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Revised summation calculations of reactor antineutrino fluxes and spectra

Lorenzo Périssé, Xavier Mougeot, Anthony Onillon, Matthieu Vivier

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DE LA RECHERCHE À L'INDUSTRIE



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The NEVFAR project:

New Evaluation of ν Fluxes At Reactors

Revisiting the summation calculation of reactor antineutrino spectra

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[International Conference on the Physics of the Two Infinities](#)

27–30 mars 2023, Kyoto

^(a)Now at ILANCE (CNRS/UTokyo), Japan

^(b)Now at TUM, Germany

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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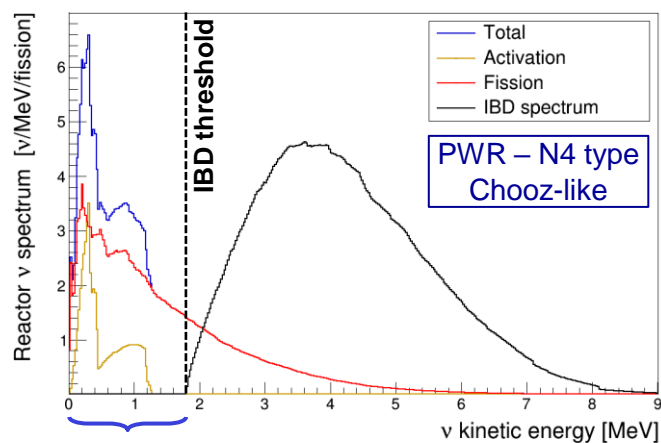
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PRESSURIZED WATER REACTOR (PWR)

- Fuel: lowly enriched uranium, ^{238}U + 3-5% ^{235}U
- High power: $\sim 3 - 4 \text{ GW}_{\text{th}}$
- Close reactor design & fuel contents for all PWR

⇒ Similar $\bar{\nu}_e$ spectra



~75% $\bar{\nu}_e$: 76% fission + 24% capture

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]

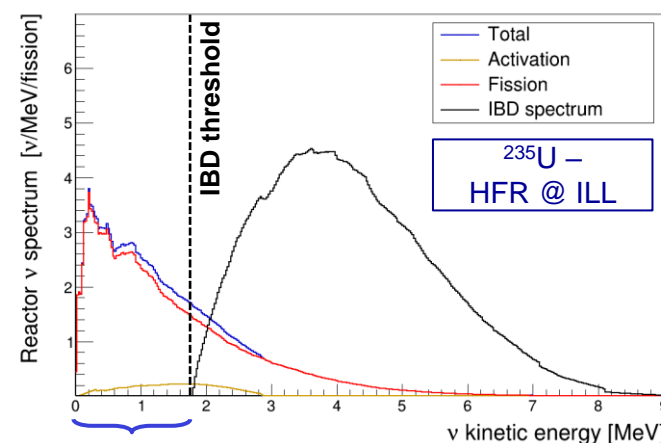
^{239}U	0.6	} ~17% $\Phi_{\bar{\nu}_e}$
^{239}Np	0.6	

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

RESEARCH REACTOR

- Fuel: highly enriched uranium, $>20\%$ ^{235}U
- Low power : $\sim 0.1 \text{ kW}_{\text{th}} - 100 \text{ MW}_{\text{th}}$ but very short baseline accessible
- Wide array of designs & fuel contents + reactor specific structural material activation

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



~69% $\bar{\nu}_e$: 94% fission + 6% capture

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 ($\sim 93\%$ ^{235}U) over a 50-day core cycle

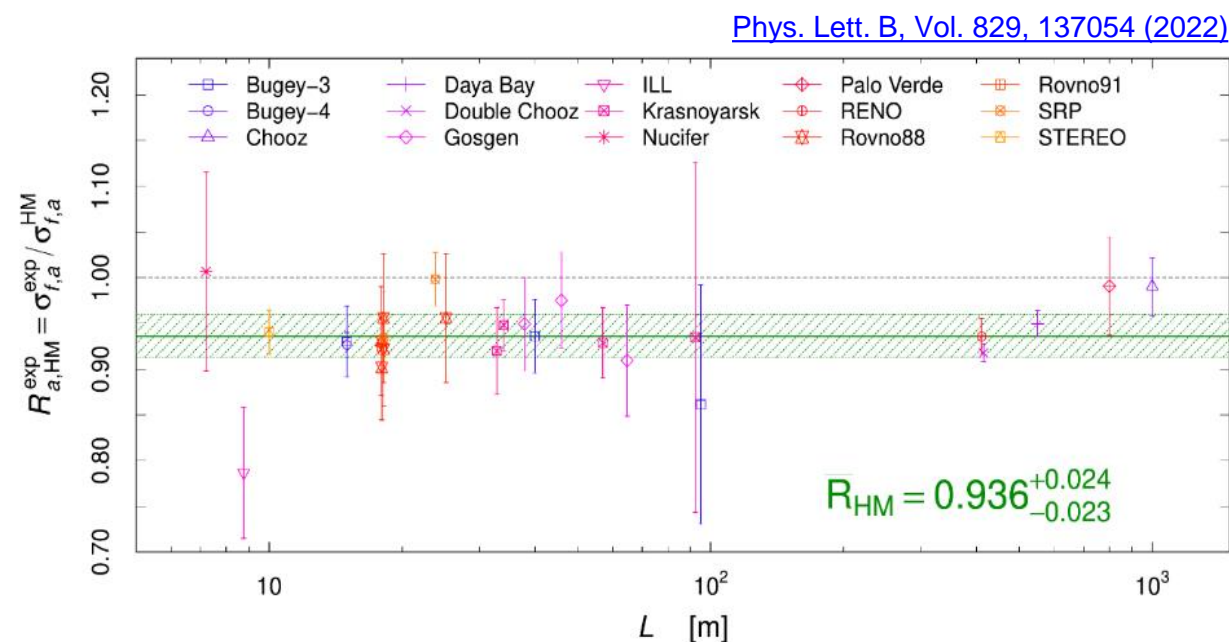
⇒ $\bar{\nu}_e$ contribution depends on reactor type and changes with time

⇒ Prediction needed for fission and activation spectra

REACTOR ANTINEUTRINO ANOMALY (RAA)

[Phys. Rev. D 83, 073006 \(2011\)](#)

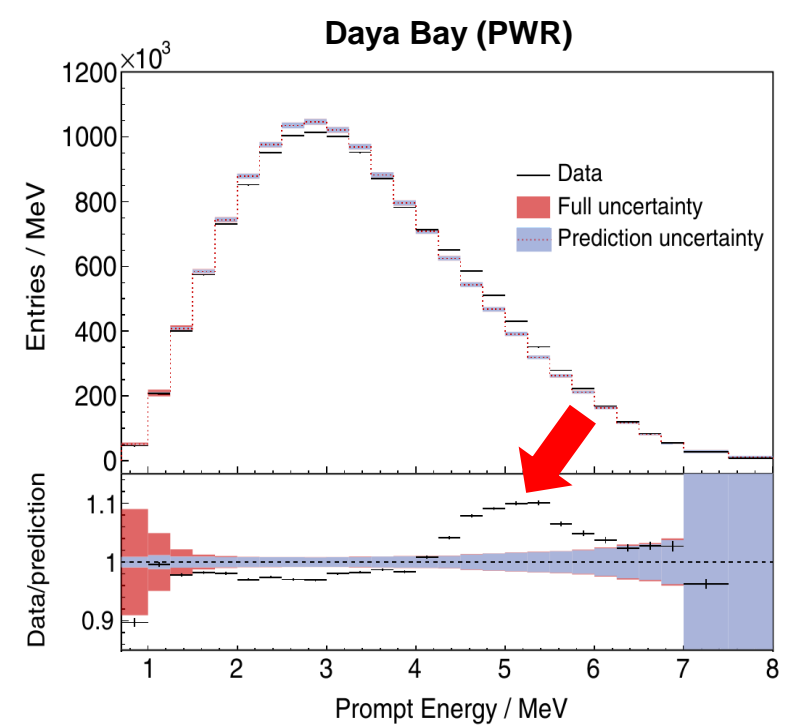
- Systematic measured **IBD rate deficit** compared to Huber-Mueller model
 - ▶ Observed in more than 20 reactor experiments
 - ▶ Confirmed in all recent reactor experiments at PWR and research reactors
- Ratio of measured over predicted IBD rate: $0.936^{+0.024}_{-0.023}$
 - ▶ Statistical significance: 2.5σ
- RAA possible origins
 - ▶ Experimental bias *Unlikely*
 - ▶ New physics (sterile neutrino)
 - ▶ **Mismodeling / underestimation of $\bar{\nu}_e$ spectrum uncertainty**



