Uncertainties in the Reactor Neutrino Fluxes/Anomaly


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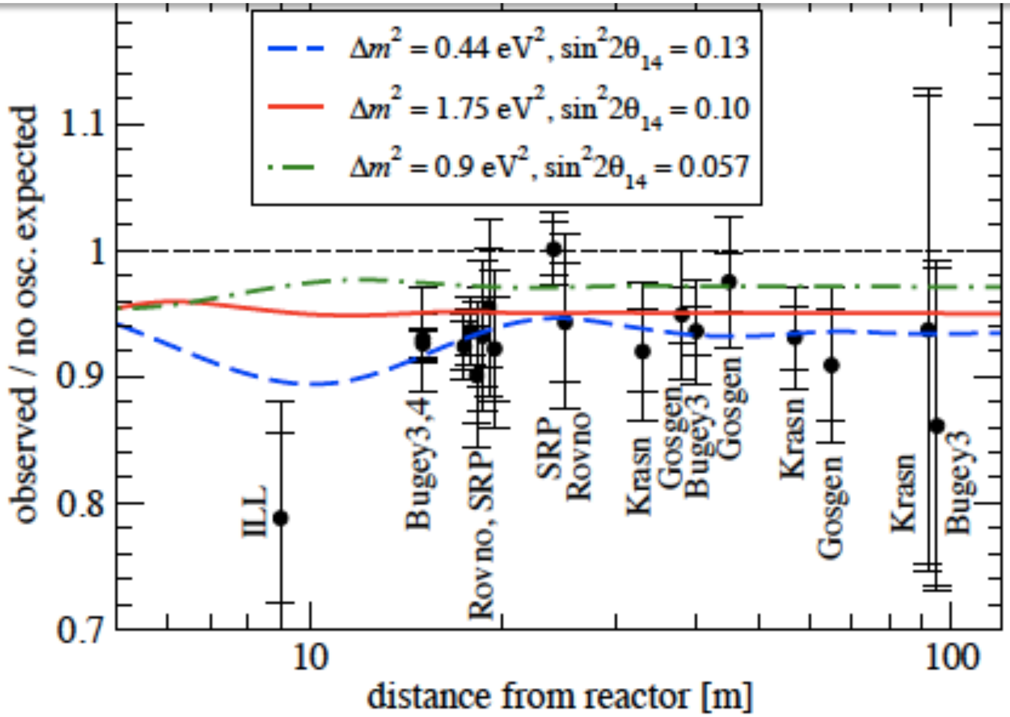
The Reactor Antineutrino Anomaly

obs/expected=0.94 (~3σ) deficit in the detected antineutrinos from short baseline reactor experiments

G. Mention et al., Phys. Rev. D 83 073006 (2011)



J. Kopp, et al.
JHEP 05 (2013)050

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011).

Additional contributions from (1) Off-equilibrium nuclei and (2)Increase in the detection cross section).

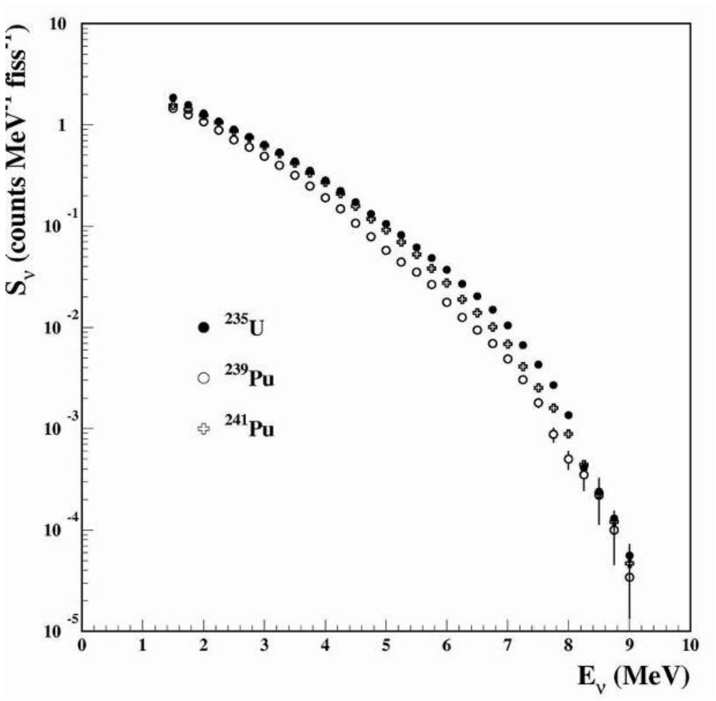
Outline

- **The origin if the anomaly**
  - Correction to beta-decay (finite size and weak magnetism)
  - The form of the corrections and their effect on the antineutrino spectrum

