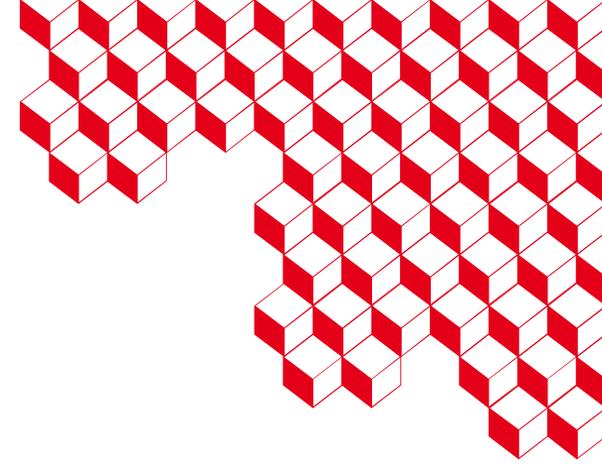




irfu



Results on $^{235}\text{U}(n_{\text{th}},f)$ isotopic fission yields using prompt and delayed gamma rays at the FIPPS spectrometer of the ILL

Thomas Materna

DPHN, Irfu, CEA Saclay

Collaboration

P. Herran, M. Ballu, A. Letourneau, D. Doré, L. Thulliez, IRFU, CEA, Université Paris-Saclay

C. Michelagnoli, Y.E. Kim, F. Kandzia, U. Köster, Institut Laue Langevin

O. Litaize, A. Chebboubi, CEA, DES, IRESNE, DER, Cadarache

Outline

- 1. Experimental campaign at FIPPS with a ^{235}U active target**
- 2. Prompt gamma data : motivations and first results on fission yields**
- 3. Delayed gamma data : motivations and first results**
- 4. Conclusions and Perspectives**



1 ■

**Experimental campaign at
FIPPS with a ^{235}U active
target**

FIPPS spectrometer at ILL



First experiment with an active target at FIPPS

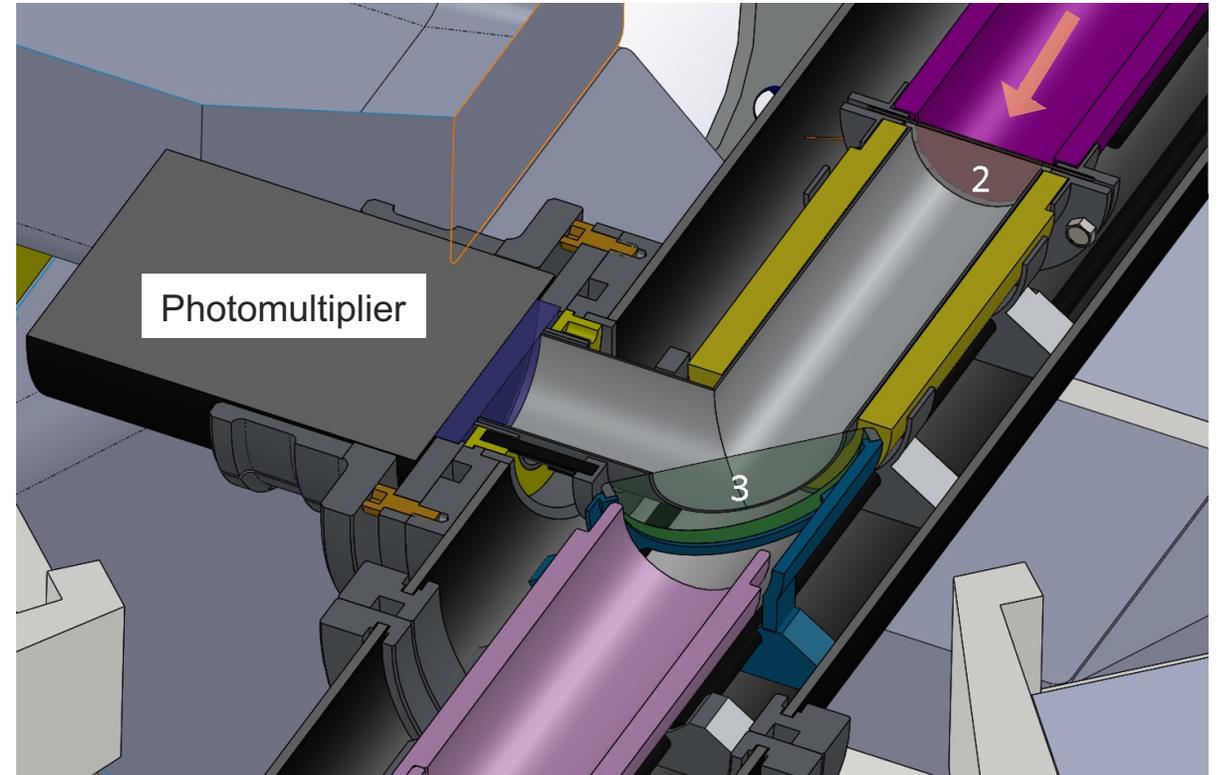
- Gamma-ray spectrometer made of 16 HPGe clover detectors
- with BGO shielding around IFIN HPGe detectors
- 10^8 neutrons/s/cm²
- Collimation : 1.5 cm diameter beam

^{235}U Active target



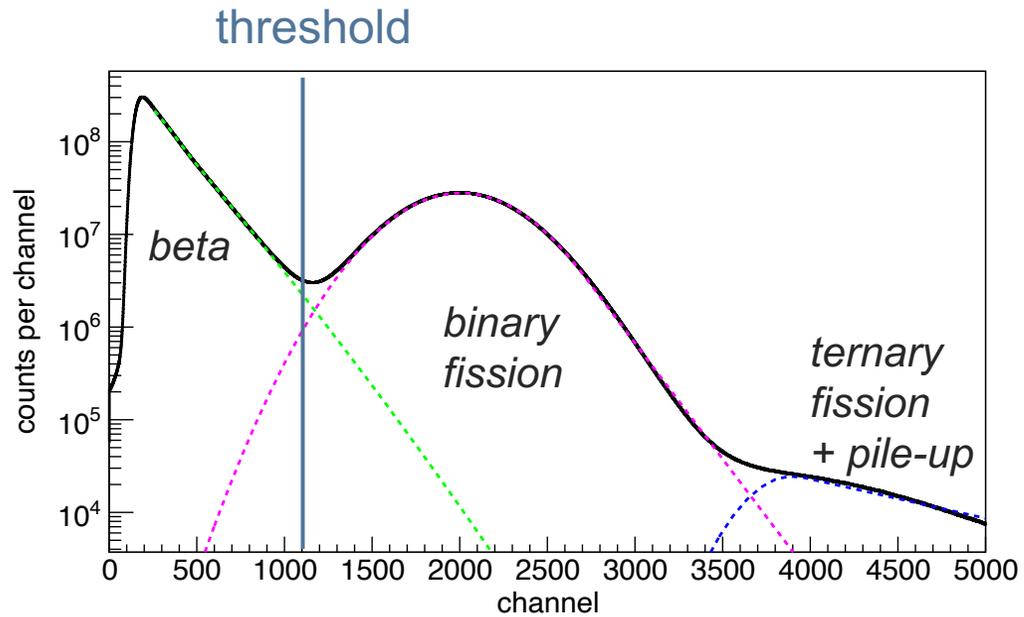
U-235 dissolved in a liquid scintillator
(deuterated toluene, naphthalene, PBBO, HDEHB)

Fission fragments stopped in liquid
Light signal used to tag fission events



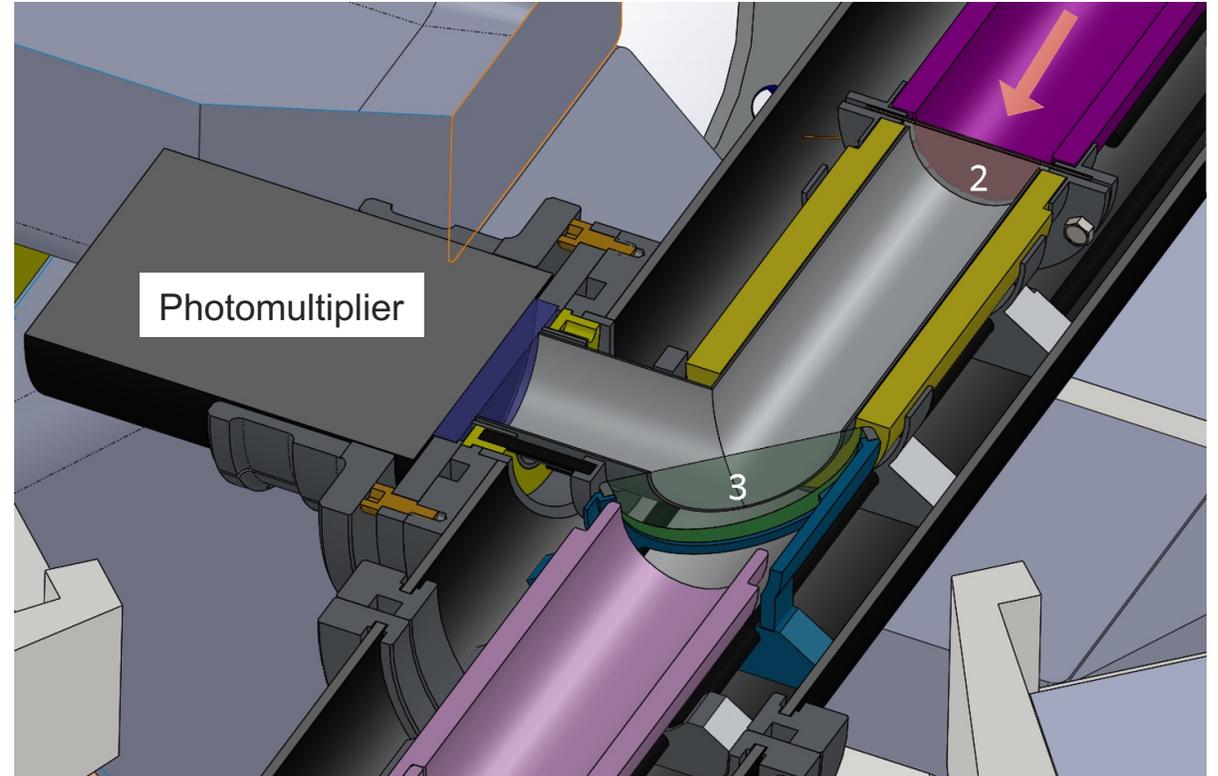
F. Kandzia et al. EPJA 2020

^{235}U Active target



2.44 10^{10} fission events

97.8 % of the events $>$ threshold are fission events

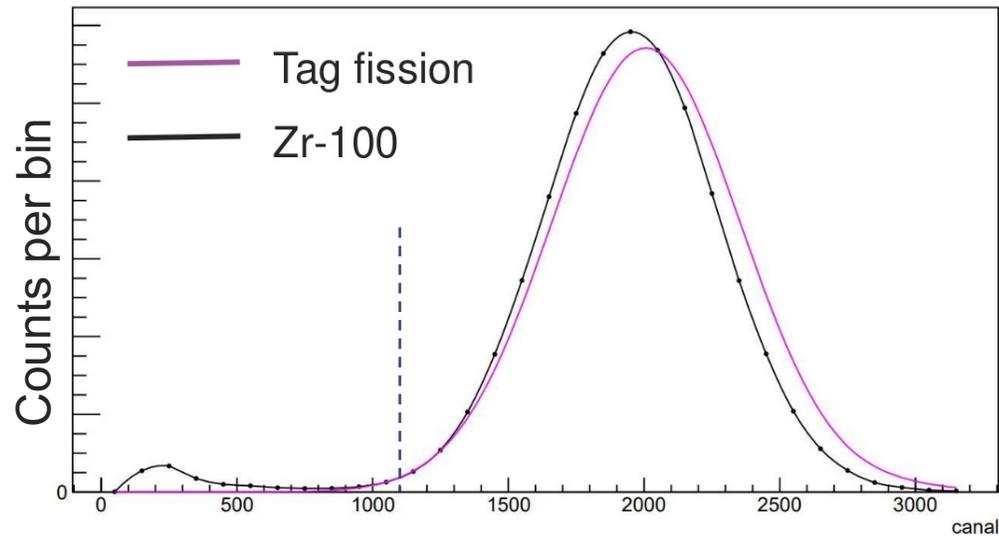


F. Kandzia et al. EPJA 2020

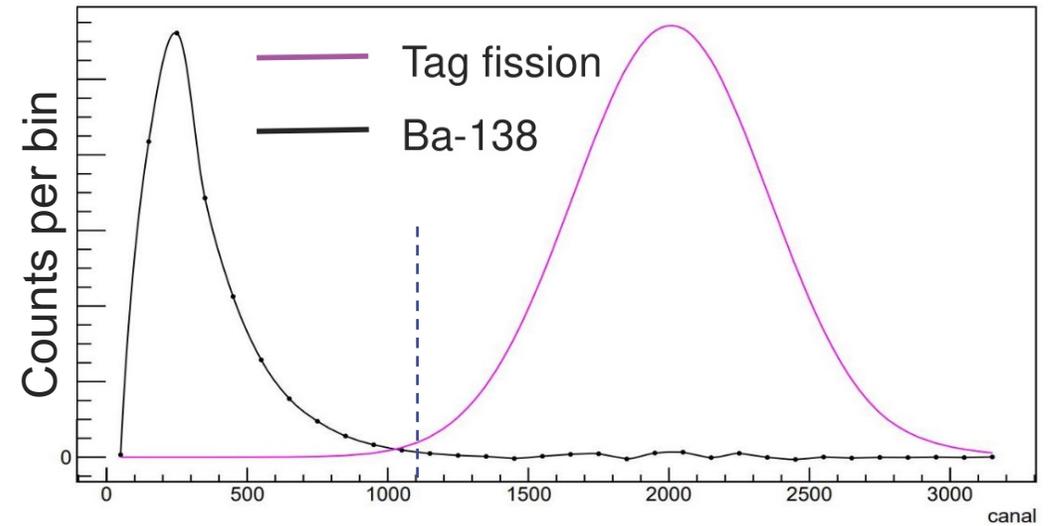
Data from the experimental campaign on FIPPS

