24ème COLLOQUE GANIL

21 au 25 septembre 2026

Bussang, France

Investigation of Shell Effect Damping in Nuclear Fission of ^{240}Pu using VAMOS and PISTA

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université PARIS-SACLAY GANIL LMCE LABORATOIRE MATIERE EN CONDITIONS EXTREMES

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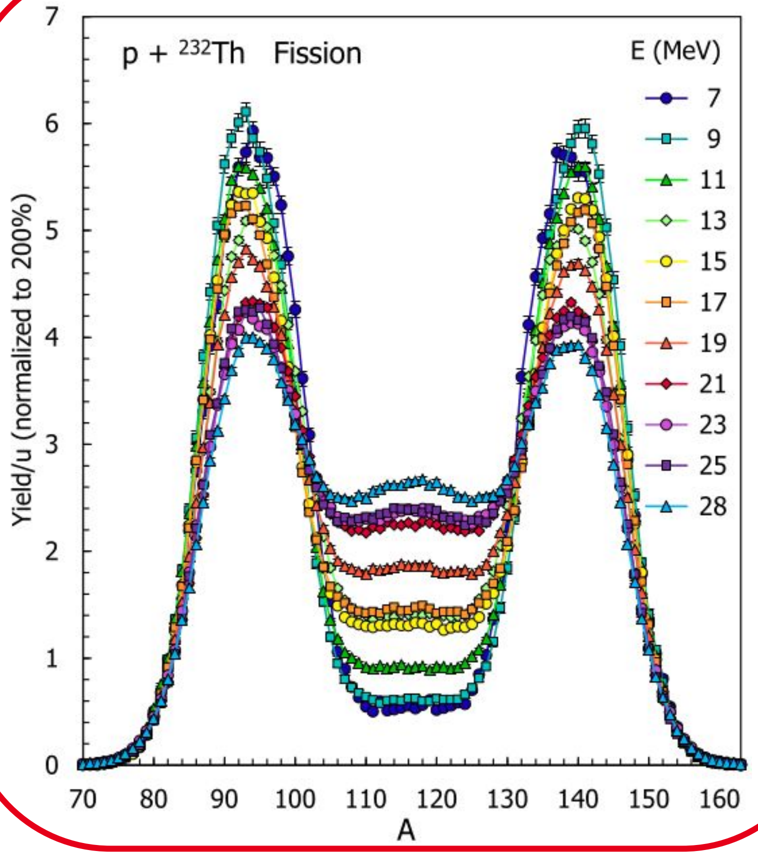
1. Experiment motivations



A.C. Berriman et al. Phys.Rev.C 105 (2022)

Shell effects damping

- Asymmetric fission for actinide driven by **deformed magicity at Z = 52 and 56**

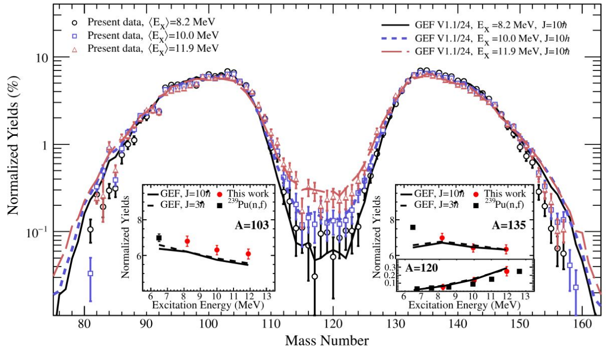
Increase of the excitation energy of the fissioning system

- Shell effects dampen
- Dampen the asymmetric yield in fission
- Highten symmetric yield

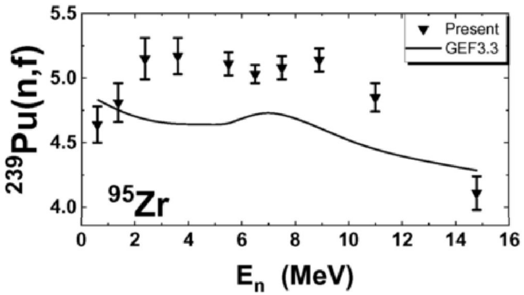
The goal is to quantify this damping

And applications, Gen IV reactor need
non-thermic neutron induced fission data

Plutonium 240 fissioning system



D. Ramos *et al.*, Phys. Rev. C **113**, 054611 (2026), Fig. 1.



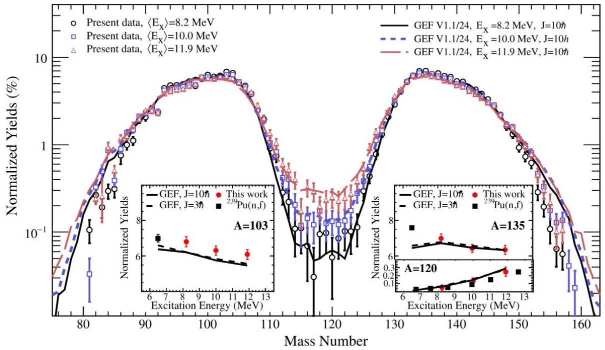
Tonchev, A. P., J. A. Silano, A. P. D. Ramirez, et al. *Nuclear Data Sheets* 202 (June 2025): 12–29.

Previous experiments

Entrance channel	Authors	E*
Spontaneous Fission	Laidler & Brown (1962) Bushuev et al (2007)	E* = 0
Thermal neutron induced fission	Schmitt et al (1984) Naik et al (2022)	E* ~ Sn = 6.53 MeV
Monoenergetic-neutron induced fission	Gindler et al (1983) **Tonchev et al (2025)**	E* ~ Sn + En : [6.7;21.3] MeV
Photofission	Naik et al (2011)	<E*> = 7.6 MeV
Transfer at GANIL SPIDER + VAMOS	Caamaño et al (2013) **Ramos et al (2026)**	E* = [4;20]MeV

Our setup probes : **finer E* resolution** than previous GANIL experiment.

Plutonium 240 fissioning system



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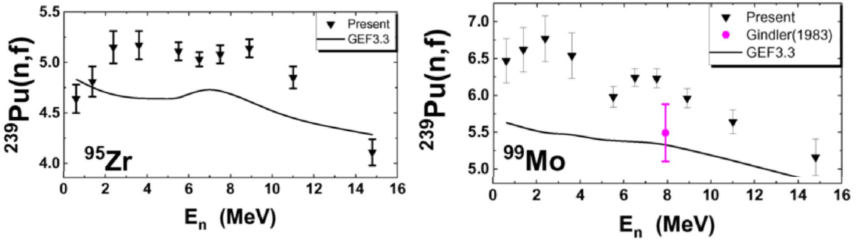


Tonchev, A. P., J. A. Silano, A. P. D. Ramirez, et al. *Nuclear Data Sheets* 202 (June 2025): 12–29.

Most recent experiments

Triangle Universities Nuclear Laboratory (TUNL) by Tonchev & al (2025)

- Activation γ**-ray spectroscopy**
- **Cumulative yields**
- Cannot probe shell effect damping

Previous experiment by D.Ramos & al

- **Spider** + VAMOS
- Lower E* resolution ~1.15 MeV

Our setup probes : **finer E* resolution** than previous GANIL experiment.

2. The setup

Experiment goals

- Isotopic fission yields as a function of the excitation energy of the fissioning system $({}^{\mathrm{A}}\mathrm{Z}_{\mathrm{Parent}})$ post neutron evaporation : **Y(A,Z,E*).**

The ingredients

1. Produce the ${}^{\mathrm{A}}\mathrm{Z}_{\mathrm{Parent}}$
2. Characterize the ${}^{\mathrm{A}}\mathrm{Z}_{\mathrm{Parent}}$ in **A Z and E***
3. Identify one of the **fission fragment in A and Z**

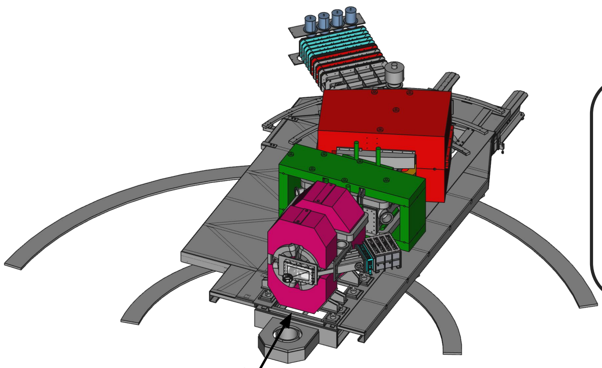
The setup

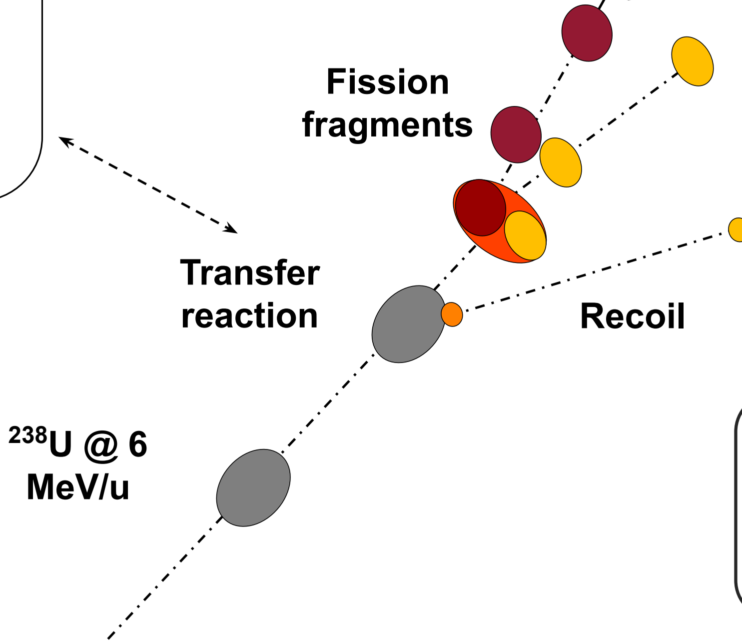
Transfer reactions

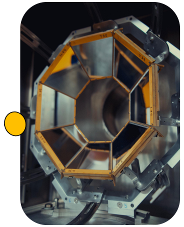
		^{240}Pu ^{10}Be	^{241}Pu ^{9}Be	^{242}Pu ^{8}Be→2α
	^{238}Np ^{12}B	^{239}Np ^{11}B	^{240}Np ^{10}B	
^{236}U ^{14}C	^{237}U ^{13}C	^{238}U ^{12}C	^{239}U ^{11}C	
	^{236}Pa ^{14}N	^{237}Pa ^{13}N	^{238}Pa ^{12}N	
		^{236}Th ^{14}O		

p

n







VAMOS
- ✓ Yield in mass and charge of fission fragments Y(A,Z)

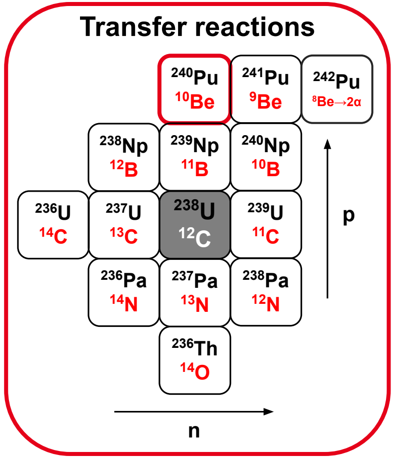
PISTA
Fissioning system
- ✓ A
- ✓ Z
- ✓ $(E_{lab},\theta_{lab}) \rightarrow E^*$

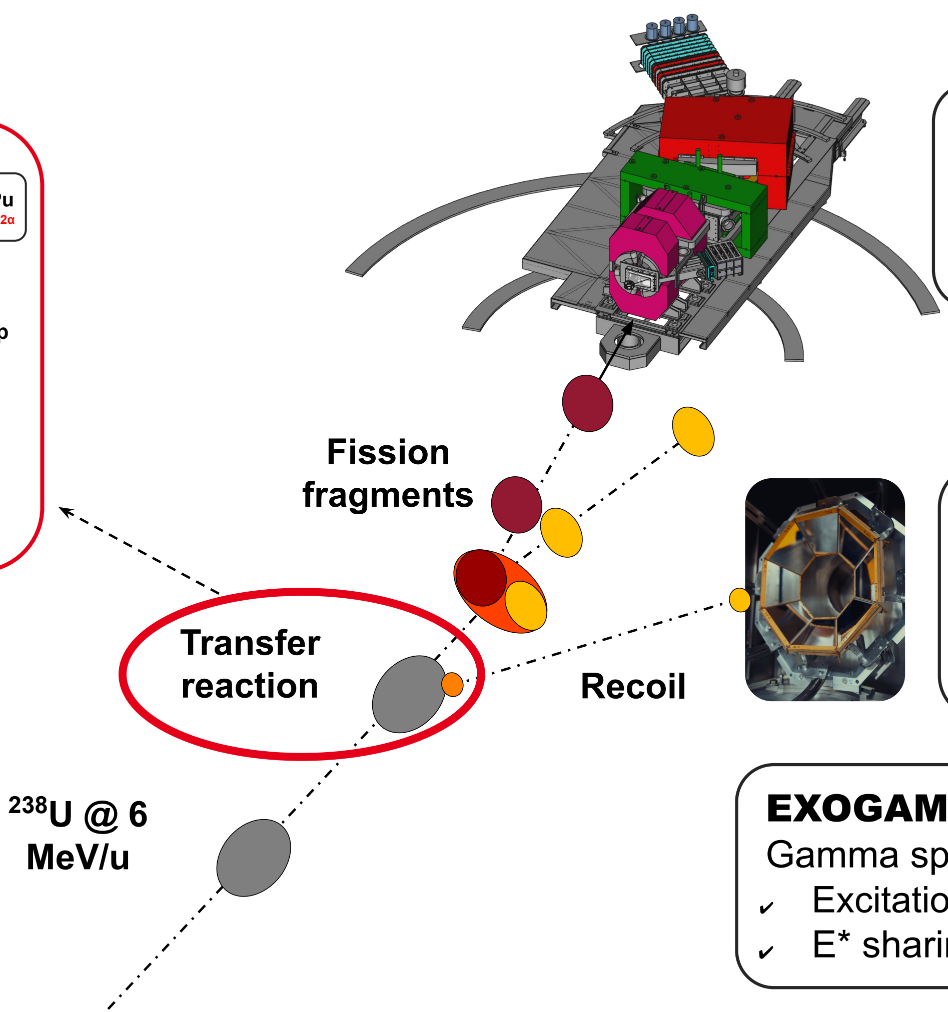
EXOGAM
Gamma spectrometer
- ✓ Excitation probability of recoil
- ✓ E* sharing between FF

