Fission induced by high energy neutrons on ^{235}U at n_TOF: final results, impact and future perspectives

Alice Manna and Elisa Pirovano for the n_TOF Collaboration

IAEA Technical Meeting on Neutron Standards - 27-31 January 2025

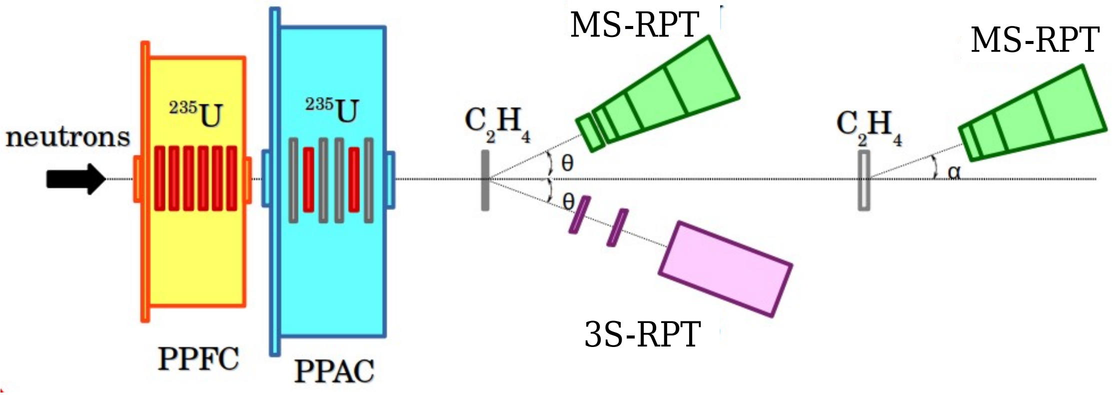
E. Pirovano *et al* 2023 *JINST* **18** P11011

A. Manna *et al* 2023 *JINST* **18** P04024

The measurement

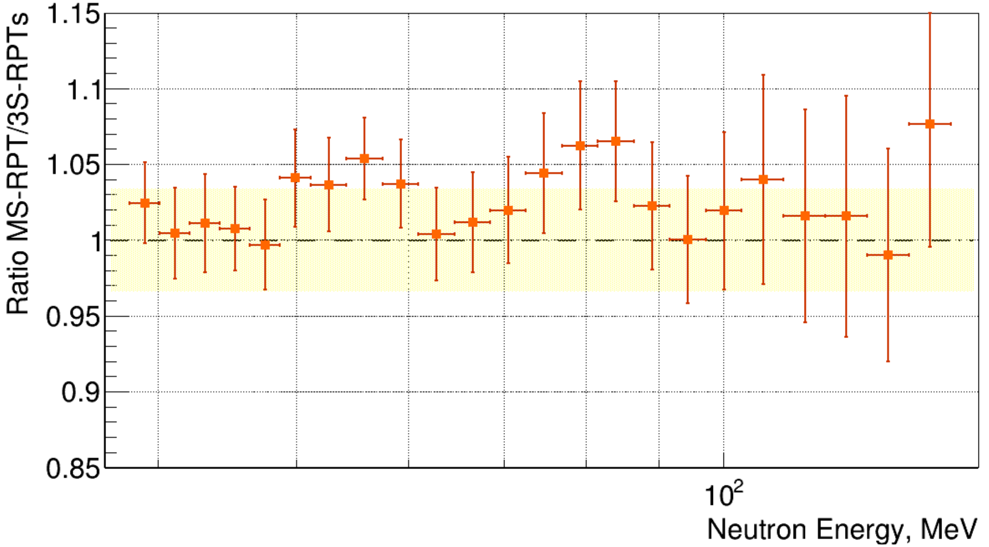
Requested protons: 4×10^{18} protons on target

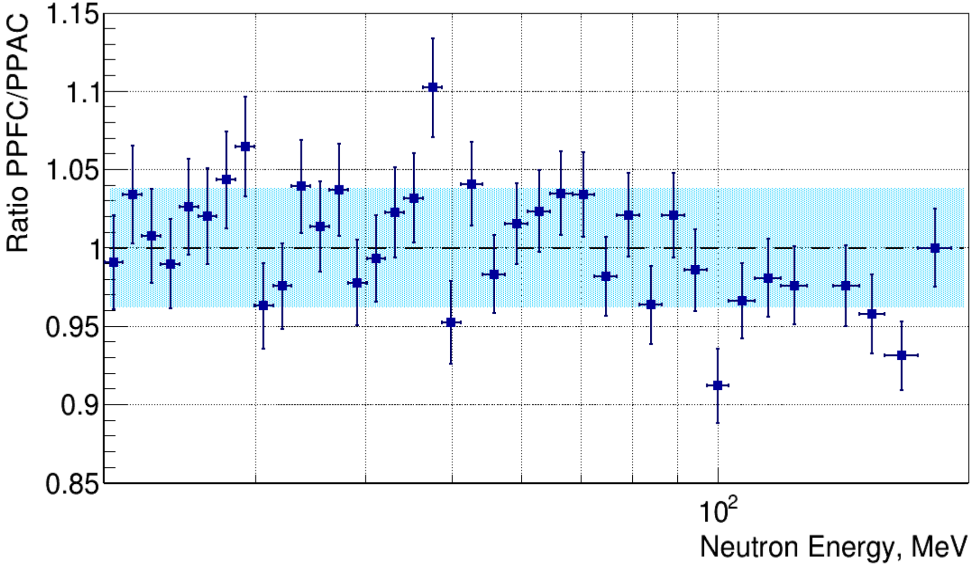
Experimental Area: EAR1



Sample	PPFC		PPAC	
	# Protons (pot)	Running time	# Protons (pot)	Running time
^{235}U	3.387×10^{18}	35 days	3.83×10^{18}	40 days

Sample	RPTs at 25°		RPT at 20°	
	# Protons (pot)	Running time	# Protons (pot)	Running time
C_2H_4 - 1 mm	7.08×10^{17}	7 days	-	-
C - 0.5 mm	3.27×10^{17}	3.5 days	-	-
C_2H_4 - 2 mm	1.11×10^{18}	11 days	-	-
C - 1 mm	3.88×10^{17}	4 days	-	-
C_2H_4 - 5 mm	7.44×10^{17}	8 days	2.07×10^{18}	20 days
C - 2.5 mm	3.14×10^{17}	3.5 days	1.55×10^{18}	16 days
Sample Out	1.48×10^{17}	1.5 days	2.23×10^{17}	2.5 days
Beam Off	-	0.25 days	-	0.25 days





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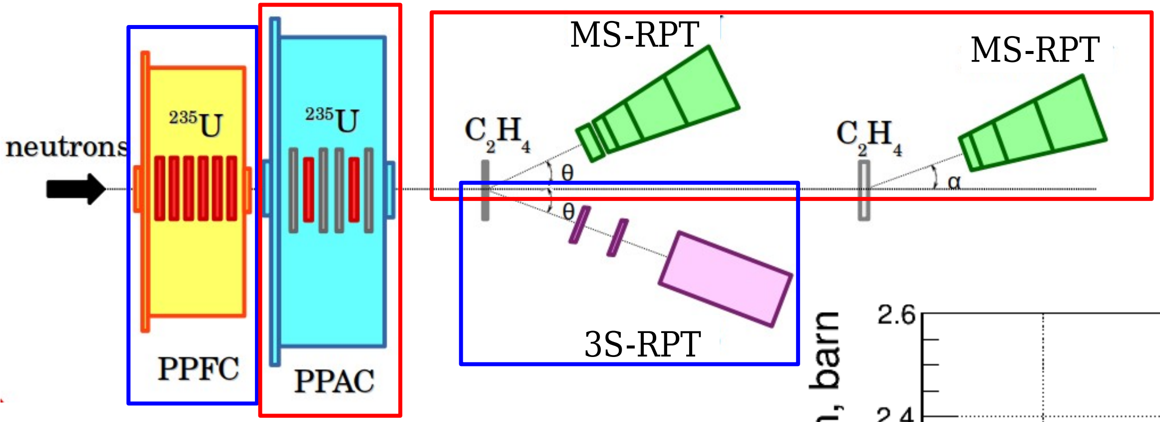
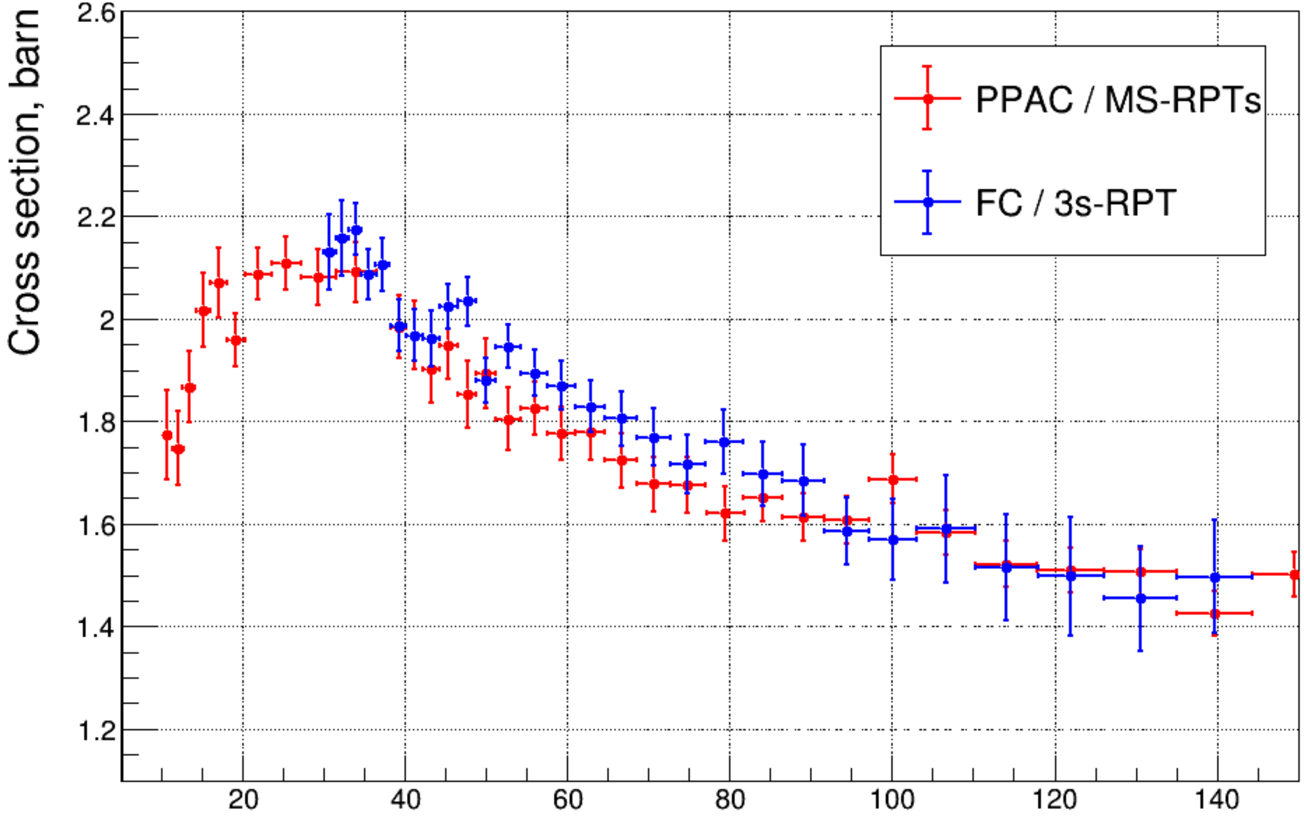
The measurement



Arndt, VL40

$$\Phi(E_n) = \frac{C_{C_2H_4}(E_n) - r_C\, C_C(E_n)}{n_H\ \varepsilon(E_n)\, d\sigma_{n,p}(E_n)/d\Omega}$$

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



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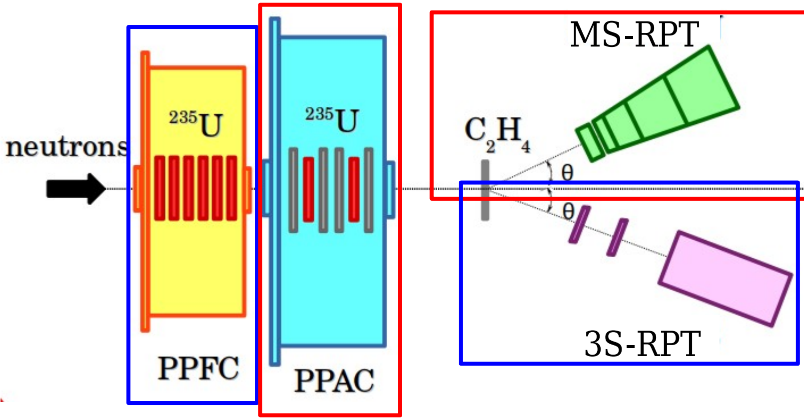
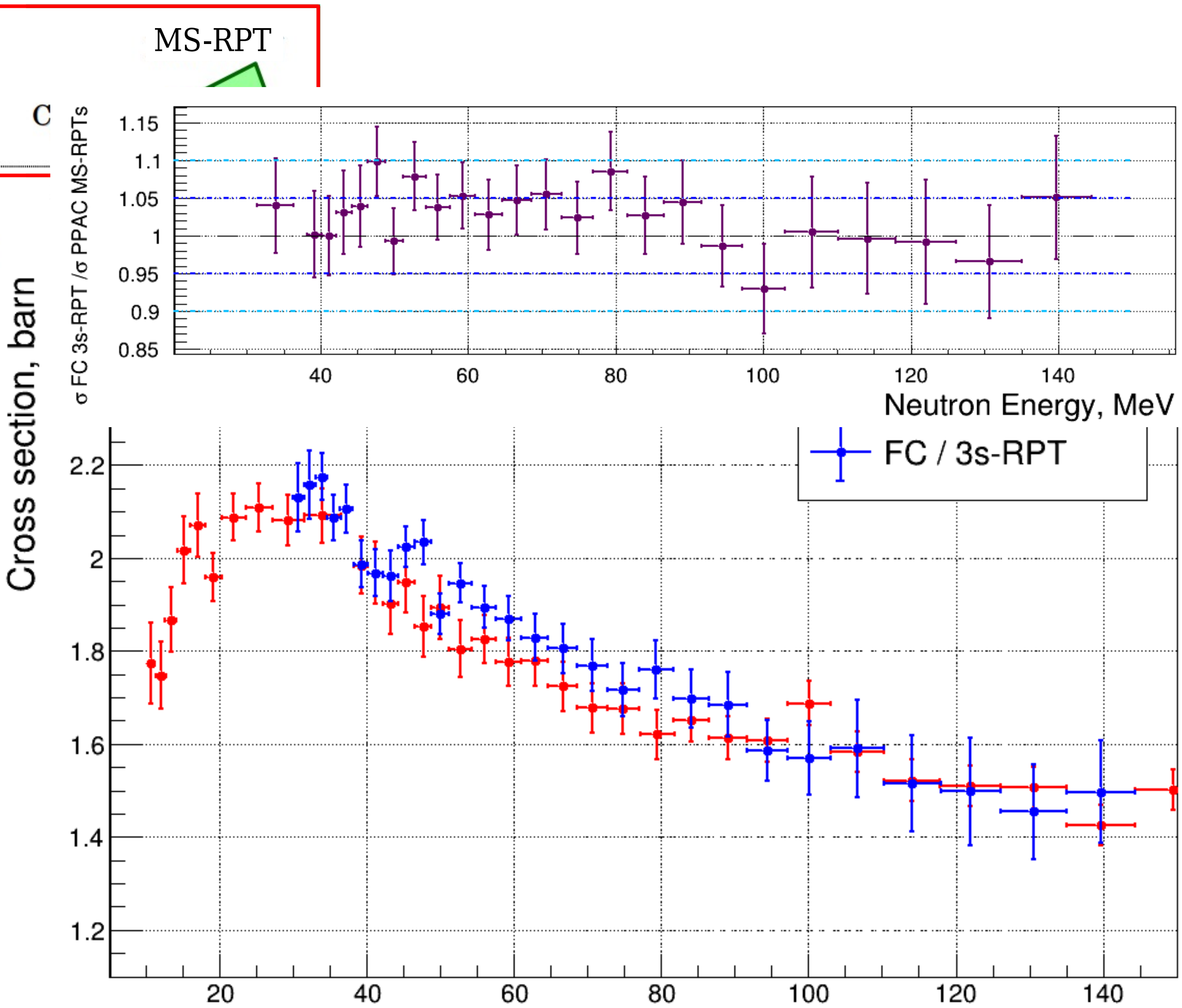
The measurement





