A new investigation path for reactor antineutrino spectra

based on arXiv:1705.09434 [hep-ex] http://arxiv.org/abs/1705.09434

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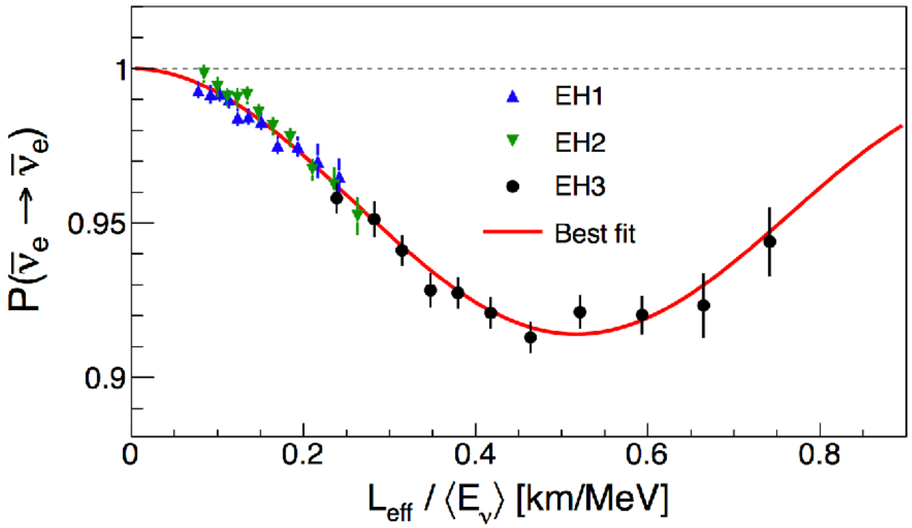
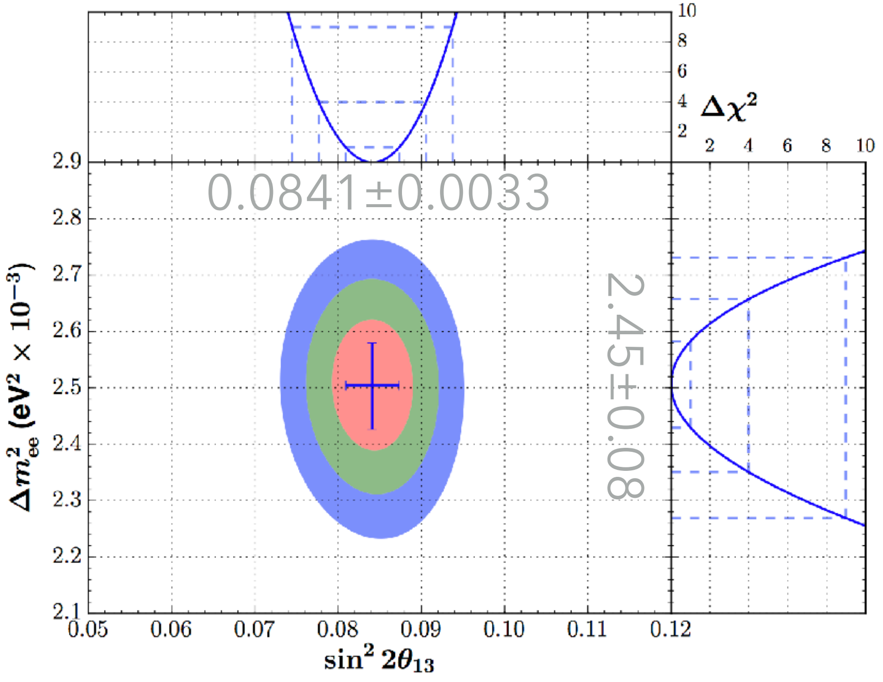
GdR Neutrino
APC Paris, May the 30th, 2017

The precision: with relative measurements

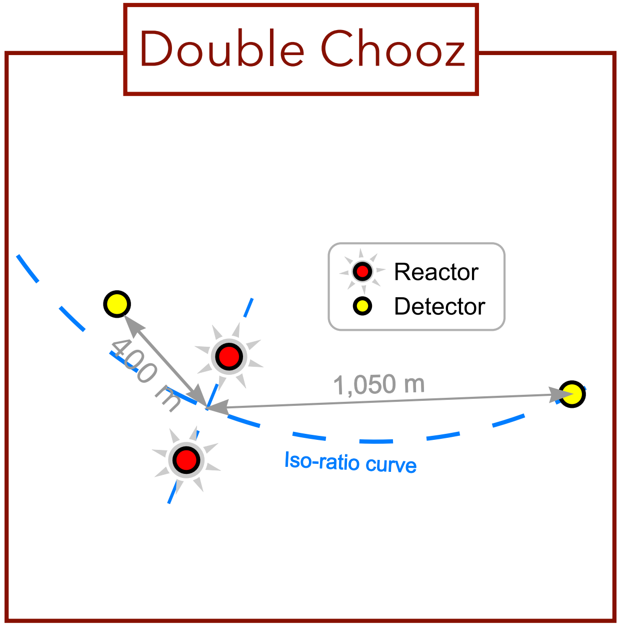
- Precision measurement for θ_{13}
- Relative measurements to get rid of reactor spectra predictions
    - measure antineutrino spectrum "before" oscillation (at short distance) with a near detector
    - measure an oscillated antineutrino spectrum near the first oscillation maximum (around 1.5 km)
- As a first approximation Far/Near spectra ratio gives access to survival probability

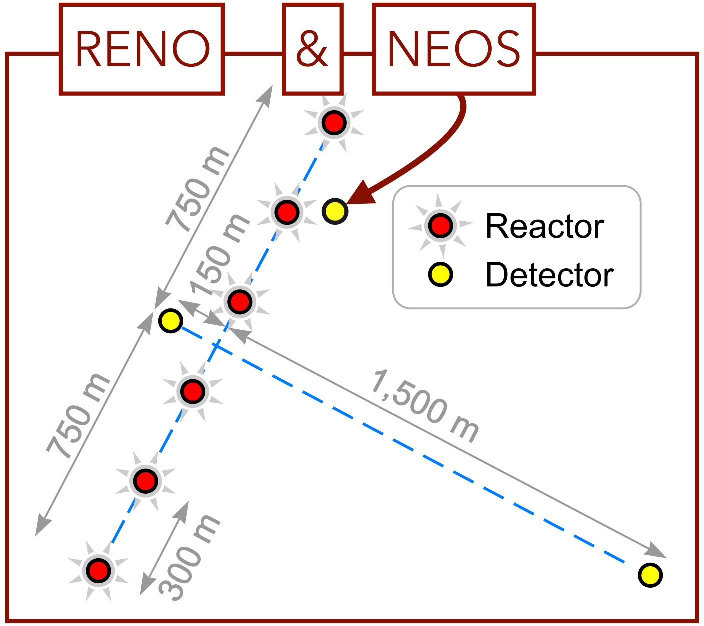


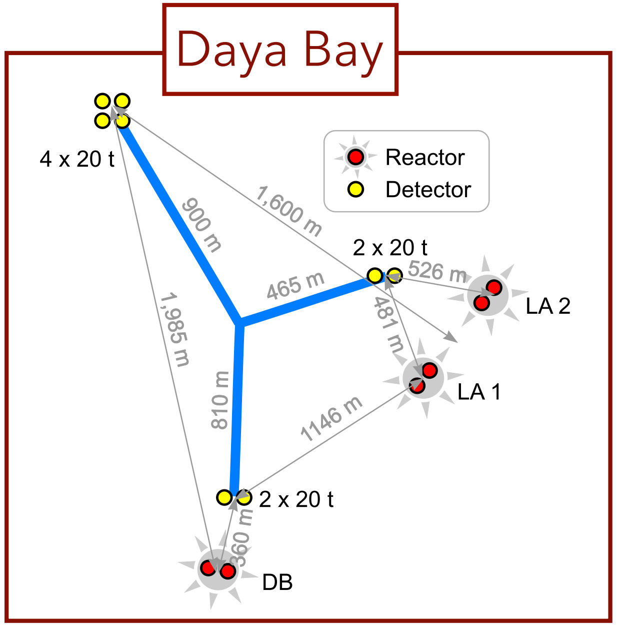


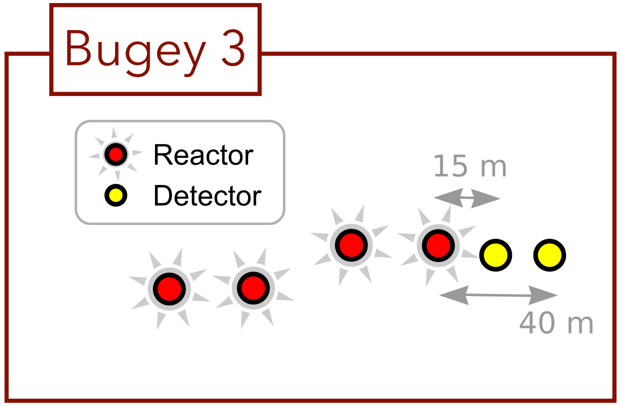
from Daya Bay's PRD. 95, 072006 - 1230 days of operations