First use of this setup (e850 exp)

June 2023

The setup





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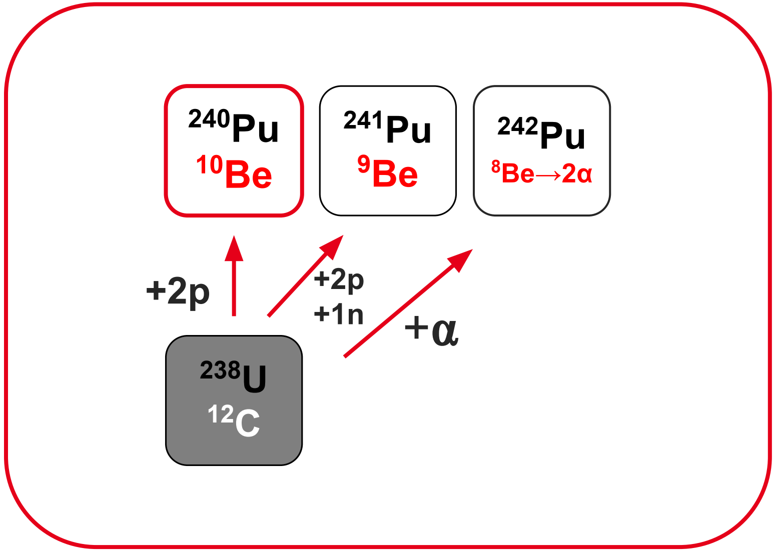
Inverse kinematics and surrogate reaction

- Some of our **fissioning systems of interest are short-lived** → Inverse kinematic enable their study (^{241}Pu ~ 14 years)
- **FF will be boosted** allowing charge identification for the full distribution
- Access desired system through **transfer reaction**

^{236}U(n+^{235}U), ^{240}Pu (n+^{239}Pu), ^{242}Pu(n+^{241}Pu)

- Identification of the **light recoil** → characterize the **fissioning system A and Z**
- Angle and kinetic energy of the light recoil → missing mass → **E* of the fissioning system**



$$^{238}U + {}^{12}C \rightarrow {}^{A}Z_{fiss} + {}^{A}Z_{recoil}$$

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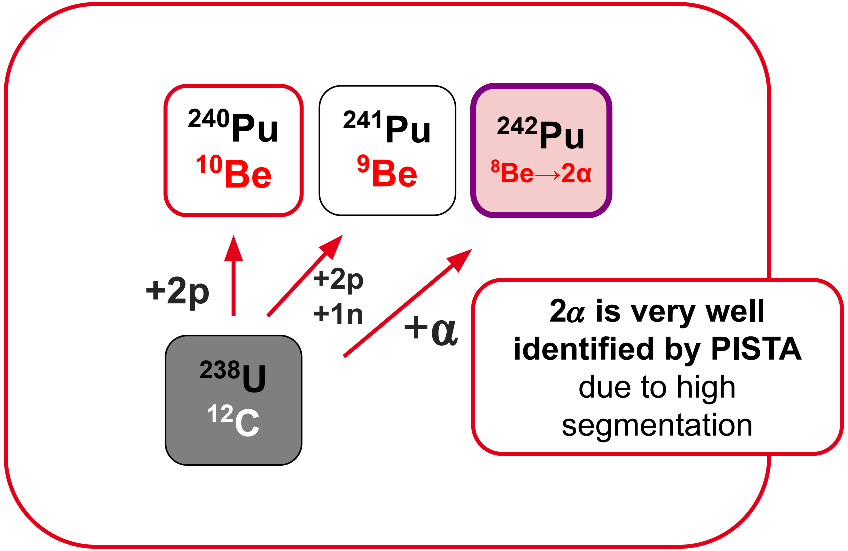
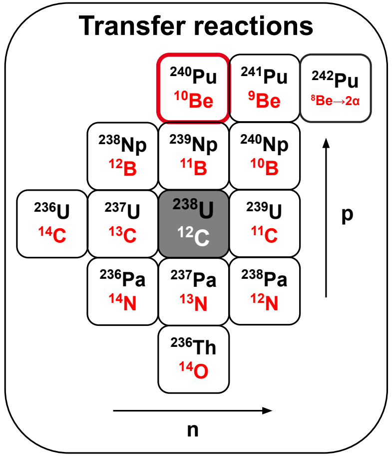
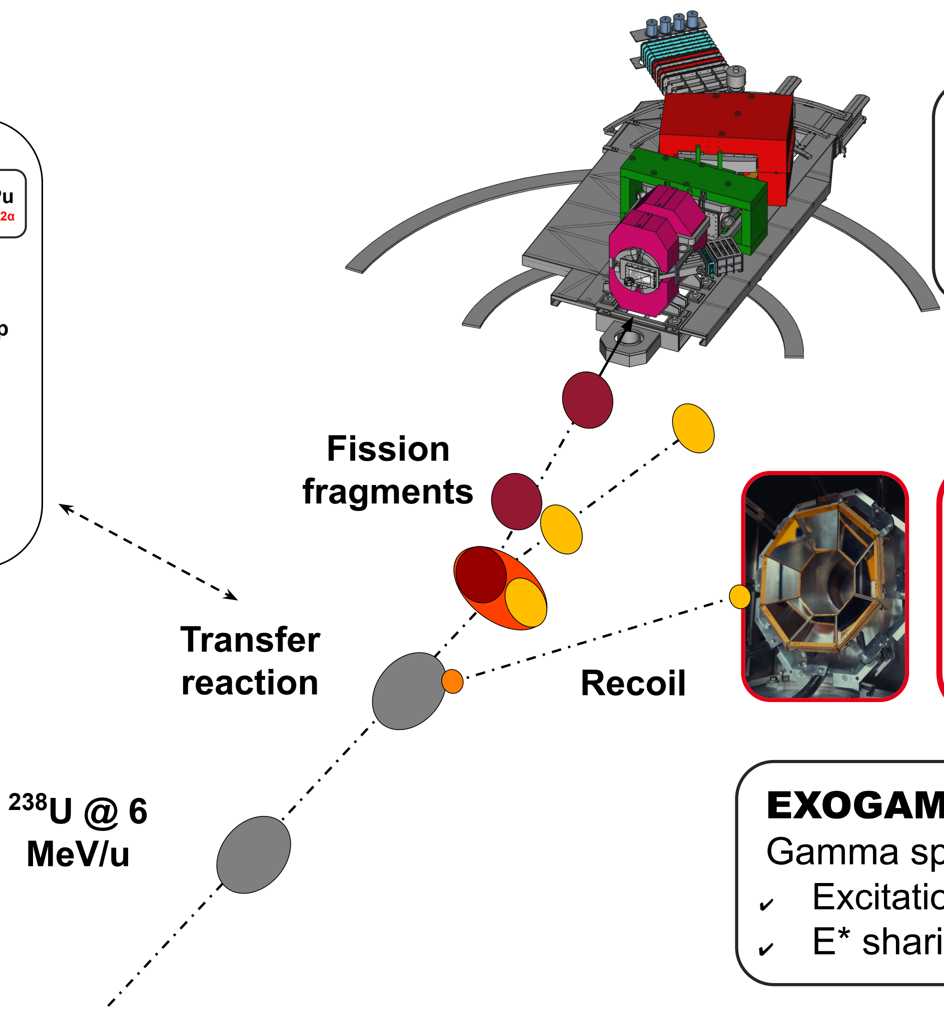


$$^{238}\mathrm{U} + {}^{12}\mathrm{C} \longrightarrow {}^{A}\mathrm{Z}_{fiss} + {}^{A}\mathrm{Z}_{recoil}$$

The setup





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Fissioning system
- A
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Gamma spectrometer
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PISTA

A CEA-DAM + GANIL collaboration

Particle Identification Silicon Telescope Array

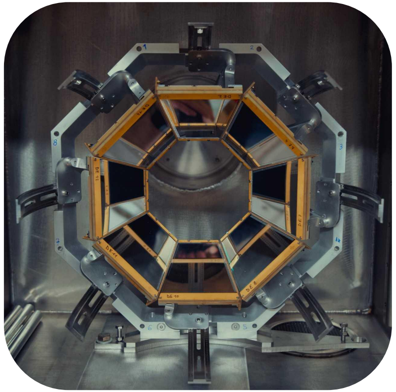
- **Silicon semiconductor**
- 8 Highly segmented ΔE-E telescope.
- **E* resolution ~ 750 keV(FWHM)**
- High count rate
- 30-60° coverage

ΔE First stage

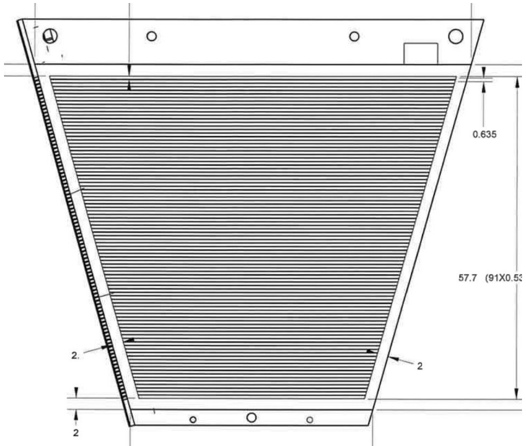
- 100 micrometer thick
- Stripped front
- 91 horizontal strips
- range : 0-60 MeV

E Second stage

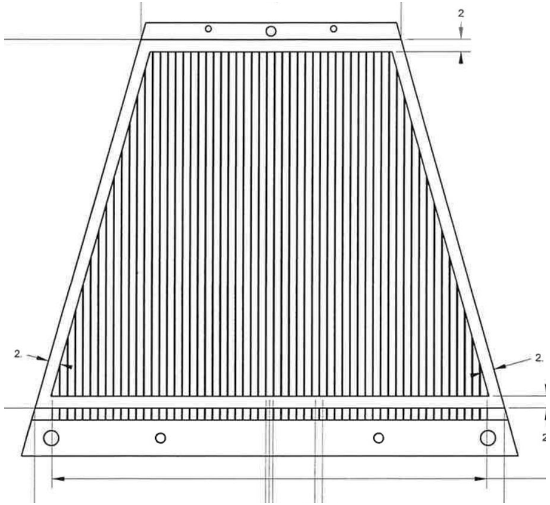
- 1mm thick
- Stripped front
- 57 vertical strips
- range : 0-200 MeV



ΔE

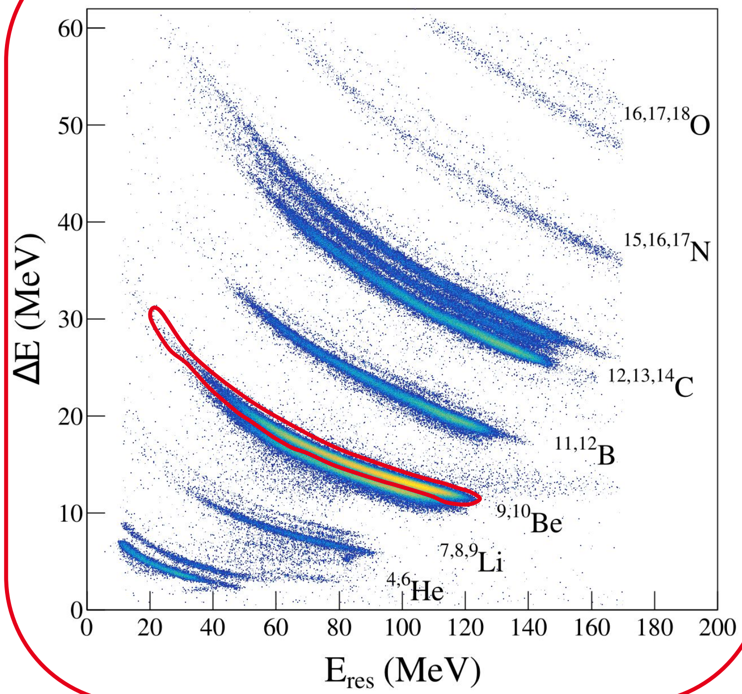


E



PID PISTA

Guillou, L. B. et al. Performances of the Particle-Identication Silicon-Telescope Array coupled with VAMOS++ magnetic spectrometer. NIMA volume 1090 2026 + PhD Thesis of Guillou



