Measurement of the cross section of $^{235}U(n,f)$ induced by high-energy neutrons relative to n-p elastic scattering performed at the n_TOF facility at CERN

A. Manna for the n_TOF Collaboration

IAEA Technical Meeting on Neutron Standards - 18-21 October 2022

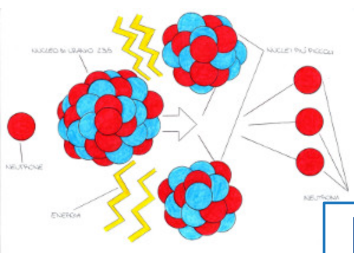
INFN
CERN
nTOF
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
PTB

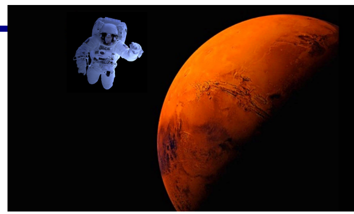
Motivations

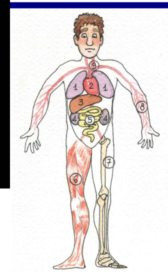
INDC International Nuclear Data Commitee

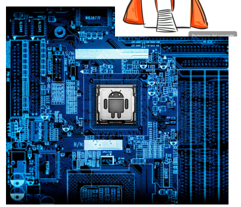
"...Our analysis indicates that the new absolute measurements of the neutron induced fission cross section (e.g. **relative to n-p scattering**) on **Uranium**, Bismuth, Lead and Plutonium have the highest priority in establishing neutron induced fission reaction standard **above 200 MeV**..."

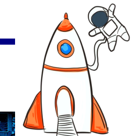
(INDC(NDS)-0681 Distr. ST/J/G/NM, IAEA 2015)

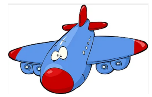




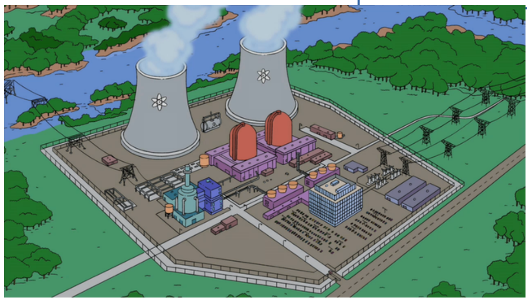


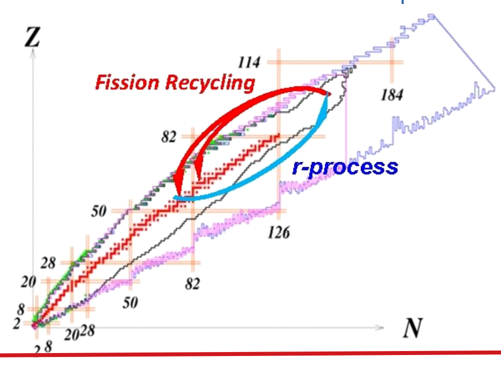


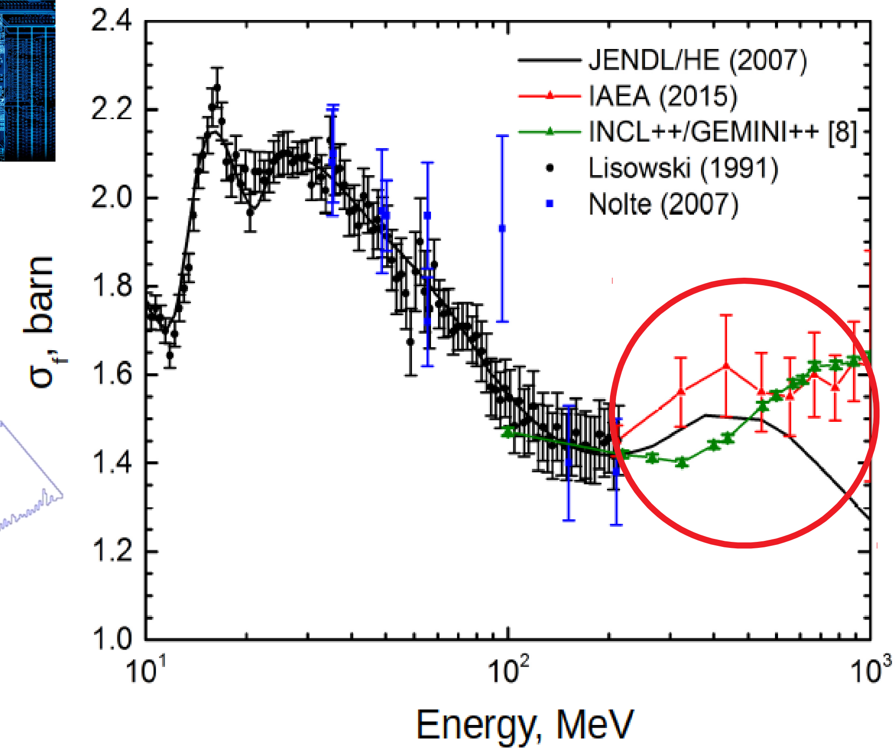




^{235}U(n,f) is one of the most significant cross-section standards at 0.025 eV and [0.15-200] MeV **BUT** there are **no experimental data above 200 MeV**

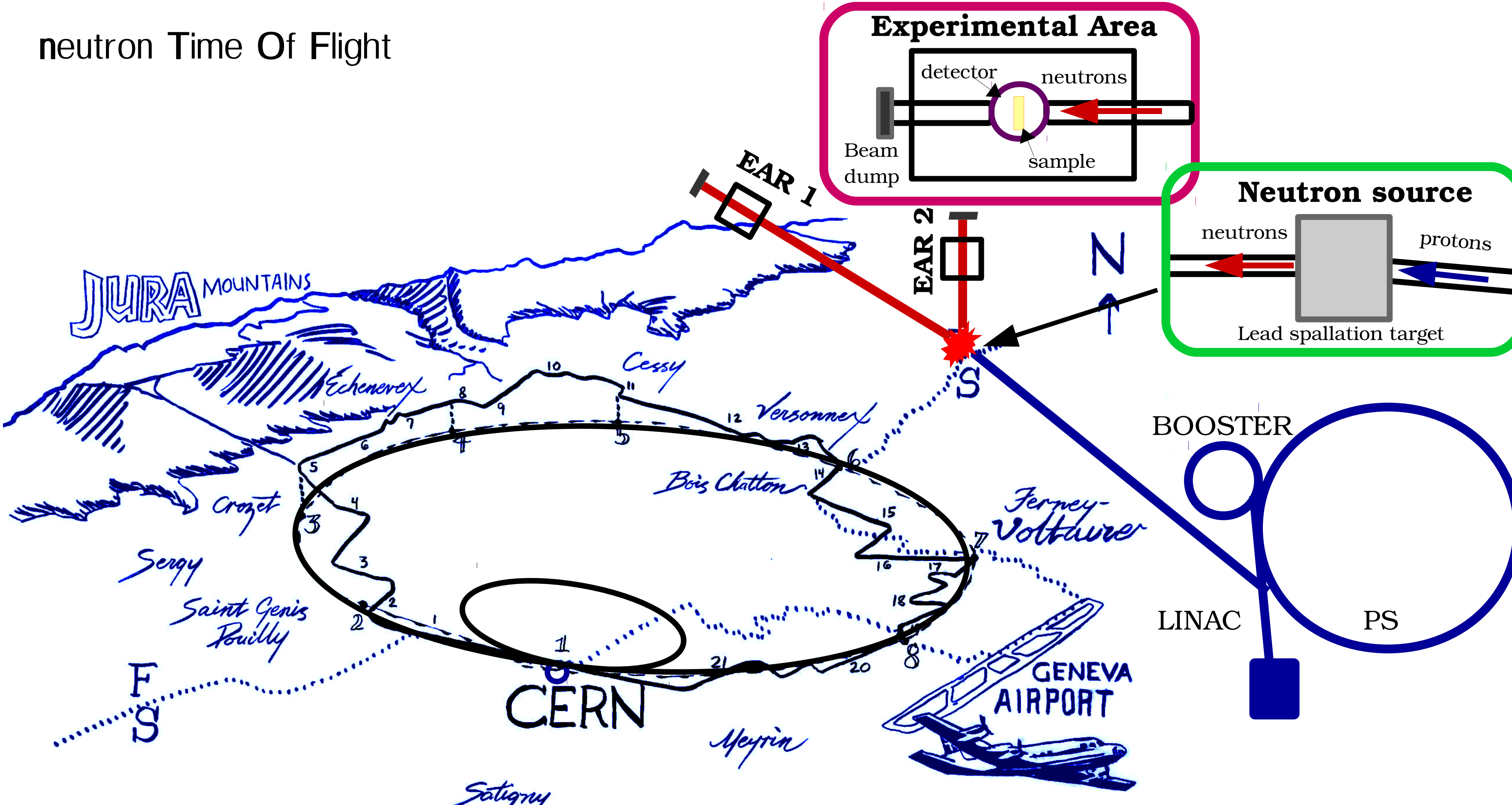






The n_TOF facility

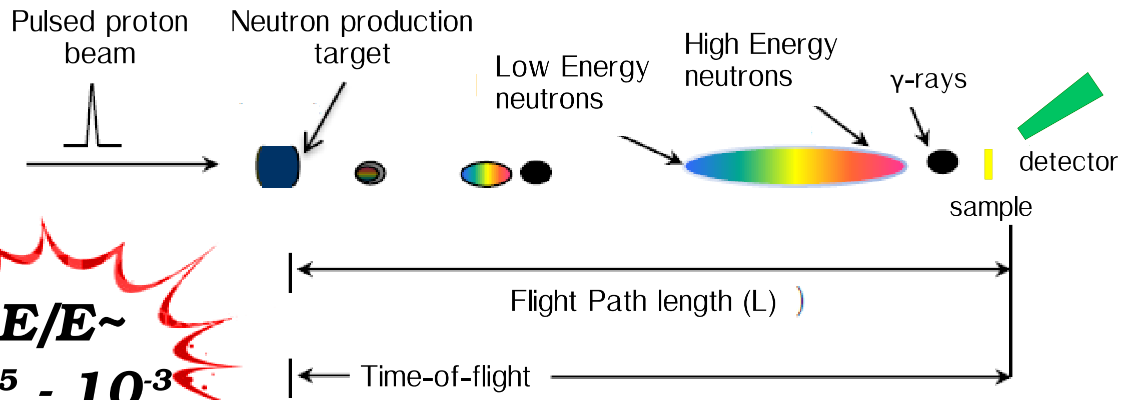
neutron Time Of Flight



The n_TOF facility

neutron Time Of Flight

- **High energy resolution**
  - → Time of Flight (ToF) technique
    with a long flight path:
    - → 185 m @ EAR 1
    - 20 m @ EAR 2

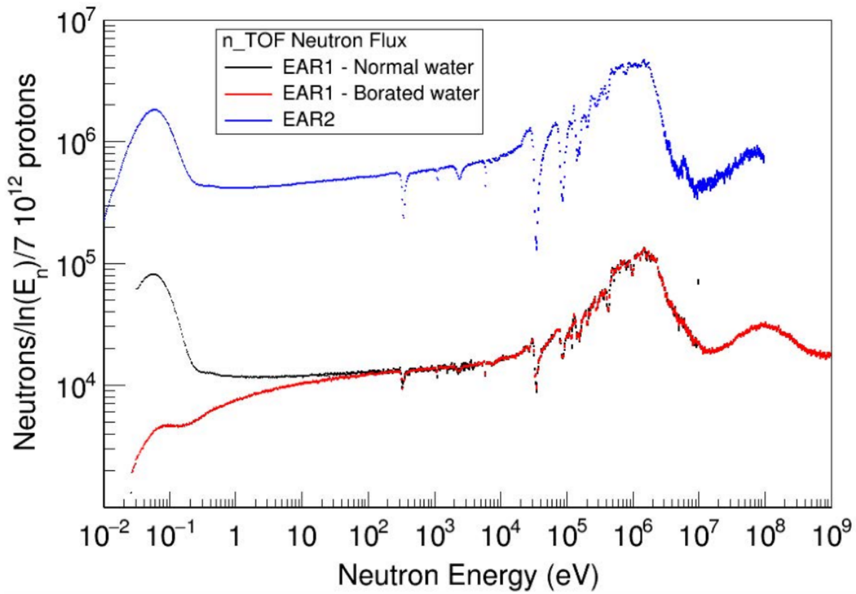


ΔE/E~ 10^{-5} - 10^{-3}

- **High neutron flux & wide energy range**
  - → Spallation reaction

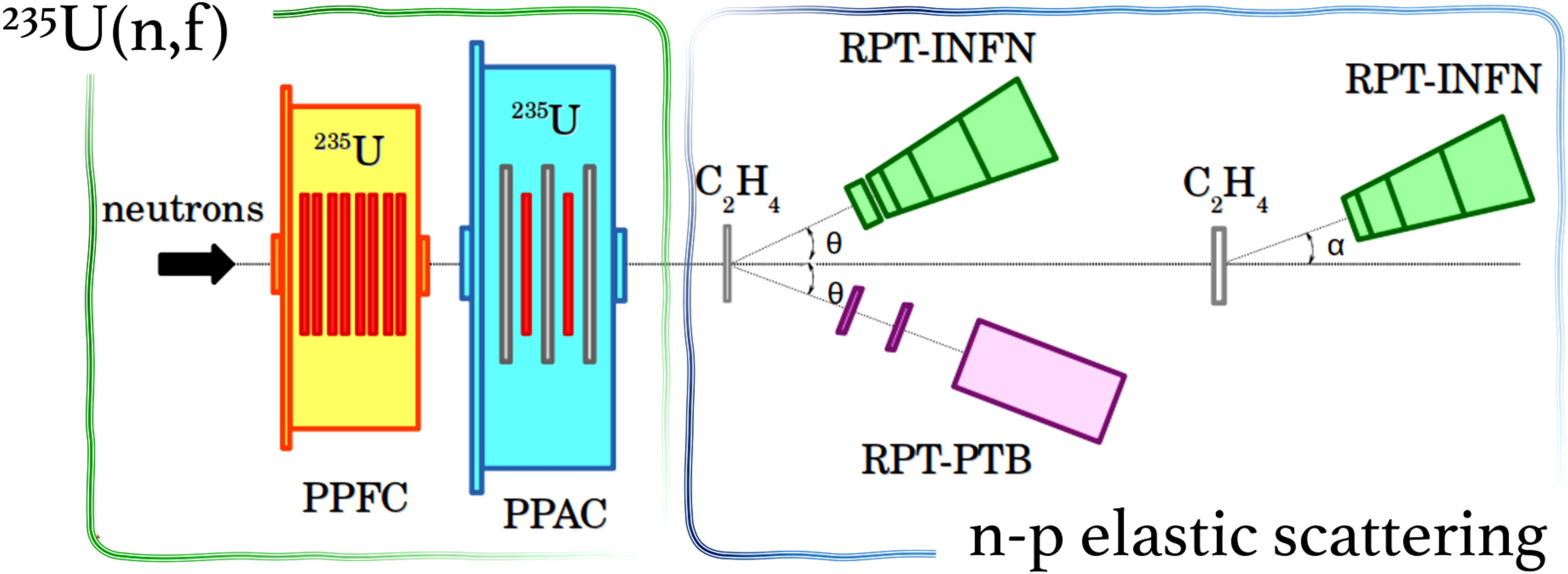
    $7 \cdot 10^{12}$ protons,
    20 GeV/c momentum
    +
    1.3 ton Pb Target

350 neutrons per incident proton



Experimental setup

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



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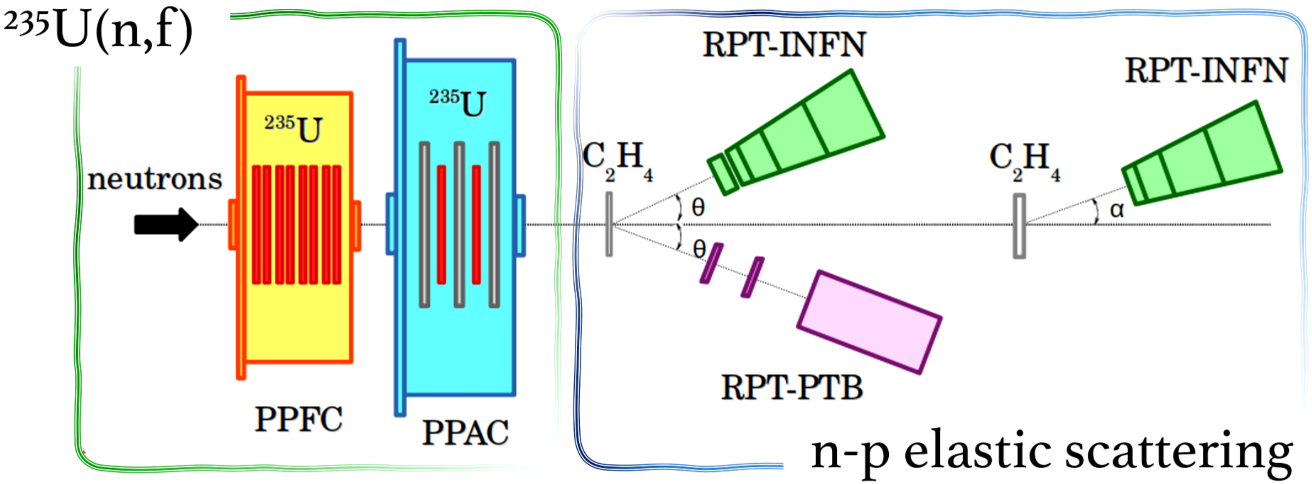
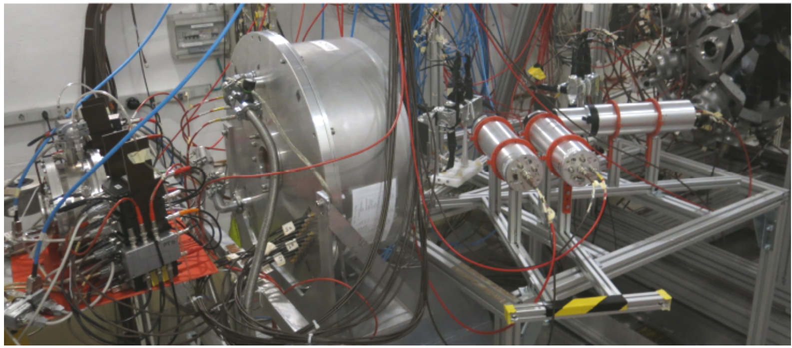




