortions in the Near Detector required a change of paradigm of MINOS analyses
- We now look for deviation from standard oscillations in the ratio of Far/Near energy spectra
  - ✓ Simultaneous fit to ν_μCC and NC data
- CC and NC samples provide sensitivity to different components of the sterile mixing
- Best constraints to-date on $\nu_\mu \rightarrow \nu_s$ disappearance for sterile neutrino mass splitting below 1eV^2





- Use best fit to NC & ν_μCC MINOS disapp.

- Combine it with the ν_e disappearance by the Bugey reactor disappearance data
  - ✓ MINOS: 90% C.L. on θ_{24}
  - ✓ Bugey: 90% C.L. on θ_{14}*
  - ✓ Construct combined limit on

    $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

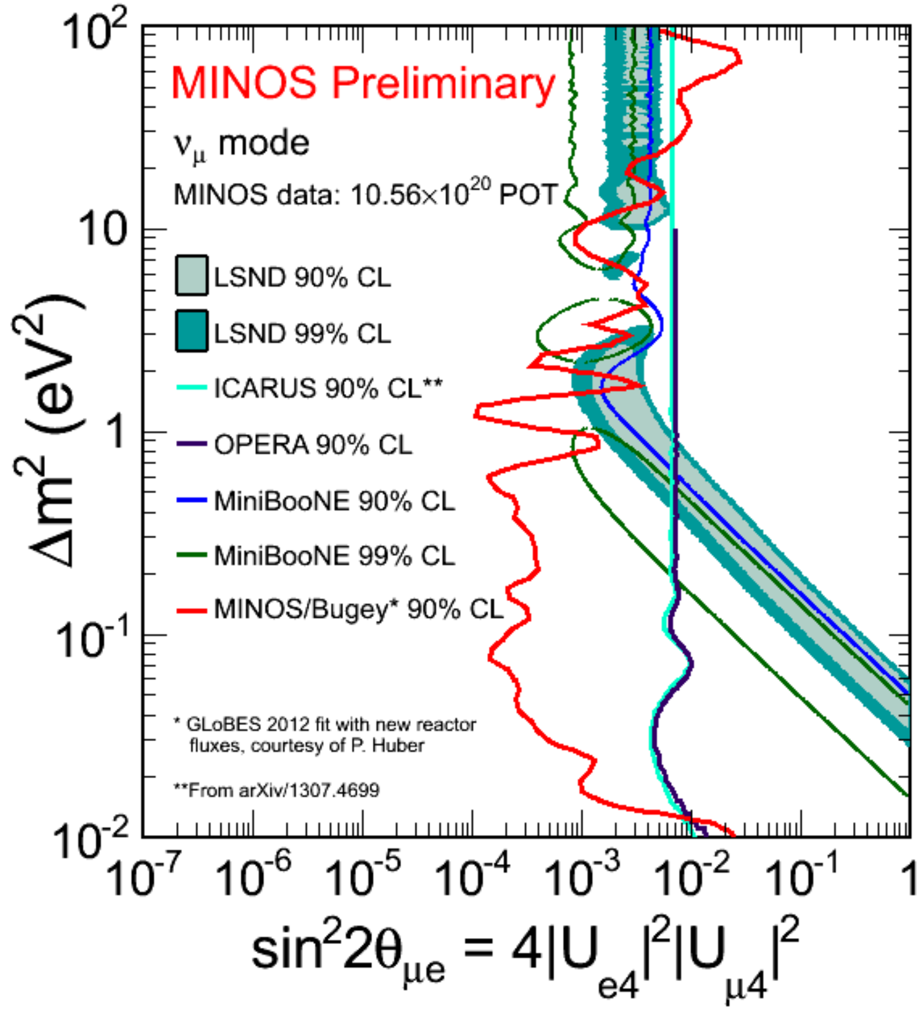
    suggested by Bilenky, Giunti, Grimus [96]
    Okada, Yasuda [96]

- Combined limits can be compared to LSND, MiniBooNE, ICARUS, and OPERA

- Collaborating with Daya Bay to perform a joint fit to be undersigned by both collaborations
  - ⇨ Improved constraints (1-10) eV^2 region
  - ⇨ aim to release simultaneously 3 papers

    1) Daya Bay limits, 2) MINOS limits, 3) combined

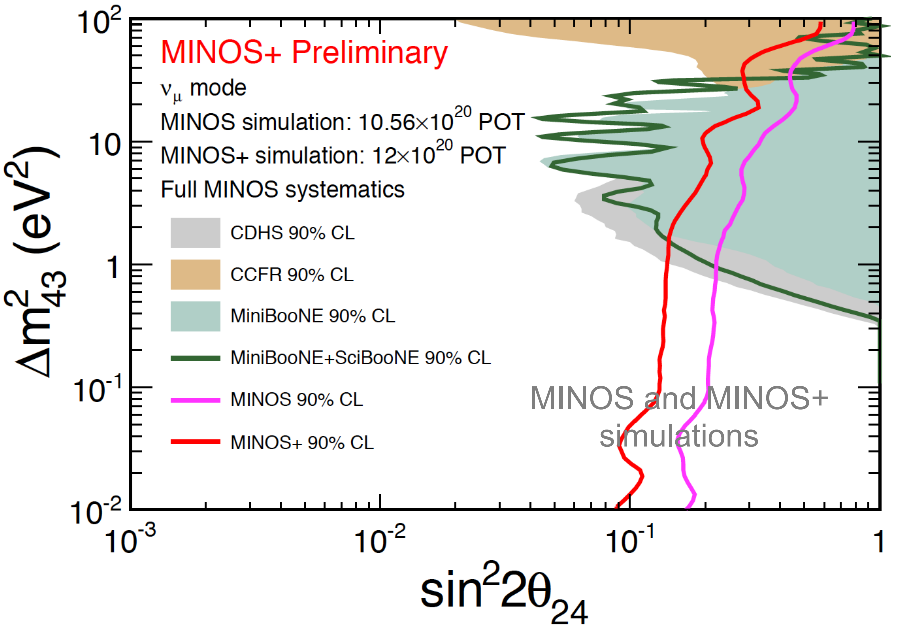
Neutrino 2014: arXiv/1502.07715



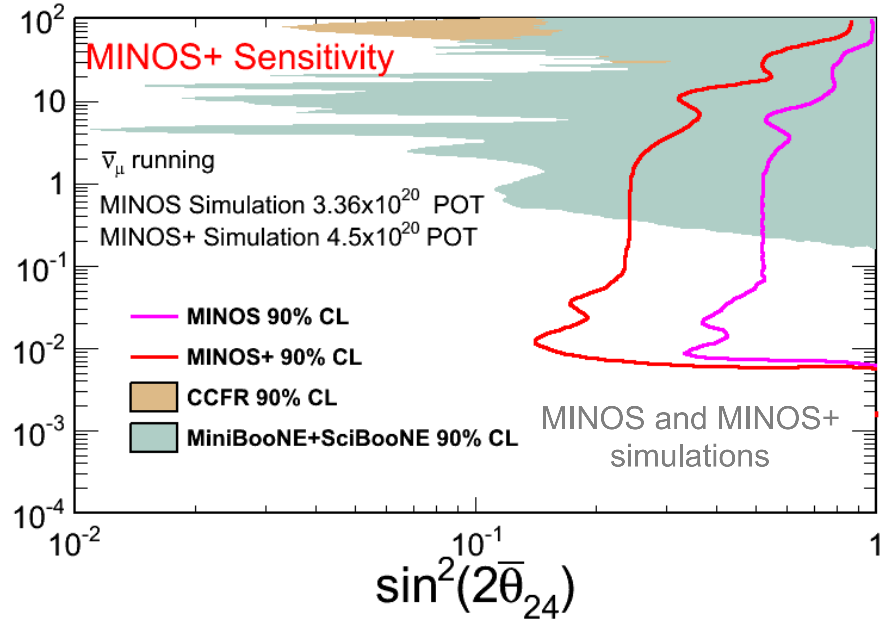
* Bugey limits computed by P. Huber using GLoBES 2012 and new reactor fluxes.

