NνDEx

HIGH PRECISION DESCRIPTION OF TWO NEUTRINO DOUBLE BETA DECAY ELECTRON SPECTRA

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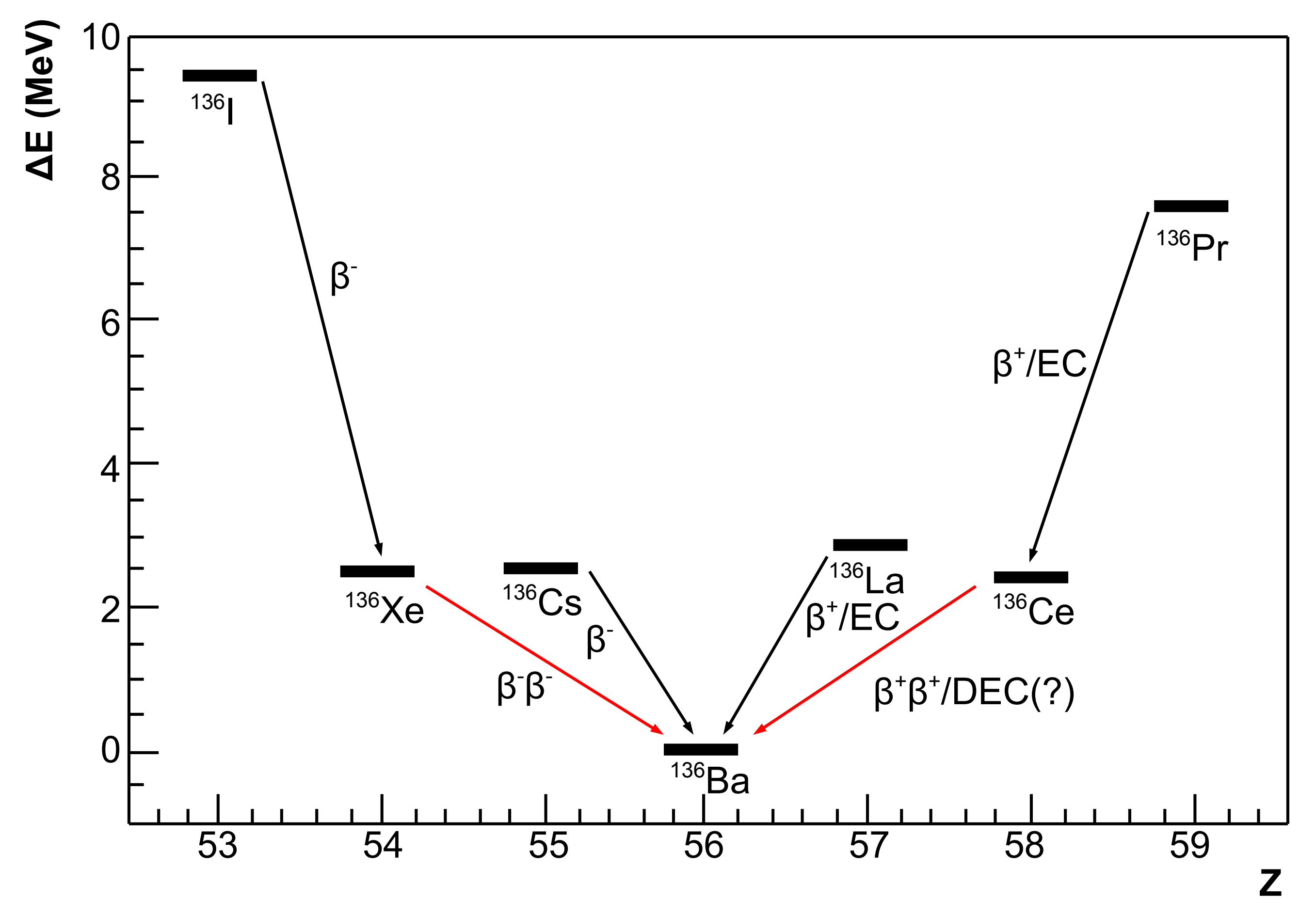
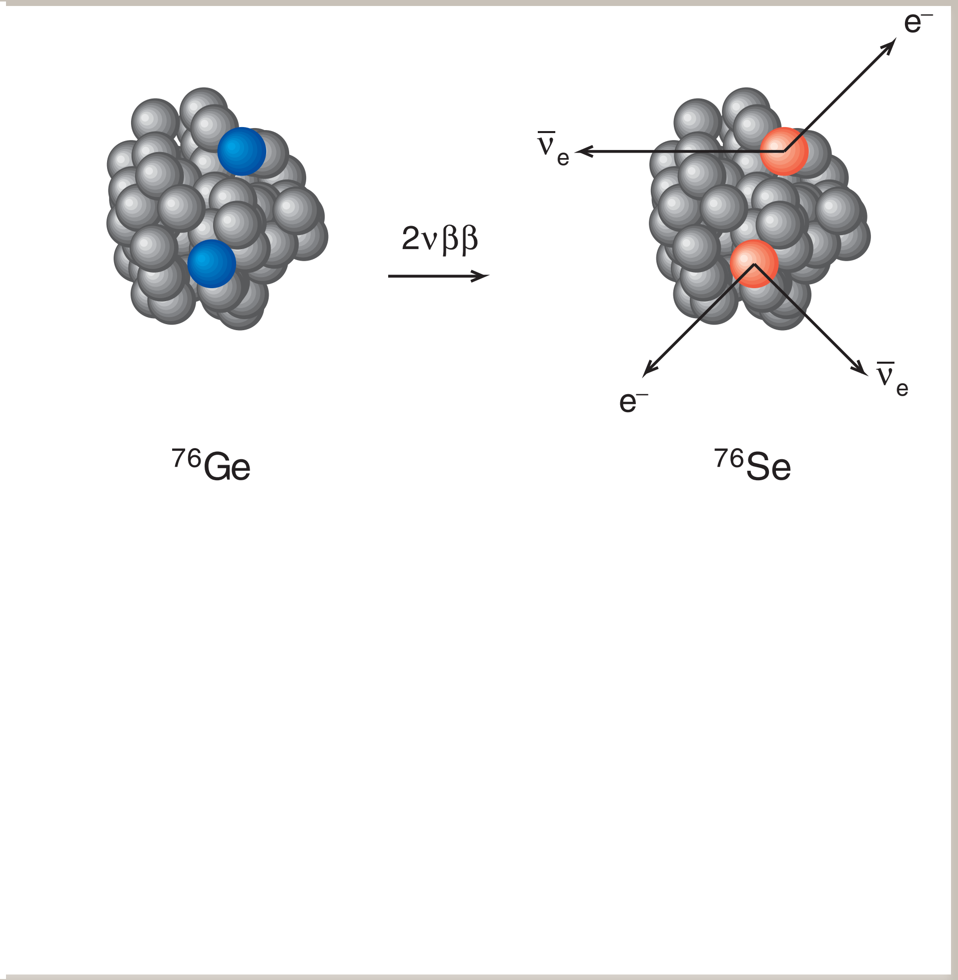
NME2023
RCNP Workshop for
"Theoretical and Experimental Approaches for Nuclear Matrix Elements of Double Beta Decay"

OUTLINE

- Background
- Experimental status
- Formalisms
- Theoretical results
- Conclusions and outlooks

