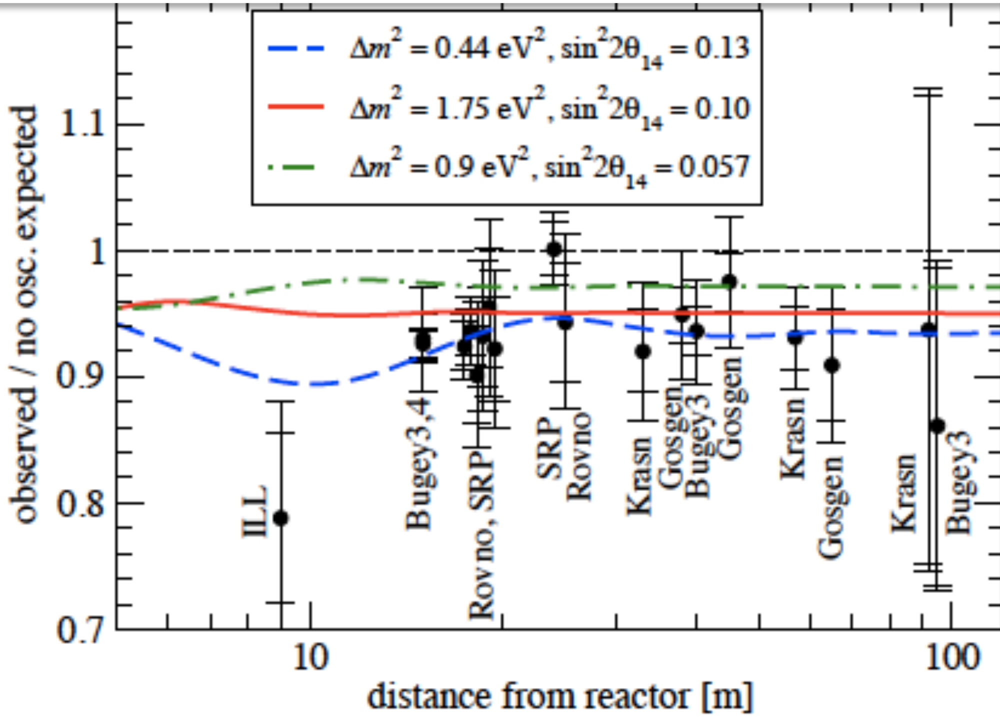
The Reactor Antineutrino Anomaly

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



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

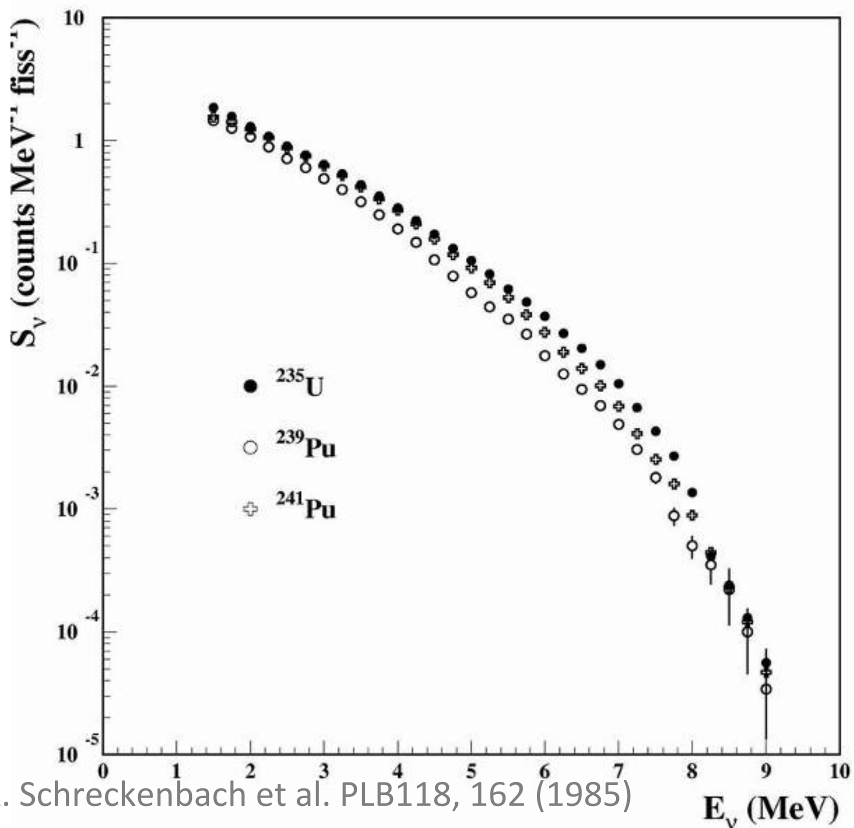
The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