^{235}U fission reaction

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

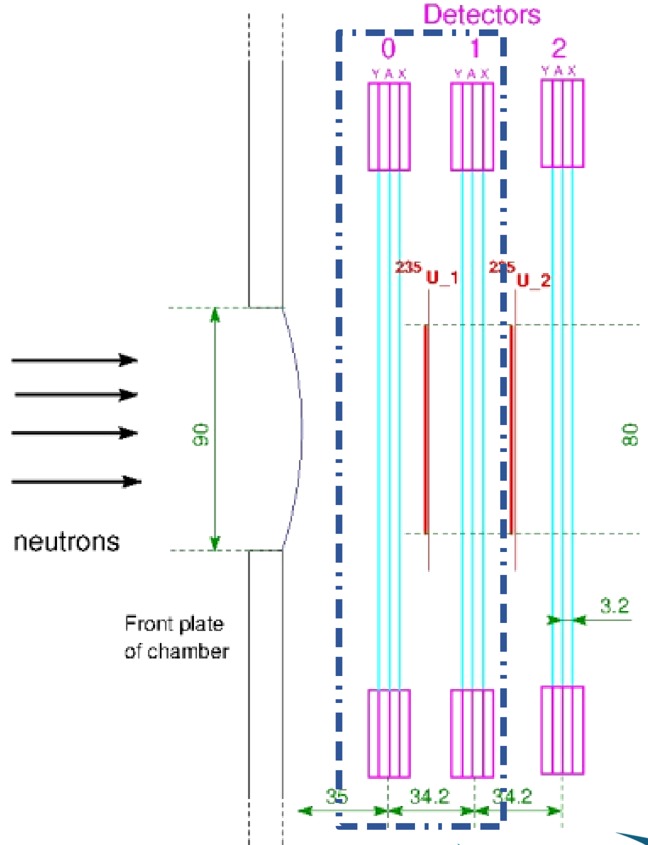
3 Proton Recoil Telescopes

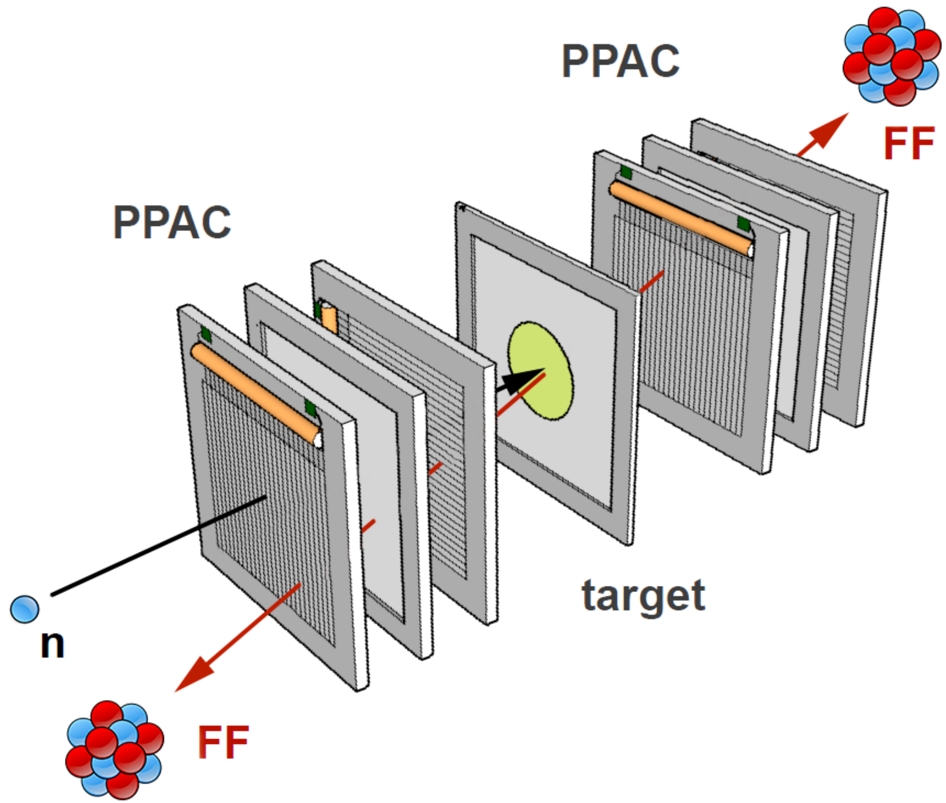
located out of the neutron beam

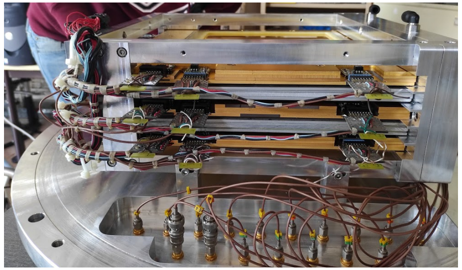
- 2 @ 25° pointing at a Polyethylene: 1/2/5 mm thick

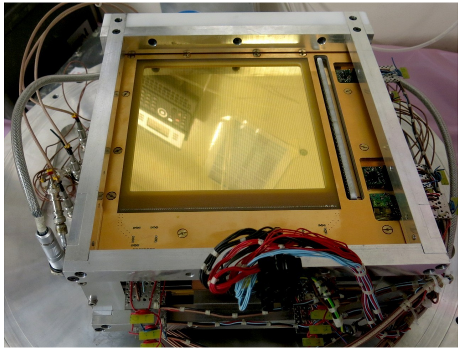
- 1 @ 20° pointing a Polyethylene: 5 mm thick

PPACs









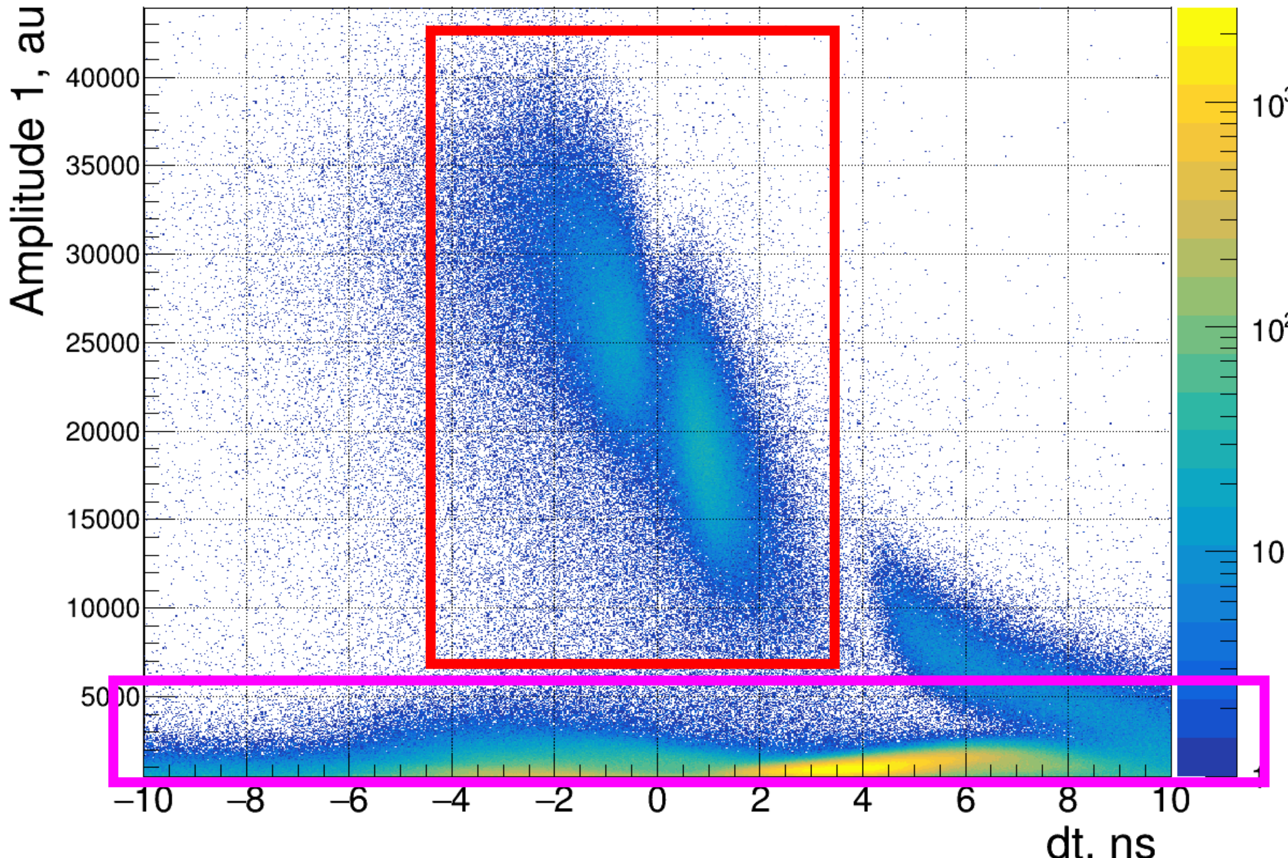
<u>The electrodes:</u>

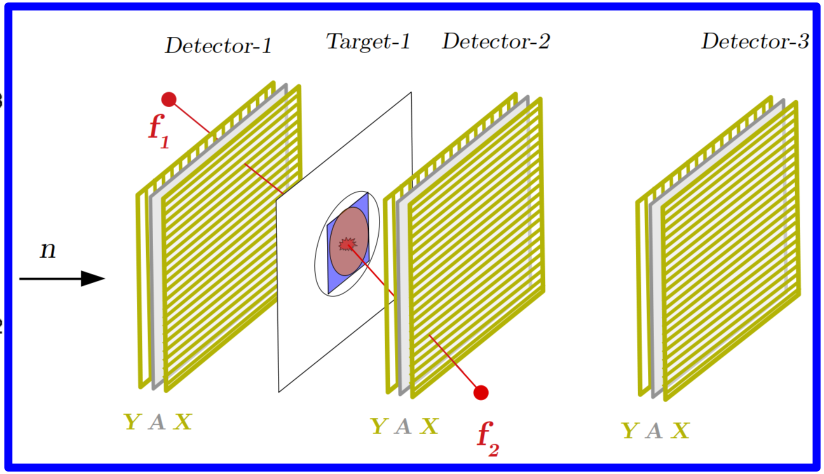
area of 20×20 cm²
1.7 μm mylar foils,
th gold, 700 nm thick