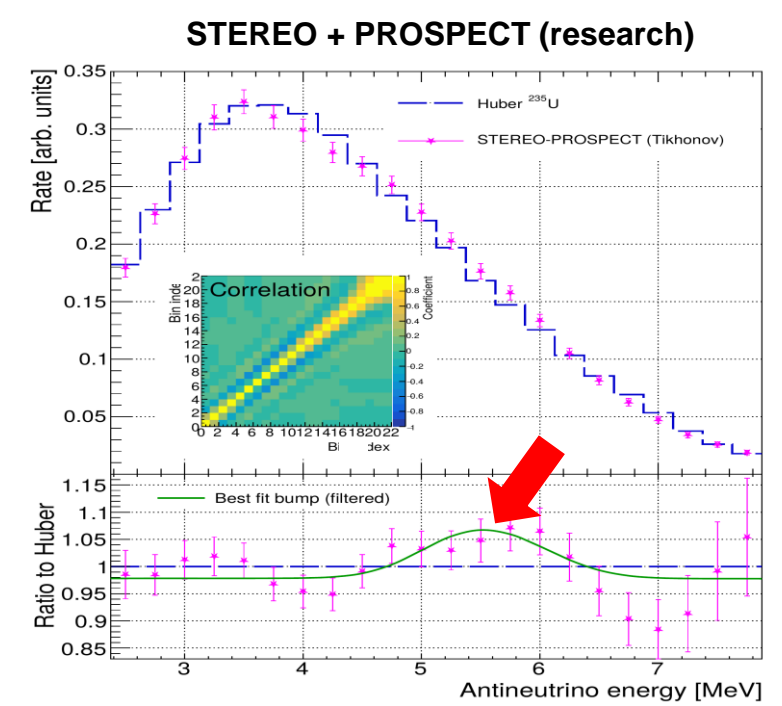
SHAPE ANOMALY

- ~8-10% difference between predictions 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) ?**



[Phys. Rev. Lett. 123, 111801 \(2019\)](https://arxiv.org/abs/1808.07409)



[arXiv:2107.03371](https://arxiv.org/abs/2107.03371)

CONVERSION METHOD

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



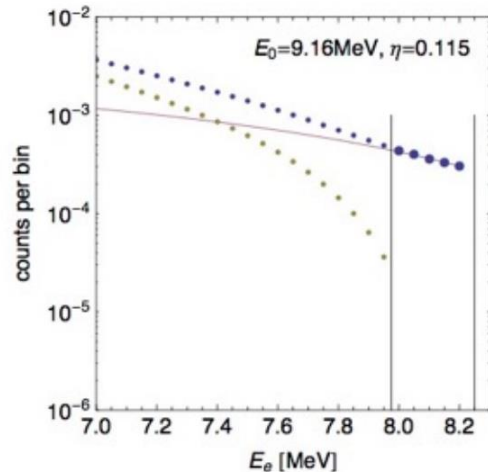
PROS

- 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 questioned → 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 \forall energy, \forall β emitter
 - ▶ CEvNS
- 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

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

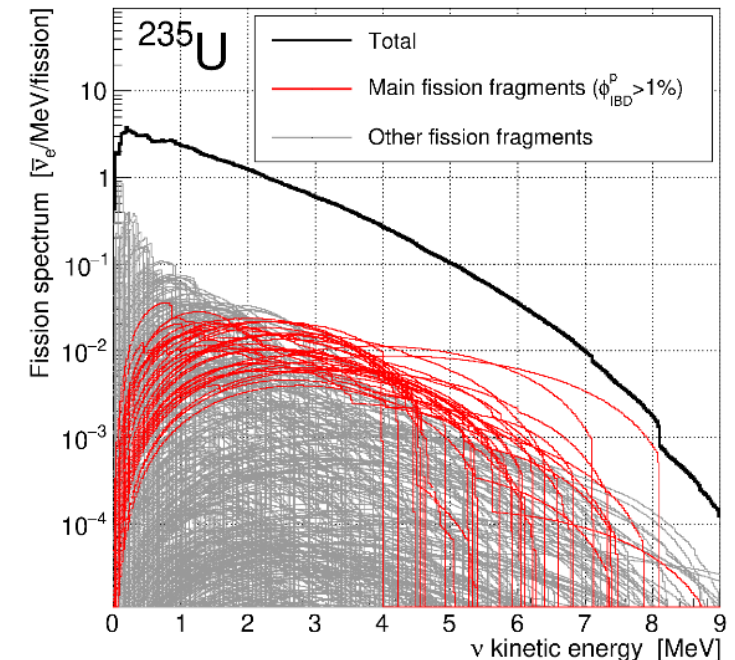
$$S_\nu(E) = S_\beta(E_0 - E)$$

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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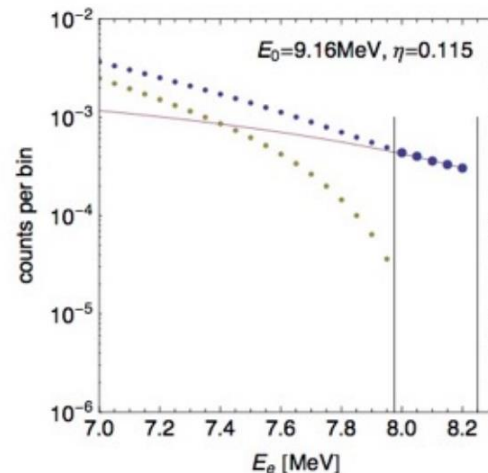
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CONS

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

\Rightarrow **Reliable summation method required for multiple purposes**

THE NE ν FAR 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 incompleteness 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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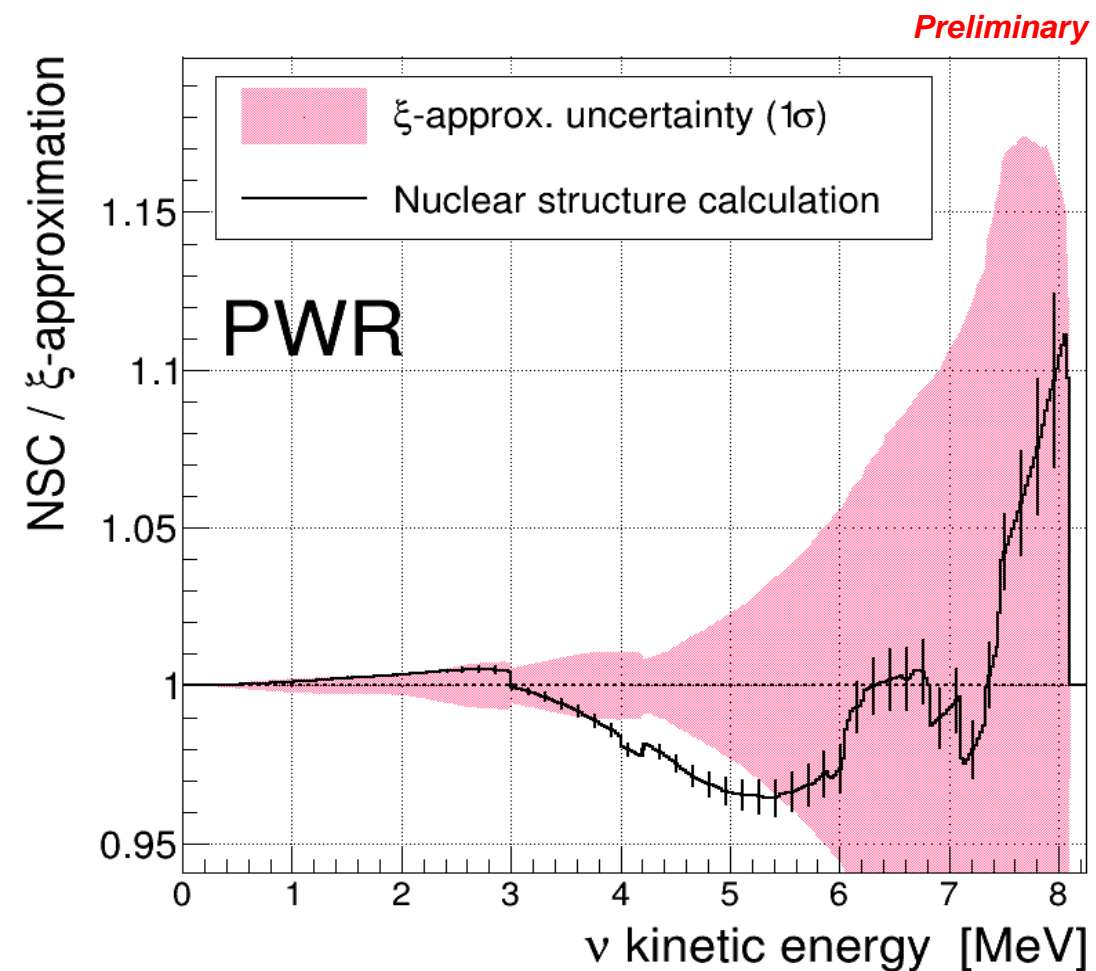
4. **Conclusion & perspectives**