- 39 days – 9095 runs of 5 minutes
- 2.44×10^{10} fission events
- Data from 60 (54) HPGe crystals (no addback) – BGO signals not used
- Gamma-ray Spectra, Coincidence $\gamma\gamma$ Matrices, $\gamma\gamma\gamma$ cubes
 - in coincidence with fission (fission tag > 1100) → “Prompt” data
 - in veto with fission (no fission tag or fission tag < 1100) → “Delayed” data
- Calibration : ^{152}Eu source + $^{27}\text{Al}(n,g)$ from target support

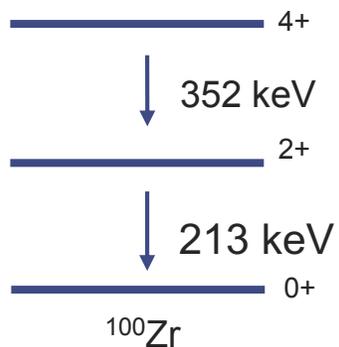
^{235}U Active target performances



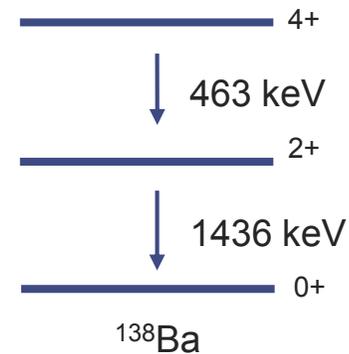
fission tag channel



fission tag channel



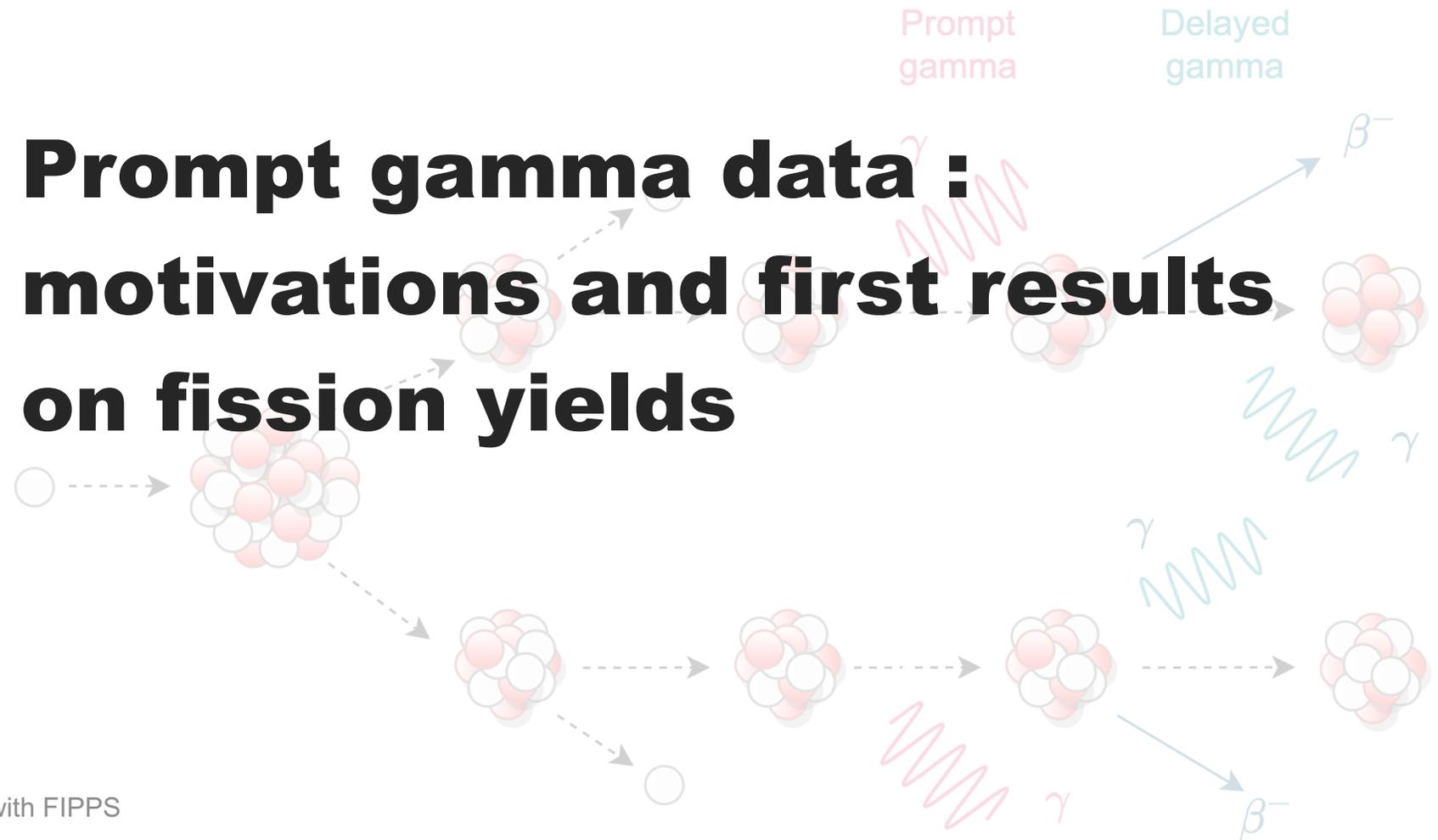
Mainly produced
by fission



Produced by beta-decay
of ^{138}Cs

2

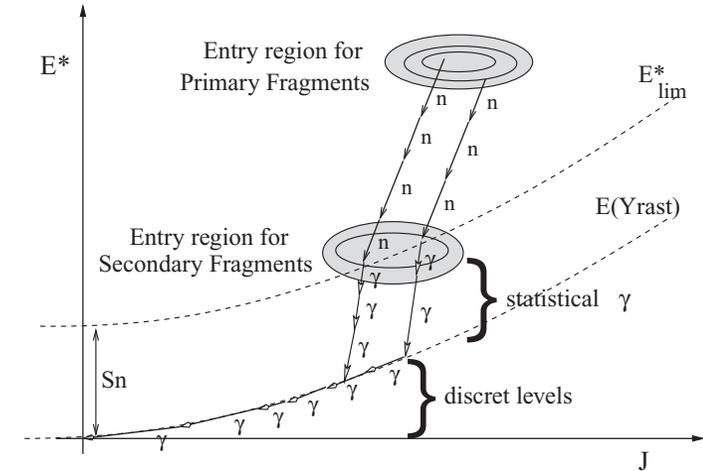
Prompt gamma data : motivations and first results on fission yields



Motivations for prompt gamma analysis

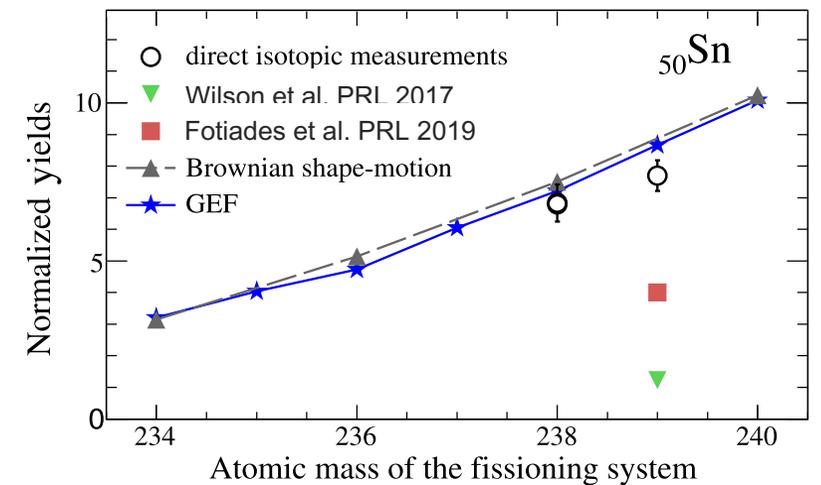
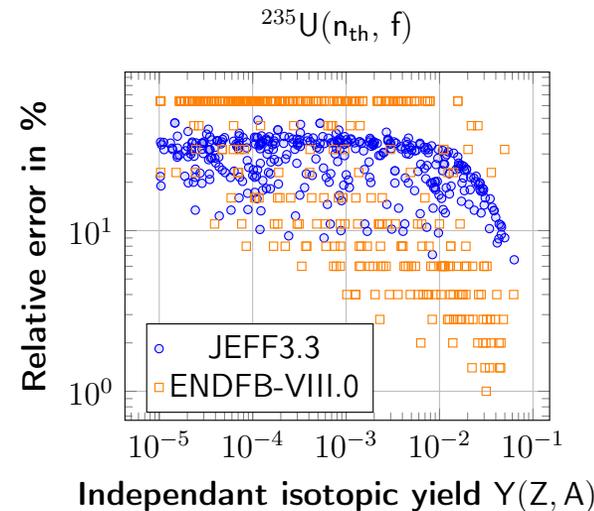
Study of the fission process via the cascade of prompt gamma-rays

- find the spin distribution of the fragments
- understand the sharing of the total excitation energy
- comparison to FF de-excitation code FIFRELIN



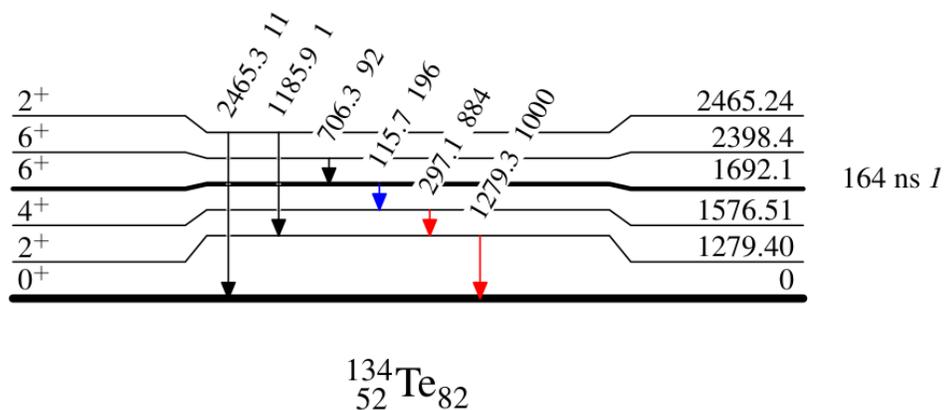
Evaluate the possibility of extracting absolute independent $Y(A,Z)$

- access to heavy fragments
- yield of ^{132}Sn



Ramos et al., PRL 123, 092503 (2019)

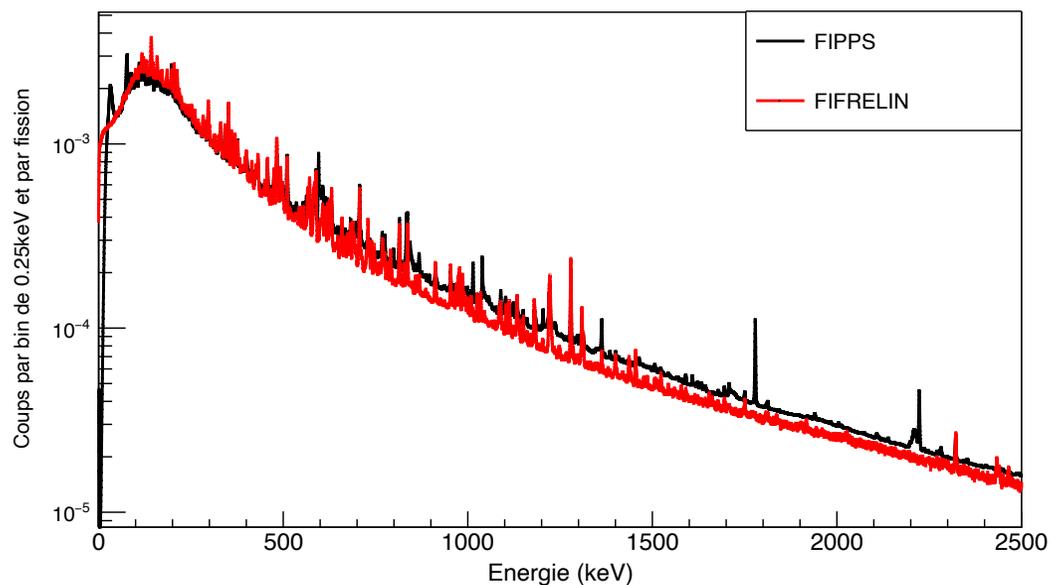
Method for extracting fission yields



$$Y = \frac{\sum N_{\gamma}(E_i)}{N_{\text{fissions}}} = \frac{1}{N_{\text{fissions}}} \left\{ \underbrace{N_{\gamma\gamma}(1279,297)}_{\text{from } \gamma\gamma \text{ matrix}} \times \frac{N_{\gamma}(1279)}{N_{\gamma}(297)} \right\} \left\{ 1 + \frac{N_{\gamma}(2465)}{N_{\gamma}(1279)} + \dots \right\}$$

