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New $^{235}\text{U}(n_{\text{th}},f)$ Evaluation of pre-neutron emission mass yields and neutron multiplicity

A. REGONESI , G. KESSEDJIAN, O. SEROT, S.M. CHEIKH

DES/IRESNE/DER/SPRC/LEPh

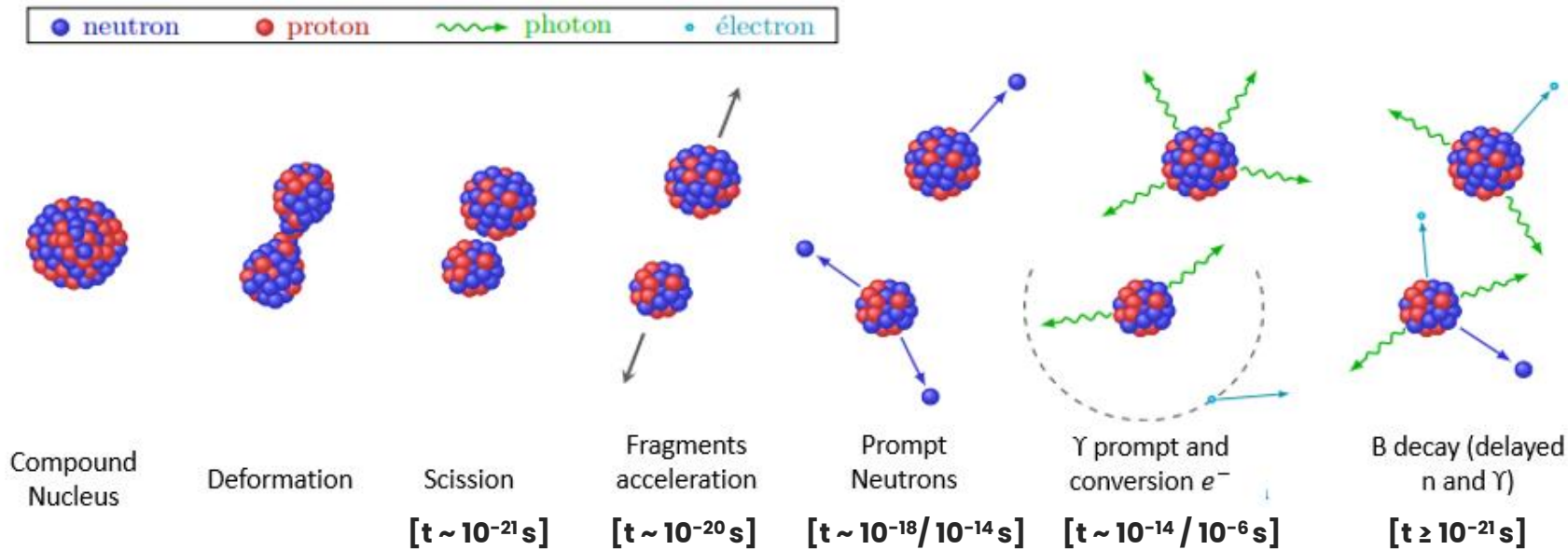
WONDER 2026 | 29th June – 3rd July 2026



Content of the presentation

- 1. FY evaluation program @ CEA Cadarache**
- 2. New methodology for evaluation of Pre-neutron mass yields : application to $^{235}\text{U}(n_{\text{th}},f)$**
- 3. Prompt neutron multiplicity analysis**
- 4. Conclusion and perspectives**

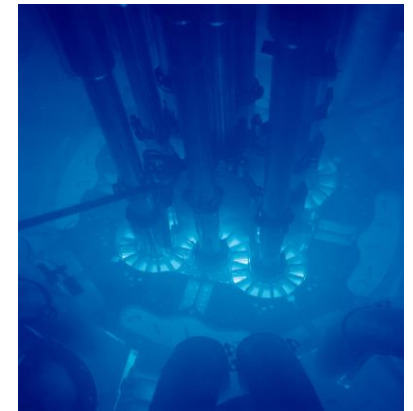
Mass Yields



PIAU, Valentin. *Prédiction par calcul des observables de fission à partir d'expériences dédiées*. 2022. Thèse de doctorat. Université Grenoble Alpes

Interpretation of integral experiments on :

- **decay heat**
 - **depletion/inventory**
 - ...
- for Gen III, IV reactors



Fission Yields (FY) = production rate of nuclei generated by a fission event, more precisely, by **mass yields** we mean the probability of formation of a nucleus with a certain mass from the fission of the initial compound nucleus.



1. FY evaluation program @ CEA Cadarache

Context: Methodology of (n_{th}, f) FY evaluation

→ S.-M. Cheikh 's PhD thesis (2023)

$Y(A, Z, m)$ Independent Yields



$C(A, Z, m)$ Cumulative Yields



$C(A)$ Chain Yields



Application



Fuel Cycle applications

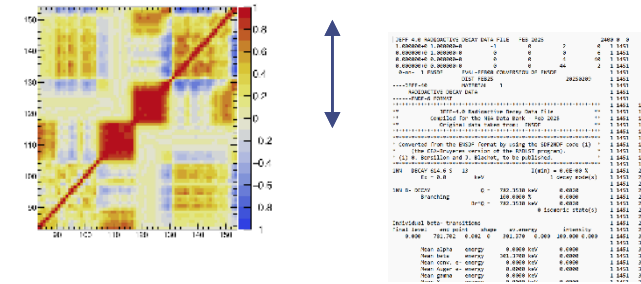
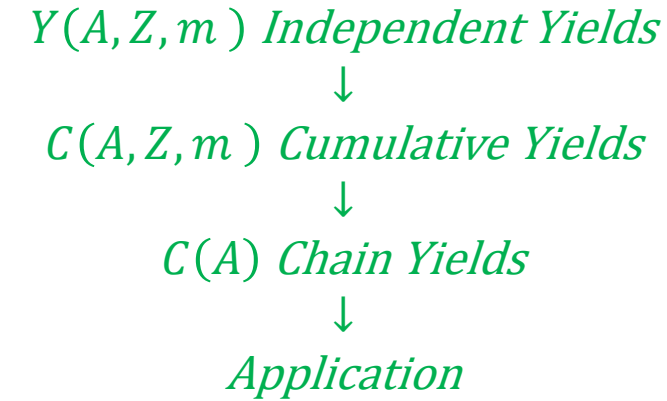
- Reactivity losses (BU)
- PIE (BU) : Post-Irradiated Experiment
- CFE
- Decay Heat

Context: Methodology of (n_{th}, f) FY evaluation

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$$Y(A, Z, E_K, I) = Y(A) \cdot P(Z|A, E_K) \cdot P(E_K|A, Z) \cdot P(m|A, Z, E_K)$$

Mass
Charge
Kinetic Energy
Isomeric



Fuel Cycle applications

- Reactivity losses (BU)
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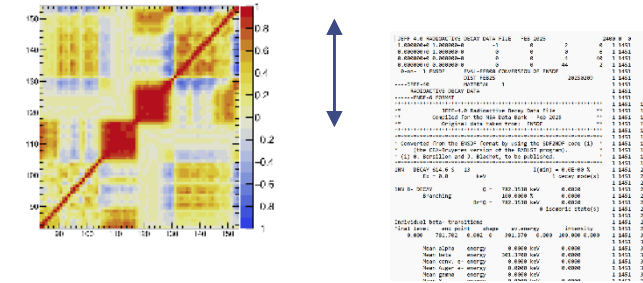
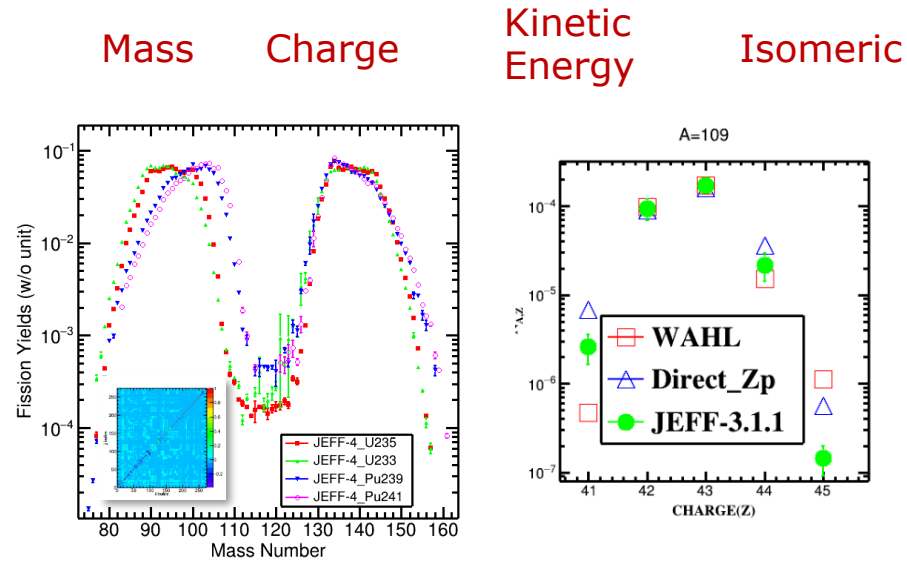
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$$Y(A^*, Z, E^*, J^\pi)$$

↔

$$Y(A, Z, E_K, I)$$

↔

$$Y(A, Z, m) \text{ Independent Yields}$$

↓

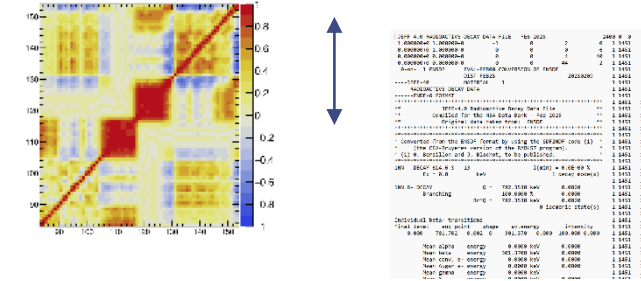
$$C(A, Z, m) \text{ Cumulative Yields}$$

↓

$$C(A) \text{ Chain Yields}$$

↓

Application



$$Y(A^*) \cdot P(Z|A^*, E^*) \cdot P(E_K|A^*, Z) \cdot P(E^*, J^\pi|A^*, Z, E^*)$$

$$Y(A) \cdot P(Z|A, E_K) \cdot P(E_K|A, Z) \cdot P(m|A, Z, E_K)$$

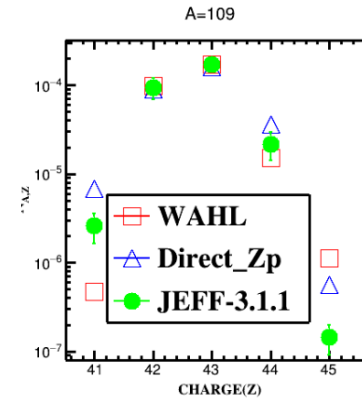
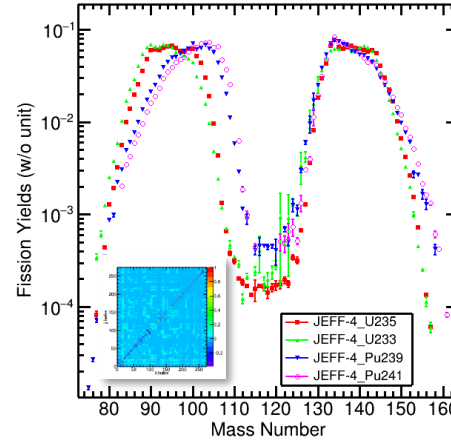
Pre-neutron Mass, charge, excitation energy

Fission models

Mass Charge

Kinetic Energy

Isomeric



(n_{th}, f) data

Radiochemical data

$\beta; \gamma$ spectrometry

ELM Mass spectrometer

→ full (A, Z) identification

→ full A & limited Z identification

→ JEFF-4.0

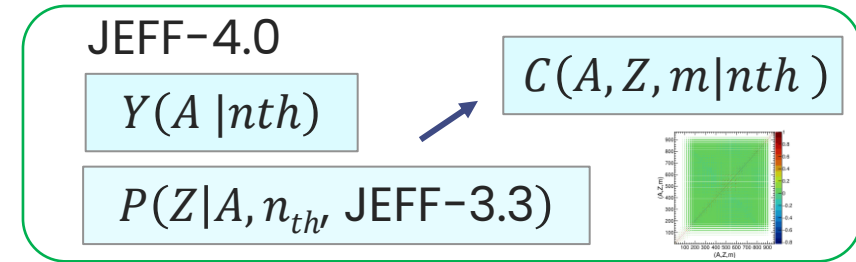
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- Reactivity losses (BU)
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Context: Methodology of (n_{th}, f) FY evaluation → S.-M. Cheikh's PhD thesis (2023)



$(nth, f) \Rightarrow$



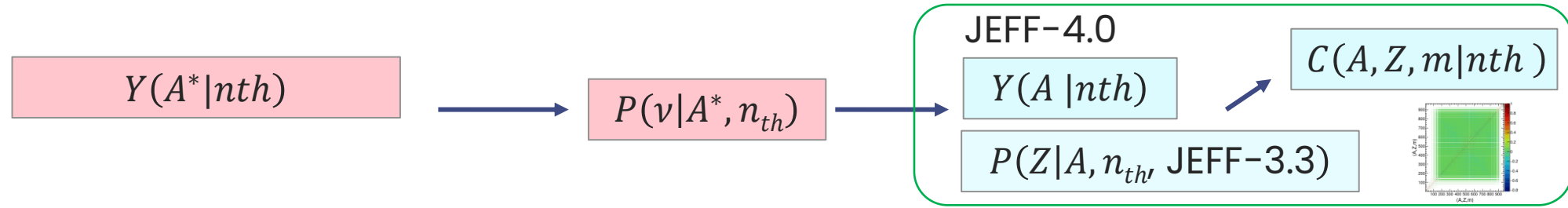
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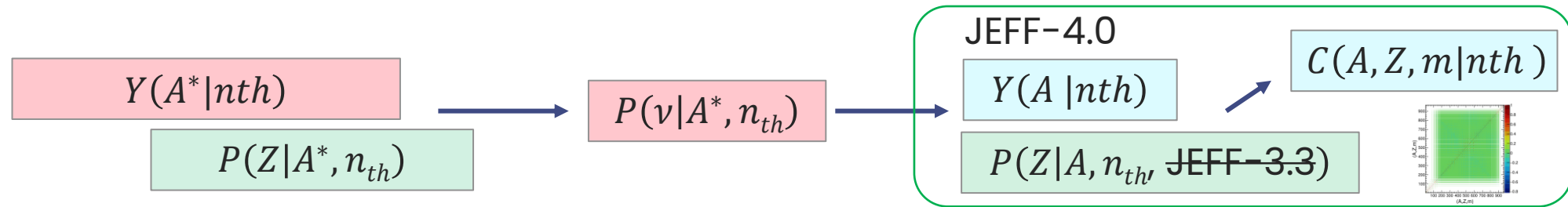
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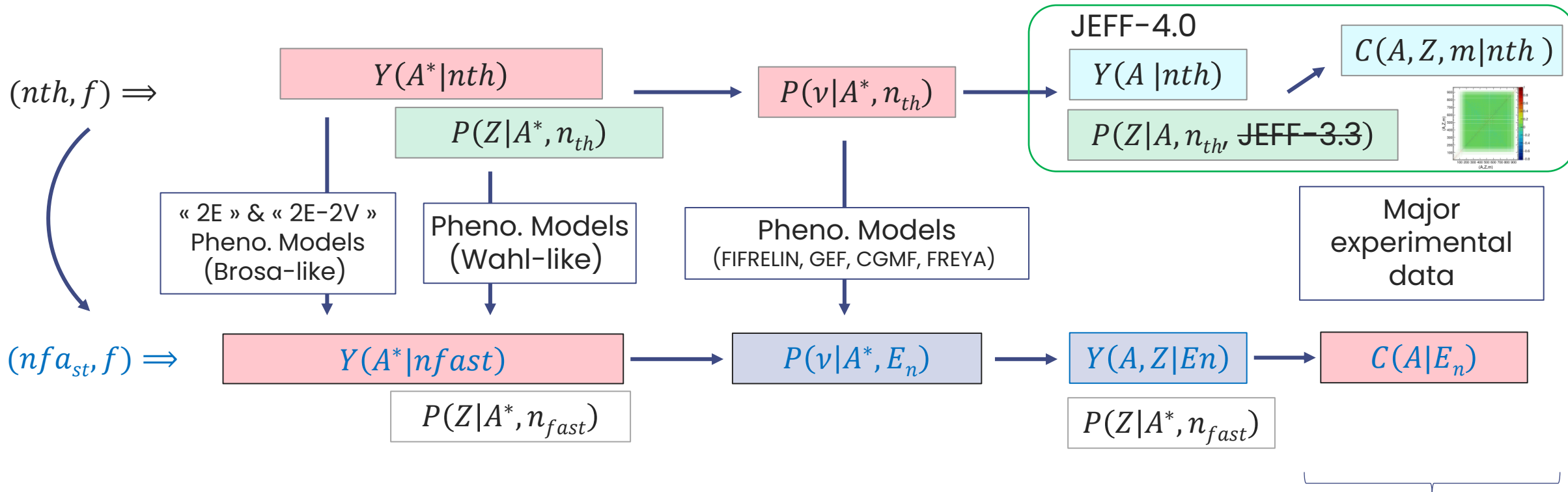


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(n_{fast}, f) data

Radiochemical data

$\beta; \gamma$ spectrometry

~~ELM Mass spectrometer~~ → full A & limited Z identification

« 2E-2V »

« 2E »

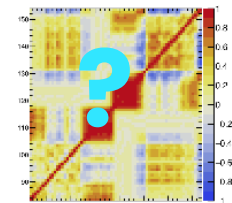
→ full (A, Z) identification

→ Limited A & A^* identification

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1.000000 1.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
2.000000 0.000000 1.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
3.000000 0.000000 0.000000 1.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
4.000000 0.000000 0.000000 0.000000 1.000000 0.000000 0.000000 0.000000 0.000000 0.000000
5.000000 0.000000 0.000000 0.000000 0.000000 1.000000 0.000000 0.000000 0.000000 0.000000
6.000000 0.000000 0.000000 0.000000 0.000000 0.000000 1.000000 0.000000 0.000000 0.000000
7.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 1.000000 0.000000 0.000000
8.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 1.000000 0.000000
9.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 1.000000
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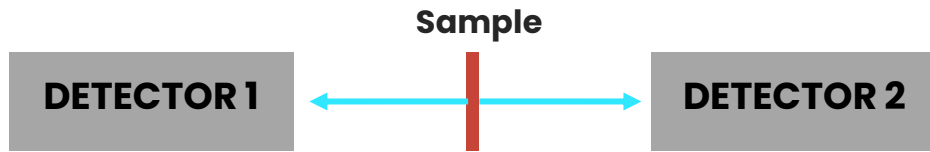
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Methods 2E and 2E-2v



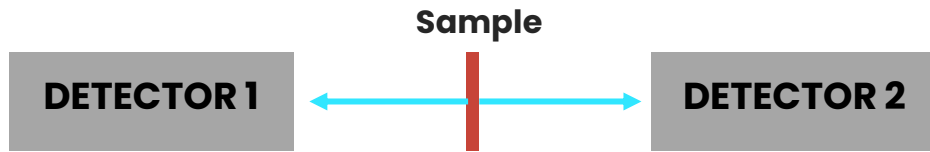
2E method



- ❑ Only the 2 energies of Fission Products (FP) are measured
- ❑ Need for an external prompt neutron multiplicity $\nu(A)$
- ❑ Iterative process to obtain Fission Fragment (FF) masses

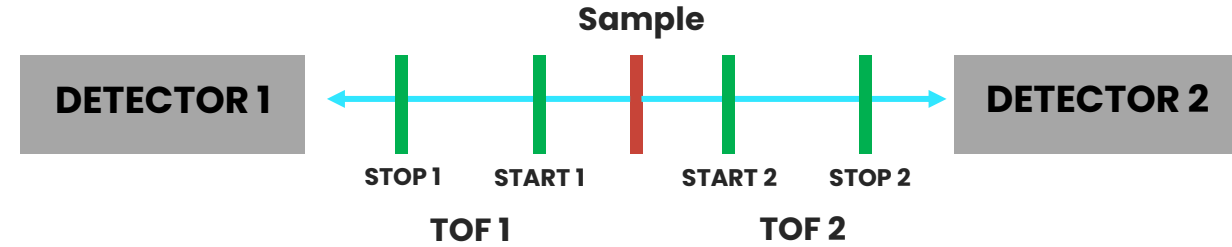
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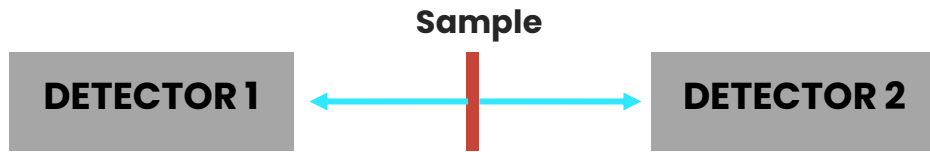
2E-2v method



- ❑ Both the 2 energies and velocities of Fission Products (FP) are measured
- ❑ Assumption of isotropic neutron emission in the CM system
- ❑ Exploit the conservation laws to obtain FF masses

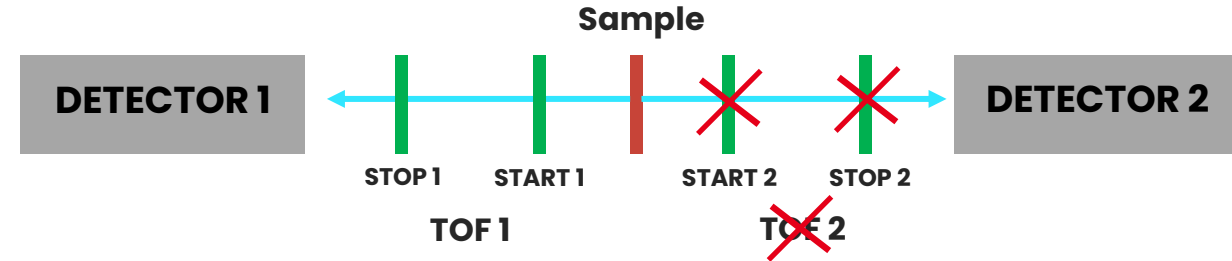
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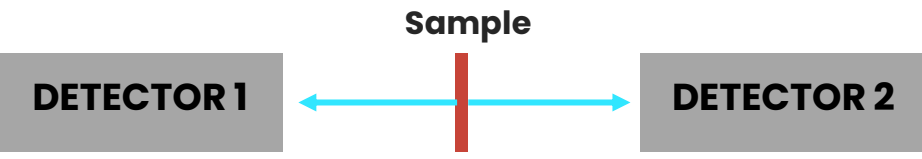
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As regards ^{235}U , there are no actual measurements of 2E-2v so far, rather, the method used is **(2E-1v)x2**, where a complementary event is used to reconstruct the complete measurement

Methods 2E and 2E-2v

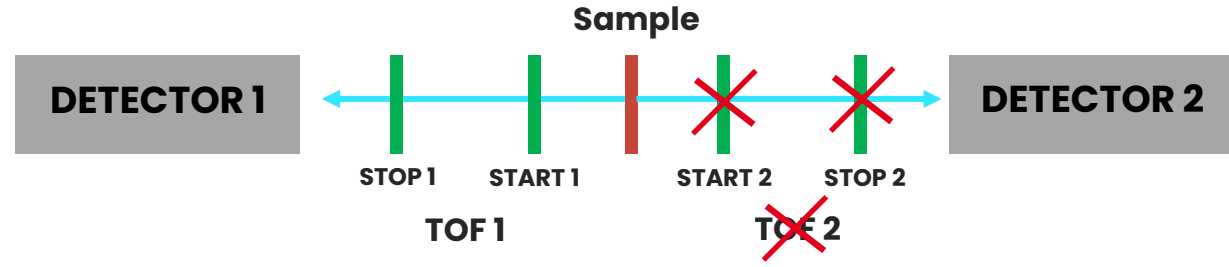


2E method



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| | $Y(A^*)$ | $\nu(A^*)$ | $Y(A)$ |
|--|----------|------------|--------|
| Geltenbort ($^{235}\text{U}, ^{239}\text{Pu}$) "Cosi-Fan-Tutte" | X | | X |
| Derengowski (^{235}U) | X | | X |
| Al-Adili (^{235}U) | X | X | |
| Hamsch (^{235}U) | X | | |
| Other 2E data ... | X | | |