Beyond θ_{13}
Reactor spectra measurements





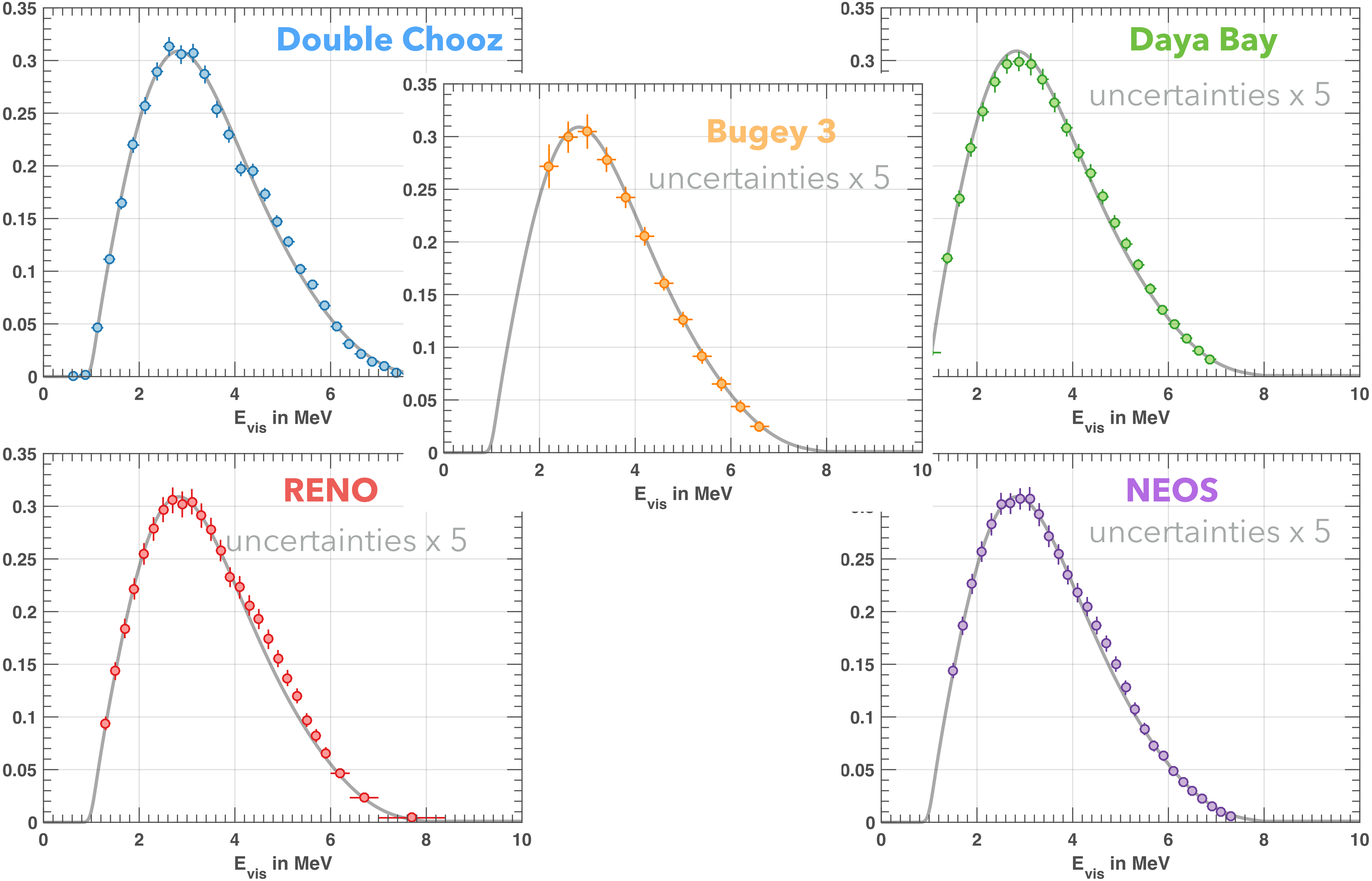




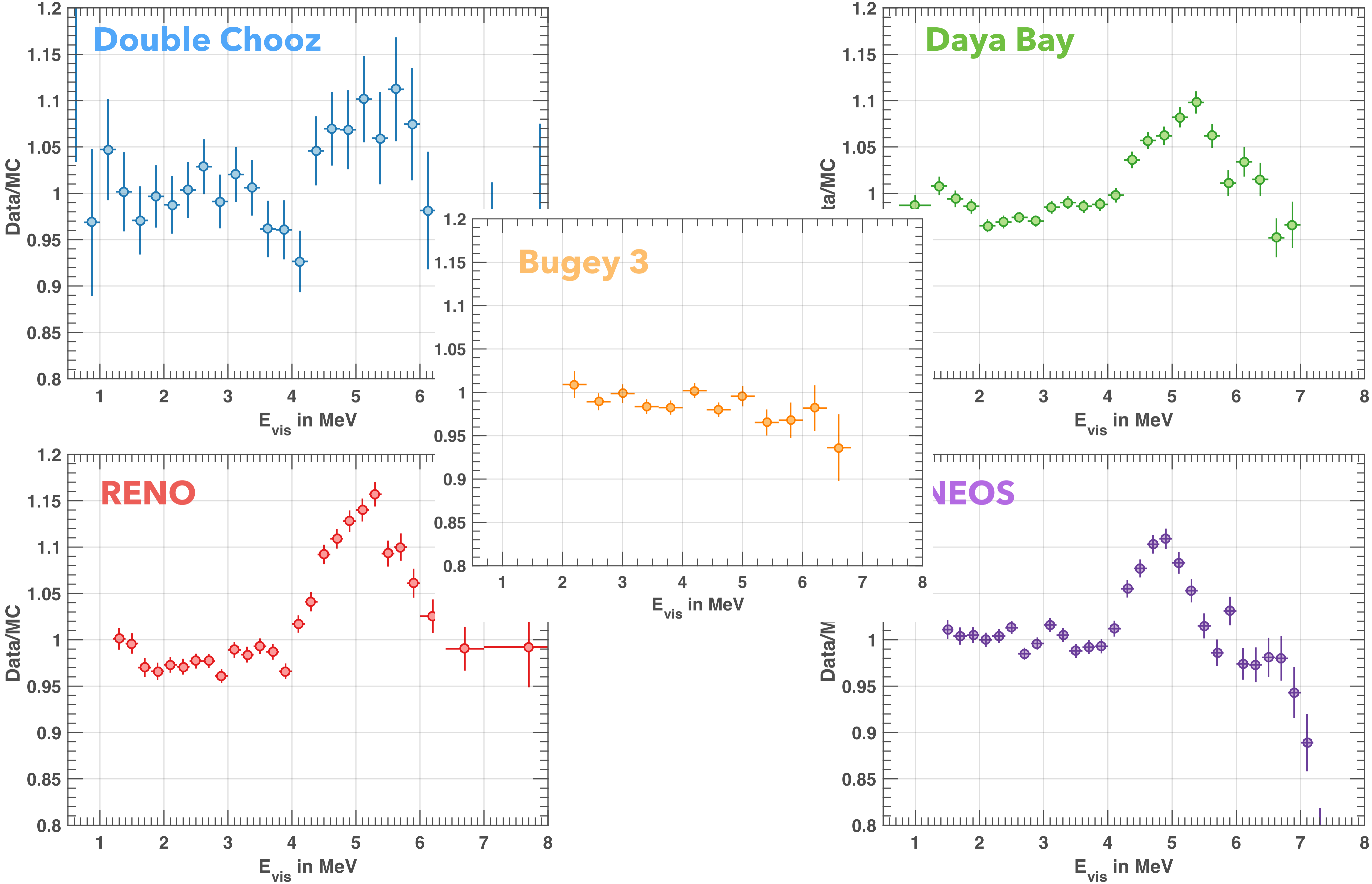
Reactor spectra comparison:

- 3 recent θ_{13} experiments: Double Chooz, Daya Bay & RENO
- statistics between 20,000 and 300,000 anti-neutrinos
- 1 oldest: Bugey 3 with 150,000 anti-neutrinos
- 1 recent short-baseline: NEOS, with 300,000 anti-neutrinos

