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Neutrino mass hierarchy and neutrino oscillation parameters with 100,000 reactor events

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see the paper for references and details

Plan of the talk

Introduction

Theoretical rate calculation: cross section and oscillation probability

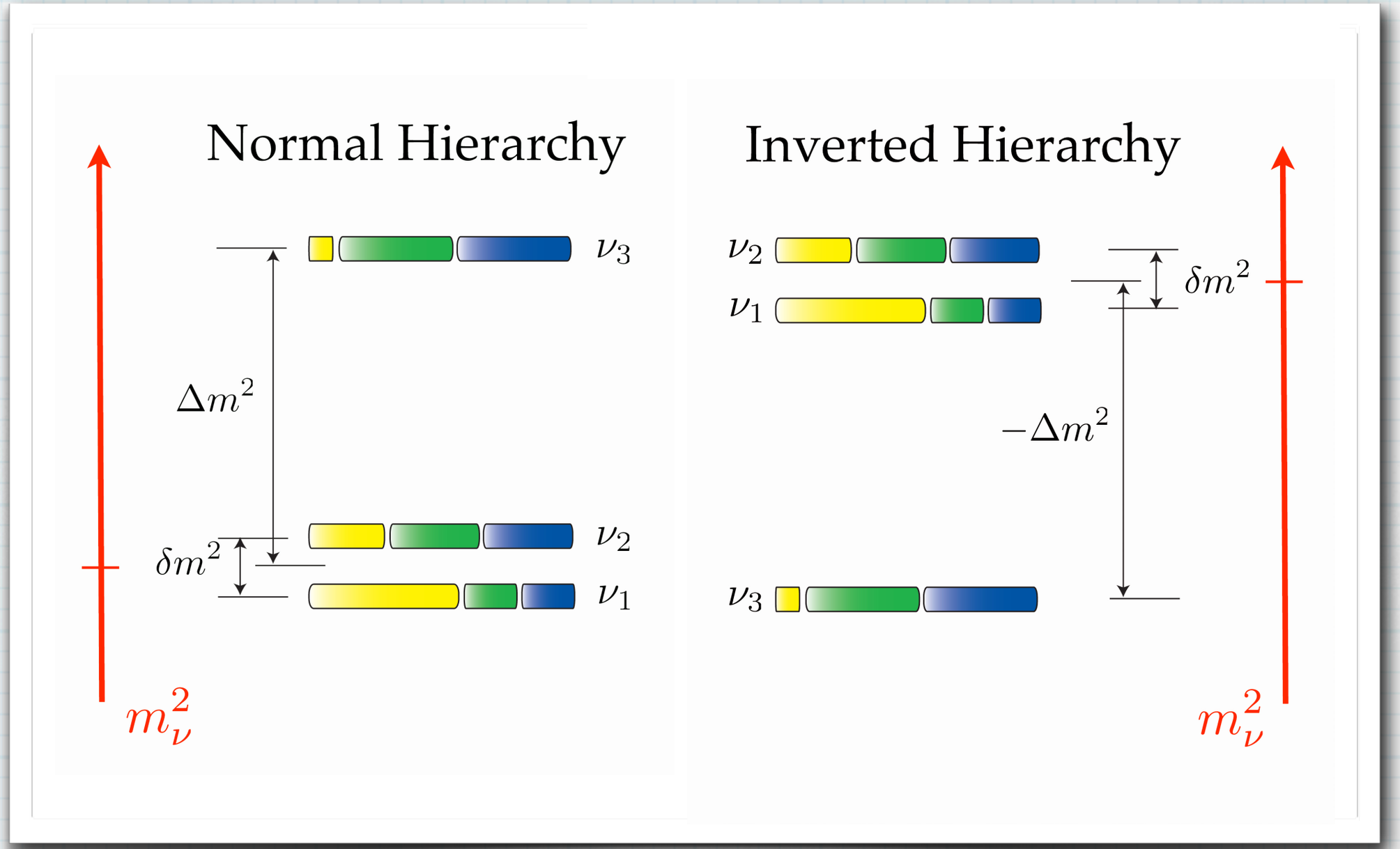
Continuous parameter α to interpolate between hierarchies

Results of the analysis of prospective data:
hierarchy and oscillation parameters

Possible impact of energy scale errors and spectral shape uncertainties

Conclusions

Notation



$$(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$$

$$c_{ij} = \cos\theta_{ij} \ , \ s_{ij} = \sin\theta_{ij}$$

$$\alpha = \begin{cases} +1 \ \text{(normal hierarchy)} \\ -1 \ \text{(inverted hierarchy)} \end{cases}$$

Medium-Baseline Reactor Neutrino Experiment (RENO-50, JUNO)

Possible discrimination of the hierarchy via high-statistics reactor neutrino experiments at medium baselines (few tens of km) was proposed more then 10 years ago

Probe mass-mixing parameters which govern oscillations at short wavelength $(\delta m^2, \theta_{12})$ and at long wavelength $(\Delta m^2, \theta_{13})$, and their tiny interference effects which depend on the mass hierarchy

Require unprecedented levels of detector performance and collected statistics, and the control of several systematics at (sub)percent level

Therefore, accurate theoretical calculations of reactor event spectra and refined statistical analyses are needed

Inverse Beta Decay cross section

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$\uparrow \qquad\qquad \uparrow$$

