Re-TOF: A novel detector for the measurement of the fission cross section induced by high energy neutrons

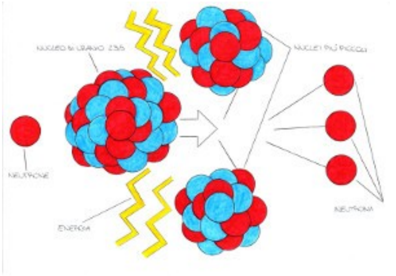
A. Manna, R. Zarrella, L. Audouin, F. Garcia-Infantes, C. Massimi, A. Mengoni, P. Morfouace, R. Mucciola, E. Pirovano, M. Spelta, J. Taieb, L. Tassan-Got, G. Vannini, A. Ventura
on behalf of the n_TOF Collaboration

European Nuclear Physics Conference, 21–26 Sept 2025 Moho

High energy neutron

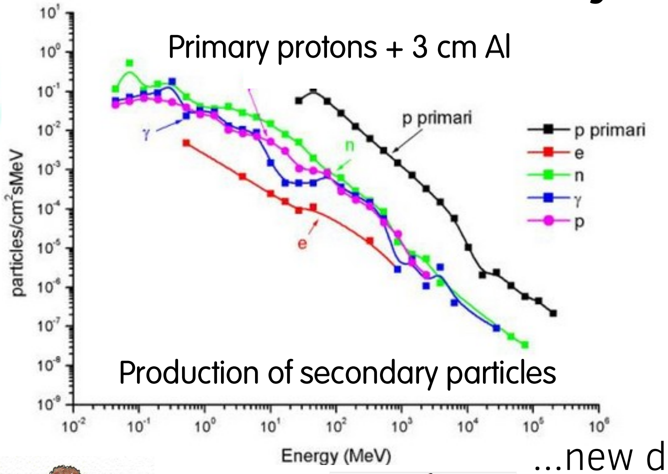
Reaction induced by high energy (> 10 MeV) neutrons...

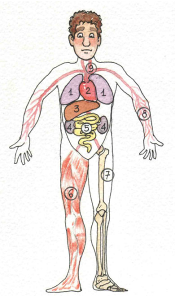
Collective → Single particle degrees of freedom in nuclei

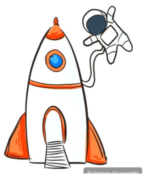


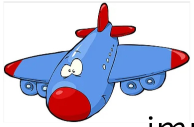
Dynamic effects of the nuclear fission process

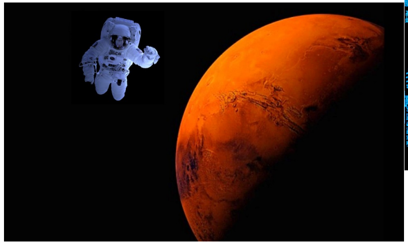
Dosimetry

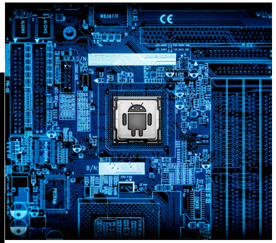




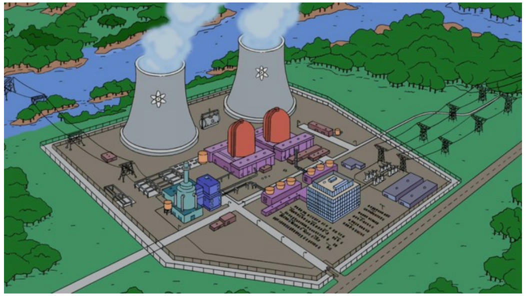




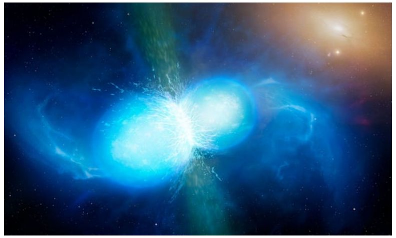




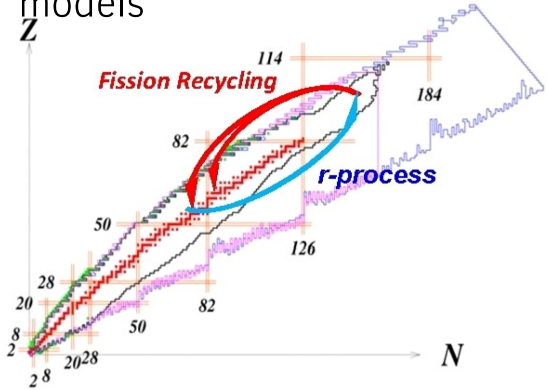
Reactor technology



Nuclear Astrophysics



...new data "outside the already known energy region" will improve the theoretical models



