First-forbidden transitions in the reactor antineutrino flux and spectral anomalies

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CNNP2020

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What's it about in 3 steps:

Where is the anomaly?

Antineutrino's from β^- decay of reactor fission fragments

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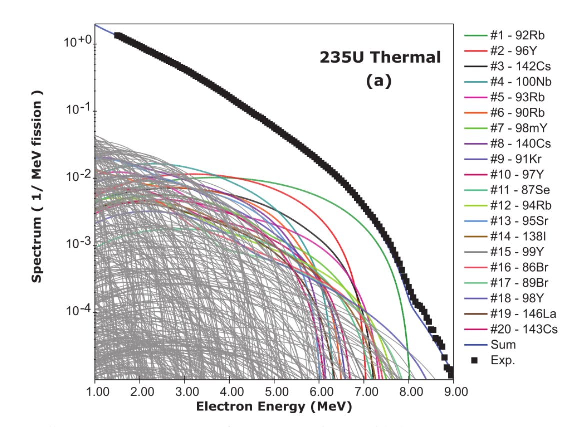
When new physics lurks, look out for quirks!

Antineutrino origin

Fission fragments from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu have many β^- branches, but can only measure cumulative spectrum.



Conversion of all β branches is **tremendous** theory challenge

A. A. Sonzogni *et al.*, PRC **91** (2015) 011301(R)

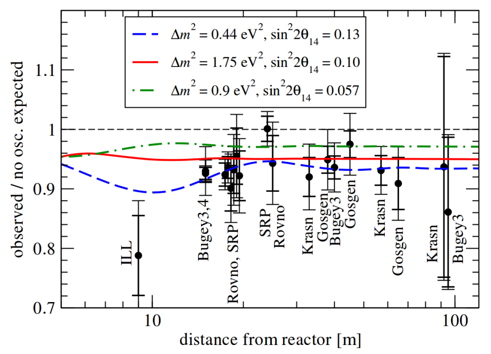
Deficiency and particle physics proposal

2011: Deficiency in neutrino count rate at 94% (2-3σ)

$$P_{SBL}(\bar{\nu}_\alpha \to \bar{\nu}_\alpha) \simeq 1 - \sin^2 2\theta_{\alpha 4} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Very exciting,

but. . . is it real?



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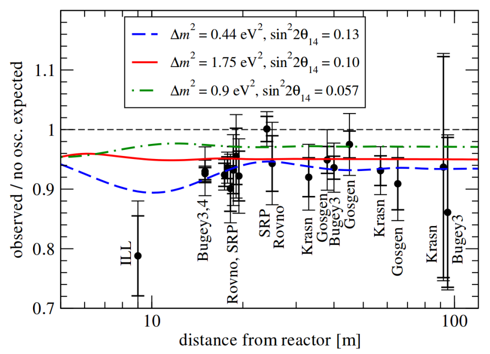
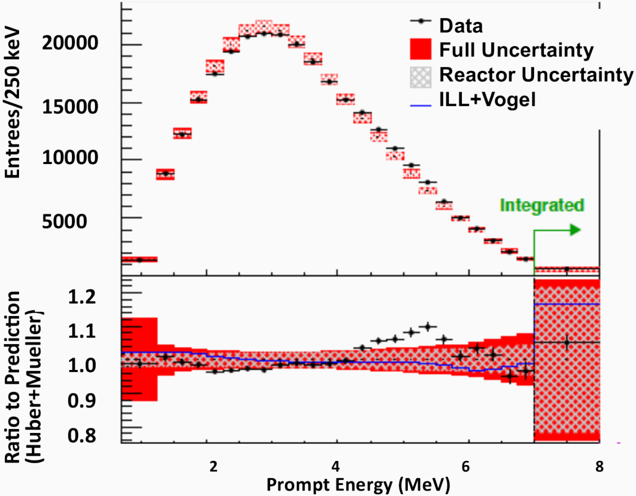
Understanding of all corrections & nuclear structure is **crucial**!



