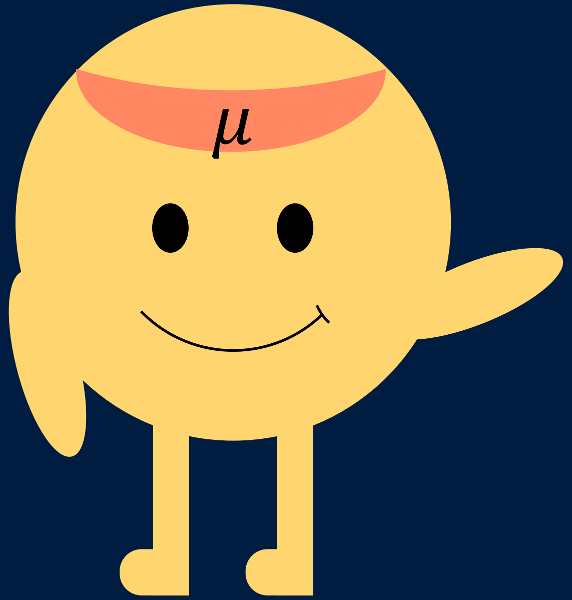
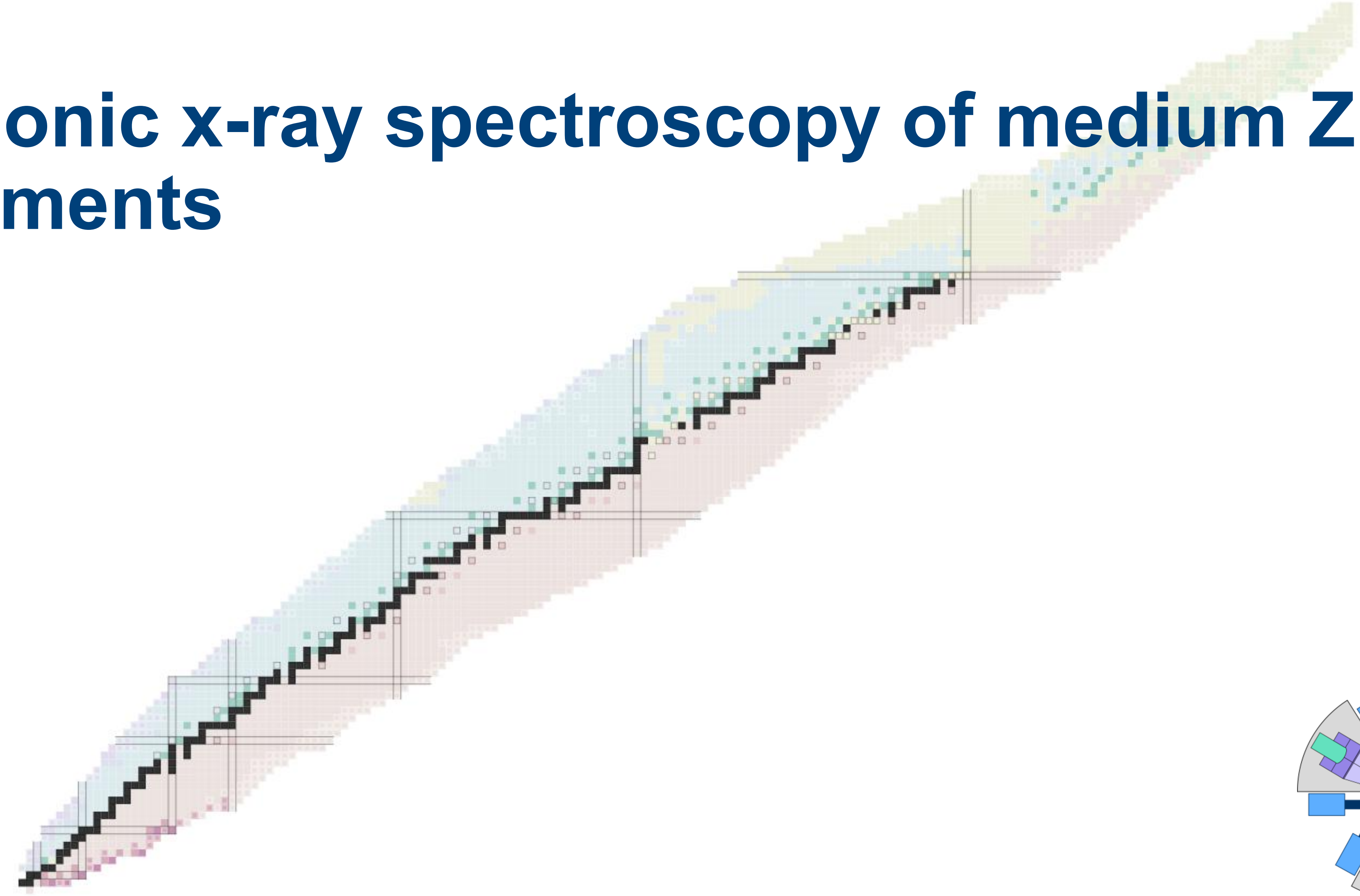


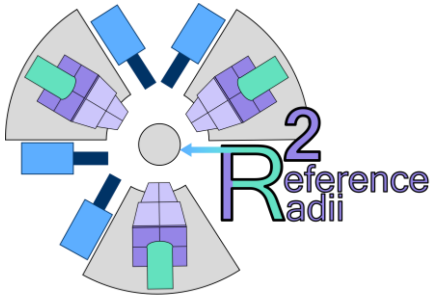
Muonic x-ray spectroscopy of medium Z elements

Marie Deseyn on behalf of the **Reference Radii collaboration**

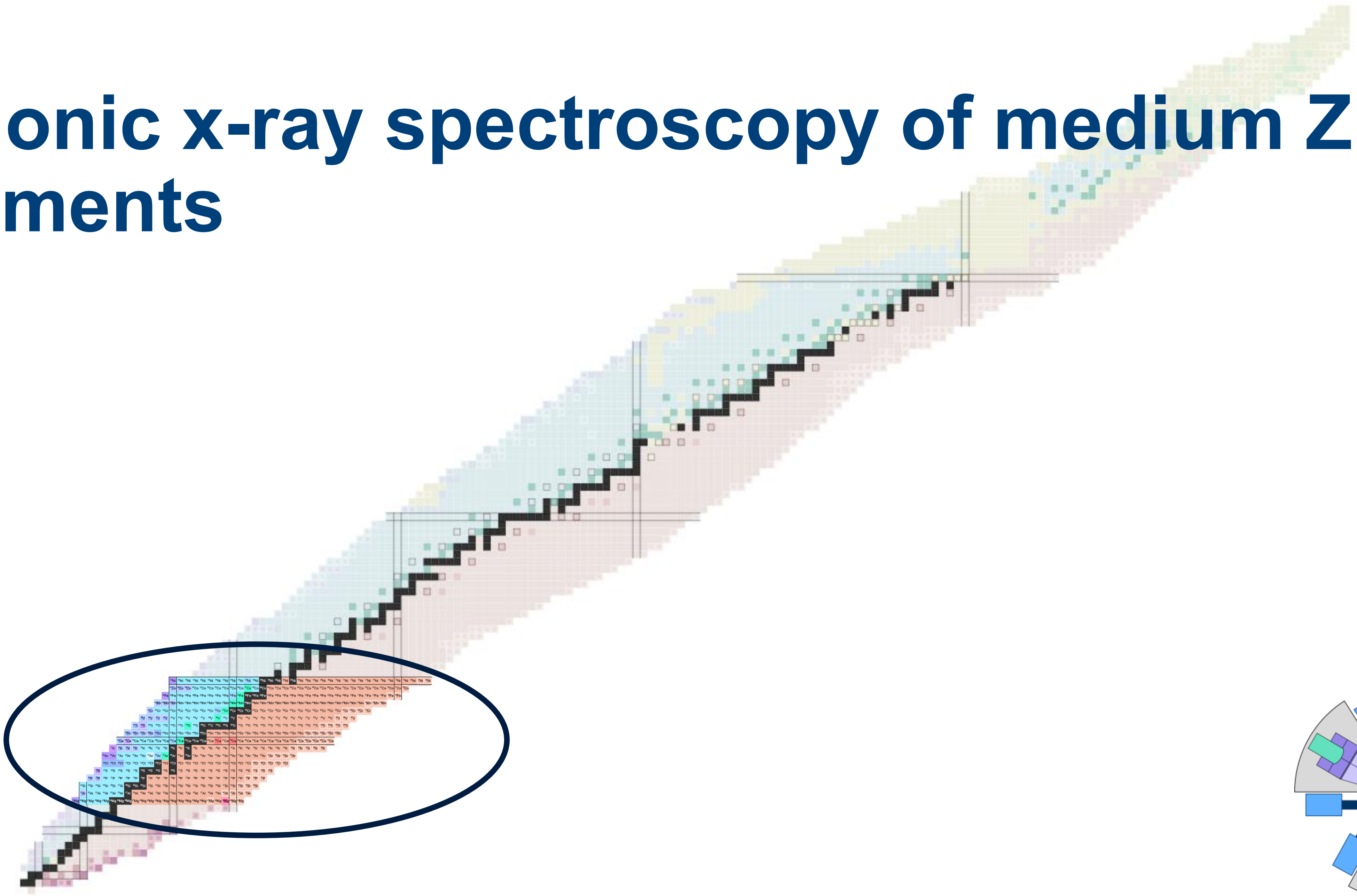
PhD Fellowship fundamental research - 11P6V24N

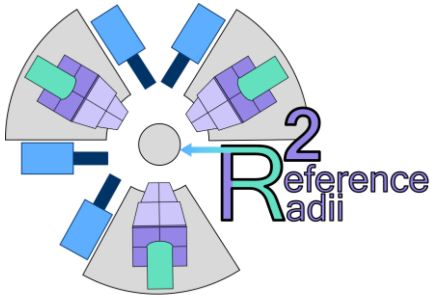
Muonic x-ray spectroscopy of medium Z elements

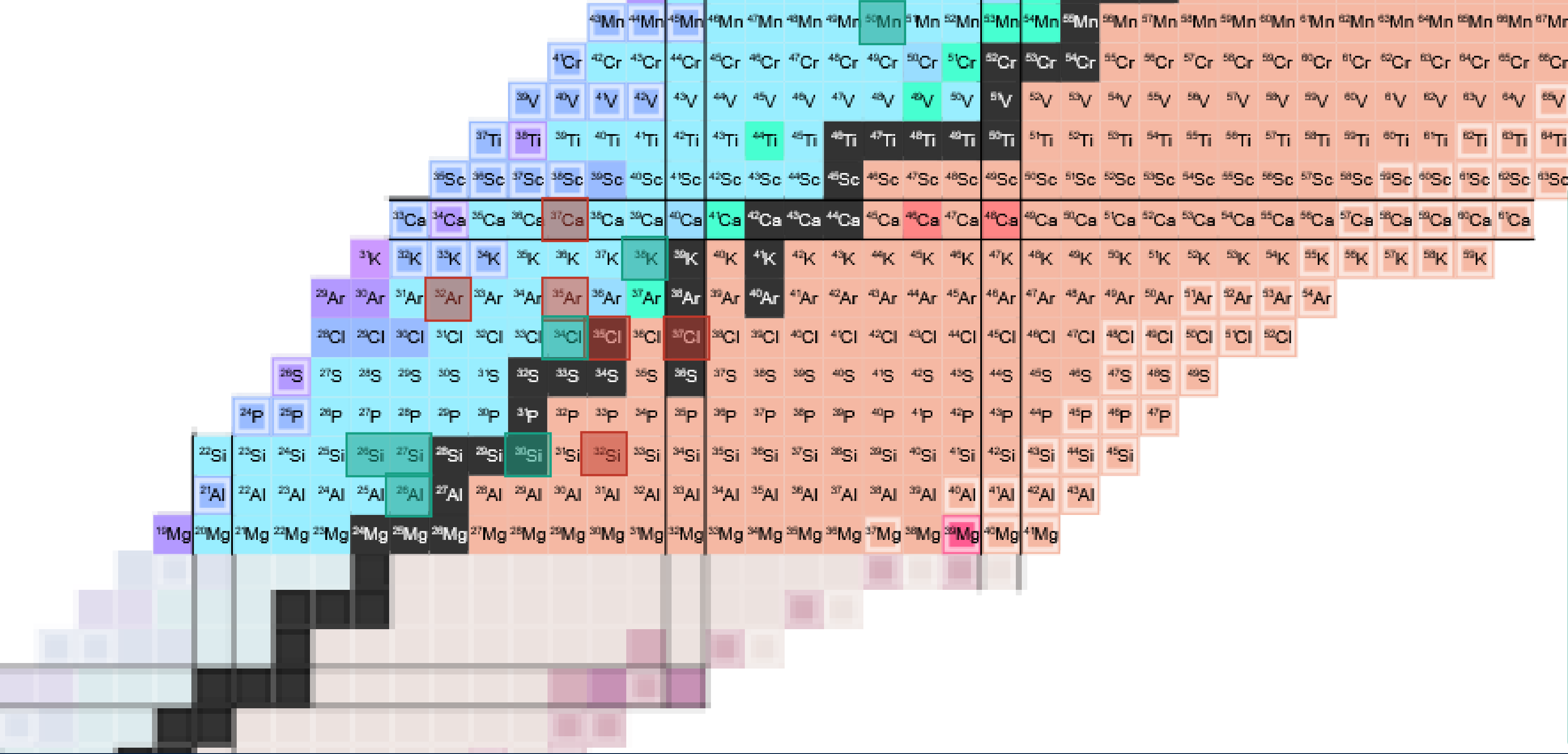


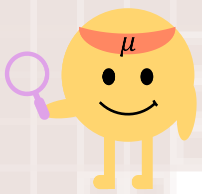


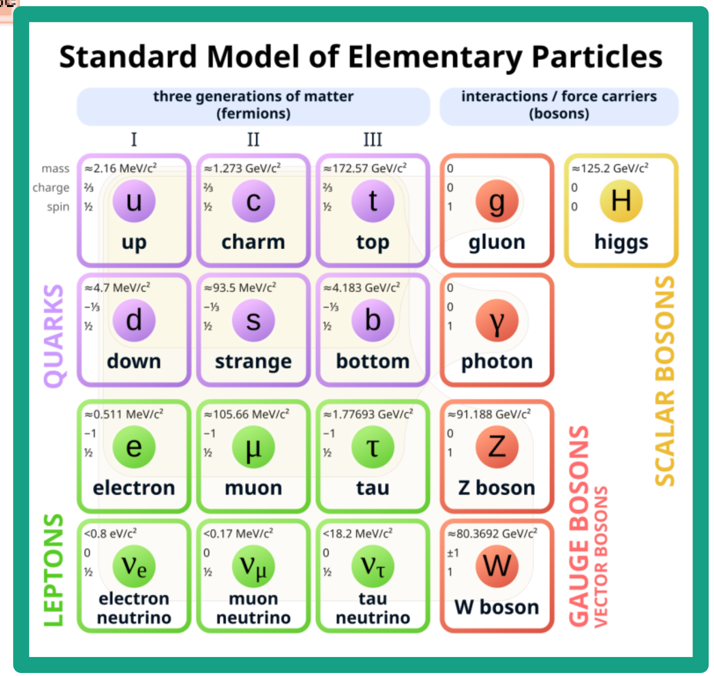
Muonic x-ray spectroscopy of medium Z elements











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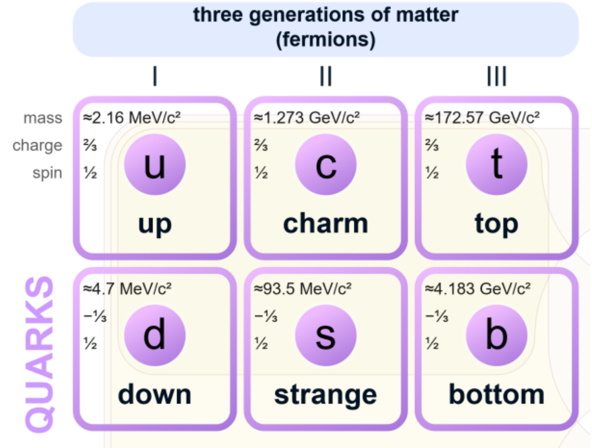
Charge radii of medium Z elements?



CKM (Cabibbo–Kobayashi–Maskawa) matrix:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Unitarity matrix in Standard Model → $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Nuclei of interest: ^{26m}Al, ^{26,27,30}Si, ^{34}Cl, ^{38m}K, ^{34,38}Ar, ^{50}Mn

N. Severijns, L. Hayen, V. De Leebeeck, et al., "F t values of the mirror β transitions and the weak-magnetism-induced current in allowed nuclear β decay," Physical Review C, vol. 107, p. 015 502, 2023; P. Plattner, E. Wood, L. Al Ayoubi, et al., "Nuclear charge radius of Al-26m and its implication for Vud in the c Physical Review Letters, vol. 131, p. 222 502, 2023.;

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Charge radii of medium Z elements?

L = slope of symmetry energy

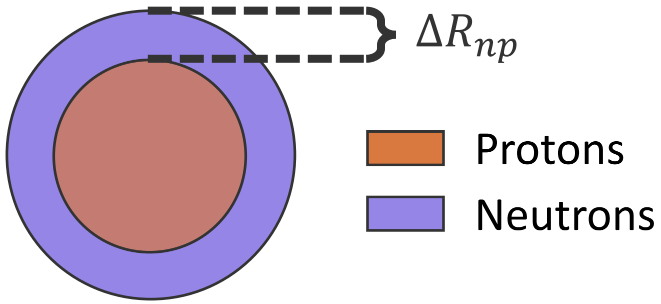
- L small: smaller, compact neutron star
- L big: larger, puffier neutron star

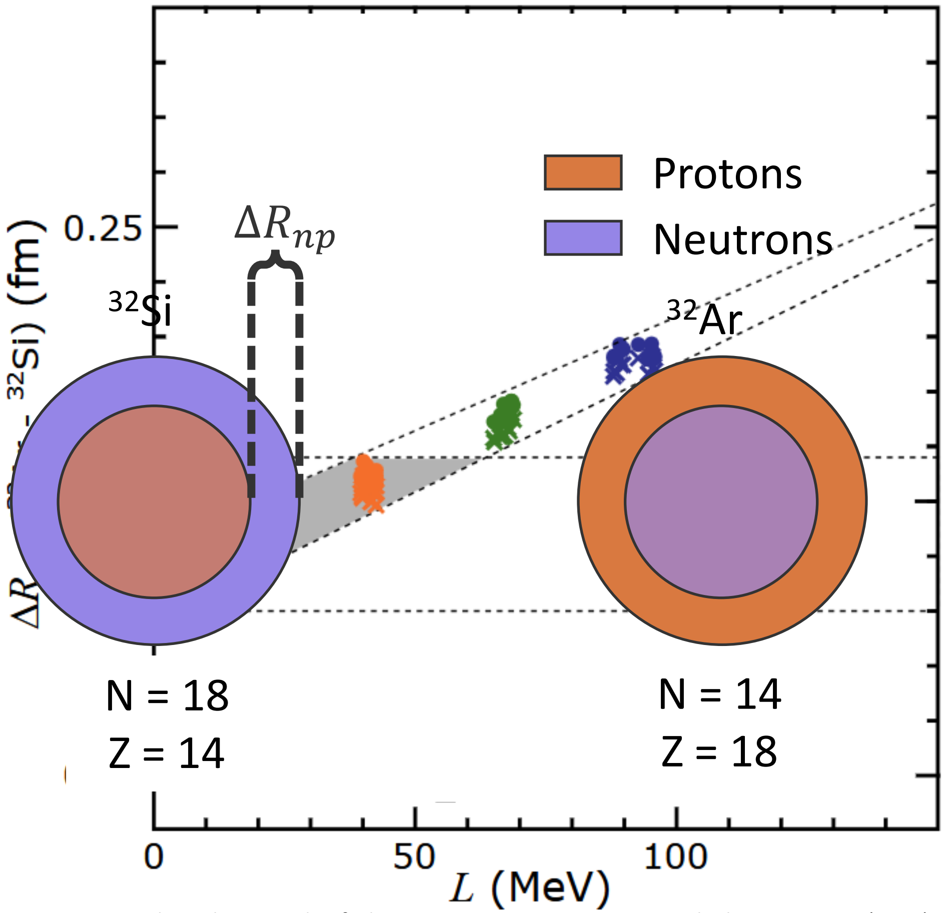
L ~ neutron skin thickness: $\Delta R_{np} \sim \mathrm{L}$

if p = n → $\Delta R_{np} = \Delta R_{ch}$ of 2 mirror nuclei

BUT e.g. Coulomb → $\Delta R_{np} \sim \Delta R_{ch}$

Interest: ^{32}Si-^{32}Ar, ^{35}Cl-^{35}Ar, ^{37}Cl-^{37}Ca





Nuclear Charge Radii of Silicon Isotopes, König, Kristian et al, Phys. Rev. Lett. (2024)

Overview RefRad at medium Z

Application	Laser spec status	Muonic status

Experiment

Data-processing

np-1s extraction

Charge radius

Overview RefRad at medium Z

Application	Laser spec status	Muonic status				
^{34}Cl → BSM ^{35,37}Cl → Eqn. of state	No laser spectroscopy	^{35,37}Cl	2023	2023-2024	2024-2025	2024-2025
			Experiment	Data-processing	np-1s extraction	Charge radius

