Measurement of the Reactor Antineutrino Flux and Spectrum of Daya Bay Experiment

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On behalf of the Daya Bay Collaboration

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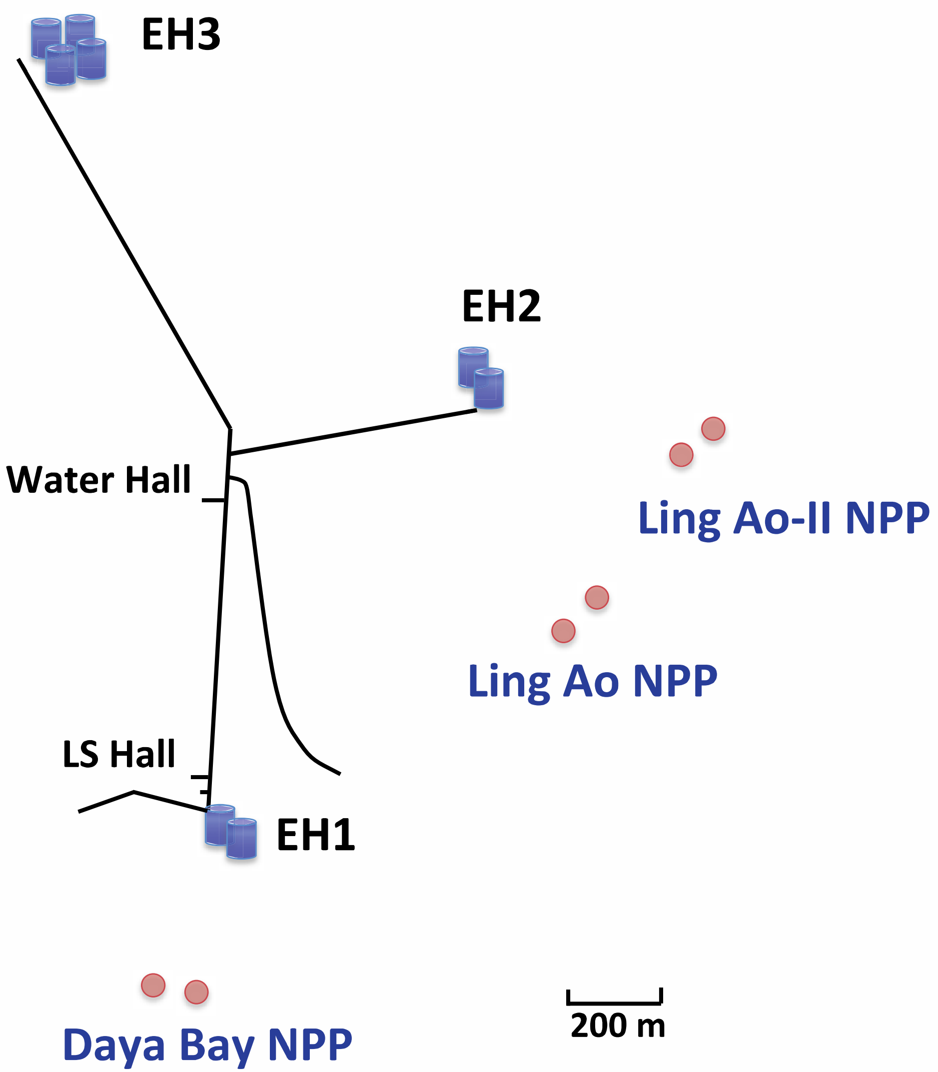
Daya Bay Experiment Layout



Reactor:

Cores: 6

Thermal Power:

2.9 GW X 6 = 17.4 GW

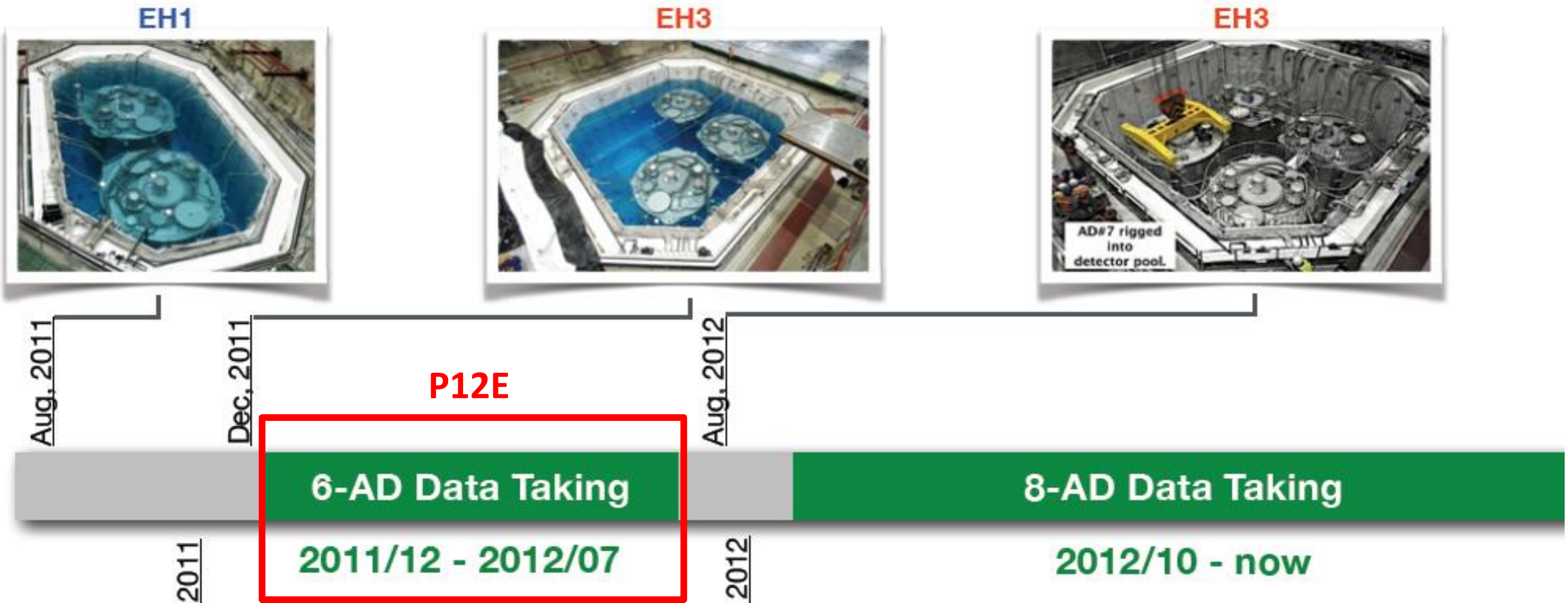
Detector:

