Simulating Neutrino Physics for JUNO

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Virginia Tech

HET Lunch Seminar - 2/14/20

Table of Contents

Neutrino Oscillation The Basics

$$m_\nu \neq 0 \Rightarrow |\nu_\alpha\rangle = U_{\alpha i} |\nu_i\rangle$$

$$U_{\text{PMNS}} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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In vacuum,

$$P_{\alpha\to\beta}(t) = \left| \left\langle \nu_\beta \middle| \nu_\alpha \left(t = \frac{L}{E} \right) \right\rangle \right|^2 \equiv |S_{\beta\alpha}|^2$$

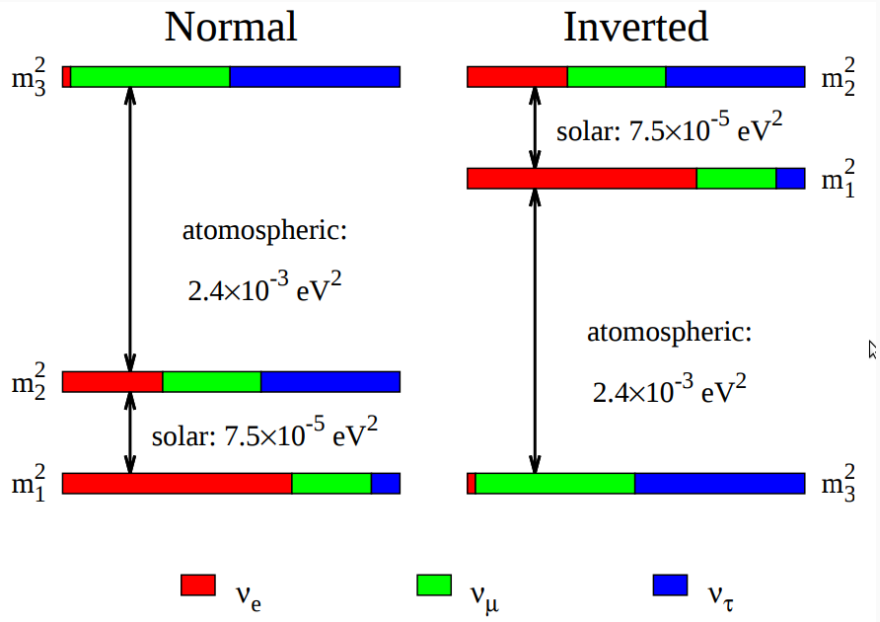
$$= \left| U_{\beta 1} U^*_{\alpha 1} + U_{\beta 2} U^*_{\alpha 2} e^{-i\frac{\Delta m^2_{21}}{2E}L} + U_{\beta 3} U^*_{\alpha 3} e^{-i\frac{\Delta m^2_{31}}{2E}L} \right|^2$$

Neutrino Oscillation Parameter Measurements

- Existence of neutrino oscillation confirmed by solar and atmospheric experiments
- Precision measurements of parameters by reactor/accelerator experiments
  - $\theta_{12} \approx 34^\circ$
  - $\theta_{13} \approx 8.6^\circ$
  - $\theta_{23} \approx 45^\circ$
  - $\Delta m^2_{21} \approx 7.4 \times 10^{-5}\,\mathrm{eV}^2$
  - $\left|\Delta m^2_{31}\right| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$
- Unknown:
  - δ_{CP}, sign of Δm^2_{31}, octant of θ_{23}

Neutrino Oscillation Determining the Mass Hierarchy

Normal (NH): $\Delta m^2_{31} > 0$
Inverted (IH): $\Delta m^2_{31} < 0$



JUNO Collaboration (arXiv:1507.05613)

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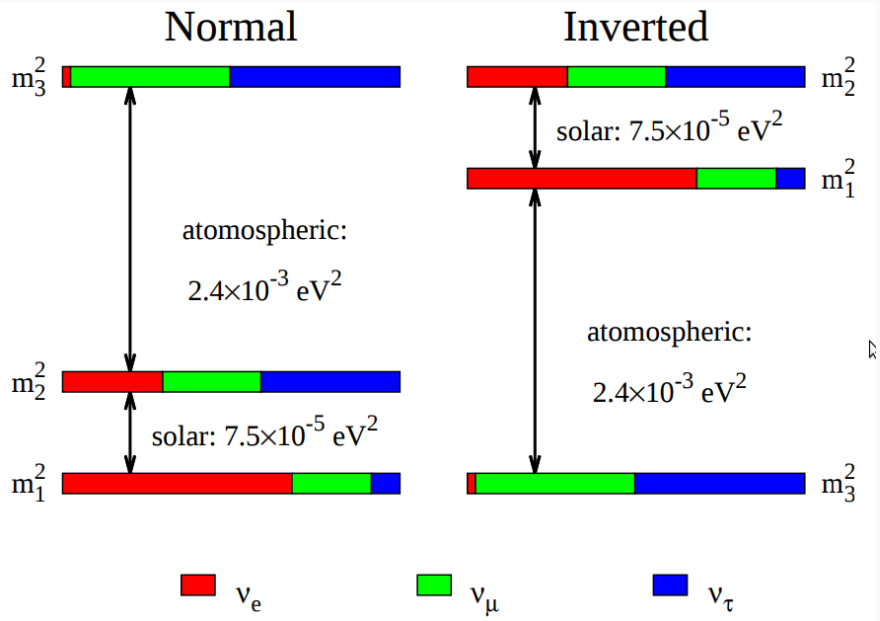

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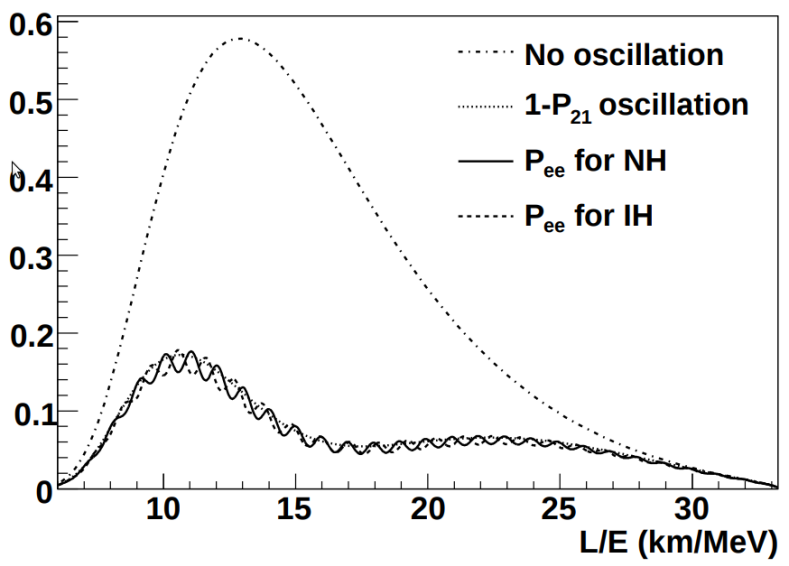
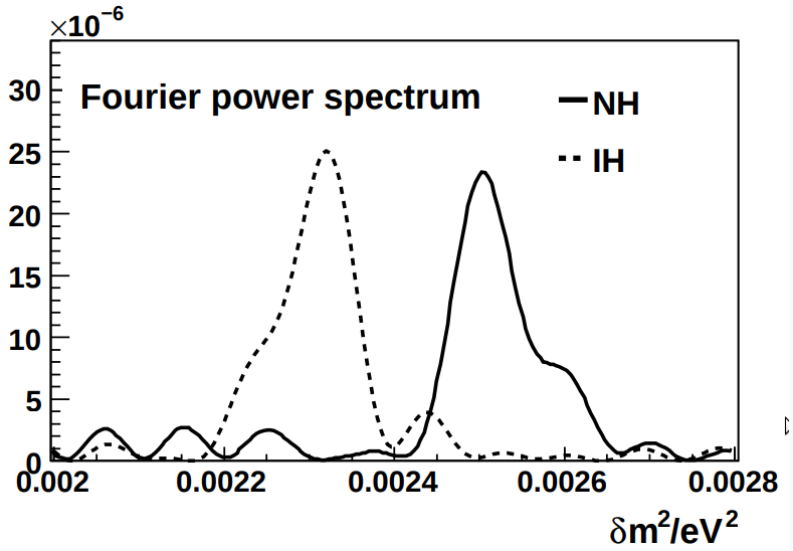


