FissionTPC Cross Section Ratio Results and Their Impact

^{239}Pu(n,f)/^{235}U(n,f)

CSWEG

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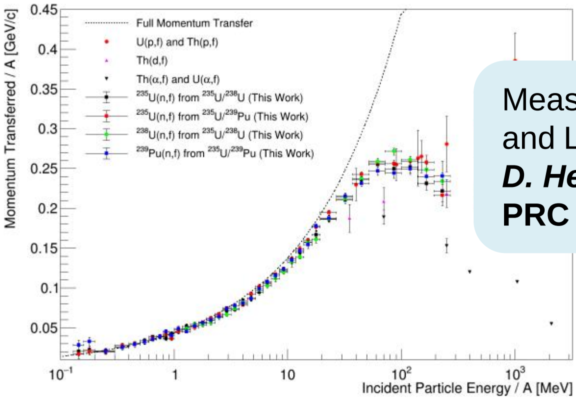
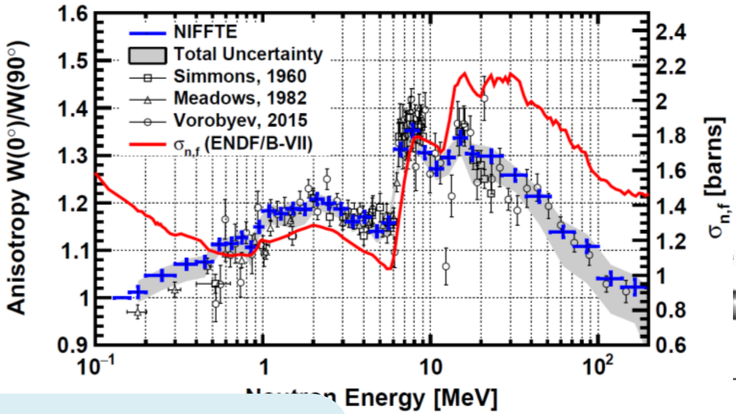
Publications

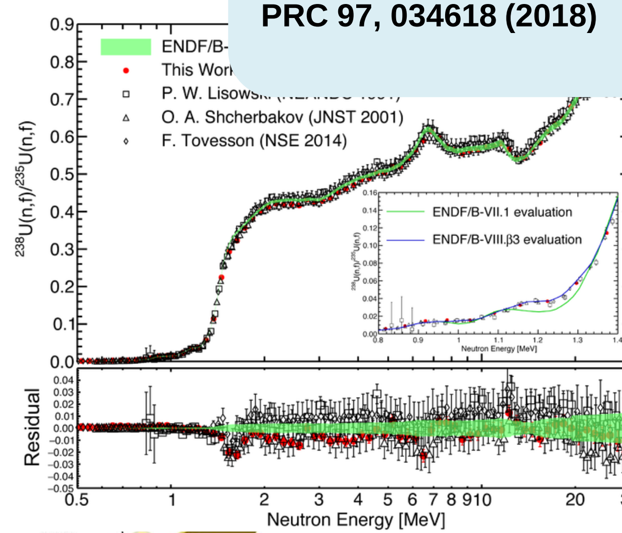


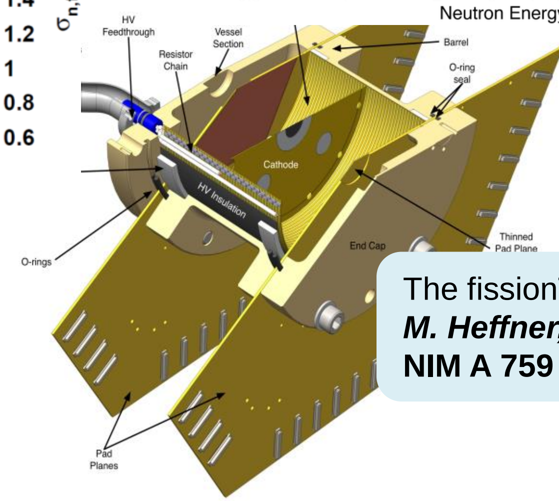
Measurement of ^{235}U Anisotropy and Linear Momentum Transfer.
D. Hensle, et al.
PRC 102, 014605 (2020)



Fission Fragment Angular Anisotropy in Neutron-Induced Fission of ^{235}U …
V. Geppert-Kleinrath, et al.
PRC 99, 064619 (2019)

Measurements of the normalized ^{238}U(n,f)/^{235}U(n,f) cross section ratio form threshold to 30 MeV …
R. Casperson, et al.
PRC 97, 034618 (2018)





The fissionTPC…
M. Heffner, et al.
NIM A 759 (2014) 50-64

Outline

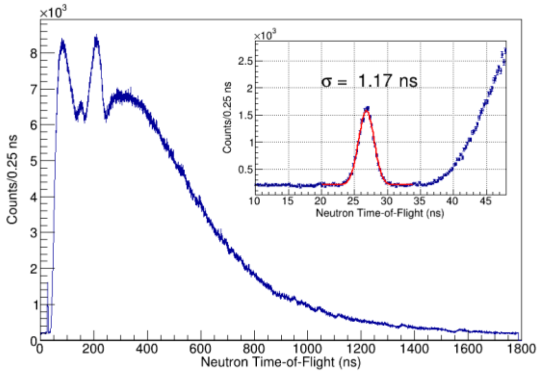
- **Part I: FissionTPC data analysis**
  - **Cross section *shape* analysis & validations presented**
  - **Efficiency and Nonuniformity in target & beam corrections**
  - **Status of absolute normalization discussed**
- **Part II: GMA Data Fit**
  - **We are assessing the impact of the new ratio measurement.**

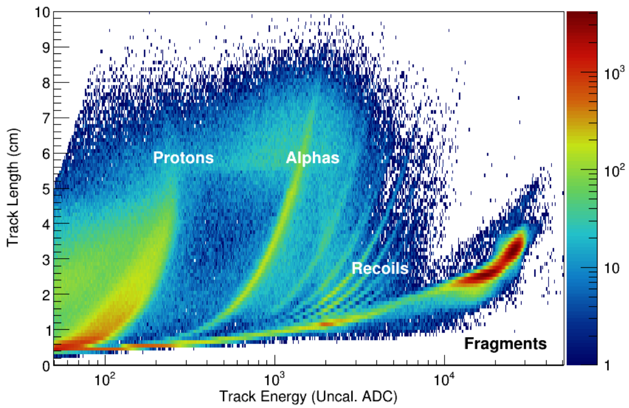
Quantities measured by the fissionTPC

Detector Efficiency | Relative neutron flux | Spatial overlap of beam and target | Backgrounds

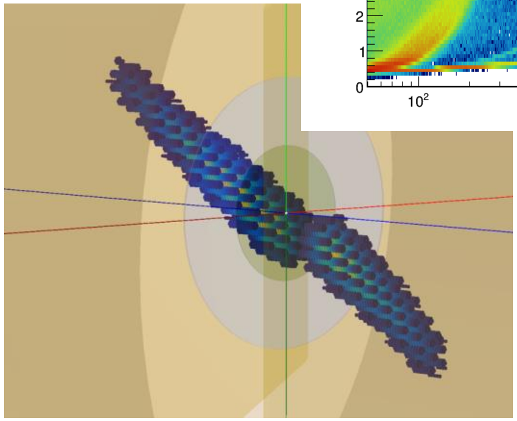
$$\frac{\sigma_x}{\sigma_s} = \frac{(\mathbb{K}^x_{att})^{-1}}{(\mathbb{K}^s_{att})^{-1}} \cdot \left[\frac{(\epsilon^x_{ff})^{-1}}{(\epsilon^s_{ff})^{-1}} \cdot \frac{\omega_x^{-1}}{\omega_s^{-1}} \cdot \frac{\Phi_x^{-1}}{\Phi_s^{-1}} \cdot \frac{N_x^{-1}}{N_s^{-1}} \cdot \frac{(\sum_{XY}(\phi_{x,i}\cdot n_{x,i}))^{-1}}{(\sum_{XY}(\phi_{s,i}\cdot n_{s,i}))^{-1}} \cdot \frac{(C^x_{ff}-C^x_b)}{(C^s_{ff}-C^s_b)}\right]$$

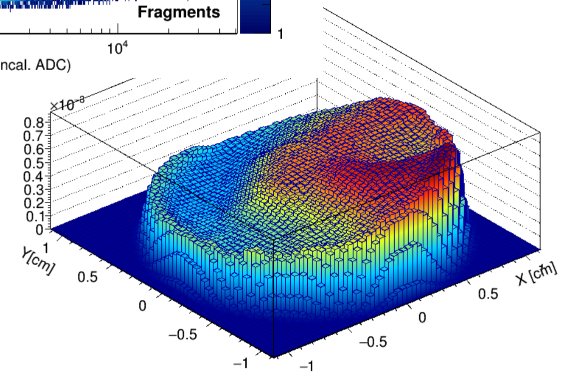
Beam Attenuation | Detector live time | # of target atoms | Measured fission fragments





- Neutron time-of-flight measured
- 3D ionization profile for individual tracks provides:
  - Track length
  - Total energy
  - Track direction
  - Bragg Peak
  - Interaction vertex

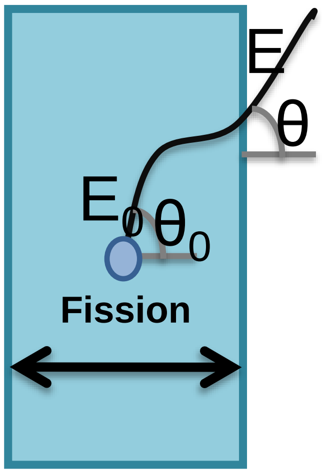


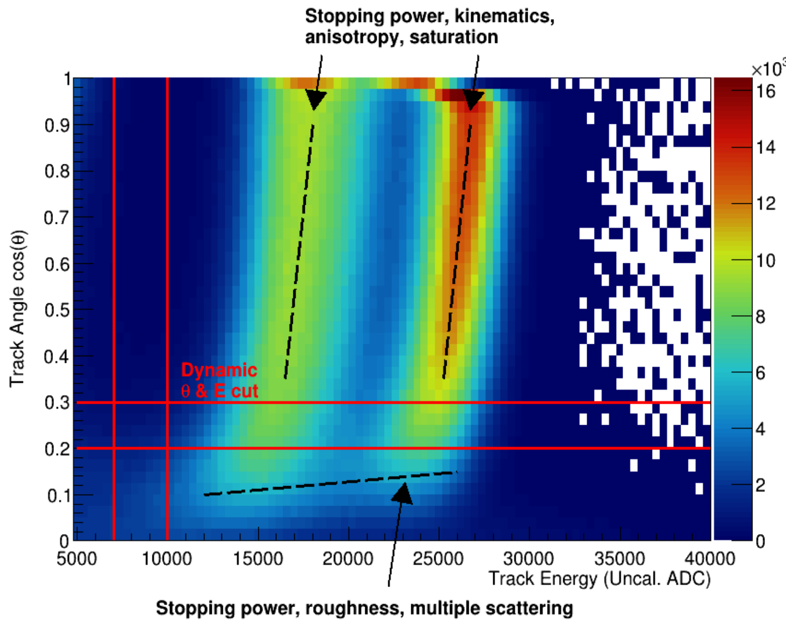


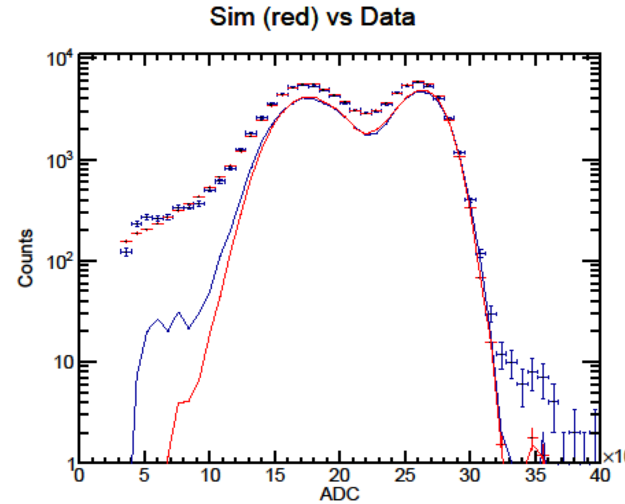
Fission Fragment Efficiency

PRC 97, 034618 (2018)

