TRIUMF

The workshop on Progress in Ab Initio Nuclear Theory

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DORON GAZIT
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NUCLEAR STRUCTURE IN BETA DECAY SEARCHES FOR *BEYOND THE STANDARD MODEL* SIGNALS

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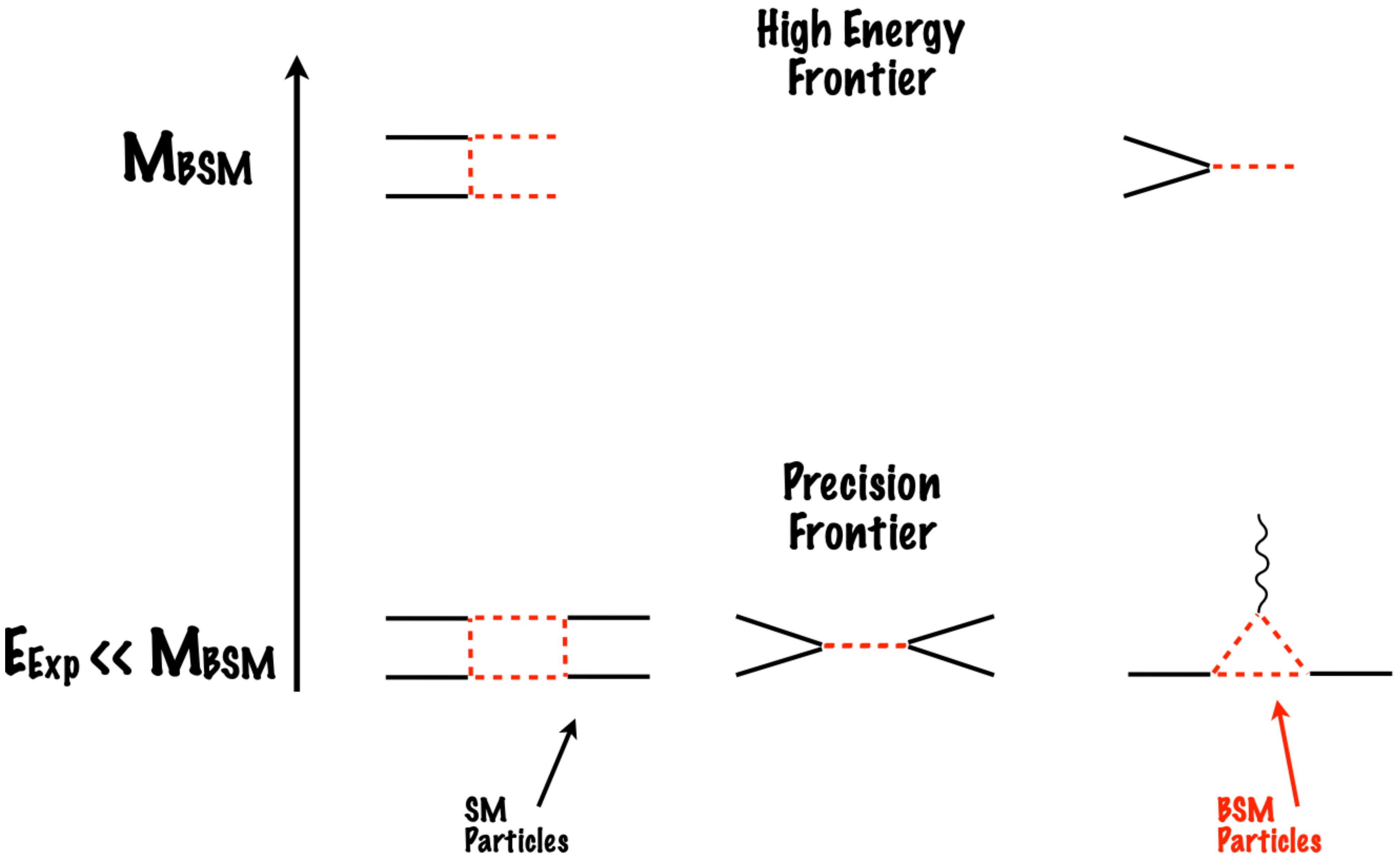
"The darkest places in hell are reserved for those who maintain their neutrality in times of moral crisis" (Dante Alighieri)

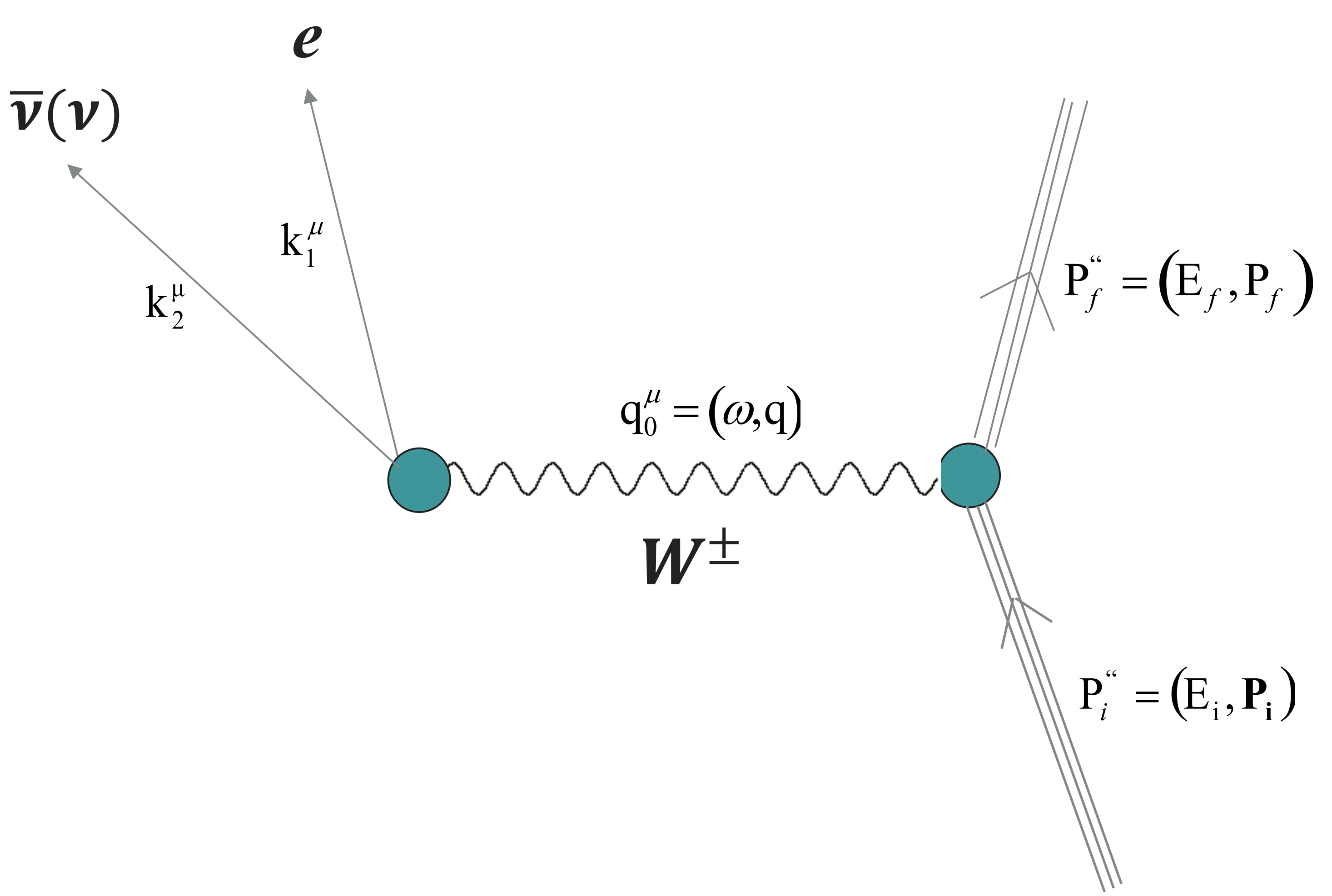
INTRODUCTION – POSSIBLE REALIZATIONS OF BEYOND THE STANDARD MODEL (BSM) EFFECTS AT LOW ENERGY



INTRODUCTION IN A NUTSHELL

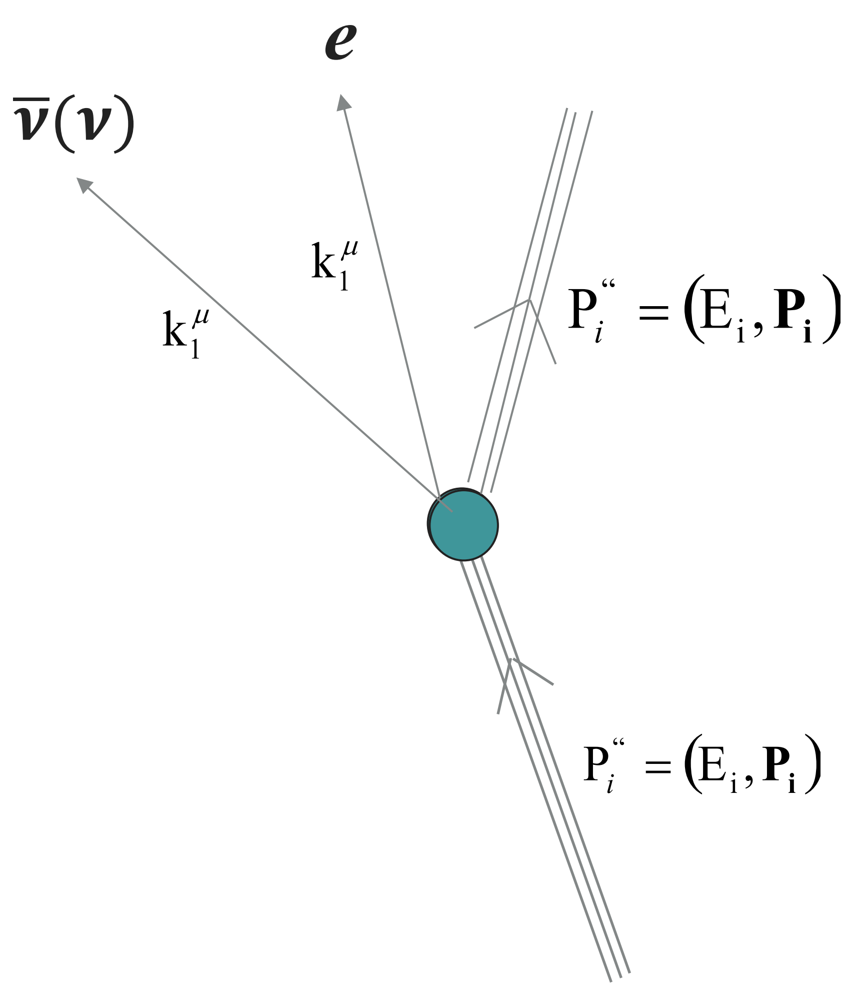
- Nuclear phenomena are a "precision frontier" in the search for BSM signatures:
  - New techniques allow unprecedented experimental precision aiming at 0.1% level precision.
  - Need an accompanying theoretical effort, to provide high precision and controlled accuracy predictions, to analyze experimental results and pinpoint new physics.
- Constraining extra interaction terms to $\approx 0.1\%$ is probing physics at few $\mathbf{TeV}$ scale.
- One of the main challenges in increasing theory accuracy is related to the nuclear structure.

BETA DECAY IN THE STANDARD MODEL



$$W,Z\ propagator = \frac{g_{\mu\nu} + \dfrac{q_\mu q_\nu}{M_W^2}}{q^2 + M_W^2}$$

BETA DECAY IN THE STANDARD MODEL



$$W,Z\ propagator = \frac{g_{\mu\nu} + \frac{q_\mu q_\nu}{M_W^2}}{q^2 + M_W^2} \rightarrow \frac{g_{\mu\nu}}{M_W^2}$$

BETA DECAY IN THE STANDARD MODEL

Coupling constant

$$\frac{\hat{\mathcal{H}}_W}{G_F^2} \sim C_{V,A} \int d^3x \; \hat{j}_\mu(\vec{x}) \; \hat{\mathcal{J}}^\mu(\vec{x})$$

