MINOS+ update

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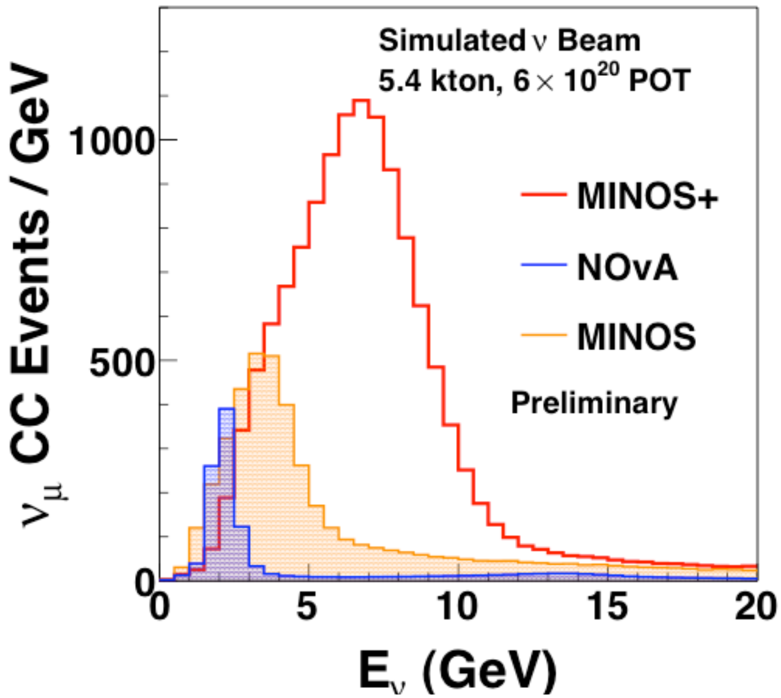
ON BEHALF OF THE MINOS+ COLLABORATION

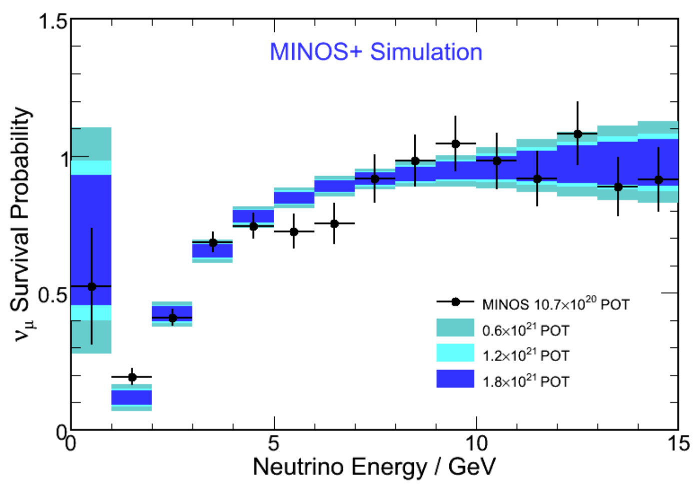
FERMILAB PAC MEETING
GLEACHER CENTER, CHICAGO, JUNE 23, 2015

Topics

1. MINOS+ Goals (reminder)
2. MINOS+ Collaboration
3. Operations
4. Analyses
   - Standard oscillations
   - Search for sterile neut.
   - Searches for “exotics”
   - Cosmic rays measurements
   - Evaluating a slip-stacking issue
5. Outlook

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





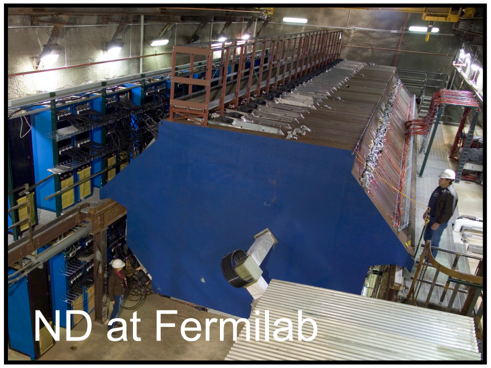
- MINOS+ (E-1016, proposed in 2012) for continued exploitation of the NuMI beam and MINOS detectors (MINOS (E-875), proposed in 1995)
  - ✓ improve measurements of "atmospheric" oscillations (by probing the multi-GeV energy region)
  - ✓ search for light sterile neutrinos
  - ✓ search for NSI and other "exotic" transitions (e.g., large extra dimensions)
  - ✓ 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

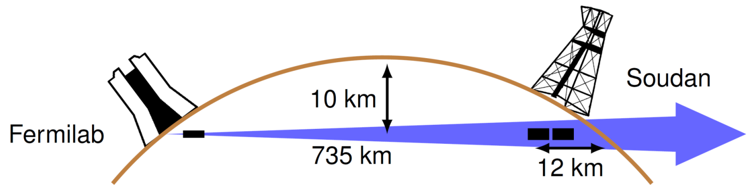
2. MINOS+ Collaboration

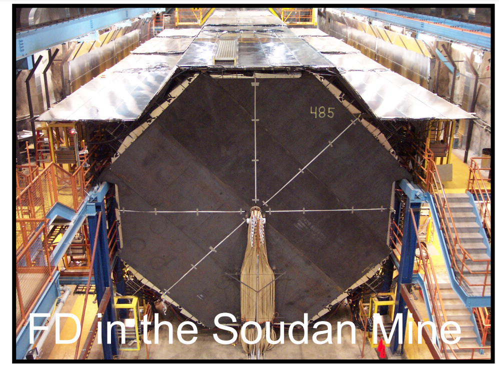
27 institutions, 72 members [26.2 FTE]

44 senior members	8 students
16 postdocs	4 technical @ Soudan

3. MINOS+ operations: overview

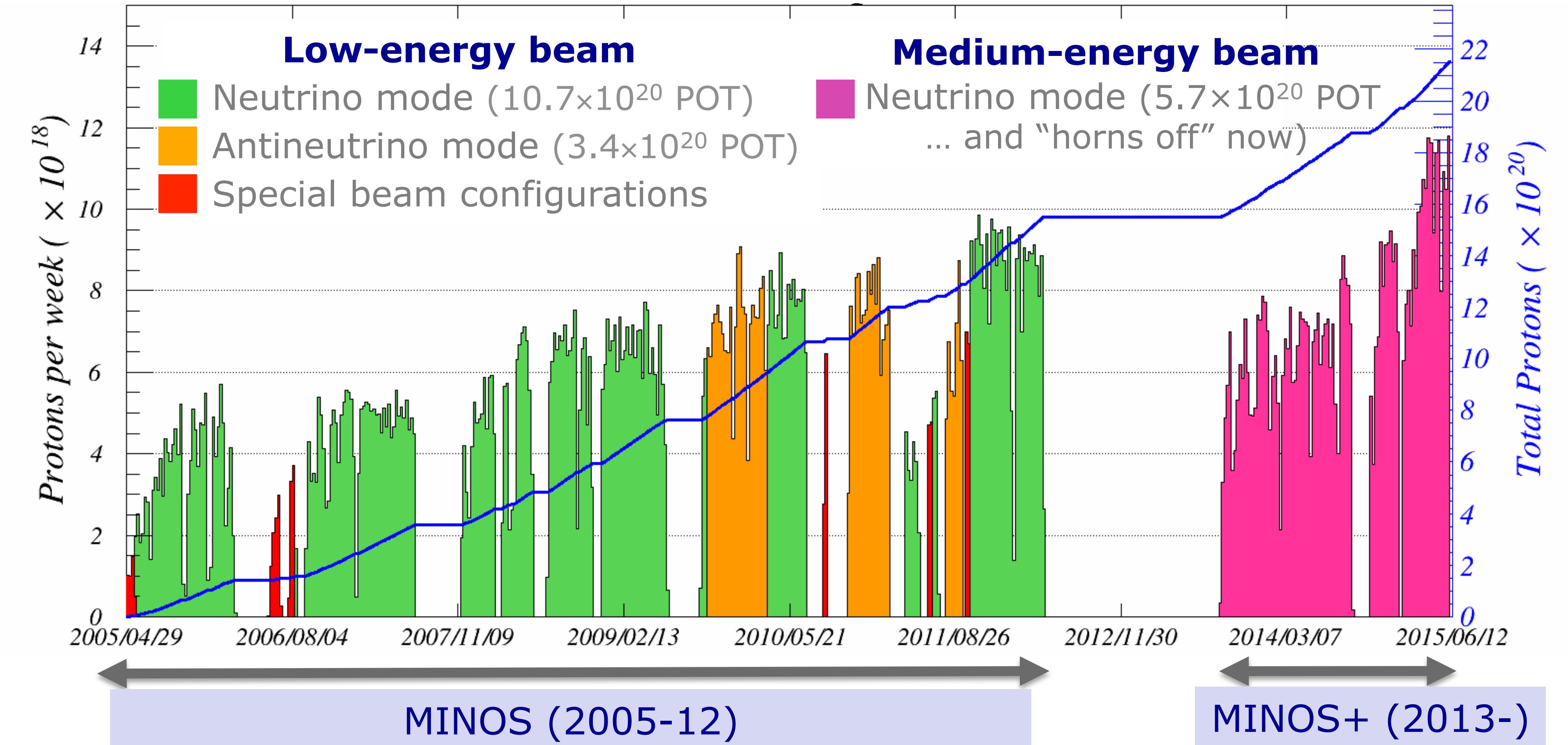






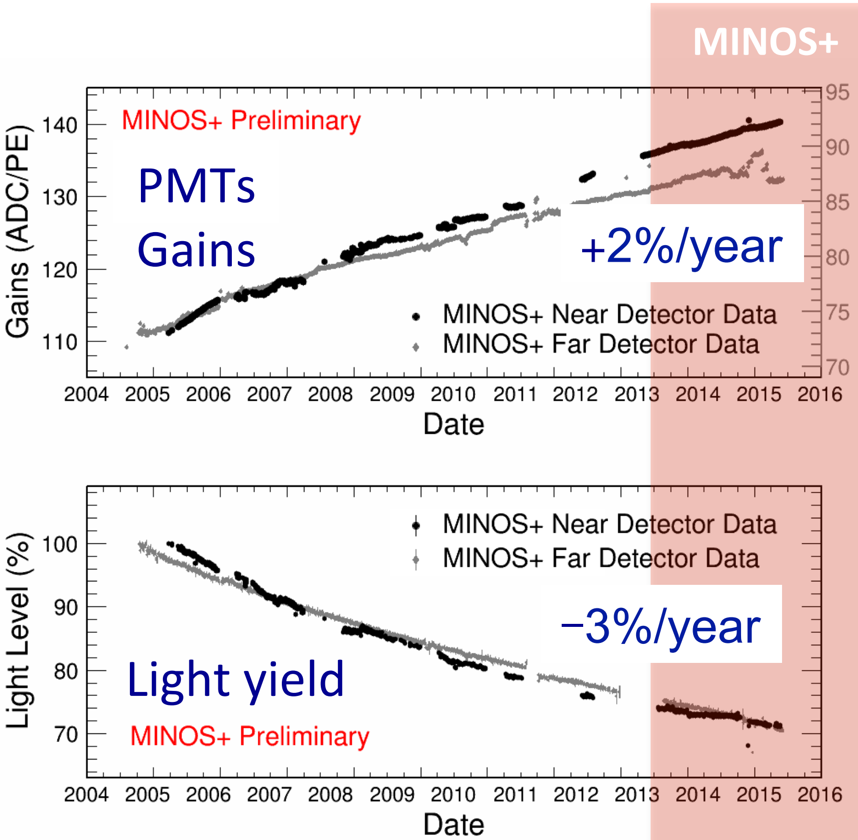
- The collaboration operates two detectors and helps in monitoring the NuMI beam line
  - ✓ a (small) crew at the Far Detector (in the Soudan Underground Laboratory)
  - ✓ a Fermilab crew at the Near Detector (ND) at Fermilab (with expertise for the two detectors)
  - ✓ collaboration members: shifts at FNAL and remote, 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 to be shared with MINERvA (still working it out…)
- 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!
  - ✓ conducted three-flavor analysis and combined beam, atmospheric neutrinos. and an electron neutrino 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+

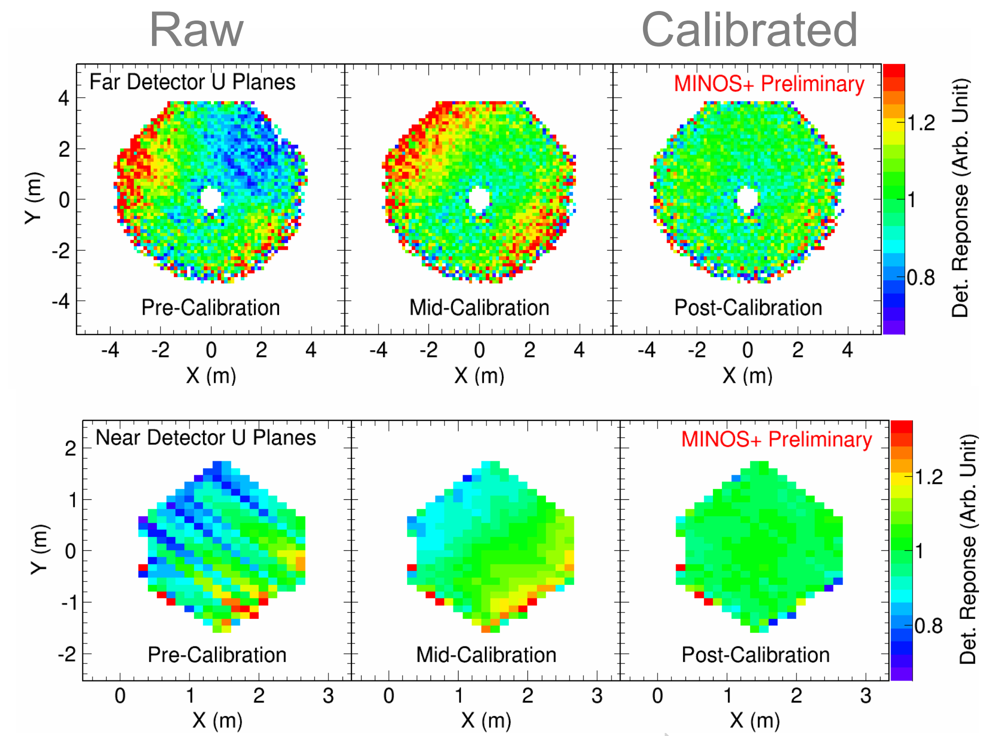
3. MINOS+ operations: POT history



- Both detectors continue to collect data with > 98% up-time
  - ✓ > 99% in the last 3 months
- Far Detector has collected > 50 kt-yr atmospheric neutrino data
- We project that we will accumulate about 11 x 10^{20} POT by end of FY16
  - ✓ Unfortunately this is much less than the originally requested 18 x 10^{20} POT

3. MINOS+ operations - calibrations



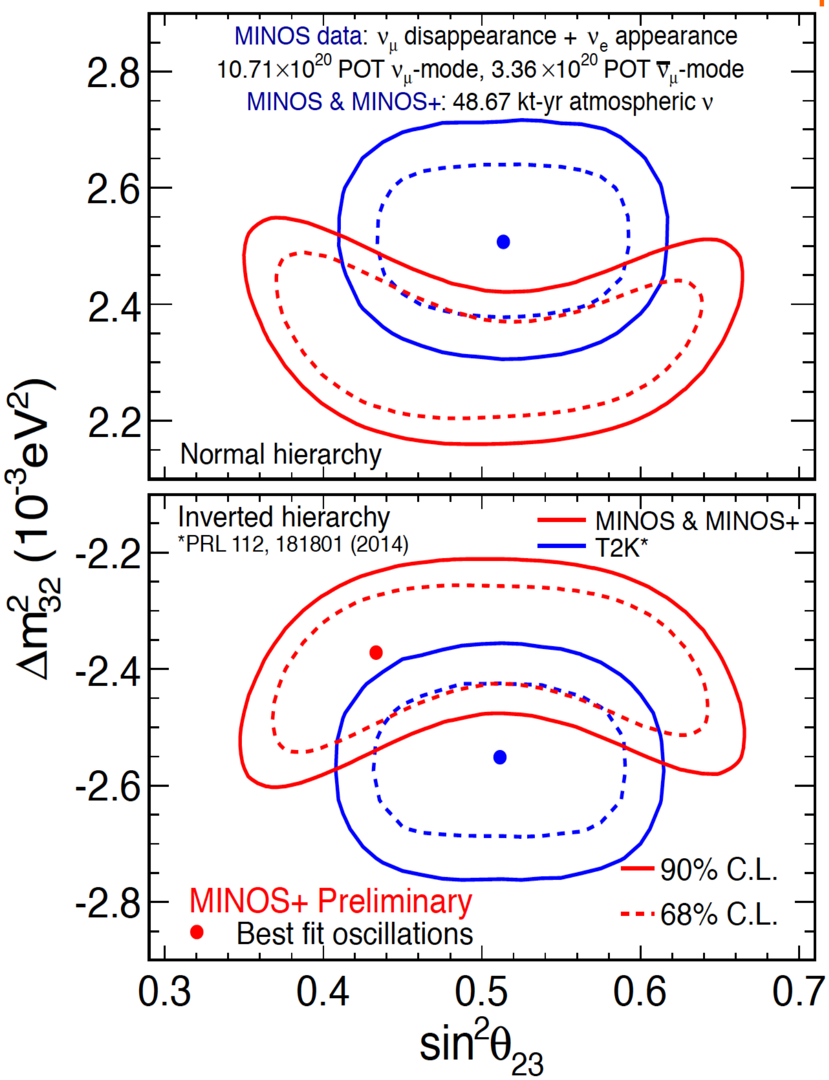


Raw Pulse Height → Linearity Correction → Drift Correction → Strip to Strip Correction → Attenuation Correction → Energy Scale → Corrected Signal

4. Analyses: standard oscillations: recent past

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

PRELIMINARY



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

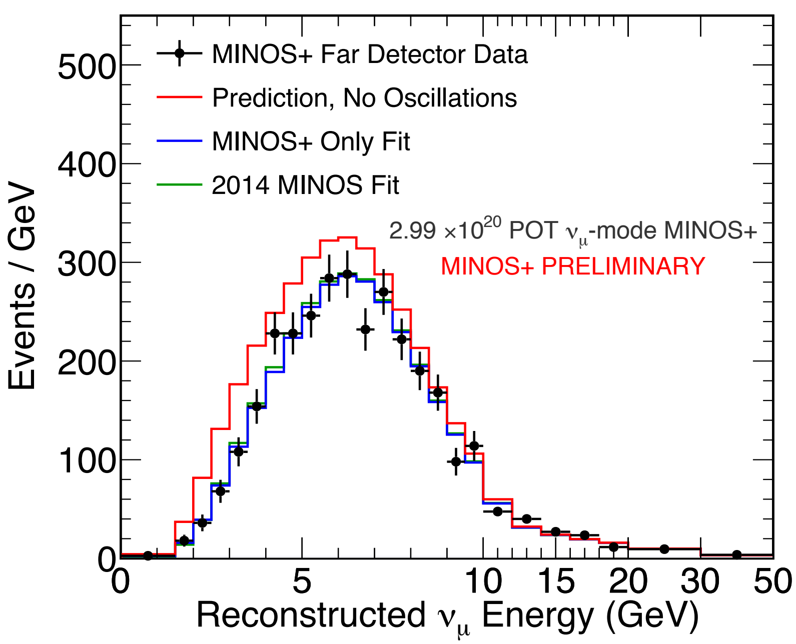
$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$$

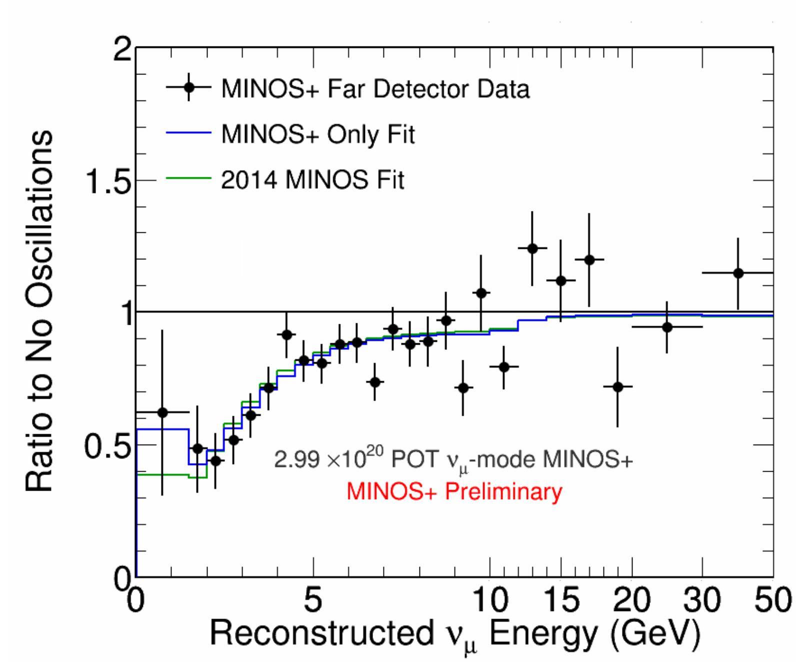
$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$

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

4. Analyses: standard oscillations: MINOS+

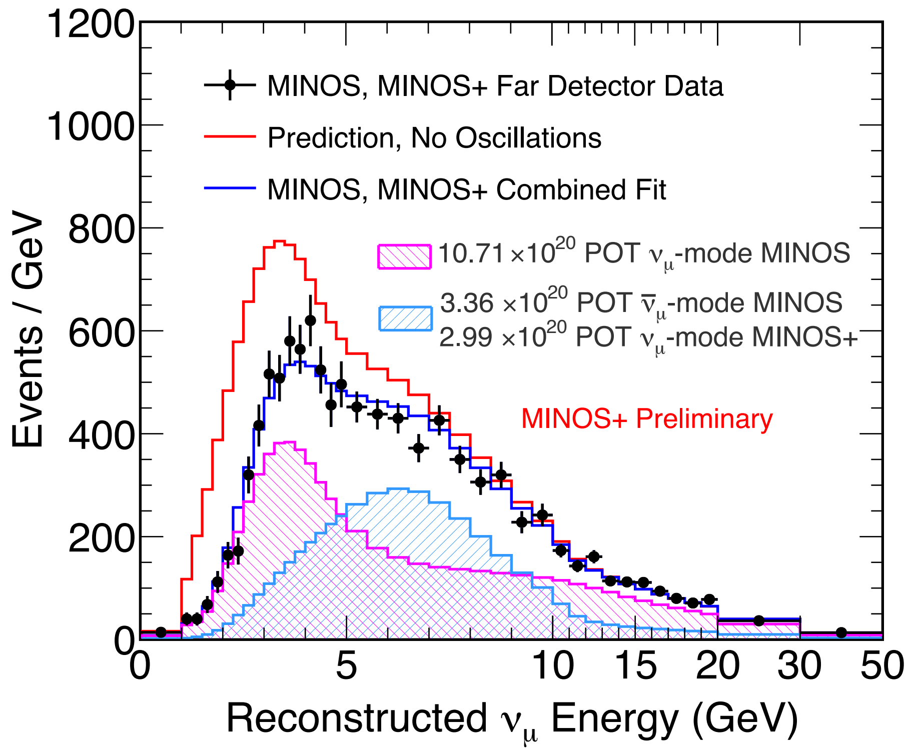
- Preliminary analysis on the first 3.0 x 10^{20}POT of MINOS+
  (data accrued from Sep 2013 to Sep 2014)
- Significant statistical improvement to rising edge of primary oscillation
  (1975 candidate ν_μ CC events in the Far Detector)
- These data allow to look for deviations from the standard 3-flavor prediction of the MINOS data
- MINOS+ spectrum consistent with the MINOS best fit point
  (χ^2 between the prediction from the "MINOS+ only fit" and "2014 MINOS fit" is 1.3)

