Weak-interaction studies with beta-delayed protons

Addendum to proposal IS678

Bertram Blank
for the WISArD collaboration

November 12, 2024

- **Hamiltonian: Lorentz invariance**

J.D. Jackson et al, Nucl. Phys. 4 (1957) 206
M. González-Alonso et al., Prog. Part. Nucl. Phys. 104, 165 (2019)

hadronic terms

leptonic terms

$$
\begin{aligned}
H = & (\overline{\psi_p}\gamma_\mu\psi_n)(C_V\overline{\psi_e}\gamma_\mu\psi_\nu + C'_V\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu) \\
& + (\overline{\psi_p}\gamma_\mu\gamma_5\psi_n)(C_A\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu + C'_A\overline{\psi_e}\gamma_\mu\psi_\nu) \\
& + (\overline{\psi_p}\psi_n)(C_S\overline{\psi_e}\psi_\nu + C'_S\overline{\psi_e}\gamma_5\psi_\nu) \\
& + \frac{1}{2}(\overline{\psi_p}\sigma_{\lambda\mu}\psi_n)(C_T\overline{\psi_e}\sigma_{\lambda\mu}\psi_\nu + C'_T\overline{\psi_e}\sigma_{\lambda\mu}\gamma_5\psi_\nu)
\end{aligned}
$$

Standard model: V-A theory

Beyond standard model physics

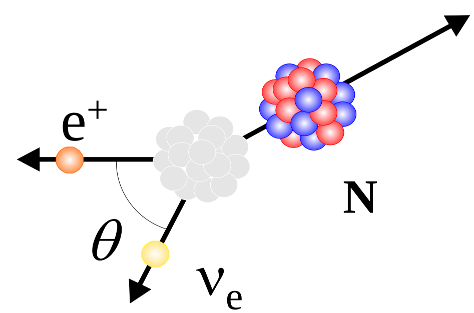
pseudoscalar current very small and neglected

coupling constant

initial wave function

current

final wave function

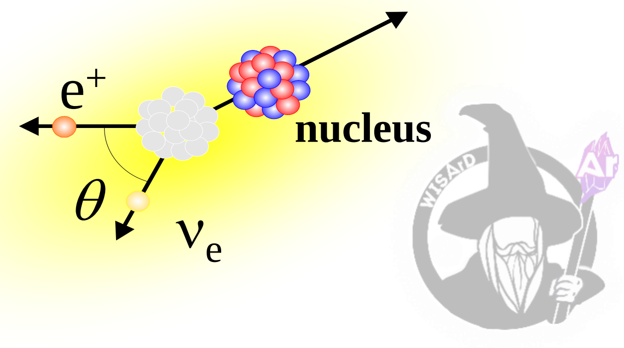


- **Standard model: V-A theory**
  - $C_S = C_S' = C_T = C_T' = C_P = C_P' = 0$
  - Maximal parity violation: $C_V = C_V'$ and $C_A = C_A'$
  - Time-reversal symmetry: C_V, C_V', C_A, C_A' real

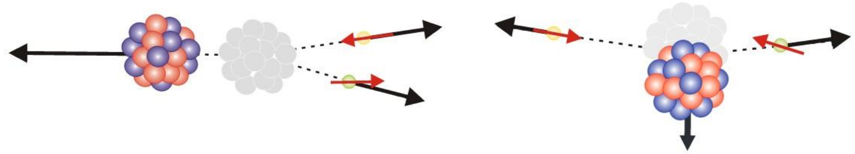
- **Beyond standard model physics (new physics "NP")**
  - C_S, C_S', C_T, C_T', C_P, C_P', $\neq 0$ ➔ search for new particles (HEP)
    ➔ deviation from theory in high-precision β decay experiments

The WISArD experiment

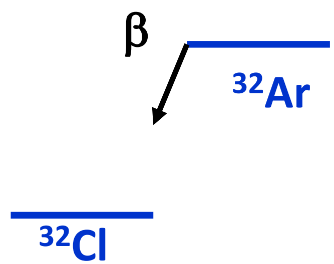
$$dW = dW_0 \times \xi \left(1 + a\,\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e}\right)$$



Pure Fermi transition (ΔJ=0, S=0) (similar for GT decays):



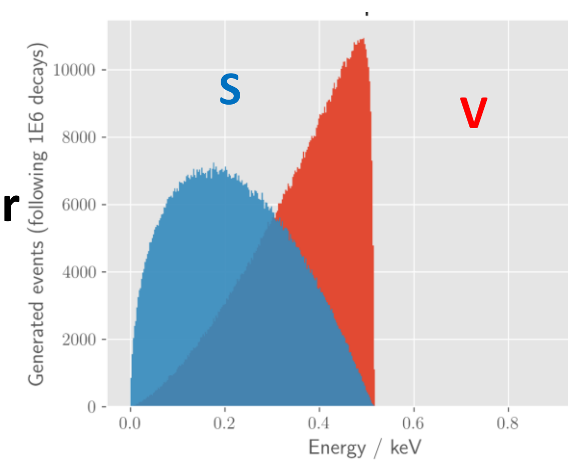
recoil of nucleus ^{32}Cl



SM: vector current	**NP: scalar current**
• **Preferred emission angle: θ = 0°** • **Maximum recoil energy**	• **Preferred emission angle: θ = 180°** • **Minimum recoil energy**

$$a^F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{C_V^2} \qquad b^F \cong \pm Re\,(\frac{C_S + C'_S}{C_V})$$

nuclear recoil:



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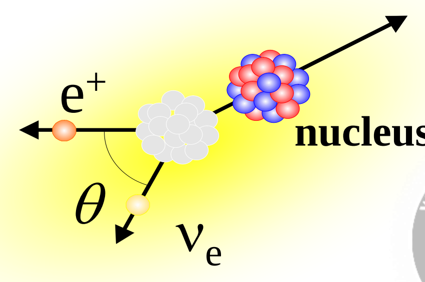

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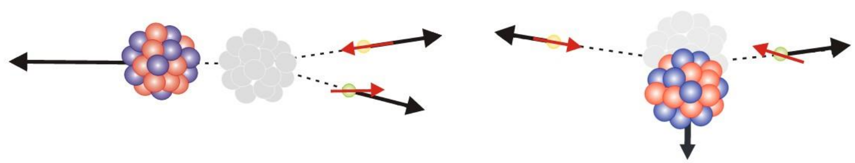
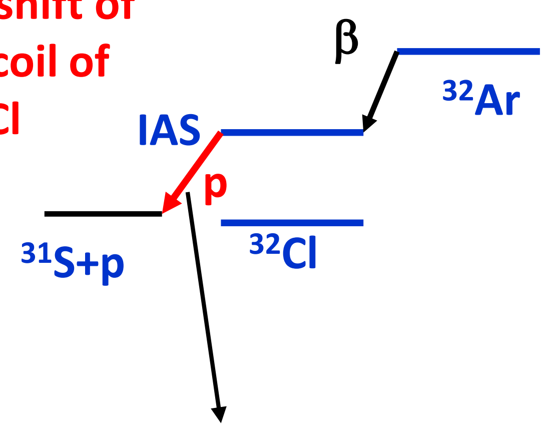


SM: vector current
- **Preferred emission angle: θ = 0°**
- **Maximum recoil energy**

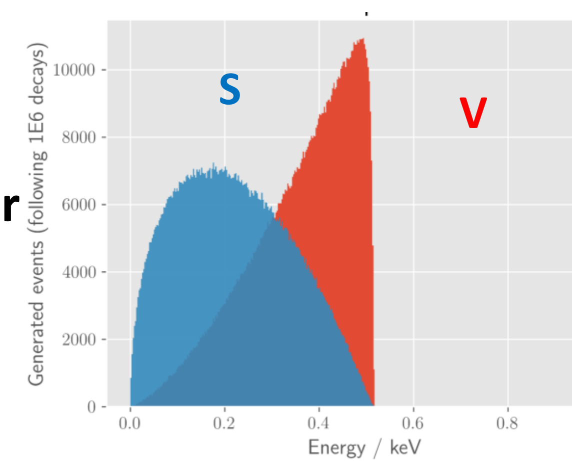
NP: scalar current
- **Preferred emission angle: θ = 180°**
- **Minimum recoil energy**

$$a^F_{\beta\nu} \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{C_V^2} \qquad b^F_{\beta\nu} \cong \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$

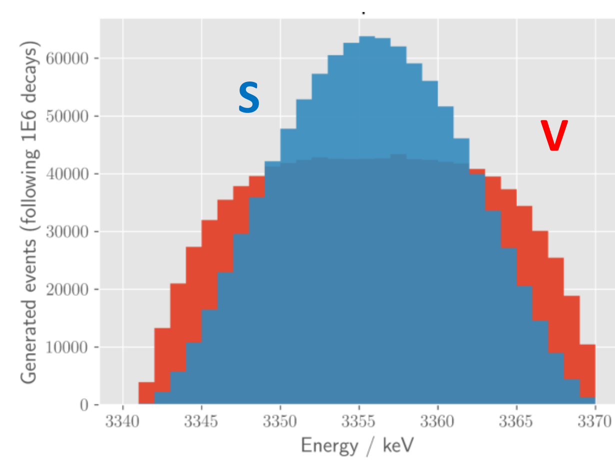
kinematic shift of proton: recoil of nucleus ^{32}Cl



nuclear recoil:



emitted proton:



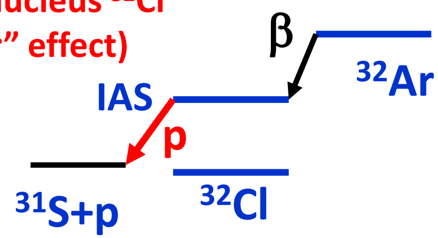
• • • The WISArD experiment

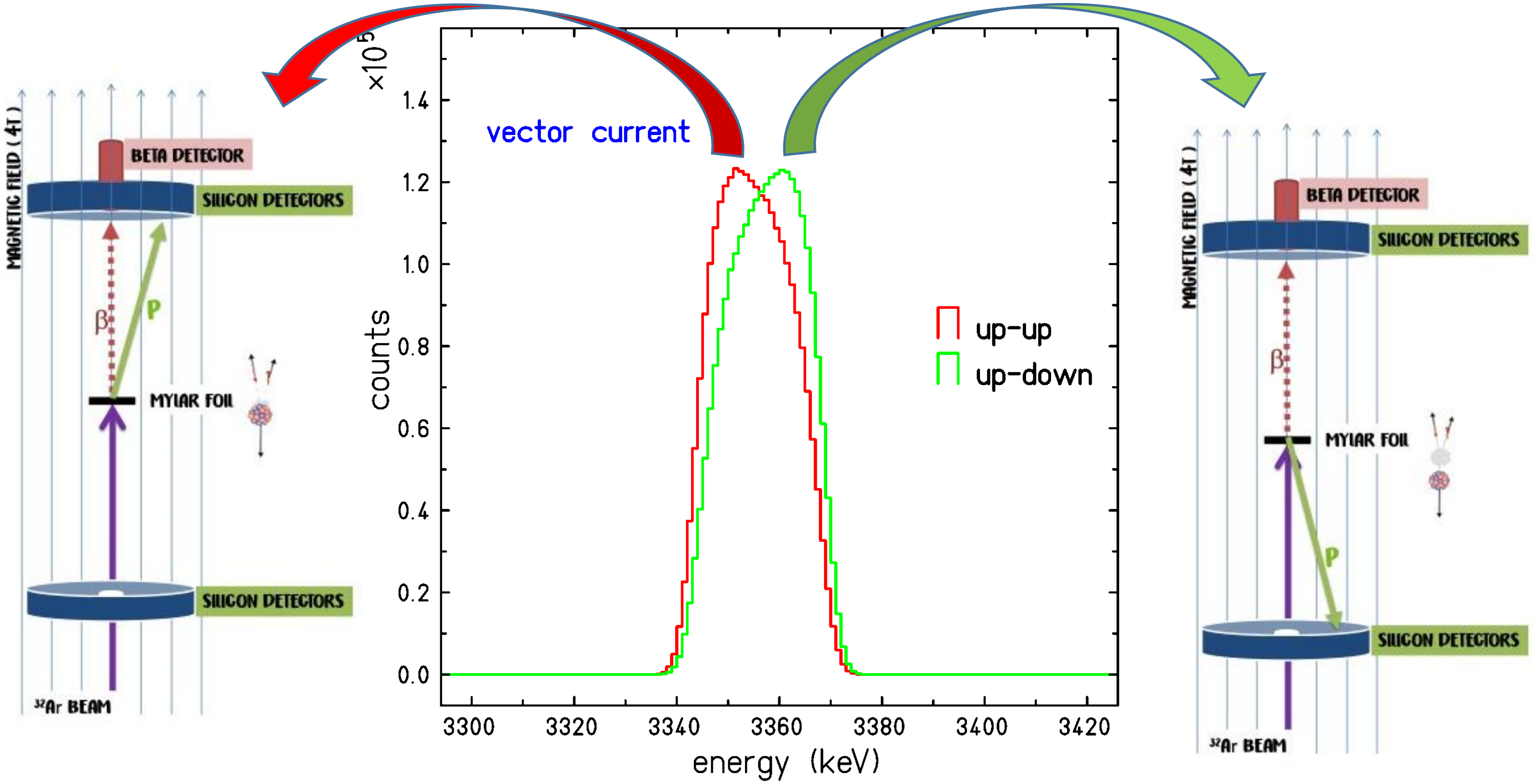
- Principle: measurement of the recoil of nucleus via an indirect measurement: β-delayed proton in a magnetic field to guide the positrons

➔ kinematical cuts with singles protons and e^+ - coincident protons

➔ increased sensitivity

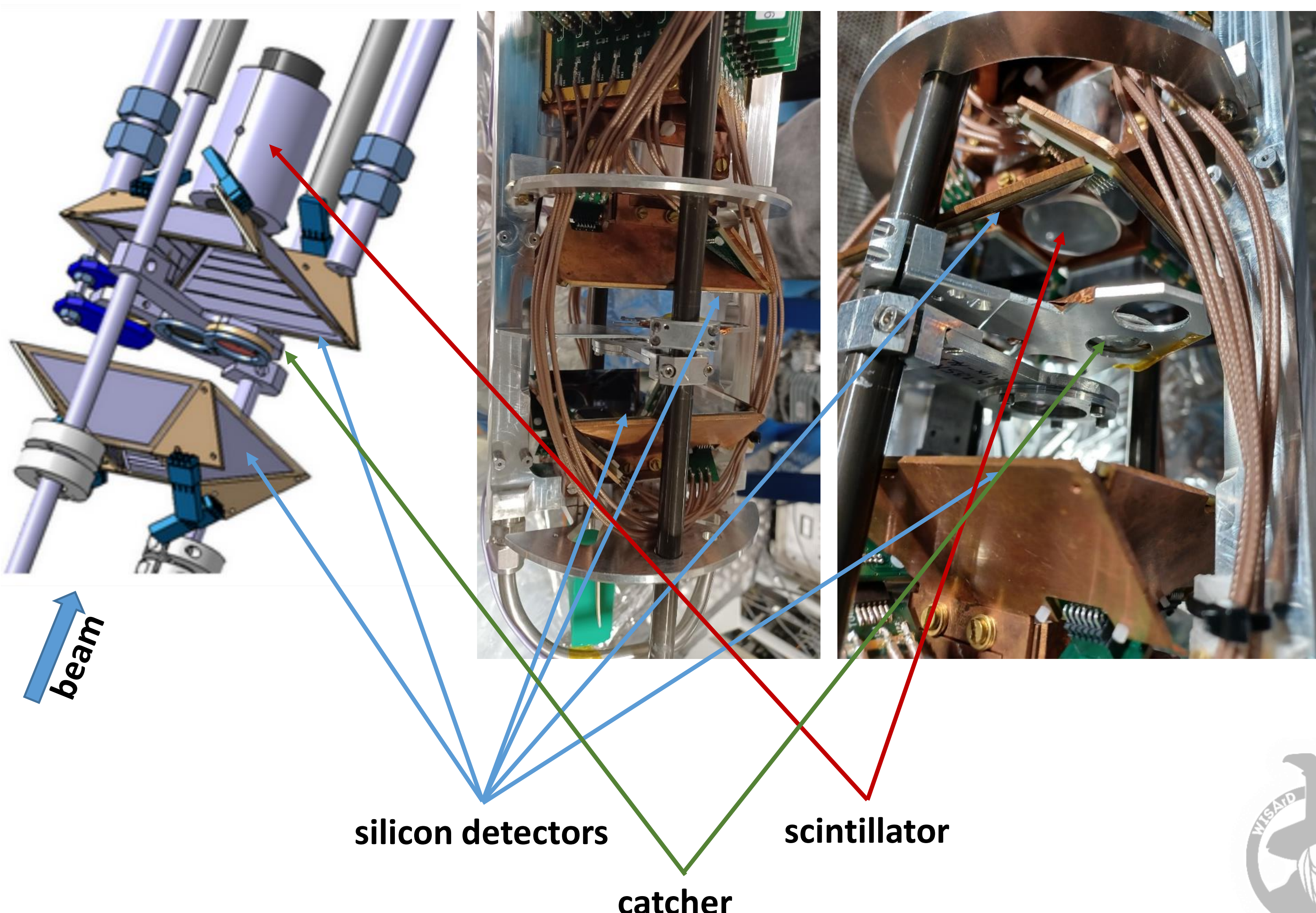
Detection of proton: recoil of nucleus ^{32}Cl ("Doppler" effect)



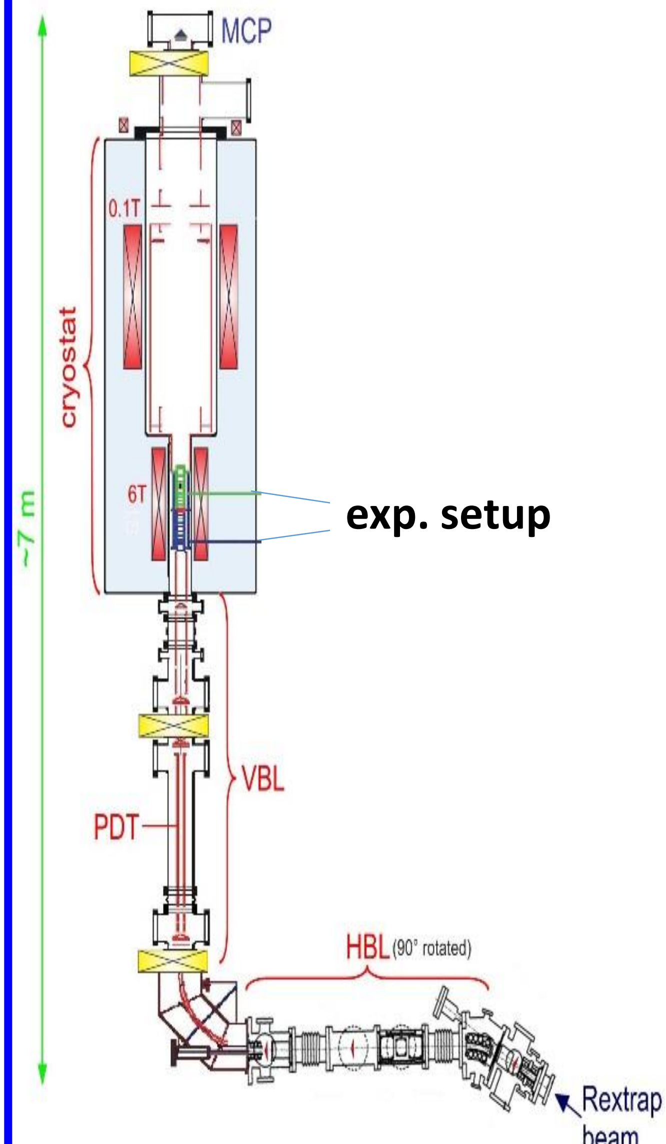


➔ exactly same reasoning for "beta down", i.e. beta not detected

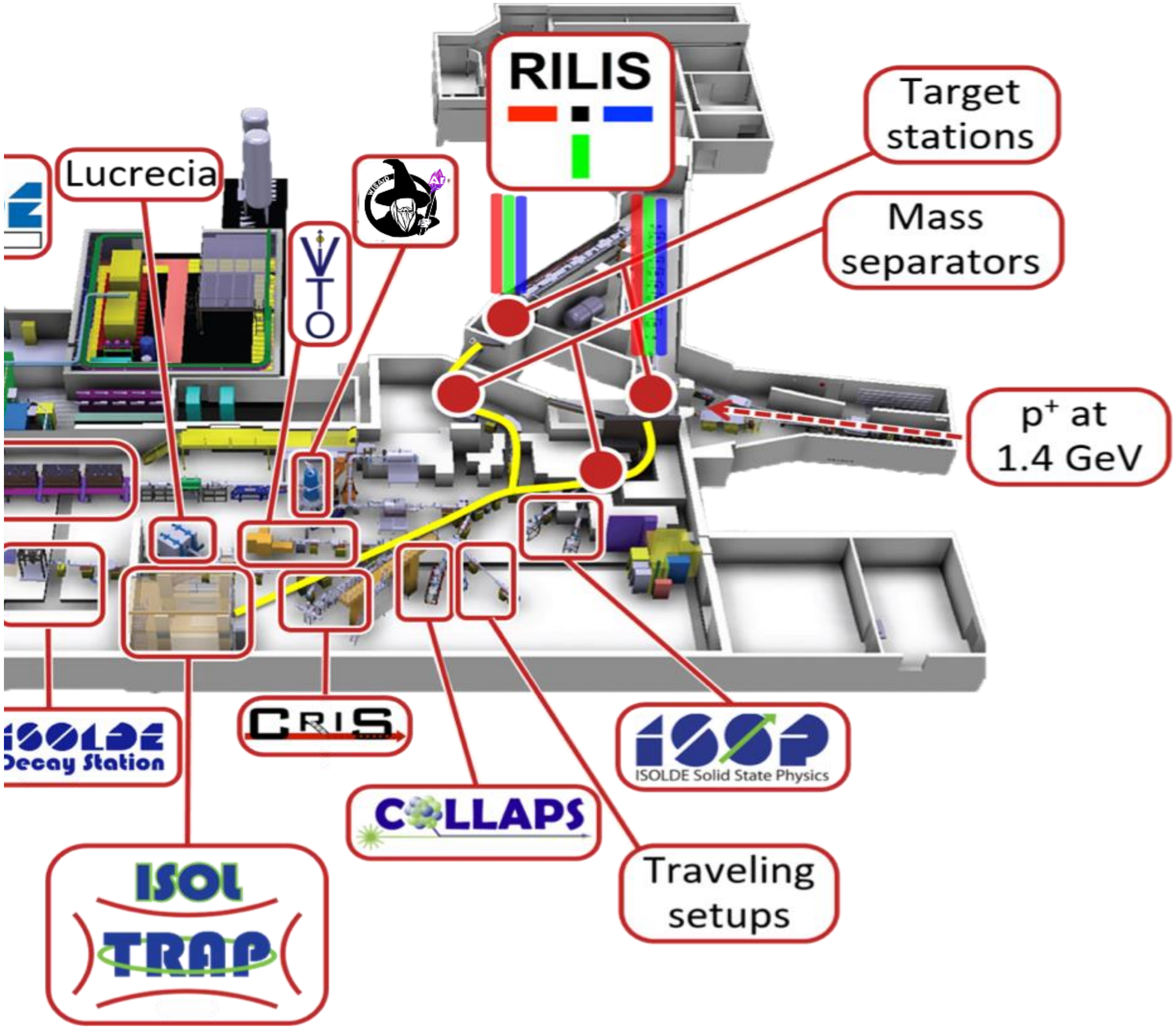
WISArD setup 2024



WISArD at ISOLDE - CERN



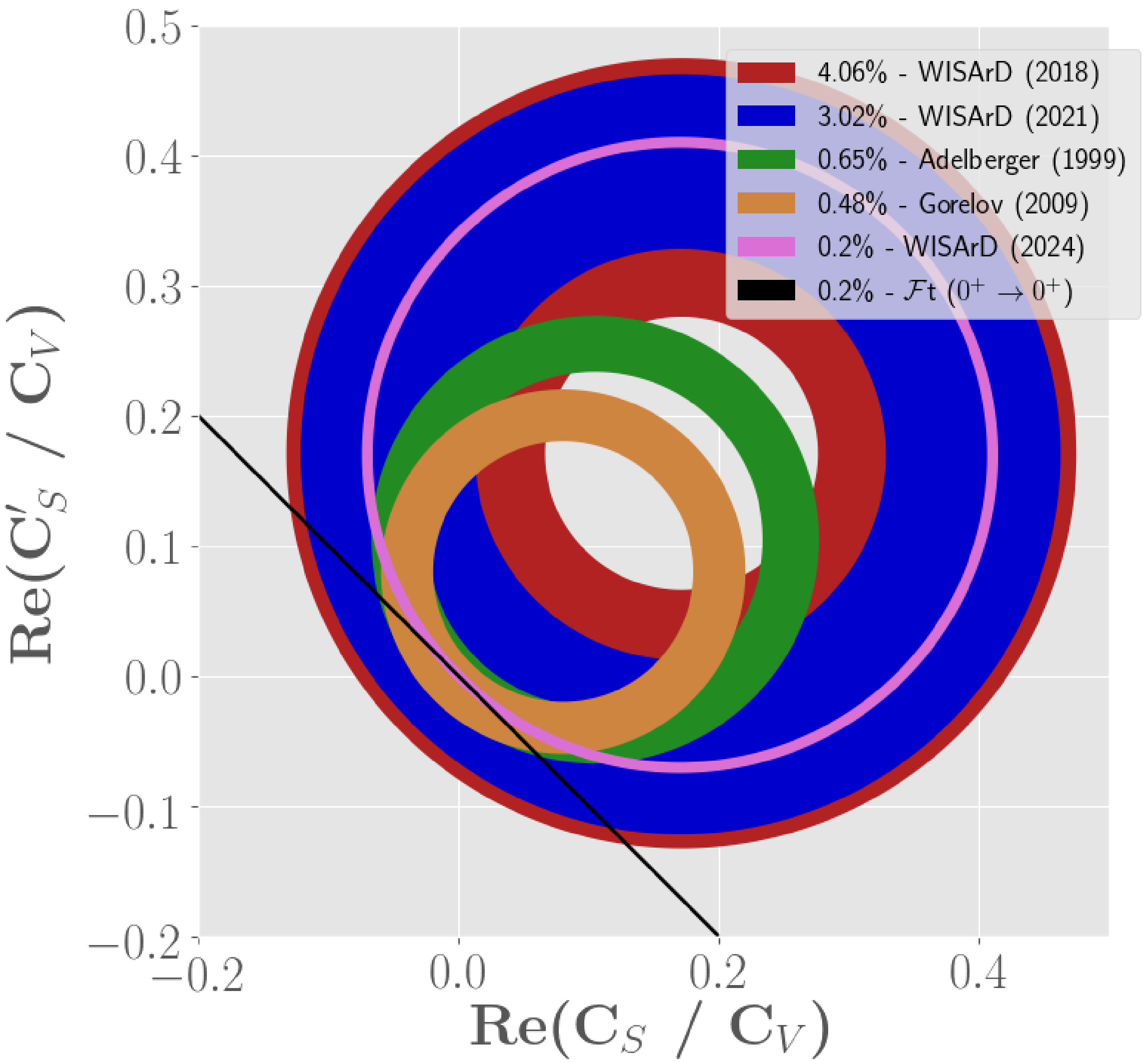
exp. setup



2018: proof of principle: $\tilde{a}_{\beta\nu}^{F} = 1.01\,(3)_{(stat)}(2)_{(syst)}$

