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Prompt Fission Neutron Emission in the Reaction $^{235}U(n,f)$

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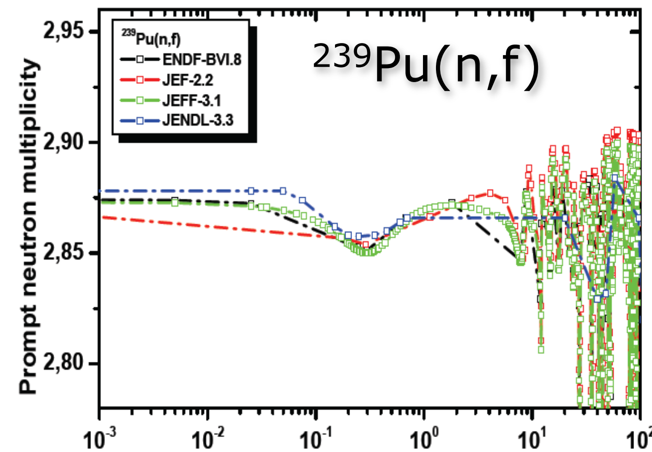
European Commission

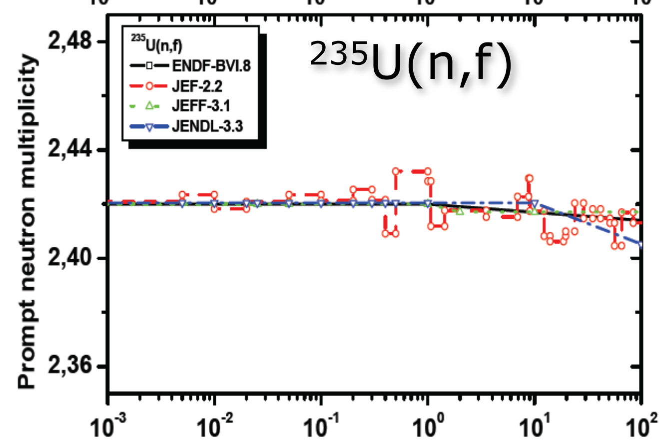
Introduction & Motivation

Prompt Fission Neutron (PFN) multiplicity in resonances

Data relevant for improved evaluations as requested by the OECD/ Working Party on Evaluation Cooperation (WPEC)

- ❑ ^{239}Pu - strong (~5%) fluctuations of neutron multiplicities $\bar{\nu}(E_n)$
- ❑ ^{235}U - minor (~1%) fluctuations of neutron multiplicities $\bar{\nu}(E_n)$
- ❑ Fluctuating $\bar{\nu}(E_n)$ can have significant impact on k_{eff}
- ➢ Measure neutron multiplicity as a function of neutron energy in the region of the resonances





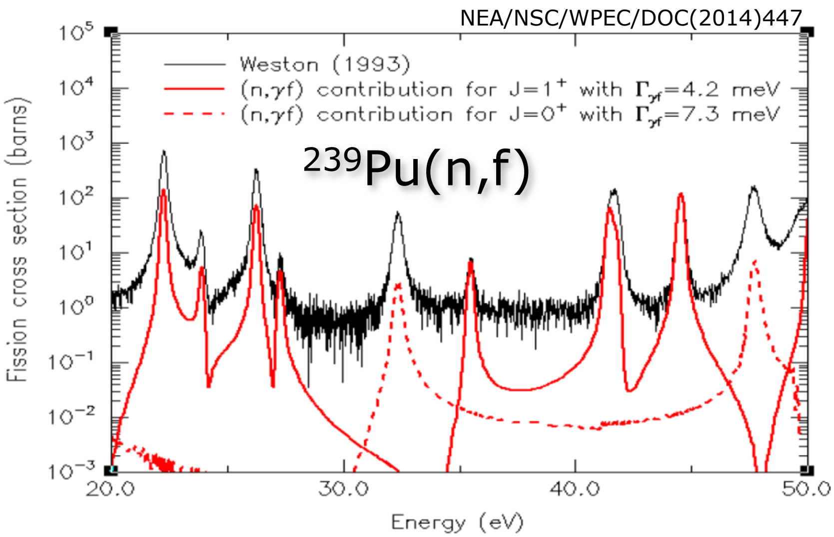
Introduction & Motivation

Why does $\bar{\nu}(E_n)$ fluctuate?

- ^{239}Pu – strongly fluctuating influence of $(n\gamma,f)$
  - Difference according to resonance spin

    0^+ : $\langle\Gamma_f\rangle$ = 2 eV : weak $\bar{\nu}$-fluctuations

    1^+ : $\langle\Gamma_f\rangle$ = 30 meV : strong $\bar{\nu}$-fluctuations
  - pre-fission photon $\langle E_\gamma\rangle \sim 1$ MeV

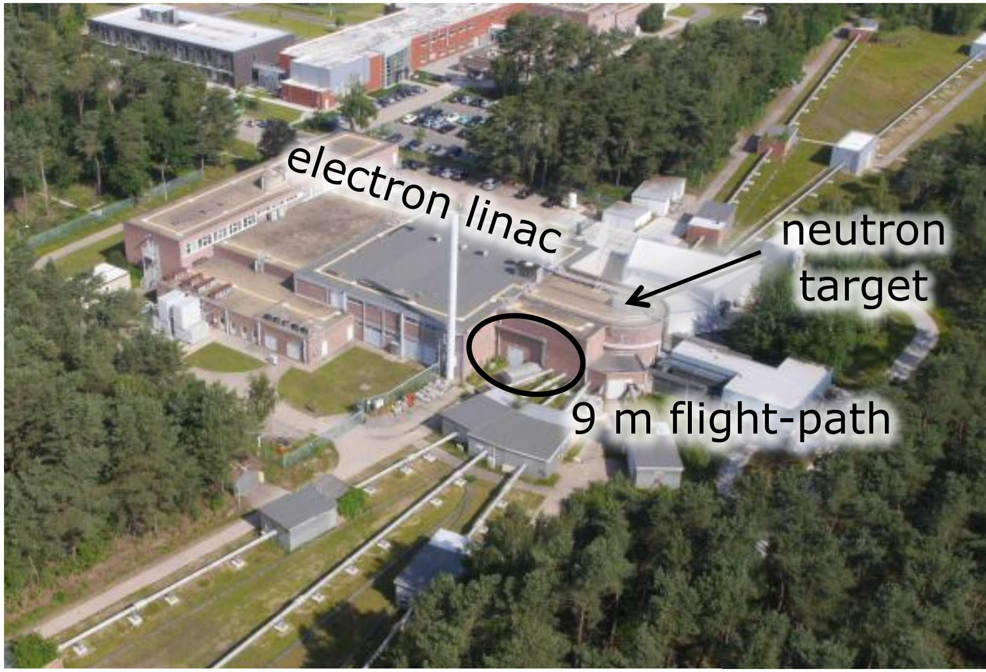


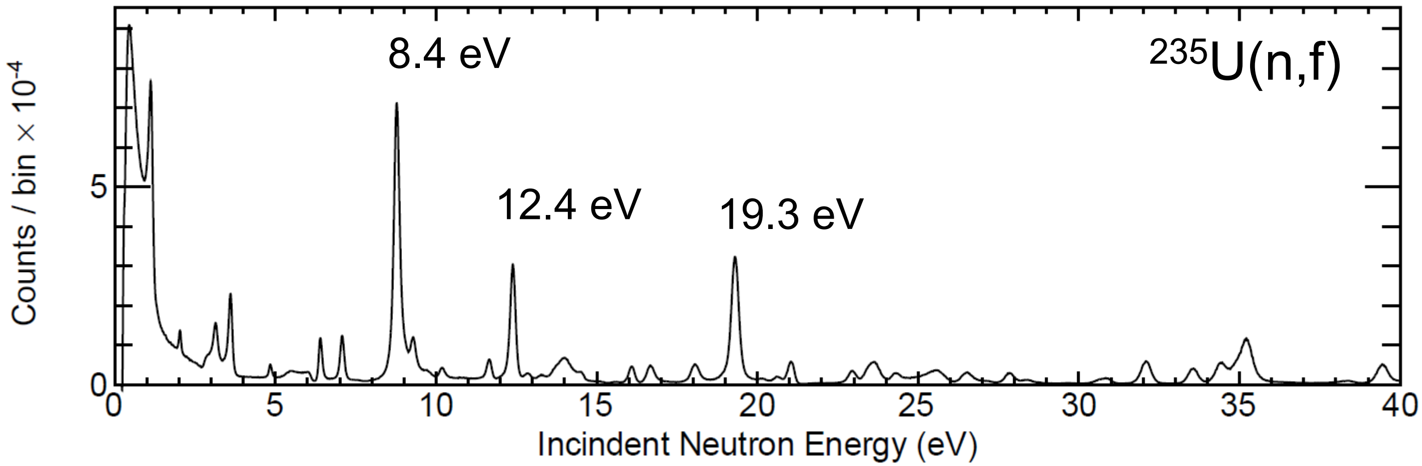
- ^{235}U – not clear?
  - No established correlation of $\bar{\nu}$ and spin
  - No established correlation of $\bar{\nu}$ and Γ_f
  - Experimental evidence for fluctuating properties of fission fragment Y(A,TKE)
- Study correlations between fragment properties and $\bar{\nu}$

Neutron Source - GELINA

GELINA ToF-facility

- Pulsed white-neutron source
  - Pulse width <1 ns (FWHM)
- Neutrons (mainly) from $^{238}U(\gamma,f)$
  - $H_2 0$ moderated
- n-energy via time-of-flight
  - 9 m flight-path
  - Resolution $\delta t \sim 1ns$ (FWHM)
  - $E_n<100$ eV : $\delta E<1$ eV





Experimental Setup

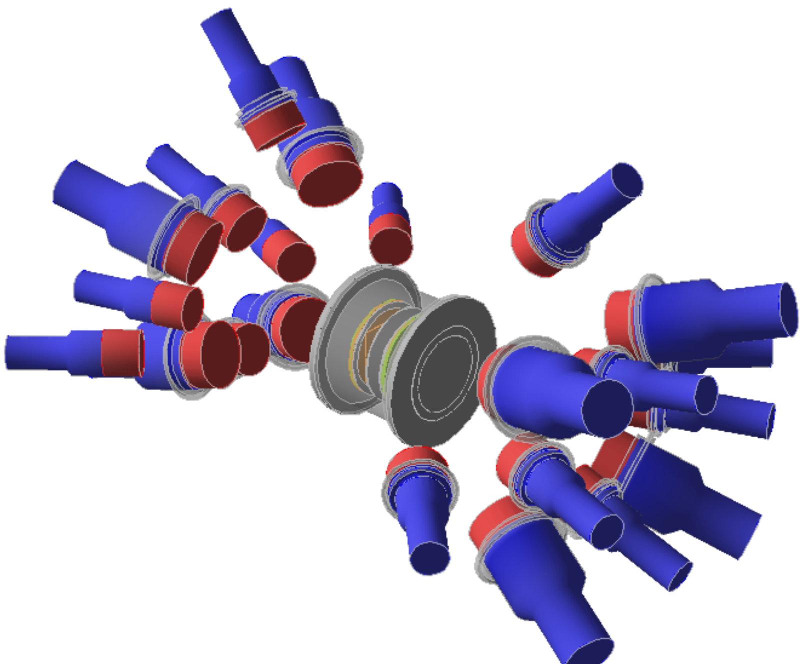
Fission fragment detector

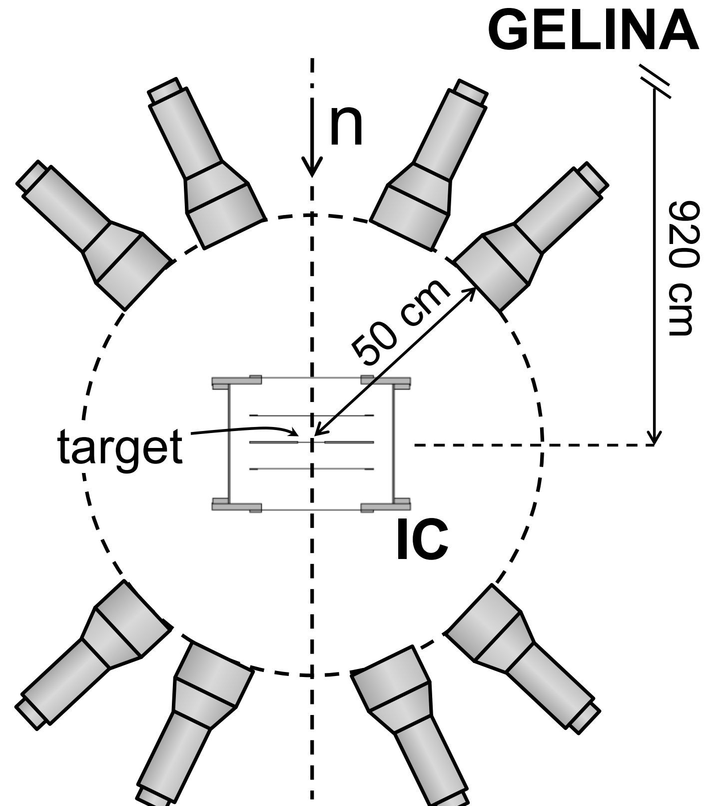
- twin ionization chamber
  - ✓ Fragment properties from 2E-technique
  - ✓ Orientation of fission-axis

Prompt neutron detection

- array of 22 scintillators

Target		
$^{235}UF_4$	67.2	μgU/cm²
gold	50	μg/cm²
polyimide	27	μg/cm²





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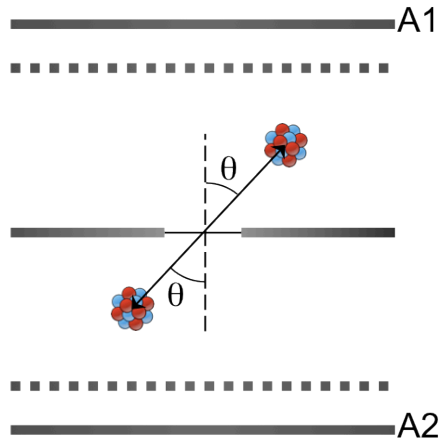
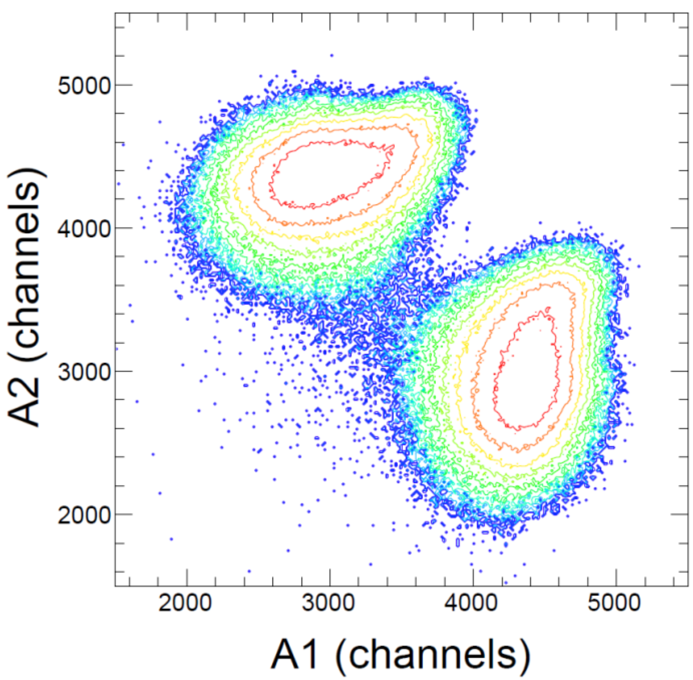
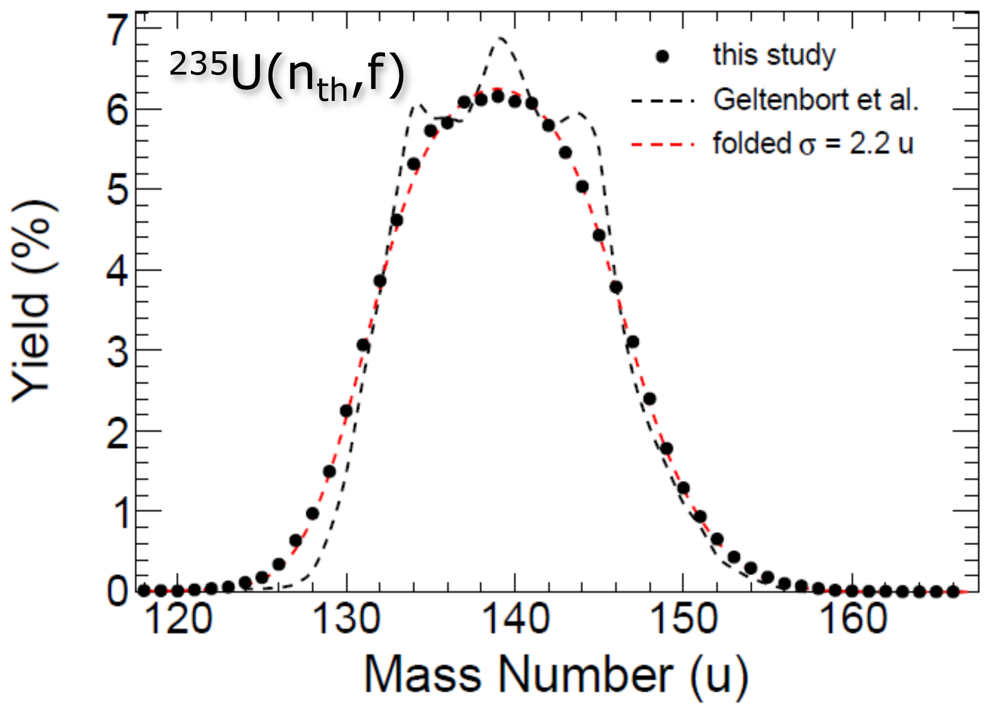
Fission Fragments



