Benefits of a Near Detector for JUNO

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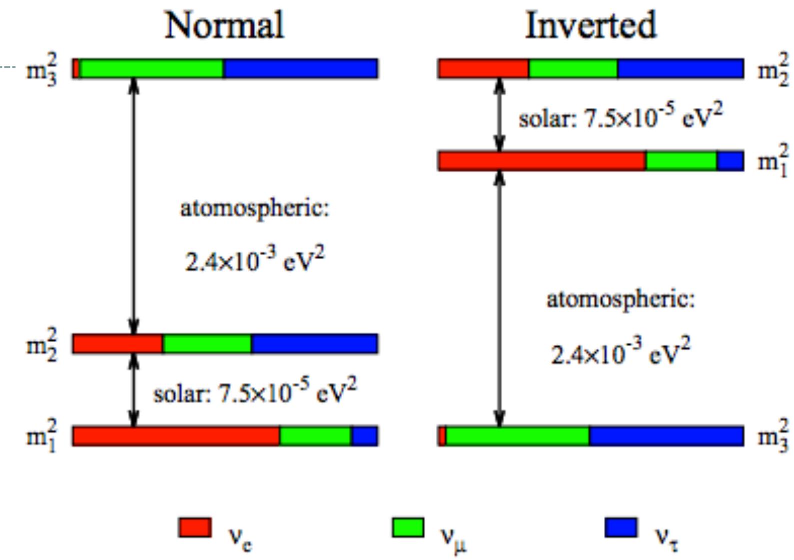
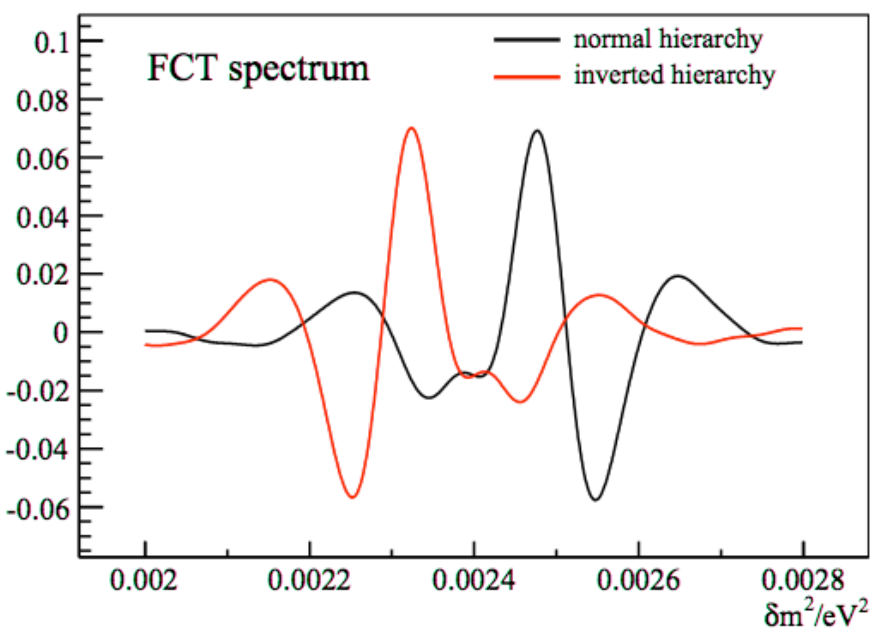
Neutrino Oscillation Parameters

- 6 independent oscillation parameters in three-flavor oscillation
  - 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
  - 2 mass-differences: Δm^2_{21}, Δm^2_{31}
  - 1 CP-violating phase: δ
- Only two remain largely unknown:
  - Sign of Δm^2_{31}
  - δ

Neutrino Mass Hierarchy



- $\Delta m^2_{21} \sim 7\times10^{-5}$ eV^2, $|\Delta m^2_{31}| \sim 2\times10^{-3}$ eV^2
- Normal (NH): $\Delta m^2_{31} > 0$
- Inverted (IH): $\Delta m^2_{31} < 0$