An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & J. Kopp et al., JHEP 05 (2013) 050

Reactor bump



Something not understood, most likely **nuclear physics** problem

Hayes & Vogel, ARNPS **66** (2016) 219

Experimental status

Very short baseline experiments

Since 2011, $\sim$ 10 experiments started setting up

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Very short ($<$10m) baseline experiments: measure oscillation directly

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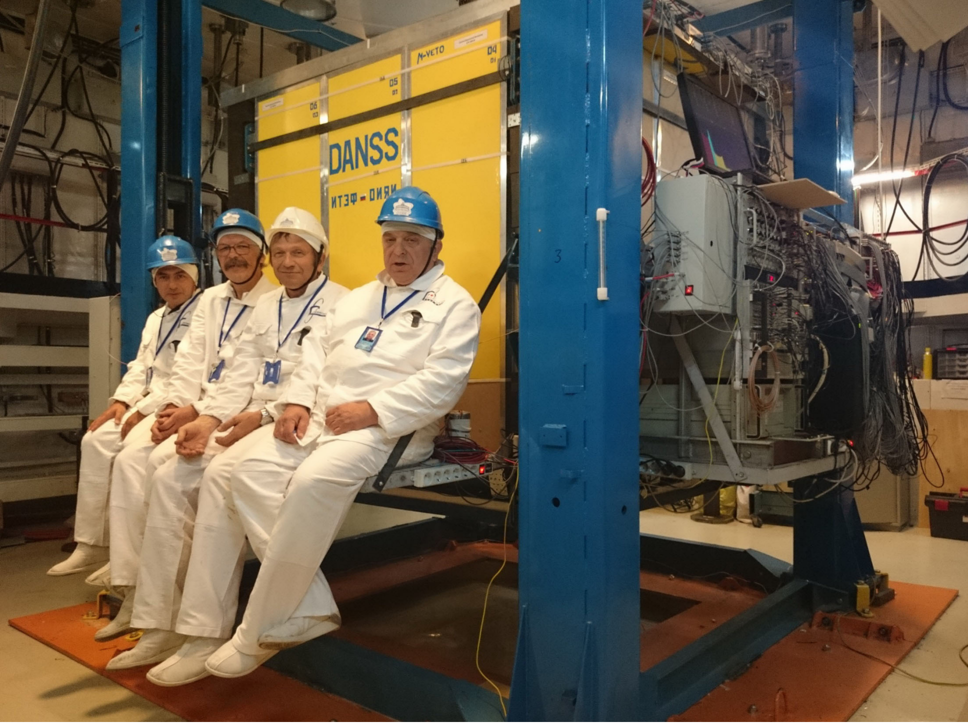
Very short (<10m) baseline experiments: measure oscillation directly

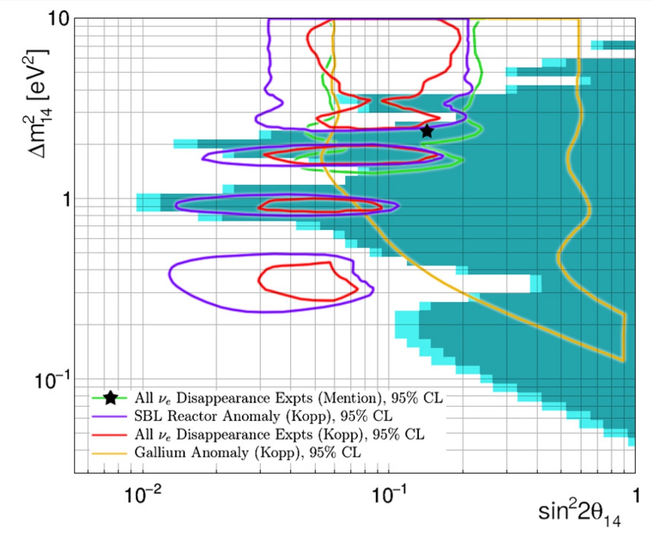
Several experiments came online late 2017/2018! Published data from

- NEOS (Korea) 1610.05134
- DANSS (Russia) 1804.04046
- STEREO (France) 1806.02096
- PROSPECT (USA) 1806.02784

Very exciting & more coming!