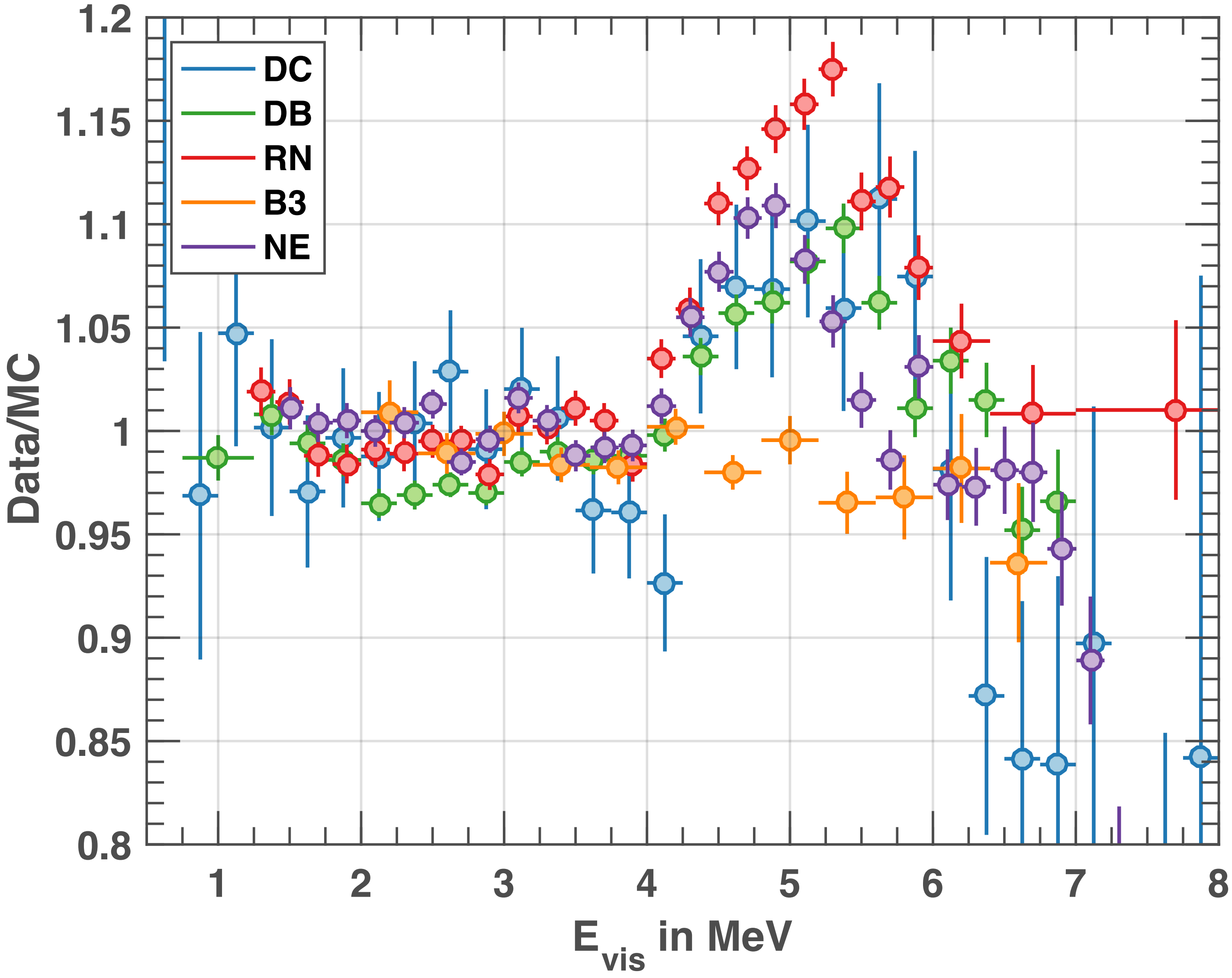
Observed and predicted spectra



Ratios


Double Chooz
Daya Bay
Bugey 3
RENO
NEOS
Data/MC
E_vis in MeV
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
1
2
3
4
5
6
7
8

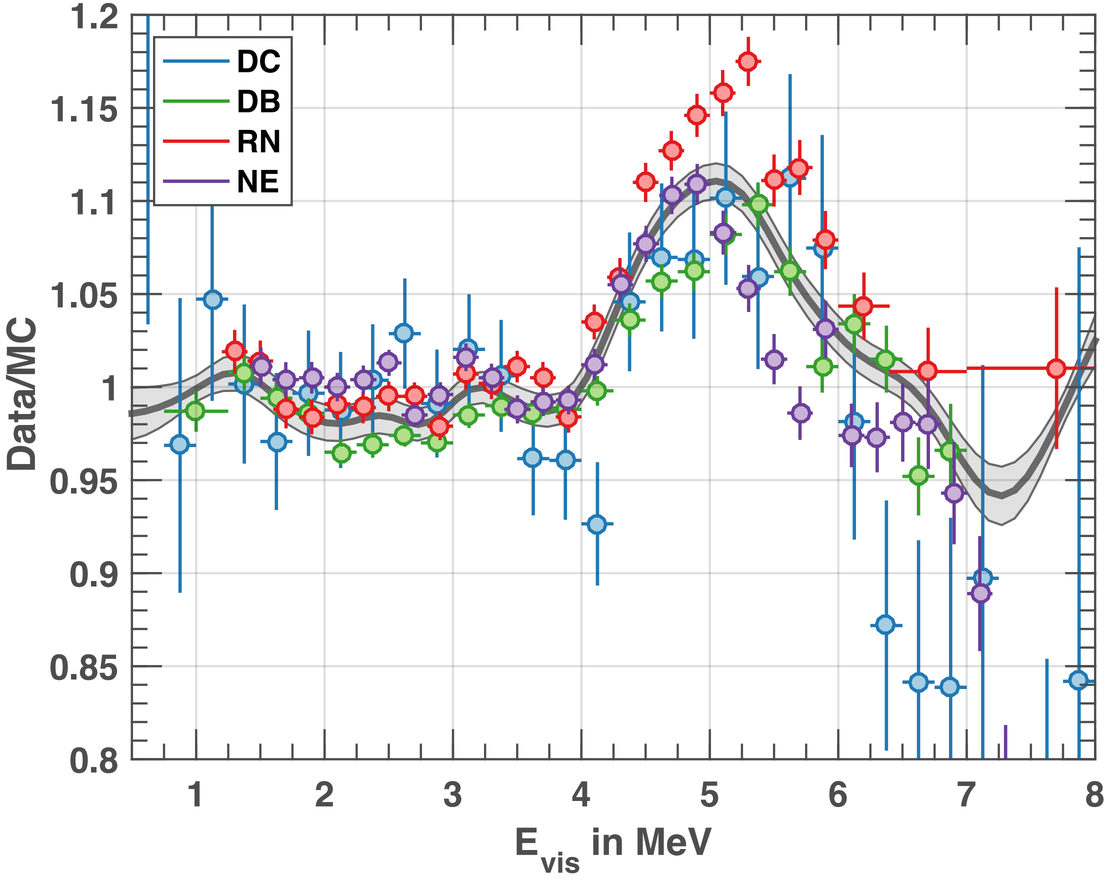
Overlay of the spectra



Are these spectra compatible? Place your bets!

Comparing these 4 measurements

Common fit to: Double Chooz, Daya Bay, RENO, NEOS



Took into account uncertainties of each experiment:

- statistical
- energy scale
- normalization

Spectral shapes are **not compatible**

Even when freeing normalization:
p-value ~ 5 10^{-10} (~ **6.4 σ** significance)

Fuel content (fission fractions)

%	U5	P9	U8	P1
B3	53.8	32.8	7.8	5.6
DC	49.6	35.1	8.7	6.6
DB	58.6	28.8	7.6	5.0
RN	56.9	30.1	7.3	5.6
NE	65.5	23.5	7.2	3.8

Including Bugey 3 even yields an **8 σ incompatibility** between spectral shape!

Looking at potential detector effects

http://arxiv.org/abs/1705.09434

Reactor antineutrino shoulder explained by energy scale nonlinearities?

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Abstract

The Daya Bay, Double Chooz and RENO experiments recently observed a significant distortion in their detected reactor antineutrino spectra, being at odds with the current predictions. Although such a result suggests to revisit the current reactor antineutrino spectra modeling, an alternative scenario, which could potentially explain this anomaly, is explored in this letter. Using an appropriate statistical method, a study of the Daya Bay experiment energy scale is performed. While still being in agreement with the γ calibration data and ^{12}B measured spectrum, it is shown that a $\mathcal{O}(1\%)$ deviation of the energy scale reproduces the distortion observed in the Daya Bay spectrum, remaining within the quoted calibration uncertainties. Potential origins of such a deviation, which challenge the energy calibration of these detectors, are finally discussed.

Keywords: Reactor, antineutrino, spectra, energy nonlinearity, statistical analysis.

1. Introduction

Reactor antineutrino experiments have played a leading role in neutrino physics starting with the discovery of the electron antineutrino in 1956 [1, 2], through the first observed oscillation pattern in KamLAND [11], up to recent high precision measurements on the θ_{13} mixing angle [3–5]. Future projects JUNO [13] and RENO50 [14] even aim at reaching sub-percent accuracy on θ_{12} on top of solving the neutrino mass hierarchy puzzle. However, two anomalies in the measured antineutrino spectra are being observed. The first is an overall rate deficit around 6% known as "The reactor antineutrino anomaly" [8]. The second one is a shape distortion in the 4–6 MeV region, often quoted as a "bump" or "shoulder" in the spectra. It should be particularly stressed out that the relation between these two anomalies is not straightforward since shape distortion does not necessarily imply a change in the total rate.

This letter focuses on the second anomaly. In Section 2, a quantitative comparison of four reactor antineutrino experiments (Bugey 3 [9], Daya Bay [4], Double Chooz [3] and RENO [5]) is performed to demonstrate their incompatibility, thus questioning nuclear effects as a common origin, as proposed in [10]. The next sections are dedicated to the study of an alternative scenario accounting for the observed distortion. Section 3 reviews the energy scale determination in such reactor antineutrino experiments. Section 4 introduces a combined analysis of the Daya Bay calibration and reactor antineutrino data. Results are presented in section 5 and show that a 1% unaccounted break at 4 MeV in the energy scale can reproduce the observed antineutrino spectrum and still comply with calibration data within uncertainties. Section 6 discusses possible origins of such an energy nonlinearity and especially questions calibration of such detectors.

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2. Reactor spectra comparison

2.1. On statistical compatibility of reactor spectra

Among all existing reactor antineutrino experiments, four of them gives precise reactor spectra shape information. The Bugey 3 experiment (B3) [9] has until recently provided the finest reactor antineutrino spectrum. The B3 measurement was in very good agreement with previous predictions [15–17]. The comparison is here updated to the most recent predictions [6, 7]. As indicated on Figure 1, the net effect is an additional 1%/MeV decrease through the full energy range. This update is still compatible with prediction within the 2% linear spectral uncertainty envelop quoted in [9]. New measurements have been provided by three experiments: Double Chooz (DC) [3], Daya Bay (DB) [4] and RENO (RN) [5]. Their ratios to the state of the art prediction [6, 7] are depicted on Figure 1 and exhibit a significant deviation from unity around 5 MeV. At first glance they clearly show a common feature which is described as a bump in the 4 to 6 MeV region. Nevertheless, to our knowledge, no quantitative comparison is available in the literature.