2021: test of new equipment: $\tilde{a}_{\beta\nu}^{F} = 1.02\,(2)_{(stat)}$

Limits on scalar currents: >2024



$a^{\mathrm{F}}_{\beta\nu}$ **= 1.01(4) (2018)**

$a^{\mathrm{F}}_{\beta\nu}$ **= 1.02(~3) (2021)**

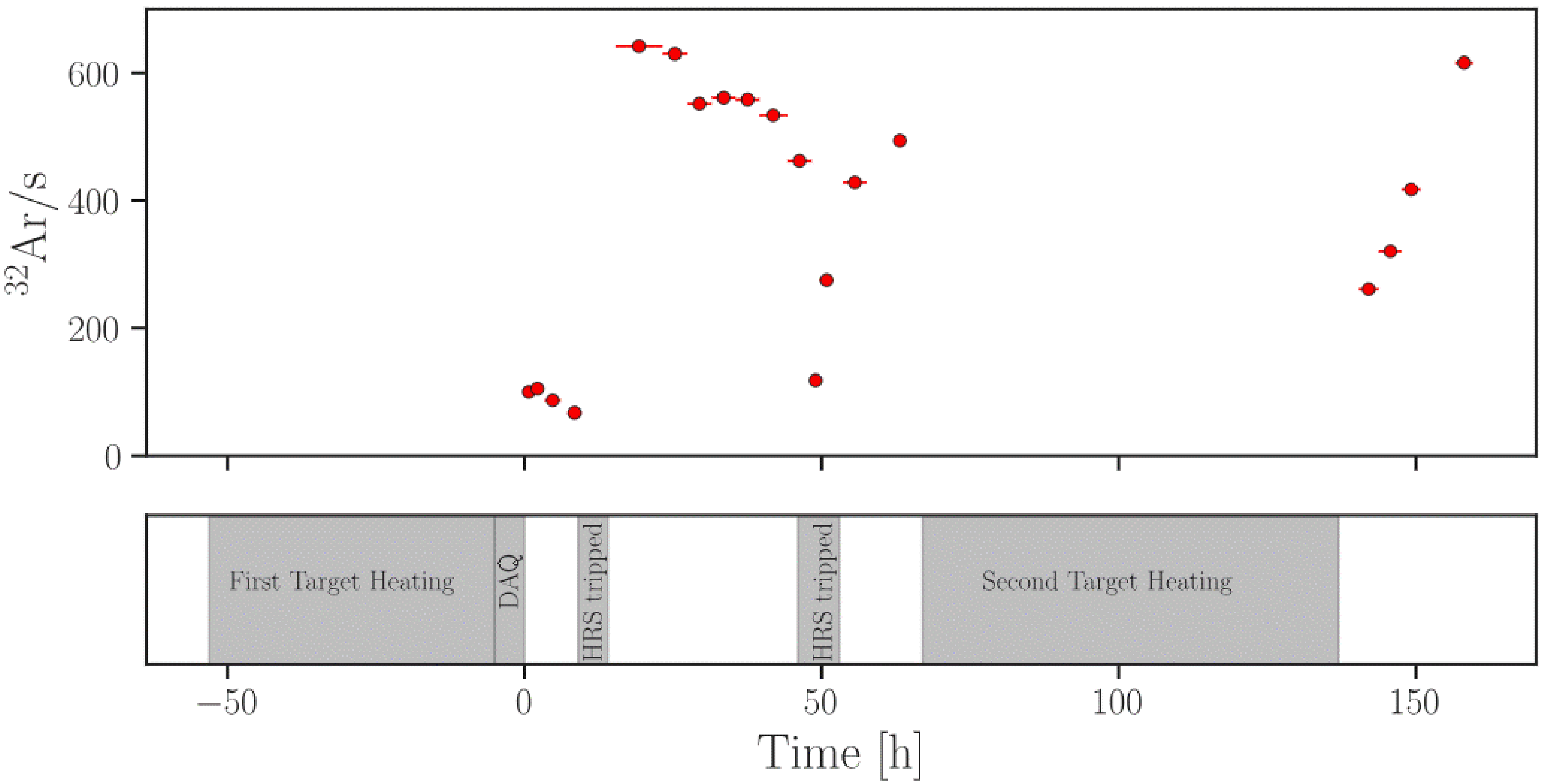
$a^{\mathrm{F}}_{\beta\nu}$ **= 0.9989(65) (Adelberger)**

$a^{\mathrm{F}}_{\beta\nu}$ **= 0.9981(48) (Gorelov)**

$a^{\mathrm{F}}_{\beta\nu}$ **= 1.0000(20) (WISArD 202x)**

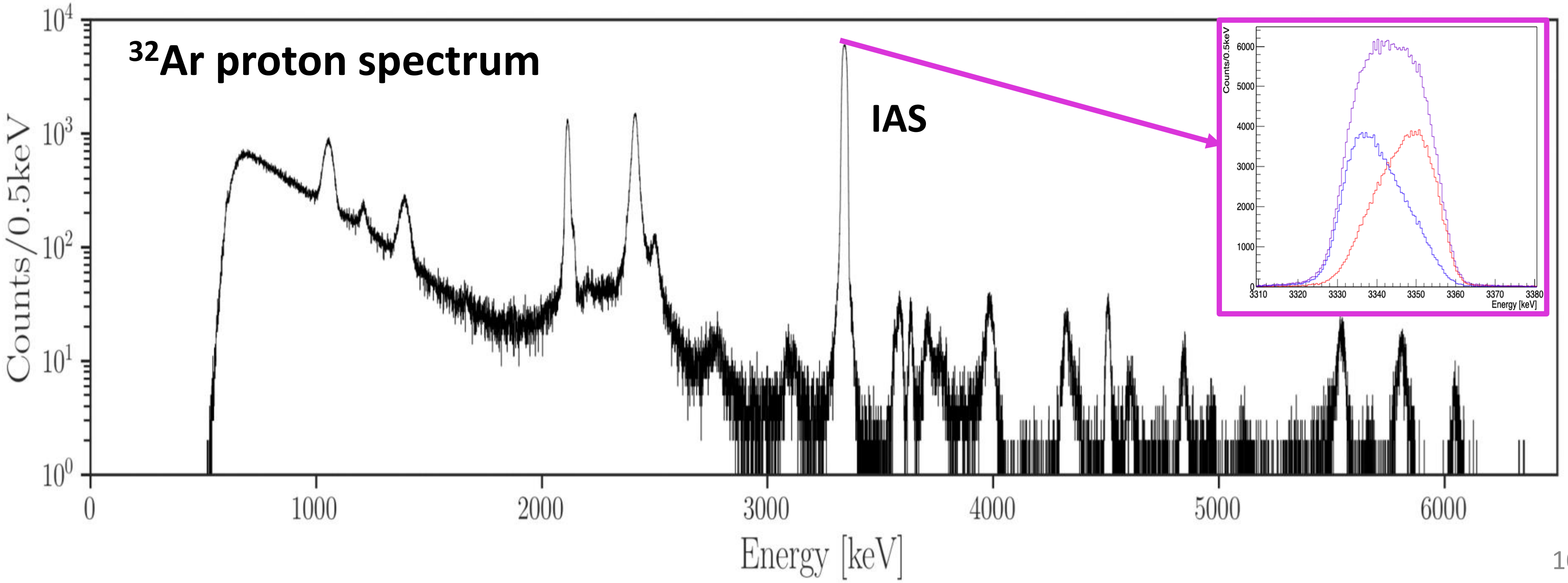
WISArD, May 2024

- 8 days of experiment, ~2.5 days with ^{32}Ar (high) production rate



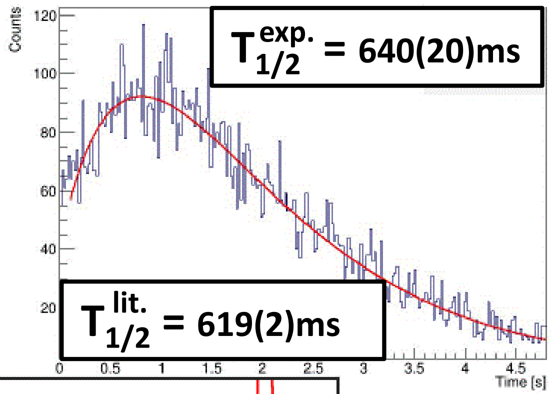
WISArD, May 2024

- 8 days of experiment, ~2.5 days with ^{32}Ar (high) production rate
- 11 x 10^6 IAS events ➪ 0.2% stat. uncertainty, best stat. uncertainty

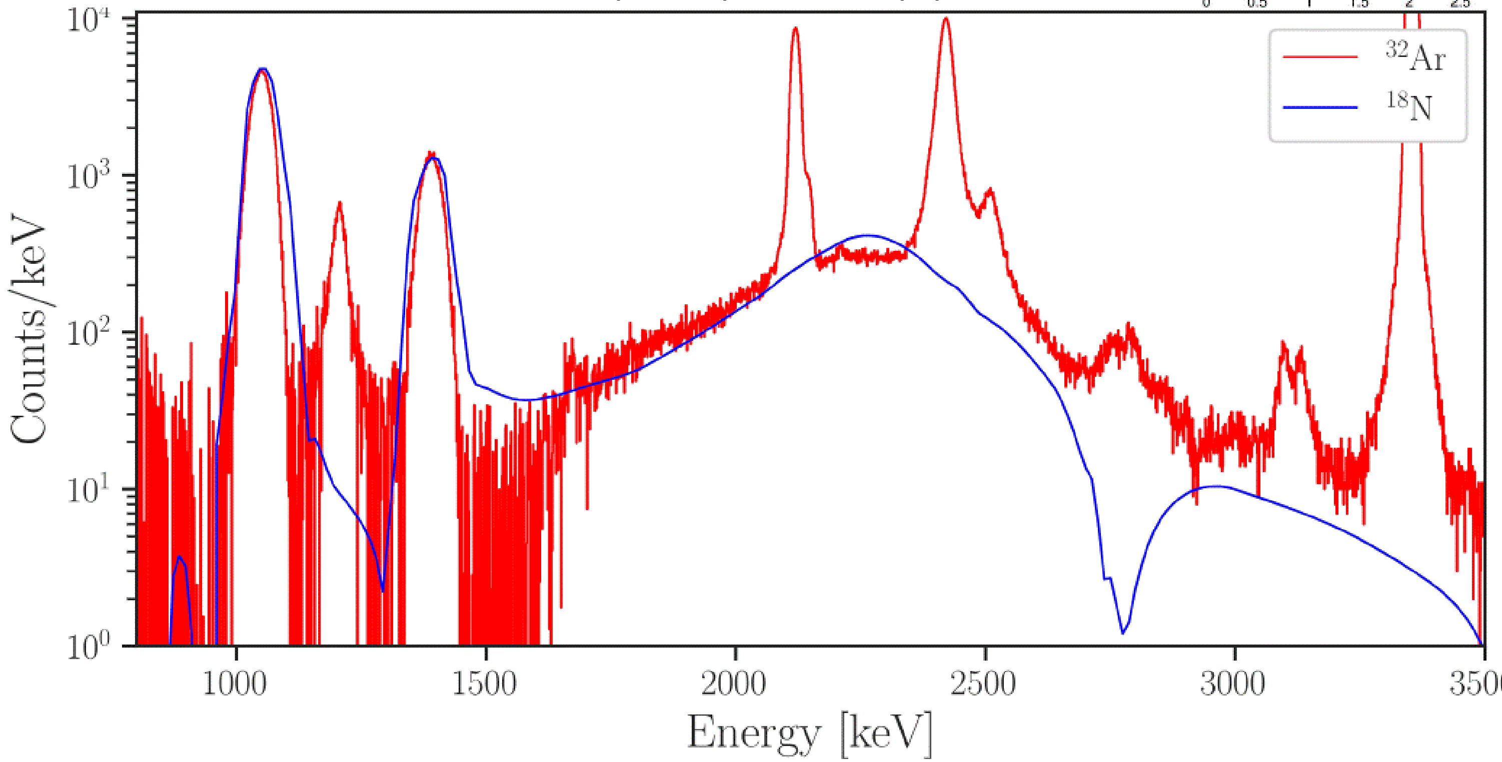


● ● ● WISArD, May 2024

- 8 days of experiment, ~2.5 days with ^{32}Ar (high) production rate
- 11 x 10^6 IAS events ➩ **0.2% stat. uncertainty**
- first problem: contaminant ^{14}N-^{18}N



^{18}N: L. Buchmann et al., PRC75 (2007) 012804(R)



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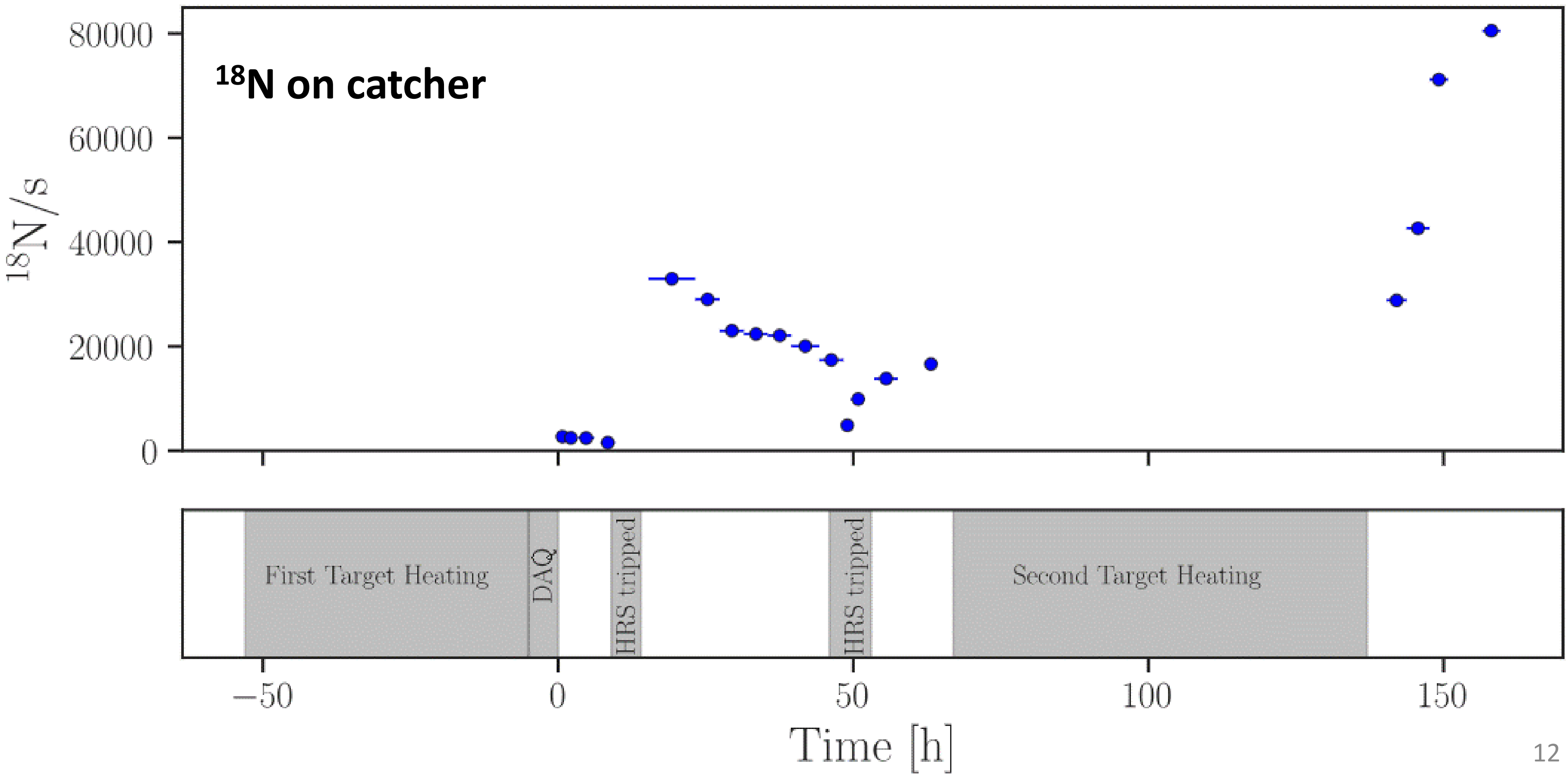

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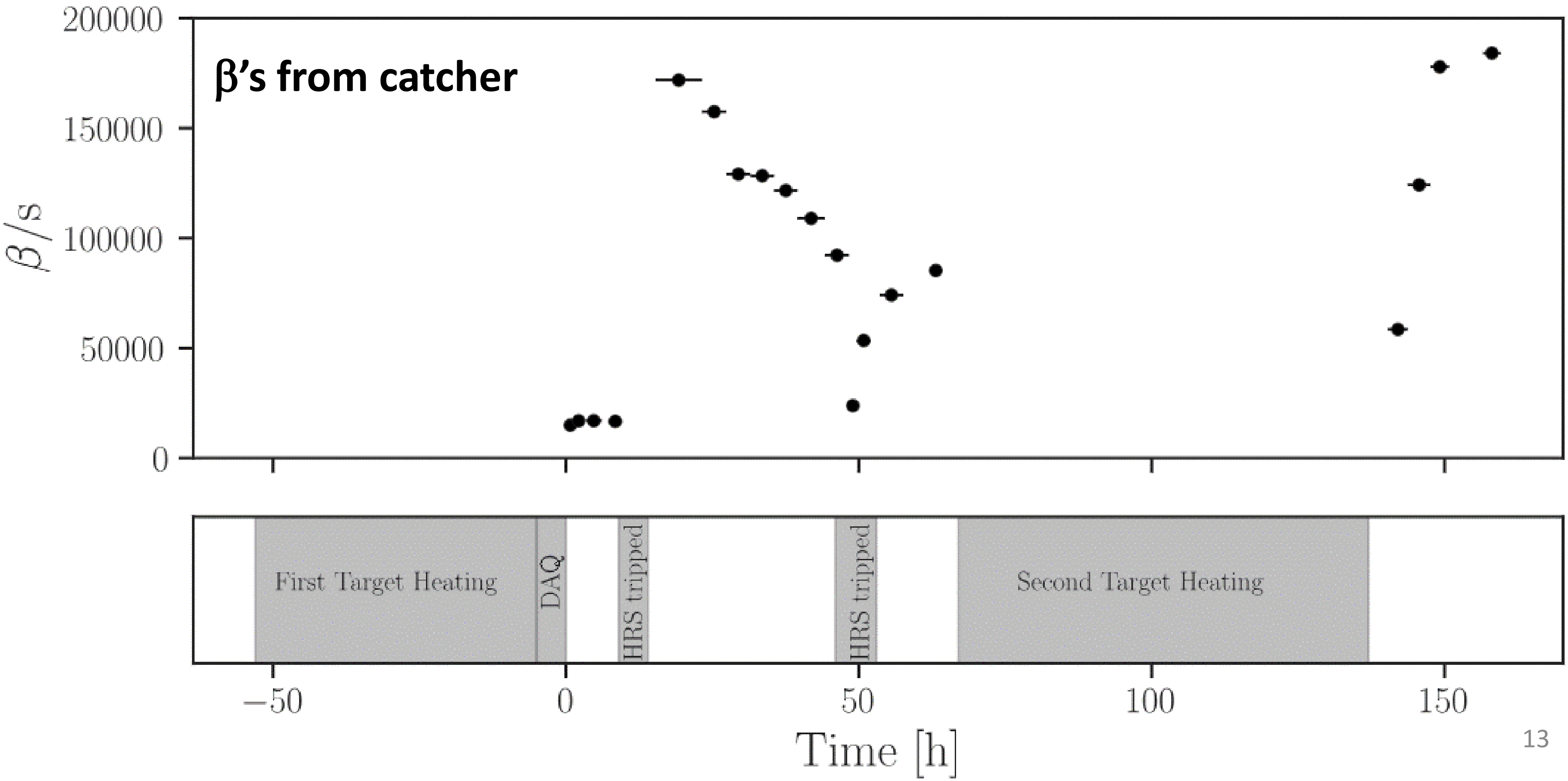

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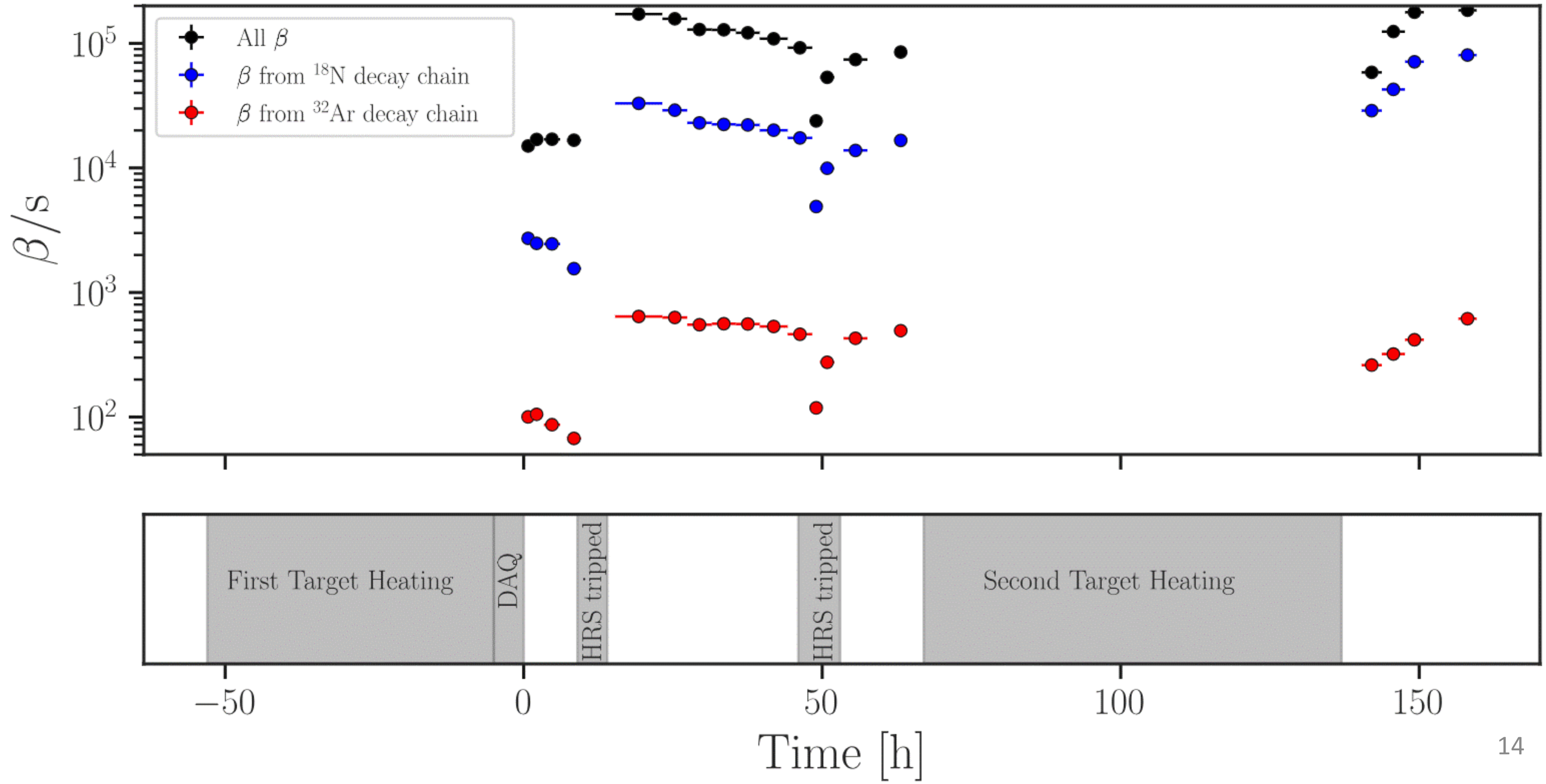