- **The large role of forbidden transitions**
  - Uncertainty in the correction
  - Uncertainty in the fit of the beta spectrum to obtain the antineutrino spectrum

- **The ‘BUMP’ in the measured antineutrino spectra**
  - Possible origins of the bump
  - Significant implications of the bump for the uncertainty in the ‘expected’ antineutrino spectrum
  - Clear need for new short baseline experiments

The antineutrino flux used in oscillations experiments is from a conversion of the aggregate beta spectra from ILL



K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1989)
P. Vogel et al., PRC 24 1543 (1981)

- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies
- Use Vogel *et al*. ENDF estimate for ^{238}U ^{238}U ~ 7-8% of fissions =>small error
- All transitions were treated as allowed GT

FIT

$$S_\beta(E) = \sum_{i=1,30} a_i S^i(E,\, E_o^i)$$

$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1 + \delta(E))$$

Known corrections to β-decay are the main source of the anomaly

$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2C(E)F(E_e,Z,A)\underline{(1+\delta(E_e,Z,A))}$$

Fractional corrections to the individual beta decay spectra:

$$\delta(E_e,Z,A)=\delta_{rad}+\delta_{FS}+\delta_{WM}$$

δ_{rad} = Radiative correction (used formalism of Sirlin)

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

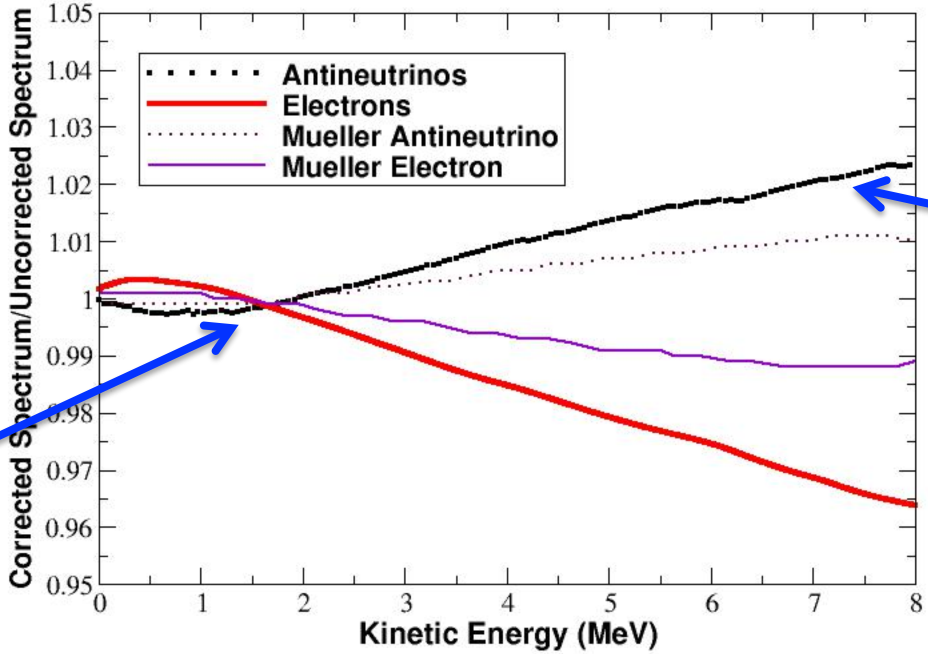
Originally approximated as:

$$\delta_{FS}+\delta_{WM}=0.0065(E_\nu-4\,MeV))$$

The difference between this original treatment and an improved treatment of these corrections is the main source of the anomaly

=> Antineutrino spectrum larger above 2 MeV

If all forbidden transitions are treated as allowed GT, the corrections lead to an anomaly - the ν_e spectrum is shifted to higher energy



$$\overline{E}_0/2$$

$$\cong \frac{1}{2}\left[\frac{4(\mu_v - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c}\right]$$

