Facing the Challenges in Medium-Baseline Reactor Oscillation Experiments

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NuFact'13, IHEP, Aug 21, 2013

- *A brief review on MH via reactors*
- *The challenge in energy scale*
- *Subtleties in statistics*
- *Summary and conclusion*

Mainly based on the following three papers in collaboration with

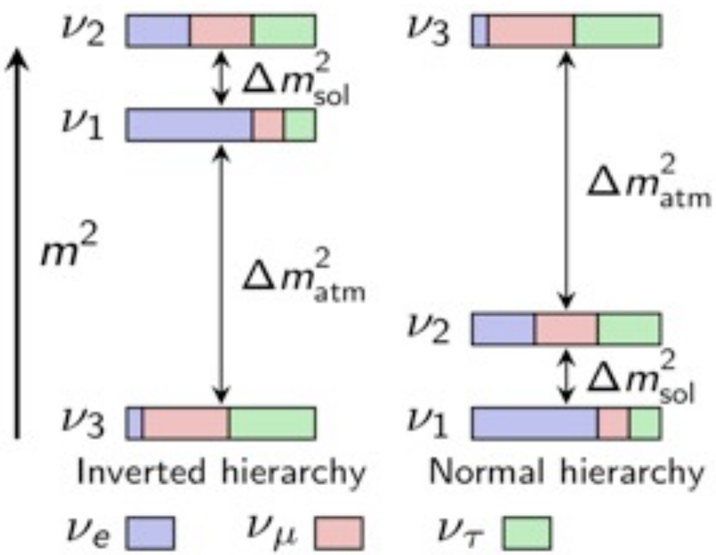
D. Dwyer, J.J. Ling, R.D. McKeown, X. Qian, A. Tan, P. Vogel, C. Zhang, and the U.S. MBRO working group:

X. Qian et al, PRD87(2013)3, 033005

X. Qian et al, PRD86(2012)113011

S. Kettell et al, arXiv:1307.7419 (Snowmass 2013)

The Gate to Mass Hierarchy is Open

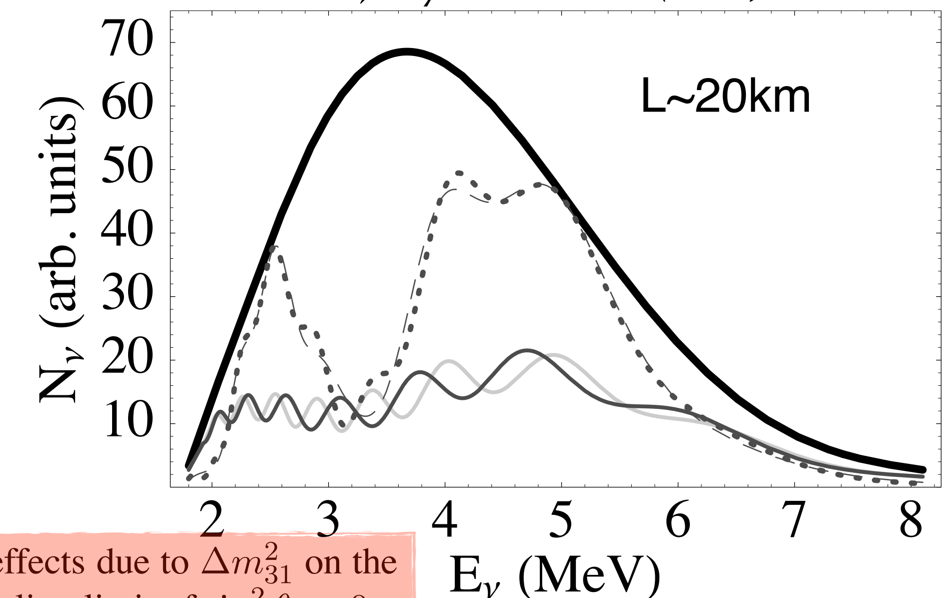


- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  - ✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



✓Mass hierarchy is reflected in the spectrum

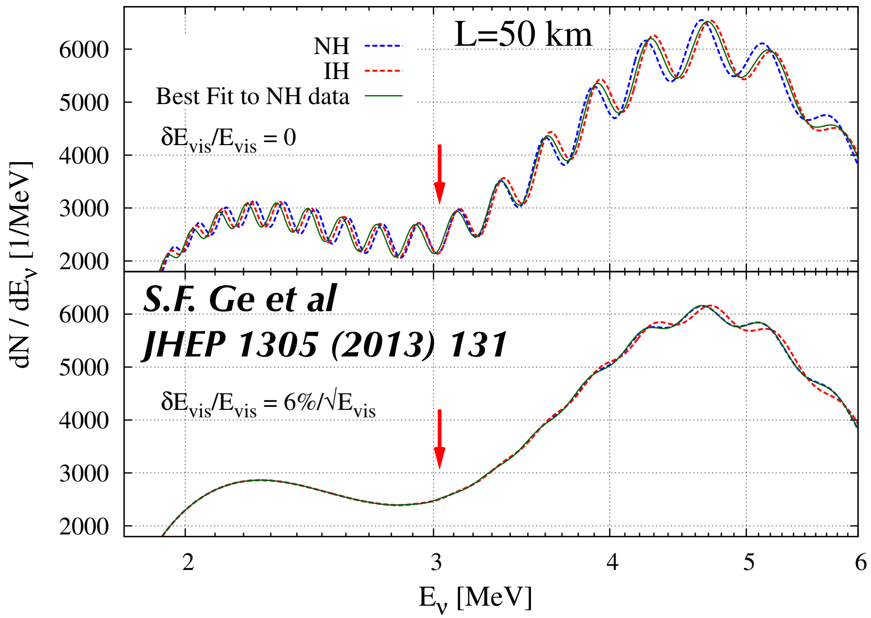
✓Signal independent of the unknown CP phase

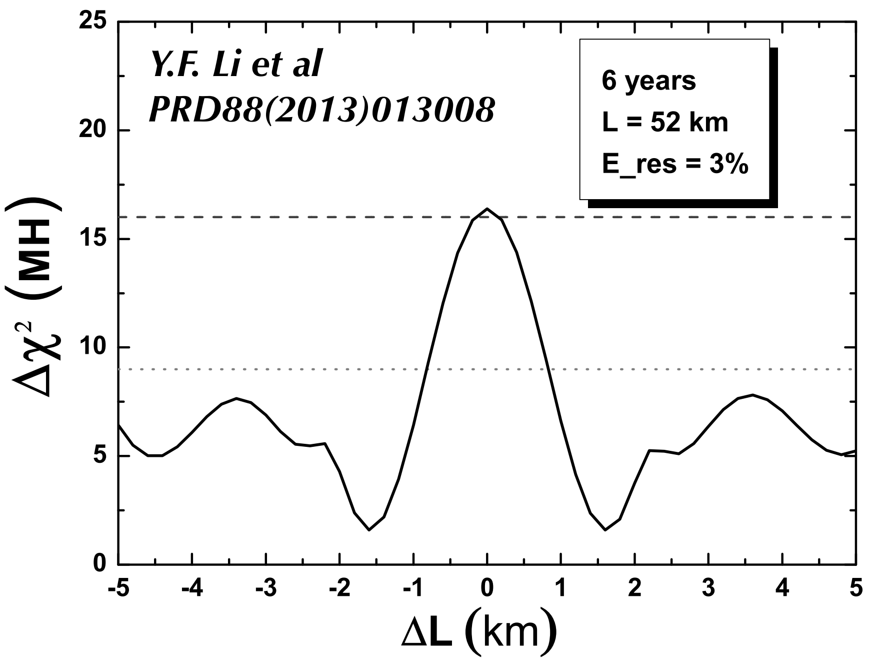
- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}$−driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302

Challenges in Resolving MH using Reactors

- Energy resolution
- **Energy non-linearity**
- **Statistics**
- Reactor distribution
  – The mass hierarchy information is in the multiple atmospheric oscillation cycles in the survival spectrum. For the valuable part of the spectrum ~3.5MeV, the oscillation length is ~3.5km.
  – Thus, if two reactor cores with equal or close powers differ by half oscillation length, the mass hierarchy signal will get cancelled.