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High energy neutron

Reaction induced by high energy (> 10 MeV) neutrons... How

Neutrons Detectors, able to measure up to GeV, ideally

1. Reaction to investigate

2. Neutron flux

High energy neutron

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fission events

Neutrons Detectors, able to measure up to GeV, ideally

1. Reaction to investigate

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The n_TOF facility

Where

- High energy resolution

  Time of Flight (ToF) technique

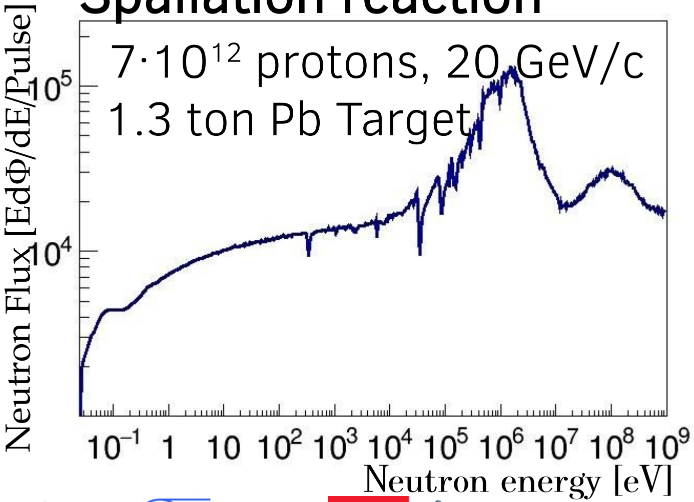
  long flight path: 185 m @ EAR 1

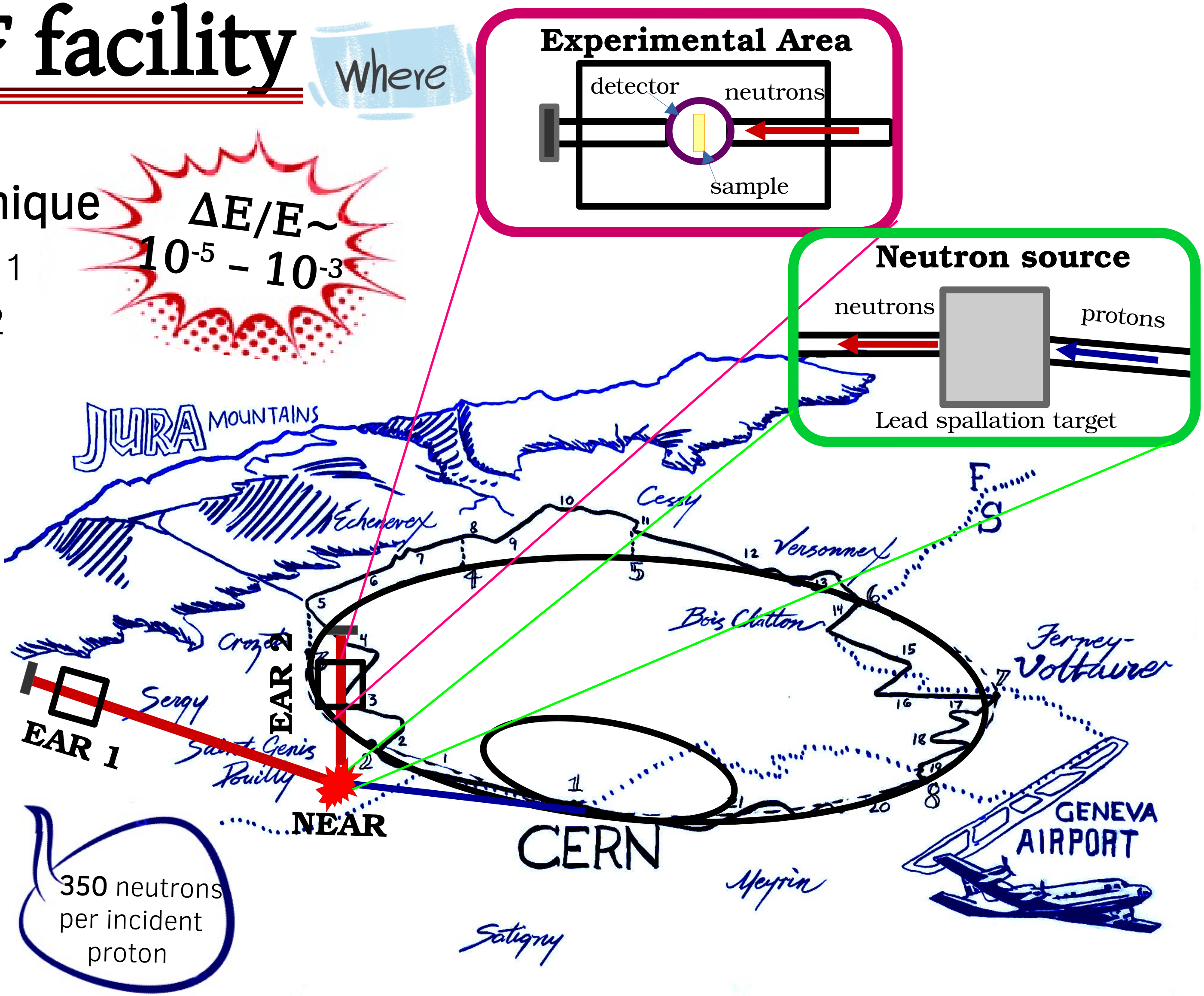
  20 m @ EAR 2

$\Delta E/E \sim 10^{-5} - 10^{-3}$

- High neutron flux & wide energy range

  Spallation reaction





High energy neutron

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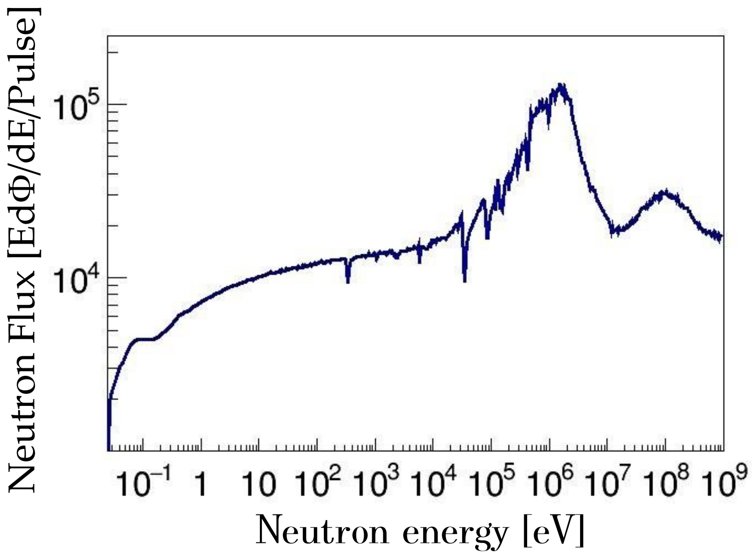
✓ Neutrons

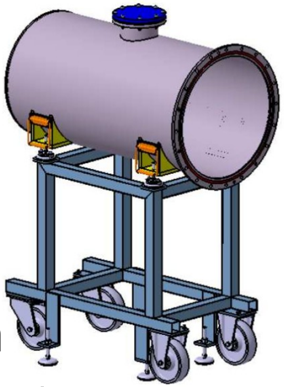
Detectors, able to measure fission events up to GeV, ideally

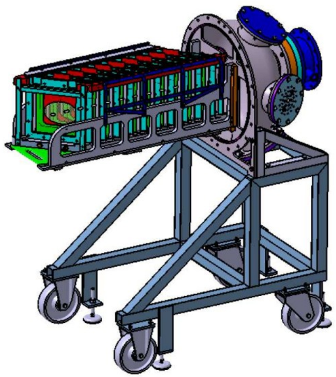


1. Reaction to investigate

PPAC ensemble:

Detector already used in cross section measurement from thermal energy to GeV





- WE NEED THIS NOW Very good time resolution
- WE NEED THIS NOW Low sensitivity to the γ-flash
- WE NEED THIS NOW Good discrimination between α particles and FFs

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High energy neutron

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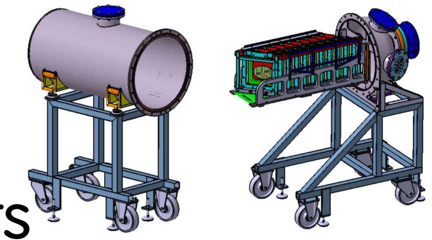
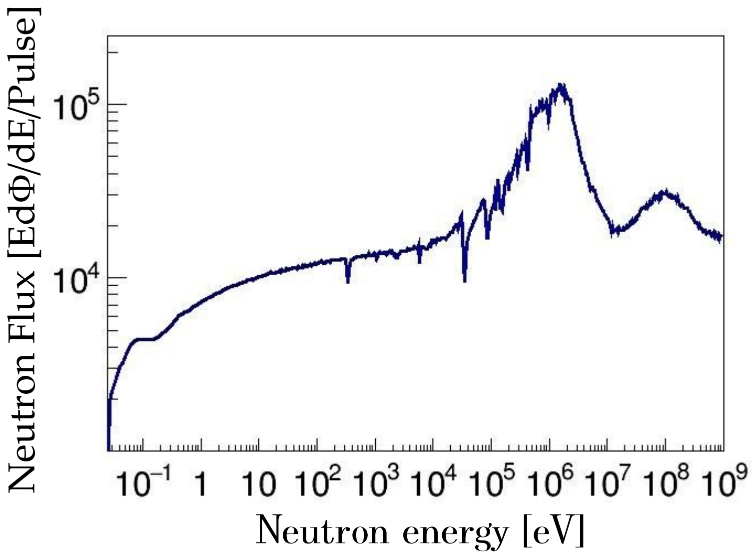
How



fission events

✓ Neutrons Detectors, able to measure ✓ up to GeV, ideally



1. Reaction to investigate

$$\sigma_f(E_n) = \frac{C(E_n)}{N\,\Phi(E_n)\,\varepsilon}$$

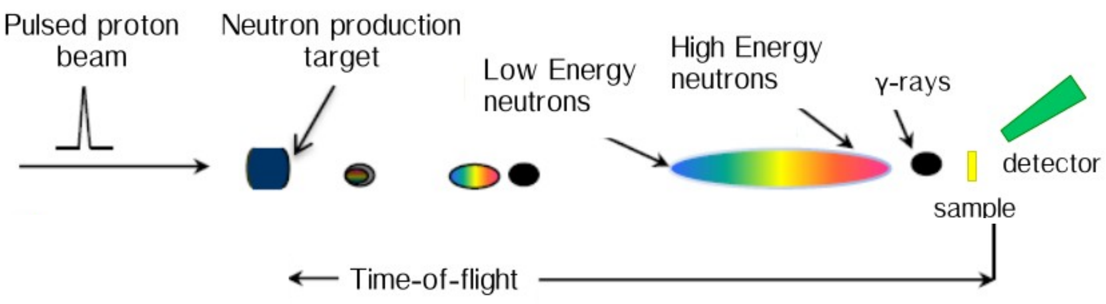
2. Neutron flux

$$\Phi(E_n) = N_\varphi \frac{C_\varphi(E_n)}{\sigma_{st}(E_n)}$$

Neutron conversion using a Standard cross section

High energy neutron

Reaction	Standard range
H(n,n)	1 keV - 20 MeV
^{3}He(n,p)	Thermal - 50 keV
^{6}Li(n,t)	Thermal - 1 MeV
^{10}B(n,α);(n,α^{1}γ)	Thermal - 1 MeV
^{nat}C(n,n)	1keV - 1.8 MeV (w angular distribution)
^{197}Au(n,γ)	200keV - 2.5MeV
^{235}U(n,f)	150keV – 200MeV + Integral [7.8 - 11] eV
^{238}U(n,f)	2 – 200MeV