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The Uncertainties

The energy range studied in different regions

↳ different detectors used or different working conditions

	Uncertainty En = [10-27] MeV	Uncertainty En = [28-38] MeV	Uncertainty En = [38-140] MeV	Uncertainty En > 140 MeV	
Systematics		4.5%	4.5%		...xs extracted with FC and 3s-RPT
Statistics		2.4-3.5%	2.2-7.3%		
Systematics	6.5%		3.5%	4.0-4.3%	...xs extracted with PPAC and MS-RPT
Statistics	2.5-4.2%		2.7-3.6%	2.6-3.7%	
			1.7-2.2%		Correlated
Total	5.7-8.1%	5.7-5.2 %	3.7-4.9%	4.8-5.6%	Final

The Uncertainties

- xs extracted with FC and 3s-RPT
- xs extracted with PPAC and MS-RPT
- Correlated

…for FF events PPFC related

Contribution	Uncertainty (average)	Single deposit
^{235}U mass fraction	0.0014 %	0.0014 %
^{235}U mass per unit area	0.2 %	0.6 %
^{235}U effective density correction k_U	0.6 %	1-2.5 %
Zero-bias efficiency	1.3 %	1.1-1.3 %
Efficiency, extrapolation below thr.	3 %	2-4.5 %
Dead-time correction k_τ	0.2 %	0.04-0.2 %

…for FF events PPAC related

Source of uncertainty	Uncertainty $E_n < 200$ MeV	Uncertainty $E_n > 200$ MeV
Sample mass	1.0%	1.0%
Trajectories reconstruction	0.4%	0.4%
Efficiency calculation fit	2.0%	2.0%
Anisotropy correction	1.2%	-

…for neutron flux measurement 3s-RPTs related

Contribution	Uncertainty
Beam transmission through PPFC, PPAC	0.5 %
Isotopic composition of PE	1.5 %
Areal density of PE sample	0.2-0.6 %
Areal density of C sample	0.2-0.9 %
Cuts the ΔE-E matrix for selecting proton events	0.5 %
Fit of MCNPX simulations to the experimental light-output distributions	≤2.5 %
Effective area of the ΔE_2 detector	0.5 %
Distance of the detectors from the PE or C sample	0.8 %
Angle relative to the neutron beam	0.1-0.6 %
Dead-time correction	0.5-1.0 %

…for neutron flux measurement MS-RPTs related

Source of uncertainty	Uncertainty $E_n = [10\text{-}30]$ MeV	Uncertainty $E_n = [38\text{-}200]$ MeV	Uncertainty $E_n > 200$ MeV
C_2H_4 mass	0.4%	0.2-0.5%	0.2-0.5%
C mass	1.4%	0.5-0.6%	0.5-0.6%
Signal Reconstruction	1.8%	0.5%	0.7%
Dead time correction	2.0%	1.0%	1.0%
Cuts in the ΔE-E matrix	5.0%	2.0%	2.0%
Telescope angle	0.6%	0.9%	1.0%
Telescope position	0.7%	0.7%	0.7%
Beam transmission	0.8%	0.8%	0.8%
Beam profile	0.5%	0.5%	0.5%

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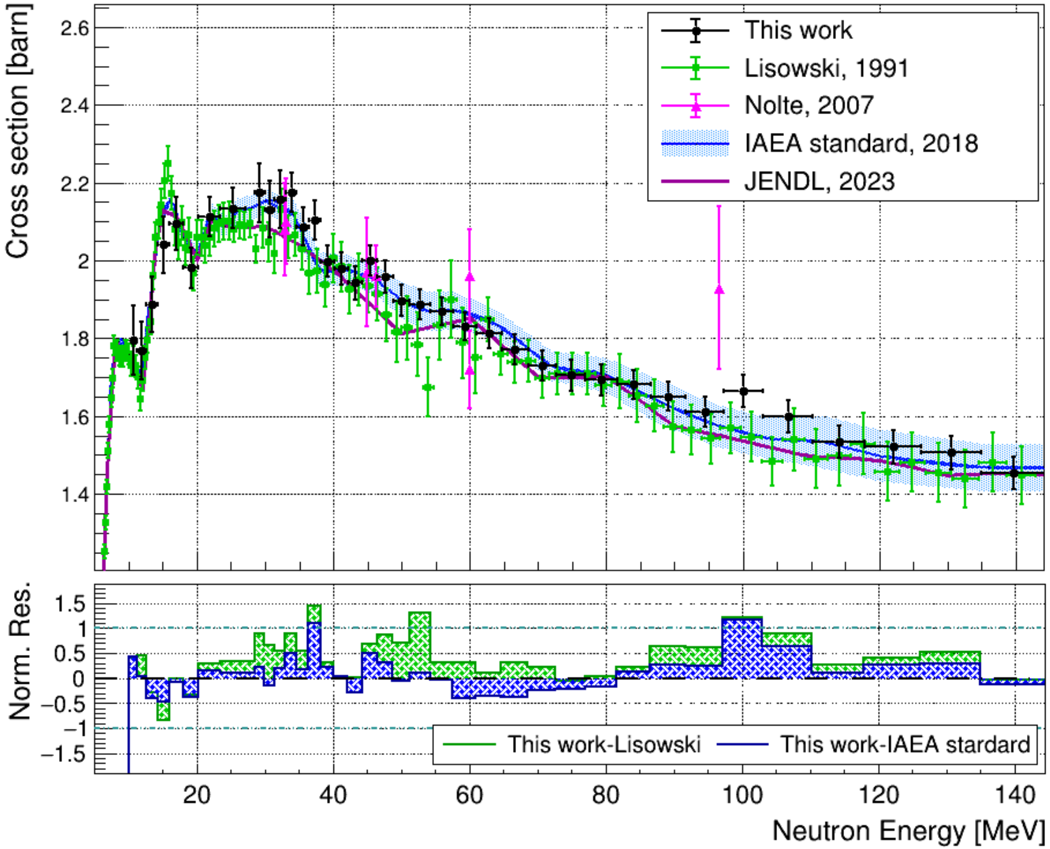
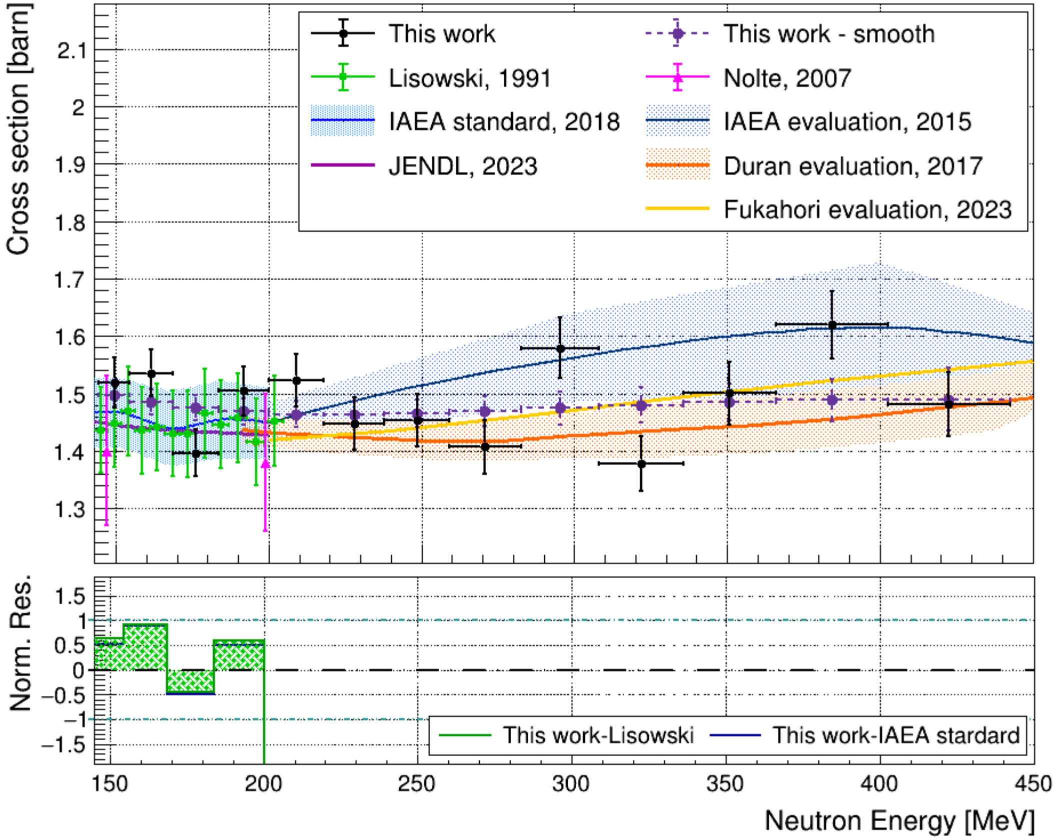
The obtained cross section

Average between
PPFC with 3S-RPT
&
PPAC with MS-RPTs



Only
PPAC with MS-RPTs



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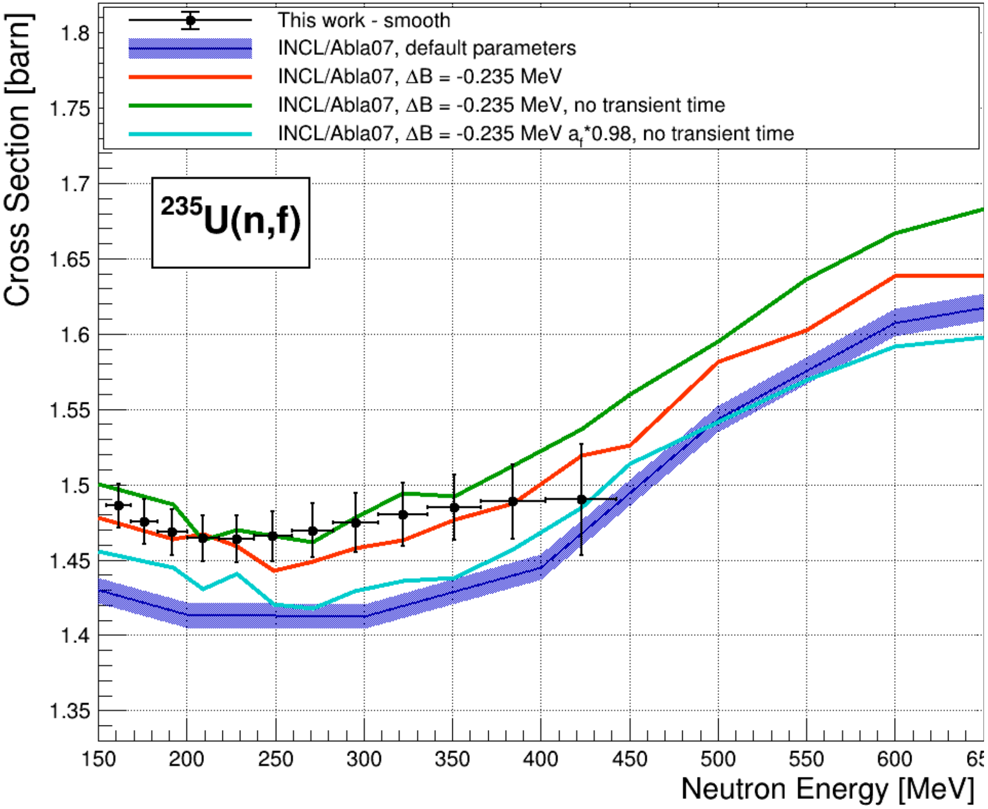
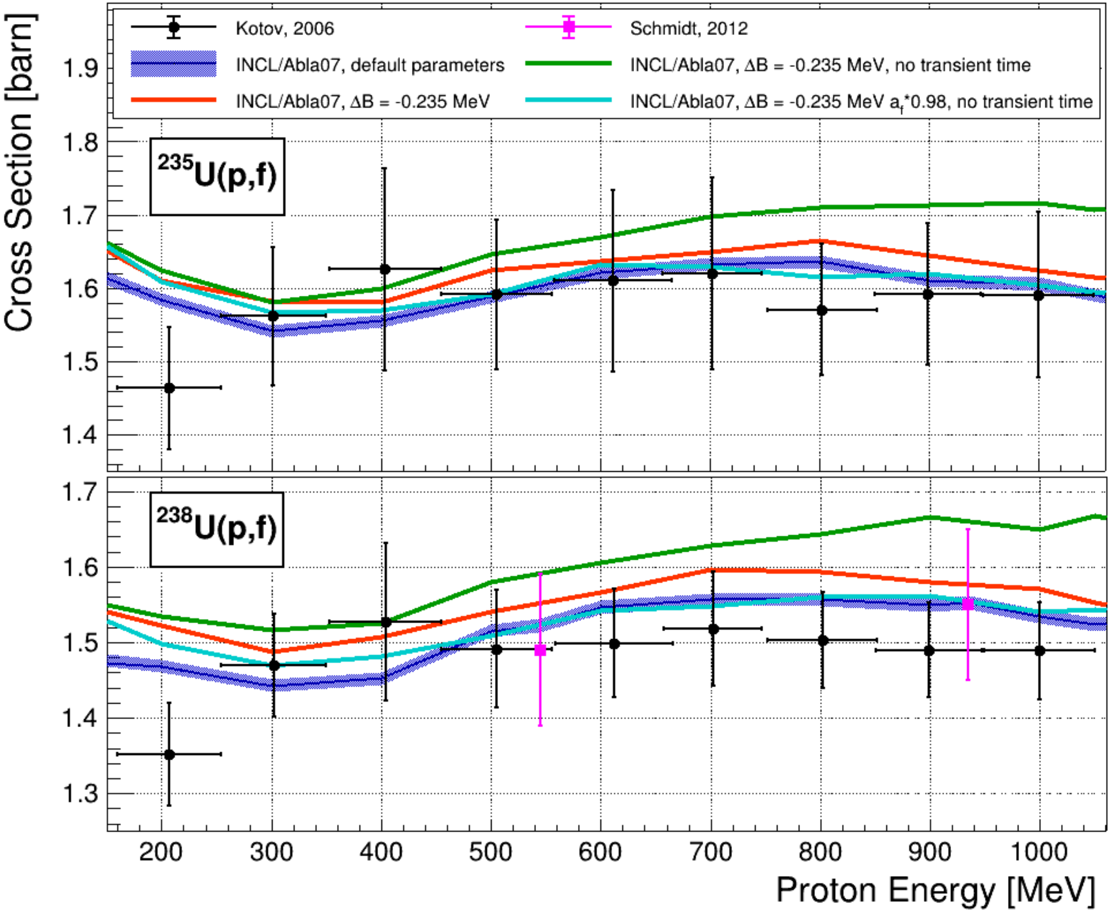
Impacts

