Precision Reactor $\bar{\nu}_e$ Spectrum Predictions and Measurements

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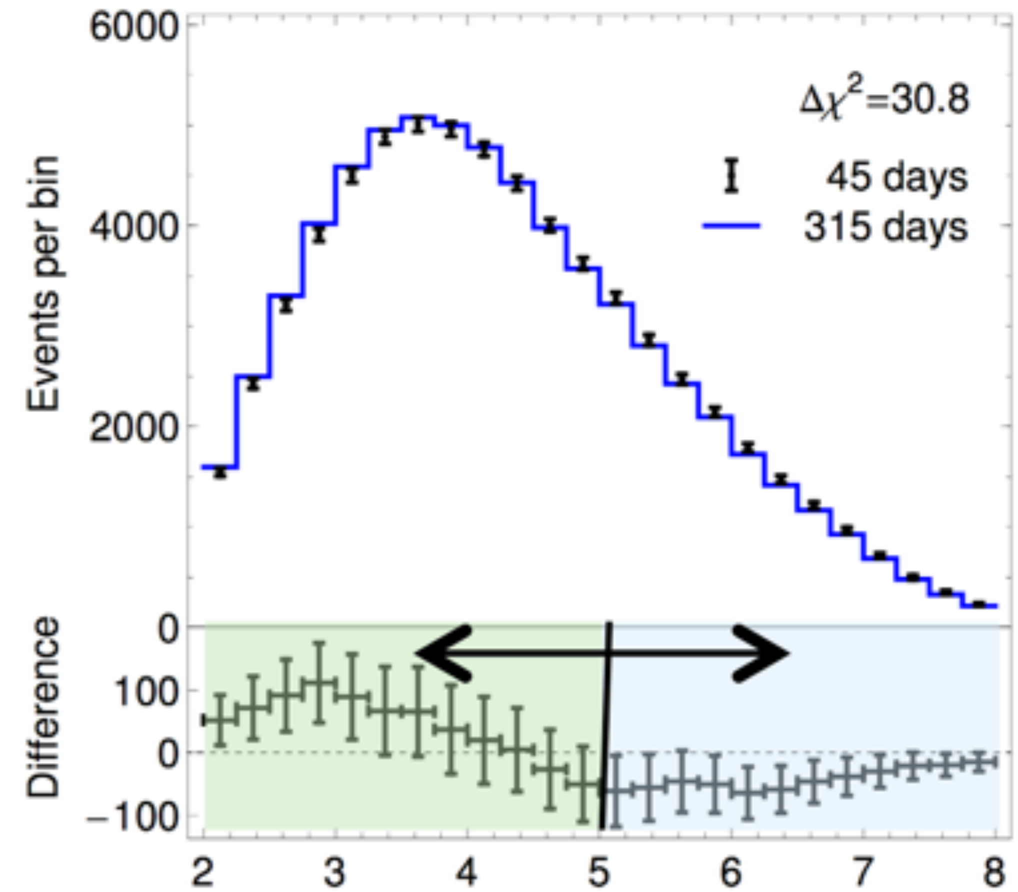
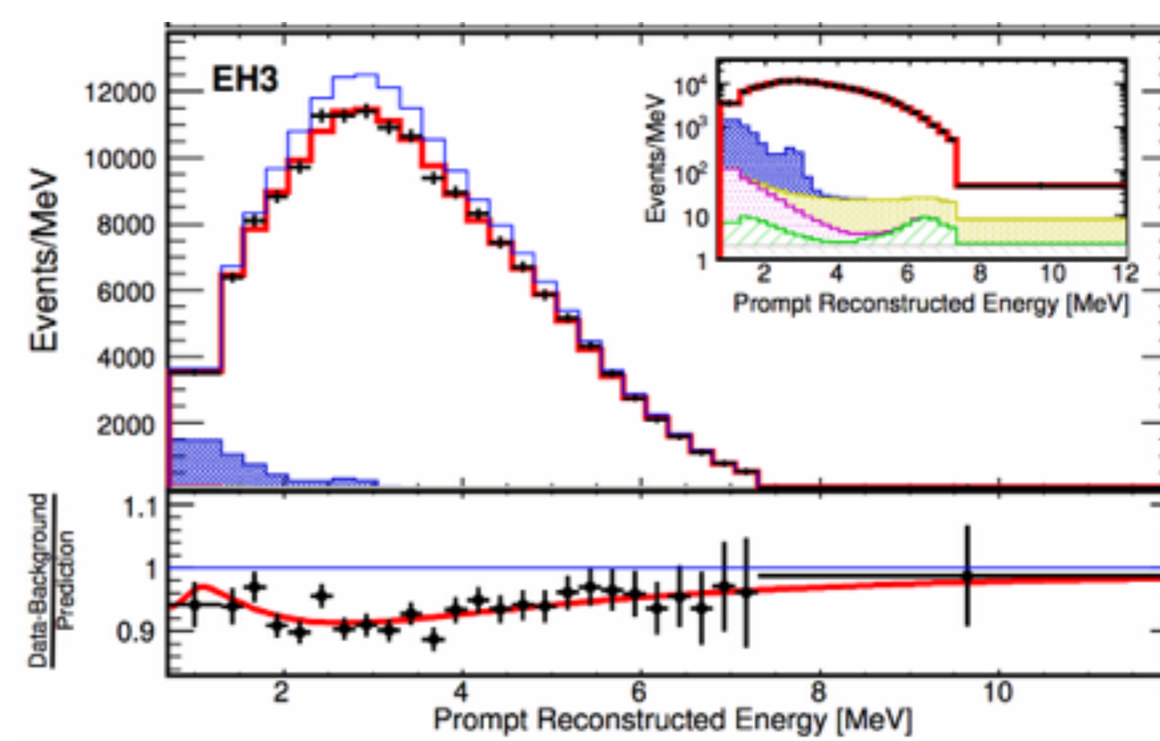
Overview

- The reactor antineutrino spectrum is a valuable handle for:
  - Neutrino oscillation physics
  - Safeguards
  - Nuclear applications
- New precision spectrum measurements now available from θ_{13} experiments: What are the implications?
- Talk outline
  - Introduction
  - Detailed look at recent results
  - Discussion and implications

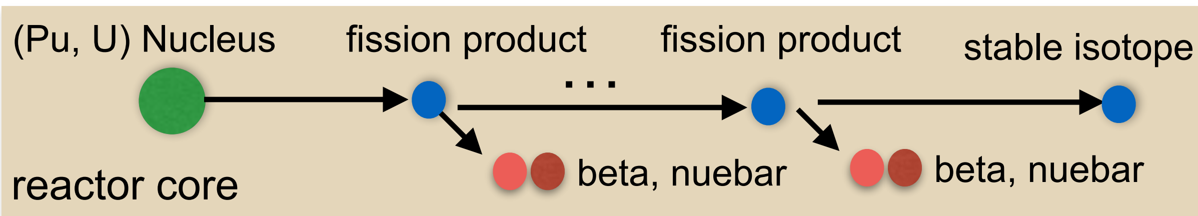


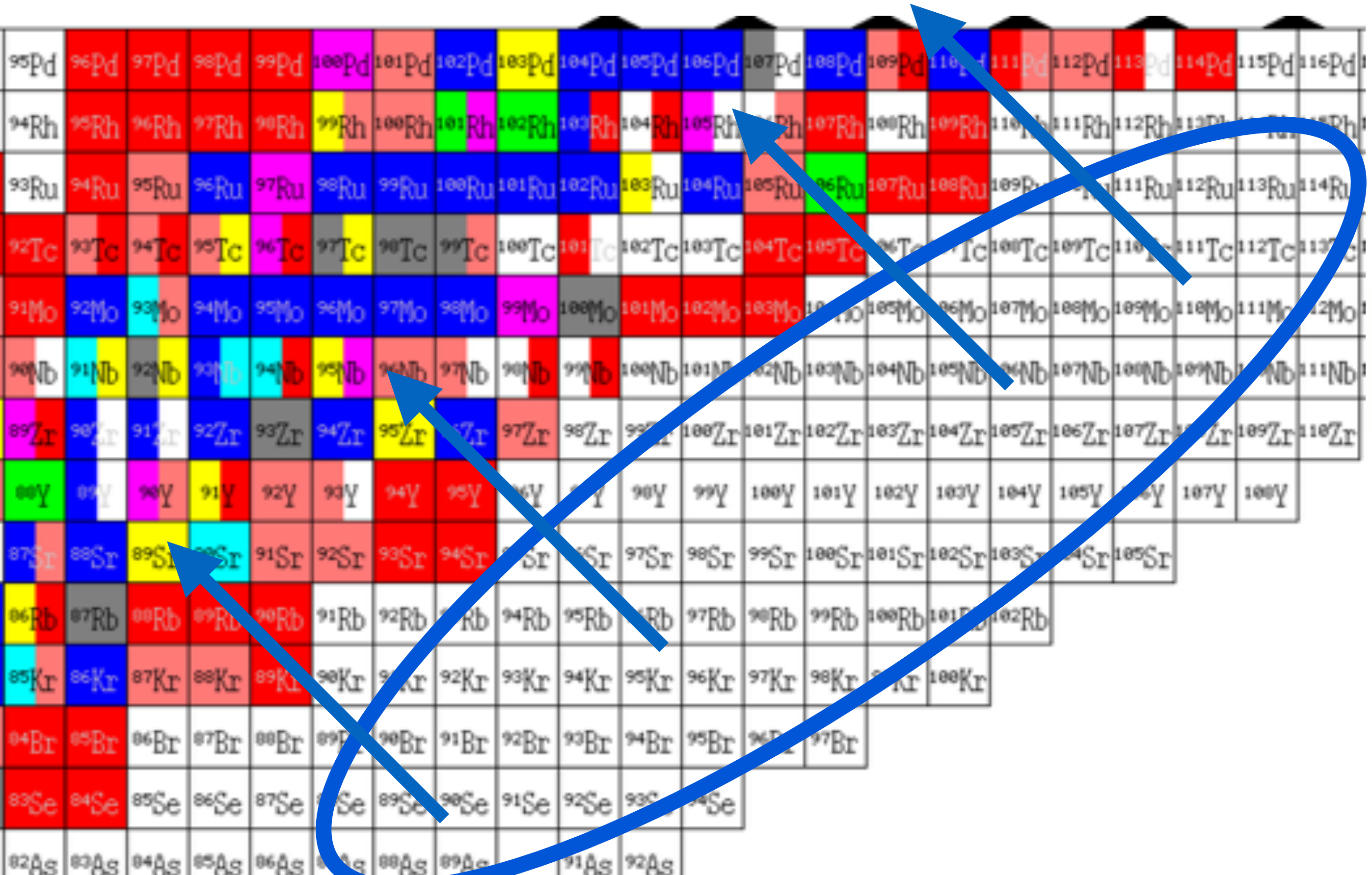


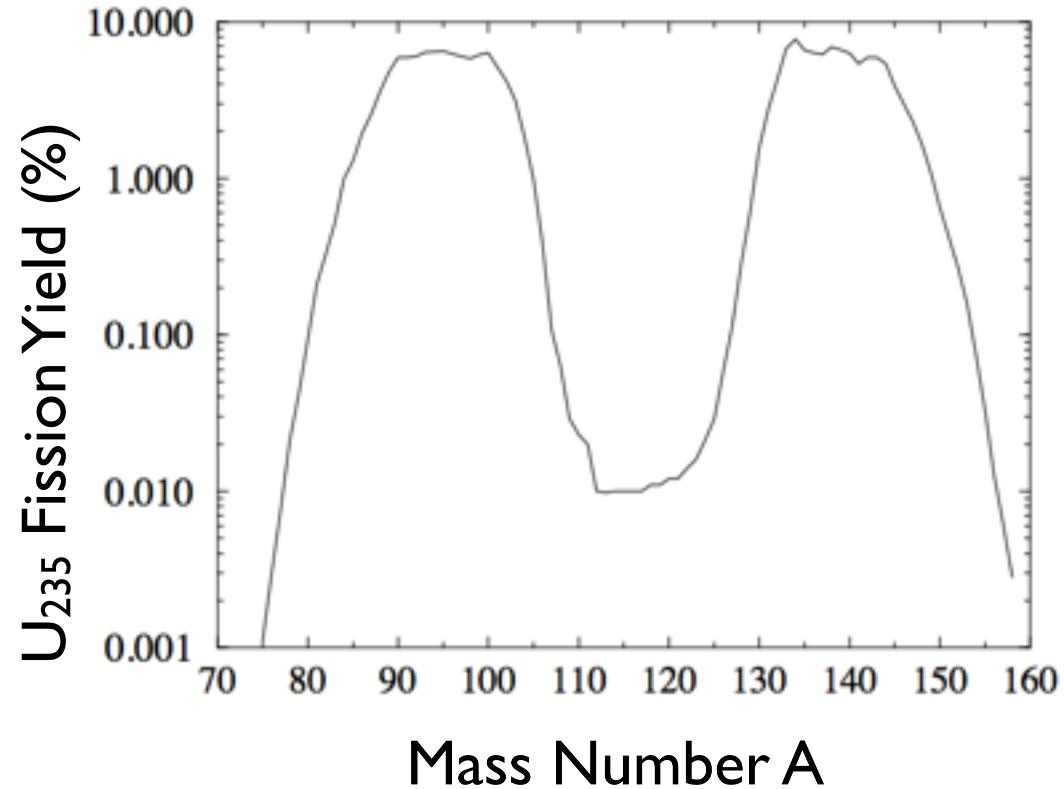
Introduction

Reactor Antineutrino Production

- Reactor $\bar{\nu}$e: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies (slightly)



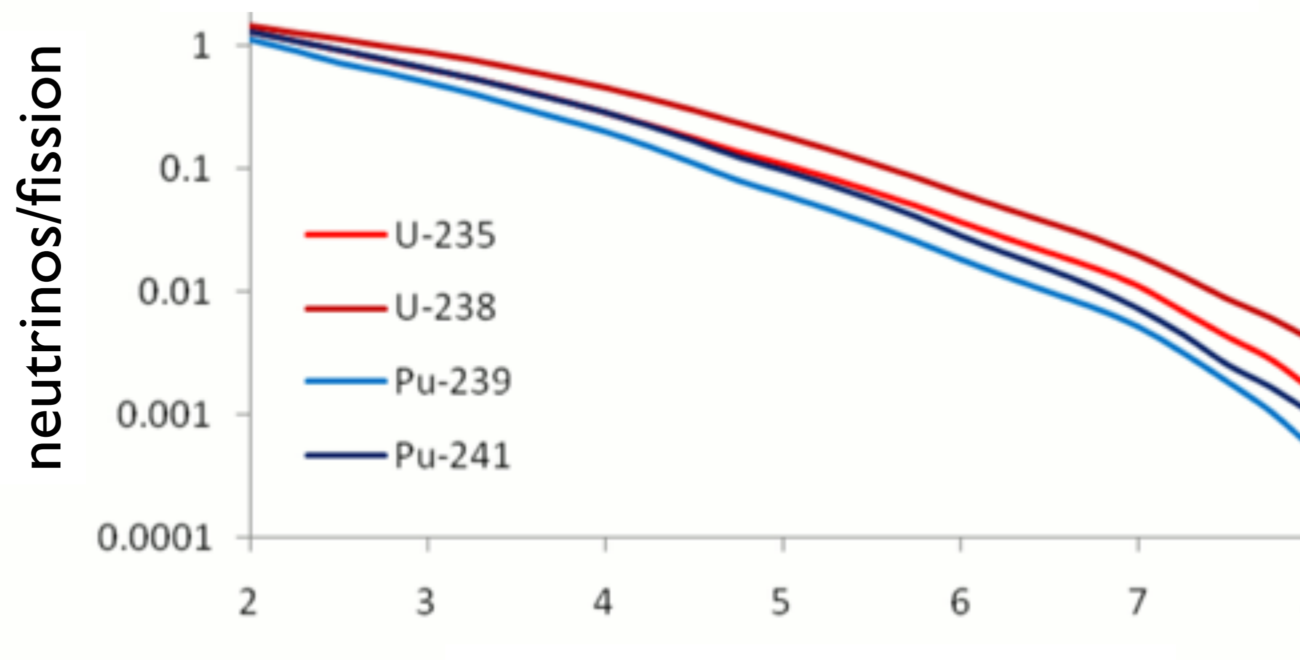




Spectrum

$$S(E) = \sum F_i S_i(E) \qquad F_i = \frac{W_{\text{th}} f_i}{\sum_k f_k E_k}$$

Fission Isotope i Flux



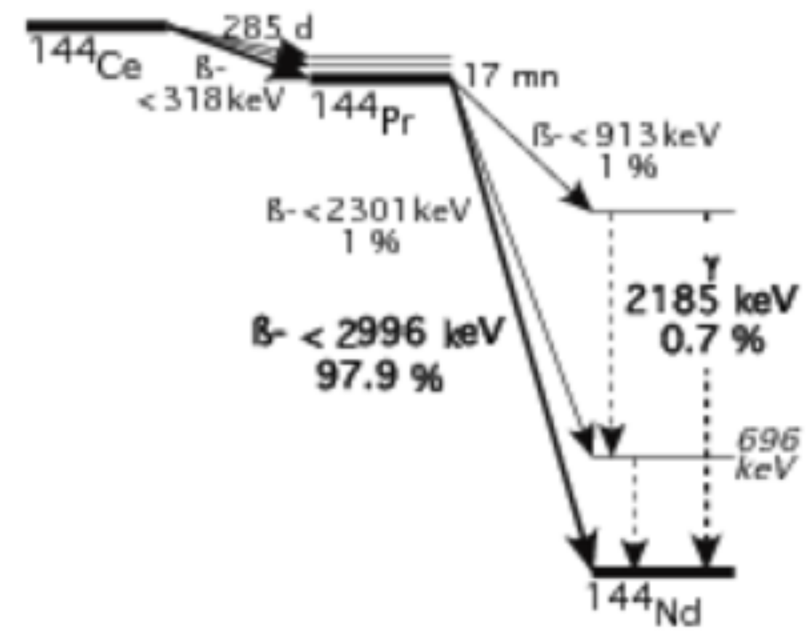
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes
  - **Problem:** Some rare beta branches with little/ incomplete information; infer these additions
- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
- Devised in 50's, each method has lost and gained favor over the years