Thermal Neutron Constants: (nth,f), (nth,el), (nth,γ) cross sections for fissile targets ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu.
Total nubar 252Cf(sf).
+ ^{197}Au(n,γ)

Evaluation of the Neutron Data Standards, Nuclear Data Sheets (2018)

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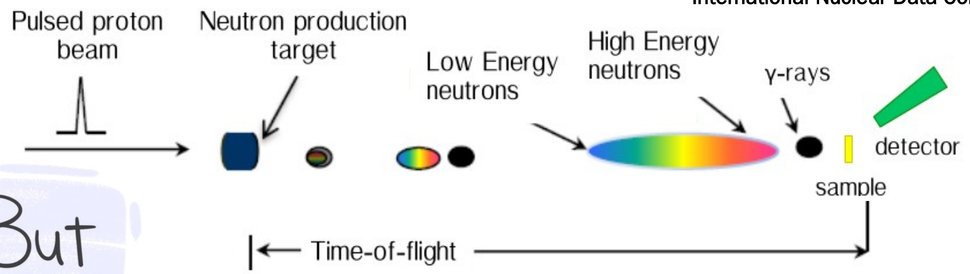
Evaluation of the Neutron Data Standards, Nuclear Data Sheets (2018)

IAEA International Atomic Energy Agency
INDC
International Nuclear Data Commitee

But



"The neutron induced fission cross sections at **high energies** are recognised as a convenient reference."

^{235}U(n,f)	0.0253 eV - 1 GeV
^{238}U(n,f)	0.0253 eV - 1 GeV
^{239}Pu(n,f)	0.0253 eV - 300 MeV
^{209}Bi(n,f)	34 MeV - 1 GeV
^{nat}Pb(n,f)	34 MeV - 1 GeV

"...Our analysis indicates that the new absolute measurements of the neutron induced fission cross sections (e.g. **relative to n-p scattering**) on **Uranium**, Bismuth, Lead and Plutonium have the highest priority in establishing neutron induced fission reaction standard **above 200 MeV**..."

(INDC(NDS)-0681 Distr. ST/J/G/NM, IAEA 2015)

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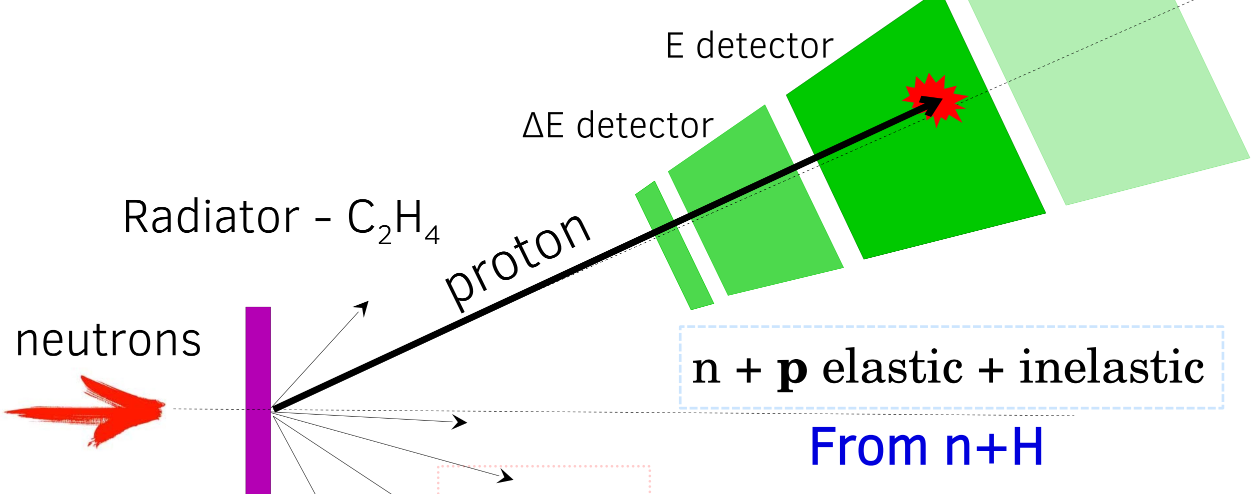
Neutron flux

n-p elastic scattering reaction



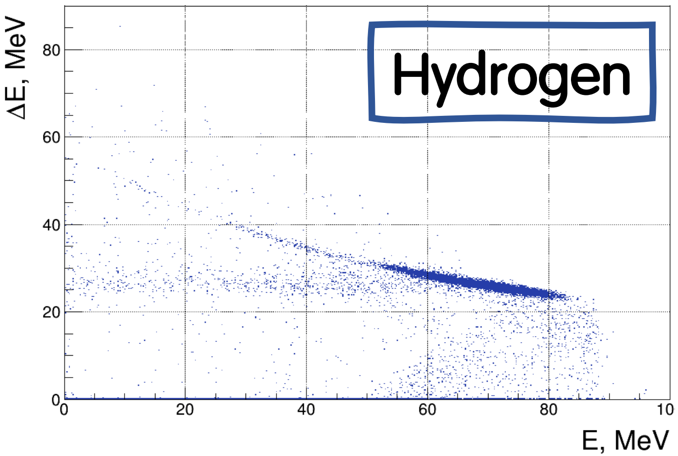
Proton Recoil Telescope (RPT)

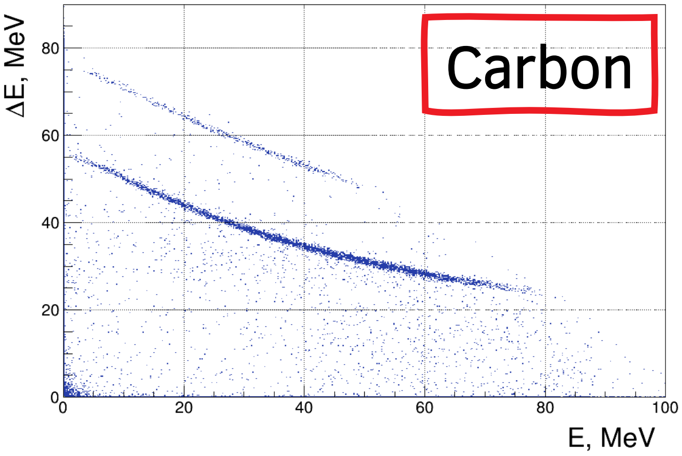
$$\Delta E \cdot E \propto k \cdot z^2 \cdot M$$

