The NEνFAR project:
New Evaluation of ν Fluxes At Reactors

DE LA RECHERCHE À L'INDUSTRIE

cea

Revisiting the summation calculation of reactor antineutrino spectra

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www.cea.fr

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OUTLINE

1. **Introduction & motivations**
   a. Reactors as antineutrino sources
   b. Experimental anomalies
   c. Modeling methods

2. **Revised summation method**
   a. β^- spectrum calculation
   b. Nuclear data content
   c. Uncertainty budget

3. **Comparison to experiments and models**
   a. Integral measurements
   b. Spectrum shape

4. **Conclusion & perspectives**

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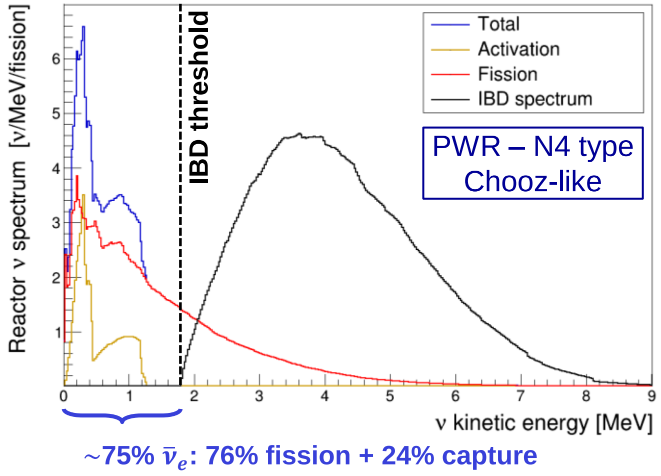
PRESSURIZED WATER REACTOR (PWR)

- Fuel: lowly enriched uranium, ^{238}U + 3-5% ^{235}U
- High power: ~3 - 4 GW_{th}
- Close reactor design & fuel contents for all PWR

⇒ Similar $\bar{\nu}_e$ spectra



Typical fission fraction

^{235}U	**0.559**	~83% $\Phi_{\bar{\nu}_e}$
^{239}Pu	**0.291**	
^{238}U	0.088	
^{241}Pu	0.062	

Activation [$\bar{\nu}_e$/fission]

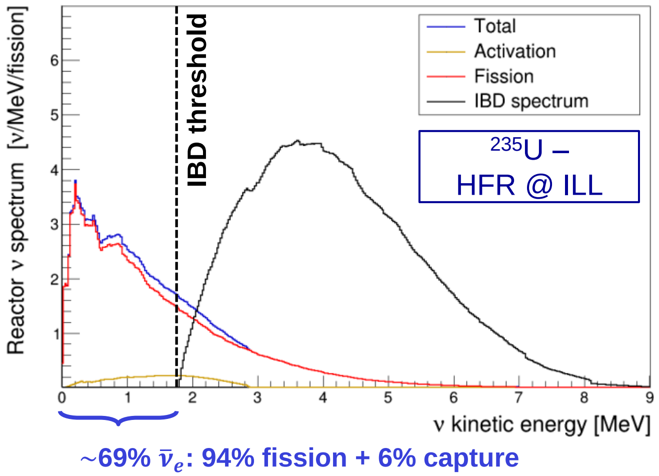
^{239}U	0.6	~17% $\Phi_{\bar{\nu}_e}$
^{239}Np	0.6	

Average event/fission for a Chooz type reactor (~4% ^{235}U) over a 12-month core cycle

RESEARCH REACTOR

- Fuel: highly enriched uranium, >20% ^{235}U
- Low power : ~0.1 kW_{th} - 100 MW_{th} but very short baseline accessible
- Wide array of designs & fuel contents + reactor specific structural material activation

⇒ Reactor-specific $\bar{\nu}_e$ spectra



Fission fraction

^{235}U	**0.993**	~93% $\Phi_{\bar{\nu}_e}$
^{239}Pu	**0.007**	

Activation [$\bar{\nu}_e$/fission]

^{239}U	0.013	~7% $\Phi_{\bar{\nu}_e}$
^{239}Np	0.013	
^{28}Al	**0.346**	
^{56}Mn	0.058	

Average event/fission for the HFR at the ILL (~93% ^{235}U) over a 50-day core cycle

⇒ $\bar{\nu}_e$ contribution depends on reactor type and changes with time

⇒ Prediction needed for fission and activation spectra

REACTOR ANTINEUTRINO ANOMALY (RAA)

Phys. Rev. D 83, 073006 (2011)

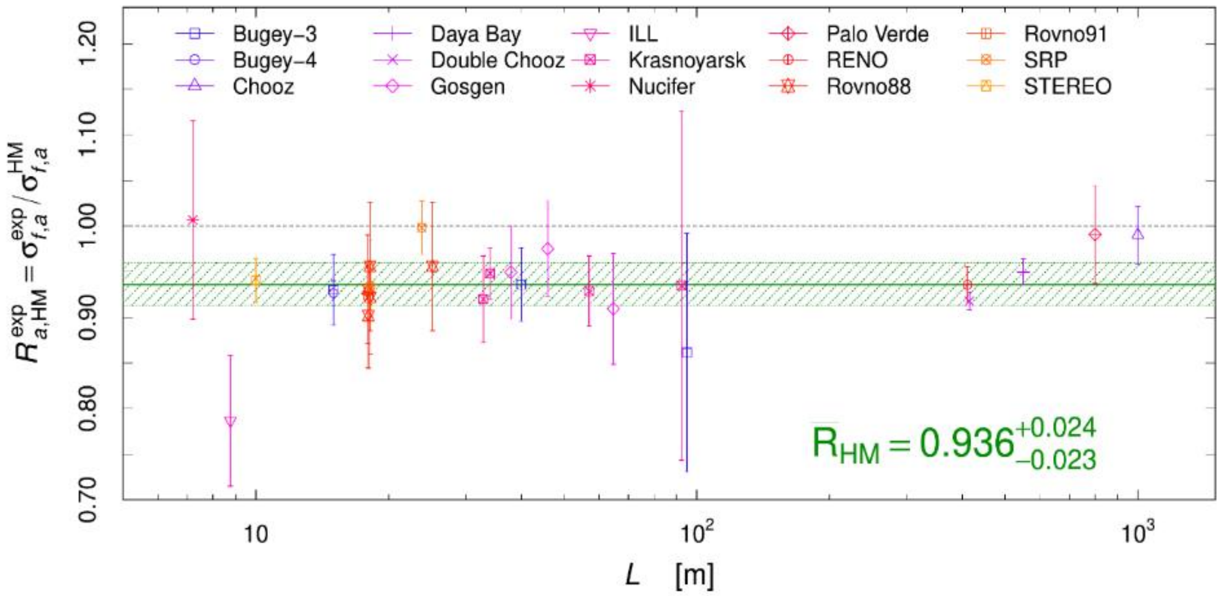
- Systematic measured IBD rate deficit compared to Huber-Mueller model
  - Observed in more than 20 reactor experiments
  - Confirmed in all recent reactor experiments at PWR and research reactors

- Ratio of measured over predicted IBD rate: $\mathbf{0.936}^{+0.024}_{-0.023}$
  - Statistical significance: **2.5σ**

- RAA possible origins
  - Experimental bias
  - New physics (sterile neutrino)

    Unlikely
  - **Mismodeling / underestimation of $\bar{\nu}_e$ spectrum uncertainty**

Phys. Lett. B, Vol. 829, 137054 (2022)

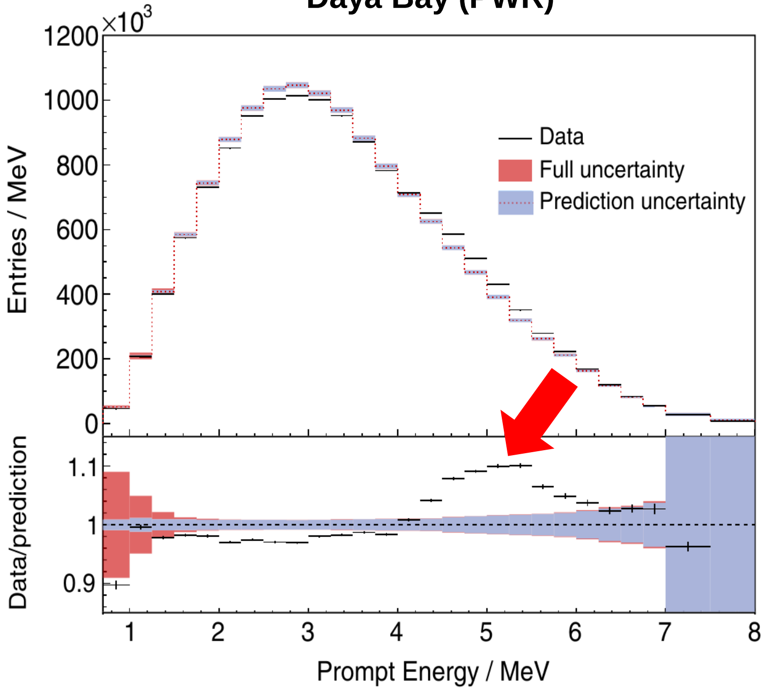


SHAPE ANOMALY

- ~8-10% difference between predicitons and data at 5-6 MeV
- First observed by Double Chooz, Daya Bay and RENO
  - Confirmed by recent very-short baseline reactor experiments (NEOS, STEREO, PROSPECT, DANSS)

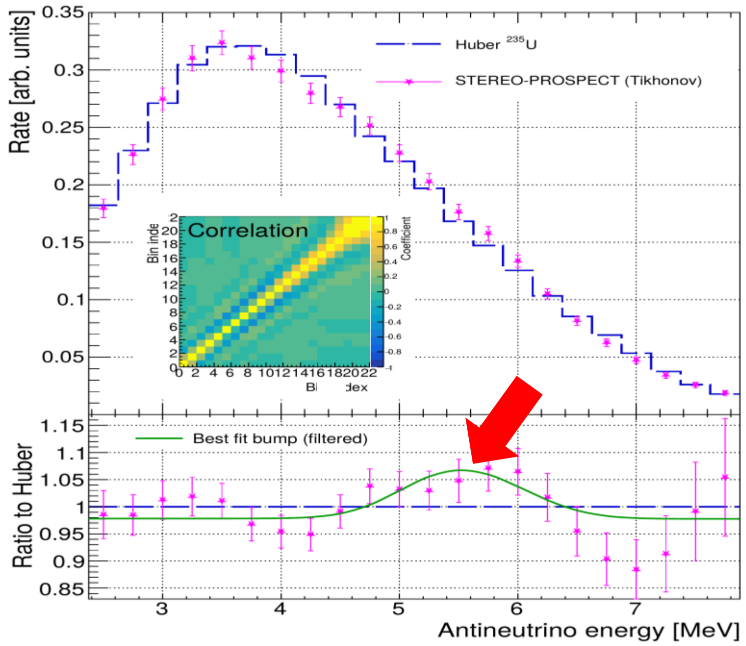
- Possible origins
  - Detector energy scale calibration *Checked*
  - Fuel composition
  - **Prediction issue, single / multiple actinide(s) ?**