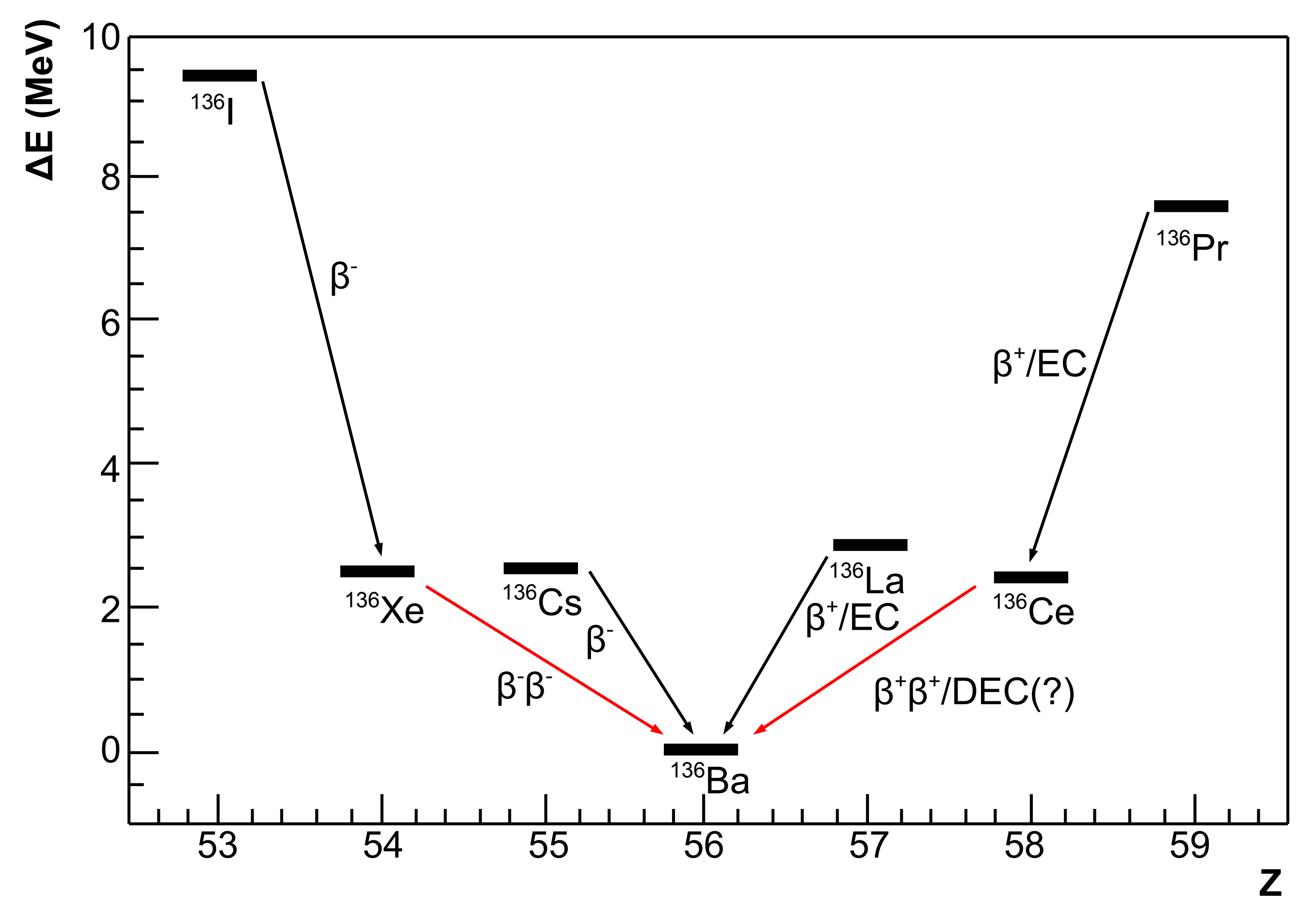
BACKGROUND

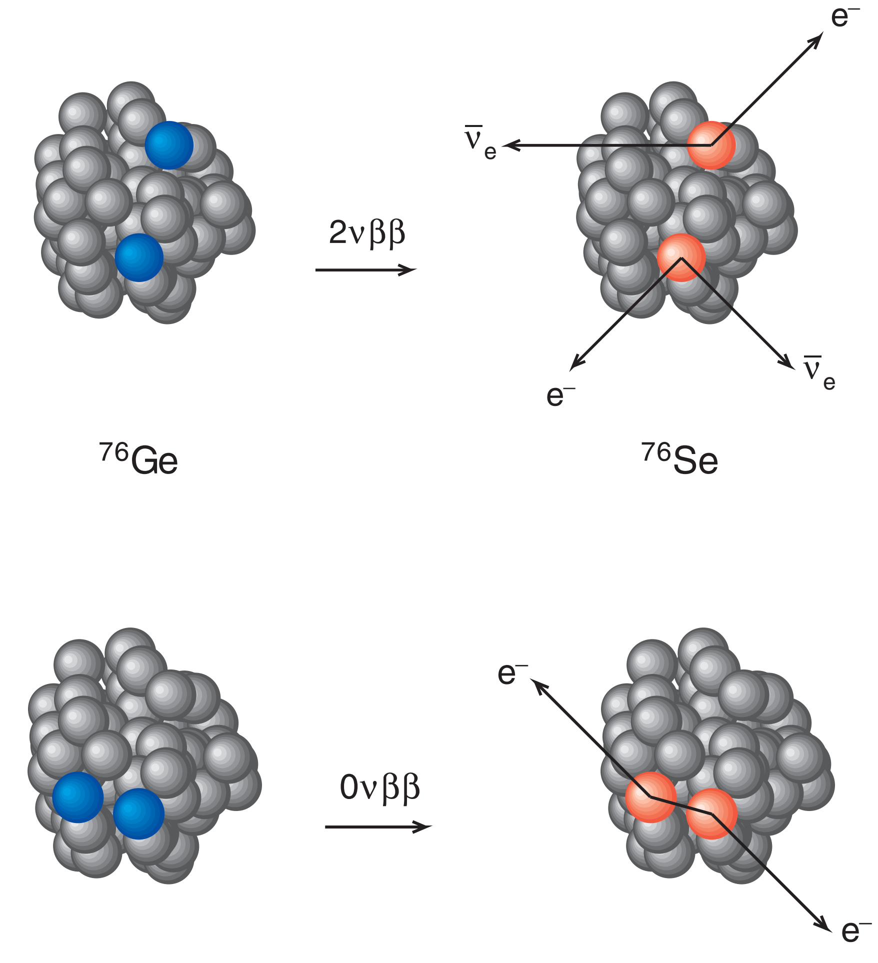




- Two neutrino double beta decay is a second order weak process

BACKGROUND



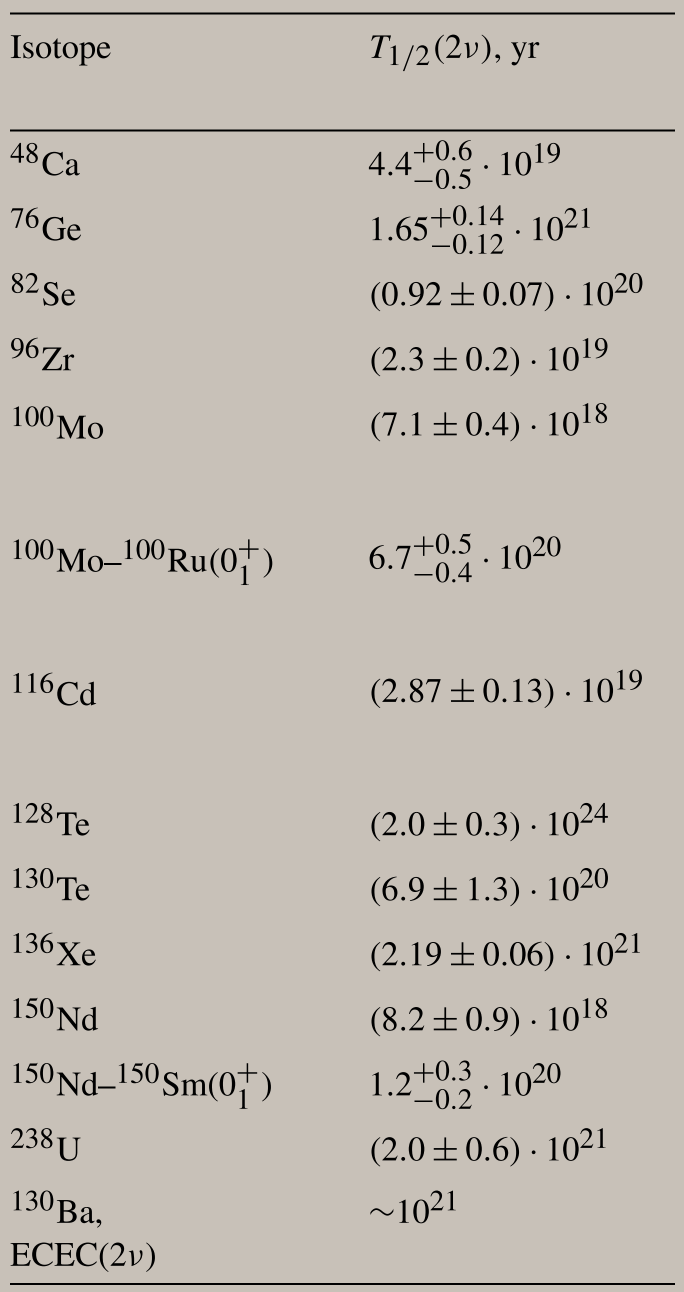


- Two neutrino double beta decay is a second order weak process

BACKGROUND

- Two neutrino double beta decay has been well studied for decades
- For theory, previously the observable is the nuclear matrix element
- This leaves too many d.o.f's

Barabash ***NPA935****,52(2015)*



Isotope	$T_{1/2}(2\nu)$, yr
^{48}Ca	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$
^{76}Ge	$1.65^{+0.14}_{-0.12} \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
^{100}Mo–^{100}Ru(0_1^+)	$6.7^{+0.5}_{-0.4} \cdot 10^{20}$
^{116}Cd	$(2.87 \pm 0.13) \cdot 10^{19}$
^{128}Te	$(2.0 \pm 0.3) \cdot 10^{24}$
^{130}Te	$(6.9 \pm 1.3) \cdot 10^{20}$
^{136}Xe	$(2.19 \pm 0.06) \cdot 10^{21}$
^{150}Nd	$(8.2 \pm 0.9) \cdot 10^{18}$
^{150}Nd–^{150}Sm(0_1^+)	$1.2^{+0.3}_{-0.2} \cdot 10^{20}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$
^{130}Ba, ECEC(2ν)	$\sim 10^{21}$

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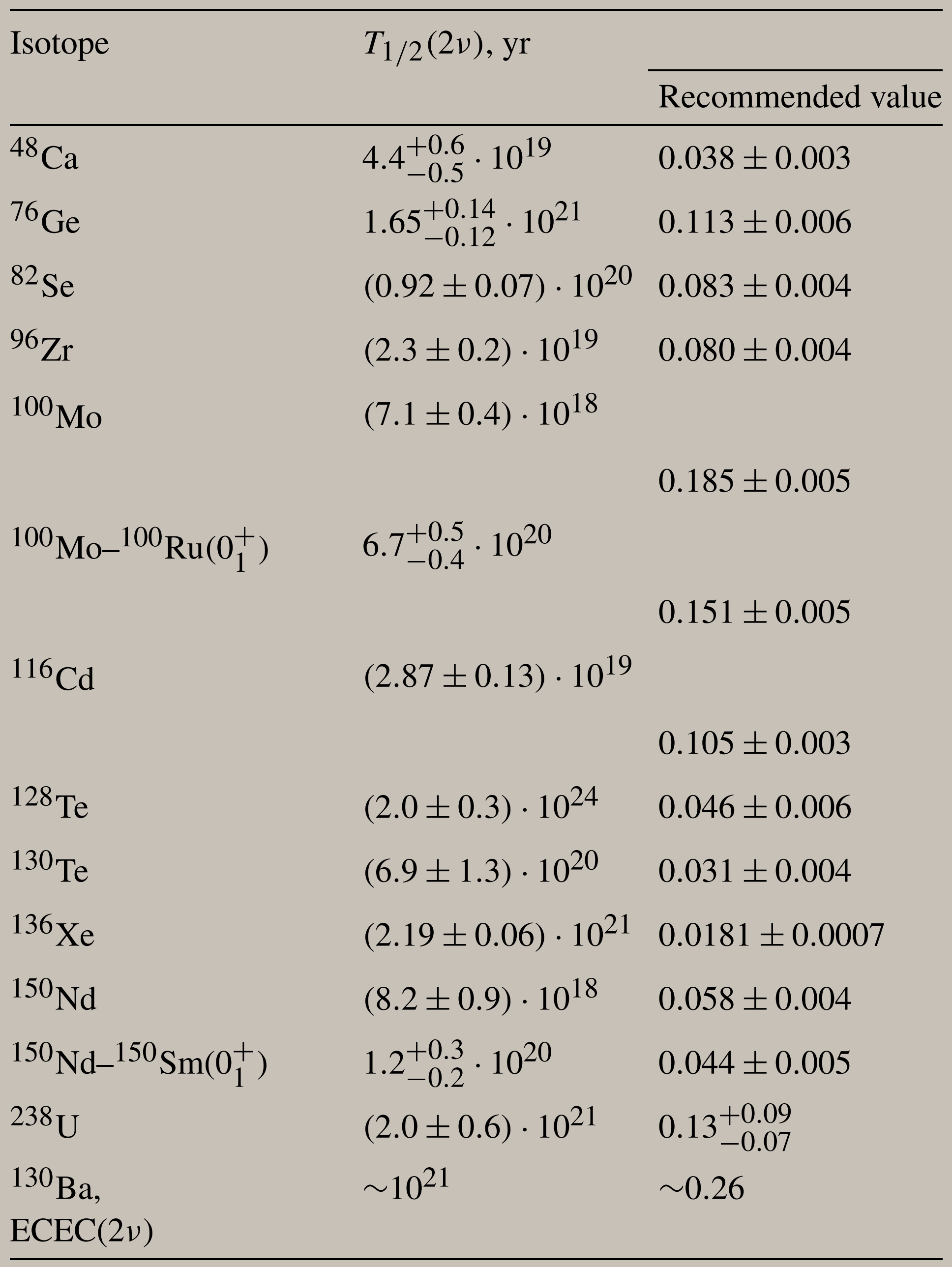


Isotope	$T_{1/2}(2\nu)$, yr	
		Recommended value
^{48}Ca	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$	0.038 ± 0.003
^{76}Ge	$1.65^{+0.14}_{-0.12} \cdot 10^{21}$	0.113 ± 0.006
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$	0.083 ± 0.004
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$	0.080 ± 0.004
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$	
		0.185 ± 0.005
^{100}Mo–^{100}Ru(0_1^+)	$6.7^{+0.5}_{-0.4} \cdot 10^{20}$	
		0.151 ± 0.005
^{116}Cd	$(2.87 \pm 0.13) \cdot 10^{19}$	
		0.105 ± 0.003
^{128}Te	$(2.0 \pm 0.3) \cdot 10^{24}$	0.046 ± 0.006
^{130}Te	$(6.9 \pm 1.3) \cdot 10^{20}$	0.031 ± 0.004
^{136}Xe	$(2.19 \pm 0.06) \cdot 10^{21}$	0.0181 ± 0.0007
^{150}Nd	$(8.2 \pm 0.9) \cdot 10^{18}$	0.058 ± 0.004
^{150}Nd–^{150}Sm(0_1^+)	$1.2^{+0.3}_{-0.2} \cdot 10^{20}$	0.044 ± 0.005
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$	$0.13^{+0.09}_{-0.07}$
^{130}Ba, ECEC(2ν)	$\sim 10^{21}$	~ 0.26