Fragment masses are determined via 2E-technique

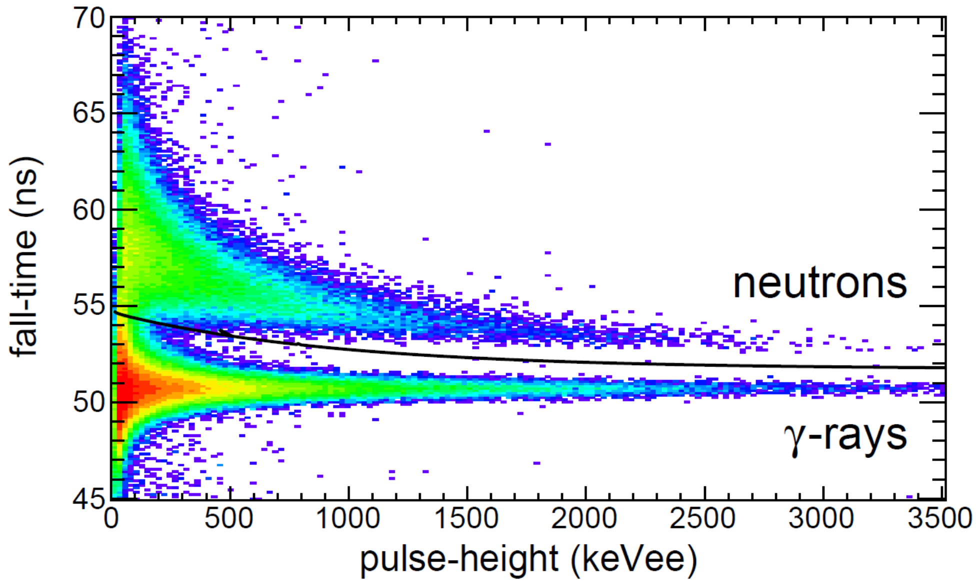
- Corrections
  - Energy loss in sample & backing
  - Neutron Evaporation
- Resolution: ~5 u (FWHM) mainly limited by PFN emission
- Good agreement with high resolution measurement

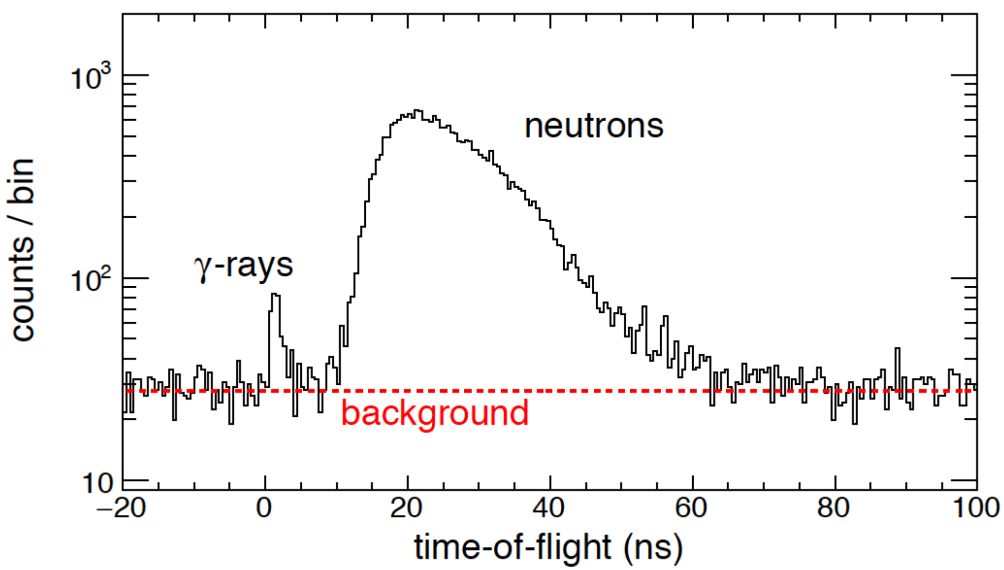




Geltenbort et al. Rad Eff 93 (1986) 393.

Prompt Fission Neutrons





Pulse-shape discrimination is used to separate prompt fission neutrons and γ-rays

Residual γ-rays supressed by applying a pulse-height threshold

PFN energy is determined from time-of-flight

Background rate determined from events to the left of the prompt γ-ray-peak is determined as a function of incident neutron energy

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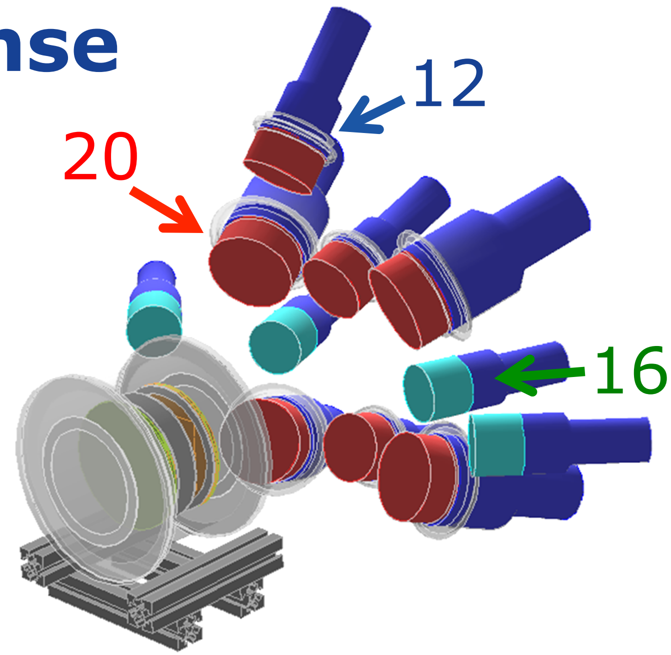
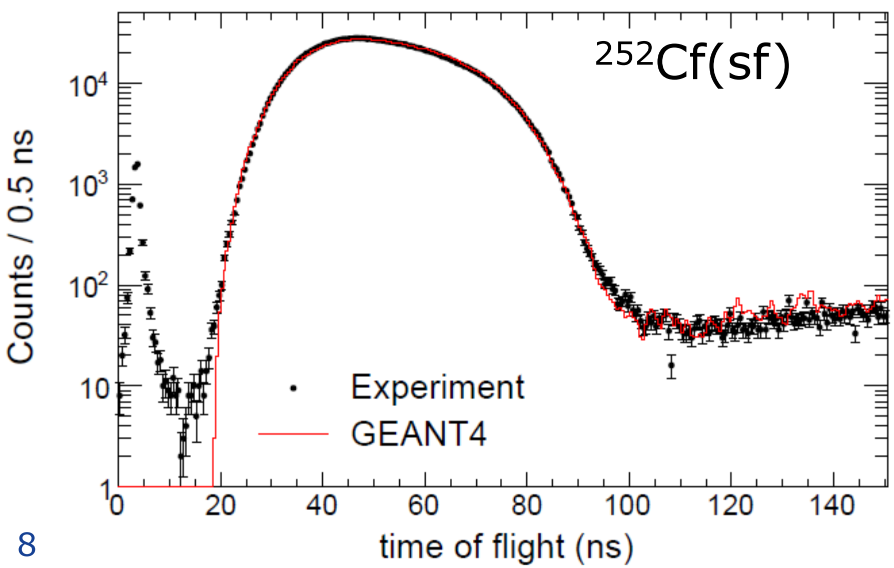
Neutron Detection Response

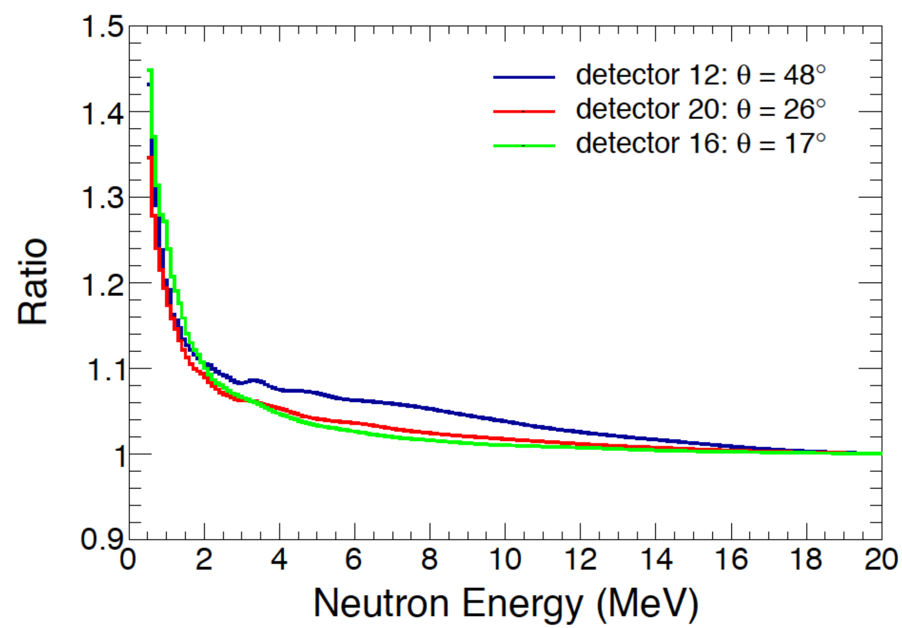
Neutron detection response is modelled with GEANT4

The simulations are benchmarked against standard PFNS of ^{252}Cf(sf)

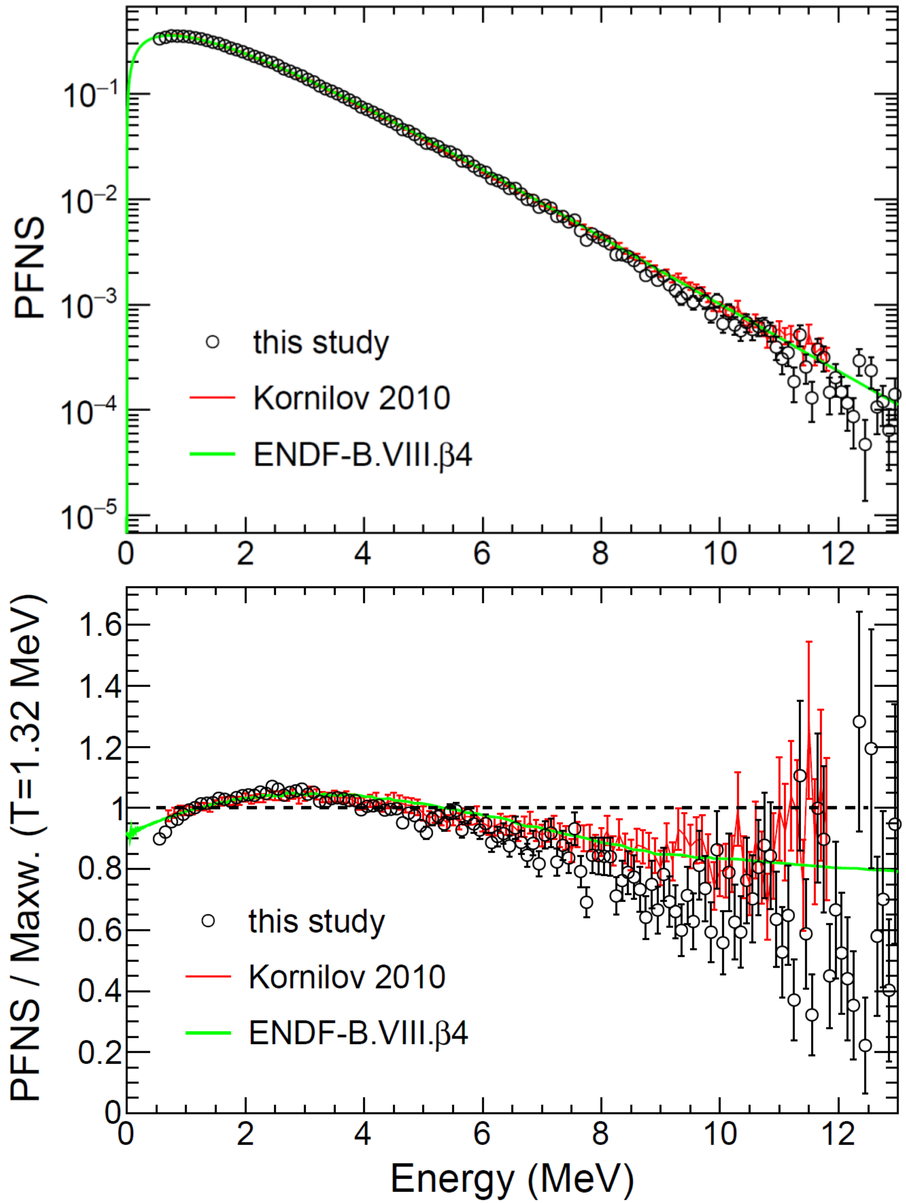
- ✓ Detection efficiency $\varepsilon(E)$
- ✓ Multiple-scattering correction
  - ✓ Ratio of observed spectrum to input spectrum in Monte-Carlo







PFN spectrum



The neutron energy spectrum

- integrated over the incident neutron energy range (0.3 eV - 45 keV)
- Generally: agreement with thermal PFNS
- The observed PFNS is slightly softer than the thermal PFNS

Kornilov 2010 – Nucl. Sci. and Eng. 165 (2010) 117

ENDF-B.VIII.β4 - IAEA (standards 2017) GMA evaluation

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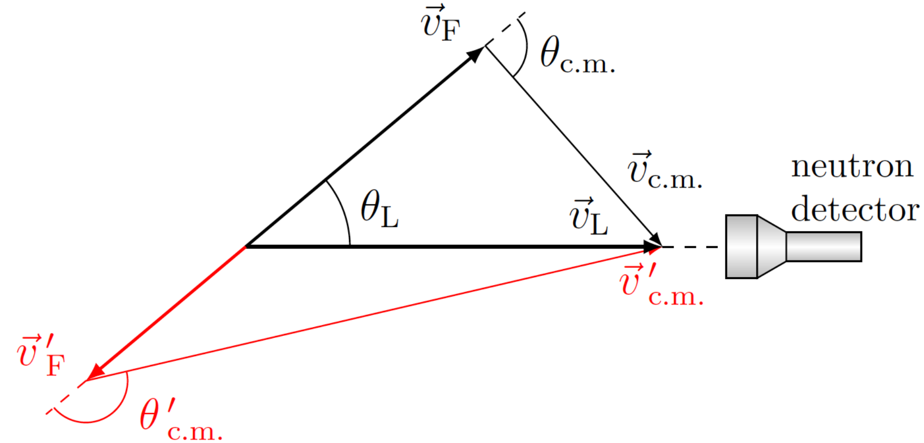
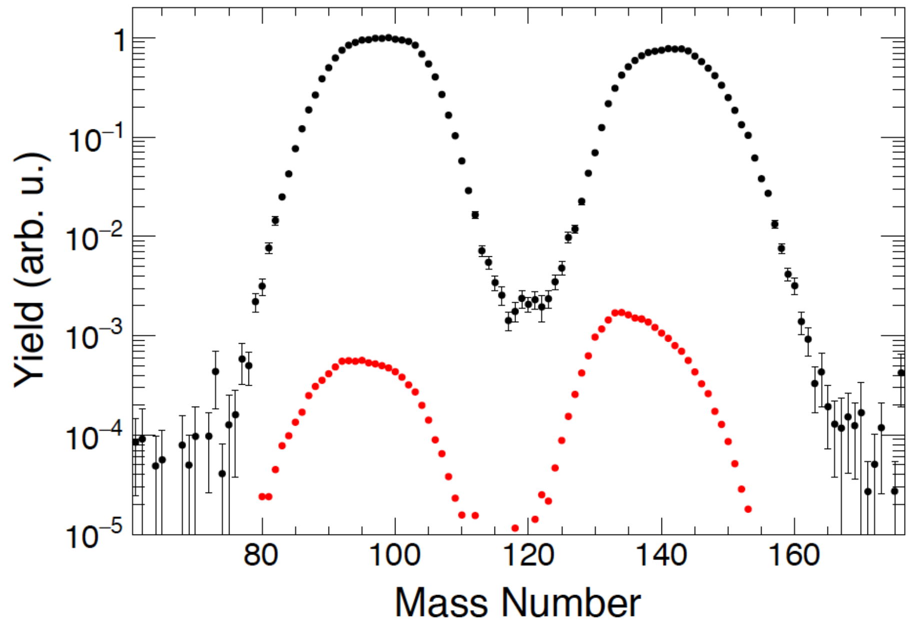
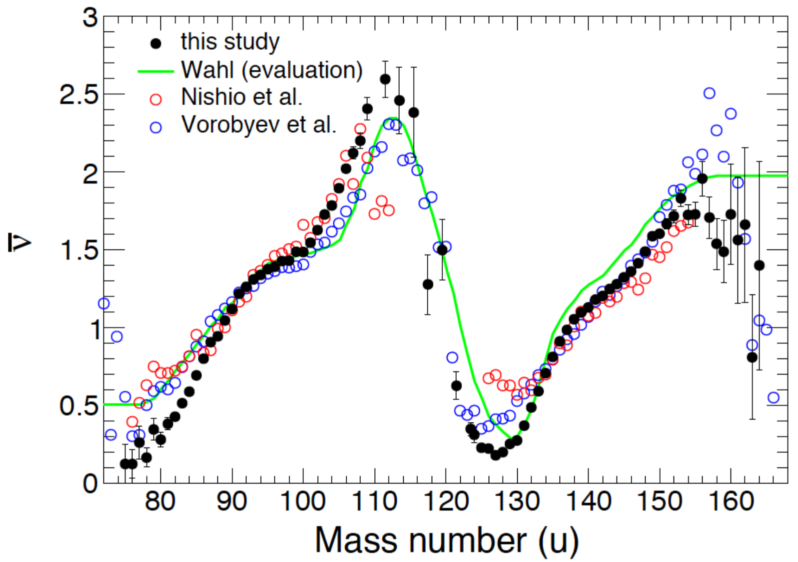
Transformation into c.m. - frame

