Revisiting the nuclear β decay input in the reactor anomaly

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Solvay Workshop, Brussels, December 1st 2017

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Anomaly Introduction

What's it about in 3 steps:

Where is the anomaly?

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

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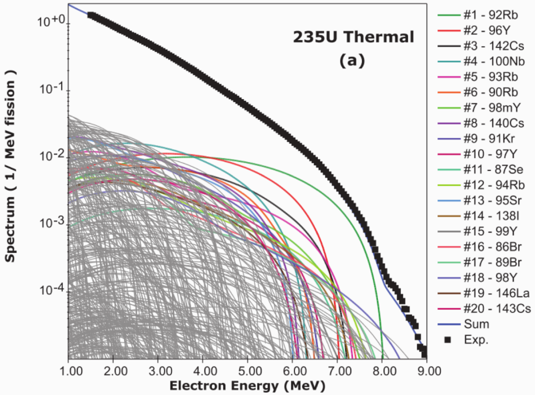
When new physics lurks, look out for quirks!

Antineutrino origin

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

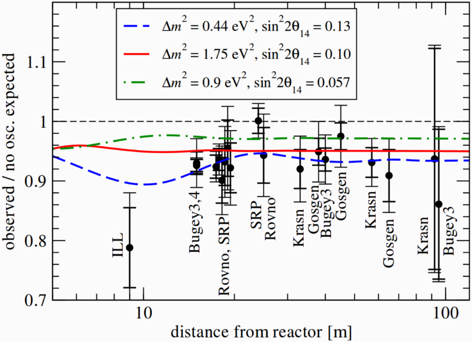


Conversion of all β branches is **tremendous** challenge

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

Deficiency and particle physics proposal

Current deficiency in neutrino count rate at 94% (2-3σ)



Very exciting, but. . . it is real?

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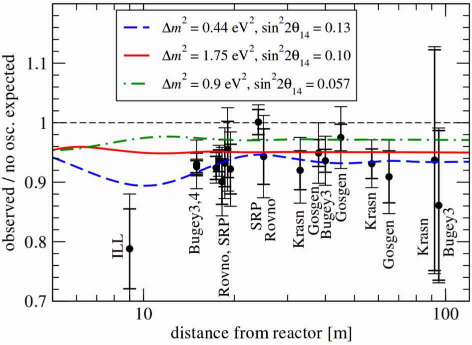

Very exciting, but. . . it is real?

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

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

Generalized weak Hamiltonian

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

Weak Hamiltonian is modified

1. Emitted β particle immersed in Coulomb field: radiative corrections
2. QCD adds extra terms in weak vertex: induced currents

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Relevant to this talk:

$$V_\mu(q^2) \rightarrow i\langle \bar{u}_p | g_V \gamma_\mu - \frac{\kappa_p - \kappa_n}{2M} \sigma_{\mu\nu} q^\nu | u_n \rangle$$

'Weak magnetism'

Analytical beta spectrum shape

Recently accomplished: Fully analytical description (hydra)

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

Main corrections and improvements:

Atomic effects: Screening, exchange, atomic mismatch, molecular effects

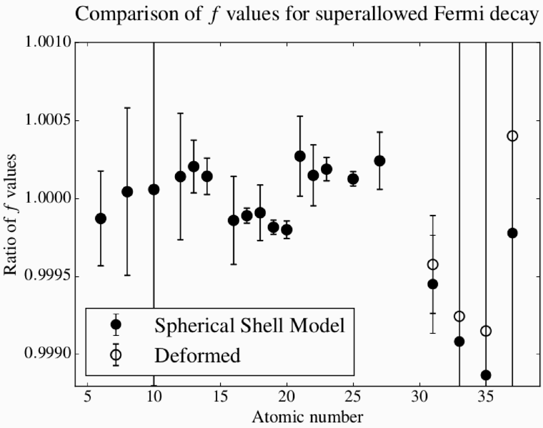
Nuclear effects: Spatial variation of wave functions, nuclear structure & deformation

L. H. *et al.*, Accepted for Rev. Mod. Phys.; arXiv: 1709.07530

Performance check

Initial test for $0^+ \to 0^+$ superallowed decays, minor influence from nuclear structure.