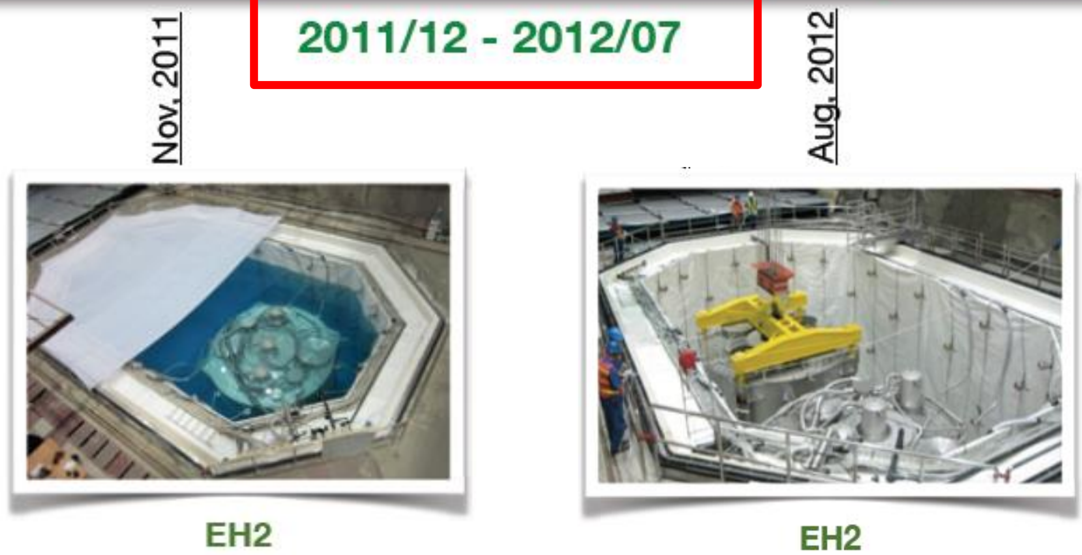
8 ADs (Antineutrino Detector)

Target Mass:

20 ton X 8 =160 ton

Antineutrino Detectors and data taking

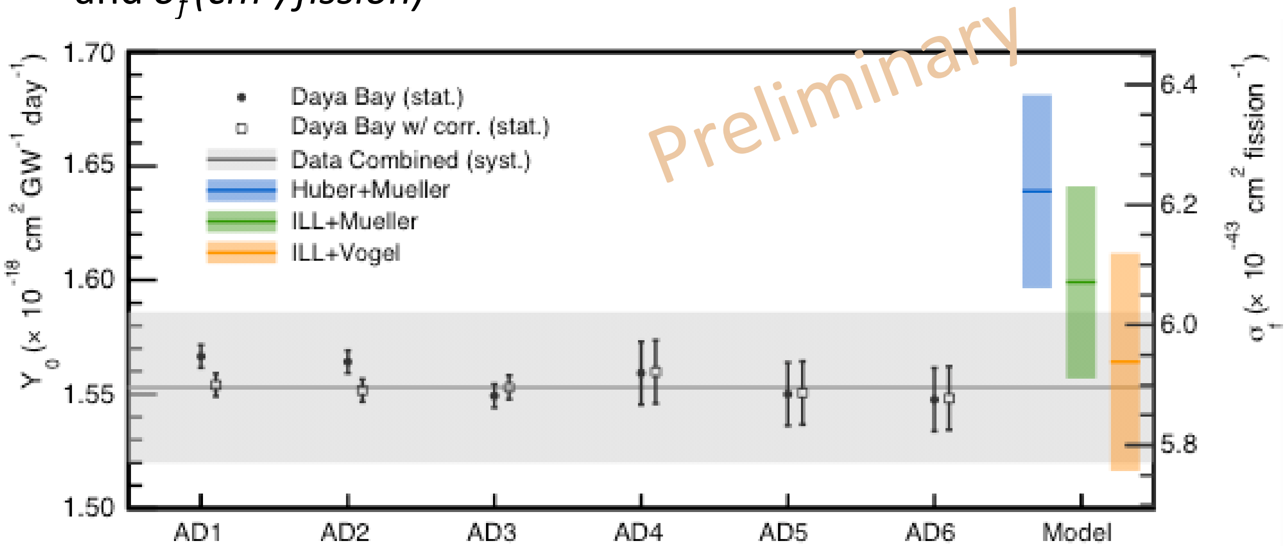




~300,000 Inverse Beta Decay (IBD) events were collected with 3 ADs of **EH1** and **EH2** in 6-AD Data Taking time (217days).