The obtained cross section

Obtained cross section compared with calculation with INCL/Abla07

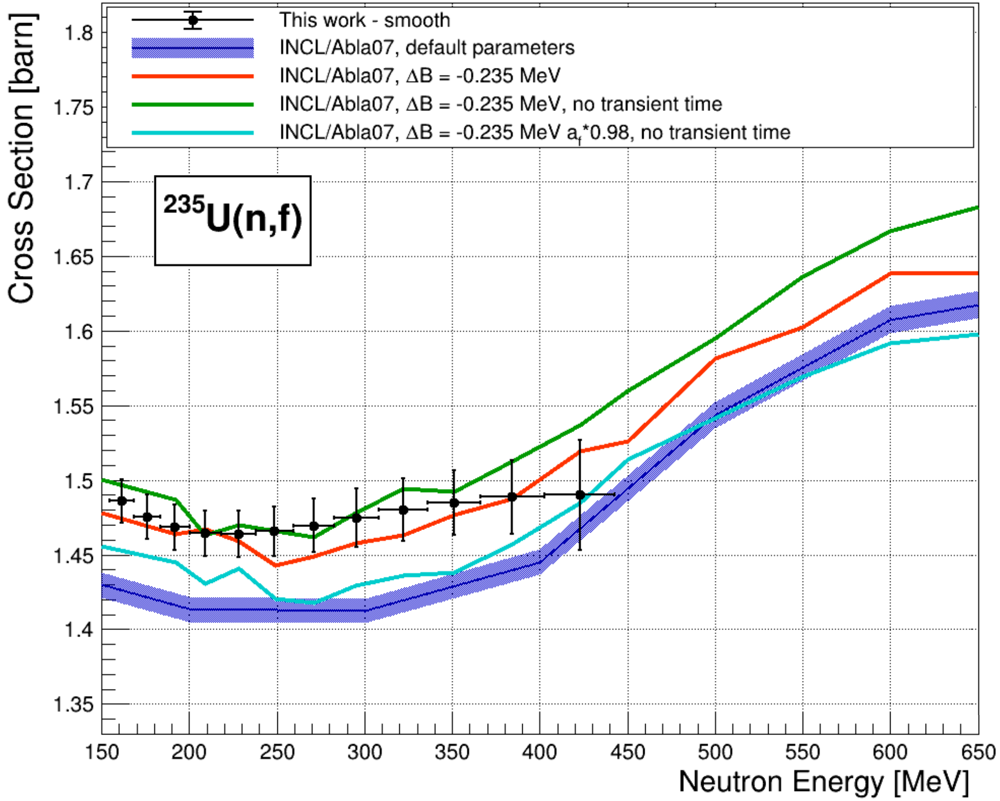




The obtained cross section

@ Alberto Ventura

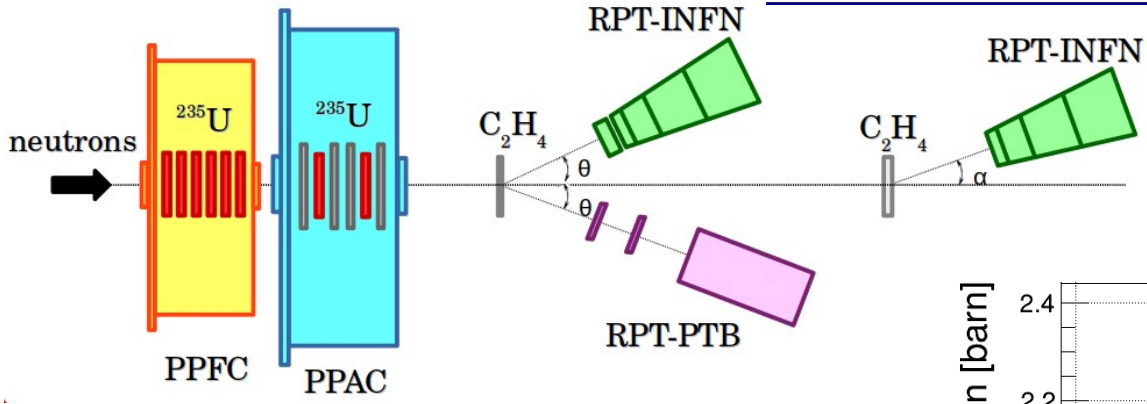
Normalization of the cross section obtained with respect to ^{235}U(n,f) with our new data:



^{238}U(n,f) first preliminary example

Preliminary

The obtained cross section

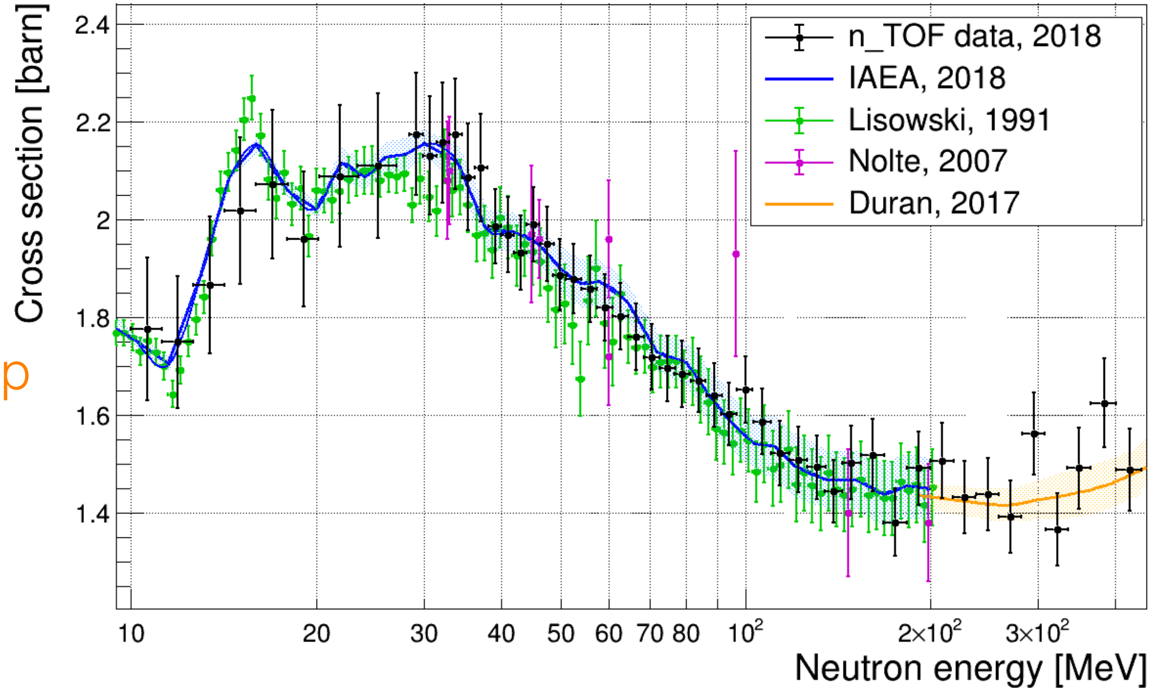


The **limitation** of the measurement:
maximal energy: 425 MeV

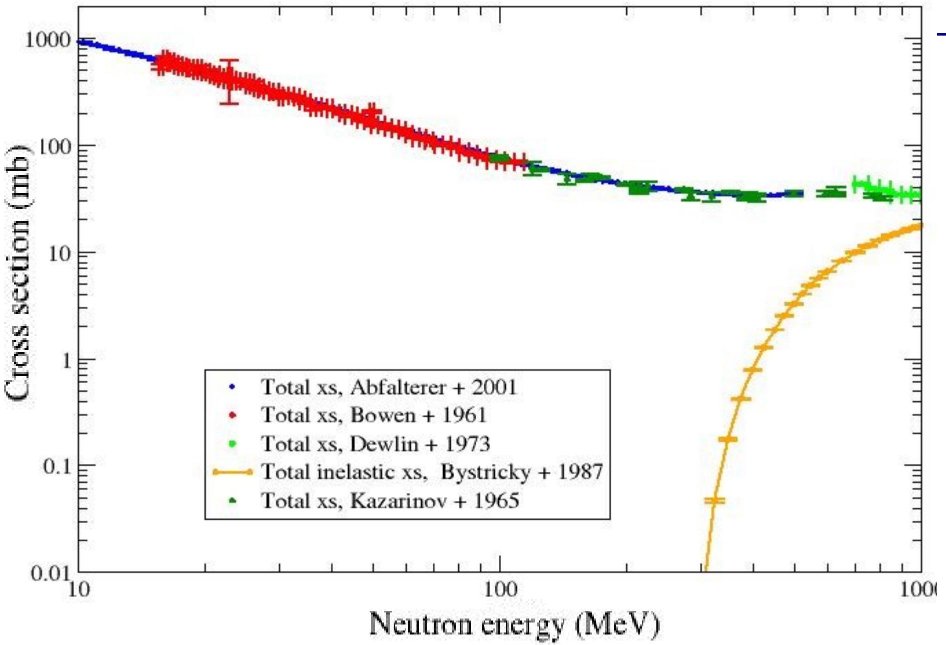
opening of the inelastic channel in the n-p scattering

above 150 MeV statistical fluctuation

when only PPAC and MS-RPT work



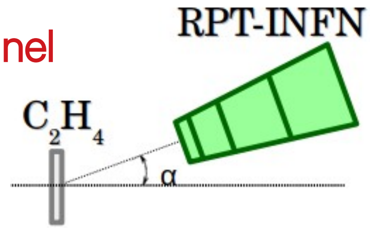
The inelastic scattering



From ~ 300 MeV:

opening of the inelastic channel

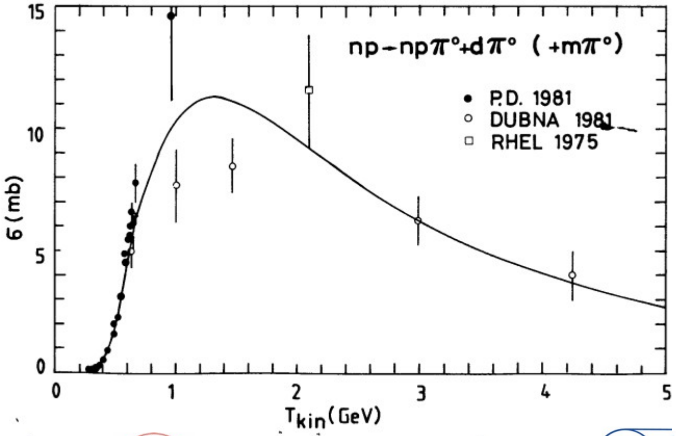
$$n + p \rightarrow N + N + \pi$$

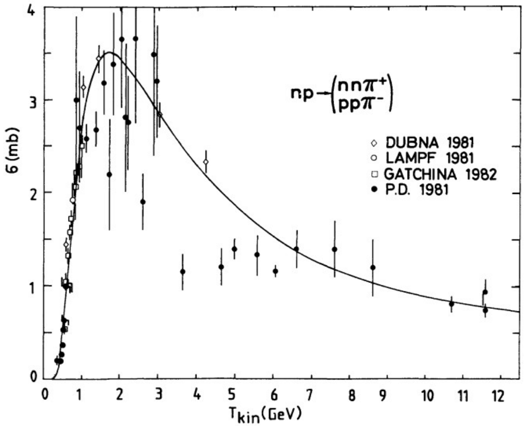


How we correct for it:

- 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

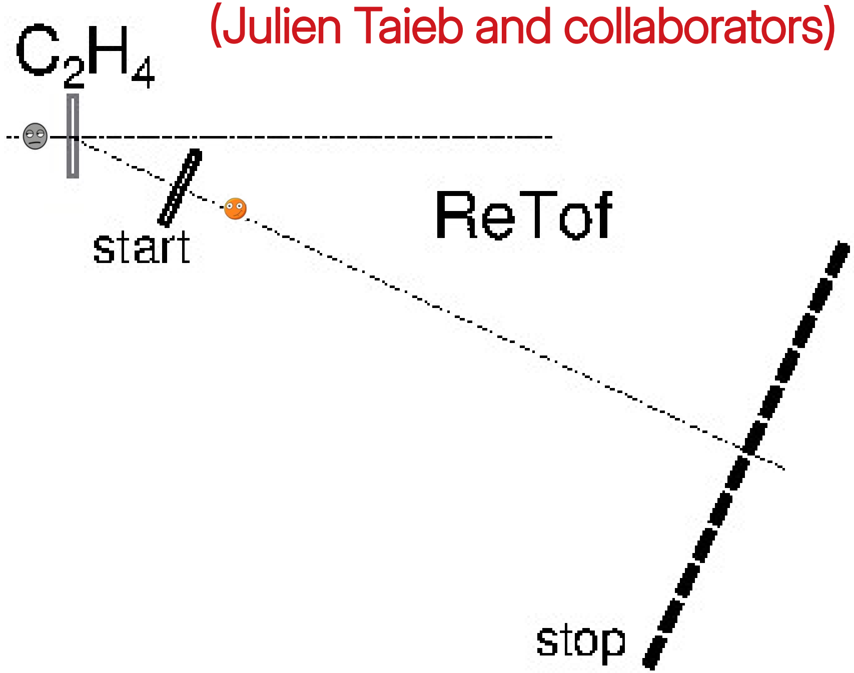




Future perspectives

The Re-TOF telescope

Collaboration with CEA
(Julien Taieb and collaborators)



neutron TOF **Re**lated to proton **TOF**

A detector able to discriminate:

protons from: $n + p \rightarrow n + p$

protons from: $n + p \rightarrow n + p + \pi^0$ m(π) = 139.6 MeV/c

$n + p \rightarrow p + p + \pi^-$

Least-favourable scenario:

1 GeV neutron

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

- a start detector : plastic scintillator
- a stop detector: a plastic scintillator “wall”
  2 m far from the start- 60 × 60 cm^2
  divided in 20 bars – 3 cm each
  coupled with 2 PMT – 1 PMT at each side of the bars

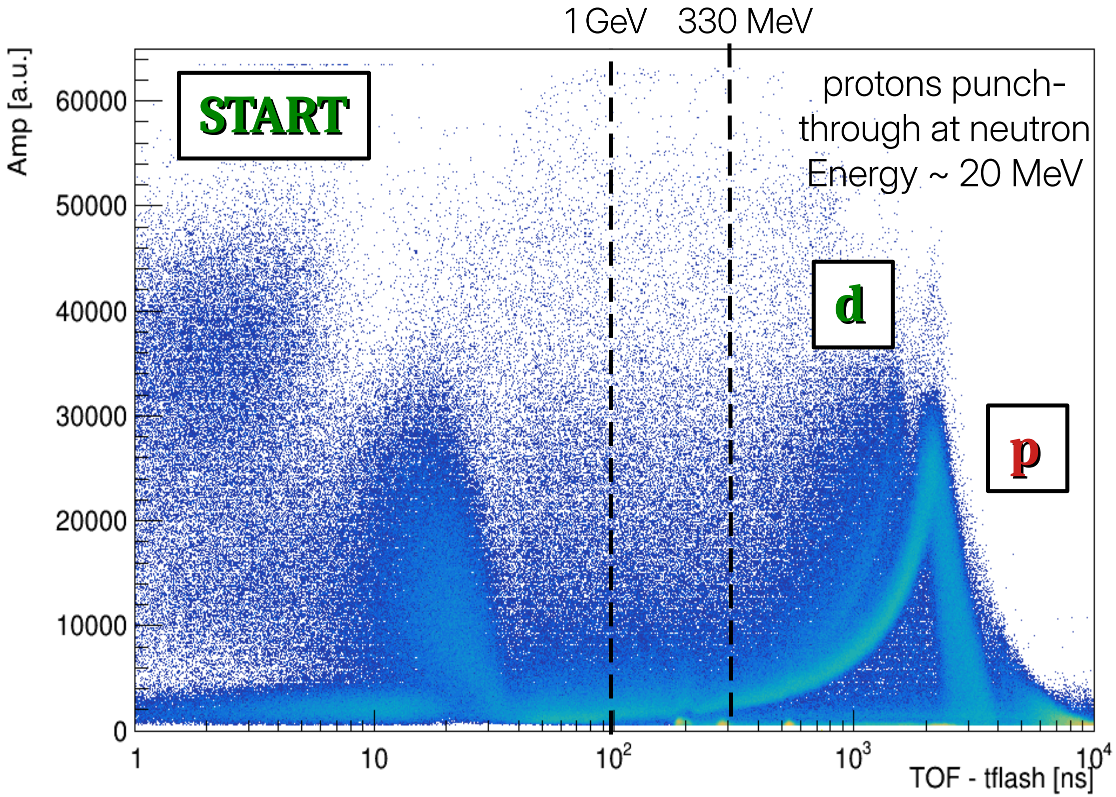
Δt (elastic - inelastic protons) = 440 ps