L. Zhang, et al (arXiv:0807.3203)



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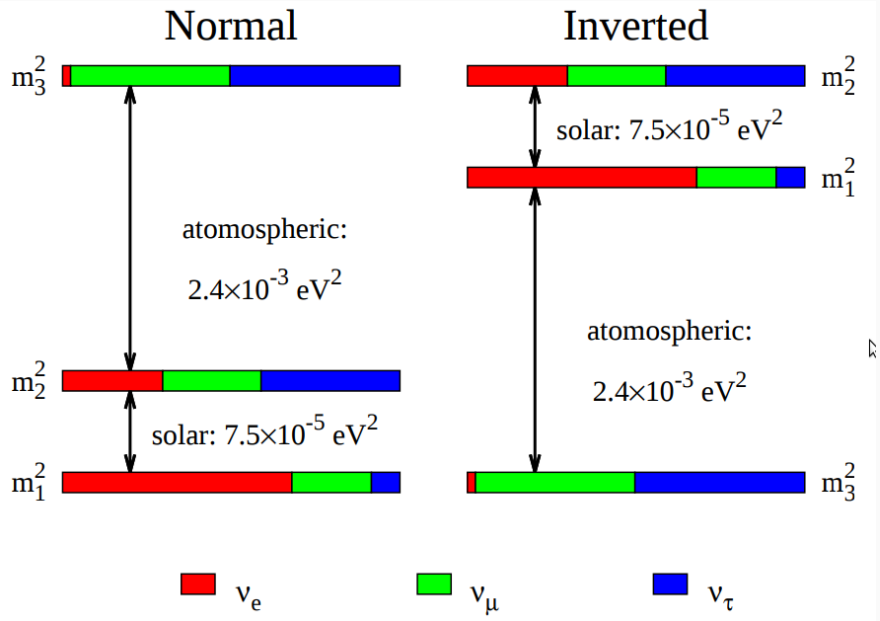

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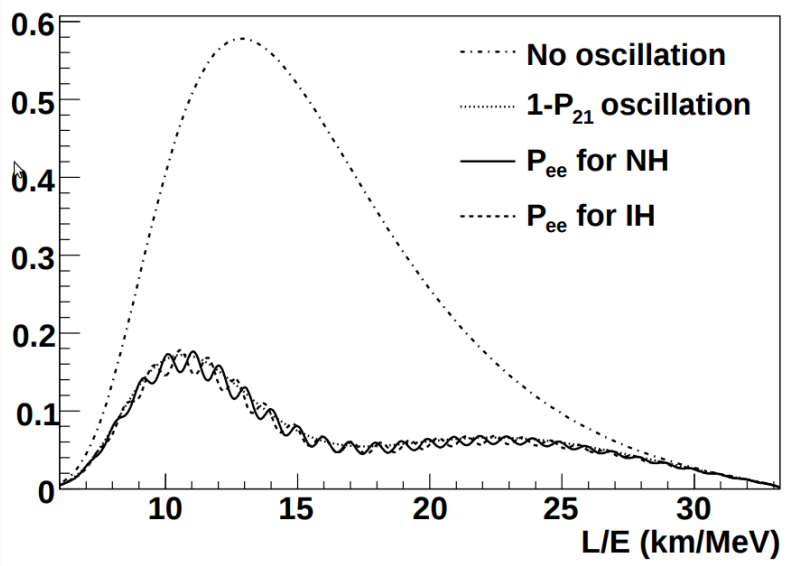

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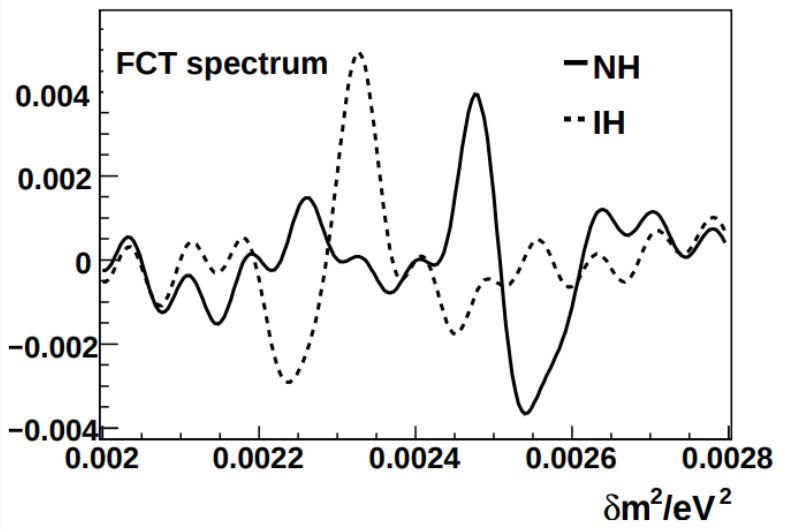
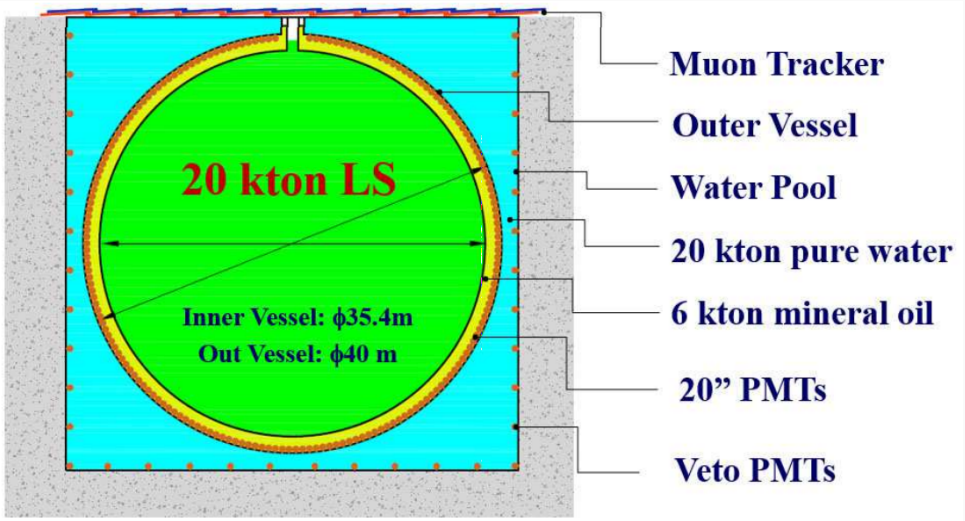