- Obtain larger effect & stronger energy dependence than Mueller because the form of our corrections are different
- Linear increase in the number of antineutrinos with E_ν>2 MeV

Two Major sources of uncertainty

- 30% of the transitions making up the spectrum are forbidden, i.e., $\Delta L \neq 0$

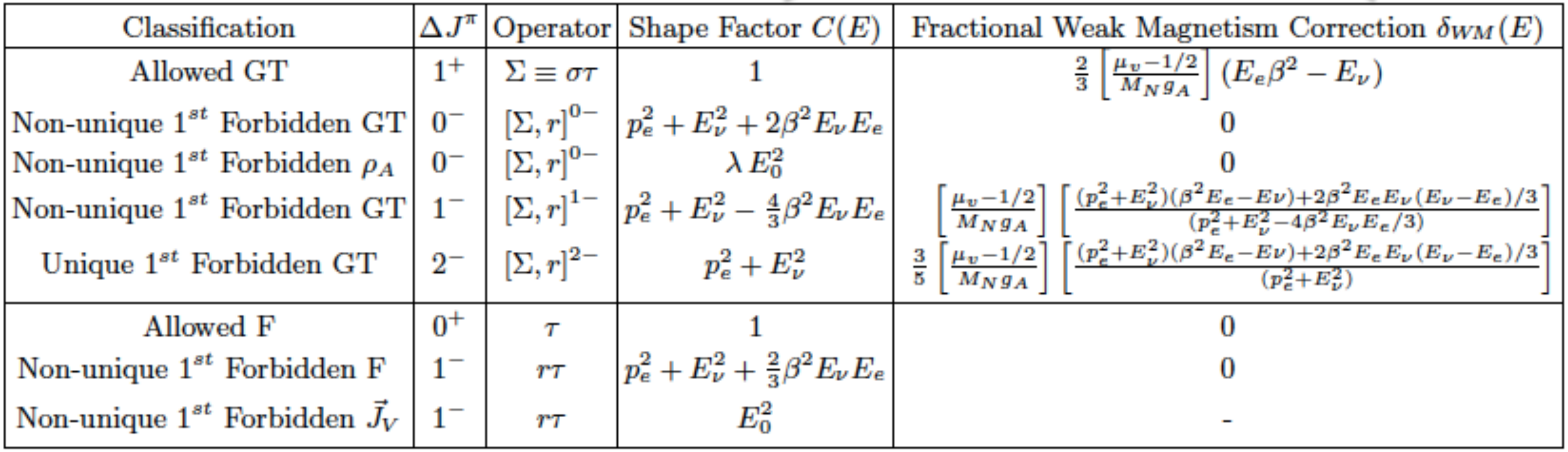
- The antineutrino spectra at Daya Bay, RENO, and Double Chooz all show a bump at E_ν=5-7 MeV relative to expectations

Forbidden transitions typically involve several operators and the corrections are operator dependent