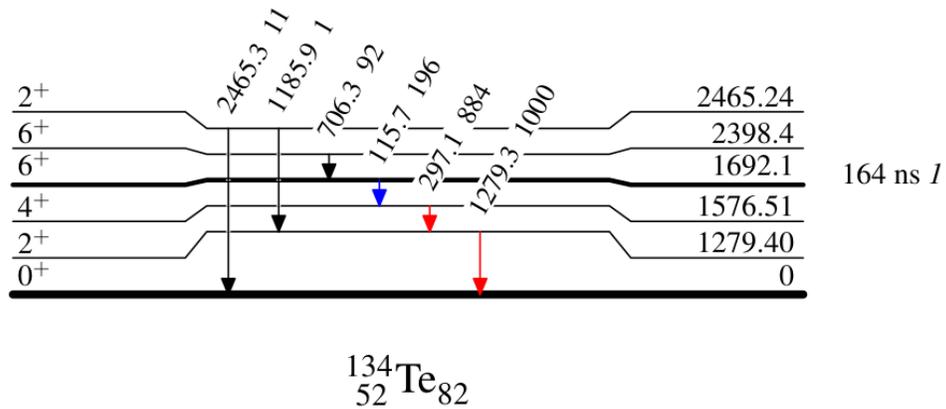
from $\gamma\gamma$ cube

Partial level scheme from ENSDF for $^{248}\text{Cm}(sf)$
with intensities from PRC 65, 017302



Prompt gamma-ray spectrum
measured with FIPPS vs
obtained with FIFRELIN + G4

Method for extracting fission yields

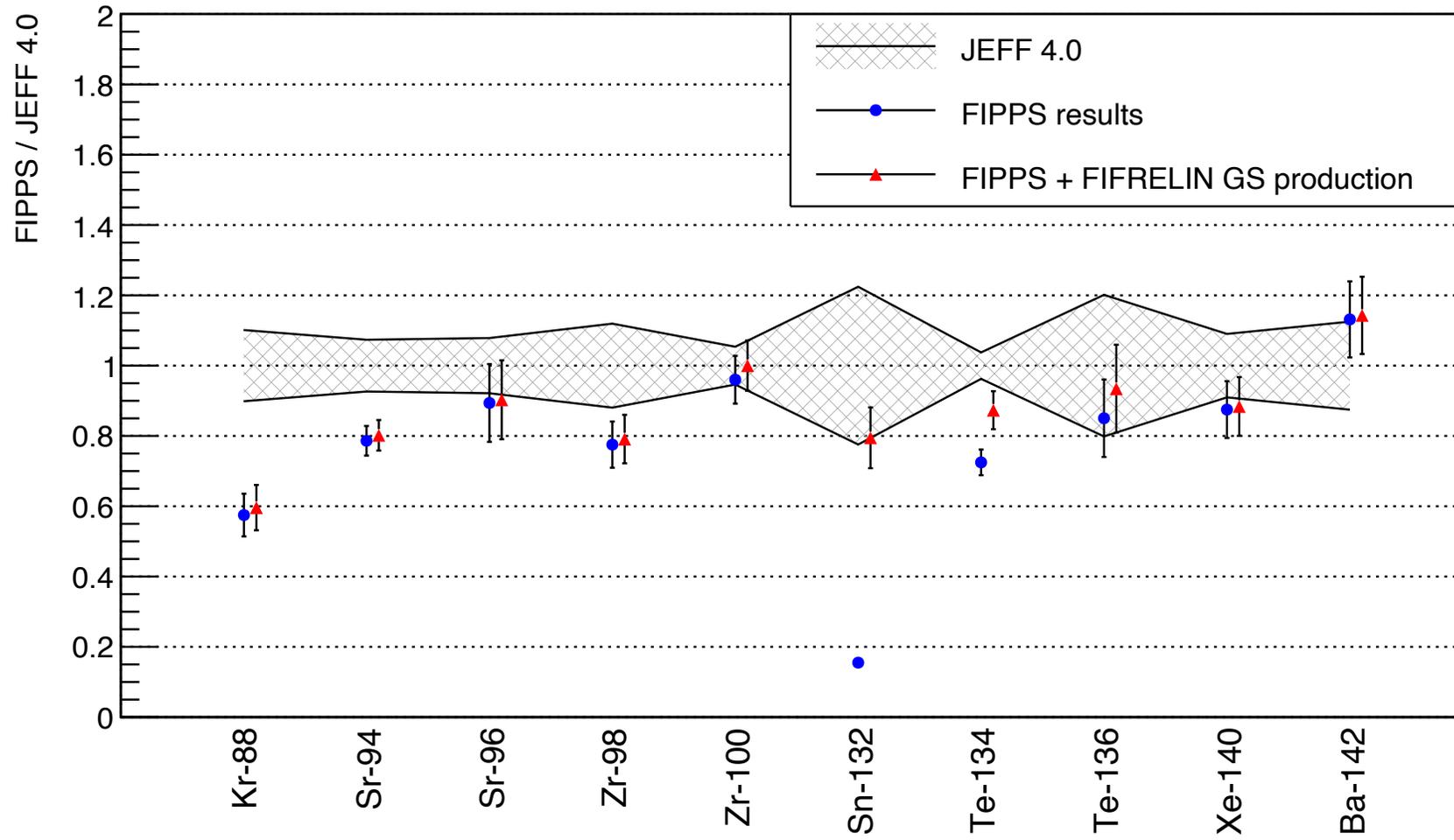


$$Y = \frac{\sum N_{\gamma}(E_i)}{N_{fissions}} = \frac{1}{N_{fissions}} \left\{ \underbrace{N_{\gamma\gamma}(1279,297)}_{\text{from } \gamma\gamma \text{ matrix}} \times \underbrace{\frac{N_{\gamma}(1279)}{N_{\gamma}(297)}}_{\text{from } \gamma\gamma\gamma \text{ cube}} \right\} \left\{ 1 + \frac{N_{\gamma}(2465)}{N_{\gamma}(1279)} + \dots \right\}$$

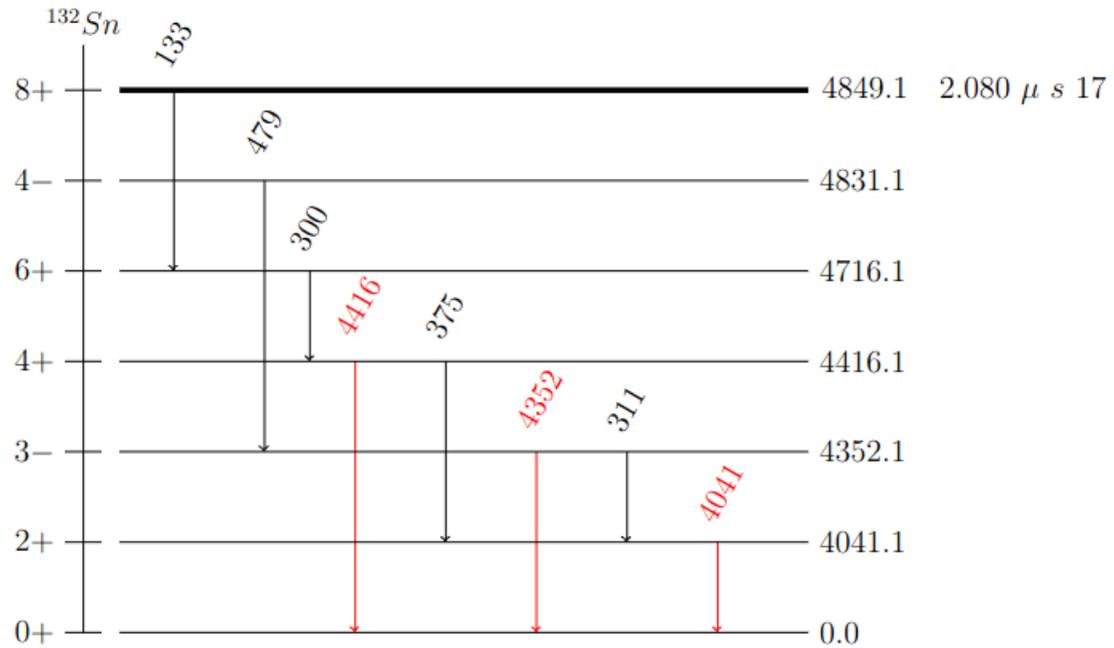
- Hypothesis : the cascade in one fragment does not depend on the other fragment
- Absolute efficiency of the spectrometer : $^{152}\text{Eu} + ^{27}\text{Al}(n,g)$
- **Corrections for**
 - dead time : 2.3 %
 - internal conversion : BRICC
 - **summing effect : FIFRELIN + GEANT4 : 13 – 18 %**
 - possible contaminations of the peaks : FIFRELIN
 - direct production of the ground state : FIFRELIN
 - isomeric state (if lifetime > coincidence time window)
- Main difficulty : fitting precisely the peaks !

Result for independent $Y(A,Z)$

Pierre Herran PhD result



^{132}Sn

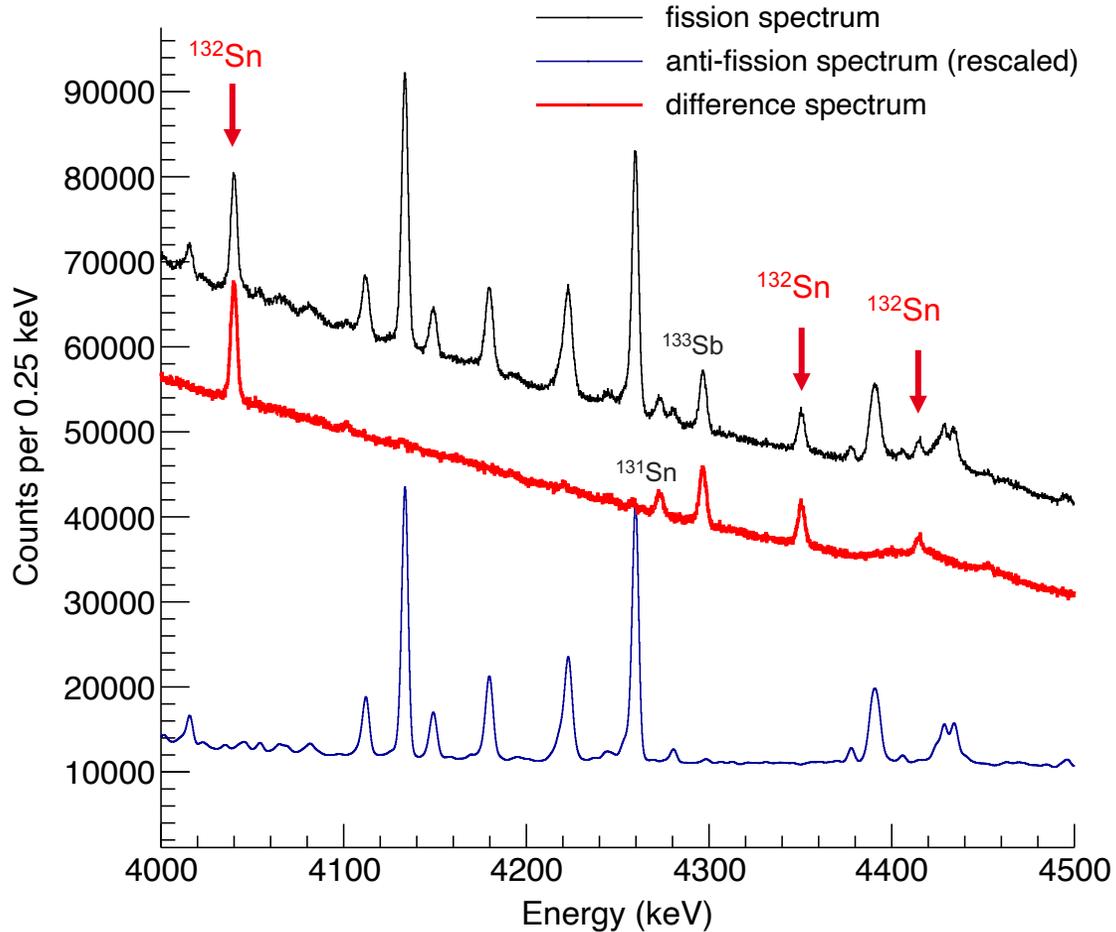


$$Y = \frac{N_{\gamma}(4041) + N_{\gamma}(4416) + N_{\gamma}(4352)}{N_{fissions}}$$