Comparison of f values to best results on the market, agrees nicely.



Performance check

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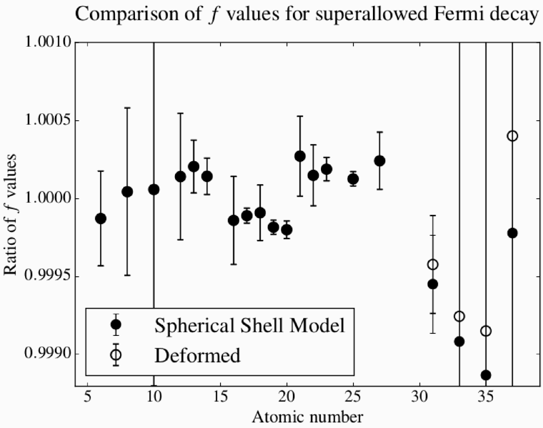
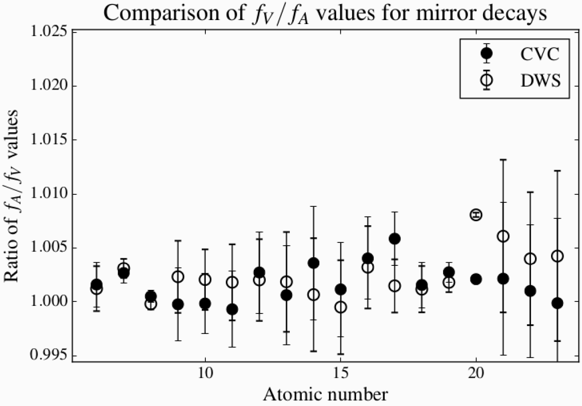
Largest deviations are for **extremely deformed** isotopes.



I. Towner & Hardy, PRC **91** (2015) 025501

Performance check

Comparison to Towner *et al.* mirror calculations, sensititive to 3 matrix elements

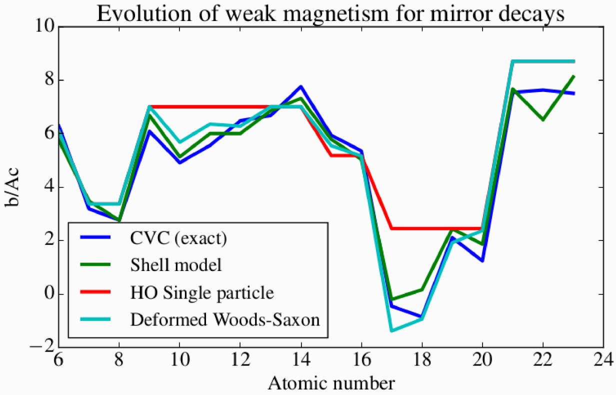


Excellent agreement within uncertainties

I. Towner & Hardy, PRC **91** (2015) 025501

Weak magnetism in $T = 1/2$ mirrors

Main nuclear structure influence in allowed decays

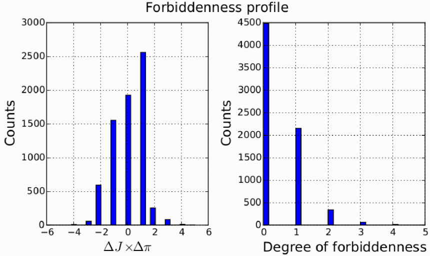


Oblate deformation for ^{33}Cl, ^{35}Ar changes sign & magnitude!

Level mixing for high Z, N is non-trivial

β participant sketch

Nuclear β decay is complicated



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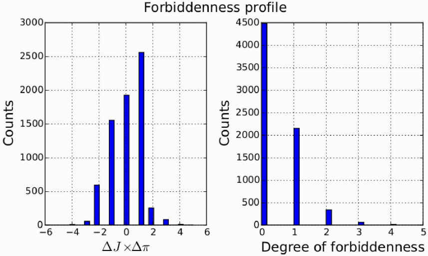

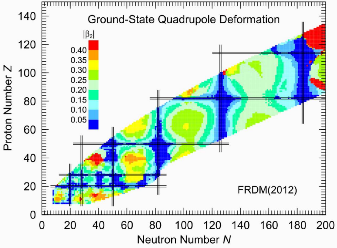

Both greatly influence the spectrum shape!