Overview RefRad at medium Z

Application	Laser spec status	Muonic status	Experiment	Data-processing	np-1s extraction	Charge radius
^{34}Cl → BSM $^{35,37}Cl$ → Eqn. of state	No laser spectroscopy	$^{35,37}Cl$	2023	2023-2024	2024-2025	2024-2025
^{38m}K → BSM	$^{36\text{-}52}K$ done	$^{39,40,41}K$	2023	2023-2024	2024-2025	2024-2025

Overview RefRad at medium Z

Application	Laser spec status	Muonic status	Experiment	Data-processing	np-1s extraction	Charge radius
^{34}Cl → BSM ^{35,37}Cl → Eqn. of state	No laser spectroscopy	^{35,37}Cl	2023	2023-2024	2024-2025	2024-2025
^{38m}K → BSM	$^{36-52}$K done	^{39,40,41}K	2023	2023-2024	2024-2025	2024-2025
^{26,27,30}Si → BSM ^{32}Si → Eqn. of state	^{28,29,30,32}Si done $^{28-36,38}$Si: measured spring 2025 (FRIB) $^{28-31}$Si : planned in Jyvaskyla (A. Koszorus and A. Kayaalp)	^{28,29,30}Si	2024	2024-2025	Planned in 2025	

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Overview RefRad at medium Z

Application	Laser spec status	Muonic status	Experiment	Data-processing	np-1s extraction	Charge radius
^{34}Cl → BSM ^{35,37}Cl → Eqn. of state	No laser spectroscopy	^{35,37}Cl	2023	2023-2024	2024-2025	2024-2025
^{38m}K → BSM	$^{36-52}$K done	^{39,40,41}K	2023	2023-2024	2024-2025	2024-2025
^{26,27,30}Si → BSM ^{32}Si → Eqn. of state	^{28,29,30,32}Si done $^{28-36,38}$Si: measured spring 2025 (FRIB) $^{28-31}$Si : planned in Jyvaskyla (A. Koszorus and A. Kayaalp)	^{28,29,30}Si	2024	2024-2025	Planned in 2025	
^{32}Ar → Eqn. of state	^{32}Ar done	^{36,38,40}Ar	1982	1982	1982	Planned in 2025

Overview RefRad at medium Z

Application	Laser spec status	Muonic status	Experiment	Data-processing	np-1s extraction	Charge radius
^{34}Cl → BSM ^{35,37}Cl → Eqn. of state	No laser spectroscopy	^{35,37}Cl	2023	2023-2024	2024-2025	2024-2025
^{38m}K → BSM	$^{36-52}$K done	^{39,40,41}K	2023	2023-2024	2024-2025	2024-2025
^{26,27,30}Si → BSM ^{32}Si → Eqn. of state	^{28,29,30,32}Si done $^{28-36,38}$Si: measured spring 2025 (FRIB) $^{28-31}$Si : planned in Jyvaskyla (A. Koszorus and A. Kayaalp)	^{28,29,30}Si	2024	2024-2025	Planned in 2025	
^{32}Ar → Eqn. of state	^{32}Ar done	^{36,38,40}Ar	1982	1982	1982	Planned in 2025
^{26m}Al → BSM	^{26m}Al done	^{26,27}Al	Test in 2024			

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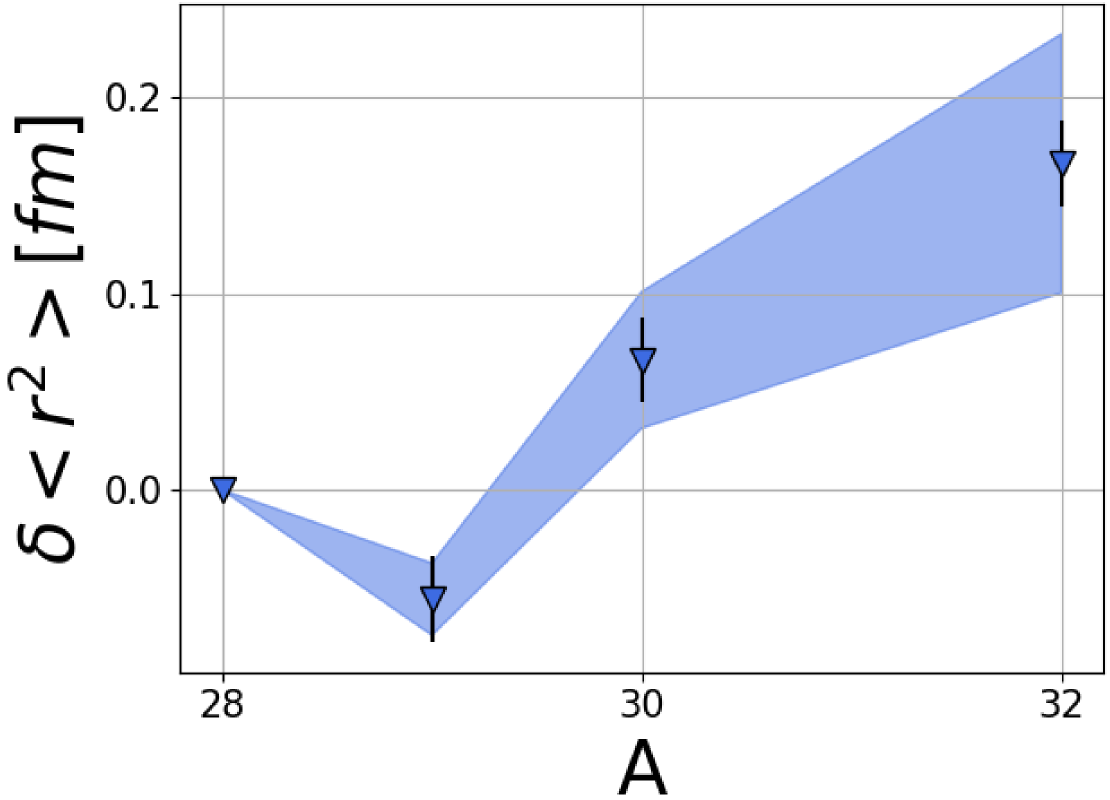
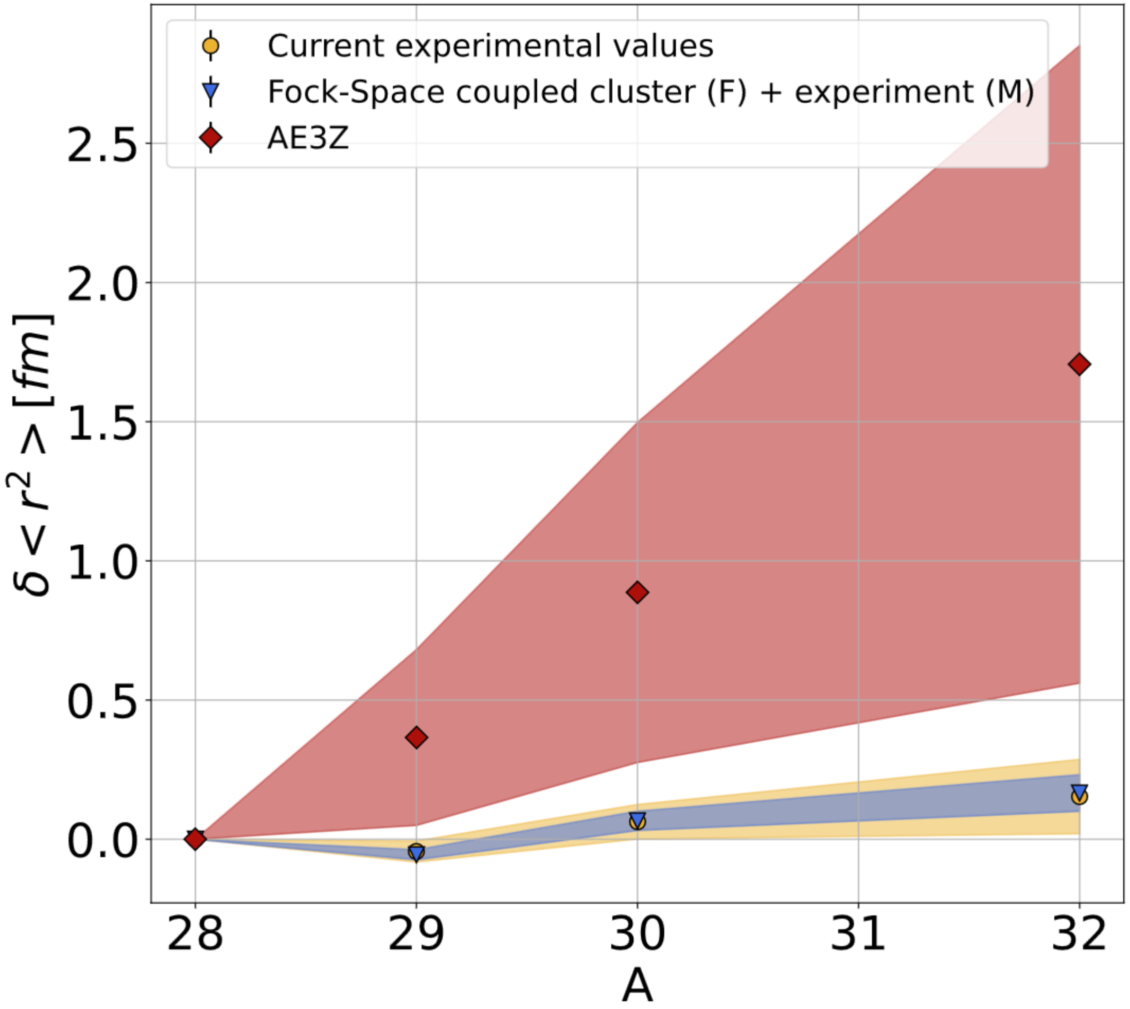
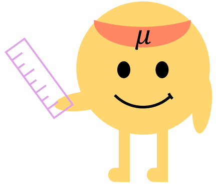
Added value of the muonic measurements?

$$\frac{AA'}{A-A'}\delta\nu^{AA'} = M_i + F_i\frac{AA'}{A-A'}\delta\langle r^2\rangle^{AA'}$$



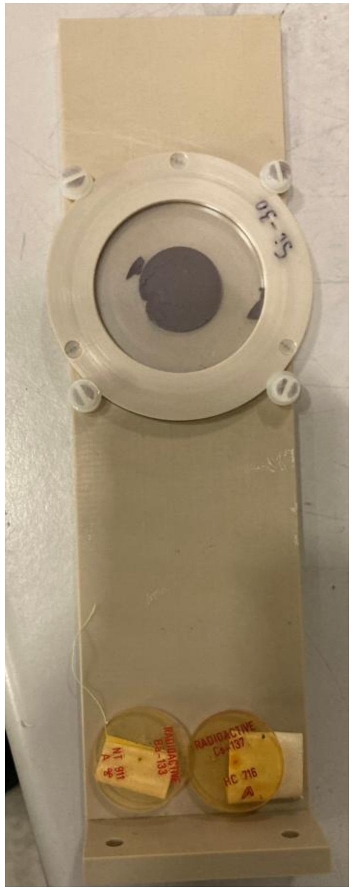




Beamtimes

2023

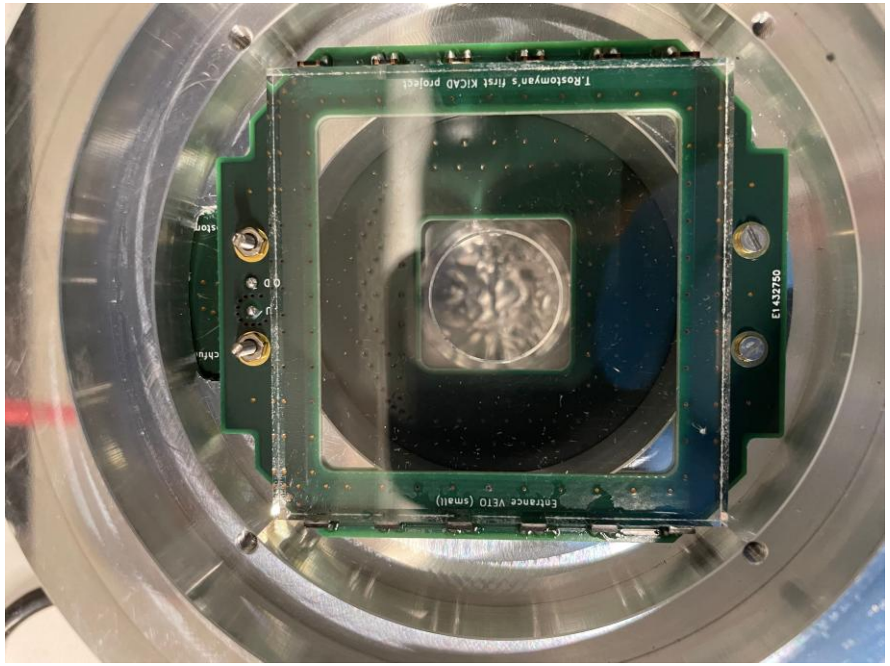
2024



Beamtimes

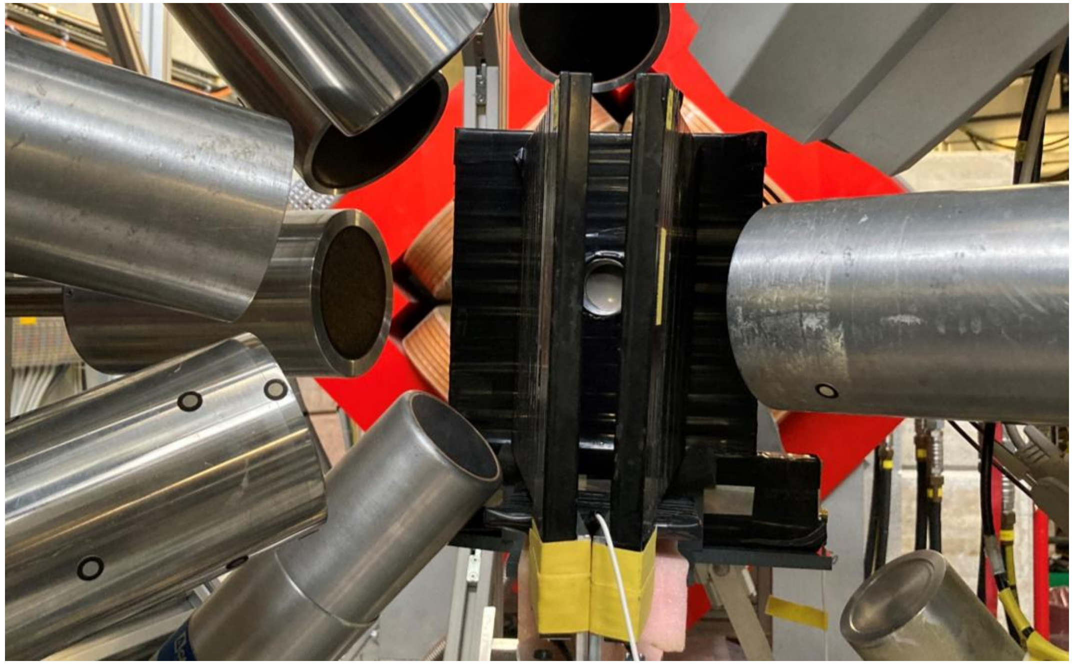
2023

- 2 muon scintillators
- 5 electron veto scintillators



2024

- 2 muon scintillators
- 6 electron veto scintillators



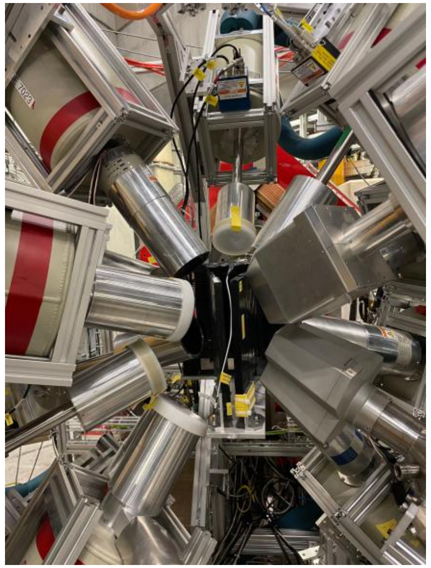
Beamtimes

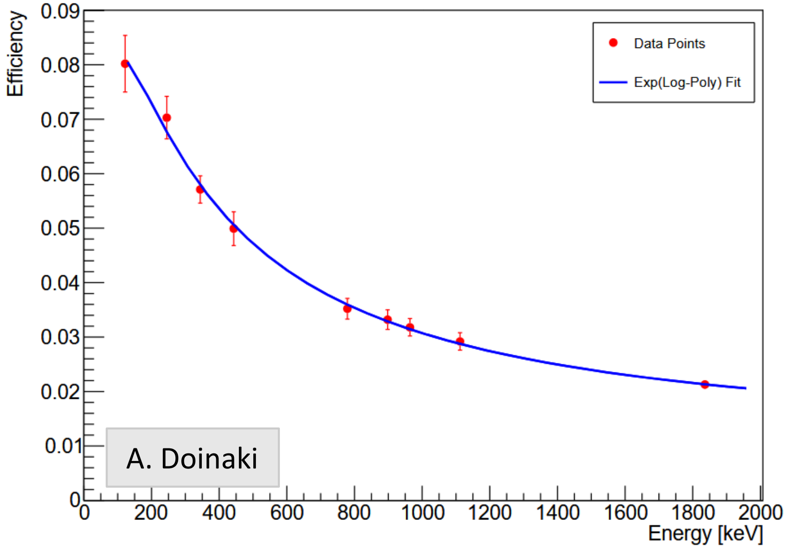
2023

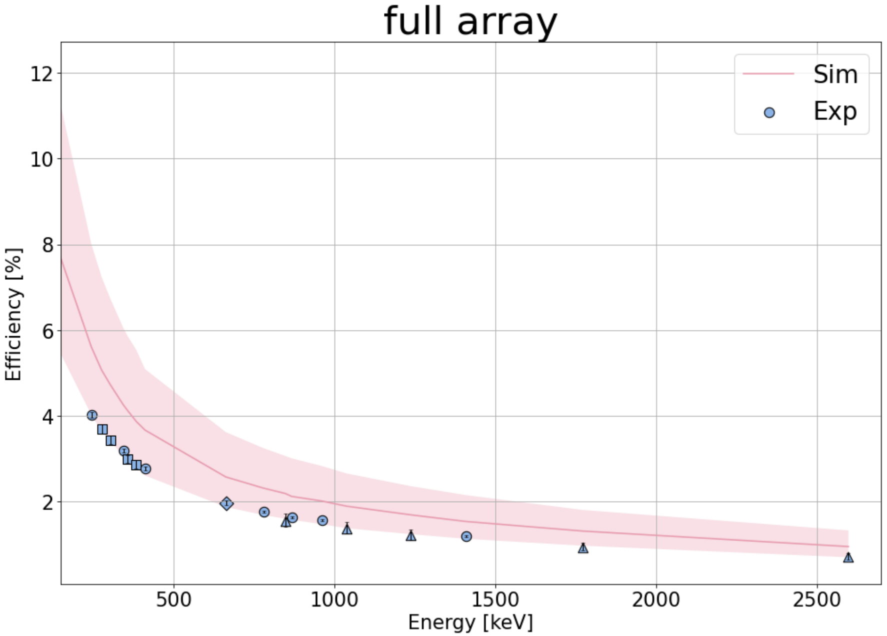
- 2 muon scintillators
- 5 electron veto scintillators
- 14 HPGe detectors

2024

- 2 muon scintillators
- 5 electron veto scintillators
- 12 HPGe detectors







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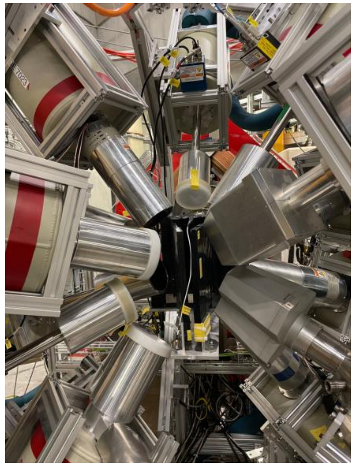
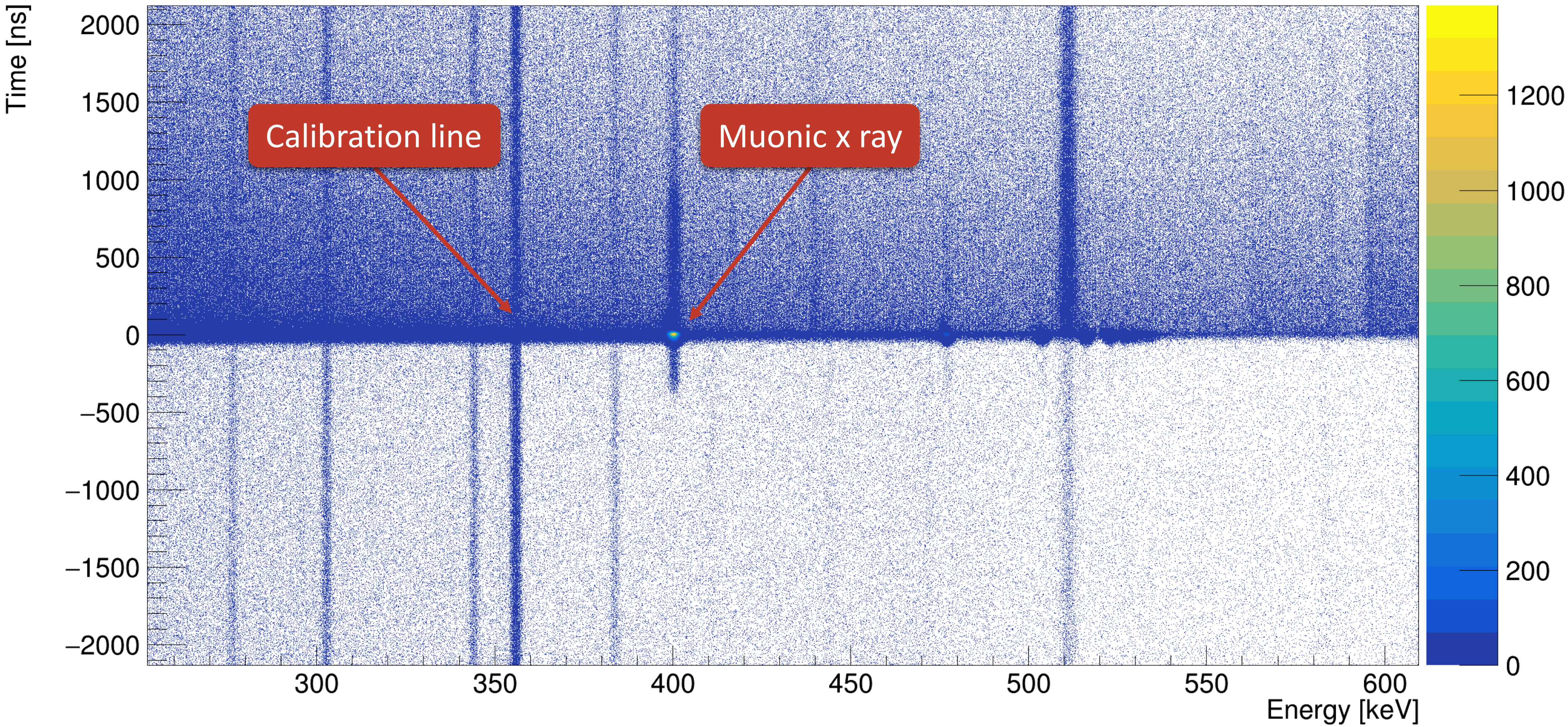
Beamtimes





