Taming the nuclear β hydra

One theoretical head at a time

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UvA, October 30th 2017

IKS, KU Leuven, Belgium

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Introduction

Three basic questions:

What's our goal?

Understand Standard Model & Go Beyond

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Where to look for it?

Quirky weak interaction!

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Quirky weak interaction!

How?

Nuclear β decay, because

- Small-medium scale experiments
- Wealth of different transitions
- Many available observables

Introduction

General Hamiltonian

$$\mathcal{H} = \sum_{j=V,A,S,P,T} \langle f| \mathcal{O}_j |i\rangle \langle e| \mathcal{O}_j [C_j + C_j^{'} \gamma_5] |\nu\rangle + h.c.$$

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Questions:

In Standard Model only V-A $\rightarrow$ where are the **others**?

Could there be *right-handed* currents? Search for V+A components

Beyond SM searches

Usual paradigm:

- High energy, high intensity

  Produce particles **on** mass shell $\rightarrow$ resonance
- Low energy, high precision

  Deviations from SM from **off**-shell effects

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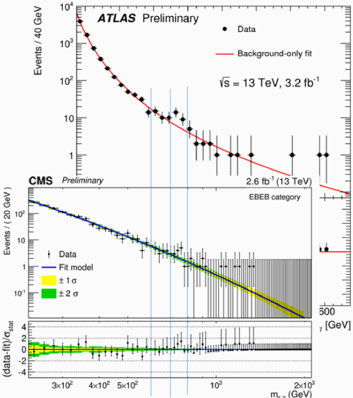
However. . .

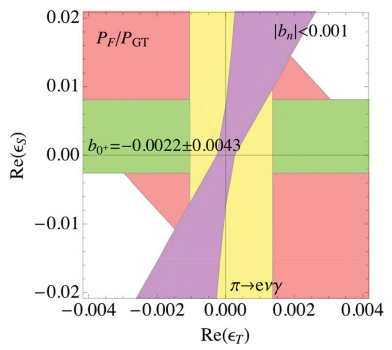
LHC came up empty-handed

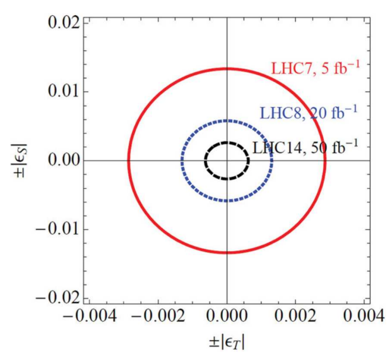
How to proceed?



Search for exotic currents

Analysis in model-independent Effective Field Theory





Low and high energy experiments are competitive & complementary!

Naviliat-Cuncic & González-Alonso, Ann. Phys. **525** (2013) 600

Minimal left-right symmetric model

Restore symmetry at high scale, introduce trivial coupling

$$\begin{pmatrix} W_L \\ W_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \end{pmatrix} \qquad M_2 \gg M_1 \ \& \ \zeta \ll 1$$

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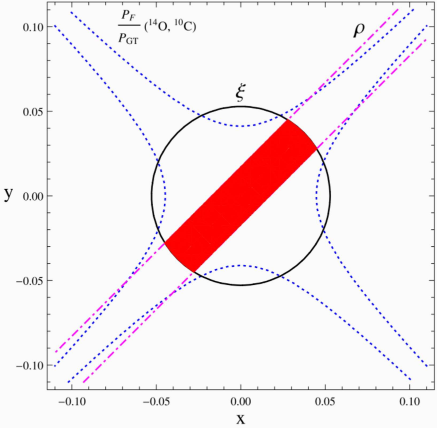

Holstein, J. Phys. G **41** (2014) 114001

BSM Observables in β decay

Typical BSM searches through correlations

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_F \frac{m_e}{E_e} + A\frac{\vec{p_e}}{E_e}\langle\vec{I}\rangle + \ldots$$

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Sensitivity comes from b_F

$$b_F = \pm\frac{1}{1+\rho^2}\left[\mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) + \rho^2\mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right)\right]$$

because it's linear in coupling constants

$\rightarrow$ measure β spectrum directly & fit for $1/E_e$

Beta spectrum shape

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:

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

$$A_\mu(q^2) \rightarrow i\langle \bar{u}_p | g_A \gamma_5 \gamma_\mu + i \frac{g_P}{2M} \gamma_5 q_\mu | u_n \rangle \quad (+\text{ induced pseudoscalar})$$

Induced pseudoscalar is typically ignored.

Beta Spectrum Shape

Exploring the Standard Model and Beyond via the allowed β spectrum shape:

$$\frac{dN}{dE_e} \propto 1 + b_{\text{Fierz}}\gamma\frac{m_e}{E_e} + b_{WM}E_e$$

b_{Fierz}: Proportional to scalar (Fermi) and tensor (Gamow-Teller) couplings

b_{WM}: Weak Magnetism (main induced current), poorly known for $A > 60$, forbidden decays

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This requires knowledge of the theoretical spectrum shape to $\leq 10^{-3}$ level!

