The Neutron Induced Fission Fragment Tracking Experiment:

High-precision Fission Cross Section Measurements with a Time Projection Chamber

N. Bowden for the NIFFTE Collaboration

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Lawrence Livermore National Laboratory

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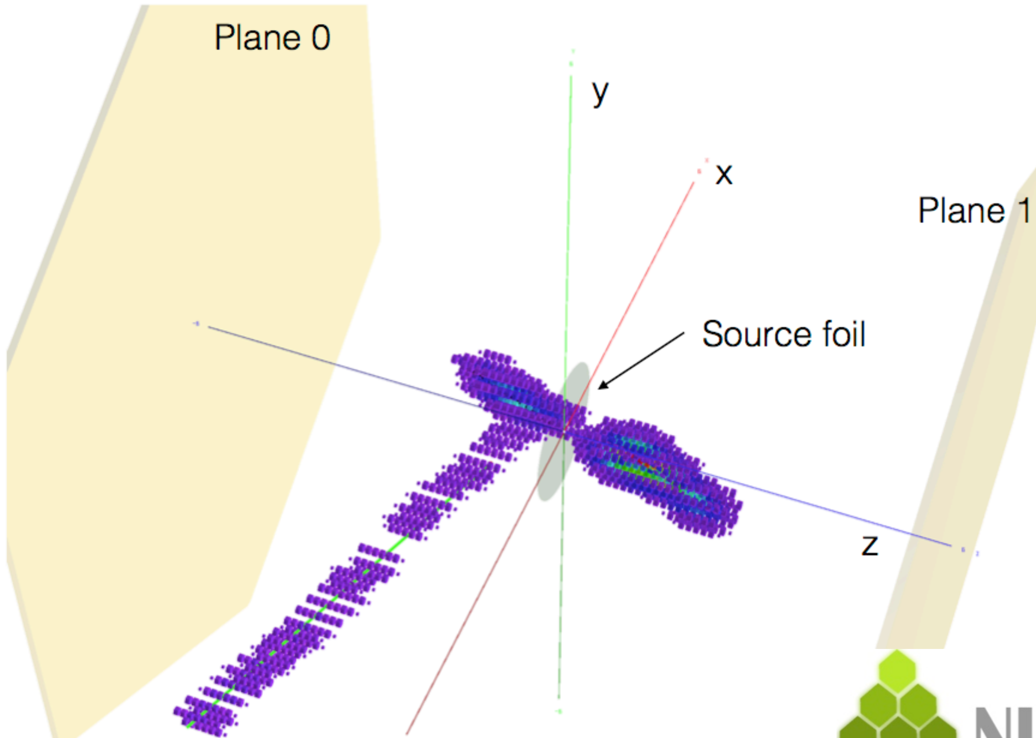
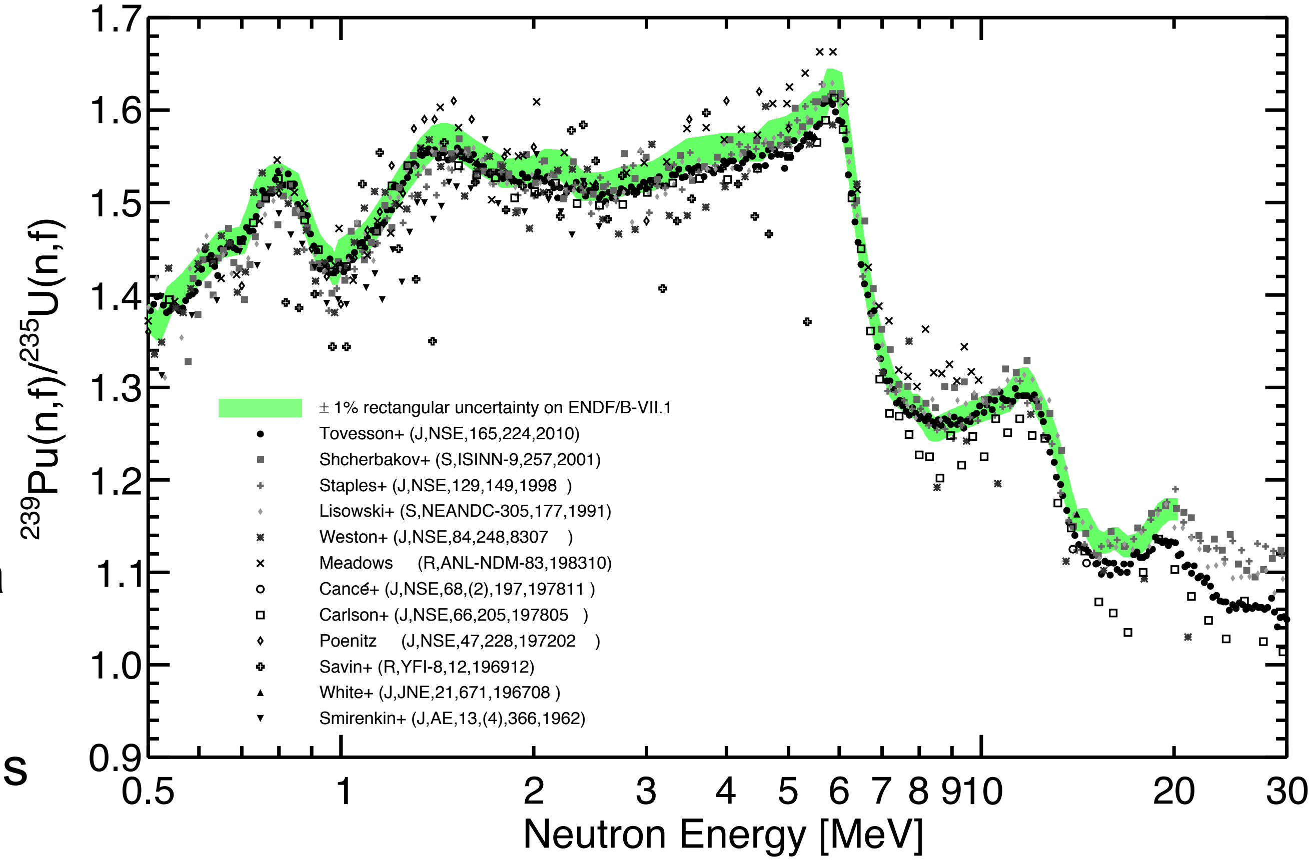
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC



