Second Workshop on the Status of Reactor Antineutrino Flux Modeling
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Theoretical studies of the effect of FF decays on the neutrino spectra

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Outline

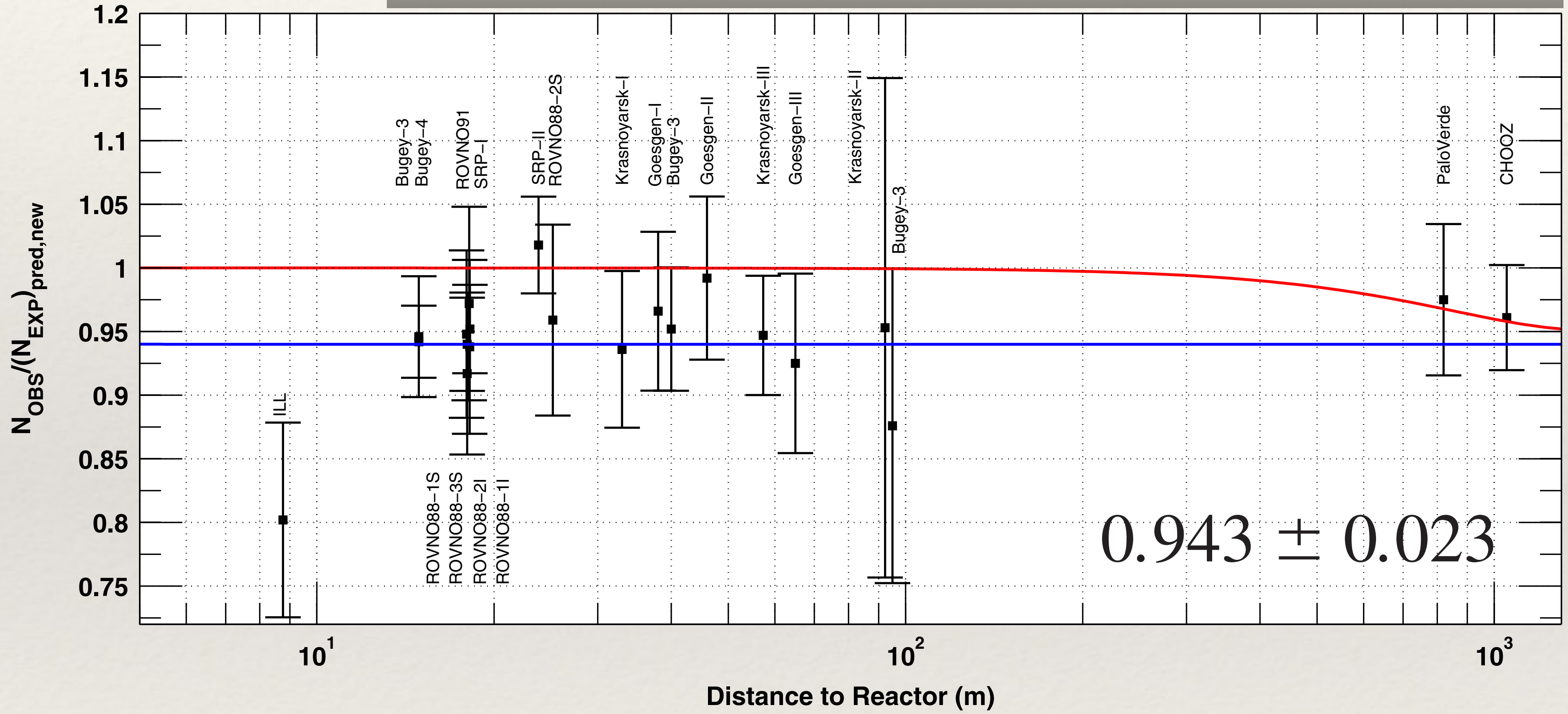
- The background
- The methods
- Our Results
- Conclusions and outlook

Background

- Neutrino was proposed by W. Pauli in 1930 in a letter to a workshop in Tübingen University
- It was discovered in 1956 by Cowan *et. al.*
- It was proved to be massive from various Experiments since 1980s
- What's next, sterile neutrino?