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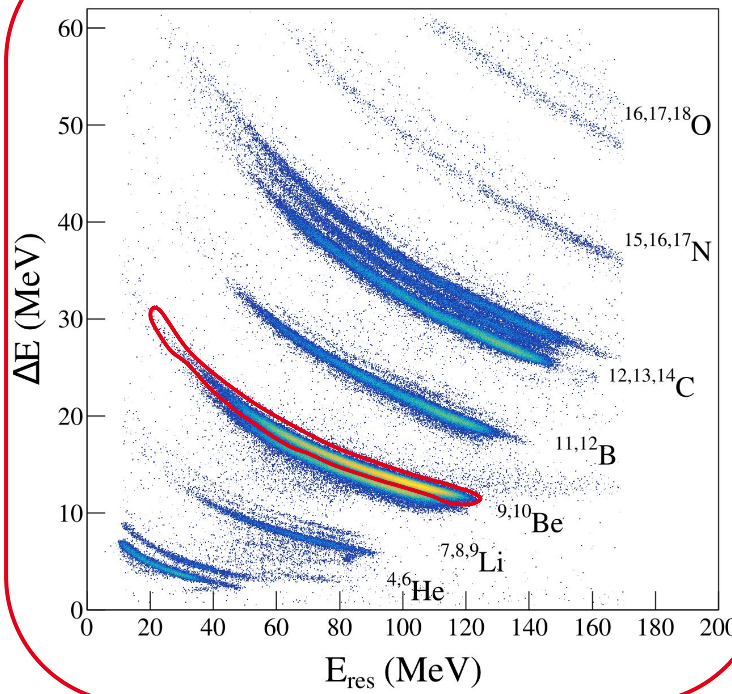

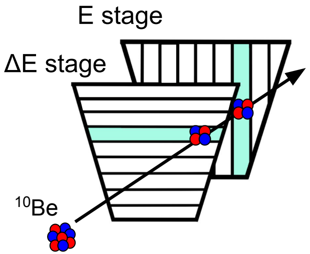

$$E_{lab}$$
$$\theta_{lab}$$

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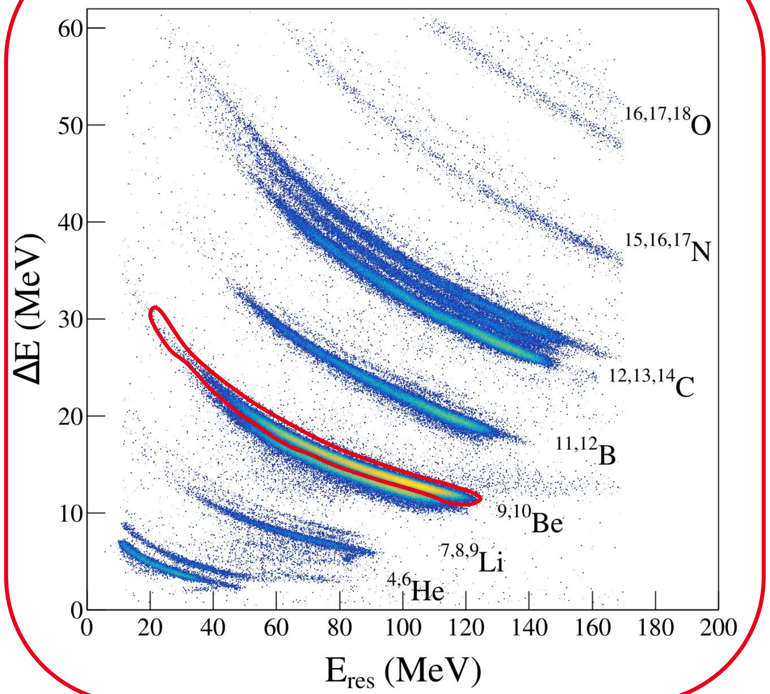
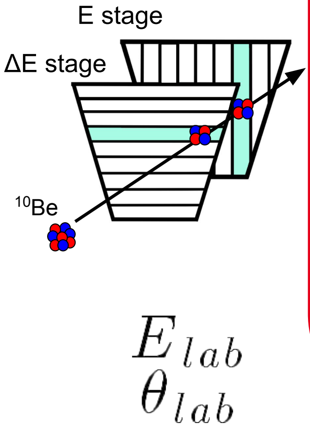
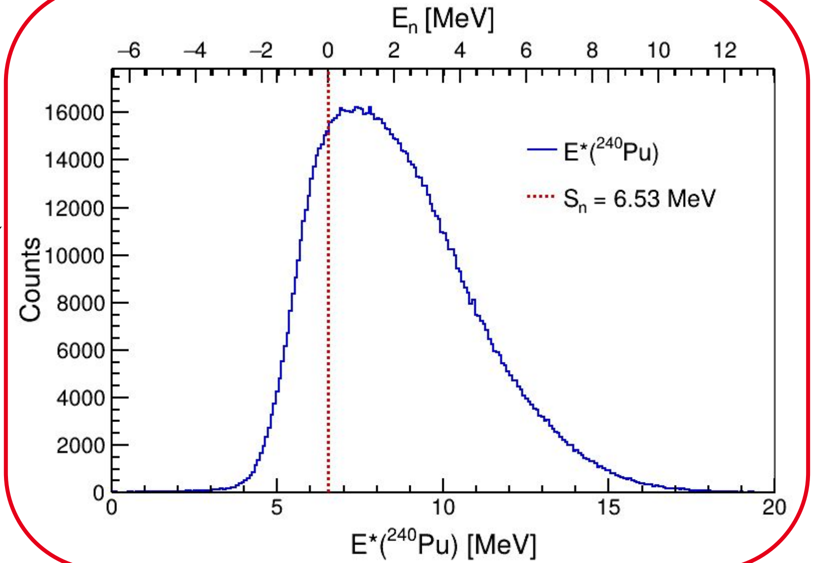
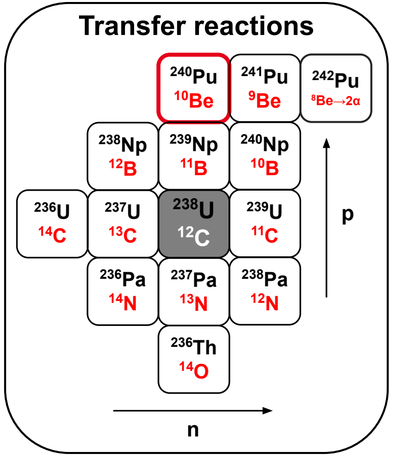
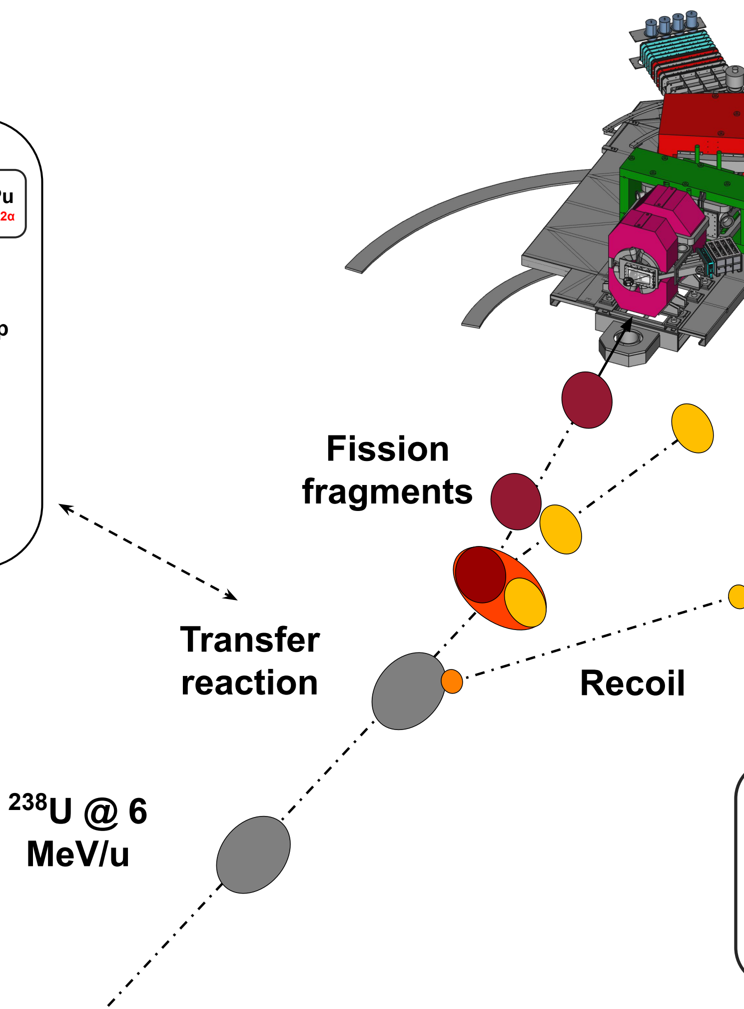






The setup

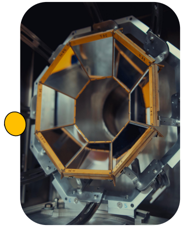




VAMOS

- Yield in mass and charge of fission fragments **Y(A,Z)**

~150-300 ns after fission
→**post neutron FF**



PISTA
Fissioning system
- A
- Z
- $(E_{lab},\theta_{lab}) \rightarrow E^*$

EXOGAM
Gamma spectrometer
- Excitation probability of recoil
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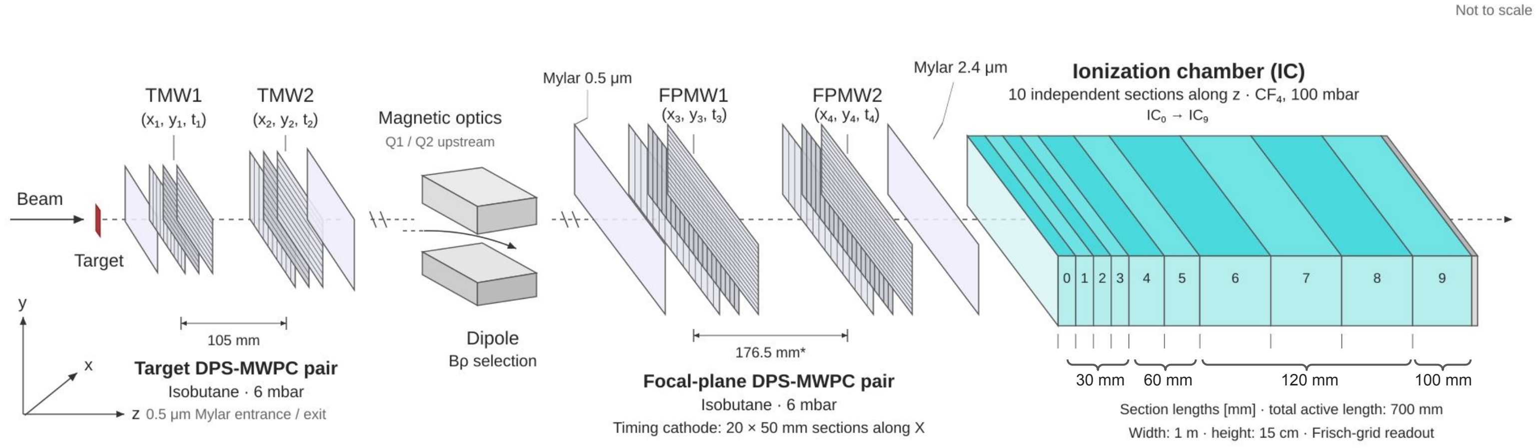
VAMOS++

VAriable MOde Spectrometer



Observable

- Magnetic rigidity Bρ
- Velocity vector
- Trajectory length
- ΔE-E

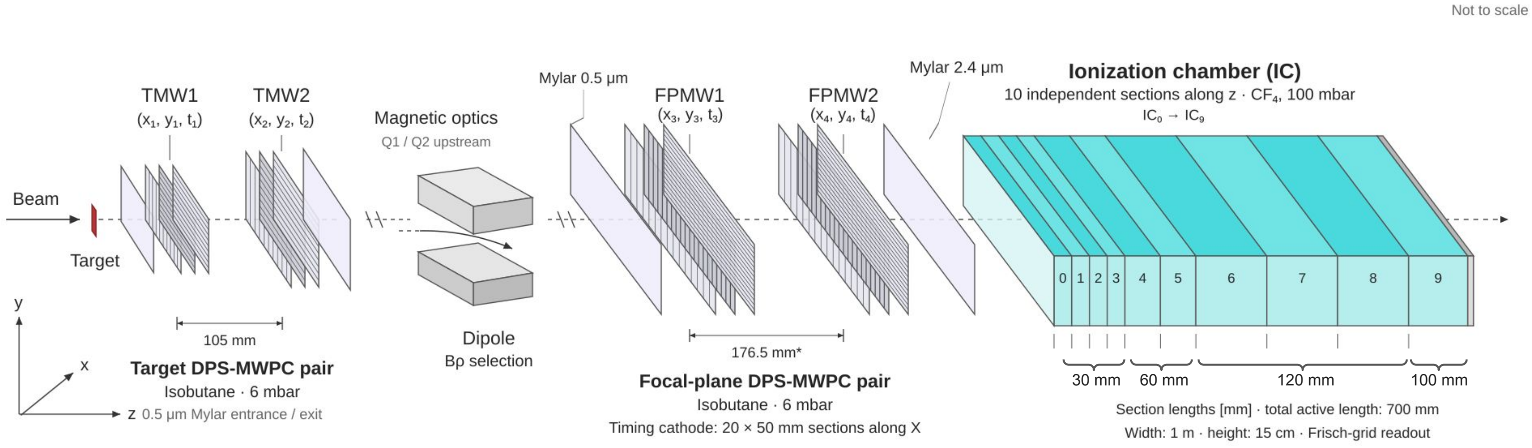
Detector

- **IC** : ΔE-E → Z
- **MWPC + IC** : ToF + Bρ + ΔE-E → A

We get total identification of one of the fission fragment from those observables.