Motivation:
Study and Improve Cross-Section Ratio Systematics

- Nuclear data uncertainties strongly influence design and operation margins in nuclear defense and energy applications

- Spread of existing data suggest uncontrolled and/or unrecognized systematic uncertainties



Quantities in the Cross Section Ratio Equation

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

Efficiency for fission fragment detection

Relative neutron flux

Total number of target atoms

Spatial overlap of beam fluence and target thickness PDFs

Detector live time

Measured fission fragments

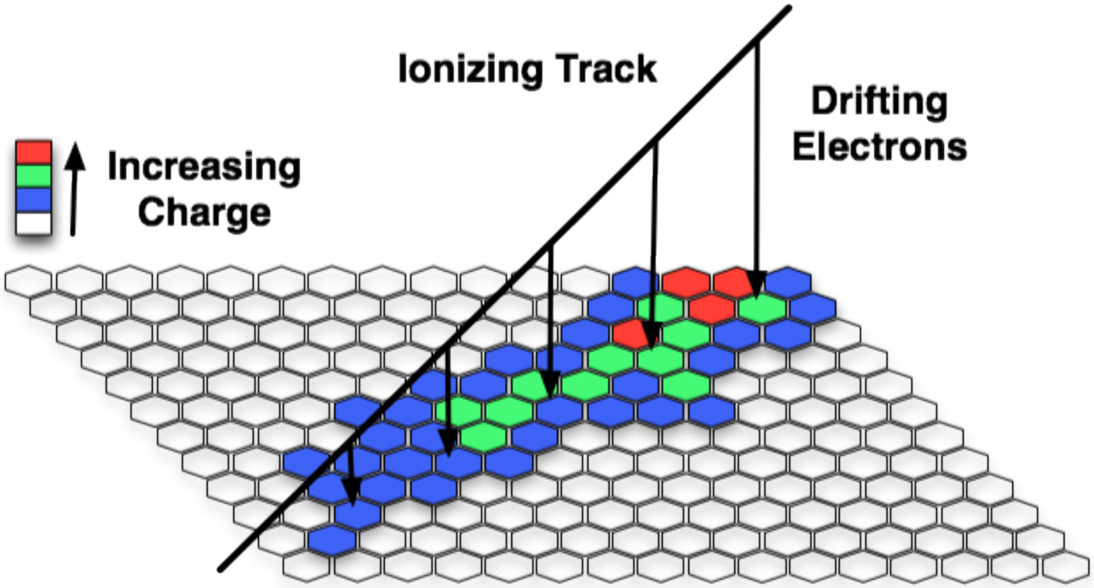
Beam-induced non-fission events

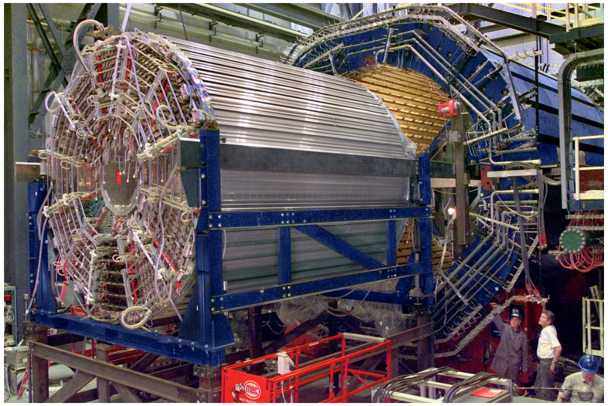
Spontaneous alpha decays

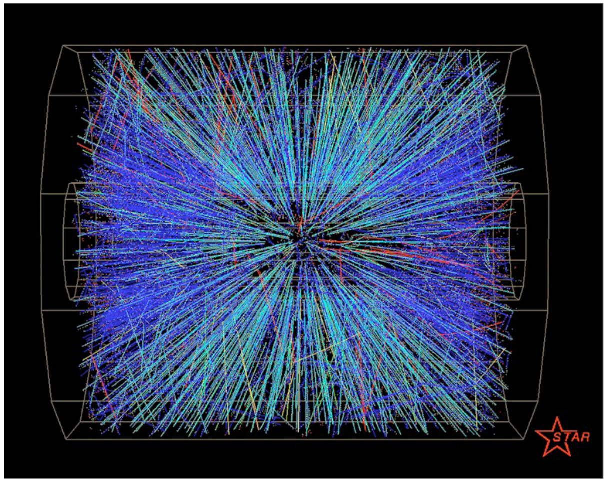
Fission fragments with incorrect neutron energy

Time Projection Chambers

- Take 3D ‘snapshots’ of charged particle tracks
- Developed since the 1970’s for high energy physics, nuclear physics, and particle astrophysics