Background

G. Mention *et. al.* PRD83,073006(2011)



- The Reactor Antineutrino Anomaly

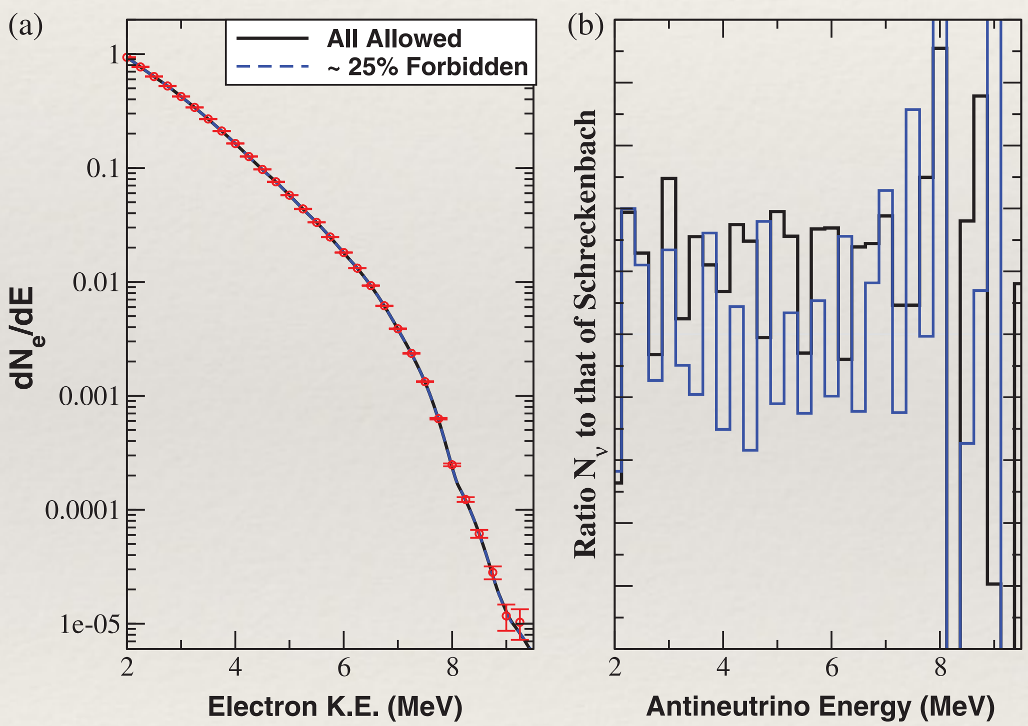
Background

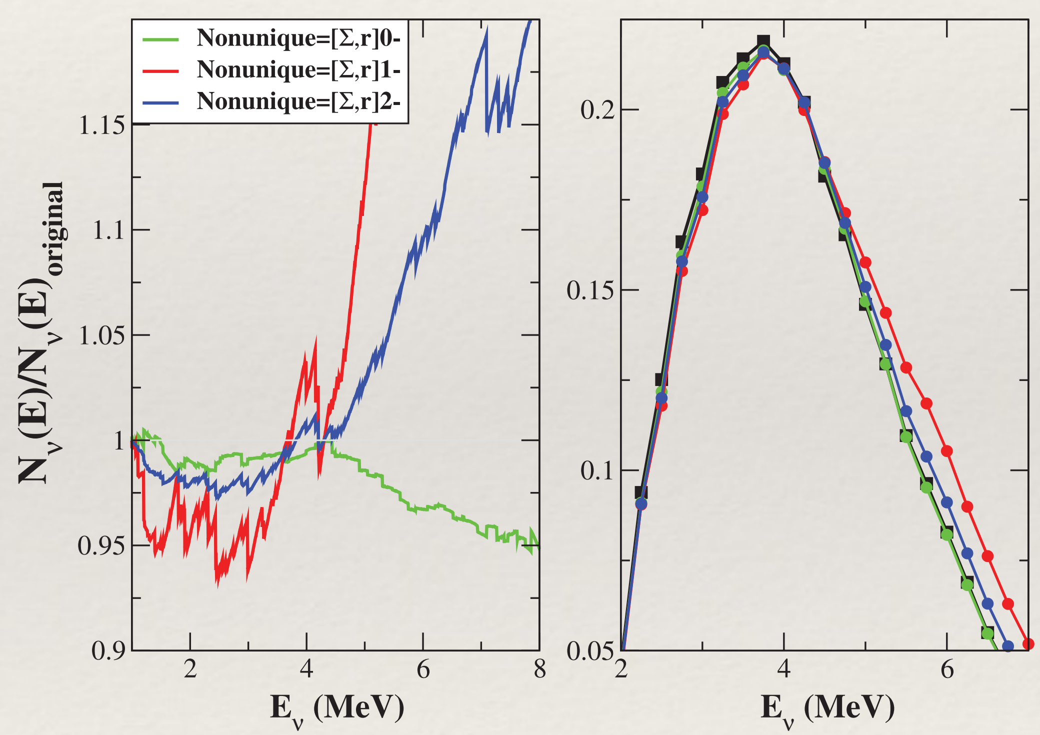
- Possible Explanations:
  - Wrong flux or its error
  - bias in all experiments
  - new physics of a fourth neutrino

