Caen, France
September 25 2025

Update of the Summation Calculations for Reactor Antineutrino Spectra

Magali Estienne, Muriel Fallot

European Nuclear Physics Conference 2025

Outline

- Motivations: Beta Decay study to probe Reactor Antineutrino Anomalies
- Summation Calculations and Nuclear Data
- Updates of the Model and a Few Selection of Results
- Conclusions and Outlooks

Beta Decay Study for Reactor Antineutrinos

- Getting access to the β decay properties and to antineutrino energy spectra

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_{e} $$

$$ \hookrightarrow {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$

- The exploitation of the products of the beta decay is multifold:
  - The **antineutrinos** escape and can be detected → essential for fundamental physics but also reactor monitoring and potential non-proliferation tool
  - **In laboratory, γ or β** measurements of well identified fission products → characterize the weak interaction properties, several physics topics in nuclear structure or nuclear astrophysics but also indirect access to antineutrino energy spectra

- Beta decay driven by some selection rules regarding the isospin and the spin-parity between the parent and daughter nuclei
  - Fermi in the 30s: $\lambda = \frac{2\pi}{\hbar}\left|V_{fi}\right|^{2}\rho(E_f), \quad V_{fi} \equiv \langle\psi_f|O_\beta|\psi_i\rangle$
  - First set of equations for the energy spectrum of electromagnetic particles emitted during a beta decay process

- Over the last 50 years, many computations and improvements of the spectra

- Two methods were revisited in 2011: the conversion and the summation methods.
  - The HM model used as reference for the neutrino experiments

First Observations of the Anomalies of Reactor Antineutrino Energy Spectra

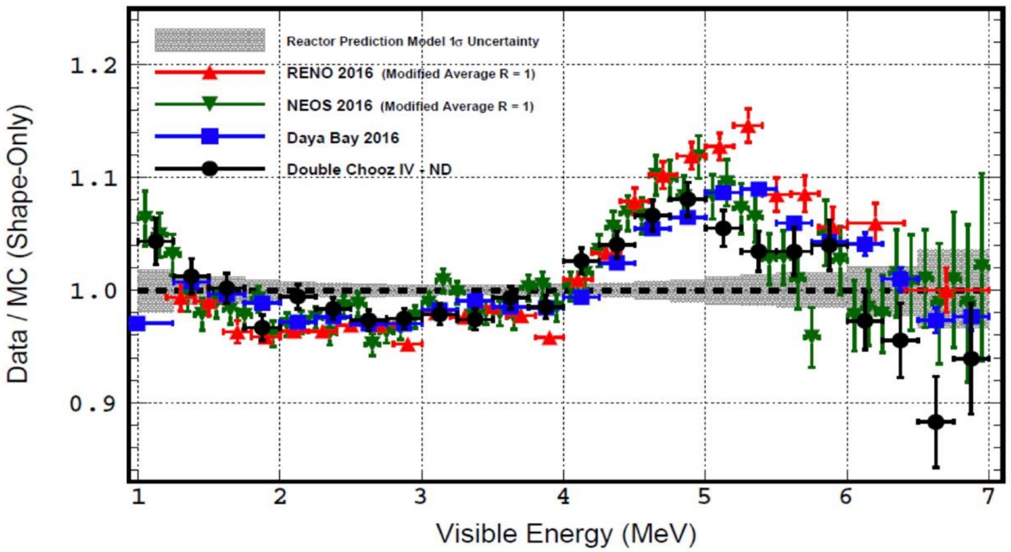
- Measurement of the θ_{13} oscillation parameter by Double Chooz, Daya Bay, Reno in 2012
  - Independent evaluation of anti-ν energy spectra using NDBs
  - 6% deficit in the measured flux at short baseline experiments compared with the best prediction based on ILL data: reactor anomaly (RAA)
  - Numerous projects in search of the existence of sterile neutrinos

Y. Abe et al Phys. Rev. Lett. 108, 131801, (2012)
F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012)
J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012)

G. Mention et al. Phys. Rev. D83, 073006 (2011)

- In 2014, the same three experiments highlighted a spectrum distortion between 4.8-7.3 MeV compared to nuclear models again! (Shape anomaly)

Nature Physics 558–564 (2020)

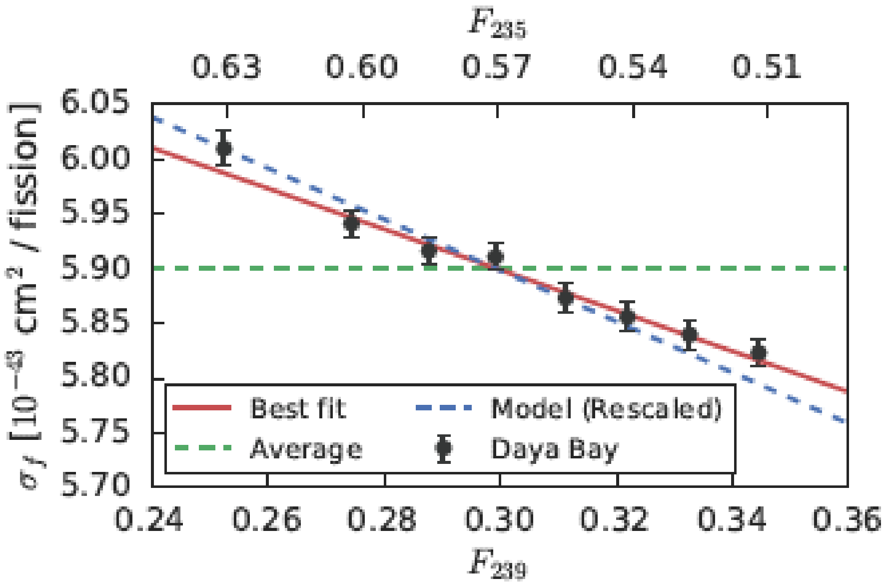


Context by End 2017

In 2017: Daya Bay's new result about the reactor anomaly: pb is in the ^{235}U spectrum!!!

F. P. An et al. (DB Collaboration), ``Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," PRL 118 (2017) 251801.
And associated APS Viewpoint by M. Fallot

σ_f = IBD yield per fission = anti-ν flux per fission



- Slope not in full agreement with H-M and global deficit of 5.1%
- Deficit in detected antineutrinos compared with predictions depends on the relative fractions of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu in the reactor.
- Flux deficit quasi all taken by ^{235}U —enough of a discrepancy to explain by itself the entire antineutrino anomaly !!!
- In contrast, the discrepancy = almost zero for ^{239}Pu fissions.

➡ **Potential issue in Schreckenbach measurement or H-M model for ^{235}U?**

New DB (ArXiv:1904.07812) **and RENO** (PRL 122 (2019) 232501) **papers re-inforce previous results**

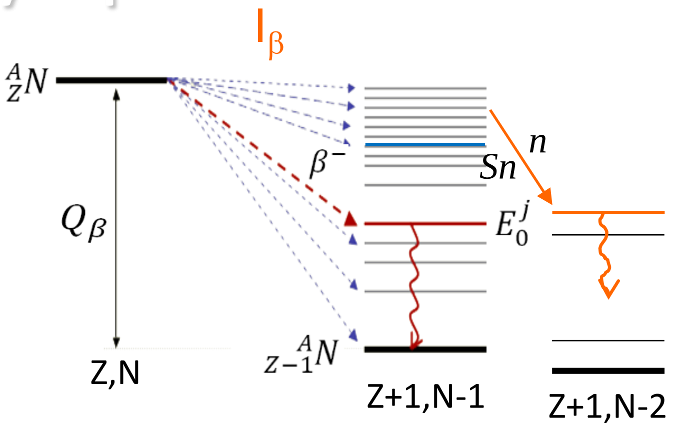
➡ **Growing interest in summation method to calculate anti-ν spectra**

The Alternative Summation Method for Getting Access to the $\bar{\nu}$ Energy Spectra of a FP

- Measurement of well identified fission products:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e $$

$$ {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$



- Total energy spectrum of a fission product:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} \boldsymbol{I_{\beta\,fp}}^{\boldsymbol{b}} \times S_{fp}{}^{b}\left(Z_{fp}, A_{fp}, \boldsymbol{E_{0\,fp}}^{\boldsymbol{b}}, E\right) $$

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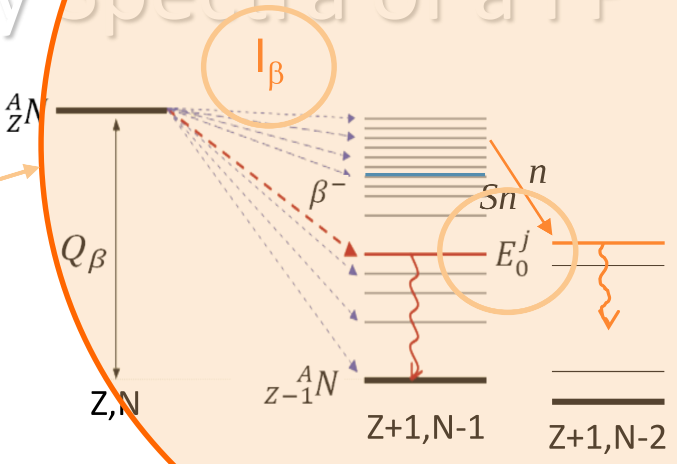