VAMOS++

VAriable MOde Spectrometer



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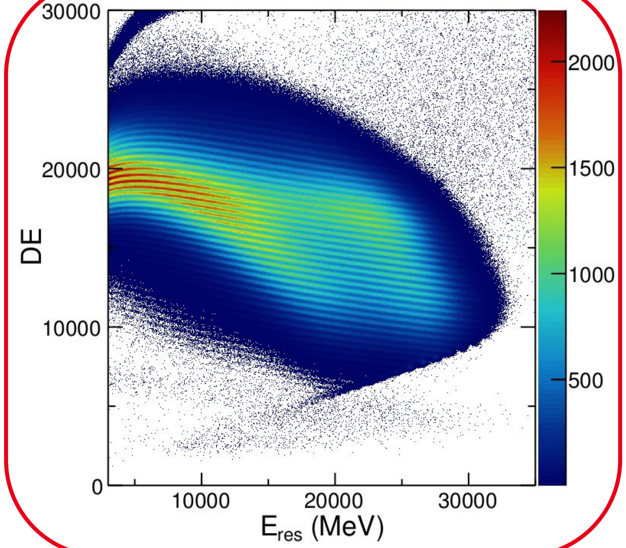
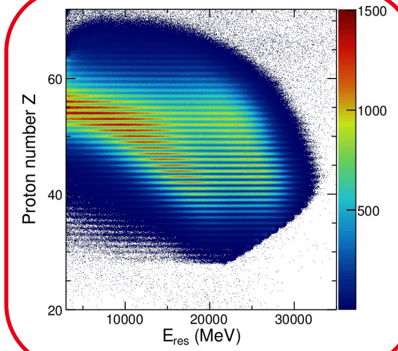
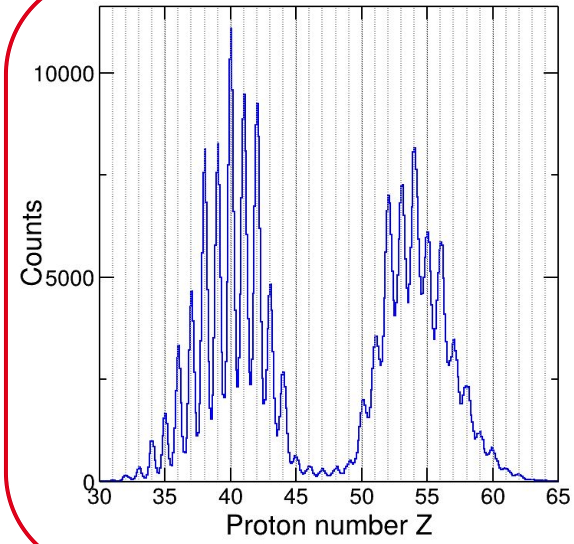
VAMOS++

Charge distribution

- ΔE-E in IC of VAMOS
- Resolution ΔZ/Z = 1.31 %

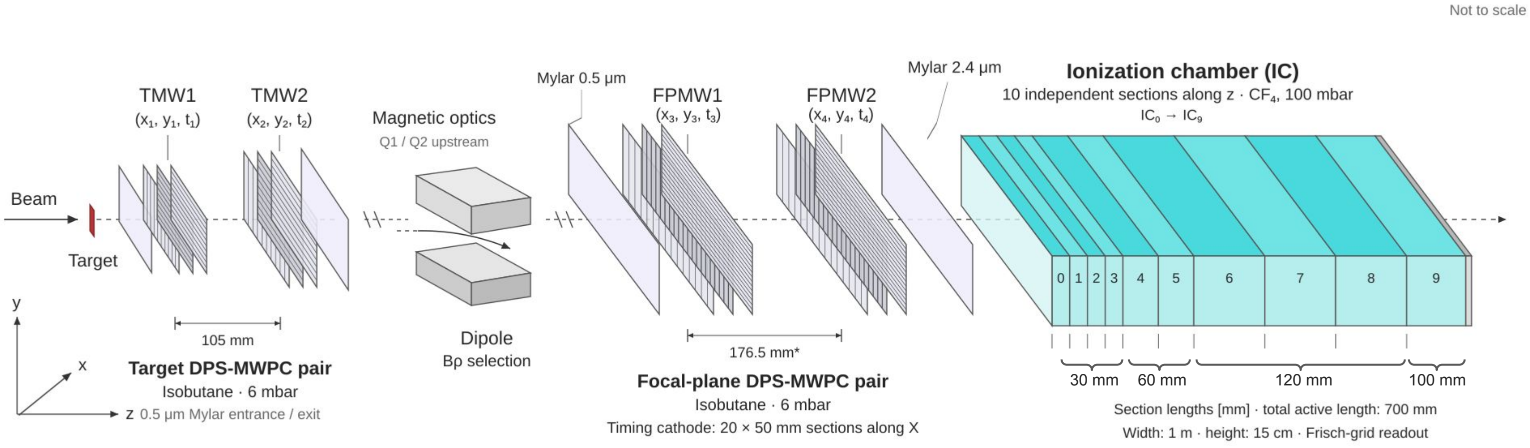






VAMOS++

VAriable MOde Spectrometer



Observable

- Magnetic rigidity Bρ
- Velocity vector
- Trajectory length
- ΔE-E

Detector

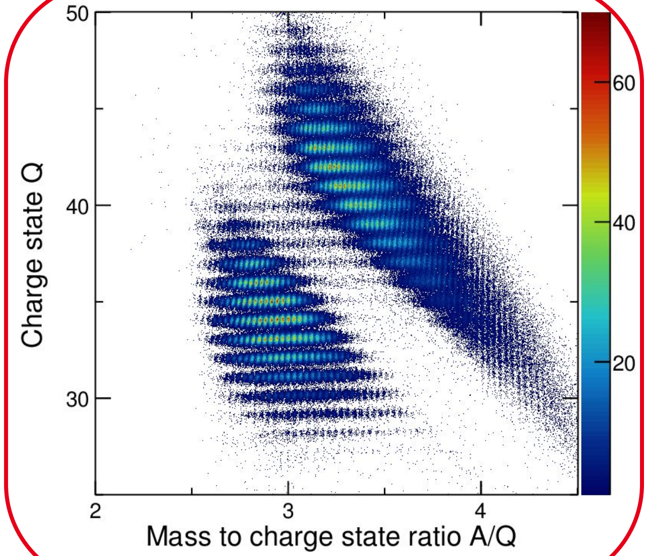
- **IC** : ΔE-E → Z
- **MWPC + IC** : ToF + Bρ + ΔE-E → A

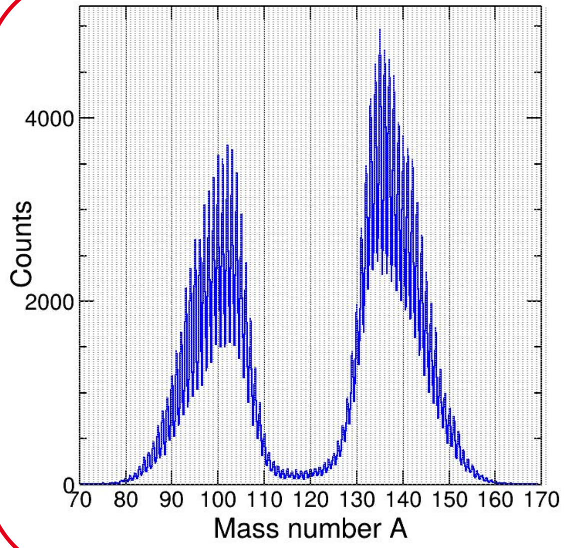
We get total identification of one of the fission fragment from those observables.

VAMOS++

Mass distribution

- Position + Timing + IC -> A
- Resolution $\Delta A/A = 0.57$ %

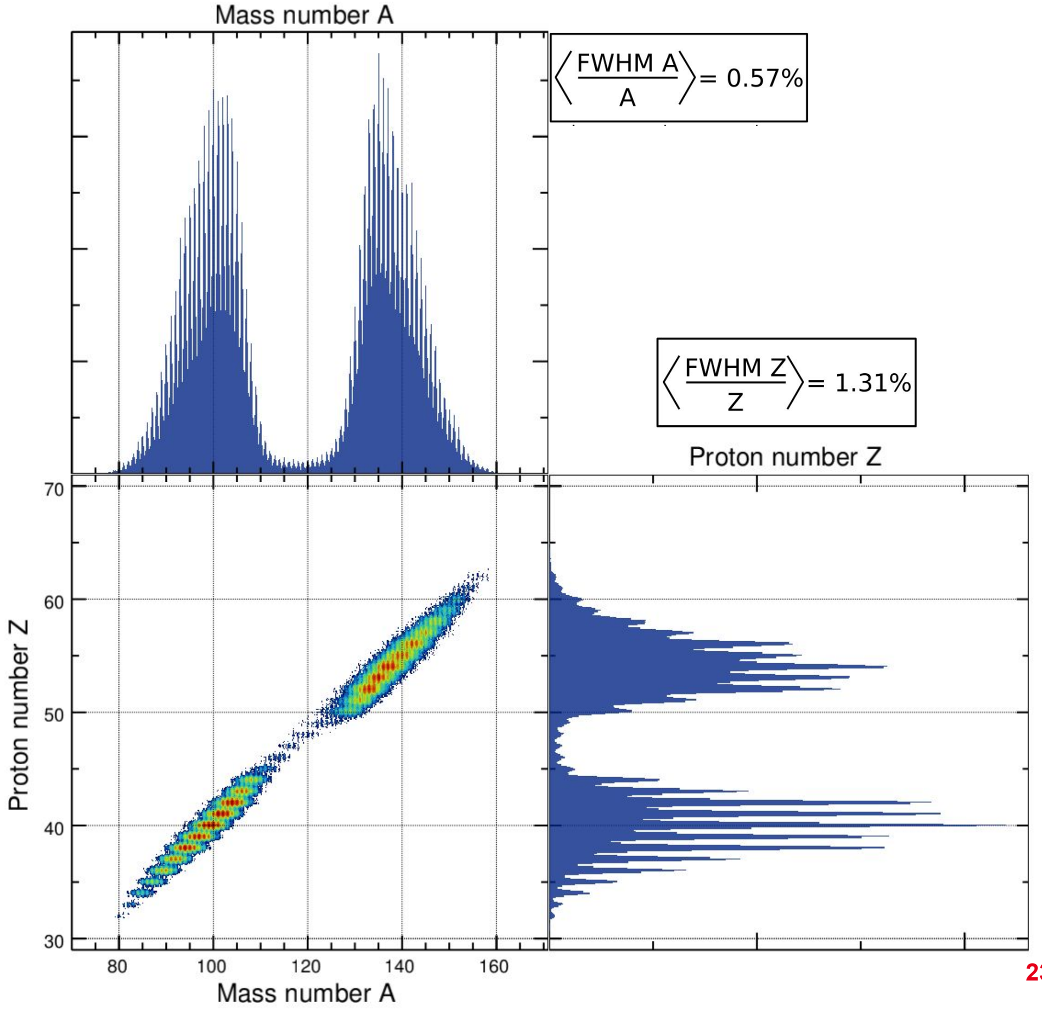




VAMOS++
VAriable MOde Spectrometer

We measure the mass using the following set of formulae

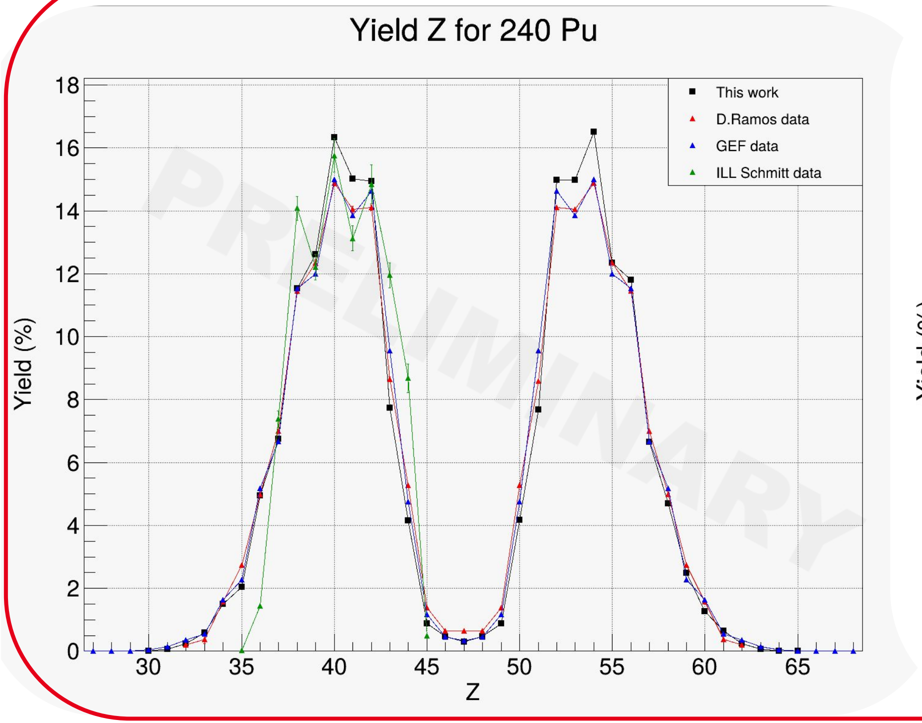
$$\begin{cases} \dfrac{A}{q} = \dfrac{B\rho}{3.107 \cdot \beta \cdot \gamma} \\[2ex] M_{inv} = \dfrac{E}{931.494(\gamma - 1)} \\[2ex] q_{int} = \dfrac{M_{inv}}{\frac{A}{q}} \\[2ex] A = \dfrac{A}{q} \cdot q_{int} \end{cases}$$

