Simultaneous measurement of the neutron-induced ^{233}U capture and fission cross sections @ n_TOF

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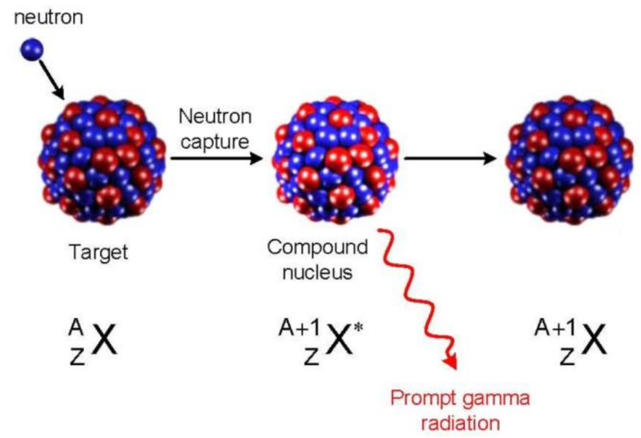
WHAT
WHERE
WHY
HOW

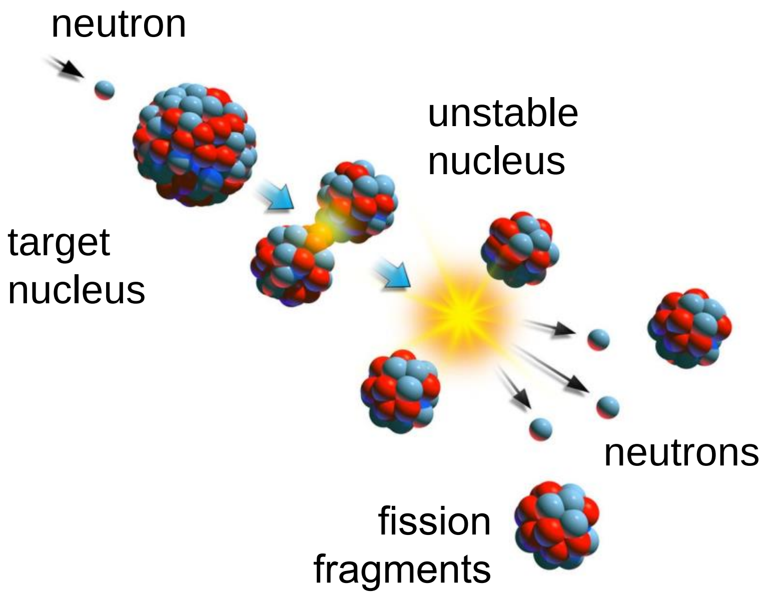
WHAT: Neutron-induced reactions

Radiative capture
(n,γ)



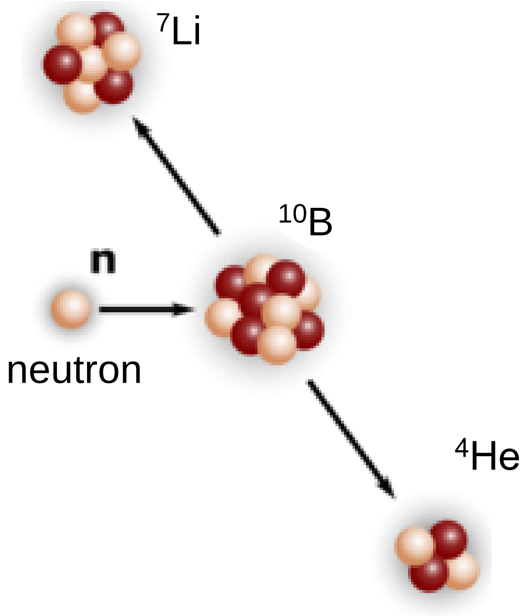
Particle to be detected:
γ-ray

Fission
(n,*f*)



Particle to be detected:
fission fragments

Charged particle emission
(n,*cp*)

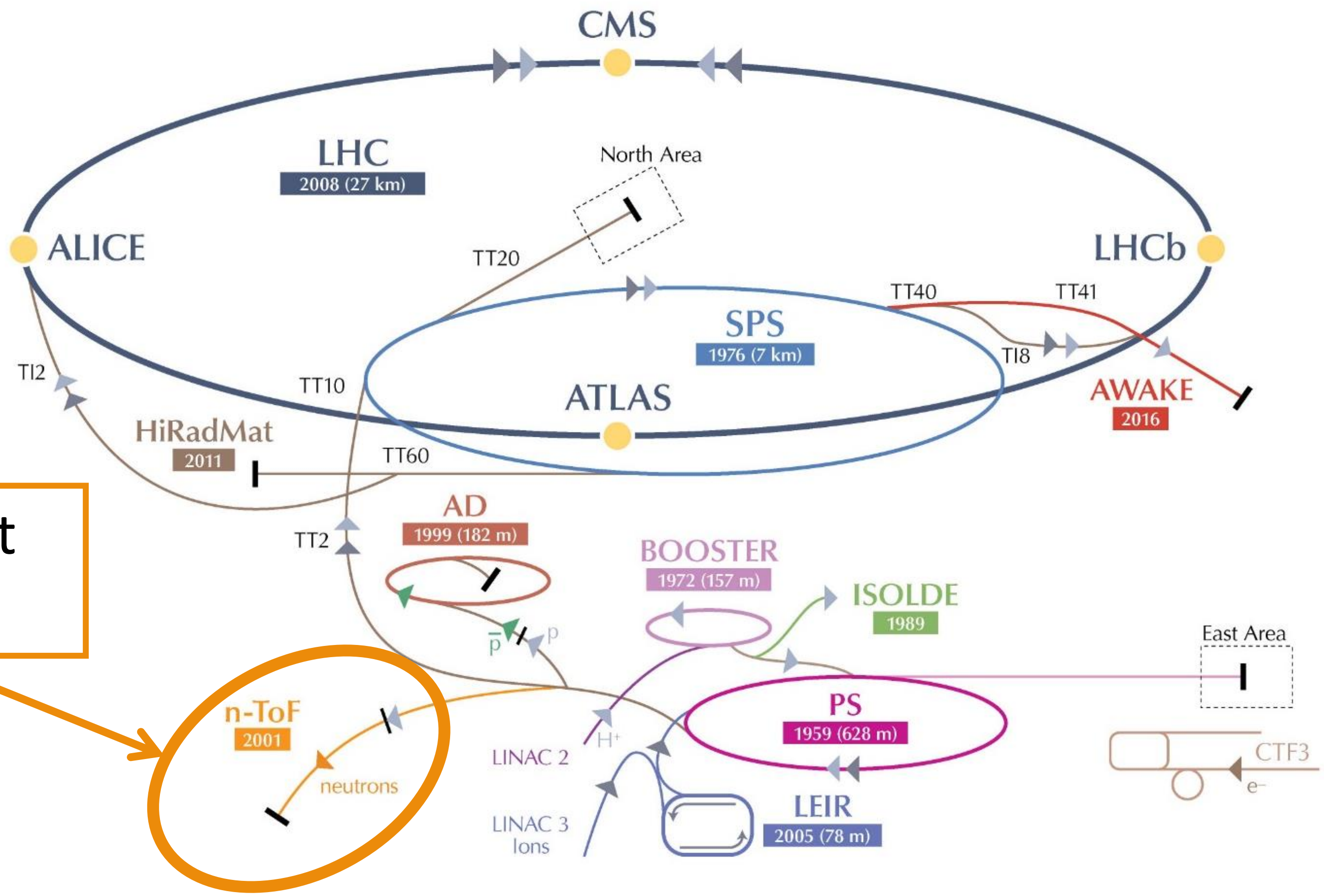


Particle to be detected:
light charged particles

WHERE: The CERN accelerator complex

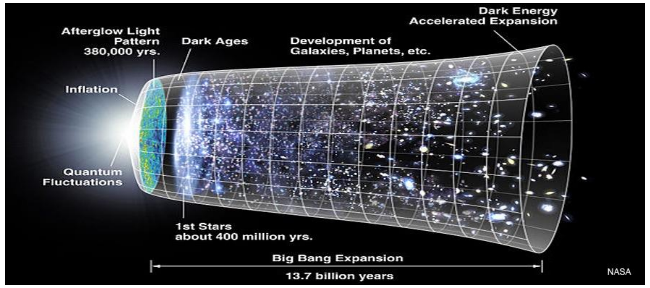
- CERN: European Organization for Nuclear Research (Geneva, Switzerland)
  - Since 1954
  - Various accelerators
  - Most recent discovery:

    2012 Higgs Boson



Neutron **T**ime **O**f **F**light facility: **n_TOF**

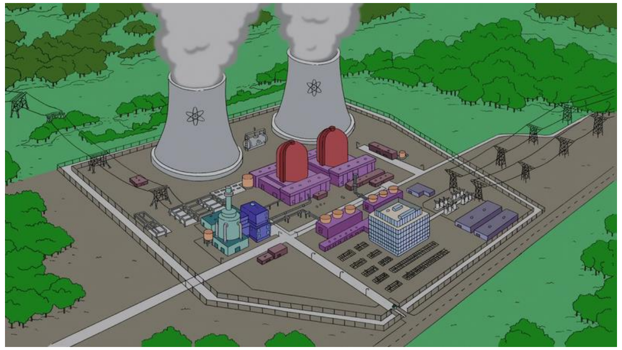
WHY: n_ToF in a nutshell

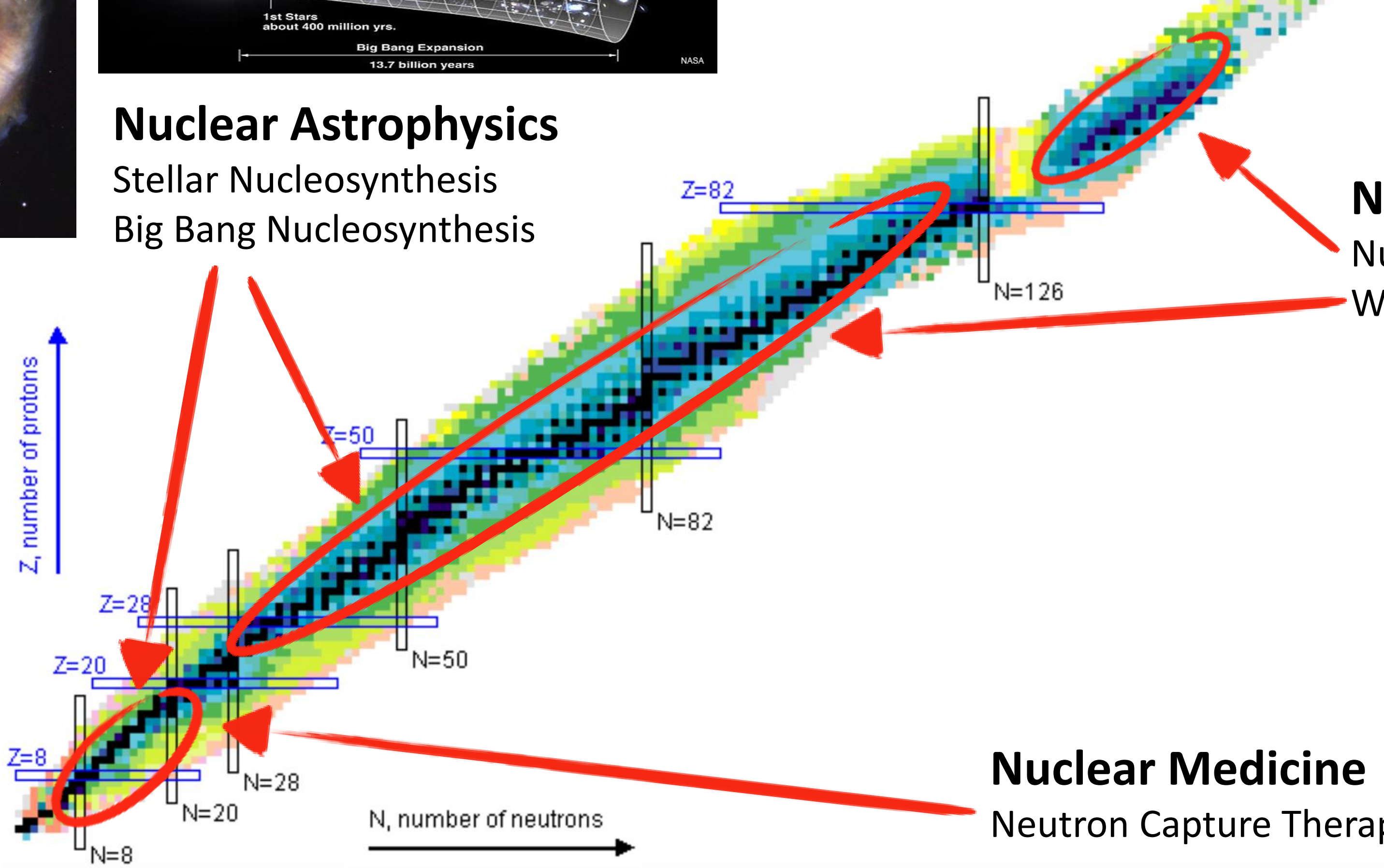


Nuclear Astrophysics

Stellar Nucleosynthesis

Big Bang Nucleosynthesis

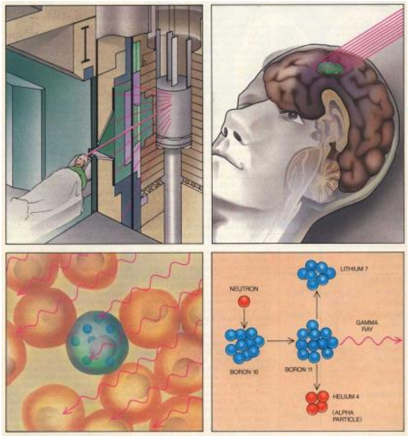




Nuclear Technologies

Nuclear reactors (energy production)