To gain quantitative insights on their compatibility, each spectrum having different bin centers and widths, a direct

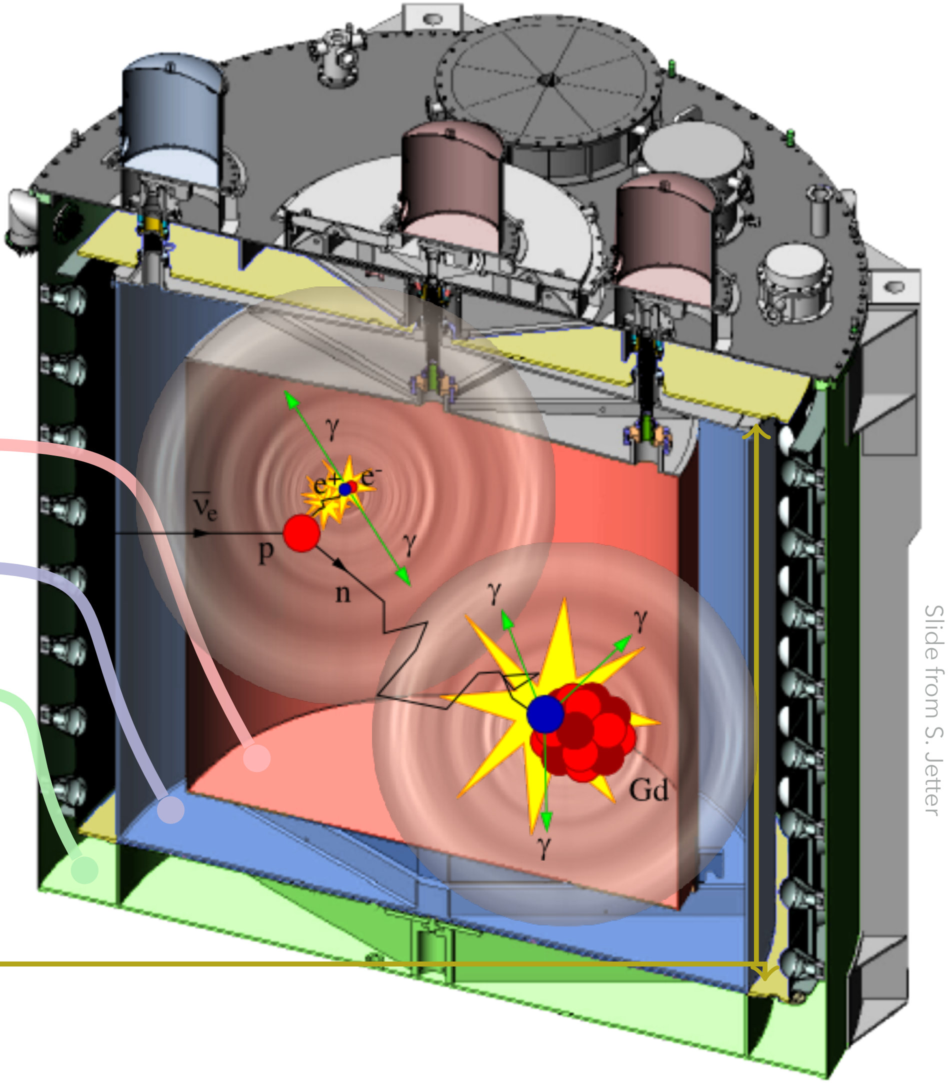
Antineutrino detector design

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



Slide from S. Jetter

True energy → Deposited → Visible light → Reconstructed Charge

Daya Bay Calibration System

3 'robots' employed along 3 z-axes

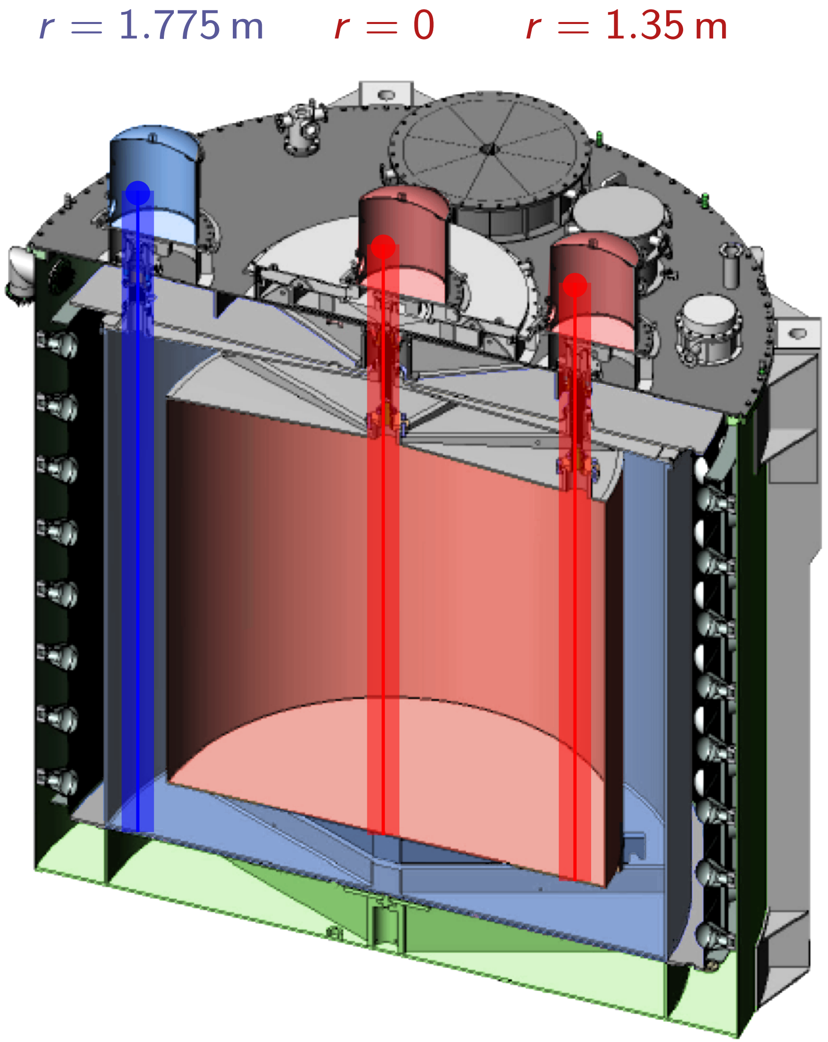
1. Center of GdLS target volume
2. Edge of GdLS target volume
3. Middle of LS gamma catcher volume

3 sources in each robot (employed weekly)

1. ^{68}Ge ($2\times511\,\mathrm{keV}\ \gamma$)
2. ^{241}Am^{13}C (n) $+^{60}$Co ($1.17+1.33\,\mathrm{MeV}\ \gamma$)
3. LED diffuser ball

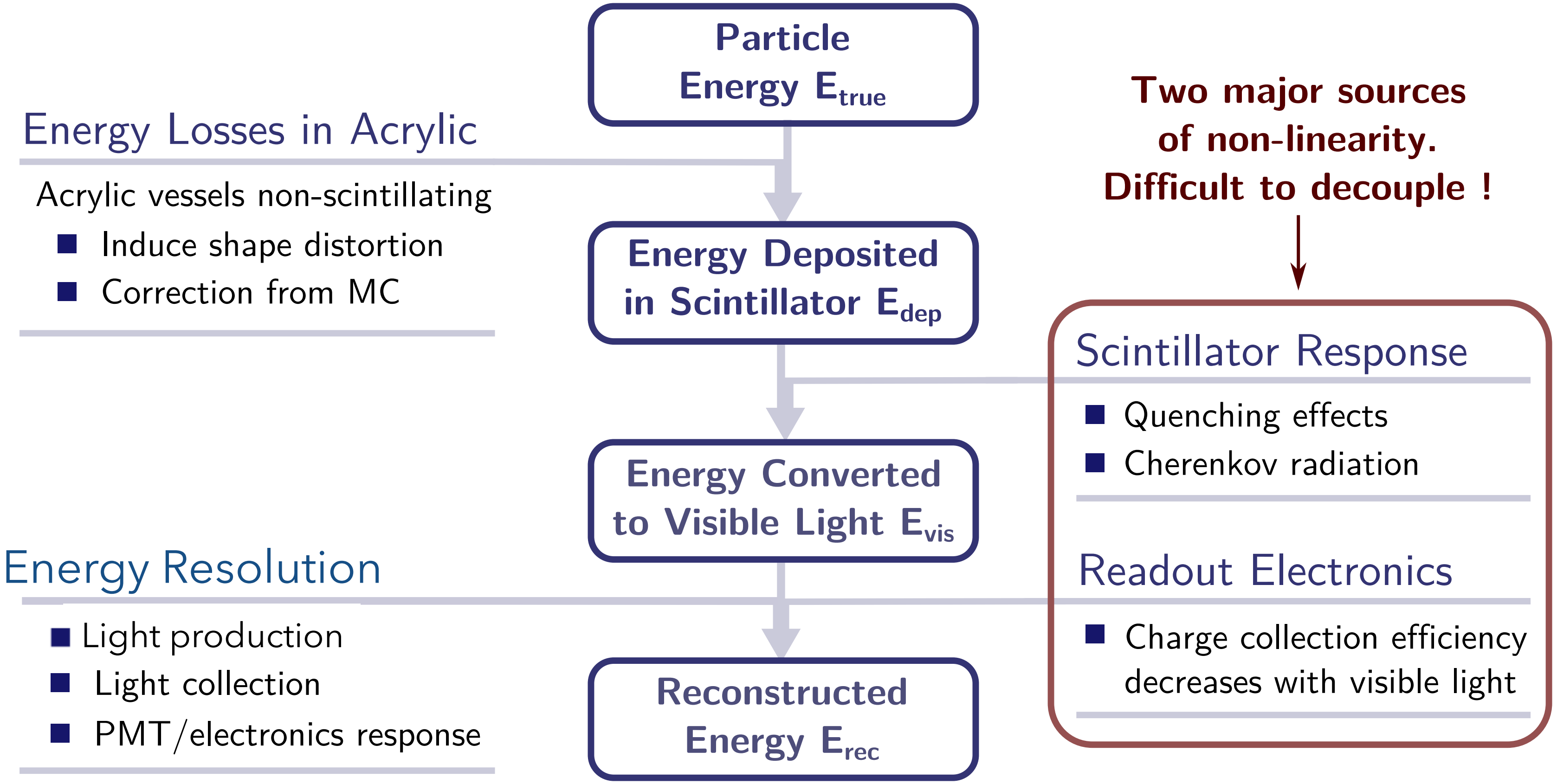
Additional temporary sources

1. Gamma sources:
    - ^{137}Cs (0.662 MeV)
    - ^{54}Mn (0.835 MeV)
    - ^{40}K (1.461 MeV)
2. Neutron sources
    - ^{241}Am-^{9}Be, ^{239}Pu-^{13}C



Slide from S. Jetter

Energy response model



Particle Energy E_{true}

Energy Deposited in Scintillator E_{dep}

Energy Converted to Visible Light E_{vis}

Reconstructed Energy E_{rec}

Energy Losses in Acrylic

Acrylic vessels non-scintillating

- Induce shape distortion
- Correction from MC

Energy Resolution

- Light production
- Light collection
- PMT/electronics response

Two major sources of non-linearity. Difficult to decouple !