Analytical beta spectrum shape

Recently accomplished: Fully analytical description

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

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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

Atomic exchange

Exchange: Probability of decaying into bound state with emission of bound e^-

$$X(E) = 1 + \sum_n \eta_{ex}^{ns}(E)$$

where

$$\eta_{ex}^{ns}(E) \propto \langle Es' | ns \rangle$$

spatial overlap between continuum and bound wave functions

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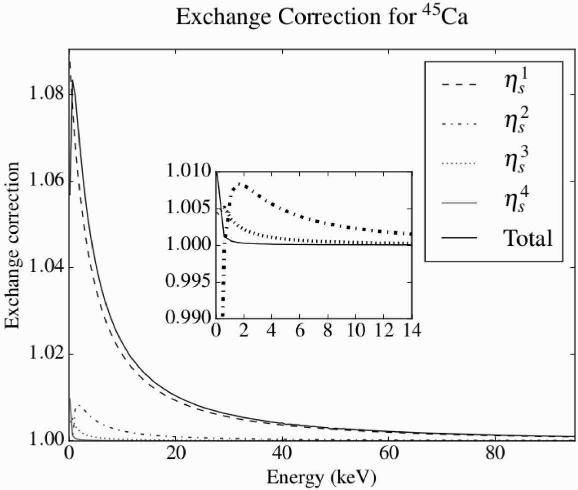
Need accurate wave functions for arbitrary potentials over the entire space $\rightarrow$ numerical!

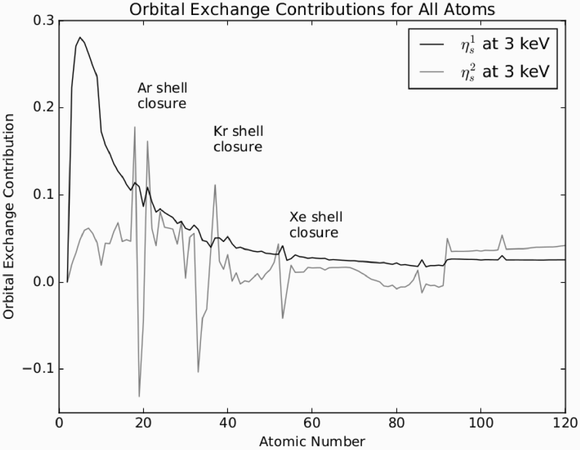
Atomic Exchange



Destructive interference for some orbitals

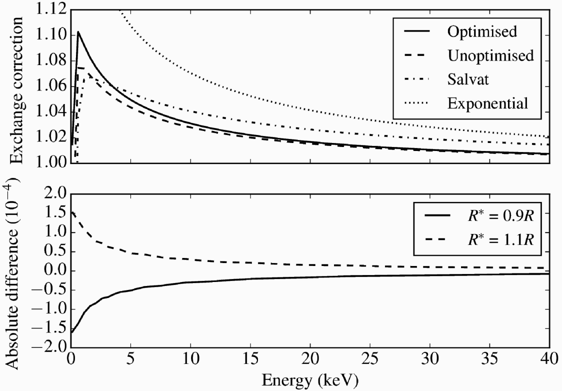
Atomic Exchange

Contributions from different orbitals → sensitive to *atomic* physics!



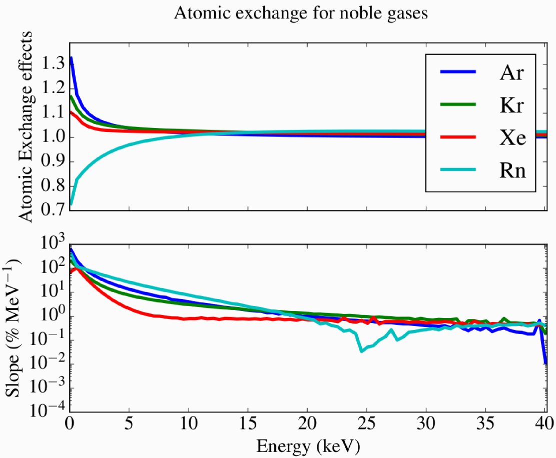
Sensitivity of calculations

Numerical calculations are non-trivial, require careful optimisation and not 'user-friendly'



Provide analytical fit to 10^{-4} level for all Z over full energy range

Measuring atomic exchange



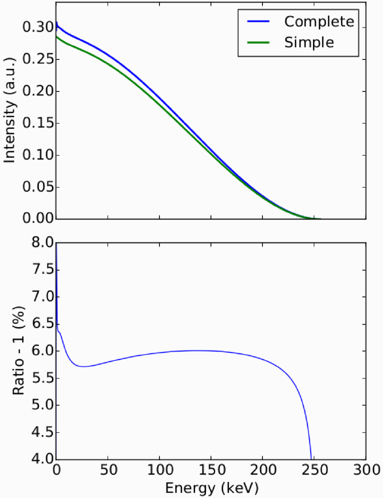
General features:

- Intensity at 0 keV is largely *Z-independent*
- Persistance increases for larger Z

Example: ^{45}Ca

Meet ^{45}Ca, an interesting physics candidate

- 99.998% g.s. to g.s.