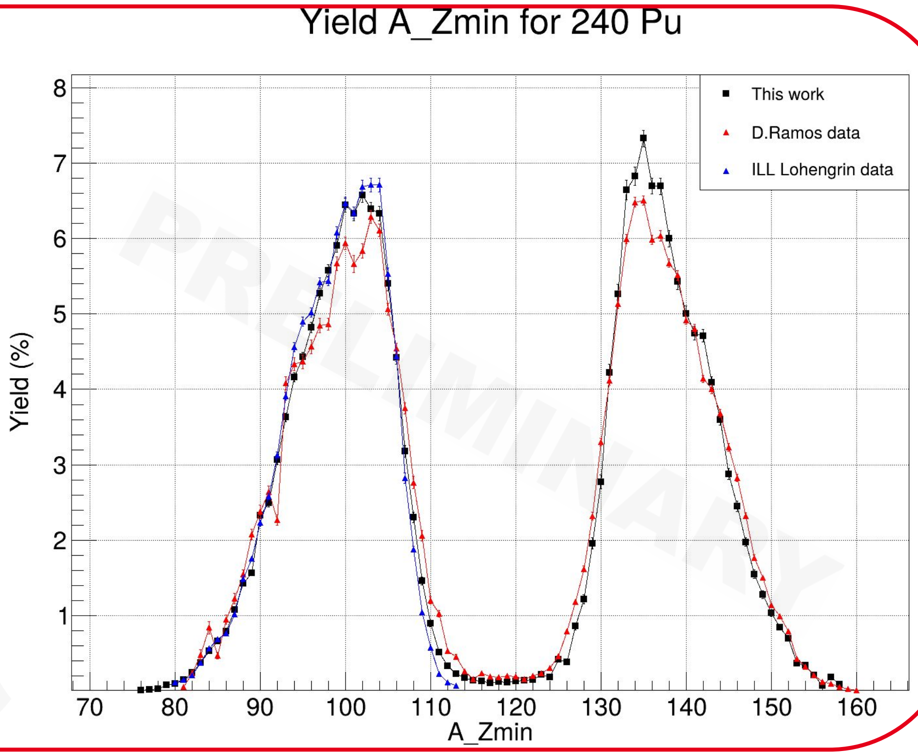


3. Preliminary results

Preliminary result

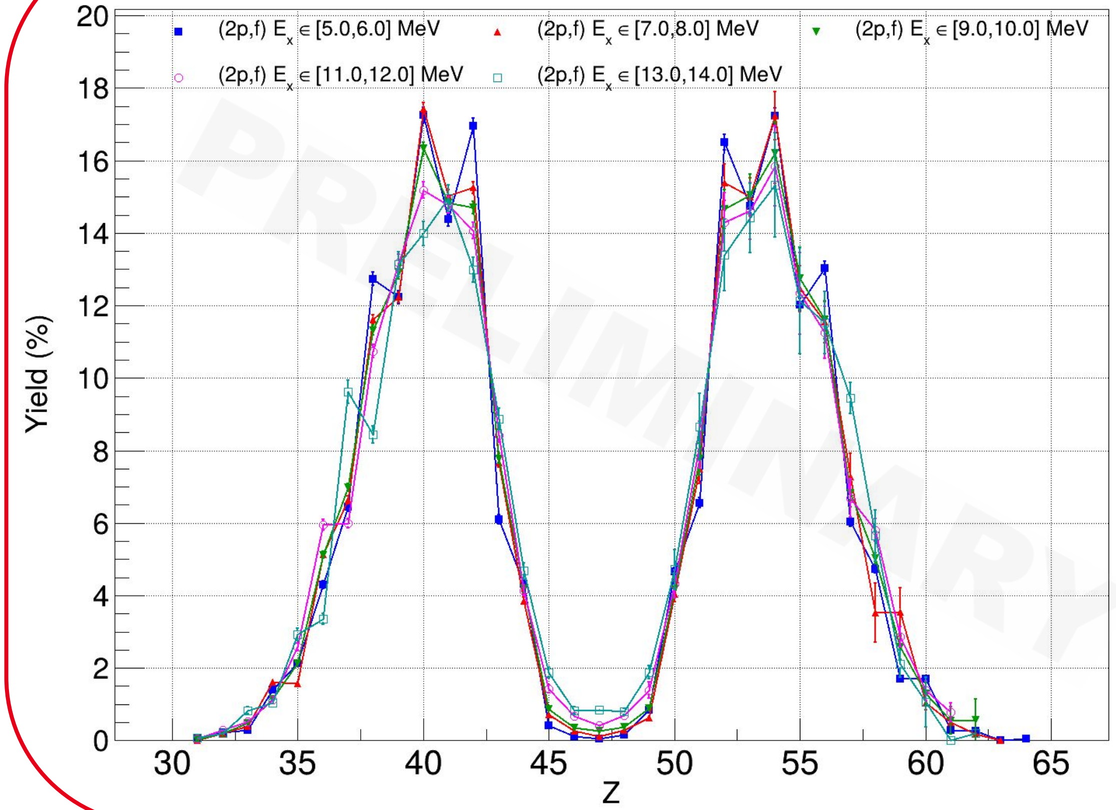
Yield Z and A for averaged E*





Preliminary result

Yield Z wrt E*



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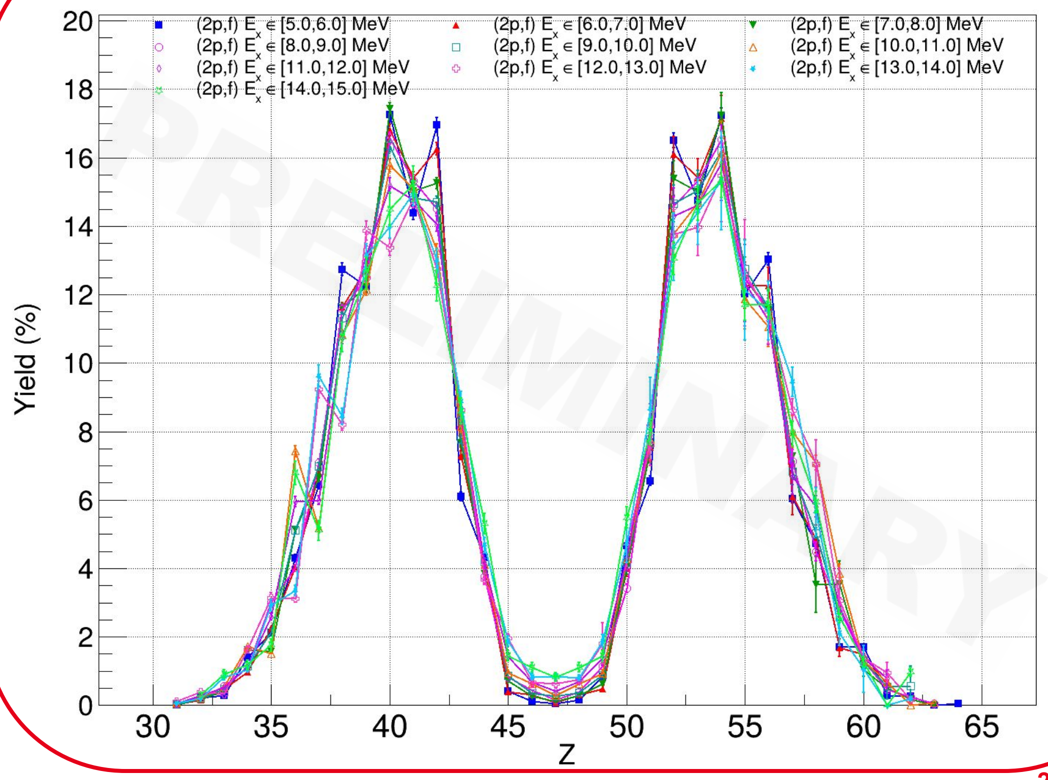

Preliminary result

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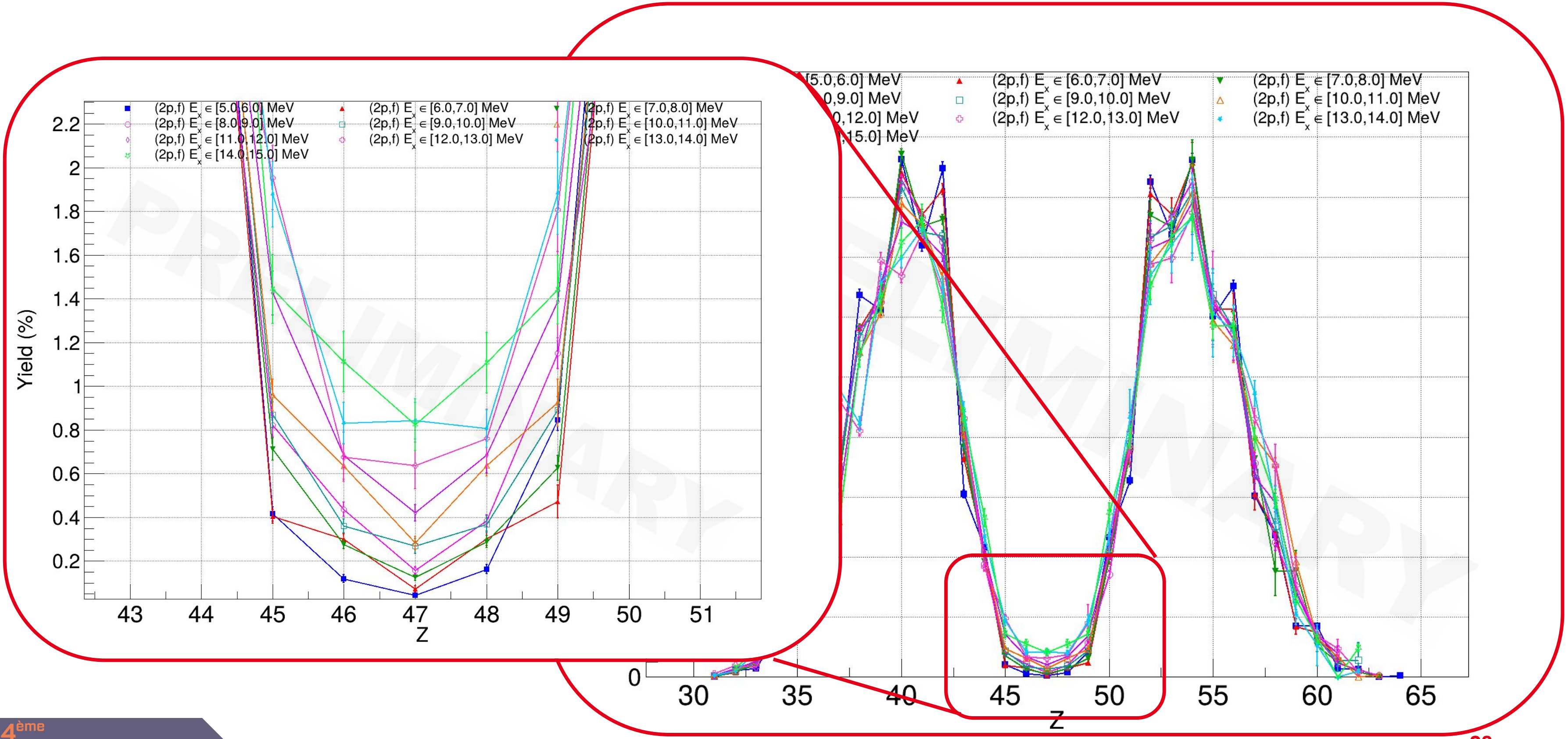
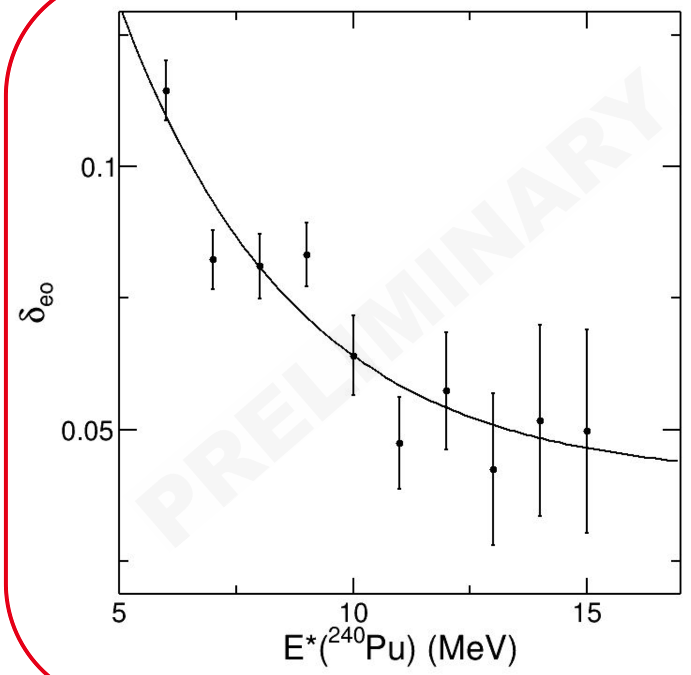