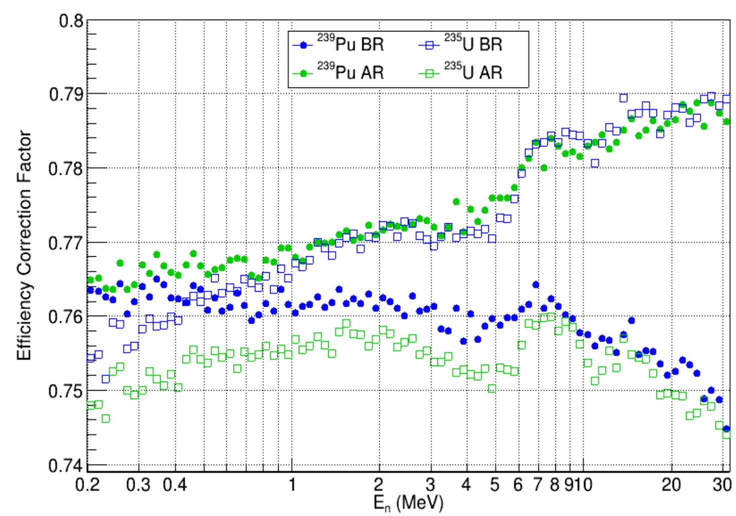
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i}\cdot n_{s,i})}{\sum_{XY}(\phi_{x,i}\cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff}-C^x_r-C^x_\alpha)-C^x_{bb}}{(C^s_{ff}-C^s_r-C^s_\alpha)-C^s_{bb}}$$







- **Parameterized model incorporating energy loss effects for fission fragments exiting target material**
- **Energy-Angle data is fit**
- **Recent inclusion of FREYA code and Geant4 in model**
- **Validation of earlier data-driven only model**



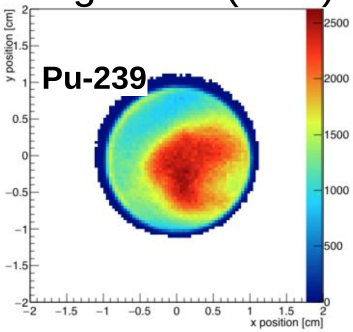
Neutron Flux Profile & Target Overlap

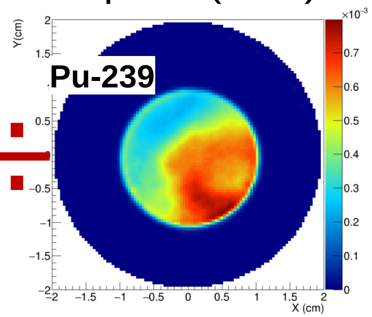
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff} - C^s_r - C^s_\alpha) - C^s_{bb}}$$

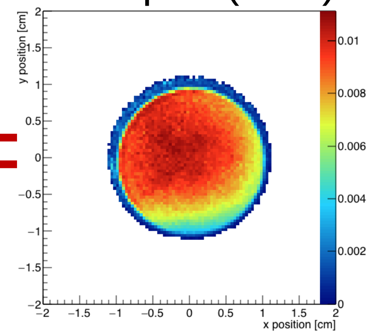
Correction required if beam *and* actinide target have spatial non-uniformity

$$\frac{\sum_{XY}\phi_{s,i} \cdot \sum_{XY} n_{s,i}}{\sum_{XY}\phi_{x,i} \cdot \sum_{XY} n_{x,i}} = 1 \neq \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})}$$

Fragments (data) ÷ Alphas (data) = FF/alpha (data)



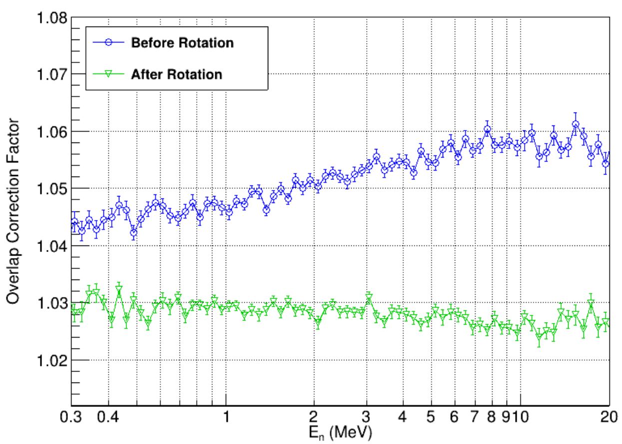




$$\mathrm{OT} = \text{Overlap Term}$$
$$= B \sum_i \frac{n_i}{\sum_j n_j} \frac{T_t}{\sum_k T_k}$$
$$= B \frac{1}{\sum_j n_j} \frac{1}{\sum_k T_k} \sum_i n_i T_i$$

$$\frac{\mathrm{OT}^{Pu}}{\mathrm{OT}^{U}} = \frac{\frac{1}{\sum_k \alpha_k^{Pu}} \sum_j \frac{f_j^u}{\alpha_j^U} \alpha_j^{Pu}}{\frac{1}{\sum_i \alpha_i^U} \sum_l f_l^U}$$

Data driven correction
"U-corrected Pu-overlap term"



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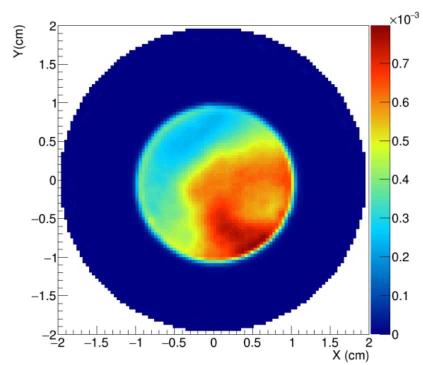
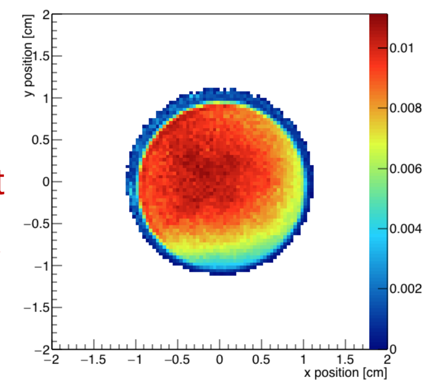


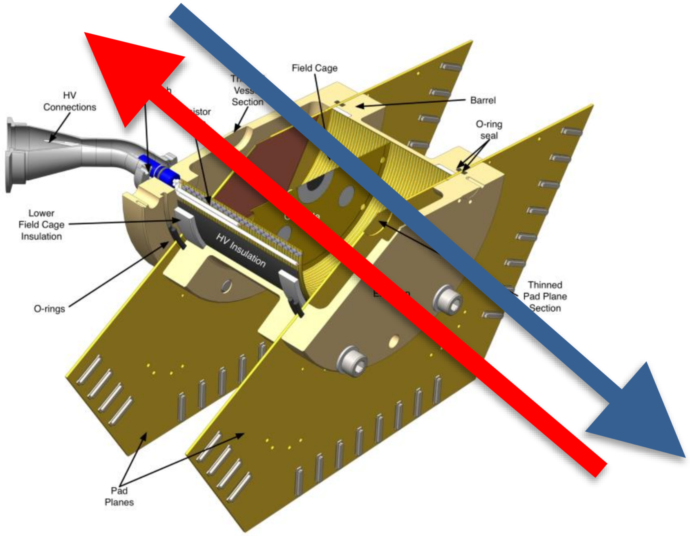
Dot product

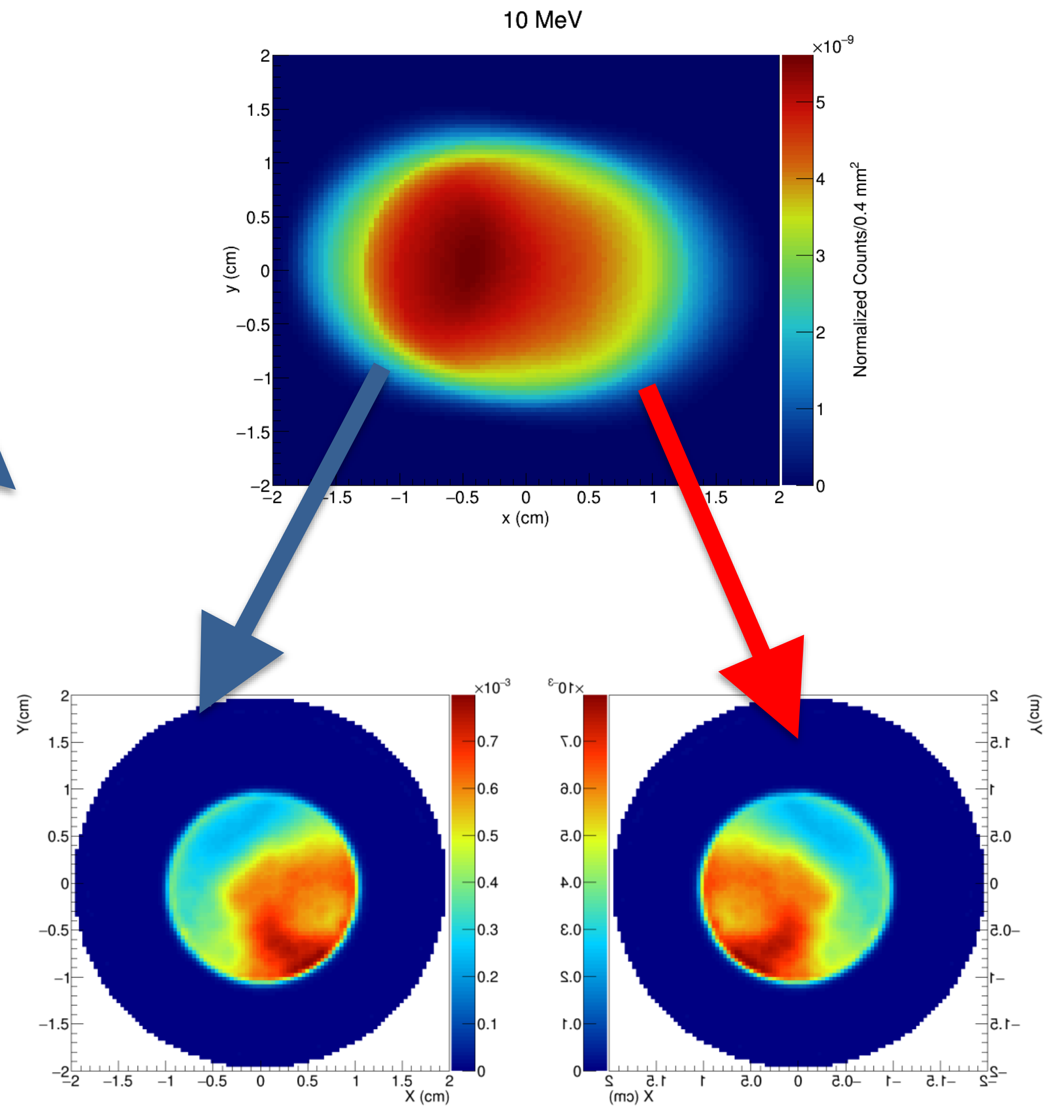


Validations and Sensitivity Studies

- **Rotation of fissionTPC**
  - Flips beam and target non-uniformity
- **XY-binned cross section**
  - Make measurement in small bins where beam is relatively uniform
  - Requires rescaling of each bin target normalization ratio
- **Radial cuts**
  - Has large effect on overlap correction
- **Tracking sensitivity studies**
  - Tracking bias, resolution
  - Target alignment
  - Space charge distortion
- **Normalization Validation**
  - Remeasure target-atom normalization
  - Remeasure cross section ratio (future work)

Rotation Validation

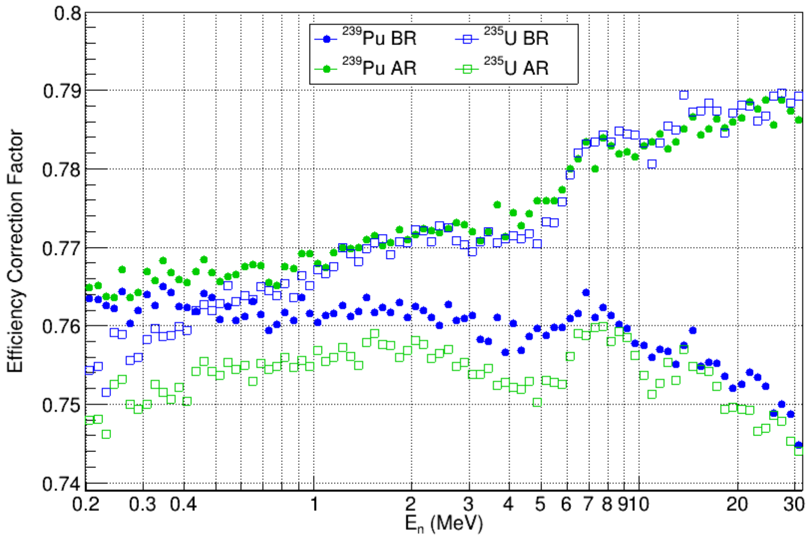


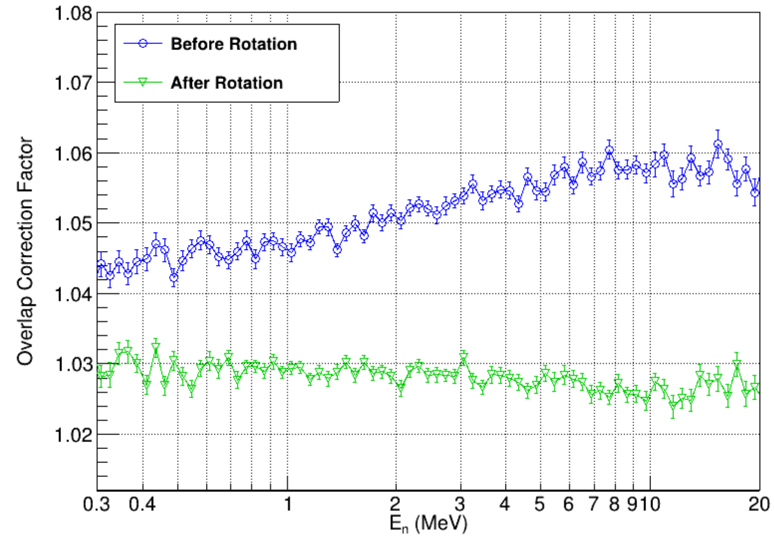


Flip beam:

- Direction alters alignment of beam and target hotspot
- Kinematic boost alters efficiency

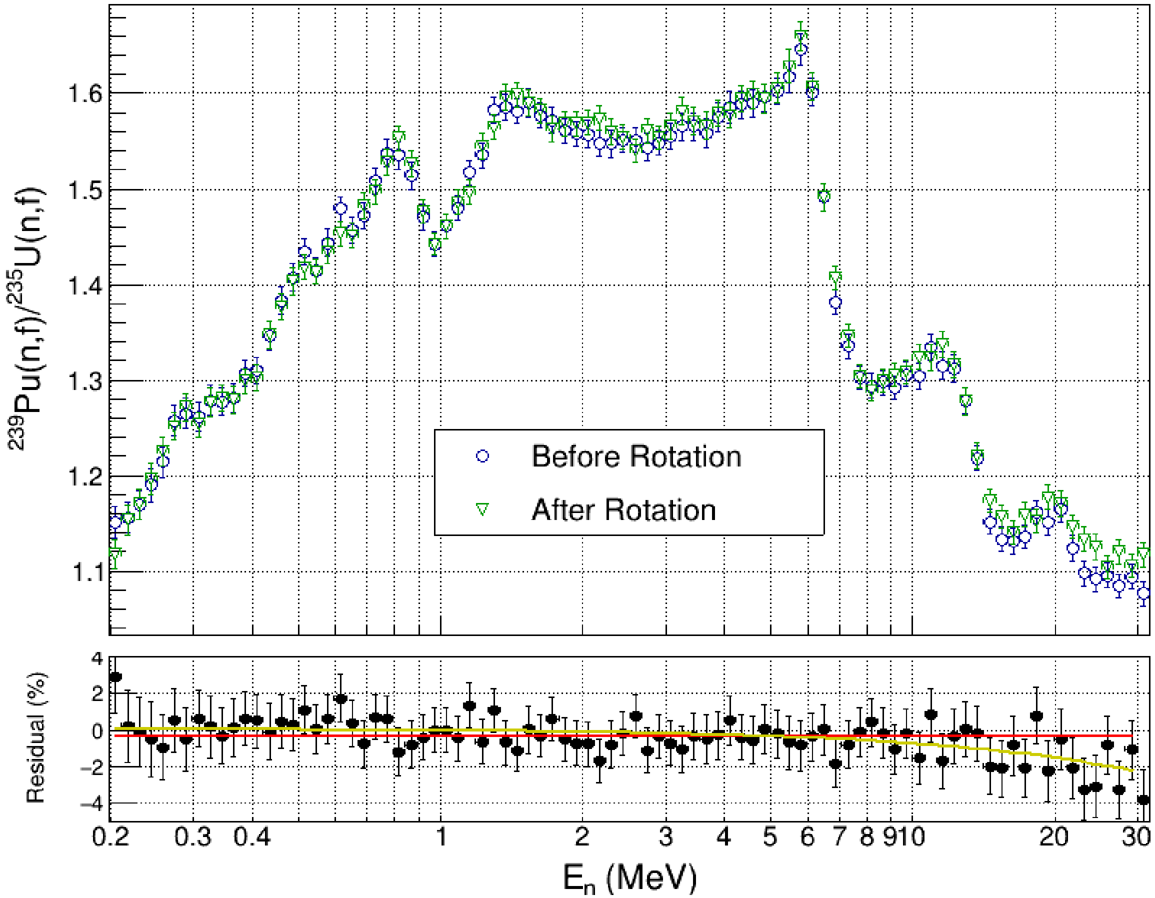
Rotation Validation





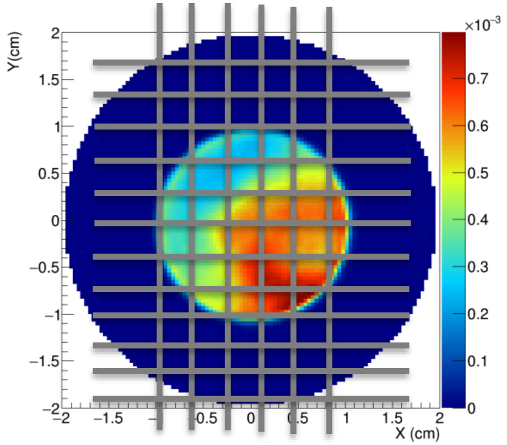
- Significant, 3-4 % change in efficiency and overlap terms
- Effects both shape and overall normalization
- Strong validation

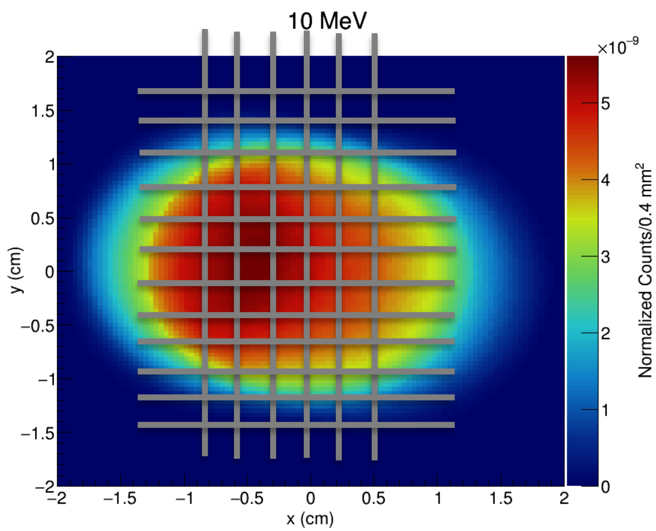
Rotation Validation



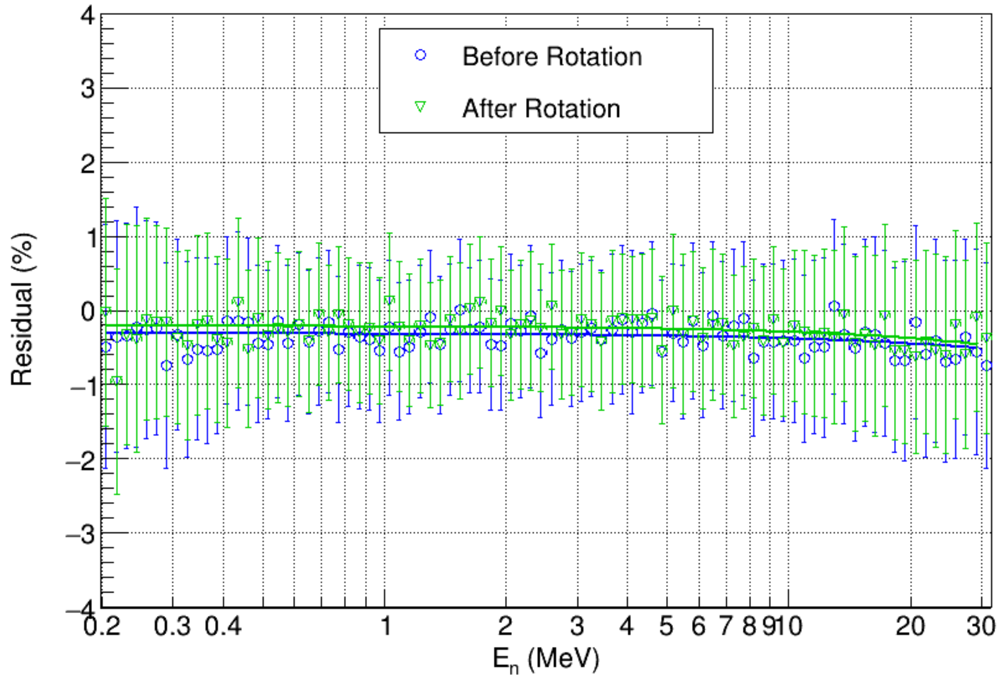
“Before” and “After” rotation cross section ratios agree

Binned Cross Section Analysis





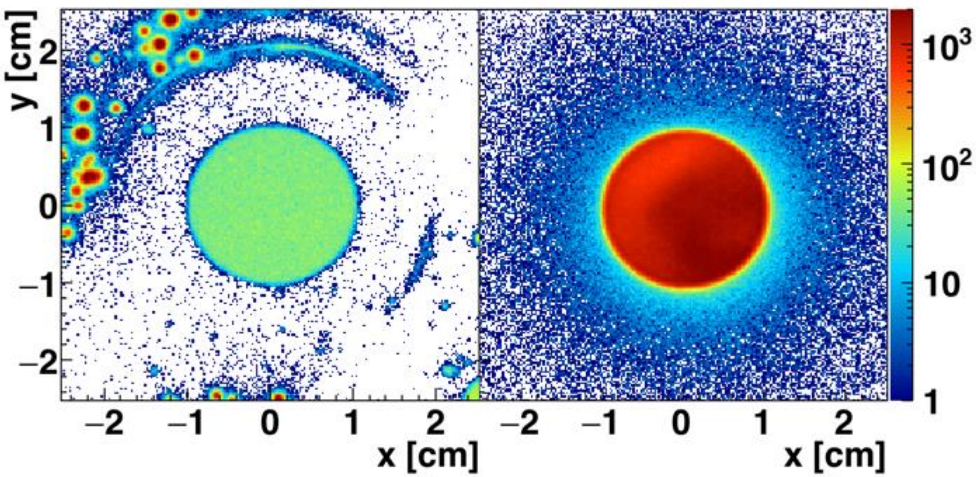
- Average many cross section ratios binned such that the beam and/or target are uniform
- Each one renormalized
- **Methods agree**

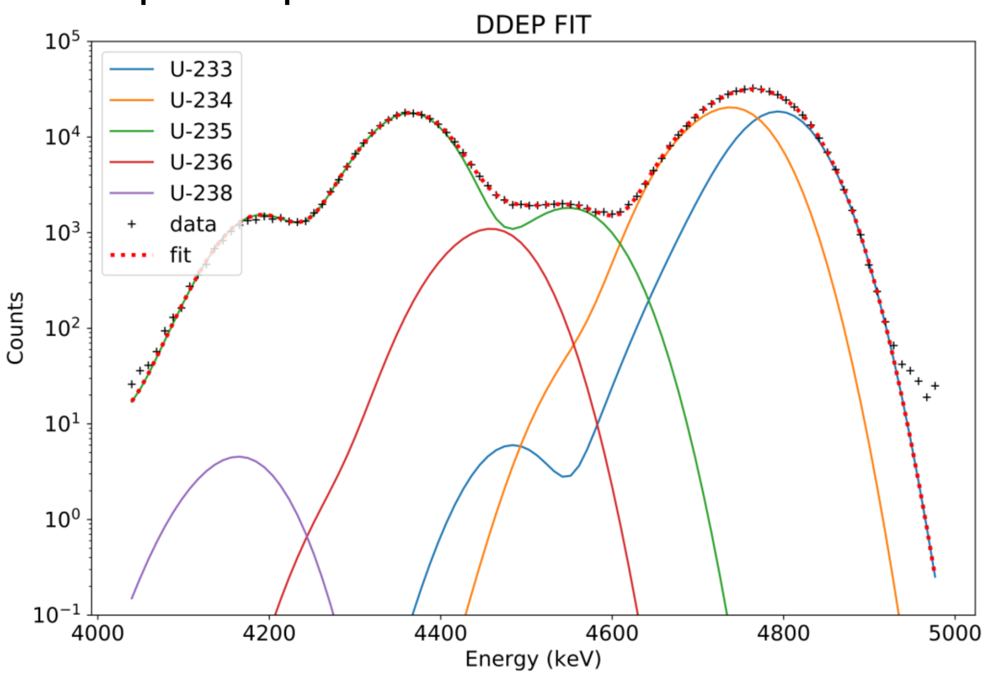


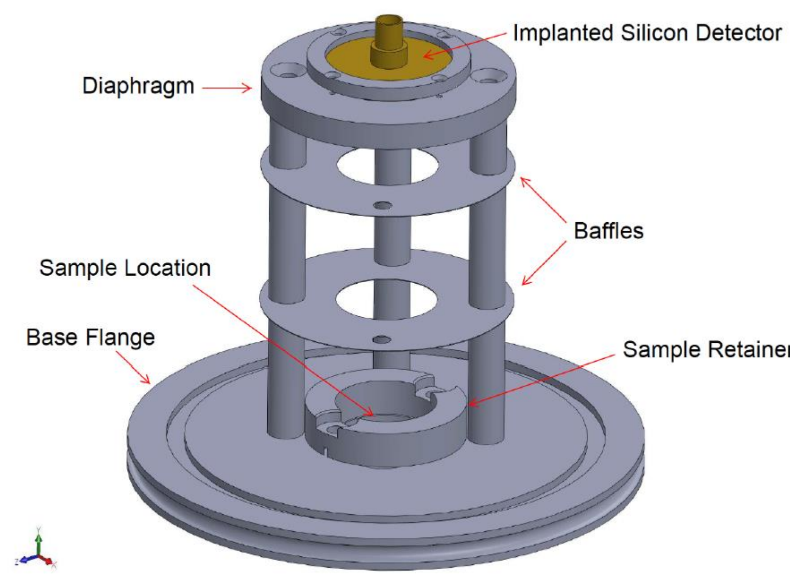
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff} - C^s_r - C^s_\alpha) - C^s_{bb}}$$