Daya Bay (PWR)



Phys. Rev. Lett. 123, 111801 (2019)

STEREO + PROSPECT (research)



arXiv:2107.03371

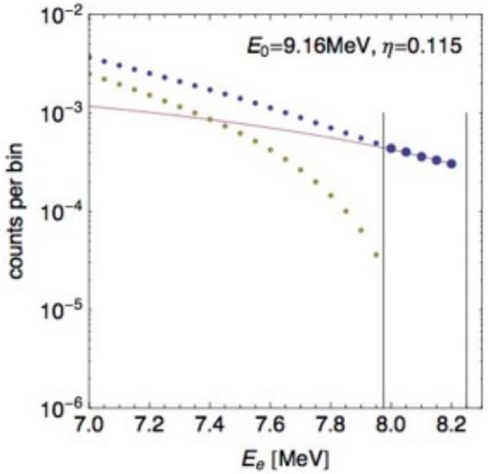
c. Modeling methods

CONVERSION METHOD

- Measure exp. β fission spectra
- Convert virtual β branch fit to $\bar{\nu}_e$ branches

PROS
- Small uncertainties ~2-3%
- Access total $\bar{\nu}_e$ fission spectrum

CONS
- Limited to exp. range, 2-8 MeV
- No activation spectrum
- HM subject to the anomalies
- BILL data questionned → Kurchatov Inst.
- Impact of forbidden branches on fit



SUMMATION METHOD

- Fission spectrum prediction = sum of all β branches listed in nuclear databases
- +900 β^- emitters ~ 10 000 β^- transitions

PROS
- Prediction ∀ energy, ∀ β emitter
  - ▸ CEνNS
- Convenient to understand physics
- Mandatory for activation spectra

CONS
- Uncomplete/biased nuclear database
- Modeling approximations
- Uncertainties very complex to estimate

⇒ **Summation method requires many input data**

W. Bühring and H. Behrens formalism (1982)

Branch spectrum

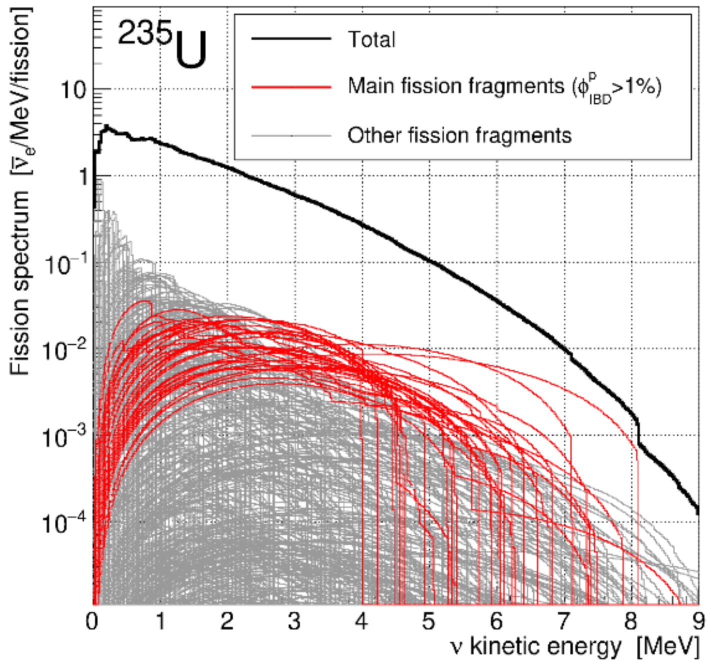
$$S_\beta = KpW(W_0 - W)^2 F_0 C(1 + \delta_{WM} + \delta_{RC})$$
$$S_\nu(E) = S_\beta(E_0 - E)$$

Isotope spectrum

$$S_i = \sum_b BR_i^b \, S_\nu^b$$

Fission spectrum

$$S_f = \sum_i FY_f^i \, S_i$$



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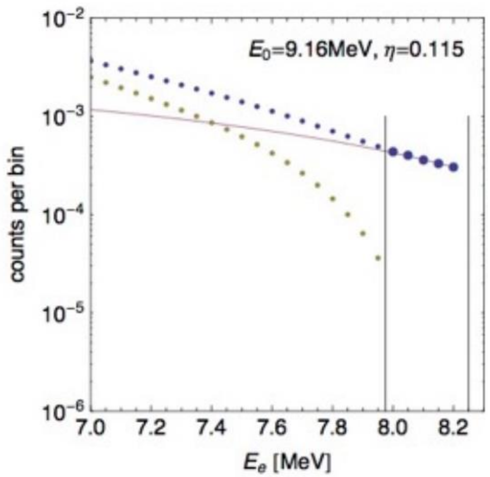

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CONS
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- Modeling approximations
- Uncertainties very complex to estimate

⇒ Reliable summation method required for multiple purposes

THE NEνFAR PROJECT

(New Evaluation of ν Fluxes At Reactor)

Revise summation method with BESTIOLE code

- Improve β-decay modeling
  - ▻ Refine non-unique forbidden transition modeling
- Impact of database uncompleteness and quality
  - ▻ Update nuclear database with Pandemonium-free data
  - ▻ Impact of nuclides with no data modeling
- Build a comprehensive uncertainty budget
  - ▻ Nuclear data and modeling uncertainties

All results are preliminary

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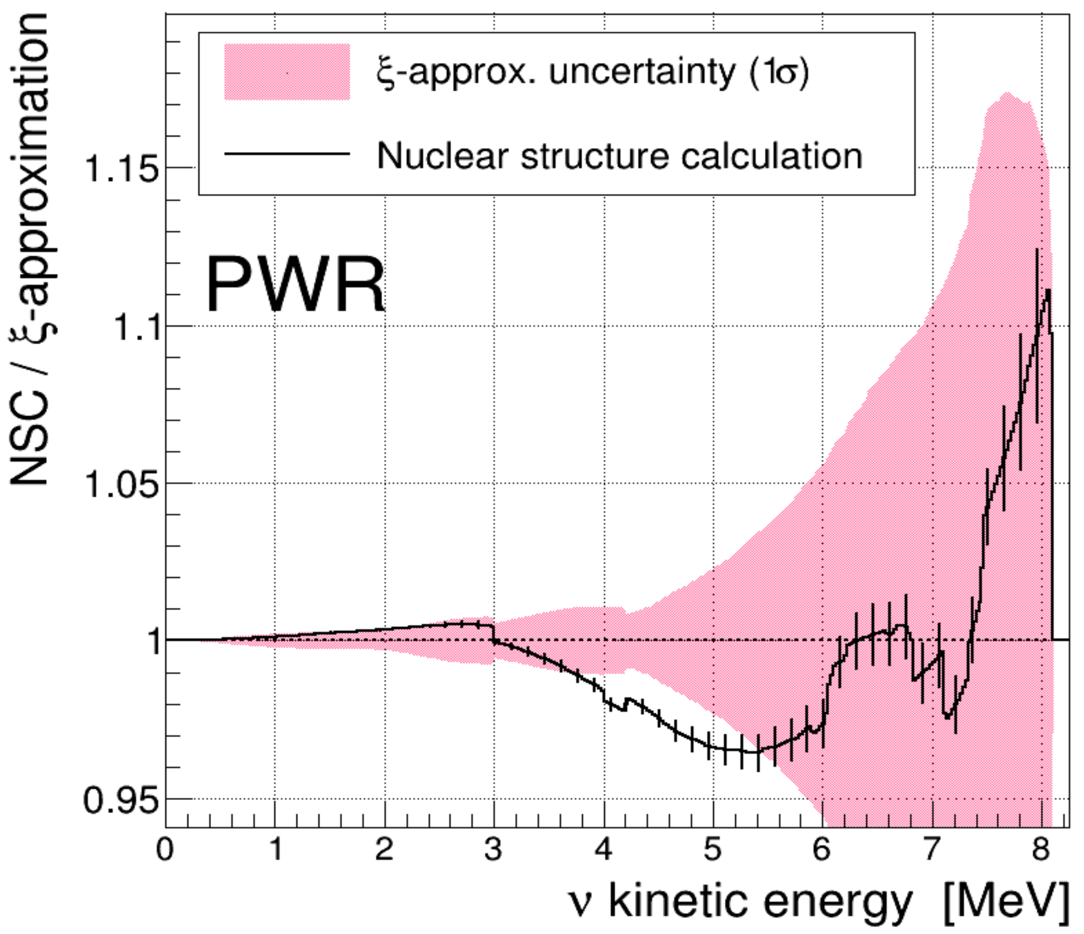
MODELING OF NON-UNIQUE TRANSITIONS

- Dismissed in previous modeling (modeled as allowed or unique forbidden)
- Hayes *et al.* (2014) + Hayen *et al.* (2019): modelings of non-unique transitions in conversion predictions → partial explanation of shape anomaly
- Nuclear structure calculation with NuShellX
  - Very time consuming (man & cpu)
  - No general nor systematic trend
- 23 non-unique forbidden transitions contribute to
  - ~27% of IBD yield
  - ~22% of CEνNS yield



⇒ Using NSC decreases IBD yield by (1.3 $\pm$ 0.2)%

TACKLING THE PANDEMONIUM EFFECT IN SUMMATION SPECTRA

- HPGe detector, high energy resolution + decreasing efficiency for increasing energies
  - β feedings to low (high) energy levels are overestimated (underestimated)

- Nuclear database are biased by the Pandemonium effect
  - Estienne et *al.* (2019): including Pandemonium-free TAGS data decreases IBD yields and shape differences