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

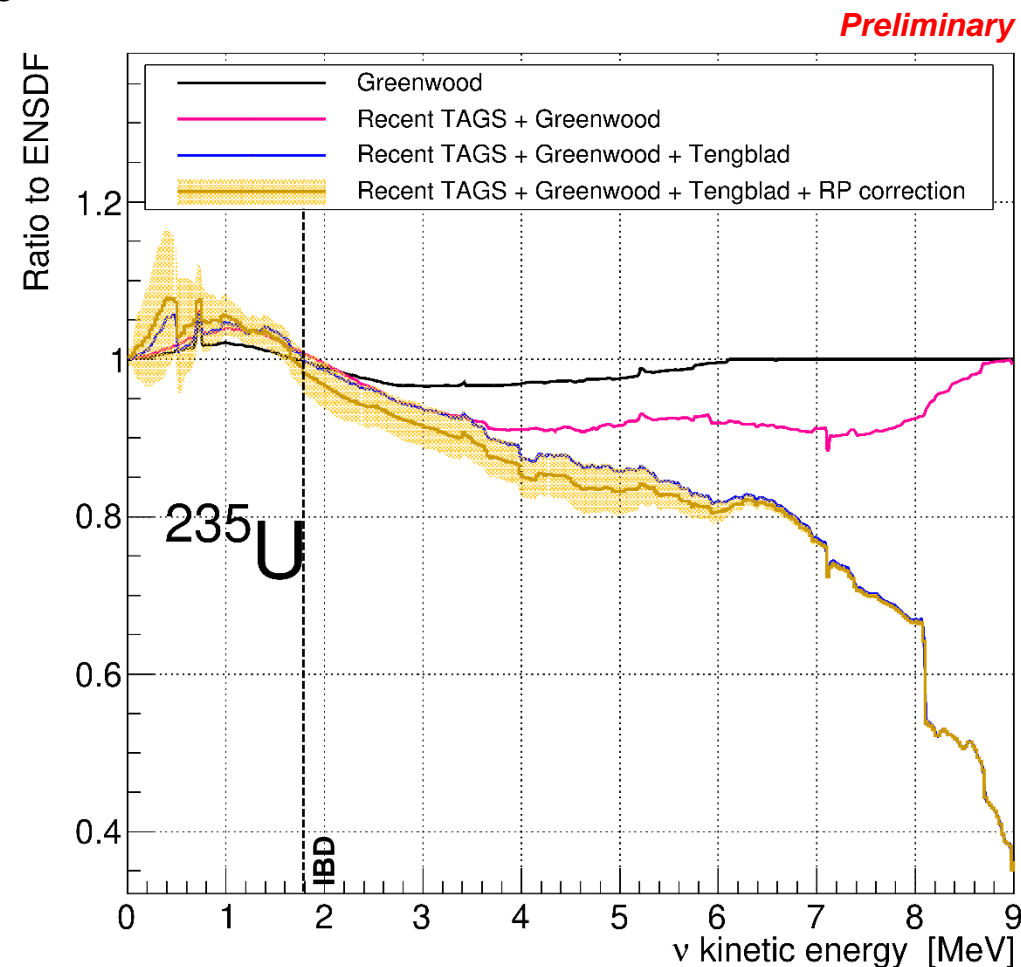
~27% of IBD yield
~22% of CE ν NS yield

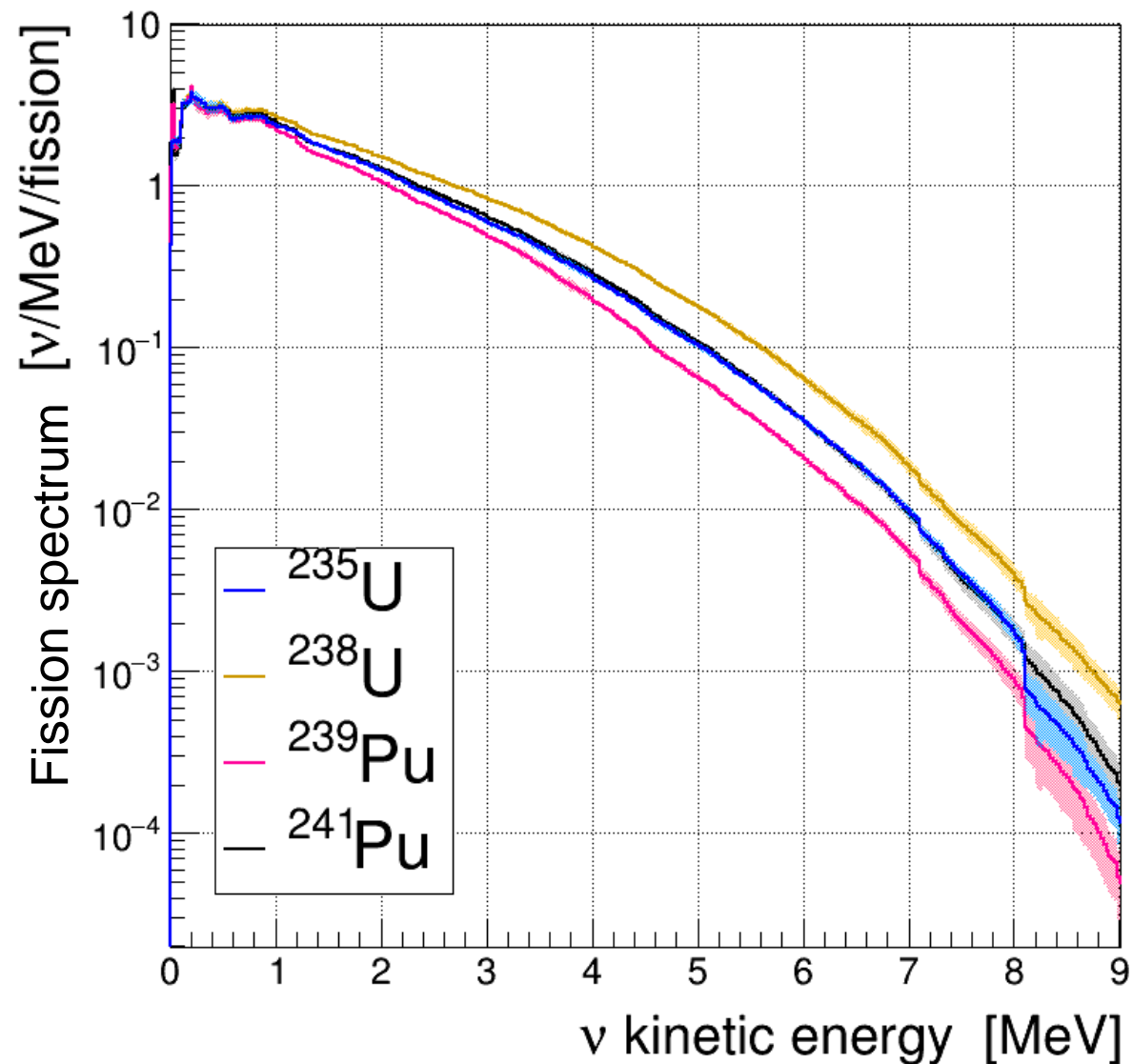
⇒ Using NSC decreases IBD yield by $(1.3 \pm 0.2)\%$



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 CE ν NS 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 CE ν NS yields





IBD yields (10^{-43} cm²/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} cm²/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