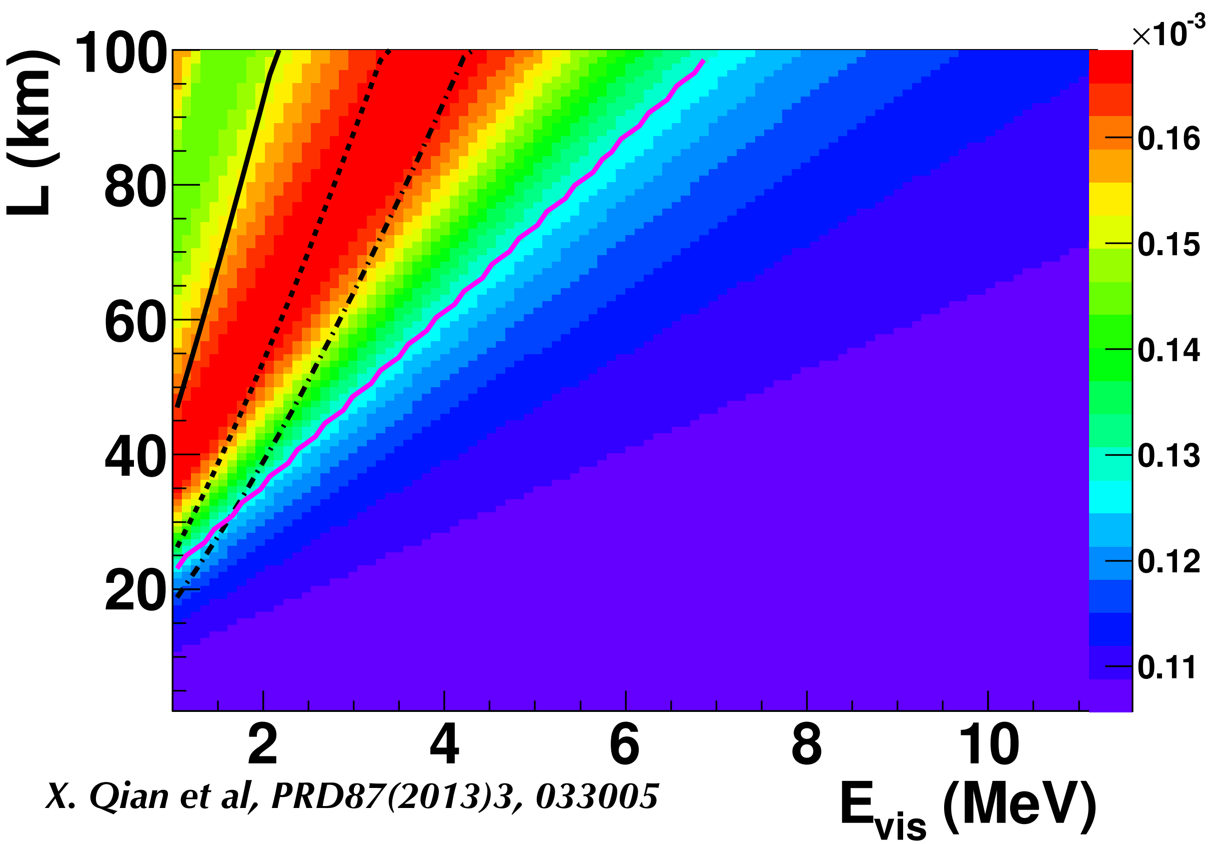


Reading the Signal in Another Way

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 2s_{13}^2 c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$$

$$+2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi)$$

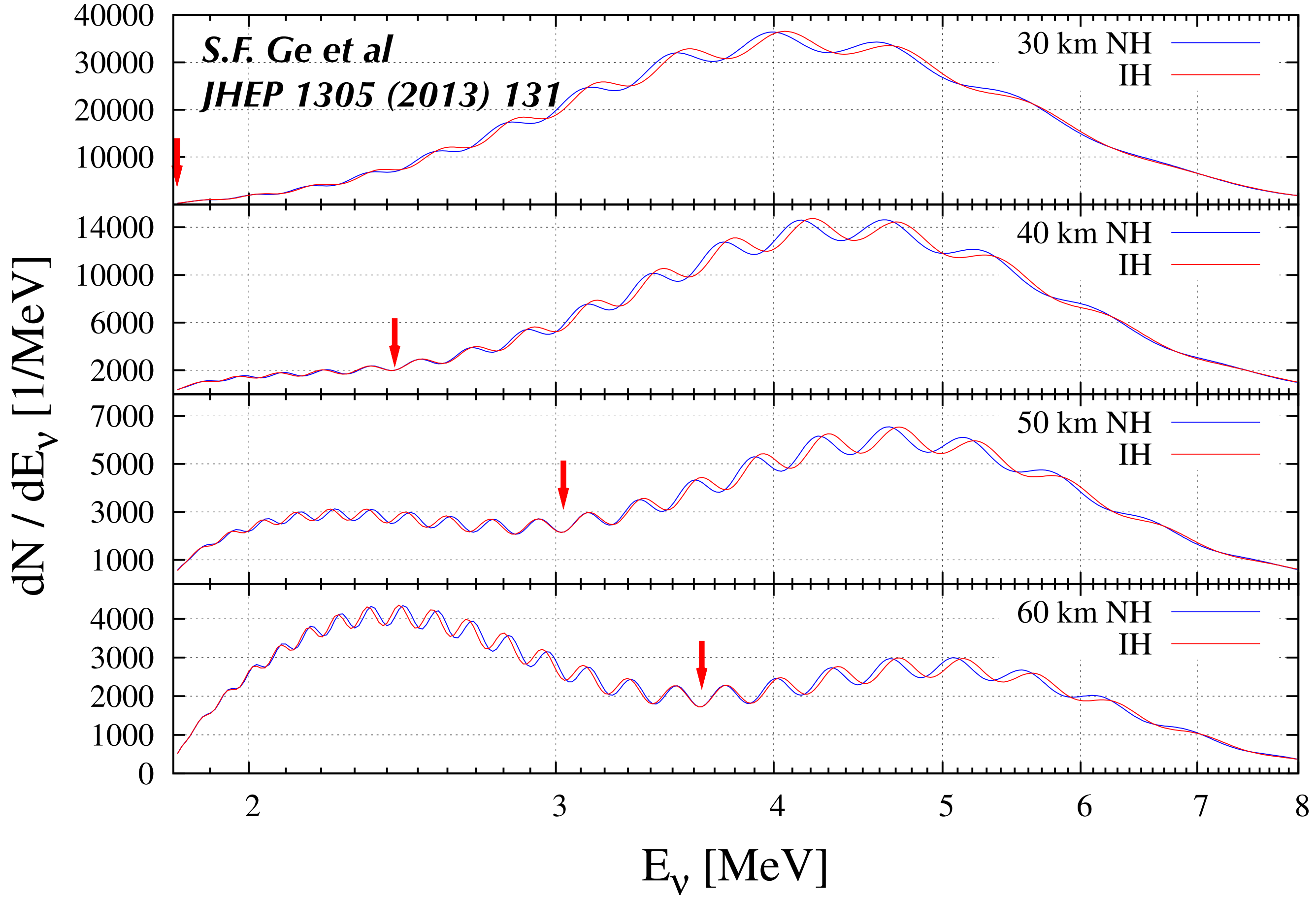
$$\tan\phi = \frac{c_{12}^2 \sin 2\Delta_{21}}{c_{12}^2 \cos 2\Delta_{21} + s_{12}^2} \Rightarrow \Delta m_\phi^2(L,E) = \frac{\phi}{1.27} \cdot \frac{E}{L}$$



X. Qian et al, PRD87(2013)3, 033005

- Reading it from a different perspective gives us, the experimentalists, a few obvious catches
  - Δm^2_{32} uncertainty is too big for the small differences caused by different mass hierarchies. The shift can be easily absorbed by the uncertainty
  - Energy resolution push the "useful" part from the left

Give The MH Signal a Closer Look



- It is obvious that the baseline is better beyond 30km
- Practically speaking (for real experiments), the power lies in the contrast between the lower part and the higher part of the inverse beta decay spectrum

- At the energy where the effective mass-squared difference shift disappears, NH and IH spectra are identical. Below and above this energy, the phase difference between NH and IH shift in different direction.

Energy Scale Places A Challenge

S.J. Parke et al, Nucl.Phys.Proc.Suppl. 188 (2009)

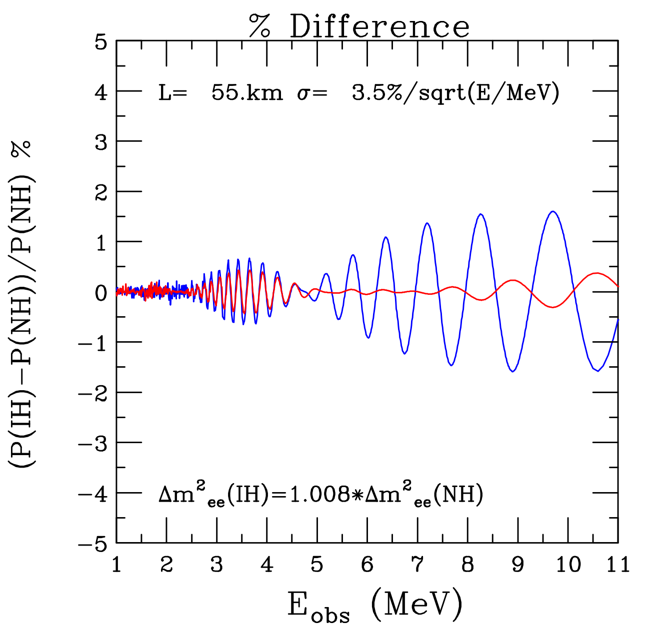
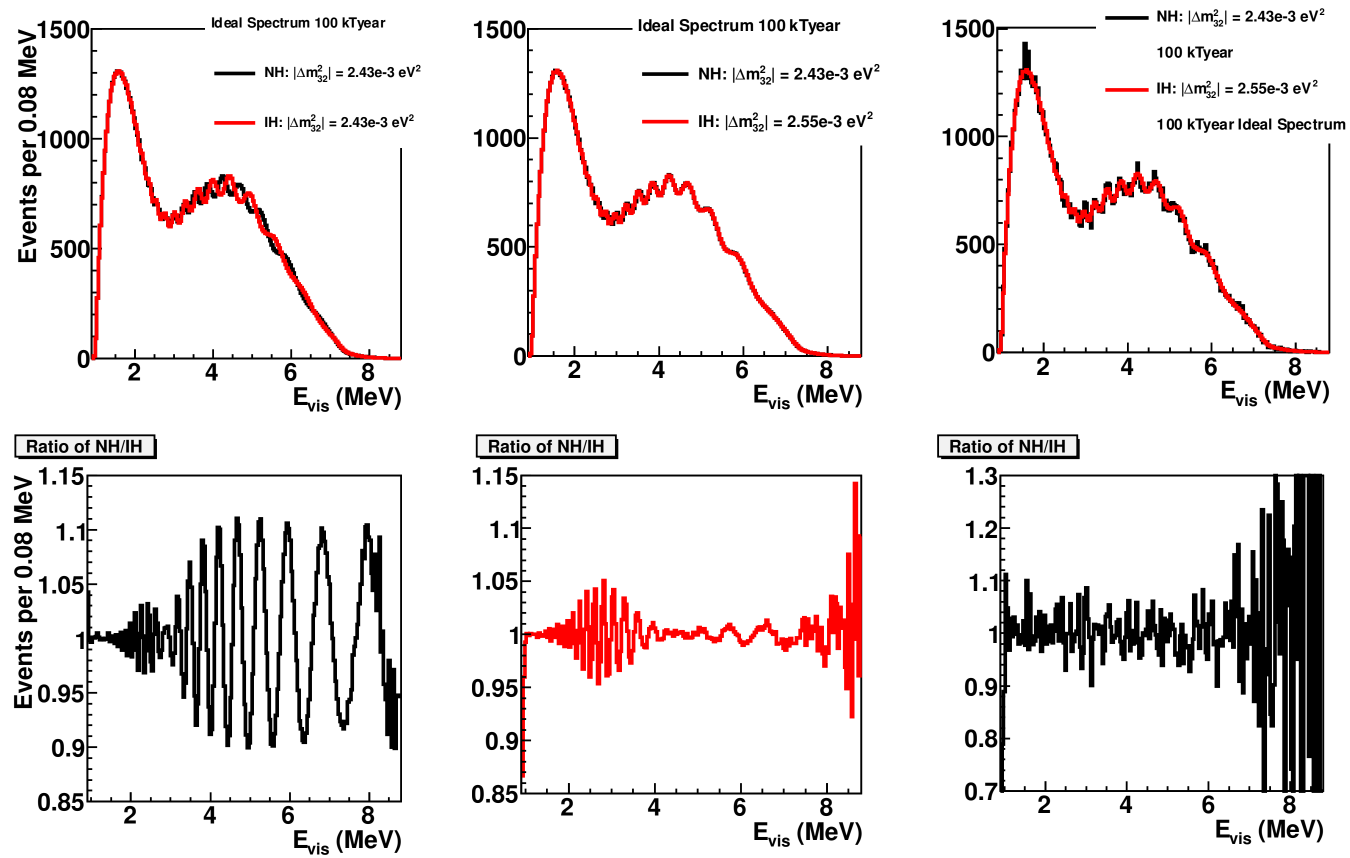