¹³²Sn



Pierre Herran PhD result



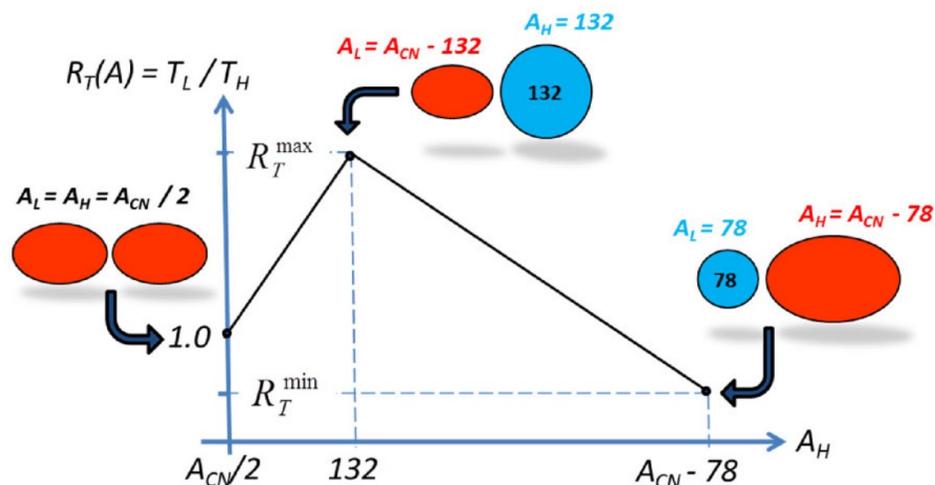
$$Y = \frac{N_{\gamma}(4041) + N_{\gamma}(4416) + N_{\gamma}(4352)}{N_{fissions}}$$

$$Y = 0.107 (5) \% \text{ with FIPPS}$$

~ 5 - 7 times smaller
than ENDF/B-VIII : $Y = 0.59 (2) \%$
or JEFF 4.0 : $Y = 0.73 (16) \%$

^{132}Sn

Pierre Herran PhD result



$$Y = \frac{N_\gamma(4041) + N_\gamma(4416) + N_\gamma(4352)}{N_{fissions}}$$

$$Y = 0.107 (5) \% \text{ with FIPPS}$$

~ 5 - 7 times smaller

than ENDF/B-VIII : $Y = 0.59 (2) \%$

or JEFF 4.0 : $Y = 0.73 (16) \%$

Most of the excitation energy goes to the fission partner of ^{132}Sn because ^{132}Sn is doubly magic

and there is no excited level below 4 MeV in ^{132}Sn

→ ^{132}Sn produced mostly in its ground state at fission

FIFRELIN simulation (CGCM + BSFGM + EGLO)

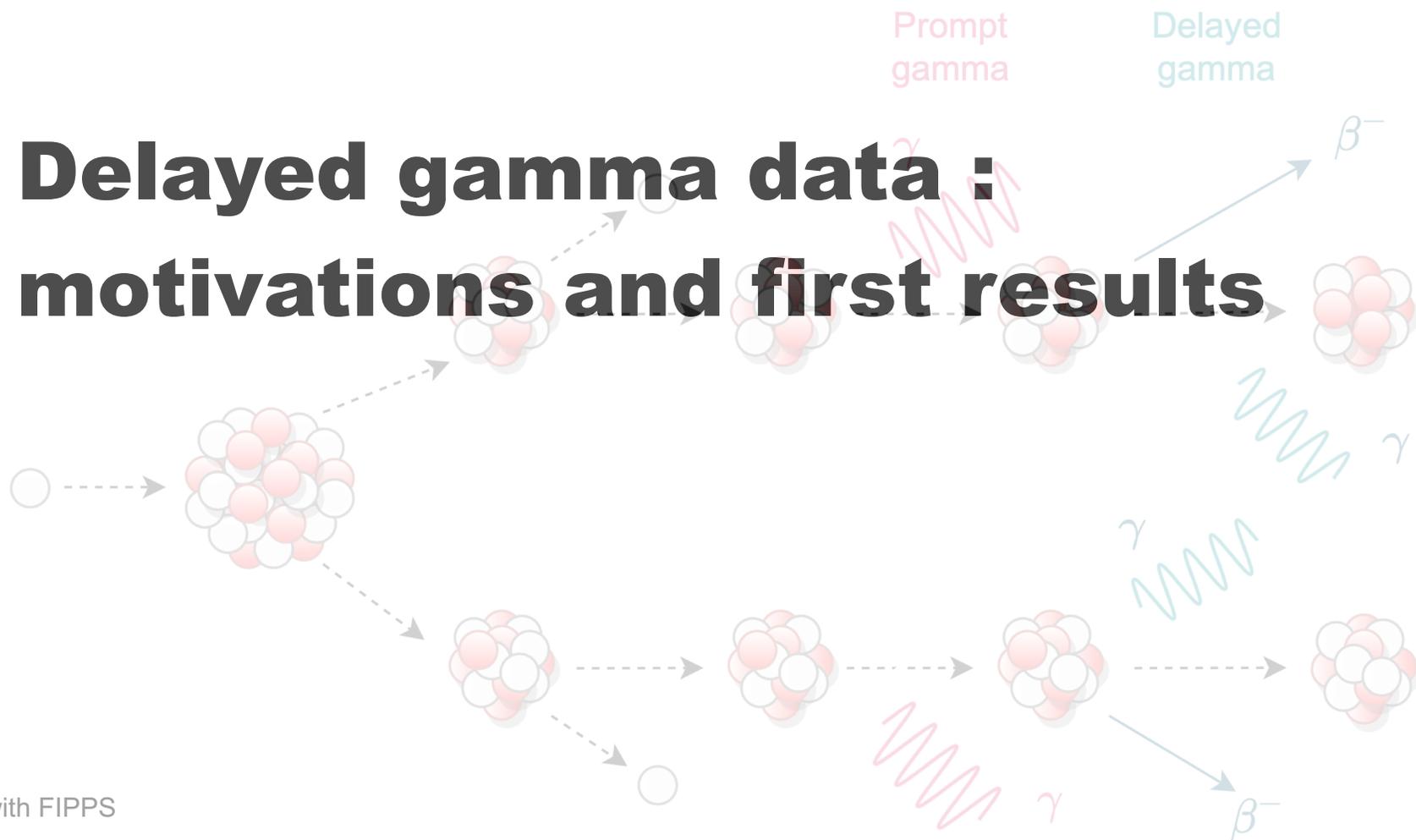
66 % of the GS directly populated by fission

14 % of the GS populated directly after neutron emission

-> 80 % with no emission of gamma

3.

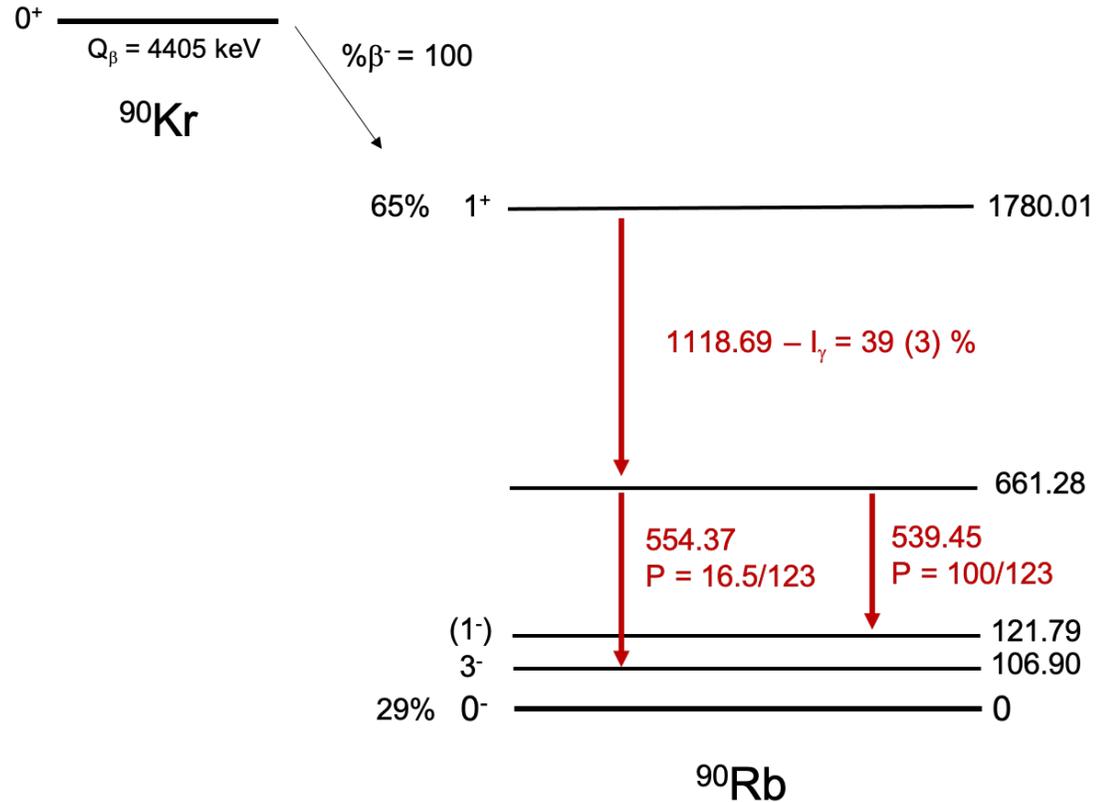
Delayed gamma data : motivations and first results



Motivations

- Context of the reactor antineutrino anomaly
- Detection of anomalies in the beta decay intensities or in fission yields
- Test of a phenomenological model of the beta strength function able to correct Pandemonium effect

Method on ^{90}Kr decay



Expected $\gamma\gamma$ coincidences per fission

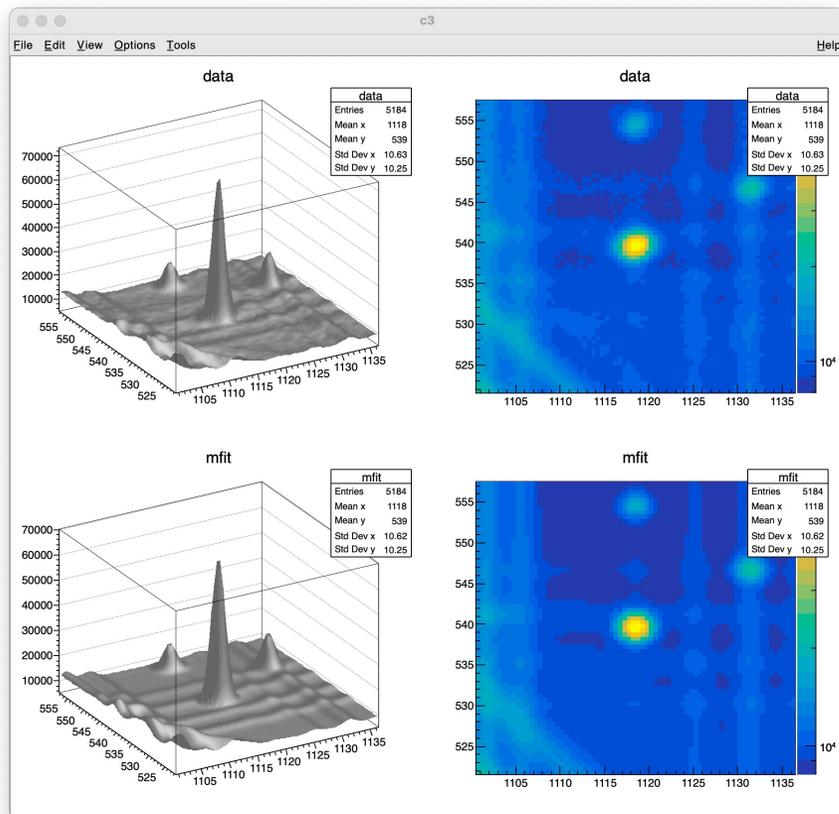
$$= Y_{\text{cum}}(^{90}\text{Kr}) \cdot I_\gamma(E_1) \cdot P_\gamma(E_2)$$

$$= 0.0472 \cdot 0.39 \cdot 100/123$$

$$= 0.0149 (12)$$

Method on ^{90}Kr decay

Data



2D fit

Expected $\gamma\gamma$ coincidences per fission

$$\begin{aligned} &= Y_{\text{cum}}(^{90}\text{Kr}) \cdot I_{\gamma}(E_1) \cdot P_{\gamma}(E_2) \\ &= 0.0472 \cdot 0.39 \cdot 100/123 \\ &= 0.0149 (12) \end{aligned}$$

