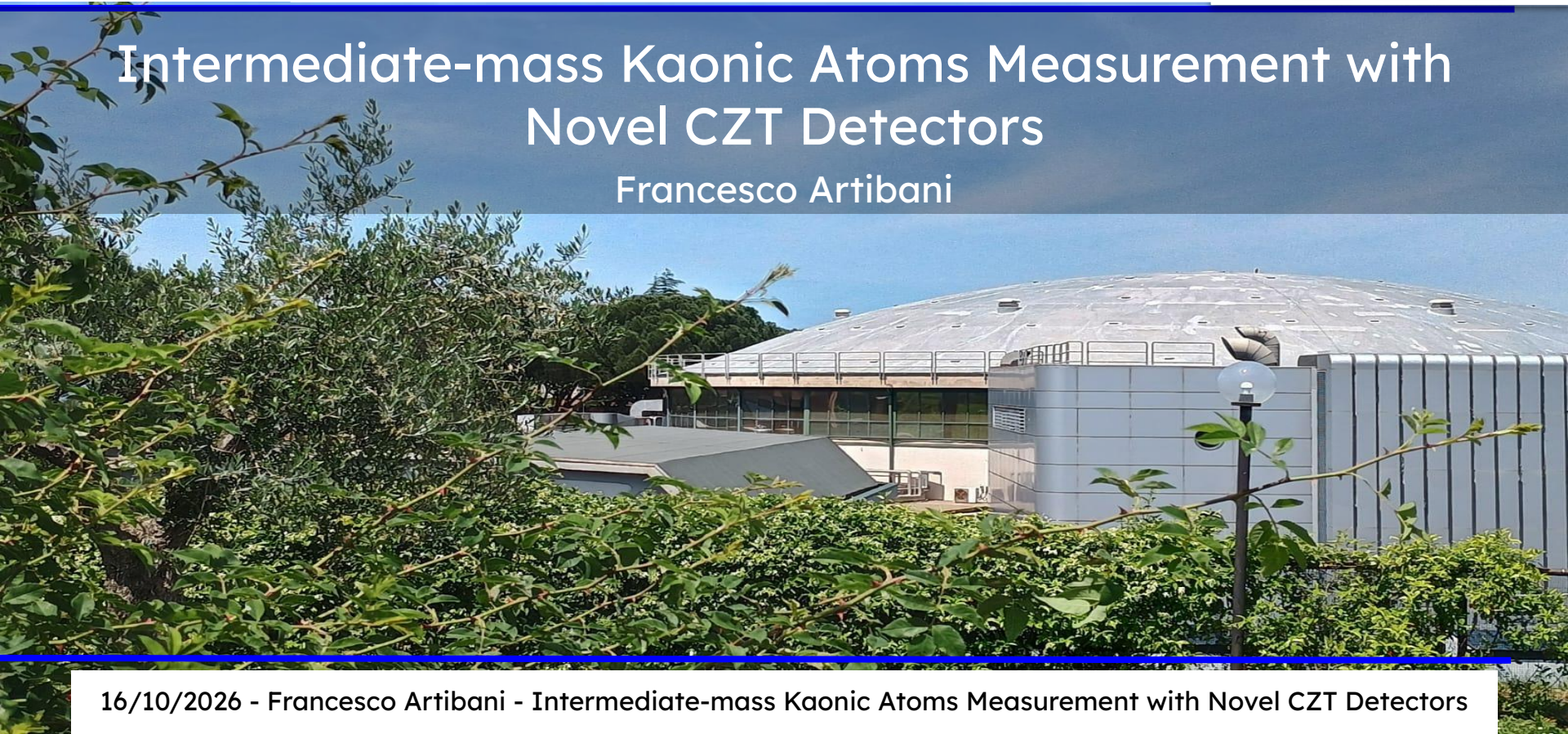
ROMA TRE
UNIVERSITÀ DEGLI STUDI

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Intermediate-mass Kaonic Atoms Measurement with Novel CZT Detectors

Francesco Artibani



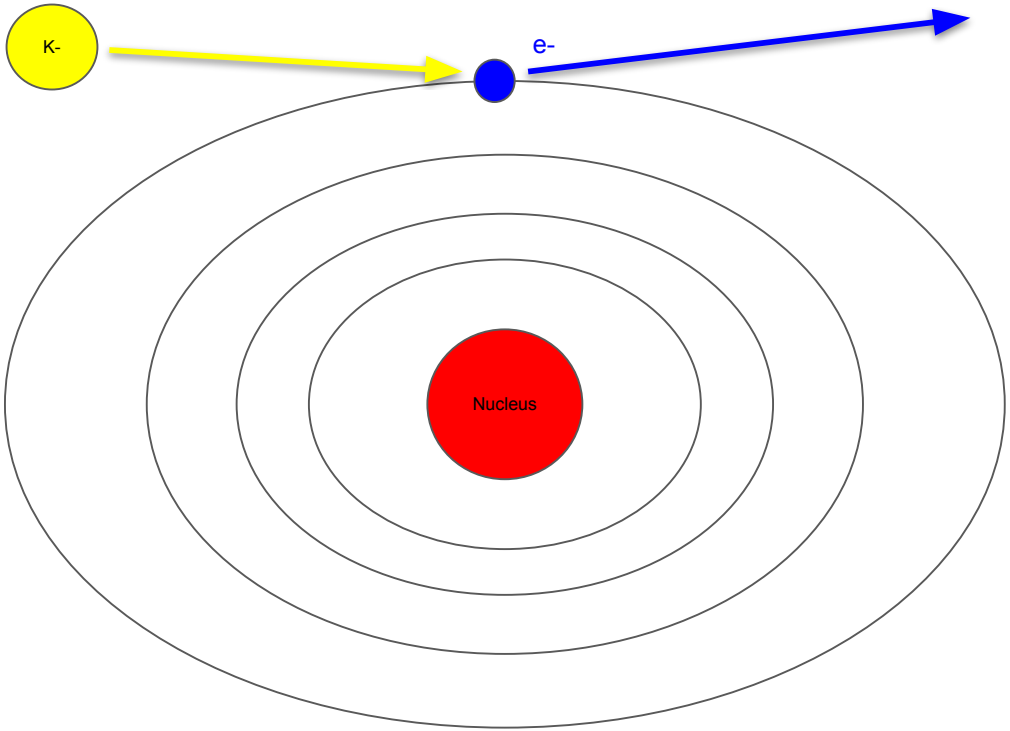
Outline

1. Kaonic Atoms Research
   a. Formation and Cascade
   b. Strong Interaction Observables

2. CZT Detectors in SIDDHARTA-2 Experiment
   a. Setup
   b. Sketch of Analysis
   c. Kaonic Atoms Measurement (KF, KCu, KAl)
   d. MC and Yield evaluation

3. Conclusions

Kaonic Atoms: Formation



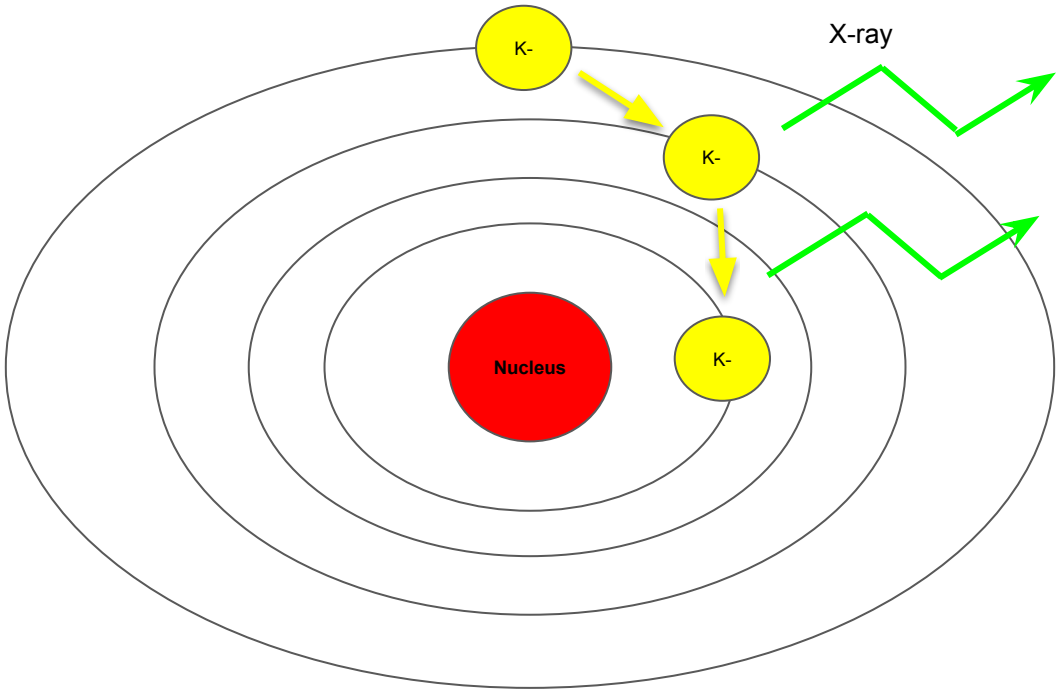
$r_b^e \sim r_b^k$

*(Prog. Part. Nucl. Phys. **61,** 512–550, 2008)*

$$n \approx \sqrt{\frac{\mu}{m_e}} n_e$$

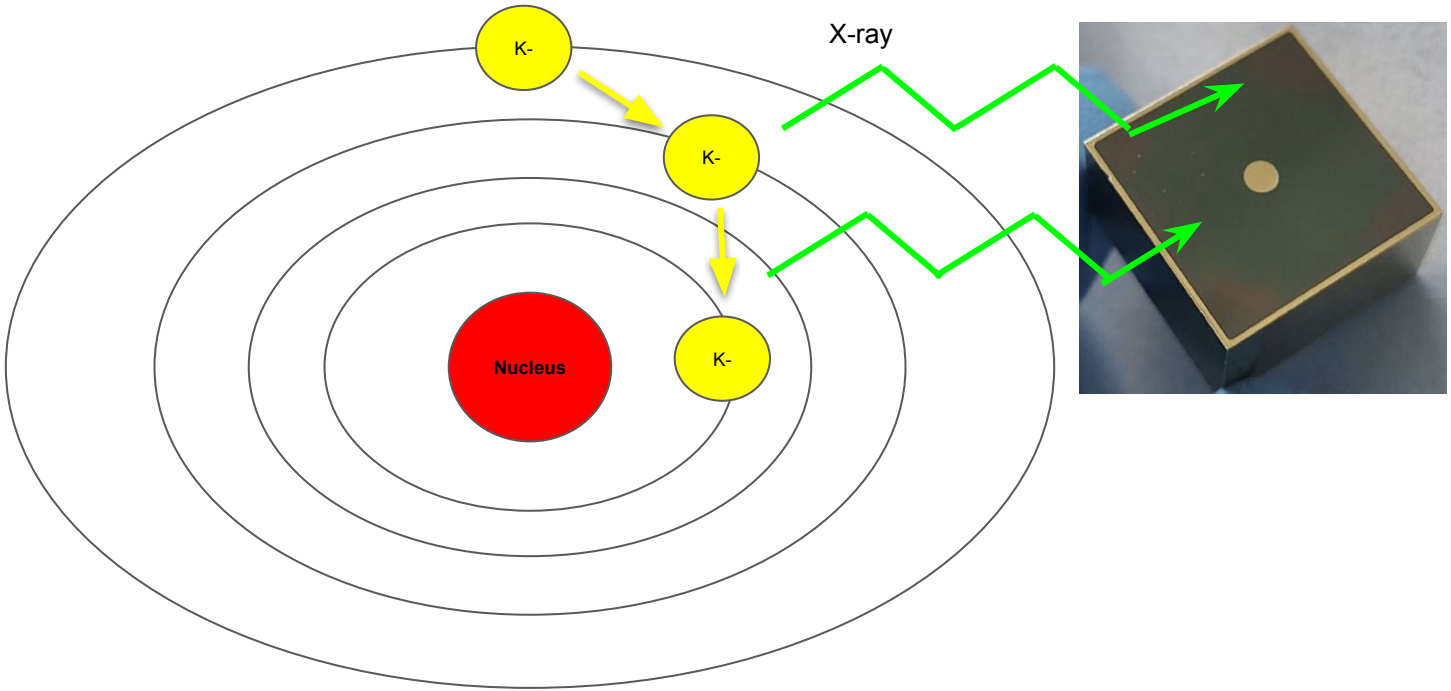
H n=1 level ~ KH n=25 level

Kaonic Atoms: Cascade



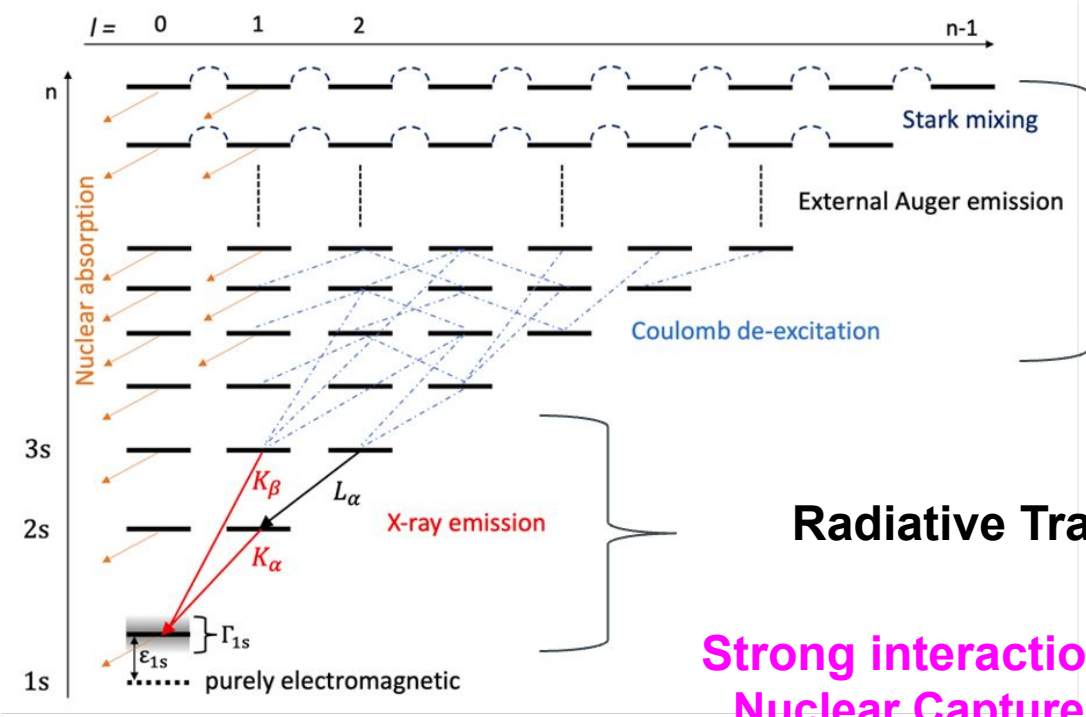
The de-excitation cascade in its last part is radiative and in the X-ray region.

Kaonic Atoms: Cascade



The de-excitation cascade in its last part is radiative and in the X-ray region.

