INSTITUTE for NUCLEAR THEORY

INT PROGRAM INT-23-1B

New physics searches at the precision frontier

May 1, 2023 - May 26, 2023

DORON GAZIT

RACAH INSTITUTE OF PHYSICS

HEBREW UNIVERSITY OF JERUSALEM

האוניברסיטה
העברית
בירושלים

PRECISION EXPERIMENTS AND ACCURATE THEORY OF NUCLEAR BETA DECAYS AS STANDARD MODEL TESTS

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U Chicago
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NC State University
Albert Young

"The darkest places in hell are reserved for those who maintain their neutrality in times of moral crisis" (Dante Alighieri)

INTRODUCTION

- The *energy frontier* (LHC) is a direct avenue to study physics Beyond the Standard Model (BSM).
- However, to date, the most important signatures for deviations from the Standard Model arose in the *precision frontier* – high precision combined theory-experiment effort: neutrino mass, W mass, and muon g-2.
- These signatures provide motivation to search for more deviations in the electroweak sector.
- Nuclear phenomena have an important role in the *precision frontier* in the search for BSM signatures:
  - New techniques allow unprecedented experimental accuracy.
  - Theory can have controlled accuracy, with high precision, description of these phenomena, to analyze experimental results and pinpoint new physics.
- Studies of *nuclear beta-decay observables* have proven in the past as very effective in pin-pointing hints for new physics.

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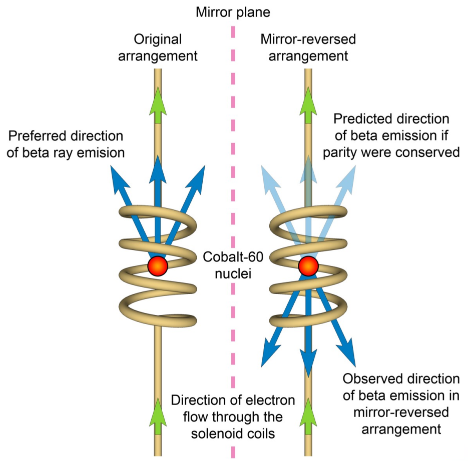
BETA DECAY OBSERVABLES – IN THE QUEST FOR BSM SIGNATURES

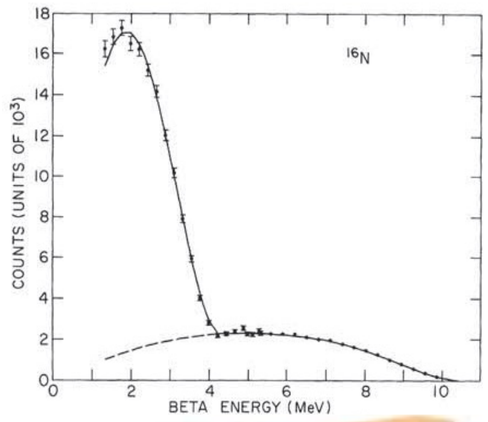
- We search for observables sensitive to interference of Standard Model currents with the new physics.
- New physics can thus appear as additionnal gauge fermion "f" vertices with W: $W - f - f'$ or new contact four fermion interactions generated by exchange of heavy particles. Thus, we expect an effect to scale as:
  $G_F \cdot \epsilon_\alpha$ where $\alpha \in \{L, R, S, P, T\}$ labels the Lorentz structure of the interaction.
- This is an effective field theory approach to the extended Standard Model, where the dimensionless couplings relate to new physics scale Λ via:
  $\epsilon_i \approx \left(\frac{v}{\Lambda}\right)^2$ with $v \approx 174\mathrm{GeV}$ the SM VEV.
- Thus, experimental sensitivity for $\epsilon_i < 10^{-3}$ can explore new physics at the largely unexplored $\Lambda = few$ TeV scale.

β decays

Precision Correlation Studies



Precision spectrum studies



V. Cirigliano, A. Garcia, DG, O. Naviliat-Cuncic, G. Savard, A. Young, Precision beta decay as a probe of new physics, arXiv:1907.02164 (2019).

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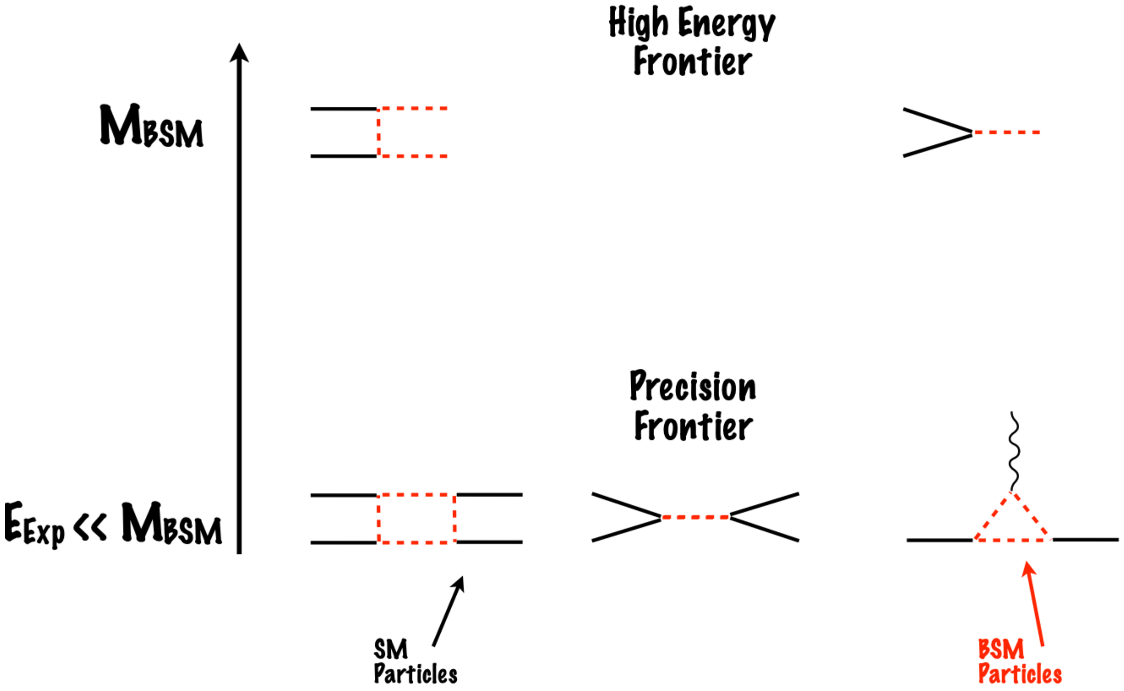

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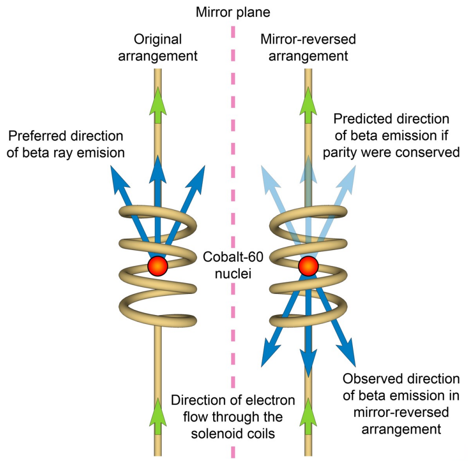

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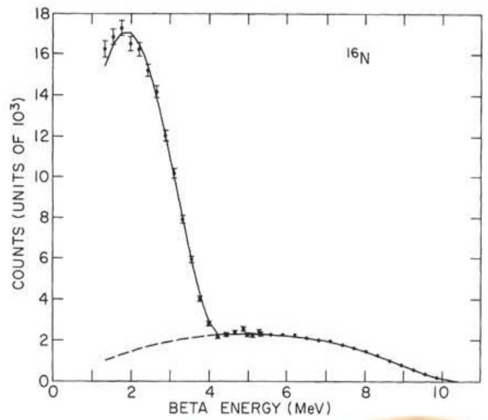

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NUCLEAR BETA DECAY EXPERIMENTS IN SEARCH FOR BSM PHYSICS (2019)

Energy spectrum

TABLE III. List of nuclear β-decay spectral measurements in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
β spectrum	GT	^{114}In	MiniBETA-Krakow-Leuven	0.1 %
β spectrum	GT	^{6}He	LPC-Caen	0.1 %
β spectrum	GT	^{6}He, ^{20}F	NSCL-MSU	0.1 %
β spectrum	GT, F, Mixed	^{6}He, ^{14}O, ^{19}Ne	He6-CRES	0.1 %

[a] Experiments specifically searching for time-reversal symmetry violation not listed here

Angular correlation

TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta-\nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta-\nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta-\nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta-\nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta-\nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas A&M	0.1 %
$\beta-\nu$	Mixed	^{11}C, ^{13}N, ^{15}O, ^{17}F	Notre Dame	0.5 %
β & recoil asymmetry	Mixed	^{37}K	TRINAT-TRIUMF	0.1 %

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BETA DECAY OBSERVABLES

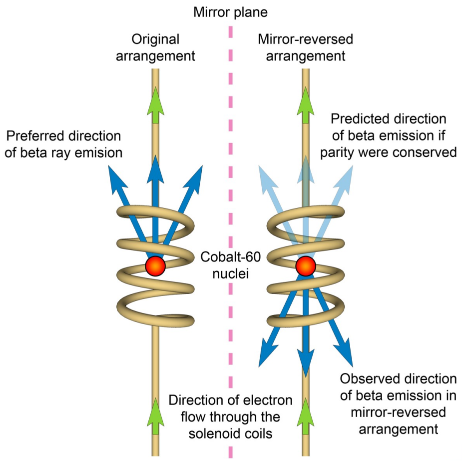
Experimental sensitivity of 10^{-4} + Theoretical calculation to 10^{-4} = New physics exploration at 10 TeV

At the ***Hebrew University***, we have combined experimental and theoretical efforts for precision β-decay studies.

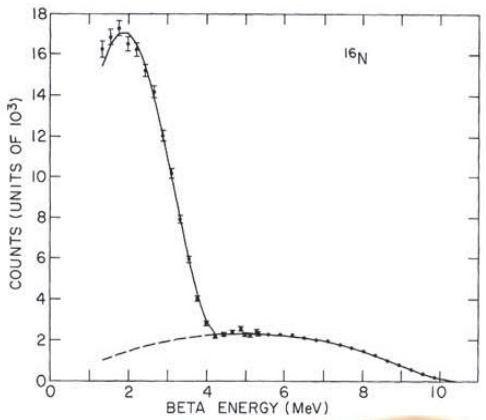
The scope of our studies is enhanced by use of short-lived radioactive nuclei, that will be produced at the **SARAF-II** accelerator in Israel.

β decays

Precision Correlation Studies



Precision spectrum studies



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BETA DECAY OBSERVABLES

Experimental sensitivity of 10^{-4}

+

Theoretical calculation to 10^{-4}

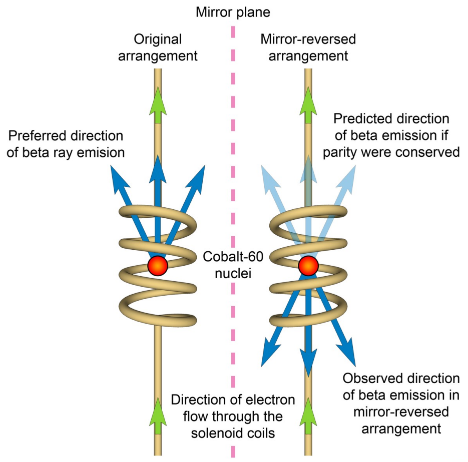
=

New physics exploration at 10 TeV

WHAT ARE THE THEORY NEEDS FOR SUCH CALCULATION?

β decays

Precision Correlation Studies



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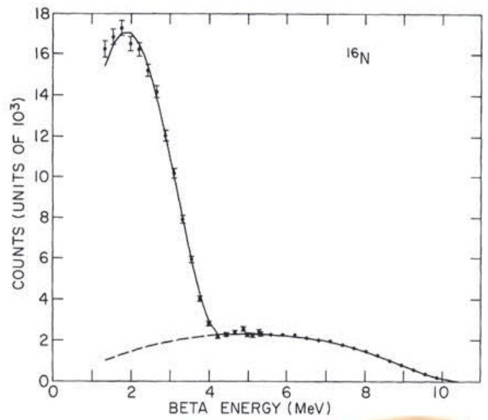

(NUCLEAR) THEORY NEEDS

- The main challenges of theory, and especially nuclear theory, include three main fronts:
  - nuclear structure corrections, to known precision and accuracy, to the interaction of the electro-weak probes with the nucleus, beyond the leading order approximation of the probes interacting with a single nucleon in the nucleus;
  - nuclear structure effects in the calculation of radiative corrections, particularly the γ-W box;

    See Misha Gorshteyn's talk
  - a lattice-QCD assessment of nucleon charges, essential to connect nuclear observables to quark-level couplings. In particular, the uncertainties in g_A, g_S, and g_T, limit the sensitivity to ε_R, ε_S, and ε_T, respectively.