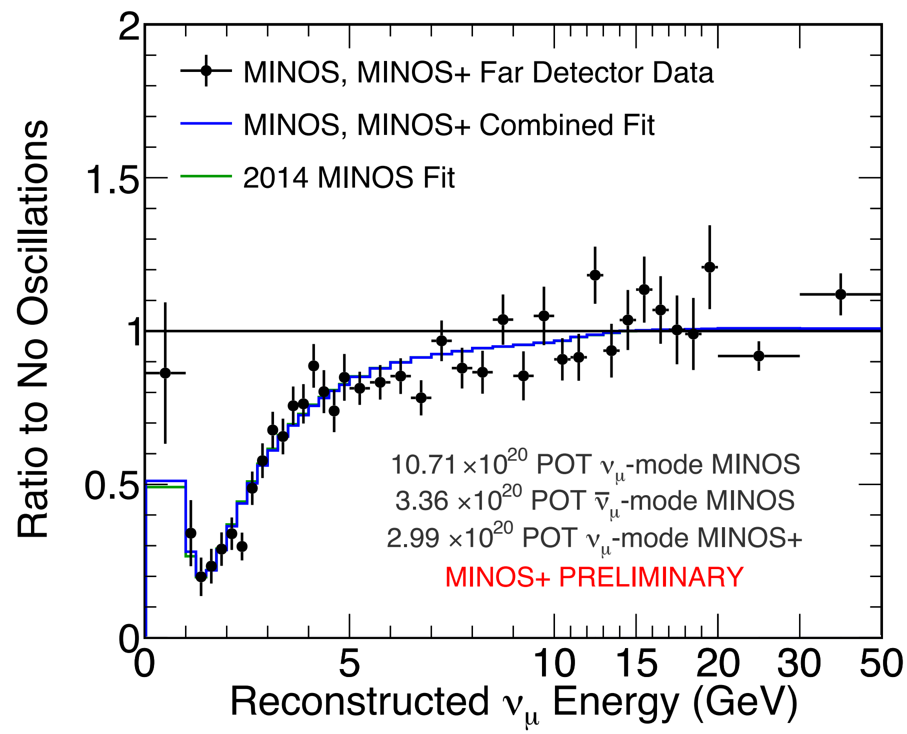




4. Analyses: standard oscillations: MINOS & MINOS+

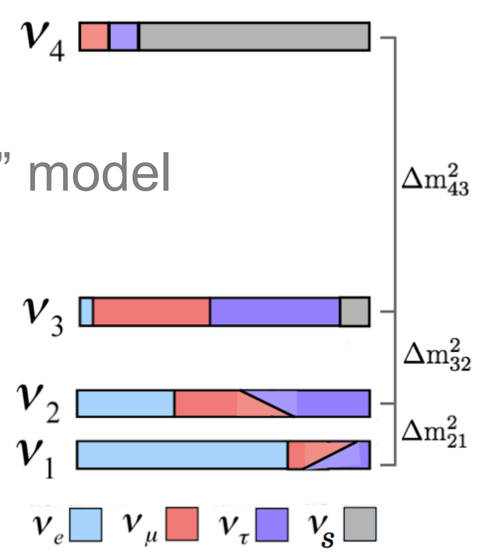
- Combined spectrum of MINOS and MINOS+ disappearance data
- Can test the rising “edge” of the spectral ratio (survival probability)
- Will later perform a combined fit of both

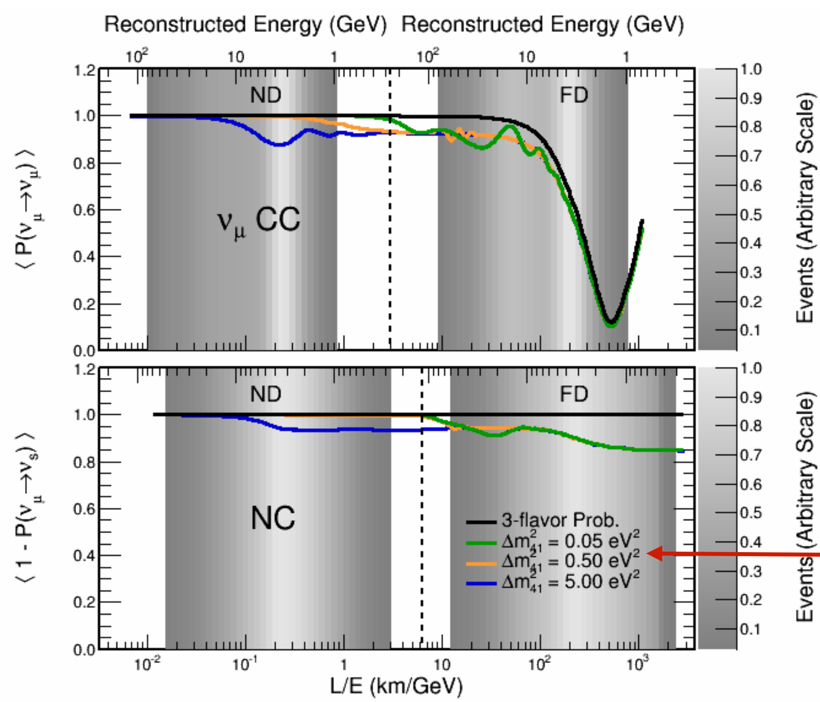




- Main signatures of sterile neutrino oscillations:
  - ✓ ν_μ CC spectrum: deviations from std. osc. due to extra mass splitting (Δm^2_{43})
  - ✓ NC spectrum: deficit due to $\nu_\mu \rightarrow \nu_s$ disappearance.
- The two detector configuration of MINOS+ enables a search for new sterile oscillation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

"3+1" model



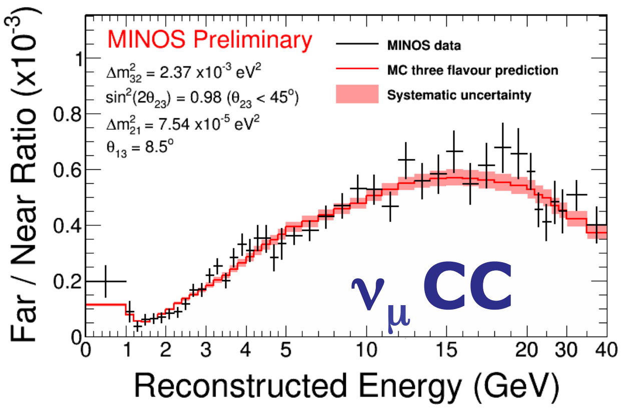


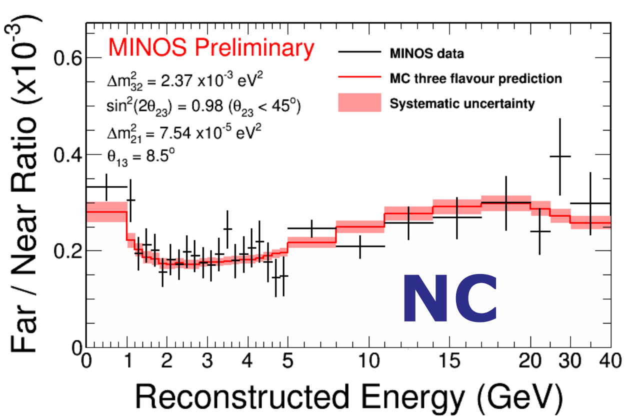
High Δm^2_{43}: oscillations in ND

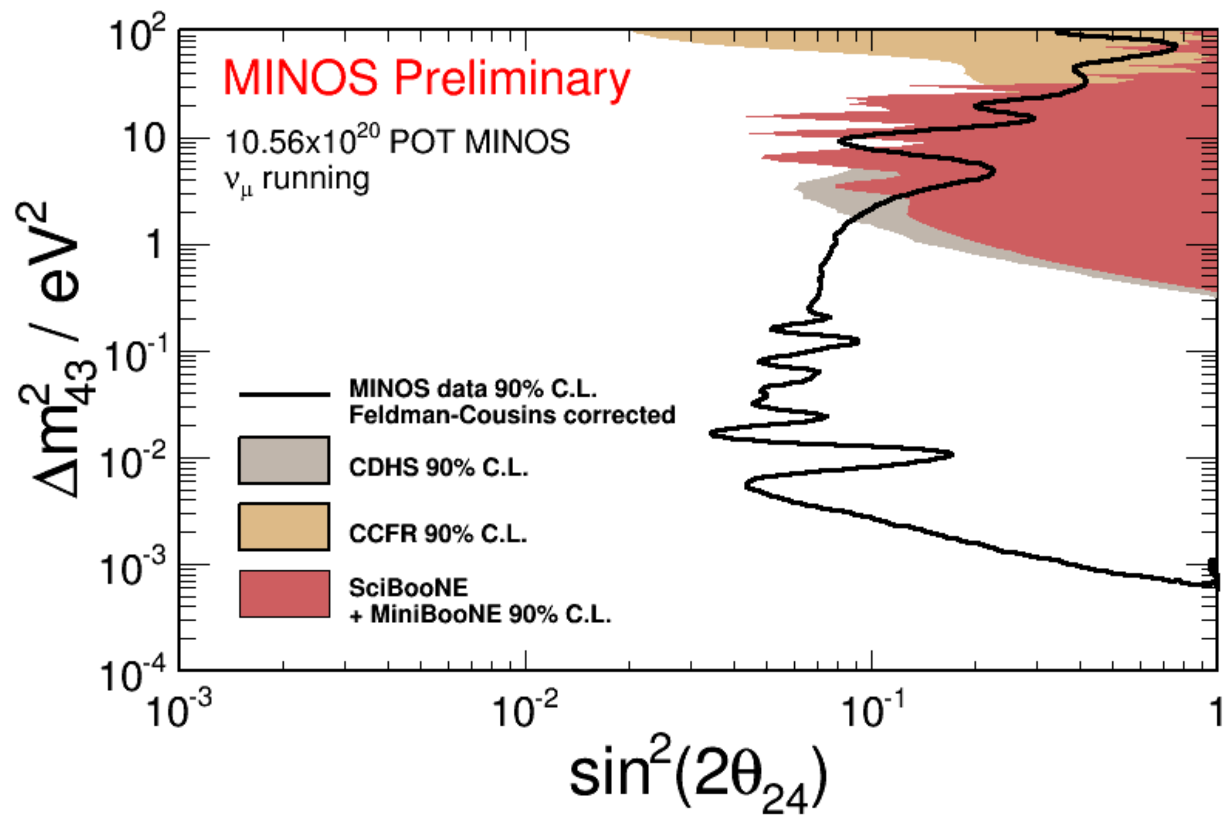
Low Δm^2_{43}: oscillations in FD

4. Analyses: search for sterile neutrinos

- Possible distortions in the Near Detector required a change of paradigm in MINOS analyses
- Look for deviation from standard oscillations in Far/Near energy spectra
  - ✓ Simultaneous fit to ν_μ CC 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





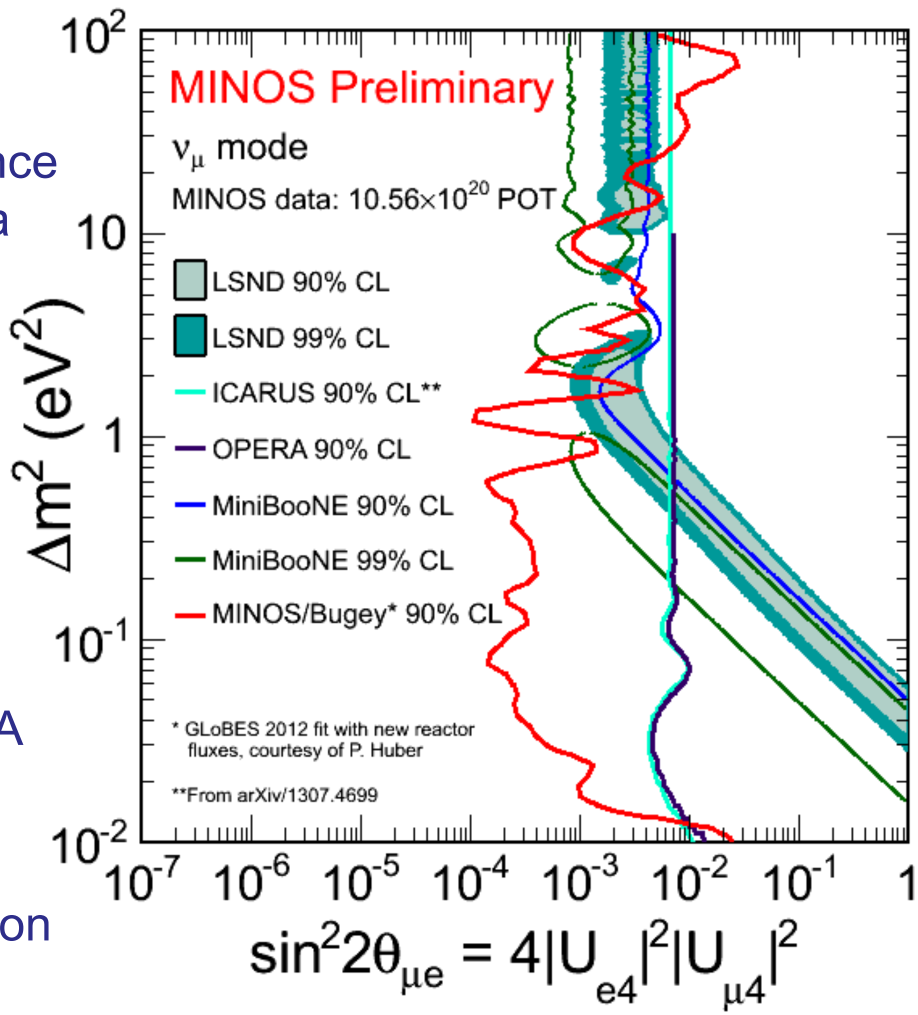


4. Analyses: MINOS & Bugey

- Use best fit to NC and ν_μCC MINOS disappearance
- Combine MINOS 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

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

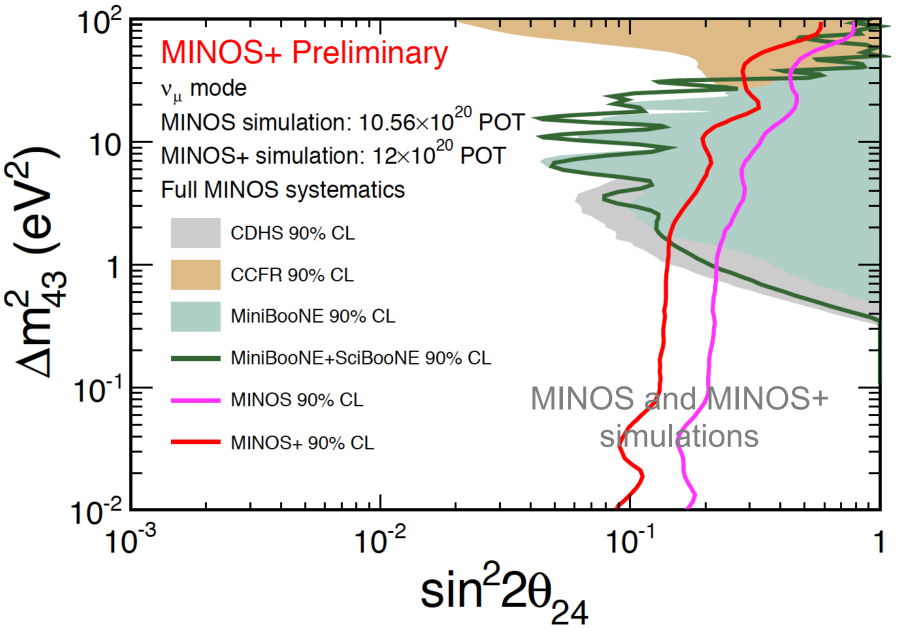
- Combined limits can be compared to MiniBooNE, LSND, ICARUS, and OPERA results
- Rule out much of $\Delta m^2_{43} < 1$ eV^2 region
- Collaborating with Daya Bay to perform a joint fit



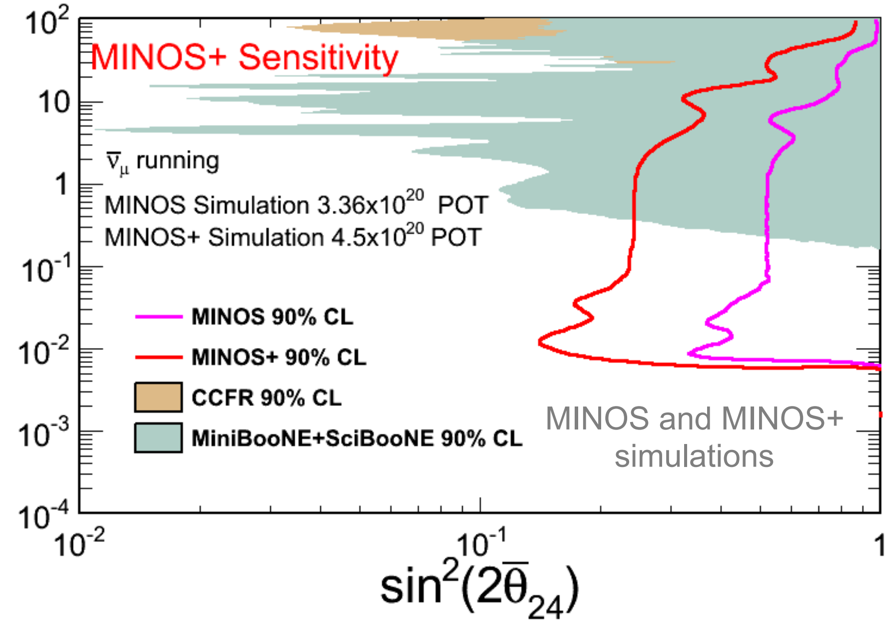
* Bugey limits computed by P. Huber using GLoBES 2012 and new reactor fluxes.

4. Analyses: future prospects for sterile neutrinos

Neutrino mode



Antineutrino mode



- 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

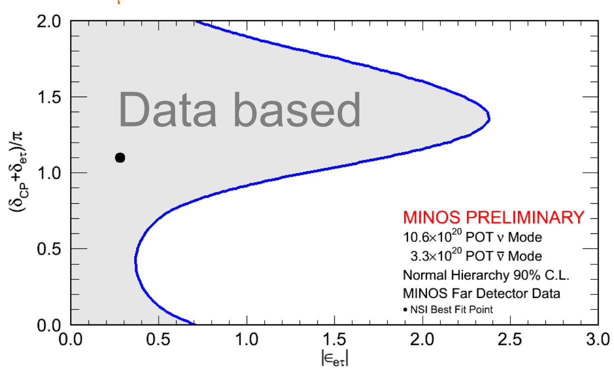
- The long baseline makes MINOS+ sensitive to potential nonstandard interactions (NSI) with matter
- NSI can be parameterized using ϵ parameters that incorporate the coupling strength of the new interaction and the mixing of the eigenstates for the NSI

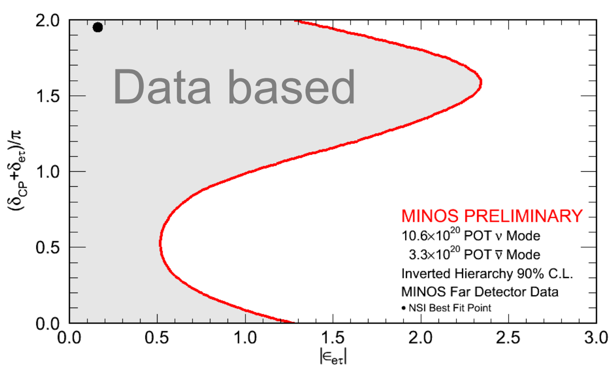
$$H = U_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger_{PMNS} + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau}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

Standard Oscillation | NSI / Matter Effect

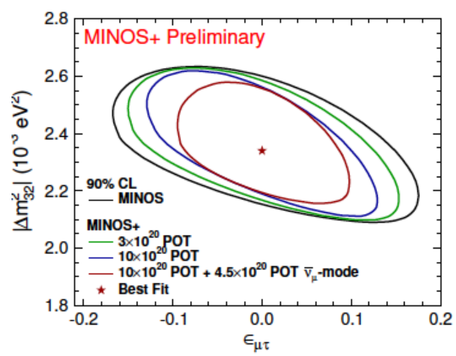
$$V_e = \sqrt{2}G_F n_e$$

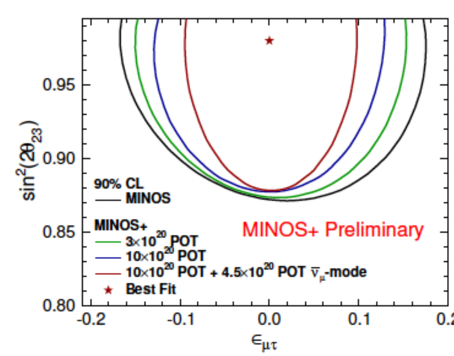
$\nu_\mu \rightarrow \nu_e$ appearance

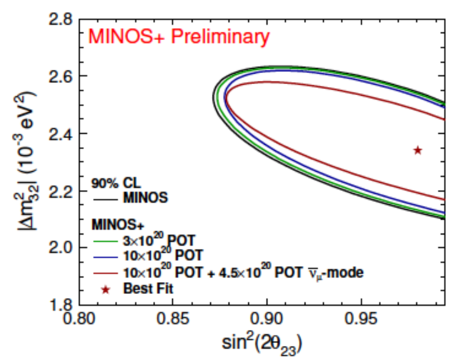




ν_μ disappearance



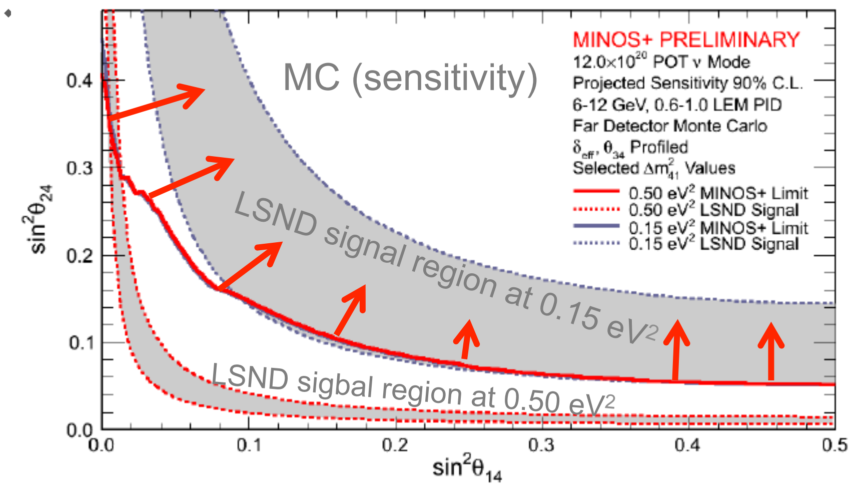


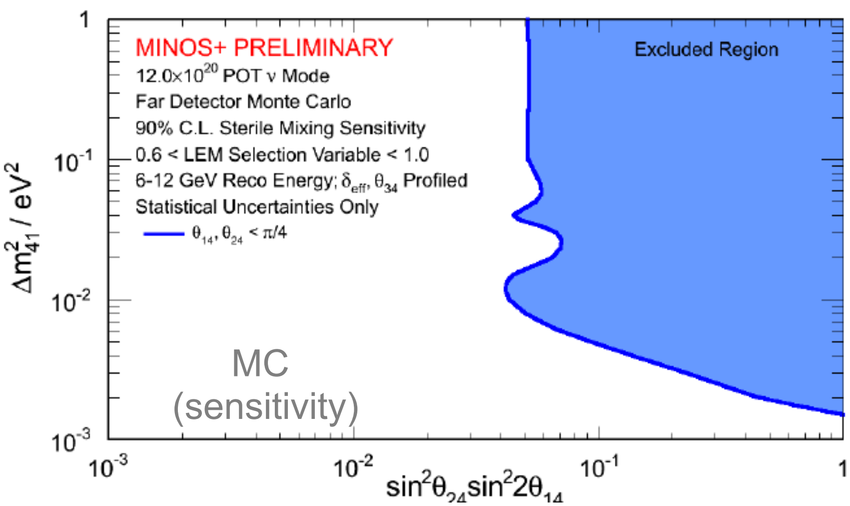


MINOS data vs MINOS+ MC

4. Analyses: searches for "exotics": $\nu_\mu \rightarrow \nu_e$ sterile search

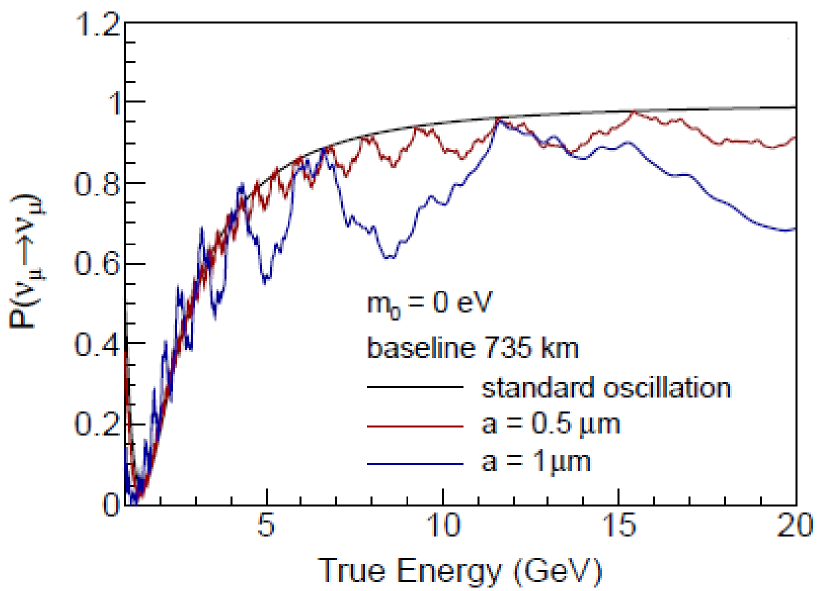
- If there is a 4th neutrino state with a mass square splitting that is greater than Δm^2_{32}, then MINOS+ can see an excess of ν_e events. Similar mechanism would cause LSND signal.



