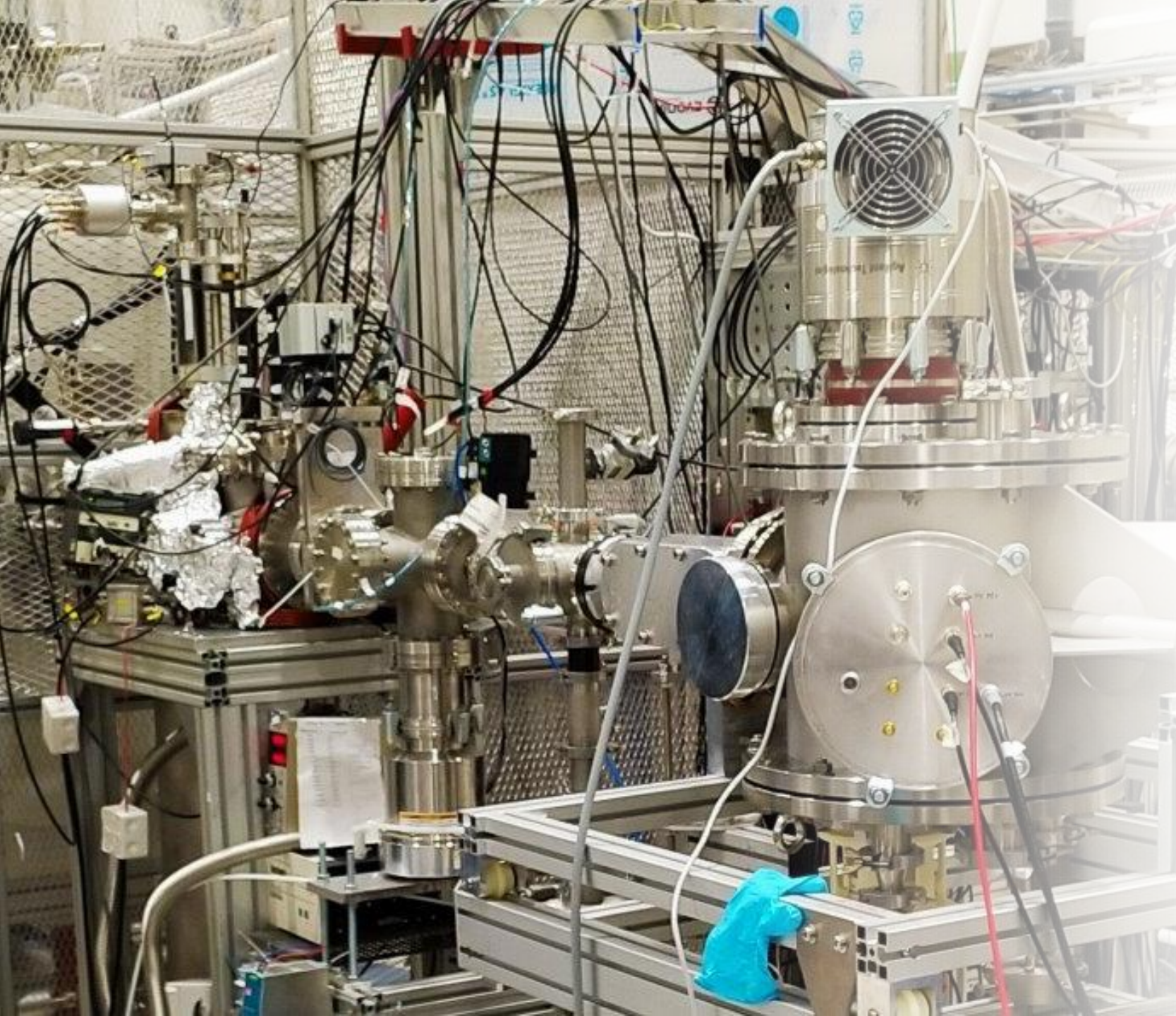

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Measurement of Beta Decay Properties of Nuclei of Interest for Nuclear Structure and Astrophysics, and Applications

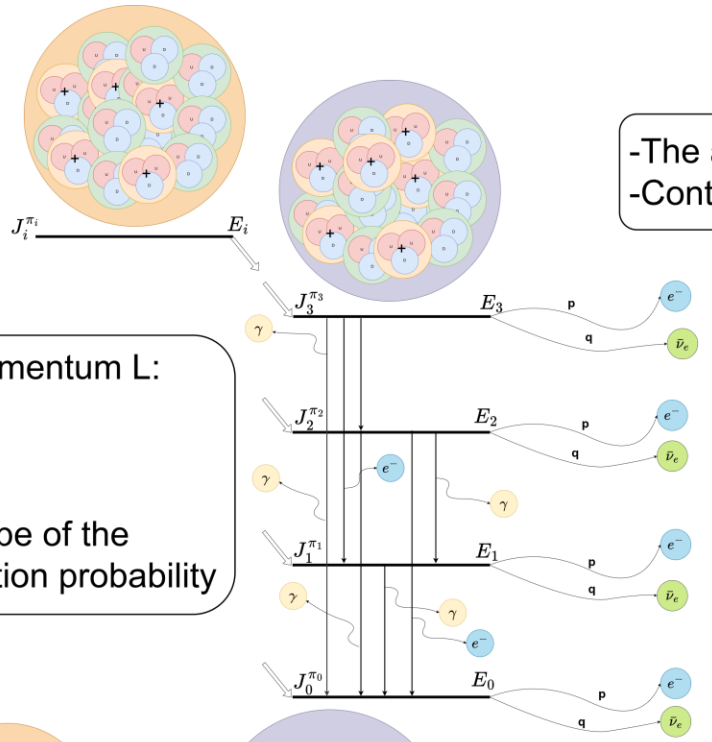
PhD Hour – DURAND Samuel

Supervisors :
ESTIENNE Magali,
FALLOT Muriel

Outline

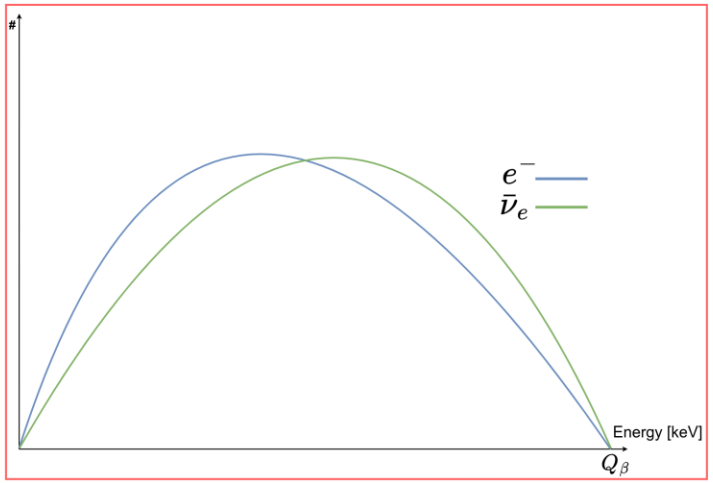
- Beta decay properties
- Physics motivations
- The e-Shape Experiment
- Detector and Geant4 Geometry
- Detector Calibration
- Data-Simulation Comparison
- Conclusions and Outlooks

Beta decay properties



-The available decay energy, called Q-value, is shared between the emitted leptons
-Continuous energy spectra for the emitted particles.

The leptons carry an angular momentum L:
-Allowed transition
ΔL = 0
-Forbidden transition
ΔL ≠ 0 -> modification of the shape of the spectrum, reduction of the transition probability



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

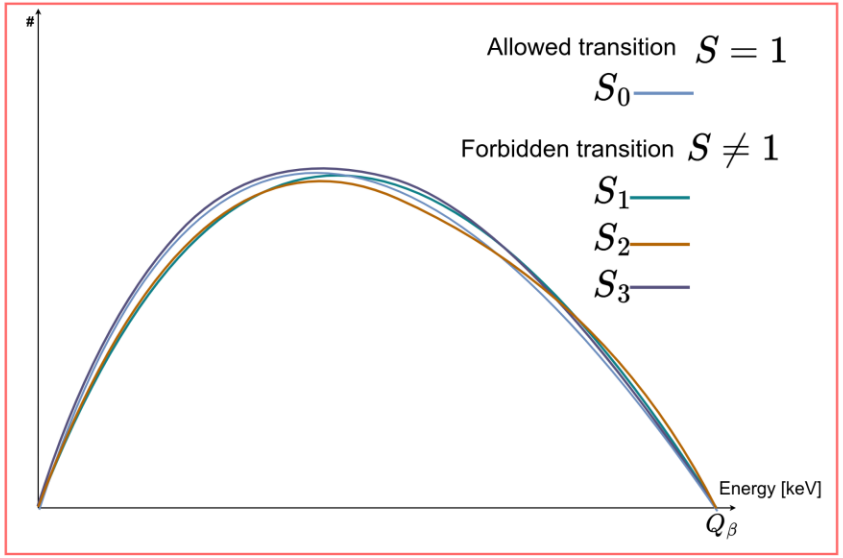
- Unlike allowed transitions, forbidden decays are much less understood
-Their accurate description remains a major challenge.

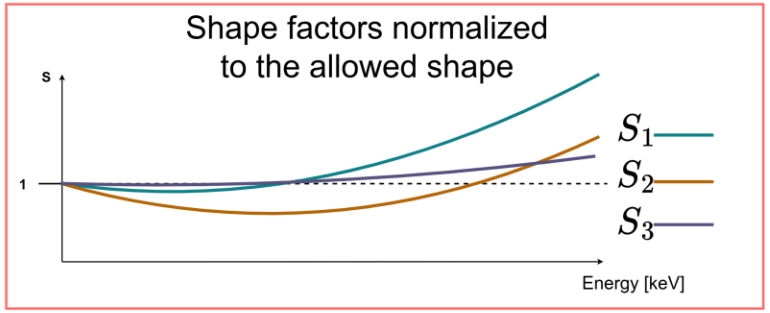
Beta decay properties

Electron energy distribution

$$N_e(p) \approx p^2(Q-T_e)^2 F(Z',p)|M_{fi}^a|^2 S(p,q)(1+\delta(Z,A,p))$$

Phase space	$p^2(Q-T_e)^2$	Kinematic term predicted by Fermi's theory
Fermi function	$F(Z',p)$	Coulomb correction between the emitted electron and the daughter nucleus
Allowed nuclear matrix element	$\lvert M_{fi}^a\rvert^2$	Energy-Independent nuclear transition strength used for allowed approximation
My analysis focus → Shape factor	$S(p,q)$	Energy-dependent nuclear transition strength term accounting for nuclear structure effects beyond the allowed approximation
Quantum corrections	$1+\delta(Z,A,p)$	Higher-order corrections, including radiative, finite-size, screening, recoil, and weak-magnetism effects