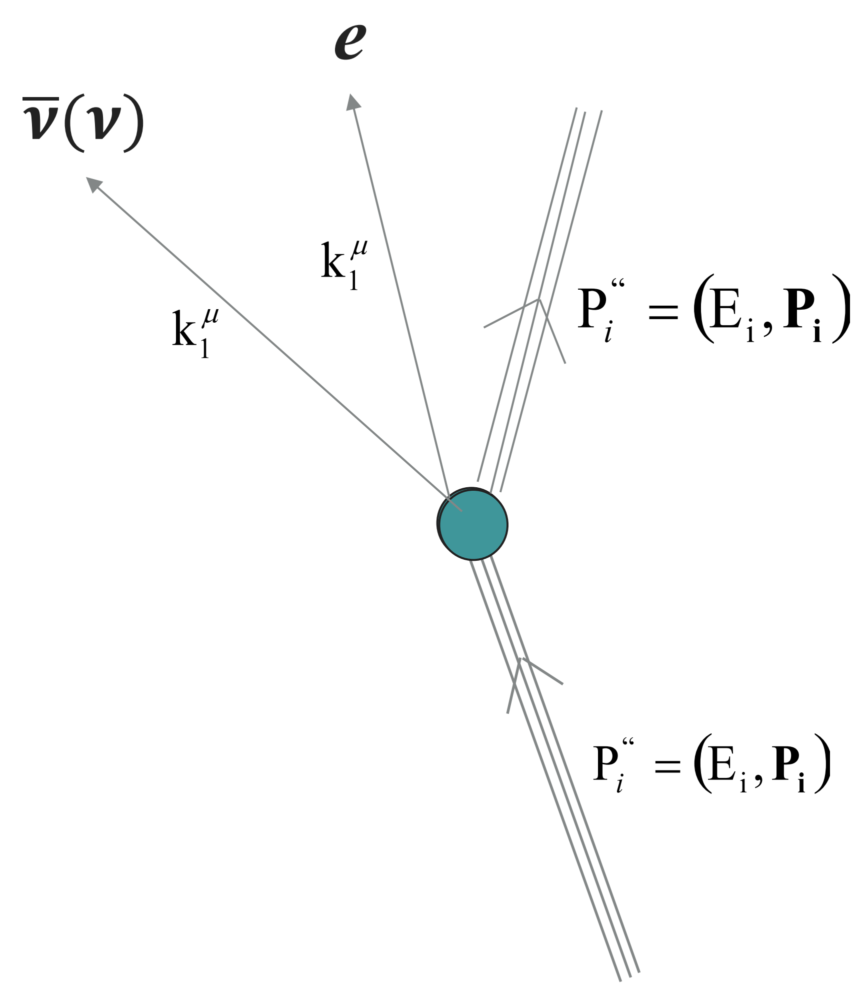
Lepton current of either V or A symmetry

Nuclear current of the same symmetry

$$C_{V,A} \sim g_{V,A} \cdot \epsilon_{V,A}$$

Nuclear charges (Form factors)

Effective theory's coefficients (Weak interaction)



BETA DECAY IN THE STANDARD MODEL

Coupling constant

$$\frac{\hat{\mathcal{H}}_W}{G_F^2} \sim C_{\mathrm{V},A} \int d^3x\, \hat{j}_\mu(\vec{x})\, \hat{\jmath}^\mu(\vec{x})$$

Lepton current of either V or A symmetry

Nuclear
same

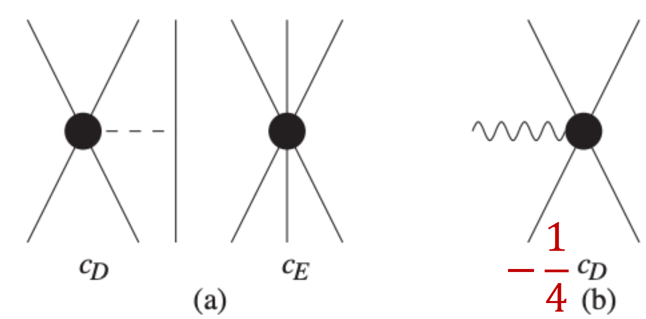
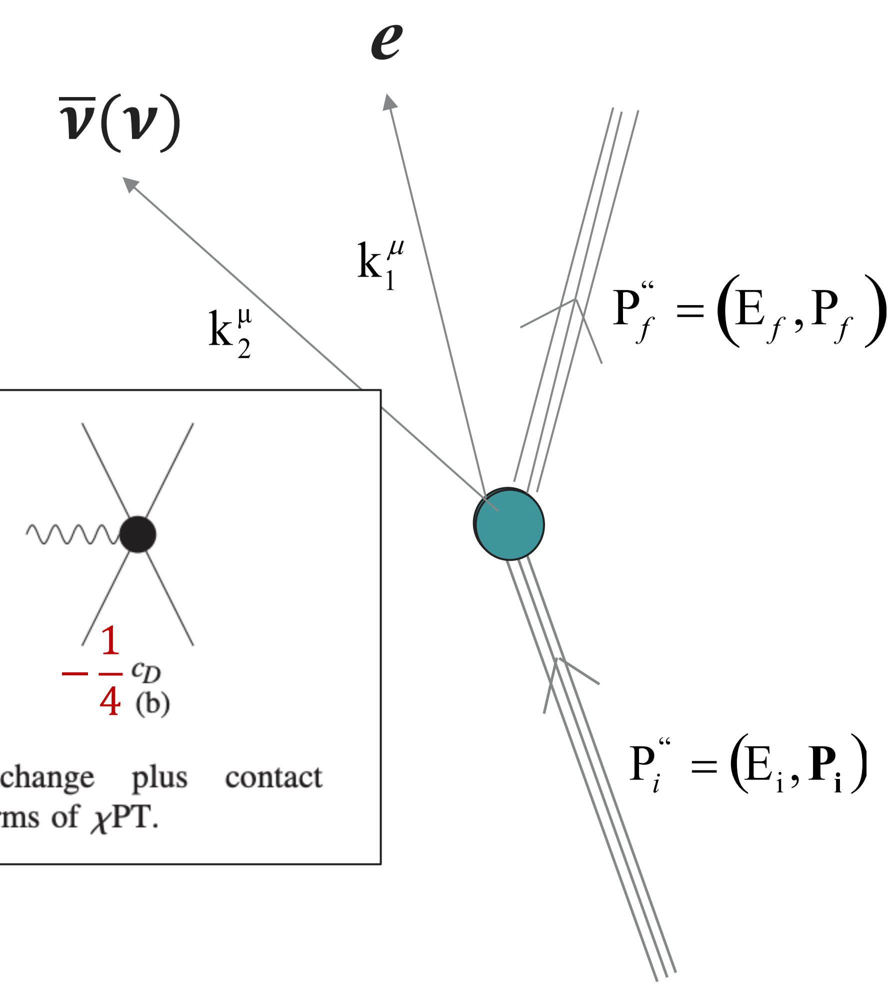


FIG. 1. Contact and one-pion exchange plus contact interaction (a), and contact MEC (b) terms of χPT.



$$C_{\mathrm{V},A} \sim g_{\mathrm{V,A}} \cdot \epsilon_{V,A}$$

Nuclear charges (Form factors)

Effective theory's coefficients (Weak interaction)

SUB-LEADING BSM TENSOR INTERACTION

Coupling constant

$$\frac{\hat{\mathcal{H}}_W}{G_F^2} \sim C_T \int d^3x\, \hat{j}_{\mu\nu}(\vec{x})\, \hat{\mathcal{J}}^{\mu\nu}(\vec{x})$$

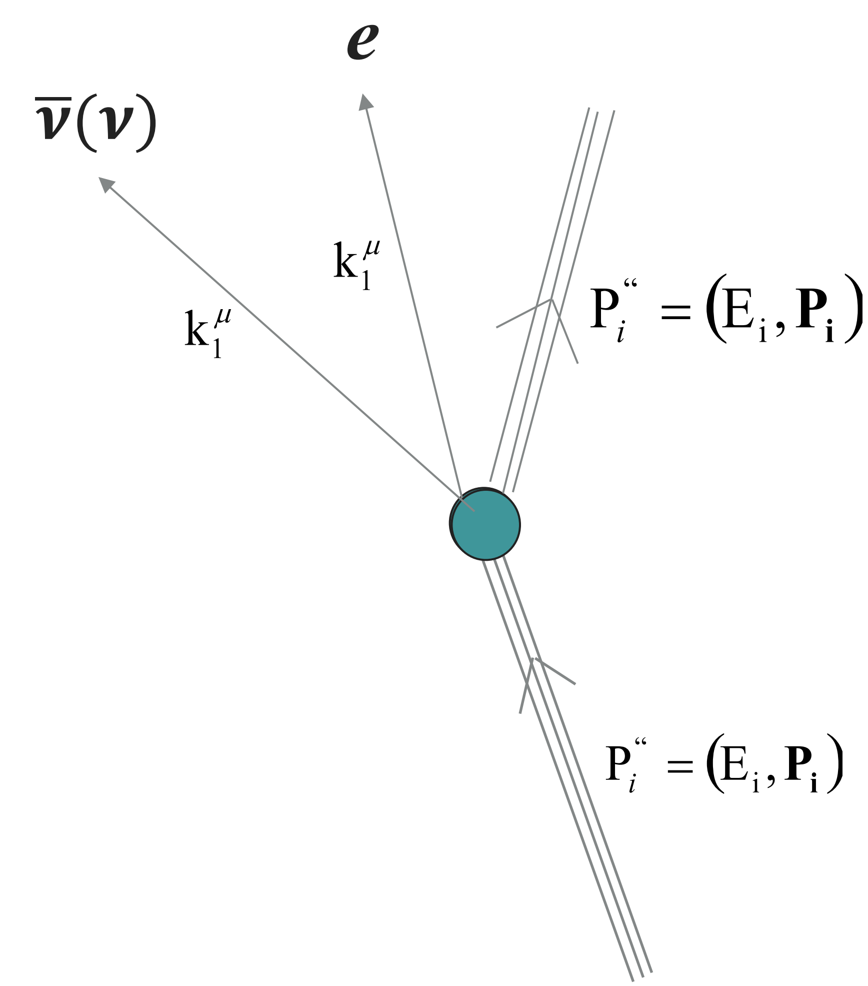
Lepton current of a known symmetry

Nuclear current of the same symmetry

$$C_T \sim g_T \cdot \epsilon_T$$

Nuclear charges (Form factors)

Effective theory's coefficients (Weak interaction)



SUB-LEADING BSM INTERACTIONS

Coupling constant

$$\frac{\widehat{\mathcal{H}}_W}{G_F^2} \sim C_{sym} \int d^3x \, \hat{j}(\vec{x}) \hat{\mathcal{J}}(\vec{x})$$

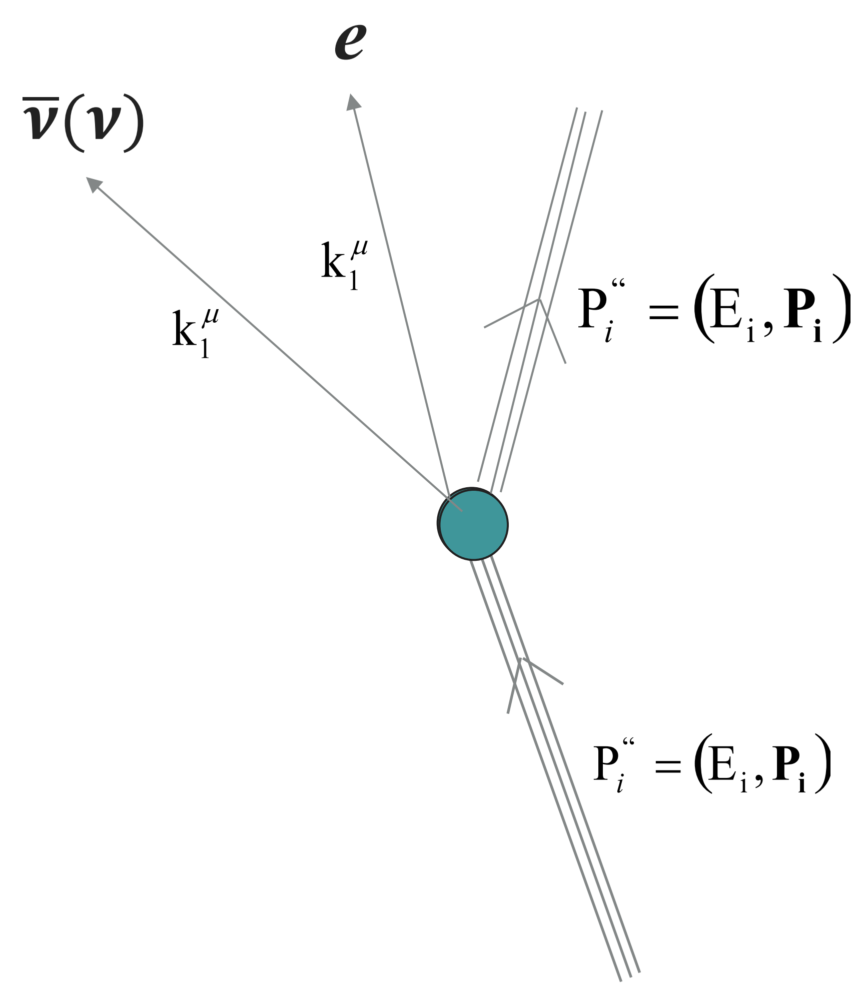
Lepton current of a known symmetry

Nuclear current of the same symmetry

$$C_{sym} \sim \mathrm{g}_{\mathrm{sym}} \cdot \epsilon_{sym}$$

Nuclear charges (Form factors)

Effective theory's coefficients (Weak interaction)