    See Ross Young's talk

האוניברסיטה העברית בירושלים

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THEORETICAL ANALYSIS OF CORRECTIONS IN AND BEYOND THE STANDARD MODEL

Glick-Magid, DG (JPhG 2022, PRD 2023)

PRECISION Β-DECAY STUDIES TO PINPOINT BSM EFFECTS

Differential β decay rate

$$\frac{d^5\omega_{\beta\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q, \vec{\beta}\cdot\hat{\nu})$$

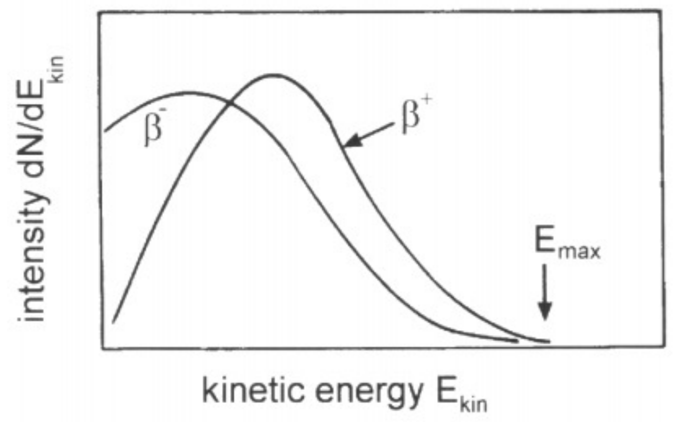
Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear independent part

$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon)\times(corrections)$$



PRECISION B-DECAY STUDIES TO PINPOINT BSM EFFECTS

$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon)\times(corrections)$$

Item	Effect	Formula	Magnitude
1	Phase space factor [a]	$pW(W_0-W)^2$	Unity or larger
2	Traditional Fermi function	F_0	
3	Finite size of the nucleus	L_0	10^{-1}-10^{-2}
4	Radiative corrections	R	
5	Shape factor	C	
6	Atomic exchange	X	
7	Atomic mismatch	r	
8	Atomic screening	S	10^{-3}-10^{-4}
9	Shake-up	See item 7	
10	Shake-off	See item 7	
11	Isovector correction	C_I	
12	Recoil Coulomb correction	Q	
13	Diffuse nuclear surface	U	
14	Nuclear deformation	D_{FS} & D_C	
15	Recoiling nucleus	R_N	
16	Molecular screening	ΔS_{Mol}	
17	Molecular exchange	Case by case	
18	Bound state β decay	Γ_b/Γ_c	Smaller than $1\cdot10^{-4}$
19	Neutrino mass	Negligible	

NUCLEAR STRUCTURE DEPENDENT (items 3–5)

NUCLEAR STRUCTURE DEPENDENT (items 11–15)

Beta Spectrum Generator: High precision allowed β spectrum shapes

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[a]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*

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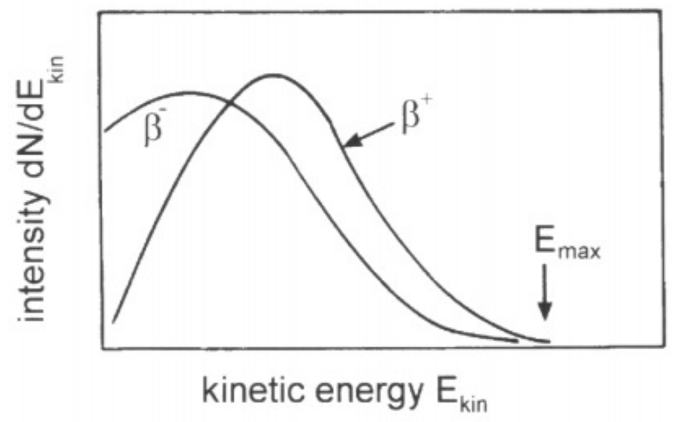
$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon)\times(corrections)$$

Classification of β decays is achieved via momentum transfer dependence:

β decay typical momentum transfers are up to 10MeV, this constitutes a small parameter:

$$\epsilon_q \equiv \frac{qR}{\hbar c} \approx 0.05\cdot A^{\frac{1}{3}}$$



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Classification of β decays is achieved via momentum transfer dependence:

$\Delta J^\pi = 0^+$	(Super)allowed - Fermi transition	$\propto q^0$
$\Delta J^\pi = 0,1^+$	Allowed – Fermi/Gamow-Teller	$\propto q^0$
$\Delta J^\pi = 0,1,2^-$	Unique First forbidden transition	$\propto q^1$

PRECISION Β-DECAY STUDIES TO PINPOINT BSM EFFECTS

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Momentum transfer

$\vec{\beta}=\frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

$$\hat{C}_{JM}(q)=\int d\vec{x}\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0(\vec{x}) \qquad \propto q^J$$

$$\hat{E}_{JM}(q)=\frac{1}{q}\int d\vec{x}\,\vec{\nabla}\times[j_J(qx)\vec{Y}_{JJM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \qquad \propto q^{J-1}$$

$$\hat{M}_{JM}(q)=\int d\vec{x}\, j_J(qx)\vec{Y}_{JJM}(\hat{x})\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \qquad \propto q^J$$

$$\hat{L}_{JM}(q)=\frac{i}{q}\int d\vec{x}\,\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}), \qquad \propto \hat{E}_{JM}$$

Nuclear dependent part – neglecting rad. corrections:

Assuming V-A structure

$$\begin{aligned}\Theta(q,\vec{\beta}\cdot\hat{\nu}) &= \frac{\Delta J}{2\Delta J+1}\Bigg\{\left[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right]\sum_{J\geq 1}\left(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2\right)\\ &\pm\hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*\\ &+\sum_{J\geq 0}\Bigg[\left[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right]|\langle\|\hat{L}_J\|\rangle|^2\\ &+\left(1+\hat{\nu}\cdot\vec{\beta}\right)|\langle\|\hat{C}_J\|\rangle|^2\\ &-2\hat{q}\cdot\left(\hat{\nu}+\vec{\beta}\right)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Bigg]\Bigg\},\end{aligned} \tag{4}$$

We have similar expressions for Tensor and Scalar structures, and interferences. Glick-Magid, DG, PRD (2023)

PRECISION Β-DECAY STUDIES TO PINPOINT BSM EFFECTS

Differential β decay rate

$$\frac{d^5\omega_{\beta\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q, \vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear dependent part – neglecting rad. corrections:

The multipole expansion naturally leads to an expansion in the momentum transfer $\epsilon_q = \frac{qR}{\hbar c} \approx 0.005 - 0.1$

$$\Theta(q, \vec{\beta}\cdot\hat{\nu}) = \epsilon_q^{\mu_0} \sum_{\mu=0}^{\infty} \epsilon_q^{\mu} \cdot \Theta_\mu(q, \vec{\beta}\cdot\hat{\nu})$$

Classification of the decay:
$\mu_0 = 0$ – *allowed*
$\mu_0 = 1$ – *forbidden…*

Beyond the Standard Model corrections distort these

PRECISION B-DECAY STUDIES TO PINPOINT BSM EFFECTS

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See also Ayala Glick-Magid's talk

EXAMPLE: GAMOW-TELLER TRANSITIONS

$$\frac{d\omega^{1^+\beta^-}}{d\epsilon\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} \propto \left[1 + a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}^{1^+\beta^-}\frac{m_e}{\epsilon}\right]\left|\left\langle \left\| \hat{L}_1^A \right\| \right\rangle\right|^2,$$

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$$a_{\beta\nu} \approx -\frac{1}{3}\left(1 - \frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\right) \qquad b = 2\frac{C_T+C_T'}{C_A}$$

Allowed Gamow-Teller decay

$0^+ \rightarrow 1^+$

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Allowed Gamow-Teller decay
$0^+ \rightarrow 1^+$

$$a_{\beta\nu}^{\mathrm{measured}} = \frac{a_{\beta\nu}}{1+b_{\mathrm{F}}\left\langle\frac{m_e}{E}\right\rangle}$$

M. González-Alonso, O. Naviliat-Cuncic, Kinematic sensitivity to the Fierz term of β-decay differential spectra, Phys. Rev. C 94 (2016) 035503.

PRECISION Β-DECAY STUDIES TO PINPOINT BSM EFFECTS

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e.g., for a typical medium-mass nucleus: Few % correction; Few 0.01% correction

Experimental precision determines where this expansion should be cut-off.

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Depends on the nuclear model

Depends on the nuclear model

EXAMPLE: GAMOW-TELLER TRANSITIONS

$$\frac{d\omega^{1^+\beta^-}}{dE\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}(E_0-E)^2 kEF^-(Z_f,E)\,C_{\text{corr}}\left|\langle\|\hat{L}_1^A\|\rangle\right|^2$$

Gamow-Teller

$$\times 3\left(1+\delta_1^{1^+\beta^-}\right)\left[1+a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu}+b_{\mathrm{F}}^{1^+\beta^-}\frac{m_e}{E}\right],$$

BSM (tensor) signatures

$a_{\beta\nu} \approx -\frac{1}{3}\left(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\right)$, and $b = 2\frac{C_T+C_T'}{C_A}$

Nuclear Structure corrections

$$a_{\beta\nu}^{1^+\beta^-} = -\frac{1}{3}\left(1+\tilde{\delta}_a^{1^+\beta^-}\right) \qquad b_{\mathrm{F}}^{1^+\beta^-} = \delta_{\mathrm{b}}^{1^+\beta^-}$$

$$\delta_1^{1^+\beta^-} \equiv \frac{2}{3}\Re\mathfrak{e}\left[-E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}(E_0-2E)\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] - \frac{4}{7}ER\alpha Z_f - \frac{233}{630}(\alpha Z_f)^2,$$

$$\tilde{\delta}_a^{1^+\beta^-} \equiv \frac{4}{3}\Re\mathfrak{e}\left[2E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}(E_0-2E)\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] + \frac{4}{7}ER\alpha Z_f - \frac{2}{5}E_0R\alpha Z_f,$$

$$\delta_b^{1^+\beta^-} \equiv \frac{2}{3}m_e\Re\mathfrak{e}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right],$$

EXAMPLE: GAMOW-TELLER TRANSITIONS

$$\frac{d\omega^{1^+\beta^-}}{dE\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}(E_0-E)^2 kEF^-(Z_f,E)\, C_{\text{corr}} \left|\langle\|\hat{L}_1^A\|\rangle\right|^2$$

Gamow-Teller

$$\times 3\left(1+\delta_1^{1^+\beta^-}\right)\left[1+a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu}+b_{\text{F}}^{1^+\beta^-}\frac{m_e}{E}\right],$$

BSM (tensor) signatures

$$a_{\beta\nu} \approx -\tfrac{1}{3}\left(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\right), \text{ and } b = 2\frac{C_T+C_T'}{C_A}$$

Nuclear Structure corrections

$$a_{\beta\nu}^{1^+\beta^-} = -\frac{1}{3}\left(1+\tilde{\delta}_a^{1^+\beta^-}\right) \qquad b_{\text{F}}^{1^+\beta^-} = \delta_{\text{b}}^{1^+\beta^-}$$

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$$\delta_b^{1^+\beta^-} \equiv \frac{2}{3}m_e\mathfrak{Re}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right],$$

Nuclear Model dependence in the wave-functions and in the structure of the operators

PRECISION Β-DECAY STUDIES TO PINPOINT BSM EFFECTS

Differential β decay rate

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q, \vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear dependent part – neglecting rad. corrections:

The multipole expansion naturally leads to an expansion in the momentum transfer $\epsilon_q = \frac{qR}{\hbar c} \approx 0.005 - 0.1$

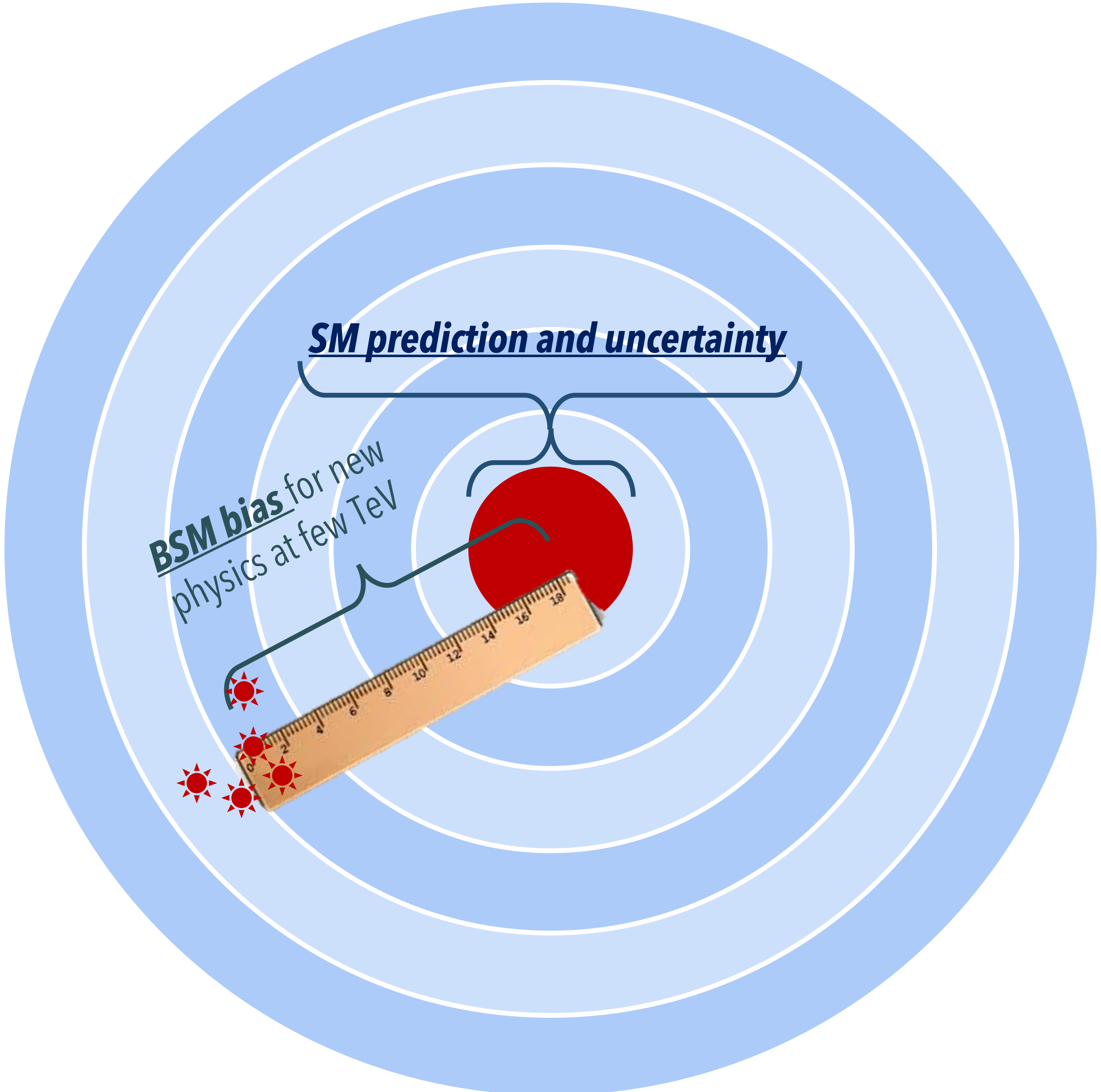
$$\Theta(q, \vec{\beta}\cdot\hat{\nu}) \approx \epsilon_q^{\mu_0}\cdot\Theta_0(q, \vec{\beta}\cdot\hat{\nu})\cdot\{1 + \epsilon_q\cdot\delta\Theta_1(q, \vec{\beta}\cdot\hat{\nu})\} + \epsilon_q^{\mu_0}\,\mathcal{O}(\epsilon_q\cdot\epsilon_{Model})$$

uncertainty

For a typical <u>medium-mass nucleus</u> a 10% theoretical uncertainty on the nuclear model allows cutting off the expansion at the sub-leading to reach a total theoretical uncertainty much better than 0.1%!

ANALYSING EXPERIMENTAL DEMANDS

- Current experiments aim at <0.1% precision, which is sufficient to significantly identify BSM signatures at the few TeV scale.
- Future experiments aim at 10^{-4} precision, probing new physics beyond LHC scale.
- Nuclear theory corrections to the standard Model are essential:
  - Should have about 10% accuracy for ongoing experiments.
  - Should have *few*-% accuracy for future experiments.
- Is it feasible to reach these theory accuracies in nuclear theory for typical nuclei?