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

Outline

- **The origin if the anomaly**
  - Corrections to beta-decay (finite size and weak magnetism)
  - The form of the corrections and the effect on the antineutrino spectrum
- **The large role of forbidden transitions**
  - Uncertainty in the corrections
  - Uncertainty in the fit of the beta spectrum to obtain the antineutrino spectrum
- **The 'BUMP' in the measured antineutrino spectra**
  - The apparent origin of the bump
  - Significant implications of the bump for the uncertainty in the 'expected' antineutrino spectrum
- **The need for new experiments**
  - A direct measurement of the antineutrino neutrino flux using two short baseline detectors

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



- 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

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

FIT

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

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

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

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

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:

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

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

The finite nuclear size correction

Normal (point-like) Fermi function:
Attractive Coulomb Interaction *increases* electron density at the nucleus
=> beta-decay rate *increases*

Finite size of Nucleus:
Decreases electron density at nucleus (relative to point nucleus Fermi function)
=> Beta decay rate *decreases*

Two contributions: nuclear charge density $\rho_{ch}(r)$ and nuclear weak density $\rho_W(r)$

For GT transitions:

$$\delta_{FS} = -\frac{3Z\alpha}{2\hbar c} < r >_{(2)} \left(E_e - \frac{E_\nu}{27} + \frac{m^2c^4}{3E_e}\right)$$

$$< r >_{(2)} = \int r\, d^3r \int d^3s\, \rho_W(|\vec{r} - \vec{s}|)\; \rho_{ch}(s)$$

-First moment of convoluted weak and charge densities
= 1st Zemach moment

The weak magnetism correction

Interference between the magnetic moment distribution of the vector current and the spin distribution of the axial current.

This *increases* the electron density at the nucleus => beta decay rate *increases*

$$J_V^\mu = \left[Q_V \,,\ \vec{J}_C + \vec{J}_V^{MEC} \right]$$

$$J_A^\mu = \left[Q_A + Q_A^{MEC} \,,\ \vec{\Sigma} \right]$$

Affects GT transitions

+

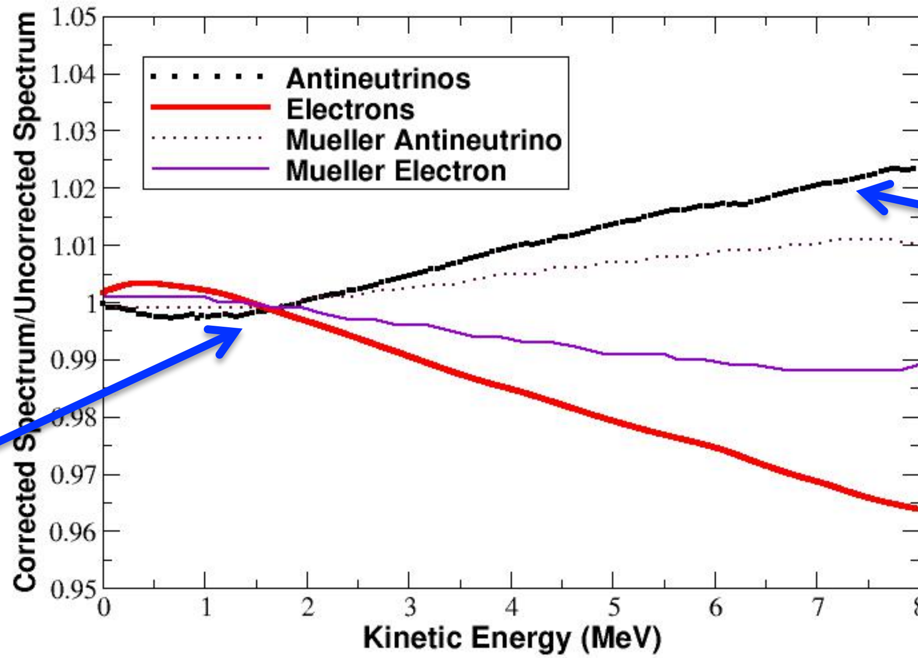
Equivalent correction for spin-flip component of forbidden transitions