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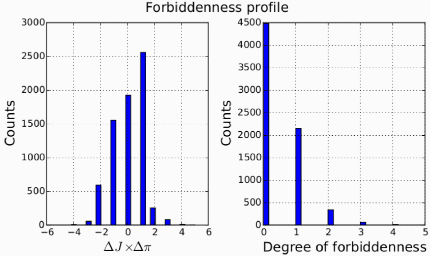
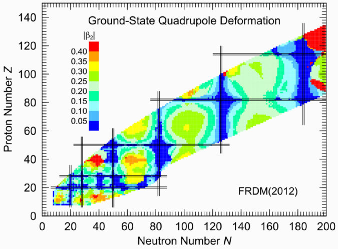


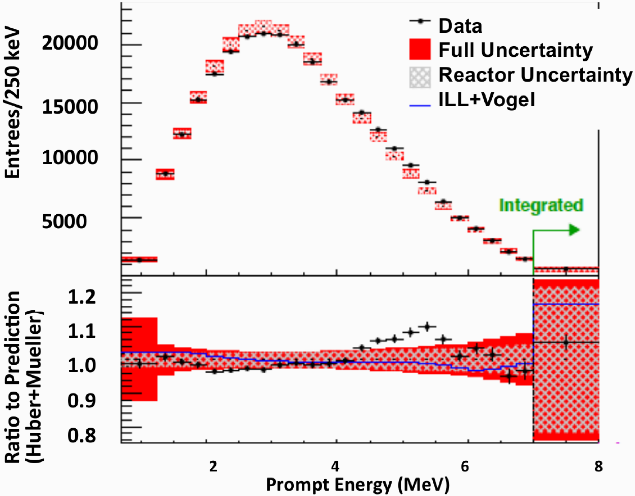


Both greatly influence the spectrum shape!

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

Möller *et al.*, ADNDT **109-110** (2016) 1; L.H. *et al.*, arXiv: 1709.07530

Reactor bump



Clearly something is not well understood, possibilities are plentiful

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

State of the art

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Approaches split up in 2:

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

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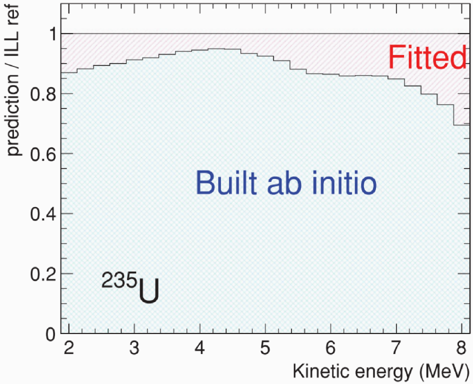
1. **Huber** method: virtual β branch fits
2. **Summation** method: Build from databases & extrapolate a la #1

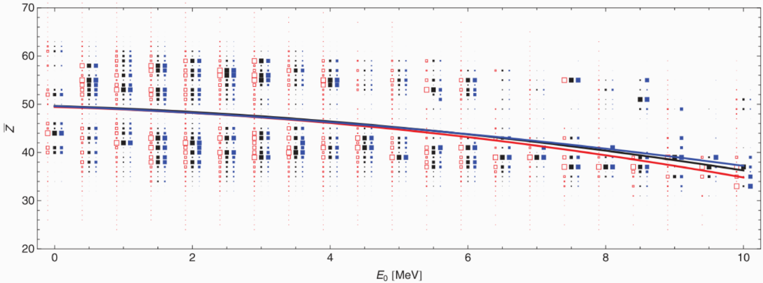


Much of *ab initio* is based on same spectral assumptions

Huber, PRC **84** (2011) 024617; Mueller *et al.*, PRC **83** (2011) 054615

Extrapolation & Virtual branches

How to construct these fictitious β branches?