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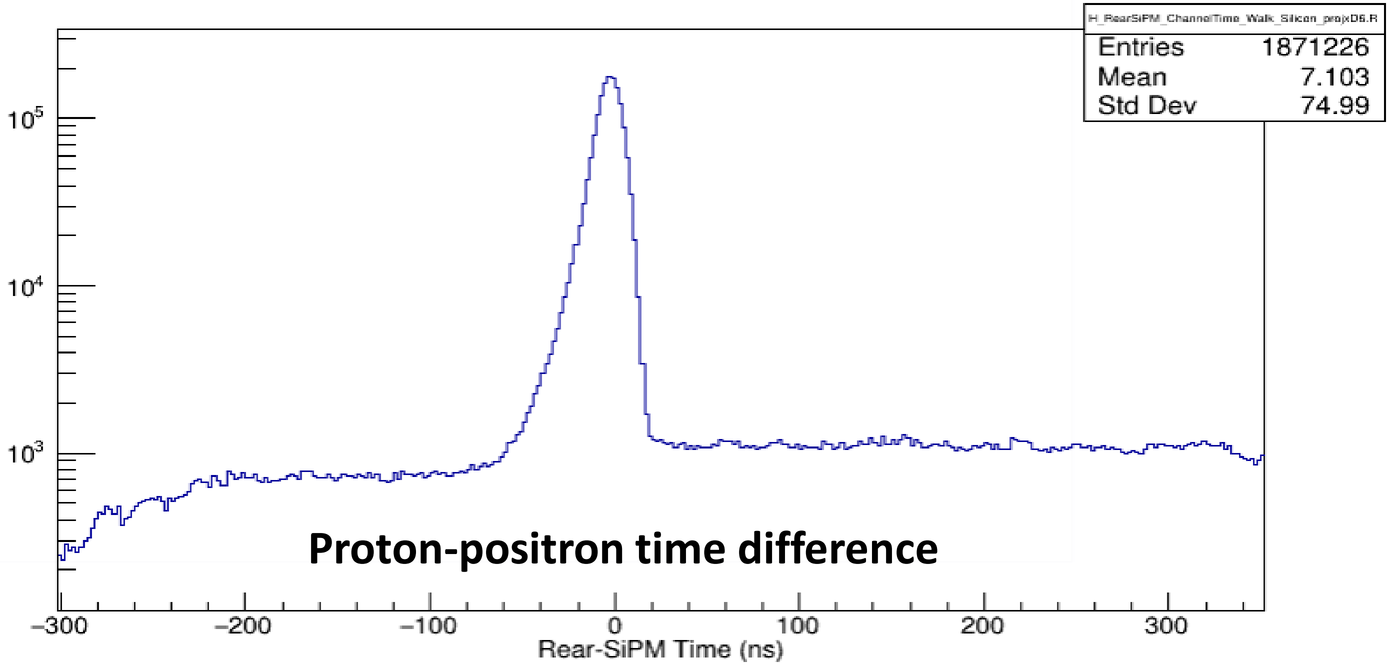
    - other contaminants: ^{15}N-^{17}N (!), ^{14}O-^{18}O (?), ^{15}O-^{17}O (?), ^{16}N-^{16}O (?)

➔➔ problem: random coincidences: ~ 0.5% ➔ systematic error ??

no….



WISArD, May 2024

- 8 days of experiment, 2.5 days with ^{32}Ar (high) production rate
- 11 x 10^6 IAS events ➪ 0.2% stat. uncertainty
- first problem: contaminant ^{14}N-^{18}N
- second problem: high beta rates ➪ 100000 pps
  - other contaminants: ^{15}N-^{17}N (!), ^{14}O-^{18}O (?), ^{15}O-^{17}O (?), ^{16}N-^{16}O (?)

➔➔ problem: random coincidences: ~ 0.5% ➔ systematic error ??
no...

- Other systematic uncertainties:

Main sources	Uncertainty				Improvement
	2018*	$\Delta\tilde{a}$	(estimated) 2024	$\Delta\tilde{a}$	
β-backscattering	~15%	17	~ 10%	< 10	Thinner catcher
Dead layer thickness	430 ± 300 nm	12	100 ± 5 nm	0.3	New detectors
Catcher thickness	6.70 ± 0.15 µm	5	0.60 ± 0.02 µm	0.3	RBS measurement
Source radius/position	± 3 mm	1	± 0.5 mm	0.2	MCP beam profile
Detector position	± 1 mm	0.3	± 0.5 mm	0.2	Laser alignment
Calibration	~ 5 keV	10	~ 1 keV	2	^{33}Ar runs, new detectors
		x10^{-3}		x10^{-3}	

WISArD, May 2024

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➔➔ problem: random coincidences: ~ 0.5% ➔ systematic error ??
maybe not….

other problems:
- DAQ loses events (on the way to be solved…) ➔ small systematic error
- bad light contact between scintillator and SiPM ➔ complicates analysis + reduced resolution

to-do list

We can improve:

- statistical error with a one-week run could be as low as 0.1%
- systematic errors from
  - positron energy threshold can be improved (factor of 2)
  - resolution of plastic scintillator can be improved (factor 1.5)
  - systematic uncertainty due to event losses → no losses

What needs to be done/tested before run:

- improve the reliability of TIS
- reduce the number of molecules with "chemistry"
- good optical connection between SiPMs and plastic scintillator
- improved data acquisition (partially done, rest in December)

On-line:

- play with the beam gate: N_2 molecules have longer release time
- close a little HRS slits (at least from one side)

Request

- 3 shifts of TIS development
  (not in written document, discussed with TIS group)
  ➔ tests to break the molecules with chemistry
  ➔ off-line tests with first TIS

- 8 days of ^{32}Ar beam
  (less not reasonable: 2.5 d for outgassing / TIS change…)

➔ ideally in 2025 (PhD)…
possibility after HIE-ISOLDE runs in October/November like in 2018 and 2021?

Thanks for your attention

LP2i Bordeaux

KU LEUVEN

lpc caen
Laboratoire de physique corpusculaire

ISOLDE

ibs Institute for Basic Science

sck cen

IFIN-HH

W

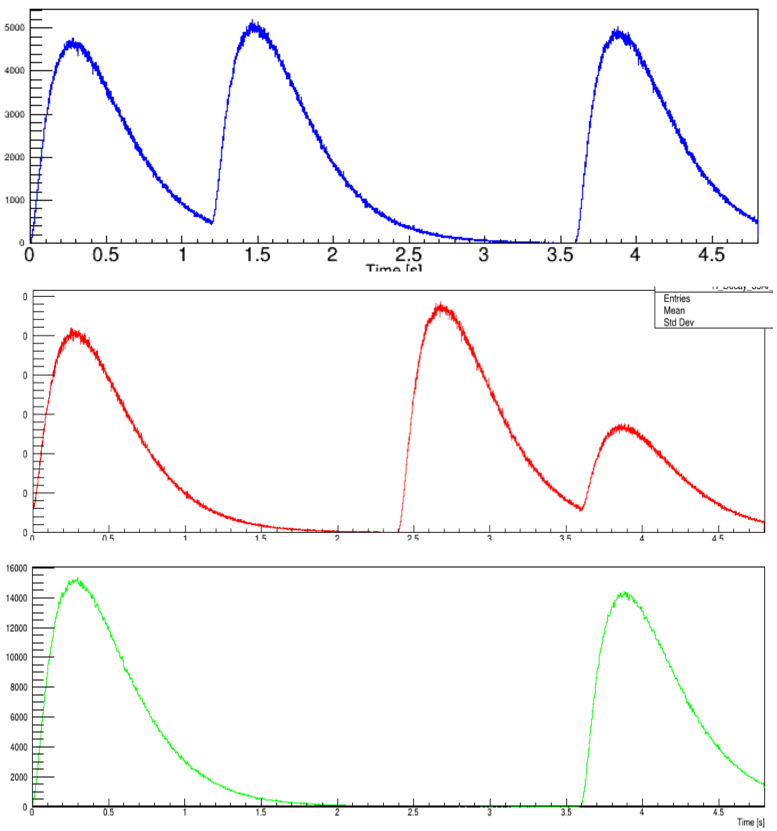
UNIVERSITY OF WARSAW

ATM

Nuclear Life Time

Contamination identification

^{33}Ar



1.2s

2.4s

3.6s

ISOLDE pulse to construct the summed release and decay curve

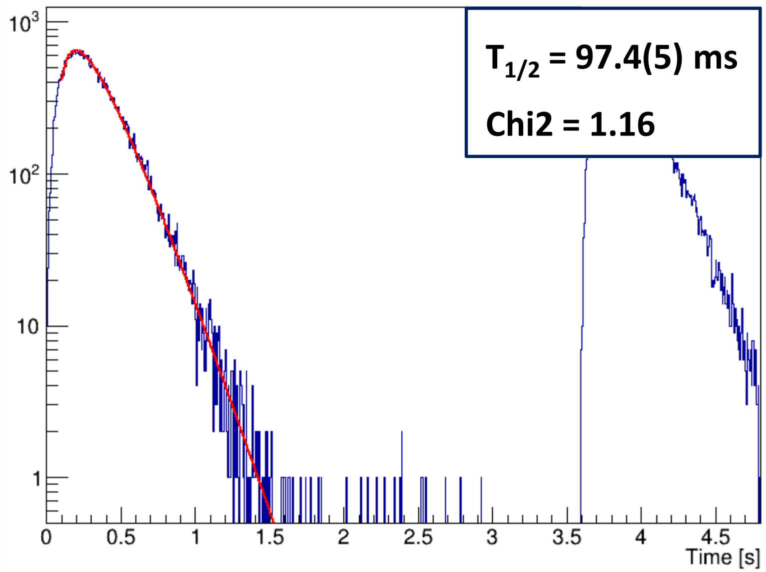
Nuclear Life Time

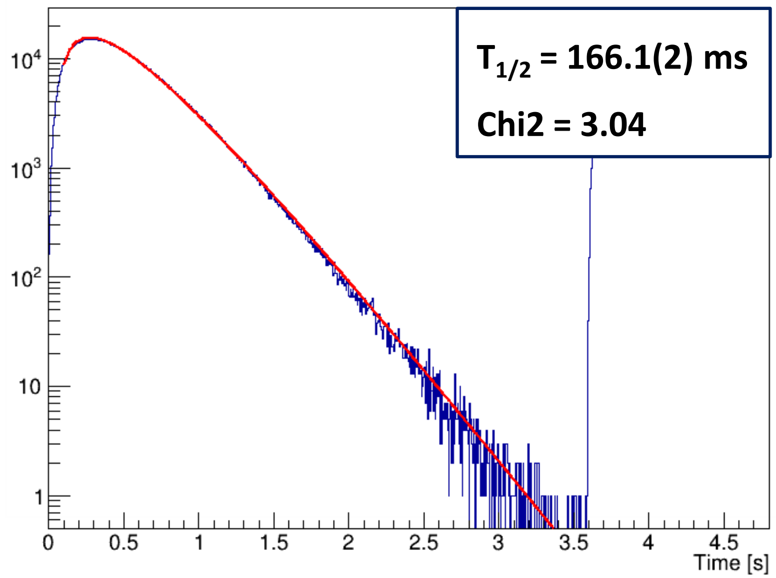
Contamination identification

^{32}Ar

$$f(t) = A(1 - e^{-\lambda_1 t})e^{-\lambda_D t}$$

^{33}Ar





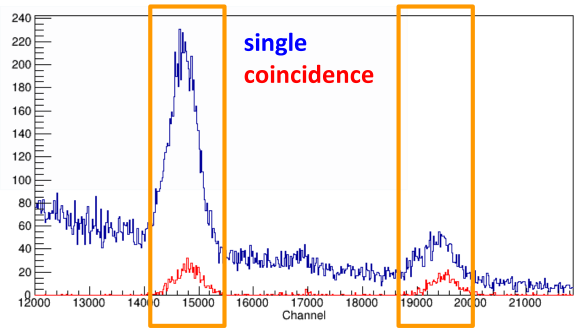
Literature : $T_{1/2}(^{32}\mathrm{Ar}) = 98 \pm 2\ ms$

$T_{1/2}(^{33}\mathrm{Ar}) = 173 \pm 2\ ms$

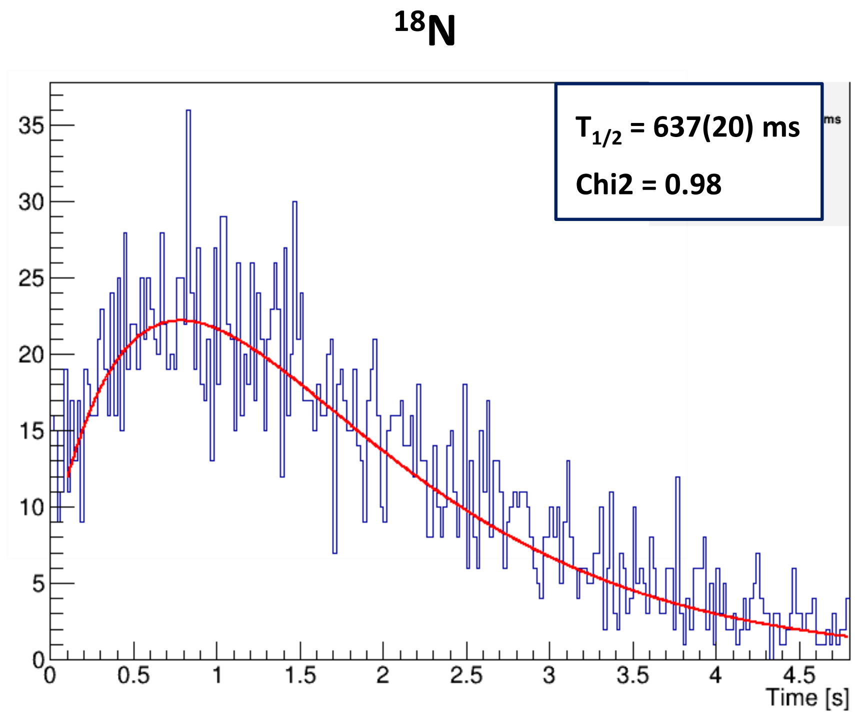
Nuclear Life Time

Contamination identification

- **Gate on the two first alpha peaks in coincidence with a beta in order to avoid the continuous background**



- **Extraction time from the target is longer than Ar (expected because N is not a noble gas)**
- **known ^{18}N production with CaO target (ISOLDE database)**

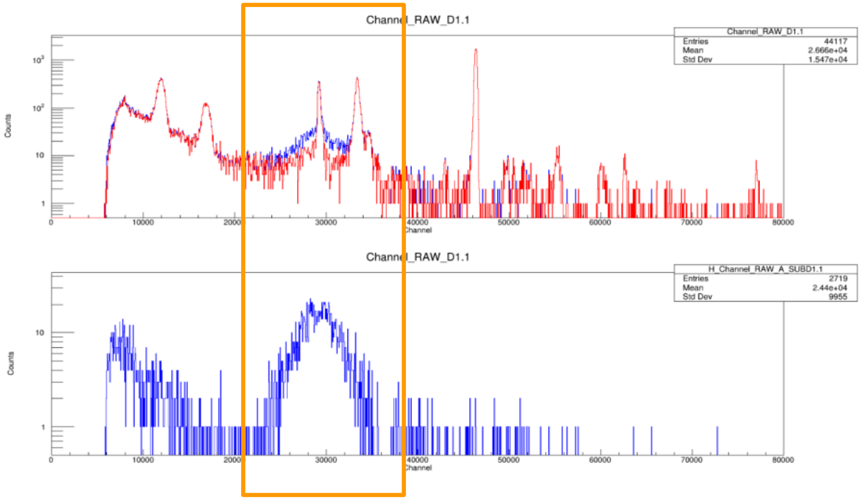


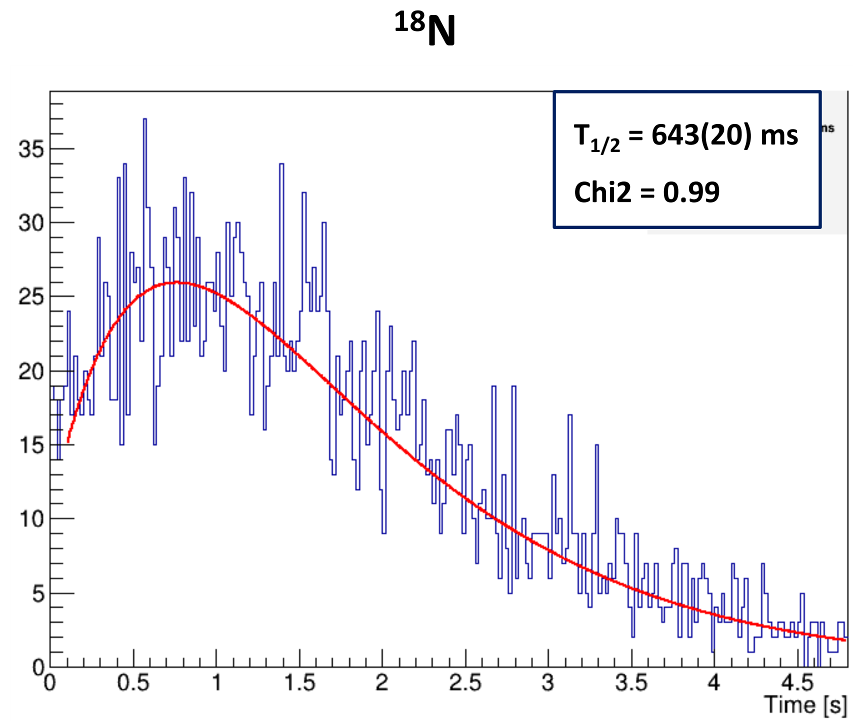
Literature : $T_{1/2}(^{18}\mathrm{N}) = 619 \pm 2\ ms$

Nuclear Life Time

Contamination identification

- Gate on the third peak alpha identified as back-to-back α-^{14}C detection





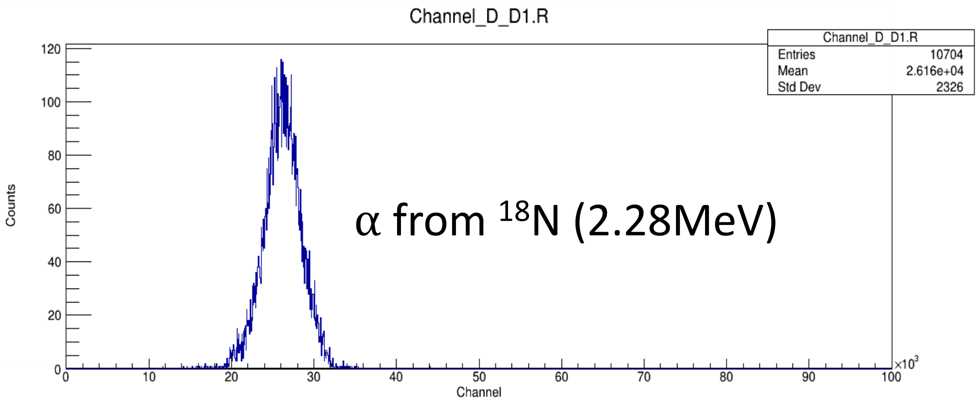
Literature : $T_{1/2}(^{18}\mathrm{N}) = 619 \pm 2\ ms$

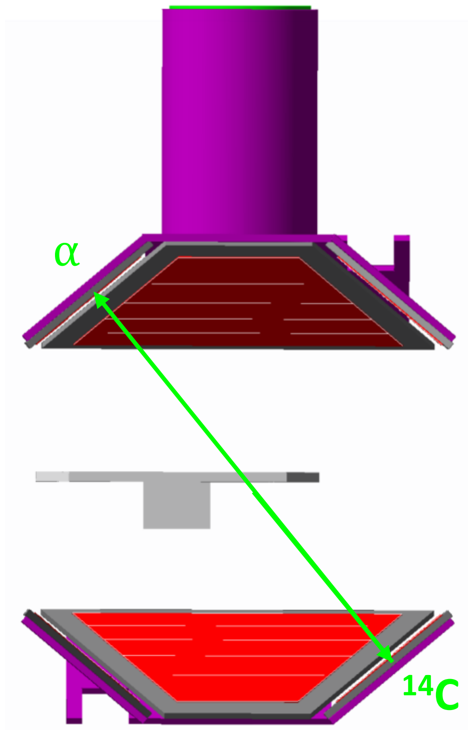
Cleaning and Selecting events

Patterns :

Pattern D : R_X+S_X & S_Y

- Diffetent silicon detectors time correlated





Why we can't detect this type of event for all alphas ?