4. Analyses: future prospects for sterile neutrinos

Neutrino mode (Monte Carlo)



Antineutrino mode (Monte Carlo)



- Full MINOS+ data set will significantly improve sensitivity in ν_μ disappearance channel (Note: At the current exposure, the data provides better constraints than predicted from the sensitivity.)
- Currently analysing antineutrino data collected by MINOS
- 1 year of MINOS+ antineutrino running would significantly extend the reach of this analysis.
- Also evaluating MINOS+ sensitivity in $\nu_\mu \rightarrow \nu_e$ appearance channel

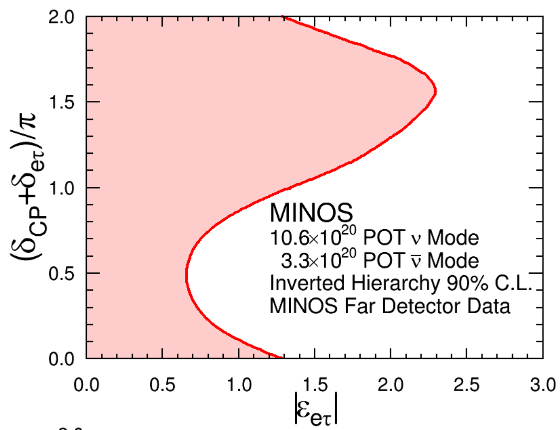
4. Analyses: searches for "exotics": non-standard interactions

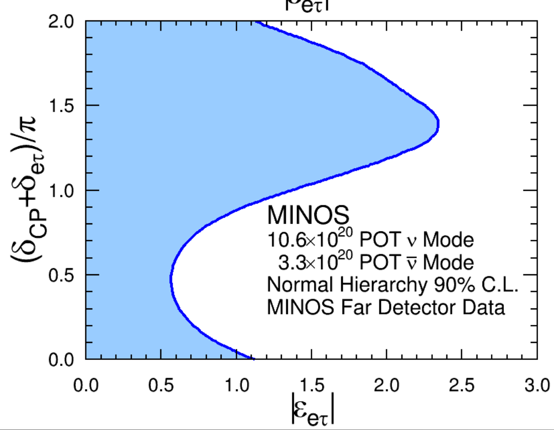
- The long baseline makes MINOS+ sensitive to non-standard interactions (NSI) with matter
- NSI can be parameterized using ϵ parameters that incorporate the coupling strength of the new interaction and the mixing of the eigenstates for the NSI

$$H_{NSI} = \sqrt{2} G_F N_e \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

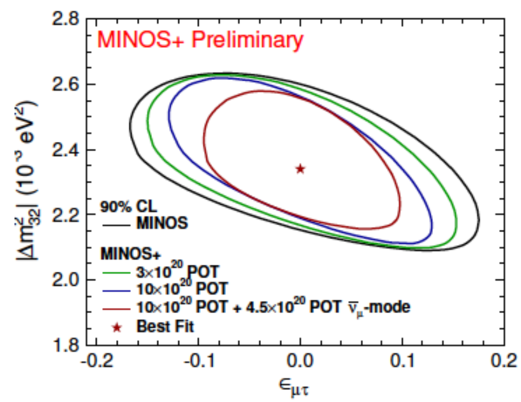
NSI / Matter Effect

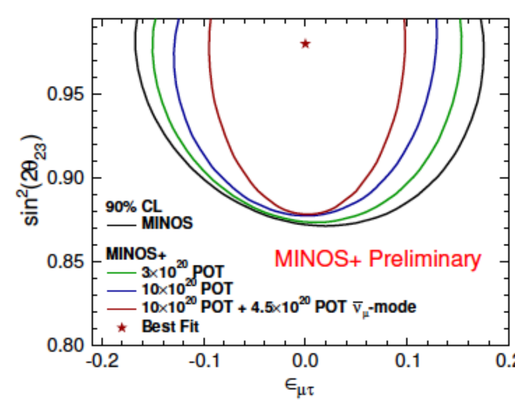
$\nu_\mu \rightarrow \nu_e$ appearance

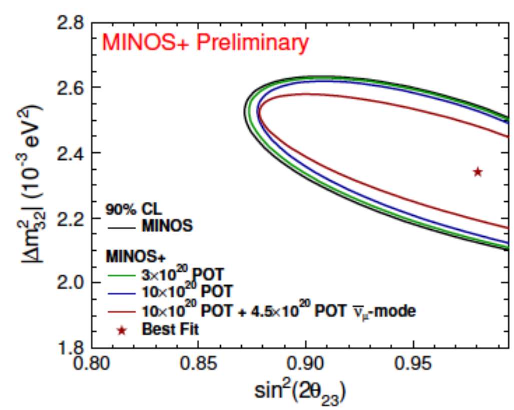




ν_μ disappearance







MINOS data vs MINOS+ MC

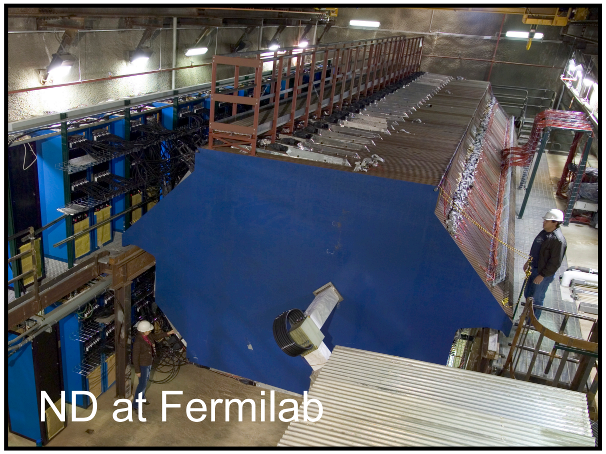
5. Conclusions and Plans

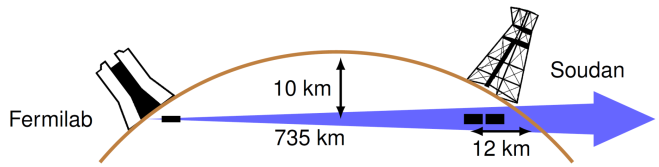
- MINOS+ collaboration effort focuses on
  - Experiment's operations
  - Completing MINOS analyses, transitioning to MINOS+ data analysis
- Short term (Neutrino 2016, ICHEP 2016)
  - Standard oscillations MINOS/MINOS+ fit [Runs XI and XII (i.e., run XIII will be analyzed later)]
  - MINOS, MINOS + Daya Bay sterile search
  - Constraints on NSI via ν_e appearance and ν_μ disappearance
  - Search for large extra dimensions
- Early switch to antineutrinos – disfavored by the MINOS+ Collaboration
  - Would further cut neutrino exposure
  - Antineutrino data - although unique - it would be challenging to have it analyzed in a timely fashion
- Long term (finishing up MINOS and MINOS+)
  - Perform all analyses, as envisaged in the proposal, albeit with exposure smaller by a factor of ~2
    - ✓ performed three-flavor analysis and combined beam, atmospheric, and an ν_e appearance channel
    - ✓ conducting "standard oscillations" analysis with MINOS & MINOS+
    - ✓ conducting searches for sterile neutrinos with MINOS & MINOS+
    - ✓ continue NSI and "exotics" analysis with MINOS & MINOS+
  - It will likely take us about two years to finalize results and publications
- We acknowledge the support for this work by DOE, NSF, STFC, DNR, and all resources provided by our universities