Parametrised $\bar{Z}(E_0)$ fit with simple polynomial

P. Huber, PRC **84** (2011) 024617

Extrapolation & Virtual branches

Typical procedure

1. Make grid for E_0 in $[2, 12]$ MeV
2. Every gridpoint $E_{0,i}$, choose $Z(E_{0,i})$
3. Assume allowed shape, extrapolate average nuclear matrix elements
4. Fit VB intensities to cumulative exp. spectrum

$$S(E_e) = \sum_i c_i S(E_e, \bar{Z}(E_{0,i}), E_{0,i})$$

5. Invert spectra using $E_\nu = E_0 - E_e$

Extrapolation & Virtual branches

Huber (conversion) method has many issues:

- Estimated average b/Ac from spherical mirrors, but highly transition and deformation dependent
- Incorrectly estimates $(\alpha Z)^{n>1}$ effects, RNA$(\langle Z \rangle^{n>1}) \neq \langle \text{RNA}(Z^{N>1}) \rangle$!
- Fixed endpoints on grid
- ^{239}Pu/^{235}U is wrong
- Only allowed transitions (dominant $0^+ \leftrightarrow 0^-$ transitions)
- Quenching of g_A is absent
- ...

Predictions are **dubious**

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

Planned improvements

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Central idea is more realistic uncertainty by assessing 3 main sources of error

- Fission yields
- Proper (forbidden) spectral shapes
- Database extrapolation

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Collaboration with SCK-CEN for FY uncertainties, Jyvaskyla for forbidden shape factors

Forbidden shape factors

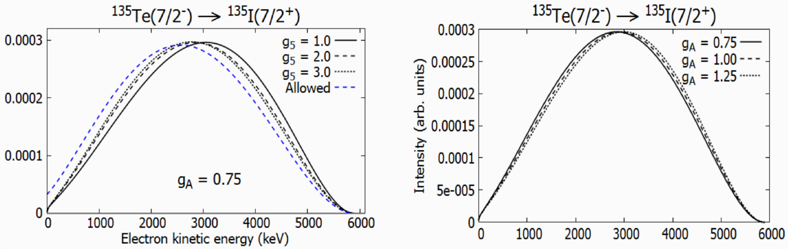
Out of thousands of β^- decays, many dominant are forbidden

Nuclide	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	GS β_2
^{96}Y	$0^- \rightarrow 0^+$	0.308
^{92}Rb	$0^- \rightarrow 0^+$	0.240
^{100}Nb	$1^+ \rightarrow 0^+$	0.412
^{135}Te	$(7/2-) \rightarrow 7/2^+$	-0.011
^{142}Cs	$0^- \rightarrow 0^+$	0.141
^{140}Cs	$1^- \rightarrow 0^+$	0.097
^{90}Rb	$0^- \rightarrow 0^+$	-0.105
^{95}Sr	$1/2^+ \rightarrow 1/2^-$	0.308
^{88}Rb	$2^- \rightarrow 0^+$	-0.073

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

Forbidden shape factors

Differences can be dramatic



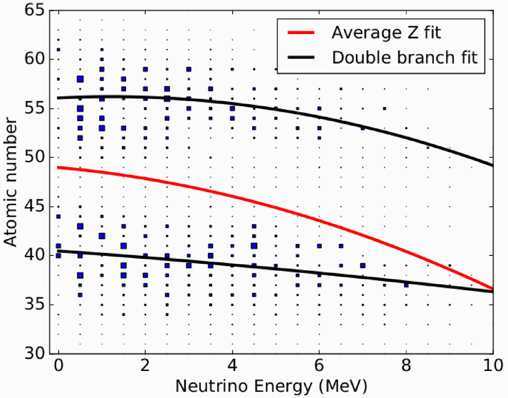
Additional uncertainty from g_A and γ_5 renormalization

Results by Joel Kostensalo (Jyvaskyla)

Database extrapolation

Database contains much more information to use

Trivial extension to improve $(\alpha Z)^2$ behaviour, fixed weights



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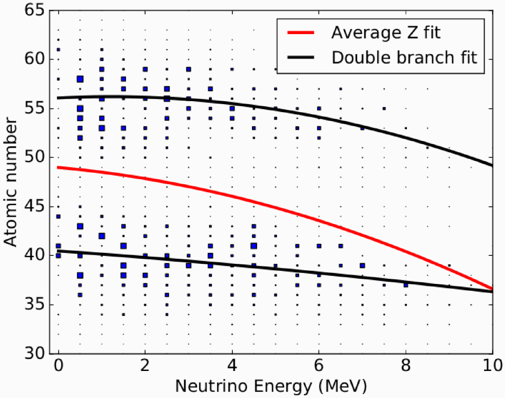
Employ Machine Learning clustering algorithms to find better patterns