- Including up-to-date Pandemonium-free data (TAGS + Direct β measurements)

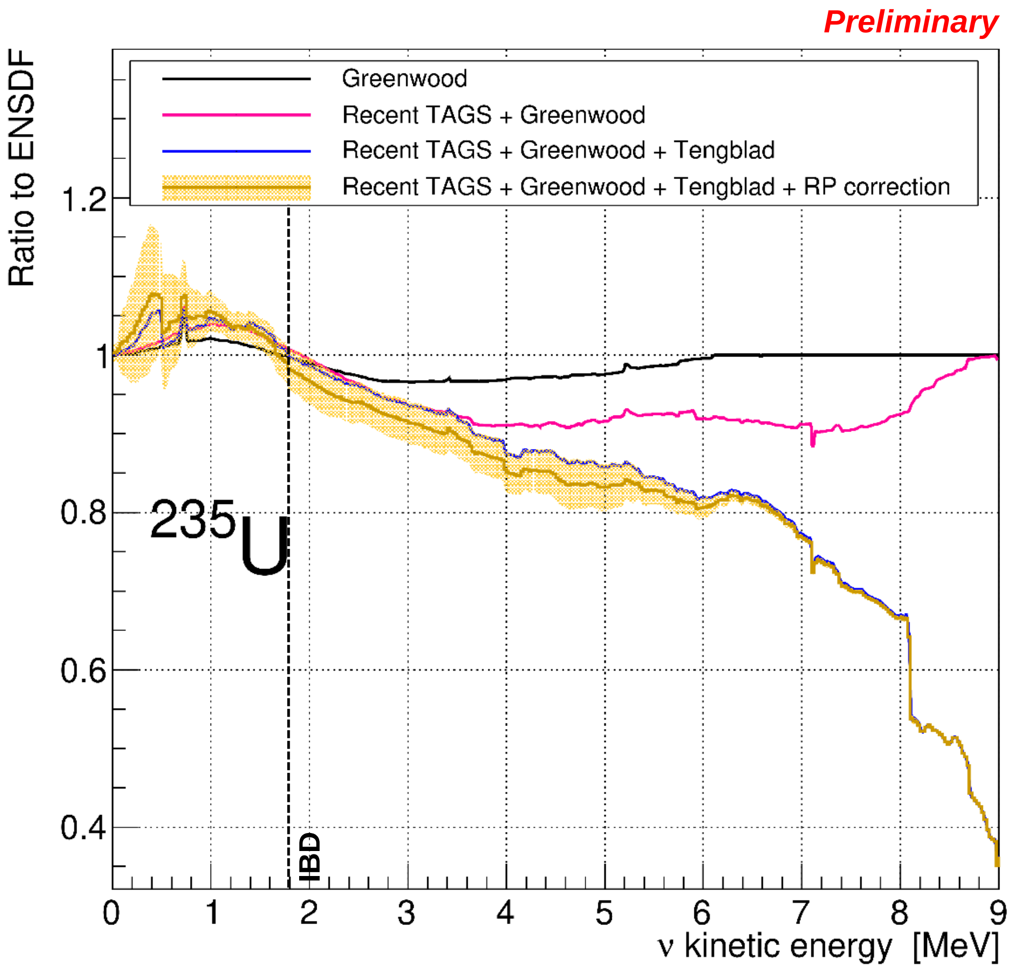
  ⇒ IBD yield decreased by (12.8 $\pm$ 1.5) %

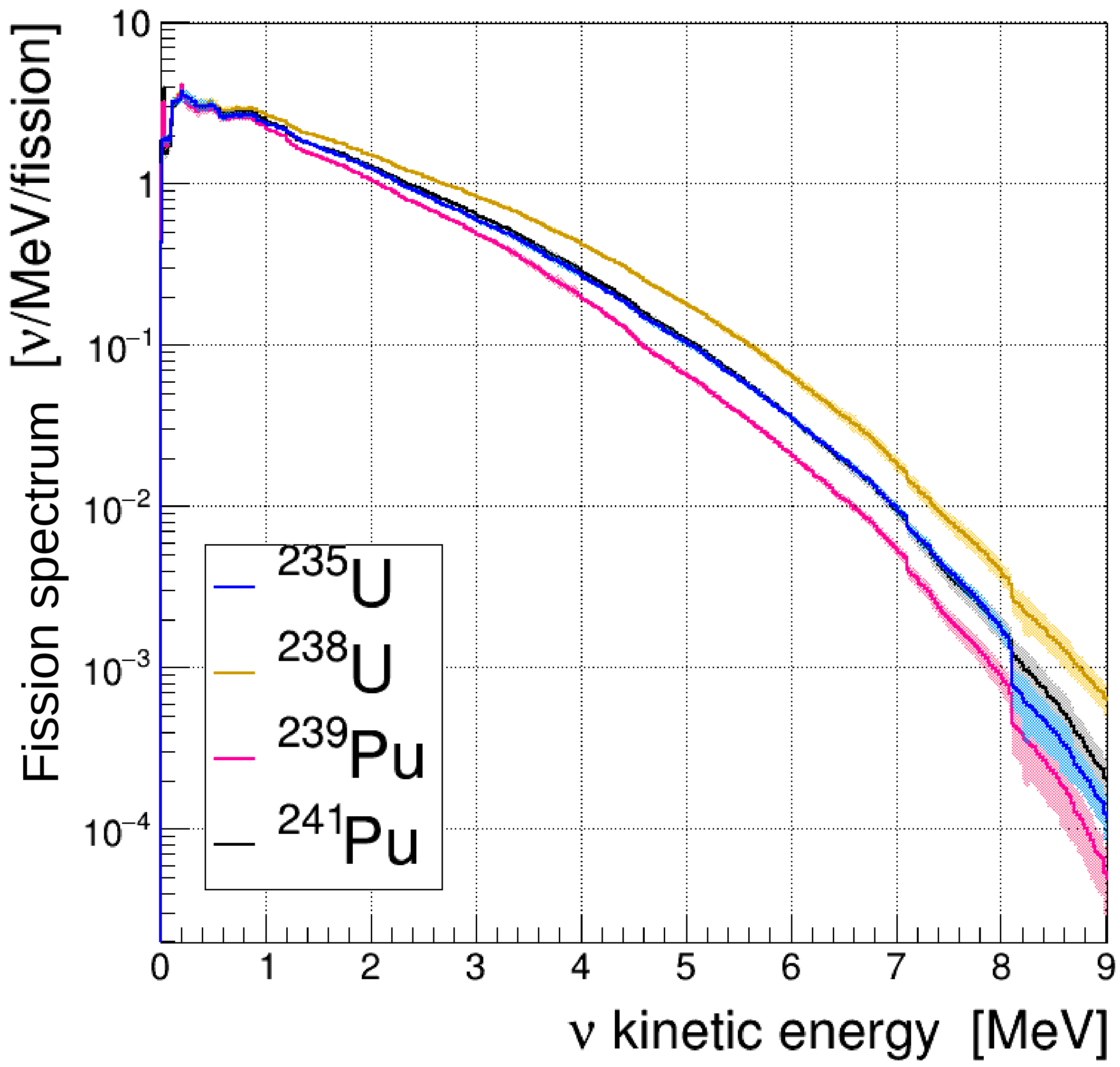
  ⇒ ~ 65% of IBD and CEνNS yields

- Remaining isotopes potentially impacted by Pandemonium in nuclear database
  - 29 isotopes identified by IAEA
  - Apply correction for residual Pandemonium effect

  ⇒ IBD yield decreased by (2.2 $\pm$ 2.4) %

  ⇒ ~ 12% of IBD and CEνNS yields





IBD yields (10^{-43} cm^2/fission)	
^{235}U:	6.25 ± 0.21
^{238}U:	10.01 ± 0.32
^{239}Pu:	4.48 ± 0.15
^{241}Pu:	6.58 ± 0.21

⇒ IBD yield uncertainty ~3%

CEνNS yields* (10^{-43} cm^2/fission)	
^{235}U:	1113 ± 34
^{238}U:	1669 ± 48
^{239}Pu:	882 ± 25
^{241}Pu:	1169 ± 33