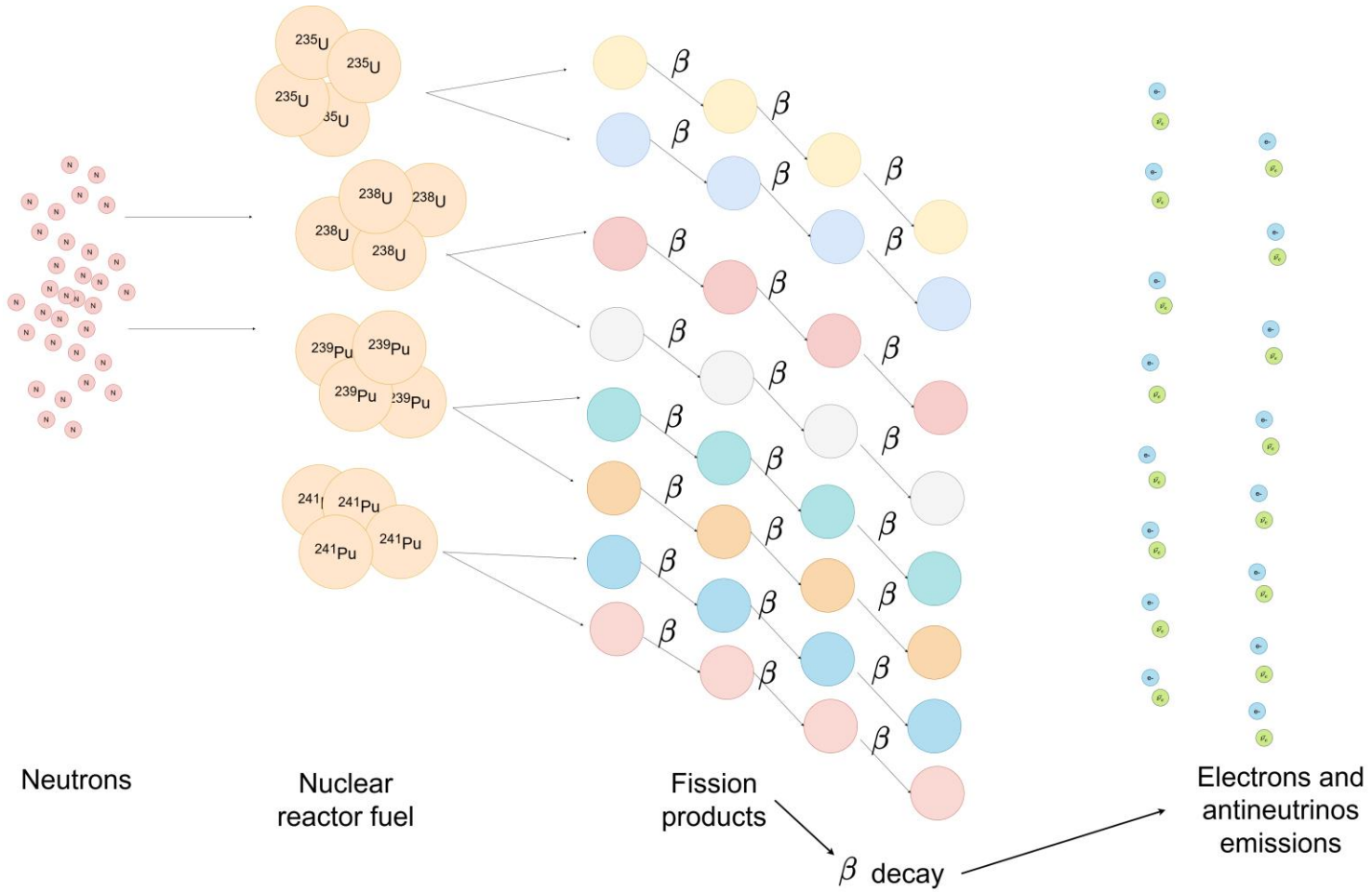




Physics motivations

Reactor antineutrino spectra prediction: introduction

- Reactor antineutrino spectra orginate from the beta decay of hundreds of fission fragments in the reactor core
- Their prediction requires combining nuclear structure and decay data: fission yields, branching ratios and beta spectra
- The spectral shape reflects detailed nuclear structure
- Accurate predictions are essential inputs for reactor neutrino experiments and oscillation measurements



Physics motivations

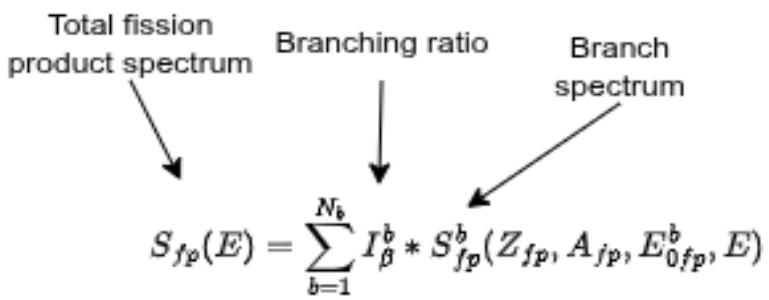
Reactor antineutrino spectra prediction: methods

Conversion method

- Fit of effective beta spectra decomposed into virtual branches to reproduce ILL integral beta spectrum measurements (1980s), converted into antineutrino spectra using beta decay theory
- Weak dependence on nuclear decay data, but subject to modeling biases in the conversion method (virtual β branches, fitting procedure)

Summation method

- Builds the spectrum by summing β-decay branches of fission products, weighted by fission yields and branching ratios
- Predictive and flexible but can be limited by nuclear data uncertainties

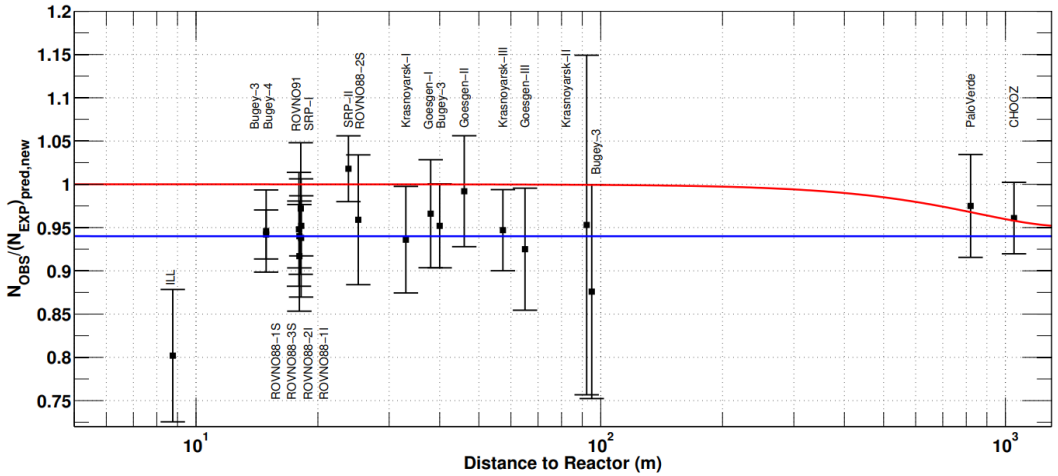


Physics motivations

Reactor antineutrino spectra prediction: anomalies

Reactor antineutrino anomaly (RAA)

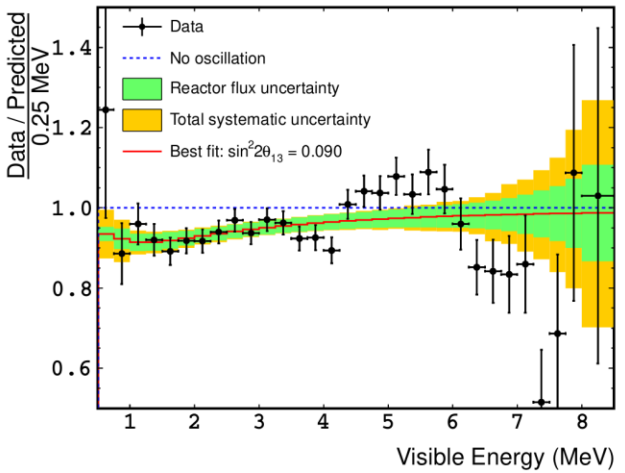
- Re-evaluation of reactor antineutrino flux predictions increased the expected flux (Huber-Mueller 2011)
- Short-baseline reactor experiments antineutrino flux measurements deficit of 6% when compared to predictions
- Possible origins : nuclear physics, experimental systematics, or new neutrino physics



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

Shape anomaly

- Distortion of the measured antineutrino energy spectrum relative to predictions
- Excess of events observed (~10%) around 5-7MeV antineutrino energy reported by multiple reactor experiments (Daya Bay, RENO, Double Chooz)
- Suggests defficiencies in reactor spectrum modeling and/or nuclear data (shape factors are a leading hypothesis)



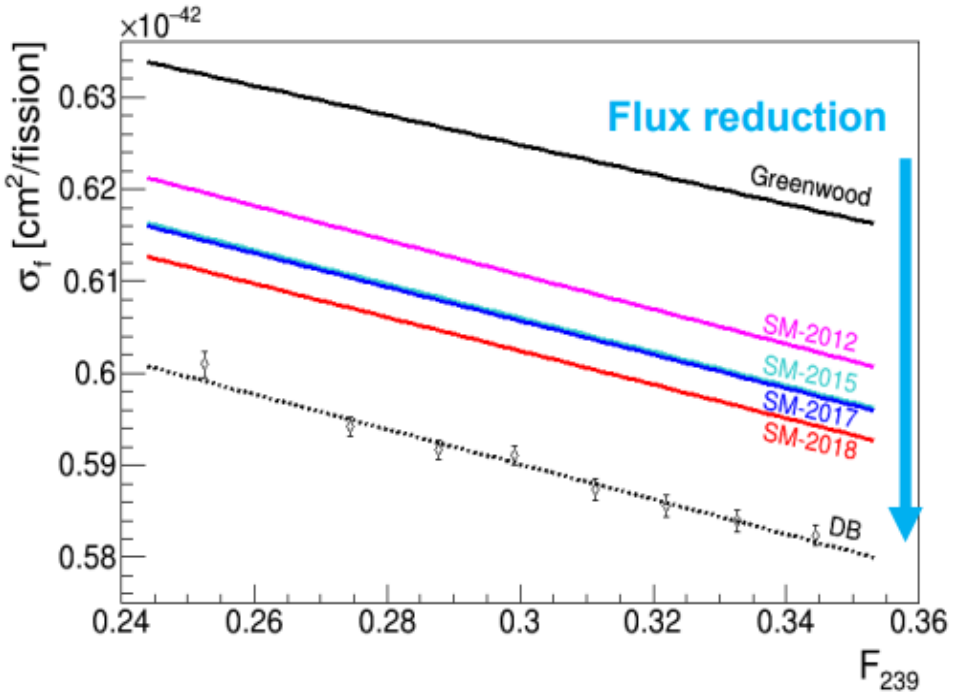
Y. Abe et al. (Double Chooz Collaboration), J. High Energy Phys. 10 (2014) 086; 02 (2015) 74