Scintillator Response

- Quenching effects
- Cherenkov radiation

Readout Electronics

- Charge collection efficiency decreases with visible light

Slide from S. Jetter

Total effective non-linearity f

$$f = \frac{E_{rec}}{E_{true}} = \frac{E_{vis}}{E_{true}} \times \frac{E_{rec}}{E_{vis}} = f_{scint}(E_{true}) \times f_{elec}(E_{vis})$$

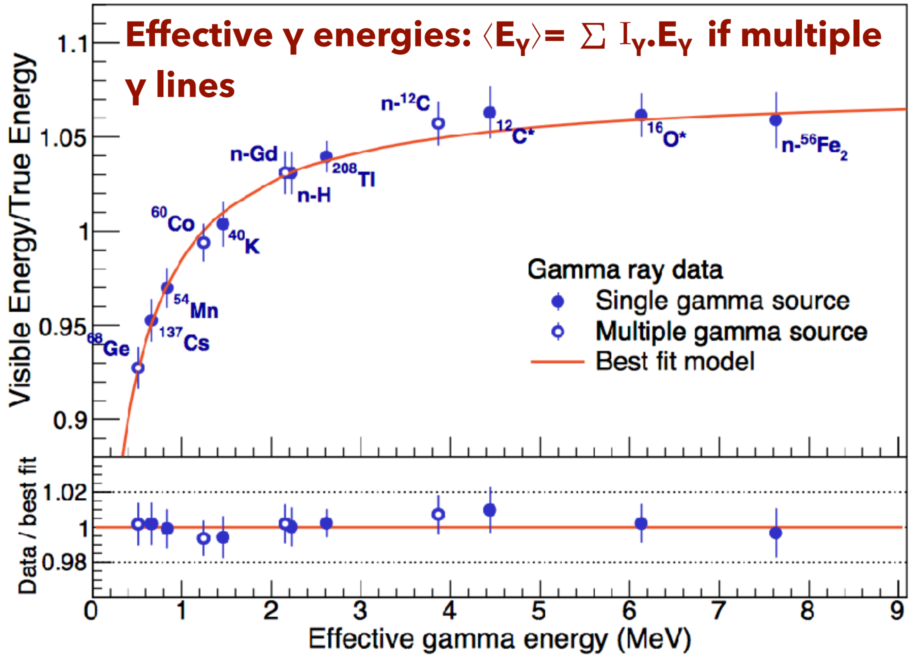
1 Scintillator non-linearity

2 Electronics non-linearity

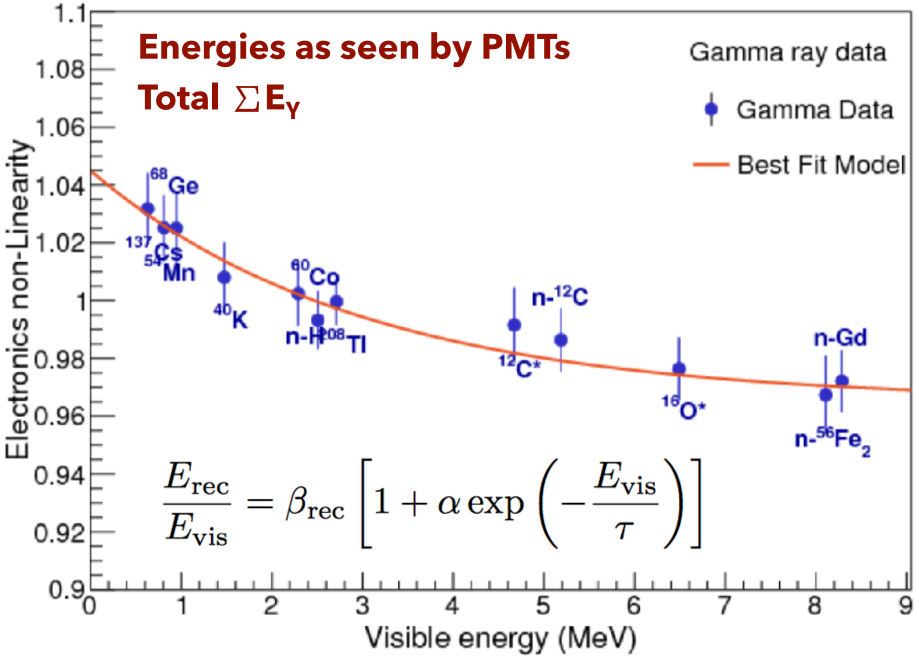
Model maps reconstructed energy E_{rec} to true kinetic energy E_{true}

- Minimal impact on oscillation measurement
- Crucial for measurement of reactor spectra

Embedded light production / propagation & electronic response



Effective γ energies: $\langle E_\gamma \rangle = \sum I_\gamma . E_\gamma$ if multiple γ lines



Energies as seen by PMTs

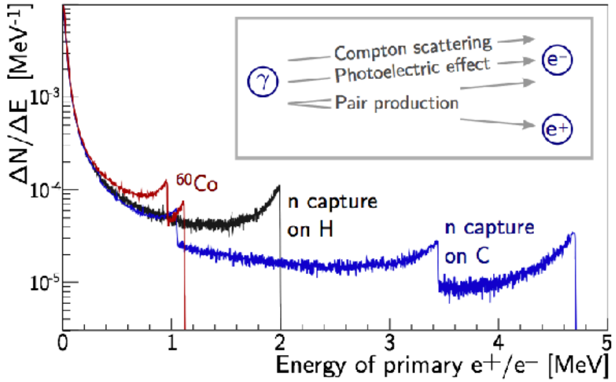
Total $\sum E_\gamma$

$$\frac{E_{\text{rec}}}{E_{\text{vis}}} = \beta_{\text{rec}}\left[1 + \alpha \exp\left(-\frac{E_{\text{vis}}}{\tau}\right)\right]$$

$$\frac{E_{\text{vis}}}{E_{\text{true}}} = \beta_{\text{vis}}\left[f_{\text{q}}(E_{\text{true}}, k_{\text{B}}) + k_{\text{c}} f_{\text{c}}(E_{\text{true}})\right],$$

γ ➛ Multi-Compton e$^-$

⇒ ionization quenching



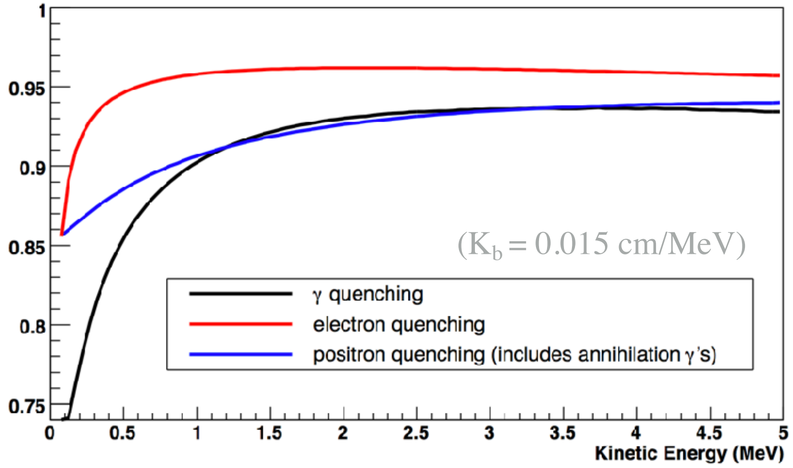
S. Jetter

γ connected to e$^-$ model through MC

$$E^{\gamma}_{\text{vis}} = \int E^{e^-}_{\text{vis}}\left(E^{e^-}_{\text{true}}\right) \cdot \frac{dN}{dE}\left(E^{e^-}_{\text{true}}\right) dE^{e^-}_{\text{true}}$$

e$^+$ and e$^-$ interacts the same way with scintillator

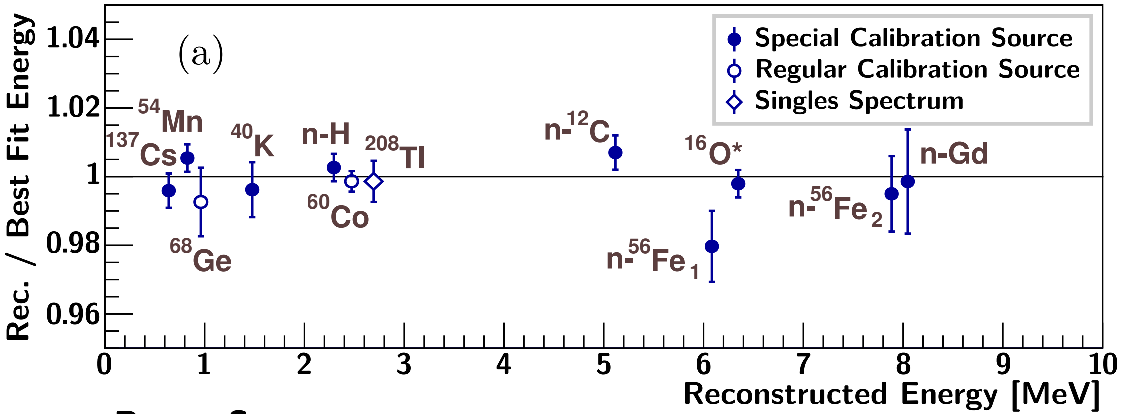
$$E^{e^+}_{\text{vis}} = E^{e^-}_{\text{vis}} + 2 \cdot E^{\gamma}_{\text{vis}}(0.511\ \text{MeV})$$