** For a Ge target nucleus and 20 eV detector threshold*

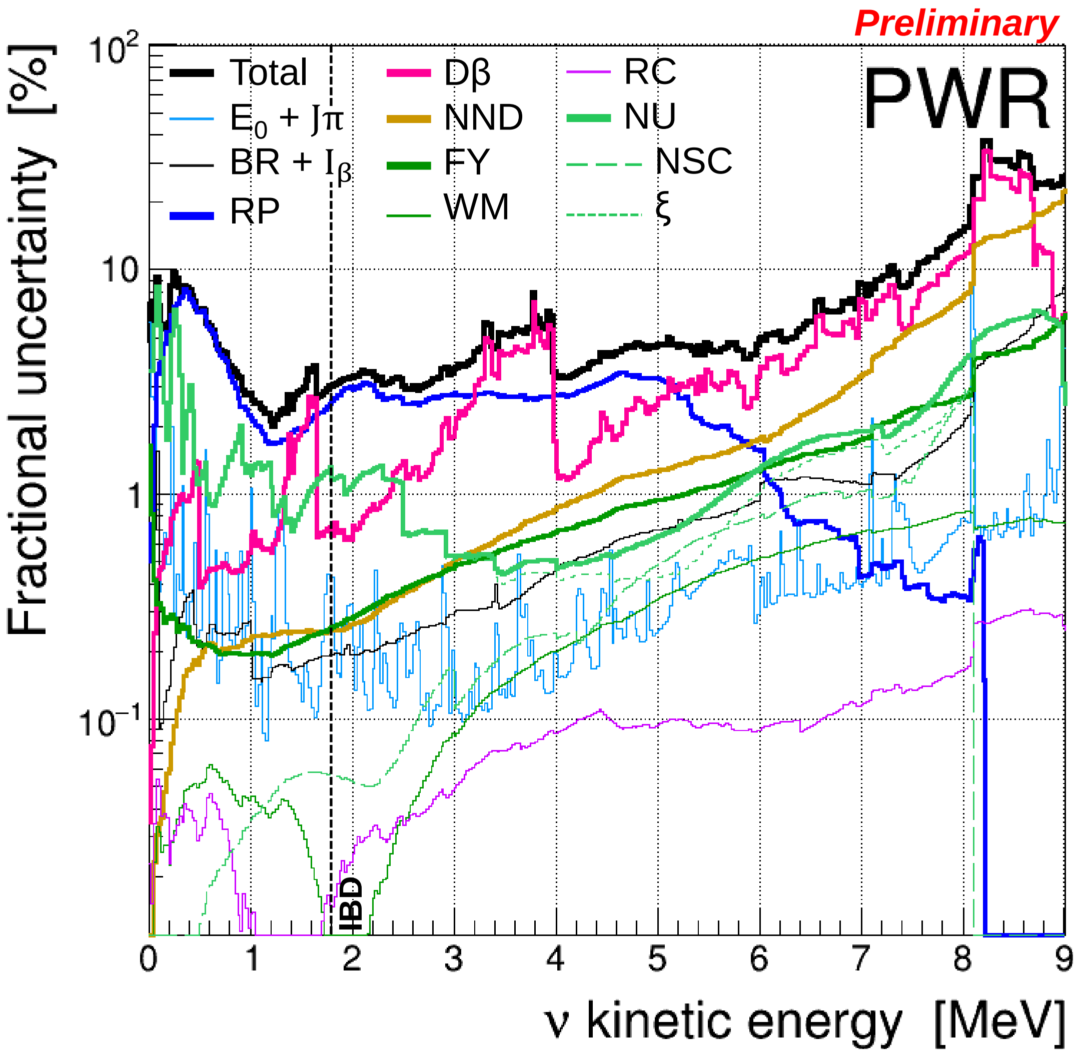
⇒ CEνNS yield uncertainty ~3%

NORMALIZATION UNCERTAINTY

	PWR			$\langle\sigma_{IBD}\rangle$	$\langle\sigma_{CE\nu NS}\rangle$*
	[10^{-43} cm^2/fission]			6.08	1090
	Uncertainty	**Abbrev.**	**Method**	**[%]**	**[%]**
DATA	Endpoint + Spin-parity	E_0 + Jπ	MC	0.1	0.1
	Branching ratio + β^- intensity	BR + I_β	MC + Analytic	0.4	0.3
	Residual Pandemonium	RP	Analytic	2.5	2.4
	Direct β measurement	Dβ	Analytic	1.5	1.2
	Nuclides with no data	NND	Pool modeling	0.8	0.5
	Fission yield	FY	Analytic	~0.7	~0.6
	Fission fraction		Analytic	~0.7	~0.7
MODELING	Weak magnetism	WM	Model comparison	0.3	0.2
	Radiative corrections	RC	Model comparison	0.1	0.1
	Non-unique transitions	NU	Model comparison	0.4	0.4
	• Nuclear struct. calcul.	NSC		0.2	0.1
	• ξ-approximation	ξ		0.3	0.3
	Cross-section		Analytic	0.1	0.5
	TOTAL			**3.1**	**2.9**

** For a Ge target nucleus and 20 eV detector threshold*

FRACTIONAL UNCERTAINTY



⇒ Uncertainty budget dominated by RP and Dβ

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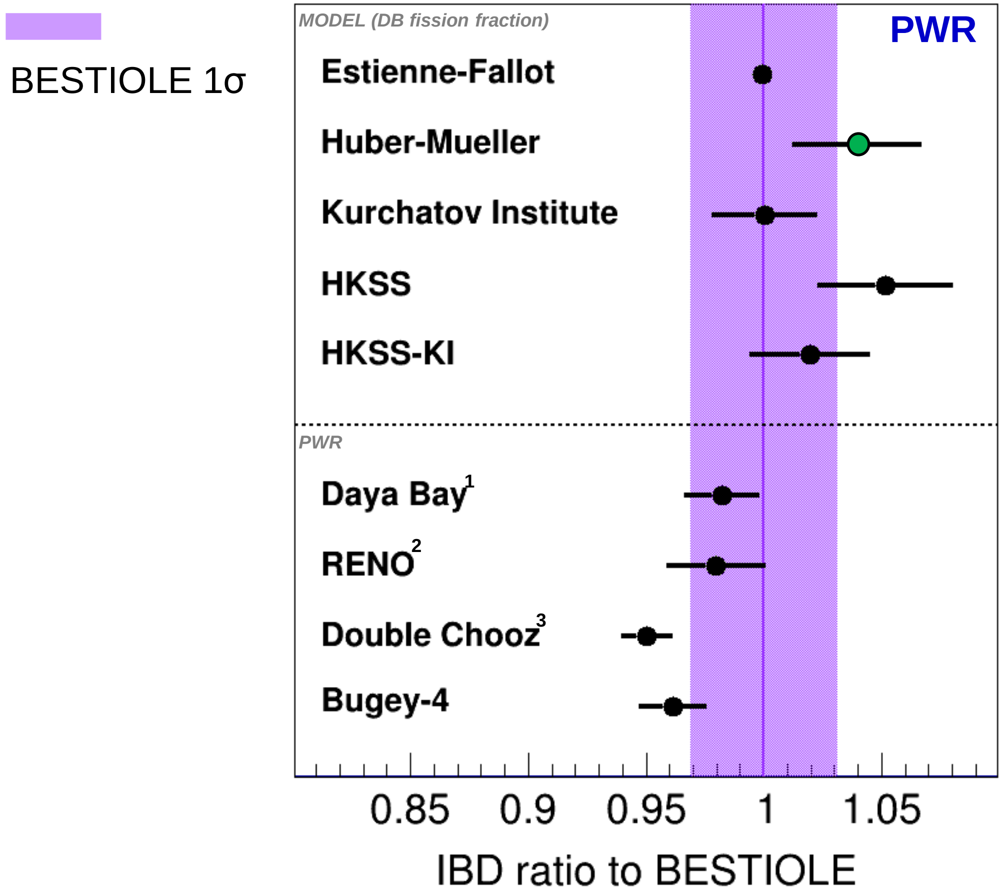
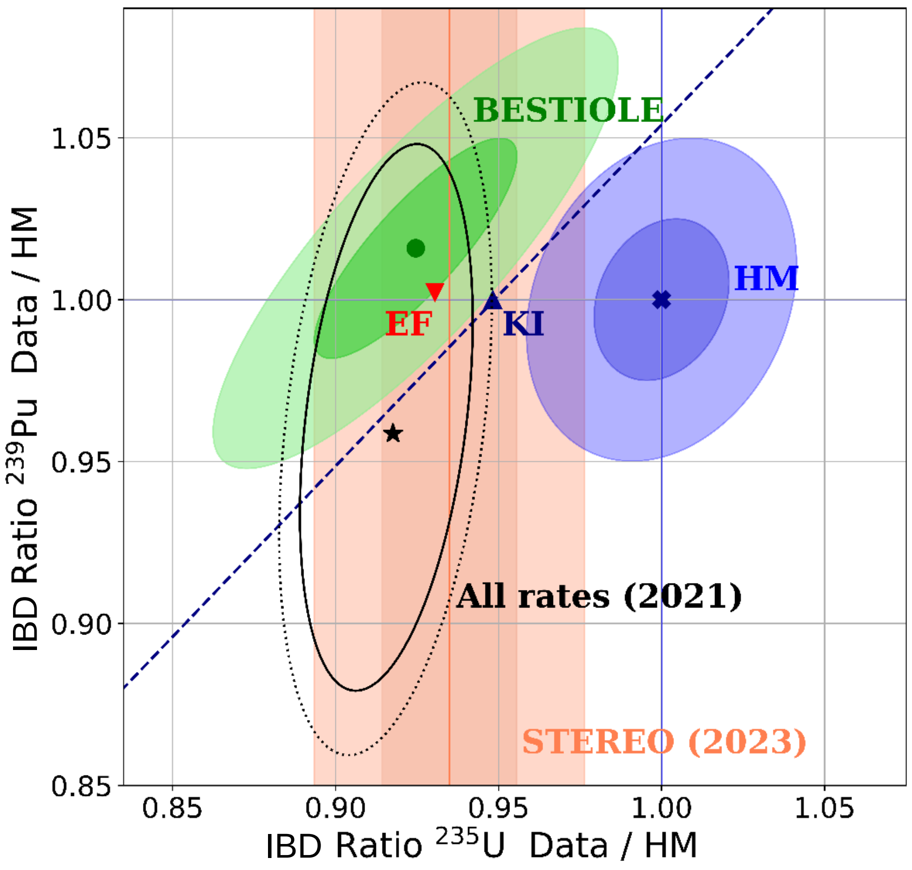
3. Comparison to experiments and models — a. Integral measurements

Predictions and Bugey-4 taken from Giunti et al., Phys. Lett. B, 829, 137054 (2022)
[1]: PRL 123, 111801 (2019) [2]: PRD 104, L111301 (2021) [3]: PRL 125, 201801 (2020)

All plots are preliminary



All rates from JHEP, No. 1, p. 167 (2021)



DB / BESTIOLE = 0.982 ± 0.015 (exp) ± 0.031 (model)

DB / HM = 0.945 ± 0.014 (exp) ± 0.024 (model)