Figure 4. The percentage difference between the inverted hierarchy and the normal hierarchy. The blue curve is assuming $E_{obs} = E_{true}$ and maximum difference is less than 2%. Whereas for the red curve we have assumed that $E_{obs} = 1.015E_{true} - 0.07$ MeV for the IH, so as to represent a relative calibration uncertainty in the neutrino energy. Here the maximum percentage difference is less than 0.5%.

X. Qian et al, PRD87(2013)3, 033005



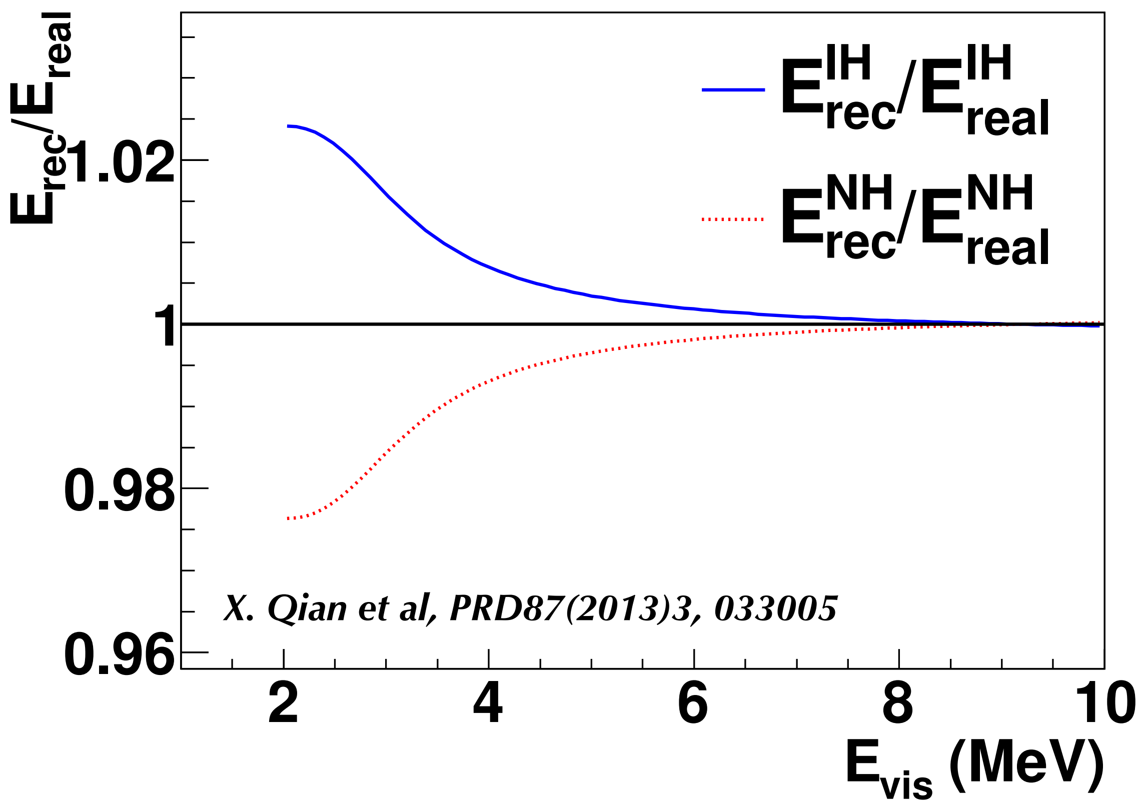
- Oscillation is governed by ~$\Delta m^2_{32}/E$, thus their uncertainties have very similar role in MH determination
- Uncertainty in Δm^2_{32} causes nearly degenerated spectra between NH and IH

Degenerated Spectrum

- Recall the survival probability

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21}$$
$$+2s_{13}^2c_{13}^2\sqrt{1-4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$

$$\Rightarrow \quad E_{rec} = \frac{2|\Delta' m_{32}^2| + \Delta m_\phi^2(E_{\bar{\nu}_e}, L)}{2|\Delta m_{32}^2| - \Delta m_\phi^2(E_{\bar{\nu}_e}, L)} E_{real}$$



Could there be identical oscillation patterns?

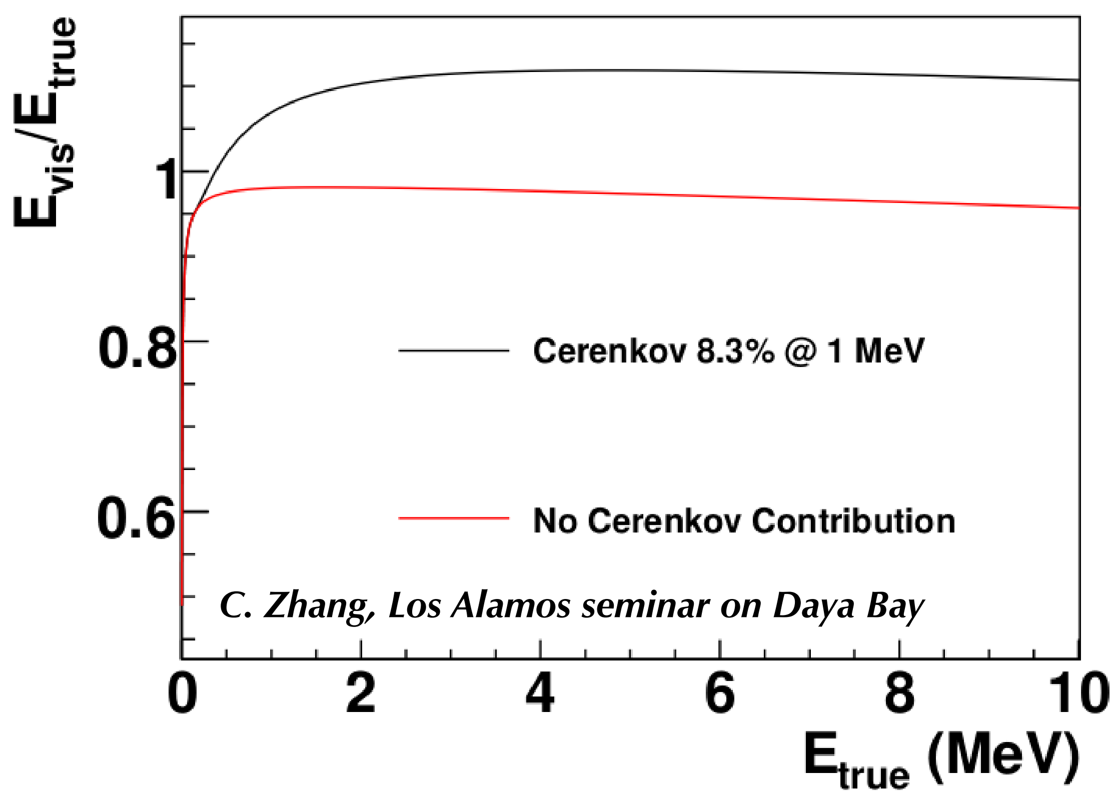
- The current uncertainty in atmospheric mass-squared difference, combined with a non-linear energy response, would create the same survival spectrum for both mass hierarchies.
- No way to resolve MH if the non-linear energy response allows such curves (unless we compensate the loss at the reactor flux spectrum level)

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- We need "free" protons and we need photons, the more the better

➡ Liquid scintillator detector seems the ideal choice: protons (H), high photon yield, and relatively cheap. It turned out to be this is the choice of all current proposals.