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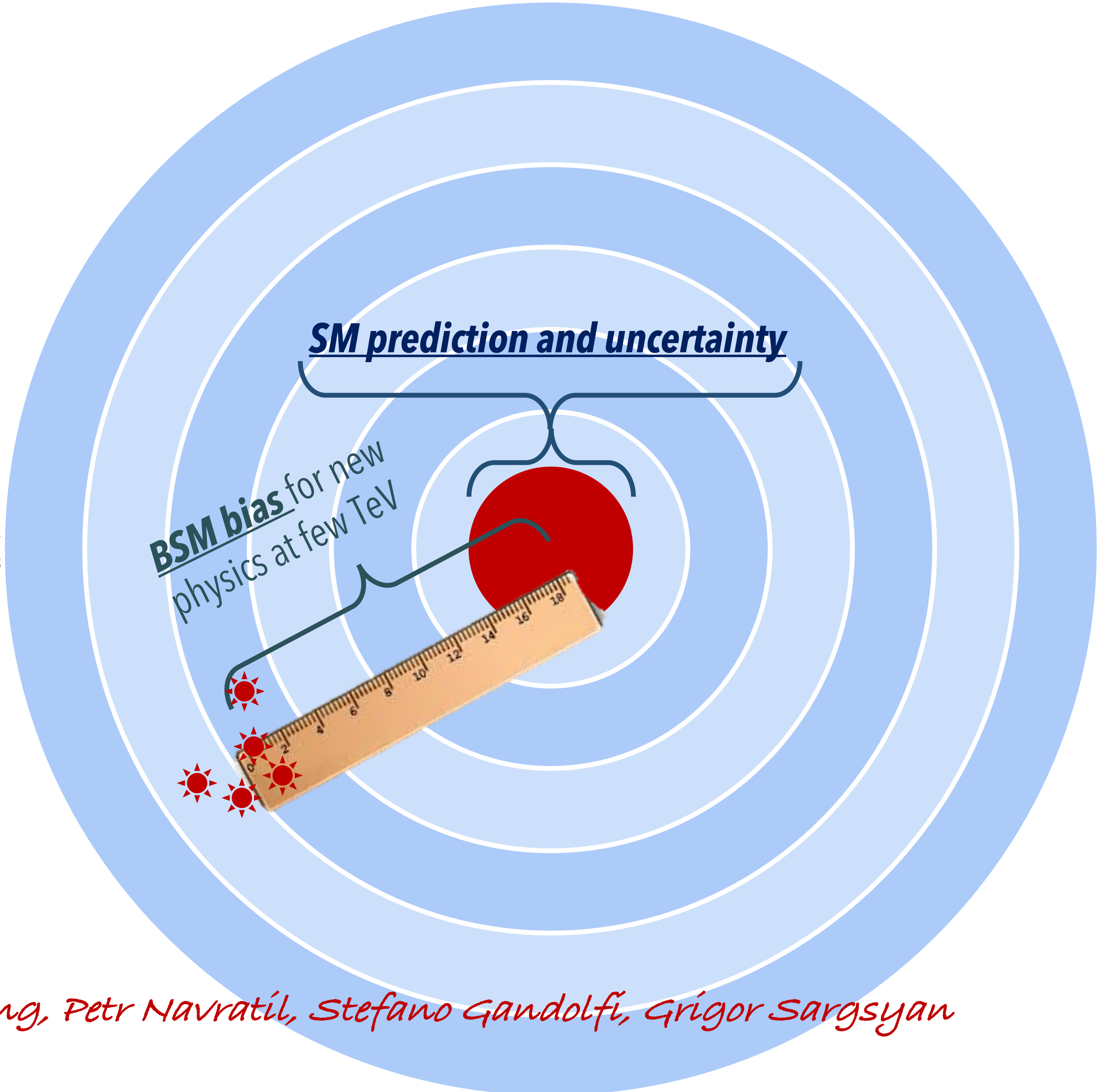
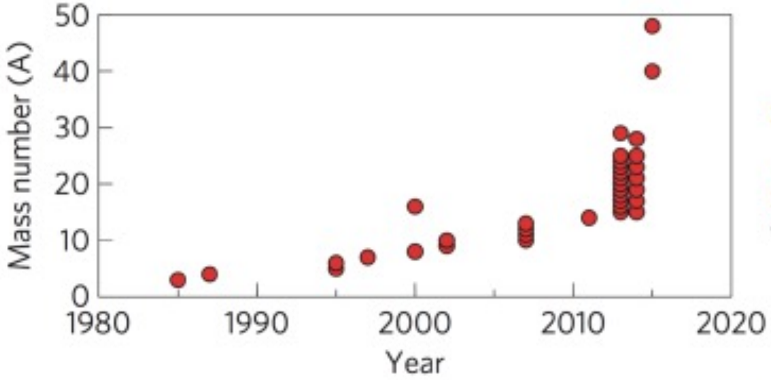


See talks by Latsamy Xayavong, Petr Navratil, Stefano Gandolfi, Grigor Sargsyan

NUCLEAR WAVE FUNCTIONS

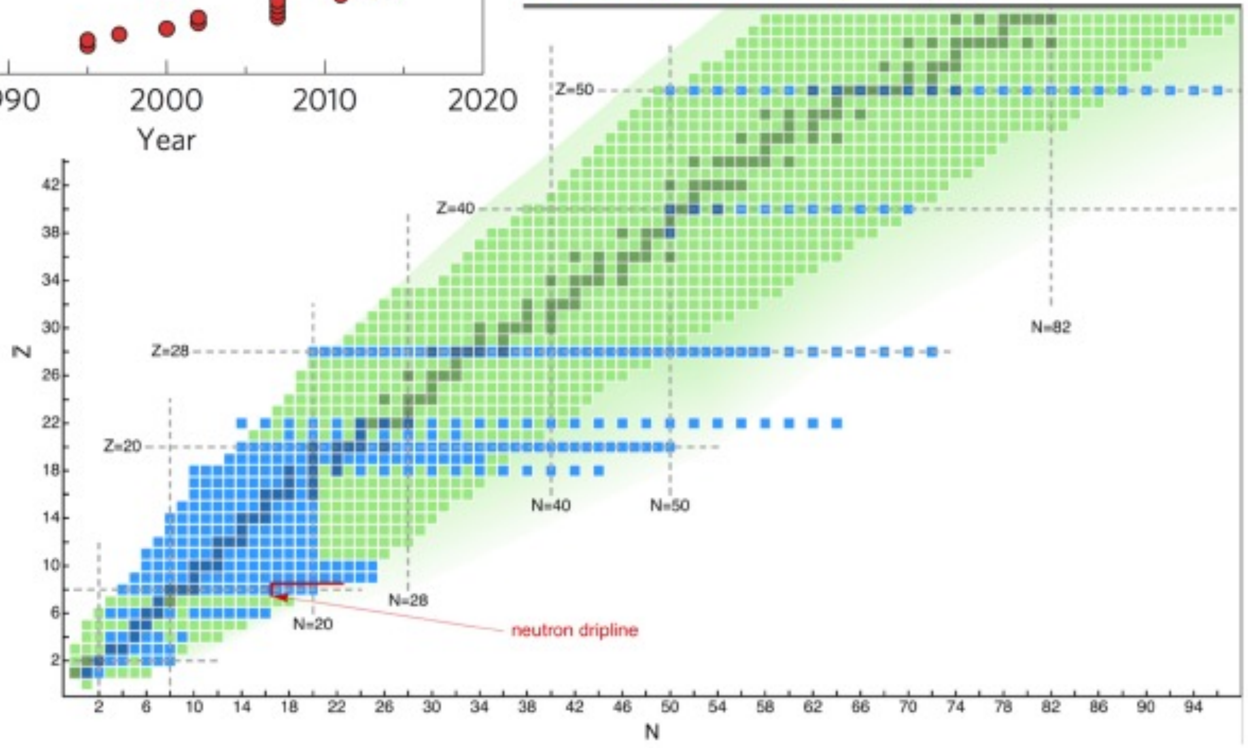
Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50



from Hagen et al., Nature Phys. (2016)

from Hergert et al., Phys. Rep. (2016)



Slide taken from Achim Schwenk, 2016

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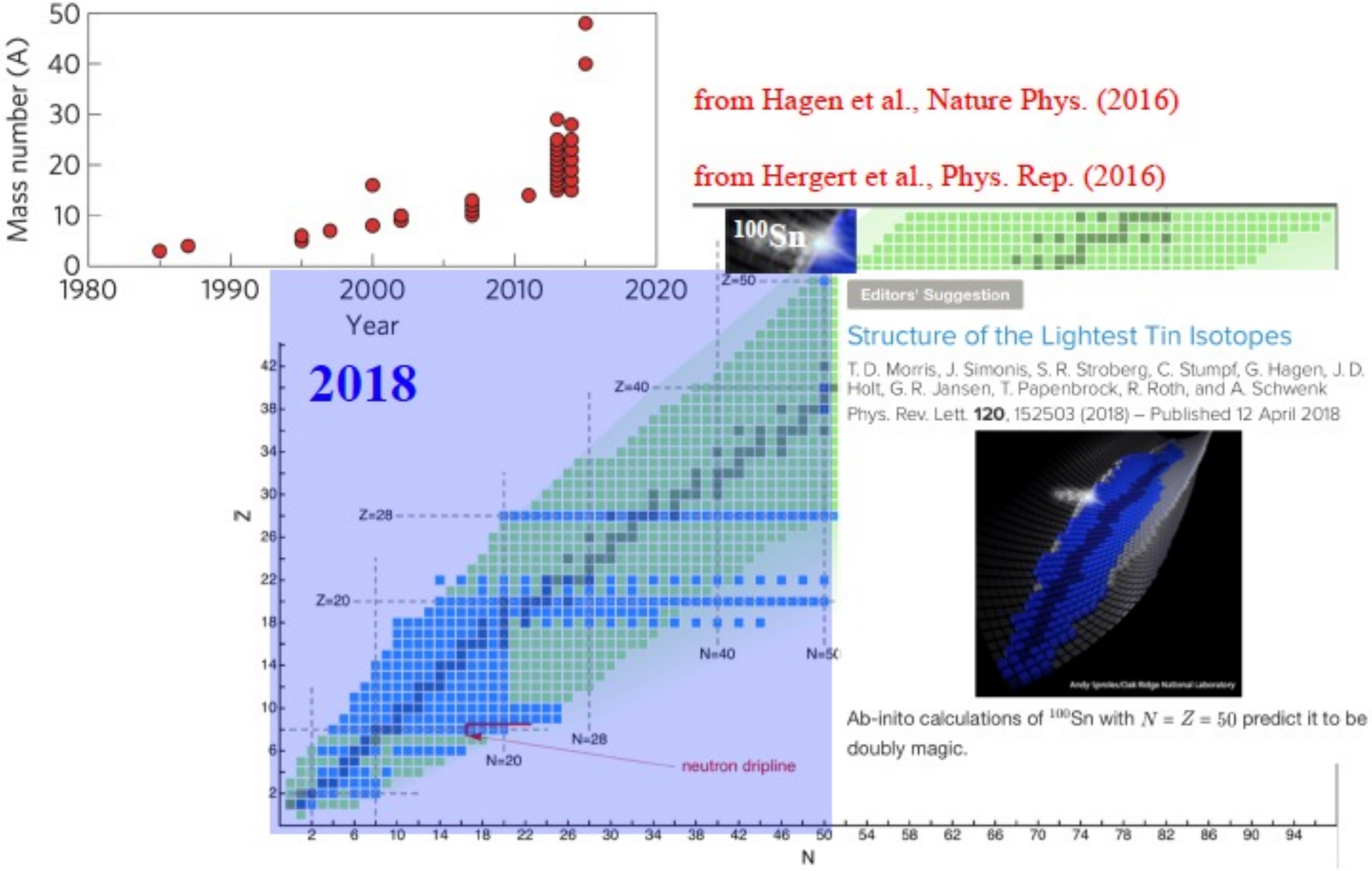

From Achim Schwenk

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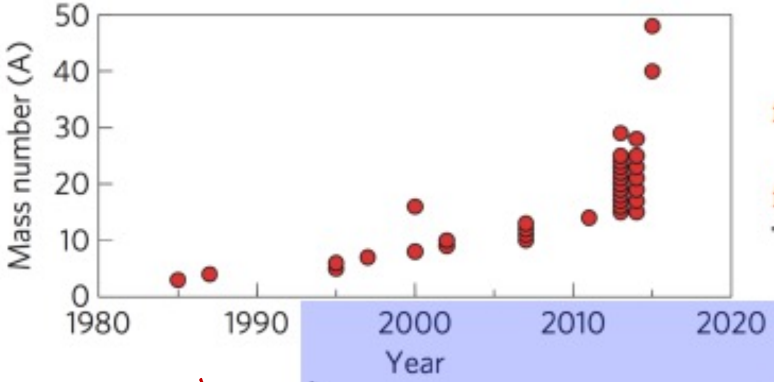

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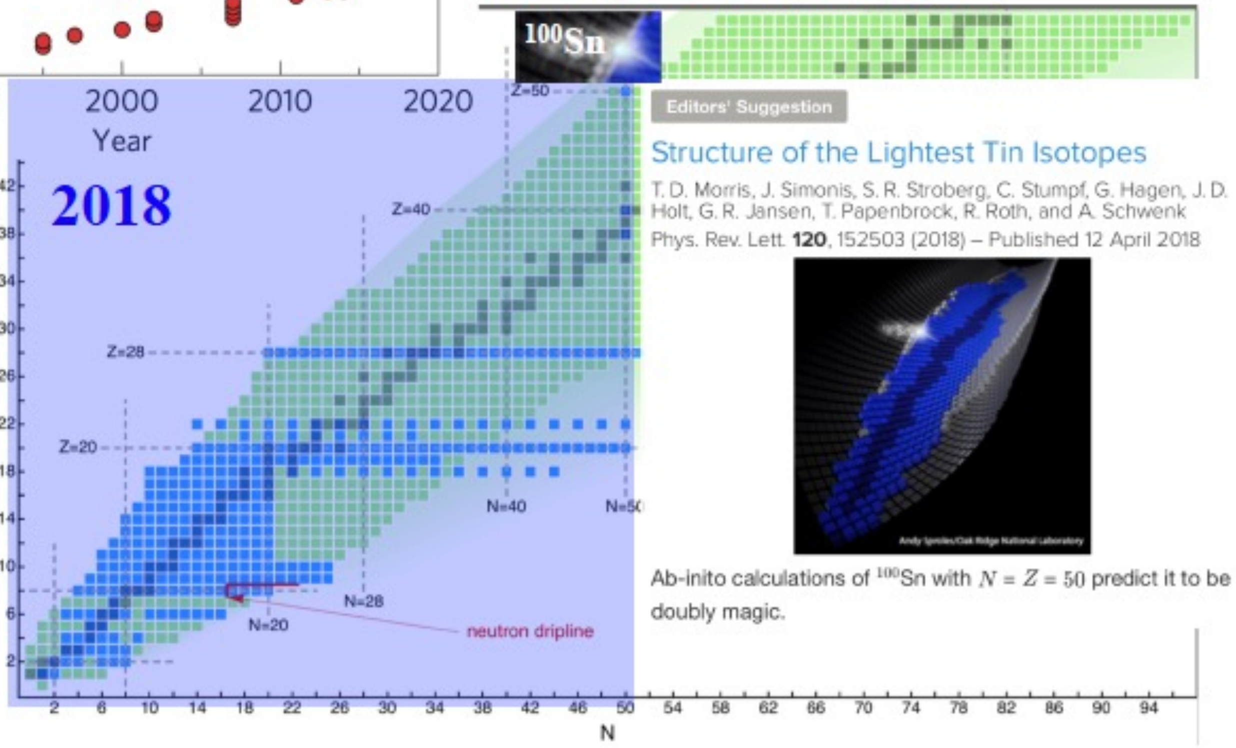

See talks by Stefano Gandolfi and Heiko Hergert for an exciting update!