See P. Vogel's talk in INT

Background

- For the first possibility, the error could come from the treatment of the beta-decay spectrum





- Inclusion of FF beta-decay

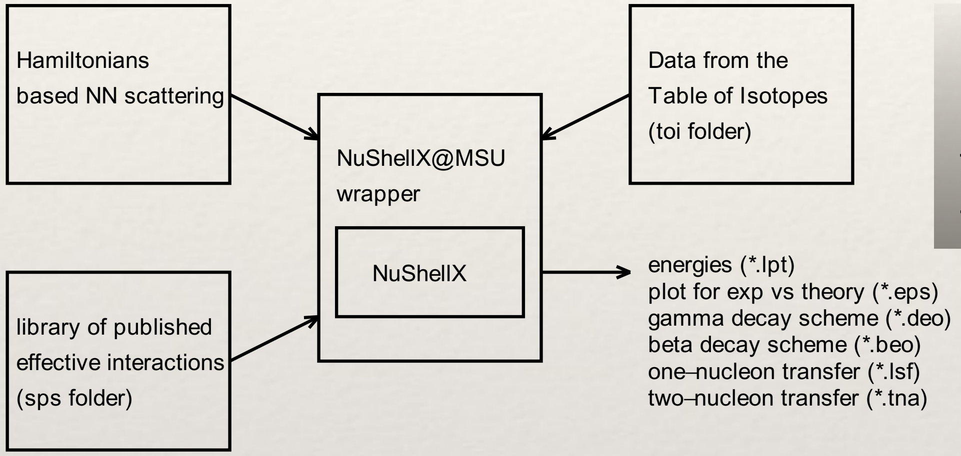
A. C. Hayes *et. al.* PRL112,202501(2014)

Methods

- Two widely used nuclear many-body approaches
  - Shell Model
    - Exact solutions, large configuration space, limited regions can be calculated
  - QRPA
    - Truncated configuration space with large model space, can be used for the whole chart

Methods

- We use the NuShellX@MSU code:



B. A. Brown and W. D. M. Raes
Nucl. Data Sheets 120,115(2015)

- M-scheme Configurations, projected to J-scheme
- Matrix elements “calculated in the fly”
- Lanczos iterations with multiple cores

Methods

- QRPA is based on the BCS or HFB theory within the quasi-particle presentations
- pn-QRPA uses the p-n two quasi-particle excitations to construct the corresponding odd-odd states
- It is suitable for the description of charge exchange reactions as well as beta-decay

Methods

- Our version of pn-QRPA:
  - s.p. levels are taken from SkX fitted for ^{132}Sn
  - pairing with a delta force or realistic forces are used
  - residue interactions (realistic G-matrix) similar to Shell Model are used
  - no self-consistency between the mean field and the residue

DLF, B. A. Brown and T. Suzuki, PRC88,034304(2013)

Results

- Microscopic descriptions of FF decays

$$f = 8896\ s^{-1}\ \lambda$$
$$= \sum_i \int_1^{\omega_{0i}} C(\omega) F(Z,\omega) p\omega (\omega_{0i}-\omega)^2 d\omega.$$