Clustering & Machine Learning

Nuclear β decays live in high-dimensional vector spaces

- Z, A
- Branching Ratio, E_0, daughter excitation
- $\Delta J^{\Delta\pi}$ (forbiddenness, unique)
- Initial and final deformation
- ...

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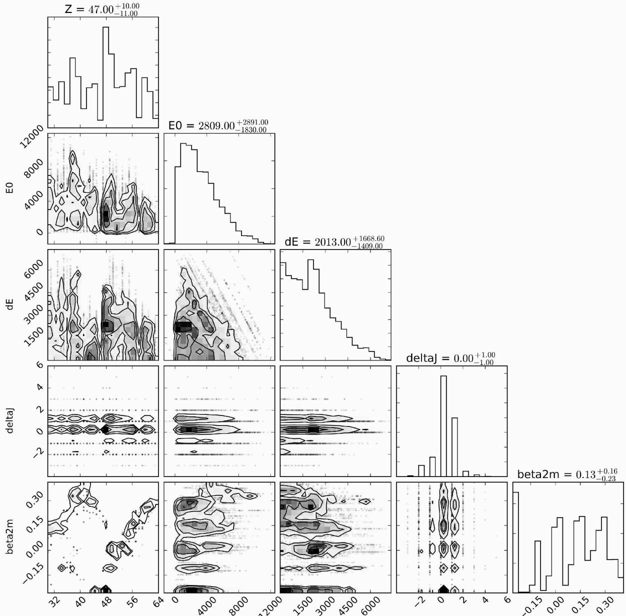
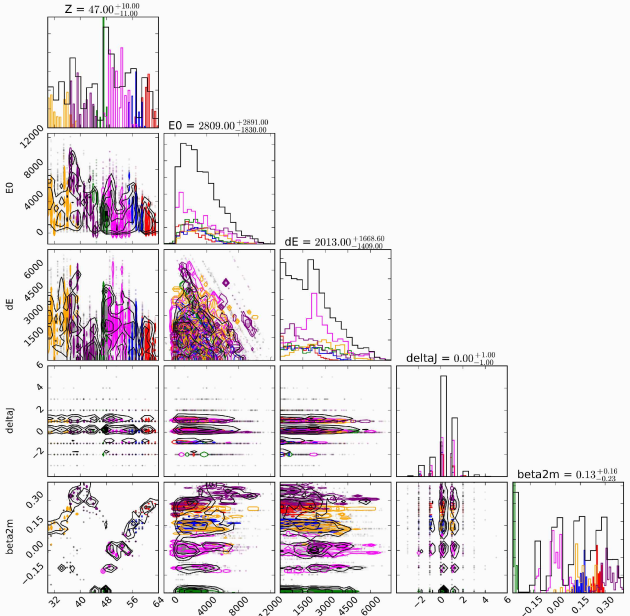
- $\ldots$