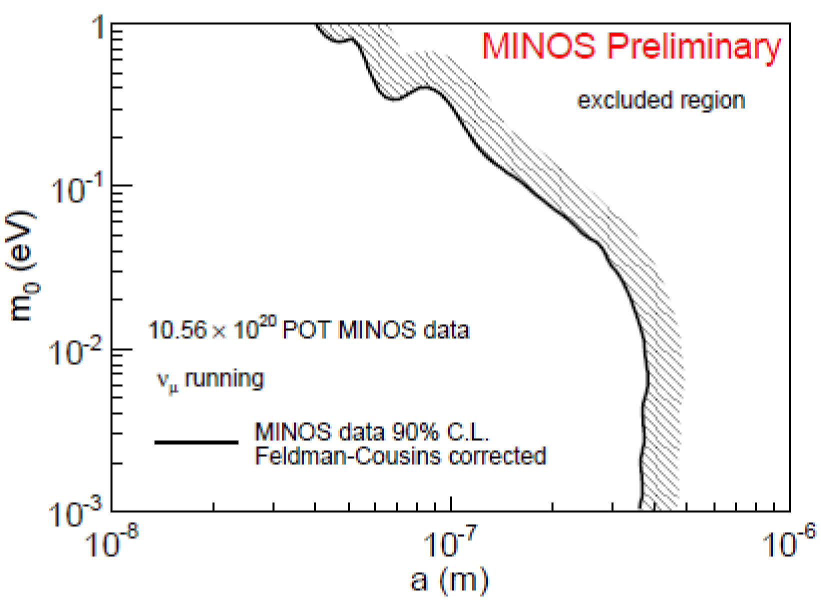


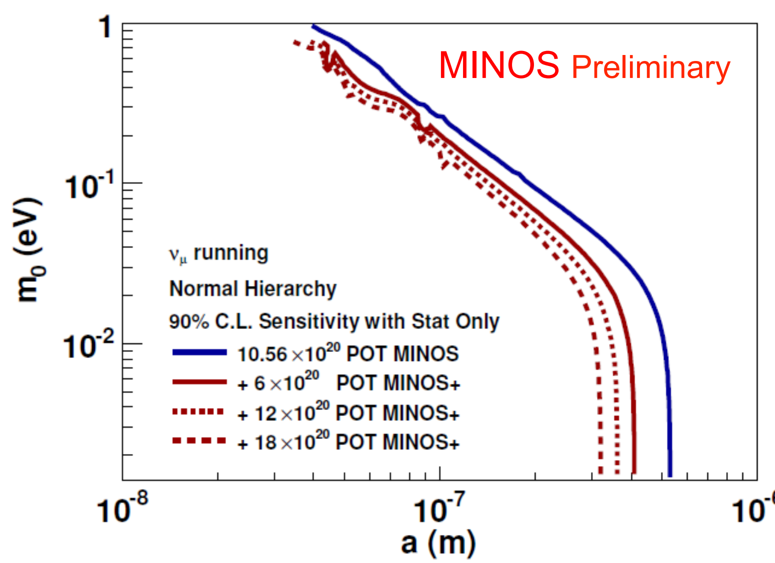
- MINOS+ is sensitive to both θ_{14} and θ_{24}

- MINOS+ has a sensitivity that is comparable to Bugey $\overline{\nu}_e$ disappearance limits
  - ✓ stats only
  - ✓ no F-C corrections



- 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

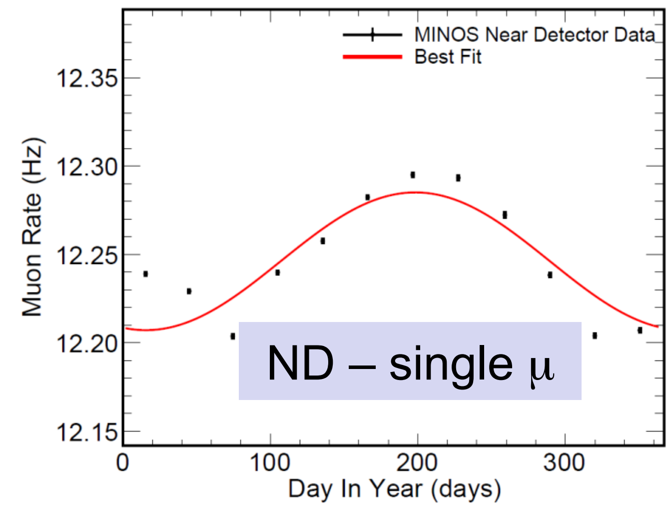


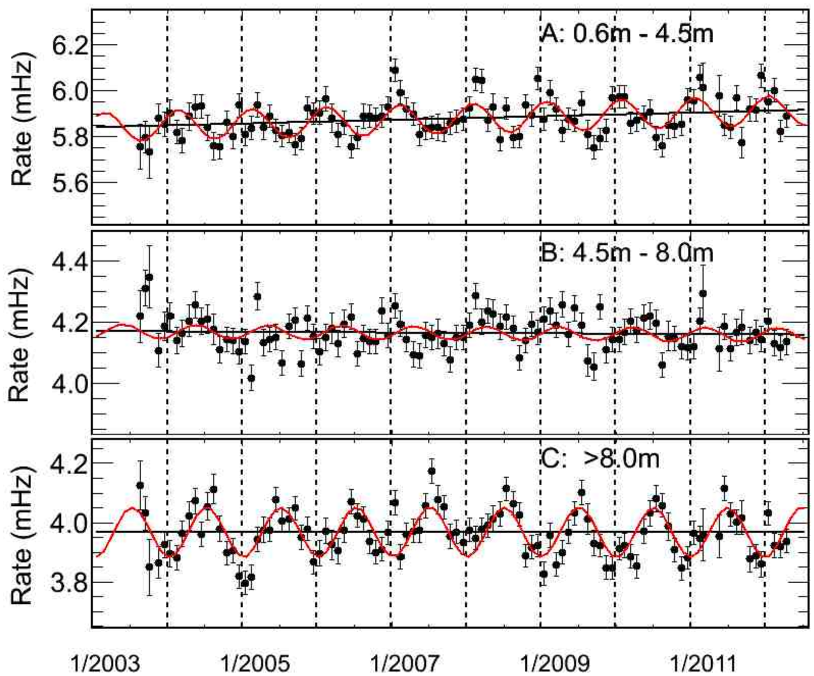


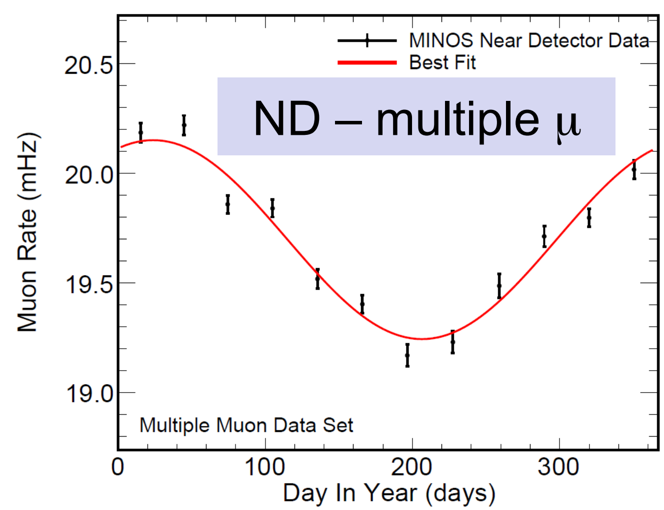
4. Analyses: UP: multiple-μ seasonal variations in the MINOS ND

- ND multiple μ seasonal variations peak in the opposite season to single μ
- In the FD, the “season” depends on μ separation (ΔS)
- We didn’t expect this and attempts to explain it are not satisfactory
- Physical Review D 91, 112006 (2015)

Summer max



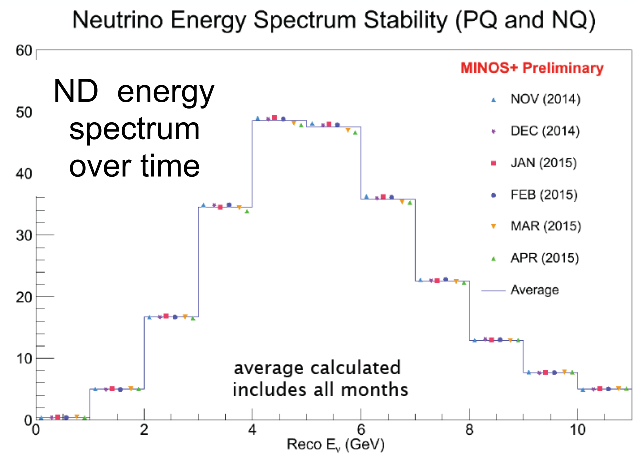


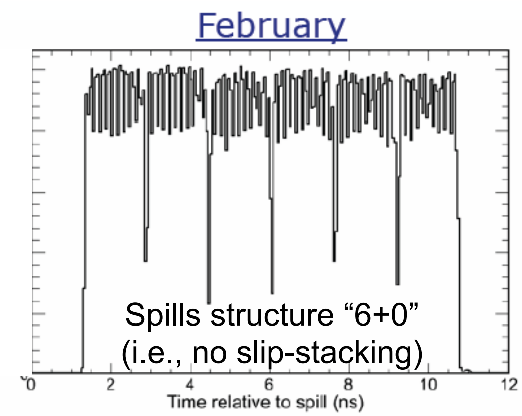


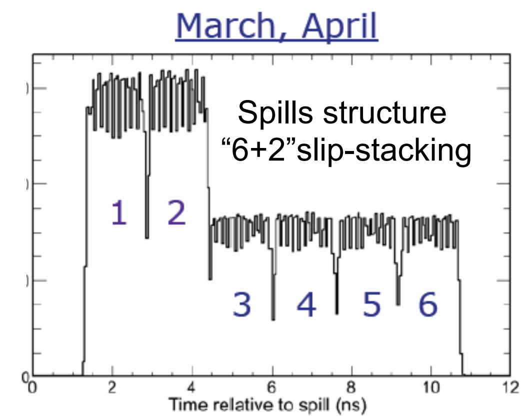
Summer min

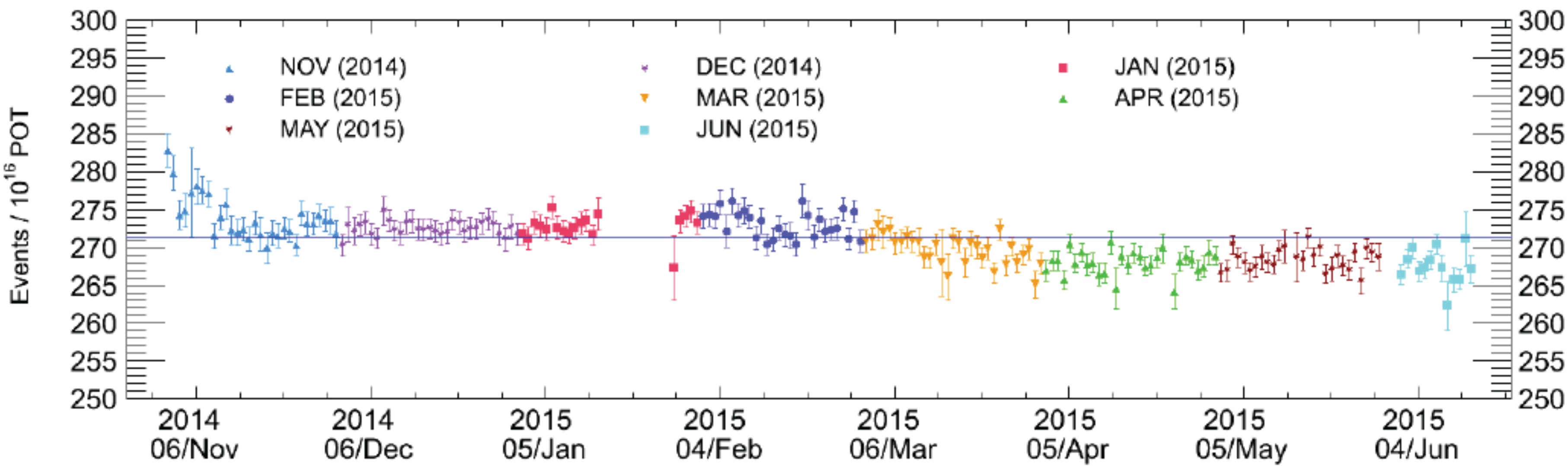
4. Analyses: a slip-stacking issue …

- While monitoring the beam …
- Likely detector reco? Any beam effects? Or both?
- Need proper MC (with correct instantaneous intensity) --> intense effort



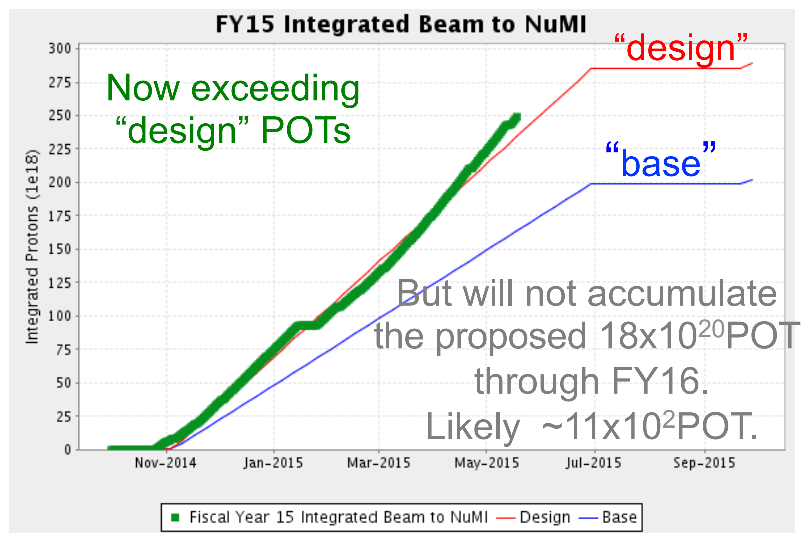






5. Outlook

- Continue MINOS analysis ➔ new results, several papers in the pipeline
- Manpower is very limited
- MINOS+ is significantly improving the physics reach of most analysis topics
- Horns-off data (currently being taken) will be put to good use in MINOS+
- We are evaluating sensitivities with an anti-neutrino beam (anticipated past FY16) and possible commitments by collaboration members. We will likely communicate to the lab our findings at the next PAC meeting (or sooner, if possible). Also – there are some anti-neutrinos in the neutrino mode…
- The MINOS+ Collaboration thanks FNAL and all funding agencies for support (and encourages them to continue doing it until we exploit all the data collected previously or in the future) - we are still very productive!



EXTRA INFO

2. MINOS+ Collaboration

DocDB-9322
August 15, 2012

MINOS+

Updated Proposal for MINOS running in the medium energy NuMI beam 2013-2016

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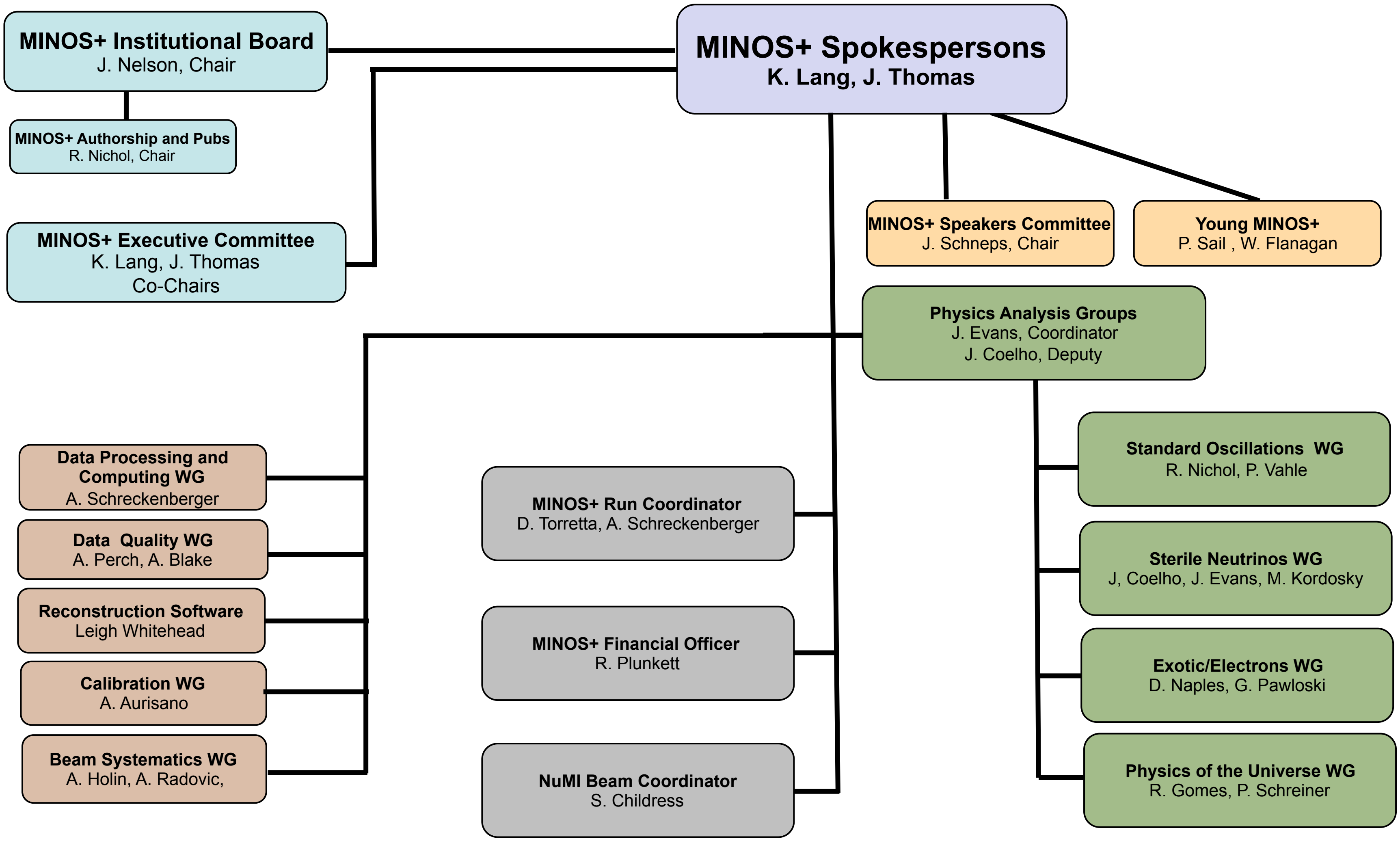
- **Harvard University**
  G.J. Feldman
- **University of Houston**
  L. Whitehead
- **Iowa State**
  I. Anghel, M.C. Sanchez
- **Lancaster**
  A. Blake
- **Los Alamos**
  G. Mills
- **University College London**
  S. Germani, A. Holin, R.J. Nichol, A. Perch, M. Pfuzner, J. Thomas, L.H. Whitehead
- **University of Manchester**
  R. Chen, J.J. Evans, A. Timmons
- **University of Minnesota Duluth**
  A. Habig
- **Univ. of Minnesota, Twin Cities**
  M. Gabrielyan,, M.L. Marshak, J.R. Meier, W.H. Miller, G. Pawloski (D. Osterholm, D. Saranen)
- **Otterbein University**
  N. Tagg
- **University of Oxford**
  G. Barr, A. Weber
- **University of Pittsburgh**
  N. Graf, D. Naples
- **University of South Carolina**
  ⇨ S.R. Mishra, X. Tian
- **Stanford University**
  S.G. Wojcicki
- **University of Sussex**
  J. Hartnell
- **University of Texas at Austin**
  T. Carroll, W. Flanagan, K. Lang, S. De Rijck, J.L. Ritchie, P. Sail, A. Schreckenberger
- **Tufts University**
  J.A.B. Coelho, W.A. Mann, J. Schneps
- **UNICAMP – Univ. of Campinas**
  C.O. Escobar
- **USP - University of Sao Paulo**
  P. Gouffon
- **University of Warsaw**
  K. Grzelak
- **William & Mary**
  M. Kordosky, J.K. Nelson, A. Radovic, P. Vahle

27 institutions, 72 people [26.2 FTE]

44 senior members	8 students
16 postdocs	4 technical @ Soudan

2. MINOS+ Collaboration



MINOS+ Organization
June 2015

2. MINOS+ Collaboration: Executive Committee

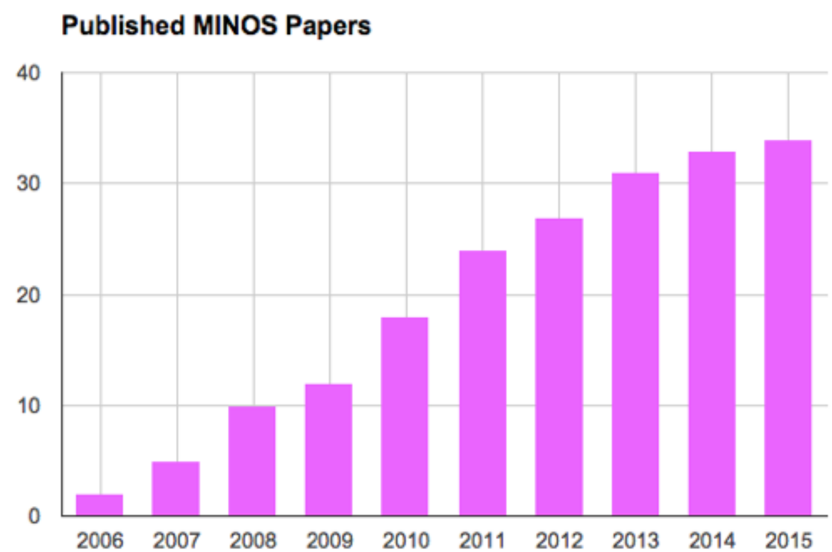
◆ Jenny Thomas	(Co-Spokes) (2010-15)
◆ Karol Lang	(Co-Spokes) (2014-17)
◆ Rob Plunkett	(Outgo. Spokes) (2014+)
◆ Stan Wojcicki	(Outgo. Spokes) (2010+)
◆ Jeff Nelson	(IB Chair) (2012-16)
◆ Tricia Vahle	(2010-15)
◆ Ryan Nichol	(2011-15)
◆ Alex Sousa	(2013-15)
◆ Mike Kordosky	(2011-16)
◆ Justin Evans	(AC, 2014-16)
◆ Andy Blake	(2015-17)
◆ Phil Adamson	(2011-17)

2. MINOS Collaboration - stats

- Since 1998, MINOS and MINOS+ has produced 74 PhD theses
- 13 faculty from postdoc transitions
- 12 papers in the pipeline
- Several more coming up with MINOS+ results