Time [ns]
2000
1500
1000
500
0
−500
−1000
−1500
−2000
300
350
400
450
500
550
600
Energy [keV]
1200
1000
800
600
400
200
0
Calibration line
Muonic x ray

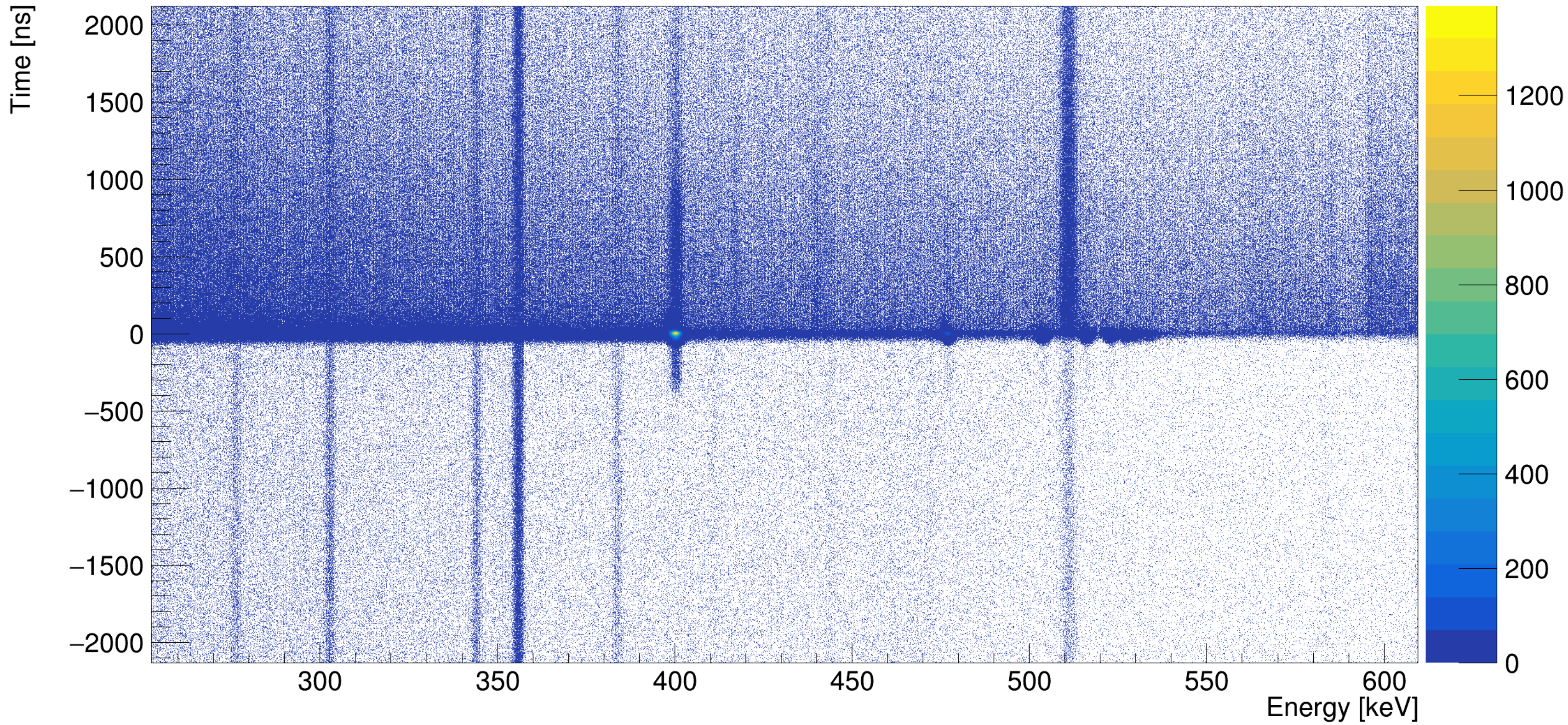
Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

ELET optimization

Energy calibration 1

Risetime correction

Recalibration



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Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

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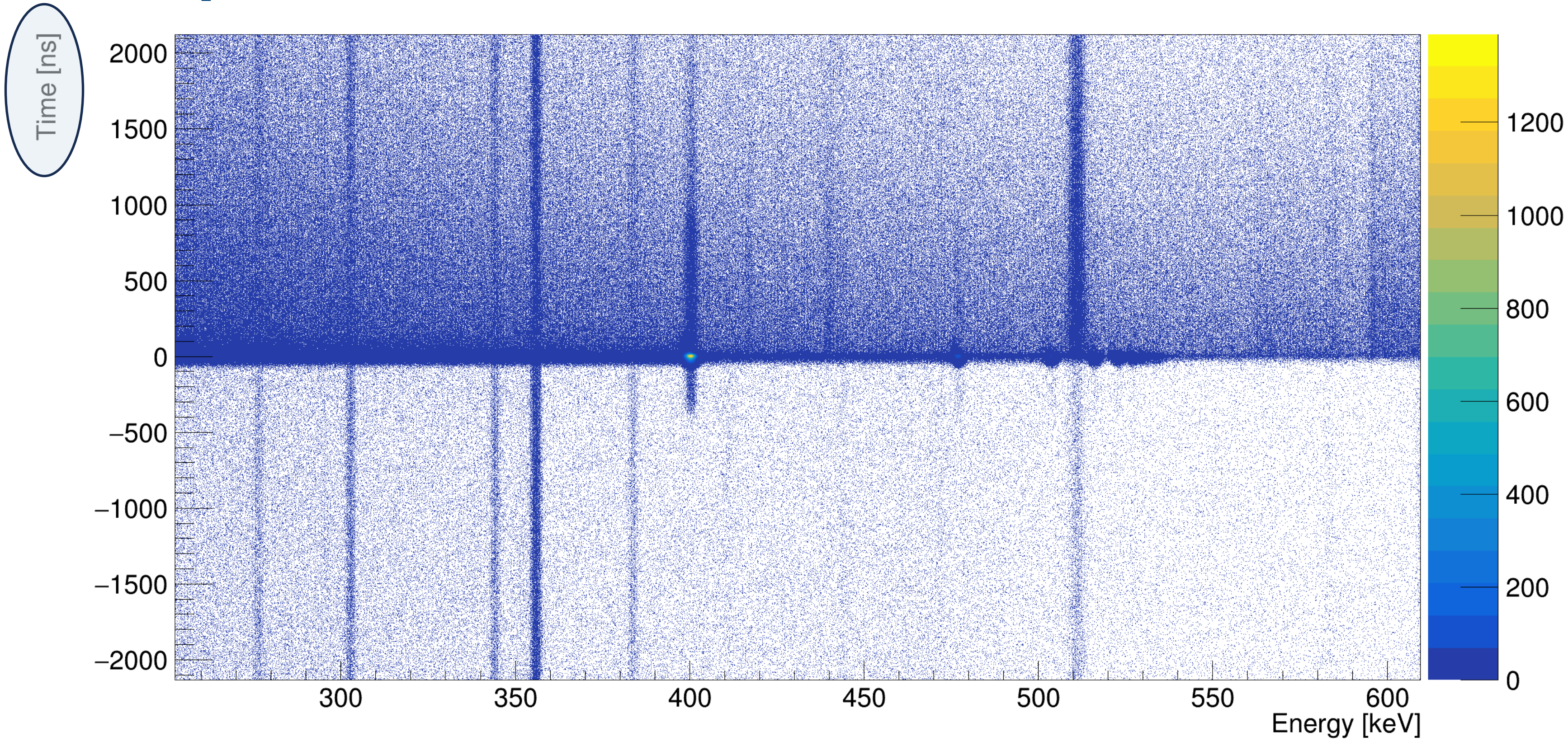
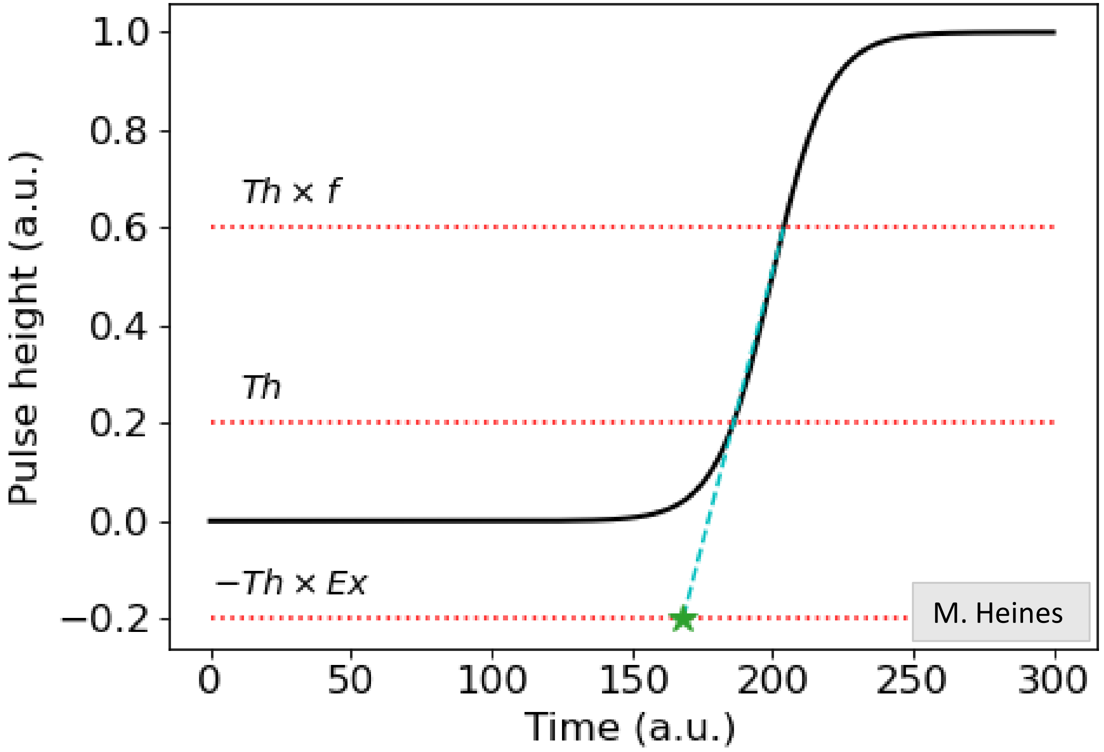
Recalibration



ELET optimization

Optimization of Th, f, Ex in each detector:

- 2023: 5-20ns (FWHM)
- 2024: 30-50ns (FWHM)



KU LEUVEN fwo

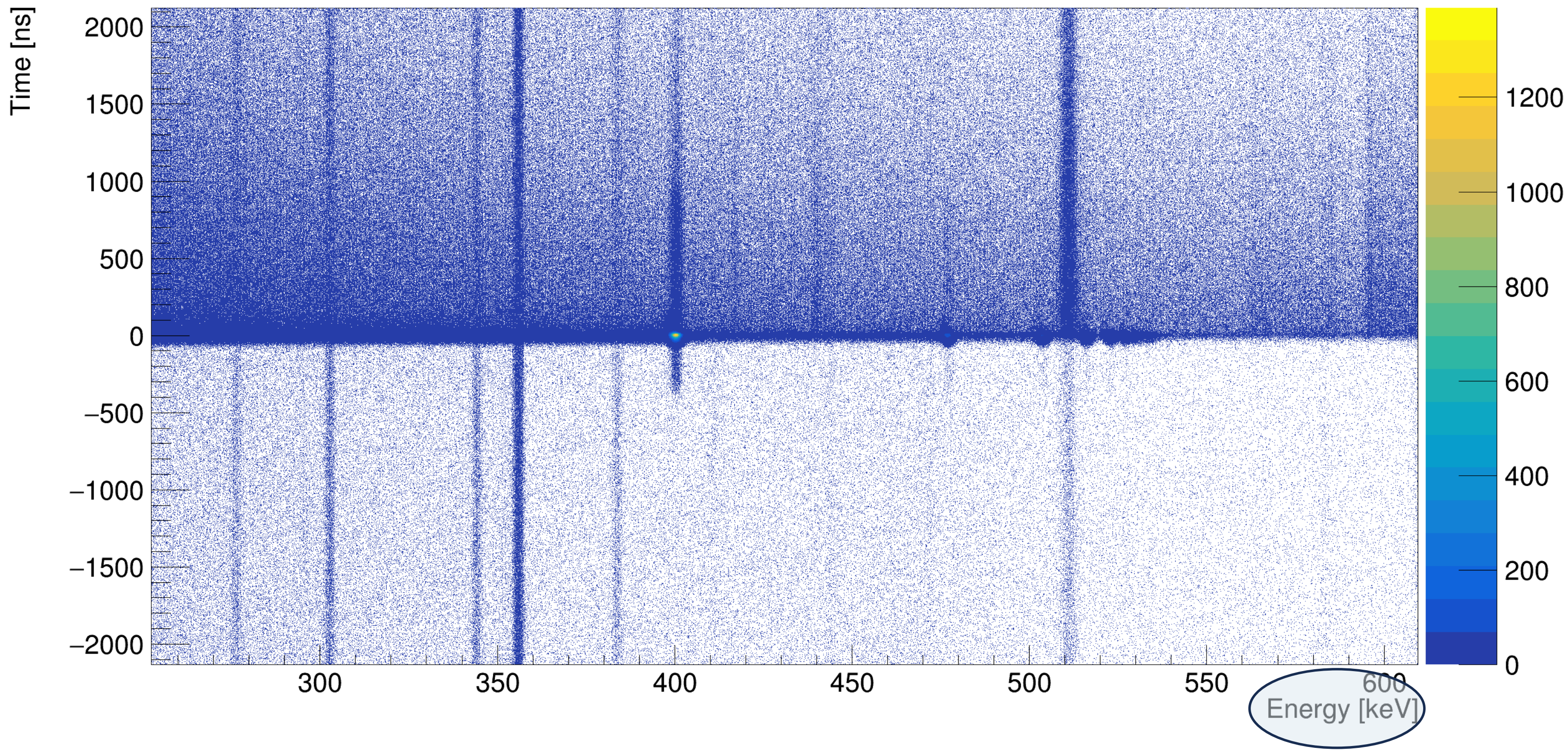
Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