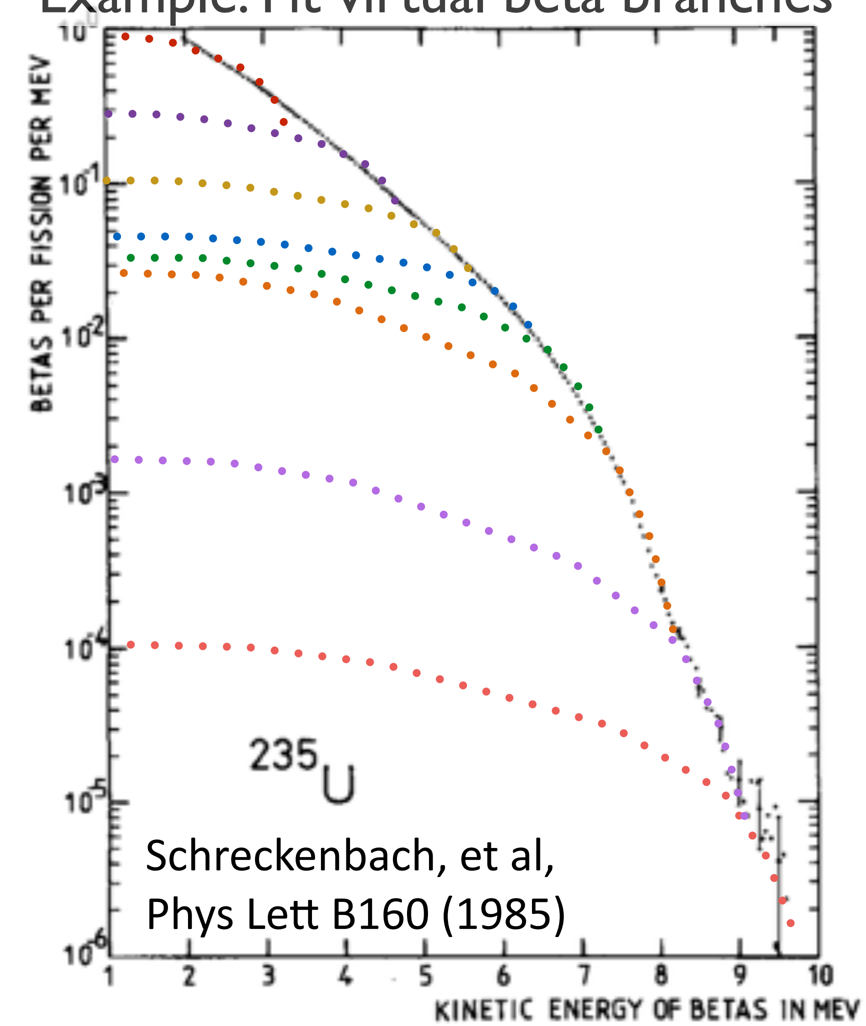
Carter, *et al*, Phys. Rev. 113 (1959)

King and Perkins, Phys. Rev. 113 (1958)

Example: Ce-144 Decay Scheme

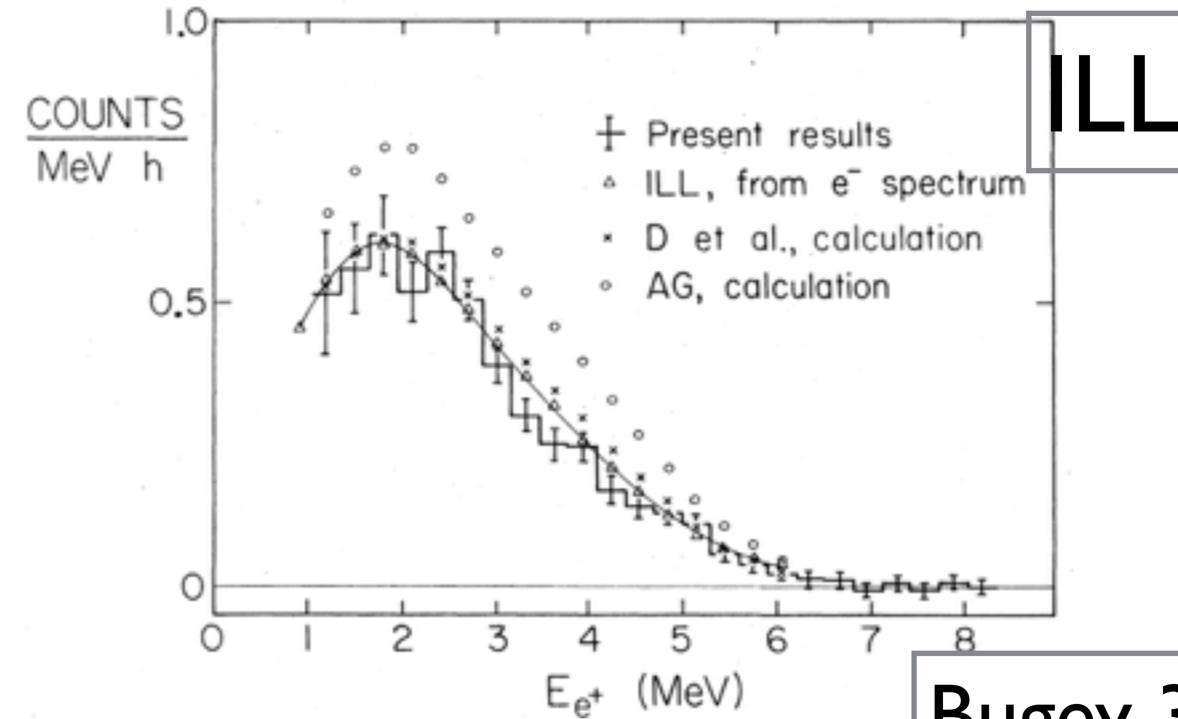


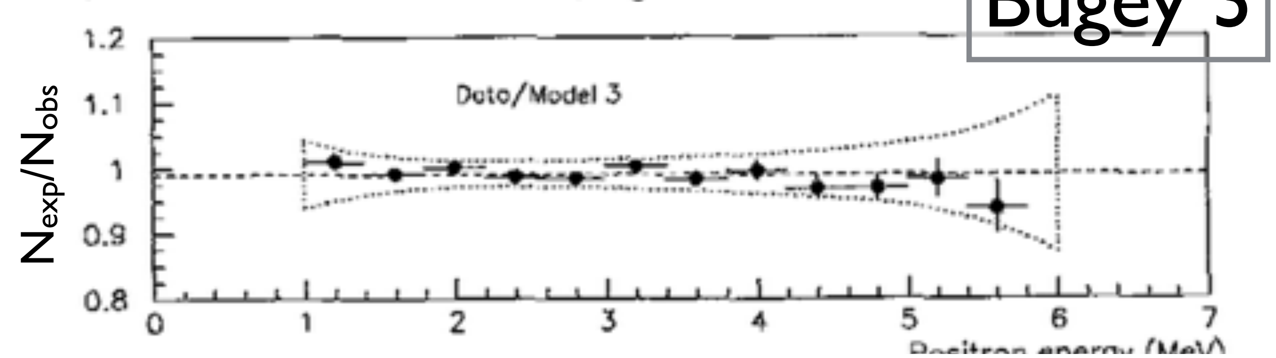
Example: Fit virtual beta branches

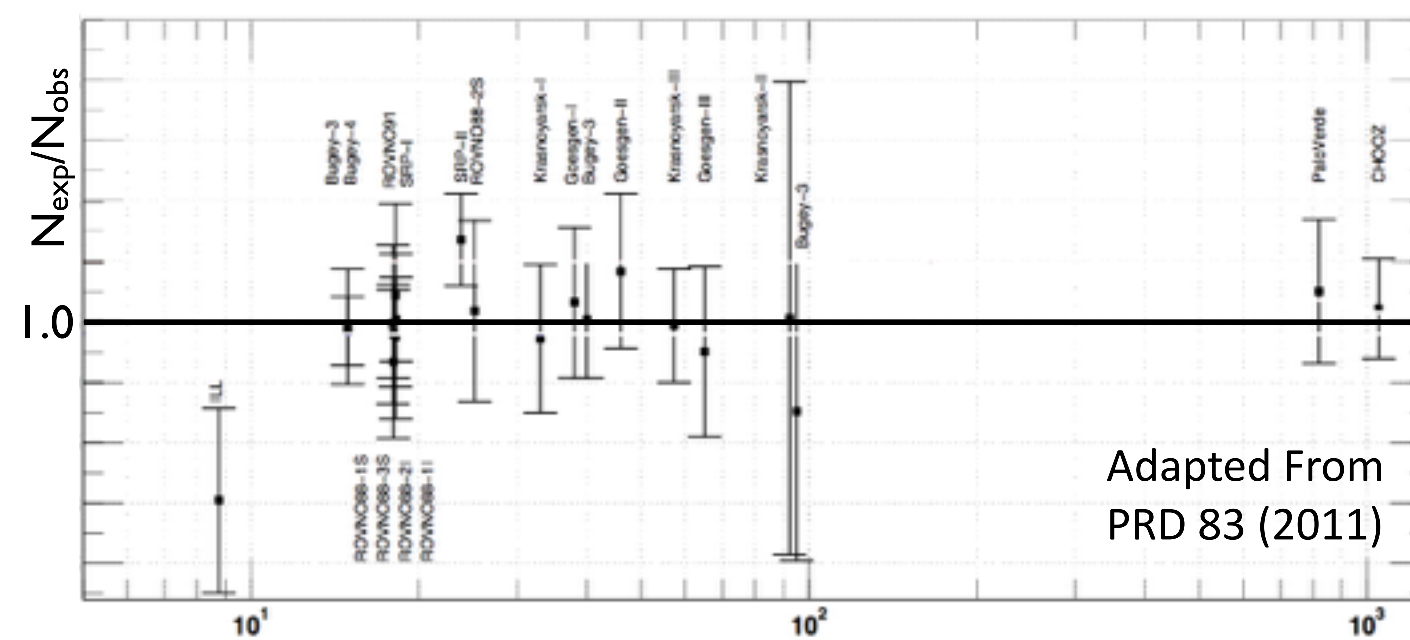


Predicting $S_i(E)$, Neutrinos Per Fission

- Early 80s: ILL $\bar{\nu}_e$ data fits newest *ab initio* spectra well
  - i.e.: Davis, Vogel, *et al.*, **PRC** 24 (1979)
  - ILL: Kwon, et al., **PRD** 24 (1981)
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics
  - Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  - Schreckenbach, *et al.*, Phys Lett **B**218 (1989)
- 1990s: Bugey measurements fit converted spectrum well
  - B. Achkar, *et al.*, Phys Lett B374 (1996)
- 1980s-2000s: Predicted, measured fluxes agree in Russian, EU, US exps.



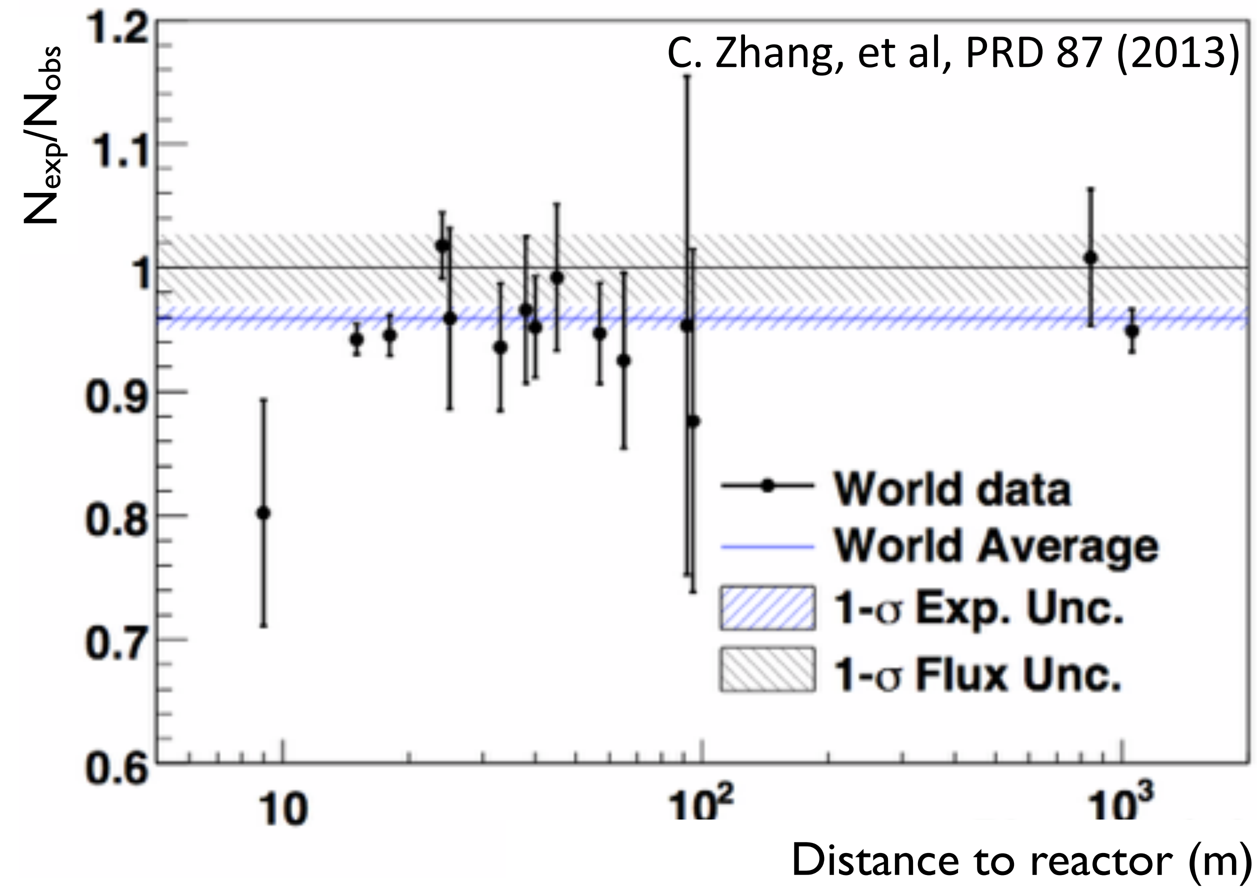


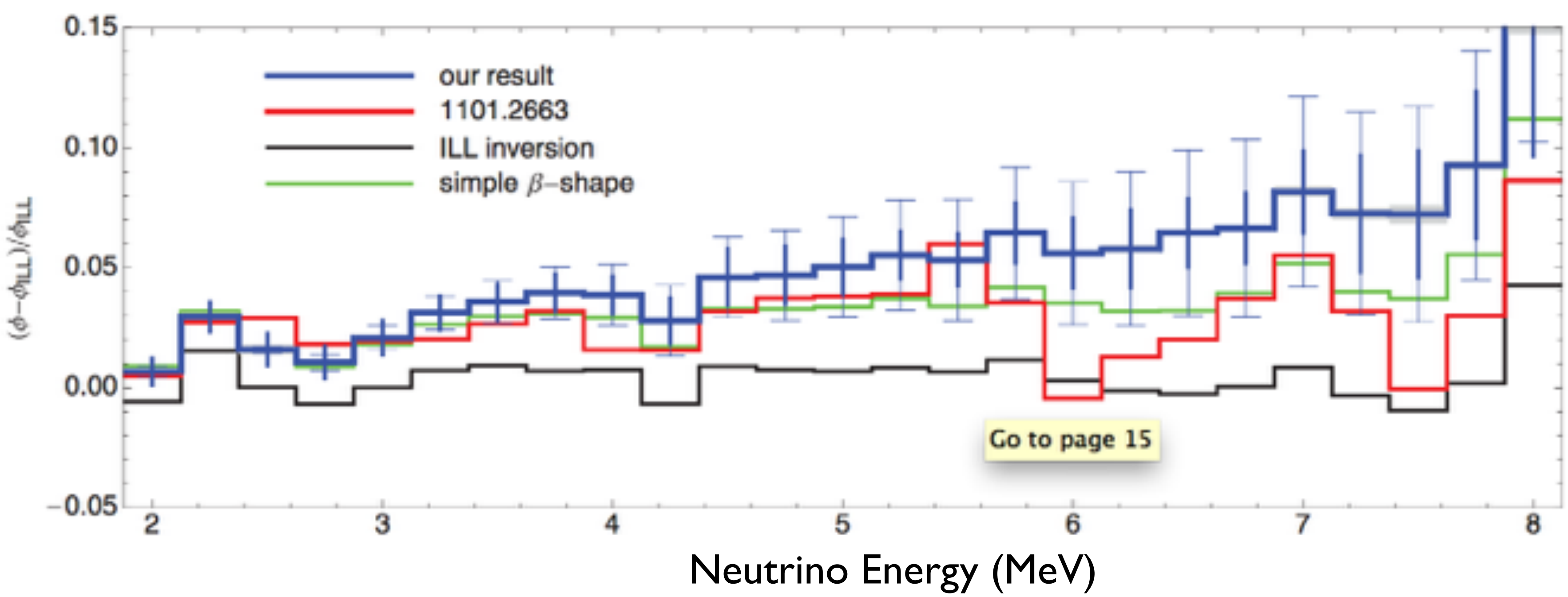


Recent History: Problems Emerge

- 2010s: Re-calculation of conversion for θ_{13} measurements
  - Start with ab initio approach
  - Subtract this from ILL beta spectra
  - Use conversion procedure on remaining beta spectrum: ~10%
  - OR Huber: virtual branches only
- Change in flux/spectrum
  - Predicted and measured fluxes no longer agree.
  - Spectrum shifted to higher energy

Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)