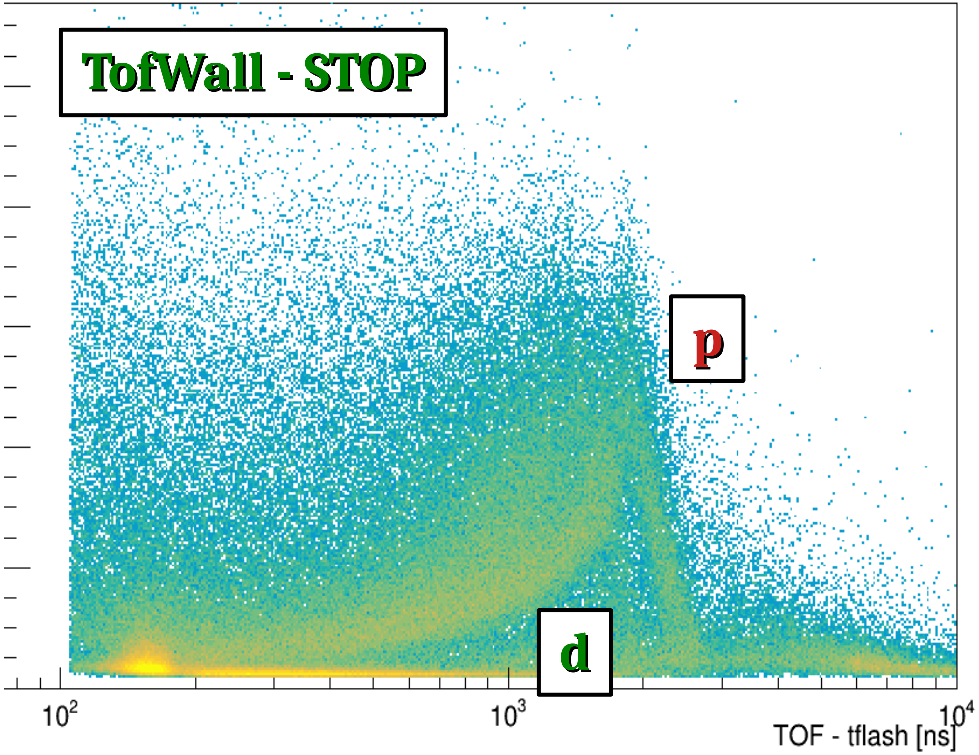
Time resolution of 300 ps

Re-TOF: Start-TofWall coincidences

From Test @EAR1

Expected TOF of elastic scattered protons $(TOF_{TW} - TOF_{ST})_{el} \simeq TOF_{p,el}(E_{p,el})$





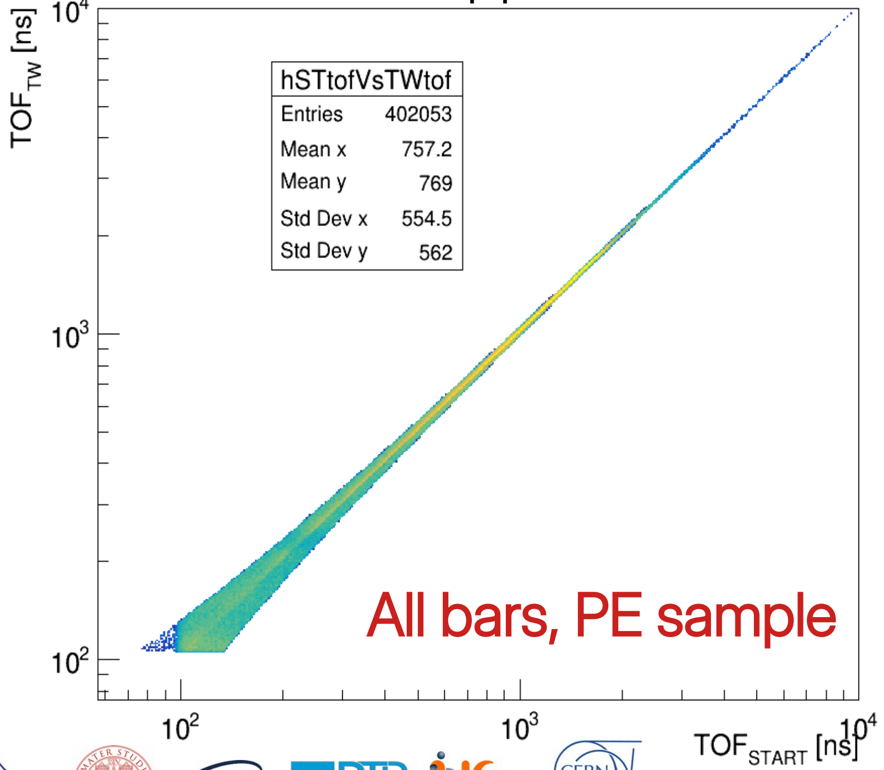
Future perspectives

Re-TOF: Start-TofWall coincidences

From Test @EAR1

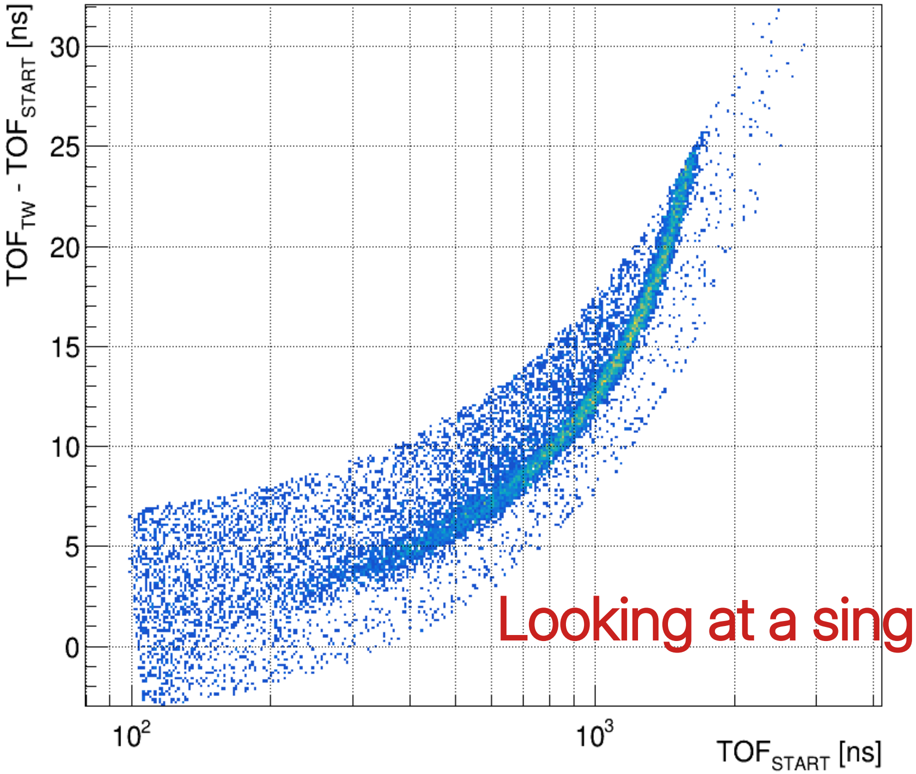
Expected TOF of elastic scattered protons $(TOF_{TW} - TOF_{ST})_{el} \simeq TOF_{p,el}(E_{p,el})$

Wide **coincidence window (30 ns)** with combinatorial approach



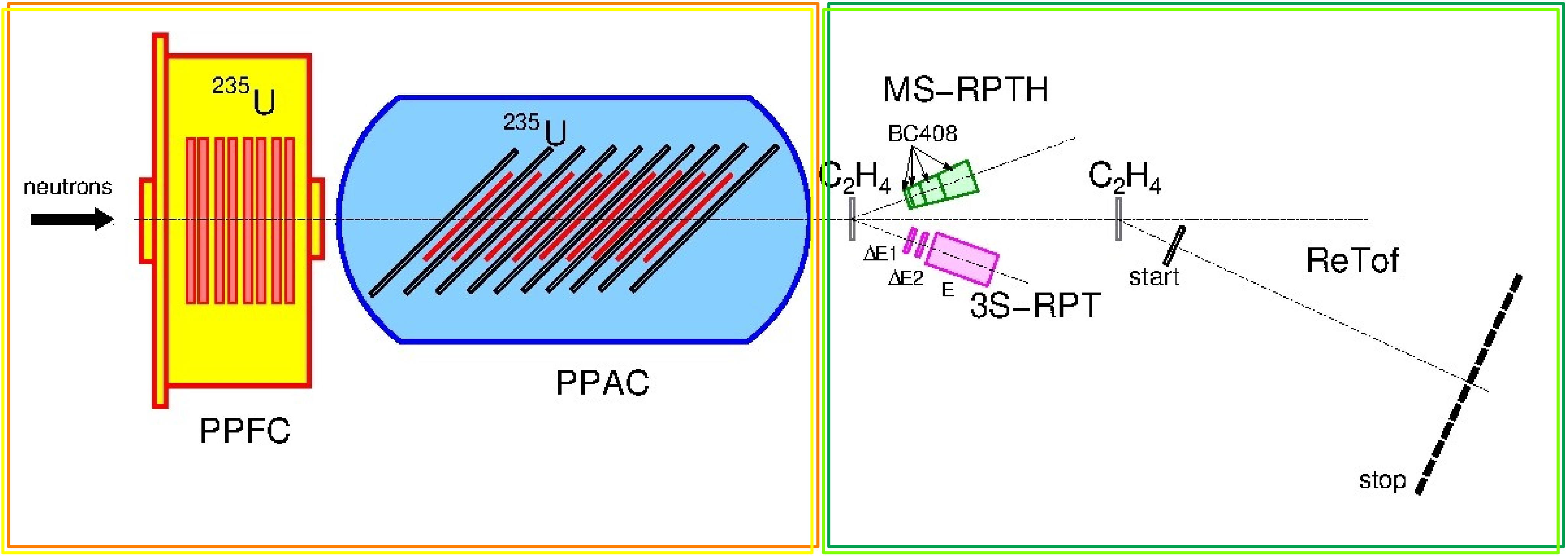
All bars, PE sample

coincidence window ±3 ns with combinatorial approach



Looking at a single bar

The complete setup



Fission events

PPAC: 10 PPAC and 9 ^{235}U samples

PPFC: 8 ^{235}U samples

Neutron flux

Re-TOF: pointing PE sample (th ~ 25 MeV) – 25° wrt neutron beam

1 or 2 RPT for the lower energy region + benchmark

Future perspectives

^{239}Pu(n,f) cross section

Lisowski, 1991

[0.5 - 260] MeV

Staples, 1998

[0.85 – 62] MeV

Shcherbakow, 2002

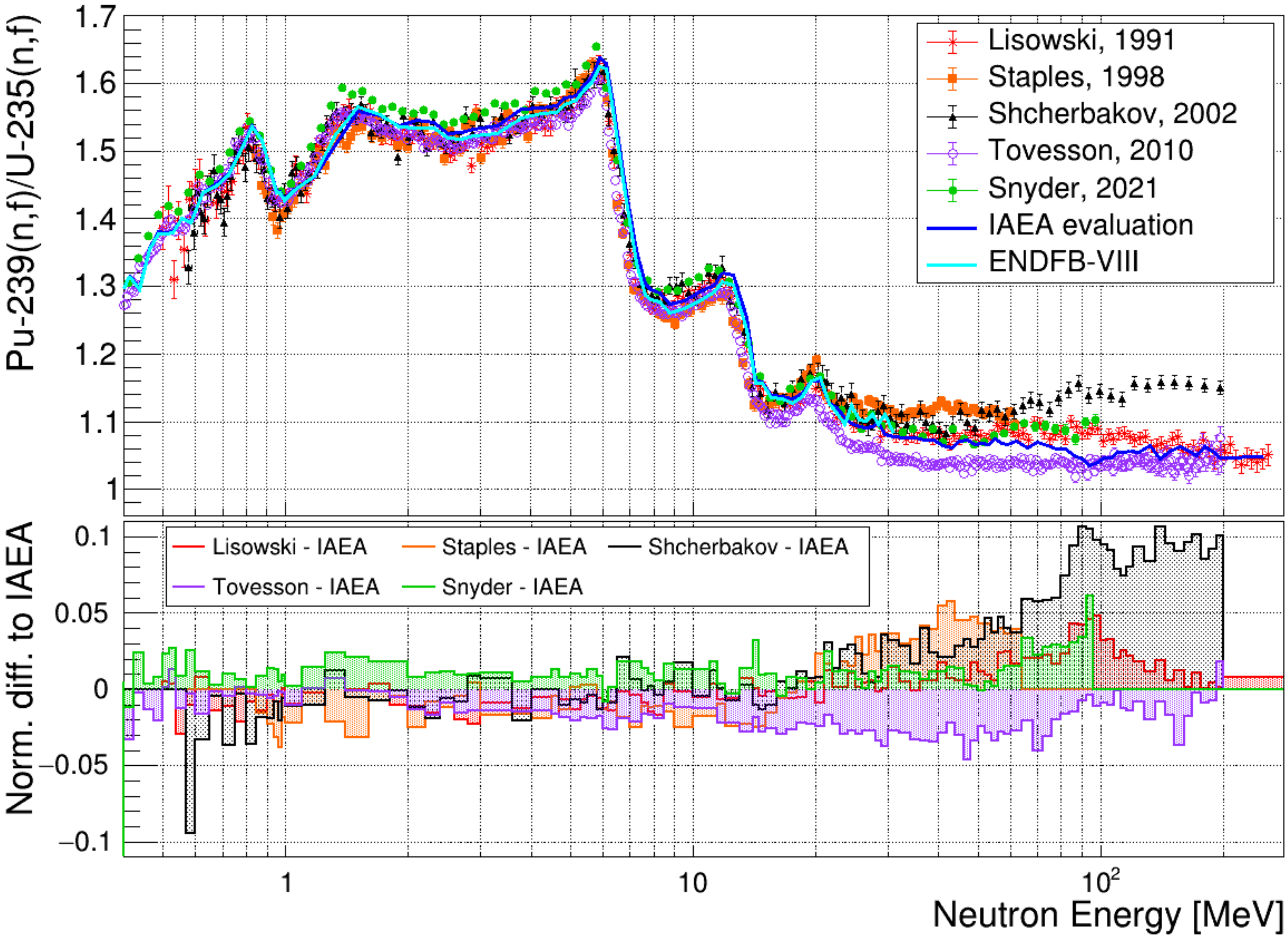
[1 - 200] MeV

Tovesson, 2010

[0.01 eV - 200 MeV]