The correction is operator dependent:

$$\delta_{WM}^{GT} = \frac{4(\mu_V - \tfrac{1}{2})}{6 M_N g_A} (E_e \beta^2 - E_\nu)$$

$$\delta_{WM}^{unique1^{st}} = \frac{3(\mu_V - \tfrac{1}{2})}{5 M_N g_A} \left[\frac{(p_e^2 + p_\nu^2)(p_e^2 / E_e - E_\nu) + \frac{2}{3}\dfrac{p_e^2 E_\nu (E_\nu - E_e)}{E_e}}{(p_e^2 + p_\nu^2)} \right]$$

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



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

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

- **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

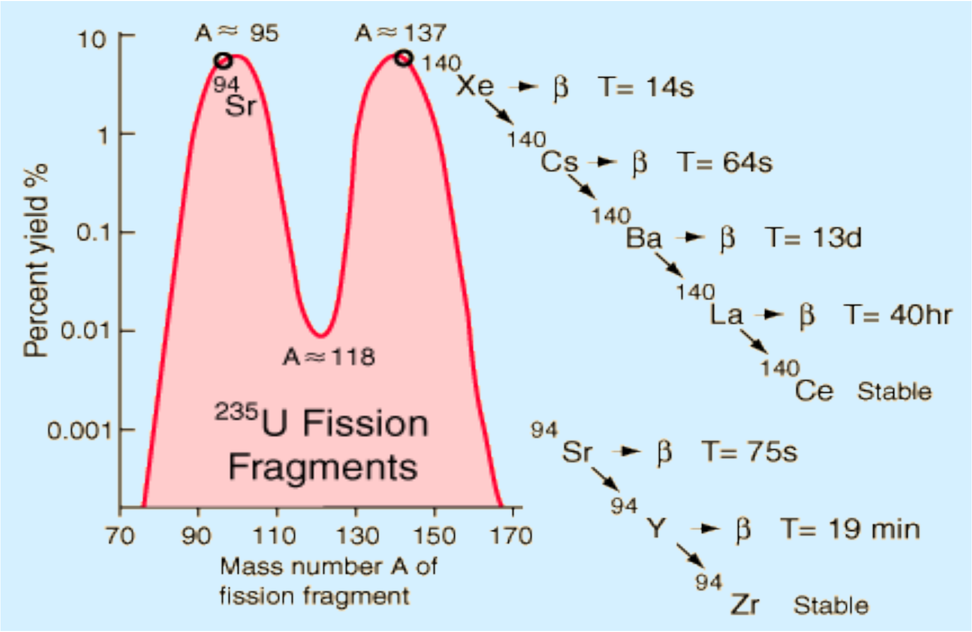
  => Corrections are largely unknown

- The newly measured antineutrino spectra show a bump relative to expectations

  => original beta-spectrum may have problems

However, 30% of the transitions are forbidden

Forbidden:
Not Fermi (0+) or GT (1+)
i.e, ΔL>0, Δπ=+/-1



A~95 Peak
Br, Kr, Rb, Y, Sr, Zr mostly forbidden
Nb, Mo, Tc often allowed GT

A~ 137 Peak
Sb, I, Te, Xe, Cs, Ba, Pr, La
- mostly forbidden

The forbidden transitions tend to dominate the high energy component of spectrum and they make up 30% of the spectrum

Unique forbidden versus non-unique forbidden transitions

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

Forbidden: $\Delta L \neq 0$; $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L}$, $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L - 1}$, $\Delta\pi = (-)^{\Delta \mathrm{L}}$

$\vec{r}^{\,L}\vec{\tau}$, $\dfrac{\vec{\nabla}\vec{\tau}}{\mathrm{M}}$, ...

Unique if $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L + 1}$, e.g., 2^-

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

Unique transitions only involve one operator & there is a unique shape change

e.g., 2- the phase space is multiplied by $C(E) = p^2 + q^2$

Also, a well defined weak magnetism correction

Non-unique transitions involve several operators

The C(E) shape factor is operator dependent

WM and FS are also operator dependent

Without detailed nuclear structure information there is no method of determining which operators determine the forbidden transitions