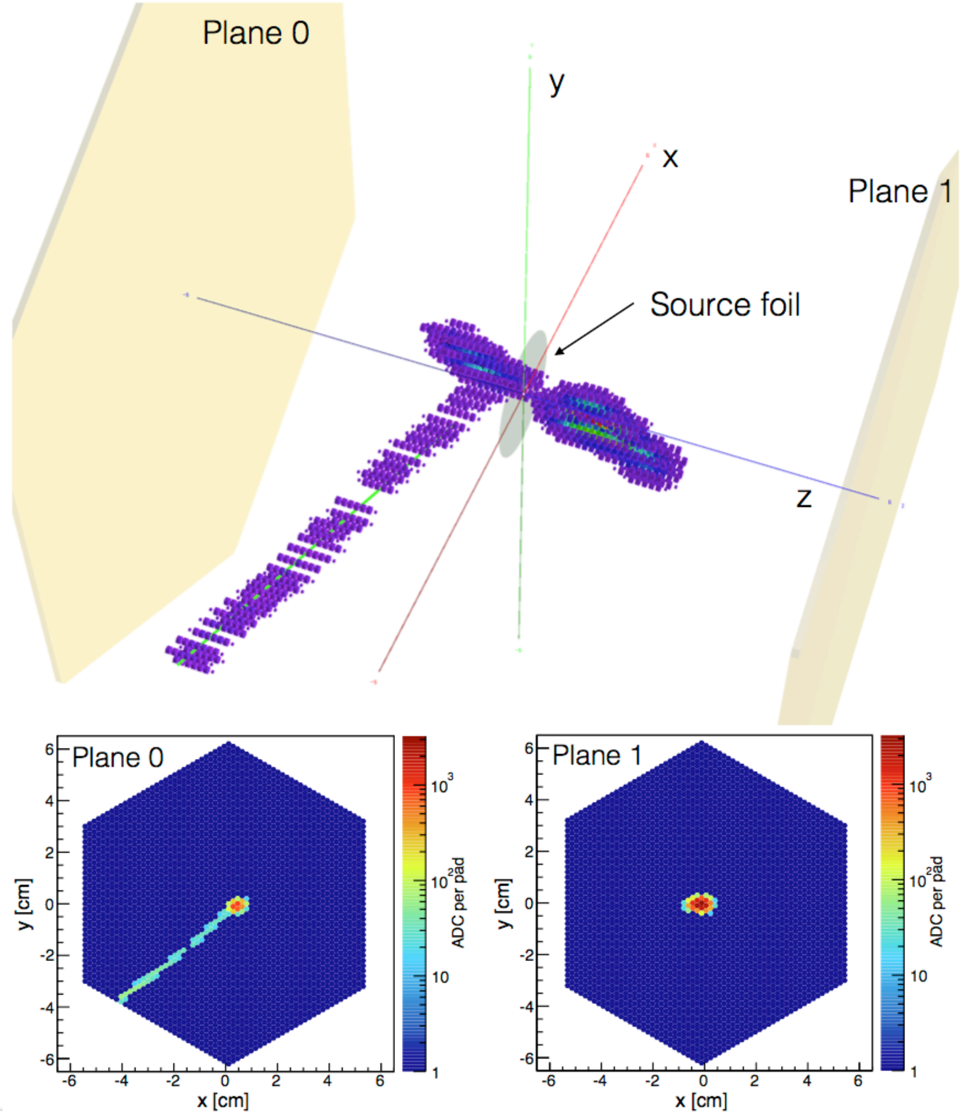


Unique features of the FissionTPC:

- First TPC to operate in a high energy neutron beam
- Wide dynamic range requirement – cover specific ionization range between protons and fission fragments
- High interaction rates (MBq α-particle activity from Pu targets)