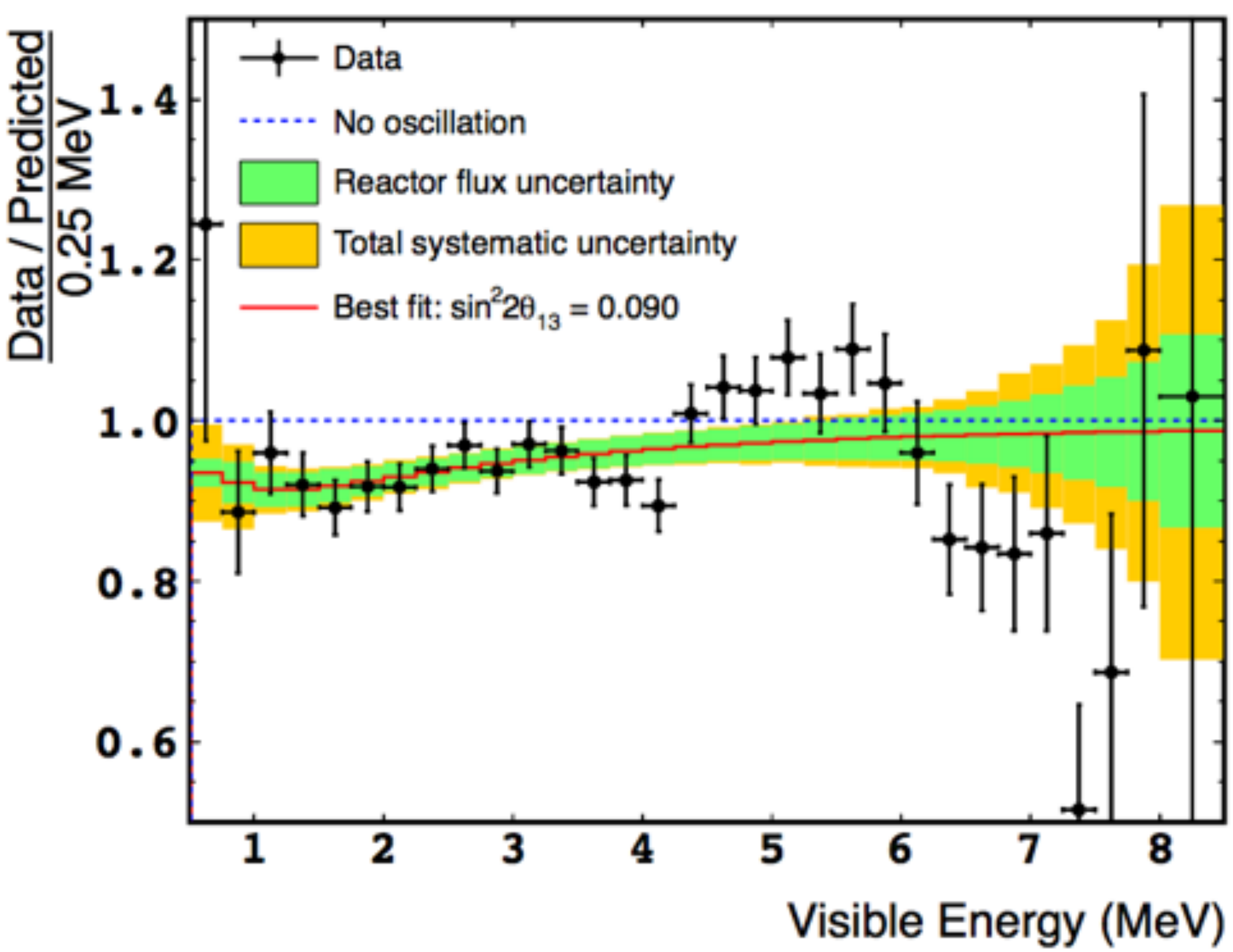




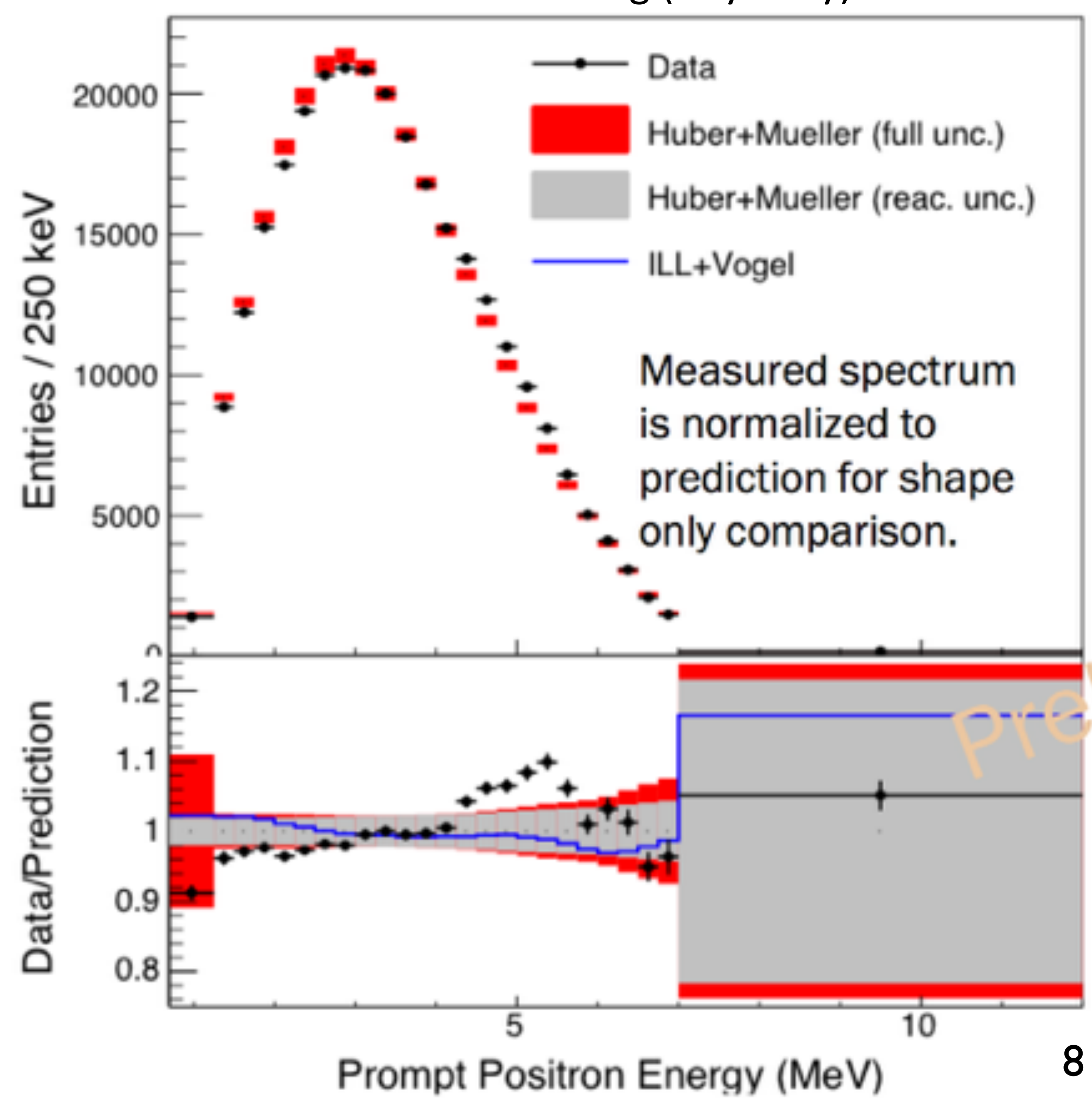
Even More Recent History: More Problems

- Spectra from θ_{13} experiments disagree with predictions
  - So now, not only the flux, but also the spectra disagree with predictions.
- Let's go over these in a little more detail.

Double Chooz, JHEP 10 (2014)



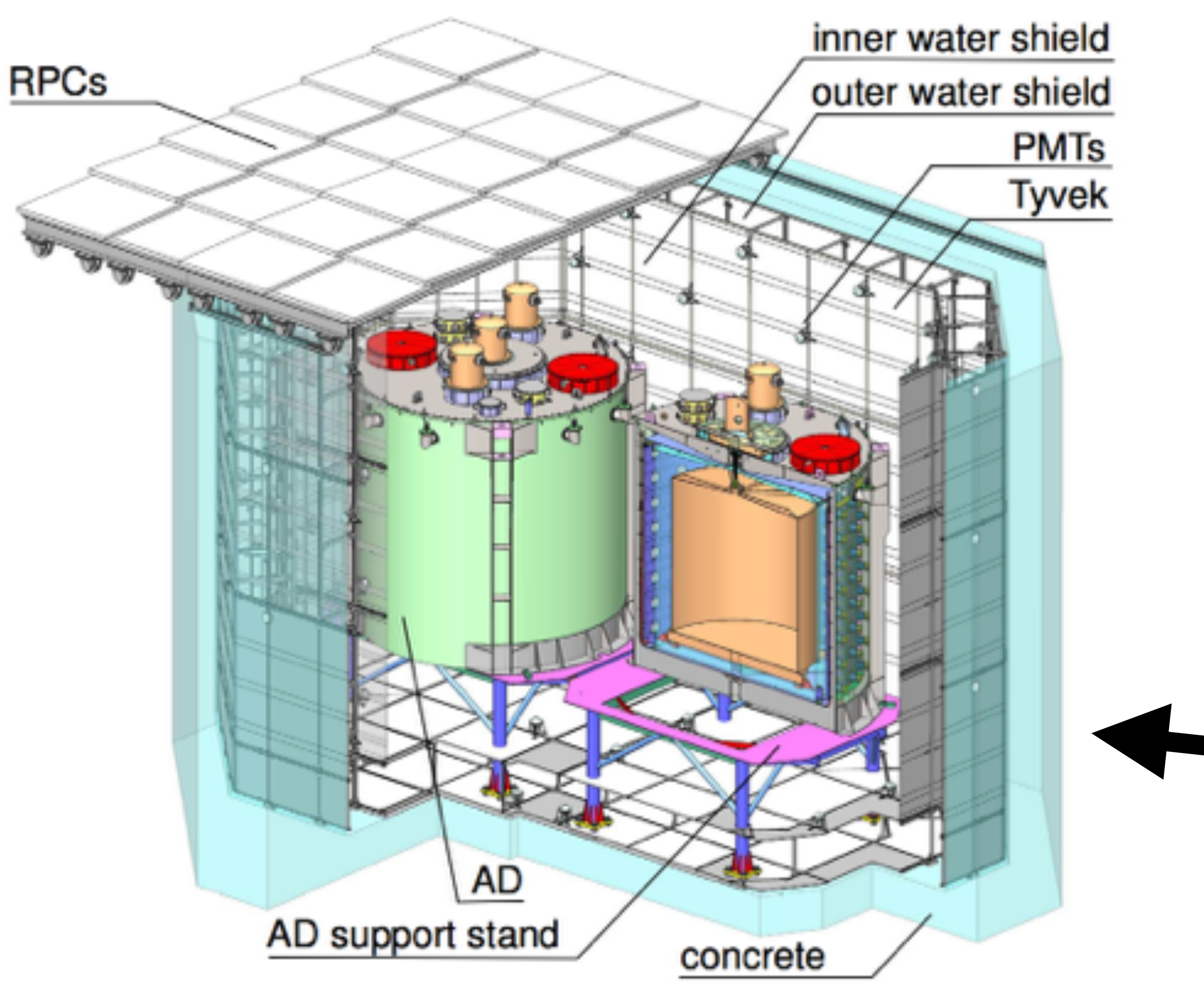
W. Zhong (Daya Bay) ICHEP 2014

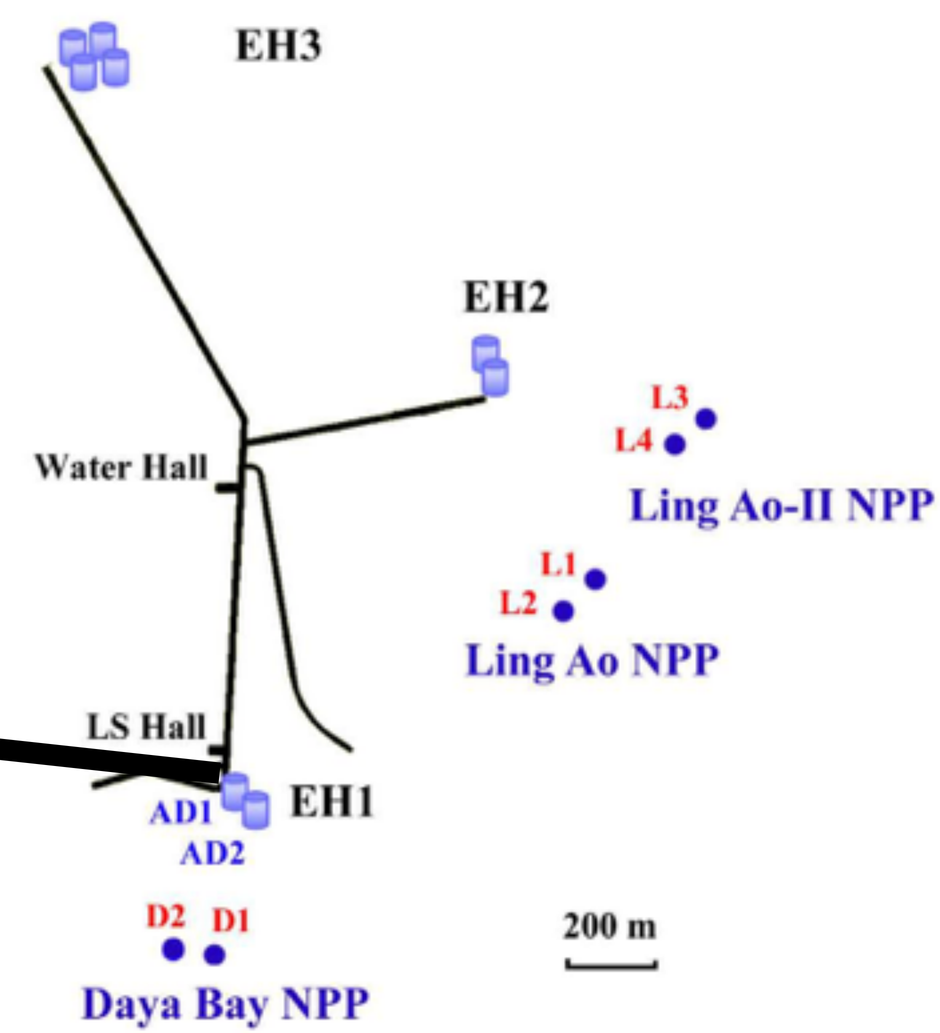


Recent Spectral Measurements

θ_{13} Experiments

- Large detectors: 10s-ton single-volume LS target
- Long baselines from conventional cores: 0.1 - 2.0 km
- 'Large' overburdens: 100+ MWE
- Qualities allow low-background, high-resolution measurements

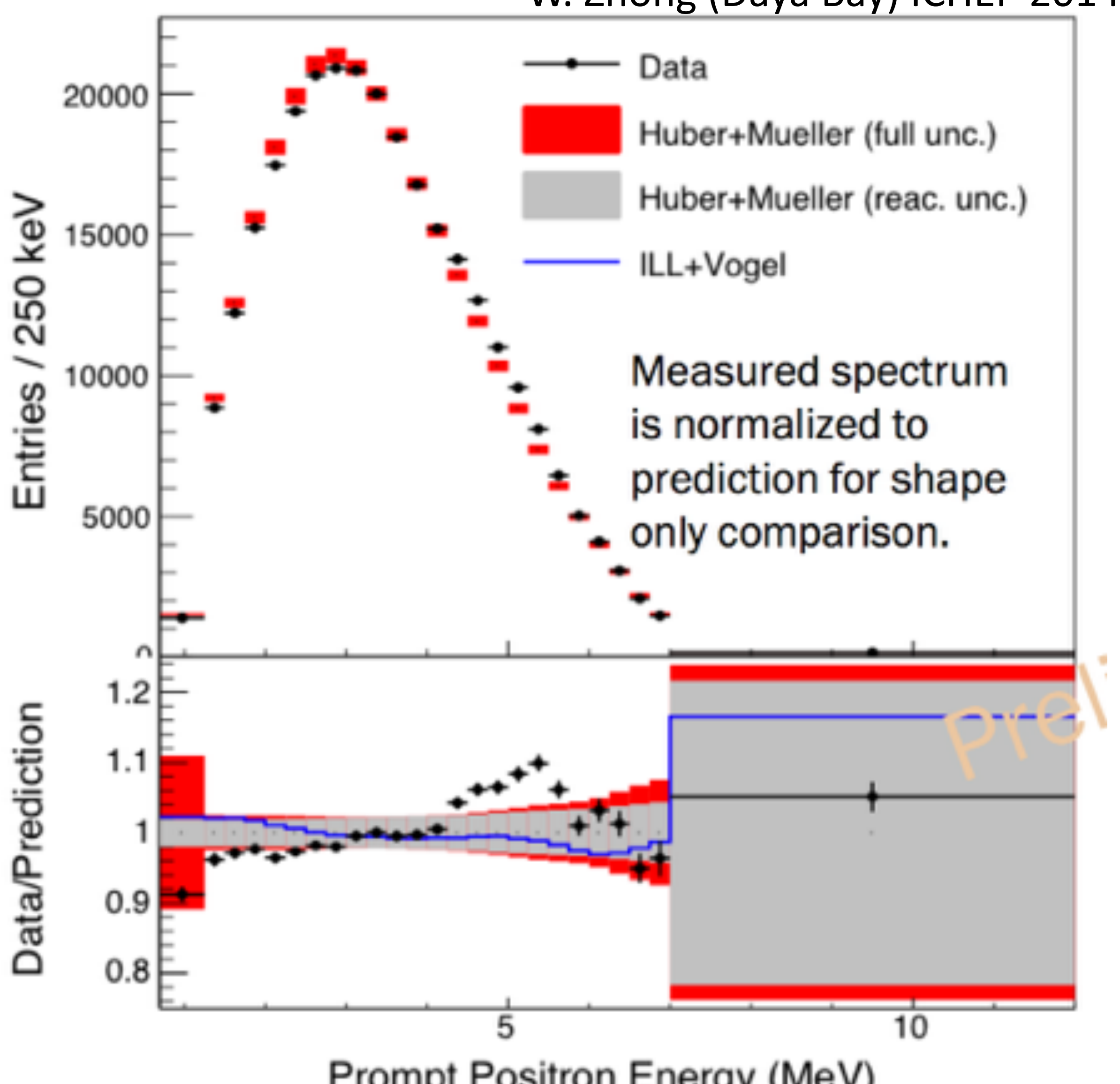




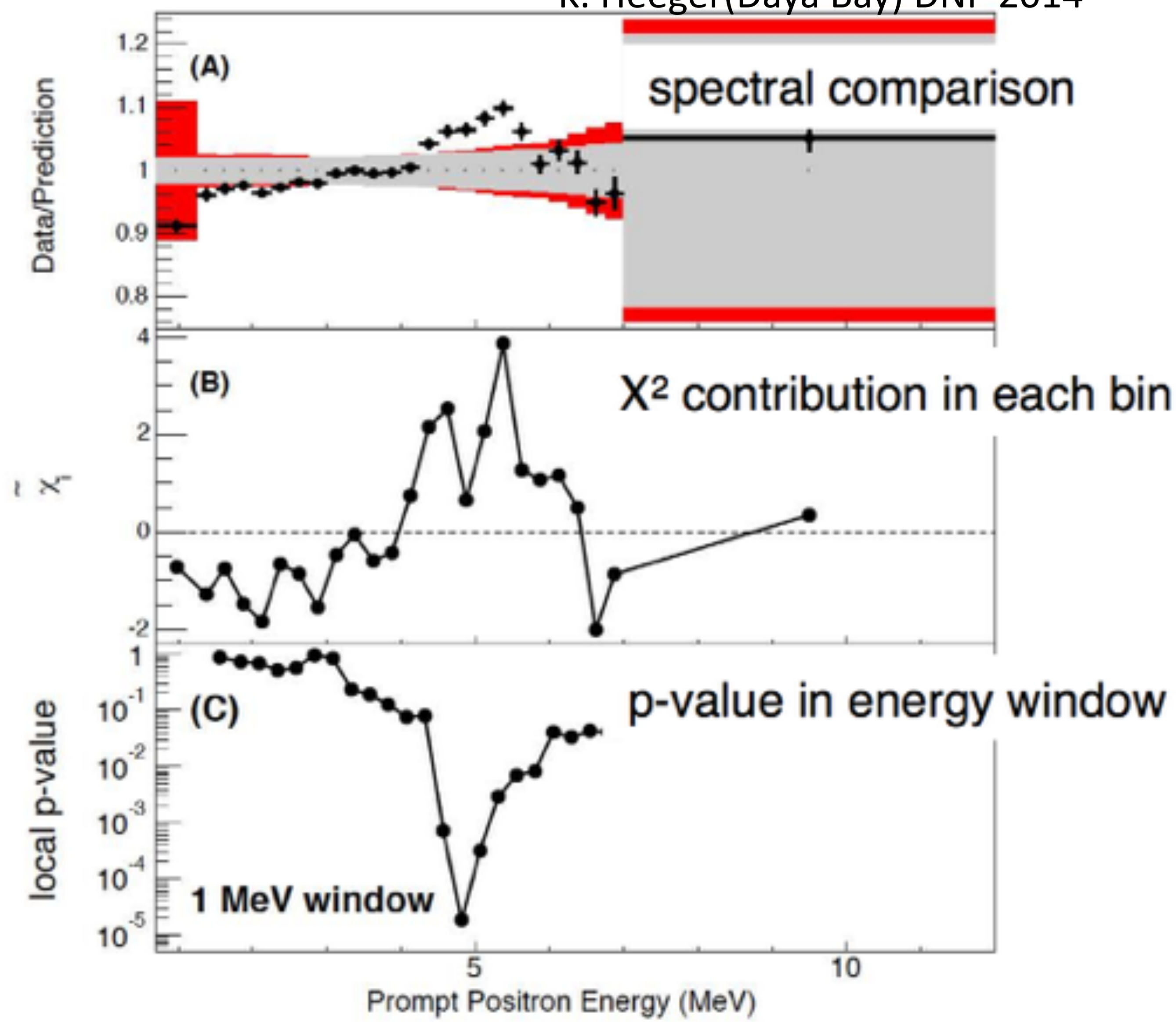
Daya Bay

- Spend a little more time on Daya Bay, since it's my specialty
  - >2σ deviation from Huber/Mueller(U238) over entire spectrum
  - Zoom in on particular region from 4-6 MeV: >4σ deviation from prediction
  - Hints at deviation in other regimes: perhaps not just a 'bump'
  - Also, don't forget the 5.3% flux deficit reported at Neutrino2014…