- Event by Event transformation into the c.m. frame
- Selection $\theta_{c.m.}$<90°
- Measured distribution consist of neutron from both fragments
  - Due to the kinematic boost the main contribution is from fragment directed towards detector
  - Complimentary fragment neutrons are treated as perturbation
  - Probability of detecting neutron from complementary fragment is calculated based on the observed c.m. neutron spectrum and assumption of isotropic emission from fully accelerated fragments





Multiplicity vs. Fragment Mass

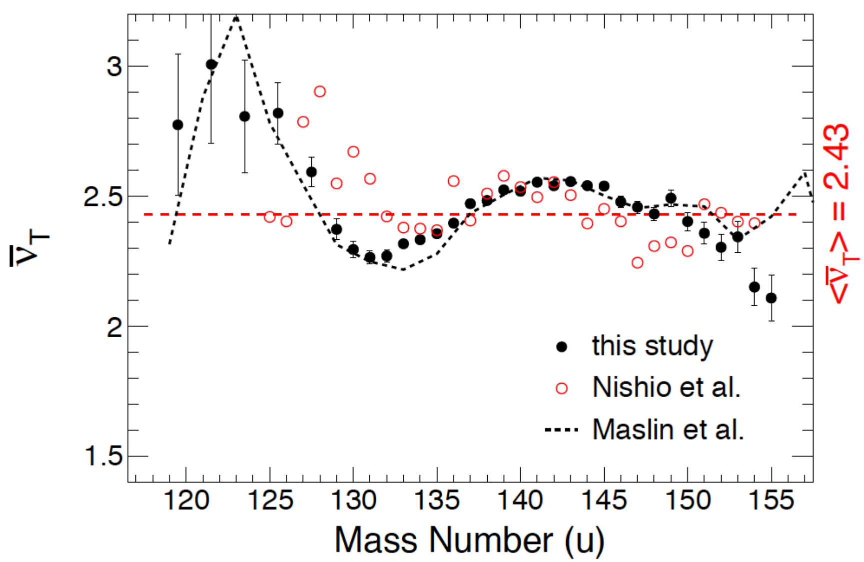


Neutrons per fragment

Saw-tooth distribution

Pronounced minima around A_L=80 and A_H=130

Additional structures around A_L=100 and A_H=140

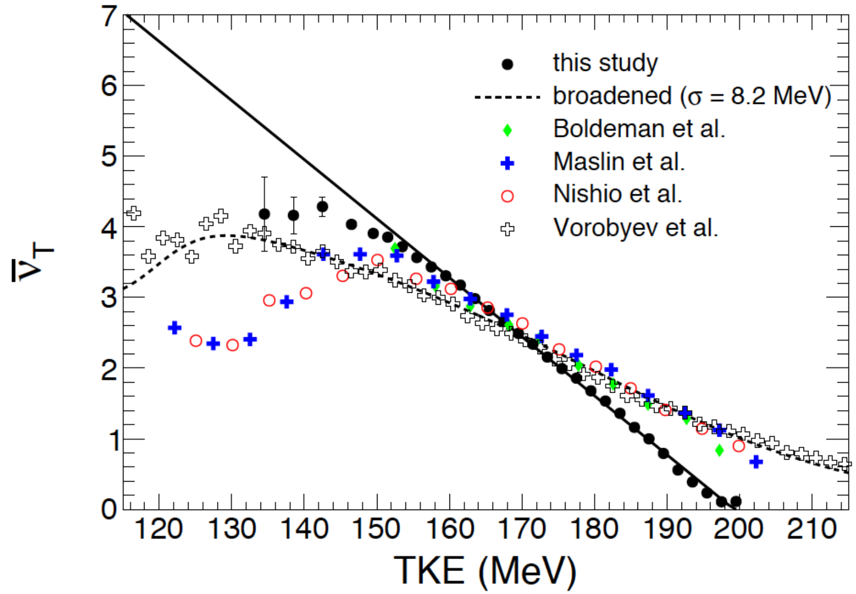


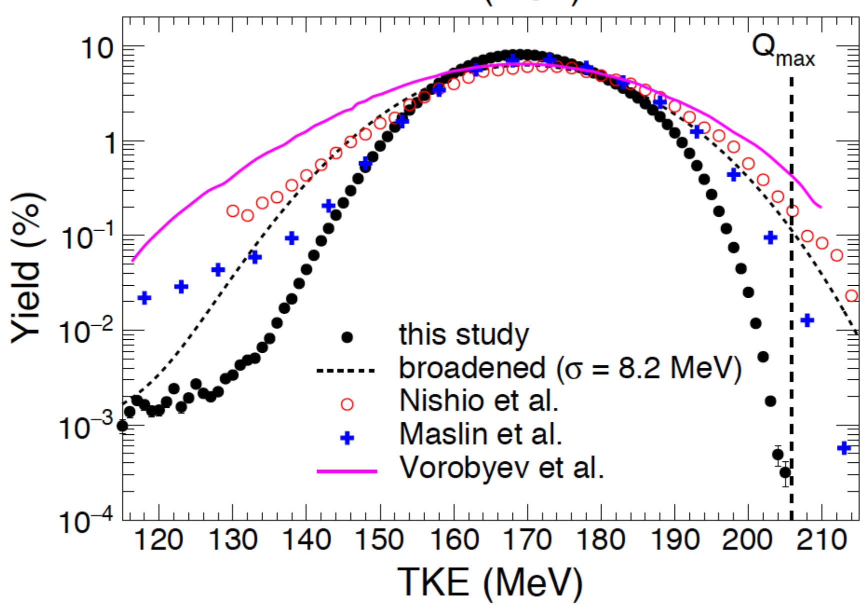
Neutrons per fission

Flatter distribution

Pronounced minimum at A_H=132 (double shell closure ^{132}Sn)

Multiplicity vs. Fragment TKE





Close to linear dependence

$$-\frac{\mathrm{dTKE}}{\mathrm{d}\bar{\nu}_T} = 12.0\ \mathrm{MeV/n}$$

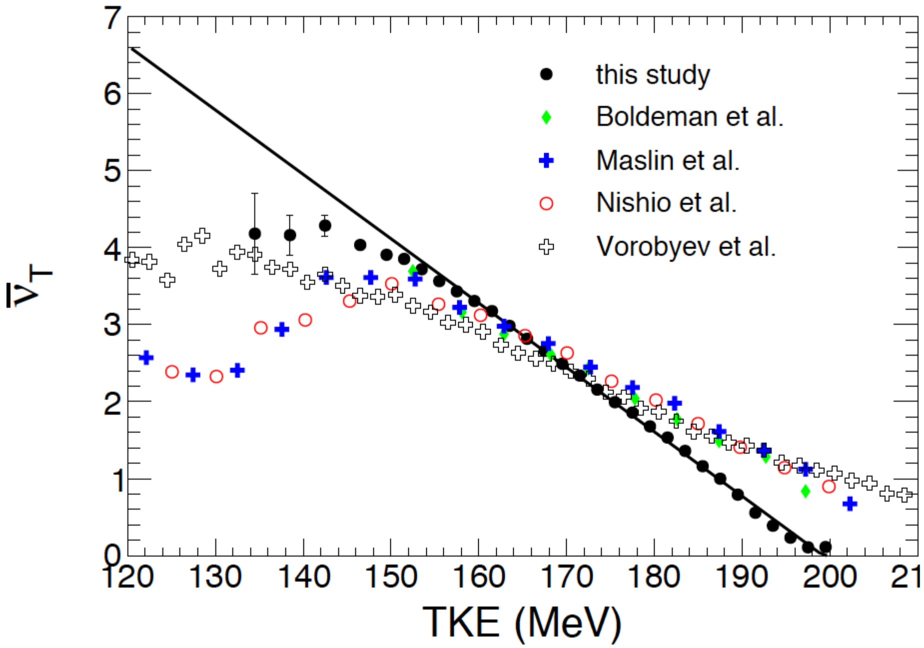
Significantly different compared to earlier studies

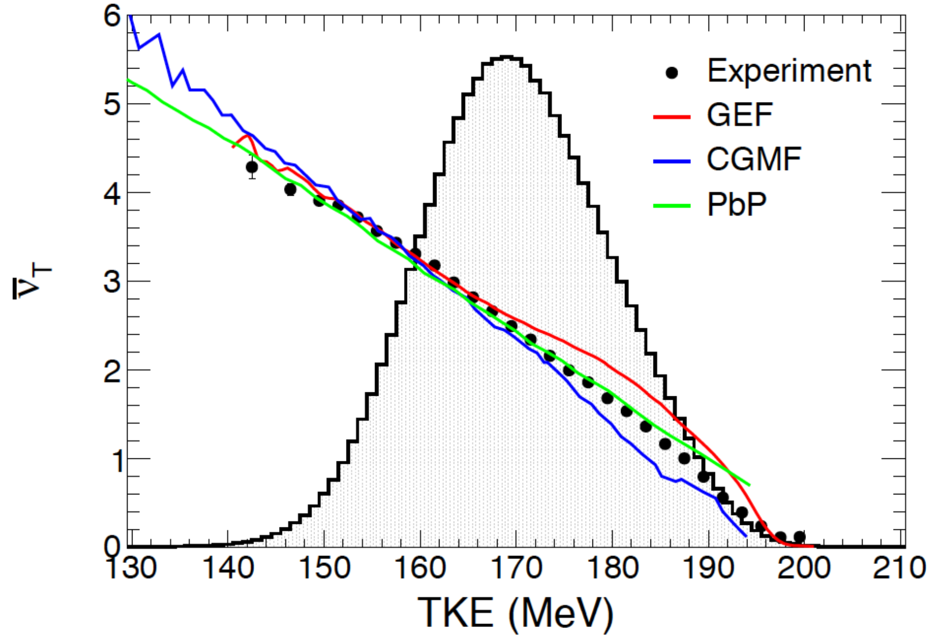
- Wide TKE-distributions
- Significant yield at TKE>Q_{max}
- Effect of TKE-resolution on $\bar{\nu}$(TKE)
  - Decreased slope
  - Increased $\bar{\nu}$ at TKE ≥ Q_{max}

Multiplicity vs. Fragment TKE

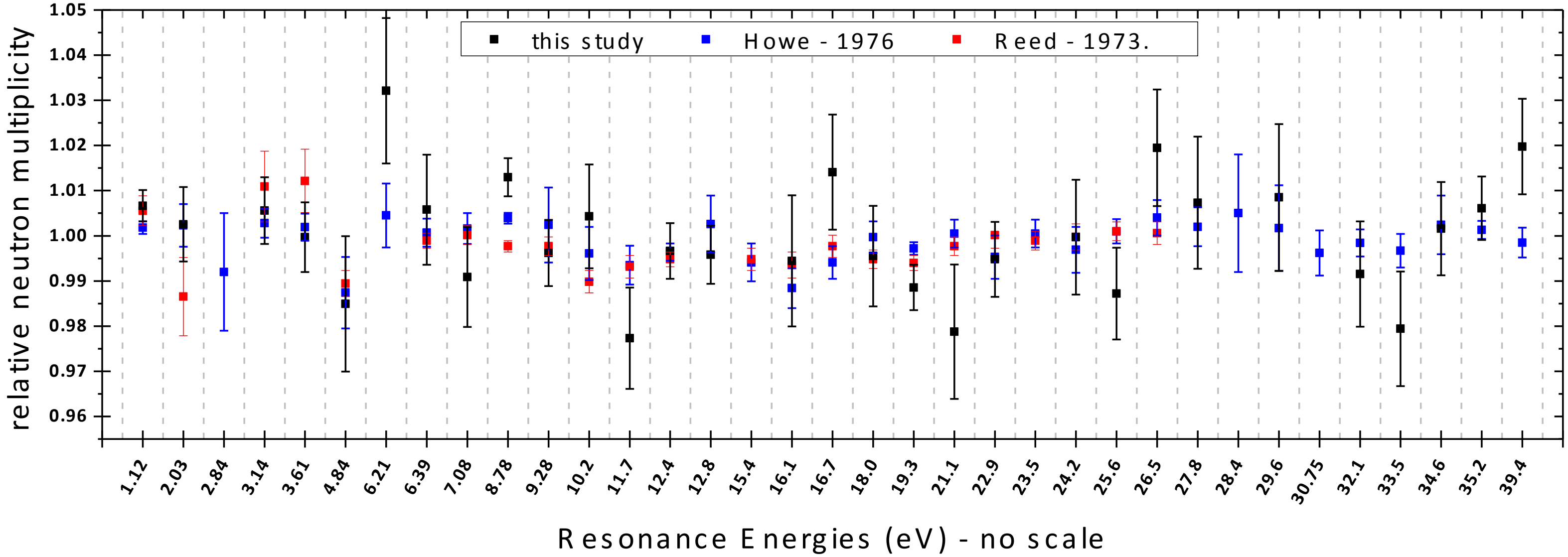
Comparison with available de-excitation models

- Major discrepancy between theory and experiment resolved
- No additional sources of neutrons necessary





Neutron multiplicity in the resonances

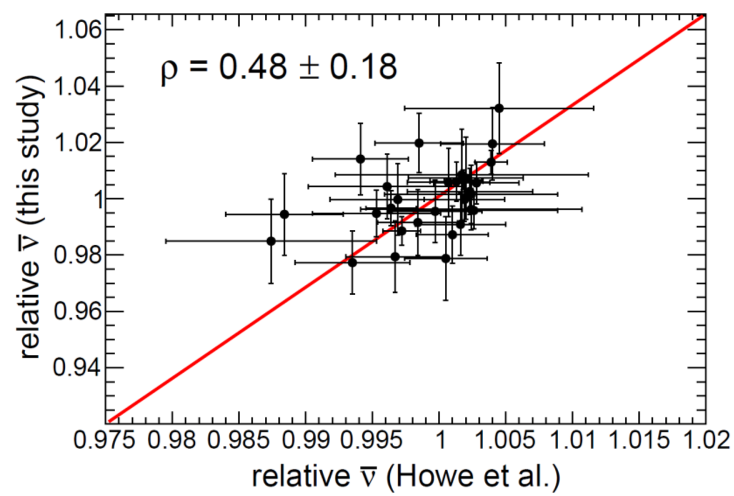


Fluctuating $\overline{\nu}(E_n)$ in the resonances

- Constant $\overline{\nu}(E_n)$: $\chi^2/\mathrm{ndf} = 47.4/30$
- Fluctuating $\overline{\nu}(E_n)$ supported by positive linear correlation with literature data