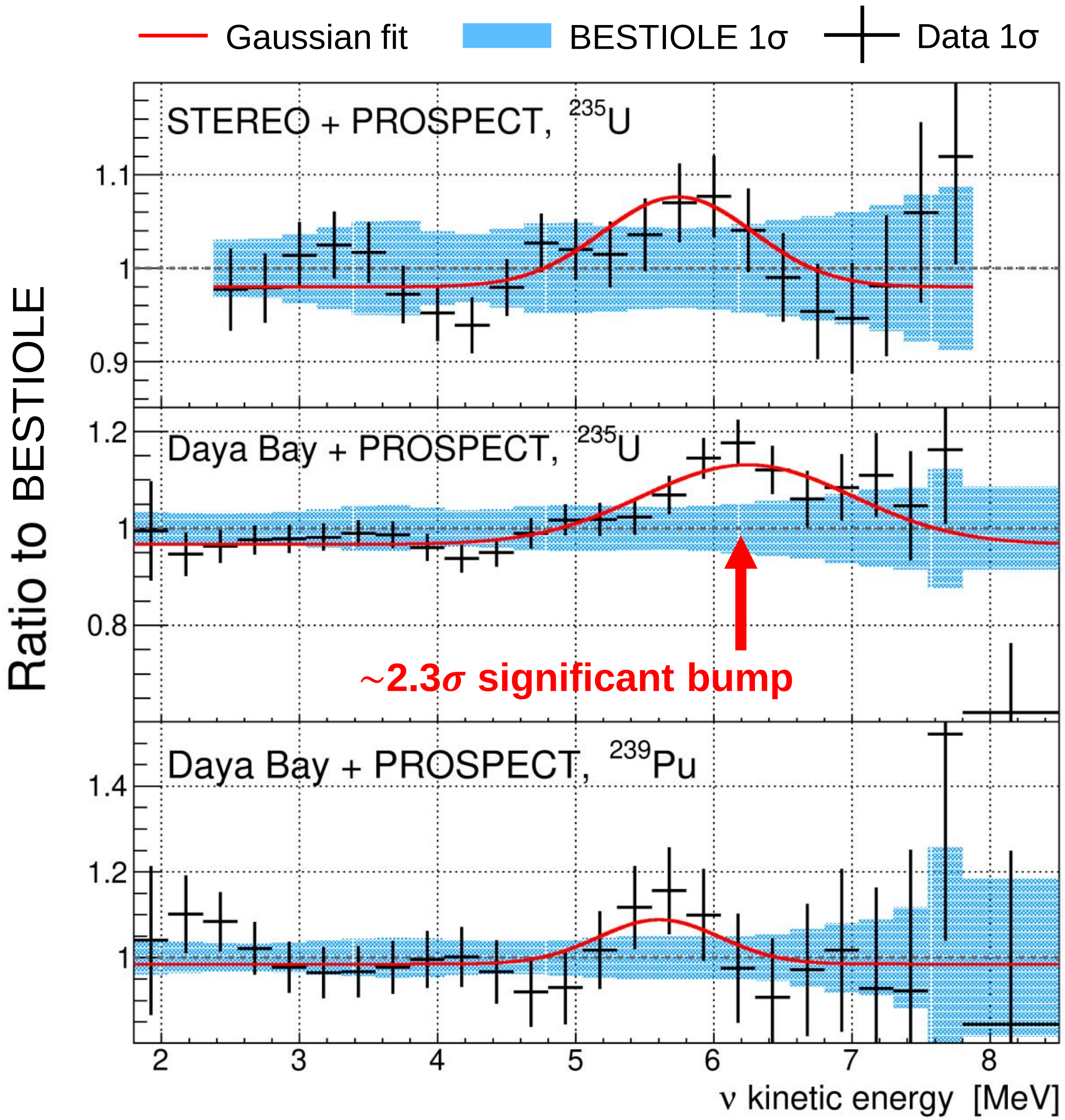
⇒ Significance at 0.5σ for BESTIOLE and 1.9σ for HM

⇒ BESTIOLE consistent within ~2σ with recent data

⇒ Discrepancy with HM favors RAA caused by ^{235}U HM flux

All plots are preliminary

RATIO OF IBD SPECTRA



- Shape only comparison, predictions normalized to data
- Gaussian distorsion not significantly favored in 5-7 MeV
  - Gaussian bump hypothesis favored by ≤2.3σ

⇒ Good agreement with experimental IBD spectra within uncertainty

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KEY POINTS OF BESTIOLE SUMMATION PREDICTION

All modeling impacts considered and quantified

- **Nuclear structure calculation** for 23 non-unique branches
  - IBD yield **decreased by (1.3 $\pm$ 0.2)%**

Quality of data checked for all data sources

- Correction for Residual Pandemonium
  - IBD yield **decreased by (2.2 $\pm$ 2.4)%**
  - Measurement needed to validate RP correction

Comprehensive uncertainty budget

- Uncertainty budget of summation model for the **first time ever**

Complete revision of summation method

- **Good overall agreement with data**
- Results favors RAA caused by ^{235}U HM flux

Final IBD and CEνNS yield uncertainty budget $\sim 3\%$

Led by RP correction

$\Rightarrow$ more Pandemonium-free data needed

$\Rightarrow$ Article coming soon with supplementary materials

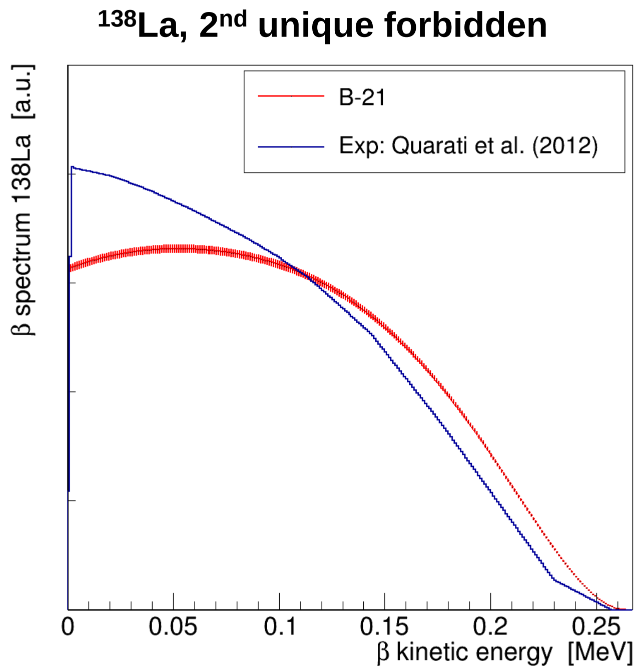
BACKUP SLIDES

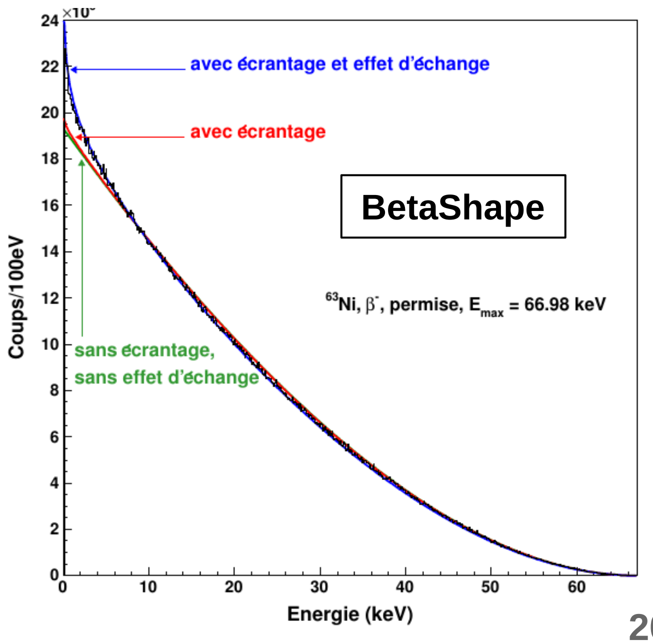
ALLOWED TRANSITION SPECTRUM CORRECTIONS

Effect	Magnitude
Phase space factor Traditional Fermi function	Unity or larger
Finite size of the nucleus Radiative corrections Shape factor Atomic exchange Atomic mismatch	10^{-1}–10^{-2}
Atomic screening Shakeup Shakeoff Isovector correction Distorted Coulomb potential due to recoil Diffuse nuclear surface Nuclear deformation Recoiling nucleus Molecular screening Molecular exchange	10^{-3}–10^{-4}
Bound state β decay Neutrino mass Forbidden decays	Smaller than 1×10^{-4}

Atomic exchange → Electron emitted into a bound state
- Rearrange the atomic electrons
- Impact the β spectrum at low energy

Atomic mismatch → Different Hamiltonian for initial and final nuclear states
- Impact the β spectrum near the endpoint energy
- Not expected to be significant for ν spectrum

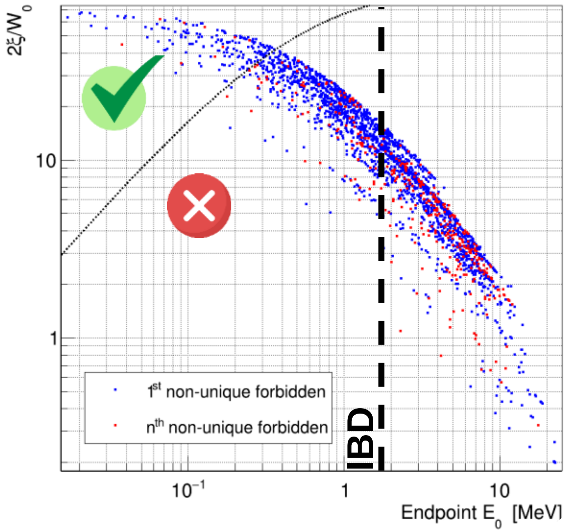


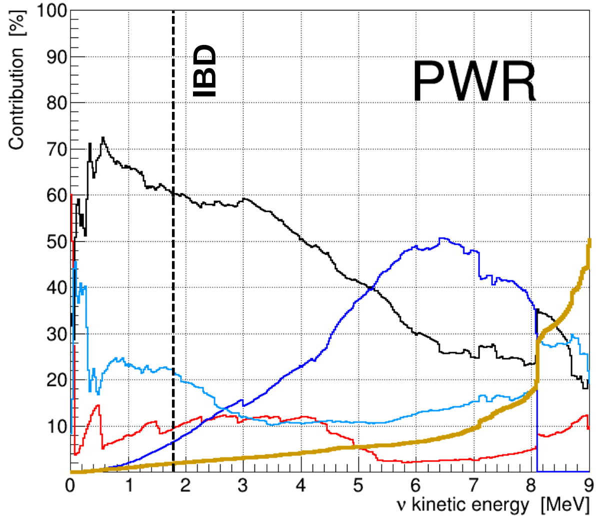


NON-UNIQUE FORBIDDEN TRANSITION MODELING WITH NUCLEAR STRUCTURE CALCULATION

$$\langle \xi_f J_f || T_\lambda || \xi_i J_i \rangle = \hat{\lambda}^{-1} \sum_{a,b} \langle a || T_\lambda || b \rangle \left\langle \xi_f J_f \left|\left| \left[c_a^\dagger \tilde{c}_b \right]_\lambda \right|\right| \xi_i J_i \right\rangle$$