W. Zhong (Daya Bay) ICHEP 2014



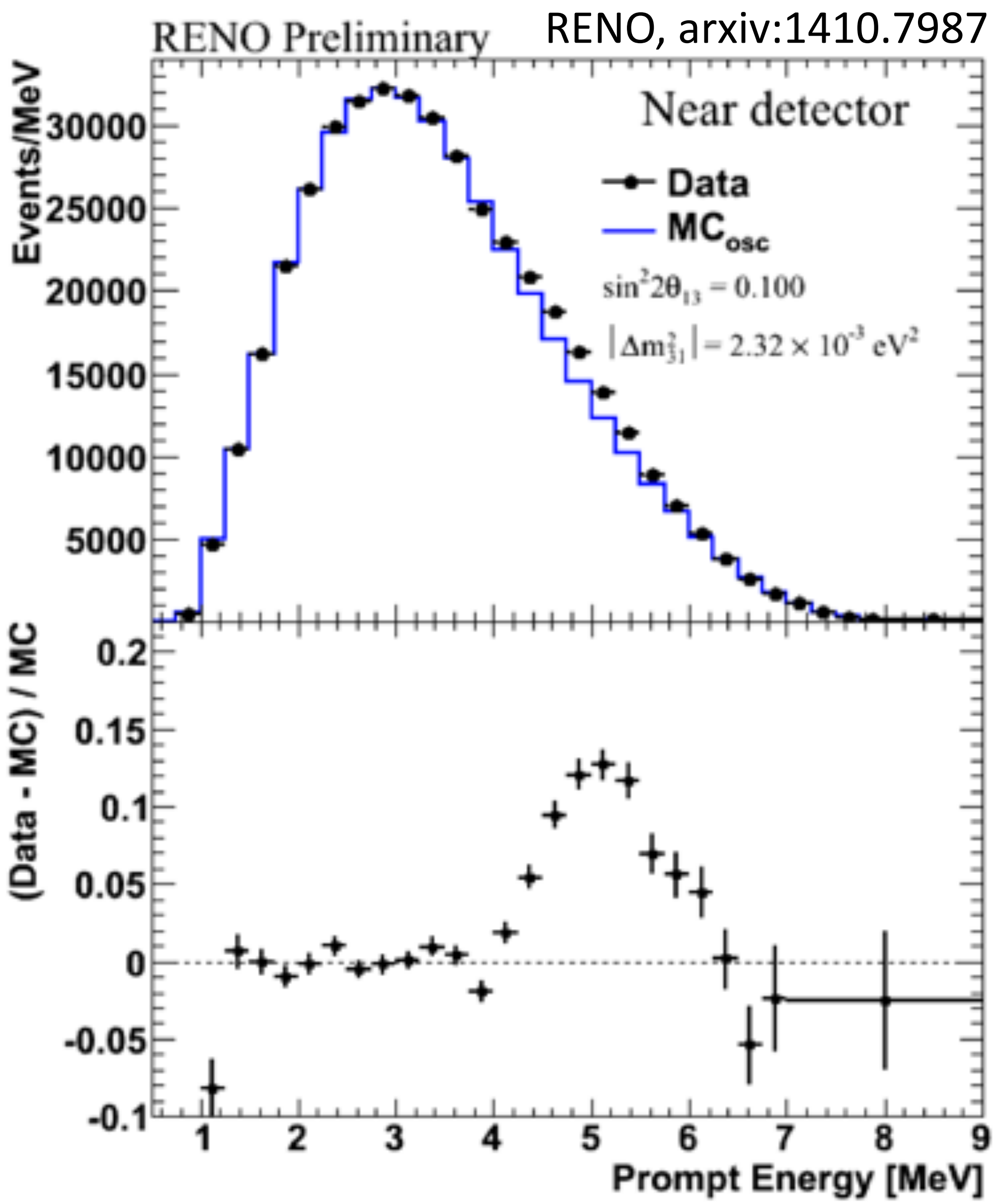
K. Heeger(Daya Bay) DNP 2014



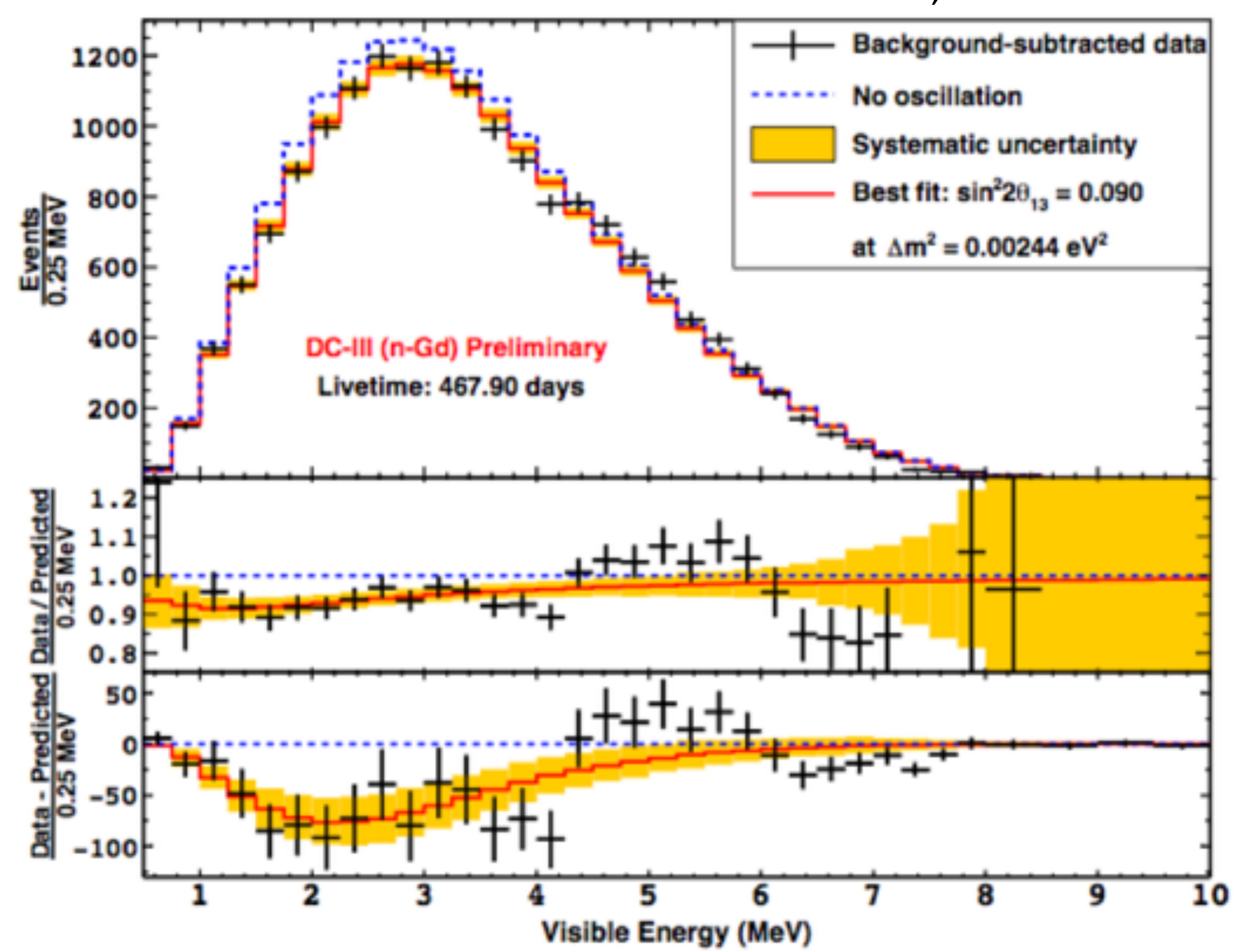
RENO and Double Chooz

- RENO: 3.5σ deviation from prediction in vicinity of 5MeV
- Double Chooz: 1.5σ deviation over full energy range
  - Coming: more stats of largely unoscillated neutrinos with new near detector
- Note that 'bump has negligible effect on θ_{13} rate+shape fits.

RENO, arxiv:1410.7987 (2014)



Double Chooz, Neutrino 2014



Skeptical Questions

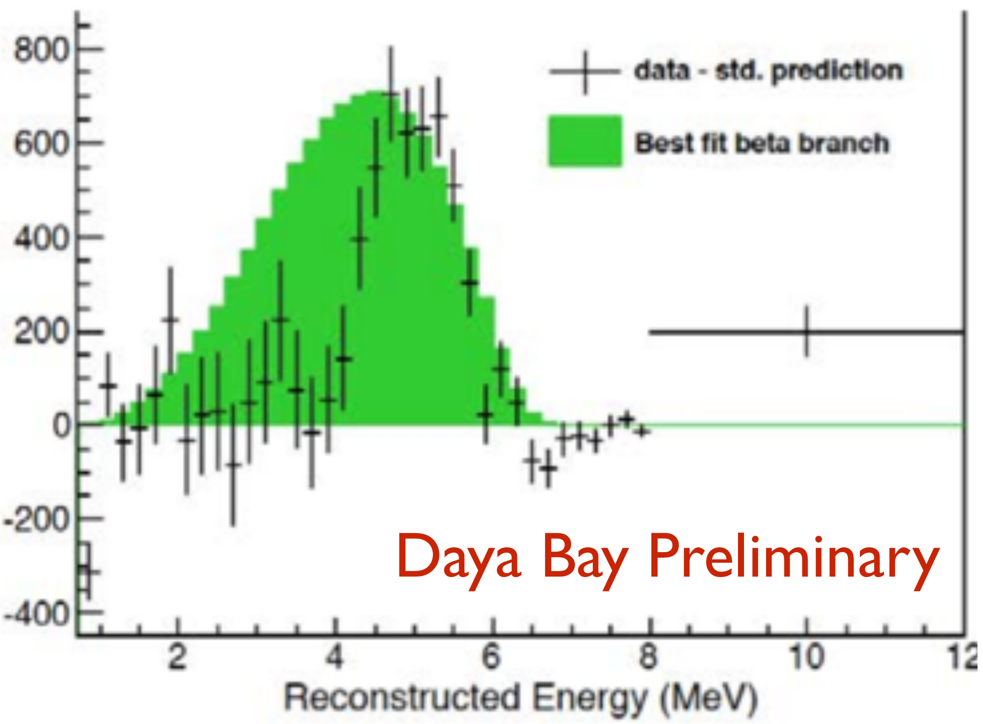
- These results indicate that measured nuebar spectra do not match predictions based on beta spectrum conversion
- Before we go there:
  - ‘Maybe it’s just a background that hasn’t been properly accounted for…’
  - ‘Maybe this is just an absolute energy scale issue’
  - ‘Is there any other strange behavior in the way this excess pops up in the data?’

???

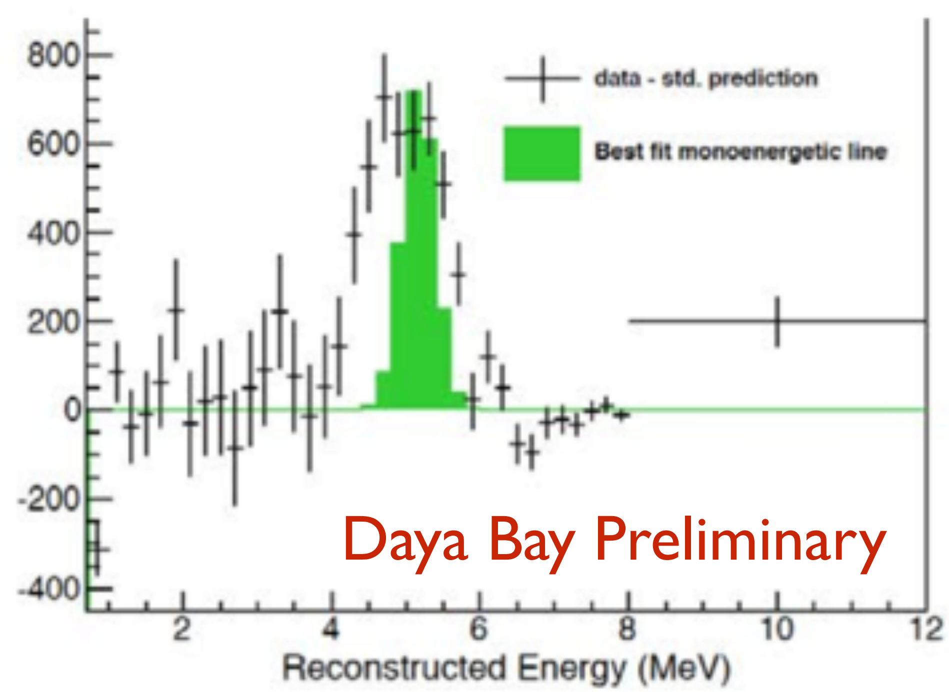
Skeptical Question 1

- 'Maybe it's just a background that hasn't been accounted for.'