<u>Anode</u>:
the coating is uniform and double sided

<u>Cathodes</u>:
the coating is divided into 2 mm wide strips

Fission events signature

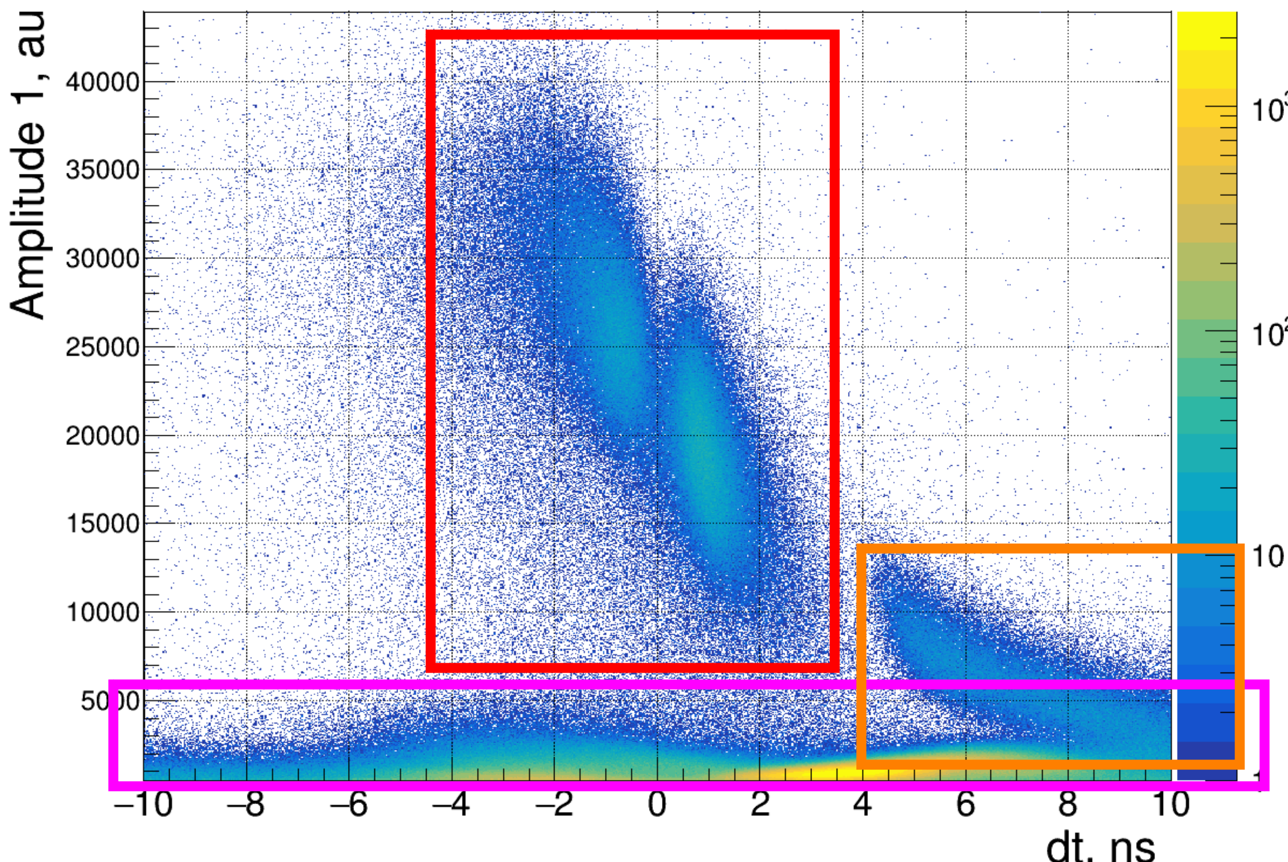




FFs from 1st ^{235}U

α from 2nd ^{235}U

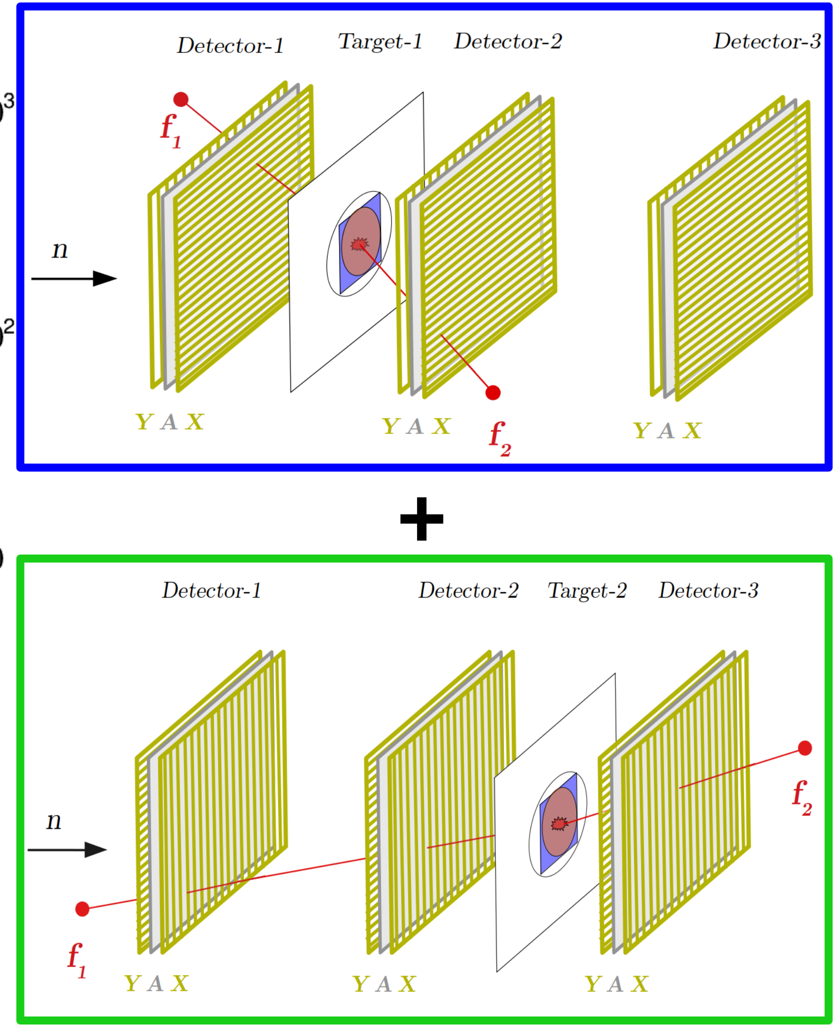
Fission events signature



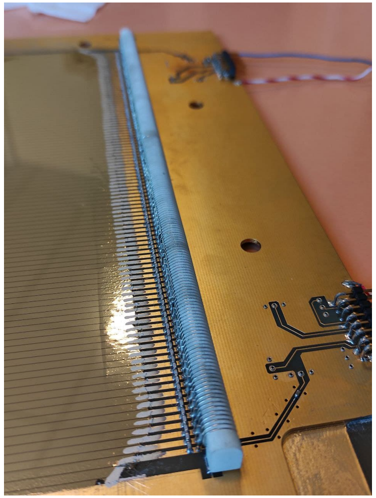
FFs from 1st ^{235}U

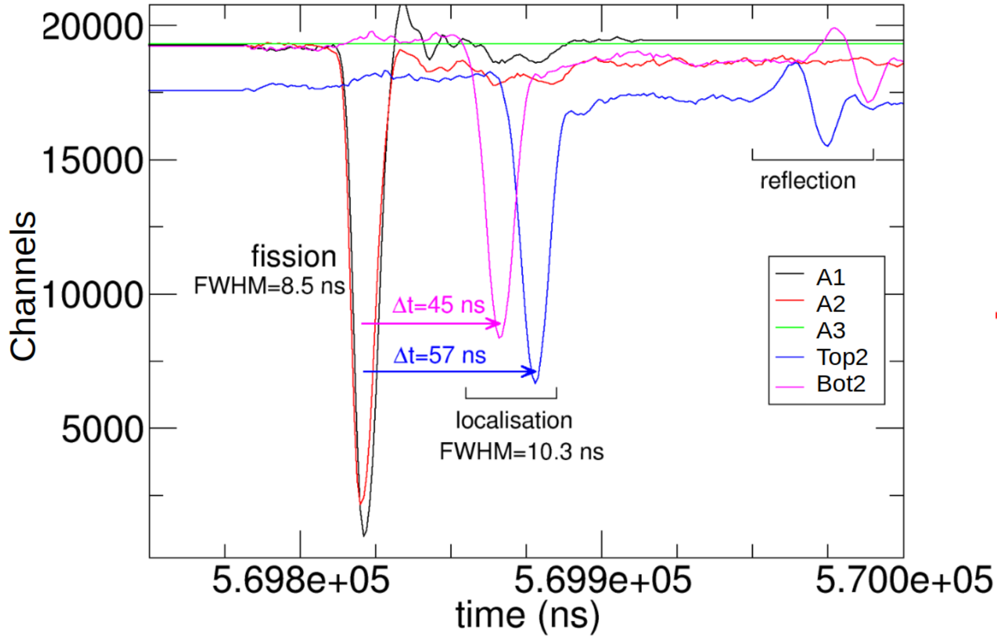
α from 2nd ^{235}U

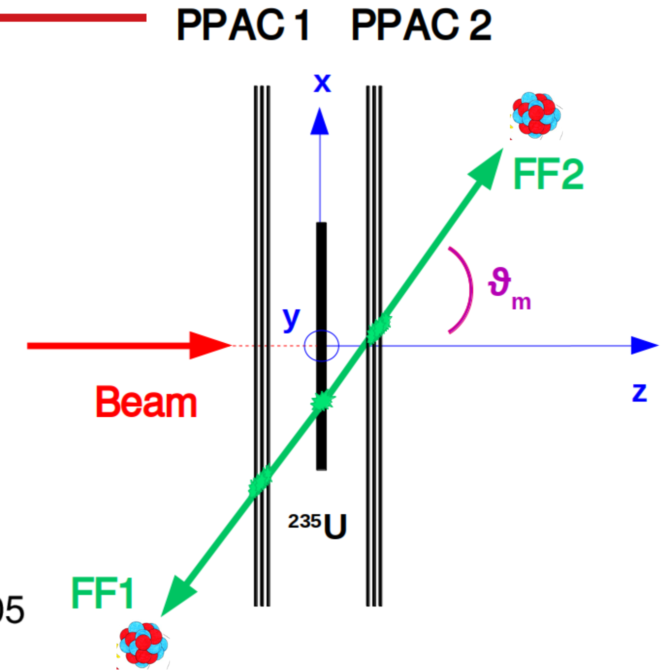
FFs from 2nd ^{235}U

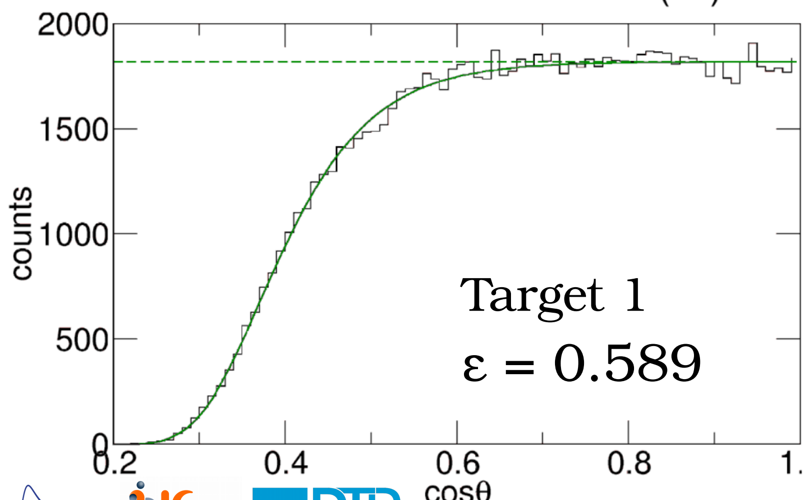


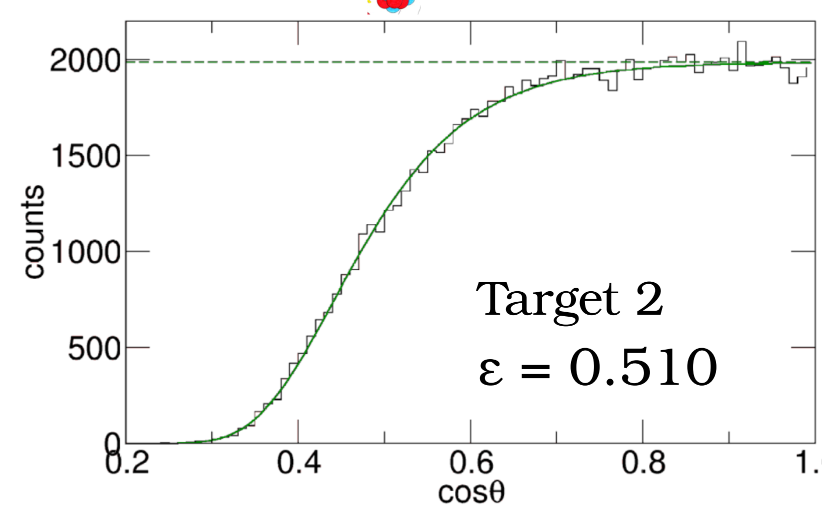
PPAC Efficiency



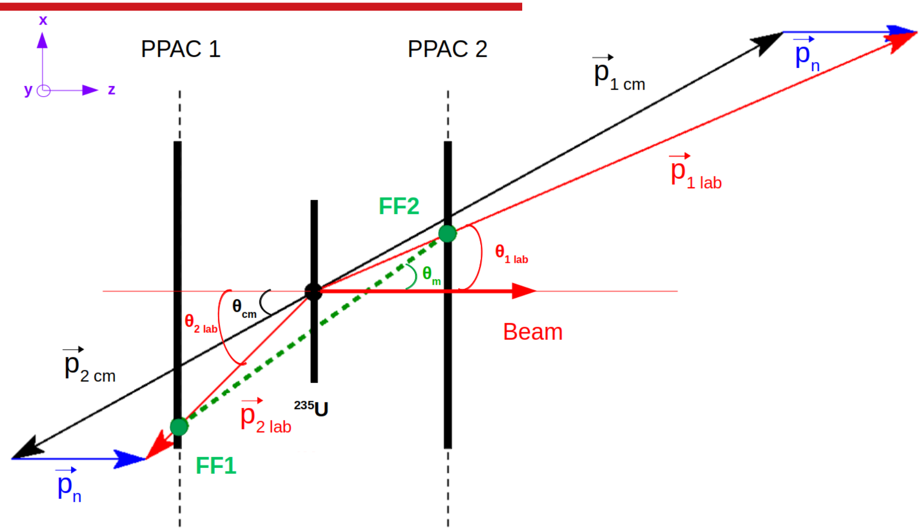




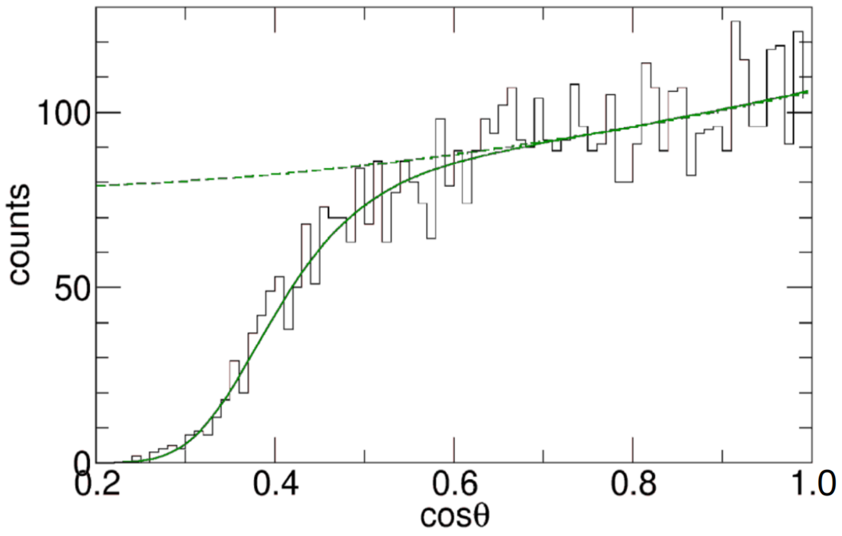




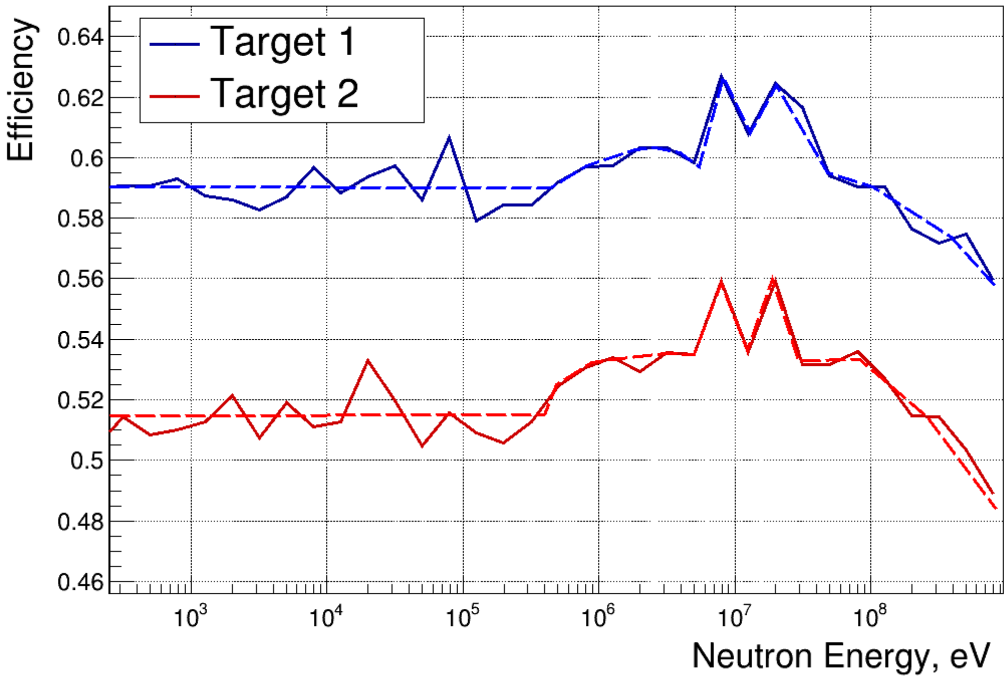
PPAC Efficiency

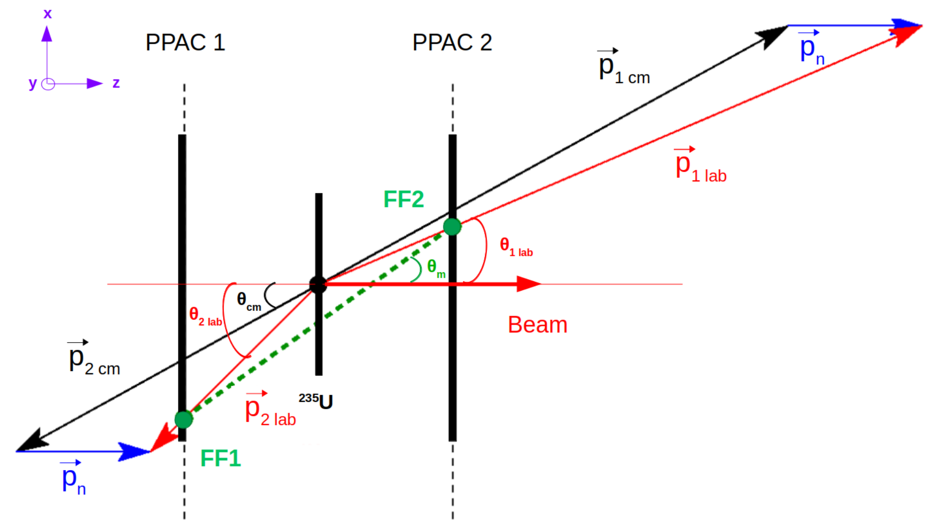


$6.3\ \mathrm{MeV} < E_n < 10\ \mathrm{MeV}$



PPAC Efficiency





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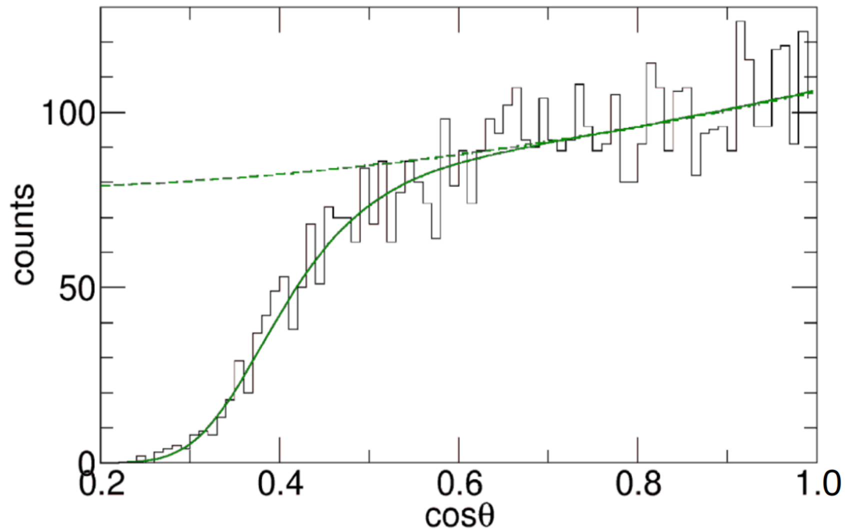


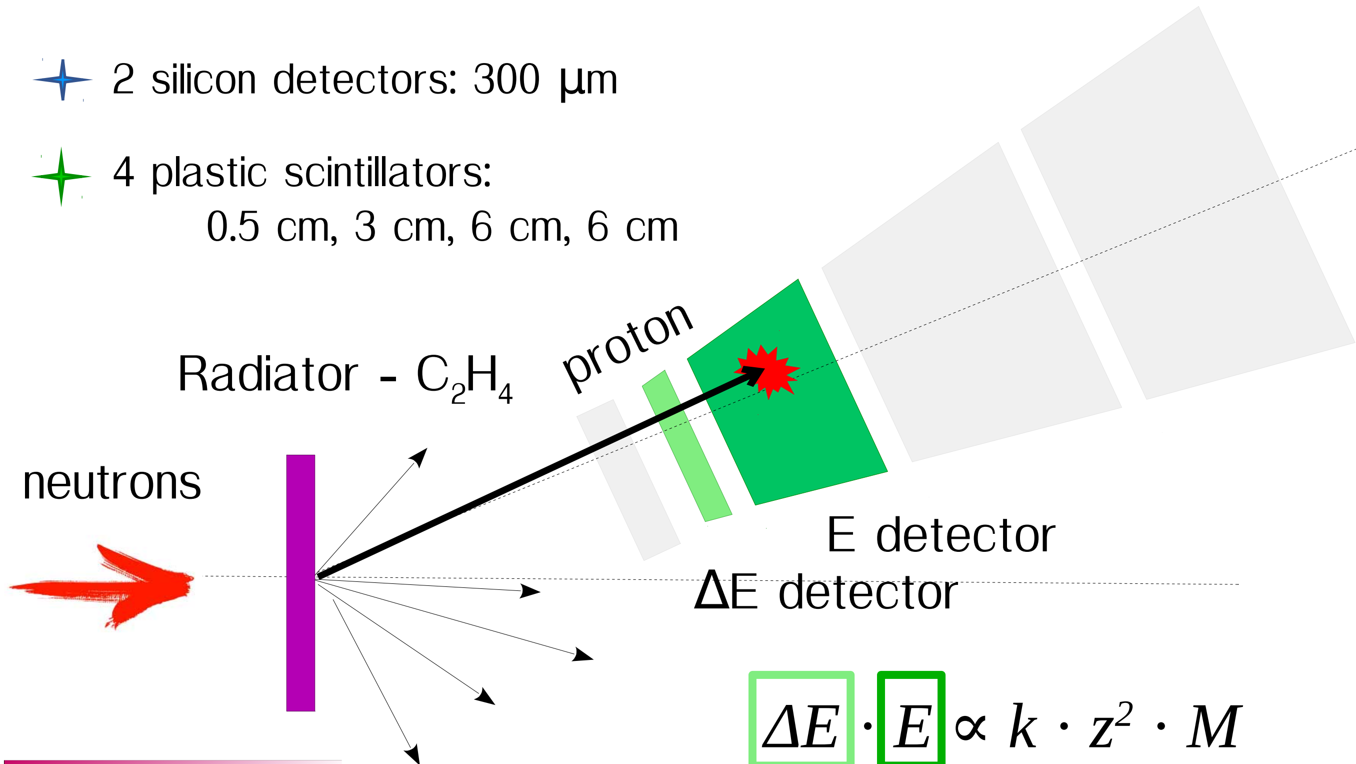
geometrical efficiency

geometrical efficiency
+
angular distribution
+
linear momentum transfer

Recoil Proton Telescope

n-p elastic scattering reaction

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



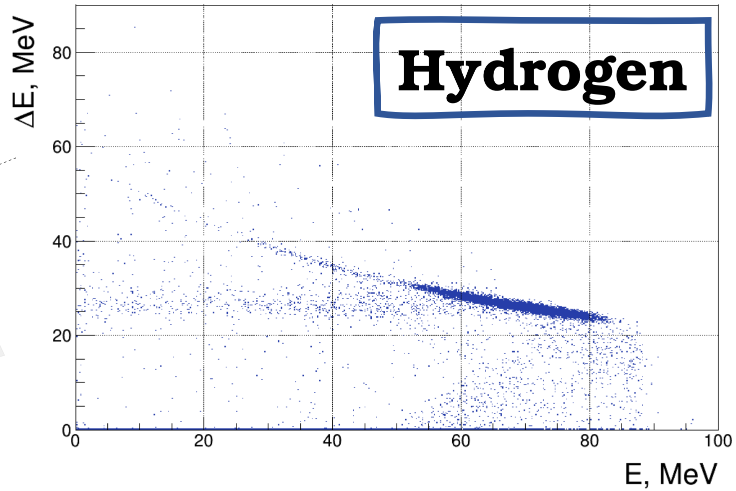
$$\Delta E \cdot E \propto k \cdot z^2 \cdot M$$