Snyder, 2021

[0.1 - 100] MeV



Future perspectives

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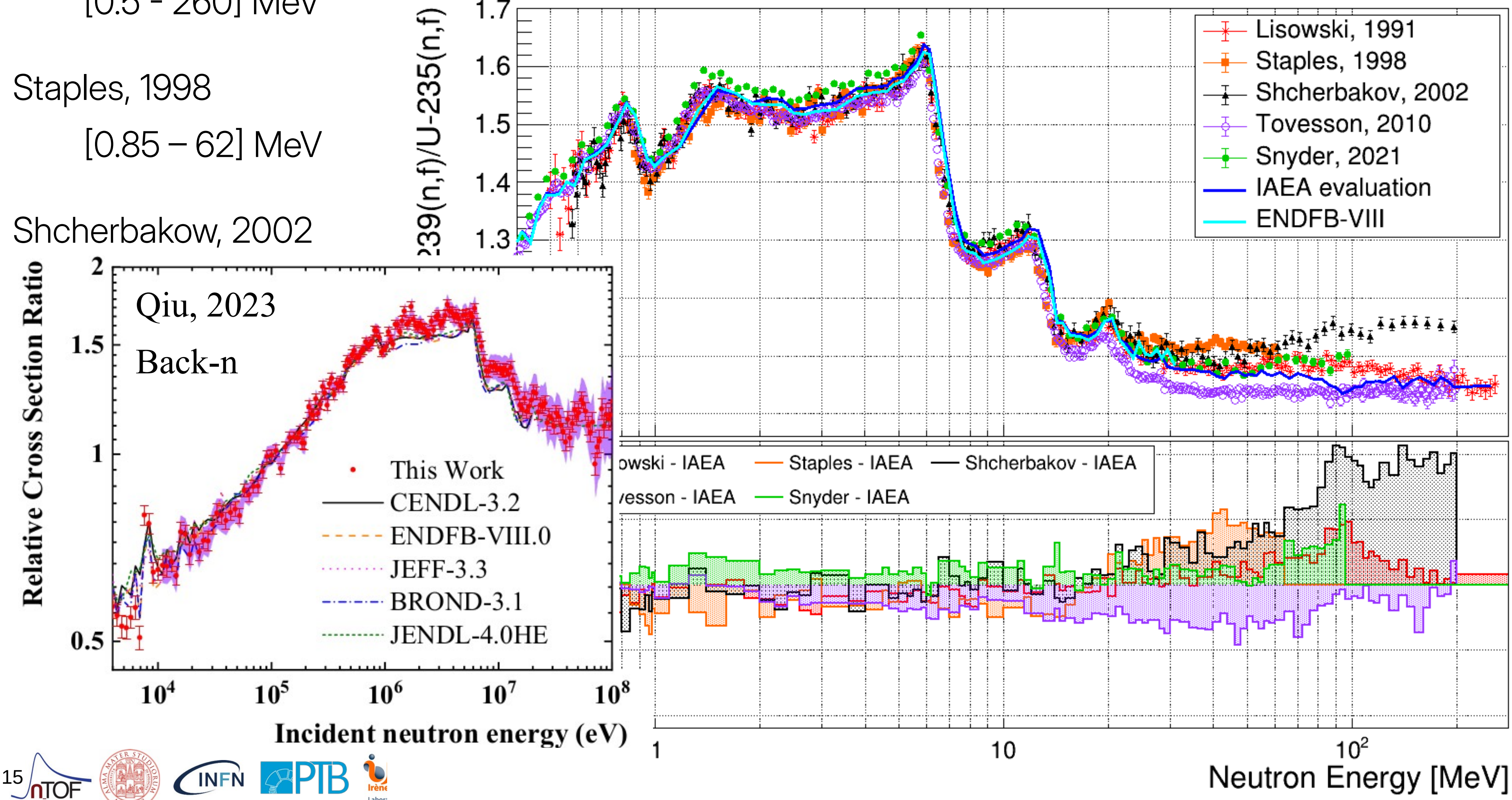
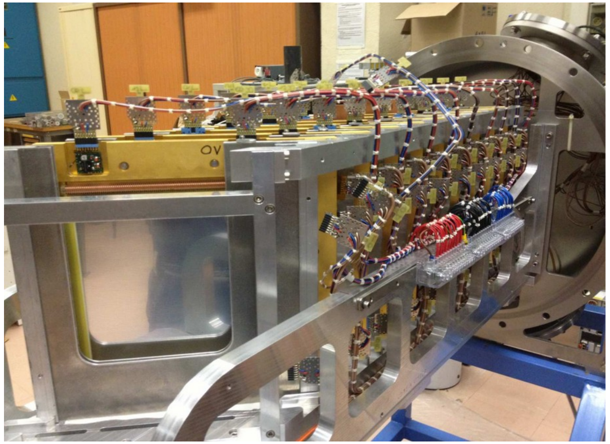


^{239}Pu(n,f) cross section

Identify the fission caused by neutrons with an energy from thermal up to 1 GeV.

Requirements:

- Very good time resolution
- Low sensitivity to the γ-flash
- Good discrimination between α particles and FFs
  (^{239}Pu activity ~2 MBq/mg).



PPAC ensemble:

9 target slots and 10 PPACs tilted by 45° with respect to the neutron beam direction

^{239}Pu material from JRC-Geel

Measurement with ^{235}U(n,f) cross section as reference from thermal energy up to GeV

+

n,p elastic scattering in the high energy range

2 REFERENCE CROSS SECTIONS

Conclusion

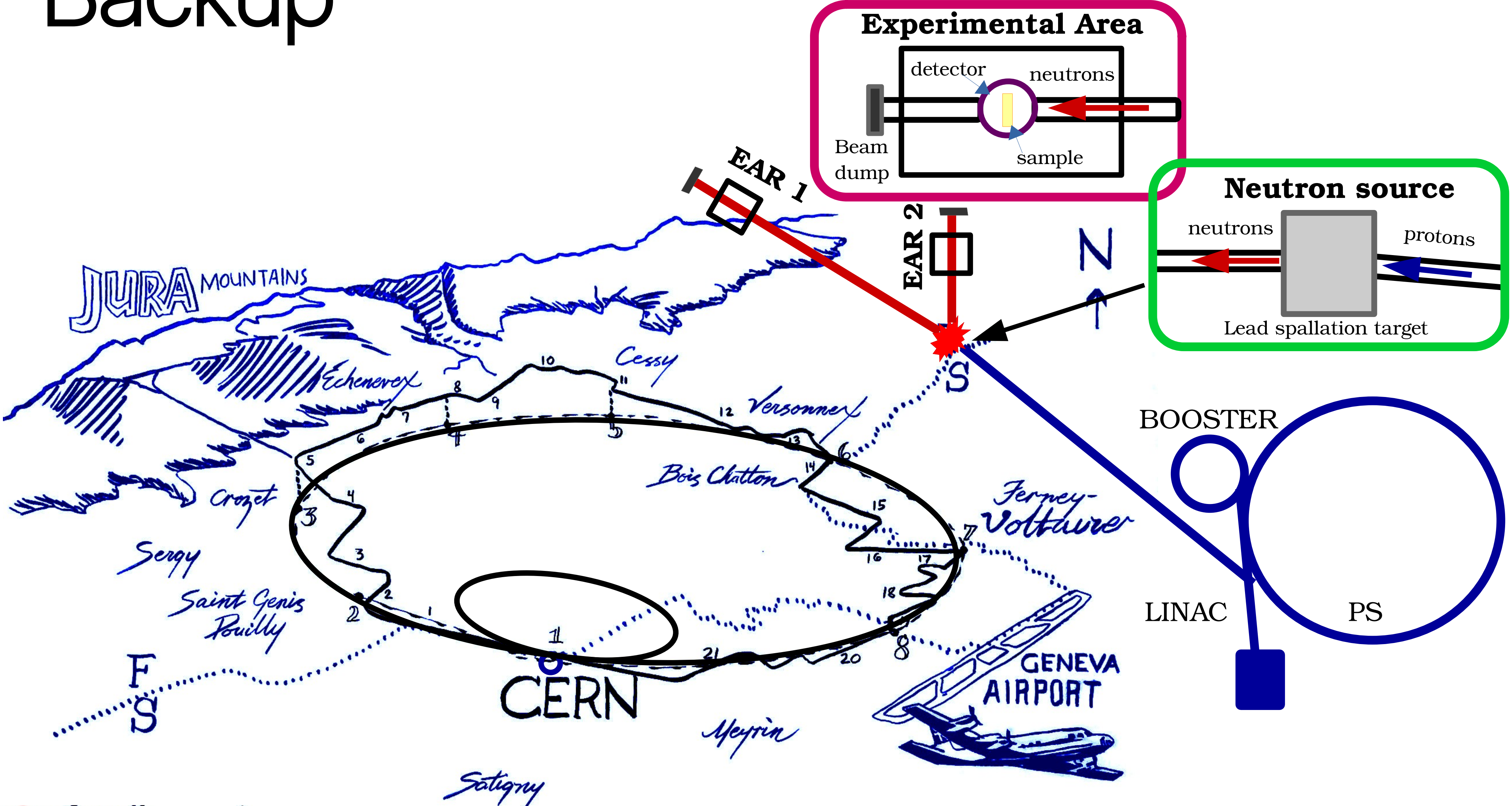
Final data for the ^{235}U(n,f) cross section extending the measured cross section of about 200 MeV

The detectors development for new projects is ongoing for the measurements:
- ^{235}U(n,f) cross section from few MeV with better statistics wrt this results
- ^{239}Pu(n,f) cross section from thermal up GeV, wrt 2 different reference xs

The paper was (finally) accepted December 2024, we are going to prepare for EXFOR 4 entries, in collaboration with Naohiko and Emmeric:

- cross section obtained with PPFC and 3S-RPT
- cross section obtained with PPAC and MS-RPTs
- average cross section obtained
- smoothed cross section in the high energy region (from 150 MeV)

Backup


Experimental Area
detector
neutrons
Beam dump
sample
EAR 1
EAR 2
N
Neutron source
neutrons
protons
Lead spallation target
BOOSTER
LINAC
PS
JURA MOUNTAINS
Echenevex
Cessy
Versonnex
Crozet
Bois Chatton
Sergy
Saint Genis Pouilly
Ferney-Voltaire
GENEVA AIRPORT
CERN
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The n_TOF facility

neutron **T**ime **O**f **F**light

High energy resolution

Time of Flight (ToF) technique

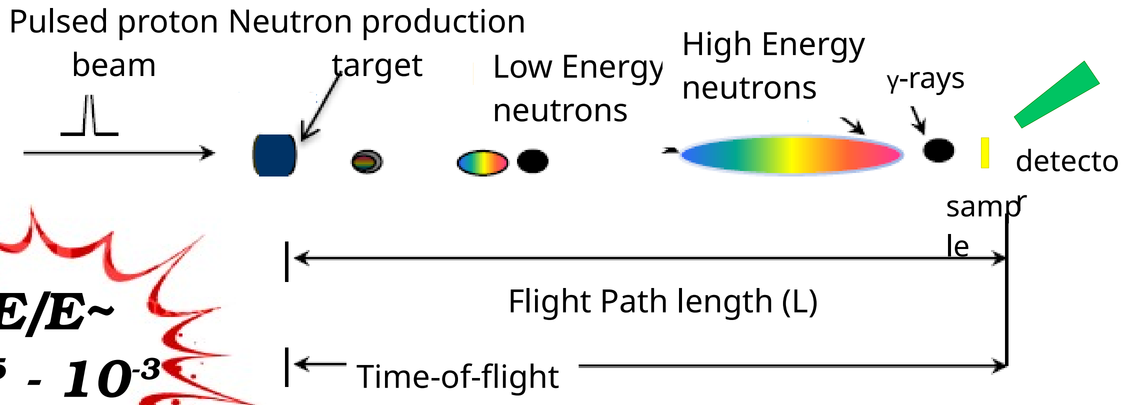
with a long flight path:

185 m @ EAR 1

20 m @ EAR 2

$\Delta E/E \sim$

10^{-5} - 10^{-3}

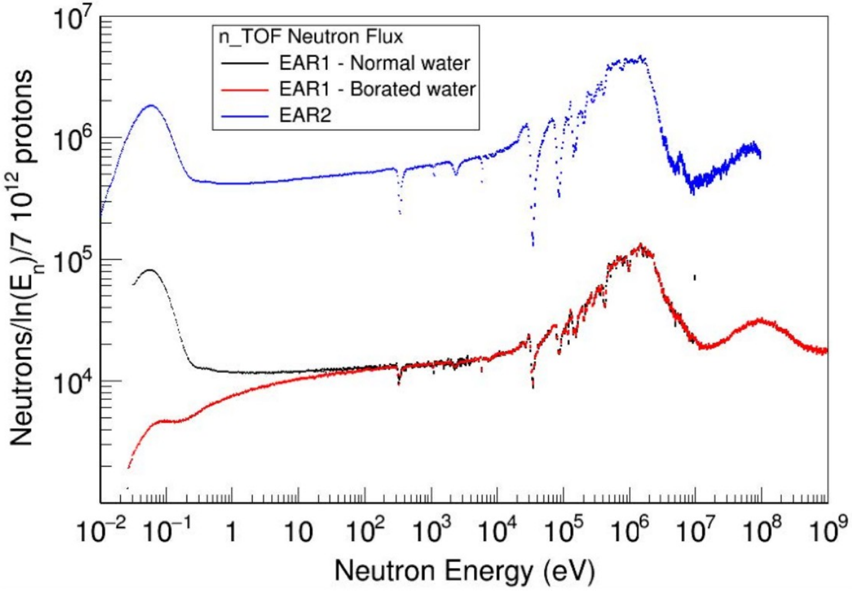


High neutron flux & wide energy range

Spallation reaction

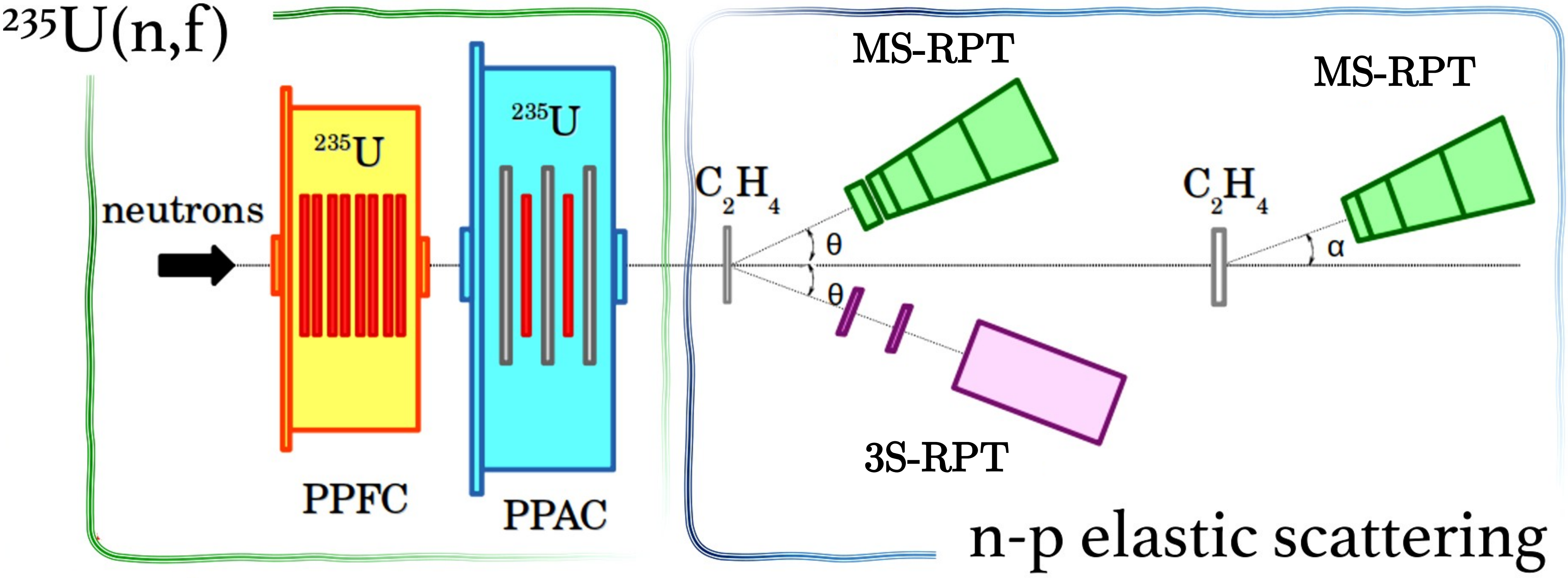
$7 \cdot 10^{12}$ protons,
20 GeV/c momentum
+
1.3 ton Pb Target