Target Atom Normalization

- A combination of a Si detector and mass spectrometry were used to determine the target atom normalization
- Si det. design based on NIST prescription



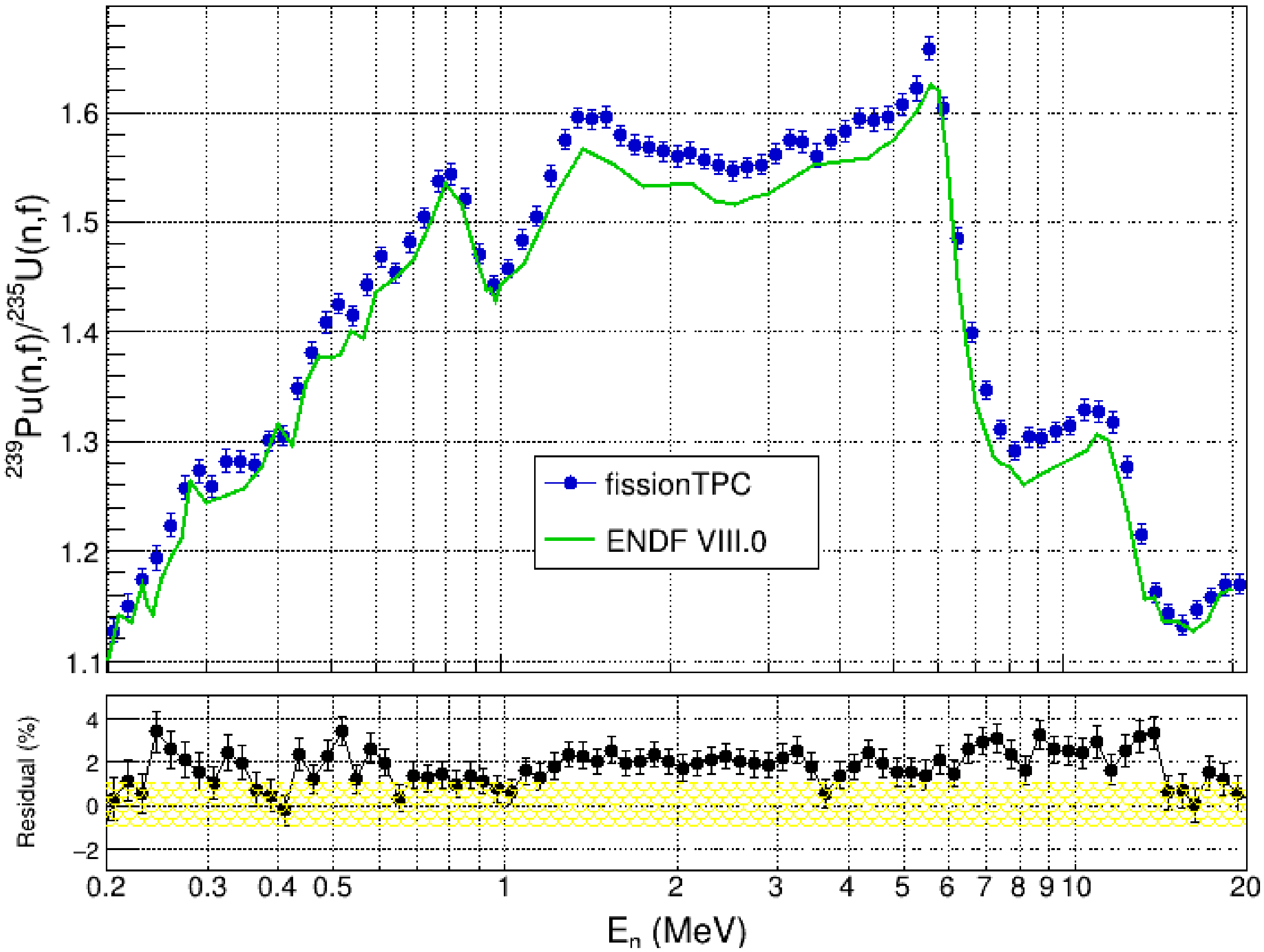




Target Atom Normalization Validation

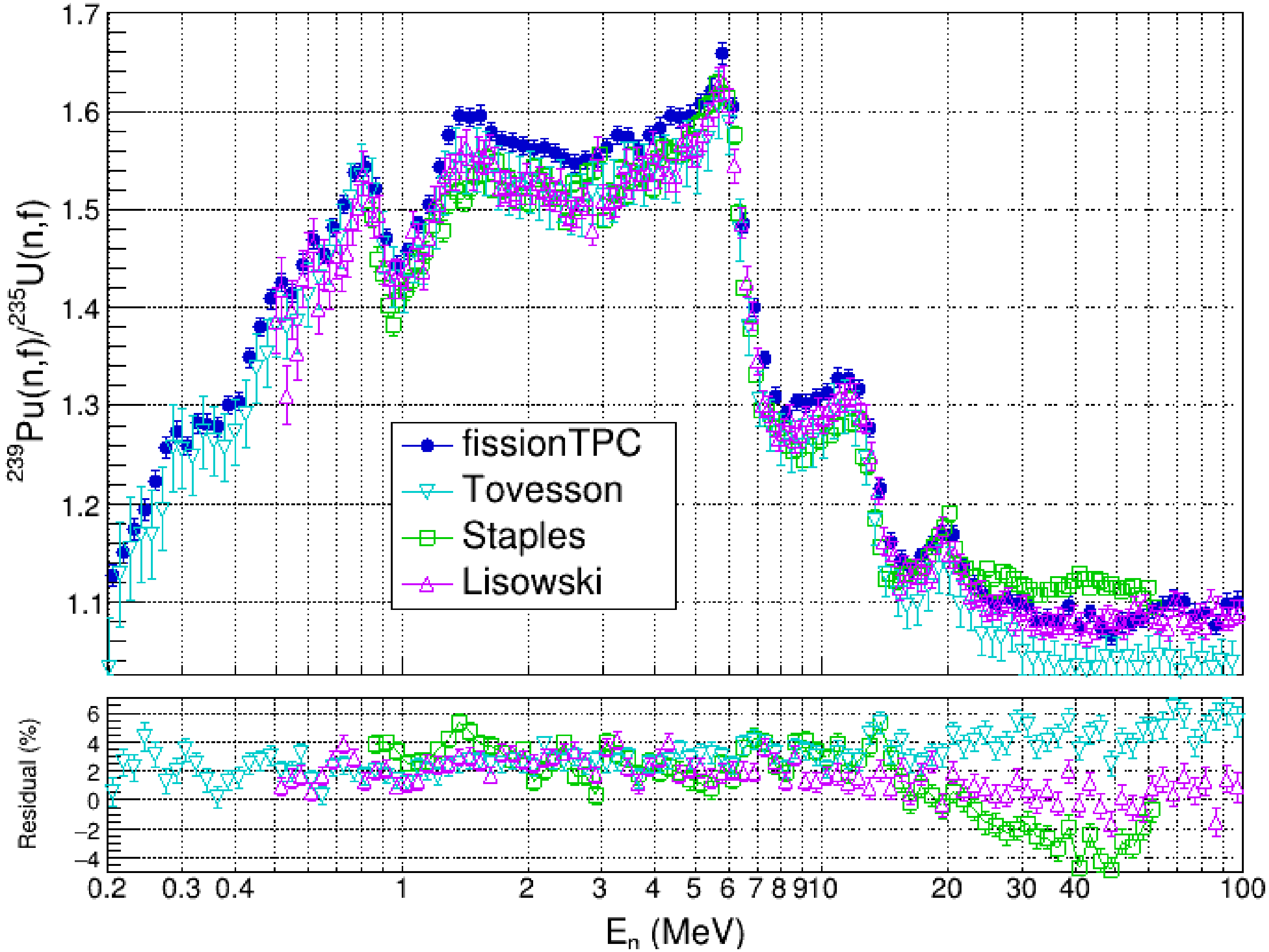
- Results are reported as a ratio of target atom number, to eliminate the need to have a precision understanding of the Si detector setup geometry
- Method depends on Mass Spec. to get a final answer
- **Mass spec**. measurements made multiple times from multiple samples over multiple years
- **Target counting measured** in detector multiple times
- **Target counting analysis** was performed independently at LANL/LLNL
- Absolute alpha counting in fissionTPC not accurate enough currently

Normalization Compared to ENDF8



- Significant systematic deviation from ENDF
- This is *not* the collaboration's stated position

Comparison to Data



- Deviation with other data is consistent with ENDF
- Larger deviations between all data at higher energies

PART I: Summary

- **We are confident of the Cross Section Shape Measurement**
- **Two obvious concerns:**
  - Is the overlap handled correctly?
  - Is the measurement of the target normalization correct?
- **Validations Performed:**
  - Rotation & radial cuts have significant effects on overlap and efficiency. *They are strong validations*
  - Two methods for nonuniformity correction agree
  - Target was remeasured and reanalyzed by multiple teams
  - Target was counted in Silicon detector *only after* beam data was collected. It is possible that it was damaged. This would have had no effect on the cross section measurement
- **We will remeasure for normalization**
- **Next Steps:**
  - Now capable of vapor deposition of ^{239}Pu
  - Characterize target before and after a new beam measurement
  - At this point we intend to publish recommended as *shape data* but will include our normalization work

Impact of the new data

Step 1

Establish our best experimental knowledge of ^{239}Pu(n,f) with a GMA evaluation.

Step 2

Fit parameters of a physical model for the simultaneous evaluation of ^{239}Pu(n,f) and other related observables.

^{239}Pu(n,f) needs revisiting

Step 1

Establish our best experimental knowledge of ^{239}Pu(n,f) with a GMA evaluation.

The GMA database: types of data

Table 2. Data Types Used in the Simultaneous Evaluation

MT	Data Type	Example
1	Absolute cross section	$\sigma_{n,f}(^{235}U)$
2	Cross section shape	$c \cdot \sigma_{n,\alpha}(^{6}Li)$, c unknown
3	Absolute cross section ratio	$\sigma_{n,f}(^{238}U)/\sigma_{n,f}(^{235}U)$
4	Ratio shape	$c \cdot \sigma_{n,f}(^{239}Pu)/\sigma_{n,\alpha}(^{6}Li)$ c unknown
5	Sum of cross sections	$\sigma_{tot}(^{6}Li) = \sigma_{n,n}(^{6}Li) + \sigma_{n,\alpha}(^{6}Li)$
6	Spectrum averaged cross section	$\sigma_{n,f}(^{239}Pu)$, Av. ^{252}Cf SF
7	Absolute ratio of cross section vs. sum of cross sections	$\sigma_{n,\gamma}(^{238}U)/\sigma_{n,\alpha}(^{10}B)$ $\sigma_{n,\alpha} = \sigma_{n,\alpha 0} + \sigma_{n,\alpha 1}$
8	Shape of type 5 data	
9	Shape of type 7 data	

From W. Poenitz and S. Aumeier Argonne National Laboratory Report ANL/NDM-139, (1997)

The GMA (Gauss-Markov-Aitken) equations

- Generalized least-squares.
- Assumes normal distribution of random variables.
- Linearization close to most probable value.
- Linear algebra problem, good numerical implementation.