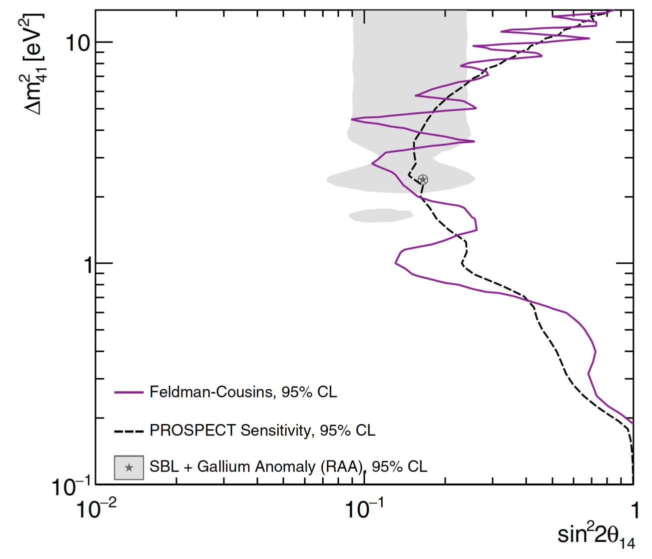

M-VETO
04
05
06
DANSS
ИТЭФ ОИЯИ

VSBL Results: DANSS



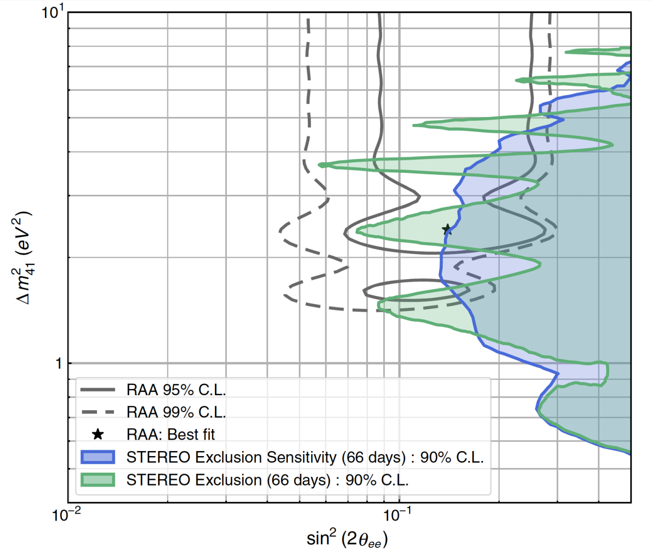
Alekseev *et al.* (DANSS) PLB 787 (2018) 56

VSBL Results: PROSPECT



Ashenfelter *et al.* (PROSPECT) PRL 121 (2018) 251802

VSBL Results: STEREO



Almazán *et al.* (STEREO) PRL 121 (2018) 161801 **Talk by Helena Almazán Friday**

Overview of reactor $\bar{\nu}_e$ decade

Faced with some interesting developments:

1. 2011: Emergence of flux anomaly, sterile neutrinos?

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Things point to deficiencies in databases & theoretical modeling

Theory status

Theory: β participant sketch

Experiment sees no steriles, what happens to theory?