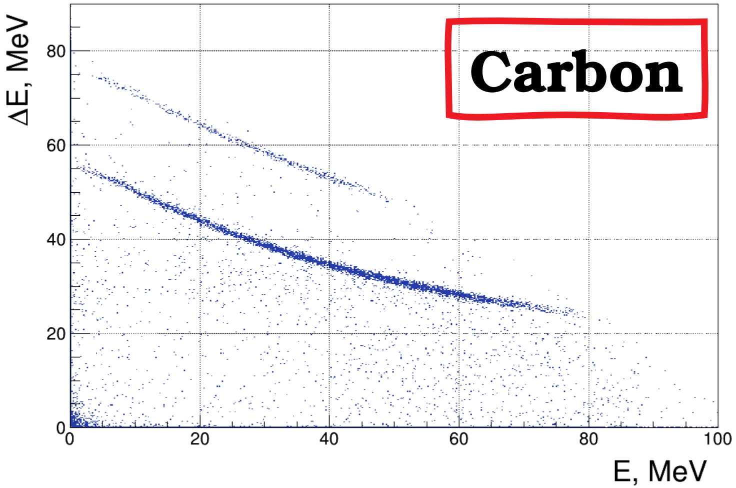
k: material absorption properties

M, E, z: interacting particle properties

*non-relativistic approximation

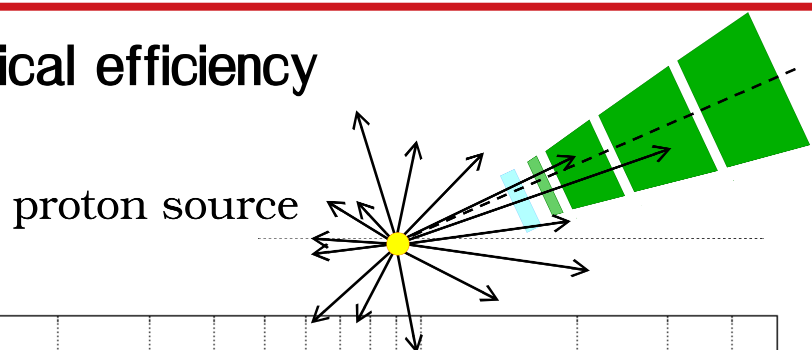
Pyramidal shape

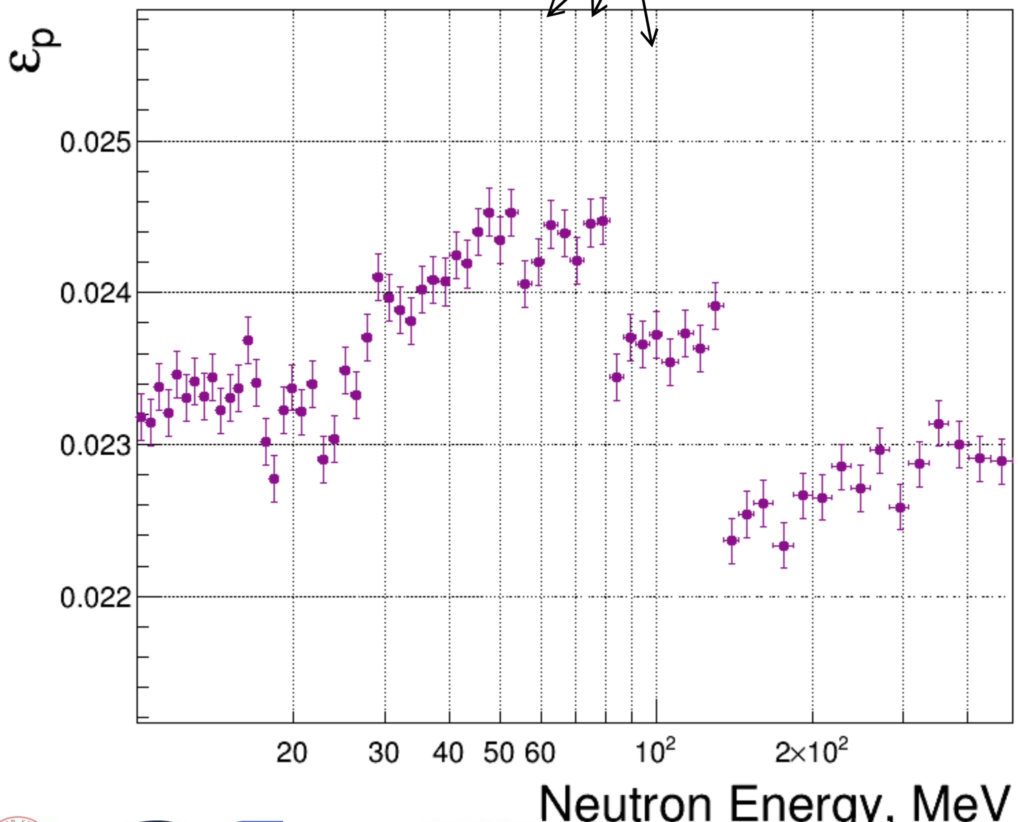




Monte Carlo simulation - RPT

Geometrical efficiency

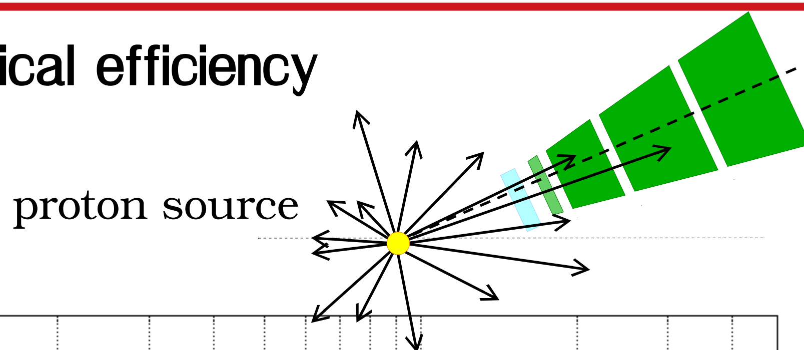


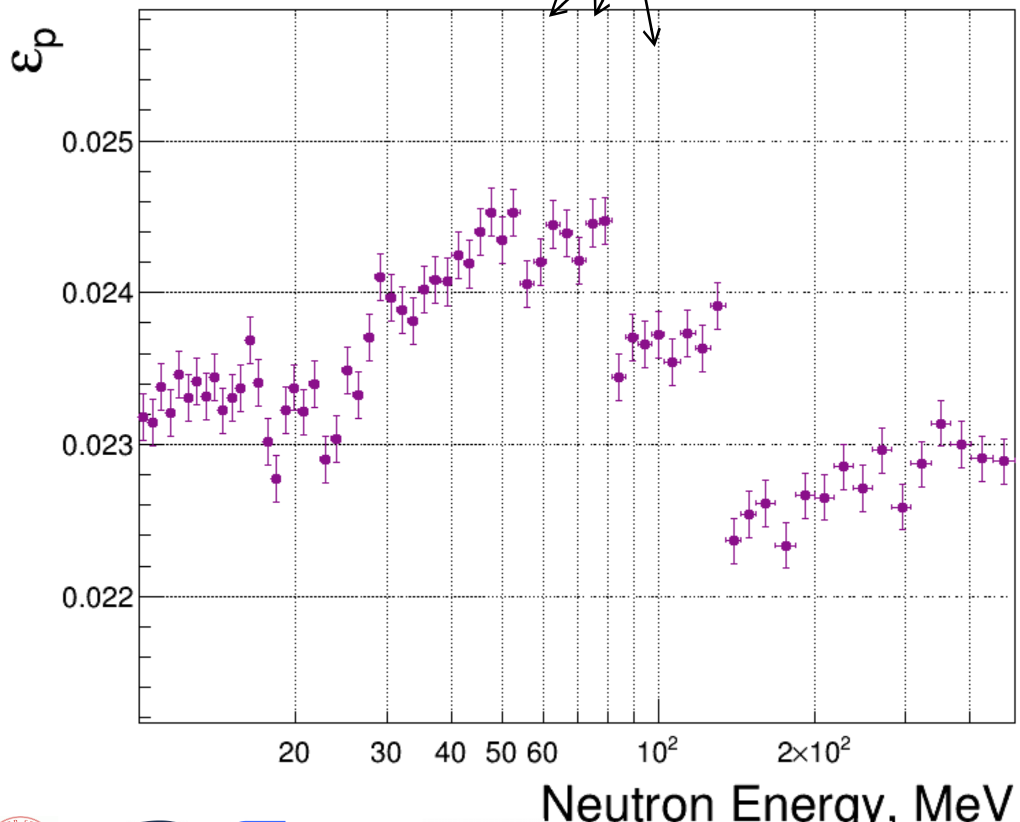


Monte Carlo simulation - RPT

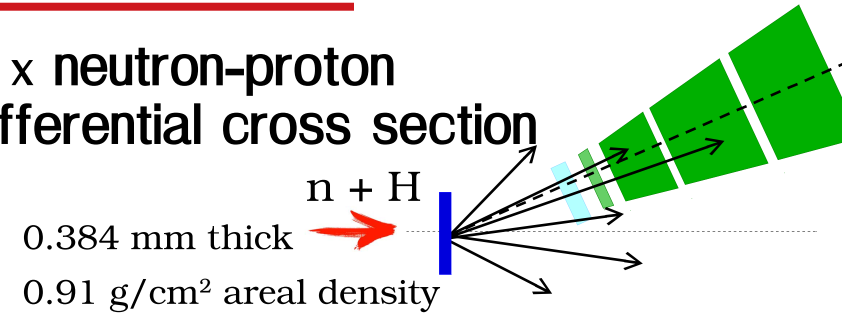
Geant4 and MCNP

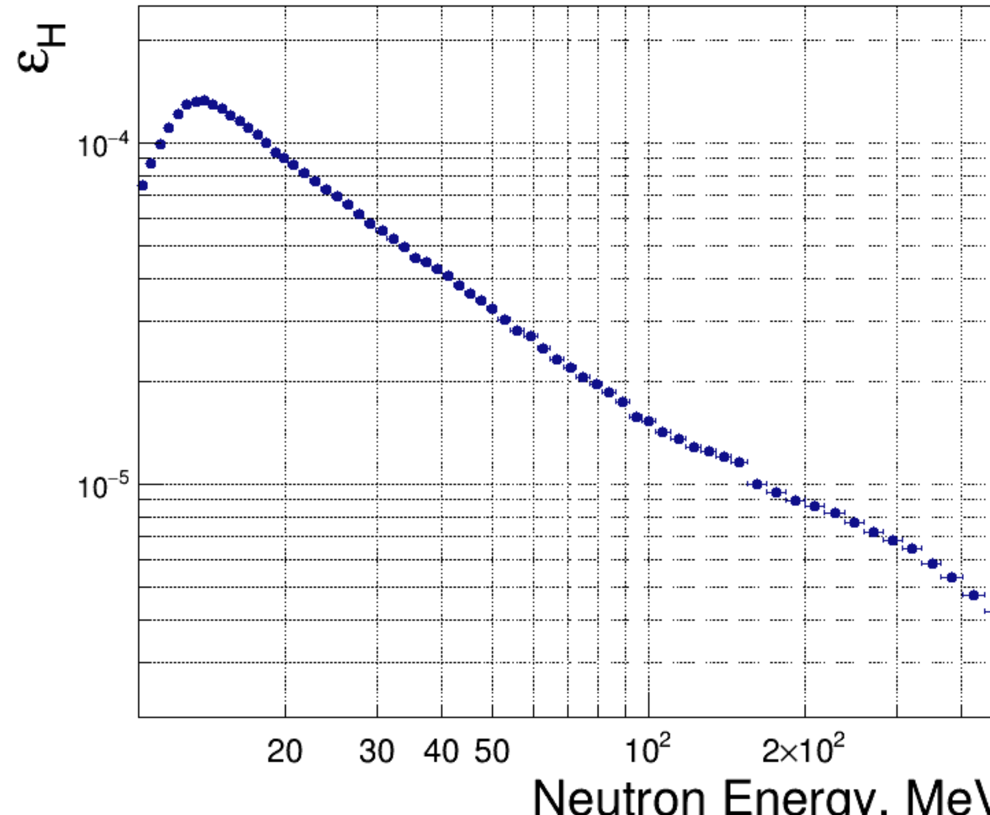
Geometrical efficiency



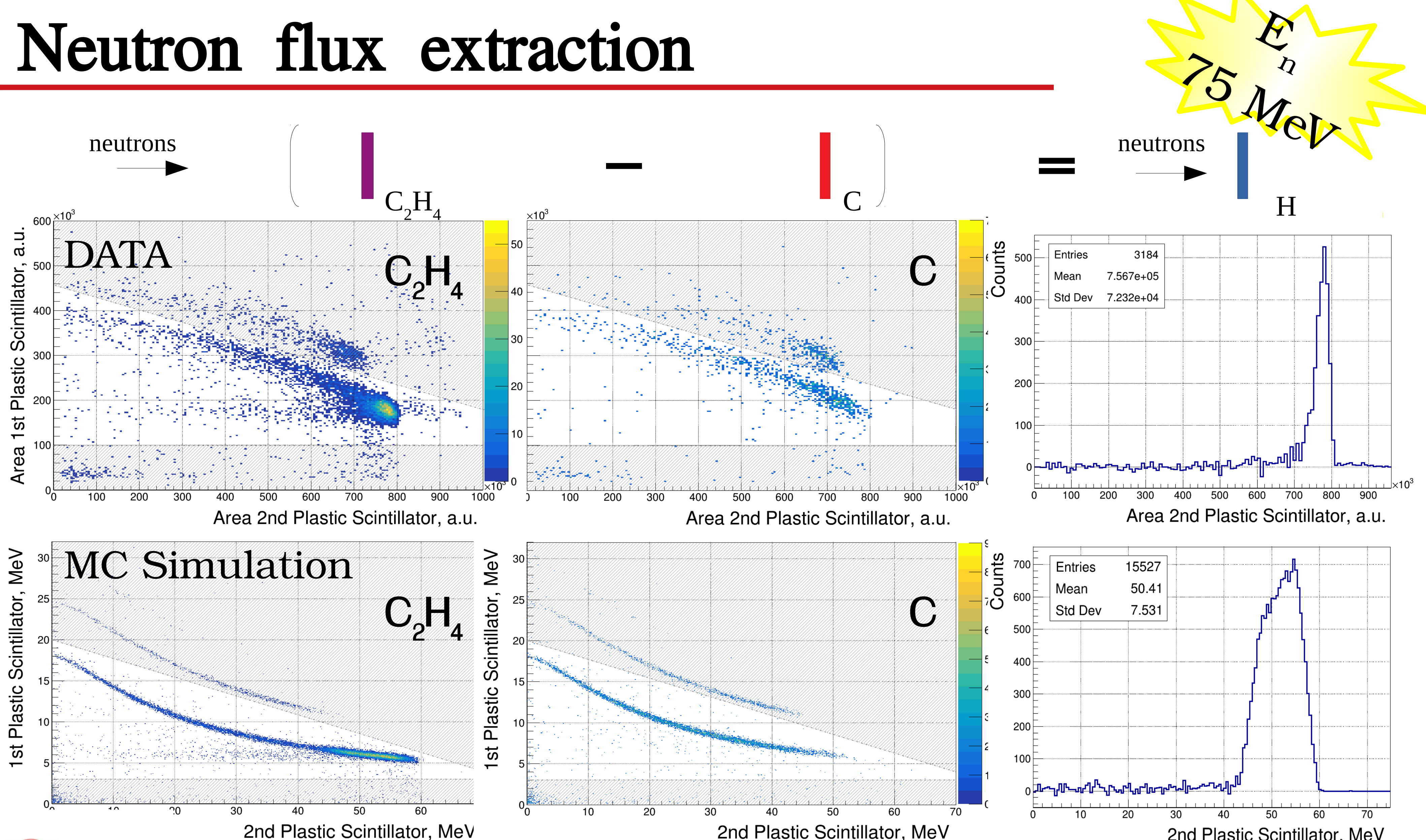


… x neutron-proton differential cross section

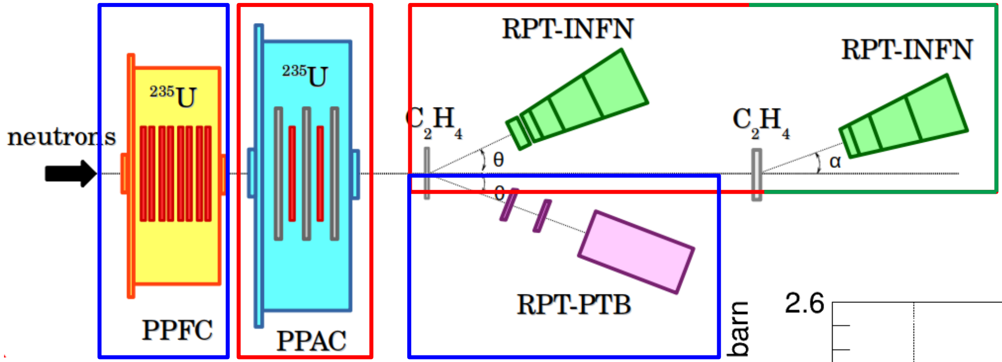




Neutron flux extraction



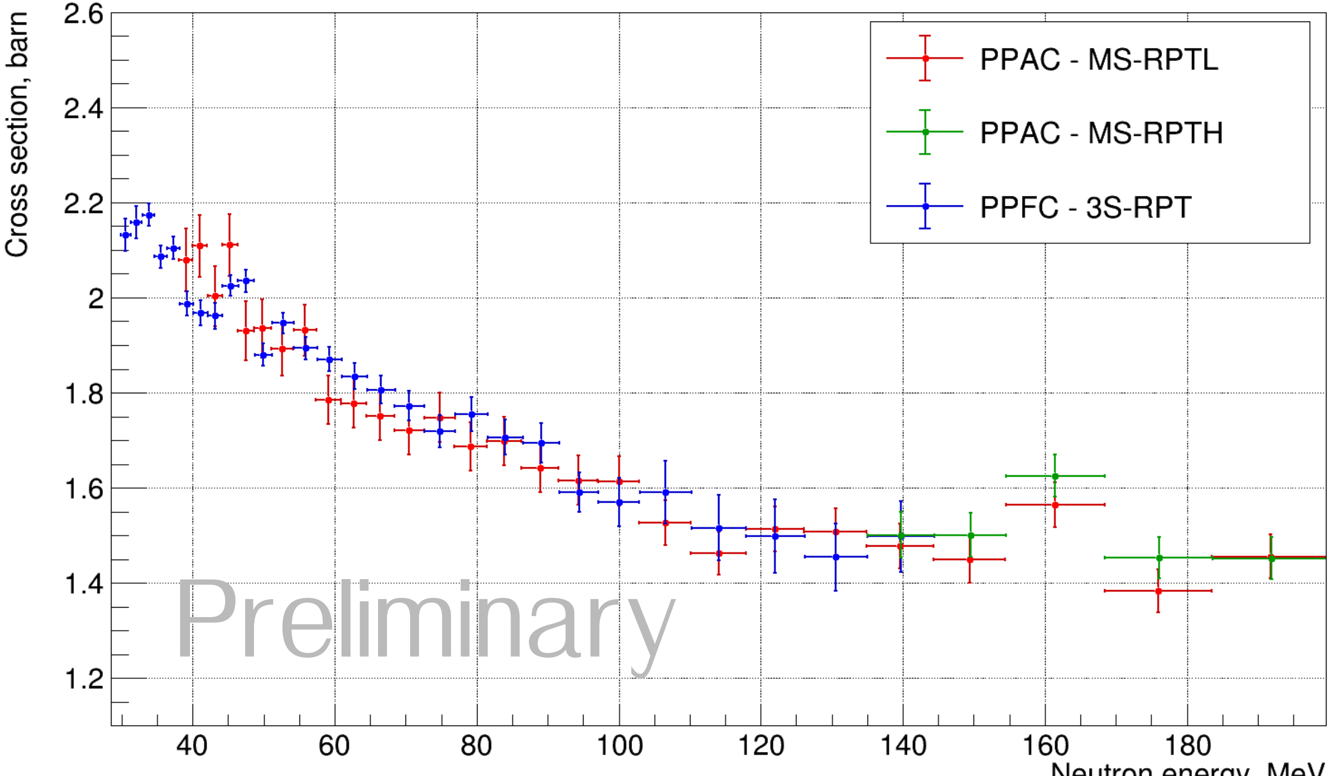
$^{235}U(n,f)$ cross section



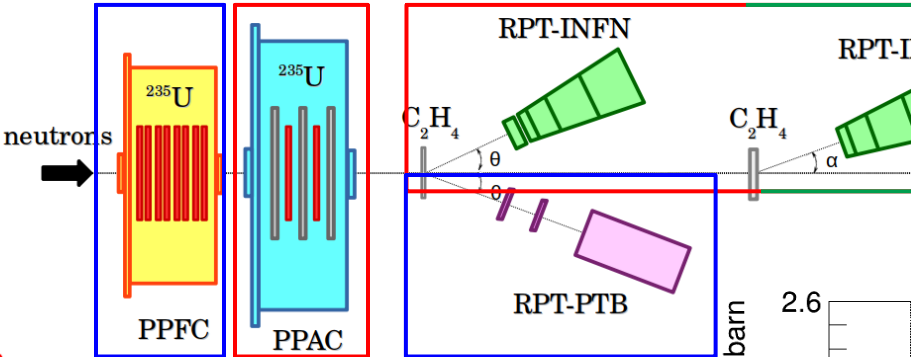
Arndt, VL40

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

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



^{235}U(n,f) cross section



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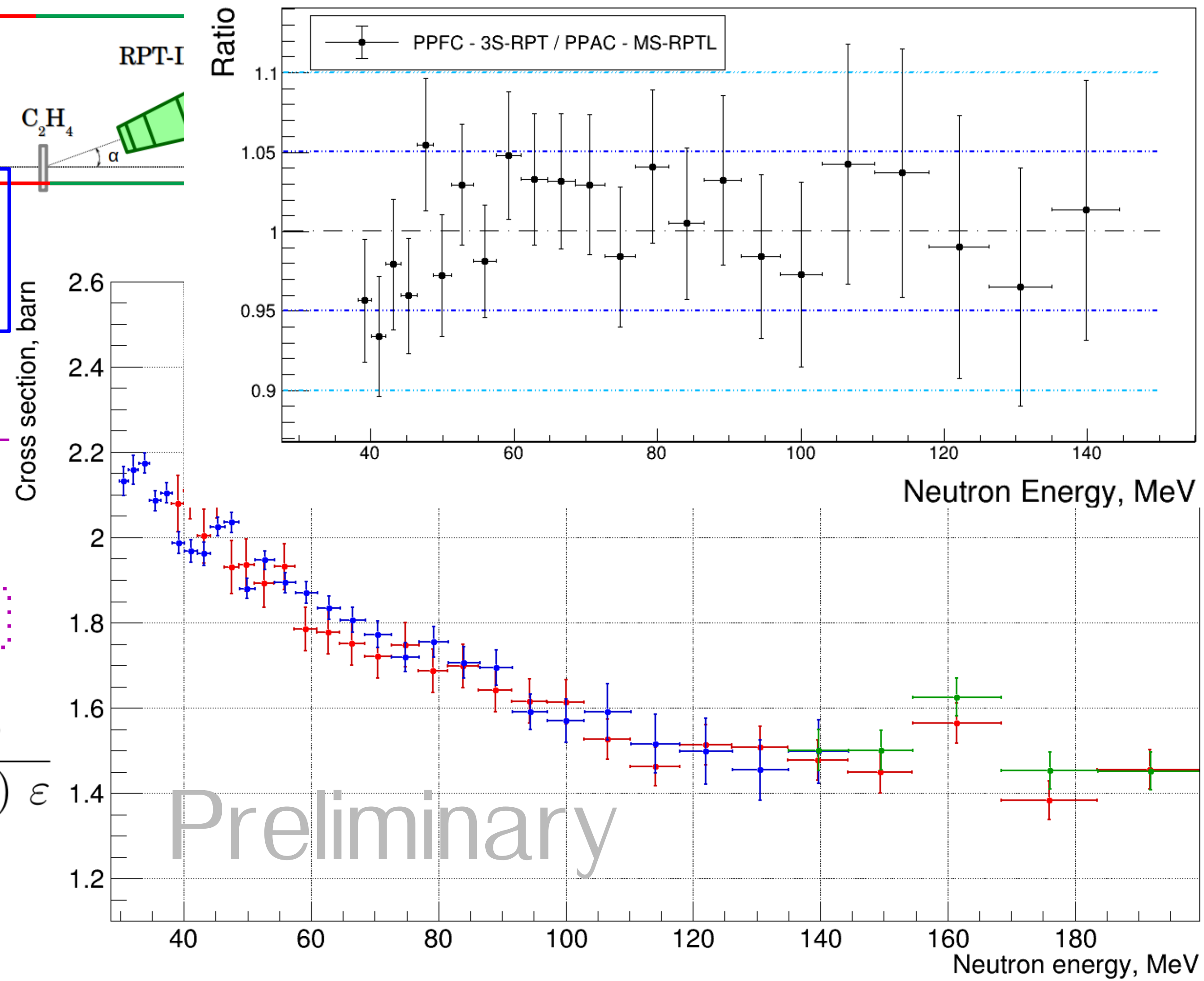

