DE LA RECHERCHE À L'INDUSTRIE

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The NEνFAR project:
New Evaluation of ν Fluxes At Reactors

Revisiting the summation calculation of reactor antineutrino spectra

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IAEA TM on Nuclear Data Needs for Antineutrino Spectra Applications
18 January 2023

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OUTLINE

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

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

3. **Preliminary comparisons**
    a. Integral measurements
    b. Spectrum shape

4. **Conclusion & perspectives**

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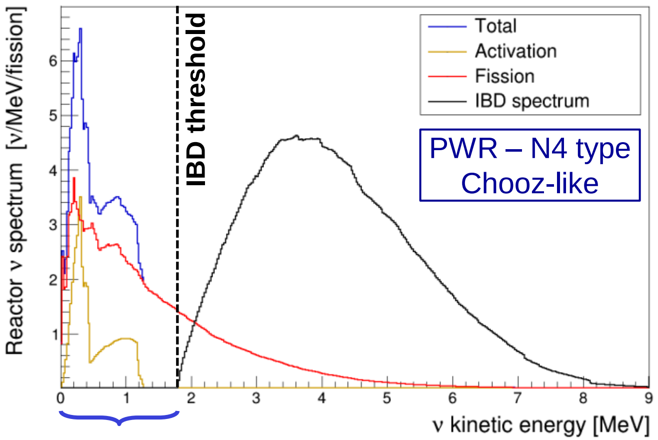
PRESSURIZED WATER REACTOR (PWR)

- Fuel: lowly enriched uranium, ^{238}U + 3-5% ^{235}U
- High power: ~3 - 4 GW_{th}
- Similar 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]

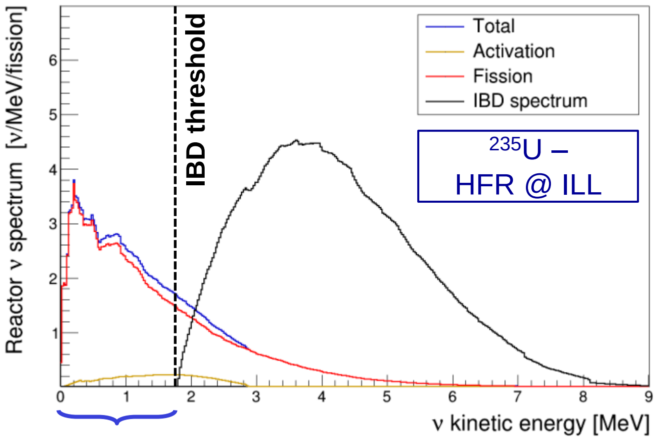
^{239}U	0.6	~17% $\Phi_{\bar{\nu}_e}$
^{239}Np	0.6	

Average event/fission for a Chooz type reactor (~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



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

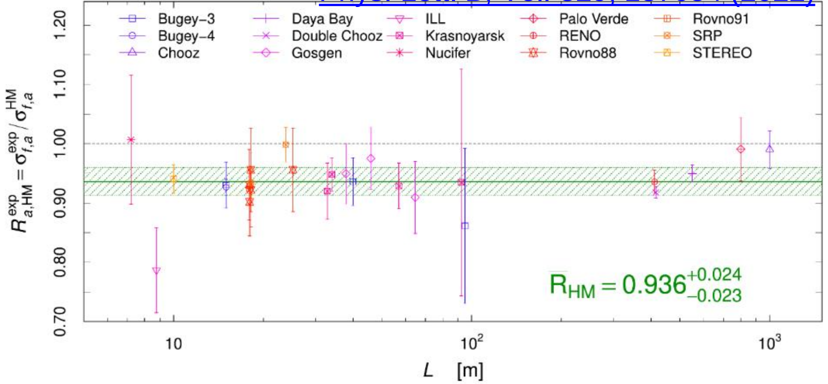
⇒ $\bar{\nu}_e$ contribution depends on reactor type and changes with time

⇒ Prediction needed for fission and activation spectra

REACTOR ANTINEUTRINO ANOMALY (RAA)

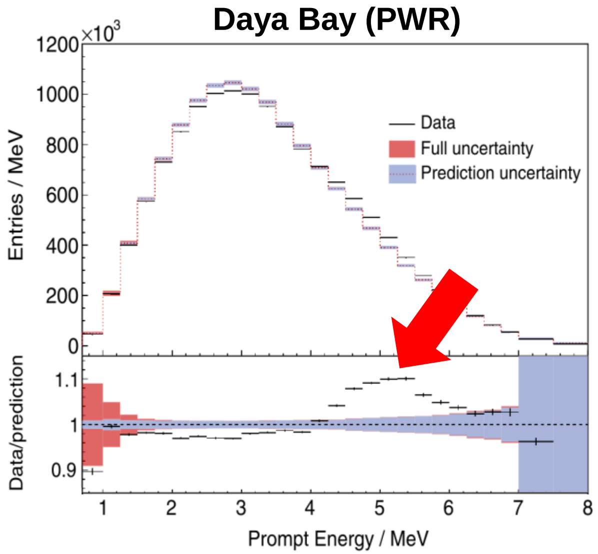
- Systematic IBD rate deficit vs to HM
- Measured/predicted IBD rate: $\mathbf{0.936^{+0.024}_{-0.023}}$ (2.5σ)
- RAA possible origins
  - Experimental bias — ***Unlikely***
  - New physics (sterile neutrino)
  - **Mismodeling / underestimation of $\bar{\nu}_e$ spectrum uncertainty**
  - **Single / multiple actinide(s) ?**

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



SHAPE ANOMALY

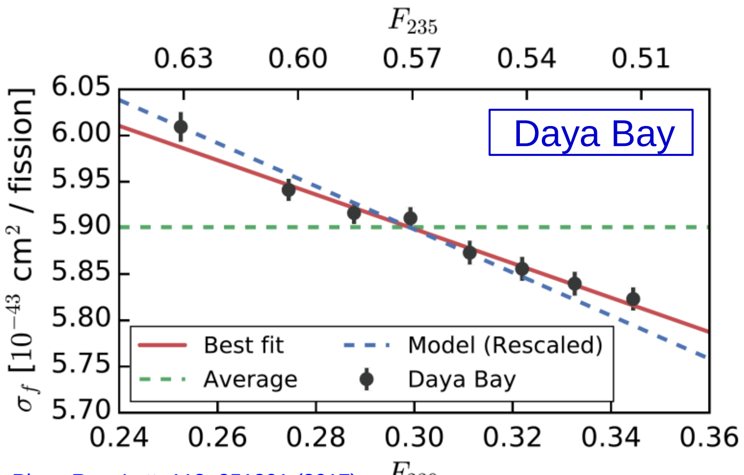
- First observed by Double Chooz, Daya Bay; RENO
  - Confirmed by recent very-short baseline reactor exp. (NEOS, STEREO, PROSPECT, DANSS)
- Possible origins
  - Detector energy scale calibration — ***Checked***
  - Fuel composition
  - **Prediction issue, single / multiple actinide(s) ?**



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

FUEL-DEPENDENT IBD RATE EVOLUTION

- IBD yield changes with fuel evolution of PWR
- Comparison between measured IBD yield evolution and predicted evolution
  - 3.1σ at Daya Bay
  - 1.3σ at RENO
- Induced by inequal fractional deficit among actinides



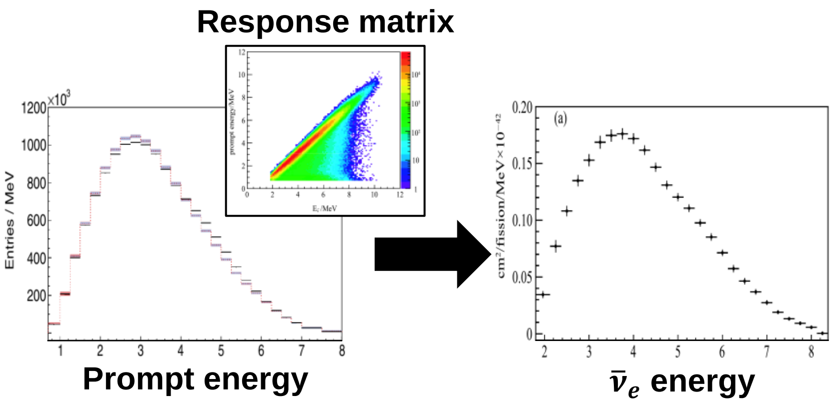
[Phys. Rev. Lett. 118, 251801 (2017)]

REACTOR DATA-DRIVEN METHOD

- Unfolding exp. prompt IBD spectrum
  - $\bar{\nu}_e$ spectrum + covariance matrix

PROS
- Model-independent (no anomalies)
- Small uncertainties

CONS
- Limited to exp. range, 1.8-9 MeV
- Small number of available datasets
- No activation spectrum

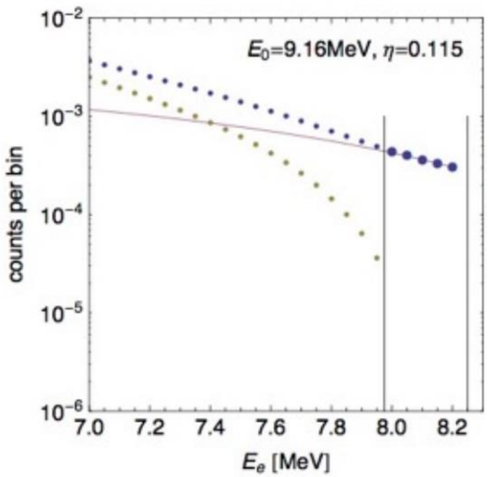


CONVERSION METHOD

- 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 → KI exp.
- Impact of forbidden branches on fit

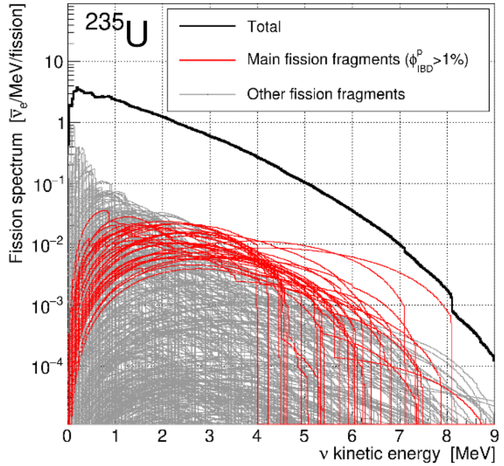


SUMMATION METHOD

- 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



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Daya Bay: Total, ^{235}U, ^{239}Pu

RENO, NEOS: Total

STEREO, PROSPECT: ^{235}U

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Huber-Mueller model (+ KI data)

⇒ ^{235}U, ^{239}Pu and ^{241}Pu from P. Huber
PRC 84, 024617 (2011)

⇒ $^{235}U/^{239}Pu$ data from KI
PRD 104, L071301 (2021)

⇒ ^{238}U from Mueller *et al.*
PRC 83, 054615 (2011)

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
    - Adjusted effective modeling for nuclides with no data
  - Build a comprehensive uncertainty budget
    - Nuclear data and modeling uncertainties

All results are preliminary

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⇒ Reliable summation method required for multiple purposes

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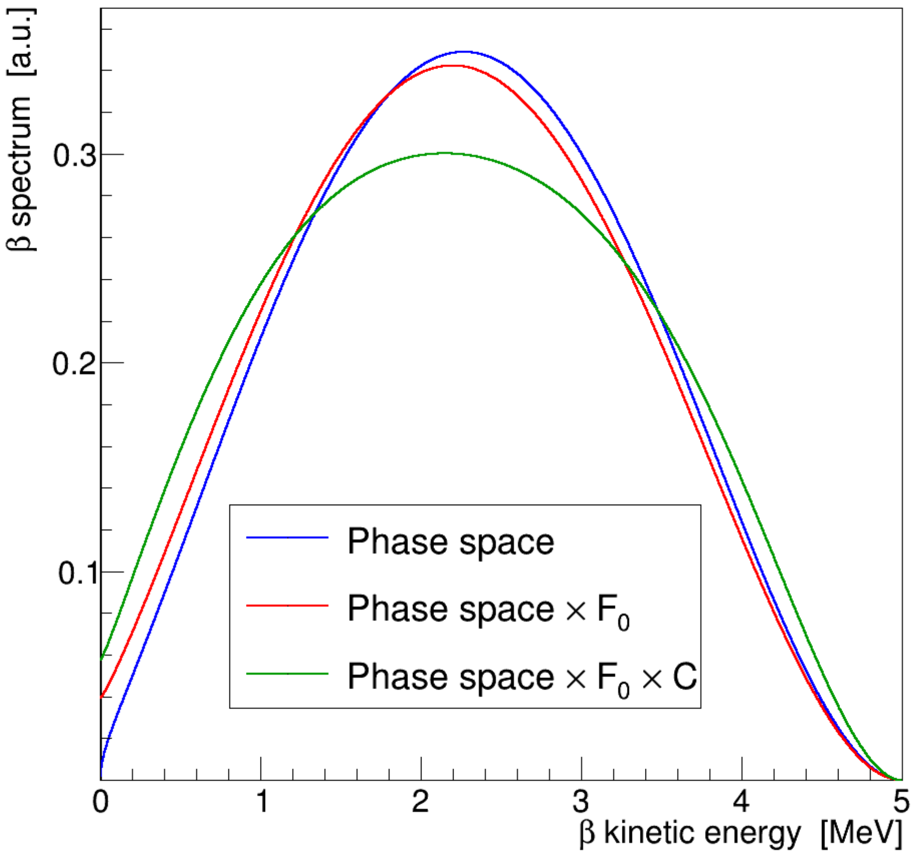
W. Bühring and H. Behrens formalism (1982)

V-A THEORY OF β-DECAY

- p: β momentum
- W: β total energy
- W_0: max available energy
- $E_0 = W_0 - m_e$: max kinetic energy
- K: normalization factor $\int \mathrm{d}W\, S_\beta = 1$

$$S_\beta(Z,A,W) = K\, pW(W_0 - W)^2\, F_0(Z,A,W)\, C(Z,A,W)\, (1 + \delta_{WM} + \delta_{RC})$$

- **Phase space**
  - ▻ Energy states accessible to the emitted β
- **Fermi function**
  - ▻ Electromagnetic interaction β / daughter nucleus
  - ▻ Depends on β wavefunction
- **Shape factor**
  - ▻ Nuclear structure effect, depends on spin-parity
  - ▻ Depends on β wavefunction