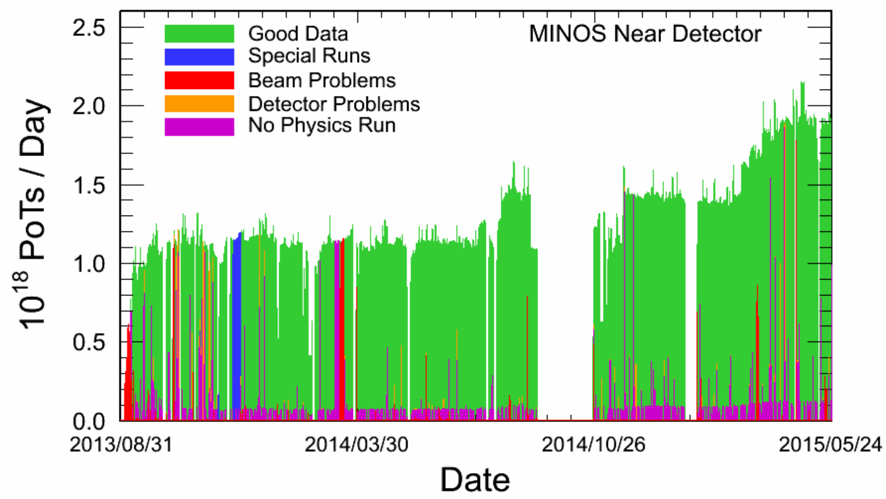
Many MINOS papers going through system:

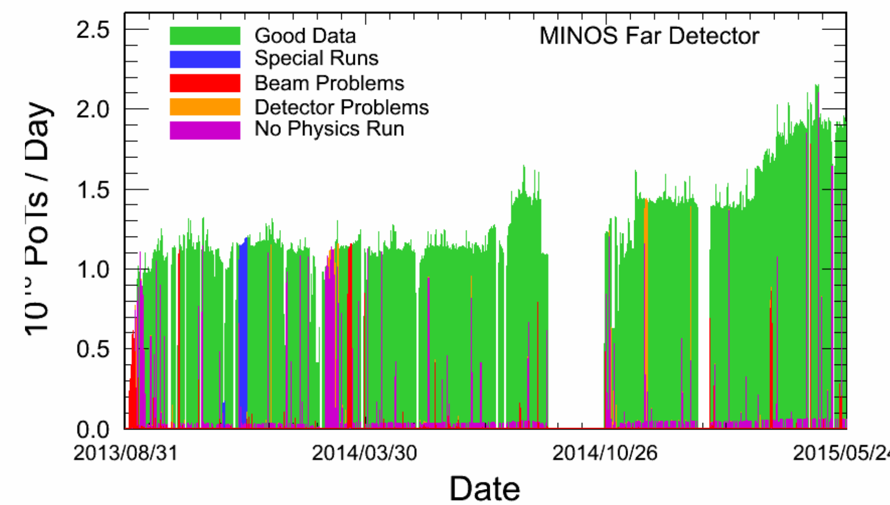
Multi-μ seasonal	Published!
Beam hardware	2nd comment
TOF	2nd comment
Transitions	1st comment
Multi-μ charge ratio	Committee
Sterile PRL	Committee
NC coherent π^0	Committee
NSI appearance	Working Group
Calibration	First draft
Disappearance PRD	First draft
Nue PRD	First draft
Atmospheric	In preparation
LED	In preparation



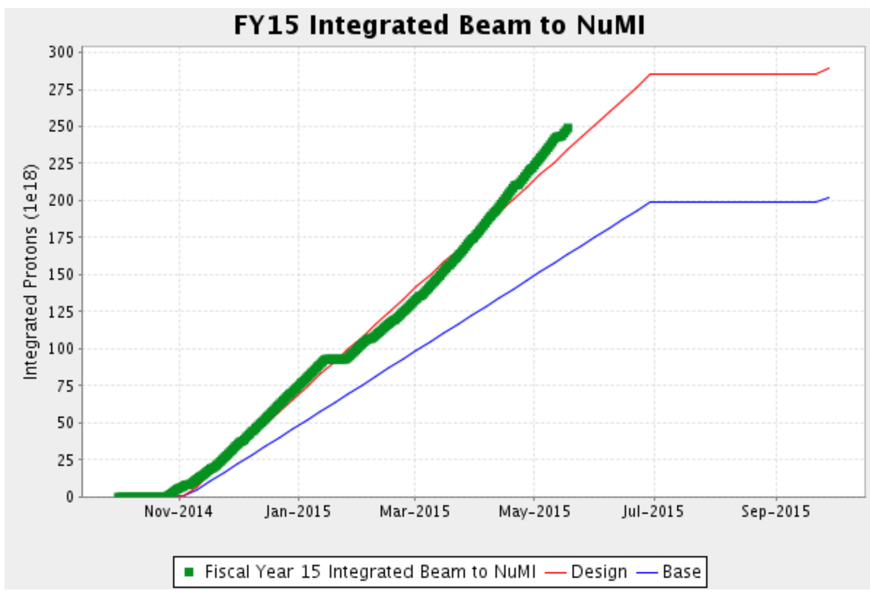
3. MINOS+ operations: detectors efficiencies and POTs

Both detectors > 99% live with beam in the last 3 months



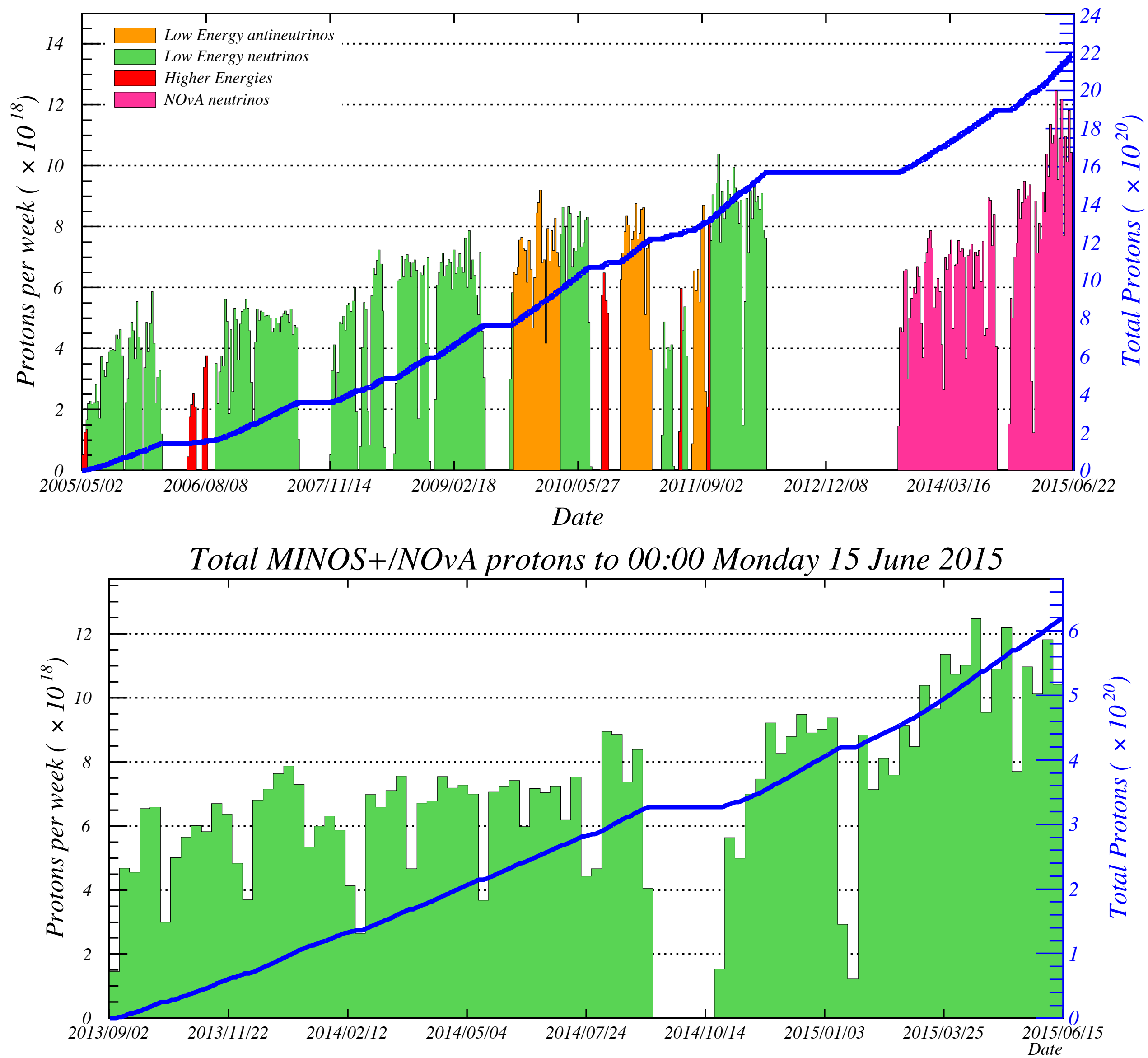


Now exceeding design POTs



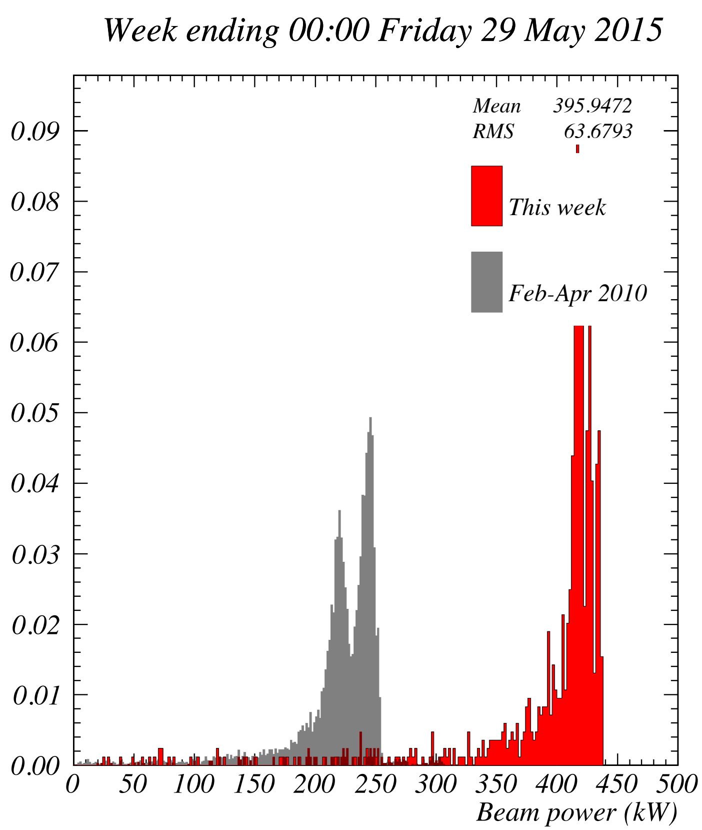
But will not accumulate the proposed 18×10^{20} POT through FY16. Likely $\sim 11 \times 10^{20}$ POT.

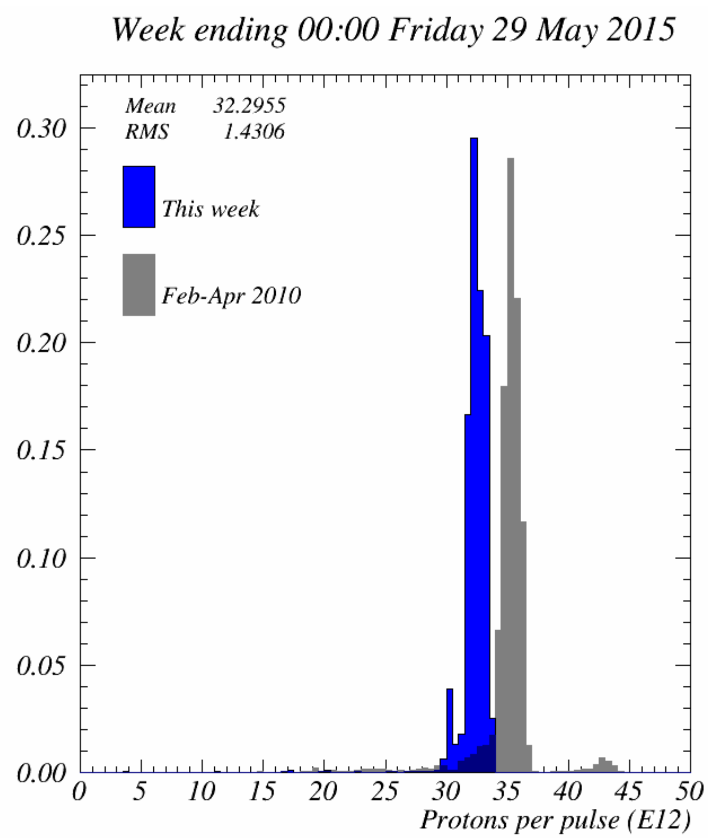
3. MINOS+ Operations



3. MINOS+ operations – beam records

- Best beam ever
- Record intensities (~4.3 e13) and power (~475 kW)
- Project ~11 x 10^{20} POT by end of FY16 (end of MINOS+ ?)



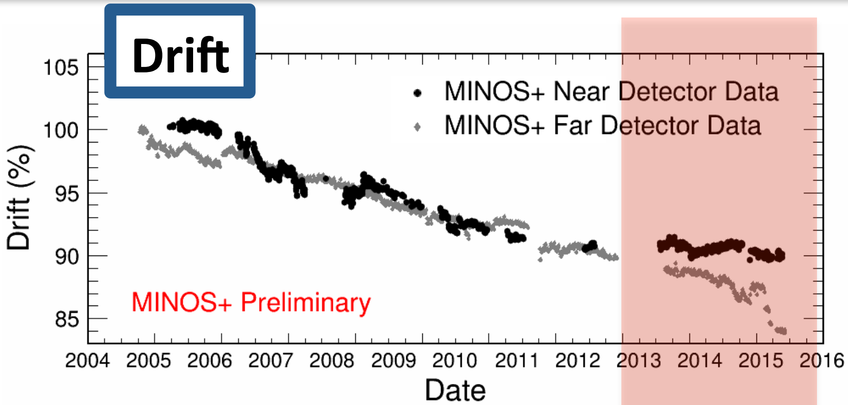


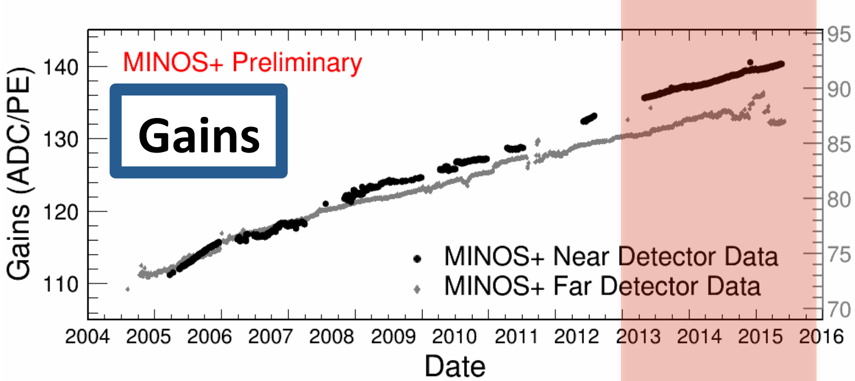
3. MINOS+ operations: MINOS+ Calibration Procedure

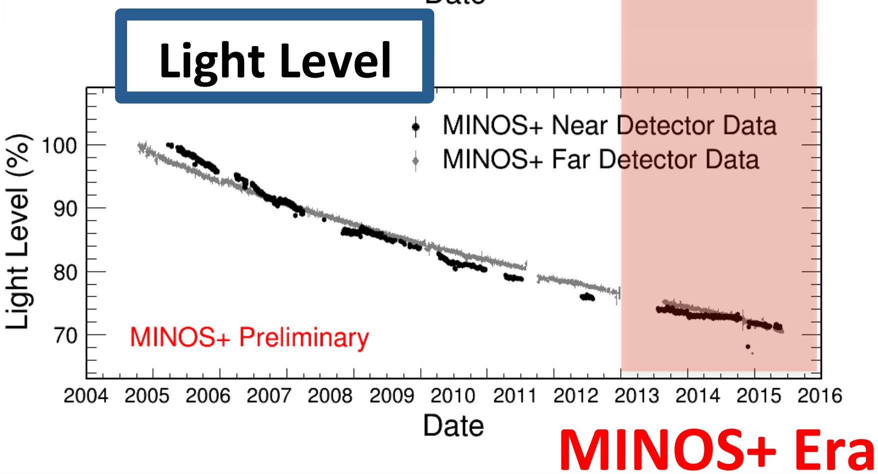
- The MINOS+ calibration procedure is meant to ensure that for a given energy deposition, the calorimetric response is uniform as a function of time and space, and uniform between the two detectors.
- The MINOS+ running period began in September 2013.
- The steps in this calibration are as follows:

Raw Pulse Height	Linearity Correction	Drift Correction	Strip to Strip Correction	Attenuation Correction	Energy Scale	Corrected Signal
Cosmic ray muons used to measure the response of the MINOS detectors.	Ensure response of each electronics channel is linear with pulse height.	Correct for variations in det. response (scintillator and electronics) versus time.	Correct differences in response b/w the individual MINOS strips and channels.	Correct for light attenuation along each strip, so transverse response is uniform.	Apply overall scale factor so that all detectors have the same uniform response.	Final corrections for timing, cross-talk, scaling for individual analyses, etc.

3. MINOS+ operations - calibrations





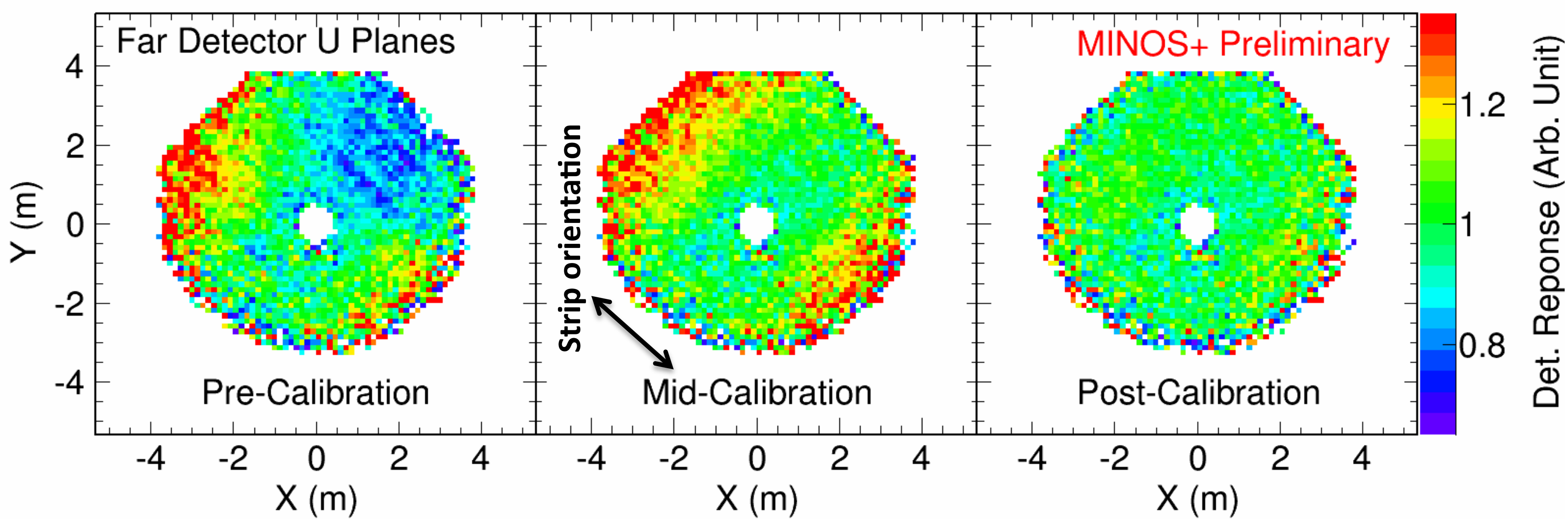


Drift: The drift measures the overall response of the detector versus time, including changes in the PMT, electronics, and scintillator. This has decreased by ~10% since 2005.

Gains: The gains have increased by approx. 3.0 ADCs/PE/year in the Near Detector, and 1.4 ADCs/PE/year in the Far Detector. The increase in gains is theorized to be due to the burning off of dynode impurities by continued PMT current.

Light Level: The detector light level is defined as Drift/Gain. The level has decreased over time, at a rate of 3.0% (3.5%) in the Near (Far) Detector per year, primarily due to the aging of scintillator.

- The scintillating strips at the MINOS Far Detector are oriented at 45° to the vertical, and at 90° with respect to neighboring planes.
- Shown below is the calibration of one of these two views.
(The NuMI neutrino beam is traveling out of the page.)



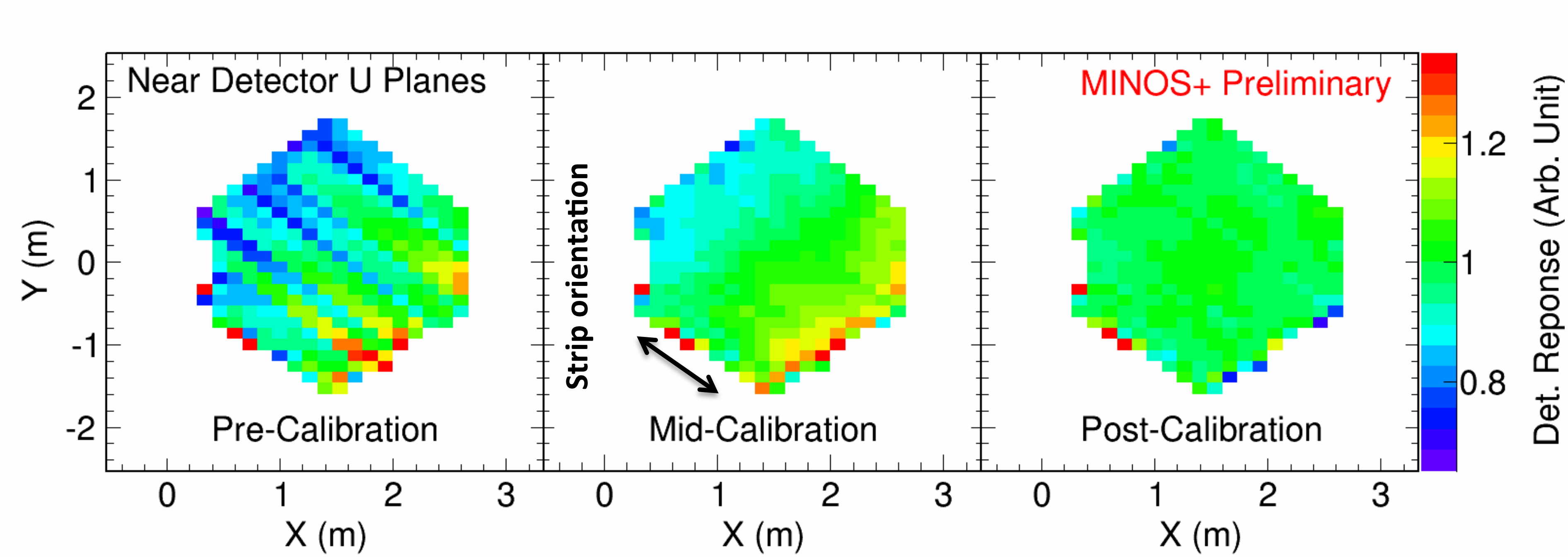
Before Calibration

Partially Calibrated Far Detector, after Linearity, Drift, and Strip to Strip corrections

Fully Calibrated Response of the Far Detector (after Attenuation and Energy Scale Calibrations)

3. MINOS+ operations - calibration of the Near Detector

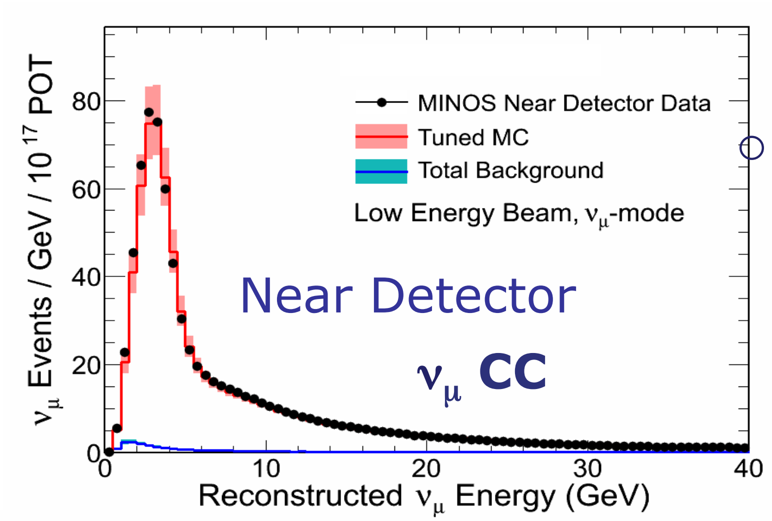
- The scintillating strips at the MINOS Near Detector are oriented at 45° to the vertical, and at 90° with respect to neighboring planes.
- Shown below is the calibration of one of these two views.
  (The NuMI neutrino beam is traveling out of the page.)