➡ But liquid scintillator has a notorious feature: energy non-linearity due to quenching and Cherenkov lights



➡ Based on past/current understanding, the "convenient" non-linearity curve which could cause degeneracy follows a similar shape to the liquid scintillator energy response.

➡ There could be difficulties in resolving MH due to the non-linearity feature of LS

MH Sensitivity Study Setups (using the JUNO design)

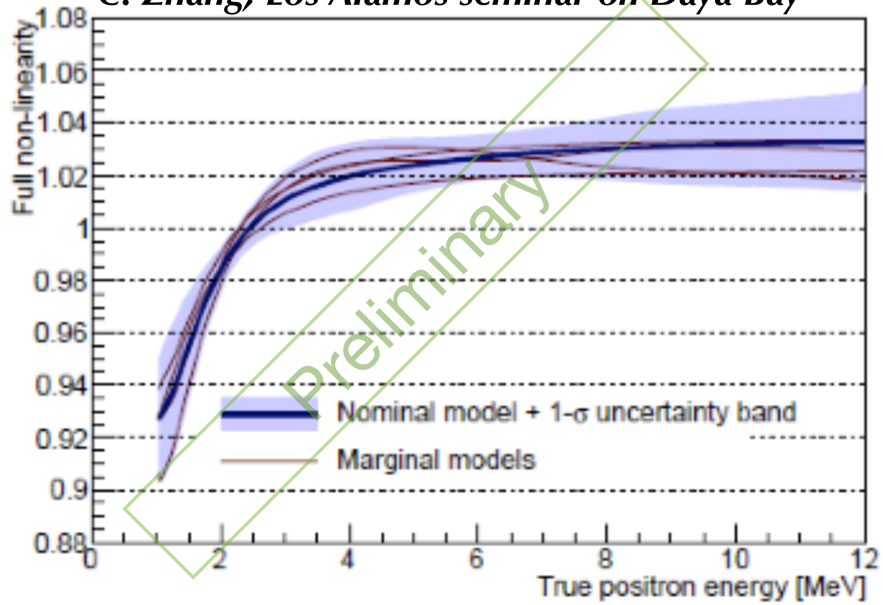
Chi-square analysis to fit the Asimov data generated assuming true MH

$$\chi^2 = \sum_{i=1}^{N} 2 \cdot (N_i^{exp} - N_i^{obs} + N_i^{obs} \cdot \log(N_i^{obs}/N_i^{exp})) + \chi^2_{penalty} \quad \Rightarrow \quad \Delta\chi^2_{\mathrm{MH}} = |\chi^2_{\mathrm{min}}(\mathrm{N}) - \chi^2_{\mathrm{min}}(\mathrm{I})|$$

Background assumptions
(Shapes from Daya Bay and Rates from KamLAND)

- Accidental background (~3000)
- Cosmogenic background (~550)
- Fast neutron background (~400)
- $^{13}C(alpha, n)^{16}O$ background (~6300)
- Geo-neutrino background (~3600)

C. Zhang, Los Alamos seminar on Daya Bay

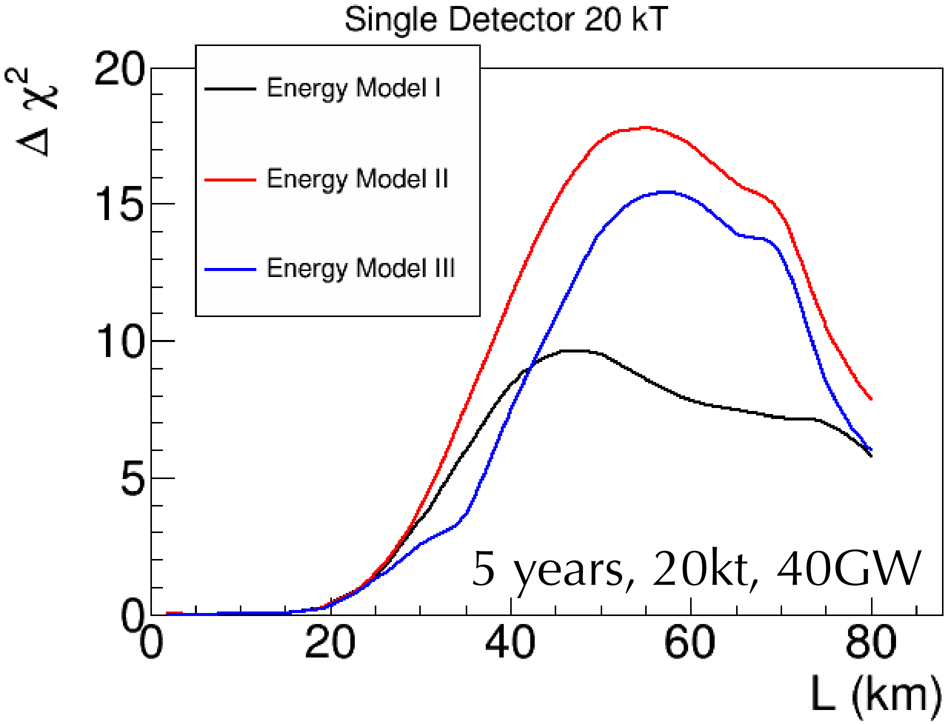


Energy model assumptions

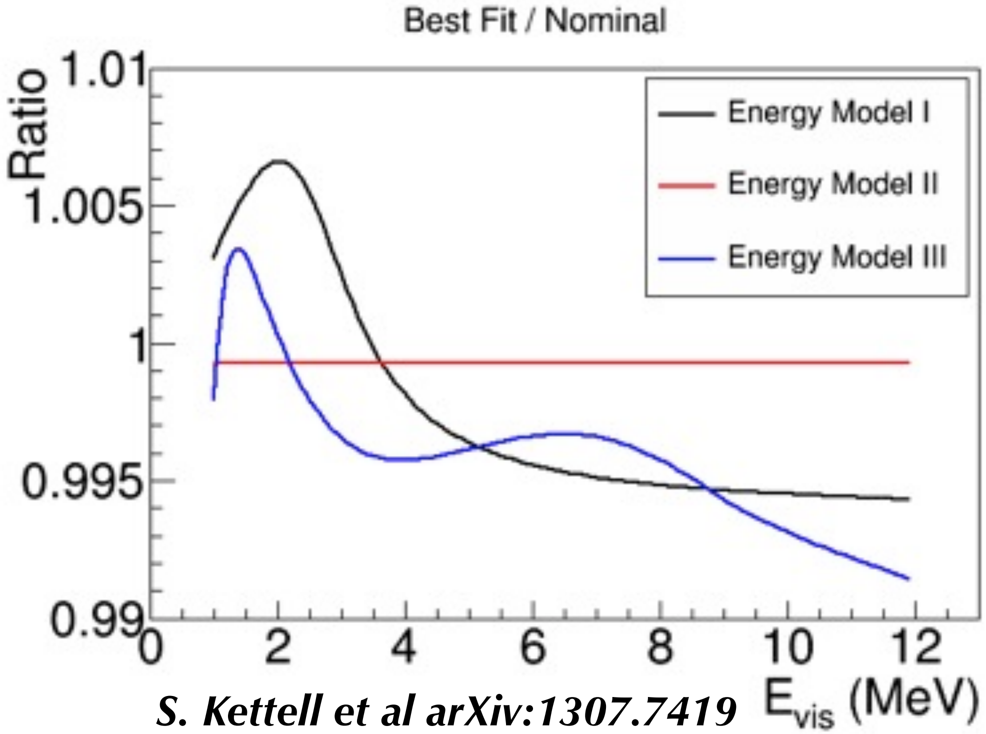
- Model I: the degeneracy energy scale model, assuming 1% uncertainty
- Model II: a straightforward linear model with 1% uncertainty
- Model III: the Daya Bay energy model **(Also see Soren's Daya Bay talk on Friday)**
  - Five equally good models (for Daya Bay data) treated independently, which allows/ generates flexibility in shape.
  - Correlations between different energy bins not reflected in the plot.

JUNO Sensitivity with Different Energy Models

S. Kettell et al arXiv:1307.7419



- Clearly, the degeneracy model has the worst impact to the sensitivity
- The current Daya Bay model, assuming 1% uncertainty, is still worse than the naive linear model



S. Kettell et al arXiv:1307.7419

- The flexibility/uncertainty in the energy scale functional format allows "pulls" on the spectrum to match the wrong MH
- The correlation between lower and higher energies constrains the allowed "pulls".
- Key: construct a more definite energy non-linearity model

How to Conquer the Energy Scale Challenge?