BACKGROUND

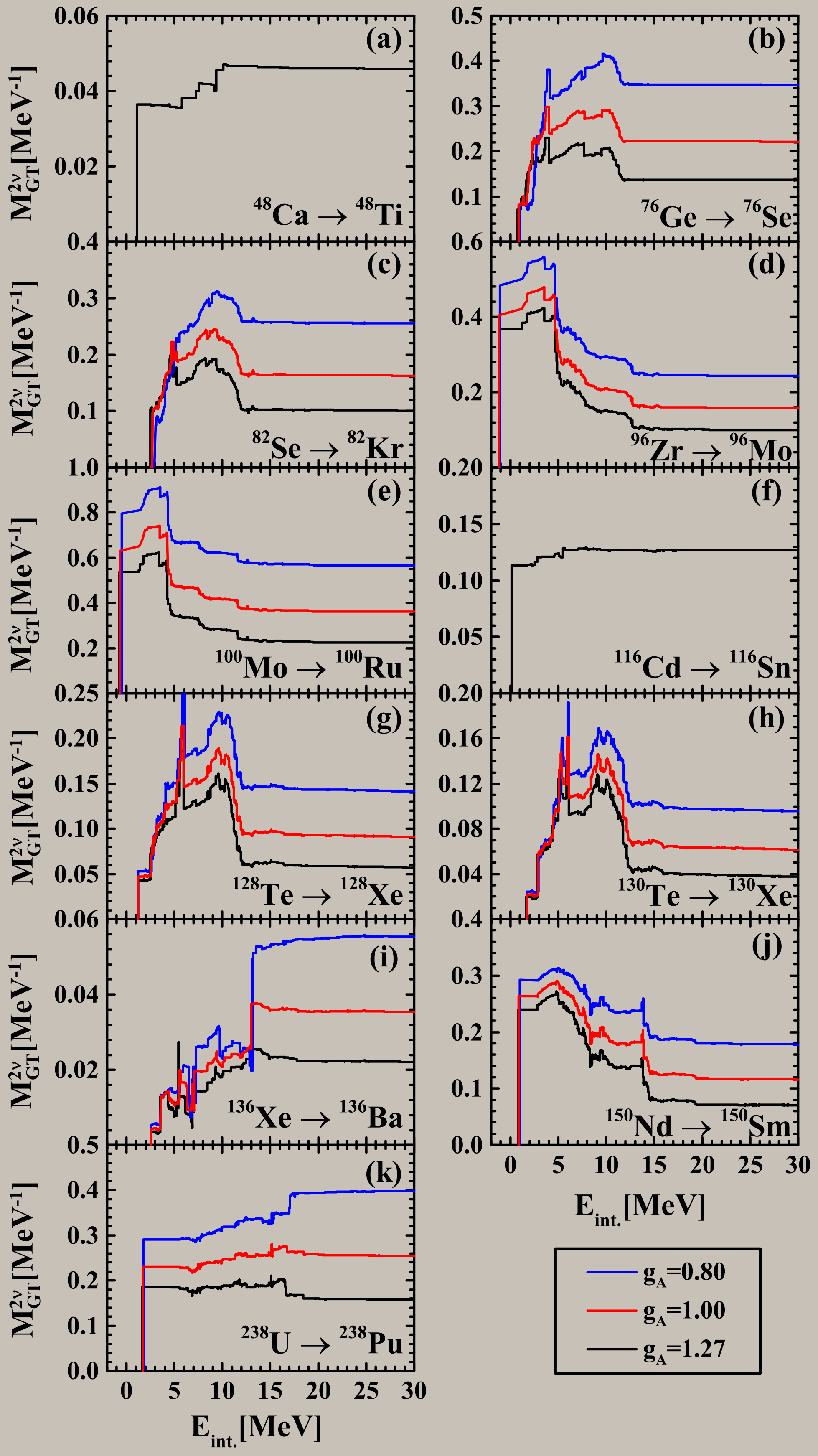
- Widely used many-body approaches for two neutrino double beta decay
  - Nuclear shell Model
    - Adjusts quenching factors to reproduce NME
  - QRPA
    - *Adjusts particle-particle interaction to reproduce NME*
  - IBM *etc.*
    - *Use closure approximation with proper closure energy to reproduce NME*

BACKGROUND

- In this sense, 2vββ spectra poses more severe constraints on theoretical studies

- And could rule out certain calculations

- Give us implications for certain calculations



*Lv et al.**PRC105**,044331(2022)*

FORMALISM

Doi et al. ***PTPS83**,1(1985)*

- Starting from S-matrix theory, one could obtain the decay width

Constant

Kinetic term

Electron w.f.

$$[T_{2\nu}(0^+ \to 0^+)]^{-1} = \frac{a_{2\nu}}{\ln 2} \int d\Omega_{2\nu}\ a(\varepsilon_1,\ \varepsilon_2) \left| \sum_a \left[M_{GTa}^{(2\nu)} - \left(\frac{g_V}{g_A} \right)^2 M_{Fa}^{(2\nu)} \right] \frac{1}{2} (K_a + L_a) \right|^2$$

- Where $M_{GTa}^{(2\nu)} \equiv -\langle 0_f{}^+ \| \sum_n \tau_n{}^+ \sigma_n \| N_a(1^+) \rangle \langle N_a(1^+) \| \sum_m \tau_m{}^+ \sigma_m \| 0_i{}^+ \rangle$

- $K_a = \{[\mu_a + (\varepsilon_1 + \omega_1 - \varepsilon_2 - \omega_2)/(2m_e)]^{-1} + [\mu_a - (\varepsilon_1 + \omega_1 - \varepsilon_2 - \omega_2)/(2m_e)]^{-1}\}$

$L_a = K_a(\omega_1 \rightleftarrows \omega_2)$ $\quad$ $\mu_a m_e = E_a - (M_i + M_f)/2$

Nuclear part

FORMALISM

Kotila et al. ***PRC85****,034316(2012)*

- Equal lepton energy approximation（ELEA）:

$$\epsilon_1 - m_e = \epsilon_2 - m_e = \omega_1 = \omega_2 = Q/4 \longrightarrow K_a \simeq L_a \simeq 2/\mu_a$$

- The nuclear and lepton parts can now be separated by inserting

$$dW_{2\nu} = (a^{(0)} + a^{(1)} \cos\theta_{12}) w_{2\nu} d\omega_1 d\epsilon_1 d\epsilon_2 d(\cos\theta_{12})$$

- With $a^{(0)} = \frac{1}{4} f_{11}^{(0)} |M_{2\nu}|^2 \tilde{A}^2 \left[(\langle K_N \rangle + \langle L_N \rangle)^2 + \frac{1}{3} (\langle K_N \rangle - \langle L_N \rangle)^2 \right]$
- And $M_{2\nu}^{\mathrm{GT}} = \dfrac{\langle 0_F^+ || \tau^+ \vec{\sigma} || 1_1^+ \rangle \langle 1_1^+ || \tau^+ \vec{\sigma} || 0_I^+ \rangle}{\frac{1}{2}(Q_{\beta\beta} + 2m_e c^2) + E_{1_1^+} - E_I}$ $\tilde{A} = Q/2 + \langle E_N \rangle - E_I$
- Finally $\left[\tau_{1/2}^{2\nu}\right]^{-1} = G_{2\nu}^{(0)} g_A^4 |m_e c^2 M_{2\nu}|^2$

FORMALISM

SSD: Single State Dominance
HSD: High-lying State Dominance

Simkovic et al. ***PRC97****,034315(2018)*

- Two commonly used $\langle E_N \rangle$: $E_{1_1^+}$ (SSD) and E_{GTR} (HSD)
- Beyond ELEA: $\mathcal{A}^{2\nu} = \left[\frac{1}{4}\left|M_{GT}^{K} + M_{GT}^{L}\right|^2 + \frac{1}{12}\left|M_{GT}^{K} - M_{GT}^{L}\right|^2\right]$
- Here $M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon_{K,L}^2}$
- With $\varepsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2$ $\varepsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2$
- With Taylor expansion, one obtains the final expression
- $$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} = \left(g_A^{\text{eff}}\right)^4 \left|M_{GT-1}^{2\nu}\right|^2 \left\{G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu} + \frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 G_{22}^{2\nu} + \left[\frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 + \xi_{51}^{2\nu}\right] G_4^{2\nu}\right\}$$

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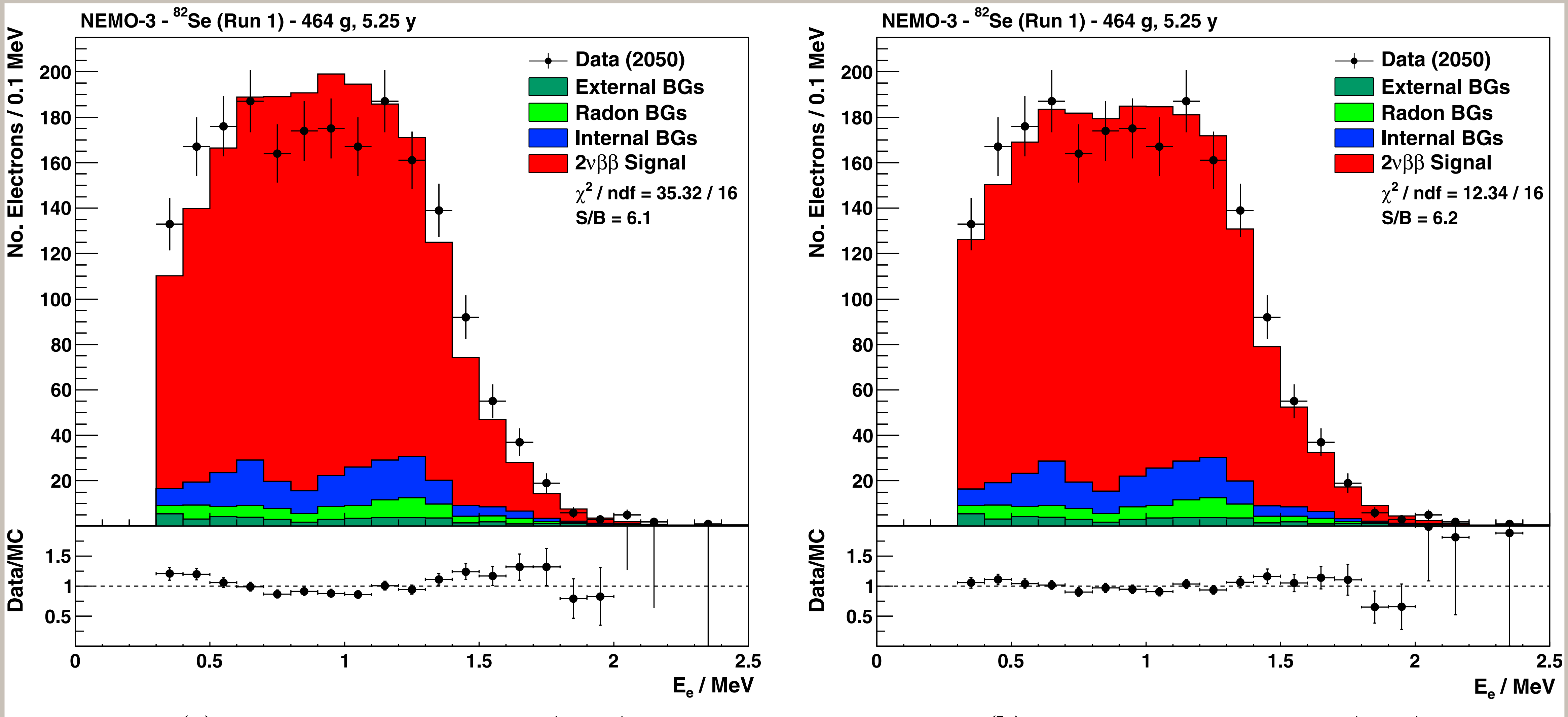
- Here $$M^{K,L}_{GT} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon^2_{K,L}}$$
- With $\varepsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2$ $\varepsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2$
- With Taylor expansion, one obtains the final expression
- $$\left[T^{2\nu\beta\beta}_{1/2}\right]^{-1} = \left(g^{\text{eff}}_A\right)^4 \left|M^{2\nu}_{GT-1}\right|^2 \{G^{2\nu}_0 + \xi^{2\nu}_{31} G^{2\nu}_2 + \tfrac{1}{3}\left(\xi^{2\nu}_{31}\right)^2 G^{2\nu}_{22} + \left[\tfrac{1}{3}\left(\xi^{2\nu}_{31}\right)^2 + \xi^{2\nu}_{51}\right] G^{2\nu}_4\}$$