NUCLEAR WAVE FUNCTIONS

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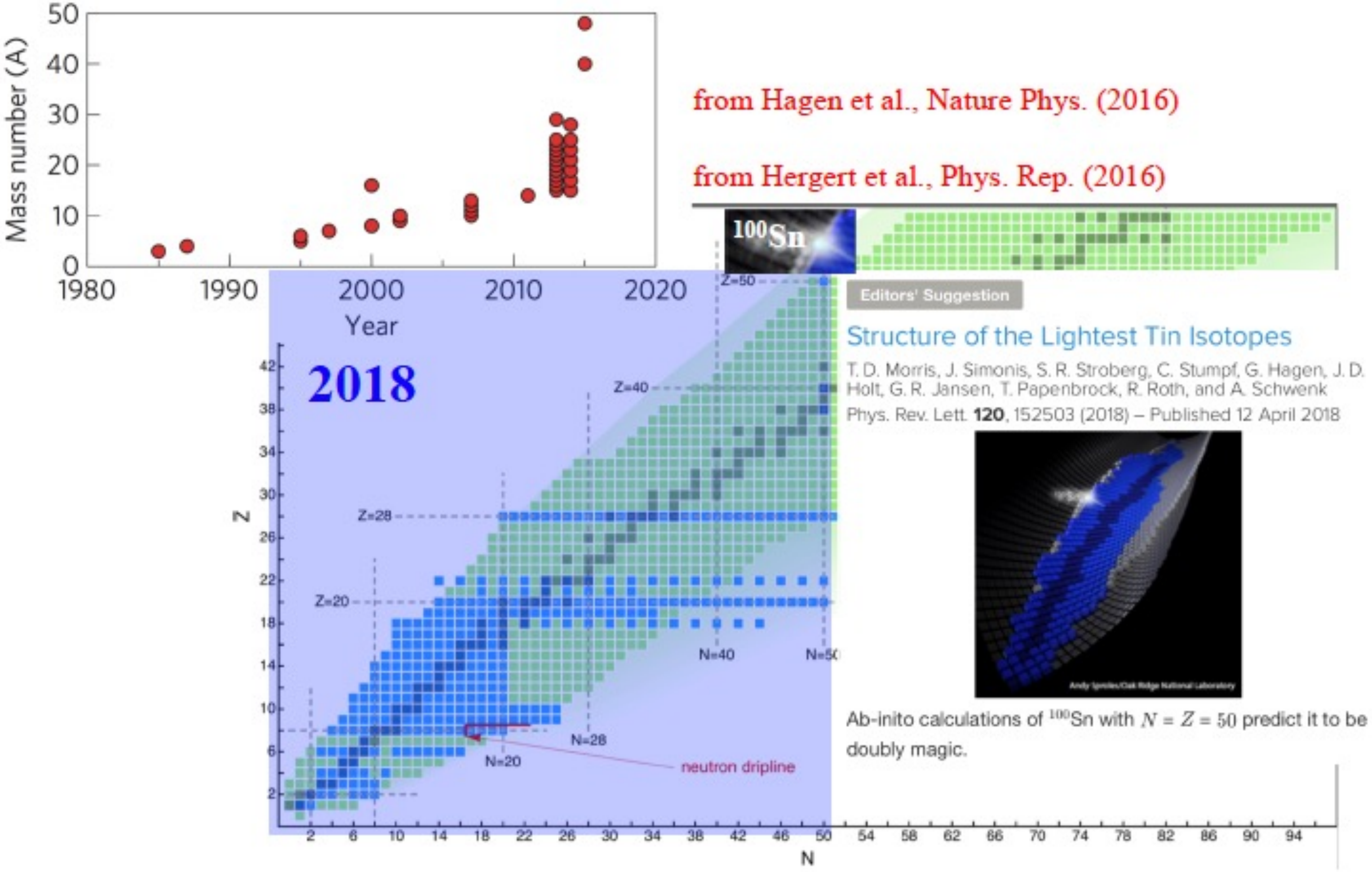
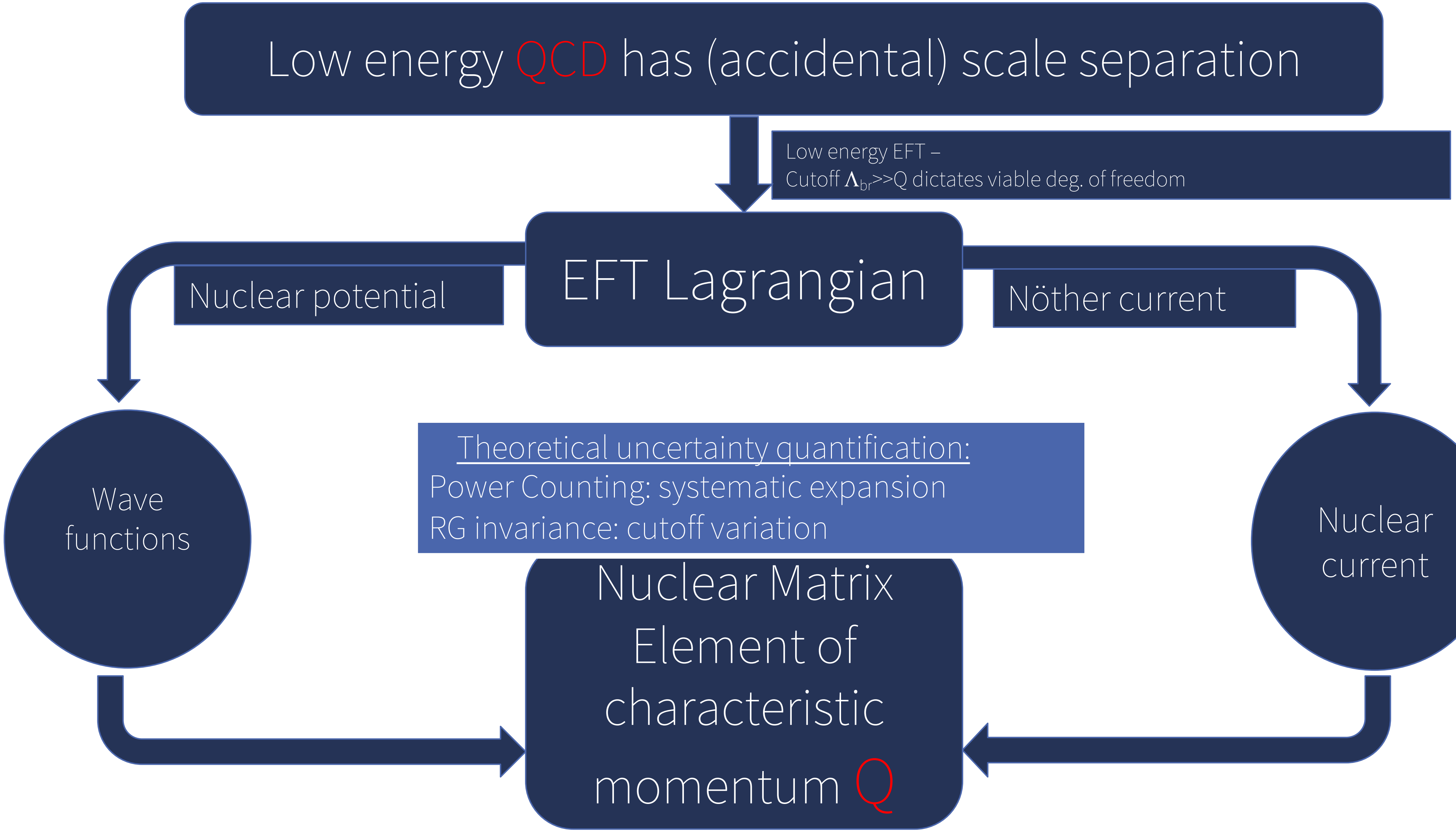


Nuclear models are ubiquitously known to have systematic errors. This is a huge problem when studying BSM effects

NUCLEUS INTERACTION WITH A PROBE, EFT POINT OF VIEW:



NUCLEUS INTERACTION WITH A PROBE, EFT POINT OF VIEW:

Low energy QCD has (accidental) scale separation

Low energy EFT –

characteristic momentum Q

Matrix element accuracy: $\epsilon_{solver}(1 + \alpha\epsilon_{EFT} + \beta\epsilon_{EFT}^{2} + \gamma\epsilon_{EFT}^{a} + \cdots)$

30% 10% 3%

α: Any basic nuclear correlations – your favorite many body technic

β: including nuclear correlations ab-initio.

γ: a state of the art nuclear calculation, including 3NF,

Accuracy significantly increased for light nuclei.

EFFECTIVE FIELD THEORY FOR THE NUCLEAR-PROBE INTERACTION

The Nuclear Current in EFT:

- EFT expansion parameter $\epsilon_{EFT} \propto \frac{\max(q,Q,\dots)}{M_{br}} \approx \frac{1}{3} - \frac{1}{5}$:
  - Breakdown scale in chiral EFT is about $4\pi f_\pi \approx 1\ \mathrm{GeV/c}$
  - Order by order expansion of the currents:

$$J_{SM} = J^{LO} + \epsilon_{EFT} \cdot J^{NLO} + \epsilon_{EFT}^{a} J^{N^a LO} \quad with\ a > 1$$

- LO – single nucleon current
- NLO – corrections to single nucleon currents
- NLO or higher orders include 2-body currents (magnetic – NLO, weak axial –$N^{7/4\div3}LO$)

$$\mathcal{J}^{\mu\dagger}(\mathbf{r}) = \sum_{i=1}^{A} \tau_i^- [\delta^{\mu 0} J_{i,1b}^0 - \delta^{\mu k} J_{i,1b}^k] \delta(\mathbf{r} - \mathbf{r}_i)$$

$$J_{i,1b}^0(p^2) = 1 - g_A \frac{\mathbf{p}\cdot\sigma_i}{2m},$$

$$\mathbf{J}_{i,1b}(p^2) = g_A \sigma_i + i\kappa_V \frac{\sigma_i \times \mathbf{p}}{2m},$$

Exchange currents

NUCLEAR CORRECTIONS – SMALL PARAMETERS

Small parameter #1: $\epsilon_q = \frac{qR}{\hbar c} \approx 10^{-2}$ **- multipole expansion**

Small parameter #2: $\epsilon_{EFT} \approx 0.3$ **- systematic uncertainty in the nuclear model.**

Small parameter #3: $\epsilon_{NR} = \frac{P_{nucleon}}{M} \approx 0.05 - 0.2$ **Non-relativistic expansion of currents.**

Small parameter #4: $\epsilon_{recoil} = \frac{q}{M} \approx 0.001$ **nucleaon recoil.**

Small parameter #5: $\epsilon_{\pi} = \frac{\omega q}{m_{\pi}^2} \approx 10^{-4}$ **Pseudo-scalar poles.**

Small parameter #6: $\epsilon_{\alpha} = \alpha Z_f \approx 10^{-2} - 1$ **Coulomb corrections.**

Small parameter #7: ϵ_{solver} **numerical error in the solution of the Schrödinger equation**

For precision beta decays, at least the leading correction needs to be calculated explicitly to reach experimental sensitivity.

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NUCLEAR REACTIONS

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

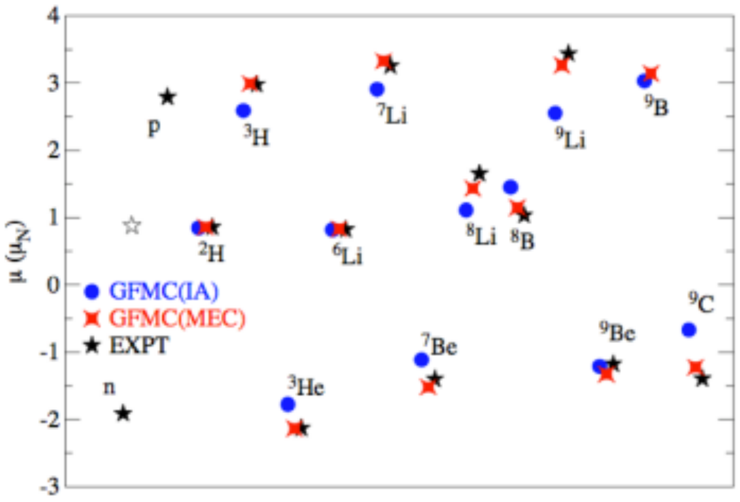
P. Gysbers[1,2], G. Hagen[3,4], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] & K. A. Wendt[7]

Frontier: Chiral EFT for electroweak currents

consistent electroweak one- and two-body (meson-exchange) currents

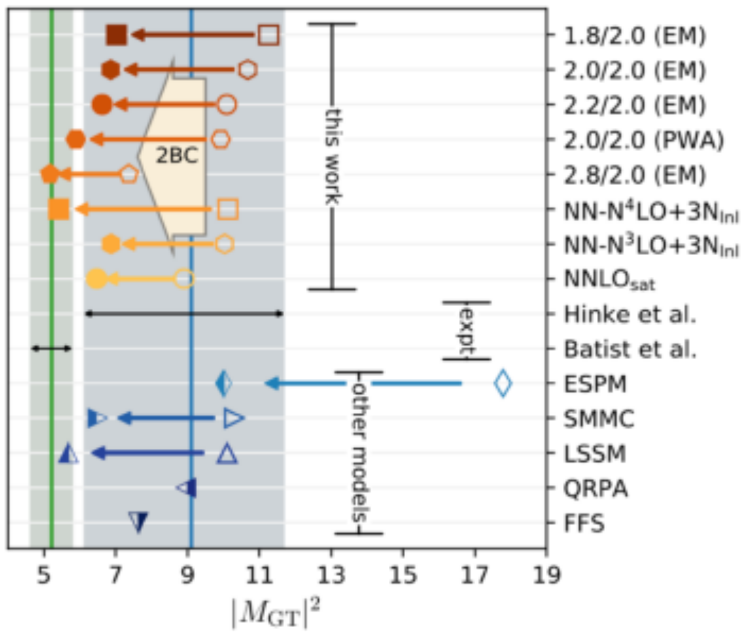
magnetic moments in light nuclei

Pastore et al. (2012-)



Gamow-Teller beta decay of ^{100}Sn

Gysbers, Hagen et al.



