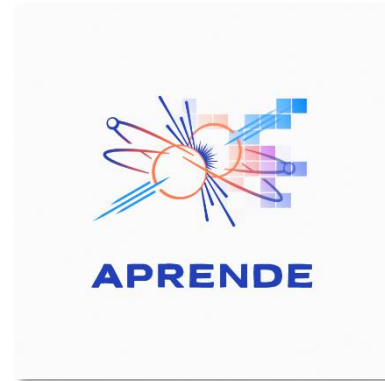




From experimental data to FY evaluation : JEFF4.0 and future program

G. Kessedjian¹, A. Regonesi¹, N. Teixeira-Rua¹, S. M. Cheikh¹, O. Serot¹,
A. Chebboubi¹, D. Bernard¹

¹CEA, DES, IRESNE, DER, SPRC, LEPh, Cadarache center, F-13108 Saint Paul
lez Durance, France



APRENDE Subtask 4.3.1 Fission yield evaluation

JEFF-4 Goal → New methodology : complete and consistent

S.-M. Cheikh, G. Kessedjian et al., Eur. Phys. J. A, 60 11 (2024) 222

• Previous FY evaluations :

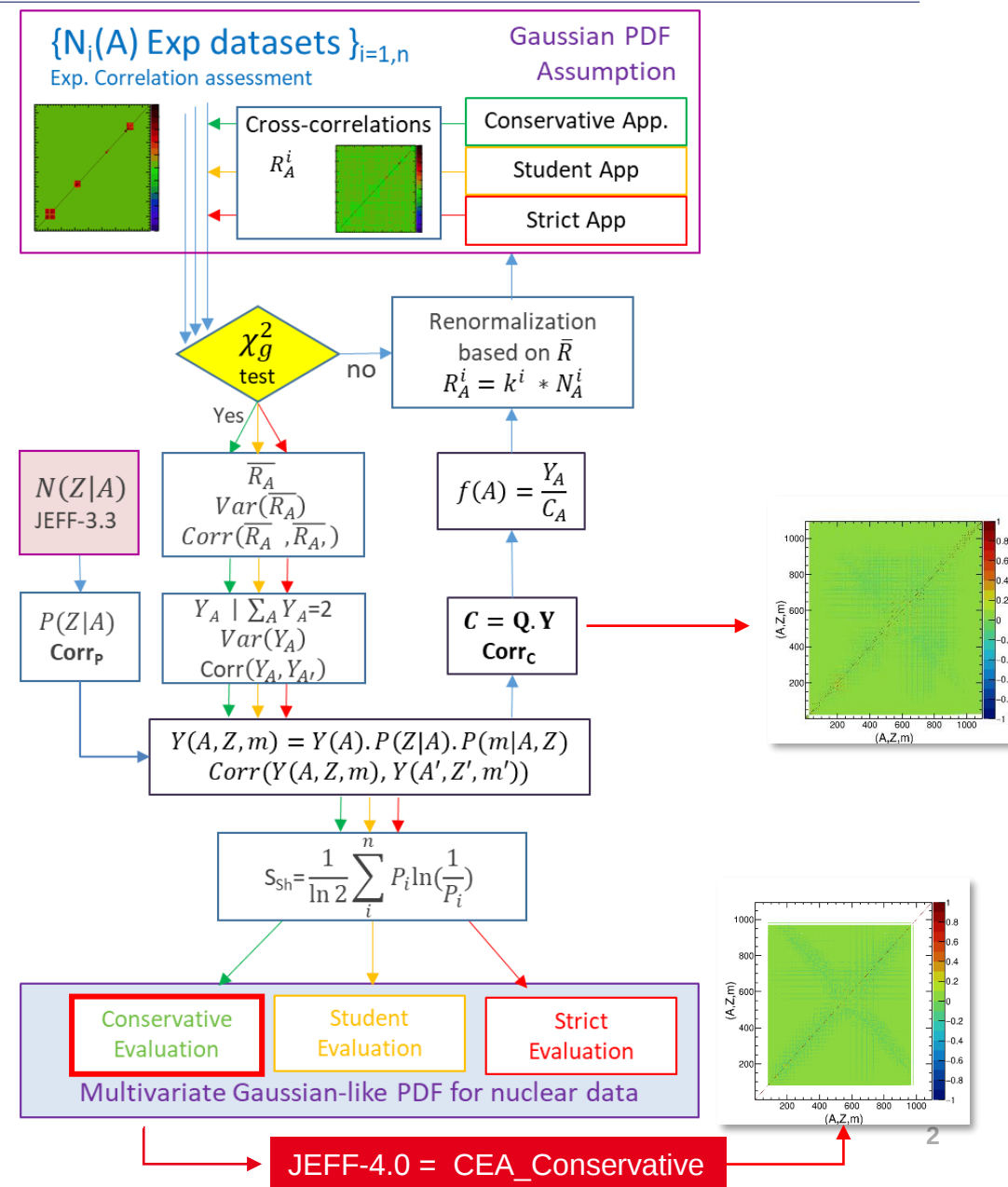
- Independent and Cumulative FY evaluations are **two different evaluations** : only mean values follow conservation laws
- Driven by the cumulative data
- **Uncertainties** of Ind. FY are **overestimated** due to the lack of correlation matrix as by-product of the analysis
- Covariance/correlation matrix of Ind FY is extrapolated assuming the C. Devillers methodology : **Assumption** $\text{Corr}(C, C') = I$

• JEFF-4 Evaluation

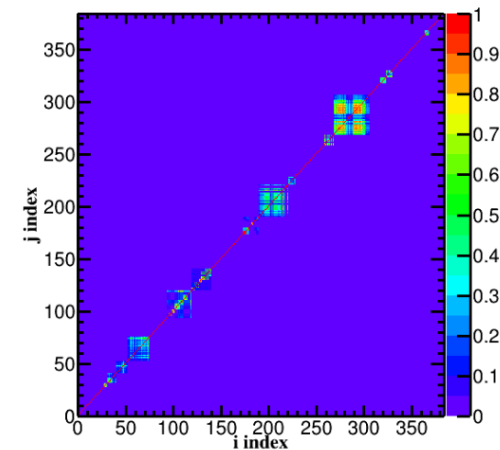
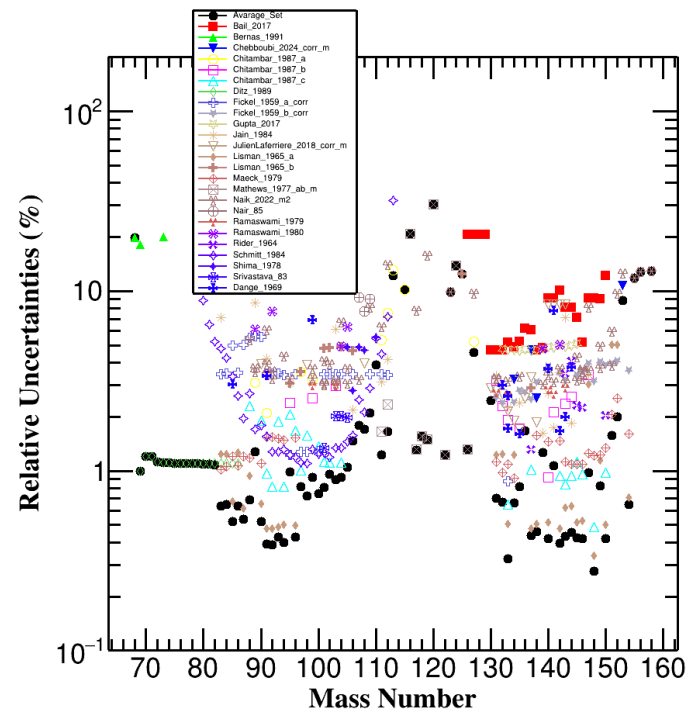
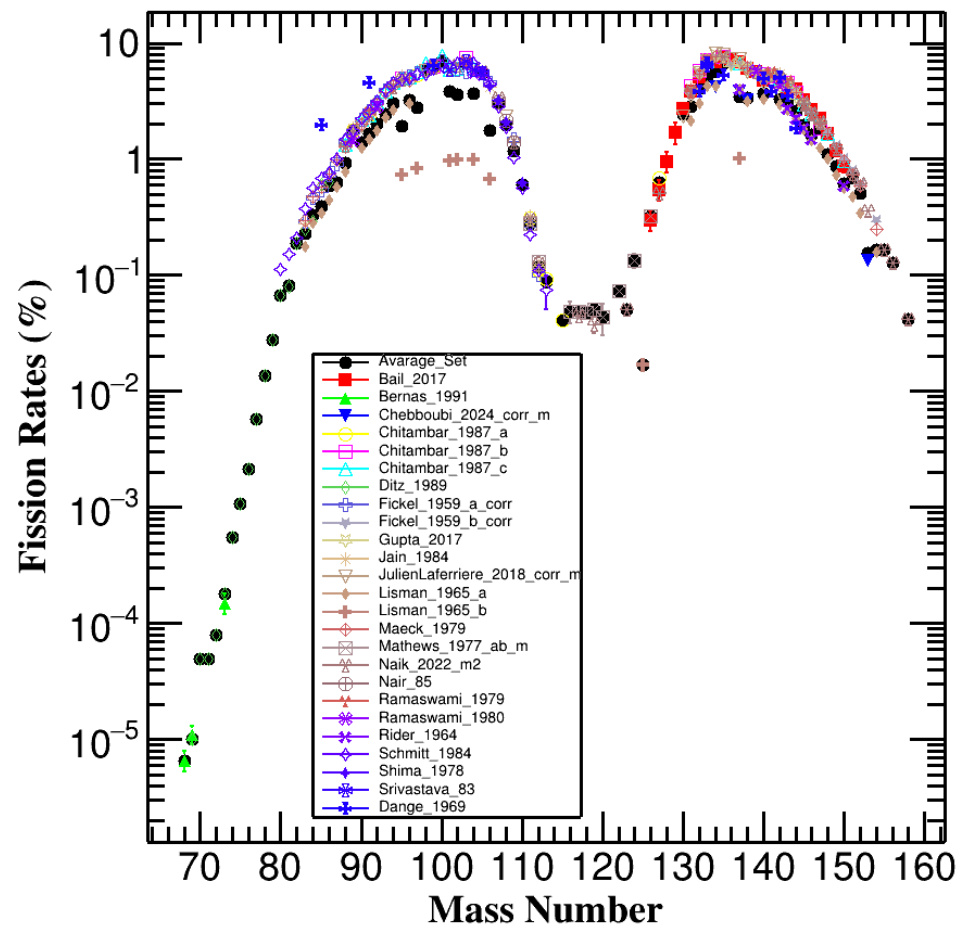
- Independent and Cumulative FY come from a **unique evaluation**
- Take into account the **experimental correlation matrix** available or deduced from literature
- **Complete description of the fission yield observables**: covariances
- **Consistent** according to the conservation laws for :
mean values, uncertainties and correlation matrices

- Monte Carlo Fission yield sampling files (MCFYF)

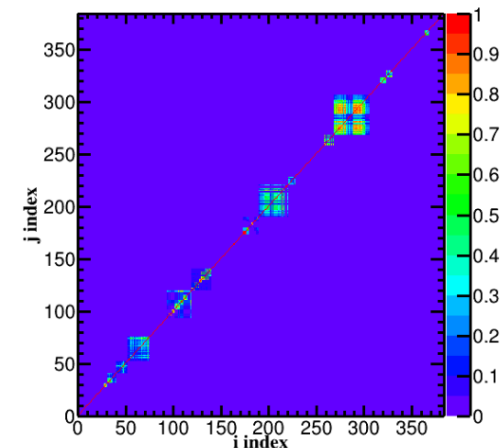
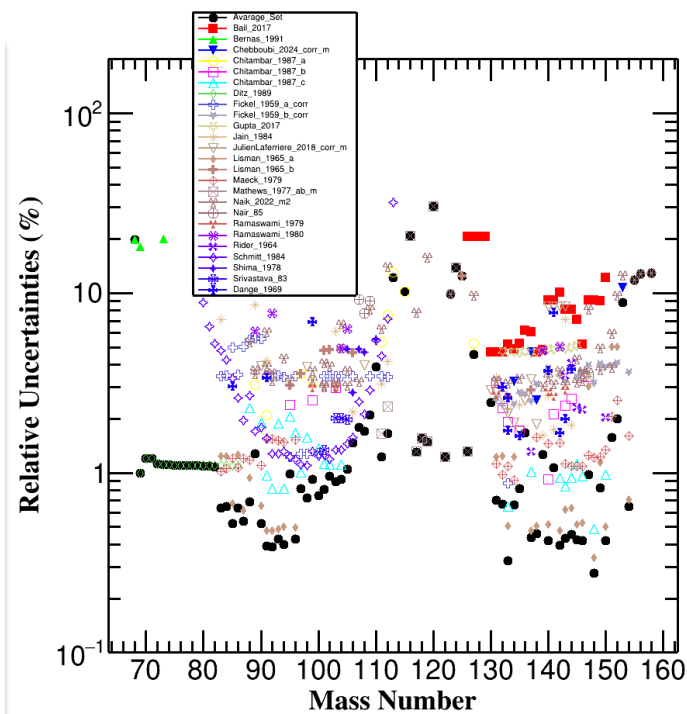
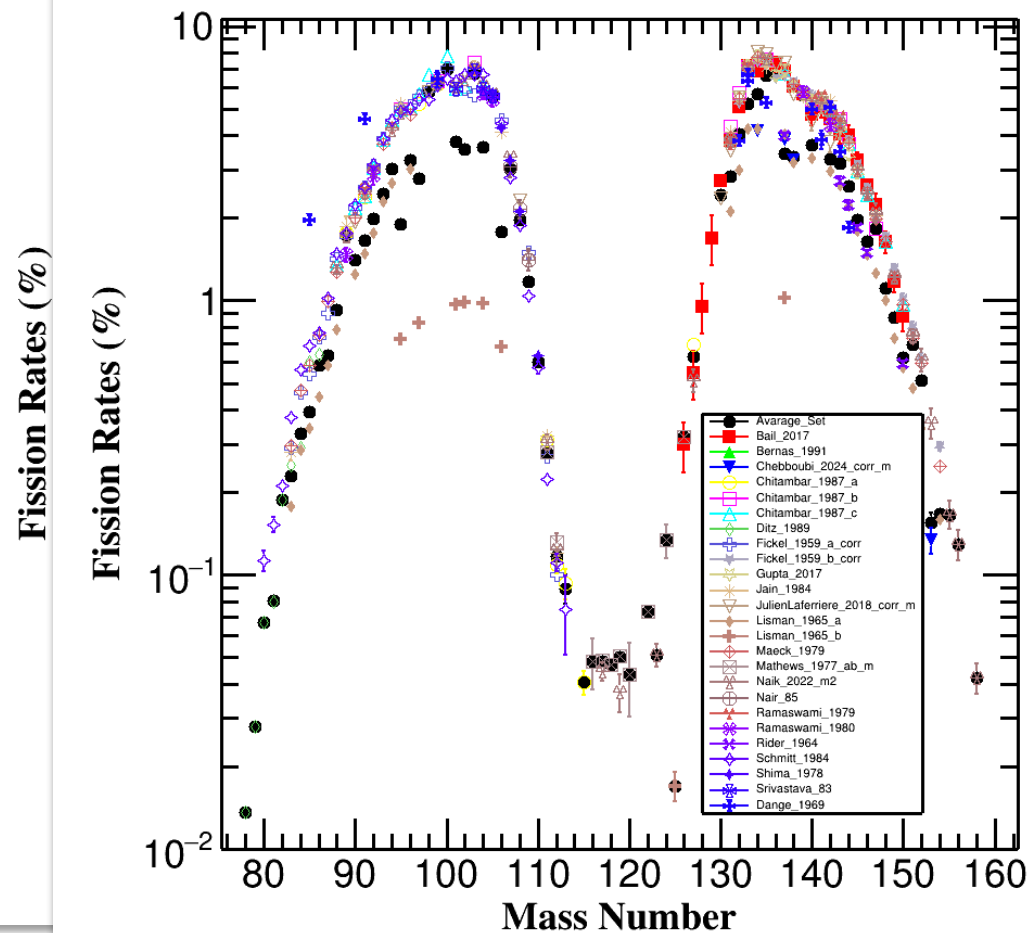
APRENDE Subtask 4.3.1 Fission yield evaluation



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: raw data



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: raw data

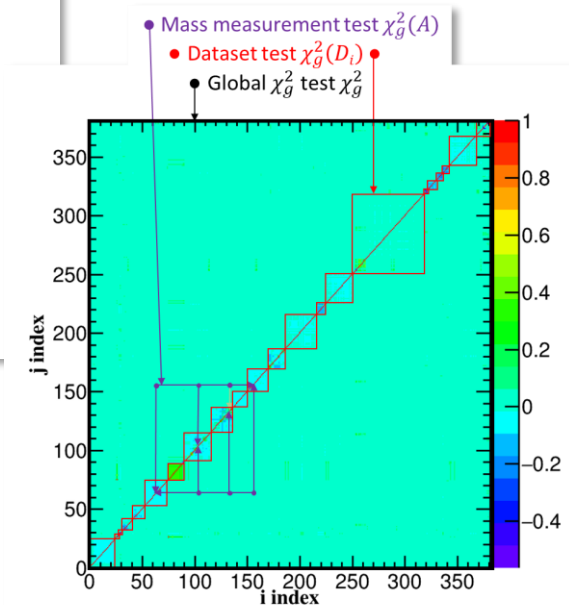
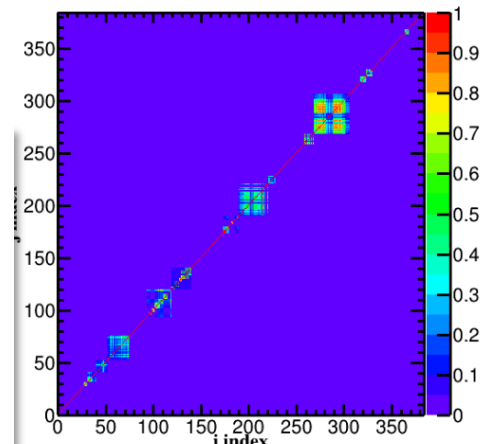
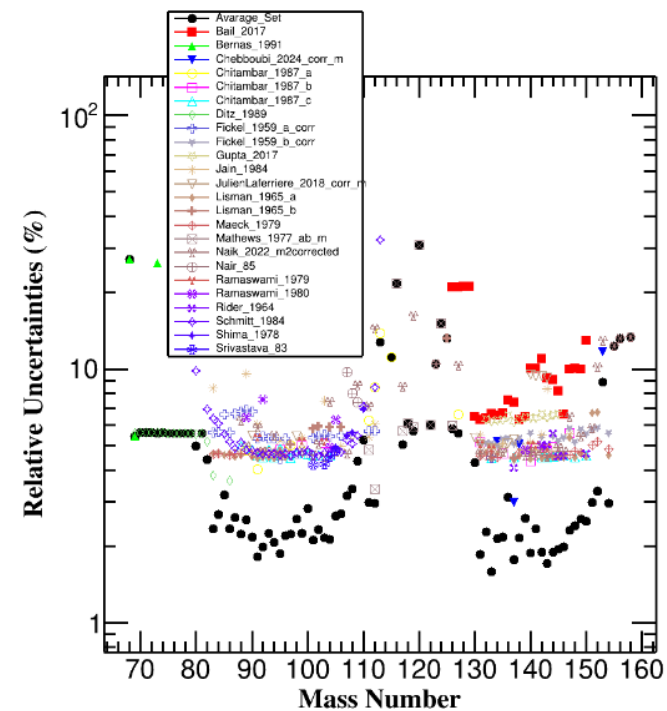
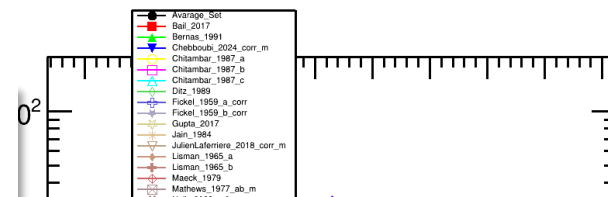
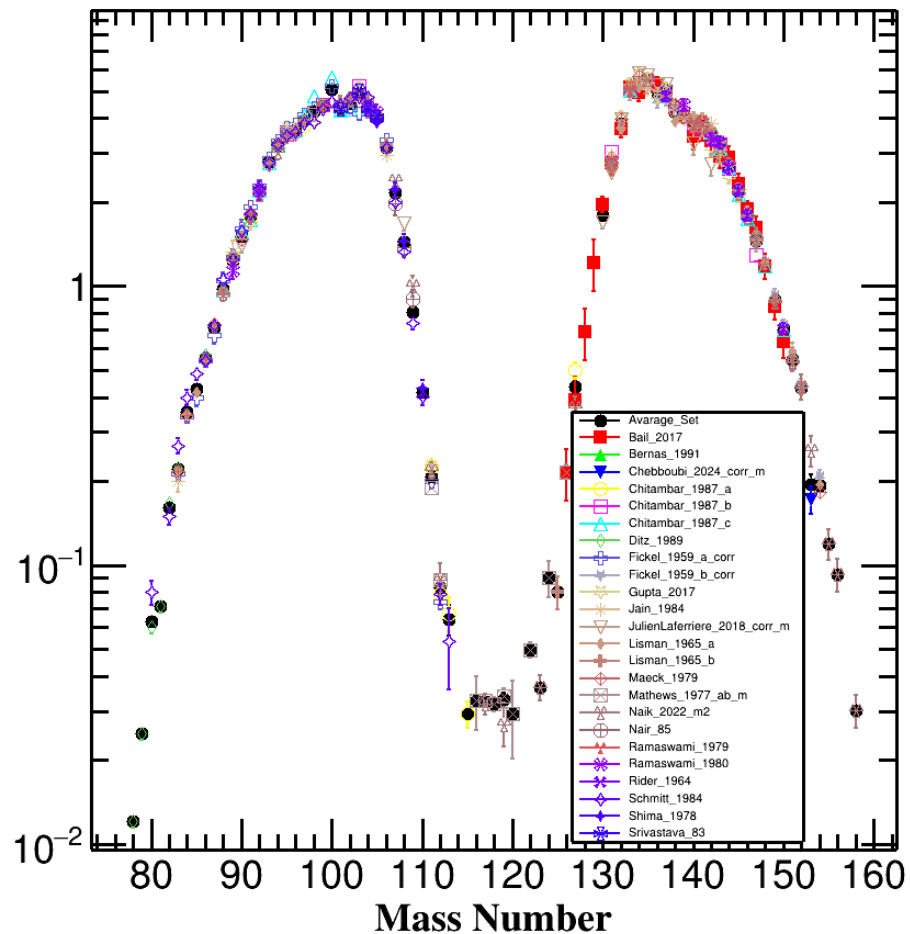