ELET optimization

Energy calibration 1

Risetime correction

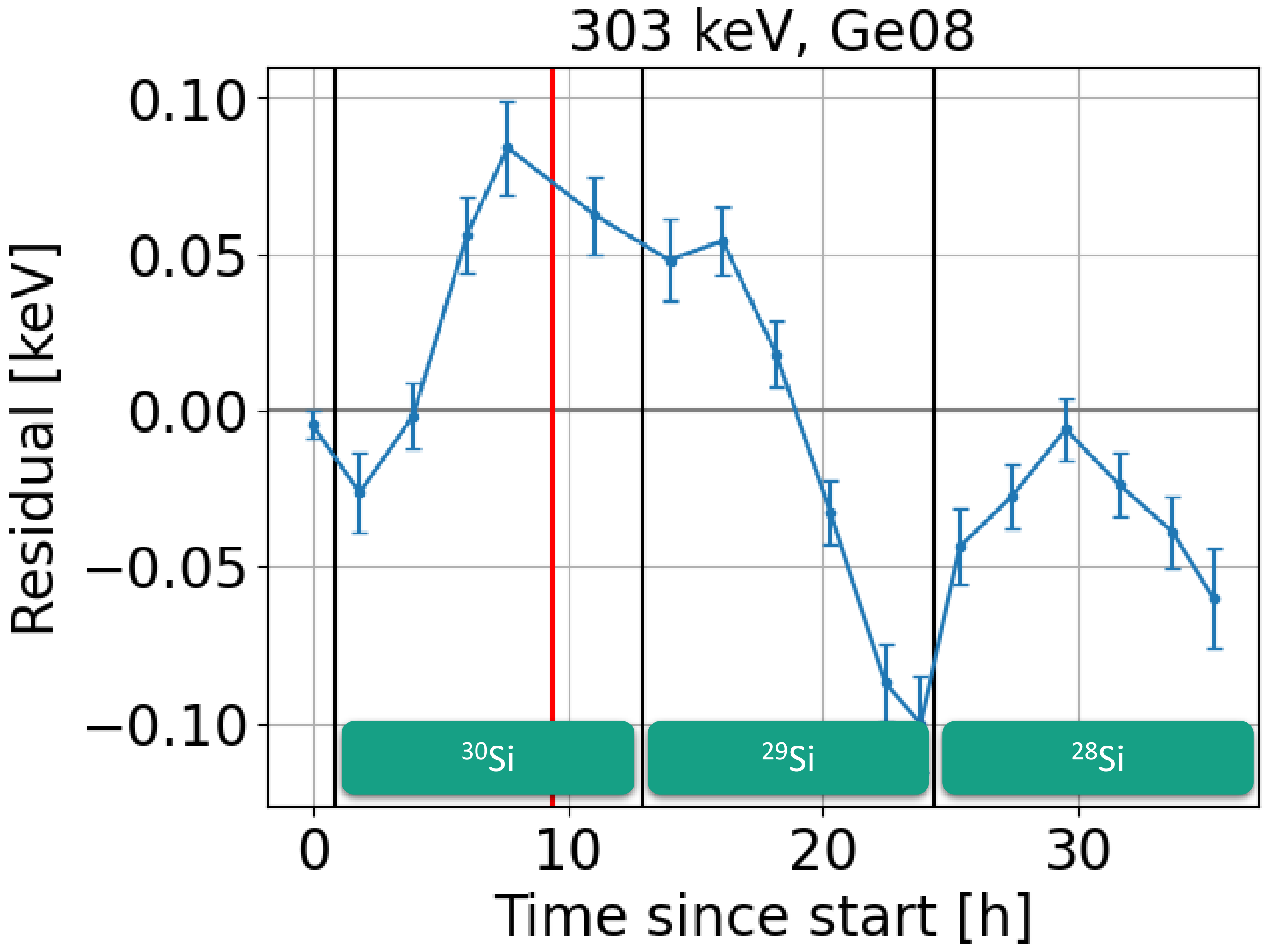
Recalibration



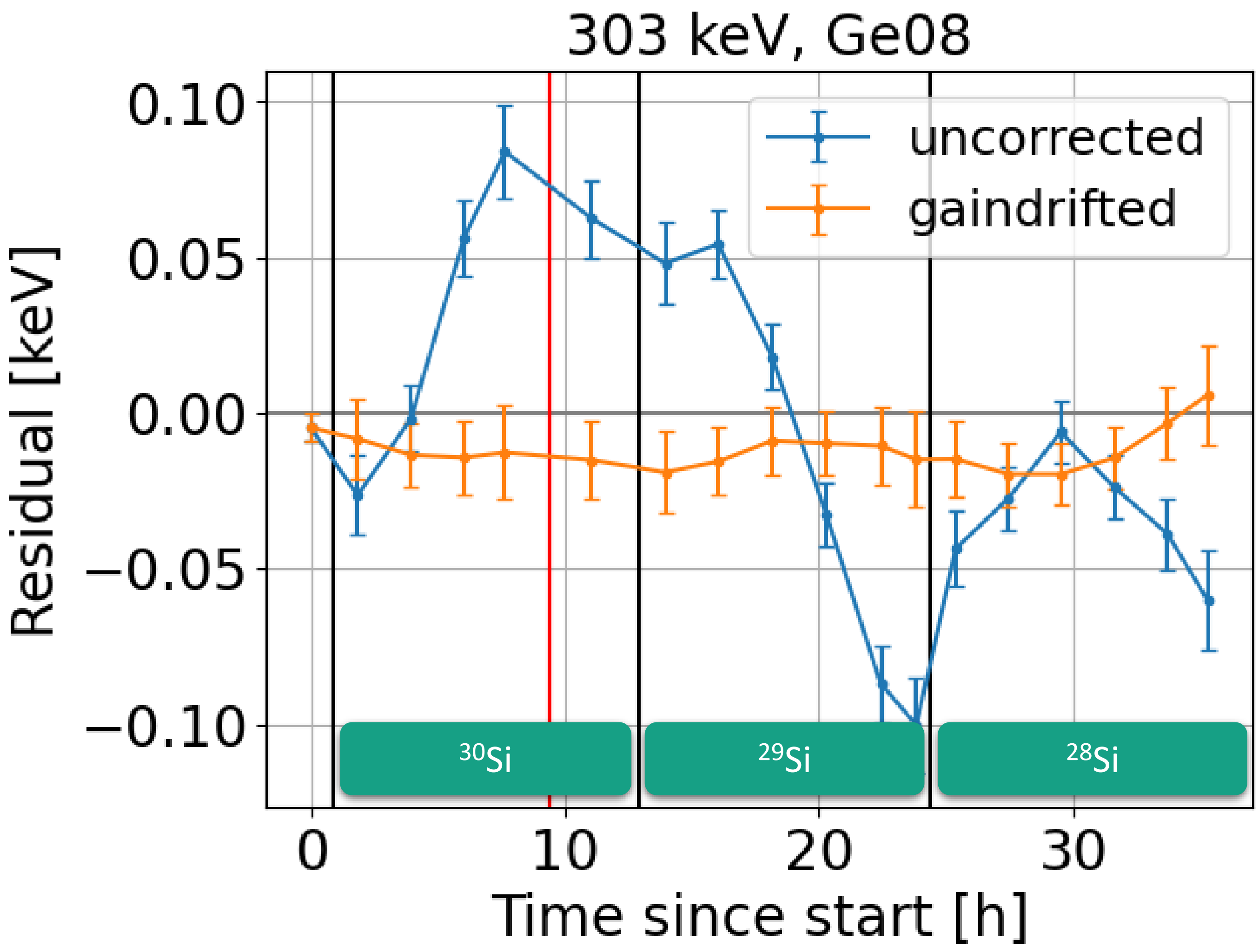
Energy calibration

- Continuous calibration

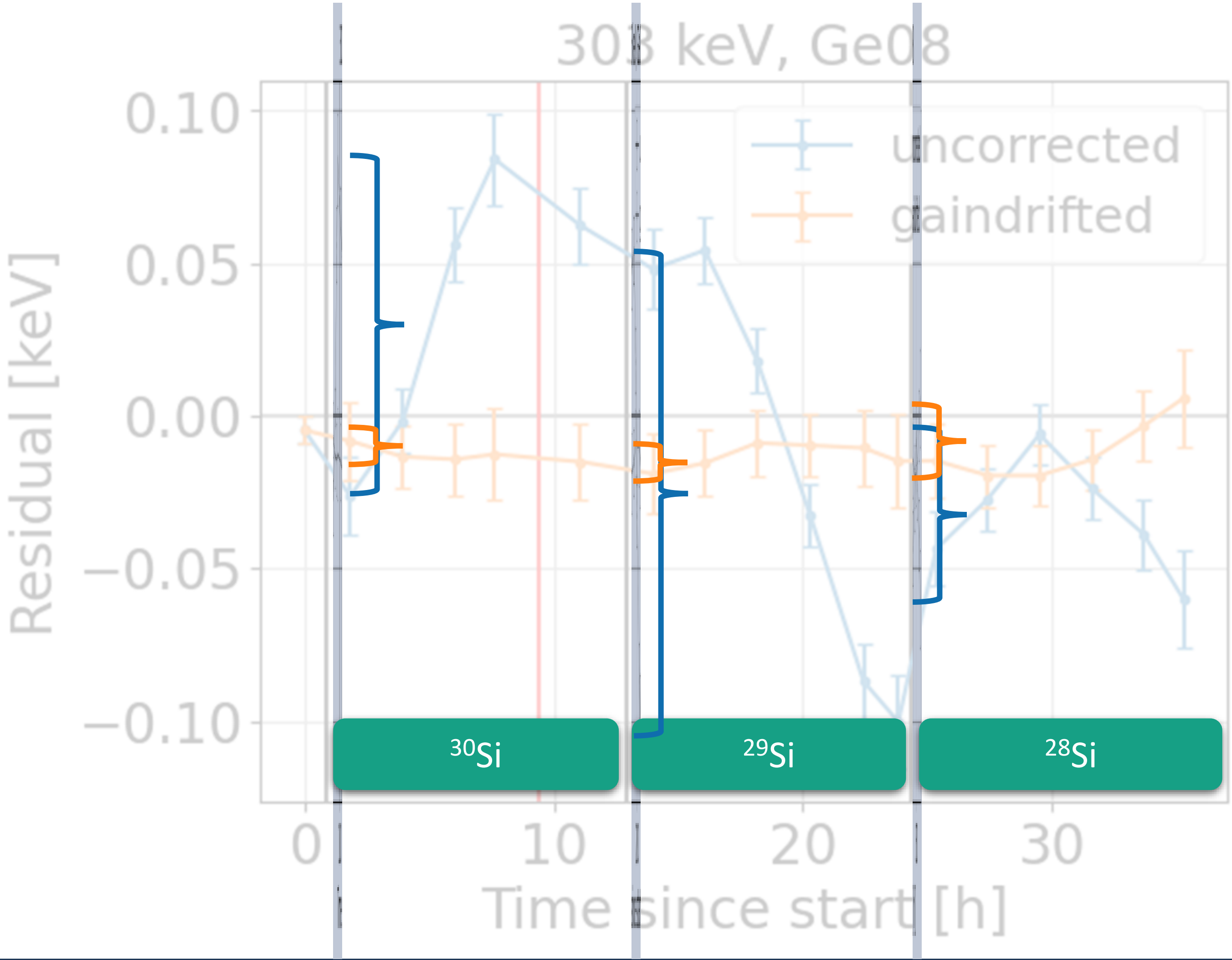
Energy calibration - gain drift



Energy calibration - gain drift



Energy calibration - gain drift



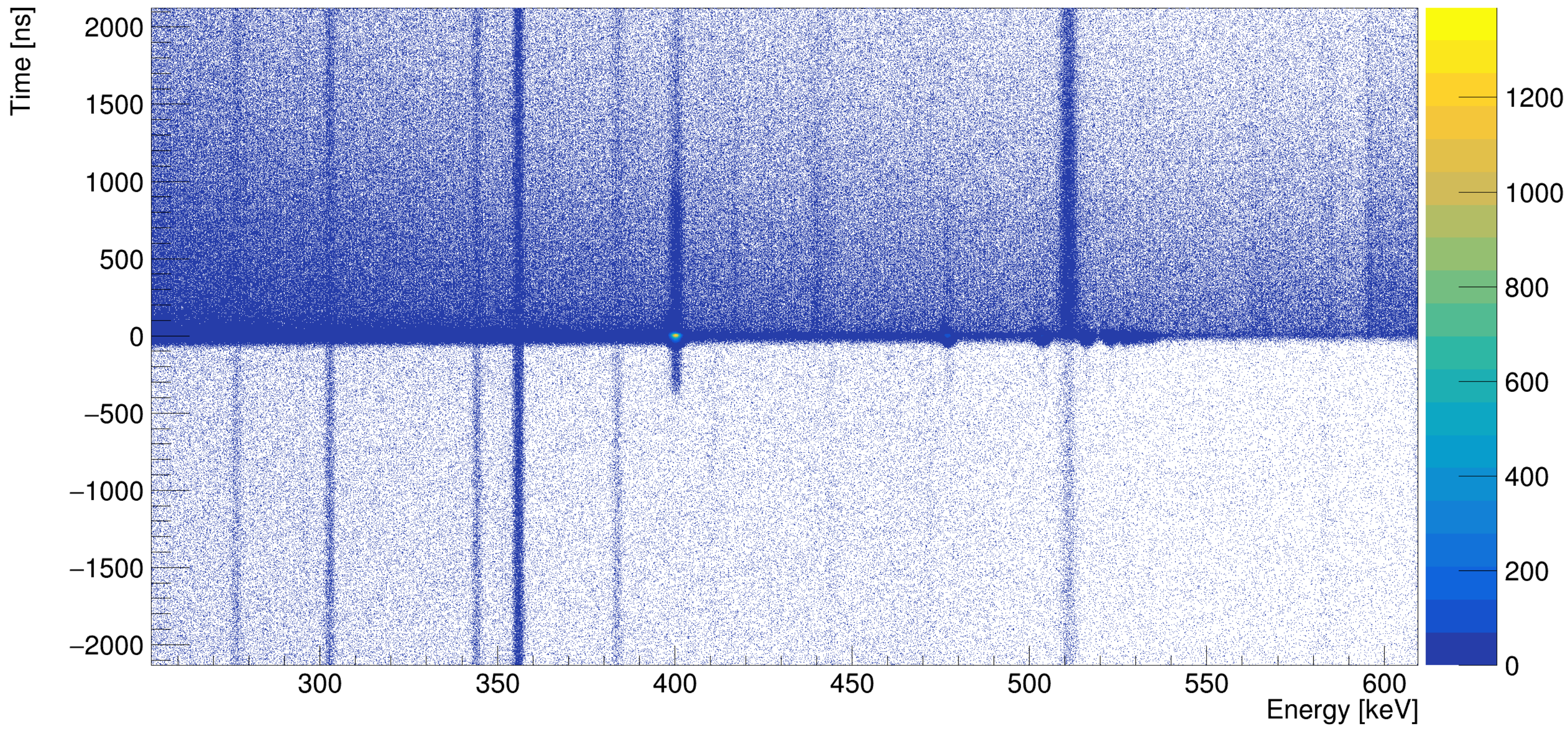
Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

ELET optimization

Energy calibration 1

Risetime correction

Recalibration



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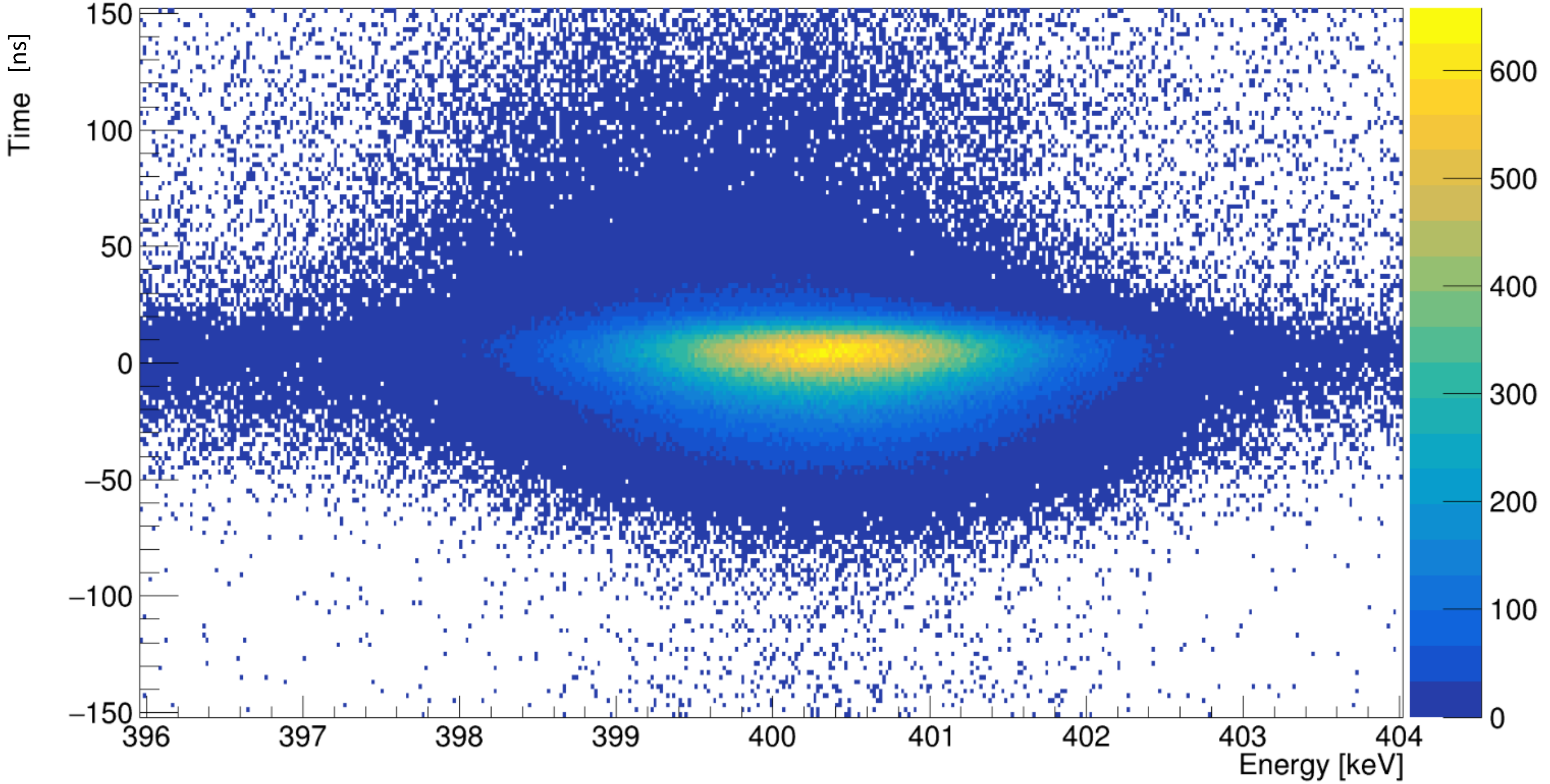
Energy vs time histogram



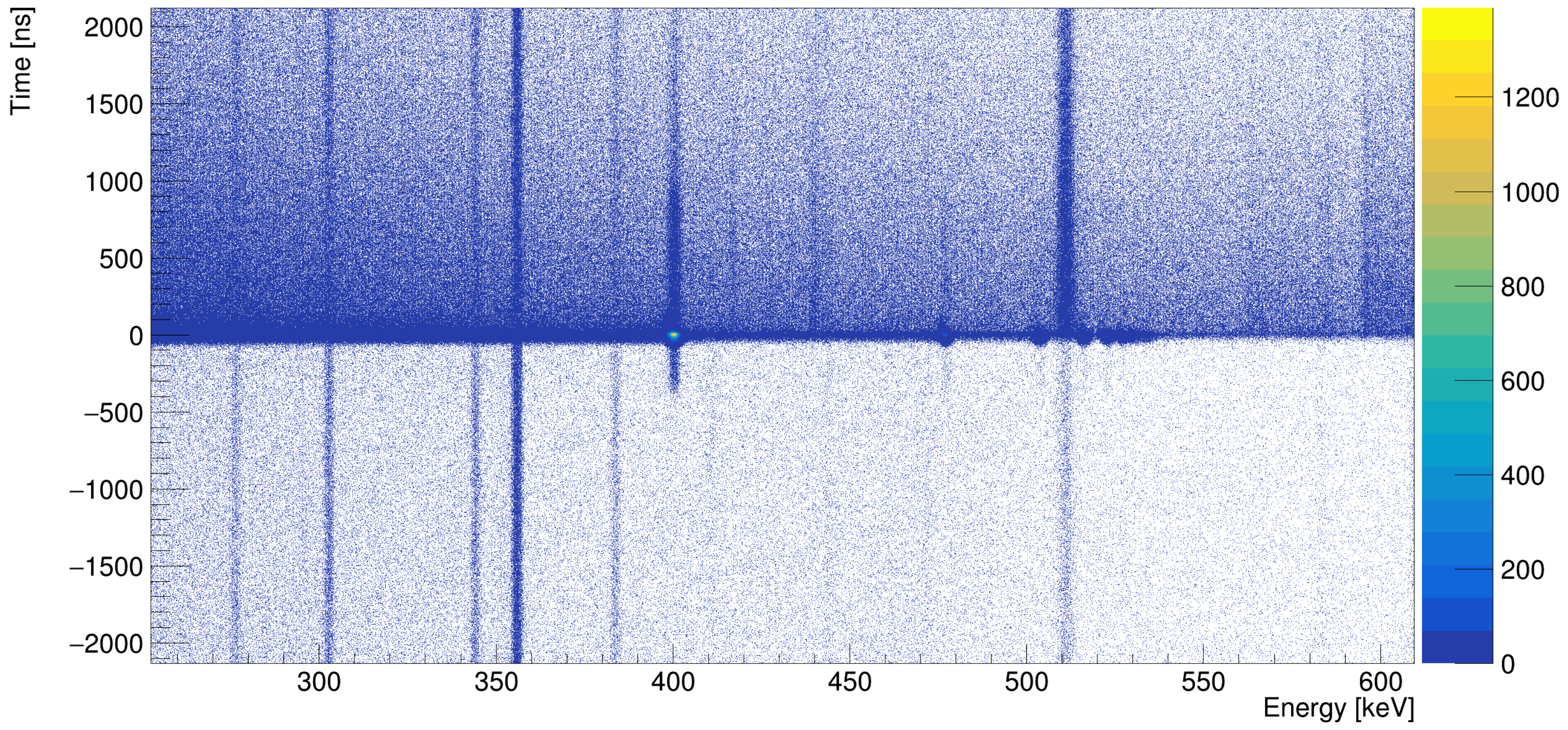
Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