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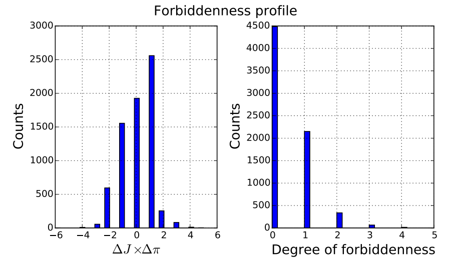
Nuclear β decay is complicated



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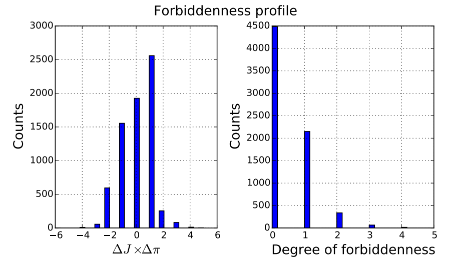

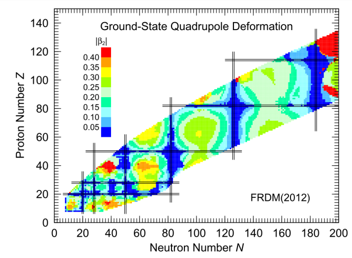

Both greatly influence the spectrum shape!

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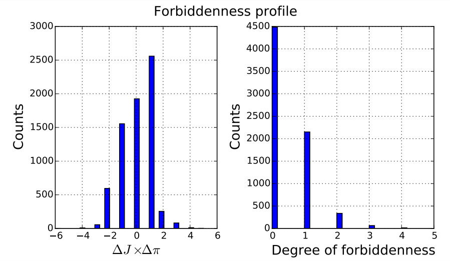

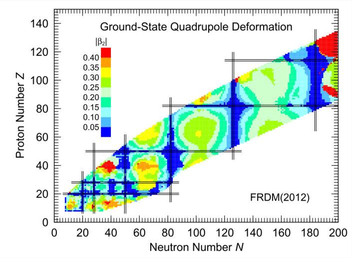

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Additional lower order effects: Atomic, electrostatic, kinematic...

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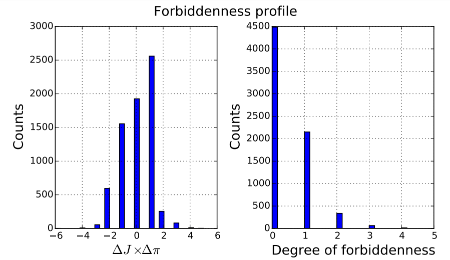

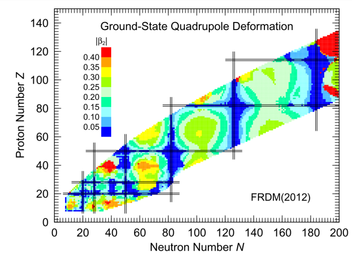

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Additional lower order effects: Atomic, electrostatic, kinematic...

Do our best and try to convert $\sim$ 8000 β branches per actinide

How to calculate the β spectrum shape

Active participation of QED, QCD & WI $\rightarrow$ Complicated system

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Large scale gap to cross:

Quark $\rightarrow$ Nucleon $\rightarrow$ Nucleus $\rightarrow$ Atom $\rightarrow$ Molecule

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$$
\begin{aligned}
N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3}\, & F_0(Z,W)\, L_0(Z,W)\, U(Z,W)\, R_N(W,W_0,M) \\
& \times\; Q(Z,W,M)\, R(W,W_0)\, S(Z,W)\, X(Z,W)\, r(Z,W) \\
& \times\; C(Z,W)\, D_C(Z,W,\beta_2)\, D_{\mathrm{FS}}(Z,W,\beta_2) \\
& \times\; pW(W_0-W)^2\, dW
\end{aligned}
$$