$$E \qquad\qquad E_e$$

In our rate calculation we use the differential cross section

$$d\sigma(E, E_e)/dE_e$$

$O(E/m_p)$ correction to the relation

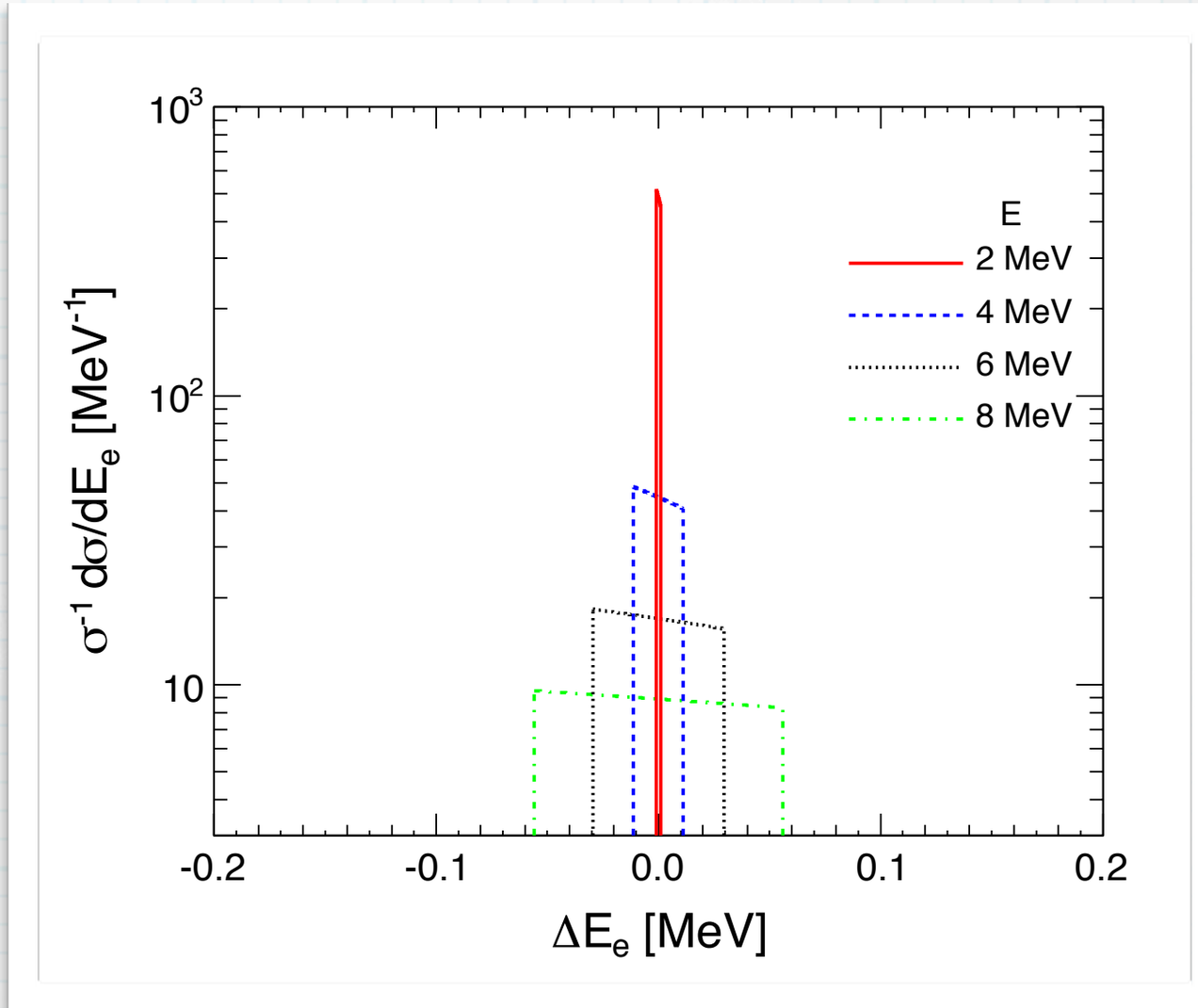
$E - E_e = m_n - m_p = 1.293$ MeV

with respect to recoilless approximation

Two effects

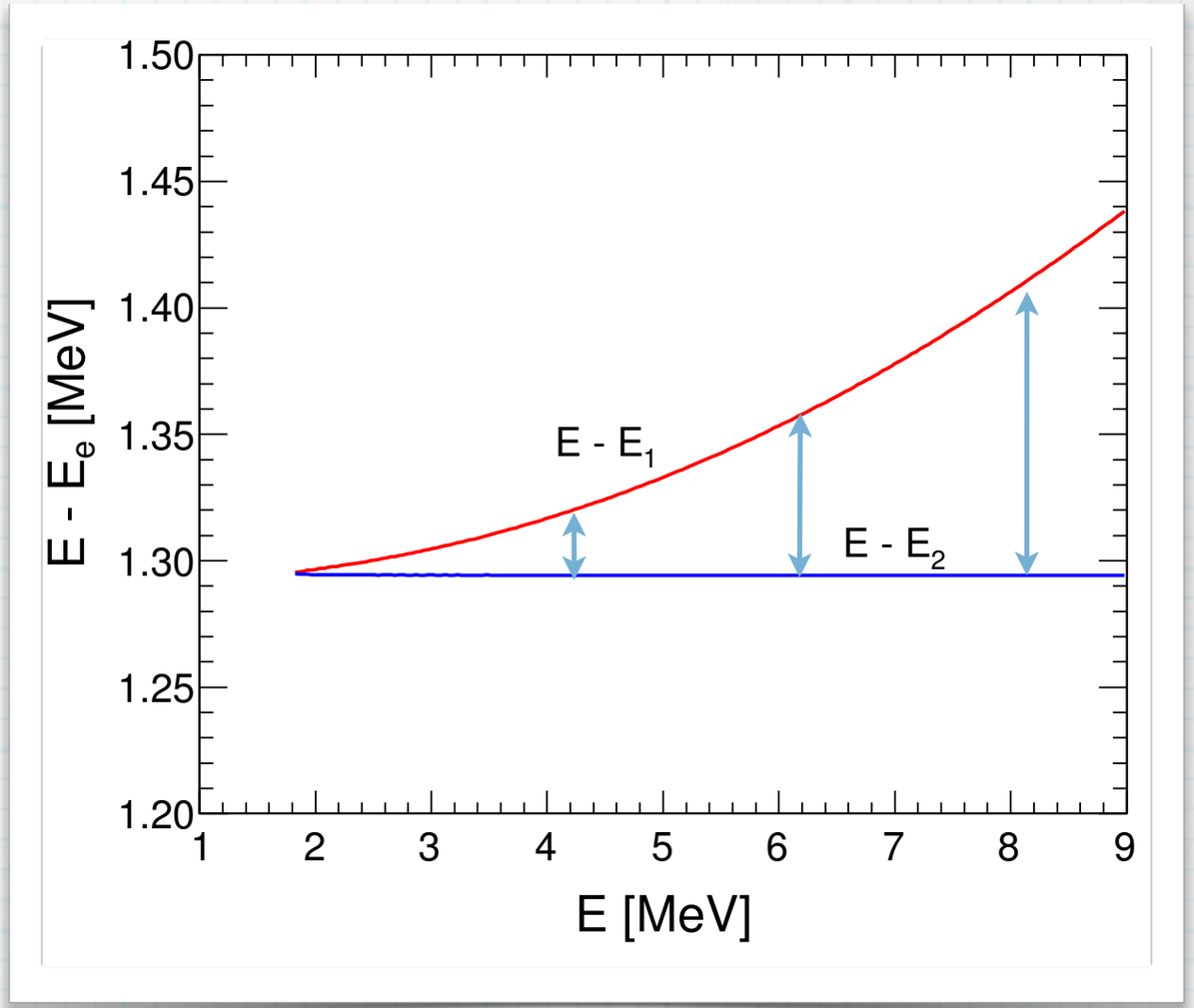
Tipical E_e displaced by $O(E/m_p)$

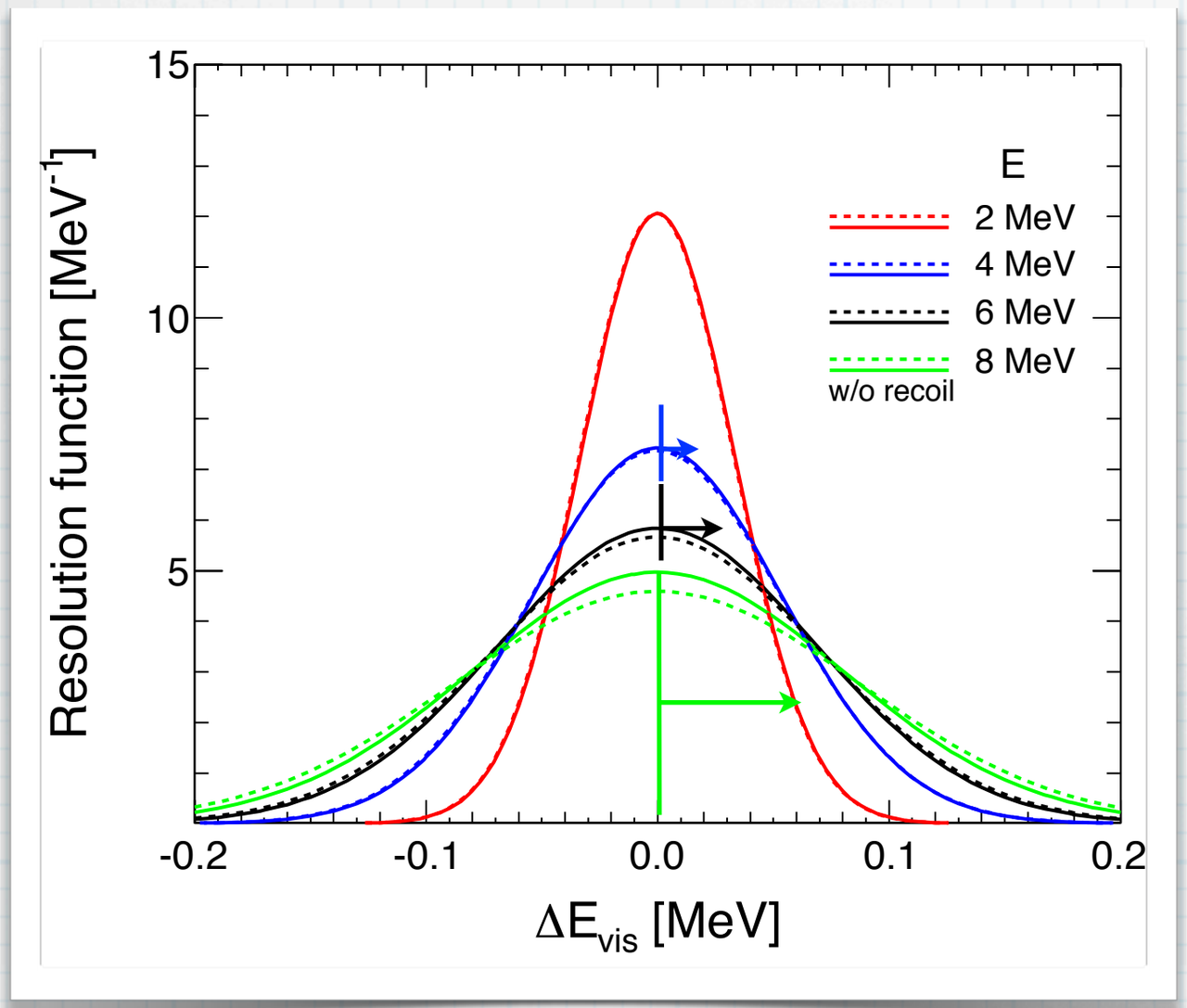
E_e spread of order $O(E/m_p)$



In the high energy part of the spectrum effect same order of energy resolution, cannot be neglected