Physics motivations

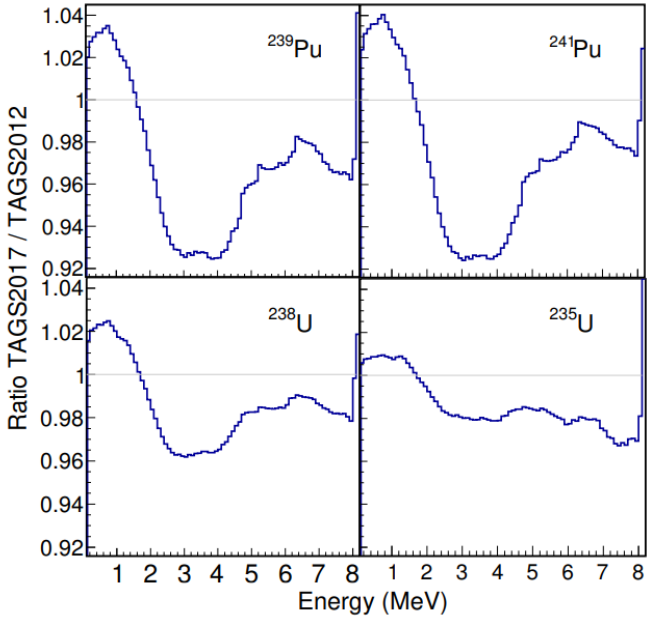
Reactor antineutrino spectra prediction: anomalies status

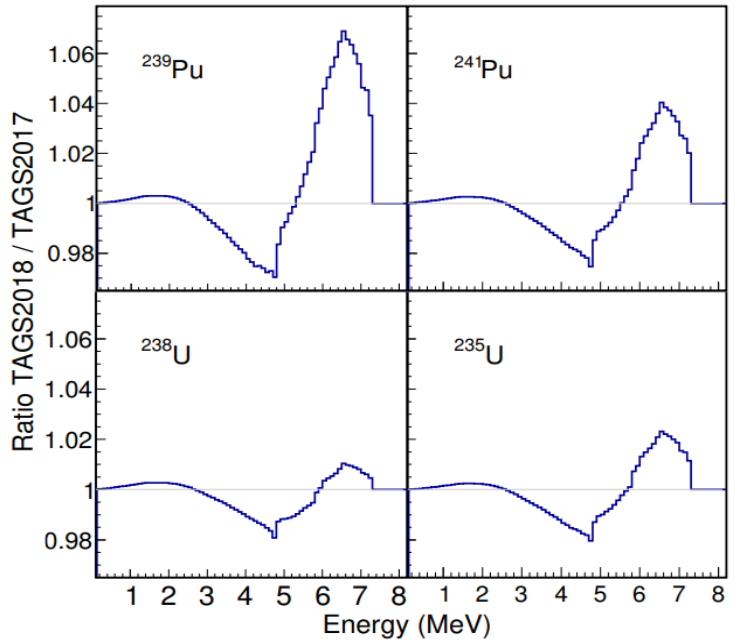
Reactor antineutrino anomaly (RAA)

- The summation method has been strongly improved over the years along with nuclear data and is now more predictive than the conversion method
- The antineutrino flux prediction improved with TAGS data being included (~1% discrepancy)



M. Estienne et al., Phys. Rev. Lett. 123 (2019) 022502





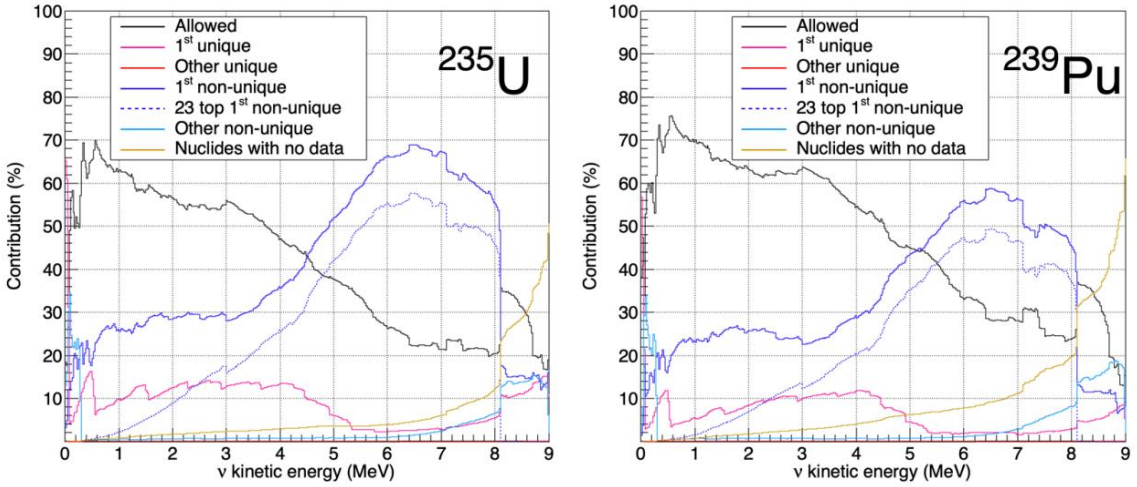
Algora, A., Tain, J.L., Rubio, B., Fallot, M., Gelletly, W. Beta-decay studies for applied and basic nuclear physics. *Eur. Phys. J. A* **57**, 85 (2021)

Physics motivations

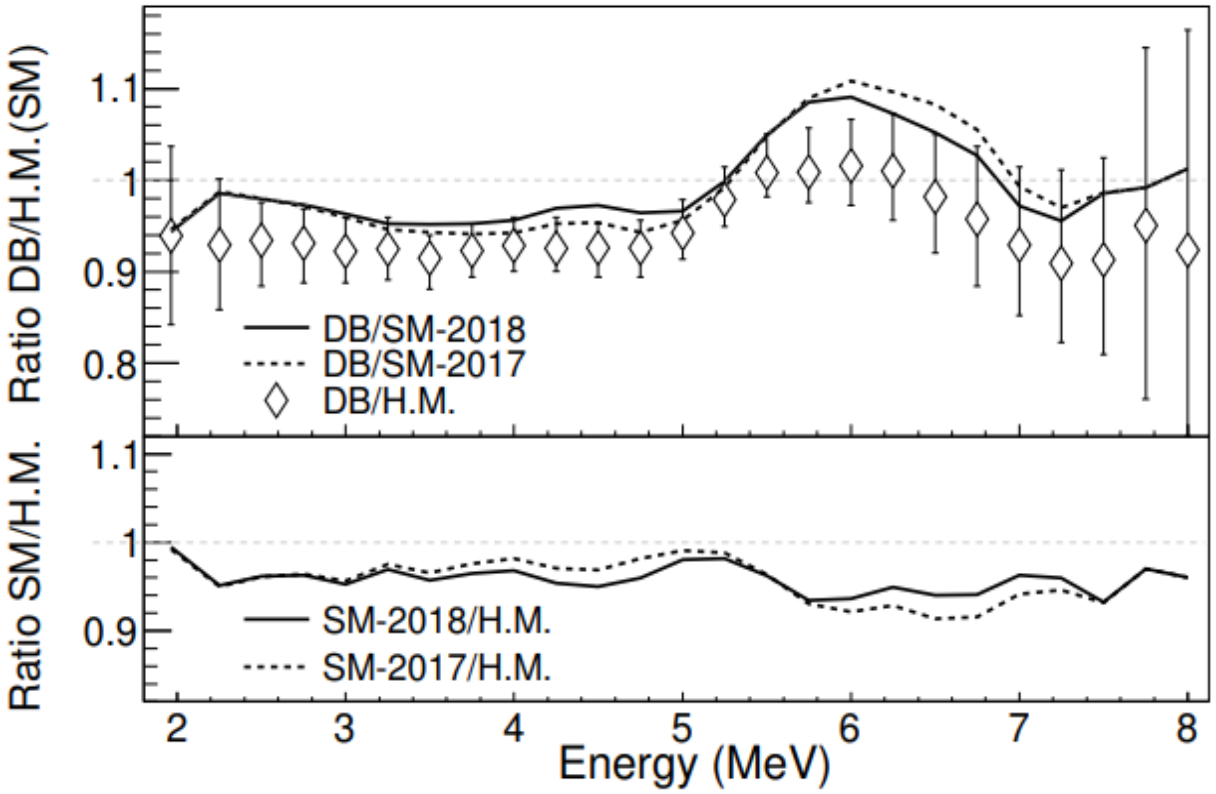
Reactor antineutrino spectra prediction: anomalies status

Shape anomaly

- Both prediction methods still observe the shape anomaly and its origin is still unknown
- Need experimental data to validate or refute the various hypotheses to explain this anomaly
- Forbidden transition shape factors are a leading hypothesis



L. Perissé et al., Phys. Rev. C 108 (2023), 055501



M. Estienne et al., Phys. Rev. Lett. 123 (2019) 022502

Physics motivations

Reactor antineutrino spectra prediction: physics cases

Physics cases for my PhD:
- ^{96}Y: small shape factor prediction, high contribution to the spectra
-^{94}Y: large shape factor prediction, moderate contribution to the spectra

TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in [12] and assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%)and ^{238}U (8.7%) for a 450 day irradiation time. and using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

Zakari-Issoufou et al. PRL 115.102503(2015)

Table I. Dominant forbidden transitions above 4 MeV. Here Q_β is the ground-state to ground-state Q-value, E_{ex} the excitation energy of the daughter level, BR the branching ratio of the transition normalized to one decay and FY the cumulative fission yield of ^{235}U from the ENDF database [43]. Transitions with small fission yields shown here contribute substantially more for ^{238}U and ^{241}Pu.