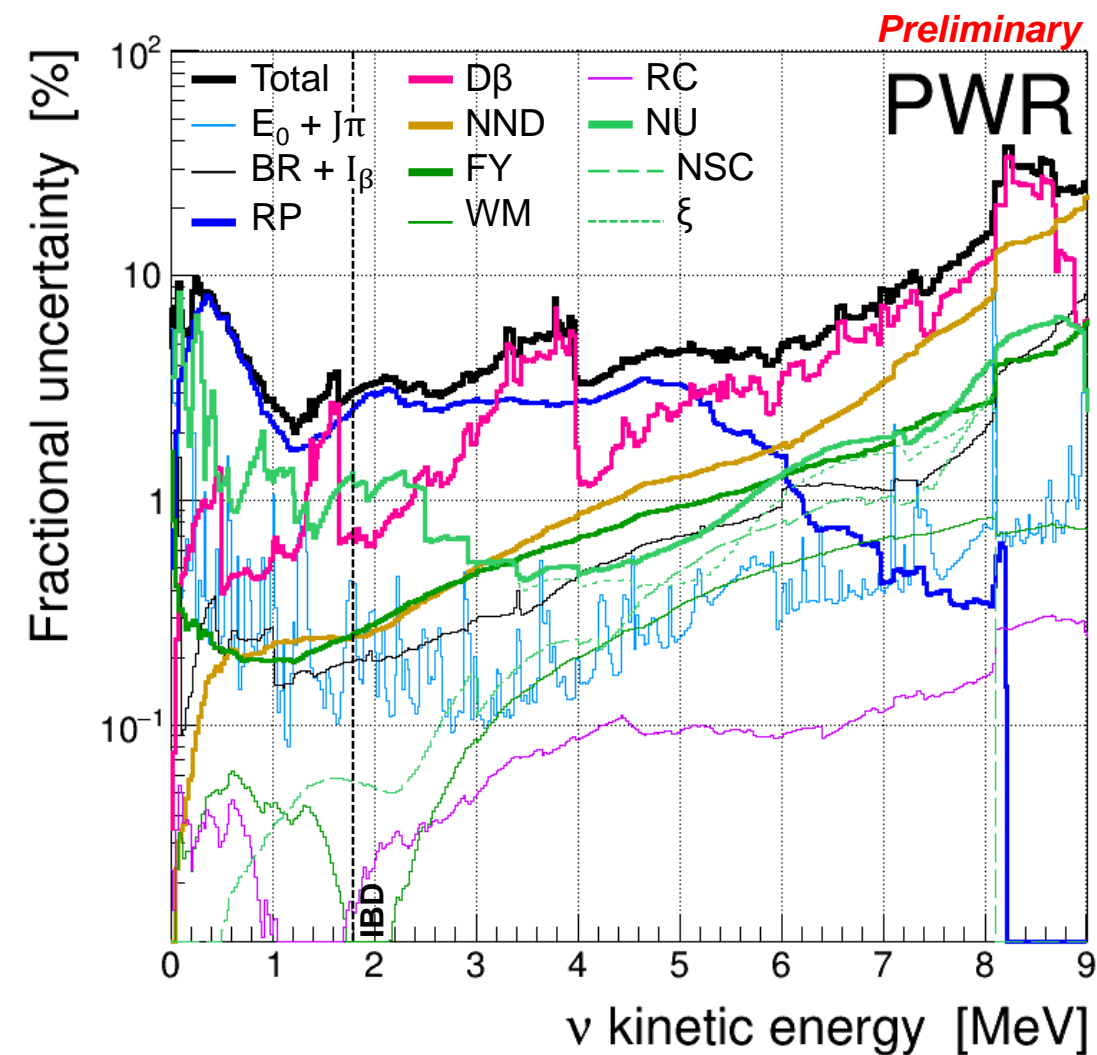
⇒ CEνNS yield uncertainty ~3%

NORMALIZATION UNCERTAINTY

PWR			$\langle\sigma_{\text{IBD}}\rangle$	$\langle\sigma_{\text{CEvNS}}\rangle^*$	
[10^{-43} cm ² /fission]			6.08	1090	
Uncertainty	Abbrev.	Method	[%]	[%]	
DATA	Endpoint + Spin-parity	$E_0 + J\pi$	MC	0.1	0.1
	Branching ratio + β^- intensity	$\text{BR} + I_\beta$	MC + Analytic	0.4	0.3
	Residual Pandemonium	RP	Analytic	2.5	2.4
	Direct β measurement	$D\beta$	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 $D\beta$

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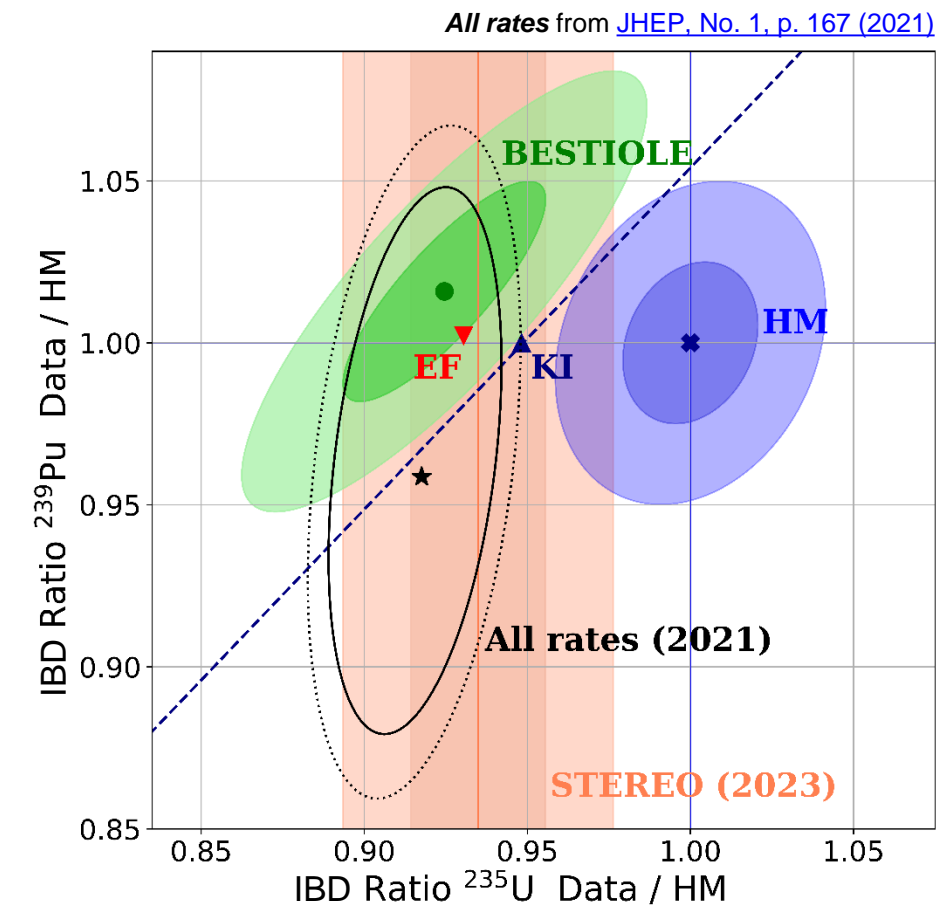
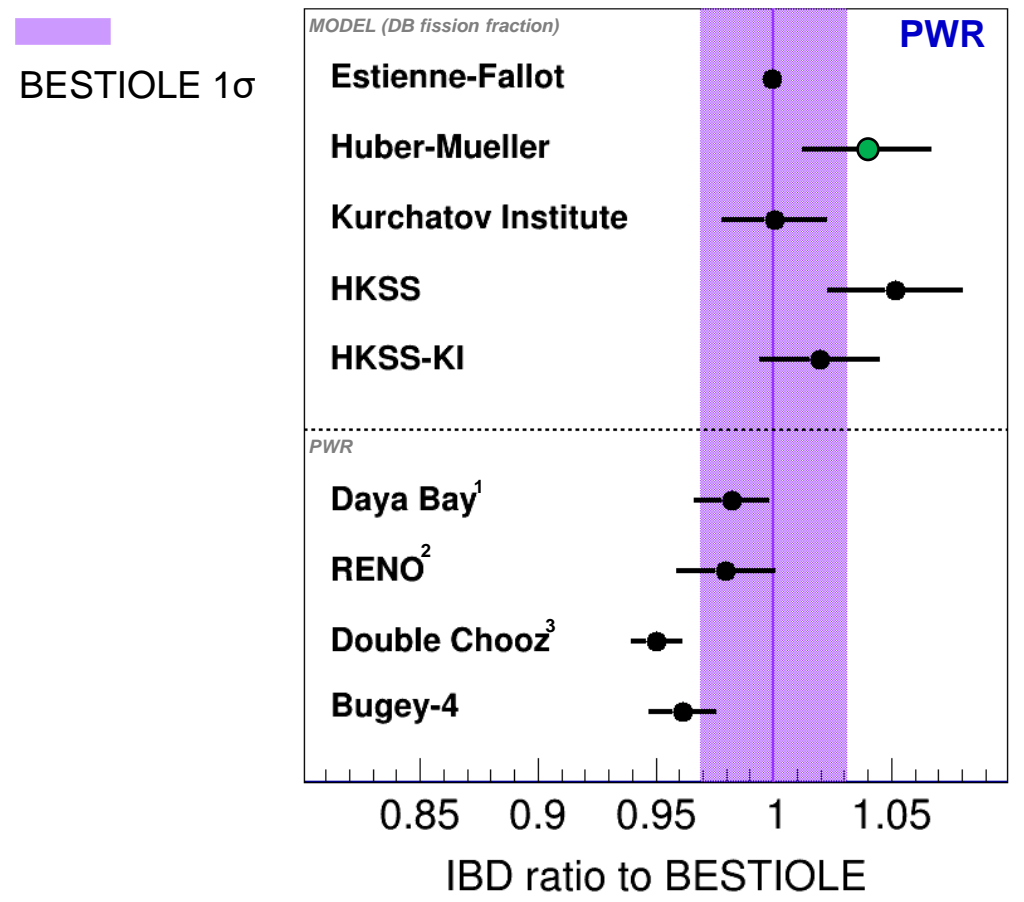
3. **Comparison to experiments and models**
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 - b. Spectrum shape

4. **Conclusion & perspectives**

3. Comparison to experiments and models a. Integral measurements

All plots are preliminary

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 \(2020\)](#)