Absolute Reactor Antineutrino Flux

- Measured IBD events (background subtracted) in each detector are normalized to Y_0 *(cm²/GW/day)* and σ_f *(cm²/fission)*



3-AD (Near Sites) measurement

$Y_0 = 1.553 \times 10^{-18}$

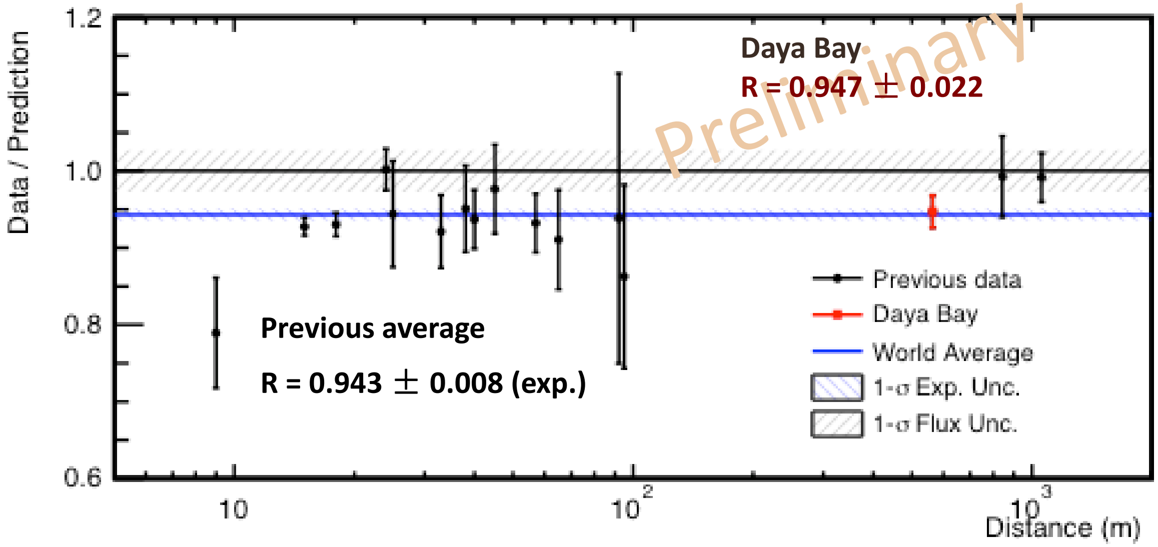
$\sigma_f = 5.934 \times 10^{-43}$

Compare to flux models:

Data/Prediction (Huber+Mueller)
0.947 ± 0.022

Data/Prediction (ILL+Vogel)
0.992 ± 0.023

- Global comparison of measurement and prediction (Huber +Mueller)



consistent with previous short baseline experiments.

Effective baseline of Daya Bay:

L_{eff} = 573m (Near site)

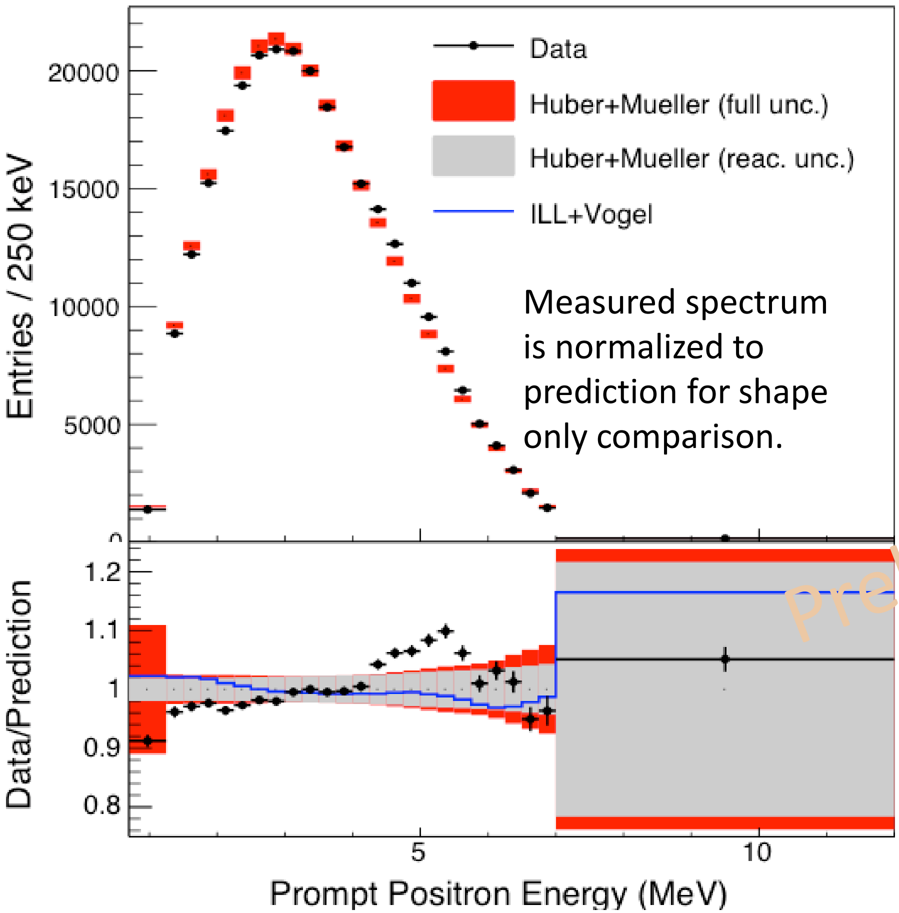
Effective fission fractions α_k of Daya Bay

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	0.076	0.288	0.050

(Near site)

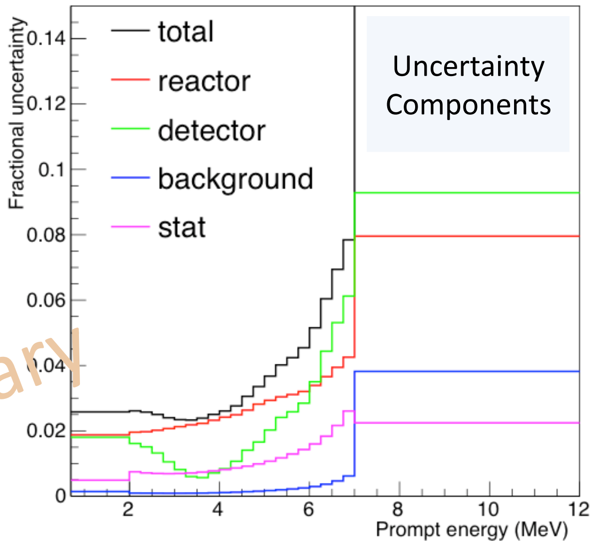
Absolute Spectrum Measurement

- The measured positron spectra of IBD events in the three near Hall ADs are combined and compared with the prediction of the same combination.