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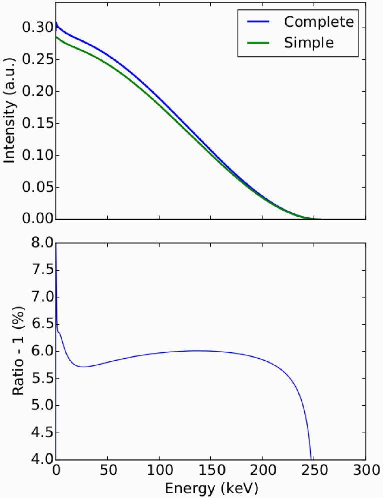

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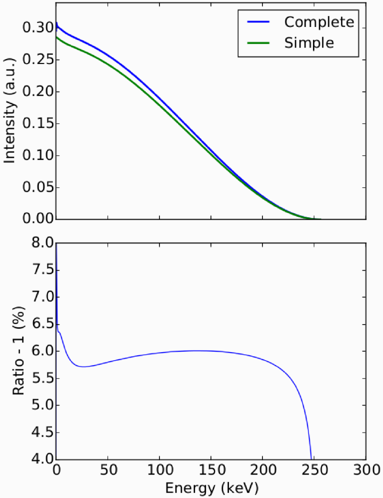

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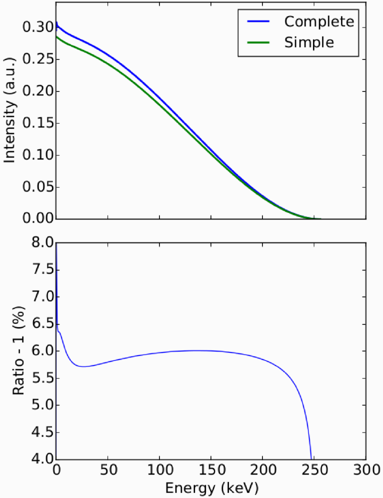
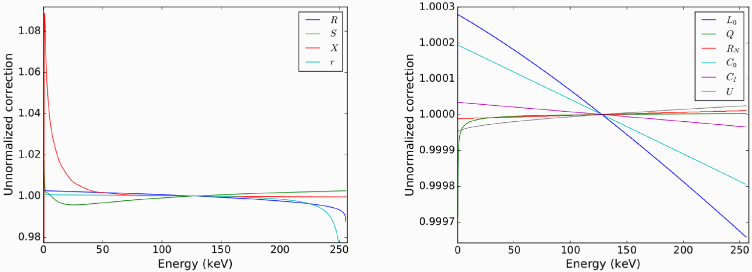


Additional pros:

- Spherical
- Odd-A, simple $f_{7/2}$ wave function

Example: ^{45}Ca

Reasonably small $Z \rightarrow$ most corrections are small

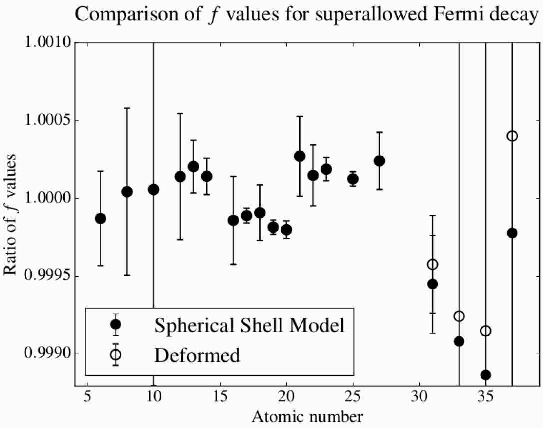


Low endpoint $\rightarrow$ Atomic effects are relatively important

Performance check

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

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



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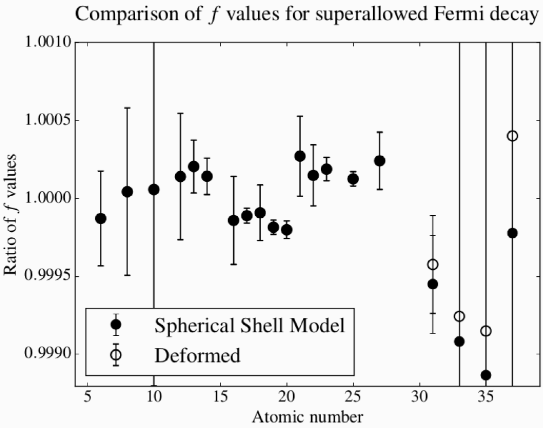
Largest deviations are for **extremely deformed** isotopes.