Conclusion: for many nuclei, it is possible to calculate nuclear matrix elements to better than 10% accuracy

two-body currents are key for quenching puzzle of beta decays

NUCLEAR REACTIONS

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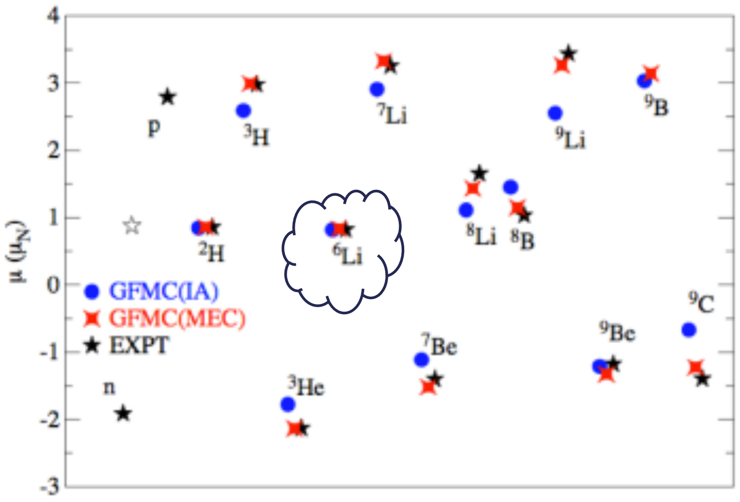

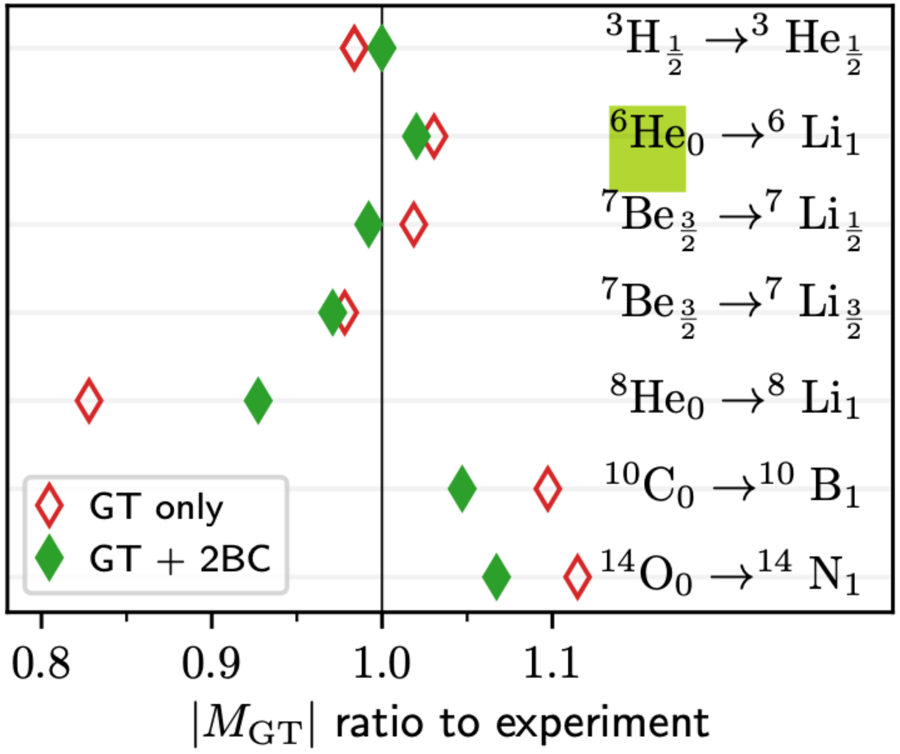

two-body currents are key for quenching puzzle of beta decays

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Wa

funct

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30% *10%* *3%*

α: Any basic nuclear correlations – your favorite many body technic

β: including nuclear correlations ab-initio.

γ: a state of the art nuclear calculation, including 3NF, 2BC

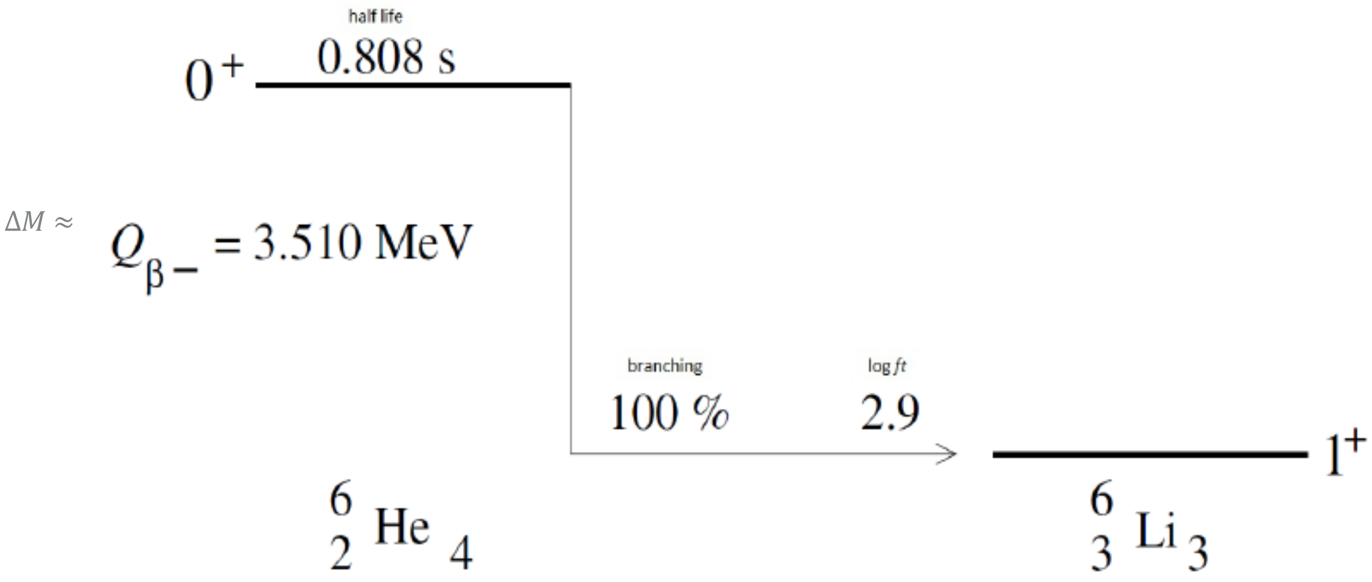
Accuracy significantly increased for light nuclei.

characteristic

$\epsilon_{EFT}\approx 0.3$ **- Small parameter determining the systematic uncertainty in the nuclear model.**

AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

Pure Gamow-Teller



Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

$$d\omega \propto \left(1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{\epsilon}\right)\left|\langle\psi_f\|\hat{L}_J\|\psi_i\rangle\right|^2$$

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\delta_1^{1^+\beta^-} &\equiv \frac{2}{3}\mathfrak{Re}\left[-E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\,(E_0-2E)\,\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] \\
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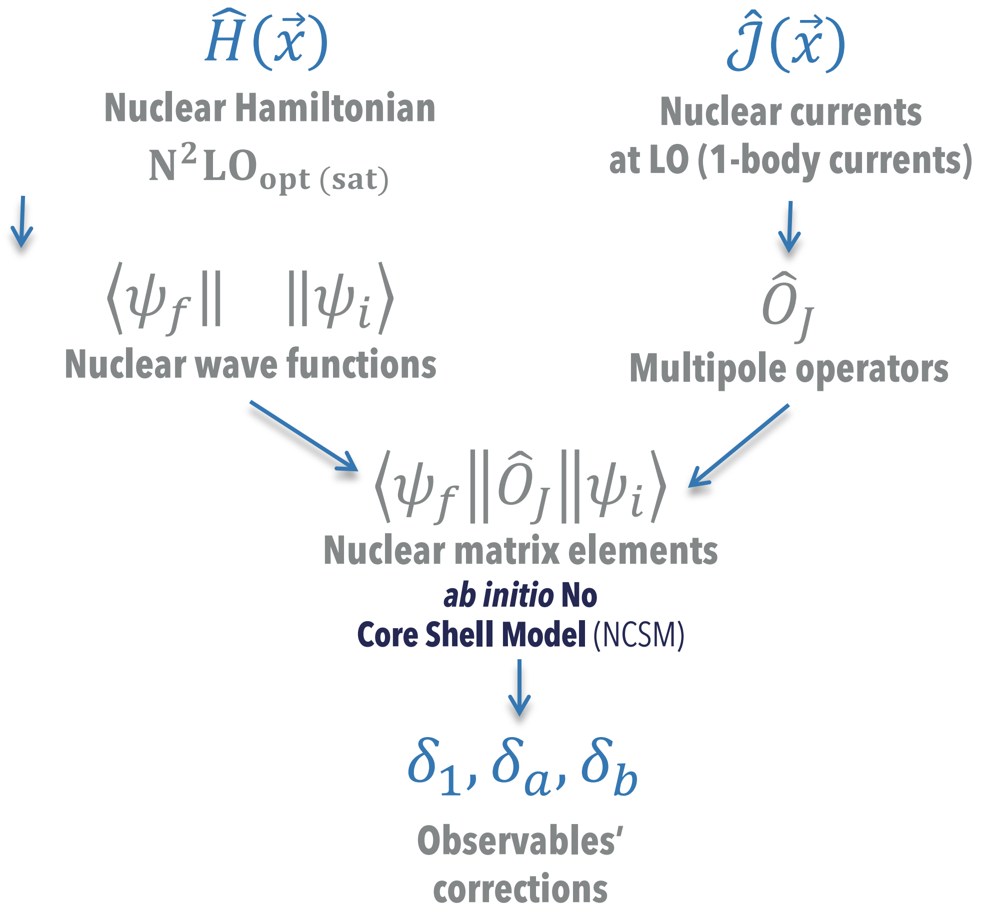

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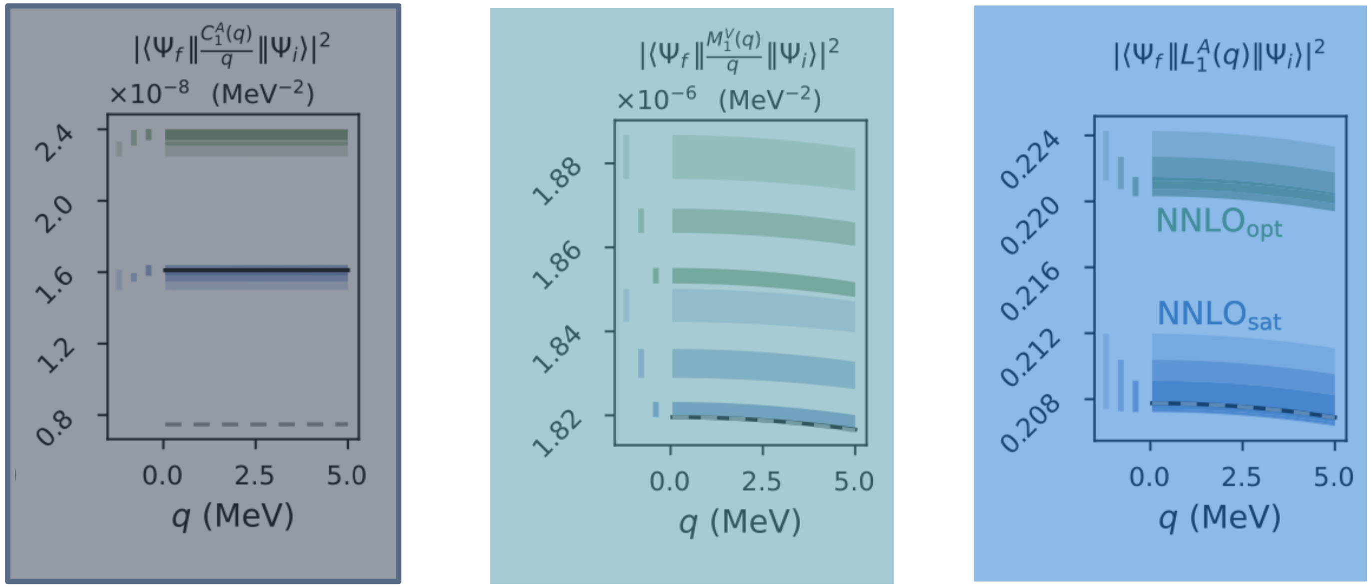

Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

האוניברסיטה העברית בירושלים

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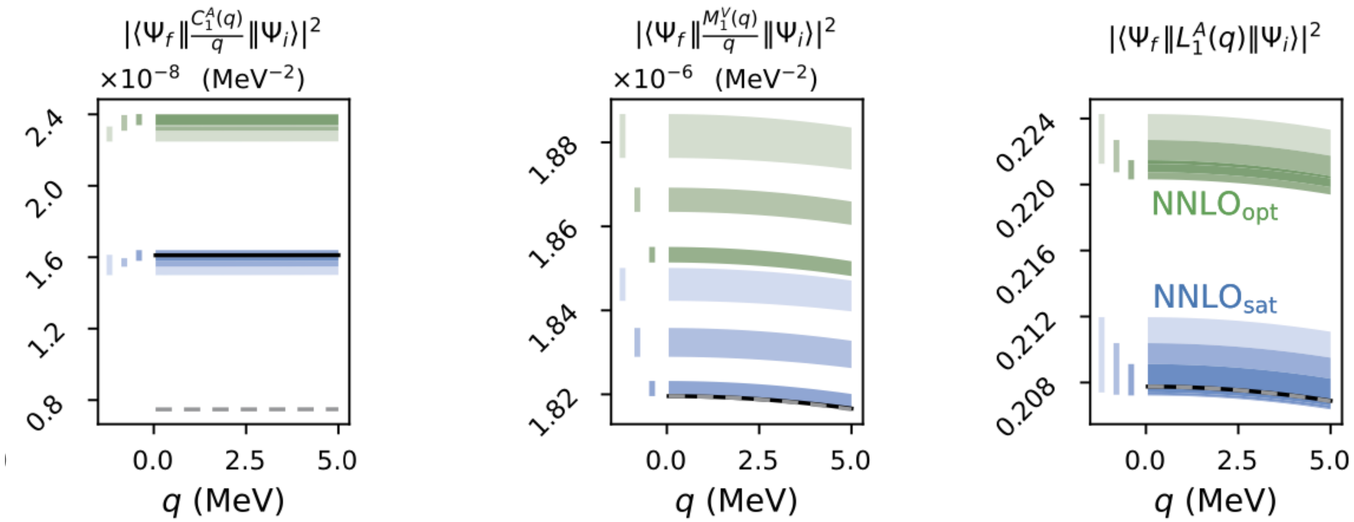


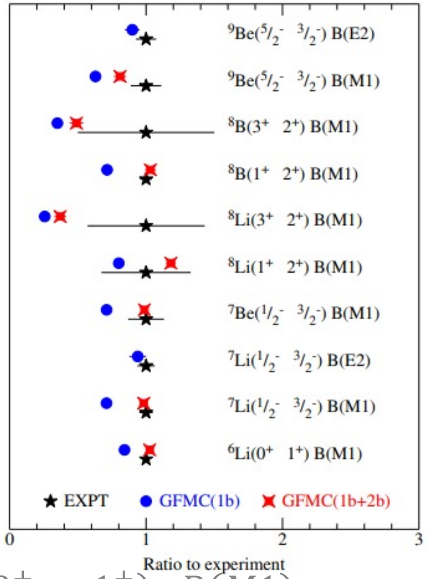
Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