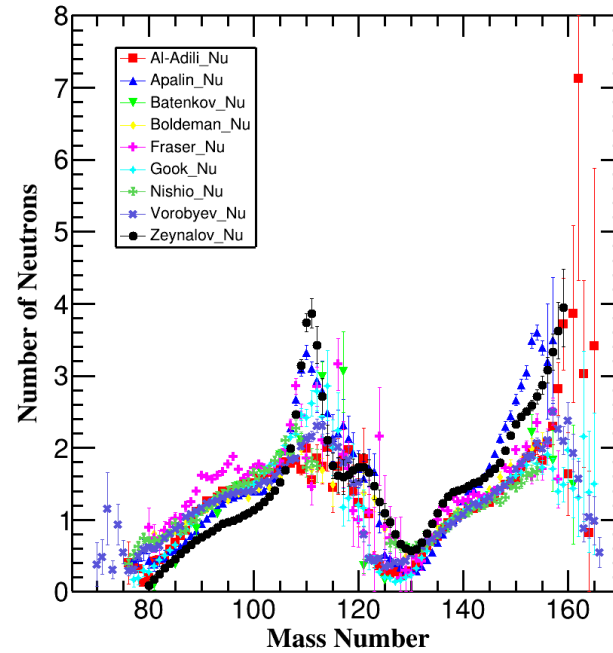
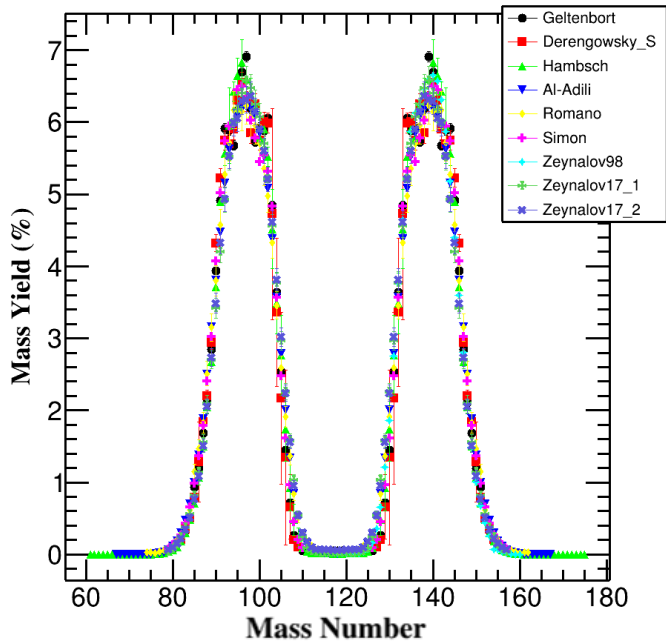


2. ■

New methodology for evaluation of Pre-neutron mass yields

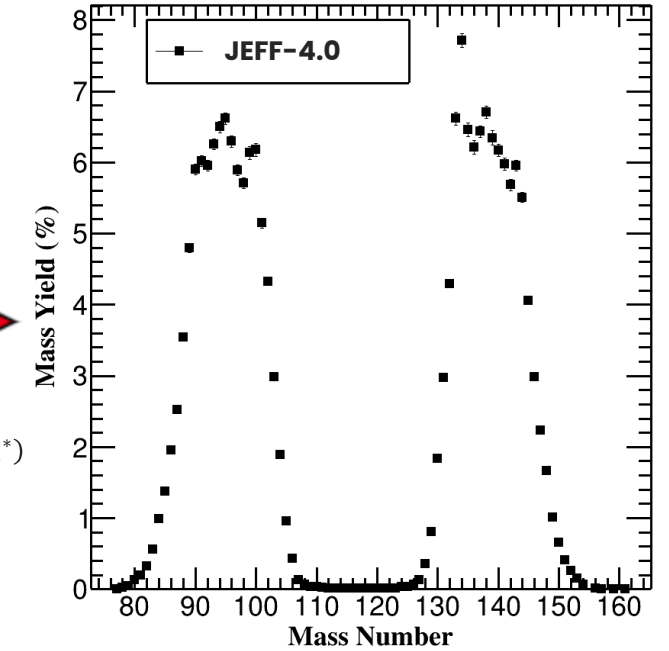
$^{235}\text{U}(n_{th},f)$ evaluation of Pre-neutron fission yields

Experimental Data for ^{235}U



$$Y_{post}(A) = \sum_{\nu} Y_{pre}(A^*) P(\nu|A^*)$$

$$A^* = A + \nu$$



Conservation laws
and symmetry

Challenge: Experimental limit of **Mass Resolutions**

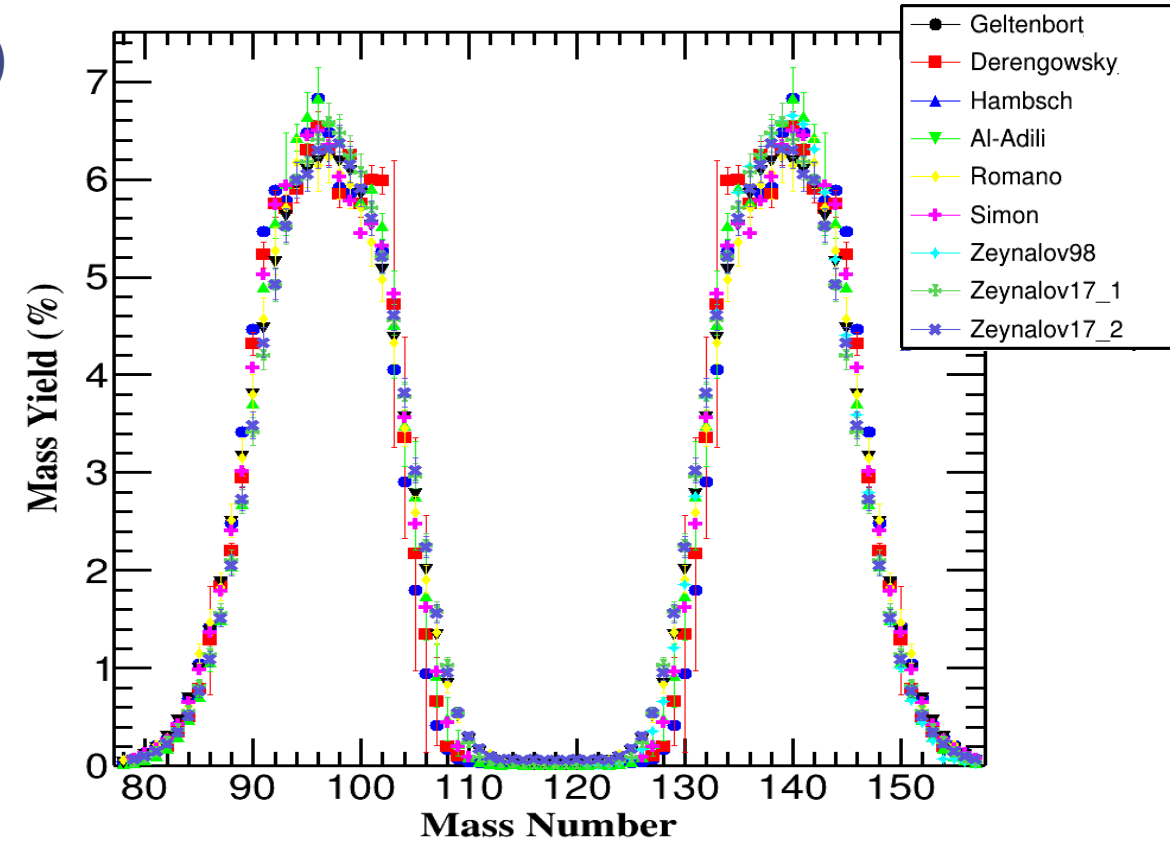
Validation on JEFF-4.0
mass yields
Full A identification

$^{235}\text{U}(n_{\text{th}},f)$ evaluation of Pre-neutron fission yields

Bibliography of Experimental Data (EXFOR database)

Experimental data

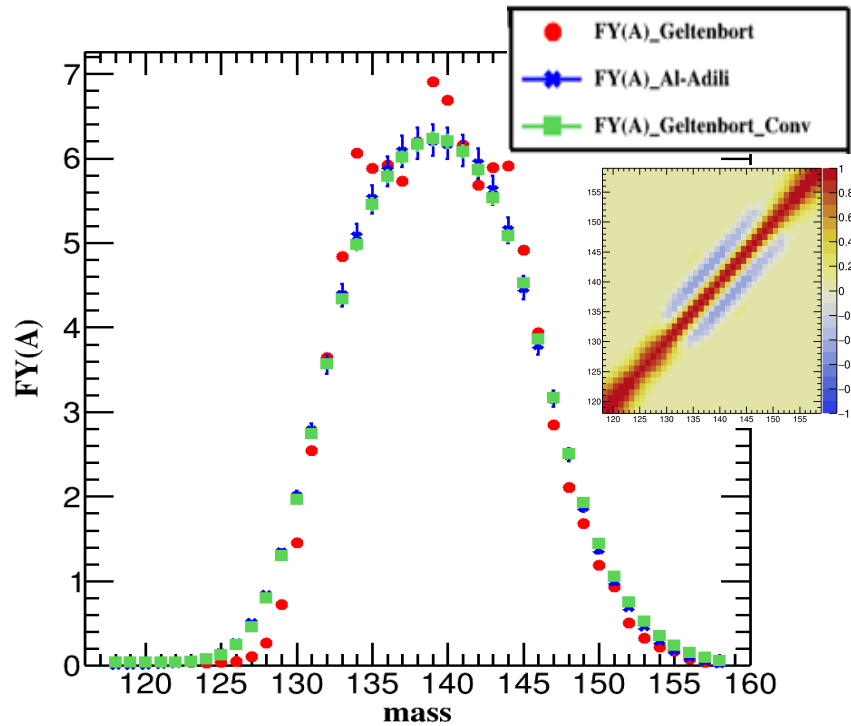
| Name | Year | Method | $\nu(A)$ | Unc. | Sym. | Mass Range |
|-----------------|------|-----------|----------------------|------|------|-----------------|
| Geltenbort (1) | 1985 | (2E-1v)x2 | No | Yes | Yes | 77-159 |
| Derengowski (2) | 1970 | (2E-1v)x2 | No | Yes | No | 78-109, 127-154 |
| Habsch (3) | 1989 | 2E | Apalin | Yes | No | 61-168 |
| Al-Adili (4) | 2020 | 2E | Wahl | Yes | No | 66-167 |
| Romano (5) | 2007 | 2E | Maslin | Yes | No | 71-165 |
| Simon (6) | 1989 | 2E | Cold frag. | No | No | 79-110, 126-157 |
| Zeynalov (7) | 2006 | 2E | Apalin | Yes | No | 118-160 |
| Zeynalov S1 (8) | 2017 | 2E | measured $\bar{\nu}$ | No | No | 79-157 |
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- ❑ 9 series of data **symmetrised** and **quasi-complete mass range** allowing **absolute normalization**
- ❑ Generalised compatibility tests (with correlations) :
 - ❖ Geltenbort et Derengowski :
 - **$Y(A^*)$ and $Y(A)$ available data**
 - **absolute mass resolutions** determined in comparison to **JEFF-4.0 $Y(A)$**
 - ❖ 2E data mass resolutions :
 - **mainly no $Y(A)$ available data**
 - **Only compatibility tests with 2E-2v measurements are possible**

$^{235}\text{U}(n_{\text{th}},f)$ evaluation of Pre-neutron fission yields

Problem due to the different mass resolutions of experimental data → Solved via convolution function and comparison in the space of convolutions



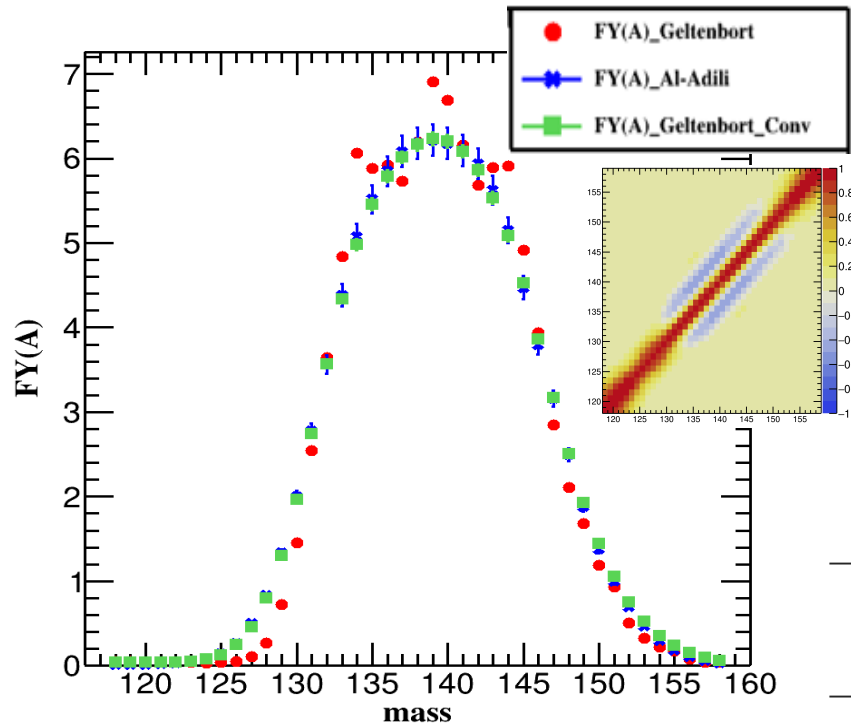
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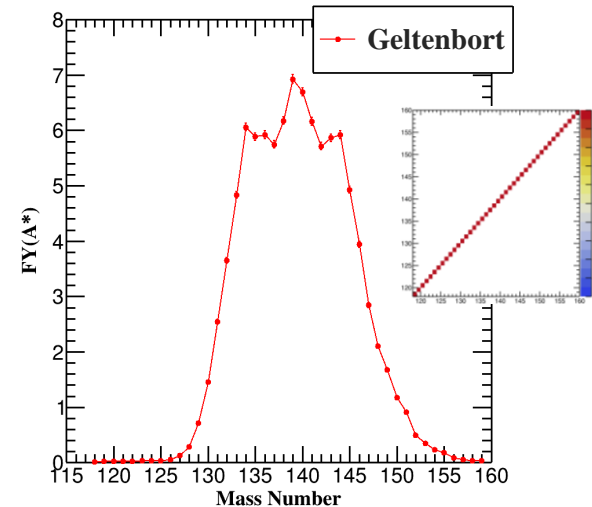
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→ Relative mass resolution
 $\sigma_{\text{Al Adili}} = 2.3 u$

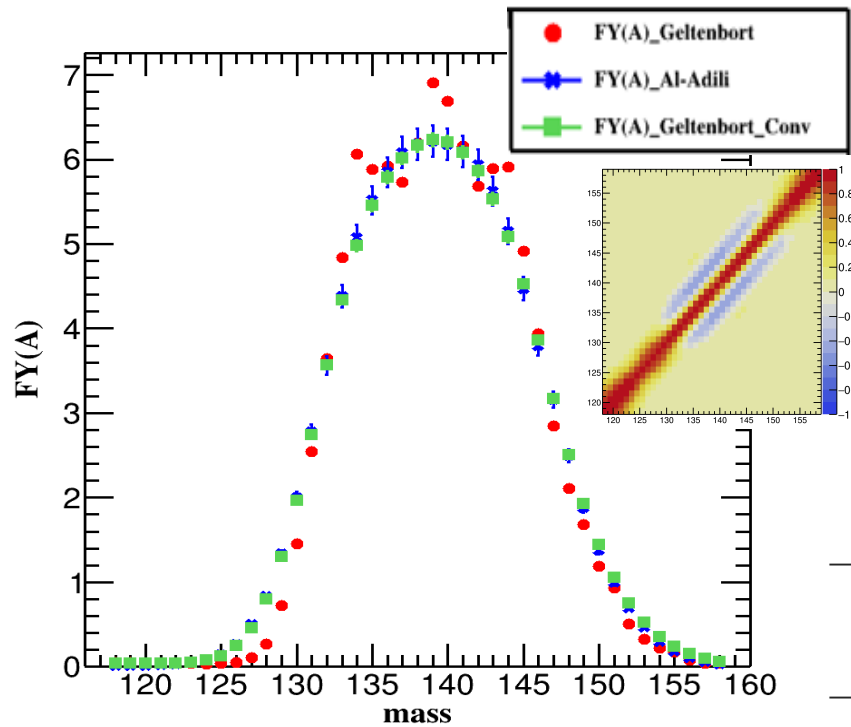
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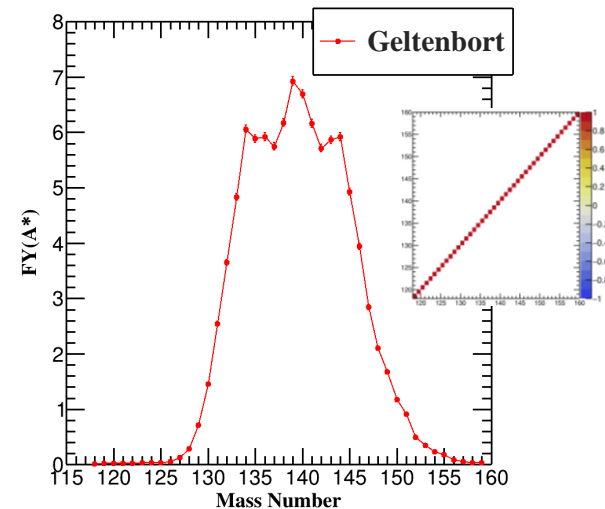
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| Selected data | | | |
|--------------------------|---------------------------|-----------------|-----------------------|
| Region ($FY \geq x\%$) | $\sigma_{\text{add}}(\%)$ | FWHM (amu) | $P'_{\text{val}}(\%)$ |
| 0% | 0.0 | 2.70 ± 0.09 | 100 |
| 0% | 0.0 | 3.06 ± 0.18 | 0.73 |
| 0% | 0.0 | 3.23 ± 0.14 | 1.55 |
| 0.1% | 2.0 | 5.66 ± 0.12 | 3.6 |
| 1% | 2.0 | 5.99 ± 0.40 | 87.0 |
| 0% | 0.0 | 3.59 ± 0.13 | 19.5 |
| 0.5% | 2.0 | 4.49 ± 0.16 | 4.02 |
| 0.5% | 1.0 | 5.55 ± 0.24 | 39.6 |
| 0.5% | 1.0 | 5.25 ± 0.23 | 24.9 |

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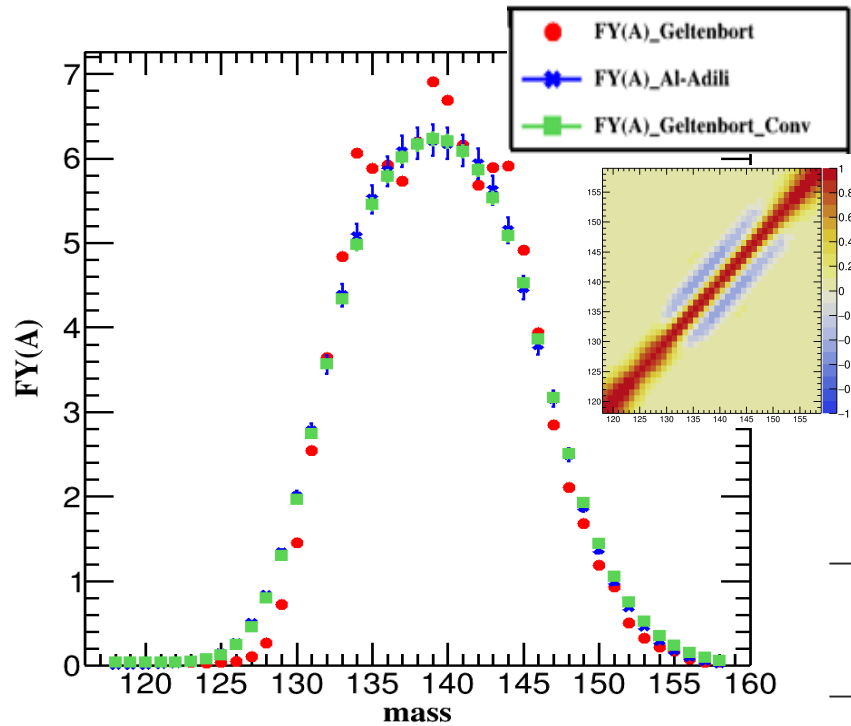
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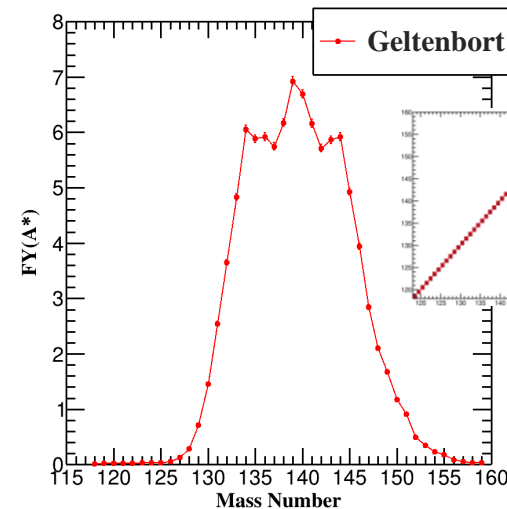
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| Selected data | | | |
|--------------------------|---------------------------|-----------------|-----------------------|
| Region ($FY \geq x\%$) | $\sigma_{\text{add}}(\%)$ | FWHM (amu) | $P'_{\text{val}}(\%)$ |
| 0% | 0.0 | 2.70 ± 0.09 | 100 |
| 0% | 0.0 | 3.06 ± 0.18 | 0.73 |
| 0% | 0.0 | 3.23 ± 0.14 | 1.55 |
| 0.1% | 2.0 | 5.66 ± 0.12 | 3.6 |
| 1% | 2.0 | 5.99 ± 0.40 | 87.0 |
| 0% | 0.0 | 3.59 ± 0.13 | 19.5 |
| 0.5% | 2.0 | 4.49 ± 0.16 | 4.02 |
| 0.5% | 1.0 | 5.55 ± 0.24 | 39.6 |
| 0.5% | 1.0 | 5.25 ± 0.23 | 24.9 |

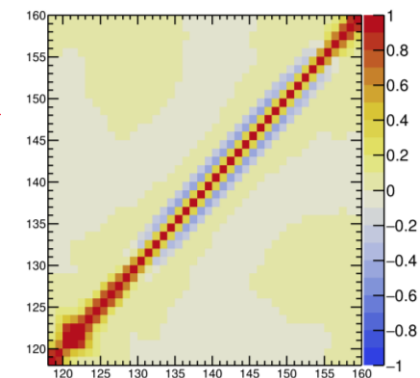
→ Relative mass resolution
 $\sigma_{\text{Al Adili}} = 2.3 \text{ u}$

→ Through mass resolution analysis, it is possible to assign an **a priori correlation matrix** to experimental data that previously did not have one

$$R^i(A^*) = \sum_{A'^*=1}^n \tilde{N}^i(A'^*) \frac{e^{-\frac{1}{2} \left(\frac{A'^* - A^*}{r_i} \right)^2}}{\sum_{A'^*=1}^n e^{-\frac{1}{2} \left(\frac{A'^* - A^*}{r_i} \right)^2}}$$

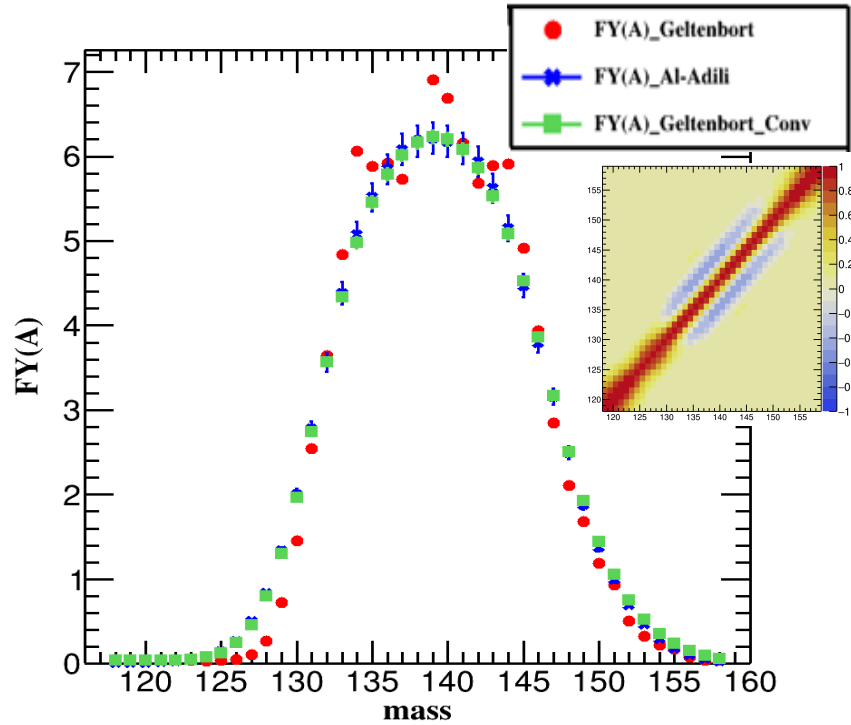


A priori correlation matrix



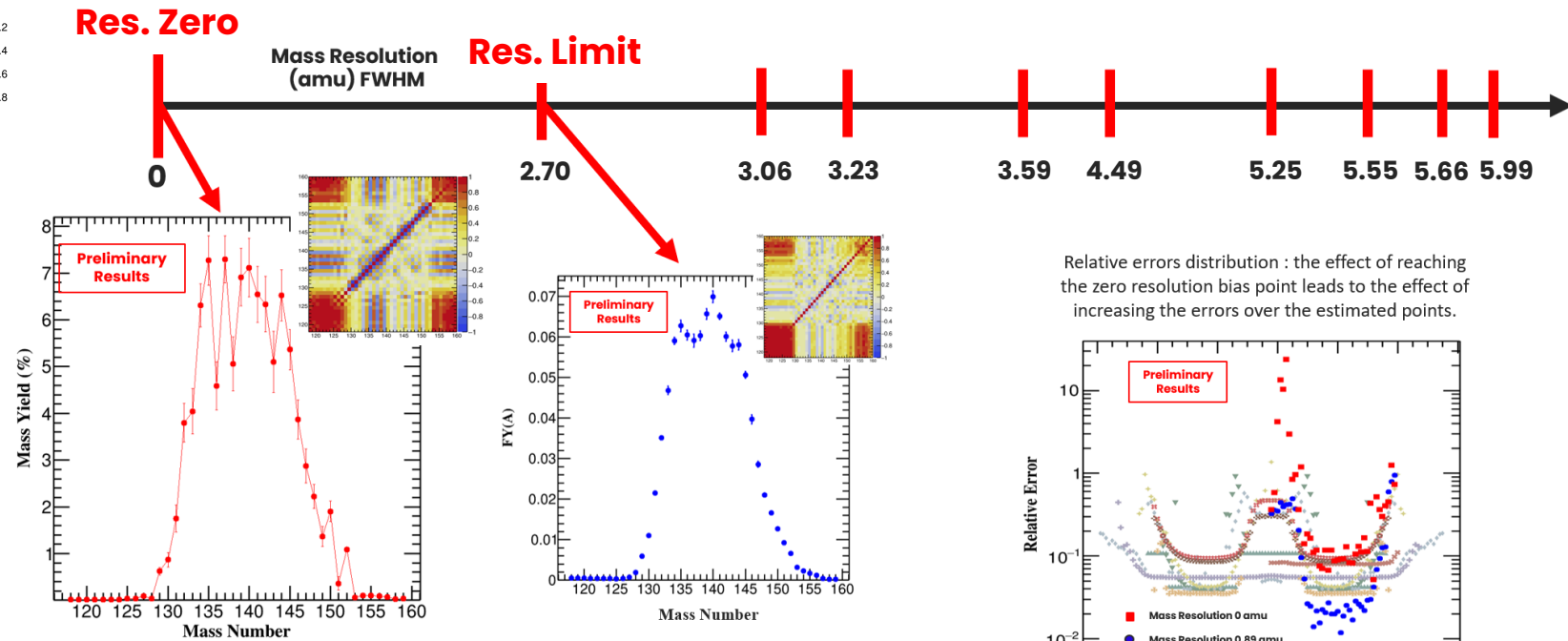
$^{235}\text{U}(n_{\text{th}},f)$ evaluation of Pre-neutron fission yields