Clusters in high dimensions are smeared in 2D projections

Data visualization

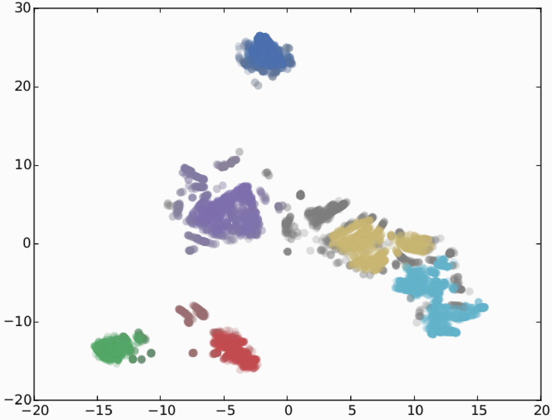


Data visualization - Clustering



Clustering visualisation

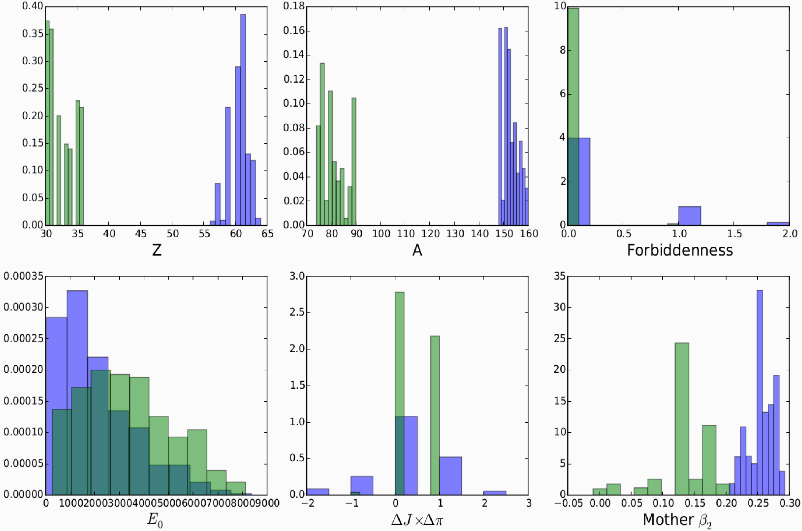
Use dimensional reduction (t-SNE) to visualise results



Clear clusters, intercluster distance irrelevant here

Intercluster comparison

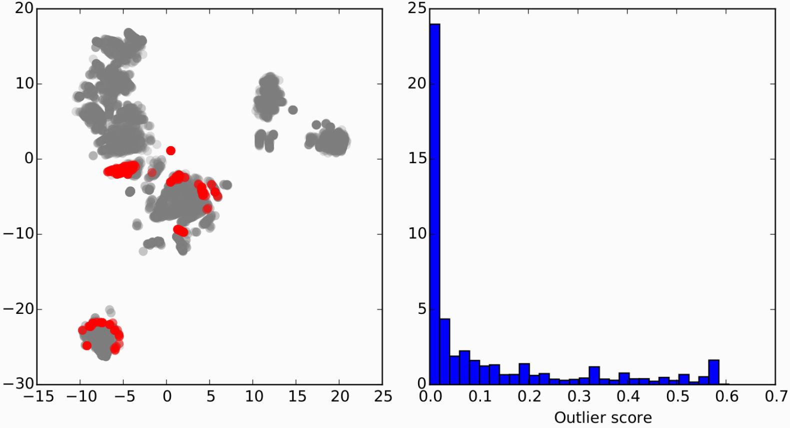
Example comparison for 2 clusters



Large differences visible for simple histograms!

Outliers

Check how many fall out of clusters



Almost all points belong firmly to a cluster!

Monte Carlo sampling

How to combine these results?

Instead of a single $Z(E_0)$ fit, use
Multidimensional Cluster Markov Chain Monte Carlo (MC^3)

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Build a **distribution** of anomaly $\rightarrow$ better uncertainty estimate

Virtual β branch creation

Procedure:

For each E_0 bin, for each cluster, build sampling distribution

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Bayes' theorem:

$$P(\theta|d) = \frac{P(\theta)P(d|\theta)}{P(d)}$$

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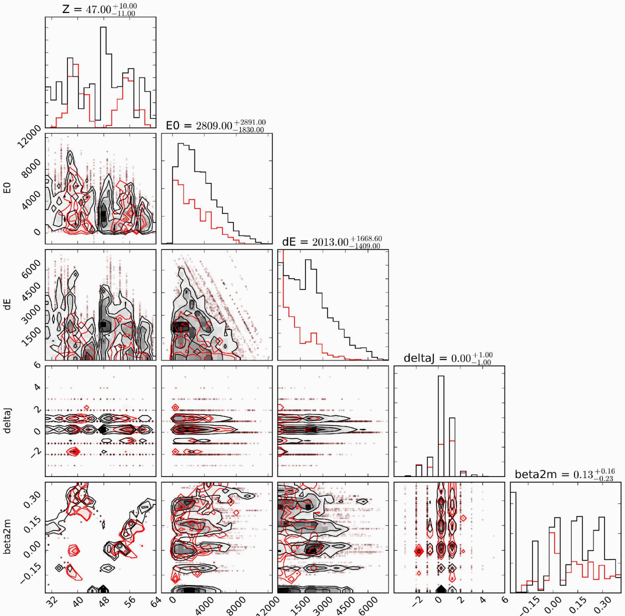
$$P(\theta|d) = \frac{P(\theta)P(d|\theta)}{P(d)}$$