ELET optimization

Energy calibration 1

Risetime correction

Recalibration



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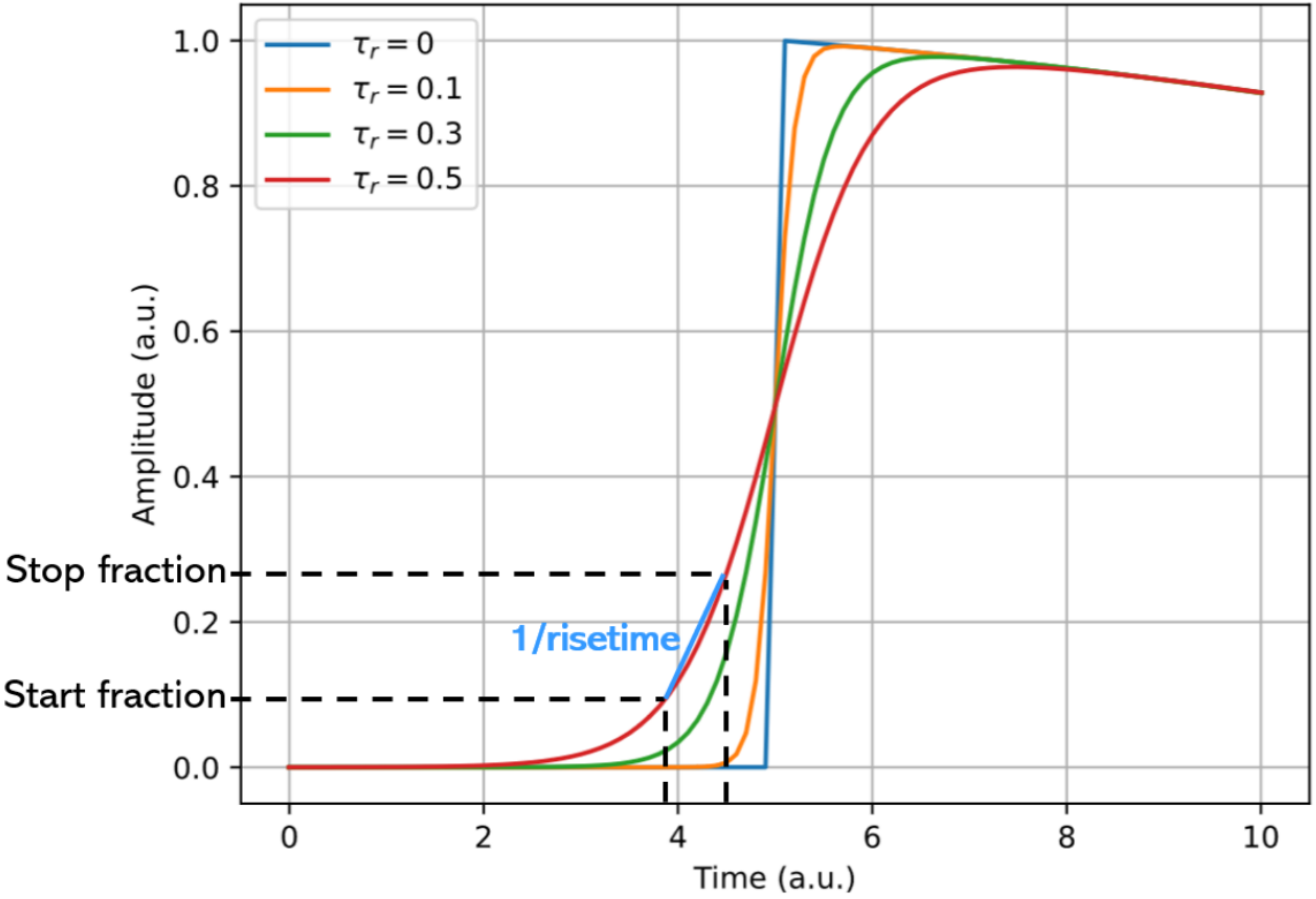
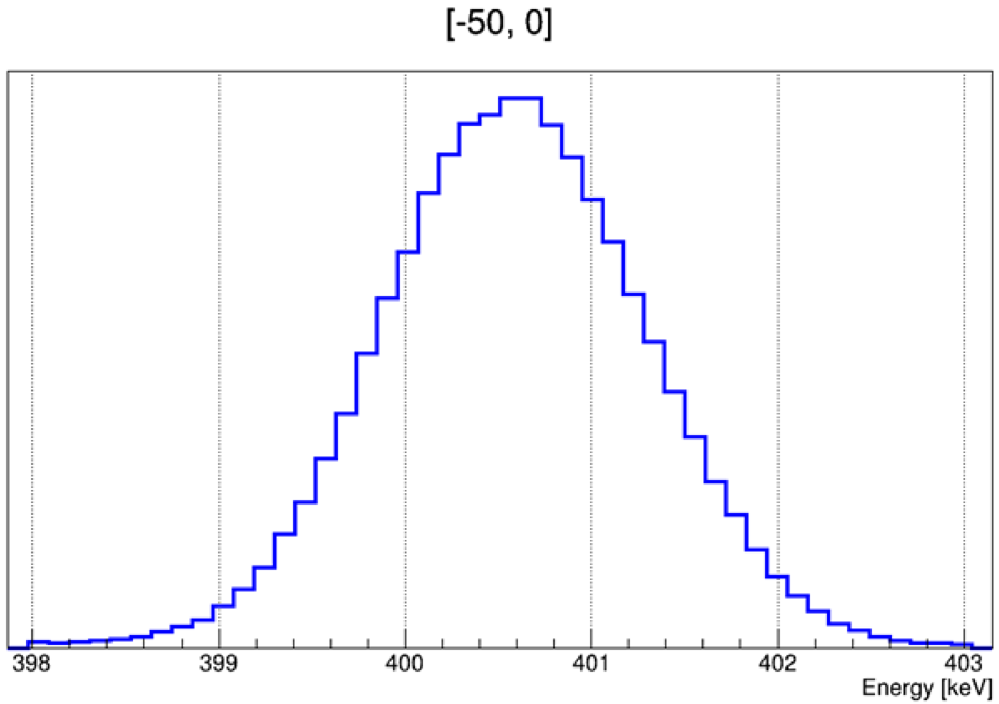
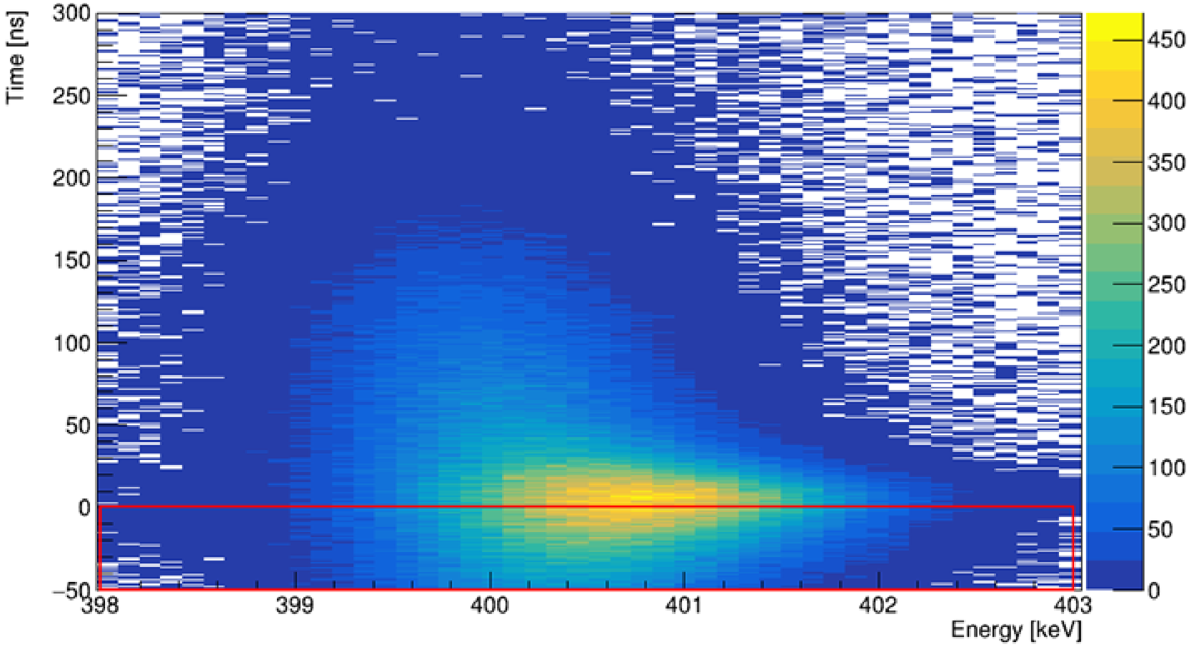
Risetime correction