350
neutrons per
incident proton

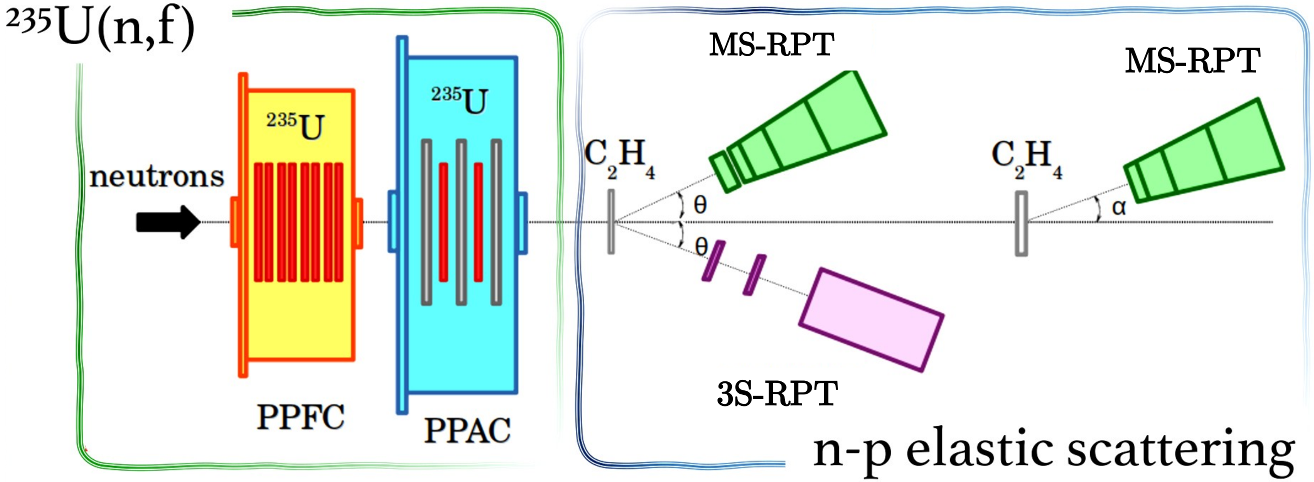


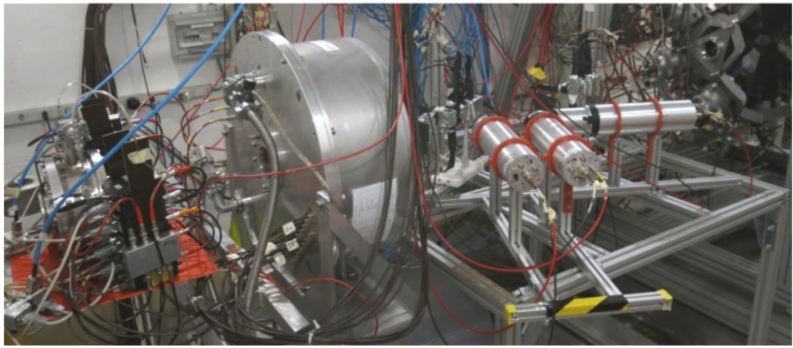
Experimental setup

$$\sigma_f\,(E_n) = \frac{N_f(En)}{n_U\,\varepsilon_f} \cdot \frac{1}{\Phi(En)} = \boxed{\frac{N_f(E_n)}{nU\,\varepsilon_f}}\;\boxed{\frac{nH\,\varepsilon_p\,\Omega}{N_p(E_n)}\;d\sigma_{(n,\,p)}/d\Omega}$$



Experimental setup





^{235}U fission reaction

Fission fragment

Parallel Plate Fission Chamber

Neutron energy: 0,025 eV - 200 MeV

4 double sided U (99.93% ^{235}U) = 32,660 mg

Parallel Plate Avalanche Counter

Neutron energy: 0,025 eV - 1 GeV

2 samples U (92.7% ^{235}U) = 28 mg

Neutron flux

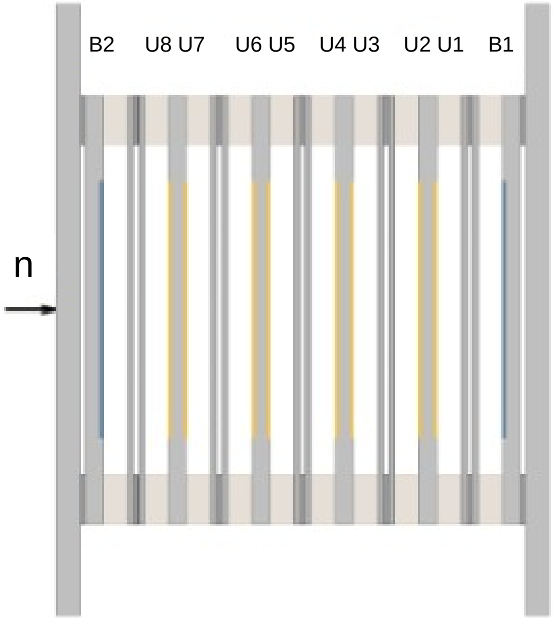
Elastic scattering

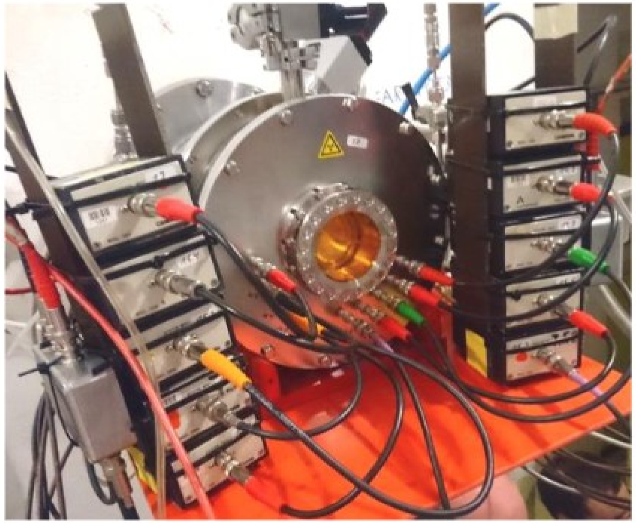
3 Proton Recoil Telescopes

located out of the neutron beam

- 2 @ 25° pointing at a Polyethylene: 1/2/5 mm thick
- 1 @ 20° pointing a Polyethylene: 5 mm thick

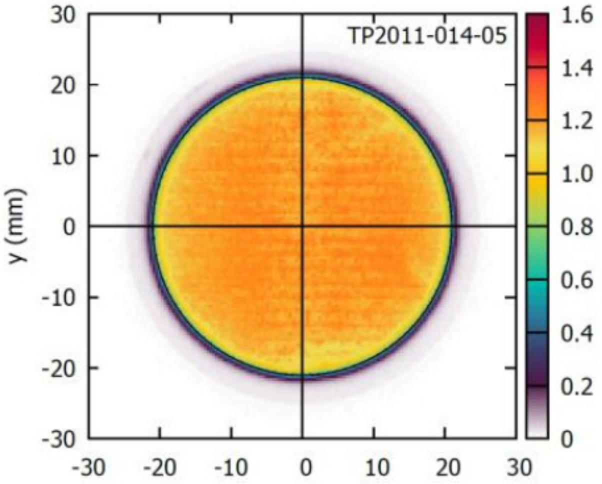
PPFC – Parallel Plate Fission Chamber

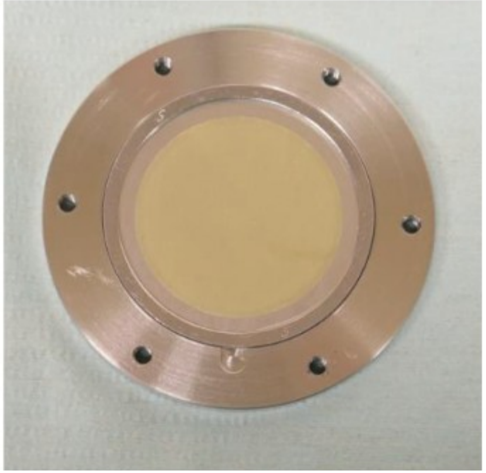




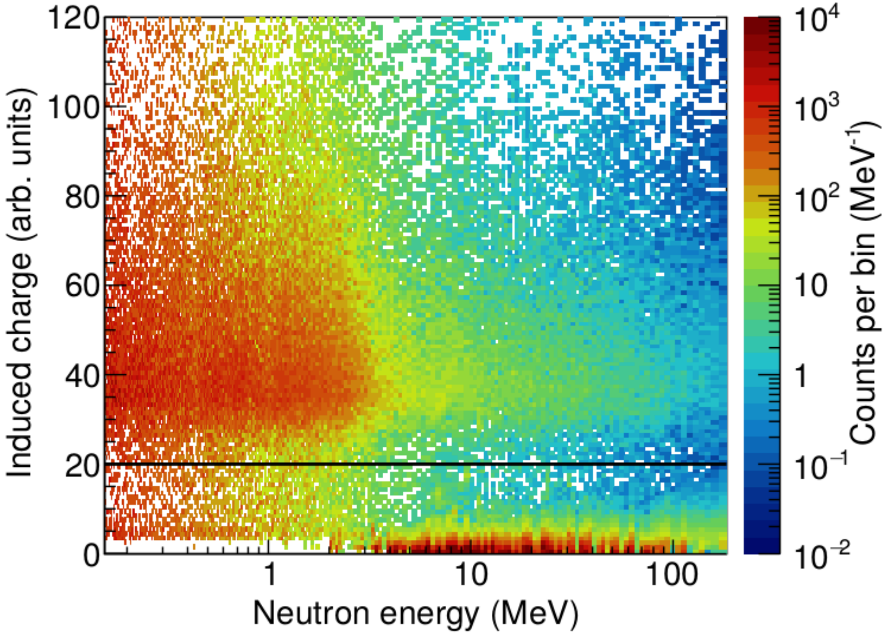
Parallel plate **ionization** chamber

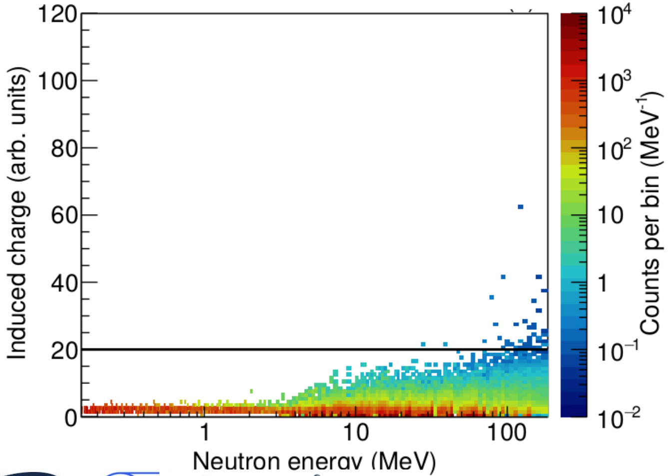
- 8× U-samples
- 2× blanks
- separate read-outs