α = 1.0MeV → E_recoil ~ 300keV
α = 1.4MeV → E_recoil ~ 300keV } below threshold

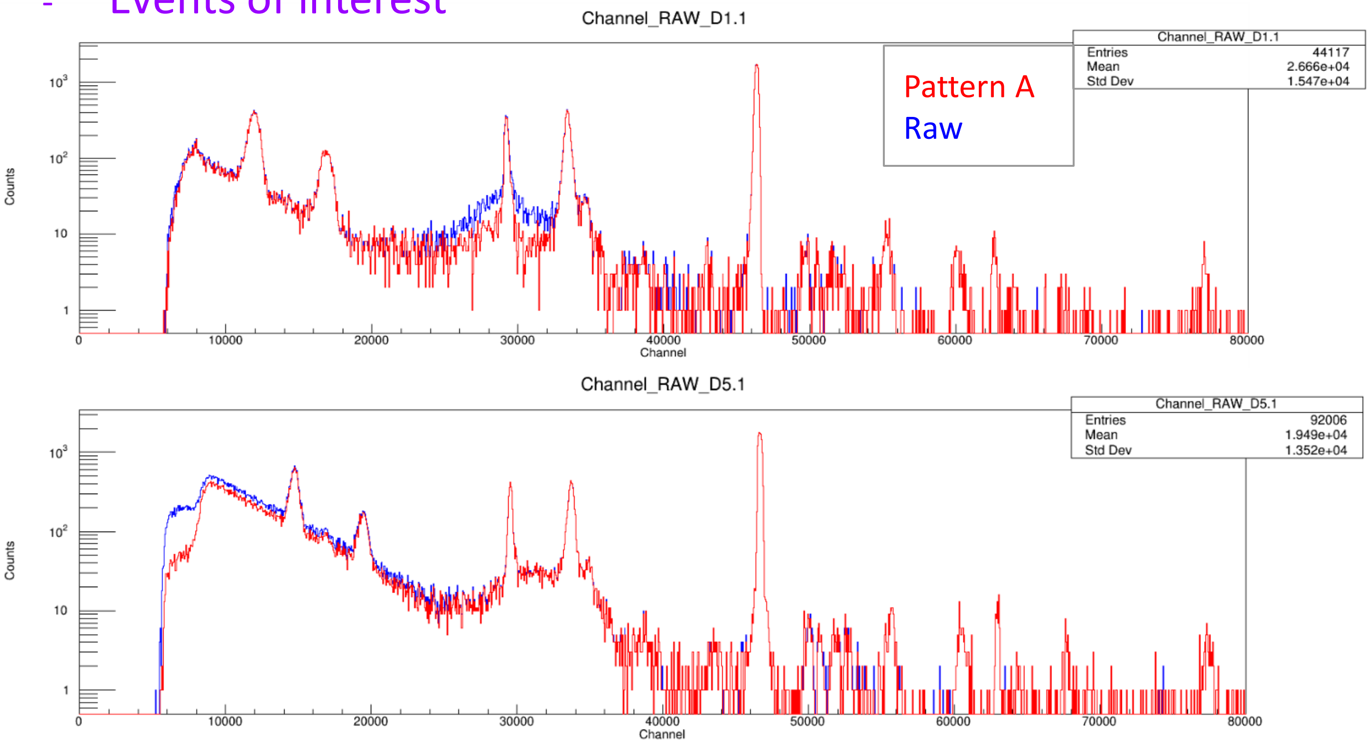
α = 2.3MeV → E_recoil ~ 600keV

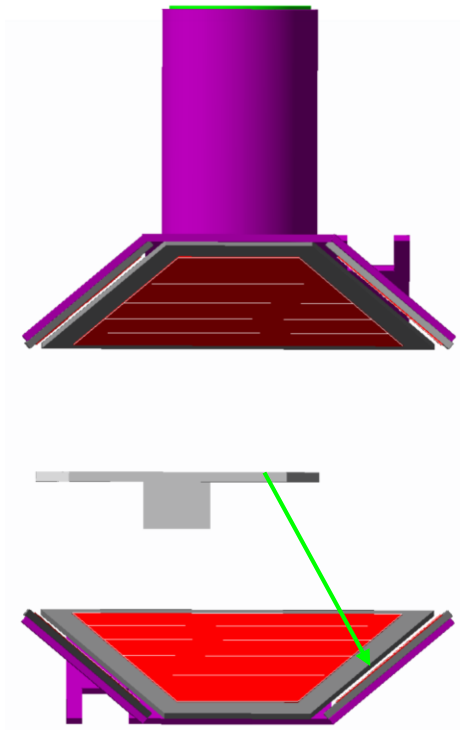
Cleaning and Selecting events

Patterns:

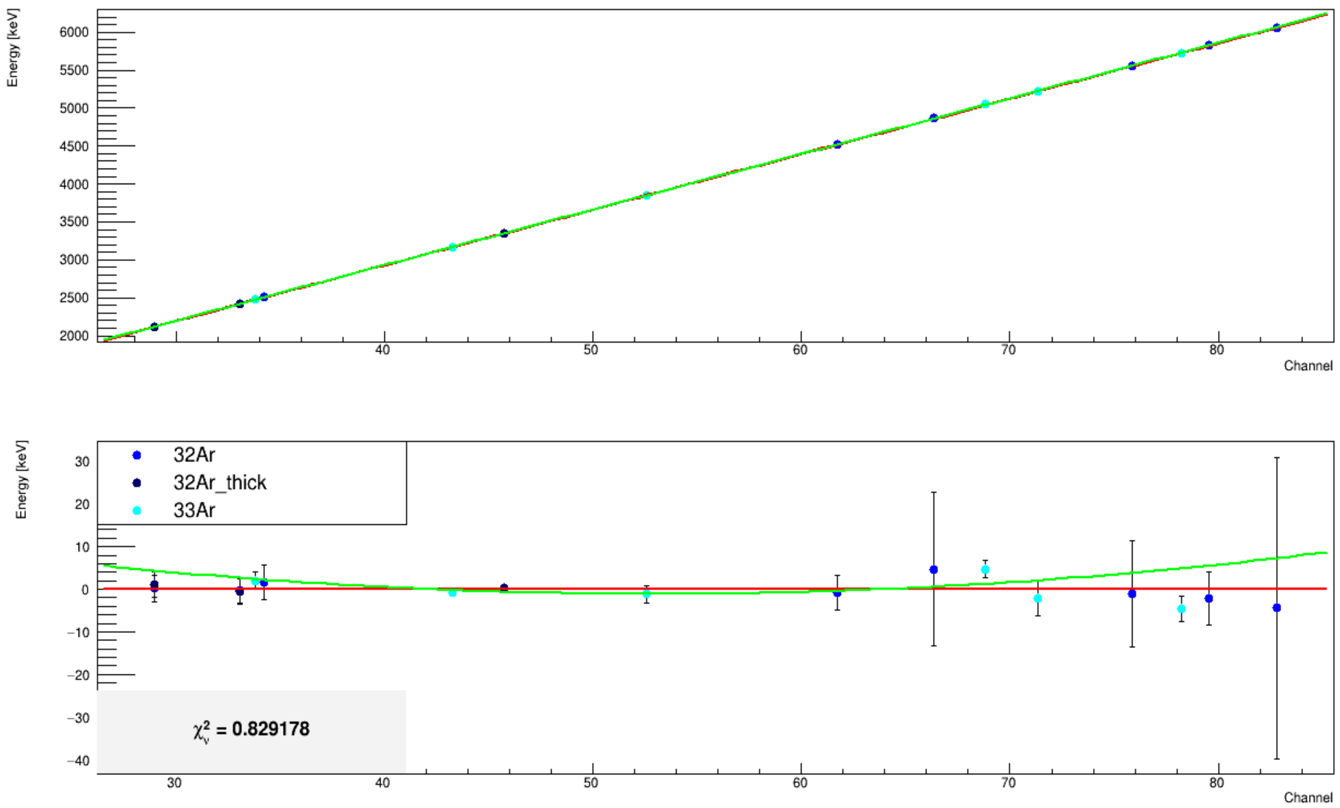
Pattern A : $R_x + S_x$

- Events of interest





Silicon Detectors Calibration



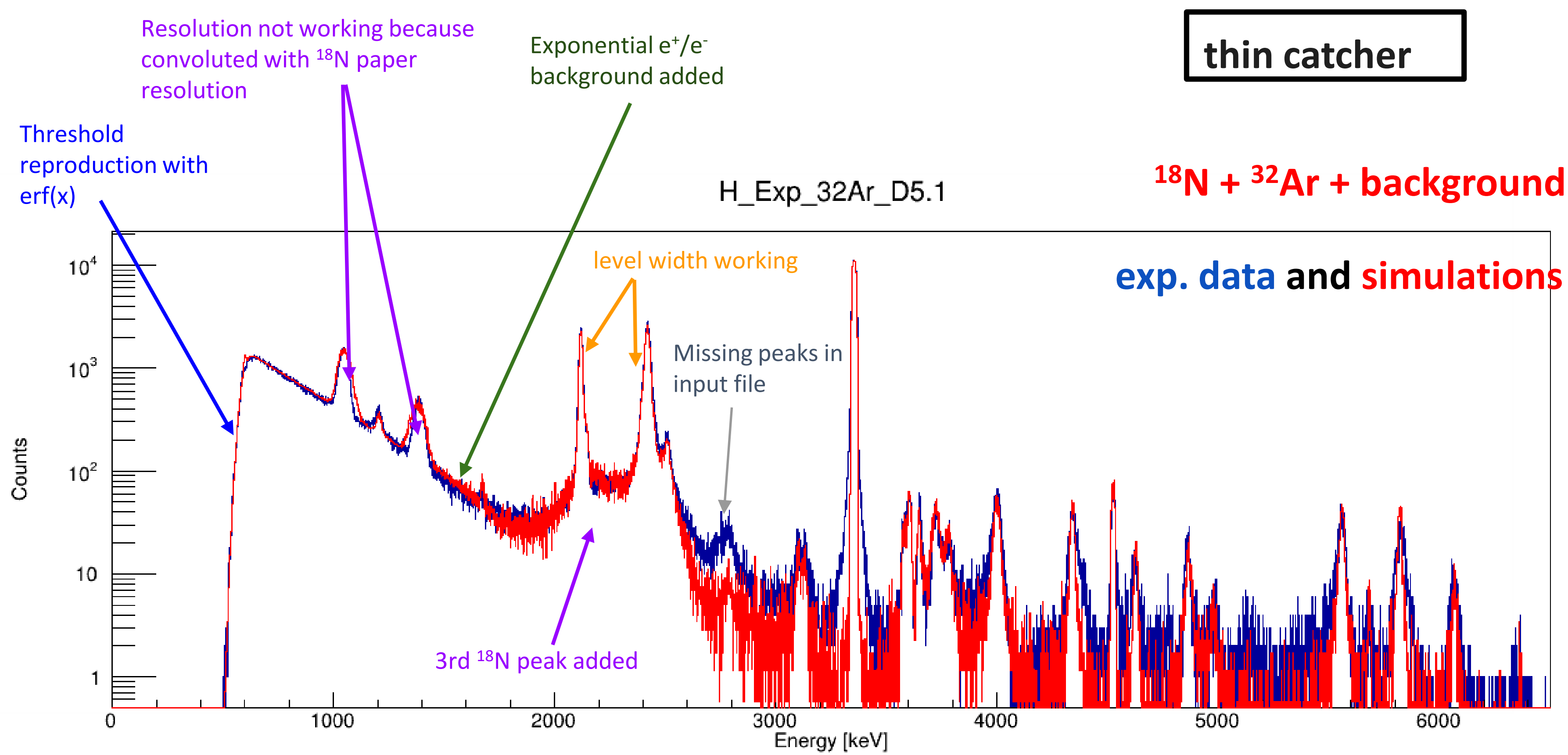
Fit :
Linear
Quadratic

- **9 peaks of ^{32}Ar**
- **3 peaks of ^{32}Ar (thick)**
- **6 peaks of ^{33}Ar**

error bar = litterature + mean error

Silicon Detectors Calibration

Calibration: lower



Silicon Detectors Calibration

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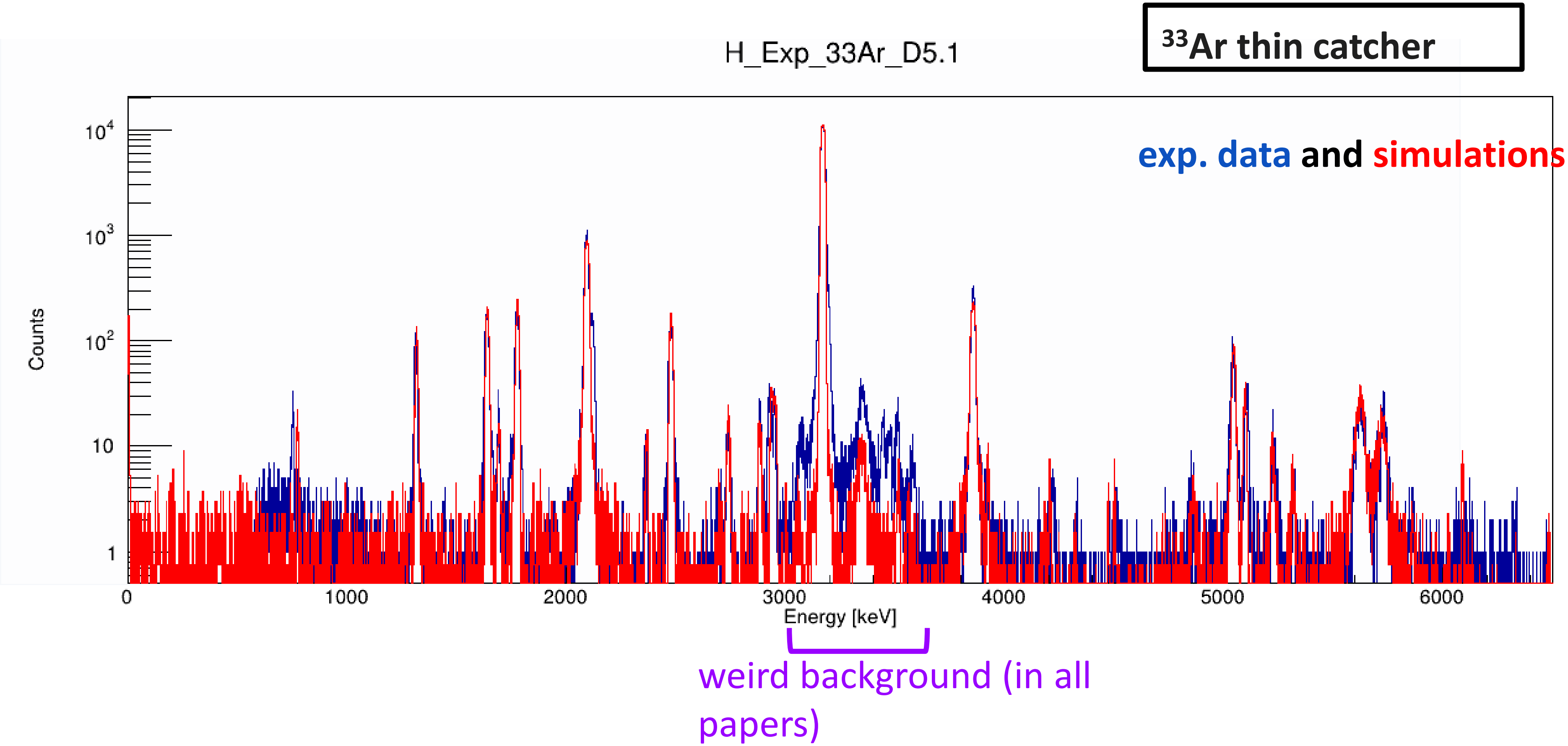


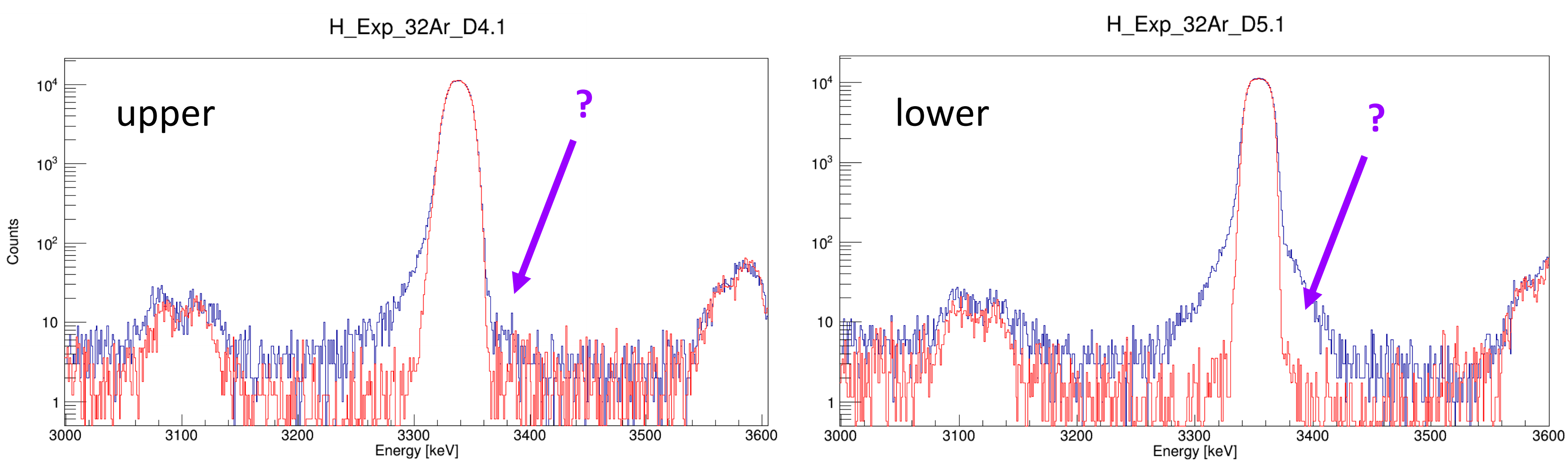
Silicon Detectors Calibration

Peak shape:

Simulation convoluted with a Gaussian: $\sigma = a + b\sqrt{E}$

^{32}Ar thin catcher

proper case calibration



exp. data and simulations

Silicon Detectors Calibration

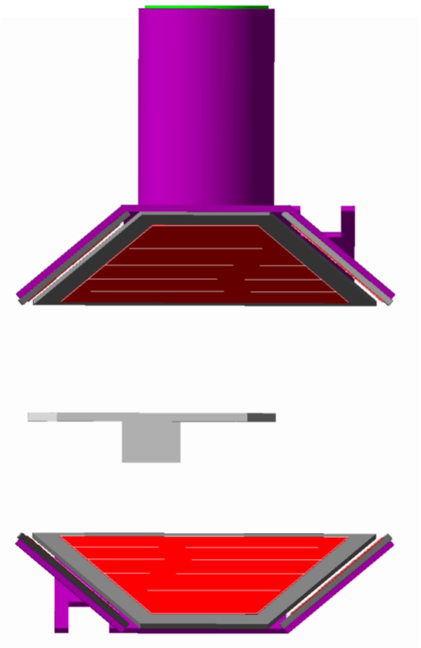
Peak shape:

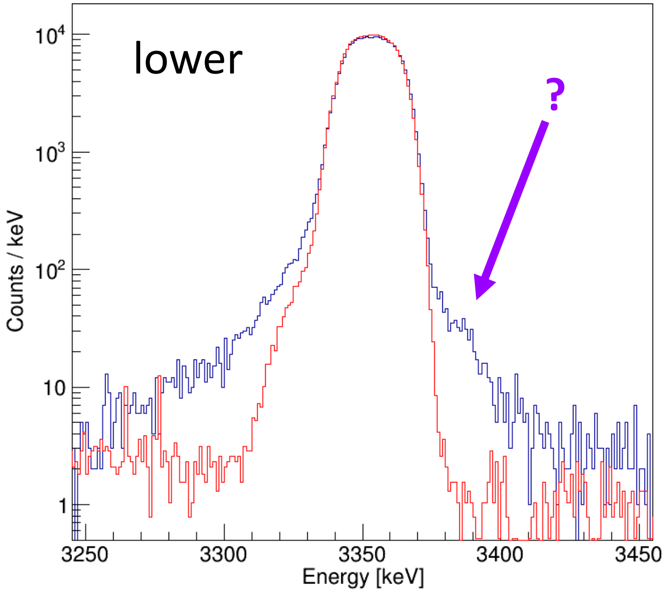
Simulation convoluted with a Gaussian : $\sigma = a + b\sqrt{E}$

^{32}Ar thin catcher

proper case calibration

- x detector behavior
- x in-flight emission
- x backscattered ion
- x beta pile-up
- x scintillation photon
- x X-ray pile-up



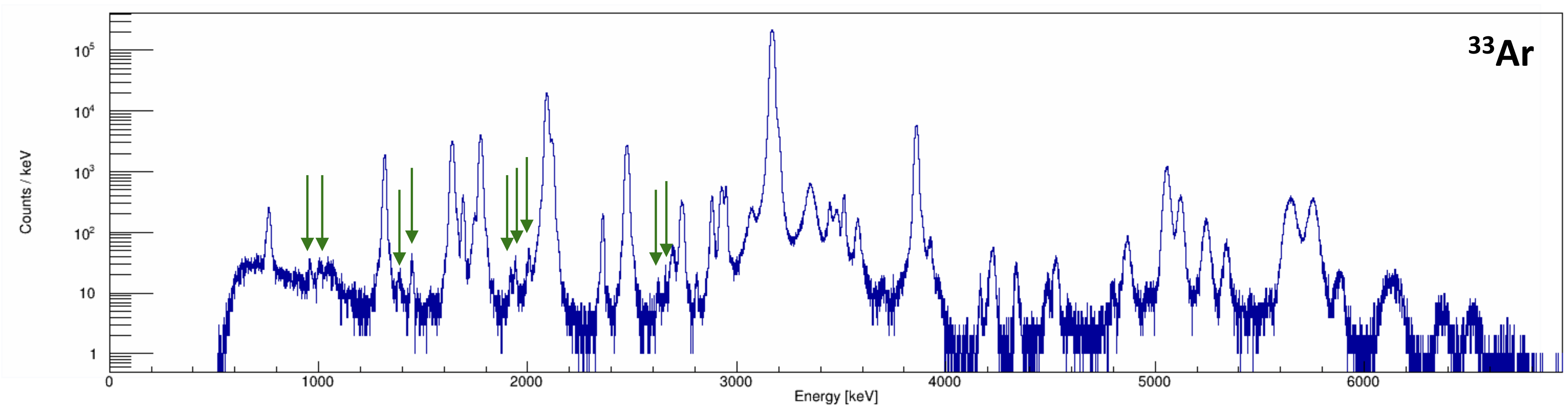


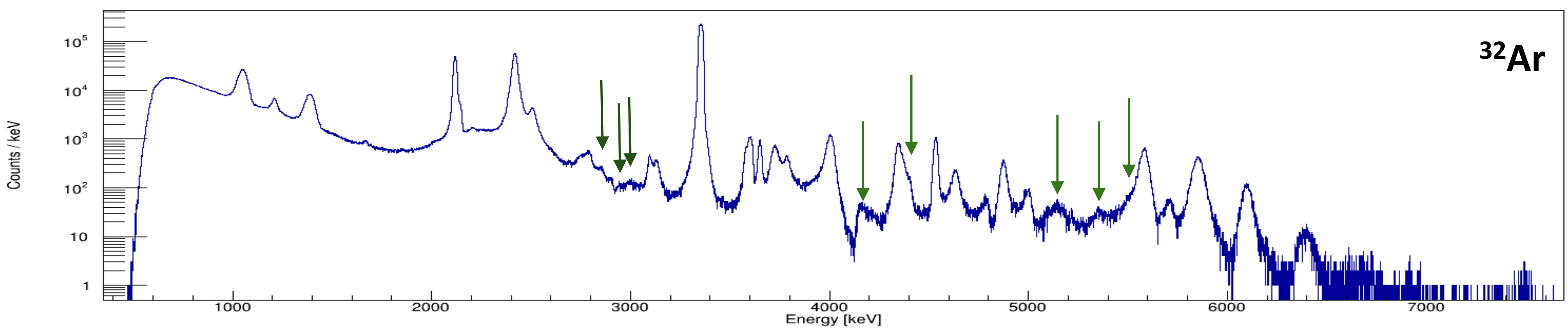
exp. data and simulations

Idea ?

Silicon Detectors Calibration

New peaks?