Kaonic Atoms: Cascade



Auger Transitions

Radiative Transitions

Strong interaction
Nuclear Capture

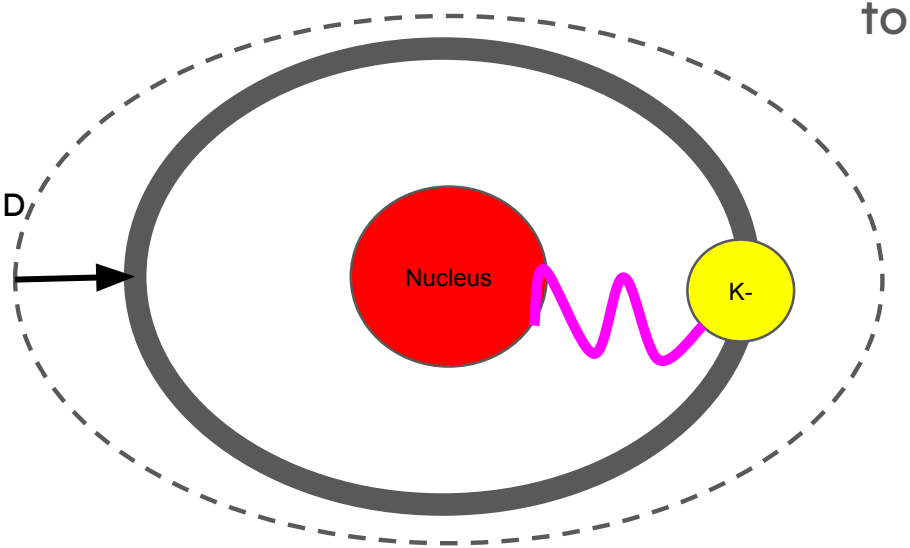
Kaonic Atoms: Strong Interaction - 1

Strong interaction Effects

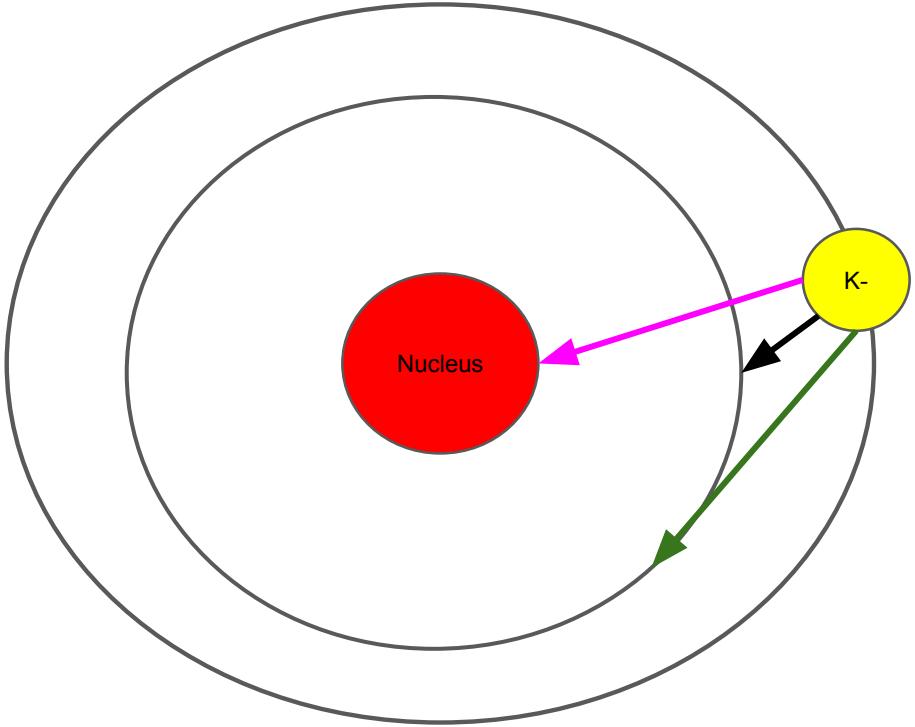
Widening (Γ) due to level lifetime

Shift

$\varepsilon = E_{Meas} - E_{QED}$



Kaonic Atoms: Strong Interaction - 2



X-ray yield per kaon stop gives info on Strong Interaction and atomic and molecular processes

Radiative Transitions

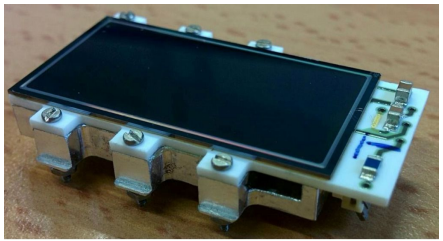
Auger Transitions

Strong interaction
Nuclear Capture

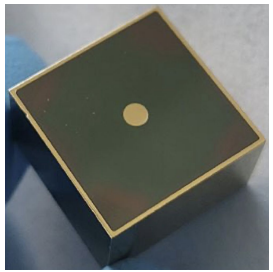
SIDDHARTA-2 Experiment

- **Goal**: Measure **K-d** to access the K-N isospin dependent interactions (elementary interactions)
- **Goal**: Measure **different kaonic atoms**: Strong interactions, BS- and strong field QED, Kaon mass, cascade models ecc…

K-d + Light mass:
SDDs (1-20 keV range)



Intermediate mass:
KAl, KCu, KF
CZT (10-500 keV range)



K-Pb:
HPGe (300 keV to MeV range)

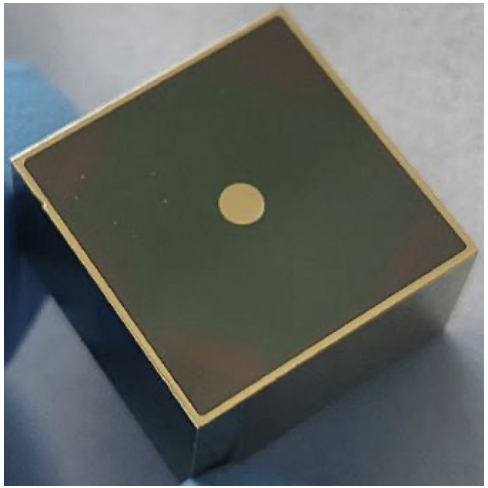


CZT Detectors: Properties

- **Compound semiconductor** (suitable to almost any application: medical imaging, astrophysics, 0-ν □ decay), **good spectroscopy performances at room temperature,** from tens to hundreds keV. Ideal to build **compact systems without the need of cooling.**

- **Never tested in accelerator experiments for fundamental physics research**

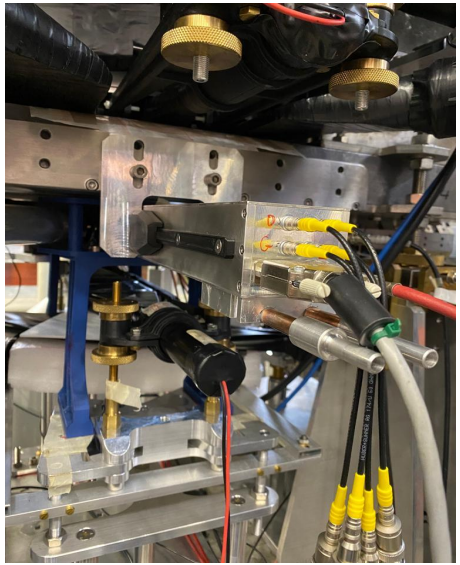
- Intense studies to upgrade the quality of the crystals and electronics in last decades can lead to a **further improvement in terms of resolution and efficiency**.



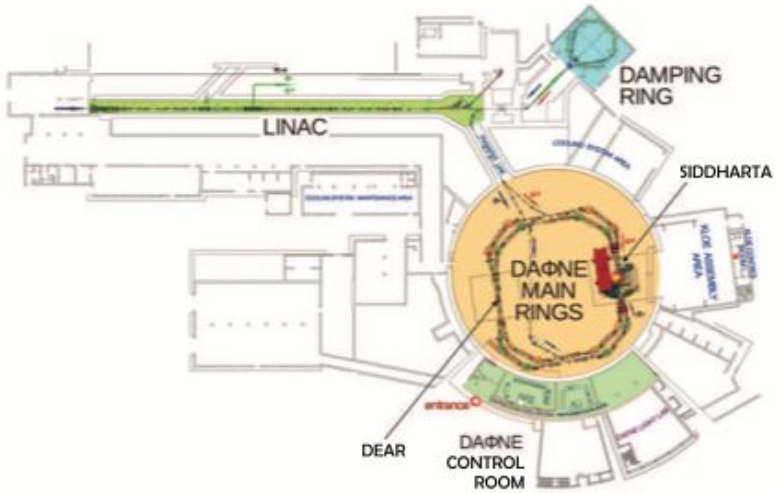
CZT Detector at DAFNE Collider

- Use of quasi-hemispherical CZT crystals grown by REDLEN (Canada) and **IMEM-CNR** (Parma)
- Expertise of the **UniPa DiFC** group for the custom electronics.
- First tests and Data Analysis done in **Frascati National Laboratories** (LNF)

★ **GOAL: Measure Intermediate Mass Kaonic Atoms.**

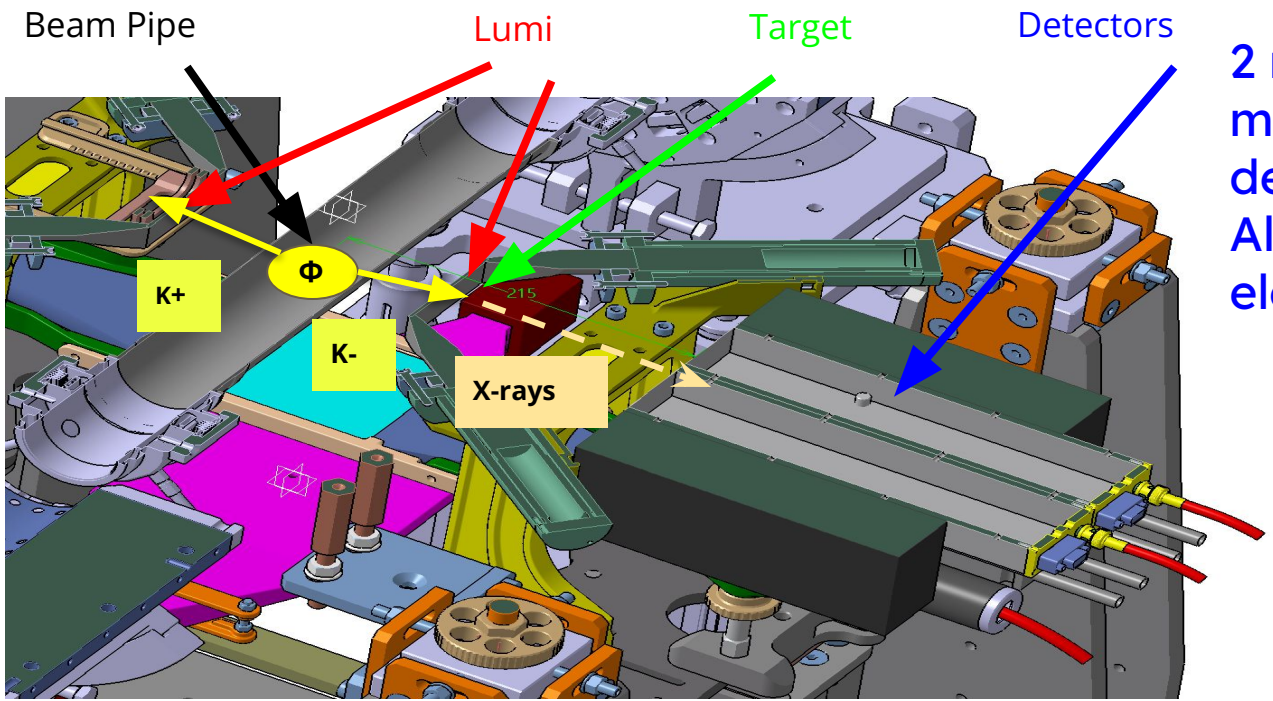


The DAΦNE Collider



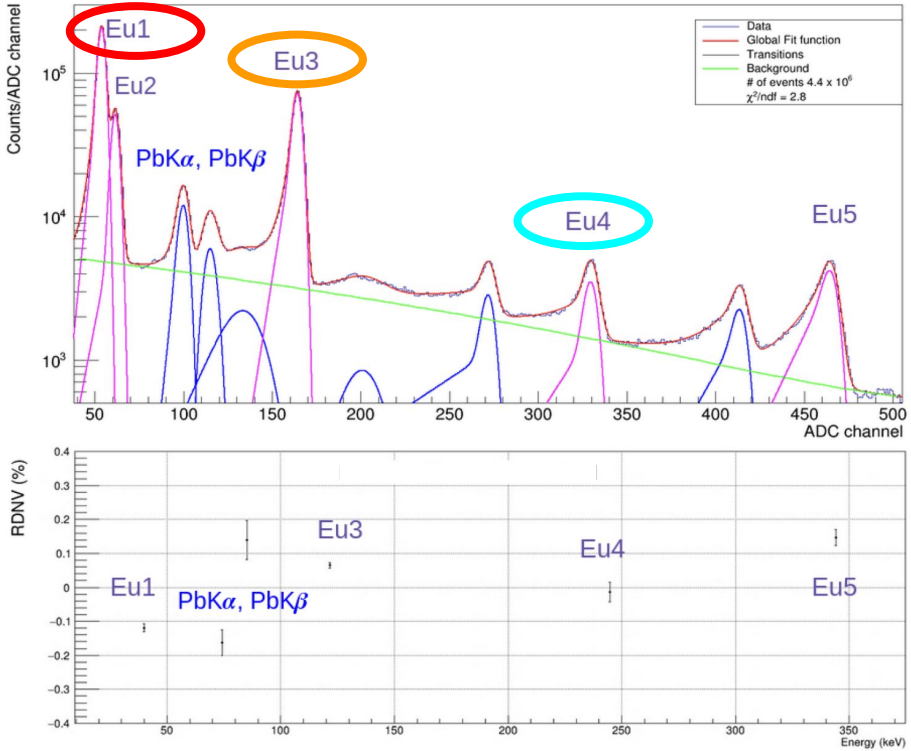
- double ring lepton collider working at the **c.m. energy of Φ resonance** (Φ-factory) (m_Φ= 1.02 GeV)
- Φ decays in a couple of charged kaons with a **BR(Φ → K^+K^-) = 48%**
- The kaons are produced almost at rest (m_K = 493 MeV ⇒ **p_K =127 MeV**, β~0.26) with a small boost through the center of the rings.
- The Ks' momentum spread is almost null ($\Delta p/p < 0.1\%$)

The Setup in DAFNE Collider



2 modules with four 13 mm x 15 mm x 5 mm CZT detectors, enclosed in an Aluminum box with the electronics.

