The neutron-induced fission cross section on ^{235}U measurement at the n_TOF facility at CERN

A. Manna, E. Pirovano, P. Console Camprini, L. Cosentino,
M. Dietz, Q. Ducasse, P. Finocchiaro, C. Le Naour, D. Mancusi,
C. Massimi, A. Mengoni, R. Nolte, D. Radeck, L. Tassan-Got,
N. Terranova, G. Vannini, A. Ventura for the n_TOF Collaboration

Compound-Nuclear Reactions and Related Topics (CNR*24), Vienna - 8-12 July 2024

The n_TOF facility

neutron Time Of Flight

ΔE/E~ 10^{-5} - 10^{-3}

High energy resolution

Time of Flight (ToF) technique

long flight path: 185 m @ EAR 1

20 m @ EAR 2

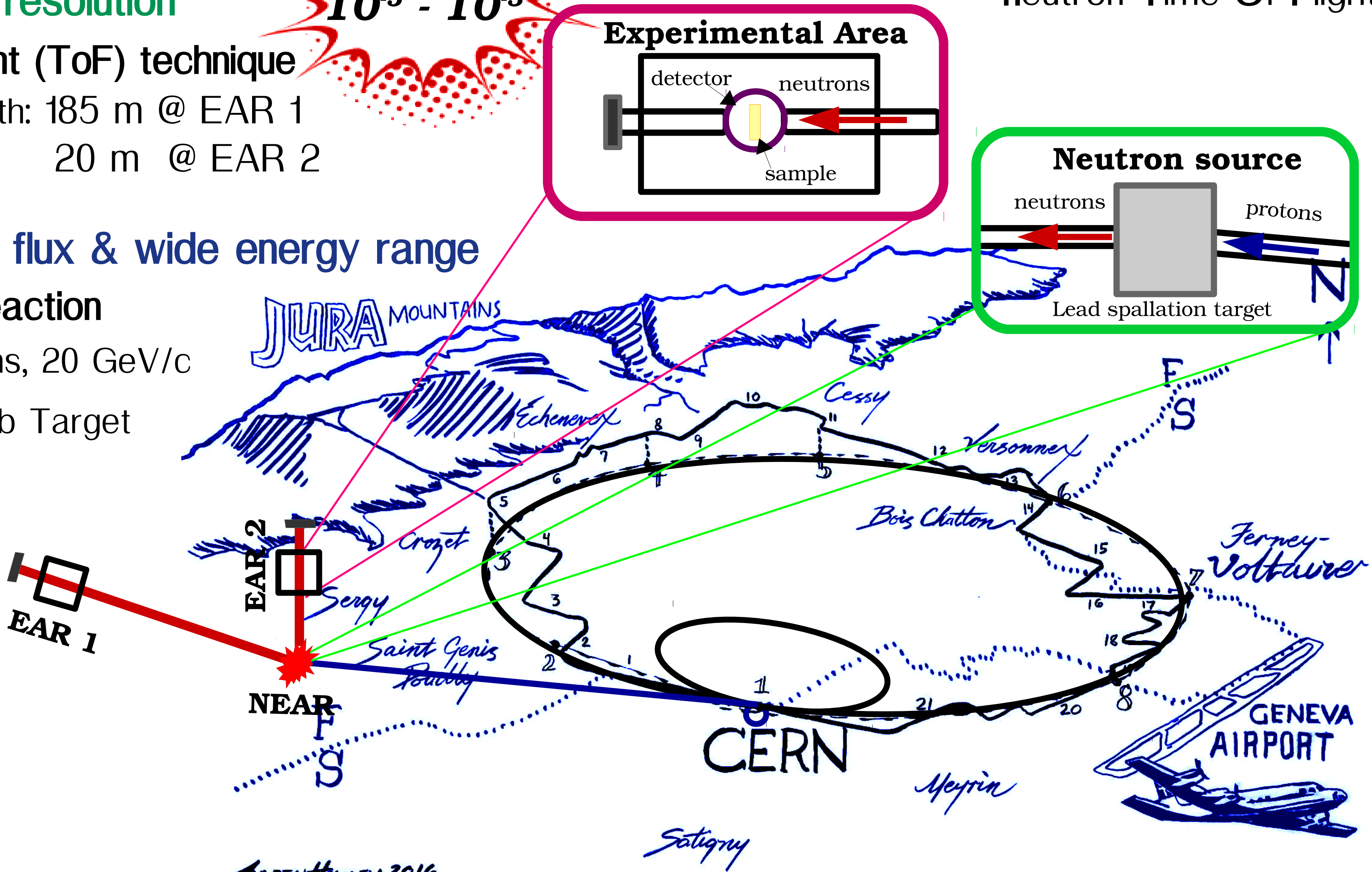
High neutron flux & wide energy range

Spallation reaction

$7 \cdot 10^{12}$ protons, 20 GeV/c

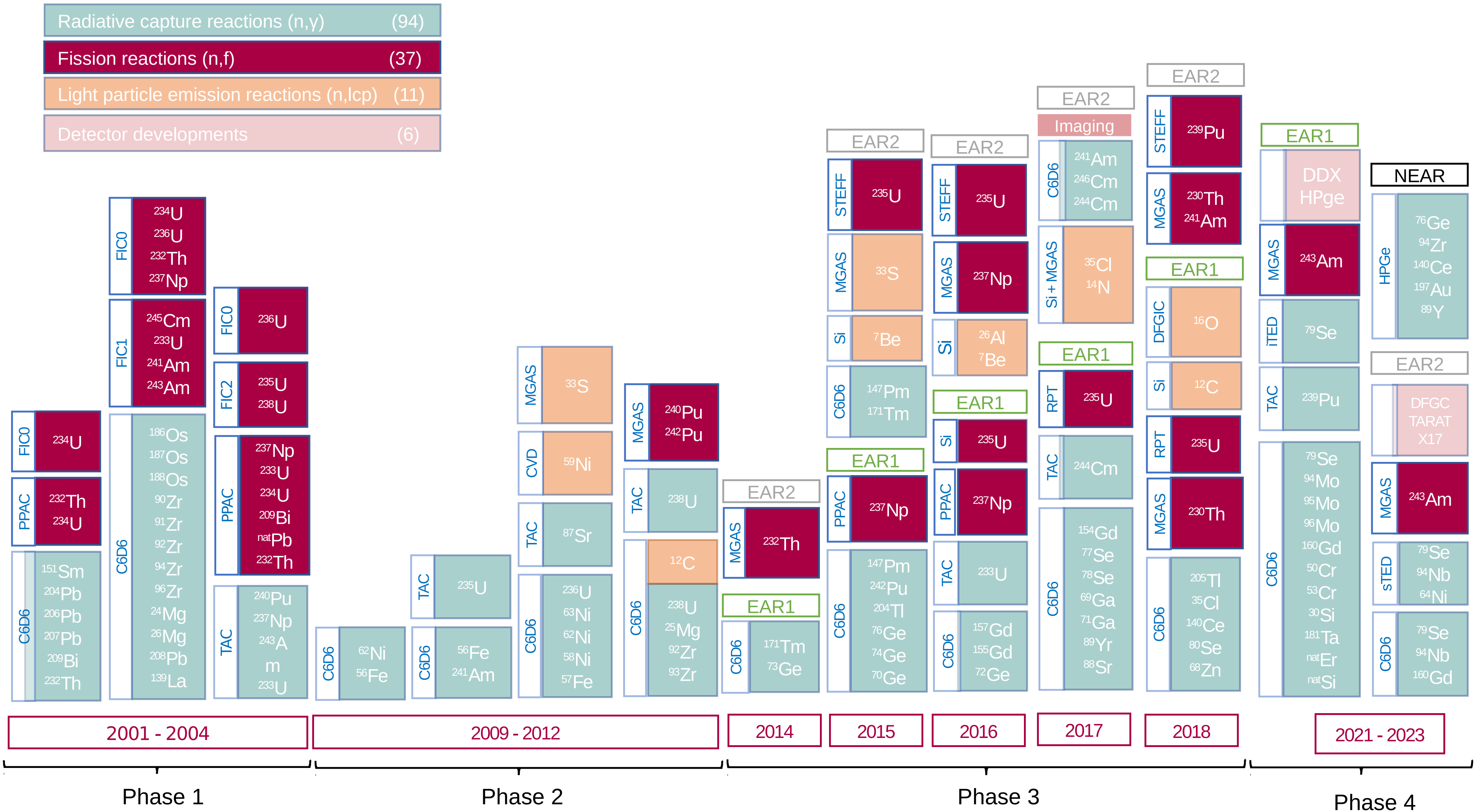
- 1.3 ton Pb Target

350 neutrons per incident proton



What we have done at n_TOF

What we have done at n_TOF



235U

What we have done at n_TOF

Simultaneous measurement of neutron-induced capture and fission reactions at CERN

C. Guerrero[1,2a], E. Berthoumieux[1,7], D. Cano-Ott[2], E. Mendoza[2], S. Andriamonje[1], J. Andrzejewski[4], L. Audouin[3], M. Barbagallo[10], V. Bécares[2], F. Bečvář[5], F. Belloni[6], M. Brugger[1], M. Calviani[1], F. Calviño[8], C. Carrapiço[9], F. Cerutti[1], E. Chiaveri[1], M. Chin[1], M. A. Cortés-Giraldo[11], M. Diakaki[25], I. Dillmann[12], C. Domingo-Pardo[13], I. Duran[14], C. Eleft... Ferrari[1], S. Ganesan[15].

TAC + MEGAS En: [6–22 eV]

Measurement of neutron induced fission of ^{235}U, ^{233}U and ^{245}Cm with the FIC detector at the CERN n_TOF facility

Marco Calviani[1,2,a], Dimitrios Karadimos[3], U. Abbondanno[4], G. Aerts[5], H. Álvarez[6], F. Álvarez-Velarde[7], S. Andriamonje[5], J. Andrzejewski[8], P. Assimakopoulos†[3], L. Audouin[9], G. Badurek[10], P. Baumann[11], F. Bečvář[12], E. Berthoumieux[5], C. Carrapiço[16,5], P. Cennini[17], V. Chepel[18], E. Chiaveri[17], N. Colonna[19],

FIC En: [0.05 eV – 2 MeV]

Fission Fragment Angular Distribution measurements of ^{235}U and ^{238}U at CERN n_TOF facility

E. Leal-Cidoncha[1,a], I. Durán[1], C. Paradela[1,30], D. Tarrío[1,32], L.S. Leong[2,33], L.Tassan-Got[2], L. Audouin[2], S. Altstadt[3], J. Andrzejewski[4], M. Barbagallo[5], V. Bécares[6], F. Bečvář[7], F. Belloni[30], E. Berthoumieux[8], J. Billowes[10], V. Bocc... M. Calviani[9], F. Calviño[12], D. Cano-Ott[6], C. Carrapico[13], ...

PPAC-ratio En: [20 – 200 MeV]

High accuracy, high resolution ^{235}U(n,f) cross section from n_TOF (CERN) in the thermal to 10 keV energy range.