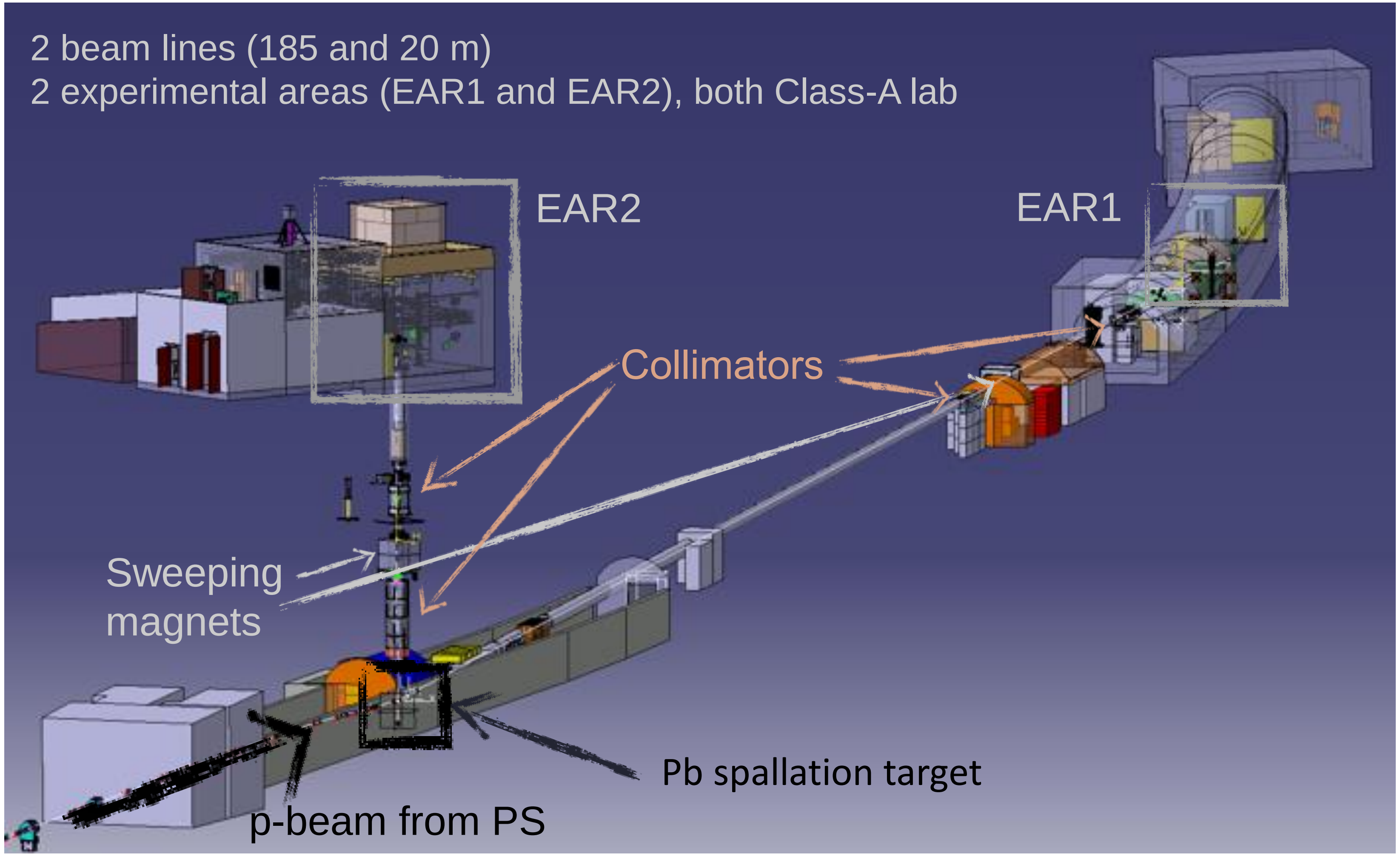
Waste management



Nuclear Medicine

Neutron Capture Therapy

HOW: n_TOF in a nutshell

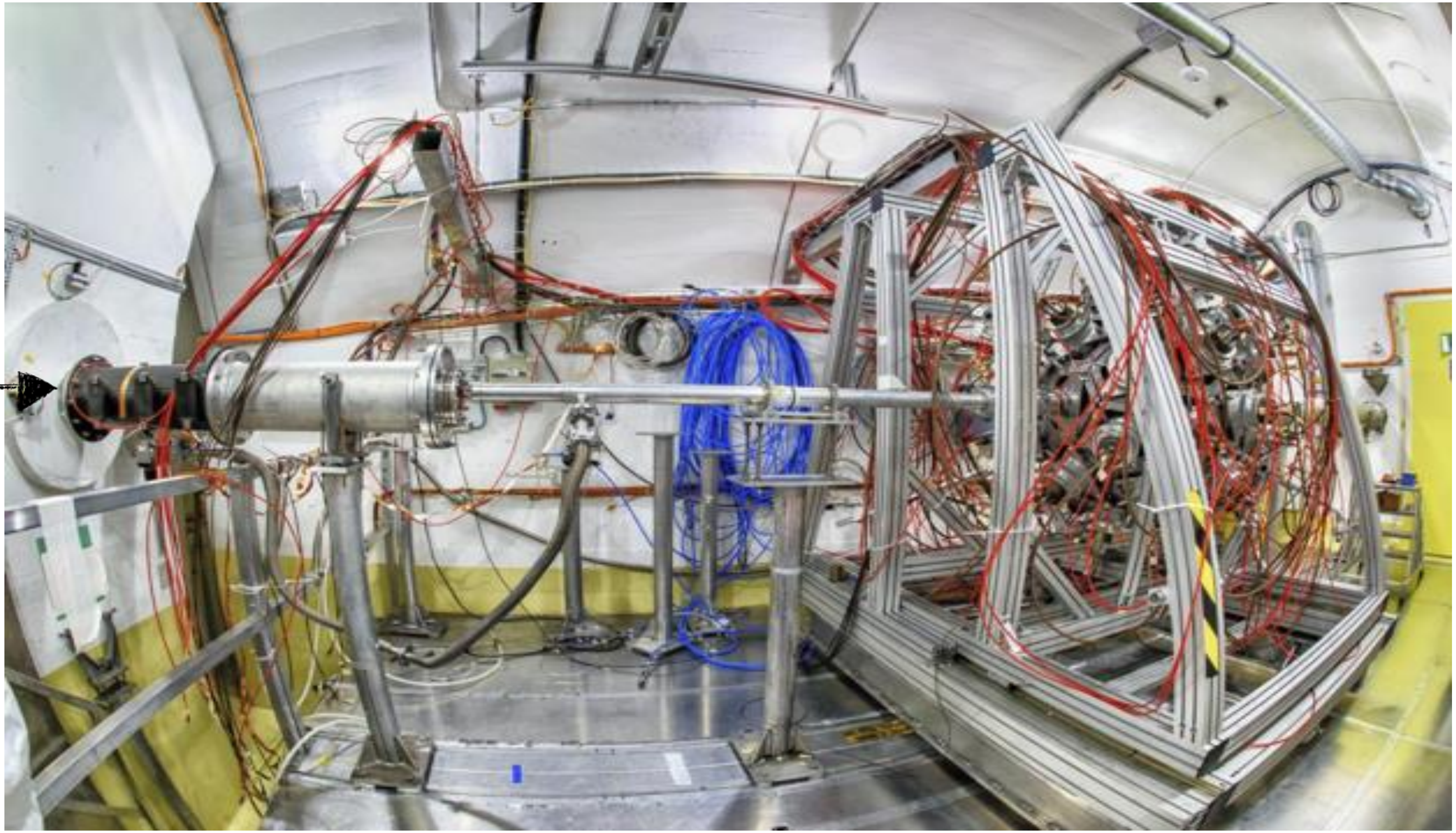


Some figures

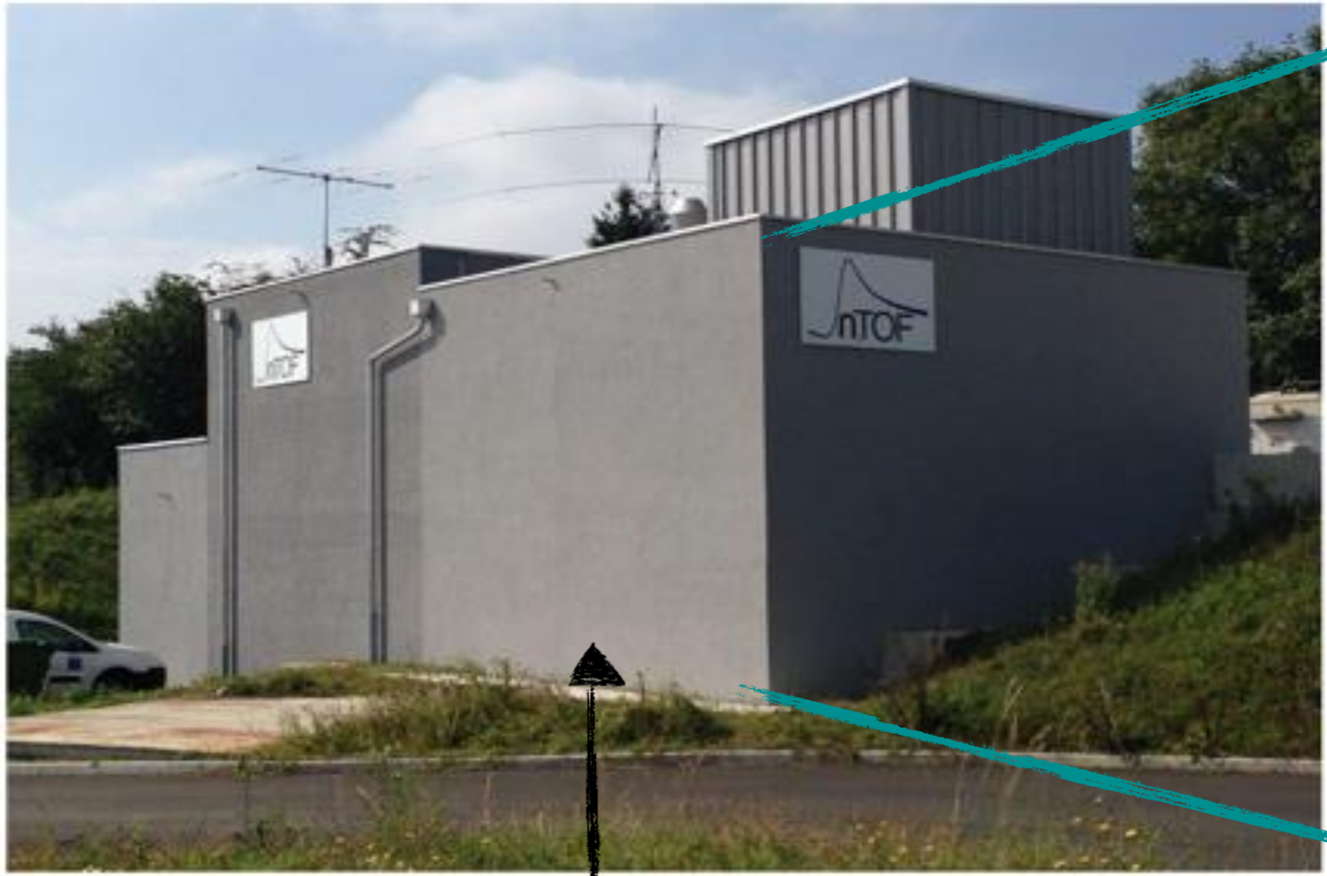
	EAR1	EAR2
Wide energy range	thermal to 1 GeV	thermal to 300 MeV
High instantaneous neutron flux	10^5 n/cm^2/pulse	10^6 n/cm^2/pulse
Low repetition rate	< 0.8 Hz (1 pulse/2.4 s max)	
High energy resolution	$\Delta E/E=10^{-4}$ (@10 eV)	$\Delta E/E=10^{-2}$ (@10 eV)

HOW: n_TOF EAR1

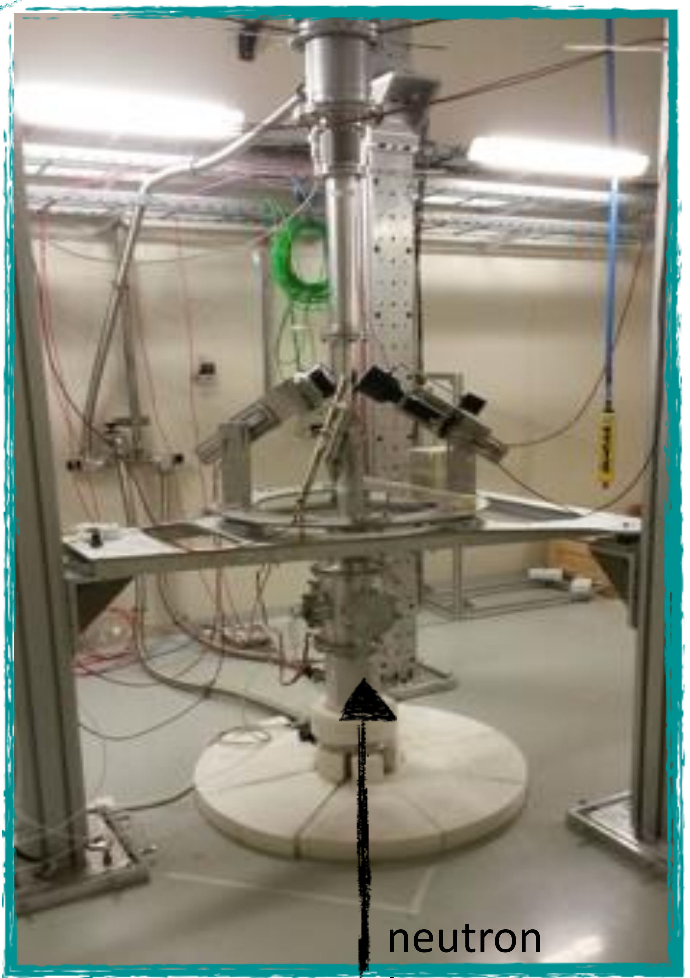
neutron
beam



HOW: n_TOF EAR2

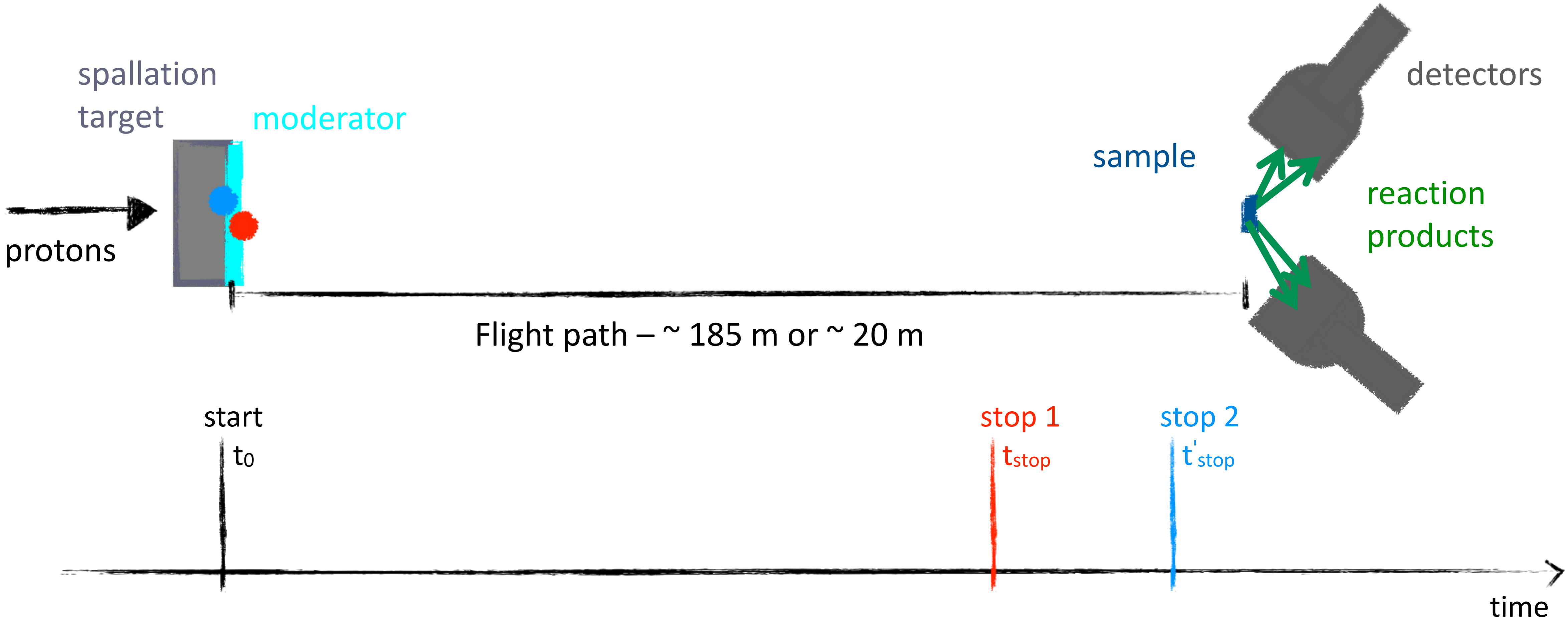


neutron beam



neutron beam

HOW: time-of-flight (TOF) technique

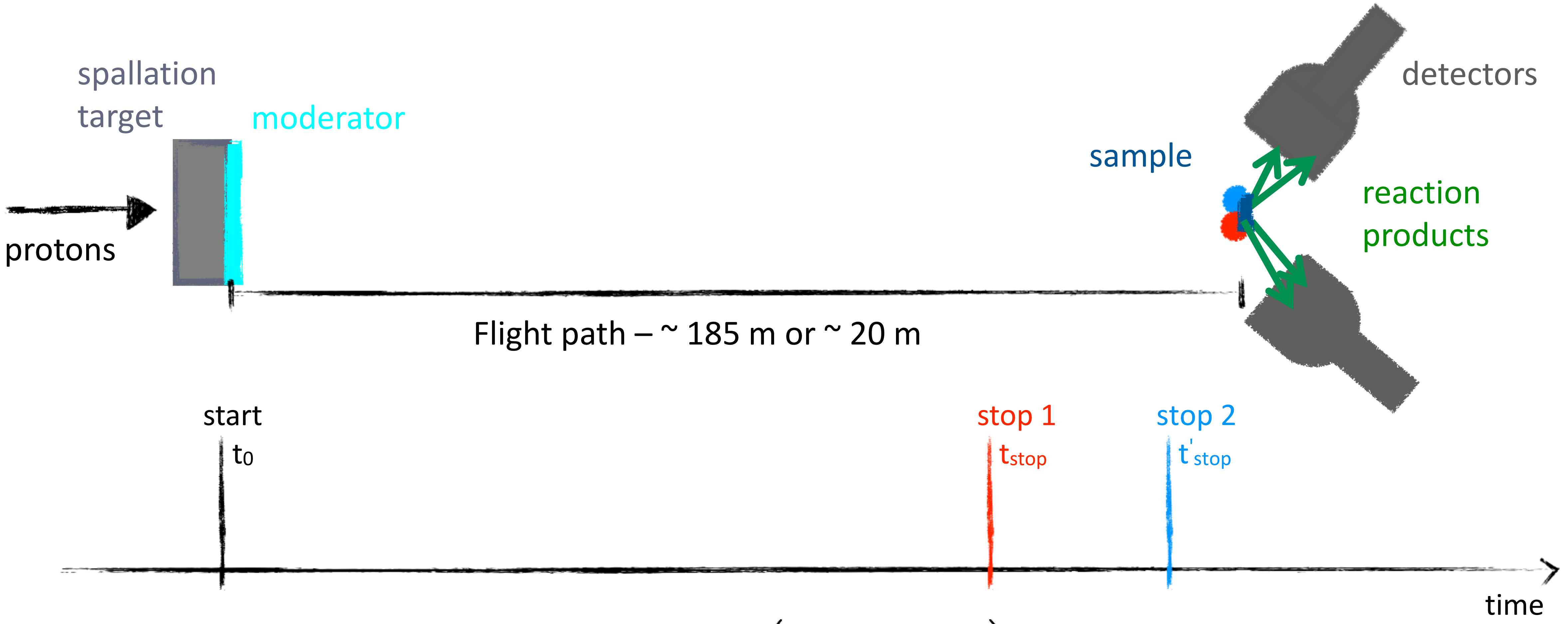


$$\mathrm{TOF} = t_{\mathrm{stop}} - t_0$$

Need of a pulsed neutron source → charged particle impinging on a heavy target

- neutrons from SPALLATION reactions induced by protons
- photoneutrons from BREMSSTRAHLUNG induced by electrons

HOW: time-of-flight (TOF) technique



$$\mathrm{TOF} = t_{\mathrm{stop}} - t_0 \longleftrightarrow E_n = m_n c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right)$$

$$\beta = \frac{v_n}{c} = \frac{\mathrm{L}}{c\,\mathrm{TOF}}$$

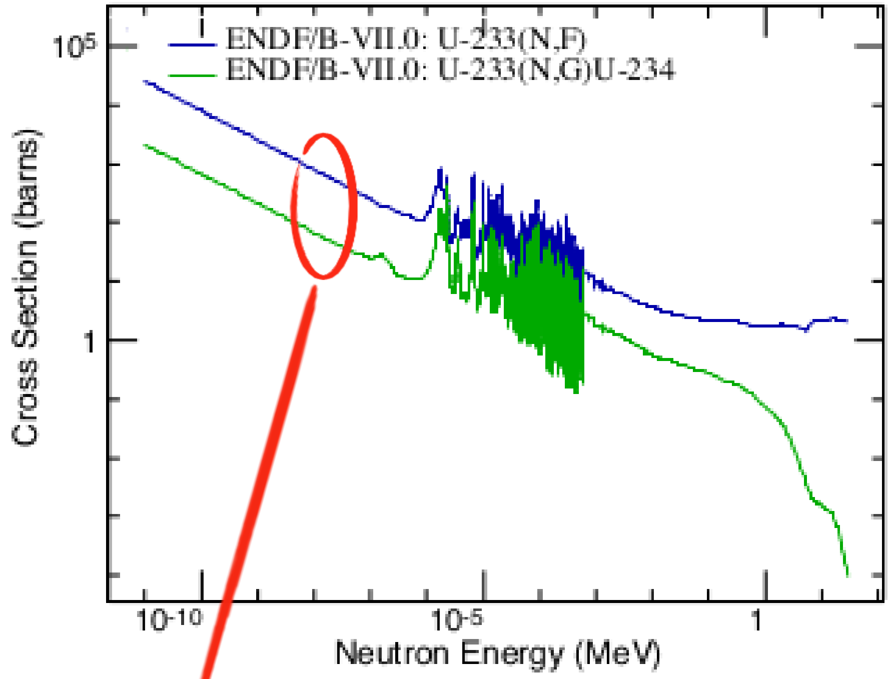
The ^{233}U case - Motivation

- Th-U fuel cycle / Gen-IV systems

- NEA Nuclear Data High Priority Request List

^{233}U(n,γ)	σ	σ
E_n	Thermal – 10 keV	10 keV – 1 MeV
Target accuracy	5%	9%

- Challenging R&D to measure (n,γ)-XS of fissile actinides



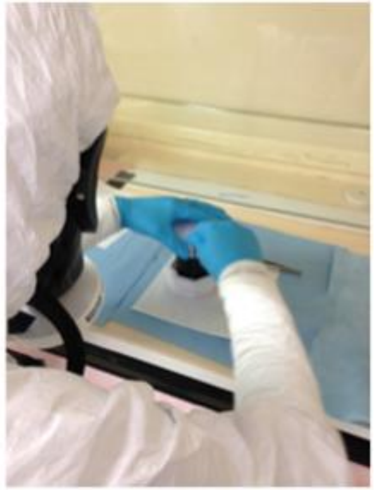
$$\frac{\sigma_f}{\sigma_\gamma} \sim 10$$ → Fission Tagging