Preliminary result

Odd even staggering



- Can see evolution of pairing with E*
- **Pairing strength damping with E***
- Future study in collaboration with D.Regnier

$$\delta_{eo} = \frac{\sum Y_{even} - \sum Y_{odd}}{\sum Y}$$

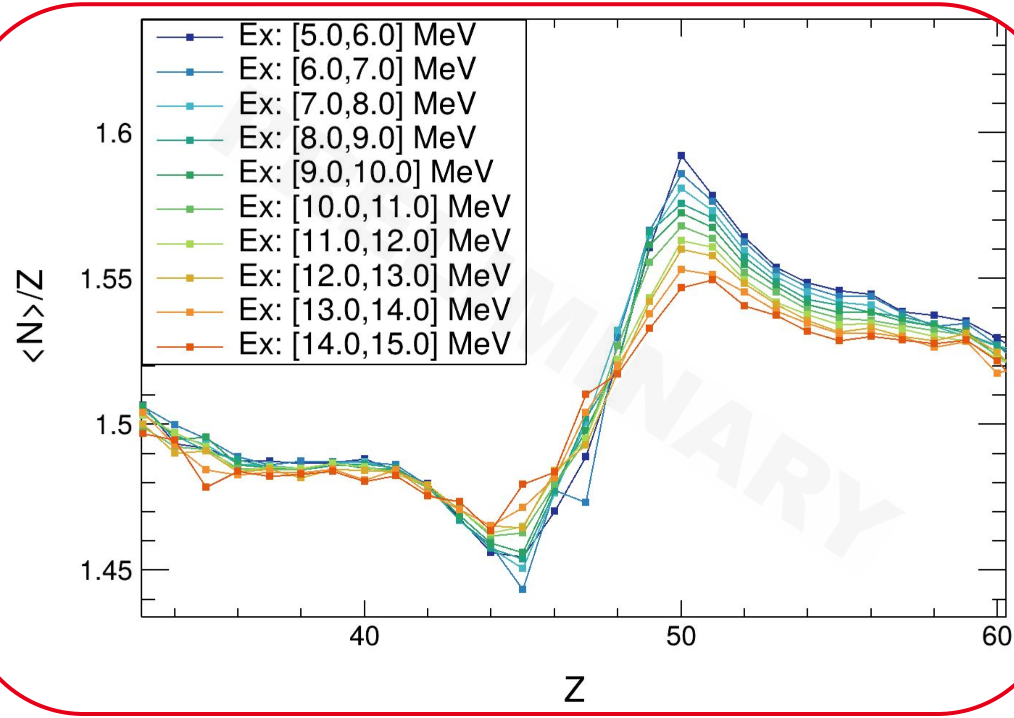
Preliminary result

Neutron excess

- E* goes in the heavy fragment

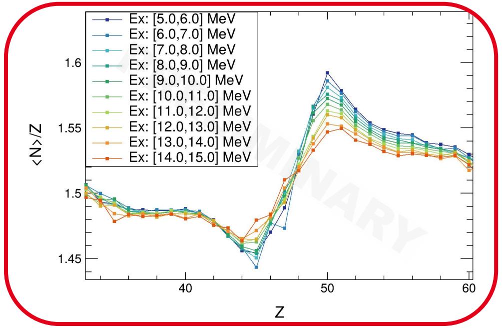
- **Energy sharing**

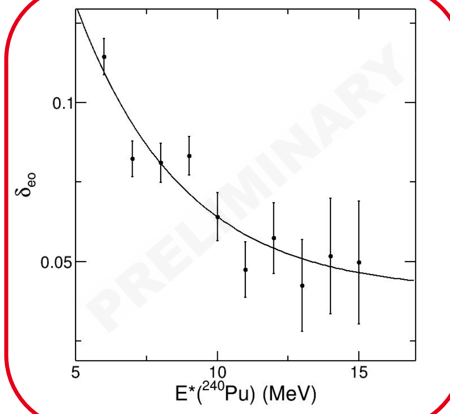
- **Beyond 11 MeV** we start to see E* going to the light



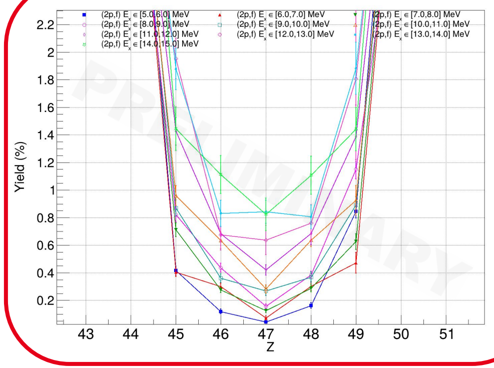
4. Conclusion

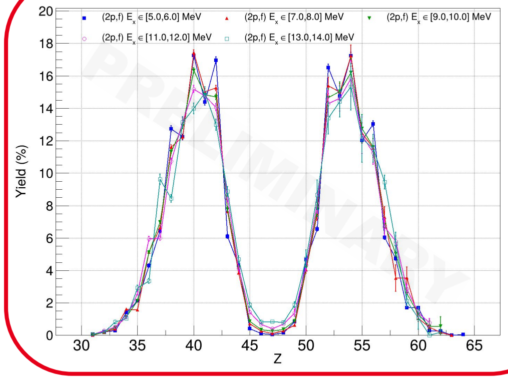
Conclusion



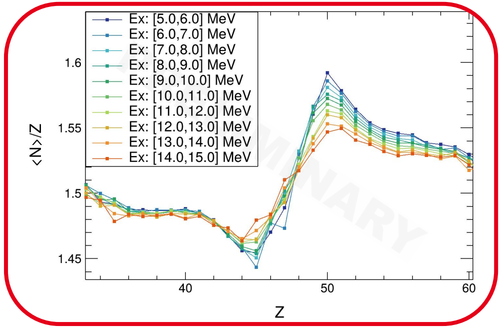


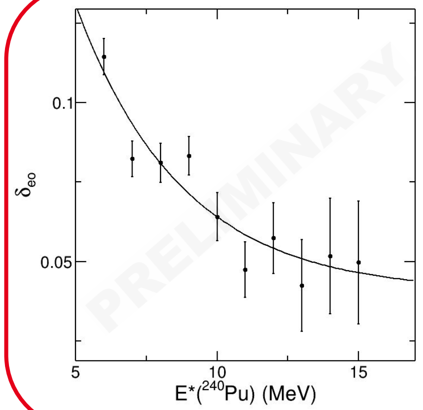
- Pu isotopes are probed using **inverse kinematic**
- **State-of-the-art detector setup** VAMOS++ PISTA
- **Better resolution** thanks to PISTA
- **Energy sharing** and **shell effect damping** can be seen
- Useful result for **GenIV reactor**



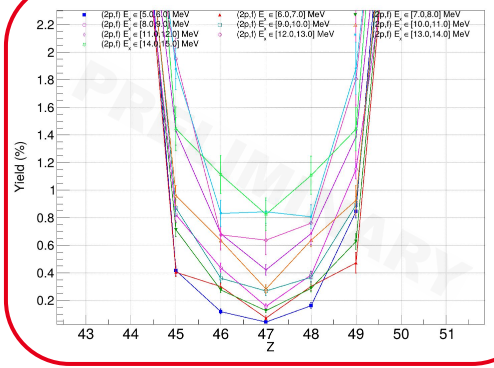


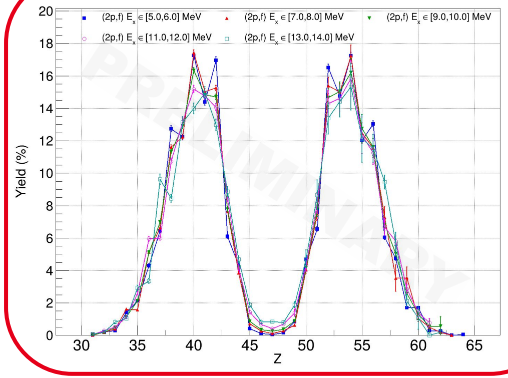
Outlook





- Final work on **acceptance** to be done
- **Uncertainty** quantification
- Comparison with **theoretical model**





24ème COLLOQUE GANIL

21 au 25 septembre 2026

Bussang, France

Thanks for your attention !

Feel free to ask questions.

T.Efremov[1,2,] , P.Morfouace[1,2] , J.Taieb[1,2], A.Chatillon[1,2], A.Graña González[1,2], C.Lenain[1,2], B.Mauss[1,2], L.Bégué-Guillou[3], A.Cobo[3], A.Francheteau[3], A.Lemasson[3], D.Ramos[3], M.Rejmund[3] and all the Fission@VAMOS collaboration …

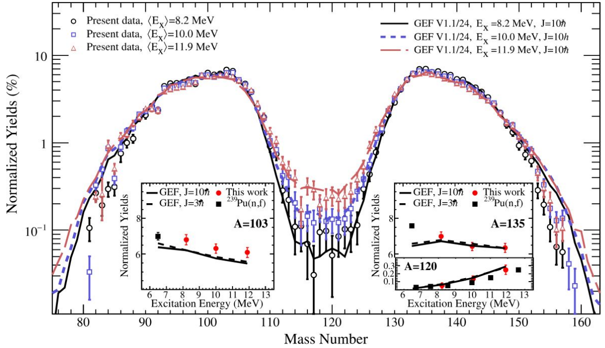
[1]CEA, DAM, DIF, Arpajon, F-91297, France
[2]Université Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes, 91680, France
[3]GANIL, CEA/DRF - CNRS/IN2P3, Caen, France

LABORATOIRE MATIERE EN CONDITIONS EXTREMES

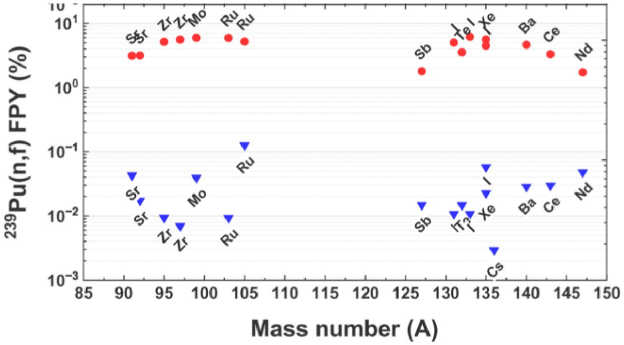
Contact : theodore.efremov@cea.fr

4. BACKUP

Plutonium 240 fissioning system



D. Ramos *et al.*, Phys. Rev. C **113**, 054611 (2026), Fig. 1.



Tonchev, A. P., J. A. Silano, A. P. D. Ramirez, et al. *Nuclear Data Sheets* 202 (June 2025): 12–29.

Previous experiments

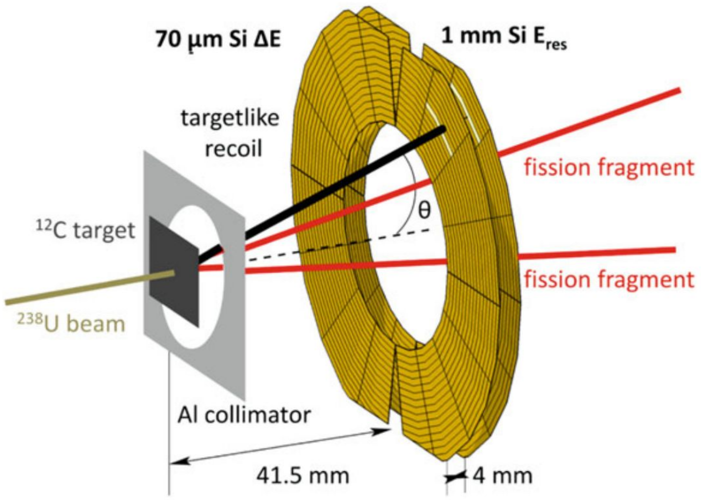
Entrance channel	**Authors**	**E***
Spontaneous Fission	Laidler & Br wn (1962) Bushuev (2007)	E* = 0
Thermal neutron induced fission	Sch N	E* ~ Sn = 6.53 MeV
Monoenergetic-neutron induced fission		E* ~ Sn + En : [6.7;21.3] MeV
Photofission		<E*> = 7.6 MeV
Transfer at GANIL SPIDER + VAMOS	**Ramos et al (2026)**	= [4;20]MeV

!

J depend on entrance channel

Our setup probes : **finer E* resolution** than previous GANIL experiment.

Previous experiment



Rodríguez-Tajes, C., F. Farget, X. Derkx, M. Caamaño, O. Delaune, K.-H. Schmidt, E. Clément, et al. « Transfer reactions in inverse kinematics: An experimental approach for fission investigations ». *Physical Review C* 89, nº 2 (24 février 2014): 024614. https://doi.org/10.1103/PhysRevC.89.024614

Spider

GANIL Caen France

- Annular detector covering 30 to 47°
- E* resolution ~ 2.7 Mev (FWHM)
- 16 rings of 1.5 mm
- 16 sectors of 11° azimuthal range
- Angular resolution of about 1°
- Lots of result [1,2,3]

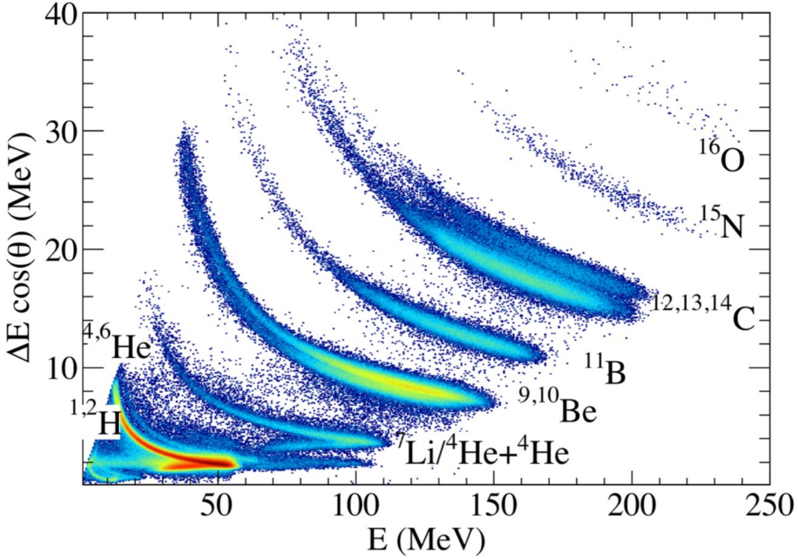
[1] M. Caamano et al. Phys. Rev. C 88 24605 (2013)
[2] C. Rodriguez-Tajes et al. Phys. Rev. C 89 024614 (2014)
[3] D.Ramos et al. Phys. Rev. C 97 054612 (2018)

Shortcoming

- E* resolution
- Some light recoil are ill-identified
- Counting rate too low for nuclear data