$$\mathrm{p} = (A^T V_y^{-1} A)^{-1} A^T V_y^{-1} \mathbf{y}$$

$$\mathrm{V}_p = (A^T V_y^{-1} A)^{-1}$$

measured covariances

measured parameters

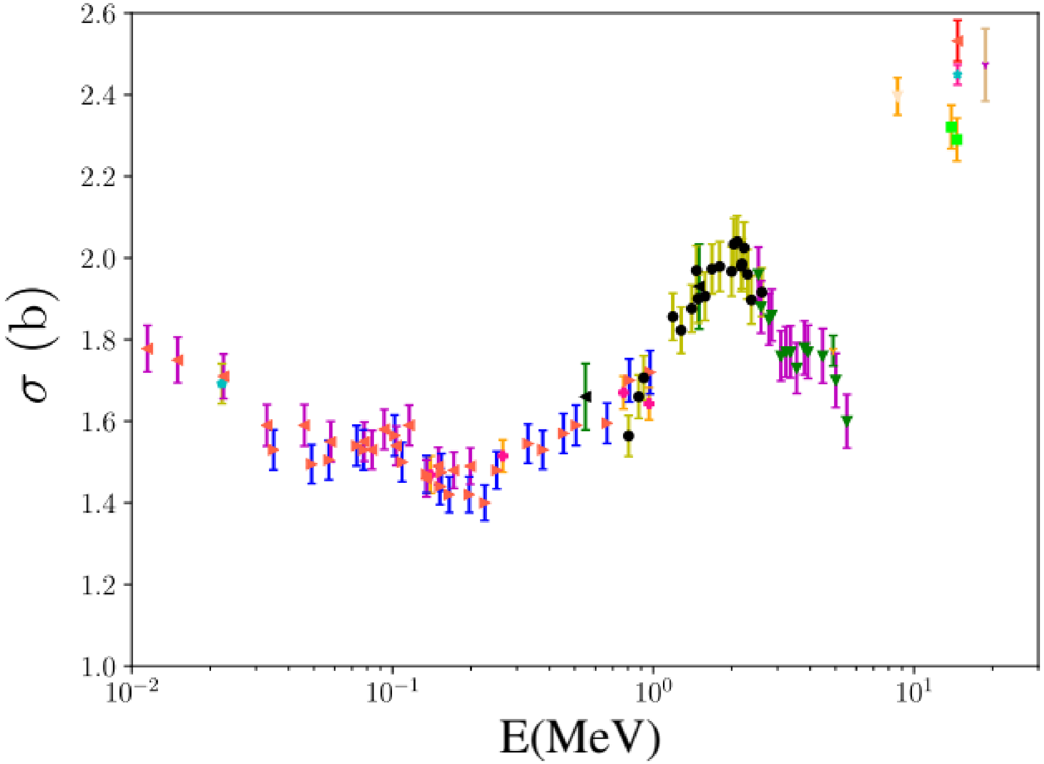
best parameters

best covariances

design matrix

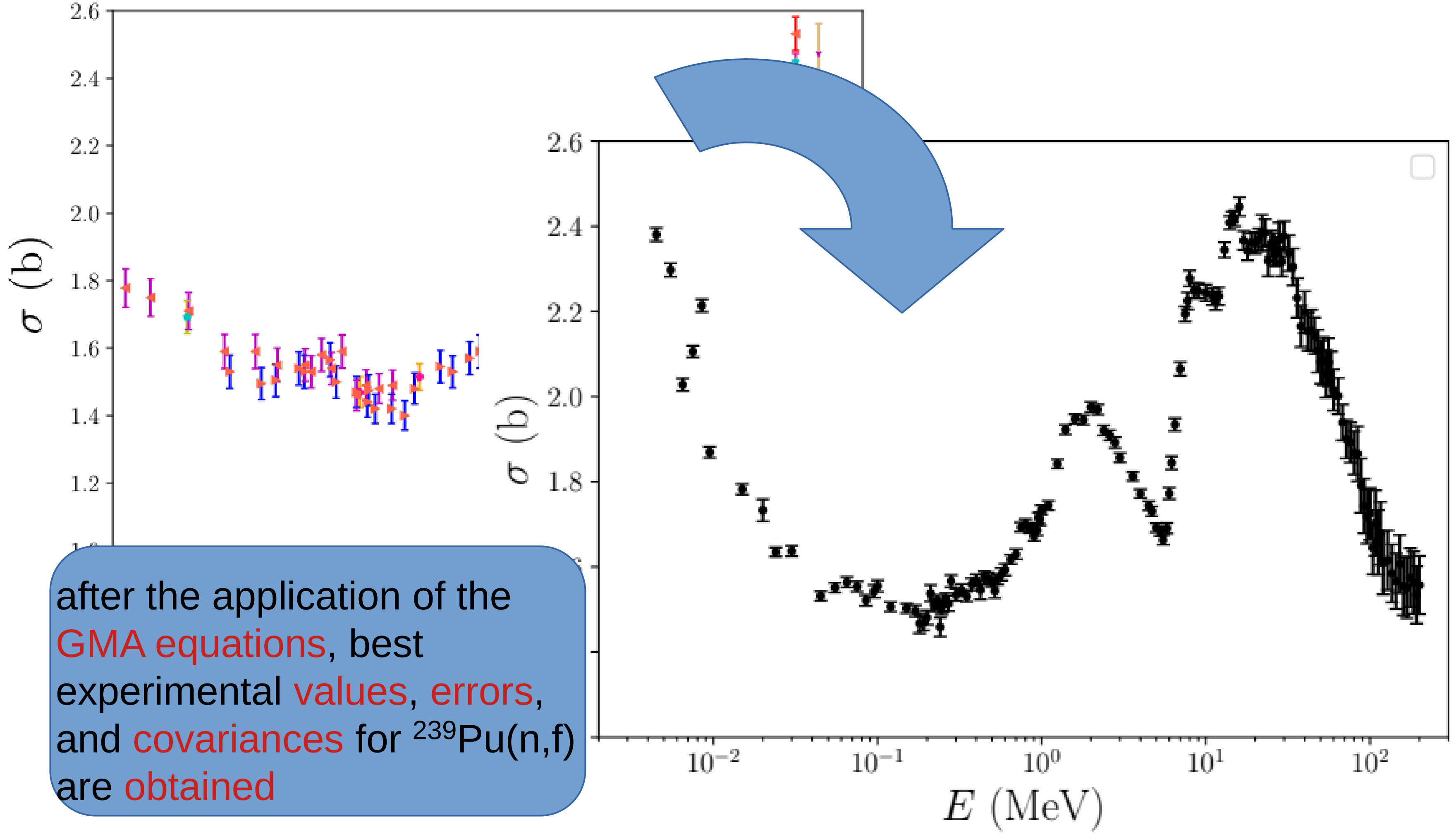
evaluation

GMA at work: implementation of GMA equations for ^{239}Pu(n,f)



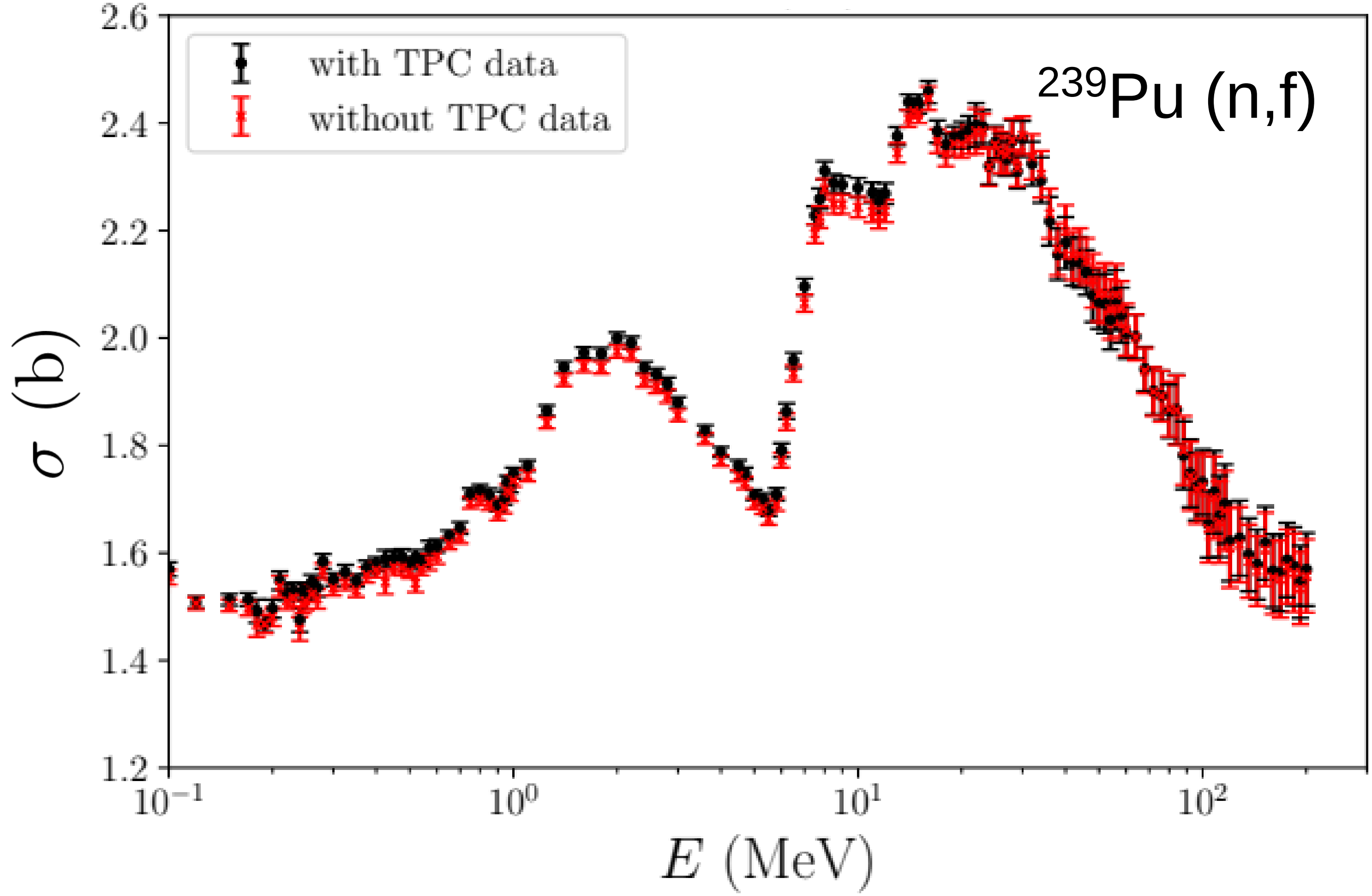
^{239}Pu(n,f) data in the GMA October 2004 database

GMA at work: implementation of GMA equations for $^{239}Pu(n,f)$

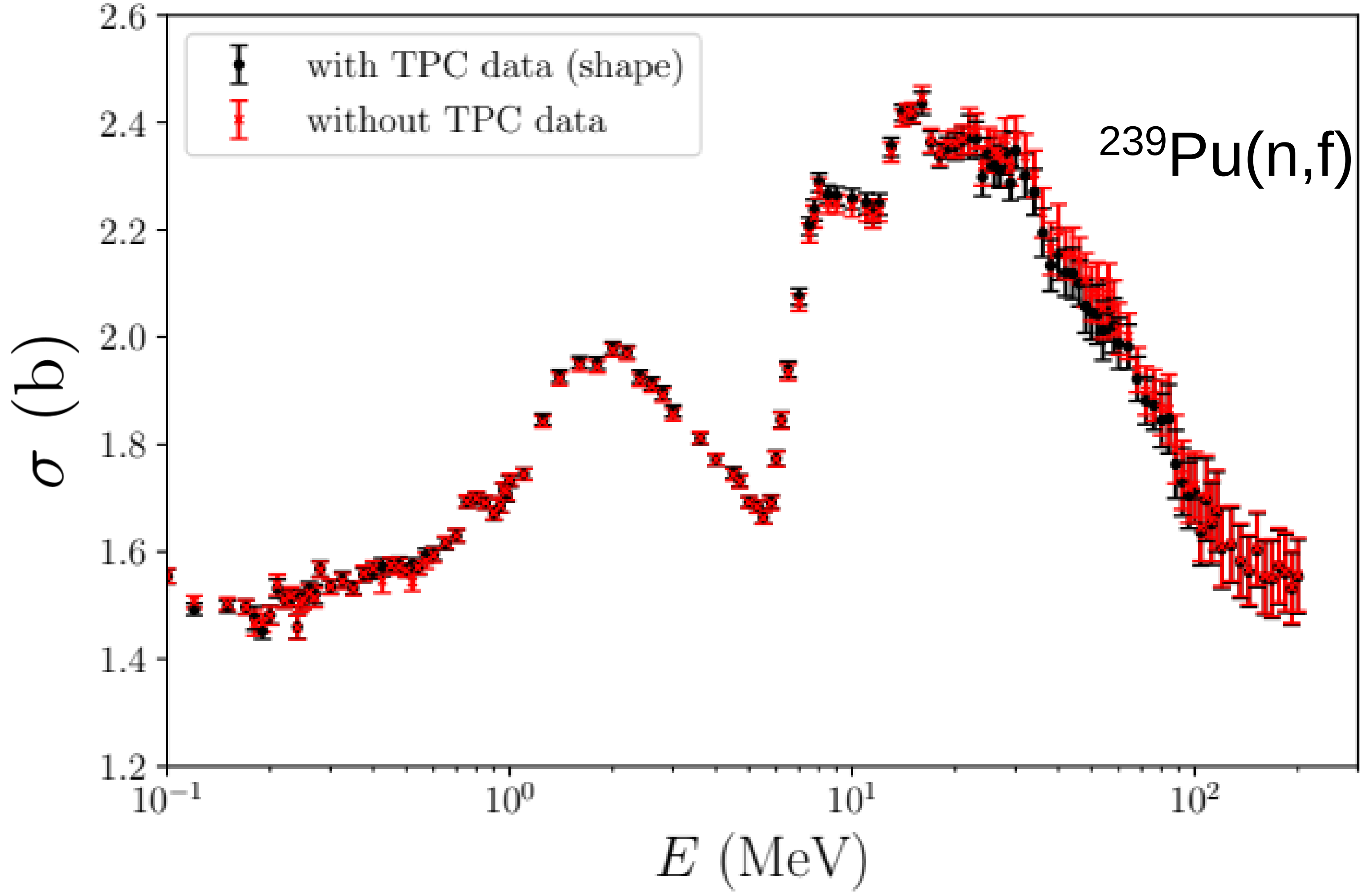


after the application of the GMA equations, best experimental values, errors, and covariances for $^{239}Pu(n,f)$ are obtained