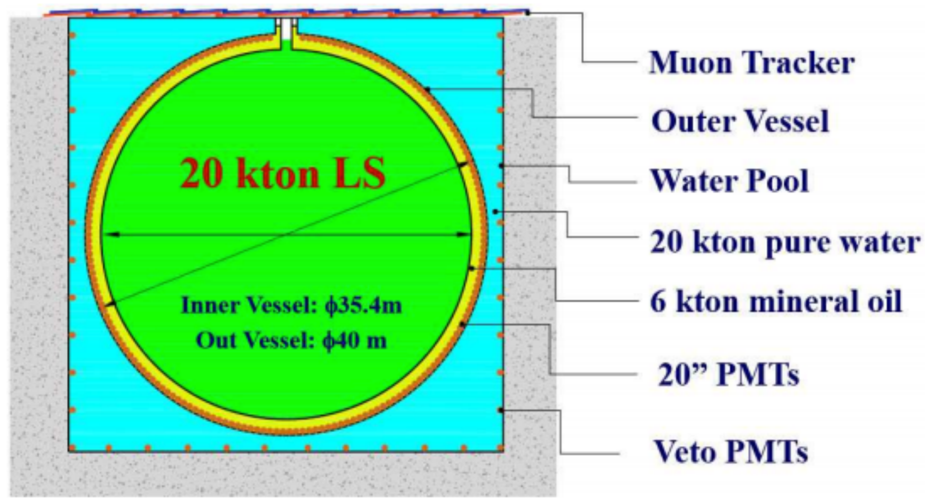


- Determination Method:
  - $L \sim 50$ km
  - Observe Beats in Oscillation Frequencies
  - Energy resolution needed: $\left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim 0.03$

JUNO Collaboration (arXiv:1507.05613)

JUNO

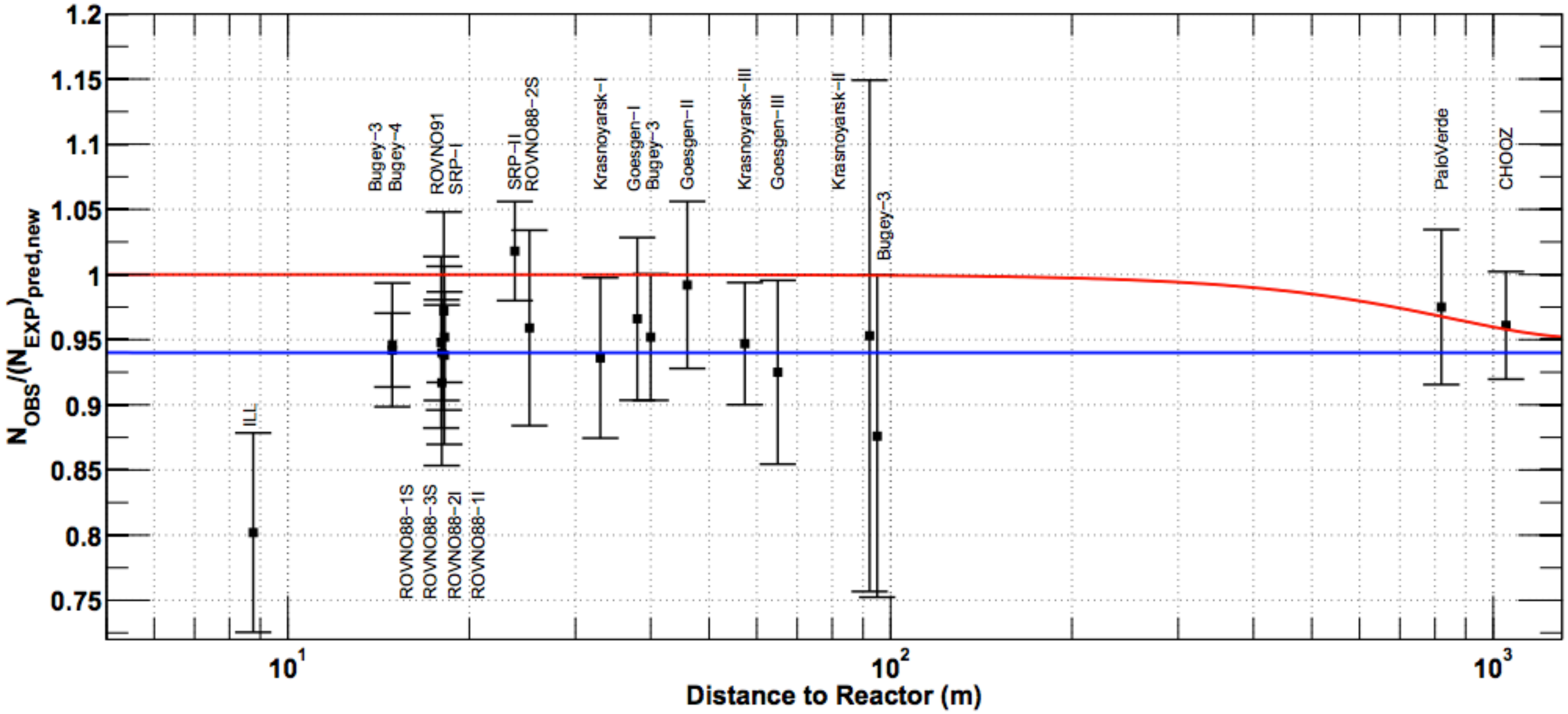
- Jiangmen Underground Neutrino Observatory
- Detector needs 3%/√E energy resolution to determine the neutrino mass hierarchy
- 20 kton of Liquid Scintillator
- Measure $\bar{\nu}_e$ disappearance from 2 reactors (each at 53 km):