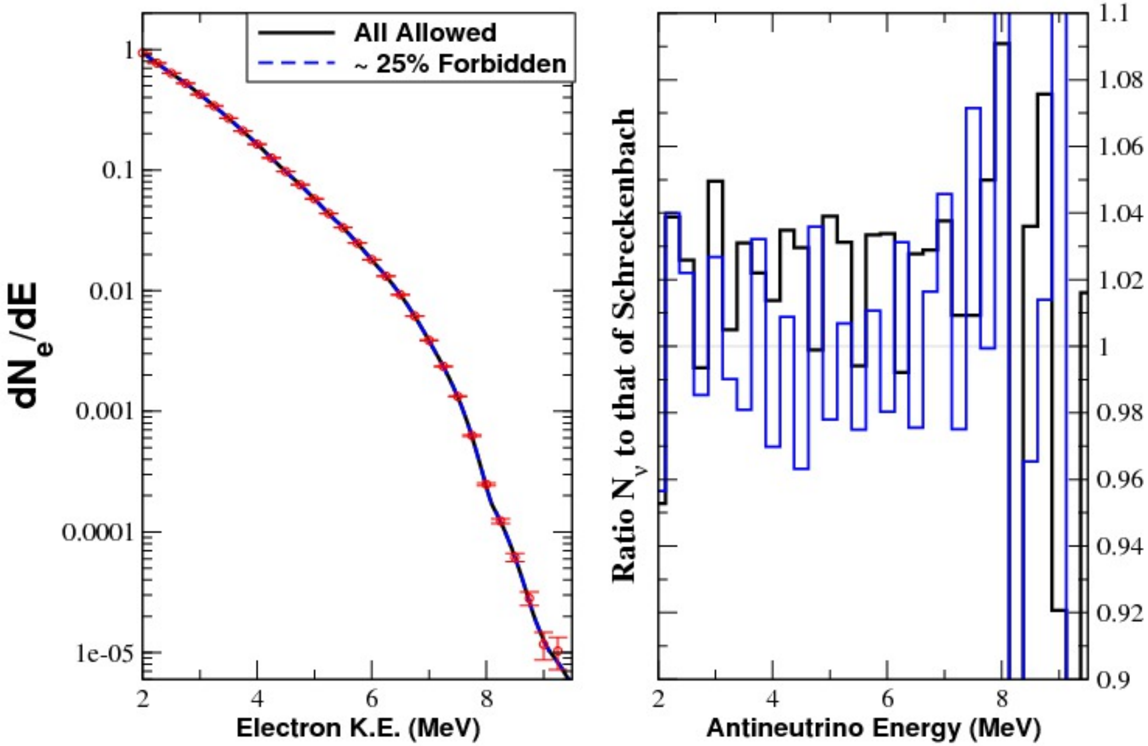
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v-1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2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

Table lists the situation for 6 operators that enter 1^{st} forbidden transitions

Many of the dominant transitions are $0^+ \rightarrow 0^-$, no weak magnetism

Have not derived a similar table for the Finite Size corrections

Fit to Schreckenbach's beta spectrum



If all allowed:
⇒ +2.2% antineutrinos

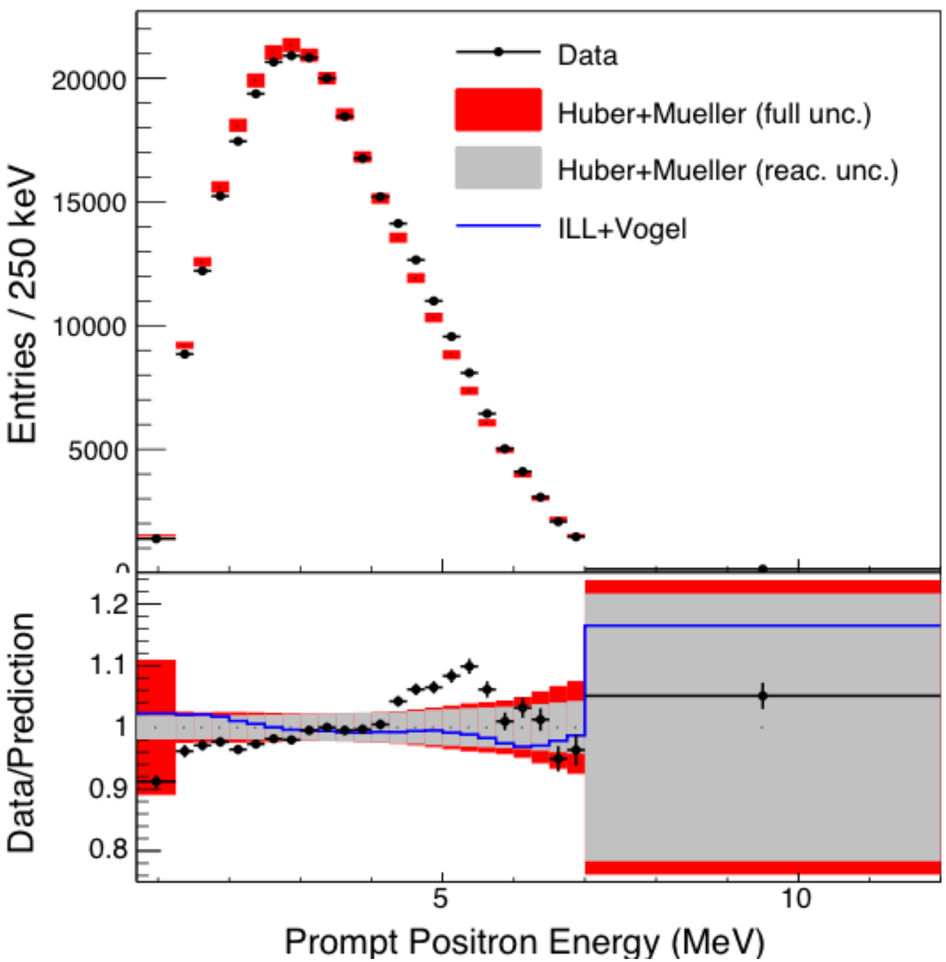
If 25% forbidden transitions
=> +0.06% antineutrinos