MINOS+ Collaboration

EXTRA INFO

3. MINOS+ operations: overview





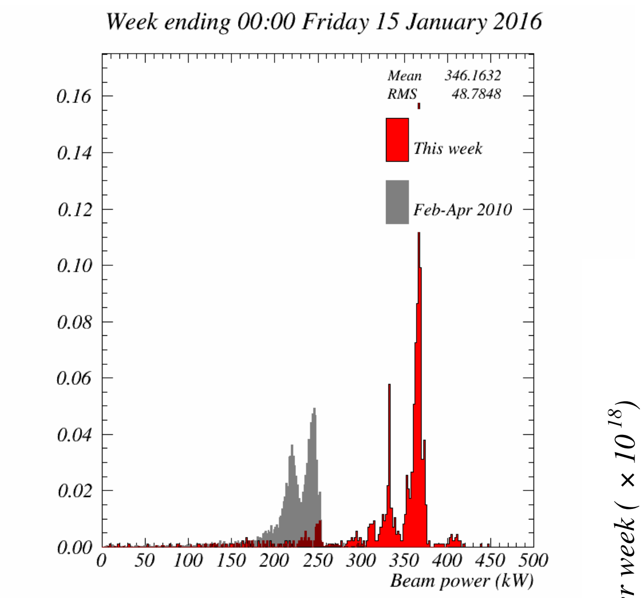
- The collaboration operates two detectors and helps in monitoring the NuMI beam line
  - ✓ ***a dedicated*** crew at the Far Detector (in the Soudan Underground Laboratory)
  - ✓ ***a dedicated*** Fermilab crew at the Near Detector at Fermilab (with expertise for the two detectors)
  - ✓ collaboration members: shifts at FNAL and many remote sites, monitoring data online and offline; (shifts on ND are shared with MINERvA)

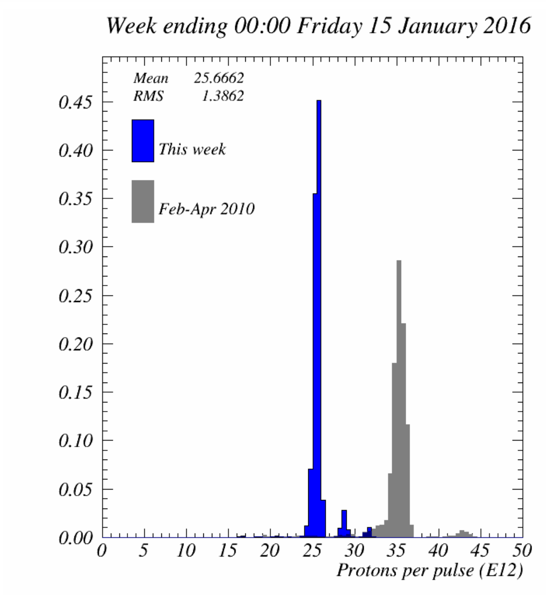
- Offline batch processing is now substantially supported by Fermilab's SCD (the "interns program")

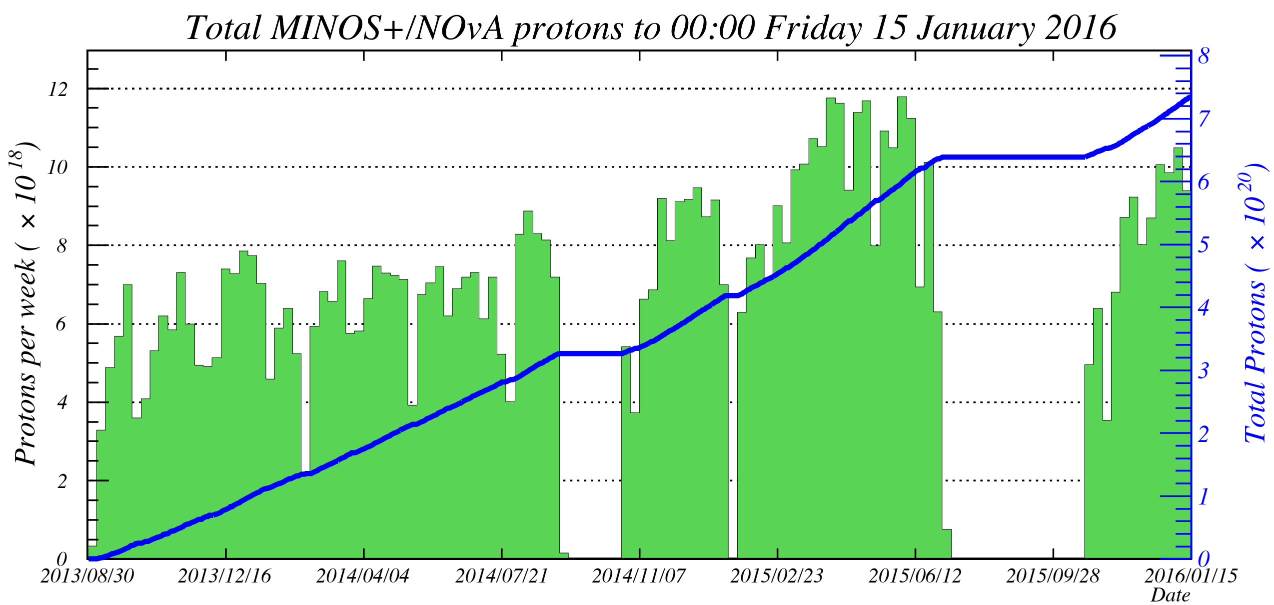
- Calibration of ND partially shared with MINERvA

- The collaboration continues exploiting data collected by MINOS and now also by MINOS+
  - ✓ MINOS (last spill on April 30, 2012) provided physics-rich data set and inspires new analyses
  - ✓ MINOS+ is doing the same!