TAGS measurements

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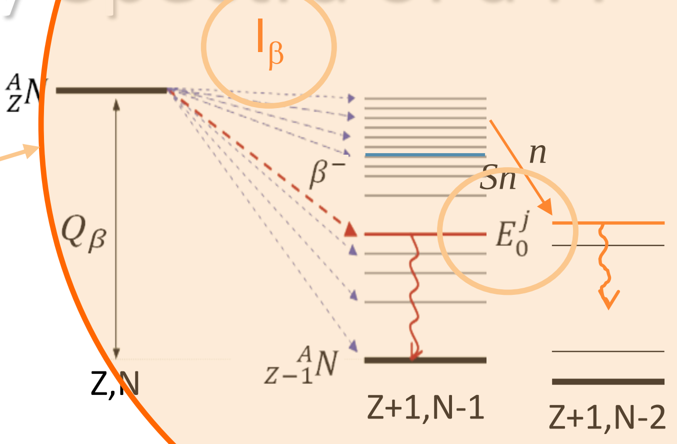

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- Energy spectrum of a b branch of a fission product:

$$S^{b}_{fp}(p) \propto \underbrace{p^2\left(Q - T_e\right)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{\boldsymbol{C(Z,p)}}_{\textbf{Shape factor}} \underbrace{\left(1+\delta(Z,A,p)\right)}_{\text{Subdominant corrections}}$$

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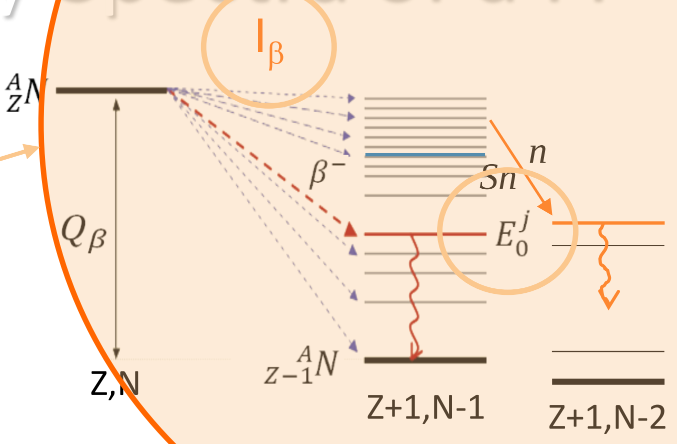

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A. Alcala et al., accepted to PRL (https://doi.org/10.1103/hyj7-l22h)
Preprint: arXiv.2505.05929

eShape measurements

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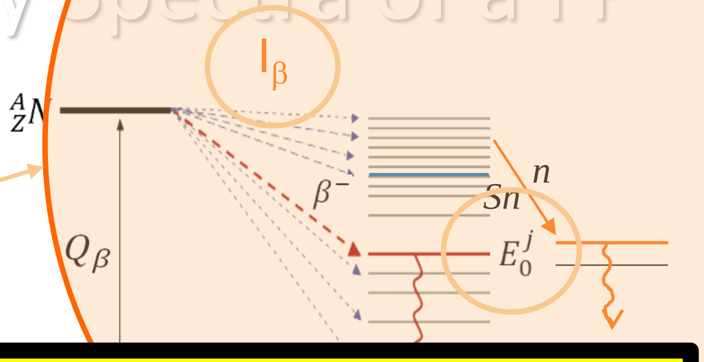

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Caveat:

Summation calculations are strongly dependent on nuclear data !

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γ Measurement Caveat

- Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy
  - Excellent resolution but efficiency which strongly decreases at high energy or because of small acceptance
  - Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daugther nuclei

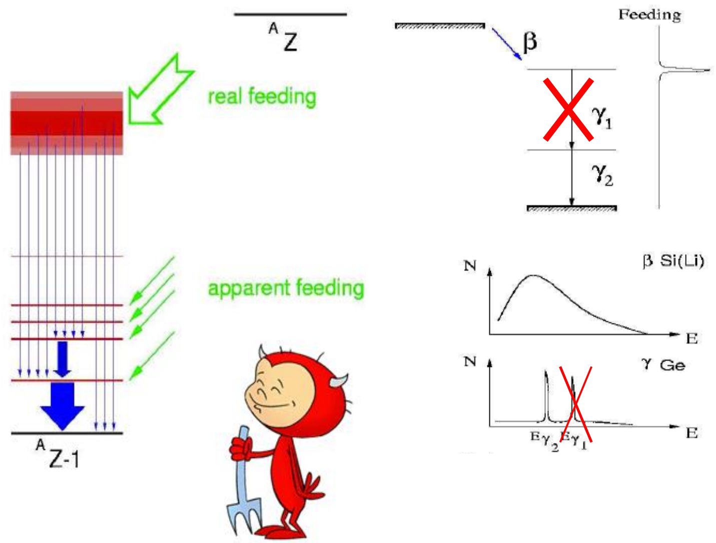
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra

- Phenomenon commonly called « pandemonium effect** »

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

➡ Expected distortion of the antineutrino energy spectra computation with SM

Picture credit: A. Algora



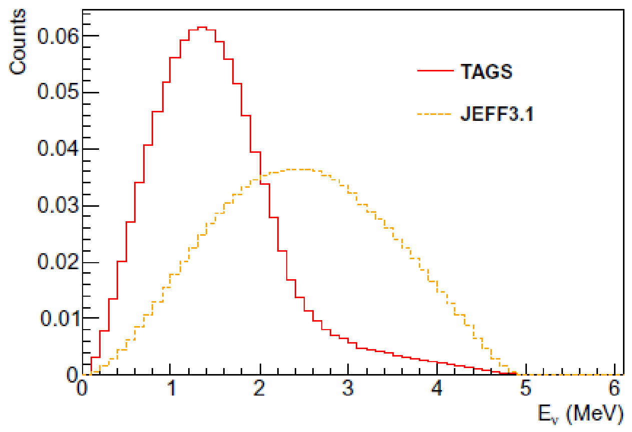
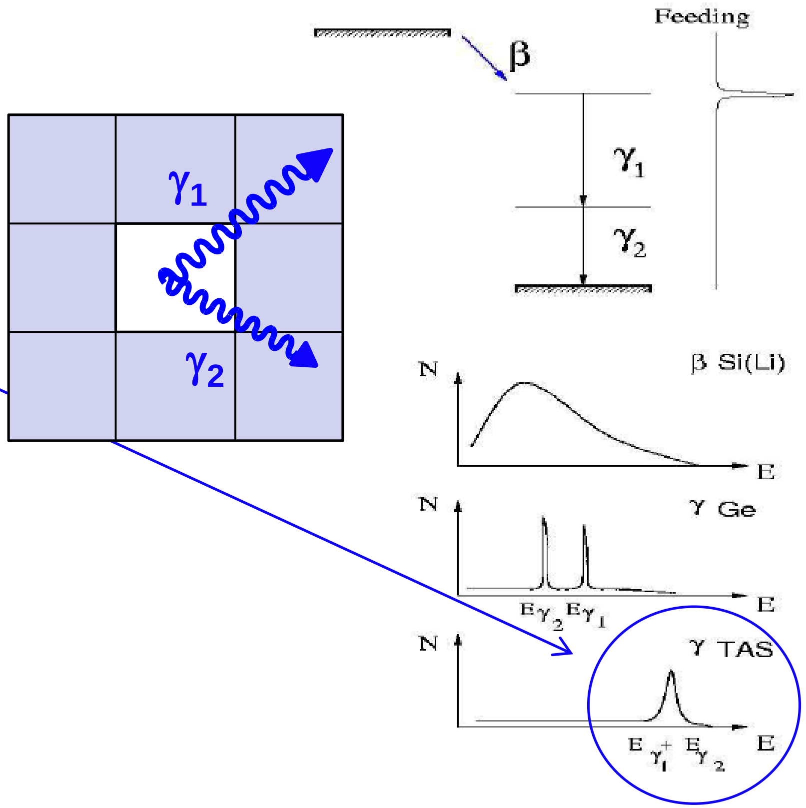


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

TAGS: a Solution to the Pandemonium Effect

- Total absorption γ-ray spectroscopy (TAGS)
  - A TAS is a calorimeter
  - It contains big crystals covering 4π
  - Instead of detecting the individual gamma rays, absorbs the full gamma energy released by the gamma cascades in the β-decay process



- First TAS developed in the 70's but too small detectors to be efficient. Development of the TAGS method efficient and systematic since the 90's (Greenwood & al.)

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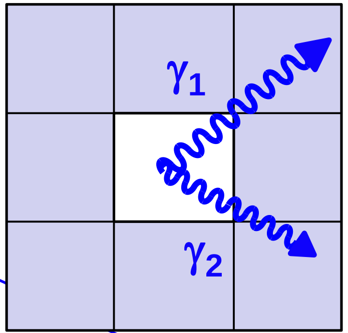

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DTAS

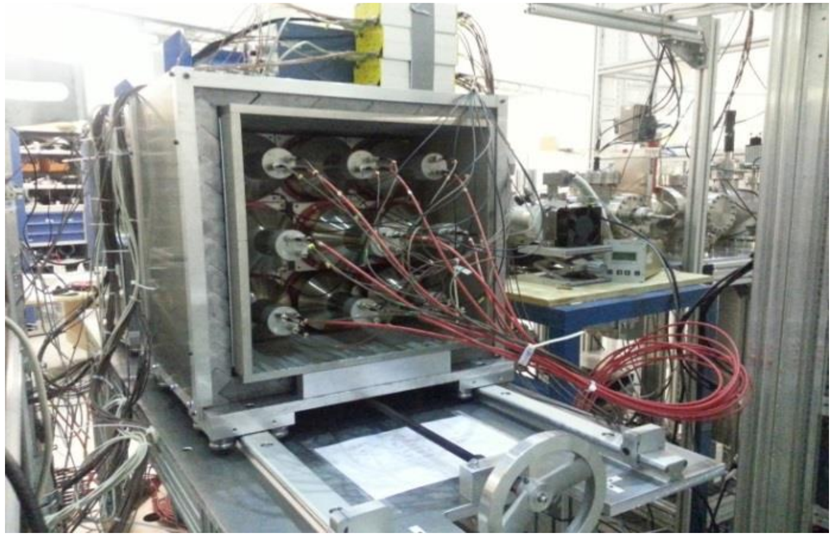
- 18 NaI(Tl) crystals of 15cm×15cm×25 cm
- Individual crystal resolutions: 7-8%
- Total efficiency: 80-90%