Nuclide	Q_β (MeV)	E_{ex} (MeV)	BR (%)	$J_i^\pi \to J_f^\pi$	FY (%)	ΔJ
^{89}Br	8.3	0	16	$3/2^- \to 3/2^+$	1.1	0
^{90}Rb	6.6	0	33	$0^- \to 0^+$	4.5	0
^{91}Kr	6.8	0.11	18	$5/2^+ \to 5/2^-$	3.5	0
^{92}Rb	8.1	0	95.2	$0^- \to 0^+$	4.8	0
^{93}Rb	7.5	0	35	$5/2^- \to 5/2^+$	3.5	0
^{94}Y	4.9	0.92	39.6	$2^- \to 2^+$	6.5	0
^{95}Rb†	9.3	0.68	5.9	$5/2^- \to 5/2^+$	1.7	0
^{95}Sr	6.1	0	56	$1/2^+ \to 1/2^-$	5.3	0
^{96}Y	7.1	0	95.5	$0^- \to 0^+$	6.0	0
^{97}Y	6.8	0	40	$1/2^- \to 1/2^+$	4.9	0
^{98}Y	9.0	0	18	$0^- \to 0^+$	1.9	0
^{133}Sn	8.0	0	85	$7/2^- \to 7/2^+$	0.1	0
^{135}Te	5.9	0	62	$(7/2-) \to 7/2^+$	3.3	0
^{135}Sb	8.1	0	47	$(7/2+) \to (7/2^-)$	0.1	0
^{136m}I	7.5	1.89	71	$(6^-) \to 6^+$	1.3	0
^{136m}I	7.5	2.26	13.4	$(6^-) \to 6^+$	1.3	0
^{137}I	6.0	0	45.2	$7/2^+ \to 7/2^-$	3.1	0
^{142}Cs	7.3	0	56	$0^- \to 0^+$	2.7	0
^{86}Br	7.3	0	15	$(1^-) \to 0^+$	1.6	1
^{86}Br	7.3	1.6	13	$(1^-) \to 2^+$	1.6	1
^{87}Se	7.5	0	32	$3/2^+ \to 5/2^-$	0.8	1
^{89}Br	8.3	0.03	16	$3/2^- \to 5/2^+$	1.1	1
^{91}Kr	6.8	0	9	$5/2^+ \to 3/2^-$	3.4	1
^{95}Rb†	9.3	0.56	6.0	$5/2^- \to (7/2^+)$	1.7	1
^{95}Rb	9.3	0.68	5.9	$5/2^- \to 3/2^+$	1.7	1
^{134m}Sb	8.5	1.69	42	$(7-) \to 6^+$	0.8	1
^{134m}Sb	8.5	2.40	54	$(7^-) \to (6^+)$	0.8	1
^{136}Te	5.1	0	8.7	$0^+ \to (1^-)$	3.7	1
^{138}I	8.0	0	26	$(1-) \to 0^+$	1.5	1
^{140}Xe	4.0	0.08	8.7	$0^+ \to 1^-$	4.9	1
^{140}Cs	6.2	0	36	$1^- \to 0^+$	5.7	1
^{143}Cs	6.3	0	25	$3/2^+ \to 5/2^-$	1.5	1
^{88}Rb	5.3	0	76.5	$2^- \to 0^+$	3.6	2
^{94}Y	4.9	0	41	$2^- \to 0^+$	6.5	2
^{95}Rb	9.3	0	0.1	$5/2^- \to 1/2^+$	1.7	2
^{139}Xe	5.1	0	15	$3/2^- \to 7/2^+$	5.0	2

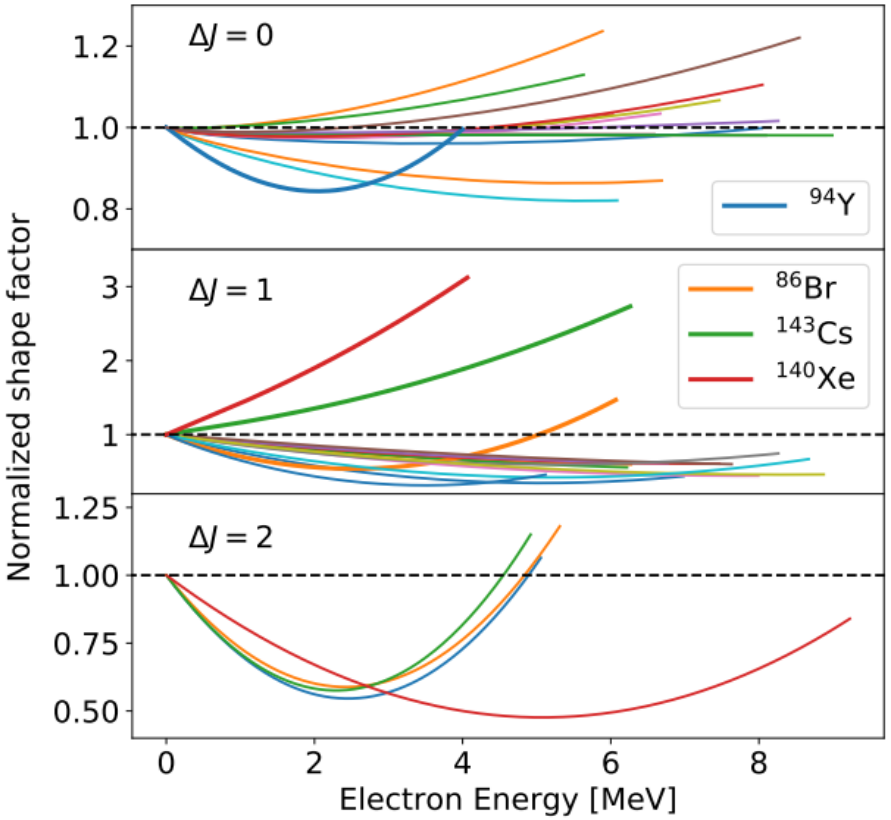
L. Hayen et al., PRC.100.054323

Physics motivations

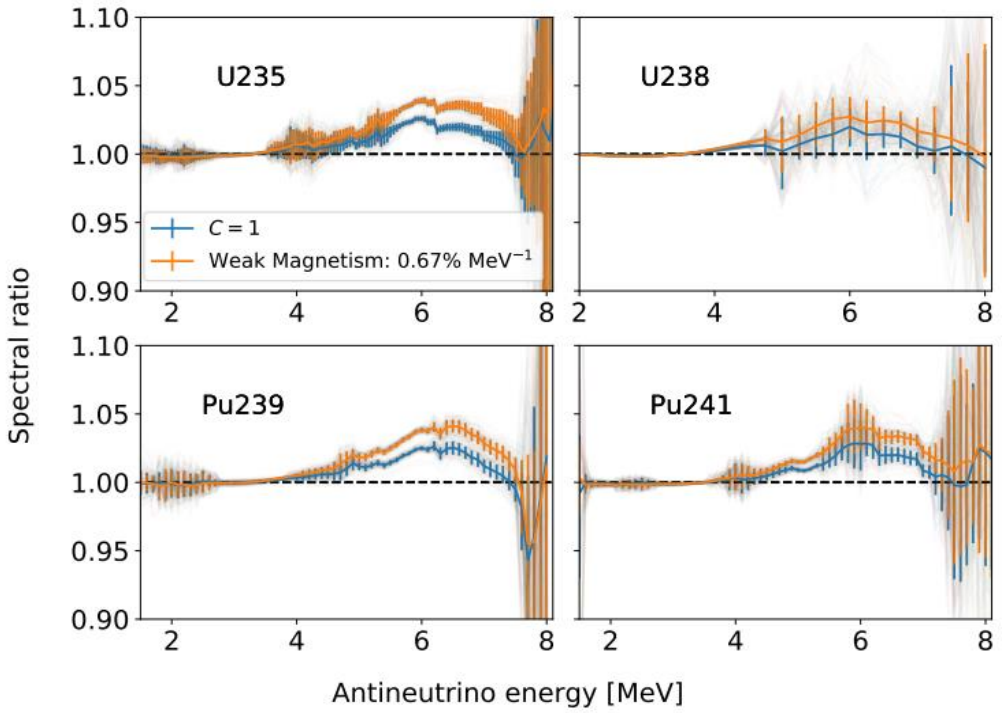
Reactor antineutrino spectra prediction: physics cases

Physics cases for my PhD:
- ^{96}Y: small shape factor prediction, high contribution to the spectra
-^{94}Y: large shape factor prediction, low contribution to the spectra

Shape factors prediction



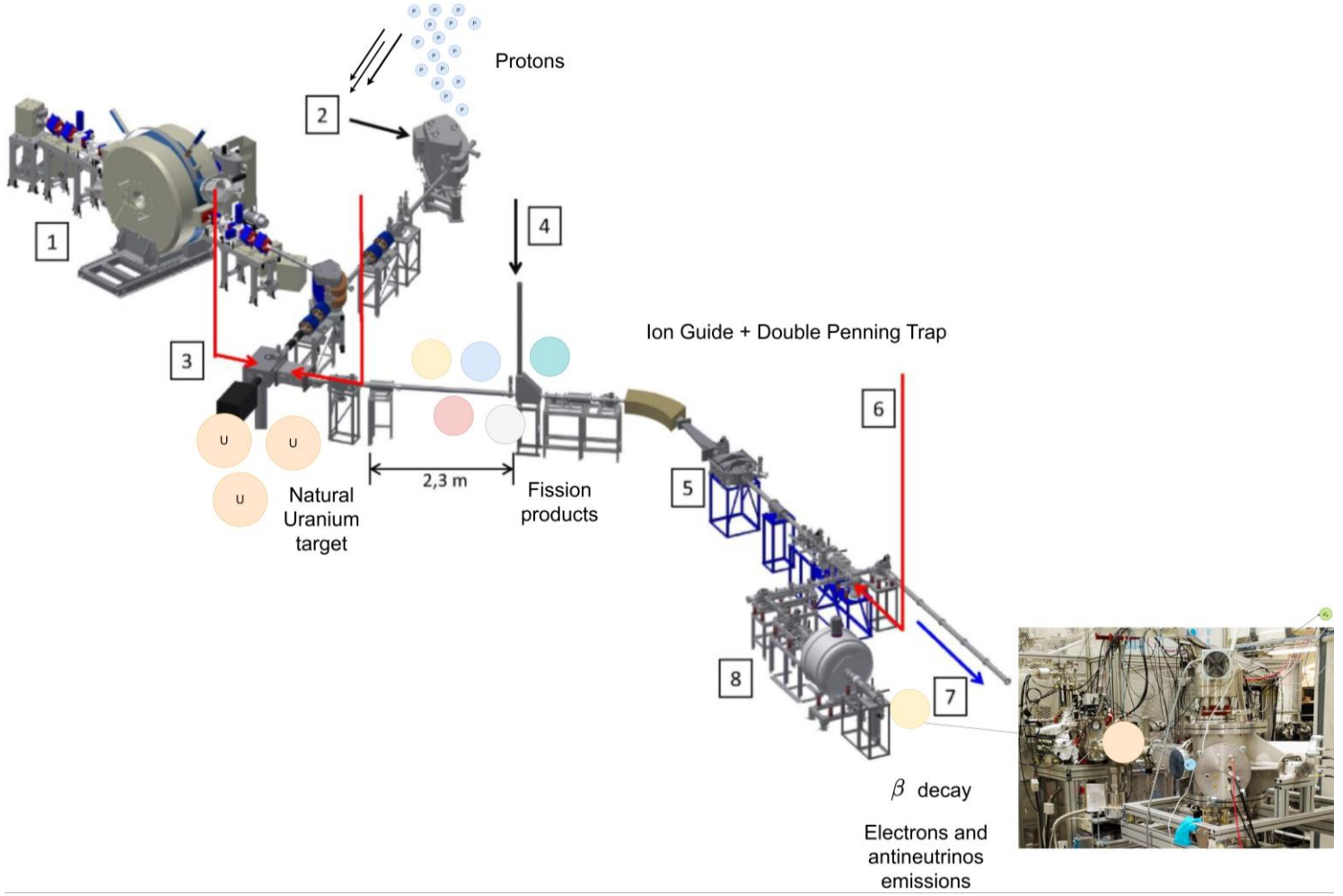
Ratio of antineutrino spectra predicted with and without those shape factors