Boundaries of the neutrino-positron energy difference $E - E_e$





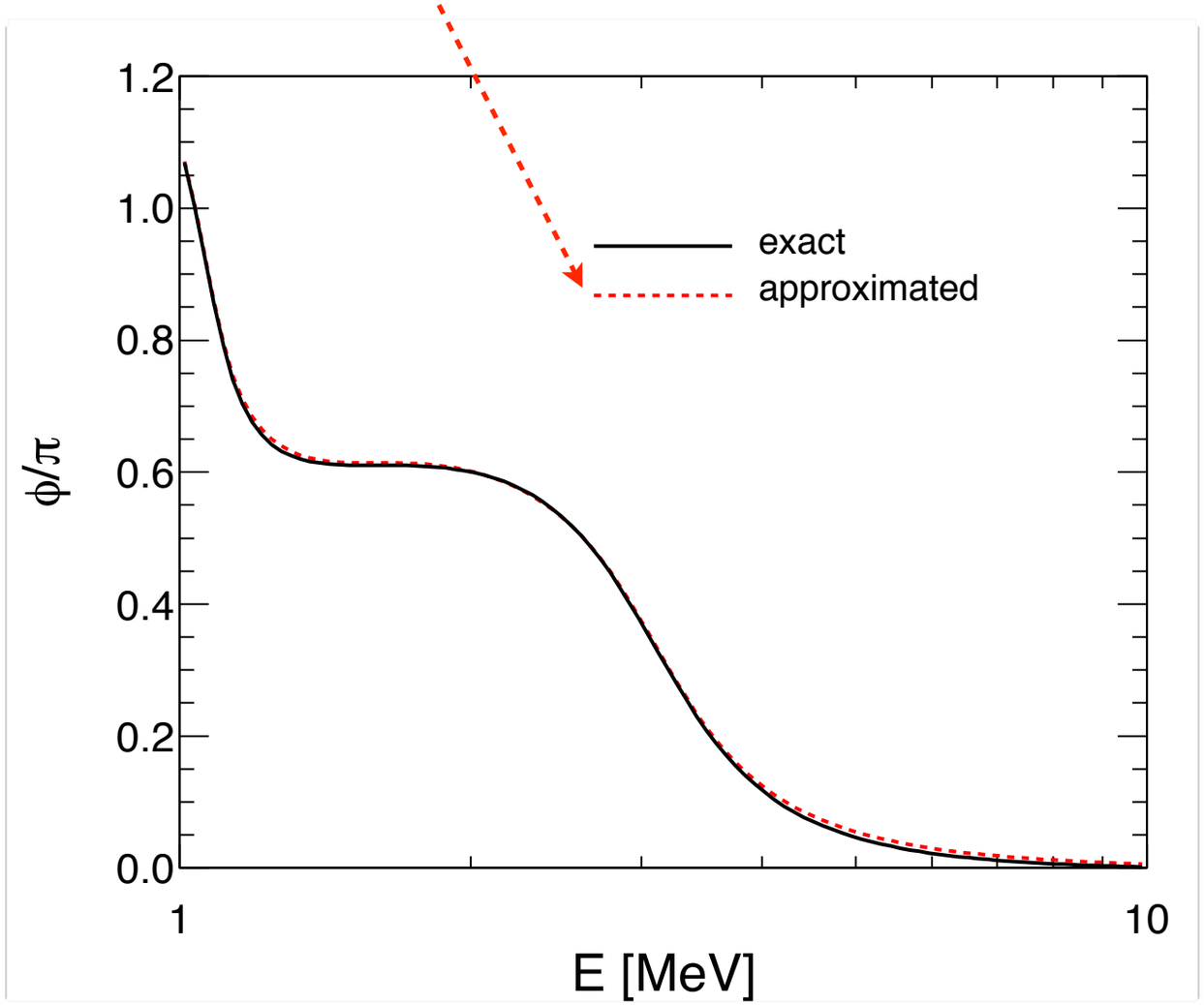
Recoil-corrected energy resolution function (functions aligned to their median value)

Oscillation probability

$$P^{3\nu}_{\rm vac} = c_{13}^4 P^{2\nu}_{\rm vac} + s_{13}^4 2 s_{13}^2 c_{13}^2 \sqrt{P^{2\nu}_{\rm vac}} \cos(2\Delta_{ee} + \alpha\varphi)$$

$$\varphi \simeq 2 s_{12}^2 \delta \left(1 - \frac{\sin\delta}{2\delta\sqrt{P^{2\nu}_{\rm vac}}} \right)$$

$$\alpha = \begin{cases} +1 \text{ (normal hierarchy)} \\ -1 \text{ (inverted hierarchy)} \end{cases}$$



continuous parameter constrained by the fit statistically appropriate for estimation test

hierarchy determination compromised if $\alpha \sim 0$ allowed or preferred

Oscillation probability: matter effects, multiple reactors

Analytical approximation for the oscillation probability in matter and for multiple reactors

$$P^{3\nu}_{\rm mat} \simeq c^4_{13} P^{2\nu}_{\rm mat} + s^4_{13} + 2 s^2_{13} c^2_{13} \sqrt{P^{2\nu}_{\rm mat}}\, w\, \cos(\Delta_{ee} + \alpha\varphi)$$

The fractional matter correction to $(\theta_{12}, \delta m^2)$ is $\sim 8 \times 10^{-3}$ in the high energy part of the spectrum, of the same size of the prospective fit accuracy

Replace $(\theta_{12}, \delta m^2) \to (\tilde{\theta}_{12}, \delta \tilde{m}^2)$ in $P^{\rm vac}_{2\nu}$

$w \longrightarrow$ Damping factor (analytical) to account for multiple reactors

Differences with the exact probability can be safely neglected in the analysis ($\lesssim 2 \times 10^{-3}$)

We consider the JUNO experimental settings

10 Reactor Cores $L \sim 52.5$ km $P = 35.8$ GW

Detector mass $M = 20$ kT

5 year exposure

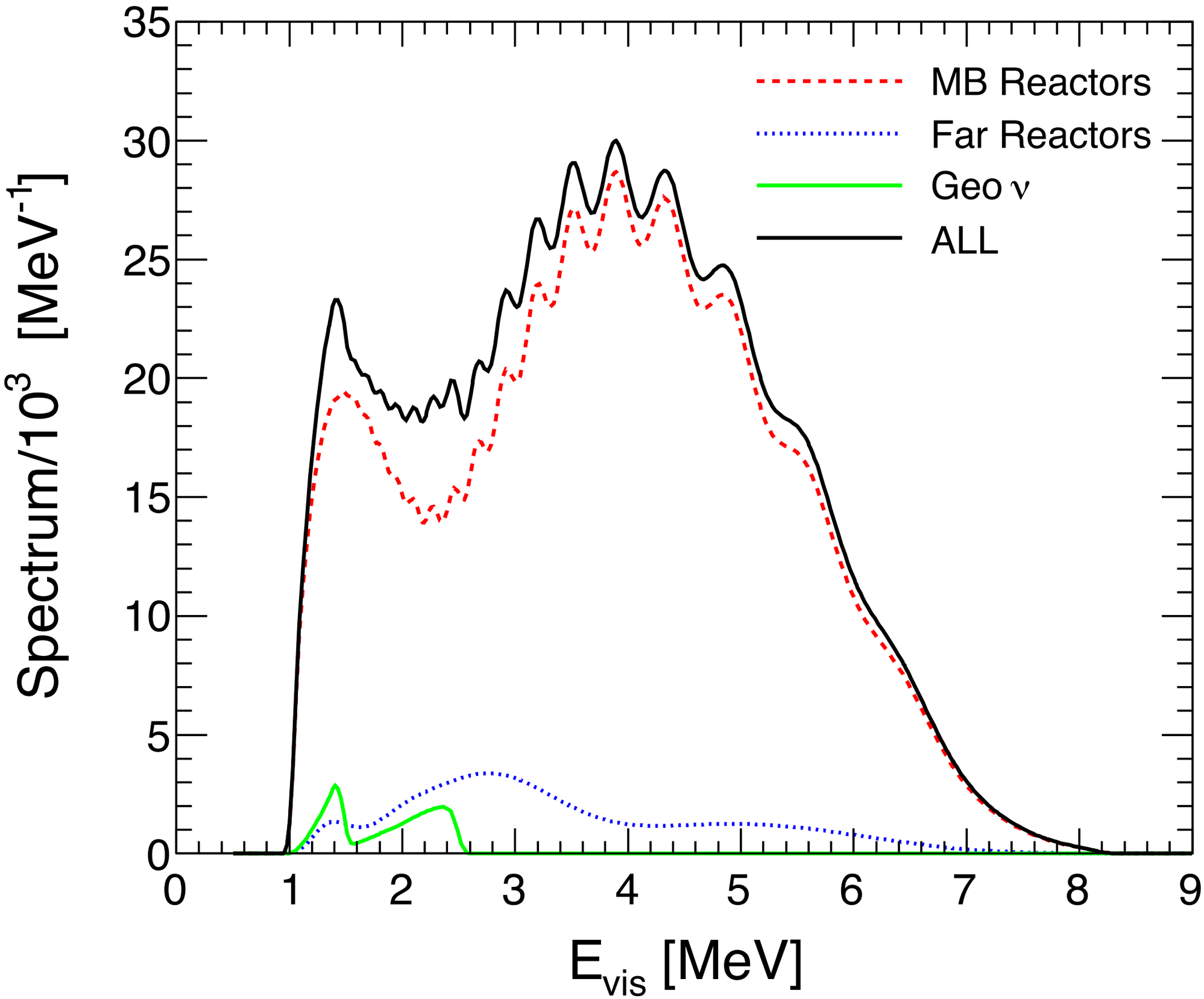
3% $\sqrt{(m_e + E_e)/\mathrm{MeV}}$ energy resolution

With these assumptions 3.4×10^5 unoscillated events

$\sim 10^5$ events with oscillations

2 Far reactors $L_1 = 215$ km, $L_2 = 264$ km $P = 17.4$ GW unoscillated events $\sim 1.65 \times 10^4$

Geoneutrinos (mostly from Uranium and Thorium) unoscillated events 3.5×10^3


MB Reactors
Far Reactors
Geo ν
ALL
Spectrum/10^3 [MeV^-1]
E_vis [MeV]
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9

DATA ANALYSIS

True spectrum calculated for global analysis best-fit values of oscillation parameters and fixed NH (IH) hierarchy

$$\chi^2 = \chi^2_{\rm stat} + \chi^2_{\rm par} + \chi^2_{\rm sys}$$

$$\chi^2 = \chi^2(\delta m^2,\, \Delta m^2_{ee},\, \theta_{12},\, \theta_{13},\, \alpha,\, f_{\rm R},\, f_{\rm U},\, f_{\rm Th})$$ (limit of infinite bins)