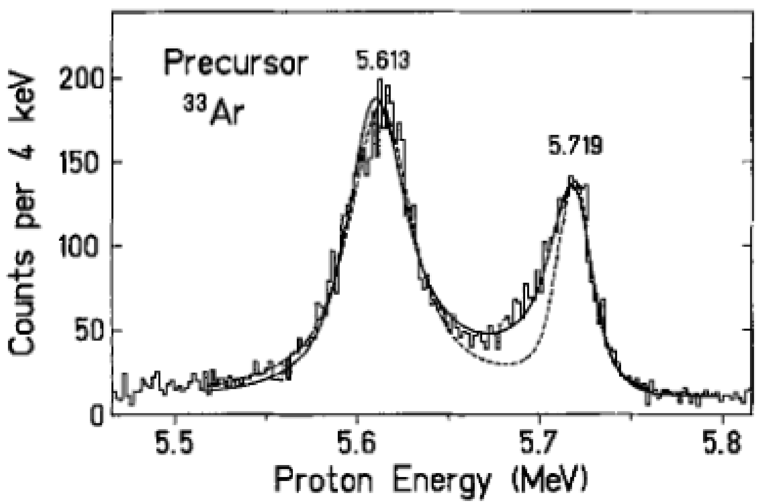


Proton peak shapes in silicon detectors

Interferences:

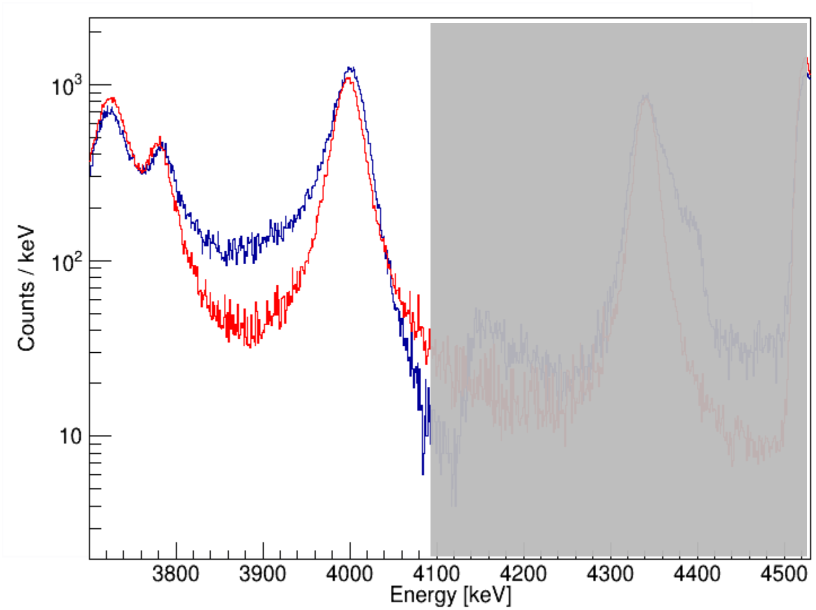
Nuclear level interference: R-matrix needed

Example from Literture



Z. Phys. A 345, 265-271 (1993)

Needed in my simulation

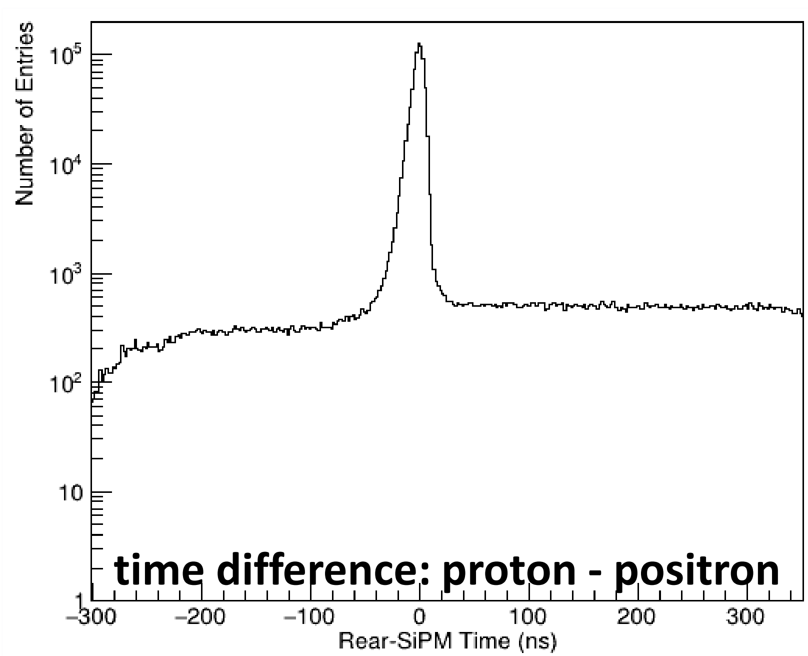


Random proton - positron coincidences

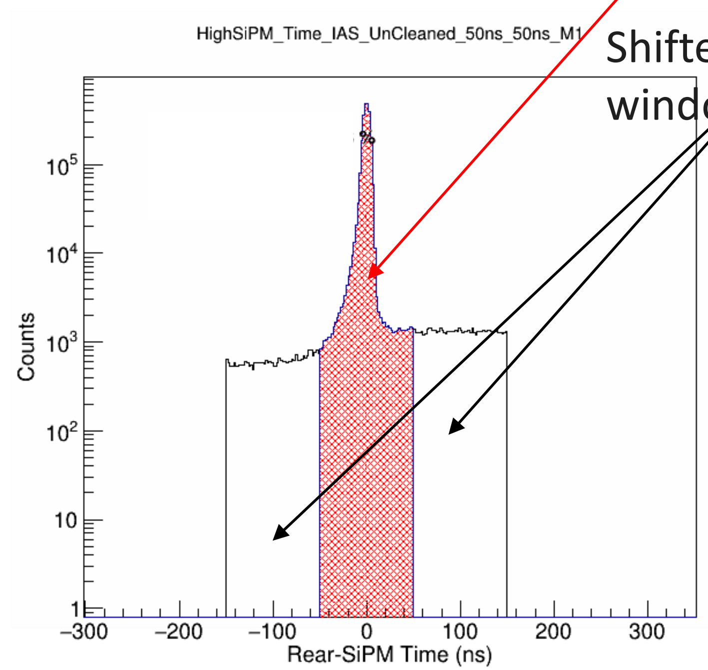
Cleaning data: Coincidence time window

run 114

random events for IAS:



Coincidence time window



Shifted time window

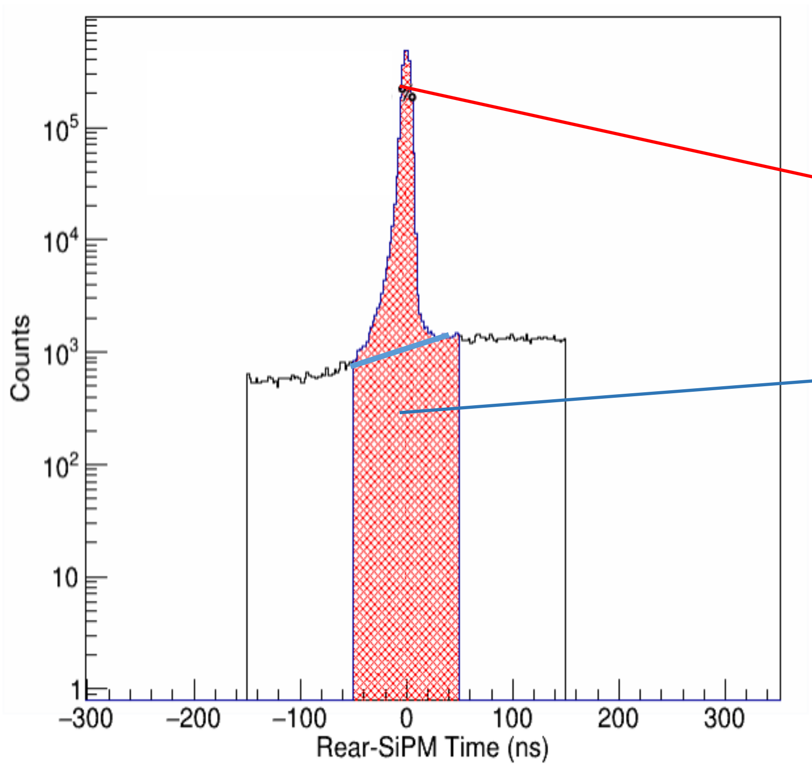
0.5% random coincidences?

Random proton - positron coincidences

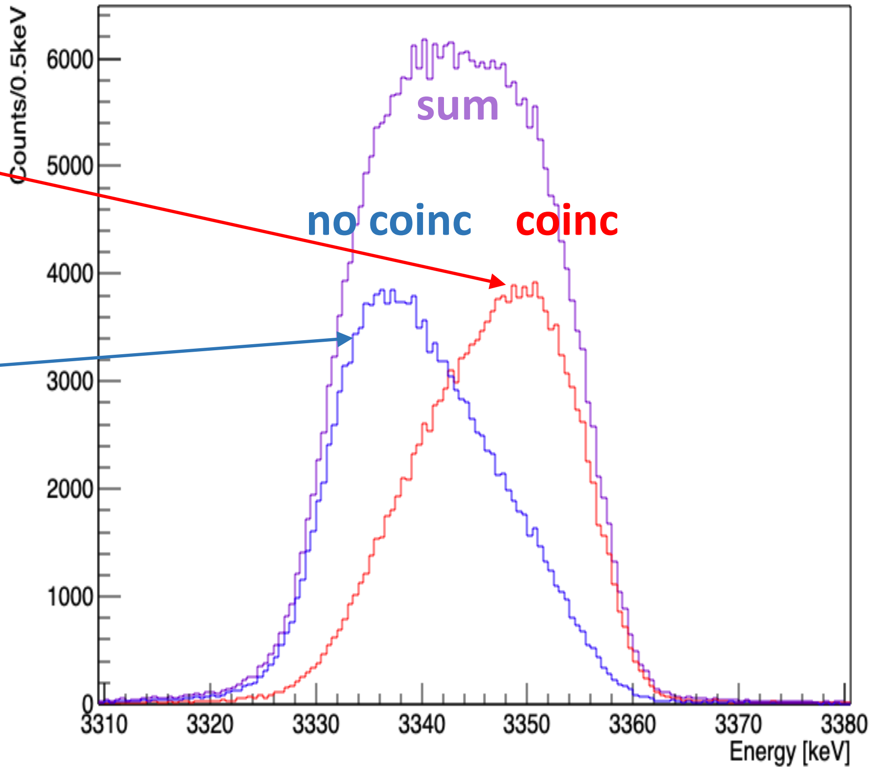
Cleaning data: Coincidence time window

run 114

random events for IAS:



lower proton detector:



- real coincidence in "red" peak
- random coincidence also in "red" peak, but should be in "blue" peak
- remove random rate (0.5%) with "blue" shape from "red" peak

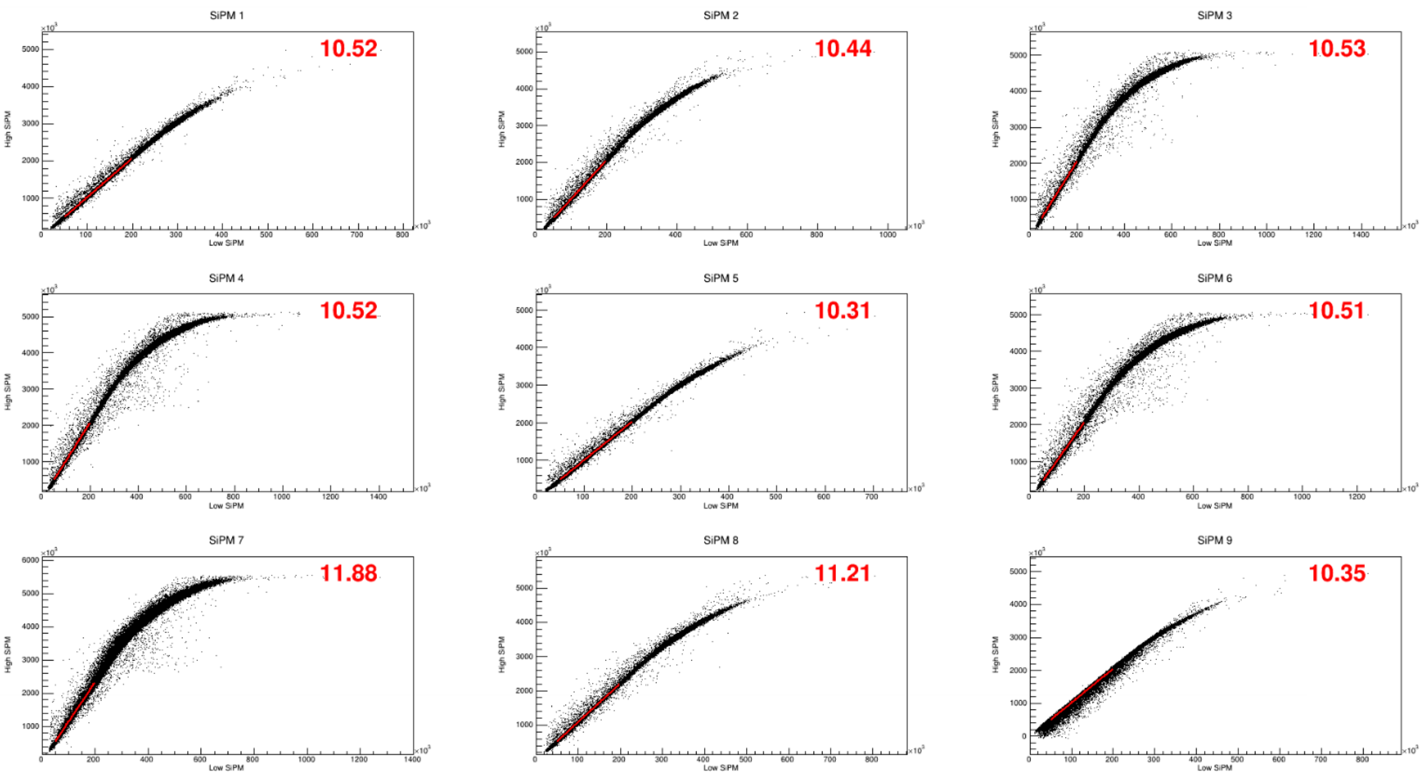
➔➔ no (or very small) systematic error

SiPMs Detectors Calibration

Gain: Low/High

^{32}Ar

Fitted Function: **High = a*Low + b**



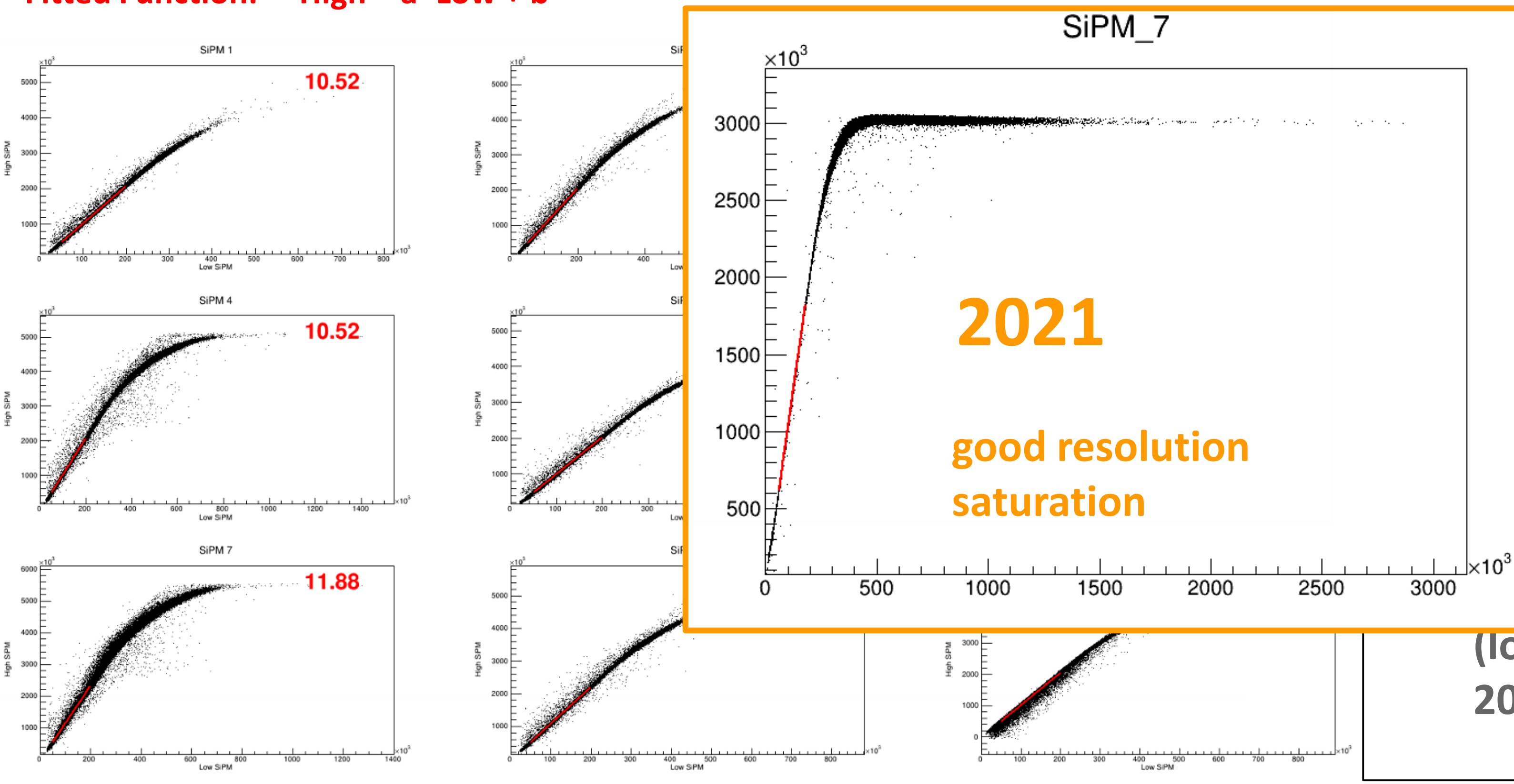
Comments:

- Almost factor of 10 for all
- No saturation (lower gain than 2021)

SiPMs Detectors Calibration

Gain: Low/High

Fitted Function: High = a*Low + b



nts:

most factor of
for all

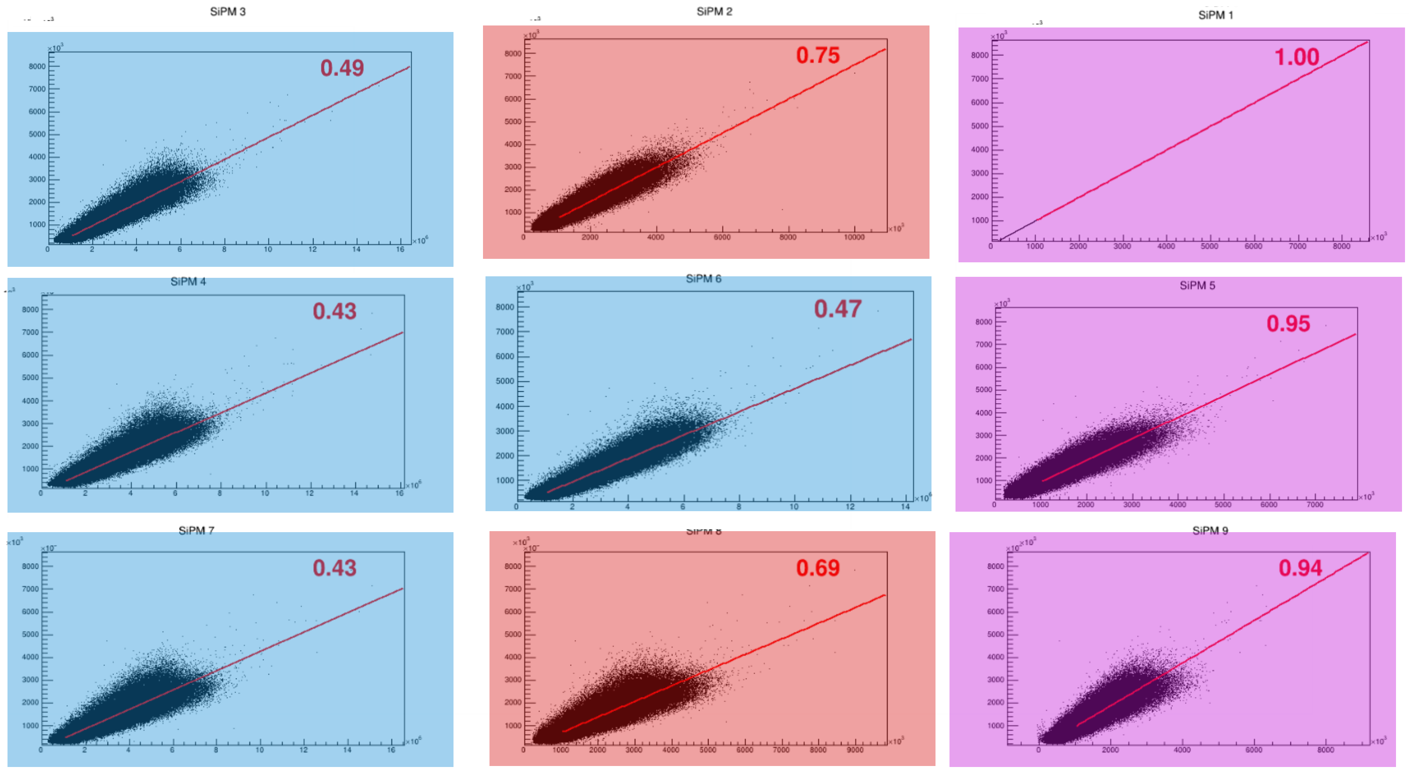
saturation
(lower gain than
2021)

SiPMs Detectors Calibration

Gain: SiPM Matching on SiPM 1

Hypothesis : All SiPMs collecting the same number of photon

Fitted Function: SiPM1 = a*SiPMx



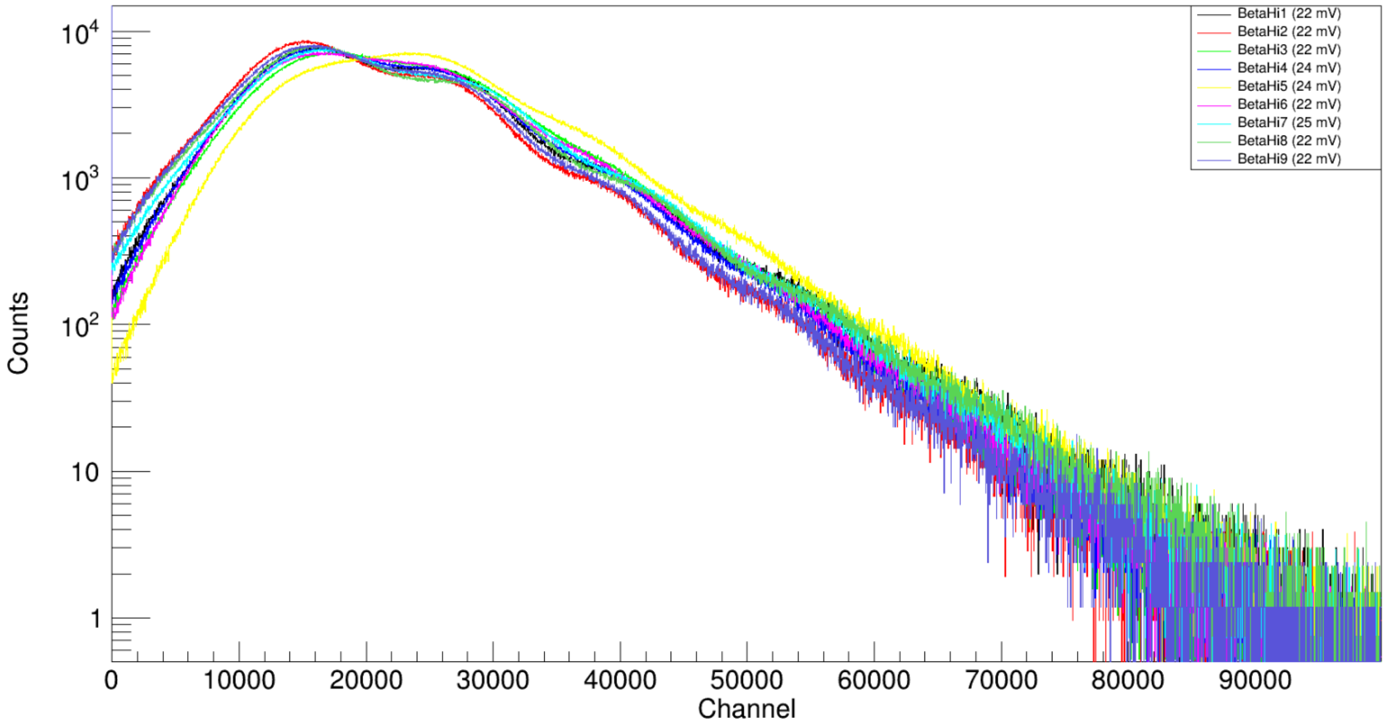
Comments:

- **"Group" of similar SiPM, ~0.5, ~0.7, ~0.9**

SiPMs Detectors Calibration

Gain: SiPM Matching on SiPM 1

Hypothesis : All SiPMs collecting the same number of photon



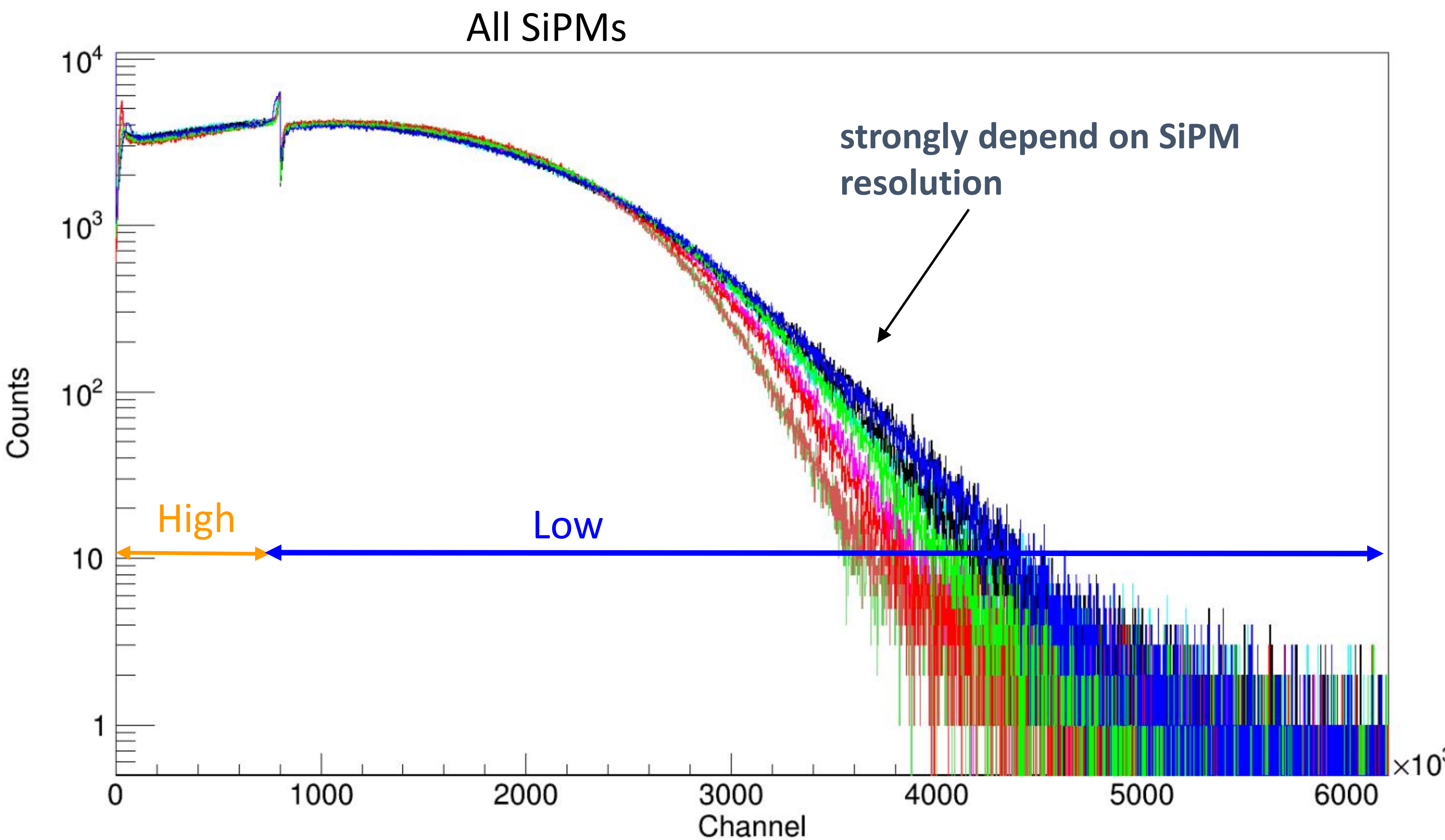
Comments:

- **All have the same gain**

SiPMs Detectors Calibration

Merging Low/High

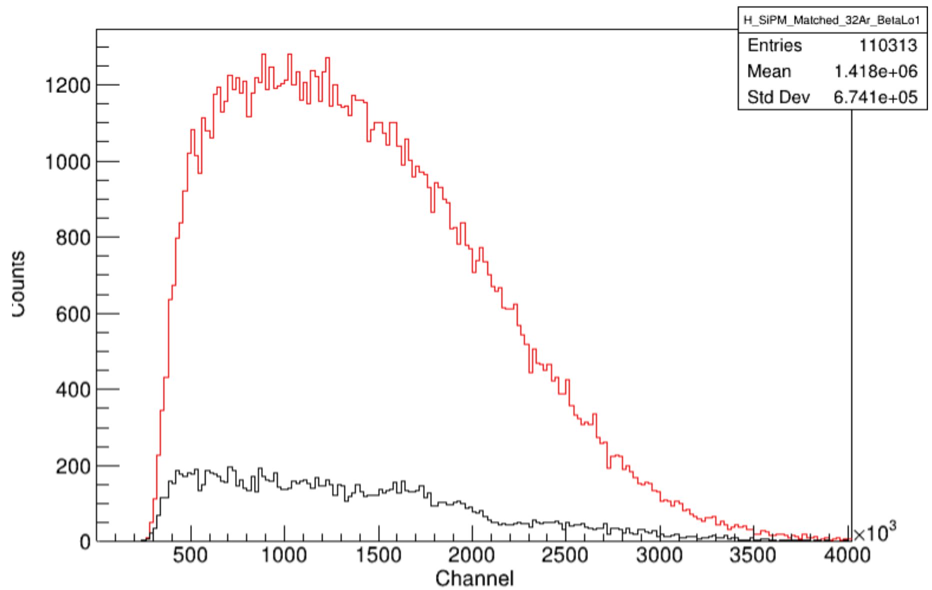
Matching Low/High + Matching SiPM



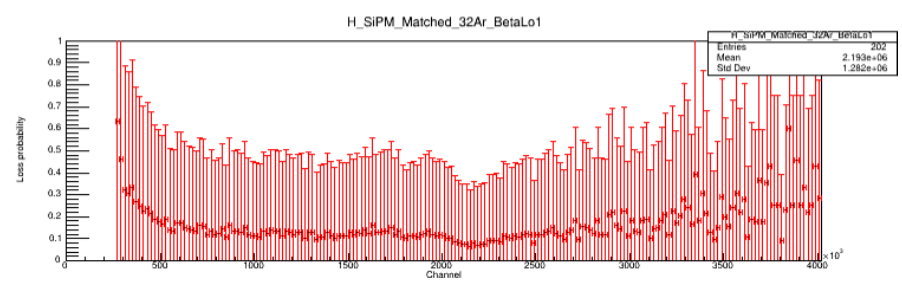
SiPMs Detectors Calibration

Losses: Low

The **red** distribution is all the counts recorded by the Low Gain SiPM 1.
The **black** distribution is all the counts recorded by the Low Gain SiPM 1 when no High Gain SiPM 1 is in the group.



This is the ratio bin per bin between the two distributions, given a “loss probability”.
Mean : 14%

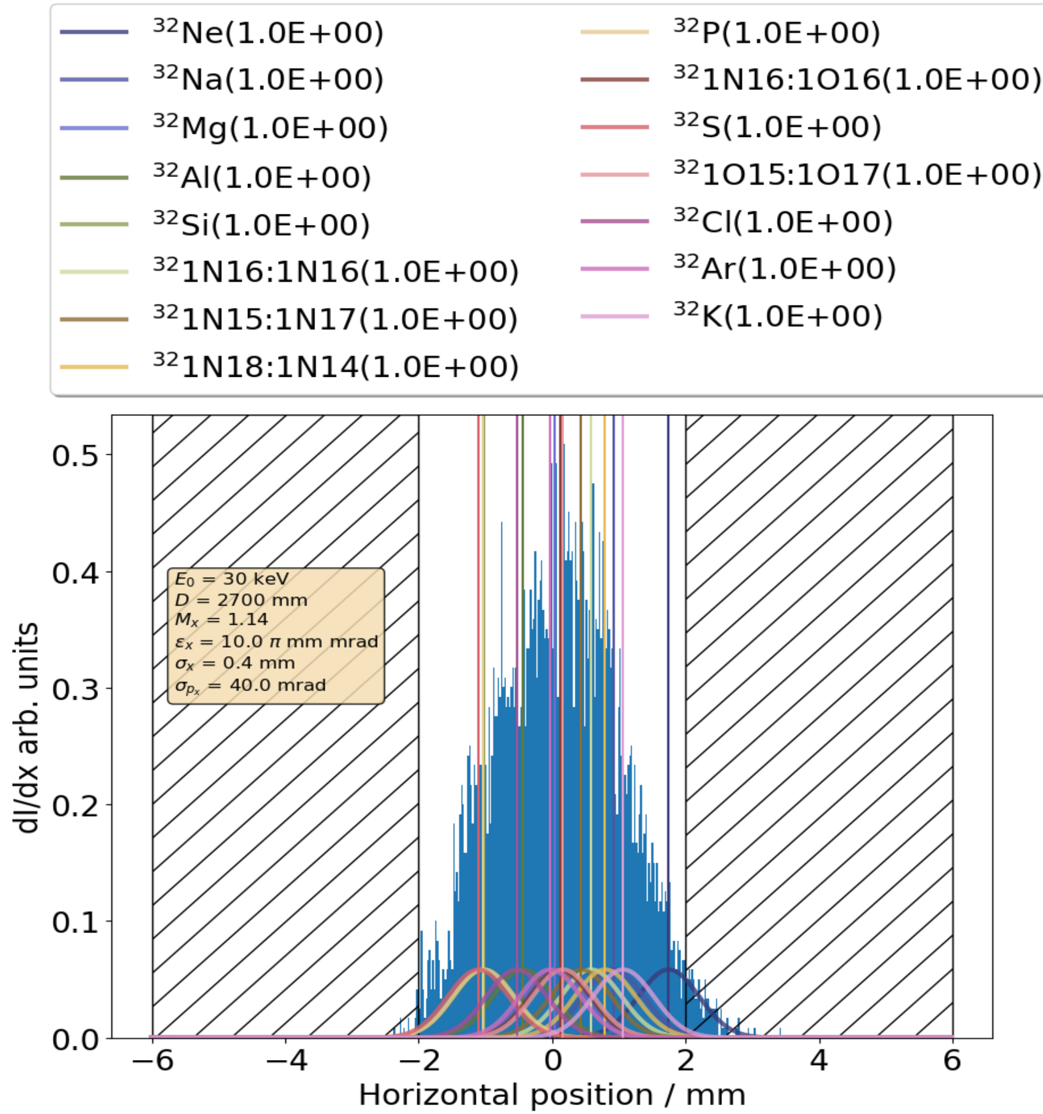


Contamination

Possibilities:

<u>Requirements:</u>

- **could be produced by CaO target**
- **ion or molecule of mass 32**



Dinko Atanasov

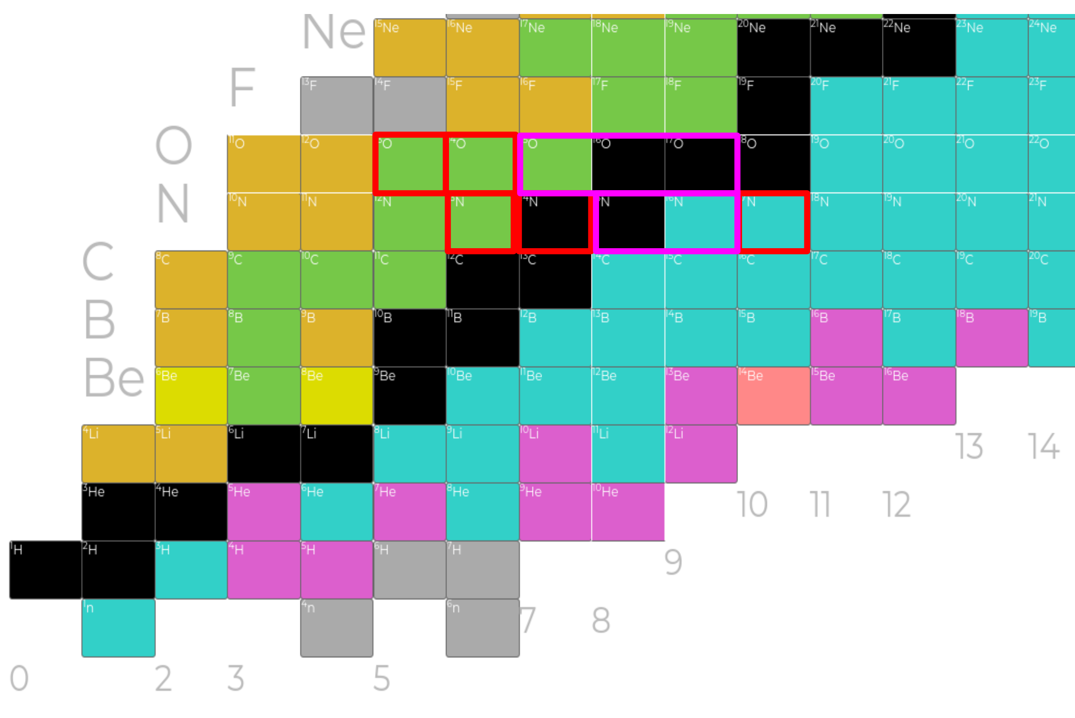
Contamination

Possibilities:

Requirements:
- Could be produced by CaO target
- Ion or molecule of mass 32
- Radioactive

β decay:
- $^{16}N^{16}N$: half life = 7s
- $^{14}O^{18}O$: half life = 70s and stable
- $^{15}O^{17}O$: half life = 4s and stable
- $^{16}N^{16}O$: half life = 7s and stable

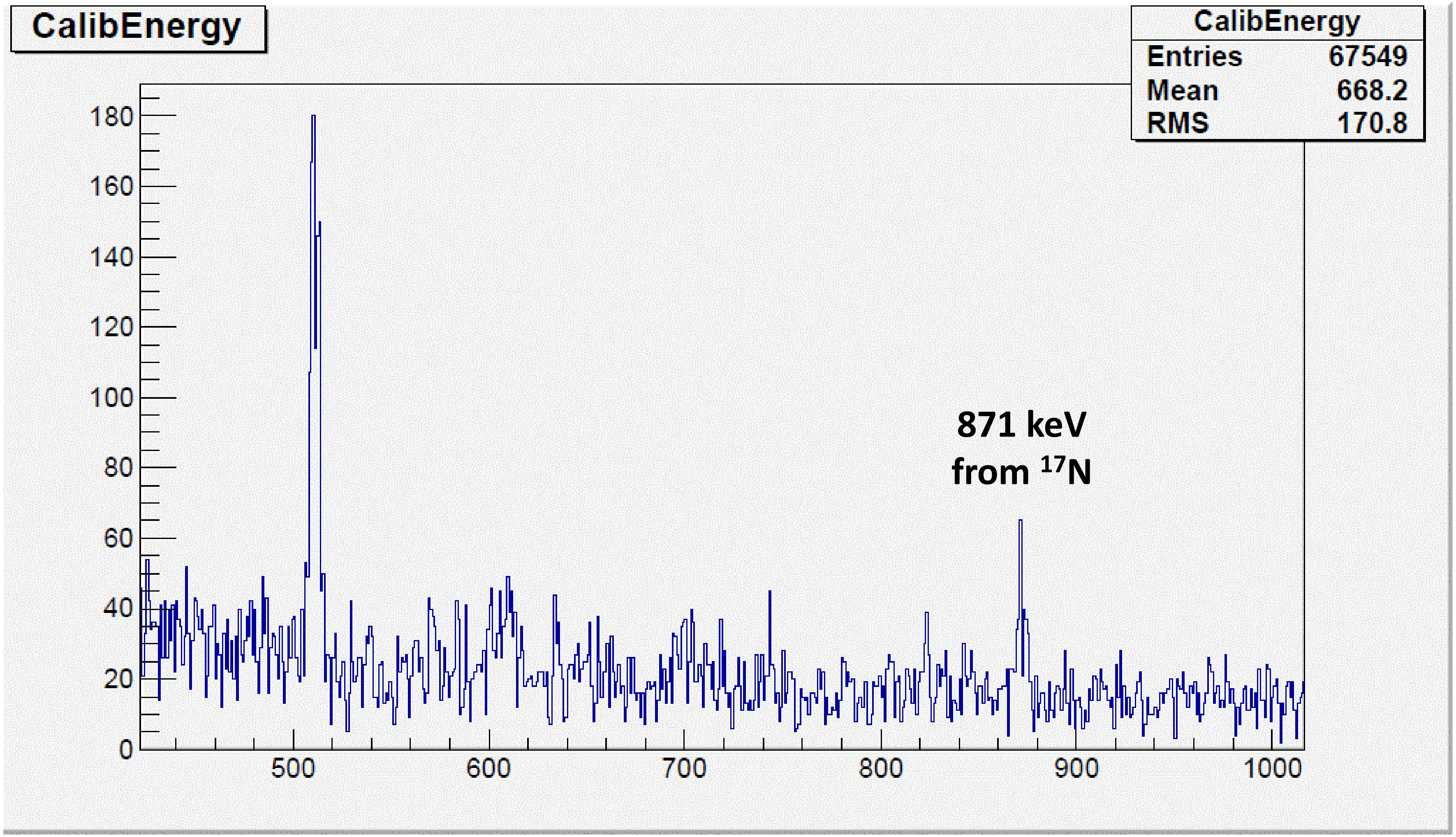
β-α decay:
- $^{18}N^{14}O$: half life = 0.6s and 70s
- $^{18}N^{14}N$: half life = 0.6s and stable
- $^{17}N^{15}O$: half life = 112s and 4s
- $^{17}N^{15}N$: half life = 4s and stable



Clearly identified: ^{17}N, ^{18}N; not seen: $^{14}0$; difficult to identify: ^{15}O,^{16}N

Contamination

Indication of ^{17}N:



➔➔ **seen also with α particles**

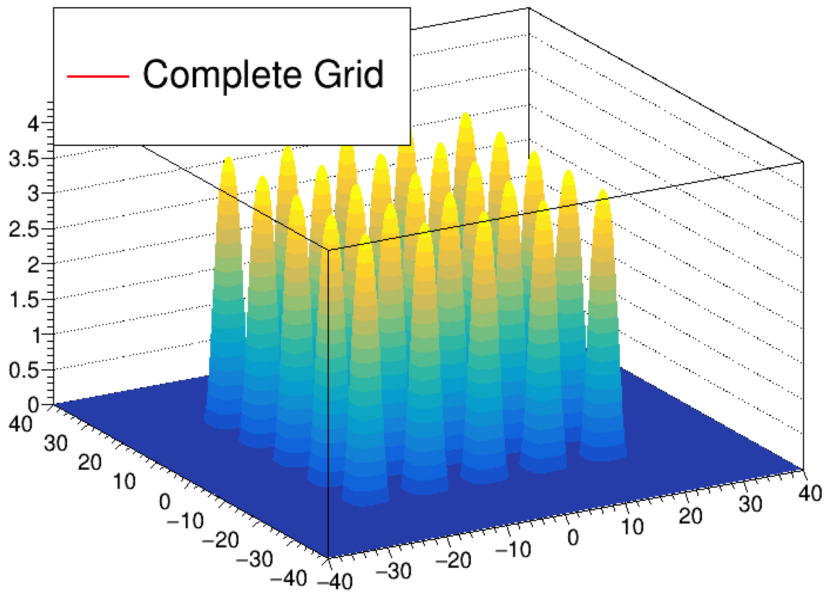
Reconstruction and Calibration

Method 2: Full function fit

$$F(x,y) = A\Sigma_i\Sigma_j\left[erf\left(\frac{x-\mu_{xij}+l/2}{\sqrt{2}\sigma_x}\right) - erf\left(\frac{x-\mu_{xij}-l/2}{\sqrt{2}\sigma_x}\right) + erf\left(\frac{y-\mu_{yij}+l/2}{\sqrt{2}\sigma_y}\right) - erf\left(\frac{y-\mu_{yij}-l/2}{\sqrt{2}\sigma_y}\right)\right]$$

Function component :

- ➔ **grid**
- ➔ **resolution**
- ➔ **circle edge**



Parameters :

- A **: cell amplitude**
- (μ_{xij}, μ_{yij}) **: cell ij center**
- l **: cell width**
- σ_x, σ_y **: MCP resolution**

Reconstruction and Calibration

Method 2: Full function fit

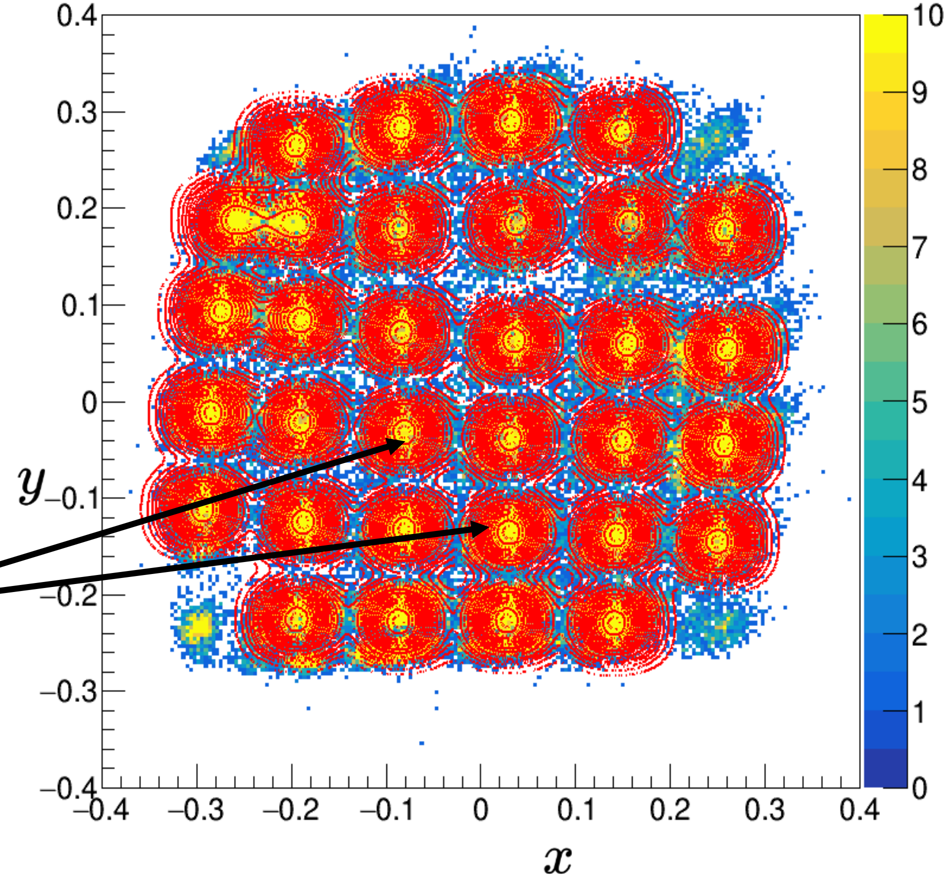
Function component :

- ➔ **grid**
- ➔ **resolution**
- ➔ **circle edge**

fitted position

(X, Y) ← (x, y)

real position

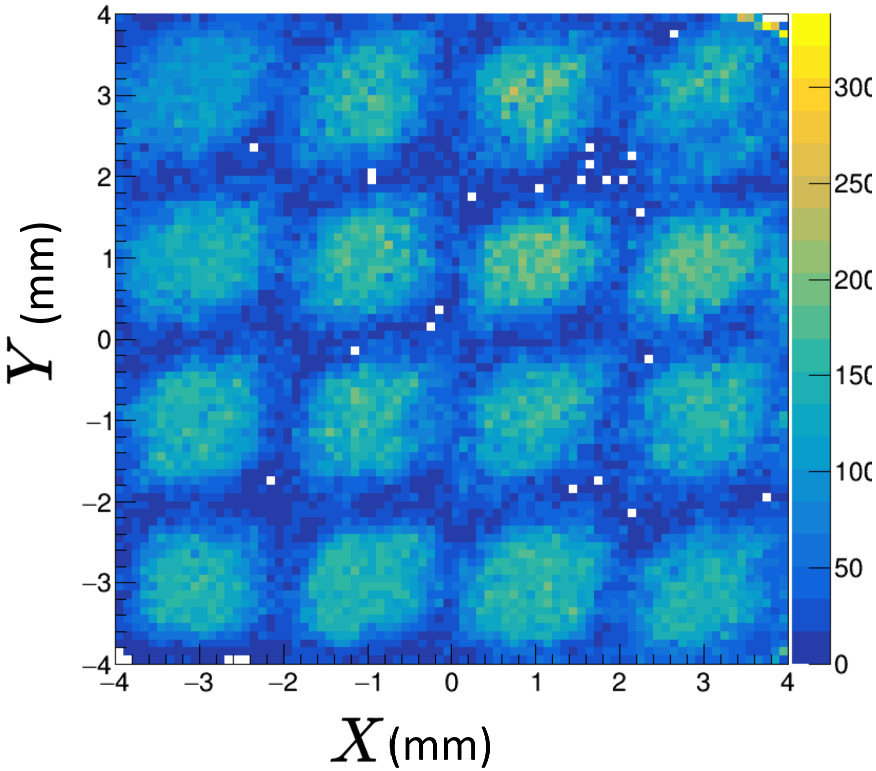


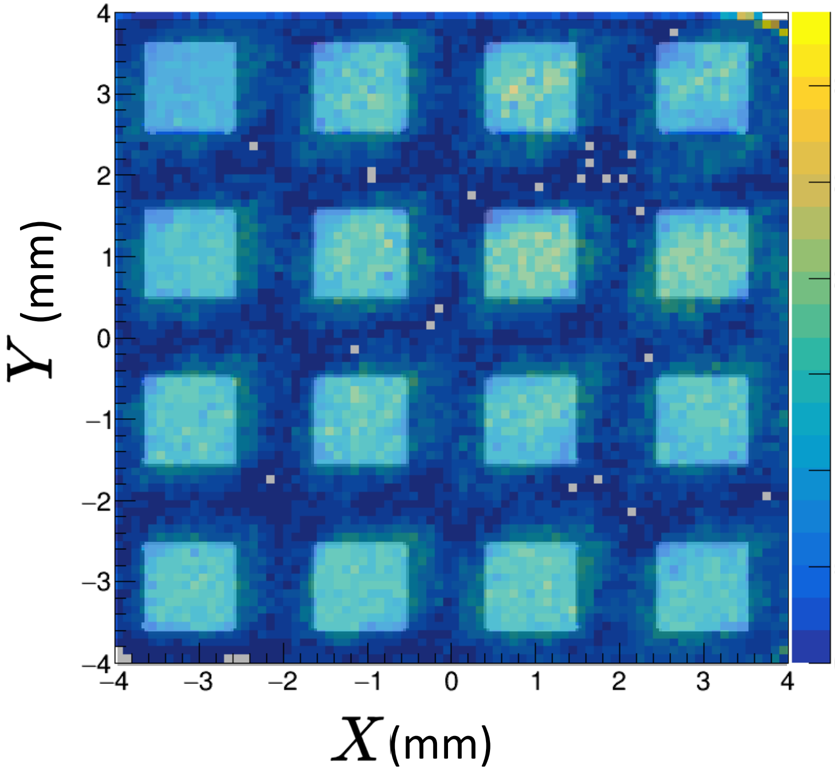
Reconstruction and Calibration

Method 2: Full function fit

Function component :