k: material absorption properties

M, E, z: interacting particle properties

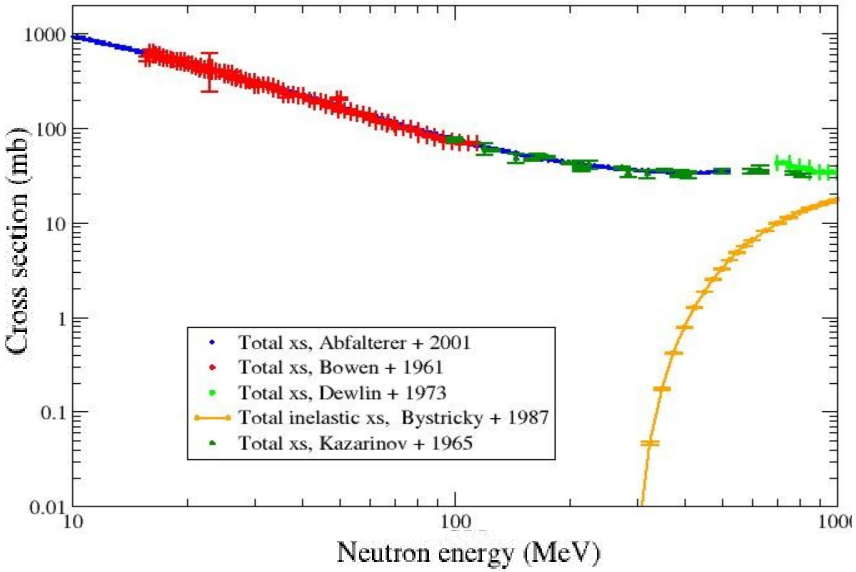
*non-relativistic approximation





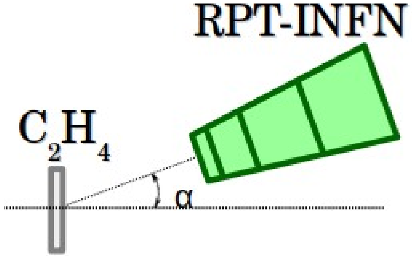
But

Neutron flux



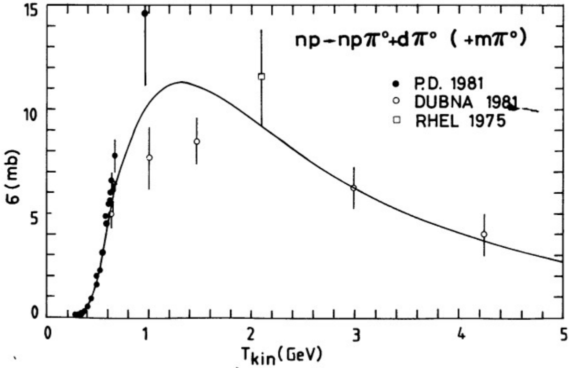
From ~290 MeV of neutron energy:
opening of the inelastic channel

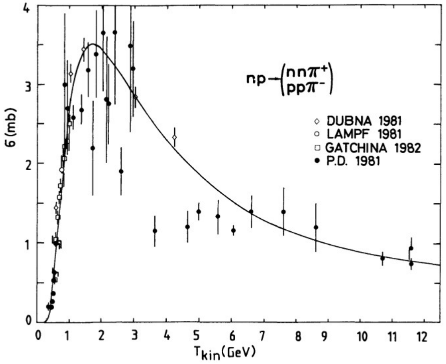
$$n + p \rightarrow N + N + \pi$$



With a Recoil Proton Telescope :

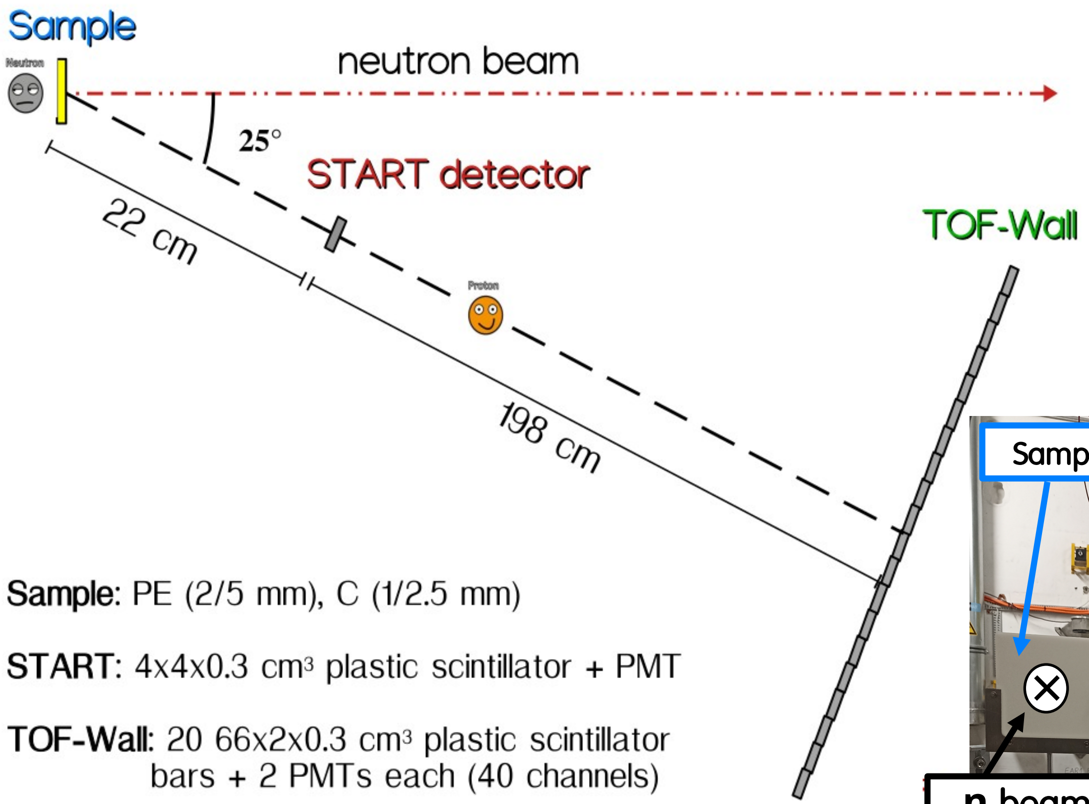
- calculate the angular distribution considering the boost effect
- simulate the proton energy distribution - 3-body





En, MeV	corr, % - 20°	corr, % - 25°
300	0.0	0.0
350	0.0	0.0
400	0.9	0.0
425	3.1	0.8
450	6.4	2.7
475	11.4	5.9
500	18.5	10.7

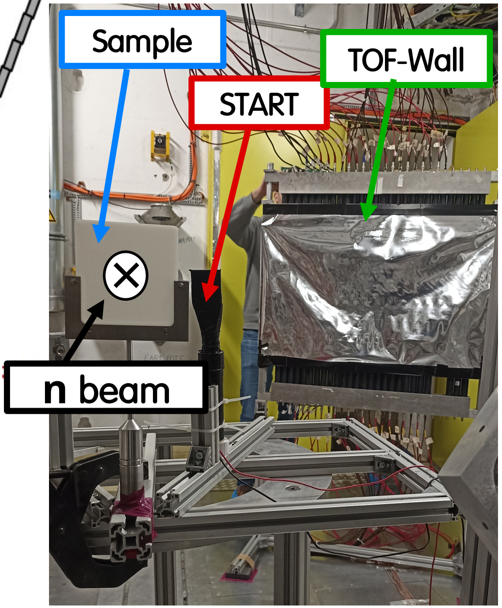
Re-TOF detector



Sample: PE (2/5 mm), C (1/2.5 mm)

START: 4x4x0.3 cm³ plastic scintillator + PMT

TOF-Wall: 20 66x2x0.3 cm³ plastic scintillator bars + 2 PMTs each (40 channels)



Wide neutron energy range:
From ~20 MeV to GeV
wide range of energy loss

Fix kinematic from the elastic channel

$$E_p = E_n \cos^2\vartheta.$$

Least-favorable scenario:

1 GeV neutron

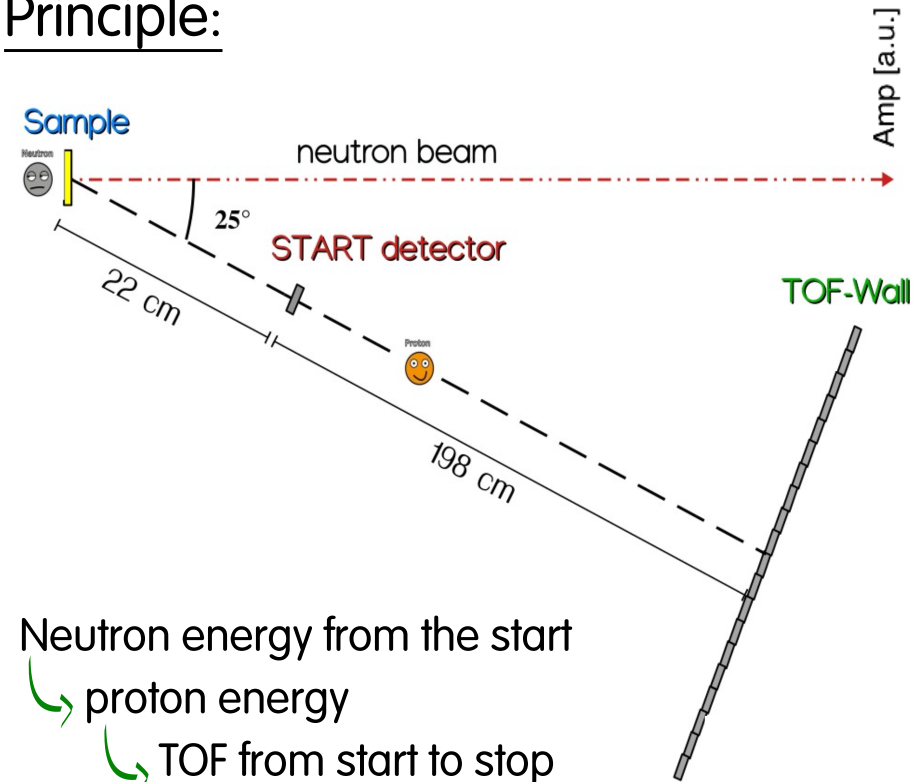
the nucleons take the full kinetic energy after creation of the pion

Δt (elastic - inelastic protons) = 440 ps

Time resolution of 300 ps

Start detector

Principle:



Neutron energy from the start

↳ proton energy

↳ TOF from start to stop

↳ Impose the coincidence window between start and stop

Start detector

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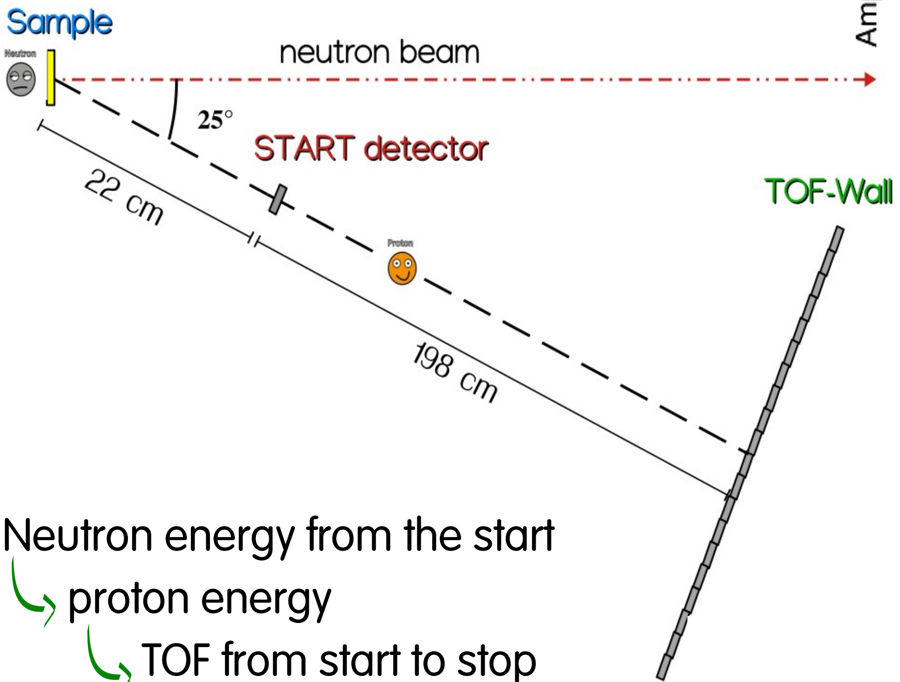