$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: renormalized and sorted

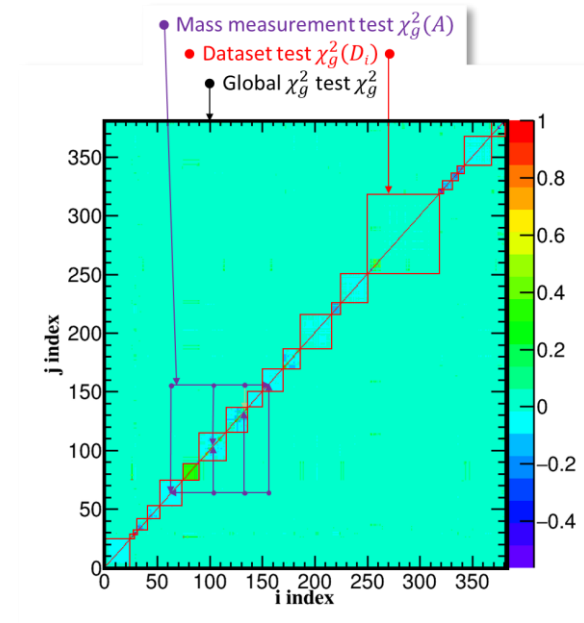
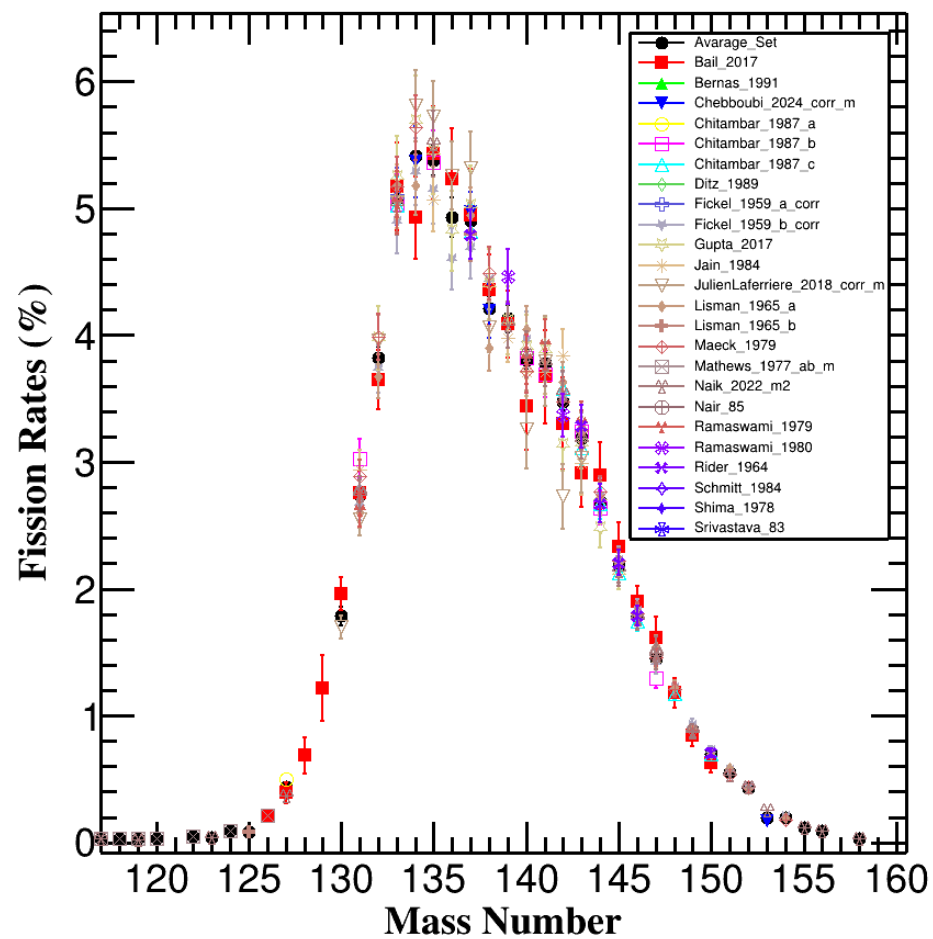
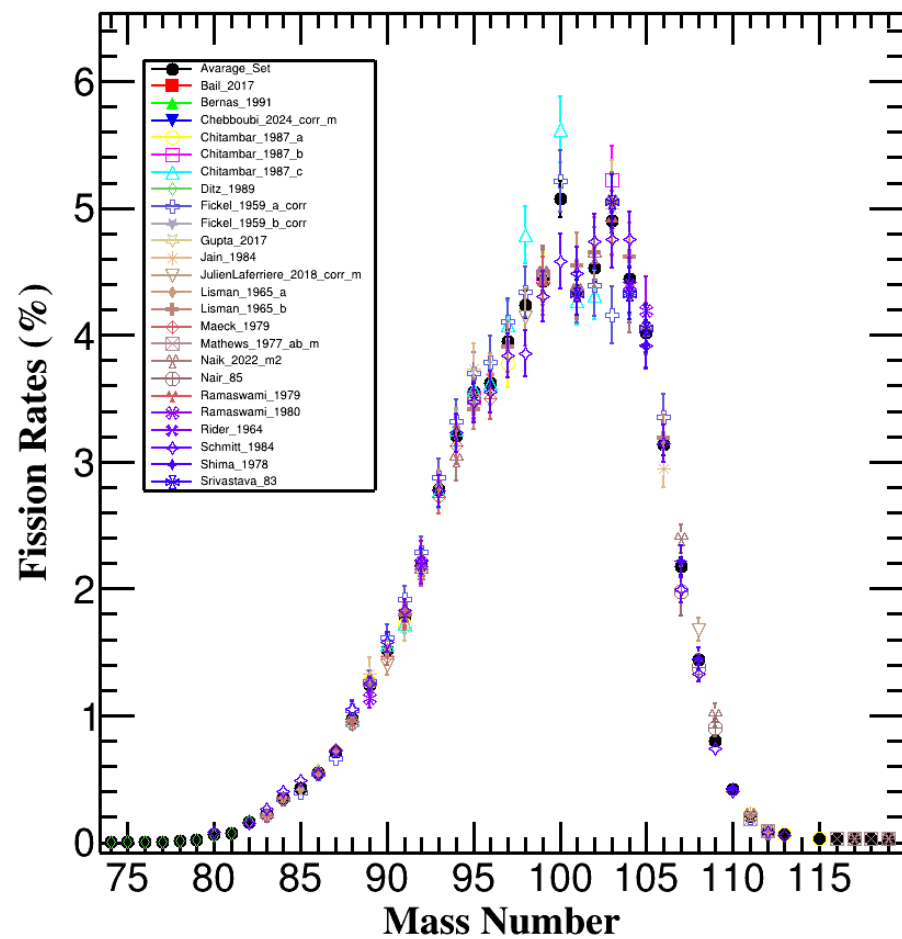
Fission Rates (%)

Fission Rates (%)

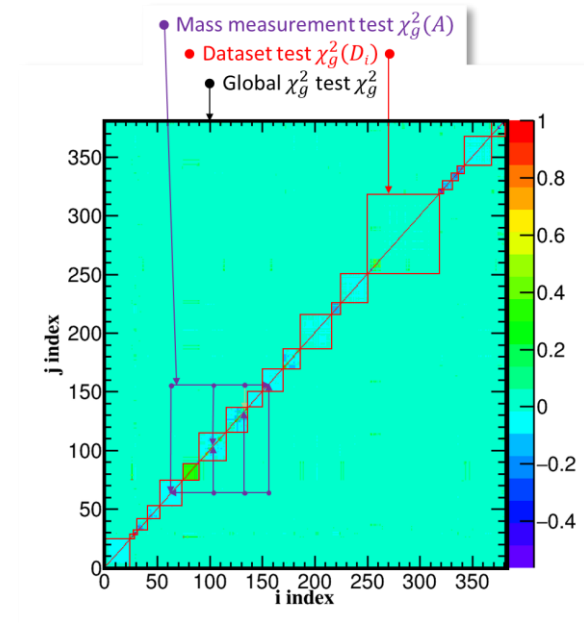
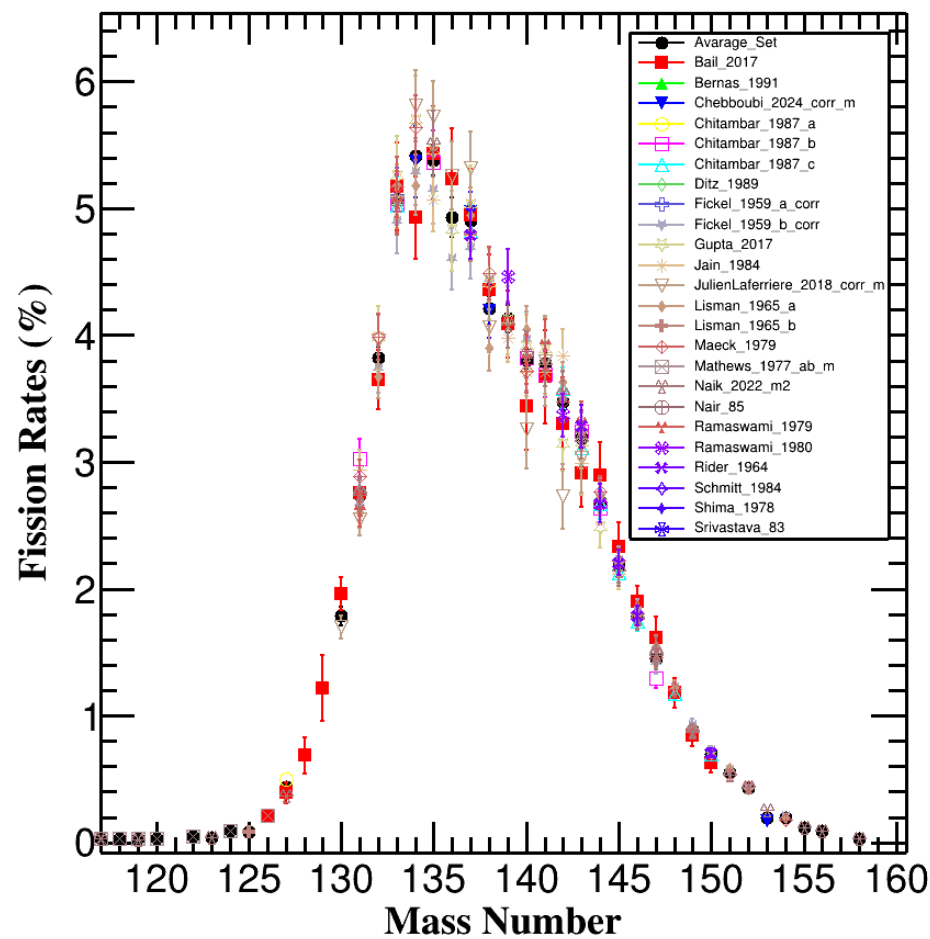
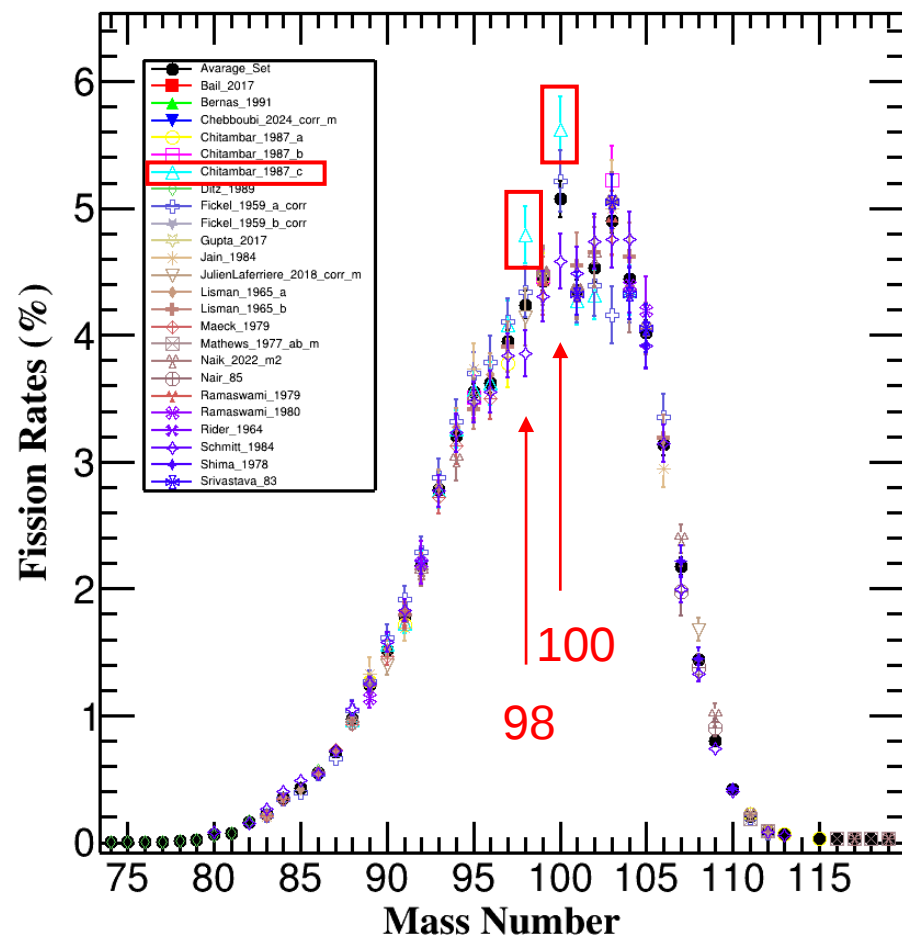
Fission Rates (%)



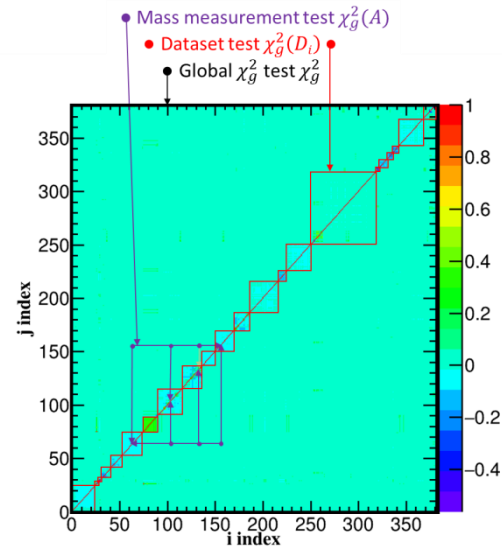
$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: renormalized and sorted



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: renormalized and sorted



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: χ^2_g test and data sorting



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: χ^2_g test and data sorting

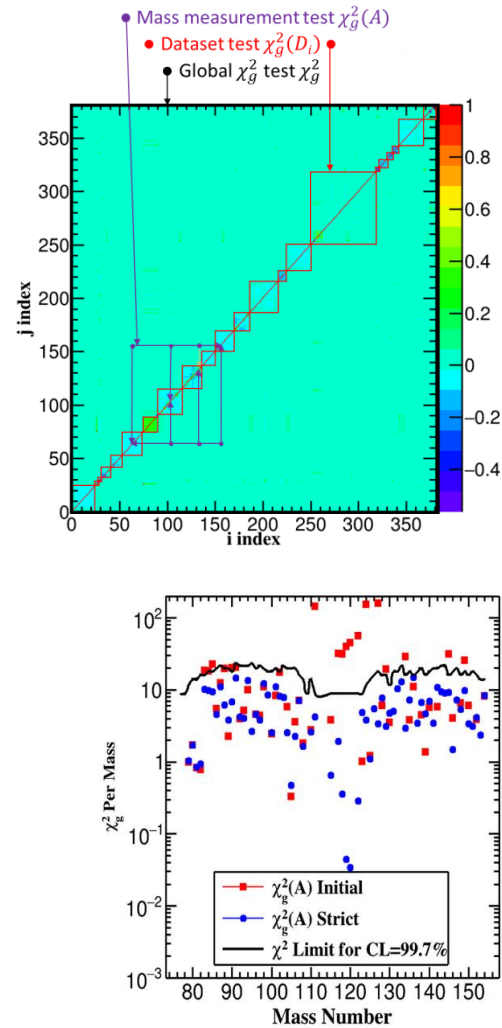


Fig. 10 Local test per mass for strict approach. Red dots represent the generalized χ^2 before regularization, blue dots after regularization in comparison to the black line corresponding to the limit for 99.7% confidence level

$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: χ^2_g test and data sorting

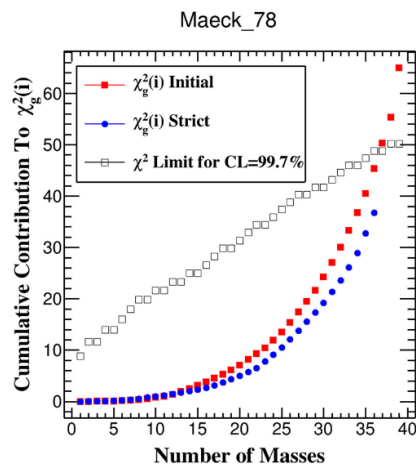
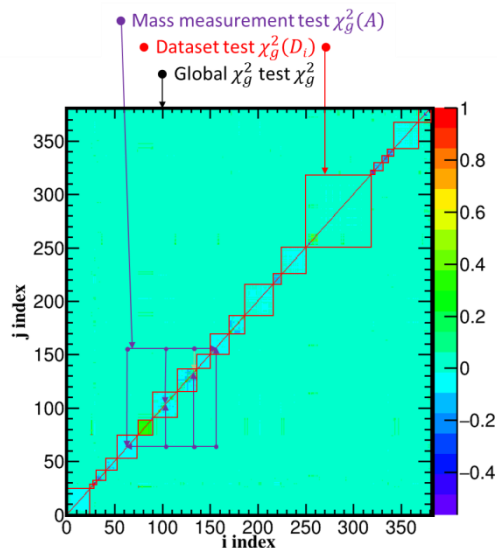


Fig. 9 Cumulative chi-square (test per dataset) as a function of the number of measurements considered for the strict approach for Maeck's dataset

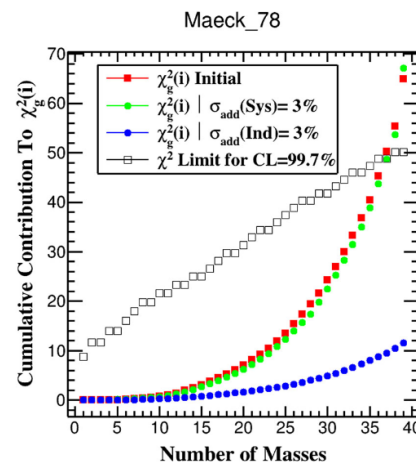


Fig. 11 Cumulative chi-square (test per dataset) as a function of the number of measurements considered for the conservative approach for Maeck's dataset

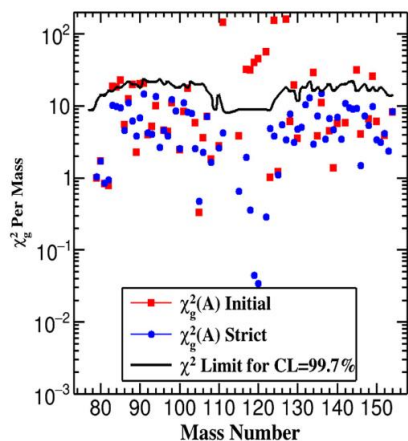


Fig. 10 Local test per mass for strict approach. Red dots represent the generalized χ^2 before regularization, blue dots after regularization in comparison to the black line corresponding to the limit for 99.7% confidence level

$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: χ^2_g test and data sorting

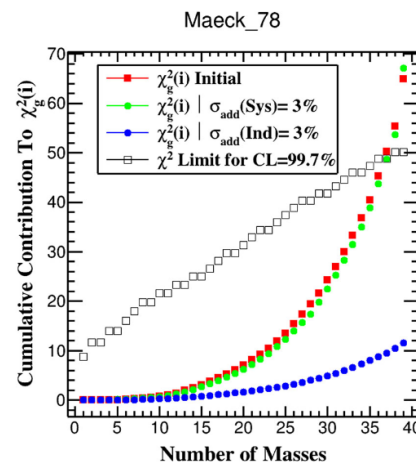
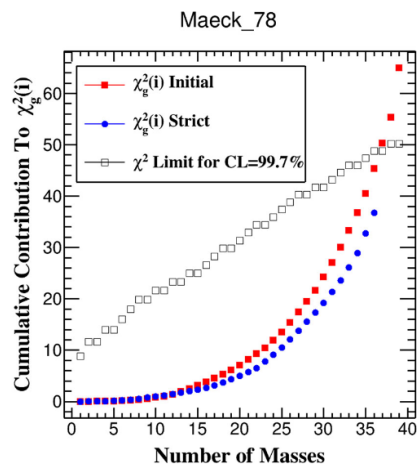
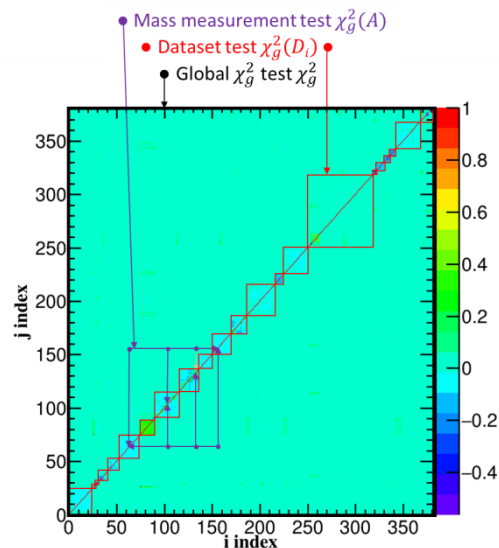