L. Hayen et al., PRC.100.054323

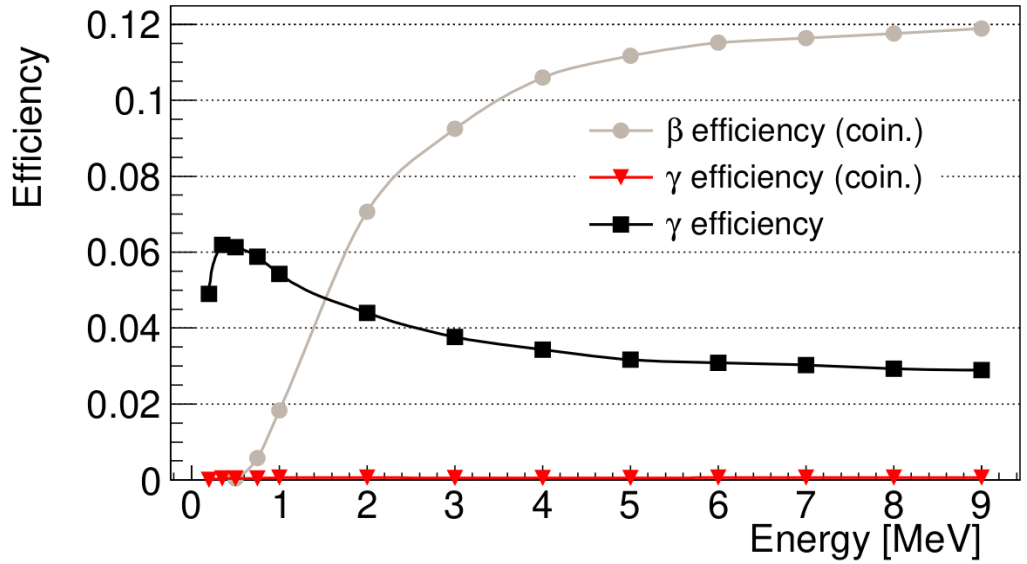
The e-Shape experiment

- Jyväskylä, Finland, IGISOL-4
- 2 experimental campaigns (2022, 2023)
- Dozen measured nuclei of interest in the 2nd campaign

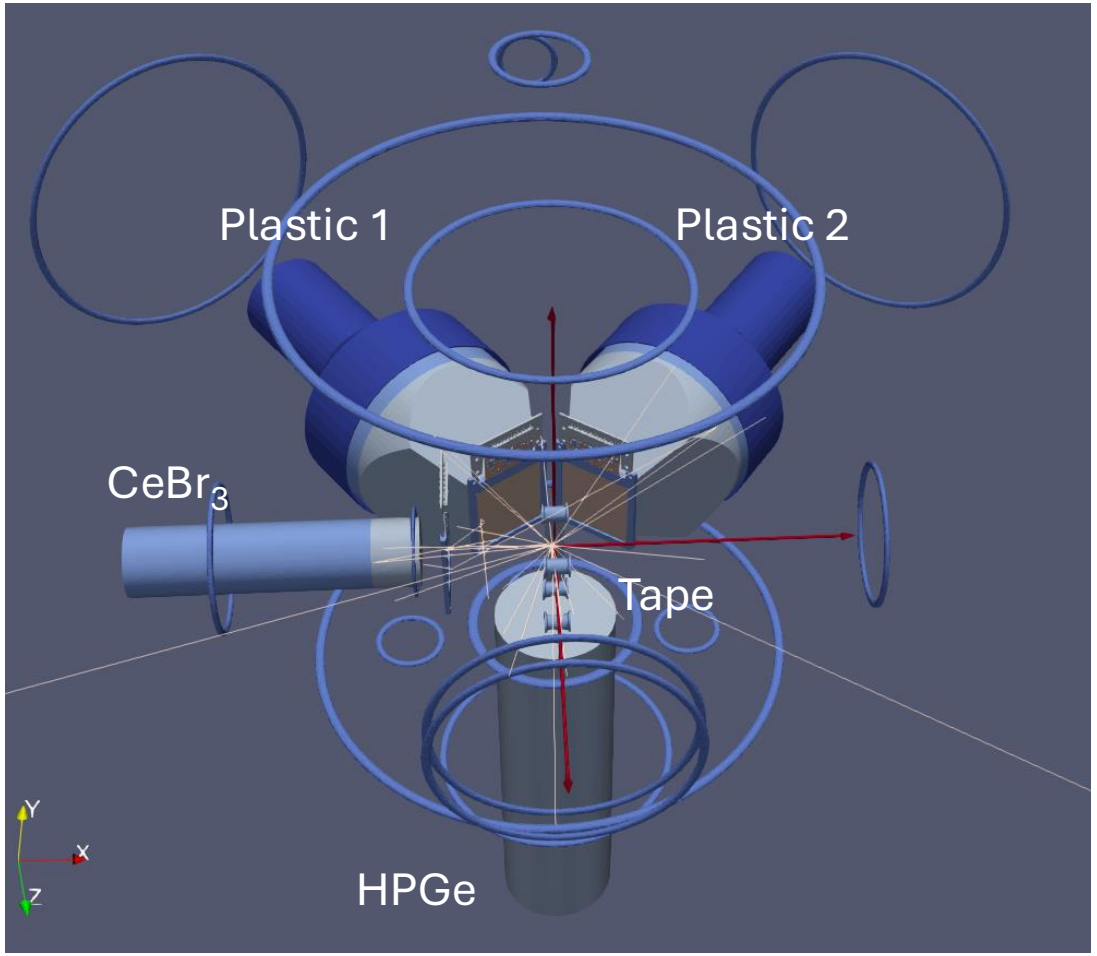


Detector and GEANT4 geometry

- 3 Telescopes + 1 HPGe
- Telescope : Scintillator (plastic or $CeBr_3$) + Semiconductor (300µm silicon for plastic telescopes and 500µm for $CeBr_3$ telescope)
- Coincidence : subtraction of most of the gamma spectrum
- For data acquisition, FASTER electronics (LPC Caen, France) was used