Calibrations during the Run



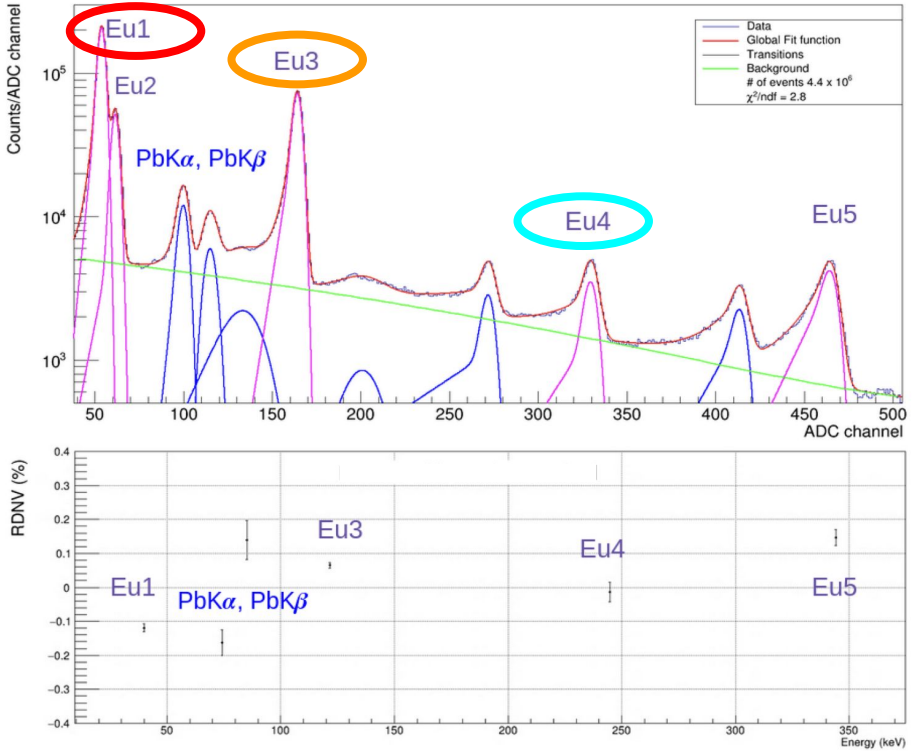
$$f_{peak}(x) = N \times \exp\left(-\frac{x-\mu}{2\sigma^2}\right) +$$

$$\epsilon \times N \times \exp\left(\frac{x-\mu}{\beta\sigma}\right) \times \mathrm{erfc}\left(\frac{x-\mu}{\sqrt{2}\sigma} + \frac{1}{\sqrt{2}\beta}\right)$$

Gaussian + Tail

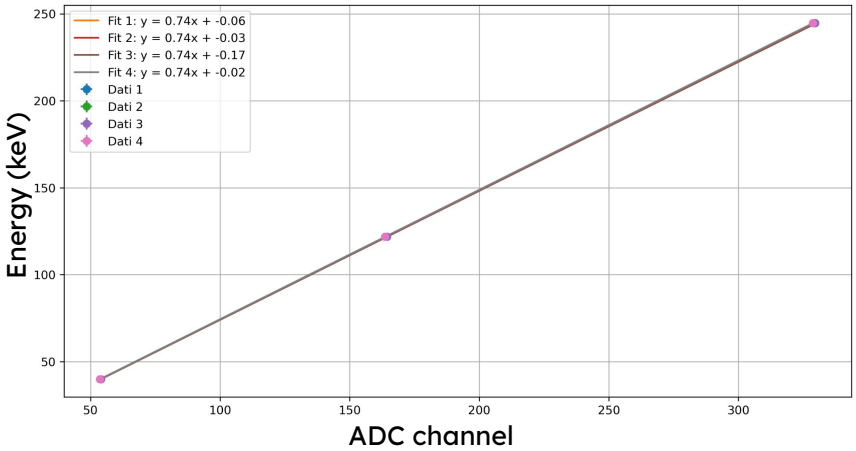
Energy (keV)	Intensity (%)	Type	Origin	ID [1]
40.1186 (-)	37.7 (5)	X $K_{\alpha 1}$	Sm	Eu1
121.7817 (3)	28.41 (13)	γ	^{152}Sm	Eu3
344.2785 (12)	26.59 (12)	γ	^{152}Gd	Eu5
39.5229 (-)	20.8 (3)	X $K_{\alpha 2}$	Sm	Eu1
45.4777 (-)	11.78 (19)	X $K_{\beta 1}$	Sm	Eu2
244.6974 (8)	7.55 (4)	γ	^{152}Sm	Eu4
46.6977 (-)	3.04 (8)	X $K_{\beta 2}$	Sm	Eu2

Calibrations during the Run



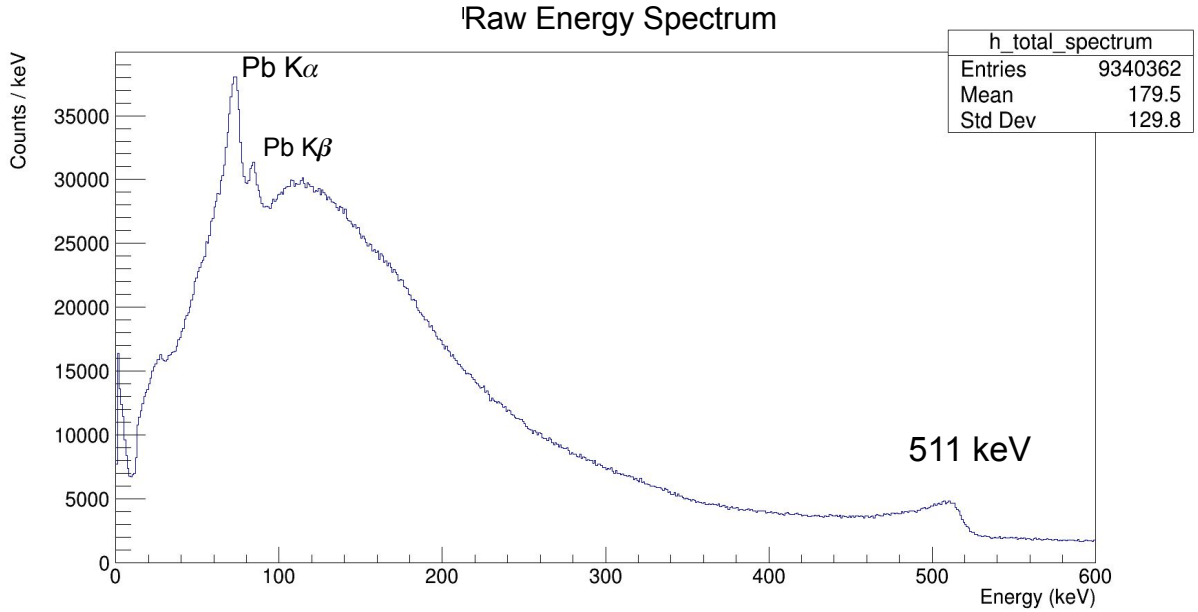
Linear fit to extract Gain and Offset:

Energy = Gain * ADC + offset



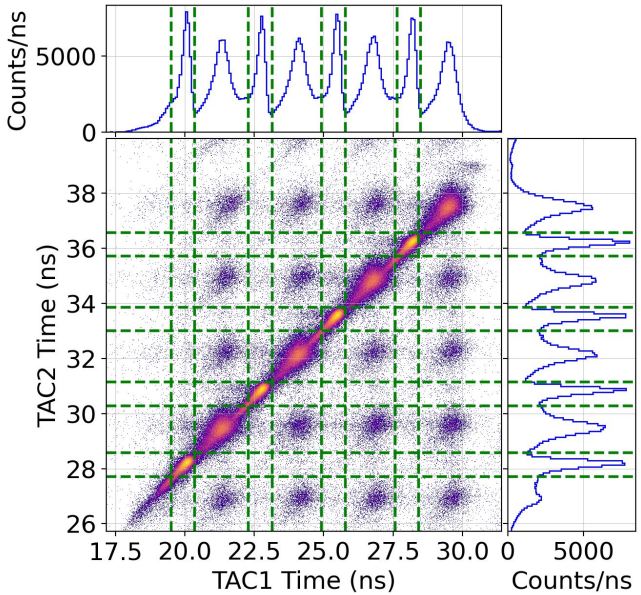
Sketch of Analysis: Time of Flight + Delta t Cuts

~ 40 pb-1 delivered

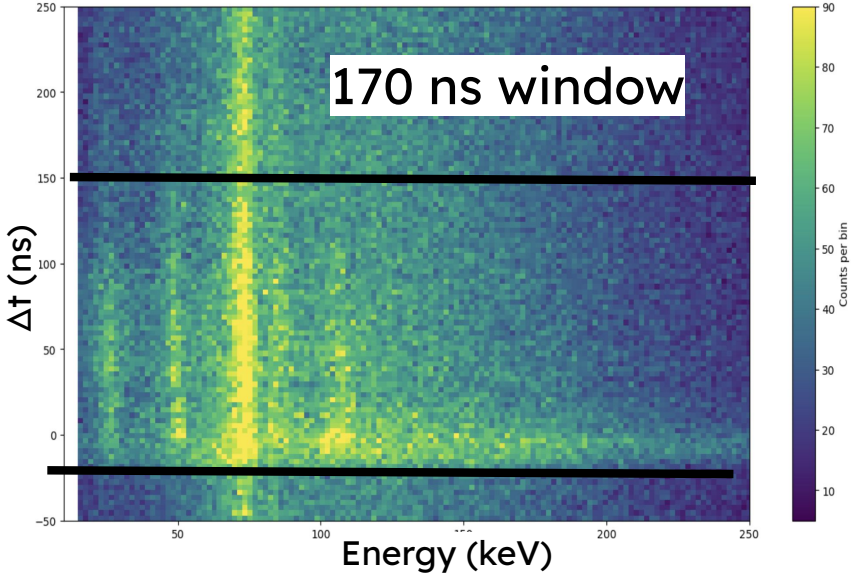


Analysis: Time of Flight + Delta t Cuts

Kaon reconstruction through time-of-flight cut with LUMI scints

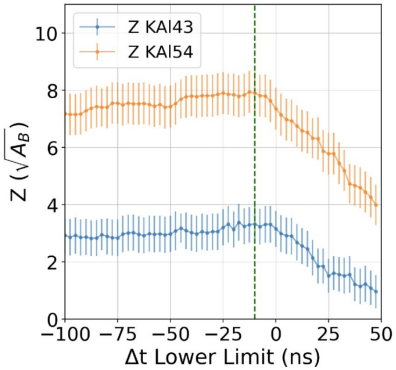


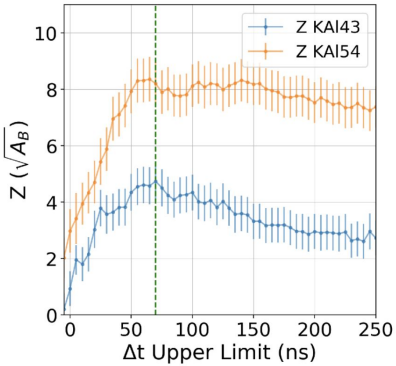
Signal selection through a cut on the time difference between trigger and event on CZT

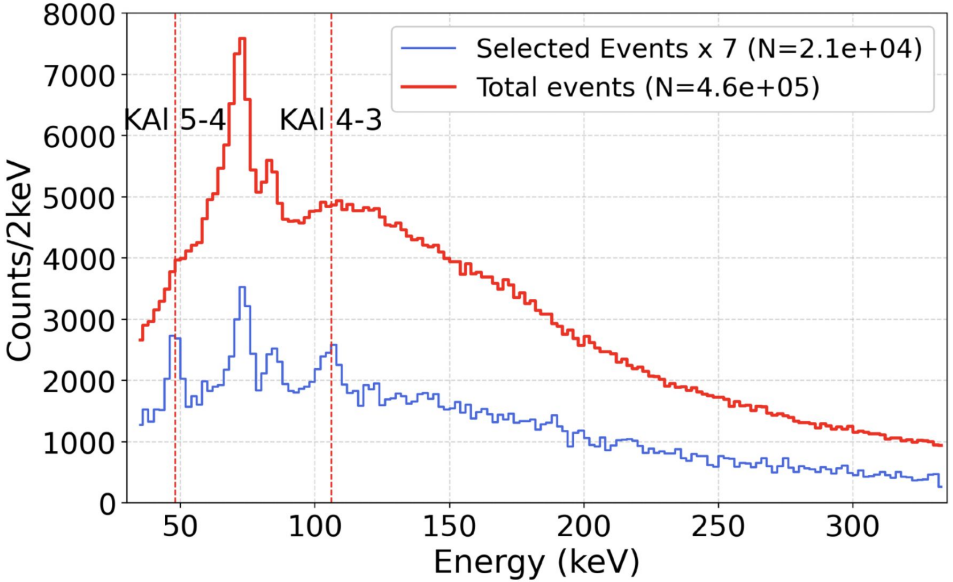


Optimization of ToF selection

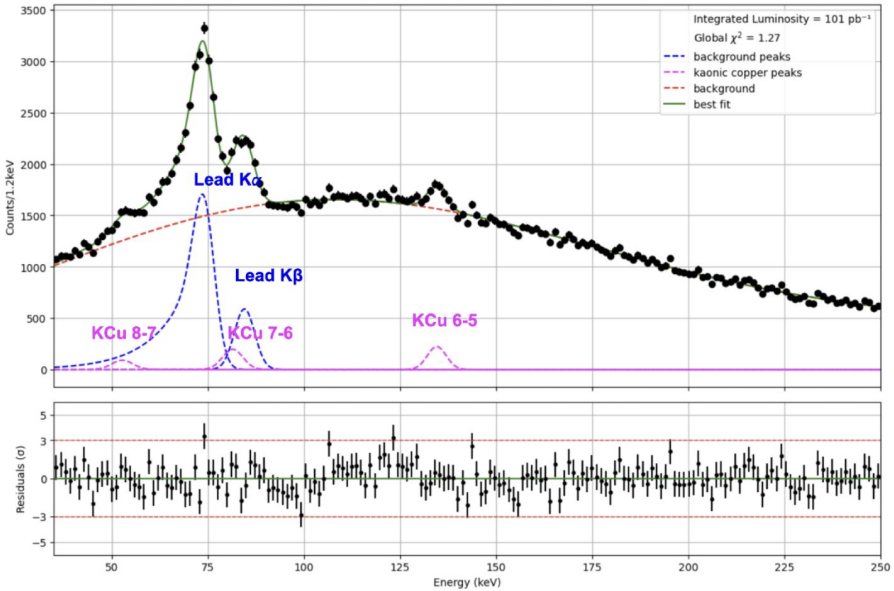
Both the timing cuts were optimised performing several fits on the dataset, to maximise the signal significance (Z)