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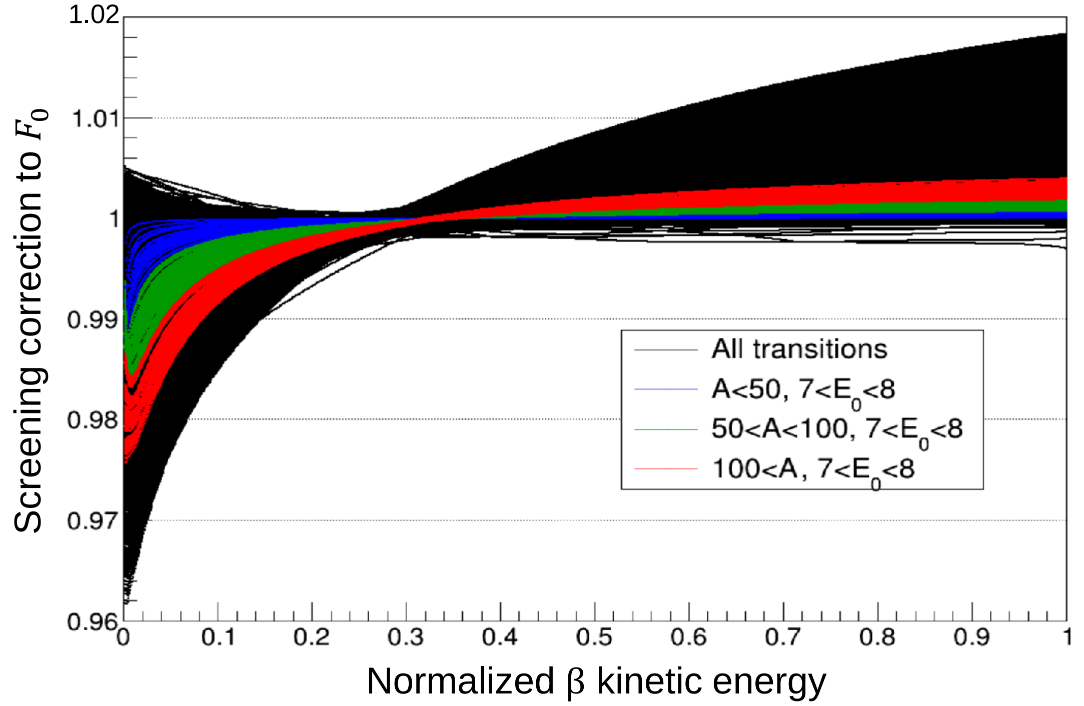
Behrens & Bürhing algorithm (1982)

- ✓ β wavefunction computation depends on nuclear potential
- ✓ Reproduce Berhens & Jänecke tables
  - Finite-size and screening corrections to **Fermi functions** and to **unique forbidden shape factors**
- ✓ Extended to any energy, for any spherical nuclear potential



⇒ **Impact of more realistic nuclear potential modeling <0.2% on fission spectrum shape and IBD yield**

W. Bühring and H. Behrens formalism (1982)

V-A THEORY OF β-DECAY

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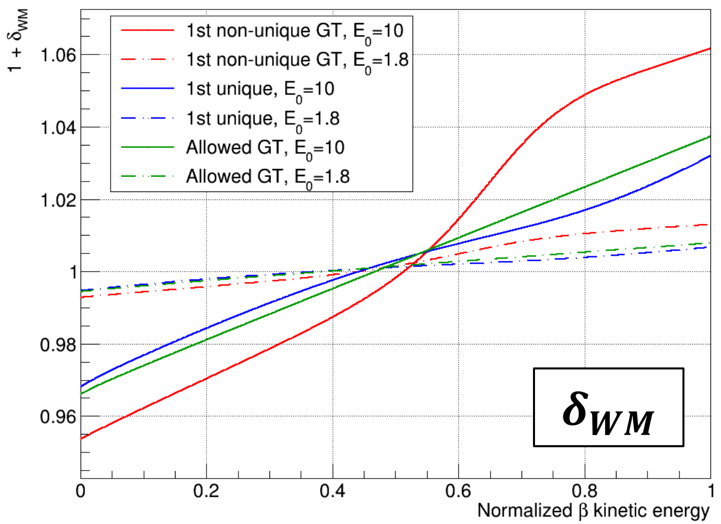
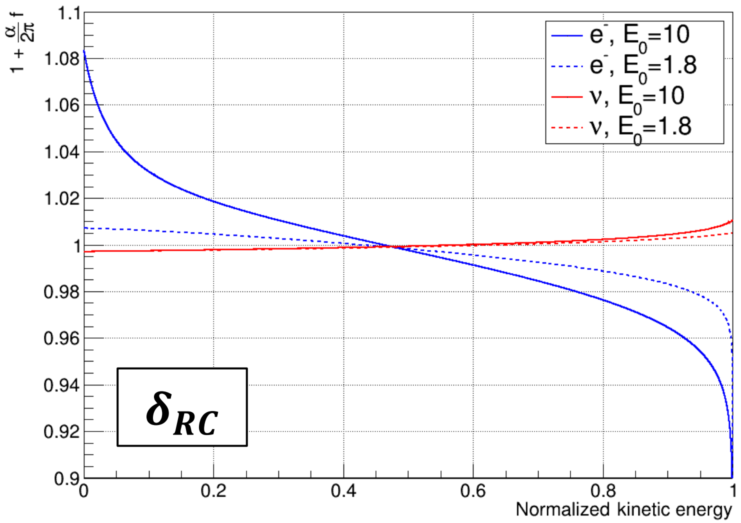
- **Radiative correction (RC)**
  - ▻ QED effect from virtual photon exchange
  - ▻ β correction ≫ $\bar{\nu}_e$ correction
- **Weak magnetism correction (WM)**
  - ▻ Nucleon structure effect
  - ▻ Depends on spin-parity info



Hayes et al., Phys. Rev. Lett. 112, 202501 (2014)



Correction β: Sirlin, Phys. Rev. 164, 1767 (1967)
Correction $\bar{\nu}_e$: Sirlin, Phys. Rev. D 84, 014021 (2011)

WM correction in Behrens & Bürhing → allowed GT and non-unique forbidden

✓ Apply WM correction of allowed GT to non-unique forbidden branches

✓ Uncertainty derived for fission spectra → $\sigma_{IBD}(WM) = 0.3\%$

Fluxes for typical PWR fission fractions

CLASSIFICATION OF β^- TRANSITIONS

β-decay type	ΔJ	$\pi_i \pi_j$	Shape factor	Calculation	$\bar{\nu}_e$ [%]	IBD [%]
Allowed	$0,1$	$+1$	1	*Robust and accurate*	61	47
Unique forbidden	$n+1$	$(-1)^n$	Polynomial in p_ν & p_e		10	9

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1st non-unique forbidden	$0,1$	-1			**24**	**38**
Main ($\varphi_{IBD} \geq 1\%$)			Nuclear struct. calcul.	*Advanced calculation*	6	27
Others			ξ-approximation	*Unknown accuracy*	18	11
nth non-unique forbidden	n	$(-1)^n$	ξ-approximation	*Unknown accuracy*	**3**	**1**

NON-UNIQUE FORBIDDEN SHAPE FACTOR

- No simple expression
  - Depends on **transition matrix elements** connecting nuclear states
  - Nuclear structure calculations or ξ-approximation

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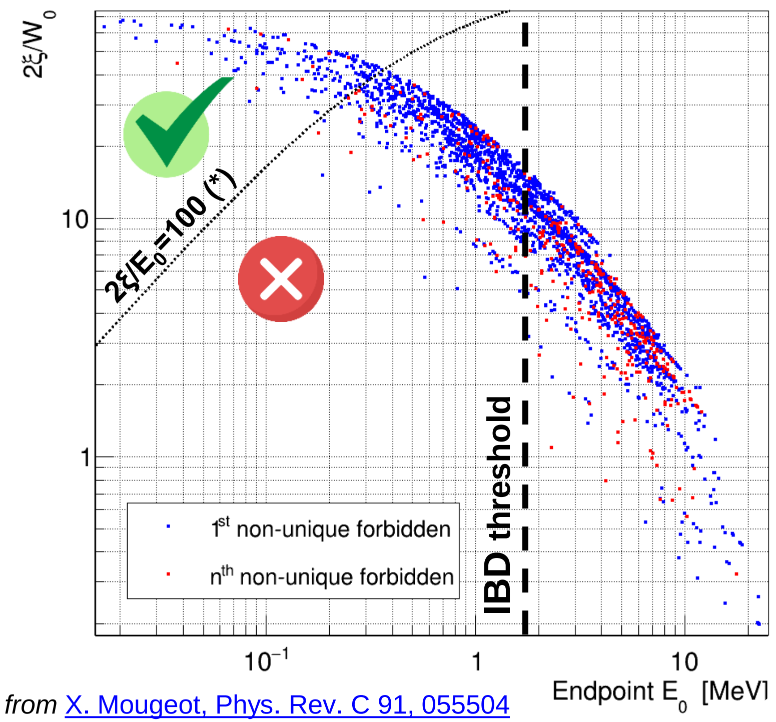
ξ-approximation

$$2\xi = \alpha Z/R_n \gg W_0$$

- α: fine structure constant
- R_n: radius of the daughter
- W_0: max available energy for the transition

- ▻ If verified: n^{th} non-unique ~ $(n-1)^{th}$ unique
- ▻ Applied to all non-unique transitions → **induce mismodeling**
  - ▪ Except 23 important non-unique transitions

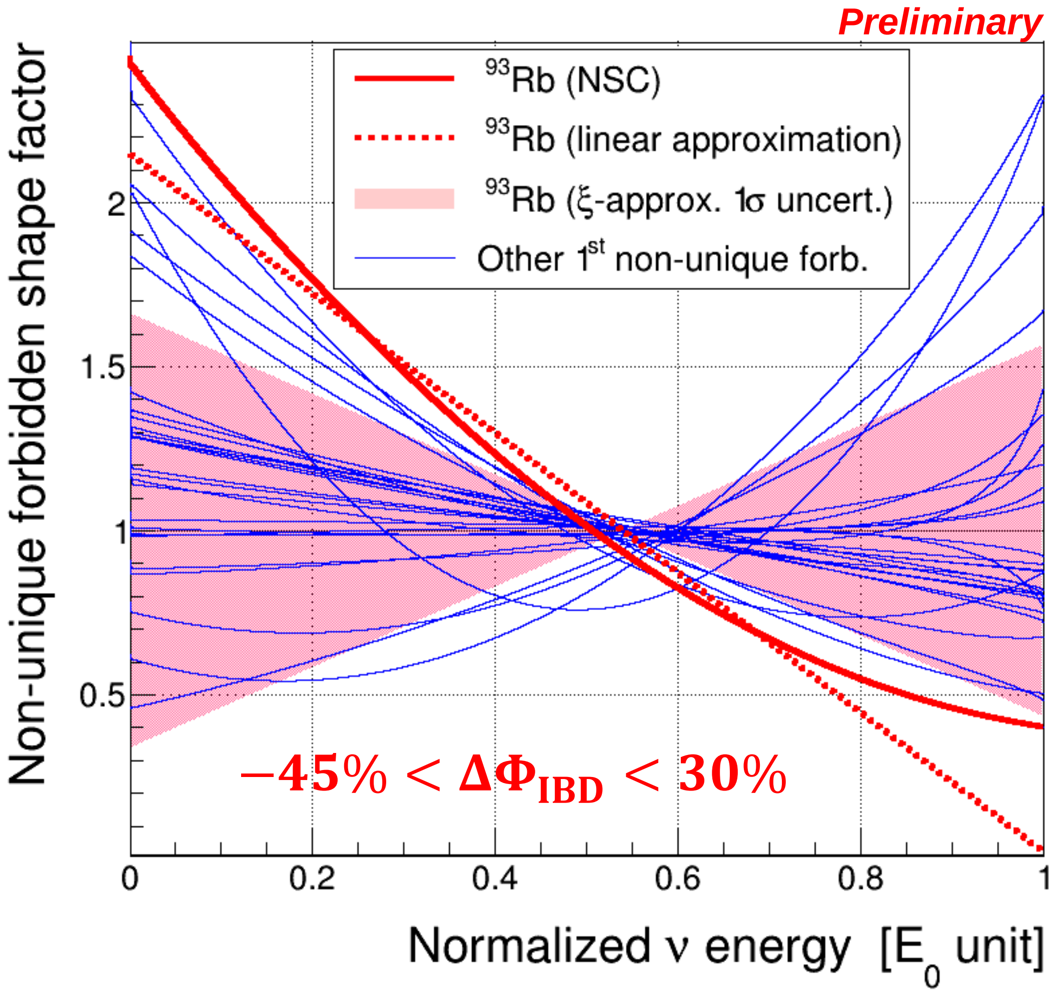


(*): *Criterion from* X. Mougeot, Phys. Rev. C 91, 055504

NUCLEAR STRUCTURE CALCULATION (NSC)

- β-decay = single nucleon transition
- Nuclear state = superposition of nucleon states
- Non-unique shape factor calculation with NuShellX program
  - NSC very time consuming (man & cpu)
  - Comprehensive calculation for 23 important non-unique transitions
  - Uncertainty derived from comparison to allowed spectrum
  - No general nor systematic trend in non-unique shape factors

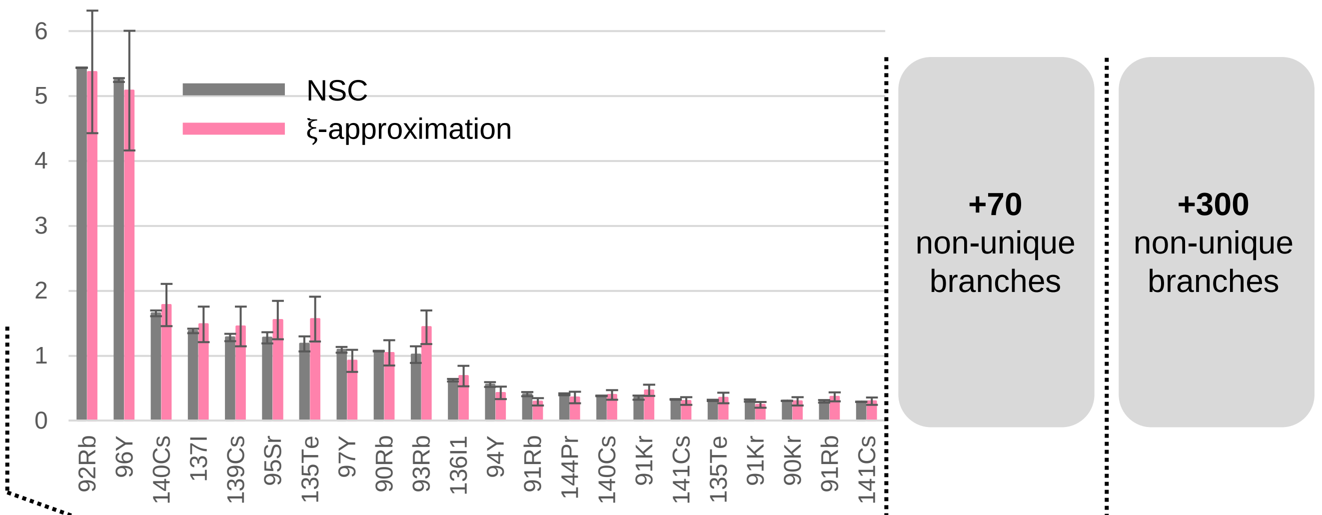
⇒ Non-unique forbidden branches treated as uncorrelated