Measured $\gamma\gamma$ coincidences per fission

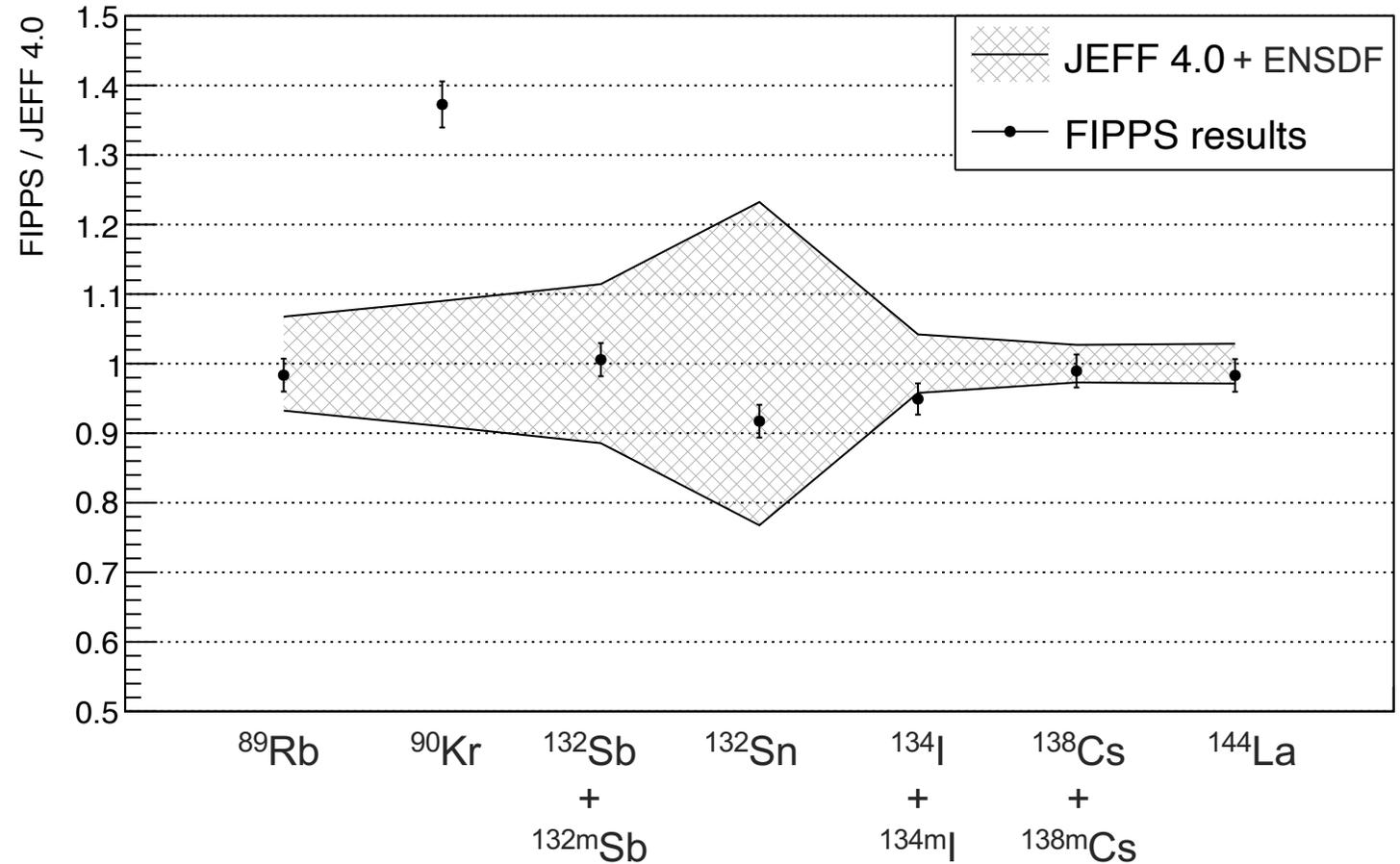
$$\begin{aligned} &= N_{\gamma\gamma}(E_1, E_2) / N_{\text{fissions}} \\ &= 0.0210 (5) \end{aligned}$$

$$\rightarrow \text{Ratio } \frac{\text{measured}}{\text{expected}} = 1.4$$

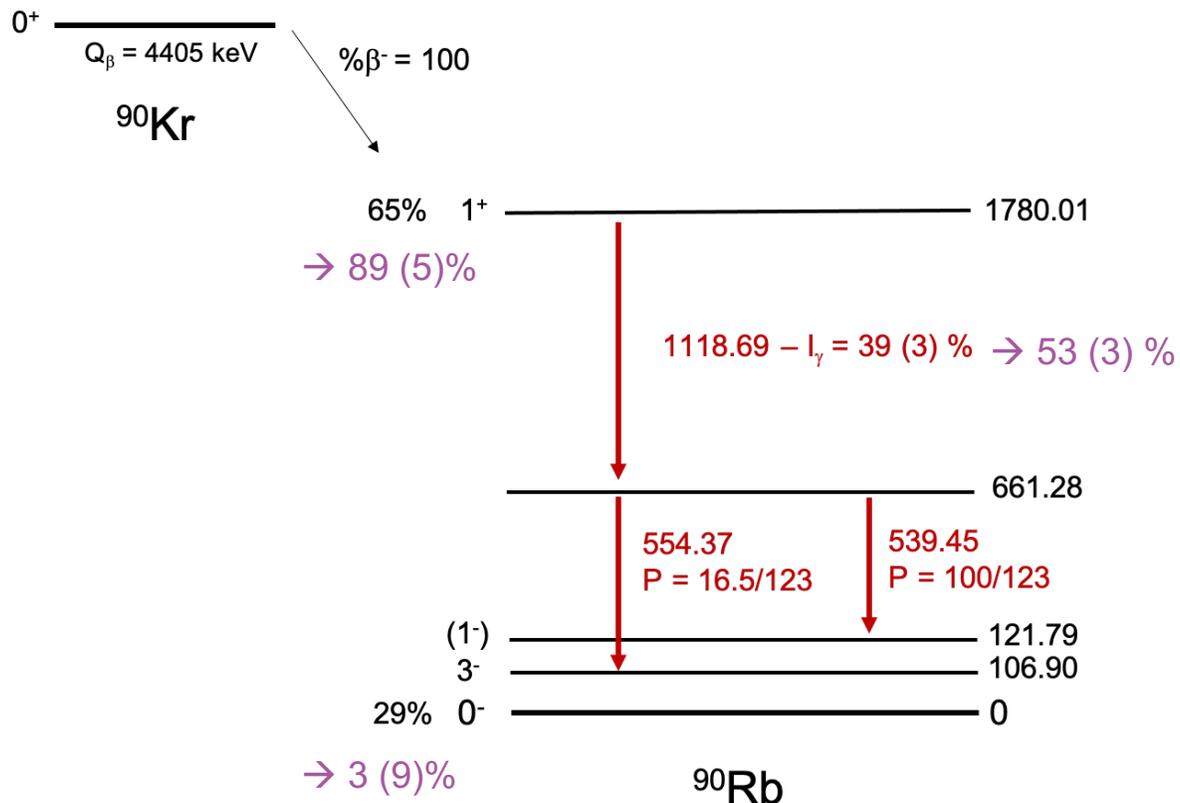
Delayed gamma-ray results

Mattéo Ballu PhD results

$$\frac{N_{\gamma\gamma}(E_1, E_2) / N_{\text{fissions}}}{Y_{\text{cum}} \cdot I_{\gamma}(E_1) \cdot P_{\gamma}(E_2)}$$



Result for ^{90}Kr decay



Expected $\gamma\gamma$ coincidences per fission

$$= Y_{\text{cum}}(^{90}\text{Kr}) \cdot I_\gamma(E_1) \cdot P_\gamma(E_2)$$

$$= 0.0484 \cdot 0.39 \cdot 100/123$$

$$= 0.0153 (14)$$

Measured $\gamma\gamma$ coincidences per fission

$$= N_{\gamma\gamma}(E_1, E_2) / N_{\text{fissions}}$$

$$= 0.0210 (5)$$

$$\rightarrow \text{Ratio } \frac{\text{measured}}{\text{expected}} = 1.4 (1)$$

\rightarrow GS feeding $\simeq 3 (9)\%$

Compatible with MTAS measurement at HRIBF by A. Fijałkowska et al., PRL 119,052503 (2017) found GS feeding of 7(1) % instead of 29(4) %



4. **Conclusions and Perspectives**

Conclusions & Perspectives

Absolute Independent Fission Yields with prompt gamma

- Possible but not applicable for all the nuclei
- Many corrections

Sn-132 mostly produced at ground state in agreement to FIFRELIN assumptions for the sharing of excitation energy

Delayed gamma-ray coincidences are promising to find anomalies in the cumulative fission yields or delayed gamma intensities

- Need cleaner data : another active target with no sapphire, no electronic problems
- Automate the analysis : ML methods for 2D fitting