Silicon Detectors En: [th – 10 keV]

M. Mastromarco[1], S. Amaducci[2,#], N. Colonna[1], P. Finocchiaro[2], L. Cosentino[2], O. Aberle[3], J. Andrzejewski[7], L. Audouin[8], M. Bacak[9,6,10], J. Balibrea[11], M. Barbagallo[6], F. Bečvář[12], E. Berthoumieux[10], J. Billowes[13], D. Bosnar[14], A. Brown[15], M. Caamaño[16], F. Calviño[17], M. Calviani[6], D. Cano-Ott[11], R. Cardella[6], A. Casanovas[17], F. Cerutti[6], Y. ... Cortés-Giraldo[18], L. A. Damone[2,19], M. Diakaki[10], C. Domingo-... Fernández-Domínguez[16], A. Ferrari[6], P. Ferreira[22], V. Furman[23]

Measurement of the ^{235}U(n, f) cross section relative to the ^{6}Li(n, t) and ^{10}B(n, α) standards from thermal to 170 keV neutron energy range at n_TOF

Silicon Detectors En: [th – 170 keV]

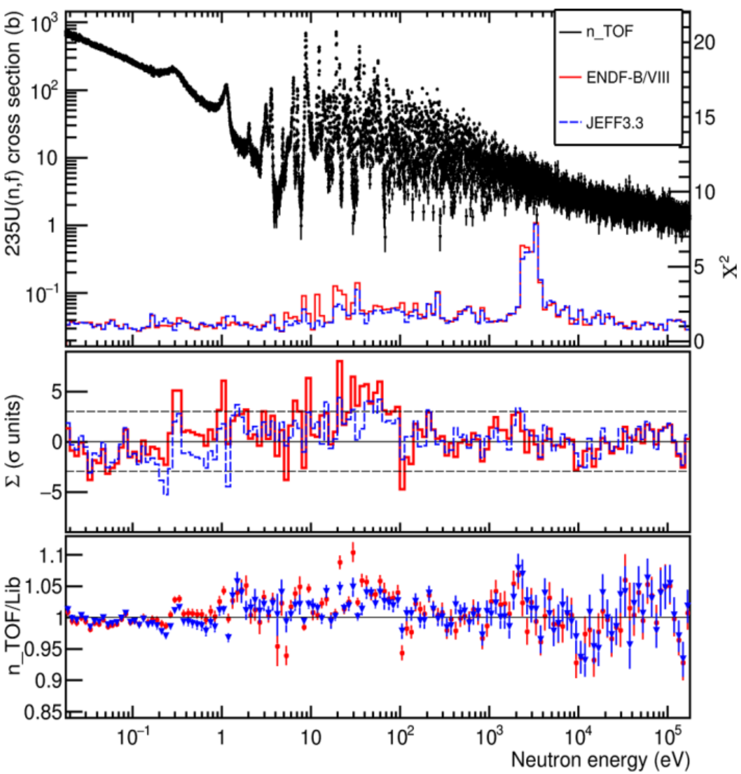
S. Amaducci[1,35], L. Cosentino[1], M. Barbagallo[2], N. Colonna[2], A. Mengoni[3,4], C. Massimi[4,5], S. Lo Meo[3,4], P. Finocchiaro[1,a], O. Aberle[6], J. Andrzejewski[7], L. Audouin[8], M. Bacak[9,6,10], J. Balibrea[11], F. Bečvář[12], E. Berthoumieux[10], J. Billowes[13], D. Bosnar[14], A. Brown[15], M. Caamaño[16], F. Calviño[17], M. Calviani[6], D. Cano-...

235U

...at low and intermediate energy

accuracy & precision

Amaducci et al. (The n_TOF Collaboration), Eur. Phys. J. A (2019) **55**: 120



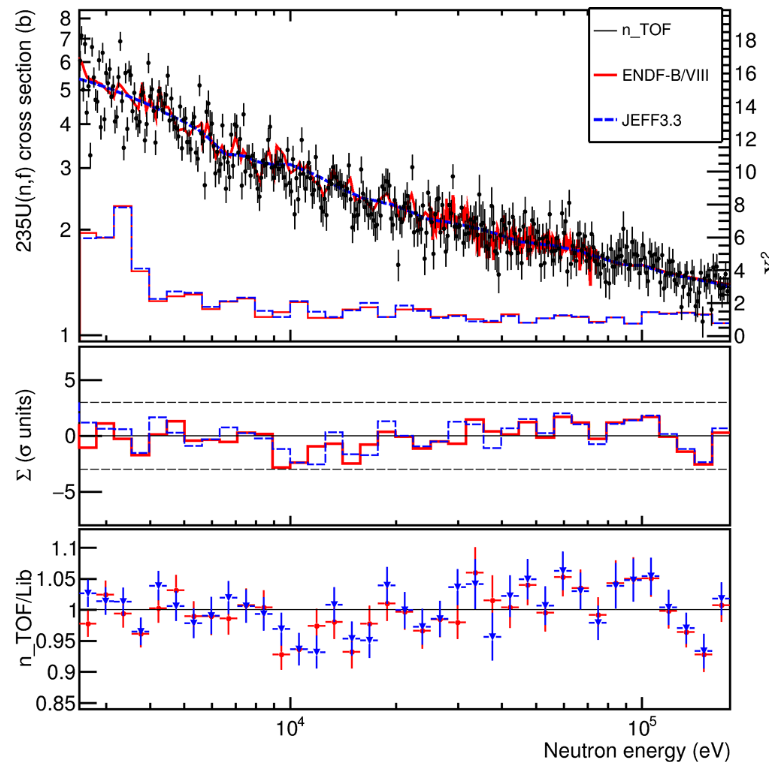
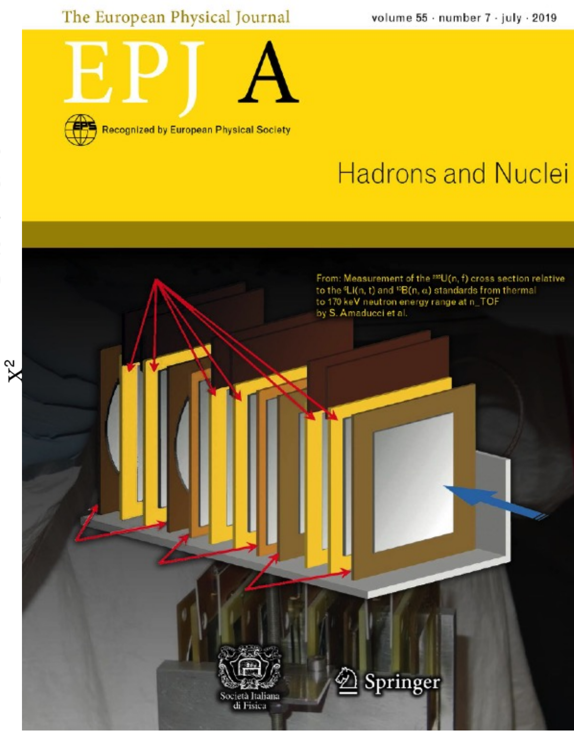


Fig. 19. ^{235}U(n, f) measured cross section of this work, in the 2–100 keV neutron energy range (with χ^2, Σ and ratio), compared to the ENDF-B/VIII and JEFF3.3 evaluations.



1.5% systematic uncertainty

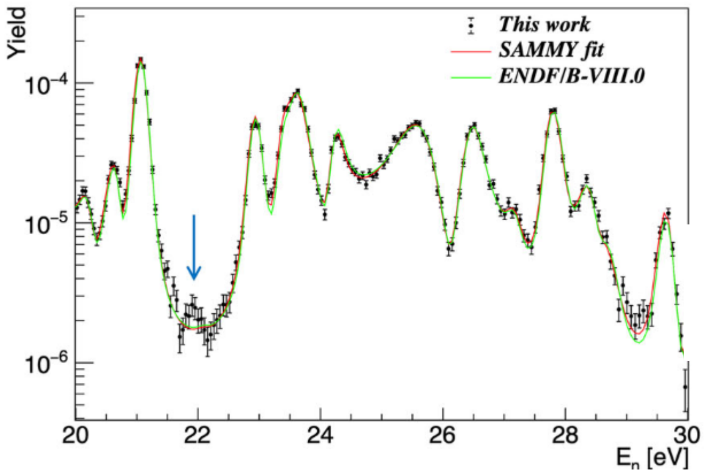
neutron energy range from 25 meV to 170 keV

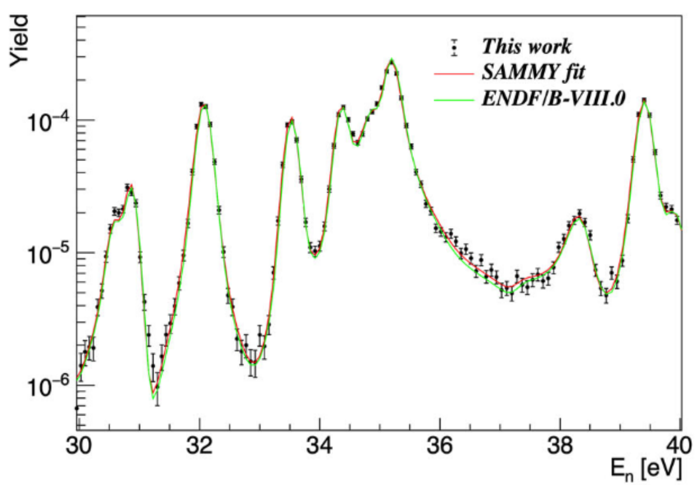
^{235}U(n,f) cross section included (adopted) in the IAEA Standards database