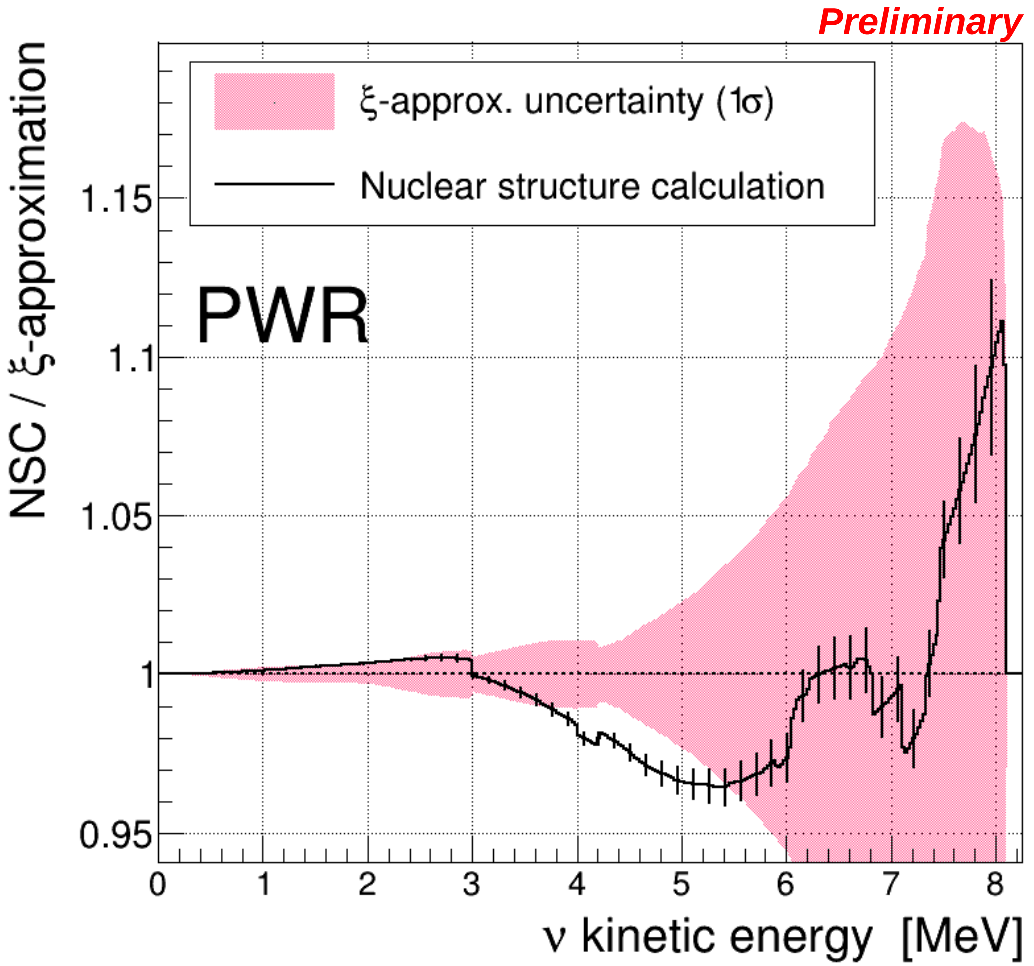
⇒ Simplistic linear model used for uncertainty of ξ-approx. non-unique transitions

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

Angeli 2013
- Nuclear radius (R_n)
  Angeli et al., At. Data Nucl. Data Tables 99(1):69-95 (2013)

ENSDF-2020
- Branching ratio (BR)
- β⁻ intensity (I_β)
- Spin-parity ($J\pi$)
- Parent energy (E_{parent})
- Daughter level energy (E_{lvl})

NUBASE-2020
- β⁻ intensity (I_β)
- Parent energy (E_{parent})

AME-2020
- Q_β energy

JEFF-3.3
- Fission yield (FY)

Branch spectrum

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

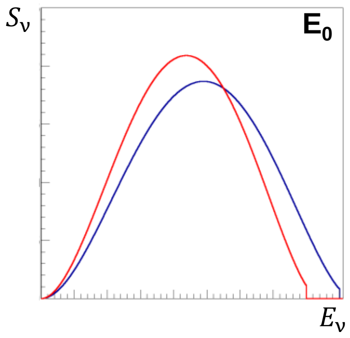
Isotope spectrum

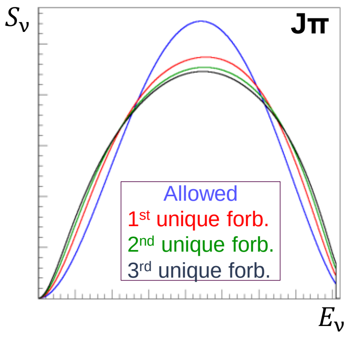
$$S_i = \sum_b BR_i^b\, S_\nu^b$$

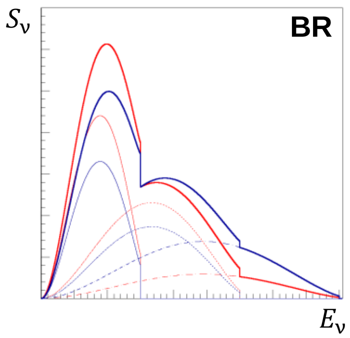
Fission spectrum

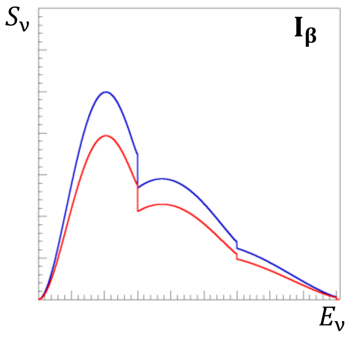
$$S_f = \sum_i FY_f^i\, S_i$$

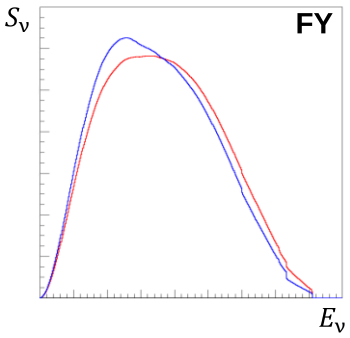
$$E_0 = Q_\beta + E_{parent} - E_{lvl}$$







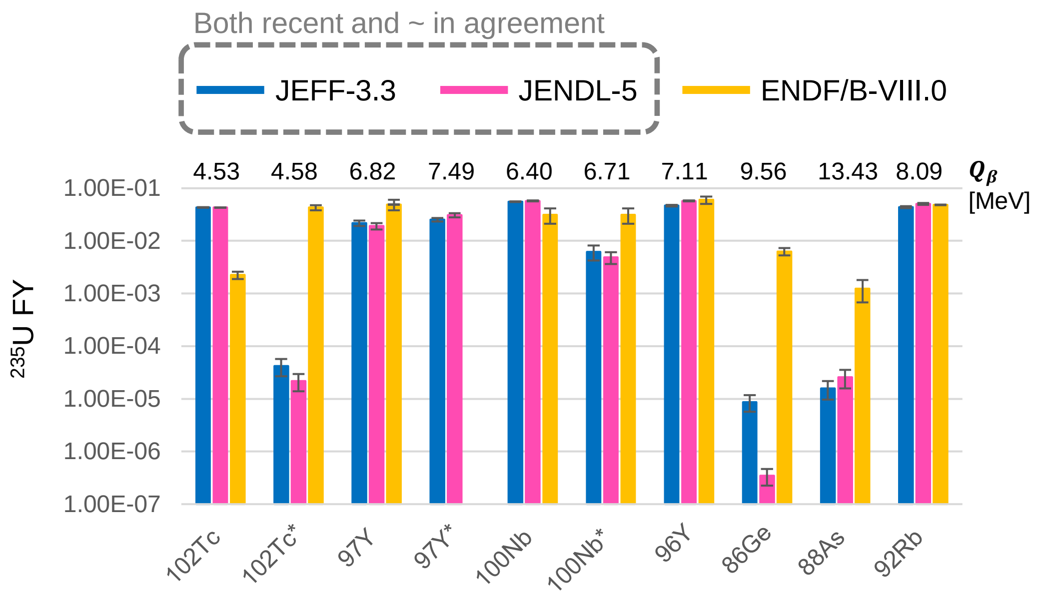


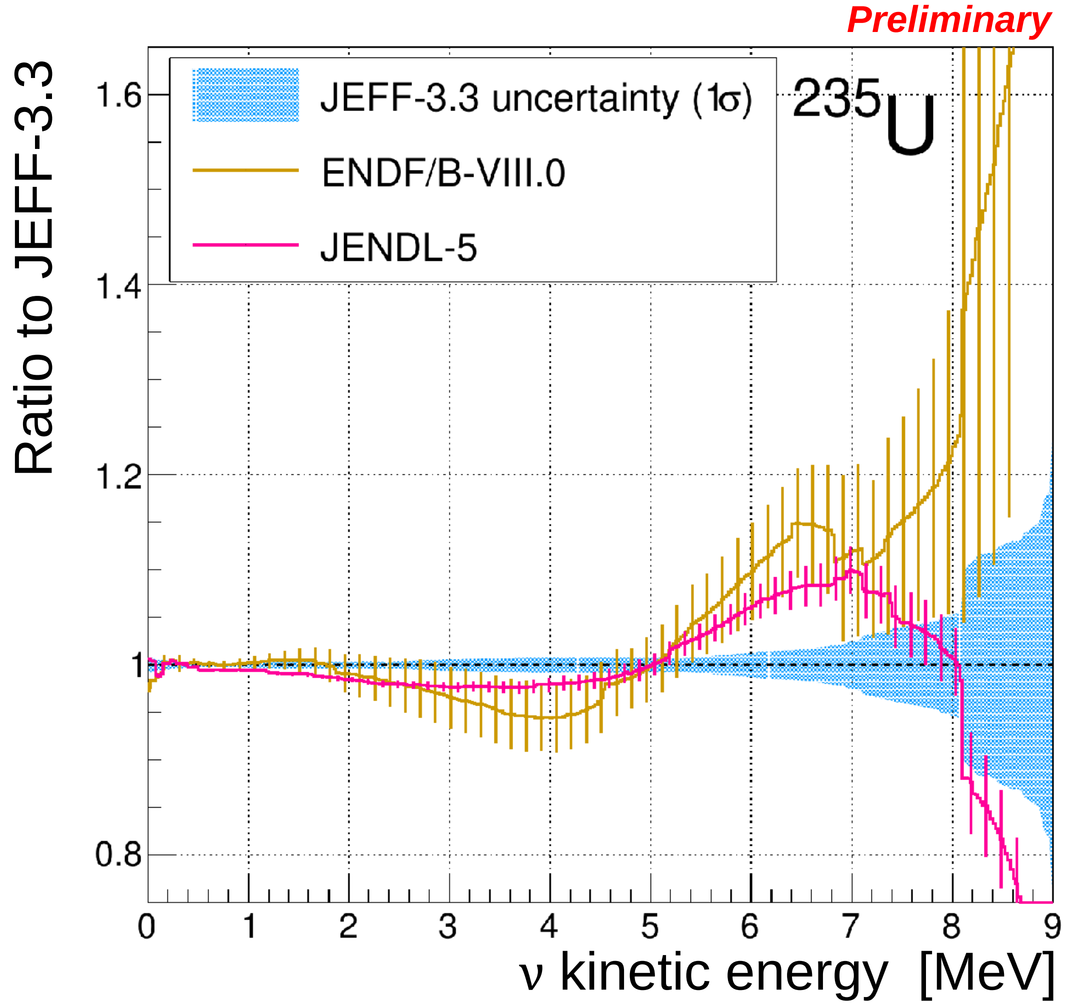


⇒ Summation method requires many input data

FISSION YIELD DATA

Discrepancies between cumulative FY data





⇒ Impacts fission spectrum shape

⇒ Impacts IBD yields

^{235}U ~ 0.5% **^{239}Pu ~ 2%**

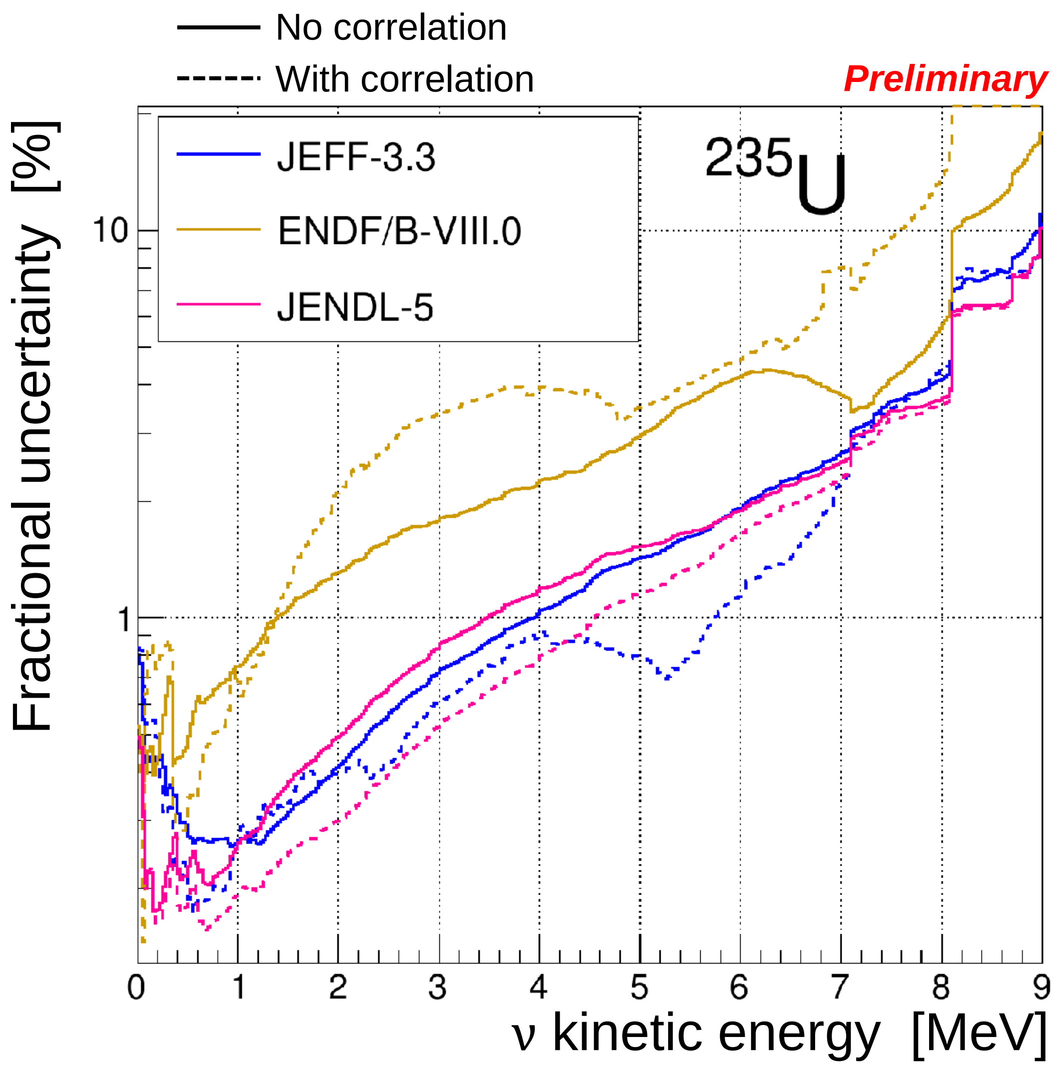
^{238}U ~ 3% **^{241}Pu ~ 2%**

FISSION YIELD DATA

Covariance matrix for cumulative FY

- Correlations derived from evaluation process
  - No correlation from fission process modeling and experimental data
- No inter-actinide correlations
  - Needed for PWR

	JEFF-3.3	ENDF/B-VIII.0	JENDL-5
Source	Matthews et al. (2021)		Provided in JENDL
$\sigma_{IBD}(FY)$ no cor.	$\sim 1\%$	$\sim 2\%$	$\sim 1\%$
$\sigma_{IBD}(FY)$ with cor.	$\sim 0.8\%$	$\sim 4\%$	$\sim 0.8\%$