Howe : $\rho = 0.48 \pm 0.18$

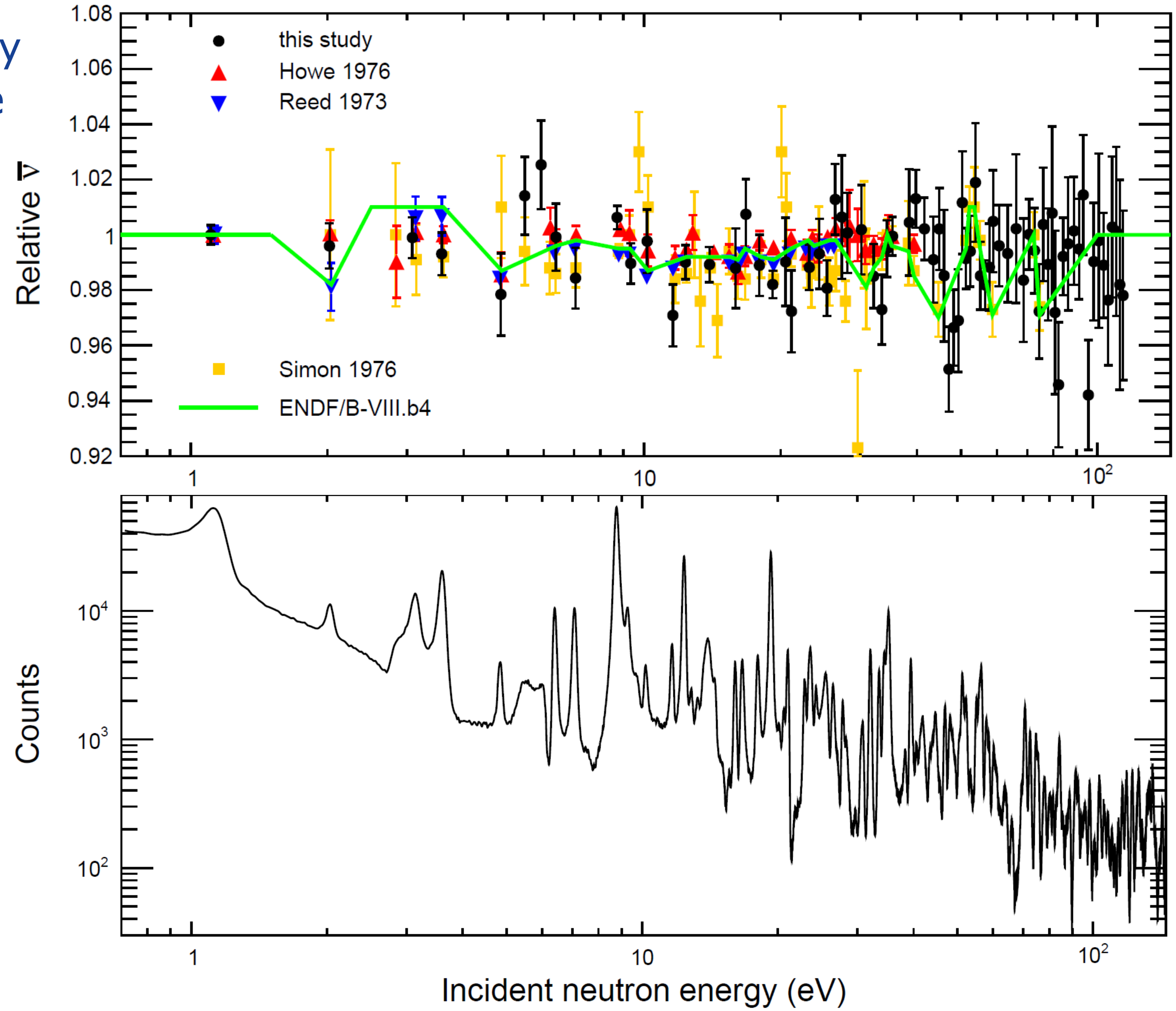
Reed : $\rho = 0.29 \pm 0.22$



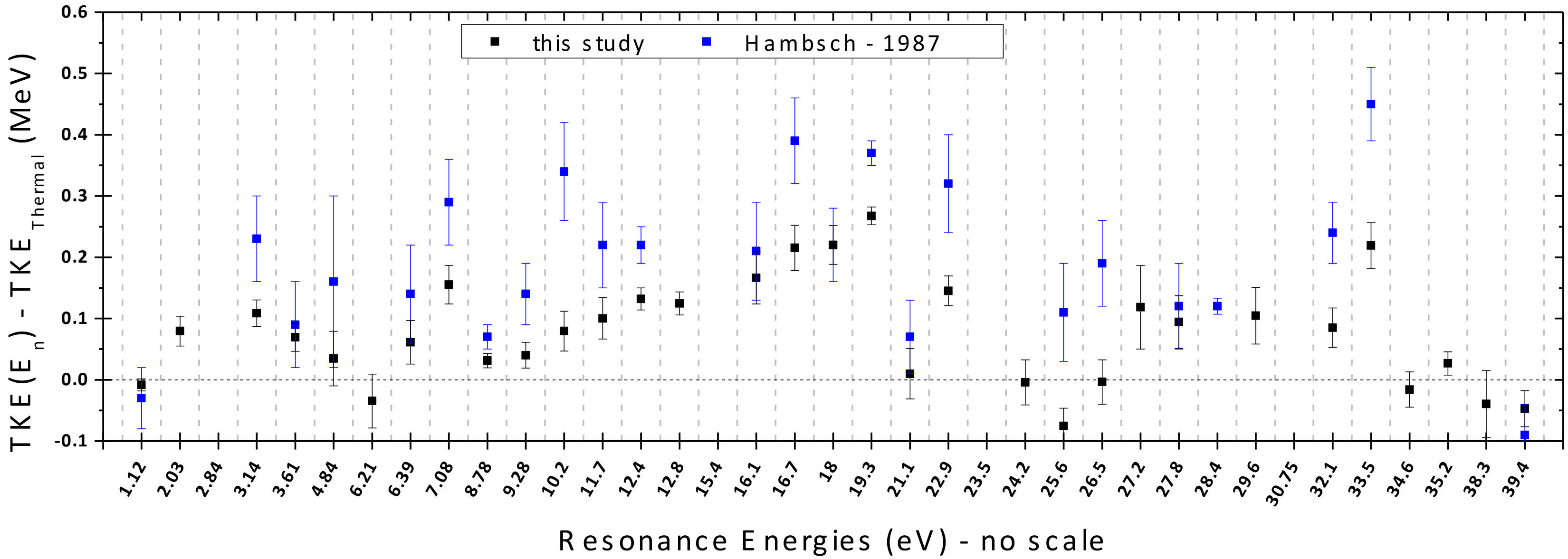
Neutron multiplicity in the resonances

Fluctuating $\overline{\nu}(E_n)$ was recently introduced in ENDF β-release (E_n<100 eV)

- ❑ E_n<~25 eV : Reed data
  - – Present study in better agreement with the data of Howe
- ❑ E_n>~25 eV : Simon Data
  - – Present data confirms the trend
  - – Considerable structure above 25 eV but only a few experimentally resolved resonances are taken into account



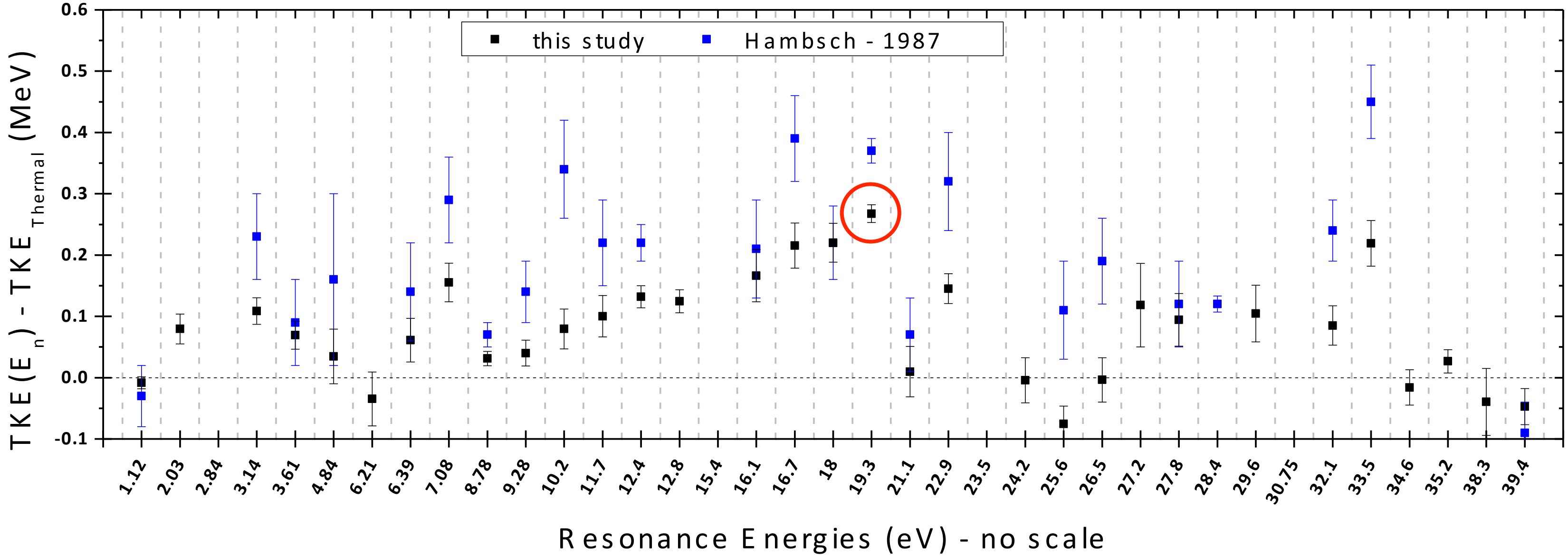
Interpretation of the $\bar{\nu}$ - fluctuations

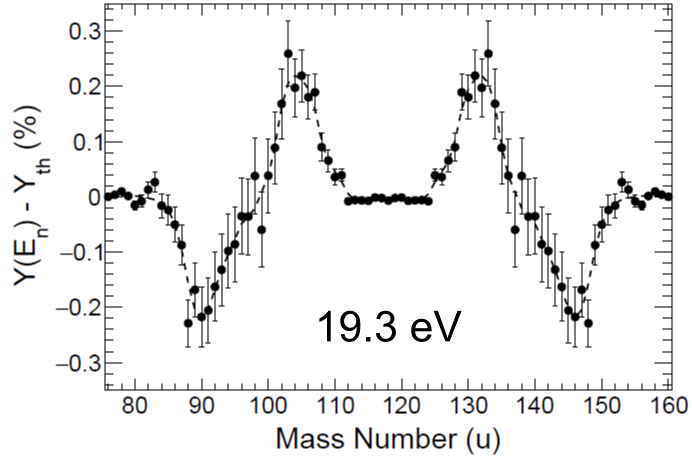


Changing TKE from resonance to resonance

- TKE in the resonances on average larger than for thermal neutron induced fission
- TKE can change by ~250 keV for a difference in incident neutron energy of ~2 eV
- Energy balance $\Rightarrow$ TKE vs $\bar{\nu}$: anti-correlation?

Interpretation of the $\bar{\nu}$ - fluctuations





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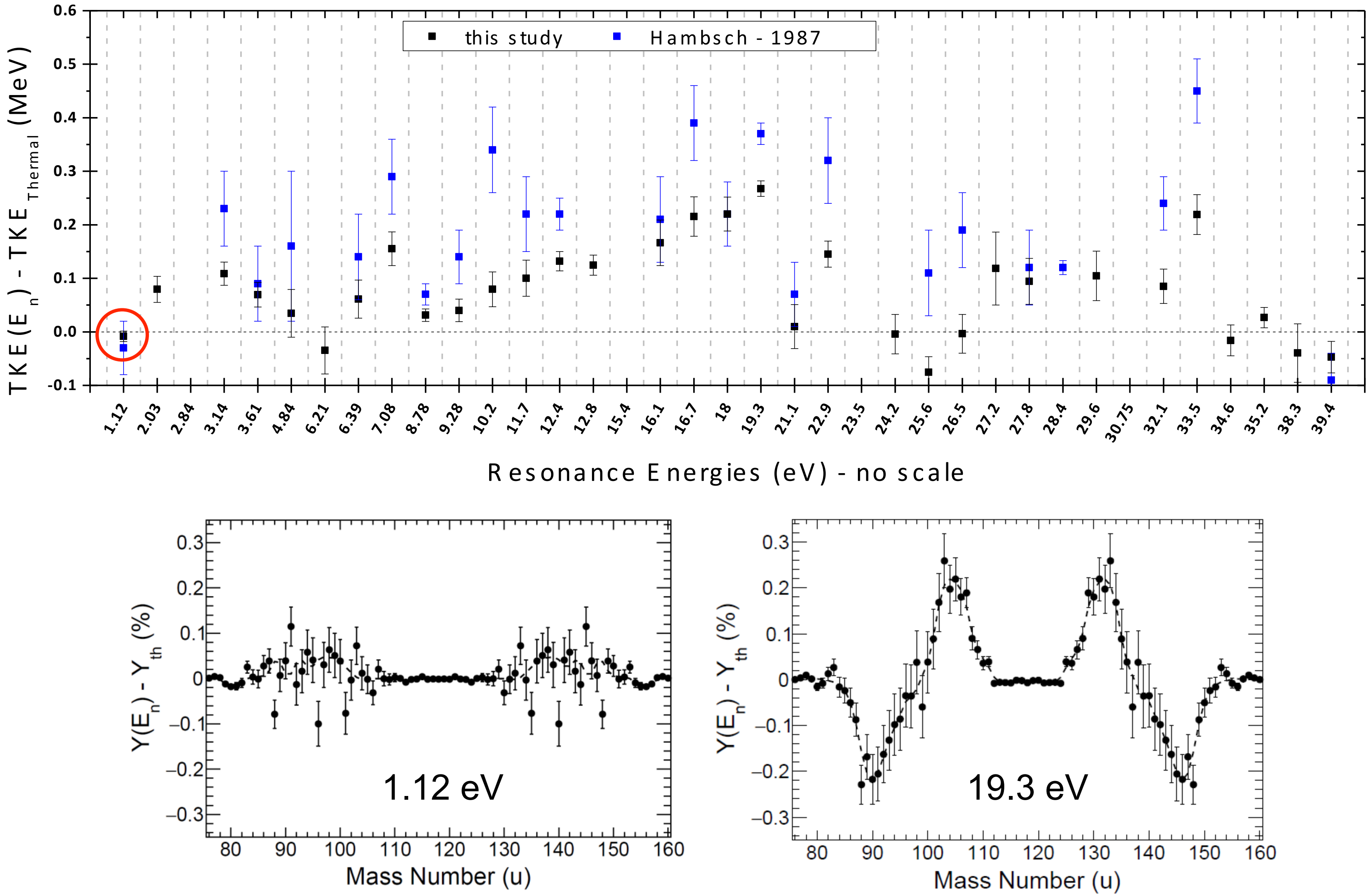
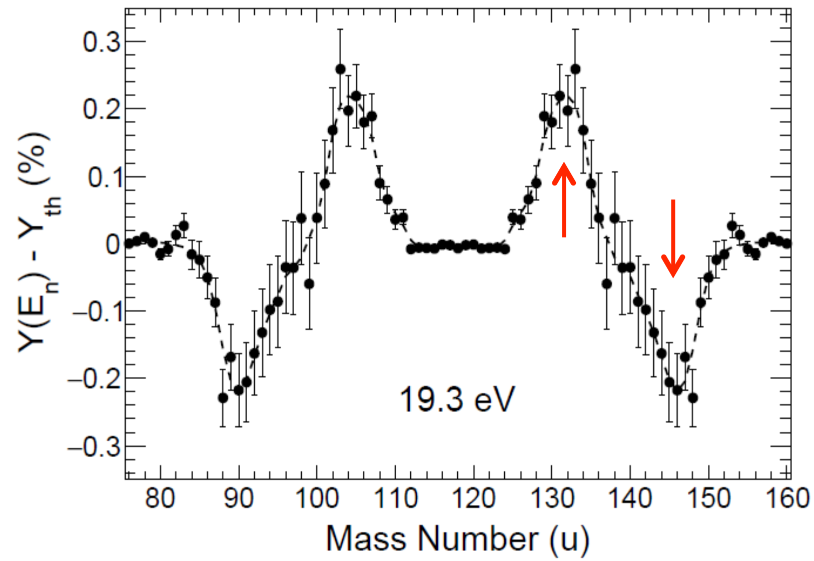
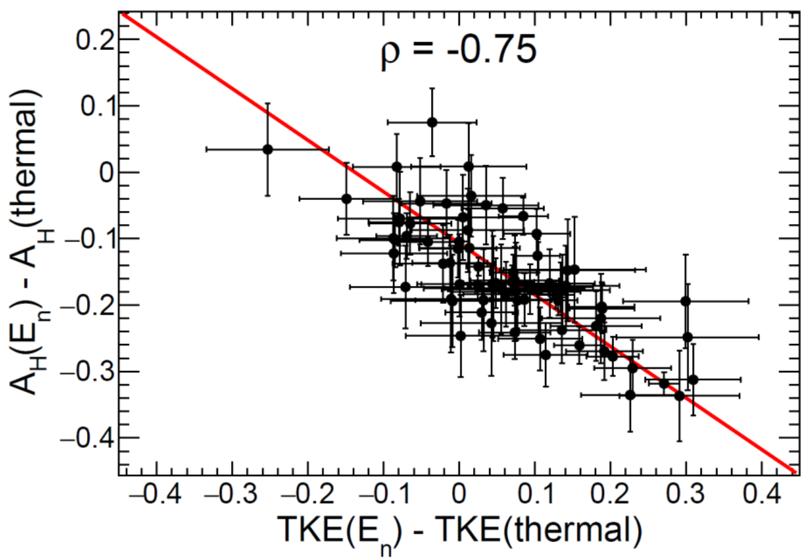
Interpretation of the $\overline{\nu}$ - fluctuations