$$\chi^2 = (N_i^{obs} - N_i^{pred}) V_{ij}^{-1} (N_j^{obs} - N_j^{pred})$$

$$V = V_{stat} + V_{reactor} + V_{detector} + V_{bkgs}$$



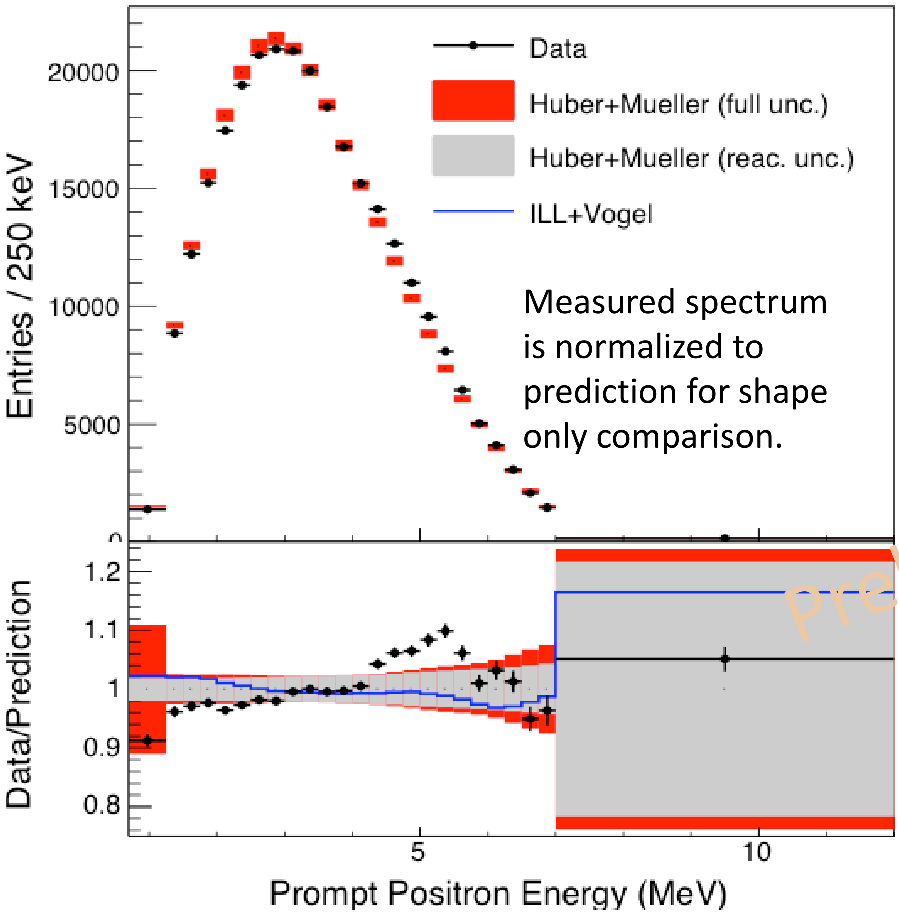
X^2 /ndf (0.7 < E < 12 MeV)