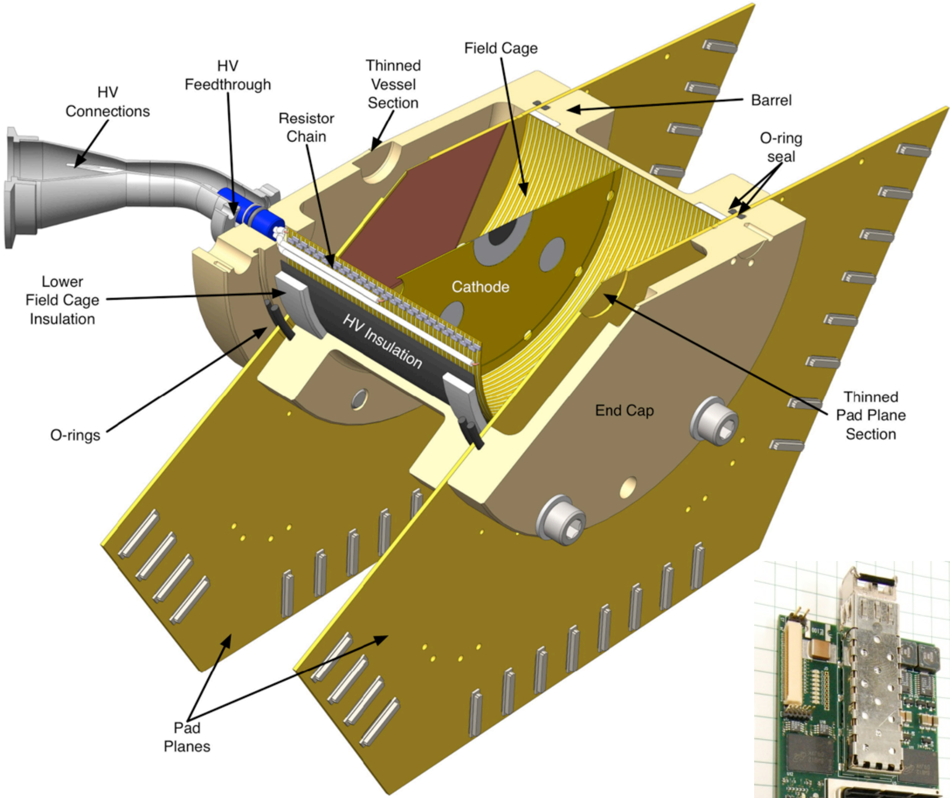
The NIFFTE fissionTPC will allow detailed study of potential systematics

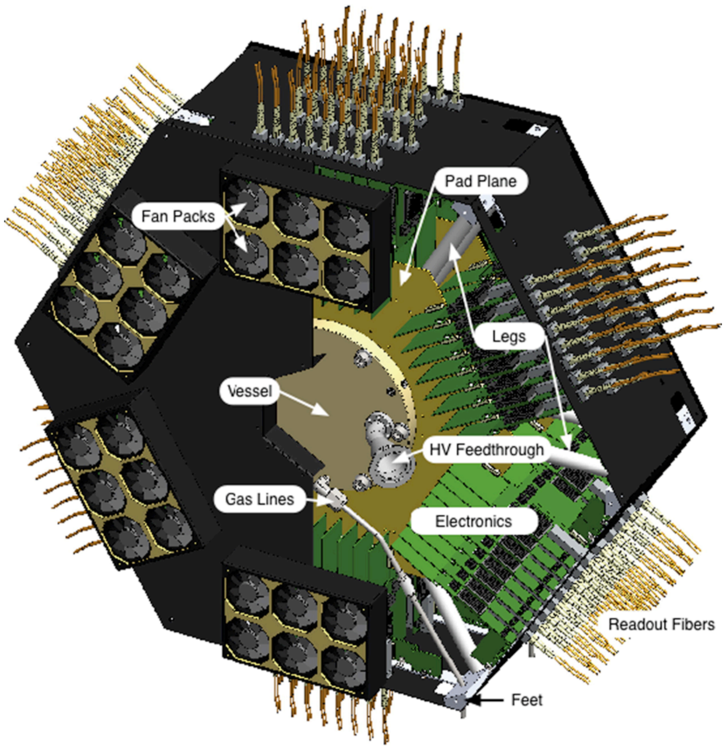
- Particle identification
  - Full track reconstruction, incl. dE/dx for PID
  - Rejection of alpha & recoil backgrounds
- Target/beam non-uniformities
  - In-situ beam profiling, target radiography
  - Multi-actinide targets
- Reference standards
  - Will use H bearing gas/target to measure (n,f) relative to ^{1}H(n,el)



fissionTPC Design

- Dual volume MICROMEGAS TPC
- 2976 x 2 hex pads (2mm), 54mm drift length
- 95% Ar / 5% isobutane drift gas