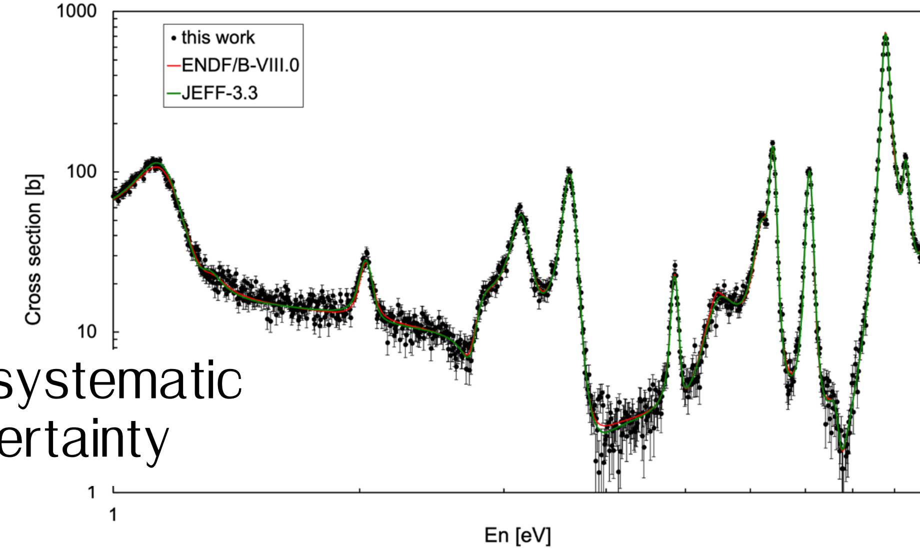
^{235}U

...at low and intermediate energy

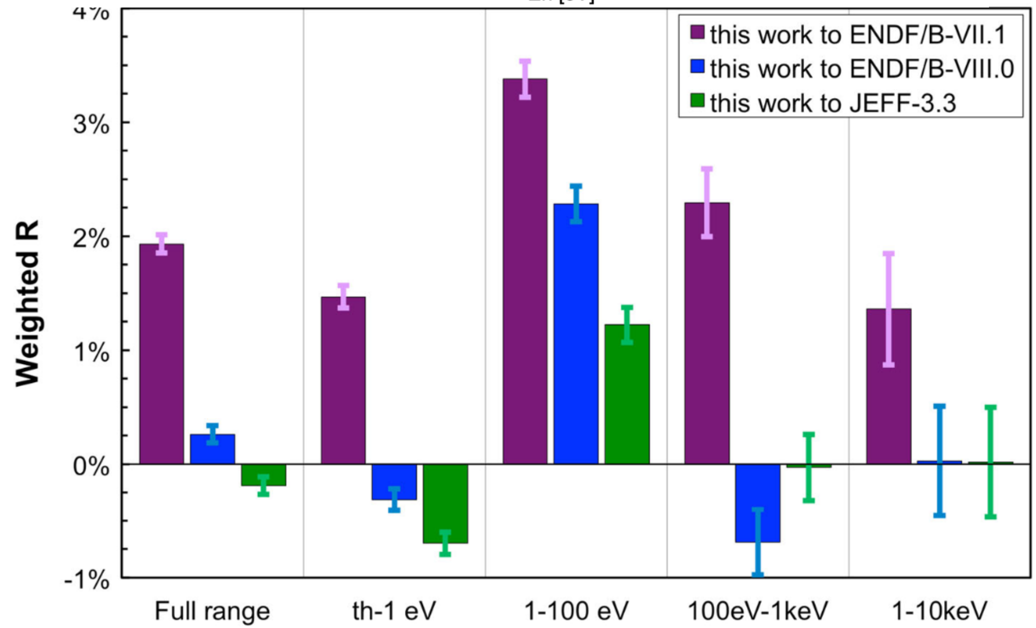
accuracy & precision







1.5% systematic uncertainty



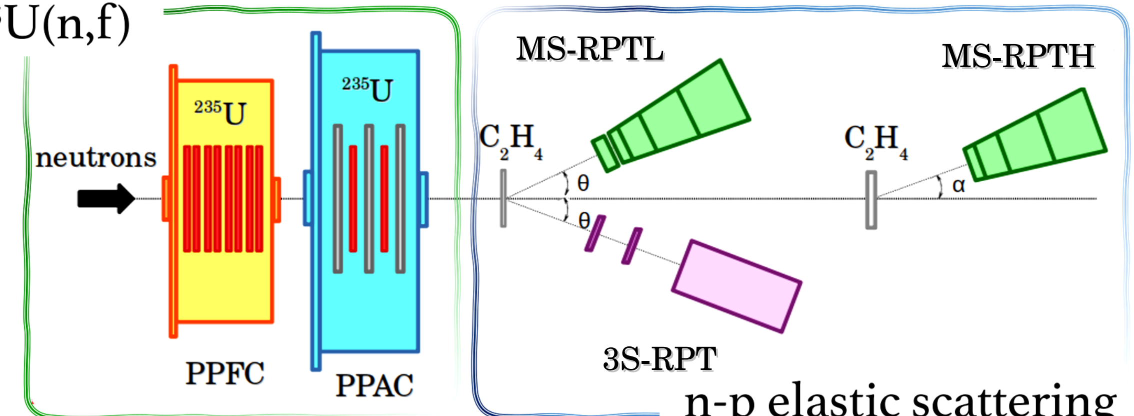
Mastromarco et al. (The n_TOF Collaboration), Eur. Phys. J. A (2022) 58:147

^{235}U

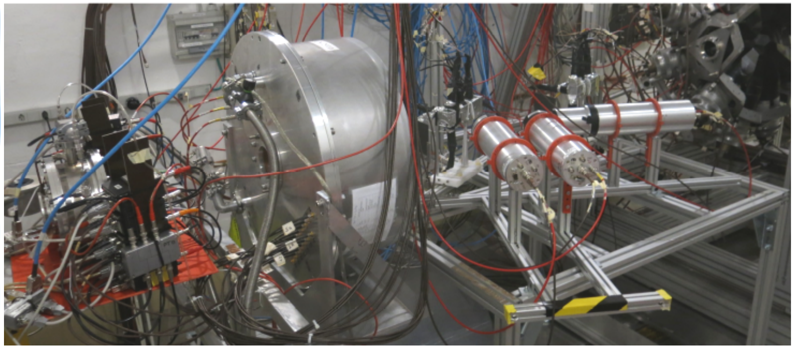
...at high neutron energy

energy limit extension

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



n-p elastic scattering

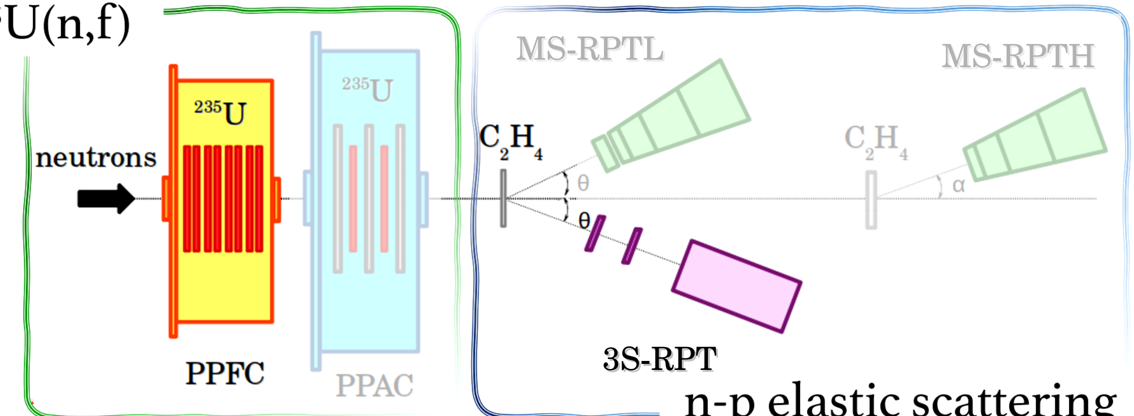


235U

...at high neutron energy

energy limit extension

235U(n,f)



n-p elastic scattering

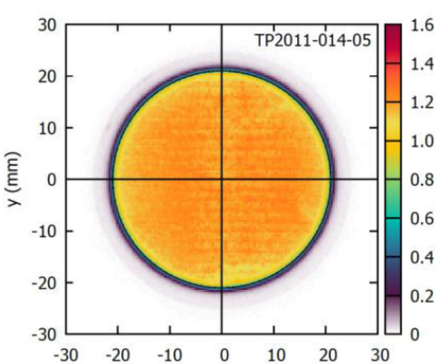
Parallel plate fission (ionization) chamber

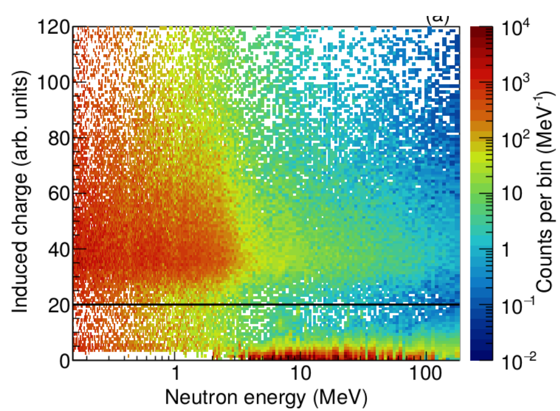
4 double sided ^{235}U (99.93% ^{235}U) = 32,660 mg

2× blanks

separate read-outs

well characterized detector in the neutron energy: 0,025 eV - 200 MeV



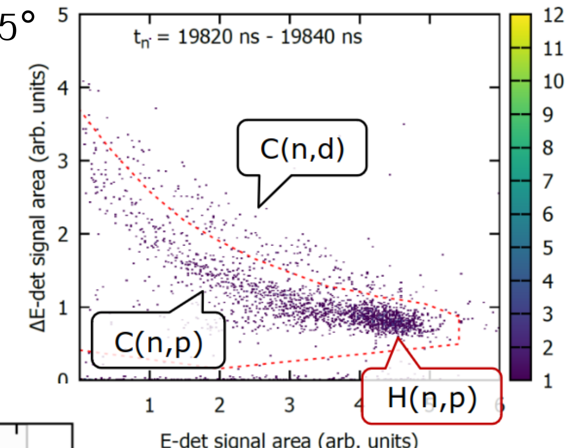


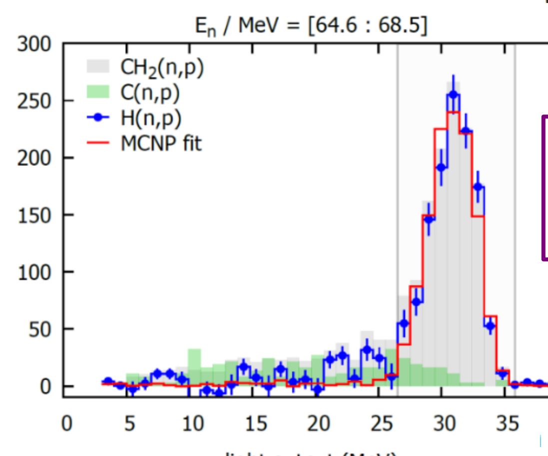
Triple Stage - Recoil Proton Telescope

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

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

3S-RPT @ 25°





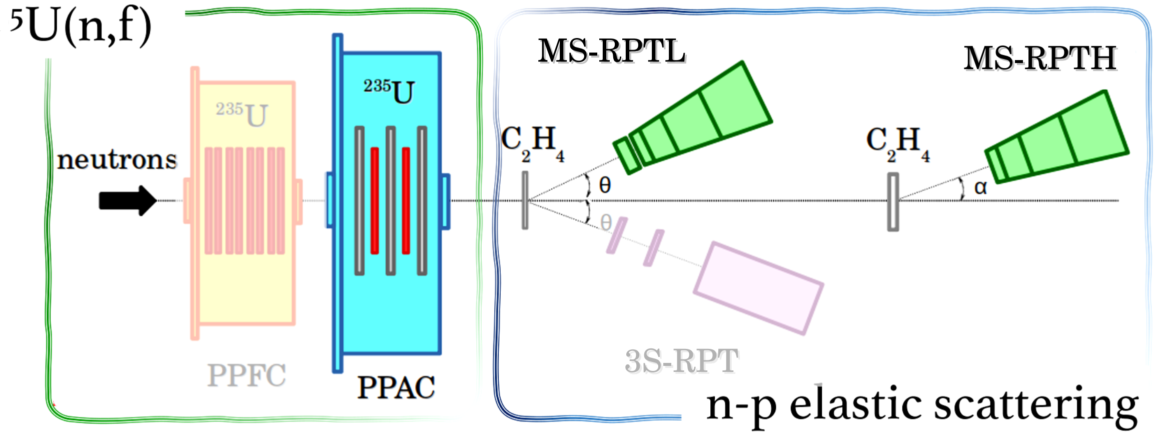
detector optimize to work in the neutron energy: 28 MeV - 140 MeV

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

235U

...at high neutron energy

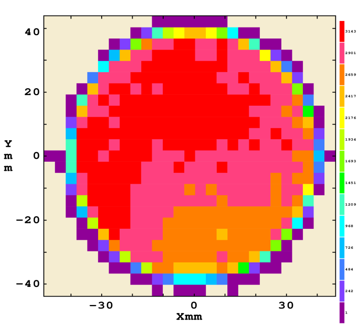
energy limit extension

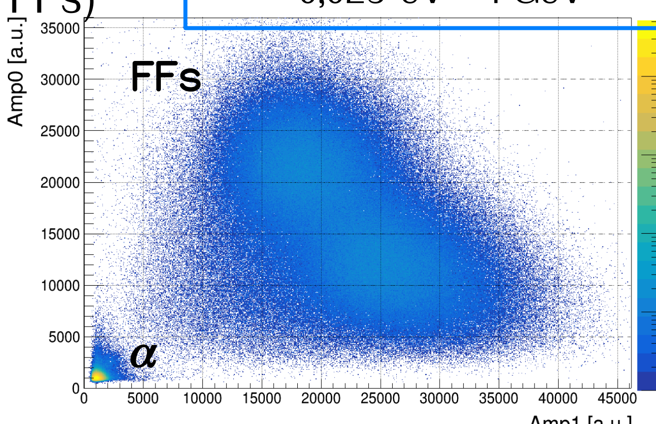


Parallel Plate Avalanche Counter

2 ^{235}U (92.7% ^{235}U) = 28 mg
coincidence analysis
(detection of the 2 FFs)

well characterized detector in the neutron energy: 0,025 eV - 1 GeV



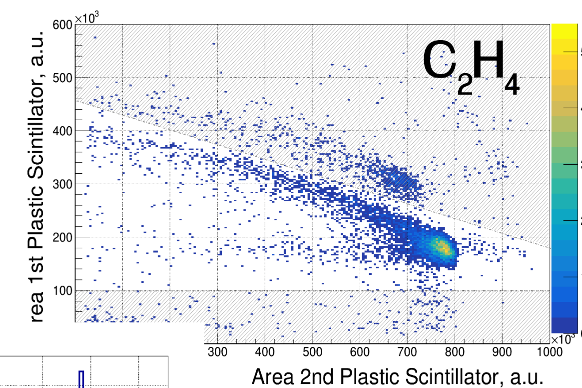


Multiple Stage - Recoil Proton Telescope

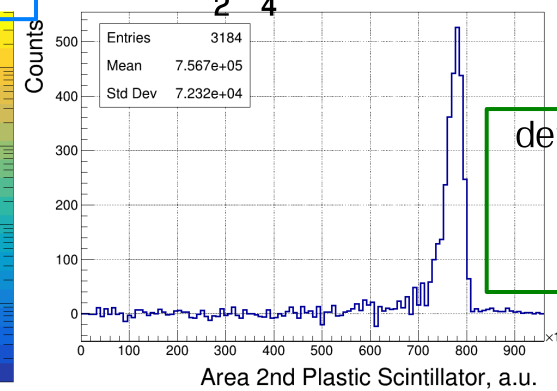
^{1}H(n,n)p events identification:

- selection of coincidences
- analysis of the ΔE-E matrix

MS-RPTL @ 25° MS-RPTH @ 20°



C_2H_4 - C



detector optimized to work in the neutron energy:
10 – 28 MeV
38 - 440 MeV

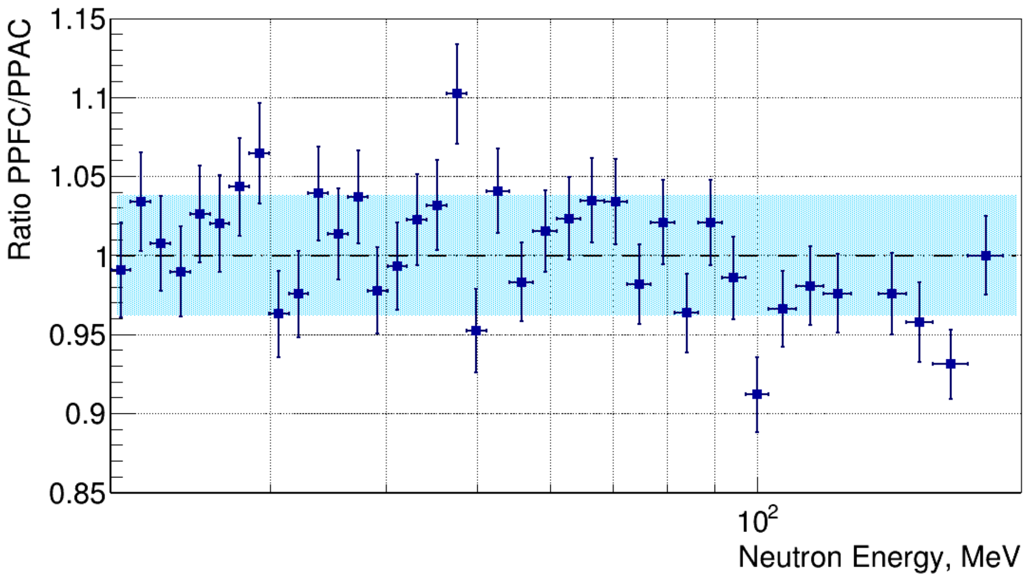
A. Manna *et al* 2023 *JINST* **18** P04024

235U

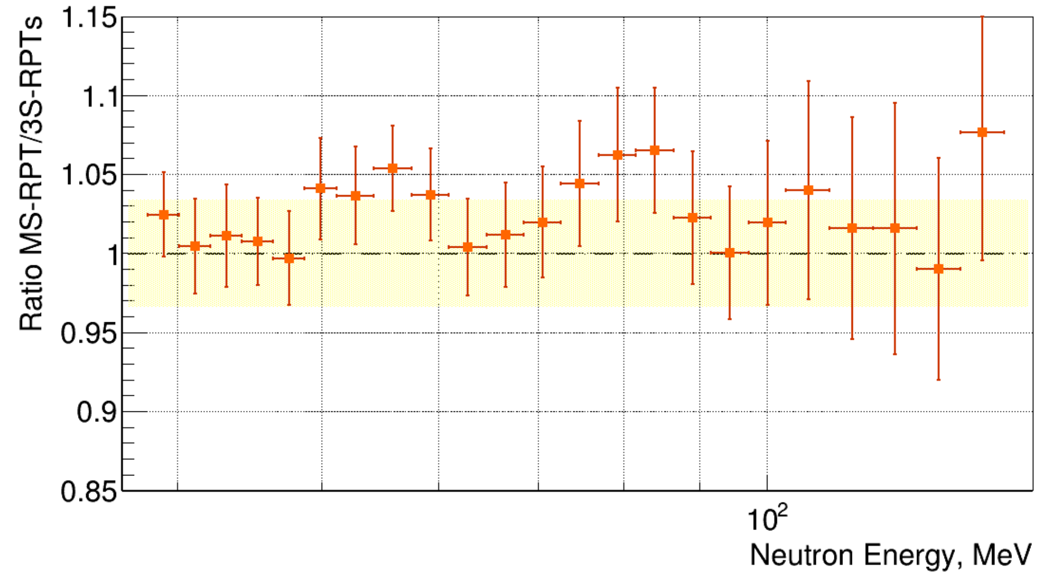
...at high neutron energy

energy limit extension

Ratio Fission Yield
PPFC/PPAC



Ratio neutron flux
MS-RPTs/3s-RPT

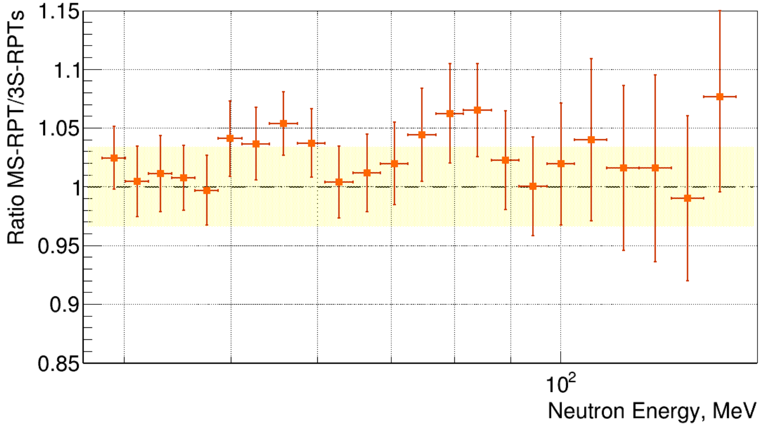


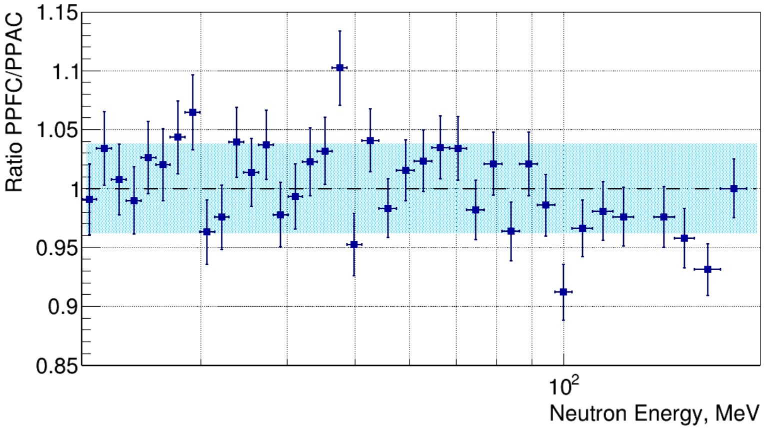
The ratios in the overlapping neutron energy region between the different detector give us the confidence for the result at higher energy