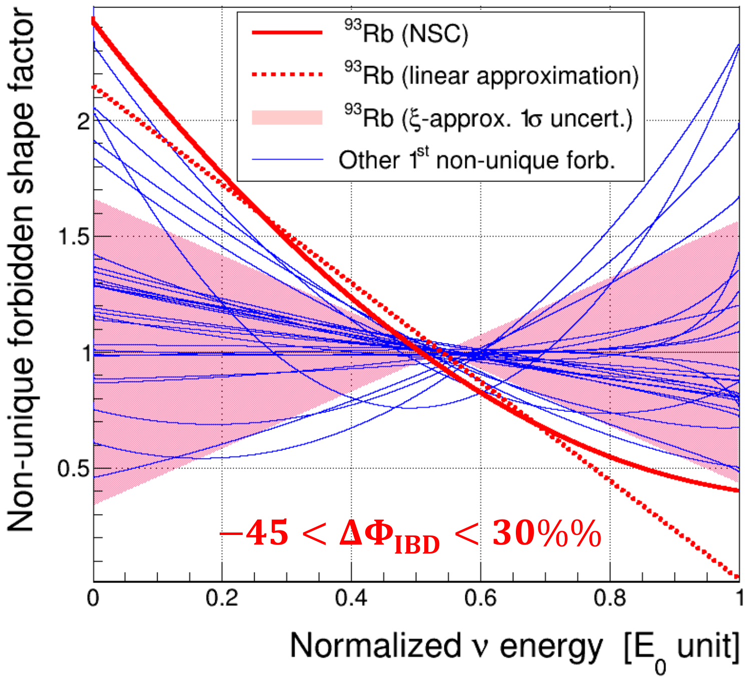
transition matrix element — tensor rank — single particle matrix element — one-body transition density





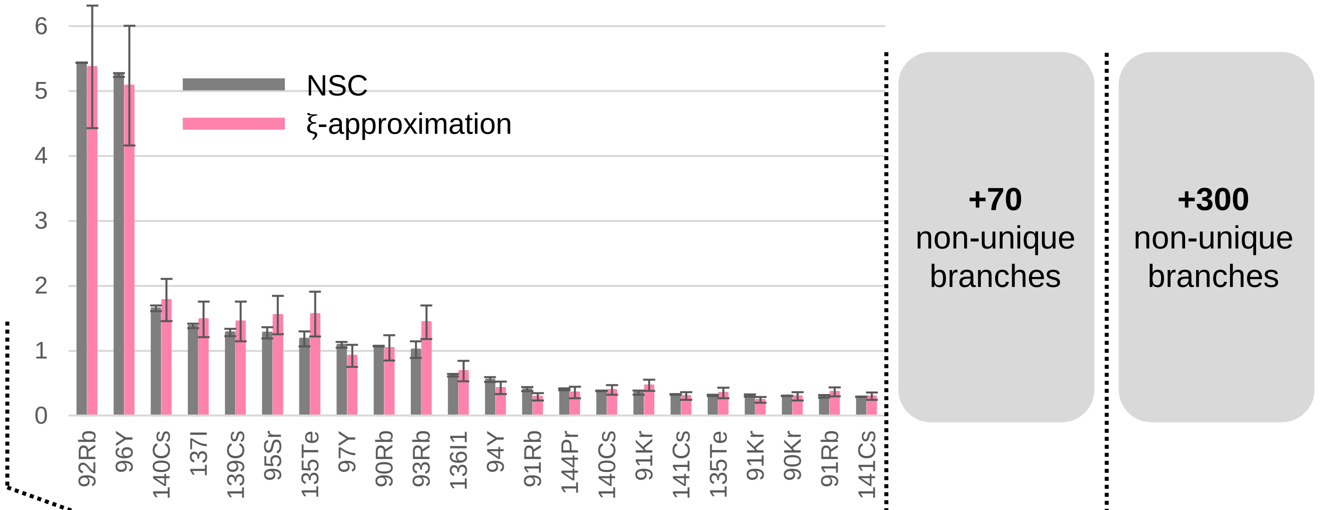
Advanced modeling:

1. Compute transition matrix element
   - One-body transition density computed with nuclear shell model
   - Sum over the superposition of all possible nucleon states
2. Use of Conserved Vector Current (CVC) hypothesis to determine the vector relativistic matrix elements
   - Coulomb displacement energy includes mismatch between initial and final nucleon wave functions
3. Free-nucleon value of the axial-vector coupling constant g_A assumed
4. Full numerical lepton current considered, without any expansion of lepton wave functions
5. Control of nuclear current expansion: all dominant contributions included over several orders of magnitude

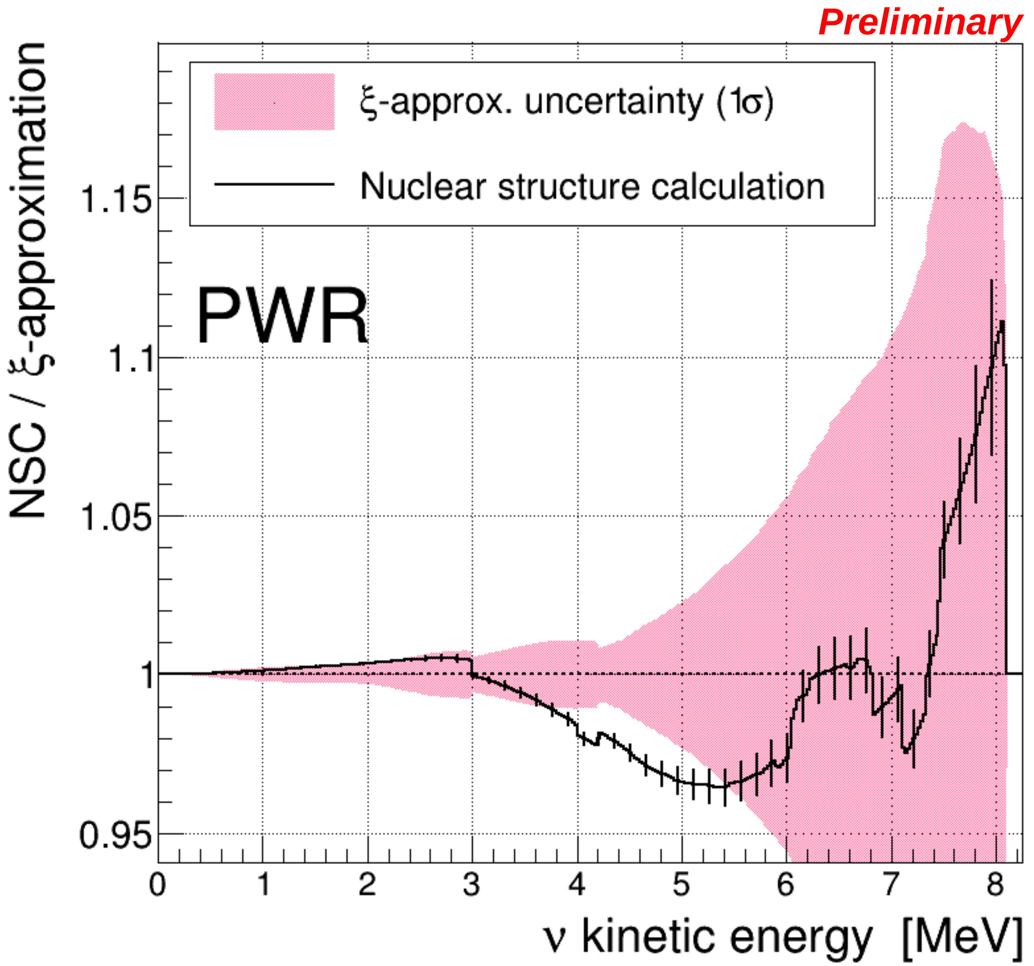


NUCLEAR STRUCTURE CALCULATION (NSC)

IBD contributions of non-unique transitions for a Chooz-like PWR



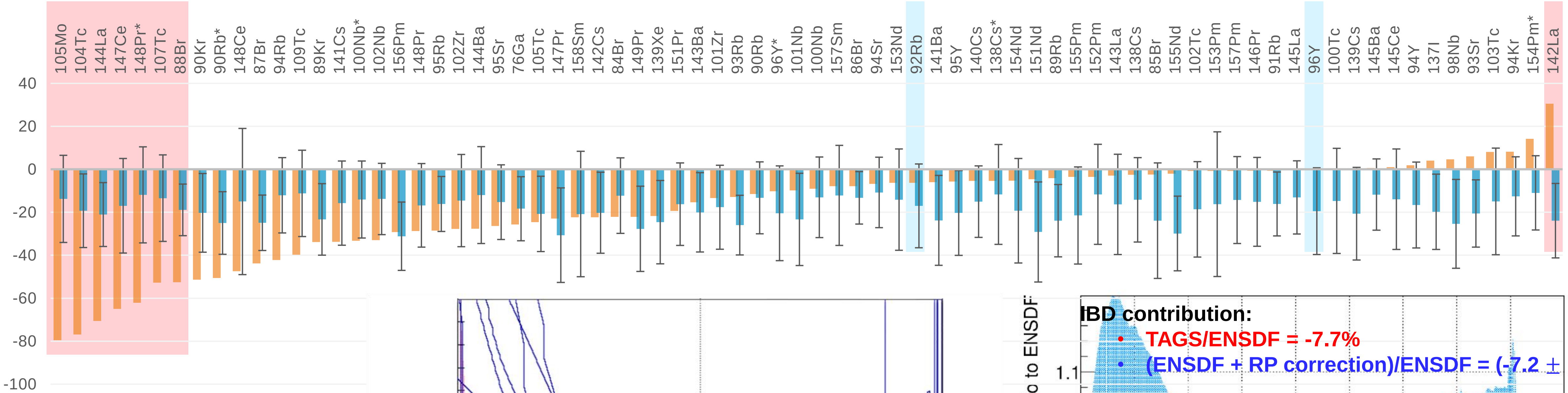
Total [%]	27	~ 35	~ 38
Non-unique [%]	69	~90	~ 99
Modeling	***Nuclear structure calculation***	***ξ-approximation***	