Problem due to the different mass resolutions of experimental data → Solved via convolution function and comparison in the space of convolutions

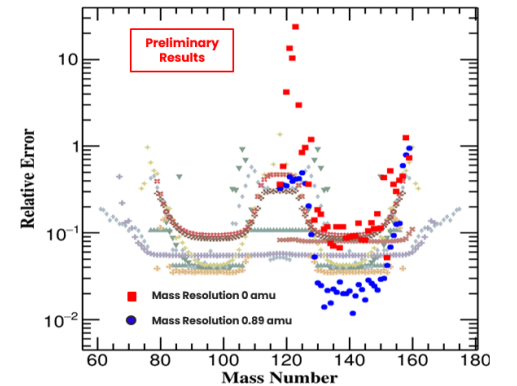


$$R^i(A^*) = \sum_{A'^*=1}^n \tilde{N}^i(A'^*) \frac{e^{-\frac{1}{2}(\frac{A'^*-A^*}{r_i})^2}}{\sum_{A^*=1}^n e^{-\frac{1}{2}(\frac{A'^*-A^*}{r_i})^2}}$$

Once identified all the mass resolutions → merging with of **MCMC code DREAM** to calculate fission yields at the best experimental resolution and at resolution zero

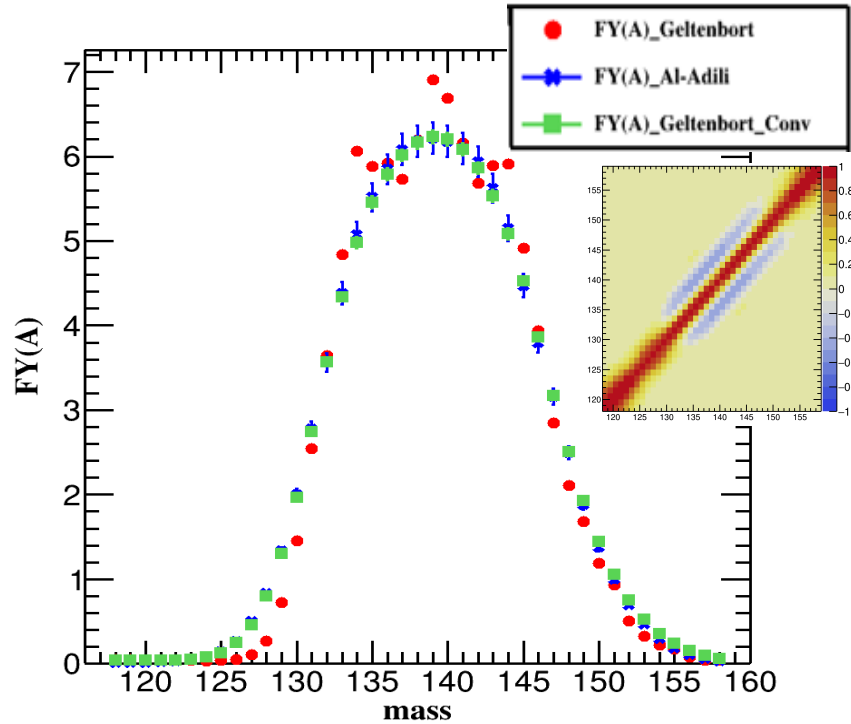


Relative errors distribution : the effect of reaching the zero resolution bias point leads to the effect of increasing the errors over the estimated points.



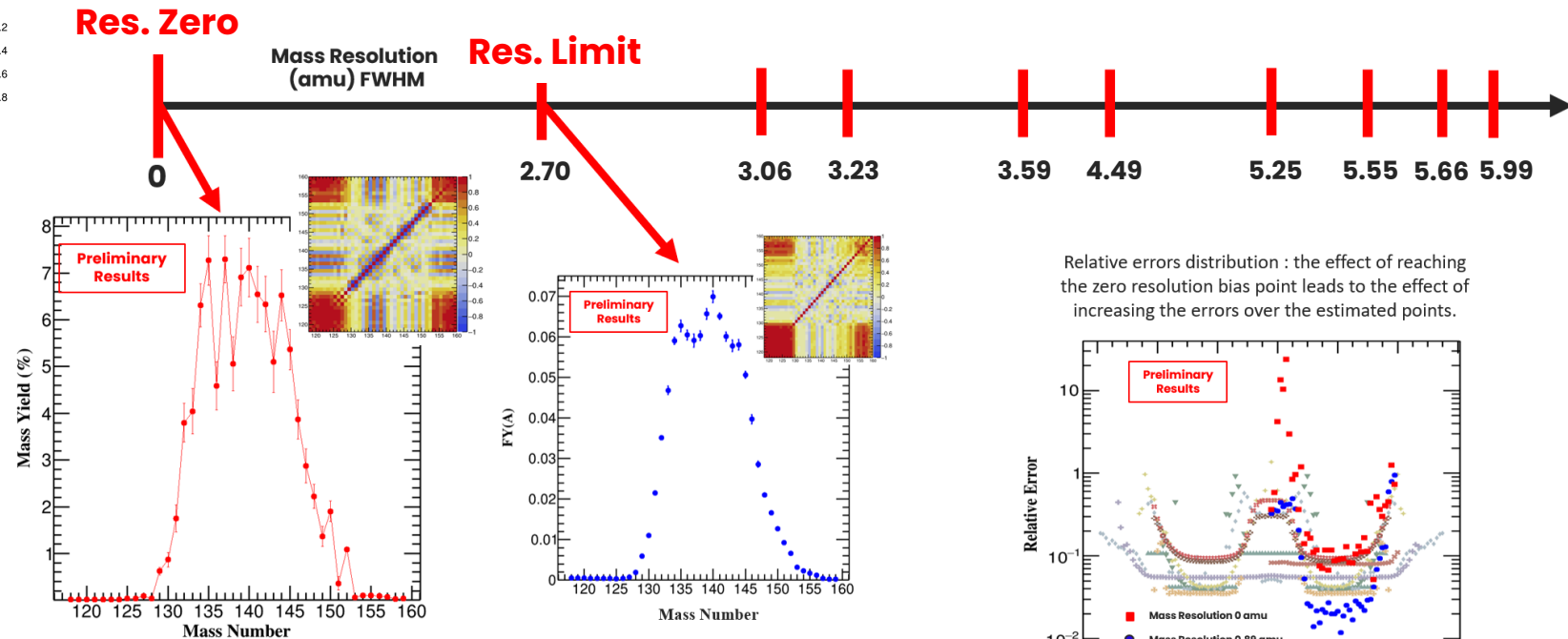
$^{235}\text{U}(n_{\text{th}}, f)$ evaluation of Pre-neutron fission yields

Problem due to the different mass resolutions of experimental data → Solved via convolution function and comparison in the space of convolutions

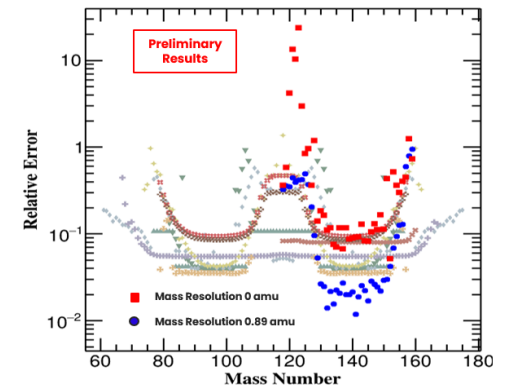


$$R^i(A^*) = \sum_{A'^*=1}^n \tilde{N}^i(A'^*) \frac{e^{-\frac{1}{2} \left(\frac{A'^*-A^*}{r_i}\right)^2}}{\sum_{A^*=1}^n e^{-\frac{1}{2} \left(\frac{A'^*-A^*}{r_i}\right)^2}}$$

Once identified all the mass resolutions → merging with of **MCMC code DREAM** to calculate fission yields at the best experimental resolution and at resolution zero

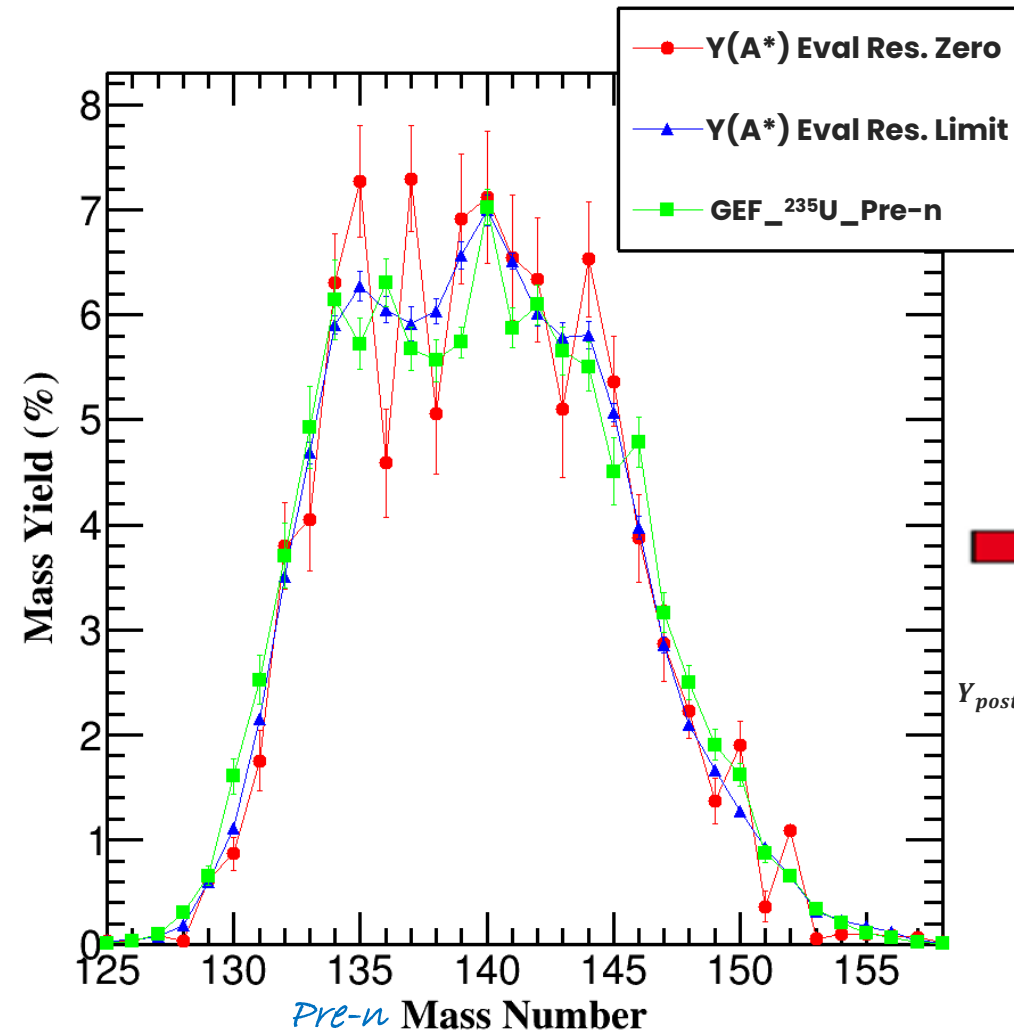


Relative errors distribution : the effect of reaching the zero resolution bias point leads to the effect of increasing the errors over the estimated points.



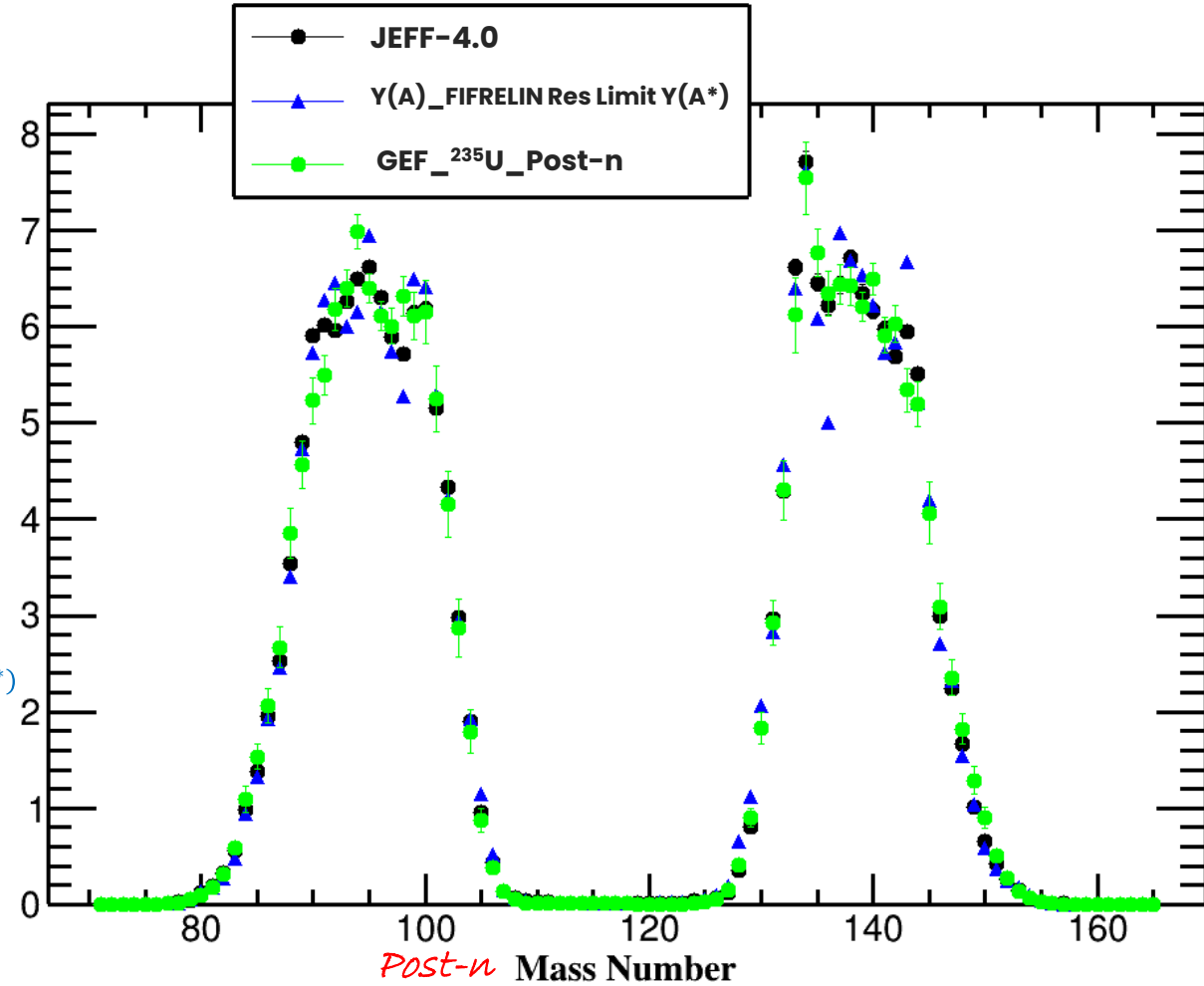
**Extrapolation biases :
high anticorrelations,
peaks position uncertain**

$^{235}\text{U}(n_{\text{th}},f)$ evaluation of Pre-neutron fission yields



$$Y_{\text{post}}(A) = \sum_{\nu} Y_{\text{pre}}(A^*) P(\nu|A^*)$$

$$A^* = A + \nu$$





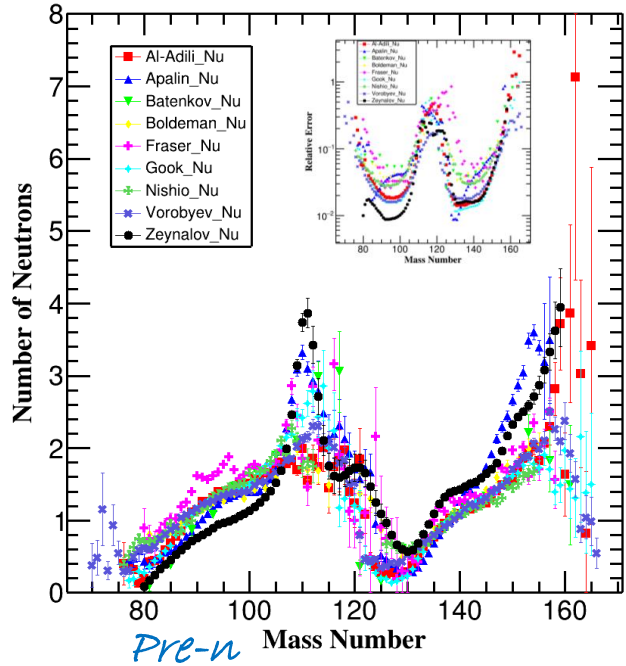
3 ■ Prompt neutron multiplicity analysis

Prompt neutrons multiplicity analysis

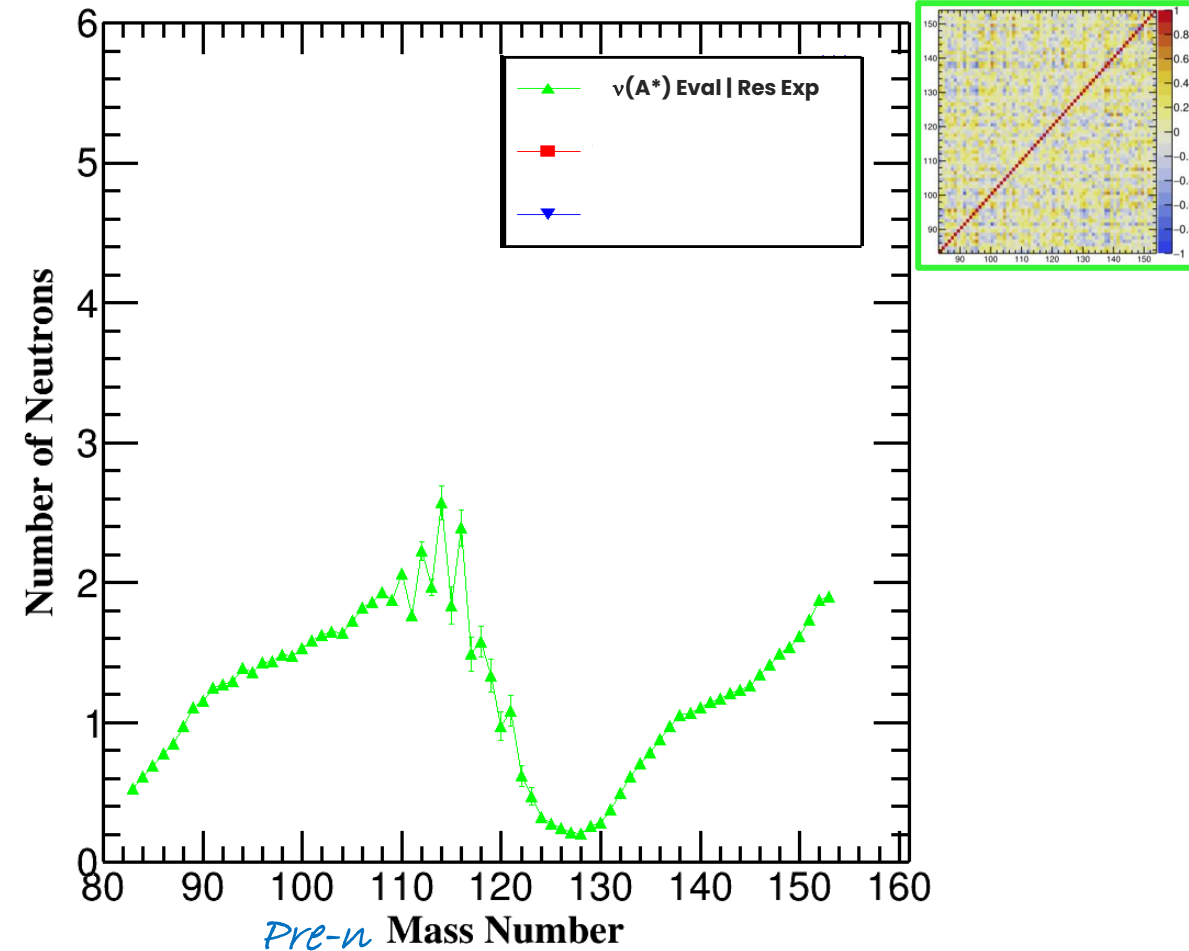


Al-Adili, Ali, et al. "Prompt fission neutron yields in thermal fission of U 235 and spontaneous fission of Cf 252." *Physical Review C* 102.6 (2020)

9 data sets available



➔ **Experimental Evaluation** With
MCMC approach at Al Adili
Reference data
(FWMH= **5.65** amu)
→ $\bar{\nu}_{A^*}$