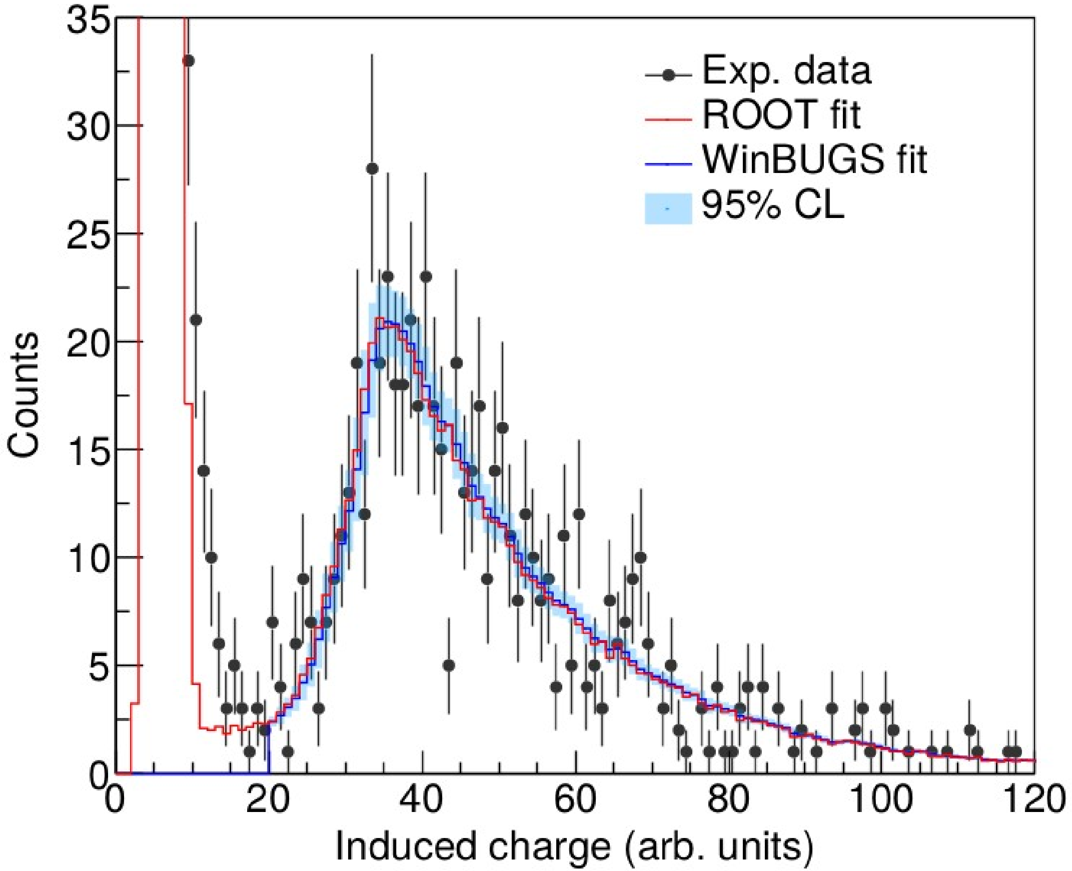




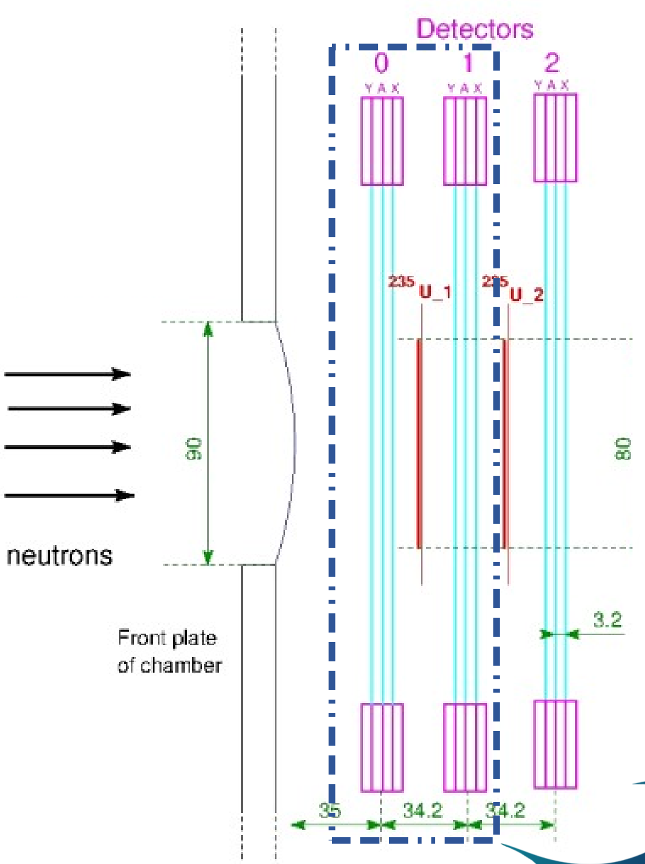
PPFC – Parallel Plate Fission Chamber

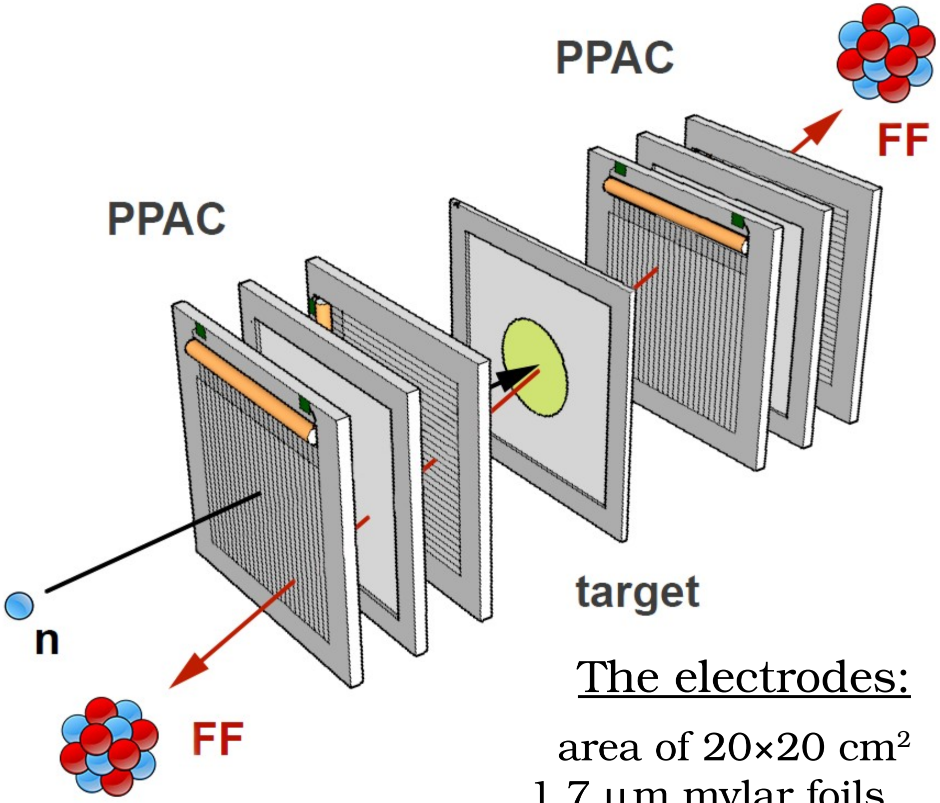


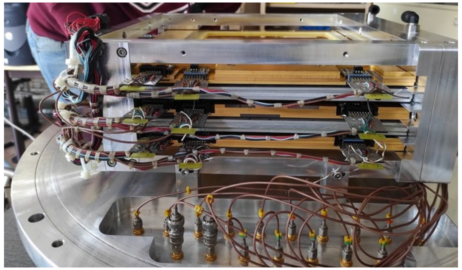


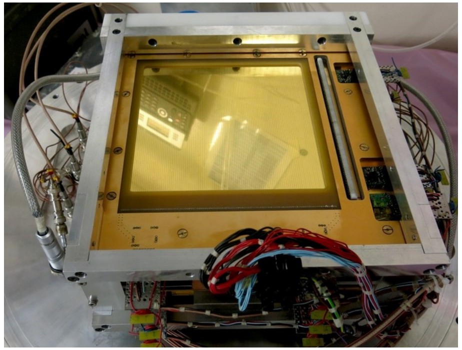


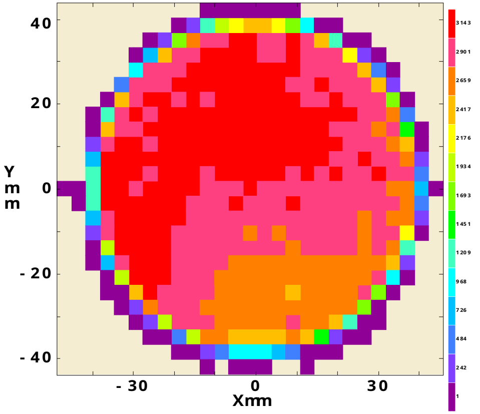
PPAC – Parallel Plate Avalanche Counters











The electrodes:

area of 20×20 cm^2
1.7 μm mylar foils,
coated with gold, 700 nm thick

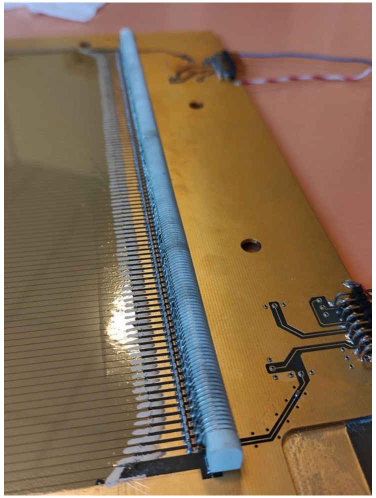
Anode:

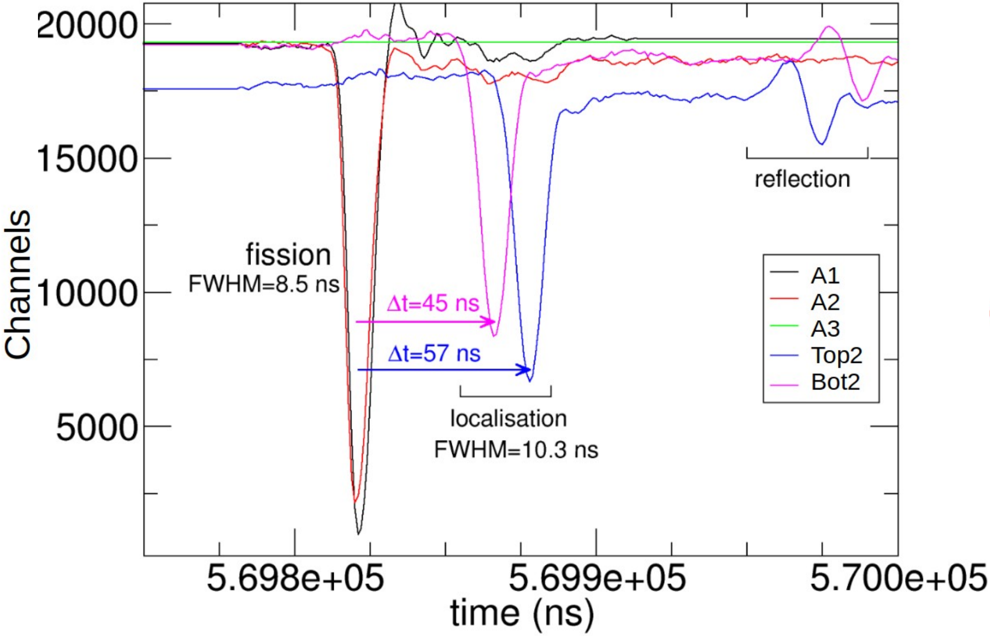
the coating is uniform and double sided

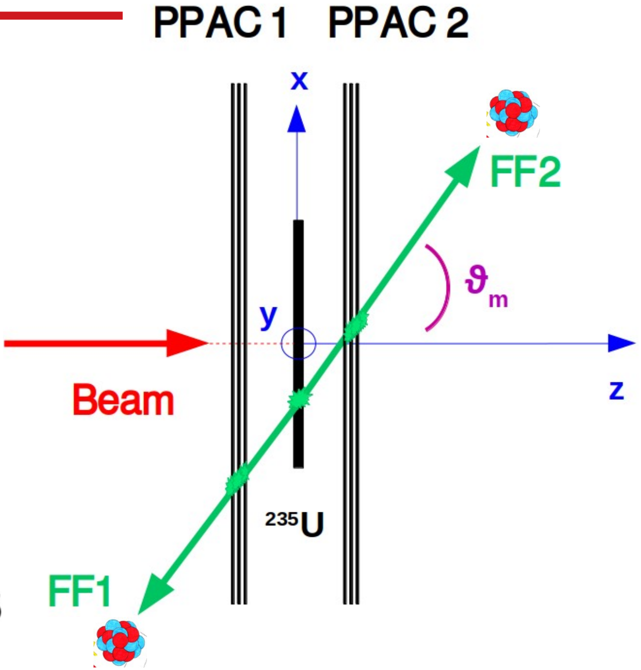
Cathodes:

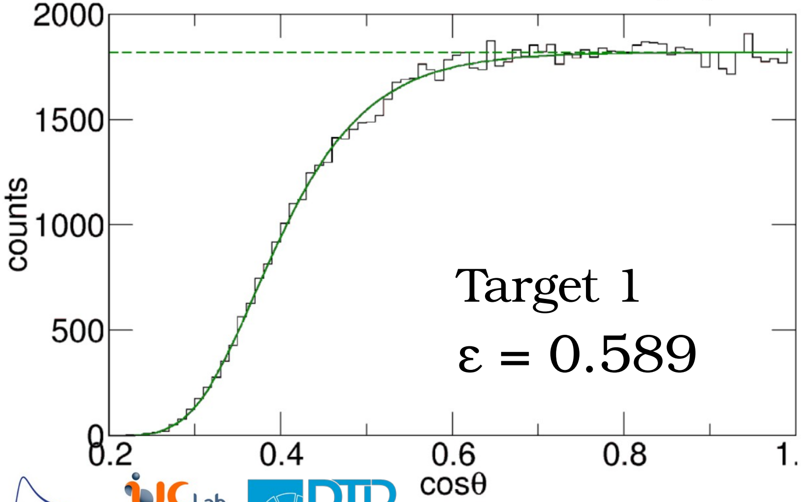
the coating is divided into 2 mm wide strips

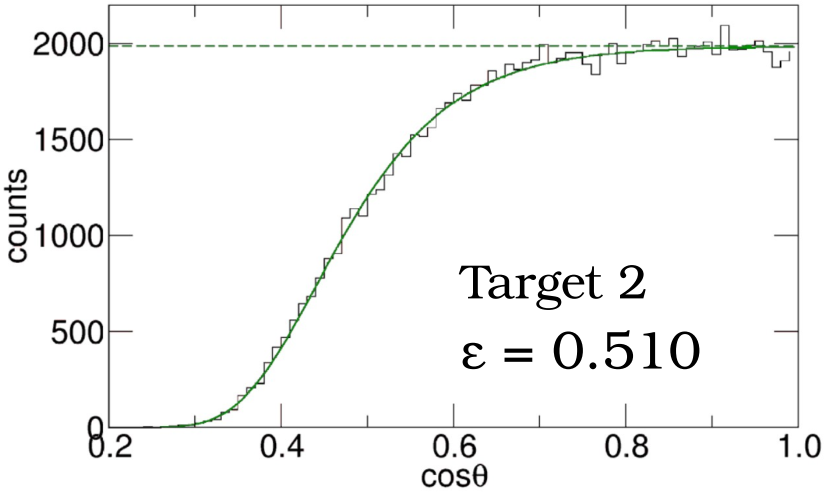
PPAC – Parallel Plate Avalanche Counters



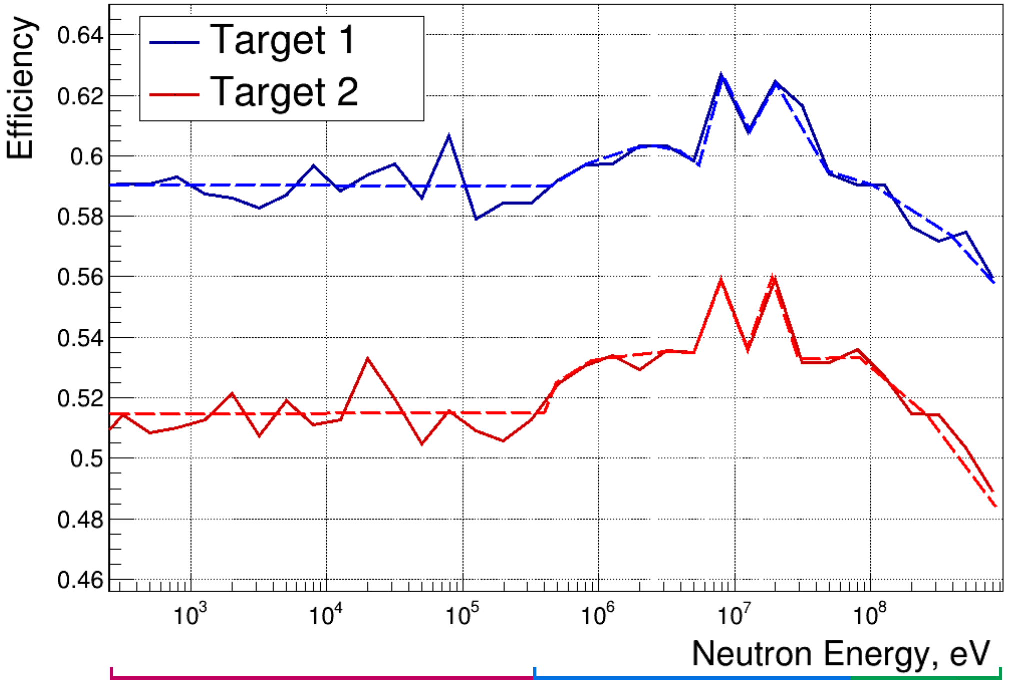








PPAC – Parallel Plate Avalanche Counters



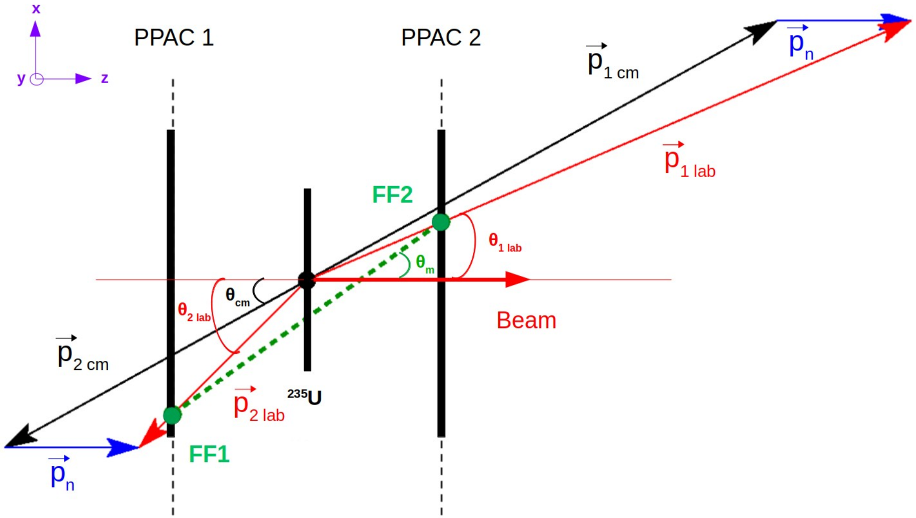
geometrical efficiency geometrical efficiency