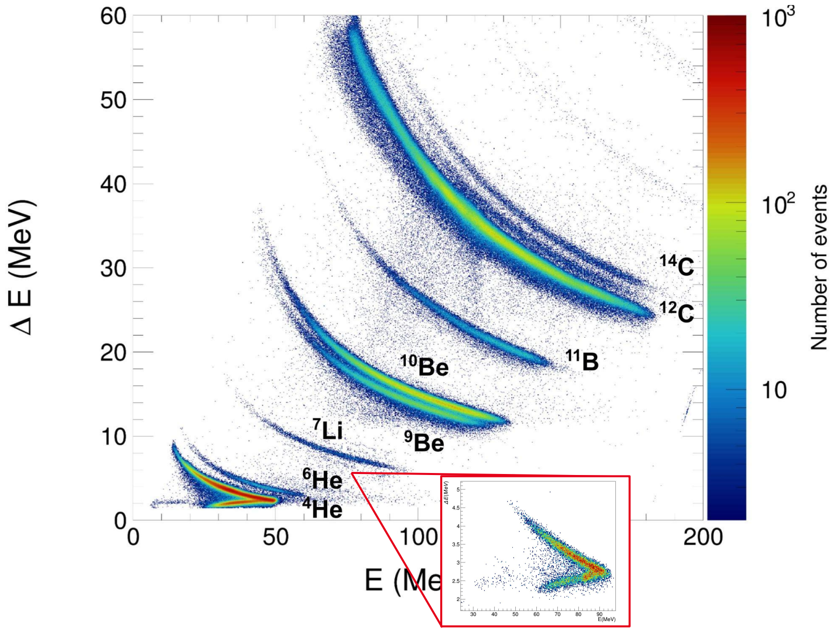
PID Comparison

Spider
(Previous generation)



Ramos, D., M. Caamaño, F. Farget, C. Rodríguez-Tajes, L. Audouin, J. Benlliure, E. Casarejos, et al. « Isotopic Fission-Fragment Distributions of U 238 , Np 239 , Pu 240 , Cm 244 , and Cf 250

PISTA



24ème COLLOQUE GANIL

AlPhaPha
8Be → 2α

PID Interpretation

Beam of 238U at ~6 Mev/A

→ **1428 Mev**

KE max of Be 8 : **200 Mev**

$$\beta = \frac{\vec{P}}{E} = \frac{\sqrt{T^2 + 2mT}}{T + m}$$

β ~ 0.22 , βγ ~ 0.23

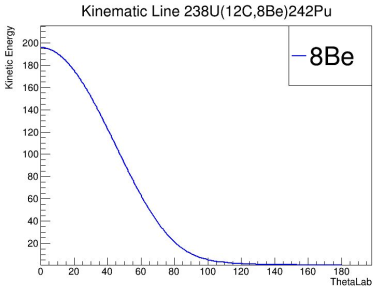
Bethe simplify

$$-\frac{1}{\rho}\left\langle \frac{dE}{dx} \right\rangle = \frac{2\pi z^2 e^4}{m_e v^2} \frac{Z}{A} N_A \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

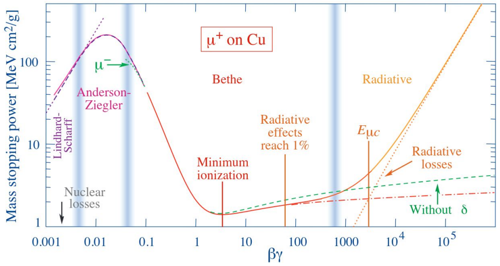
Source : Matthew Charles detector courses

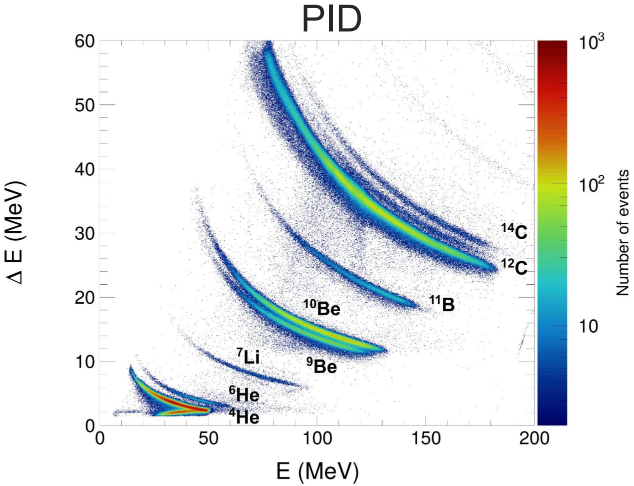
$$\frac{dE}{dx} \propto \frac{z^2}{v^2} \propto \frac{z^2 M}{T}$$

$$\boxed{\Delta E = \frac{Z^2 A u}{E}}$$



Source : PDG



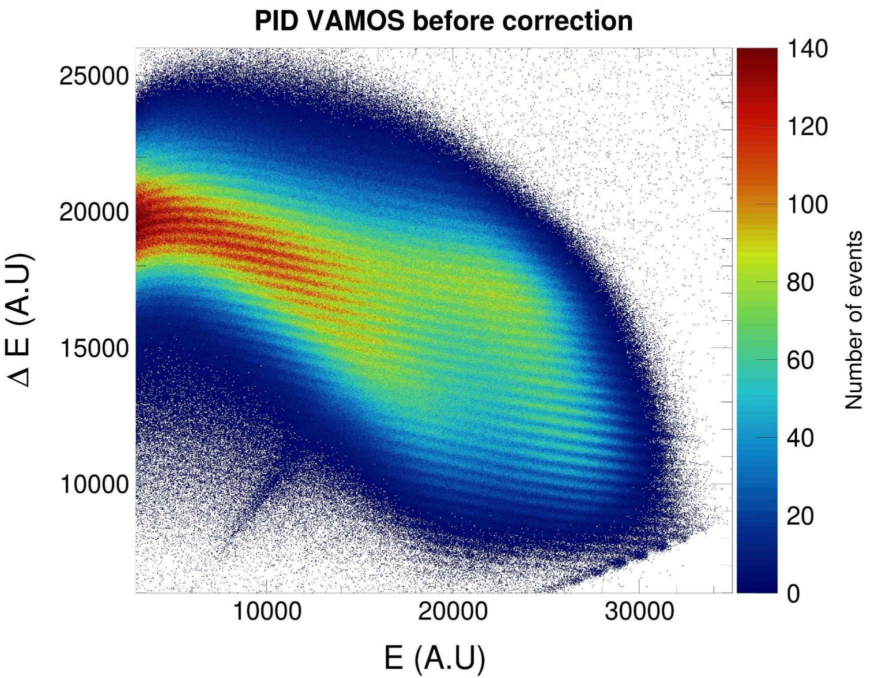


Work done on VAMOS

Enhancement of Z Resolution

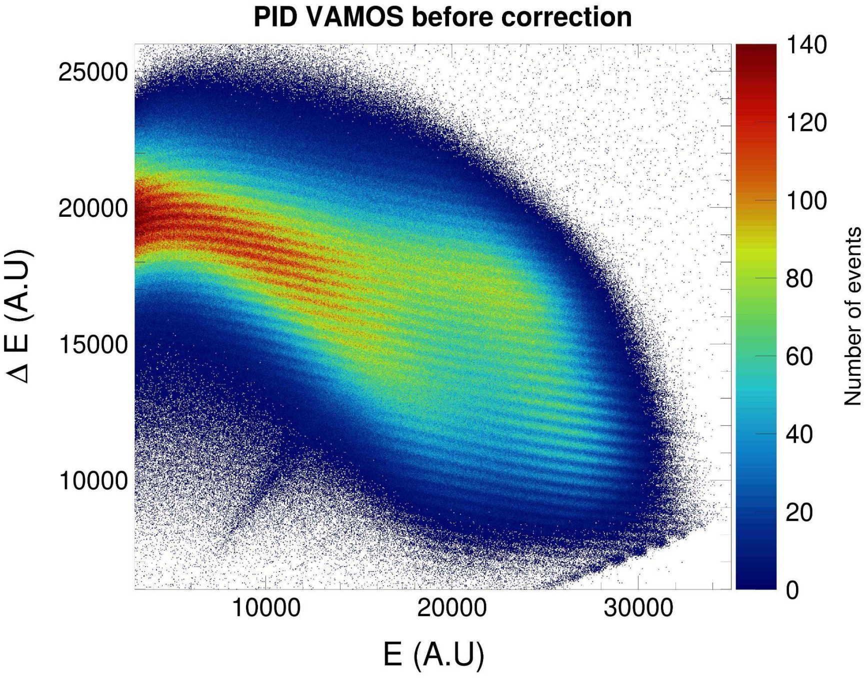
Corrections on IC output :

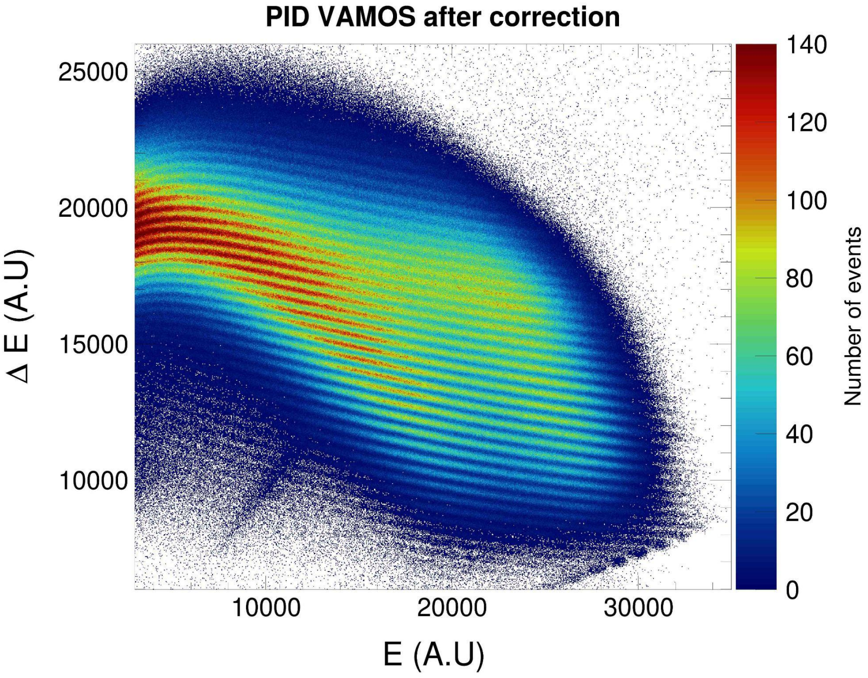
- As a function of Xf and Yf for the two first layer of the IC
- As a function of Yf for the later IC layer
- As a function of Θ_f



Work done on VAMOS

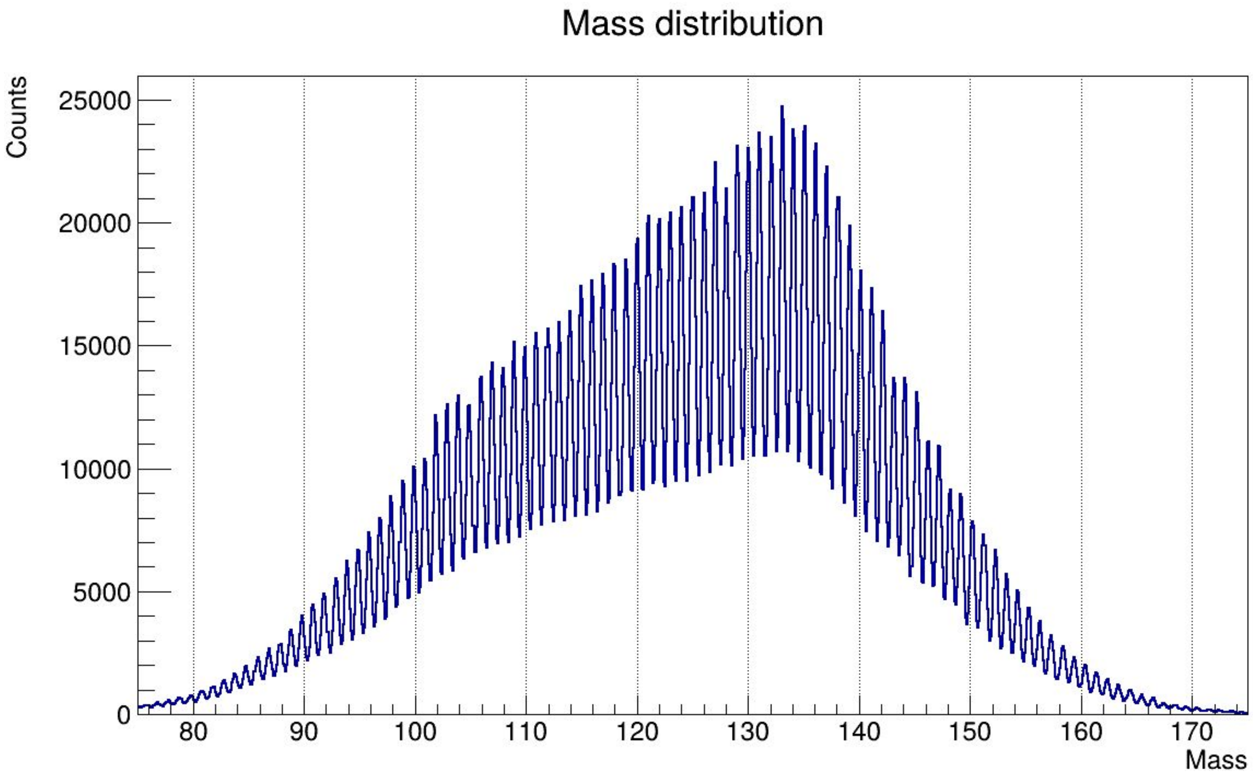
Enhancement of Z Resolution





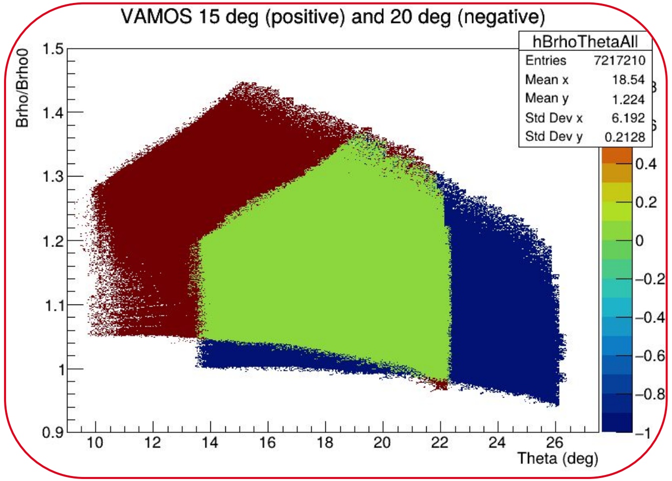
Work done on VAMOS

Mass calibration



2. VAMOS++ Acceptance

Setting matching



- We probe **different Fission Fragments with different VAMOS rotation**
- We need **a way to merge the data of different rotation**
- There is an **overlap in phase space**

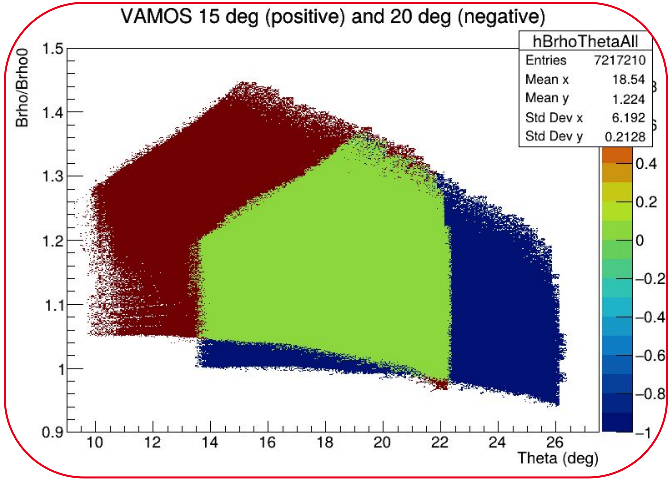
We have to find a way to **give each event a weight**.