SUB-LEADING BSM INTERACTIONS

Coupling constant

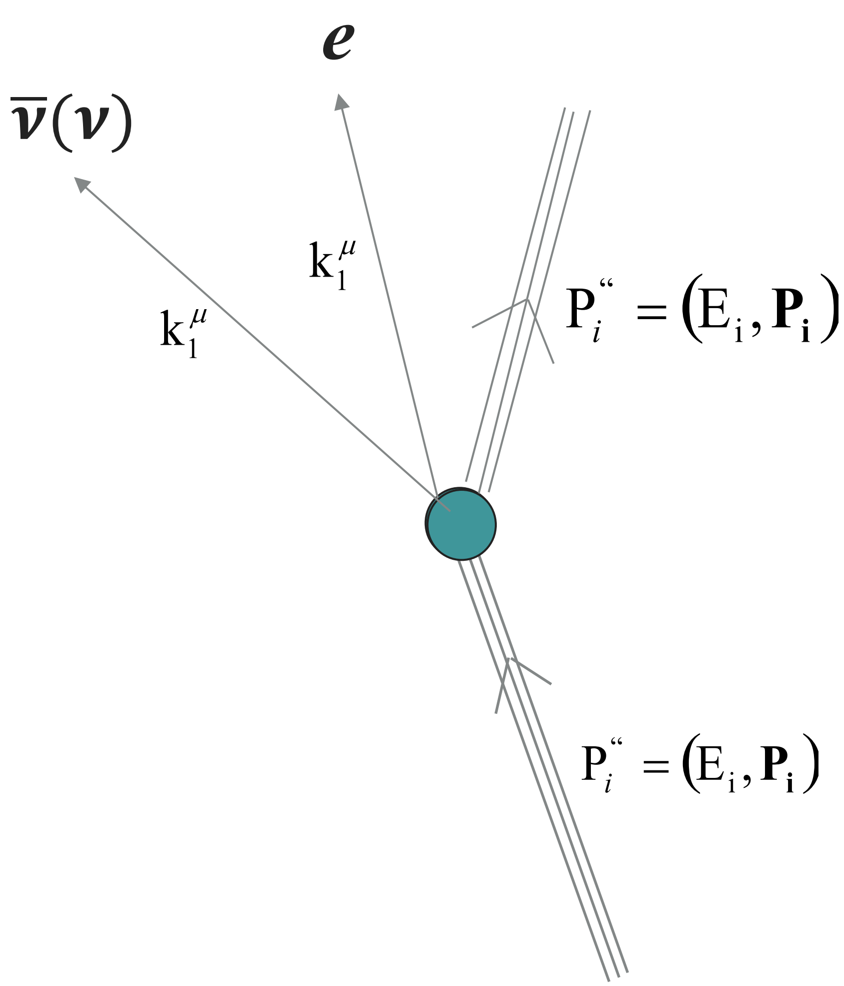
$$\frac{\hat{\mathcal{H}}_W}{G_F^2} \sim C_{sym} \int d^3x \hat{j}(\vec{x}) \hat{\mathcal{J}}(\vec{x})$$

$$C_{sym} \sim g_{sym} \cdot \epsilon_{sym}$$

Nuclear charges (Form factors)

Charge	Value
g_A	1.278(33)
g_T	0.987(55)
g_S	1.02(11)
g_P	349(9)

M. Gonzalez-Alonso, *et al.*, PPNP 104 165-223 (2019)



SUB-LEADING BSM INTERACTIONS

Coupling constant

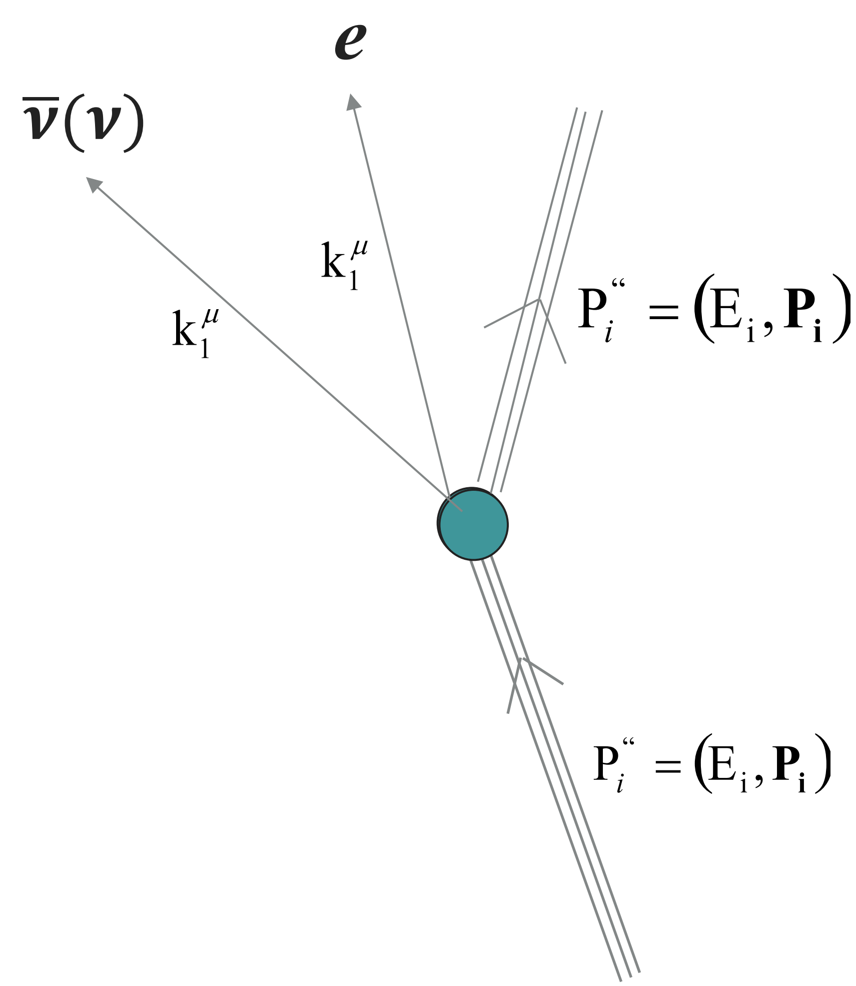
$$\frac{\hat{\mathcal{H}}_W}{G_F^2} \sim C_{sym} \int d^3x\, \hat{j}(\vec{x}) \hat{\mathcal{J}}(\vec{x})$$

$$C_{sym} \sim g_{\mathrm{sym}} \cdot \epsilon_{sym}$$

$$\epsilon_{\mathrm{sym}} \propto \left(\frac{m_W}{\Lambda}\right)^n$$

n=0 for sym=V-A
n≥2 for sym≠V,A

The effective theory scale ⟷ New physics scale



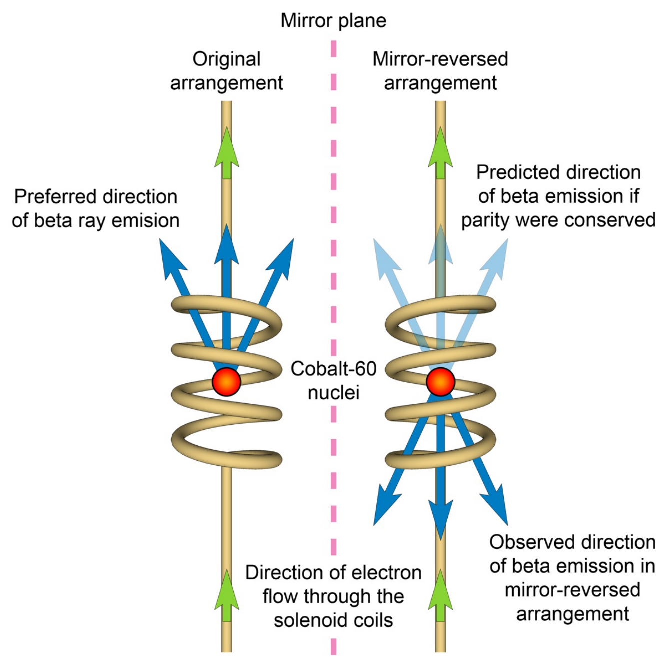
For the simplest BSM operators ($n = 2$): few TeV scale ⟷ $\epsilon_{\mathrm{sym}} \sim 10^{-3}$

Needed accuracy of calculations & measurements $\sim 10^{-4} - 10^{-3}$

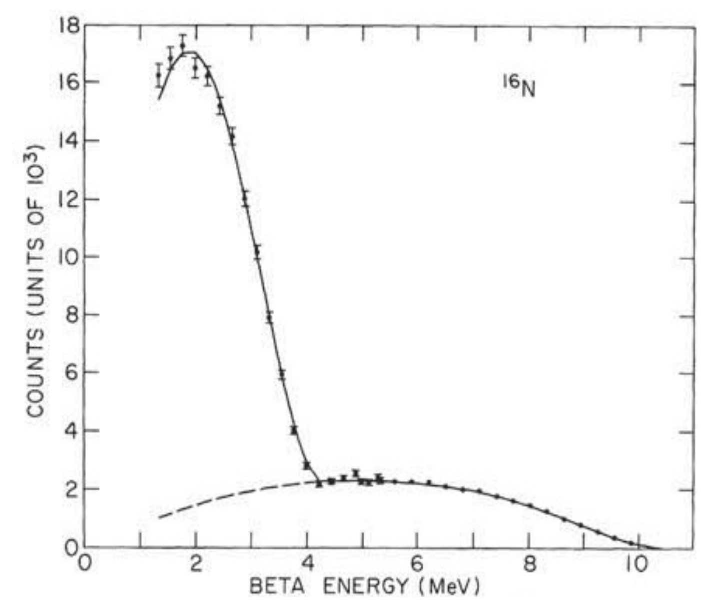
BETA DECAYS OBSERVABLES IN ON-GOING EXPERIMENTAL SEARCHES

β decays

Precision Correlation Studies



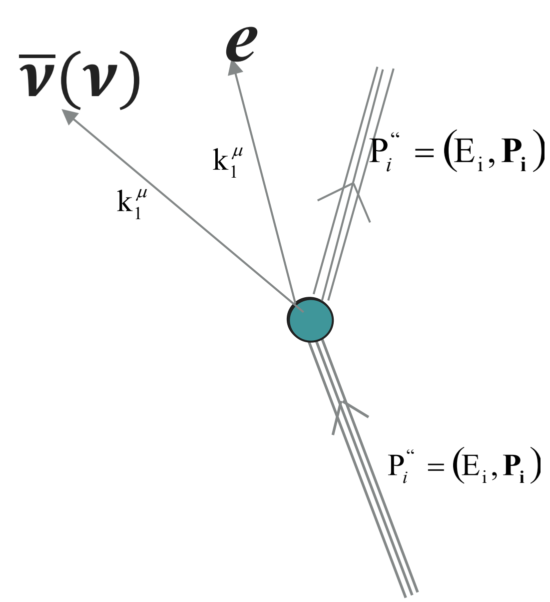
Precision spectrum studies



Mirror transitions

Superallowed beta-decays

See Ragnar's talk



NUCLEAR STRUCTURE EFFECTS IN BETA-DECAYS

- Nuclear regime effects in the effort to predict beta-decay observables:
  - *nuclear structure* corrections 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;
  - 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 $\boldsymbol{\varepsilon}_R$, $\boldsymbol{\varepsilon}_S$, and $\boldsymbol{\varepsilon}_T$, respectively.
  - *nuclear structure* effects in the calculation of radiative corrections, particularly the **γ**-W box;

NUCLEAR STRUCTURE EFFECTS IN BETA-DECAYS

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  - *nuclear structure* effects in the calculation of radiative corrections, particularly the **γ**-W box;

See Michael Gennari's talk

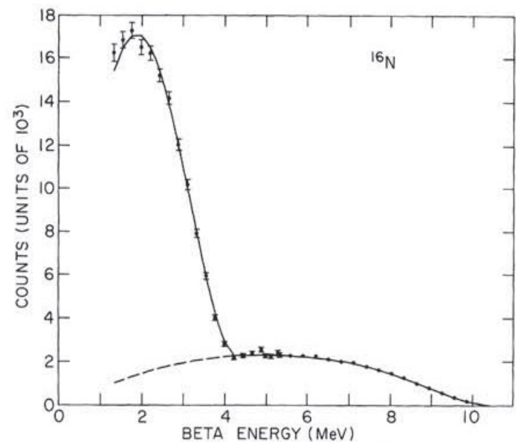
BETA DECAYS OBSERVABLES IN ON-GOING EXPERIMENTAL SEARCHES

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

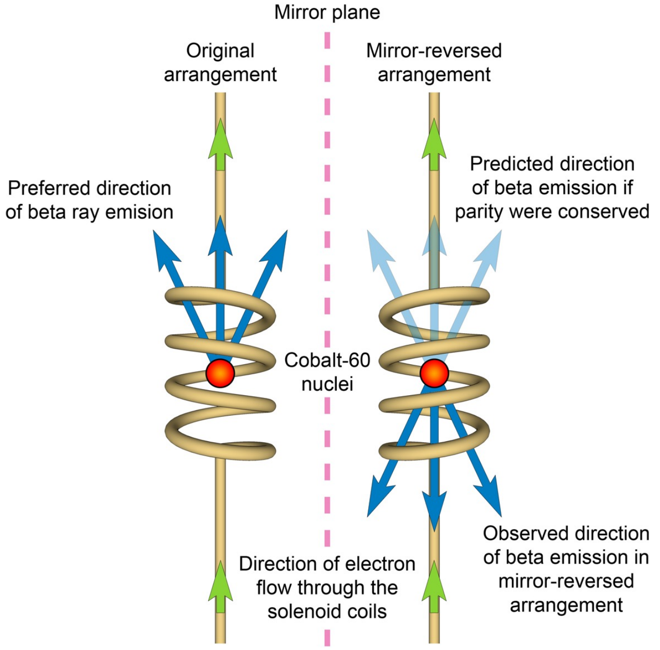


Angular correlation

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



In this talk, I outline a formalism to assess the accuracy of nuclear-structure weak interaction effects in precision **β**-decay studies, and show the detailed studies of ^{6}He (and ^{23}Ne).