Combining the TPC data with the GMA database

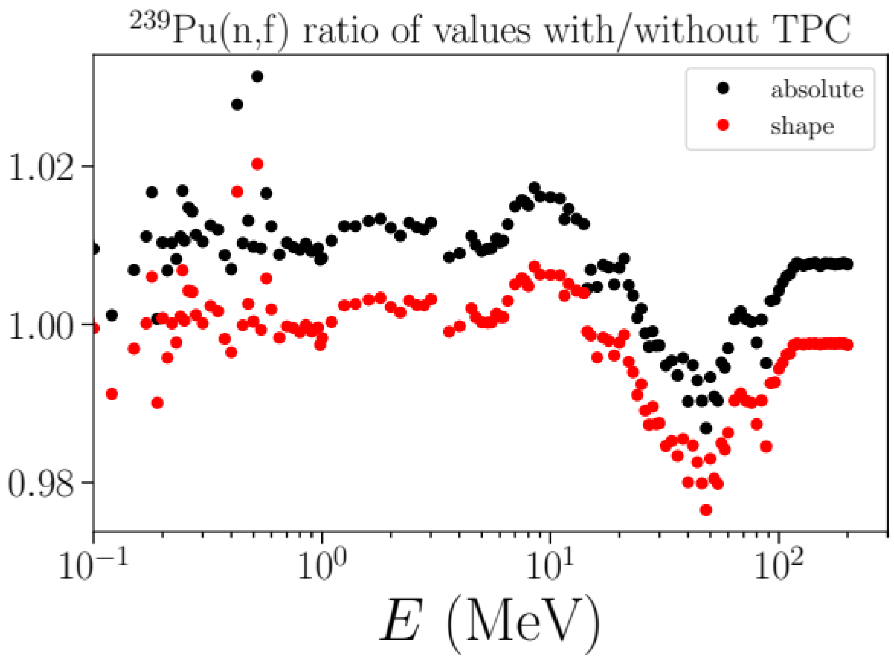


Combining the TPC data with the GMA database: converting to shape data

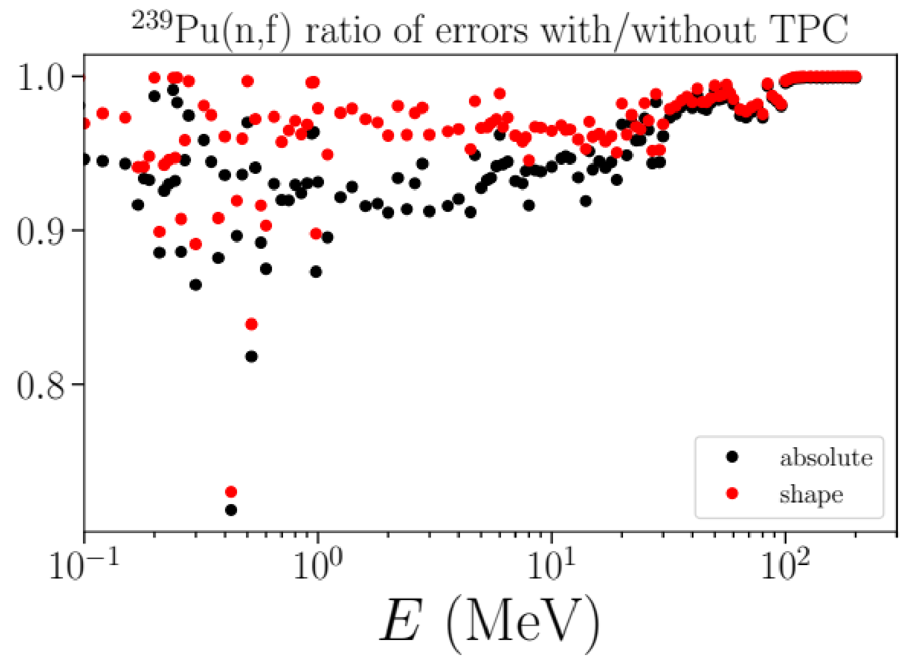


Combining the TPC data with the GMA database

Ratio of values with TPC data /without TPC data



Ratio of errors with TPC data /without TPC data

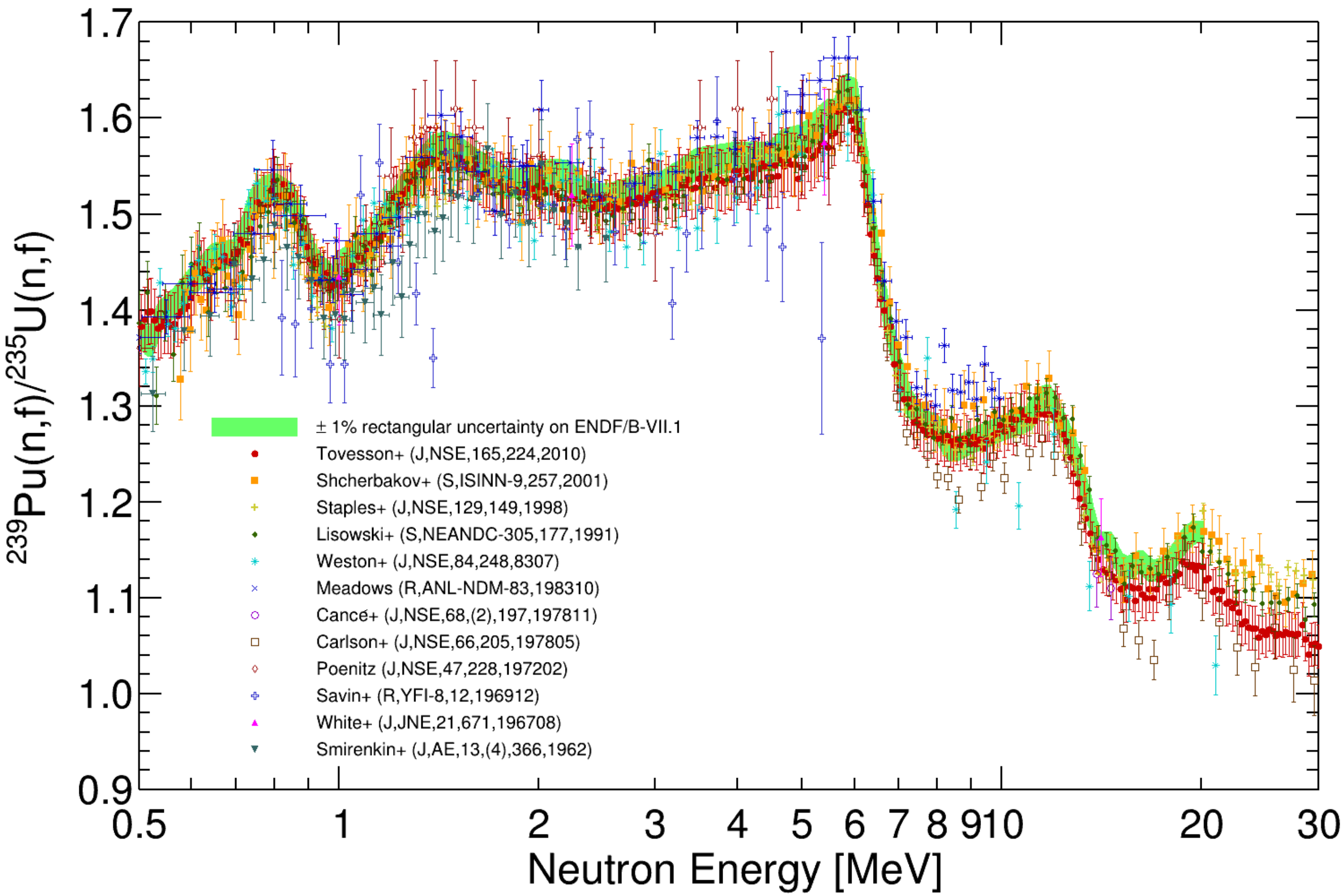


Part II: Summary

- We are assessing the impact of the new ratio measurement.
- As a first step, we presented here the GMA evaluation, which establishes the status of our experimental knowledge of ^{239}Pu(n,f) cross sections, uncertainties, and covariances.
- Next step: fit of the physical parameters of a Hauser-Feshbach+Coupled Channels model of reaction and decay → work in progress.

Backup

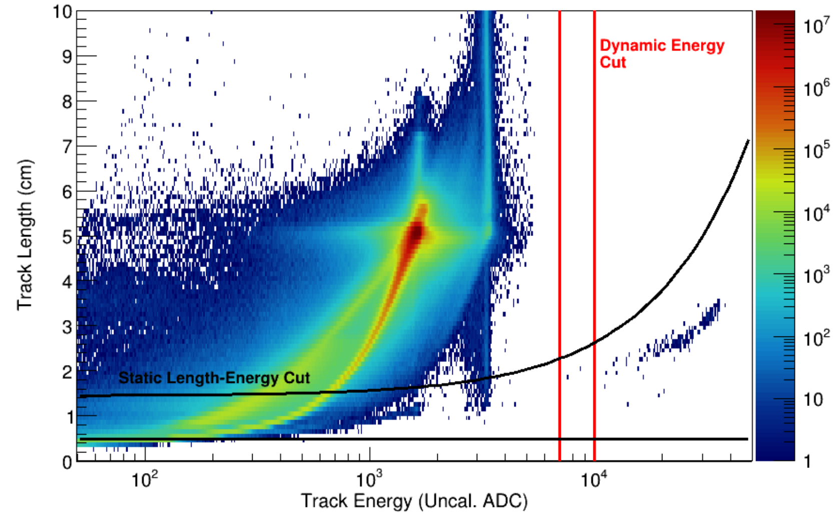
Motivation: Spread in $^{239}Pu(n,f)/^{235}U(n,f)$ data does not justify a 1% evaluation

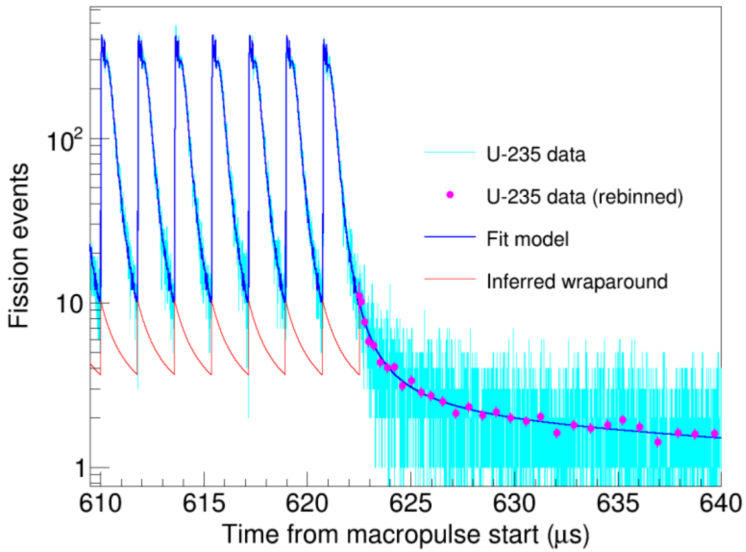


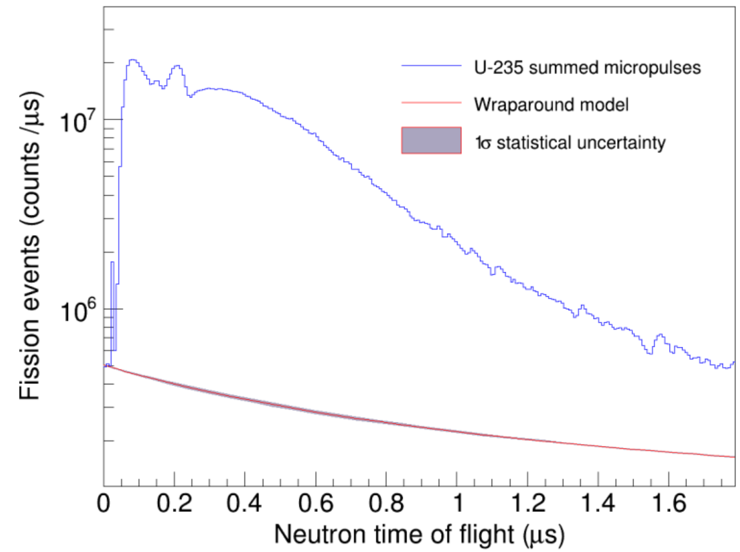
Background terms

$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff} - C^s_r - C^s_\alpha) - C^s_{bb}}$$