LH *et al.*, Rev. Mod. Phys. 90 (2018) 015008; 1709.07530

β spectrum shape

Central element in analysis is knowledge of β spectrum shape

$$\frac{dN}{dW} \propto pW(W_0 - W)^2 F(Z, W) C(Z, W) \dots$$

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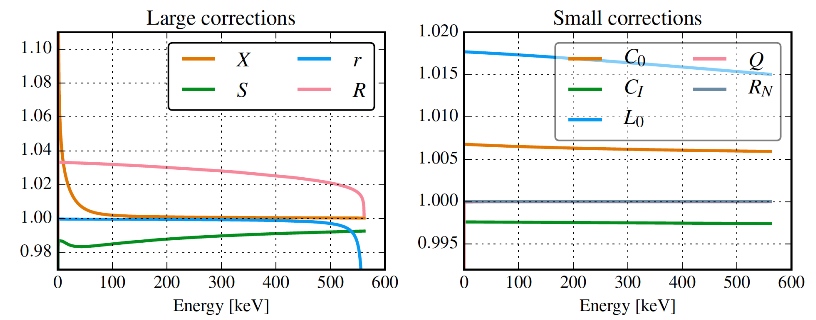

LH, Severijns, Comp. Phys. Comm. 240 (2019) 152; github.com/leenderthayen/BSG

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- allowed ($C \approx 1$)
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but maybe not the best?

Forbidden shape factors

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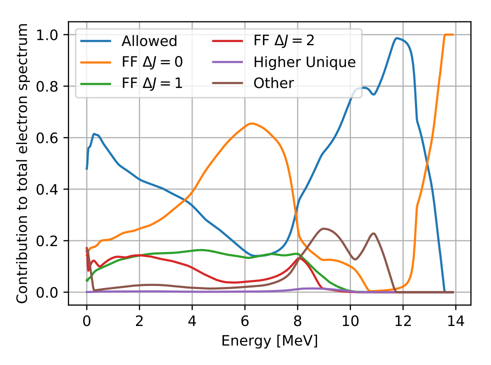

Experimental ROI (2-8 MeV) is dominated by forbidden decays

LH *et al.*, PRC 99 (2019) 031301(R), LH *et al.*, PRC 100(2019) 054323

Shape factor

Back to the chalk board!

General shape factor

$$C(Z,W)=\sum_{k_e,k_\nu,K}\lambda_{k_e}\left\{M_K^2(k_e,k_\nu)+m_K^2(k_e,k_\nu)\right.$$
$$\left.-\frac{2\mu_{k_e}\gamma_{k_e}}{k_eW}M_K(k_e,k_\nu)m_K(k_e,k_\nu)\right\},$$

λ_k,μ_k Coulomb functions of $\mathcal{O}(1+(\alpha Z)^2)$

Behrens, Bühring, Electron radial wave functions, 1982

First-forbidden transitions

Depending on spin-parity change, C can be relatively simple

$$C_{0^-} \propto 1 + \mathcal{O}(10^{-2})$$

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very difficult

$$C_{1^-} \propto 1 + aW + \mu_1\gamma_1\frac{b}{W} + cW^2$$

or rather simple, again

$$C_U \propto \sum_{k=1}^{L} \lambda_k \frac{p^{2(k-1)}q^{2(L-k)}}{(2k-1)![2(L-k)+1]!}$$

First-forbidden transitions

Cause for despair, but there's a helping hand:

Higher in E you go, fewer branches contribute

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Higher in E you go, fewer branches contribute