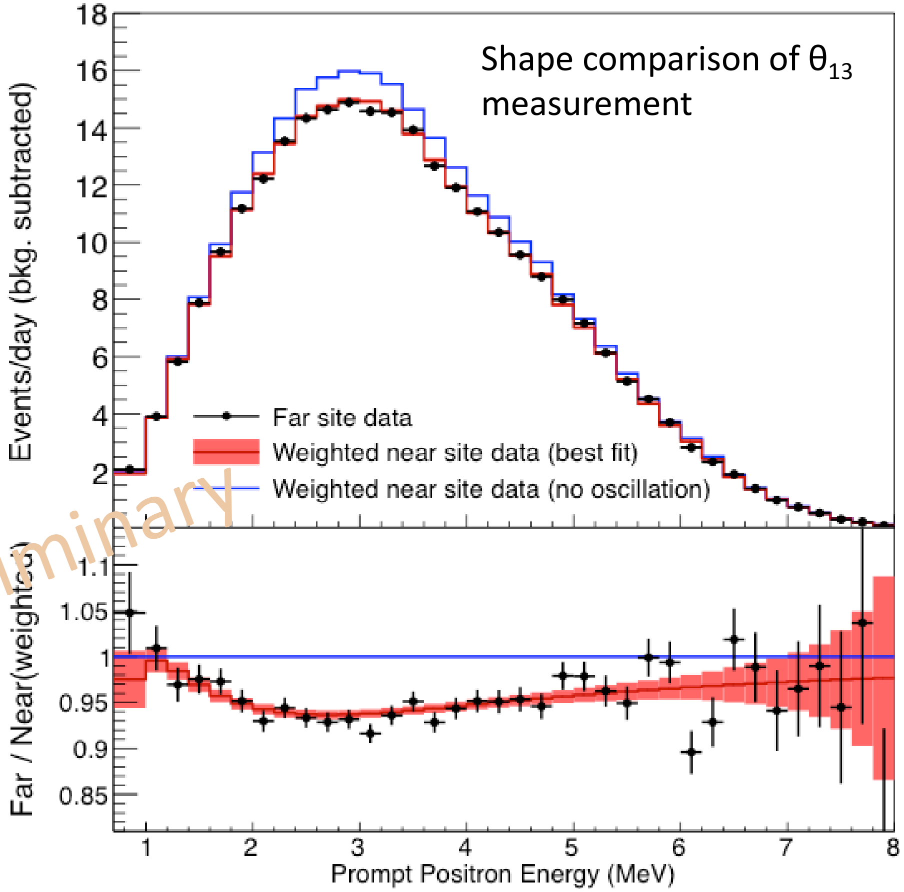
41.4/24

P-value = 0.015, 2.4σ

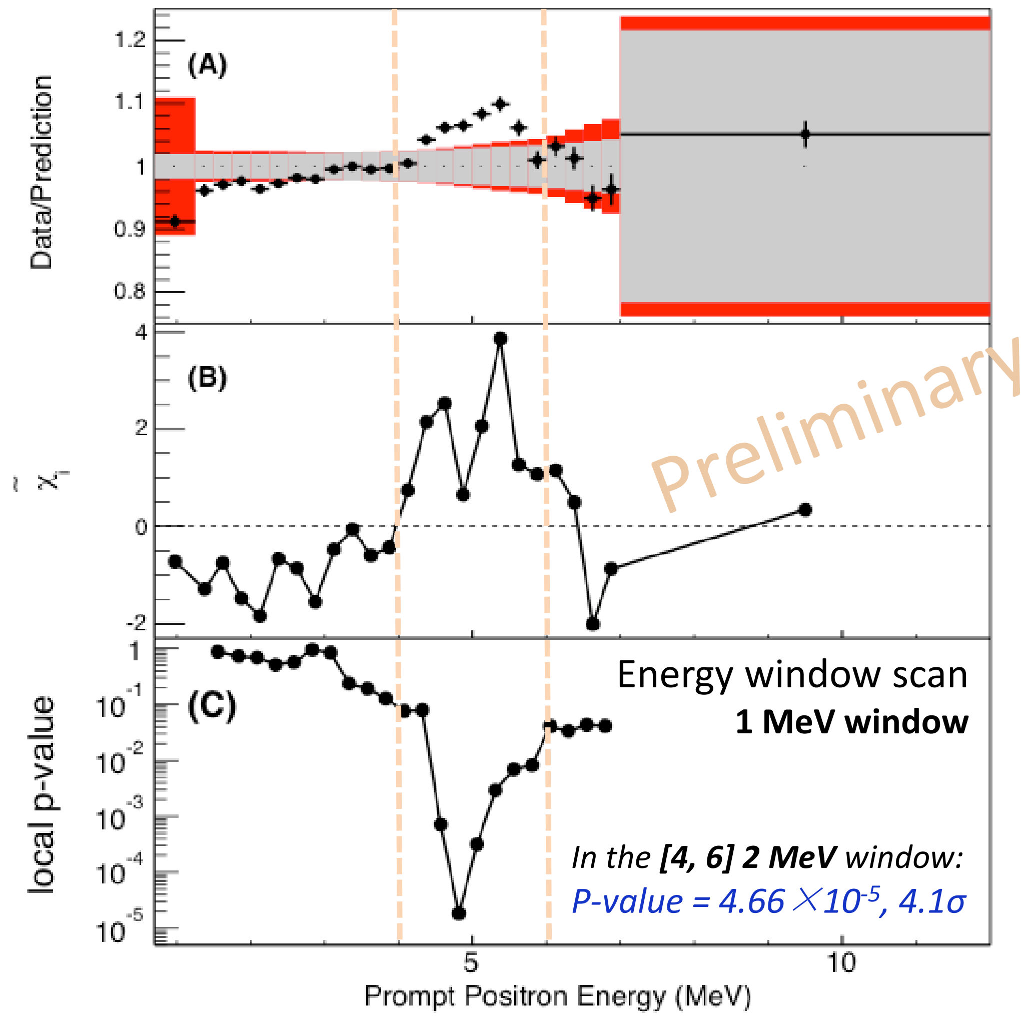
Absolute Spectrum Measurement

- Absolute shape comparison of data and prediction: $\chi^2/ndf = 41.8/21$
- Primarily relative shape comparison among detectors: $\chi^2/ndf = 134.7/146$





Local significance of deviations



(A) Spectral comparison of data and prediction (Huber +Mueller)
(P-value=0.015, 2.4σ)

(B) χ^2 contribution of each bin, evaluated by:

$$\tilde{\chi}_i = \frac{N_i^{obs} - N_i^{pred}}{|N_i^{obs} - N_i^{pred}|}\sqrt{\frac{1}{2}\sum_j(\chi_{ij}^2 + \chi_{ji}^2)}$$

$$where\ \chi_{ij}^2 = (N_i^{obs} - N_i^{pred})(V^{-1})_{ij}(N_j^{obs} - N_j^{pred})$$

(C) P-value of $\Delta\chi^2$/ndf in a certain energy window (e.g. 1 MeV)

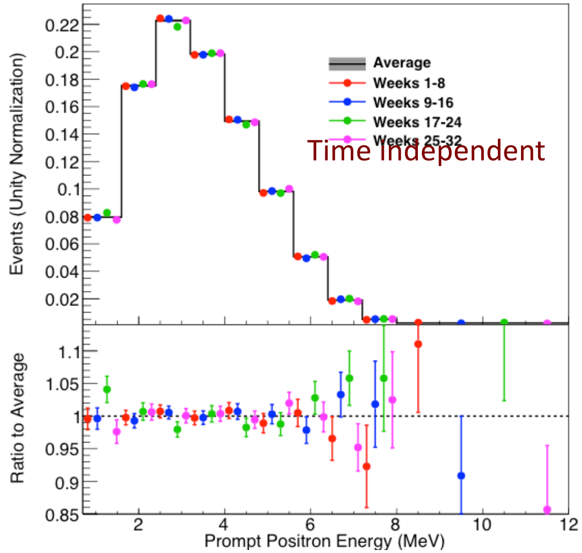
Introduce N (# of bins) nuisance parameters with no pull terms to oscillation fitter.