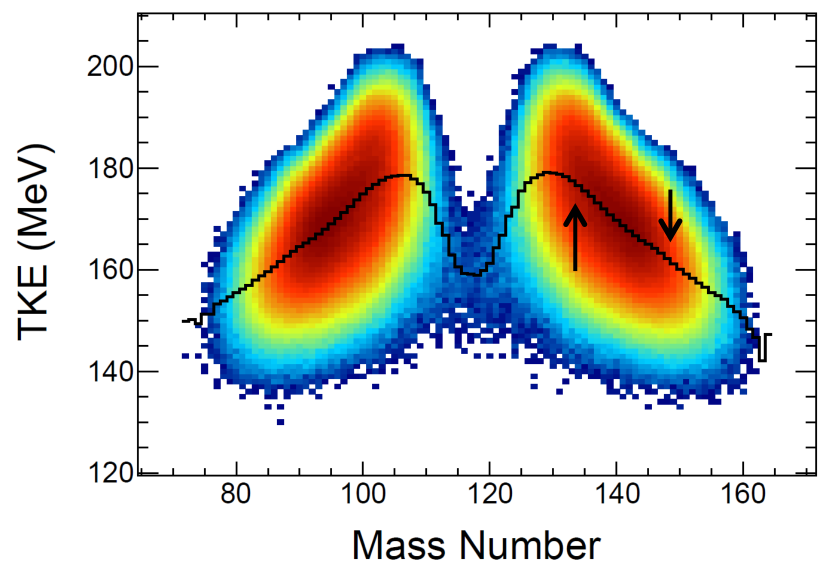


Fragment properties

Changes in TKE are caused by changes in the mass yield



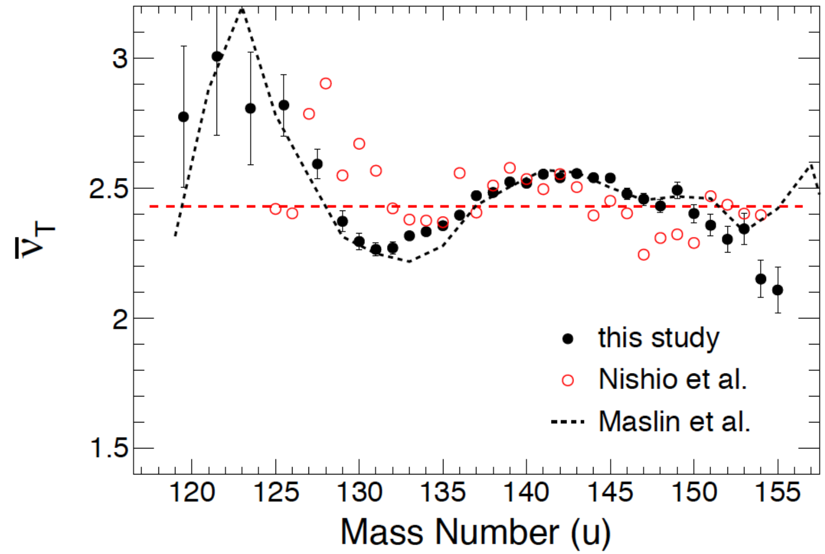


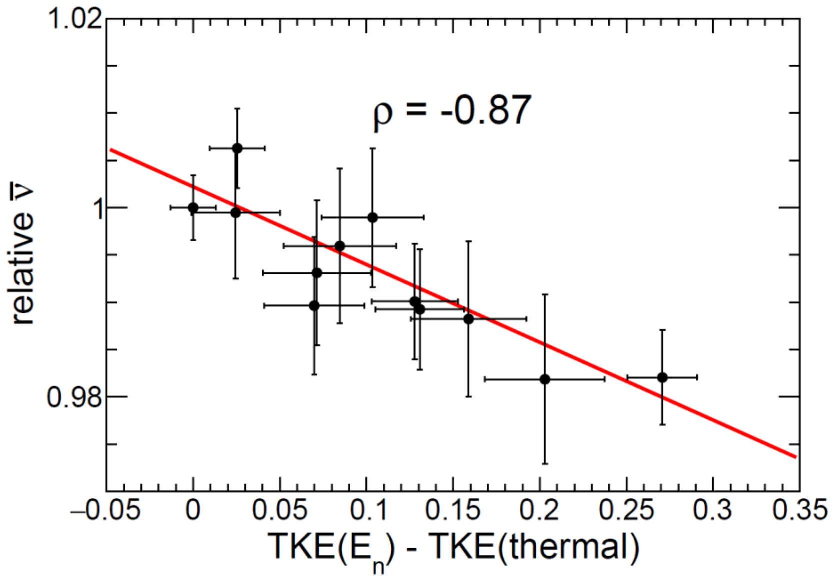


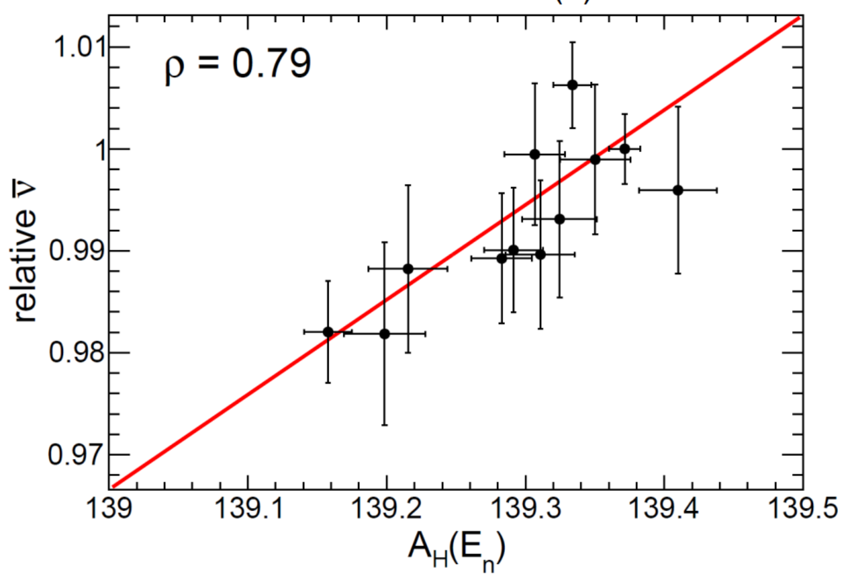
Fragment properties and neutrons

Correlation between the changes in Y(A) and $\bar{\nu}$

- Established for resonances with $\delta\bar{\nu} / \bar{\nu} < 1\%$
- Explains $\bar{\nu}$ - fluctuations







Summary and Conclusions

Correlations between properties of **fission fragment and prompt neutrons** has been studied **in ^{235}U(n,f) induced by resonance neutrons at GELINA.**

The TKE dependence of the number of neutrons emitted per fission shows an inverse slope **dTKE/dν ~35% smaller** than observed in studies of thermal neutron induced fission. The **difference can be explained by improved fission fragment TKE resolution** in the present experiment.

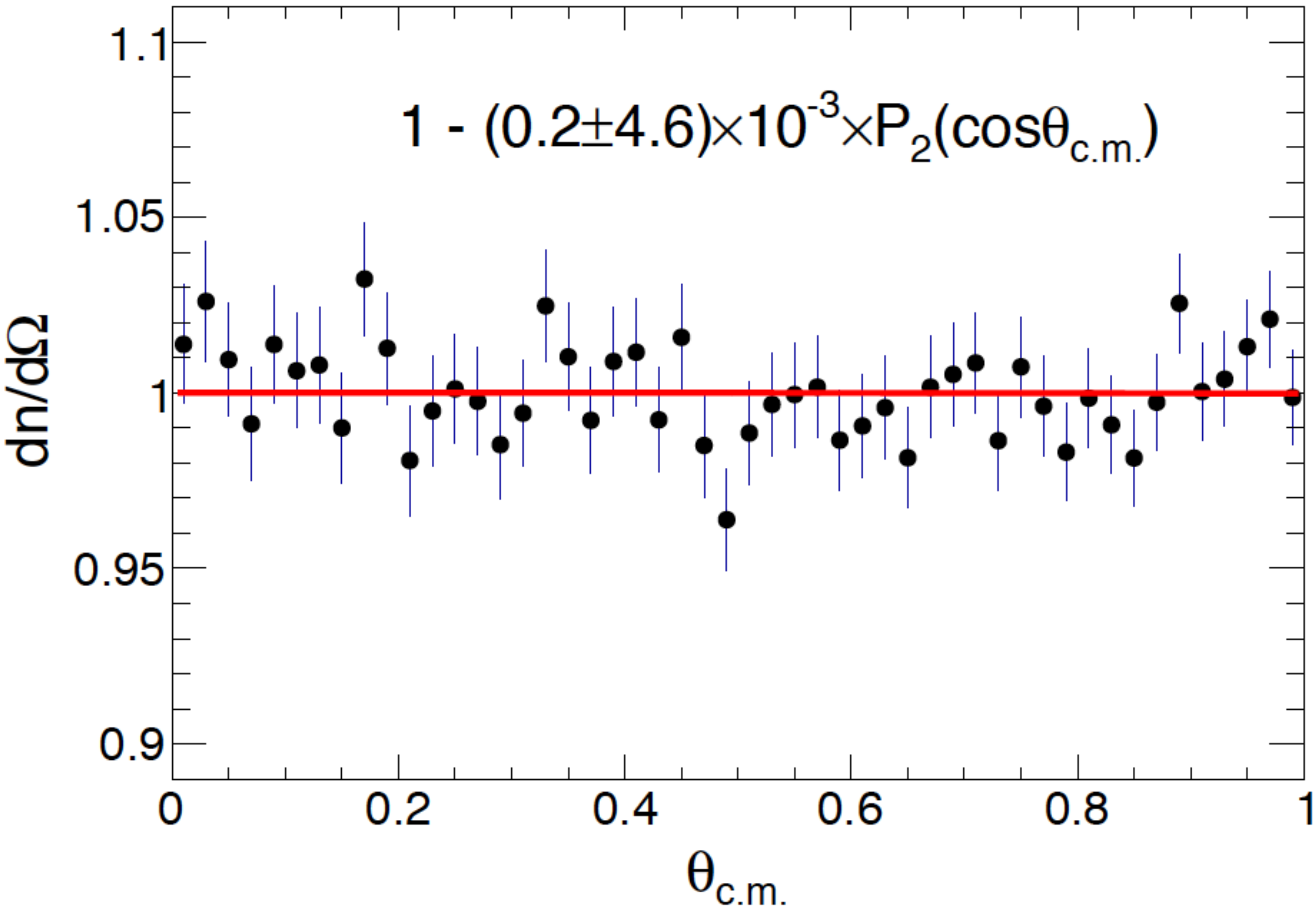
Correlated fluctuations in the fission fragment **mass distribution and TKE as a function of resonance neutron-energy** is confirmed, with **increased accuracy**.

Structures in $\bar{\nu}$ as a function of resonance neutron-energy is **confirmed** as well.

Due to increased statistical accuracy in the fission fragment data, a **clear correlation between the changes in $\bar{\nu}$ and the changes in fission fragment mass distributions could be established**.

Thank you for the attention!

Angular Distribution in c.m. - frame

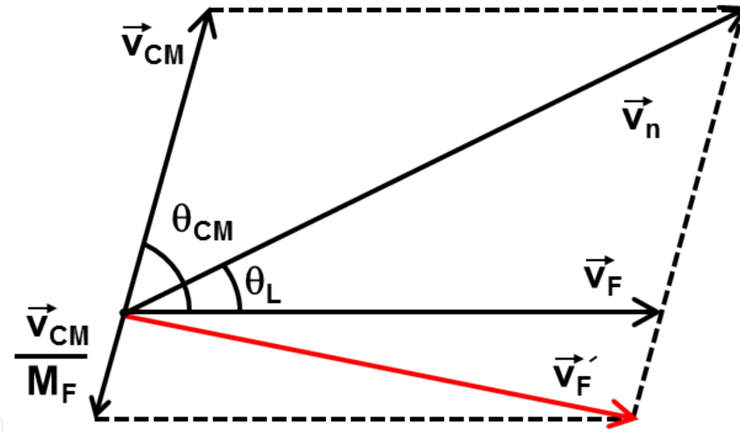


Neutron Recoil to fragment

Momentum transfer

➔ fragment energy change

$$E_{\rm post} = E_{\rm pre}\frac{m_{\rm post}}{m_{\rm pre}} - \frac{p_{\rm n}\,p_{\rm pre}}{m_{\rm pre}}\cos\theta_{c.m.}$$



Isotropic emission

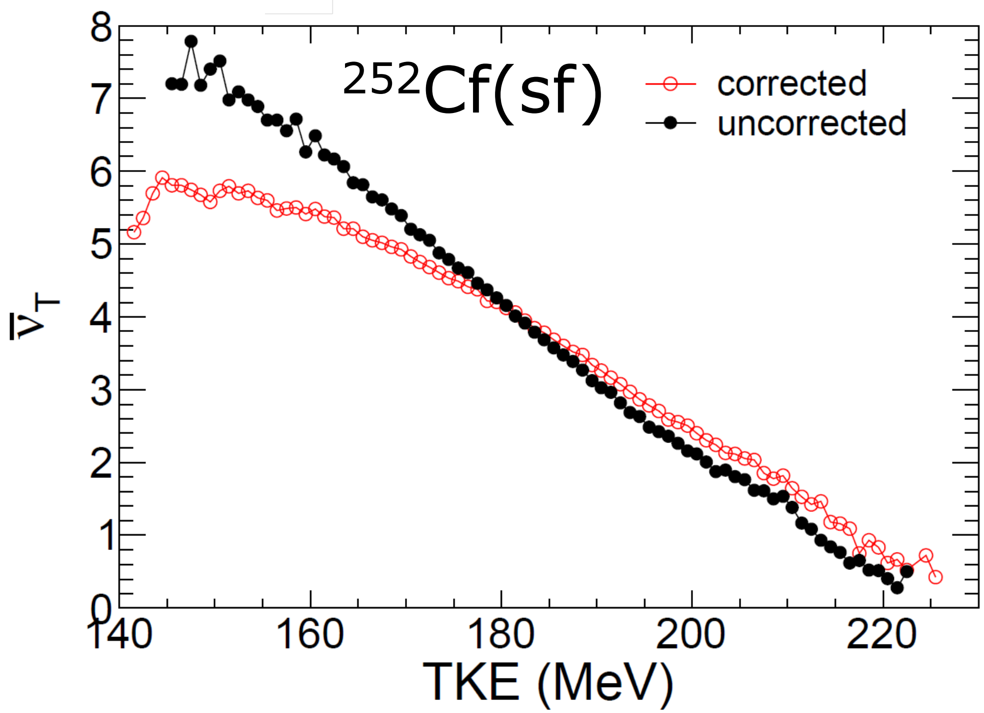
➔ 2nd term averages out

$$\langle\cos\theta_{c.m.}\rangle = 0$$

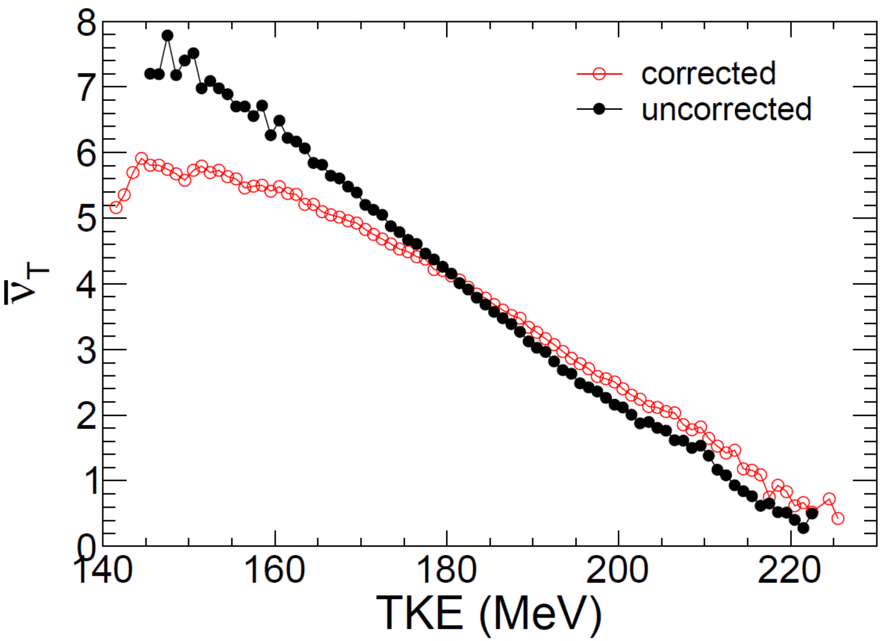
Fragment neutron coincidence

➔ biased selection

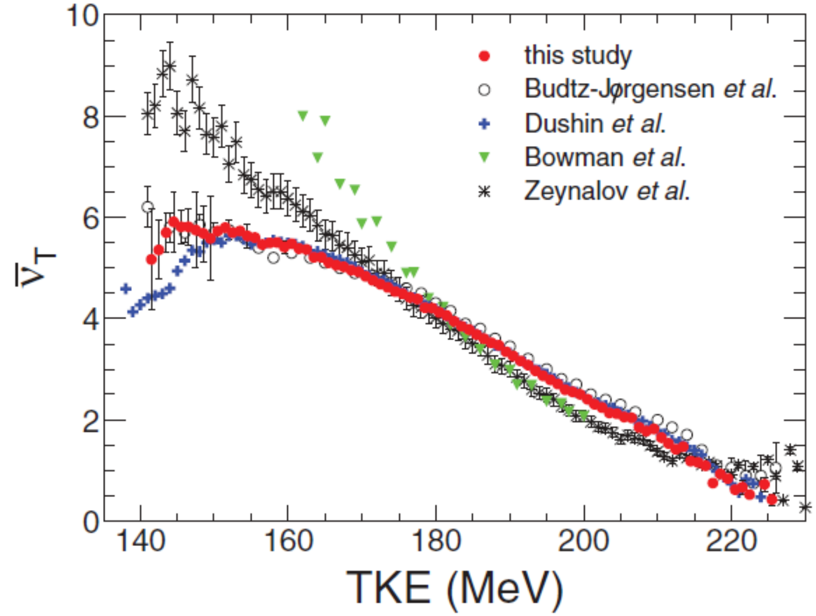
$$\langle\cos\theta_{c.m.}\rangle \neq 0$$