This weight **should not induce a bias in the yield** for the experiment with more stat.

We'll give each event a weight **depending on it's experiment and if it's in the overlap zone**

2. VAMOS++ Acceptance

Setting matching

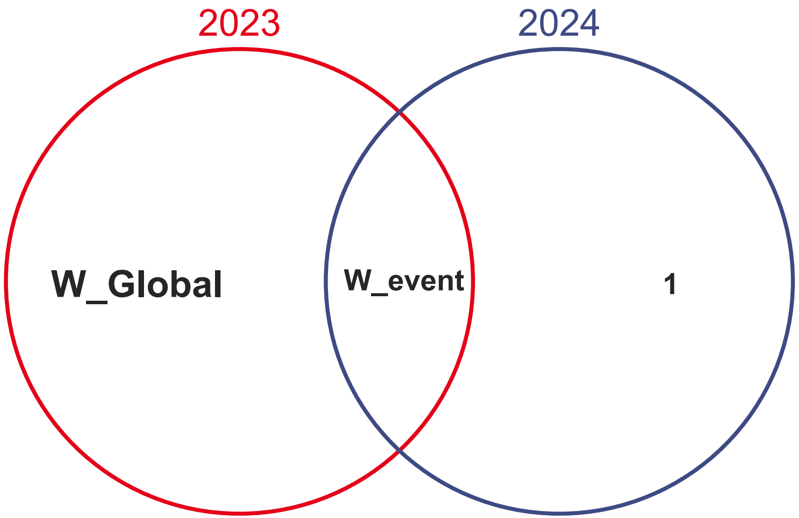


$$W_{2024} = \frac{N^{2024}_{overlap}}{N^{tot}_{overlap}}$$

Merged Tree

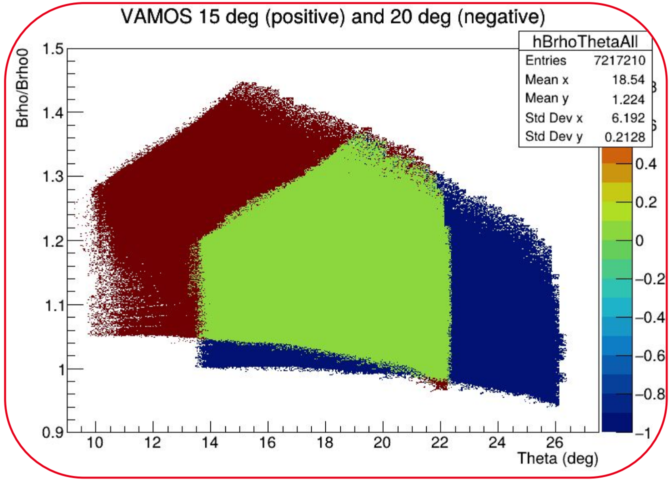
i'll use those to fill a new branch

-> OverlapWeight.



With W_event different depending if the event is from 2023 or 2024

2. VAMOS++ Acceptance
Setting matching



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Merged Tree

i'll use those to fill a new branch
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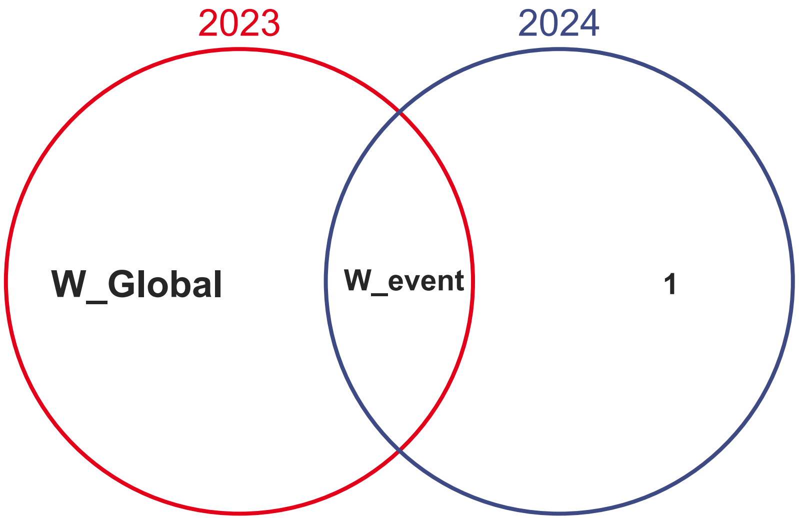


With W_event different depending if the event is from 2023 or 2024

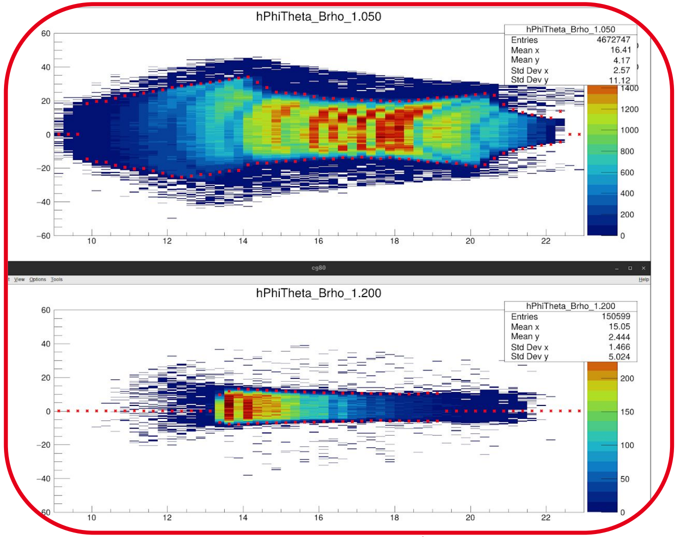
2. VAMOS++ Acceptance

PhiAcceptance

- Azimuthal acceptance of vamos wrt the beam axis.
- Different for each polar angle and rigidity
- **This should be flat for each theta brho couple.**

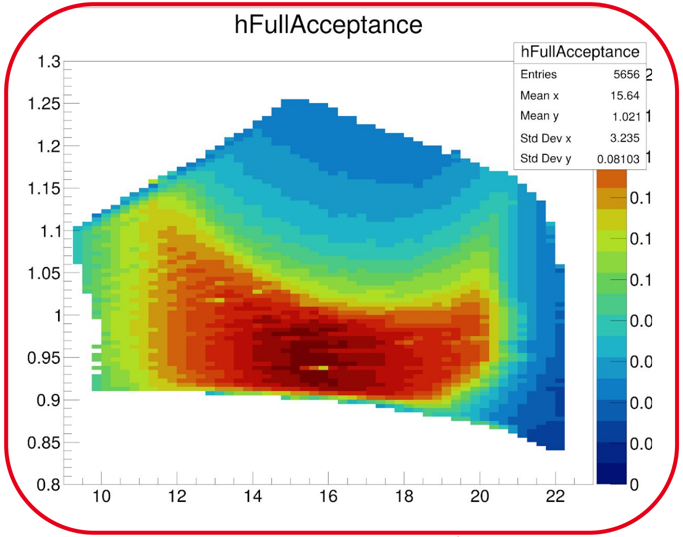
For each theta brho possible in VAMOS we create a contour, **give a weight inverse to the accepted angle percentage covered**

φ



θ

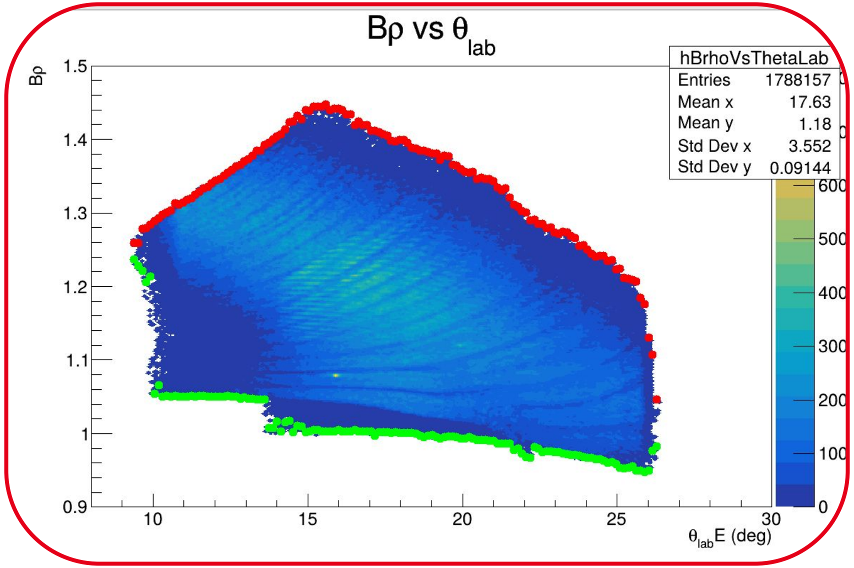
δ



θ

2. VAMOS++ Acceptance
ThetaCmAcceptance

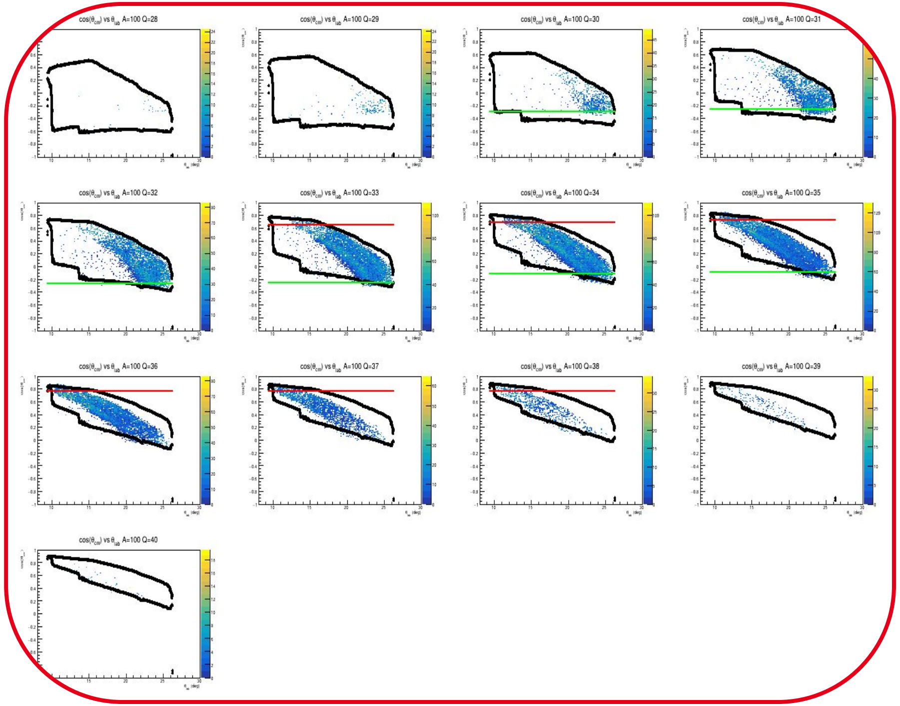
- This is the acceptance in the **polar angle of VAMOS**
- There is a **strong effect of the dipole**
- There is a **physical limit of where can the fission fragment be emitted.**



2. VAMOS++ Acceptance

ThetaCmAcceptance

- This is the acceptance in the **polar angle of VAMOS**
- There is a **strong effect of the dipole**
- There is a **physical limit of where can the fission fragment be emitted.**
- To properly characterise it we take only **a polar angle range where all the charge state of given nuclei are accepted by VAMOS**



2. VAMOS++ Acceptance
ThetaCmAcceptance

- This is the acceptance in the **polar angle of VAMOS**
- There is a **strong effect of the dipole**
- There is a **physical limit of where can the fission fragment be emitted.**
- To recover properly characterise it we take only **a polar angle range where all the charge state of given nuclei are accepted by VAMOS**
- **Then use an inversely proportional weight**