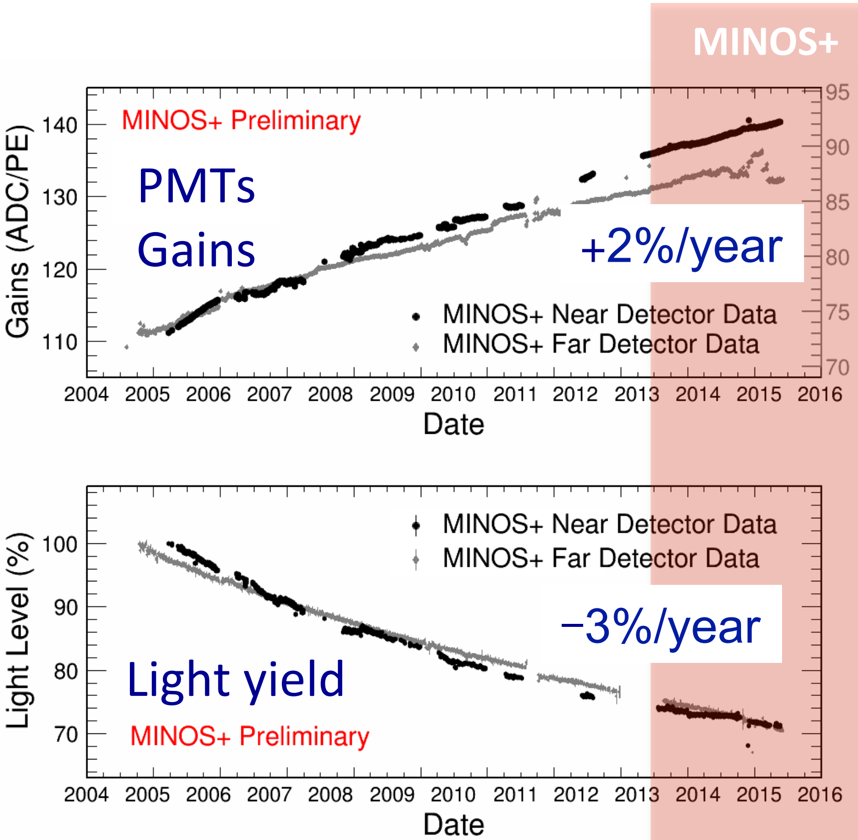
3. MINOS+ operations: POT history

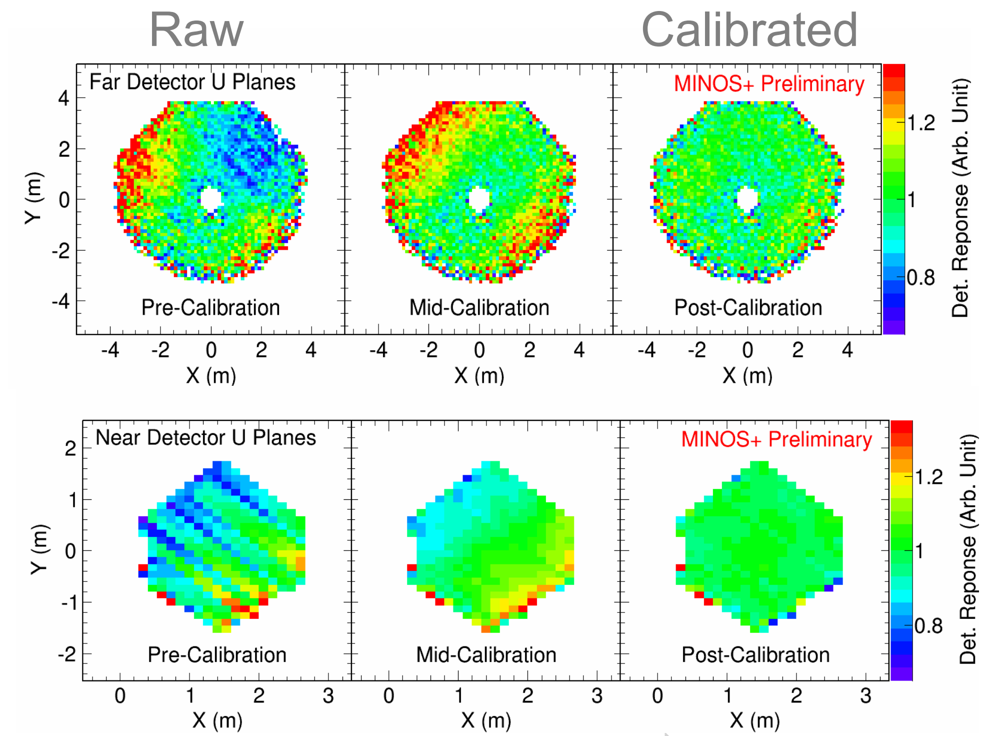


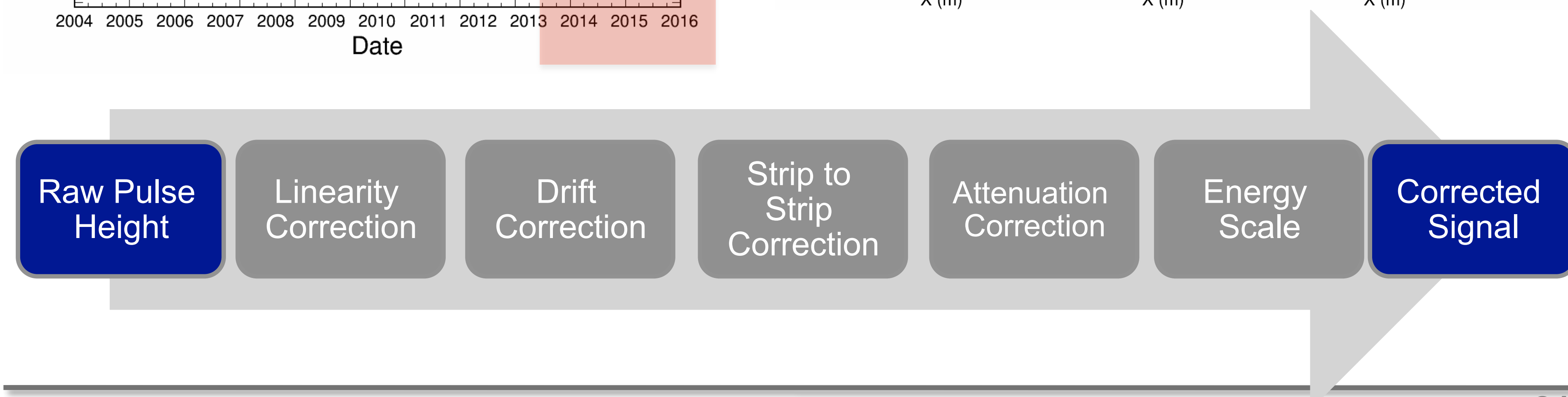




3. MINOS+ operations - calibrations



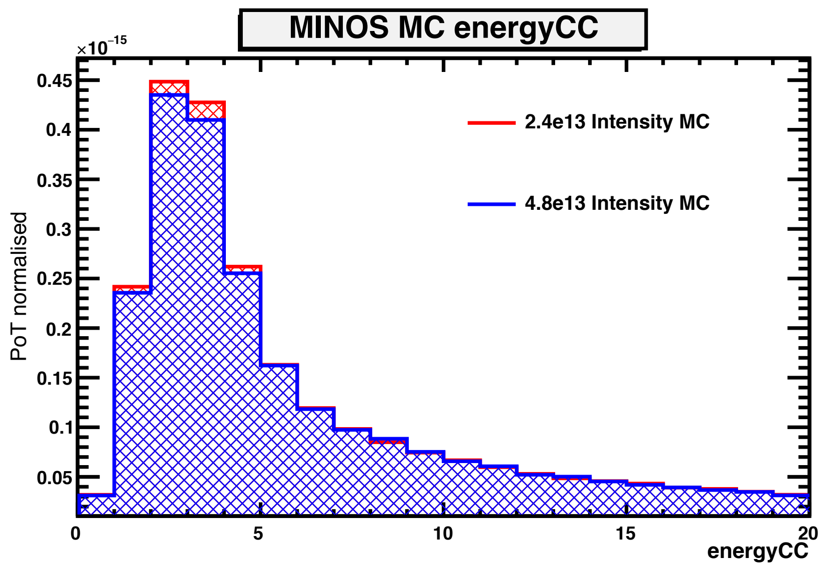




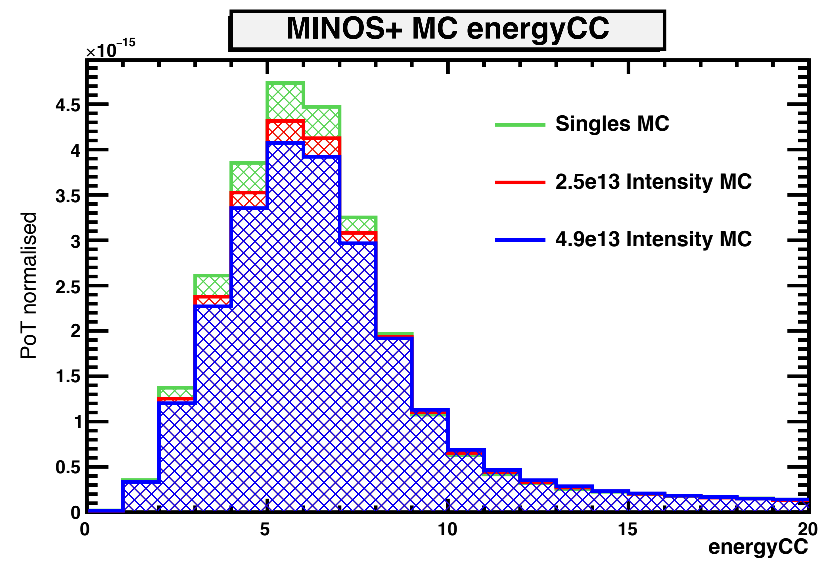
4. Analyses: Low versus high occupancy

- MC singles overlays simulates intensity effects
- In analyses must assure correct occupancies