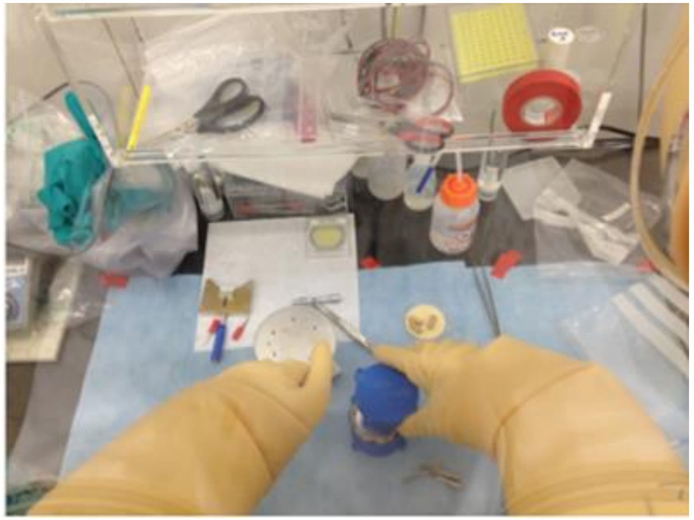
^{233}U targets

- Molecular plated by JRC-Geel

- 14 unsealed spots
  - 4 cm diameter
  - 46.5 mg total mass
  - 264.5 µg/cm² on average

Isotope	w%
^{233}U	99.936
^{234}U	0.0496
^{235}U	0.0012
^{236}U	0.0002
^{238}U	0.0128



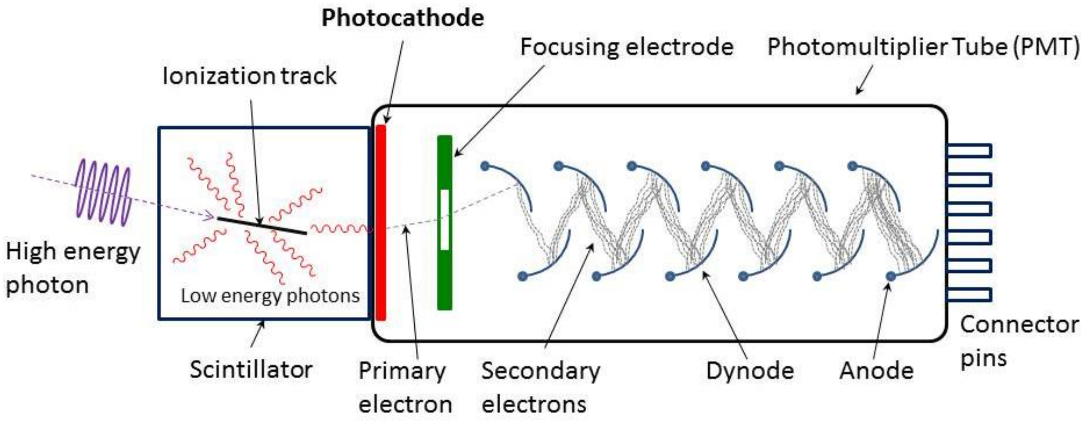


- Complicated mounting in glove box
  - risk of contamination due to self-sputtering and high activity (1.2 MBq per target)

Measuring (n,γ) & (n,f)

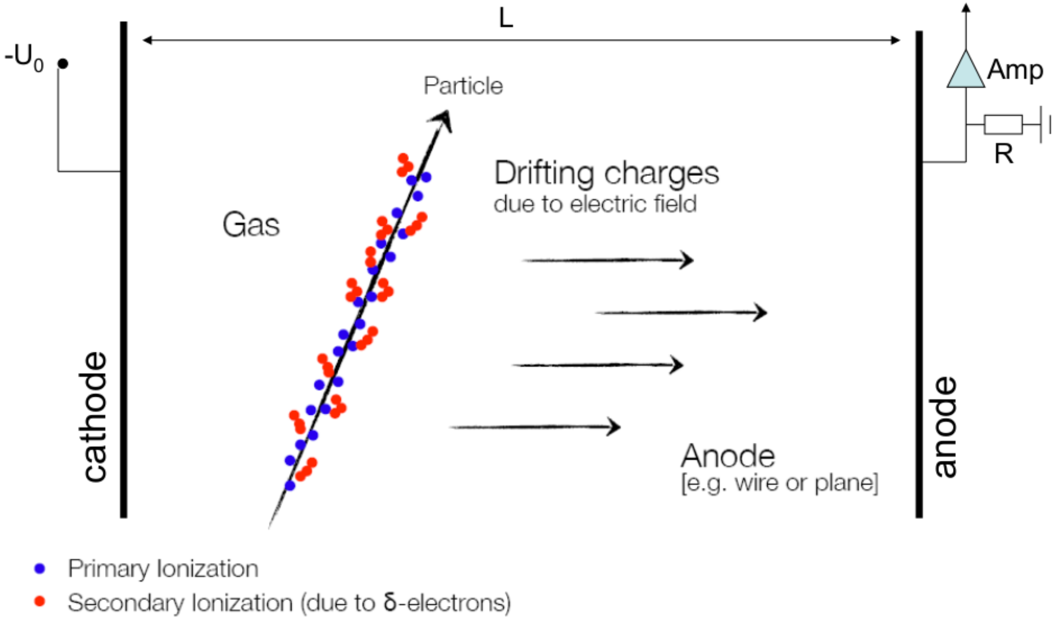
Radiative capture (n,γ)

Detection of γ-rays
i.e. with scintillators



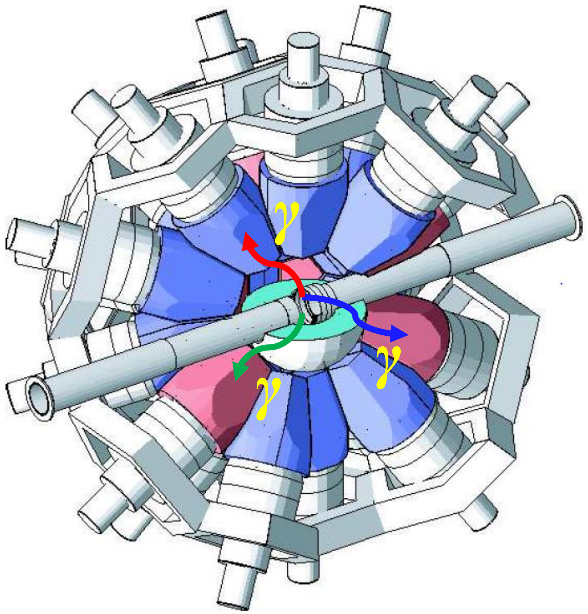
Fission (n,f)

Detection of heavy charged particles
i.e. with a gaseous detector



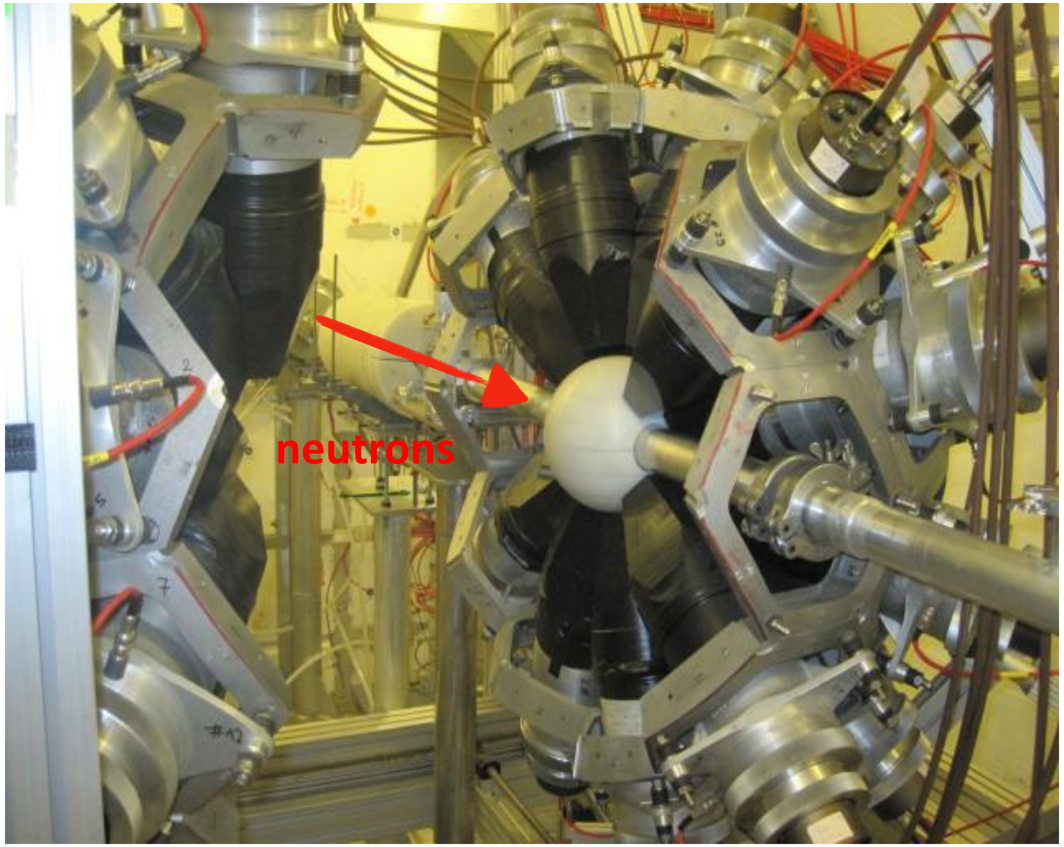
Experimental Setup I

- **(n,γ)** with **Total Absorption Calorimeter** TAC
  - Spherical array of 40 BaF_2 crystals
  - Inner diameter 20 cm
  - Absorber (polyethylene + 7.5% Li) to reduce neutron scattering into the BaF_2



$$E_{Sum} = E_1 + E_2 + E_3$$

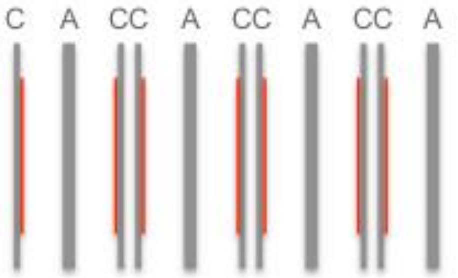
$$m_{cr} = 1 + 1 + 1$$

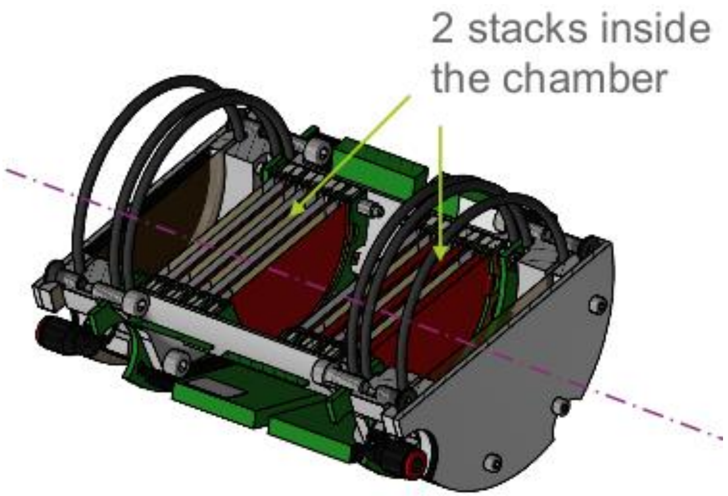


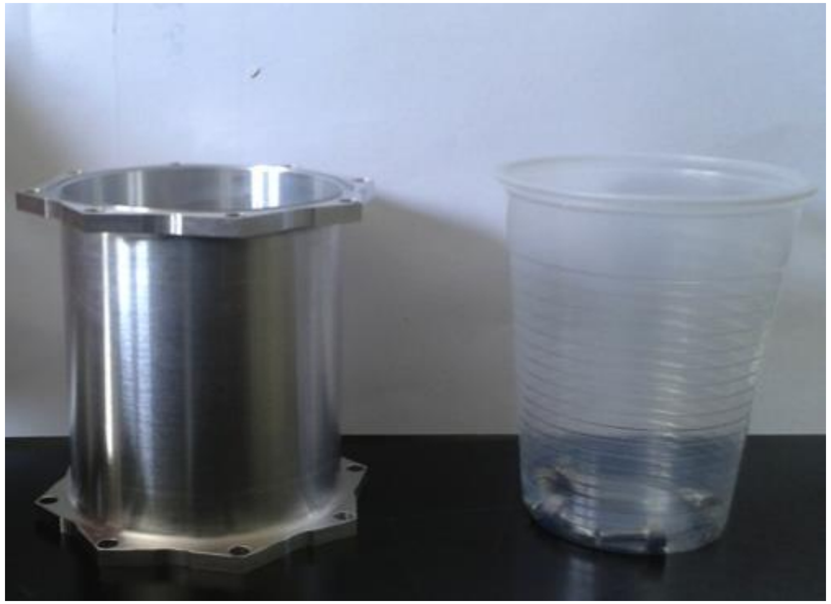
n_TOF CERN cea CENBG European Commission Joint Research Centre TU WIEN

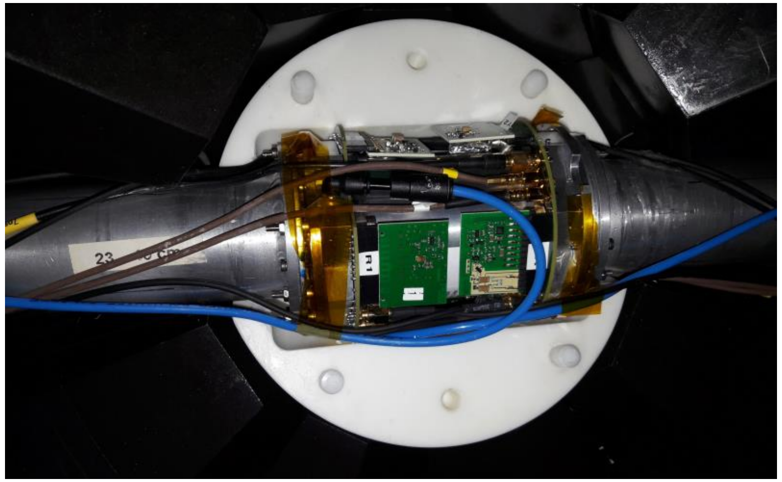
Experimental Setup II

- **(n,*f*)** with **compact ionisation chamber** (FICH) for fission tagging
  - Must fit in TAC/absorber
  - High α-count rates require:
    - Fast ionizing gas CF_4 @ 1100 mbar
    - Dedicated electronics (CEA/DAM/DIF)
  - Dummy for background measurement