$$\xi^{2\nu}_{31} \equiv M^{2\nu}_{GT-3}/(m_e M^{2\nu}_{GT})$$

$$M^{2\nu}_{GT-3} \equiv 4m_e^3 \sum_m [\langle 0^+_f || \sigma\tau^+ || m \rangle \langle m || \sigma\tau^+ || 0^+_i \rangle)/E^3_m]$$

EXPERIMENT STATUS

NEMO-3 ***EPJC78****,821(2018)*

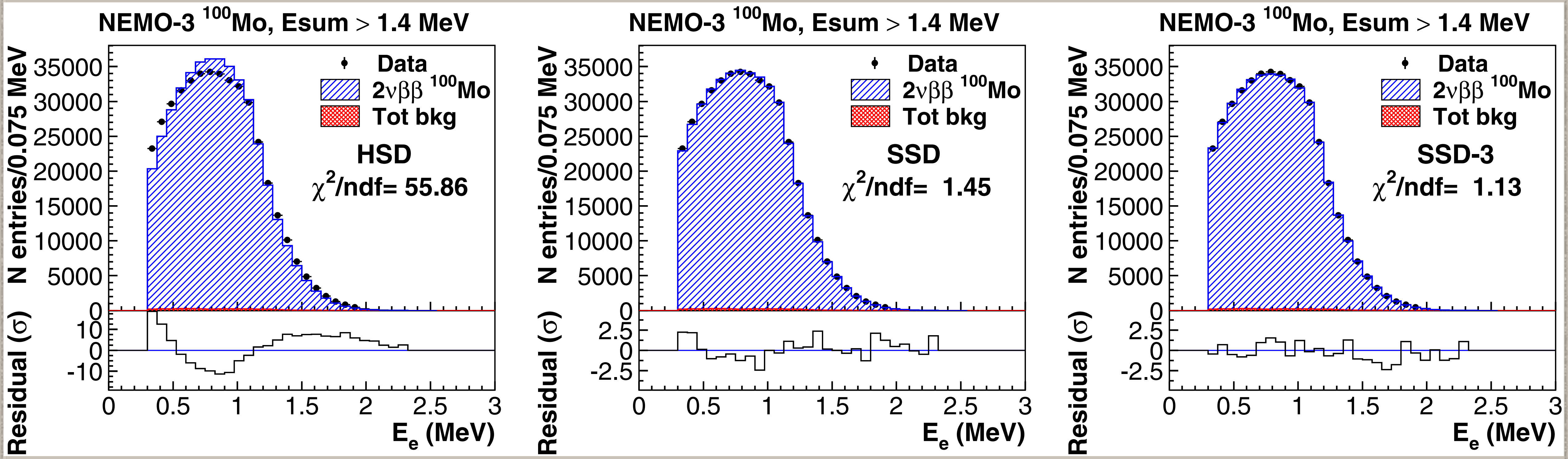


(a) Higher-state Dominated (HSD) **(b)** Single-state Dominated (SSD)

- Results from NEMO-3 for ^{82}Se, favors SSD

EXPERIMENTAL STATUS

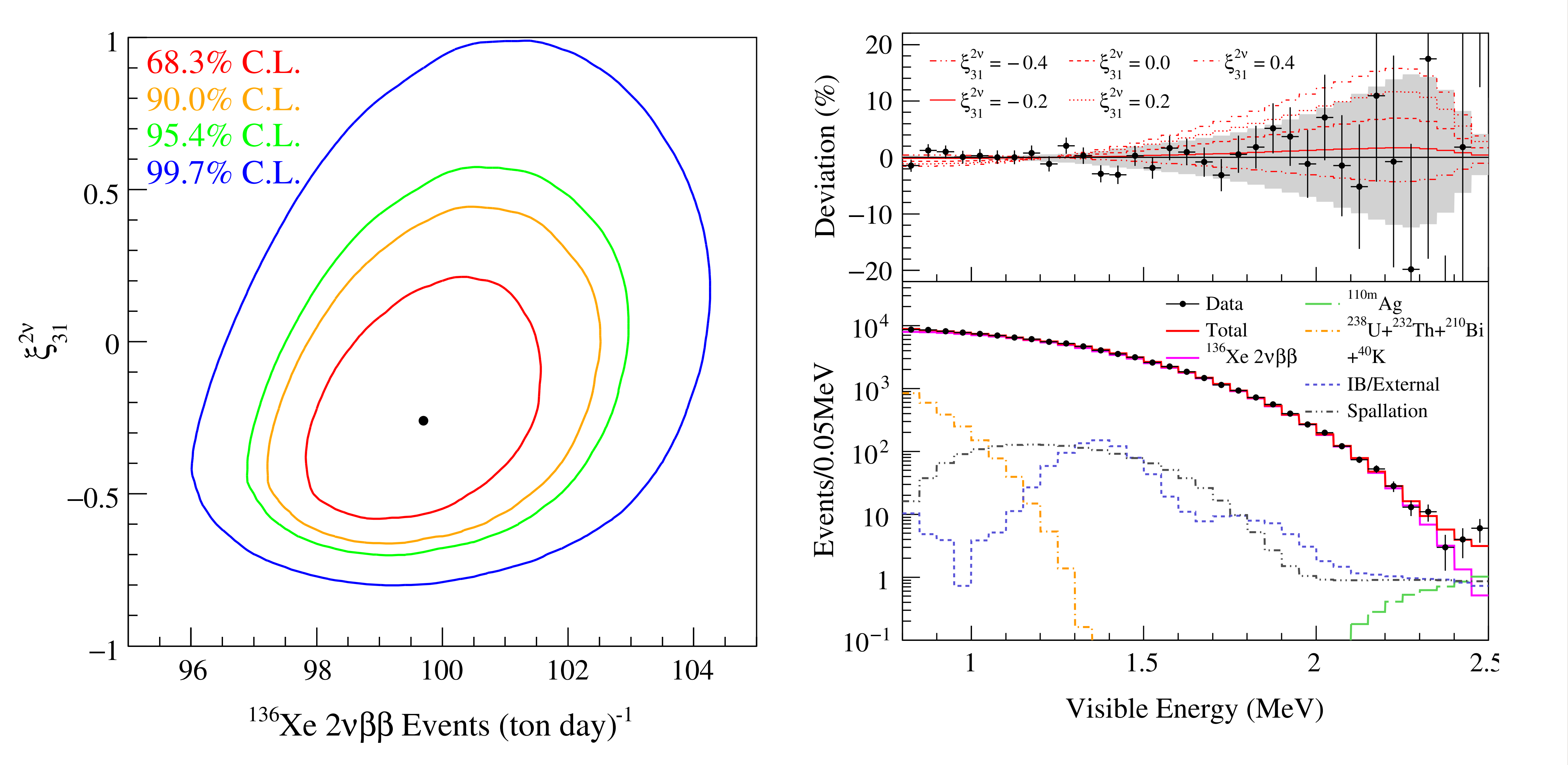
*NEMO-3 **EPJC79**,440(2019)*



- Results from NEMO-3 for ^{100}Mo
- Indication of strong SSD

EXPERIMENTAL STATUS

KamLand-Zen ***PRL122****,192501(2019)*



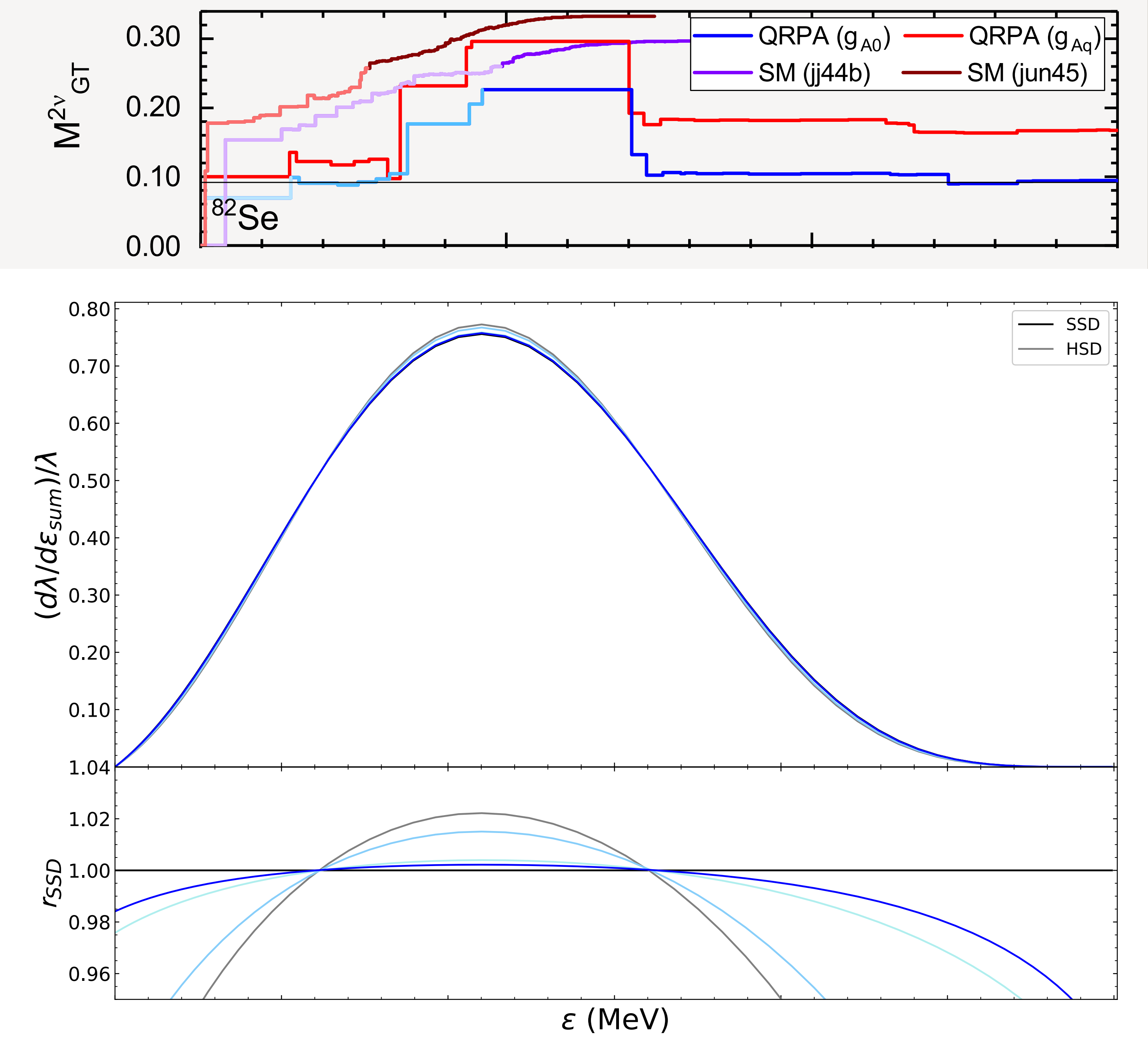
- KamLand-Zen offers more precise spectra preferring HSD