Allowed: Fermi τ and Gamow-Teller $\Sigma = \sigma\tau$

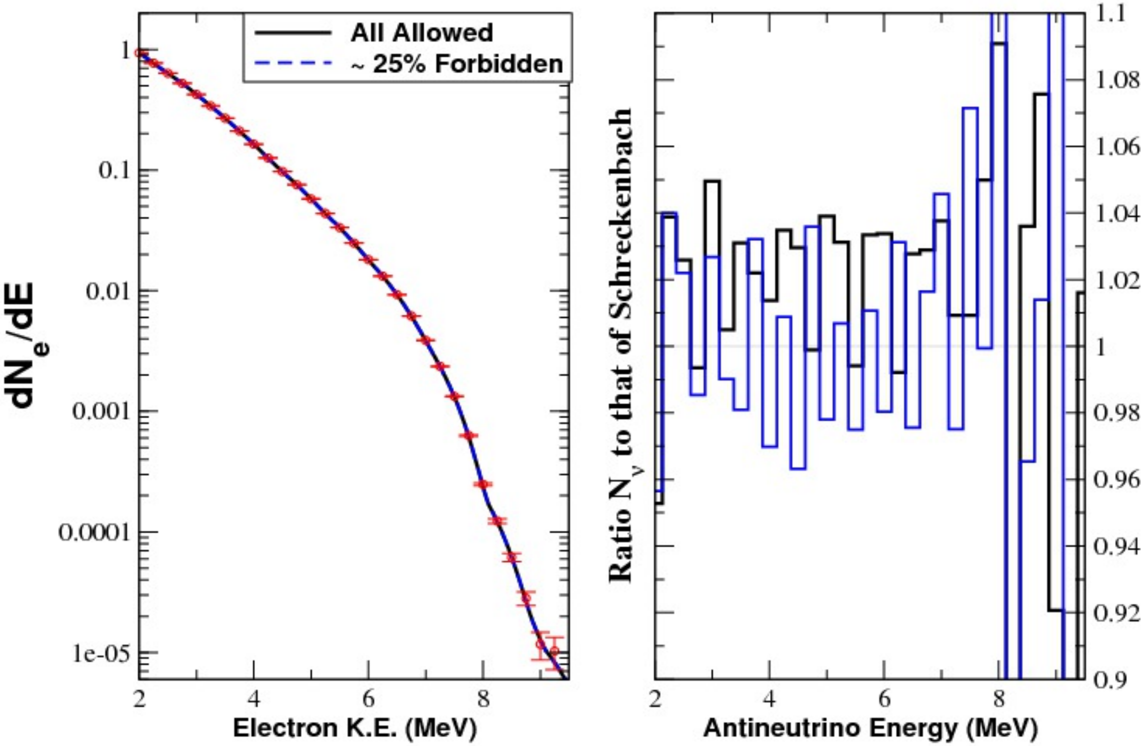
Forbidden: $\Delta L \neq 0$; $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L}$, $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L - 1}$, $\vec{r}^{\,L}\vec{\tau}$, $\dfrac{\vec{\nabla}\vec{\tau}}{\mathrm{M}}$, …

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 \underline{C(E)} F(E_e, Z, A)(1 + \delta(E_e, Z, A))$$



Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1st Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1st Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1st Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2 - 4\beta^2 E_\nu E_e/3)}\right]$
Unique 1st Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2)}\right]$
Allowed F	0^+	τ	1	0
Non-unique 1st Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1st Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

Fit to Schreckenbach's beta spectrum



If all allowed:
⇒ +2.2%   antineutrinos

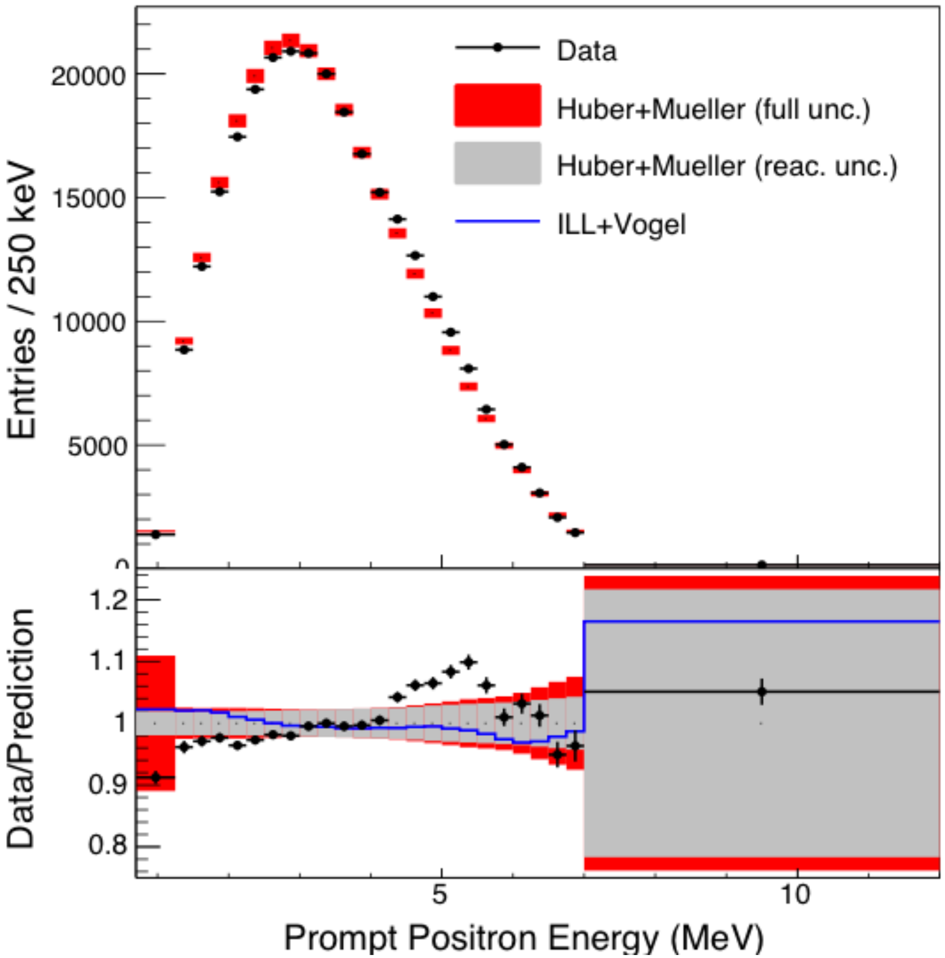
If 25% forbidden transitions
=> +0.06% antineutrinos