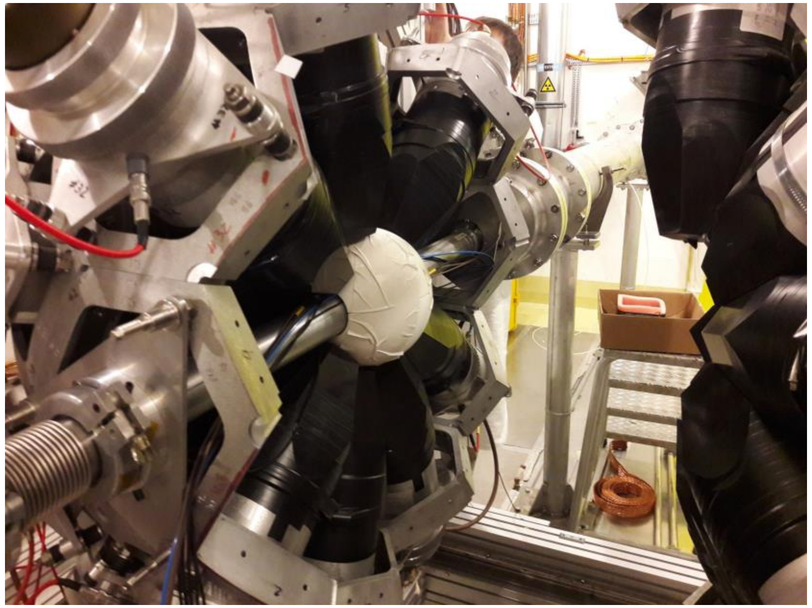


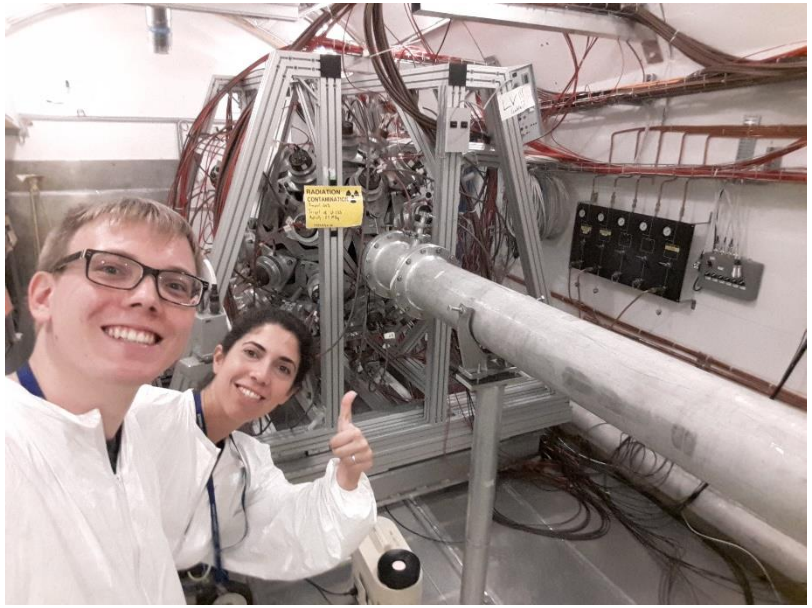






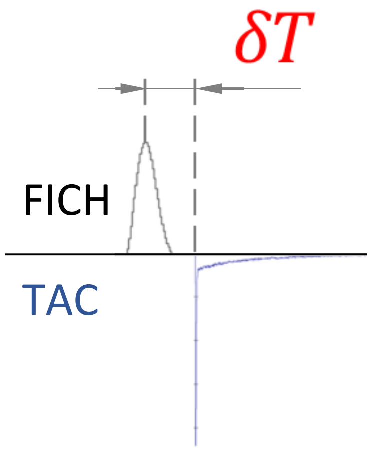
The Analysis





$T^{TAC-FICH}_{coinc}$

TAC ↔ FICH

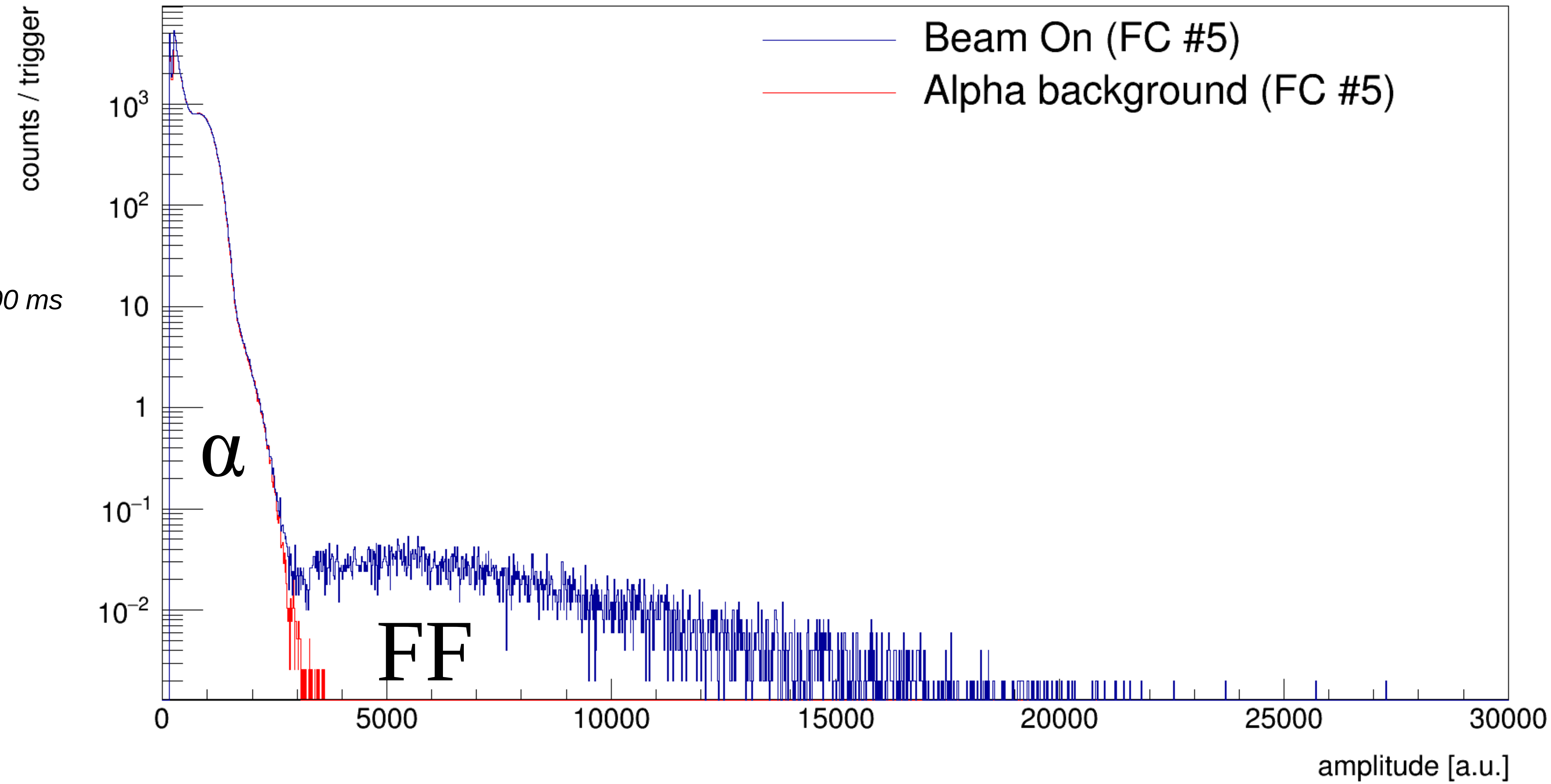


Coincidence
(fission)

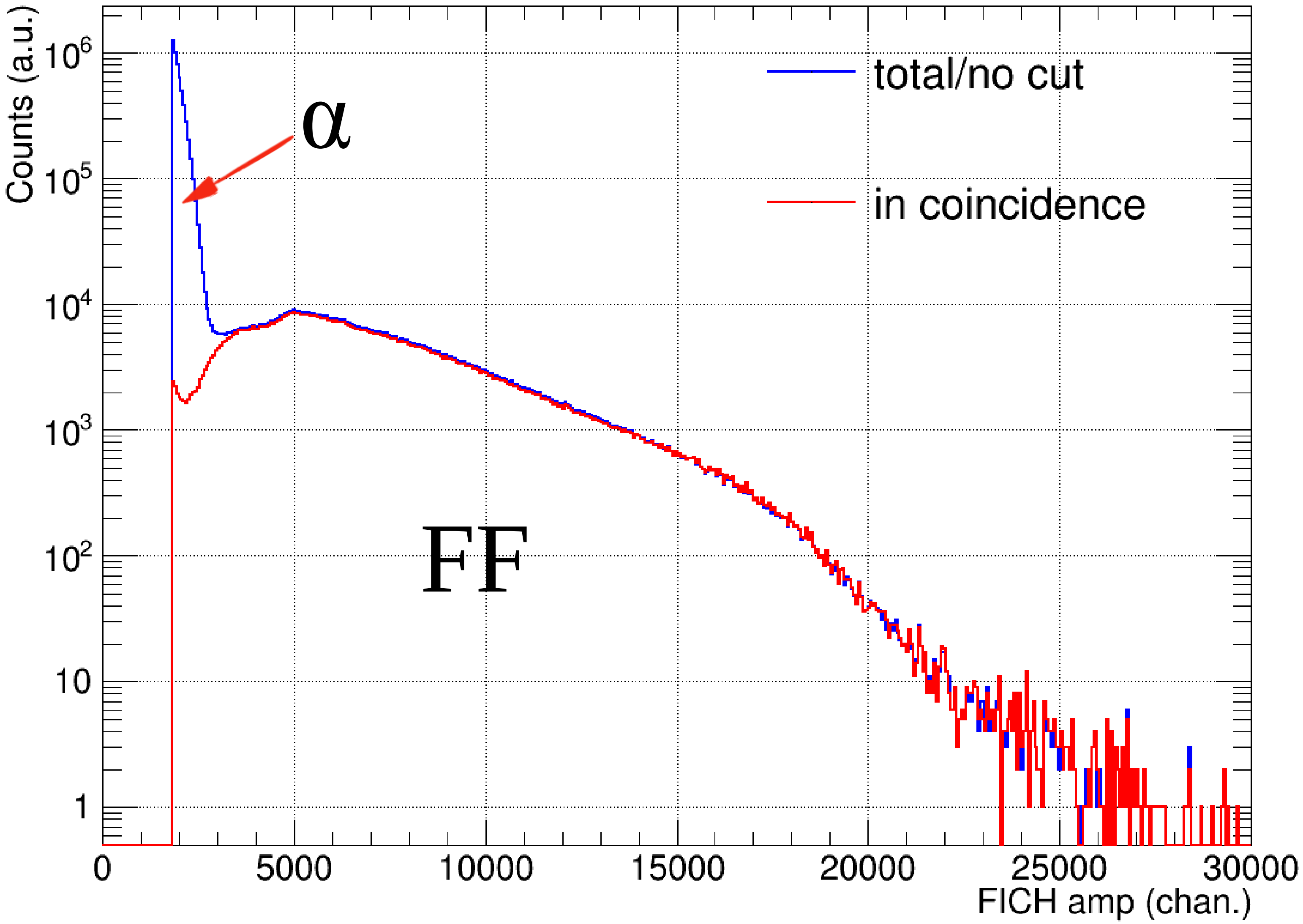
Anti-Coincidence
(capture + background)

FICH – total amplitude spectrum

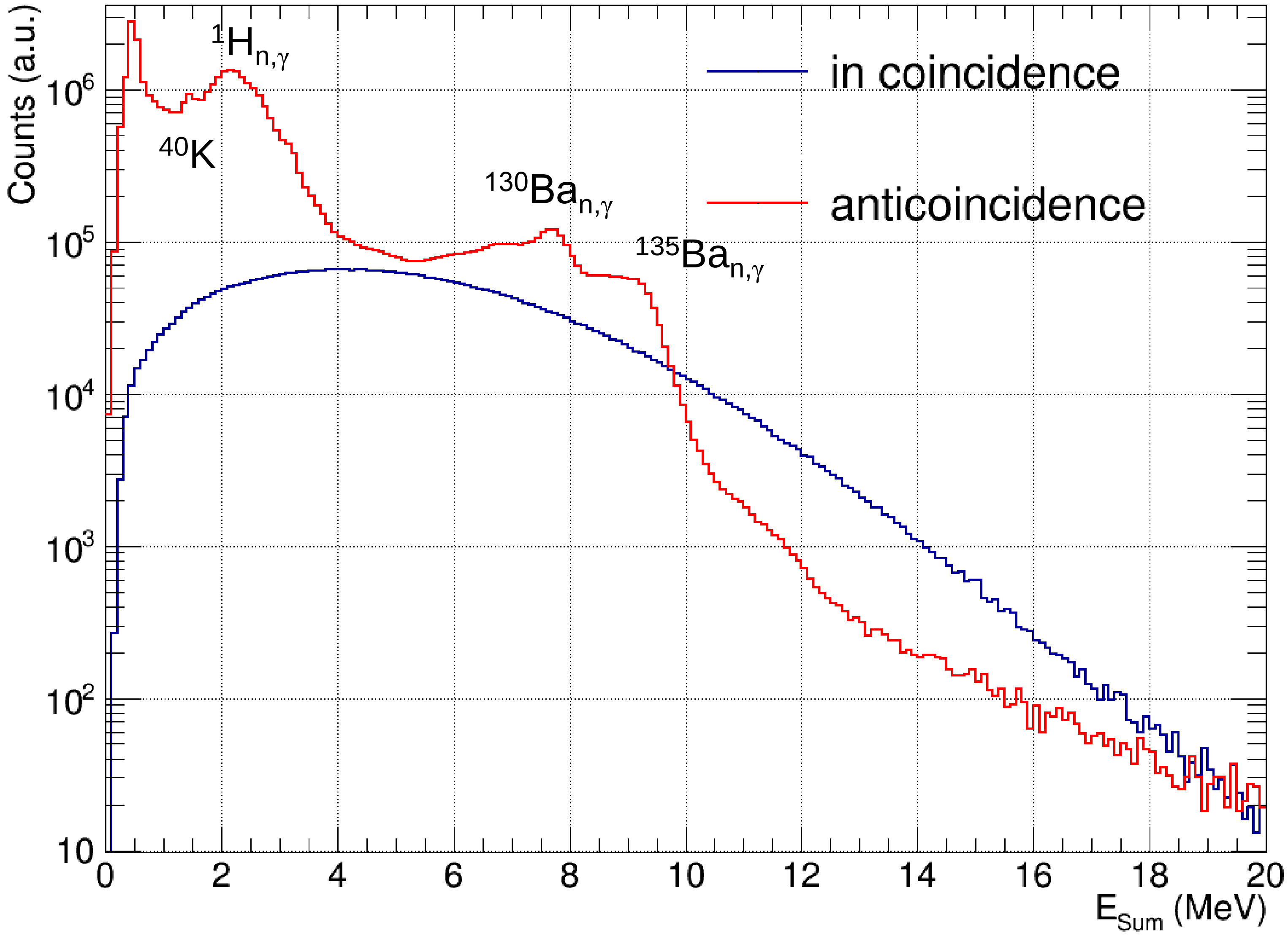
1 trigger = 100 ms



FICH – Fission events in coincidence



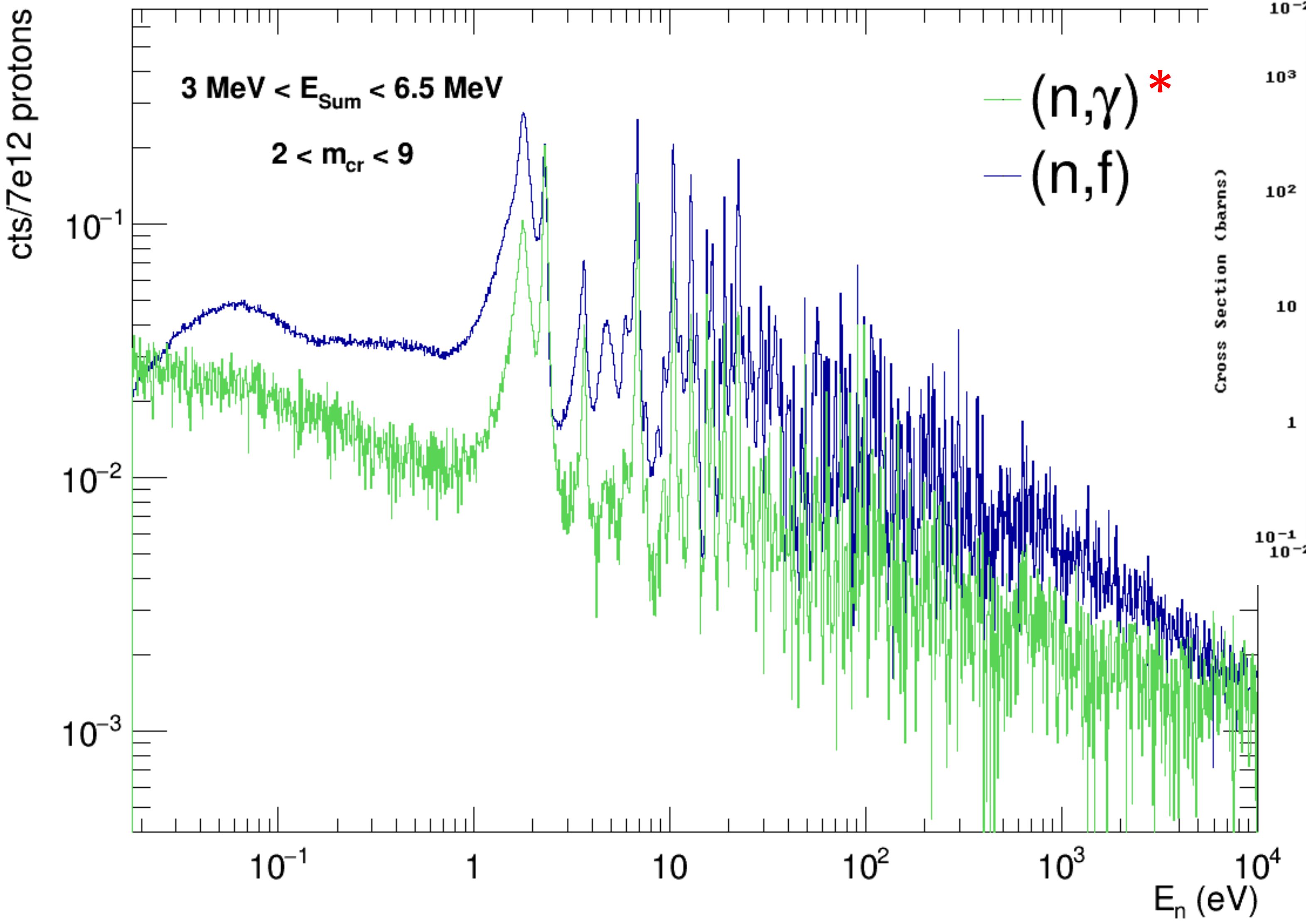
Anti-/Coincidence - E_{Sum}

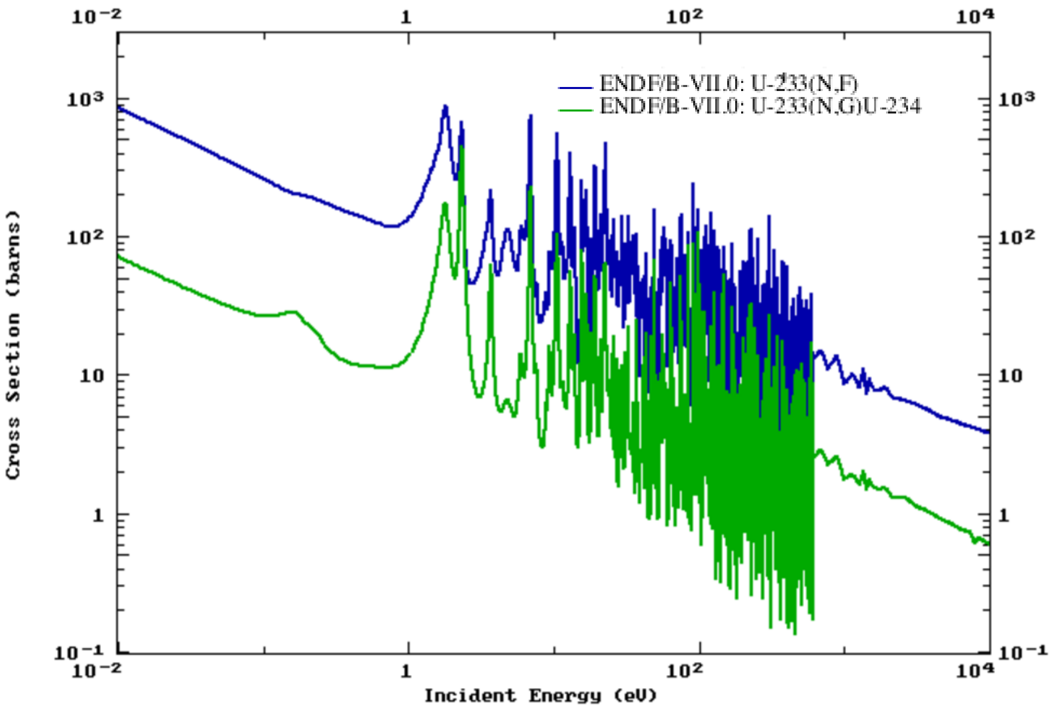


$$T_{coinc}^{TAC} = 10\ ns$$

$$T_{coinc}^{TAC-FICH} = 40\ ns$$

Fission vs. Capture – 10% of statistics





*(n,γ) = AntiCoincidence

– BeamOn Dummy

– BeamOff ^{233}U in

$T_{coinc}^{TAC} = 10\ ns$

$T_{coinc}^{TAC-FICH} = 40\ ns$

$E_{dep}^{BaF_2} = 100\ keV$

Summary & Outlook

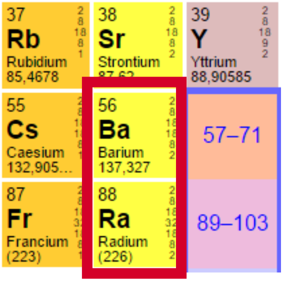
- Successful data taking
  - 4.4e18 protons on target
  - 1.5 months of beam time
  - Auxilliary measurements
    - Gold for normalization
    - Dummy/Background
    - Calibrations with radioactive sources
  - 950 TB of data
- Extraction of preliminary count rates