- C has the form $C(\omega) = K_0 + K_1\omega + K_{-1}/\omega + K_2\omega^2$

- For 0⁻ $C^{\Delta_J=0}(\omega) = K_0 + K_{-1}/\omega$

- For 1⁻ $C^{\Delta_J=1}(\omega) = K_0 + K_1\omega + K_{-1}/\omega + K_2\omega^2$

- For 2⁻ $C^{\Delta_J=2}(\omega) = K_0 + K_1\omega + K_2\omega^2$

- Finally $$\frac{dN_\nu}{d\omega_\nu} = C(\omega_0-\omega_\nu) F(Z,\omega_0-\omega_\nu)\omega_\nu^2 \sqrt{(\omega_0-\omega_\nu)^2-1}$$

Results

- details of K's T. Suzuki et. al. PRC 85,015802(2012)
- 0 -

$$K_0 = \zeta_0^2 + \frac{1}{9}\left(M_0^S\right)^2, \quad K_{-1} = -\frac{2}{3}\mu_1\gamma_1\zeta_0 M_0^S$$

- 1 -

$$K_0 = \zeta_1^2 + \frac{1}{9}(x+u)^2 - \frac{4}{9}\mu_1\gamma_1 u(x+u) + \frac{1}{18}w_0^2(2x+u)^2 - \frac{1}{18}\lambda_2(2x-u)^2,$$

$$K_1 = -\frac{4}{3}uY - \frac{1}{9}w_0(4x^2+5u^2),$$

$$K_{-1} = \frac{2}{3}\mu_1\gamma_1\zeta_1(x+u),$$

$$K_2 = \frac{1}{18}[8u^2 + (2x+u)^2 + \lambda_2(2x-u)^2],$$

- 2 -

$$K_0 = \tfrac{1}{12}z^2\left(w_0^2 - \lambda_2\right), \quad K_1 = -\tfrac{1}{6}z^2 w_0, \quad K_2 = \tfrac{1}{12}z^2(1+\lambda_2),$$