From 5 MeV onwards: $\gtrsim$ 90% of flux with less than 50 branches

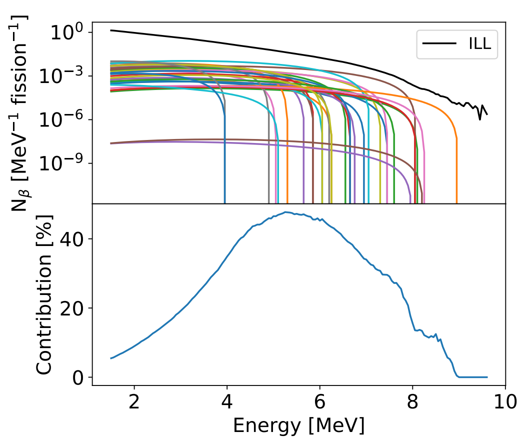
Nuclide	Q_β (MeV)	GS BR (%)	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	Contr. (%)
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	6.3
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	6.1
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	5.5
^{135}Te	5.9	62(3)	$(7/2^-) \rightarrow 7/2^+$	3.7
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	3.5
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	3.4
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{95}Sr	6.1	56(3)	$1/2^+ \rightarrow 1/2^-$	3.0
^{88}Rb	5.3	77(1)	$2^- \rightarrow 0^+$	2.9

Breakdown ^{235}U @ 5 MeV

Sonzogni *et al.*, 91 (2015) 011301

Forbidden shape factors

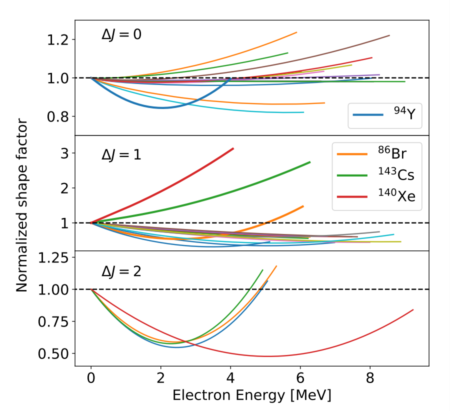
Picked 36 dominant forbidden transitions



explains $> 40\%$ of flux in ROI (4-7 MeV)

Forbidden shape factors

Picked 36 dominant forbidden transitions, calculated shape factor in nuclear shell model



Forbidden shape factors

Picked 36 dominant forbidden transitions, calculated shape factor in nuclear shell model

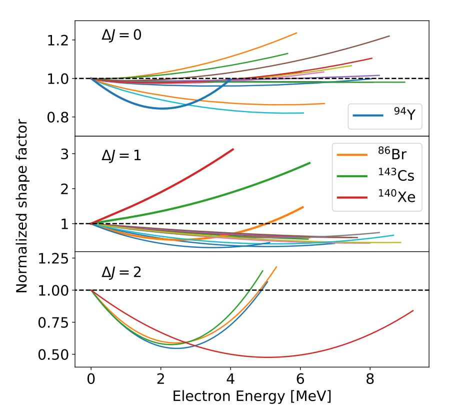
$$\frac{dN}{dE} \propto pE(E_0 - E)^2 F(Z, E)$$