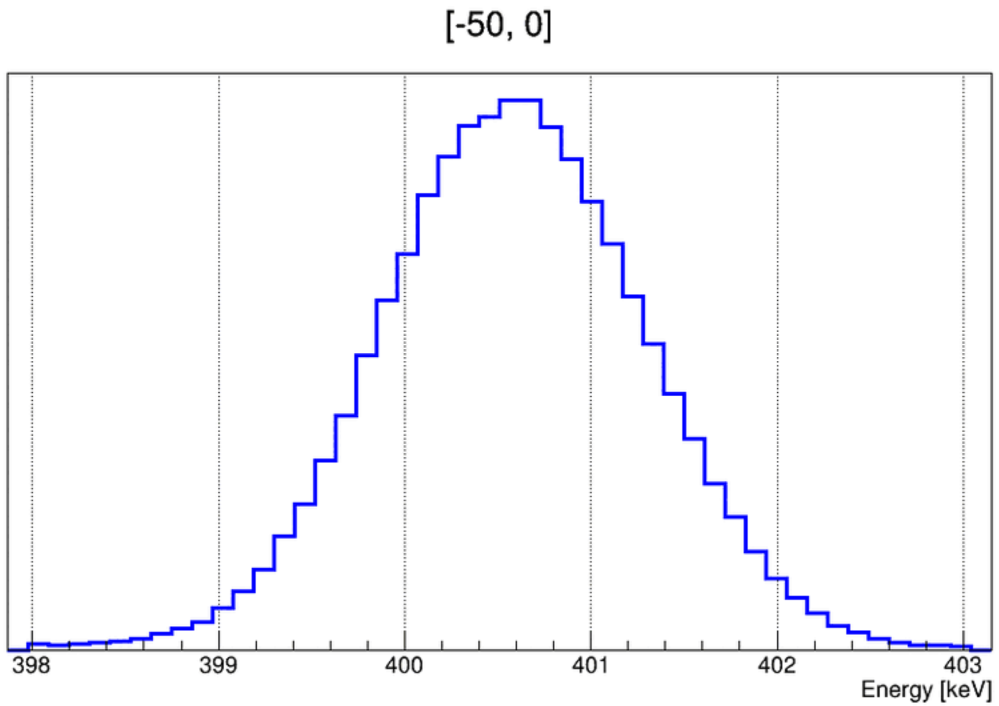


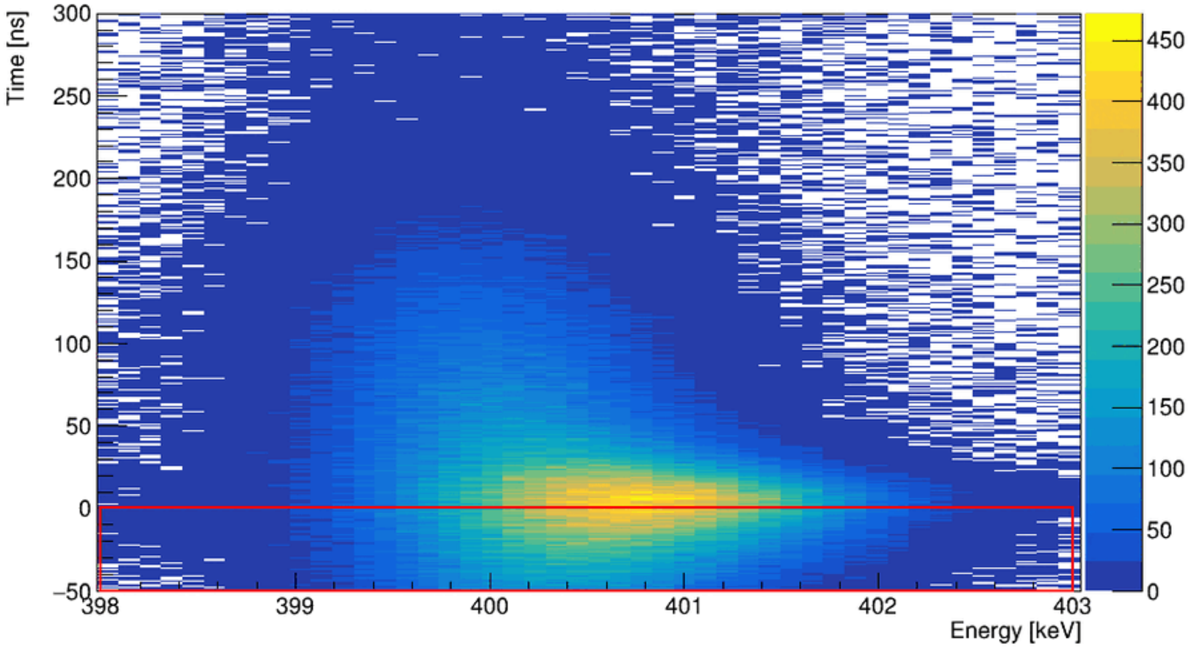
Risetime correction



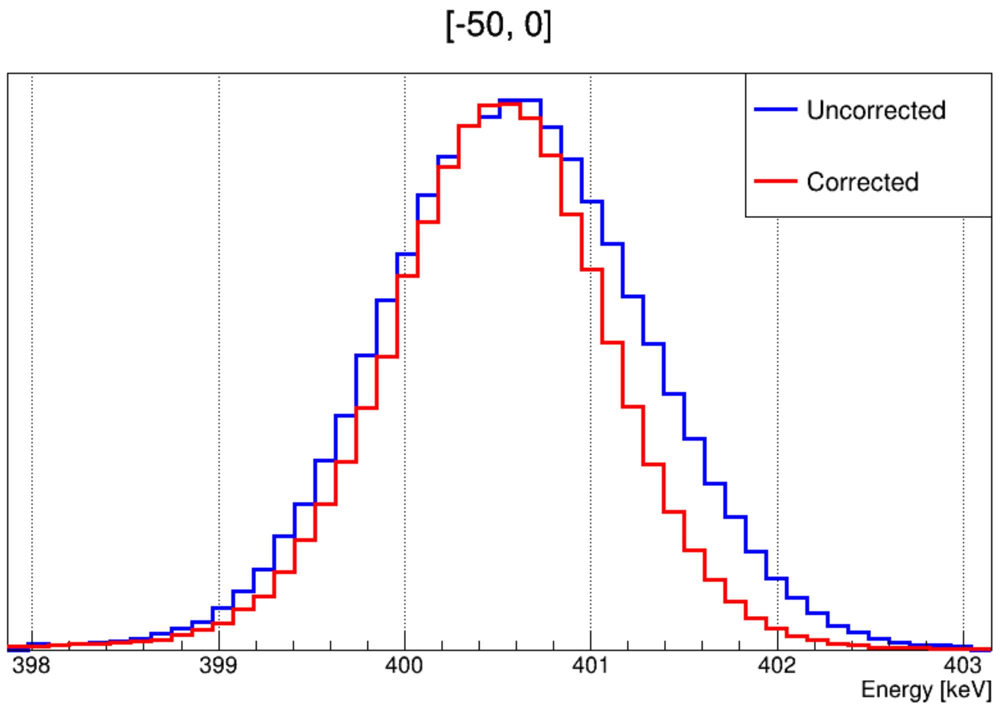


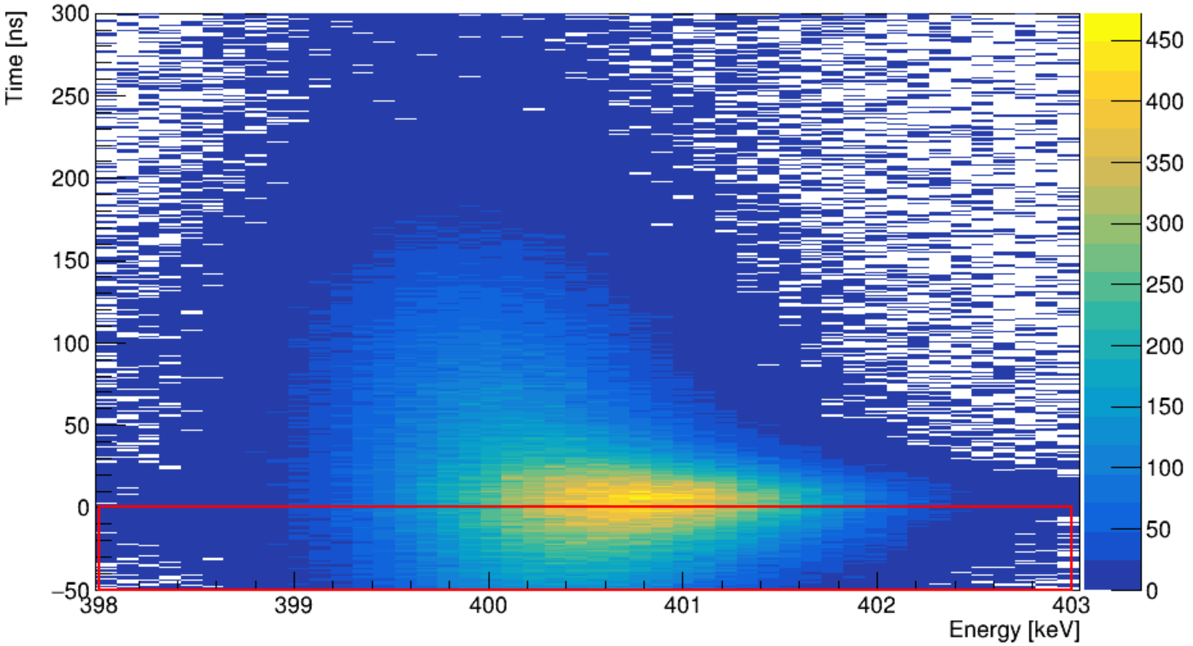
Risetime correction



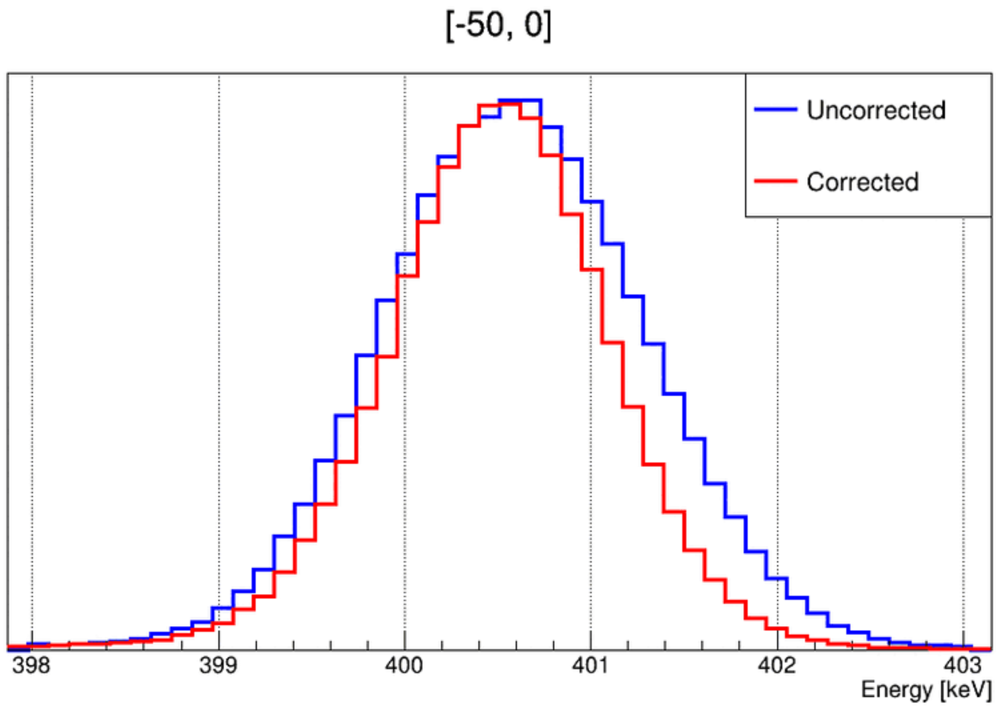


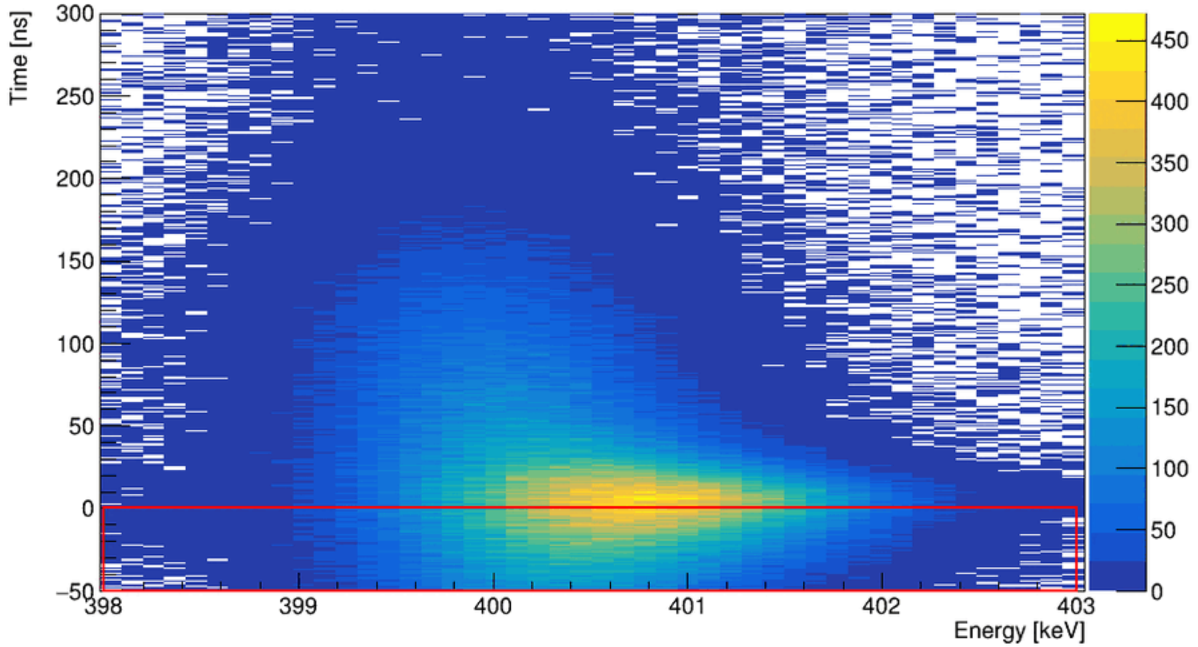
Risetime correction



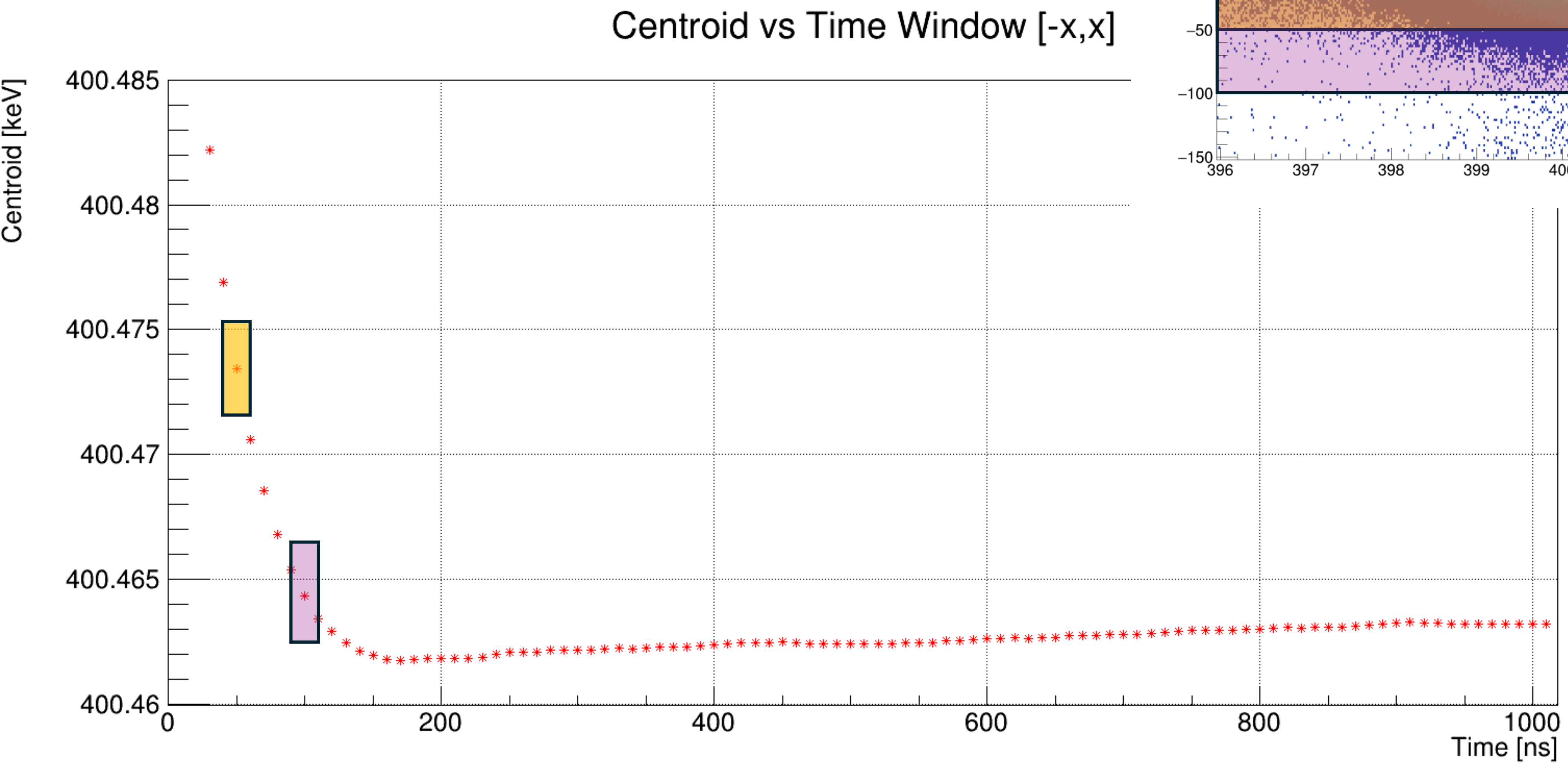


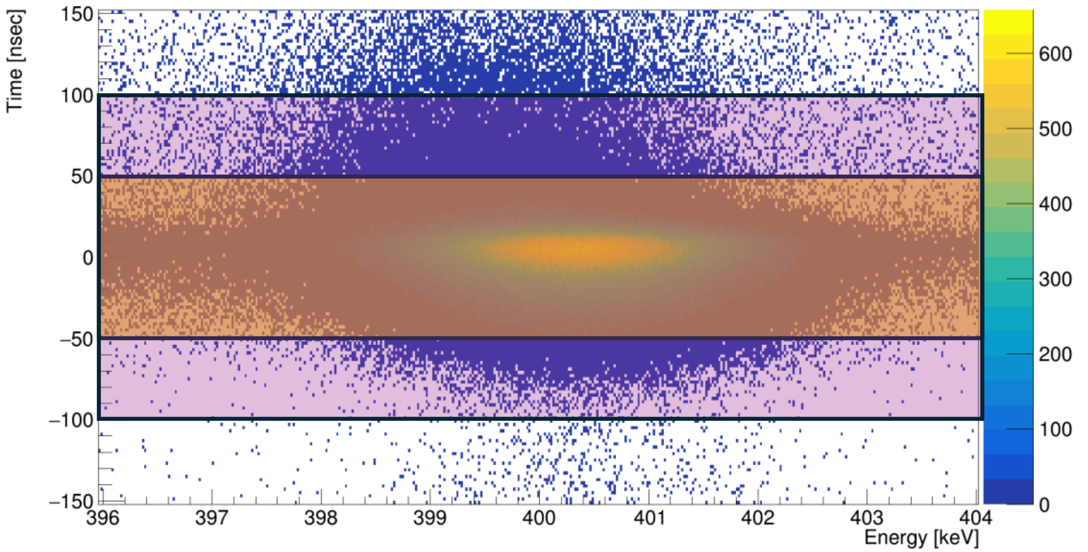
Risetime correction





Risetime correction





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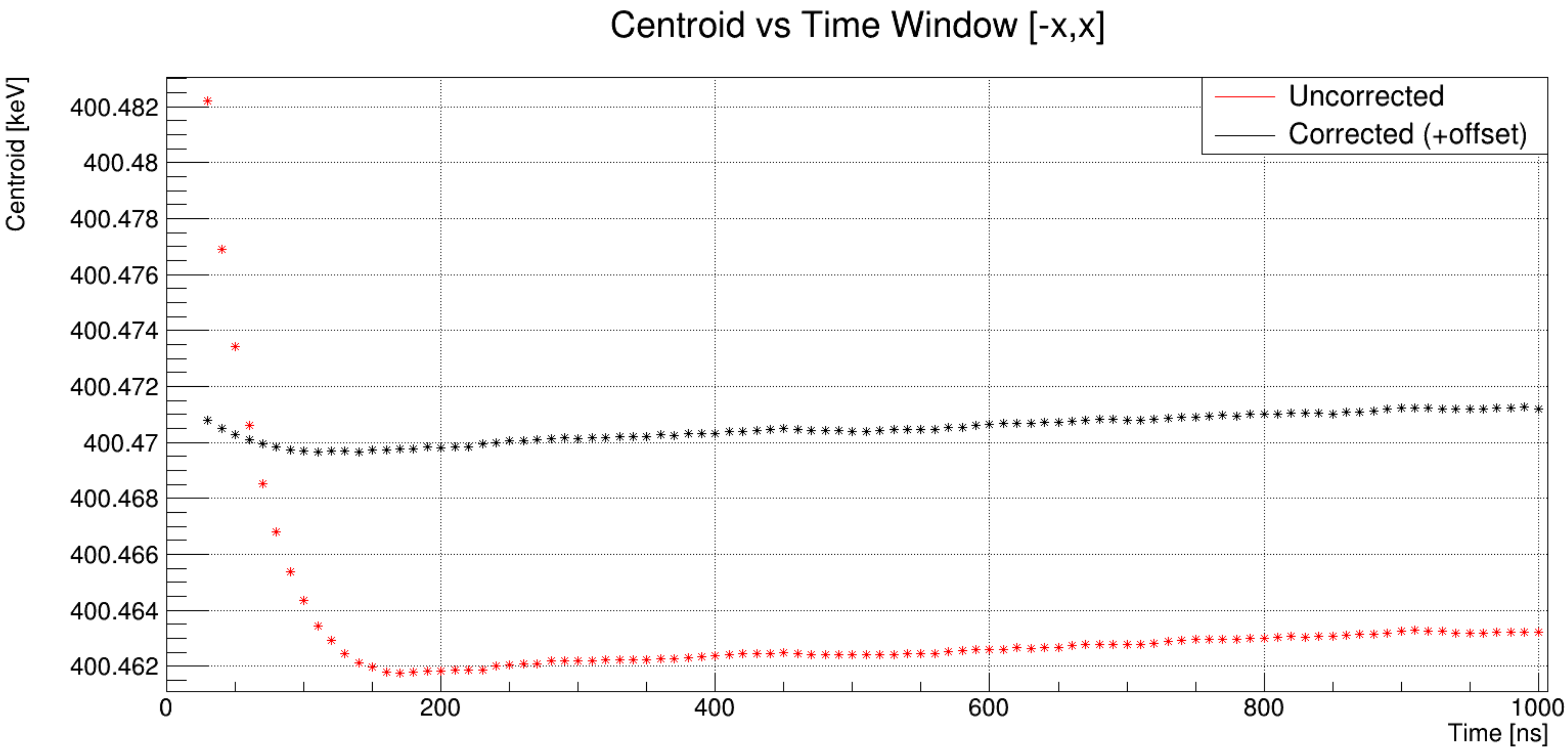
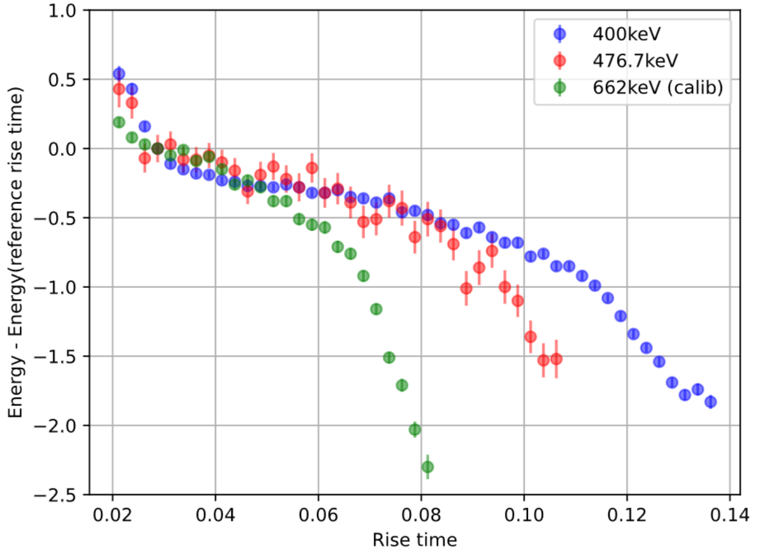
Risetime correction

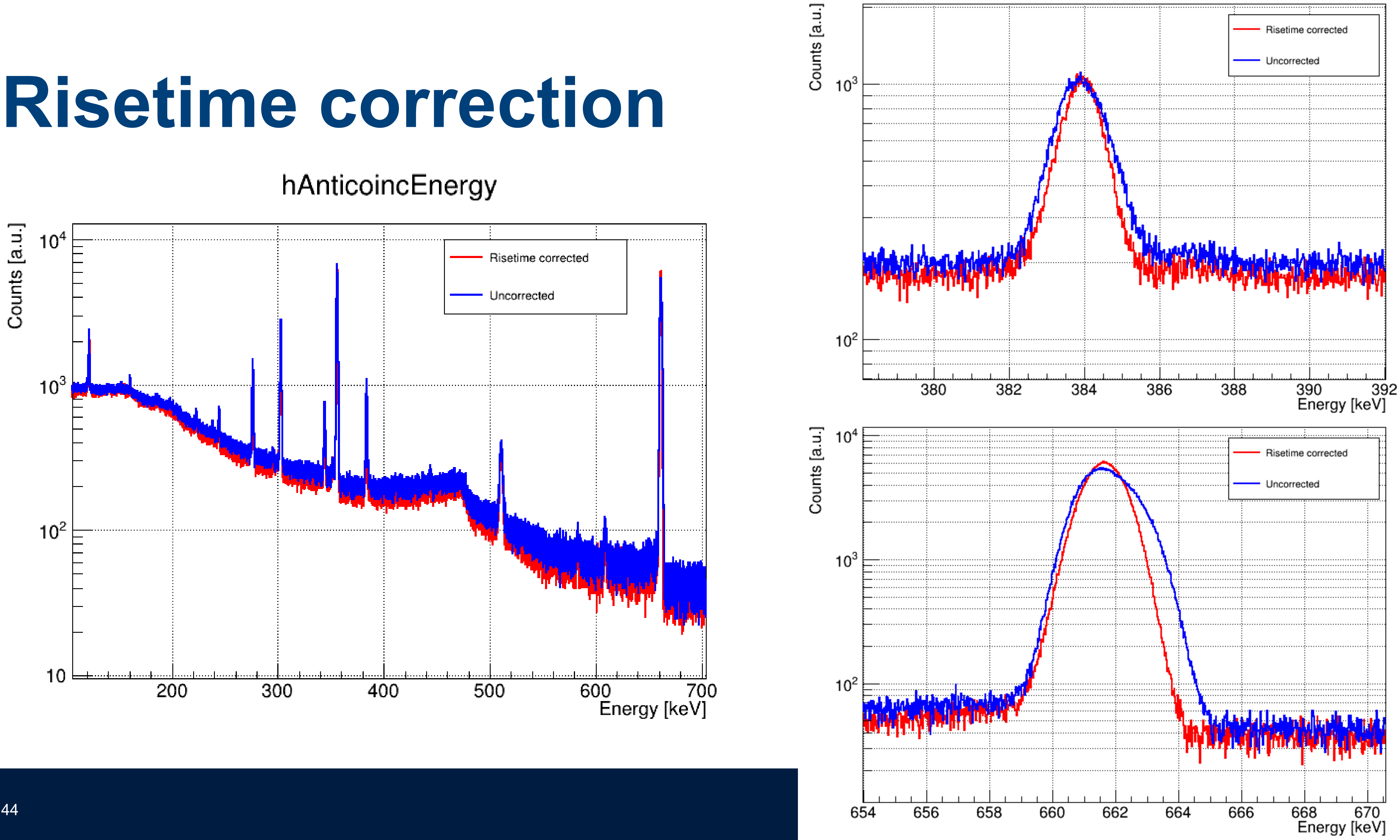


Risetime correction

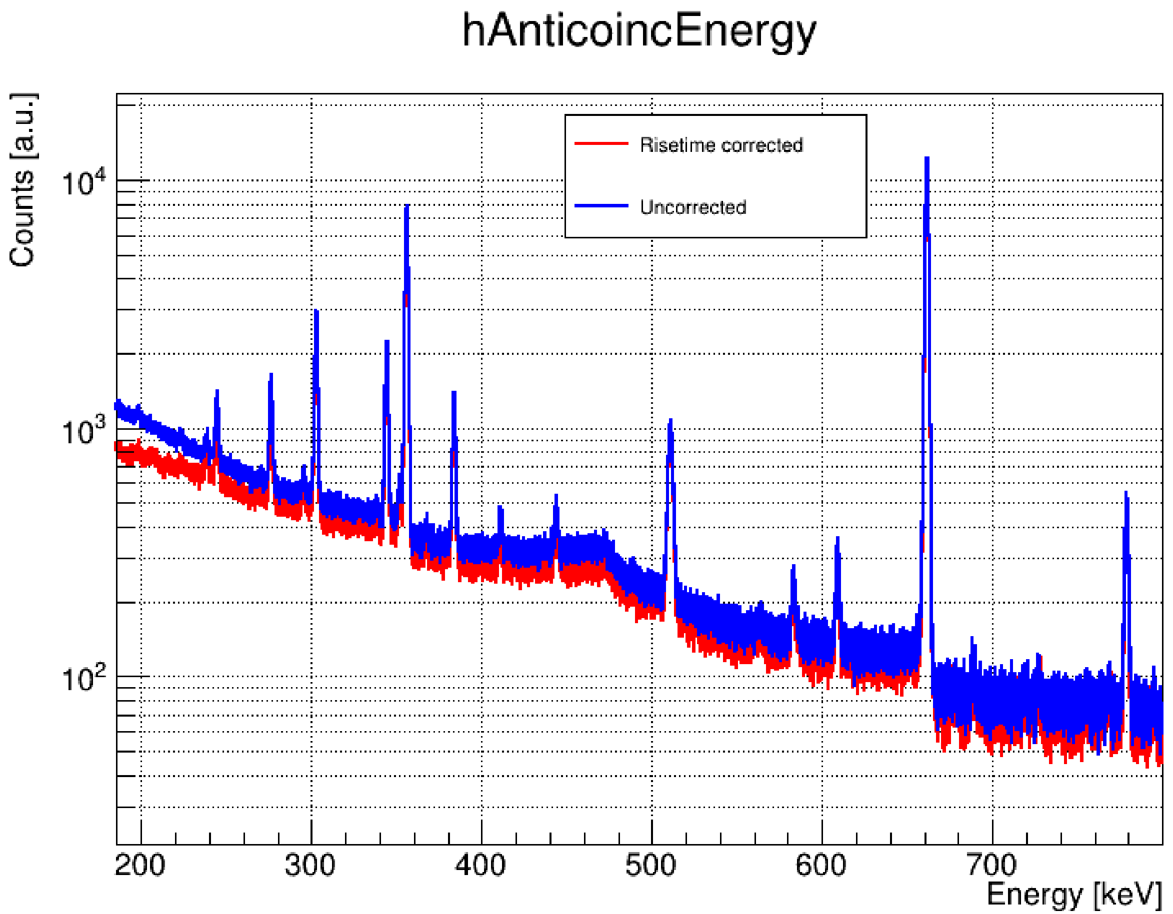
- Muonic x rays: have time 0 (= when the muon arrives) → Clear shift
- Calibration lines: don't have time 0,
  BUT different risetimes contribute to main peak →Improvement in resolution

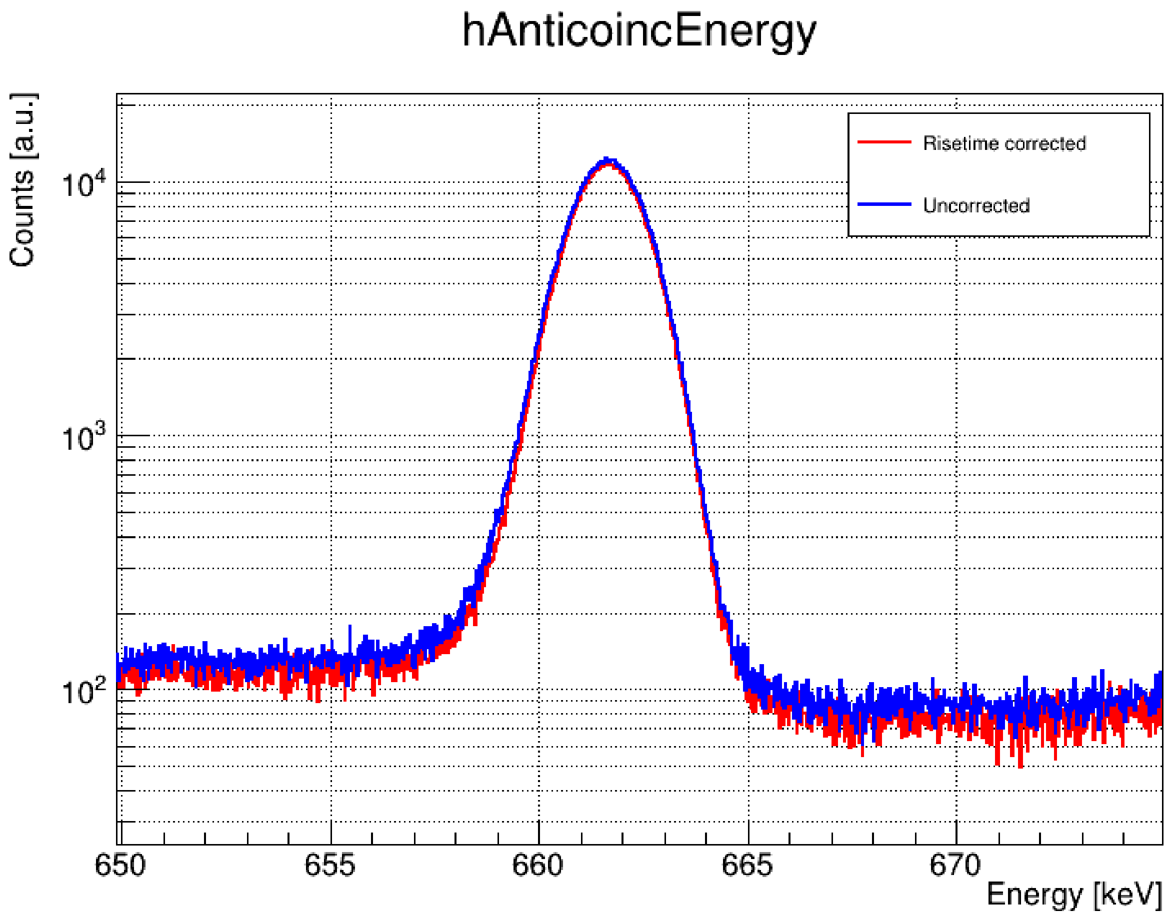


Risetime correction



Risetime correction





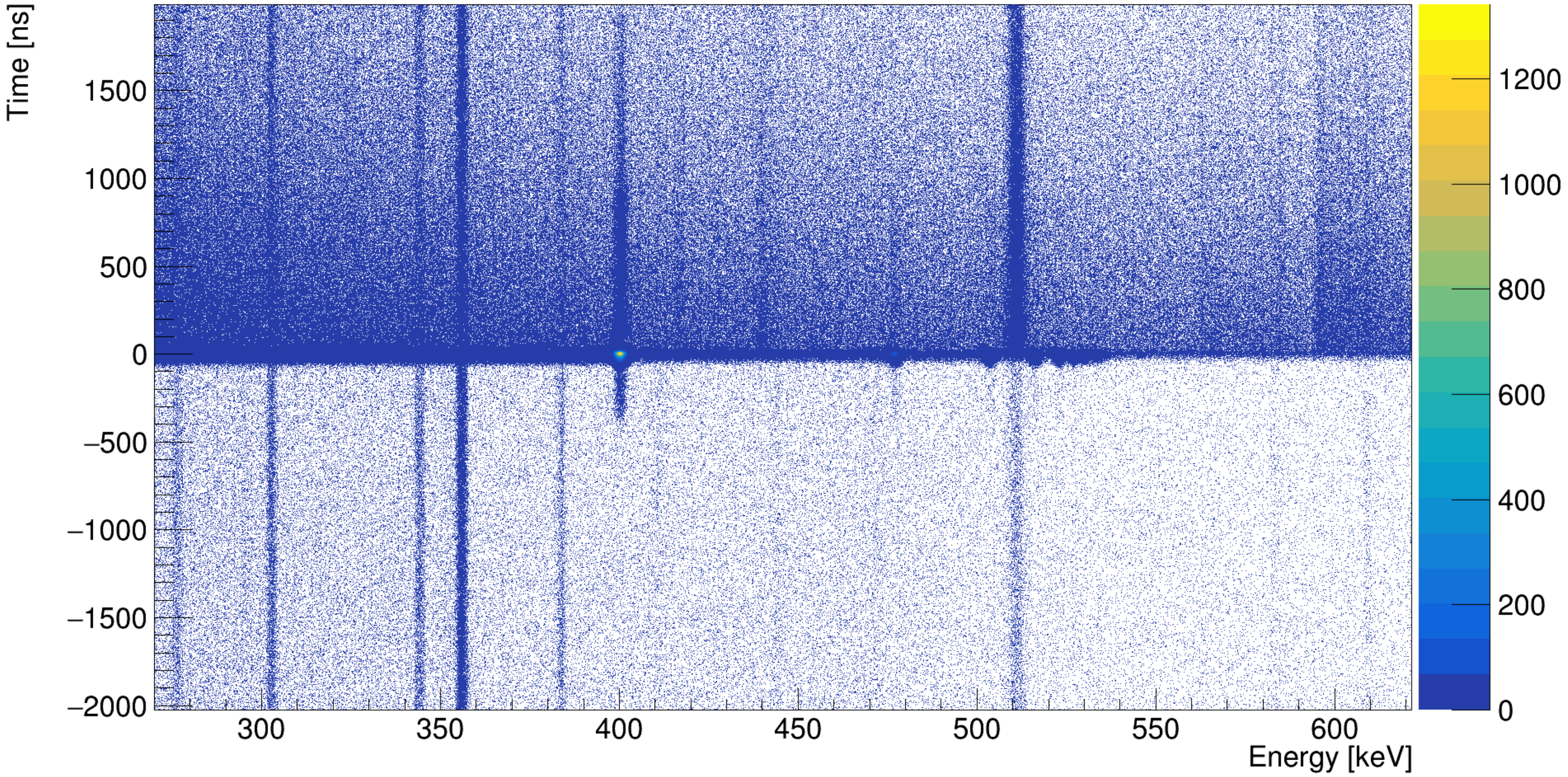
Data-processing: From Muonic X-rays to np-1s energies: Our Analysis Pipeline