Effect of neutron recoil correction ^{252}Cf(sf)



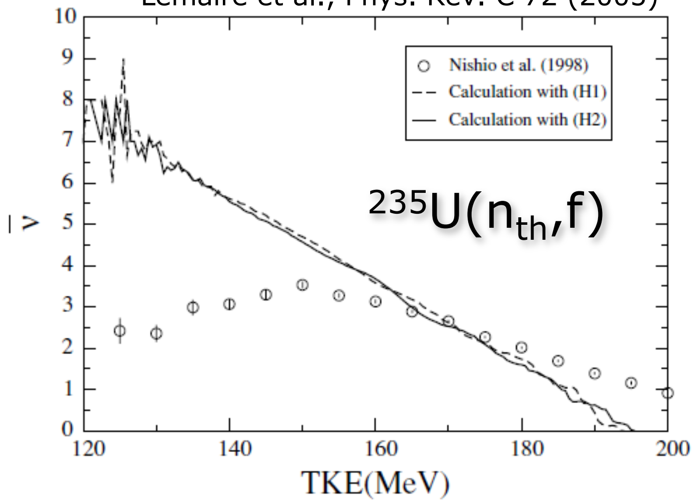
PHYSICAL REVIEW C **90**, 064611 (2014)



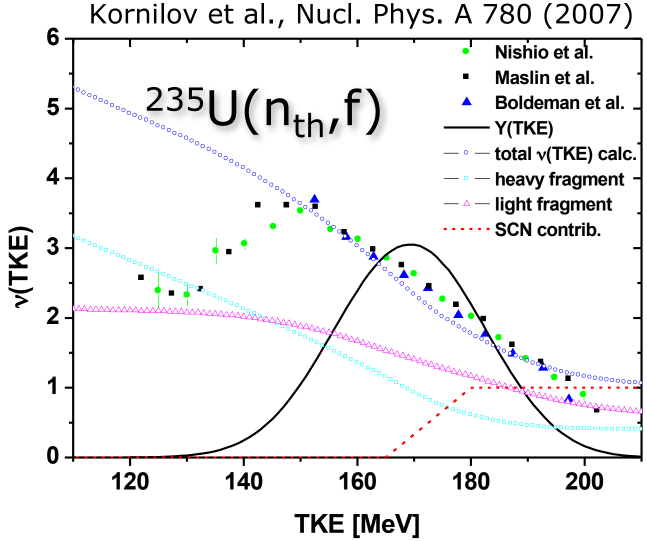
- Results show consistency with literature data
- Specifically with methods that do not suffer from neutron recoil bias
  - (Dushin et al.) Gd-loaded 4π scintillator tank

PFN multiplicity correlations with fragment observables

Lemaire et al., Phys. Rev. C 72 (2005)



Kornilov et al., Nucl. Phys. A 780 (2007)



Fission fragment de-excitation models

- ❑ Evaluation tools
- ❑ Detailed modelling (CGMF, Fifrelin, Freya…)
  - – successfully reproducing correlations
  - – in the case $^{235}U(n,f)$
    - » difficulties: in particular $\bar{\nu}$(TKE)

Lemaire et al. (2005)

*"…a **dramatic deviation** between calculation and experiment on ν is observed **at low TKE** that would indicate the presence of **additional opened channels**"*

Kornilov et al. (2007)

*"The **incorporation of** the **SCN emission** leads to a much **better agreement** between theoretical and experimental data for ν(TKE) in the high energy range. However, the assumption of **SCN emission at high TKE should be confirmed with direct experimental data**"*

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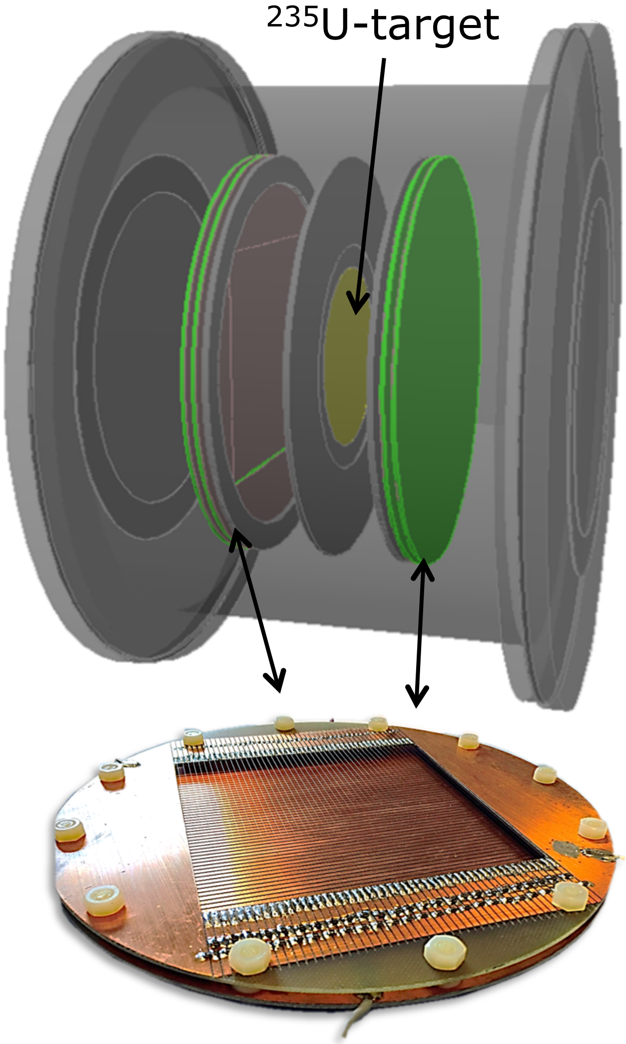
Fission fragment detector

Twin Ionization Chamber

- ✓ Energies and Masses of fission fragments
- ✓ Large Geometrical Efficiency
- ✓ Timing resolution ~1 ns (FWHM)
- ✓ Polar angle θ of fission axis relative to the chamber axis

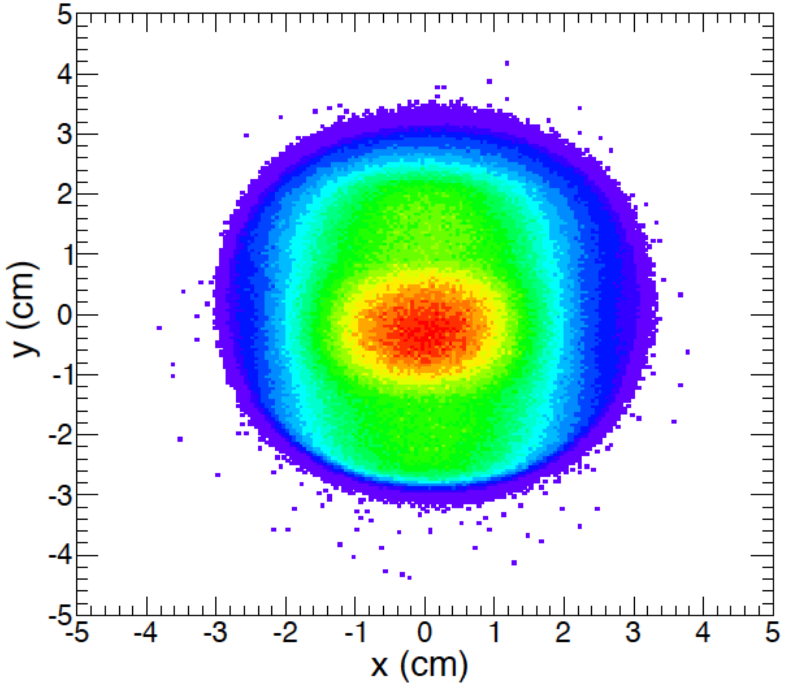


Position Sensitive Electrodes

- ➢ Replaces anodes
  - ➢ wire plane + strip anode

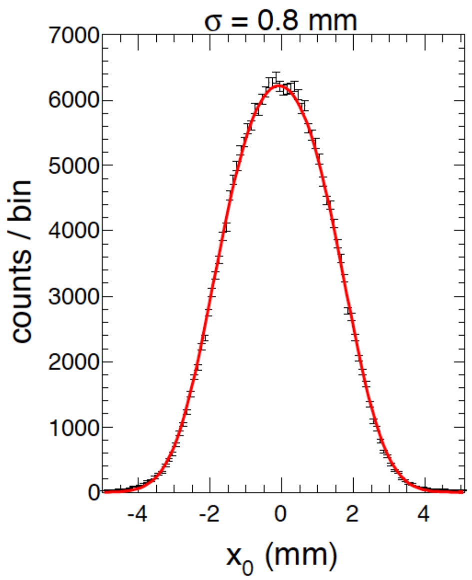
  Projection of fission-axis on the electrode – plane
- ✓ Fission axis orientation in 3D

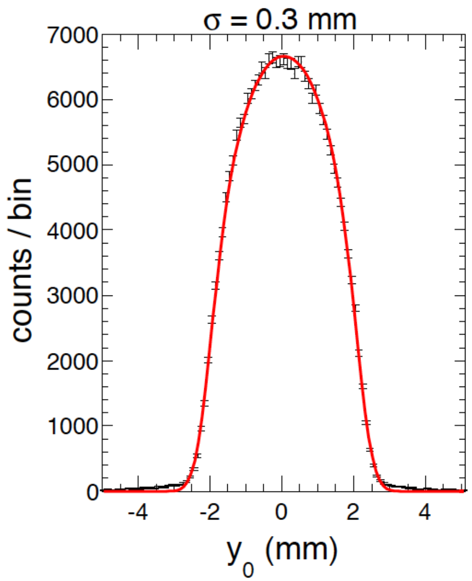
Position sensitive ionization chamber



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

Distribution of fission events on the target plane. Determined by linear interpolation between the coordinates of fission fragments detected on opposite side of the ionization chamber.





^{252}Cf – source

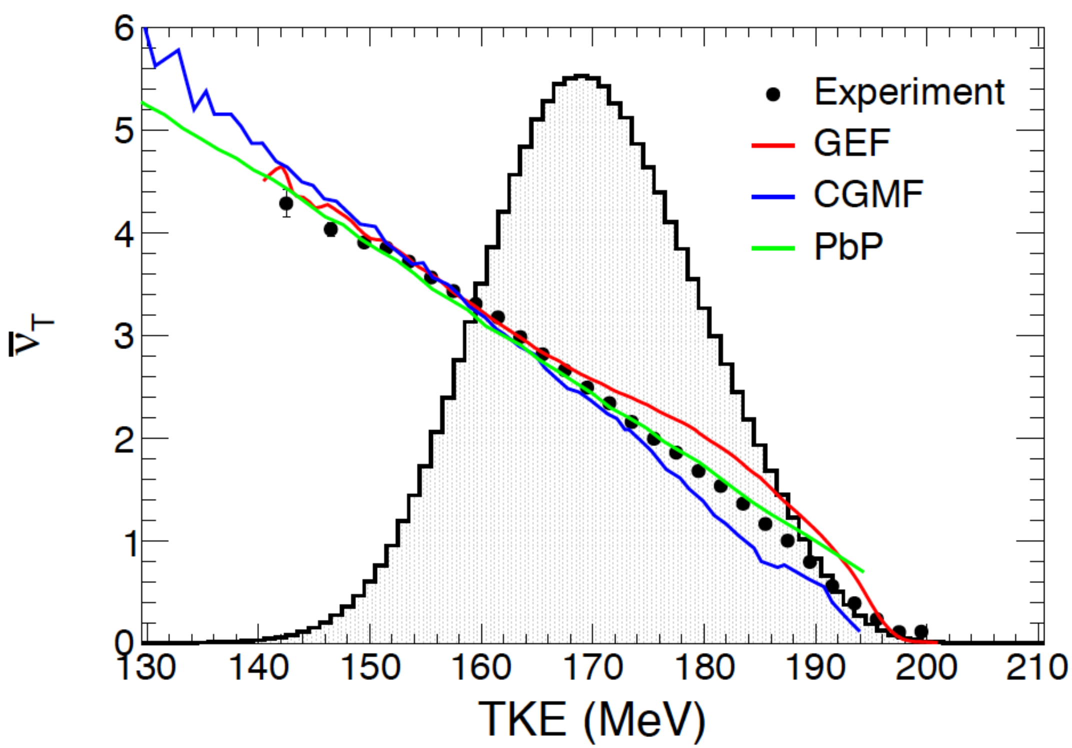
- Circular spot
- 5 mm diameter

Multiplicity vs. Fragment TKE

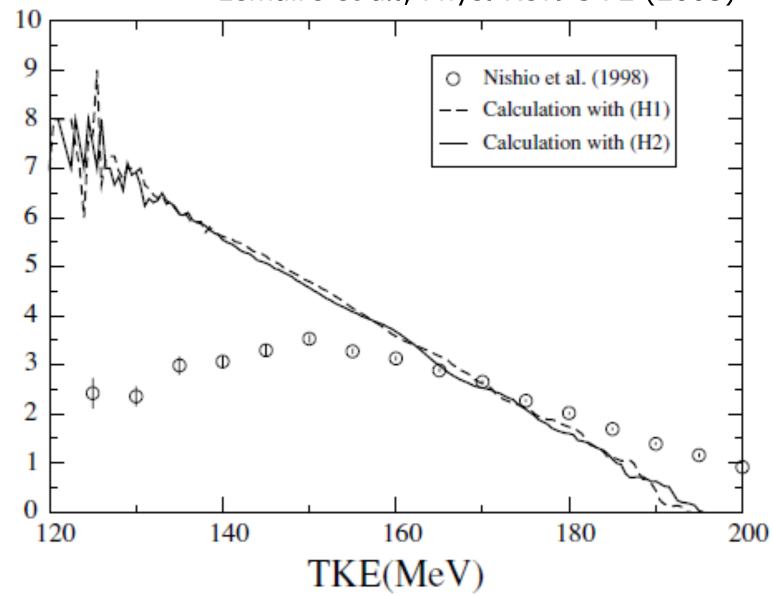
Comparison with available de-excitation models

- Major discrepancy between theory[*] and experiment resolved
- No additional sources of neutrons necessary

[*] Nucl. Data Sheets 131 (2016)



Lemaire et al., Phys. Rev. C 72 (2005)



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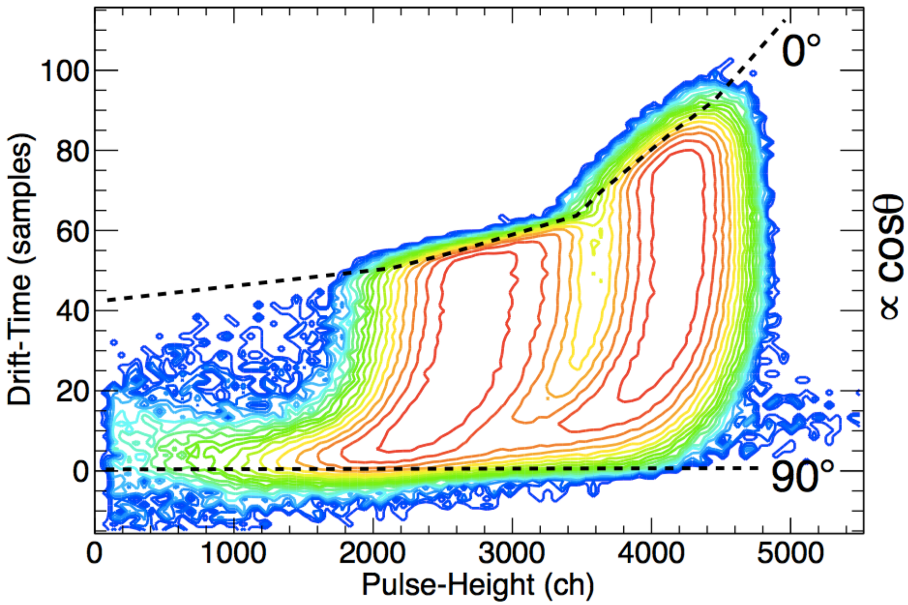
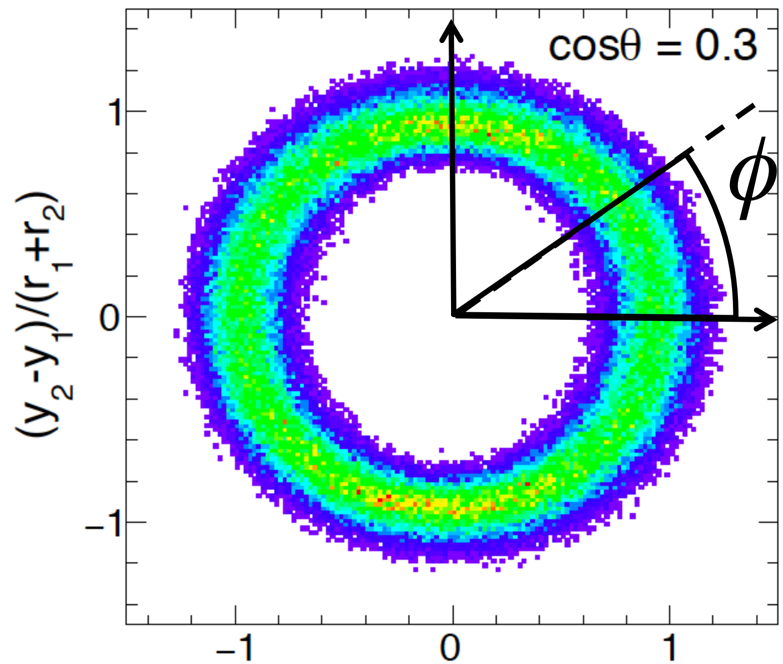
Determining the Fission Axis Orientation