THEORETICAL RESULTS

- We adopt two many-body approaches in our calculations:
  - pnQRPA
    - Well predicted GTR but strength not well fragmented
  - Shell Model:
    - Severely truncated model space leads to missing GTR

THEORETICAL RESULTS

- Results for ^{82}Se:
  - From QRPA calculations we find that the spectra are sensitive to the low-lying states
  - And the strength which cancellation at higher excitation energy will not contribute to the spectra



DLF arXiv:2309.13328

THEORETICAL RESULTS

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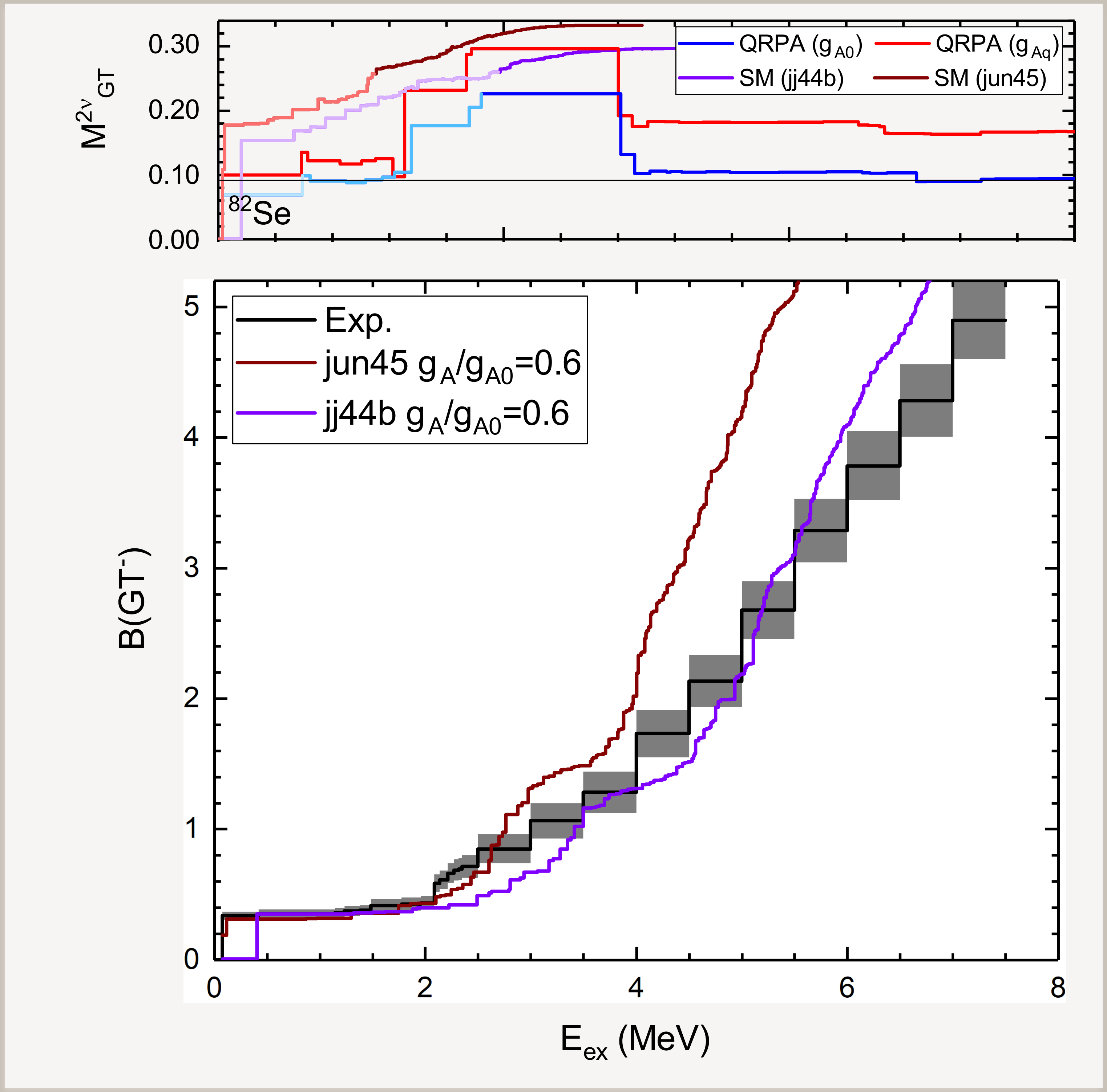


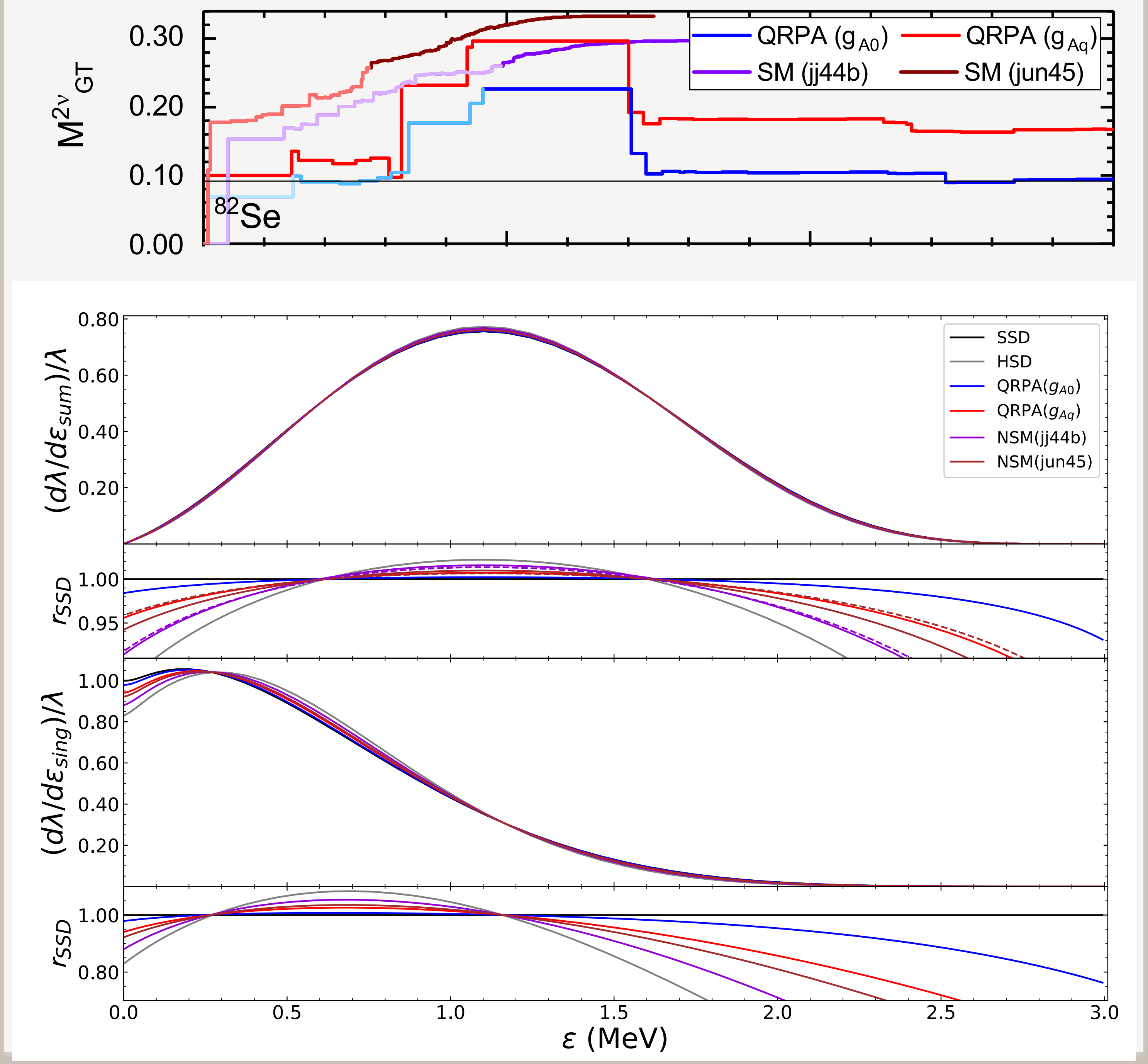
- If we assume that for NSM the decay strength saturates at 5MeV, we will obtain a quenched gA~0.5

- However, this contradicts the quenched gA values ~0.6 from fitting the charge exchange reaction

THEORETICAL RESULTS

- Previous conclusion could help us to resolve the puzzle from shell model calculations

- If we assume a strong cancellation at high excitation energy, using the quenched gA from charge exchange reaction, we obtain consistent results



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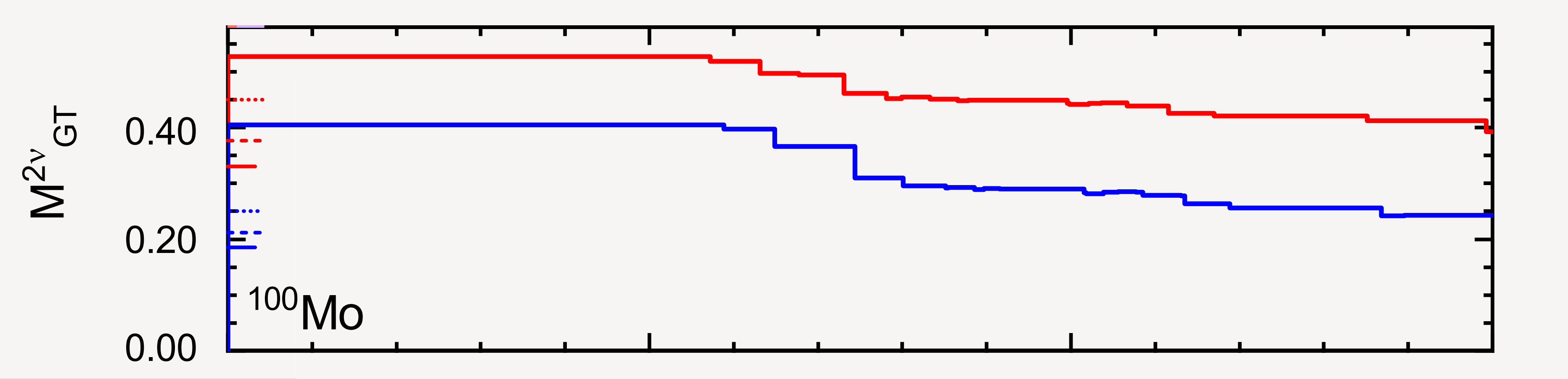