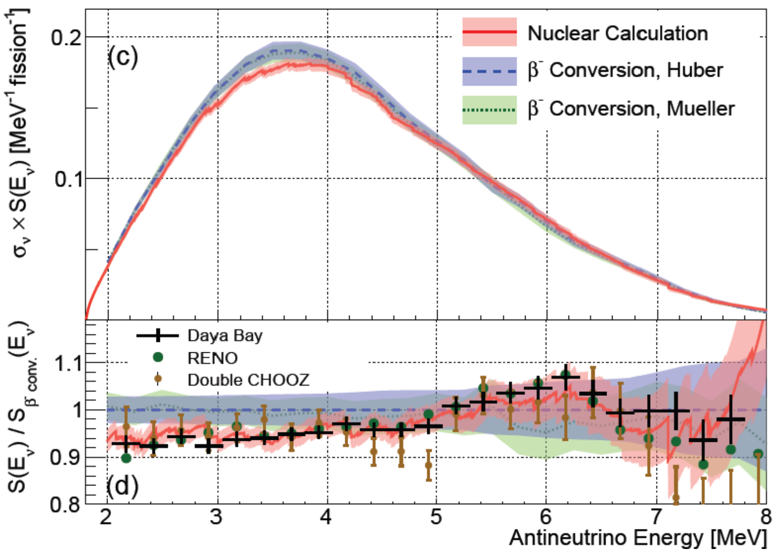
Expect the χ^2 difference after introducing the N nuisance parameters follows a χ^2 distribution with N-1 dof.

Investigation of events in [4, 6] MeV

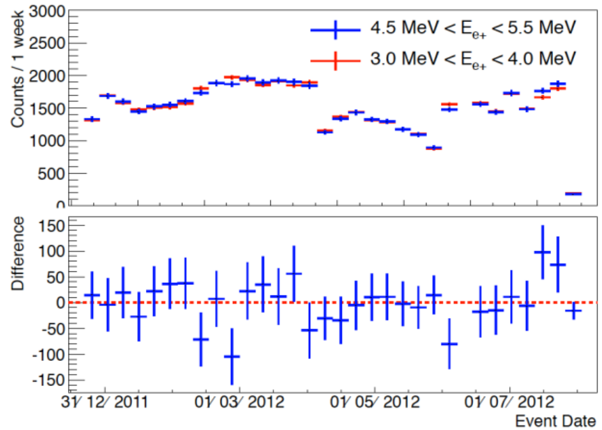
- The events match all IBD event characteristics:
  - Neutron capture time and distance distributions, prompt event position distribution, etc.
  - Disfavors unexpected backgrounds
- ^{12}B spectrum does not have local structure at [4, 6] MeV.
  - Disfavors electronics and nonlinear energy model distortion
- The events are reactor power correlated & time independent.
- May be due to a specific set of fission daughters, as pointed out by D. A. Dwyer and T. J. Langford : arXiv:1407.1281

Weekly IBD positron spectrum comparison



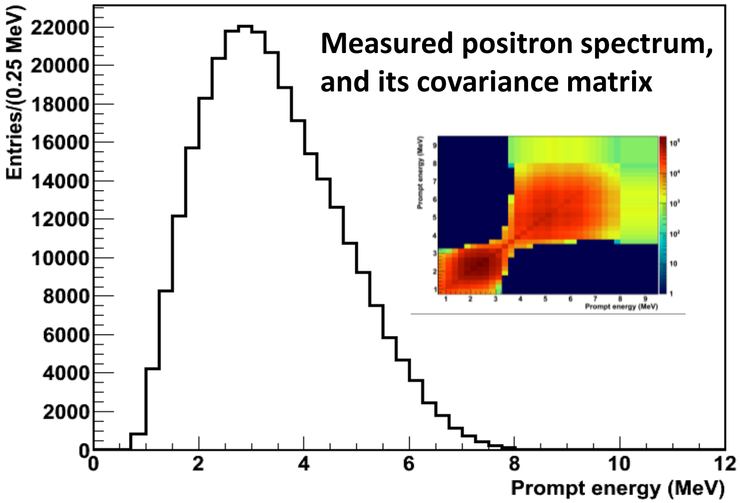


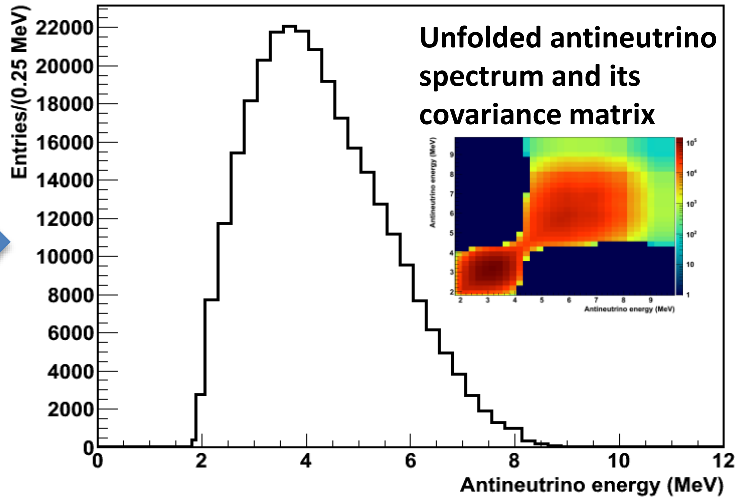
Time distributions of events in [4.5, 5.5] MeV and IBD events in [3, 4] MeV.