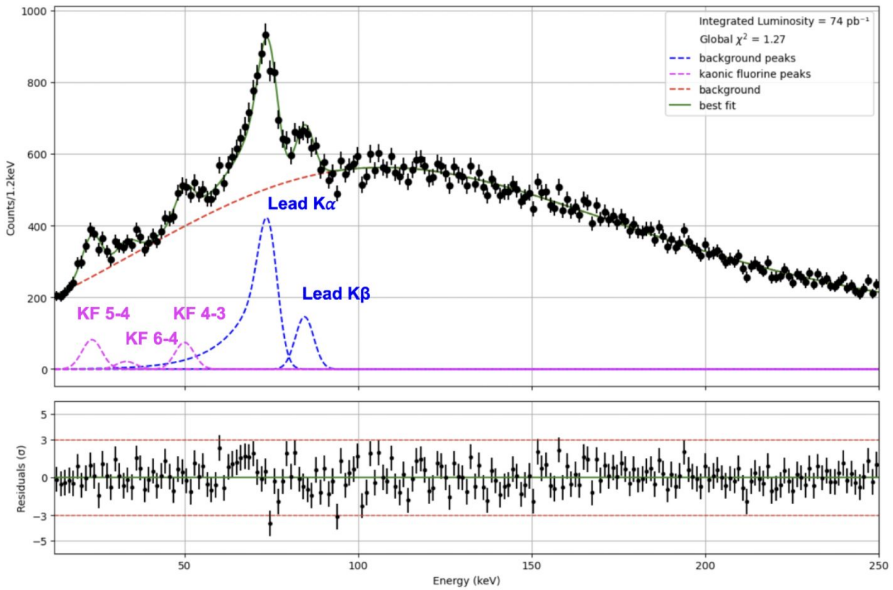




Firsts Results

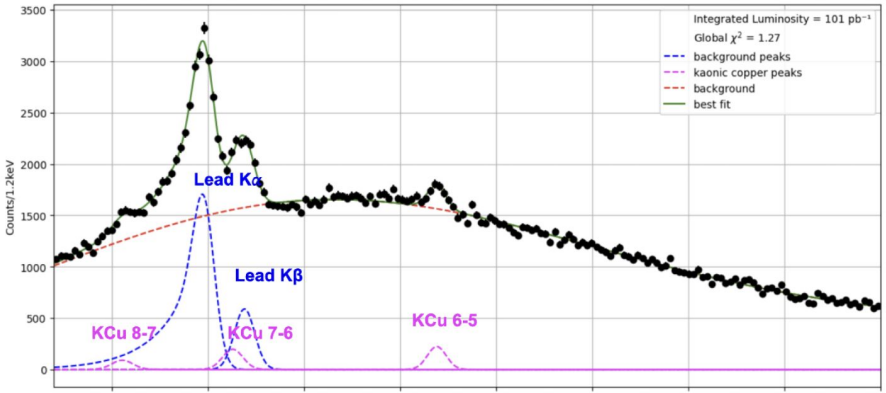


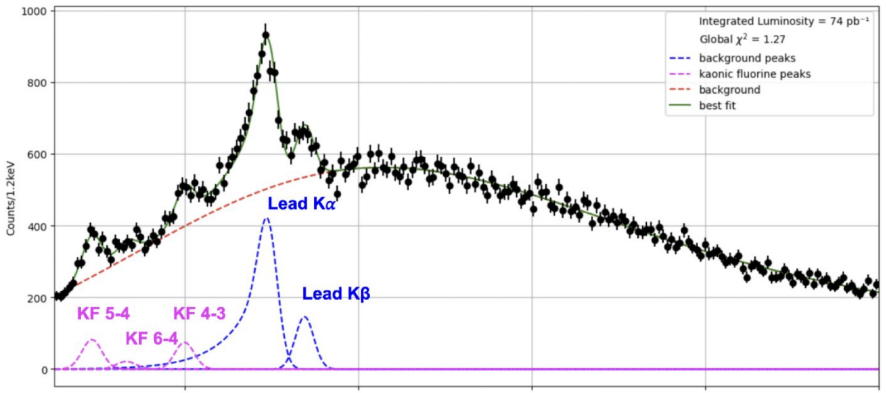
Copper Target



Teflon Target

Firsts Results

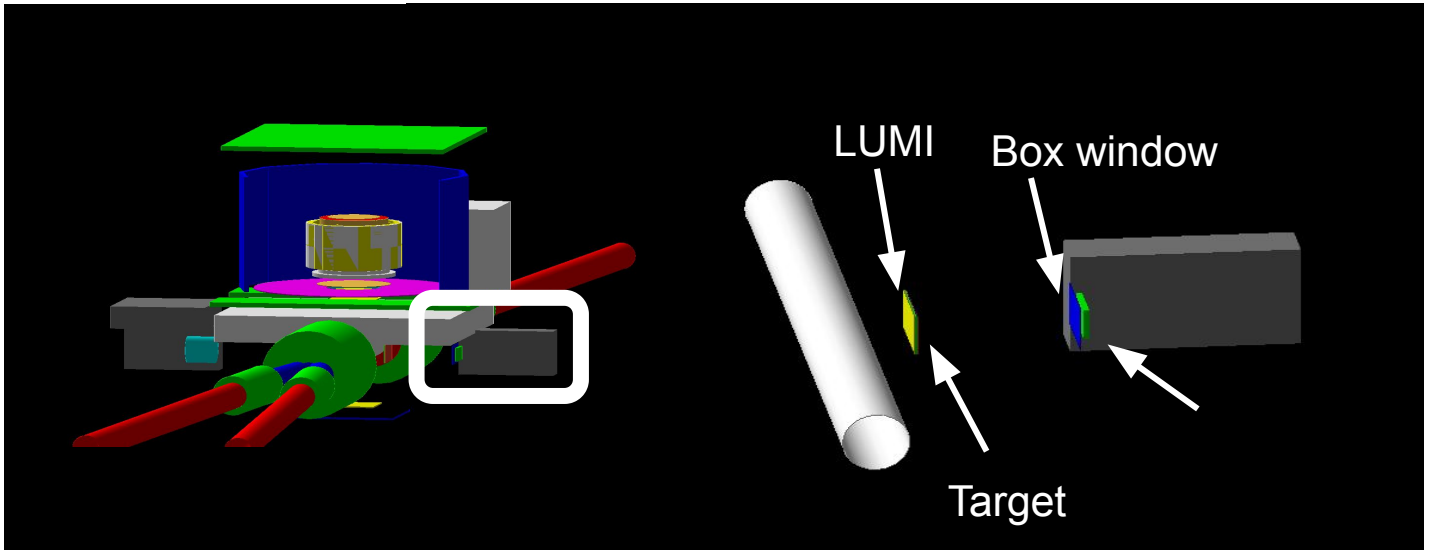




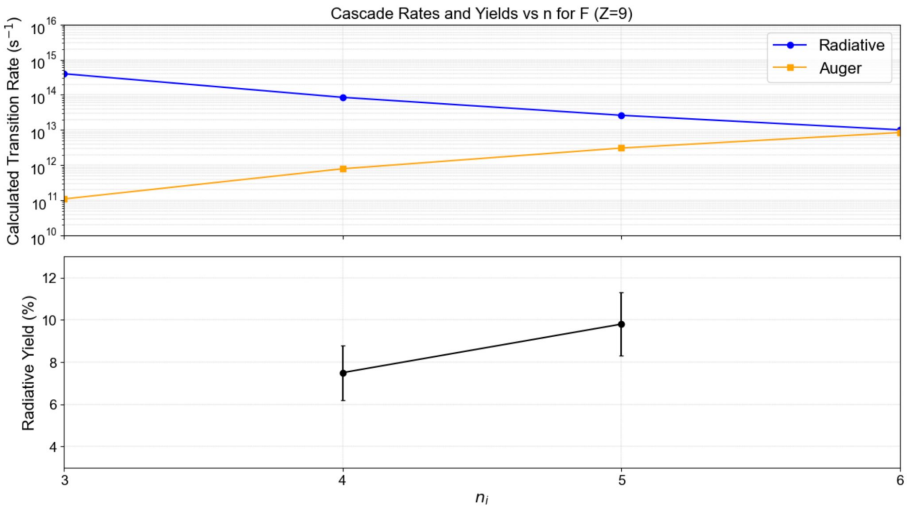
Transition	Measured Energy ± stat. ± sys. (keV)	Theoretical Energy (keV)	Number of Events ± stat. ± sys.
	Fluorine		
KF $5 \rightarrow 4$	$23.34 \pm 0.34 \pm 0.09$	23.33	$488 \pm 72 \pm 30$
KF $4 \rightarrow 3$	$50.14 \pm 0.54 \pm 0.15$	50.59	$427 \pm 74 \pm 42$
	Copper		
KCu $8 \rightarrow 7$	$52.89 \pm 0.50 \pm 0.30$	52.63	$578 \pm 84 \pm 38$
KCu $7 \rightarrow 6$	$80.89 \pm 0.98 \pm 0.60$	81.17	$1078 \pm 297 \pm 190$
KCu $6 \rightarrow 5$	$134.48 \pm 0.35 \pm 0.31$	134.81	$1206 \pm 132 \pm 42$

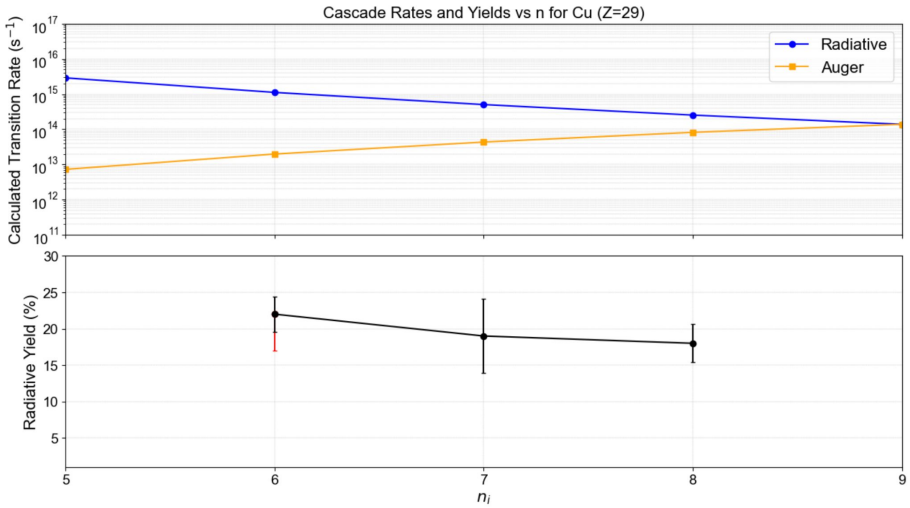
Monte Carlo Simulation

Total Yields evaluation obtained through a detailed MC of the apparatus.

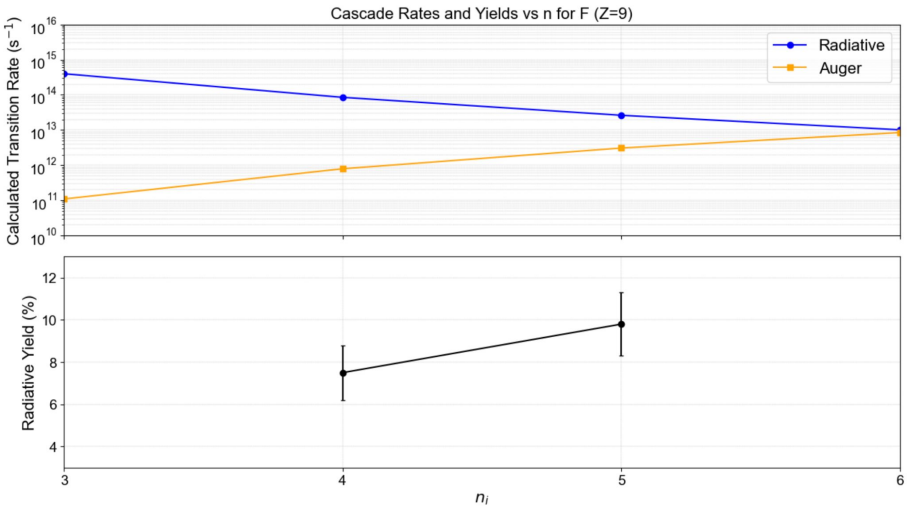


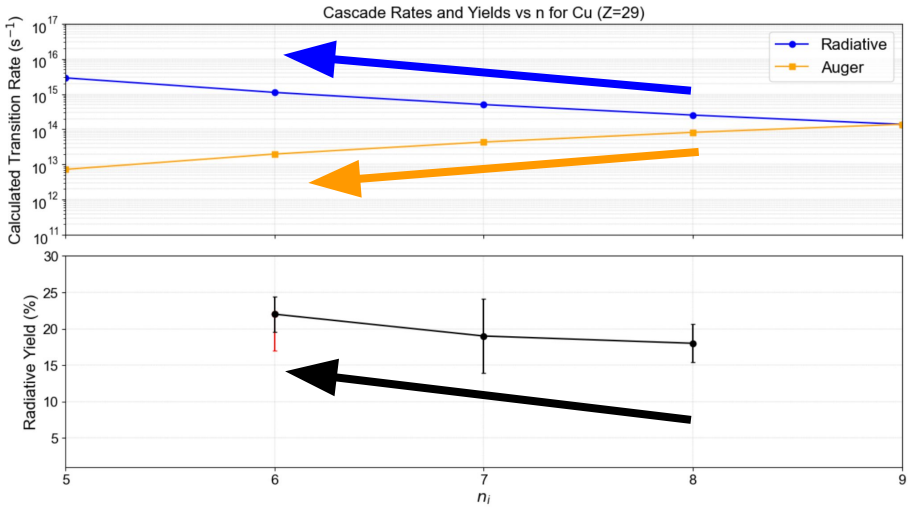
Yield per Kstop Measurement



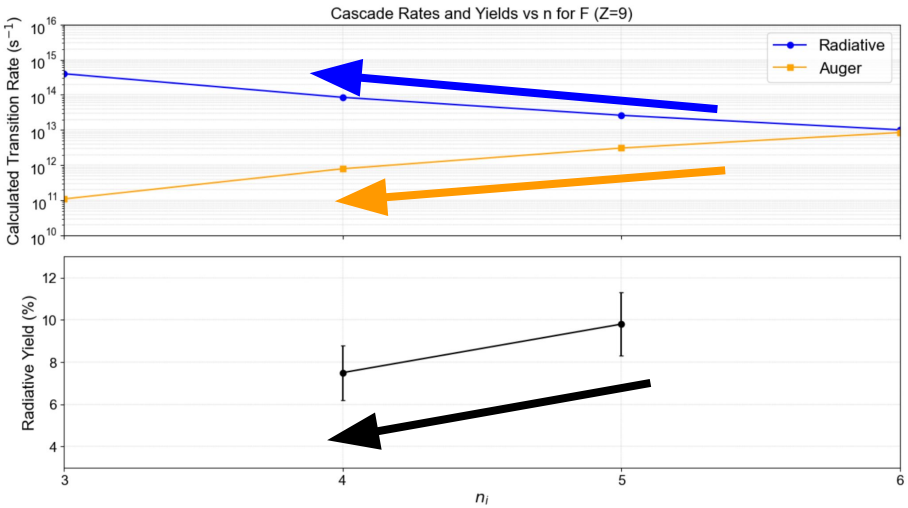


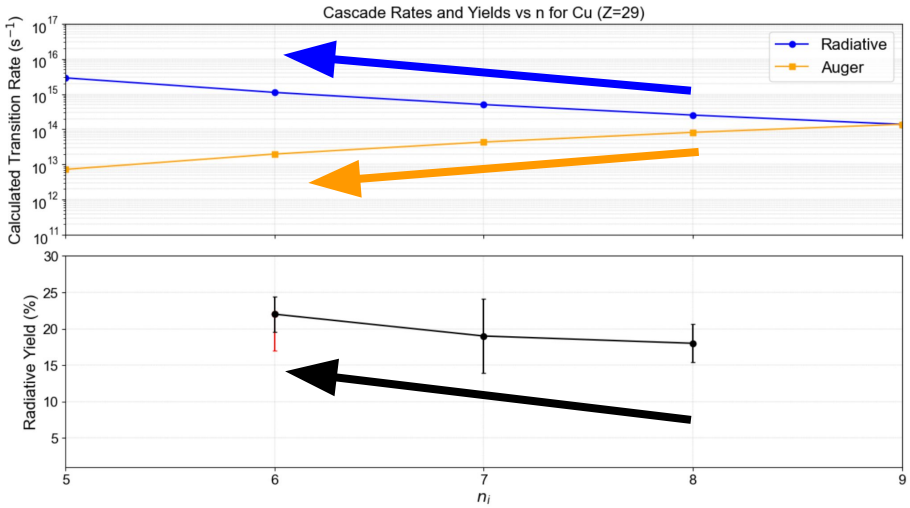
Yield per Kstop Measurement





Yield per Kstop Measurement

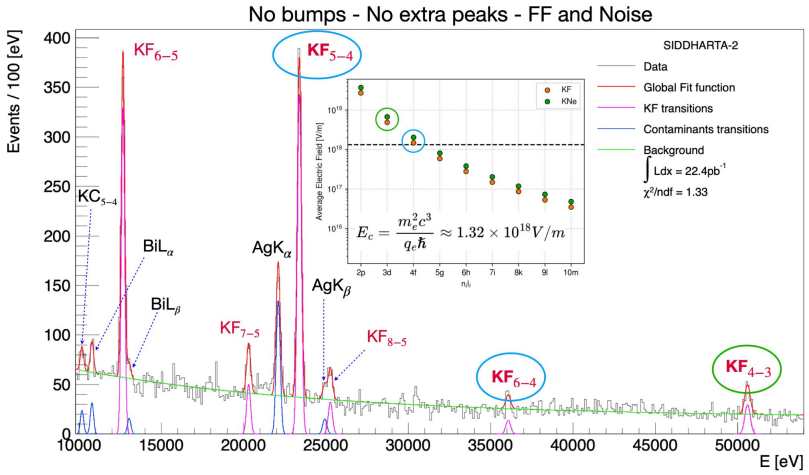


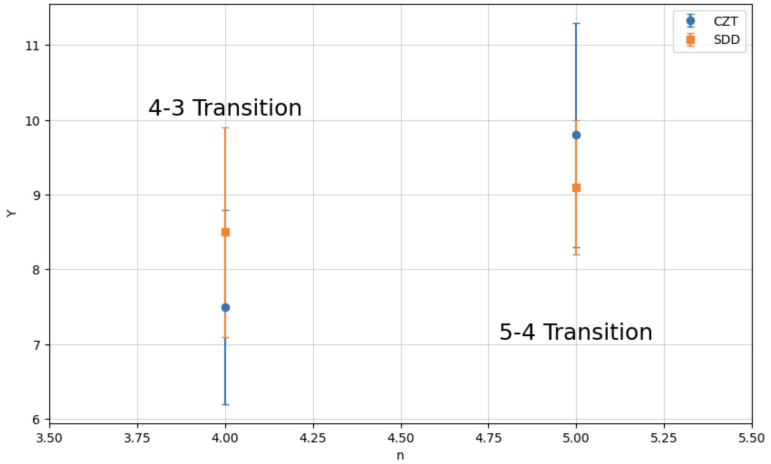


Limit on Strong Interaction at level n = 4 in fluorine:

$\Gamma^{n=4}_{strong} > 0.0036$ eV https://iopscience.iop.org/article/10.1088/1361-6471/ae9f75