E. Valencia et al., PRC 95, 024320 (2017)

Rocinante

- 12 BaF_2 covering 4π
- Detection efficiency of γ ray cascade >80% (up to 10 MeV)

See J. Pépin, Monday 22 – 2:45pm (NSSD)
See A. Porta, Tuesday 23 – 3:05pm (NSSD)
See M. Fallot, Thursday 25 – 2:20pm (AI)



J.L. Tain et al., NIMA 803 (2015) 36
V. Guadilla et al., NIM A 854 (*2017*) 134

New Summation Model in 2012 – SM-2012

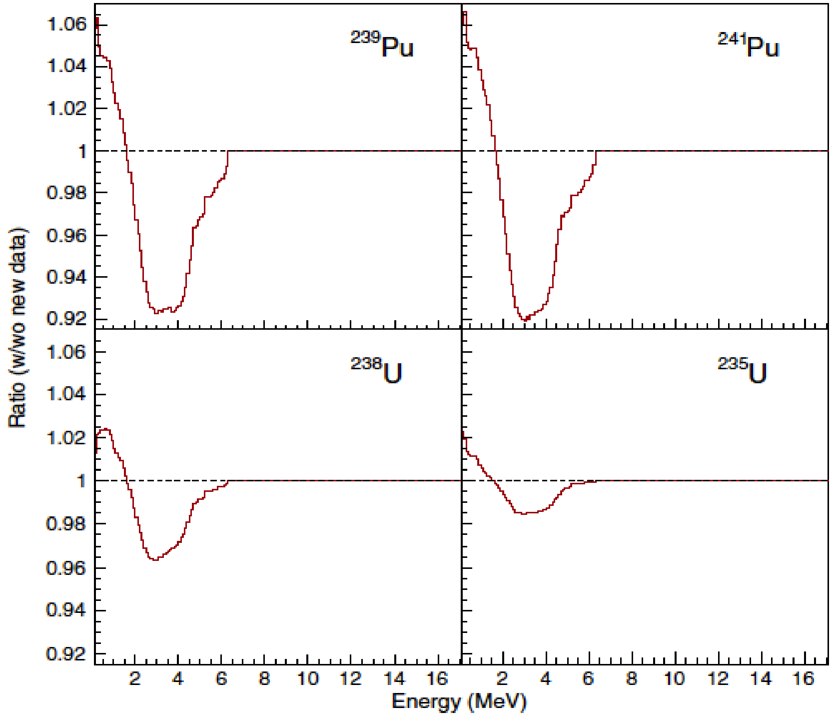
- All fission products in the JEFF3.1.1 fission yields databases taken into account

- To reproduce the experimental conditions of Schrekenbach et al., we simulated irradiation times with MURE: 12 h for ^{235}U, 1.5 d for $^{239;241}$Pu, and 450 d for ^{238}U.

- We highlighted the necessity:
  - To use nuclear databases Pandemonium free and proposed a cocktail of nuclear databases to follow to reduce as much as possible experimental biases
  - To complete the full list of FP involved in the calculation using models or the Qbeta approximation at minimum.

- Taking into consideration the TAS data of the $^{102;104–107}$Tc, ^{105}Mo, and ^{101}Nb isotopes measured in 2007 @ Jyväskylä Algora *et al.*, PRL 105, 202501 (2010).
  - ~850 nuclei included
  - Noticeable deviation from unity (1.5 to 8% decrease)

M. Fallot *et al.*, PRL 109, 202504 (2012)



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typical from Pandemonium: increases the spectrum before 2-3 MeV and decreases it above => strong impact on the IBD yield!

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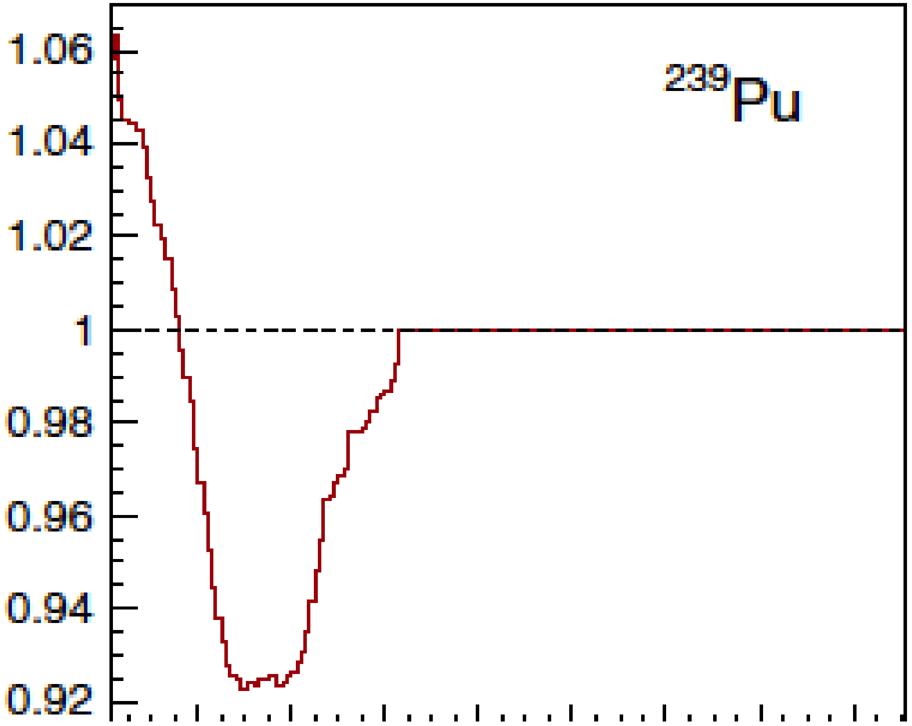

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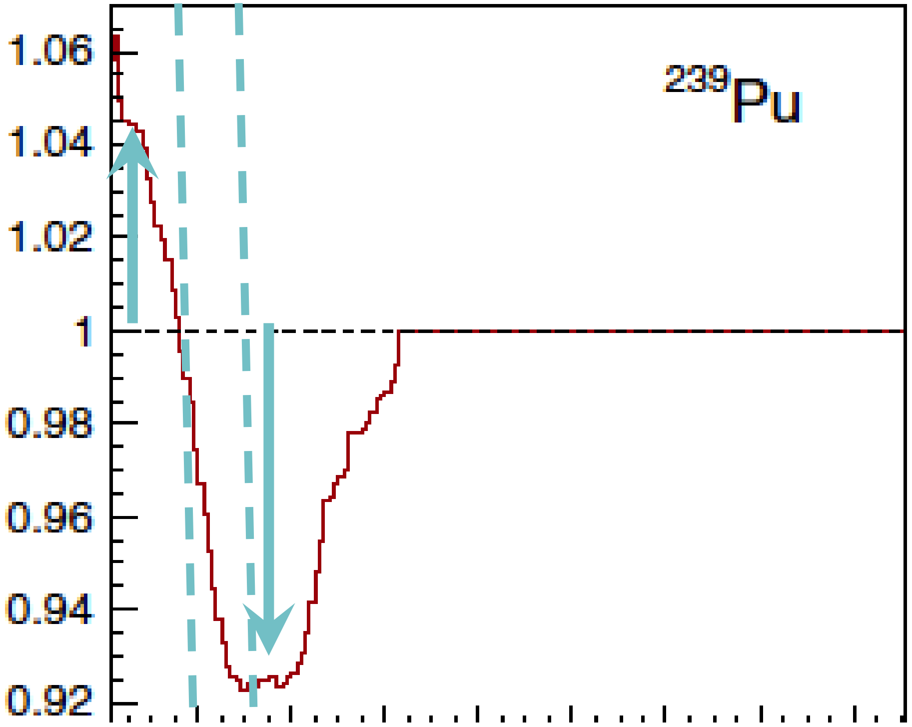

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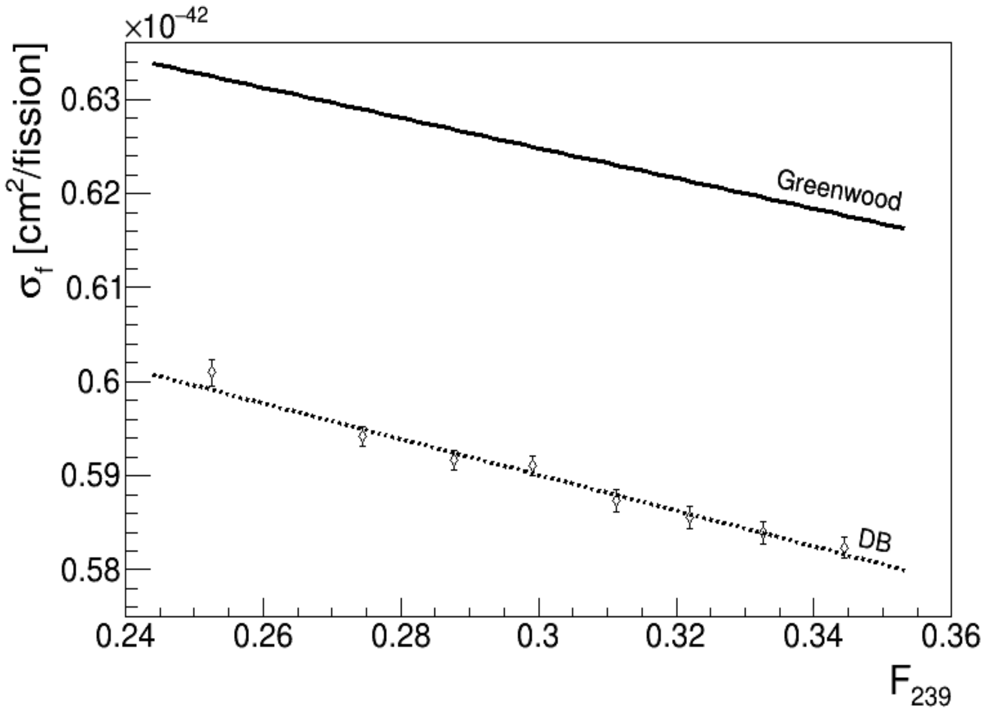

Pandemonium is a systematic effect!