Holstein (70's), Behrens & Bühring (70's), Hayen, Young (2021). Cirigliano, DG et al., arXiv:1907.02164v2 (2019)

Differential β decay rate

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

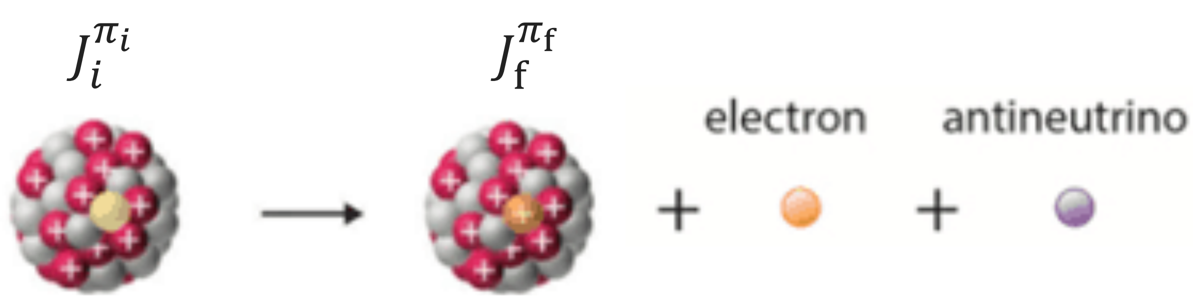
Momentum transfer

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

$\vec{\nu}$ neutrino momentum

Nuclear independent part

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



$$\Theta(q,\vec{\beta}\cdot\hat{\nu}) \propto \left|\langle\psi_f\|\hat{\mathcal{H}}_W\|\psi_i\rangle\right|^2 \propto \sum_{J=0}^{\infty} f_J(\vec{\beta},\hat{\nu})\,\langle\psi_f\|\hat{O}_J\|\psi_i\rangle\langle\psi_f\|\hat{O}_J\|\psi_i\rangle^*$$

$$J_i^{\pi_i}\to J_f^{\pi_f}$$
$$|J_i-J_f|\le J\le J_i+J_f$$
$$\Delta\pi = \pi_i\cdot\pi_f$$

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

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$\vec{\nu}$ neutrino momentum

Nuclear independent part

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

Classification of β decays

$\Delta J^\pi = 0^+$	(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	$\propto q^1$

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

Item	Effect	Formula	Magnitude
1	Phase space factor [a]	$pW(W_0 - W)^2$	
2	Traditional Fermi function	F_0	Unity or larger
3	Finite size of the nucleus	L_0	
4	Radiative corrections	R	
5	Shape factor	C	10^{-1}-10^{-2}
6	Atomic exchange	X	
7	Atomic mismatch	r	
8	Atomic screening	S	
9	Shake-up	See item 7	
10	Shake-off	See item 7	
11	Isovector correction	C_I	
12	Recoil Coulomb correction	Q	10^{-3}-10^{-4}
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 $1 \cdot 10^{-4}$
19	Neutrino mass	Negligible	

NUCLEAR STRUCTURE DEPENDENT (items 4–5)

NUCLEAR STRUCTURE DEPENDENT (items 11–15)

Beta Spectrum Generator: High precision allowed β spectrum shapes

L. Hayen[a,*], N. Severijns[a]

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

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

$$\Theta(q,\vec{\beta},\hat{\nu}) \propto \left|\langle\psi_f\|\widehat{\mathcal{H}}_W\|\psi_i\rangle\right|^2 \propto \sum_{J=0}^{\infty} f_J(\vec{\beta},\hat{\nu})\,\langle\psi_f\|\hat{O}_J\|\psi_i\rangle\langle\psi_f\|\hat{Q}_J\|\psi_i\rangle^*$$

$$\widehat{\mathcal{H}}_W \sim C\int d^3x\, \hat{j}(\vec{x})\hat{\mathcal{J}}(\vec{x})$$

coupling constant

Lepton current

nuclear current

Observables hiding new physics

Multipole operators

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:

Assuming V-A structure

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

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

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

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

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

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:

Assuming V-A structure

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

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

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

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

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

Nuclear-probe coupling operators

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:

Tensor symmetry probe multipole expansion

- The currents are *antisymmetric* tensors $\hat{j}^{\mu\nu}(\vec{x}),\ \hat{\mathcal{J}}^T_{\mu\nu}(\vec{x})$.
- No Coulomb multipole $\hat{C}^T_J$
- From symmetry principles:
  - $\Delta\pi = (-)^{J-1}$: "Axial vector" like tensor operators:

$$\hat{L}^T_J \approx -\frac{i}{\sqrt{2}}\frac{g_T}{g_A}\hat{L}^A_J$$

  - $\Delta\pi = (-)^J$: "Vector" like tensor operators: $\hat{L}^{T\prime}_J \propto \frac{q}{m_N} \approx 0$

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

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

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

Nuclear-probe coupling operators

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

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:

Assuming V-A+c*T structure (for pure axial transition)

$$\Theta^{J^A}\left(q,\vec{\beta}\cdot\hat{\nu}\right) = \frac{|C_A|^2+|C_A'|^2}{2\,|g_A|^2}\left|\left\langle\left\|\hat{L}_J^A\right\|\right\rangle\right|^2\frac{2J+1}{J}\left(1+\delta_1^{J^A}+\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\right)\cdot$$
$$\cdot\left\{1-\frac{1}{2J+1}\hat{\nu}\cdot\vec{\beta}\left(1+\tilde{\delta}_a^{J^A}-2\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\right)+\right.$$
$$\left.+\frac{J-1}{2J+1}\frac{\epsilon(\omega-\epsilon)}{q^2}\left[\beta^2-\left(\hat{\nu}\cdot\vec{\beta}\right)^2\right]\left(1-\delta_1^{J^A}-2\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\right)\mp\frac{m_e}{\epsilon}\left(0+\delta_b^{J^A}+2\Re\mathfrak{e}\frac{C_AC_T^*+C_A'C_T'^*}{|C_A|^2+|C_A'|^2}\right)\right\}+\mathcal{O}\left(\epsilon_{qR}^{2J}\right)$$

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

e.g., allowed transitions $\Delta J^{\pi} = 0,1^{+}$

$$d\omega^{V-A} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot$$

$$\cdot \left\{ \frac{|C_V|^2 + \left|C_V'\right|^2}{2} \left(1 + \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{C}_0^V \right\| J_i \right\rangle\right|^2 + \frac{|C_A|^2 + \left|C_A'\right|^2}{2} 3 \left(1 - \frac{1}{3} \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{L}_1^A \right\| J_i \right\rangle\right|^2 \right\}$$

Fermi

Gamow–Teller

Correlation coefficient

Neglected are all finite momentum transfer terms, i.e., nuclear physics is neglected.

e.g., allowed transitions $\Delta J^{\pi} = 0,1^{+}$

Assuming V+T structure

$$d\omega^{V+T} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot$$

$$\cdot \left\{ \frac{|C_V|^2 + \left|C_V'\right|^2}{2} \left(1 + \hat{\nu} \cdot \vec{\beta}\right) \left| \left\langle J_f \left\| \hat{C}_0^V \right\| J_i \right\rangle \right|^2 \right.$$

$$\left. + \frac{|C_T|^2 + |C_T'|^2}{2} 3 \left(1 + \frac{1}{3} \hat{\nu} \cdot \vec{\beta}\right) \left| \left\langle J_f \left\| \hat{L}_1^A \right\| J_i \right\rangle \right|^2 \right\}$$

e.g., allowed transitions $\Delta J^{\pi} = 0{,}1^{+}$

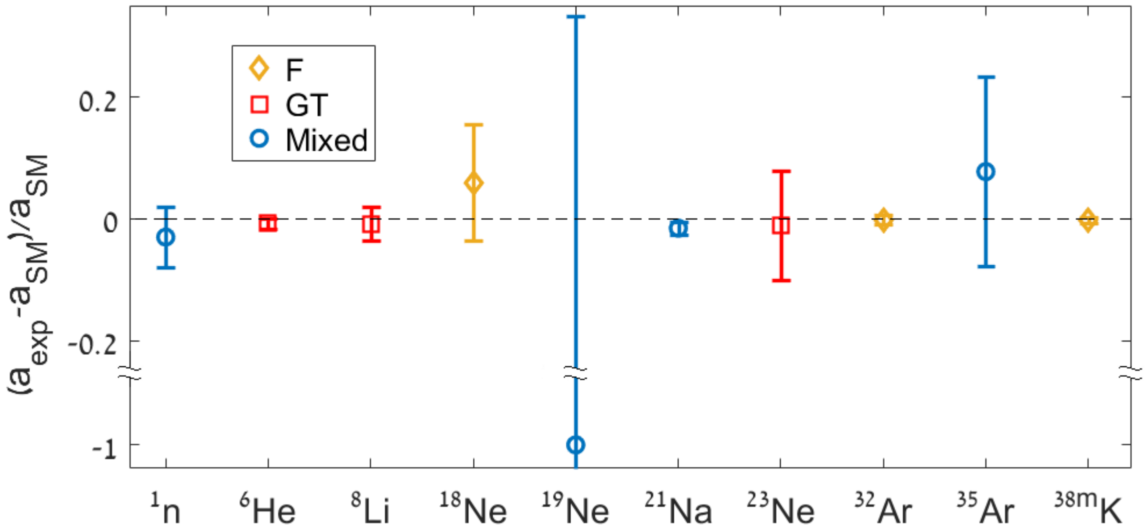
$$d\omega^{V-A} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}\frac{1}{2J_i+1}\cdot$$
$$\cdot\left\{\frac{|C_V|^2+\left|C_V'\right|^2}{2}\left(1+\hat{\nu}\cdot\vec{\beta}\right)\left|\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle\right|^2 + \frac{|C_A|^2+\left|C_A'\right|^2}{2}3\left(1-\frac{1}{3}\hat{\nu}\cdot\vec{\beta}\right)\left|\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle\right|^2\right\}$$

Fermi

Gamow-Teller

Correlation coefficient

Neglected are all finite momentum transfer terms and other nuclear corrections.



e.g., pure GT transitions $\Delta J^{\pi} = 1^{+}$

$$d\omega \propto 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_F \frac{m_e}{\epsilon}$$

Correlation coefficient $a_{\beta\nu} = -\frac{1}{3}\left(1 + \delta_a + \frac{|C_T|^2 + |C_T'|^2}{2|C_A|^2}\right)$

GT | SM (nuclear) correction | BSM signature

Terms with Fierz-like spectral behavior $b_F = 0 + \delta_b + \frac{C_T^* + C_T'^*}{C_A}$

Naïvely, the correlation coefficient has quadratically weaker sensitivity to BSM terms. However…

e.g., pure GT transitions $\Delta J^{\pi} = 1^{+}$

$$d\omega \propto 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_F \frac{m_e}{\epsilon}$$

Correlation coefficient $$a_{\beta\nu} = -\frac{1}{3}\left(1 + \delta_a + \frac{|C_T|^2 + |C_T'|^2}{2|C_A|^2}\right)$$

Terms with Fierz-like spectral behavior $$b_F = 0 + \delta_b + \frac{C_T^* + C_T'^*}{C_A}$$

Measured correlation coefficient: $$a_{\beta\nu}^{measured} = a_{\beta\nu}\cdot\left(1 + b_F\left\langle\frac{m_e}{\epsilon}\right\rangle_{experiment}\right)^{-1}$$

Since $\left\langle\frac{m_e}{\epsilon}\right\rangle \approx 0.01 - 10$, this creates a linear sensitivity to BSM signatures even in the angular coefficients, albeit (usually) suppressed compared to b_F.

DG, Ron (in prep. 2023)

ASSESSING THE SIZE AND UNCERTAINTIES OF THE NUCLEAR STRUCTURE CORRECTIONS TO BETA DECAY OBSERVABLES

SHAPE AND RECOIL CORRECTIONS – SMALL PARAMETERS

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

Small parameter #2: $\epsilon_{EFT} \approx 0.1 - 0.4$ - 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: $\epsilon_{recoil} = \frac{q}{M} \approx 0.002$ 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_{Model} is related to the implementation of the Nuclear Model

Small parameter #8: ϵ_{solver} numerical error in the solution of the Schrödinger equation

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

SHAPE AND RECOIL CORRECTIONS

These are nuclear structure dependent corrections, beyond the leading usual elementary particle zero momentum transfer approach.

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

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

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

$$\hat{L}_{JM}(q) = \frac{i}{q} \int d\vec{x}\, \vec{\nabla}[j_J(qx) Y_{JM}(\hat{x})] \cdot \hat{\vec{\mathcal{J}}}(\vec{x}), \quad \approx \sqrt{\frac{J}{J+1}} \hat{E}_{JM}$$

$$\epsilon_q = \frac{qR}{\hbar c} \approx 0.005 - 0.1$$

Natural kinematical suppression of the correction!

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$$\frac{1}{(2J+1)!!}$$

$$\epsilon_q = \frac{qR}{\hbar c} \approx 0.005 - 0.1$$

Natural kinematical suppression of the correction!

SHAPE AND RECOIL CORRECTIONS

These are nuclear structure dependent corrections, be... the leading usual elementary particle zero momentum transfer approa...

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Analyze Nuclear-probe coupling operators scaling, to understand how explicit NME calculation increases accuracy

In beta decays, shape corrections are few per-milles, thus the first correction should be calculated explicitly to reach needed accuracy

SHAPE AND RECOIL CORRECTIONS

These are nuclear structure dependent corrections.

Needed accuracy of the calculation $\approx 10^{-4} - 10^{-3}$

This dictates the number of corrections needed to be calculated explicitly.