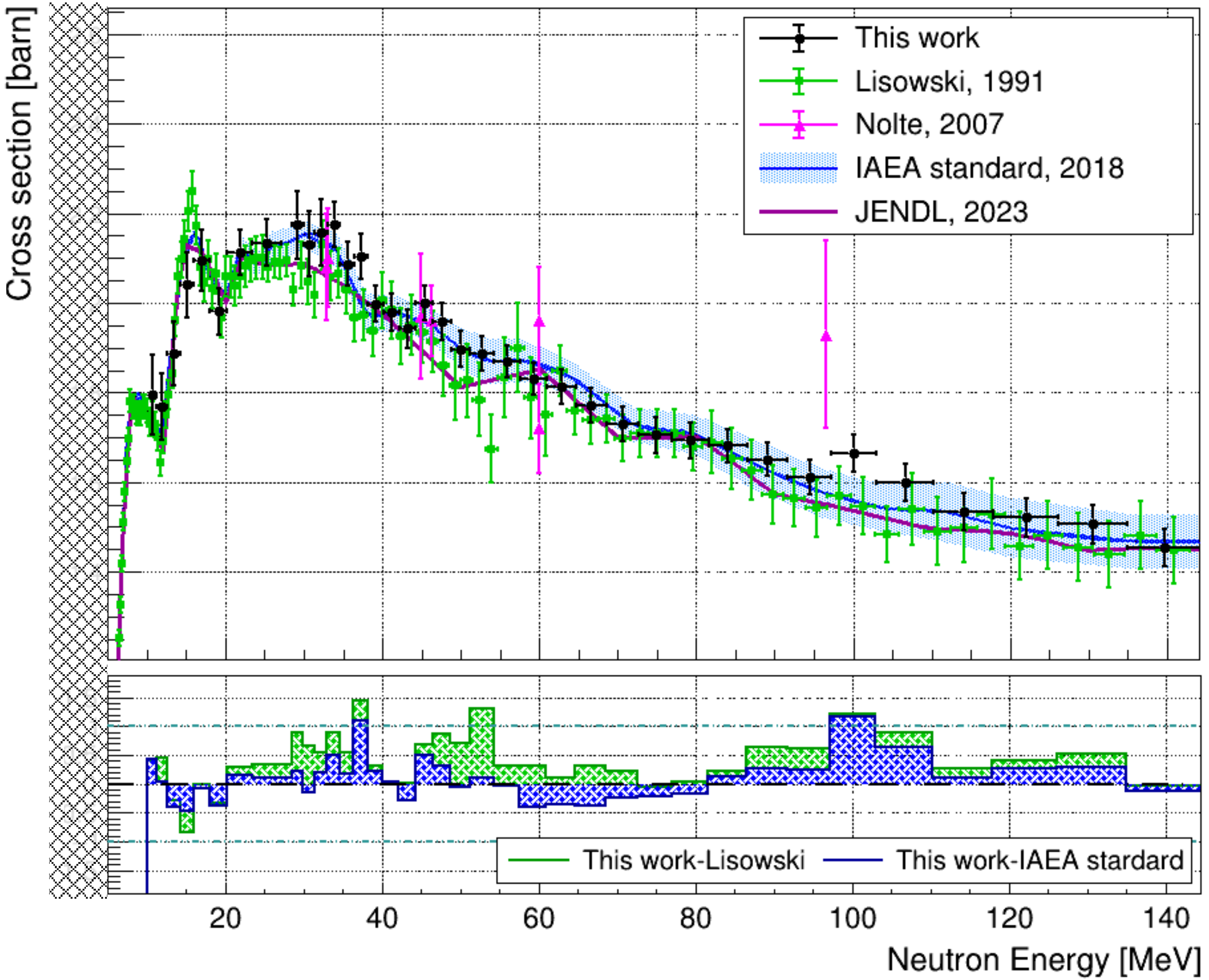
...at high neutron energy

^{235}U

energy limit extension



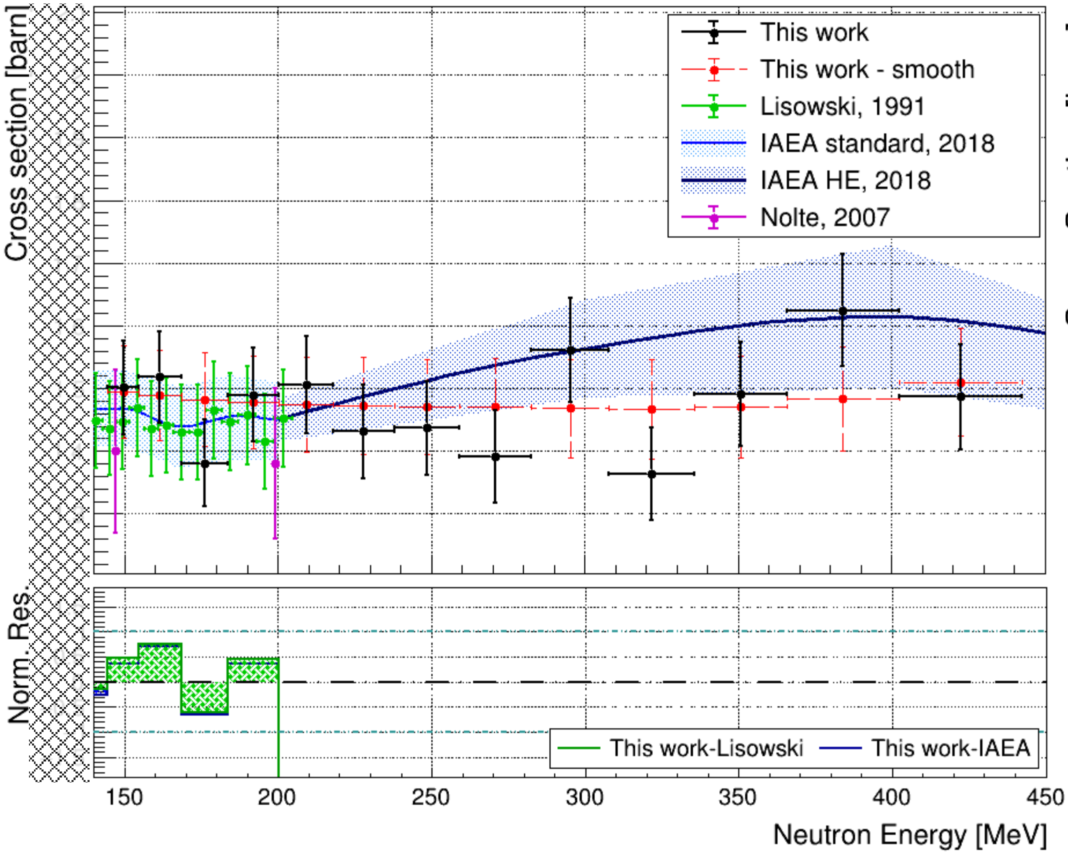


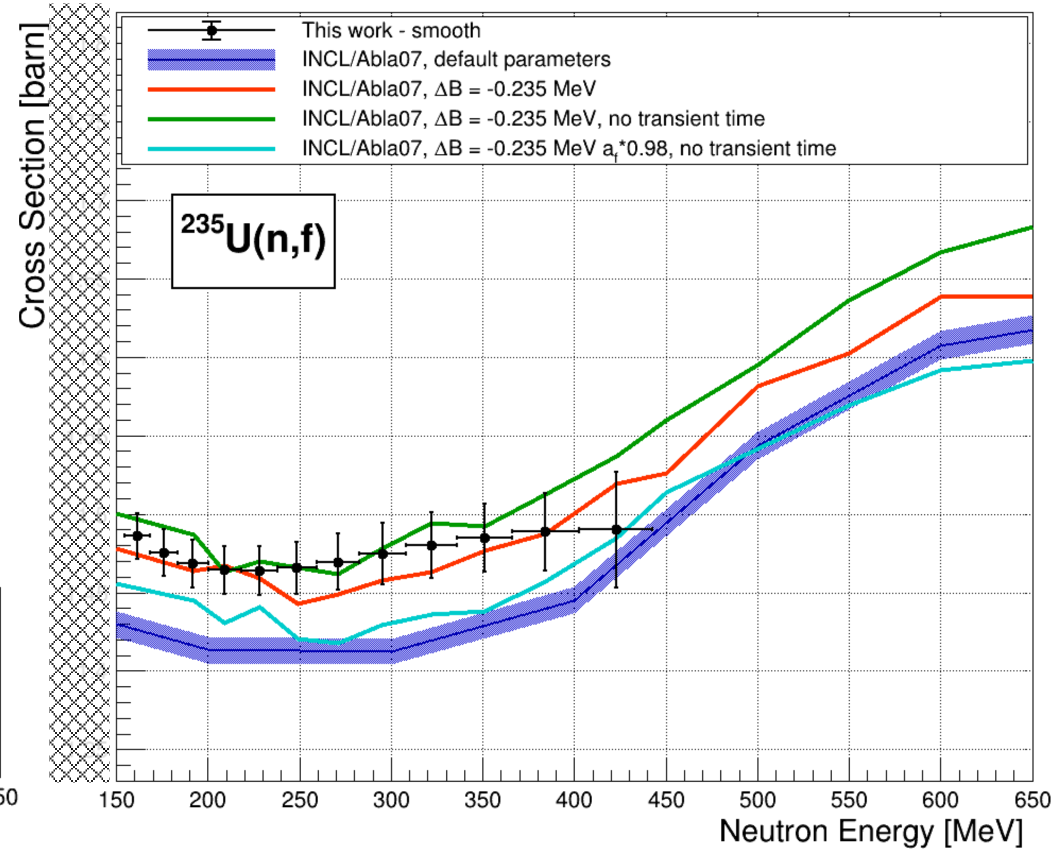


...at high neutron energy

energy limit extension

Comparison with model calculation

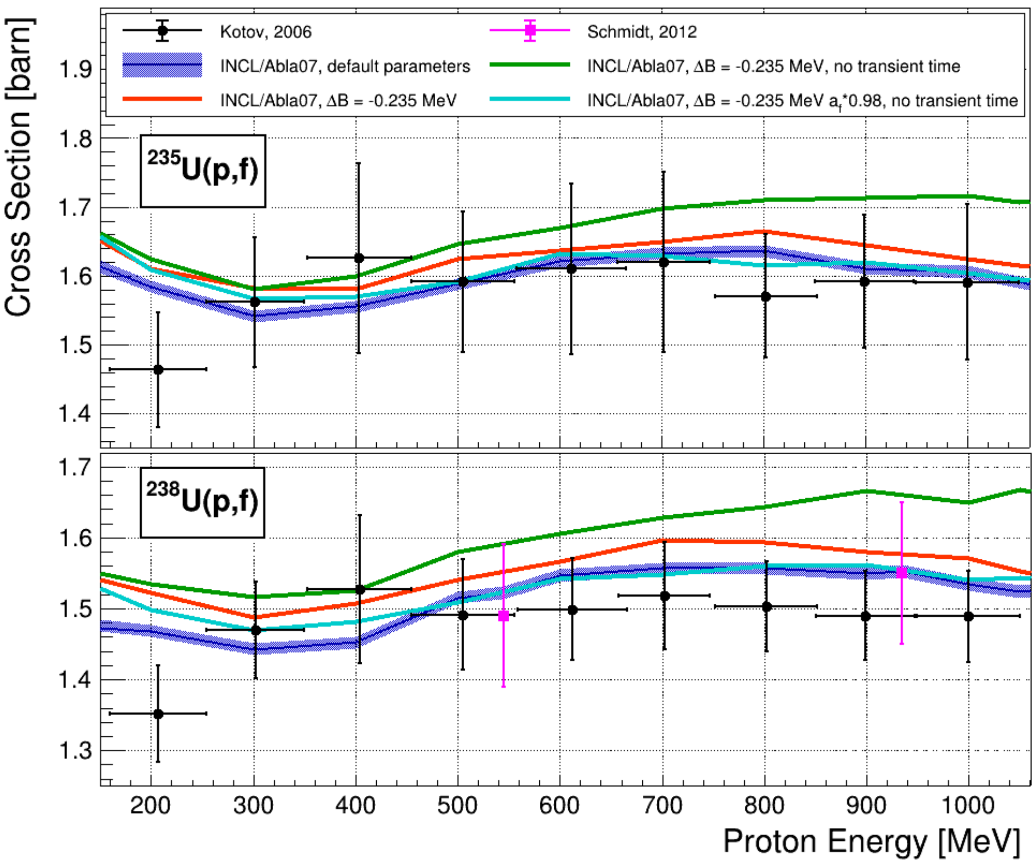




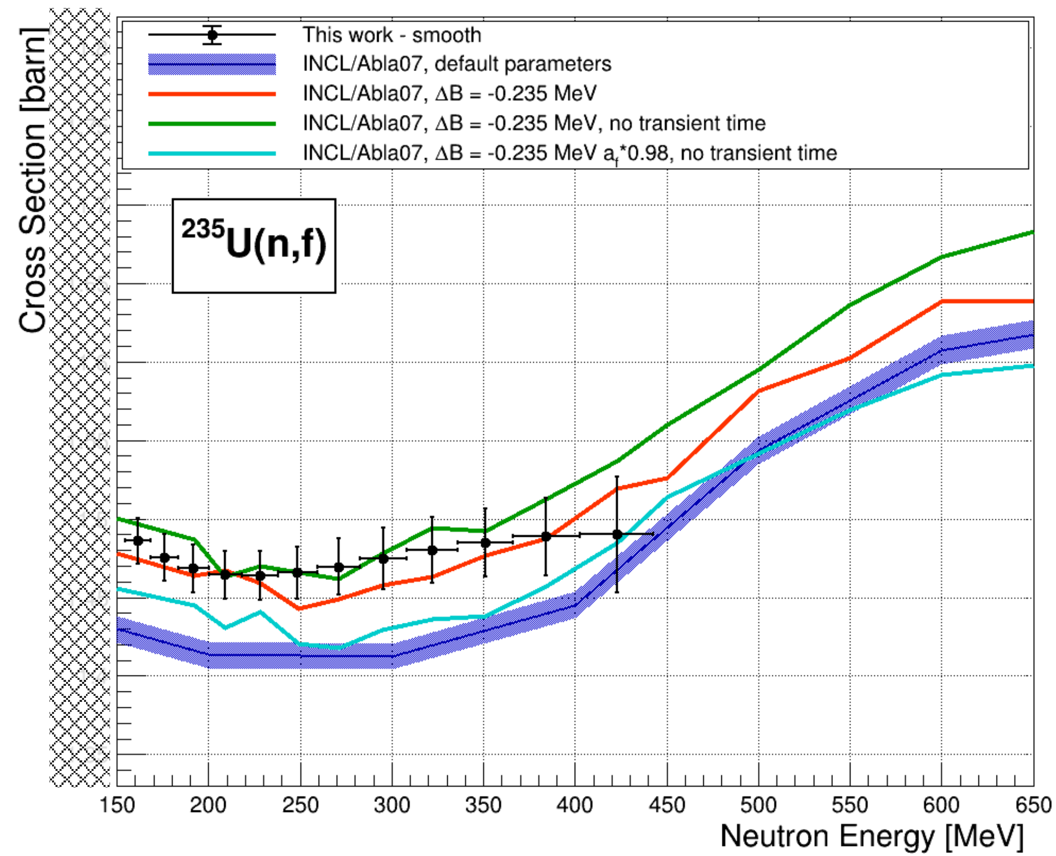
...at high neutron energy

energy limit extension

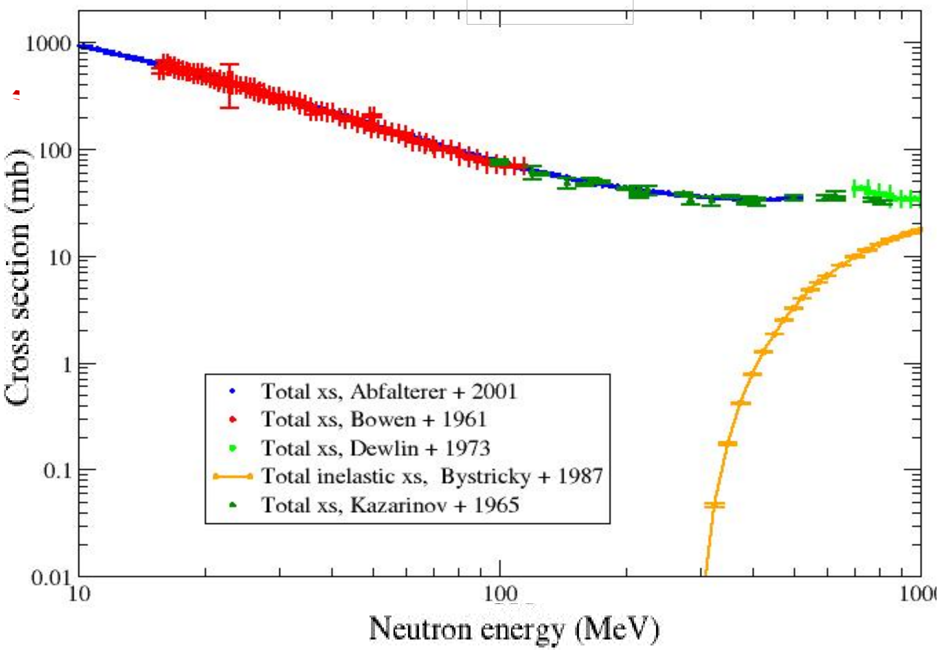
Calculation applied to (p,f)



Comparison with model calculation



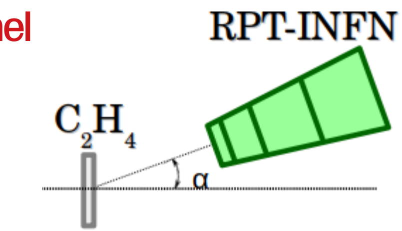
What's Next?



From ~ 300 MeV:

opening of the inelastic channel

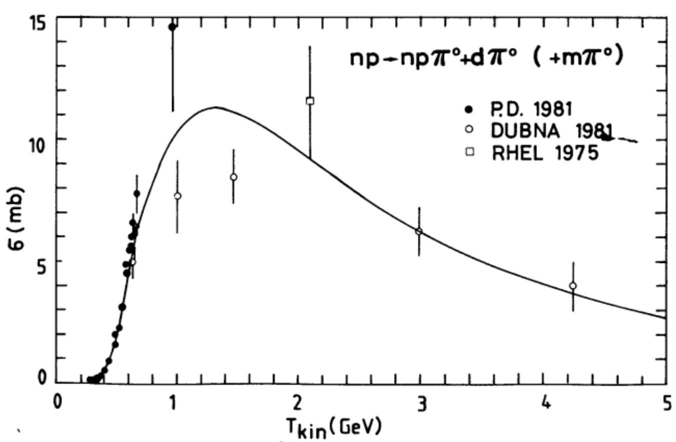
$$n + p \rightarrow N + N + \pi$$

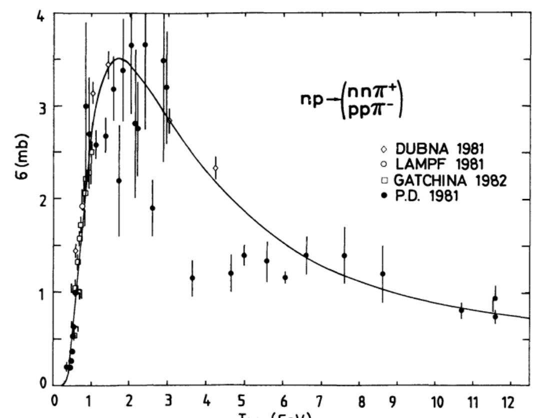


How we correct for it:

- calculate the angular distribution considering the boost effect

- simulate the proton energy distribution - 3-body



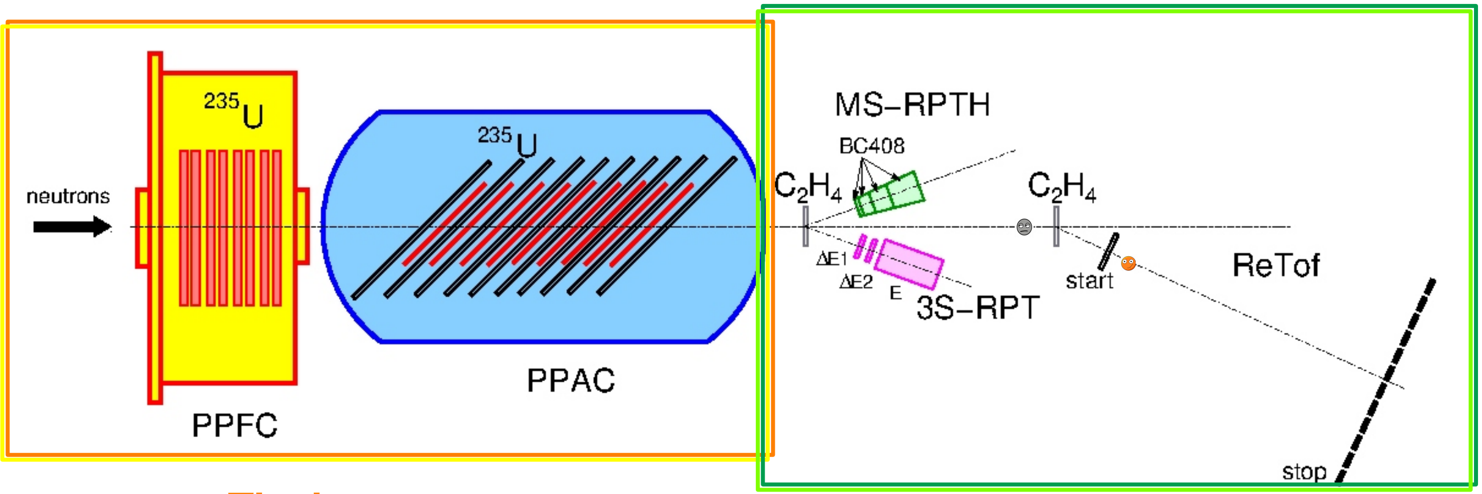


En, MeV	corr, % - 20°	corr, % - 25°
300	0.0	0.0
350	0.0	0.0
400	0.9	0.0
425	3.1	0.8
450	6.4	2.7
475	11.4	5.9
500	18.5	10.7

^{235}U

What's Next?

energy limit extension



Least-favourable 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

Fission events

PPFC: 8 ^{235}U samples