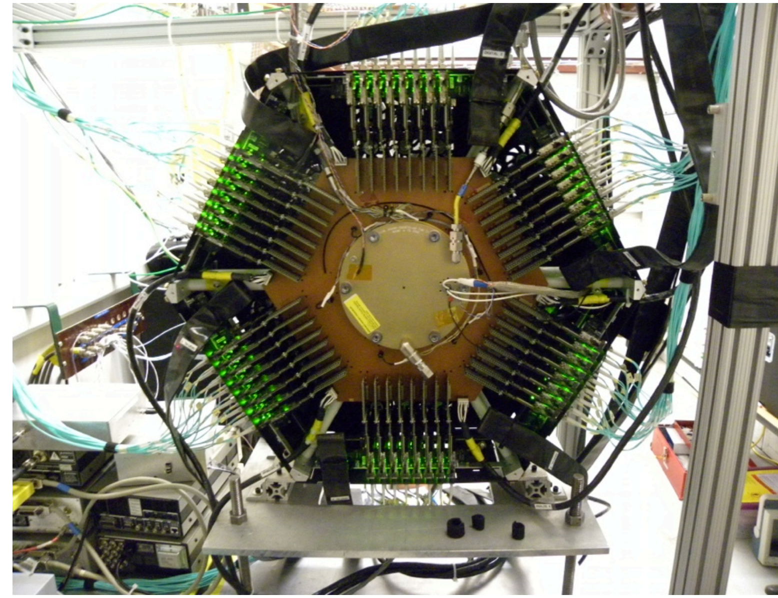


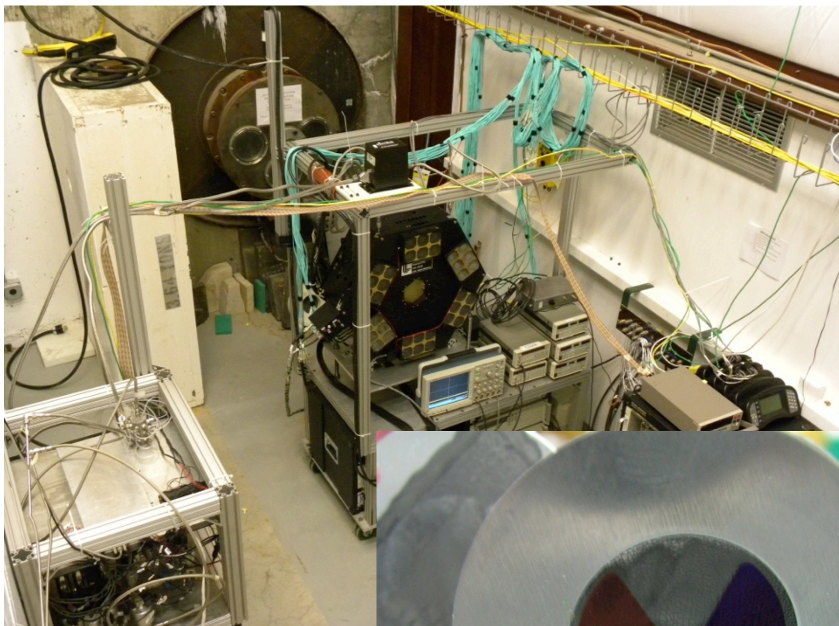
- Custom DAQ
  - Every pad recorded at 50MHz
  - Cathode recorded at 1GHz for neutron TOF measurement
  - $55 per channel