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{12})\cos^4\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right) - \sin^2(2\theta_{13})\left[\cos^2\theta_{12}\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)\right]$$

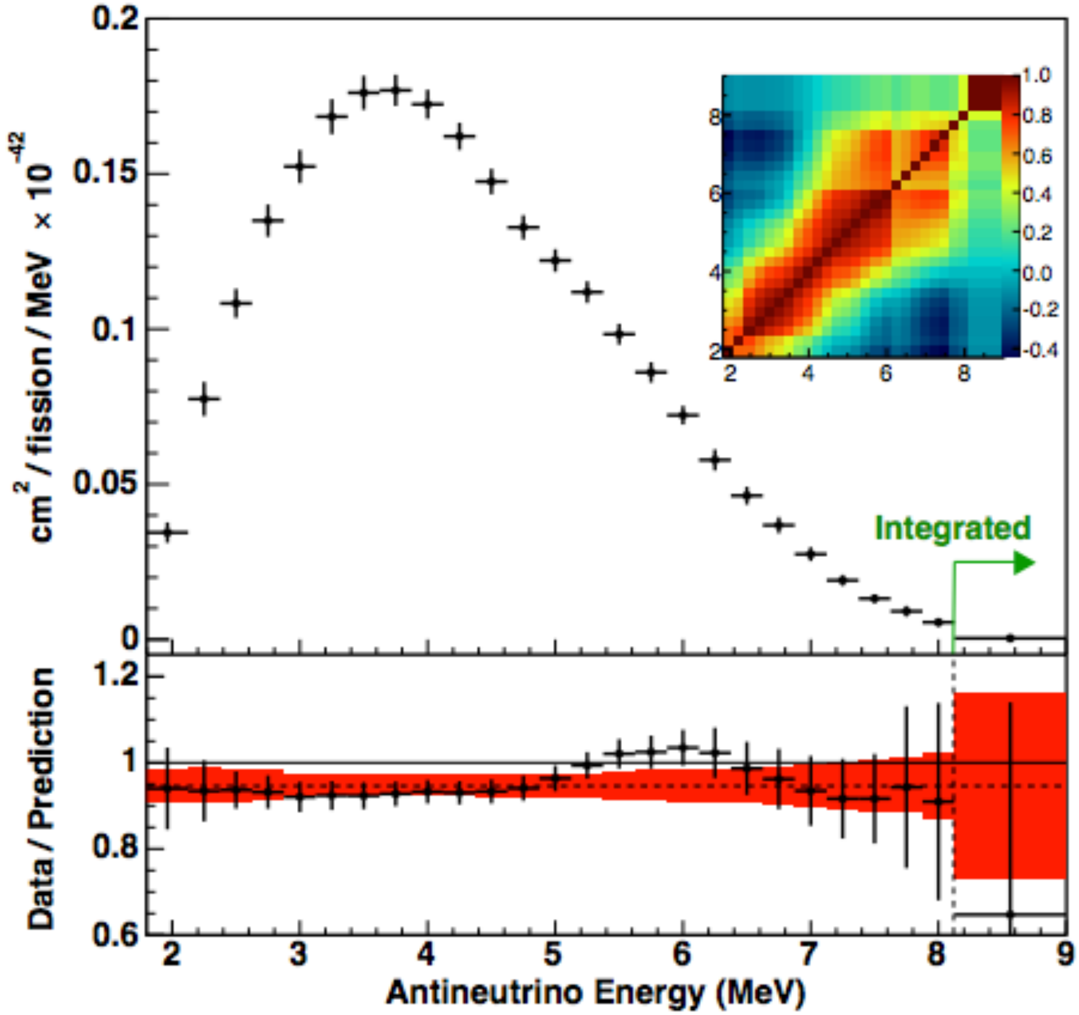
Reactor Antineutrino Anomaly

- Disagreement between measured antineutrino energy spectrum from nuclear reactors and updated theoretical calculations



Mention, et al. (arXiv:1101.2755)

Reactor Antineutrino Anomaly Cont'd



Daya Bay Collaboration (arXiv:1508.04233)