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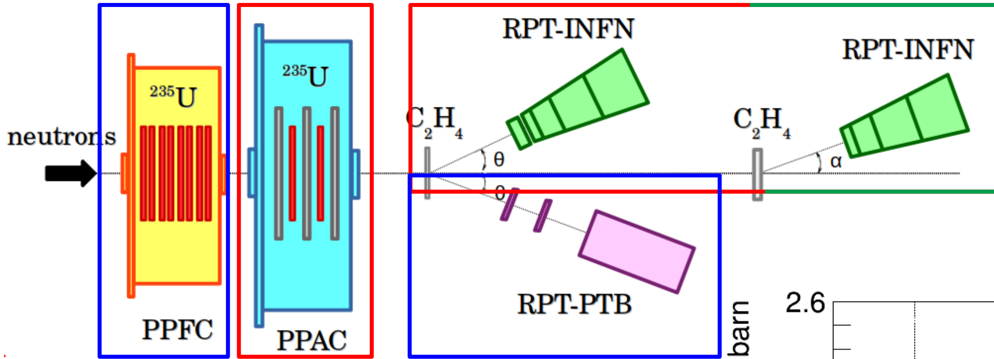

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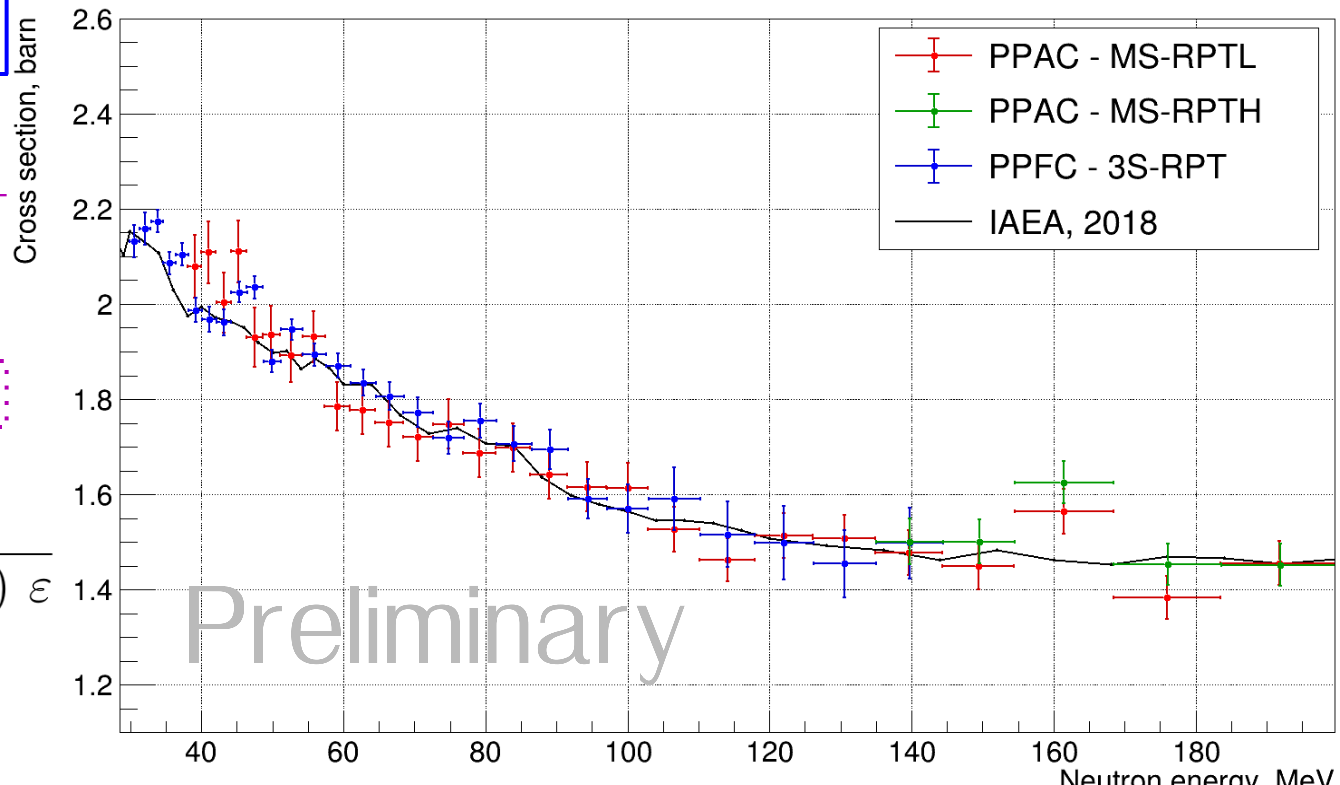
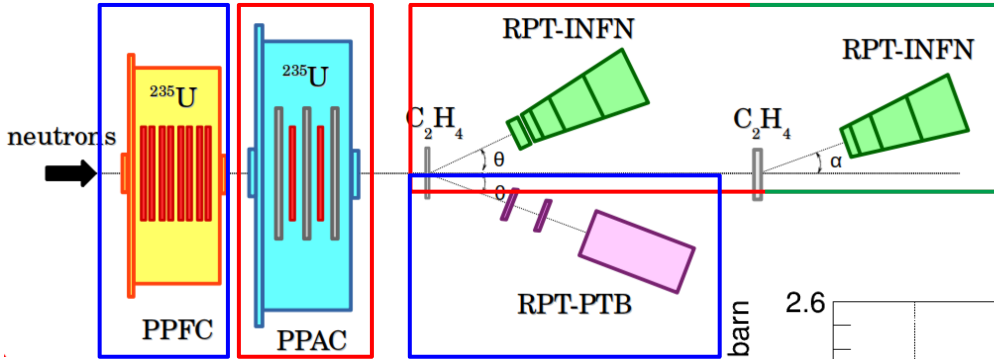


$^{235}U(n,f)$ cross section



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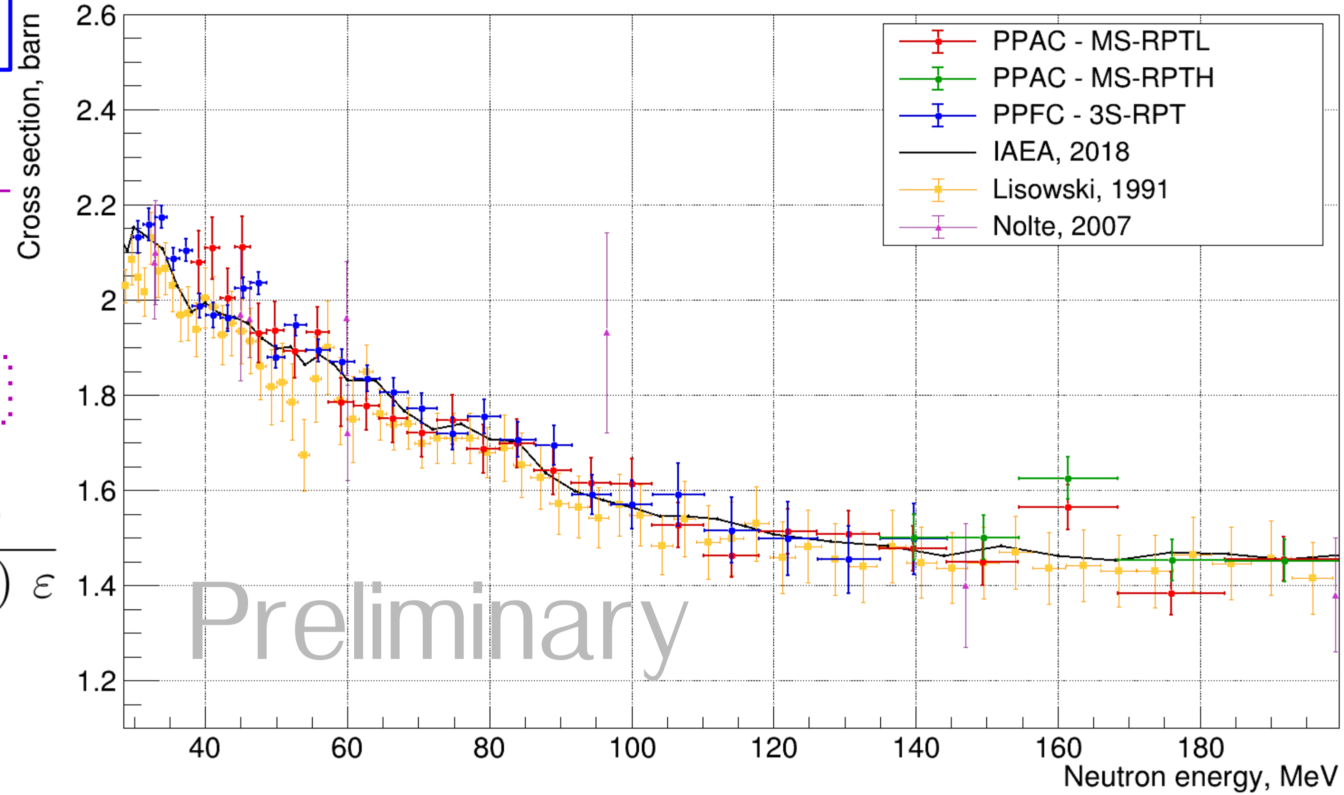
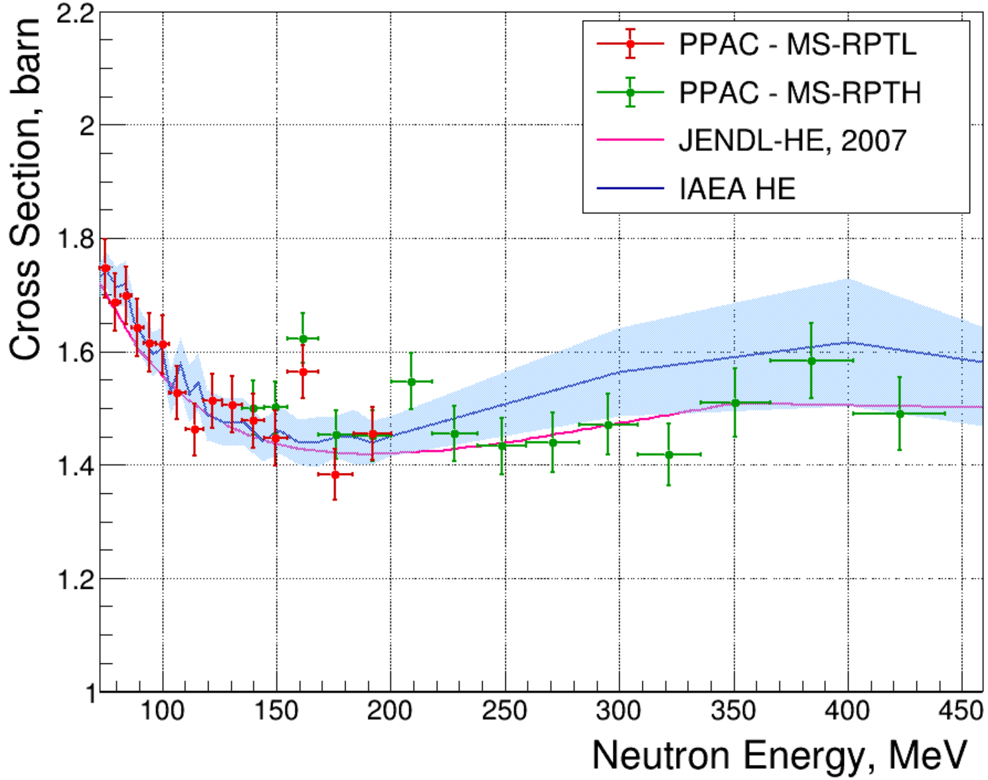


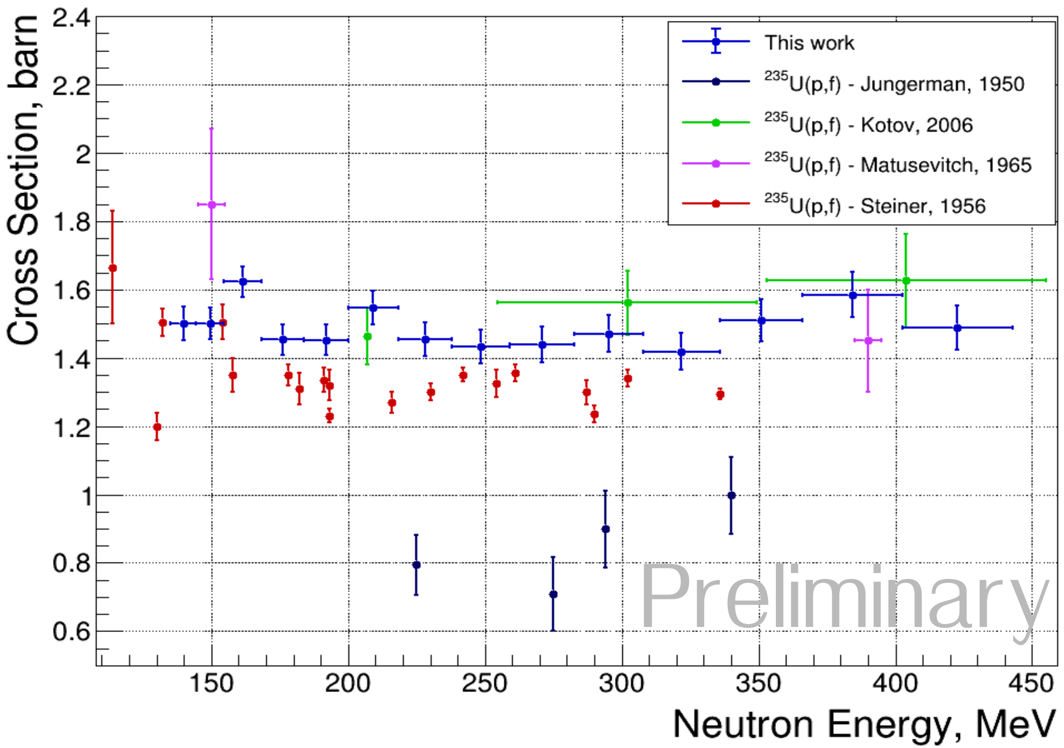
^{235}U(n,f) cross section

First ^{235}U(n,f) cross section above 200 MeV

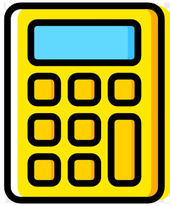
Comparison with models



Comparison with ^{235}U(p,f) data



Uncertainties



The energy range studied by the RTPL-INFN into three regions

→ different detectors used or different working conditions

	Uncertainty En = [10-30 MeV]	Uncertainty En = [38-200 MeV]	Uncertainty En > 200 MeV
Systematics	6.1%	2.8%	2.8%
Statistics	1.7-3.8%	1.0-2.4%	1.8-4.5%
Systematics	2.5%	2.5%	2.2%
Statistics	2.5-4.2%	2.5-4.2%	2.0-3.1%
Systematics	6.6%	3.8%	3.7%
Statistics	3.0-5.7%	2.7-4.8%	2.7-5.5%