I. Towner *et al.*, PRC **91** (2015) 025501

Mirror transitions

Harder case: $T = 1/2$ mirror decays, mixed Fermi and Gamow-Teller, but

- Exact benchmark for weak magnetism through CVC
- Mixing ratio doesn't enter comparison

Need to calculate 3 nuclear matrix elements, real test

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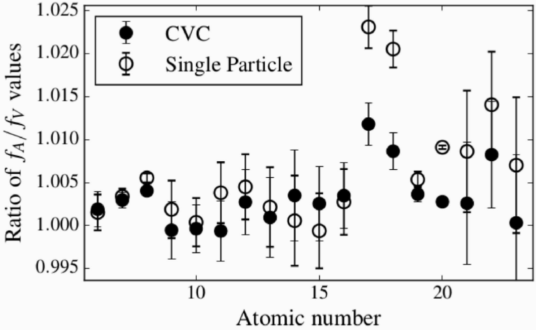
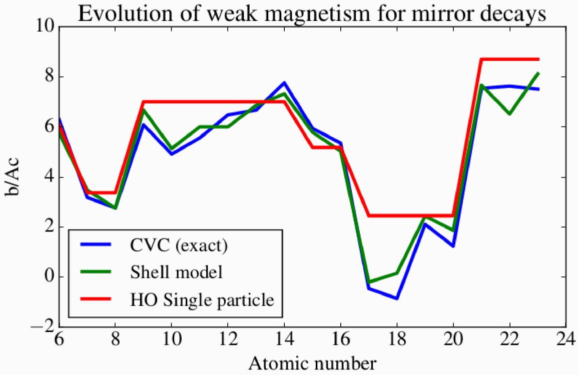


Weak magnetism

Weak magnetism has a large influence, so let's check how we're doing



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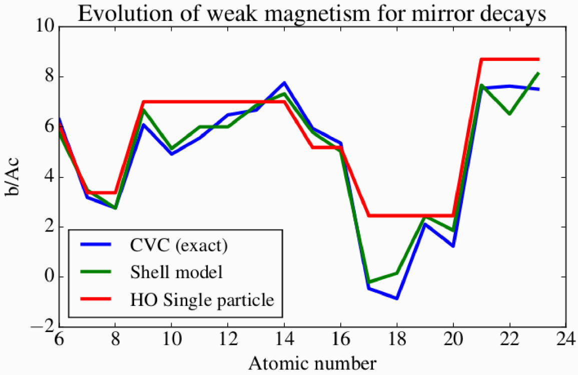

General features are reproduced, but still strong deviations → give up and blame nuclear structure?

Nuclear deformation

We can do better than that, and still use extreme single particle

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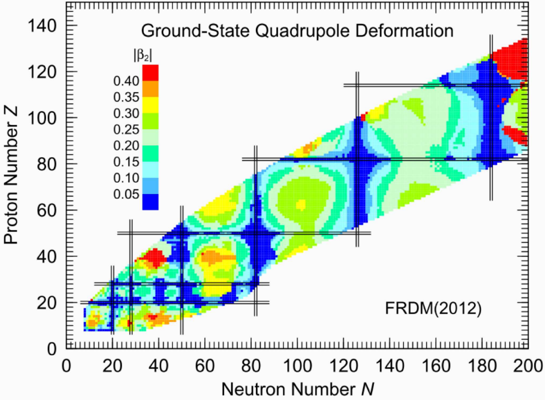
Heavier cases suffer from high deformation



P. Möller *et al.*, arXiv:1508.06294 (2015)

Deformed Woods-Saxon

Use axially deformed Woods-Saxon (DWS) potential instead of simple *jj*-coupling scheme $\rightarrow$ reformulate matrix elements in terms of Nilsson-like wave functions

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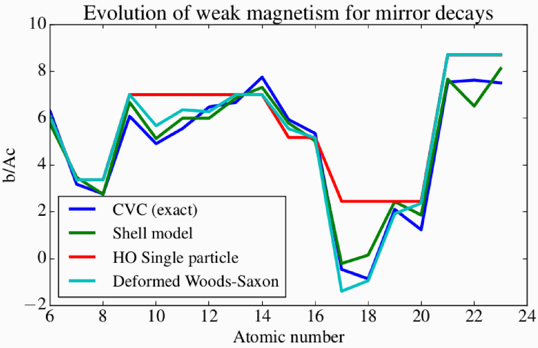
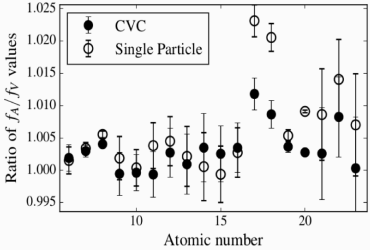


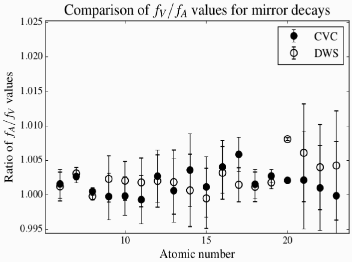
Differences smaller than 20%, correct sign always reproduced.