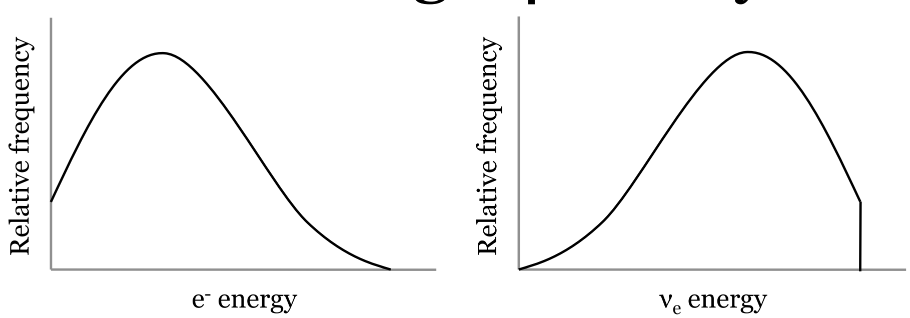
- Possible Implications:
  - shows ignorance of what is going on in the reactor
    - (i.e. reactor ν_e spectrum)
  - something is happening to the neutrinos on short length scales after creation
    - (e.g. sterile ν)

JUNO Cont'd

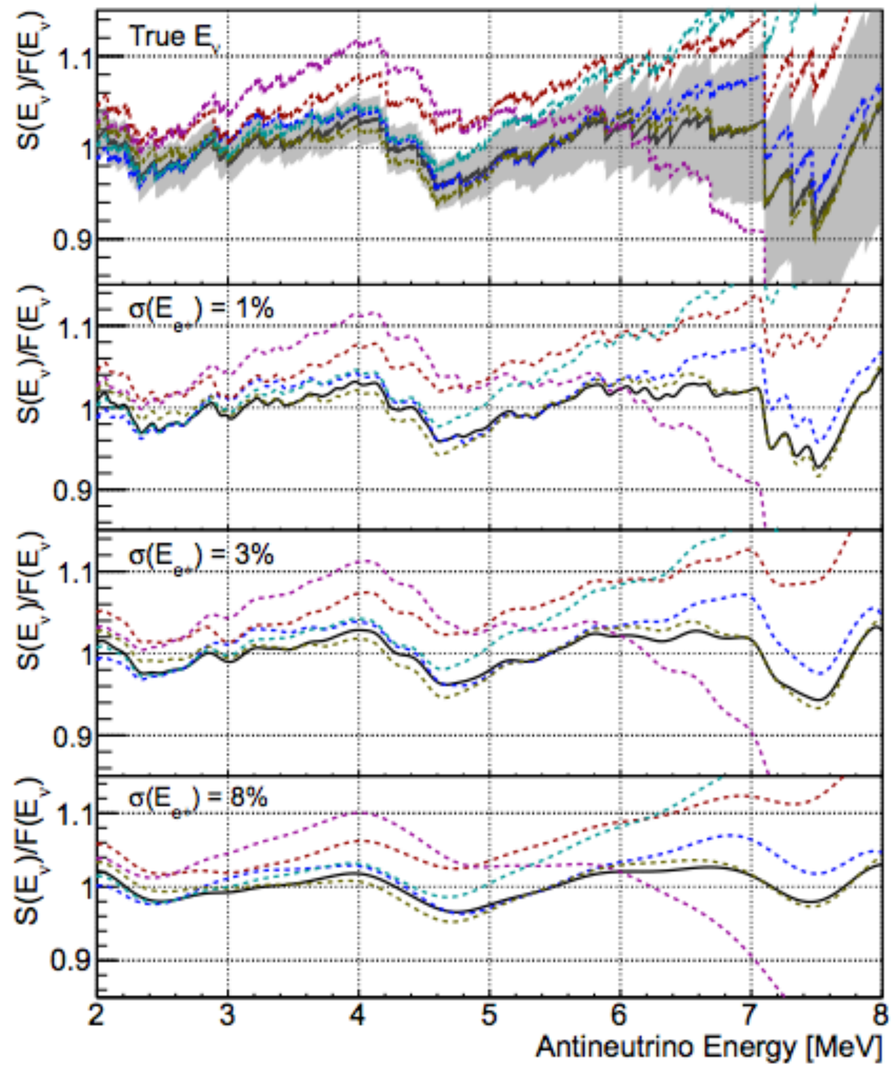
- Had been proposing to use Daya Bay data to obtain a reference neutrino energy spectrum
  - Daya Bay used virtually identical detectors for near and far detectors
  - Spectrum measured at energy resolution of $8\%/\sqrt{E}$

Possible Problem

- Fine structure in antineutrino energy spectrum coming from nuclear reactor
  - For single β-decay:



  - Obscured at 8%/√E
  - Possibly visible at 3%/√E



Dwyer, et al. (arXiv:1407.1281)