- ➔ **grid**
- ➔ **resolution**
- ➔ circle edge

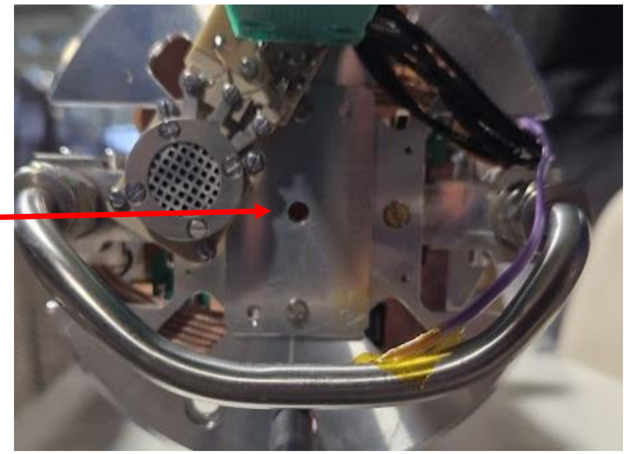


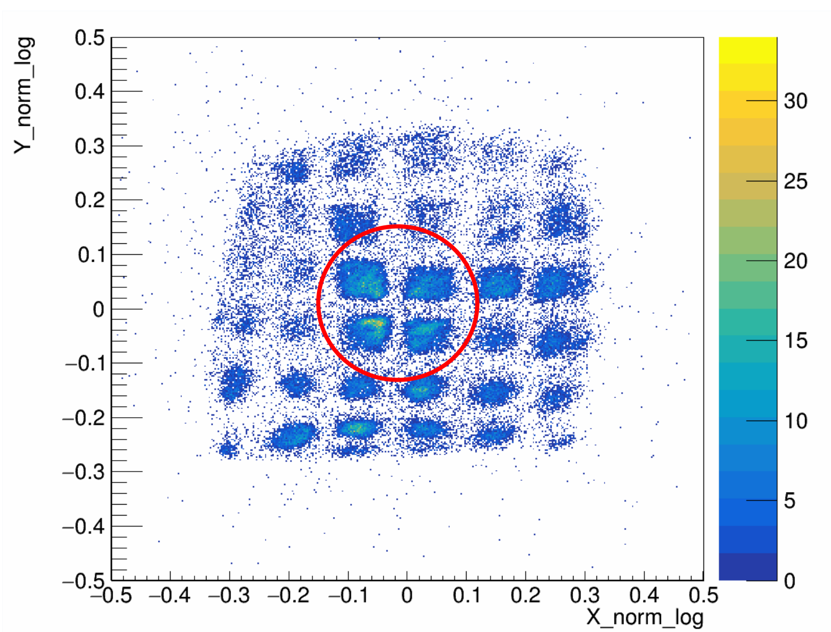


Beam size

Measurement: MCP_010_4T_0001.fast

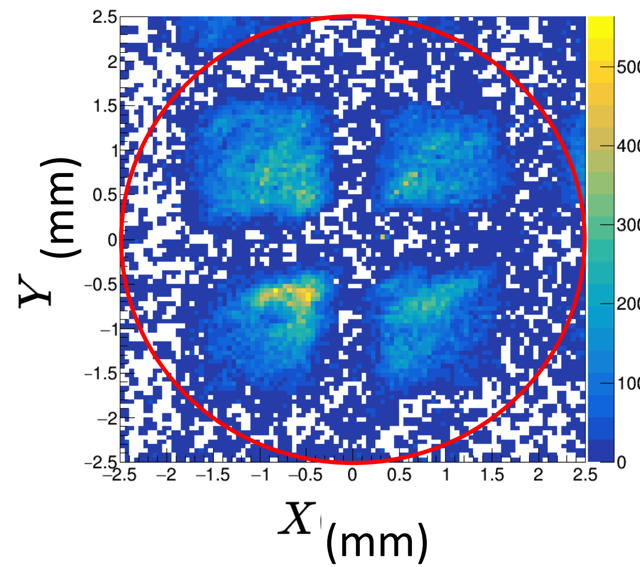
ROI : collimator (⌀=5 mm)





$$X(x,y) = \Sigma_i \Sigma_j a_{ij} x^i y^j$$
$$Y(x,y) = \Sigma_i \Sigma_j b_{ij} x^i y^j$$

(using the previous fit for reconstruction)

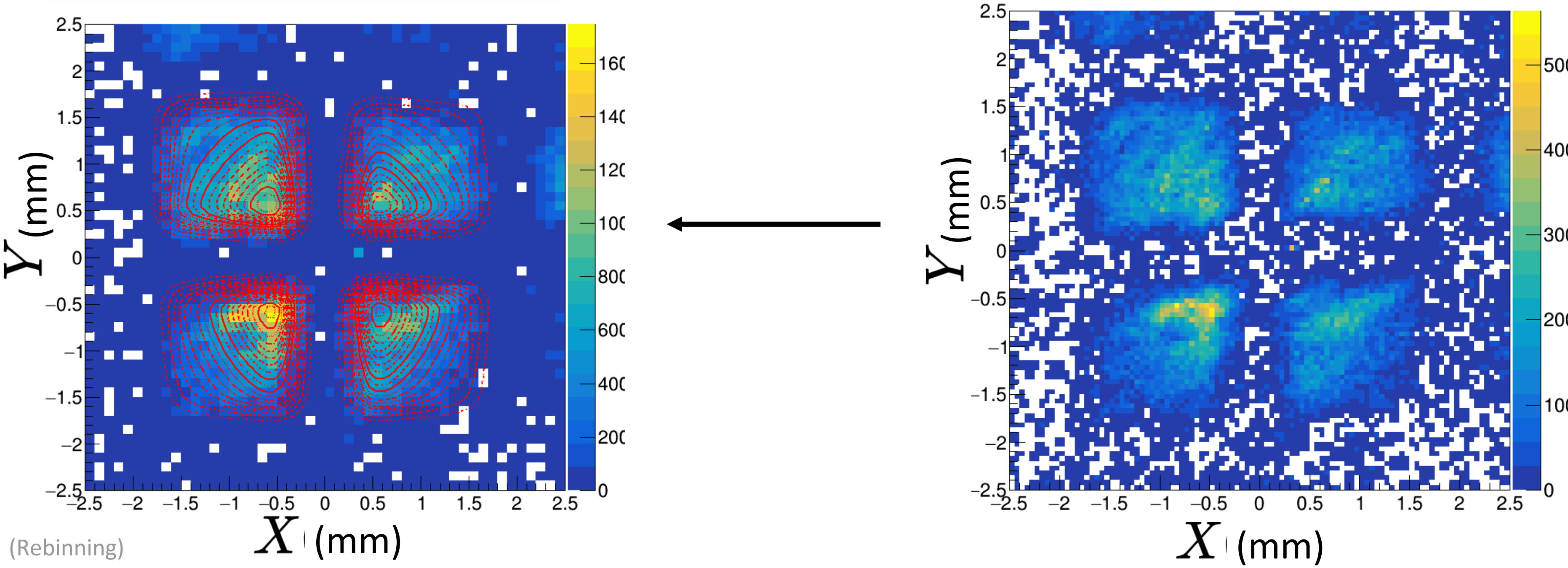


Beam size

Measurement: MCP_010_4T_0001.fast

Fitting function:

- **Grid function →** $F(x, y)$
- **Beam → Gaussian 2D**



β-decay probability

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + \boxed{a} \frac{\mathbf{p_e} \cdot \mathbf{p}_\nu}{E_e E_\nu} + \boxed{b} \frac{m_e}{E_e} + \underbrace{\frac{<\mathbf{J}>}{J} \cdot \left[\boxed{A} \frac{\mathbf{p_e}}{E_e} + (\boxed{B} + b_B \frac{m_e}{E_e}) \frac{\mathbf{p}_\nu}{E_\nu} + \boxed{D} \frac{\mathbf{p_e} \times \mathbf{p}_\nu}{E_e E_\nu} \right]}_{\text{for aligned spins only}} \right\} \ldots$$

β–ν correlation coefficient
CP conserving

Fierz interference term
CP conserving

β-asymmetry parameter
P violating

ν-asymmetry parameter
P violating

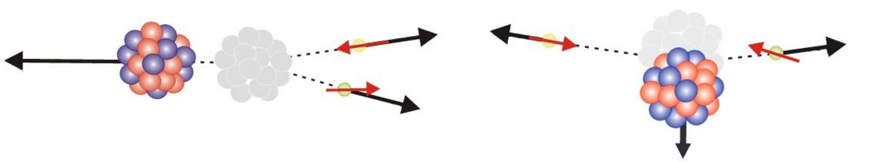
« D » coefficient
CP violating

for aligned spins only

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a \frac{\mathbf{p_e} \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right\}$$

pure Fermi transitions ΔJ=0

➪ S=0 : spin of leptons anti-parallel



SM: vector current

- Preferred emission angle: θ = 0°
- Maximum recoil energy

NP: scalar current

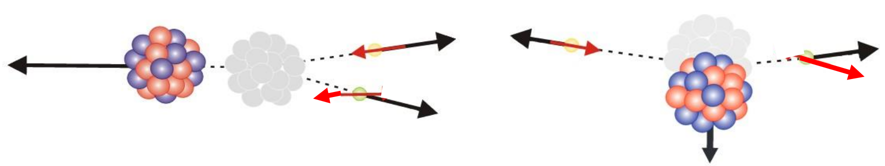
- Preferred emission angle: θ = 180°
- Minimum recoil energy

$$a^F_{\beta\nu} \cong 1 - \cancel{\frac{|C_S|^2 + |C'_S|^2}{C_V^2}}$$

$$b^F_{\beta\nu} \cong \pm Re\,(\cancel{\frac{C_S + C'_S}{C_V}})$$

pure Gamow-Teller transitions

➪ S=1 : spin of leptons parallel



NP: tensor current

- Preferred emission angle: θ = 0°
- Maximum recoil energy

SM: axial-vector current

- Preferred emission angle: θ = 180°
- Minimum recoil energy

$$a^{GT}_{\beta\nu} \cong -\frac{1}{3}[1 - \cancel{\frac{|C_T|^2 + |C'_T|^2}{C_A^2}}]$$

$$b^{GT}_{\beta\nu} \cong \pm Re\,(\cancel{\frac{C_T + C'_T}{C_A}})$$

First experiment: ISOLDE 1993

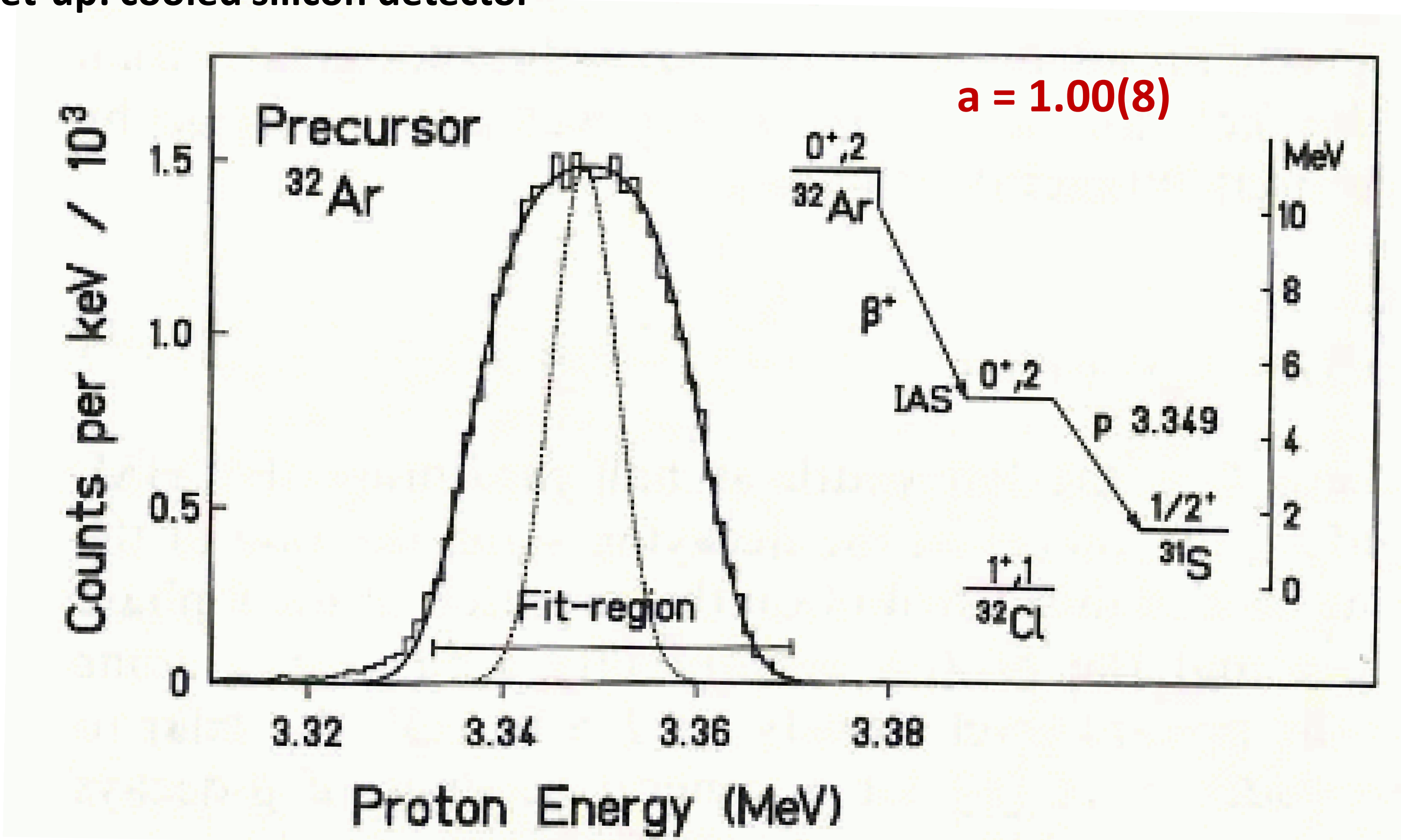
Beta-neutrino recoil broadening in β-delayed proton emission of ^{32}Ar and ^{33}Ar

D. Schardt[1], K. Riisager[2]

[1] GSI, Postfach 110552, W-6100 Darmstadt 11, Germany
[2] Institute of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

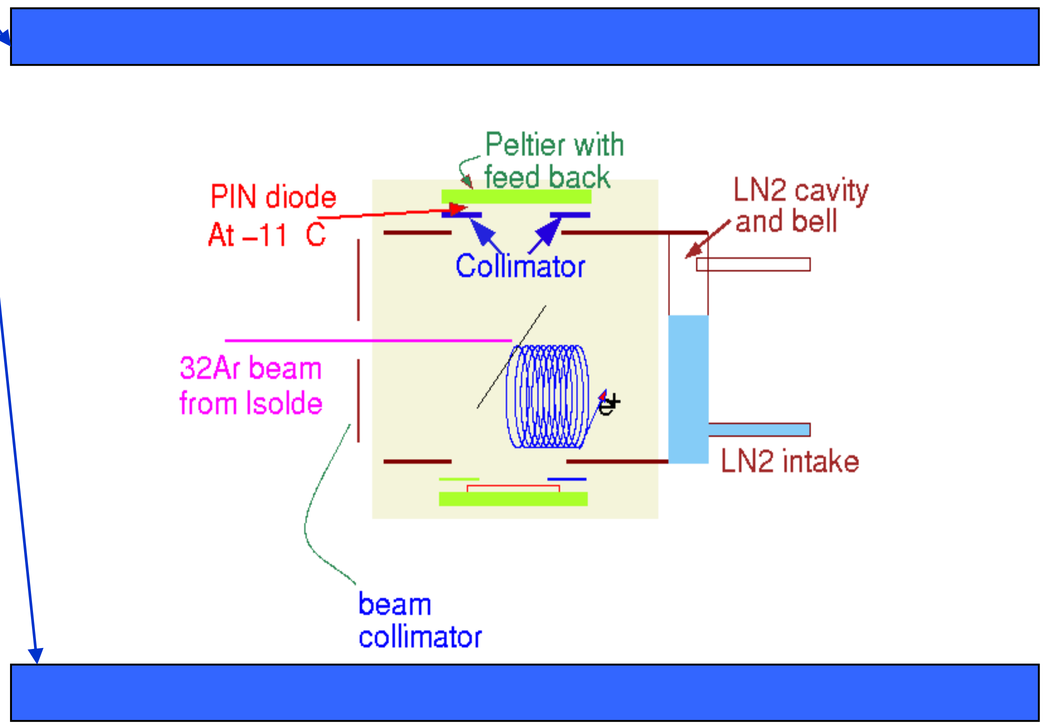
ZPA 345 (1993) 265

Set-up: cooled silicon detector

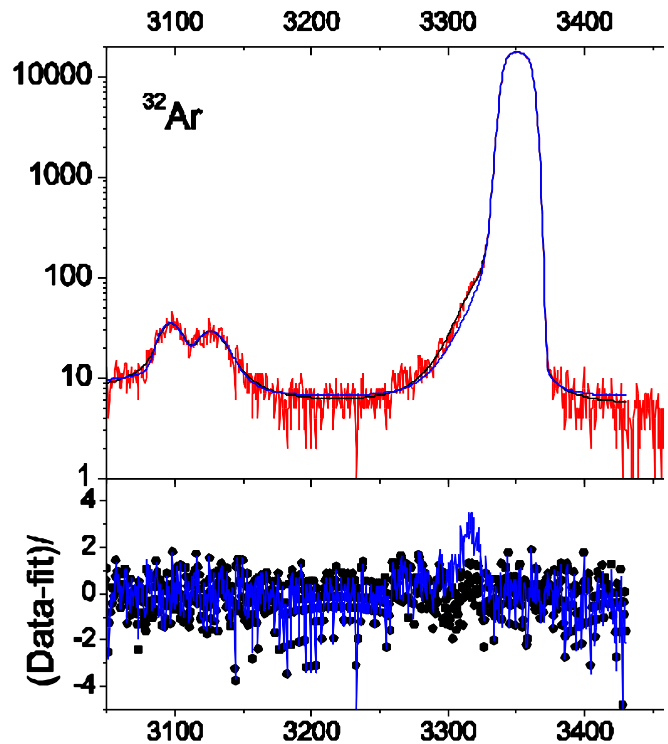


Second experiment: ISOLDE 1999

Super-conducting solenoid
B=3.5 Tesla



cooled detectors

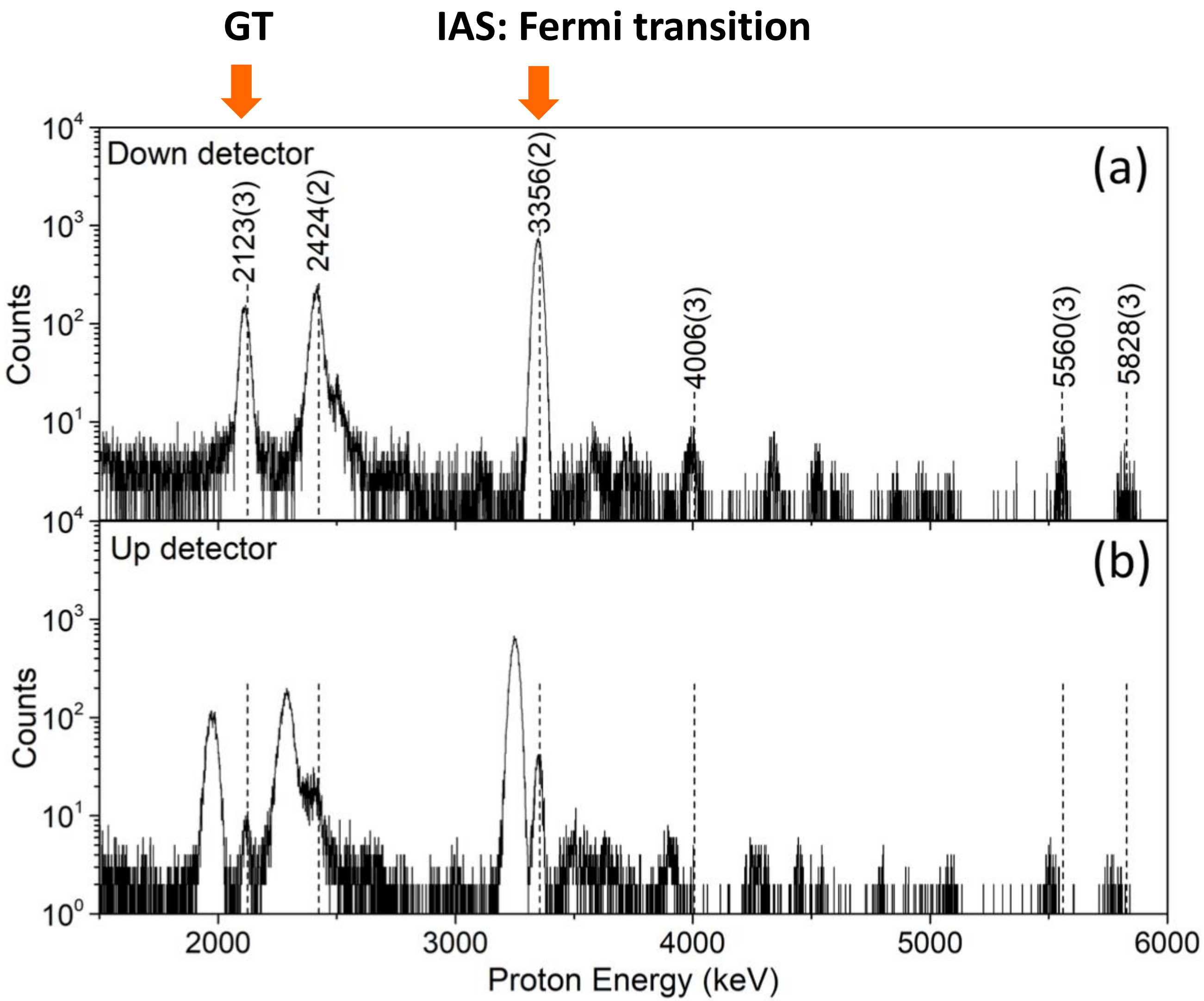


Result:
ã=0.9989(65)

E. G. Adelberger et al., PRL 83 (1999) 1299
A. Garcia et al., Hyperfine Interact. 129 (2000) 237

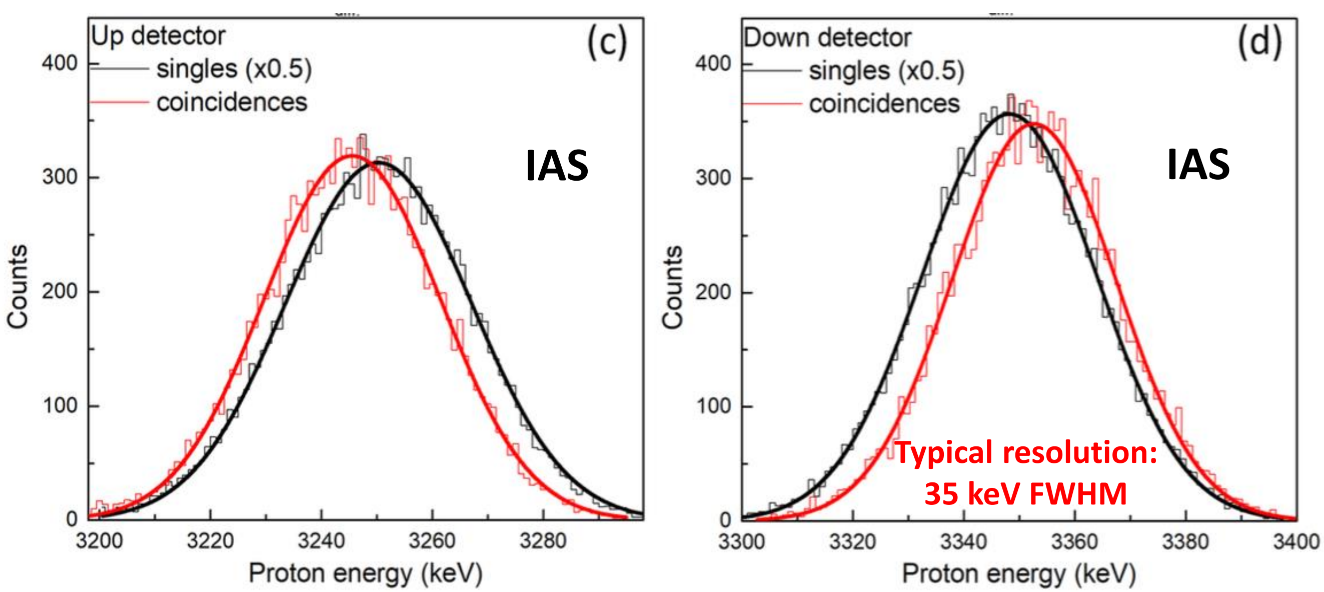
The WISArD experiment: proof-of-principles (2018)