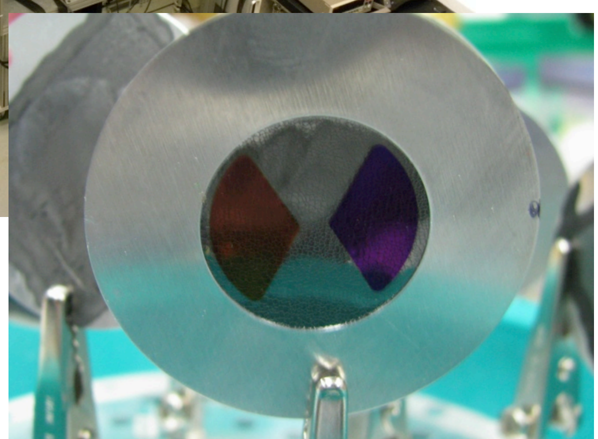
TPC description: M.Heffner, et. al., NIMA, 10.1016/j.nima.2014.05.057
DAQ design: M.Heffner, et. al., IEEE TNS **60** (2013) 2196

fissionTPC Operation

- Cross-section measurements performed at LANSCE 90L beamline
  - Data volume ~ 100s of TB/yr

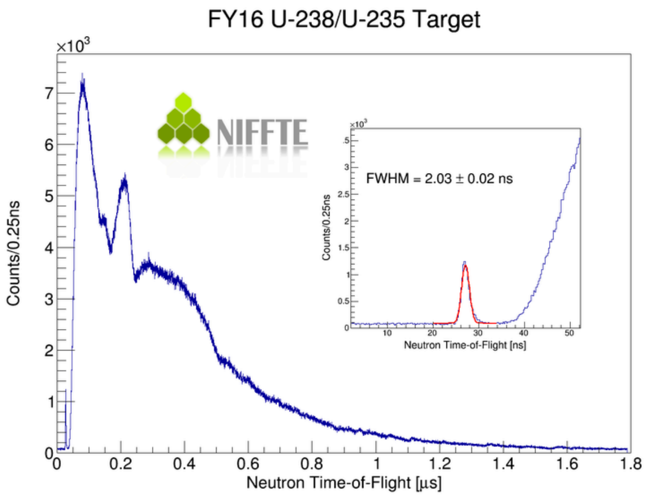


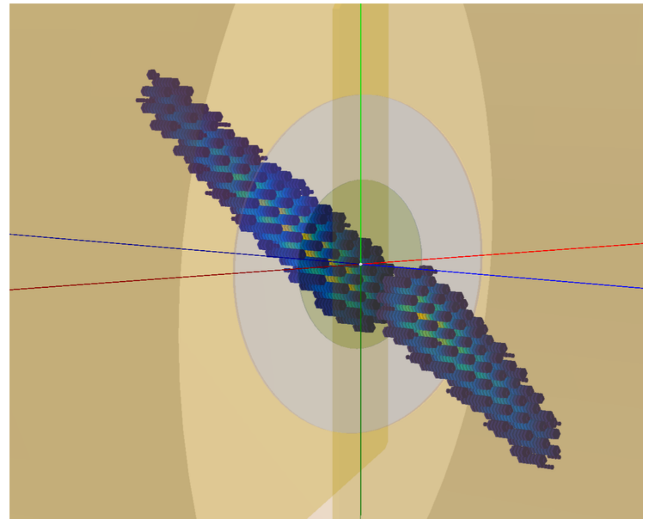


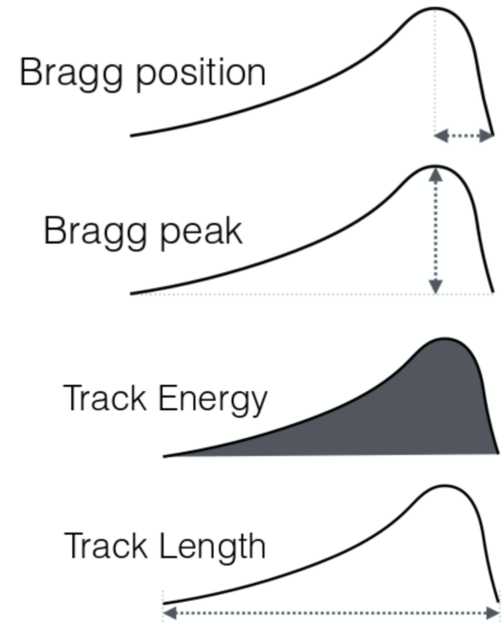


- Wide variety of targets used & planned:
  - ^{239}Pu, ^{235}U, ^{238}U, ^{252}Cf, ^{244}Cm
  - multi-actinde
  - thin & hydrogenous backings