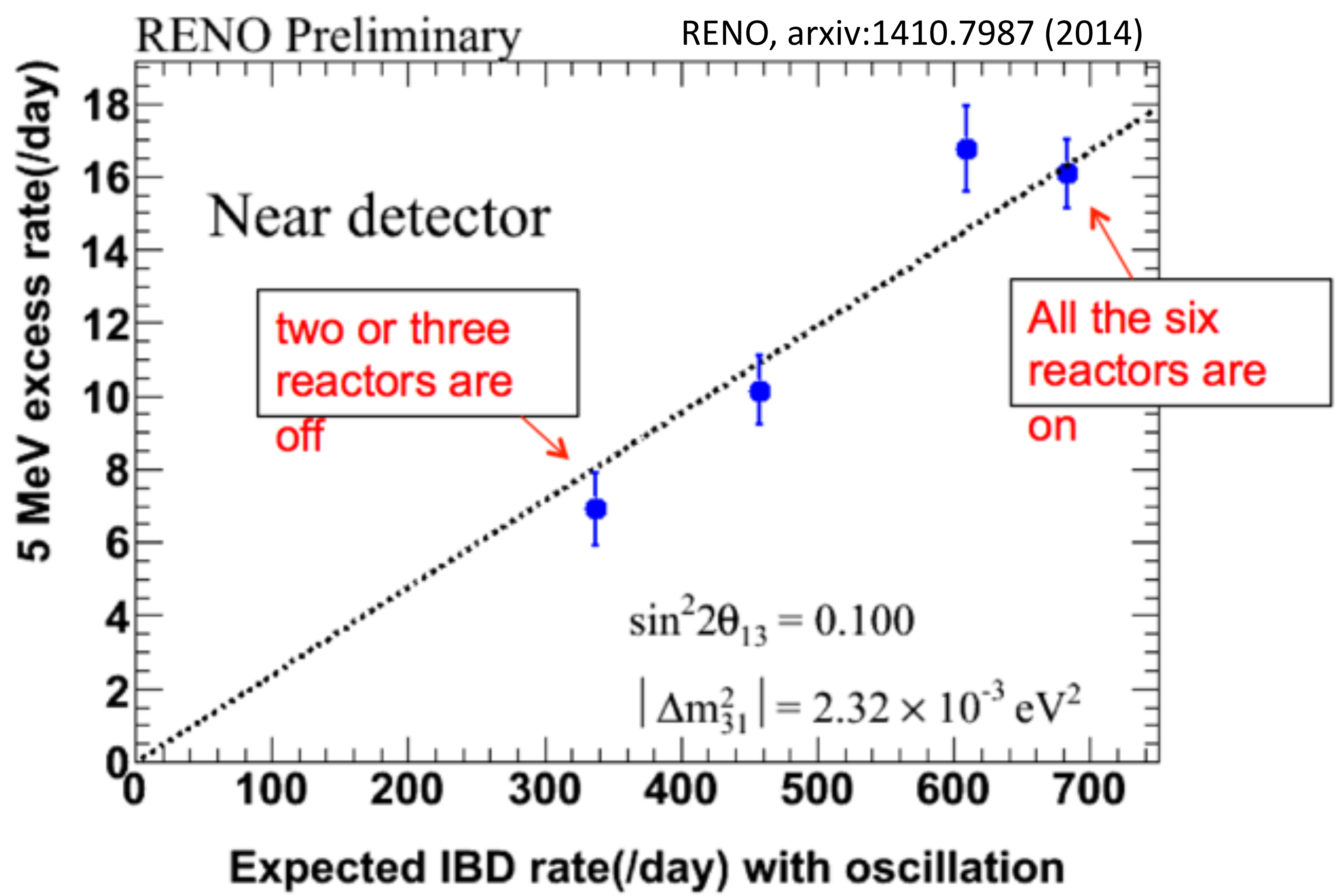
Not a beta-branch



Not a delta function



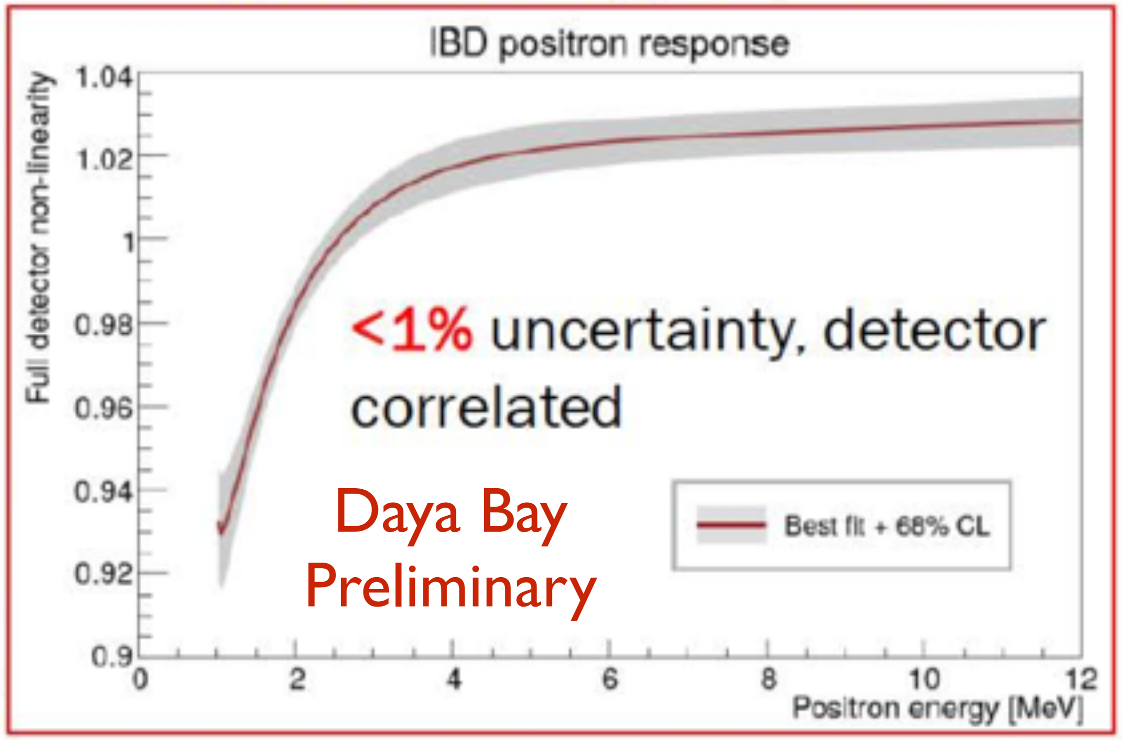
RENO, arxiv:1410.7987 (2014)



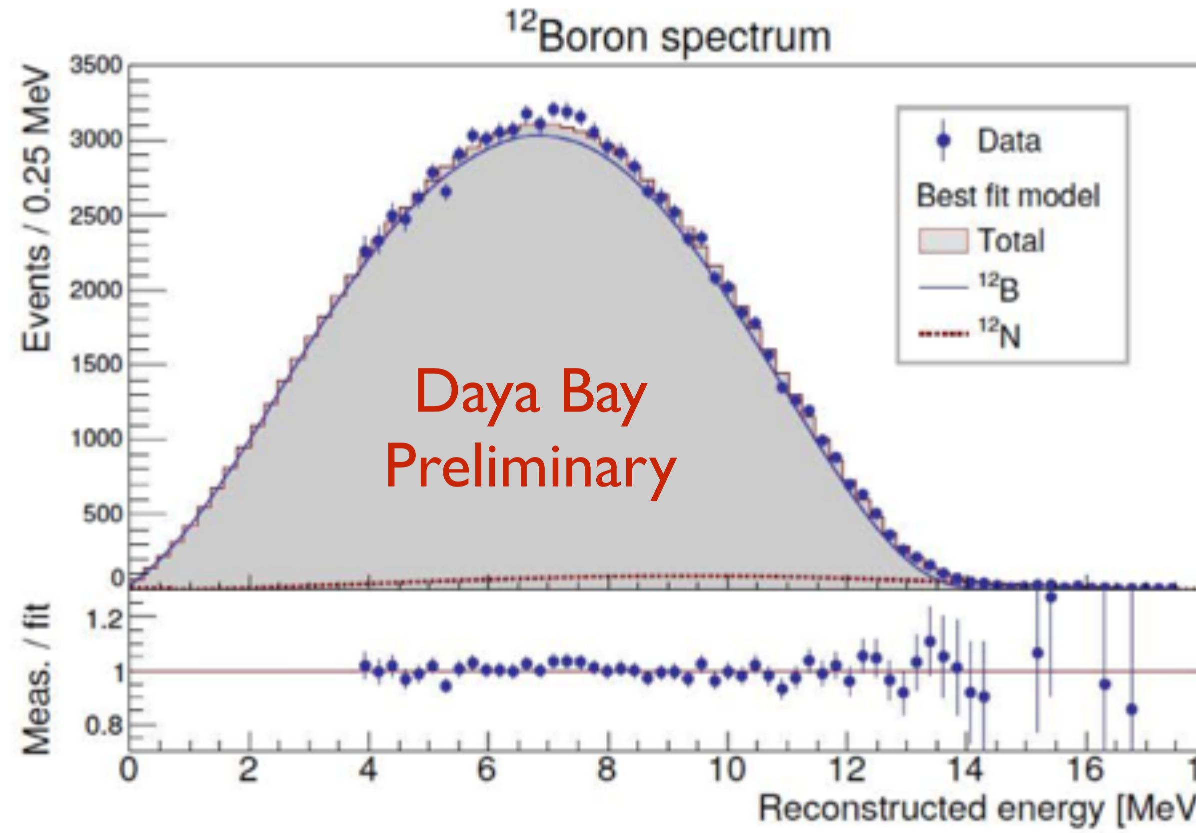
5 MeV excess scales with reactor power

Skeptical Question 2

- 'Maybe this is just an absolute energy scale issue'

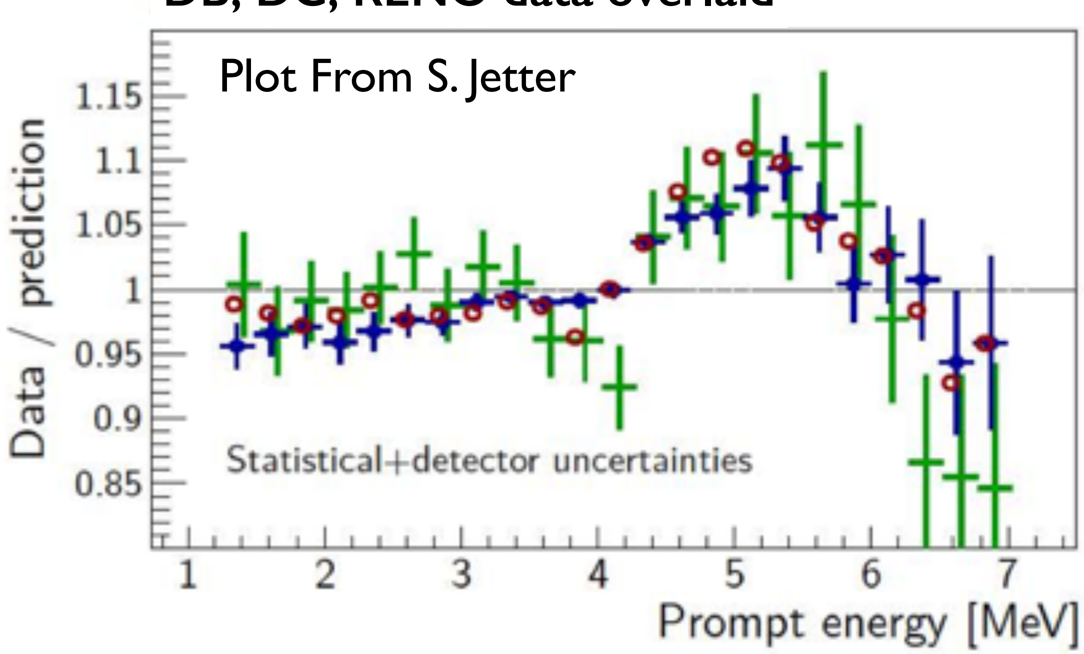


E-scale non-linearity is smooth, especially at high energy!



No bump or other strange behavior in B-12 spectrum WRT prediction

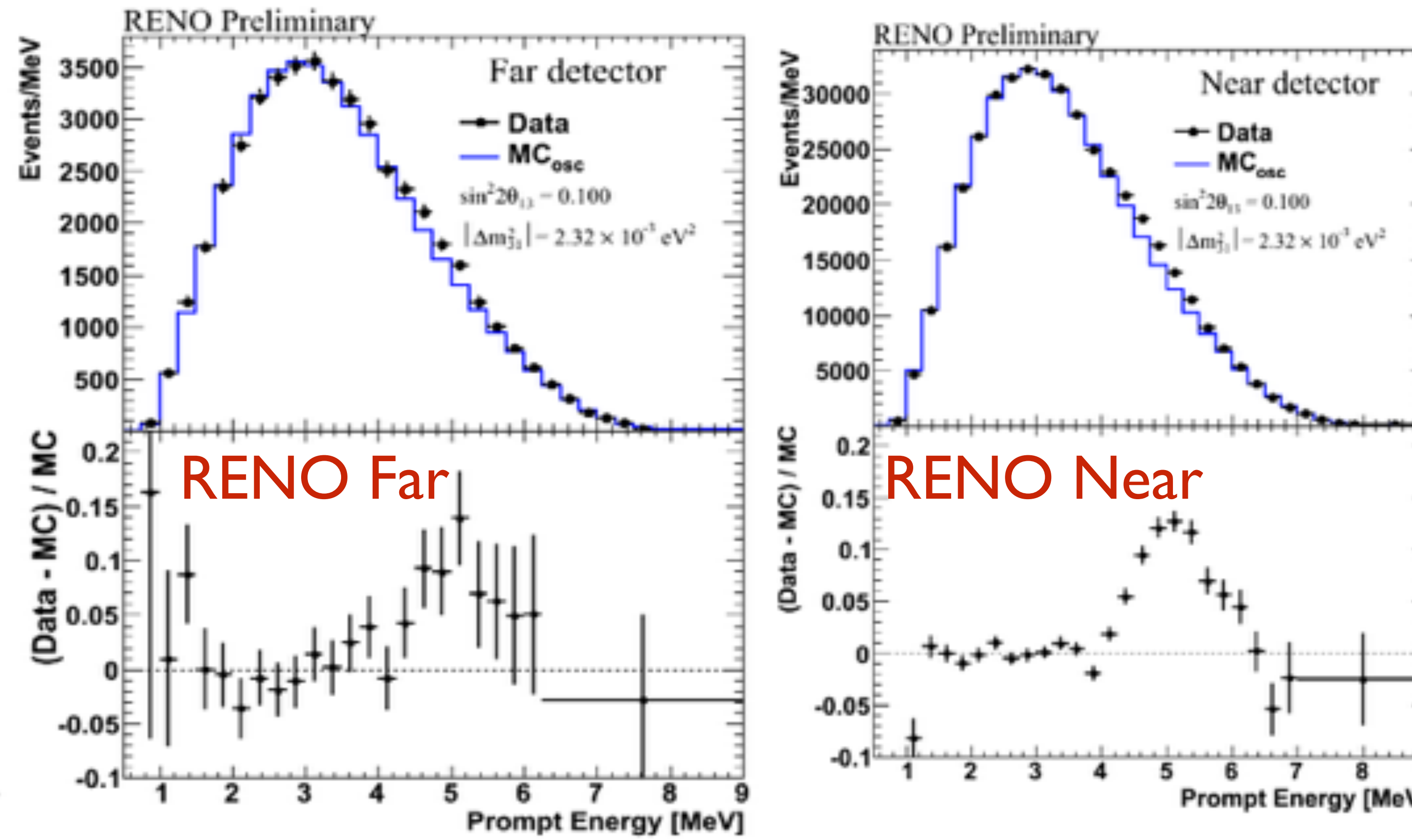
DB, DC, RENO data overlaid



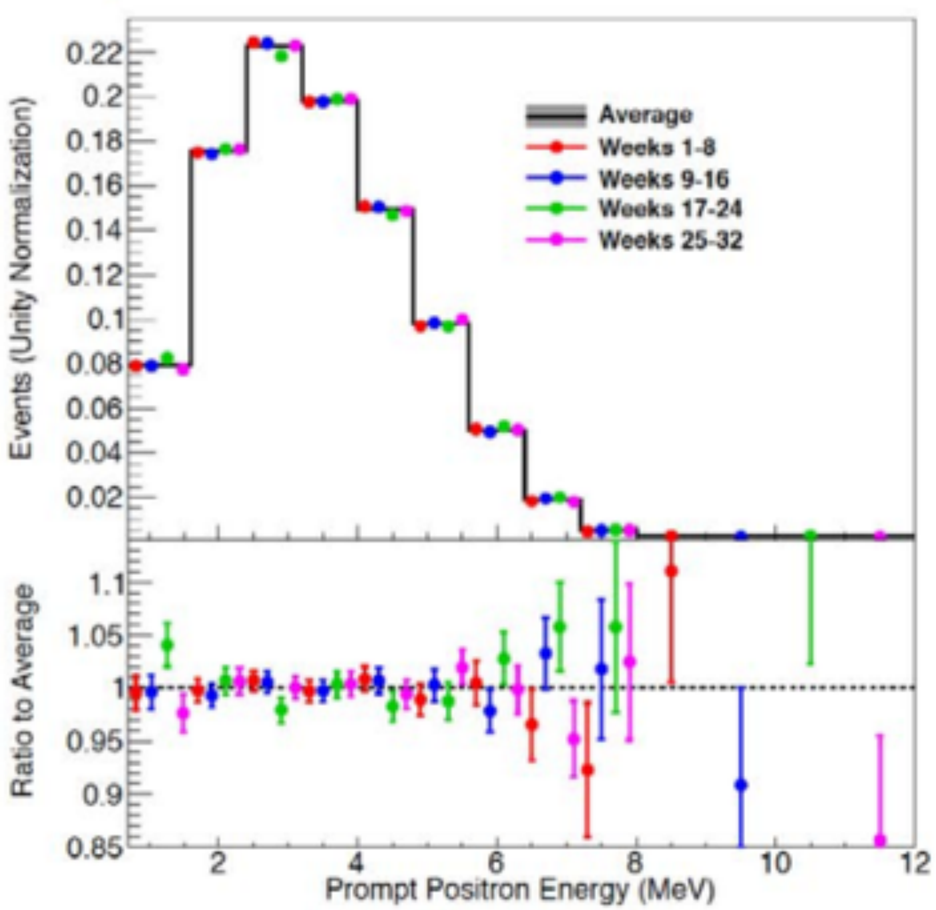
Experiments' electronics (and attendant non-linearities) differ greatly, but all see the same structure.

Skeptical Question 3

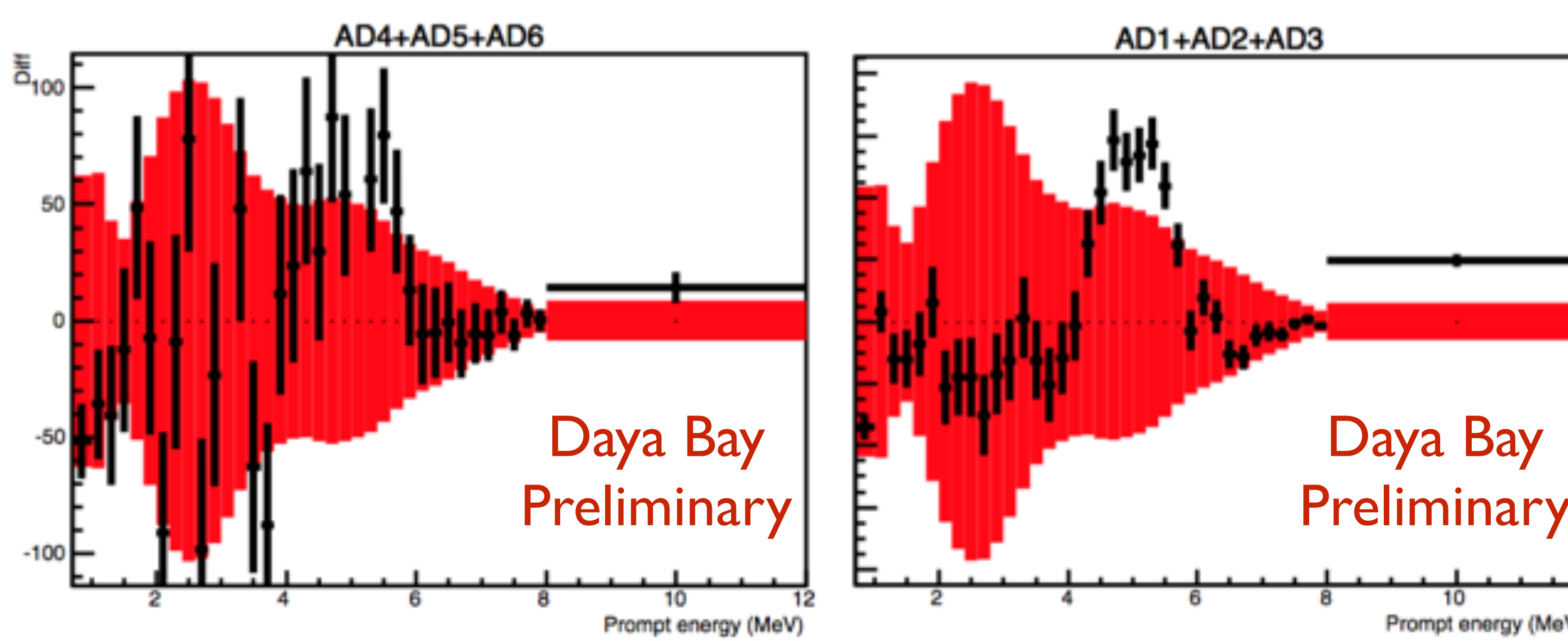
- 'Is there any other strange behavior in the way this excess pops up in the data?'