Less than 2% discrepancy with DB IBD yield.

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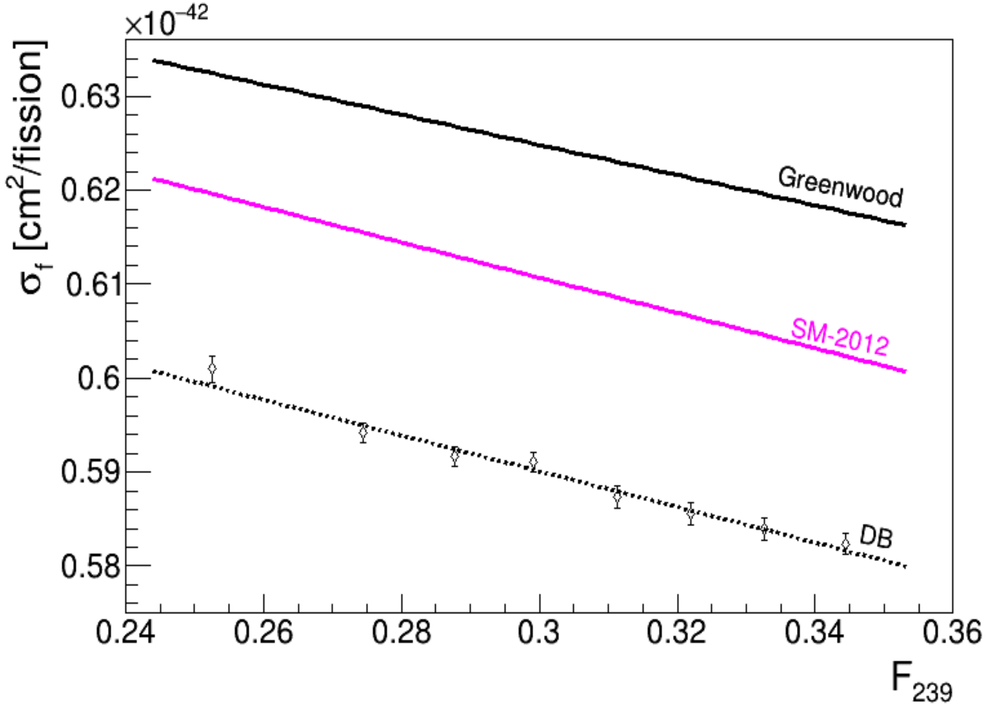

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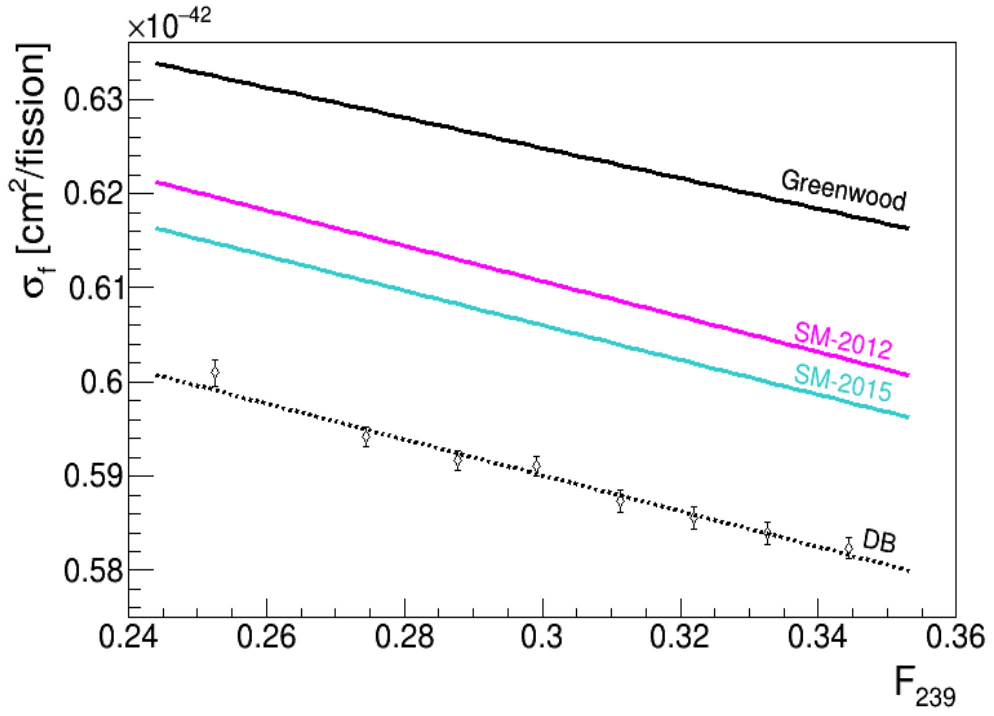

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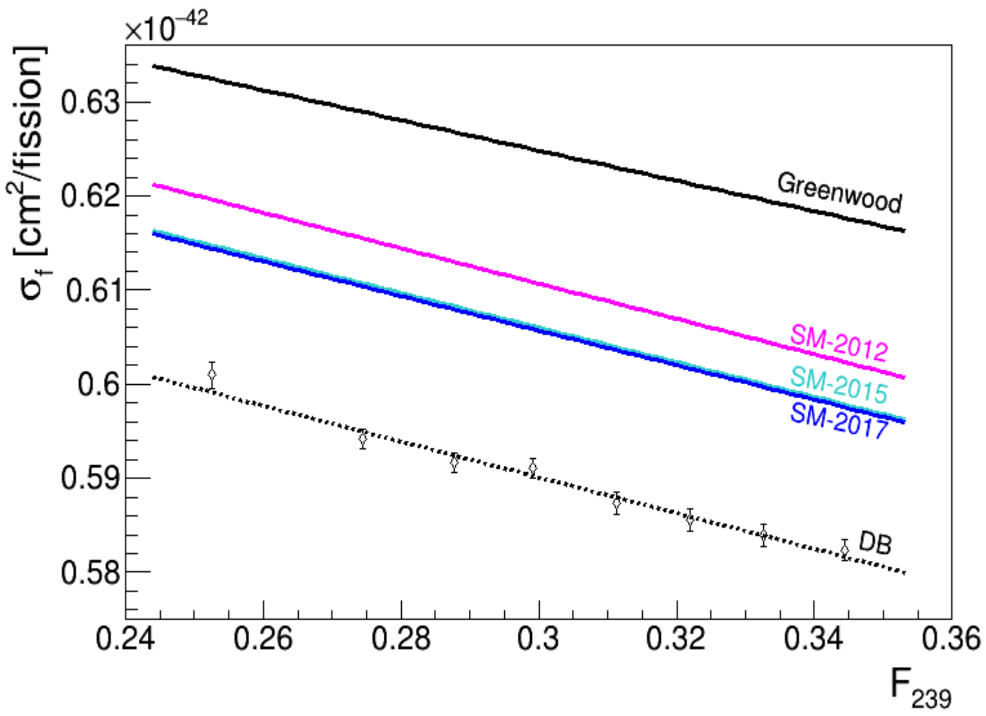

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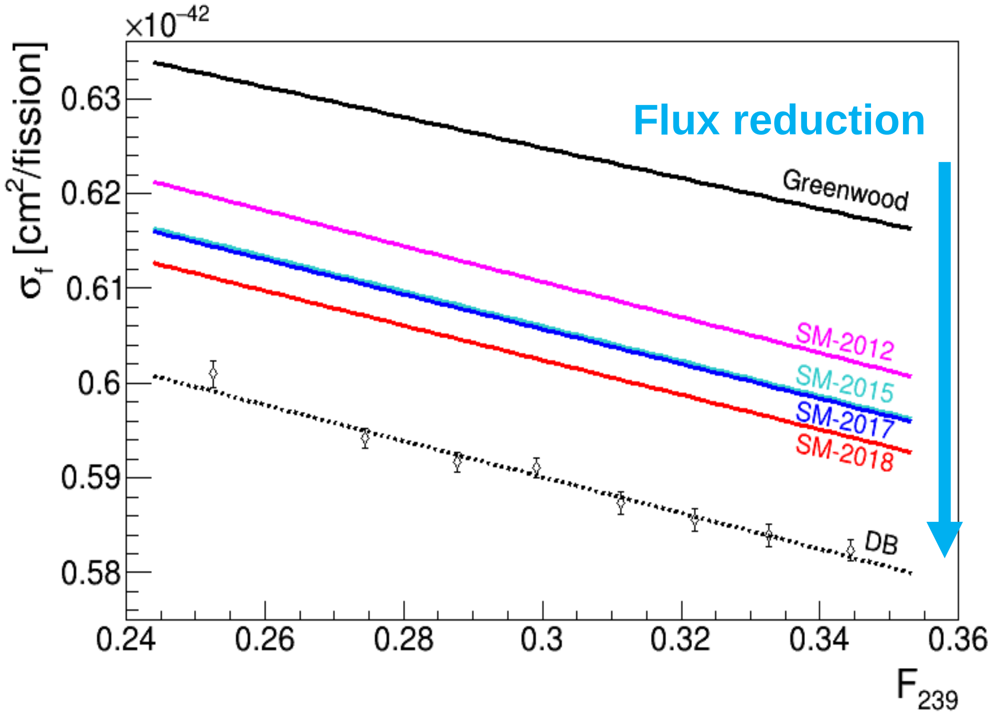