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

tilted detector

↓

Fission Fragment Angular Distribution

Neutron flux

1 or 2 RPT already used for the lower energy region + benchmark

Re-TOF:

1 start + 1 stop detector ~2 m

Pointing @ PE sample – 25°

Detector Test @ October

Conclusion

- For more than 20 years, an extensive fission measurement program has been carried out @ n_TOF

- Recently, the most significant result obtained for ^{235}U(n,f) cross section:
  - **extension** of the neutron energy range of **more than 200 MeV** (with respect to the previous limit – Lisowski data)
    - Transient time effect in neutron-induced fission
    - Isospin effect in the high energy region

Next?

- Further extension of the energy limit → GeV
- + simultaneous FFAD measurement

only possible at n_TOF

Conclusion

- For more than 20 years, an extensive fission measurement program has been carried out @ n_TOF

- Recently, the most significant result obtained for ^{235}U(n,f) cross section:
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Next?

- Further extension of the energy limit → GeV
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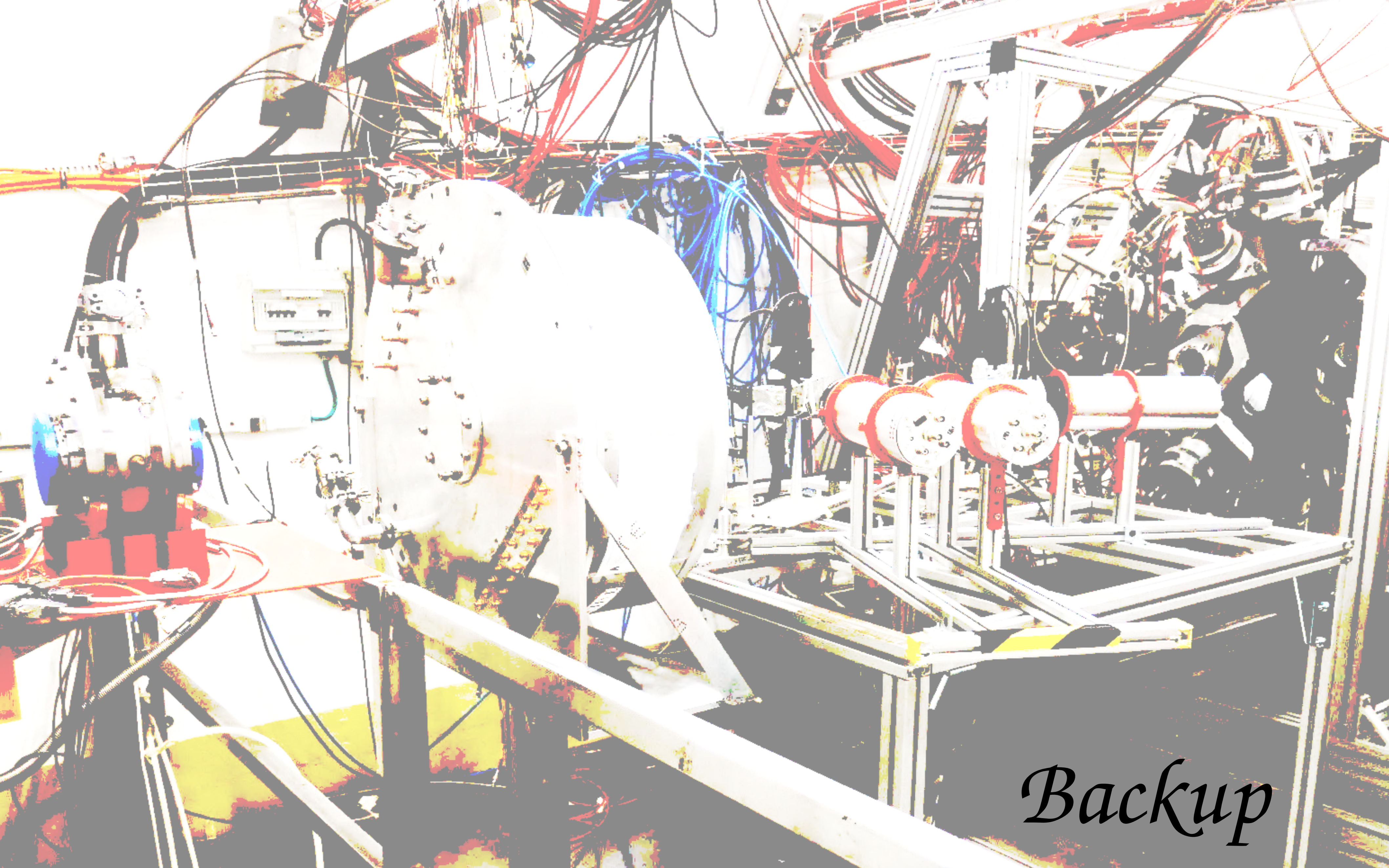
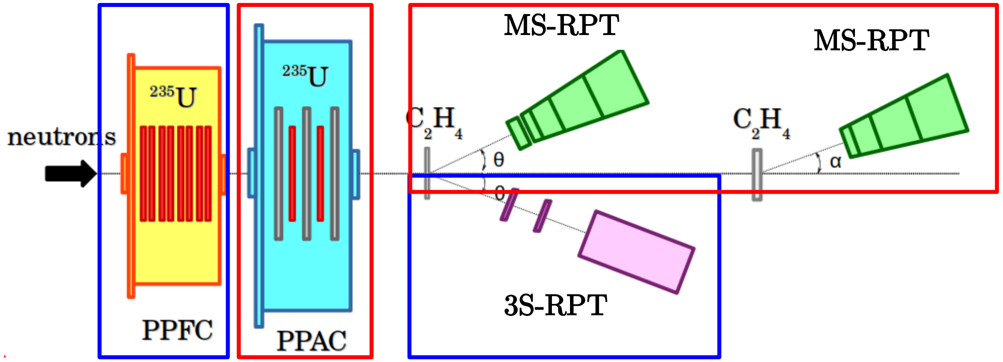
only possible at n_TOF