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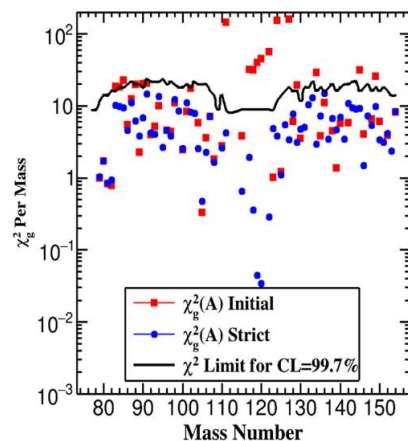
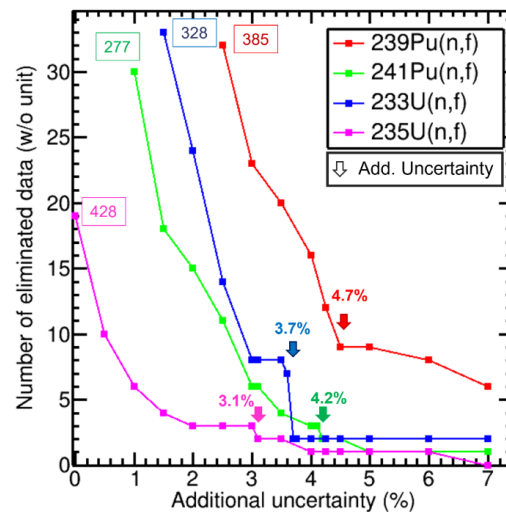


Fig. 10 Local test per mass for strict approach. Red dots represent the generalized χ^2 before regularization, blue dots after regularization in comparison to the black line corresponding to the limit for 99.7% confidence level





$^{239}\text{Pu}(n_{th},f)$ Mass yield data: χ^2_g test and data sorting

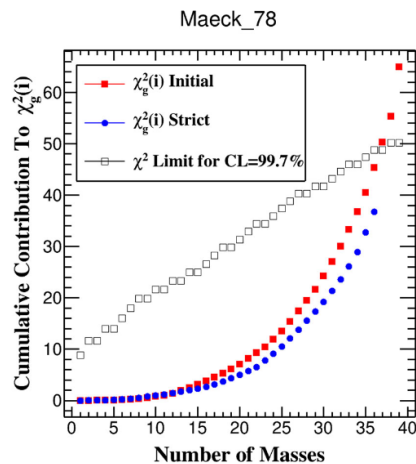
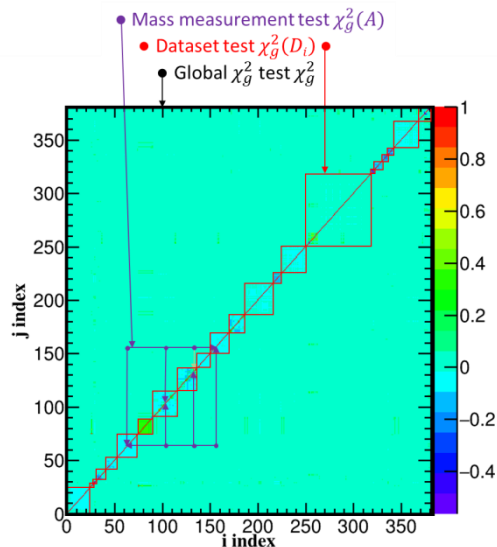


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Fig. 9 Cumulative chi-square (test per dataset) as a function of the number of measurements considered for the strict approach for Maeck's dataset

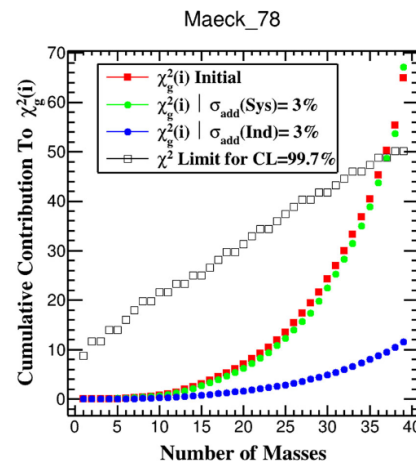


Fig. 11 Cumulative chi-square (test per dataset) as a function of the number of measurements considered for the conservative approach for Maeck's dataset

Table 4 Eliminated data using conservative approach for $^{235}\text{U}(n_{th},f)$ and $^{239}\text{Pu}(n_{th},f)$ reactions with the additional uncertainties show in Fig. 45

Reaction	dataset	Eliminated data
$^{235}\text{U}(n_{th},f)$	Maeck_78	(135+136) unresolved
Additional uncertainty 3.1%	Tsoukatos_68_1	153
	Dilorio_77	153
	Koblik	all dataset
$^{239}\text{Pu}(n_{th},f)$	Fickel_1959_a_corr	109
	Shima_1978	106
	Maeck_1979	85, 150
Additional uncertainty 4.5%	Chitambar_1987_b	132
	Schmitt_1984	81, 111
	Ditz_1989	84, 85
	Dange_1969	all data set
	Chebboubi_2024_corr	133
	Mathiews_1977	121



$^{239}\text{Pu}(n_{\text{th}},f)$ Mass yield data: χ^2_g test and data sorting

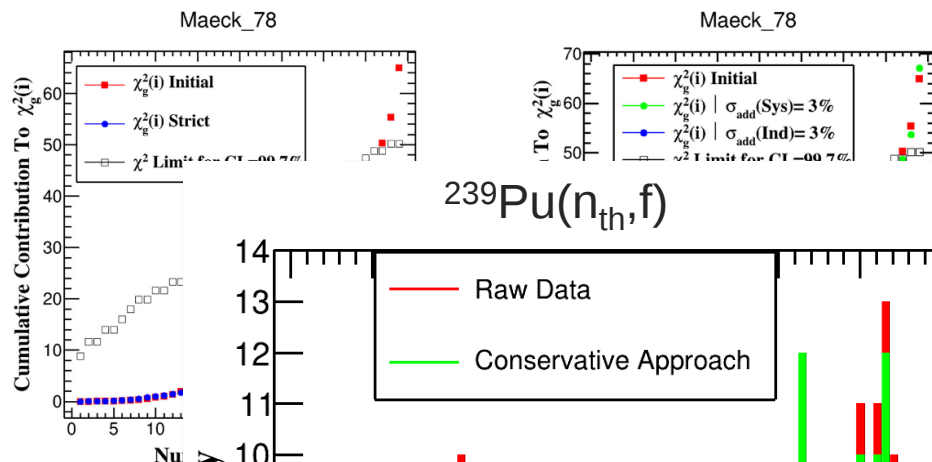
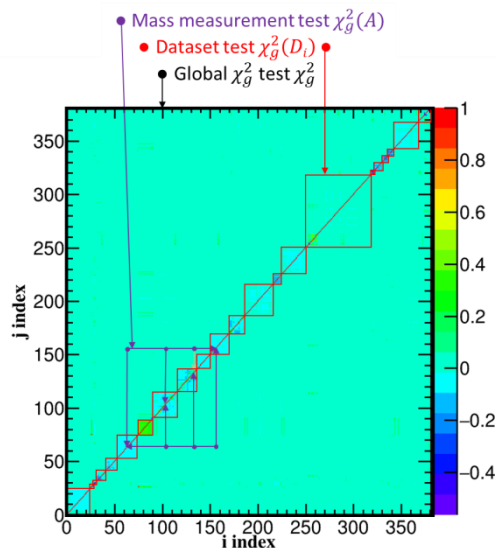


Fig. 10 Local test per mass for strict approach. Red dots represent the generalized χ^2 before regularization, blue dots after regularization in comparison to the black line corresponding to the limit for 99.7% confidence level

Fig. 9 Cumulative chi-square number of measurements considered dataset

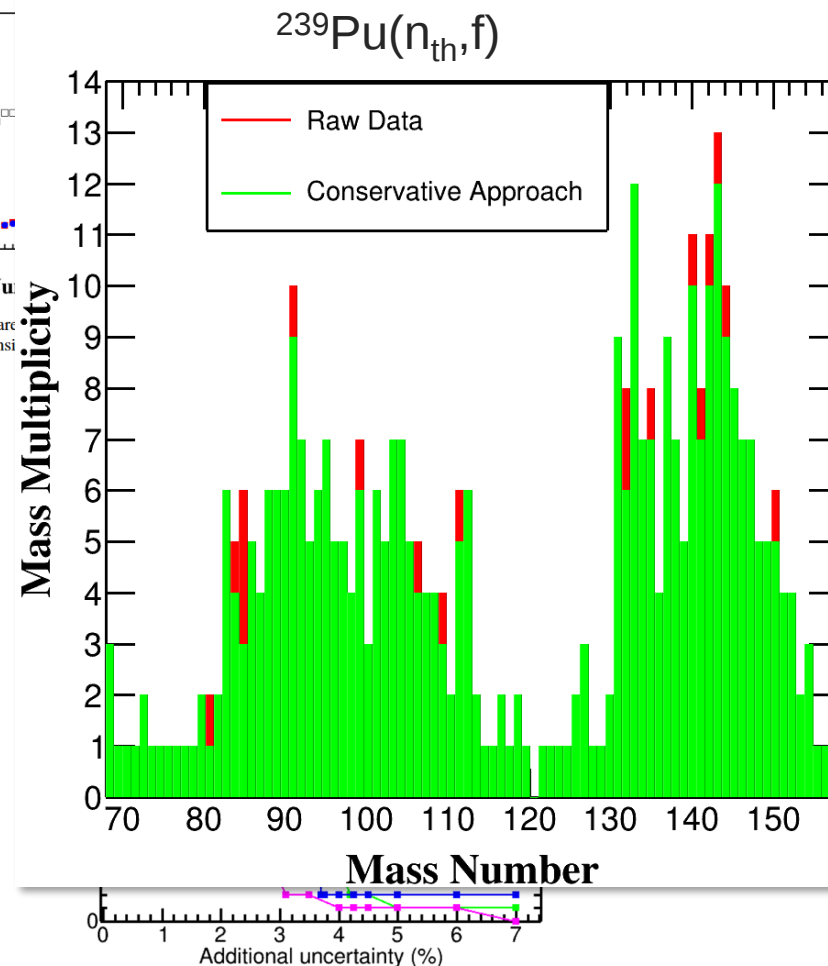
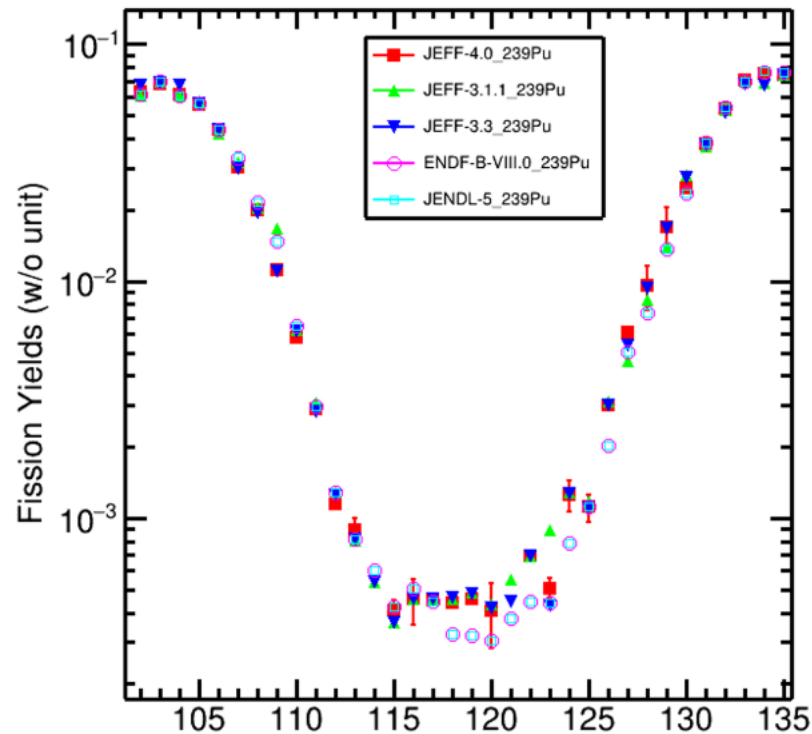
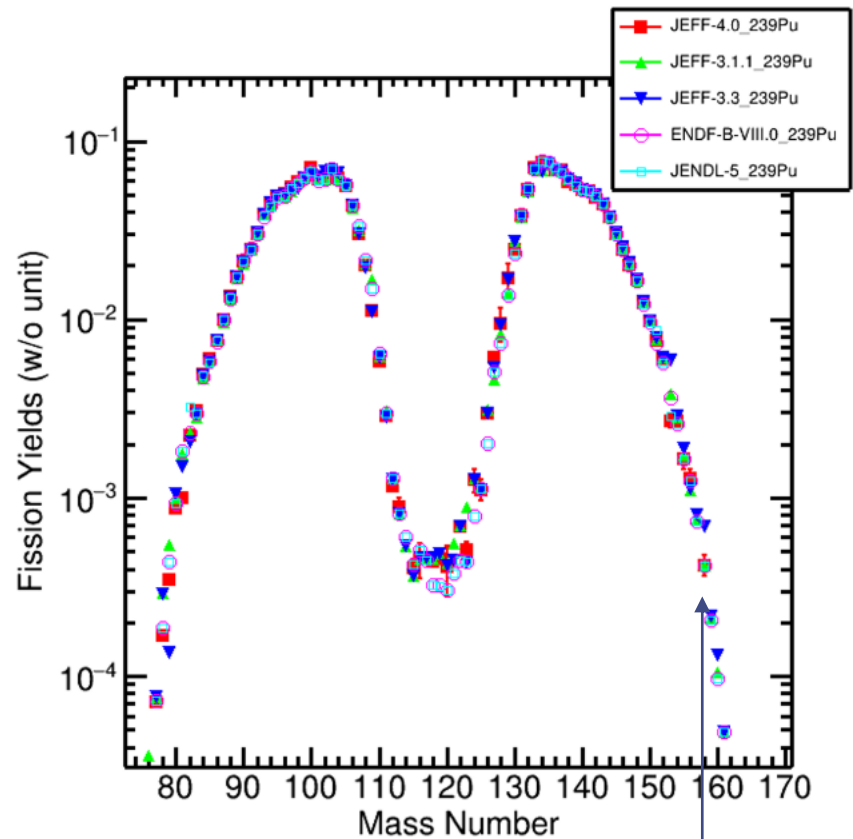


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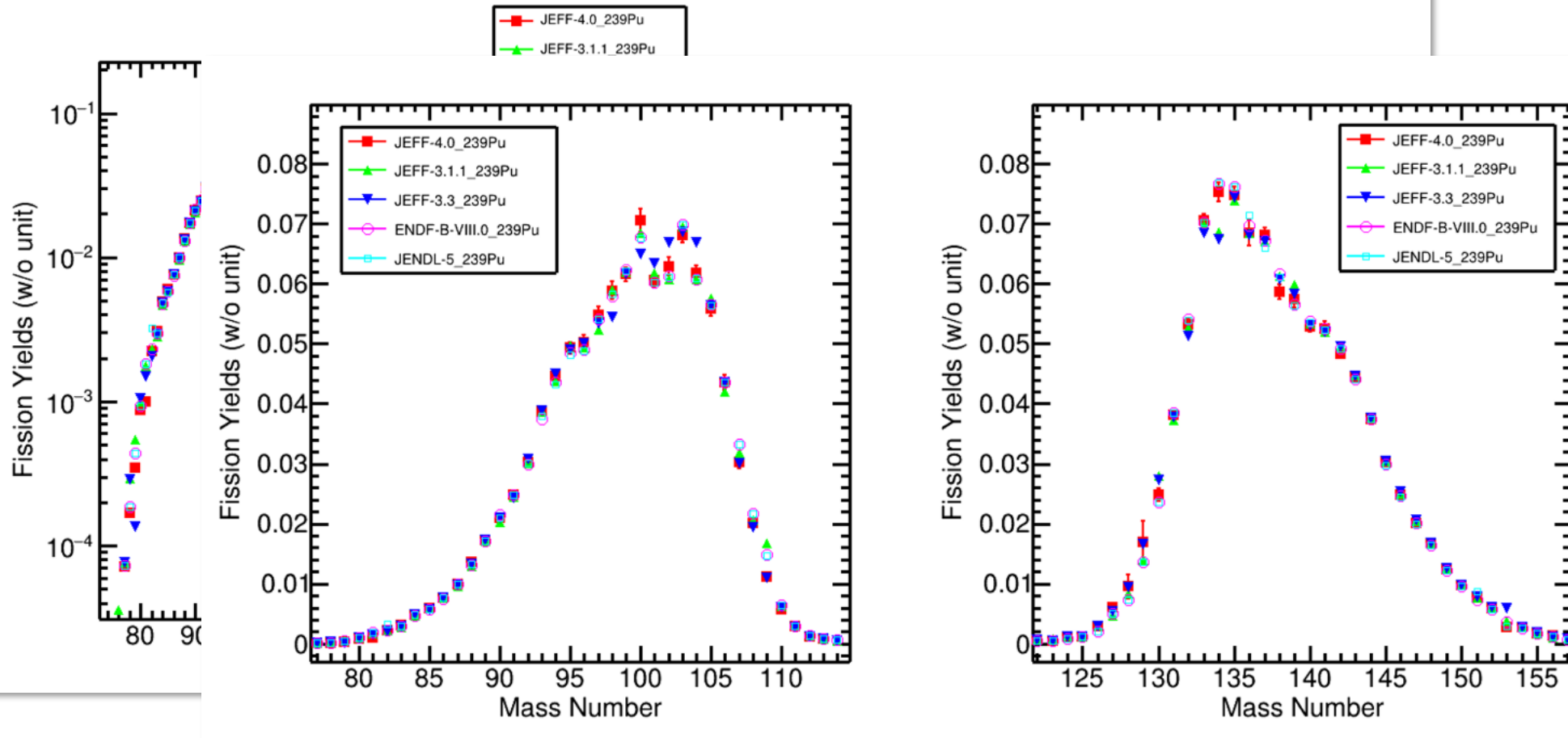
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	Mathews_1977	121

JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Mass yields

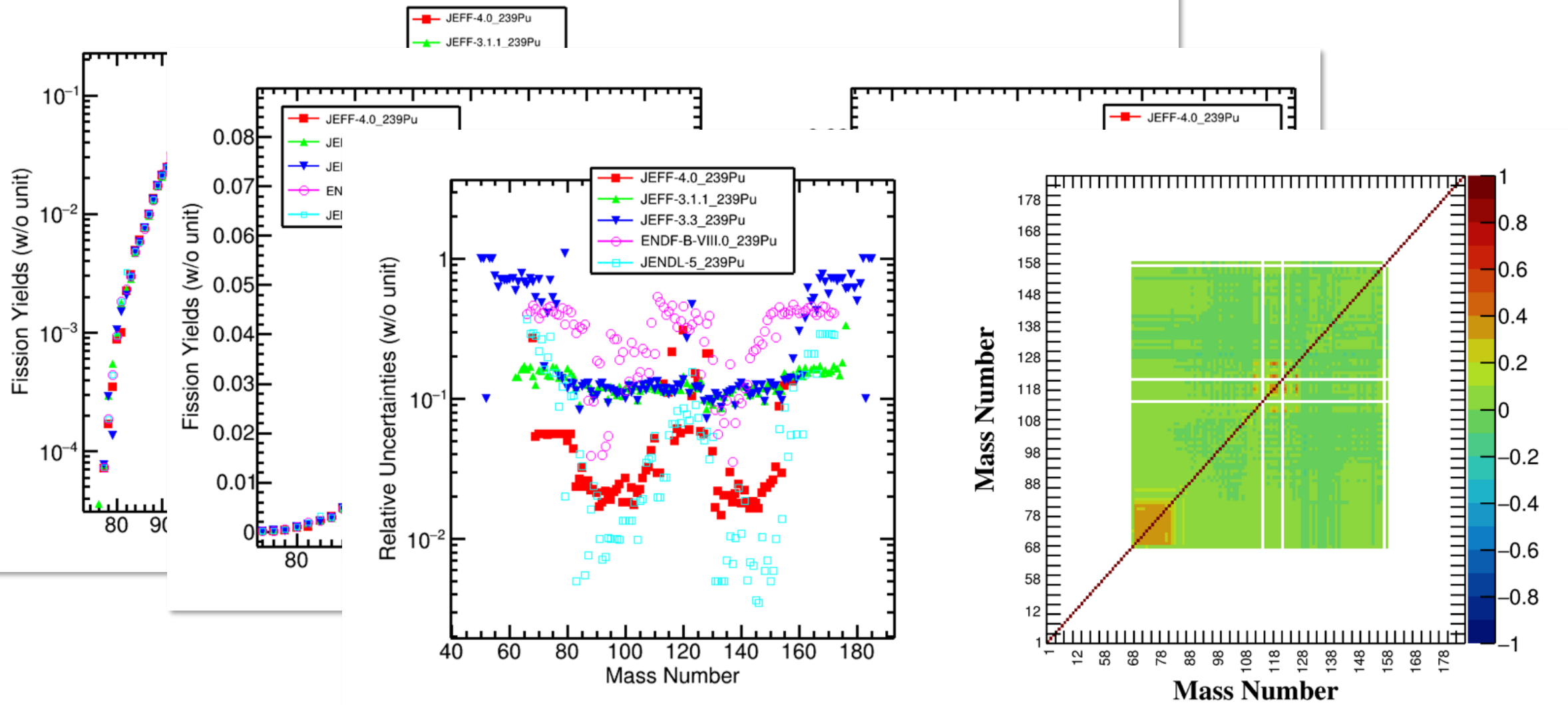


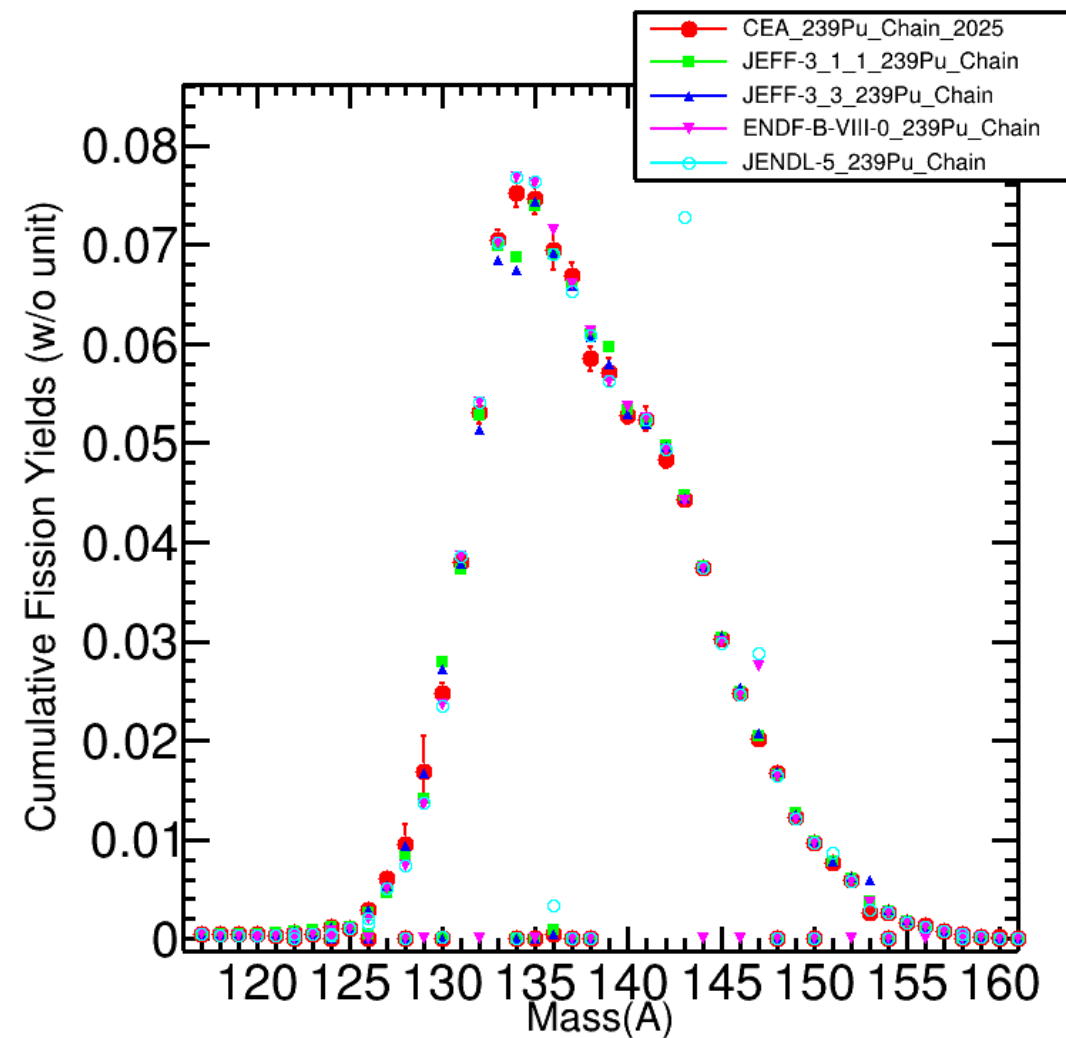
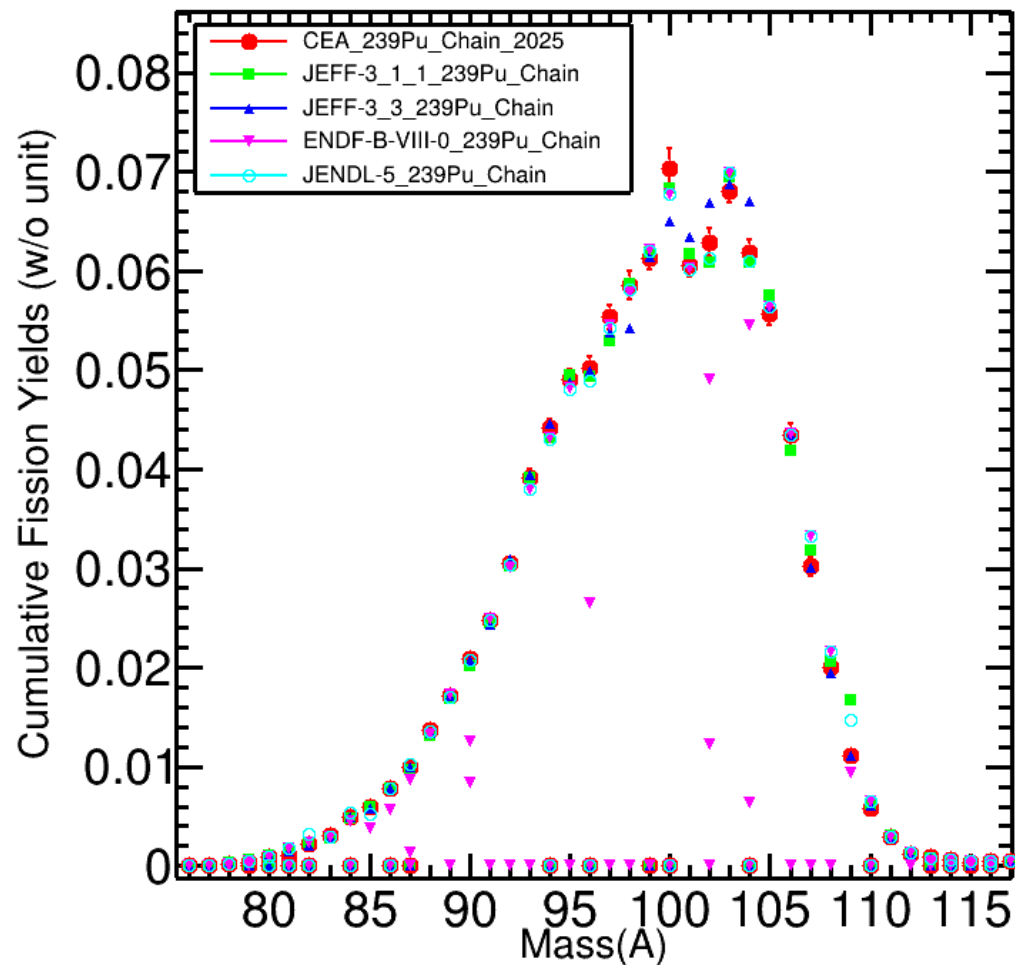
Heaviest
measurement

JEFF-4T4 $\rightarrow$ T5 $\rightarrow$ JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Mass yields



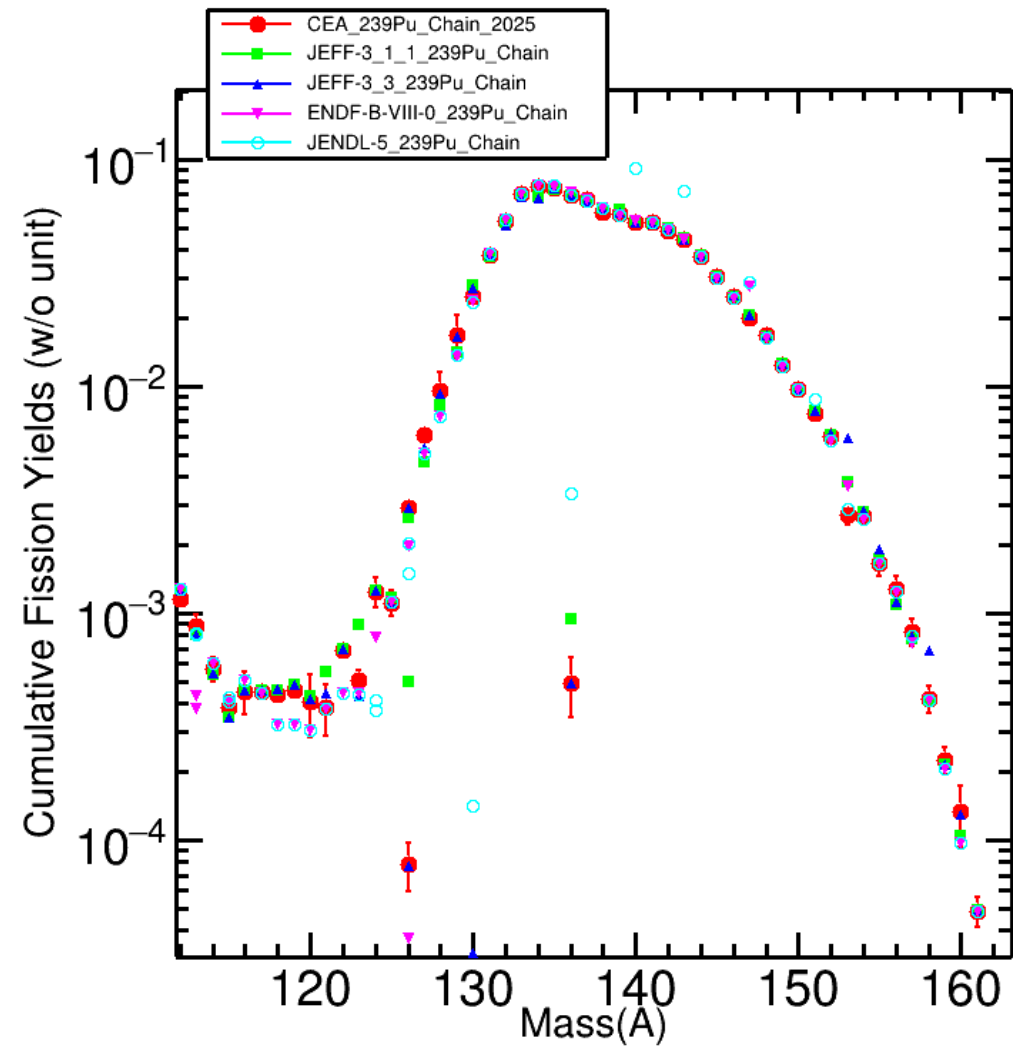
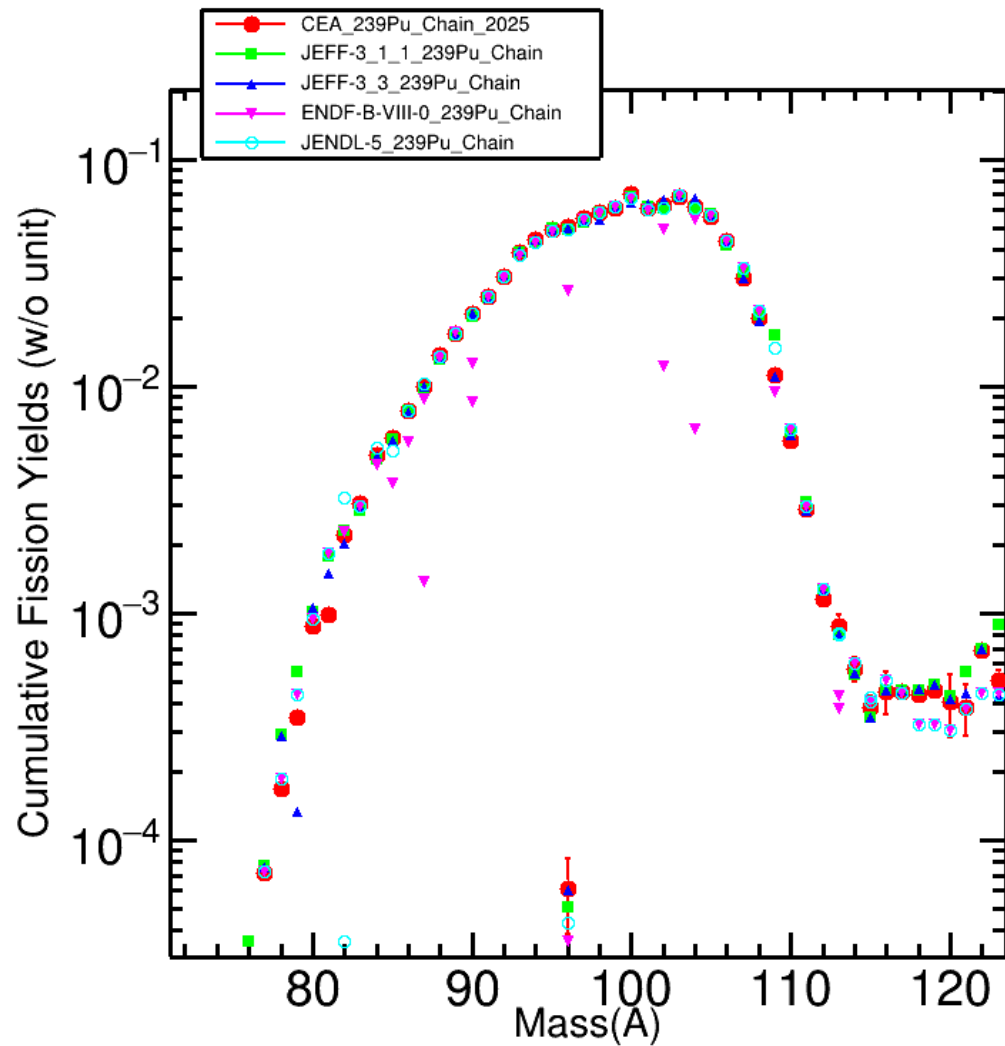
JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Mass yields





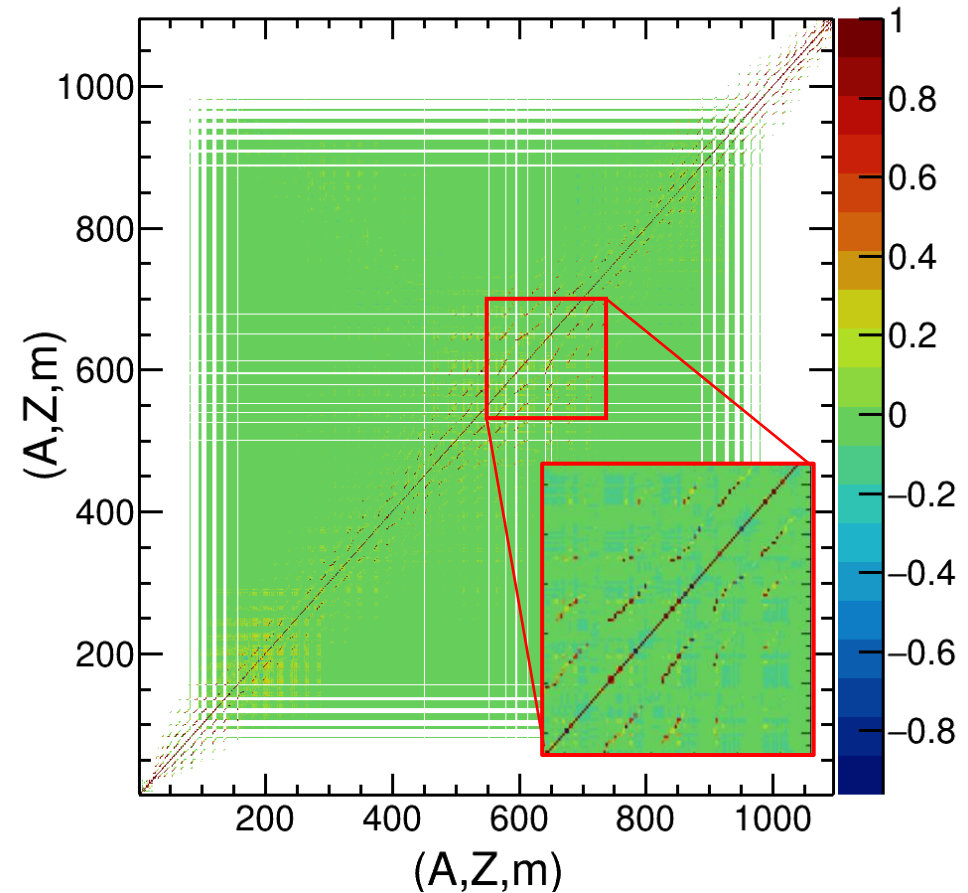
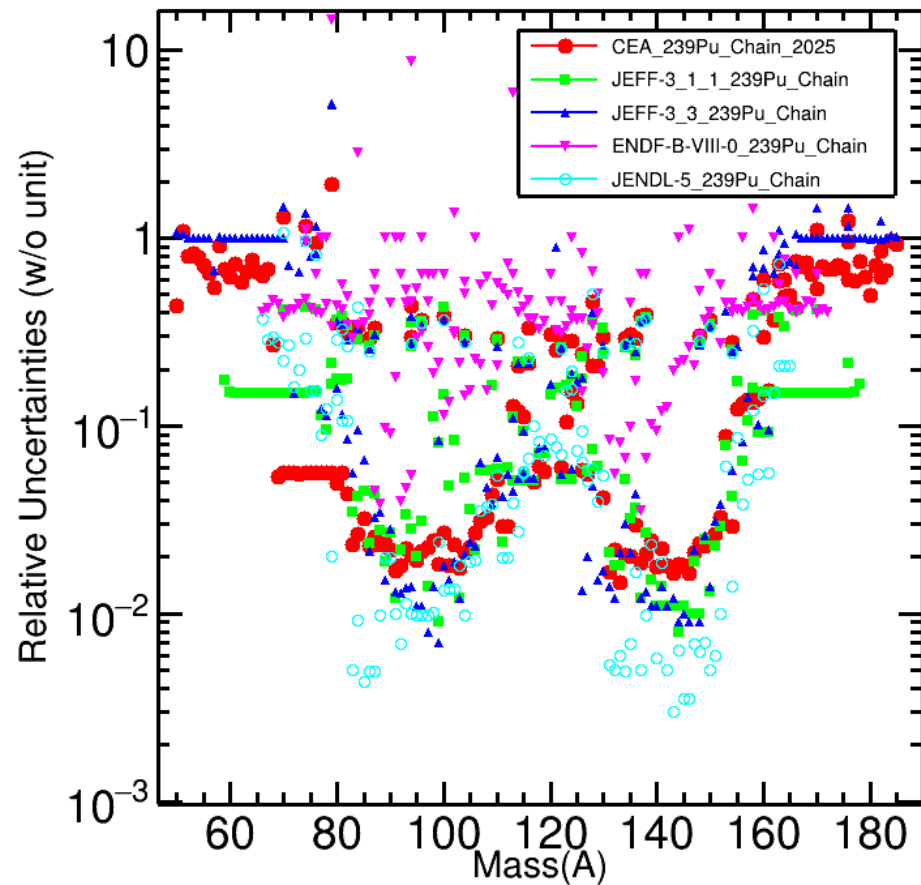
$$T_{1/2}^{\text{cut-off}} = 1000 \text{ y}$$

JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Chain yields



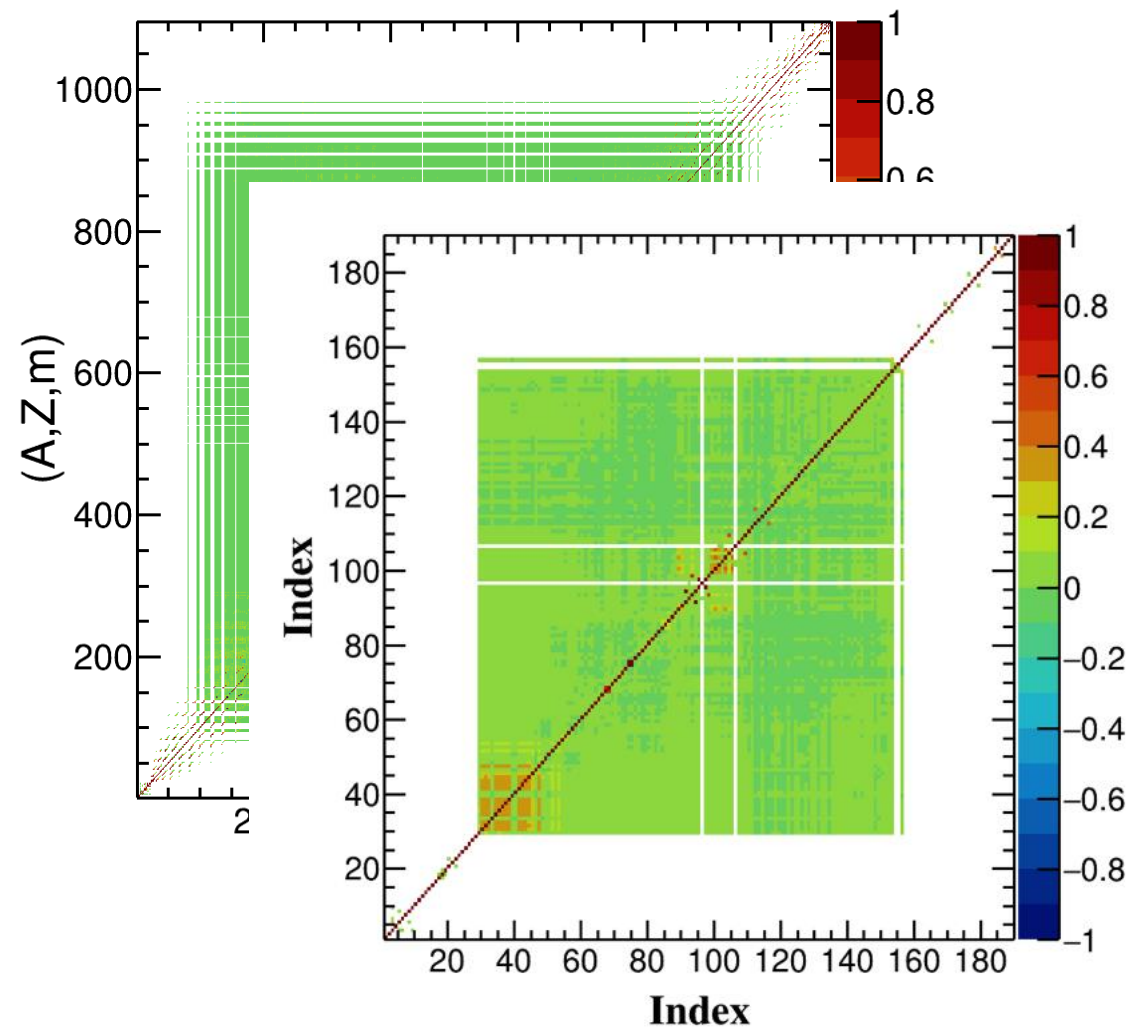
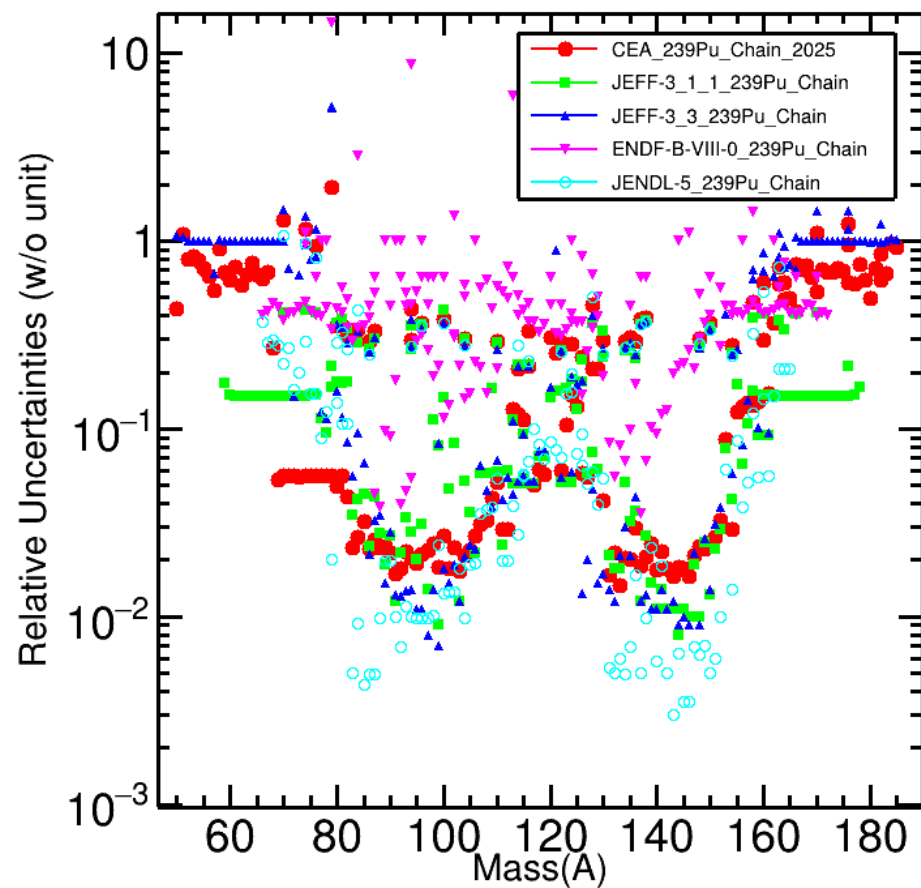
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JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Chain yields