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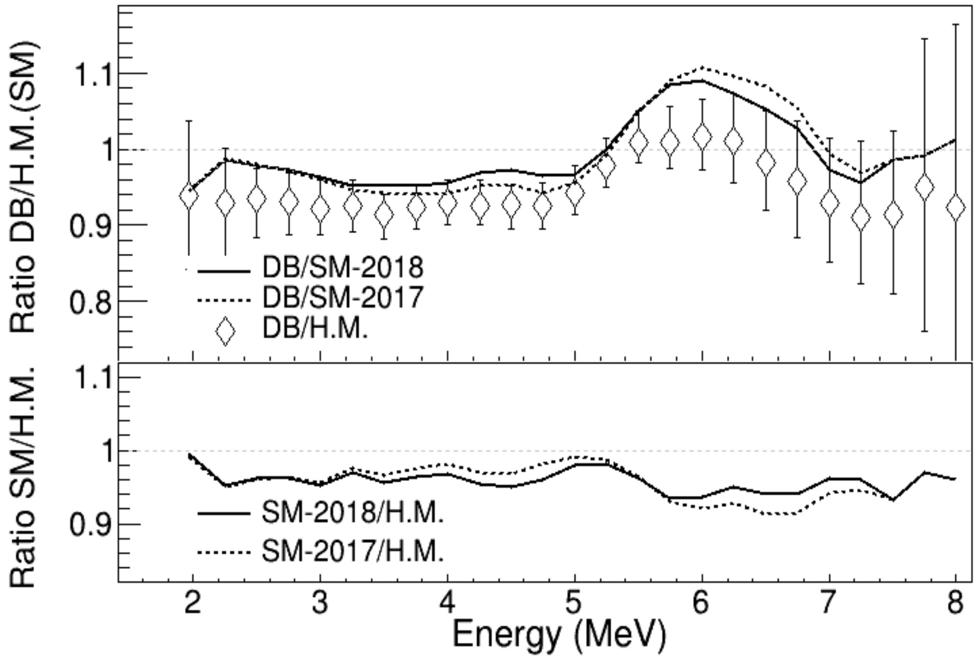
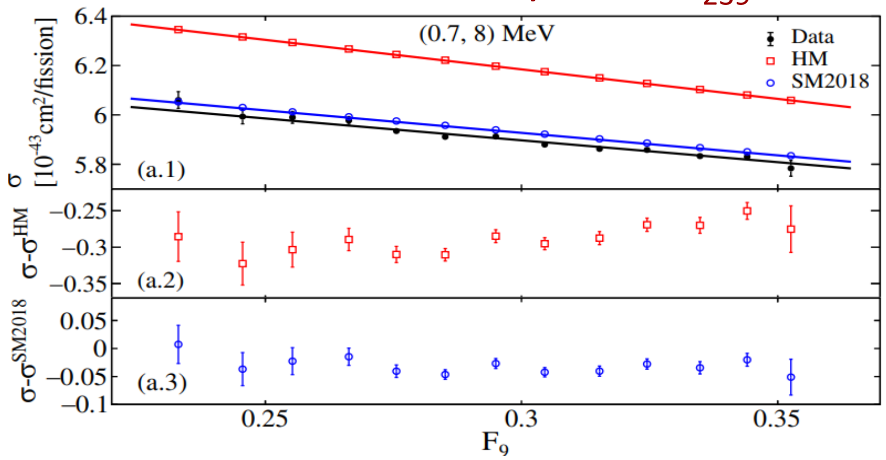
First full spectrum prediction without any renormalization.
Pandemonium correction contributes to reduce the bump but it is still there.



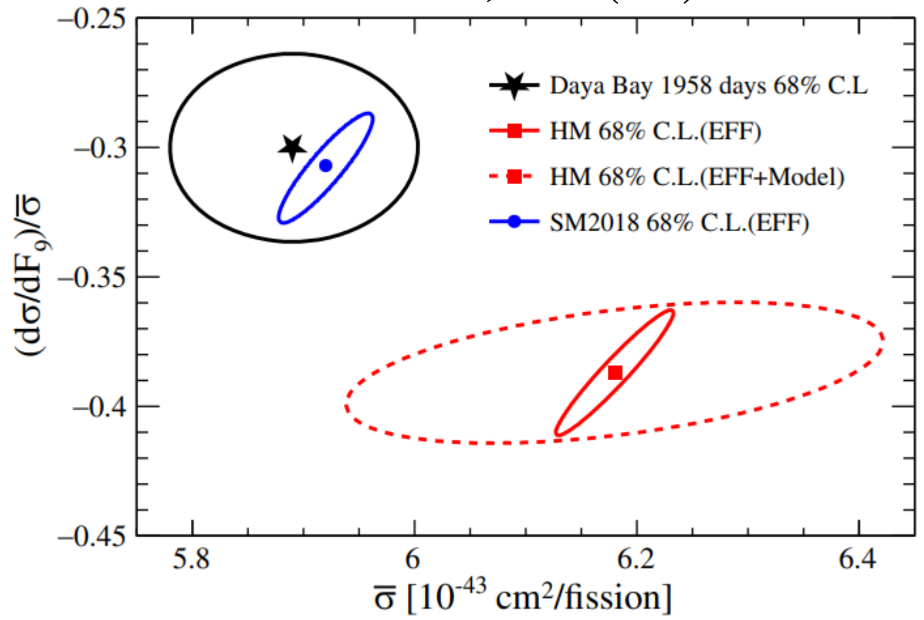
2023 Results from Daya Bay

- Evolution of the total IBD yield vs F_{239}



- Using of 1958-day data sample (~6 years of measurement 2011-2017), study of the total IBD yield.
- Spent nuclear-fuel contribution and out-of-equilibrium effect taken into account as a function of antineutrino detector and time.
- Data sorted into 13 groups of ^{239}Pu fission fraction.

DB collaboration, PRL 10 (2023) 211801



- H-M predictions for $\bar{\sigma}$ and $[\frac{d\sigma}{dF_9}]/\bar{\sigma}$ rejected at 3.6 and 3 standard deviations.
- SM18 consistent with DB

RAA relieved by SM-2018 but not the spectrum shape

- Issue with the ^{235}U measurement from Schrekenbach et al. Confirmed

Summation Model Updates - 2025

- Ingredients of our model core calculation (SM-2023) :
  - 1keV energy bins
  - Collaboration with L. Hayen: Screening corrections: Rose replaced by Salvat (**L. Hayen, N. Severijns et al. Rev. Mod. Phys. 90, 015008 (2018)**)
  - Nubase 2020 for Q_β approximation
  - 65 nuclei from Rudstam / Tengblad et al. (elimination of those in agreement with JEFF/ENDFB8, and a few « odd » ones)

⇒ Small change in the global flux (~+0.25%)

- 2014 TAGS campaign: quantification of the impact of 7 new nuclei :
  - ^{95}Rb et ^{137}I: 2 nuclei from V. Guadilla et al. **Phys. Rev. C 100, 044305 (2019)**
  - ^{96gs}Y and ^{96m}Y (Pandemonium): 2 nuclei from V. Guadilla et al. **Phys. Rev. C 106, 014306 (2022)**
  - ^{99}Y, ^{142}Cs and ^{138}I: 3 Pandemonium nuclei from L. Le Meur et al., **in preparation**