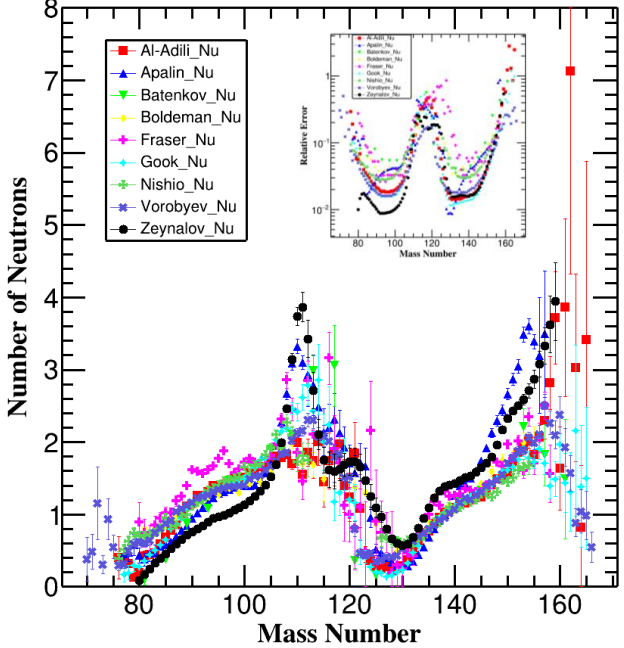


Prompt neutrons multiplicity analysis

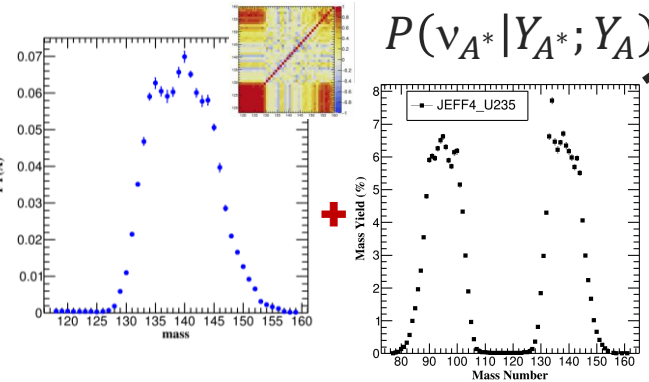
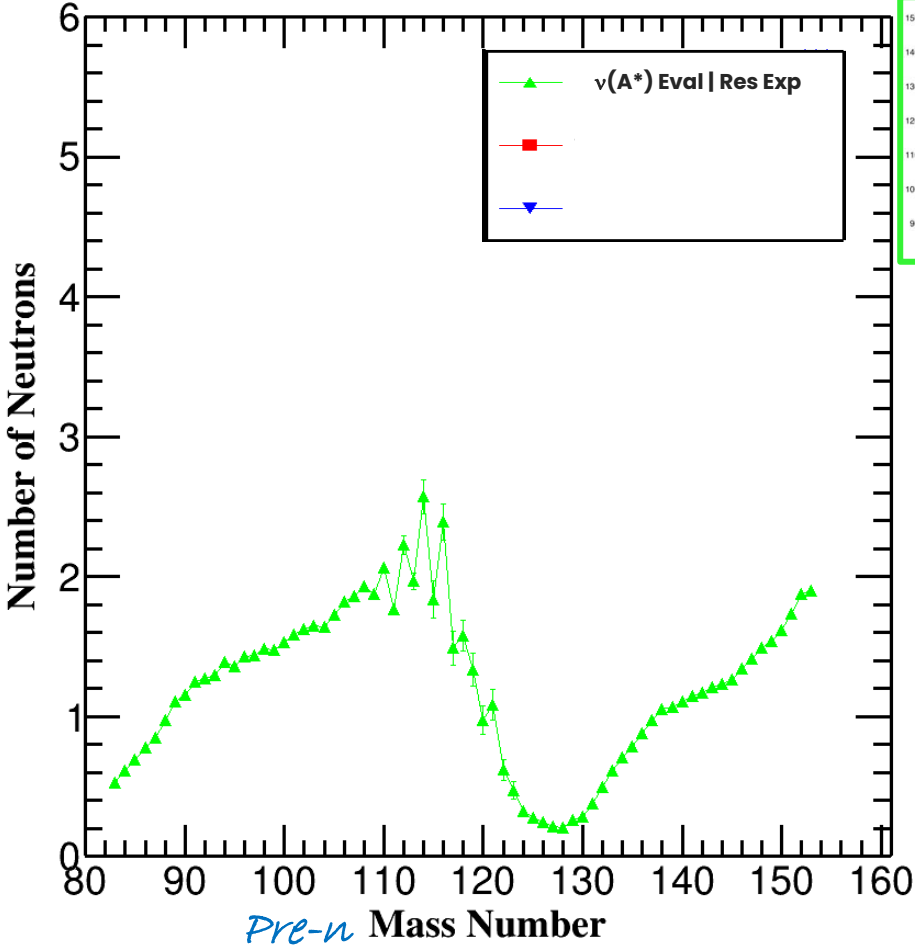


Al-Adili, Ali, et al. "Prompt fission neutron yields in thermal fission of U 235 and spontaneous fission of Cf 252." *Physical Review C* 102.6 (2020)

9 data sets available



➔ **Experimental Evaluation** With MCMC approach at Al Adili Reference data (FWMH= **5.65** amu) → $\bar{\nu}_{A^*}$



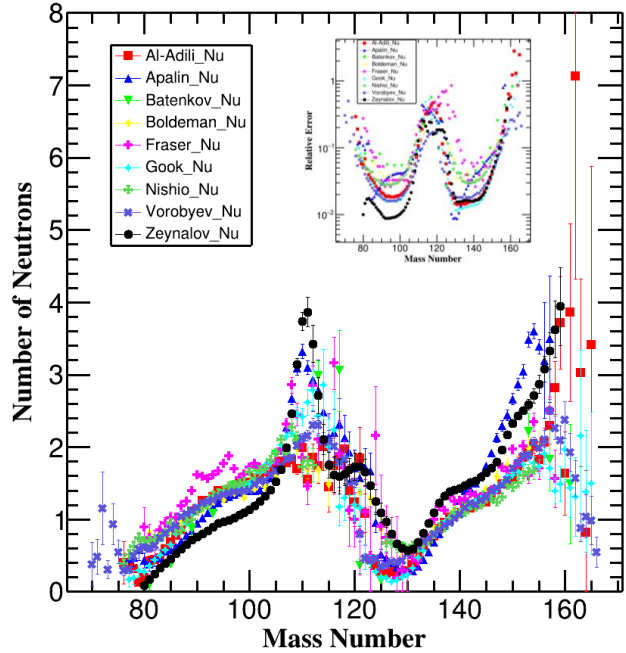
➔ **Calculations :**

$$P(\nu_{A^*} | Y_{A^*}; Y_A)$$

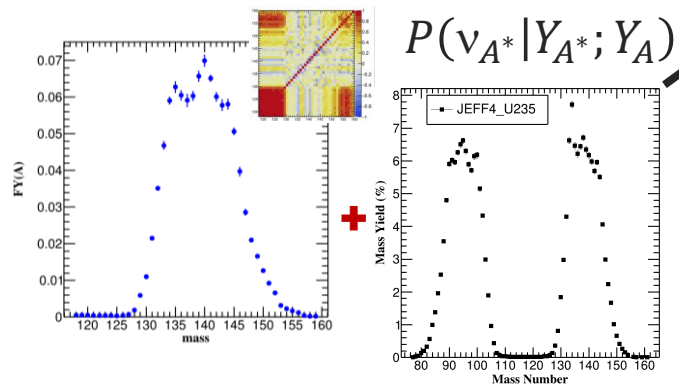
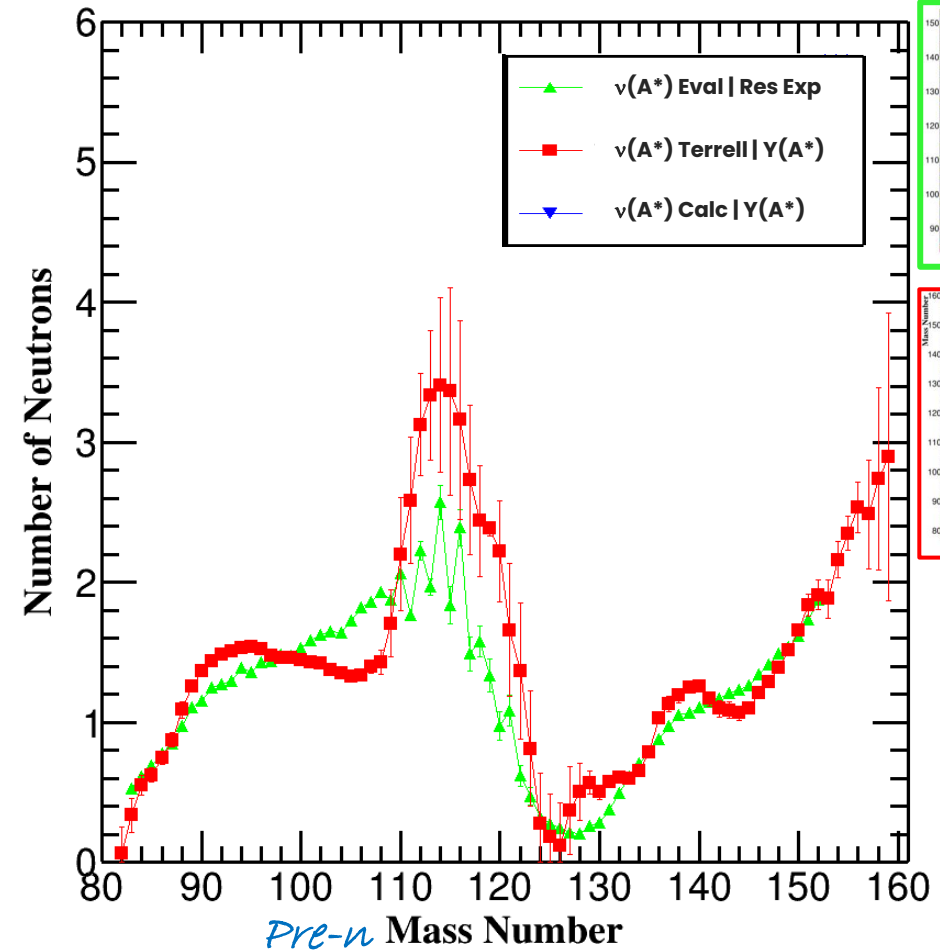
Prompt neutrons multiplicity analysis

Al-Adili, Ali, et al. "Prompt fission neutron yields in thermal fission of U 235 and spontaneous fission of Cf 252." *Physical Review C* 102.6 (2020)

9 data sets available



➔ **Experimental Evaluation** With MCMC approach at Al Adili Reference data (FWMH= **5.65** amu) → $\bar{\nu}_{A^*}$



➔ **Calculations :**

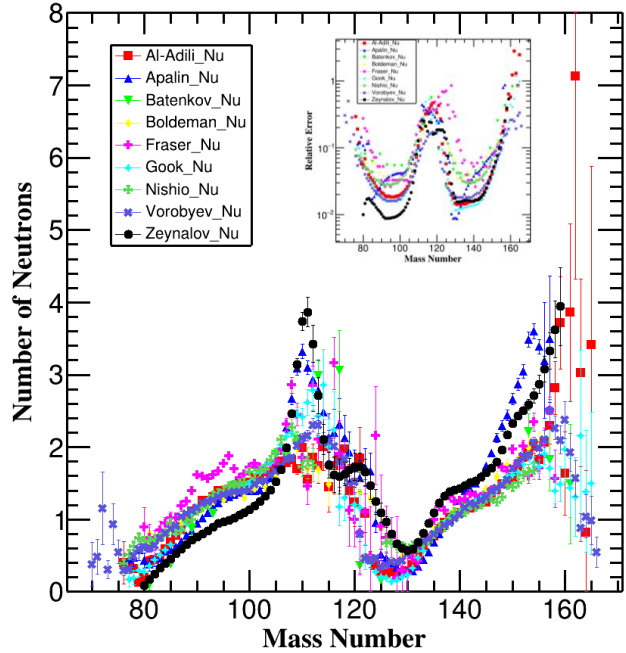
- **Terrell** approach → $\bar{\nu}_{A^*}$

Prompt neutrons multiplicity analysis

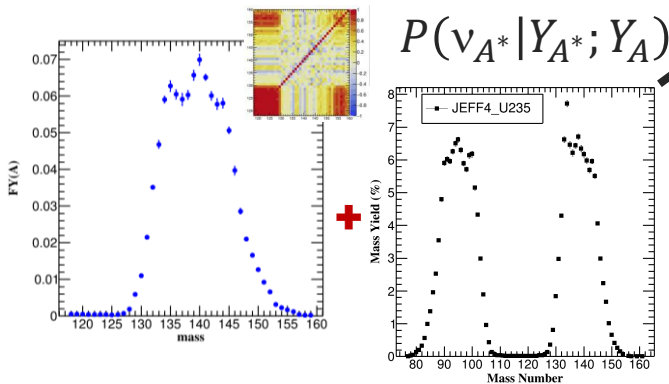


Al-Adili, Ali, et al. "Prompt fission neutron yields in thermal fission of U 235 and spontaneous fission of Cf 252." *Physical Review C* 102.6 (2020)

9 data sets available

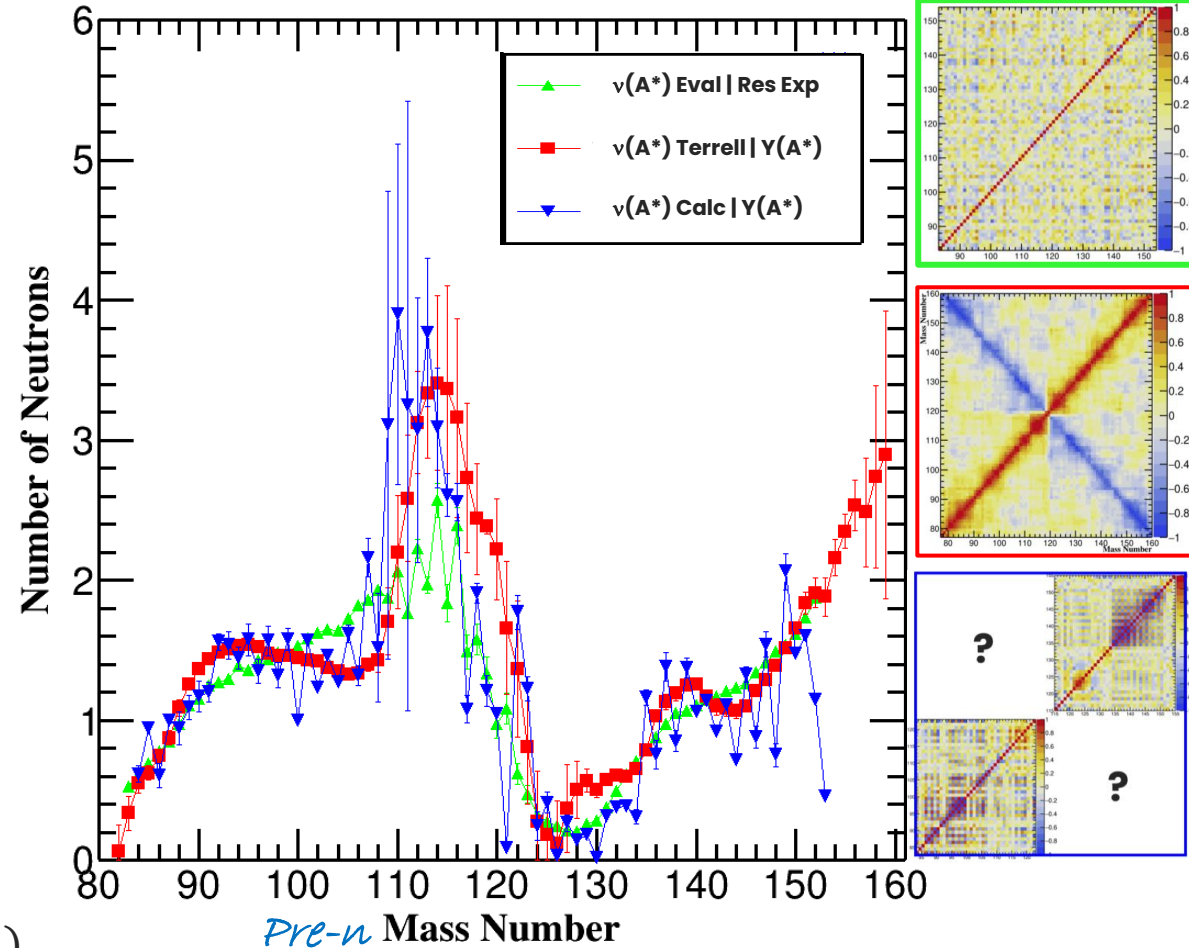


➔ **Experimental Evaluation** With
MCMC approach at Al Adili
Reference data
(FWMH= **5.65** amu)
→ $\bar{\nu}_{A^*}$

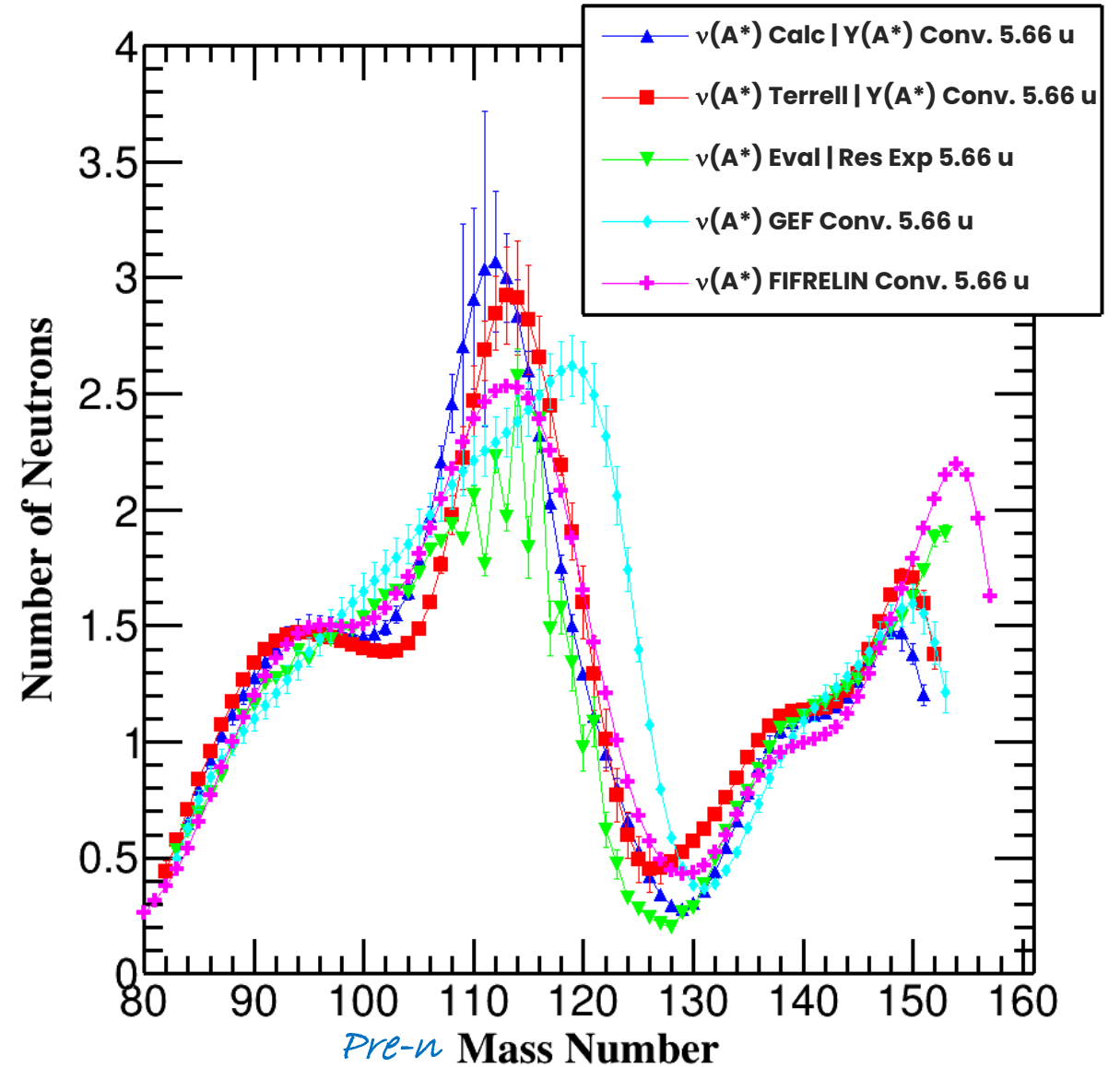
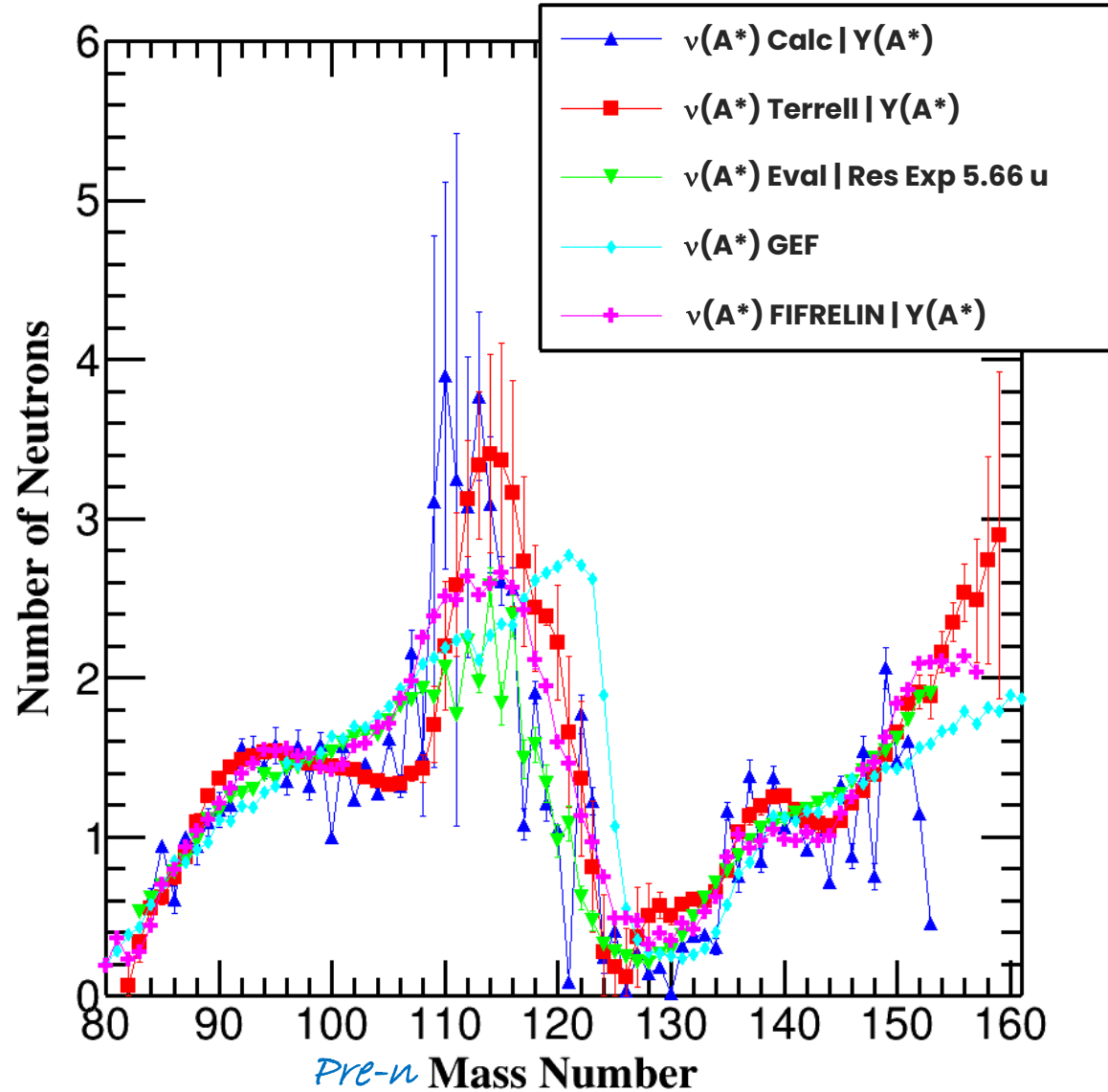


Calculations :

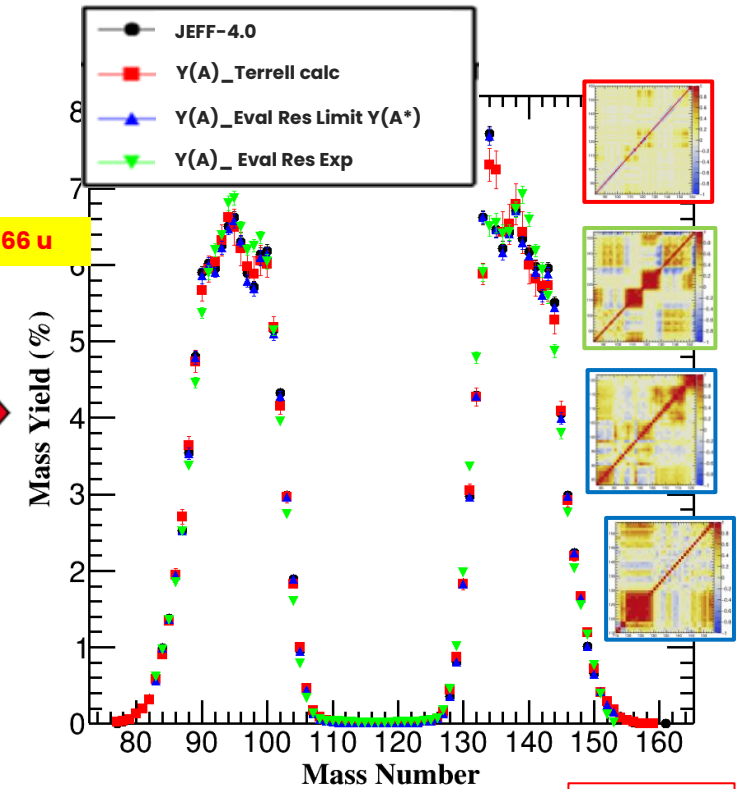
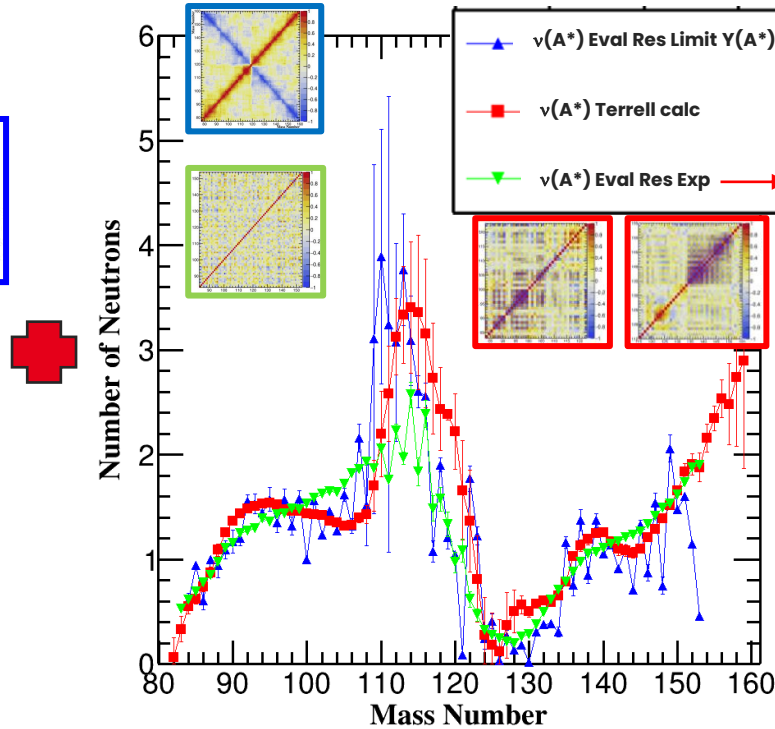
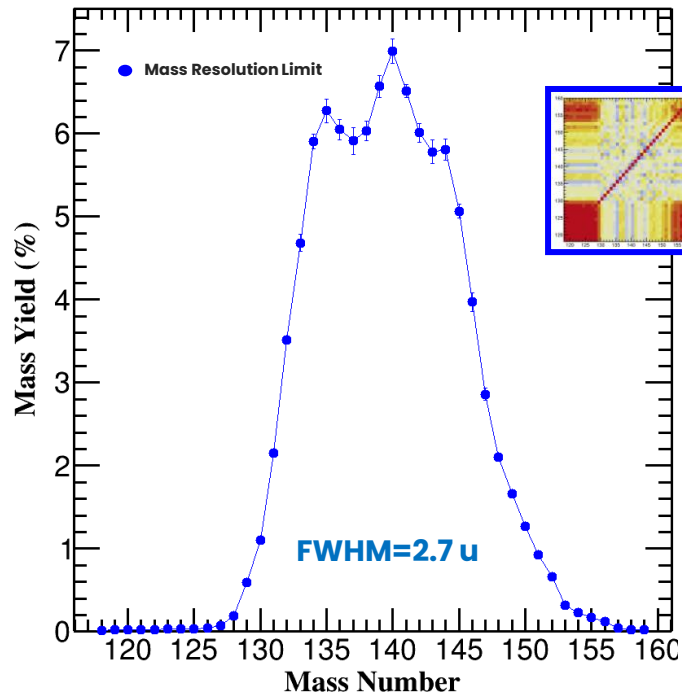
- **Terrell** approach
→ $\bar{\nu}_{A^*}$
- **MCMC** approach
 $P(\nu|A^*) = G_t(\nu; \bar{\nu}_{A^*}; \sigma_{L/H})$