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

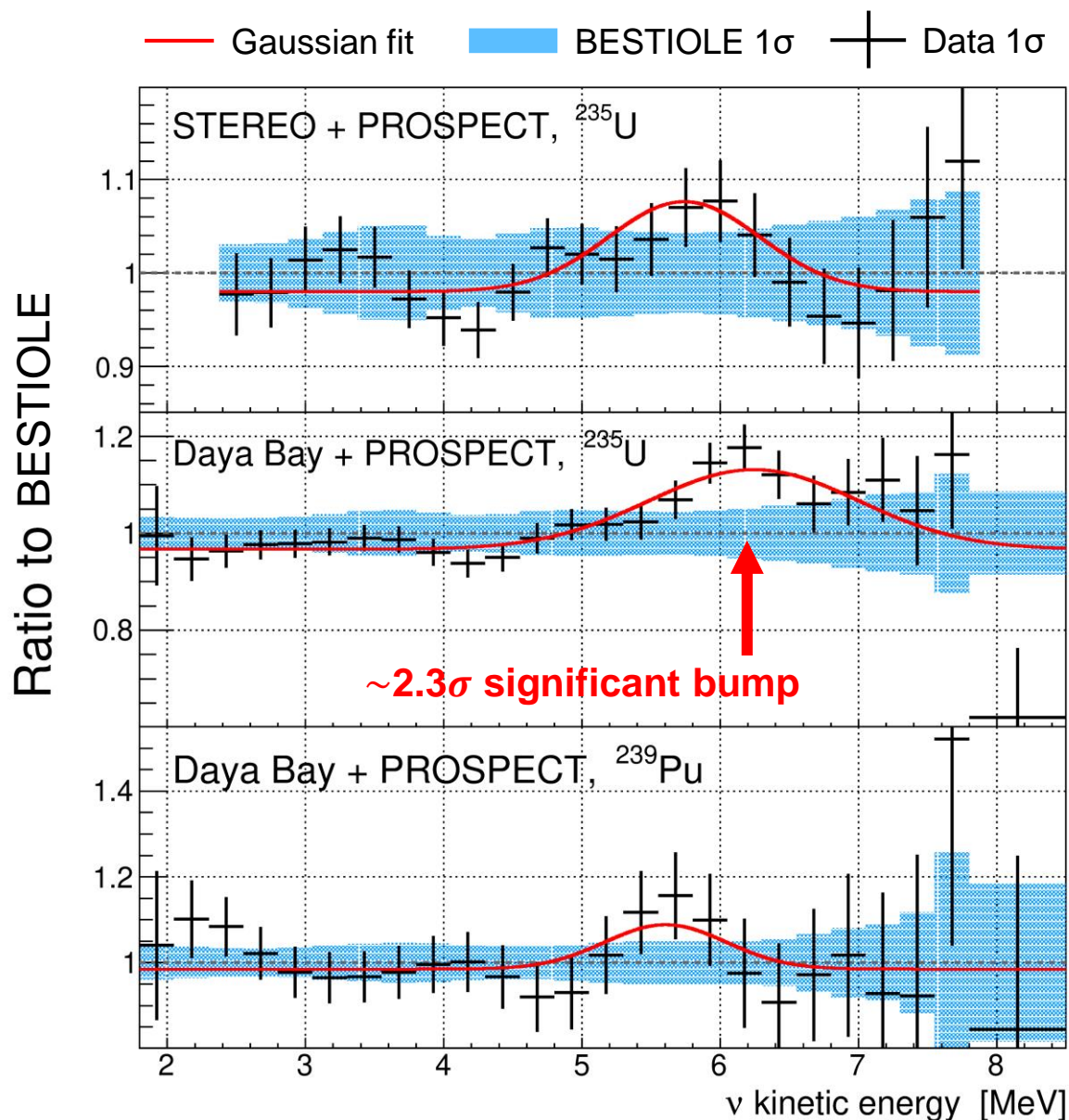
DB / HM = 0.945 ± 0.014 (exp) ± 0.024 (model)

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

⇒ **BESTIOLE consistent within $\sim 2\sigma$ with recent data**

⇒ **Discrepancy with HM favors RAA caused by ²³⁵U HM flux**

RATIO OF IBD SPECTRA



- Shape only comparison, predictions normalized to data
- Gaussian distortion not significantly favored in 5-7 MeV
 - Gaussian bump hypothesis favored by $\leq 2.3\sigma$

\Rightarrow 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 $\text{CE}_{\nu\text{NS}}$ 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}

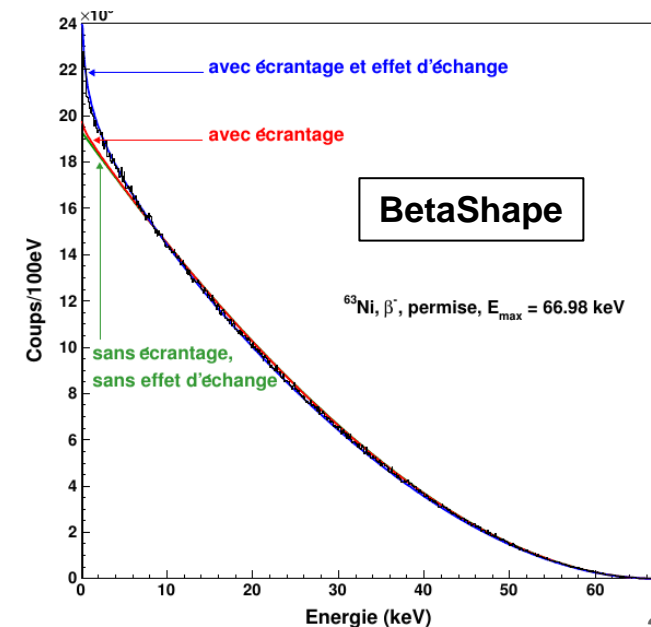
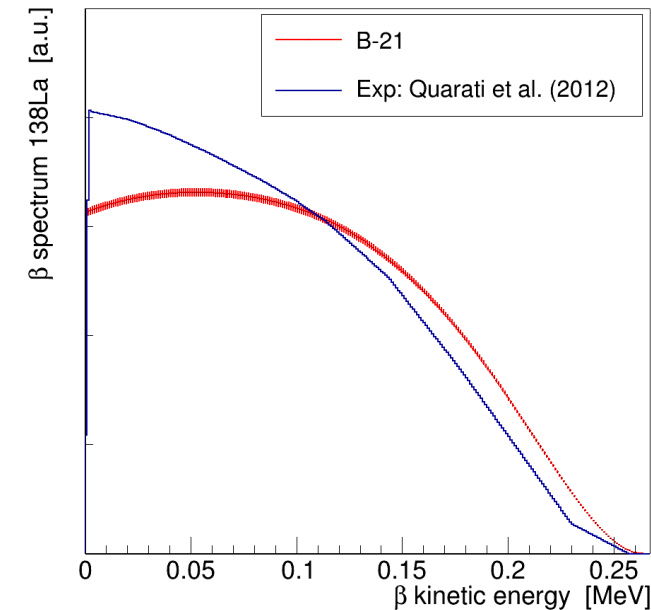
Electron emitted into a bound state

- Rearrange the atomic electrons
- Impact the β spectrum at low energy

Different Hamiltonian for initial and final nuclear states

- Impact the β spectrum near the endpoint energy
- Not expected to be significant for ν spectrum

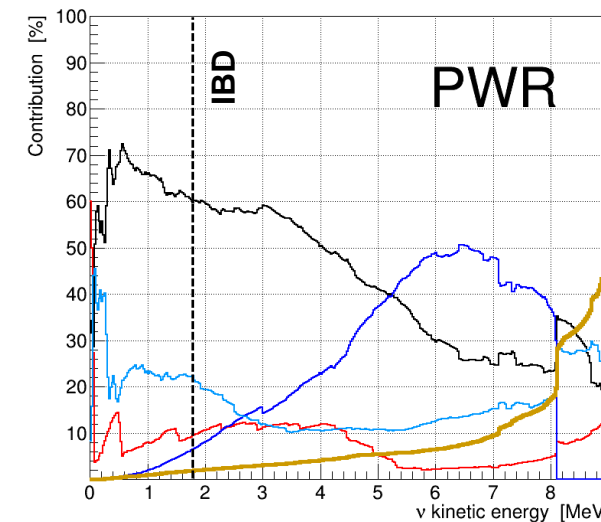
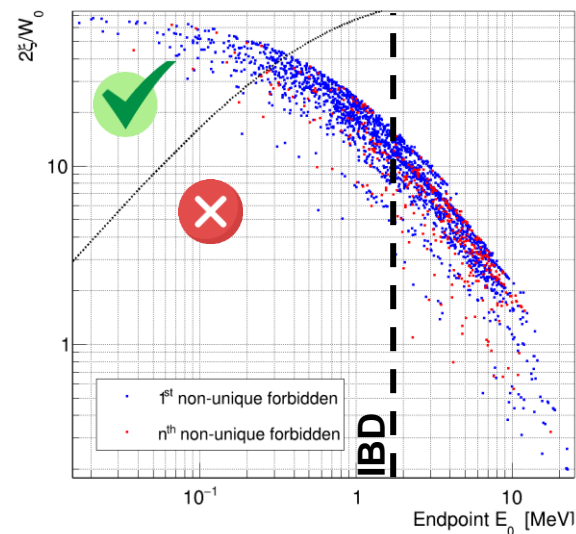
¹³⁸La, 2nd unique forbidden