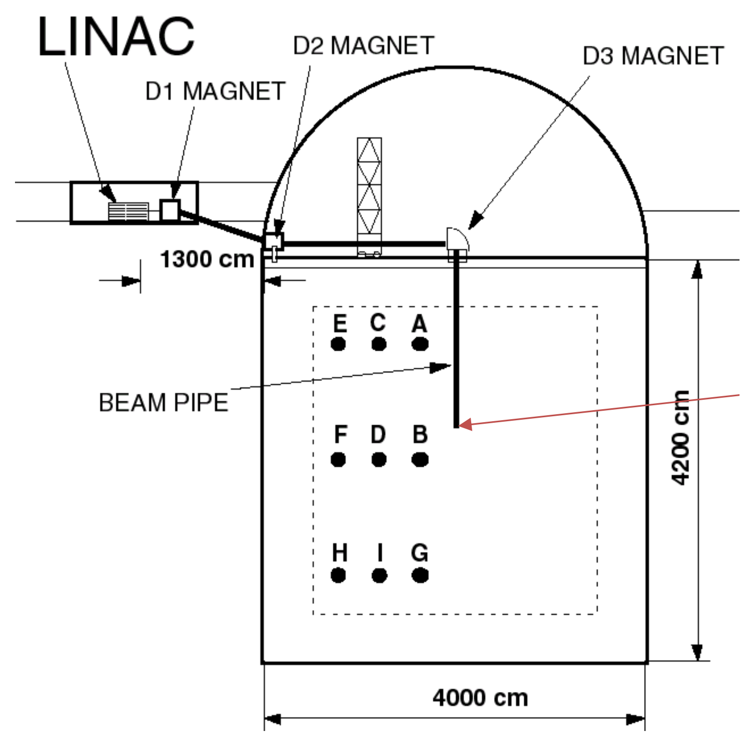
- Improve the energy calibration accuracy. (Plausibility?)
- Dual detector to mitigate the energy scale challenge? (Possibility?)
  - See E. Ciuffouli et al, arXiv:1211.6818
- Which approach is more effective?

S. Kettell et al arXiv:1307.7419

2nd Detector	$\Delta\chi^2$	$\Delta\chi^2\ (\sigma_{scale}/4)$
20kt at 53km	4.2	14.3
0.1kt at 2km	4.9	11.5
5kt at 30km	10.3	13.6

- To reach the same level of improvements, energy scale uncertainty needs to be greatly improved.
  - Remark: Super-K solar does reach the level of 0.6% in absolute energy scale using an electron LINAC
  - Could we realize this accuracy in a JUNO-like detector?
    Proposed R&D: a positron and electron gun to cover the whole inverse beta decay spectrum.

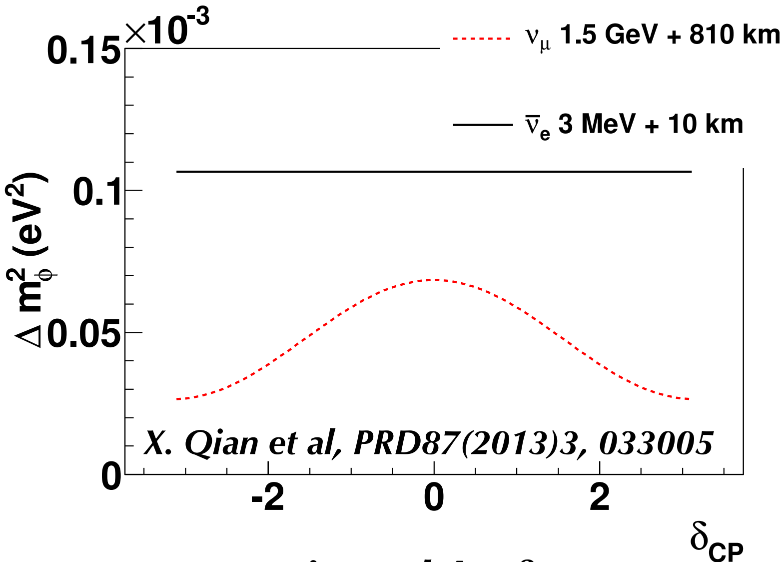
Super-K LINAC calibration (courtesy of T. Kajita)

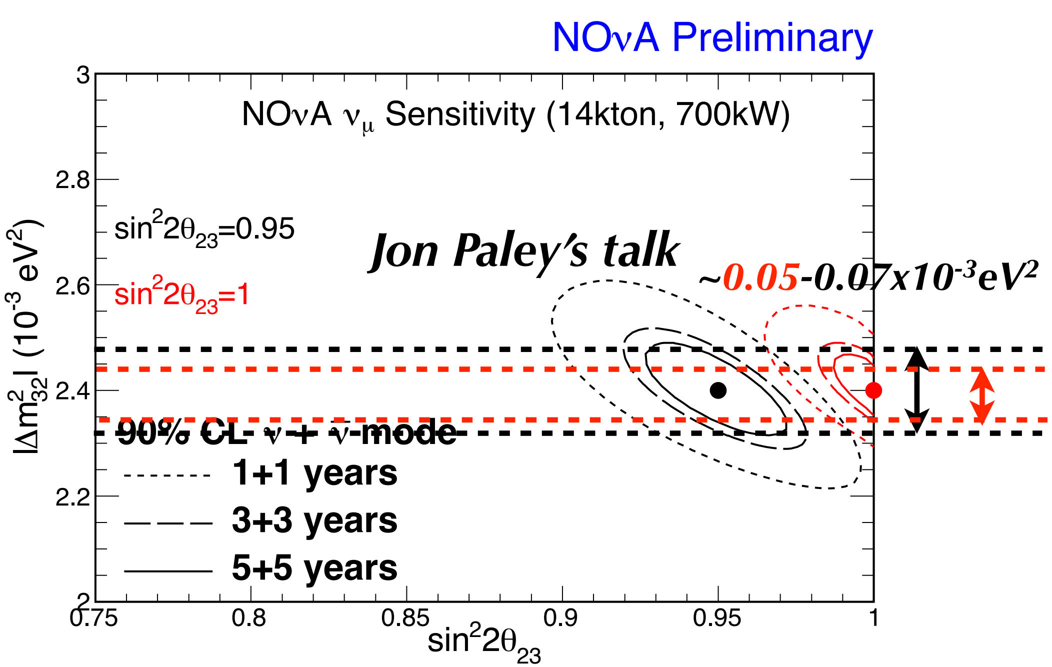


- Beam energy: 5 ~ 16 MeV/c

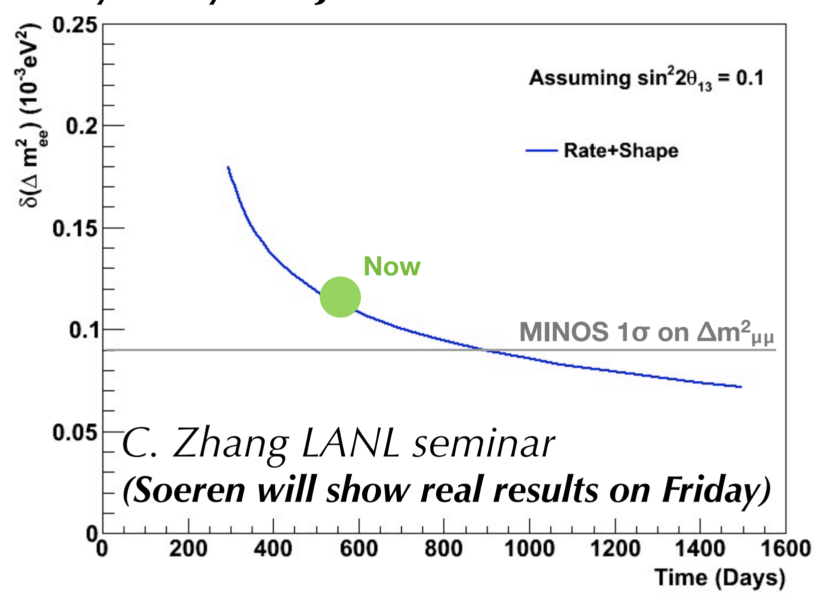
What Can Further Improve the MH Sensitivity? (I)

- Nonukawa et al pointed out that if Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ measured precise&accurate sufficiently, MH can be resolved. See *PRD72 (2005) 013009*.
- Yufeng et al showed that if future $\Delta m^2_{\mu\mu}$ measurement could be improved to ~1%, the sensitivity can be improved significantly. (NOvA? T2K/T2HK/Hyper-K?)





Daya Bay Projected Δm^2_{ee}



- Combining future MH experiments (INO? PINGU?) Mattias will show PINGU+JUNO

What Can Further Improve the MH Sensitivity? (II)

- Reactor flux uncertainty improvements can also improve the sensitivity.

Uncertainty improvement	$\Delta\chi^2$ (Model I)	$\Delta\chi^2$ (Model II)	$\Delta\chi^2$ (Model III)
Current ~3%	9.5	17.3	13.9
Factor 2	11.5	21.7	18.4
Factor 3	12.1	23.2	19.9
Factor 4	12.4	23.8	20.5
Factor 5	12.6	24.1	20.9

S. Kettell et al arXiv:1307.7419

- Currently, ^{238}U fission products antineutrino spectrum is based on *ab initio* approaches by P. Vogel and updated by Mention *et al* in 2011. Uncertainties are ~10-20% and correlations between energies are "very difficult to evaluate".
  - Different assumptions lead to very different uncertainty in normalization, 2.2%-3.5%
- Which experiment(s) can provide better reactor flux predictions? (FRM-4? Daya Bay? RENO? Very short-baseline reactor experiments?)