MINOS MC

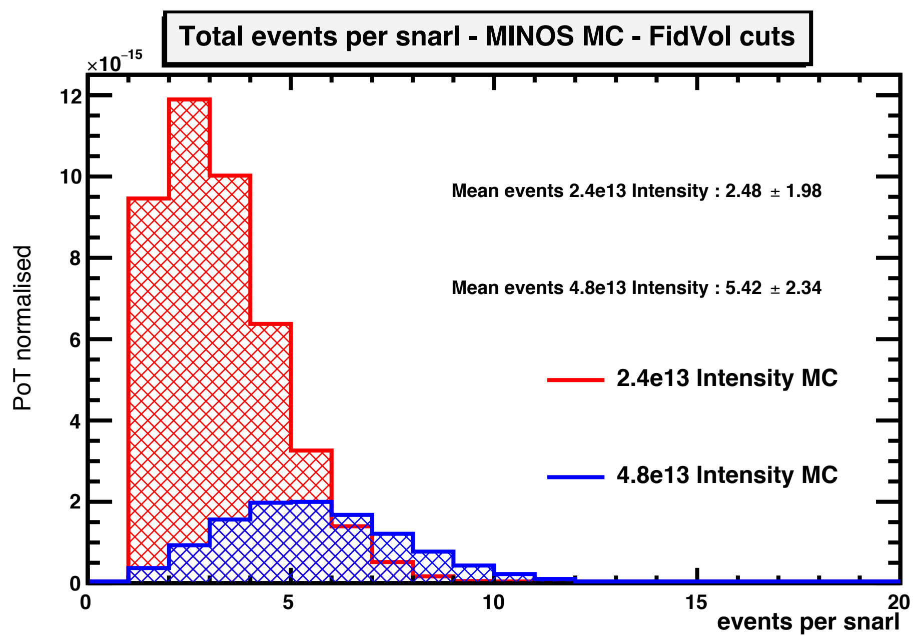


MINOS+ MC

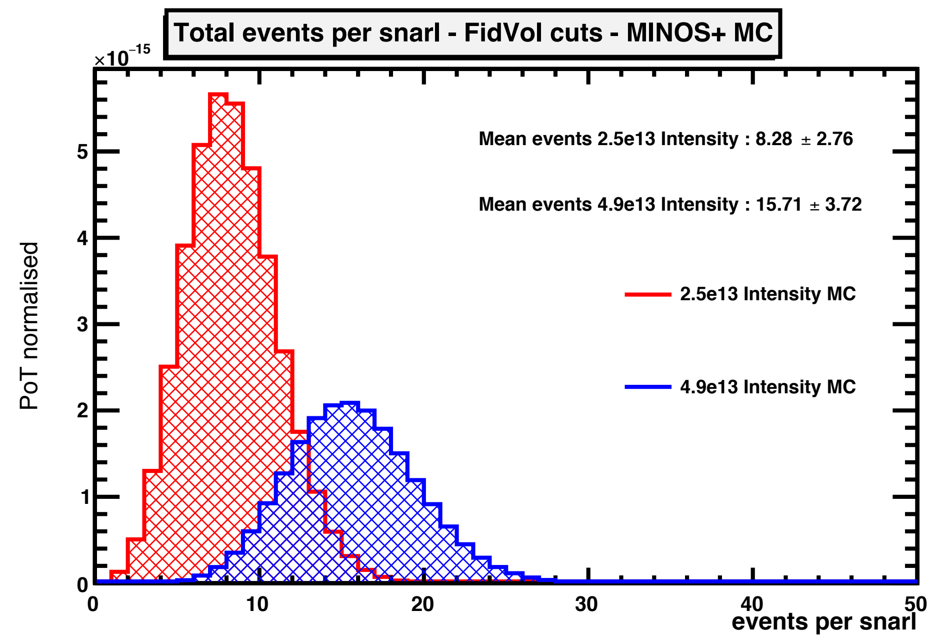


4. Analyses: Slip-stacked versus non-slip-stacked
occupancy (not just intensity) differences

MINOS

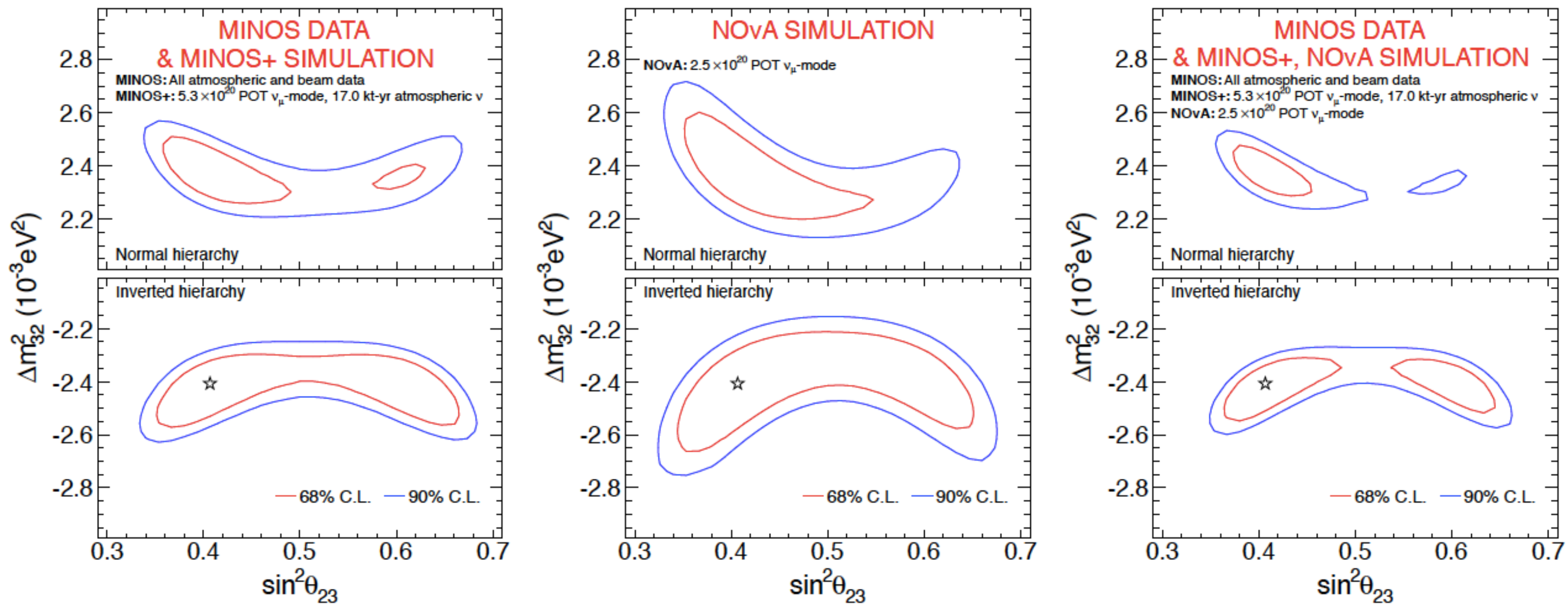