V. Guadilla et al 2024 JINST 19 P02027

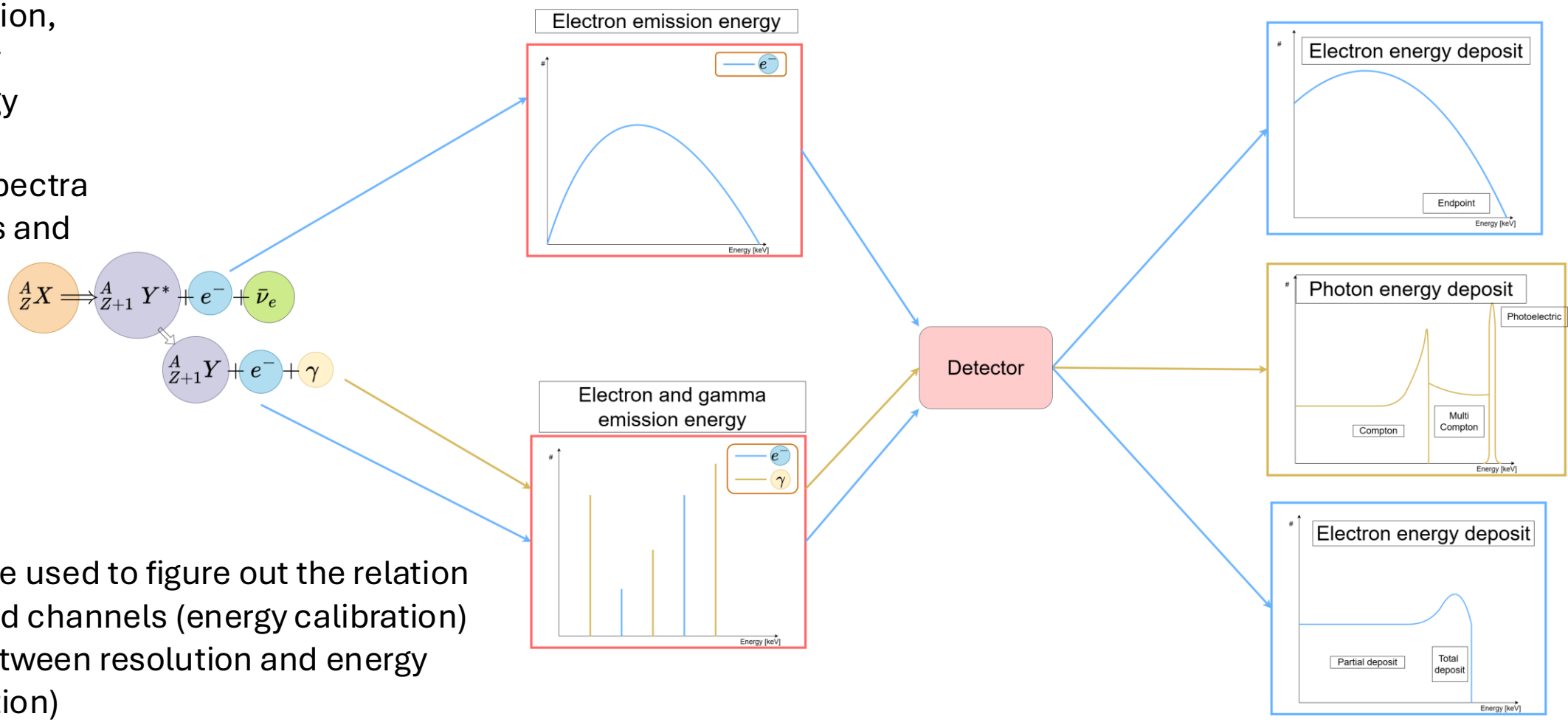


Samuel Durand

Detectors calibration

Calibration peaks identification : introduction

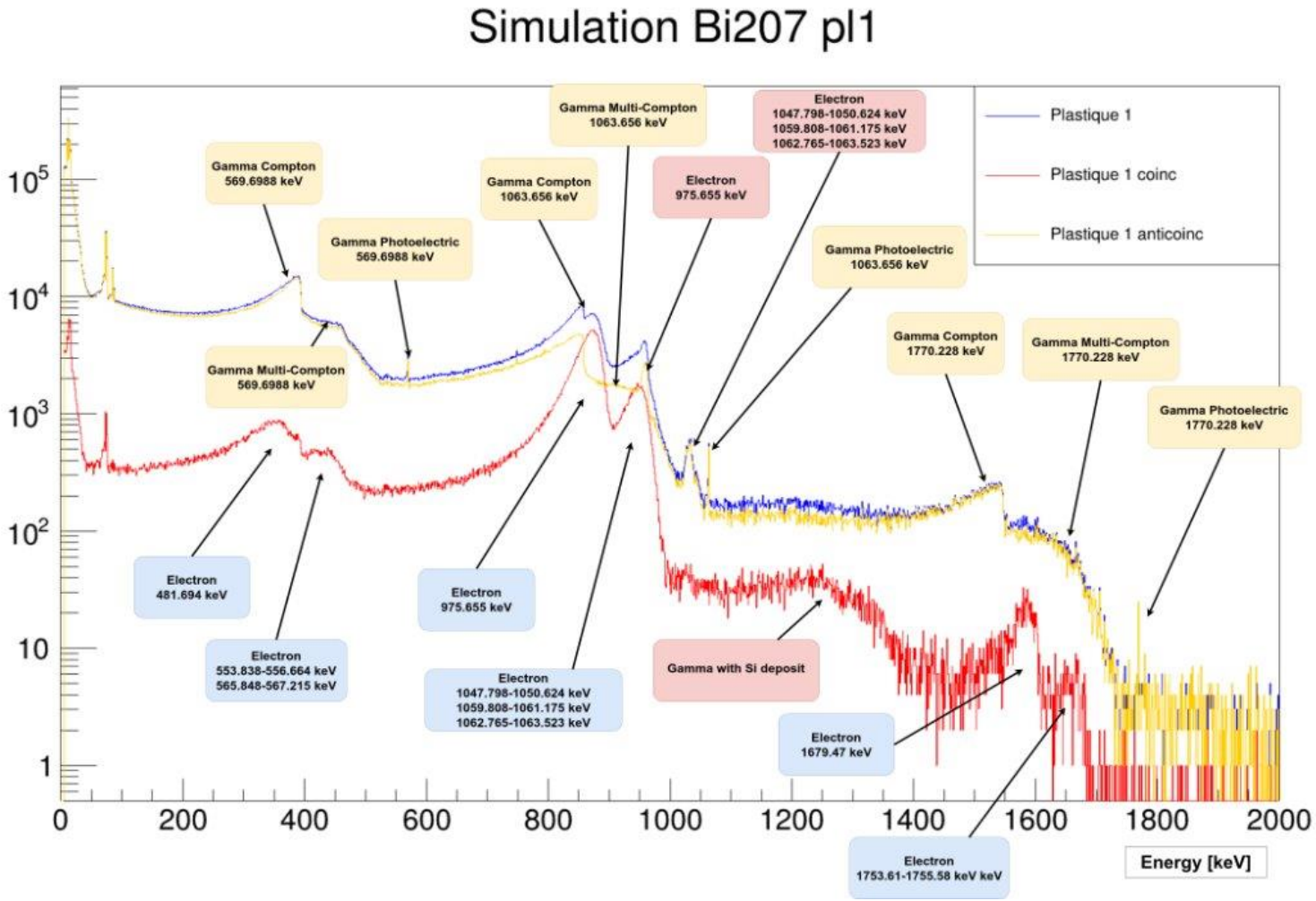
To perform calibration, we need to identify structures of energy deposit within the electromagnetic spectra in both simulations and measurements



Once done it can be used to figure out the relation between energy and channels (energy calibration) and the relation between resolution and energy (resolution calibration)

Detectors calibration

Calibration peaks identification



Identification of calibration peaks in nuclei/background spectra for each detector over ~0–8 MeV, accounting for peak merging and resolution effects.

Samuel Durand

CALIBRATION PEAKS USED SO FAR

- Fitting known structures both in measurements and simulation
- For γ rays in HPGe and $CeBr_3$ detectors, photopeaks were used whereas in plastic detectors compton edges were used due to their different energy deposit response
- Due to their design, silicon detector calibration was performed using only conversion electrons below 1.1MeV

	^{207}Bi	^{40}K	^{208}Tl	^{98}Nb	^{114}Ag	^{91}Rb	^{90}Rb	^{96}Y	^{92}Rb
only for silicon detecotrs	c.e. 482	γ 1461	γ 2615	ep 4600	ep 5072	ep 5899	ep 6579	ep 7096	ep 8096
only for silicon detecotrs	c.e. 554-557					γ 94			
	γ 570					γ 346			
	γ 1064					γ 439			
only for plastic and silicon	c.e. 976					γ 593			
only for plastic and silicon	c.e. 1047-1064					γ 603			
	γ 1770					γ 1137			
						γ 1616			
						γ 1971			
						γ 2564			
						γ 3147			
						γ 3600			
						γ 4078			

only for HPGe and $CeBr_3$

only for $CeBr_3$

Note : Due to the design of the setup, plastic scintillators see mostly electrons with an emission energy higher than ~400keV and for $CeBr_3$ ~1600keV,

ep : endpoint
c.e. : conversion electron

Energy is in keV

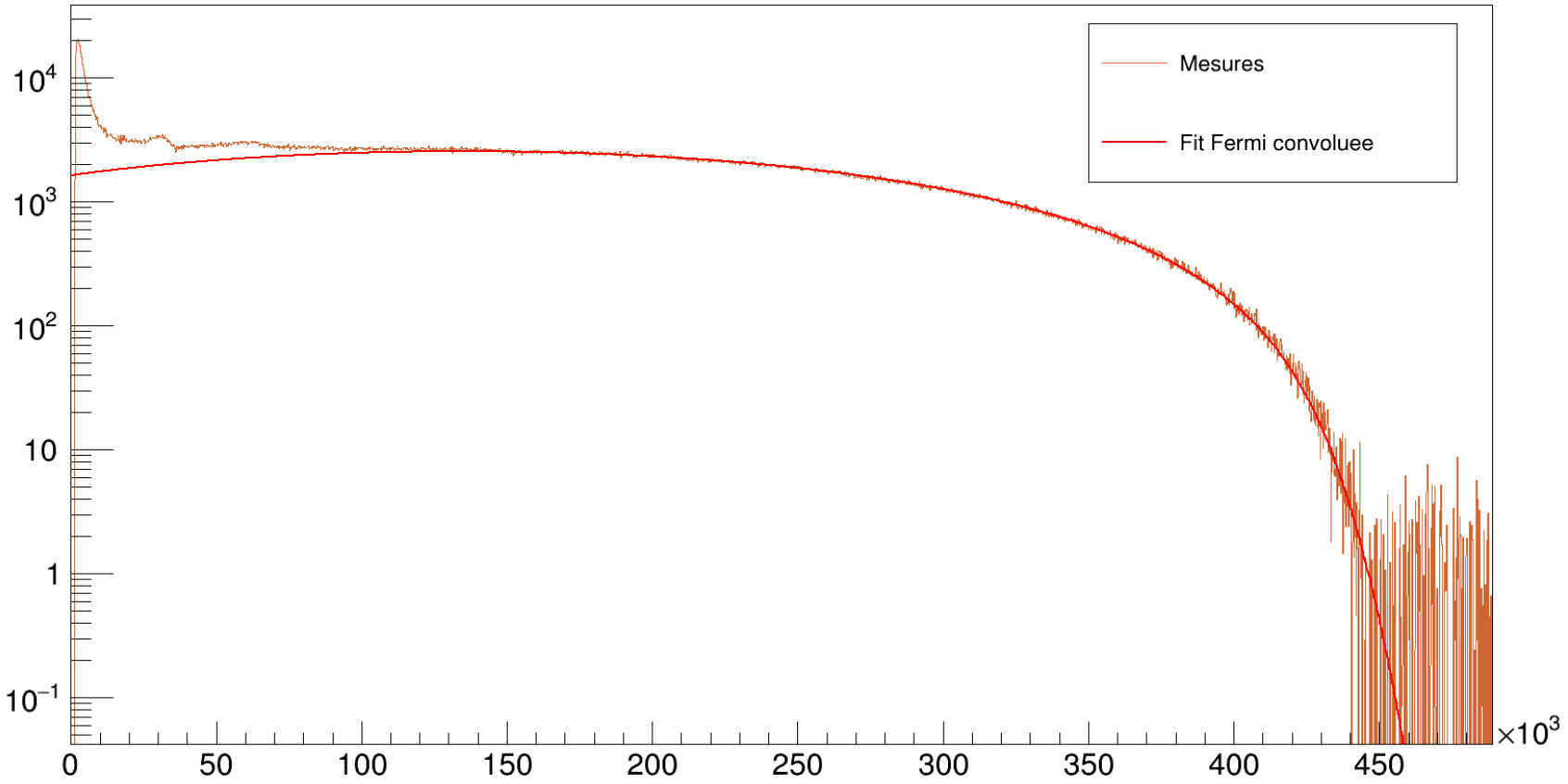
Detectors calibration

Fitting the calibration peaks

- Fitting known structure both in measurements and simulation
- Conversion electron
- Compton edge
- Photopeak
- Endpoint