...for neutron flux measurement RPTs-INFN related

...for FF events PPAC related

Total

Uncertainties

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	0.9%	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%
Counting statistics	1.7-3.8%	1.0-2.4%	2.8-4.5%
Total	6.2 - 7.1%	2.9 - 3.7%	4.4 - 5.4%

...for neutron flux measurement
RPTs-INFN related

...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%	-
Counting statistics	2.5 - 4.2%	2.0 - 3.1%
Total	3.6 - 4.9%	3.0 - 3.8%

Conclusion

First measurement of neutron-induced fission cross section on ^{235}U in the energy range between 200 and 450 MeV

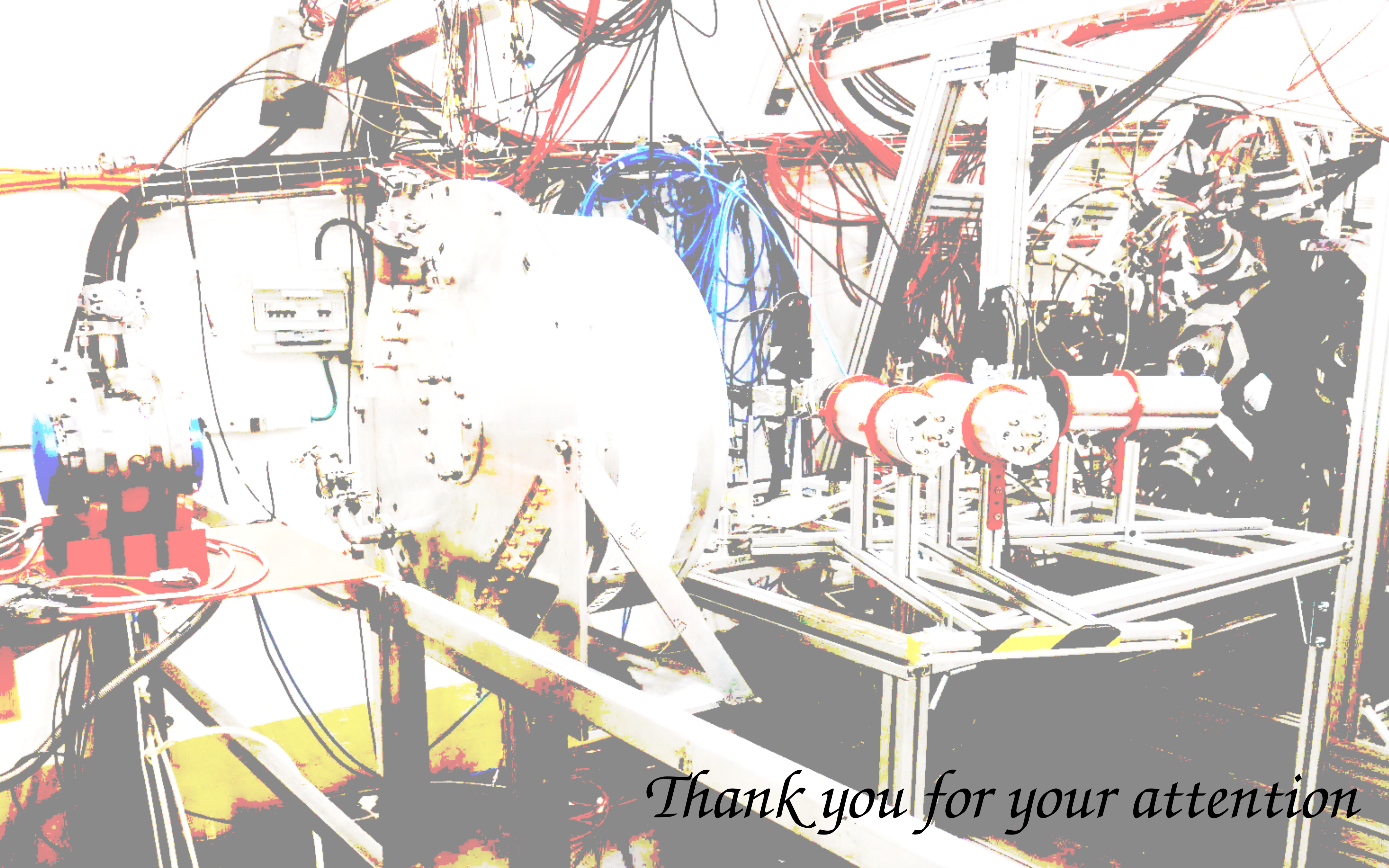
First measurement of the n_TOF flux in the energy range between 20 and 450 MeV

reliability of results by agreement with previous measurements
at lower energies (20-200 MeV)

...and perspectives

- Further campaign with ^{235}U with the aim to:
  - improve the accuracy (increase the statistics)
  - reach a higher neutron-energy value (FFs already detected up to 1 GeV)
  - measure simultaneously cross section and FFs angular distribution

- Extend the study to other isotopes



Thank you for your attention

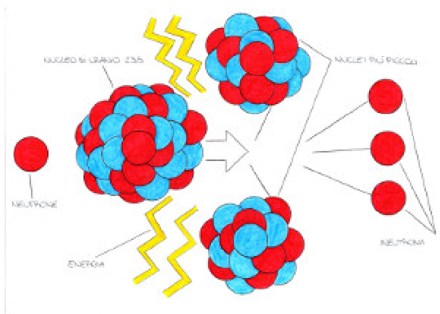
Motivations

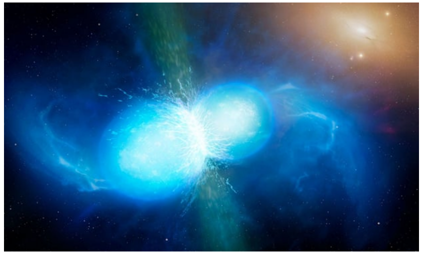
IAEA International Atomic Energy Agency

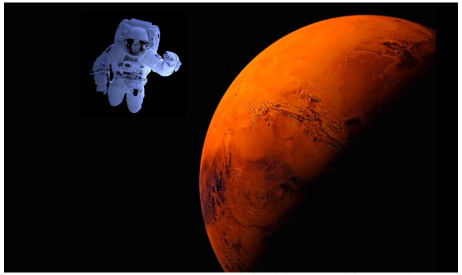
INDC International Nuclear Data Commitee

"…Our analysis indicates that the new absolute measurements of the neutron induced fission cross section (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**…"

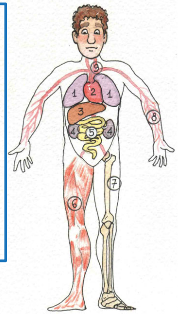
(INDC(NDS)-0681 Distr. ST/J/G/NM, IAEA 2015)

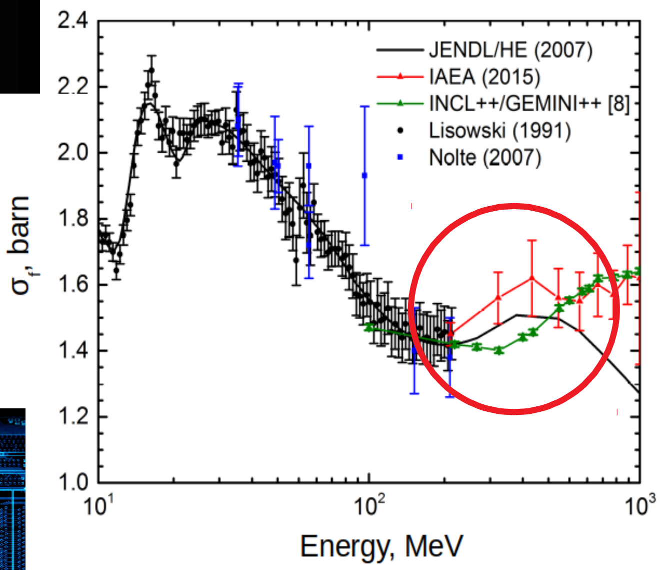


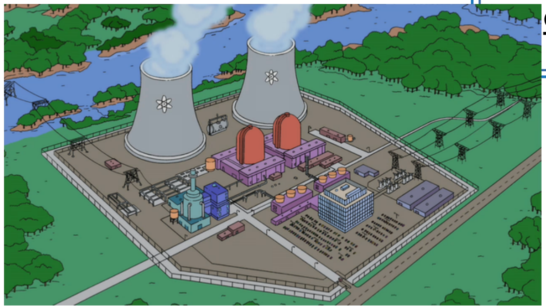


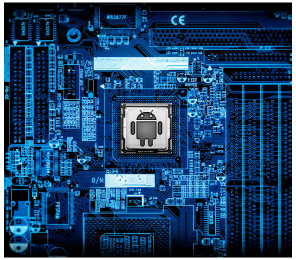


^{235}U(n,f) is one of the most significant cross-section standards at 0.025 eV and [0.15-200] MeV **BUT** there are **no experimental data above 200 MeV**



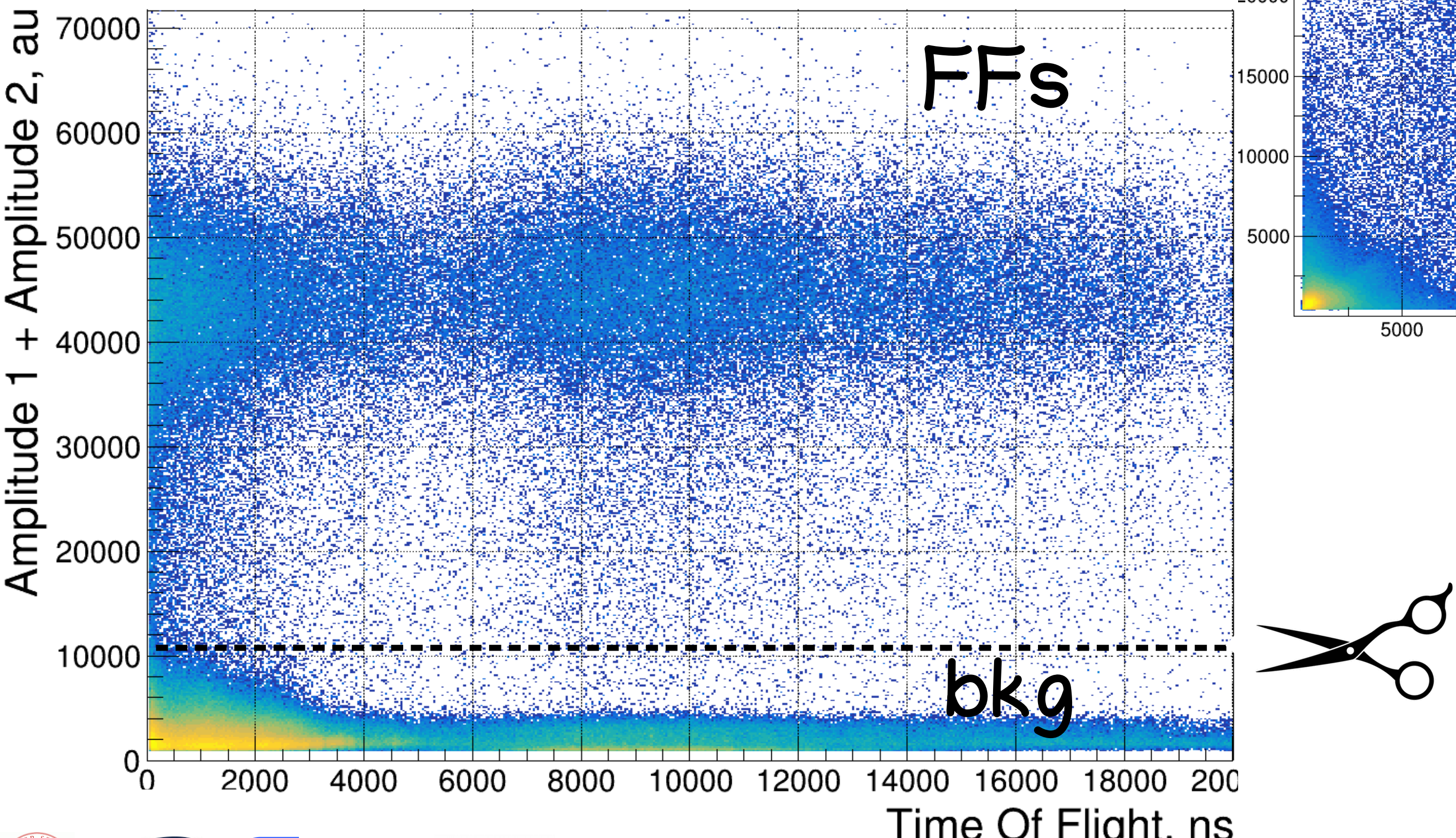


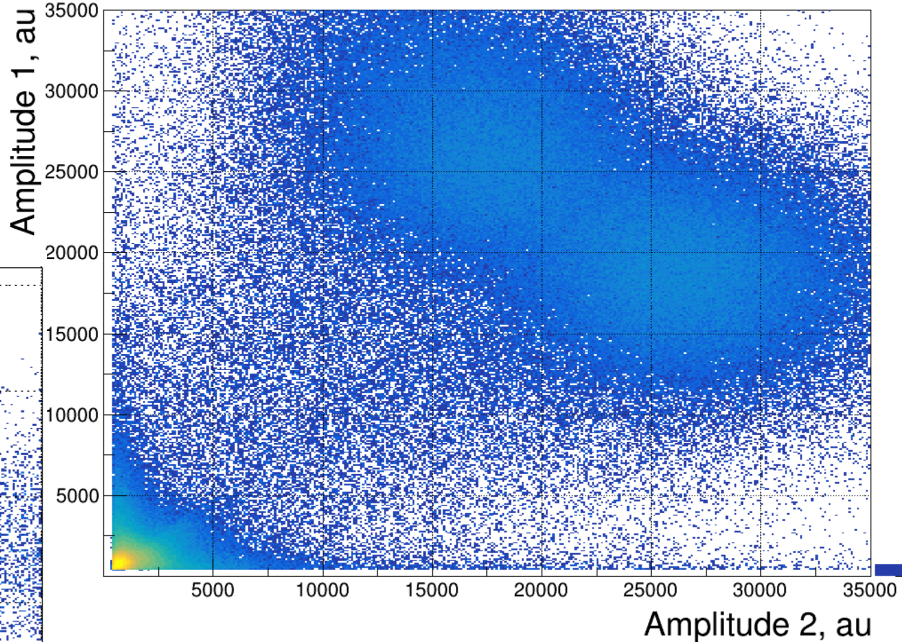




INFN CERN nTOF IJCLab Irène Joliot-Curie PTB

Fission events signature





Polyethylene samples

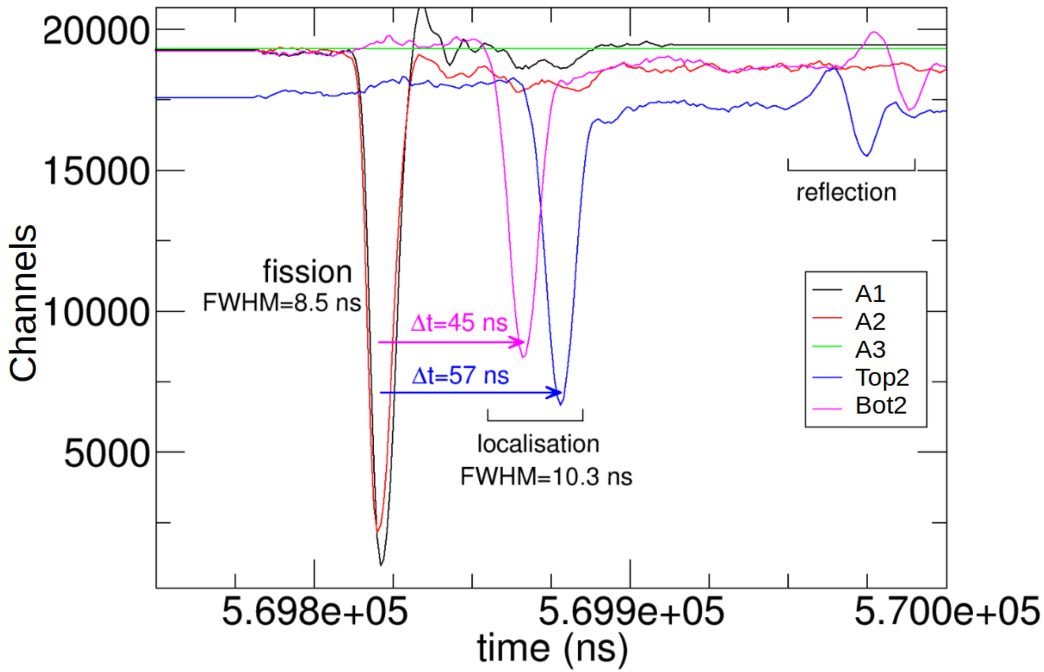
Characterization

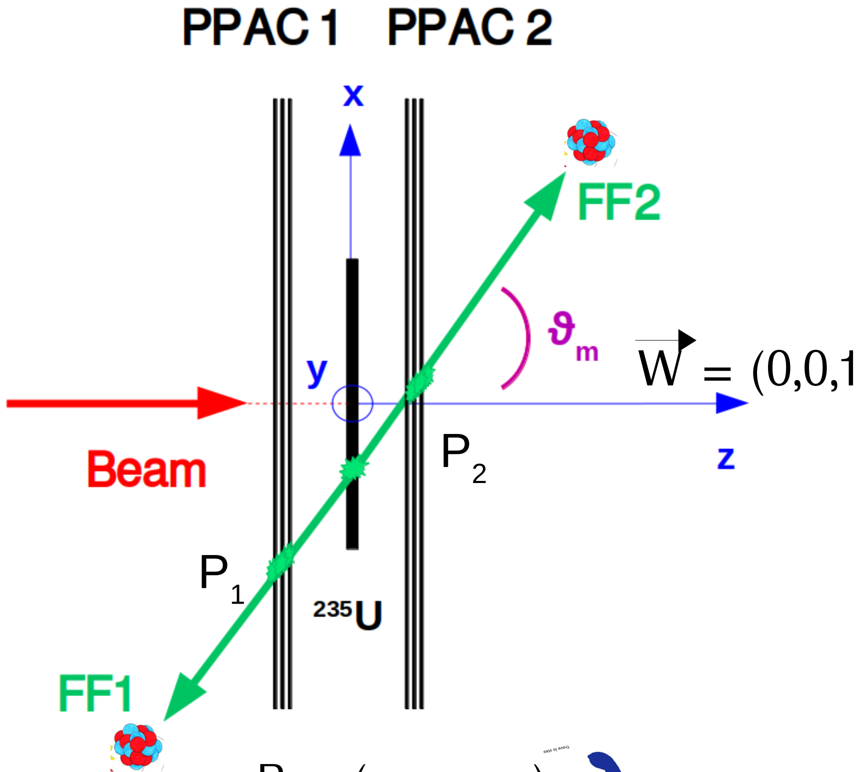
- mass density from hydrostatic weighing (PTB)
- thickness: precision measurement of the profile (PTB)
- uncertainty on the areal density: 0.2-0.6%