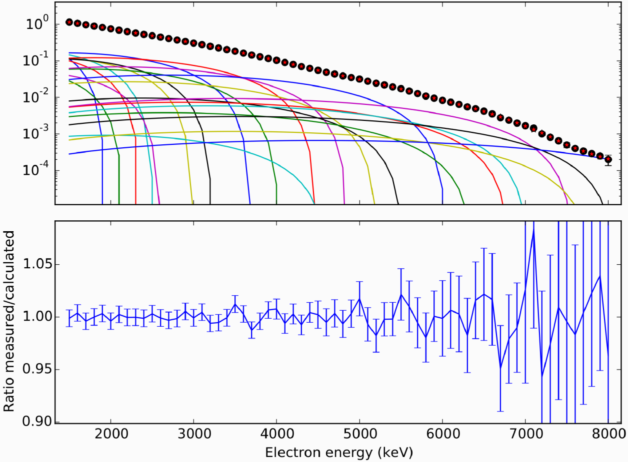
Prior ($P(\theta)$): intrinsic probability for a β branch,
fission yield $\times$ BR
Likelihood ($P(d|\theta)$): probability for point to belong to cluster

Continue with affine-invariant MCMC (shape-insensitive)

Weighted visualization



Virtual β branch creation



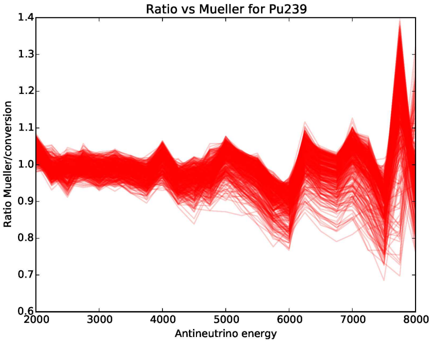
Electron Schreckenbach fits are typically well below 1% with limited # branches

Statistical Conditions

After

conversion to $\bar{\nu}_e$ spectrum,

obtain ratio R_i $(i = 5, 8, 9, 1)$



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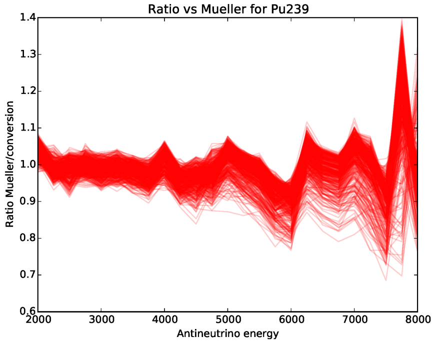