- Recoil and alpha backgrounds (C_r, C_α) found to be negligible, i.e. TPC has good PID capabilities
- Any uncertainty from this assumption accounted for in efficiency model
- Wraparound corrected for with standard methods



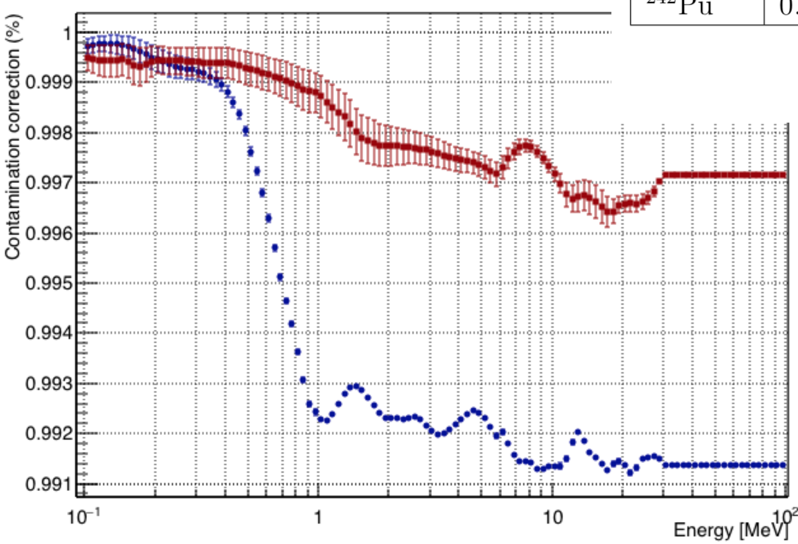




Contamination correction

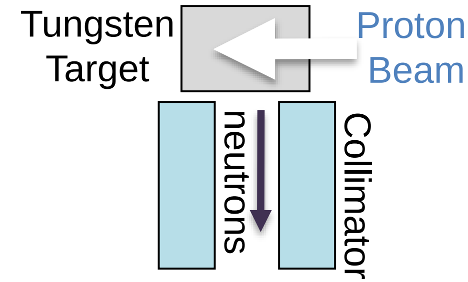
Isotope	Atom %	Alpha Activity (%)	Overlapping with peak of interest (POI)?	Fission Cross-Section at 10 MeV	Fission Yield at 10 MeV (%)
^{233}U	.018862	29.1	No	2.25	0.024
^{234}U	.03448	34.4	No	2.16	0.042
^{235}U	99.6767	34.7	POI	1.76	99.7
^{236}U	0.17009	1.78	Yes	1.53	0.15
^{238}U	0.09984	0.00548	Yes	1.00	0.057
^{238}Pu	0.0002	0.84	Yes	2.82	0.00025
^{239}Pu	99.1323	95.97	POI	2.24	99.1
^{240}Pu	0.8675	3.19	Yes	2.24	0.87
^{241}Pu	<0.0015	<0.00001	Yes	1.99	<0.0013
^{242}Pu	0.00242	0.00016	No	1.92	0.00021

Table 2: Isotopics and effects on cross-section measurement.

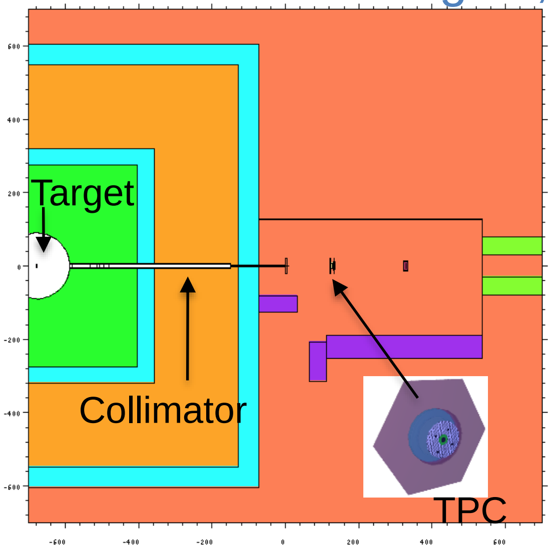


Neutron Flux Profile & Attenuation

$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff} - C^s_r - C^s_\alpha) - C^s_{bb}}$$



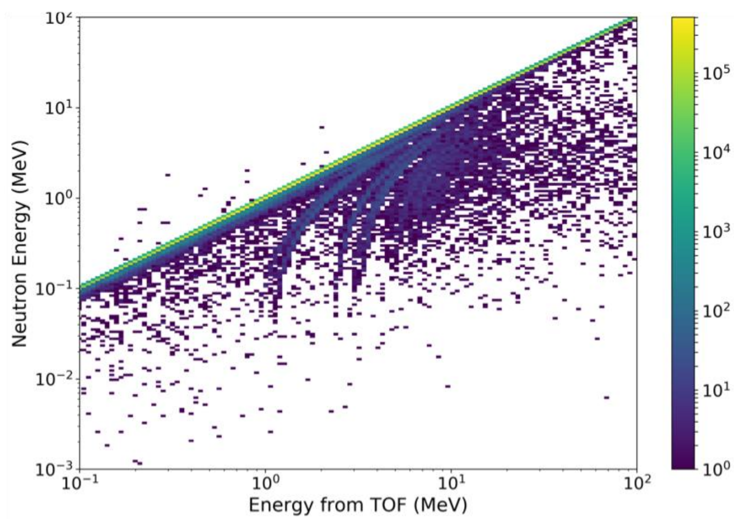
Detailed MCNP model gives neutron flux spatial profile for both actinide targets, as a function of neutron energy

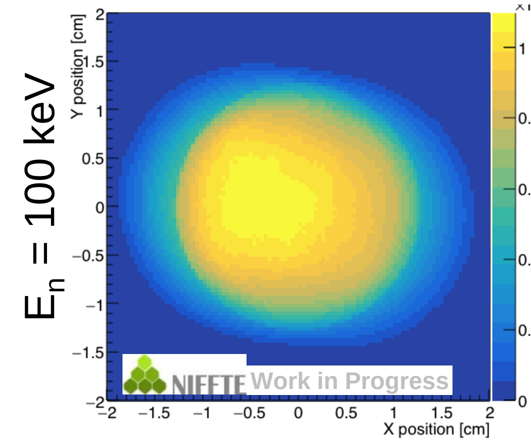


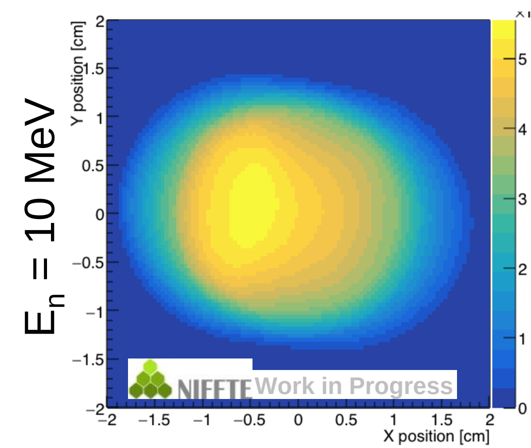
- Proton beam energy loss in the spallation target results in a non-uniform neutron beam profile
- Importantly, the spatial profile varies with neutron energy (at the TPC)

We use the MCNP model to account for:

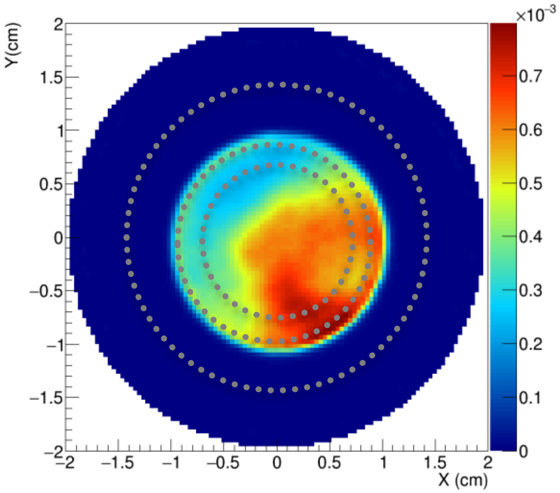
- flux attenuation in the target backing
- scattering (change in energy) between TOF measurement and fission initiation



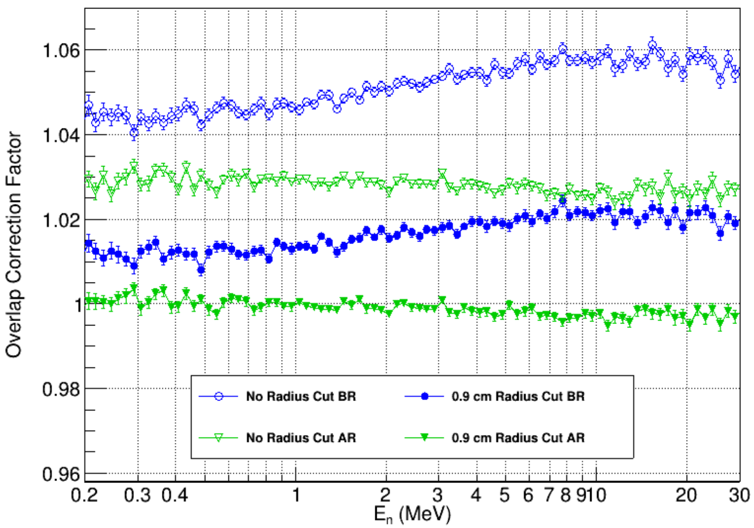


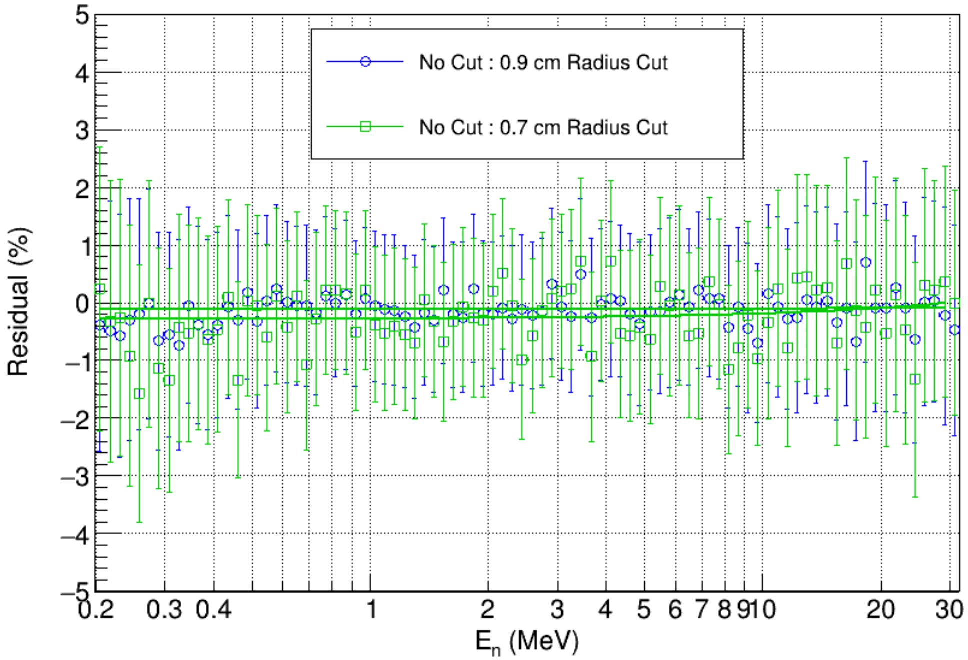


Radius Cut Validation

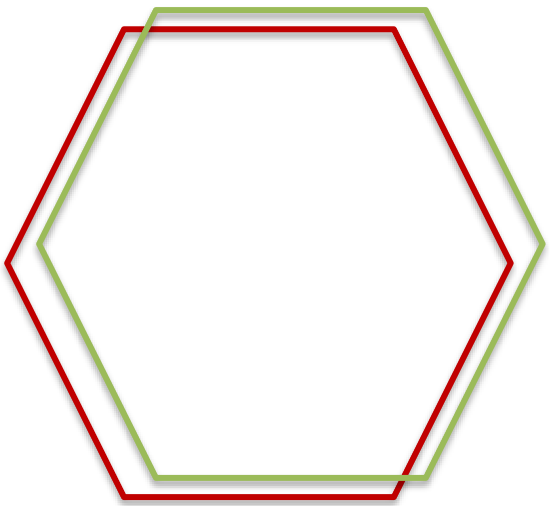


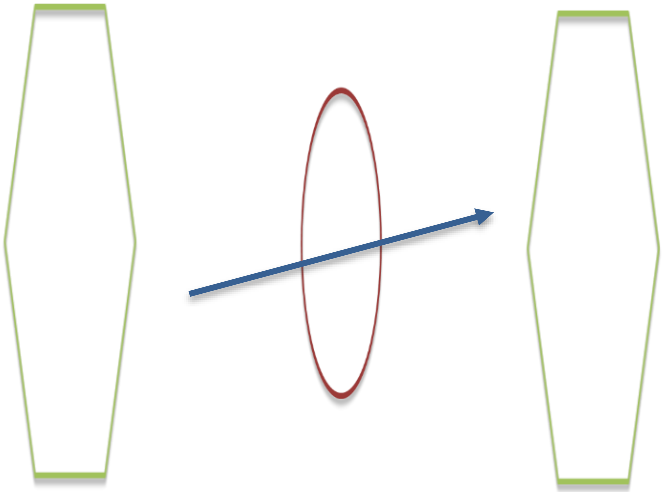
- Aggregate shape changes
- Target Edge alignment constitutes large nonuniformity
- Large impact on the overlap term and target renormalization
  (1mm rad. cut -> ~7% change normalization)