Thank you for your attention



Backup

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

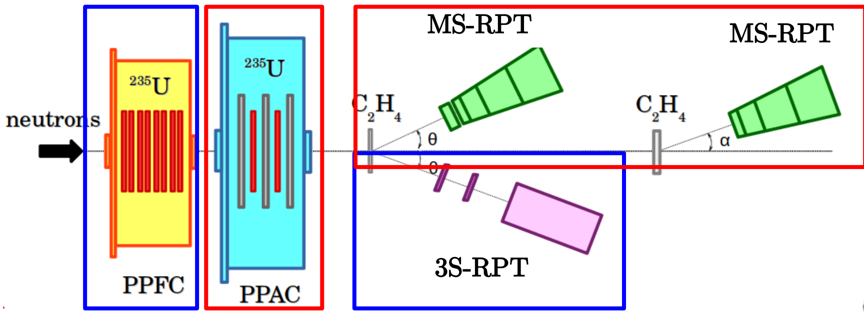


Arndt, VL40

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

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

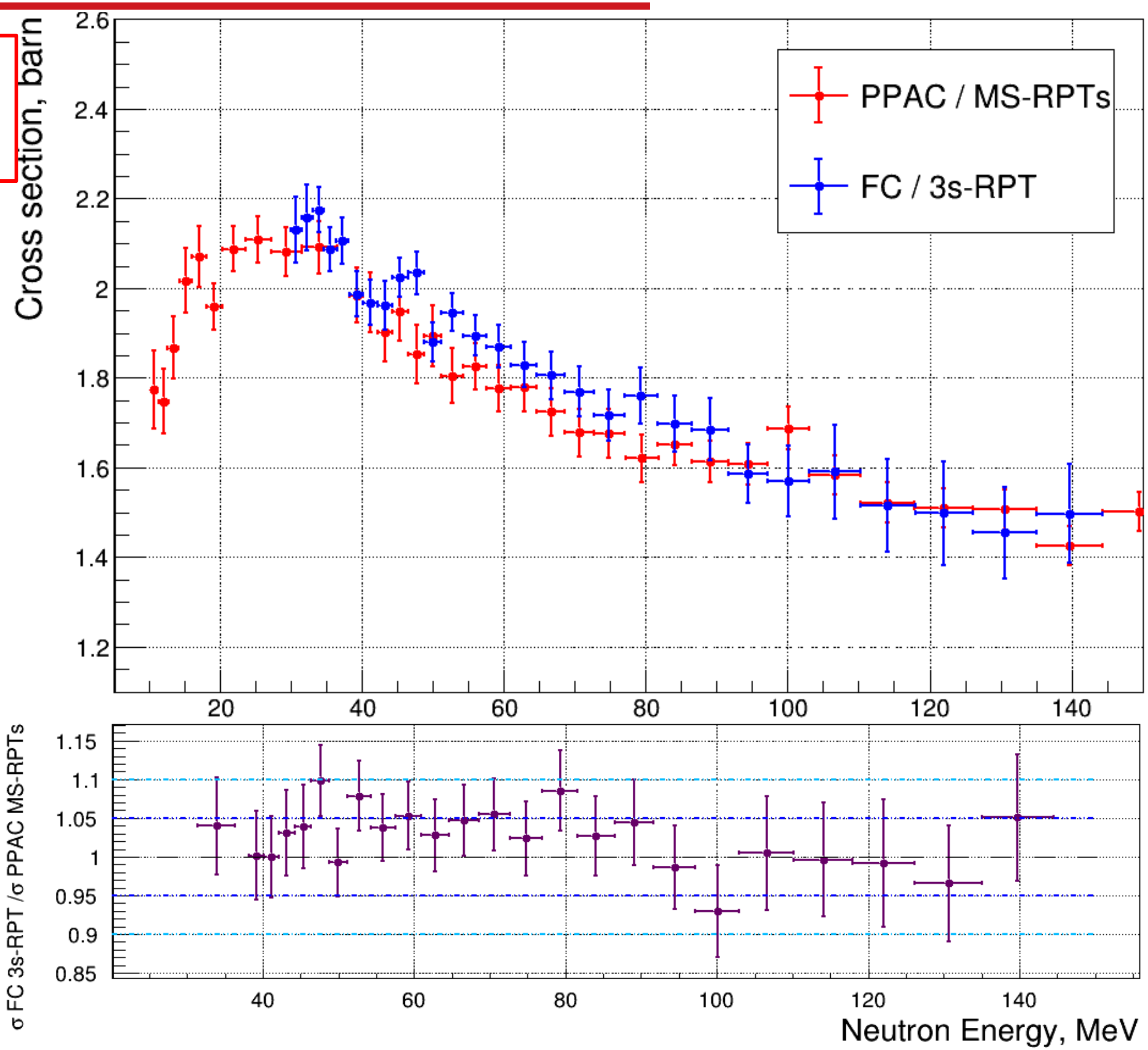
$^{235}U(n,f)$ cross section



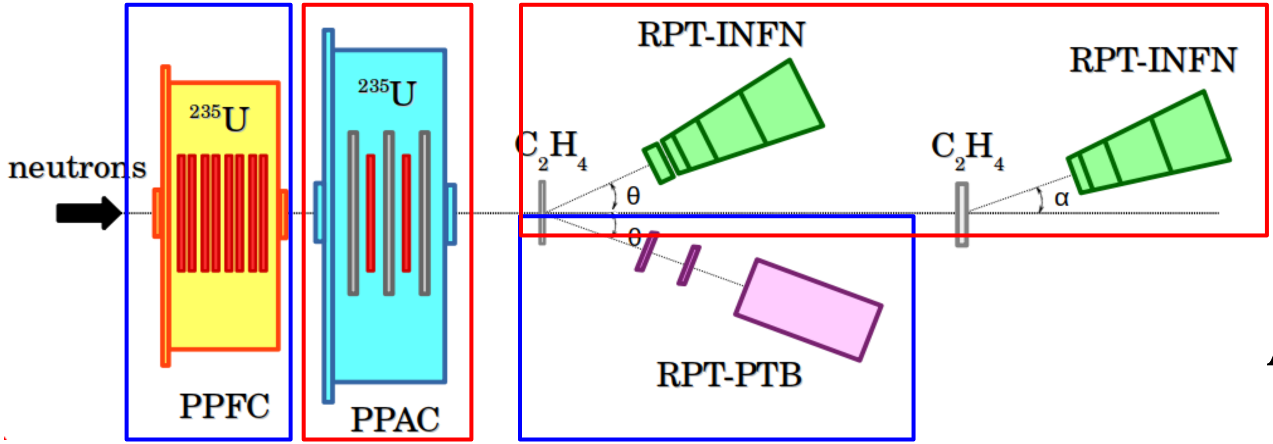
Arndt, VL40

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

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



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



Recoil Proton Telescopes

- Efficiency
- Events selection
- Angle relative to the neutron beam
- Dead-time correction
- Distance of the detectors from the PE or C sample

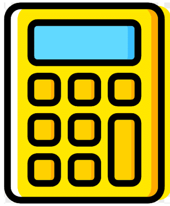
Fission Chambers:

- ^{235}U mass
- ^{235}U effective density
- Efficiency

+ Correlated uncertainties

- Beam transmission through PPFC, PPAC
- Isotopic composition of PE
- Areal density of PE sample
- Areal density of C sample

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

Uncertainties

...for FF events PPFC 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 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 (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 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%

Polyethylene samples

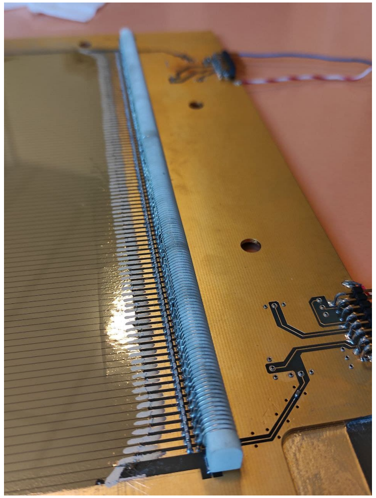
Characterization

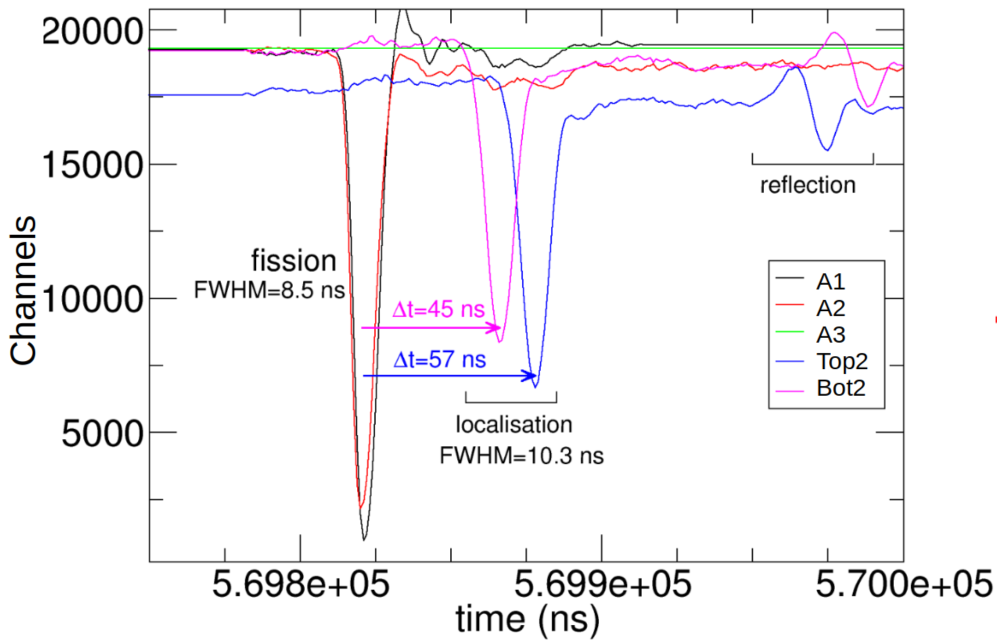
- mass density from hydrostatic weighing (PTB)
- thickness: precision measurement of the profile (PTB)
- uncertainty on the areal density: 0.2-0.6%