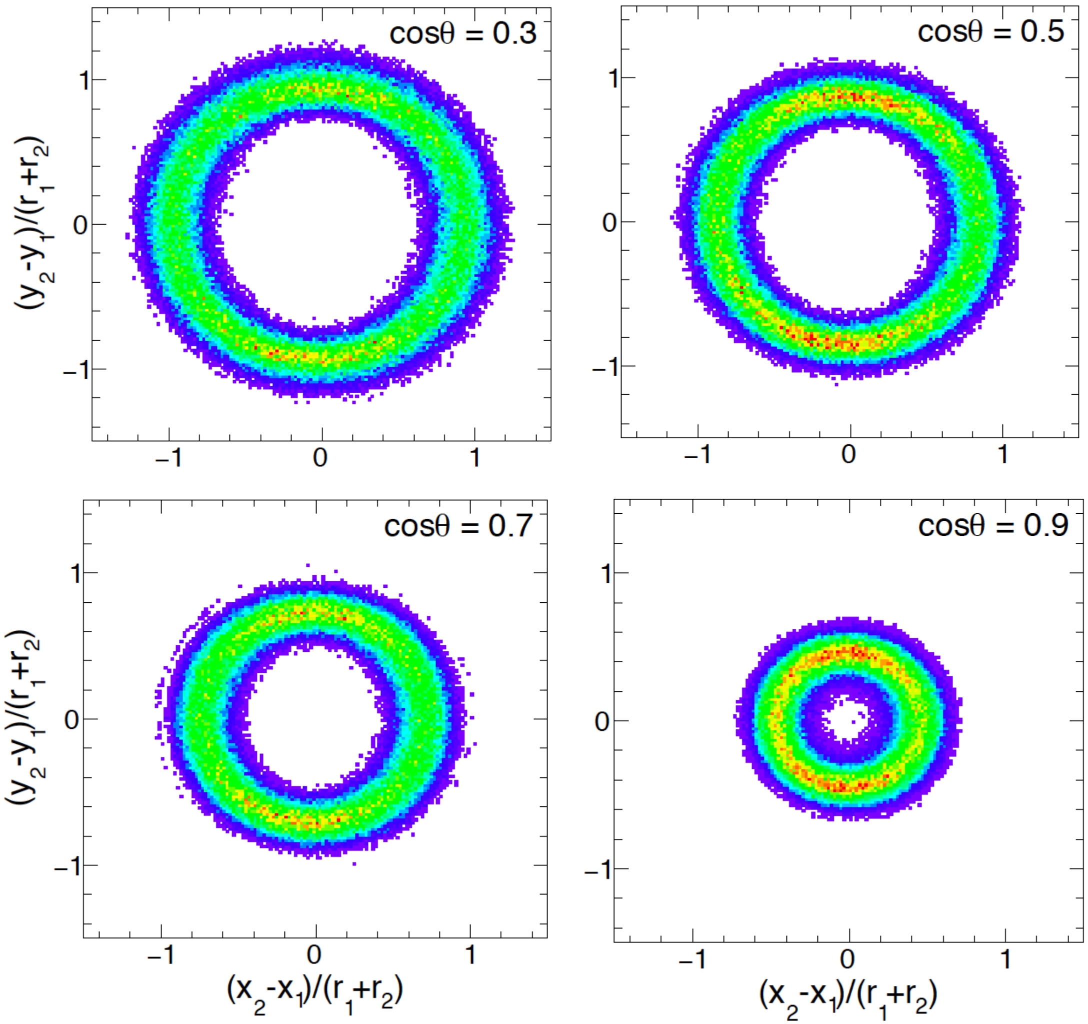
The polar Angle θ
from drift time of free electrons in the gas.



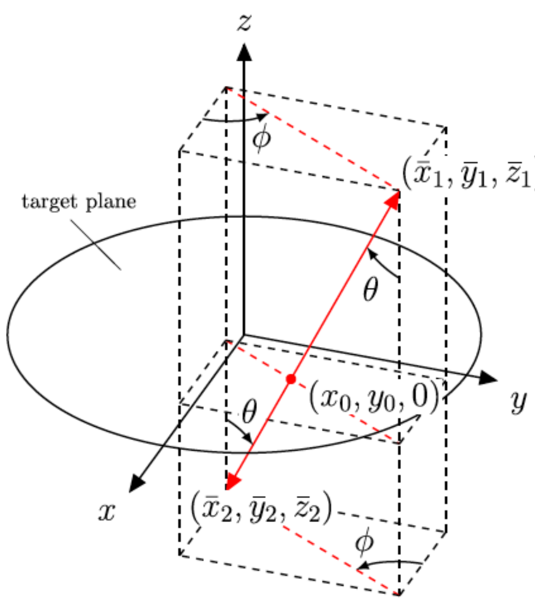
Azimuthal angle ϕ
from difference in x-coordinates and y-coordinates for the fission fragments detected on the opposite chamber sides.



Position sensitive ionization chamber



Difference in x-coordinates and y-coordinates of the bragg-peak for the fission fragments detected on the opposite chamber sides.



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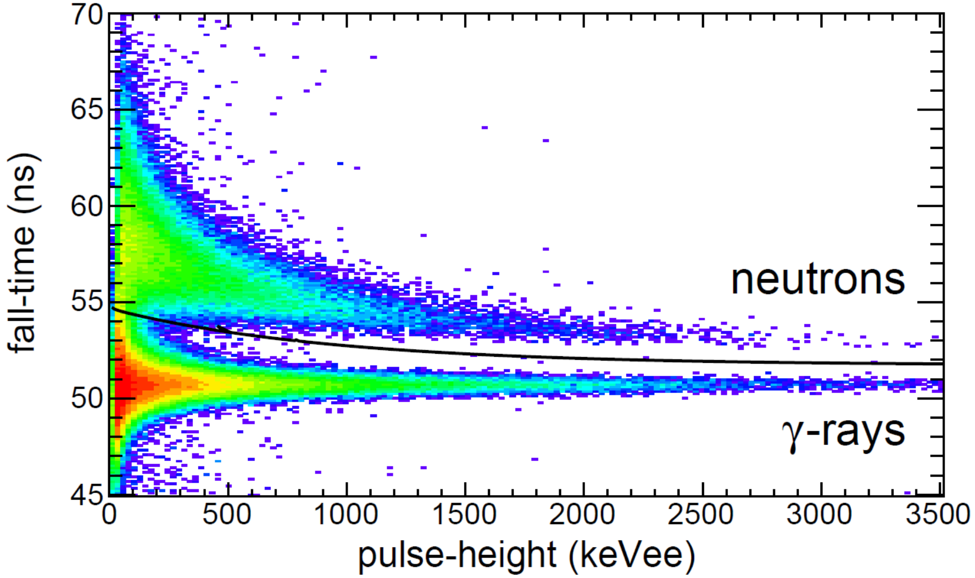
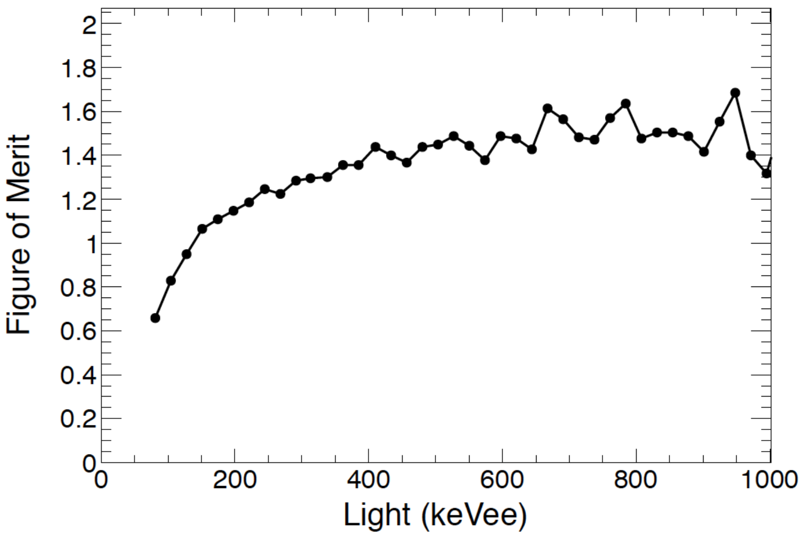
Selection of prompt neutrons

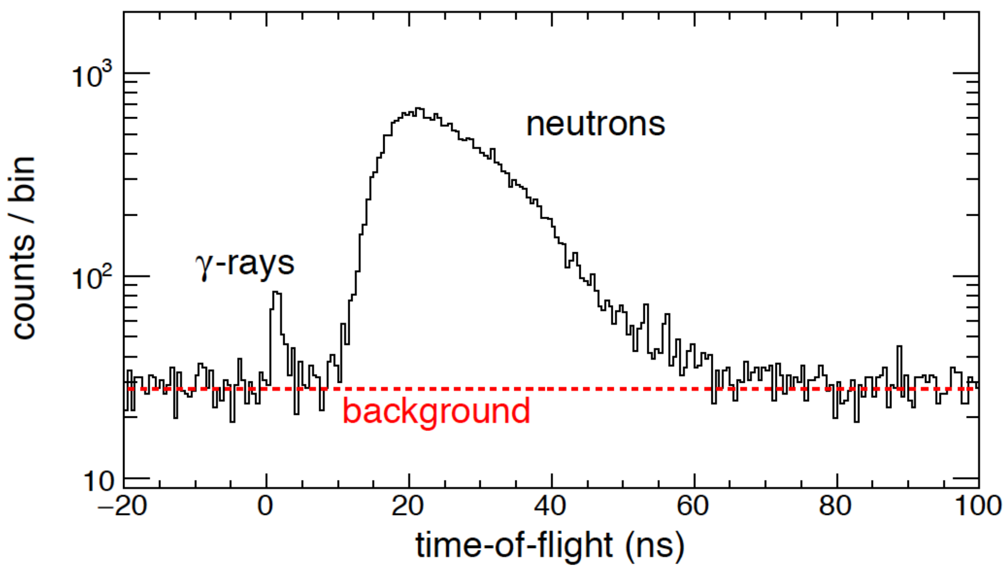


Pulse-shape discrimination is used to separate prompt fission neutrons and γ-rays

Residual γ-rays supressed with pulse-height threshold

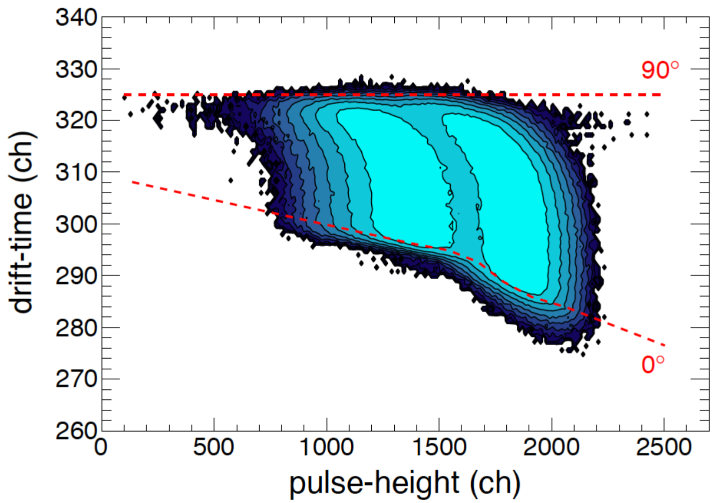
Background rate determined from events to the left of the prompt γ-ray-peak

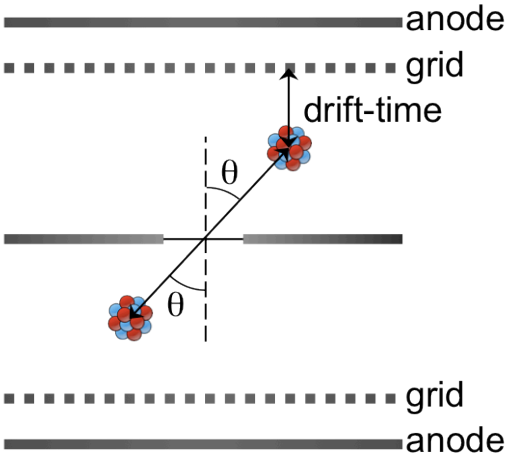


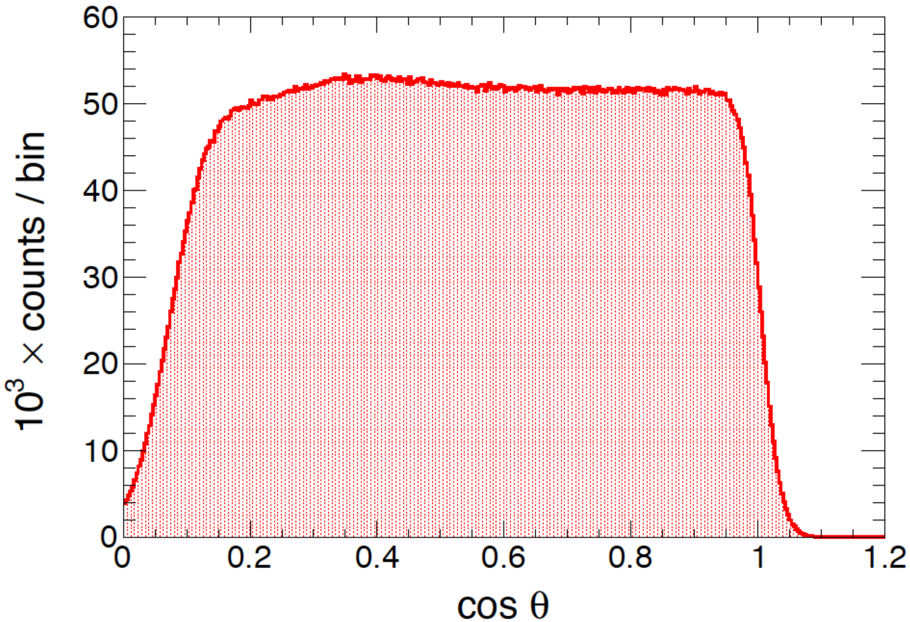


Determining the Fission Axis Orientation

Orientation of fission axis relative to chamber symmetry axis is determined from drift time of ionization electrons



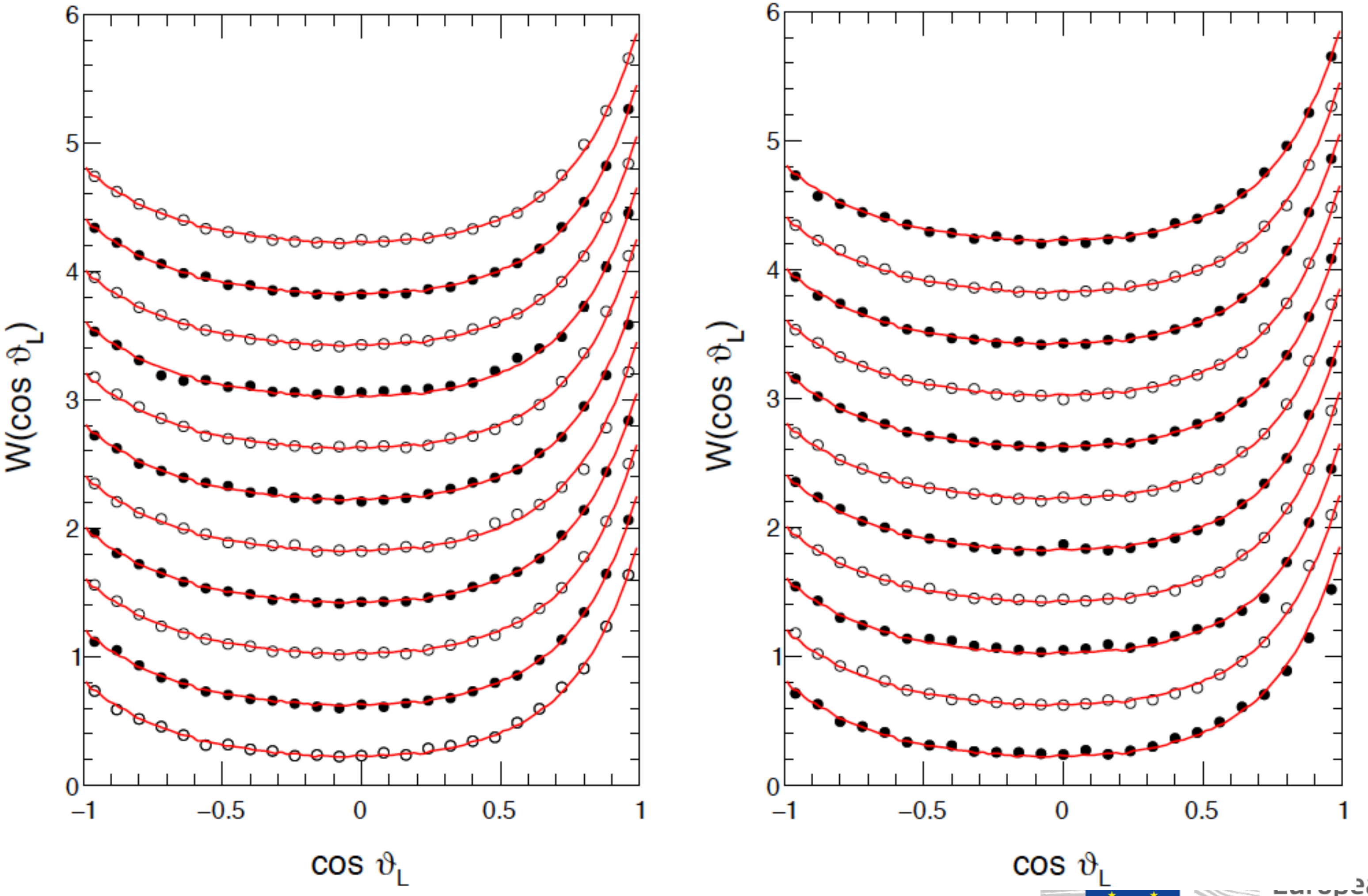




Neutron Angular Distributions

-relative to the light fragment direction

- Consistent results from the 22 individual detectors

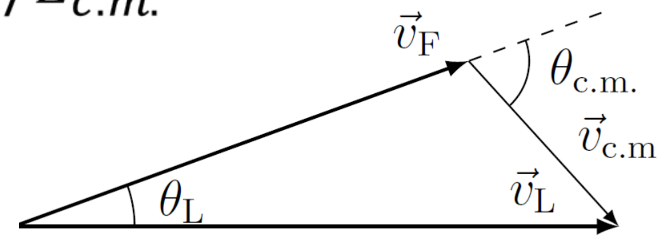


Analysis of PFN angular distributions

Assuming emission from accelerated fragments

$$n_L(E_L,\theta_L) = n_{c.m.}(E_{c.m.})\emptyset(\theta_{c.m.})\sqrt{E_L/E_{c.m.}}$$