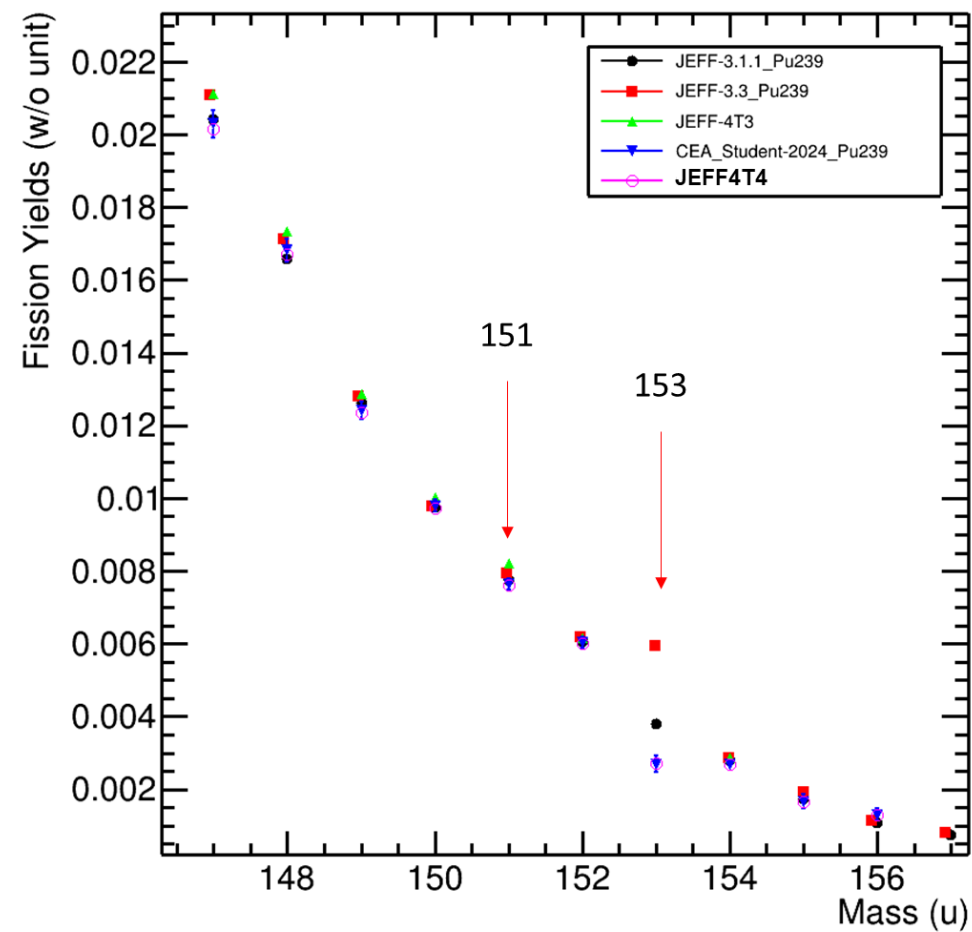
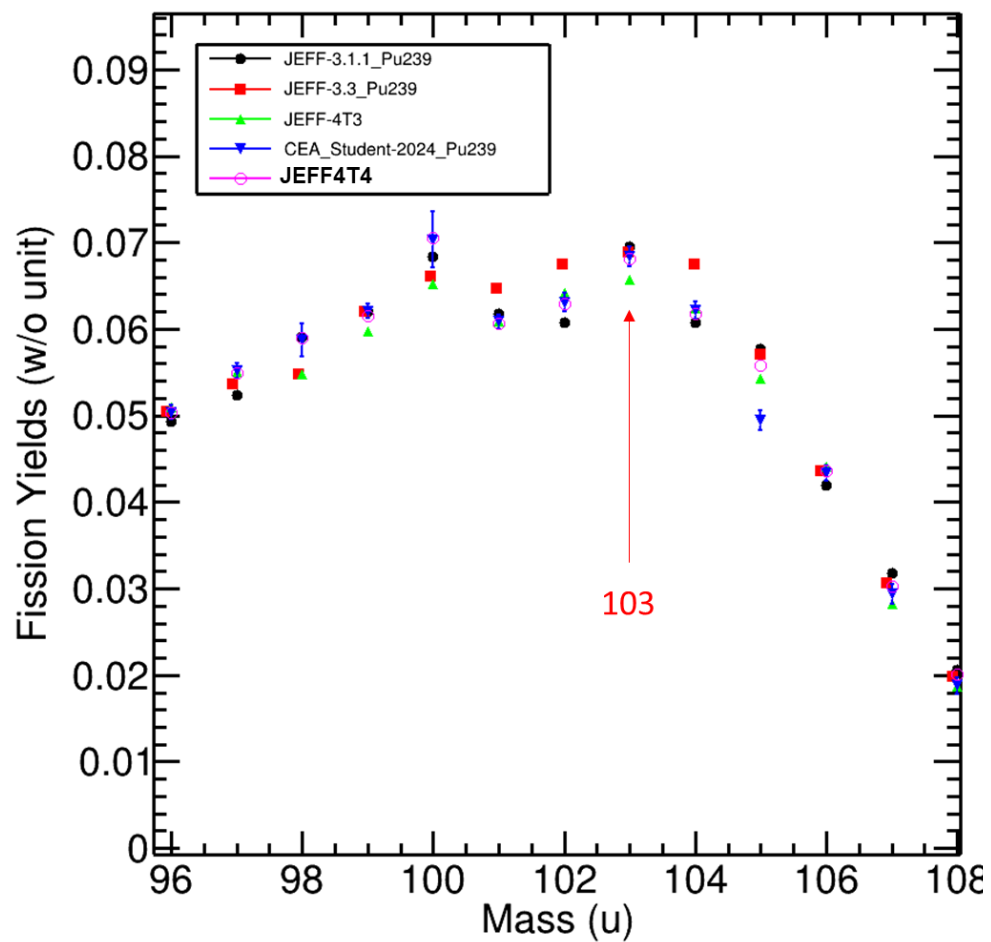


$$T_{1/2}^{\text{cut-off}} = 1000 \text{ y}$$

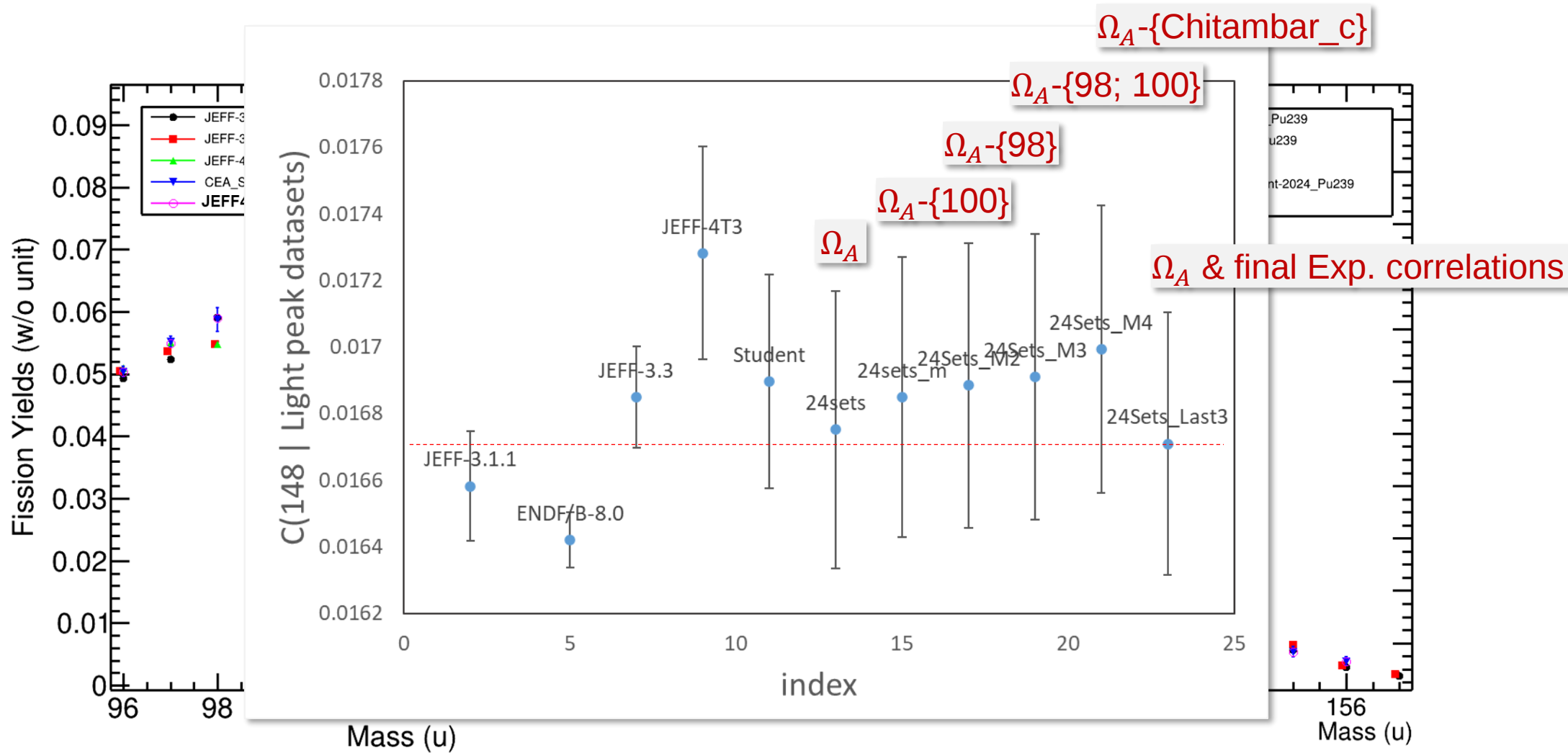
JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f)$ Chain yields



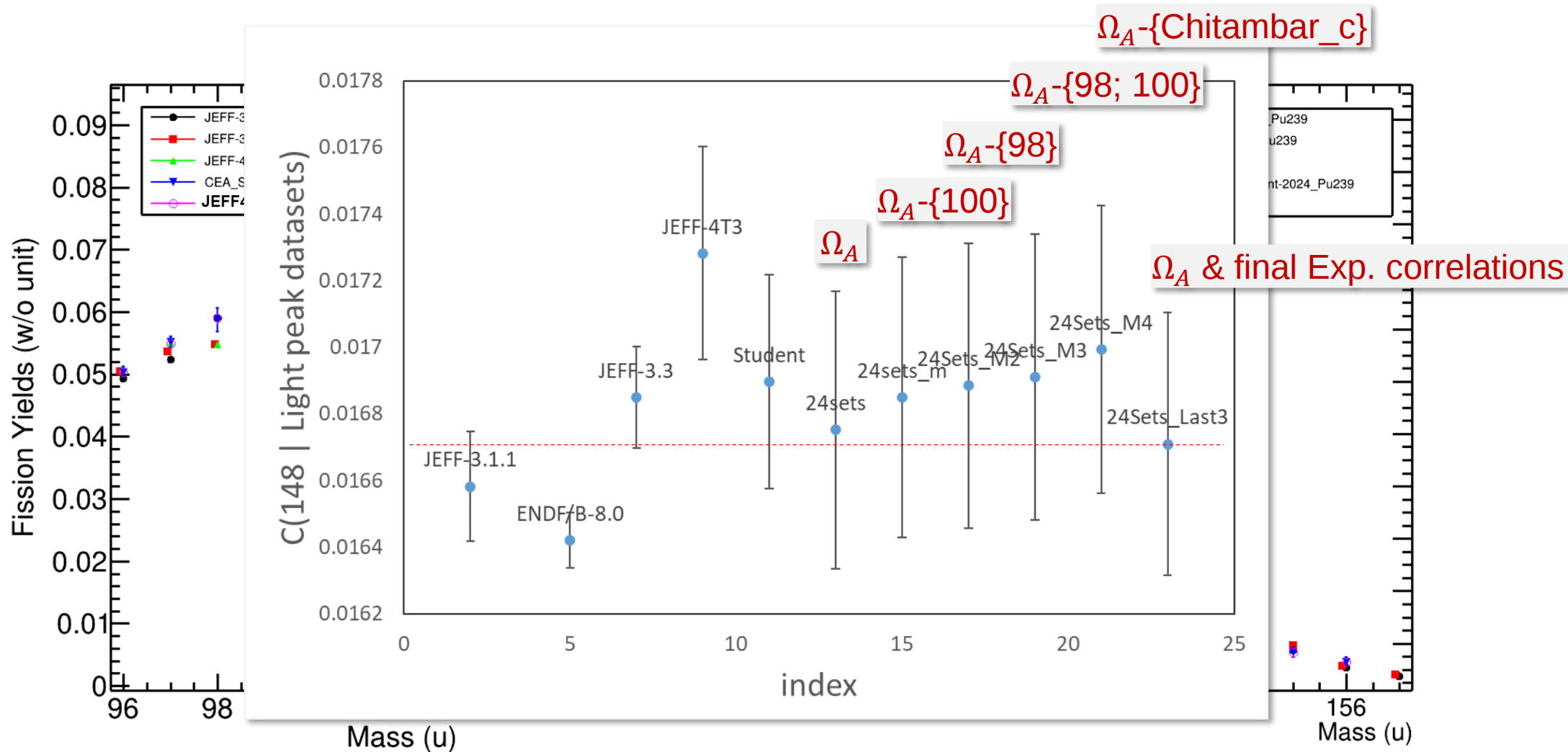
JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f) \rightarrow$ Impact of database and data sorting



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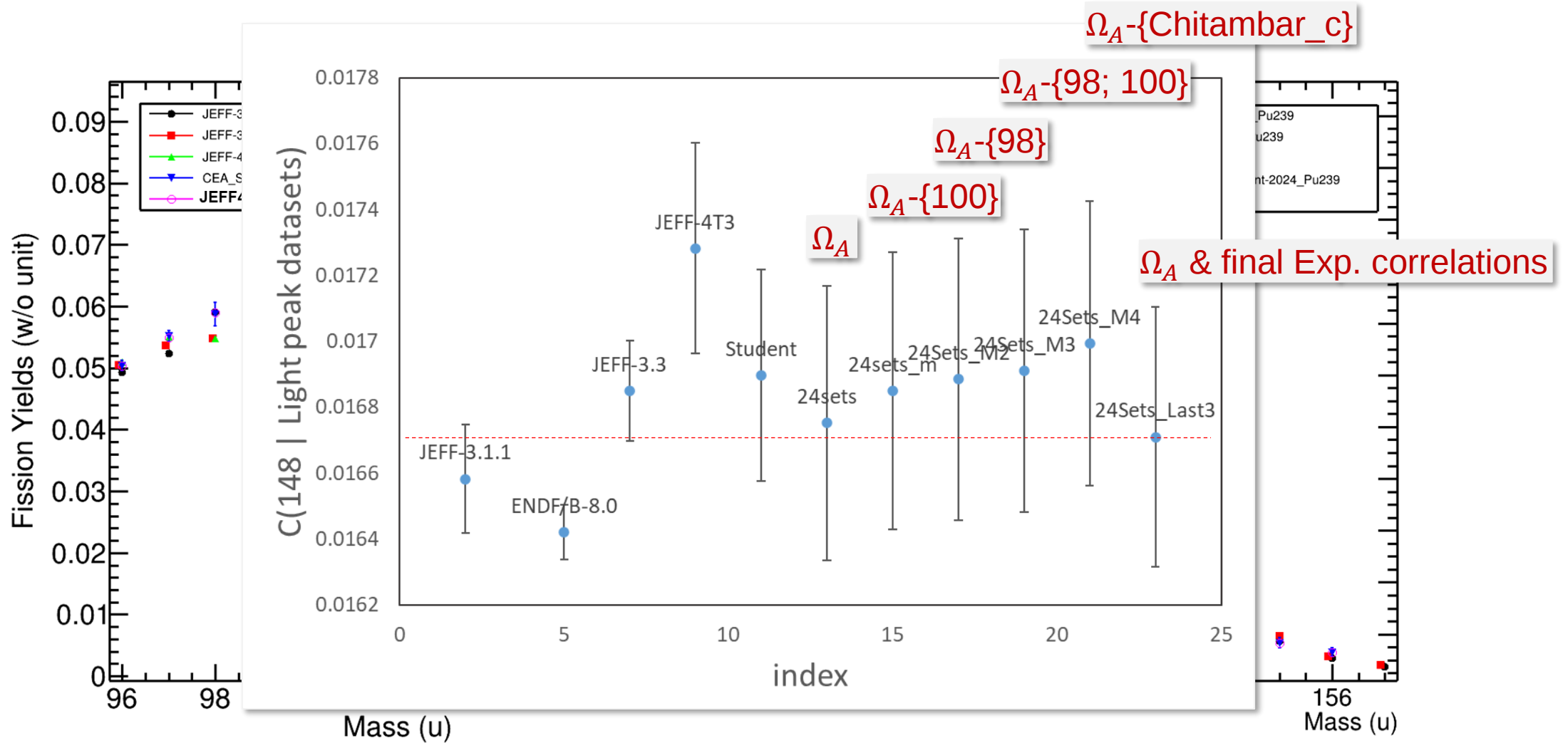


JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f) \rightarrow$ Impact of database and data sorting



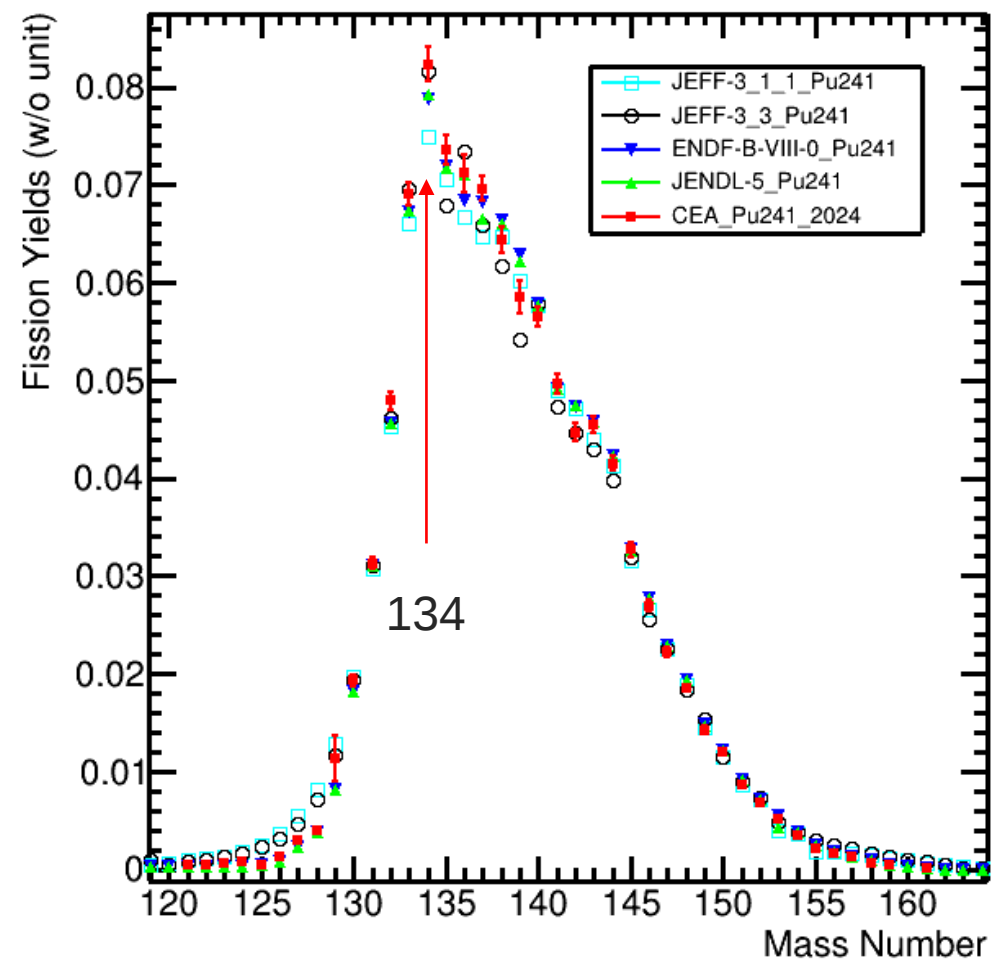
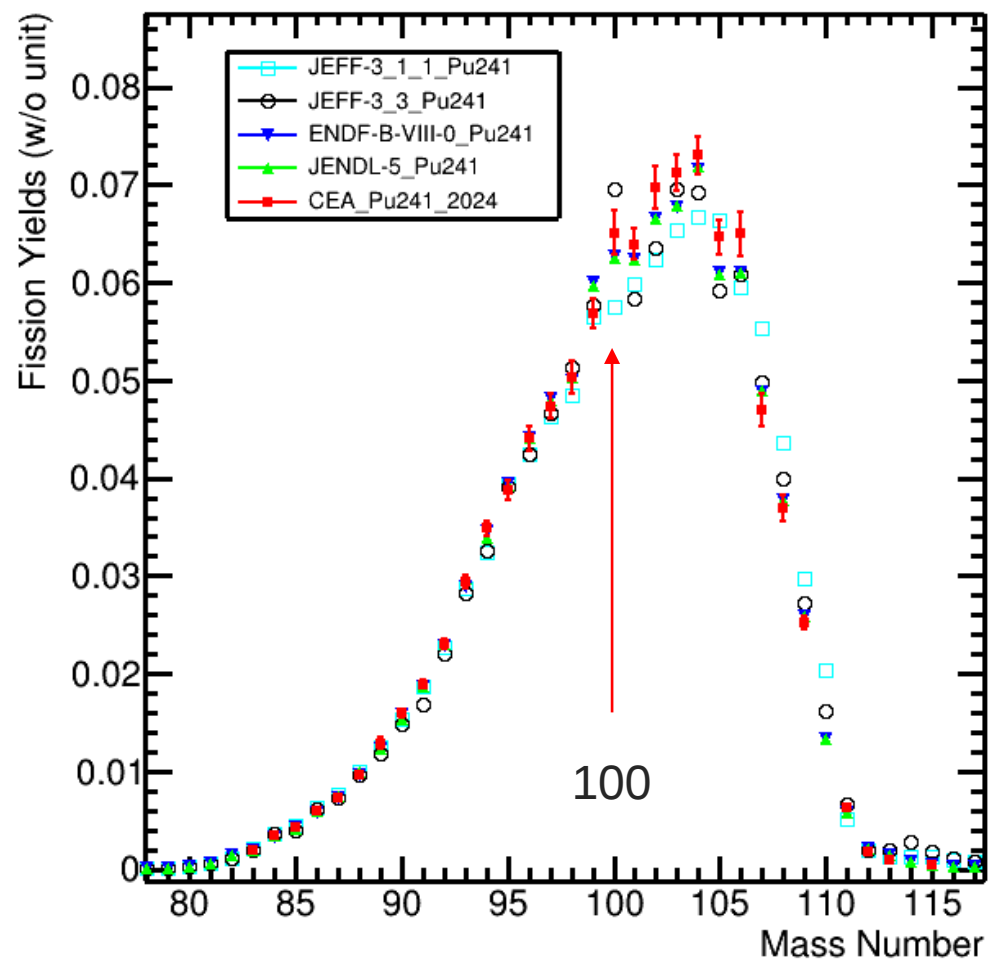
Chitambar_1987_c: 98 & 100 masses drive the absolute normalization and then the heavy peak $\rightarrow Y(148) \rightarrow C(148\text{Nd})$