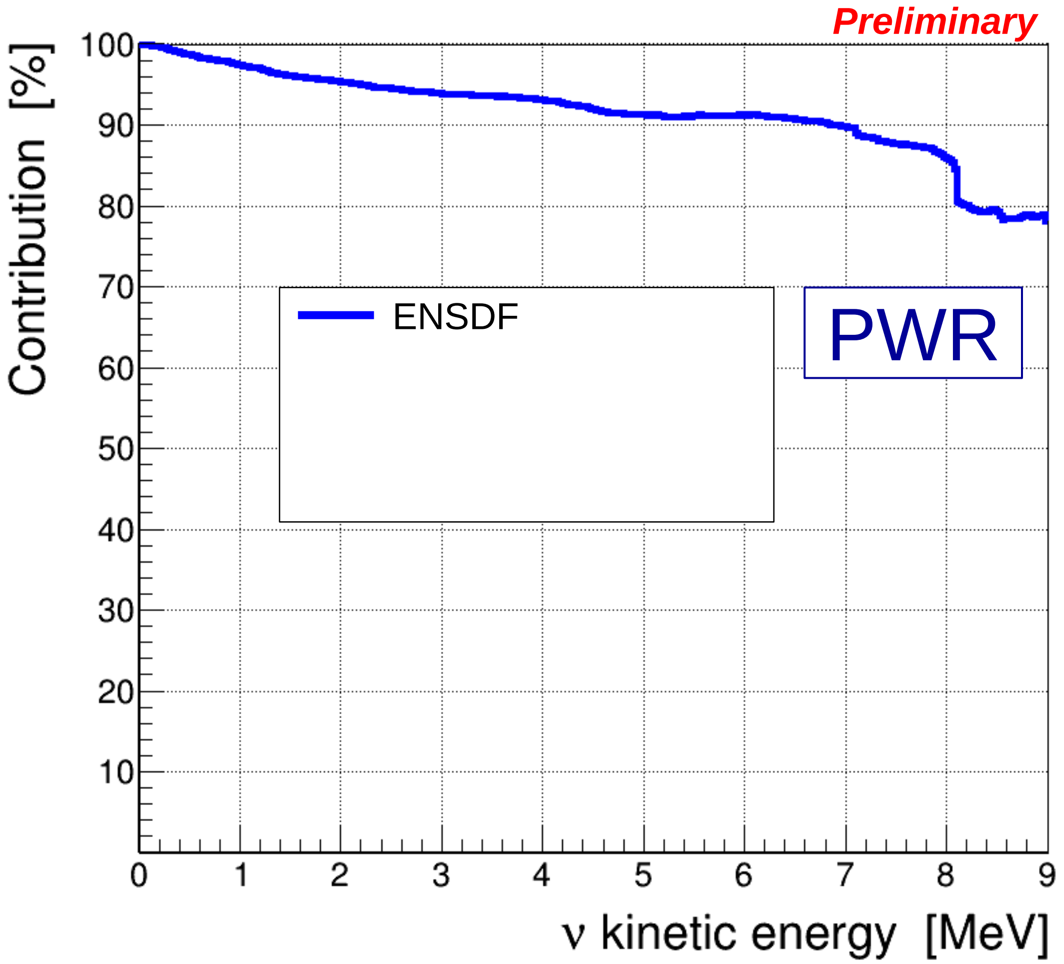
⇒ Conservative choice for JEFF-3.3 is the « no correlation » case

		β^- emitters from JEFF-3.3	
		NUBASE-2020	ENSDF-2020
	^{235}U	793	566
	^{238}U	778	536
	^{239}Pu	851	625
	^{241}Pu	860	603
PWR	$\bar{\nu}_e$ flux contribution [%]		**97**
PWR	IBD yield contribution [%]		**92**

2 issues with ENSDF database

- Database completeness
- Quality of experimental data and evaluation

⇒ **Pandemonium effect**



		β⁻ emitters from JEFF-3.3	
		NUBASE-2020	ENSDF-2020
	^{235}U	793	↘ 448
	^{238}U	778	↘ 419
	^{239}Pu	851	↘ 507
	^{241}Pu	860	↘ 485
PWR	$\bar{\nu}_e$ flux contribution [%]		↘ **55**
PWR	IBD yield contribution [%]		↘ **27**

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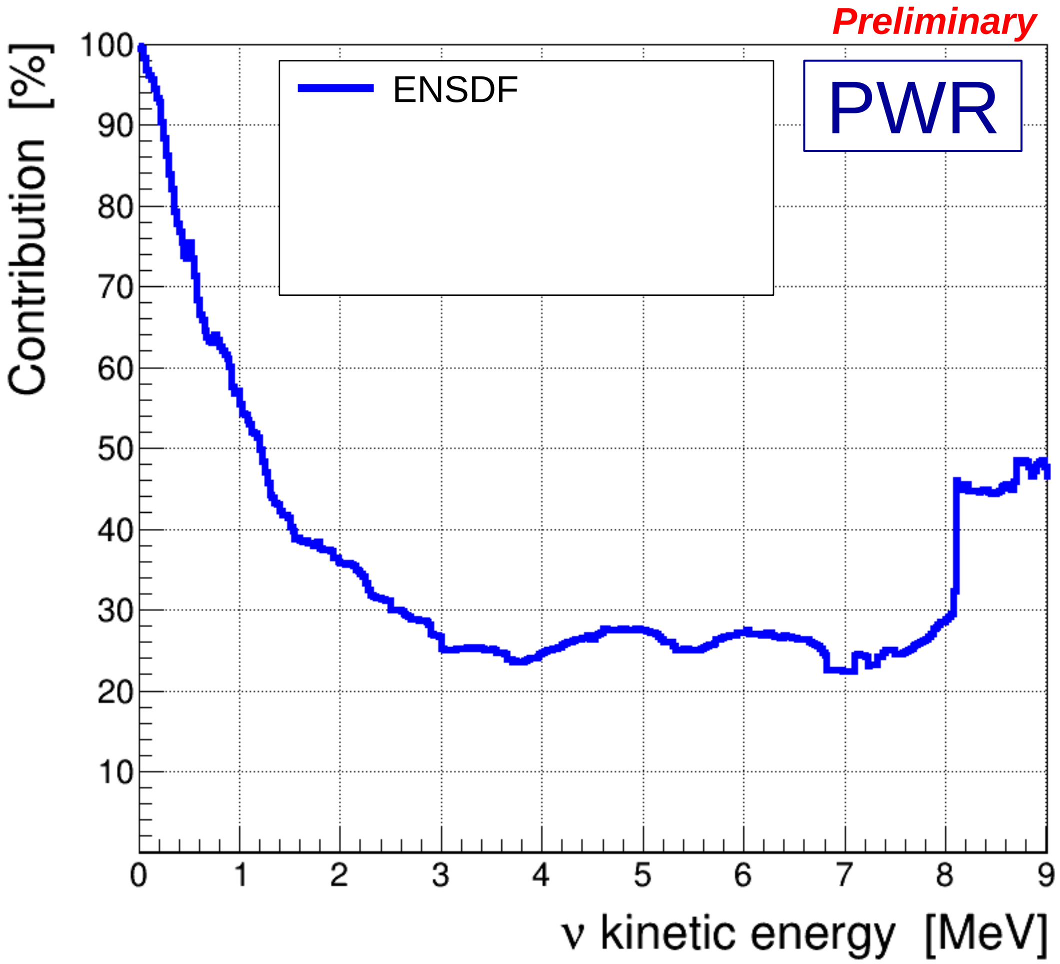
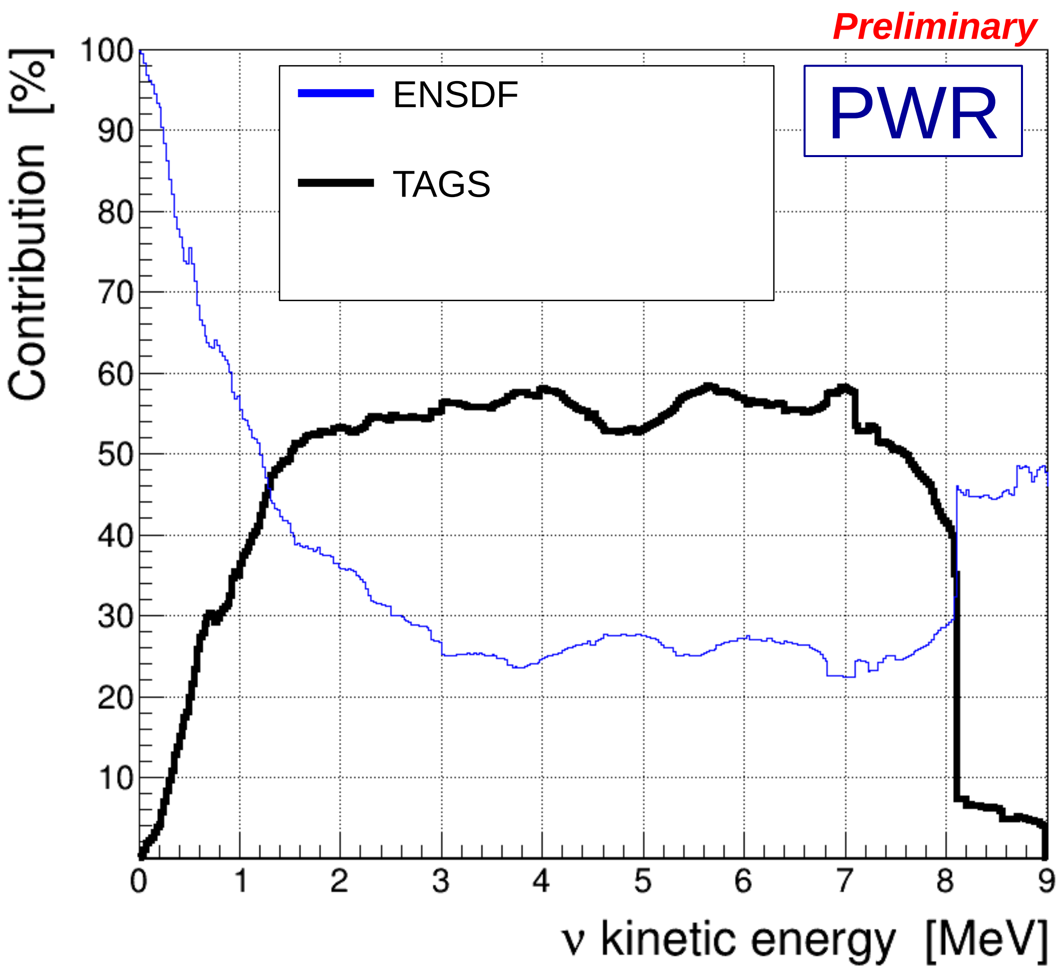


		β^- emitters from JEFF-3.3		
		NUBASE-2020	ENSDF-2020	TAGS
	^{235}U	793	448	84
	^{238}U	778	419	83
	^{239}Pu	851	507	84
	^{241}Pu	860	485	84
PWR	$\bar{\nu}_e$ flux contribution [%]		**55**	**36**
PWR	IBD yield contribution [%]		**27**	**55**

TAGS data are Pandemonium-free
- Priority over ENSDF data
- $\bar{\nu}_e$ spectra shifts toward low energy

⇒ IBD yield decreased by 8% with TAGS data



Quality of nuclear data
- Acceptable: TAGS

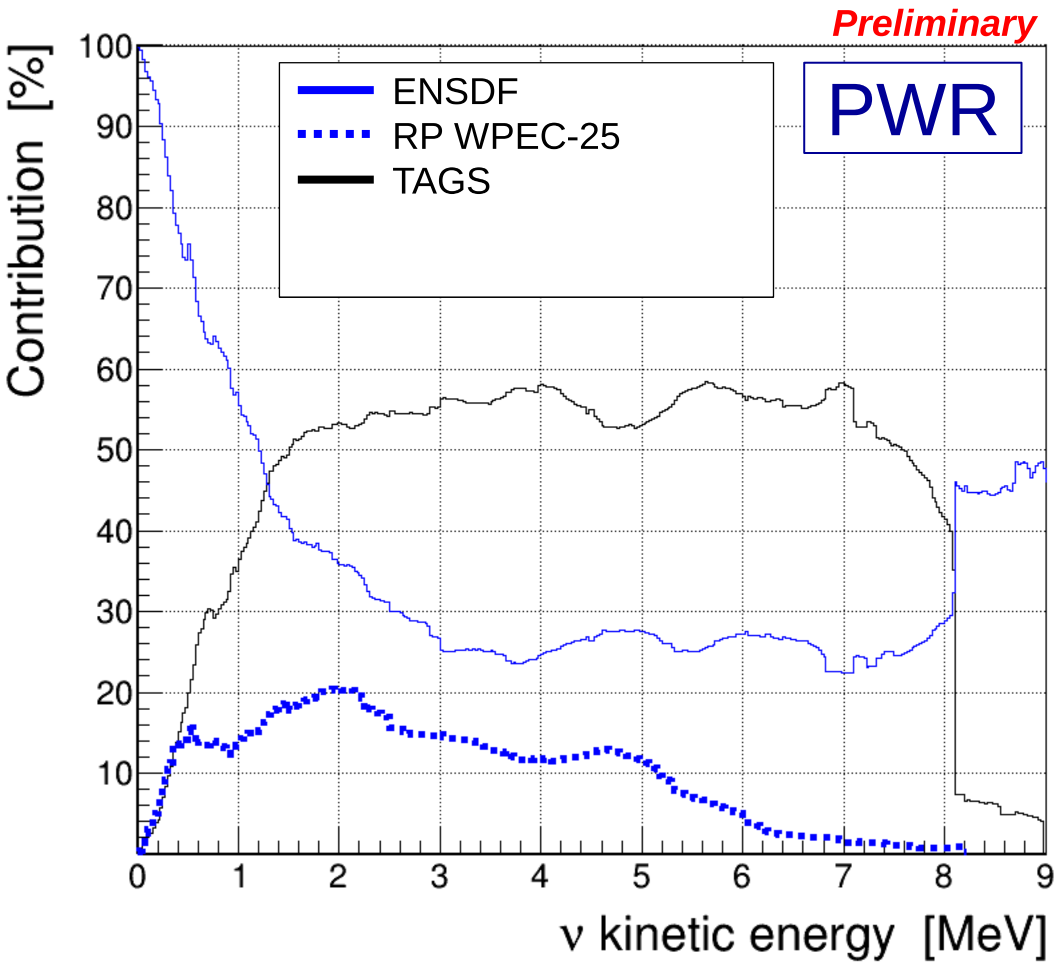
		β^- emitters from JEFF-3.3		
		NUBASE-2020	**ENSDF-2020**	**TAGS***
	^{235}U	793	448	84 (29)
	^{238}U	778	419	83 (29)
	^{239}Pu	851	507	84 (29)
	^{241}Pu	860	485	84 (29)
PWR	**$\bar{\nu}_e$ flux contribution [%]**		**55**	**36 (14)**
PWR	**IBD yield contribution [%]**		**27**	**55 (11)**

*Residual Pandemonium in parenthesis, list from INDC(NDS) - 0551. IAEA (2009) and INDC(NDS) – 0676. IAEA (2015)

Residual Pandemonium effect (RP) in ENSDF data

- RP WPEC-25
  - ▻ 29 isotopes identified by IAEA WPEC-25
  - ▻ IBD contribution: 10-12%