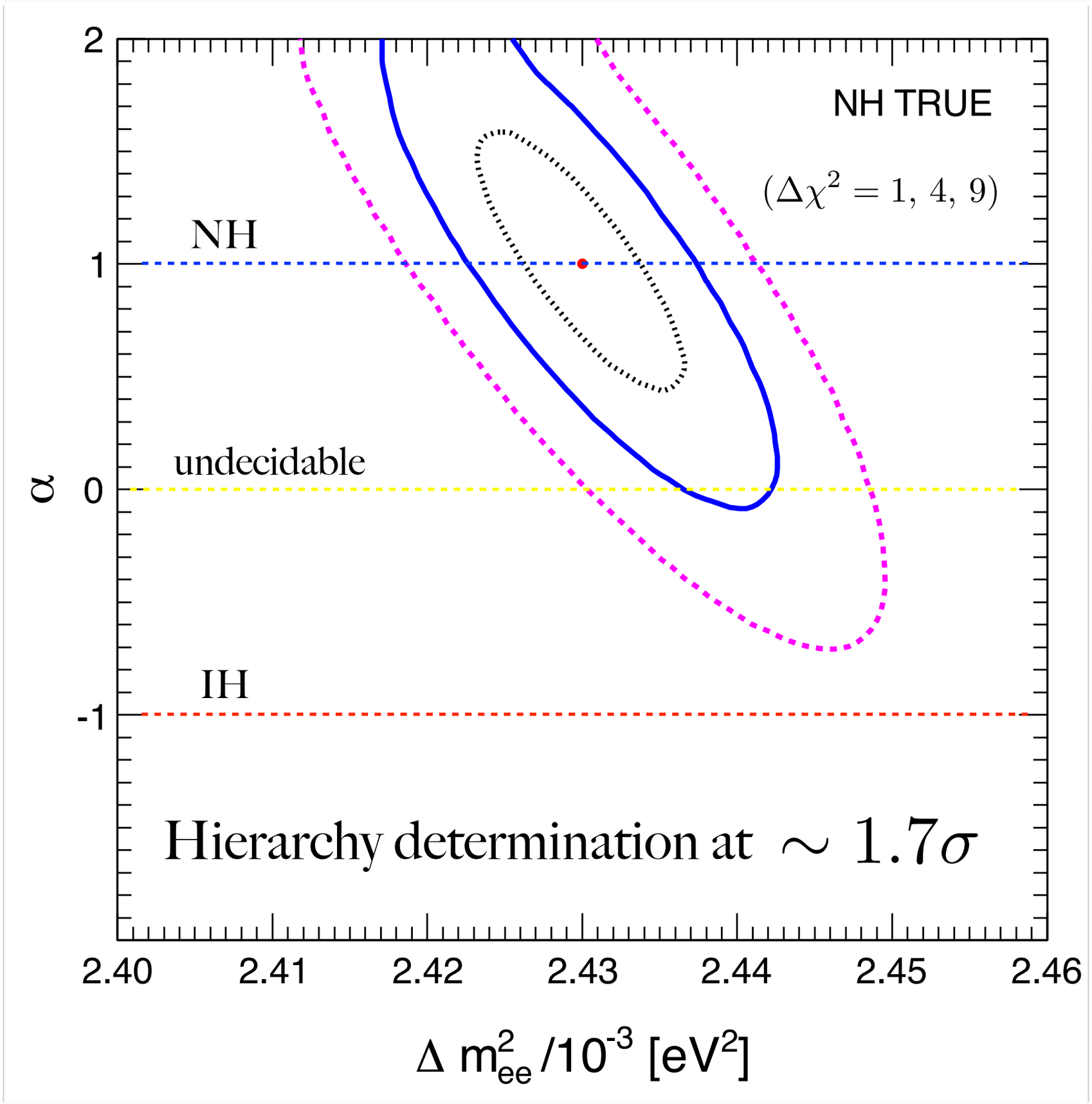
$$\chi^2_{\rm par} = \sum_{i=1}^{4} \left(\frac{p_i - \overline{p}_i}{\sigma_i} \right)^2 \qquad \chi^2_{\rm sys} = \sum_{j={\rm R,U,Th}} \left(\frac{f_j - 1}{s_j} \right)^2$$

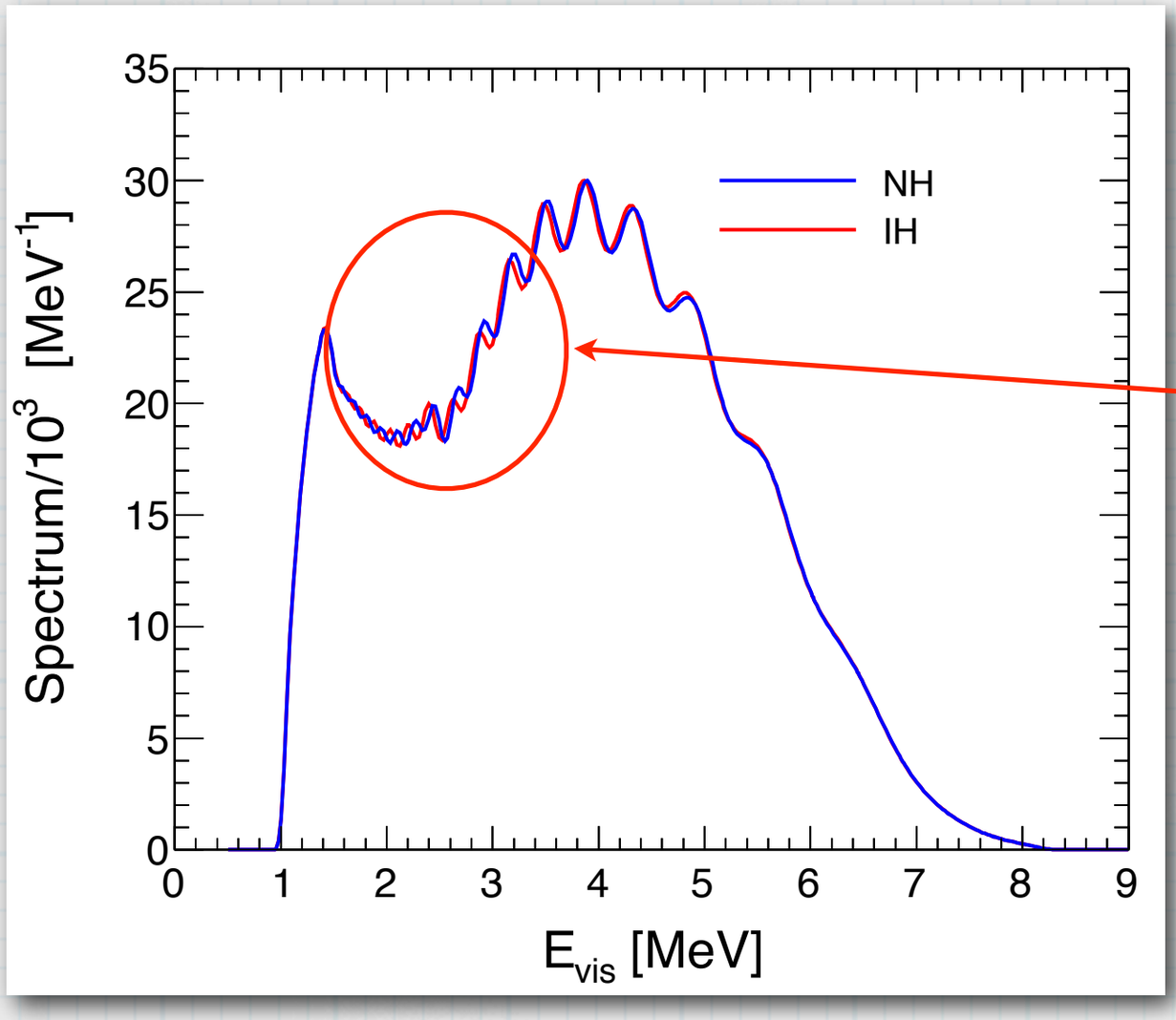
Parameter	% error (prior)	% error after fit (NH true) all data	all − far	all − geo	% after fit (IH true) all data	all − far	all − geo
α	∞	59.2	59.0	57.0	56.2	55.3	54.0
Δm^2_{ee}	2.0	0.26	0.25	0.26	0.26	0.25	0.25
δm^2	3.2	0.22	0.21	0.16	0.21	0.21	0.16
s^2_{12}	5.5	0.49	0.47	0.39	0.49	0.46	0.42
s^2_{13}	10.3	6.95	6.88	6.95	6.84	6.77	6.84
f_R	3.0	0.66	0.66	0.64	0.65	0.65	0.64
$f_{\rm Th}$	20.0	15.3	14.6	—	15.5	15.4	—
$f_{\rm U}$	20.0	13.3	13.3	—	13.3	13.3	—

Distance between NH and IH $(\alpha = \pm 1)$ at $\sim 3.4\sigma$

We recover the approximate "factor of two" reduction of the sensitivity with respect to naive expectations