Before Calibration

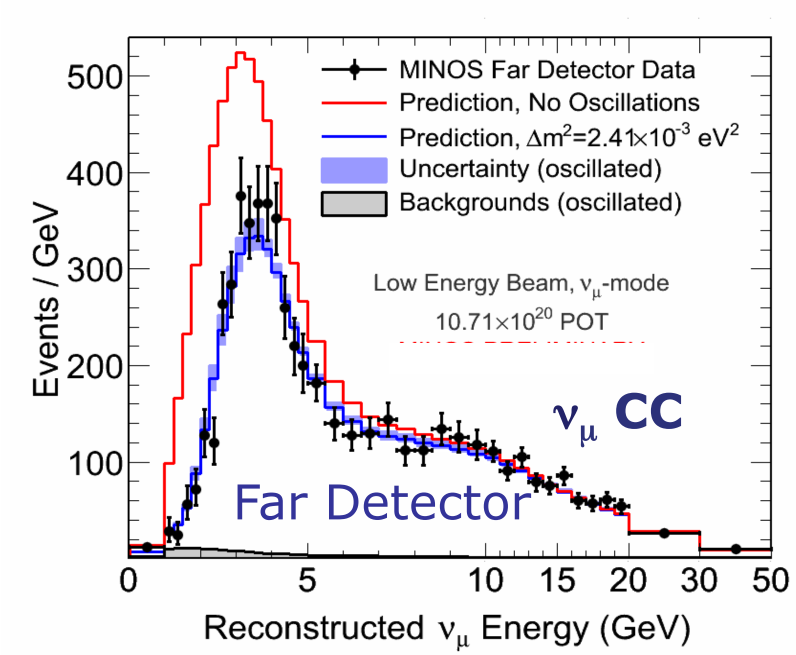
Partially Calibrated Far Detector, after Linearity, Drift, and Strip to Strip corrections

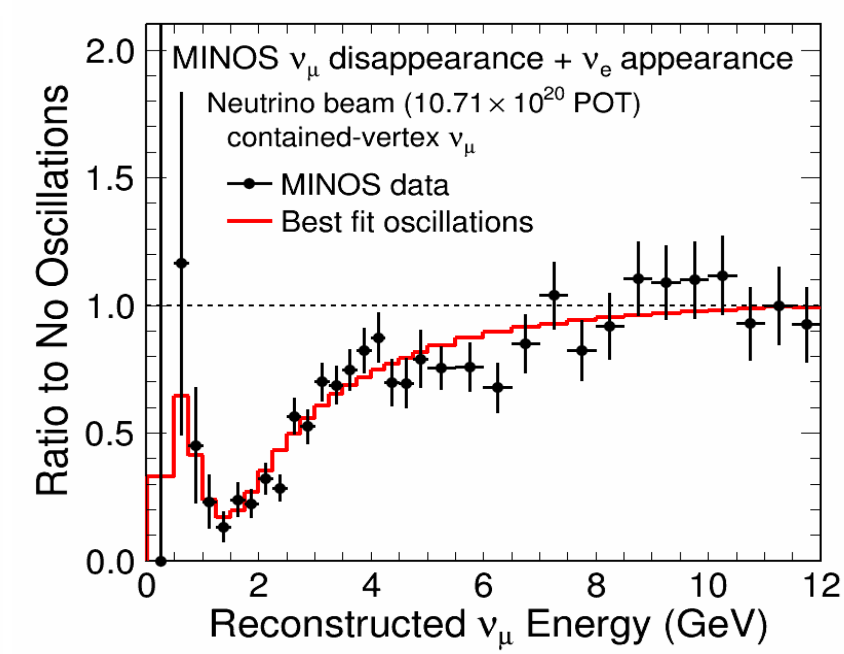
Fully Calibrated Response of the Far Detector (after Attenuation and Energy Scale Calibrations)



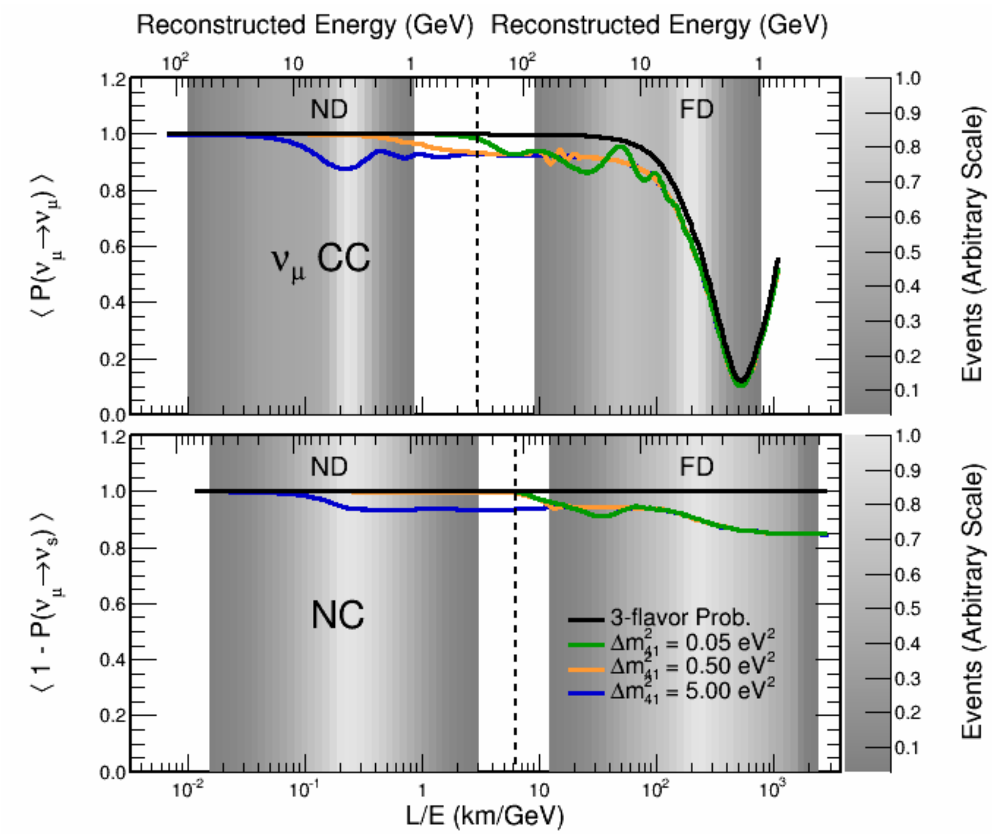
Published results on Δm^2_{32}, θ_{23}, θ_{13}:

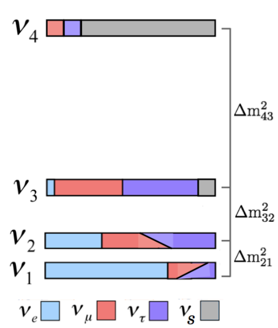
- ✓ ν_μ disappearance (PRL 110, 251801, 2013)
- ✓ $\nu_\mu \rightarrow \nu_e$ appearance (PRL 110, 171801, 2013)
- ✓ Combined analysis (PRL 112, 191801, 2014)





4. Analyses: search for sterile neutrinos





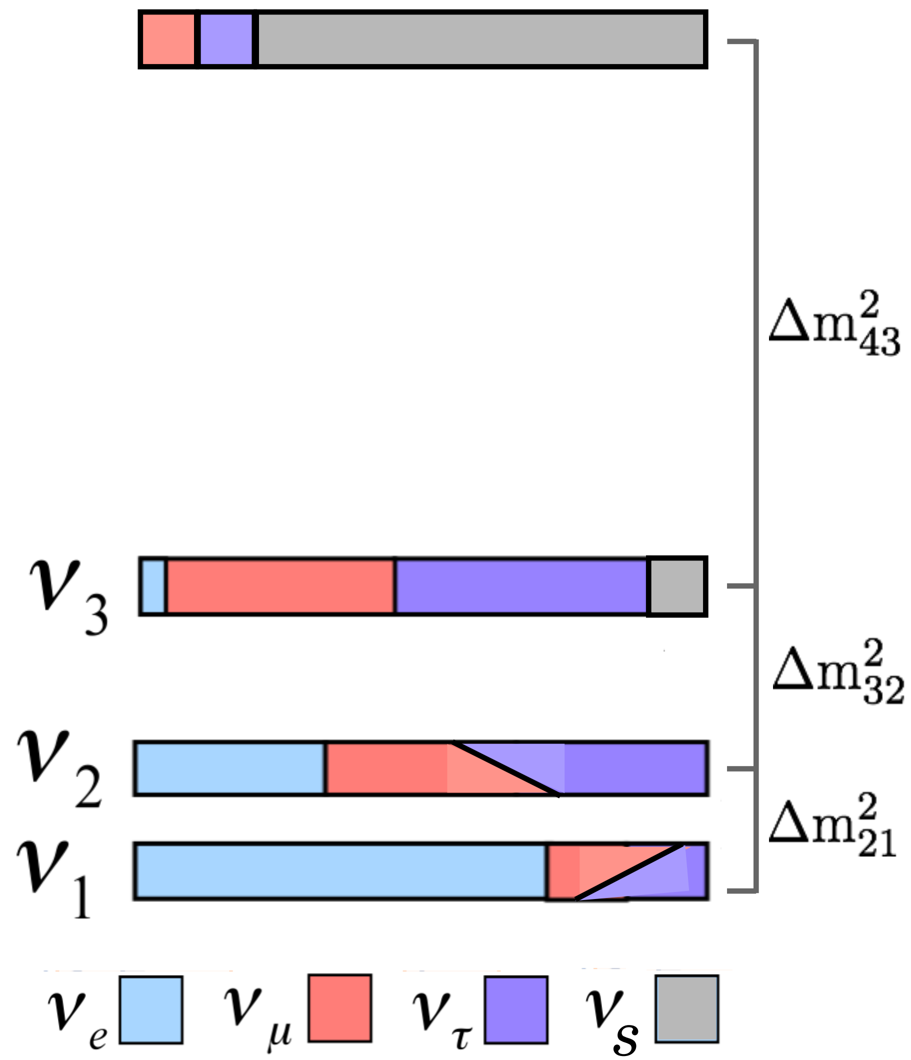
- Several neutrino anomalies are consistent with the existence of a light sterile neutrino
- The two detector configuration of MINOS+ enables a search for new sterile oscillation modes at a wide range of Δm^2 values
- The higher energy spectrum of MINOS+ enhances the sensitivity to spectral distortions beyond the standard oscillation framework

Sterile neutrino analysis assumptions

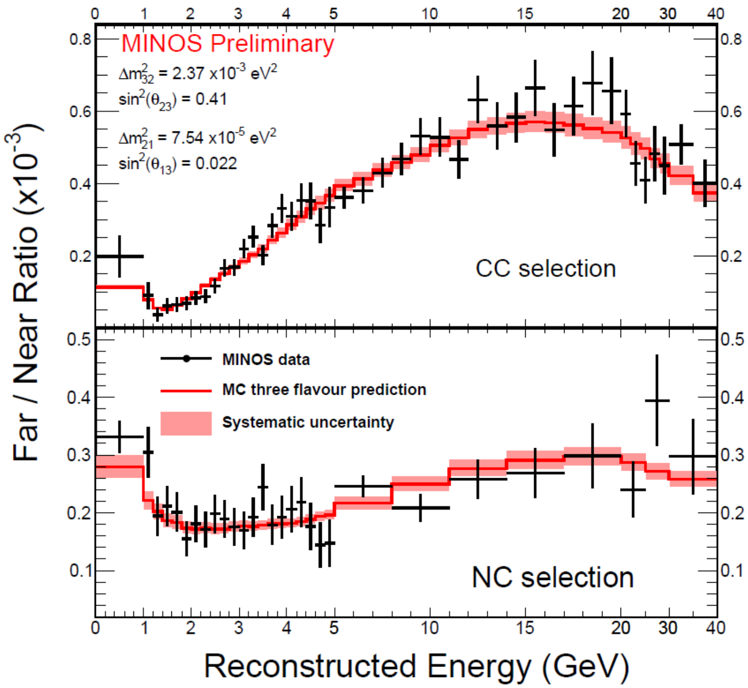
- The MINOS disappearance data in the 3 + 1 model:
    - 3 active flavours (ν_e, ν_μ, ν_τ)
    - Add 1 sterile flavour (ν_S)
    - Add 1 extra mass state (ν_4)

  $\Rightarrow$ 4 × 4 neutrino mixing matrix

- Neutrino mixing parameters:
    - Standard 3-flavour parameters:
        - Δm^2_{32}, Δm^2_{21}
        - θ_{12}, θ_{23}, θ_{13}, δ_{13}
    - Additional 4-flavour parameters
        - Δm^2_{43}
        - θ_{14}, θ_{24}, θ_{34}, δ_{14}, δ_{24}

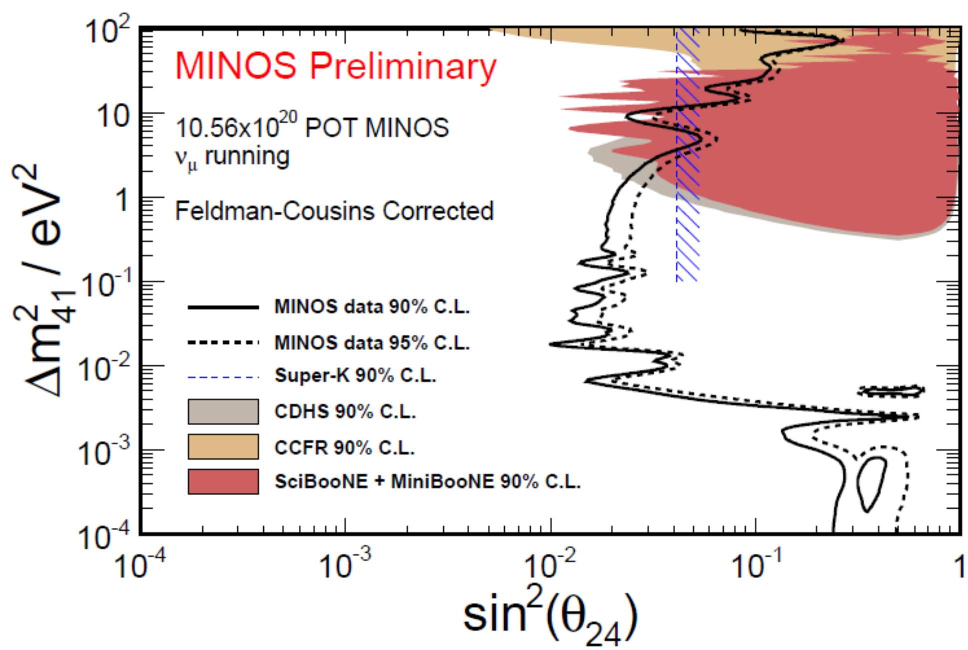


4. Analyses: search for sterile neutrinos

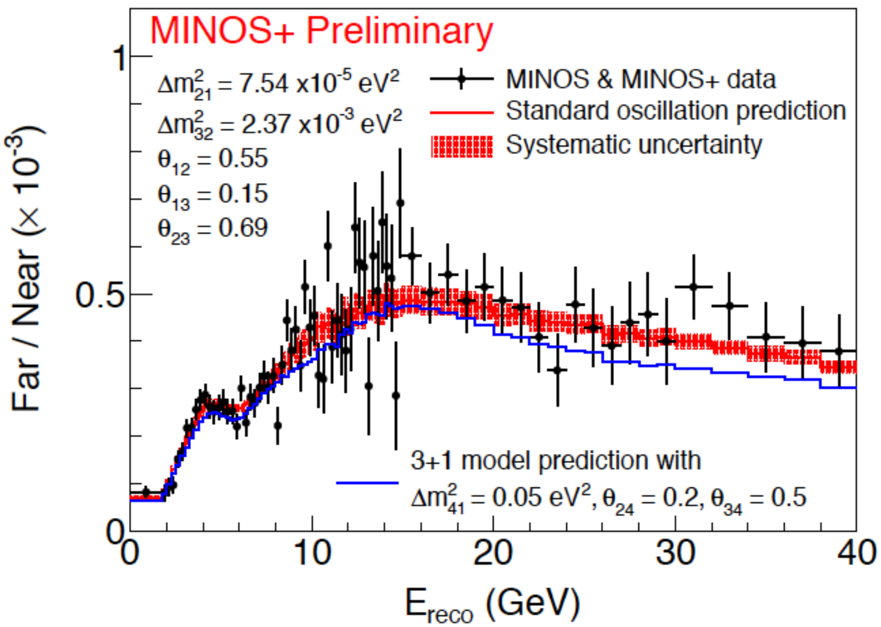


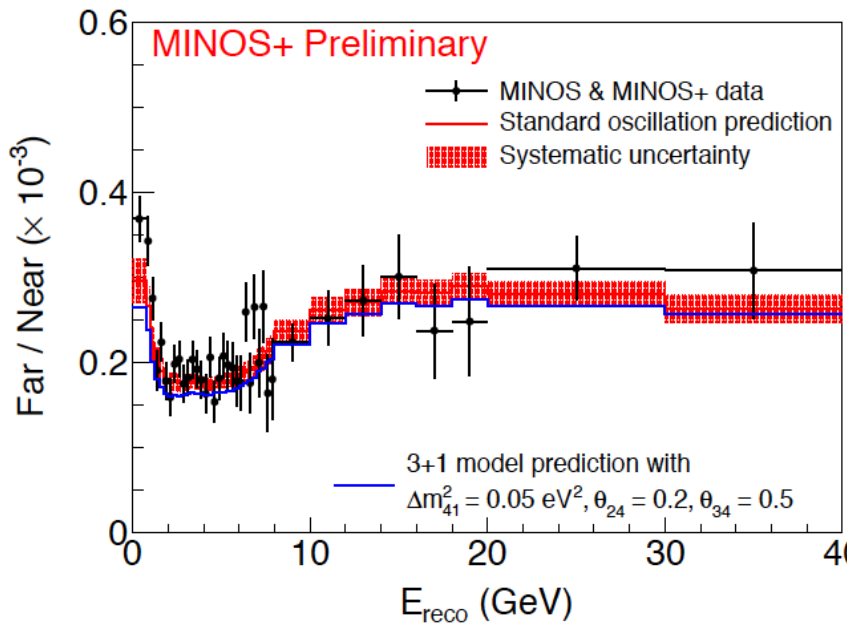
- Possible oscillations in the Near Detector required a change of paradigm in MINOS analyses
- We measure the ratio of Far and Near detector event rates as a function of energy
- CC and NC samples provide sensitivity to different components of the sterile mixing

- Our results significantly extend the region of parameter space excluded by disappearance searches
- Our pioneering work explores very low Δm^2 regions where interference occurs between the sterile and atmospheric scales

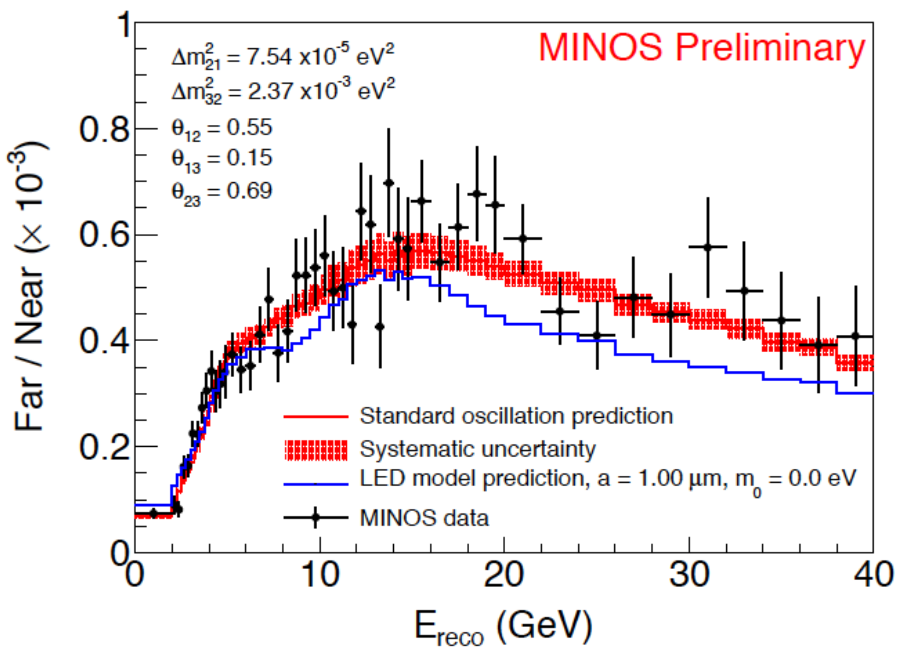


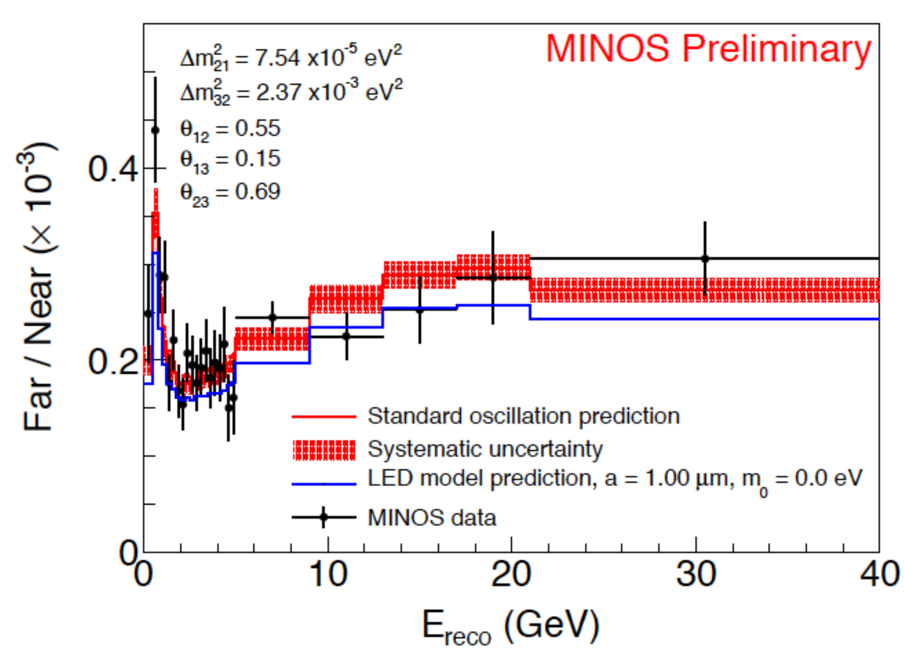
◆ Steriles: NC & CC





◆ LED: NC and CC


MINOS Preliminary
$\Delta m^2_{21} = 7.54 \times 10^{-5}\ eV^2$
$\Delta m^2_{32} = 2.37 \times 10^{-3}\ eV^2$
$\theta_{12} = 0.55$
$\theta_{13} = 0.15$
$\theta_{23} = 0.69$
Standard oscillation prediction
Systematic uncertainty
LED model prediction, a = 1.00 μm, m_0 = 0.0 eV
MINOS data
Far / Near ($\times 10^{-3}$)
E_{reco} (GeV)