Prompt neutrons multiplicity analysis



Validation with JEFF-4.0:



$Y(A^*)$ Evaluation with error propagation and covariance matrix using Monte-Carlo-Markov-Chain (MCMC):

→ at best experimental resolution

Analysis of $v(A^*)$ from:

- ❑ Experimental data at the best experimental mass resolution
 - Evaluation (resolution limit)
- ❑ Calculations from $Y(A^*)$ and $Y(A)$ using:
 - MCMC
 - Terrell method

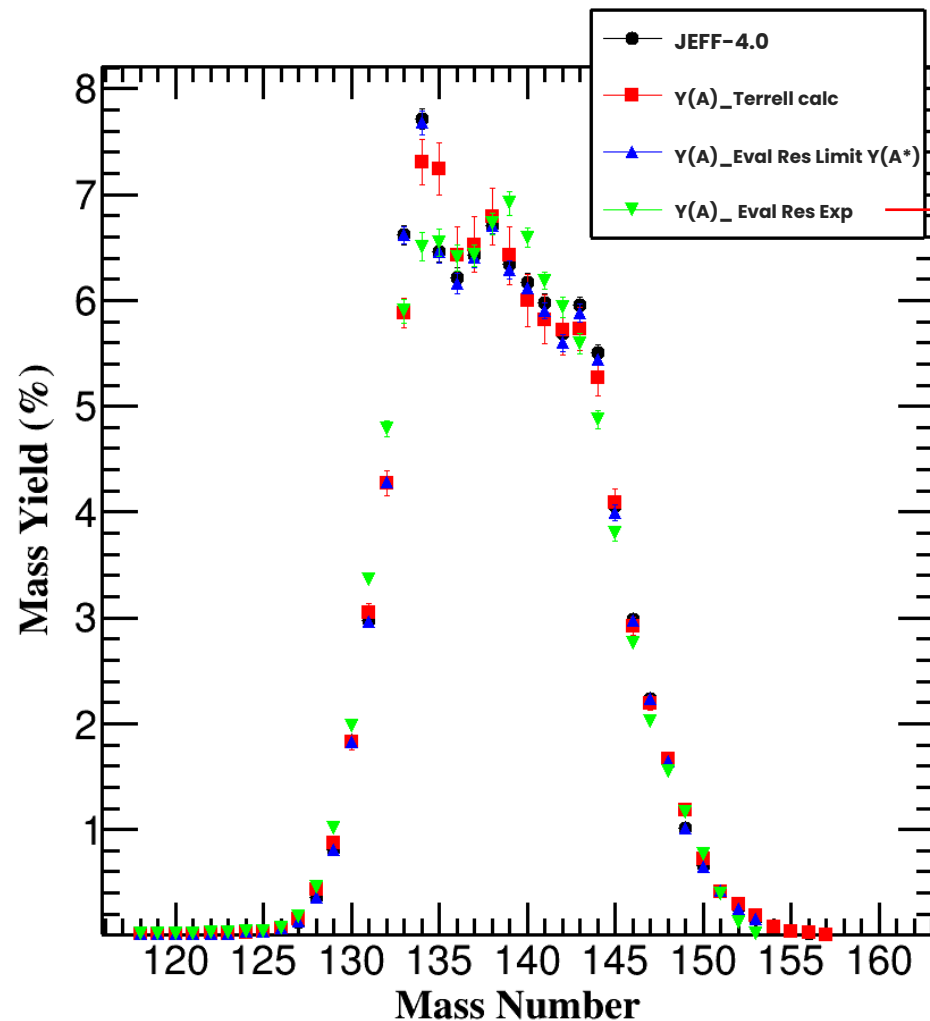
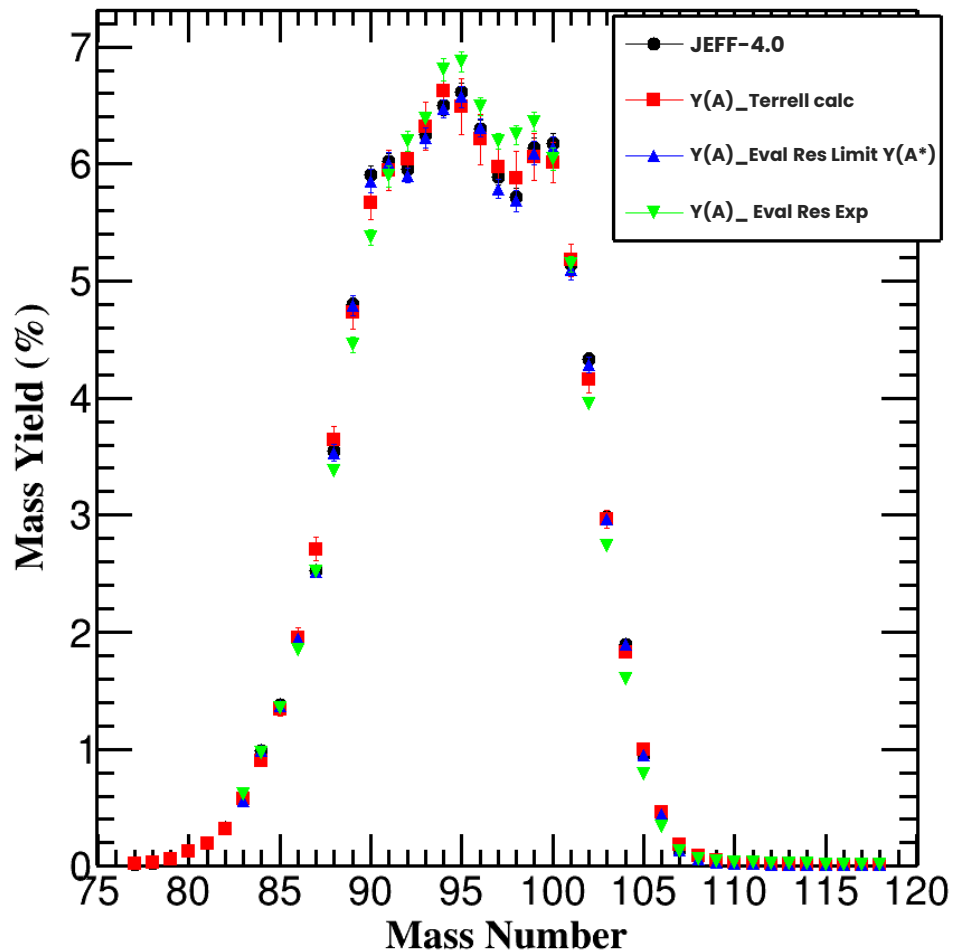
Validation on JEFF-4.0 $Y(A)$:

$$Y_{post}(A) = \sum_v Y_{pre}(A+v) P(v|A+v)$$

↓
Gauss, Poisson...

Validation with JEFF-4.0

$P_{\text{value}} > 1 - \text{CL} \rightarrow \text{Accepted } \chi_g^2 \text{ test}$

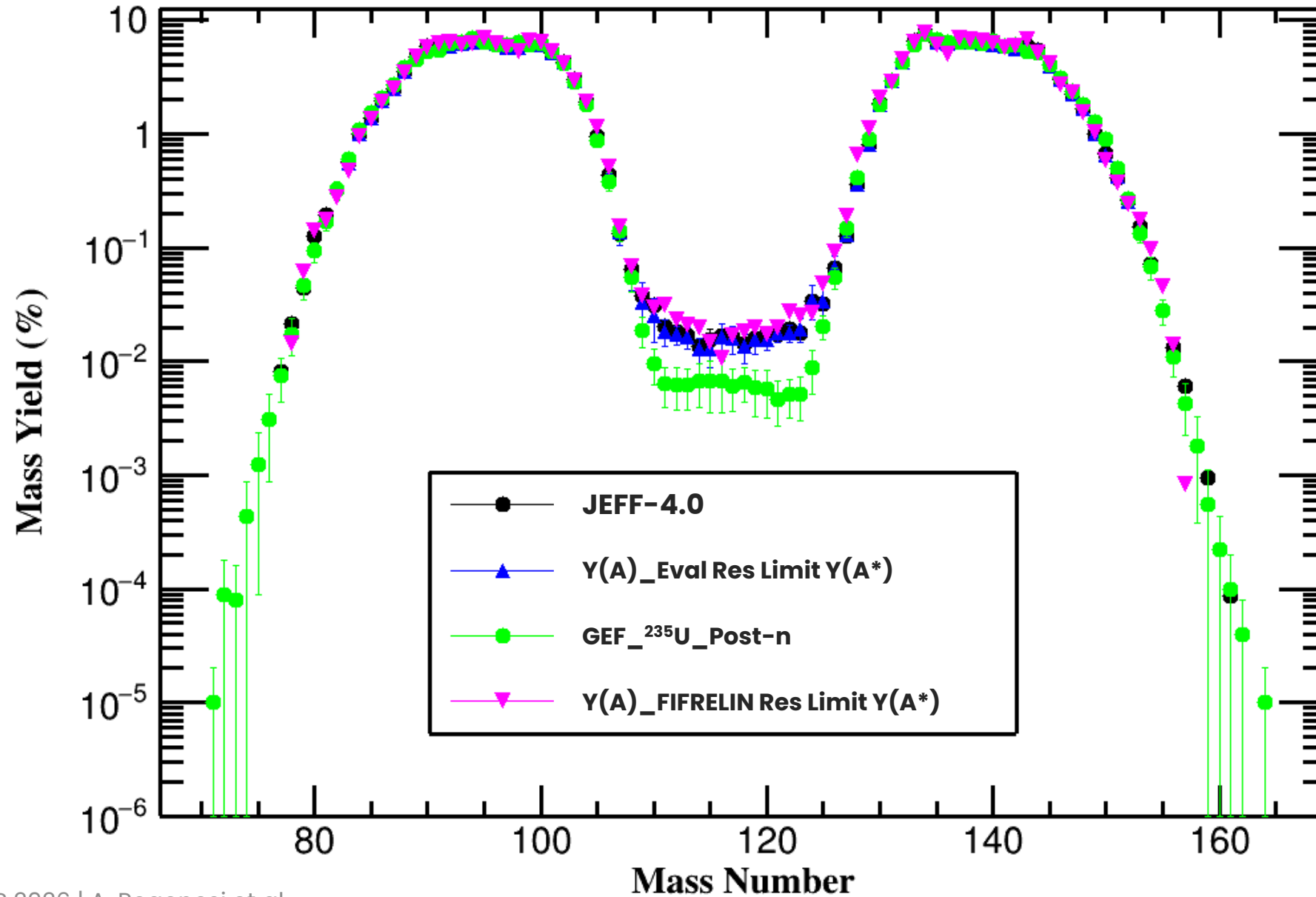


MCMC Calculation (blue points) reproduces the best JEFF-4.0 data

Light peak
 $\rightarrow P_{\text{value}} = 0.226 > 1 - 0.997 (3\sigma)$

Heavy peak
 $\rightarrow P_{\text{value}} = 0.072 > 1 - 0.997 (3\sigma)$

Validation with JEFF-4.0





4 ■ Conclusion and perspective

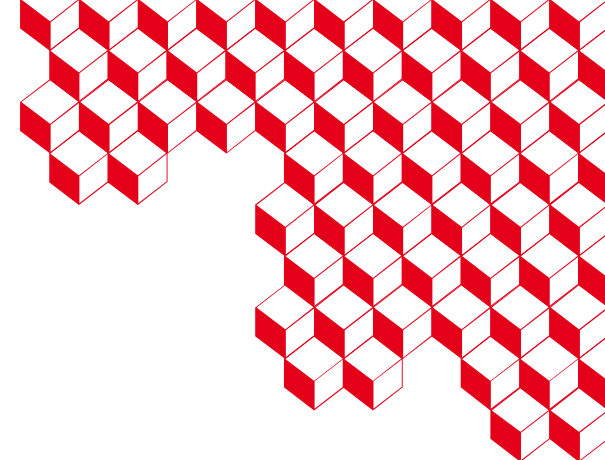
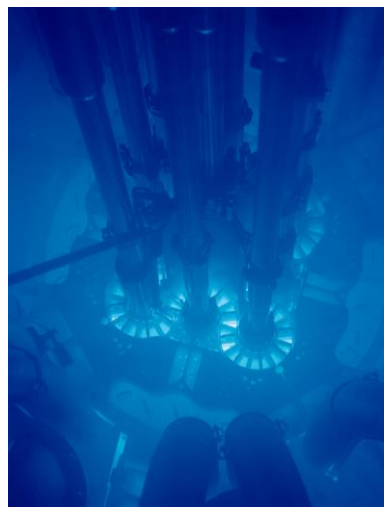
Conclusion



- ❑ Evaluation methodology of 2E & 2E2V data
 - **reinterpretation** Exp. mass resolutions
 - complete the JEFF-4.0 evaluation methodology
- ❑ Evaluation of pre-n mass yields, with
 - **full assessment of uncertainties and correlations for the first time**
 - Two Evaluations: at Limit Resolution and Resolution Zero
 - physical **reinterpretation** of mass structures (work in progress...)
- ❑ Calculation & evaluation of the prompt neutron multiplicity coupling pre-n & post-n yields satisfying χ_g^2 test (correlation matrix) → **for the first time**
- ❑ **Statistical test of data has to be defined at the same mass resolution**



- ❑ The same process has to be carried out also for $^{239}\text{Pu}(n_{th}, f)$
- ❑ Finalization of the evaluation process and comparison with GEF (physical interpretation)
- ❑ Investigation of physical models (Brosa-like) to be compared to our evaluations
- ❑ Adjustment of the parameters of the models on the basis of experimental data on independent yields (as a function of E_n) at different energies



Thank you for your attention

Any questions?

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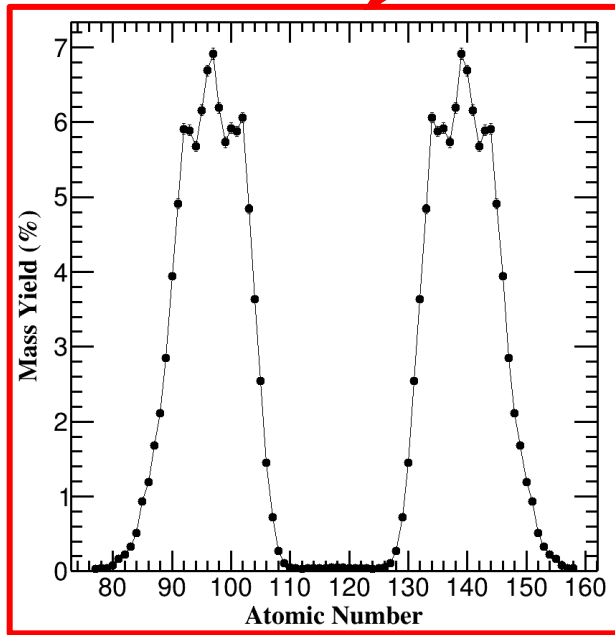
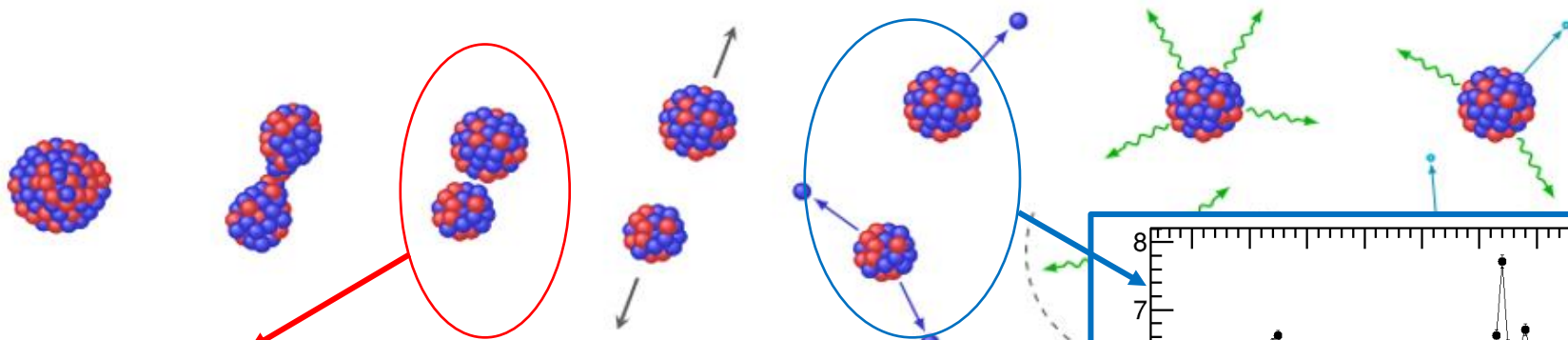


5 ■ Backup

Mass Yields



● neutron ● proton ~ photon ● électron

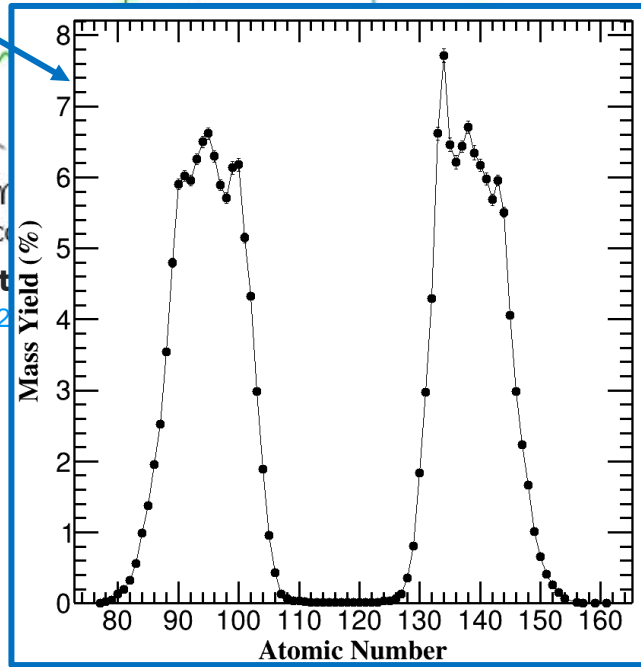


Pre-n Fission Yields

- Symmetrical
- They contain information on the physics of the fission process

Fragments acceleration [t ~ 10⁻²⁰ s]
 Prompt Neutrons [t ~ 10⁻¹⁸ / 10⁻¹⁴ s]
 Yields [t ~ 10⁻¹⁴ s]

Yields de fission à partir d'expériences dédiées. 2021



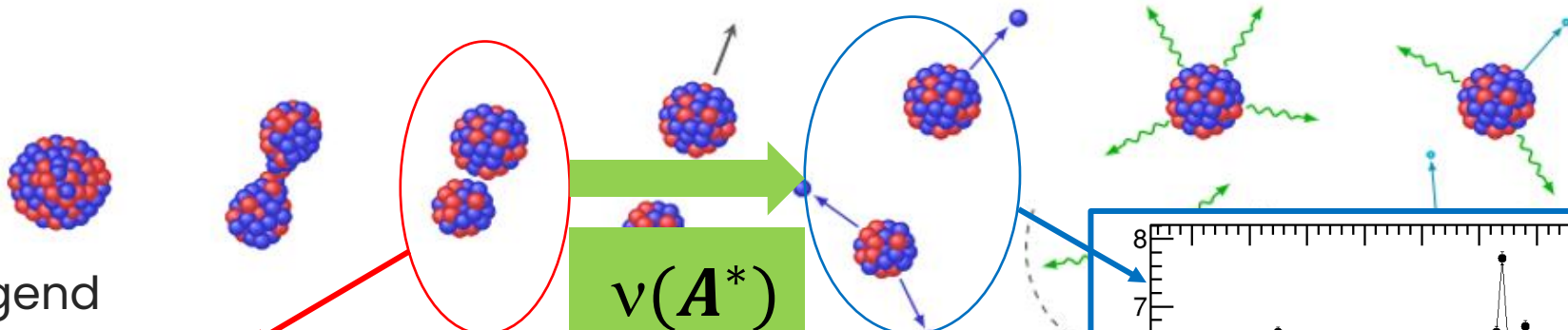
Post-n or independent Fission Yields

- Asymmetrical
- Important for determining quantities useful for reactor operation

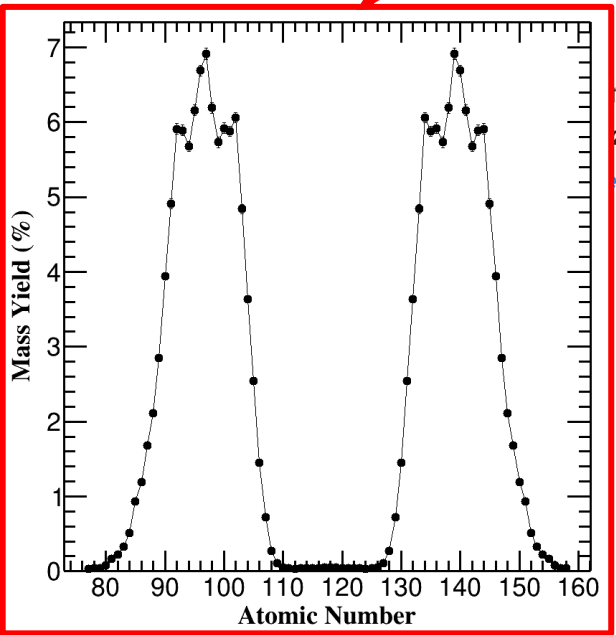
Mass Yields



● neutron ● proton ~ photon ● électron



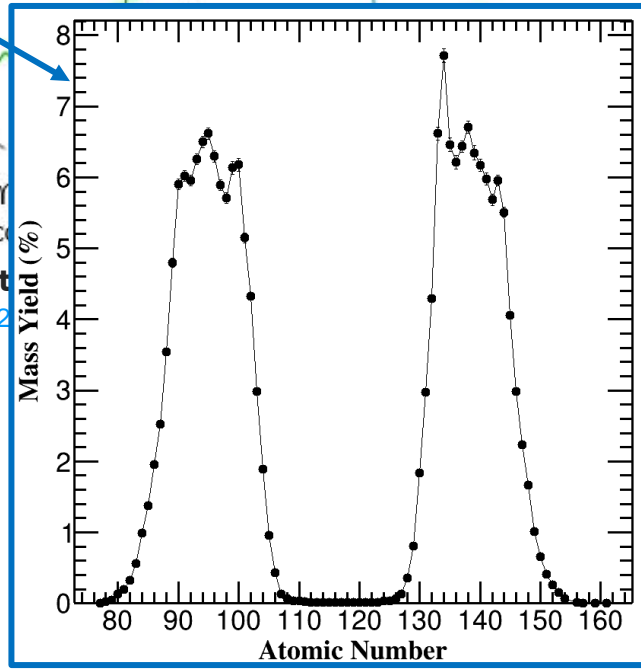
Legend



- Pre-n Fission Yields**
- Symmetrical
 - They contain information on the physics of the fission process

$$\nu(A^*)$$

Fragments acceleration [t ~ 10⁻²⁰ s] Prompt Neutrons [t ~ 10⁻¹⁸ / 10⁻¹⁴ s]