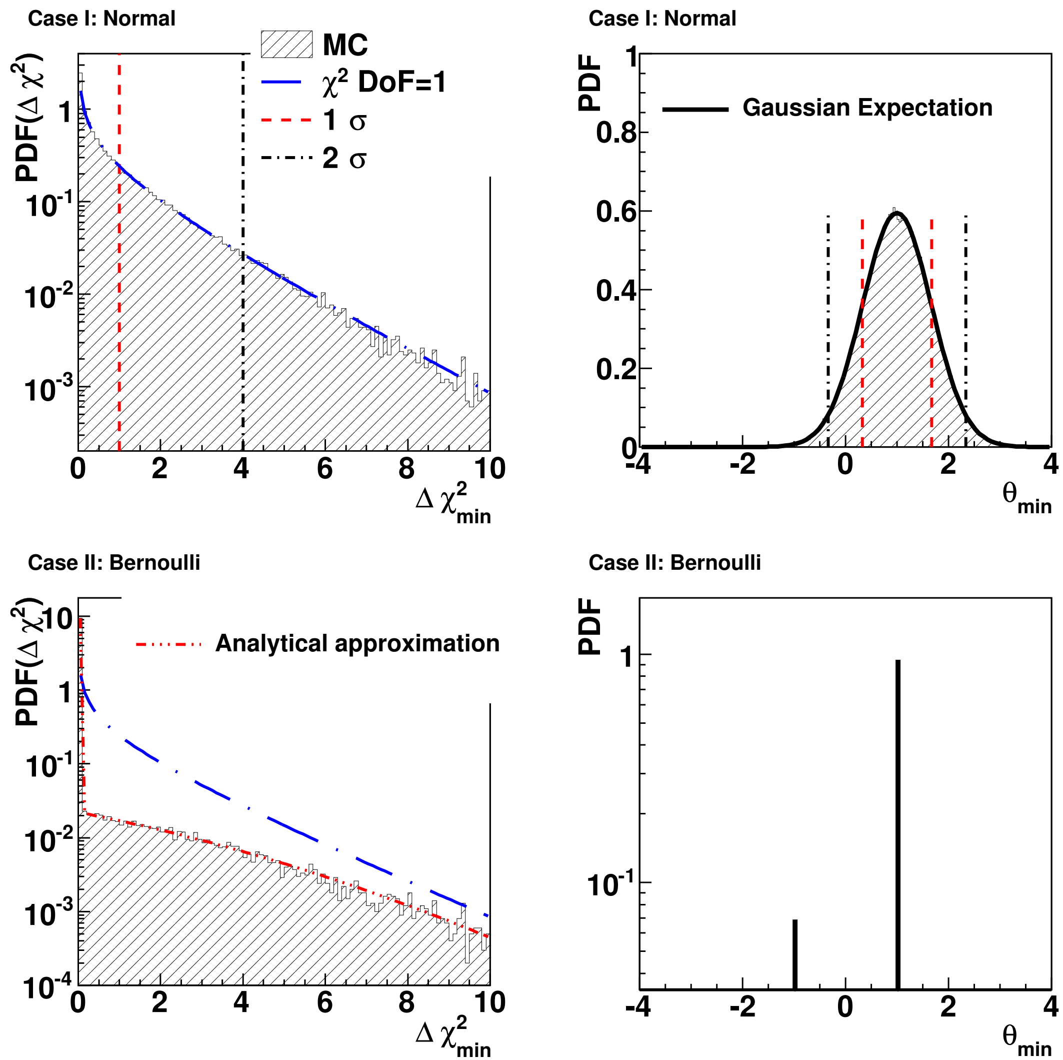
Daya Bay Projected Flux Precision (Snowmass'13)

3. **Absolute reactor flux measurement:** In addition to a shape analysis, an absolute flux measurement tests our understanding of reactor flux predictions and can, in principle, shed light on the issue whether there is an apparent deficit in the measured reactor neutrino flux at short baselines, also known as the "reactor anomaly". An analysis of past measurements and reactor flux predictions has revealed a discrepancy of about 5.7%. While Daya Bay has demonstrated superb relative detector uncertainties, an absolute measurement will be systematics limited. A statistical precision of 0.1% will be achievable. Improvements in the analysis may eventually reduce absolute detector uncertainties to <1%. An absolute flux measurement will be limited by our knowledge of the reactor flux normalization: this includes a theoretical uncertainty of 2.7% in the reactor flux predictions. One can compare Daya Bay data to previous reactor flux measurements by "anchoring" it to the absolute Bugey-4 measurement with an uncertainty of 1.4%. Daya Bay's measured flux and spectrum will provide important input to test the reactor anomaly.

The Special Statistical Case of MH Determination

- A common practice to show the quality of proposed/designed experiments is to use the delta chi-square method using the so-called Asimov data set.
  - It is meant to evaluate the performance of the most probable or the median experimental results without any statistical fluctuations.
  - We quote the squared root of the delta chi-square as the confidence interval or sensitivity in unit of sigma, which is based on Wilks Theorem.
  - Not proper for the mass hierarchy case due to its discrete nature.
- This is simply a special case that Feldman-Cousins pointed out long ago: when parameters are constrained, setting confidence intervals correctly needs MC

X. Qian et al, PRD86(2012)113011

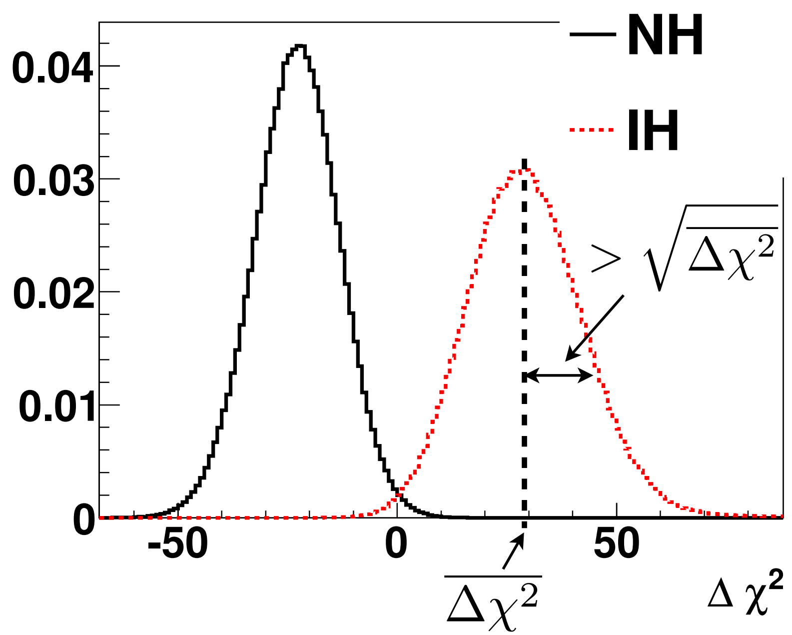


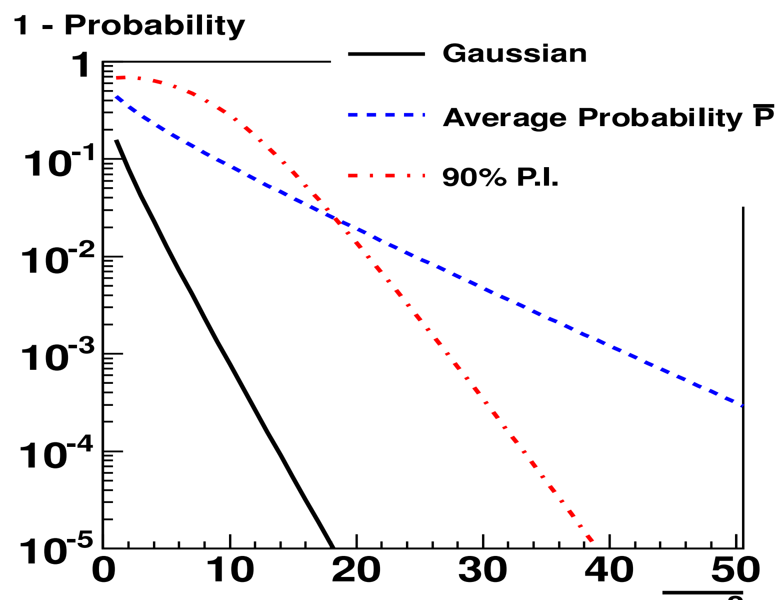
Cross-checks & Confirmations:
S.F. Ge et al JHEP 1305 (2013) 131; E. Eiuffoli et al arXiv:1305.5150

The MH Sensitivity

- The median sensitivity (Asimov dataset) is reduced by half if counted in unit of sigma's for the reactor MH sensitive. (A model w/o considering systematics. Other types of experiments, if signal has no large amount of statistics should check with MC)

$$N_i = \mu_i^{NH} + \sqrt{\mu_i^{NH}} \cdot g_i \quad \Rightarrow \quad \begin{cases} \overline{\Delta\chi^2} \equiv \sum_{i=1}^{n} \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2}{\mu_i^{IH}} \\ \sigma_{\Delta\chi^2} \equiv 2\sqrt{\sum_{i=1}^{n} \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2 \cdot \mu_i^{NH}}{(\mu_i^{IH})^2}} \\ \quad = 2\sqrt{\sum_{i=1}^{n} \left(\frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2}{\mu_i^{IH}} + \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^3}{(\mu_i^{IH})^2} \right)} \\ \quad \approx 2\sqrt{\overline{\Delta\chi^2}} \end{cases}$$