Collaboration

DPhN, Irfu, DRF, CEA-Saclay, France

T. Materna, A. Letourneau, D. Doré, L. Thulliez,
P. Herran (PhD), M. Ballu (PhD)

Institut Laue Langevin, Grenoble, France

C. Michelagnoli, Y.E. Kim, F. Kandzia, U. Köster,

SPRC, DER, Iresne, DES, CEA-Cadarache, France

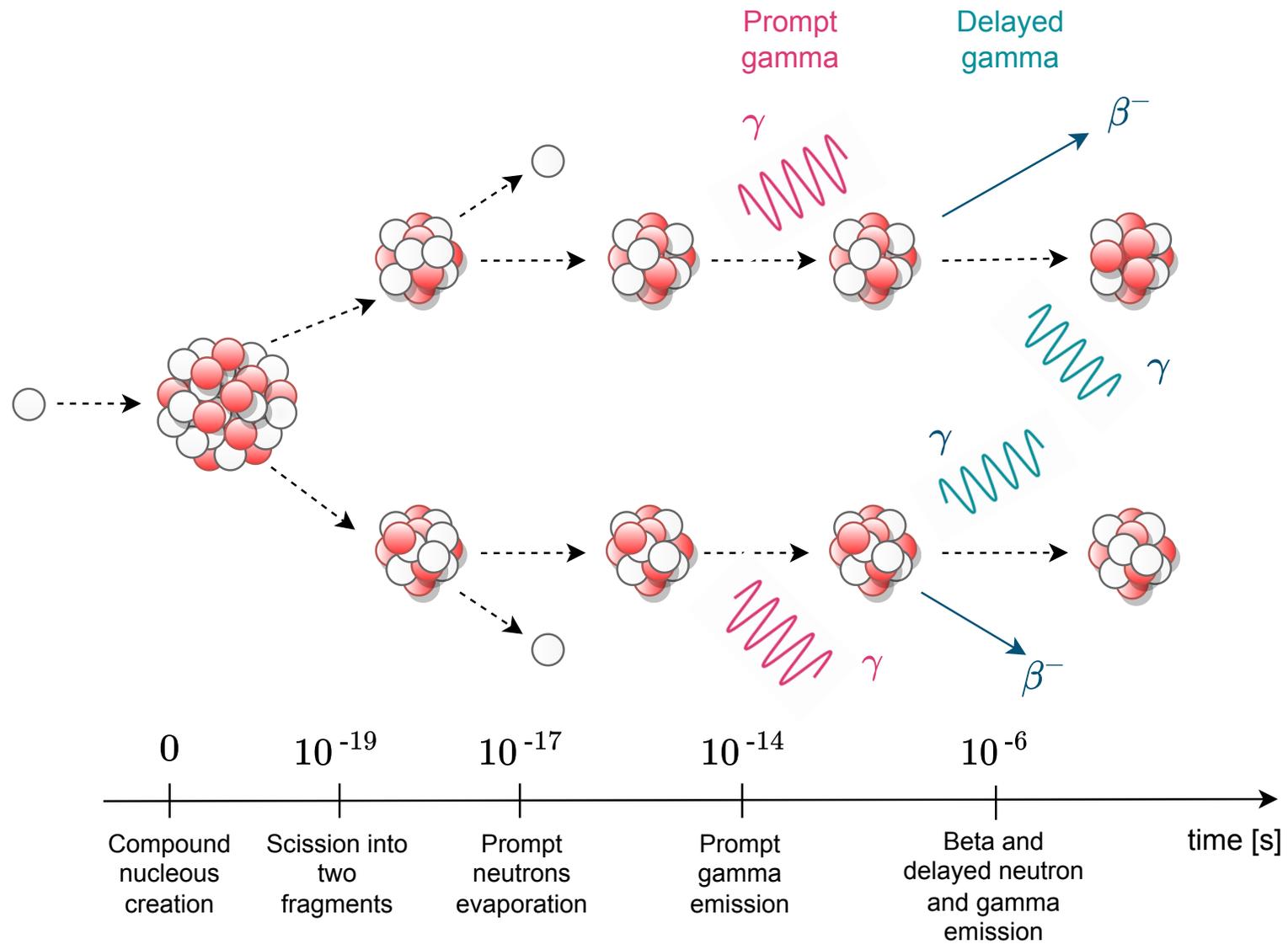
O. Litaize, A. Chebboubi

+ CEA-DAM, IP2I Lyon, IFIN-HH, Univ INFN Milan, PAN Cracovie, Univ. Warsaw

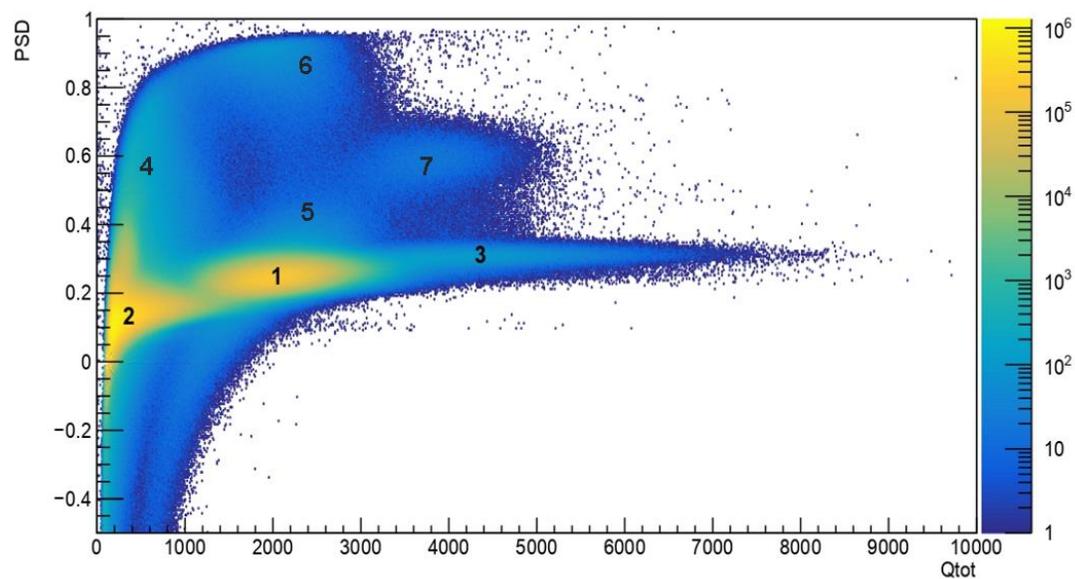




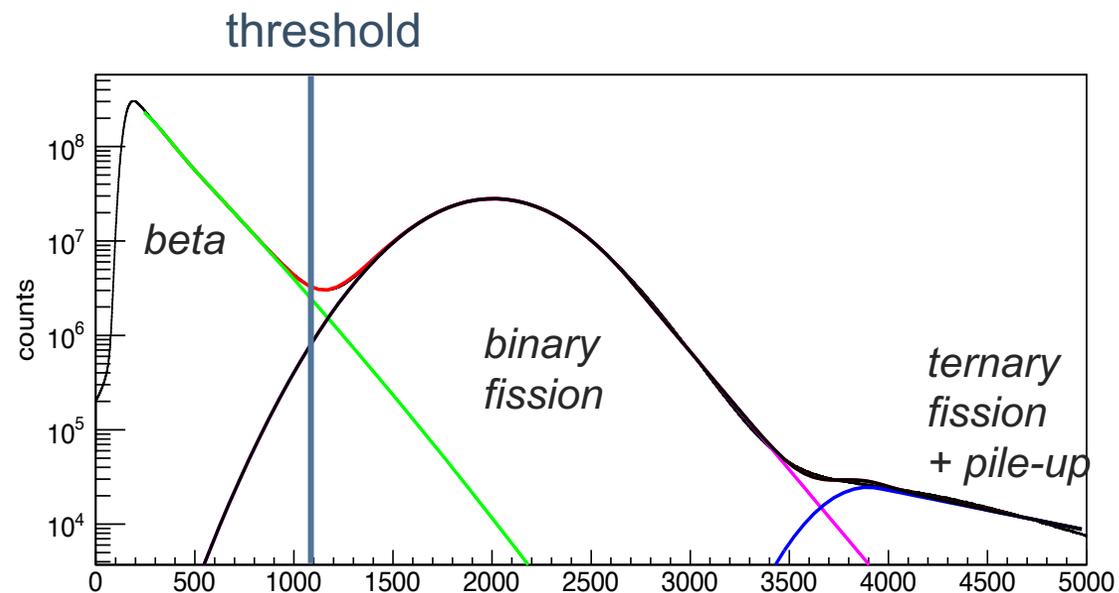
Additional slides



^{235}U Active target



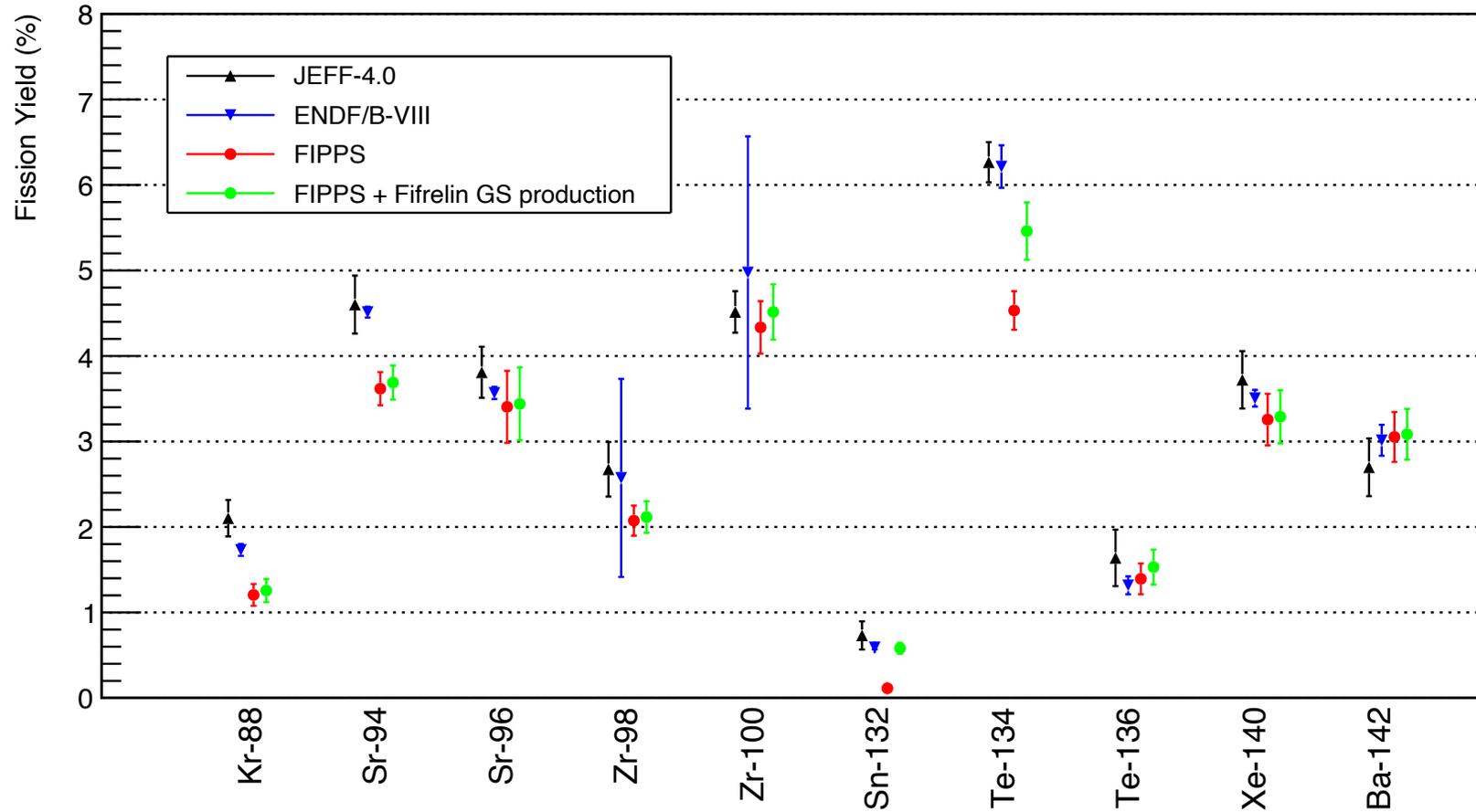
- (1) binary fission, (2) beta, (3) ternary fission
- (4) $\beta\beta$ pile-up (5,6) fission- β pile-up
- (7) fission-fission pile-up



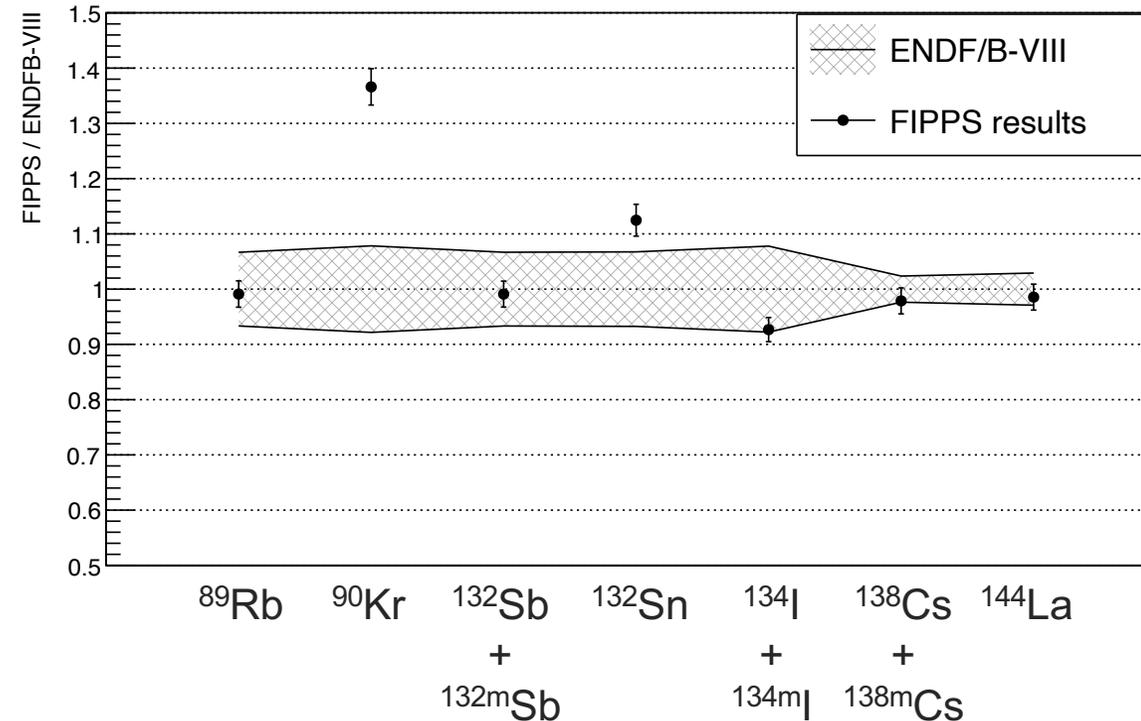
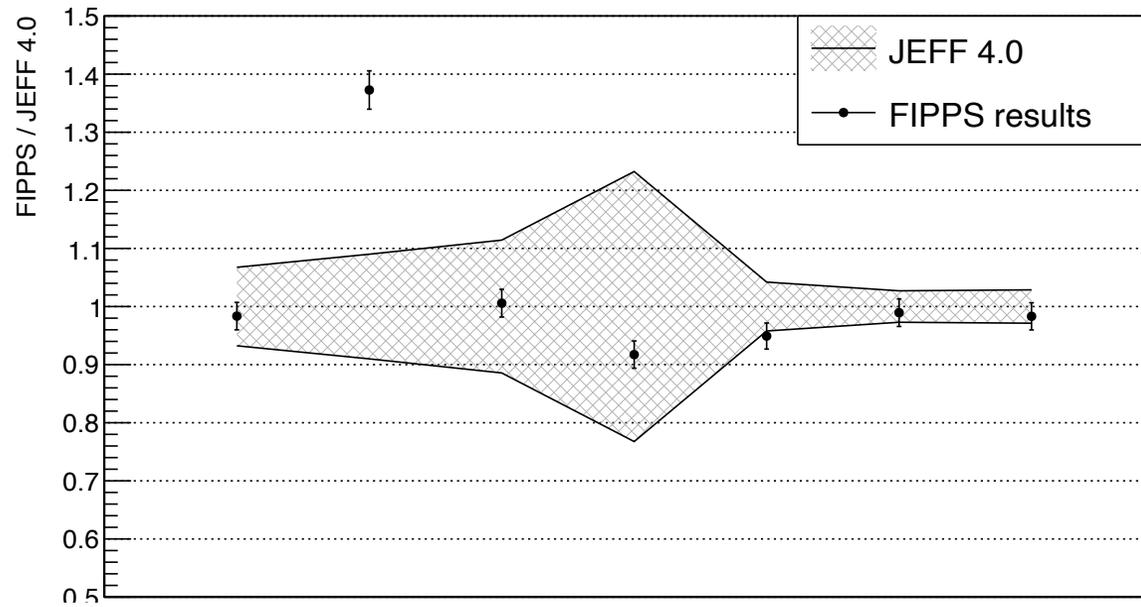
2.44 10^{10} fission events

97.8 % of the events $>$ threshold are fission events

Result for independent $Y(A,Z)$



Delayed gamma-ray results



$$\frac{N_{\gamma\gamma}(E_1, E_2) / N_{\text{fissions}}}{Y_{\text{cum}} \cdot I_{\gamma}(E_1) \cdot P_{\gamma}(E_2)}$$