MINOS Preliminary
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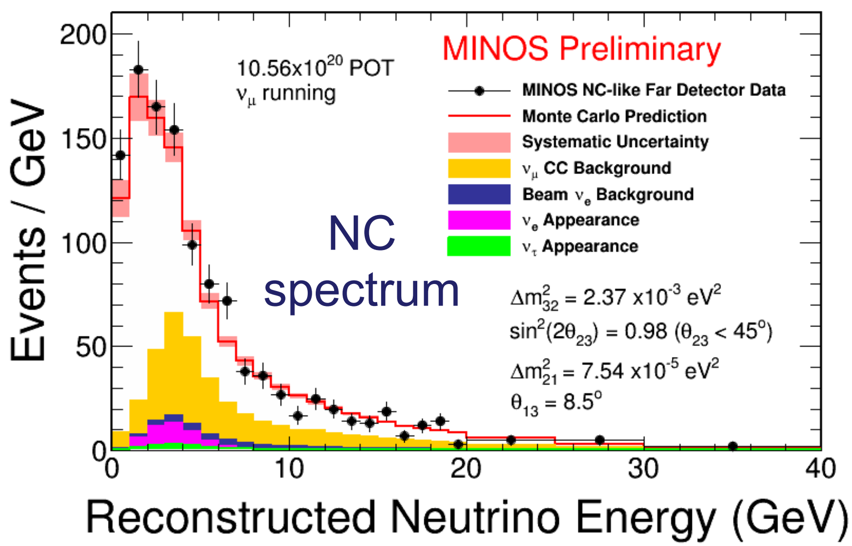
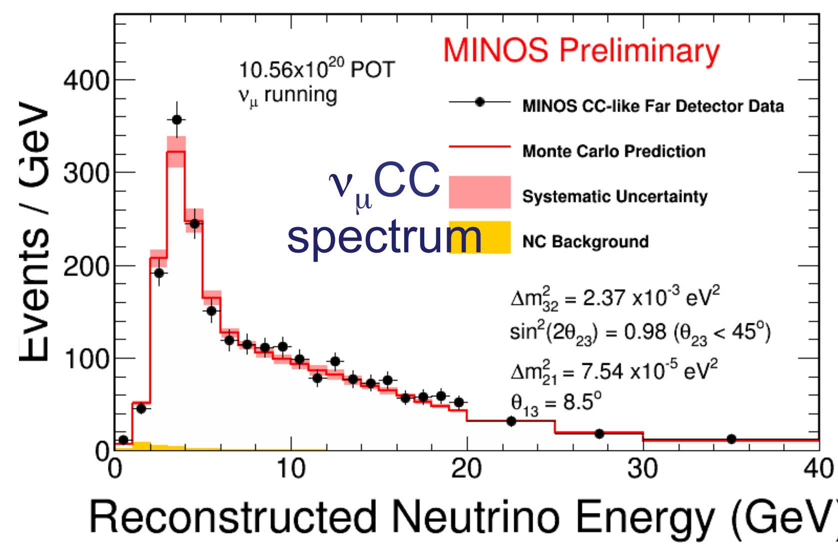
$\theta_{13} = 0.15$
$\theta_{23} = 0.69$
Standard oscillation prediction
Systematic uncertainty
LED model prediction, a = 1.00 μm, m_0 = 0.0 eV
MINOS data
Far / Near ($\times 10^{-3}$)
E_{reco} (GeV)

4. Analyses: search for sterile neutrinos

Sterile analysis: NC + CC event spectra

- Energy spectra at the Far Detector for ν_μ events
- Observed (black crosses) vs predicted assuming no sterile neutrinos (red)





$$R = \frac{N_{data} - \sum Backgrounds_{\text{Pred CC}}}{Signal_{\text{Pred NC}}}$$

Far Detector stats (0- 40 GeV):

◇ 2563 ν_μ CC events
◇ 1211 NC events

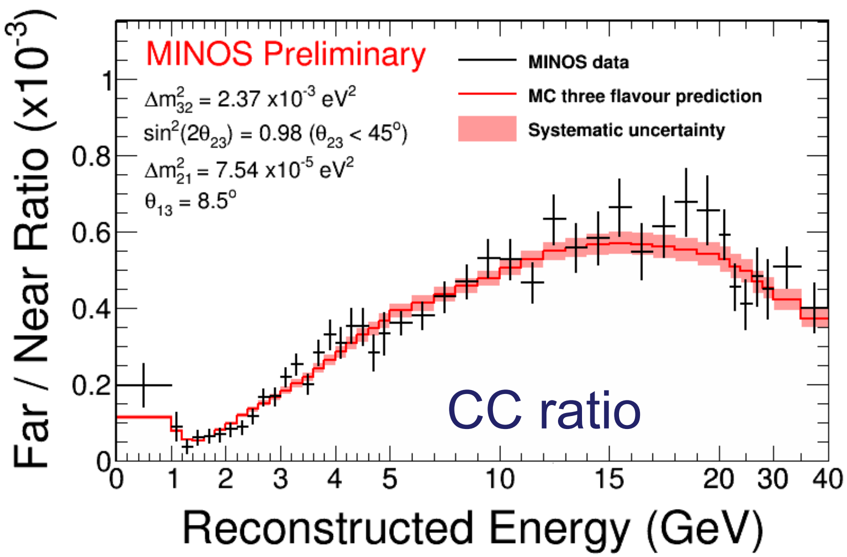
$$R = 1.08 \pm 0.11 \quad (0 \ \text{-} \ 40 \text{ GeV})$$

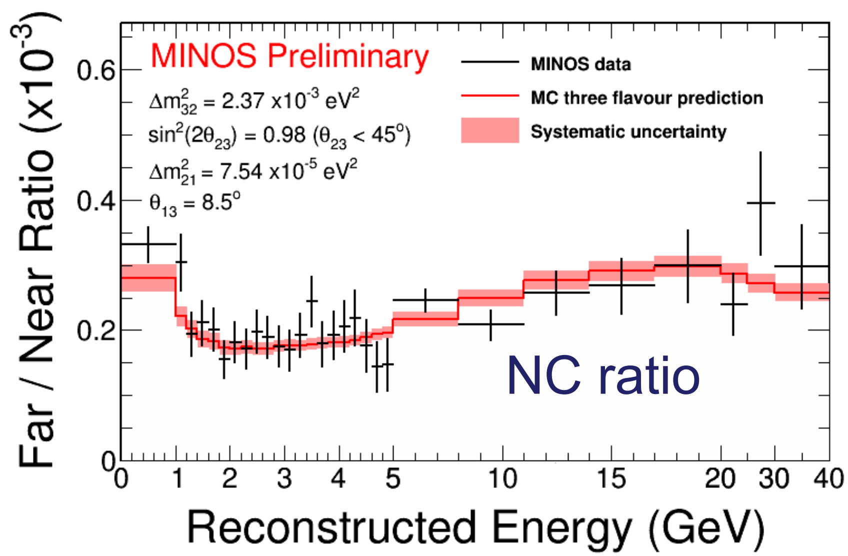
$$R = 1.11 \pm 0.10 \quad (0 \ \text{-} \ 3 \text{ GeV})$$

4. Analyses: search for sterile neutrinos

MINOS ratios of FD/ND energy spectra

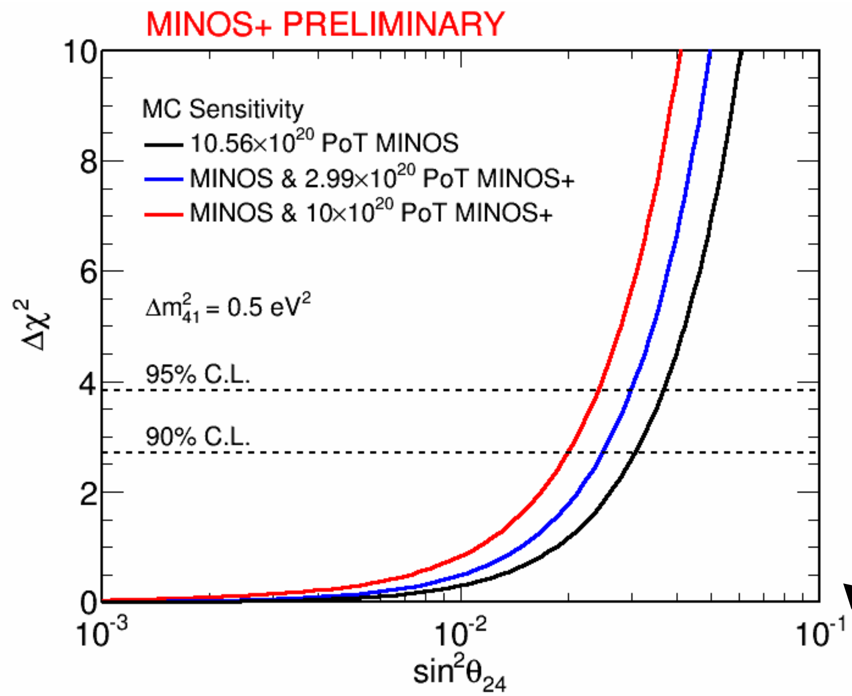
- Ratios of energy spectra at the Far Detector to Near Detector using ν_μ events.
- Observed (black crosses) vs predicted assuming no sterile neutrinos (red)



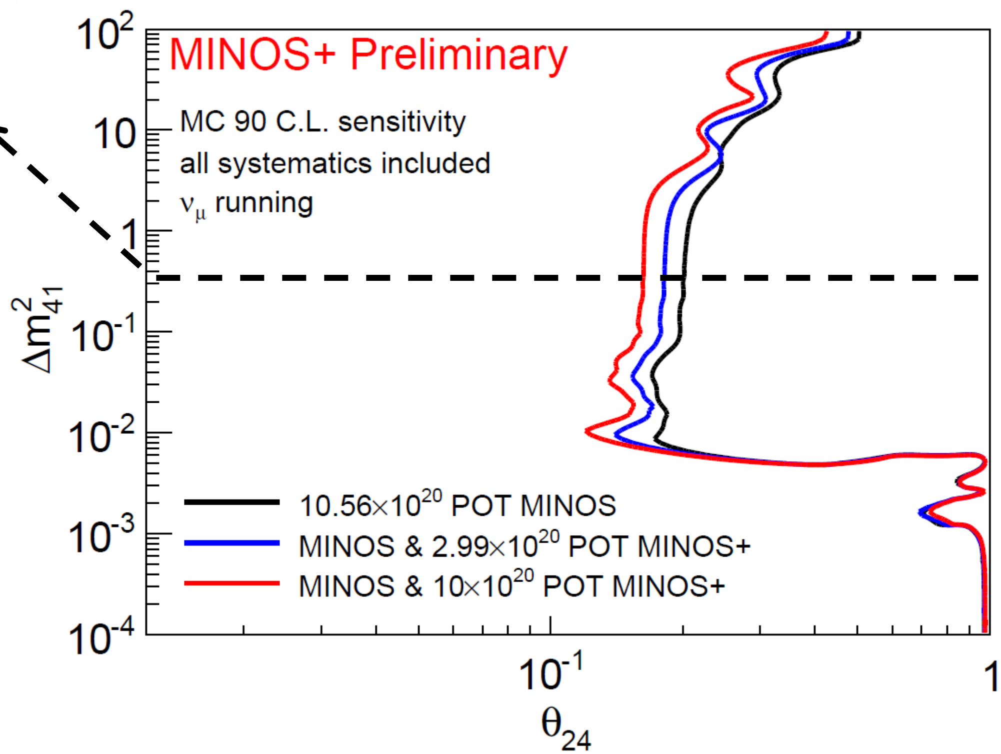


- Fit the observed FD/ND ratios for CC and NC
- Use $|\Delta m^2_{43}|$, $|\Delta m^2_{32}|$, θ_{23}, θ_{24}, θ_{34} and fix other parameters
- Systematics with the covariance matrix
- CLs use Feldman-Cousins recipe

4. Analyses: search for sterile neutrinos



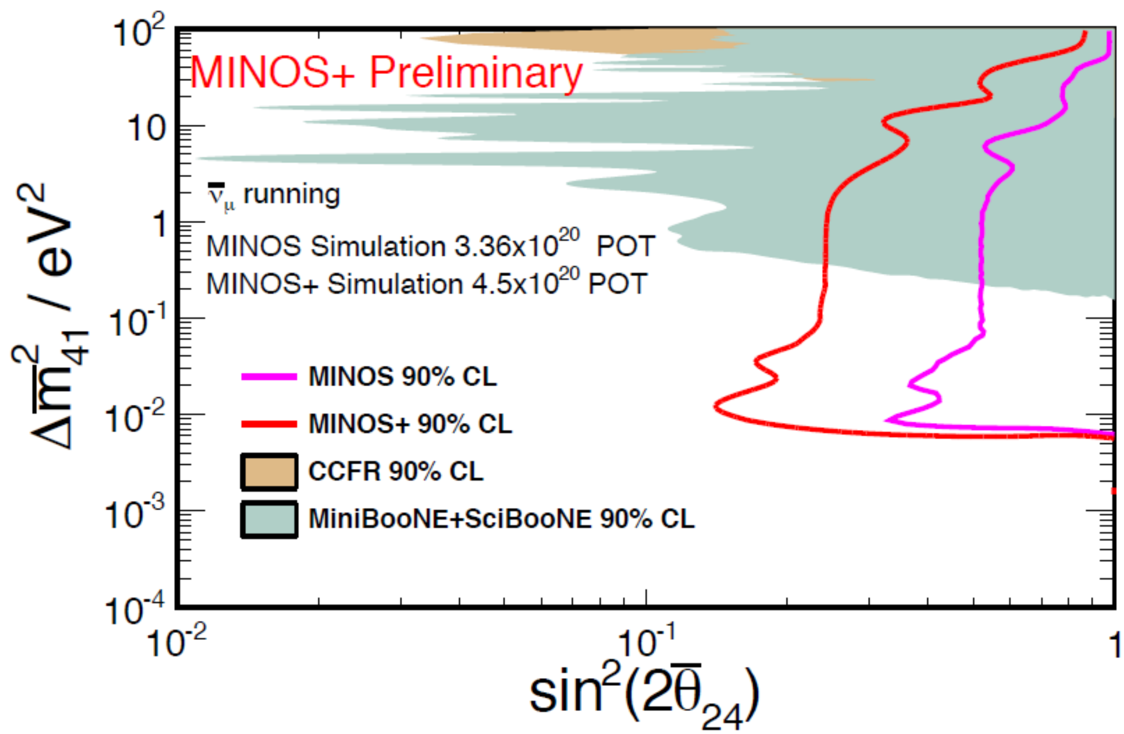
- MINOS & MINOS+ have collected over 6000 neutrino events in the Far Detector of either beam CC or NC interactions
- Still expect some improvement with the addition of new MINOS+ data
- However, we are approaching the limit of our sensitivity due to systematic uncertainties



- At specific values of Δm^2_{41}, we can set direct limits on the mixing angles
- At 0.5 eV^2, this is effectively a counting experiment and we are approaching the limit of our normalization uncertainty

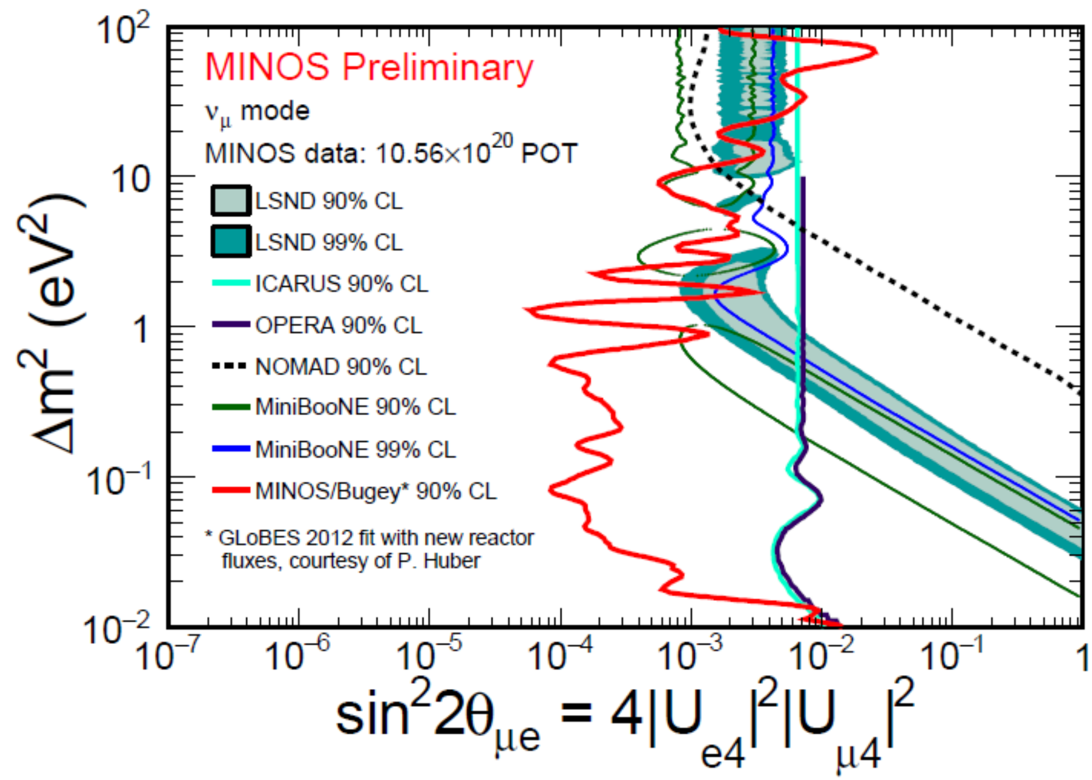
4. Analyses: search for sterile neutrinos

- Antineutrinos provide an important check on the CPT symmetry
- MINOS is able to explore new regions of parameter space
- Current antineutrino exposure is still small and this analysis is statistically limited
- A year of MINOS+ antineutrino data would have great impact on our sensitivity



4. Analyses: search for sterile neutrinos

- The LSND and MiniBooNE anomalies are sensitive to the product of $|U_{e4}|^2$, which drives ν_e disappearance, and $|U_{\mu 4}|^2$, which relates to ν_μ disappearance
- Results from neutrino disappearance in accelerator and reactor experiments can thus be combined to provide strong tests of the sterile neutrino interpretation of the short baseline ν_e appearance anomaly.
- By combining data from the MINOS and Bugey experiments, our results show strong tension between appearance and disappearance observations



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

- Due to it's long baseline, MINOS+ is sensitive to potential nonstandard interactions (NSI) with matter
- These additional interactions can be parameterized using ϵ parameters that incorporate the coupling strength of the new interaction and the mixing of the eigenstates for the non-standard interaction

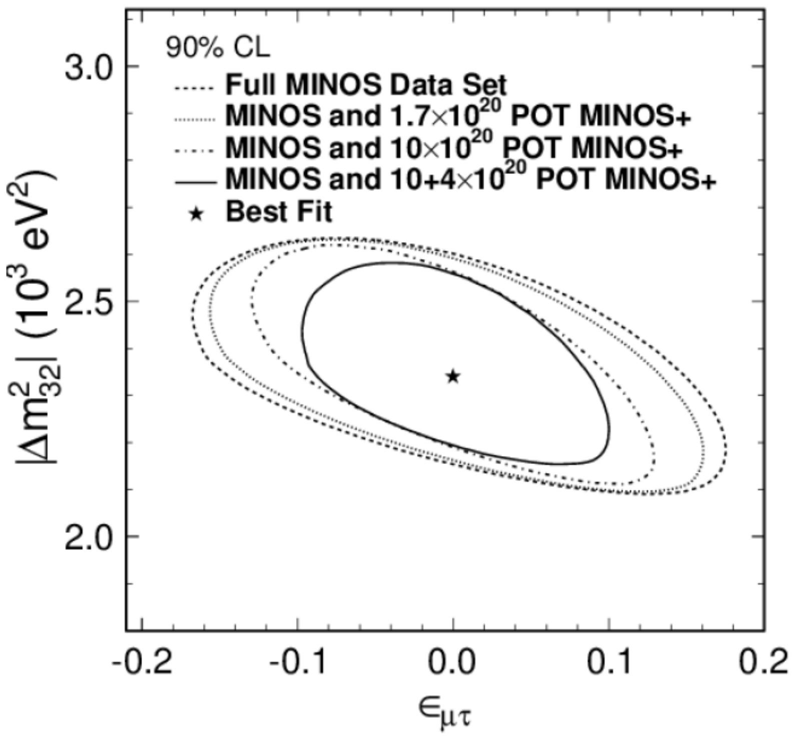
$$P_{\alpha\to\beta} = \left|\langle\nu_\beta|\, e^{-iHt}\,|\nu_\alpha\rangle\right|^2$$

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

Standard Matter Effect

NSI Matter Effect

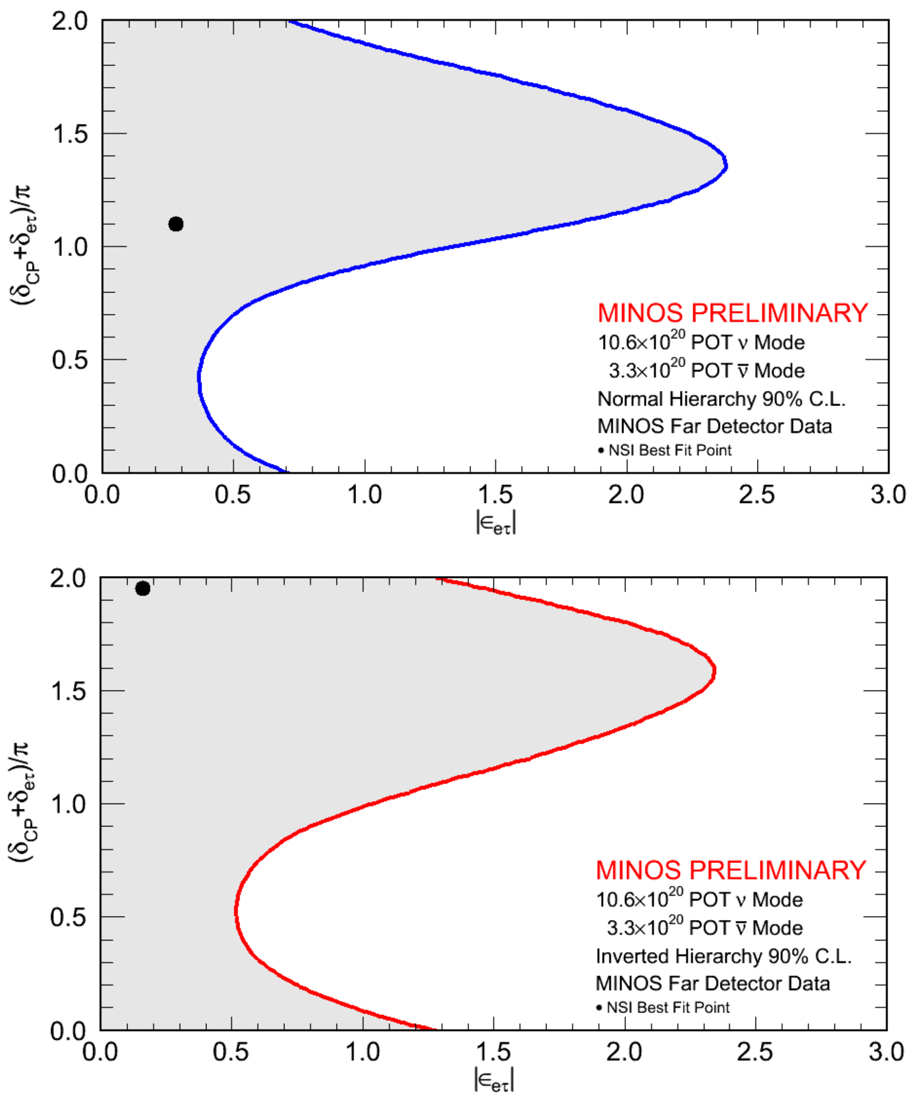
$$V_e = \sqrt{2}G_F n_e$$



- MINOS published constraints on the parameter
- $\varepsilon_{\mu\tau}$ by studying the ν_μ disappearance rate
- MINOS+ can significantly improves these constraints with 10^{21} POT of FHC
- MINOS+ can improve the contours even more with RHC data

- Will release results this year with Full MINOS Data Set and 1.7×10^{20} POT of MINOS+ data
- Next results will be with full MINOS+ FHC data set and then potential RHC data set…

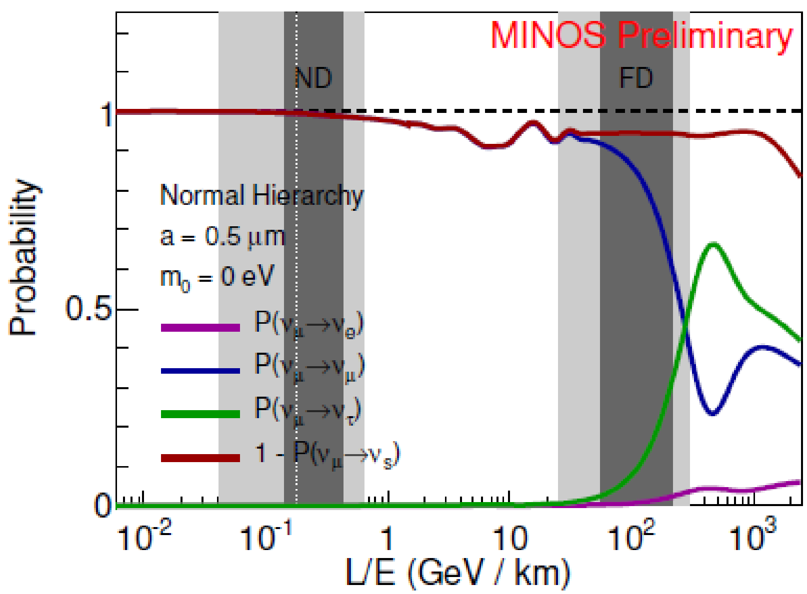
4. Analyses: searches for “exotics”: non-standard interactions