⇒ Measurements needed, meanwhile RP correction is applied



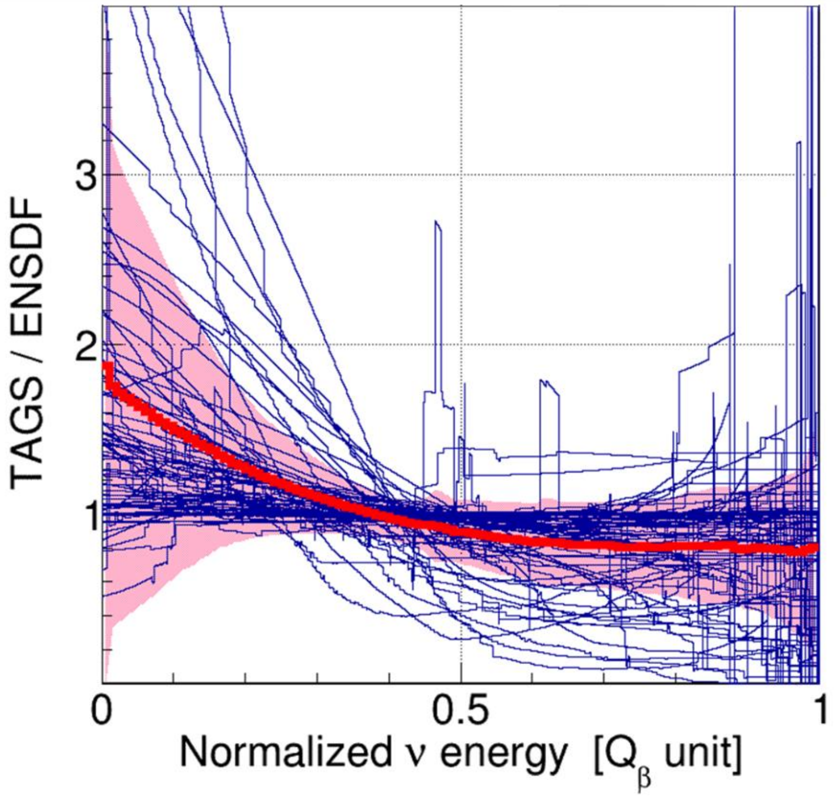
Quality of nuclear data

- Acceptable: TAGS, ENSDF
- Questionable: residual Pandemonium
  - ▻ **29 isotopes identified**
  - ▻ Measurement needed

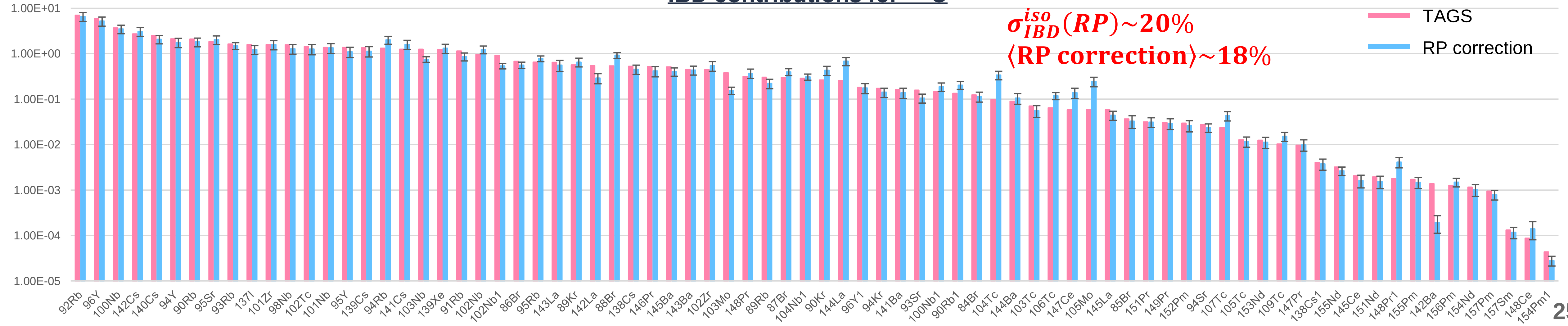
RESIDUAL PANDEMONIUM CORRECTION

Buiding

- Correction + uncertainty based on 81 isotopes having both TAGS and ENSDF data
- Correction = average ratio TAGS/ENSDF
- Uncertainty = dispersion of ratios
  - Fully correlated between isotopes and actinides



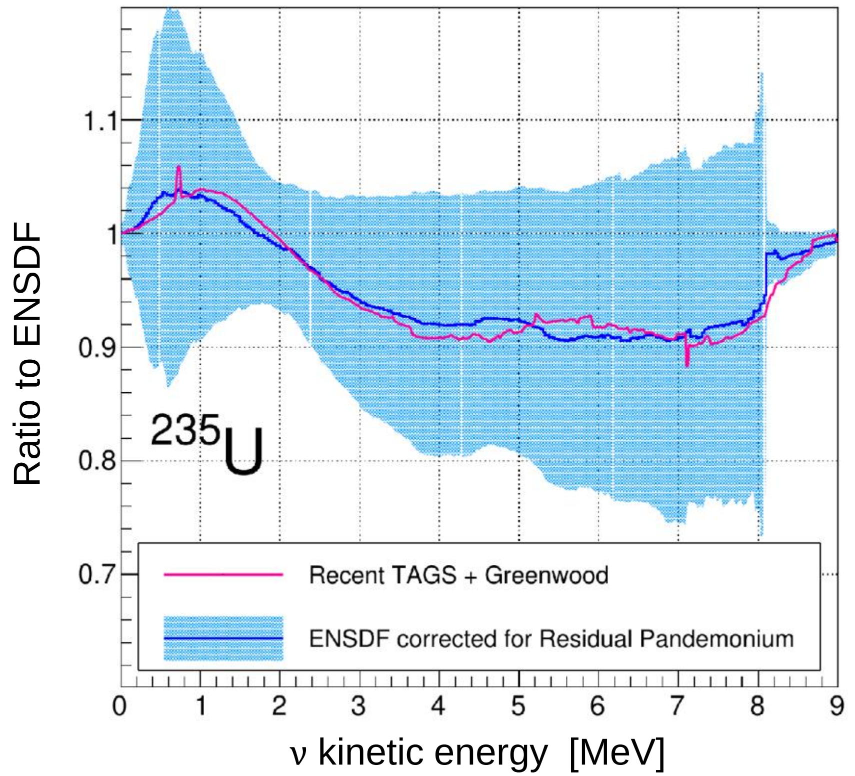
IBD contributions for ^{235}U

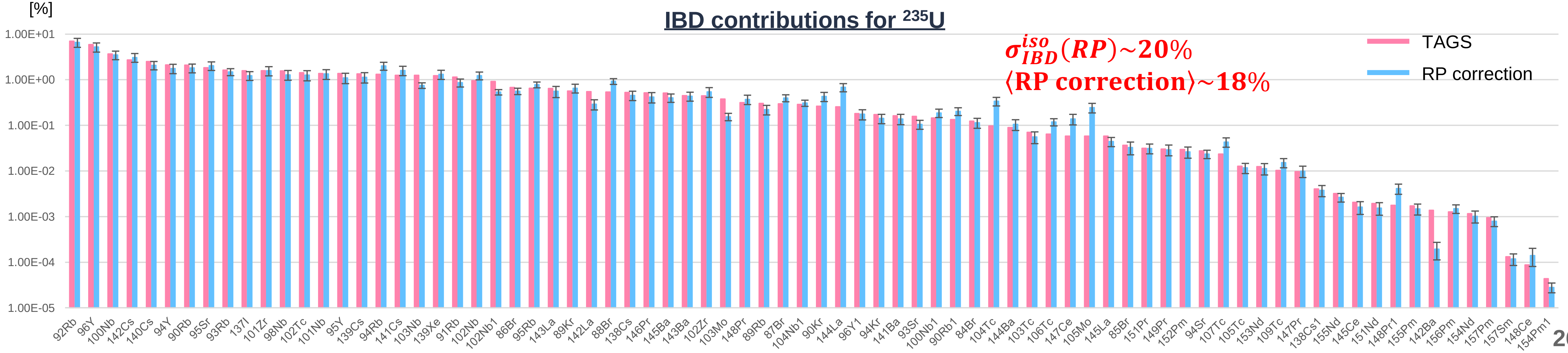


RESIDUAL PANDEMONIUM CORRECTION

Testing on ^{235}U

- ^{235}U IBD yield compared to using only ENSDF
  - Using TAGS data → -7.7%
  - Using RP correction → (-7.2 ± 10.5)%



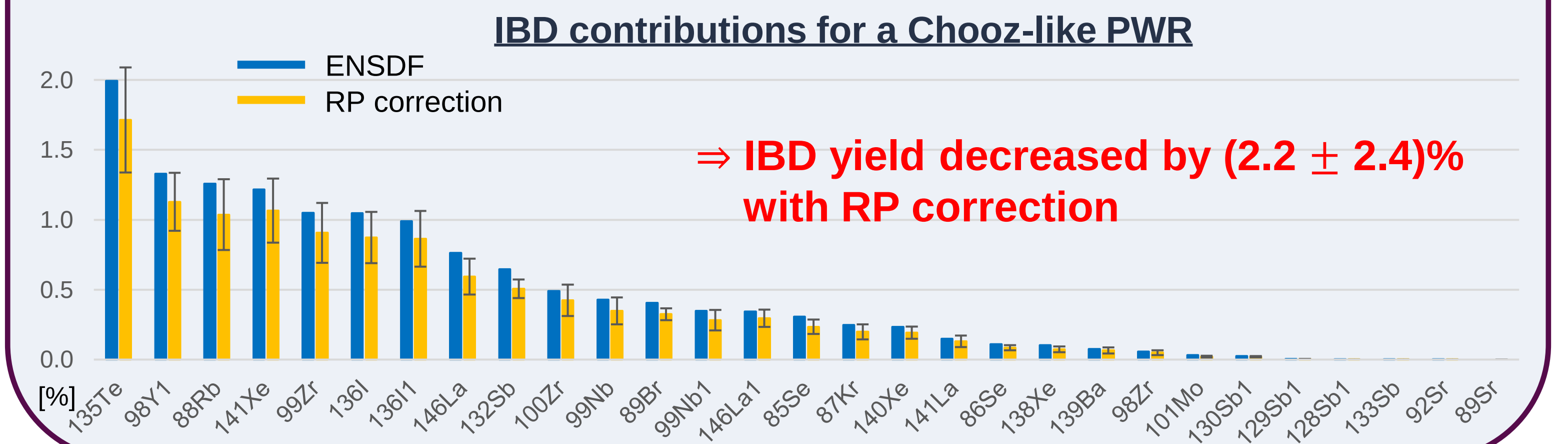


	β⁻ emitters from JEFF-3.3		
	NUBASE-2020	ENSDF-2020	TAGS*
^{235}U	793	448	84 (29)
^{238}U	778	419	83 (29)
^{239}Pu	851	507	84 (29)
^{241}Pu	860	485	84 (29)
PWR $\bar{\nu}_e$ flux contribution [%]		**55**	**36 (14)**
PWR IBD yield contribution [%]		**27**	**55 (11)**

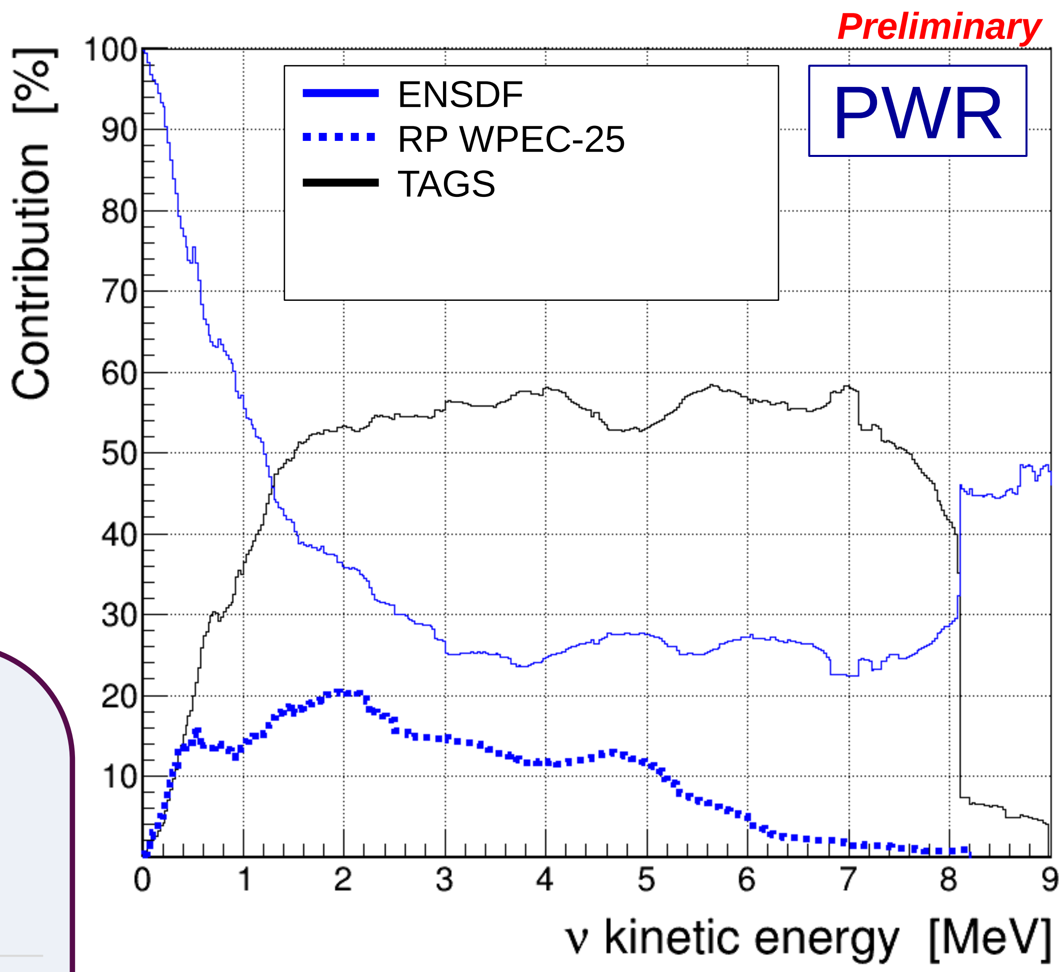
*Residual Pandemonium in parenthesis, list from INDC(NDS) - 0551. IAEA (2009) and INDC(NDS) – 0676. IAEA (2015)

RESIDUAL PANDEMONIUM CORRECTION

- Apply RP correction on the 29 isotopes from WPEC-25



⇒ **IBD yield decreased by (2.2 ± 2.4)% with RP correction**



Quality of nuclear data

- Acceptable: TAGS, ENSDF
- Questionable: residual Pandemonium
  - ▻ **29 isotopes identified**
  - ▻ Measurement needed

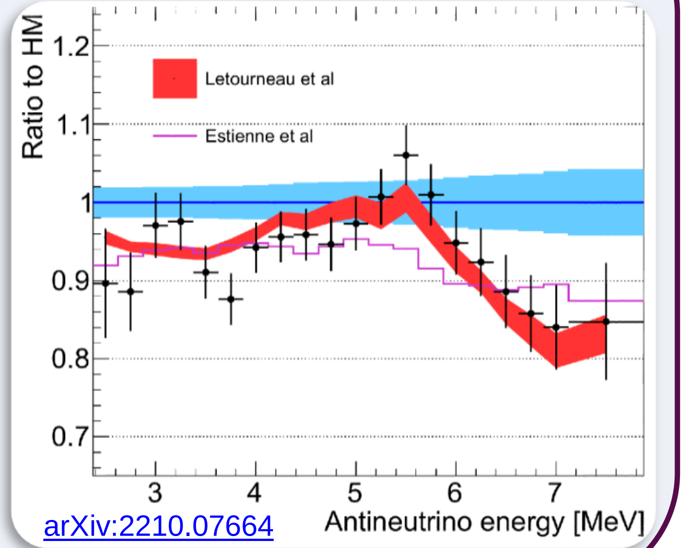
	β^- emitters from JEFF-3.3		
	NUBASE-2020	ENSDF-2020	TAGS*
^{235}U	793	448	84 (29)
^{238}U	778	419	83 (29)
^{239}Pu	851	507	84 (29)
^{241}Pu	860	485	84 (29)
PWR $\bar{\nu}_e$ flux contribution [%]		**55**	**36 (14)**
PWR IBD yield contribution [%]		**27**	**55 (11)**