No time-dependent spectral changes observed

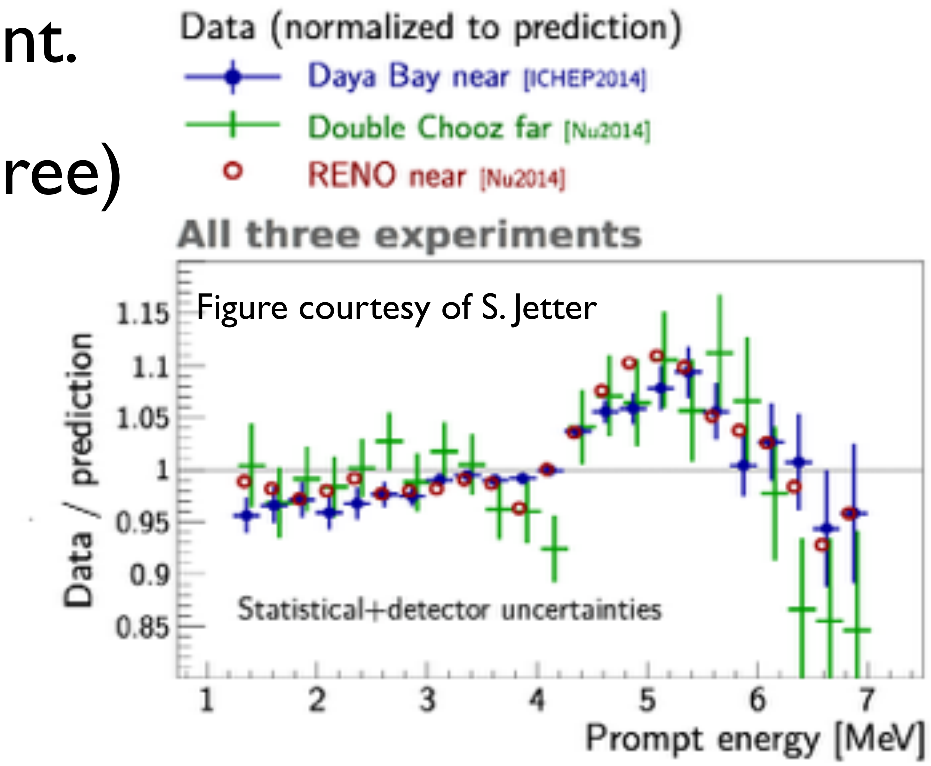


Detectors see the same general feature



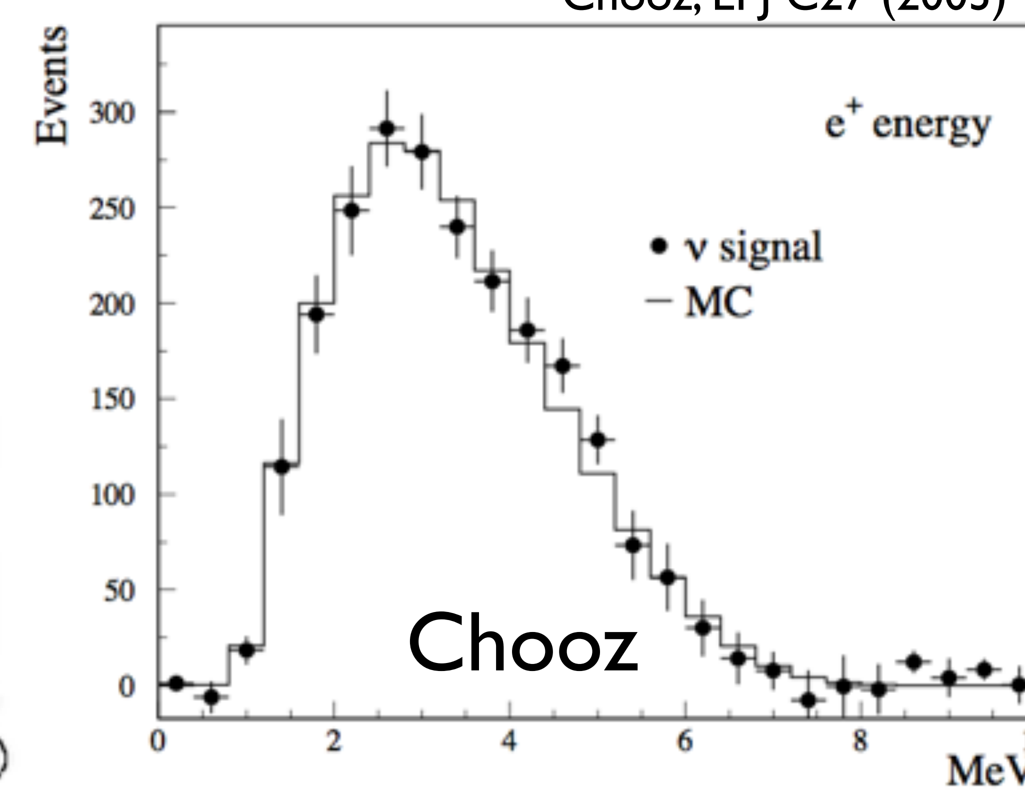
Piling On

- **Re-emphasize — All three experiments see the same thing!!!**
  - Not just one faulty experiment — broad agreement.
  - Different electronics and scintillator (to some degree)
  - Overburdens, backgrounds vary widely between experiments

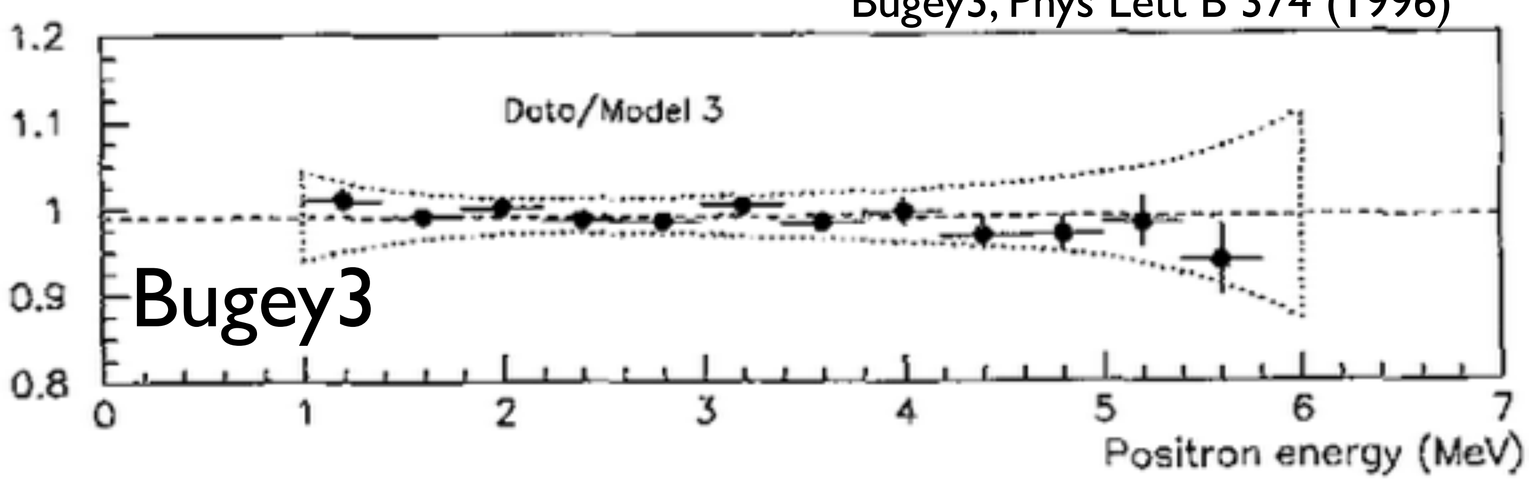


- **Other notable results:**
  - CHOOZ: A hint present, low CL
  - Bugey3: Seems like no feature is present?
    - Large non-scintillating volume in target? Binning?
    - Something else?

Chooz, EPJ C27 (2003)



Bugey3, Phys Lett B 374 (1996)



Discussion and Implications

Discussion

- Visible discrepancy between measured and predicted fluxes
- Root cause could be systematics in θ_{13} experiments, but good evidence exists to doubt this
- Could predictions be the root cause? How exactly?
- What else can we do to clarify the picture?
- How does this relate to non-proliferation? Applications?

Forbidden Decay Handling in Conversion

- Conversions make simple assumptions about forbidden-ness of involved beta branches

$$N_\beta(W) = K\; \underbrace{p^2(W - W_0)^2}_{\text{phase space}}\; F(Z, W)$$

From nuclear matrix element: Extra factors of p,E pop for forbidden decays ($\to K$)

Fermi correction: Nucleus-beta Coulomb interaction ($\to F(Z, W)$)

- **Hayes, et. al, PRL 112 (2014): conversion result highly dependent on forbidden-ness of virtual branches**
  - Capable of shifting predicted flux downward by 5%
  - Has not been shown what forbidden decay treatment would reproduce both reactor beta and nuebar spectra — but it might be possible to do so

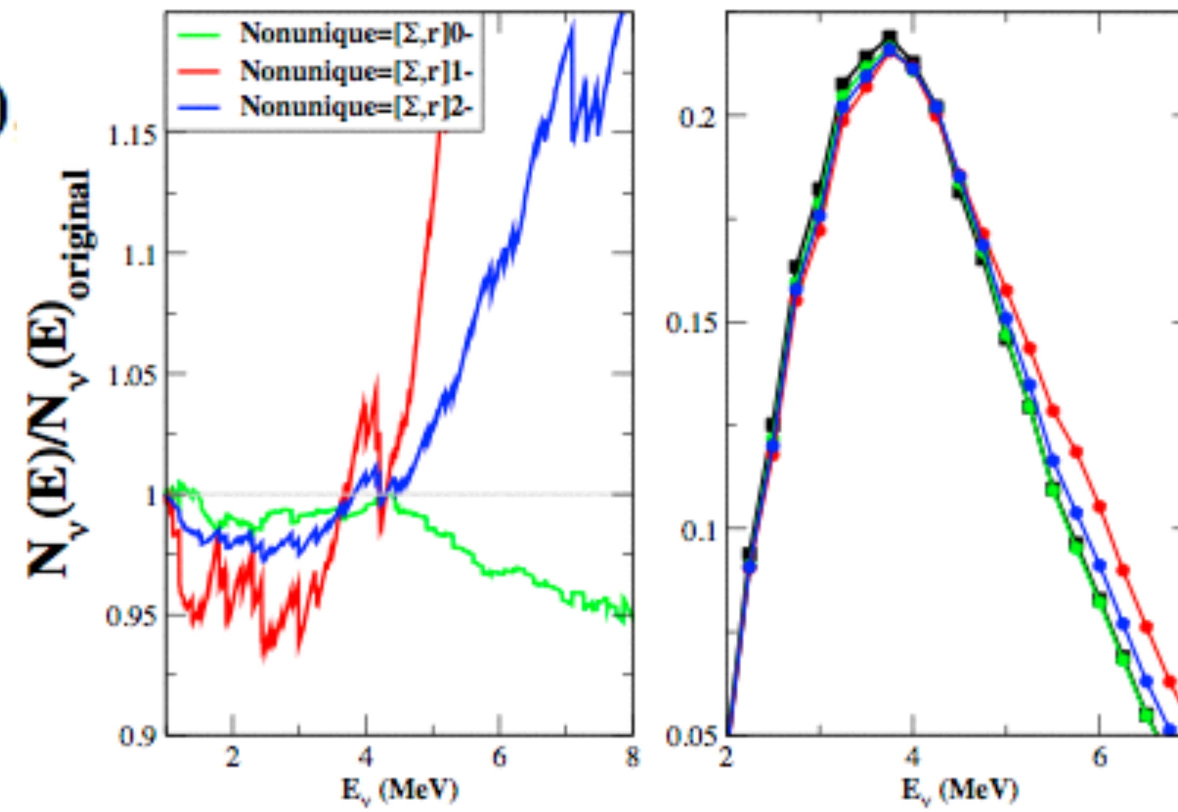


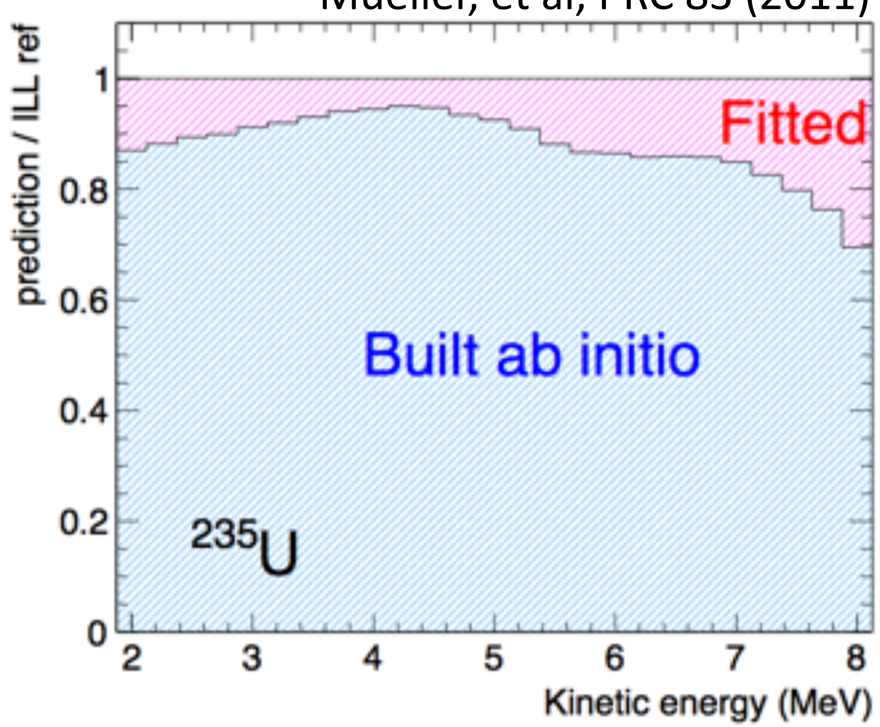
FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the 0^-, 1^-, and 2^- forbidden operators, respectively.

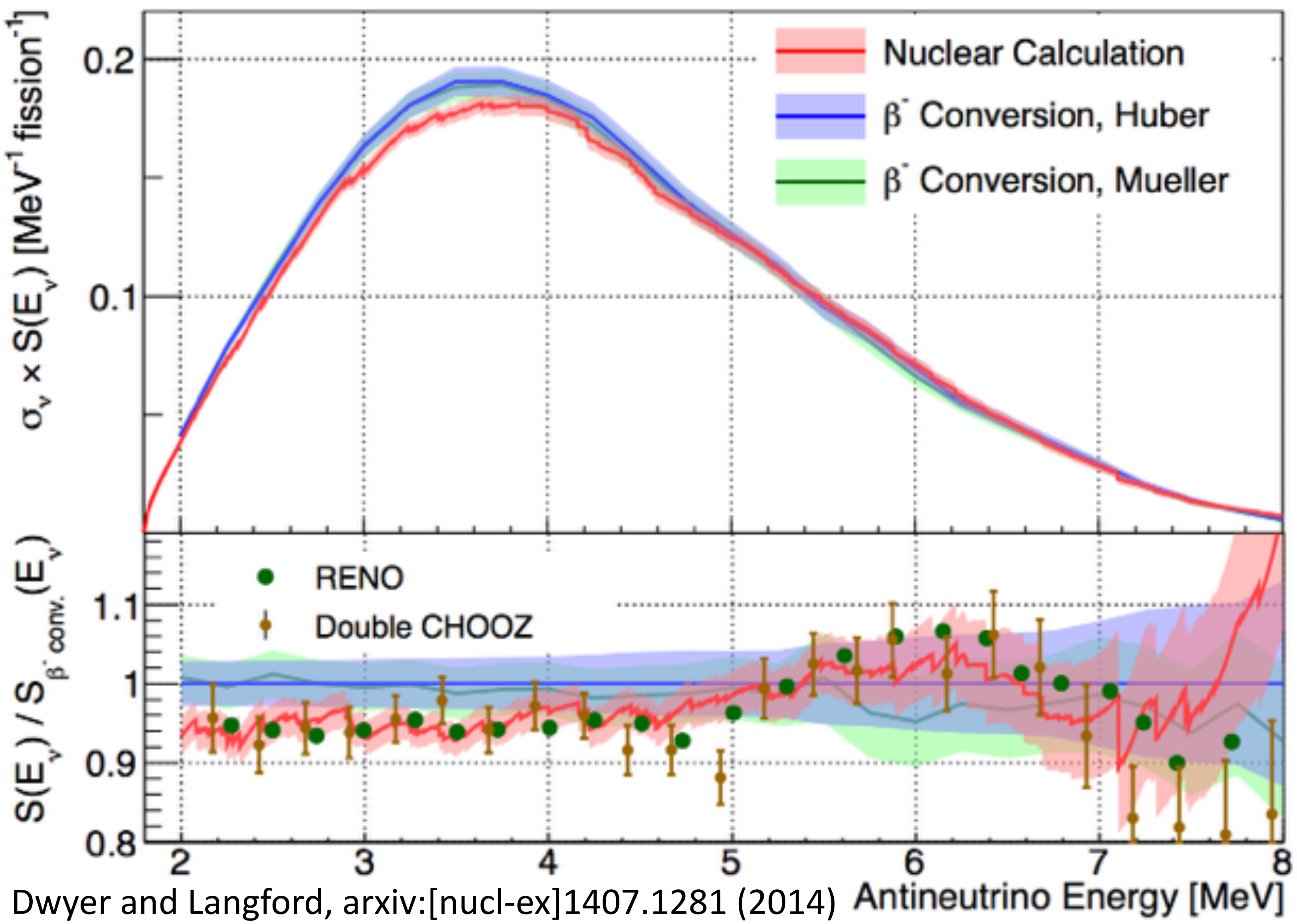
Recent Ab Initio Predictions

- What if we just compare measured shape directly to *ab initio*?
  - Much better agreement in spectrum
  - Not so much on the overall flux…
  - Some spectral features also present in *ab initio* calculations from Mueller, *et al.*

- Dwyer/Langford: Maybe it's some inherent problem in the beta spectrum measurement?