⇒ IBD yield decreased by (1.3 ± 0.2)% compared to full ξ-approximation

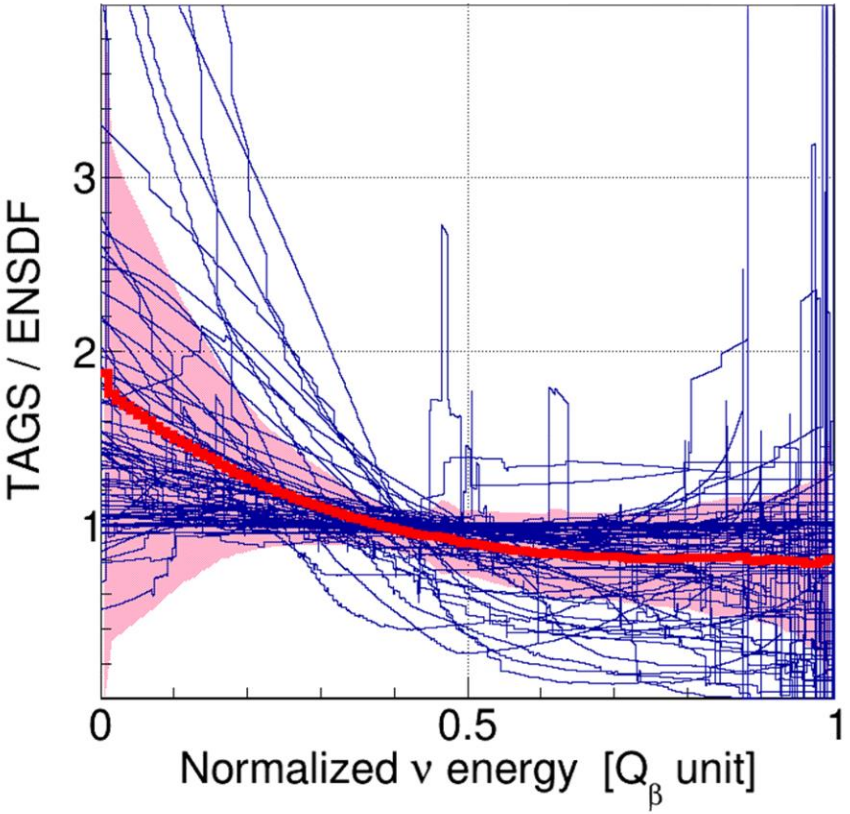
RESIDUAL PANDEMONIUM EFFECT

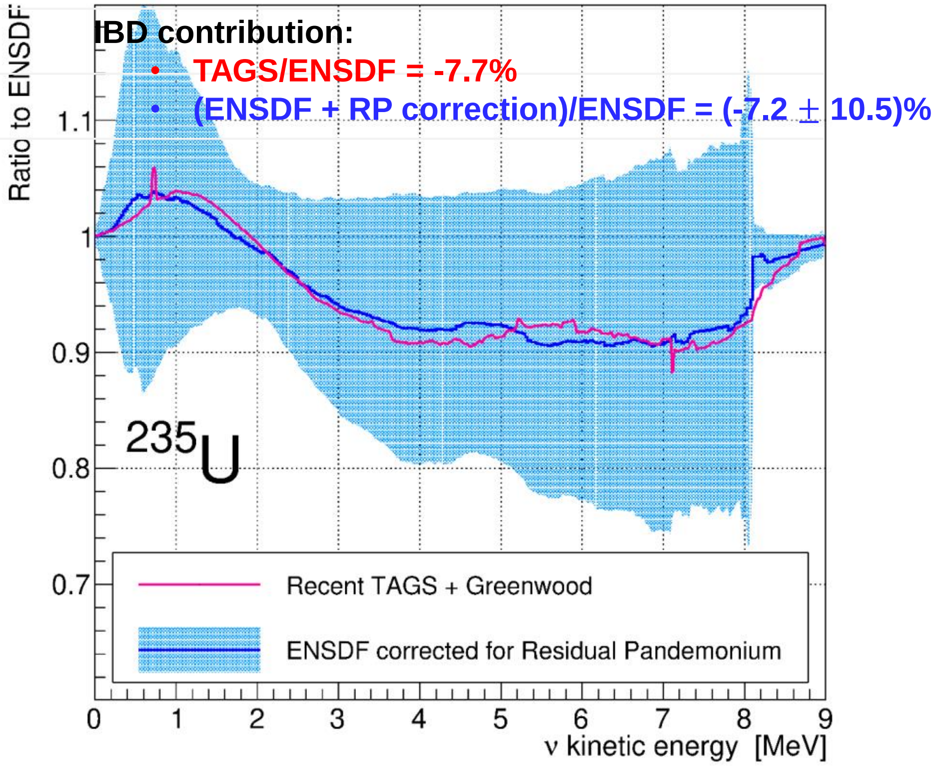
Diff > 2σ



TAGS/ENSDF - 1

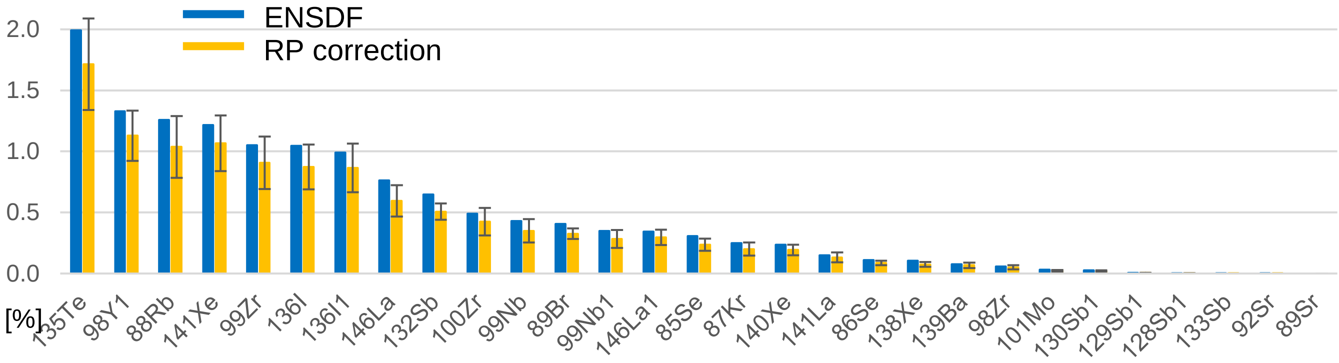
Correction/ENSDF - 1





RESIDUAL PANDEMONIUM CORRECTION FOR A PWR

- Apply RP correction on the 29 isotopes from WPEC-25
- IBD yield decreased by (2.2 $\pm$ 2.4)% with RP correction



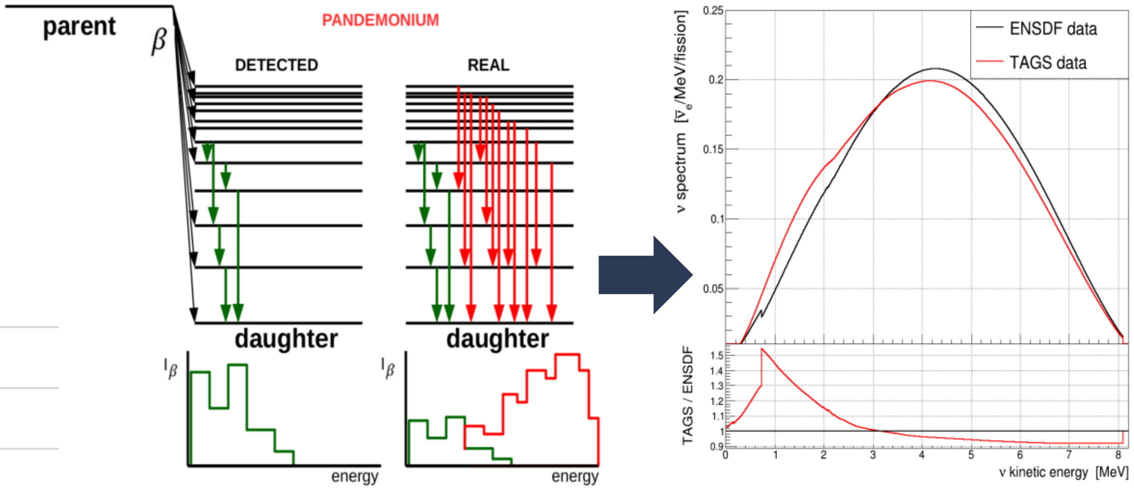
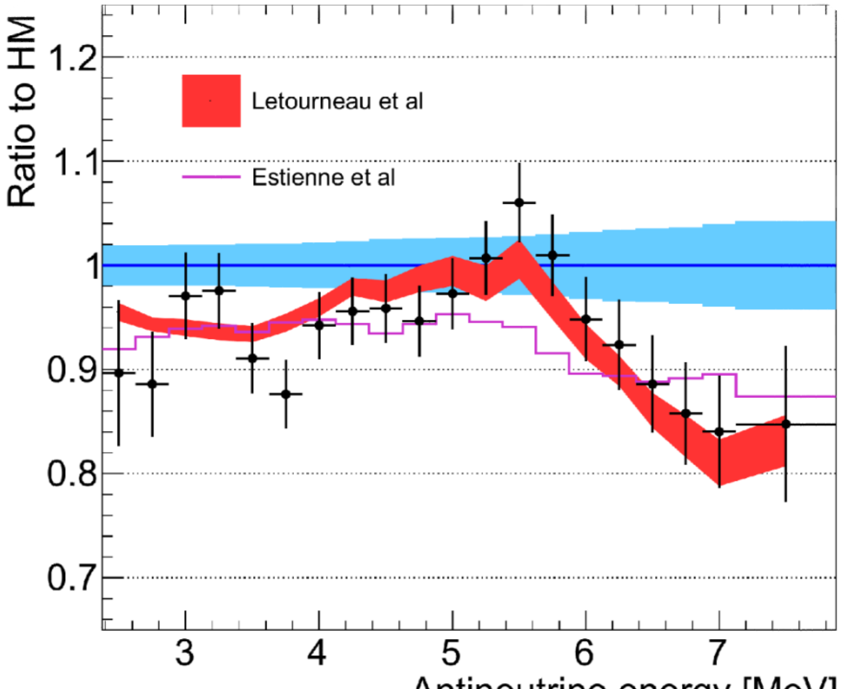


Illustration of the Pandemonium effect impact on the $\bar{\nu}_e$ spectrum of ^{92}Rb