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

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

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$$\hat{L}_{JM}(q) = \frac{i}{q} \int d\vec{x} \vec{\nabla}[j_J(qx) Y_{JM}(\hat{x})] \cdot \hat{\vec{\mathcal{J}}}(\vec{x}), \quad \approx \sqrt{\frac{J}{J+1}} \hat{E}_{JM}$$

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

$$J^0_{i,1b}(p^2) = 1 - g_A \frac{\mathbf{p} \cdot \boldsymbol{\sigma}_i}{2m},$$

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

Chiral suppression
additional factor 3-5

Exchange currents

In beta decays, shape corrections are few per-milles, thus the first correction should be calculated explicitly to reach needed accuracy

EFFECTIVE FIELD THEORY FOR THE NUCLEAR-PROBE INTERACTION

- EFT expansion parameter $\epsilon_{EFT} \propto \frac{\max(q,Q,\ldots)}{M_{br}} \approx \frac{1}{10} - \frac{1}{3}$:
  - Breakdown scale in chiral EFT is about $4\pi f_\pi \approx 1\ \mathrm{GeV/c}$
  - Order by order expansion of the currents:

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

- LO – single nucleon current
- NLO – corrections to single nucleon currents
- NLO or higher orders include 2-body currents (magnetic – NLO, weak axial –$N^{7/4 \div 3}LO$)

Pavon Valderama, Phillips; PRL (2015)

EXAMPLE: SM PREDICTION FOR GT TRANSITION

$$\frac{d\omega^{1^+\beta^-}}{dE\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}(E_0-E)^2 kEF^-(Z_f,E)\,C_{\rm corr}\left|\langle\|\hat{L}_1^A\|\rangle\right|^2 \times 3\left(1+\delta_1^{1^+\beta^-}\right)\left[1+a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu}+b_{\rm F}^{1^+\beta^-}\frac{m_e}{E}\right], \quad (1)$$

Gamow-Teller

Shape $\delta_1^{1^+\beta^-}$

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

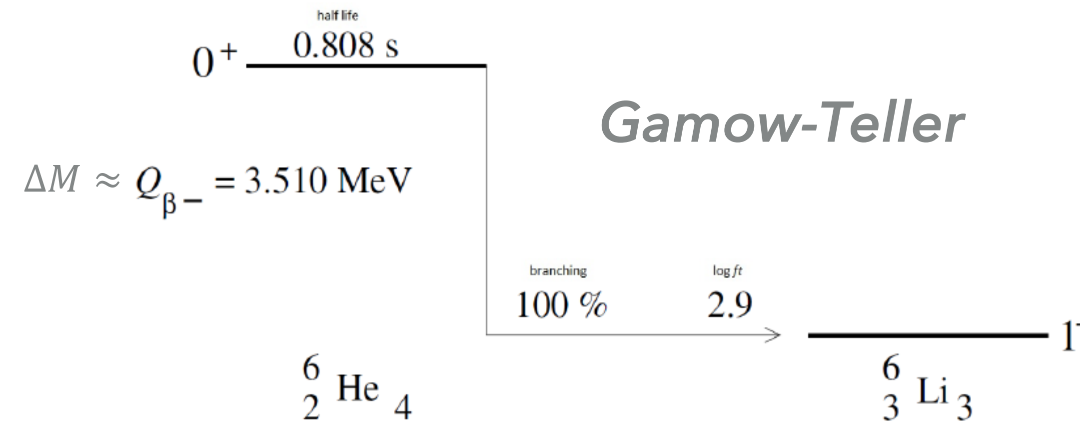
Angular correlation $\tilde{\delta}_a^{1^+\beta^-}$

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

Induced Fierz-like spectral correction $\delta_b^{1^+\beta^-}$

$$\equiv \frac{2}{3}m_e\mathfrak{Re}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right], \quad (4)$$

$^{6}\mathrm{HE} \xrightarrow{\beta^-} {}^{6}\mathrm{LI}$



Gamow-Teller

$$\langle \| \hat{L}_1^A \| \rangle \sim 1$$

$$d\omega \;\propto\; \left(\tilde{1} + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{\epsilon}\right) \left|\langle {}^{6}\mathrm{Li}\ 1^+ \| \hat{L}_1^A \| {}^{6}\mathrm{He}\ 0^+ \rangle\right|^2$$

β energy spectrum (shape) → $1 + \delta_1$

Angular correlation → $-\frac{1}{3}(1 + \delta_a)$

Induced Fierz-like spectral term → $0 + \delta_b$

$$\epsilon_{\mathrm{NR}} \equiv \frac{P_{fermi}}{m_N} \approx 2 \cdot 10^{-1}$$
$$\epsilon_{qr} \equiv qR \approx 5 \cdot 10^{-2}$$
$$\epsilon_c \equiv \alpha Z_f \approx 2 \cdot 10^{-2}$$
$$\epsilon_{\mathrm{recoil}} \equiv \frac{q}{m_N} \approx 4 \cdot 10^{-3}$$

- $\delta_1 = f_1\left(\frac{\langle \| \hat{C}_1^A \| \rangle}{\langle \| \hat{L}_1^A \| \rangle}, \frac{\langle \| \hat{M}_1^V \| \rangle}{\langle \| \hat{L}_1^A \| \rangle}\right) + \mathcal{O}\left(\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2\right)$

Glick-Magid & DG (JPhG 2022)

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

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

$$\begin{aligned}
\delta_1^{1^+\beta^-} &\equiv \frac{2}{3}\mathfrak{Re}\left[-E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\left(E_0 - 2E\right)\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] \\
&\quad - \frac{4}{7}ER\alpha Z_f - \frac{233}{630}\left(\alpha Z_f\right)^2, \\
\tilde{\delta}_a^{1^+\beta^-} &\equiv \frac{4}{3}\mathfrak{Re}\left[2E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\left(E_0 - 2E\right)\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] \\
&\quad + \frac{4}{7}ER\alpha Z_f - \frac{2}{5}E_0R\alpha Z_f, \\
\delta_{\rm b}^{1^+\beta^-} &\equiv \frac{2}{3}m_e\mathfrak{Re}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right],
\end{aligned} \tag{4}$$

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

Nuclear Hamiltonian

$\mathrm{N^2LO_{opt\ (sat)}}$

↓

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

Nuclear wave functions

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

Nuclear currents at LO (1-body currents)

↓

$\hat{O}_J$

Multipole operators

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

Nuclear matrix elements

***ab initio* No Core Shell Model** (NCSM)

↓

$\delta_1, \delta_a, \delta_b$

Observables' corrections

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

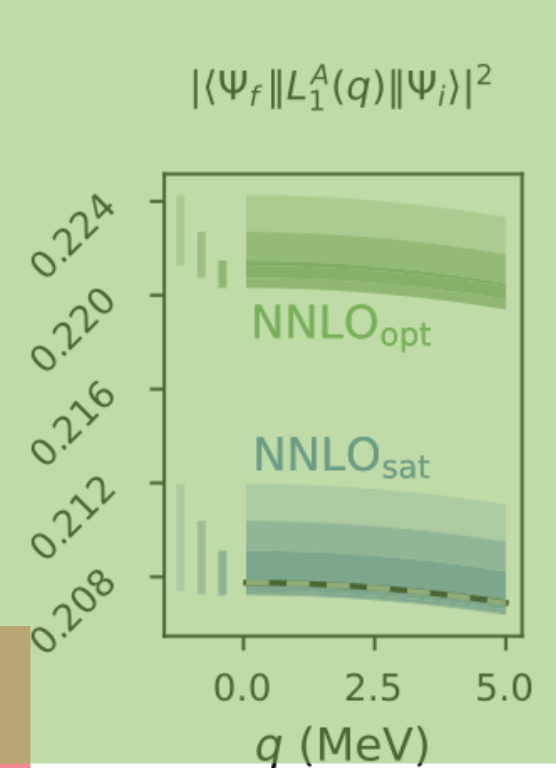
AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

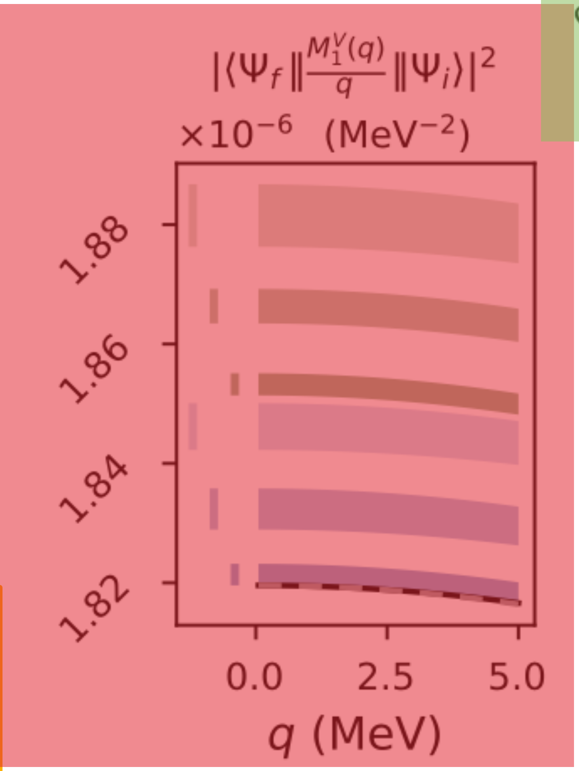
$$d\omega \propto \left(1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\rm F}\frac{m_e}{\epsilon}\right) |\langle\psi_f \| \hat{L}_J \| \psi_i\rangle|^2$$

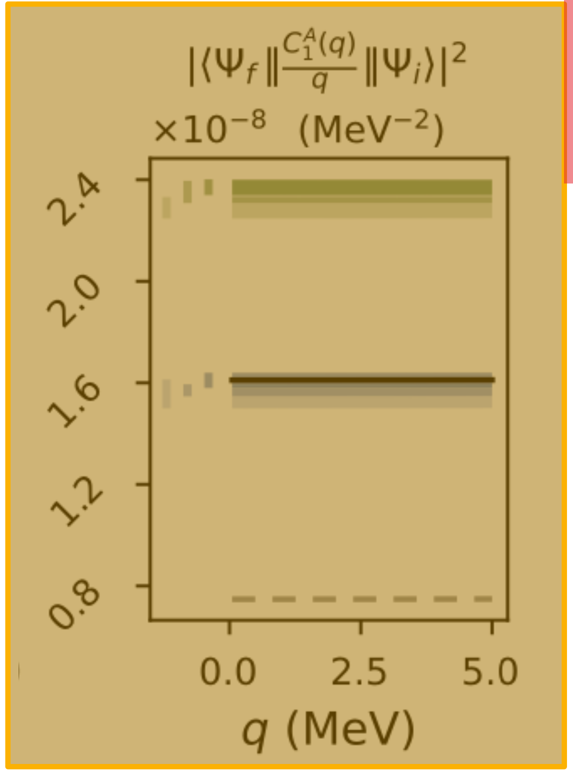
$$\delta_1^{1^+\beta^-} \equiv \frac{2}{3}\mathfrak{Re}\left[-E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\,(E_0-2E)\,\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] - \frac{4}{7}ER\alpha Z_f - \frac{233}{630}(\alpha Z_f)^2,$$

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

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







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

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

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

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

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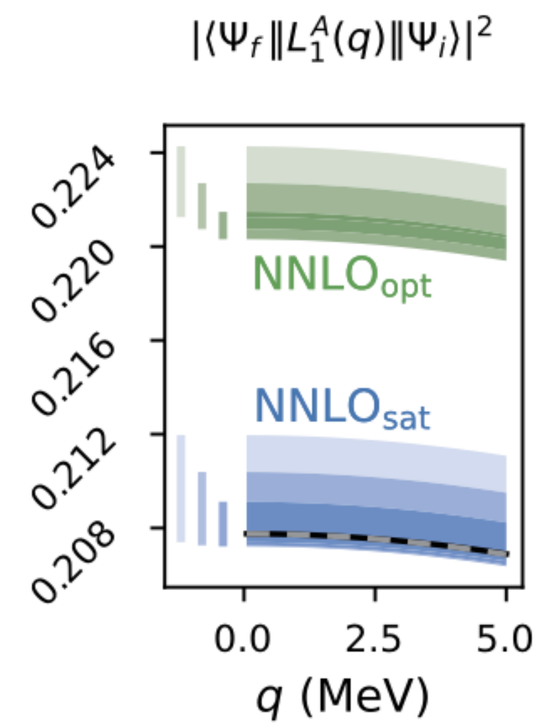
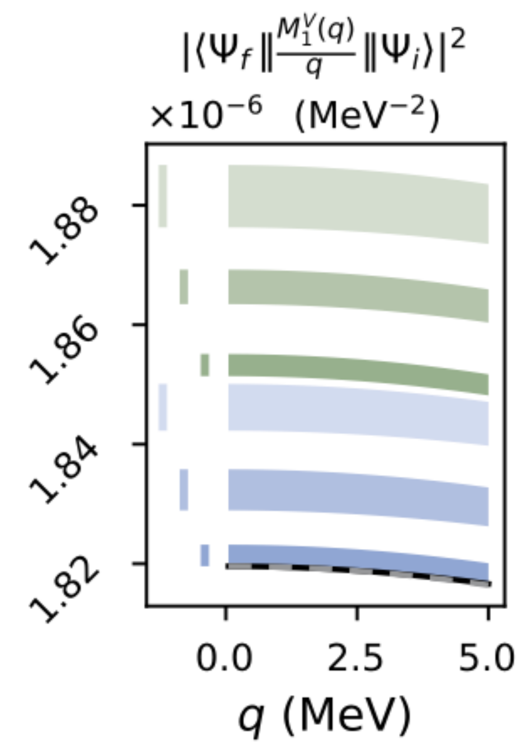
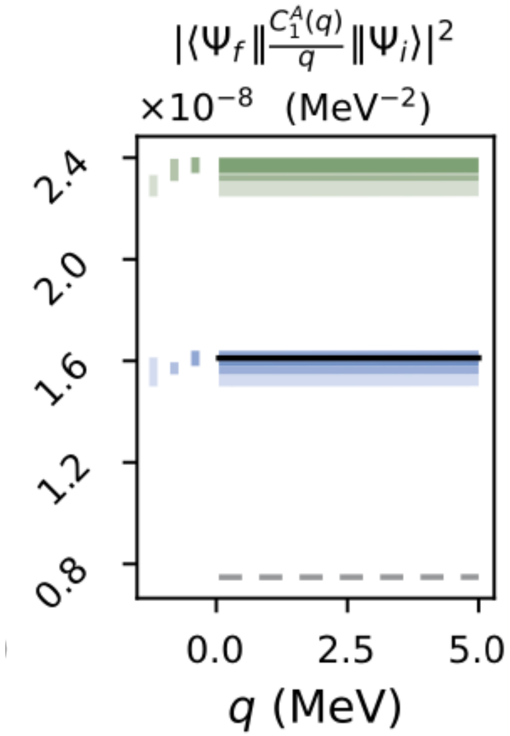
$$\delta_{\mathrm{b}}^{1^+\beta^-} \equiv \frac{2}{3}m_e\mathfrak{Re}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle} + \sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right],$$