JUNO Simulations

- Used GLoBES
- JUNO's specs for far detector
  - 20 kt liquid scintillator
  - 53 km away from source
  - $3\%/\sqrt{E}$ energy resolution
- Added near detector
  - 5 ton liquid scintillator
  - 0.5 km away from source
  - Varied energy resolution

JUNO Simulations Cont'd

- Rate data divided into 100 energy bins

  $\phi_i^I \equiv$ detection rate in ith bin

- Nuissance parameters added for each bin

$$\tilde{\phi}^I_{fit_i} = (1+\xi_i)\left(\phi^I_{fit_i}\right)^o, \text{ where } \phi^I_{fit_i} = \sum_j M_{ij}\tilde{\phi}^I_{fit_j}$$

  - Accounts for uncertainty in energy spectrum

- Accounted for non-linearity in detector energy response $\frac{E_{rec}}{E} = 1 + \sum_{k=0}^{n} \alpha_k E^k$

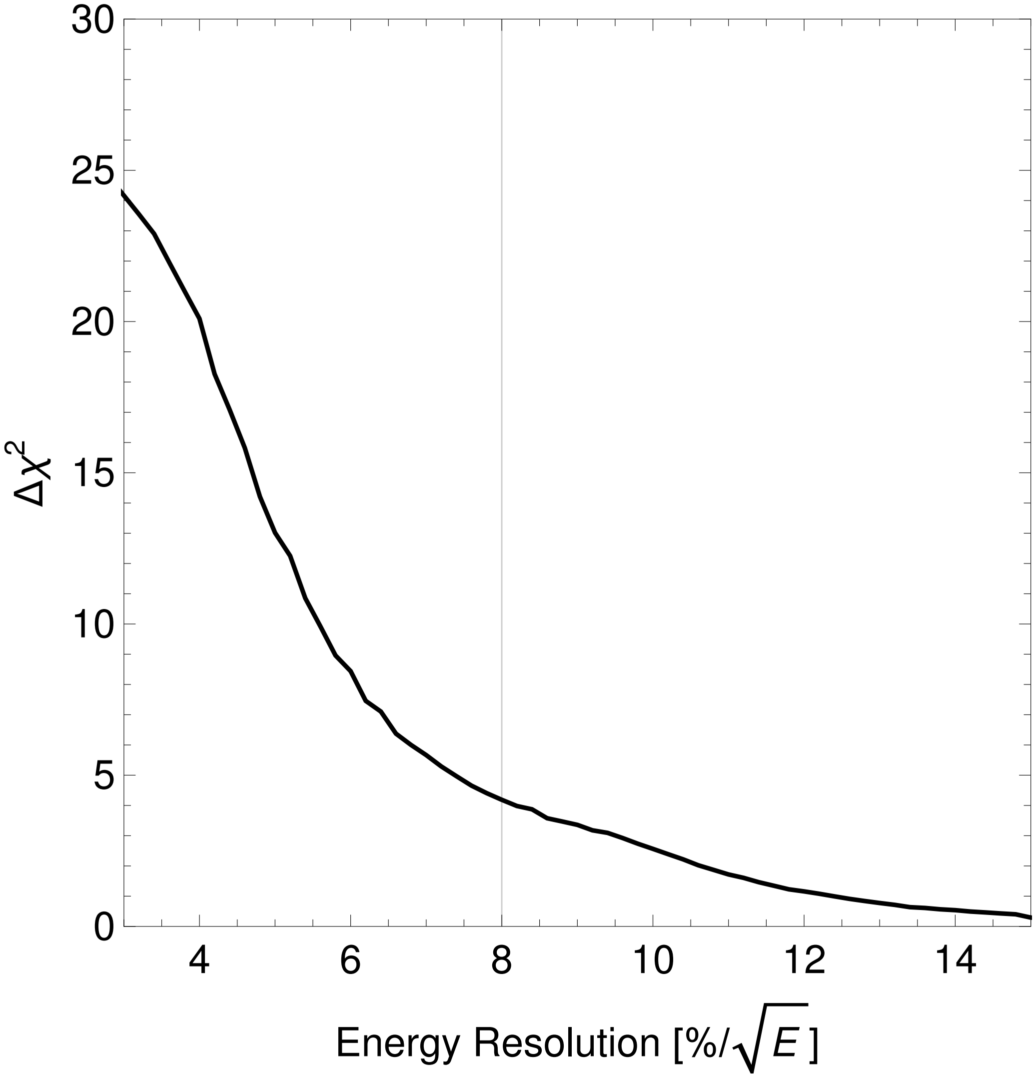
  - Allowed differences between detectors