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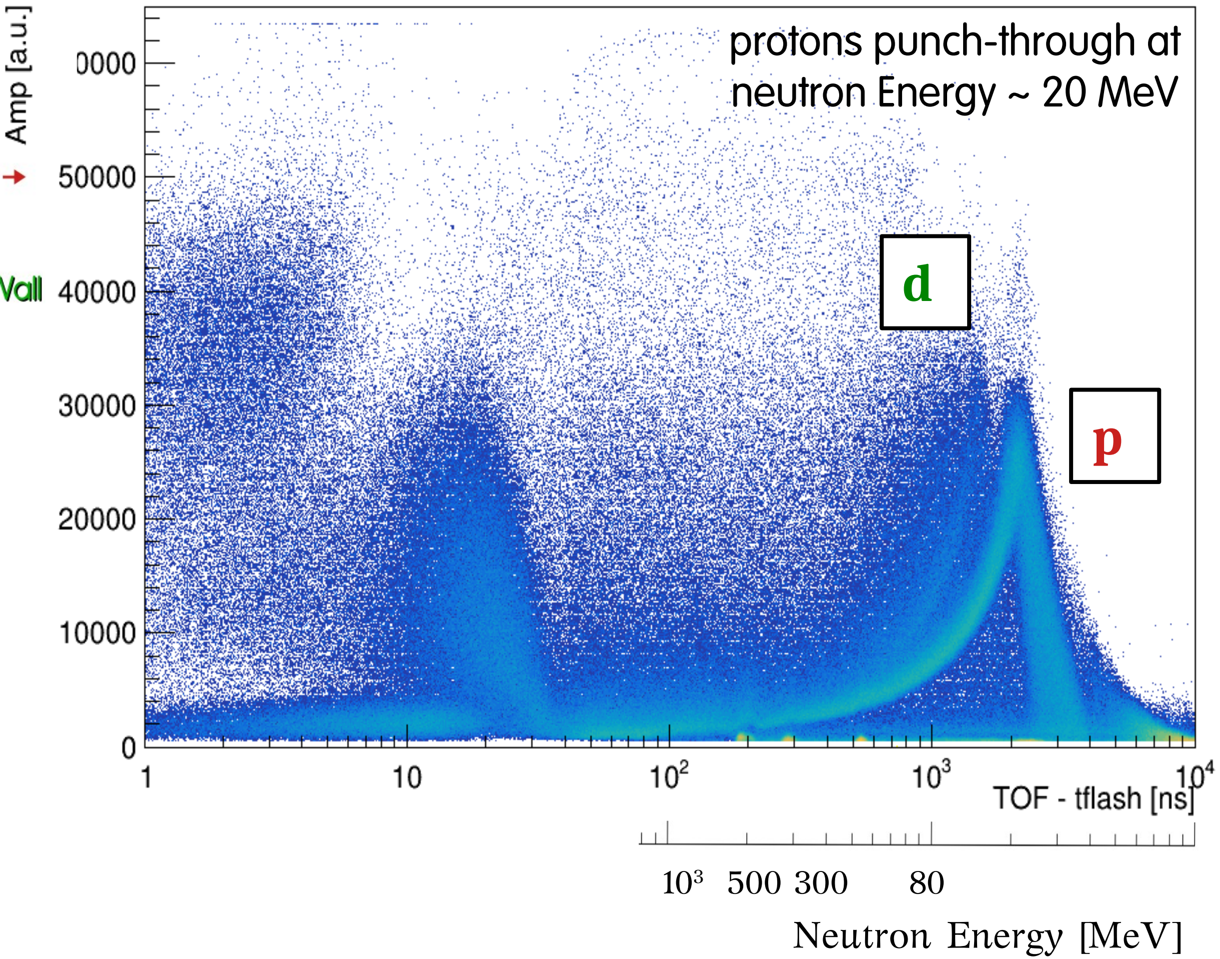
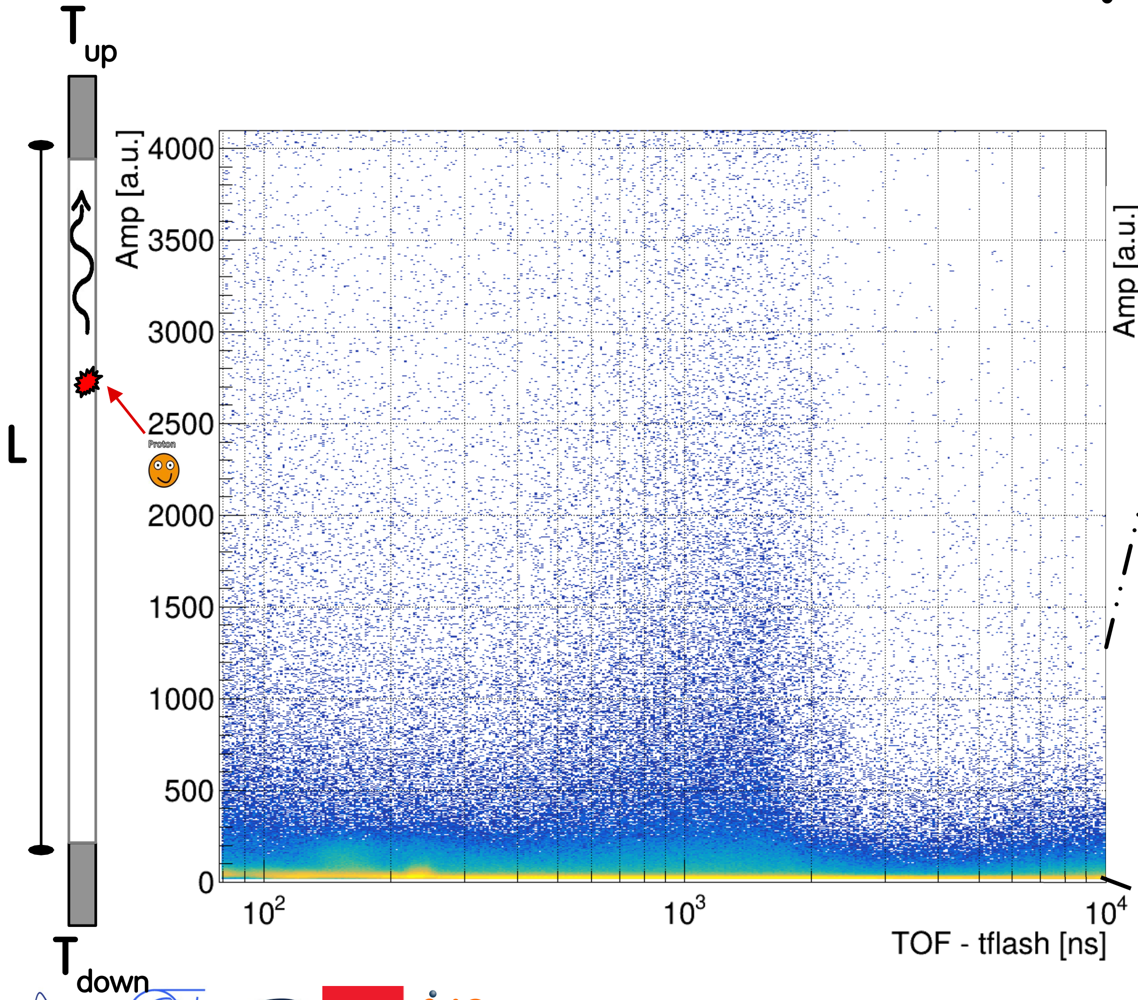
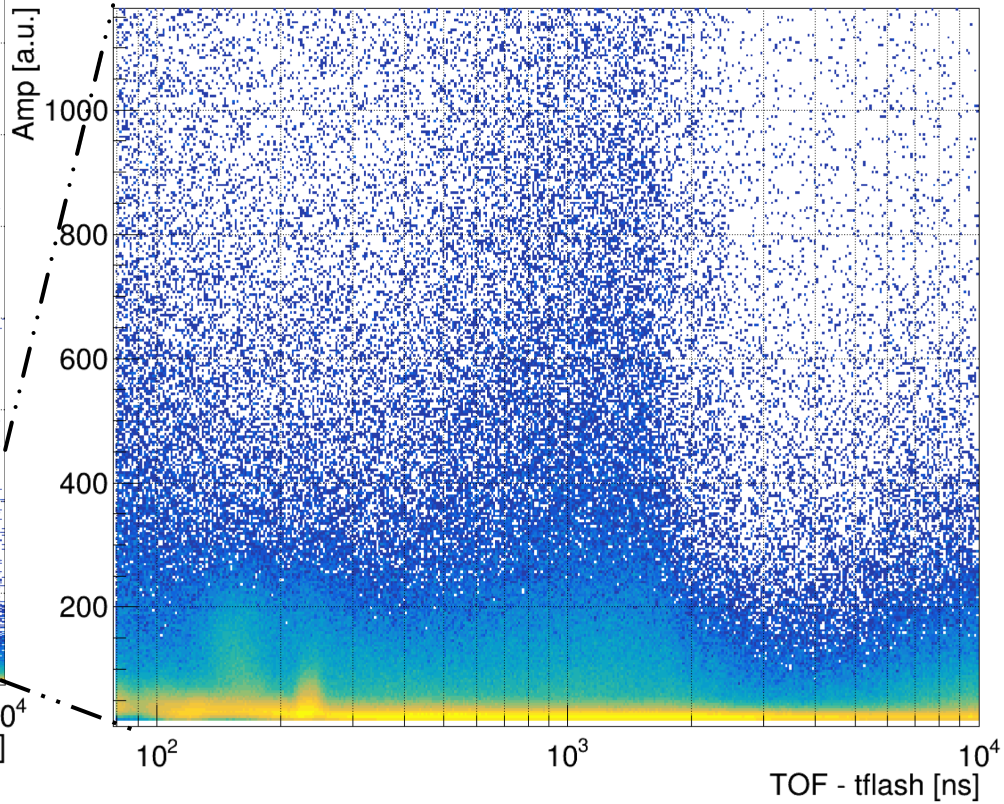


Stop detector - Tof-Wall

- Attenuation along bar
- No structure clearly visible but…

Readout at both ends of the bars
→ look for coincidences!