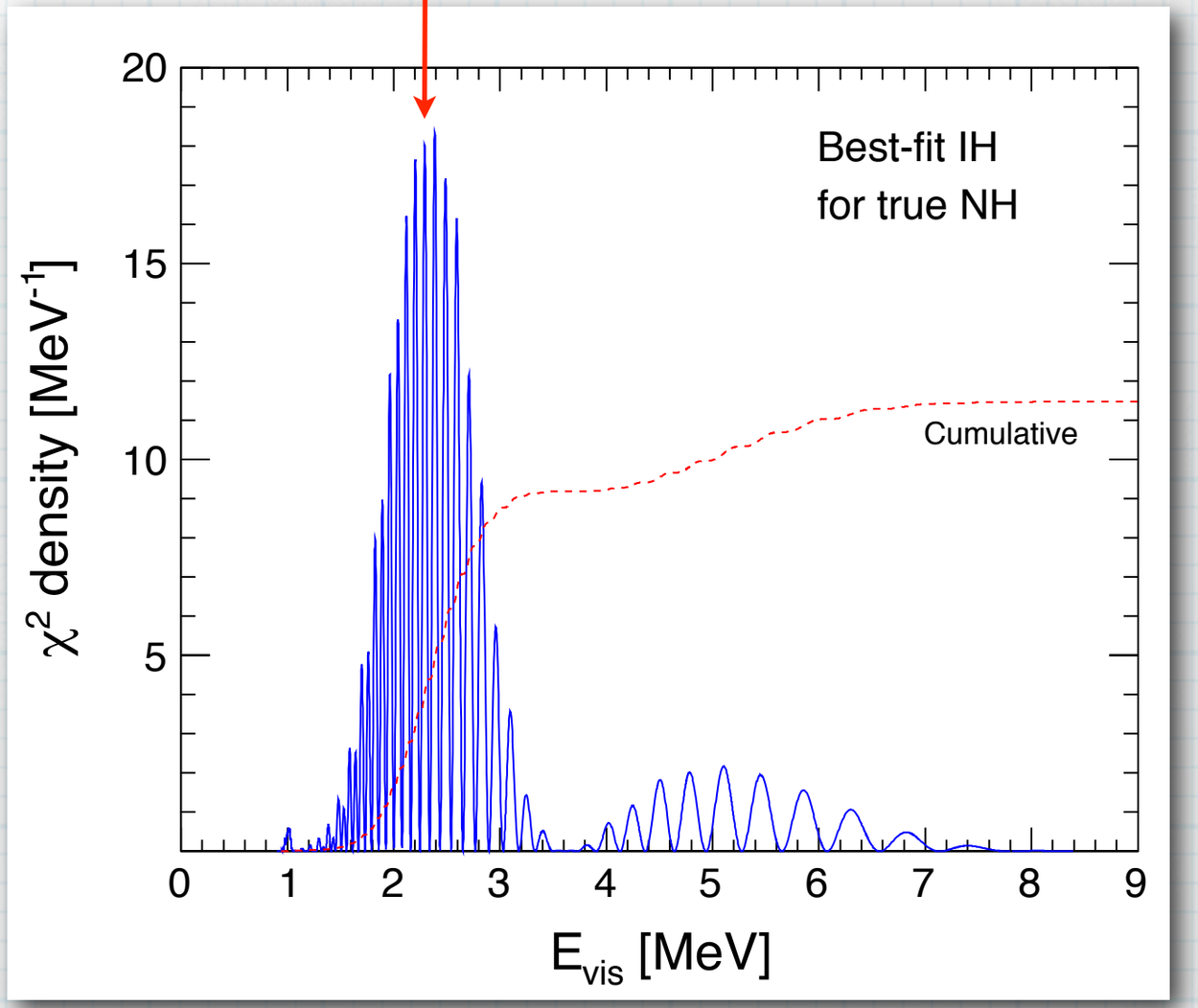
$$N_\sigma \simeq 0.5\sqrt{\Delta\chi^2(\mathrm{NH}-\mathrm{IH})}$$





Comparison between NH and IH, at central value oscillation parameters

Most of the discriminating power in the energy range $2-3$ MeV



Comparison between NH reference data point and best fit for IH

Energy Scale Error: possible nonlinear $E \to E'$ transformation

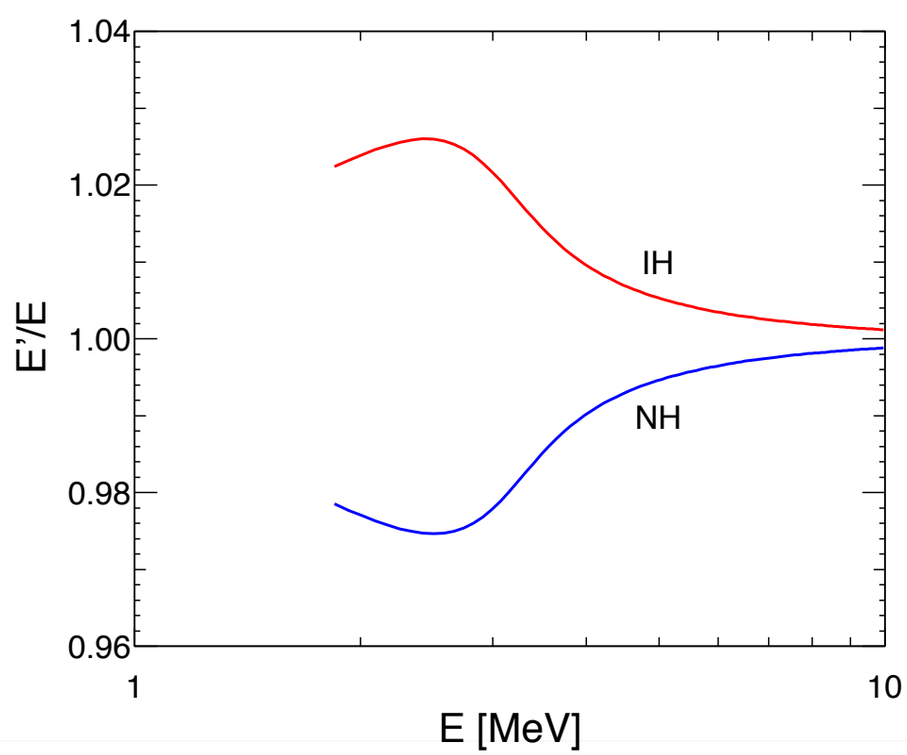
Hierarchy degeneracy
$\alpha = \pm 1 \to \alpha = \mp 1$
if $E \to E'$ satisfies

$$\frac{\Delta m^2_{ee}\, L}{2E} \pm \varphi(E) = \frac{\Delta m^{2\,\prime}_{ee}\, L}{2E'} \mp \varphi(E')$$

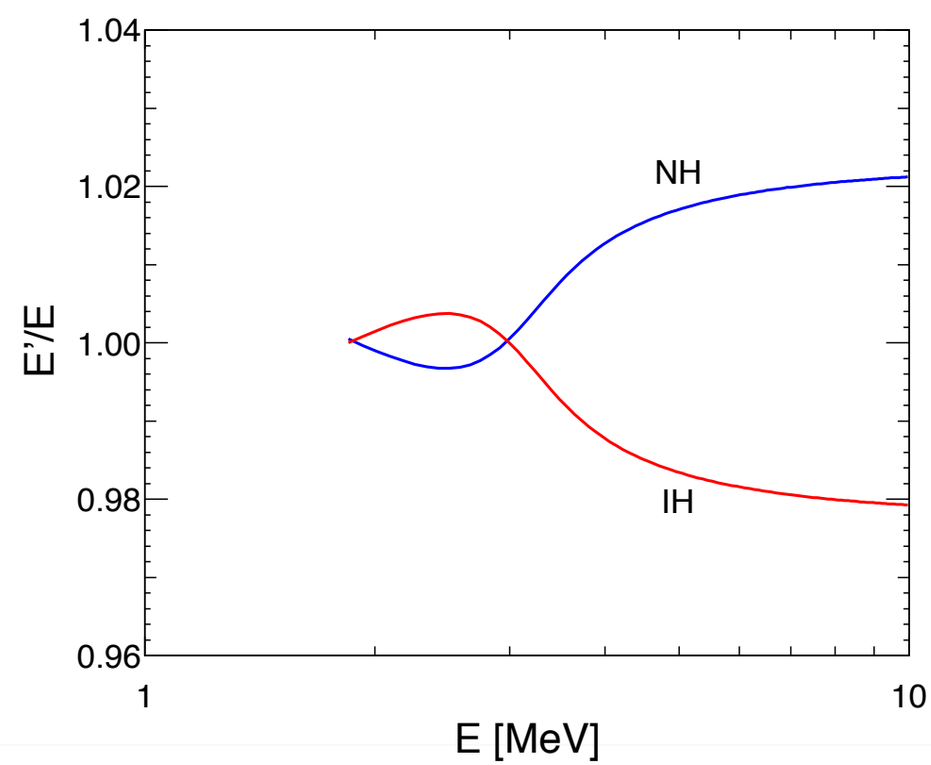
Good approximation $$\frac{E'}{E} \simeq \frac{\Delta m^{2\prime}_{ee}}{\Delta m^2_{ee}} \mp 2 s^2_{12} \frac{\delta m^2}{\Delta m^2_{ee}} \left(1 - \frac{\sin \delta(E)}{2\delta(E)\sqrt{P^{2\nu}_{\rm vac}(E)}} \right)$$