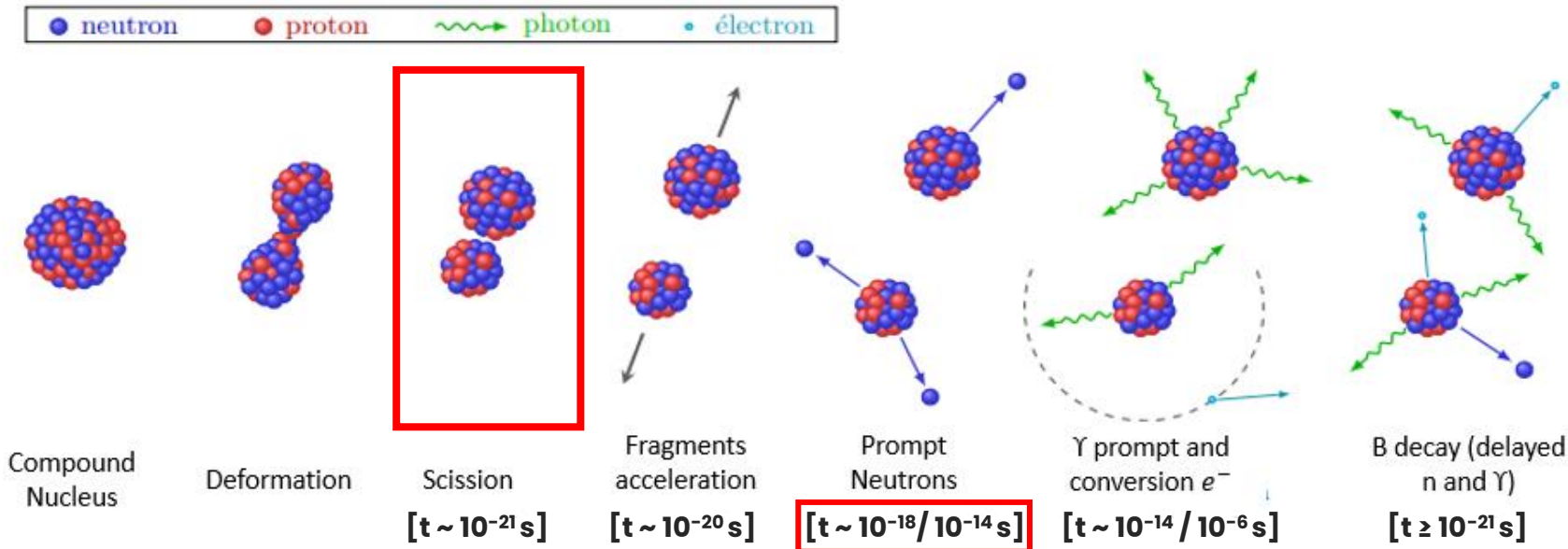


Post-n or independent Fission Yields

- Asymmetrical
- Important for determining quantities useful for reactor operation

Legend

Mass Yields



PIAU, Valentin. *Prédiction par calcul des observables de fission à partir d'expériences dédiées*. 2022. Thèse de doctorat. Université Grenoble Alpes

No direct Measurements
of fragment yields after full acceleration but before prompt neutrons

$2E$
 $2E - 2v$

Upgraded methodology



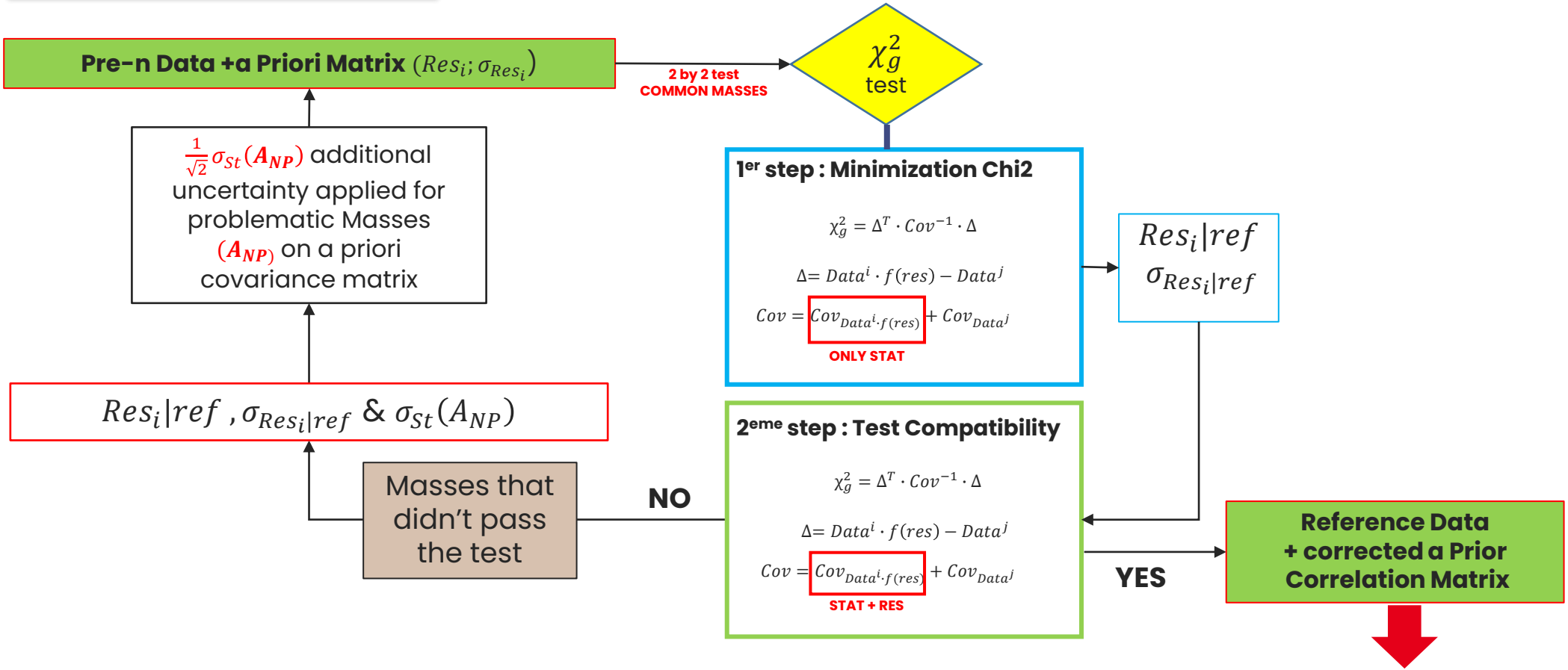
First step : if Post-n FY exist



Upgraded methodology



second step : Pre-n FY

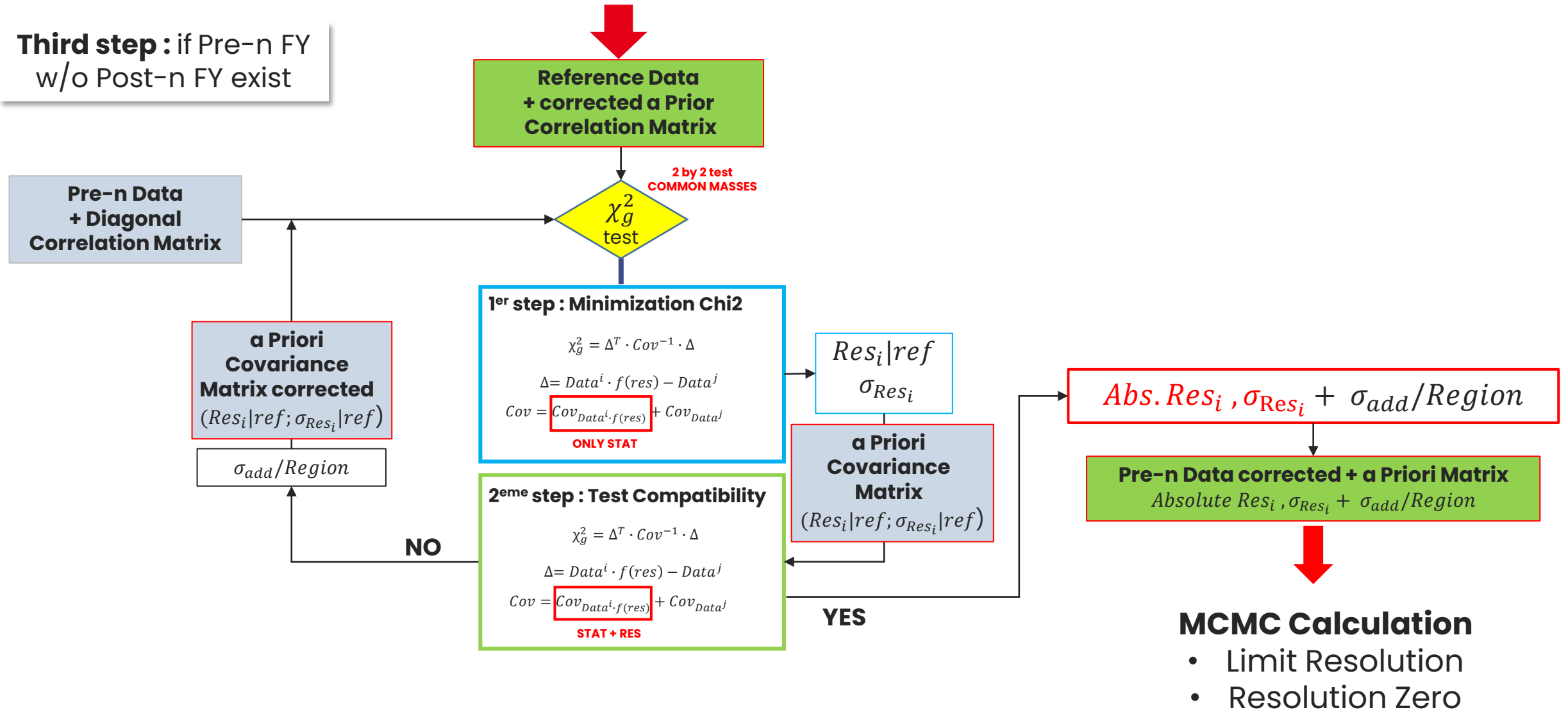


Third step : if Pre-n FY w/o Post-n FY exist

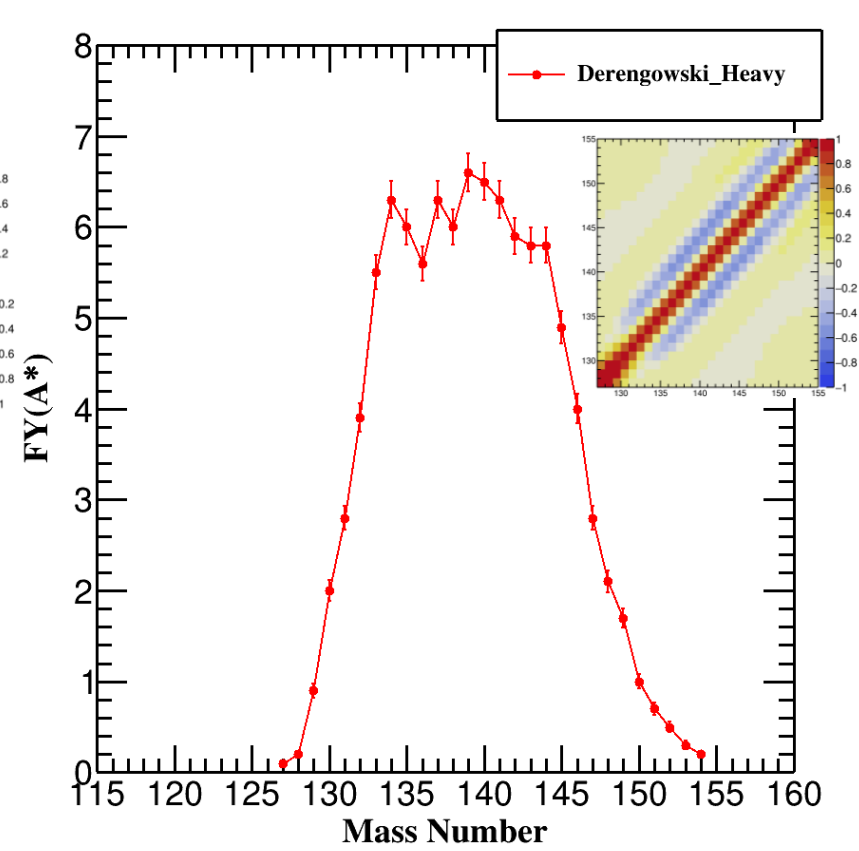
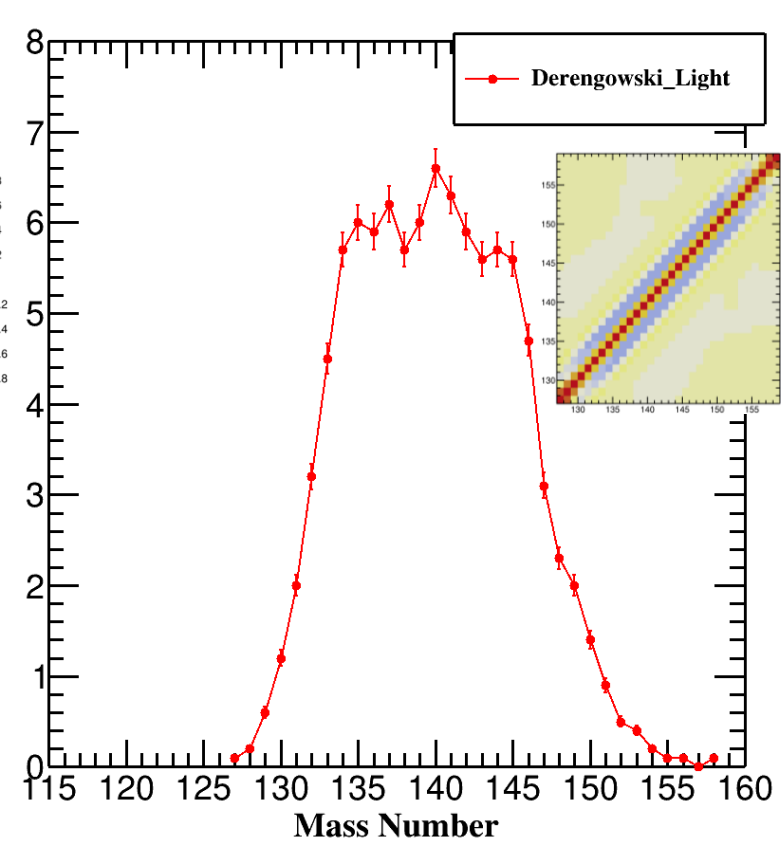
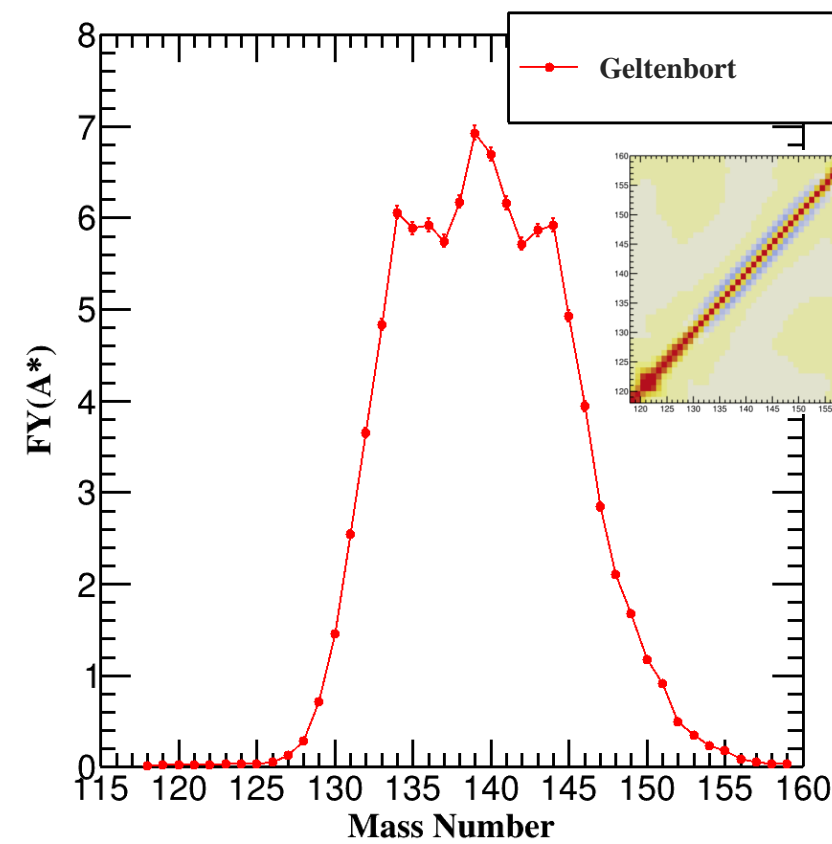
Upgraded methodology



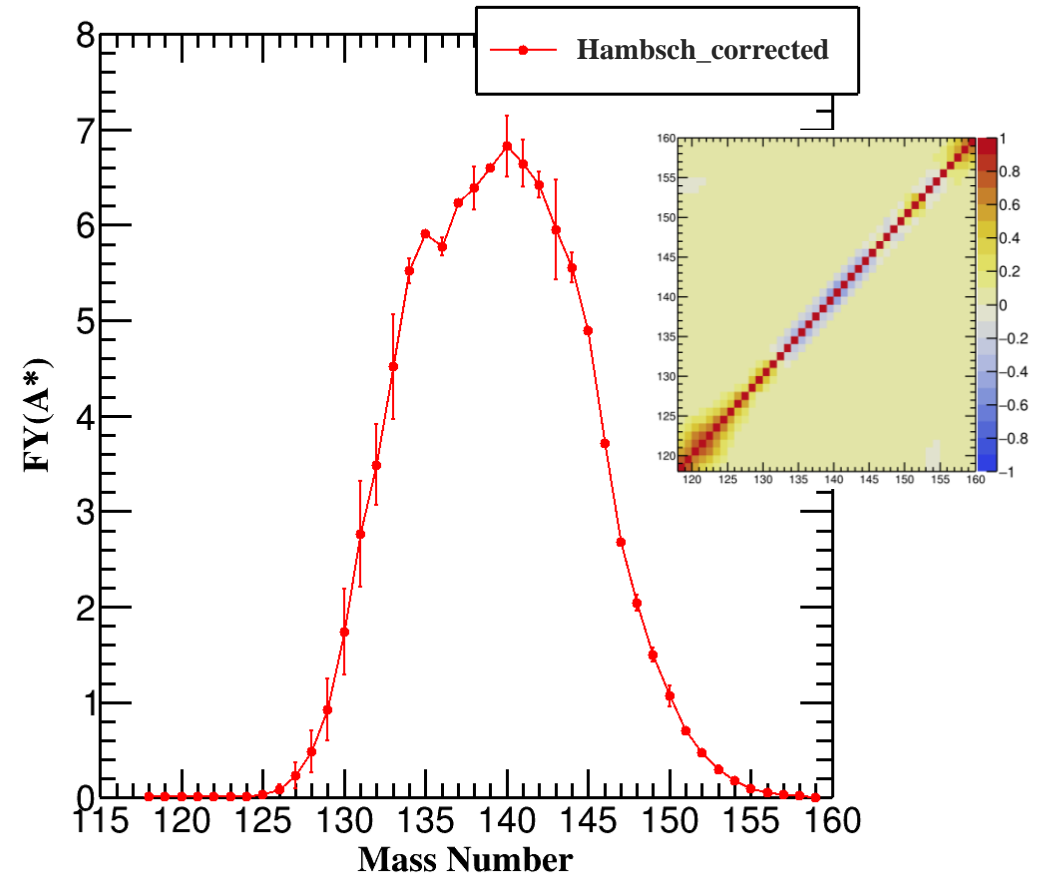
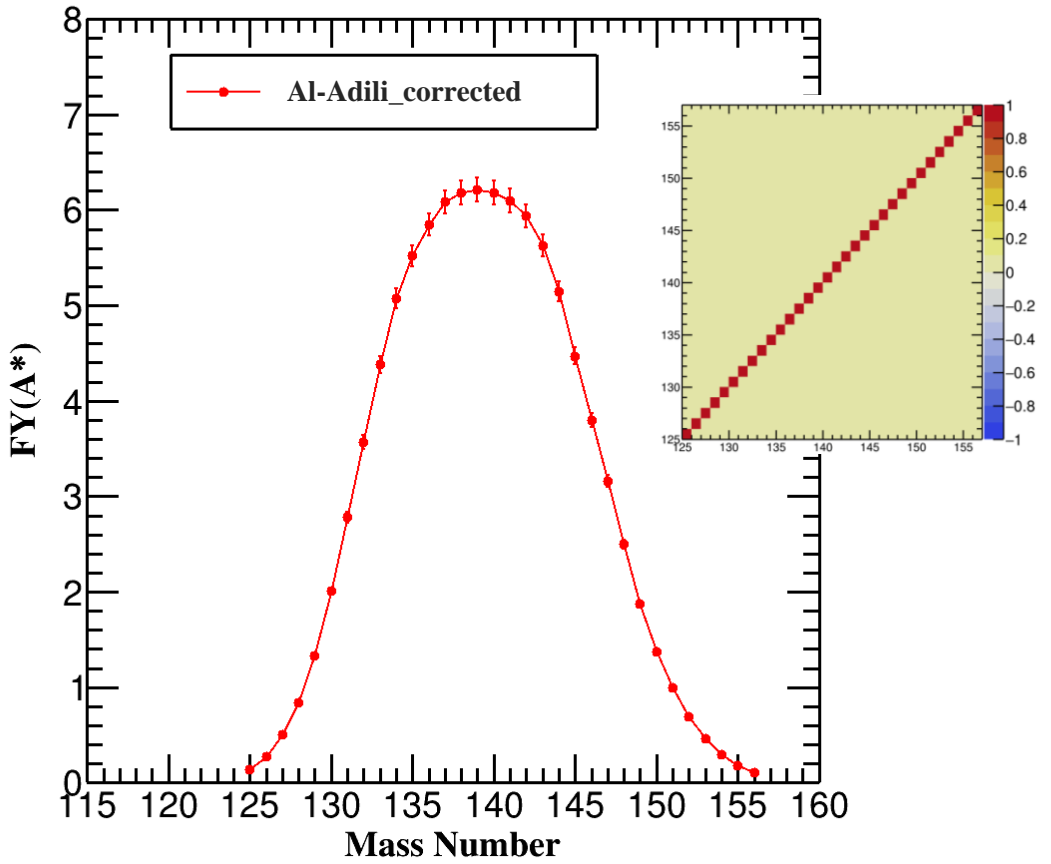
Third step : if Pre-n FY w/o Post-n FY exist



Assignment of a priori correlation matrix



Assignment of a priori correlation matrix

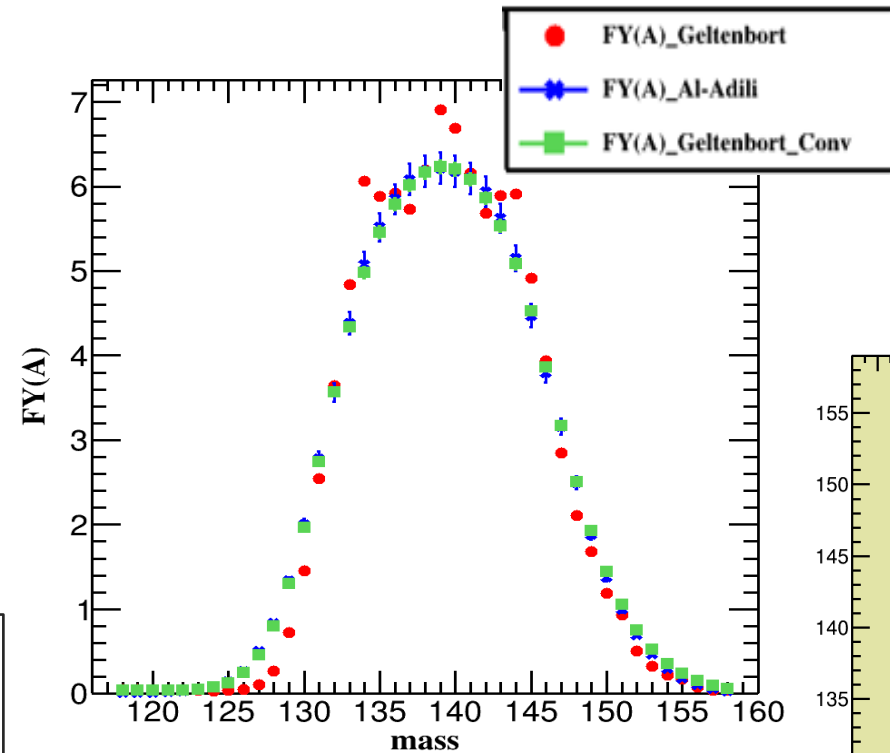


Data compatibility tests (generalized χ^2)

Effect of mass resolution

- ❑ Example of the effect of **mass resolution** (data blurring)
- ❑ Taking into account the effect of mass resolution by a convolution function