Performance check

Comparison to Towner *et al.* mirror calculations



(a) Simple Harmonic Oscillator



(b) Deformed Woods-Saxon

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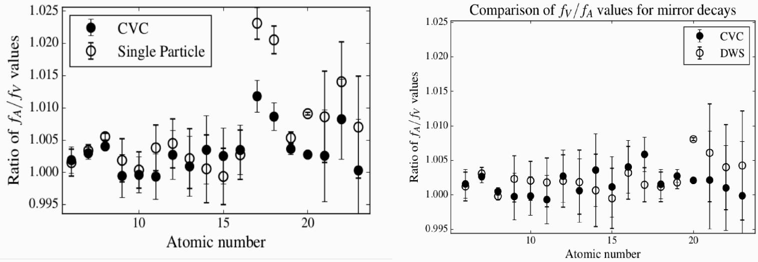

(a) Simple Harmonic Oscillator **(b)** Deformed Woods-Saxon

Two important remarks:

1. Deformation effects are **indispensible** and agree very well
2. Large deviations due to b_{wm}, but shell model roughly as precise as DWS $\rightarrow$ Towner *et al.* are only precise to $\mathcal{O}(10^{-3})$.

I. Towner *et al.*, PRC **91** (2015) 025501

Induced Pseudoscalar: Validity of neglect

Induced pseudoscalar is typically neglected because $\mathcal{O}(g_P W_0/M^2)$.

Applying nucleon PCAC gives

$$g_P(q^2) = -g_A(q^2)\frac{(2M_n)^2}{m_\pi^2 - q^2},$$

so for neutrons $g_P(0) \approx -229$, **not negligible**.

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so for neutrons $g_P(0) \approx -229$, **not negligible**.

However, in nuclear medium g_P is modified through meson exchange and is quenched, but value uncertain.

Retaining induced pseudoscalar

Keeping g_P corresponds to

$$C(Z,W) \to C(Z,W) + \Phi\,\mathcal{P}(Z,W)$$

with

$$\Phi = \frac{g_P}{g_A}\frac{1}{(2M_nR)^2} \lesssim 0.1$$

with relative differences $\mathcal{O}(10^{-3})$ (unquenched), similar to experimental σ!

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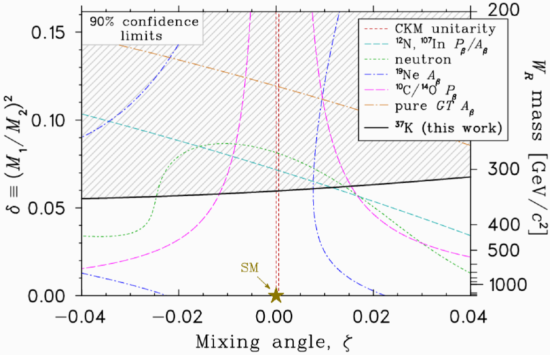
Knowledge of g_P becomes crucial for increasing precision & V_{ud} extraction from mirrors

Experiment: Spin-polarized ^{37}K @ TRIUMF

Most precise published measurement:

$$A_\beta = -0.5707(12)_{\text{syst}}(13)_{\text{stat}}(5)_{\text{pol}}$$

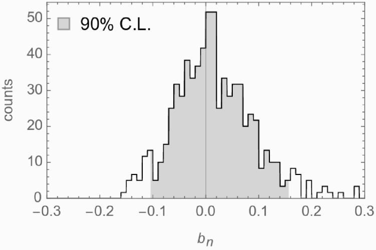


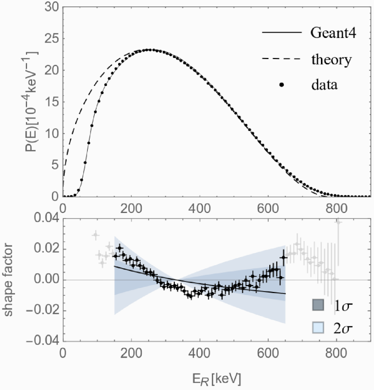
B. Fenker *et al.*, arXiv: 1706.00414

Experiment: UCNA @ LANSCE

First extraction of b_F from spectrum shape

$$b_F = 0.067 \pm 0.005_{\text{stat}}\,{}^{+0.090}_{-0.061}\,{}_{\text{syst}}$$

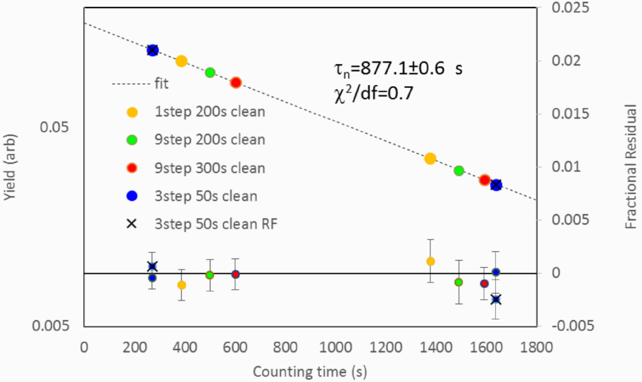




Hickerson *et al.*, arXiv: 1707.00776

Experiment: UCNτ @ LANSCE

Bottle neutron lifetime



First time corrections < syst. error!

Pattie Jr. *et al.*, arXiv: 1707.01817

Outlook

New results from UCNA, aCORN

Several experiments ongoing

- ^{6}He, ^{20}F @ MSU
- ^{8}Li @ Argonne
- Nab @ ORNL
- ^{32}Ar @ ISOLDE
- . . .