Sample	Thickness (mm)	Density g/cm^3	Areal density g/cm^2	(rel. unc.)
PE 1mm	1.025(4)	0.9534(20)	0.0978(4)	(0.4%)
PE 2mm	1.824(11)	0.9555(20)	0.1743(11)	(0.6%)
PE 5mm	4.925(4)	0.9597(20)	0.4726(11)	(0.2%)
C 0.5mm	0.500(4)	1.7749(27)	0.0887(8)	(0.9%)
C 1mm	1.000(5)	1.7364(86)	0.1736(12)	(0.7%)
C 2.5mm	2.500(4)	1.7512(32)	0.4378(11)	(0.3%)

- H/C ratio via combustion analysis, two measurements (Forschungszentrum Jülich, TU Braunschweig): 1.98(3) and 2.00(3)
- In the simulations: assumed nominal stichometry H/C=2

Fission fragment trajectory

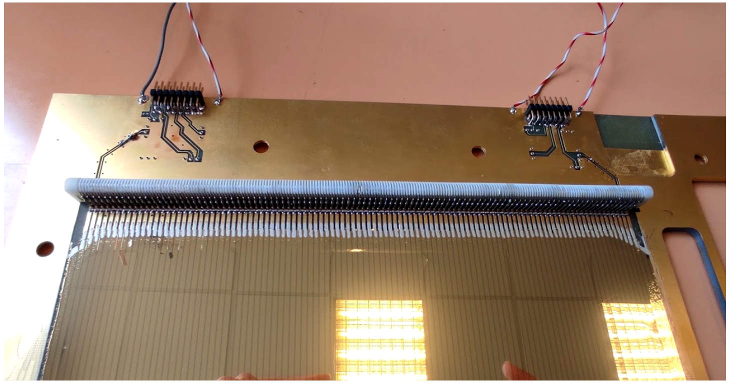


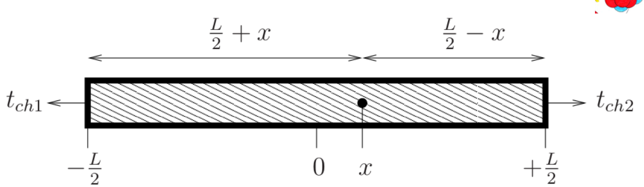


$P_1 = (x_1, y_1, z_1)$

$P_2 = (x_2, y_2, z_2)$

$\vec{V}$





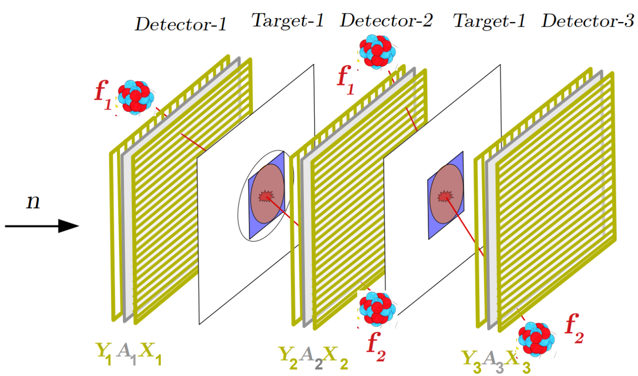
$$(t_{ch1}-t_o)+(t_{ch2}-t_0)=DLT$$

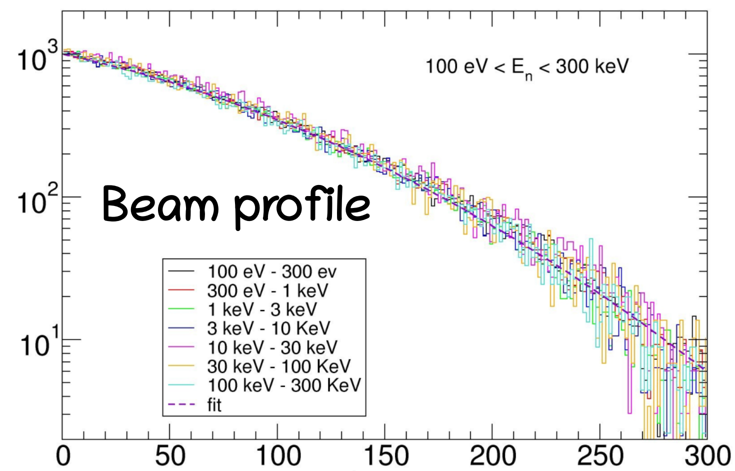
$$\cos\vartheta=\frac{\vec{V}\cdot\vec{W}}{|\vec{V}|\cdot|\vec{W}|}$$

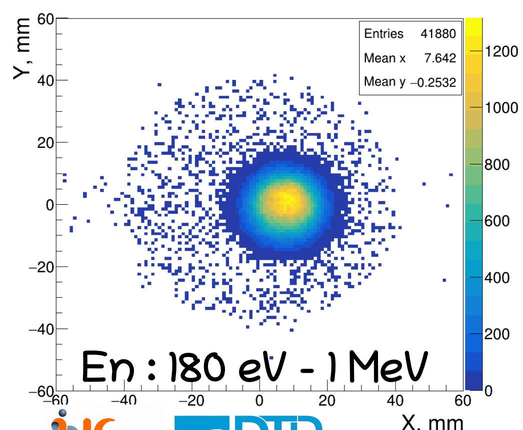
Fission fragment trajectory

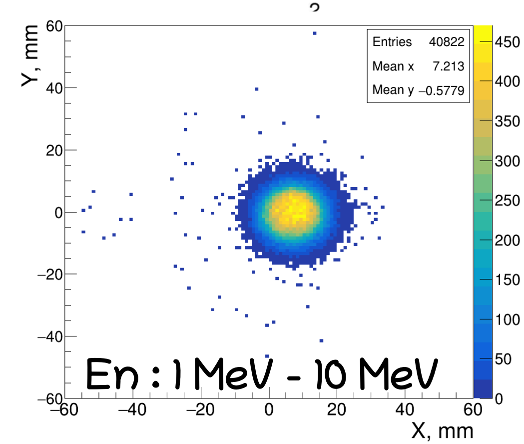
The strips, which are read at both ends of the delay line, allow a localisation of the FFs impact positions

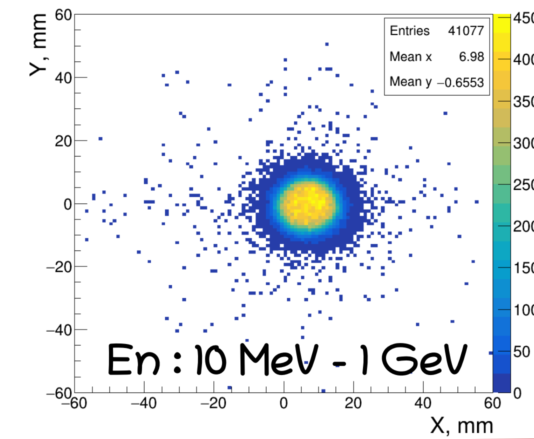
→ the reproduction of the hitting point of the neutrons in the sample