JEFF-4T4 → T5 → JEFF-4.0 : $^{239}\text{Pu}(n_{\text{th}},f) \rightarrow$ Impact of database and data sorting

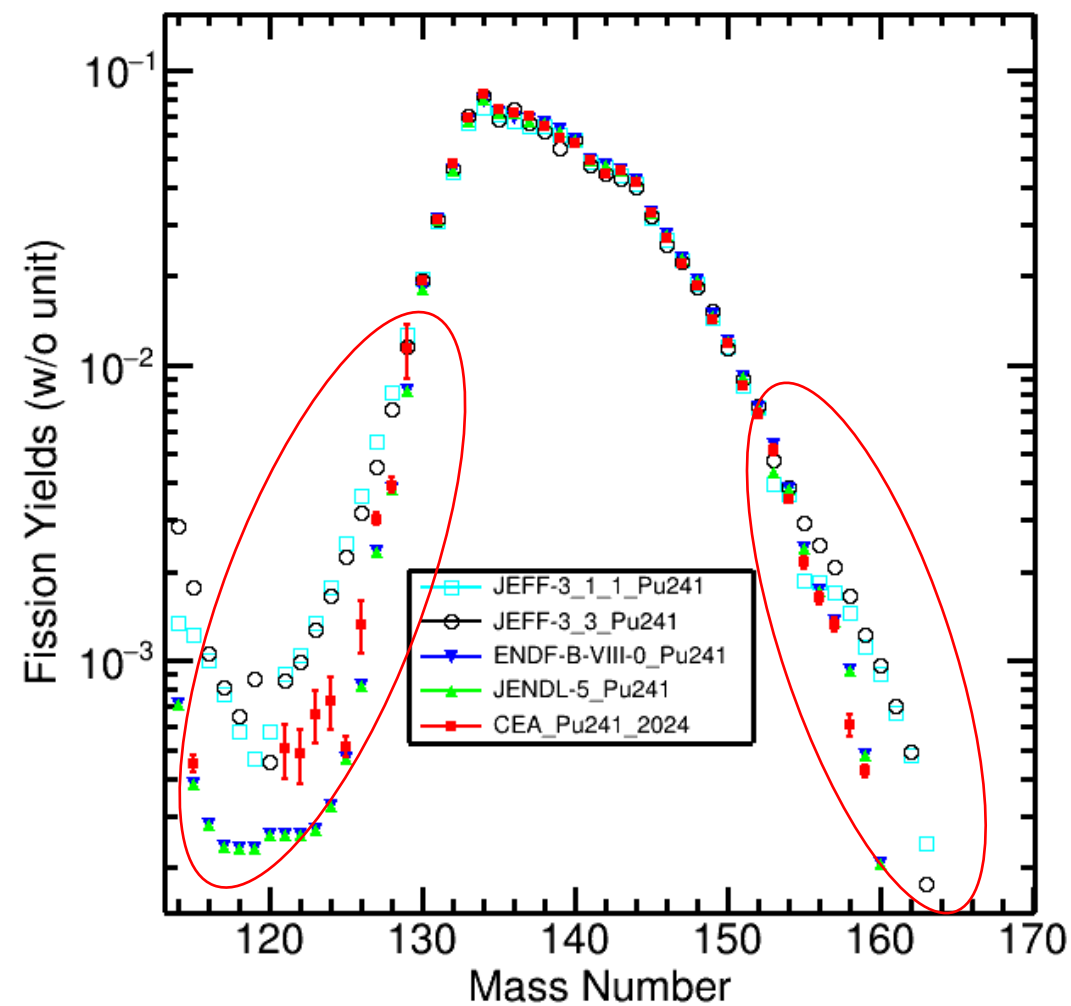
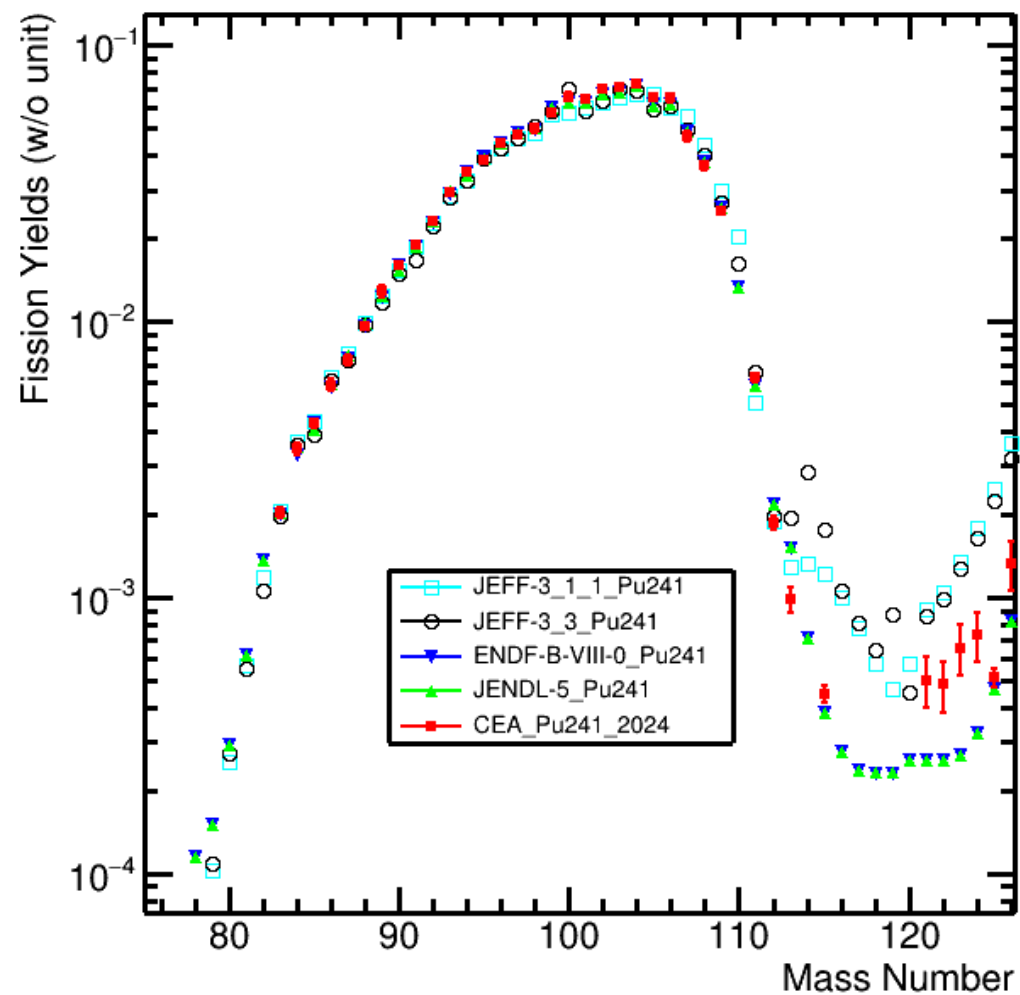


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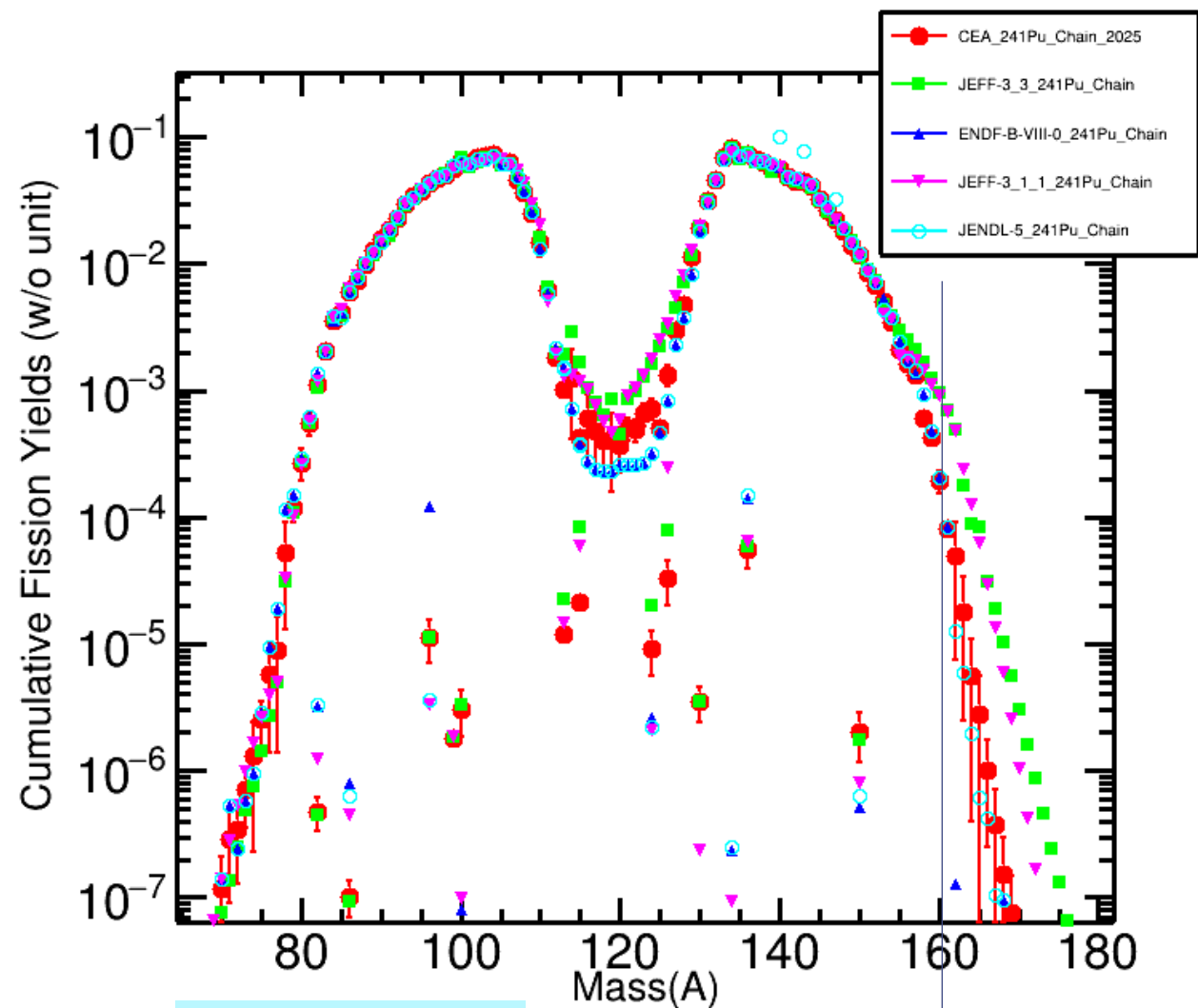
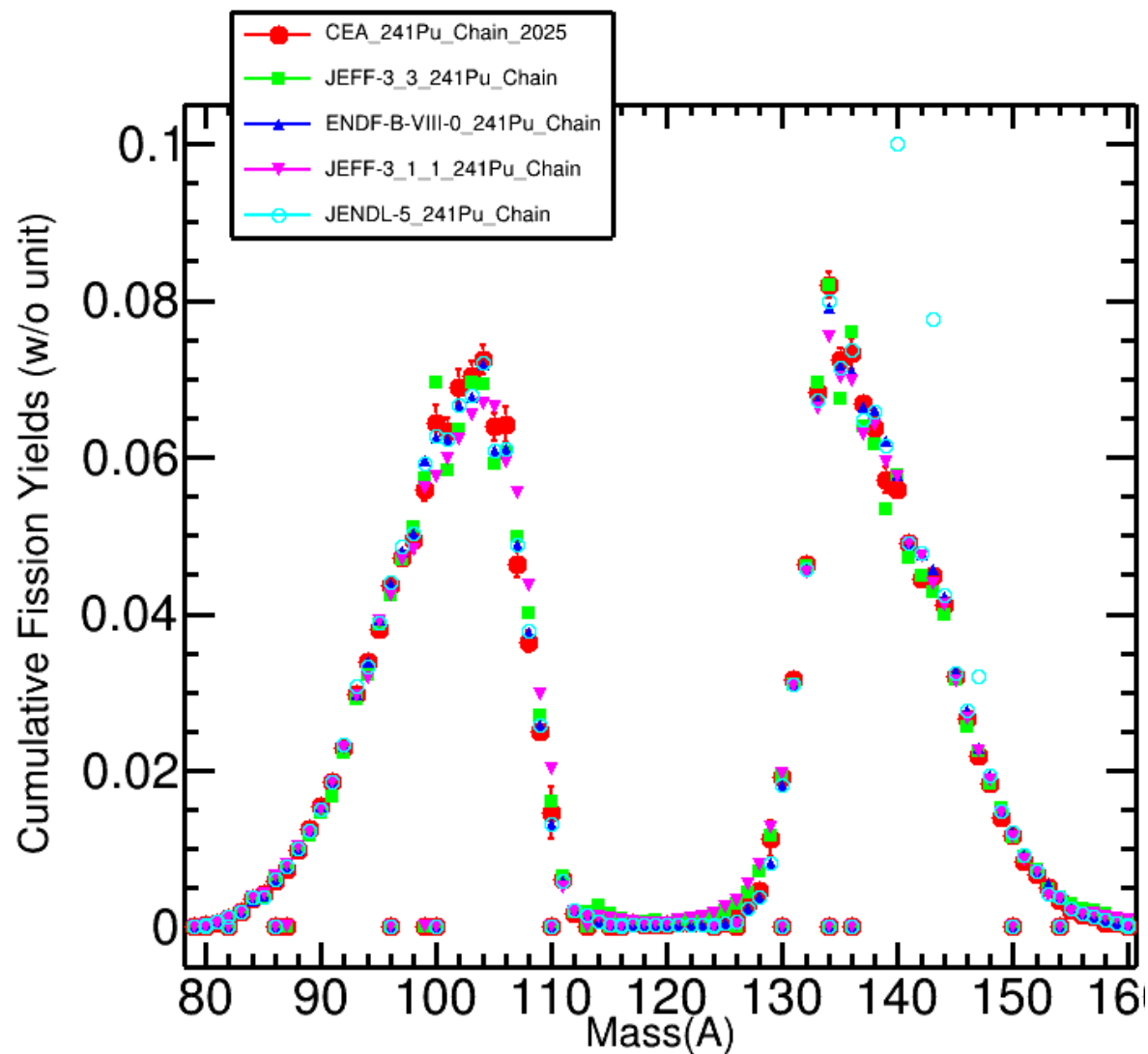
JEFF-4.0: $^{241}\text{Pu}(n_{\text{th}},f)$ Mass yields



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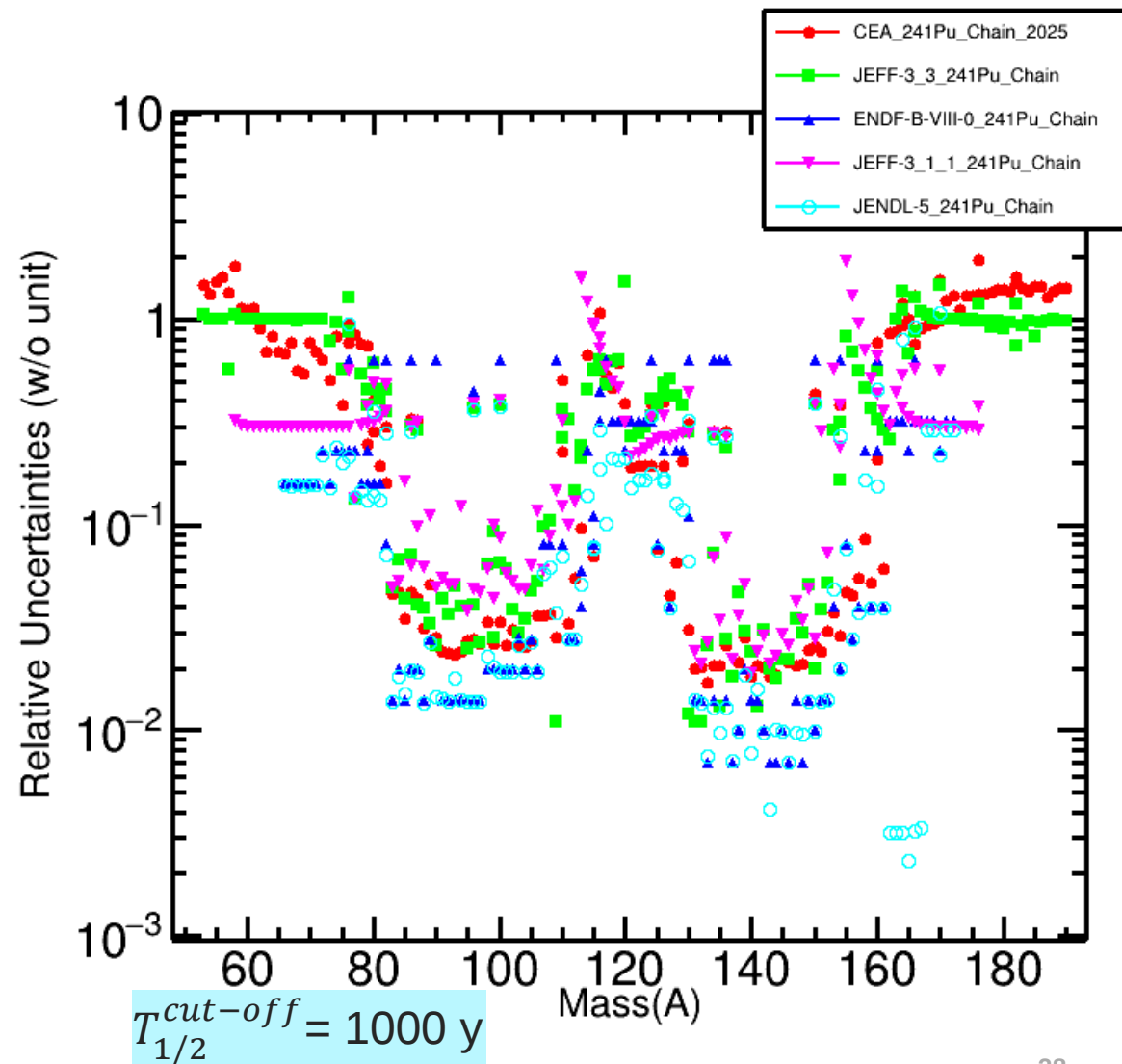
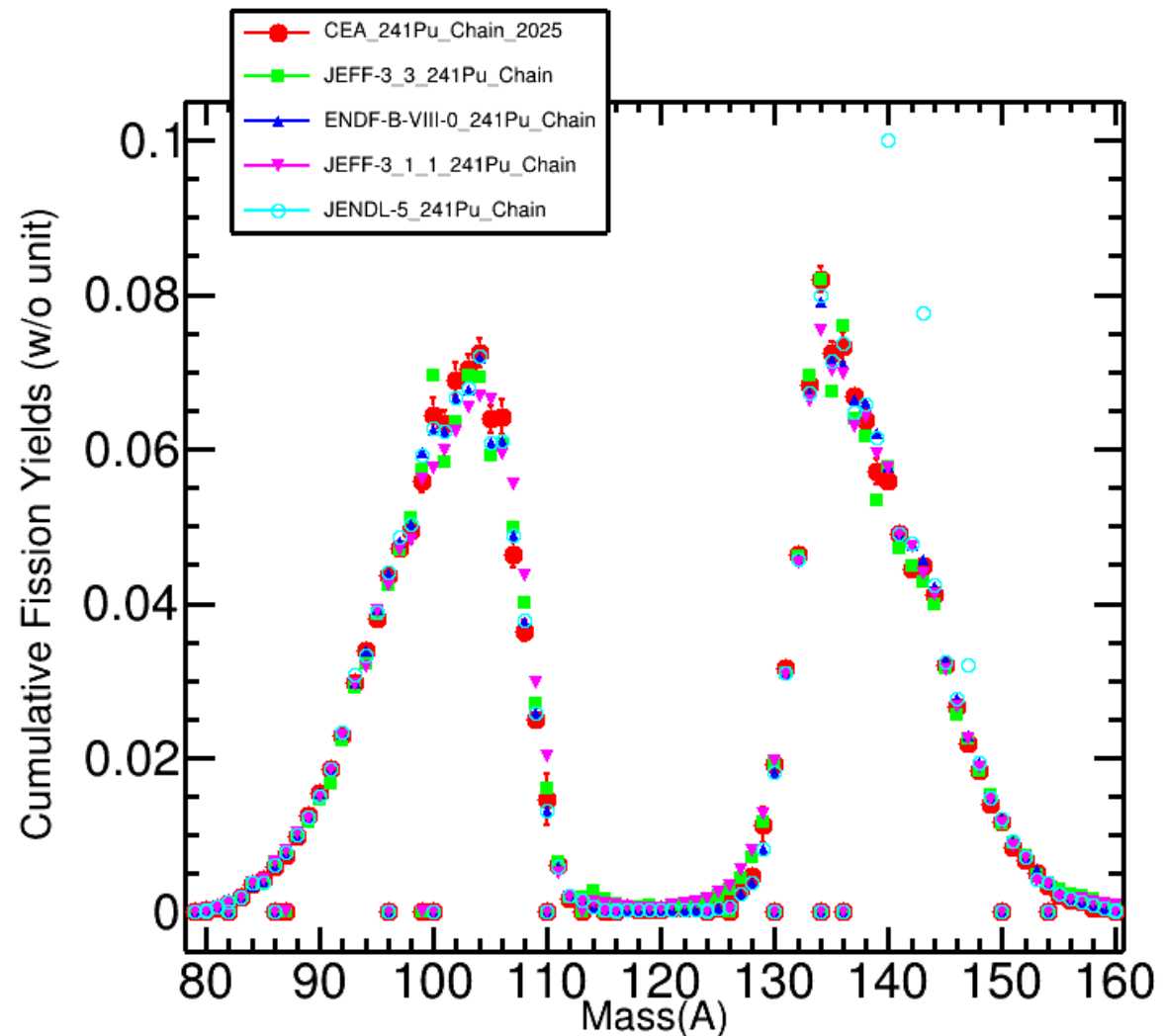