*Residual Pandemonium in parenthesis, list from INDC(NDS) - 0551. IAEA (2009) and INDC(NDS) – 0676. IAEA (2015)

PHENOMENOLOGICAL DECAY STRENGHT MODEL

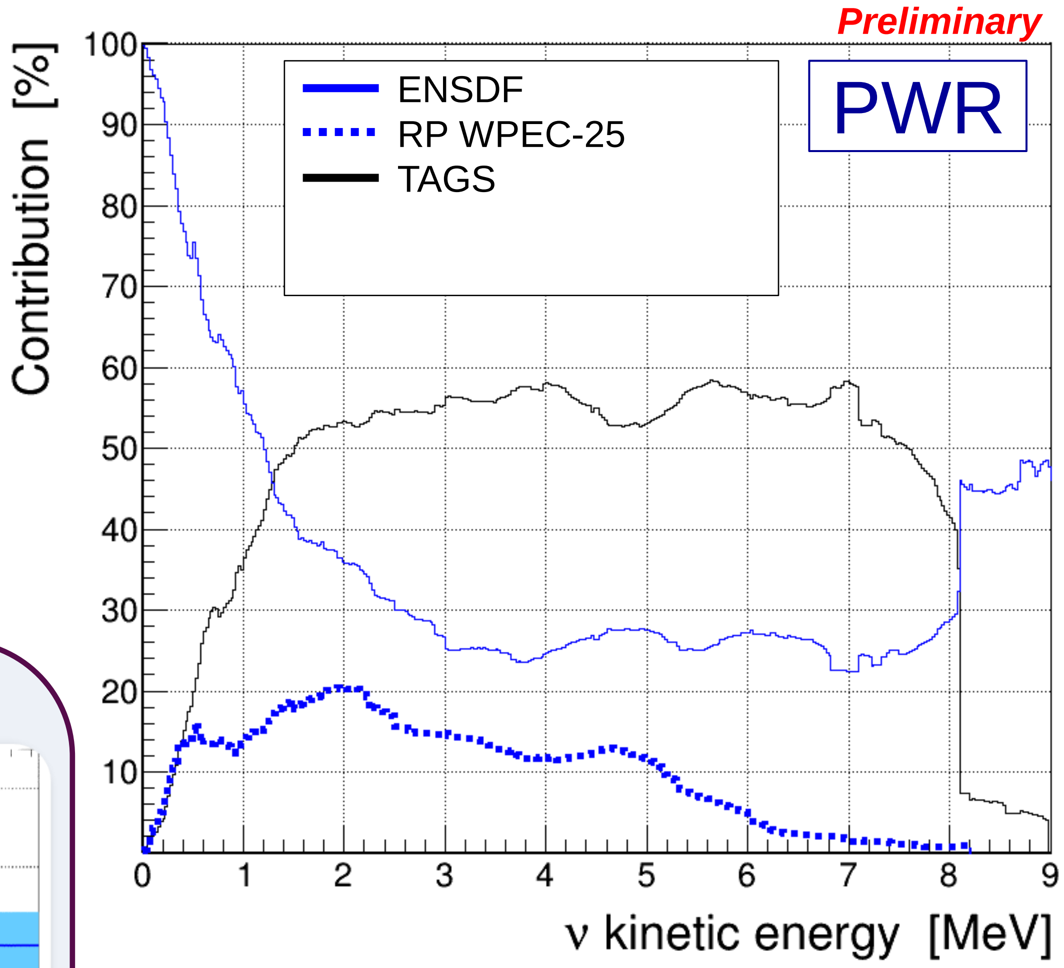
- 1 parameter Gamow-Teller strength model
- Generate missing transitions for all fission products from ENSDF
  - Correct Pandemonium effect and missing transitions
- Letourneau et al., PRL 130, 021801 (2023)

⇒ **Very good agreement with STEREO**



arXiv:2210.07664

Preliminary



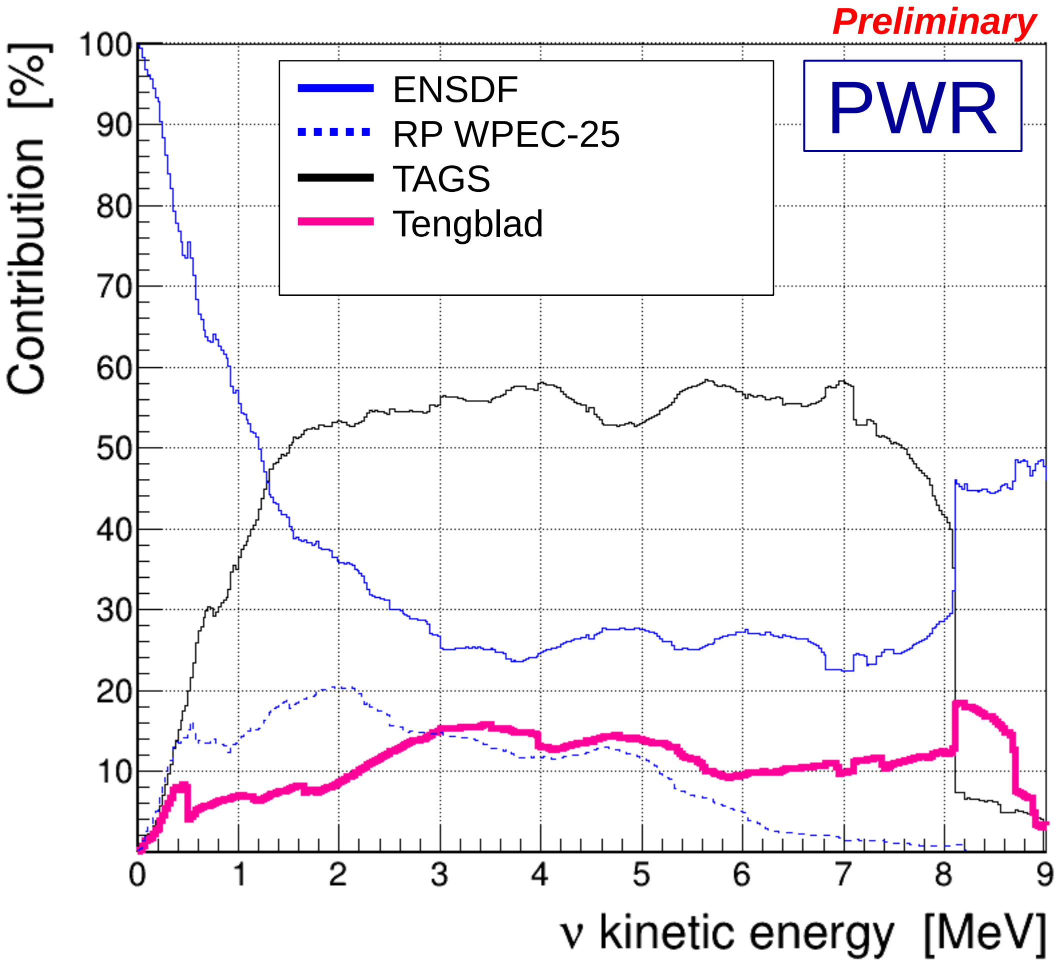
Quality of nuclear data

- Acceptable: TAGS, ENSDF
- Questionable: residual Pandemonium
  - **29 isotopes identified**
  - Measurement needed

		β⁻ emitters from JEFF-3.3			
		NUBASE-2020	ENSDF-2020	TAGS	Direct β*
	^{235}U	793	448	84 (29)	44
	^{238}U	778	419	83 (29)	44
	^{239}Pu	851	507	84 (29)	44
	^{241}Pu	860	485	84 (29)	44
PWR	**$\bar{\nu}_e$ flux contribution [%]**		**55**	**36 (14)**	**8**
PWR	**IBD yield contribution [%]**		**27**	**55 (11)**	**13**

*Rudstam et al., At. Data Nucl. Data Tables 45(2):239-320 (1990)

Direct β measurements are Pandemonium-free
- Priority over ENSDF but after TAGS
- β spectra converted to $\bar{\nu}_e$ spectra



Quality of nuclear data
- Acceptable: TAGS, ENSDF, Direct β
- Questionable: residual Pandemonium

⇒ IBD yield decreased by (4.8 ± 1.4)% with Direct β measurements

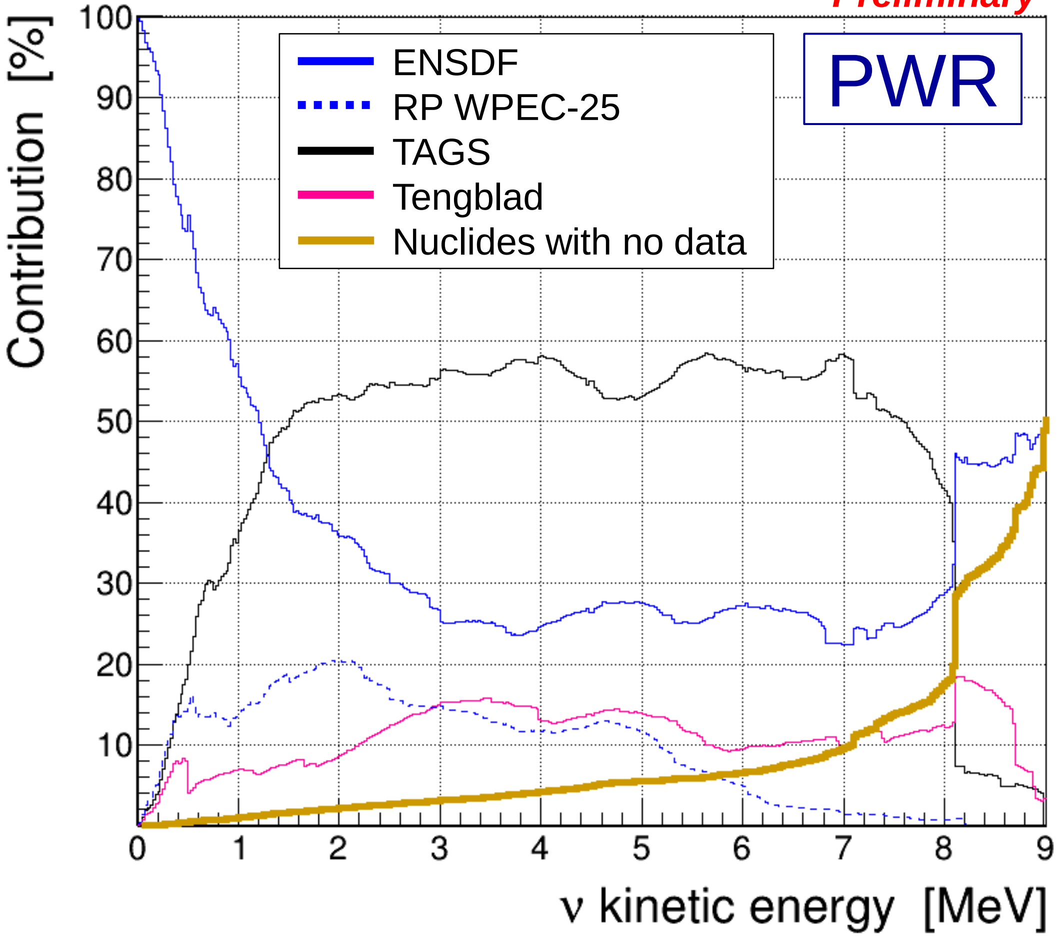
		β^- emitters from JEFF-3.3				
		NUBASE-2020	ENSDF-2020	TAGS	Direct β	No data
	^{235}U	793	448	84 (29)	44	217
	^{238}U	778	419	83 (29)	44	232
	^{239}Pu	851	507	84 (29)	44	216
	^{241}Pu	860	485	84 (29)	44	247
PWR	$\bar{\nu}_e$ flux contribution [%]		**55**	**36 (14)**	**8**	**1**
PWR	IBD yield contribution [%]		**27**	**55 (11)**	**13**	**5**

How to model nuclides with no data (NND) ?

- Different modelings already tested in other summation models
  - Q_β model with n branches, Gross theory
  - No modeling uncertainty

⇒ Measurements needed, meanwhile modeling of NND + uncertainty

Preliminary



Quality of nuclear data

- Acceptable: TAGS, ENSDF, Direct β
- Questionable: residual Pandemonium
- Poor: nuclides with no data

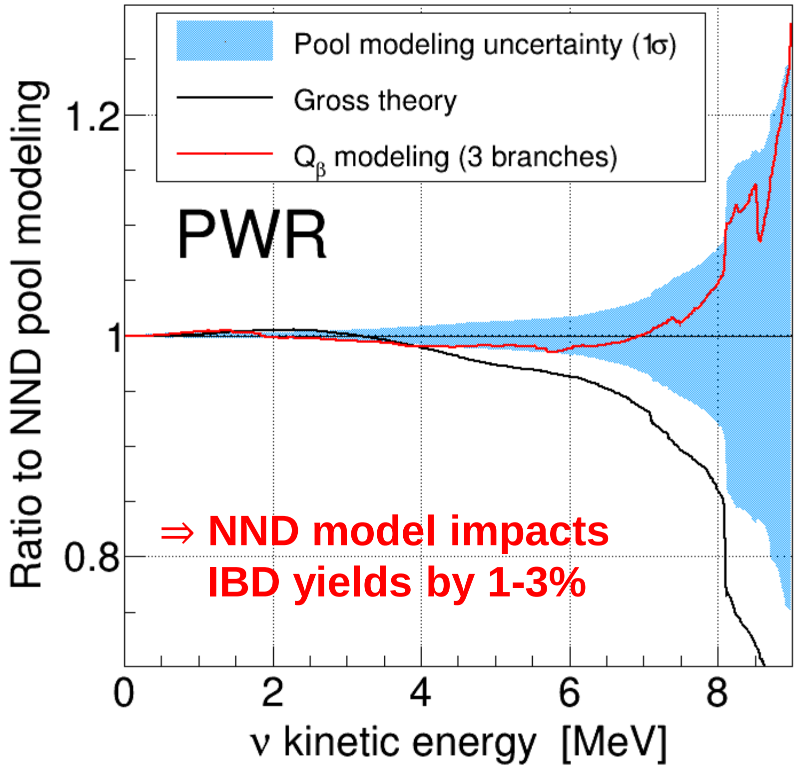
Important >7 MeV

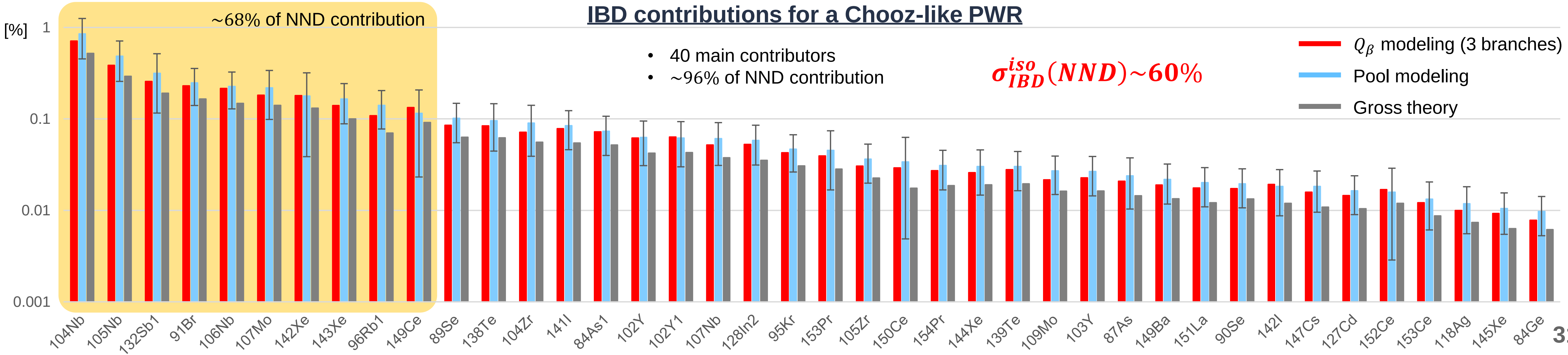
POOL MODELING OF NUCLIDES WITH NO DATA (NND)