- 3 components for 0 -, 5 for 1 - and 1 for 2 -

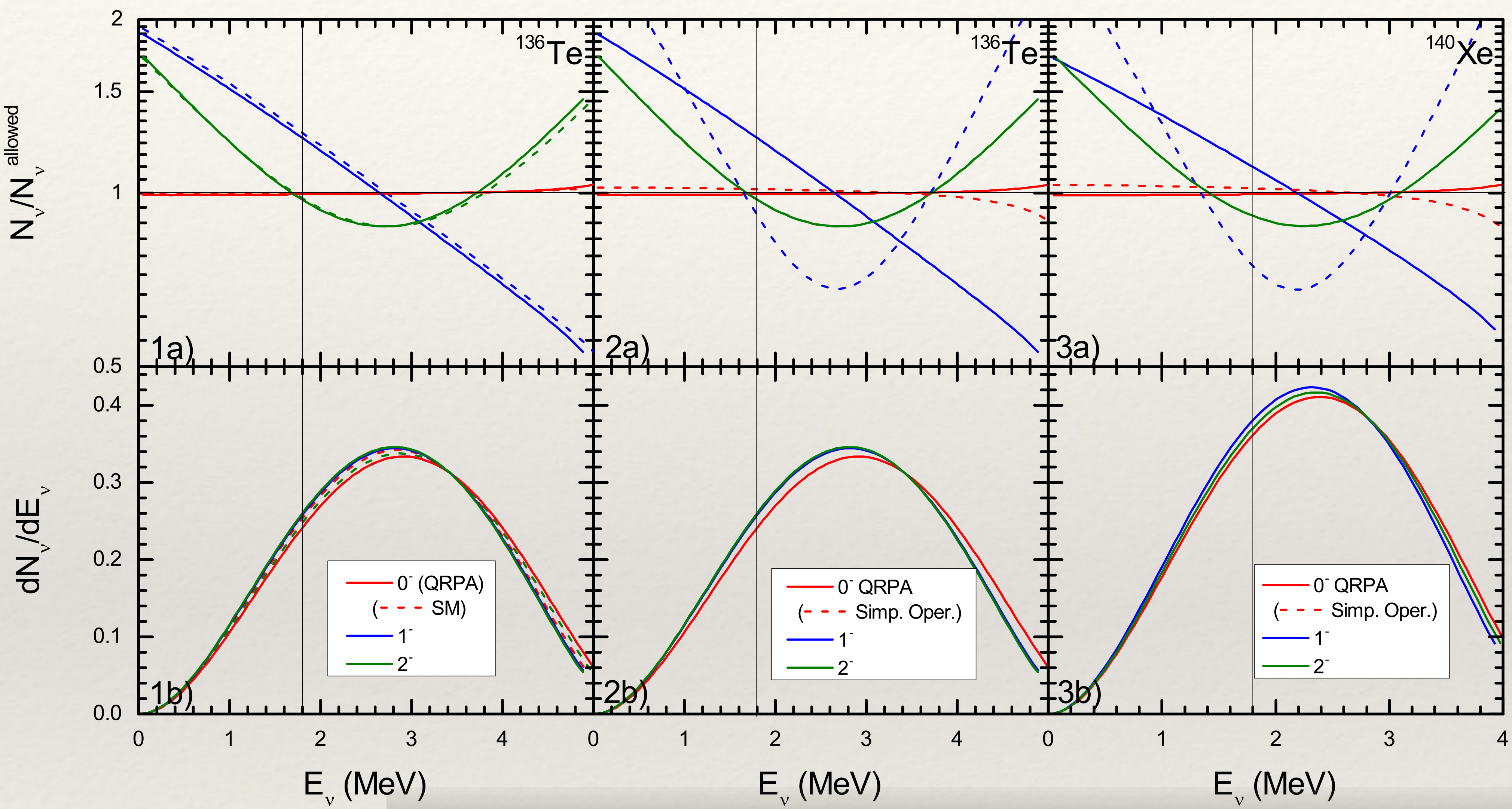
Results

	J_i^π	t(s)	Exp. [13] J_f^π	E_{ex}	$\log ft$	ShM J_f^π	E_{ex}	$\log ft$	QRPA J_f^π	E_{ex}	$\log ft$
^{136}Te	0^+	17.63	(1^-)	0	>6.7	1^-	0	6.85	0^-	0	6.37
			$(0^-, 1, 2^-)$	0.222	7.23	2^-	0.095	7.37	1^-	0.171	6.95
			$(0^-, 1)$	0.334	6.27	0^-	0.133	6.41	2^-	0.194	7.89
			$(0^-, 1)$	0.631	6.28	1^-	0.426	6.26	2^-	0.541	6.99
			$(0^-, 1, 2^-)$	0.738	7.57	2^-	0.507	6.71	1^-	0.747	6.13
^{140}Xe	0^+	13.6	$1^-, 0^-$	0.080	6.14				0^-	0	6.15
			$(0, 1^-)$	0.515	6.82				1^-	0.127	6.77
			$0^{(-)}, 1^{(-)}$	0.653	5.98				2^-	0.365	7.01
			$(1, 2^-)$	0.800	≈ 7.1				1^-	0.586	6.05
			$1^{(-)}$	0.966	6.77				1^-	1.353	6.75

DLF and B. A. Brown, Submitted to PRC

- Comparison of FF decay branches among two calculations and the measurements

Results



DLF and B. A. Brown, Submitted to PRC

- changes of spectra for single decay branches

Results

- by defining:

$$\delta = \frac{1 - n_{FF}(E < E_t)}{1 - n_{GT}(E < E_t)}$$

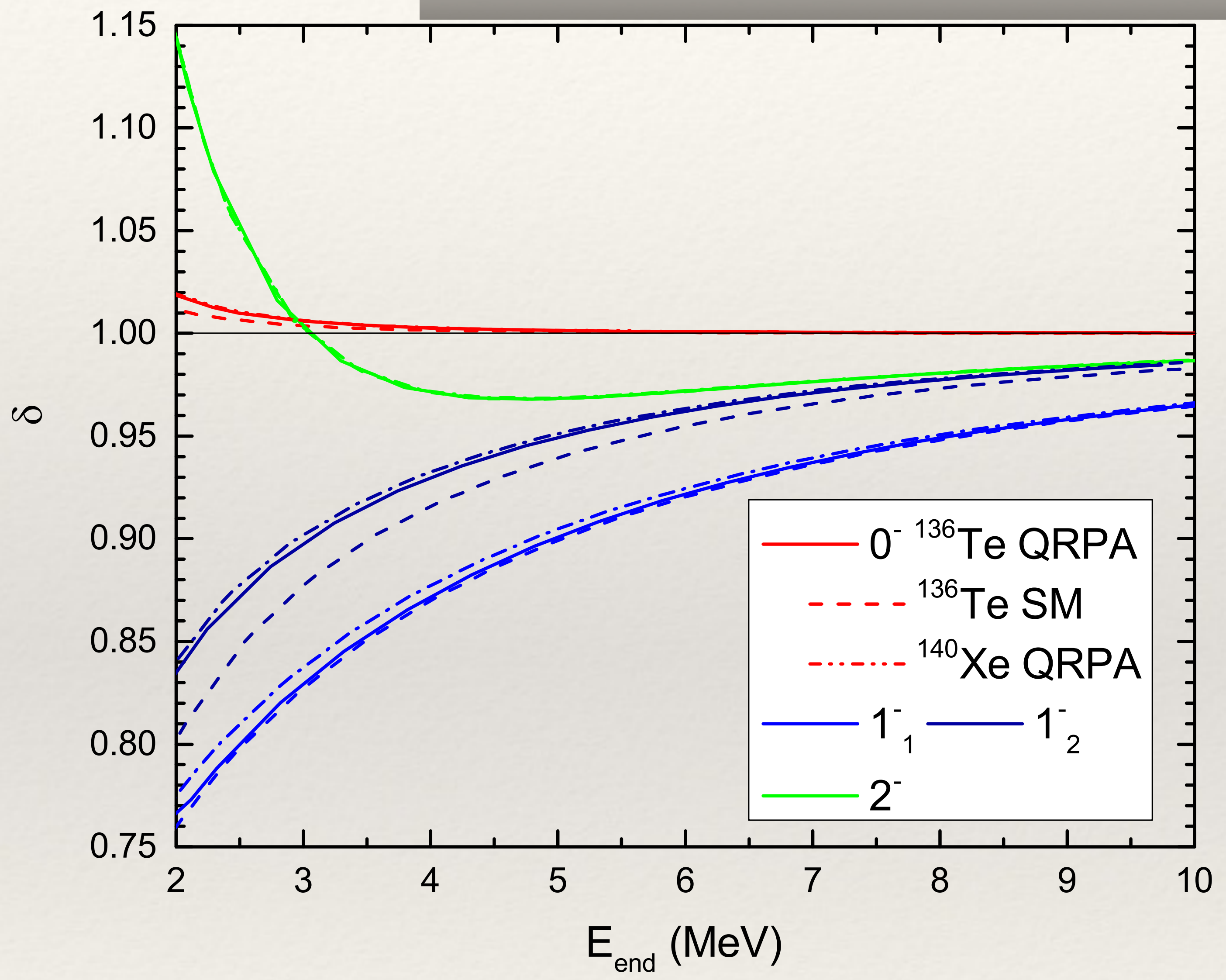
$$n_I(E < E_t) = \int_0^{E_t} \frac{dN}{dE_\nu}(E_\nu)dE_\nu$$

	E^Q_{ex}	δ^Q	$\delta^Q_{simp.}$	E^S_{ex}	δ^S	E^Q_{ex}	δ^Q	$\delta^Q_{simp.}$
0^-	0.0	1.002	0.995	0.133	1.001	0.0	1.003	0.990
1^-_1	0.171	0.899	0.929	0.0	0.902	0.127	0.875	0.949
1^-_2	0.747	0.938	0.971	0.426	0.933	0.586	0.919	0.981
2^-_1	0.194	0.968		0.065	0.970	0.060	0.971	
2^-_2	0.541	0.968		0.507	0.982	0.365	0.976	