Two interesting cases

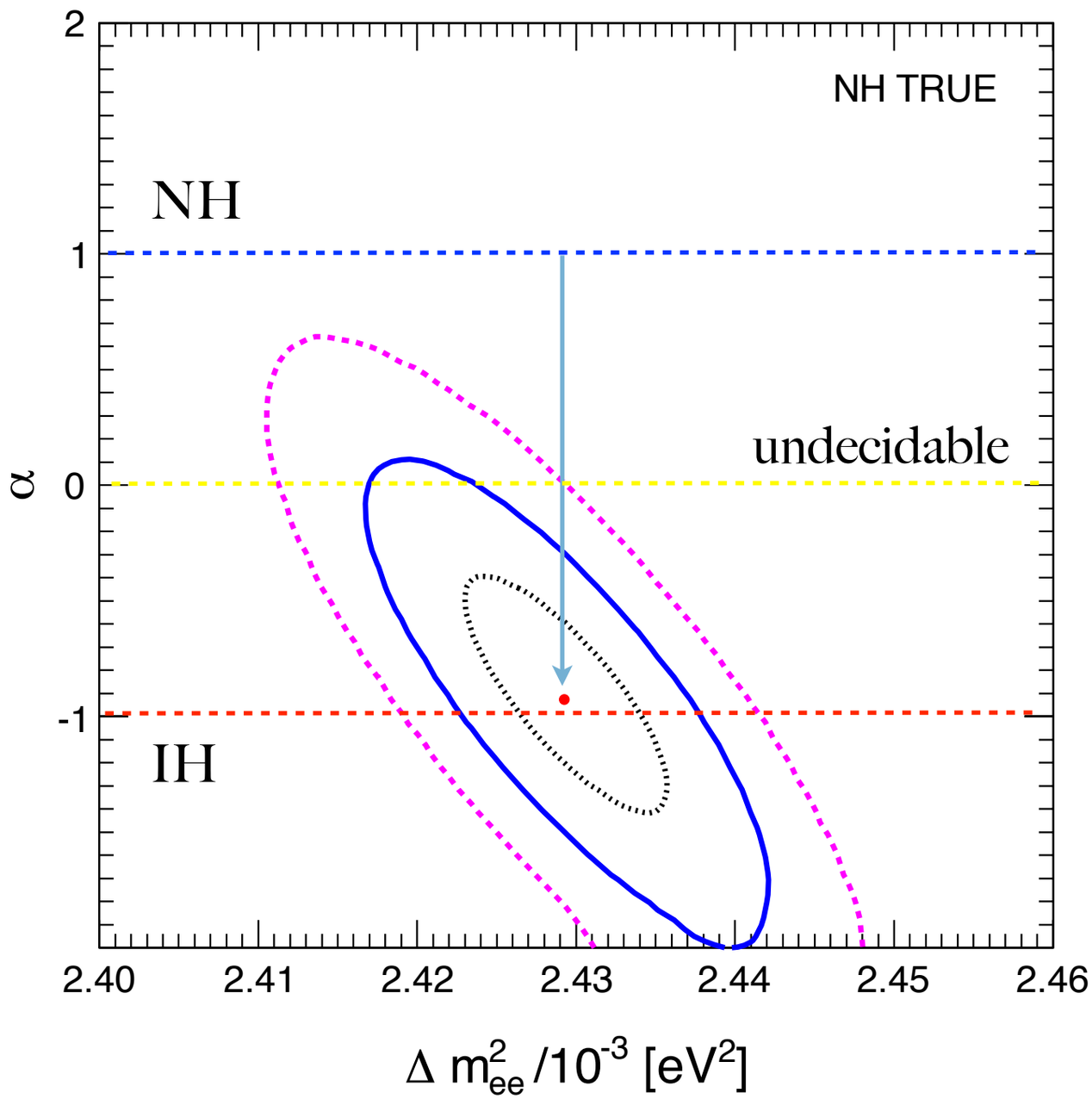
$(E \to E'$ with $E = E'$ at $\infty)$



$E \to E'$ with $E = E'$ at $E = E_T$



Analysis with energy scale error



Assume NH true

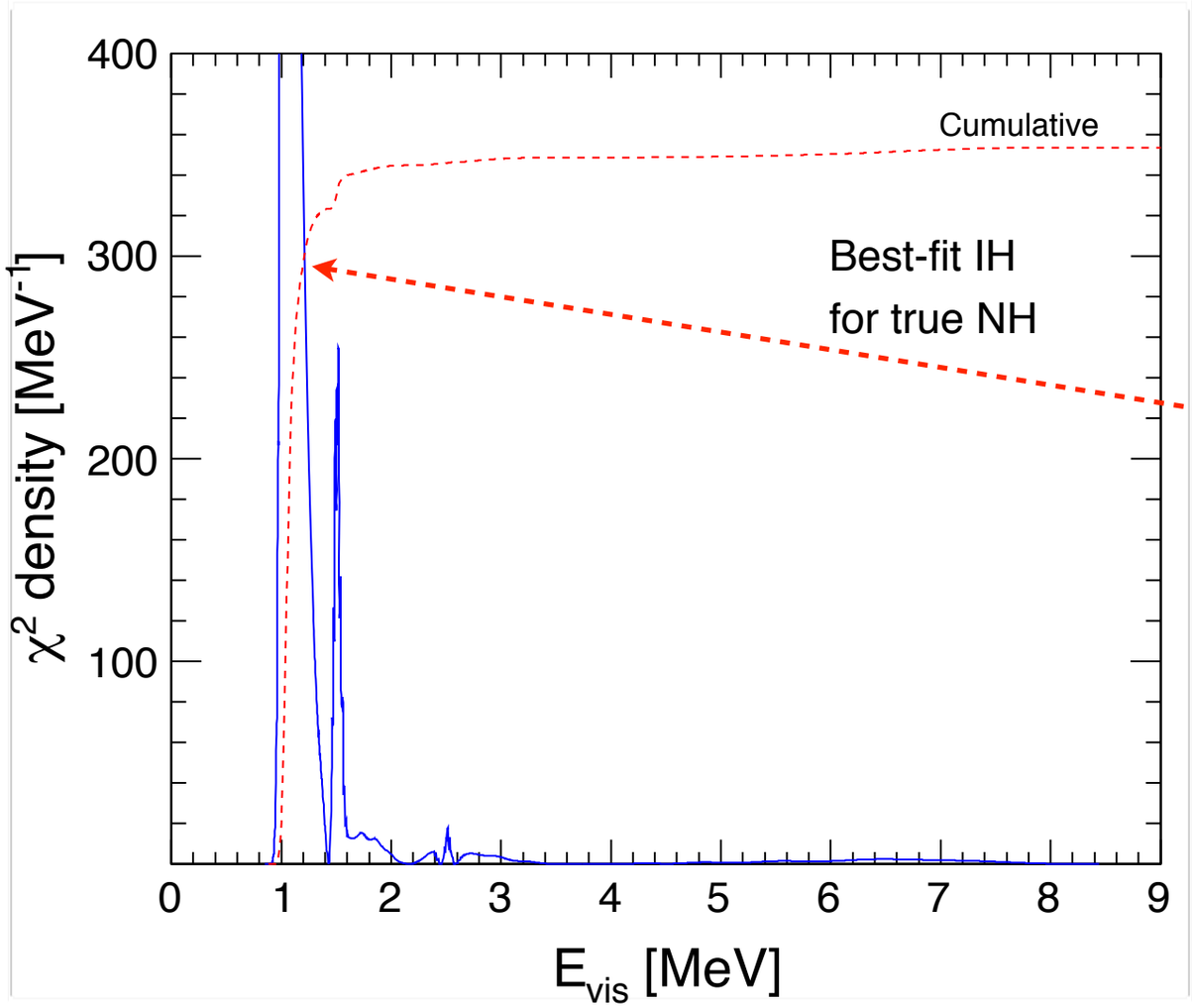
Energy scale error

$(E \to E' \text{ with } E = E' \text{ at } \infty)$

Hierarchy flipped
IH preferred

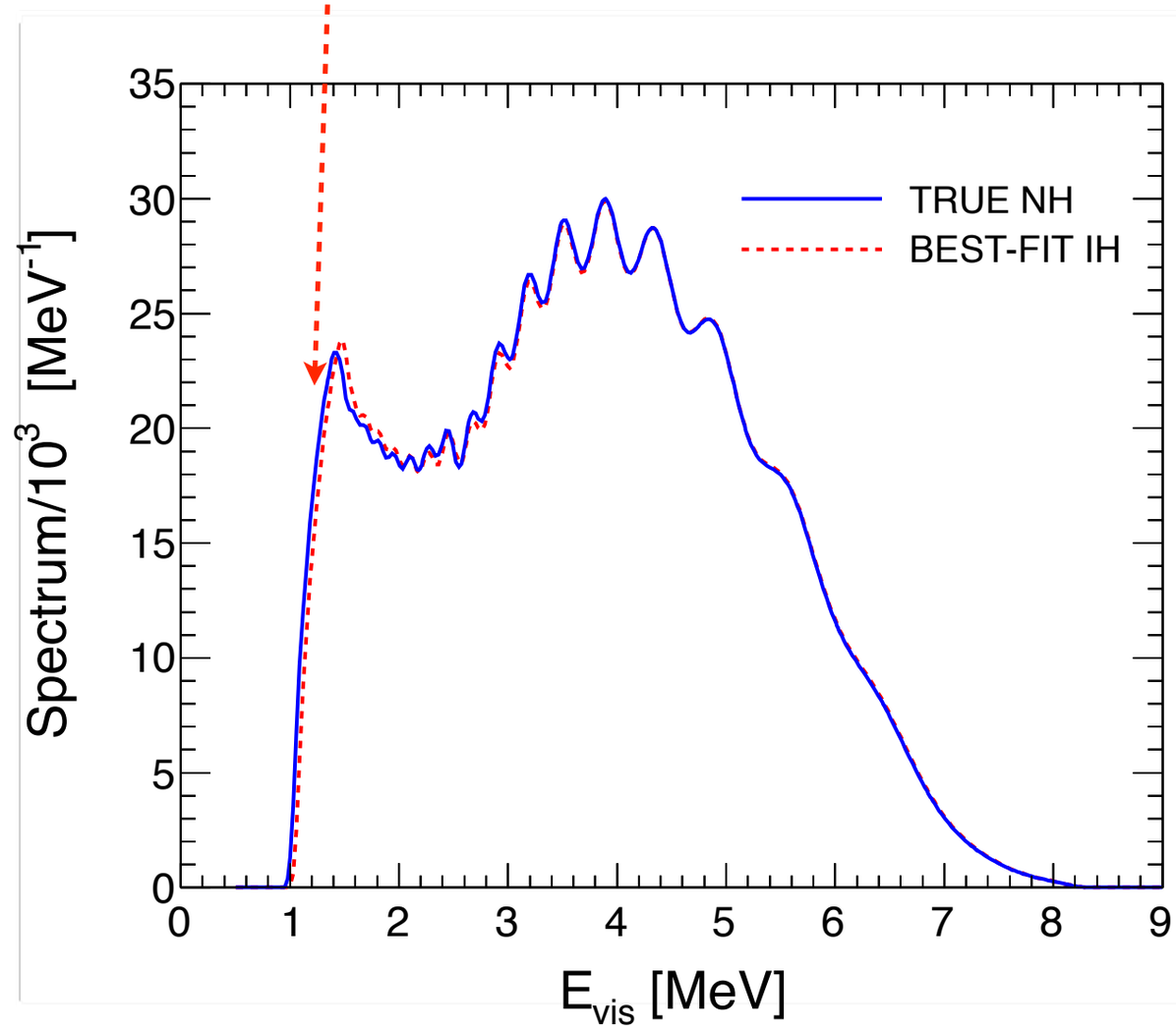
NH excluded at
more than 3σ

but ...