האוניברסיטה העברית בירושלים

ESTIMATING ϵ_{EFT} IN THE 6HE CASE

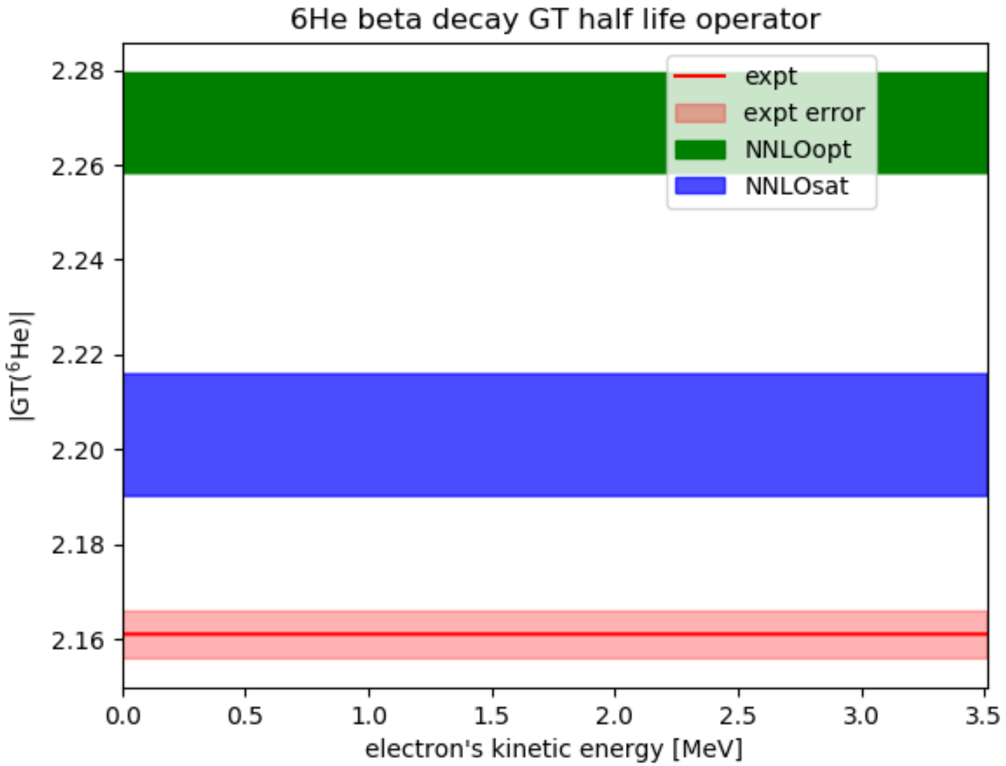
Pastore *et al.*, PRC87 035503 (2013)
Friman-Gayer *et al.*, PRL126 102501 (2021)

Electro-magnetic transitions



$^6\mathrm{Li}(0^+ \rightarrow 1^+)$: $B(M1)$

2b: $\langle \| \widehat{M}_1^V \| \rangle \sim 10\% \sim \mathcal{O}(\epsilon_{EFT})$



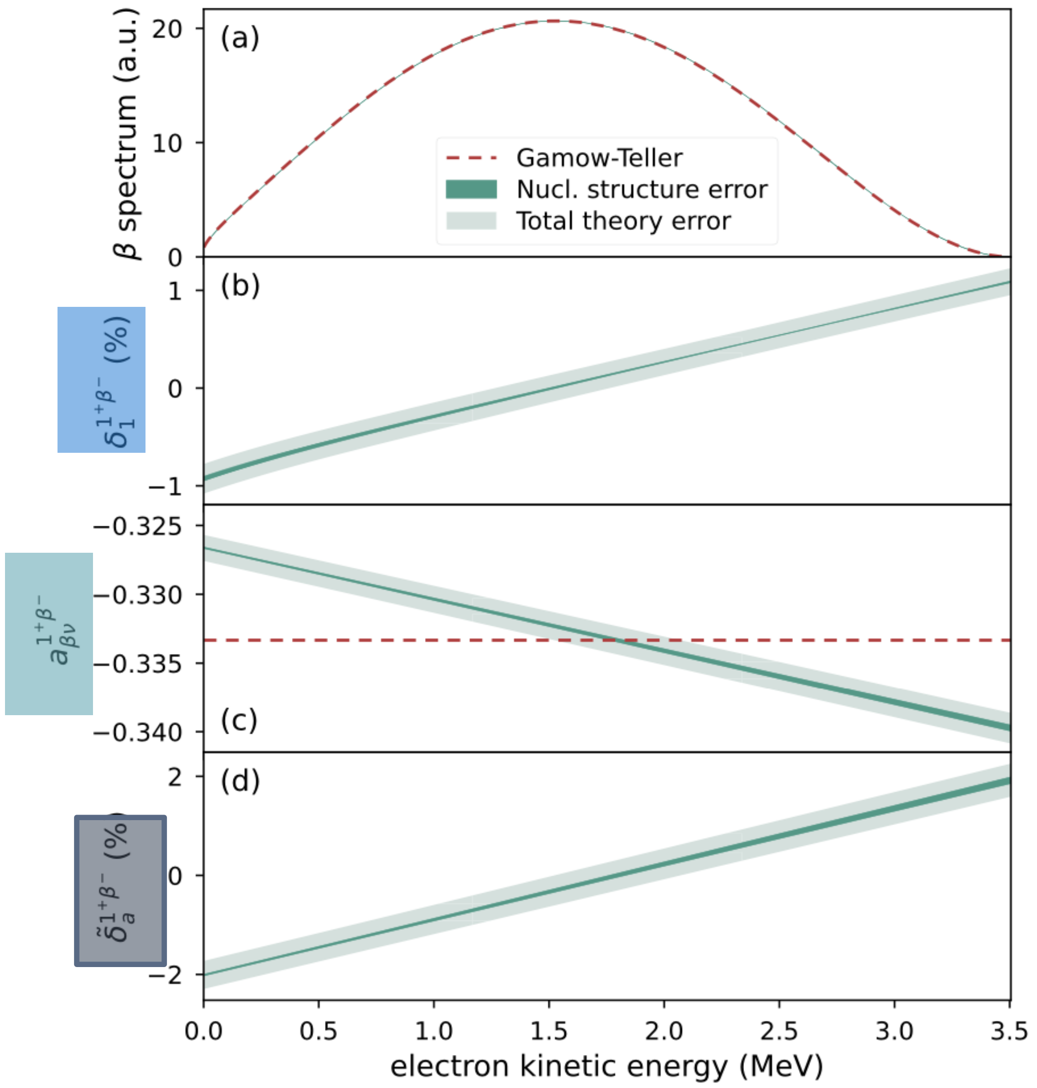
$\epsilon_{EFT} \sim 15\%$

Using the recent King et al, PRC (2023), who go further in EFT (exchange currents) validates this estimate, and allows reaching higher accuracy!

Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

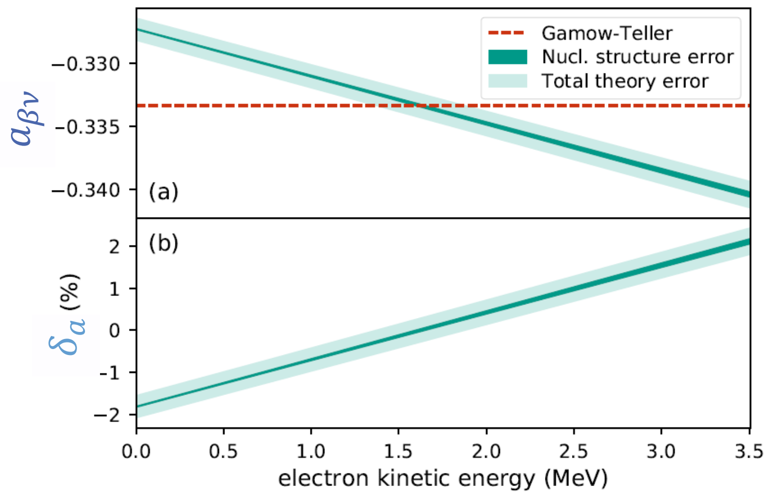
AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

$$\frac{d\omega}{dE d\Omega_k d\Omega_\nu} \propto \left(1 + \delta_1^{1^+\beta^-}\right) \cdot \left(1 + a_{\beta\nu}^{1^+\beta^-} \vec{\beta} \cdot \hat{\nu} + \tilde{\delta}^{1^+\beta^-} \frac{m_e}{\epsilon}\right)$$



Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

^{6}He→^{6}Li – Angular Correlation



Experiments are aiming at ~few 0.1% precision.

- $$a_{\beta\nu} = -\frac{1}{3}\left(1 + \tilde{\delta}_a + \frac{|C_T|^2+|C_T'|^2}{2|C_A|^2}\right)$$

GT — SM correction — BSM

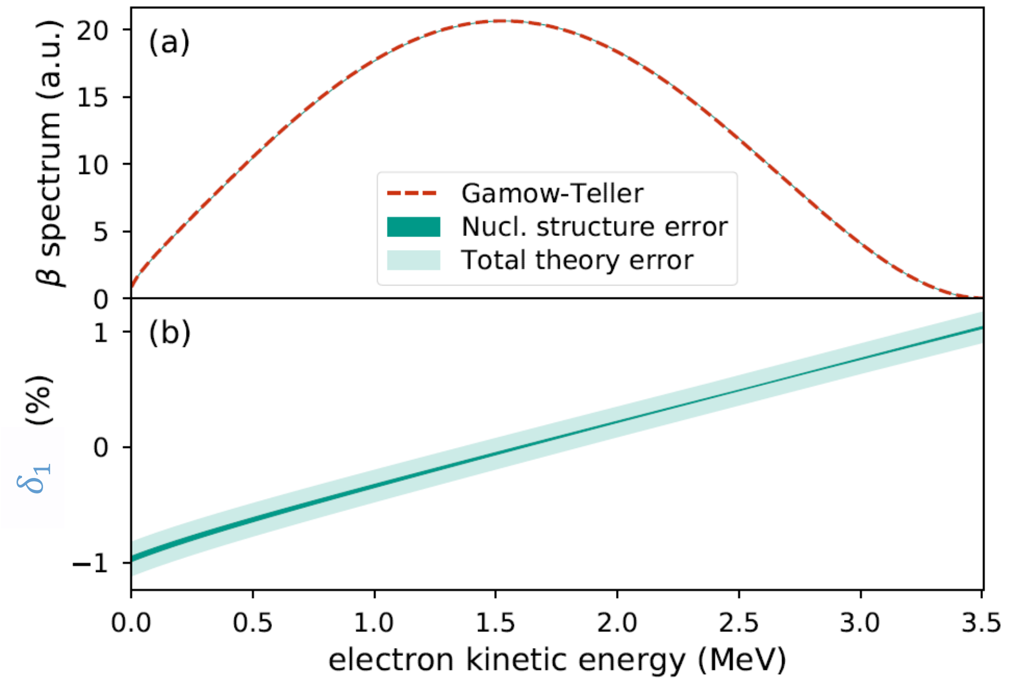
$$a_{\beta\nu}^{\text{measured}} = \frac{a_{\beta\nu}}{1+b_F\langle \frac{m_e}{E}\rangle}$$

$$a_{\beta\nu} = a_{\beta\nu}^{\text{measured}} - a_{\beta\nu}^{\text{GT}}\left(\left\langle\tilde{\delta}_a^{1^+\beta^-}\right\rangle - b_F^{1^+\beta^-}\left\langle\frac{m_e}{E}\right\rangle\right)$$
$$= a_{\beta\nu}^{\text{measured}} - 0.70\,(24)\cdot 10^{-3},$$

Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, PLB 2022

Using the recent King et al, PRC (2023), reduces the uncertainty 5-fold!

$^{6}He \rightarrow\ ^{6}Li$ INDUCED FIERZ-LIKE SPECTRAL TERM



The spectrum is used to find induced Fierz-like behavior term

GT / SM correctio n / BSM

$$b_F = 0 + \delta_b + \frac{C_T^* + C_T'^*}{C_A}$$

- Looking for $\frac{C_T^*+C_T'^*}{C_A} \sim 10^{-3}$
- $\delta_b = -1.46(17) \cdot 10^{-3}$
- Uncertainty $< 2 \cdot 10^{-4}$

Using the recent King et al, PRC (2023), reduces the uncertainty 5-fold!

Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil (PLB 2022)

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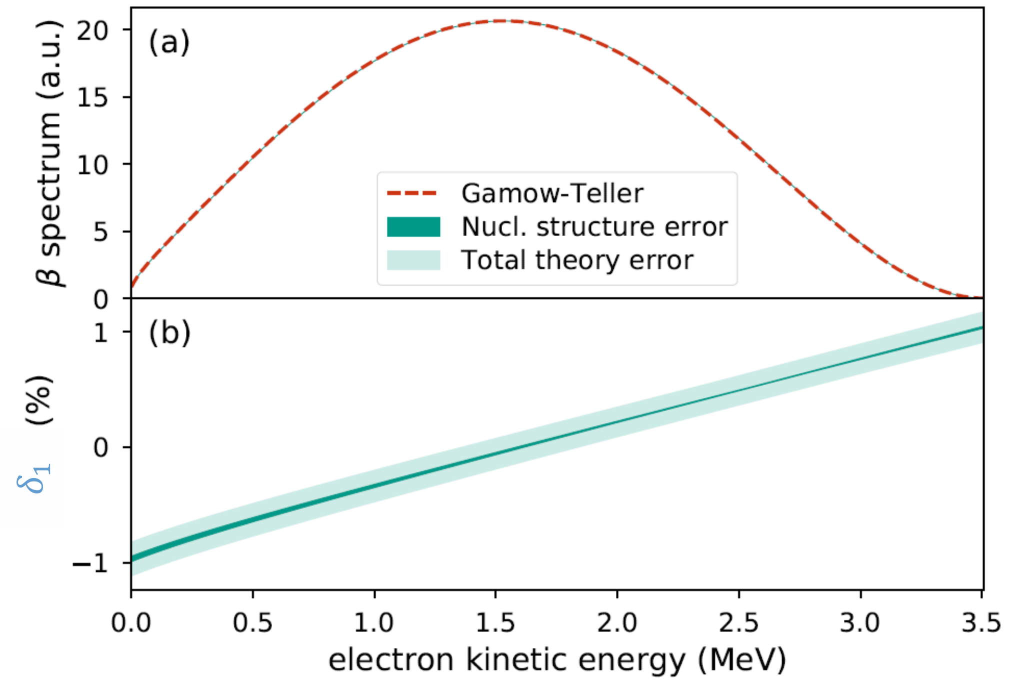
^{6}HE → ^{6}LI INDUCED FIERZ-LIKE SPECTRAL TERM



Theory is ready for the next generation ^{6}He experiments!

Current experiments aim at

$b<10^{-3}$,

leading to

$\epsilon_T < 1.5 \cdot 10^{-4}$ or $\Lambda > 14$ TeV

- Looking for … 10^{-3}
- $\delta_b = -1.46(17) \cdot 10^{-3}$
- Uncertainty $< 2 \cdot 10^{-4}$

Essential!