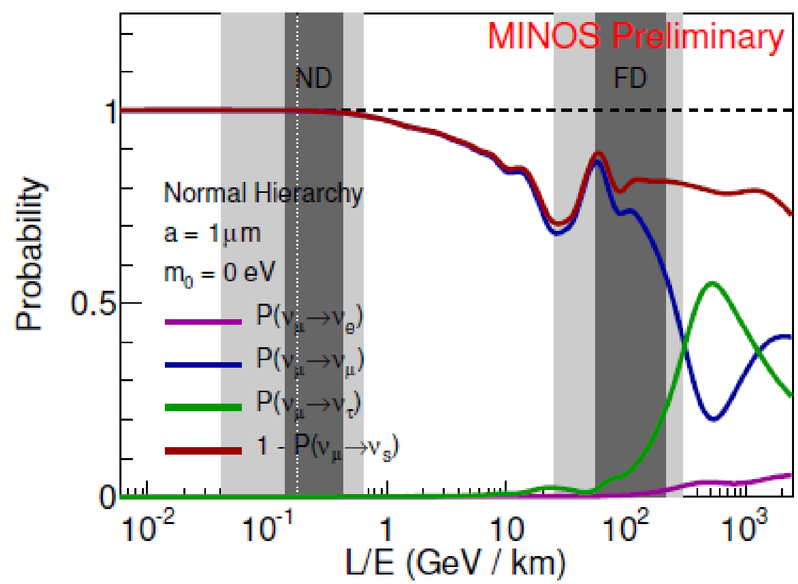


- Appearance data can be used to constrain $\varepsilon_{e\tau}$
- Will submit publication this year on results

4. Analyses: searches for “exotics”: large extra dimensions

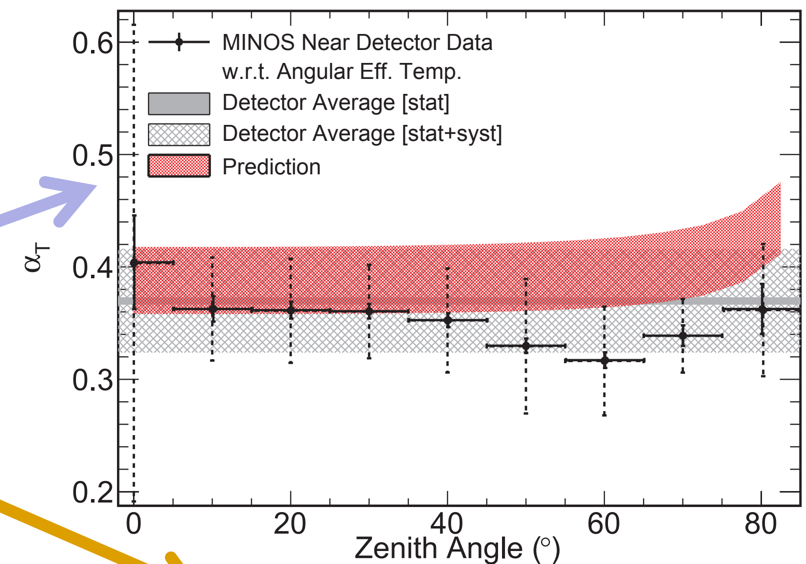
- If large extra dimensions exist, then the active neutrinos can oscillate to the KK-states of the right handed neutrinos.
- The oscillations to these KK-states are governed by the mass (m_0) of the lightest neutrino and the size (a) of the extra dimensions
- In the approximation that there is only one extra dimension the oscillation probability is as shown

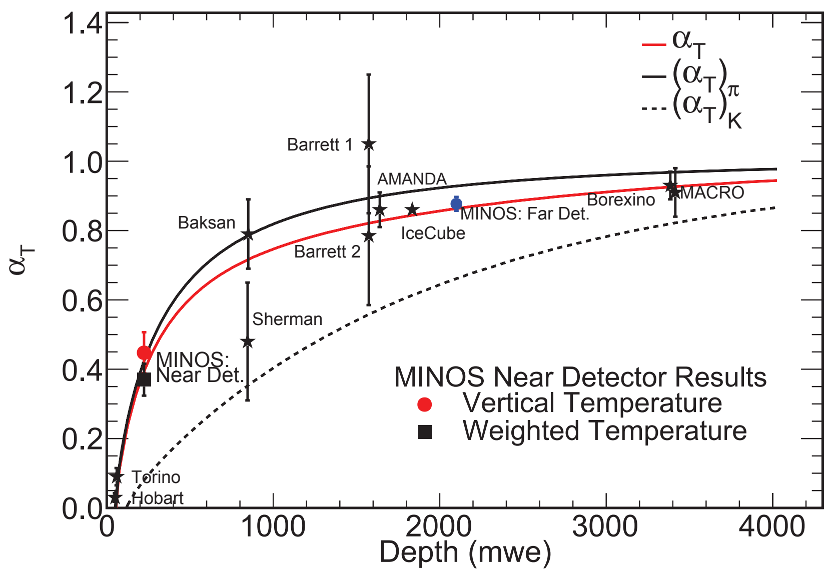


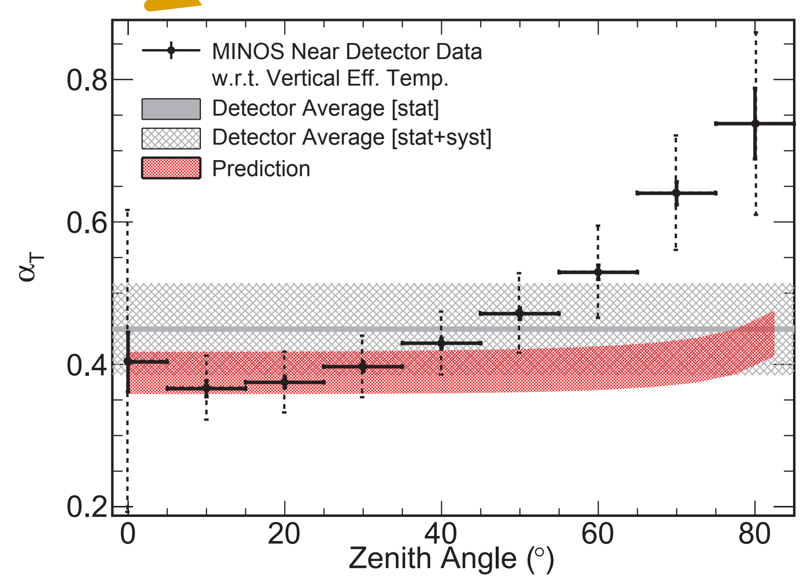


4. Analyses: UP: Seasonal Variations in the MINOS ND

- Earlier MINOS measured seasonal variations with the far detector and showed sensitivity to the π/K ratio
- The correlation of the muon rate with Temperature is $\alpha_T \equiv \Delta N_\mu/\Delta t_{eff}$
- For shallow depths, the zenith angle matters, and MINOS came up with a **new** method to handle this better than **before**.
- $\alpha(\text{zenith}) = 0.387 \pm 0.003 \pm 0.052(\text{sys})$
- Published Phys. Rev. D 90, 012010 (2014)







4. Analyses: UP: multiple μ charge ratio

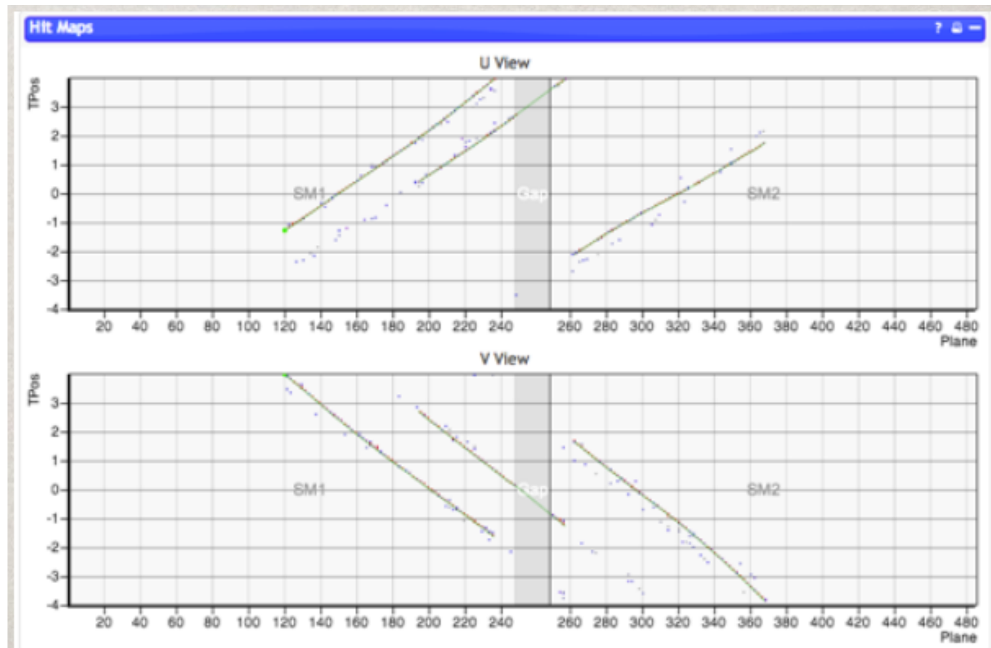
- Previously, MINOS measured the first rise in the single muon charge ratio at TeV energies (previously 1.28 from 100 MeV - 100 GeV, 1.37 at ~1TeV in MINOS) and showed its sensitivity to the K+/K- ratio
- For multiple muons, extensive Monte Carlo was needed to determine the reconstruction efficiency and the charge ID efficiency

For multiple muon events the measured charge ratio is:

$$R_{meas} = 1.091 \pm 0.005(stat.)$$

and the efficiency corrected charge ratio is:

$$R_{true} = 1.104 \pm 0.007(stat.)^{+0.009}_{-0.010}(syst.)$$



- Paper under internal Review

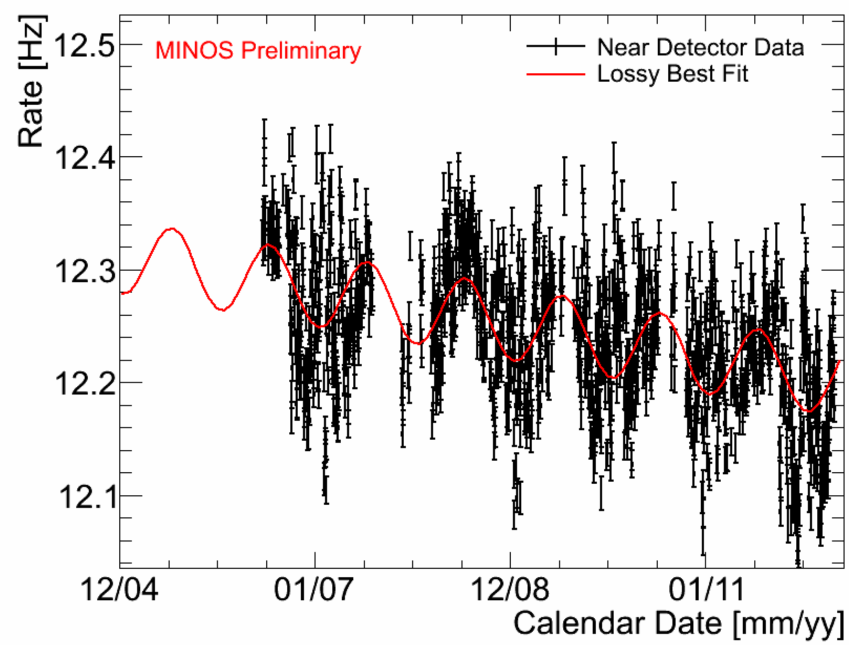
4. Analyses: UP: solar cycle variations?

- During analyses for seasonal variations, we also observed a small long term decline in the muon rates in both ND and FD, described by “f” in:

$$R = R_0(1 - fT)\left(1 + A\cos\left(\left(\frac{2\pi}{365.25}\right)(x - x_0)\right)\right)$$

Best Fit for the Near Detector
f=(0.102+/-0.001)%/year

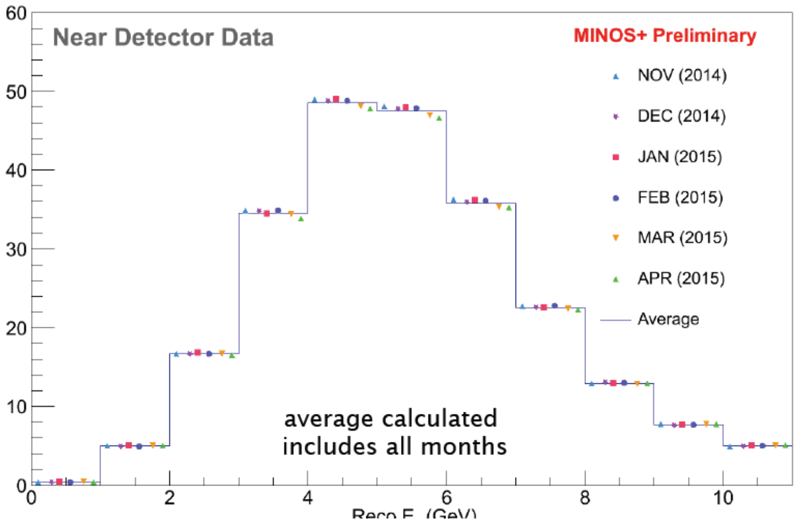
Best Fit for the Far Detector is
f=(0.014+/-0.004)%/year

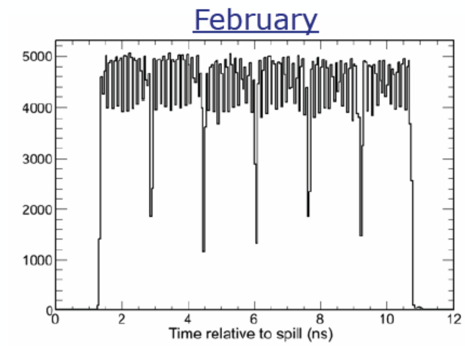


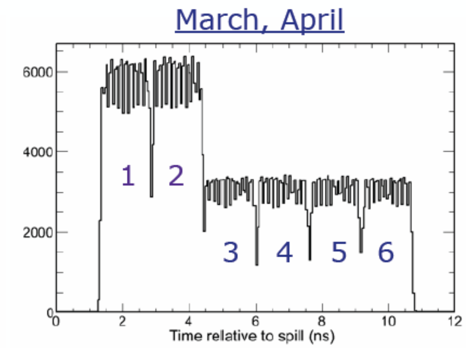
- It is consistent with an effect due to changes in the rigidity cutoff of the solar wind due to the solar cycle.
- Other explanations are possible.
- This analysis could benefit from additional data through the solar cycle.

◆ Slip-stacking (instantaneous intensity) issues?

Neutrino Energy Spectrum Stability (PQ and NQ)

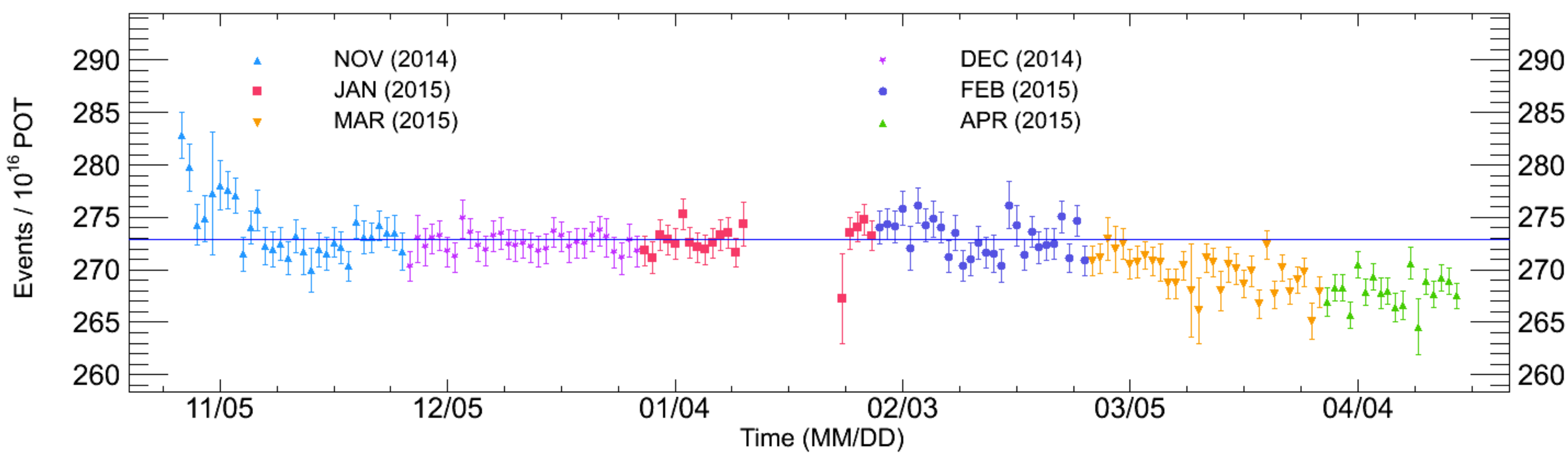






Is it beam?
Is the the detector/reco?
Is it both?

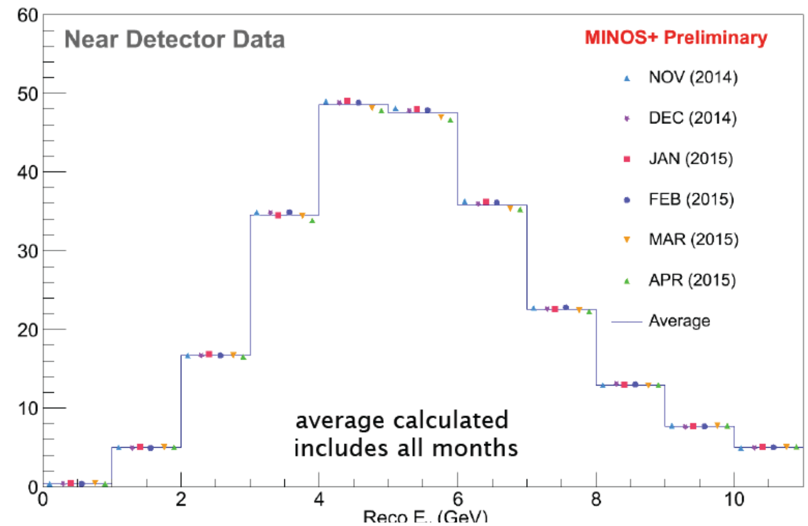
Total Muon Events Per POT v.s. Time



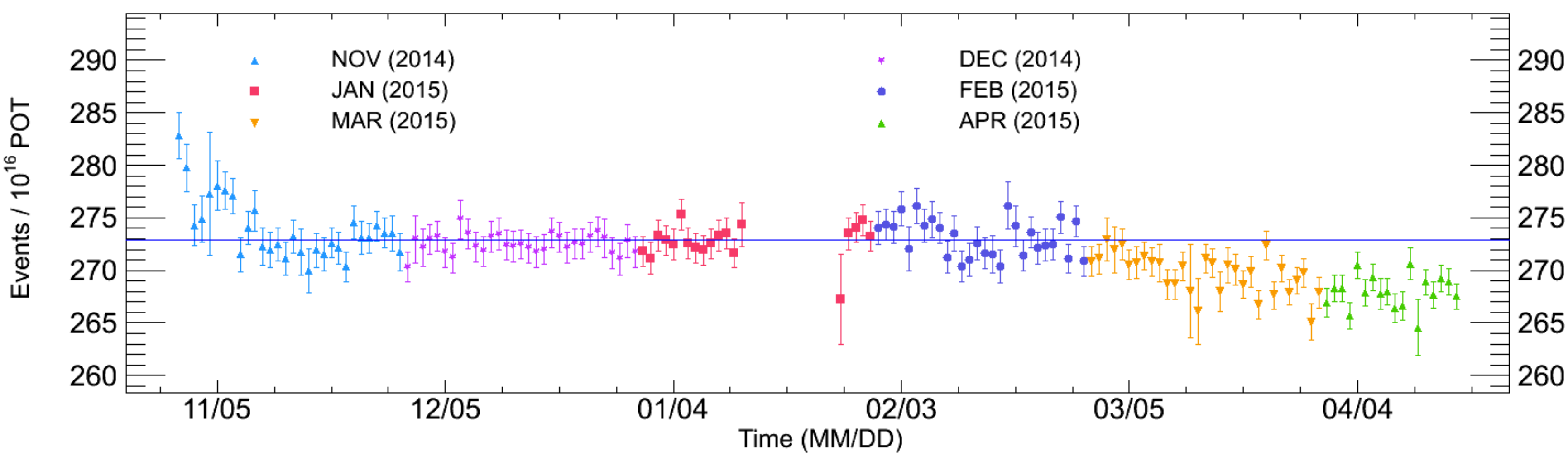
4. Operations – challenges (slip-stacking)

◆ Slip-stacking (instantenous intensity) issues?