- Numerical simulations:
  - GARFIELD: fission chamber
    - E_{dep} for FF/α
    - α pile-up correction
    - Efficiency
  - Geant4: TAC/full setup
    - E_{Sum} and m_{cr}
    - Efficiency
    - Dead time correction
    - Background study
- Extraction of final cross sections
- R-Matrix analysis of resonances

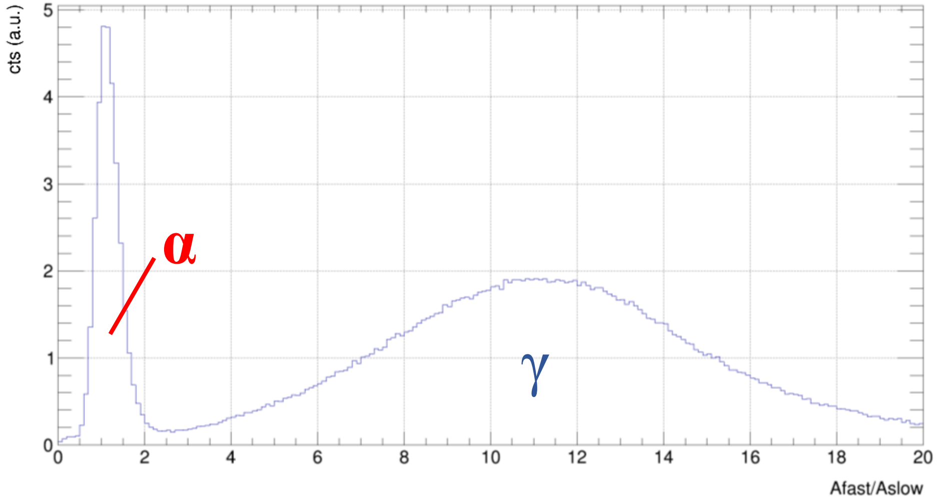
Merci beaucoup

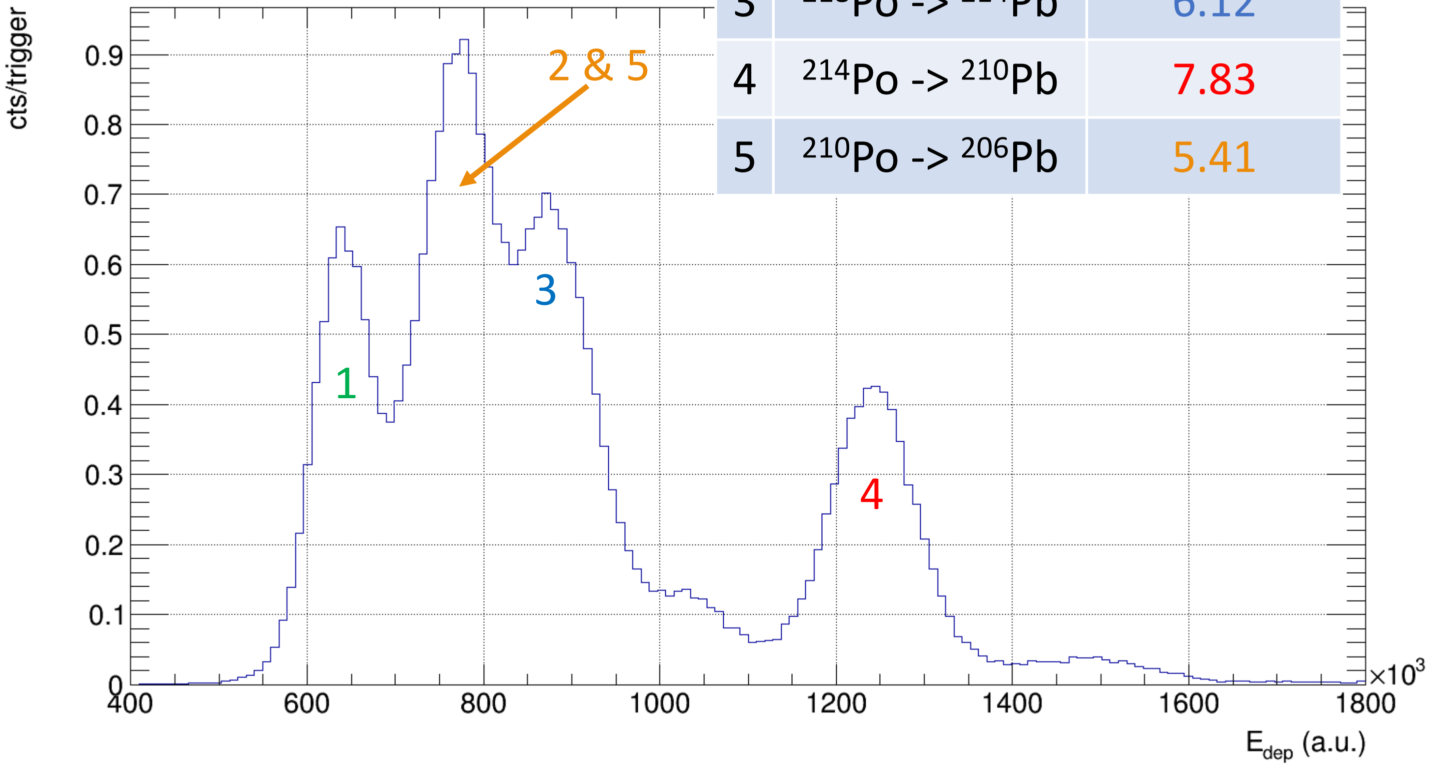
Gain drift correction

- ^{226}Ra impurities in the crystals from production
- Leads to alpha decay chain
- Can be distinguished by pulse shape

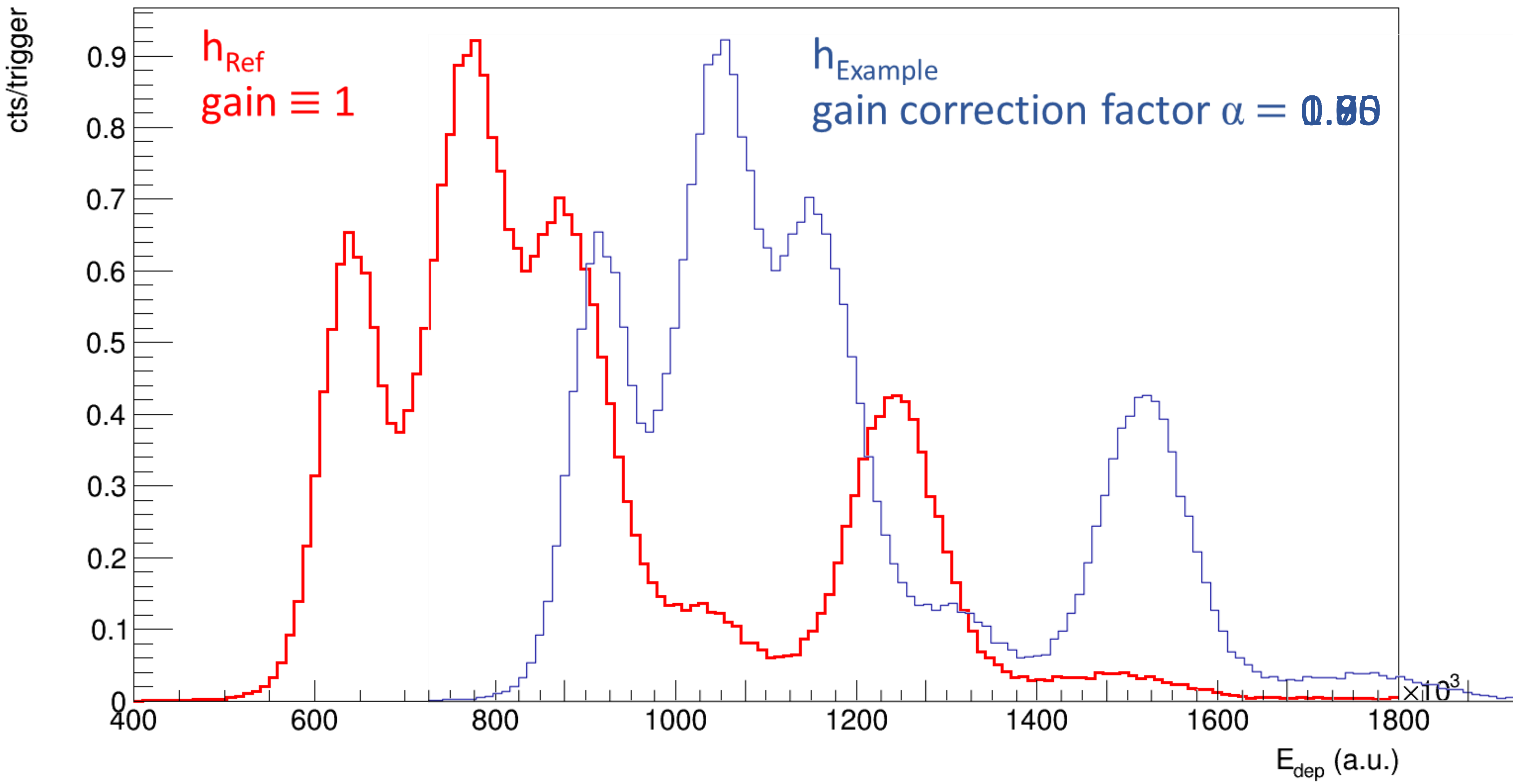


#	Decay	E_α (MeV)
1	^{226}Ra -> ^{222}Rn	4.87
2	^{222}Rn -> ^{218}Po	5.59
3	^{218}Po -> ^{214}Pb	6.12
4	^{214}Po -> ^{210}Pb	7.83
5	^{210}Po -> ^{206}Pb	5.41





Gain drift correction II

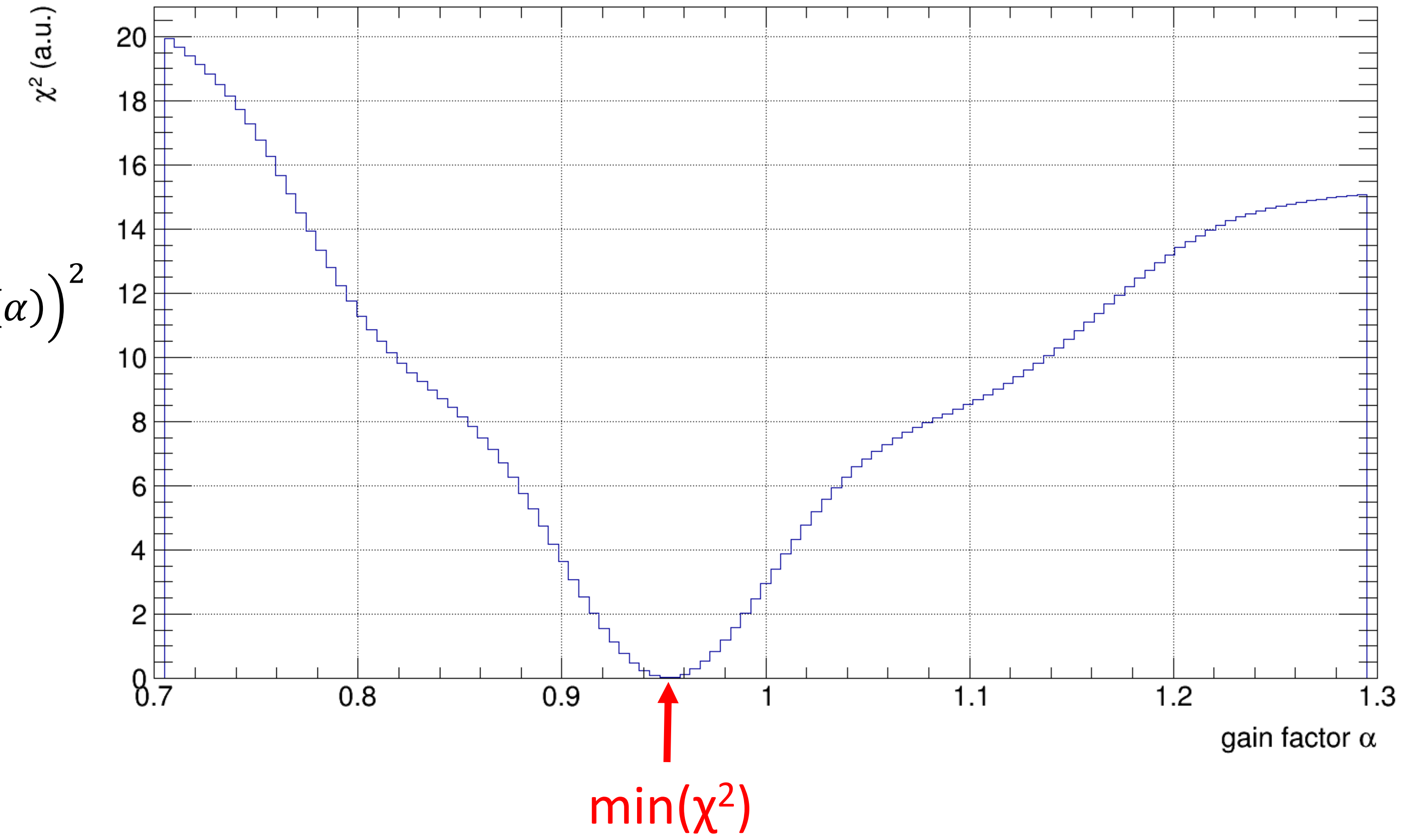


Gain drift correction III

- χ^2 method* for varying gain factor α

$$\chi^2(\alpha) = \sum_{i=1}^{nbins} \left(h_{Ref}[i] - h_{Example}[i](\alpha) \right)^2$$

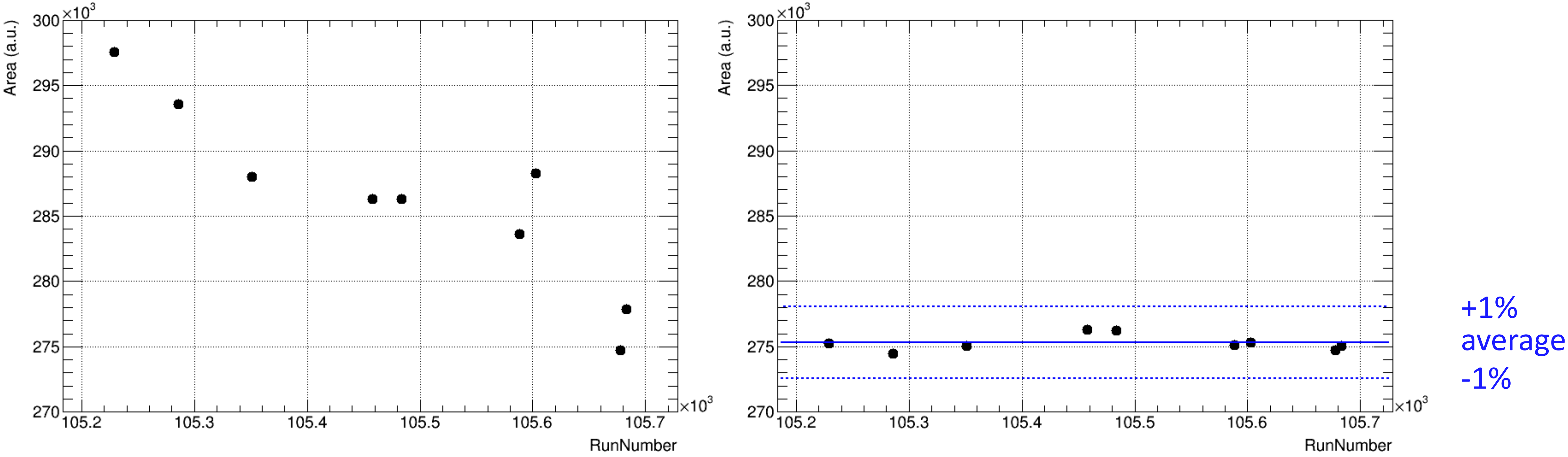
- Gain factor = min(χ²)