- Functions used :
- Crystal Ball
- Gaussian
- Fermi function x Phase space

Endpoint fit on a ^{92}Rb measurement in Plastic scintillator



Detectors calibration

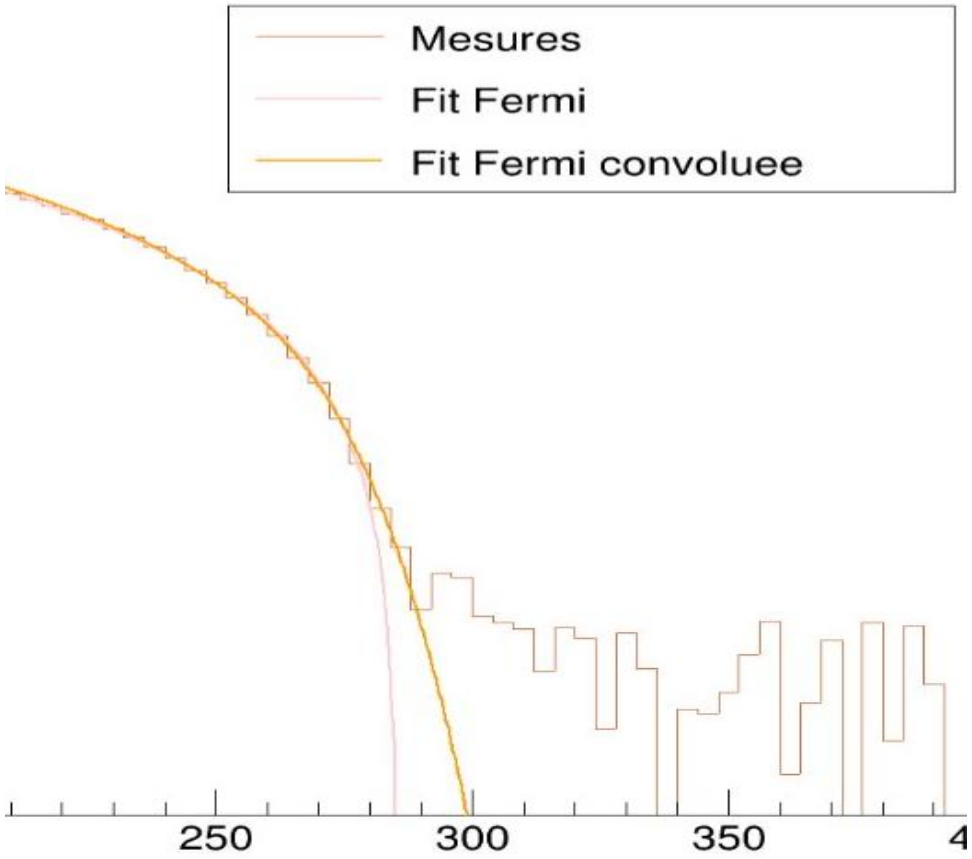
Resolution modeling

Independent C++ implementation of convolution code for gaussian resolution with analytical re-derivation

Convoluted function = function $*$ gaussian

$$F[i] = (f * G)[i] = \sum_{j=-\infty}^{+\infty} f[j]G[i-j]$$

Can be applied to simulated spectra as well as fit functions



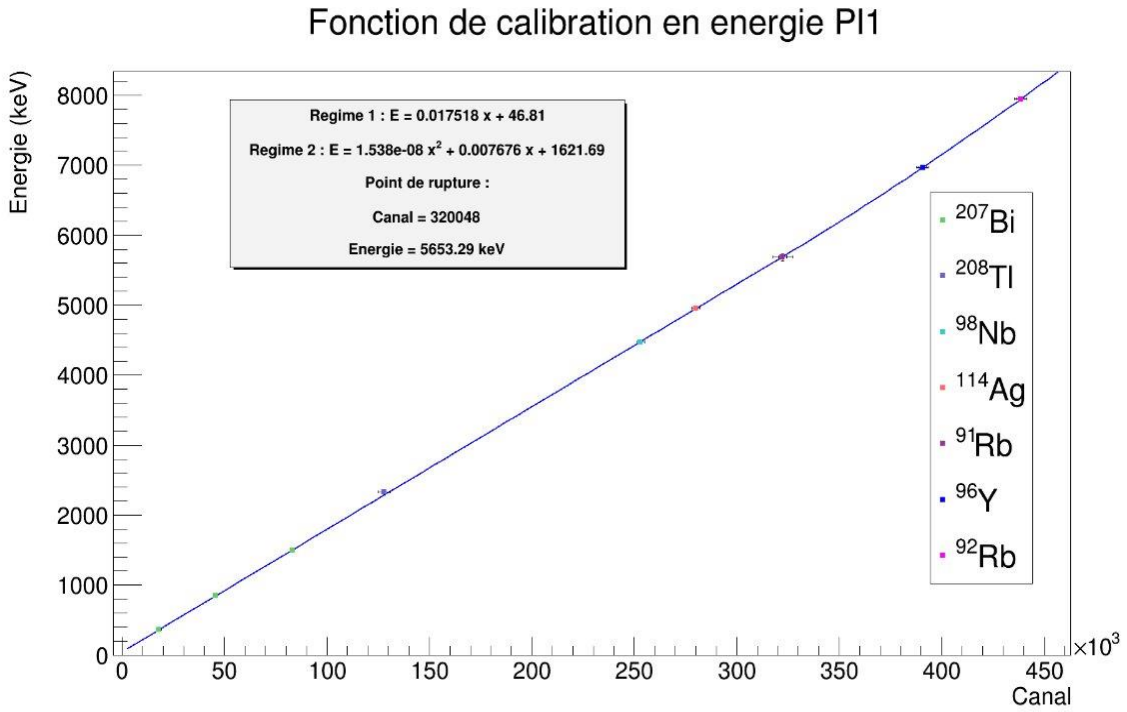
Standard endpoint fit

(Fermi function x Phase space) * Convolution -> Endpoint + Resolution informations

Detectors calibration

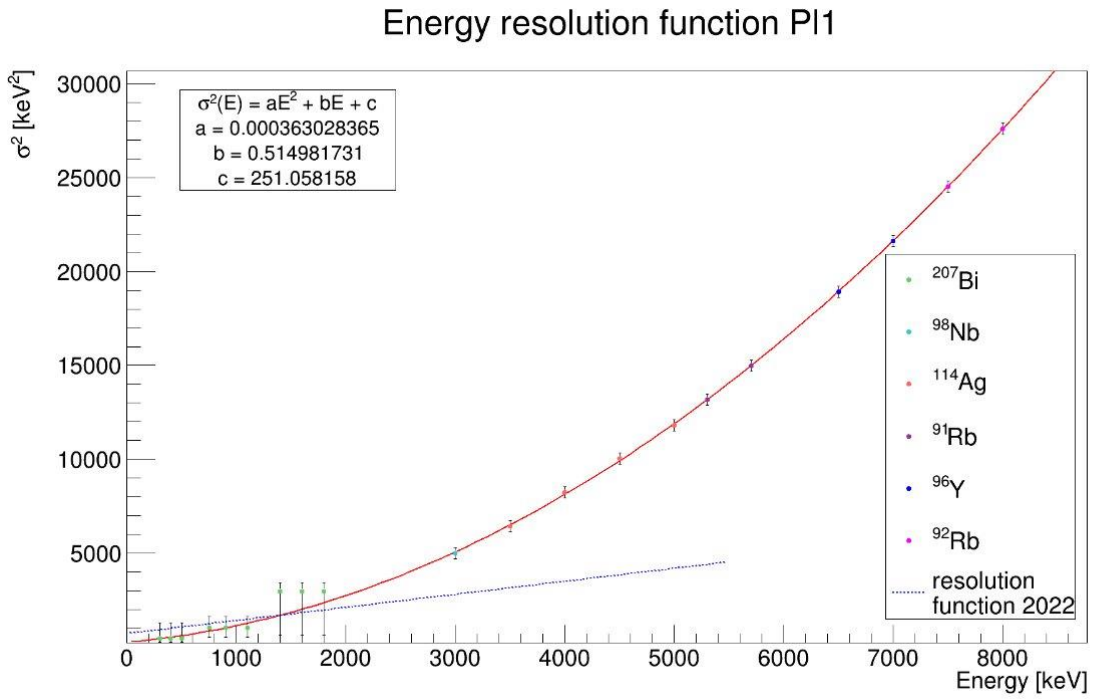
Calibration functions

Energy calibration function in Plastic scintillator 1



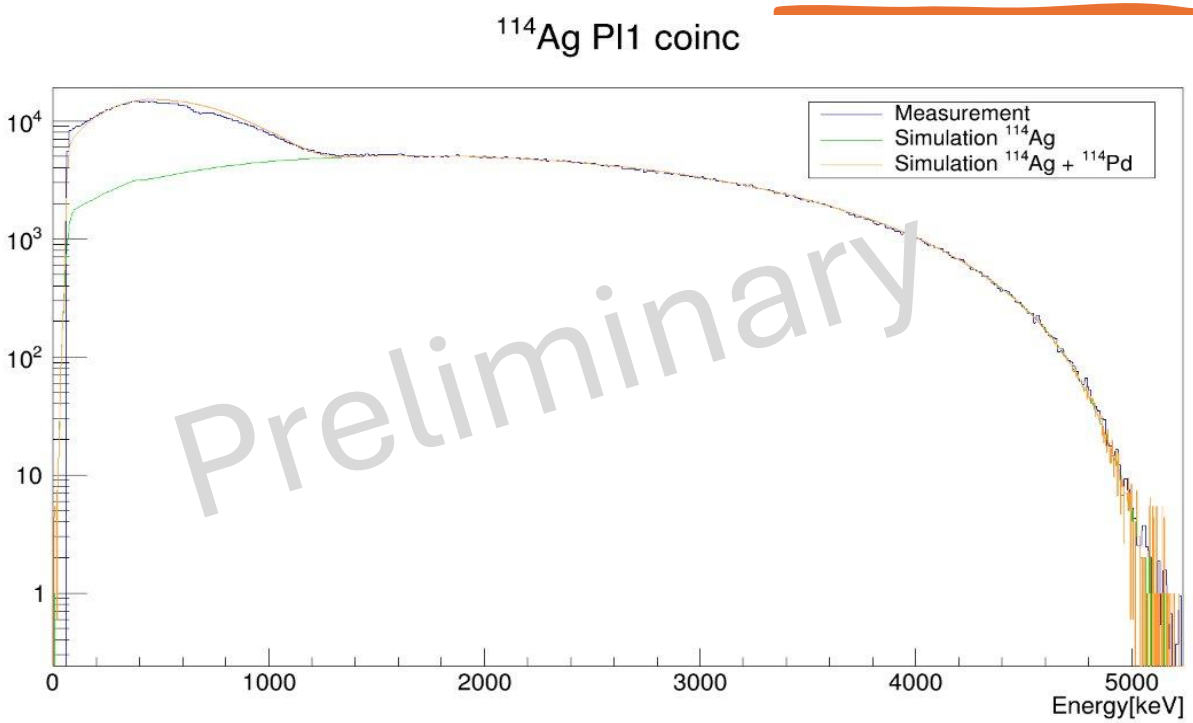
Linear regime then quadratic regime

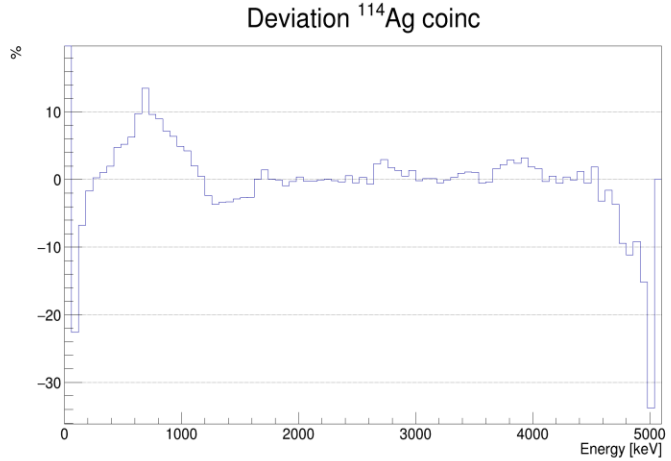
Energy resolution function in Plastic scintillator 1