JUNO: Jiangmen Underground Neutrino Observatory

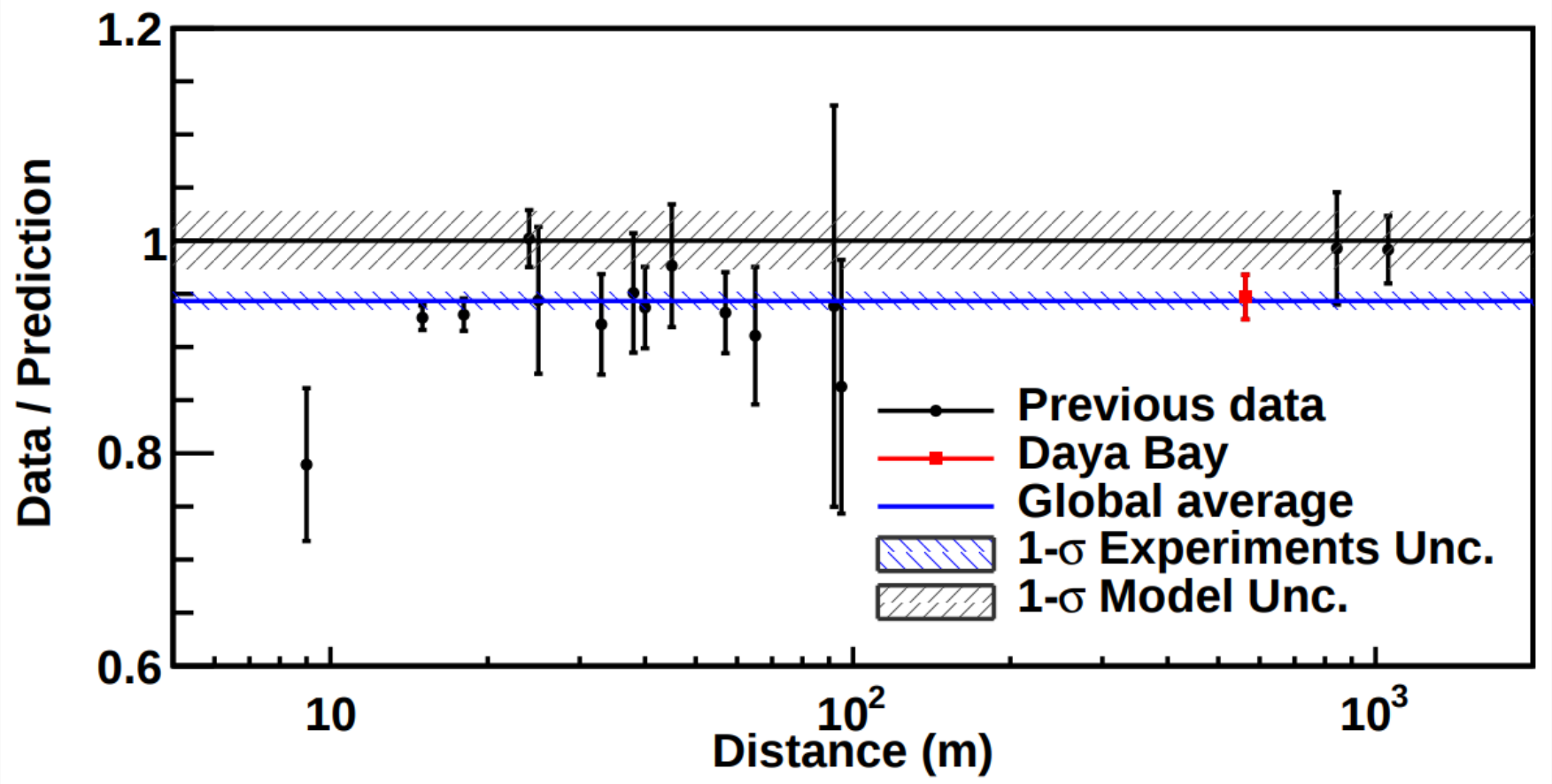
- 53 km from reactors at Yangjiang and Taishan
  - Reactors produce $\bar{\nu}_e$ via beta decay
- 20 kton Liquid Scintillator Detector
  - Measure $\bar{\nu}_e$ disappearance
- Need $3\%/\sqrt{E}$ energy resolution
  - PMT coverage $\geq 75\%$
  - PMT quantum efficiency $\geq 35\%$
  - LS attenuation length ≥ 20 m at 430 nm



JUNO Collaboration (arXiv:1507.05613)

Problem: Reactor Antineutrino Anomaly

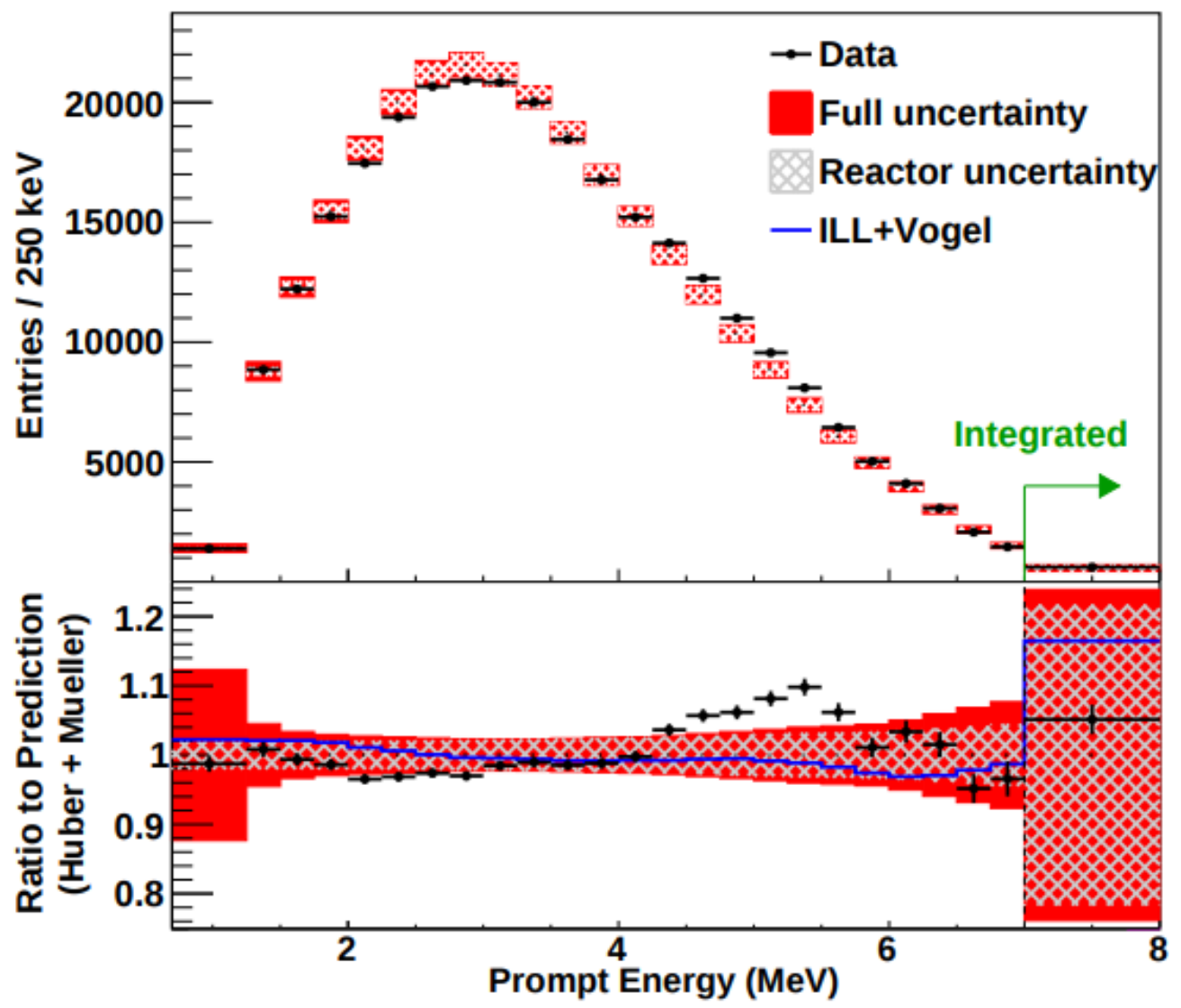
After updated calculations of expected $\bar{\nu}_e$ energy spectrum from reactors, a deficit of $\bar{\nu}_e$ is observed in experiments.