Strong Interaction in Fluorine





Transition	Yield (SDDs)	Yield (CZT)	Combined
KF 4-3	(8.4 ± 1.4) %	(7.5 ± 1.2) %	(7.96 ± 0.95) %
KF 5-4	(9.13 ± 0.84) %	(9.8 ± 1.5) %	(9.28 ± 0.77) %
KF 6-4	(1.35 ± 0.46) %	//	(1.35 ± 0.46) %

Strong Interaction in Fluorine

$$R = \frac{I_X[(n, l) \to (n-1, l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i, l+1) \to (n, l)] + I_X[(i, l) \to (n, l-1)]}.$$

→ Measurable, at least with i = n+1

Strong Interaction in Fluorine

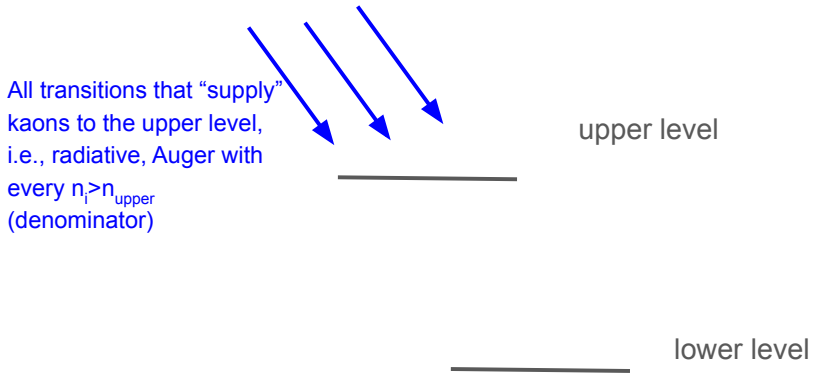
$$R = \frac{I_X[(n,l)\to(n-1,l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i,l+1)\to(n,l)] + I_X[(i,l)\to(n,l-1)]}.$$

Measurable, at least with i = n+1

$$Y = \frac{I_X[(n,l)\to(n-1,l-1)]}{\sum_{i=n+1}^{\infty} [I_{XA}[(i,l+1)\to(n,l)] + I_{XA}[(i,l-1)\to(n,l)]},$$

Observable + correction from rate calculations and cascade models

Practically:



Strong Interaction in Fluorine

$$R = \frac{I_X[(n,l) \to (n-1,l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i,l+1) \to (n,l)] + I_X[(i,l) \to (n,l-1)]}.$$

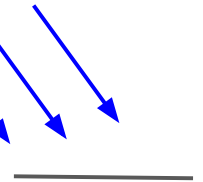
Measurable, at least with i = n+1

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Observable + correction from rate calculations and cascade models

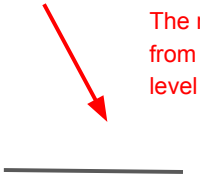
Practically:

All transitions that "supply" kaons to the upper level, i.e., radiative, Auger with every $n_i > n_{upper}$ (denominator)



upper level

The rate of radiative transitions from the upper to the lower level (numerator)



lower level

Strong Interaction in Fluorine

$$R = \frac{I_X[(n,l)\to(n-1,l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i,l+1)\to(n,l)] + I_X[(i,l)\to(n,l-1)]}.$$

Measurable, at least with i = n+1

$$Y = \frac{I_X[(n,l)\to(n-1,l-1)]}{\sum_{i=n+1}^{\infty} [I_{XA}[(i,l+1)\to(n,l)] + I_{XA}[(i,l-1)\to(n,l)]},$$

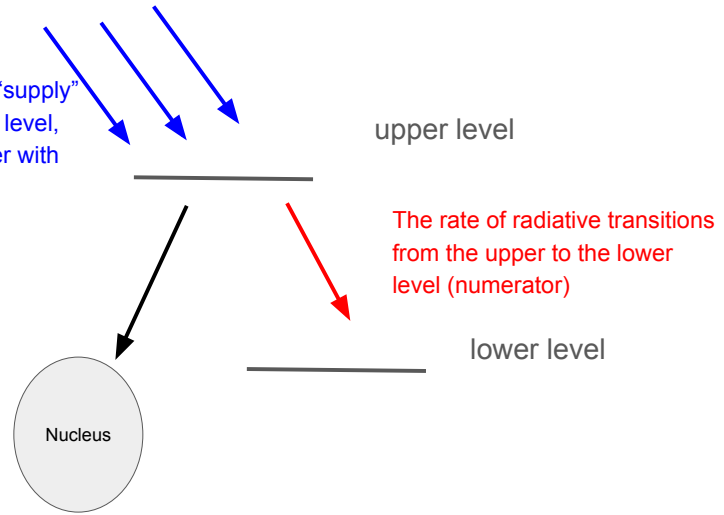
Observable + correction from rate calculations and cascade models

$$Y = \frac{\Gamma_X}{\Gamma_u + \Gamma_X},$$

Through Y you can measure upper level width

Practically:

All transitions that "supply" kaons to the upper level, i.e., radiative, Auger with every $n_i > n_{upper}$ (denominator)



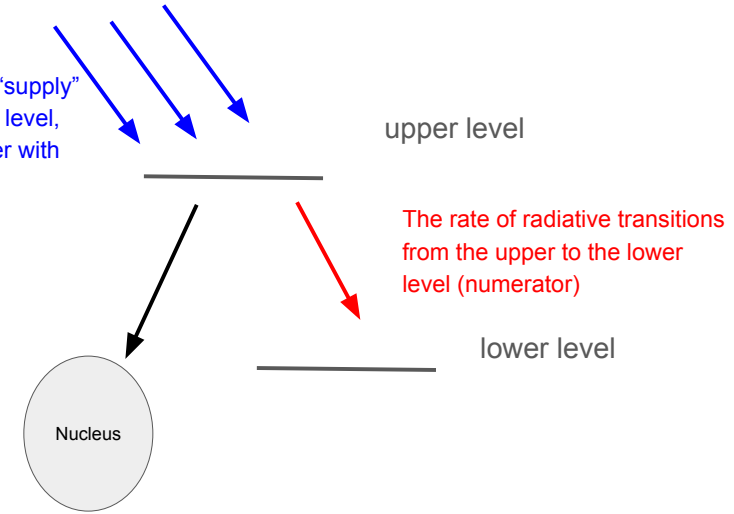
Strong Interaction in Fluorine

$$Y = \frac{\Gamma_X}{\Gamma_u + \Gamma_X},$$

$$\Gamma_{rad}^{(n,n-1)} = 3.52 \times 10^{-6} \varepsilon^2 \frac{M_K}{M_e} Z^4 \frac{2^{4n} n^{2n-4} (n-1)^{2n-2}}{(2n-1)^{4n-1}} \text{(eV)}$$

Practically:

All transitions that “supply” kaons to the upper level, i.e., radiative, Auger with every $n_i > n_{upper}$ (denominator)



Strong Interaction in Fluorine

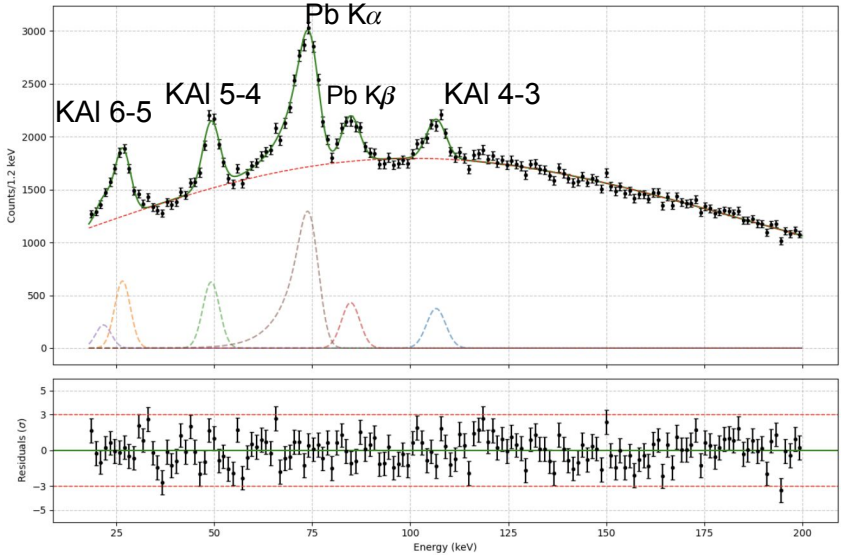
Computed **radiative transition rate** (5,4) → (4,3)
in Fluorine (Cascade + Fried-Martin = Z): **0.083 eV**

Estimated **Y: 0.72 ± 0.12 (stat) (CZT + SDDs) + n→4, n>6 contributions : 0.5%**

Dataset	**Γ (n=4) KF**
CZT + SDD	**(33 ± 13) meV**
SDD	**(24 ± 16) meV**

Firsts Results: Aluminum

L = 100 pb-1



Transition	Energy (keV)	Th. Energy (keV)	Yield
KAl 4-3	106.46 ± 0.20 ± 0.2	106.57	(9 ± 2 ± 2) %
KAl 5-4	49.13 ± 0.10 ± 0.10	49.23	(13 ± 2 ± 1) %
KAl 6-5 + 8-6	26.70 ± 0.14 ± 0.10	26.707	(16 ± 2 ± 1) %

Firsts Results: Aluminum

Useful to confirm old measurements

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
Al	$4 \rightarrow 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04

Assuming a **2% contribution from Δn≥2** supplying the level n=5,

Y parameter for KAl43/KAl54: **0.562 ± 0.052 (stat)** ± 0.014 (syst fit) ± 0.018 (syst MC) [eV]

Estimated nuclear absorption rate: **0.288 ± 0.061 (stat)** ± 0.017 (syst fit) ± 0.021 (syst MC) [eV]

Firsts Results: Aluminum

Useful to confirm old measurements

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
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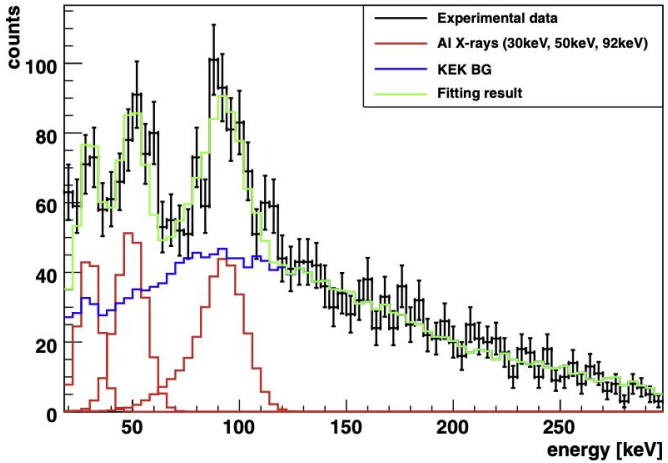
https://doi.org/10.1016/j.astropartphys.2013.08.003

+ **Useful to test cascade models**

In a previous work, different parameters of cascade models were tested with antiprotonic aluminum, namely

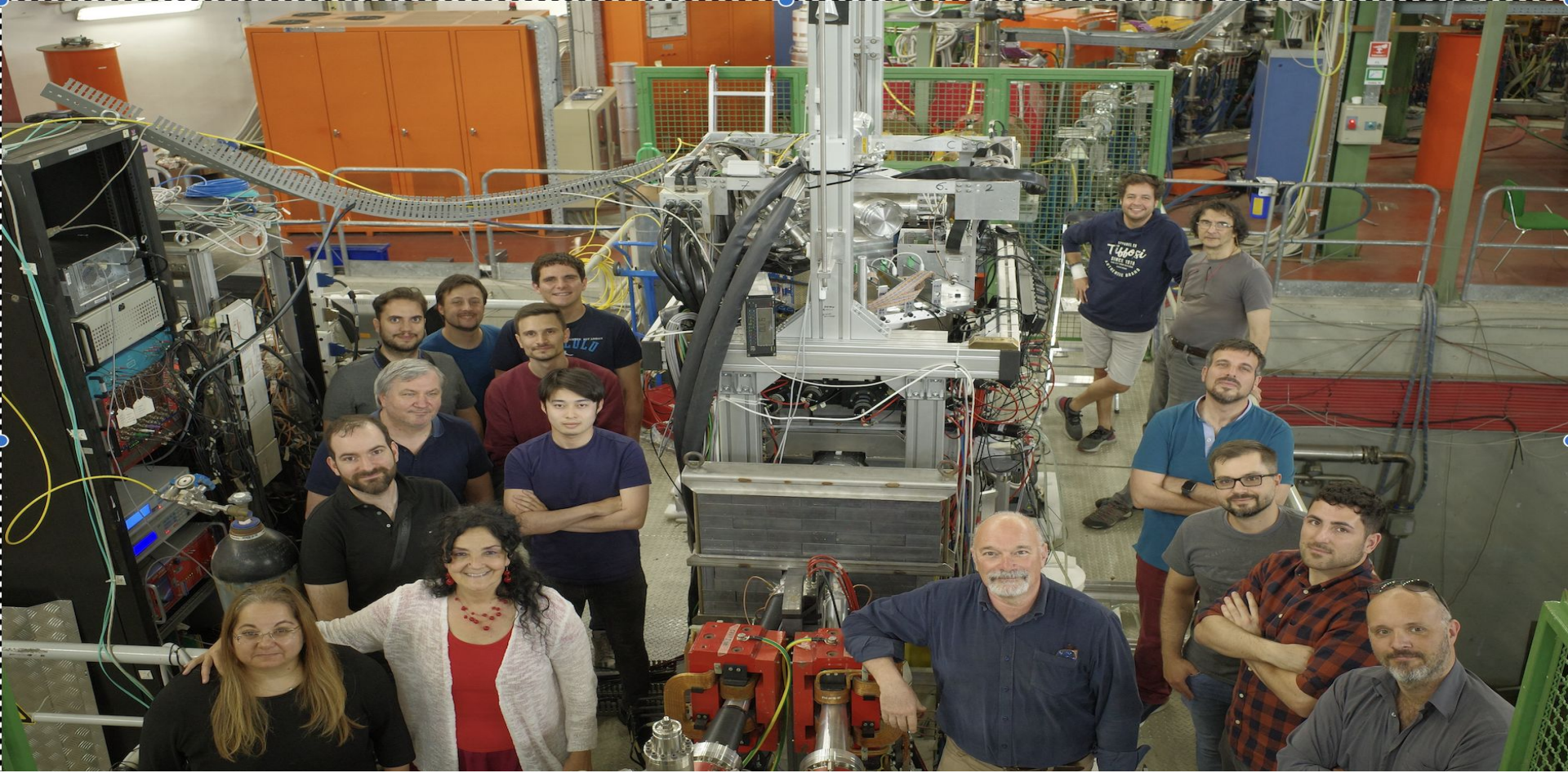
- Initial Kaon l distribution
- Refilling Rate
- Strong Interaction Parameter