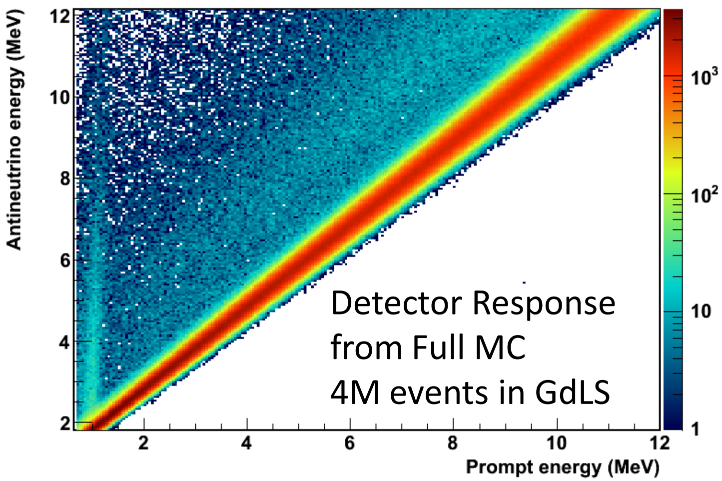


Deduced antineutrino spectrum

- Antineutrino spectrum from measurement
  - Unfold the measured positron spectrum of 3 ADs in near Halls







Input of unfolding:

1. Measured positron spectrum, covariance matrix
2. Detector response matrix

Unfolding methods:

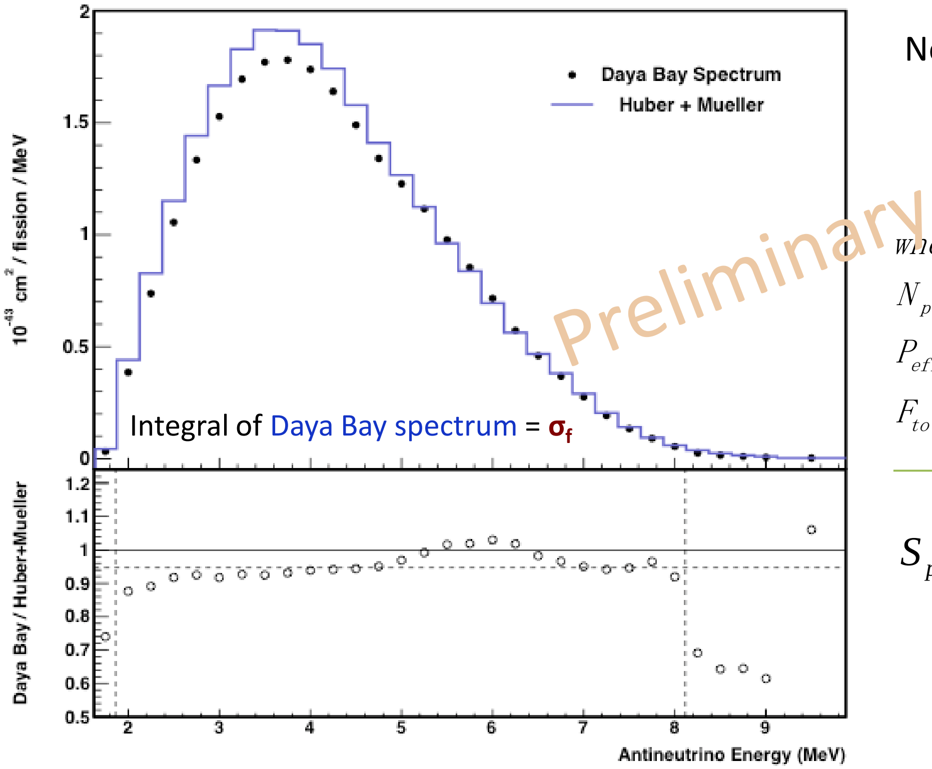
Bayesian iterative and SVD (Singular Value Decomposition)

Output of unfolding:

Antineutrino spectrum, covariance matrix

Deduced antineutrino spectrum

- Extract a reactor antineutrino spectrum $S_{obs\_v}(E_v)$:
  - It supplies data outside [2, 8] MeV and could be used for flux and spectrum prediction.



Normalize the unfolded spectrum to ***cm²/fission/MeV***.

$$S_{obs\_\bar{\nu}_e}(E_{\bar{\nu}_e}) = \frac{S_{unfolded}(E_{\bar{\nu}_e})}{P_{eff}(E_{\bar{\nu}_e}, L) \cdot N_p \cdot F_{total}}$$

where

N_p is number of protons per unit target mass;

$P_{eff}(E_{\bar{\nu}_e}, L)$ is suvival probability of $\bar{\nu}_e$ weighted by flux;

F_{total} is total number of fissions of all reactors.

$$S_{pred\_\bar{\nu}_e}(E) = (\sum_k \alpha_k S_k(E) + c^{ne}(E) + SNF(E)) \cdot \sigma_{IBD}(E)$$

where

α_k are the effective fission fractions of Daya Bay

- Compare Daya Bay spectrum $S_{obs\_v}(E_v)$ and Huber+Mueller Prediction $S_{pred\_v}(E_v)$:
  - Same rate deficit as flux measurement, and same shape deviation structure as in comparison of positron spectrum.

Effective fission fractions

Definition: $f_i \equiv \frac{F_i}{F_{total}}$ → Effective average total fission numbers of isotope ***i***

where $F_i = \sum_d \sum_r \frac{1}{4\pi L_r^2} \cdot F_{total}^{rd} \cdot \alpha_{ird}$

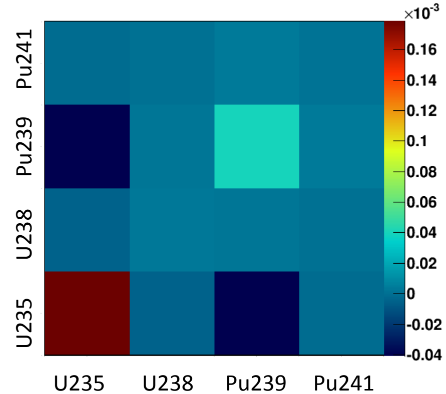
- F_{total}^{rd}: Daily total fission number of reactor ***r***. Detector efficiencies are included
- L_r: Baselines
- α_{ird}: Daily fission fractions

Index: i -> *ith* fissile isotope, r-> reactor, d -> day

Effective fission fractions values for the deduced antineutrino spectrum from Daya Bay measurement