- For each NND, spectrum + covariance matrix derived from pool of isotopes with data

Pool selection

- Isotope with data such that Q_β within $\pm$10% of the NND Q_β
  - 10-100 isotopes with data
- Spectrum = pool average
- Covariance matrix = pool dispersion
  - Uncertainties uncorrelated between isotopes
  - Cover other NND models at isotope level

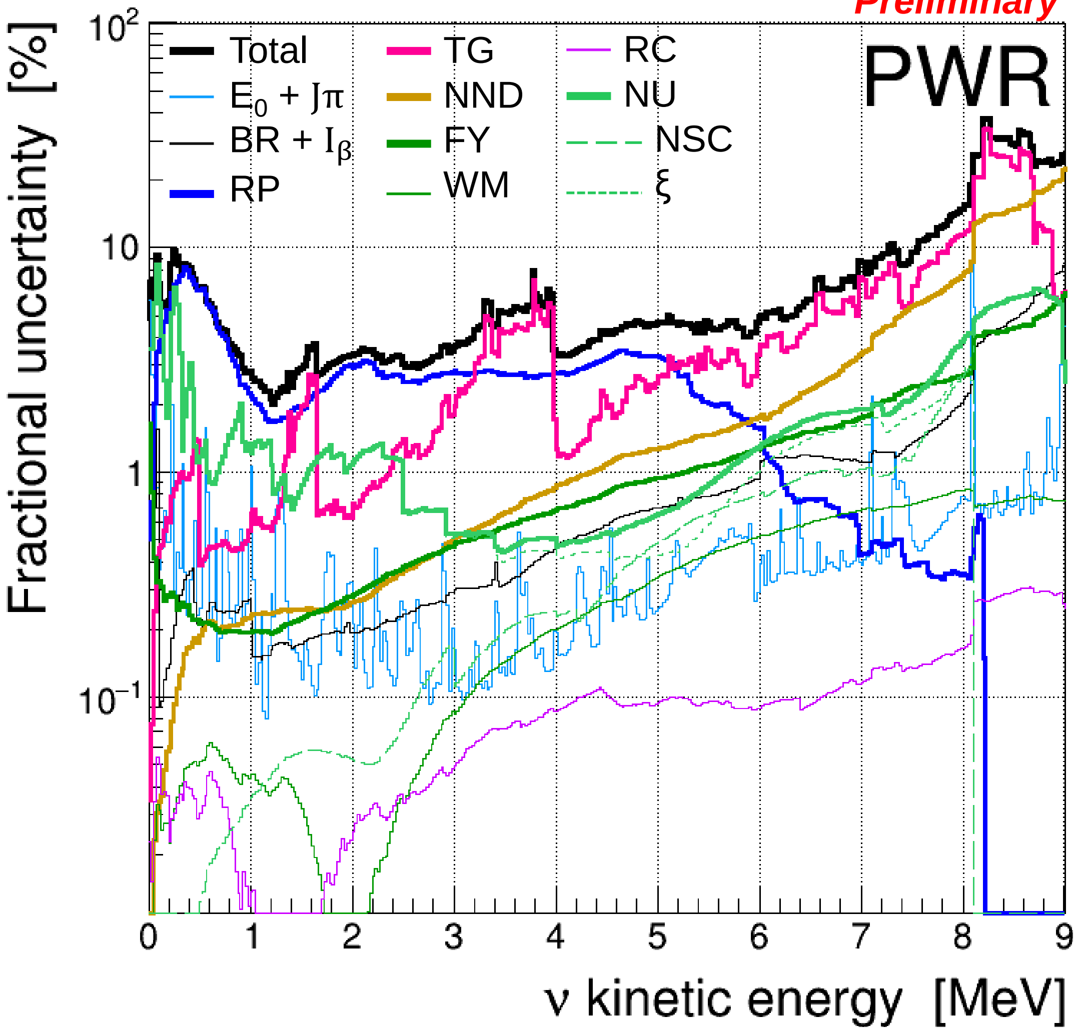




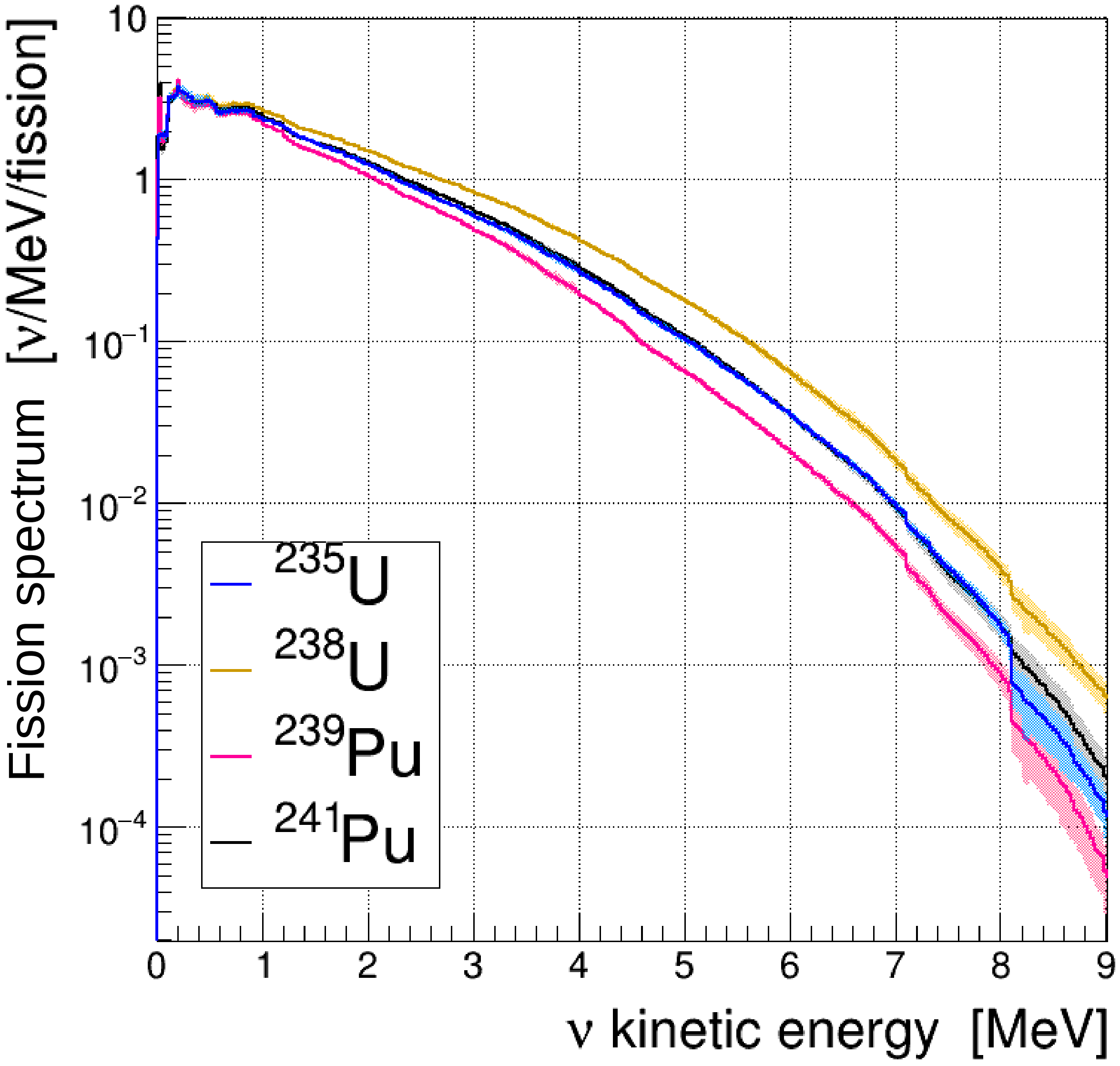
NORMALIZATION UNCERTAINTY

PWR				
$\langle\sigma_{IBD}\rangle$		6.08 x 10^{-43} cm^2/fission		
	Uncertainty	Abbrev.	Method	[%]
DATA	Endpoint + Spin-parity	$E_0 + J\pi$	MC	0.1
	Branching ratio + β^- intensity	$BR + I_\beta$	MC + Analytic	0.4
	Residual Pandemonium	RP	Analytic	2.5
	Tengblad	TG	Analytic	1.5
	Nuclides with no data	NND	Pool modeling	0.8
	Fission yield	FY	Analytic	~0.7
	Fission fraction		Analytic	~0.7
MODELING	Weak magnetism	WM	Model comparison	0.3
	Radiative corrections	RC	Model comparison	0.1
	Non-unique transitions	NU	Model comparison	0.4
	• Nuclear struct. calcul.	NSC		0.2
	• ξ-approximation	ξ		0.3
	IBD cross-section		Analytic	0.1
TOTAL				**3.1**

FRACTIONAL UNCERTAINTY



⇒ Uncertainty budget dominated by RP and TG (+ NND at high energy)



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 budget ~3%

OUTLINE

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

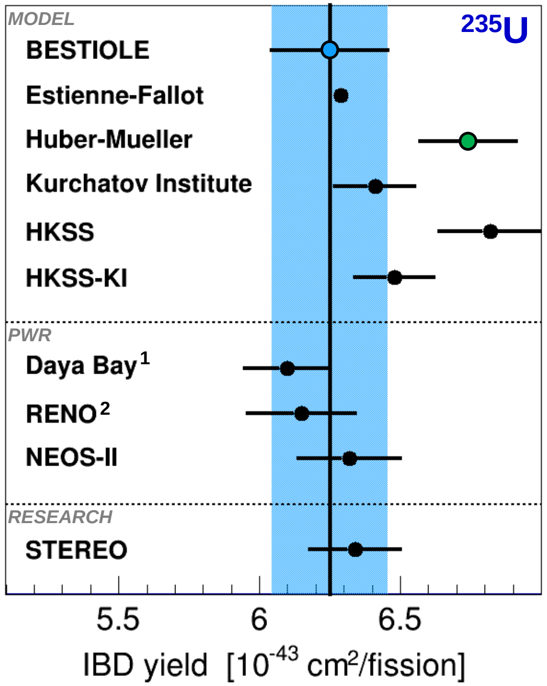
2. **Revised summation method**
   a. β^- spectrum calculation
   b. Nuclear data content
   c. Uncertainty budget

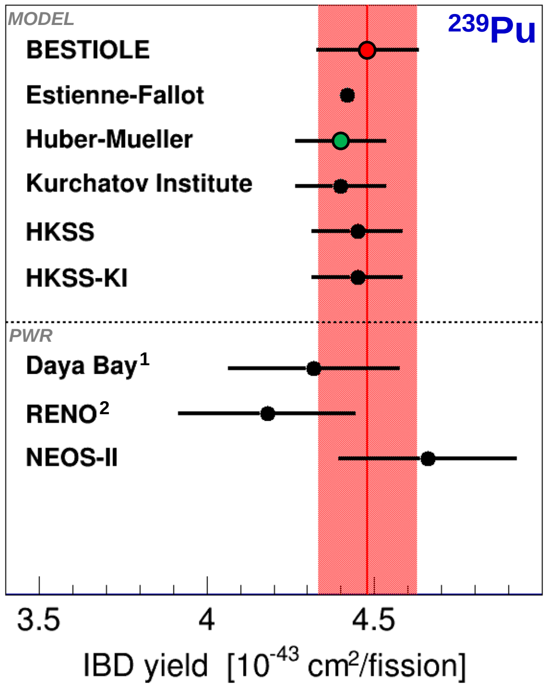
3. **Preliminary comparisons**
   a. Integral measurements
   b. Spectrum shape