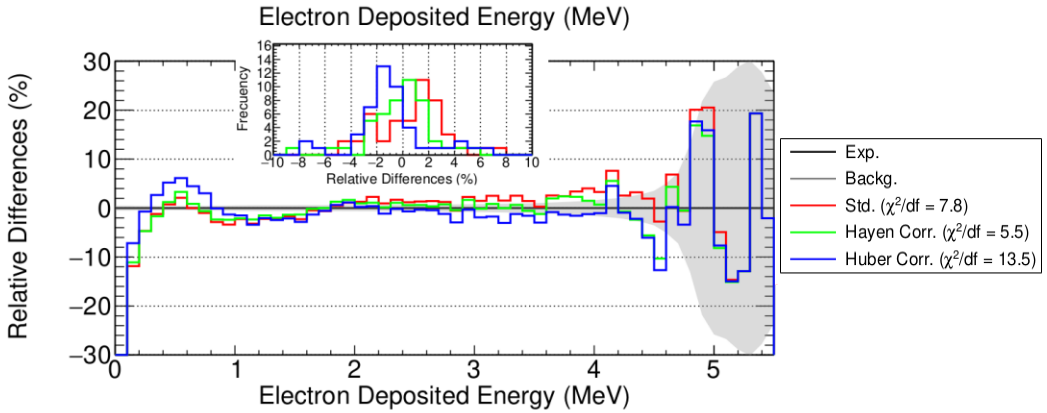
In 2022 : Linear function evaluated up to 2MeV
My work: Quadratic function evaluated up to 8MeV

Data-Simulation comparison





Comparable to 2022 analysis

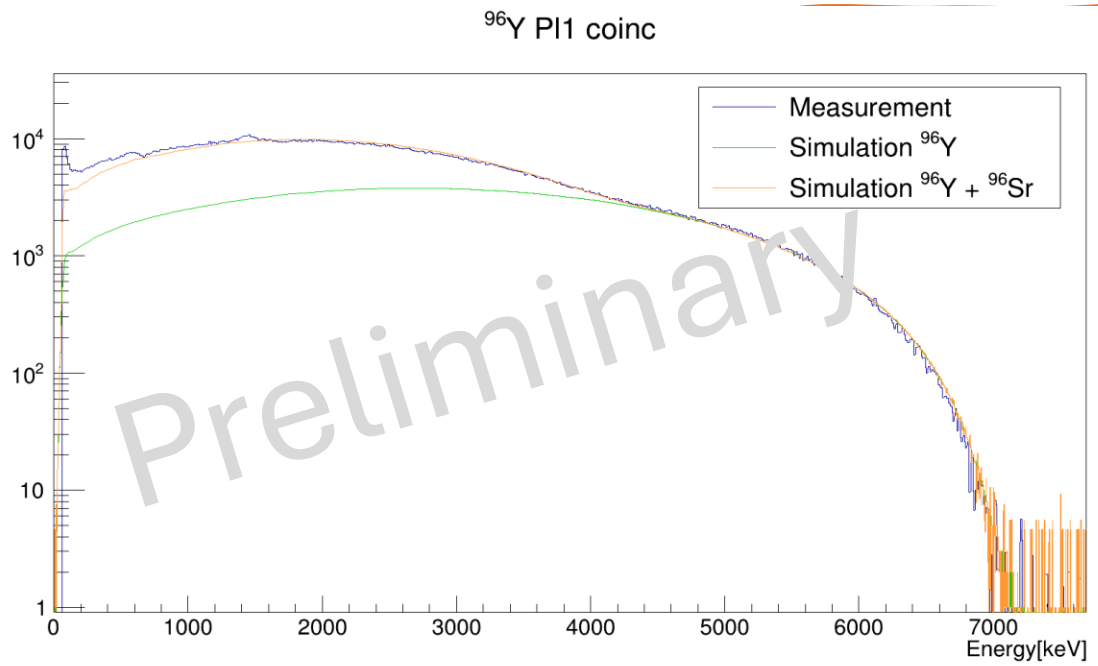


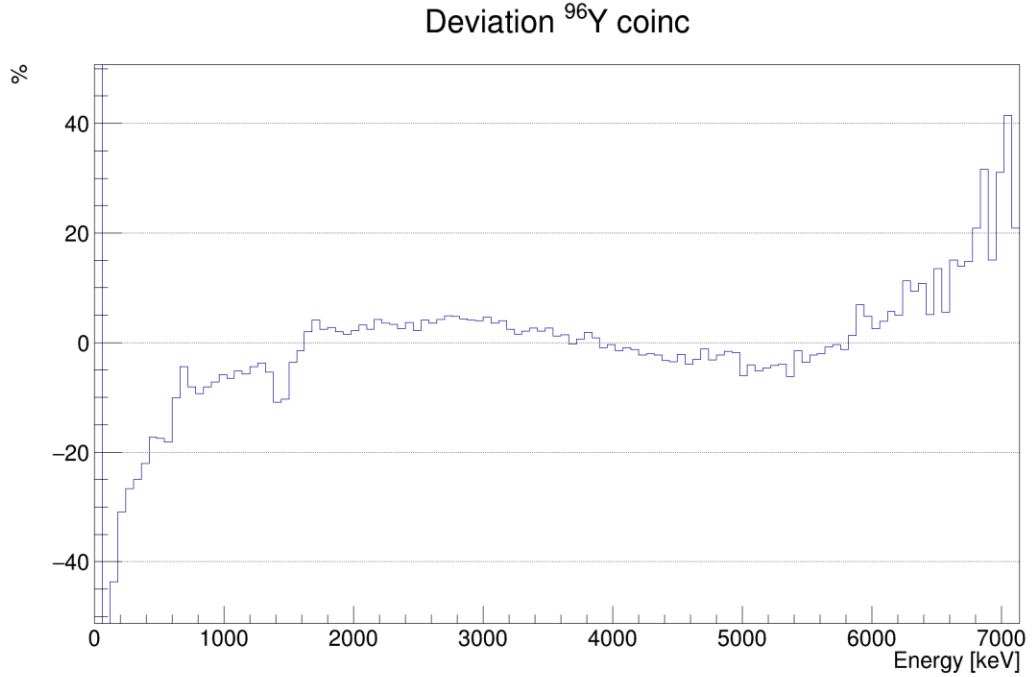
-First validation of the simulation data reproduction (below 5% of deviation)

-Still need to apply quantum corrections to the simulated spectra

Alcalá et al. PRL Phys. Rev. Lett. 135, 142502 (2025).

Data-Simulation comparison





-Work in progress but a fair agreement is already obtained

-Some cases like ^{96}Y need TAGS data to be included in the event generator for better reproduction

-Still need to apply quantum corrections to the simulated spectra

Conclusion and Outlook

What have been done

- Geometry of the detectors fully reproduced in GEANT4
- Convolution code and calibration techniques have been developed
- Detectors calibration have been performed through several radioactive nuclei spectra (still a work in progress)

Quite soon

- Application of corrections (and TAGS data when needed) to the event generator
- Detector response matrix
- Deconvolve the measured beta spectra

What's to be done

Near future

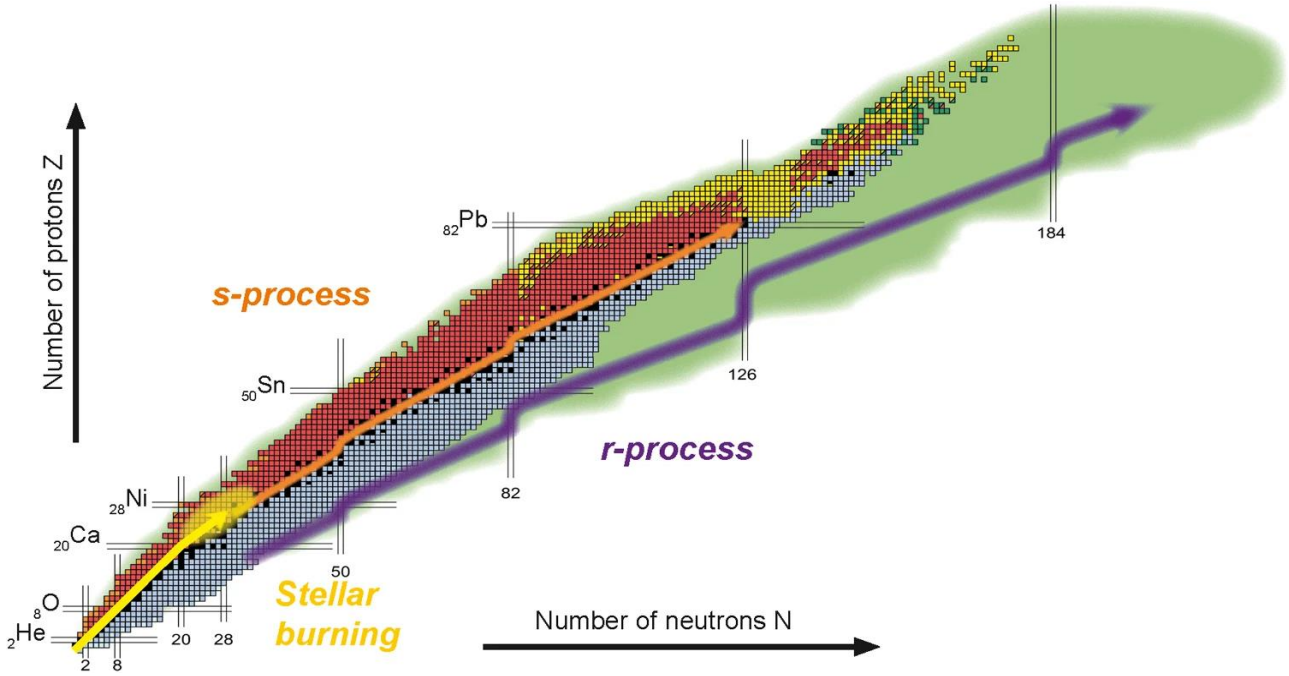
- ^{96}Y and ^{94}Y shape factors evaluation and comparison to theory predictions

Final goal if we have time

- Include those shape factors to summation method

Physics motivations

Nuclear astrophysics : r-process calculations



credit: EMMI, GSI/Different Arts

- The r-process synthesizes about half of the elements heavier than iron
- Beta decays govern the evolution of matter back toward stability
- Many r-process nuclei are expected to exhibit significant forbidden transitions contributions
- Improved beta decay modeling benefits both reactor antineutrino predictions and r-process calculations