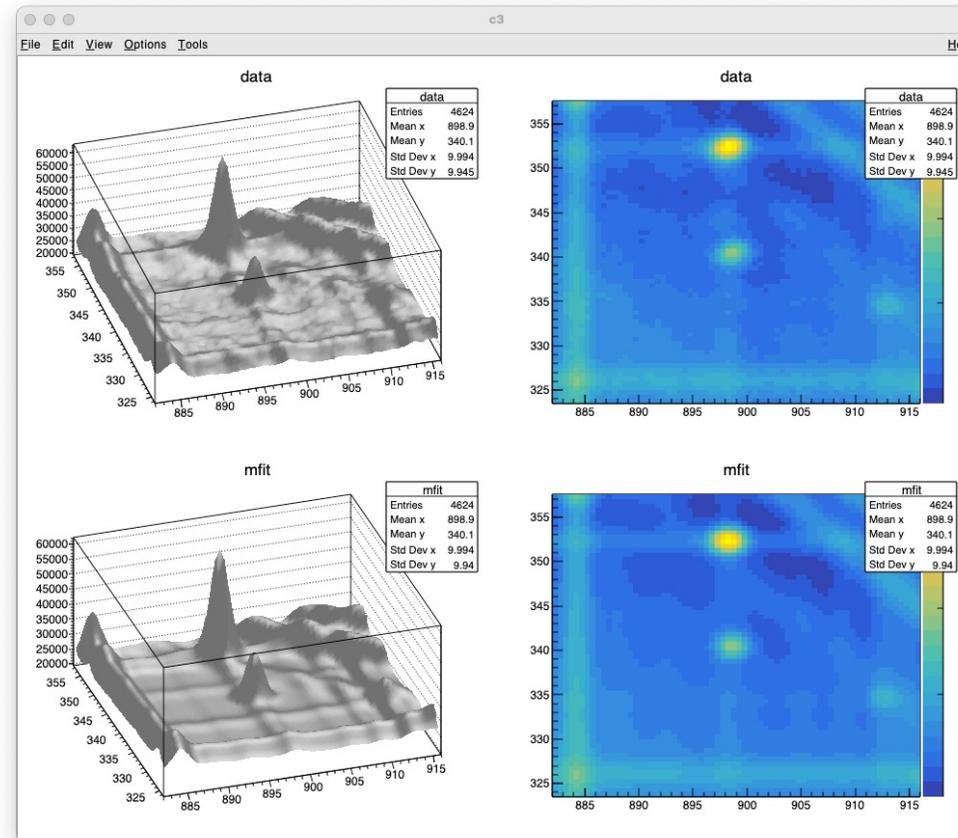
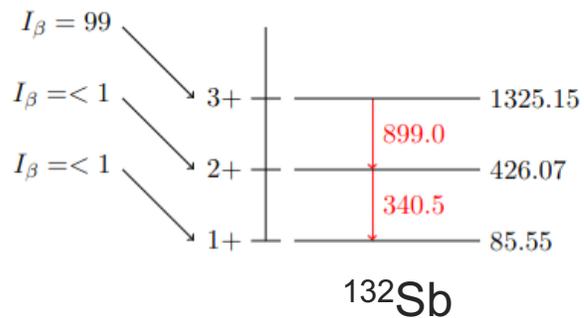
$$Y_{\text{cum}} \cdot I_{\gamma}(E_1) \cdot P_{\gamma}(E_2)$$

Results for ^{132}Sn cumulative yield

$$Y_{\text{cum}}(^{132}\text{Sn}) = Y(^{132}\text{Sn}) + Y_{\text{cum}}(^{132}\text{In})$$

$$= 0.999 Y(^{132}\text{Sn})$$

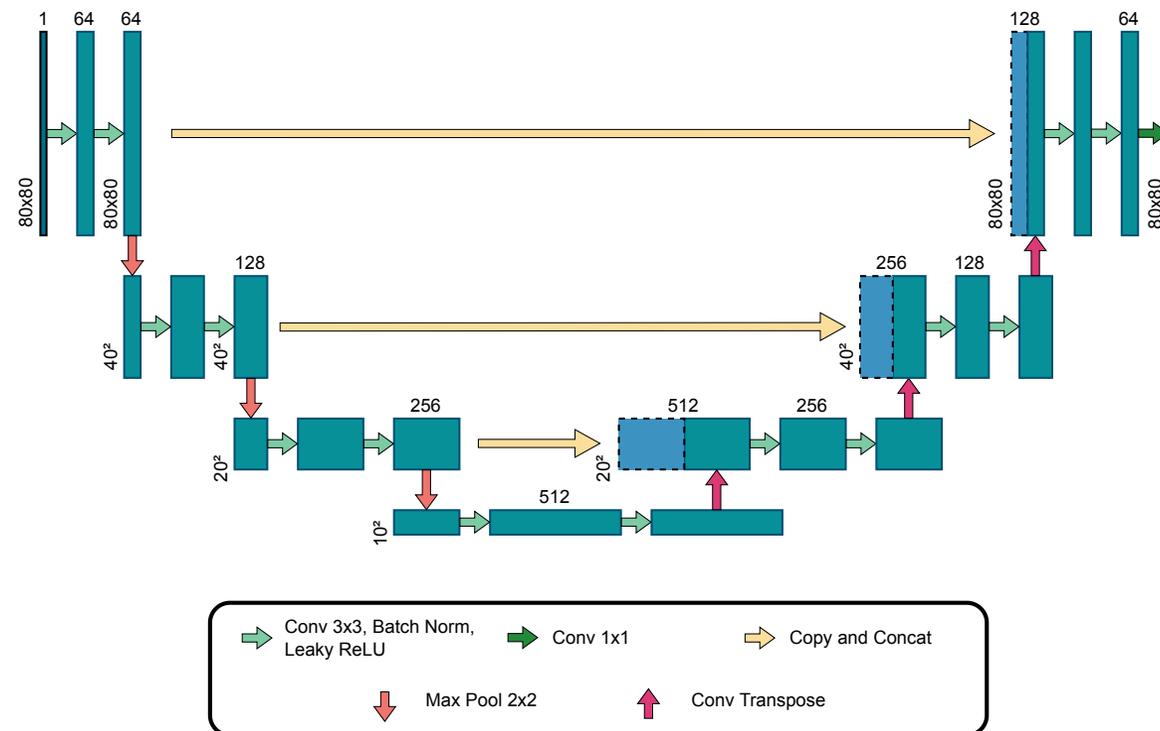
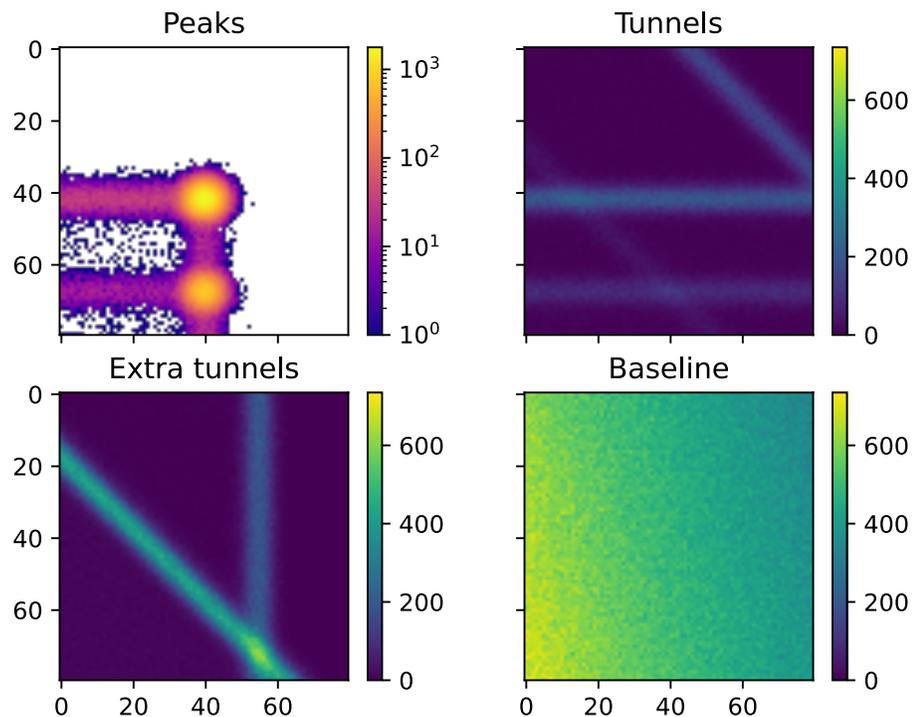
^{132}Sn



ML method - Motivations

- Classical method of fitting 2D and 3D γ -ray peaks is not satisfactory (gating, background gating, subtractions, 1D fitting)
- Fitting peaks in 2D is better but time consuming and requires initial values
- Find a way to automatize the analysis or help fitting
→ Machine Learning

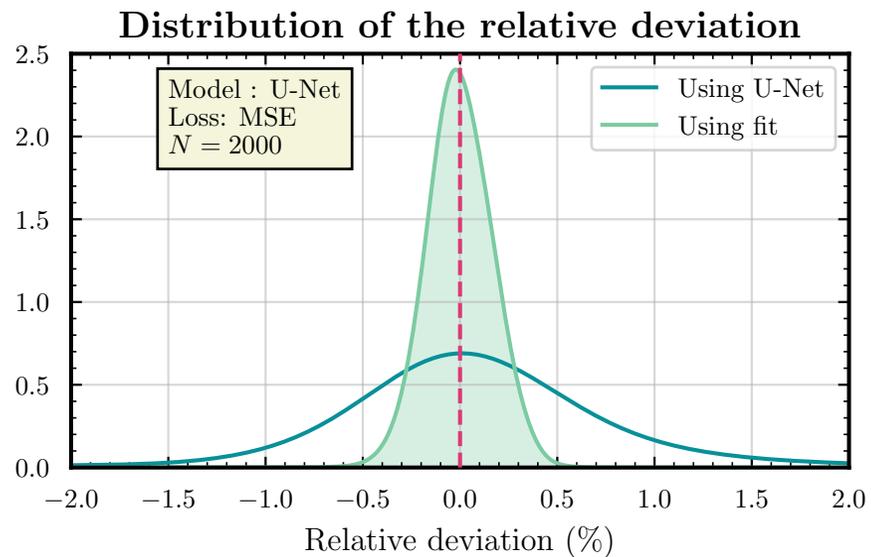
ML method - First tests



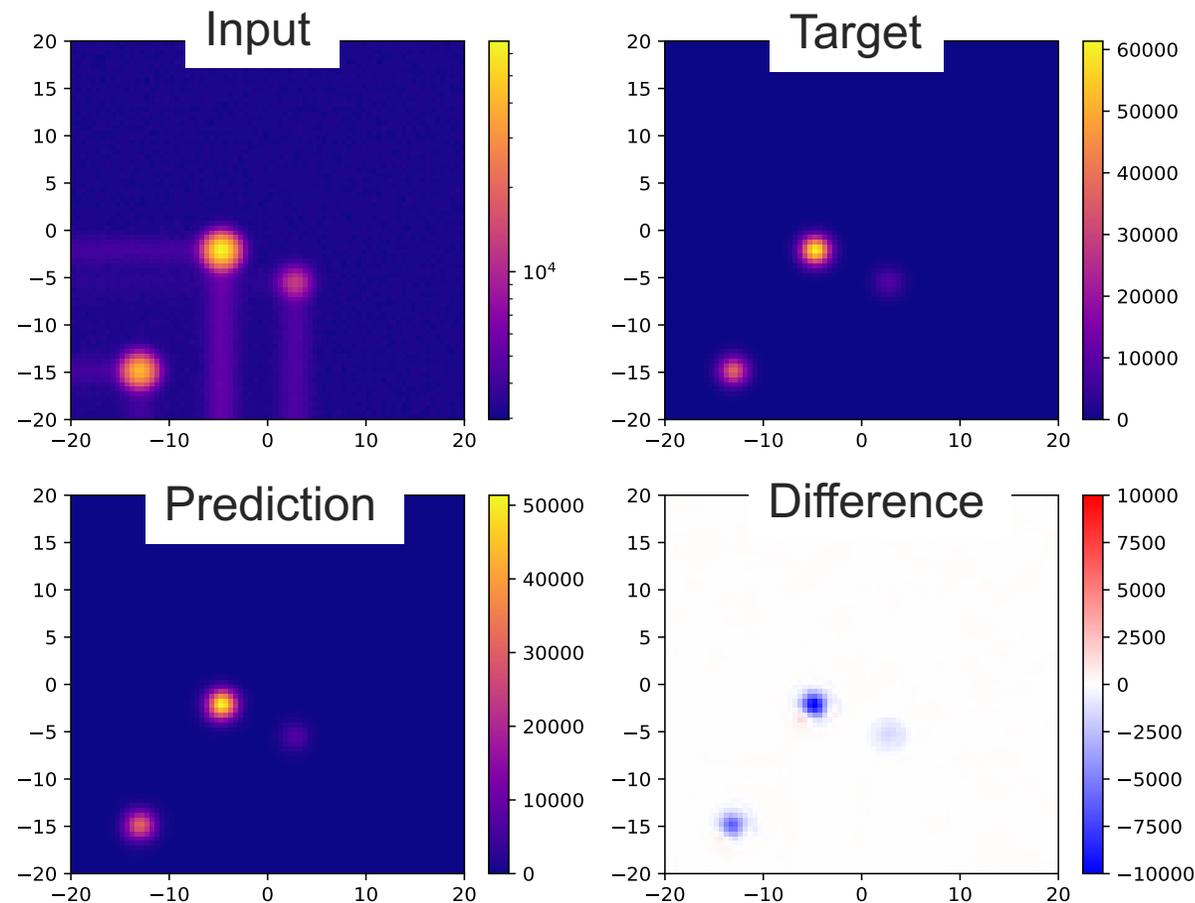
Production of 1 million synthetic 2D histograms (40 x 40 keV²) for training