JUNO Simulations Cont'd

- Huber-Mueller model used for source antineutrino energy spectrum
- Assumed normal hierarchy to be true for generating data
- Calculated χ^2 values for fits using the normal and inverted hierarchies

$$\chi^2 = \sum_{i,I} \frac{\left(\phi^I_{true_i} - \phi^I_{fit_i}\right)^2}{\phi^I_{true_i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2$$

Results



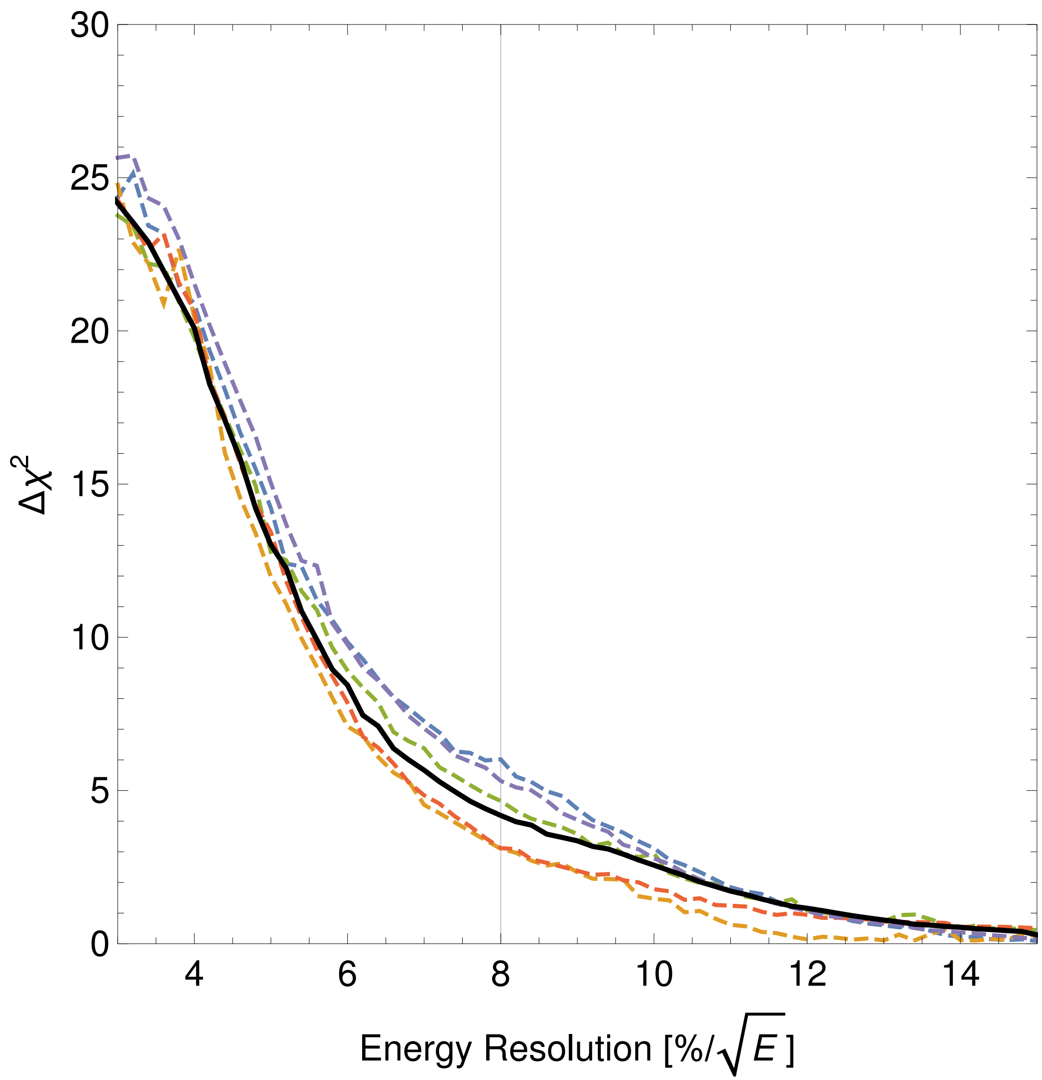
30
25
20
15
10
5
0
$\Delta\chi^2$
4
6
8
10
12
14
Energy Resolution [%/$\sqrt{E}$]

Consistency Check #1

- Used alternative spectra to generate data
  - Add up antineutrino spectra produced from a randomly chosen (with weights) sample of beta decay branches
  - Renormalize spectrum to match Huber-Mueller model at $8\%/\sqrt{E}$ energy resolution
- Fit data to Huber-Mueller model
  - Meddled with internal structures of GLoBES