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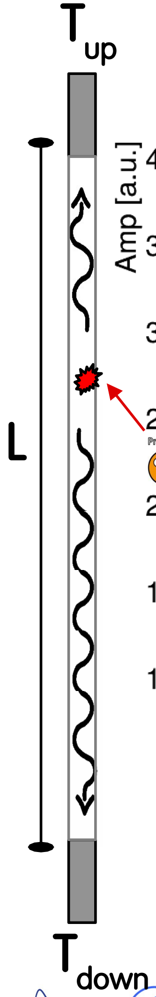
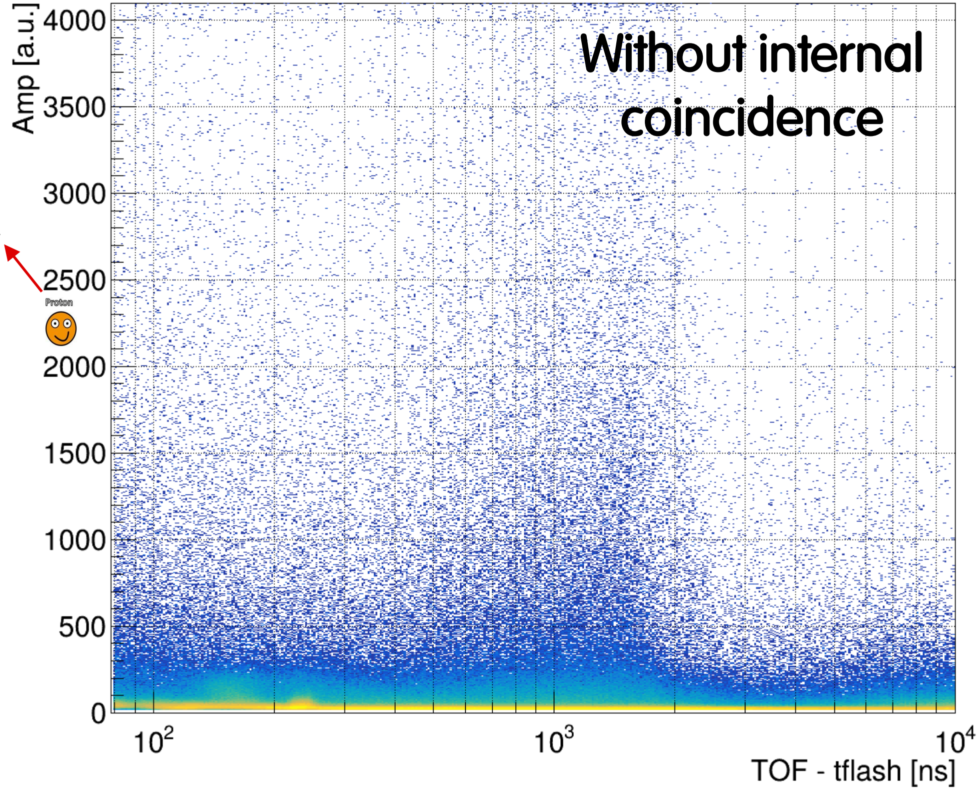
Stop detector - Tof-Wall

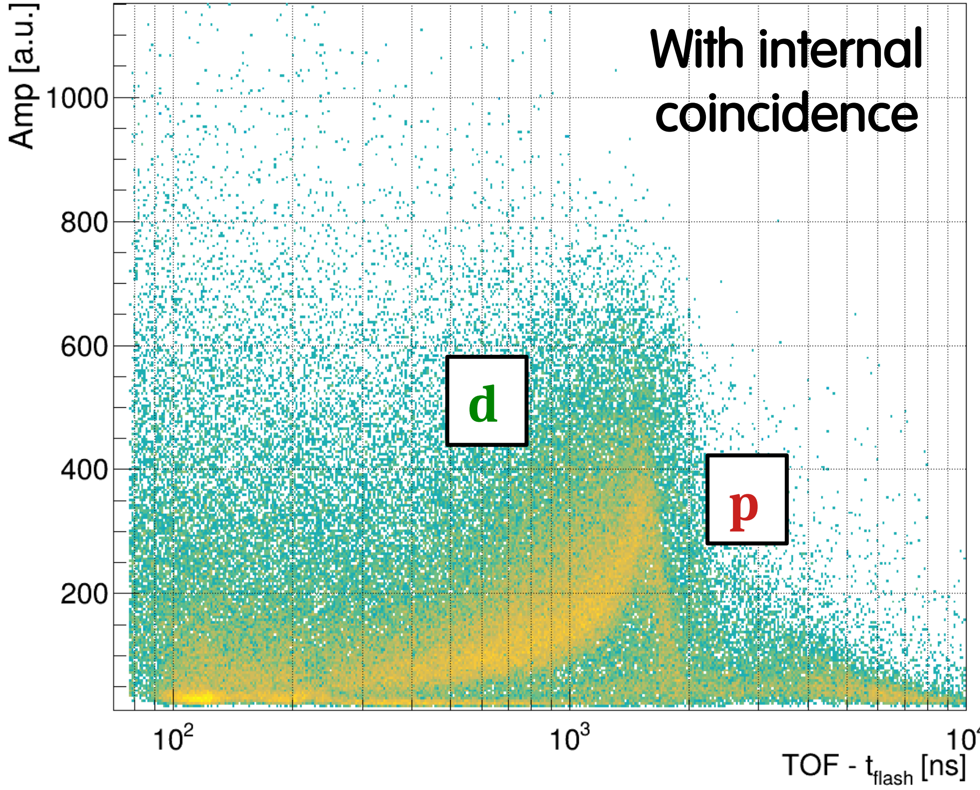
$$max\,[\Delta(T_{up} - T_{down})] \pm 5 \text{ ns}$$ ⇨ Time coincidence window for each bar

$$A_{bar} = \sqrt{A_{up} \cdot A_{down}}$$ ⇨ Remove dependence on hit position



Single channel response





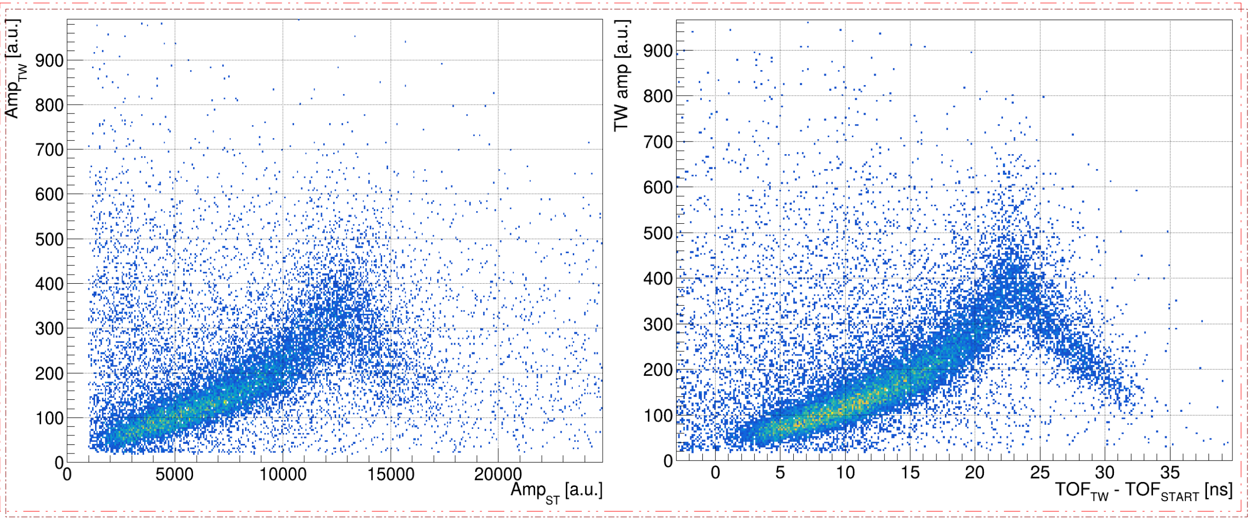
Without imposed coincidence with start detector!!!