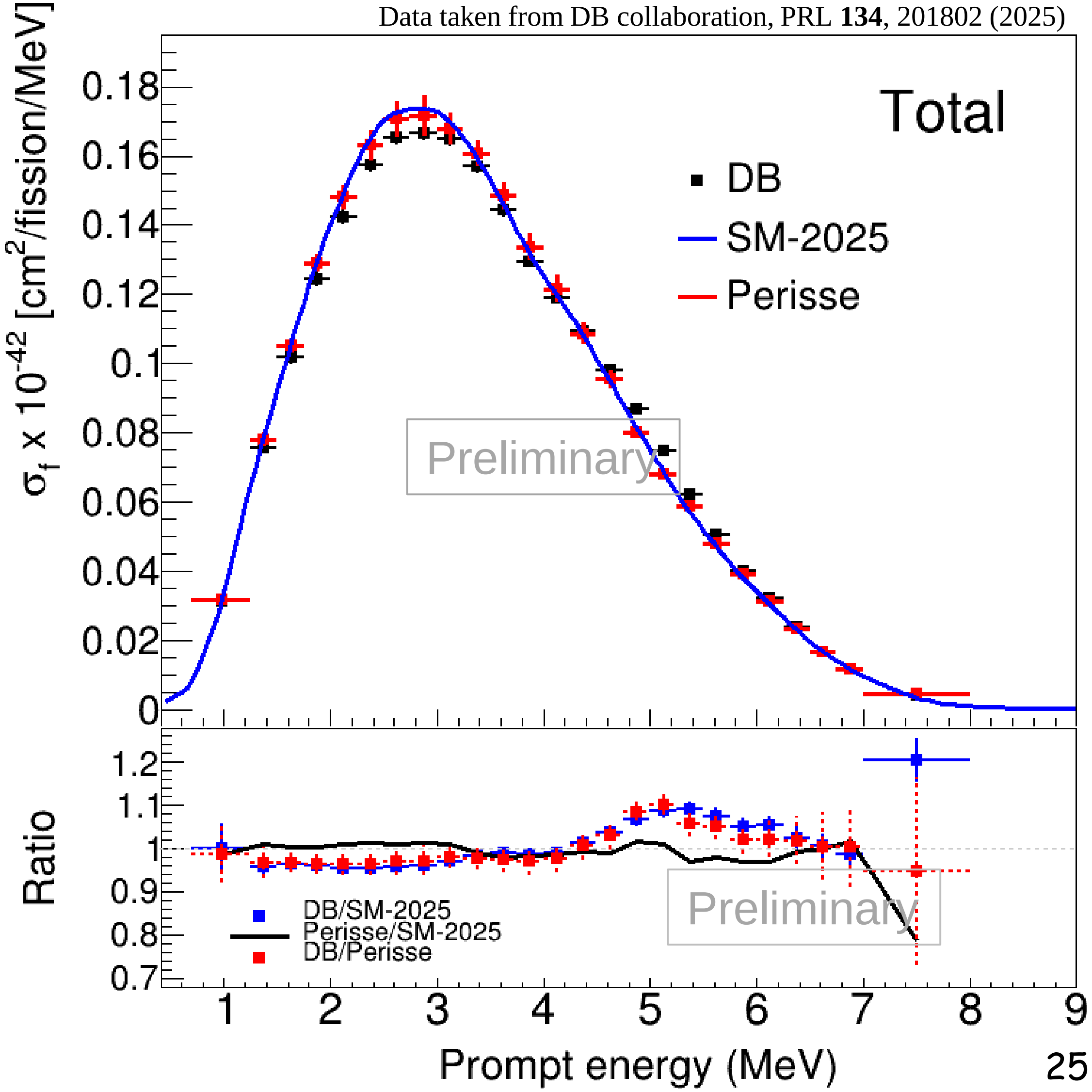
Total Prompt Energy Spectra Comparison

- SM-2025 total prompt energy spectrum compared with DB and Perissé.

  - ❑ Convolution of our summation calculations with DB response matrix
  - ❑ As already seen, the bump is still there and we are below DB between 1.5 and 3 MeV in the dominant IBD cross section region by 4 to 5%. We reach 2% difference between 3 and 4 MeV before the bump.
  - ❑ With our updated model, good agreement with Perissé et al.
  - ❑ Discrepancies +1% in the 2 to 3 MeV region and -2-3% between 5.5 and 6.5 MeV.

=> Two SM compatible within Perissé et al.'s uncertainties but we have more TAGS Decay Data included

Data taken from DB collaboration, PRL **134**, 201802 (2025)

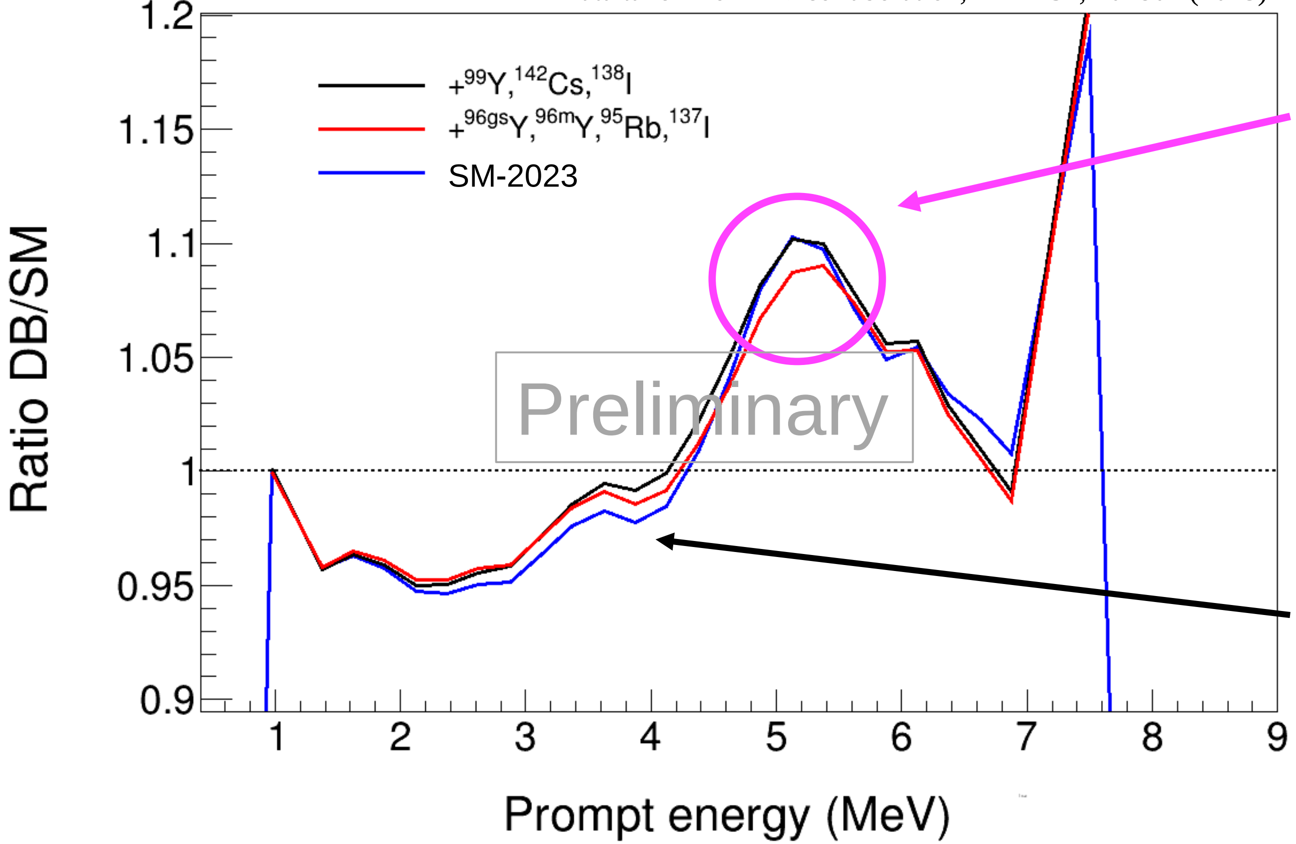


Impact of the « TAGS » Nuclei Added in the Model

Ratio Daya Bay Spectrum 2025 over SM-2025

- Comparison of the SM-2023 and SM-2025 to DB in prompt energy of the total spectrum.
- Out of equilibrium effects corrected in both cases.

Data taken from DB collaboration, PRL **134**, 201802 (2025)

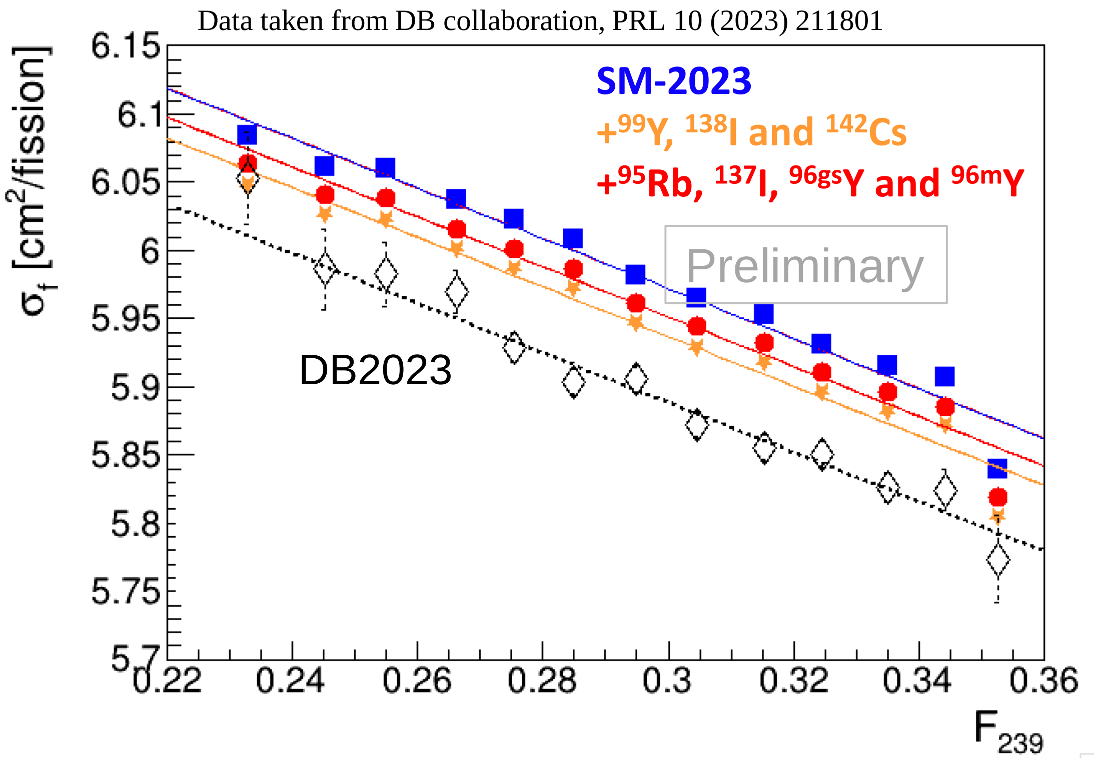


2) Erosion of the bump: -2% on 4 points, without moving the low energy part (not just global shift downward)