Mueller, et al, PRC 83 (2011)





Dwyer and Langford, arxiv:[nucl-ex]1407.1281 (2014)

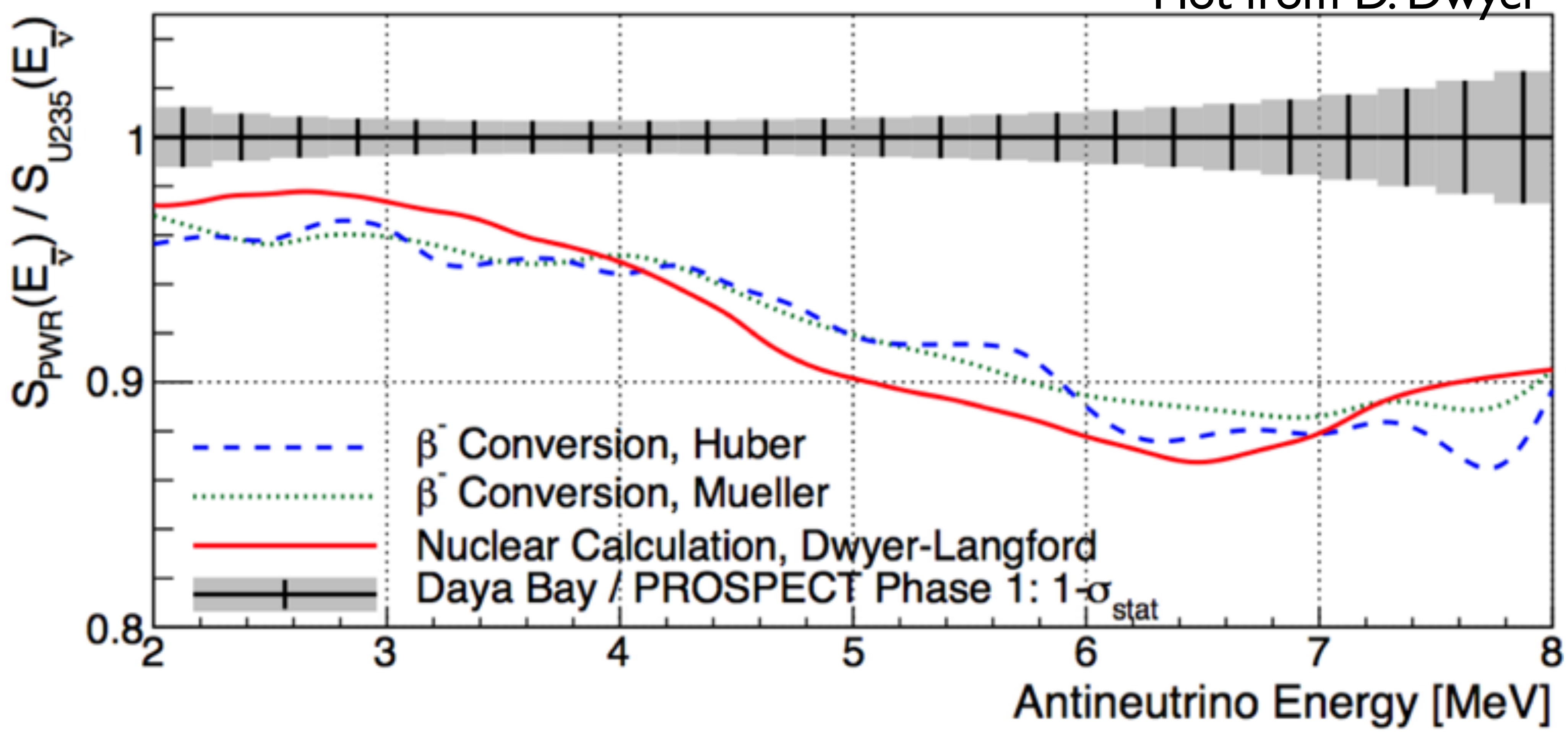
New Data, New Constraints

- Q: How do we clarify this picture?
  - A: Make new measurements, get more handles!
- Upcoming short-baseline experiments have opportunity to measure absolute spectrum while searching for oscillations
  - High statistics: certainly on par with θ_{13} measurements
  - Better resolution = better discrimination power between models
  - HEU spectrum measurement = additional handle to test models
- Further clarity can be valuable to neutrino, nuclear, non-proliferation, and applications communities

Implications for Non-Proliferation

- **What is spectral shape difference between U-235 and Pu-239?**
  - Huber, Mueller predict spectral difference, but don't predict the right spectrum
  - *Ab initio* calculations also suggest a spectral difference, but not identically
- Without this knowledge, more uncertainty in modelling/ demonstrating Pu239 production monitoring with antineutrinos
  - Measuring this difference directly could resolve this uncertainty, provide fodder for model-fitting

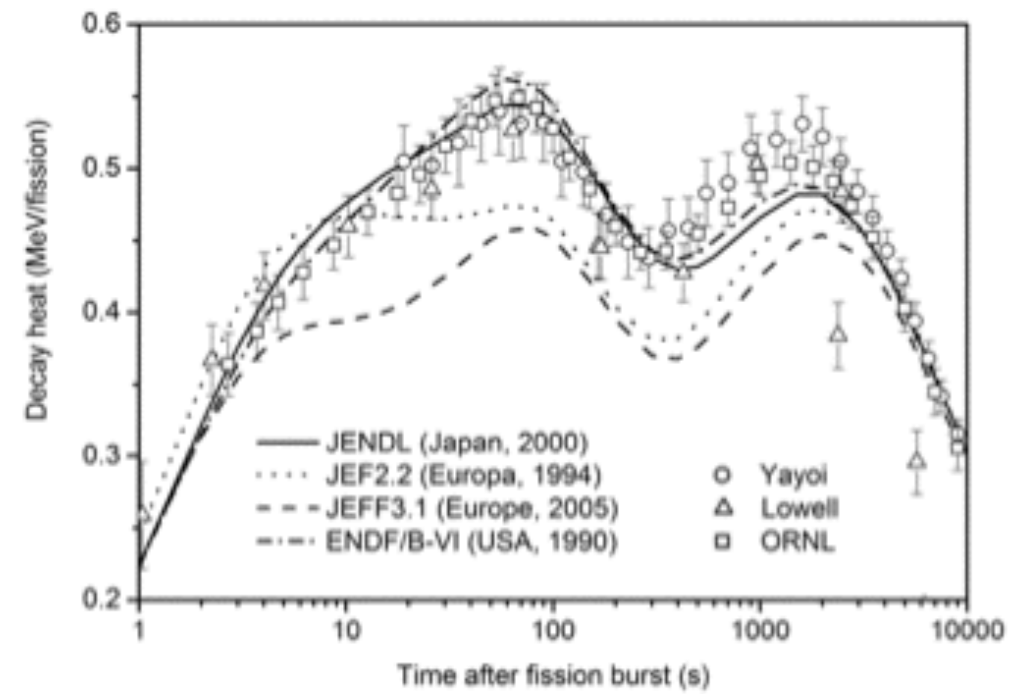
Plot from D. Dwyer

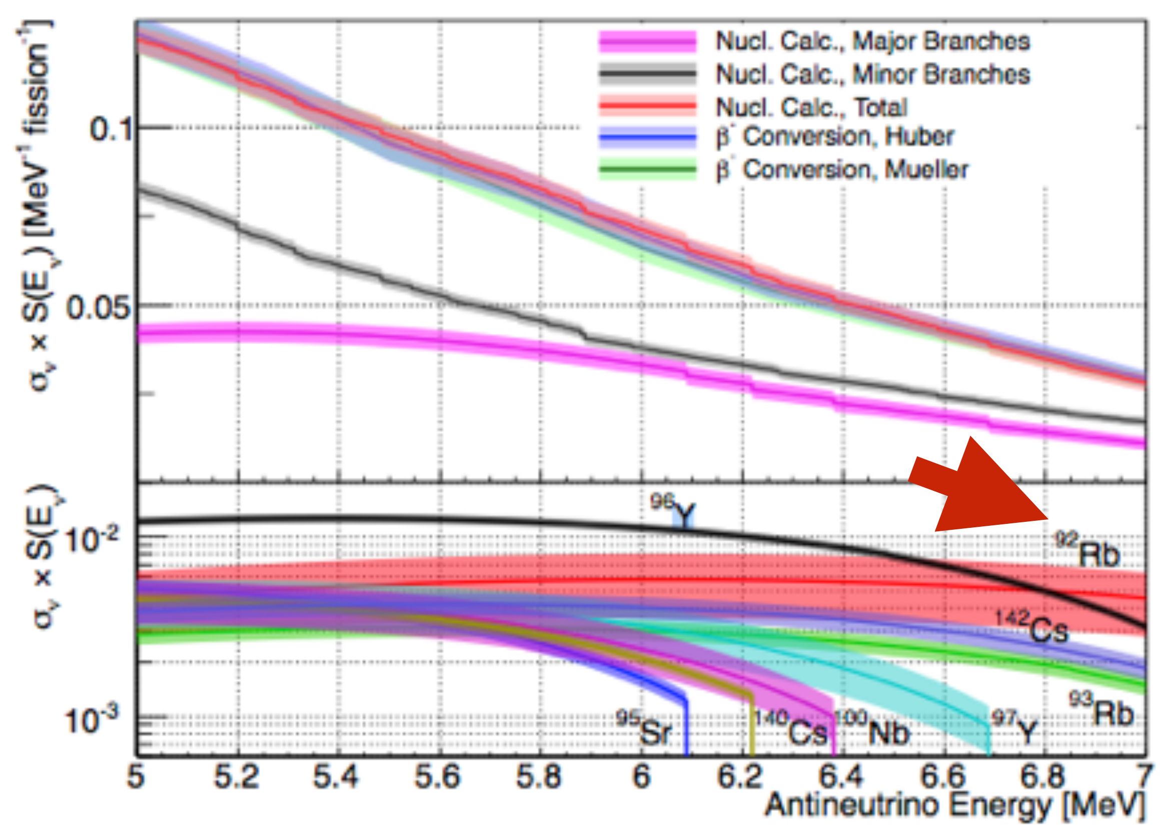


Implications for Nuclear Applications

- Why is there more decay heat than predicted 3-3000s after a reactor is turned off???
- Means we need higher cooling safety factors during reactor-off periods: this costs $$$!!!
- 5 MeV nuebar 'bump' produced by many isotopes of great concern to this decay heat measurement
- High-res measurement may constrain individual isotopes
  - Direct check on concerning ENSDF nuclear data
    - TOTALLY different systematics!
  - Isotopes: Rb-92, Sr-97, Cs-142

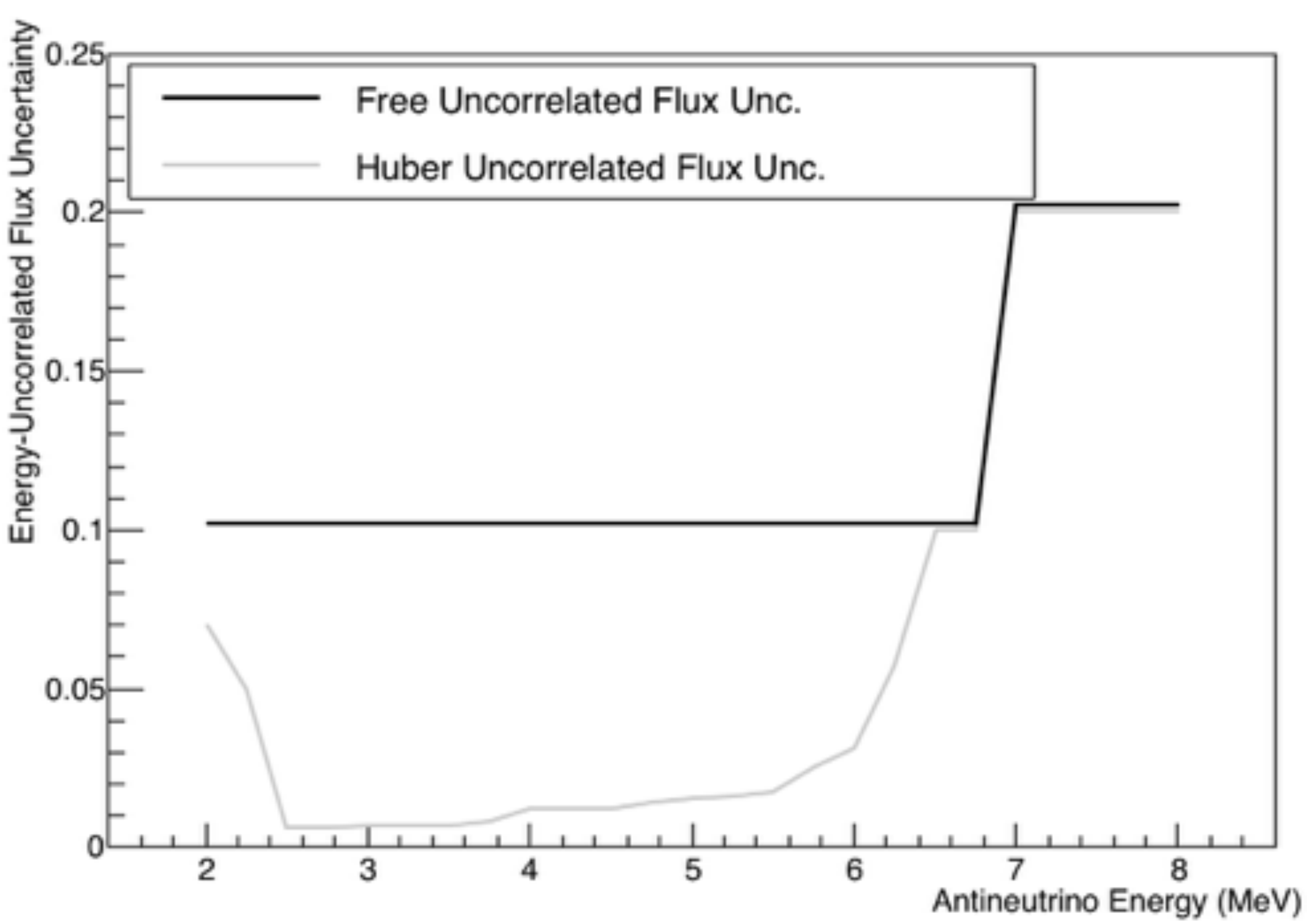
Figure 3. Electromagnetic decay heat following thermal fission burst of ^{239}Pu – data from JENDL, JEF-2.2, JEFF-3.1 and ENDF/B-VI are shown together with experimental data from Yayoi, Lowell and Oak Ridge National Laboratory