NON-UNIQUE FORBIDDEN TRANSITION MODELING WITH NUCLEAR STRUCTURE CALCULATION

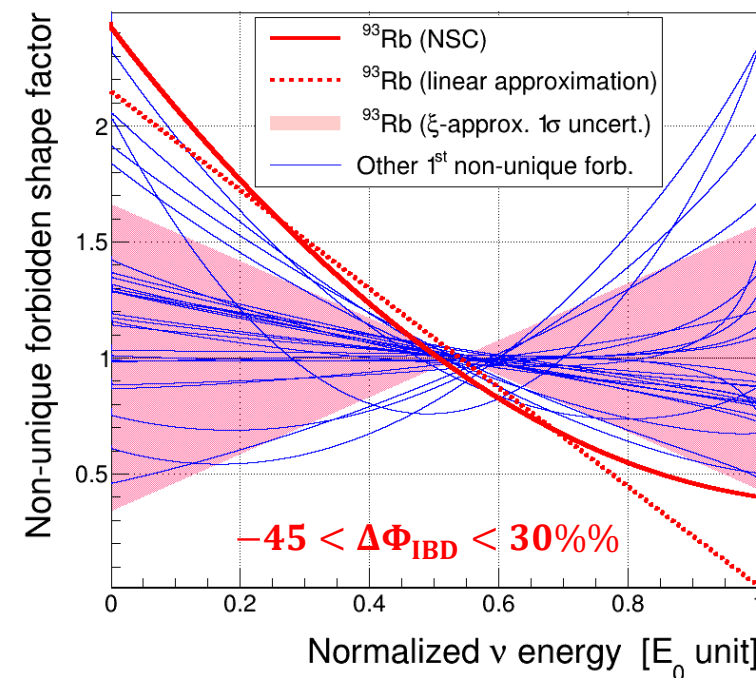
$$\langle \xi_f J_f || T_\lambda || \xi_i J_i \rangle = \hat{\lambda}^{-1} \sum_{a,b} \langle a || T_\lambda || b \rangle \langle \xi_f J_f || [c_a^\dagger \tilde{c}_b]_\lambda || \xi_i J_i \rangle$$

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



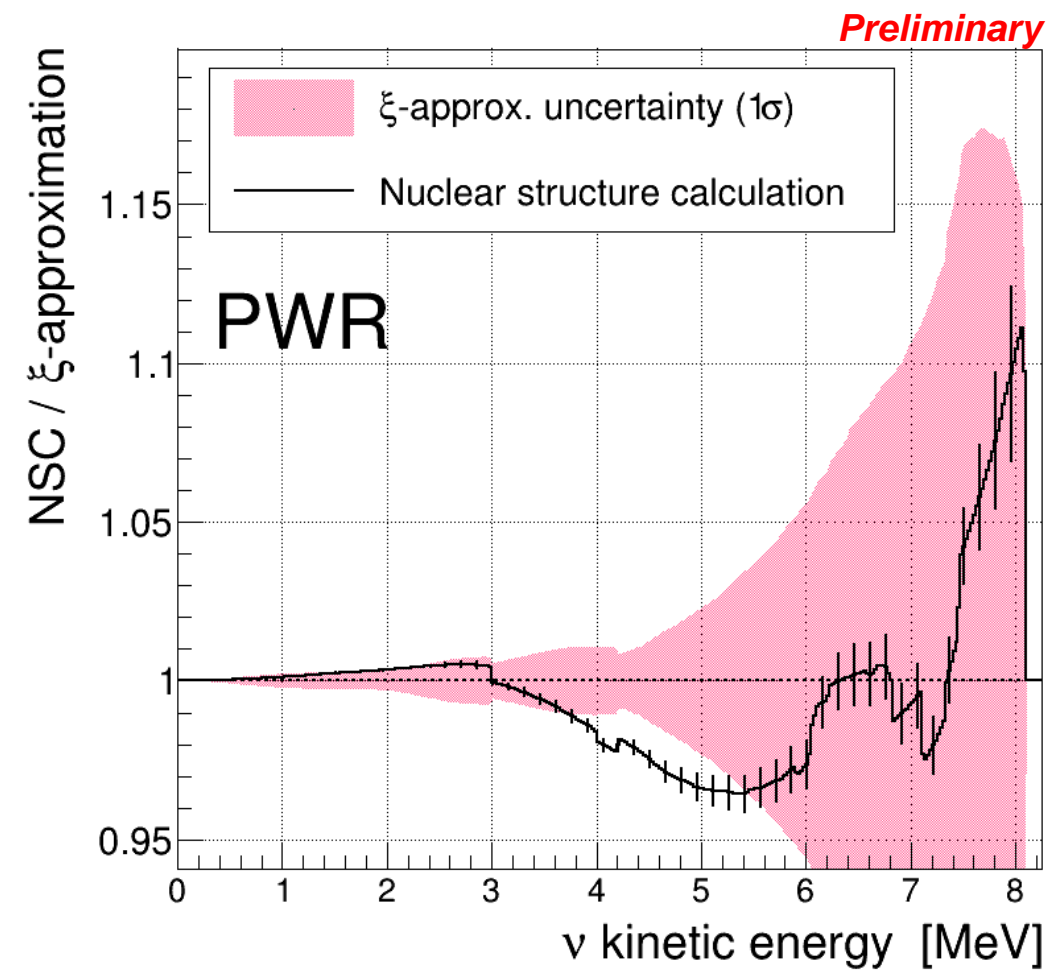
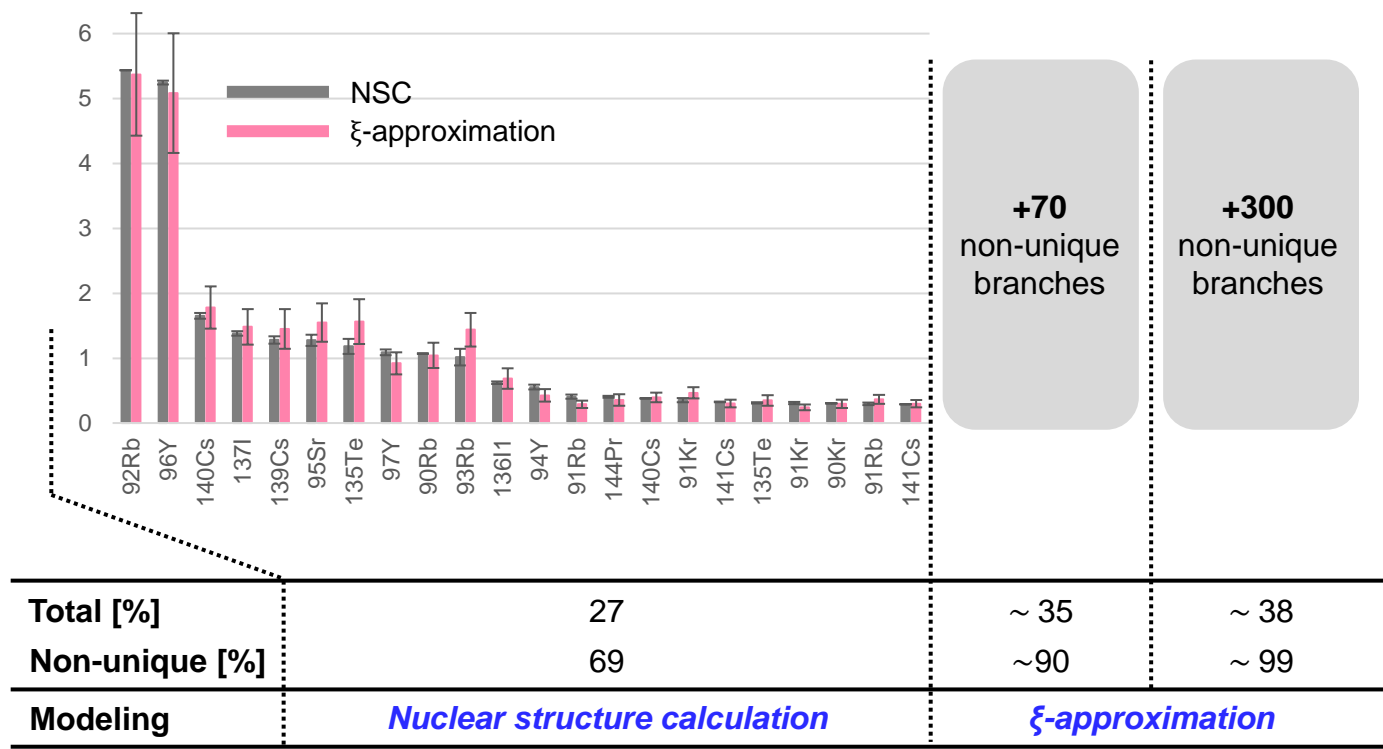
Advanced modeling:

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)

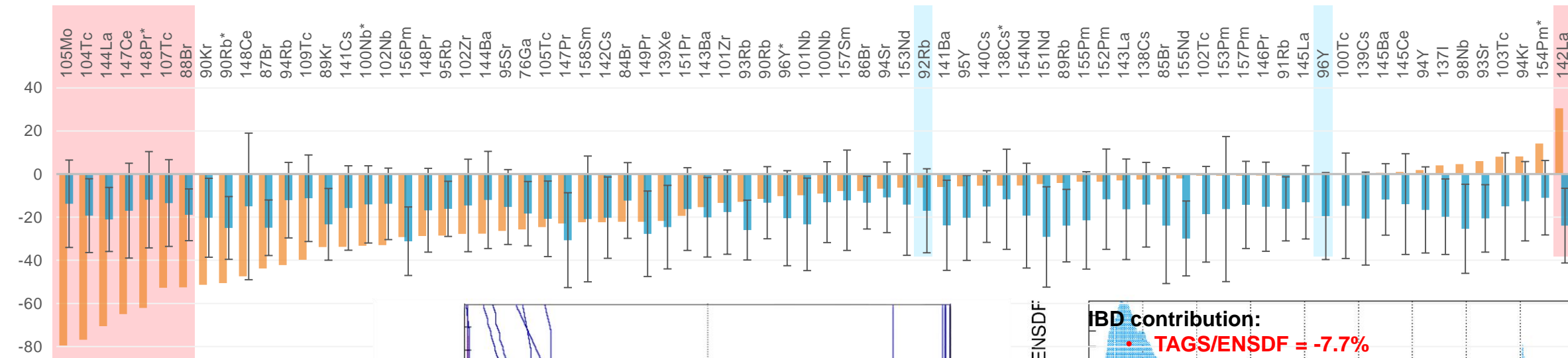
IBD contributions of non-unique transitions for a Chooz-like PWR