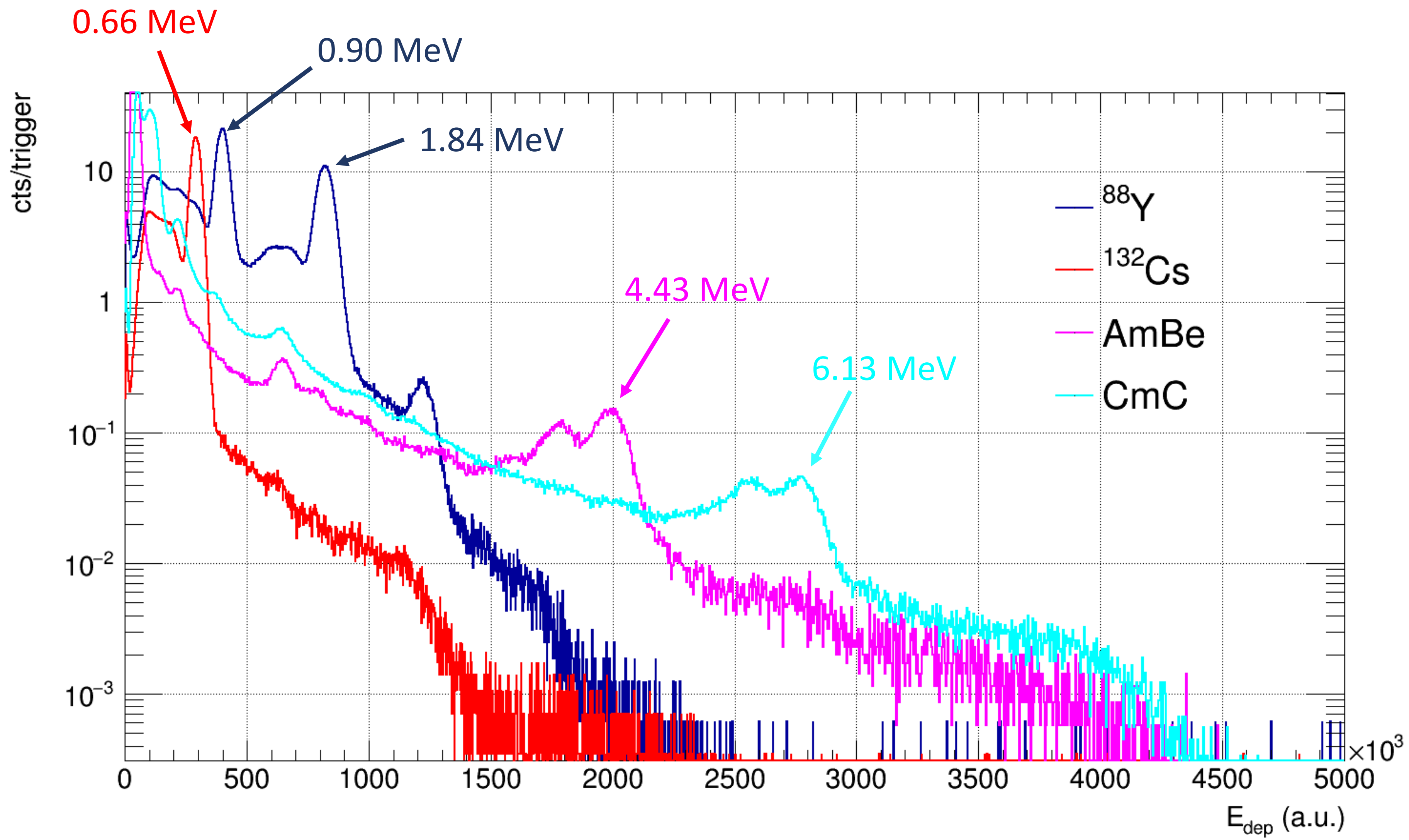
*Javier Balibrea Correra & CIEMAT

Gain drift correction II

- Proof it works with Cs peak positions throughout the campaign



Energy Calibration I – γ-sources



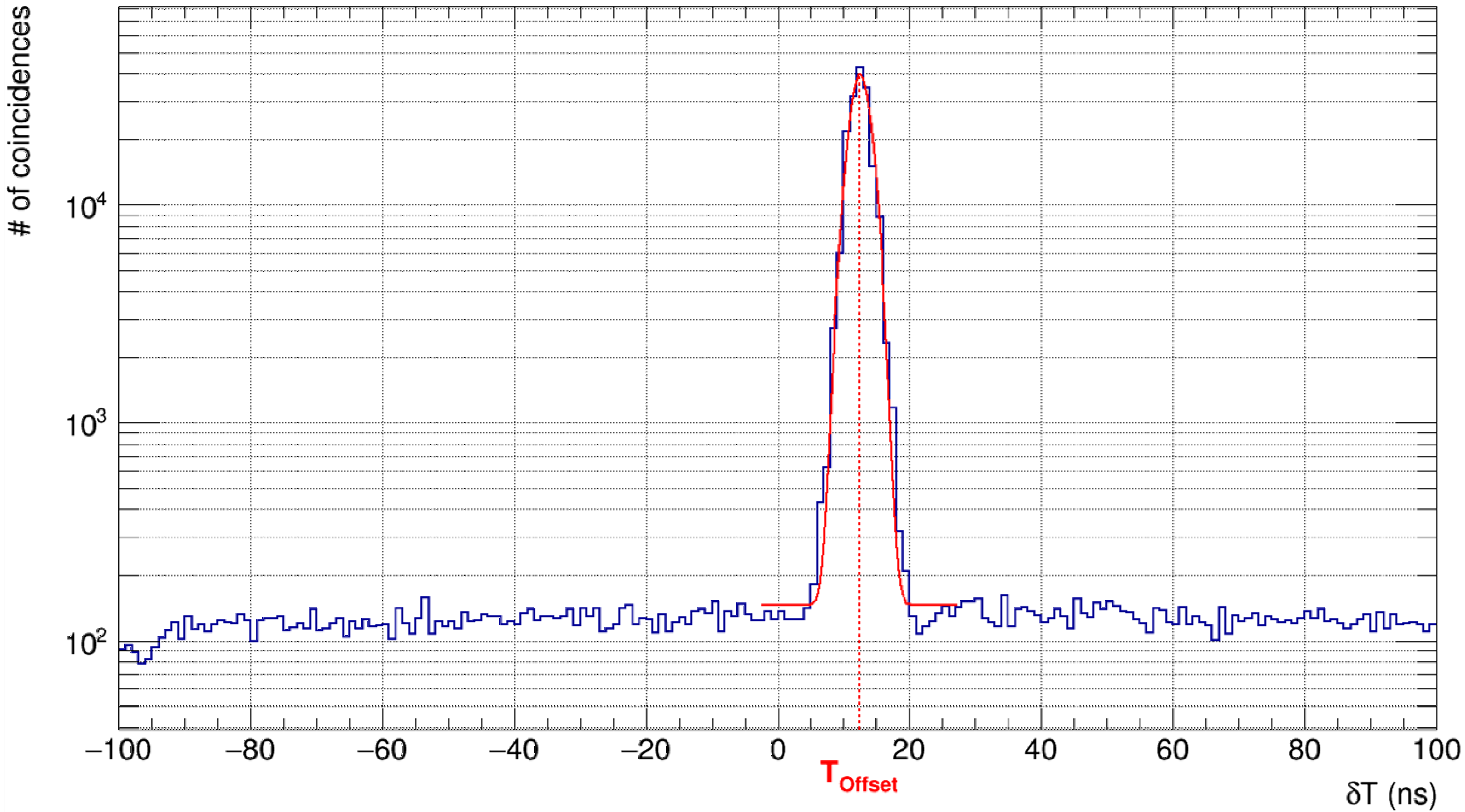
Time Calibration I - method

- Detectors misaligned in time due to different electronic chains, i.e. cable lengths
- Coincidence analysis requires alignment of the detectors
- Method:
  - Use ^{88}Y source (2 simultaneous γ)
  - Choose one reference detector (#29)
  - Look for coincidences with other detectors in a big time window (±100 ns) and calculate the time difference δT:

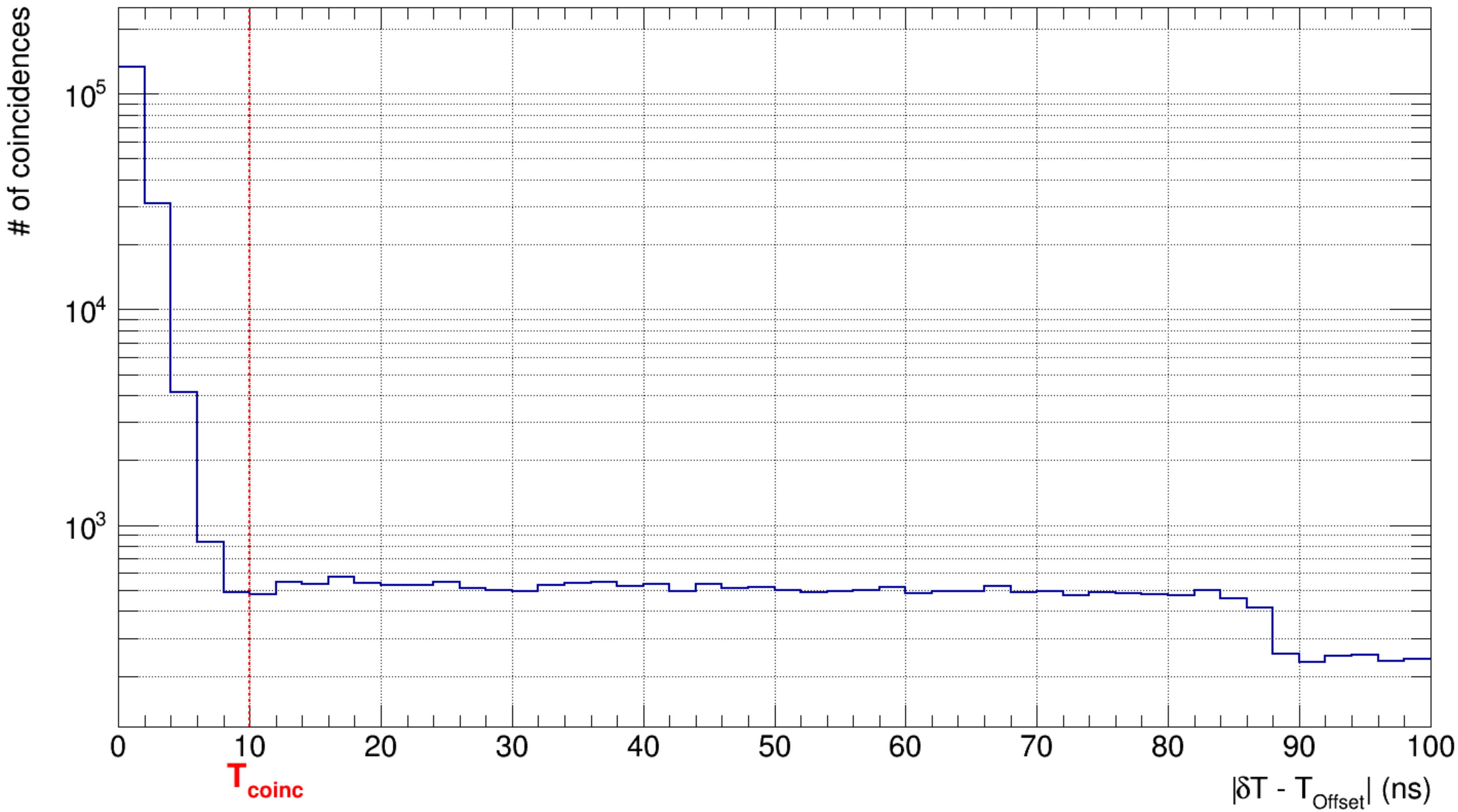
$$\delta T = tof_{Ref} - tof_{det}$$

  - Expected δT shape : sharp peak (real coincidences) sitting on constant background
  - Determine the centroid of the peak which will corresponds to the T_{Offset} between the detectors