+

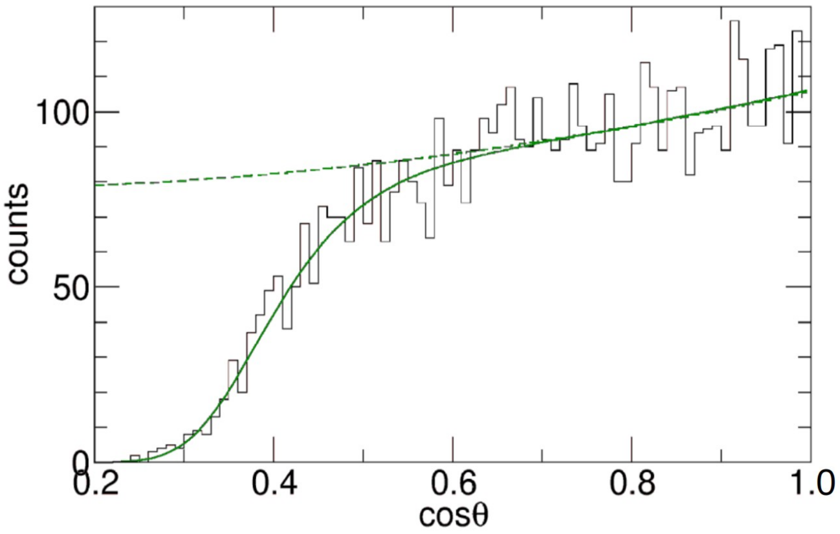
angular distribution

+

linear momentum transfer

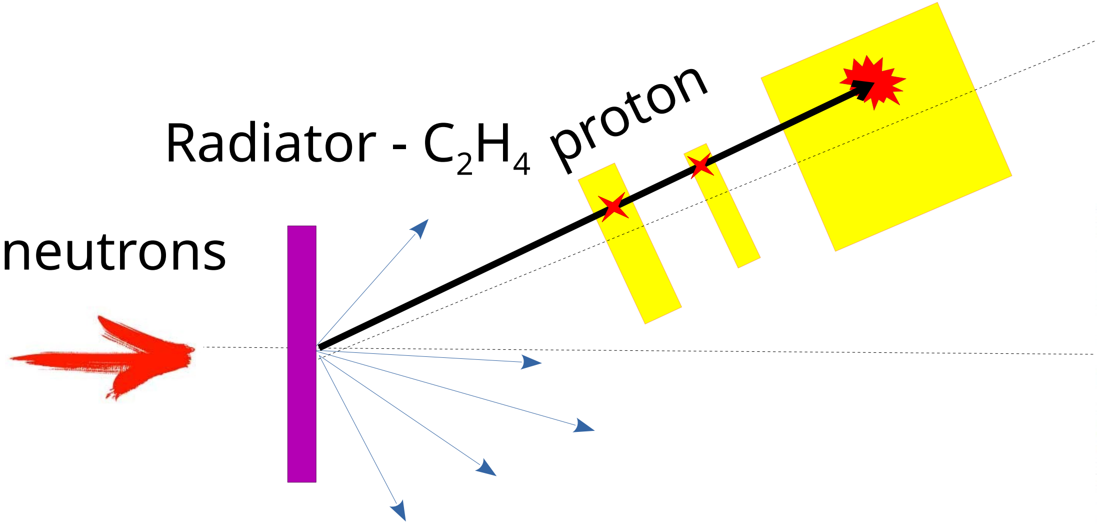


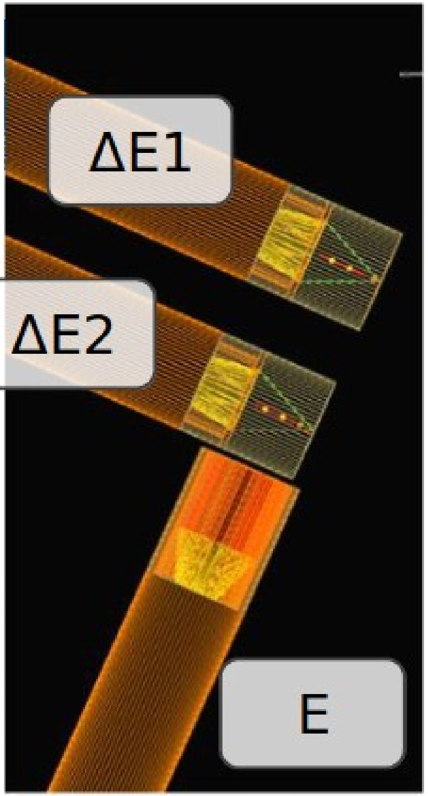
$6.3\ \text{MeV} < E_n < 10\ \text{MeV}$



Recoil Proton Telescope - 3s-RPT

n-p elastic scattering reaction



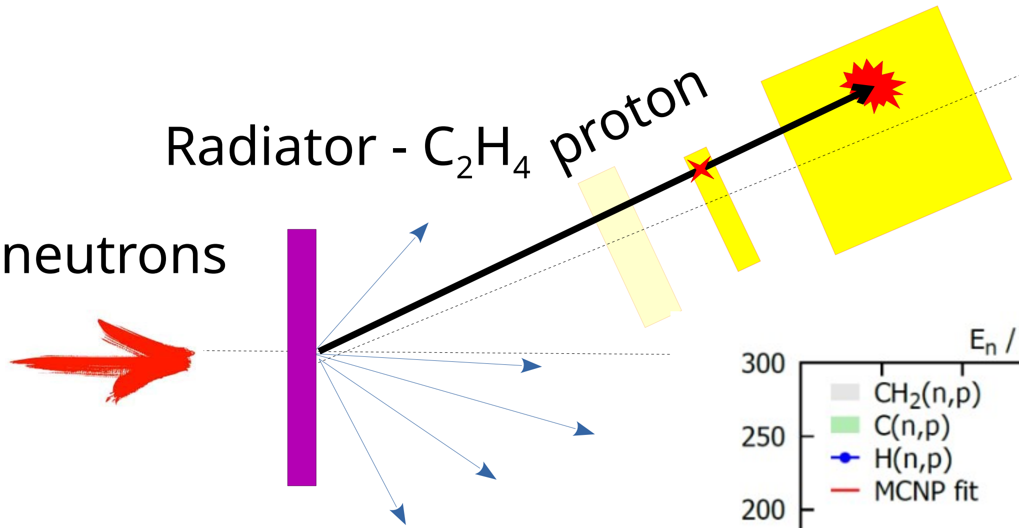


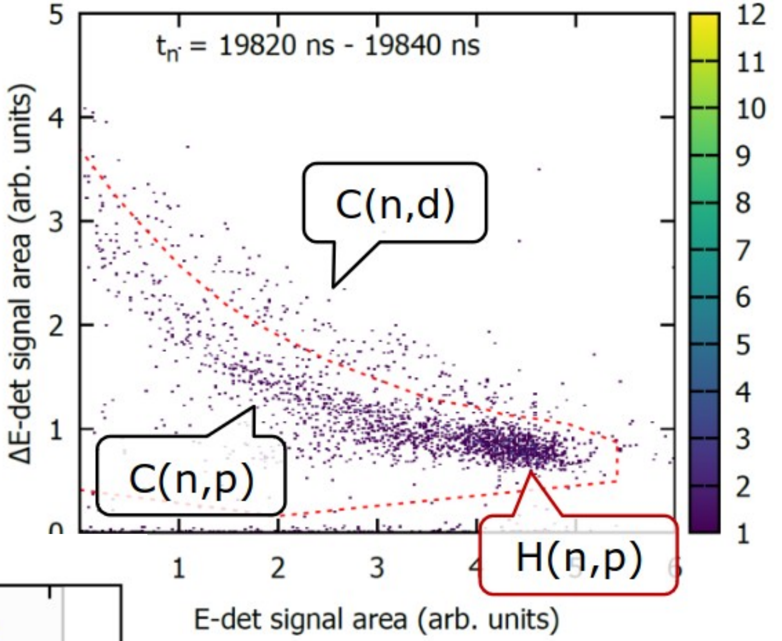
- 3 plastic scintillators

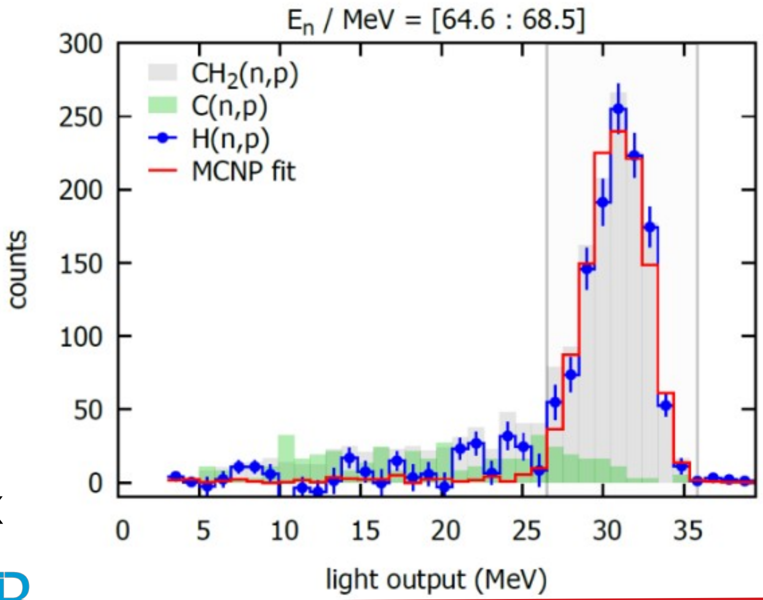
  in 3 different configurations :
  - 0.5 mm, 0.5 mm, 50 mm – (30-100) Me
  - 1 mm, 1 mm, 50 mm - (35-100) MeV
  - 2 mm, 2 mm, 100 mm - (50-150) MeV

Recoil Proton Telescope - 3s-RPT

n-p elastic scattering reaction







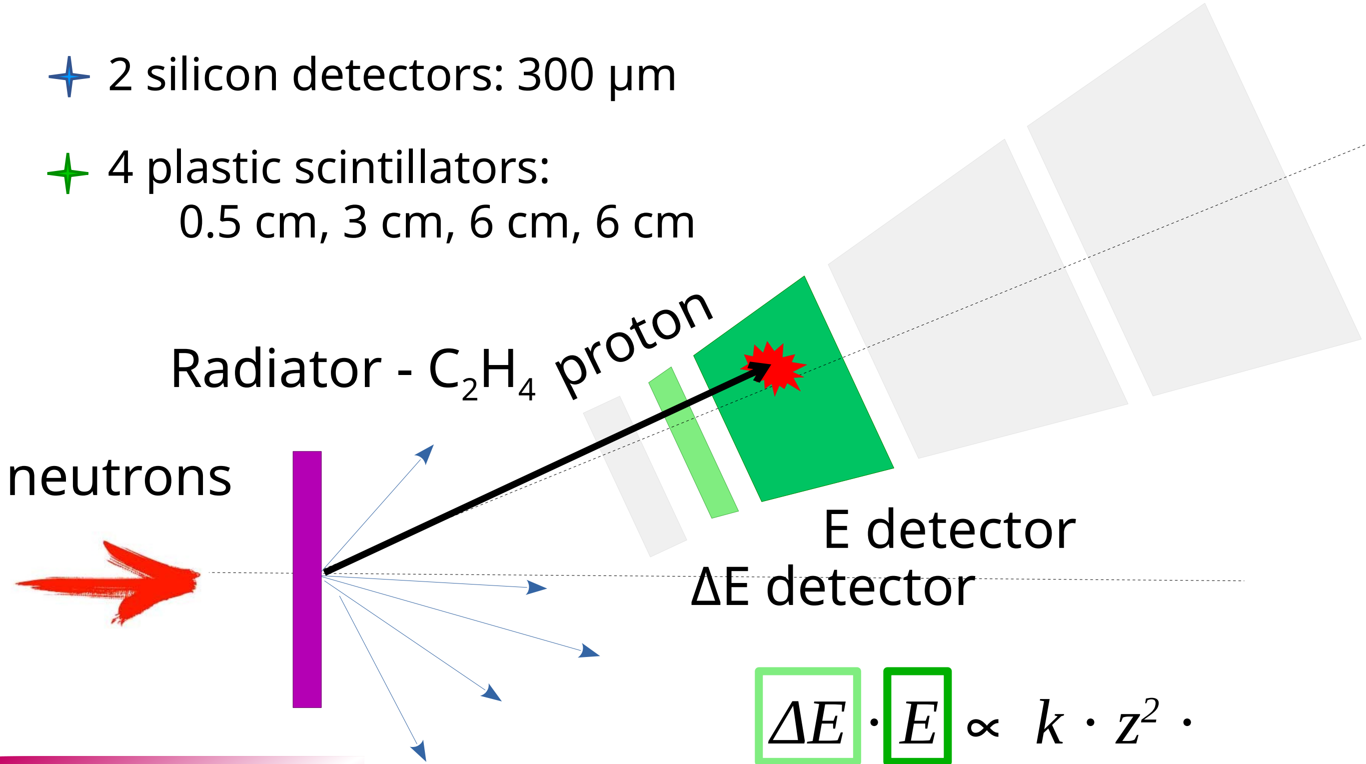
^{1}H(n,n)p events identification:

- selection of triple coincidences
- analysis of the ΔE2-E matrix

Recoil Proton Telescope - MS-RPT

n-p elastic scattering reaction

- 2 silicon detectors: 300 μm
- 4 plastic scintillators:
  0.5 cm, 3 cm, 6 cm, 6 cm



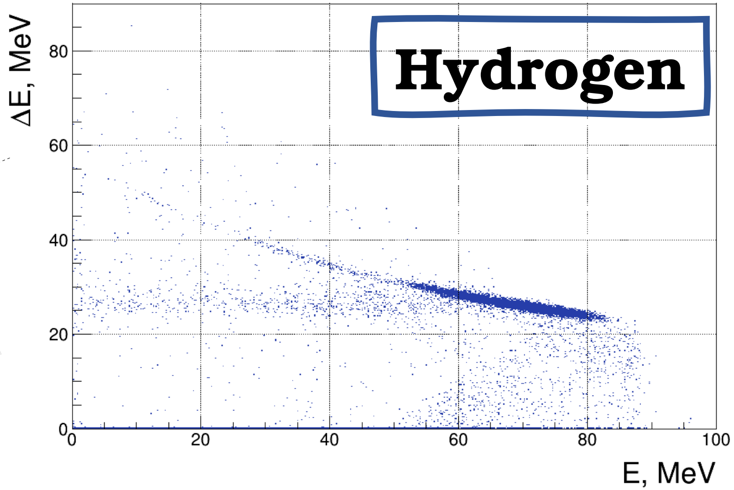
Pyramidal shape

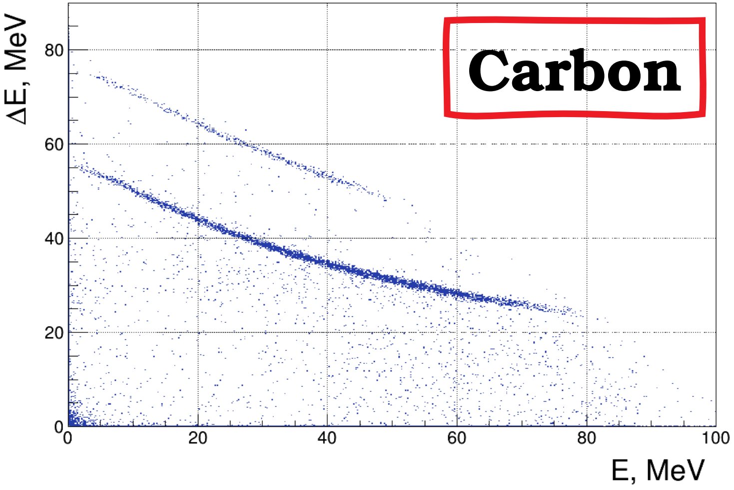
$$\boxed{\Delta E} \cdot \boxed{E} \propto k \cdot z^2 \cdot M$$

k: material absorption properties

M, *E*, *z*: interacting particle properties

*non-relativistic approximation





Recoil Proton Telescope - MS-RPT

En
75 MeV