1) Clear impact of ^{99}Y, ^{142}Cs and ^{138}I on the global flux but not on the bump

Impact on the IBD yield

- Ratio Daya Bay 2023 IBD flux vs SM-2025



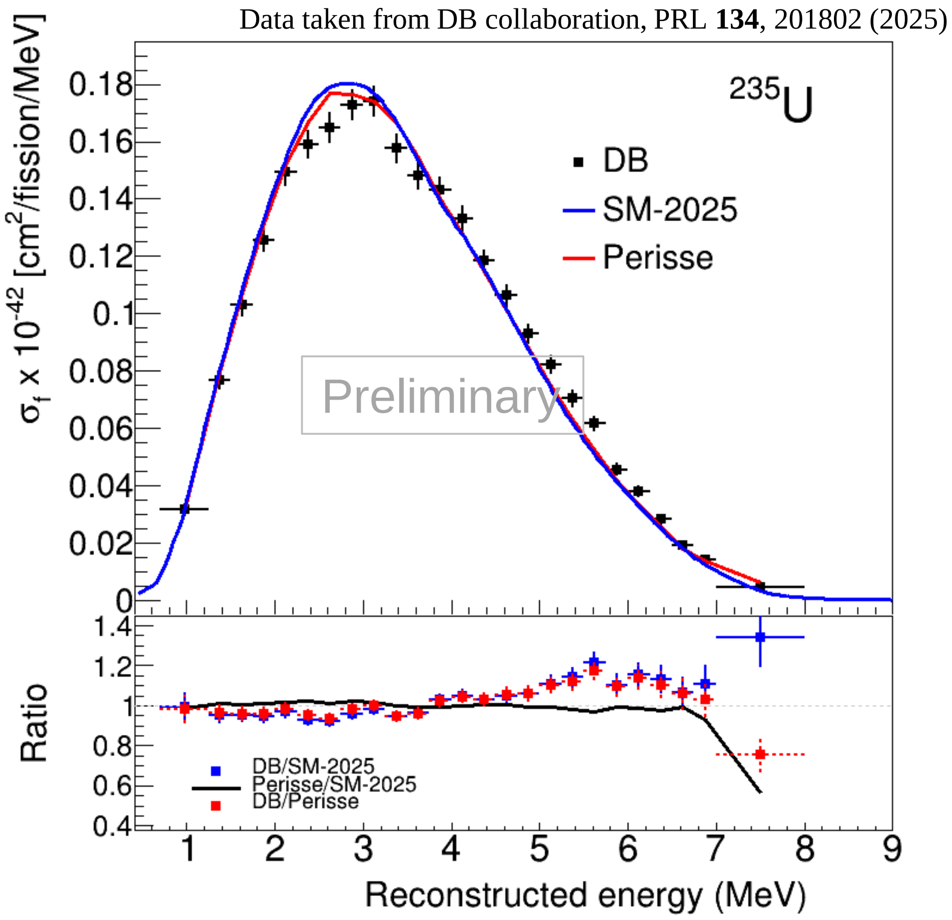
- **SM-2025 is ~1.5% above DB2023**:
- +0.25% increase due to update of the model (SM-2023)
- -0.6% due to ^{142}Cs, ^{138}I and ^{99}Y
- +0.25% due to $^{96,\,96m}$Y, ^{137}I and ^{95}Rb
- +0.25% due to new Daya Bay points

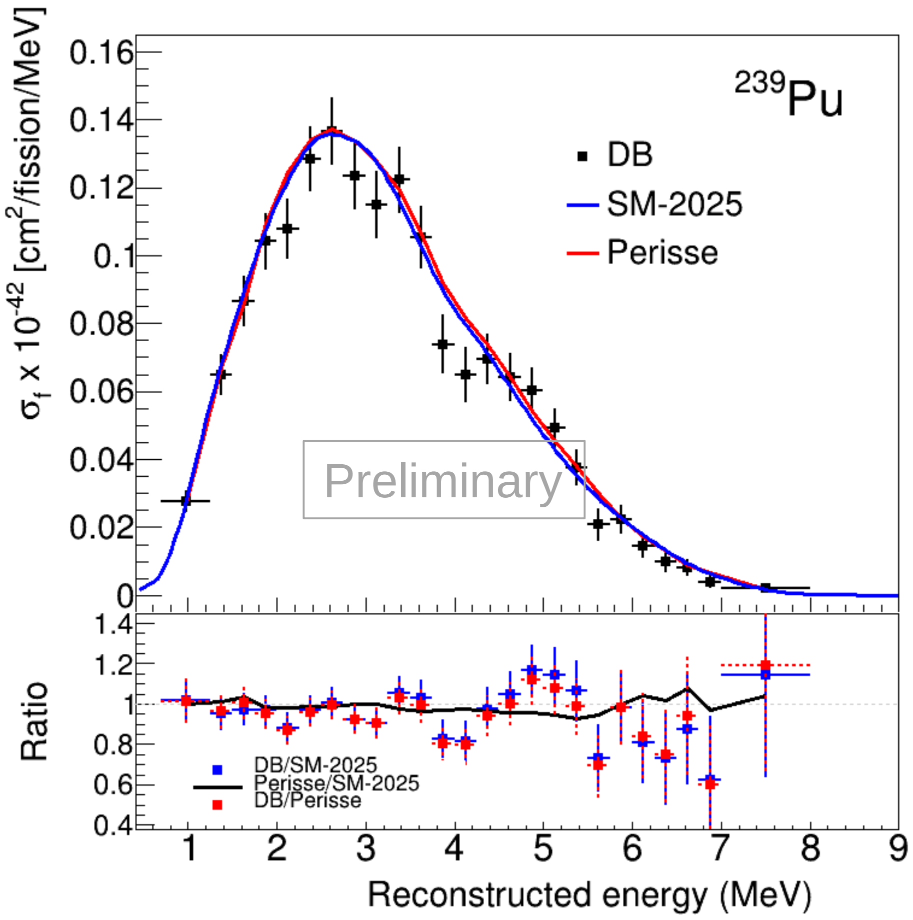
- Pandemonium correction still decreases the discrepancy but some nuclei are corrected from other systematic effect (i.e. w.r.t. Rudstam or new data for isomer)

- Still systematic trend reducing the flux including pandemonium free data
- SM-2025 is the most up-to-date in terms of TAGS decay data (most dominant uncertainty)
- More to come with new TAGS campaign

^{235}U and ^{239}Pu Prompt Energy Spectra Comparisons

- SM-2025 prompt energy spectrum compared with DB and Perissé.





- More pronounced bump in the case of ^{235}U wrt ^{239}Pu but too large DB uncertainties to quantify the deviation in the ^{239}Pu case.
- SM models in good agreement in both cases. Largest discrepancy for ^{239}Pu in the range 4.5 to 5.5 MeV

Conclusions & Perspectives

- TAGS data (Pandemonium free) correct NDB from Pandemonium effect
- SM-2018 updated to SM-2025 :
  - Internal ingredients changed or updated to newer databases
  - Seven TAGS nuclei added either Pandemonium free or different from previous database taken as reference
- Pandemonium systematic still observed and improvement in both flux (1.7%) and shape (-2%) in the bump region wrt to DB
- Good agreement in flux with Daya Bay and Perissé
- Still some discrepancies in shape with DB and good agreement with Perissé et al. except in an energy range in the bump region for ^{239}Pu
- **SM-2025 most up-to-date Pandemonium free data**
- More to come with new TAGS data and eShape data to take into account forbidden non unique corrections

Thank you!

The TAS Collaboration

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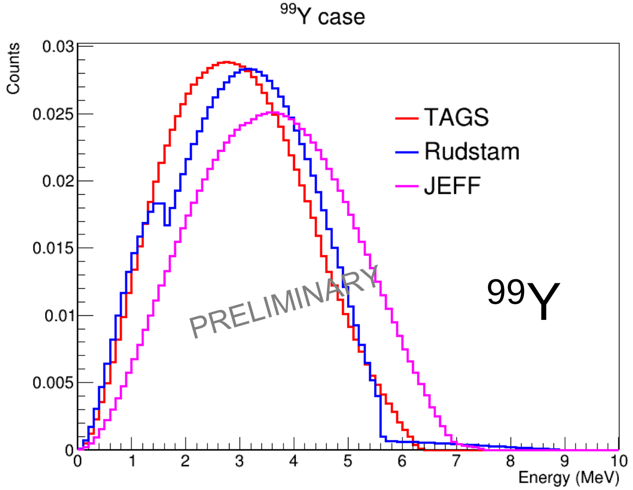
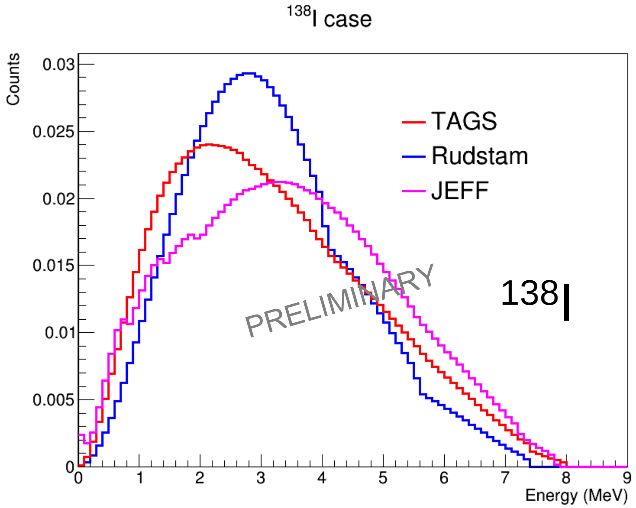
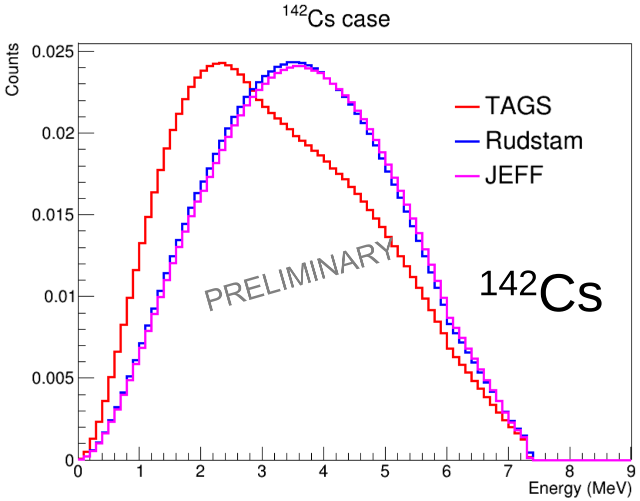
Extra