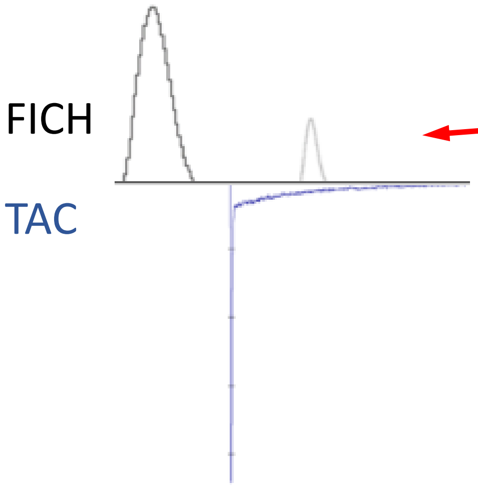
Time Calibration II

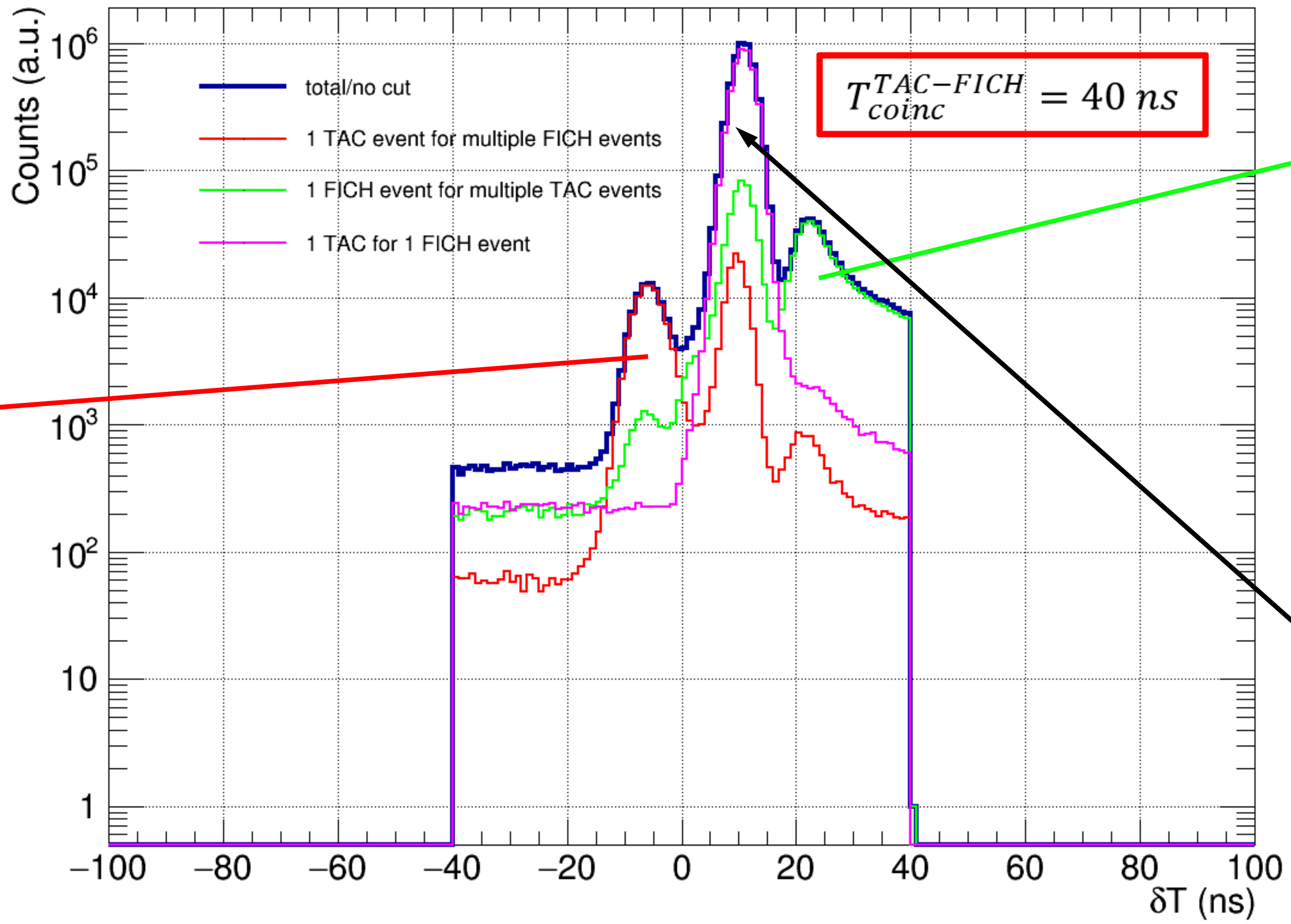


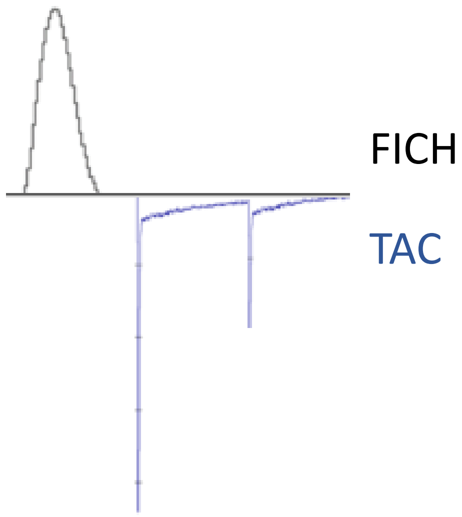
Time Calibration III



Coincidence - δT





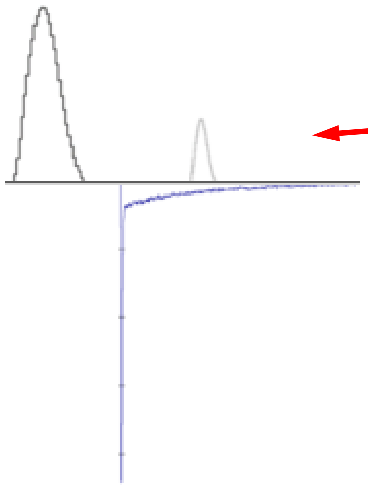


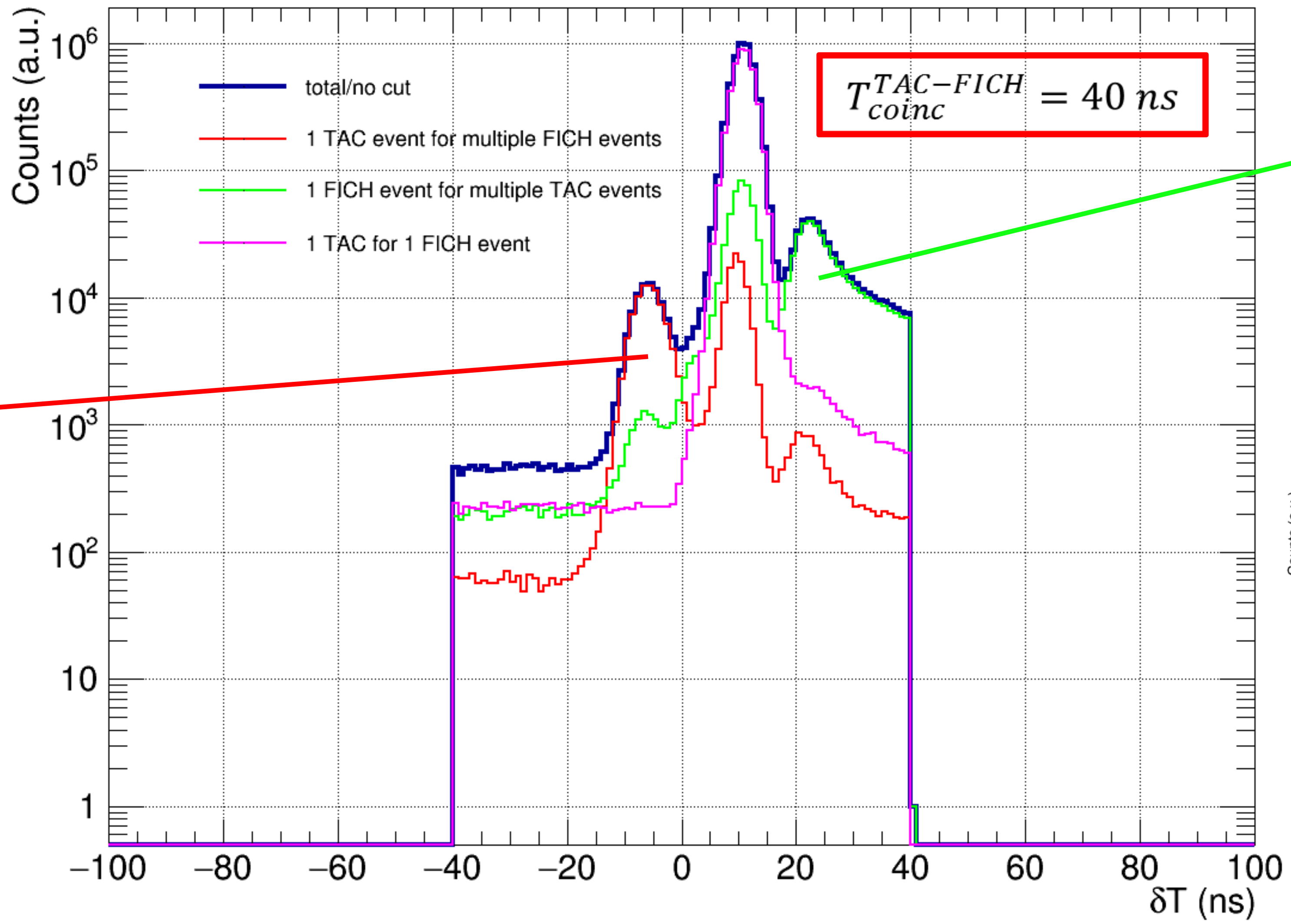
„main“ coincidences

Coincidence I - δT

FICH

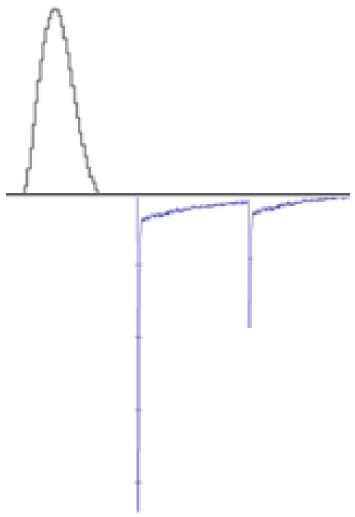
TAC

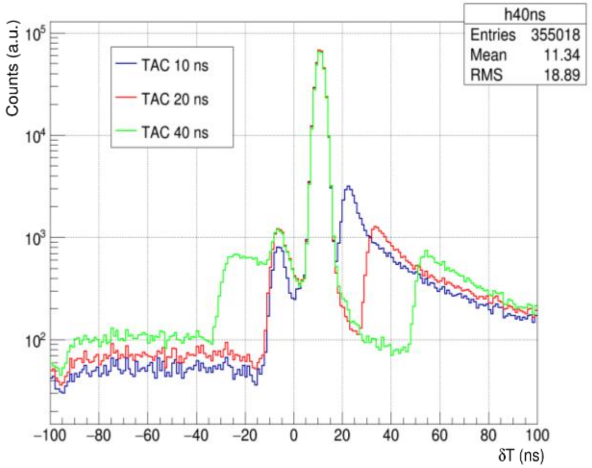




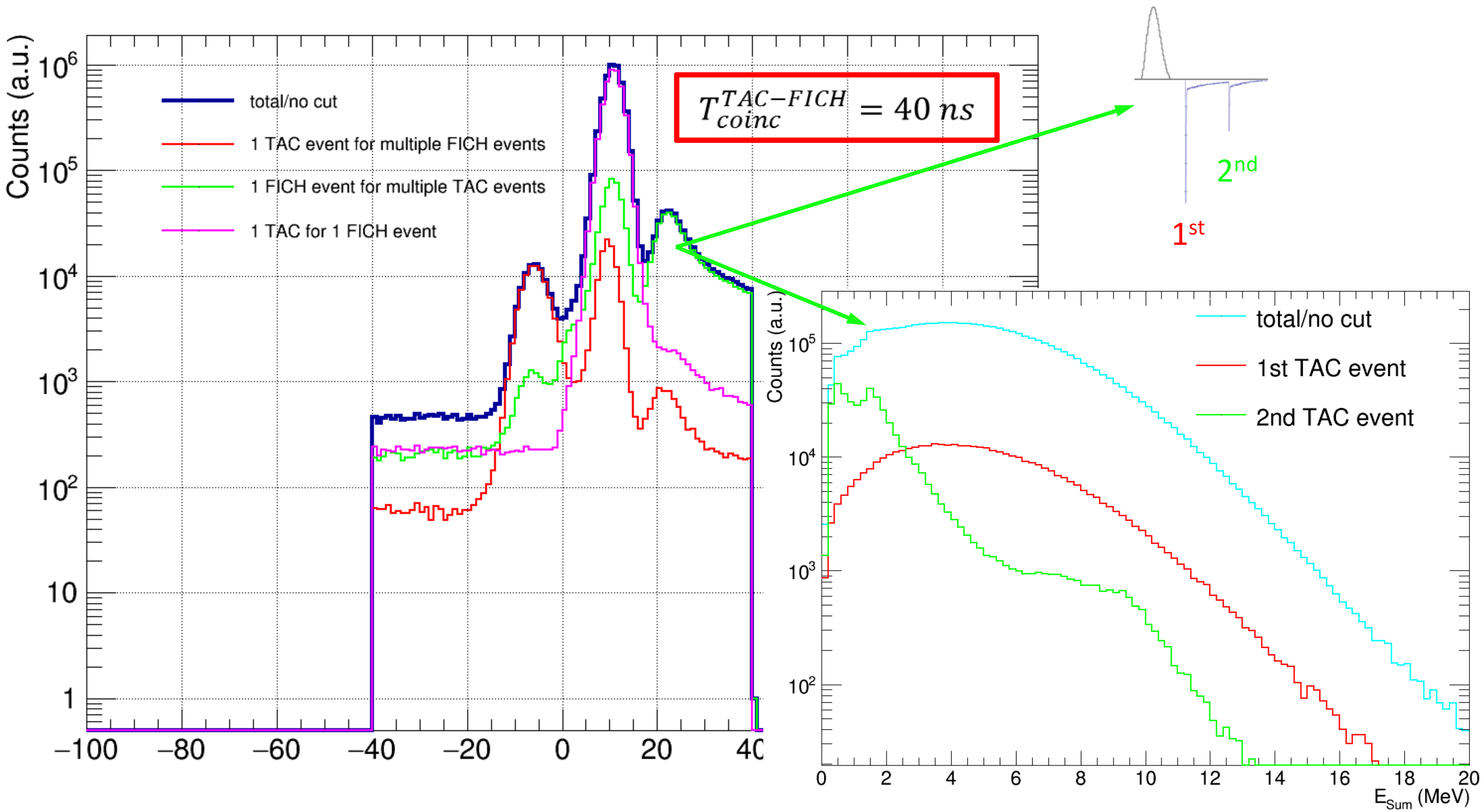
FICH

TAC

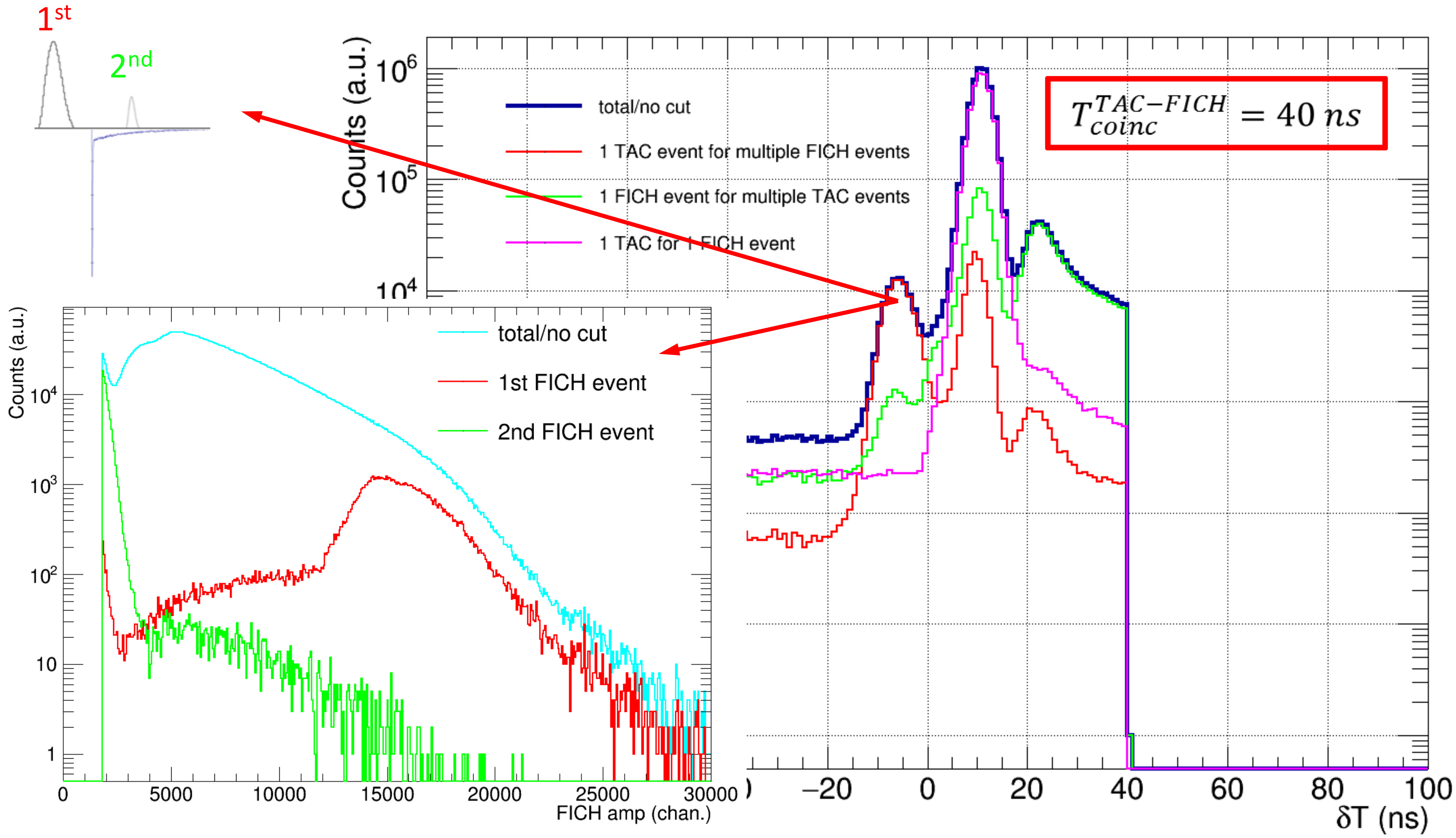




Coincidence II - δT



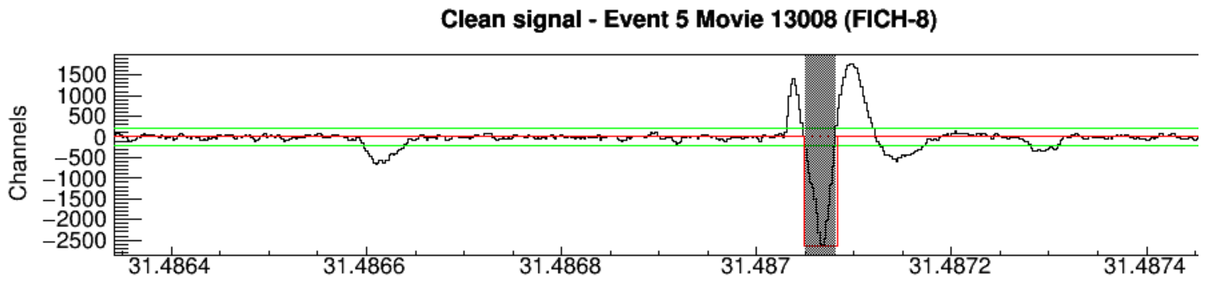
Coincidence III - δT

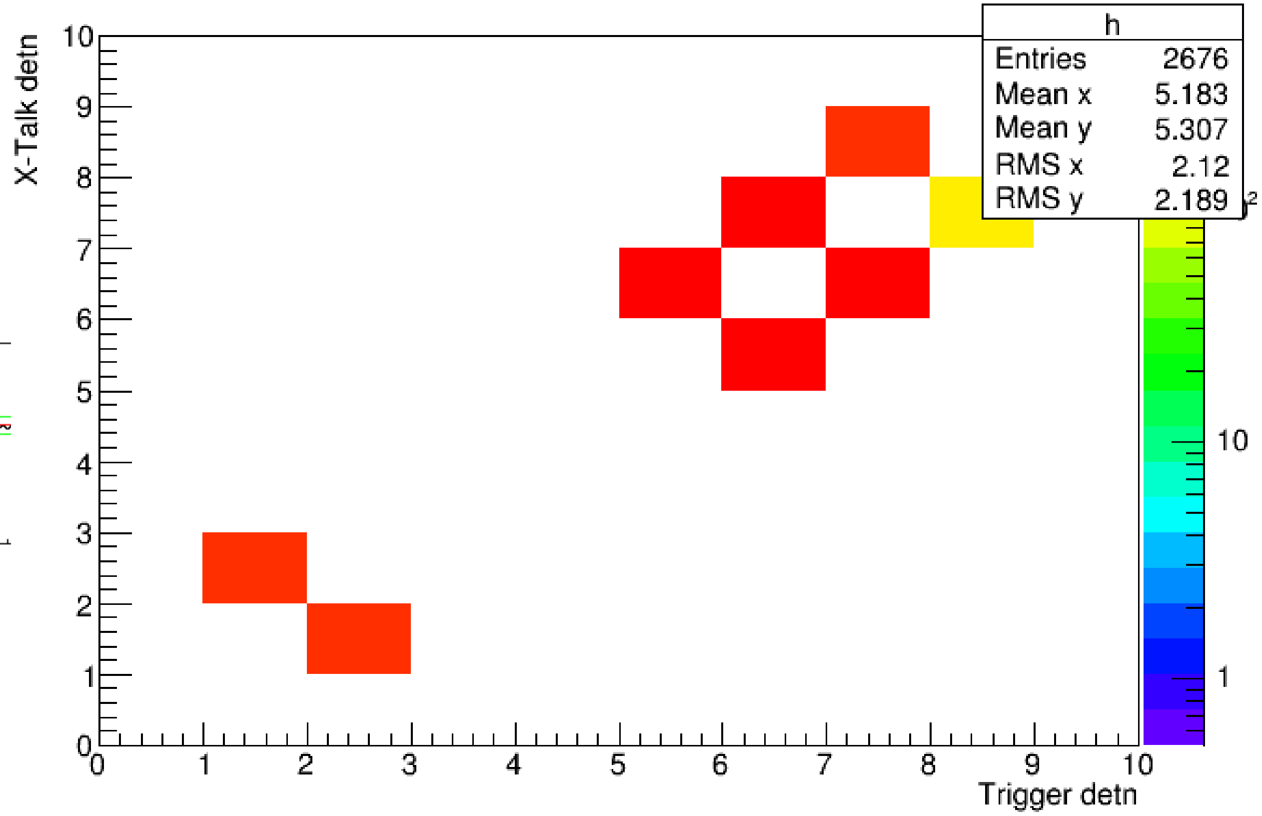


Coincidence IV - δT

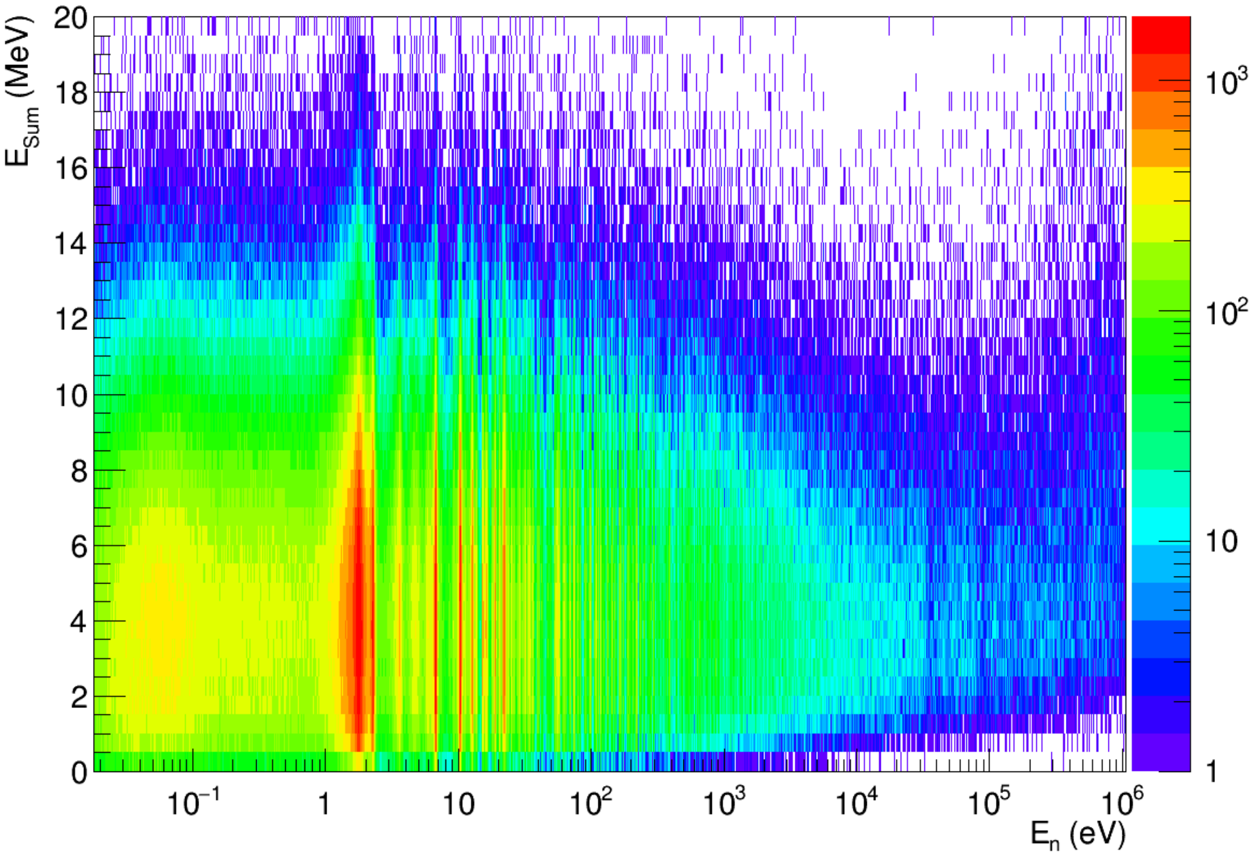
- Left peak:
  - Strict time correlation (16 ns)
  - Mostly appears after high amplitude fission signal