ELET optimization

Gain drift

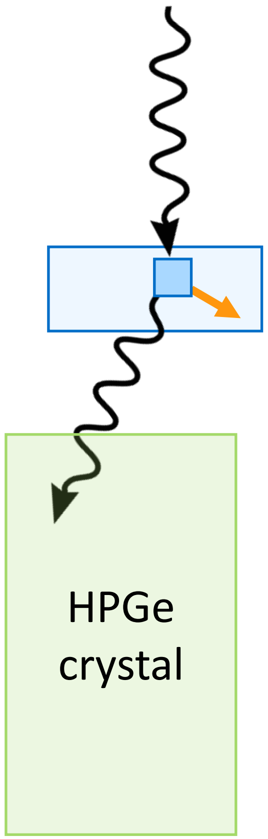
Risetime correction

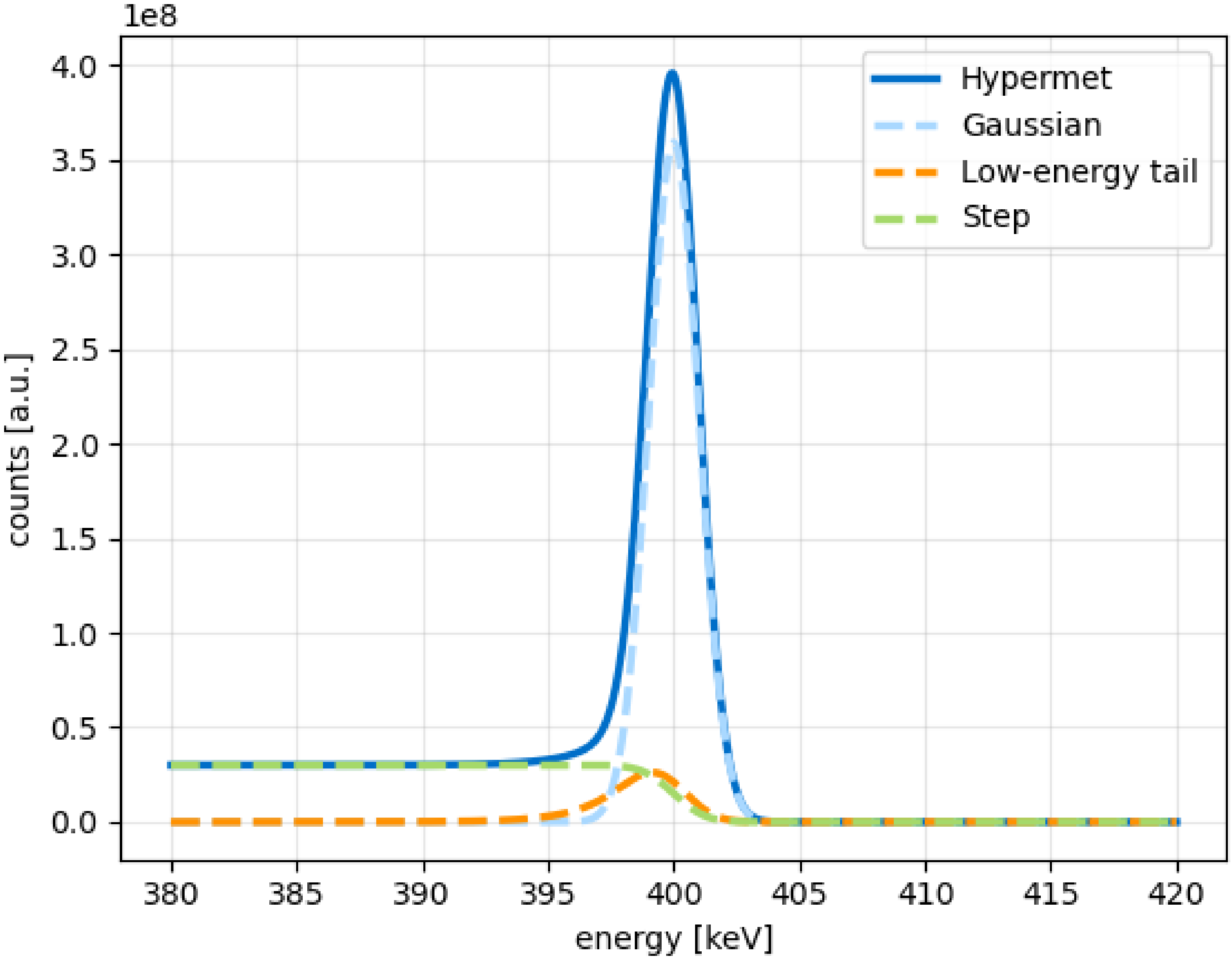
Recalibration



Recalibration

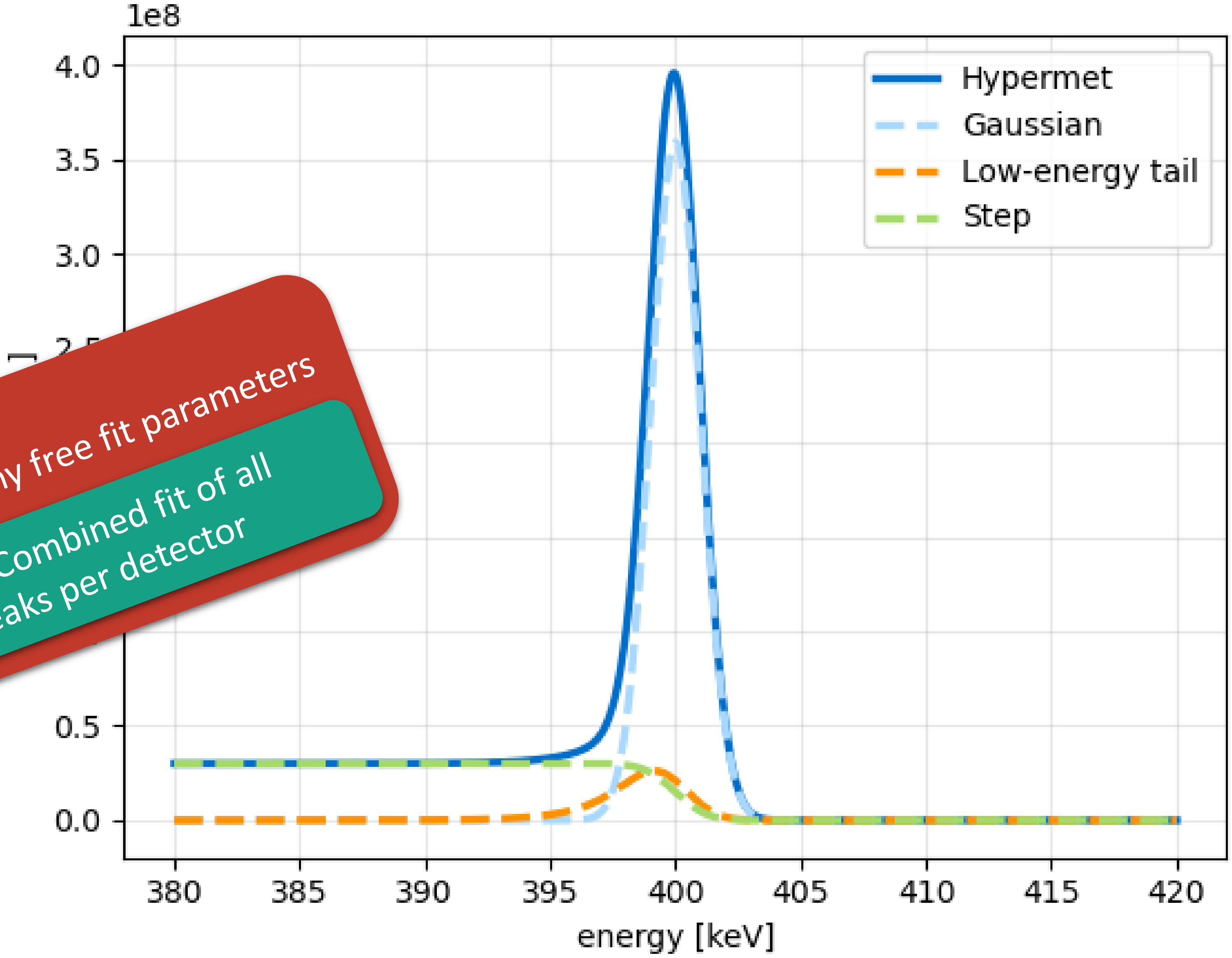
Hypermet lineshape





Recalibration

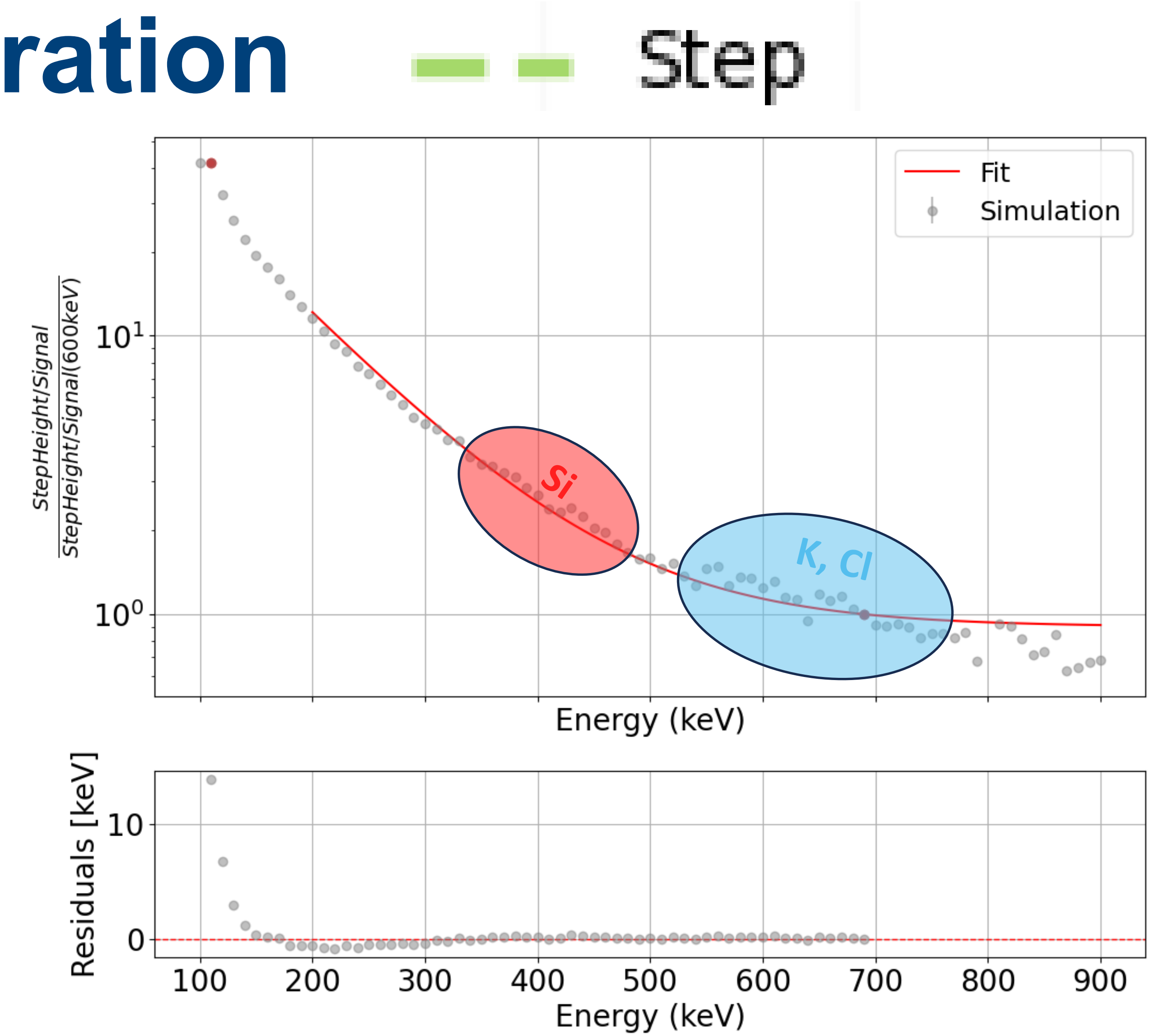
Hypermet lineshape



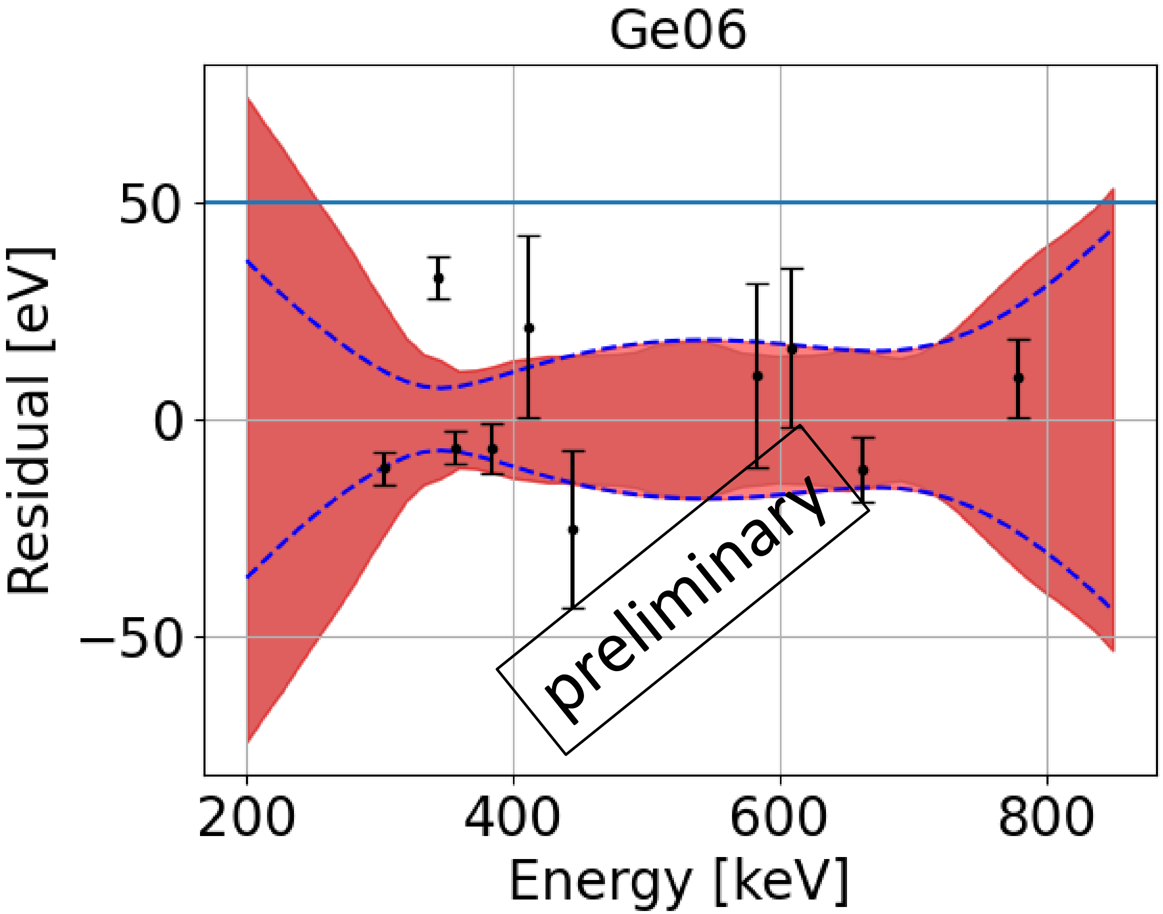
Too many free fit parameters

→ Combined fit of all peaks per detector

Recalibration

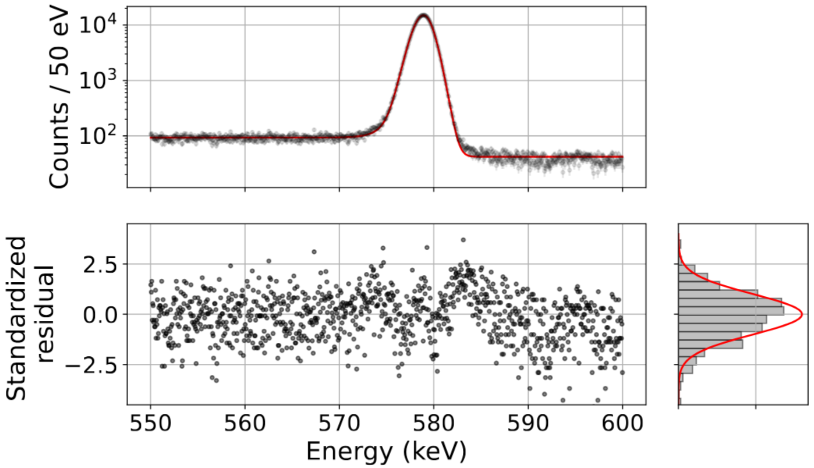


Recalibration

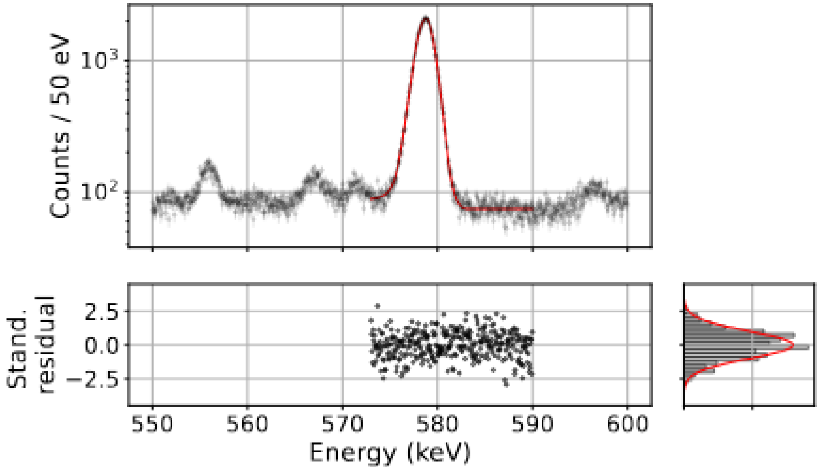


np-1s energy extraction

^{35}Cl



^{37}Cl



Beyer, K. A., et al. "Modern approach to muonic x-ray spectroscopy demonstrated through the measurement of stable Cl radii." *arXiv preprint arXiv:2506.08804* (2025).