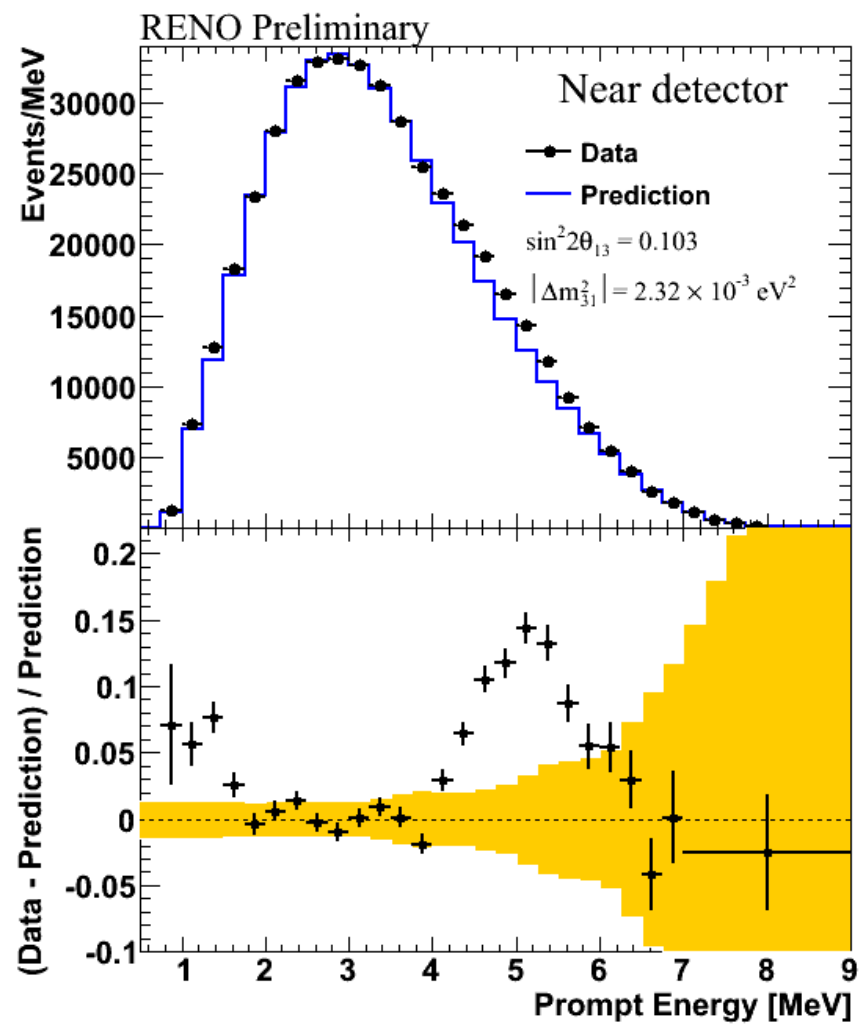
Different fitting procedures: (1) all allowed; (2)all branches either allowed or forbidden; (3) 30% forbidden equally spaced ;(4) 30% forbidden with a bias to higher energies + several different combinations of forbidden operators