\Rightarrow IBD yield decreased by $(1.3 \pm 0.2)\%$ compared to full ξ -approximation

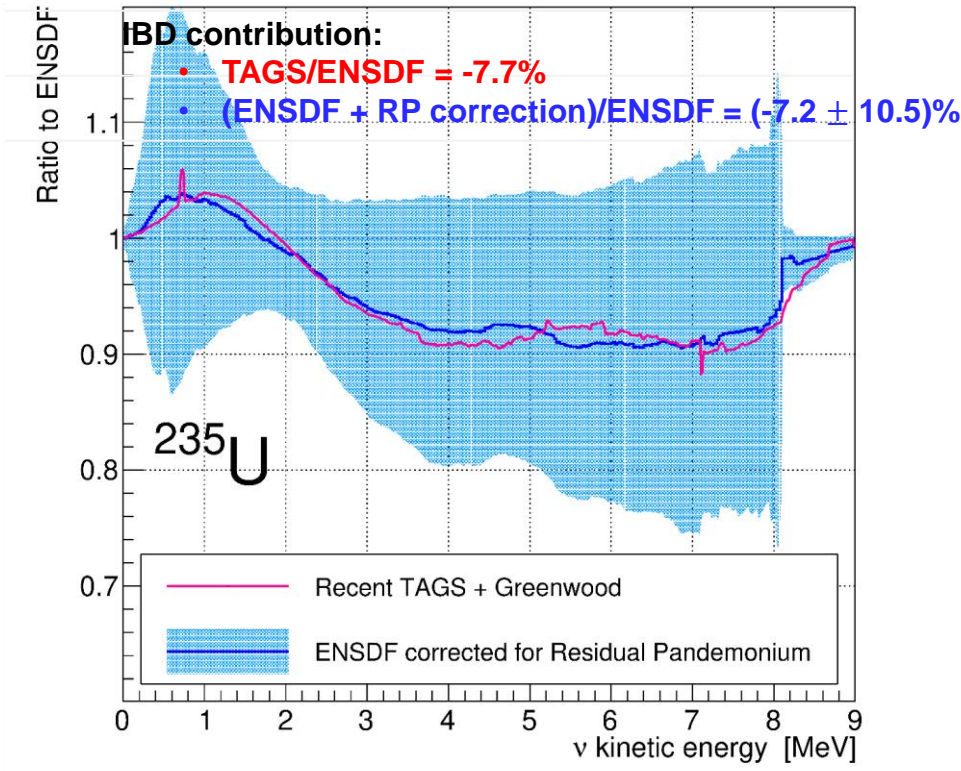
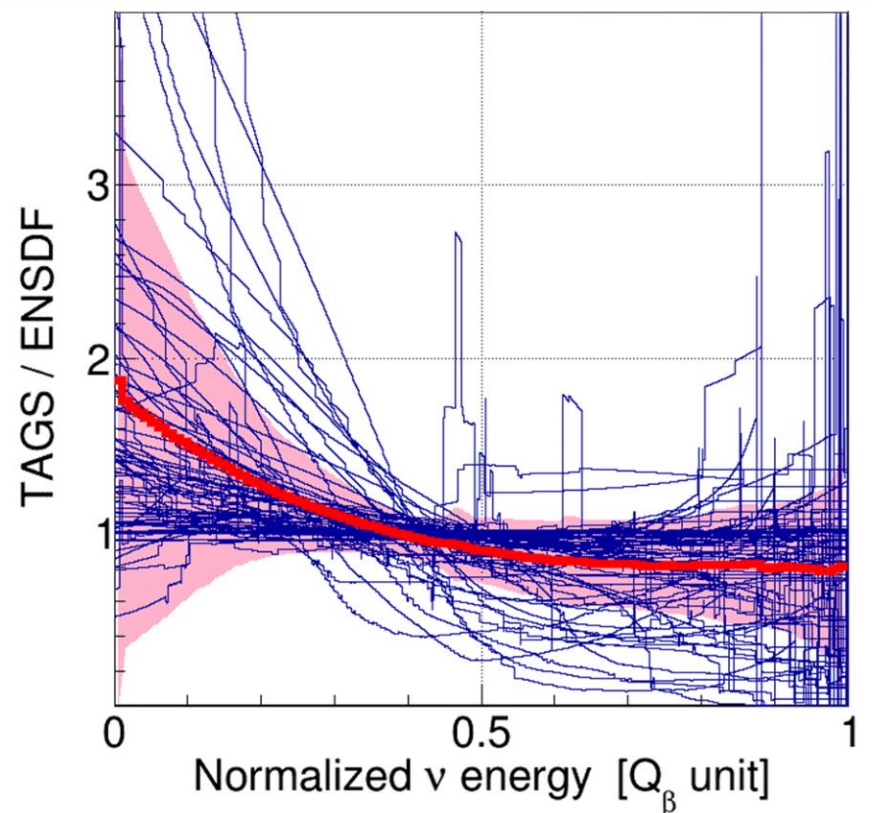
RESIDUAL PANDEMONIUM EFFECT

Diff > 2σ



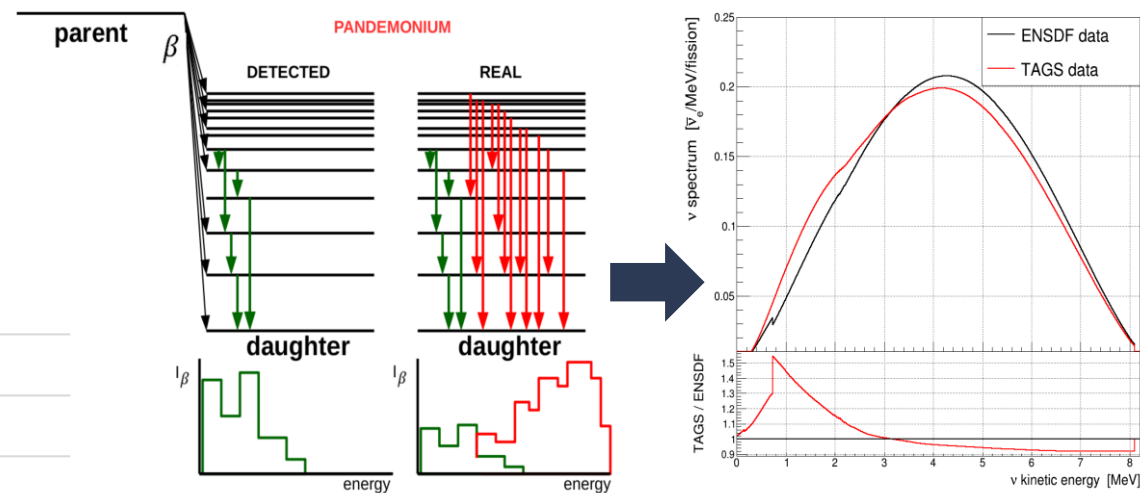
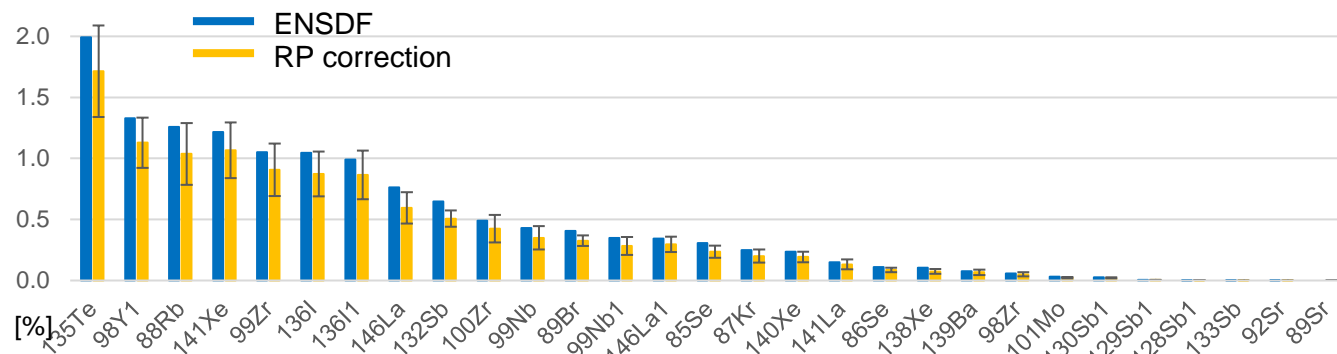
TAGS/ENSDF - 1