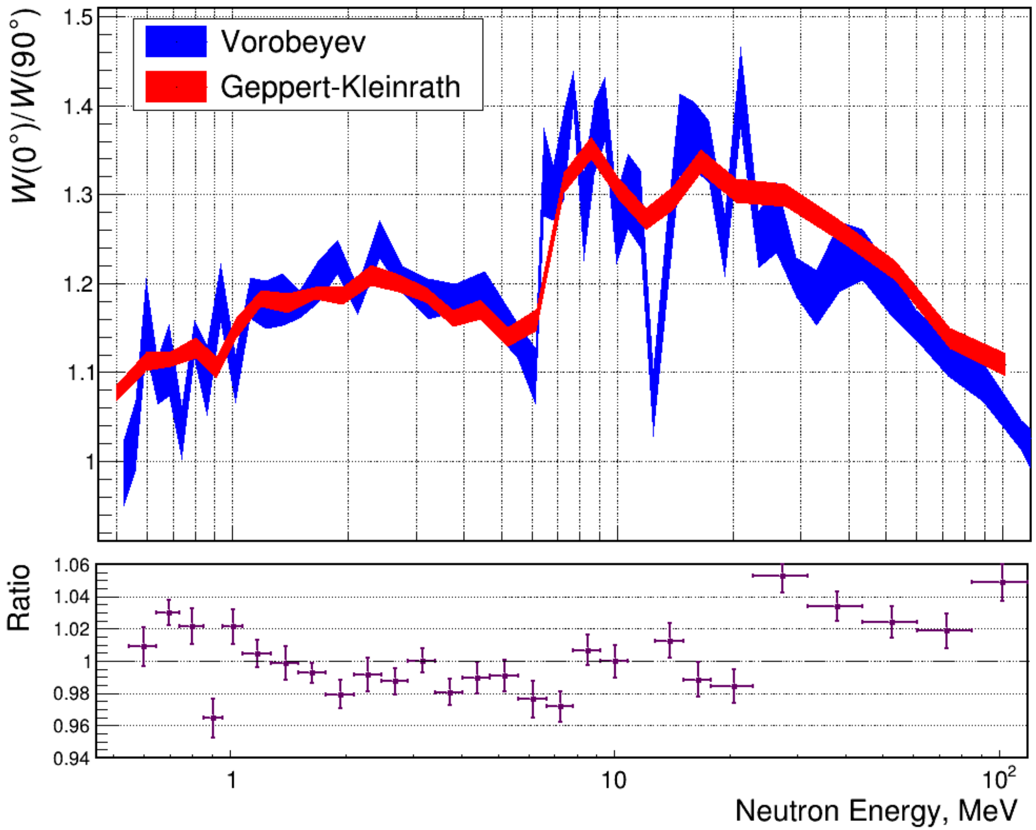


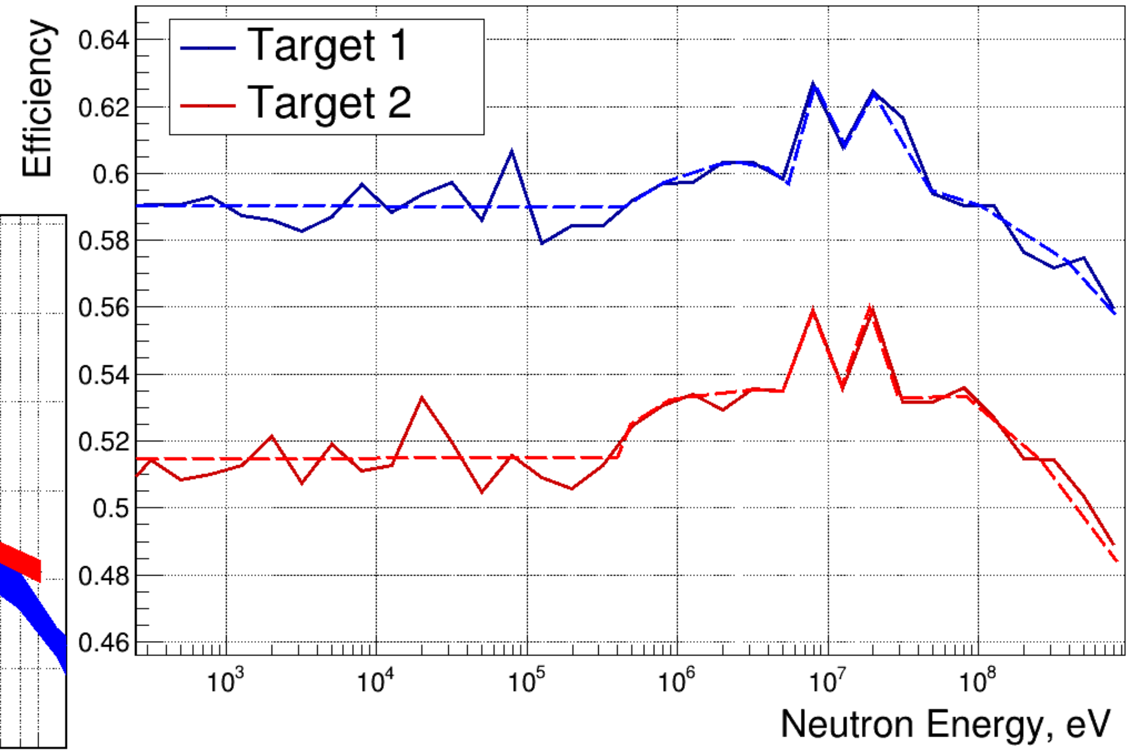






PPAC Efficiency



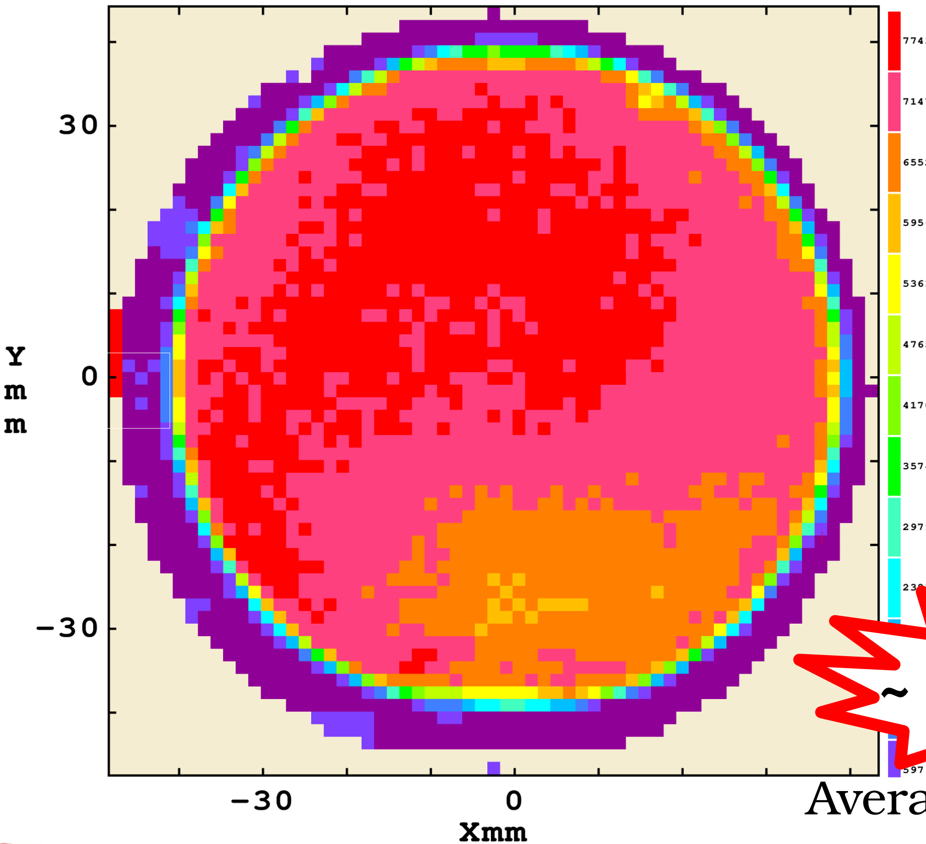


^{235}U Sample characterisation

Coulomb scattering

Proton beam

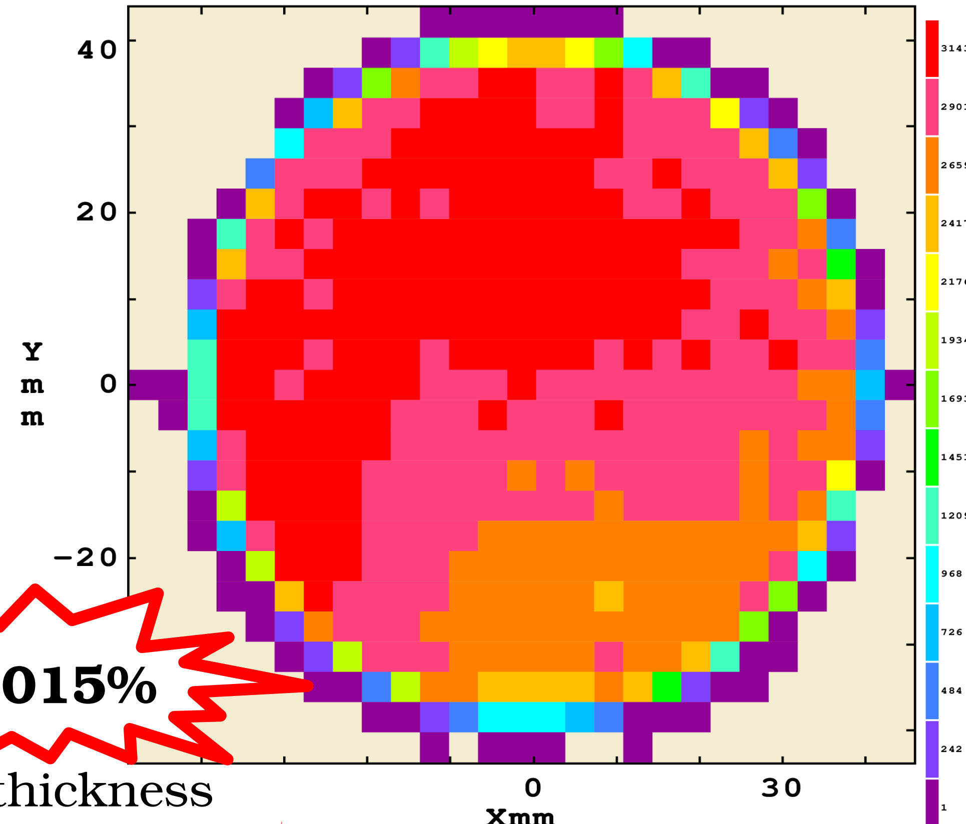
Spatial Resolution = 1.5 mm



α activity → ^{234}U

^{234}U/^{235}U = 0.007472

Spatial Resolution = 3.5 mm

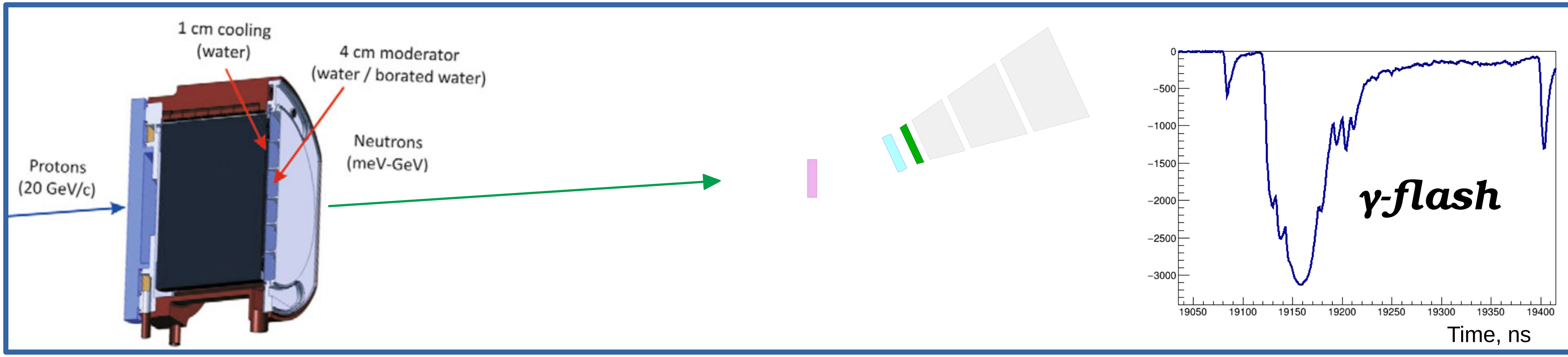


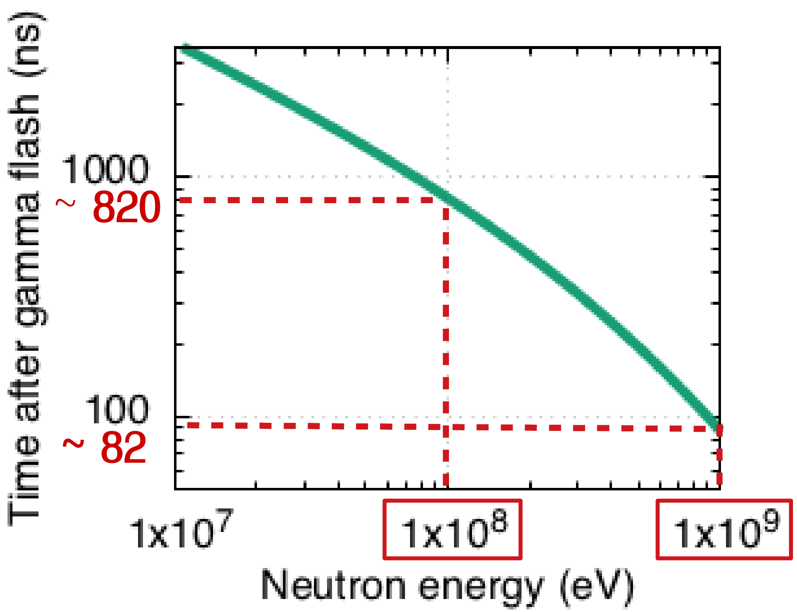
~ +1.015%

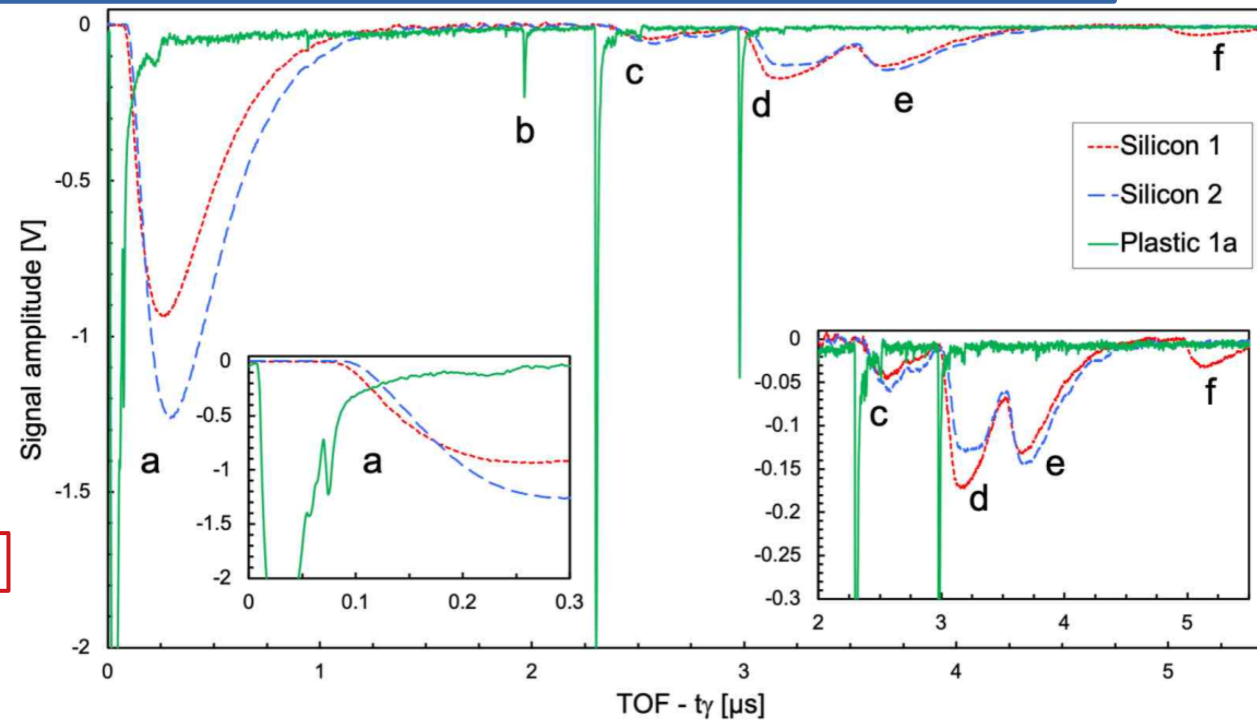
Average thickness

14.0 mg/50 cm^2

Proton Recoil Telescope







Monte Carlo simulation - RPT

Geant4 and MCNP

...but the sample was C_2H_4

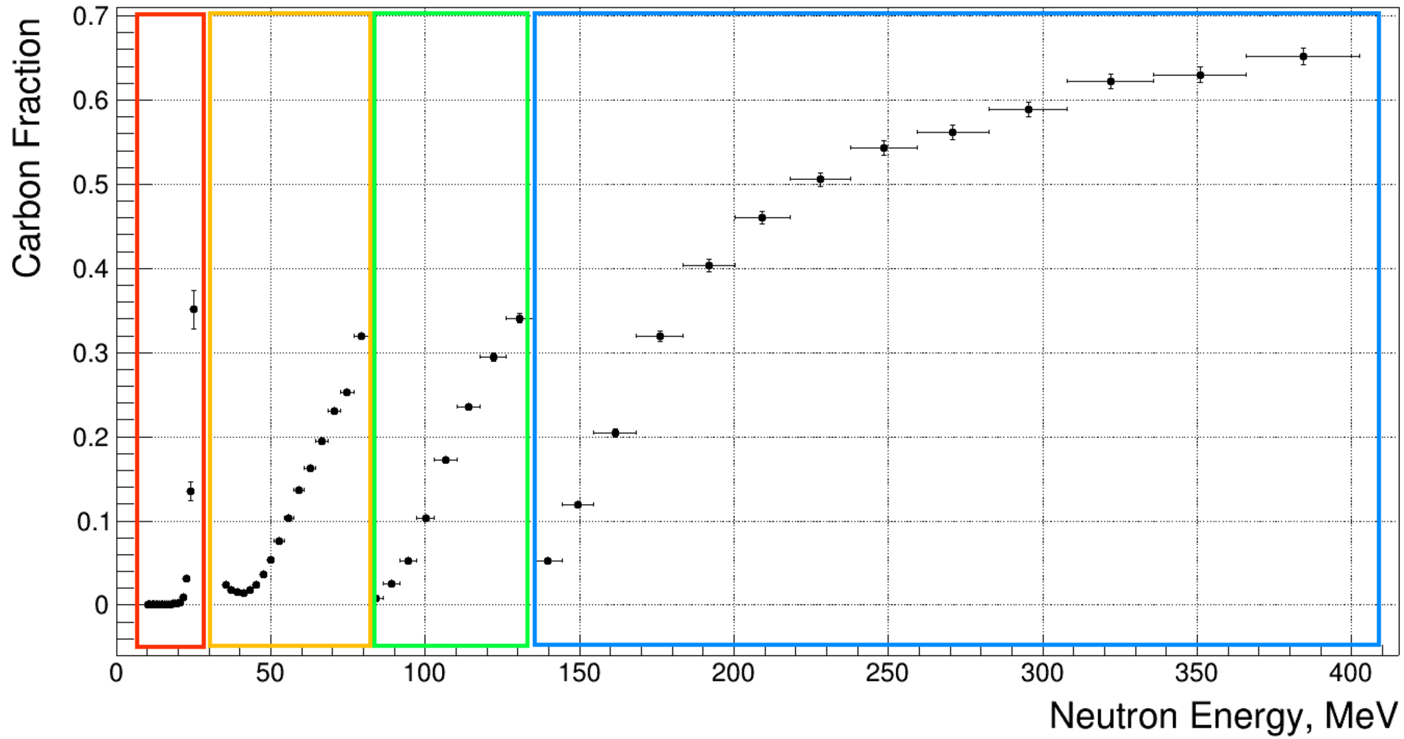
Study of the background components:

n+C → protons
→ other light particles (d, t, α...) ⇨ ΔE-E matrix

$$\frac{\text{protons from n + C}}{\text{total protons from the target}}$$

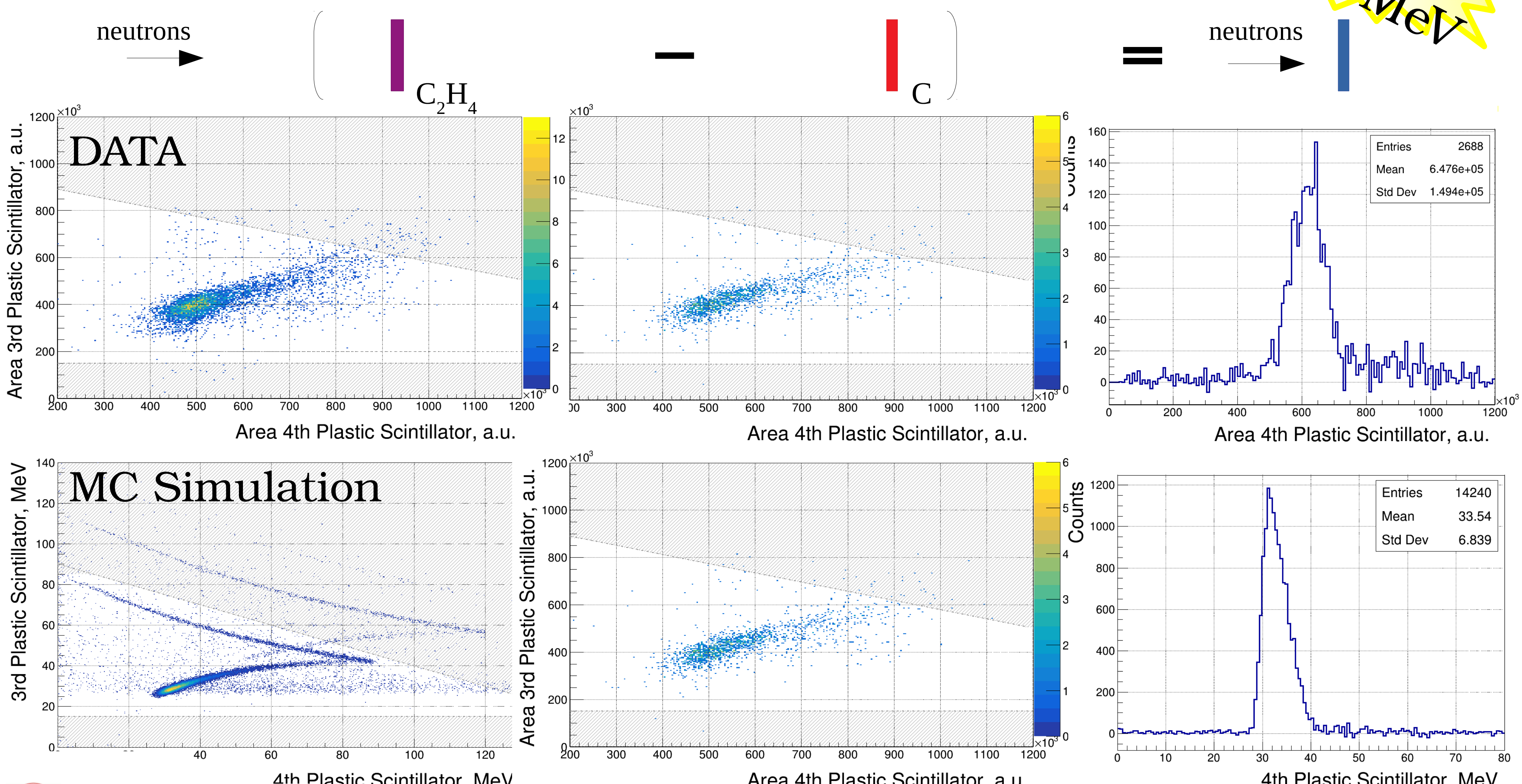
Segmentation

of the proton recoil telescope



Neutron flux extraction

E_n 260 MeV



Neutron flux extraction

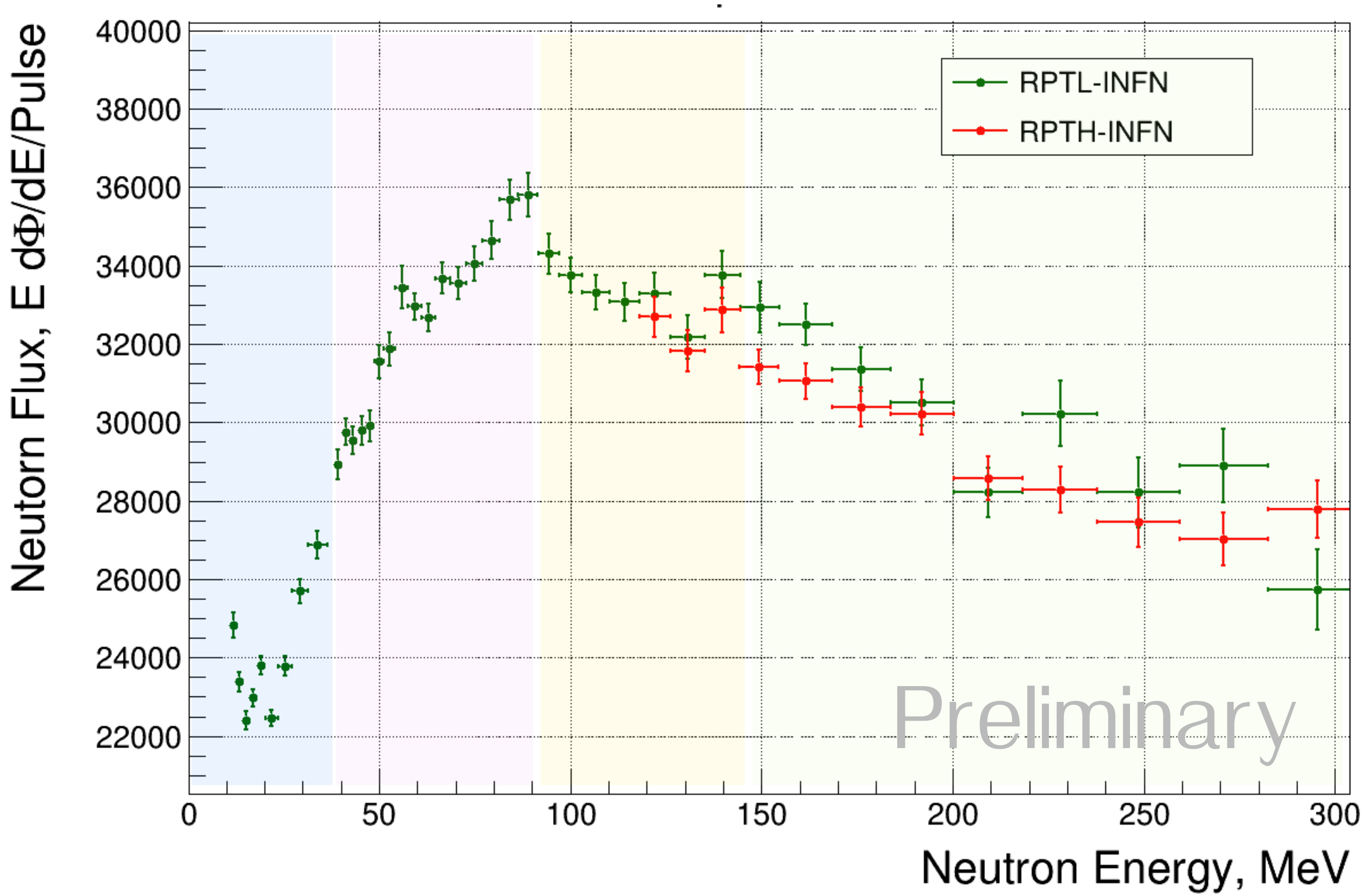
Segmentation + Coincidences

Coinc Silicon 1-2: PE1 + PE2
12-30 MeV

Coinc Scint 1-2: PE2
37-90 MeV

Coinc Scint 1-2-3: PE2 + PE5
91-145 MeV

Coinc Scint 1-2-3-4: PE5
>146 MeV



Neutron flux extraction