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

The BUMP in the Antineutrino Spectra at Daya Bay, RENO and Double Chooz

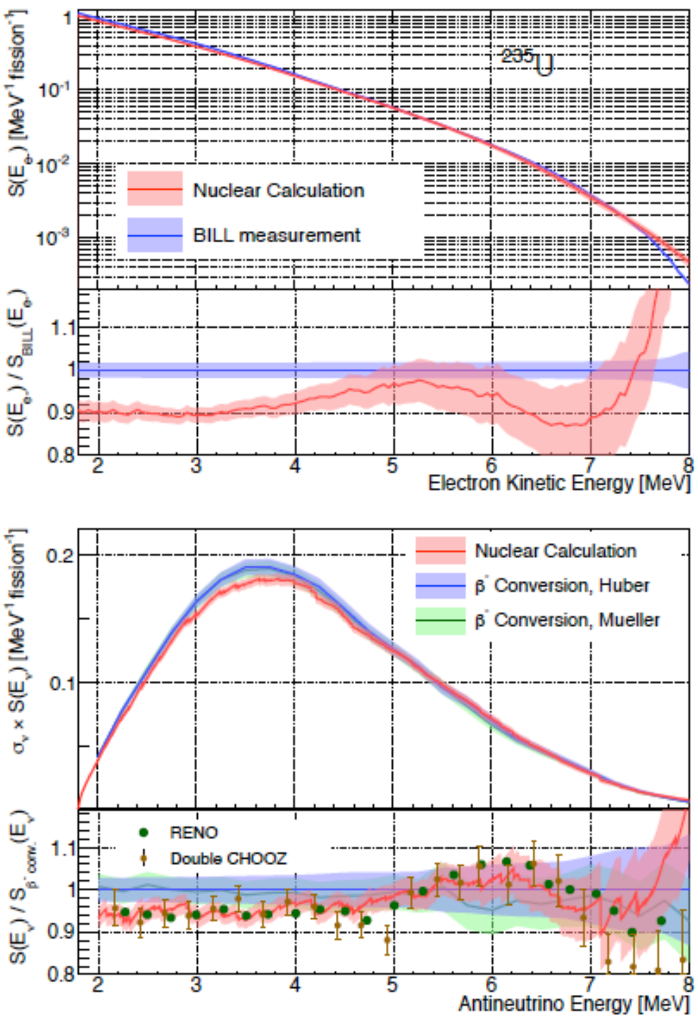
Significant Shoulder seen in the Near Detector at E_{promt}~4-6.5 MeV at both Dayabay and RENO. Also seen in the far detectors

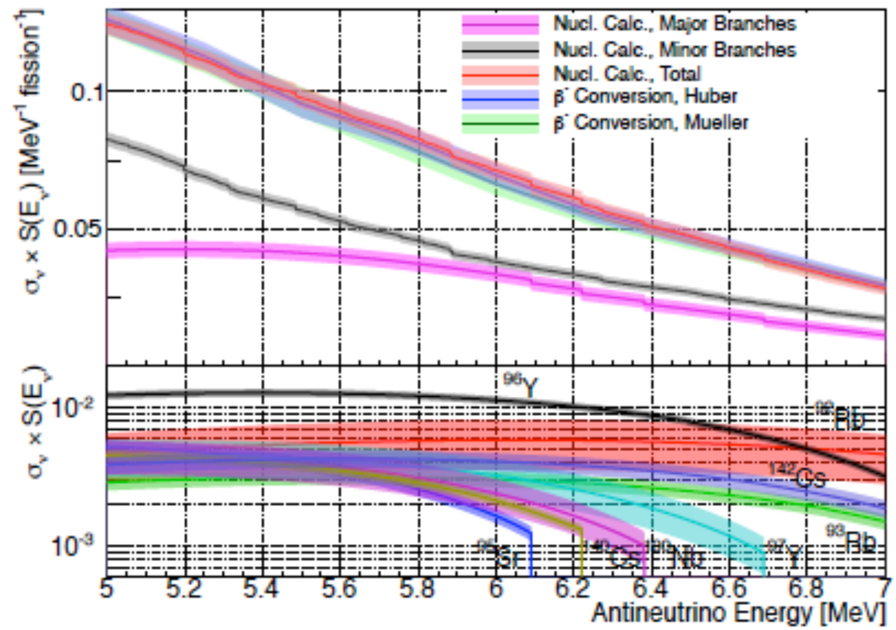




Analysis of Dwyer and Langford of Database for a subset of the transitions within ENDF shows that the bump is predicted