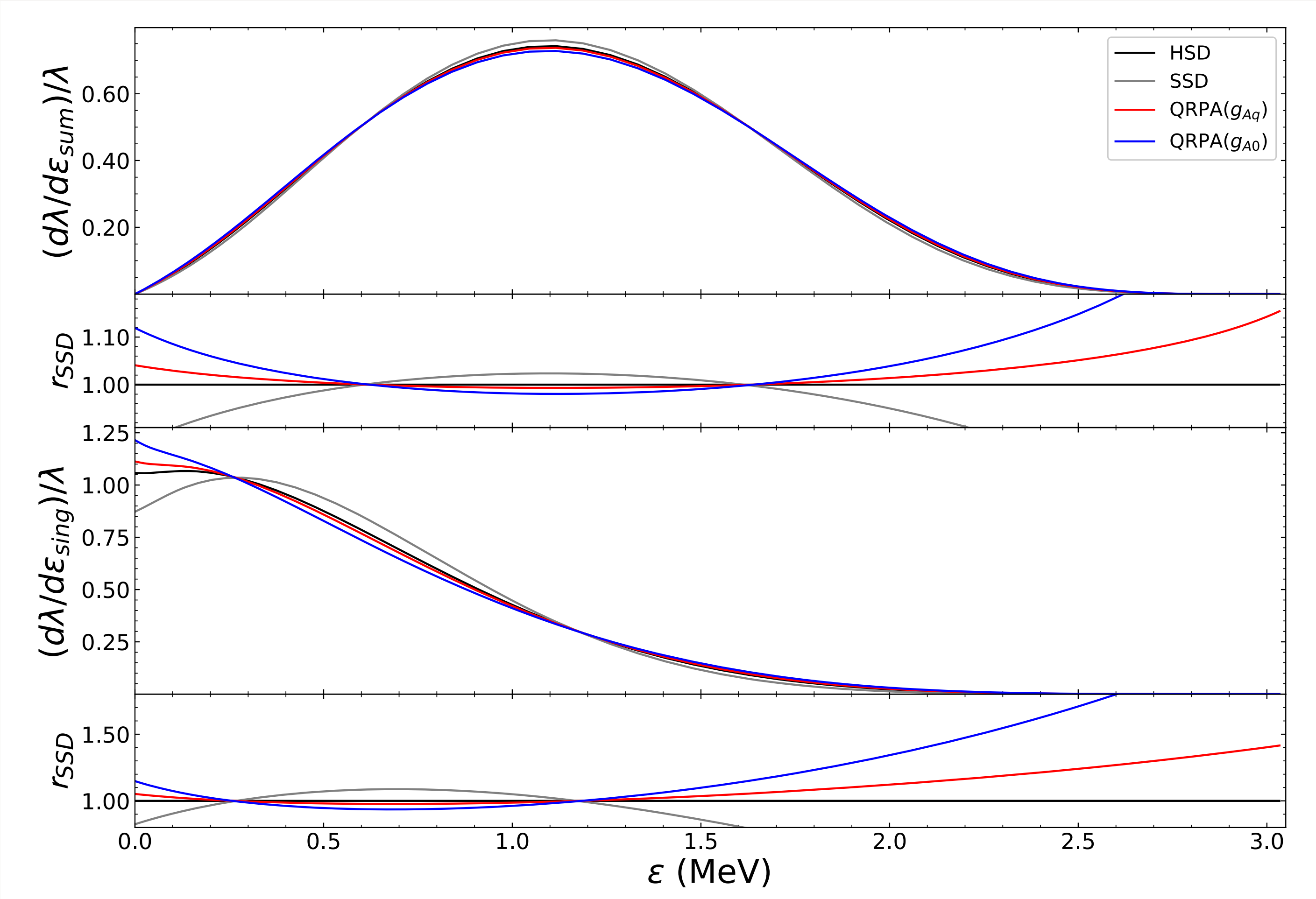

- Results for ^{100}Mo, beyond SSD
- Consistent with NEMO-3 experiment

THEORETICAL RESULTS

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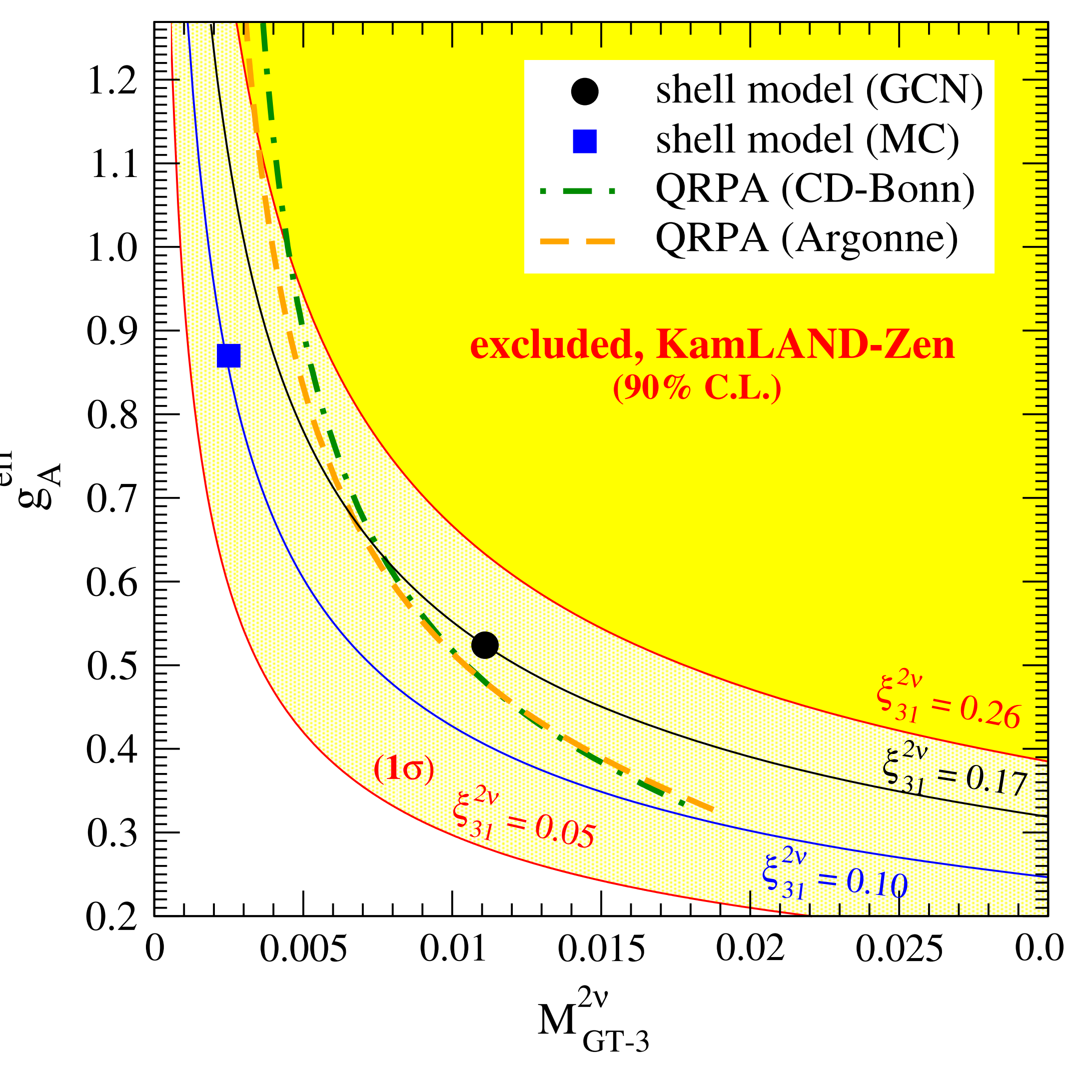
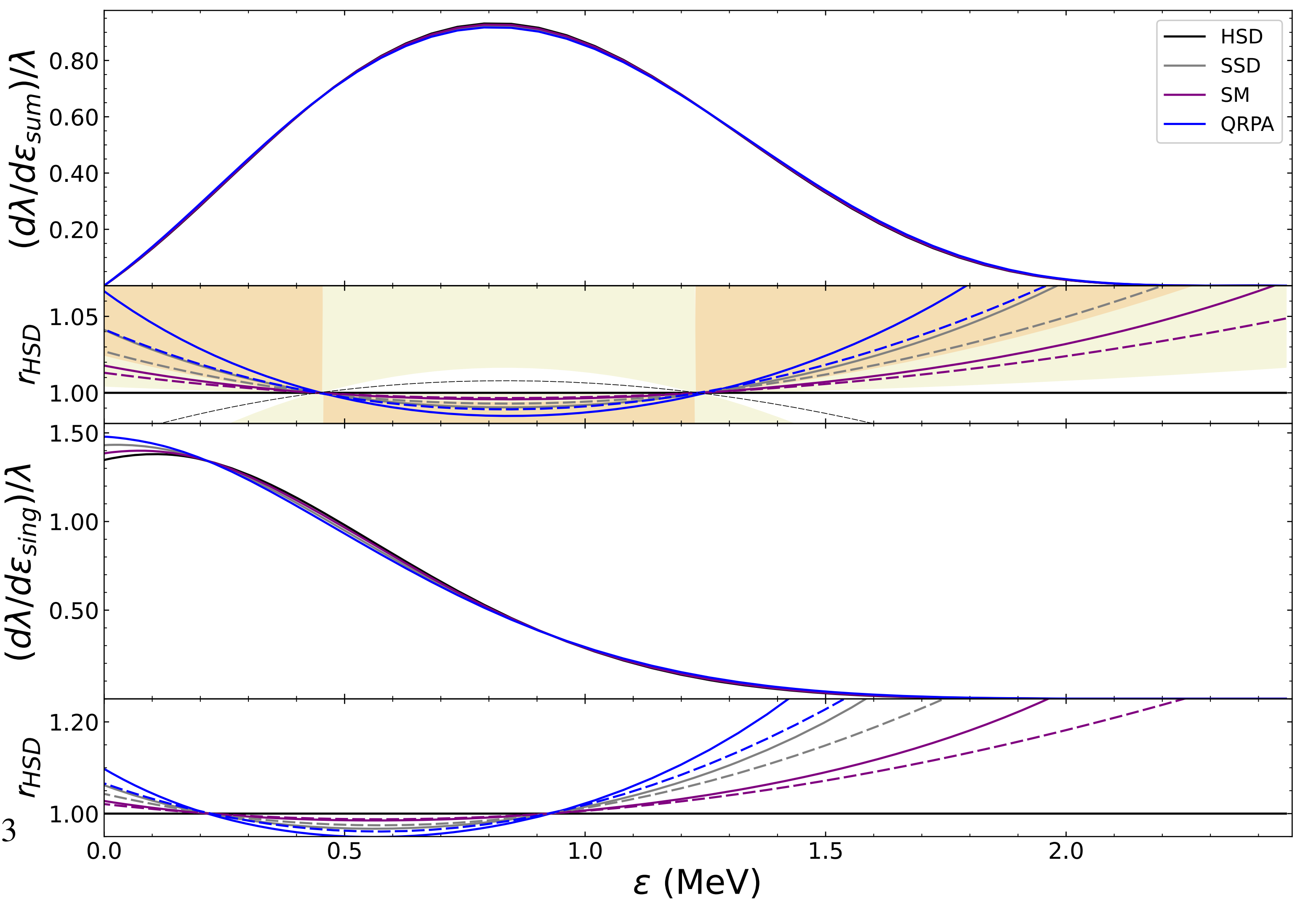