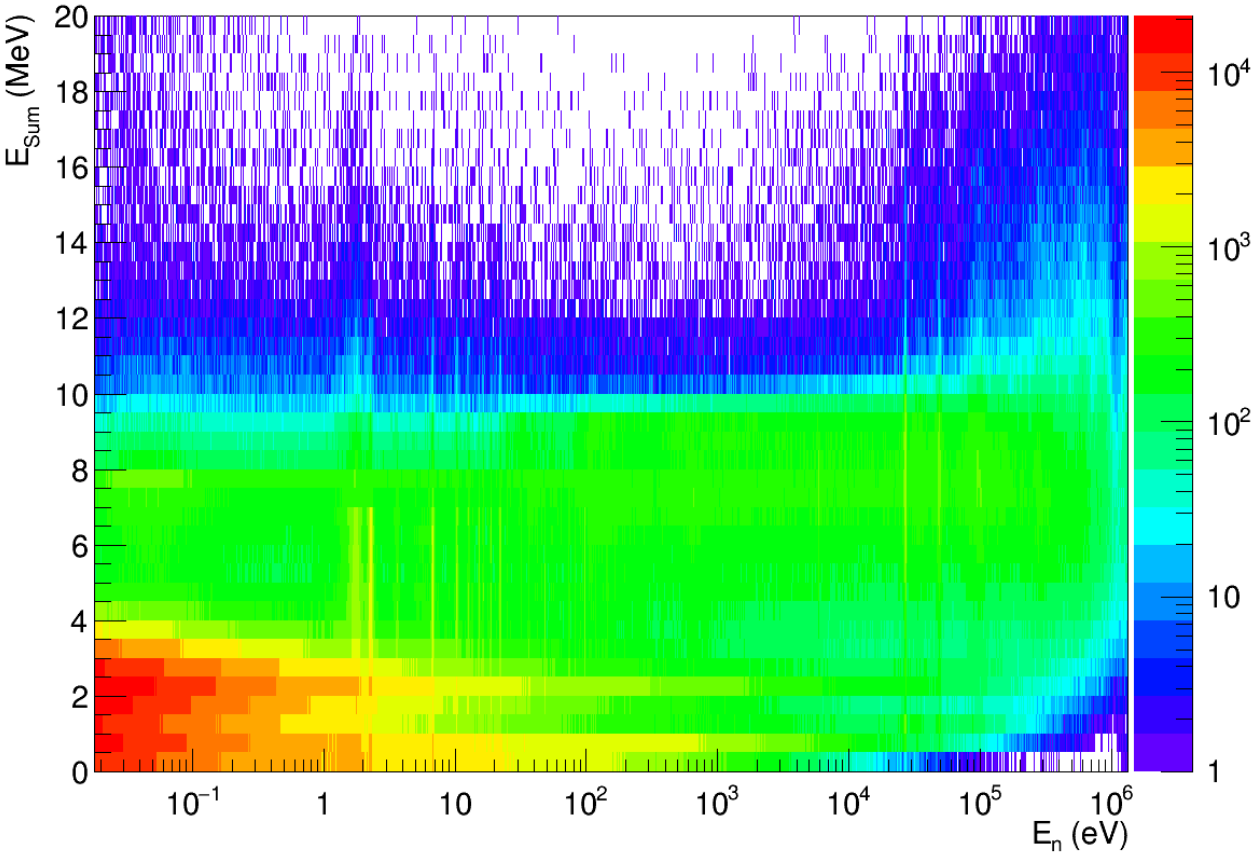
- Conclusion: Induced signals/X-Talk





E_{Sum} – Fission vs. „Capture"



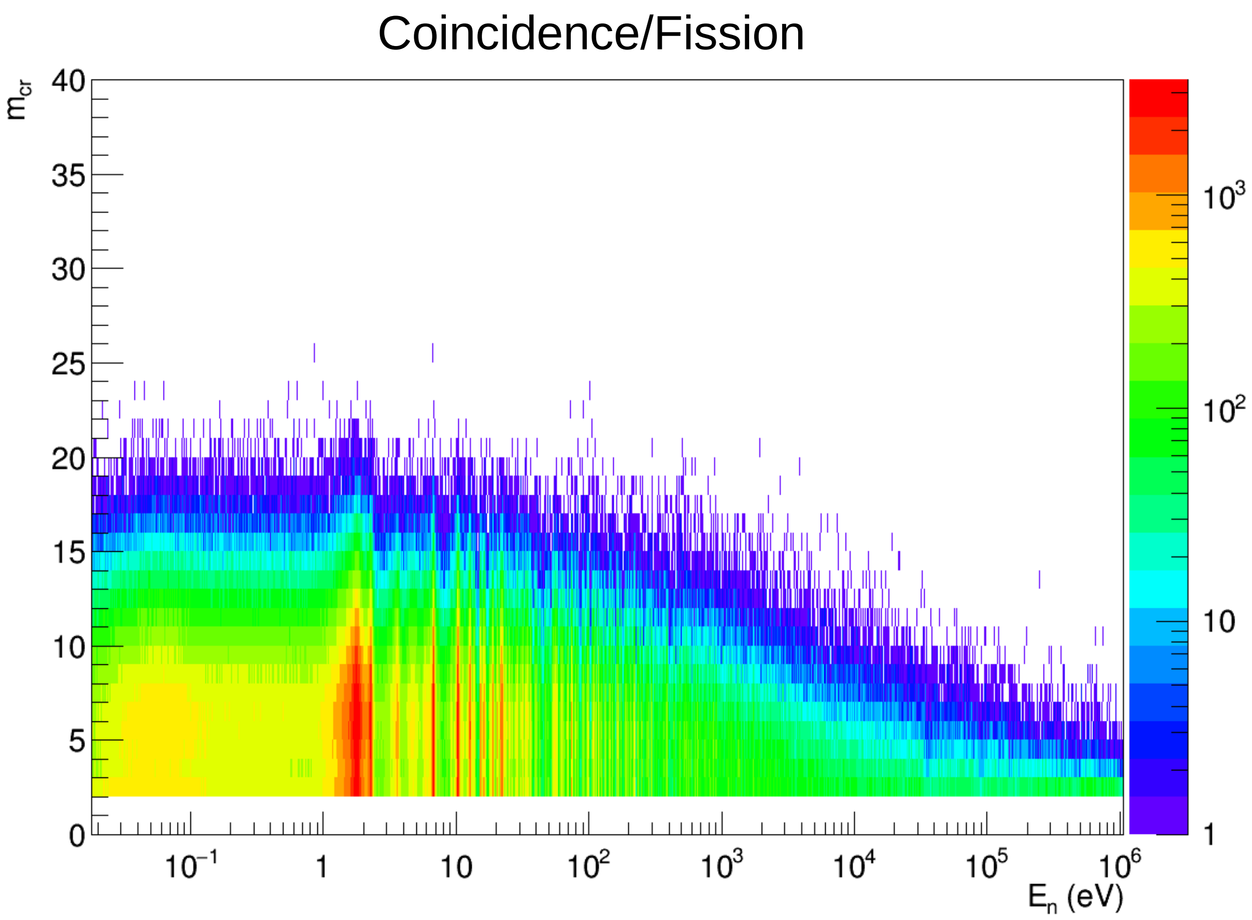


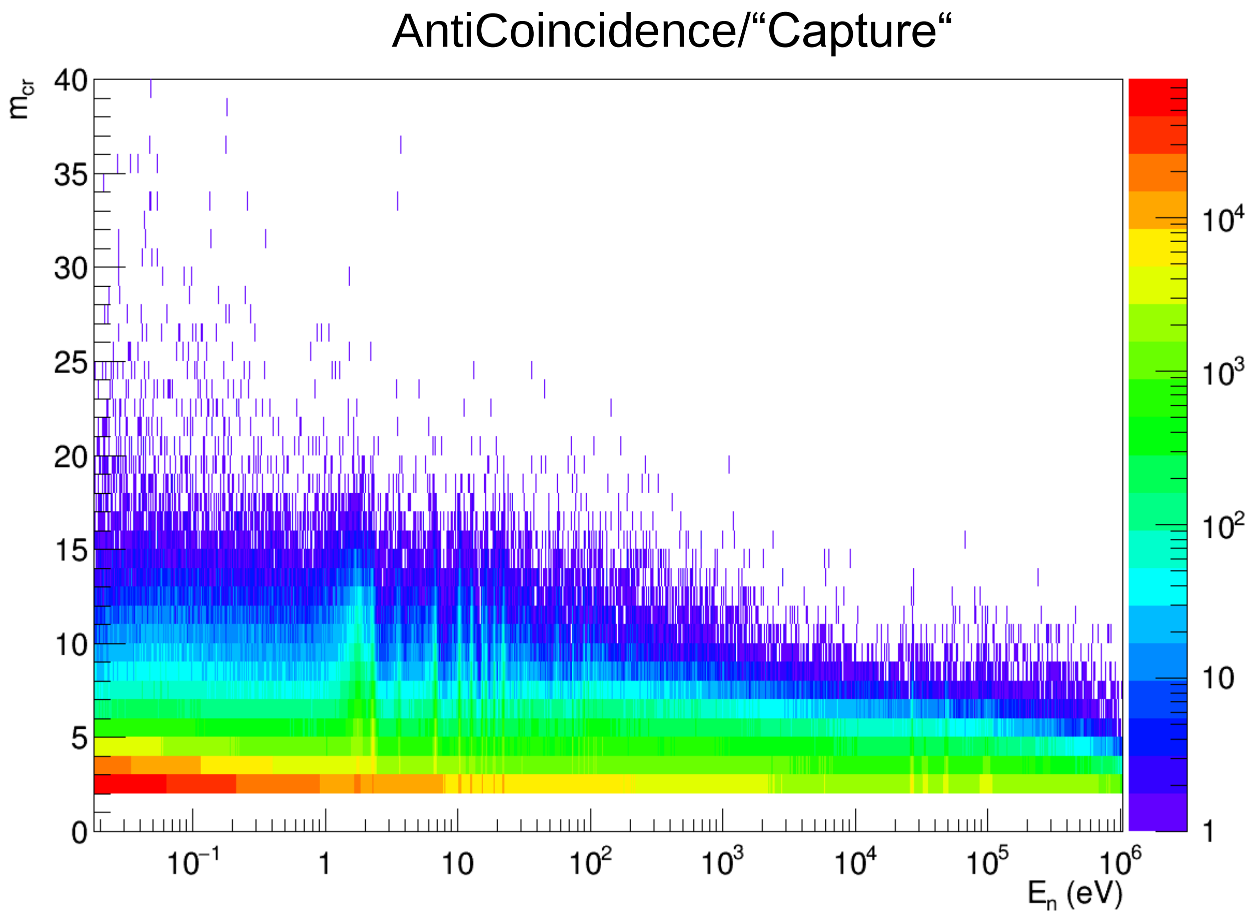
$T_{coinc}^{TAC} = 10\ ns$

$T_{coinc}^{TAC-FICH} = 40\ ns$

$E_{dep}^{BaF_2} = 100\ keV$

Multiplicity m_{cr} – Fission vs. „Capture“



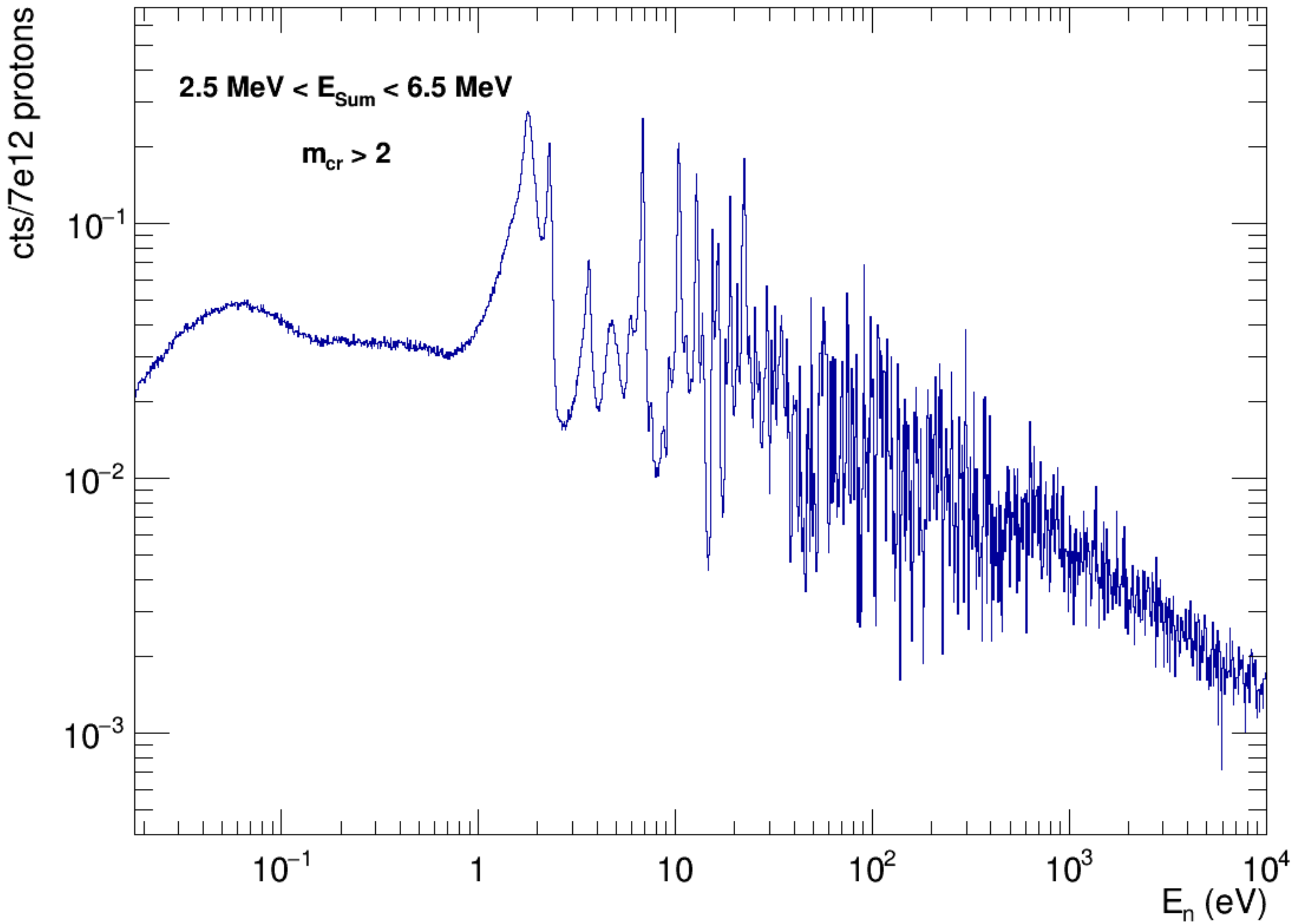


$T_{coinc}^{TAC} = 10\ ns$

$T_{coinc}^{TAC-FICH} = 40\ ns$

$E_{dep}^{BaF_2} = 100\ keV$

Coincidence – Fission

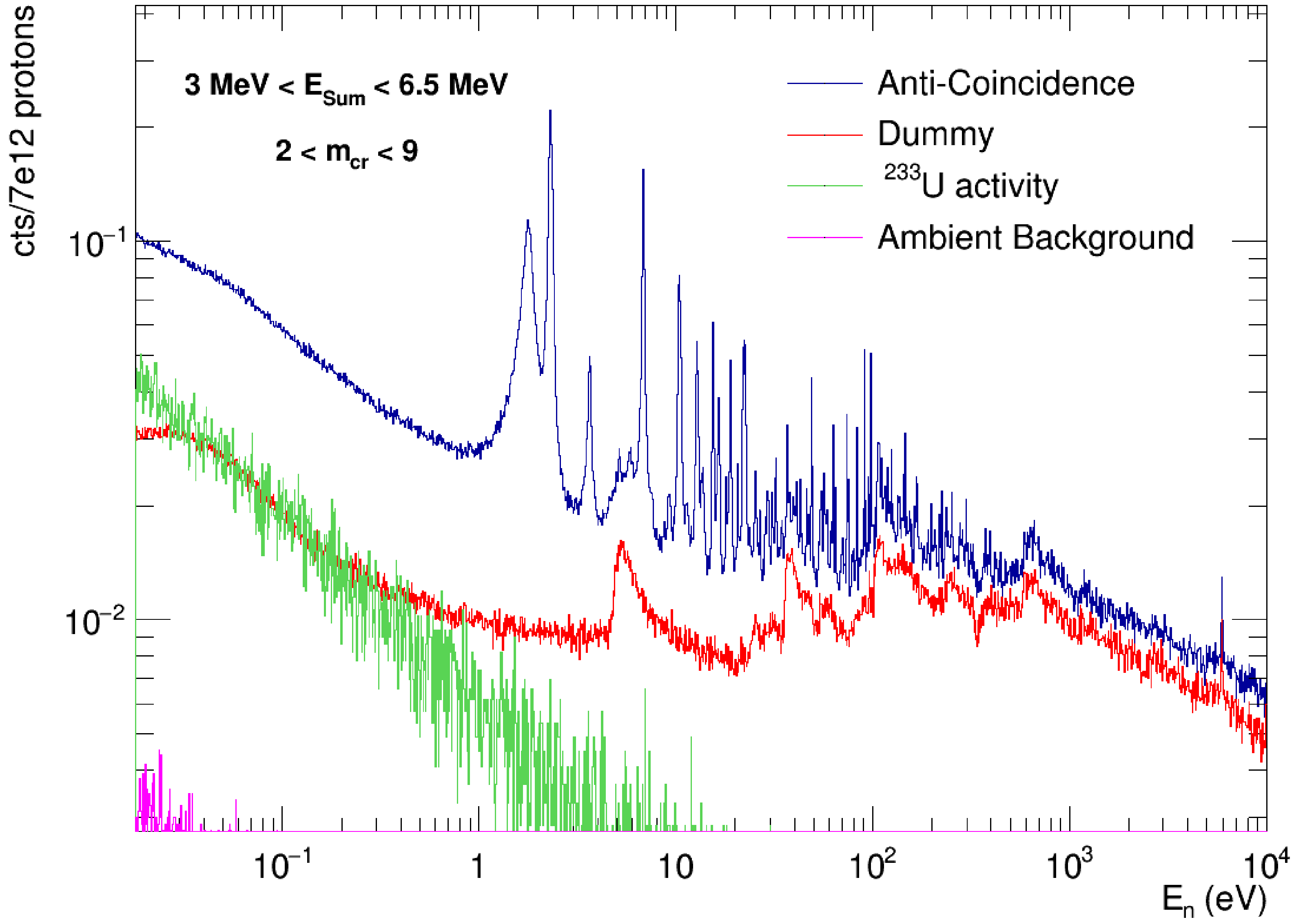


$$T_{coinc}^{TAC} = 10\ ns$$

$$T_{coinc}^{TAC-FICH} = 40\ ns$$

$$E_{dep}^{BaF_2} = 100\ keV$$

AntiCoincidence – „Capture“



$T_{coinc}^{TAC} = 10\ ns$

$T_{coinc}^{TAC-FICH} = 40\ ns$

$E_{dep}^{BaF_2} = 100\ keV$

nTOF CERN cea CENBG European Commission Joint Research Centre TU WIEN