Different fitting procedures: (1) all allowed; (2)all branches either allowed or forbidden; (3) 30% forbidden equally spaced ;(4) 30% forbidden with a bias to higher energies + several different combinations of forbidden operators

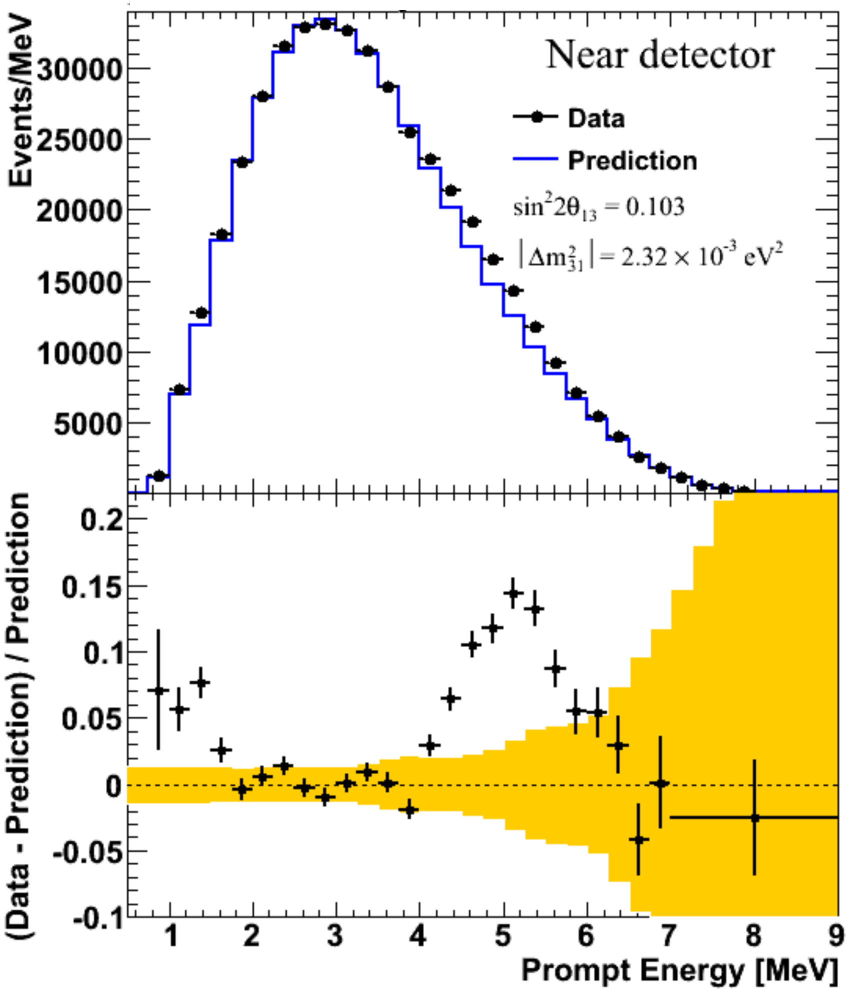
Changes in the antineutrino spectrum range from 0-4%
Problem arises because of lack of knowledge on how to treat forbidden transitions

The BUMP

Significant Shoulder seen in the Near Detector at E_{prompt}~4-6.5 MeV at both Daya Bay and RENO. Also seen in all far detectors.