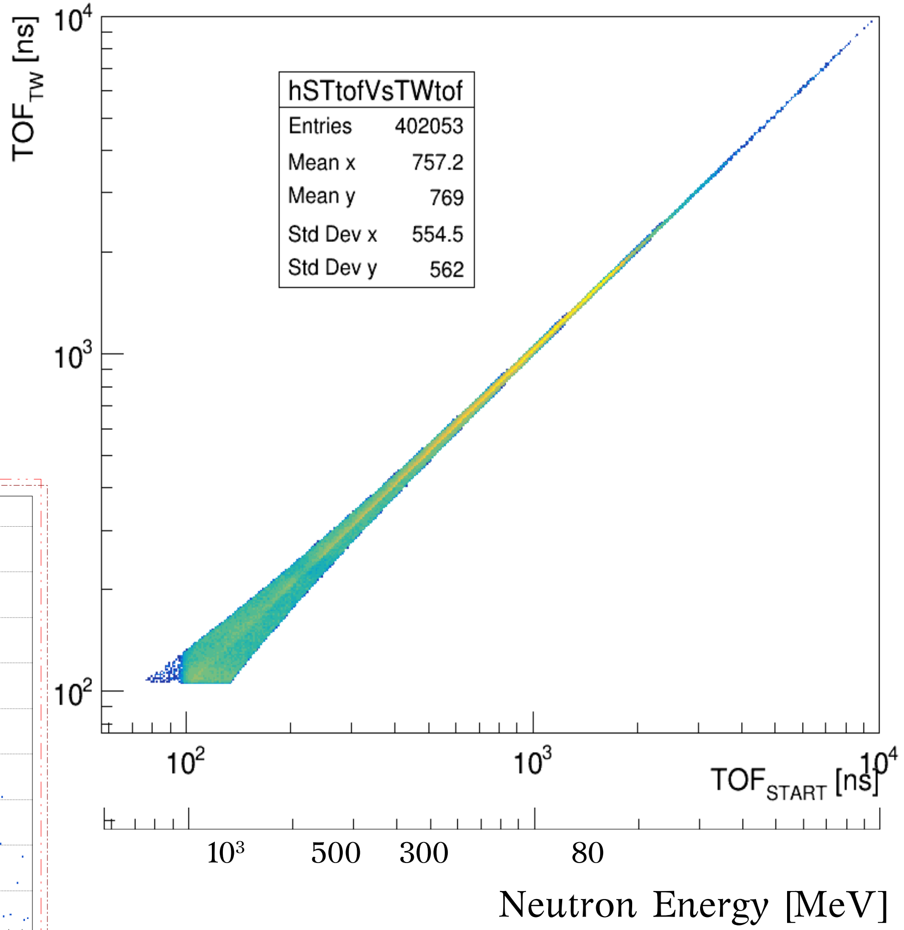
Re-TOF coincidences

Start and Tof-Wall coincidences

Expected TOF of elastic scattered protons

$$(TOF_{TW} - TOF_{ST})_{el} \simeq TOF_{p,el}(E_{p,el})$$





Wide coincidence window (30 ns)

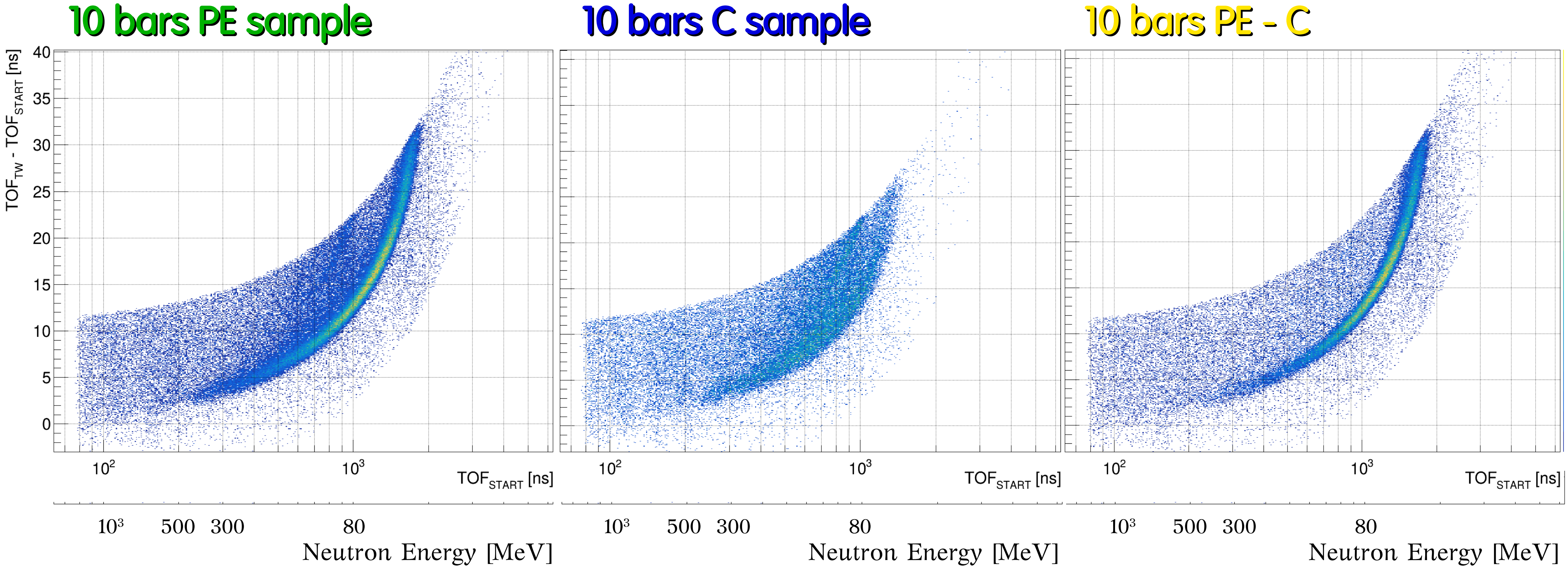
Background from combinatorial approach

Re-TOF coincidences

Start and Tof-Wall coincidences

Each bar at slightly different angle → Angle coverage of 0.5°

TOF coincidence window optimization per bar → sum of 10 bars

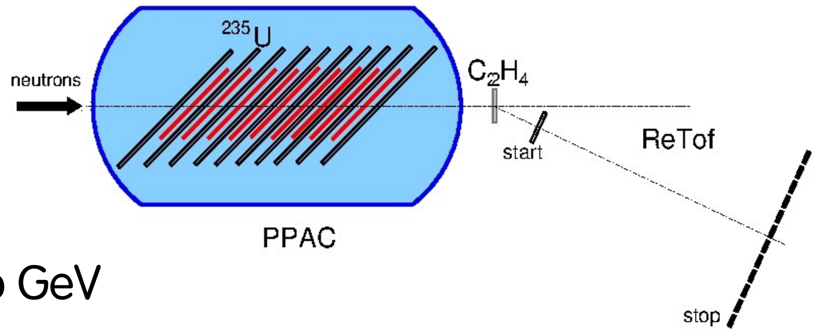


Conclusions

Re-TOF is a neutron flux detector based on the neutron-proton elastic scattering reaction

Optimizing the analysis of the performed test, of the events selection for the high energy region it will be possible to use Re-TOF from 20 MeV to GeV neutron energy.

Why



How — Re-TOF detector together with the PPAC detector

Where — @ n_TOF in EAR1, thanks to the wide neutron flux, up to GeV

What — the first measurement of ^{235}U and ^{239}Pu fission cross section and fission angular distribution up to GeV of neutron energy will be possible

Measurements already approved by the CERN scientific committee

Conclusions

Thank you for your attention

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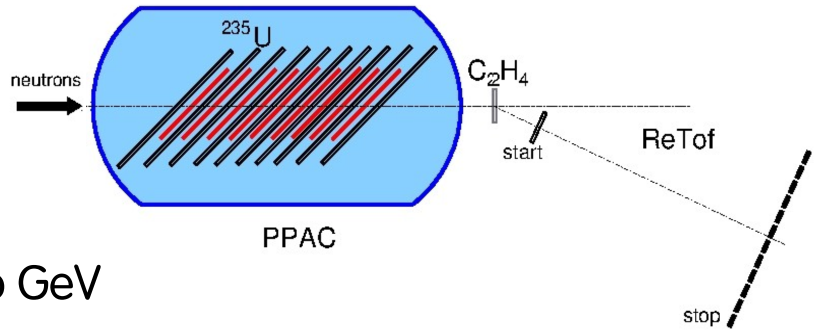
How Re-TOF detector together with the PPAC detector



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