Daya Bay Collaboration (arXiv:1508.04233)

Problem: Reactor Antineutrino Anomaly

Also, the shape of the observed spectrum is different.



Daya Bay Collaboration (arXiv:1508.04233)

Solution

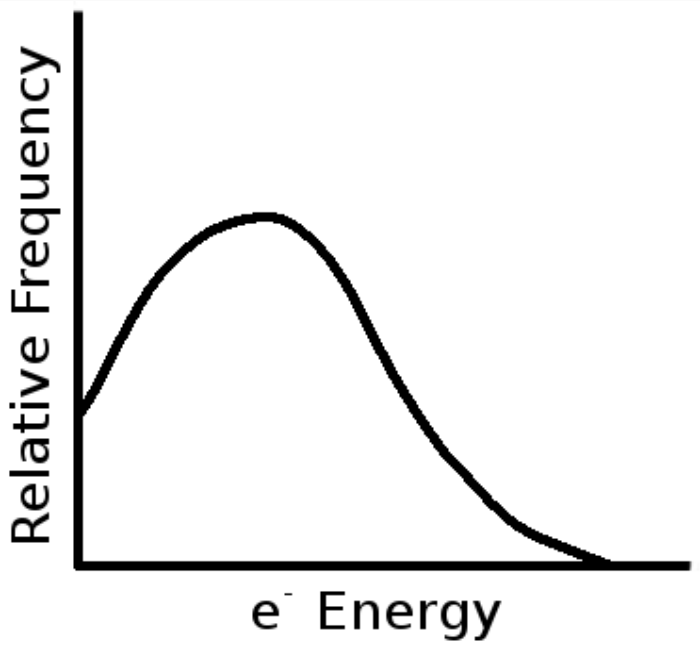
- Common: add a near detector
  - $$$

Solution

- Common: add a near detector
  - $$$
- JUNO: use Daya Bay's measured spectrum
  - $8\%/\sqrt{E}$ energy resolution

Problem: Fine Structure in the Reactor Spectrum

For a single beta decay,



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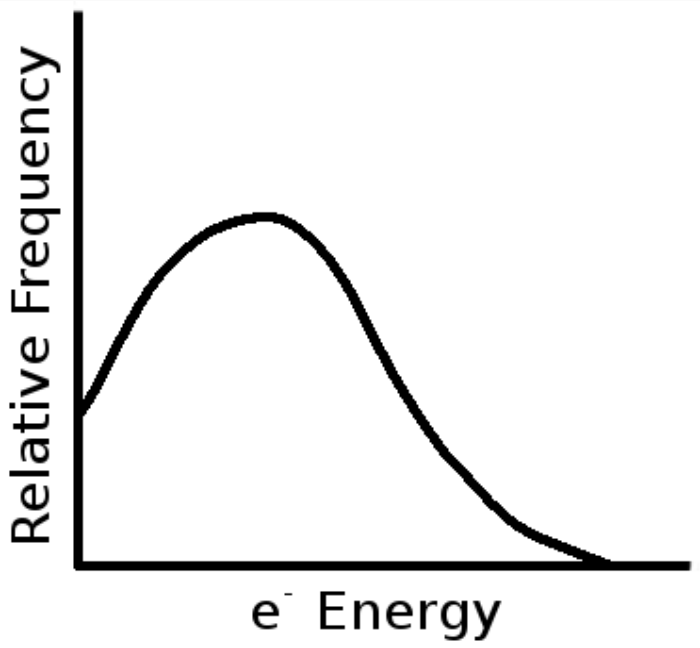

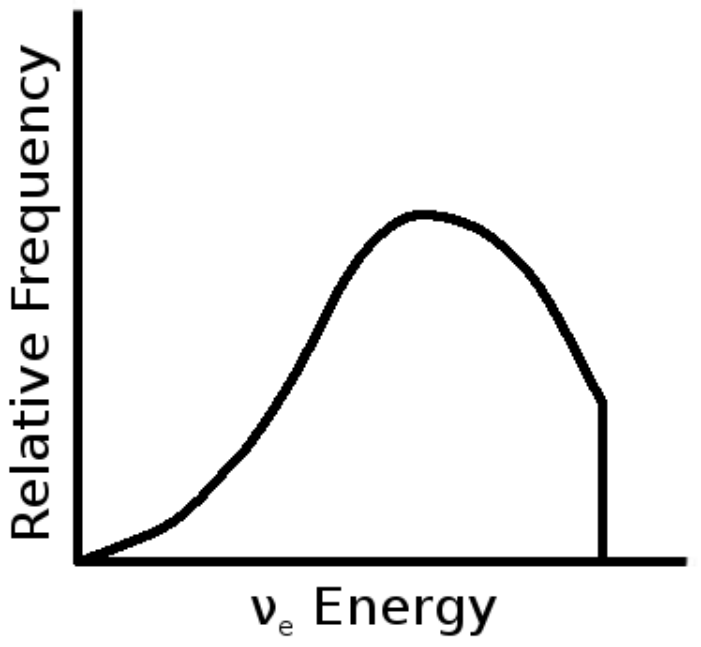

Problem: Fine Structure in the Reactor Spectrum

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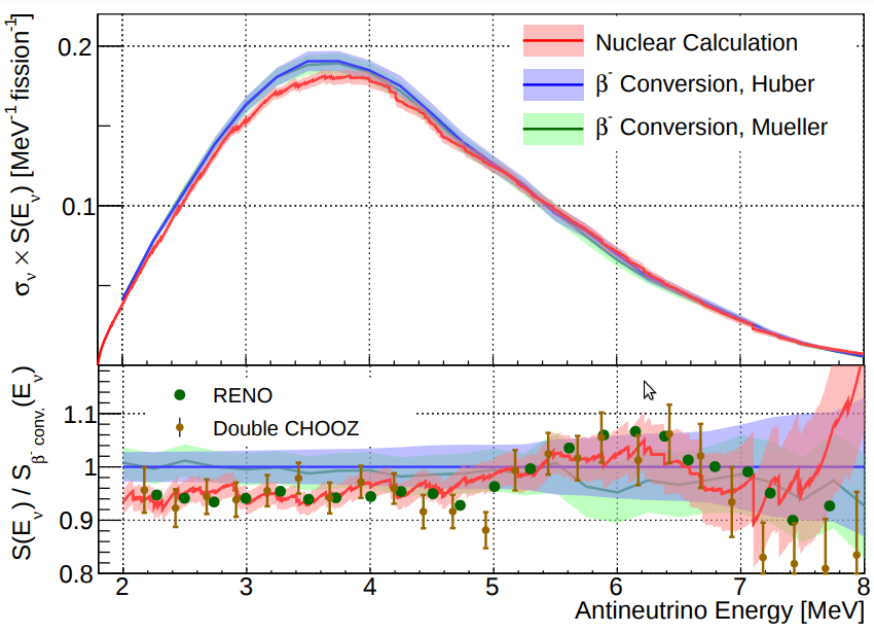
- Invert the spectrum from each decay branch individually:



D. Dwyer, et al (arXiv:1407.1281)

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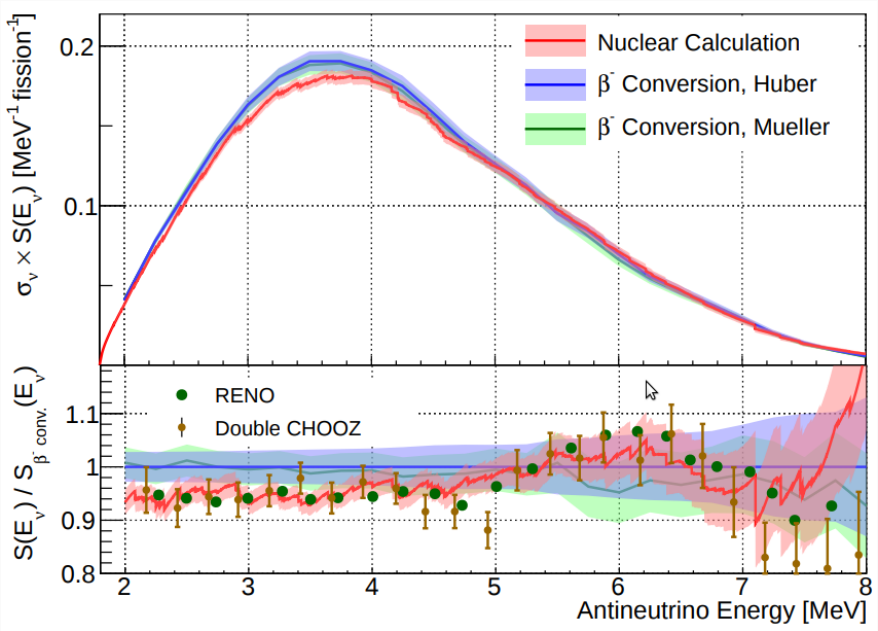

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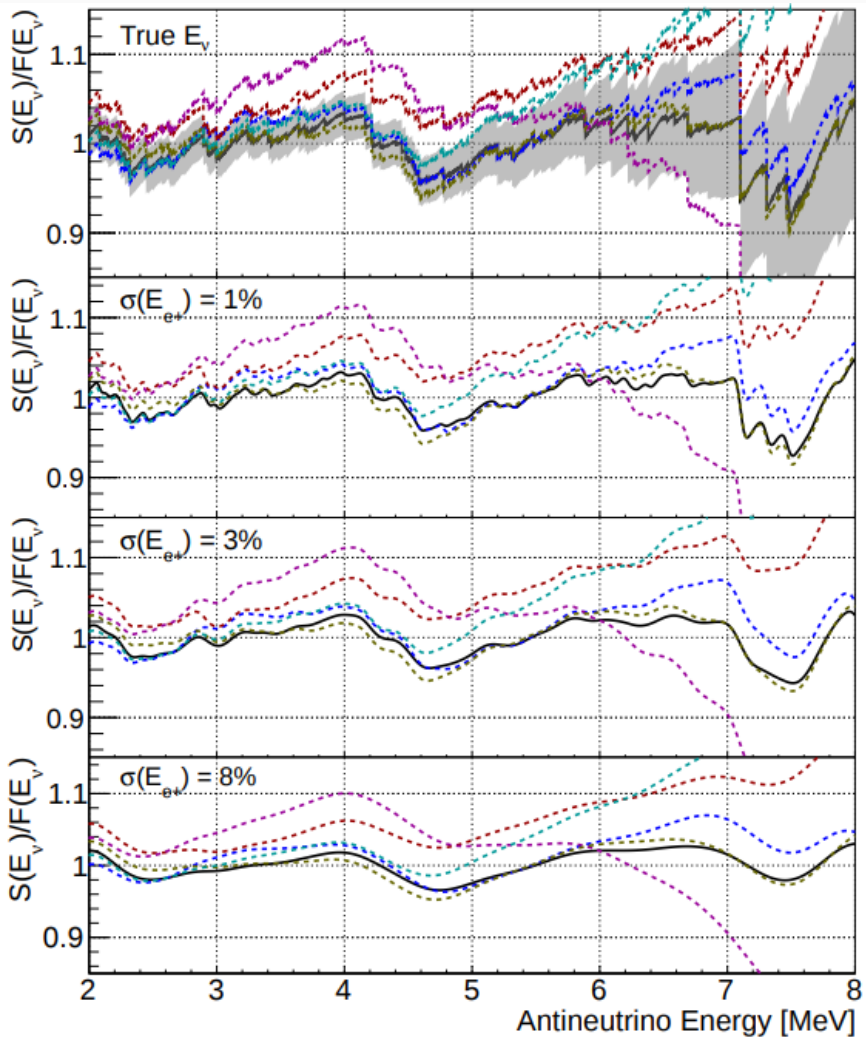

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1 Introduction

2 **Benefits of a Near Detector for JUNO**
(D. Forero, *R. Hawkins*, P. Huber)

3 Interference between the Atmospheric and Solar Oscillation Amplitudes
(P. Huber, H. Minakata, *R. Pestes*)

4 Summary

Simulating JUNO Set Up

In GLoBES,

- Far detector with JUNO's specs
- Near detector added
  - 5 ton liquid scintillator
  - 0.5 km from reactor
  - variable energy resolution
- Huber-Mueller model for source
- Assumed NH for simulated data

Simulating JUNO Added Systematics

- Energy Spectrum Uncertainty
  - 100 energy bins ($\phi_i^l \equiv$ detection rate in ith bin for detector l)
  - Nuisance parameter added for each bin:

$$\tilde{\phi_{\text{fit}^l i}} = (1 + \xi_i)\left(\phi_{\text{fit}i}^l\right)^{\circ},$$

    where $\phi_{\text{fit}i}^l = \sum_j M_{ij} \tilde{\phi_{\text{fit}^l i}}$
- Detector Energy Response Uncertainty
  - Accounted for uncertainty being non-linear:

$$\frac{E_{\text{rec}}}{E} = 1 + \sum_{k=0}^{n} \alpha_k E^k$$

  - Differences between detectors allowed

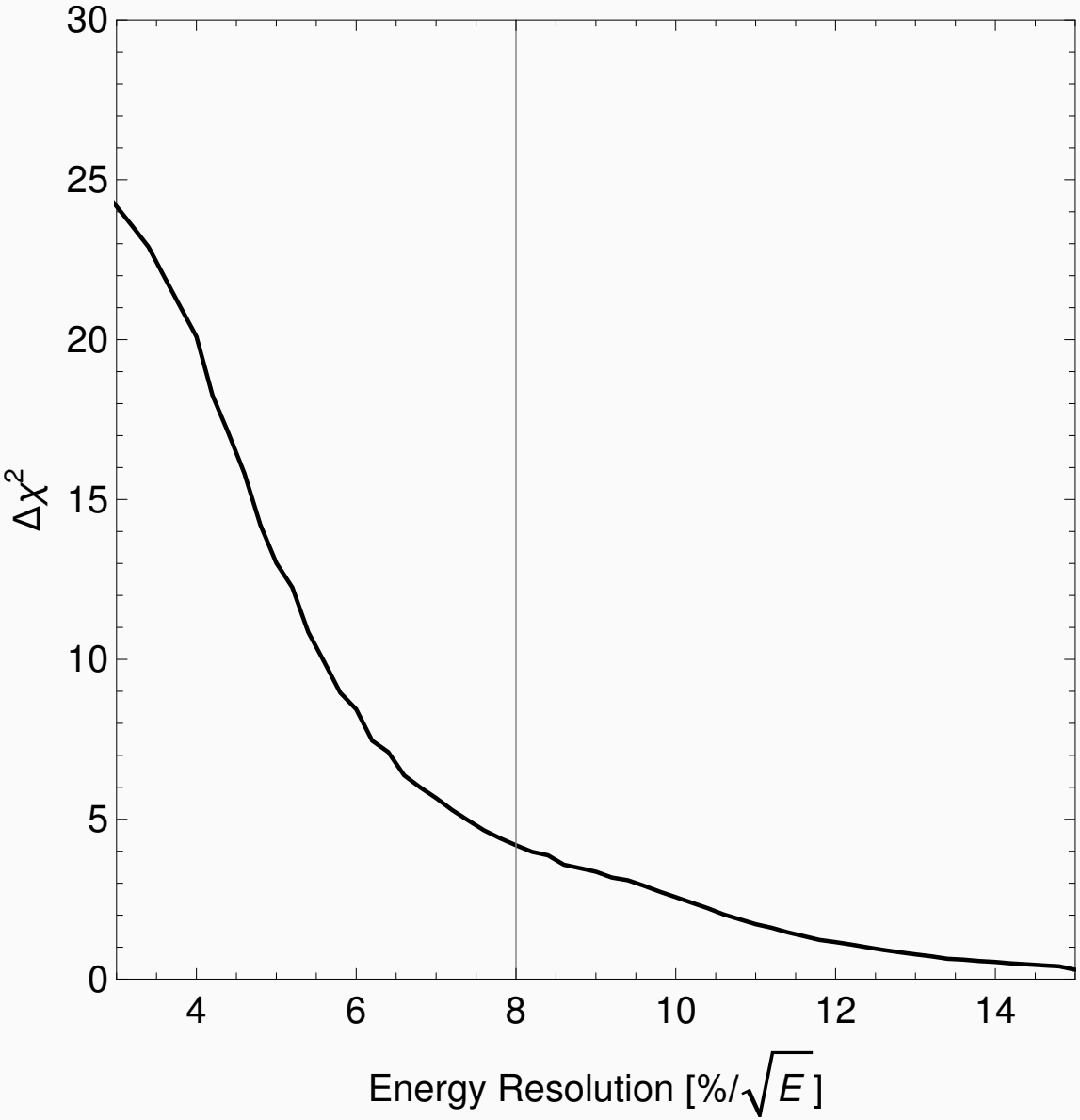
Simulating JUNO χ^2 Calculation

- χ^2 calculated for fits both to NH and to IH

$$\chi^2 = \sum_{i,l} \frac{\left(\phi^l_{\text{true}i} - \phi^l_{\text{fit}i}\right)^2}{\phi^l_{\text{true}i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2$$

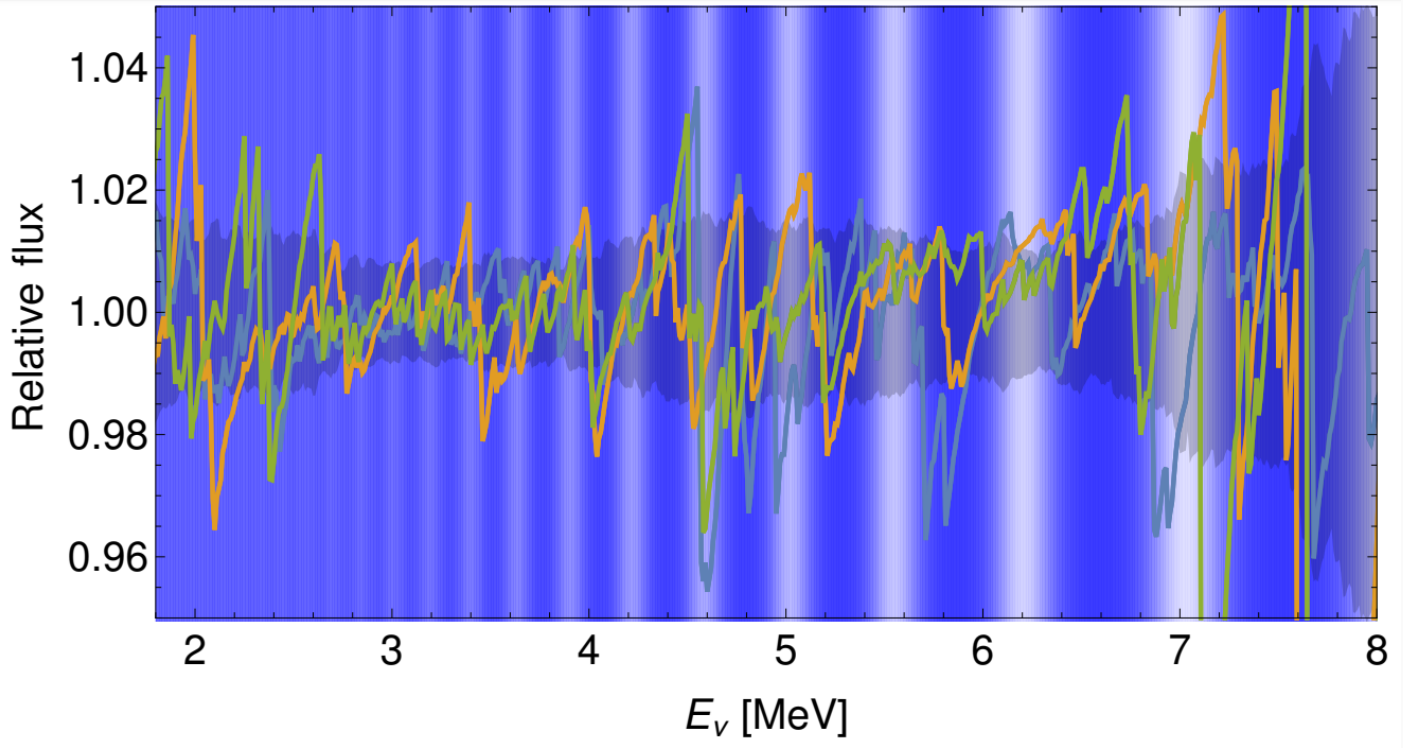
  - Minimized over oscillation and systematic parameters