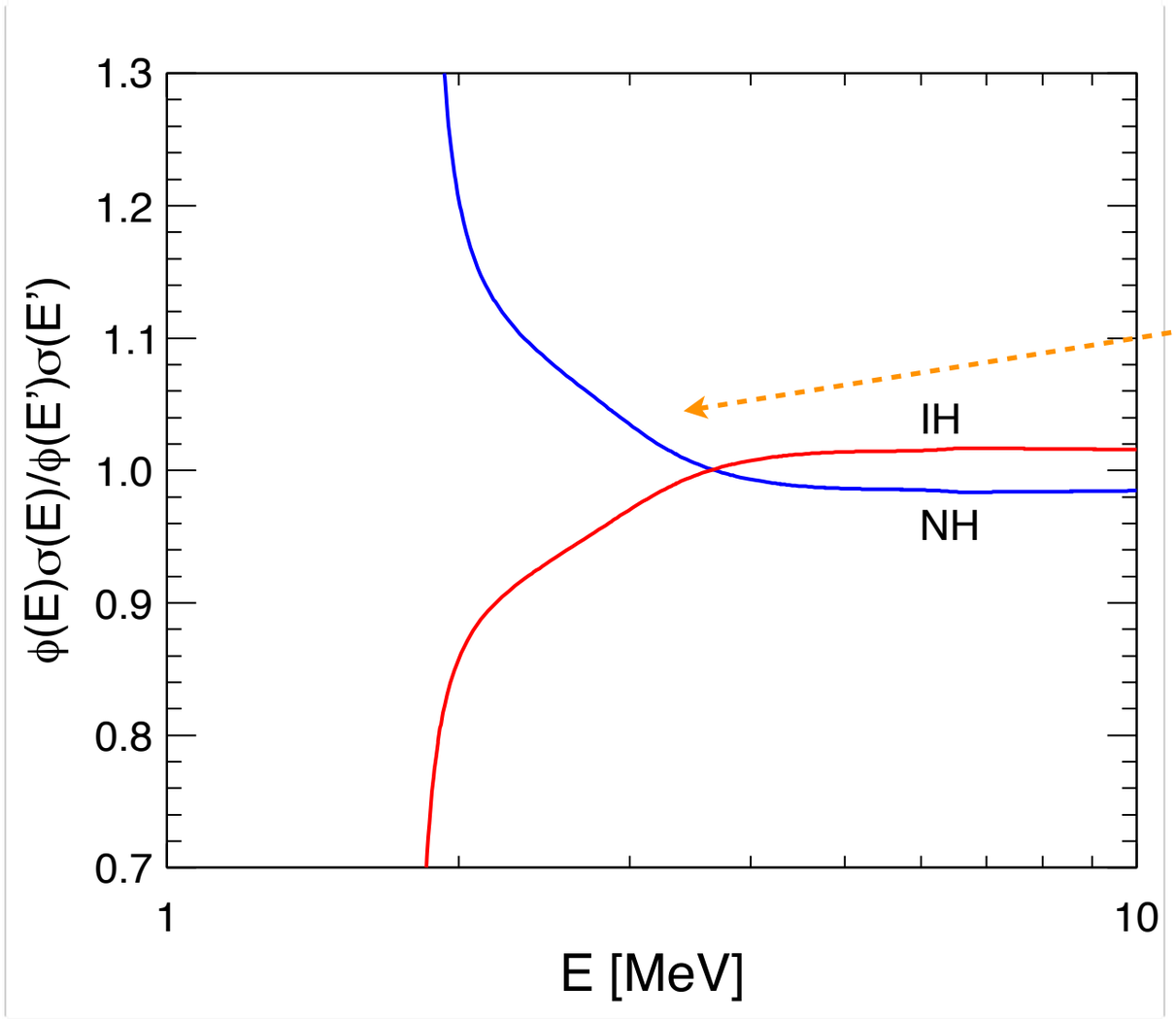


Fit very poor $\chi^2 \sim 360$

Mismatch of spectra near the threshold and at geoneutrino spectral steps



The low-energy tail of the observed spectrum may act as a self-calibrating tool to diagnose energy scale shifts at percent level near the threshold



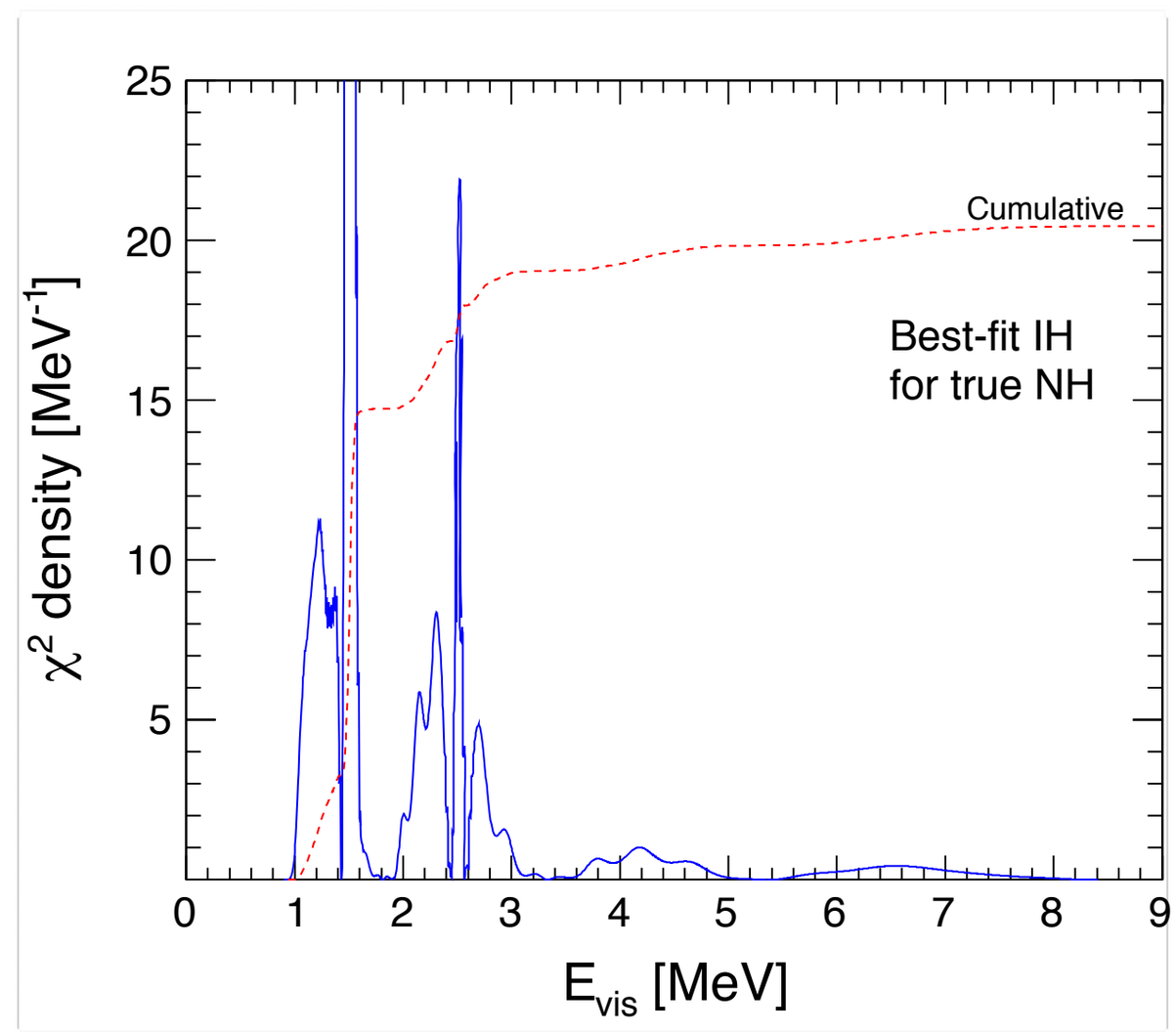
If the shape errors in the observable reactor spectrum could compensate the change

$$\Phi(E)\sigma(E) \to \Phi(E')\sigma(E')$$

they could almost undo the low-energy spectral changes and adjust the fit

the degeneracy $\alpha = \pm 1 \to \alpha = \mp 1$
is then almost complete $\chi^2 \sim 22$