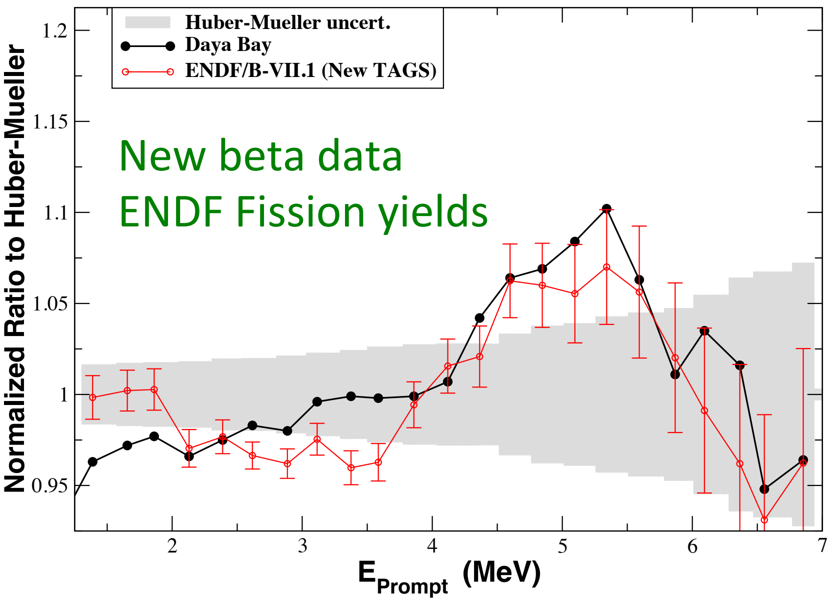
arXiv: 1407:1281

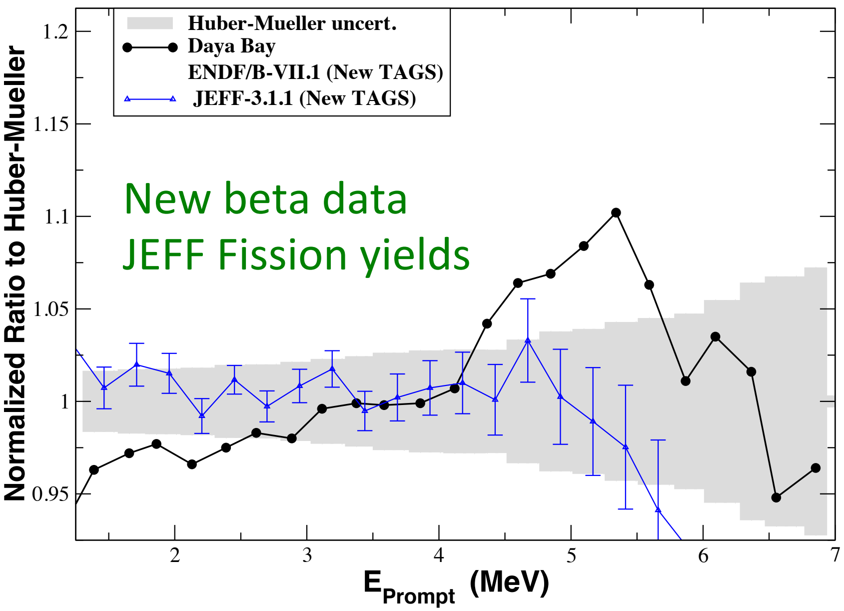


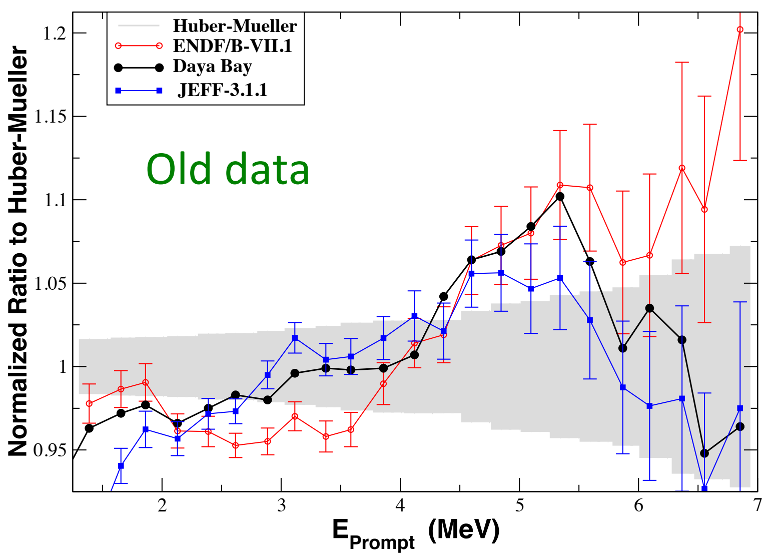


However, there are large uncertainties in the databases
This database is very different from the more modern database used by Sonzogni et al.