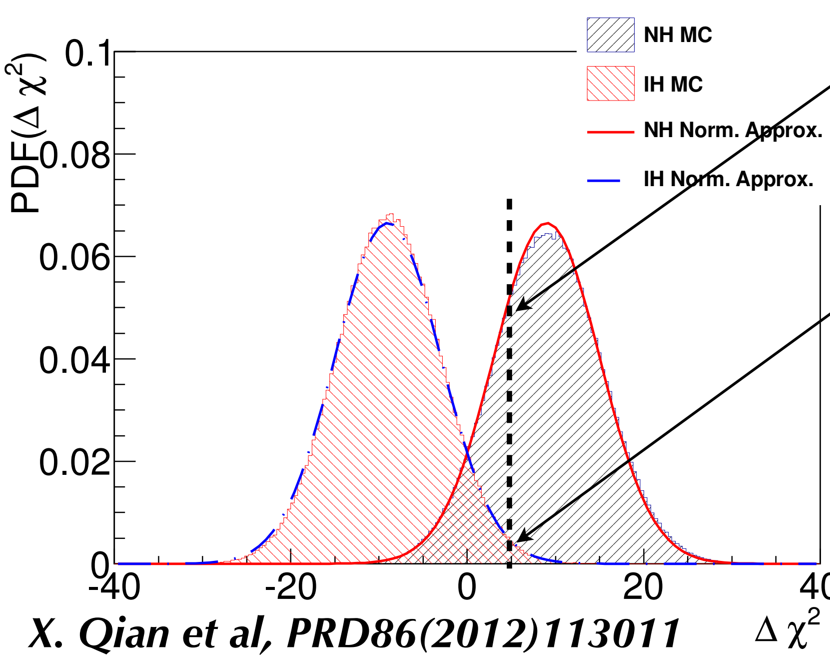


X. Qian et al, PRD86(2012)113011

Confidence Interval using Discriminator PDFs

- The neutrino mass hierarchy measurement is basically a model comparison case, or hypothesis test.
- Not complete if evaluating sensitivity only based on the sign of delta chi-square from Asimov dataset.
- We suggest a confidence interval setting method using discriminator PDFs. (This method has been effectively used in **L. Zhan et al., PRD79(2009)073007** based on Monte Carlo)

$$P(NH|\Delta\chi^2) = \frac{P(\Delta\chi^2|NH)\cdot P(NH)}{P(\Delta\chi^2)} = \frac{P(\Delta\chi^2|NH)}{P(\Delta\chi^2|NH)+P(\Delta\chi^2|IH)} = \frac{1}{1+e^{-\Delta\chi^2/2}}$$



X. Qian et al, PRD86(2012)113011

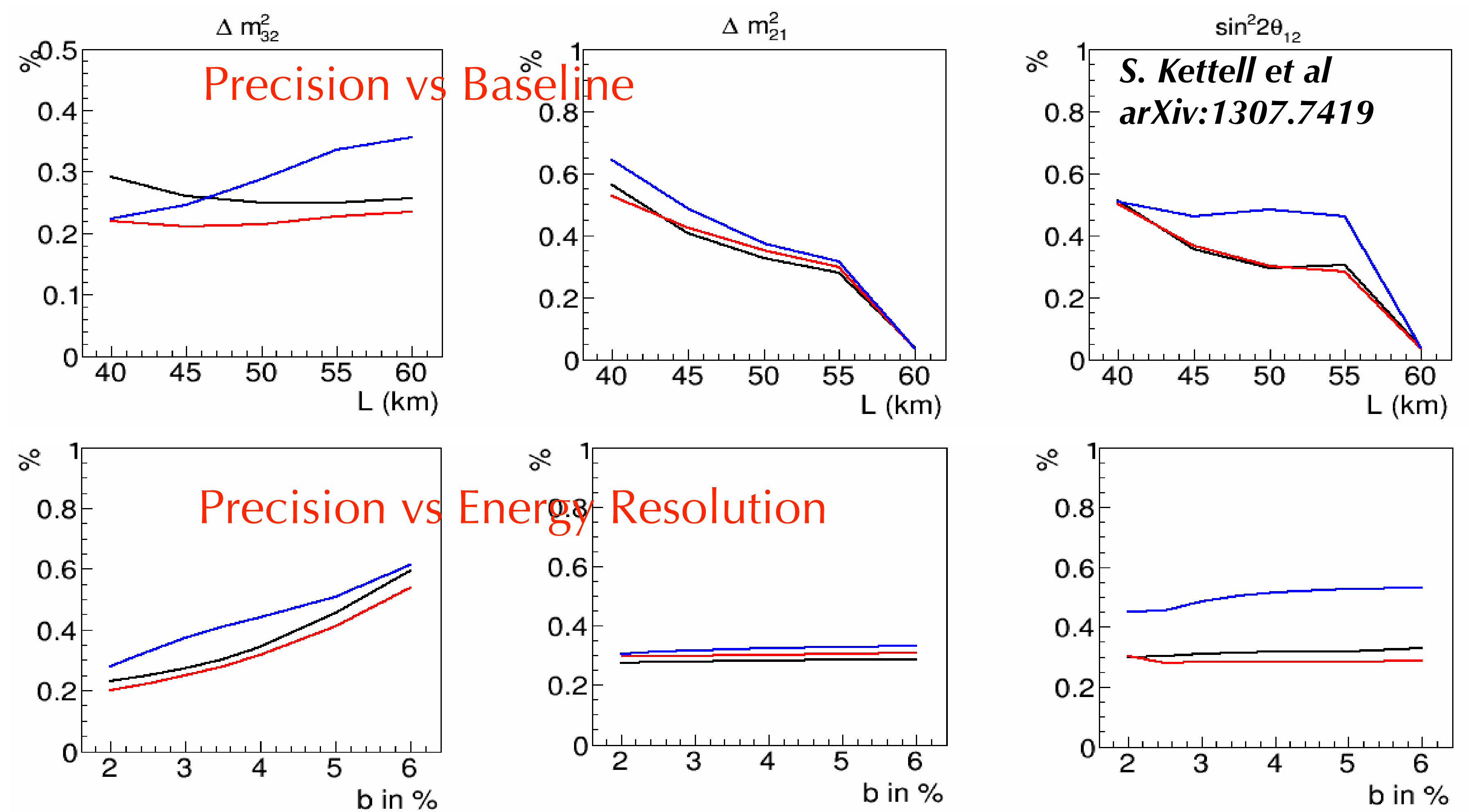
NOTE:

- The left example here is a 2-value binomial case, close to the reactor mass hierarchy resolution, sufficient to illustrate key points
  - Sensitivity value, now confidence level considering the PDFs, is between the values obtained from the square root value approach and the >0 probability approach.
- To be accurate, one should do complete MC to obtain PDFs like in **L. Zhan et al., PRD79(2009)073007.**

See also: G. Cowen et al Eur.Phys.J. C71 (2011) 1554

One Brief Remark: Precision Measurements Warranted

- If JUNO performance reaches goals, sub-percent level precision measurements are less sensitive to the energy scale uncertainty and warranted
  - Neutrinoless double beta decay needs precise theta12 measurement
  - Enable a future ~1% level PMNS unitarity test
- Miao will present official JUNO sensitivities on Thursday. Also see Y.F. Li et al arXiv:1303.6733

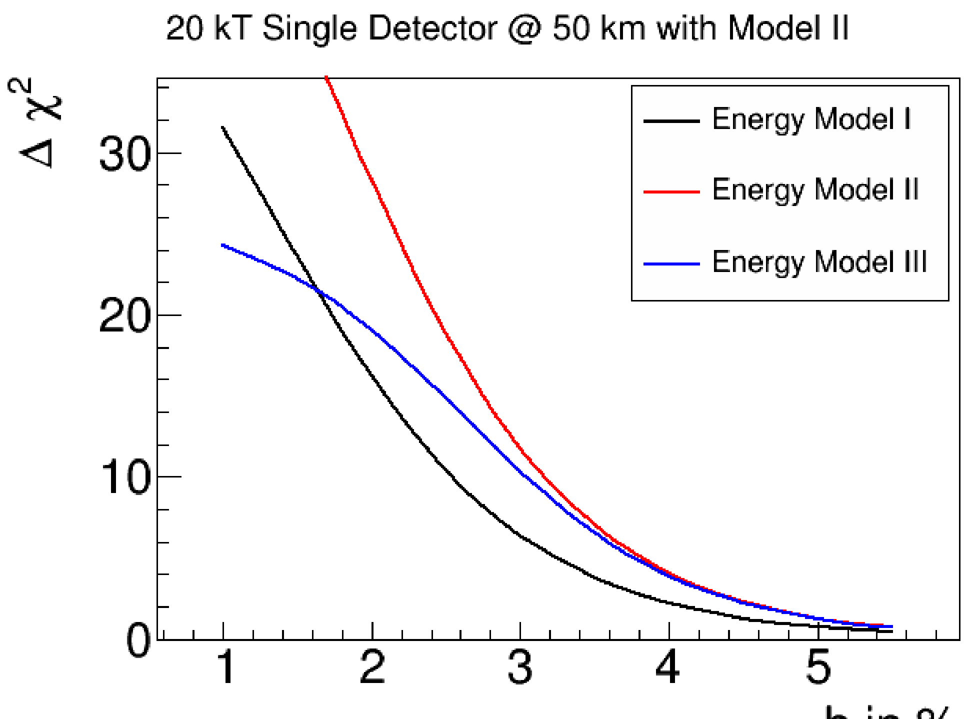


Summary and Conclusion

- The mass hierarchy information is definitely in the survival spectrum of reactor antineutrinos (optimized baseline: ~60km)
- To resolve the mass hierarchy, medium-baseline reactor experiments face unprecedented challenges
  - Energy resolution <3%/√E (absolutely necessary. JUNO is attacking it from multiple directions)
  - **Energy scale uncertainty needs to be controlled <1%** (essential.)
    - A 2nd detector can mitigate the challenge to some level.
    - Or sub-percent energy scale uncertainty is needed. Sub-percent uncertainty not achieved in massive LS detectors but realized in Super-K solar sector.
  - **Statistics (higher $\Delta\chi 2$ needed)** (inconvenient)
    - The statistical case of determining mass hierarchy is different from quantities whose measurements can be approximated by normal distributions.
  - No “sabotage” reactors (plan carefully. JUNO has answered the question :)
- A case worth pursuing but we need well planned R&D programs to face and to conquer these unprecedented challenges.
  - We have suggested a R&D program to address these challenges. Please check our Snowmass white paper: ***S. Kettell et al, arXiv:1307.7419***