Simulating JUNO Result



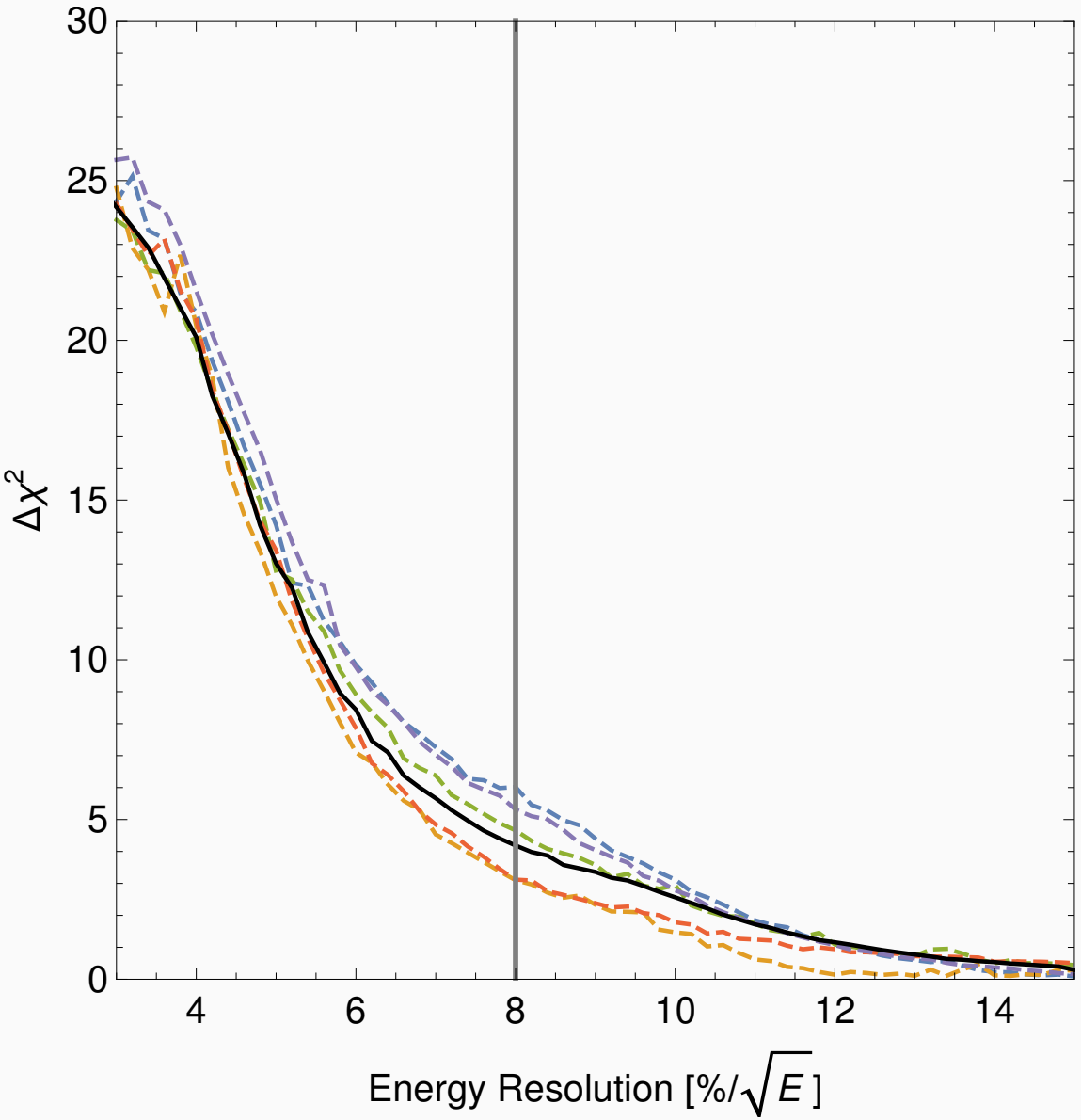
Simulating JUNO Consistency Check #1

- Generated data using alternative source spectra
  - Randomly choose beta decay branches and weights
  - Add up spectra produced from choices
  - Renormalize to match Huber-Mueller model at $8\%/\sqrt{E}$
- Fit data to Huber-Mueller model



D. Forero, et al (arXiV:1710.07378)

Simulating JUNO Consistency Check #1 Result



Simulating JUNO Consistency Check #2

- No near detector
- Instead, used Daya Bay's covariance matrix
  - Scheme A: 1 nuisance parameter per Daya Bay bin

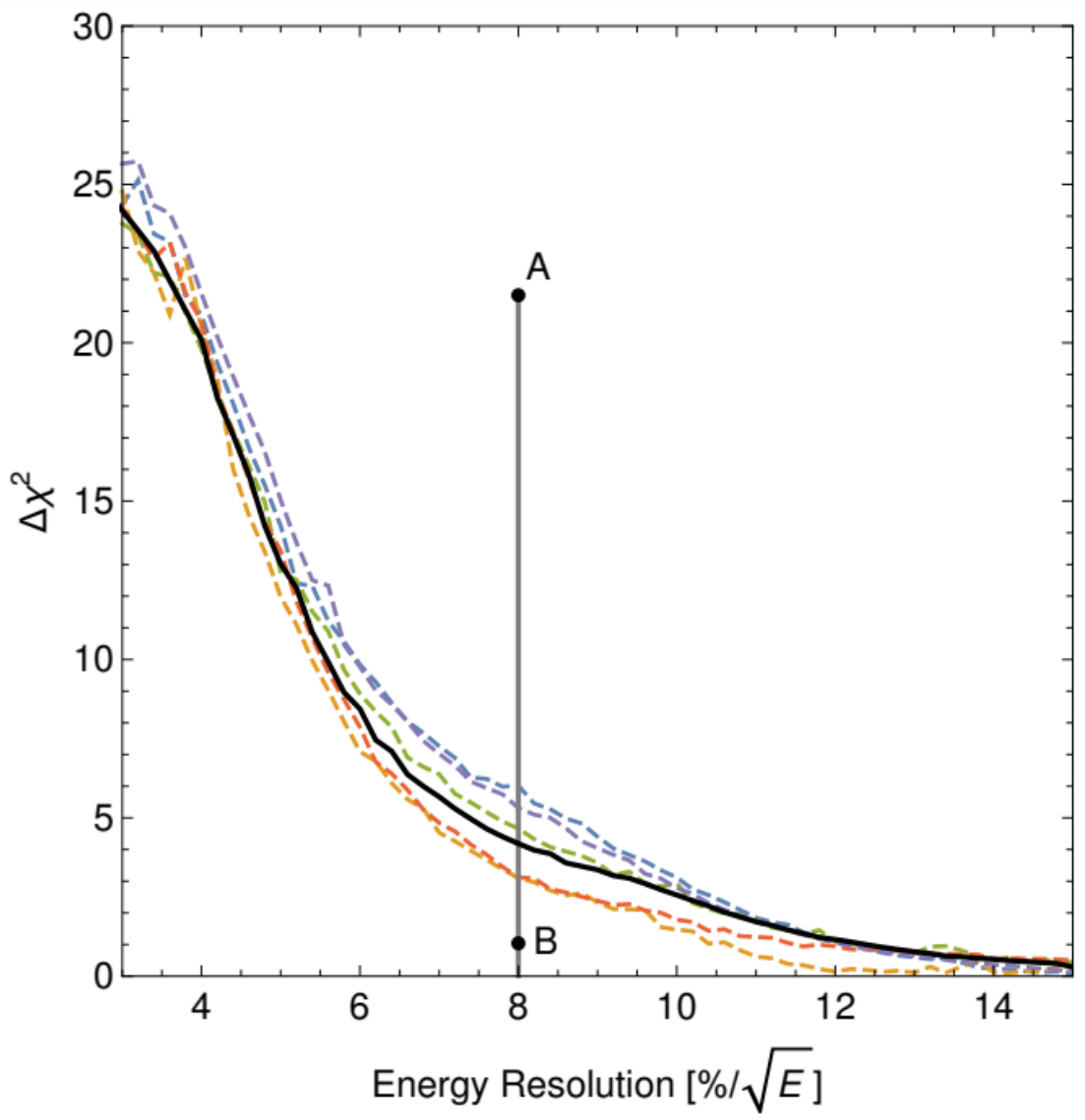
$$\chi_A^2 = \sum_i \frac{\left(\phi_{\text{true}i} - \phi_{\text{fit}i}\right)^2}{\phi_{\text{true}i}} + \sim_j \left(\frac{s_j}{\sigma_j}\right)^2 + \sum_{m,n} \xi_n \left(V^{-1}\right)_{nm} \xi_m$$

  - Scheme B: 1 nuisance parameter per far detector bin

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

where $\alpha_n = \frac{\sum_{i \in N_n} \phi^{\circ}_{\text{fit}i} \xi_i}{\sum_{i \in N_n} \phi^{\circ}_{\text{fit}i}}$

Simulating JUNO Consistency Check #2 Result



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4 Summary

Interference Term In Vacuum

$$S_{\beta\alpha} = U_{\beta 1} U^*_{\alpha 1} + U_{\beta 2} U^*_{\alpha 2} e^{-i\frac{\Delta m^2_{21}}{2E}L} + U_{\beta 3} U^*_{\alpha 3} e^{-i\frac{\Delta m^2_{31}}{2E}L}$$