KamLAND, T. Classen PhD. Thesis

Daya Bay’s extensive calibration scheme

Gamma Sources



γ calibration sources:

^{60}Co : 2γs in cascade 1.17+1.33 MeV

^{40}K: EC, E_γ~1.46 MeV

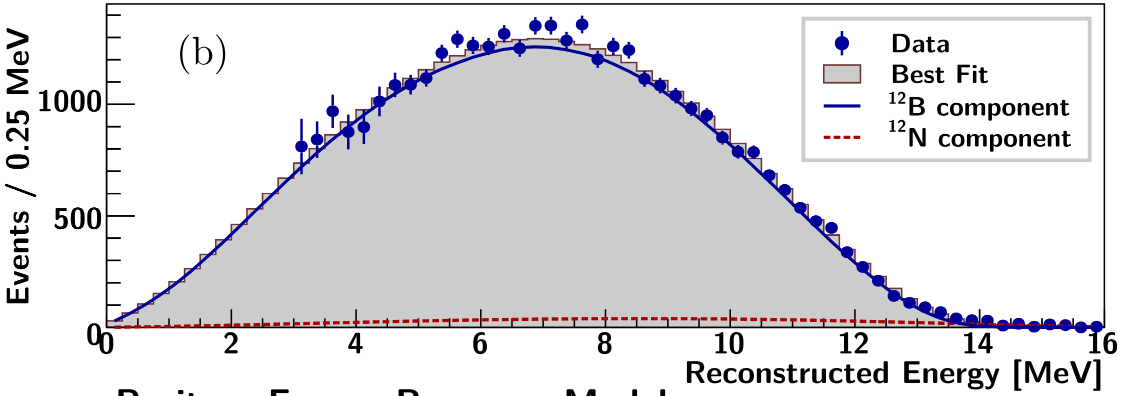
n-H: n capt. E_γ ~ 2.2 MeV

n-^{12}C: Σγ’s ~ 4.9 MeV

…

n-^{157}Gd: Σγ’s ~ 8 MeV

Boron Spectrum



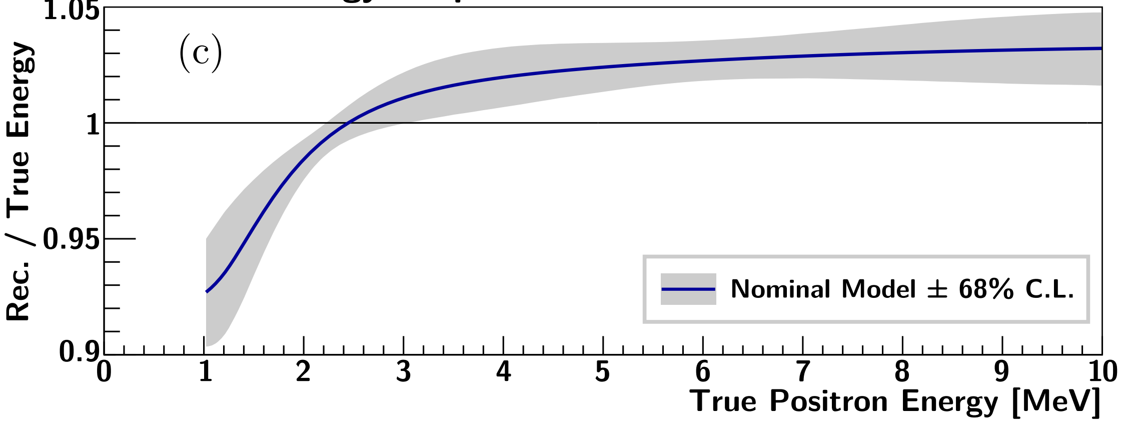
Daya Bay - PRL. 112, 061801

^{12}B: spallation from cosmic μ on ^{12}C

β^- decay with Q_β = 13.4 MeV

Below 3-4 MeV: a lot of backgrounds (unreliable data)

Positron Energy Response Model



e^+ relative response: require MC simulation

e^- are quenched (Birk’s law)

e^+ are 🔗 e^- except for the 2 annihilation γ’s of e^+

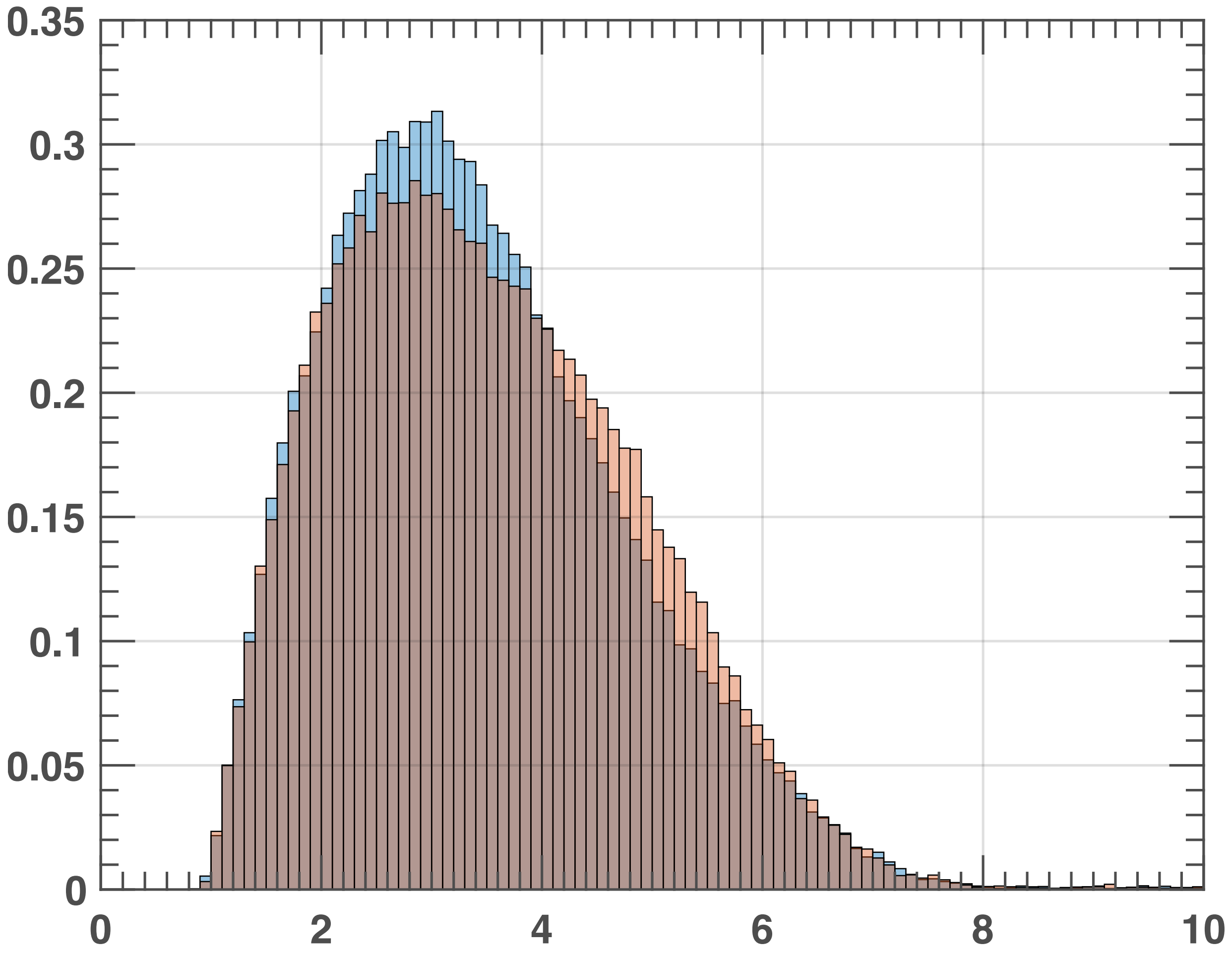
$E_{vis,e+} = E_{vis,e-} + E_{vis,\gamma}$ (0.511 MeV)

How to search for energy distortion?

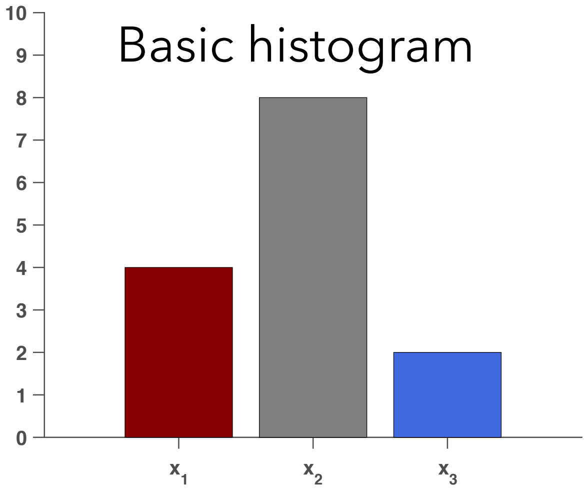
X scale distortion… how to get it?