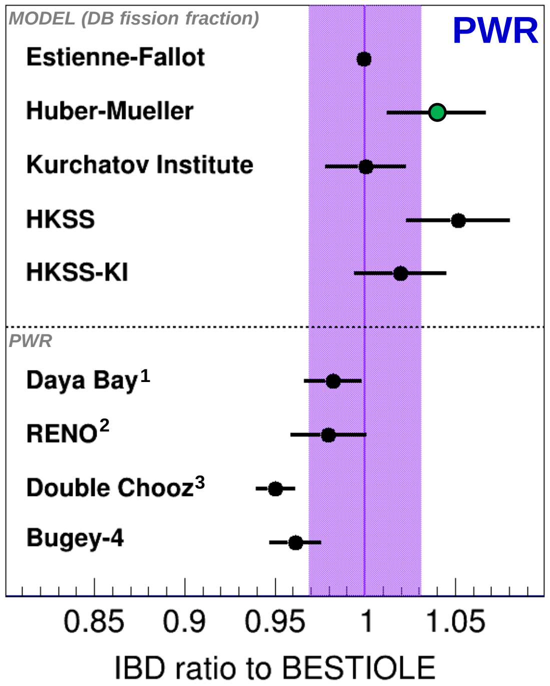
4. **Conclusion & perspectives**

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

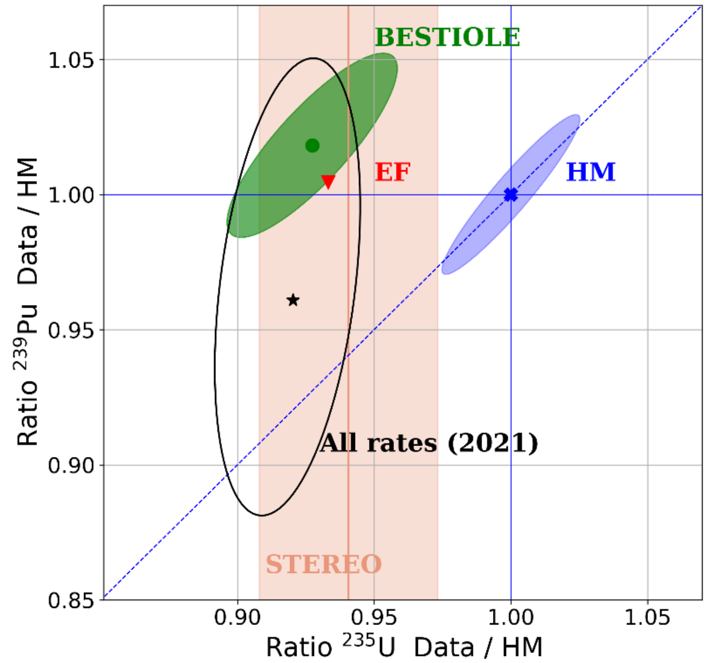
All plots are preliminary







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



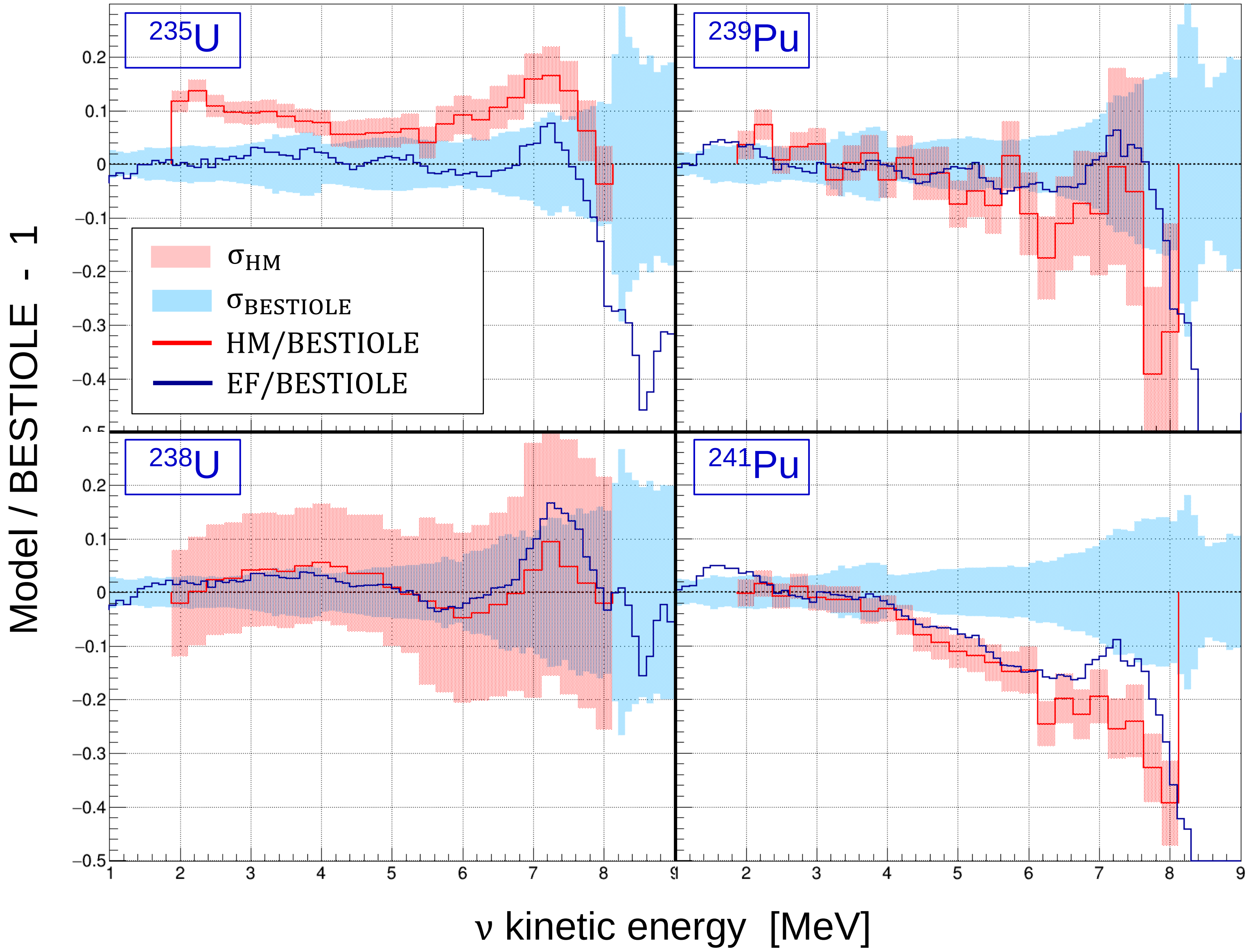
- ^{235}U, ^{238}U and ^{239}Pu : BESTIOLE consistent within ~1σ with other data
- ^{241}Pu: small tension with other data (1.5 - 2σ)
  - ▻ Important contribution of NND in BESTIOLE

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

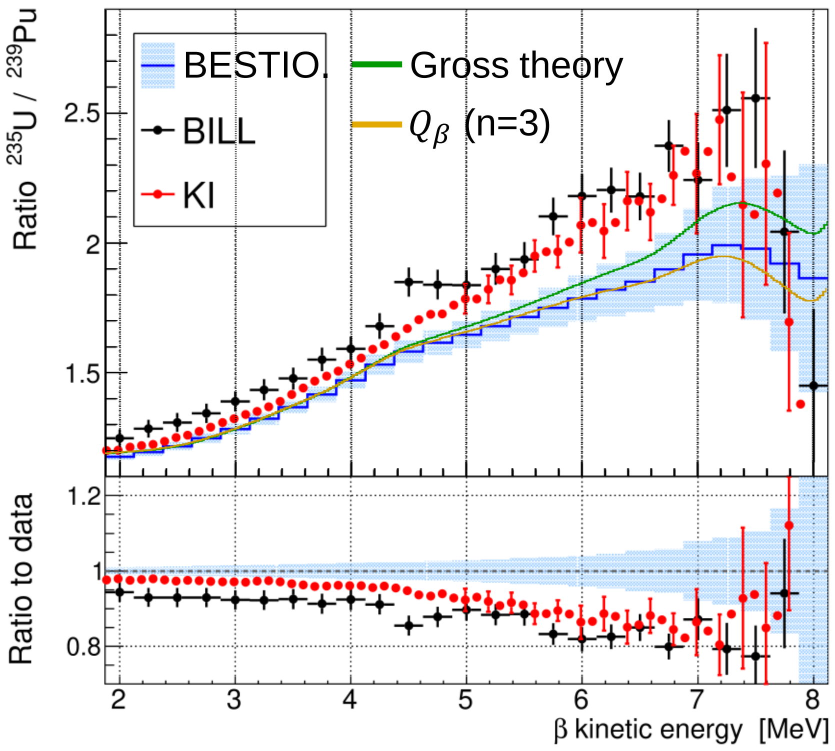
DB / HM = 0.945 ± 0.014 (exp) ± 0.024 (model)

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

All plots are preliminary



IMPACT OF NND MODEL

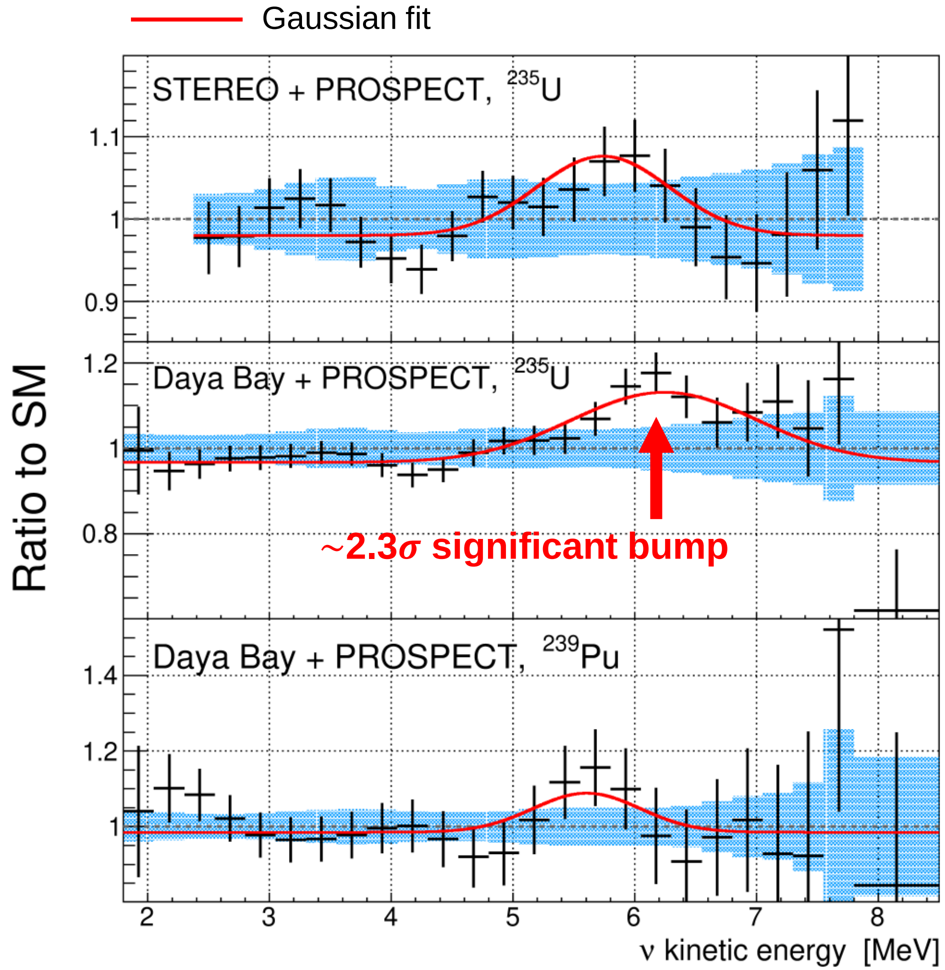


⇒ Impact of NND modeling observed >6 MeV, important >7 MeV

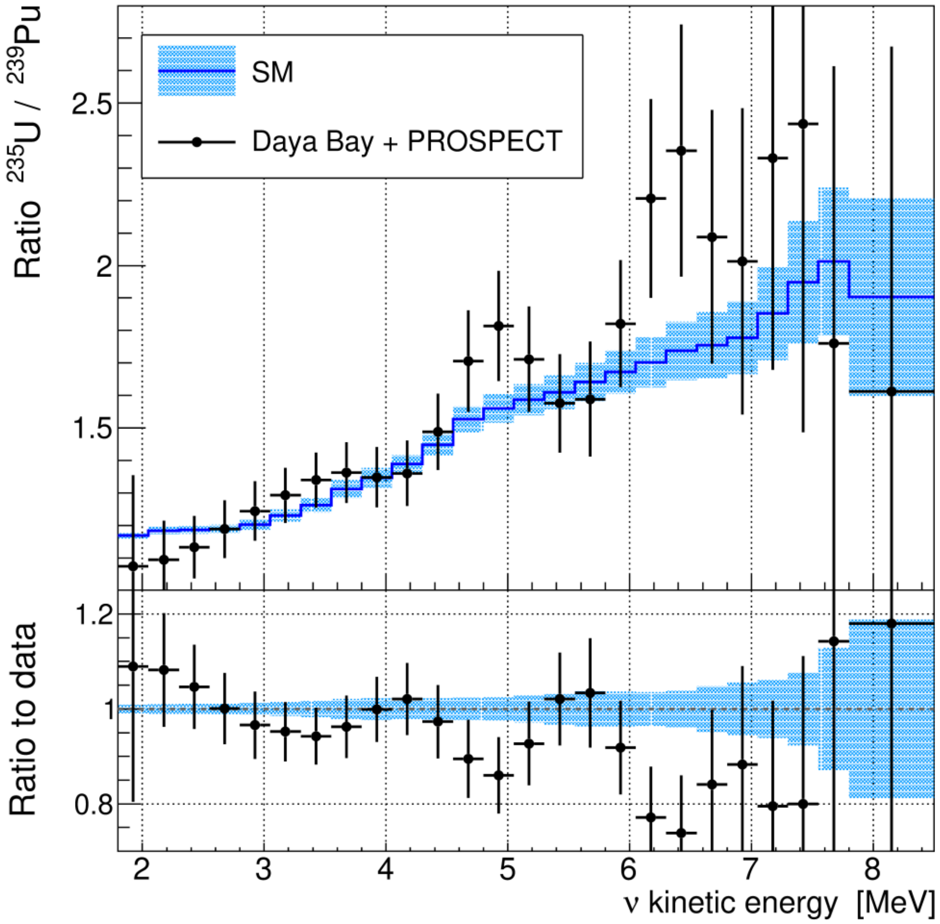
STEREO + PROSPECT data from Almazán et ak. (2022)
Daya Bay + PROSPECT data from An et al. (2022)

All plots are preliminary

RATIO OF IBD SPECTRA



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



⇒ Good agreement with experimental IBD spectra, no significant observation of deviation in 5-7 MeV

OUTLINE

KEY POINTS OF BESTIOLE SUMMATION PREDICTION

Modeling of non-unique forbidden transitions

- 23 non-unique forbidden branches computed with **nuclear structure calculation**
  - IBD yield **decreased by (1.3 $\pm$ 0.2)%**
- ξ-approximation uncertainty at fission spectrum level **$\sim$0.3% uncertainty**

Impact of TAGS data

- IBD yield **decreased by 8%**
- Residual Pandemonium correction, IBD yield **decreased by (2.2 $\pm$ 2.4)%**
  - Measurement needed, can also be used to validate RP correction

Modeling nuclides with no data

- Different NND modelings impact IBD yields by **1-3 %**
- Important for fission spectra **above 7 MeV**
  - Measurement needed, priority for high-energy spectrum comparison

Comprehensive uncertainty budget

- Uncertainty budget of summation model for the **first time ever**
  - Impact of FY correlations to be confirmed

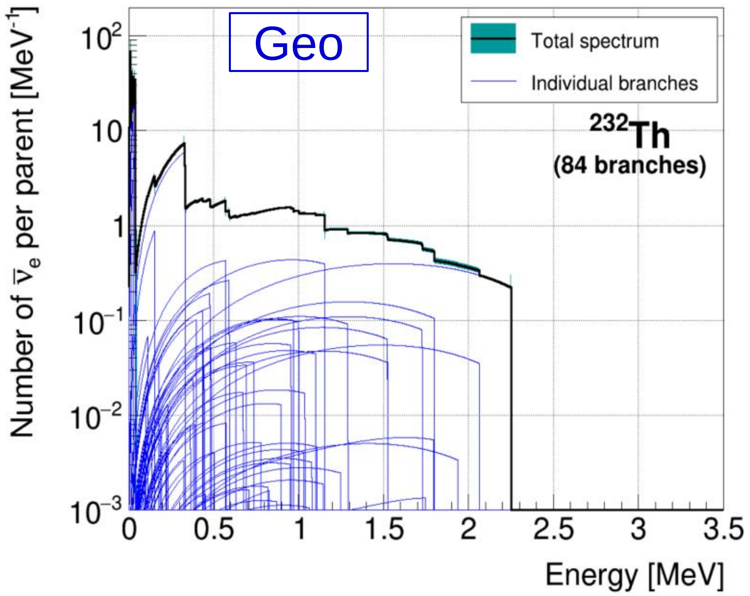
Final uncertainty budget $\sim 3\%$

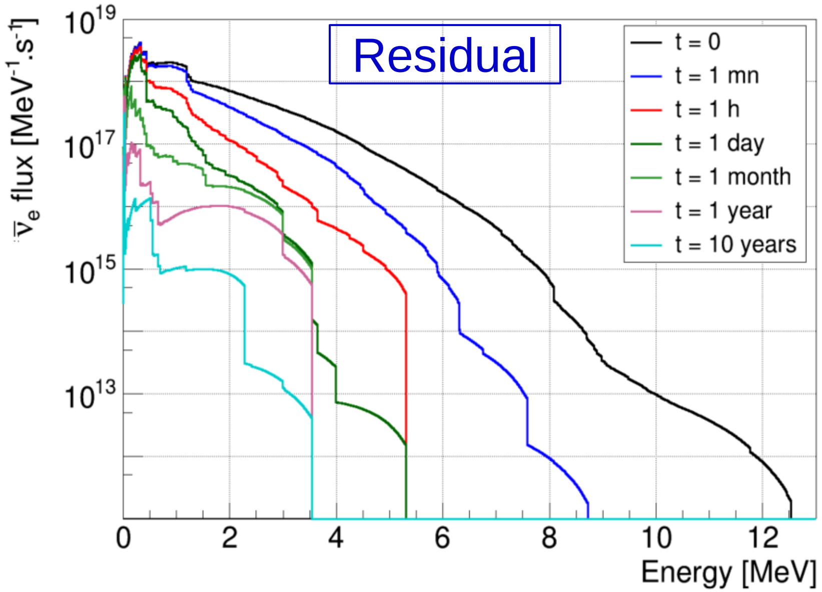
Led by RP correction

$\Rightarrow$ more TAGS data should be the priority

$\Rightarrow$ Article in preparation, coming soon with supplementary materials

Reach of a comprehensive summation model, needed for validation





See talk by Anthony Onillon