- The differences of the observed neutrinos

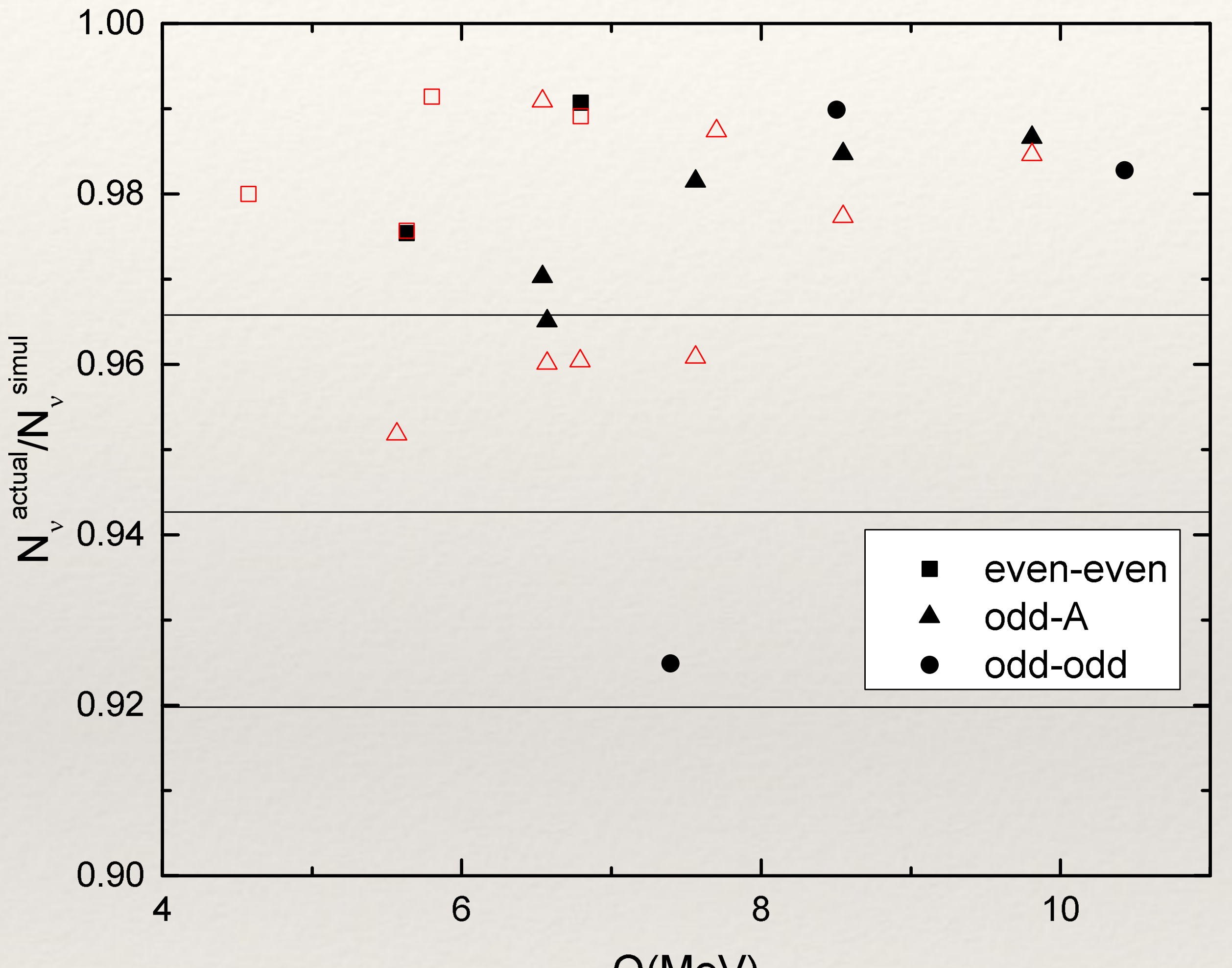
Results

DLF and B. A. Brown, Submitted to PRC



- vary the end-point energies

Results



- changes (δ) for several fission products around ^{140}Xe region

Outlook

- Various corrections such as finite size of nucleus, weak magnetism should be included
- Fission data is needed for actual estimations
- For branches which are experimentally unknown we may turn to theoretical calculations

Conclusions

- We have started the first step of the estimation of neutrino spectra from microscopic calculations
- We have calculated the neutrino spectra for FF decay branches with two nuclear many-body approaches
- Our results implies that the missing neutrino from Reactor neutrino anomaly may come from the mistreatment of the neutrino spectra
- further realistic estimations are needed

Thanks