Assume an x scale distortion produces orange histogram from blue one

How to get it?

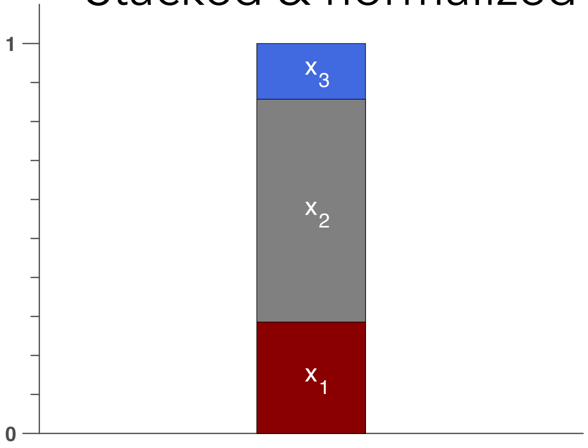


How to draw a random sample from an histogram

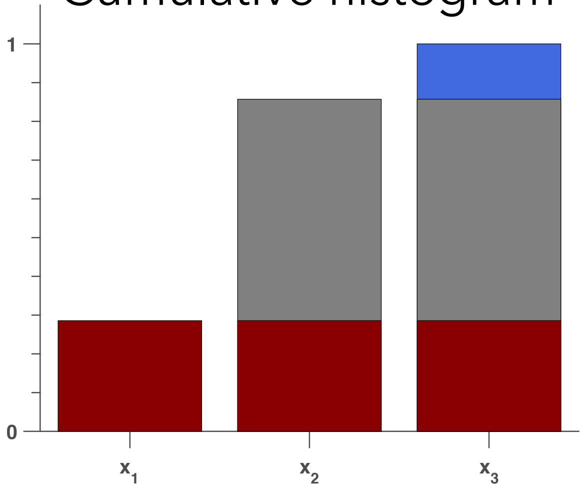

Basic histogram

Random sampling in [0;1]