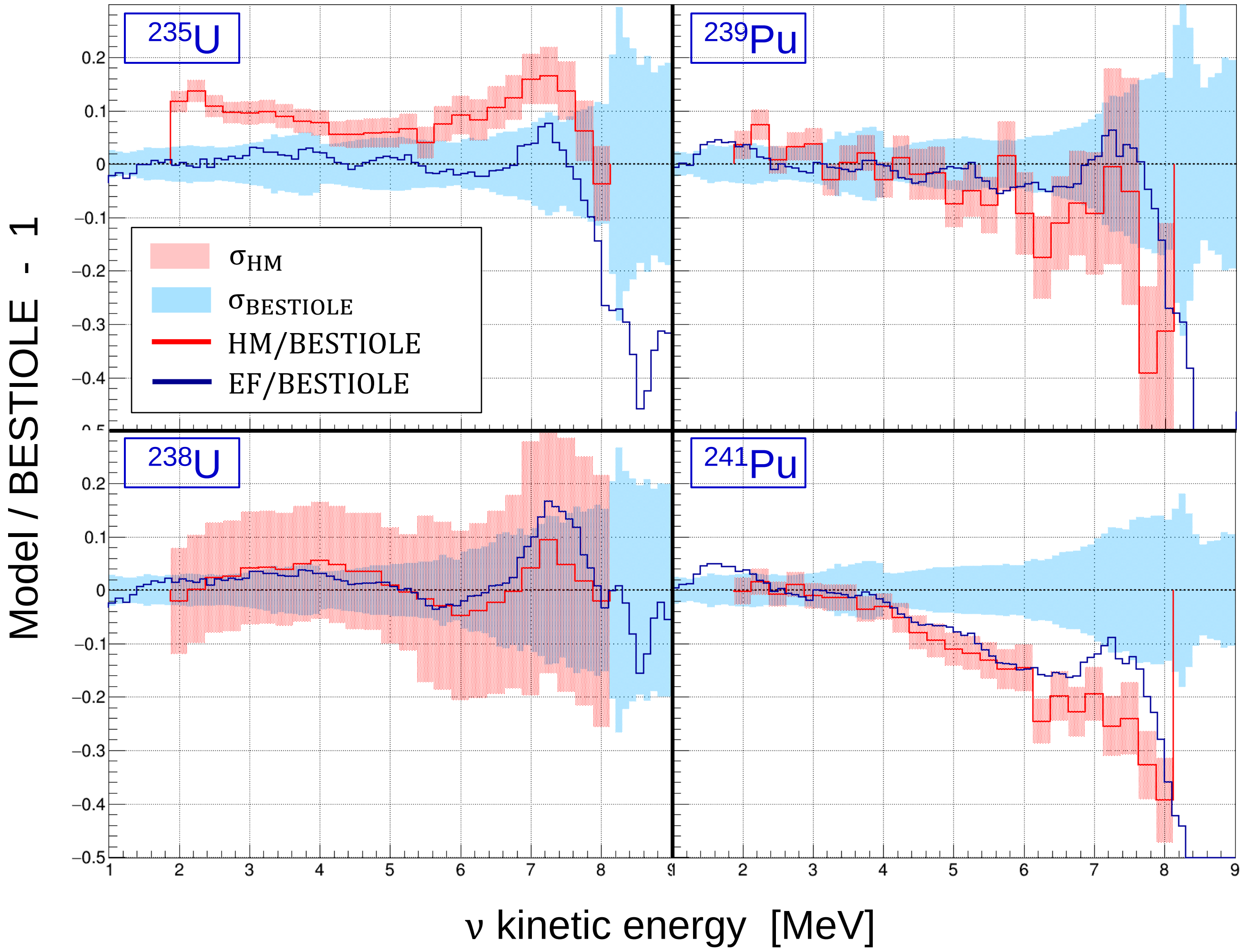
PHENOMENOLOGICAL DECAY STRENGHT MODEL

- 1 parameter Gamow-Teller strength model
- Generate missing transitions for all fission products from ENSDF
  - Correct Pandemonium effect and missing transitions
- [Letourneau et al., PRL 130, 021801 (2023)]
- Very good agreement with STEREO



arXiv:2210.07664

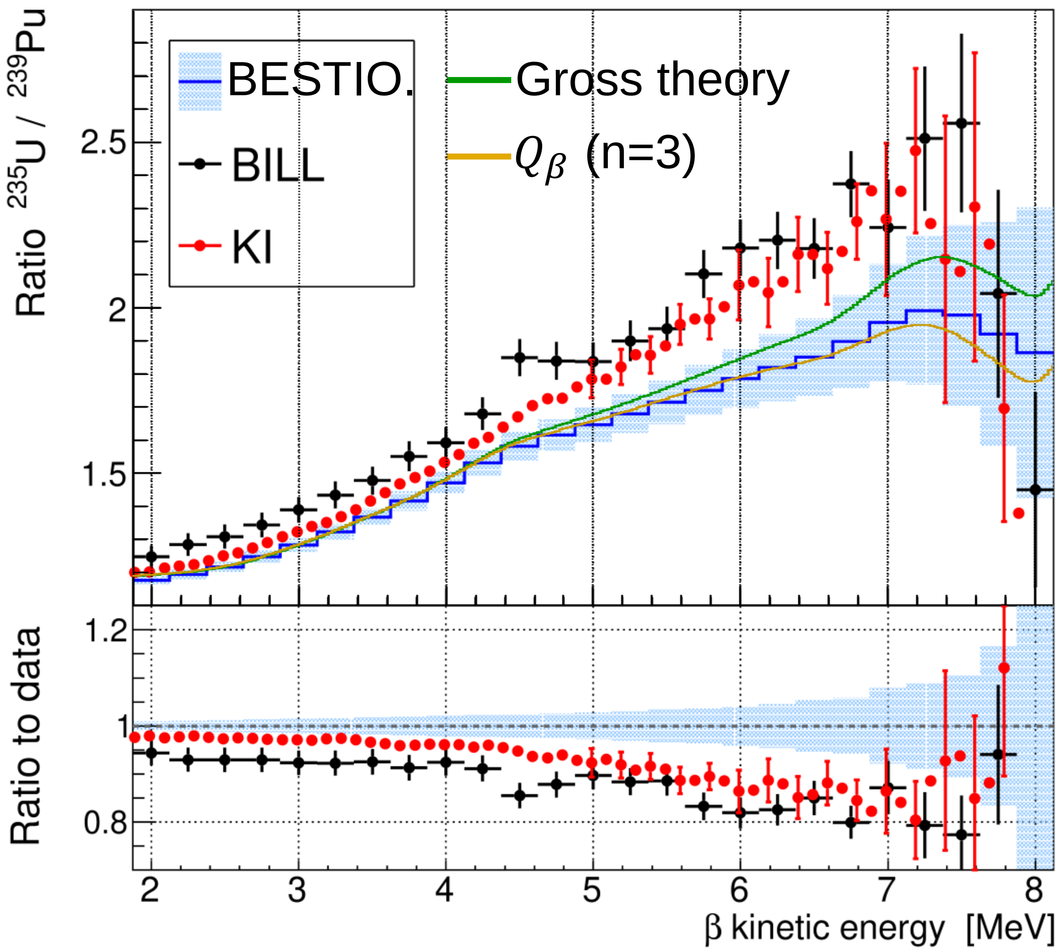
COMPARISON TO OTHER MODELS



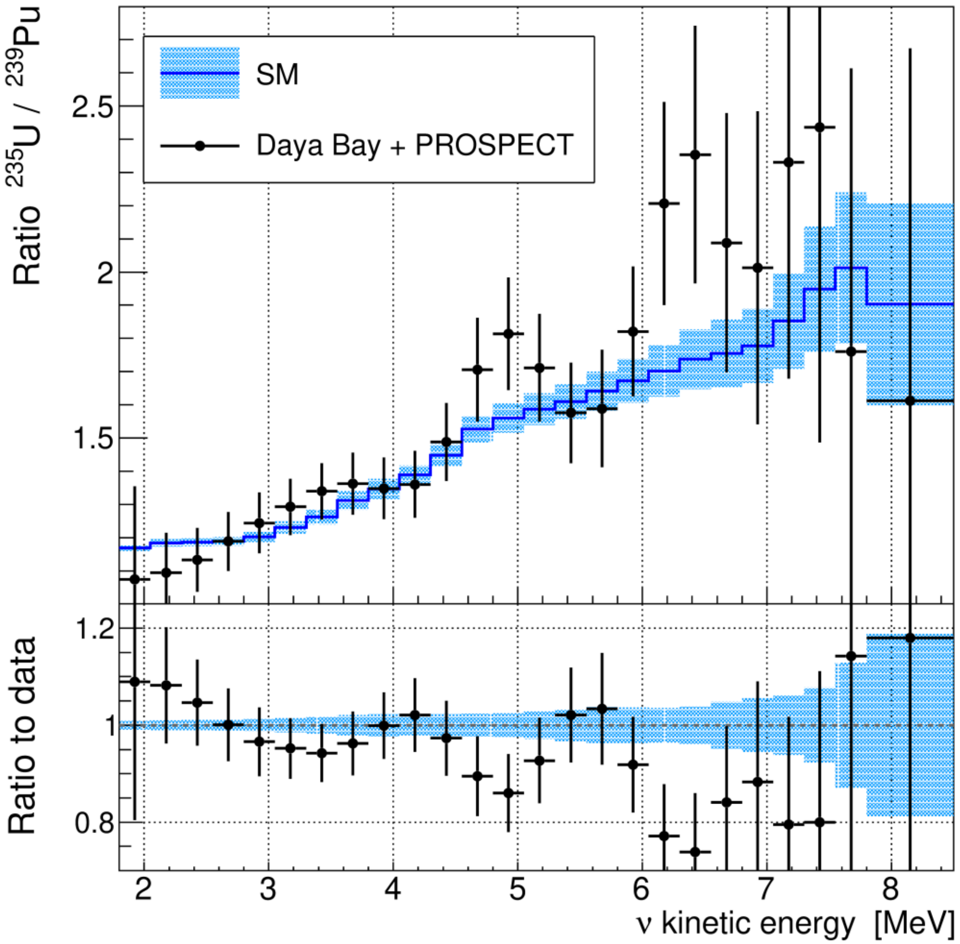
Differences with Estienne-Fallot (EF):

- FY data (JEFF-3.1.1 vs JEFF-3.3)
- NND modeling (>7 MeV)

IMPACT OF NND MODEL



^{235}U/^{239}Pu RATIO OF IBD SPECTRA



⇒ Impact of NND modeling observed >6 MeV, important >7 MeV