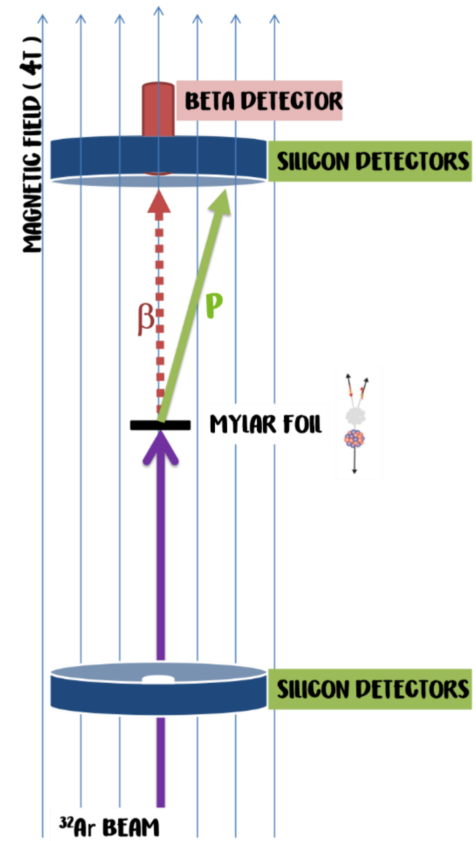
first results (nov. 2018): proton spectra



V. Araujo-Escalona et al, PRC 101 (2020) 055501

first results: (nov. 2018)





Average shift:
Δ = 4.49(3) keV

by means of GEANT4 MC calculations:

$$\tilde{a}_{\beta\nu}^{\mathrm{F}} = 1.01(3)_{(stat)}(2)_{(syst)} \qquad \tilde{a}_{\beta\nu}^{\mathrm{GT}} = -0.22(9)_{(stat)}(2)_{(syst)}$$

V. Araujo-Escalona et al, PRC 101 (2020) 055501

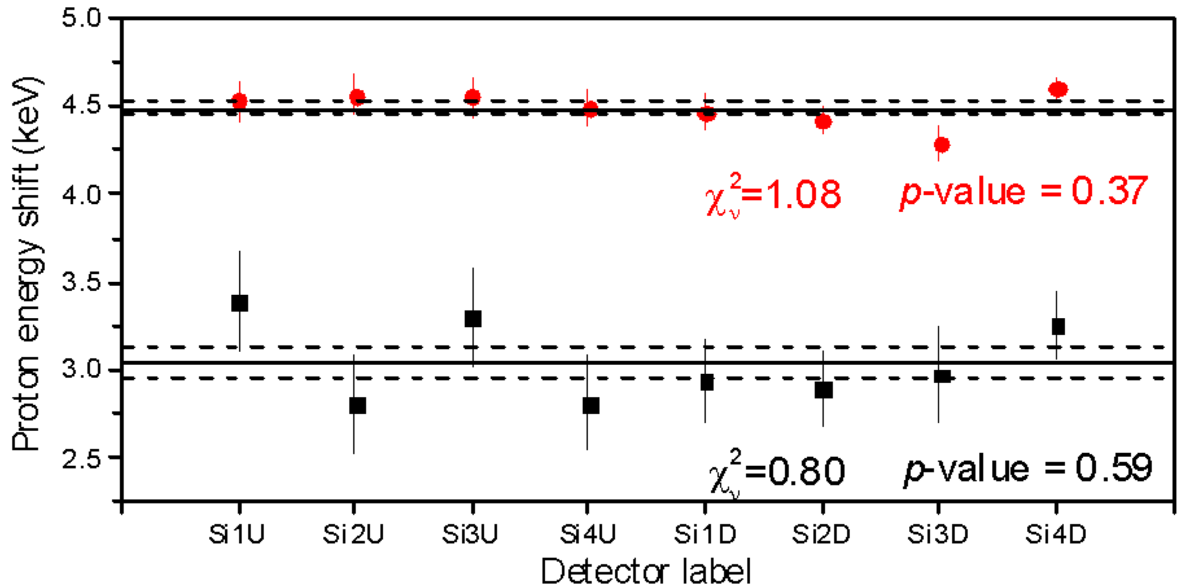
First WISArD experiment: results

Weighted average energy shifts

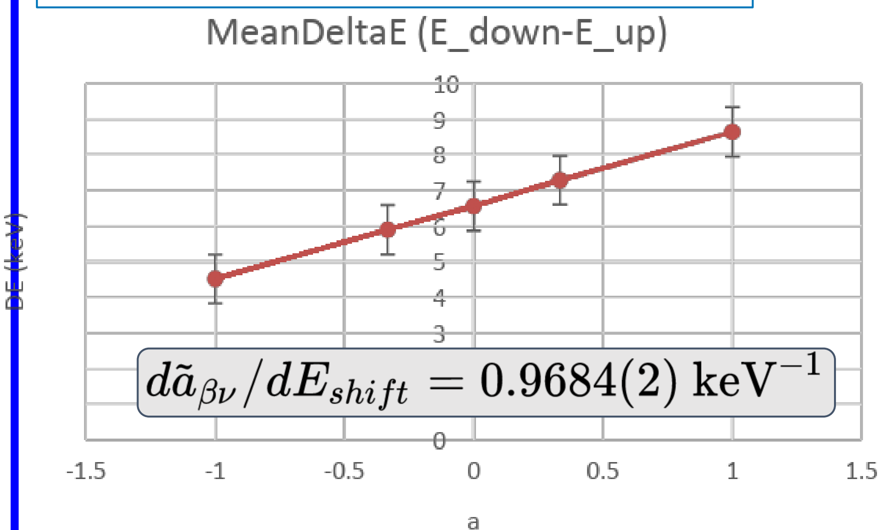
$$\Delta E = \left|\bar{E}_{coinc} - \bar{E}_{single}\right|$$

$$\Delta E_F = 4.49(3)\ keV$$

$$\Delta E_{GT} = 3.05(9)\ keV$$



Monte Carlo simulations



Extracted modified correlation β-υ

$$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$$

$$\tilde{a}_{GT} = -0.222(86)_{stat}(16)_{syst}$$

WISArD upgrades 2019 - 2021

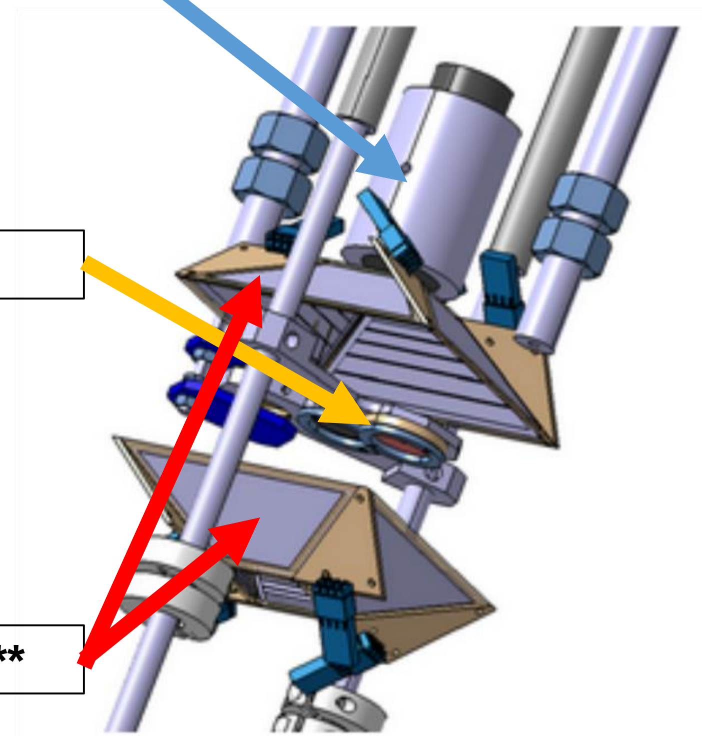
2018

2021

Beta detector* + SiPM

Catcher***

proton detectors planes**

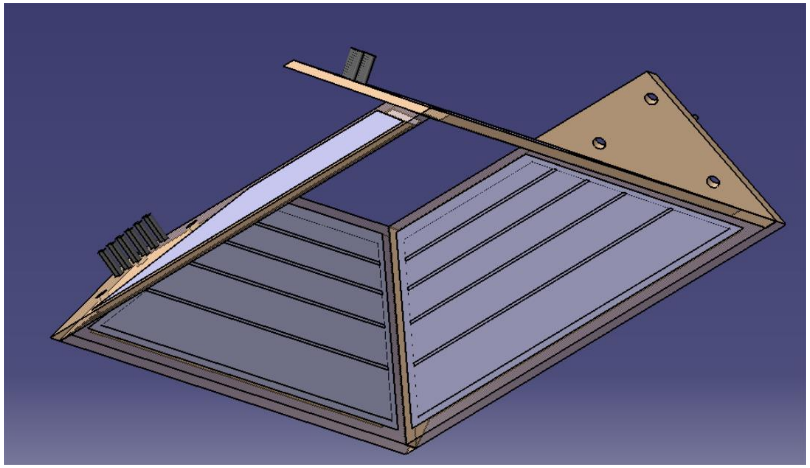


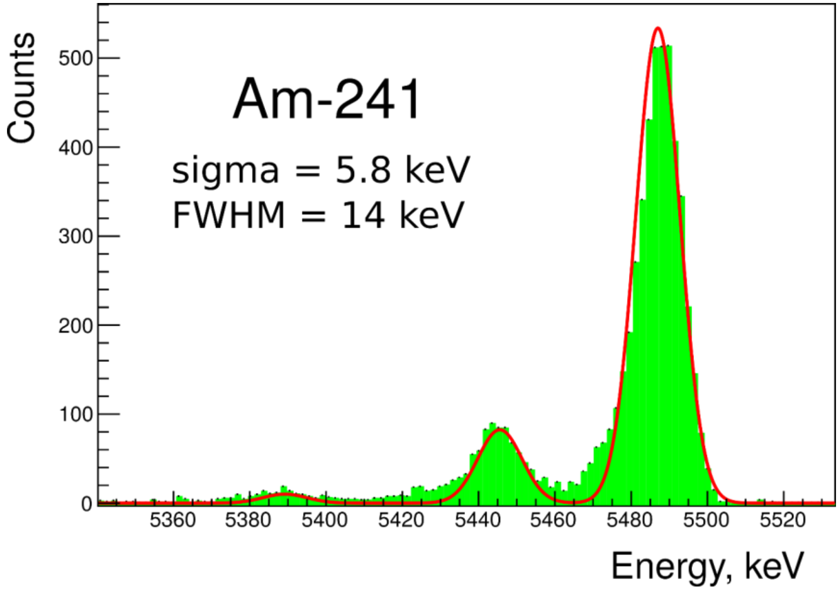
* Plastic scintillator;
** Silicon surface-barrier (thickness = 300 µm);
*** Aluminized Mylar (thickness = 6.7 µm)

* Plastic scintillator – EJ200;
** MICRON single-sided silicon-strip (thickness = 300 µm);
*** Aluminized Mylar (thickness = 0.5 µm)

WISArD upgrades 2019 – 2021: silicon detectors

- proton resolution 10-15 keV (FWHM)
- 8 segmented quadrants with 5 strips each
- improved geometry – solid angle 40%
- actively cooled to -30 °C



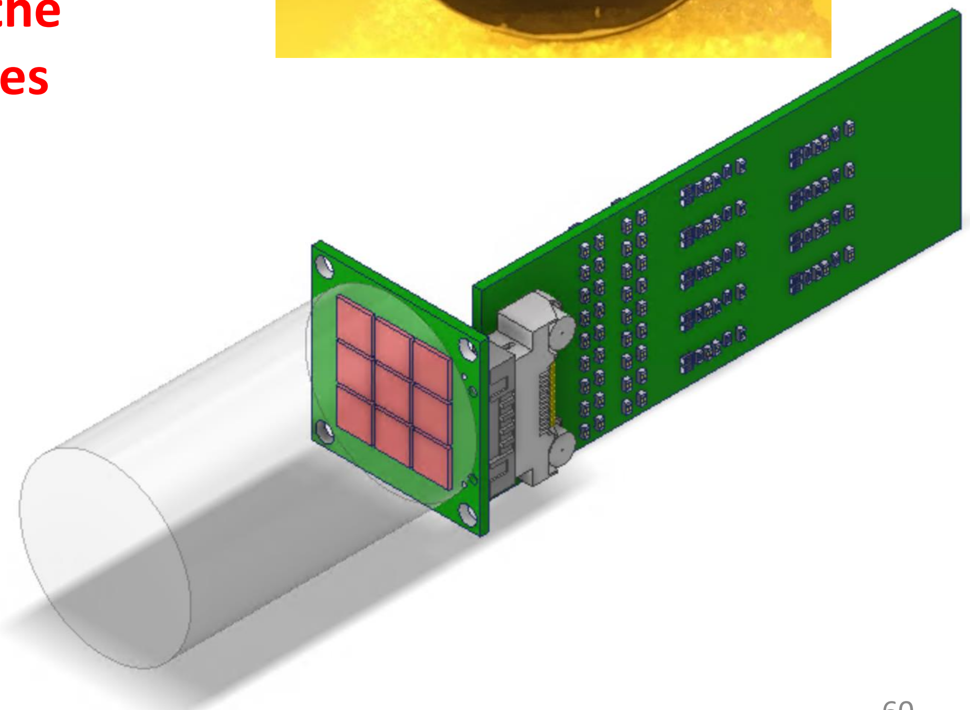


WISArD upgrades 2019 – 2021: plastic scintillator + 9 SiPM

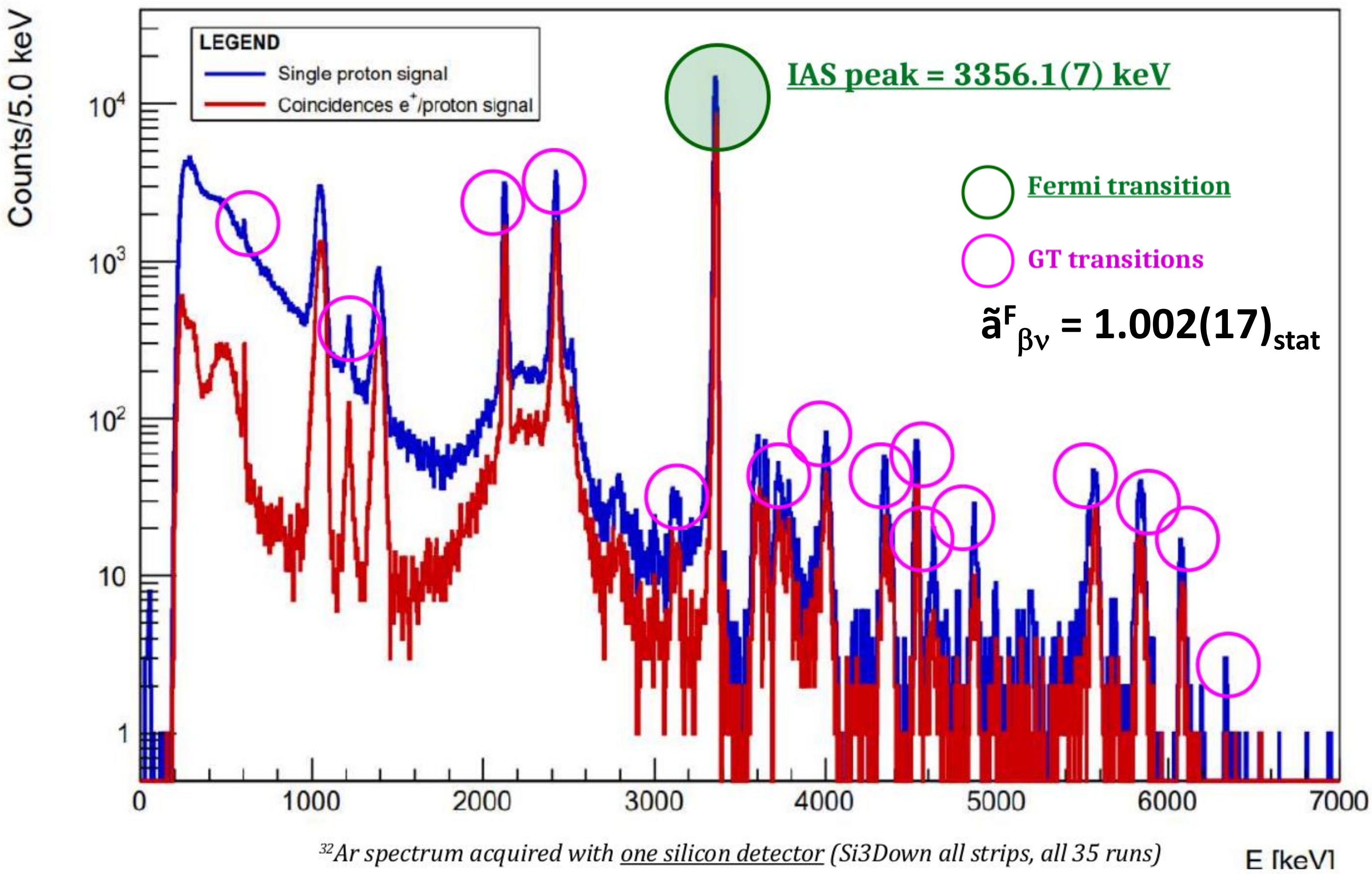
Plastic scintillator (EJ-200) polystyrene
+ 3x3 SiPM array

- **diameter = 30mm**
- **length = 50 mm (~10 MeV β)**
- **dual gain output available**

Improve S/N ratio by improving the collection efficiency + coincidences between SiPMs

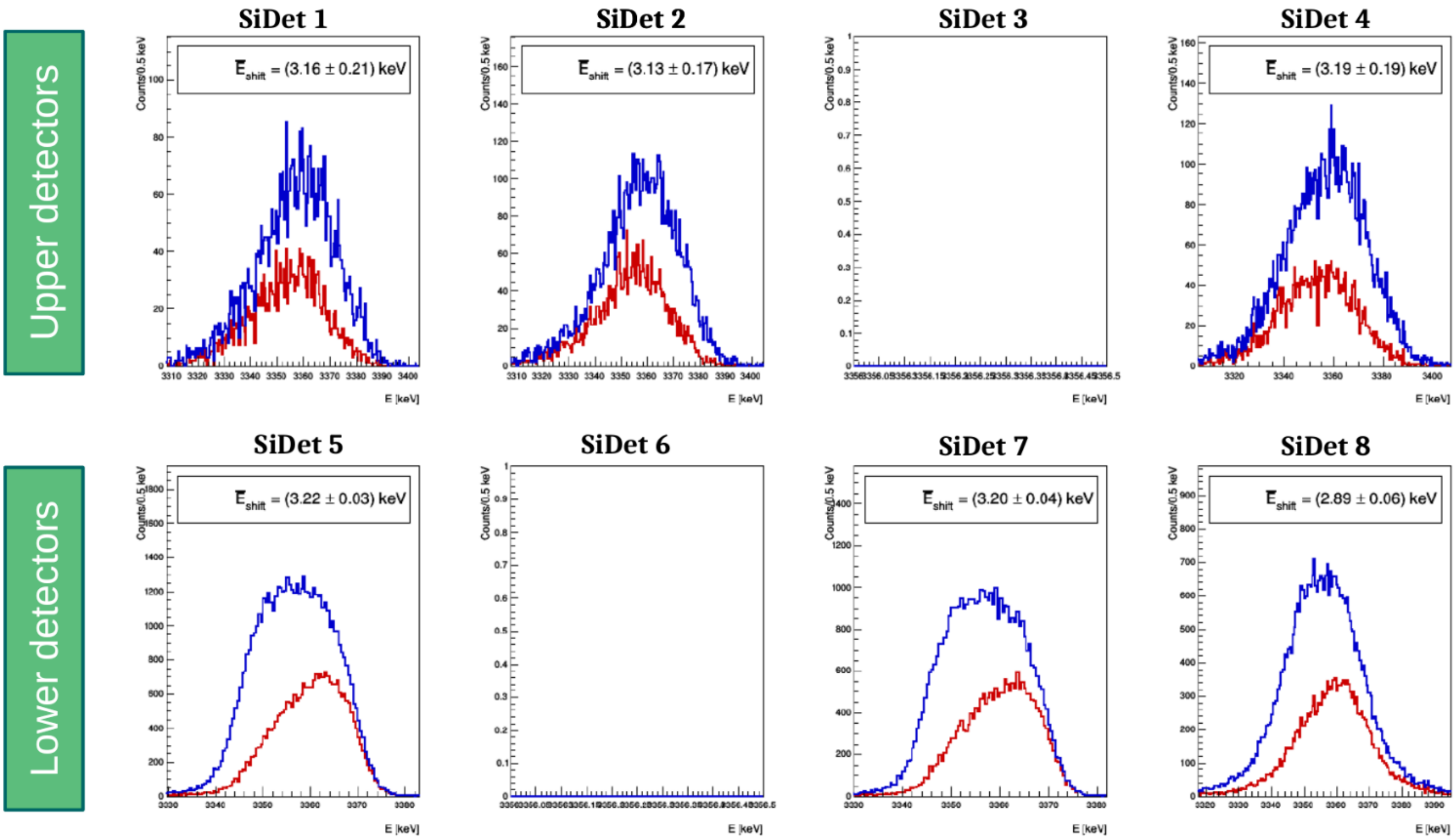


WISArD 2021 test experiment

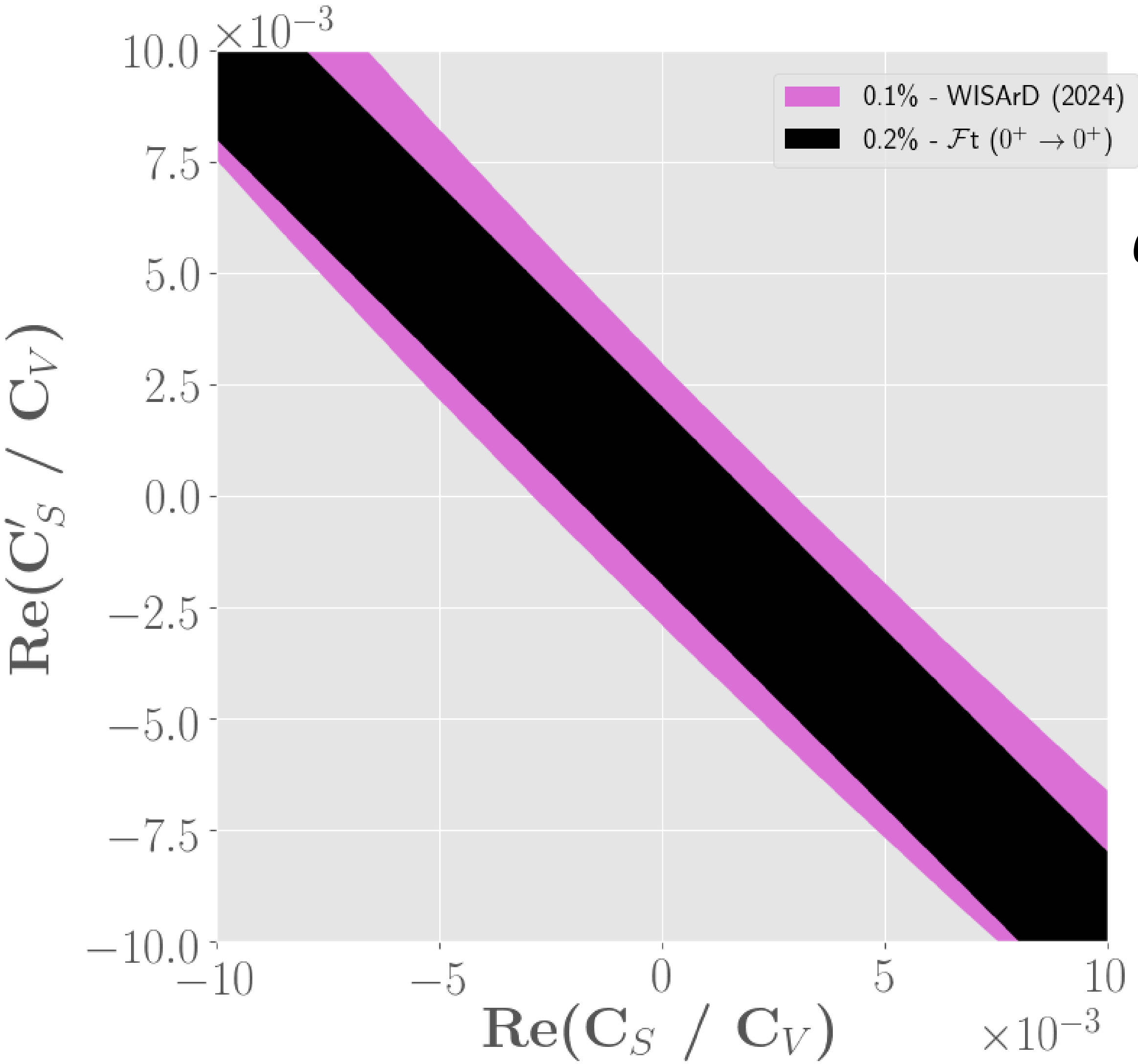


^{32}*Ar spectrum acquired with* *<u>one silicon detector</u>* *(Si3Down all strips, all 35 runs)*

First WISArD experiment: 2021 results



Limits on scalar currents: >2024



$$a_{\beta\nu}^{F} = 1.0000(10)$$

(WISArD 2024)