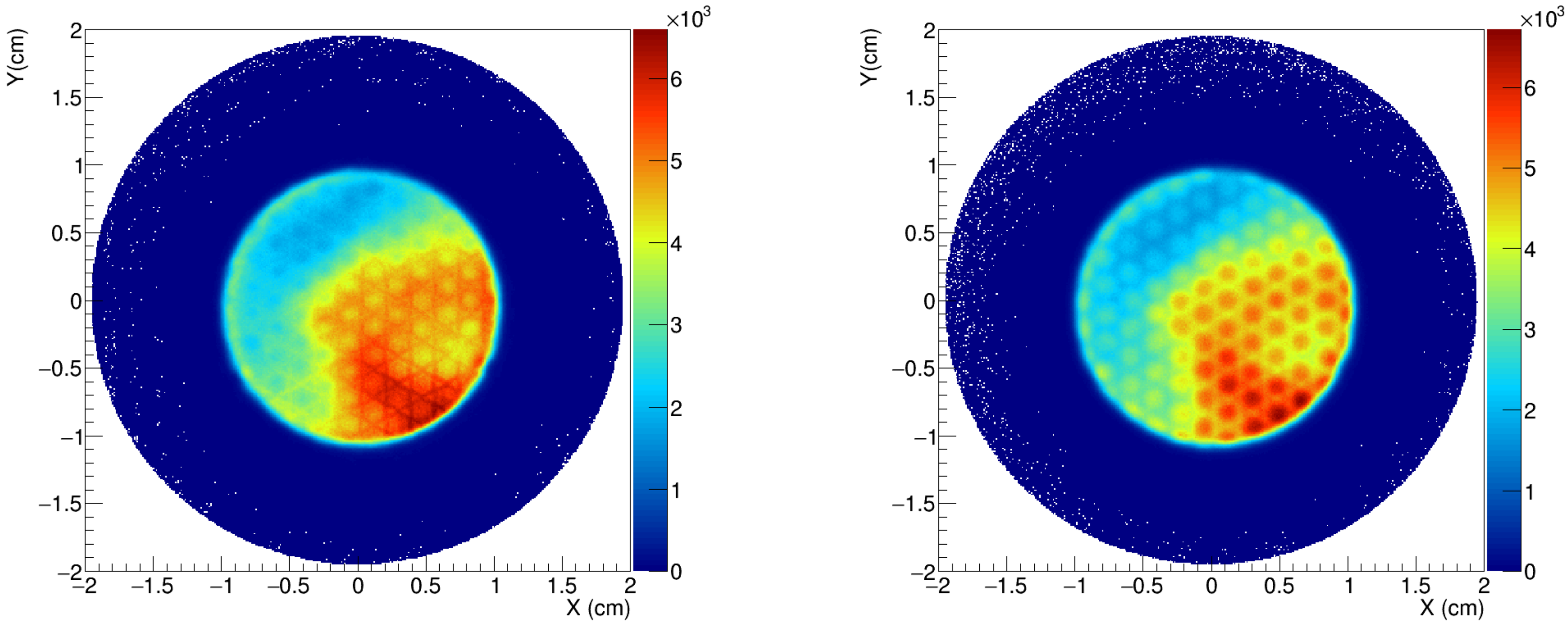
FissionTPC Padplane Alignment Sensitivity





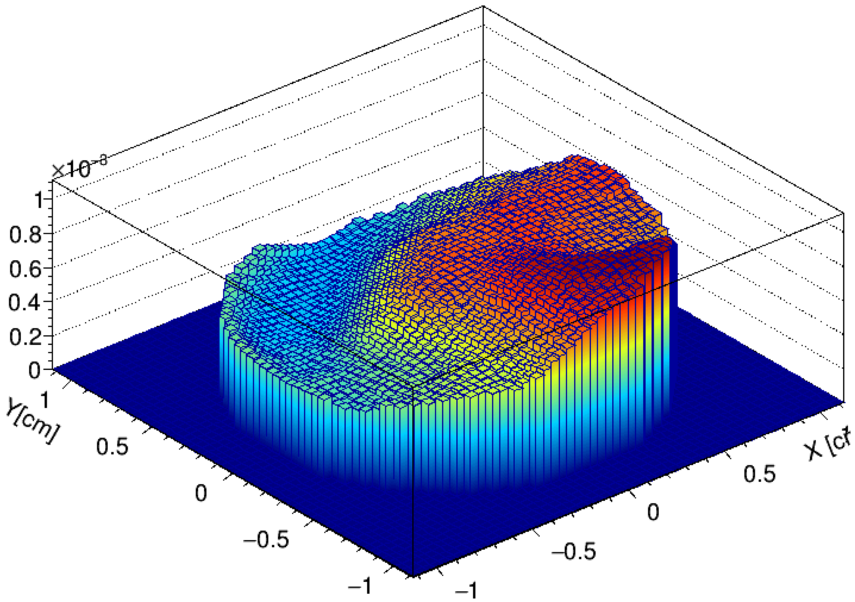
- Misalignment of padplanes could cause an apparent misalignment of the targets (reconstructed vs. real)
- Beam induced events with enough energy to “punch-through” the central cathode are used to determine the alignment
- Potential misalignment of up to 200 µm expected as a result of construction technique

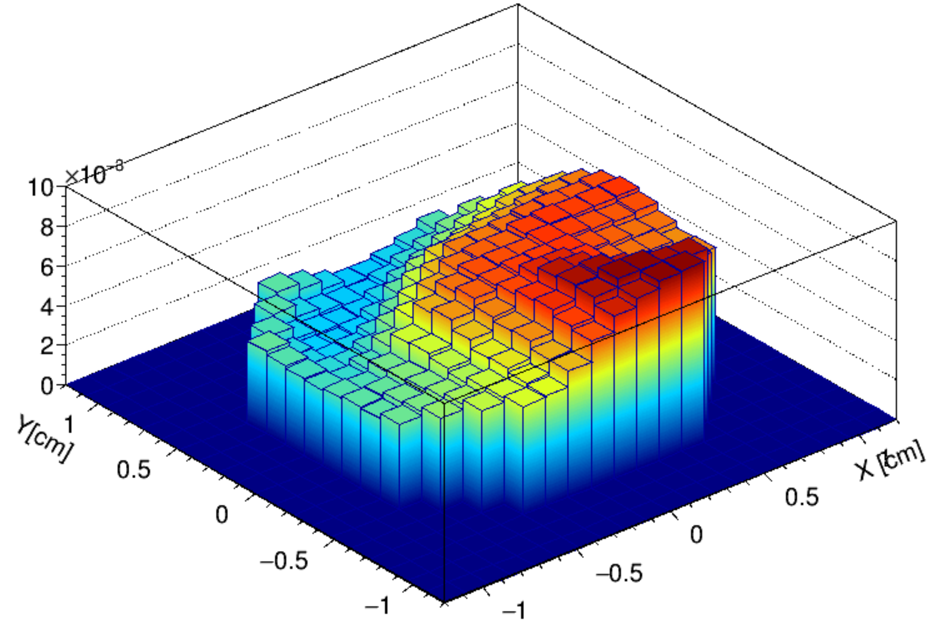
Track Bias Sensitivity



- Tracking algorithm is "focused" to eliminate hexagonal biasing of track vertices
- There is a polar angle dependence such that the average is un-biased but some angle ranges make it mare apparent

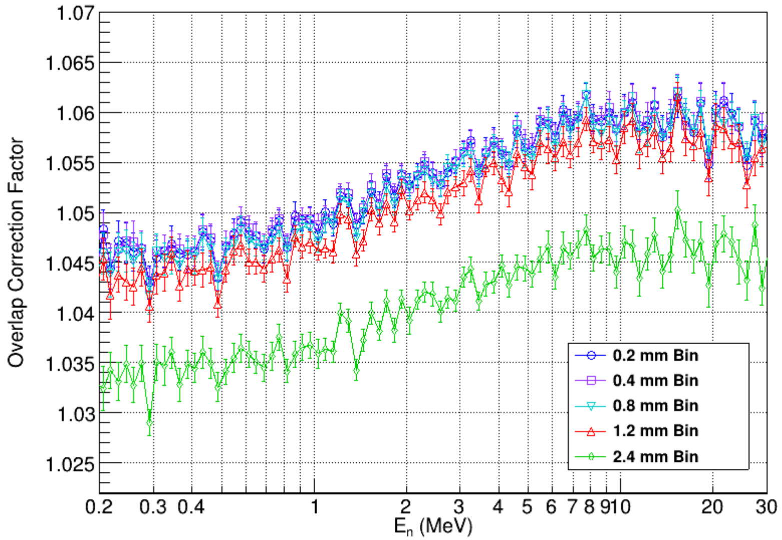
Pointing Resolution and Bin Size

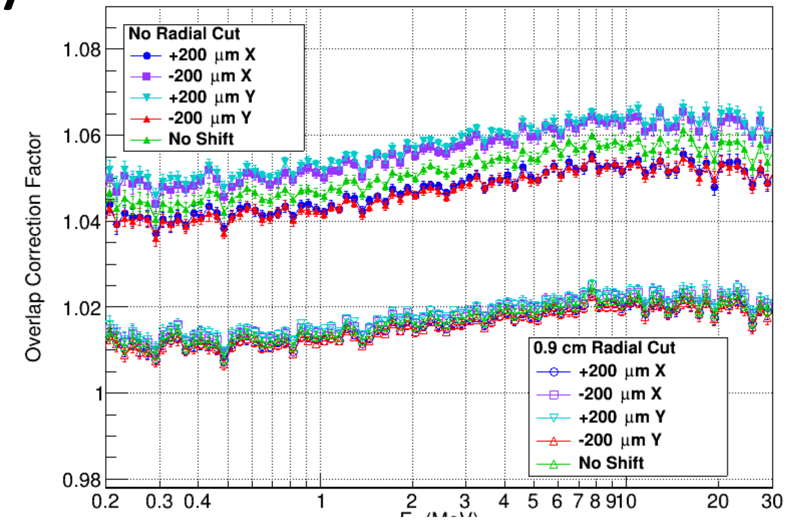


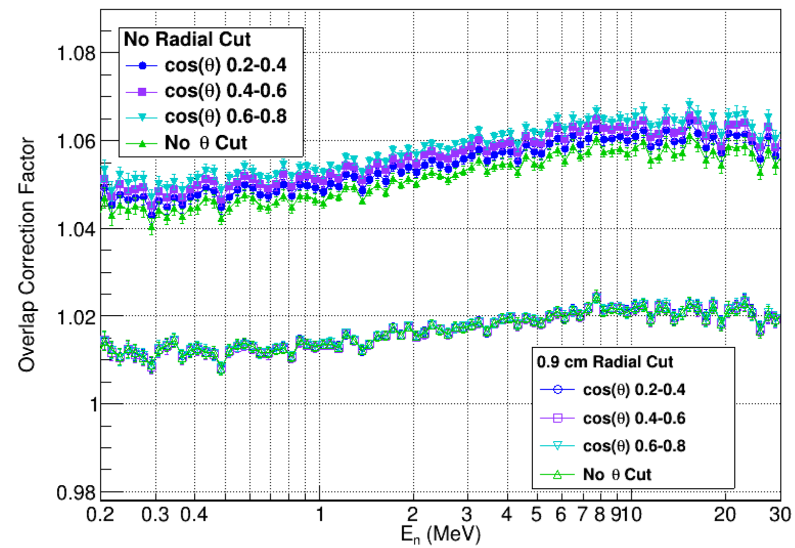


- Tracking resolution is ~300 μm
- Overlap term has normalization some sensitivity to bin size
- Edge of target represent large nonuniformity

Tracking Studies Summary







- Normalization *Sensitivities* up to 1%
- Tracking effects on overlap all corrected for. Uncertainties < 1%
- **No effect on shape**

FissionTPC Future

- Advanced, well characterized instrument
- X(n,cp)Y measurement
- XS, Angle, A/Z, multi-particle
- Workshop March 2018 Identified 6Li(n,t)a