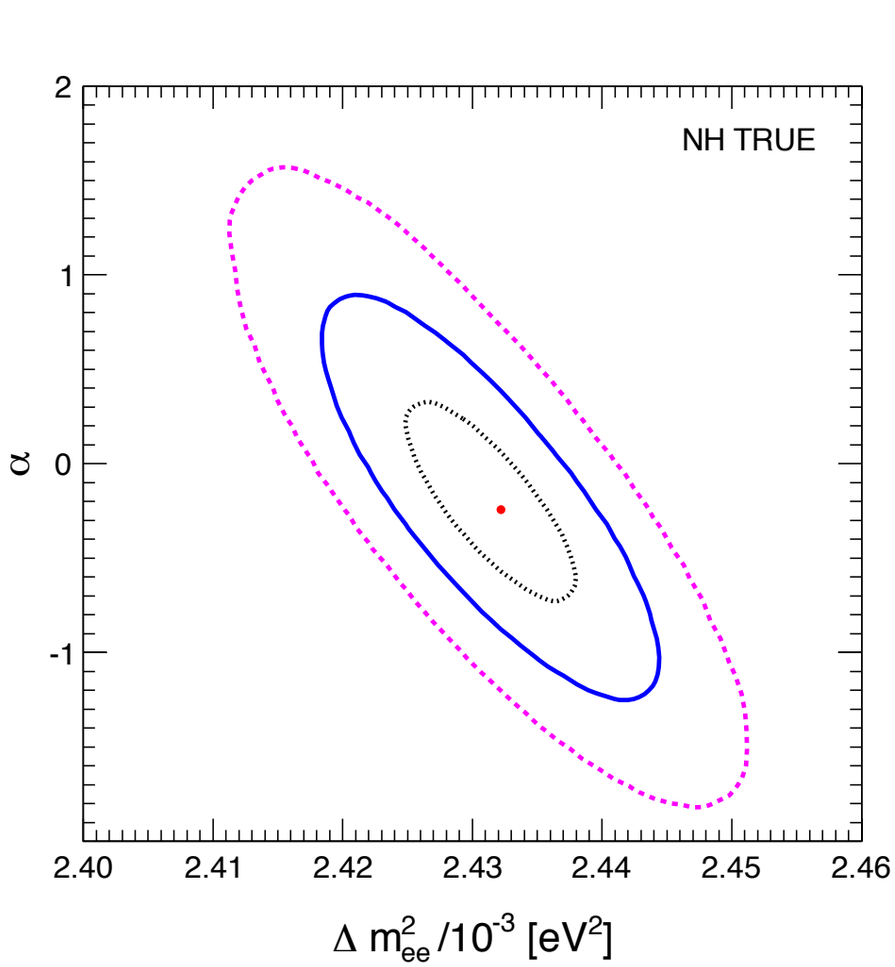
Analogue results for the case
$E \to E'$ with $E = E'$ at $E = E_T$

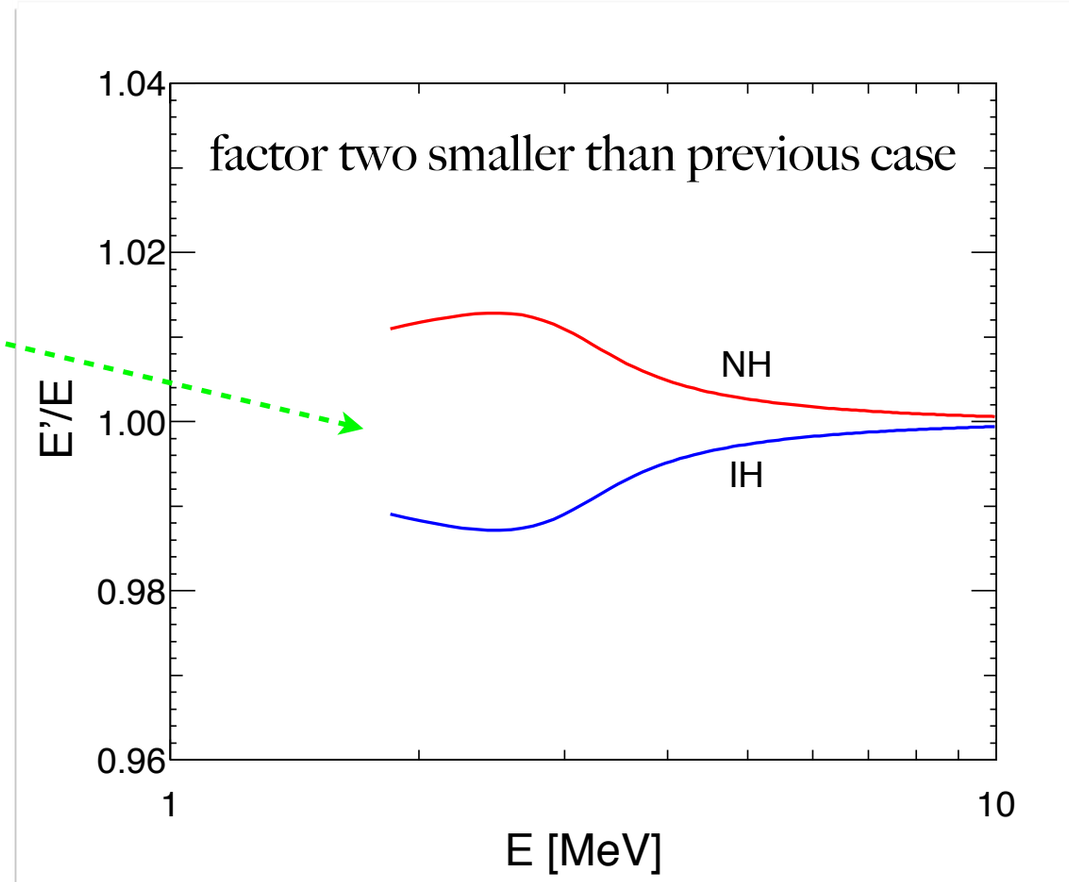


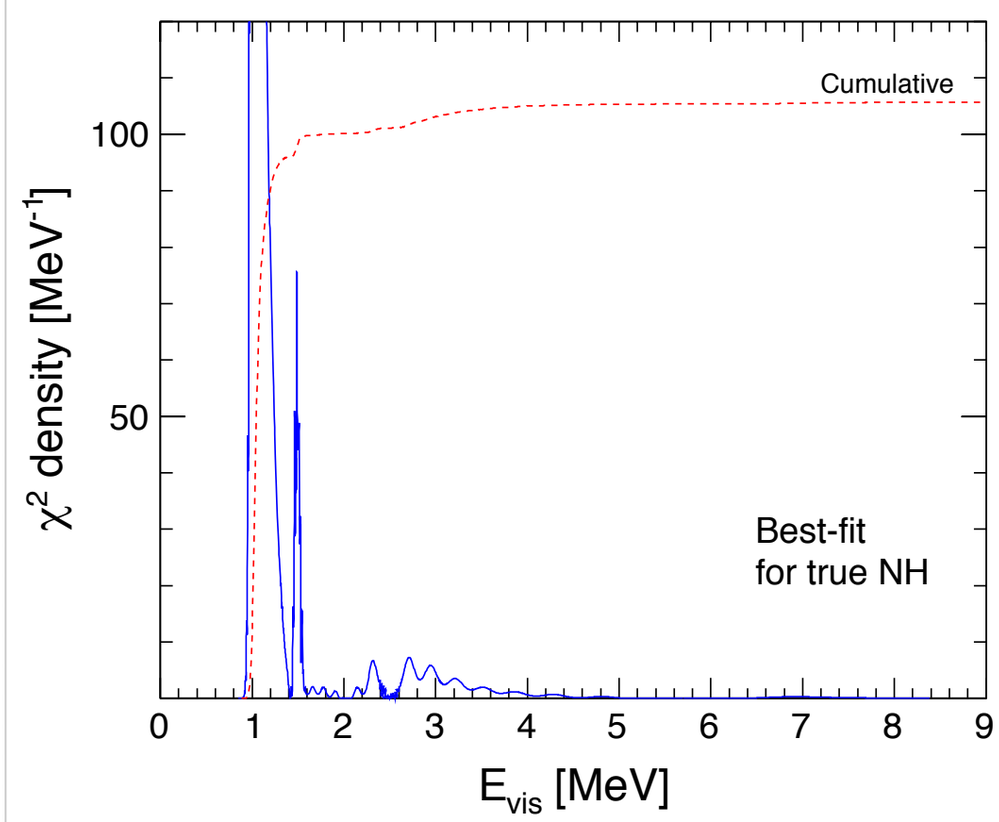
The "undecidable" case

$$E \to E' \text{ so that } \alpha = \pm 1 \to \alpha = 0$$

Hierarchy determination compromised







Conclusions

MBL reactor neutrino experiment purpose is to probe with unprecedented precision some oscillation parameters and the hierarchy. High precision required on both experimental and theoretical side

To this end we include

recoil effects in the cross section calculation (analytically)

matter effects in the oscillation probability (analytically)

multiple reactors effects by means of a damping factor (analytically)

Moreover, we treat α as a continuous parameter to solve issues related to the statistical interpretation of the data analysis

If energy scale errors are under control, with $\sim 10^5$ events

hierarchy determination at $\lesssim 2\sigma$

One order of magnitude better measure of $(\delta m^2, \Delta m^2, \sin^2\theta_{12})$