Traditionally

use fit results & uncertainty

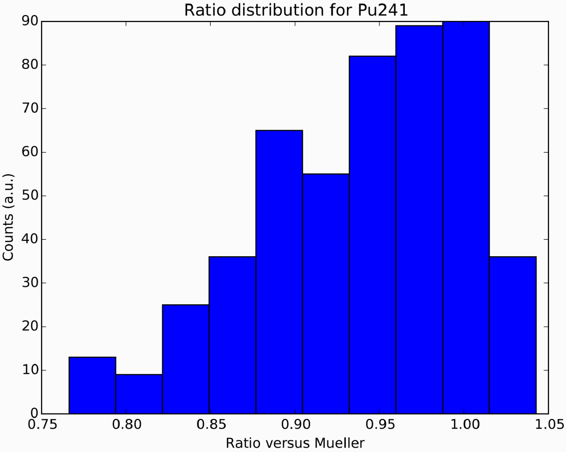
from χ^2 minimization

Only

correct when underlying pdf

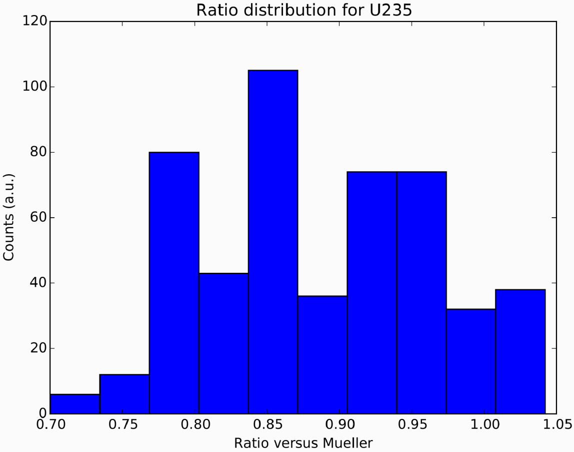
- Symmetric
- Unimodal
- Gaussian

Proof of concept results



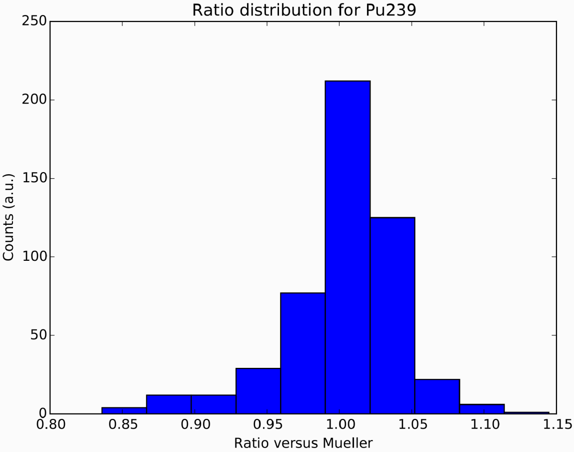
~~Symmetric~~

Proof of concept results



~~Unimodal~~

Proof of concept results



~~Gaussian~~

Statistical validity

Results are very much **preliminary**, prepare salt

However, interesting trends appear to

- violate previously used statistical inference methods
- increase uncertainties significantly

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Still simplest case, haven't even used cluster information, or nuclear structure!

Sensitivity to weak magnetism

Main allowed correction matrix element

$$\frac{b}{Ac} = \frac{1}{g_A}\left[g_M + g_V\frac{M_L}{M_{GT}}\right]$$

From low-Z mirror systems, $b/Ac \sim 5$, however

- For $I \pm 1/2 \to I \pm 1/2$ transitions, $b/Ac \propto \pm I$

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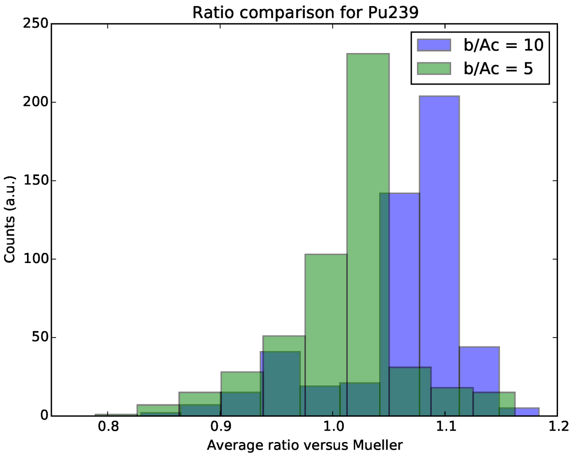
- For $I \pm 1/2 \to I \pm 1/2$ transitions, $b/Ac \propto \pm I$
- $I \pm 1/2 \to I \mp 1/2 =$ constant, but deformation mixes oscillator shells
- Strong g_A quenching in heavy systems

Pretty easily see this going upward, subject of further study

Sensitivity to weak magnetism



Doubling of weak magnetism produces shift $\sim$ anomaly, however prepare salt!

Summary

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Current anomaly analysis has shaky foundation

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Triple-pronged approach to better assess (mean, σ)

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Triple-pronged approach to better assess (mean, σ)

Nuclear β decays live in high-dimensional clusters, use of Machine Learning to investigate