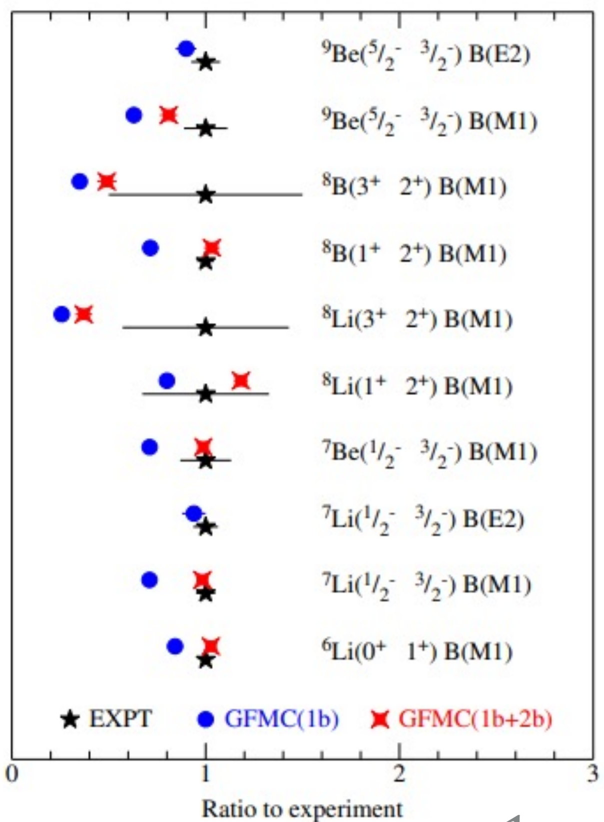


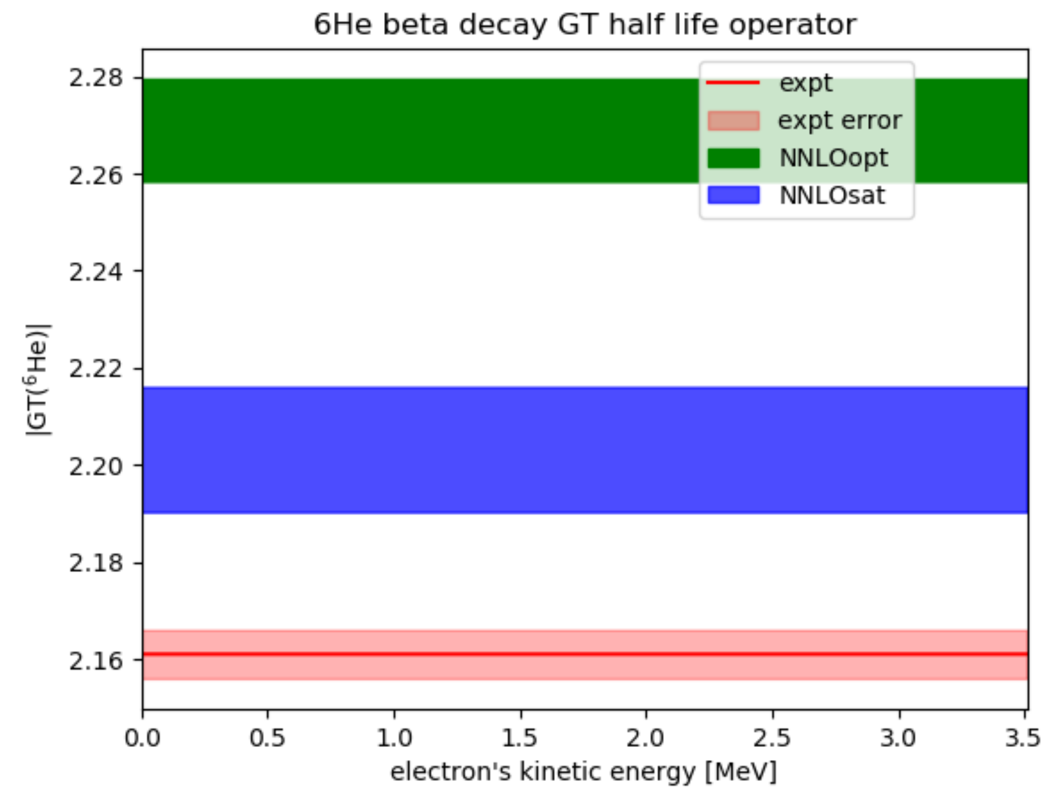


Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, (PLB 2022)

ESTIMATING ϵ_{EFT} IN A SPECIFIC CASE: AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

Electro-magnetic transitions





$$^6\text{Li}(0^+ \to 1^+):\ B(M1) = \frac{1}{3}\left|\langle\|\widehat{M}_1^V\|\rangle\right|^2$$

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

$$\left|GT(\,^6\text{He})\right| = \frac{\sqrt{12\pi}}{g_A}\left|\langle\|\hat{L}_1^A\|\rangle\right|^2$$

2b: $\langle\|\hat{L}_1^A\|\rangle, \langle\|\hat{C}_1^A\|\rangle \sim few\ \% \sim \mathcal{O}(\epsilon_{EFT}^{1.75-3})$

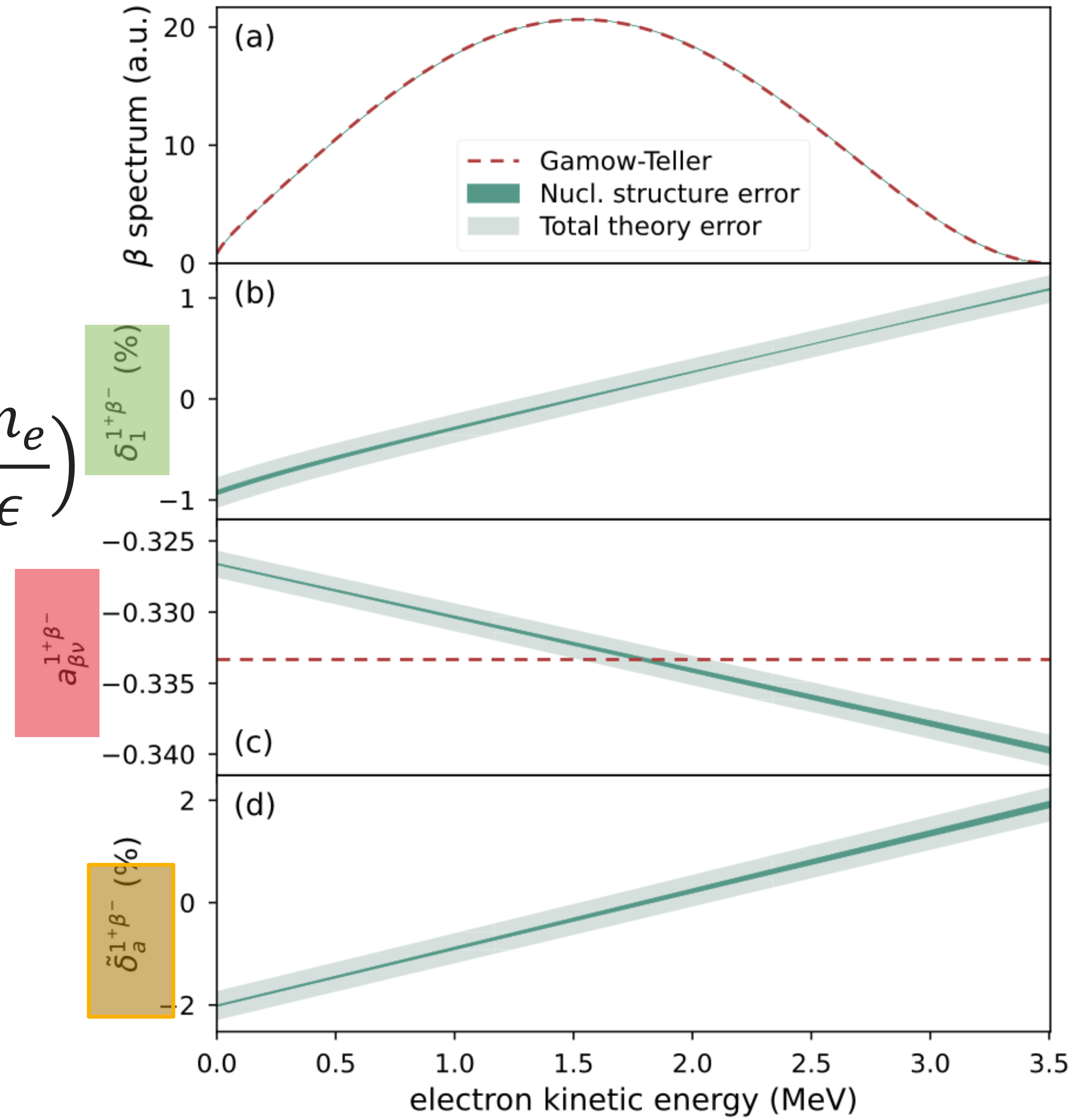
$$\epsilon_{EFT} \sim 15\%$$

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

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

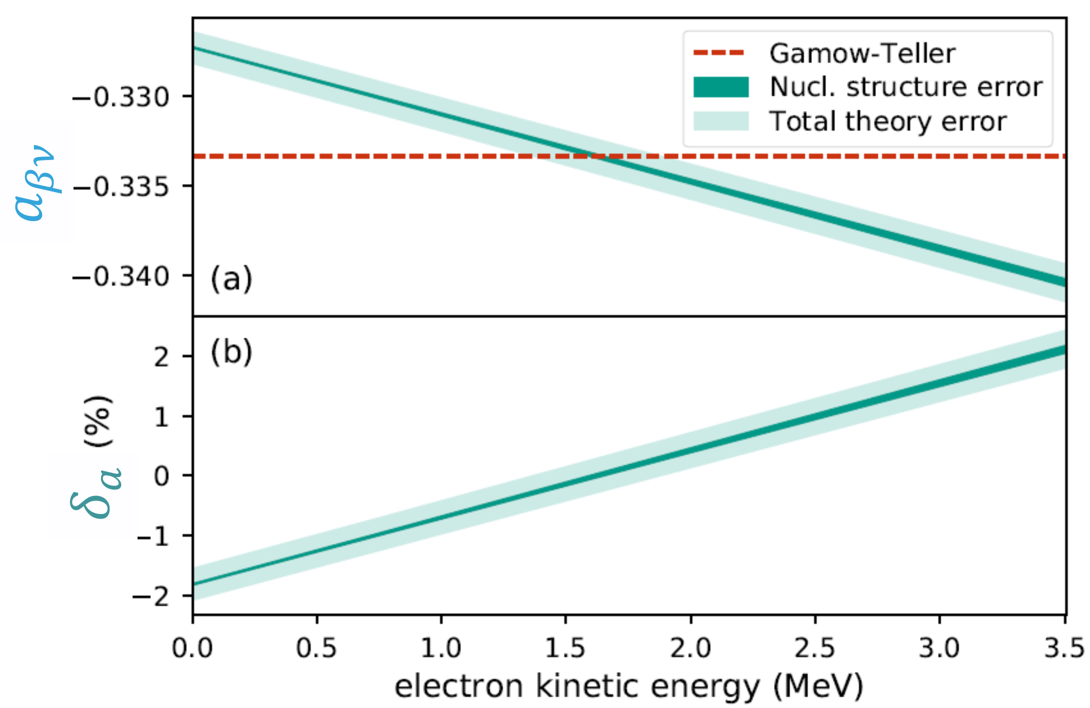
AB-INITIO CALCULATION OF ^{6}HE BETA DECAY INTO ^{6}LI

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



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

^{6}He → ^{6}Li ANGULAR CORRELATION



- Experiments are aiming at ~few 0.1% precision.