Exciting times!

Reactor antineutrino anomaly

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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Prediction error (mean, σ) or sterile neutrino's, something else

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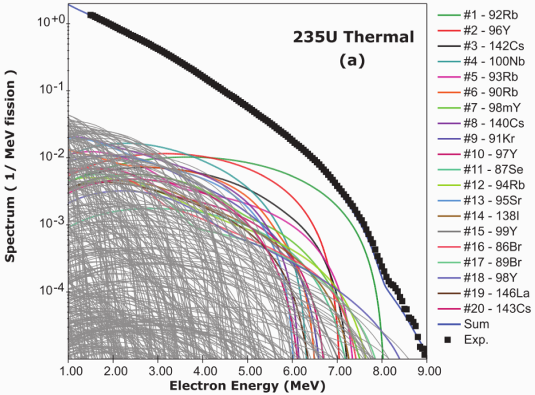
When new physics lurks, look out for quirks!

Antineutrino origin

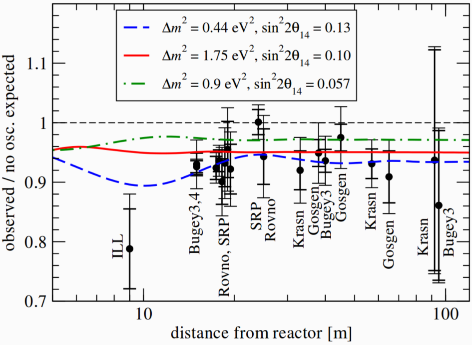
Fission fragments from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu have many β^- branches, but can only measure cumulative spectrum.



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

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

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



Very exciting, but. . . it is real?

Deficiency and particle physics proposal

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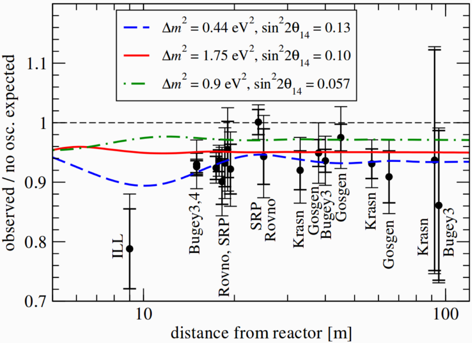
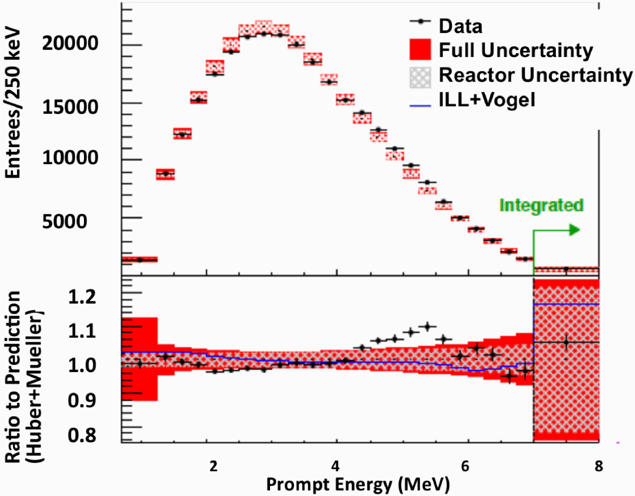


Very exciting, but. . . it is real?

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

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

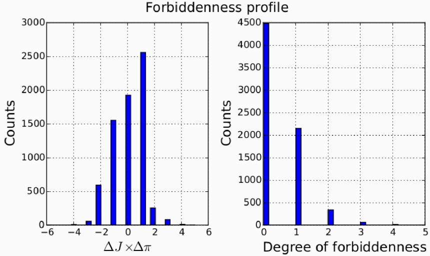
Reactor bump



Clearly something is not well understood, possibilities are plentiful

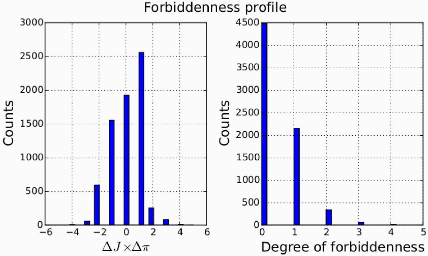
β participant sketch

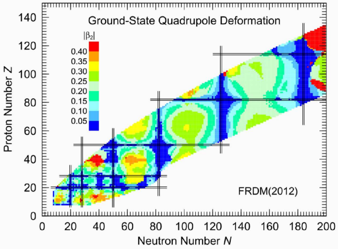
Nuclear β decay is complicated



β participant sketch

Nuclear β decay is complicated





Both greatly influence the spectrum shape!