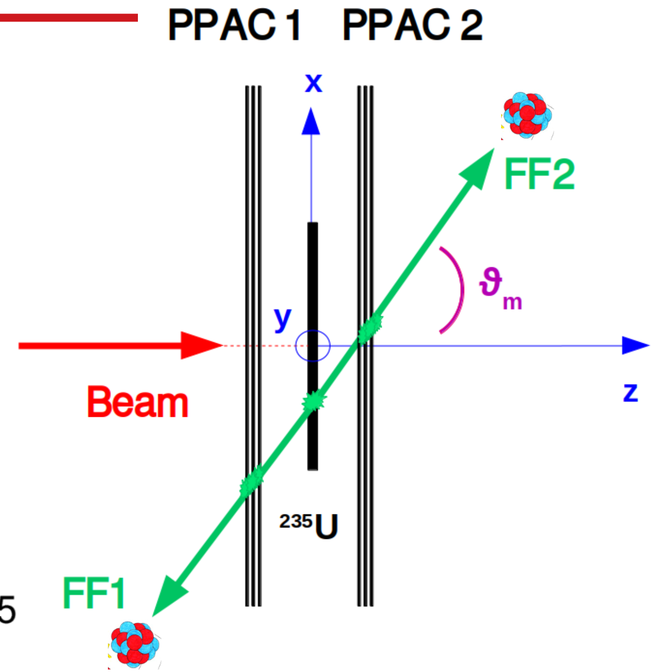
Sample	Thickness (mm)	Density g/cm^3	Areal density g/cm^2	(rel. unc.)
PE 1mm	1.025(4)	0.9534(20)	0.0978(4)	(0.4%)
PE 2mm	1.824(11)	0.9555(20)	0.1743(11)	(0.6%)
PE 5mm	4.925(4)	0.9597(20)	0.4726(11)	(0.2%)
C 0.5mm	0.500(4)	1.7749(27)	0.0887(8)	(0.9%)
C 1mm	1.000(5)	1.7364(86)	0.1736(12)	(0.7%)
C 2.5mm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

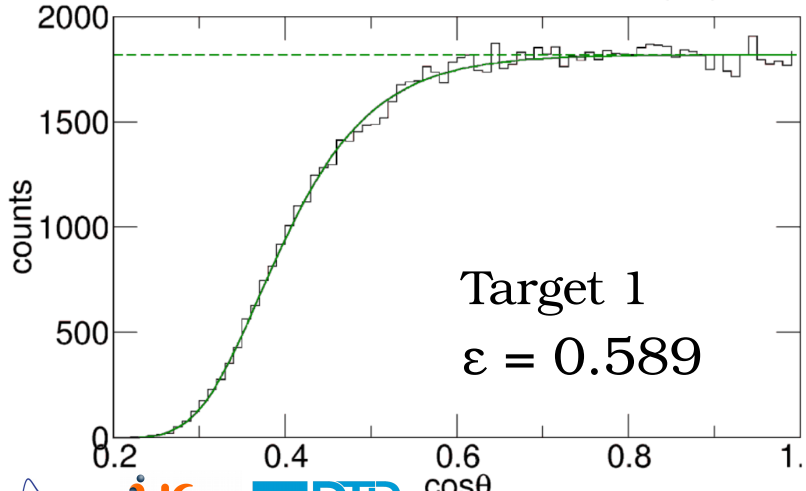
- H/C ratio via combustion analysis, two measurements (Forschungszentrum Jülich, TU Braunschweig): 1.98(3) and 2.00(3)
- In the simulations: assumed nominal stichometry H/C=2

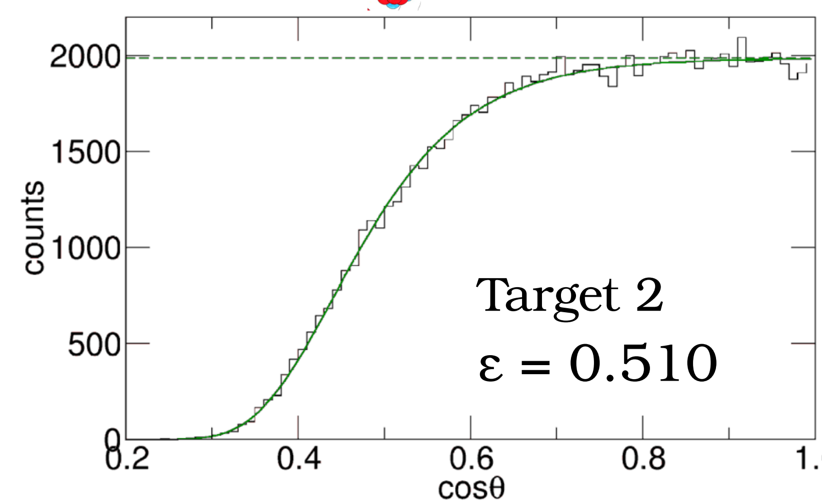
PPAC – Parallel Plate Avalanche Counters











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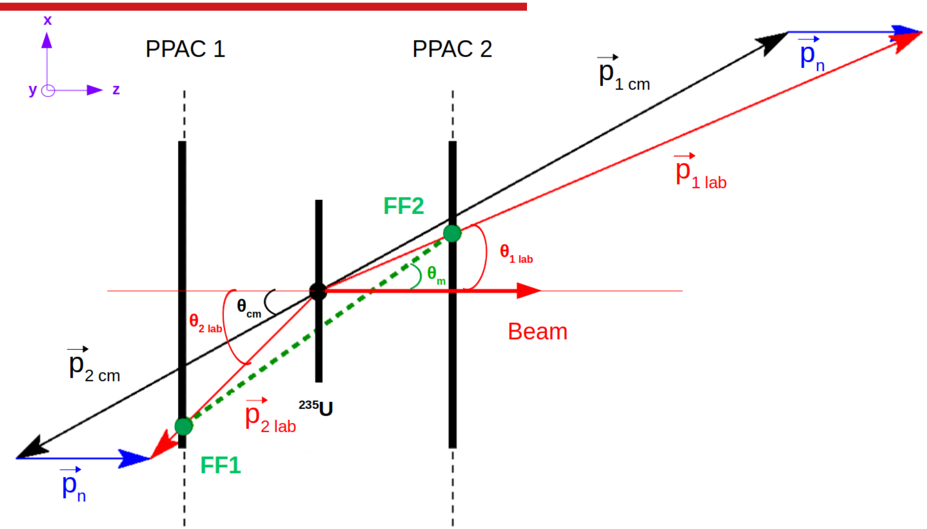
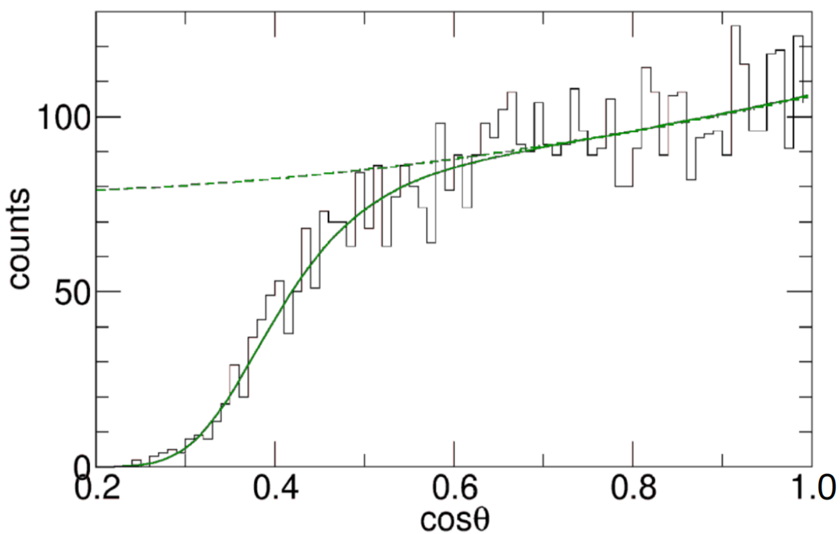


6.3 MeV < E_n < 10 MeV



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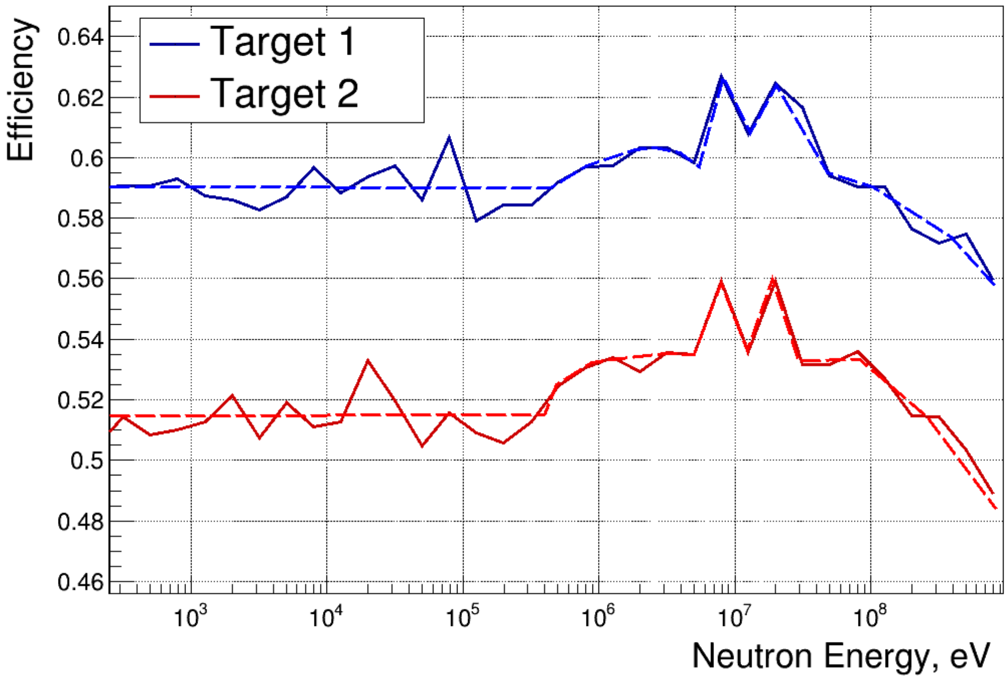
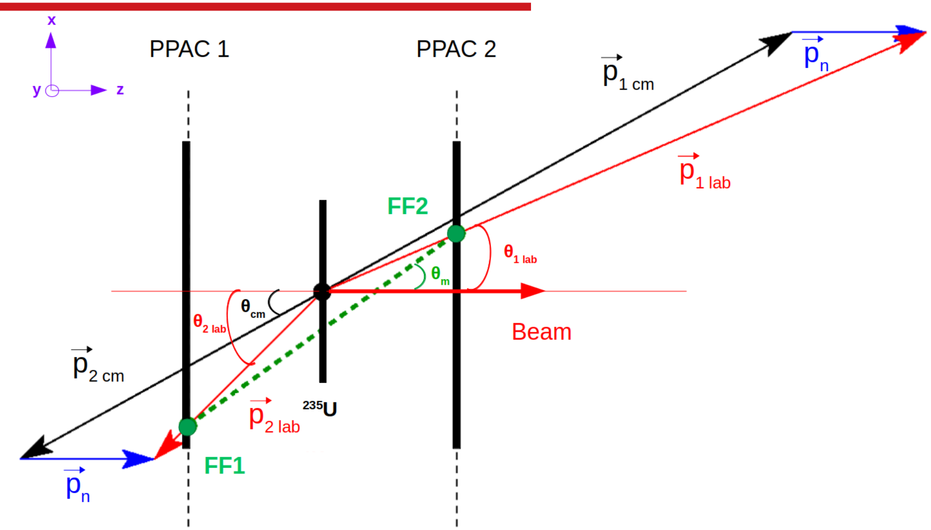


geometrical efficiency

geometrical efficiency
+
angular distribution
+
linear momentum transfer



6.3 MeV < E_n < 10 MeV