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

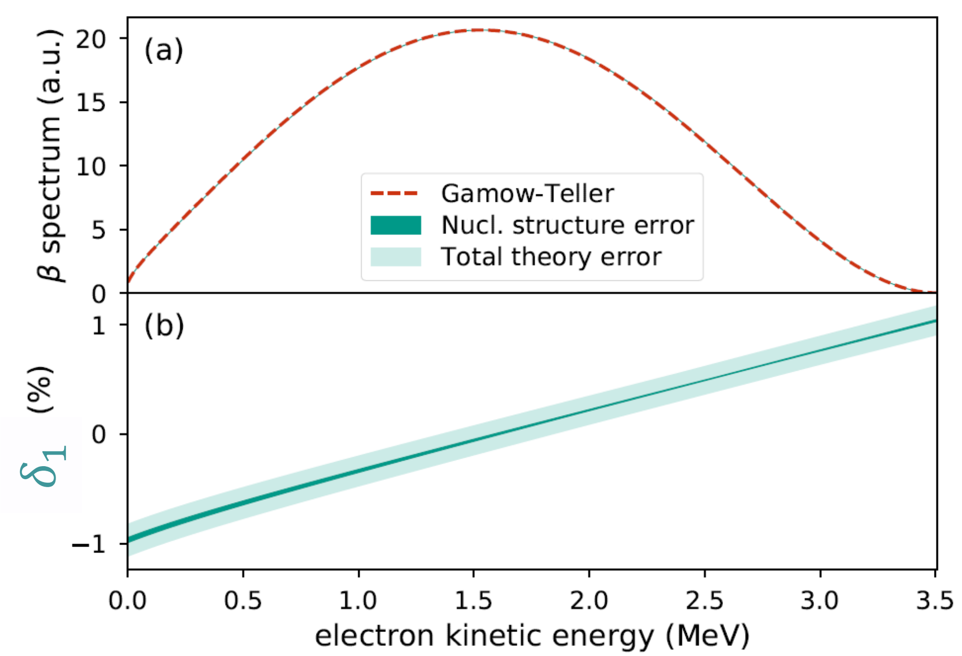
GT — SM correction — BSM

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

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

Johnson et al., Phys.Rev.132.3; Gluck, Nucl.Phys.A628;
Gonzalez-Alonso & Naviliat-Cuncic, Phys.Rev.C94
Glick-Magid, Forssén, Gazda, DG, Gysbers & Navrátil, PLB 2022

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



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

GT | SM correction | BSM

$$b_{\mathrm{F}} = 0 + \delta_b + \frac{C_T^* + C_T'^*}{C_A}$$

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

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

EXPERIMENTAL STATUS AROUND THE WORLD

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

^{23}NE → ^{23}NA

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

Nuclear Hamiltonian
USDB (USD) ~10% uncertainty

$\langle\psi_f|| \quad ||\psi_i\rangle$
Nuclear wave functions

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

Nuclear currents at LO (1-body currents)

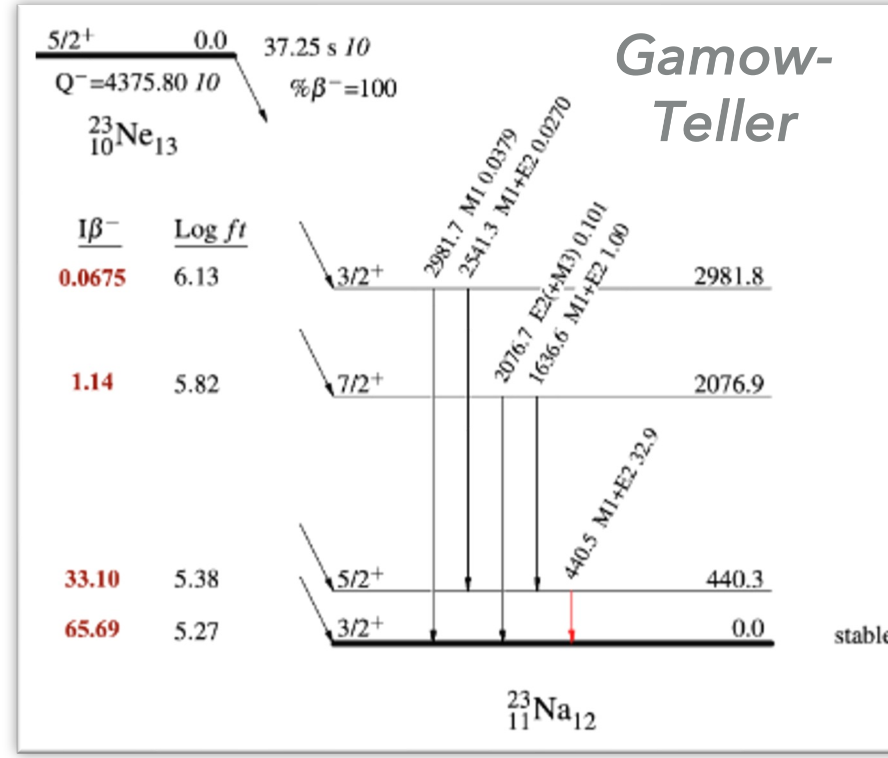
$\hat{O}_J$
Multipole operators

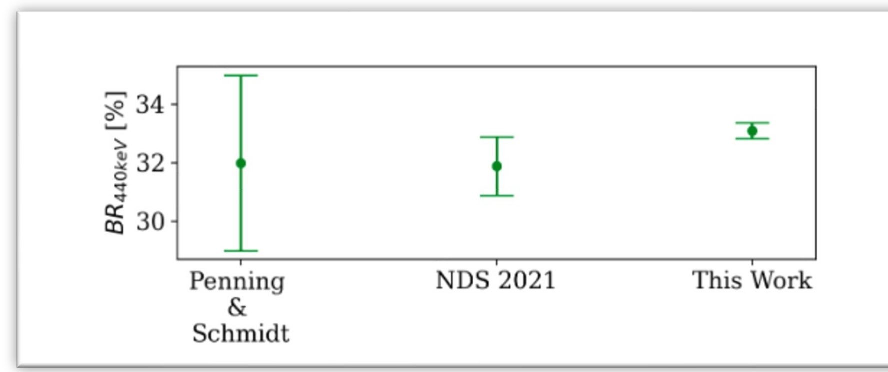
$\langle\psi_f||\hat{O}_J||\psi_i\rangle$
Nuclear matrix elements
Shell Model (NCSM)

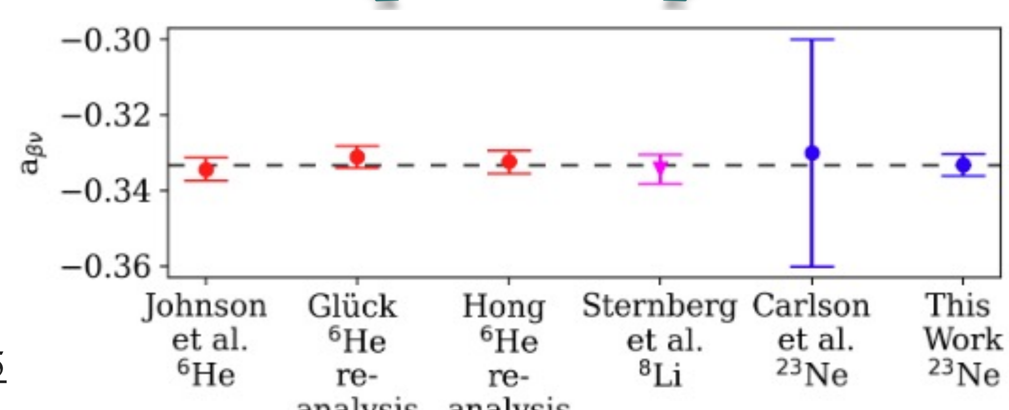
$\delta_1, \delta_a, \delta_b$

Observables' corrections

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







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

Some Future Opportunities

COULOMB EFFECTS ON THE BETA WAVE FUNCTION

- The energy endpoints of beta decays range a few orders of magnitude.
- Coulomb corrections in beta transitions, which are related to the interference of the beta particle wave function with the atomic wave function, create an effect related to the dimensionless parameter:

$$\frac{\alpha Z}{\left(\frac{p_e}{m_e}\right)} \approx 10^{-4} - 10.$$

- This is a significant correction, which is well known for allowed decays.

Jackson, Treiman, Wyld, Nuclear Physics 4 (1957) 206.
DG, Glick-Magid (in prep 2023)

COULOMB EFFECTS ON THE BETA WAVE FUNCTION

- This effect creates the following effects on the angular correlations and Fierz terms:

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

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

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

This is a small parameter for high energy beta decay endpoints.

- But not that small for low-endpoint beta decays:
  - ^{3}H – 19 keV: $\frac{\alpha Z}{\left(\frac{p_e}{m_e}\right)} > \frac{\alpha Z}{\sqrt{\frac{2E_0}{m_e}}} \approx 0.05$
  - **^{187}Re – *2.6keV:*** $\frac{\alpha Z}{\left(\frac{p_e}{m_e}\right)} > 6$

- A linear BSM sensitivity.

DG, Ron, analysis of low energy endpoint beta decay for BSM studies, 2023 (in preparation).

NEAR FUTURE: OPPORTUNITIES IN FORBIDDEN DECAYS

$$\Theta^{J^A}\left(q,\vec{\beta}\cdot\hat{\nu}\right)=\frac{2J+1}{J}\left(1+\delta^{J^A}_{\text{Shape}}\right)\cdot$$

$$\cdot\left\{1-\frac{1}{2J+1}\hat{\nu}\cdot\vec{\beta}\left(1+\tilde{\delta}^{J^A}_{\beta\nu}\right)+\frac{J-1}{2J+1}\left[\beta^2-\left(\hat{\nu}\cdot\vec{\beta}\right)^2\right]\frac{\epsilon\left(\omega-\epsilon\right)}{q^2}\left(1-\delta^{J^A}_{\text{Shape}}\right)\right\}\left|\left\langle\left\|\hat{L}^A_J\right\|\right\rangle\right|^2+\mathcal{O}\left(\epsilon^{2J}_{qR}\right)$$

Vanishes for allowed

$$\delta^{J^A}_{\text{Shape}}=\frac{2}{2J+1}\mathfrak{Re}\left\{-J\left[\Delta B-\frac{m_e^2}{\epsilon}\right]\frac{\left\langle\left\|\hat{C}^A_J/q\right\|\right\rangle}{\left\langle\left\|\hat{L}^A_J\right\|\right\rangle}\pm\sqrt{J\left(J+1\right)}\left[\Delta B-2\epsilon+\frac{m_e^2}{\epsilon}\right]\frac{\left\langle\left\|\hat{M}^V_J/q\right\|\right\rangle}{\left\langle\left\|\hat{L}^A_J\right\|\right\rangle}\right\}$$

$$\Theta(q,\vec{\beta}\cdot\hat{\nu})\propto 1\pm 2\gamma_0\frac{C_T+C_T'}{C_A}\frac{m_e}{\epsilon}$$

$$-\frac{1}{5}\left(2(\hat{\nu}\cdot\vec{\beta})-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right)\left(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\right).$$

Unique first forbidden $\Delta J^{\pi}=2^{-}$

$$\propto\ 1-\left(\hat{\beta}\cdot\hat{\nu}\right)^2$$

Glick-Magid, DG, et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

$$\Theta(q, \vec{\beta}\cdot\hat{\nu}) \propto 1 \pm 2\gamma_0 \frac{C_T + C_T'}{C_A}\frac{m_e}{\epsilon} - \underbrace{\frac{1}{5}\left(2(\hat{\nu}\cdot\vec{\beta}) - (\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right)}\left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right).$$

$$\propto \quad 1 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2$$

Spectrum, i.e., integration over angle. Sensitivity to BSM:

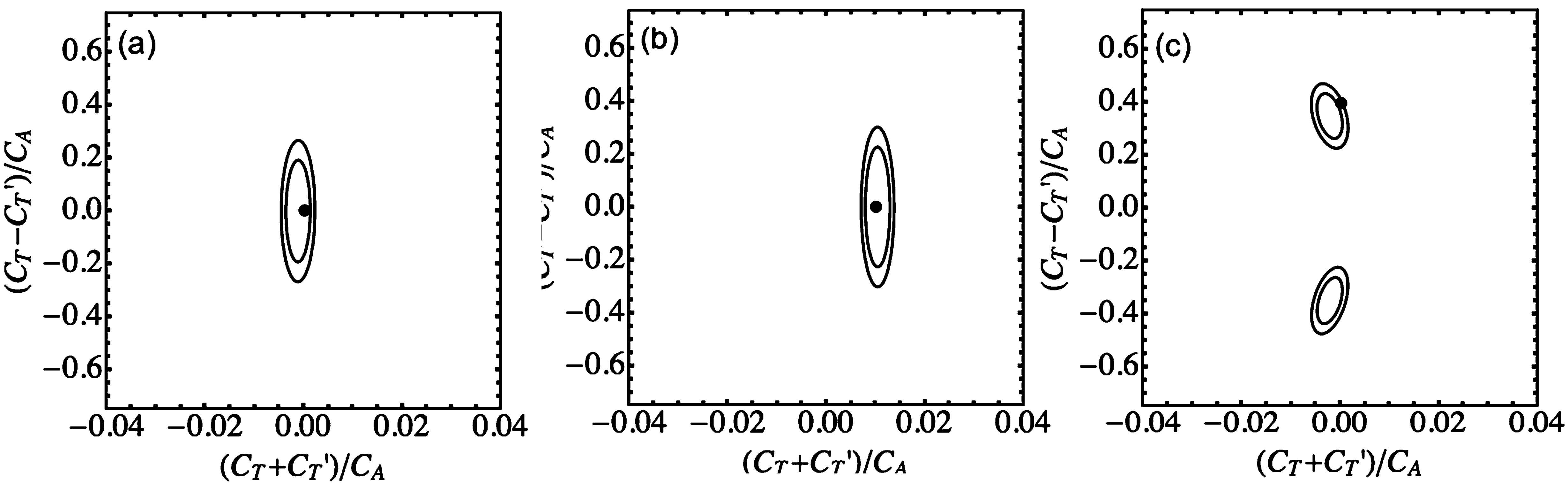
$$\frac{dw_{\beta^{\mp}}}{d\epsilon} \propto \Sigma(\epsilon)\left(2 + 4\gamma_0 \frac{C_T + C_T'}{C_A}\frac{m_e}{\epsilon} + \frac{\beta}{5}\frac{(a^2-1)\tanh^{-1}(a) + a}{a^2} \times \left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right)\right),$$