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By unitarity,

$$U_{\beta 1}U^*_{\alpha 1} = \delta_{\beta\alpha} - U_{\beta 2}U^*_{\alpha 2} - U_{\beta 3}U^*_{\alpha 3}$$

$$\begin{aligned}\Rightarrow S_{\beta\alpha} =& \delta_{\beta\alpha} + U_{\beta 2}U^*_{\alpha 2}\left(e^{-i\frac{\Delta m^2_{21}}{2E}L} - 1\right) + U_{\beta 3}U^*_{\alpha 3}\left(e^{-i\frac{\Delta m^2_{31}}{2E}L} - 1\right)\\ \equiv& \delta_{\beta\alpha} + S^{\text{sol}}_{\beta\alpha} + S^{\text{atm}}_{\beta\alpha}\end{aligned}$$

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So, the oscillation probability is

$$\begin{aligned}P_{\alpha\to\beta} =& \left|S^{\text{sol}}_{\beta\alpha}\right|^2 + \left|S^{\text{atm}}_{\beta\alpha}\right|^2 + \delta_{\beta\alpha}\left(1 + 2\,\text{Re}[S^{\text{sol}}_{\beta\alpha} + S^{\text{atm}}_{\beta\alpha}]\right)\\ &+ 2\,\text{Re}[S^{\text{sol}}_{\beta\alpha}\left(S^{\text{atm}}_{\beta\alpha}\right)^*]\\ \equiv& P^{\text{non-inter}}_{\alpha\beta} + P^{\text{inter}}_{\alpha\beta}\end{aligned}$$

Interference Term In Vacuum

Let $\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$.

For $\nu_\mu \to \nu_e$,

$$P_{\mu e}^{\text{inter}} = 8\left[J_r \cos(\delta + \Delta_{32}) - s_{12}^2 s_{13}^2 c_{13}^2 s_{23}^2 \cos(\Delta_{32})\right] \sin(\Delta_{21}) \sin(\Delta_{31}),$$

where $J_r = s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin(\delta)$.

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where $J_r = s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin(\delta)$.

For $\nu_e \to \nu_e$,

$$P_{ee}^{\text{inter}} = 2 s_{12}^2 \sin^2(2\theta_{13}) \sin(\Delta_{21}) \sin(\Delta_{31}) \cos(\Delta_{32})$$

and

$$P_{ee}^{\text{non-inter}} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) - 4 s_{12}^2 c_{13}^2 \left(1 - s_{12}^2 c_{13}^2\right) \sin^2(\Delta_{21}).$$

Interference Sensitivity Set Up

$$P_{ee}^{\text{inter}} = 2s_{12}^2 \sin^2(2\theta_{13}) \sin(\Delta_{21}) \sin(\Delta_{31}) \cos(\Delta_{32})$$

and

$$P_{ee}^{\text{non-inter}} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) - 4s_{12}^2 c_{13}^2 \left(1 - s_{12}^2 c_{13}^2\right) \sin^2(\Delta_{21}) \,.$$

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$$P_{e\to e}^{\text{test}} = P_{ee}^{\text{non-inter}} + qP_{ee}^{\text{inter}}$$

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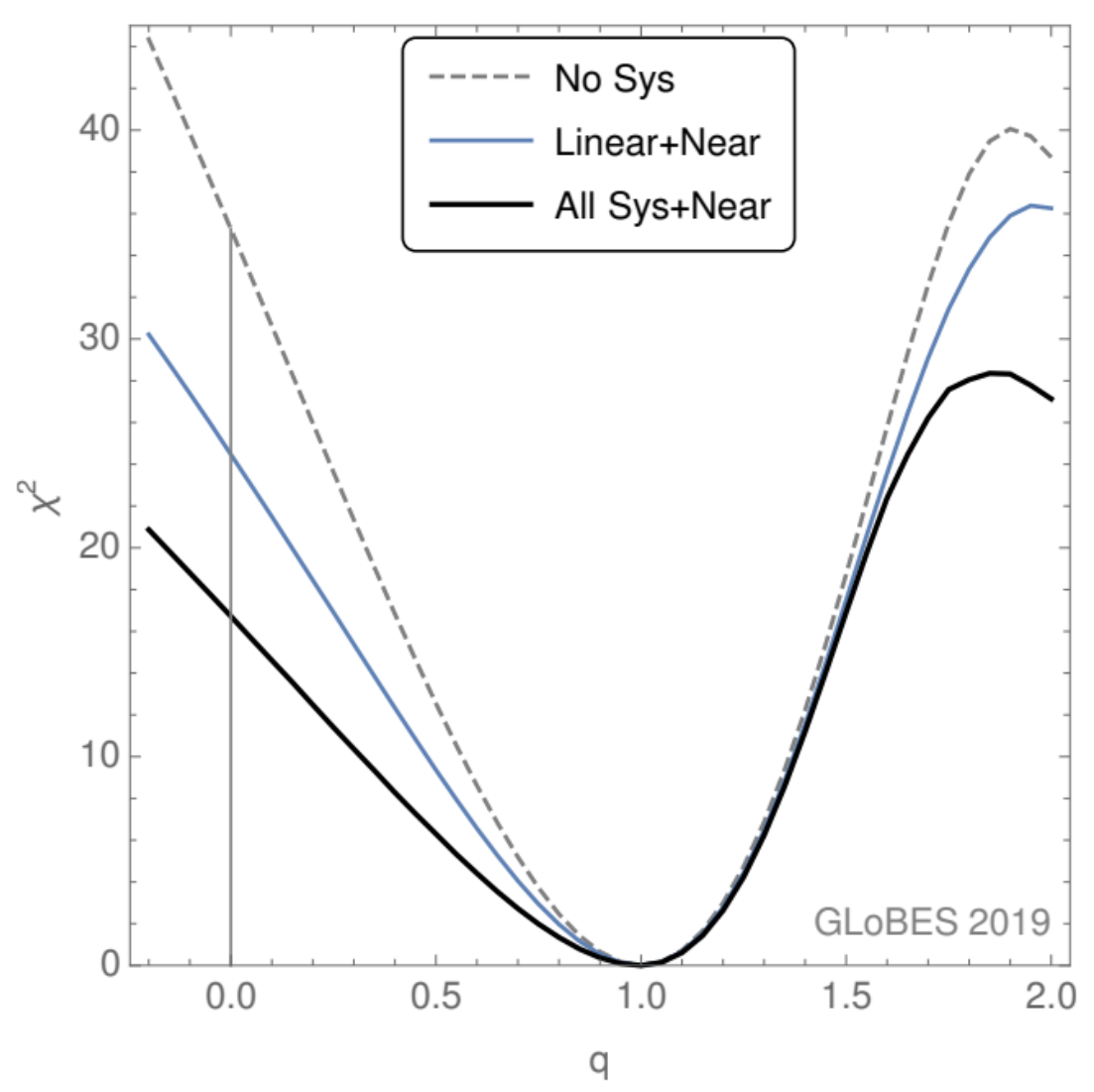
$$P_{e\to e}^{\text{test}} = P_{ee}^{\text{non-inter}} + qP_{ee}^{\text{inter}}$$

Simulation in GLoBES, as before...

- Using new probability function (simulated data assumes q=1)
- Near detector included (JUNO-TAO)
  - $1.7\%/\sqrt{E}$ energy resolution
  - 30 m from a core of the reactor
- Systematics same as before

Interference Sensitivity Results



P. Huber, et al (arXiv:1912.02426)

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4 **Summary**

Summary

- Due to spectral uncertainties, JUNO needs a near detector
  - JUNO-TAO proposed
- Part of interference independent of δ_{CP}
- With JUNO-TAO, JUNO can see interference at $> 4\sigma$