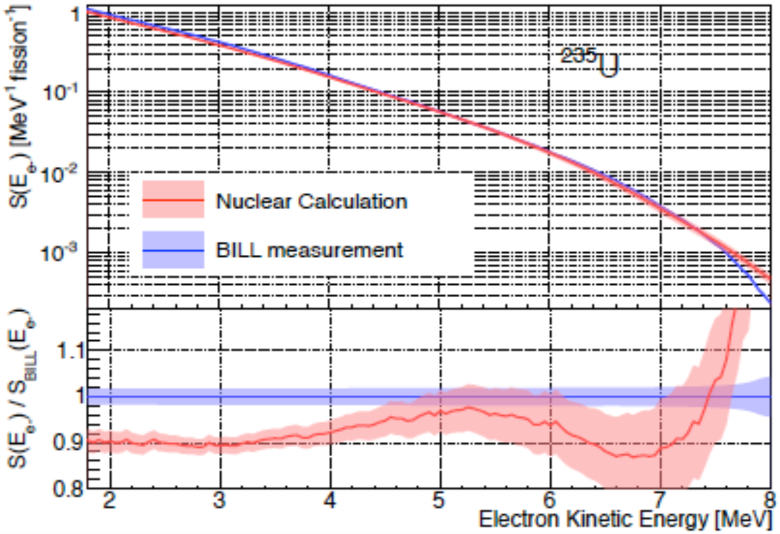


Day Bay

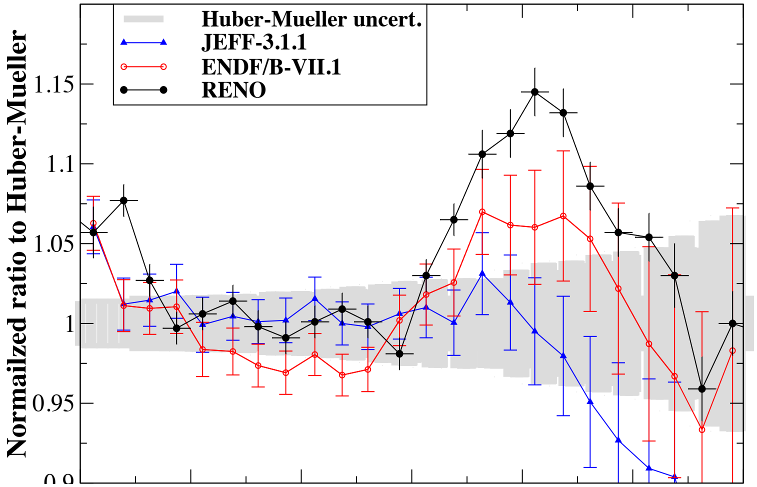


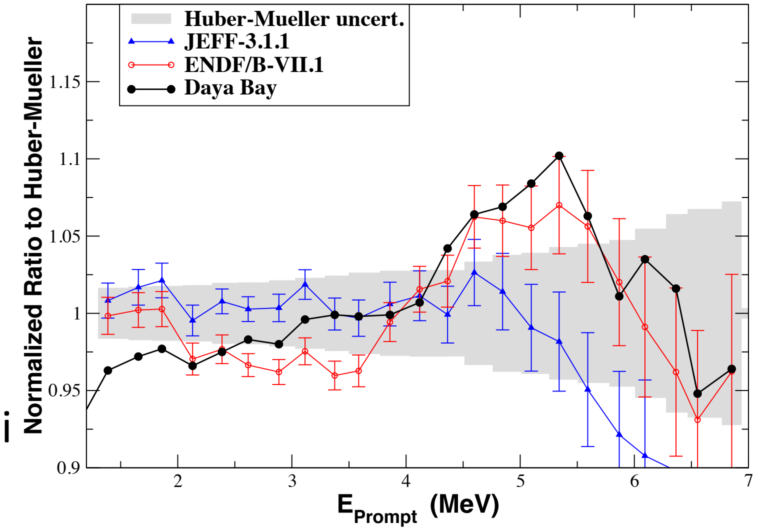
RENO

The different nuclear database do not agree on the origin of the Bump - the uncertainties in the databases are large



Dwyer & Langford, PRL, 114 012502 (2015)