MINOS+

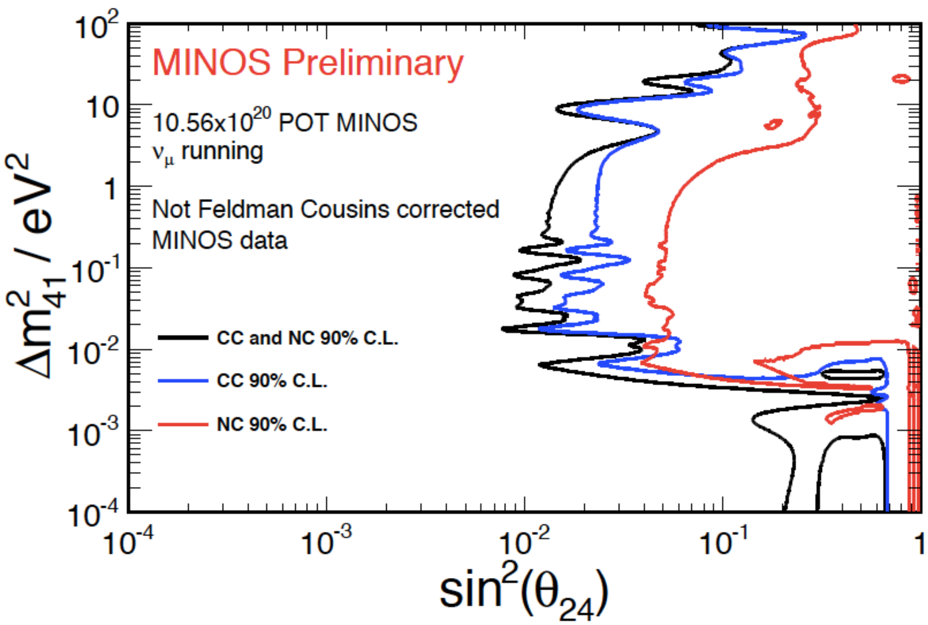


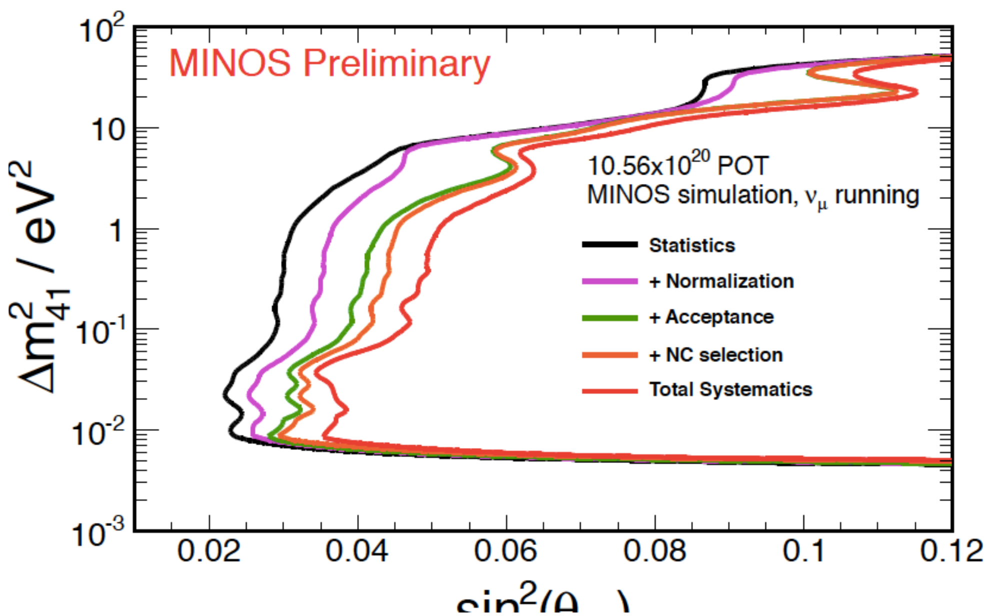
4. Analyses: MINOS/MINOS+ & NOvA

Neutrino 2014: arXiv/1502.07715



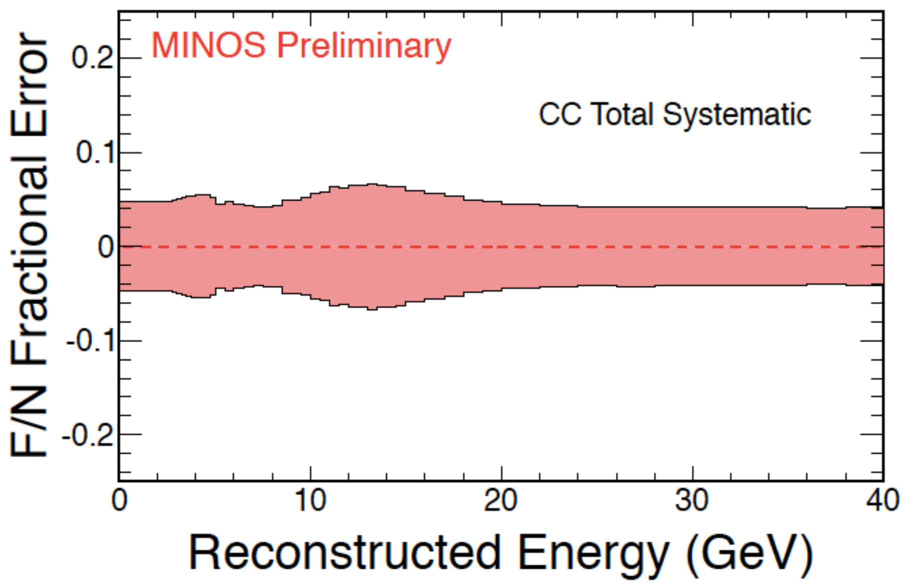
- CC and NC contributions
- Systematic uncertainties