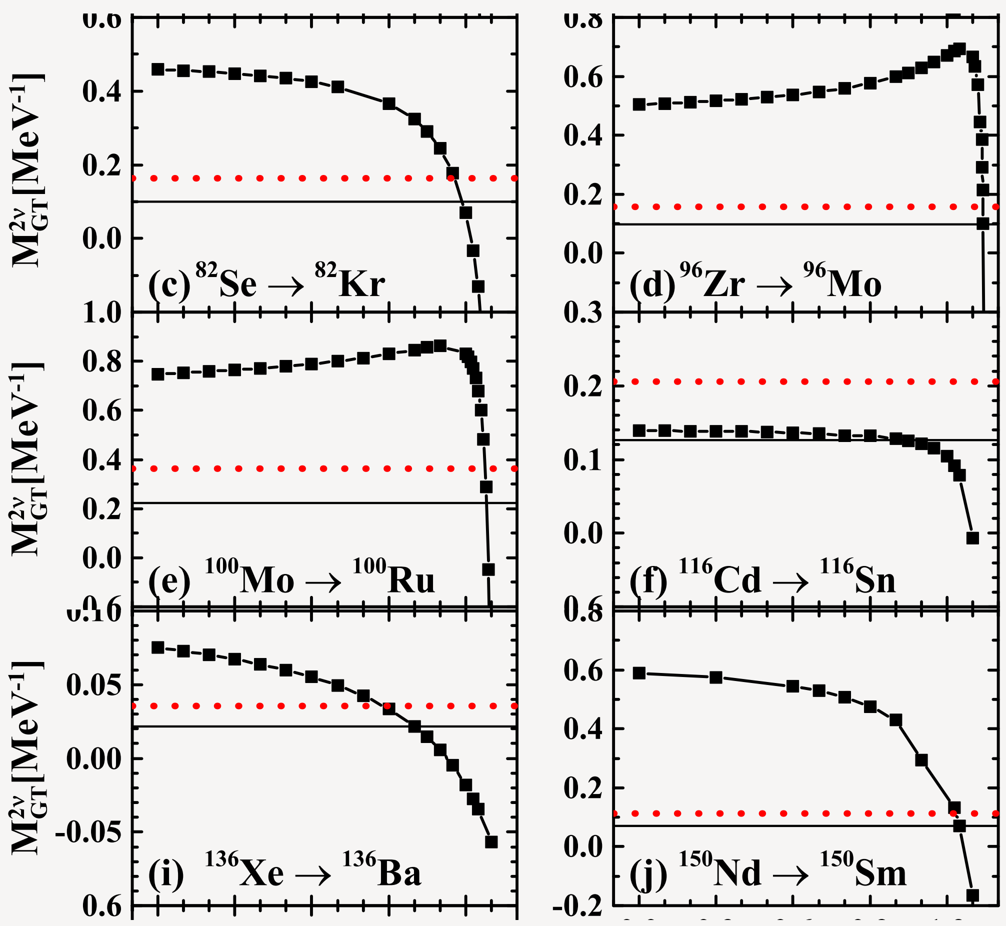


- Failures of QRPA and NSM for predicting the spectra

THEORETICAL RESULTS

*Lv et al.****PRC105****,044331(2022)*

- For the fitting procedure in QRPA calculations, by default we assume the NME is "positive"
- But this has not firm physics foundation
- And ββ spectra could offer the answer



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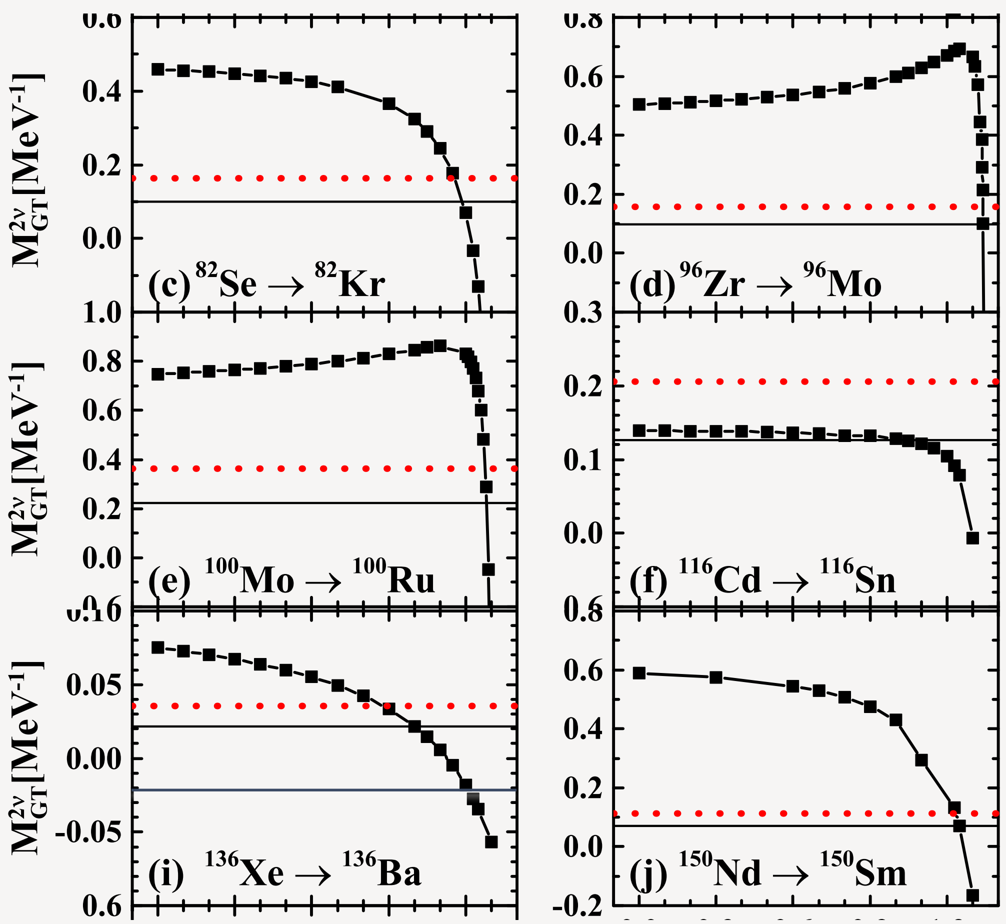

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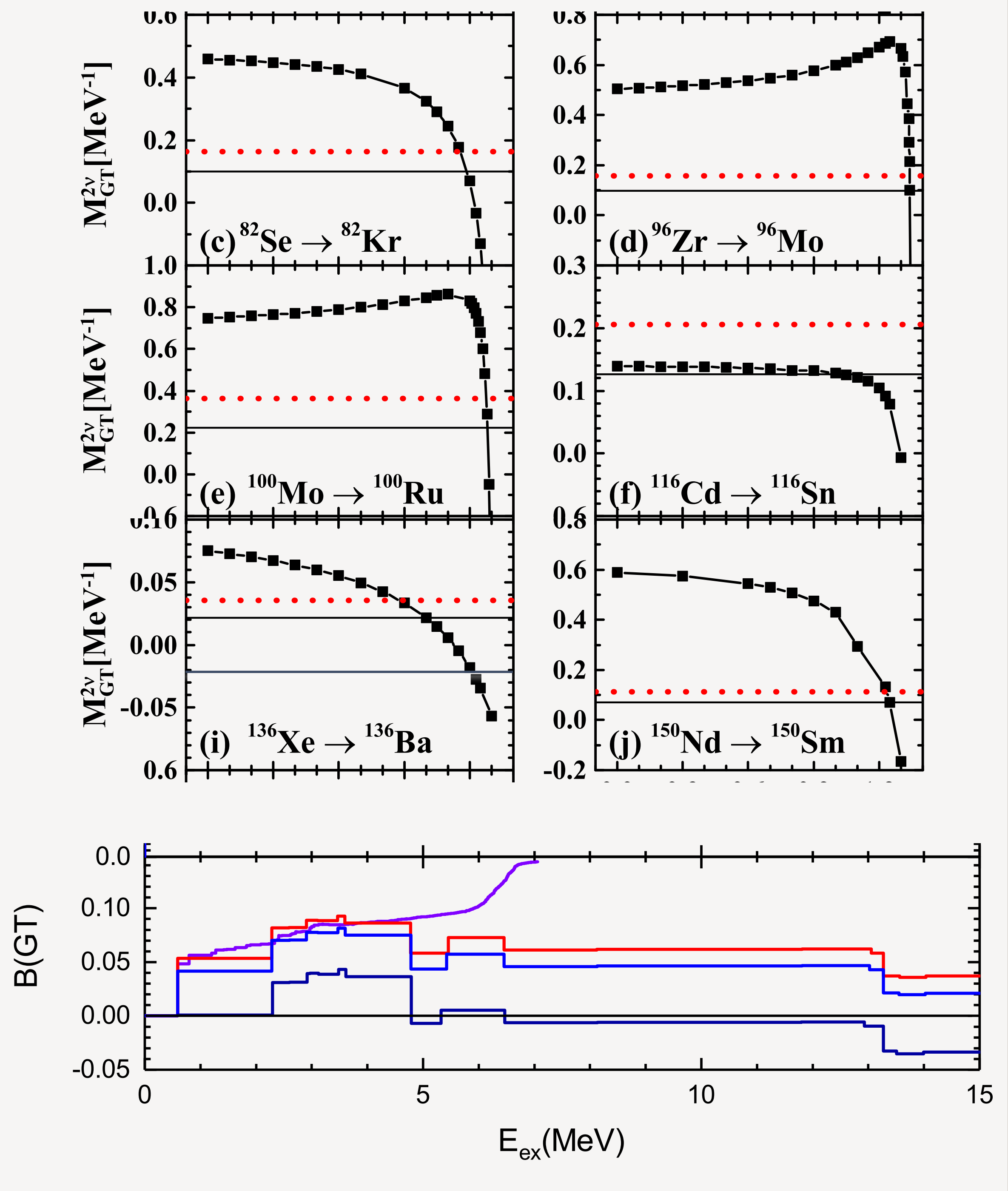