Now we have the **same target** in two **different exotic systems**



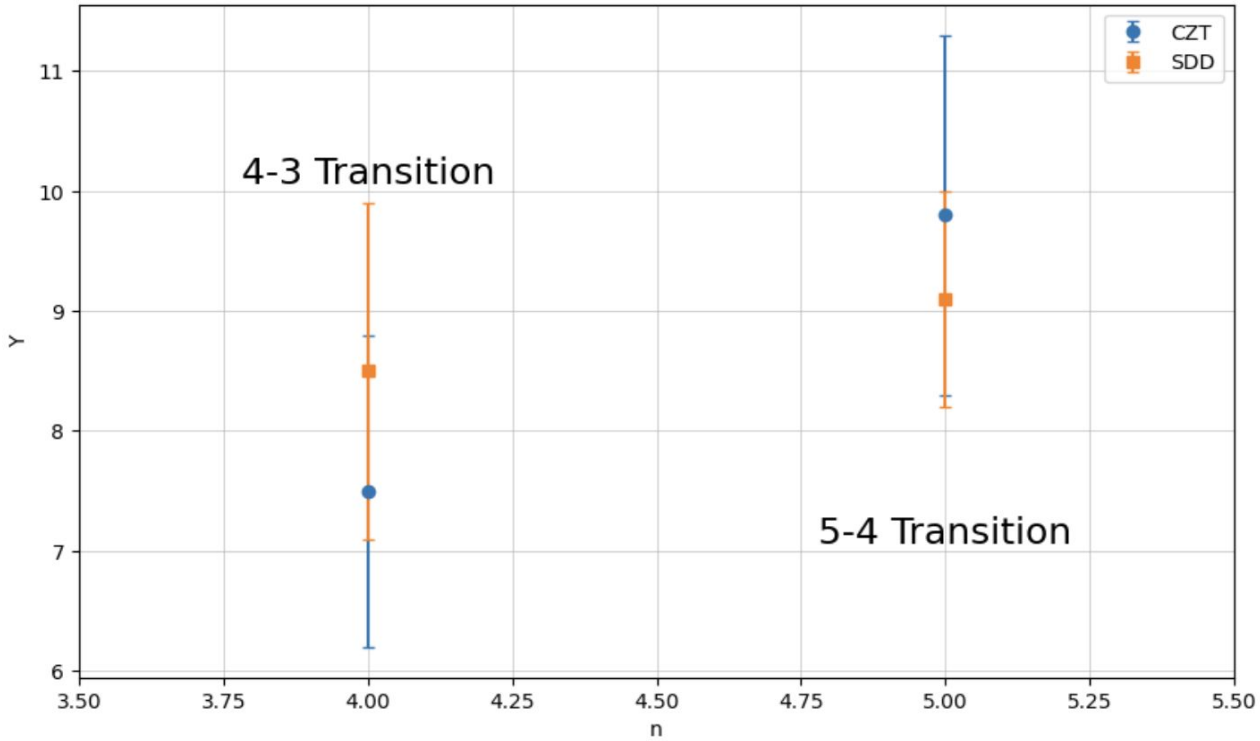
Conclusions

- Room temperature **CZT Detectors tested** for the first time **in a collider environment**
- Successful measurement of K-F, K-Cu, that led to the **observation of the onset of strong interaction in K-F system.**
- K-Al transitions and total yields evaluation measurement
  - Confirmation of old measurements
  - **Important testbed for cascade models**



THANK YOU FOR YOUR ATTENTION

Strong Interaction in Fluorine



Strong Interaction in Fluorine

$$R = \frac{I_X[(n,l) \to (n-1, l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i, l+1) \to (n, l)] + I_X[(i, l) \to (n, l-1)]}.$$

Measurable, at least with i = n+1

Practically:

Strong Interaction in Fluorine

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Measurable, at least with i = n+1

$$Y = \frac{I_X[(n,l) \to (n-1,l-1)]}{\sum_{i=n+1}^{\infty} [I_{XA}[(i,l+1) \to (n,l)] + I_{XA}[(i,l-1) \to (n,l)]},$$

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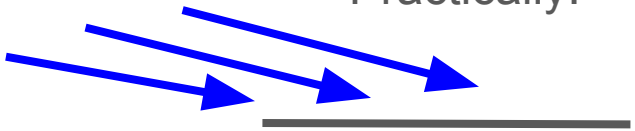
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$$Y = \frac{\Gamma_X}{\Gamma_u + \Gamma_X},$$

Observable + correction from rate calculations and cascade models

Practically:



lower level

Strong Interaction in Fluorine

$$R = \frac{I_X[(n,l)\to(n-1,l-1)]}{\sum_{i=n+1}^{n+4} I_X[(i,l+1)\to(n,l)] + I_X[(i,l)\to(n,l-1)]}.$$

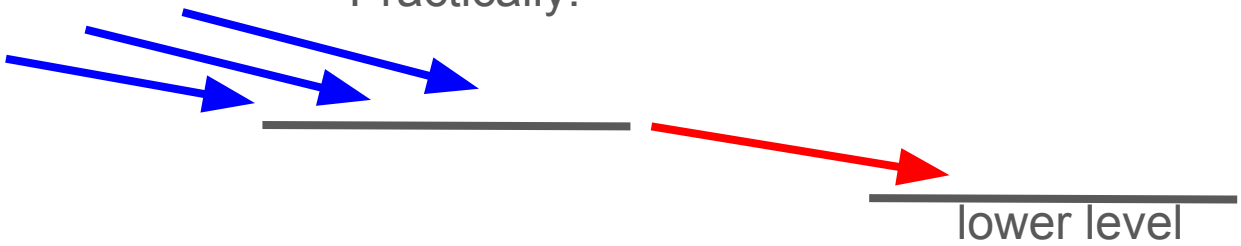
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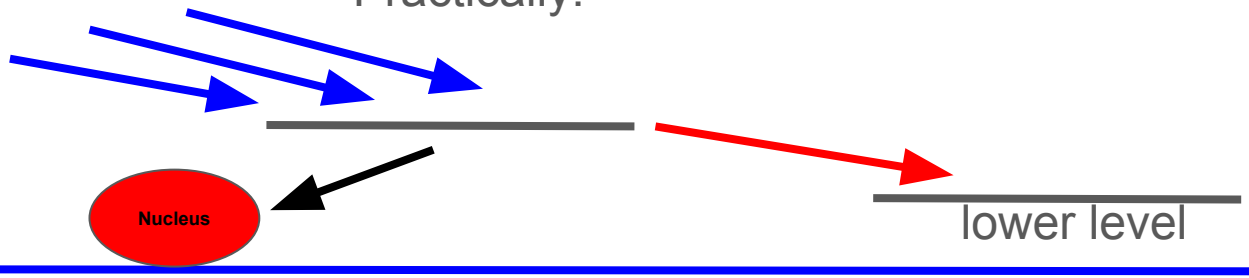
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Observable + correction from rate calculations and cascade models

$$Y = \frac{\Gamma_X}{\Gamma_u + \Gamma_X},$$

Through Y you can measure **upper level width**

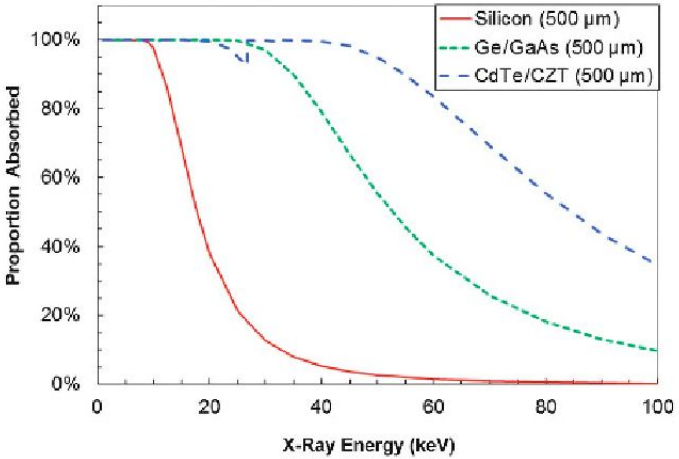
Practically:



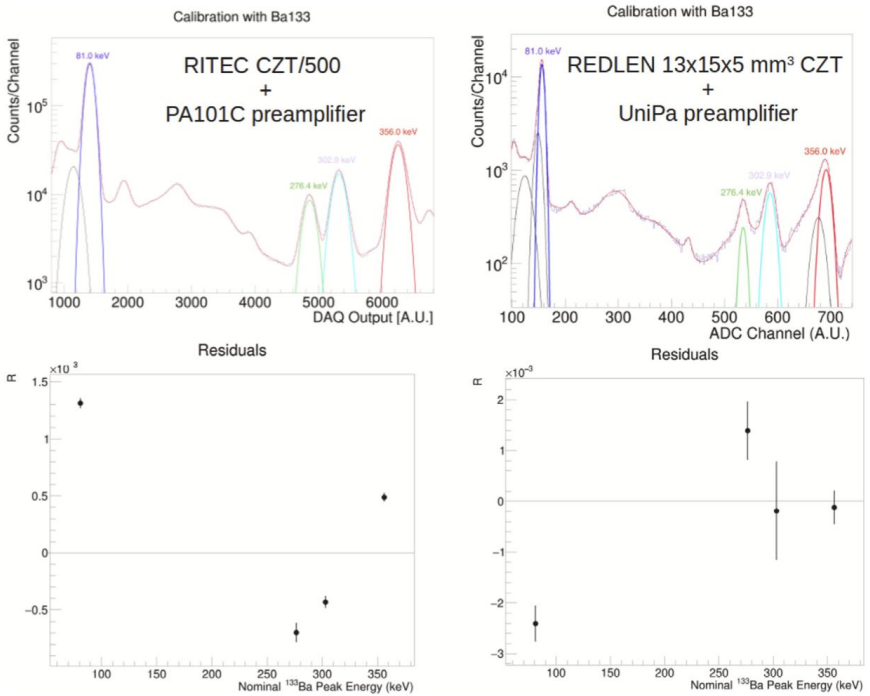
Why Cadmium Zinc Telluride?

- **Silicon** represents the best semiconductors in terms of availability, efficiency and resolution, to build a compact X-ray detecto
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- **Germanium** is a natural semiconductor, which is
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Calibration with Ba133
RITEC CZT/500
+
PA101C preamplifier
Counts/Channel
DAQ Output [A.U.]
81.0 keV
276.4 keV
302.9 keV
356.0 keV
Residuals
Nominal ^{133}Ba Peak Energy (keV)
Calibration with Ba133
REDLEN 13x15x5 mm³ CZT
+
UniPa preamplifier
ADC Channel (A.U.)
Residuals

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
C	3 → 2	−0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20
O	4 → 3	−0.025 ± 0.018	0.017 ± 0.014	–	–
Mg	4 → 3	−0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03
Al	4 → 3	−0.130 ± 0.050	0.490 ± 0.160	–	–
		−0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04
Si	4 → 3	−0.240 ± 0.050	0.810 ± 0.120	–	–
		−0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06
P	4 → 3	−0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	4 → 3	−0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36
		−0.43 ± 0.12	2.310 ± 0.170	–	–
		−0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5
Cl	4 → 3	−0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7
		−0.94 ± 0.40	3.92 ± 0.99	–	–
		−1.08 ± 0.22	2.79 ± 0.25	–	–
Co	5 → 4	−0.099 ± 0.106	0.64 ± 0.25	–	–
Ni	5 → 4	−0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3
		−0.246 ± 0.052	1.23 ± 0.14	–	–
Cu	5 → 4	−0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8
		−0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1

- Incompatible measurements
- Measurement with wide errors
- Relative yields not always measured
- Total yields almost unknown

Requirements in a Collider

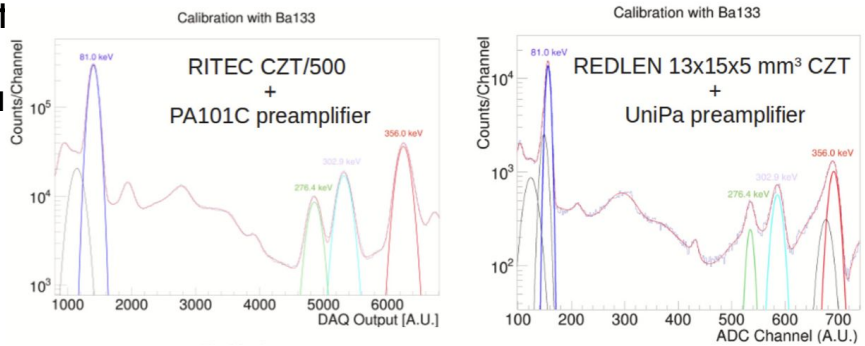
To perform measurements in DAFNE, an X-ray detector needs

- **A good energy resolution** → to resolve shifts and widths in months of data-taking.
- **A compact setup** to be as closer as possible to beam-pipe compatibly with other systems.
- **High resistance to radiation damage and stability** over the months of data-taking.
- A good timing for **background rejection capability.**

Requirements in a Collider

To perform measurements in DAFNE, an X-ray detect

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	RITEC CZT/500		REDLEN M1535	
^{133}Ba Peak (keV)	R (10^{-3})	FWHM/E	R (10^{-3})	FWHM/E
81.0	1.3	0.110	-2.4	0.064
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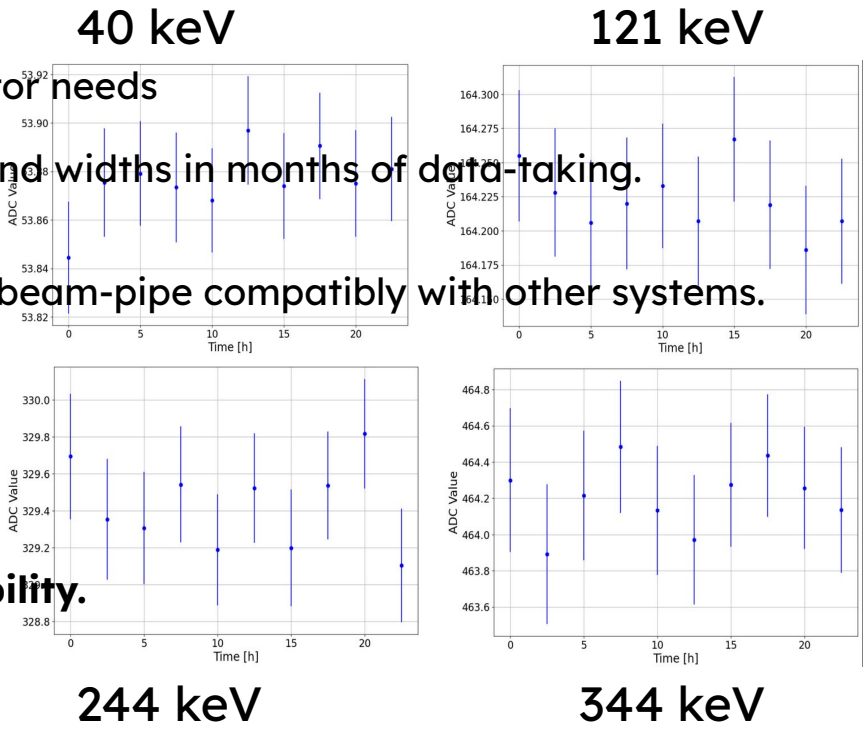


~ 20 cm from IP

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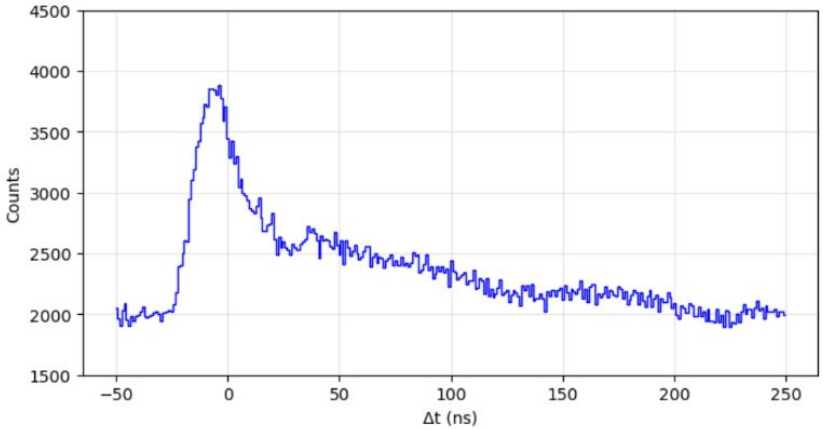
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Requirements in a Collider

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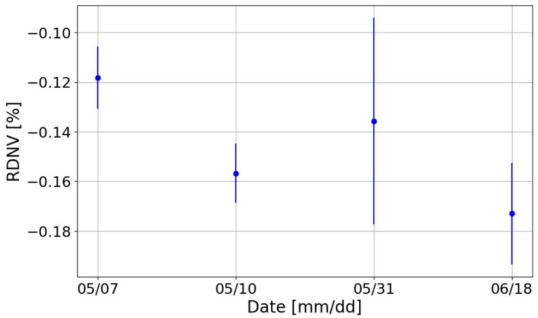
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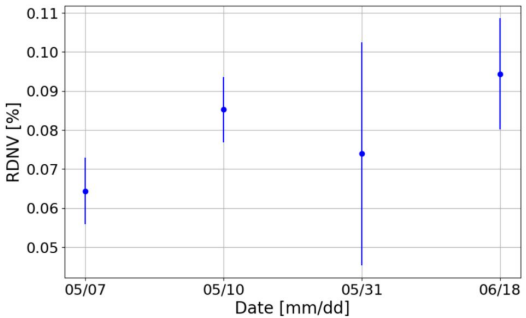
Time difference between trigger and signal ~10-100 ns