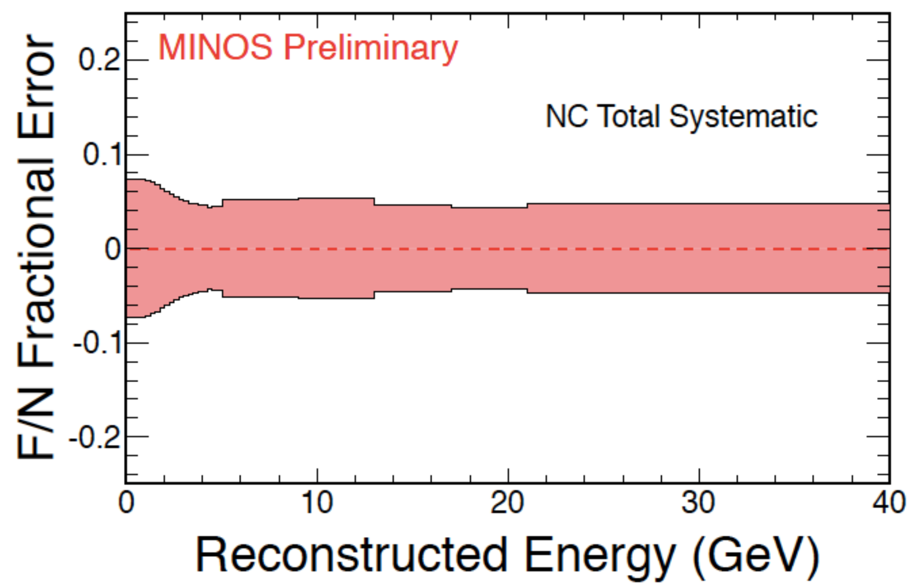




4. Analyses: search for sterile neutrinos

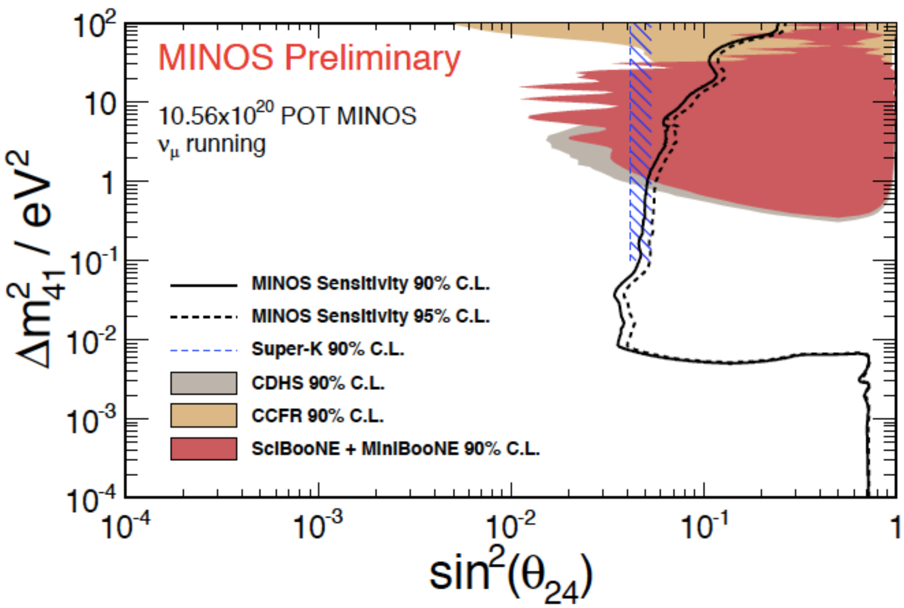
- CC and NC contributions
- Systematic uncertainties

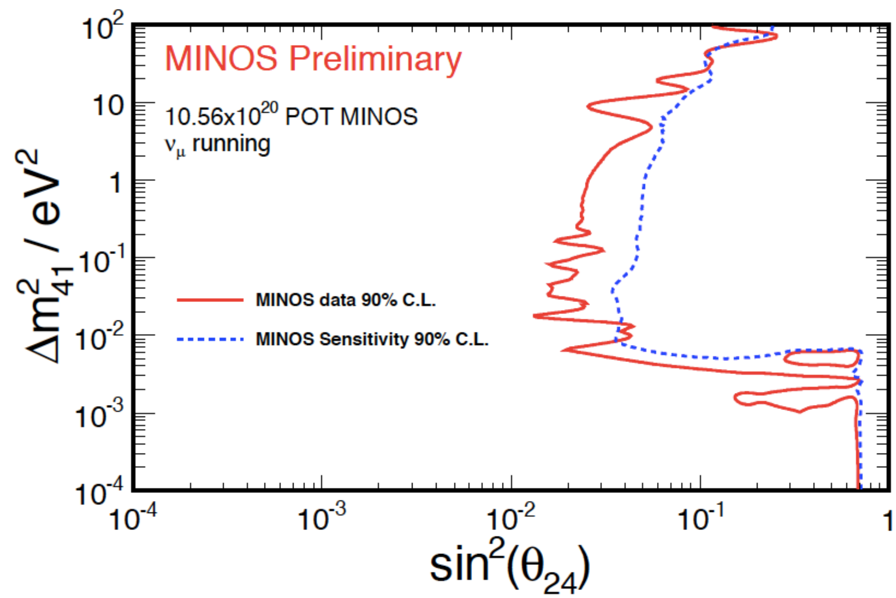




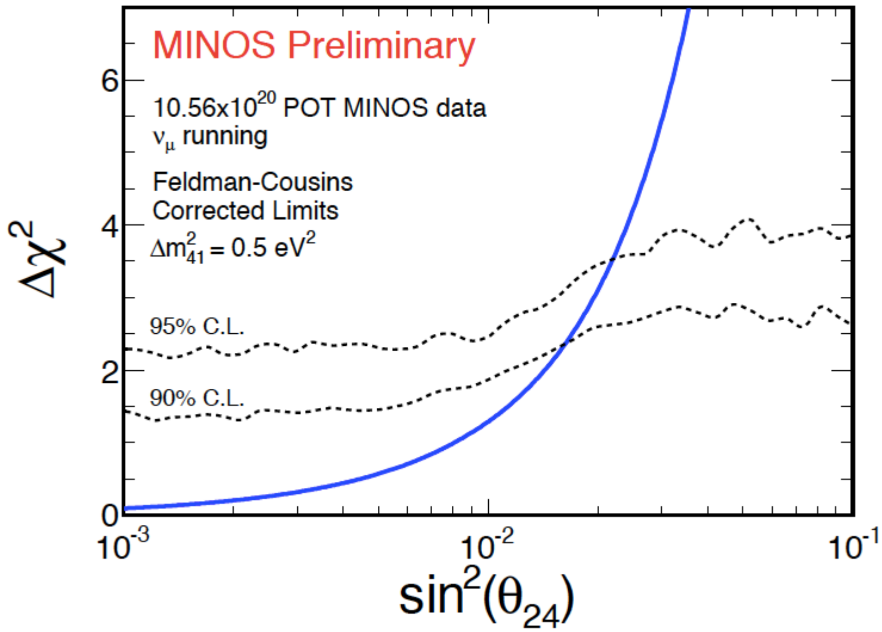
4. Analyses: search for sterile neutrinos