$$\boldsymbol{C(Z, E)}$$

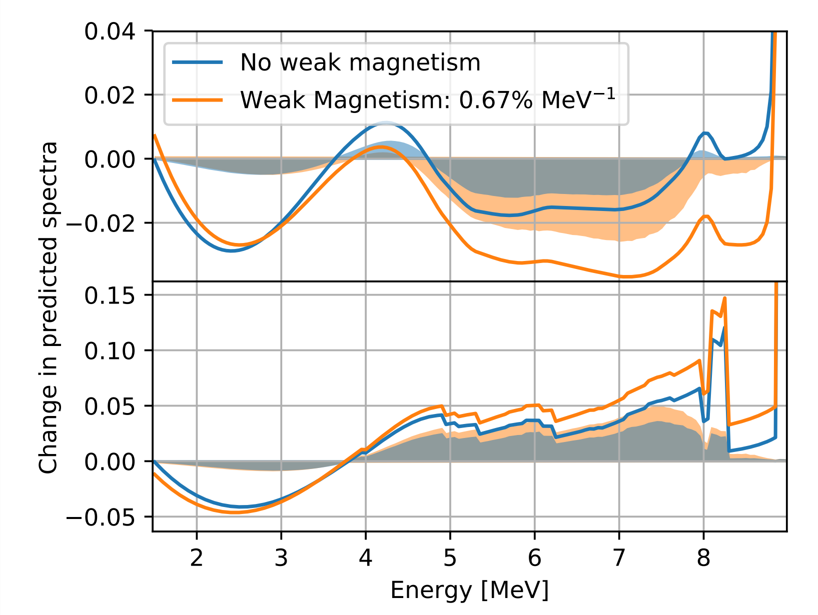
Allowed: $C \approx 1$

As expected,

large spectral changes



Spectral changes



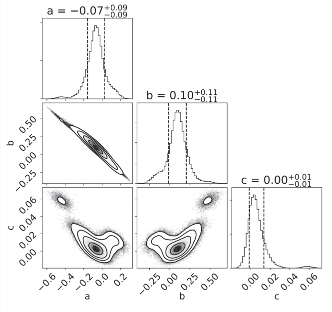
Parametrization

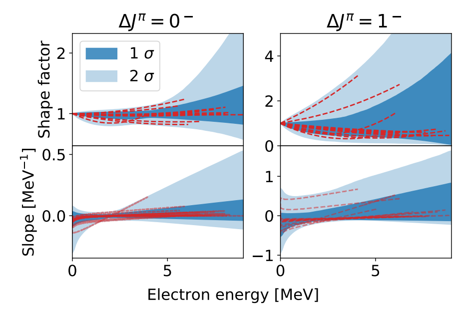
Calculated 36 $\rightarrow$ what about the others?

Parametrization

Calculated 36 $\rightarrow$ what about the others?

Construct conservative shape factor distributions for each ΔJ



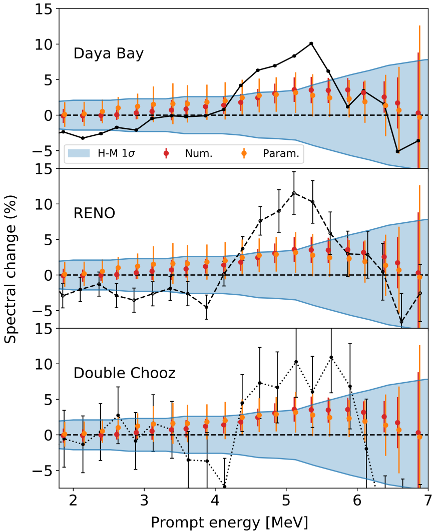


Monte Carlo sampling for remaining 2500 branches

$\rightarrow$ Uncertainty due to forbidden branches (first time)

Forbidden transitions & the bump

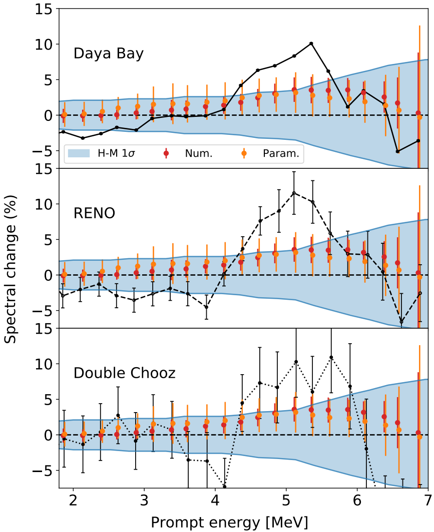
Use spectrum changes forcing agreement with experimental e^- spectrum



Forbidden transitions & the bump

Use spectrum changes forcing agreement with experimental e^- spectrum

Bump
mitigated + increased theoretical uncertainties



LH *et al.*, PRC 99 (2019) 031301(R), LH *et al.*, PRC 100(2019) 054323

Looking forward

Allowed transitions

Upon closer inspection, allowed transitions were also (strongly) approximated

- Induced matrix elements (weak magnetism, induced tensor, pseudoscalar) partially/not included
- Average value for weak magnetism used for every branch, but not every branch contributes equally