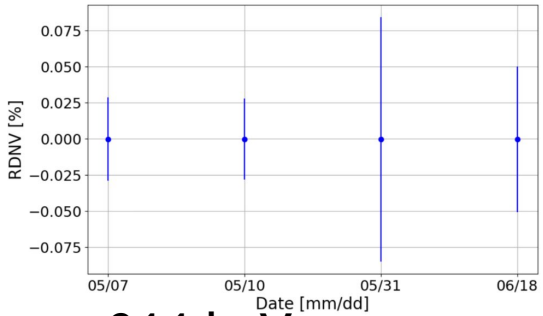
Analysis: Calibration and Stability

40 keV

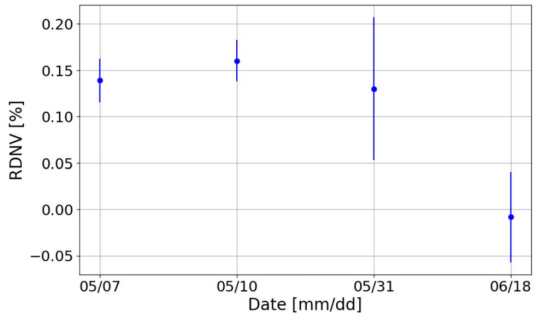


121 keV





244 keV

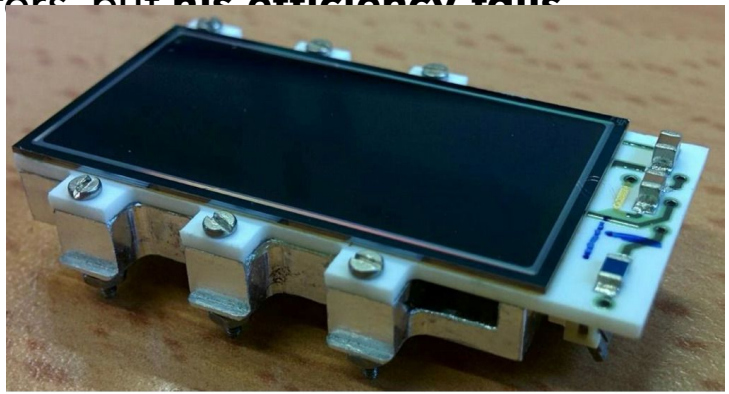


344 keV

All Relative Differences respect to Nominal Value (RDNV) are 1‰ or below, from 40 keV to 344 keV

Why Cadmium Zinc Telluride?

- **Silicon** represents the best semiconductors in terms of availability, efficiency and resolution, to build a compact X-ray detectors, but **his efficiency falls down fast after tens of keV energies**.



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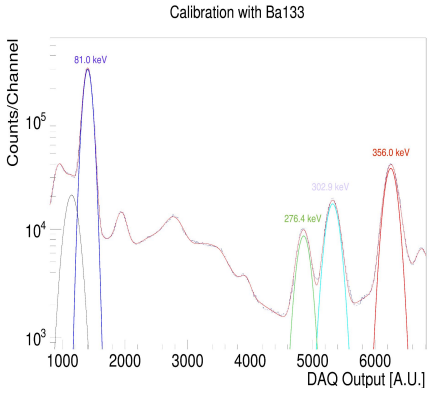
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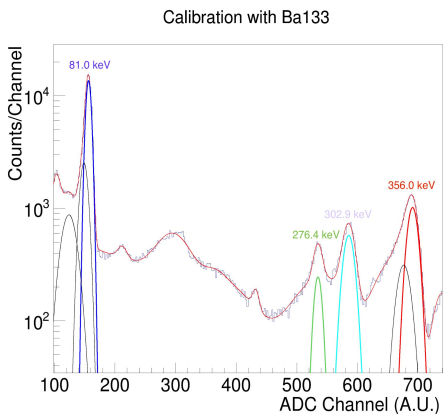
Roadmap to first Measurements with CZT

- First test to show the improvements wrt commercial detectors
- Studies on stability and radiation damage + calibration
- Studies on timing performance
- Effective analysis strategy

First Tests

- A CZT detector was never used in a collider
- The new detector was tested for the first time in 2023.
- The first tests were focused on **demonstrating the improvement in terms of resolution** thanks to the new custom electronics made in Palermo





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^{133}Ba Peak (keV)	R (10^{-3})	FWHM/E	R (10^{-3})	FWHM/E
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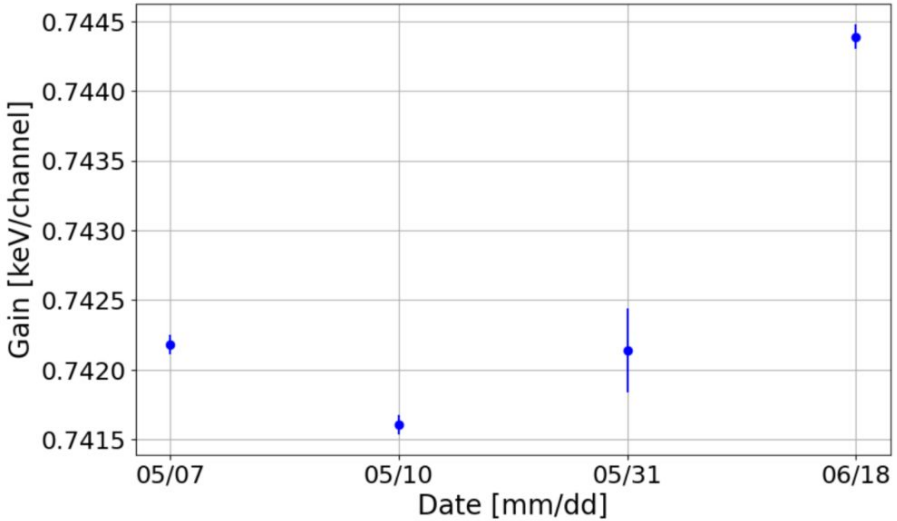
Table 1: Summary of the results obtained with the two systems employed during the tests

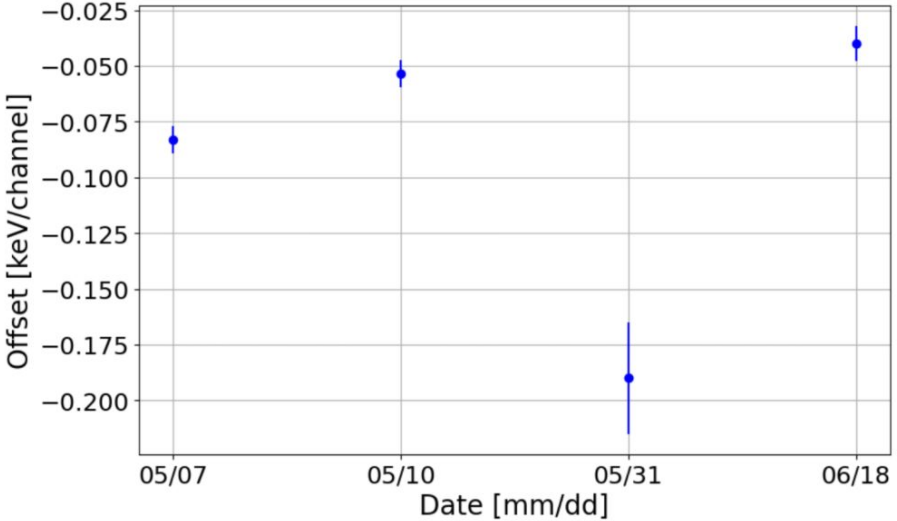
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Stability Studies

- During the Data Taking in 2023-2024, at first, the stability was studied



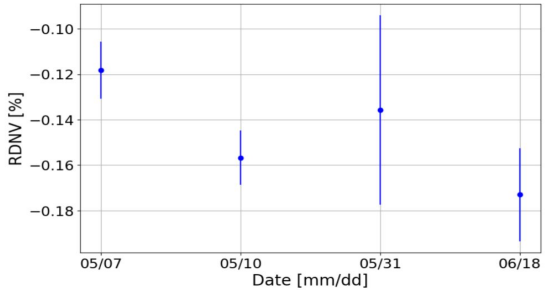


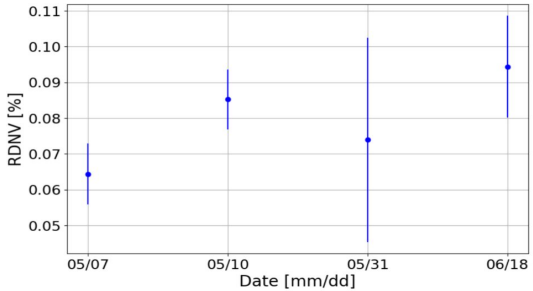
Gain and Offset of **calibration are extremely stable over a month**

Stability Studies

Also the Relative Differences to Nominal Values (RDNVs), were found to be **stable at the ‰ level in the range 40-344 keV**, confirming the effectiveness of the calibrations

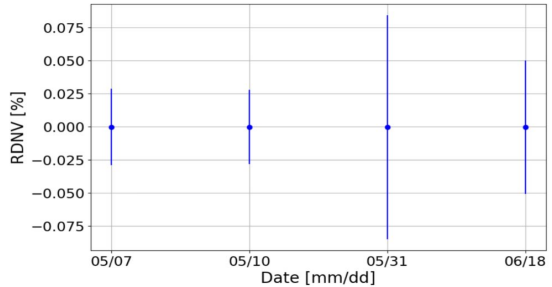
40 keV

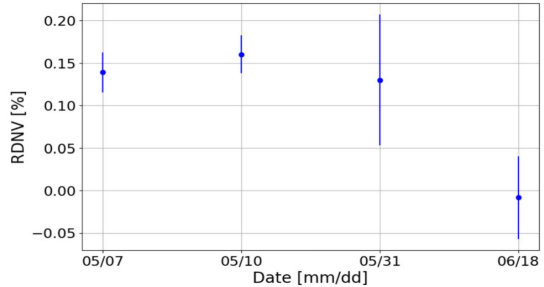




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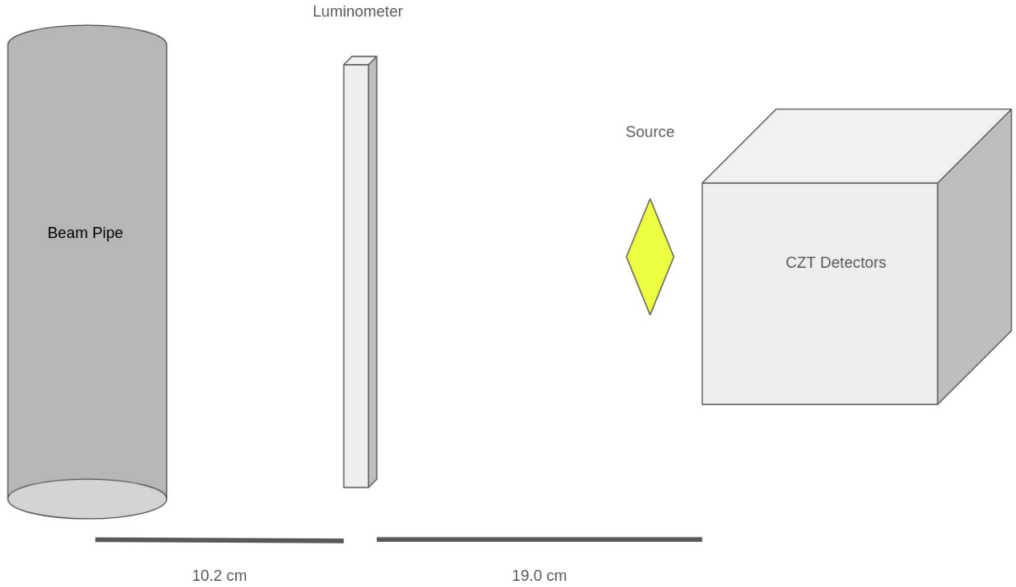


344 keV

Stability Studies with DAΦNE on

We also investigated the performances when the collider is on, to **confirm that the strong currents and the strong background of the environment does not alter the performances.**

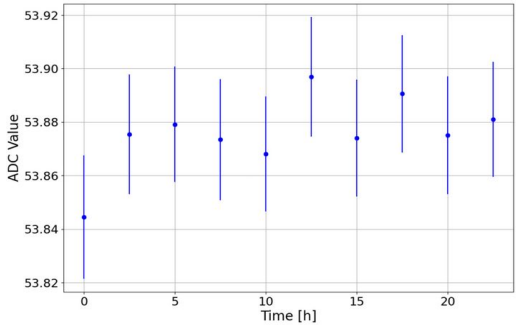
A radioactive Eu source was placed in the setup during a run with the collider on.

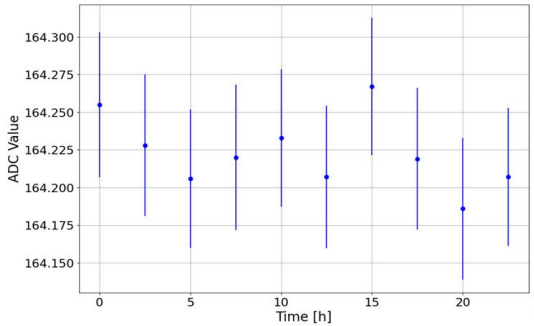


Stability Studies with DAΦNE on

The stability of the ADC during the run was optimal

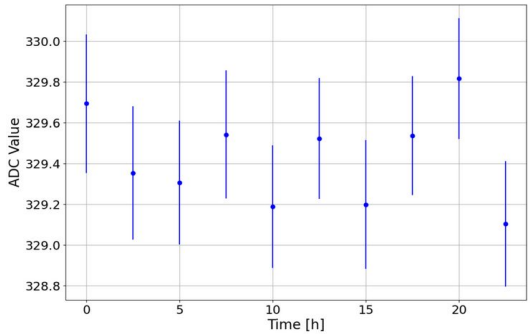
40 keV

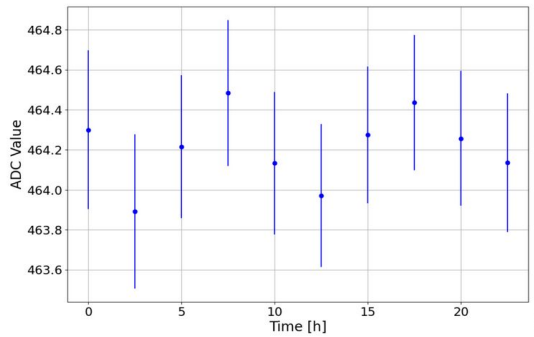




121 keV

244 keV



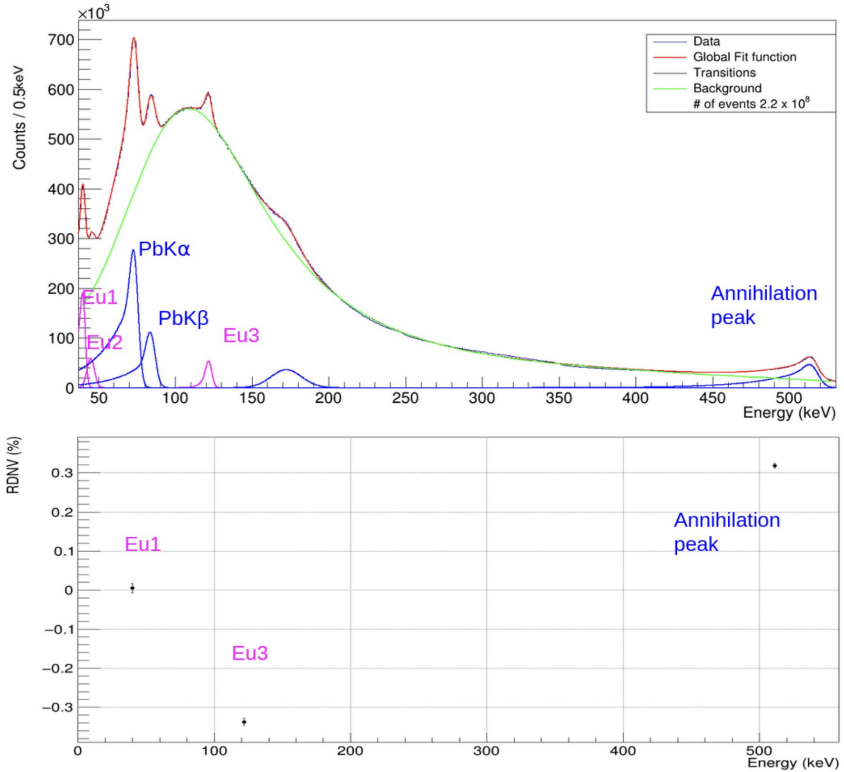


344 keV

Stability Studies with DAΦNE on

The data from 4 CZT detectors were also calibrated with the aim to measure the Eu lines, and the result spectrum is reported on the right.