Correction/ENSDF - 1



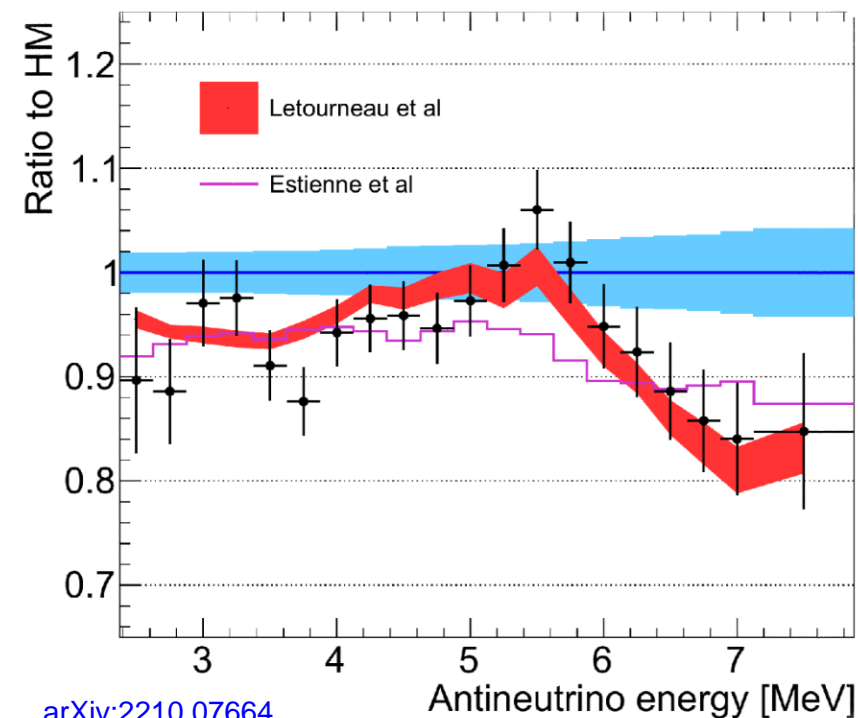
RESIDUAL PANDEMONIUM CORRECTION FOR A PWR

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

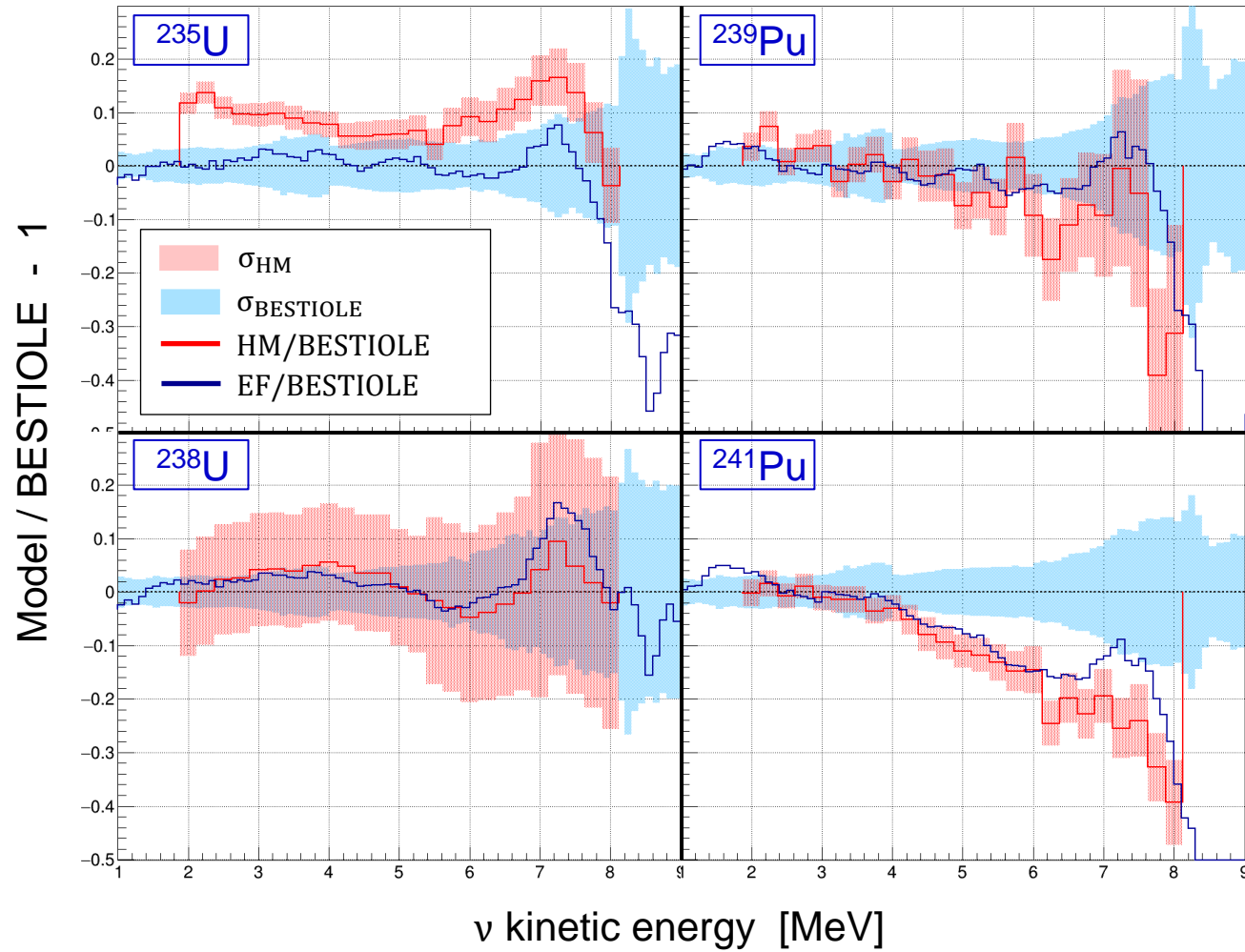


PHENOMENOLOGICAL DECAY STRENGTH MODEL

- 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

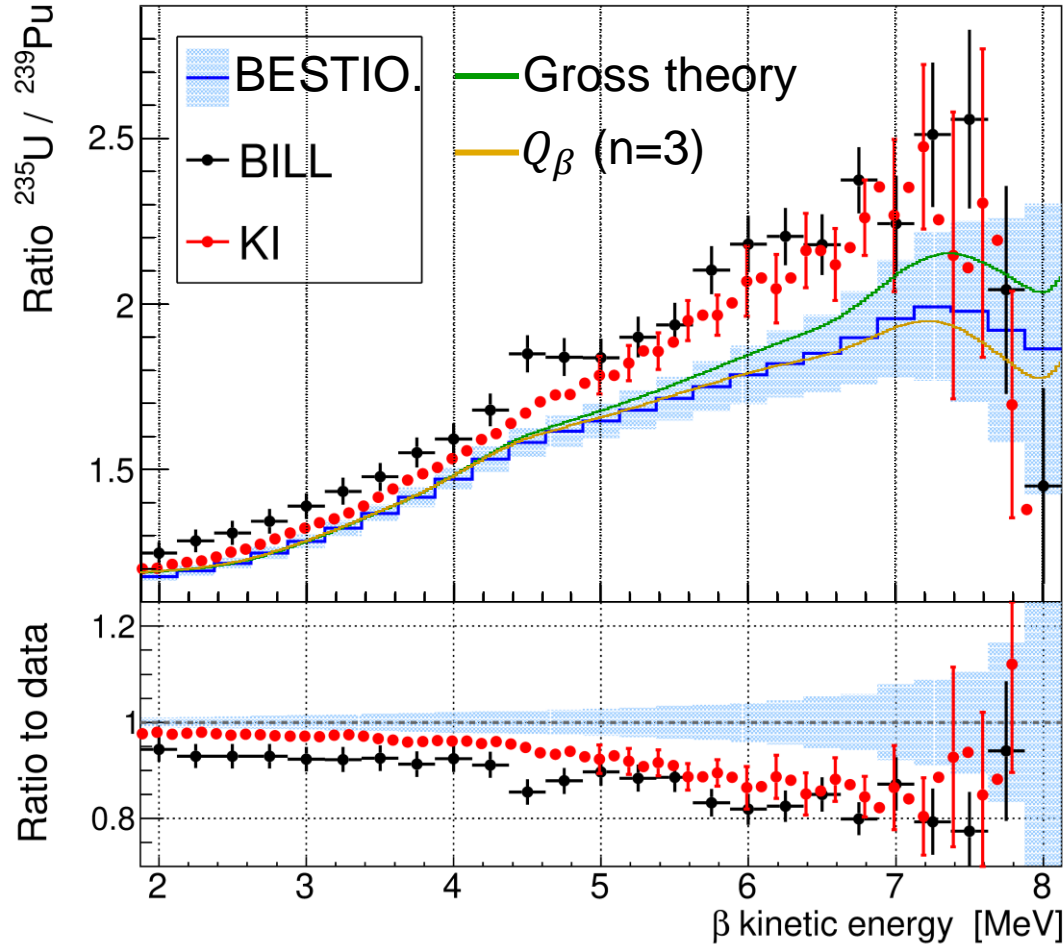


COMPARISON TO OTHER MODELS

Differences with Estienne-Fallot (EF):

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

IMPACT OF NND MODEL



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

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