Convolutional Neural Network (UNET)

ML method - First tests

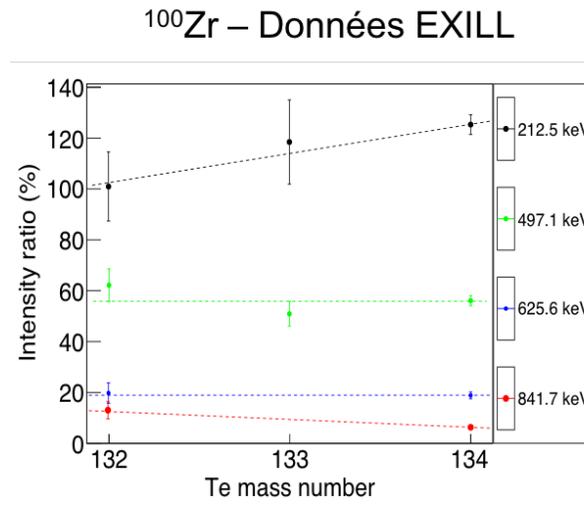
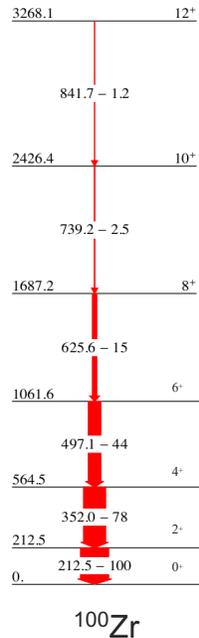


First results on 2D histograms with a single peak



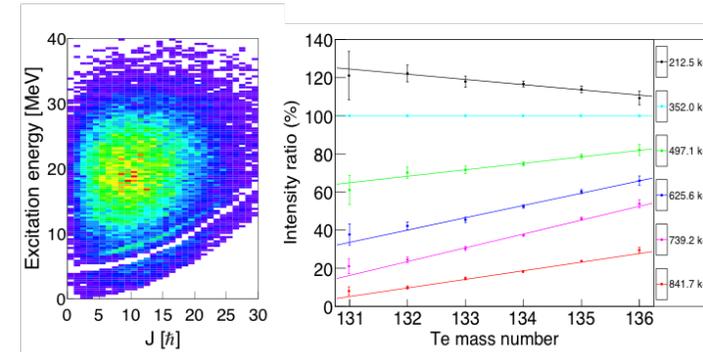
First results on 2D histograms with many peaks

Dependence of the main cascade with the fission partner - EXILL results

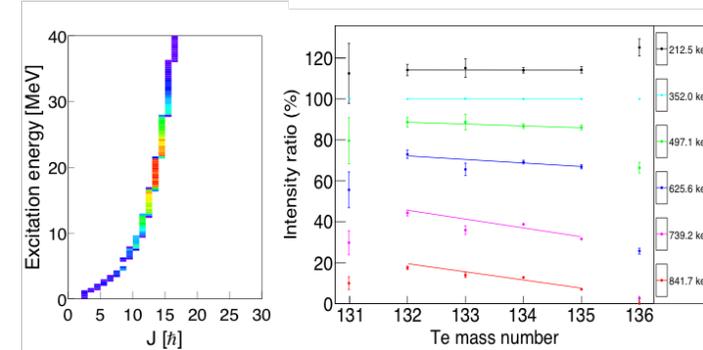


There is no visible strong dependence of the cascade with the fission partner.

^{100}Zr - SIMU FIFRELIN - MODELE CONSTANT

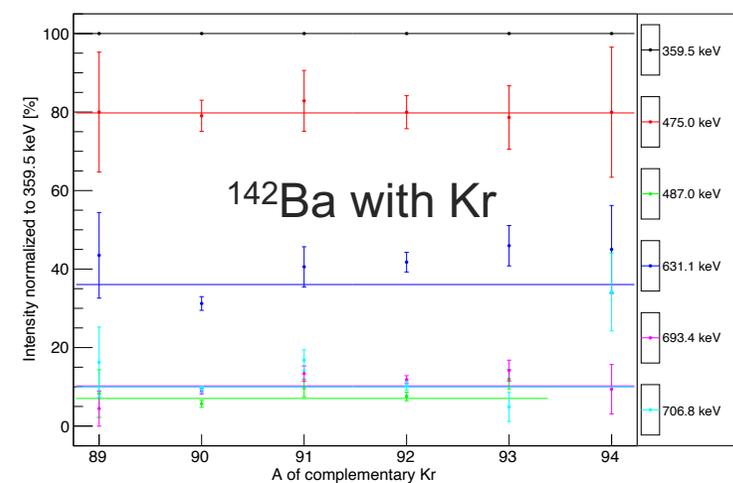
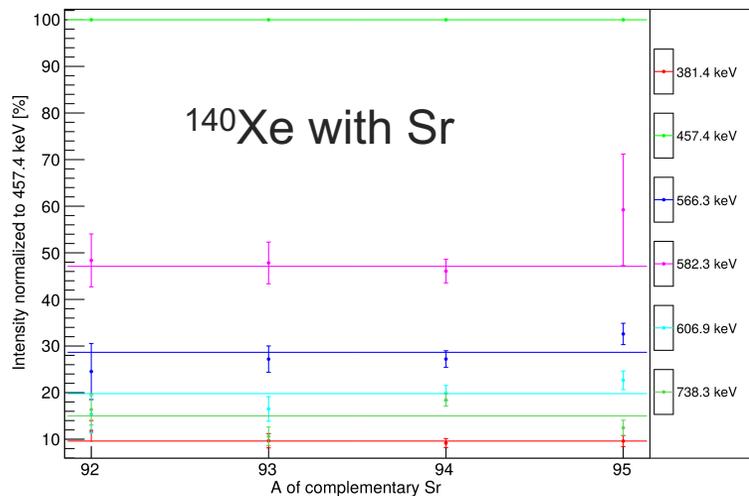
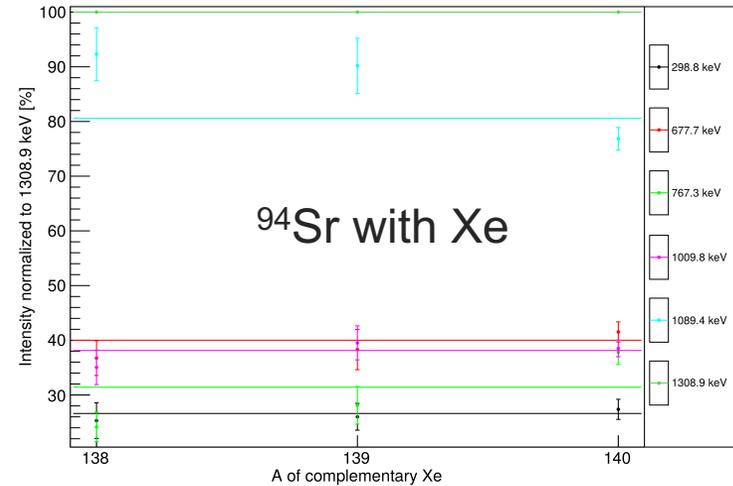
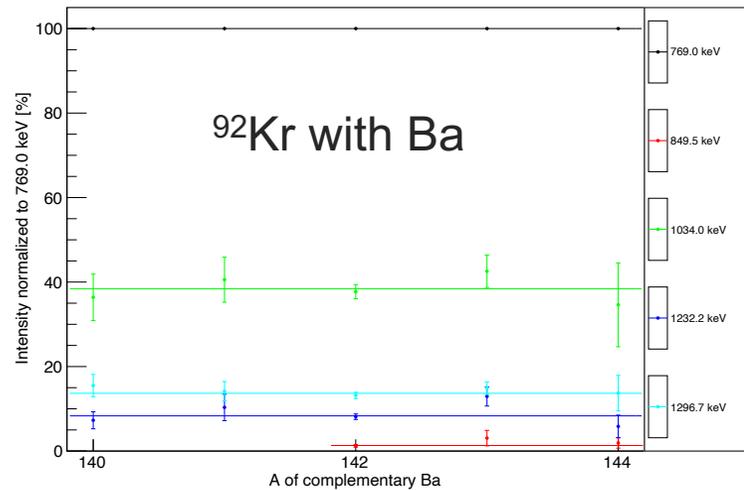


^{100}Zr - SIMU FIFRELIN MODELE BSFGM



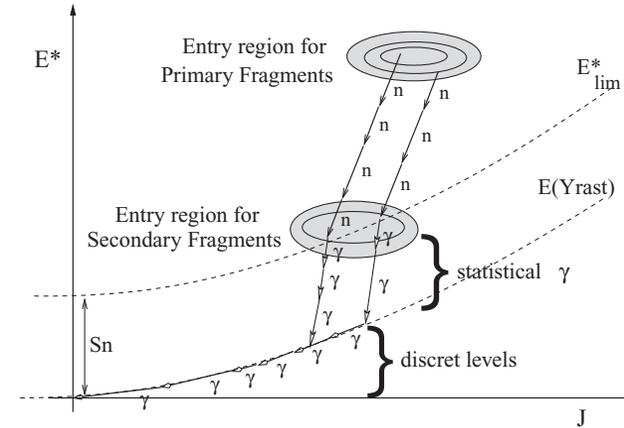
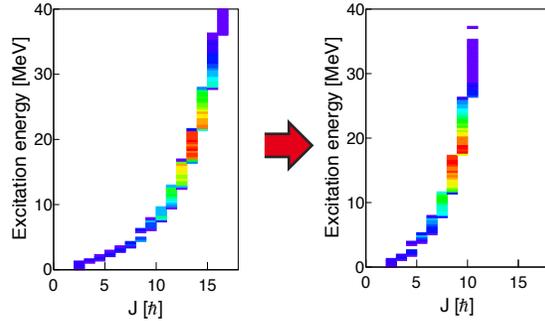
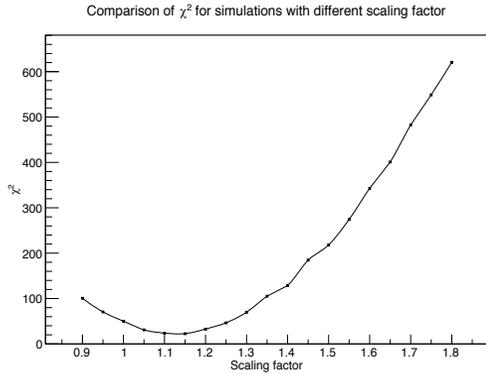
A spin distribution that does not vary with the excitation energy is not very consistent with the data.

Dependence of the main cascade with the fission partner – other EXILL results

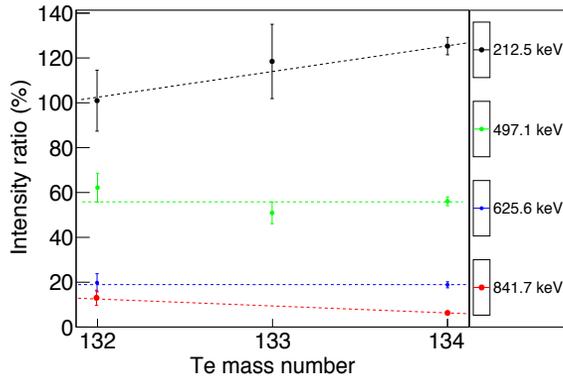


There is no visible strong dependence of the cascade with the fission partner.

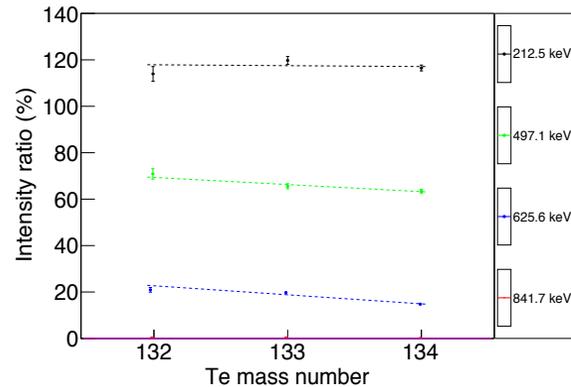
Angular momentum of the fission fragments - EXILL results



^{100}Zr - EXILL DATA



^{100}Zr - SIMU BSFGM 1.2



Gamma-ray cascade data favour a distribution of the primary fragments with lower spin than postulated in FIFRELIN, closer to the statistical most probable spin of the nuclei according to their level density

Angular momentum of the fission fragments - FIPPS

very preliminary results