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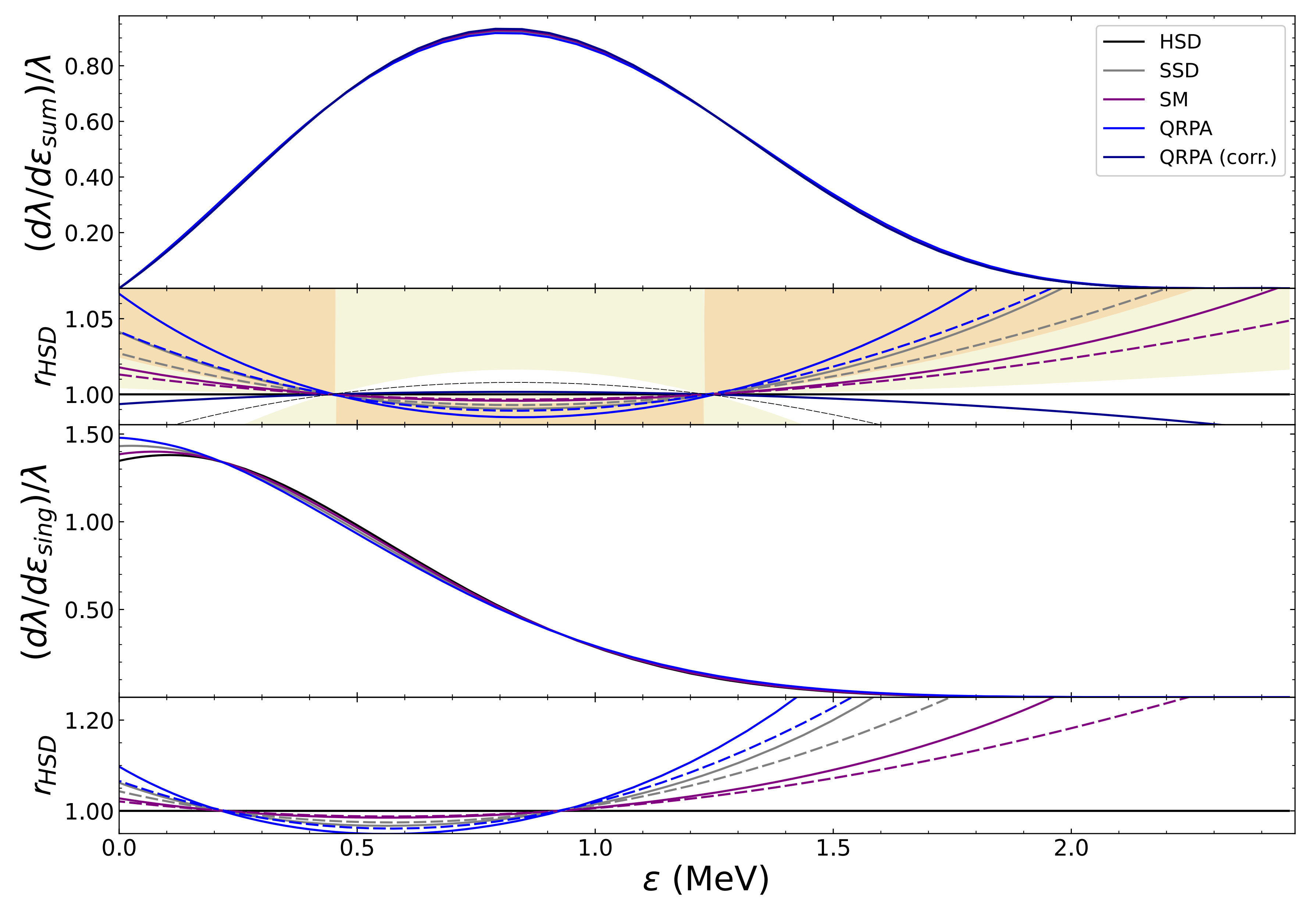

- KamLand-Zen results offers the probability

THEORETICAL RESULTS

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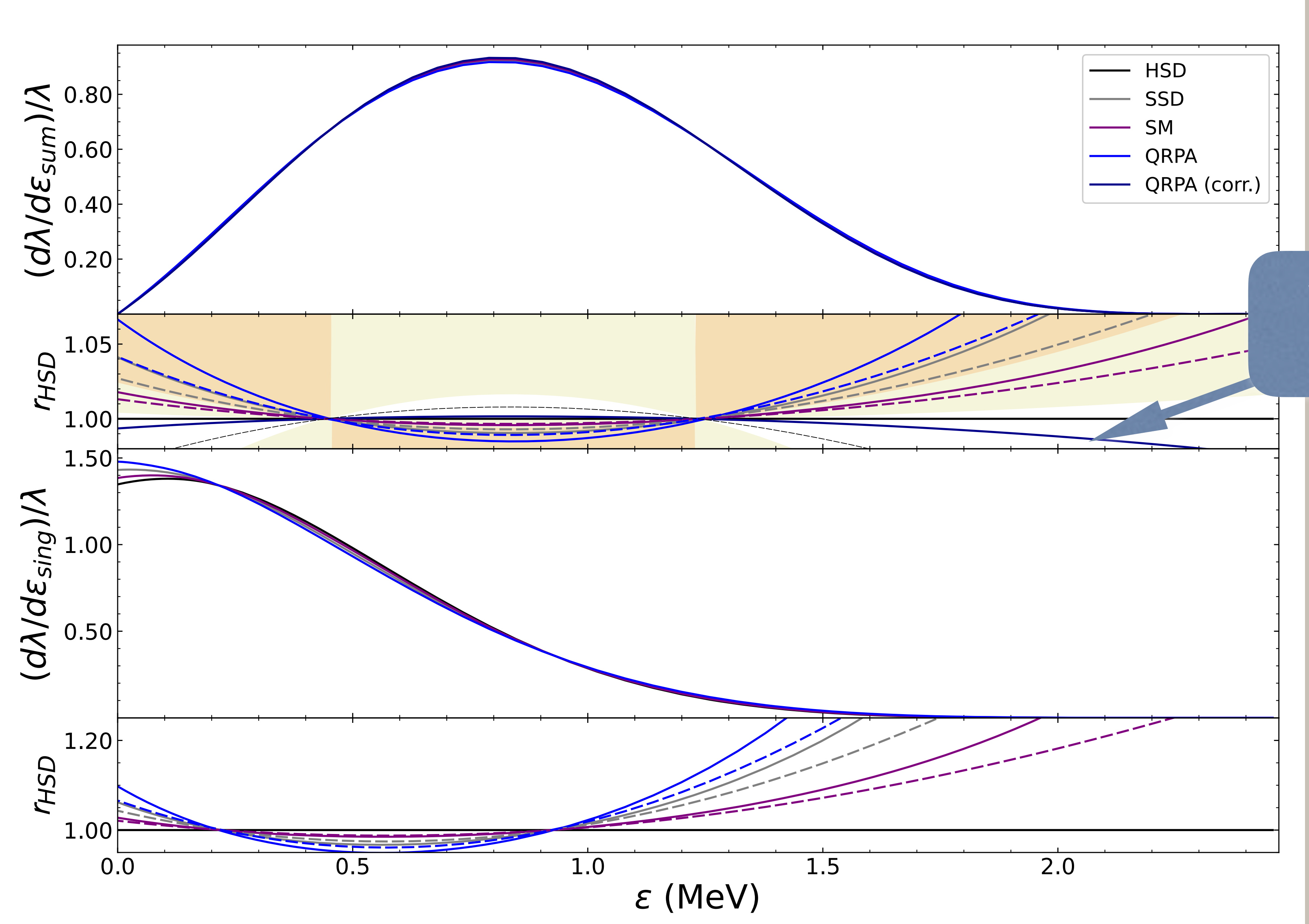
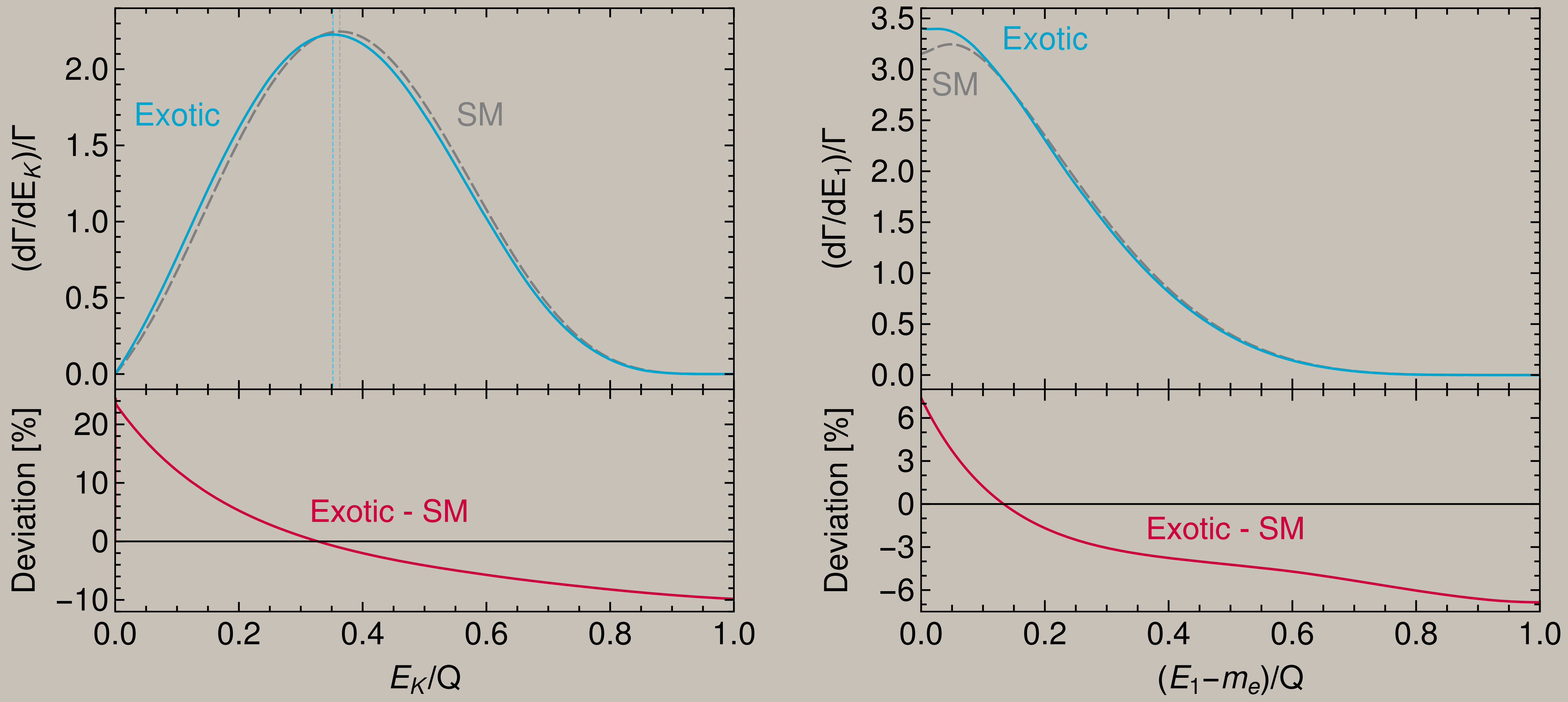


With a strong cancellation

- KamLand-Zen results offers the probability

NEW PHYSICS

*Deppisch et al.**PRL125**,171801(2023)*



- Right-handed gauge boson and weak current

CONCLUSION AND OUTLOOK

- $2\nu\beta\beta$ spectra as an addition to the half-life measurement can well constrain the nuclear theory
- Current results suggest cancellation on decay strength mediated by high-lying intermediate states for ^{82}Se and ^{136}Xe
- These need to be verified with future charge exchange experiments
- All these analyses will shed light on neutrinoless double beta decay studies

Thanks