$$E_{c.m.} = E_L + \frac{E_F}{A_F} - 2\sqrt{\frac{E_L E_F}{A_F}}\cos\theta_L$$



Simplified model

- **single fragmentation**

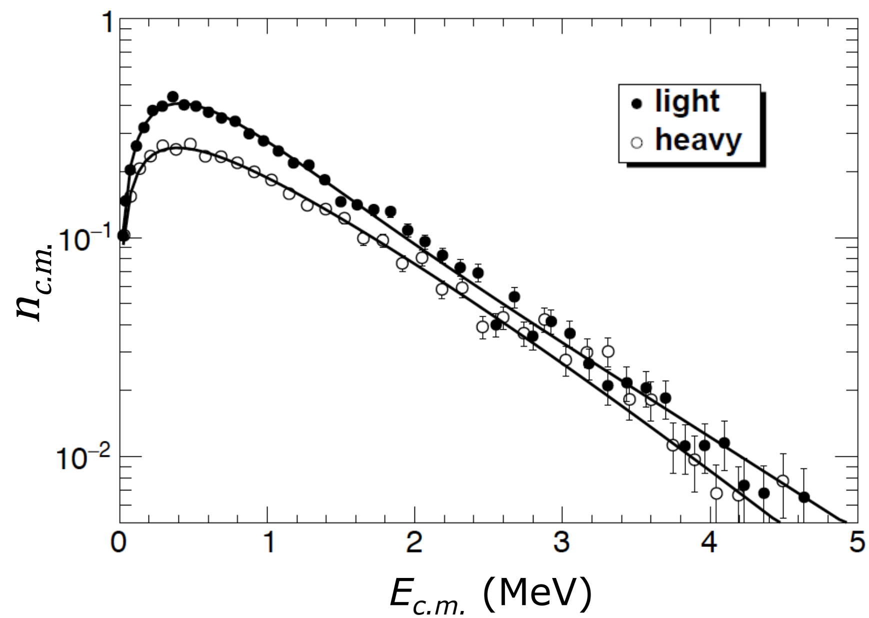
  $\left(E_F/A_F\right)_{\text{light}} = (1.02 \pm 0.01)$ MeV/u

  $\left(E_F/A_F\right)_{\text{heavy}} = (0.491 \pm 0.005)$ MeV/u

- **Isotropic emission in c.m.**

  $\emptyset(\theta_{c.m.}) = 1$

- **PFNS in c.m. determined from small angle data**



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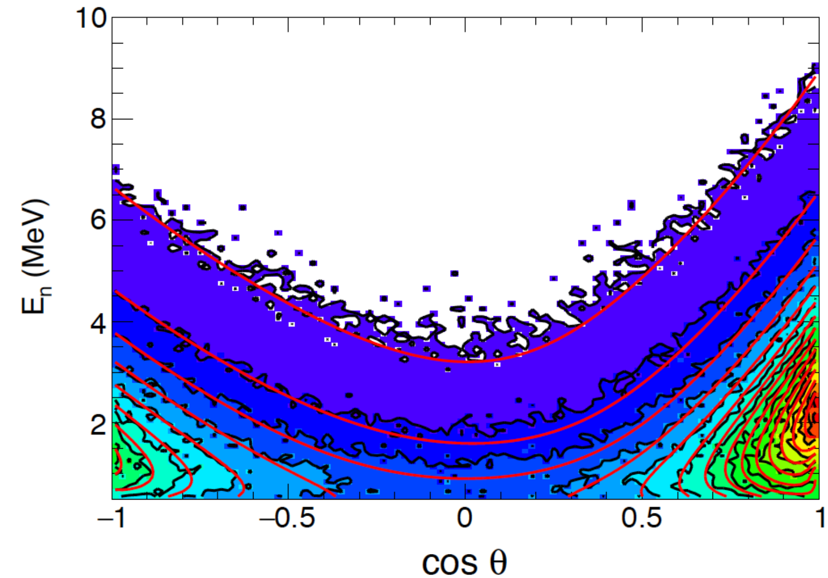
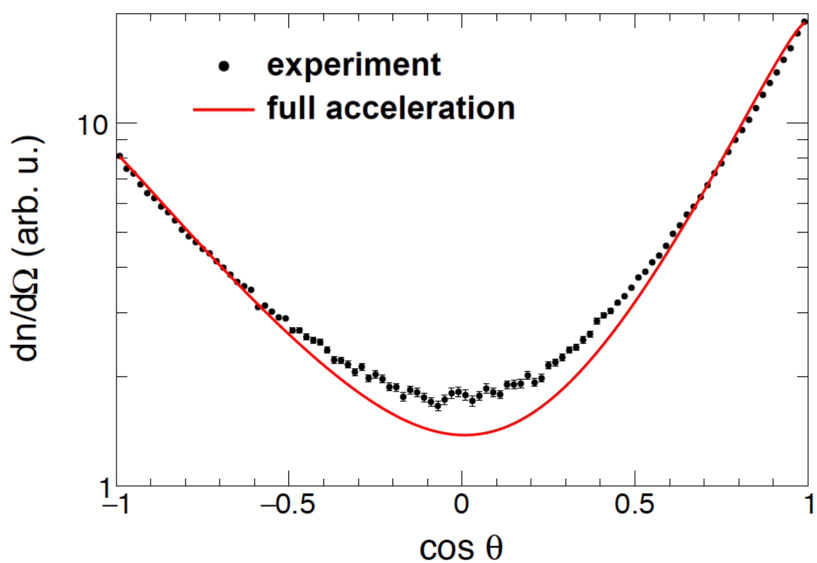
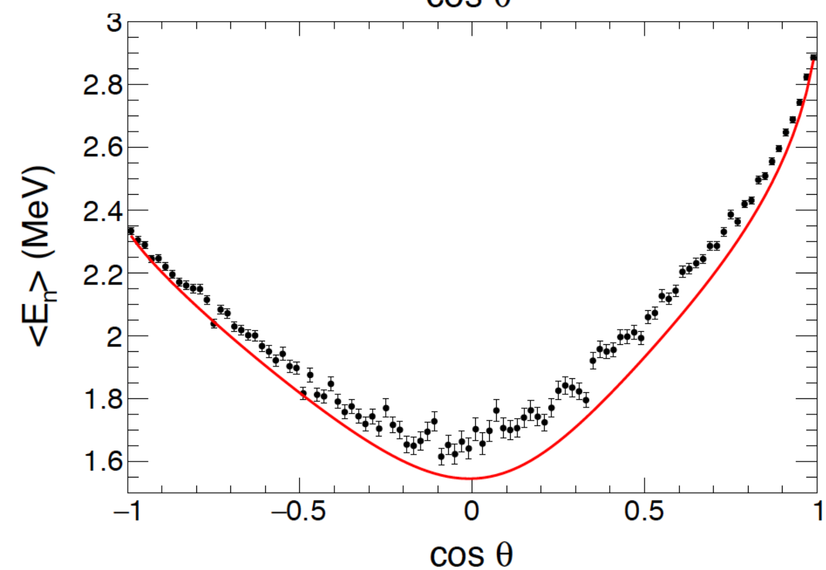
Analysis of PFN angular distributions

- Generally good description
  - Underestimation of yield at large angles
    - 2.5% of the total number of neutrons
  - Underestimation of $\langle E_n \rangle$ at large angles
  - Indicates presence of anisotropy or scission neutrons?

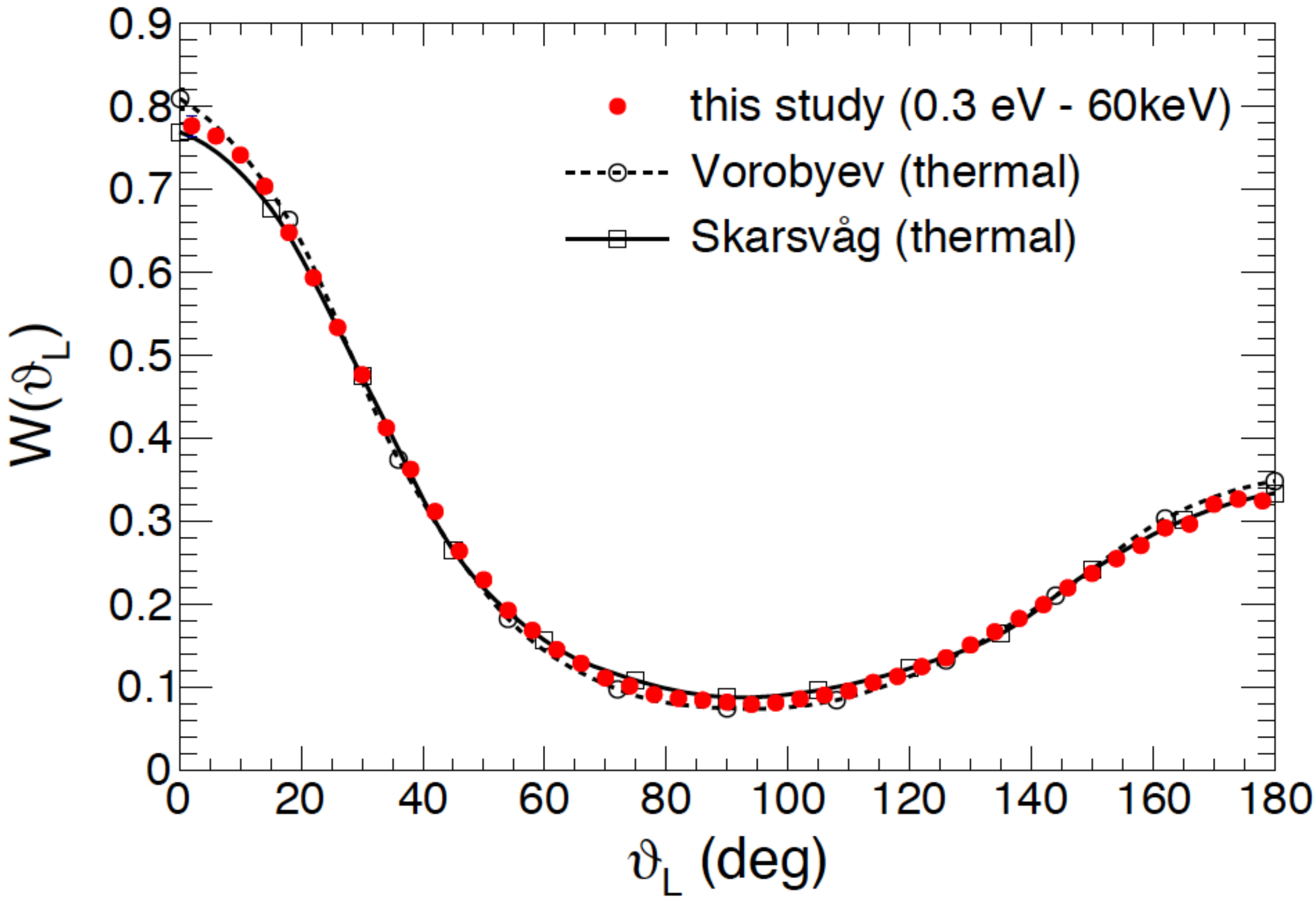






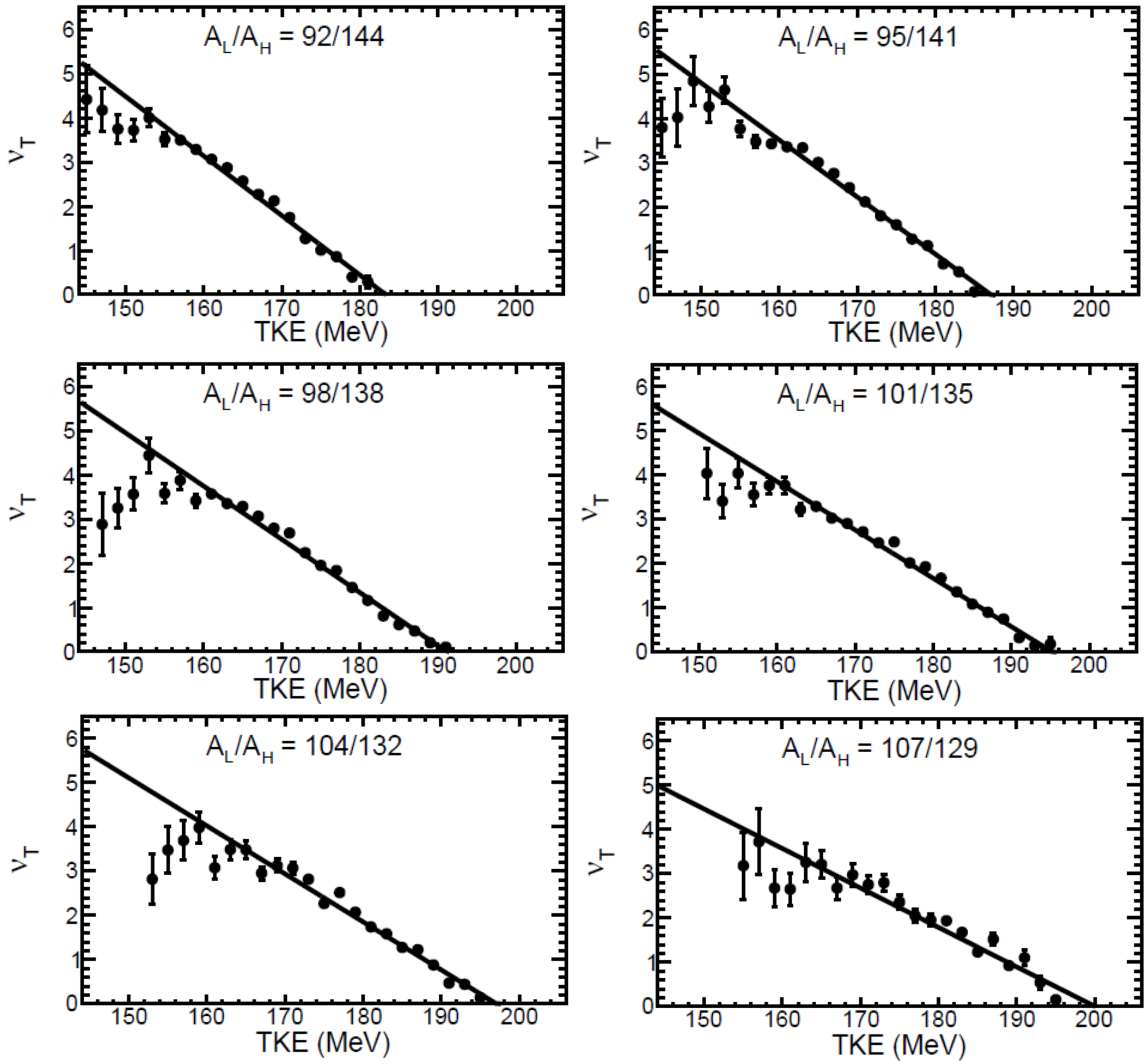
PFN angular distributions

Integral angular distribution of PFN relative to the fission axis



Multiplicity vs. Fragment TKE

For selected fragment pairs



Slope gives directly the change in TXE per emitted neutron

$$\mathrm{TXE} = \mathrm{Q}_0 - \mathrm{TKE}$$

$$\frac{\mathrm{dTXE}}{\mathrm{d}\,\overline{\nu}_T} = -\frac{\mathrm{dTKE}}{\mathrm{d}\,\overline{\nu}_T}$$

Outline

- Motivation & Introduction
- Experimental Details
- Experimental Results
    - PFNs correlation with fragment properties
    - PFNs multiplicity in the resonances
- Summary and conclusions