Consistency Check #1

- Generated data with alternative spectra
- Fit using Huber-Mueller model



Consistency Check #2

- No Near Detector
- Used Daya Bay's Covariance Matrix, instead

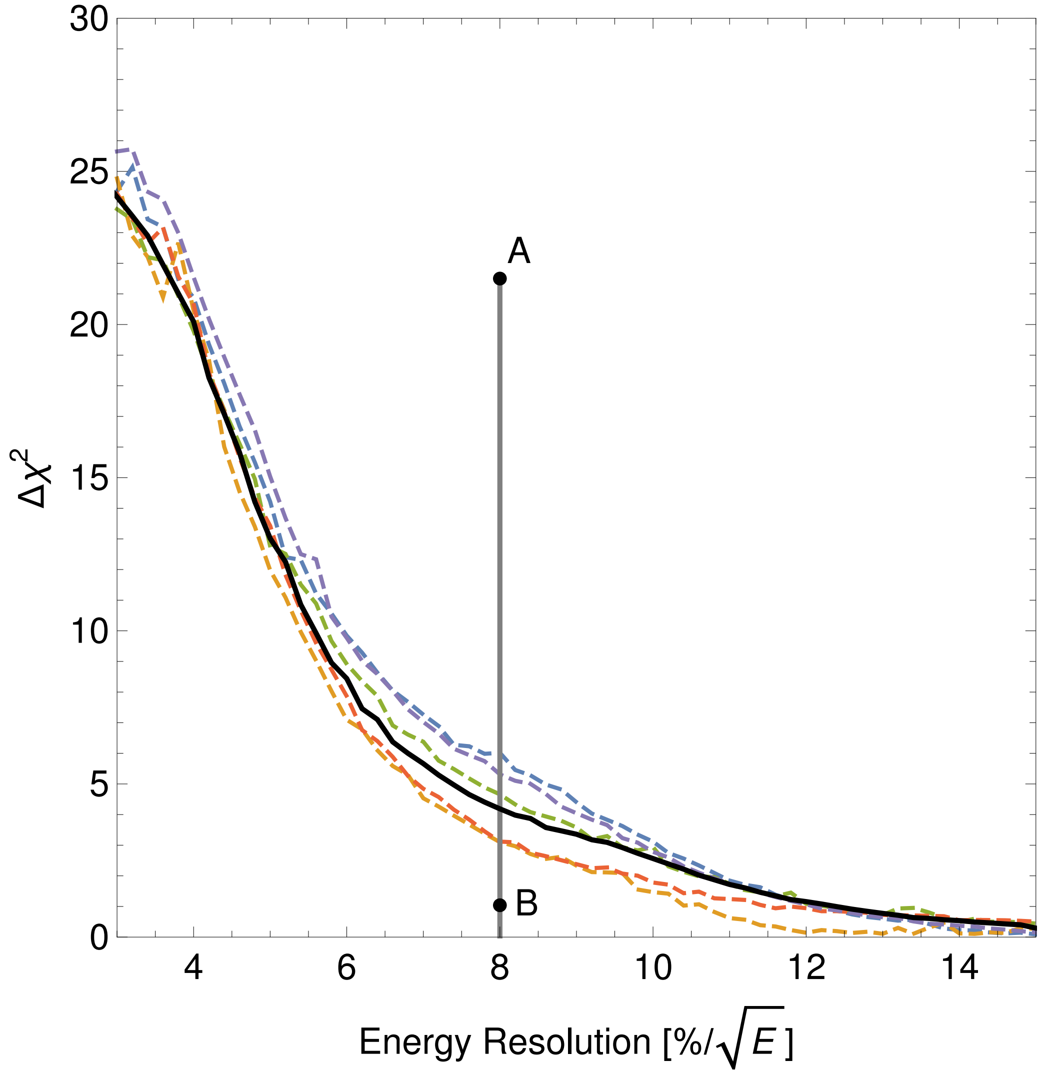
$$\chi_A^2 = \sum_i \frac{\left(\phi_{true_i} - \phi_{fit_i}\right)^2}{\phi_{true_i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2 + \sum_{n,m} \xi_n \left(V^{-1}\right)_{nm} \xi_m$$

$$\chi_B^2 = \sum_i \frac{\left(\phi_{true_i} - \phi_{fit_i}\right)^2}{\phi_{true_i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2 + \sum_{n,m} \alpha_n \left(V^{-1}\right)_{nm} \alpha_m$$

$$\text{where } \alpha_n = \frac{\sum_{i \in N_n} \phi^o_{fit_i} \xi_i}{\sum_{i \in N_n} \phi^o_{fit_i}}$$