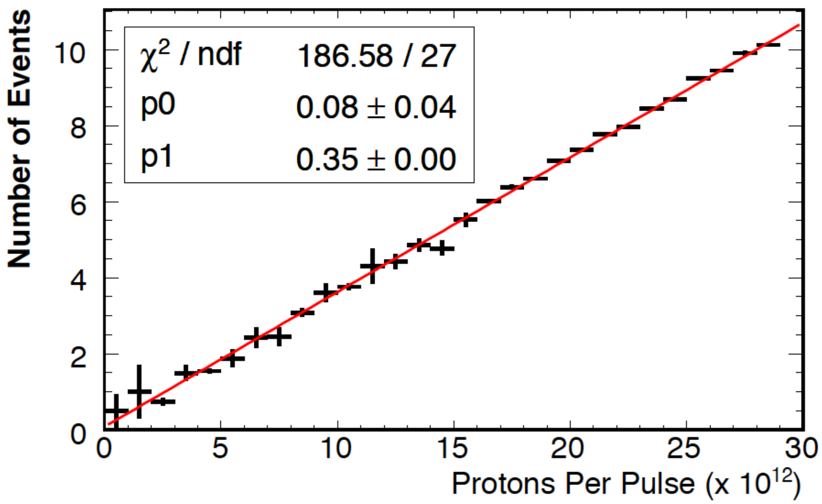
Neutrino Energy Spectrum Stability (PQ and NQ)

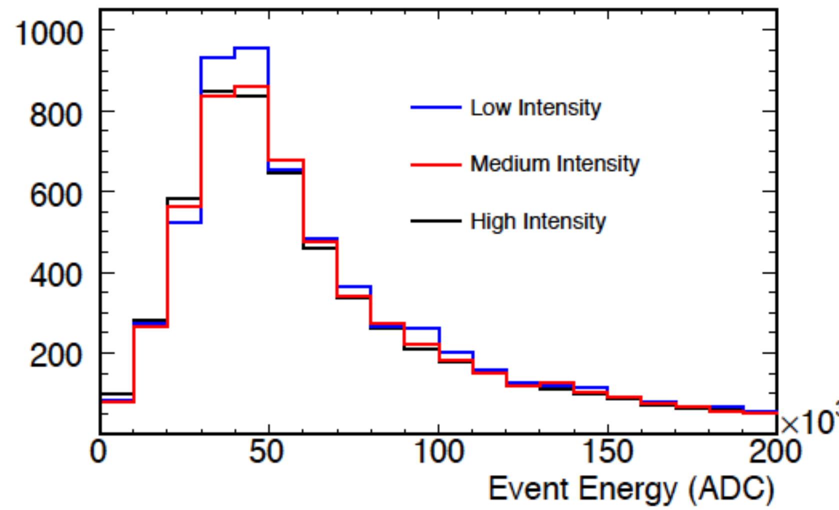


Total Muon Events Per POT v.s. Time



◆ From Tom Osiecki's thesis/talks and in DocDB 1542





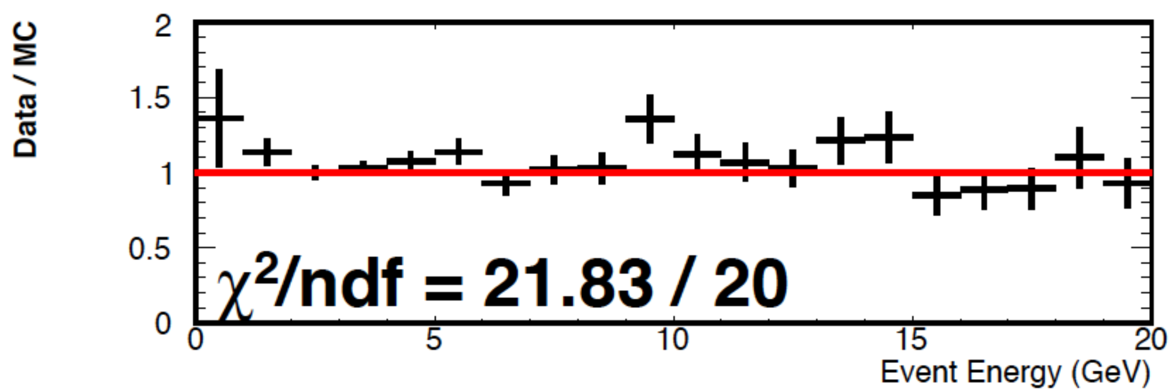
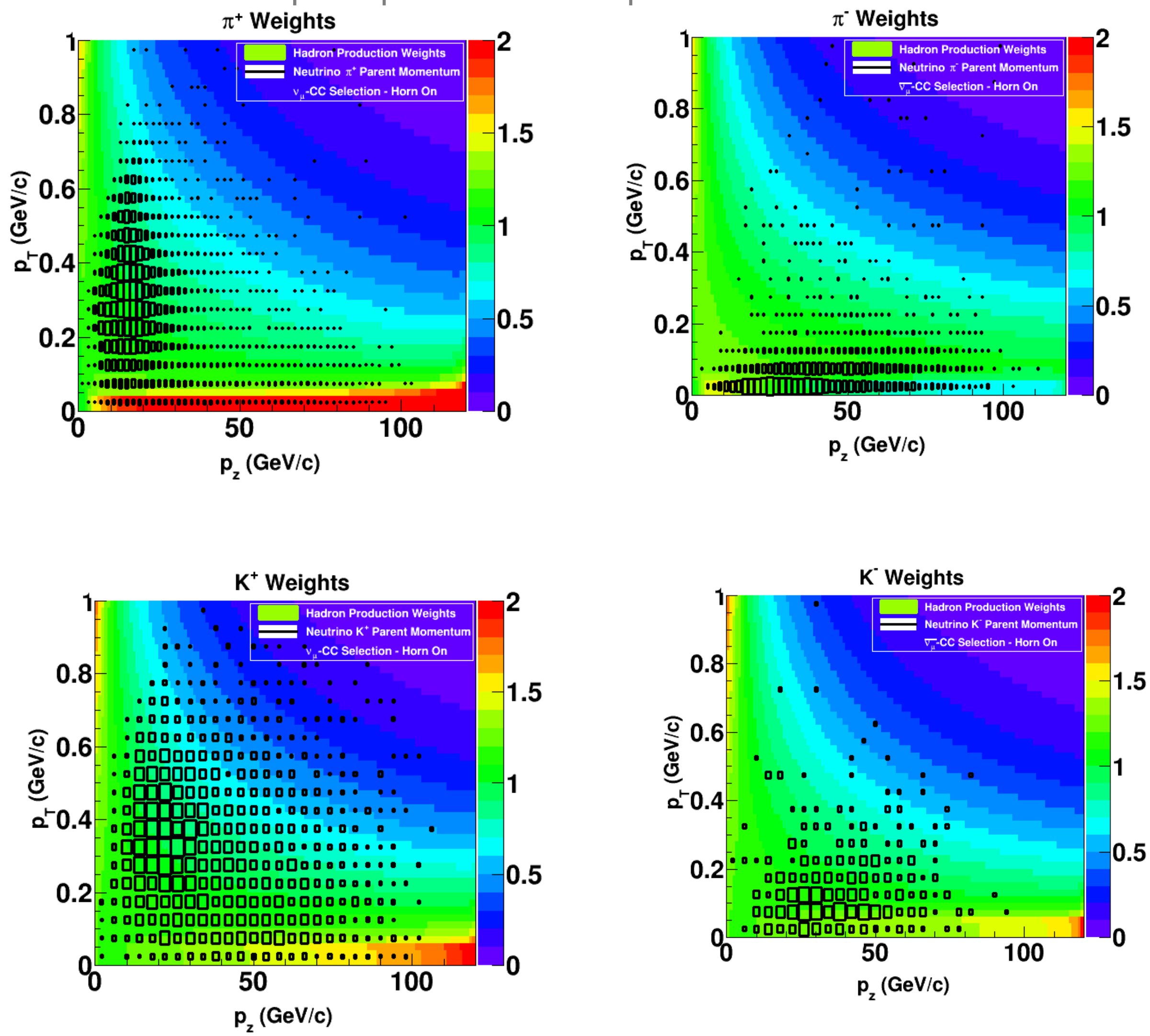


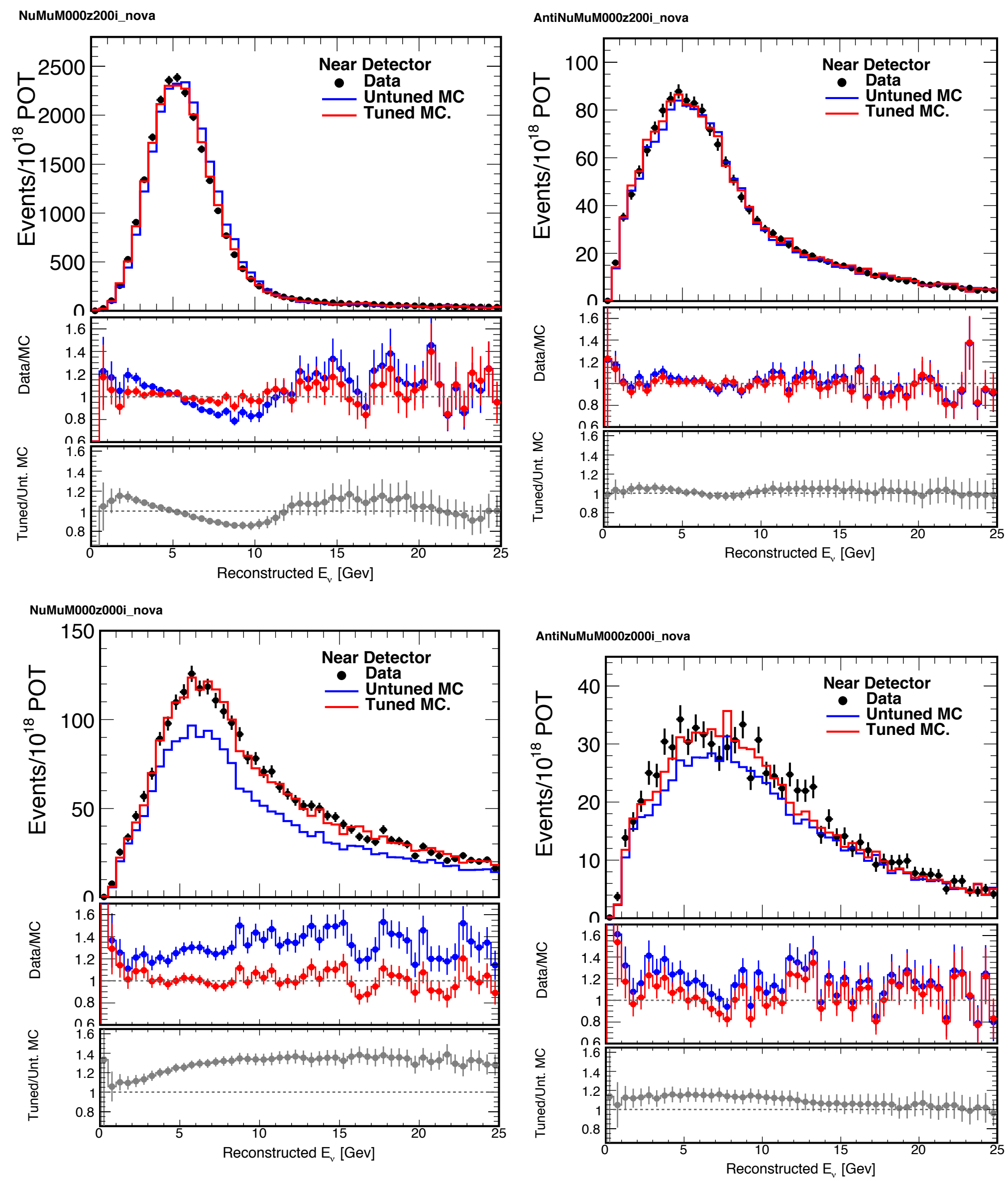
Figure 6.18: Comparison of the charged current total energy for low and high intensities.

- The MINOS+ Beam Fits improve the Data/MC agreement significantly
- We reweight the neutrinos based on fitting the hadron production of the parent hadrons in pT pZ phase space as they exit the NuMI target

Hadron Production weights from beam fits with superimposed neutrino parents – horn on

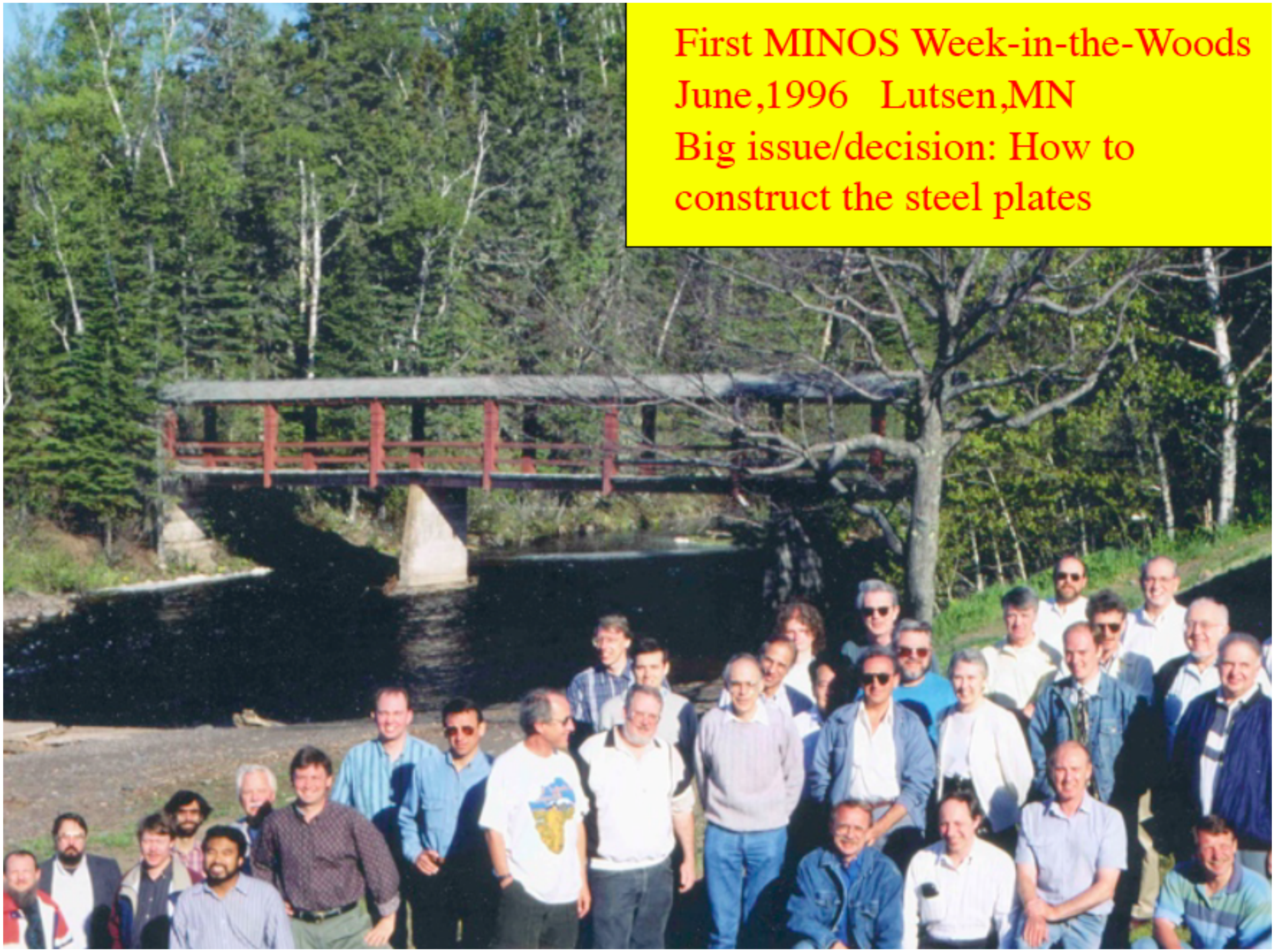


- The MINOS+ Beam Fits improve the Data/MC agreement significantly
  - ✓ Chi2/NDF=265.2/251



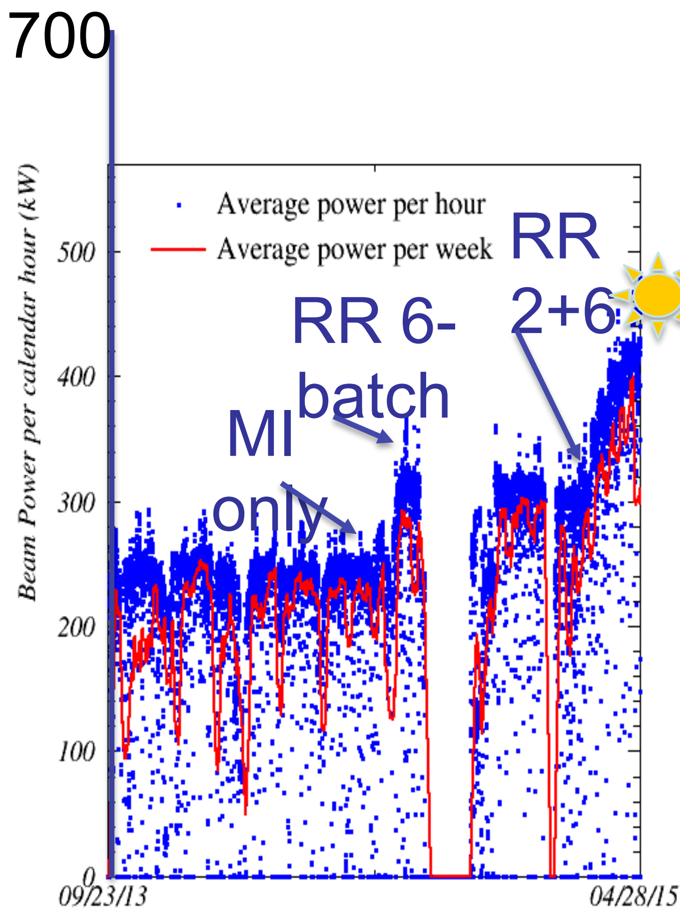
- Blue – MC before fit
- Red – MC after fit
- Gray – Change to MC

MINOS is reaching a “drinking” age (now 20)

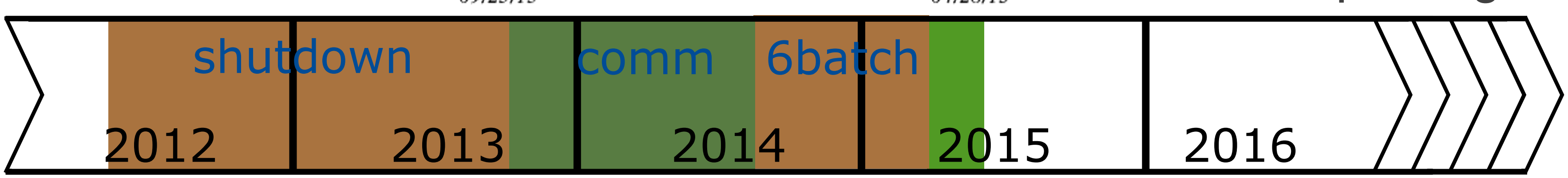


1. Beam – from Phil A. in lieu of his talk

Roadmap to 700kW

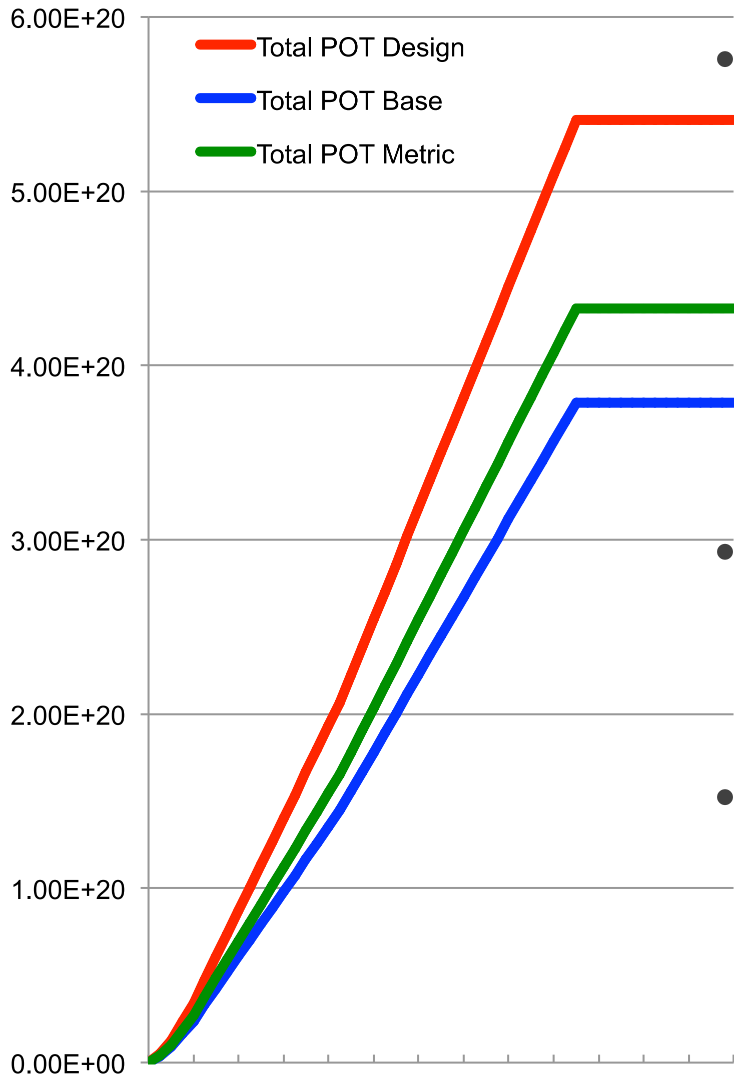


- February 2016
  - 6+6 slip-stacking operational at 700kW (4.3E12 per booster batch)
  - Needs 9.8 Hz booster pulsing



1. Beam - from Phil A. in lieu of his talk

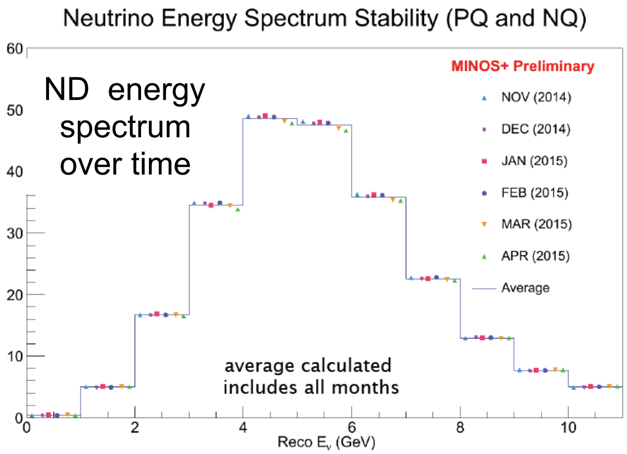
FY16 projections

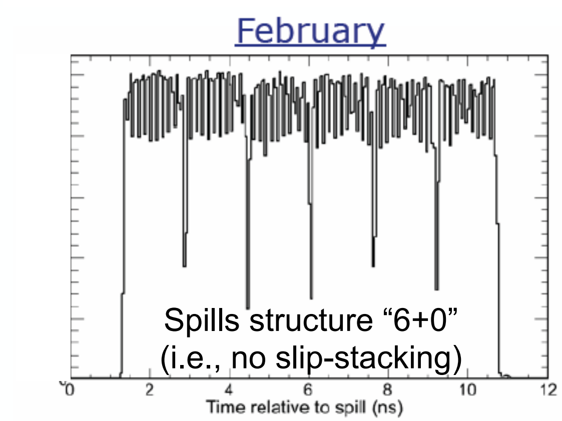


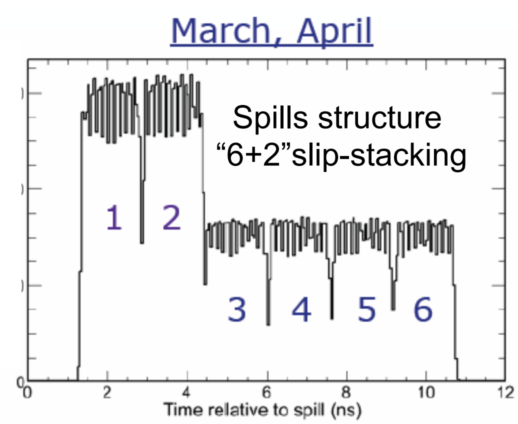
- These are still in draft status, but are pretty realistic
  - Newly recalculated
  - Red "design" curve: everything goes well
  - Blue "base" curve: we get unlucky
- Major difference between April 2014 and now is that the summer shutdown got longer
- My personal guess is that we might have a total of 11E20 protons in MINOS+ by July 2016
  - (right now, we have 6E20)

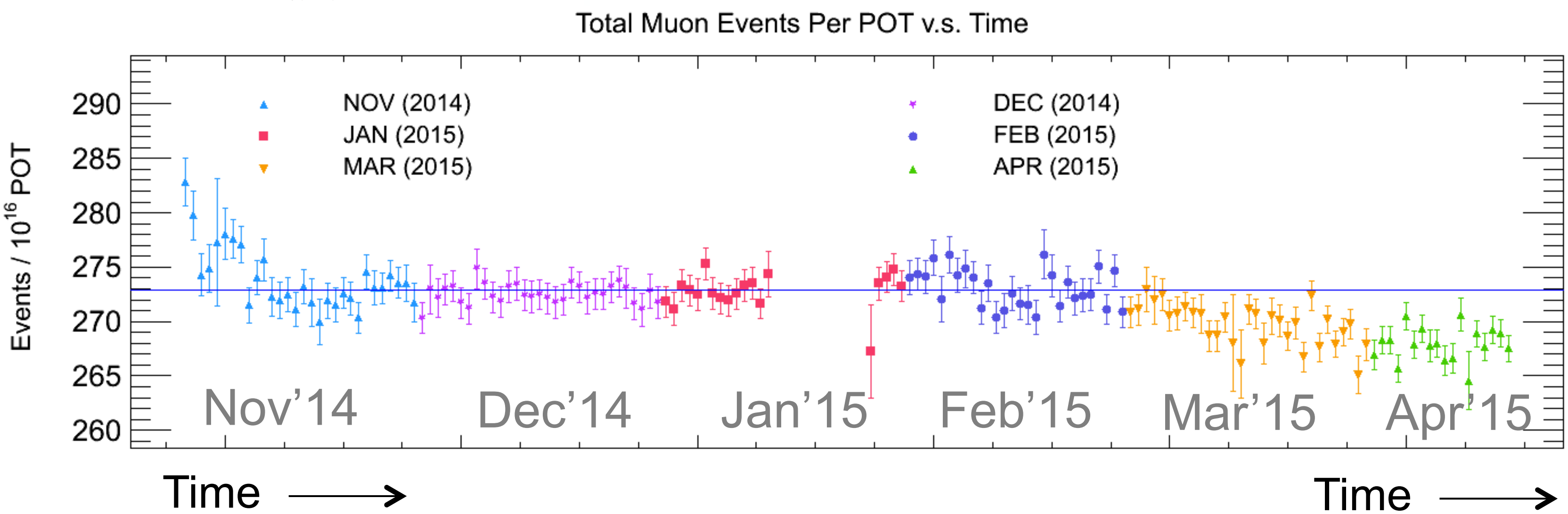
4. Analyses: a slip-stacking issue …

- While monitoring the beam …
- Likely detector reco? Any beam effects? Or both?
- Need proper MC (with correct instantaneous intensity) --> intense effort









END