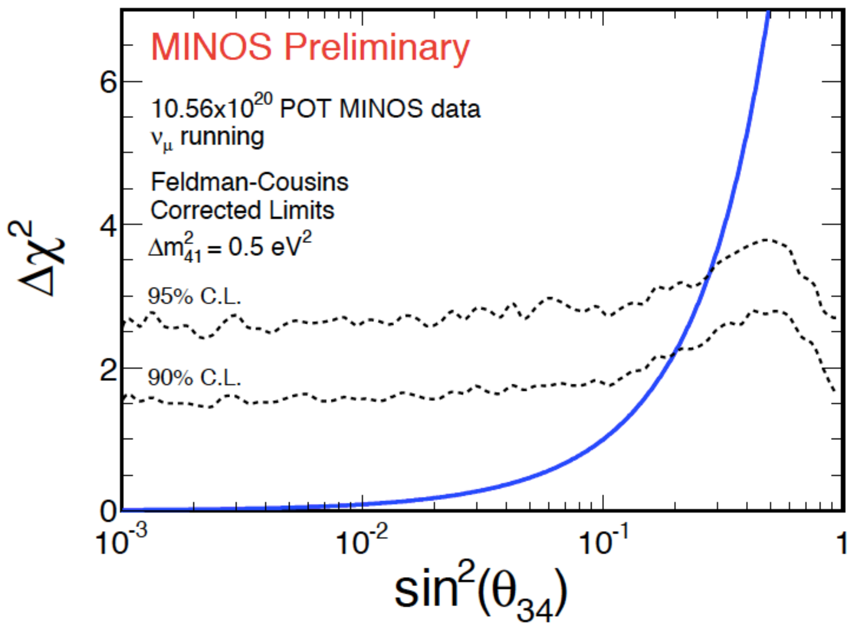
◆ Sensitivity versus data





◆ Sterile mixings constraints





The $\Delta\chi^2$ distribution for

θ_{24} for $\Delta m_{41}^2 = 0.5 eV^2$

$\sin^2(\theta_{24}) < 0.016$ at 90% $C.L.$

$\sin^2(\theta_{24}) < 0.022$ at 95% $C.L.$

The $\Delta\chi^2$ distribution for

θ_{34} for $\Delta m_{41}^2 = 0.5 eV^2$

$\sin^2(\theta_{34}) < 0.20$ at 90% $C.L.$

$\sin^2(\theta_{34}) < 0.28$ at 95% $C.L.$

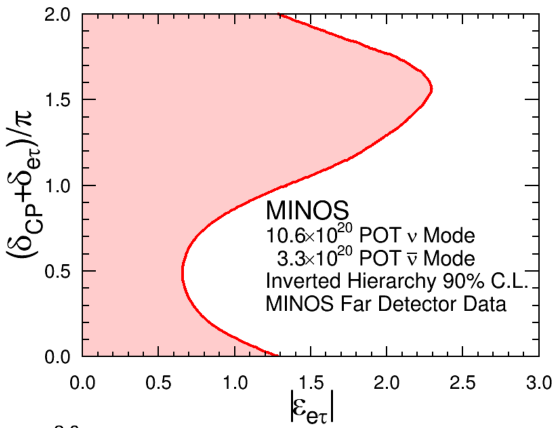
4. Analyses: searches for "exotics": non-standard interactions

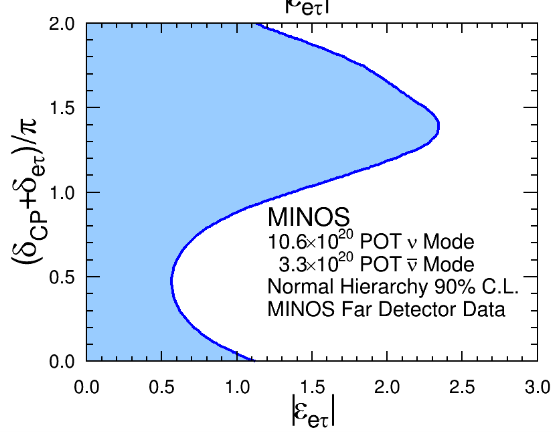
- The long baseline makes MINOS+ sensitive to non-standard interactions (NSI) with matter
- NSI can be parameterized using ϵ parameters that incorporate the coupling strength of the new interaction and the mixing of the eigenstates for the NSI

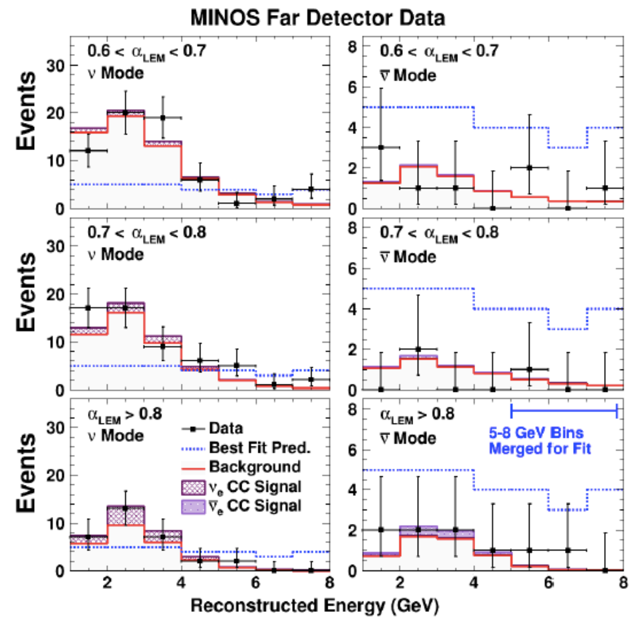
NSI / Matter Effect

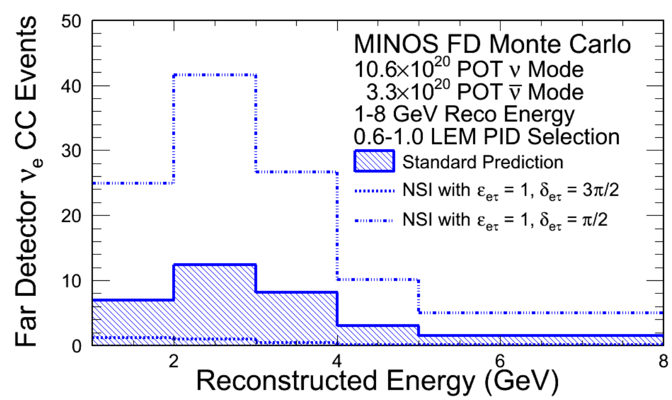
$$H_{NSI} = \sqrt{2}G_F N_e \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

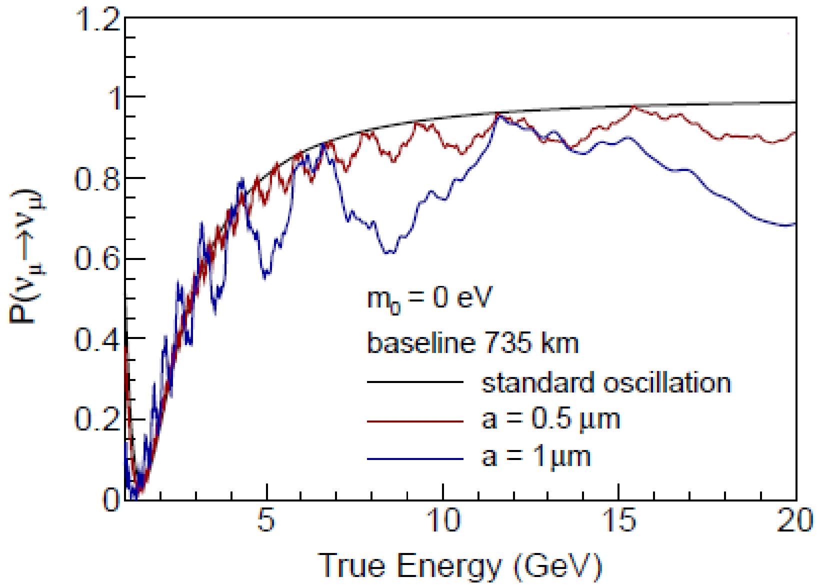
$\nu_\mu \rightarrow \nu_e$ appearance











- If LED exist, then the disappearance rate will have extra wiggles from oscillation to the KK-modes
- Inclusion of MINOS+ data increases sensitivity to high energy wiggles and hence sensitivity to LED
- Paper will be submitted this year with MINOS results