Individual Anti-ν Energy Spectra: ^{99}Y, ^{138}I and ^{142}Cs

- Comparison of the individual antineutrino energy spectra between DTAS and the preferred nuclear database that was used for our previous calculation (Rudstam).
  - Rudstam β spectra converted
  - Non pandemonium free data in JEFF 3.1.1
  - Shift vs low energy in TAS: apparent biases in Rudstam measurement and large error bars
  - Impact the total antineutrino spectrum



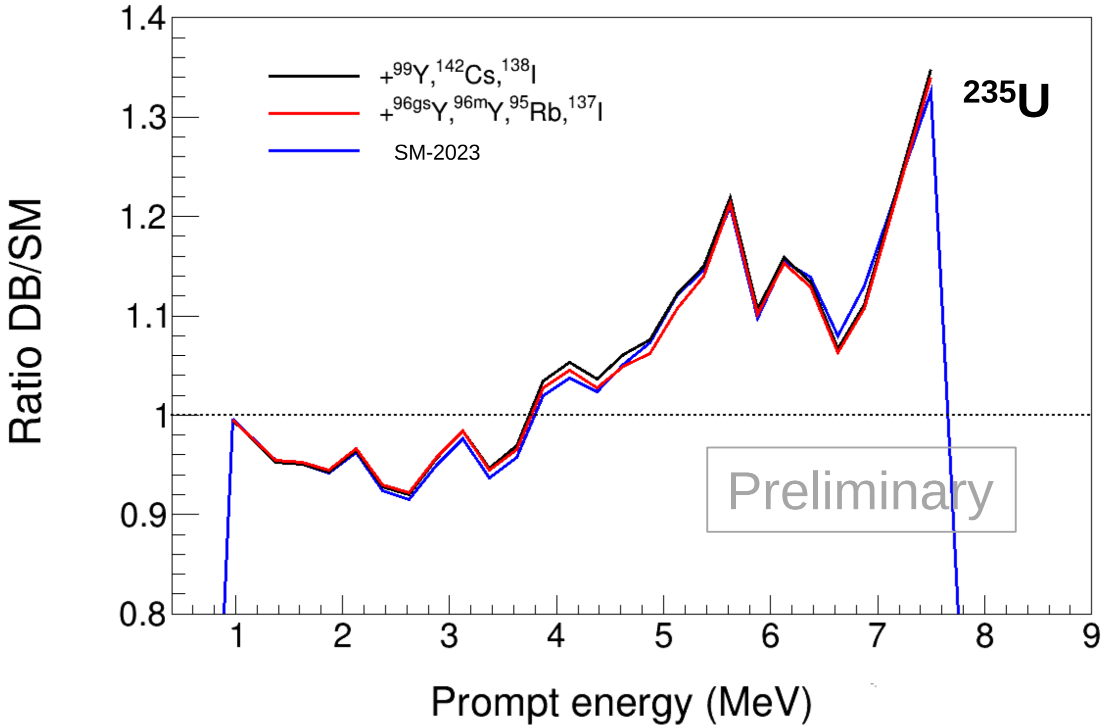


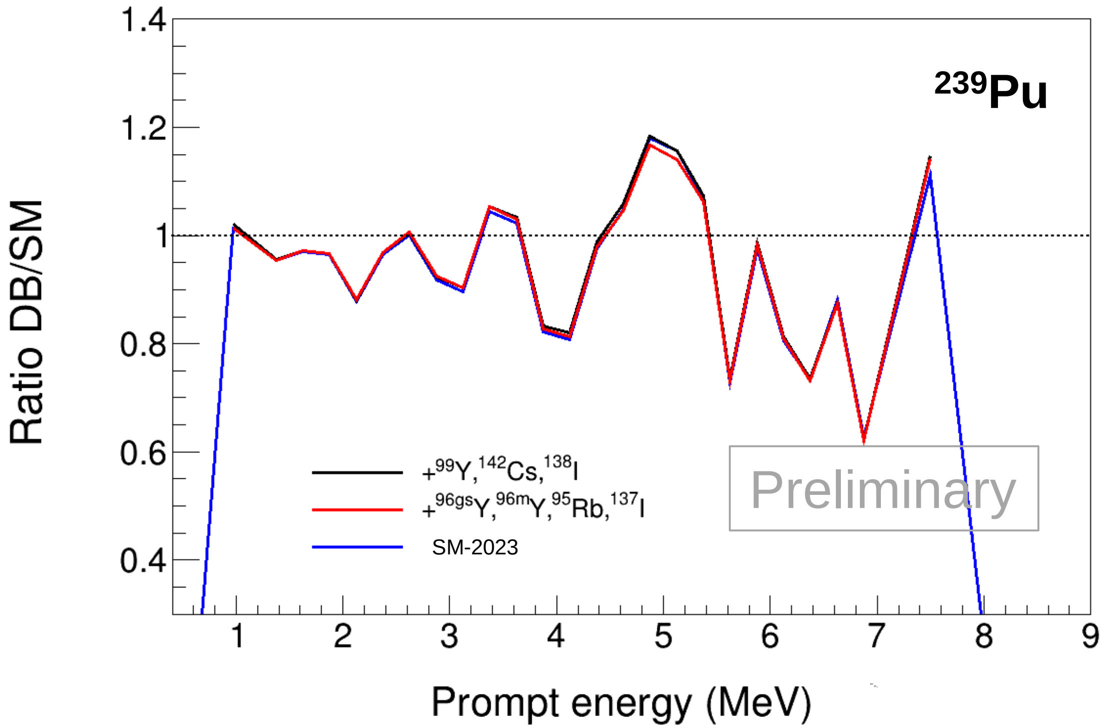


Decay	$\overline{E}$	DTAS [keV]	JEFF [keV]	ENDF [keV]
^{142}Cs	“	$1526.3^{+83}_{\neq 54}$	676.48	952.37
	—	$2535.0^{+25}_{\neq 39}$	2919(178)	2919(179)
^{99}Y	“	$1584^{+46}_{\neq 31}$	917	1006
	—	$2379^{+15}_{\neq 22}$	2949(146)	2931(208)
^{138}I	“	$2005^{+106}_{\neq 99}$	1325	1420
	—	$2475^{+64}_{\neq 33}$	2721(125)	3068(290)

PhD Thesis work:
Loïc Le Meur (Subatech, Nantes)
Publication in preparation

Impact as a Function of the Isotope ^{235}U or ^{239}Pu





- ❑ Larger impact in the global normalisation in the region E_{rec} = 2.5-4MeV in the case of ^{235}U
- ❑ Clear bump in ^{235}U spectrum slightly reduced taking into account the ^{95}Rb, ^{137}I, ^{96}Y, ^{96gs}Y nuclei.
- ❑ ^{239}Pu prompt spectrum less impacted in shape and flux than the ^{235}U spectrum (strong fluctuations in DB measurements)
- ❑ Small bump in the ^{239}Pu spectrum slightly affected as well by correcting the databases of these nuclei

Propagation of Yield Uncertainties

	DB (x10^{-43} cm^2/fission)	SM-2025
σ_f	5.84+/-0.07	5.93+/-0.13
σ_5	6.16+/-0.04(stat)+/-0.08(syst)+/-0.18(model)	6.22
σ_9	4.16+/-0.07(stat)+/-0.09(syst)+/-0.18(model)	4.34
$d\sigma_f/dF_{239}$	-1.96+/-0.11(stat)+/-0.07 (syst)	-1.83

Consistent wrt SM-2025 (1% deficit)

4.3% déficit wrt SM-2025

- Using the (improved) GEF covariance matrices of the yields and an analytical error propagation
- **Study of the dependence on beta decay uncertainties which are underestimated in nuclear BDD in many cases: assuming 4 uncertainties, all the same for all nuclei: 5, 10, 15, 20%**

Δ_{DD} = 5%	**Δ_{DD} = 10%**	**Δ_{DD} = 15%**	**Δ_{DD} = 20%**
$\Delta\sigma_f$ = +-1.00%	**$\Delta\sigma_f$ = +-1.33%**	**$\Delta\sigma_f$ = +-1.70%**	**$\Delta\sigma_f$ = +-2.2%**

- **Note that this calculation was performed a long time ago…**
  - Yields are very correlated
  - Final uncertainty is quite small, even when assuming 20% on all decay data

⇒ **On-Going work**

⇒ **Truth is some BDD should have less than 20% and some more (100%)**