U235	U238	Pu239	Pu241
0.586	0.076	0.288	0.050

Covariance Matrix of effective fission fractions



Prediction using Daya Bay deduced antineutrino spectrum

- Spectrum prediction for a new reactor experiment ***X***

DYB deduced spectrum

DYB effective fission fraction

$$S_X = \frac{1}{4\pi L_X^2} \cdot F_X \cdot \left(S_{DYB} + \sum_i (f_{DYB}^i - \alpha_X^i) S_{ILL}^i \right)$$

Baselines

Total fission number

Fission fraction of experiment x reactor

ILL spectrum

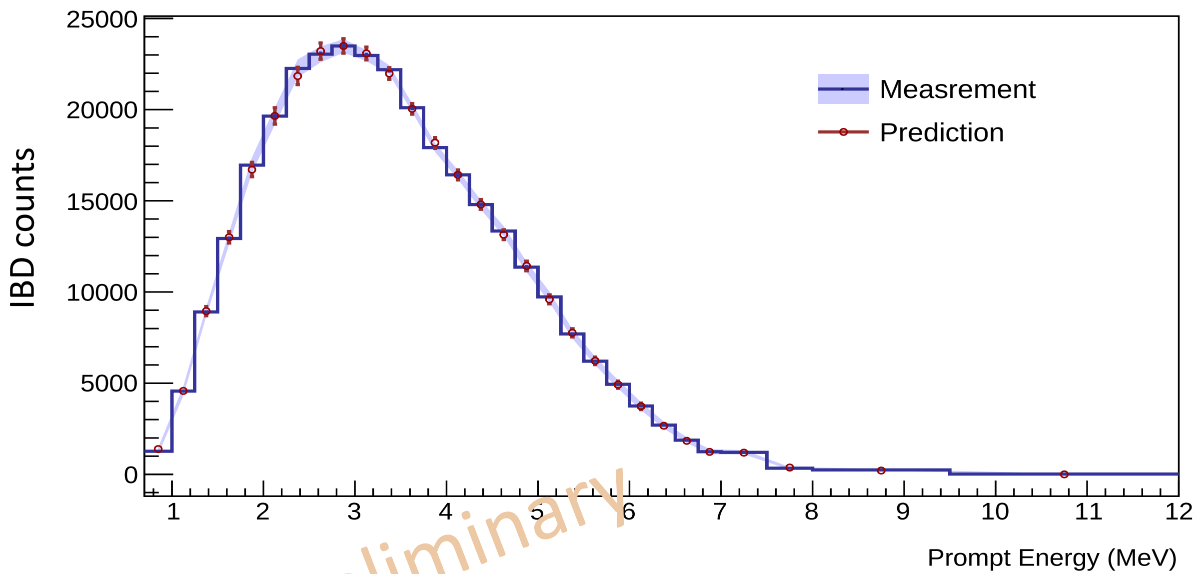
- Uncertainty: $V = V_X + V_{DYB} + V_{ILL}$

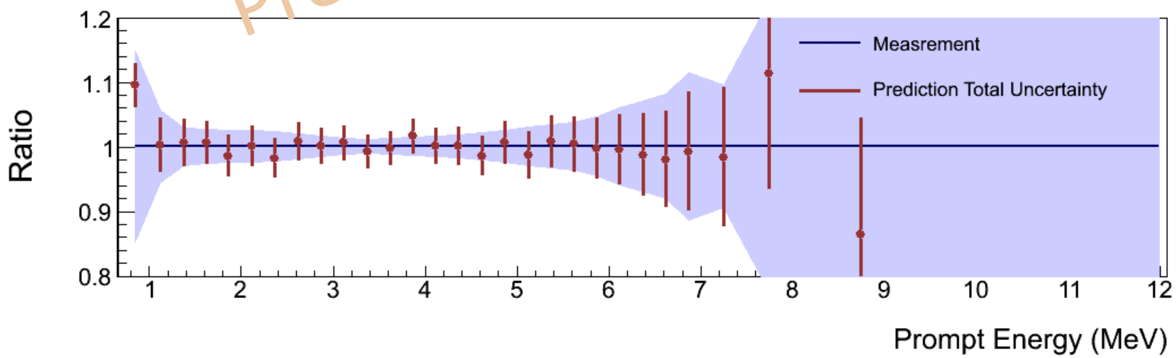
Traditional prediction (ILL based model) for reference: ⟶ $S_X = \frac{1}{4\pi L_X^2} \cdot F_X \cdot \left(\alpha_X^i \cdot S_{ILL}^i \right)$

Prediction using Daya Bay deduced antineutrino spectrum

An exammple: Use Daya Bay Sub dataset as an independent experiment
Dataset ***X***: 2012-10-24~2013-04-11 AD1+AD2+AD3+AD4 (Near Sites)

Spectrum Prediction of the dataset





Effective fission fraction difference

dataset	235U	238U	239Pu	241Pu
X	0.5292	0.0765	0.3303	0.0618
P12E	0.586	0.076	0.288	0.050

- Central values are within 1σ uncertainty range
- the ratio is flat

The prediction is self-consistent

Summary

- Daya Bay has made a precise flux and spectrum measurement of IBD events in three ADs of near site.
  - Absolute flux is consistent with previous measurements:
    - $\sigma_f = (5.934 \pm 0.136) \times 10^{-43}$ (cm^2/fission)
    - ^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu = 0.586: 0.076: 0.288: 0.050
  - The absolute positron spectrum measurement is not consistent (~2.4σ) with predictions of different reactor antineutrino models.
    - The deviation in [4, 6] MeV is ~4σ.
    - The events in [4, 6] MeV are power correlated as other IBD events.
  - The positron spectrum was converted into an antineutrino spectrum with an universal unit (cm^2/fission/MeV) for general use , e.g. do reactor spectrum prediction.
  - Daya Bay can provide a new option of reactor spectrum prediction for reactors with similar fission fractions, which has a definite uncertainty. While the uncertainties of the spectrum derived from the ILL measurements may be underestimated.
  - (A.C. Hayes, et al arXiv:1309.4146; G. Garvey's report in Neutrino2014).

THANKS!