JEFF-4.0: $^{241}\text{Pu}(n_{\text{th}},f)$ Chain yields

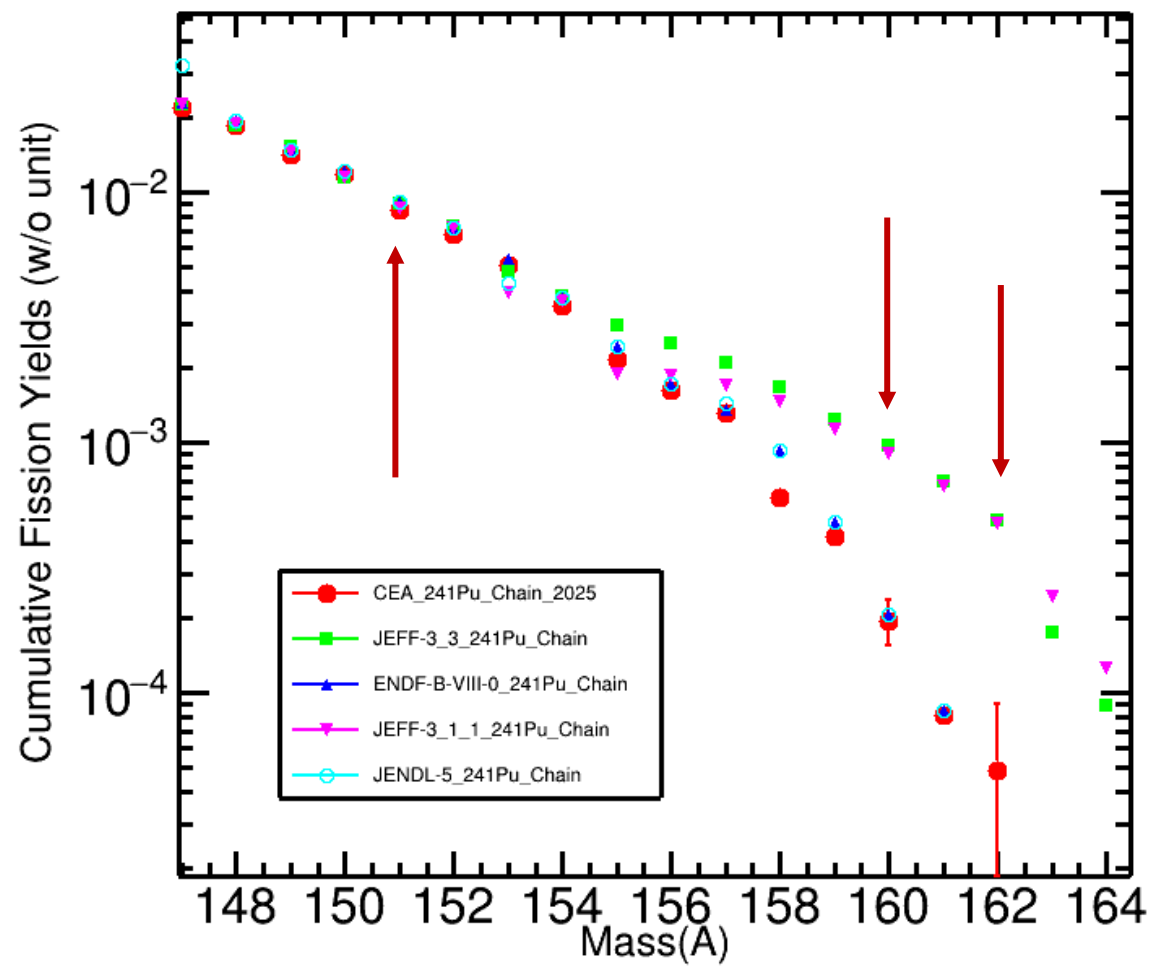
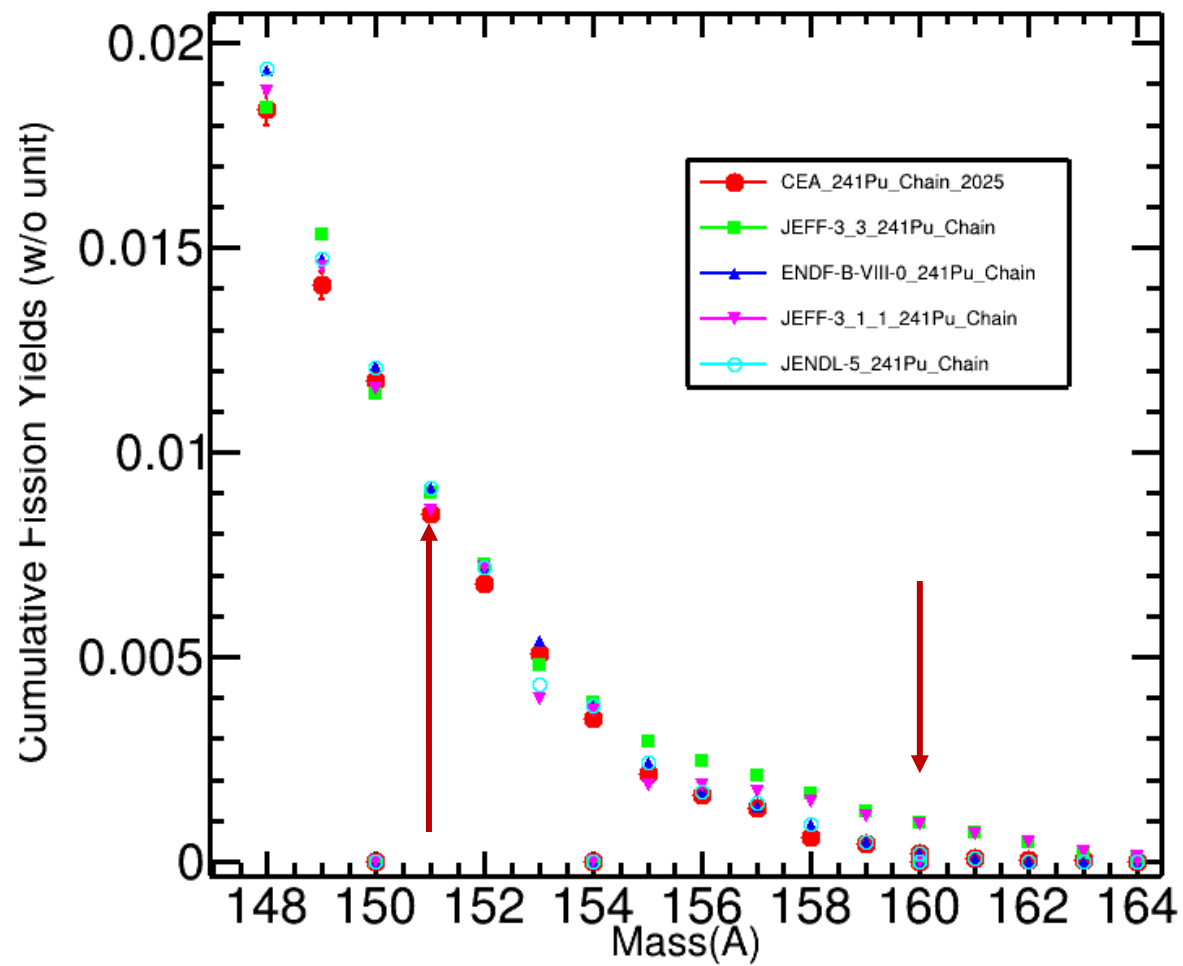


$$T_{1/2}^{\text{cut-off}} = 1000 \text{ y}$$

JEFF-4.0: $^{241}\text{Pu}(n_{\text{th}},f)$ Chain yields



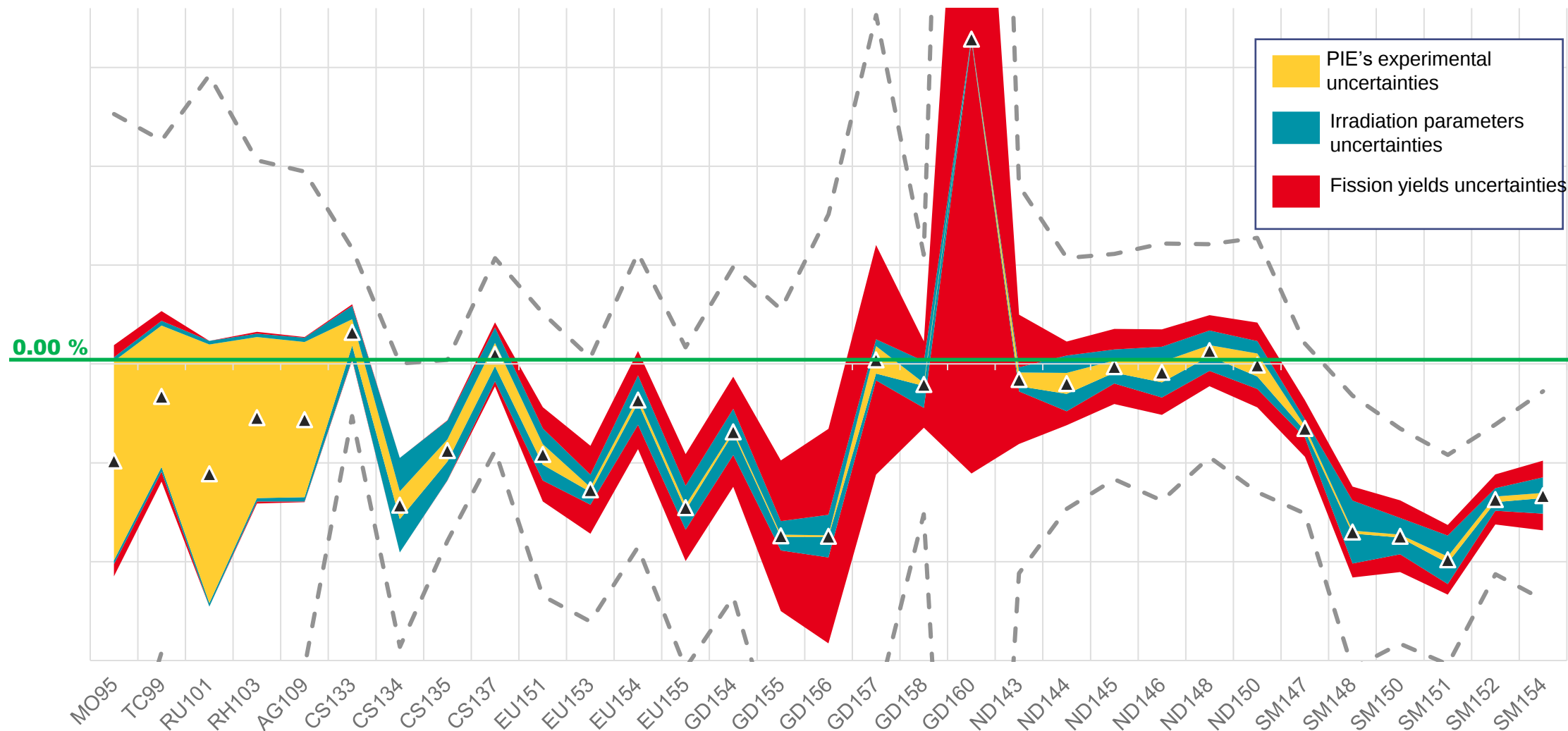
JEFF-4.0: $^{241}\text{Pu}(n_{\text{th}},f)$ Chain yields



$$T_{1/2}^{cut-off} = 1000 \text{ y}$$

Test and validation of JEFF-4.0

C/E-1 of isotopic content in the fuel rod after irradiation



From JEFF-4.0 to JEFF-4.1

$(nth, f) \Rightarrow$

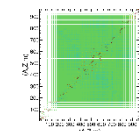
$$P(Z|A^*, n_{th})$$

JEFF-4.0

$$Y(A | nth)$$

$$C(A, Z, m | nth)$$

$$P(Z|A, n_{th}, \text{JEFF-3.3})$$



(n_{fast}, f) data

Radiochemical data → full (A, Z) identification

$\beta; \gamma$ spectrometry

~~ELM Mass spectrometer~~

« 2E-2V »

« 2E »

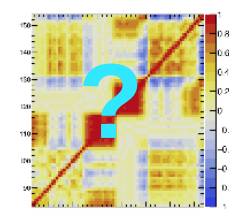
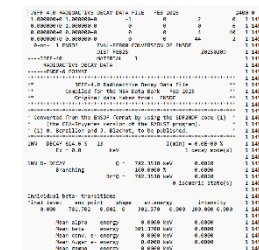
→ full A & limited Z identification

→ Limited A & A^* identification

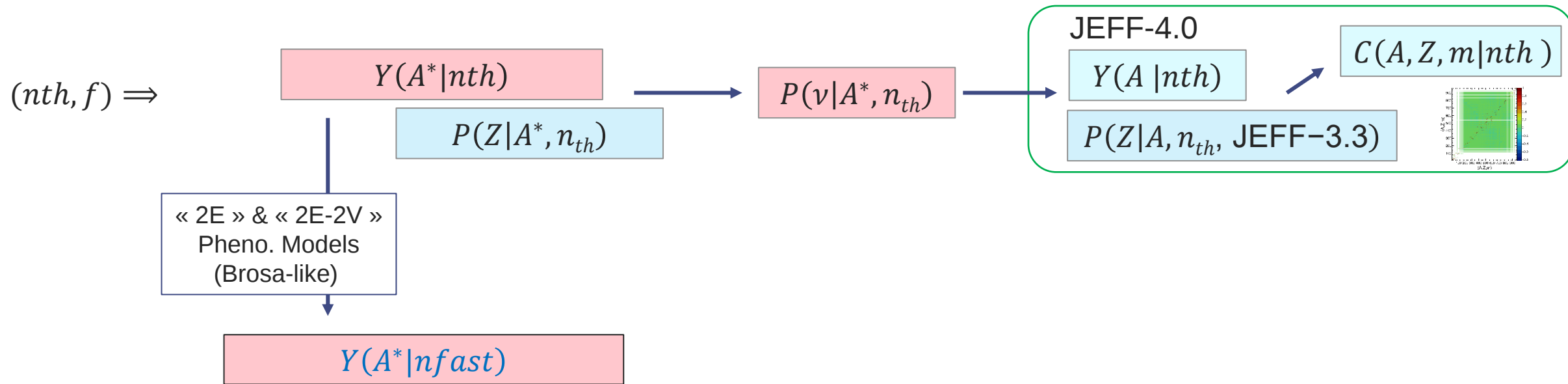
(x, f) data

VAMOS, SOFIA ...

→ full Z & limited A identification



From JEFF-4.0 to JEFF-4.1



(n_{fast}, f) data

Radiochemical data → full (*A*, *Z*) identification

$\beta; \gamma$ spectrometry

~~ELM Mass spectrometer~~

« 2E-2V »

« 2E »

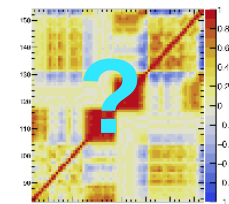
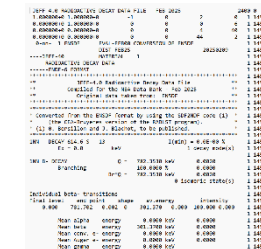
→ full A & limited Z identification

→ Limited A & A^* identification

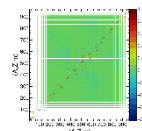
(x,f) data

VAMOS, SOFIA ...

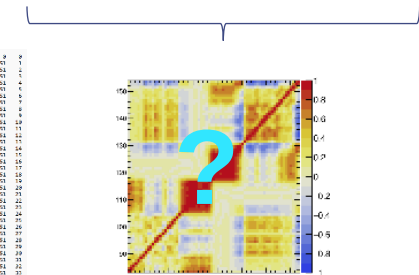
→ full **Z** & limited **A** identification



→ N. Teixeira Rua PhD (2025-2028)

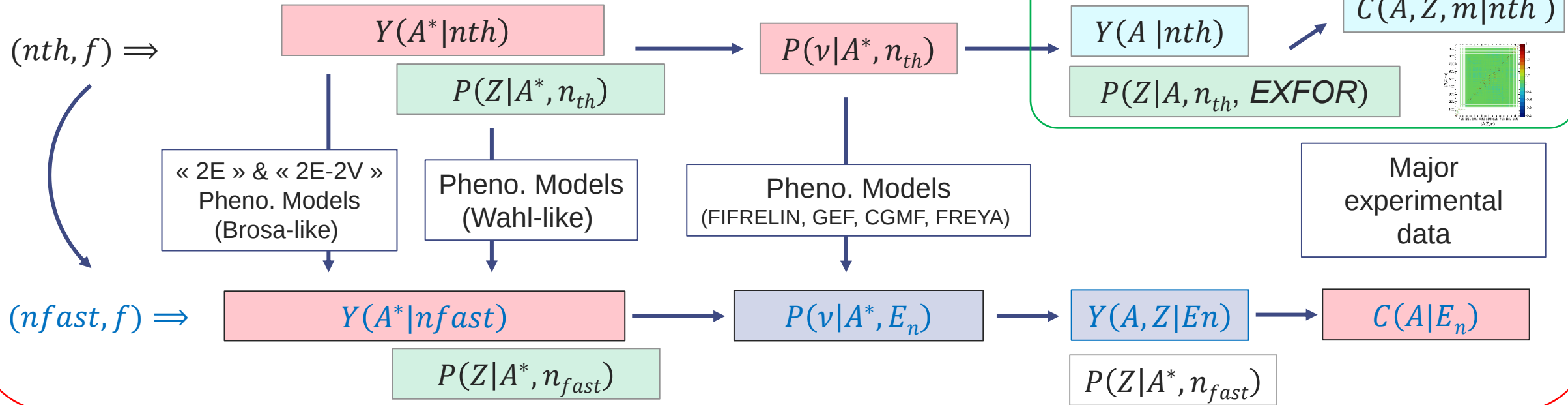


→ full **Z** & limited **A** identification



From JEFF-4.0 to JEFF-4.1

JEFF-4.0 → JEFF-4.1



(n_{fast}, f) data

Radiochemical data → full (A, Z) identification

$\beta; \gamma$ spectrometry

~~ELM Mass spectrometer~~

« 2E-2V »

« 2E »

(x, f) data

VAMOS, SOFIA ...