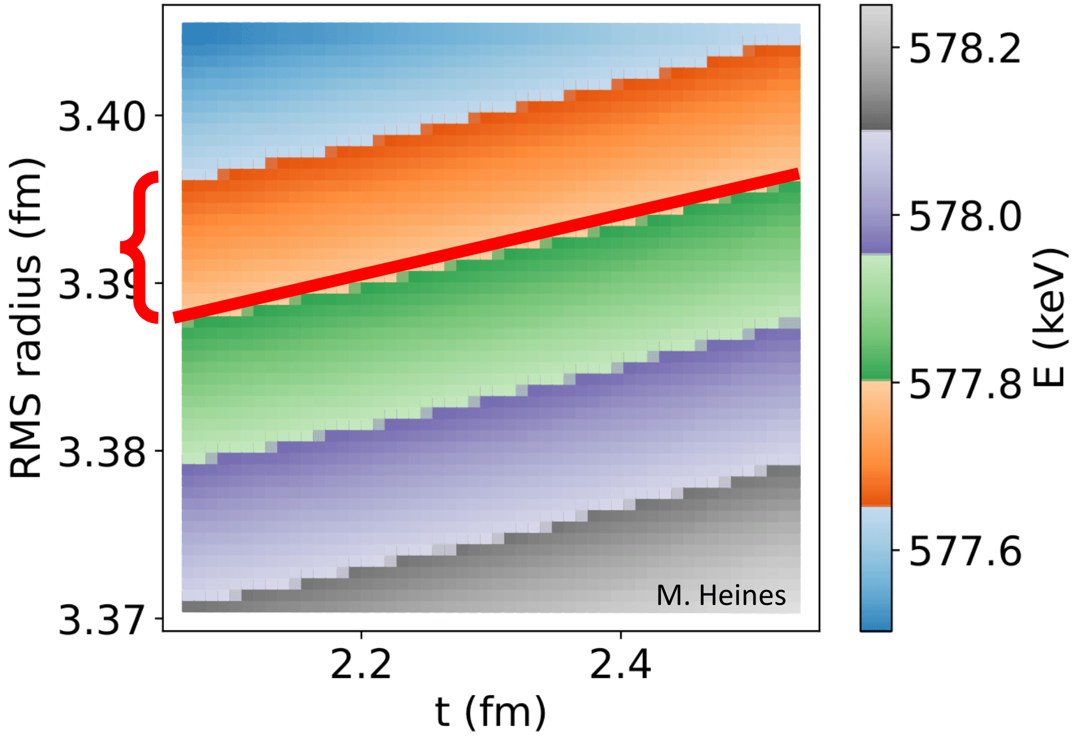
np-1s energy → Charge radius

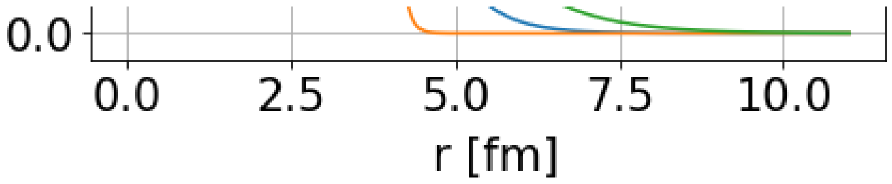
Experiment → E

QED
NP
→ E(R)

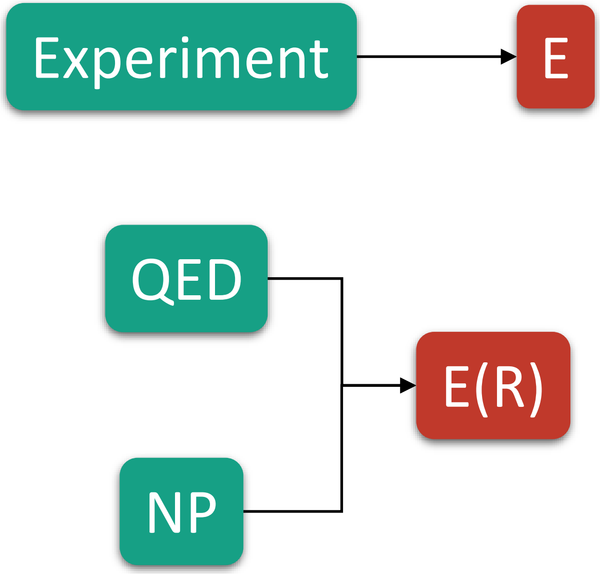
Done?

Very charge distribution model dependent



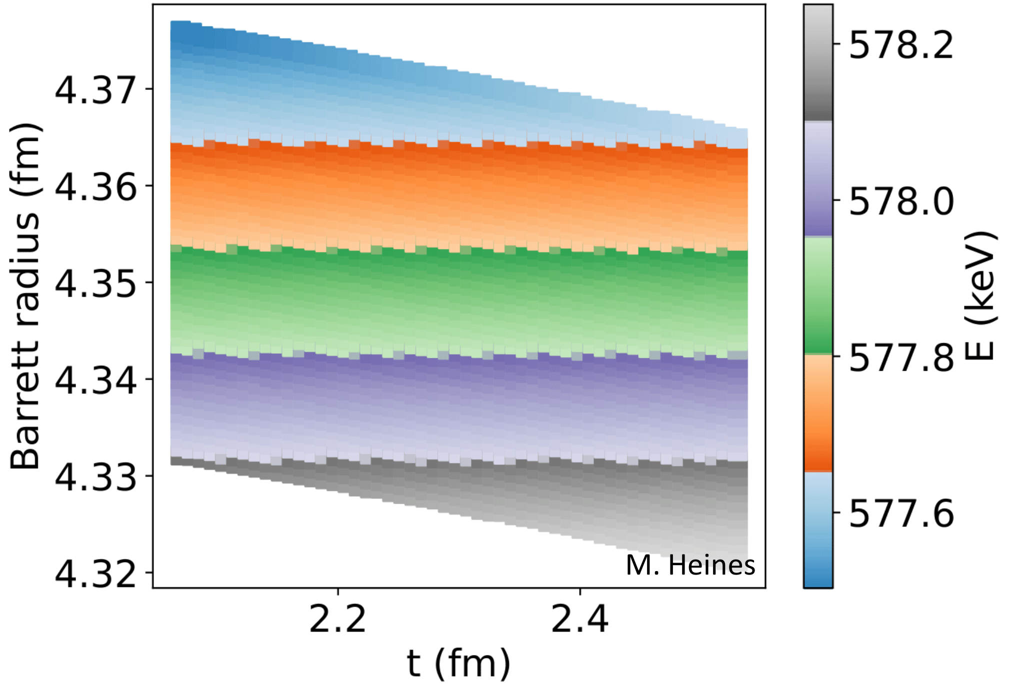


np-1s energy → Charge radius

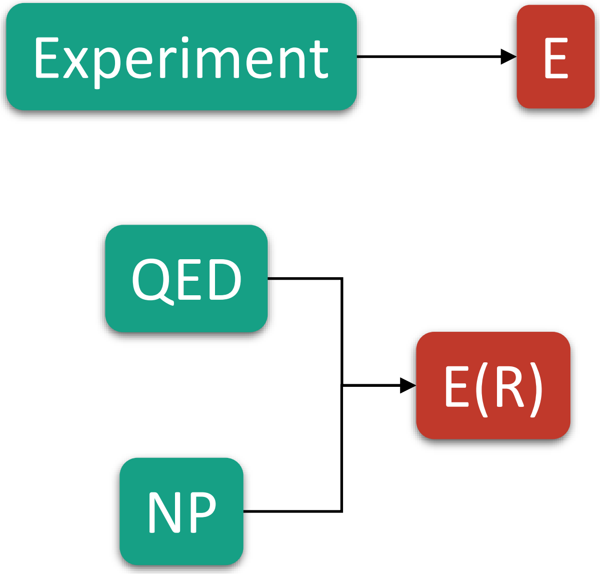


Barret radius

Radius of solid sphere that has same Barret moment ($< r^k e^{-\alpha r} > = \int_0^\infty r^{k+2} e^{-\alpha r} \rho(r)\, dr$) as nucleus of interest



np-1s energy → Charge radius

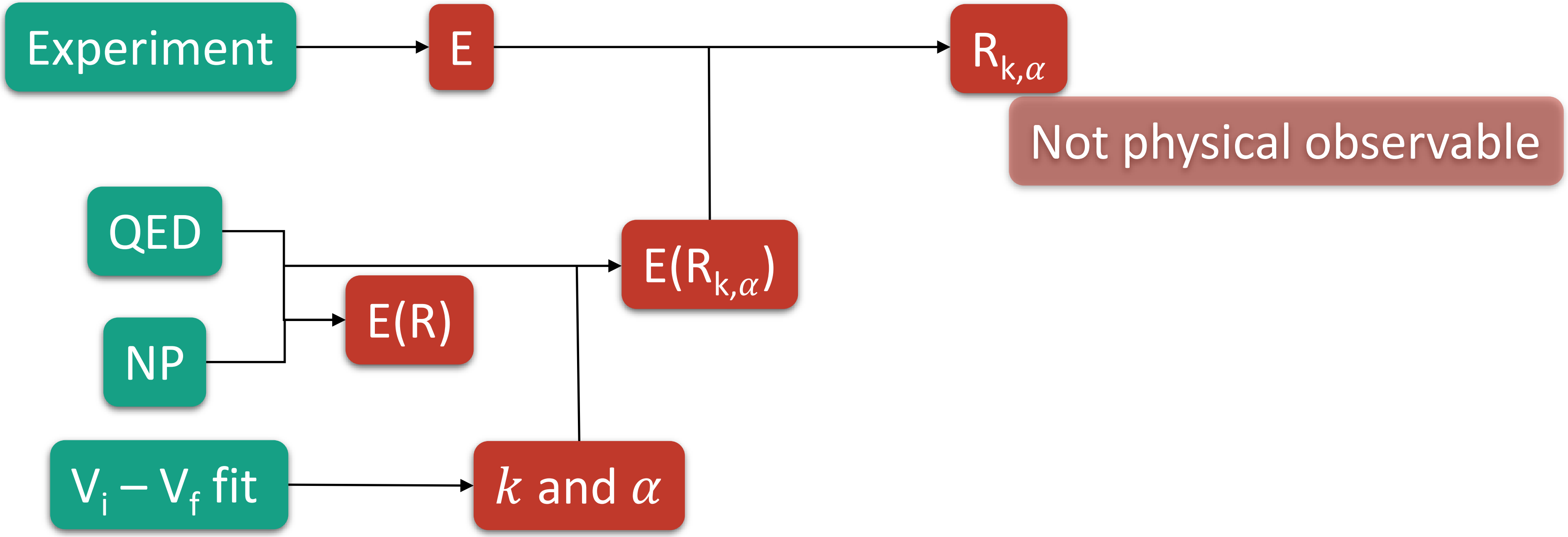


Barret radius

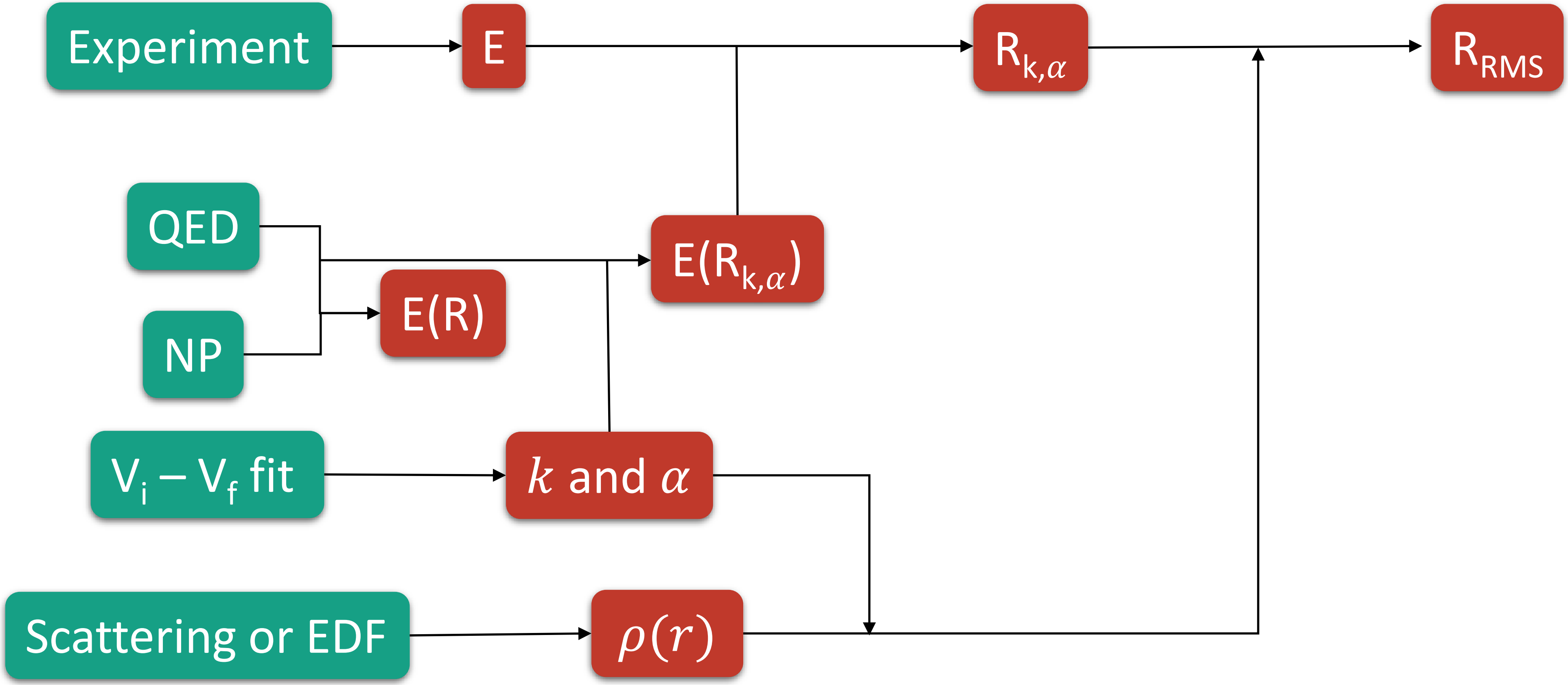
Radius of solid sphere that has same Barret moment ($< r^{k} e^{-\alpha r} > = \int_0^\infty r^{k+2} e^{-\alpha r} \rho(r)\, dr$) as nucleus of interest

k and α are determined from fit of the potentials

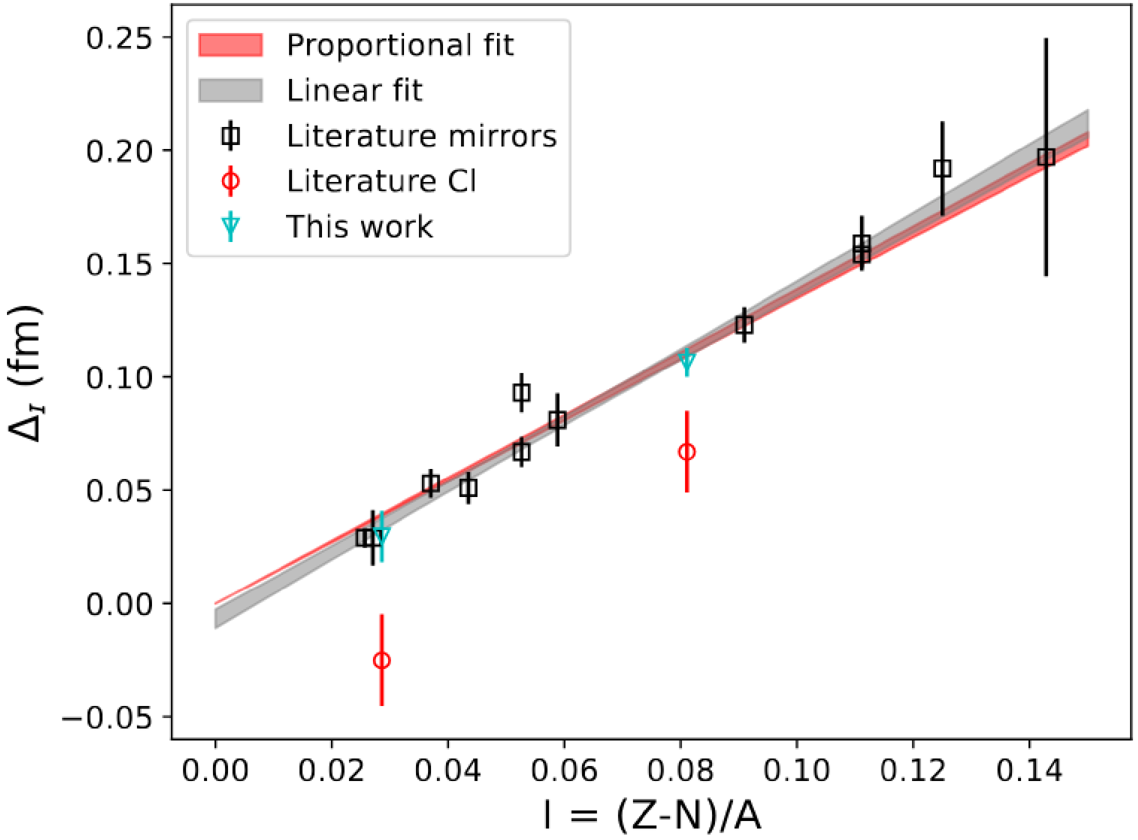
np-1s energy → Charge radius

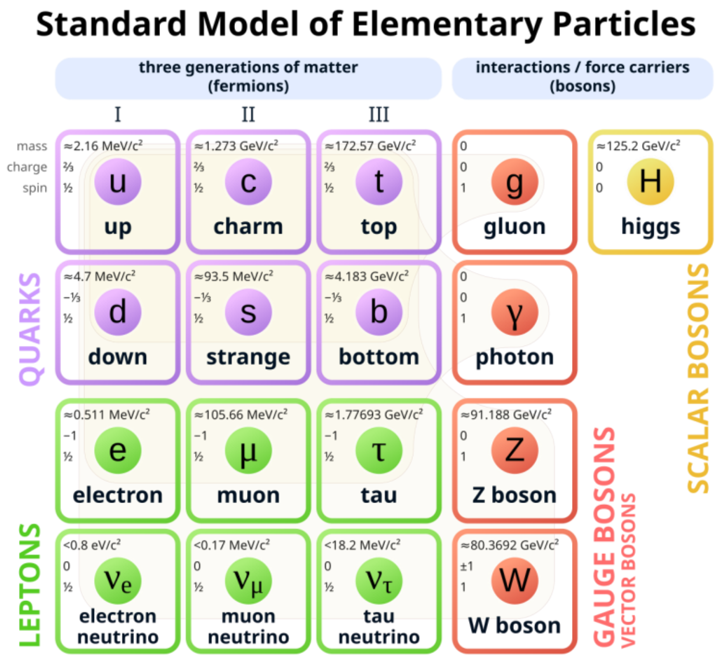


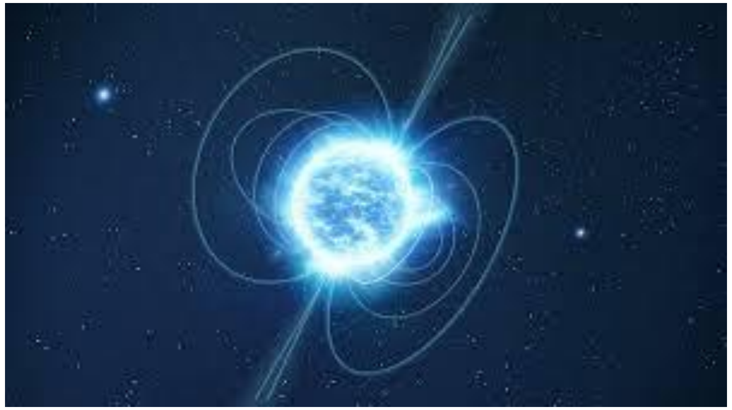
np-1s energy → Charge radius



Np-1s extraction







Beyer, K. A., et al. "Modern approach to muonic x-ray spectroscopy demonstrated through the measurement of stable Cl radii." *arXiv preprint arXiv:2506.08804* (2025).

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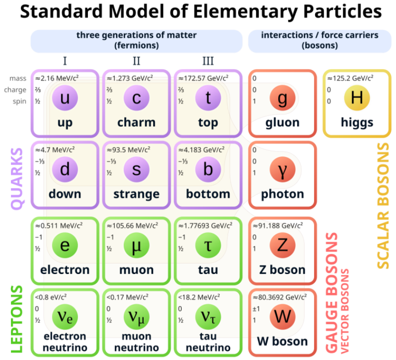
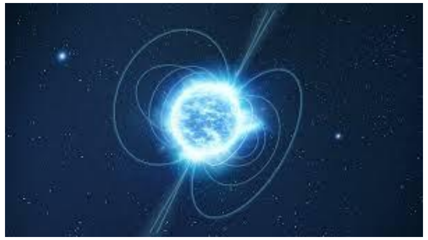
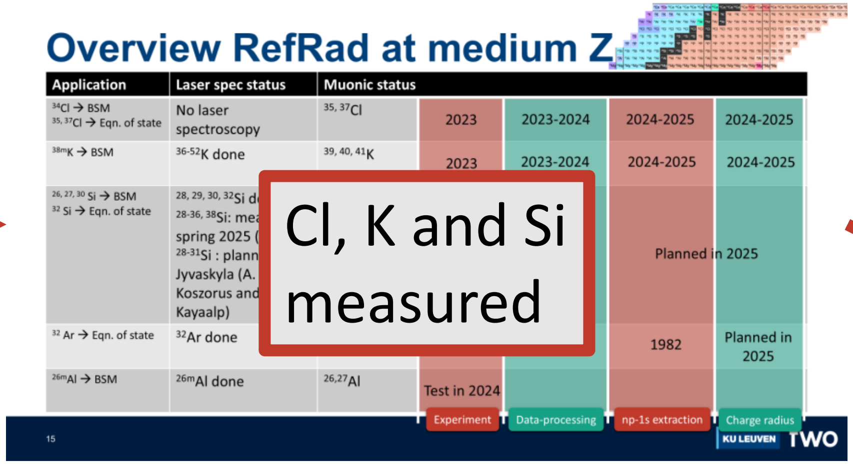
Conclusion

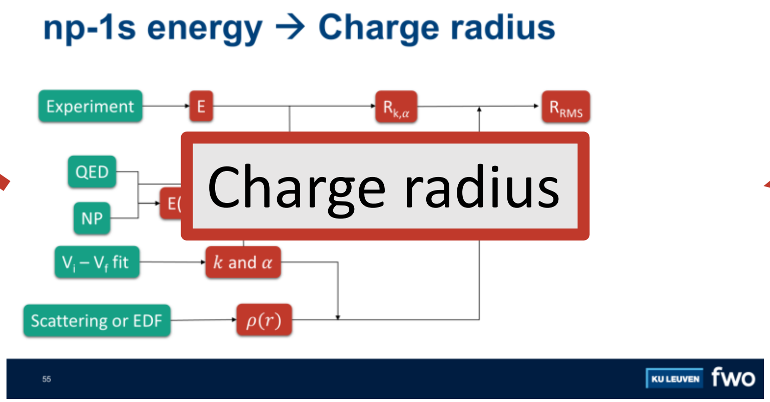






Cl, K and Si measured

Data analysis and charge radius extraction pipeline



Charge radius

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Thank you!

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EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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PhD Fellowship fundamental research - 11P6V24N