Consistency Check #2

- No Near Detector
- Used Daya Bay's Covariance Matrix, instead
- A: One nuissance parameter for each of Daya Bay's bins
- B: One nuissance parameter for each of the far detector's bins



Forero, et al. (arXiv:1710.07378)

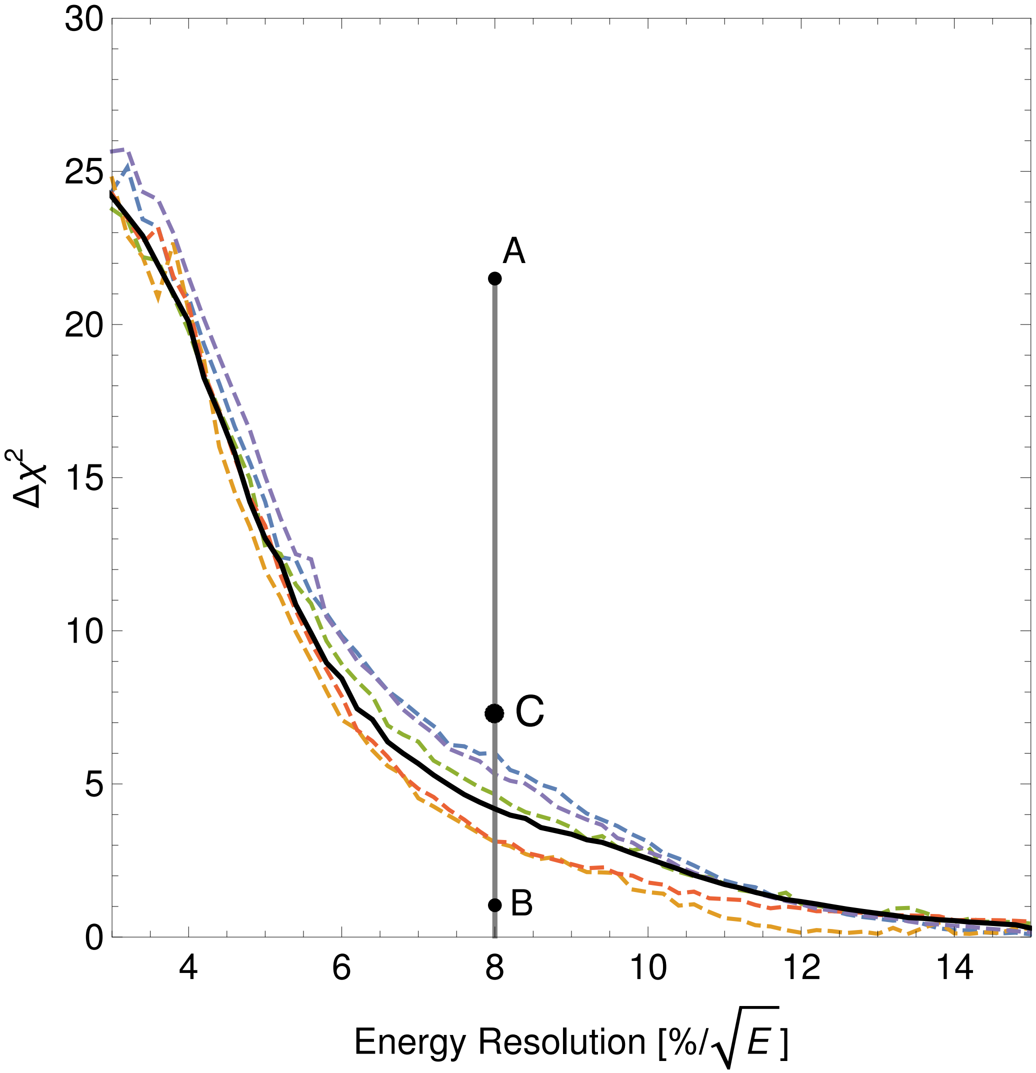
Consistency Check #3

- No Near Detector
- Used the covariance matrix for an idealized detector, instead

$$\chi_C^2 = \sum_i \frac{\left(\phi_{true_i} - \phi_{fit_i}\right)^2}{\phi_{true_i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2 + \sum_{i,k} \xi_i \left(V^{-1}\right)_{ik} \xi_k$$

Consistency Check #3

- No Near Detector
- Used Idealized Covariance Matrix, instead
- C: One nuissance parameter per Daya Bay energy bin



Summary

- Can't trust theoretical reactor antineutrino spectrum
- Antineutrino spectrum fine structure prevents extrapolation to lower energy resolutions
  - JUNO can't use Daya Bay's data
- So, JUNO needs a near detector in order to resolve the mass hierarchy
  - Energy resolution $\leq 3\%/\sqrt{E}$