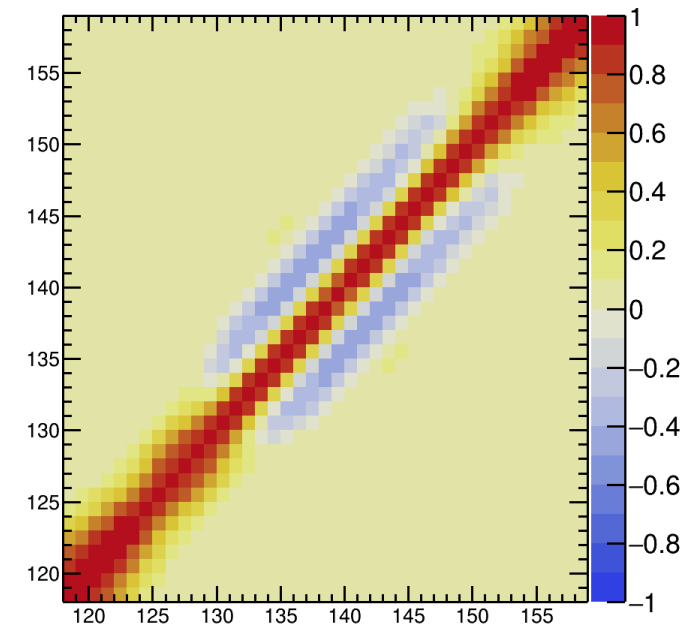
$$R^i(A^*) = \sum_{A'^*=1}^n \tilde{N}^i(A'^*) \frac{e^{-\frac{1}{2}(\frac{A'^*-A^*}{r_i})^2}}{\sum_{A'^*=1}^n e^{-\frac{1}{2}(\frac{A'^*-A^*}{r_i})^2}}$$



Example

Mass Res. $\approx 2.3u$ but P_{value} not OK
for all the mass range
→ Keep only $FY \geq 1\%$

correlation matrix of the convoluted data set



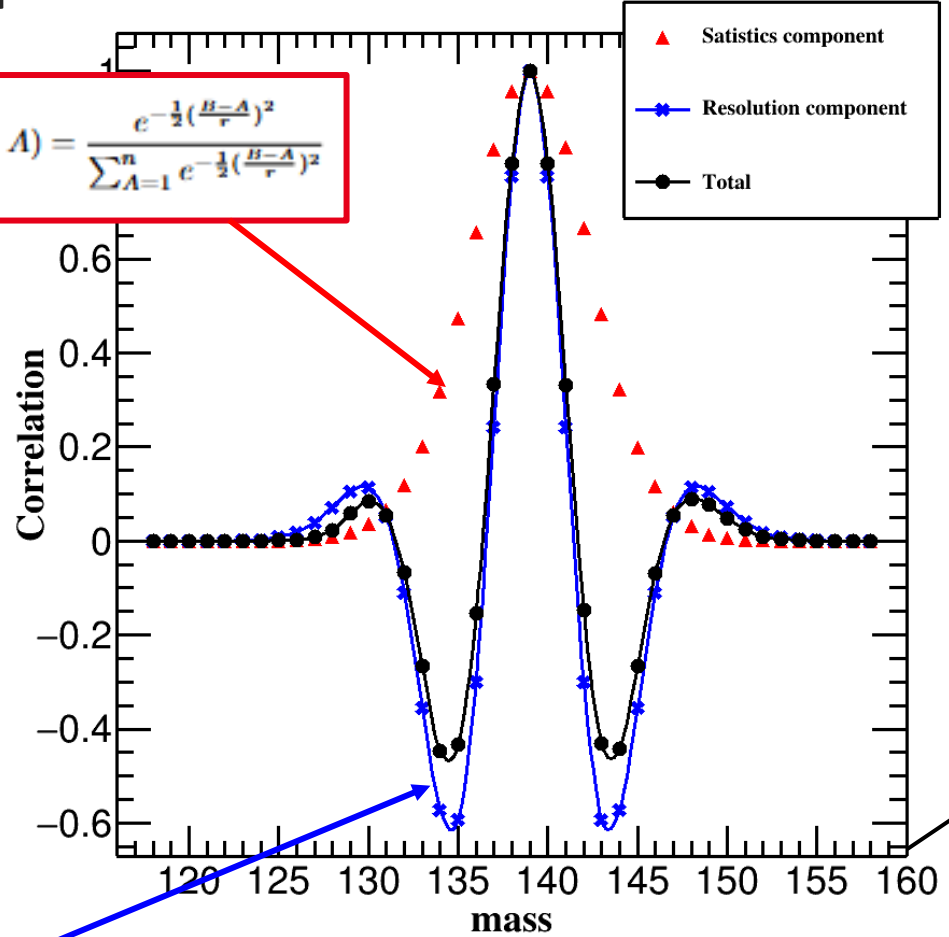
Components of the Matrix of Covariances



2 main components :

$$\left(\frac{\partial R_A^i}{\partial \bar{N}_B^i}\right) = P_i(B \rightarrow A) = \frac{e^{-\frac{1}{2}\left(\frac{B-A}{\tau}\right)^2}}{\sum_{A=1}^n e^{-\frac{1}{2}\left(\frac{B-A}{\tau}\right)^2}}$$

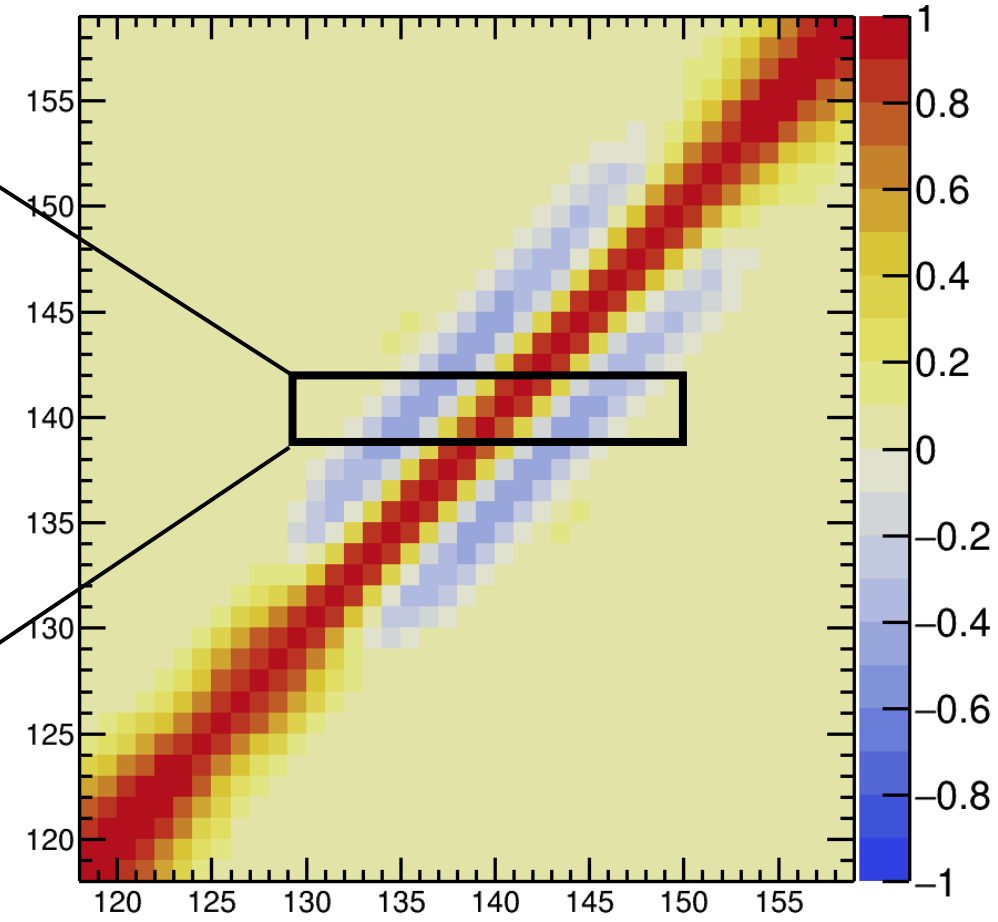
One due to the spreading of the contribution of each mass yields on the nearby masses (red dots)



$$\left(\frac{\partial R_A^i}{\partial r_i}\right) = \sum_B \bar{N}_B^i \cdot \left[\frac{\left(\frac{B-A}{\tau}\right)^2 \xi_B \sum_{A=1}^n \xi_B - \frac{\xi_B}{\tau^2} \sum_{A=1}^n (B-A)^2 \xi_B}{\left(\sum_{A=1}^n e^{-\frac{1}{2}\left(\frac{A-B}{\tau}\right)^2}\right)^2} \right]$$

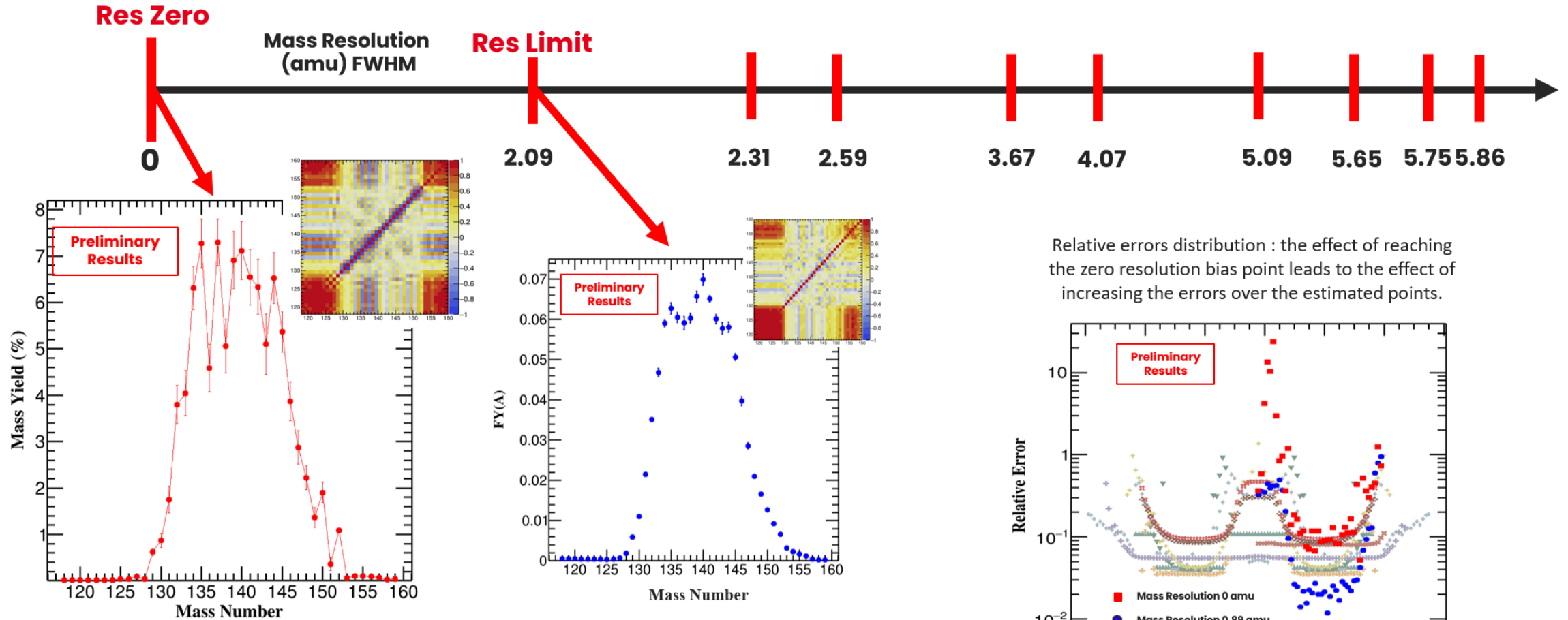
Another to the effect of the uncertainty on the mass resolution (blue crosses)

correlation matrix of the convoluted data set



$^{235}\text{U}(n_{\text{th}},f)$ Pre-neutrons fission yields evaluation

Once identified all the mass resolutions \rightarrow merging with of **MCMC code DREAM** to calculate fission yields at the best experimental resolution and at resolution zero



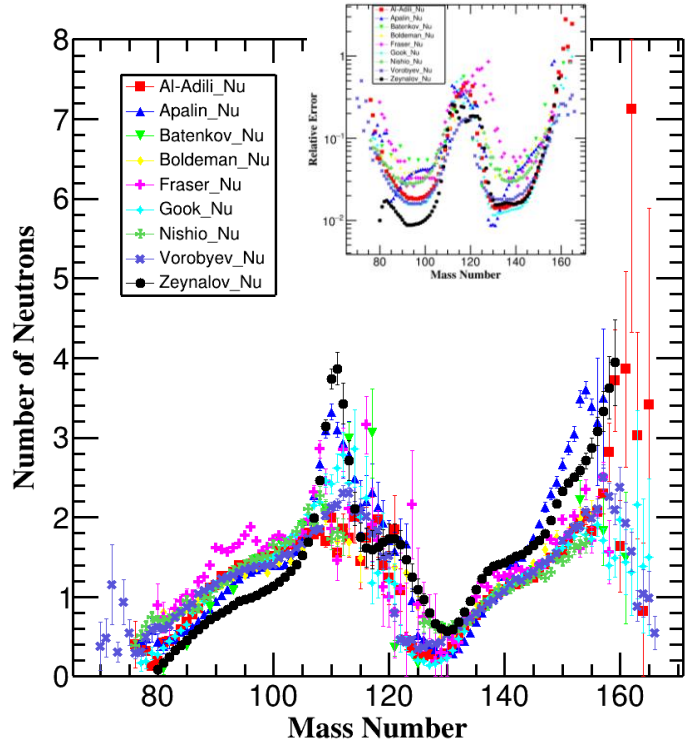
Relative errors distribution : the effect of reaching the zero resolution bias point leads to the effect of increasing the errors over the estimated points.

Graph des données sélectionnées

Prompt neutrons multiplicity analysis from :

Experimental data

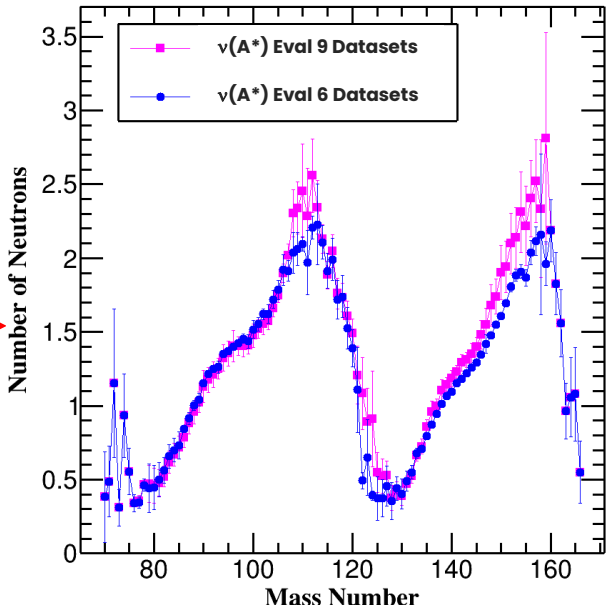
9 data sets available



Weighted mean or STUDENT distribution

- over the 6 most compatible sets or
- over the 9 data sets available

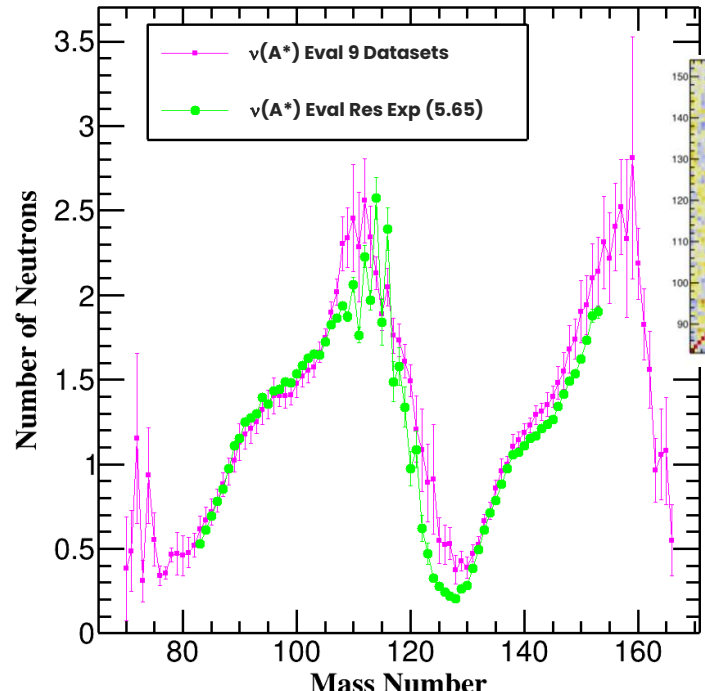
Effective resolution unknown



No Correlation matrix

Evaluation MCMC at Al-Adili resolution (FWHM = 5.65)

Al-Adili, Ali, et al. "Prompt fission neutron yields in thermal fission of U 235 and spontaneous fission of Cf 252." *Physical Review C* 102.6 (2020)



With correlation matrix

No more Student !!!

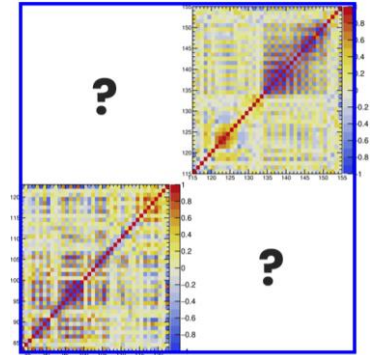
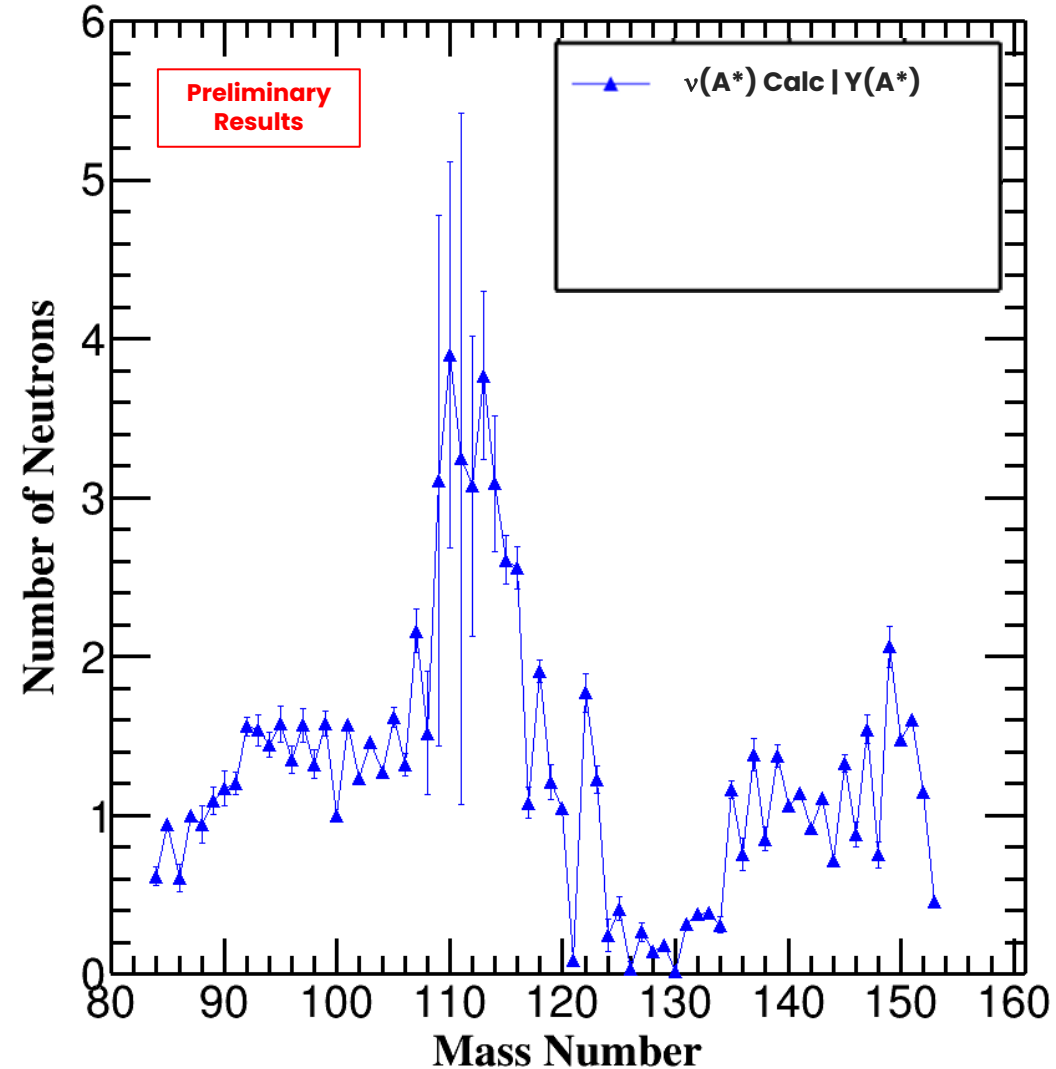
Prompt neutrons multiplicity analysis from : Calculation using $Y^{\text{Eval}}(A^*)$ and $Y^{\text{JEFF4.0}}(A)$



□ Monte Carlo Markov Chains (MCMC) DREAM code

- Capable of accounting for covariance matrices at each step
- 2 peaks calculated separately to reduce computational costs

S. M. Cheikh, PhD thesis, Université Grenoble Alpes, 2023





Prompt neutrons multiplicity analysis from : Calculation using $\nu^{Eval}(A^*)$ and $\nu^{JEFF4.0}(A)$

Monte Carlo Markov Chains (MCMC) DREAM code

- Capable of accounting for covariance matrices at each step
- 2 peaks calculated separately to reduce computational costs

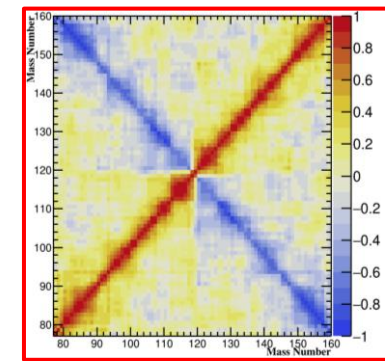
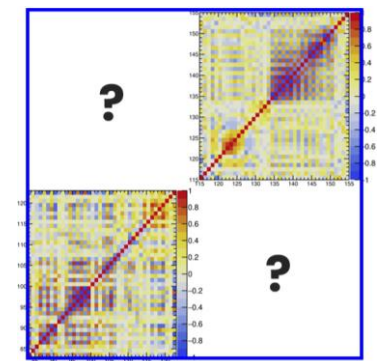
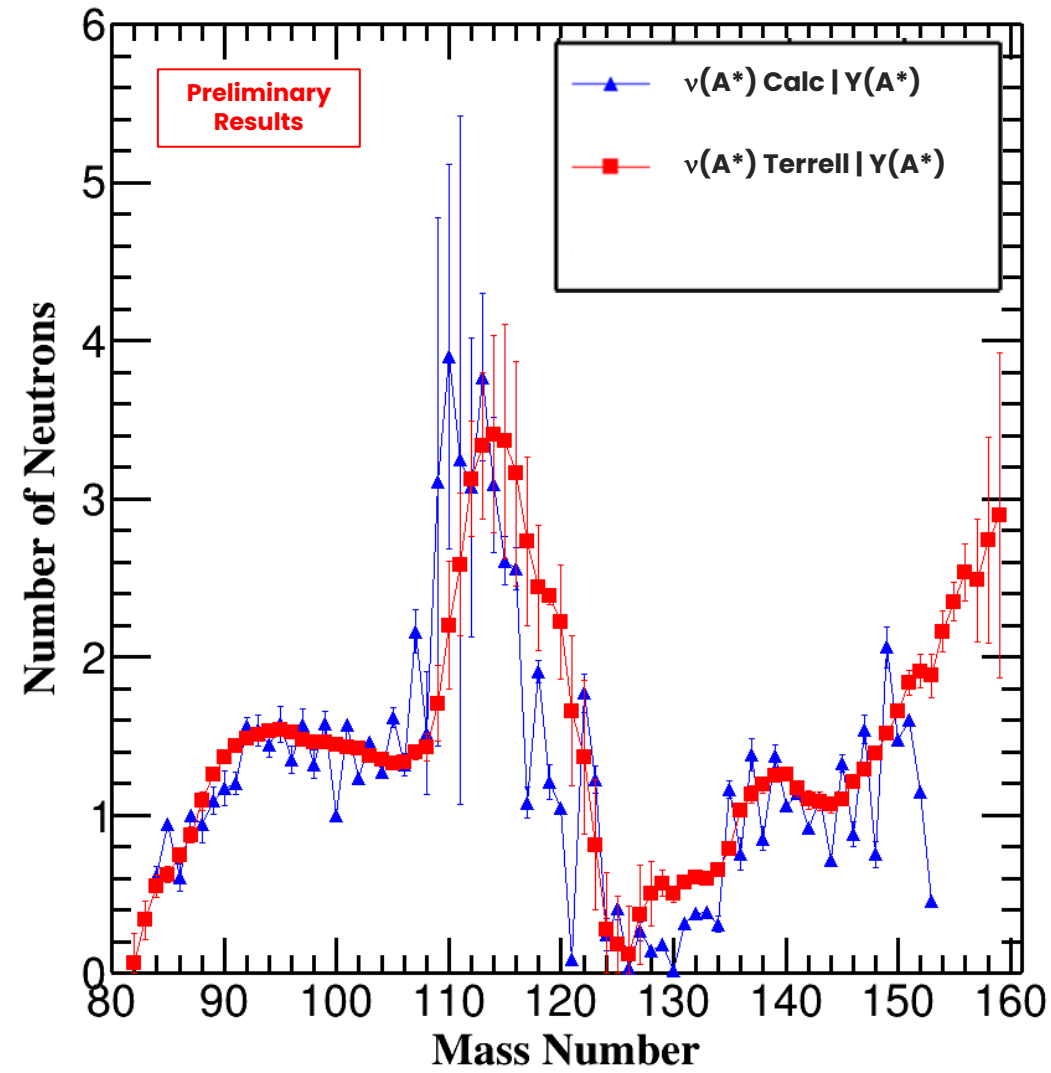
S. M. Cheikh, PhD thesis, Université Grenoble Alpes, 2023