$$a = 2k\nu/(k^2 + \nu^2)$$

Glick-Magid, DG, et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

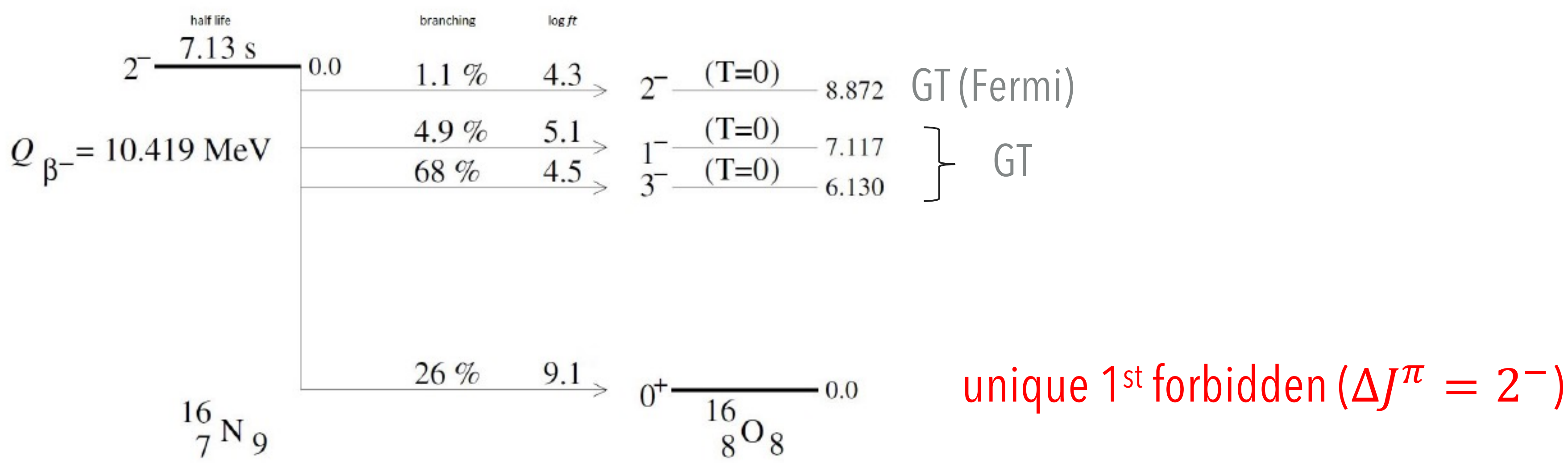
Unique possibility to separate between left and right-handed couplings!



$C_T = C'_T = 0$ $\quad$ $C_T/C_A = C'_T/C_A = 0.005$ $\quad$ $C_T/C_A = -C'_T/C_A = 0.2$

Glick-Magid, DG, et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique First forbidden: Planned $^{16}N \rightarrow {}^{16}O$ experiment (SARAF)



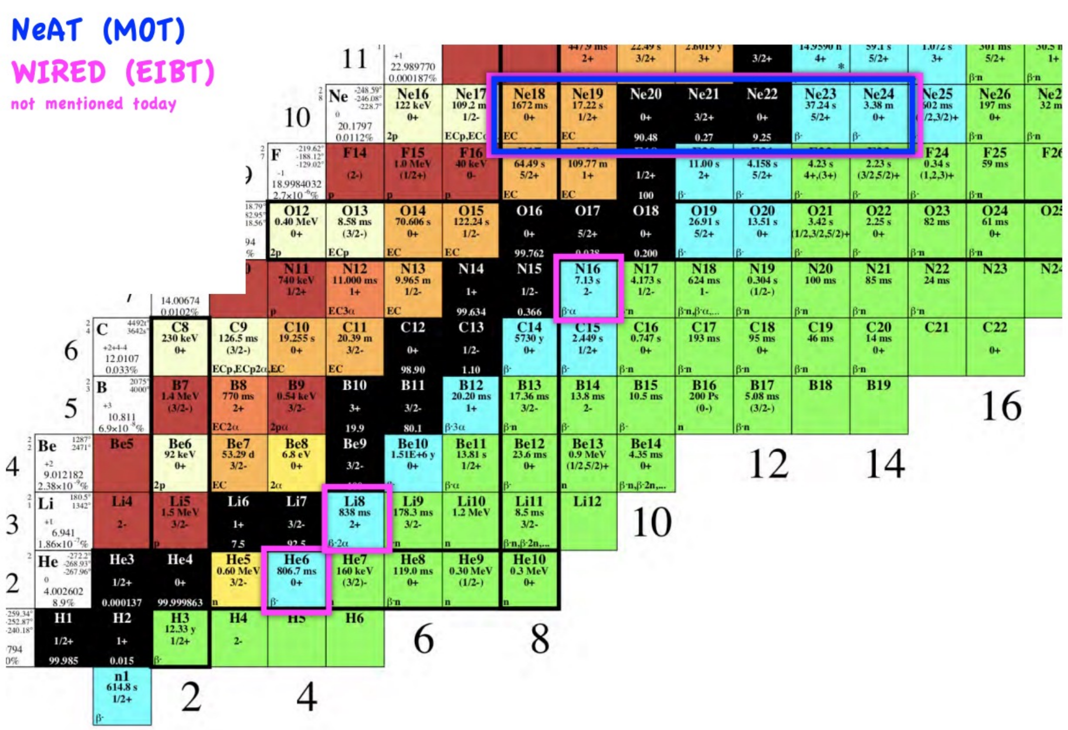
Ideal case study:

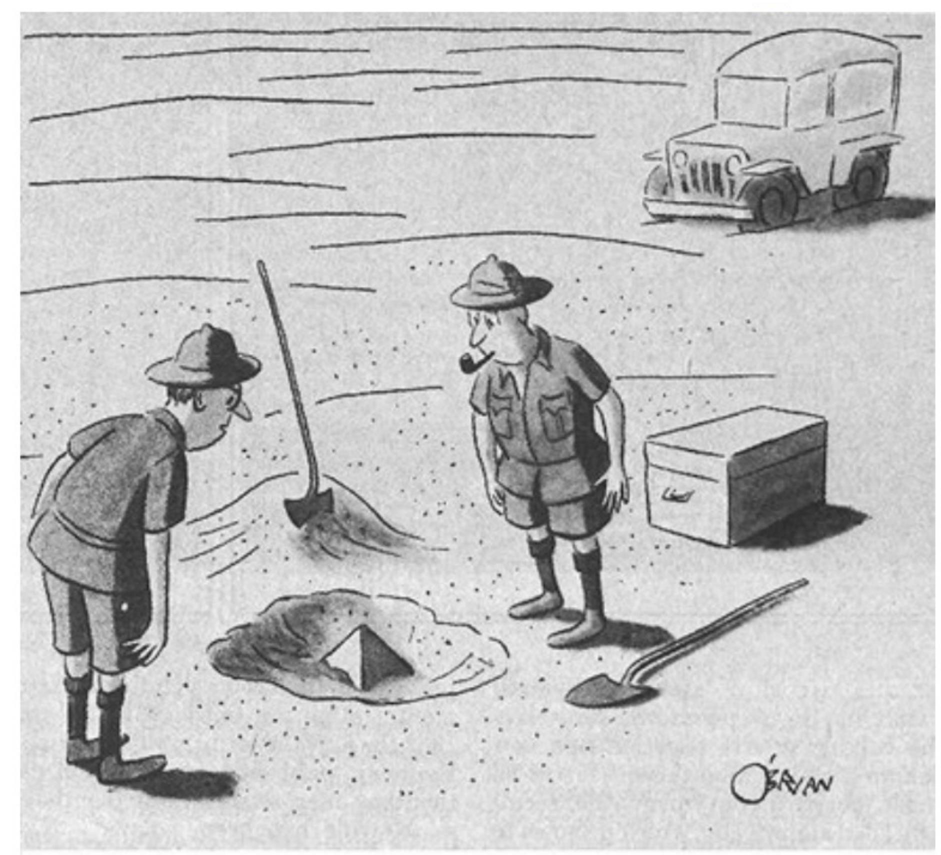
- Experimentally, due to energy separation between its forbidden and allowed branches
- Theoretically, since it is light enough to study *ab-initio*, and since different transitions in the same nucleus allow minimization of nuclear model bias.

Ohayon, Chocron, DG, *et al.*, Hyp.Int.239,57 (2018)

OTHER ON GOING EXPERIMENTAL AND THEORETICAL EFFORTS AT HUJI

- Unique first forbidden decay of ^{90}Y into ^{90}Zr ($Q \approx 2.3\ MeV$).
- Electron capture on ^{131}Cs, as a side-gain from the HUNTER experiment in search of sterile neutrino.
- ^{6}He, ^{16}N, and Neon isotopes beta decays (production @SARAF stage II-2025).

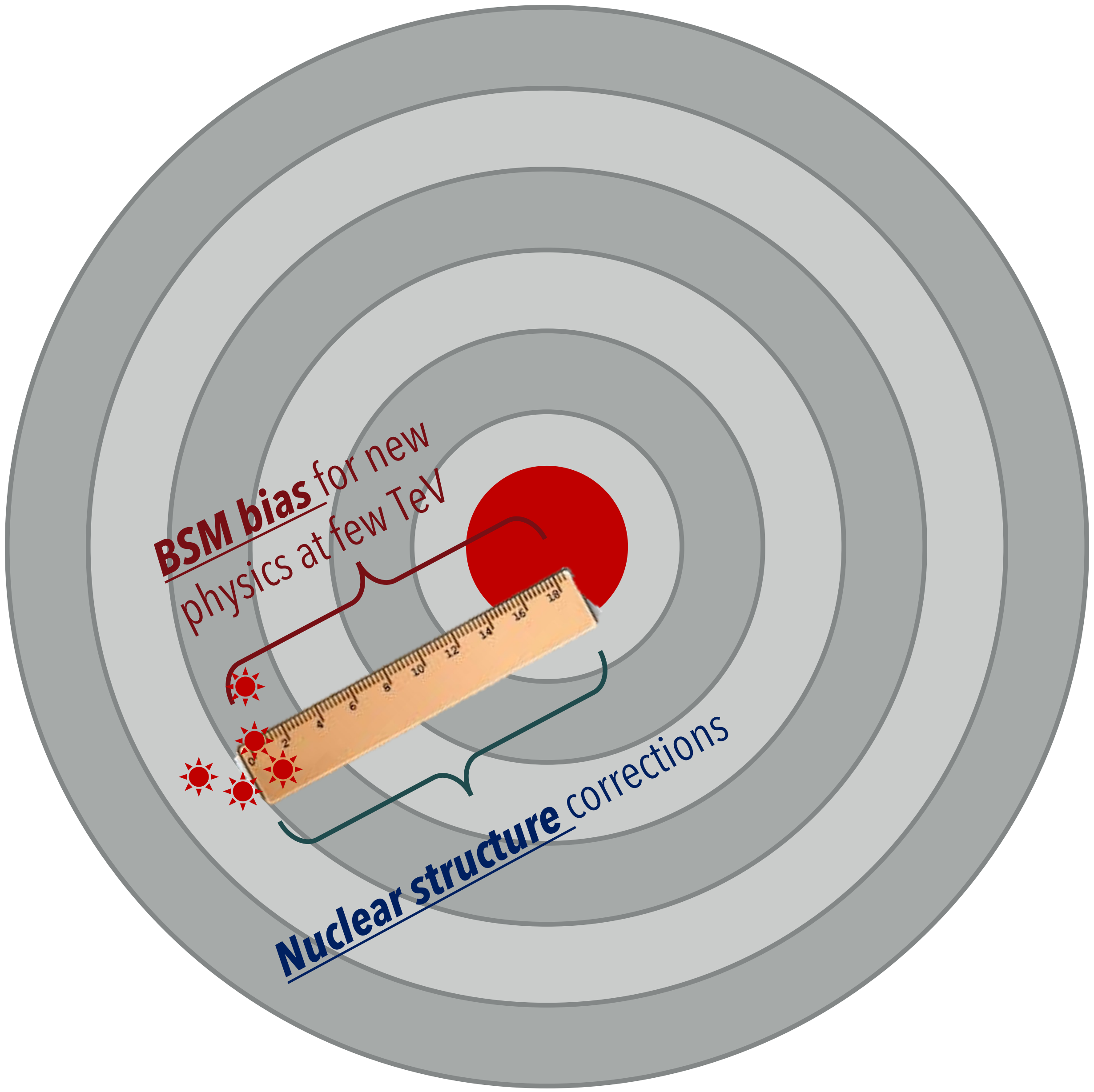




"This could be the discovery of the century. Depending, of course, on how far down it goes."

SUMMARY

Future experiments aim at <0.1% precision, which is sufficient to significantly identify BSM signatures at the few TeV scale



Correcting the ***nuclear theory bias with controlled accuracy*** is an essential ingredient in the new generation of beta decay precision measurements, already giving stringent constraints on Beyond the Standard Model physics.