The RDNVs of ‰ and good energy resolutions were confirmed.

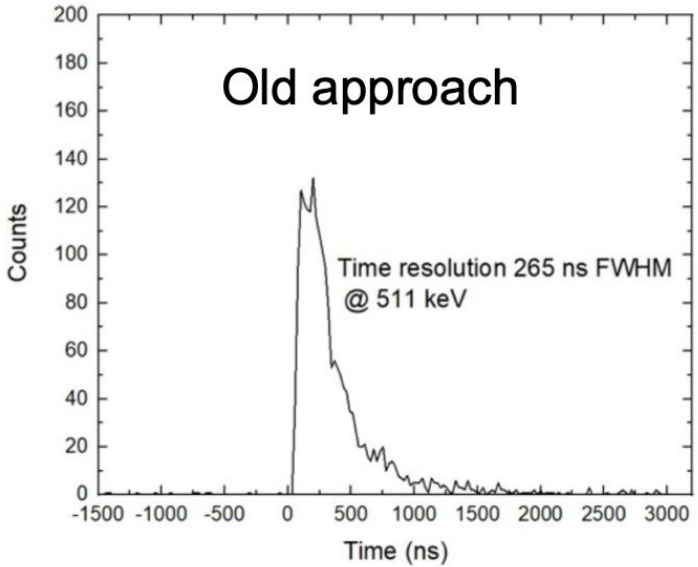


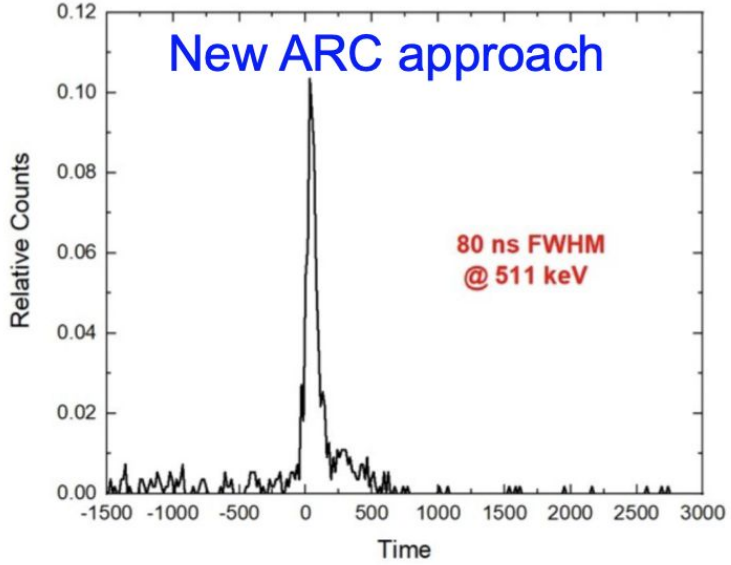
Roadmap to first Measurements with CZT

- ✅ First test to show the improvements wrt commercial detectors
- ✅ Studies on stability and radiation damage + calibration
- Studies on timing performance
- Effective analysis strategy

Timing Studies

This also improved timing resolution → more powerful background rejection





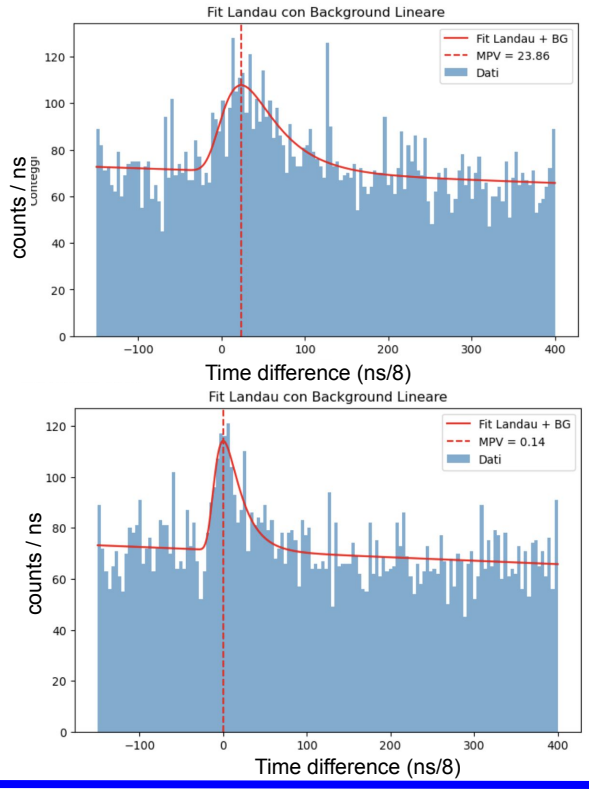
Roadmap to first Measurements with CZT

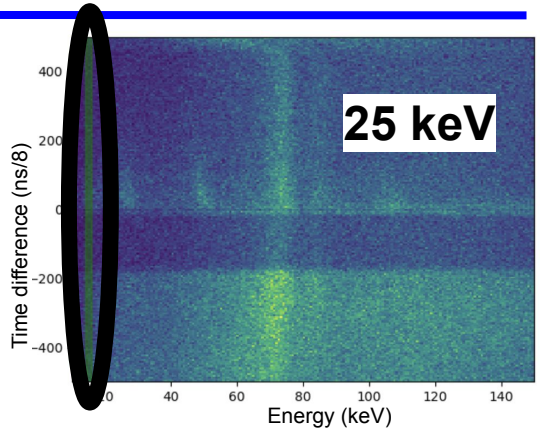
- ✔ First test to show the improvements wrt commercial detectors
- ✔ Studies on stability and radiation damage + calibration
- ✔ Studies on timing performance
- Effective analysis strategy

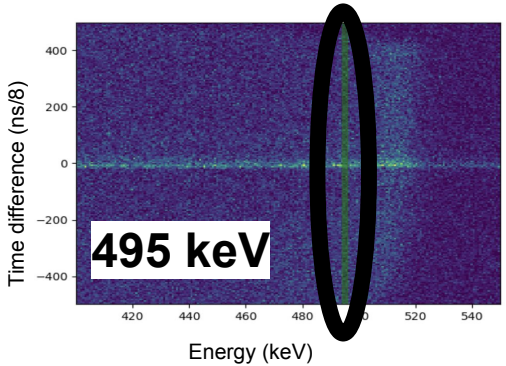
Timing Studies

An important feature for any kind of measurements in a collider is timing.
Time analysis to reduce the background are essential to obtain clean spectra in a particle collider, and to reduce the high background coming from the machine.

My analysis on timing revealed a dependency of timing on the energy of the particles:

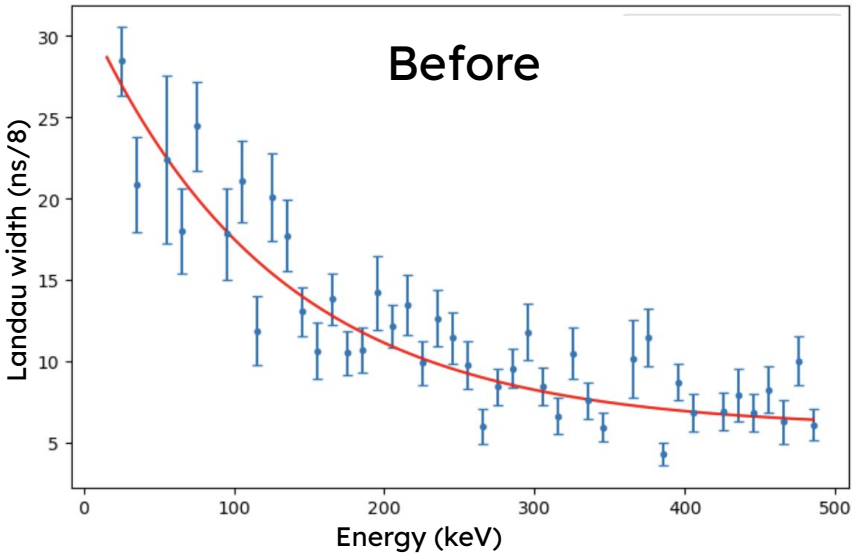


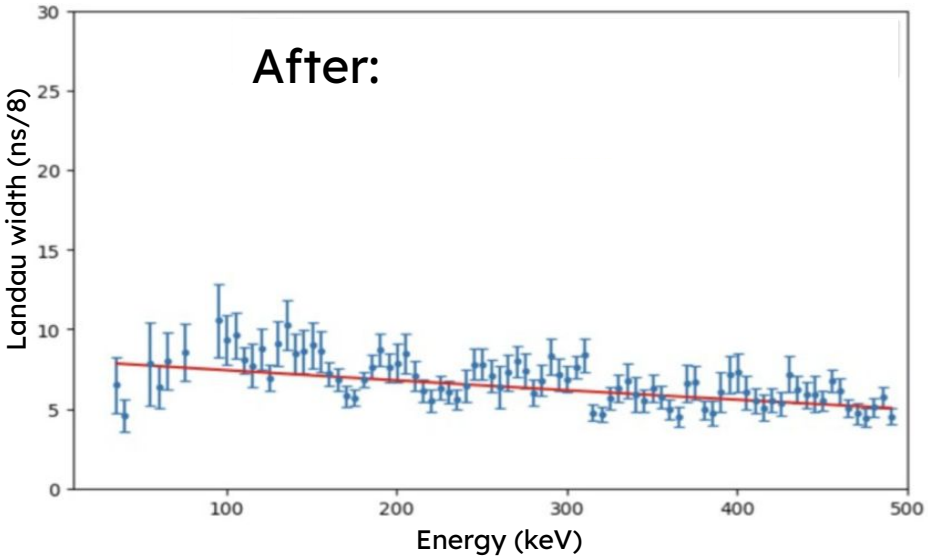




Timing Studies

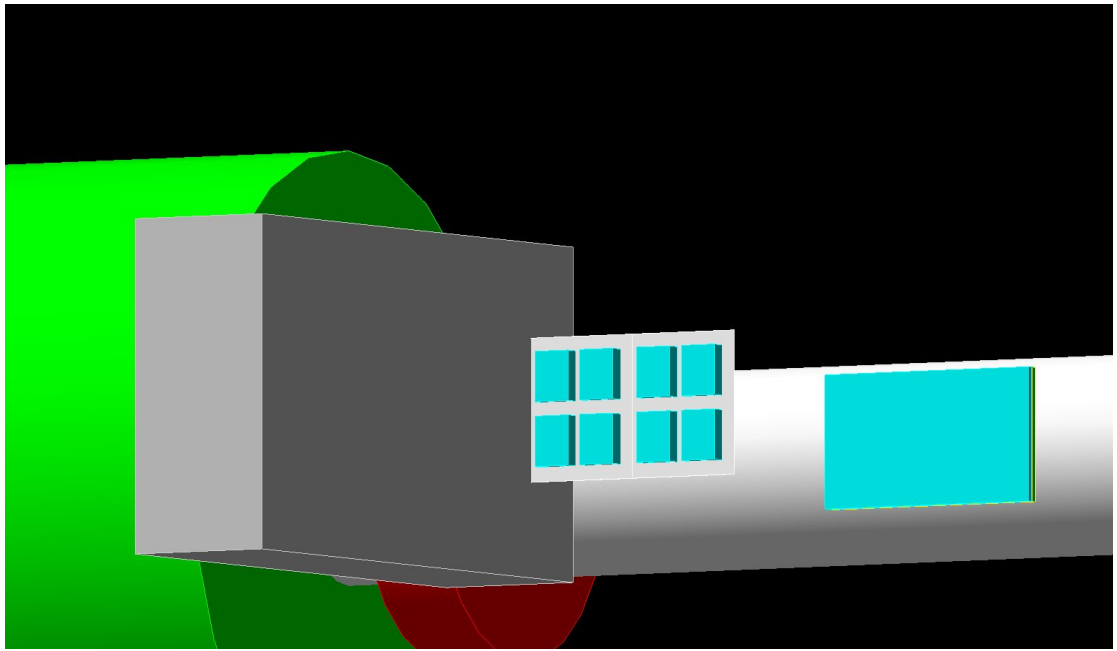
This dependence was eliminated by developing a new Amplitude and Rise time Compensated analysis (ARC), developed in UniPa





Monte Carlo Simulation

Total Yields evaluation obtained through a detailed MC of the apparatus.



Strong Interaction in Fluorine

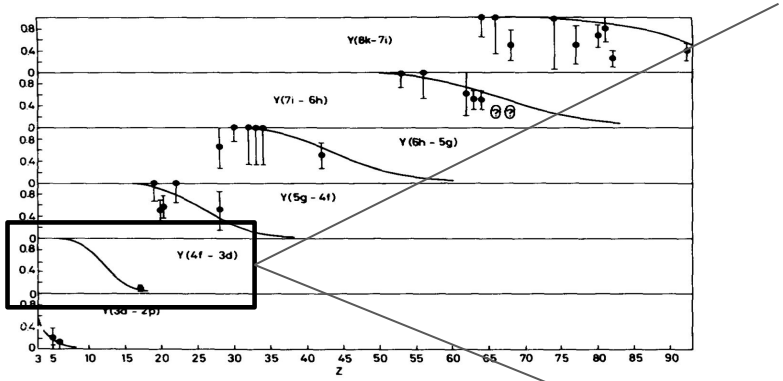
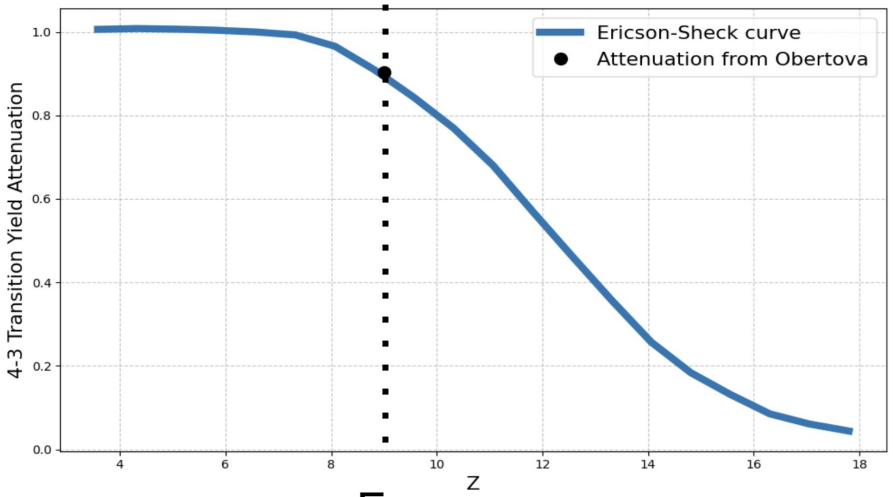


Fig. 1. Yields of kaonic X-rays versus Z. The solid curves are the theoretical values using the $\bar{K}N$ scattering lengths and a matter density proportional to the proton density obtained from ref. [12]. For simplicity they have been smoothed out in this figure. The data points are taken from ref. [1], and are defined according to eq. (8). Errors are added quadratically. Calculated values obtained perturbatively using point Coulomb wave functions and $\mathrm{Im}\,A = 0.7$ fm.



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Ericson-Scheck, Nuc. Phys. B **90**, 1970
https://www.sciencedirect.com/science/article/pii/0550321370903615?via%3Dihub

Obertova: private comunication