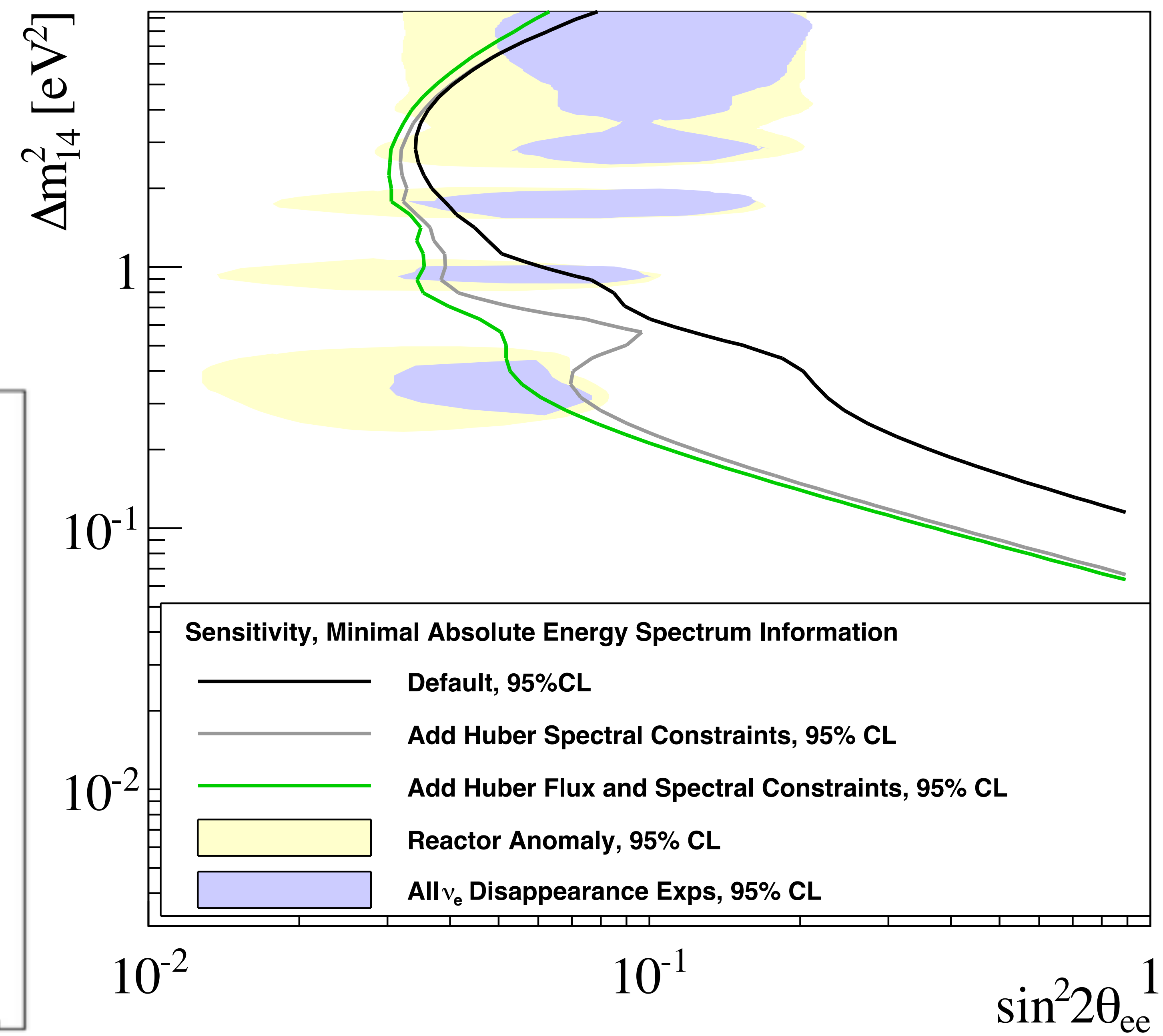




Implications for Oscillation Physics

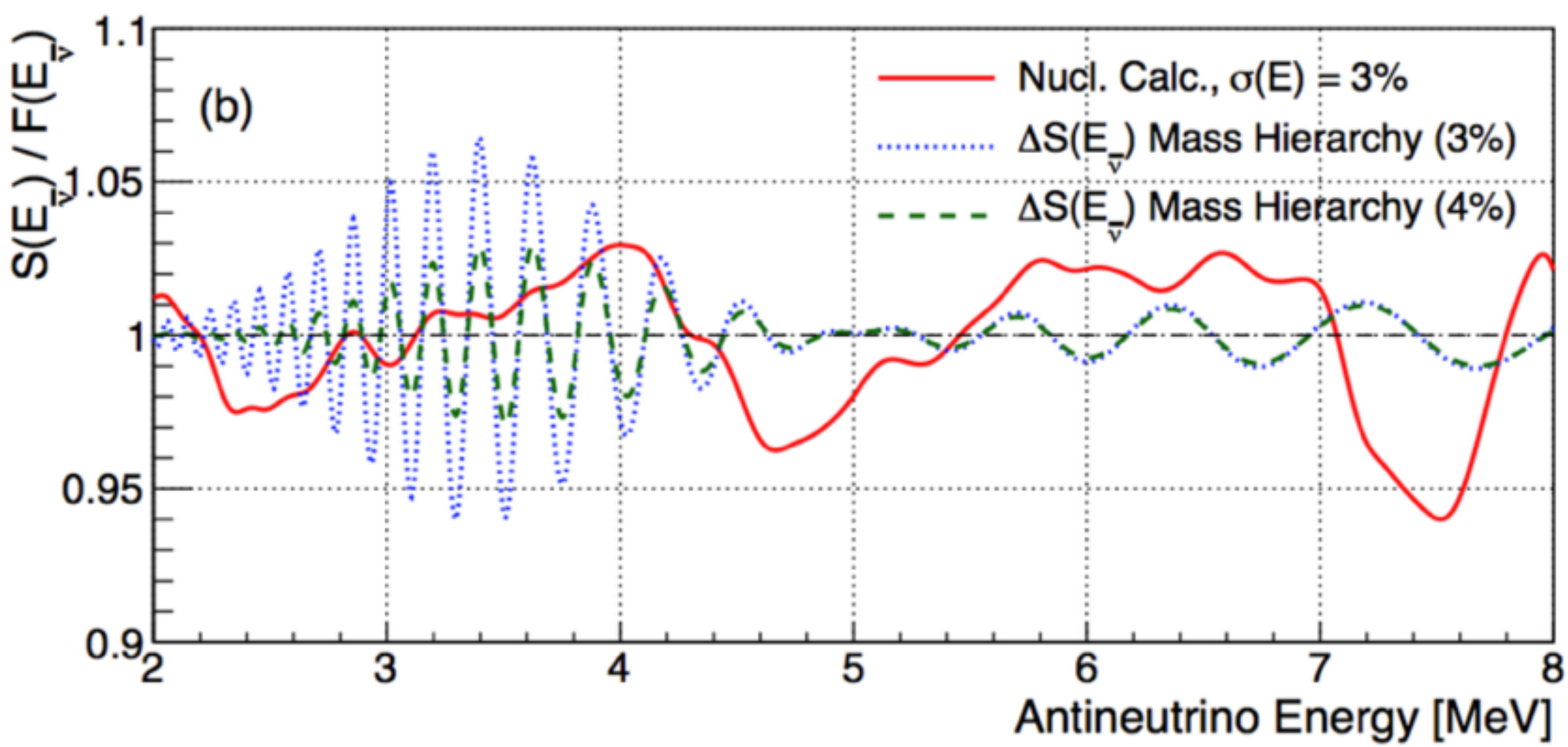
- Pointed out yesterday: can we really use existing flux uncertainty estimates in our SBL sterile searches?
  - θ_{13} experiments appear to show these error bands are too small
  - Increasing error bars means relying on only purely relative information between different detector baselines.
  - SBL sensitivities should take this into account!





Implications for Oscillation Physics

- Will fine structure affect measurement of mass hierarchy?
  - Magnitude of spectral features in flux comparable to that of mass hierarchy
  - However, hierarchy gives very distinct energy-dependent signature
- Knowledge of underlying structure will improve confidence in a hierarchy-related spectral distortion measurement



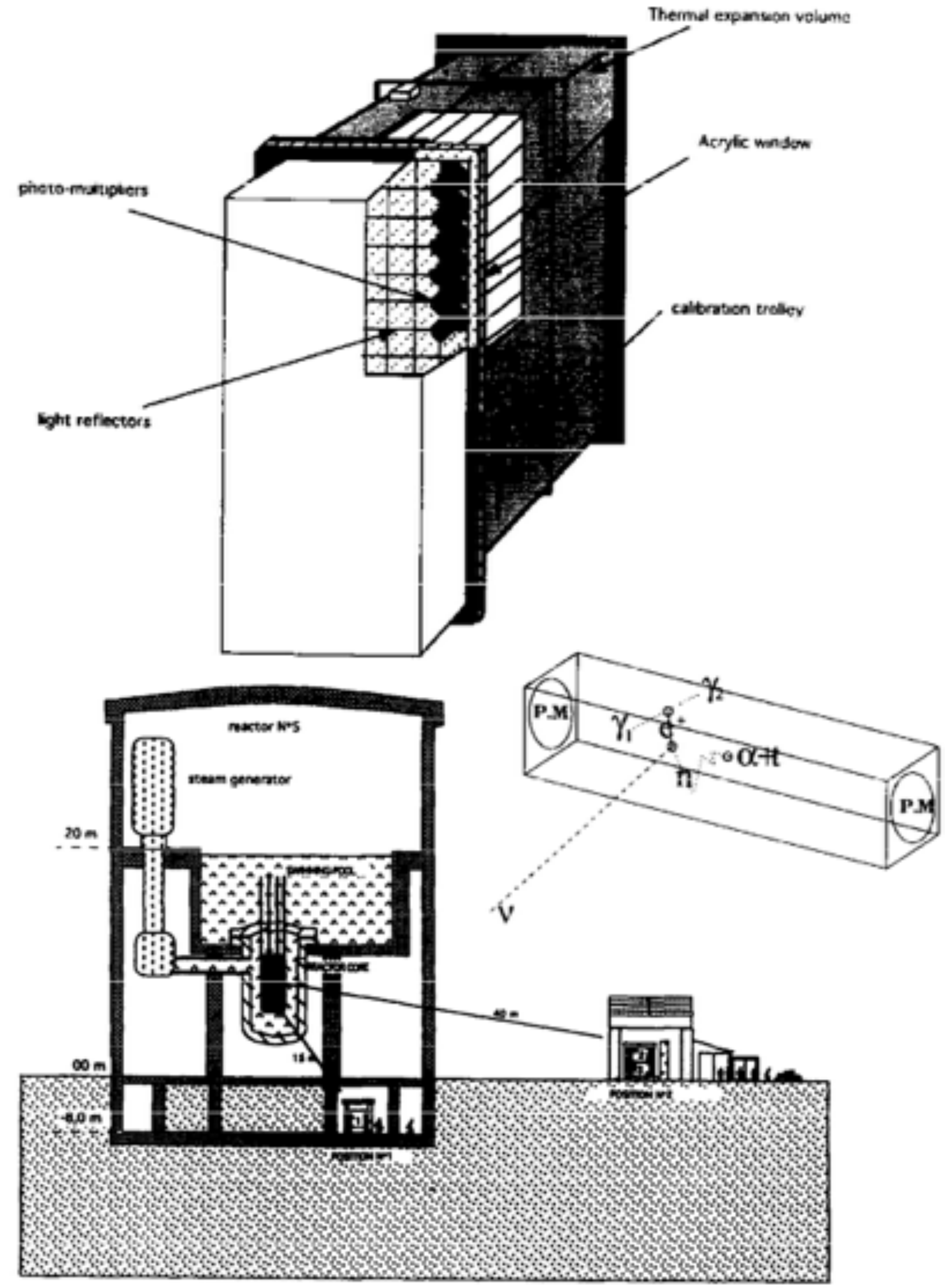
Summary

- State-of-the-art reactor spectrum predictions are not matched by recent direct nuebar spectrum measurements
- These are the same predictions used to:
  - Produce reactor flux estimates for the 'reactor antineutrino anomaly'
  - Benchmark neutrino oscillation results
  - Demonstrate Pu-239 production monitoring using antineutrinos
- New high-resolution measurements of HEU and LEU fuel will be essential to clarifying this picture

END

Historical Context

- A similar experimental setup in the past: Bugey-3
  - Segmented short-baseline LiLS detector
- PROSPECT Pros:
  - Smaller reactor core, closer to core: better for SBL oscillation search
  - Stable scintillator: Bugey's degraded after a few months in near detector!
  - Smaller target dead volume: ~2% versus >15% for Bugey
  - Aim for better light yield, PSD
- PROSPECT Con: No Overburden
  - 14+ mwe (Bugey-3), <10 mwe (PROSPECT)
  - Bugey had 25:1 S:B



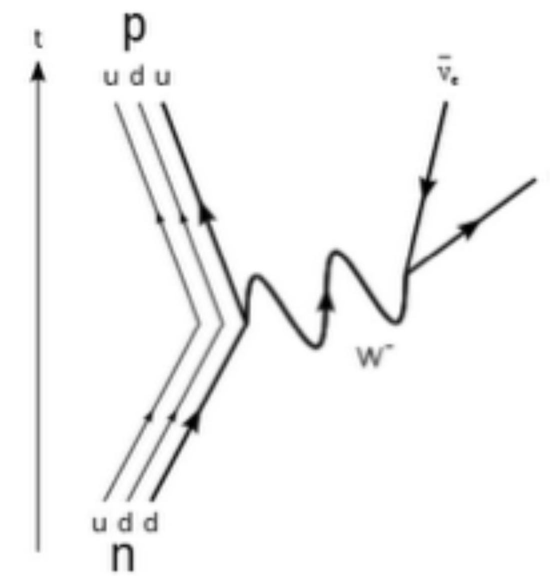
Beta Decay Recap

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate:

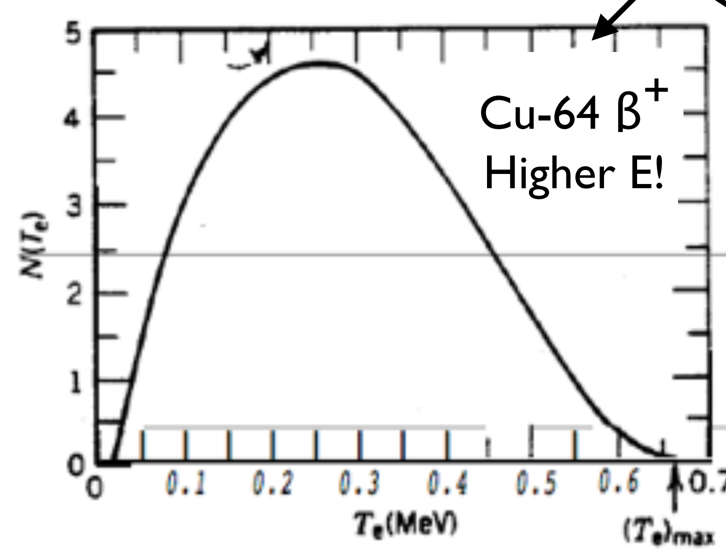
$$N_\beta(W) = K\, \underbrace{p^2 (W - W_0)^2}_{\text{phase space}}\, F(Z, W)$$

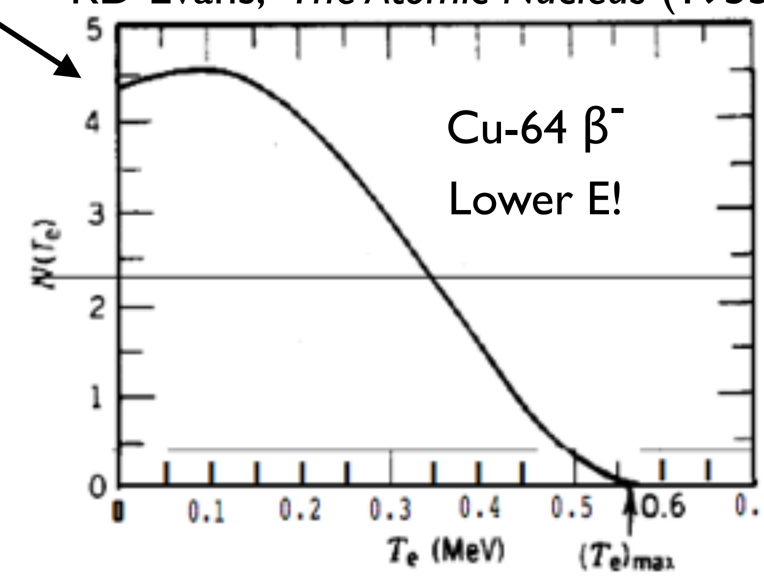
From nuclear matrix element (K): Extra factors of p pop in here for beta decays

QED correction (F(Z, W)): semi-classicaly, positive nucleus attracts product beta; lowers its energy

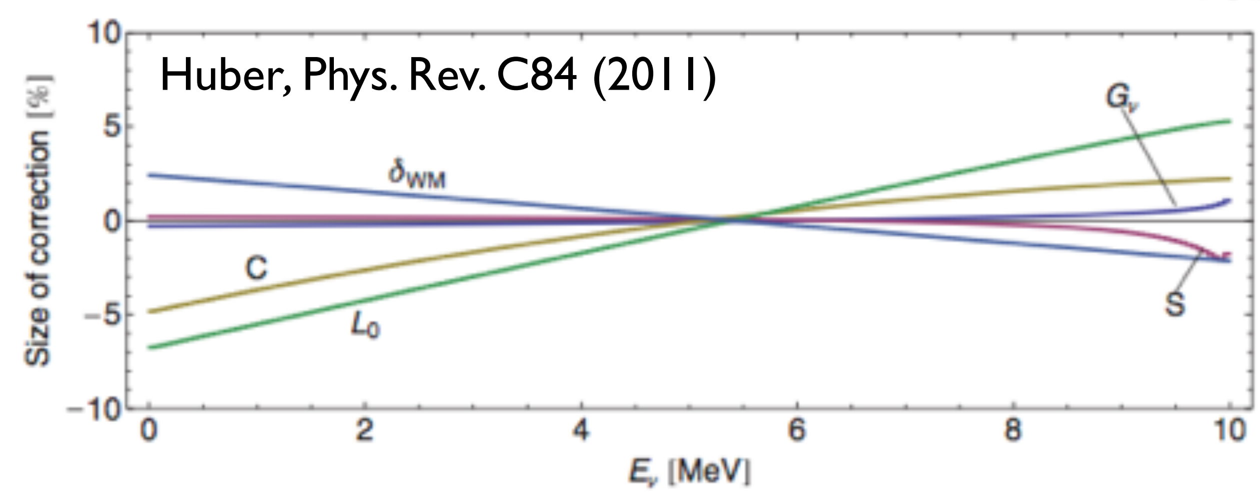


RD Evans, *The Atomic Nucleus* (1955)



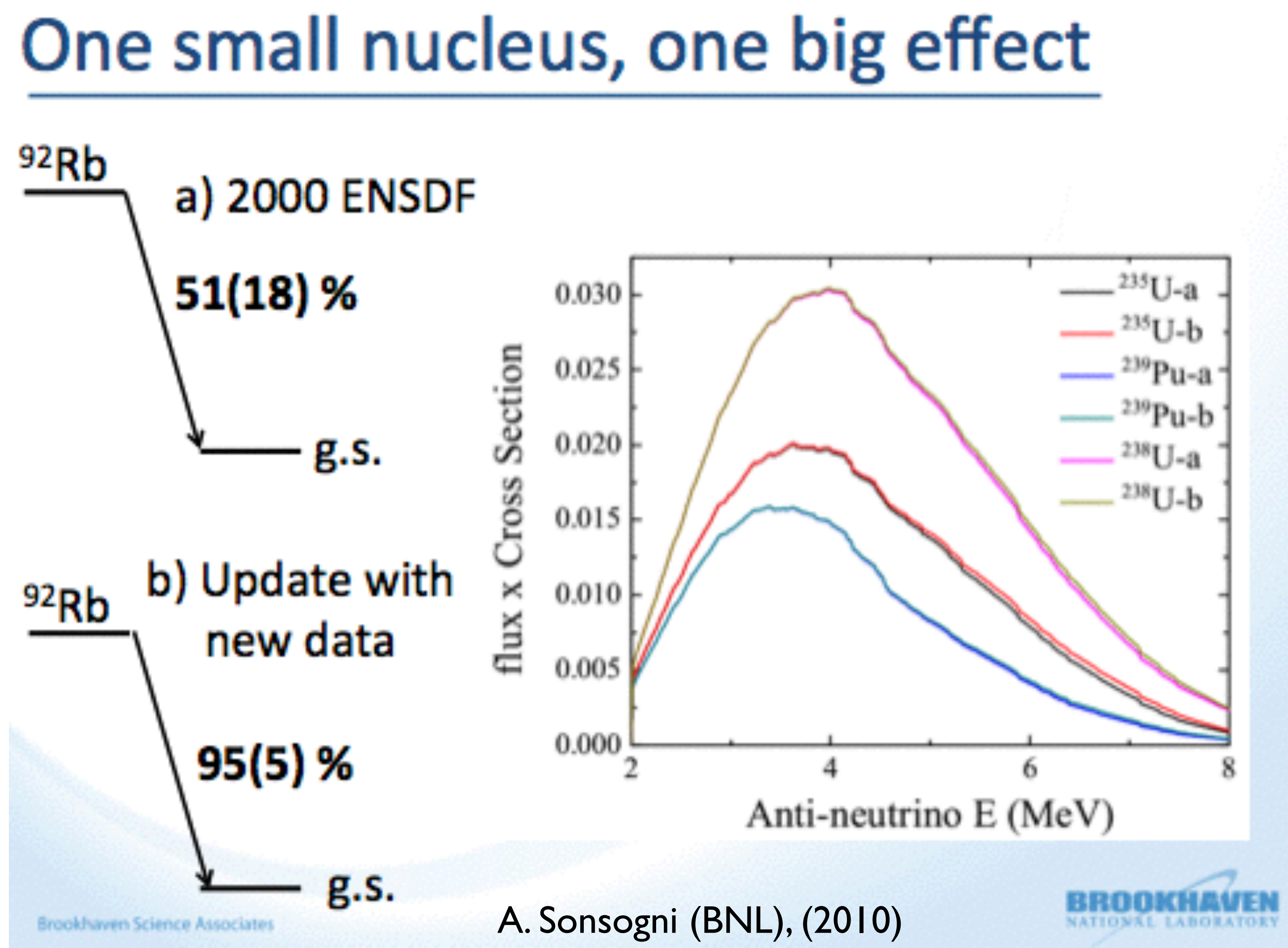


- Other corrections:
  - Finite size: C, L_0
  - Electron screening: S
  - Radiative corrections: C
  - Weak magnetism: d_{wm}



Reactor Spectroscopy: Example

- TAGS:
  Total absorption gamma spectroscopy
- Measure total gamma energy, not individual gamma energies
- Allows ID of levels, BRs much easier



A. Sonsogni (BNL), (2010)

- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = $$$ saved.