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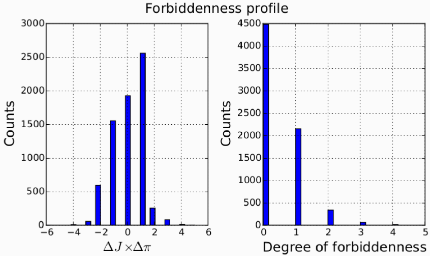
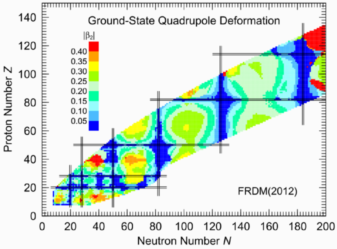




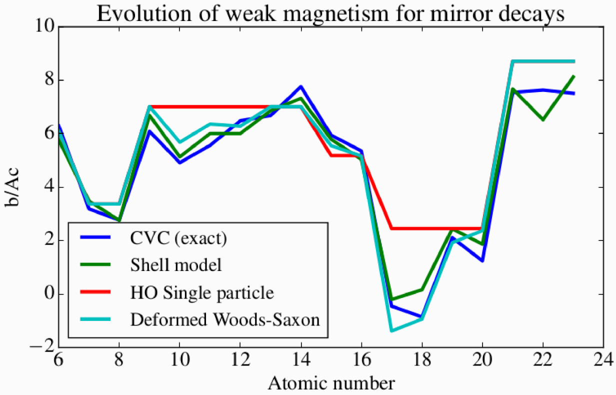
Both greatly influence the spectrum shape!

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

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

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

State of the art

Approaches split up in 2:

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

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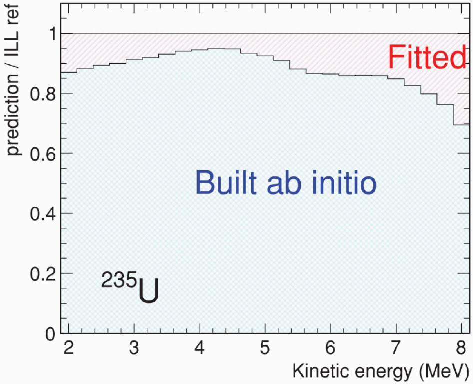
Approaches split up in 2:

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

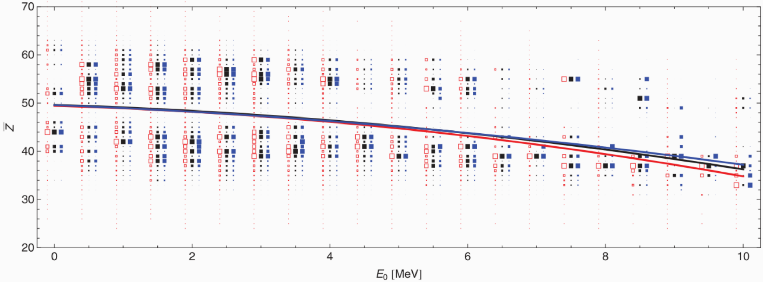


Much of *ab initio* is based on same spectral assumptions

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

Extrapolation & Virtual branches

How to construct these fictitious β branches?



Parametrised $Z(E_0)$ fit with simple polynomial

Assume allowed shape, extrapolated average nuclear matrix elements

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

Extrapolation & Virtual branches

Huber (extrapolation) model has many issues:

- Estimated average b/Ac from spherical mirrors, but highly transition and deformation dependent
- Incorrectly estimates $(\alpha Z)^2$ effects, $\mathrm{RNA}(\langle Z\rangle^2) \neq \langle \mathrm{RNA}(Z^2)\rangle$!
- ^{239}Pu cross section does not agree with experiment
- Only allowed transitions (dominant $0^+ \leftrightarrow 0^-$ transitions)
- Quenching of g_A is absent
- ...

Predictions are **dubious**

Planned improvements

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

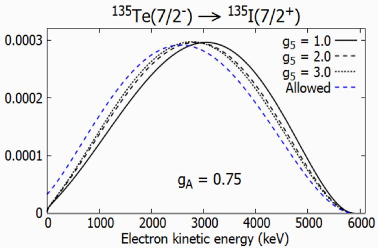
Out of thousands of β^- decays, many dominant are forbidden

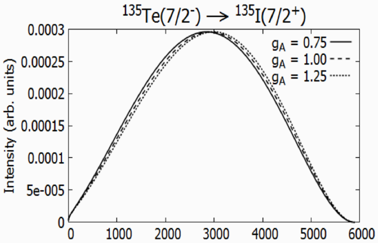
Nuclide	$J^\pi_{gs} \to J^\pi_{gs}$	Contr. (%)	GS β_2
^{96}Y	$0^- \to 0^+$	6.3	0.308
^{92}Rb	$0^- \to 0^+$	6.1	0.240
^{100}Nb	$1^+ \to 0^+$	5.5	0.412
^{135}Te	$(7/2-) \to 7/2^+$	3.7	-0.011
^{142}Cs	$0^- \to 0^+$	3.5	0.141
^{140}Cs	$1^- \to 0^+$	3.4	0.097
^{90}Rb	$0^- \to 0^+$	3.4	-0.105
^{95}Sr	$1/2^+ \to 1/2^-$	3.0	0.308
^{88}Rb	$2^- \to 0^+$	2.9	-0.073