Using the recent King et al, PRC (2023), reduces the uncertainty 5-fold!

Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil (PLB 2022)

NUCLEAR BETA DECAY EXPERIMENTS IN SEARCH FOR BSM PHYSICS (2019)

Energy spectrum

TABLE III. List of nuclear β-decay spectral measurements in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
β spectrum	GT	^{114}In	MiniBETA-Krakow-Leuven	0.1 %
β spectrum	GT	^{6}He	LPC-Caen	0.1 %
β spectrum	GT	^{6}He, ^{20}F	NSCL-MSU	0.1 %
β spectrum	GT, F, Mixed	^{6}He, ^{14}O, ^{19}Ne	He6-CRES	0.1 %

[a] Experiments specifically searching for time-reversal symmetry violation not listed here

Angular correlation

TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta - \nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta - \nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta - \nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta - \nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta - \nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas A&M	0.1 %
$\beta - \nu$	Mixed	^{11}C, ^{13}N, ^{15}O, ^{17}F	Notre Dame	0.5 %
β & recoil asymmetry	Mixed	^{37}K	TRINAT-TRIUMF	0.1 %

[a] Experiments specifically searching for time-reversal symmetry violation not listed here

V. Cirigliano, A. Garcia, DG, O. Naviliat-Cuncic, G. Savard, A. Young, Precision beta decay as a probe of new physics, arXiv:1907.02164 (2019).

BETA DECAY OF ^{23}NE INTO ^{23}NA: PRELIMINARY

$\hat{H}(\vec{x})$

Nuclear Hamiltonian
~10% uncertainty

$\langle \psi_f || \quad || \psi_i \rangle$

Nuclear wave functions

$\hat{J}(\vec{x})$

Nuclear currents
at LO (1-body currents)

$\hat{O}_J$

Multipole operators

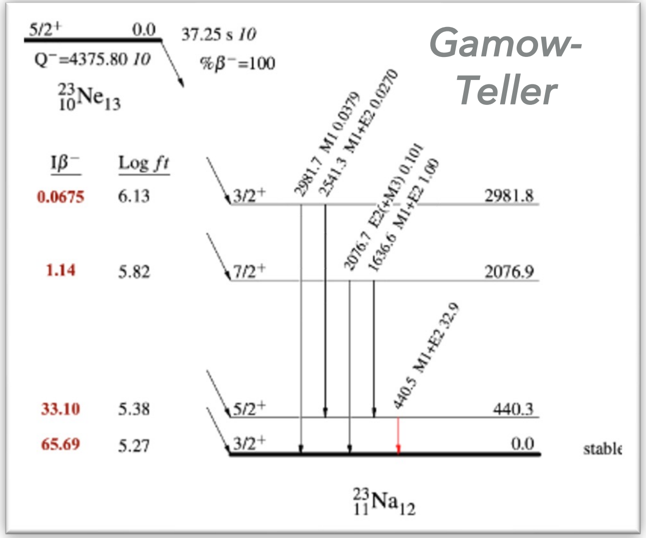
$\langle \psi_f || \hat{O}_J || \psi_i \rangle$

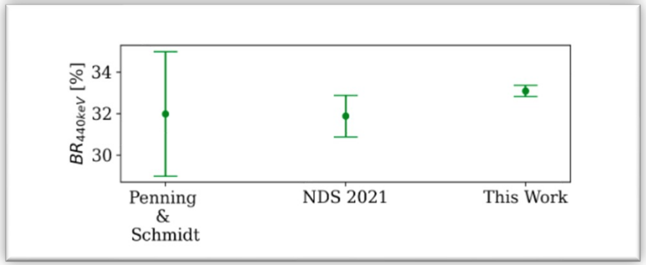
Nuclear matrix elements
Shell Model (NCSM)

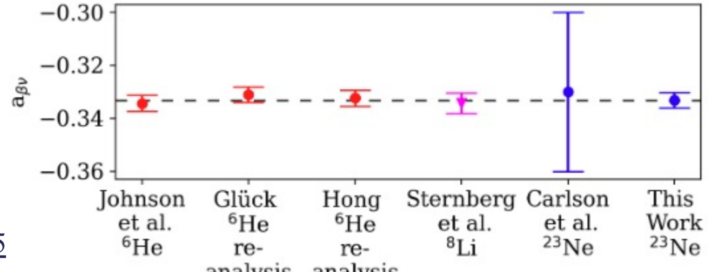
$\delta_1, \delta_a, \delta_b$

Observables' corrections

SARAF: measuring ^{23}Ne's branching ratio with a ~ 0.5% uncertainty



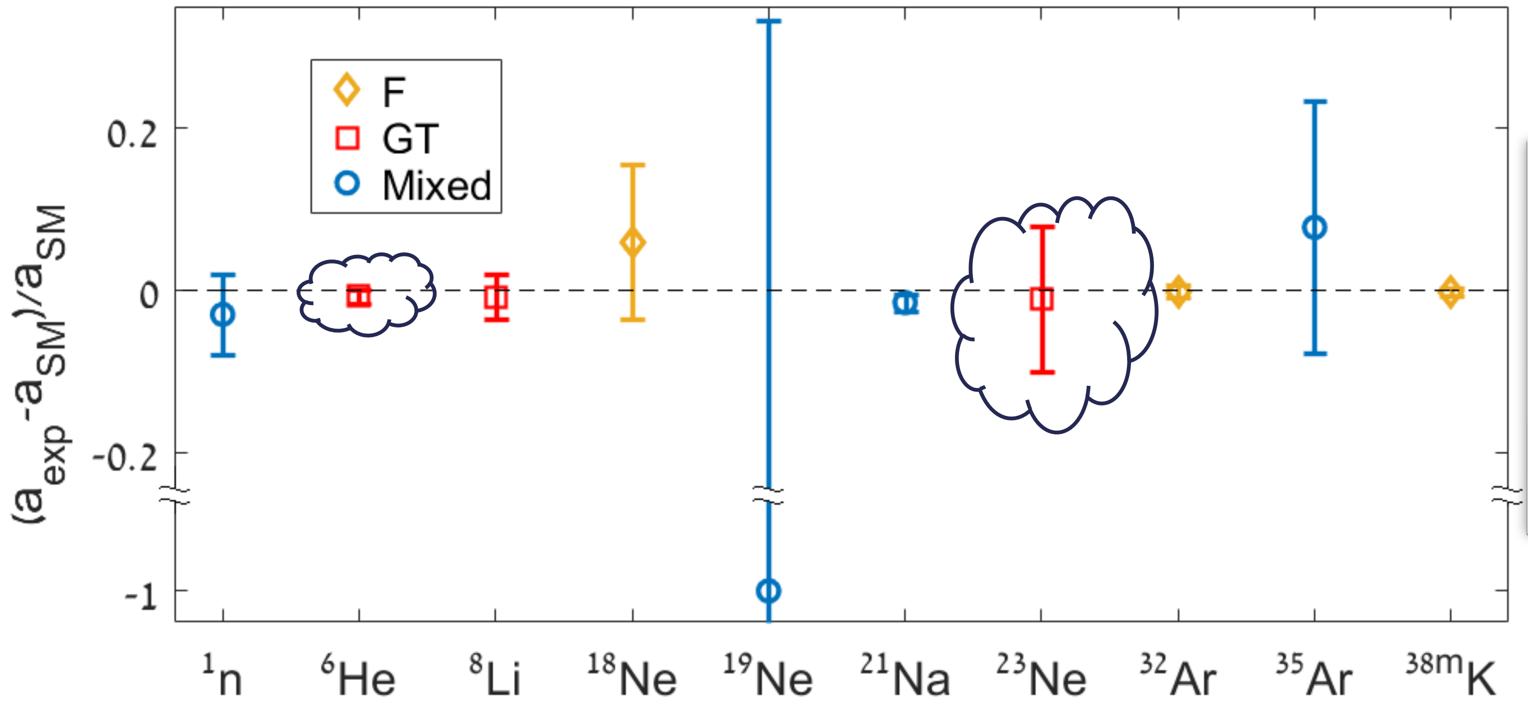


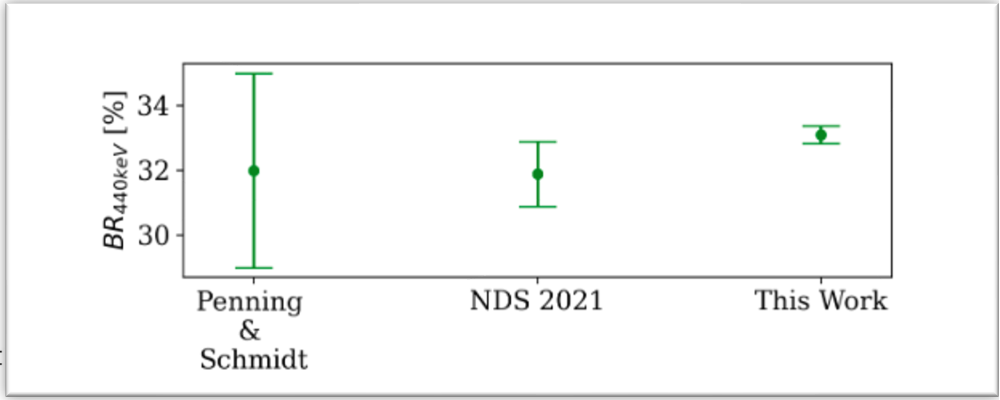


Mishnayot, Glick-Magid, DG, *et al.*, arXiv:2107.14355

BETA DECAY OF ^{23}NE INTO ^{23}NA: PRELIMINARY

Novel SARAF measurement together with reanalysis of Carlson's old measurements allow a joint assessment of $a_{\beta\nu}$ and b_F simultaneously for ^{6}He and ^{23}Ne





Mishnayot, Glick-Magid, DG et al, in prep.

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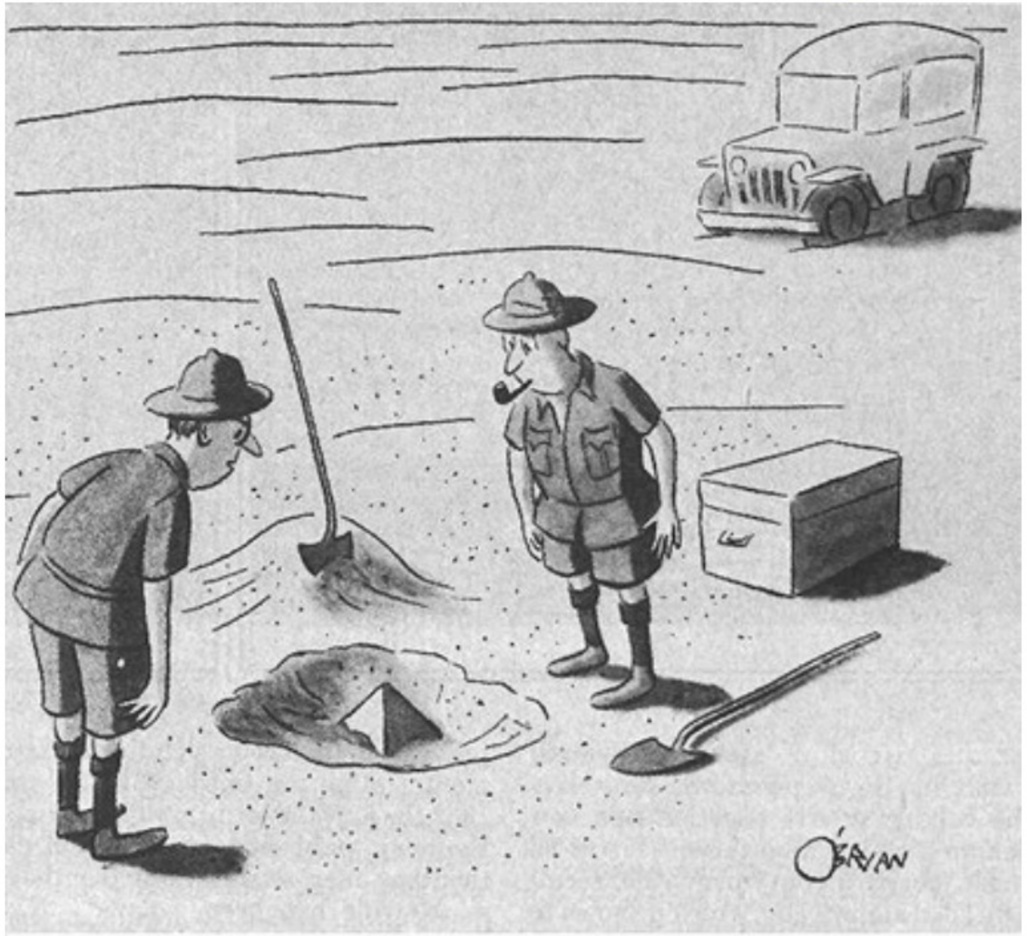
Some preliminary thoughts on future opportunities



"This could be the discovery of the century. Depending, of course, on how far down it goes."