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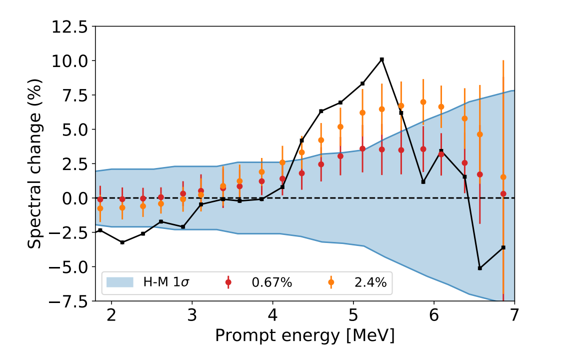
Key idea: Reactor $\bar{\nu}_e$ IBD flux $\propto$ slope_β^{-1} and bump effect of forbidden transitions $\propto$ slope_β

Allowed transitions & the bump

Increase in average allowed transition slope can solve both **rate** and **shoulder** anomaly with forbidden transitions



(Proof of concept, ongoing)

LH *et al.*, PRC 100(2019) 054323

IAEA: Delegates of major experiments & theorists

IAEA
International Atomic Energy Agency

INDC(NDS)-0786
Distr. G, EN, ND

INDC International Nuclear Data Committee

Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

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Several publications since 2011 have pointed out that the total uncertainties were significantly underestimated [19, 20, 21, 22] (cf. the summaries of the presentations of A. Hayes, P. Huber and L. Hayen for more details).

→ **Consensus** that uncertainties are *significantly underestimated*

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Targeted lists of forbidden non-unique transitions that contribute significantly to the antineutrino energy spectra based on the theoretical calculations of A. Sonzogni, A. Hayes and L. Hayen have been published [19, 22] and could serve as a guidance for measurements.

- We recommend estimating the impact of the largest shape factors predicted by theory by including these shape factors computed by Hayen et al. (see presentation in this report) in the summation calculations and in conversion calculations.

Plans for several measurements by different groups to measure β decay spectra and validate theory results

$\rightarrow$ please measure forbidden β spectra with high impact!

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Re-analysis of allowed transitions could **maybe** solve both flux and bump problems

Backup

Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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Approaches split up in 2:

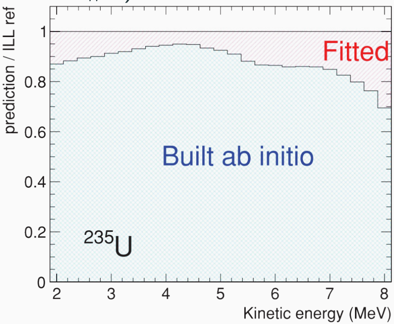
1. **Conversion** method: virtual β branch fits

Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

Approaches split up in 2:

1. **Conversion** method: virtual β branch fits
2. **Summation** method: Build from databases (& extrapolate a la #1)



Much of *summation* is based on same spectral assumptions Huber, PRC **84** (2011) 024617; Mueller *et al.*, PRC **83** (2011) 054615

Thoughts on state of the art

2 elements which require pause

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1. Central problem when comparing to ILL data

Everything below 1.8 MeV in electron spectrum is unconstrained, but ends up all over the antineutrino spectrum

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Everything that changes the shape below 1.8 MeV changes the anomaly $\rightarrow$ essential to get this right

Thoughts on state of the art

2 elements which require pause

2. Depending on method, questionable approximations
   - Incorrectly estimates $(\alpha Z)^{n>1}$ effects, $\mathrm{RAA}(\langle Z \rangle^{n>1}) \neq \langle \mathrm{RAA}(Z^{N>1}) \rangle$!
   - Estimated average b/Ac from spherical mirrors, but highly transition and deformation dependent
   - All transitions assumed allowed/unique
   - No Coulomb corrections to unique shape factors
   - ...

An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & Hayes *et al.*, arXiv:1707.07728

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Challenging, but attempt to establish uncertainty