Some Details

The Energy Resolution Requirement



S. Kettell et al arXiv:1307.7419

- In order to see the atmospheric scale oscillations in the survival spectrum, to the first order, the energy resolution should be at least the ratio between solar mass-squared difference and the atmospheric one is ~3%

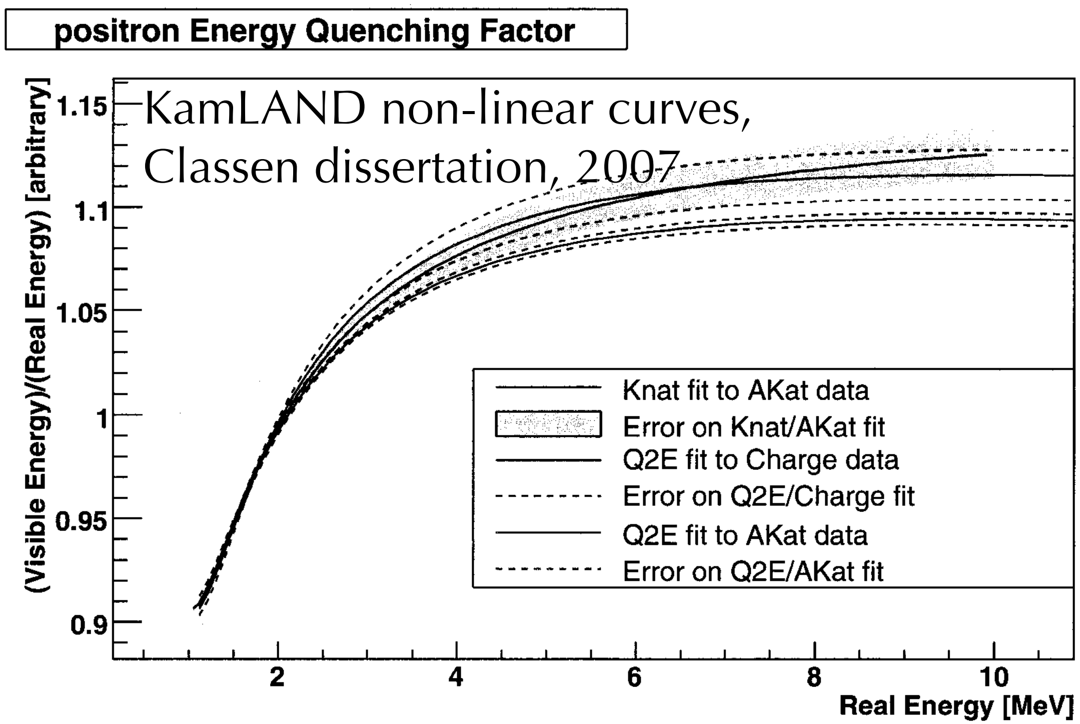
$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

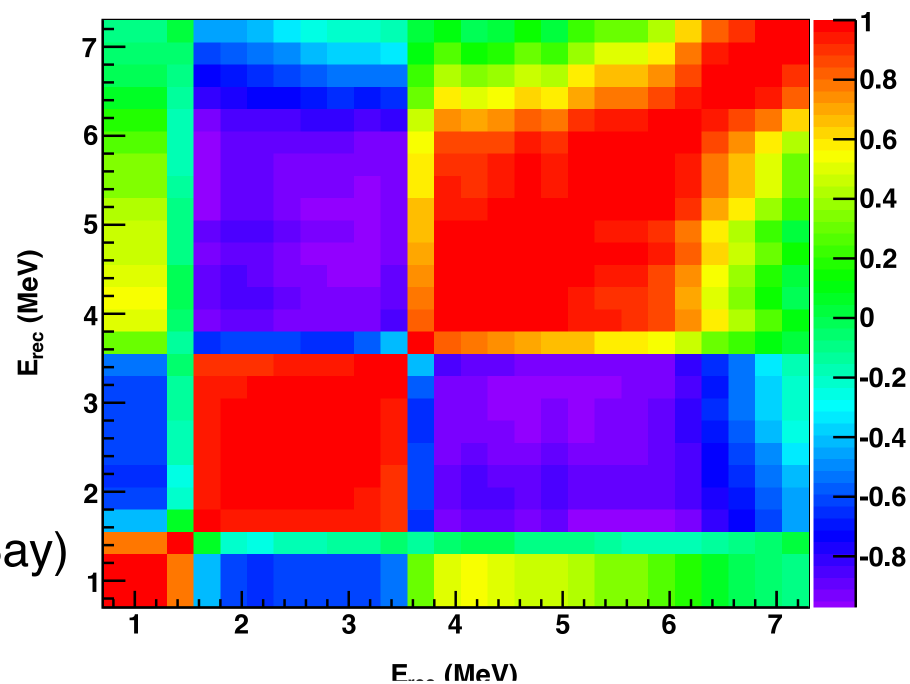
Leakage & non-uniformity (a)

Photon statistics (dominant). needs <3% (b)

Noise (c)

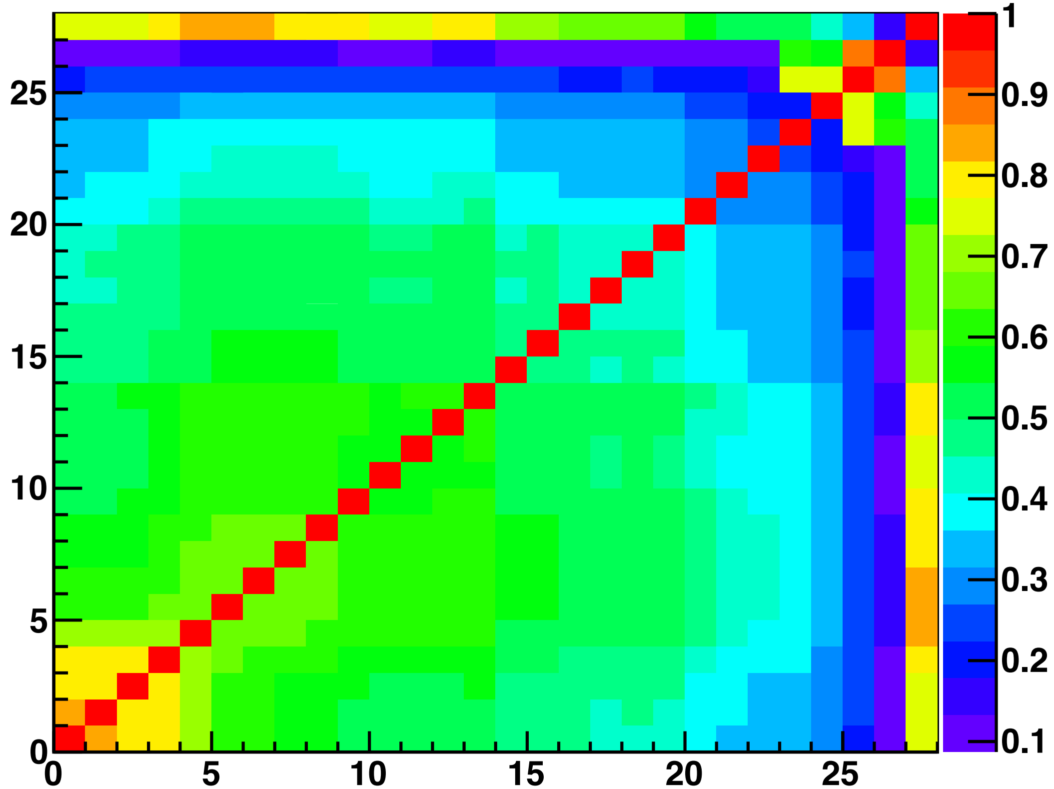
Energy Scale References





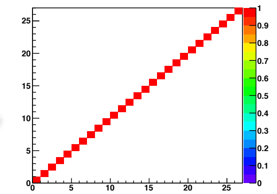
Correlation between energies
caused by energy model (Daya Bay)

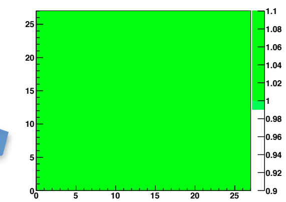
Correlation between energies
and with norm (Daya Bay core1)

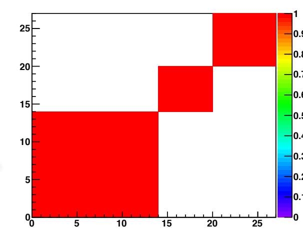


Isotope Uncertainties

- We have4 options for the ^{238}U uncertainty and correlation treatment
  1. Uncorrelated (private communication with Lhuillier)
     - "In practice we assumed no correlations but we added in quadrature a 10% global normalization error."
  2. Correlated with other isotopes
  3. Correlated between bins but uncorrelated with others (a new proposal)
  4. Locally correlated between bins but uncorrelated with others (claimed treatment by Lhuillier et al in their paper)







Option	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Avg	ILL+ French	ILL+ Vogel
#1							2.00%	2.5%	2.5%
#2							3.44%		
#3							2.46%		
#4							2.24%		

You Don't Have to See the Details Here.