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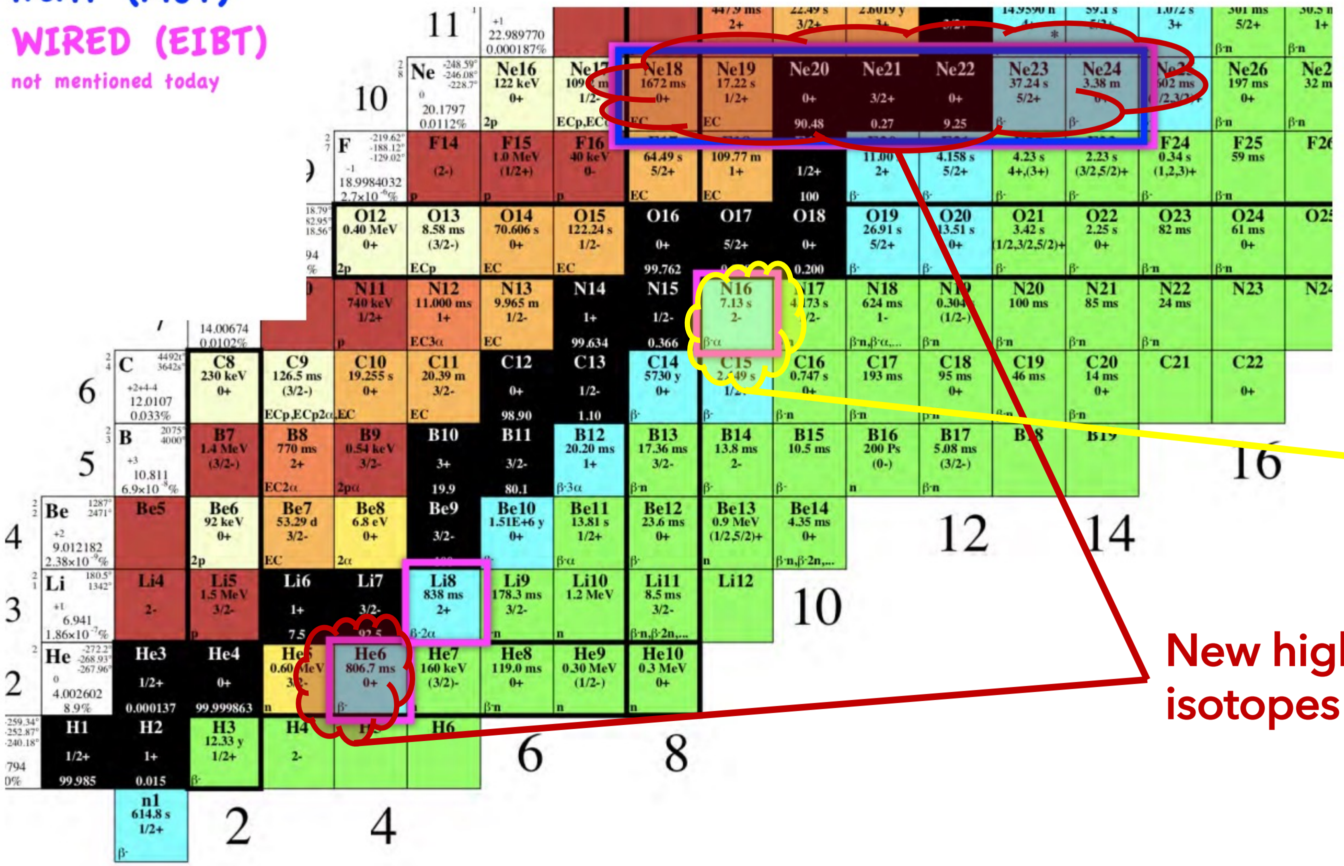
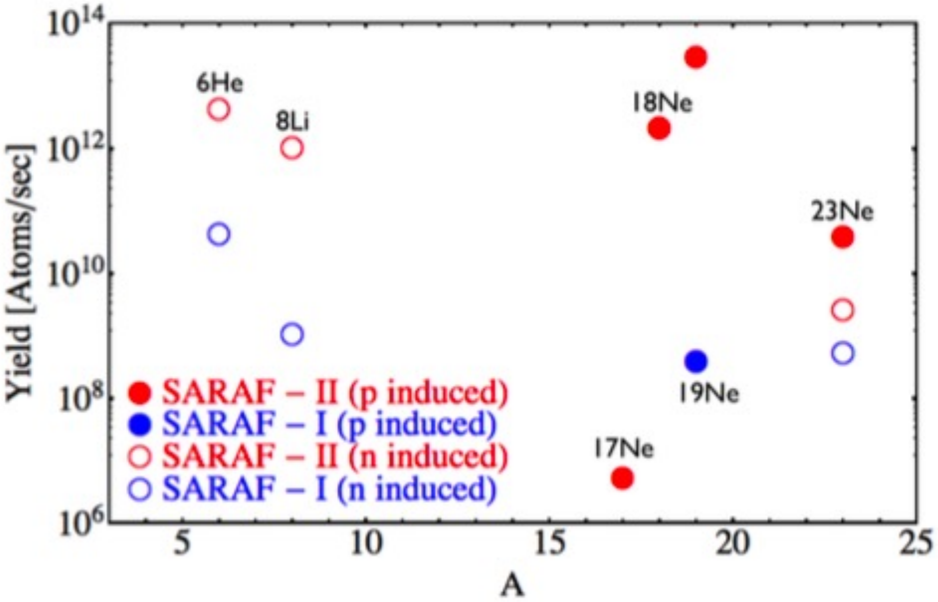
ISOTOPES TO BE PRODUCED @ SARAF-II (2025)

NeAT (MOT)

WIRED (EIBT)

not mentioned today





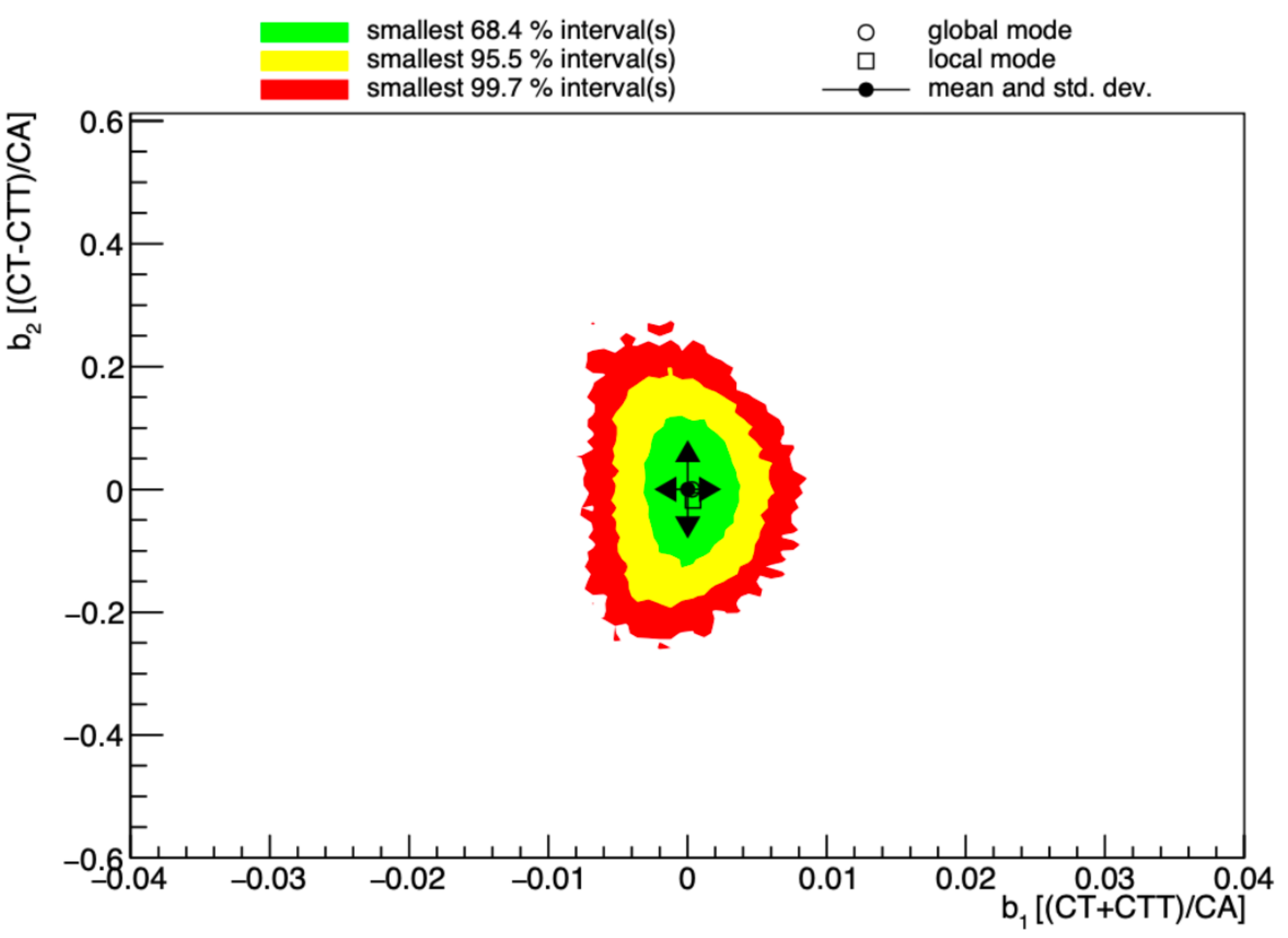
Spectrum of the Unique first forbidden decay of ^{16}N – different BSM sensitivity (see Ayala Glick Magid's talk)

New high flux ^{6}He, and Neon isotopes beta decays measurements

Glick Magid, DG et al, PLB (2017), Ohayon, Chocron, DG, *et al.*, Hyp.Int (2018)

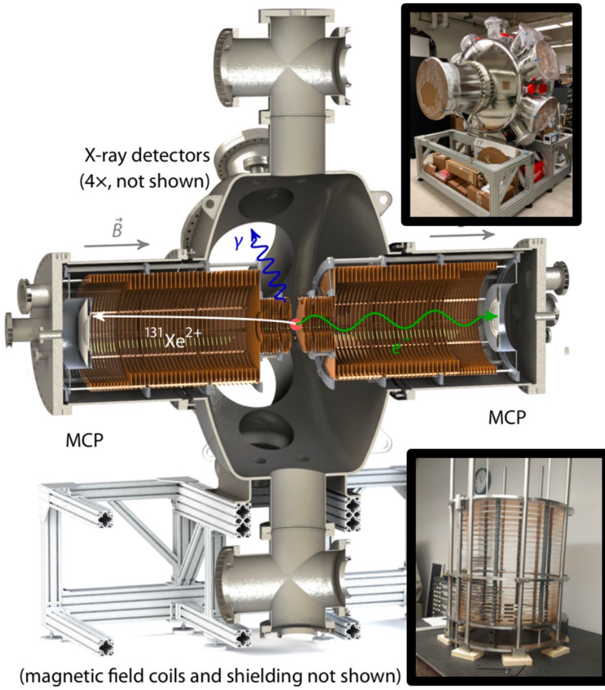
NEW EFFORTS AT HUJI: UNIQUE FIRST FORBIDDEN DECAY OF ^{90}Y INTO ^{90}ZR

- Unique first forbidden decay with 2.3 MeV end-point
- Efficient production method.
- Feasible calculation to 10% accuracy.



NEW EFFORTS AT HUJI: ^{131}CS ELECTRON CAPTURE ASYMMETRIES

- The HUNTER experiment is a large-scale experiment (located at UCLA) designed to search for sterile neutrinos using trapped ^{131}Cs.
- ^{131}Cs decays via electron capture (EC). EC is a two-body decay, and as such it is significantly simpler to analyze than β-decay reactions, amenable to complete kinematical reconstruction.
- We intend to use HUNTER infrastructure to study the asymmetries in the capture, which are sensitive to various BSM couplings.
- This would be the first BSM constraint from EC decay, and we expect 0.5% precision.
- Calculation are feasible to few~10% accuracy via shell-model. cf. 131Xe.



NEW OPPORTUNITIES IN BETA DECAYS WITH VERY LOW ENERGY ENDPOINTS

- The energy endpoints of beta decays range a few orders of magnitude.
- Low endpoints have increased sensitivities in certain cases (see neutrino mass measurements).

DG (in prep 2023)

NEW OPPORTUNITIES IN BETA DECAYS WITH VERY LOW ENERGY ENDPOINTS

- The energy endpoints of beta decays range a few orders of magnitude.
- Low endpoints have increased sensitivities in certain cases (see neutrino mass measurements).
- In particular, for nuclear recoil, terms imitating the spectral behavior of Fierz-term $\frac{m_e}{E_e}$ are significantly enhanced, while other recoil correction are significantly suppressed.

$$\frac{d\omega^{1^+\beta^-}}{d\epsilon \frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} \propto \left[1 + a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}^{1^+\beta^-}\frac{m_e}{\epsilon}\right]$$

^{3}H – 19 keV: $\frac{m_e}{E_e} > \frac{m_e}{E_0} \approx 26$

^{187}Re – 2.6 keV: $\frac{m_e}{E_e} > \frac{m_e}{E_0} \approx 200$

$$a_{\beta\nu}^{1^+\beta^-} = -\frac{1}{3}\left(1+\tilde{\delta}_a^{1^+\beta^-}\right) \qquad b_{\mathrm{F}}^{1^+\beta^-} = \delta_{\mathrm{b}}^{1^+\beta^-}$$

$$\delta_1^{1^+\beta^-} \equiv \frac{2}{3}\mathfrak{Re}\left\{-\omega\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}(\omega-2\epsilon)\frac{F_A^{(1)}}{F_1^{(1)}}\frac{C_A^*C_V + C_A'^*C_V'}{|C_A|^2+|C_A'|^2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right\},$$

$$\tilde{\delta}_a^{1^+\beta^-} \equiv \frac{4}{3}\mathfrak{Re}\left\{2\omega\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}(\omega-2\epsilon)\frac{F_A^{(1)}}{F_1^{(1)}}\frac{C_A^*C_V + C_A'^*C_V'}{|C_A|^2+|C_A'|^2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right\},$$

$$\delta_{\mathrm{b}}^{1^+\beta^-} \equiv \frac{2}{3}m_e\mathfrak{Re}\left\{\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\frac{F_A^{(1)}}{F_1^{(1)}}\frac{C_A^*C_V + C_A'^*C_V'}{|C_A|^2+|C_A'|^2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right\},$$

DG (in prep 2023)

NEW OPPORTUNITIES IN BETA DECAYS WITH VERY LOW ENERGY ENDPOINTS

- The energy endpoints of beta decays range a few orders of magnitude.
- Low endpoints have increased sensitivities in certain cases (see neutrino mass measurements).
- In particular, terms like $\frac{\alpha Z}{\left(\frac{p_e}{m_e}\right)}$ and $\frac{m_e}{E_e}$ create enhanced sensitivity to new BSM coupling terms:

$$\frac{d\omega^{1^+\beta^-}}{d\epsilon \frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} \propto \left[1 + a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}^{1^+\beta^-}\frac{m_e}{\epsilon}\right]$$

^{3}H - 19 keV: $\frac{m_e}{E_e} > \frac{m_e}{E_0} \approx 25$

^{187}Re - 2.6 keV: $\frac{m_e}{E_e} > \frac{m_e}{E_0} \approx 200$

$$\xi = |M_F|^2(|C_S|^2+|C_V|^2+|C'_S|^2+|C'_V|^2) + |M_{GT}|^2(|C_T|^2+|C_A|^2+|C'_T|^2+|C'_A|^2) \quad (A.3)$$

$$a\xi = |M_F|^2\left\{[-|C_S|^2+|C_V|^2-|C'_S|^2+|C_V|^2] \mp \frac{\alpha Z m}{p_e} 2\,\mathrm{Im}\,(C_S C_V^* + C'_S C'_V{}^*)\right\} + \frac{|M_{GT}|^2}{3}\left\{[|C_T|^2-|C_A|^2+|C'_T|^2-|C'_A|^2] \pm \frac{\alpha Z m}{p_e} 2\,\mathrm{Im}\,(C_T C_A^* + C'_T C'_A{}^*)\right\} \quad (A.4)$$

$$b\xi = \pm 2\gamma\,\mathrm{Re}[|M_F|^2(C_S C_V^* + C'_S C'_V{}^*) + |M_{GT}|^2(C_T C_A^* + C'_T C'_A{}^*)] \quad (A.5)$$

Jackson, Treiman, Wyld, Nuclear Physics 4 (1957) 206.

In particular we suggest that **concurrent study of triton and neutron** decay can significantly enhance BSM constraints

DG (in prep 2023)

האוניברסיטה העברית בירושלים

SUMMARY

- Nuclear beta decays are an important front for “new physics” discoveries.
- New experiments will have <0.1% precision.
- In order for theory to reach these precision levels – explicit calculations of nuclear corrections are needed.
- A complete formalism was built to assess theory accuracy, with particular emphasis on the EFT systematic uncertainty.
- Coming years hold the premise for many cutting-edge efforts that will constrain BSM physics at energies comparable to the LHC.

To the 10 Tev and beyond