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

Forbidden shape factors

Differences can be dramatic





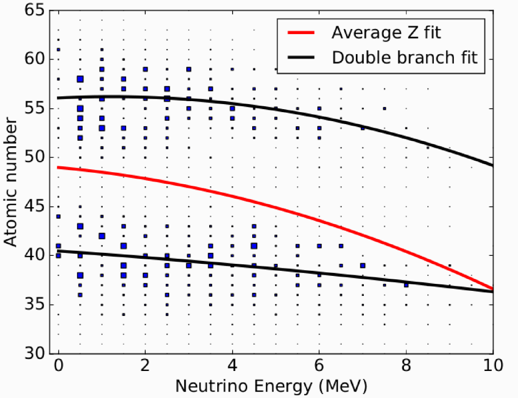
Additional uncertainty from g_A and γ_5 renormalization

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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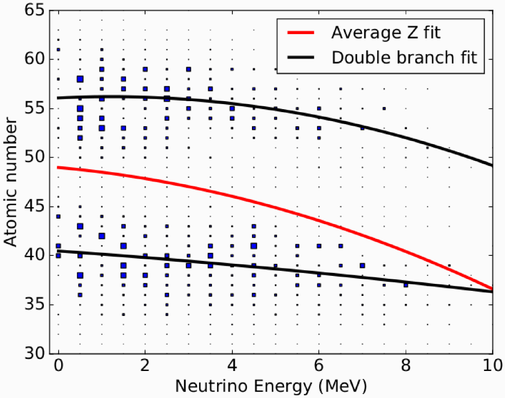
Employ Machine Learning clustering algorithms to find better patterns



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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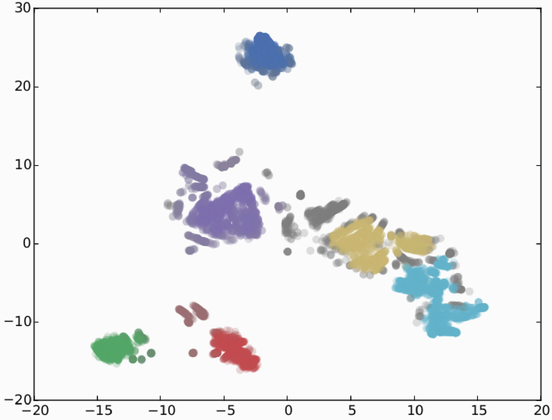
Clusters in high dimensions are smeared in 2D projections

Clustering visualisation

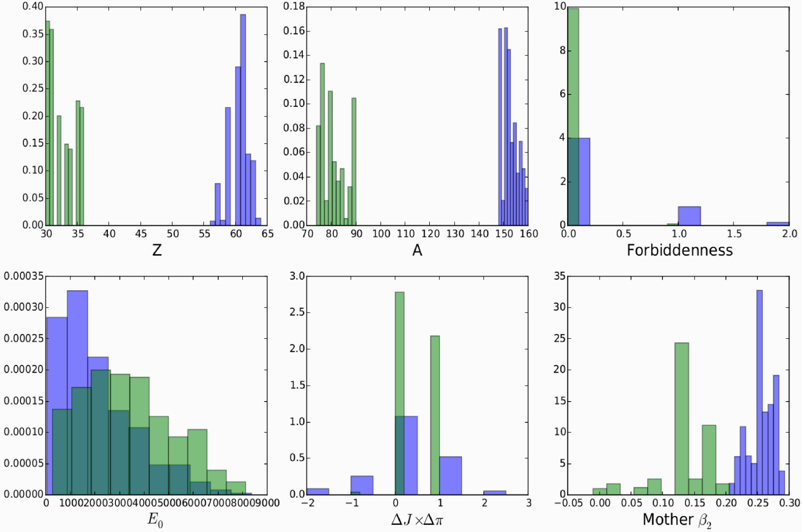
Use dimensional reduction (t-SNE) to visualise results



Clear clusters, intercluster distance irrelevant here

Intercluster comparison

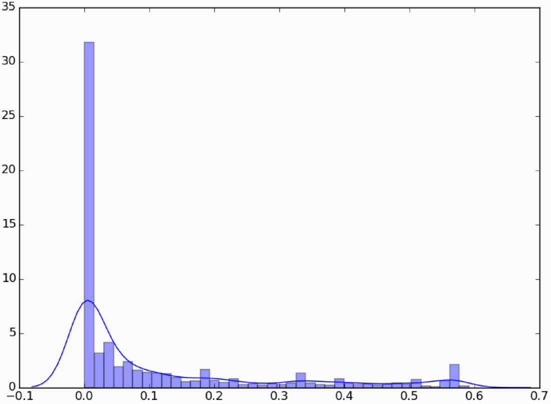
Example comparison for 2 clusters



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 Monte Carlo to sample

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

Anomaly Summary

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

Summary & Outlook

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Reactor anomaly most likely artefact from oversimplified β spectrum analysis $\rightarrow$ to be fixed, new techniques!


"It's a
dangerous
business, going
out your
door."