- ENDF/B-VII.1 predicts that it results from an analogous shoulder in the ILL ^{235}U β spectrum
  -Also predicts a large bump for ^{238}U
- JEFF-3.1.1 does not predict a bump for ^{235}U or ^{239}Pu
  - Agrees with Schreckenbach for both these nuclei
  - But predicts a significant bump for ^{238}U

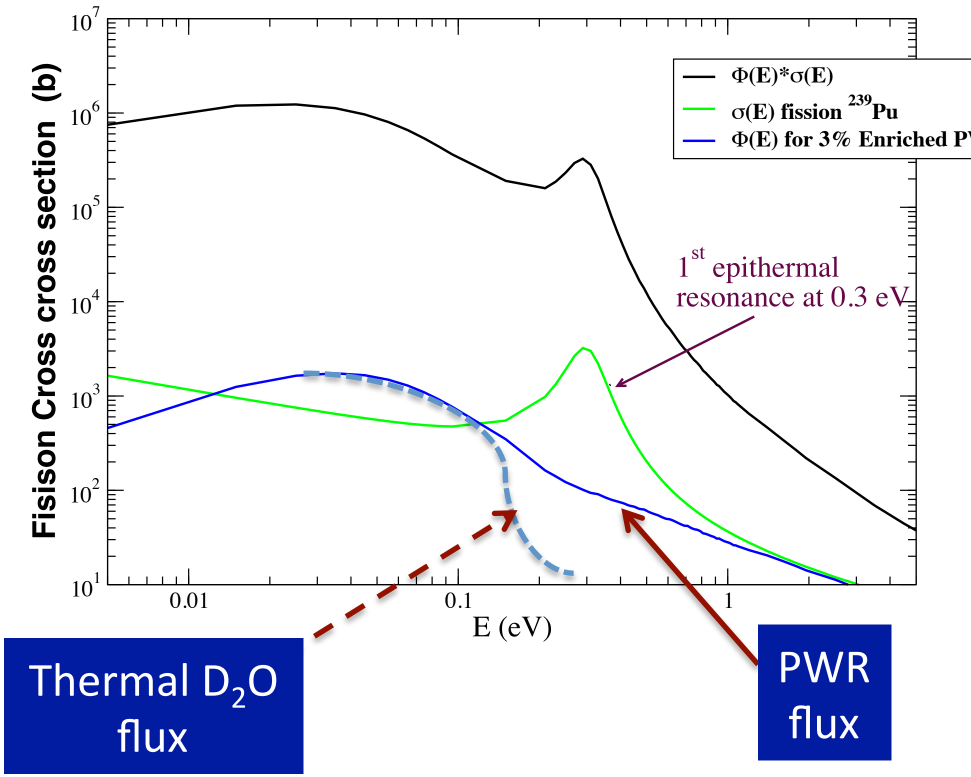
The hardness of the reactor spectrum could be an issue

- The original fission aggregate beta spectra were measured at D_2O ILL reactor
  ⇒Extremely thermal

- The Daya Bay, RENO and Double Chooz measurements are all at PWR reactors
  ⇒Significant epithermal neutron component to the flux

- There is some experimental evidence that fission yields for the epithermal resonances differ from those for a purely thermal spectrum

- However, there are no (thermal or epithermal) fission fragment yields for the nuclei dominating the bump region



Thermal D_2O flux

PWR flux

25% of the ^{239}Pu fissions involve the 0.3 eV resonance in a PWR, but not at ILL

Clear Need for New Experiments

A new set of reactor experiments is needed at short baselines.

- To address the anomaly and the possible existence of a 1 eV sterile neutrino, two detectors at different distances viewing the same reactor are needed.
  - Many planned experiments: PROSPECT, SOLID, STEREO, NUCIFER, …
- To quantify the role of the neutron flux spectrum one measurement should be at a very thermal reactor and the another at a reactor with a harder neutron spectrum.
  - ILL, NIST versus MOL, OSIRIS, or HFIR
- The use of highly enriched ^{235}U fuel has the advantage of restricting the resulting antineutrino flux to fragments produced by a single actinide.
  - ILL, MOL, HFIR (93% ^{235}U enriched)
- If ^{238}U and/or ^{239}Pu play a significant role in the anomaly or the bump, measurements from fuel that is of low enrichment will be needed
  - OSIRIS (20% ^{235}U enriched), compared to DAYA BAY, RENO, Double Chooz (<5%)