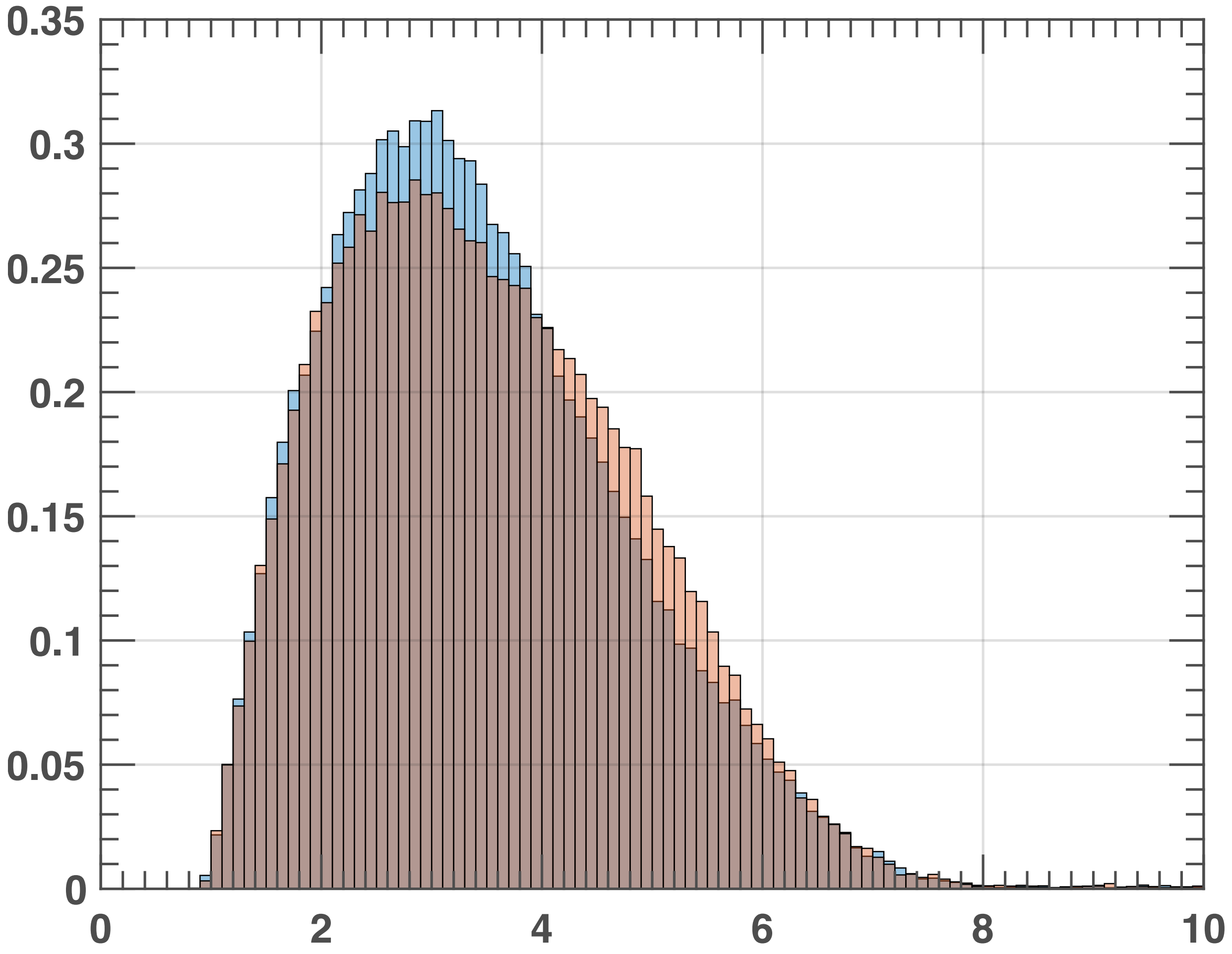
Stacked & normalized



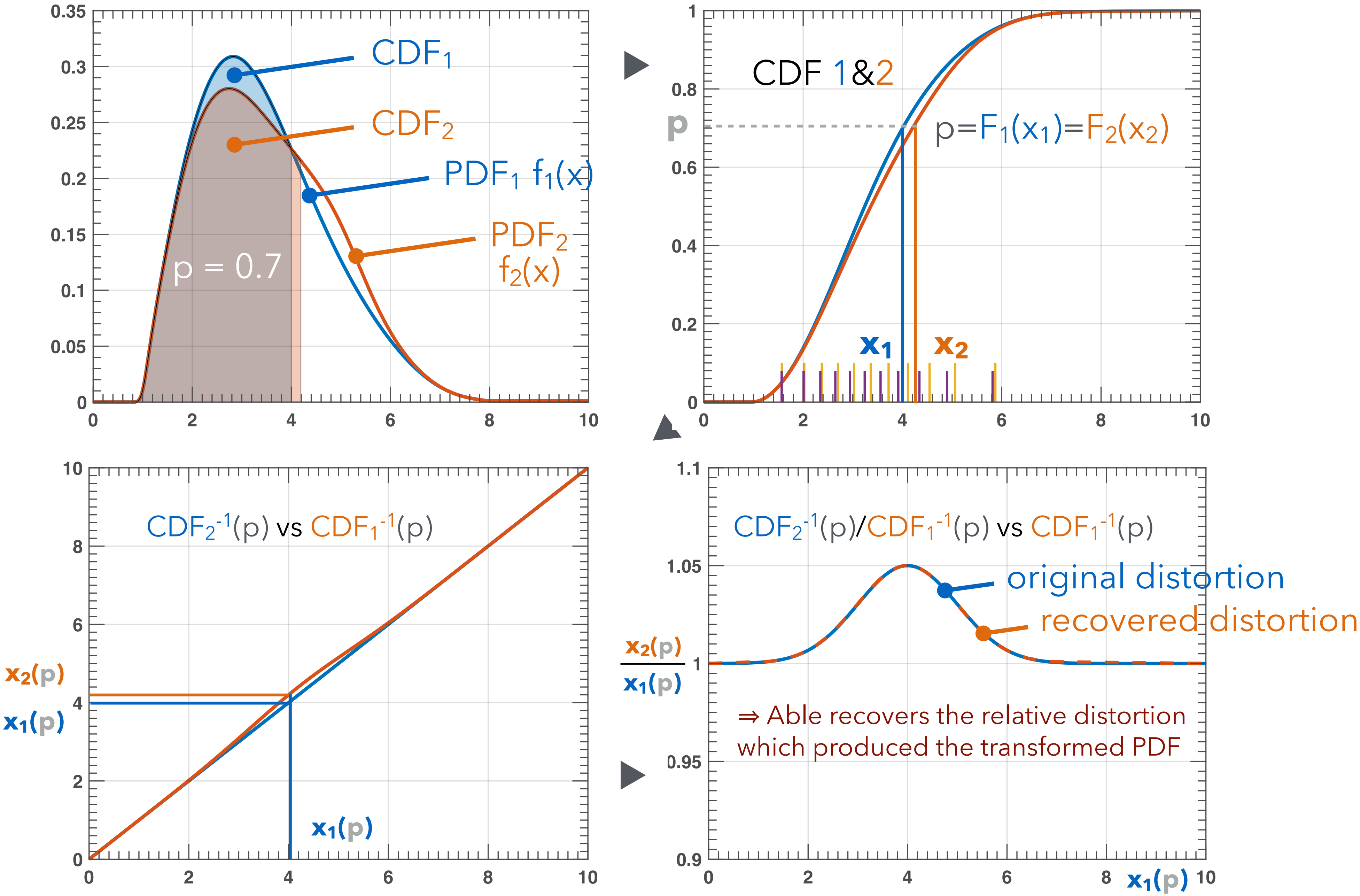
Cumulative histogram



Histograms are probability density estimators

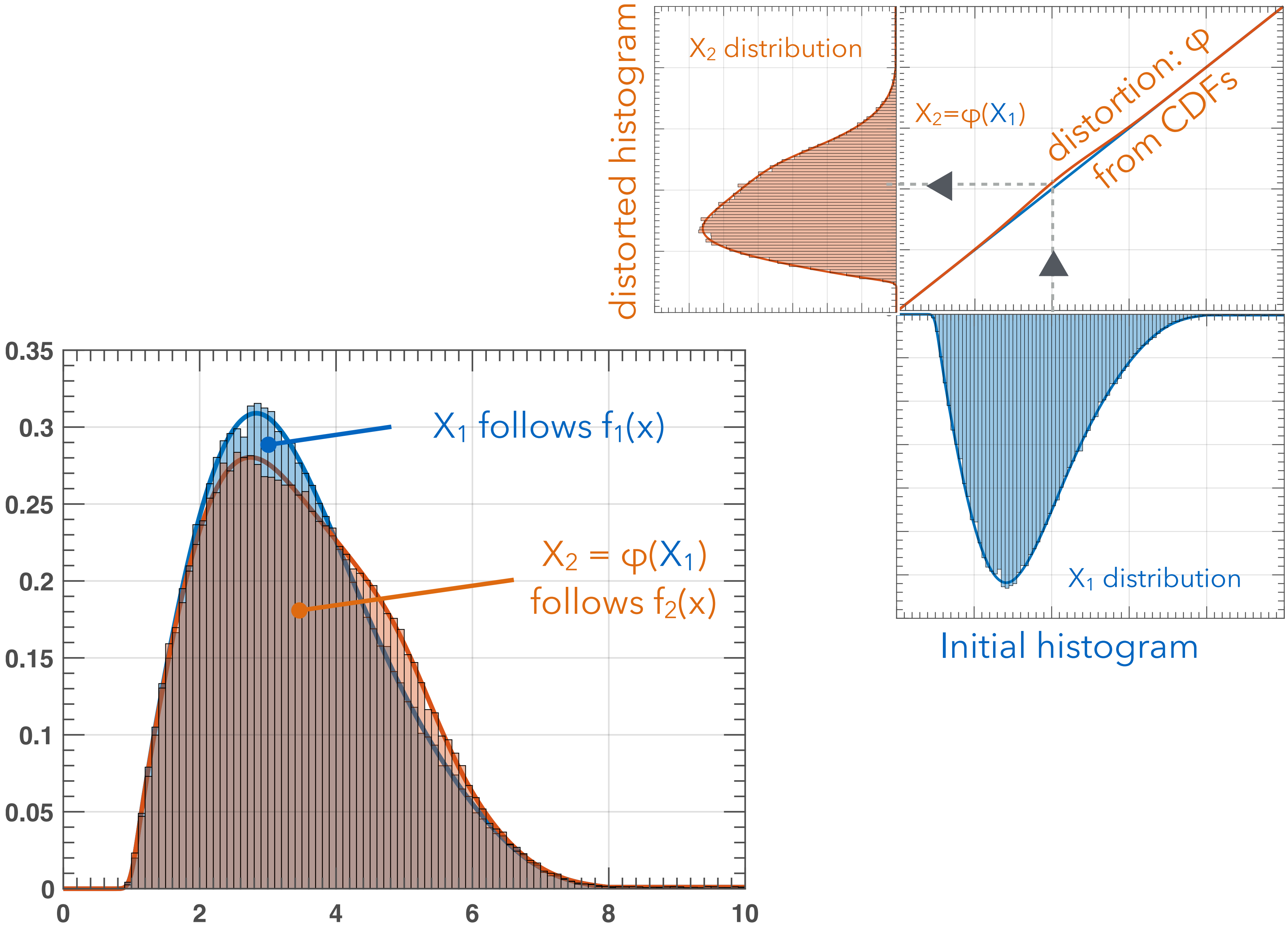


X scale distortion

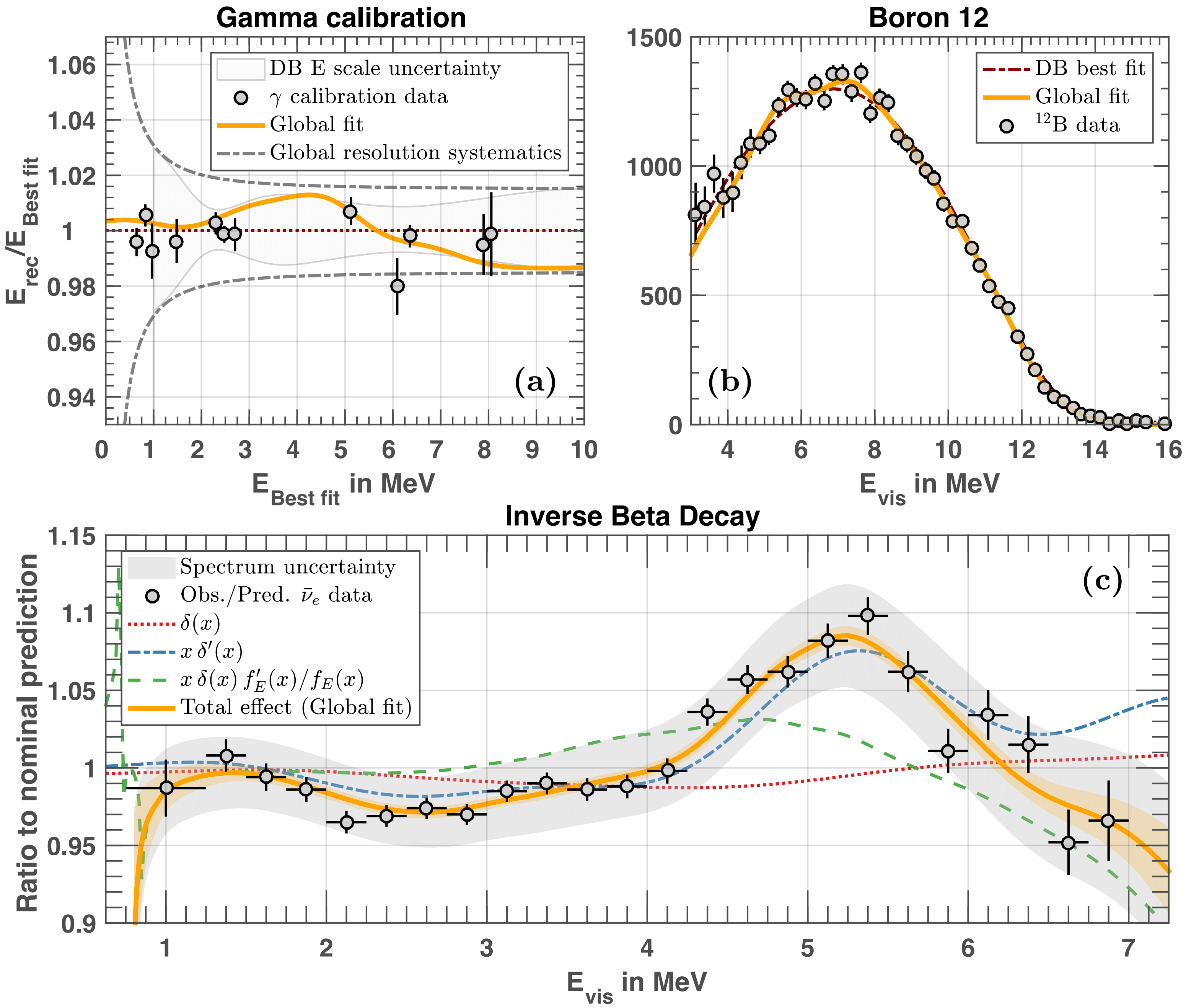


⇒ Able recovers the relative distortion which produced the transformed PDF

Cross-check: it works!



Nominal fit


Gamma calibration
DB E scale uncertainty
γ calibration data
Global fit
Global resolution systematics
(a)
$E_{rec}/E_{Best\ fit}$
1.06
1.04
1.02
1
0.98
0.96
0.94
0
1
2
3
4
5
6
7
8
9
10
$E_{Best\ fit}$ in MeV
Boron 12
DB best fit
Global fit
^{12}B data
(b)
1500
1000
500
0
4
6
8
10
12
14
16
E_{vis} in MeV
Inverse Beta Decay
Spectrum uncertainty
Obs./Pred. $\bar{\nu}_e$ data
$\delta(x)$
$x\,\delta'(x)$
$x\,\delta(x)\,f'_E(x)/f_E(x)$
Total effect (Global fit)
(c)
Ratio to nominal prediction
1.15
1.1
1.05
1
0.95
0.9
1
2
3
4
5
6
7
E_{vis} in MeV

Conclusion

- Observed reactor antineutrino spectra are not compatible with each other within published uncertainties
- No simple fuel evolution scenario could make them compatible
- We investigated at potential detector effect
- We found that a 1% bias on Energy scale around 4 MeV could recover Daya Bay's observed antineutrino spectrum from the predicted one
- No calibration available in this region
- If antineutrino spectra distortions are due to energy scale nonlinearies, it is a migration effect accross bins and do not modify the rate. It has therefore no link to the reactor antineutrino anomaly in rate.