The modern databases have been updated to include TAGS beta-decay data
These β−γ−coincidence data greatly reduce high-energy decays







The TAGS data show that older experiments suffer from the pandemonium effect
- Branching ratios to ground states were too large.

The prediction of the 'BUMP' now strongly depends on the fission split to isomers – model dependent

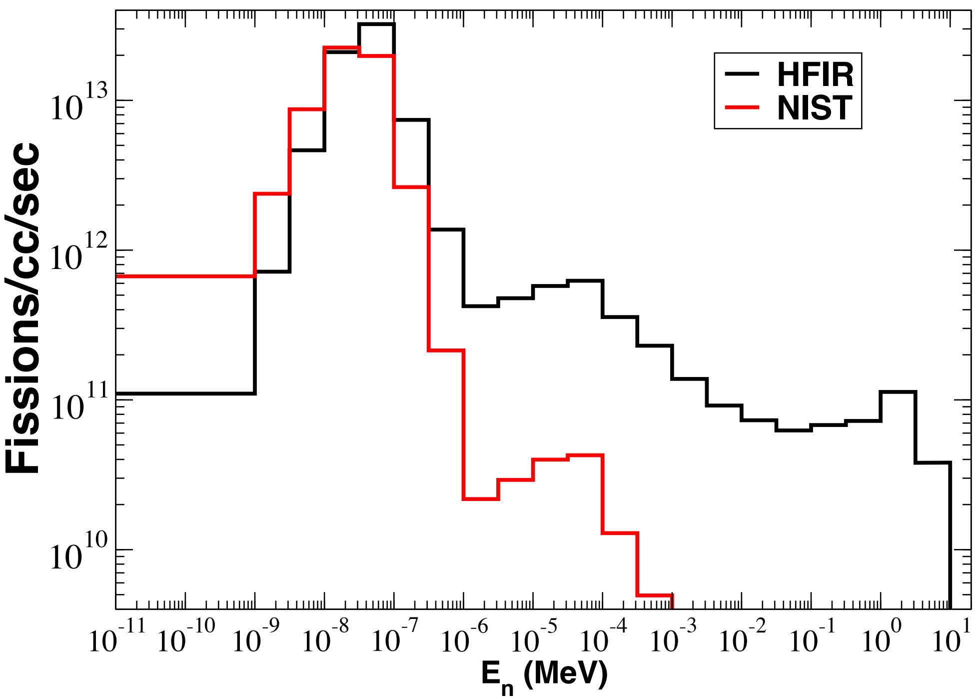
The new ENDF prediction for the bump looks better
The new JEFF prediction causes the bump to go away

The difference in the two database predictions arises through differences in the spin distribution of fission fragments

ENDF traditionally concentrates on fast fission, but the model should be applicable to thermal energies
 - thermal yields may be closer to epithermal

JEFF concentrates on thermal fission

The uncertainty in both databases is too large to make any definitive statements



The ILL reactor involved D_2O
⇒ Very thermal
⇒ Similar to NIST (shown here)

PWR reactors involve considerably larger epithermal component

It is not clear whether these neutron spectrum differences could are important

Clearly a Need for New Experiments

What are the best experiments and at which reactors?

Considerations:

1. A new aggregate beta spectrum may not be the answer to many questions
   - It falls off over 5 orders of magnitude in energy region of interest –difficult to measure
   - There appears to be too much uncertainty in converting it to neutrino spectrum
   - To determine the relative normalization of U to Pu, a β-spectrum measurement is not as challenging as an absolute measurement and seems like the way to go

2. Would like a small core but one with a high antineutrino flux
   - Limits us to specialized research or isotope production reactors

3. The enrichment of the fuel has two effects
   - If highly enriched (~93%), then all fissions come from ^{235}U –nice check of one nucleus
   - Neutron moderation also changes the ratio of fast to thermal flux
   - Not a serious issue as fast fission are a very small fraction of the total

5. Experiments such as PROSPECT, SOLID, NUCIFER, STEREO address most questions