Terrell Method

$$\sum_0^{M_0 - \nu_f(M_0) - \frac{1}{2}} Y_{post}(M) = \sum_0^{M_0 - \frac{1}{2}} Y_{pre}(M) + \frac{1}{2} \left(\frac{dY_{pre}}{dM} \right) \langle \sigma^2(\nu_f; M) \rangle + \dots$$

Terrell, J. (1962). Neutron yields from individual fission fragments. *Physical Review*, 127(3), 880

Commencer per Terrell



Prompt neutrons multiplicity analysis from : Calculation using $Y^{Eval}(A^*)$ and $Y^{JEFF4.0}(A)$



Monte Carlo Markov Chains (MCMC) DREAM code

- Capable of accounting for covariance matrices at each step
- 2 peaks calculated separately to reduce computational costs

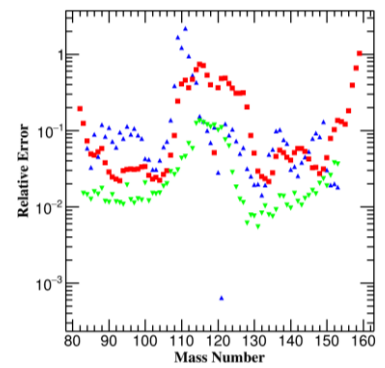
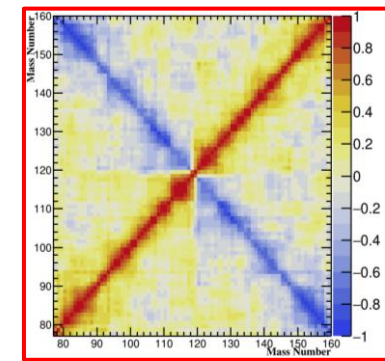
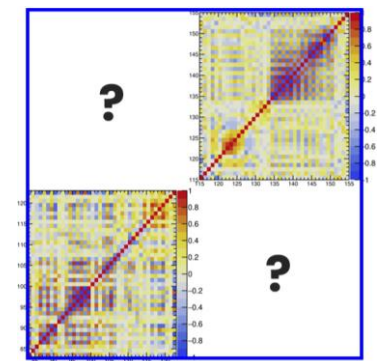
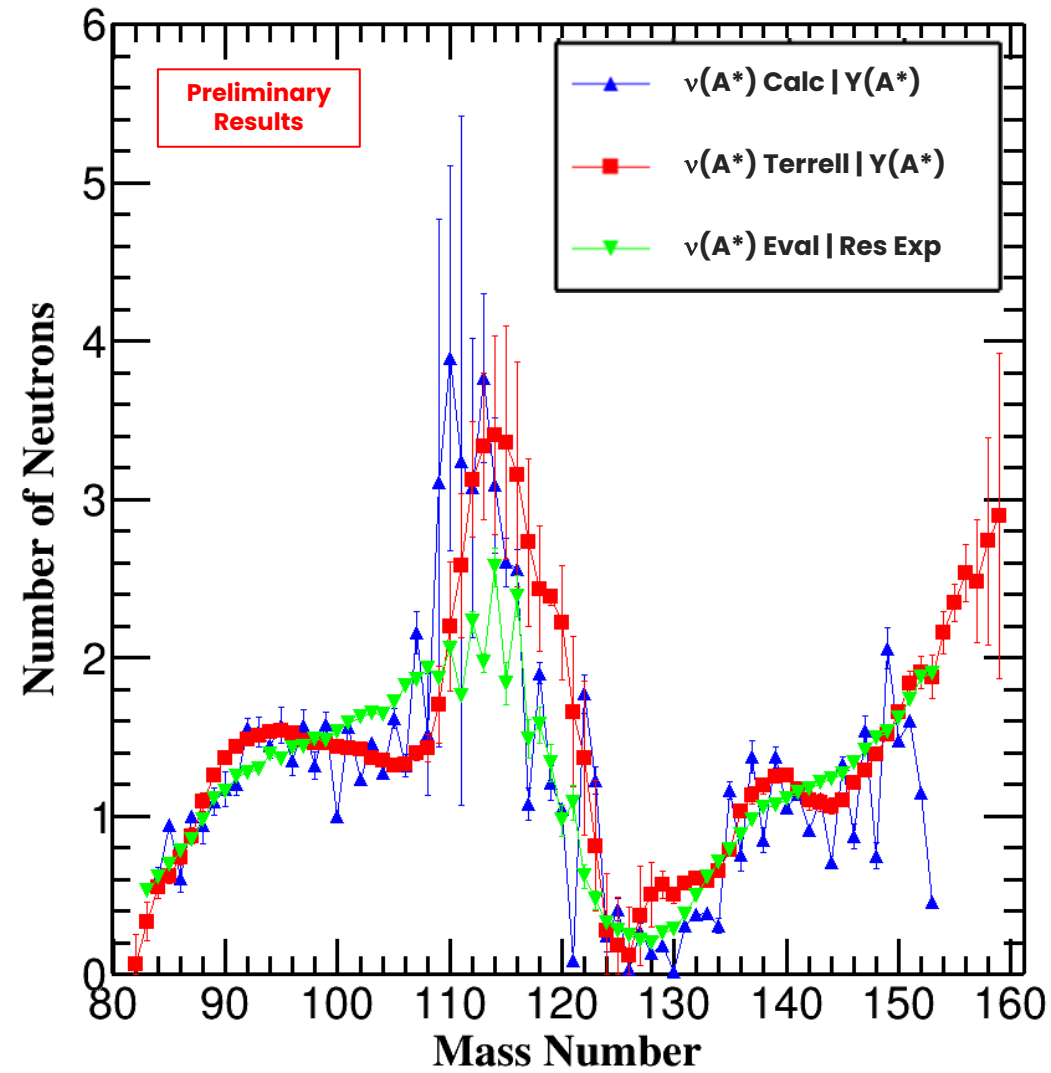
S. M. Cheikh, PhD thesis, Université Grenoble Alpes, 2023

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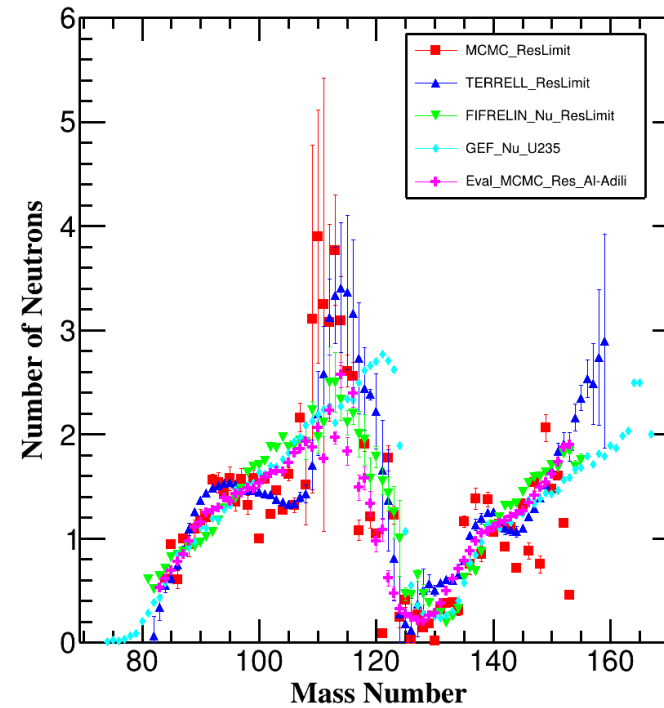
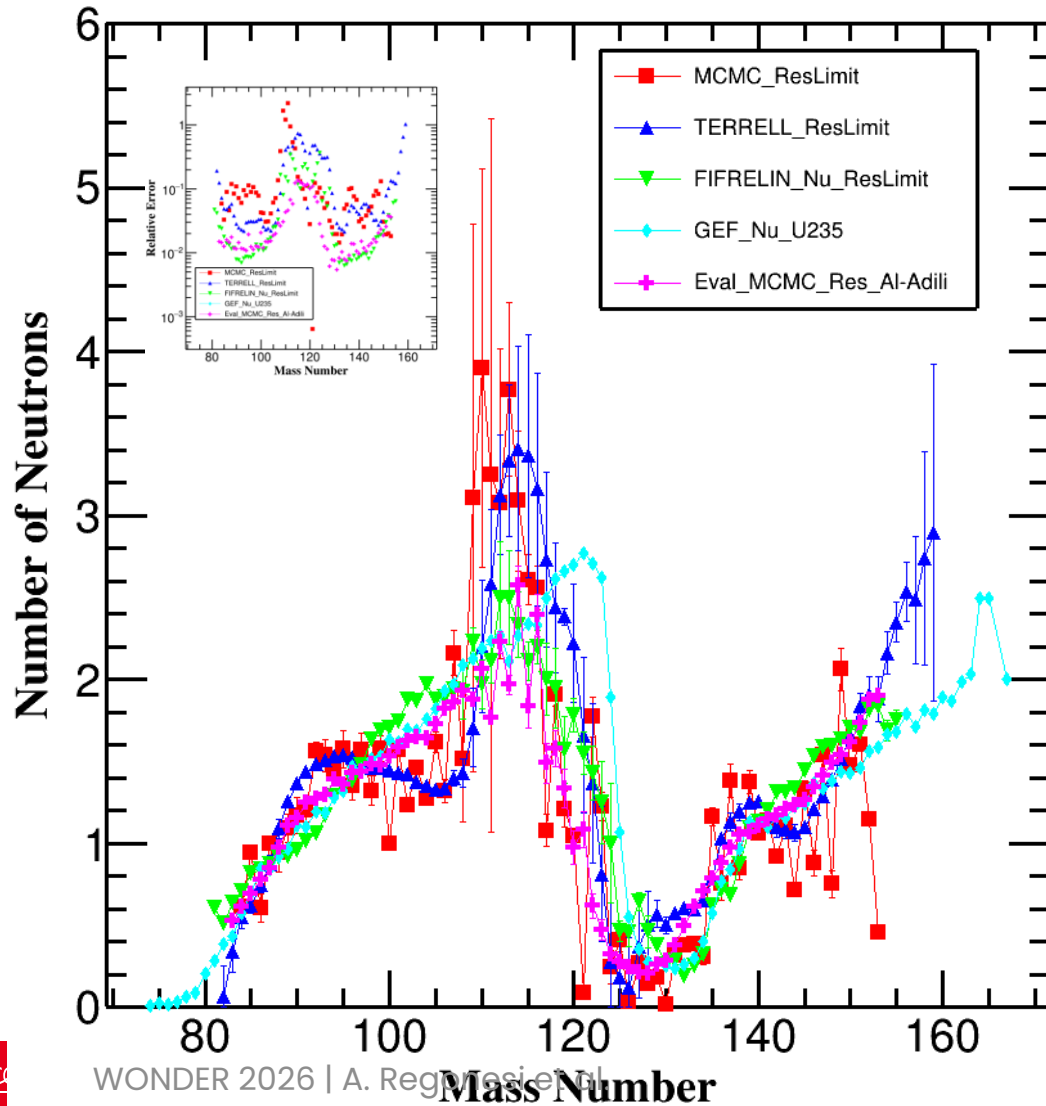
Terrell, J. (1962). Neutron yields from individual fission fragments. *Physical Review*, 127(3), 880

Add FIFRELIN and GEF



Saw-Tooth $\nu(A^*)$ - Comparaison

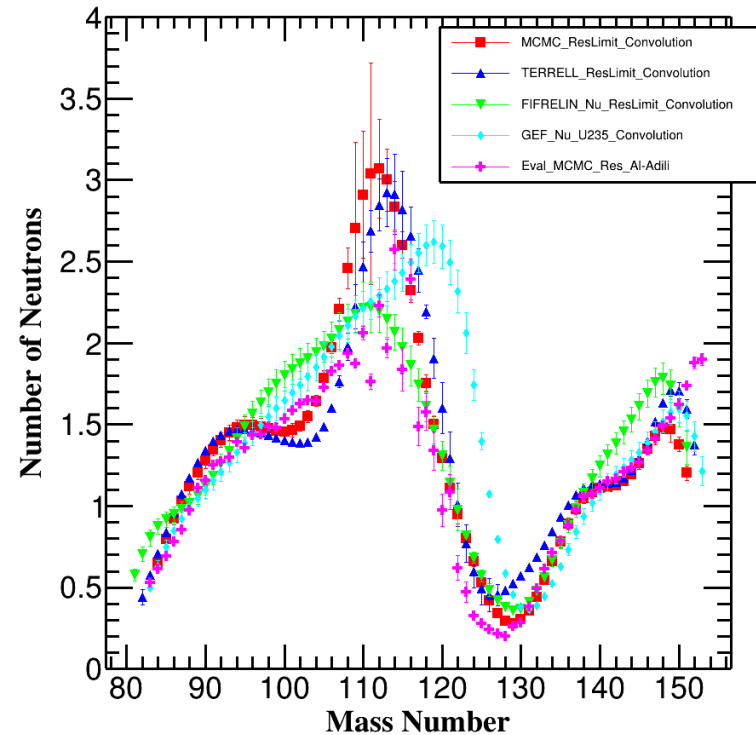
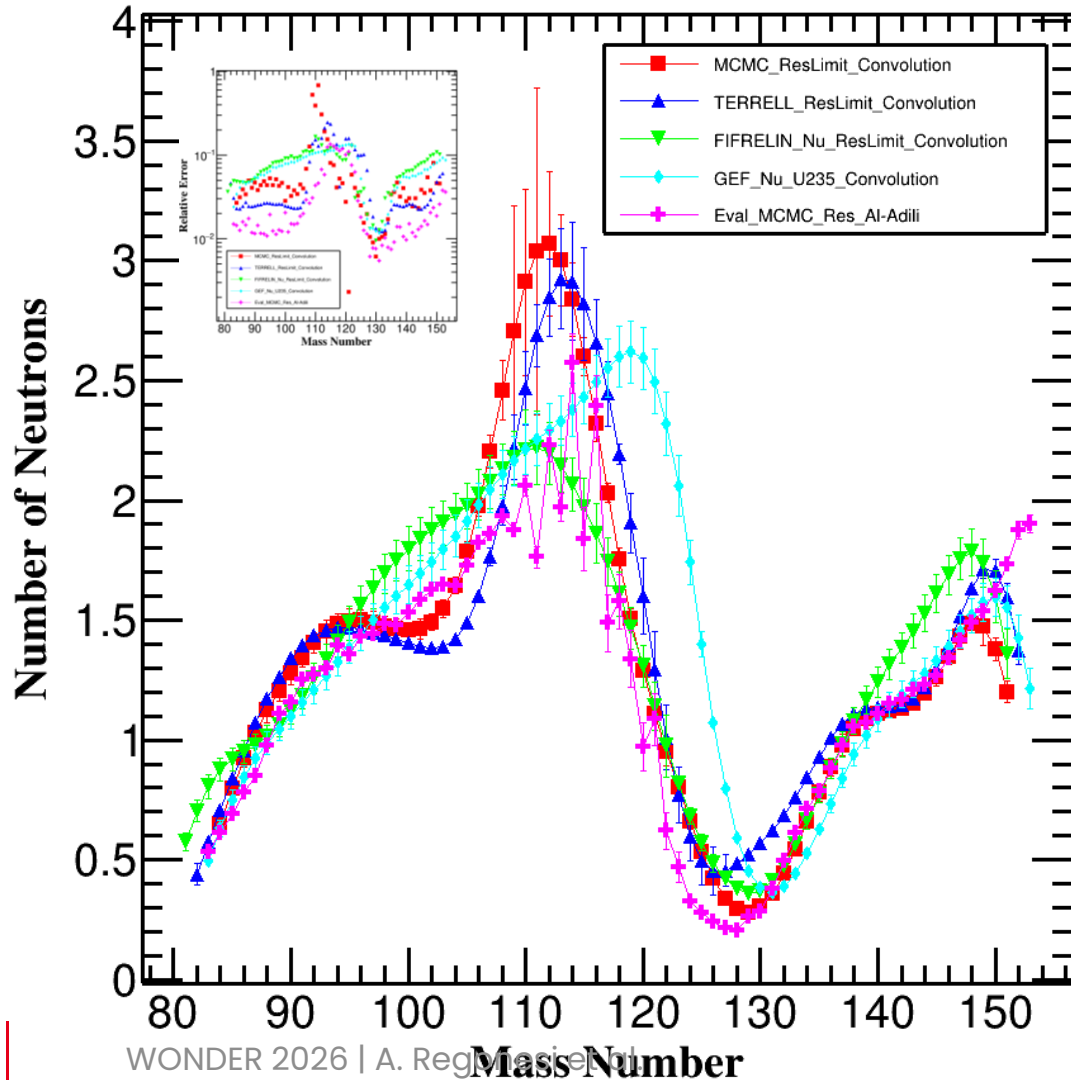
Entre Calcul MCMC resLim | Calcul TERRELL resLimit | FIFRELIN res Limit | GEF | Eval MCMC res AI-Adili



Saw-Tooth $\nu(A^*)$ - Comparaison

Entre Calcul MCMC resLim | Calcul TERRELL resLimit | FIFRELIN res Limit | GEF | Eval

MCMC res AI-Adili \pm convolé à la résolution d'AI-Adili (2.69 u.m.a.)



Context: methodology of FY Evaluation for thermal neutron induced fission



Theoretically
 $Y(A^*, Z, E^*, J^\pi)$



Experimentally
 $Y(A, Z, E_K, I)$



Application

$Y(A, Z, m)$ Independent Yields



$C(A, Z, m)$ Cumulative Yields



$C(A)$ Chain Yields



```

      1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100
    
```

- Fuel Cycle applications
- Reactivity losses (BU)
 - PIE (BU) : Post-Irradiated Experiment
 - CFE
 - Decay Heat

$$Y(A^*) \cdot P(Z|A^*, E^*) \cdot P(E_K|A^*, Z) \cdot P(E^*, J^\pi|A^*, Z, E^*)$$

$$Y(A) \cdot P(Z|A, E_K) \cdot P(E_K|A, Z) \cdot P(m|A, Z, E_K)$$

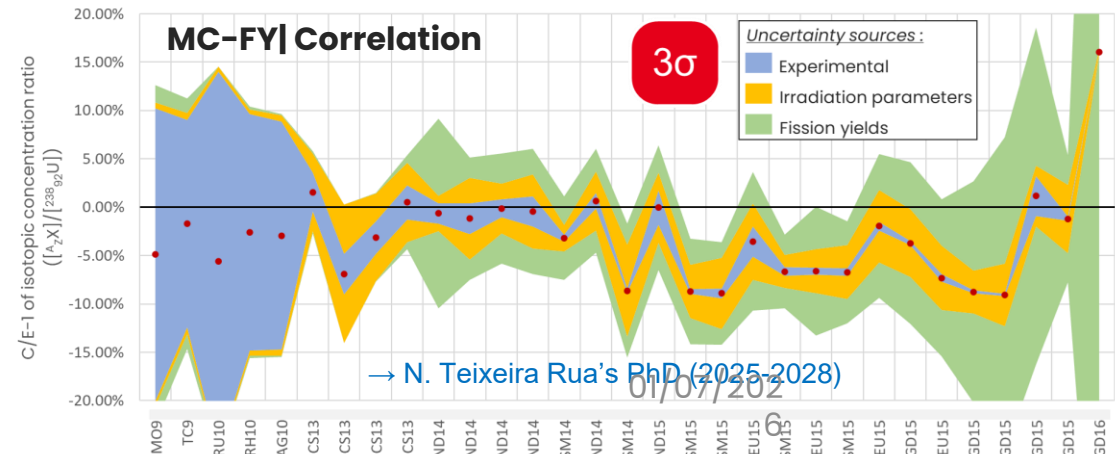
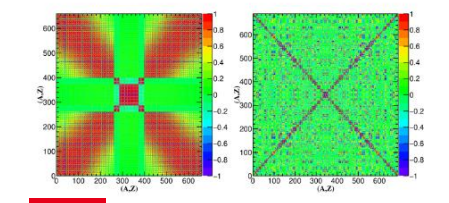
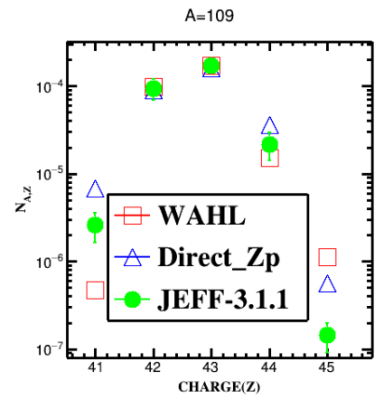
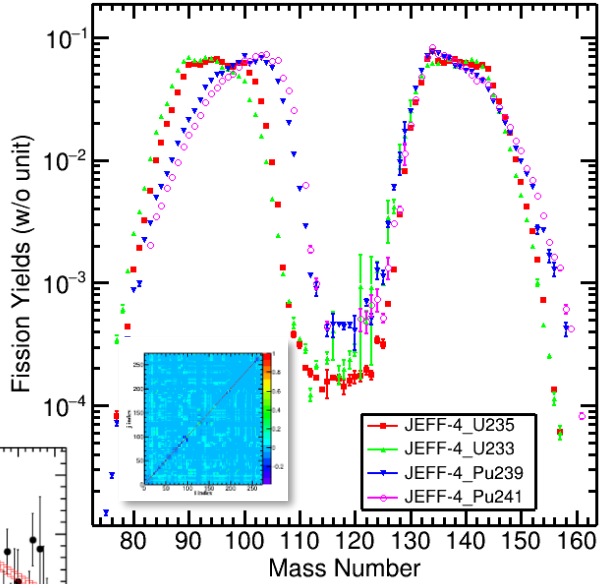
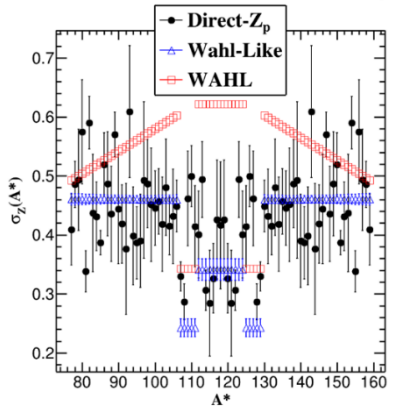
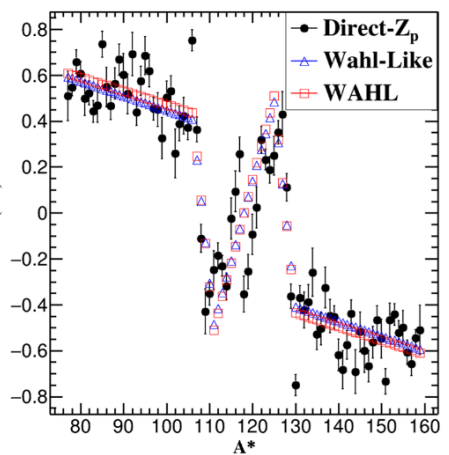
$$Y(A, Z, m)$$

Pre-neutron Mass, charge, excitation energy

Mass Charge

Kinetic Energy Isomeric

Fission models

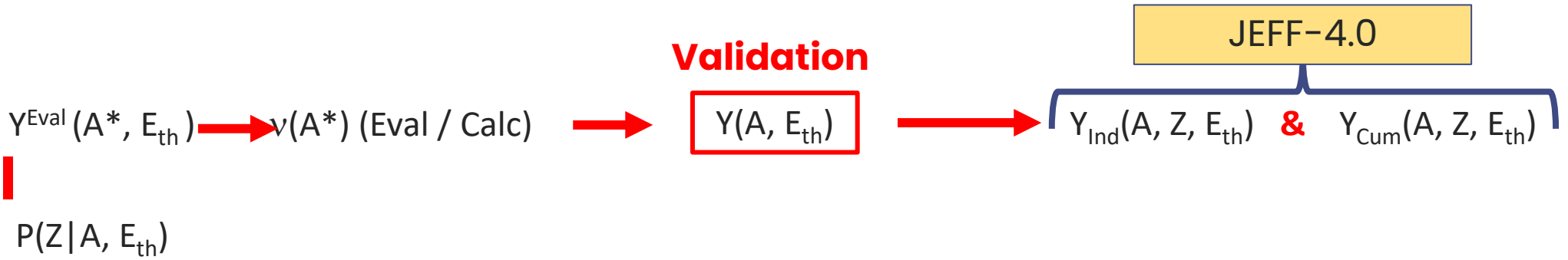


→ N. Teixeira Rua's PhD (2025-2028)

Overview: why they are important?



Thermal



- ❑ Application of Brosa fission model coupled with microscopic models for fine structures
- ❑ Adjustment of the model parameters on the basis of available experimental data as a function of E_n

Fast