→ full A & limited Z identification

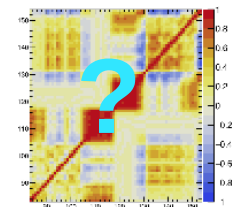
→ Limited A & A^* identification

→ full Z & limited A identification

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JEFF-4.0 RADIOCHEMICAL DATA FILE
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Conclusion & perspectives: P(ND)² -3

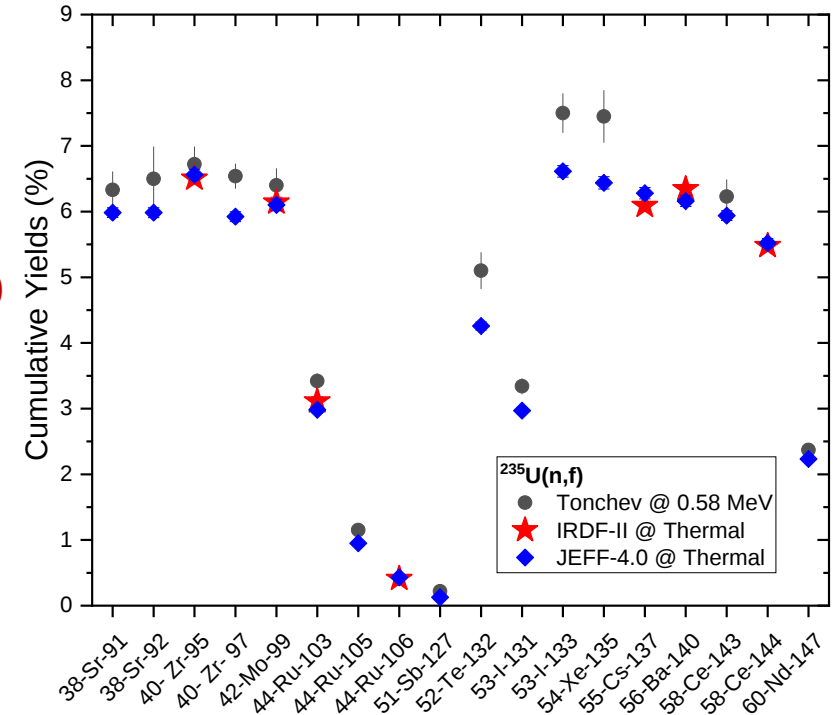
NEEDS for JEFF-4.1:

- New charge distribution in the region of Eu and Sm
- New **complete mass yield** measurements of $^{239}\text{Pu}(n_{\text{th}},f)$
- **Symmetric and far asymmetric mass yields** measurements of $^{241}\text{Pu}(n_{\text{th}},f)$

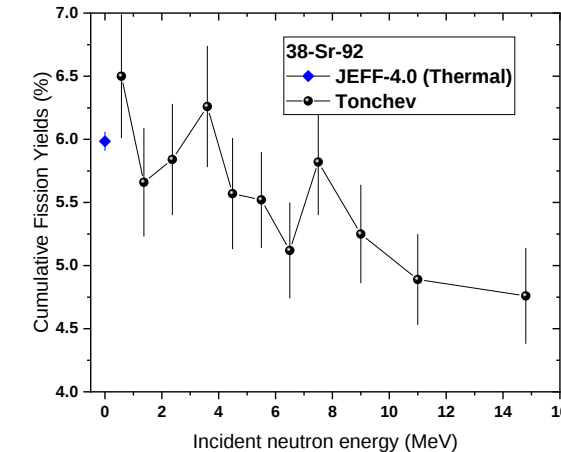
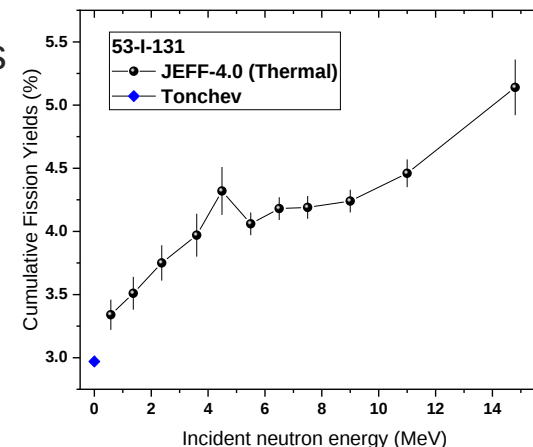
Program for the next Decade:

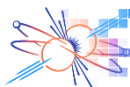
- Complete the (n_{th},f) FY evaluations
- Develop methodology of **Evaluation from pre-n observable to PIE**
- Adjust phenomenological models considering :
 - **correlation** matrices at all steps **to propagate uncertainties**
 - **default model** to estimate the biases
 - **statistical tests** to validate the uncertainty and the biases
- Adjusted fission model parameters in order to interpreted **fast neutron energy range** data [0; 6 MeV]
- **Evaluation as a function of incident neutron energy**

→Towards JEFF-4.1

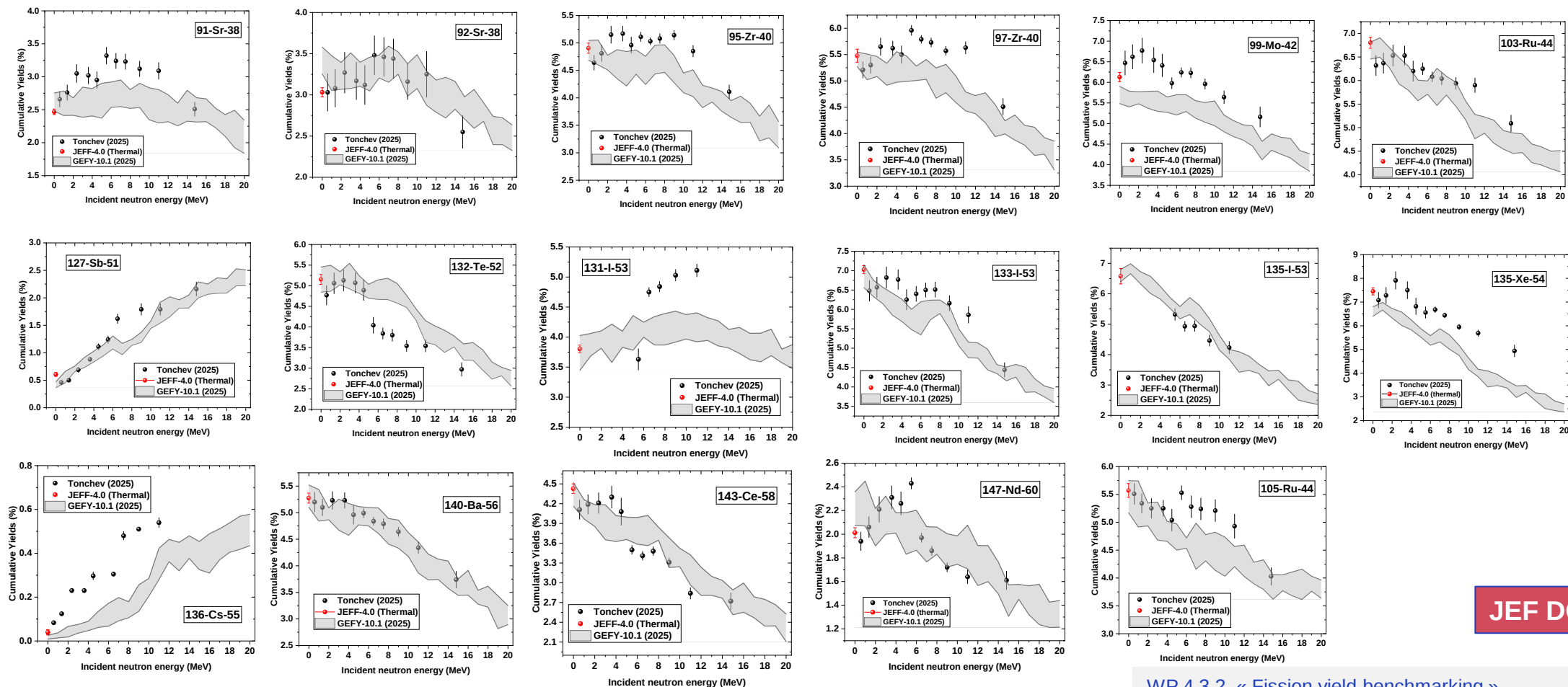


A. Tonchev et al., Nuclear Data Sheets 202, 12 (2025)





Overview of the 17 Cumulative Fission Products yields measured by Tonchev



JEF DOC 2550

WP 4.3.2 « Fission yield benchmarking »
Project NIFPYF :
« Neutron Induced Fission Product Yields in Fast energy range »



Funded by
the European Union

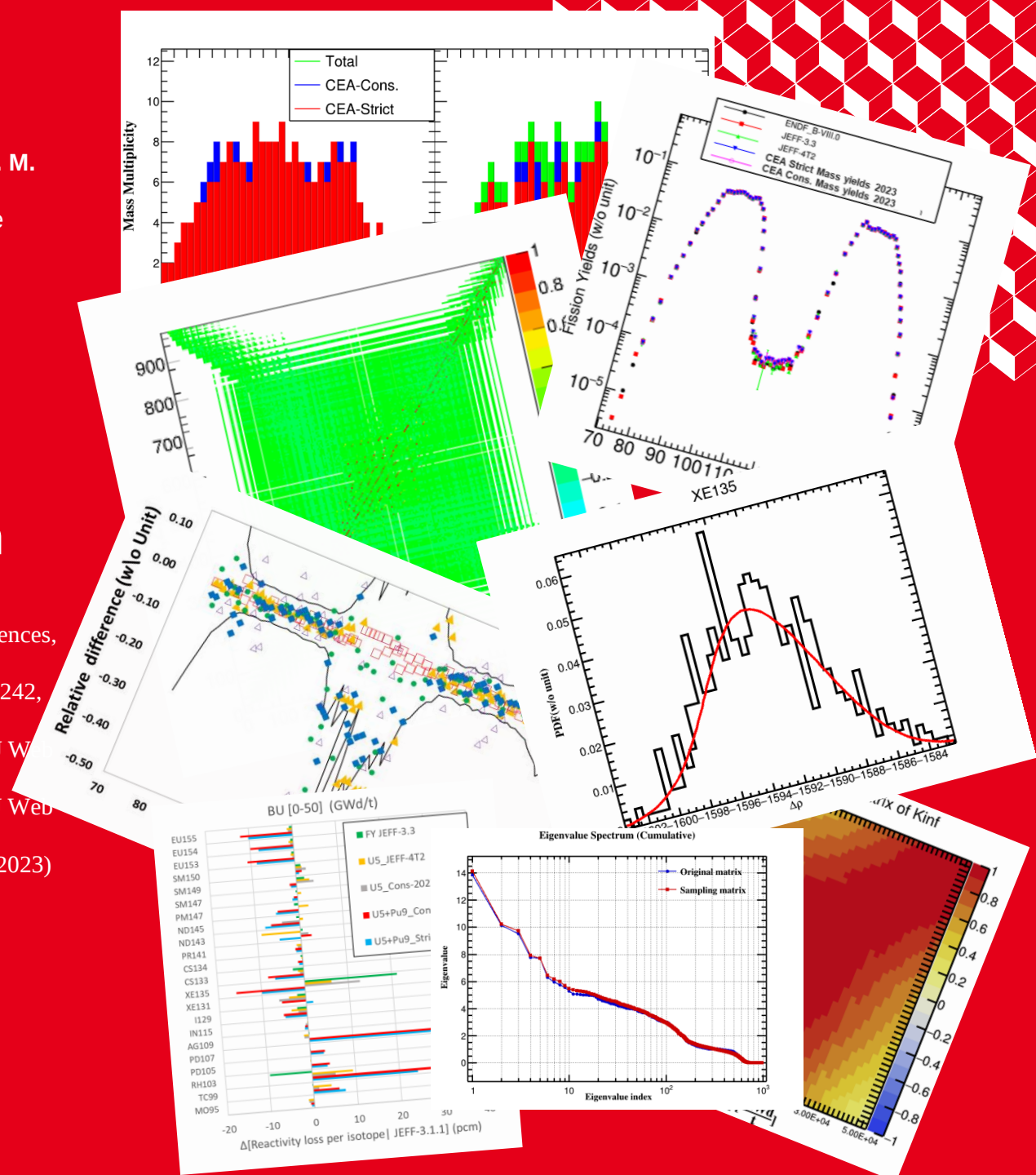
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.



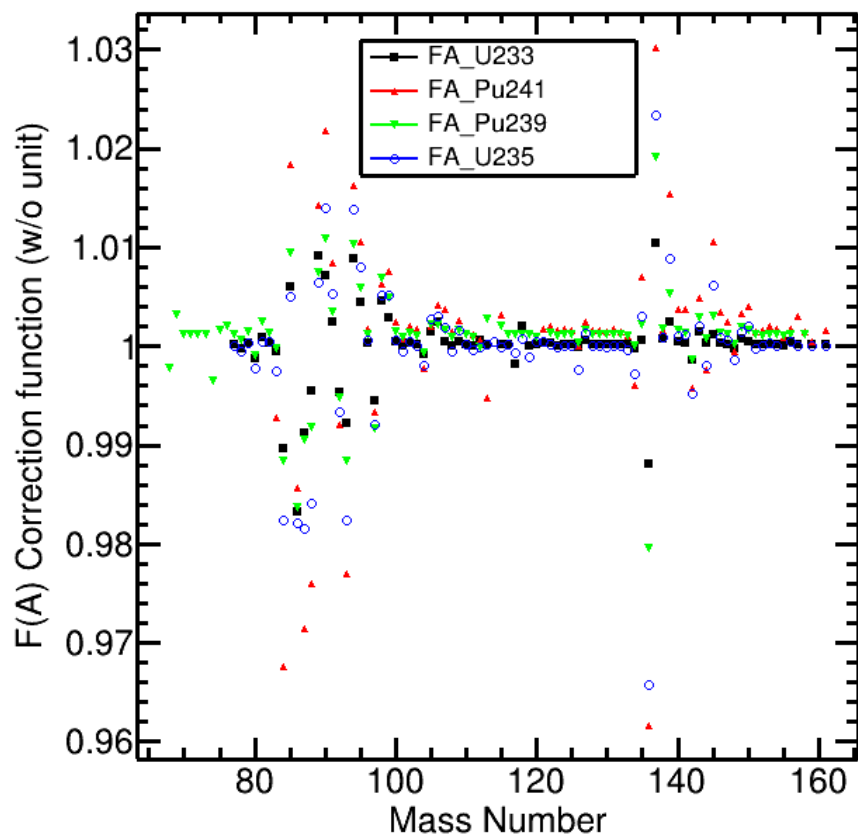
G. Kessedjian¹, A. Regonesi¹, N. Teixeira-Rua¹, S. M. Cheikh¹, O. Serot¹, A. Chebboubi¹, D. Bernard¹
CEA, DES, IRESNE, DER, SPRC, LEPH, Cadarache
center, F-13108 Saint Paul lez Durance, France

Thank you for your attention

- B. Voirin, G. Kessedjian et al, EPJ N - Nuclear Sciences & Technologies, EDP Sciences, 4, pp.26 (2018)
- G. Kessedjian, S.-M. Cheikh et al., FPY 2019, Santa Fe, EPJ Web of Conferences 242, 05001 (2020)
- S.-M. Cheikh, G. Kessedjian et al., Covariance Workshop 2022, Tokyo, Japan, EPJ Web of Conferences 281, 00023 (2023)
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- S.-M. Cheikh, G. Kessedjian et al., M&C2023 conference, Niagara Falls, Canada (2023)
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<https://doi.org/10.1080/00295639.2024.2347693>
- S.-M. Cheikh, PhD thesis, UGA, 18 Oct. 2023
- S.-M. Cheikh, G. Kessedjian et al., Eur. Phys. J. A, 60 11 (2024) 222
- G. Kessedjian et al, ND 2025, Madrid
- CRP IAEA on Fission Yields 2020-2024, submitted
- JEFF-4.0 library article, on going
- JEFF-4.0 Fission yields evaluations, on going

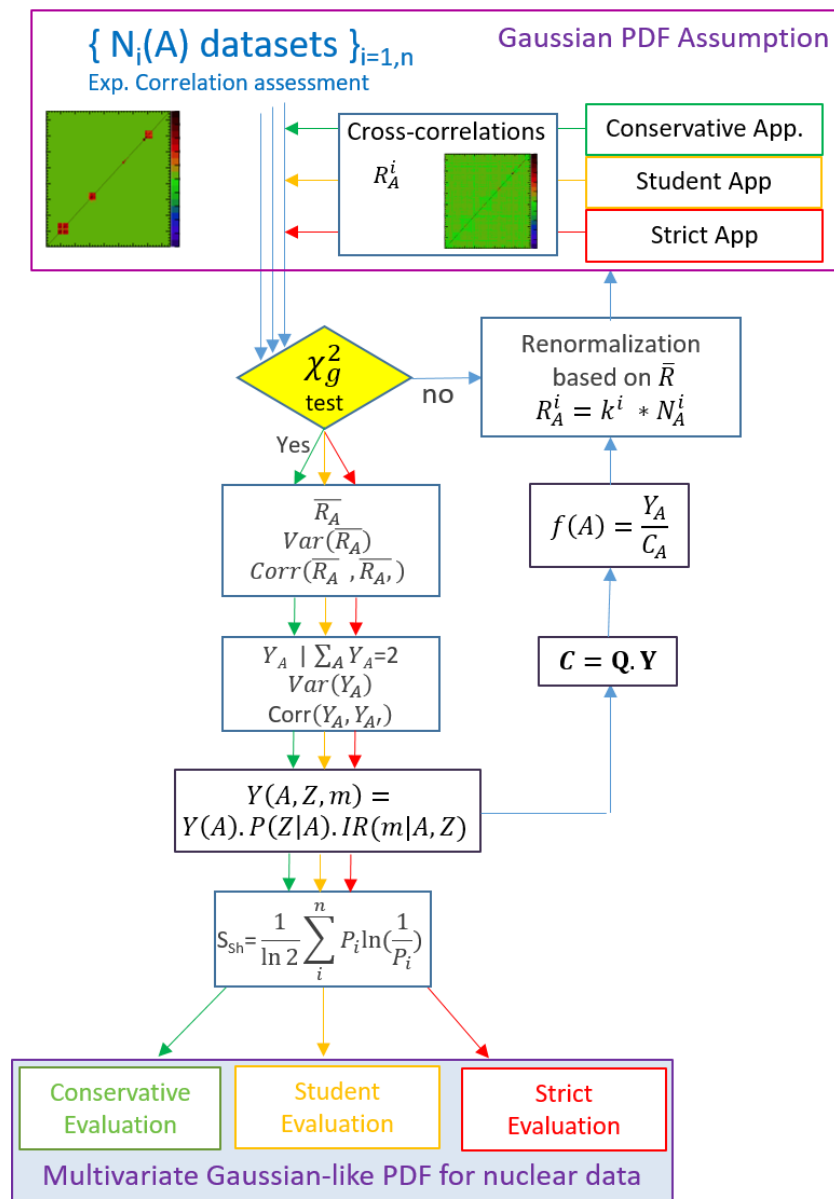


Decay data for JEFF-4.1 : Delayed neutron probabilities



Up to 7% effect of JEFF-3.3 Decay Data in the combination of mass yield and chain yield datasets

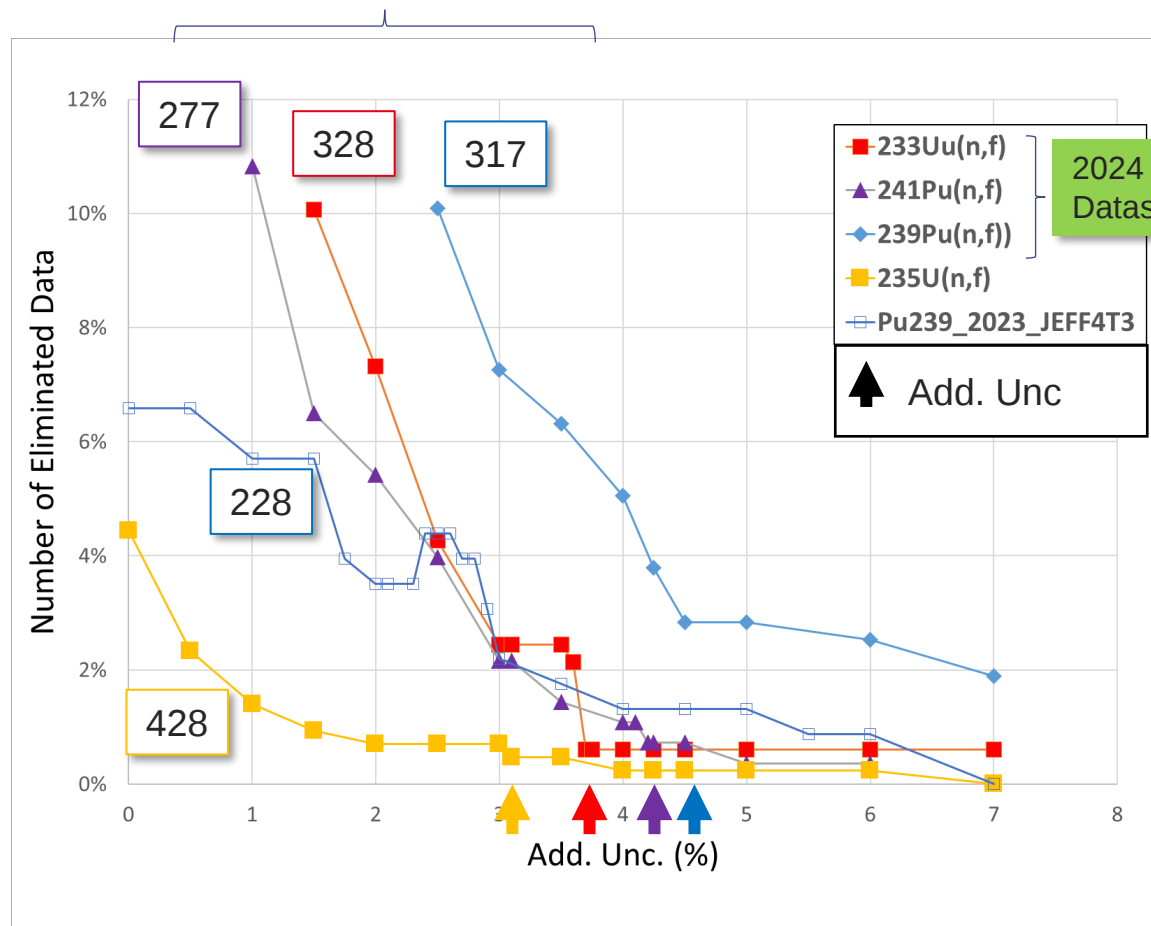
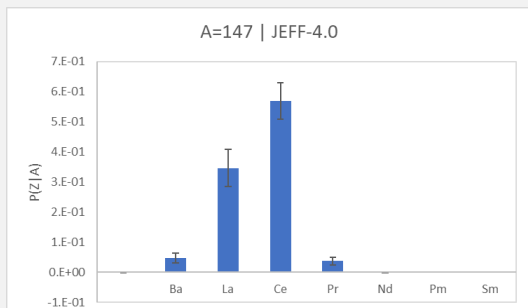
- ❖ Combined analysis of Mass & chain yields with delayed neutron probability in order to update the Decay data & the charge distributions



Test and sorting of available experimental data for the 4 main fissile nuclei

Integrating several cumulative yields $\equiv$ chain yields
according to $P(Z|A, \text{JEFF3.3})$ sorting

- ❖ Only mass yields and chain yields used in these analyses for ^{235}U
- ❖ But quasi-chain for ^{233}U , ^{239}Pu and ^{241}Pu , sorting of experimental data depends to $P(Z|A)$ distribution



sorting depends on
mean nuclear charge