  - activities as high as ~MBq

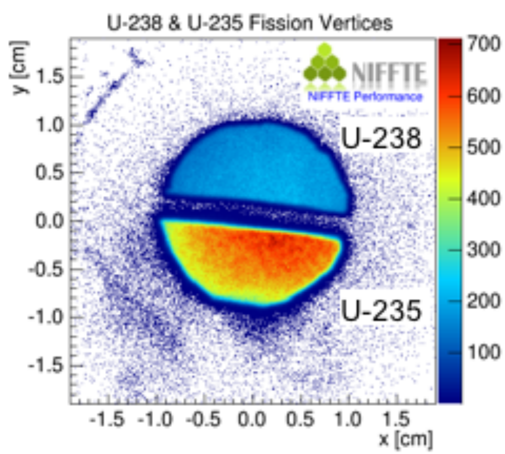
Quantities measured by the TPC

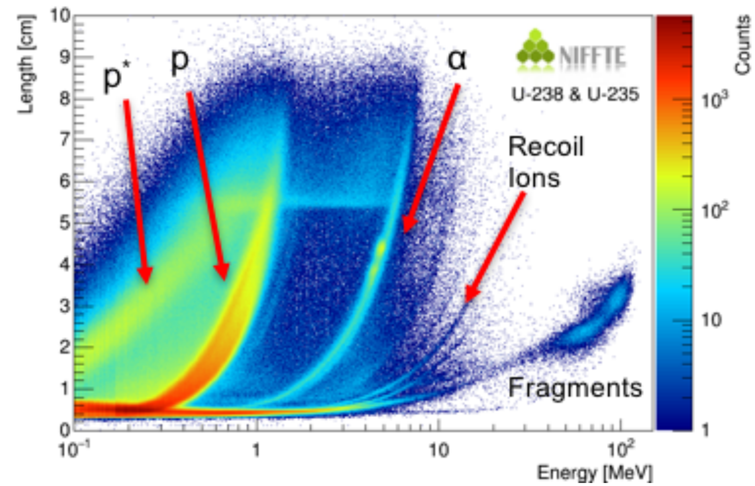






- Neutron time-of-flight measured to infer neutron energy.
- 3D ionization profile for individual tracks provides:
  - Track length
  - Total energy
  - Location & value of max ionization
  - Interaction vertex
  - Track direction





Target Atom Number Ratio

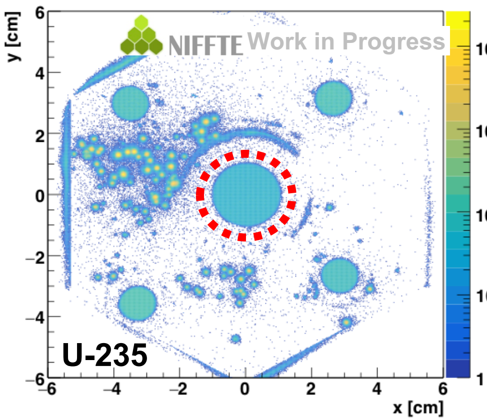
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff}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

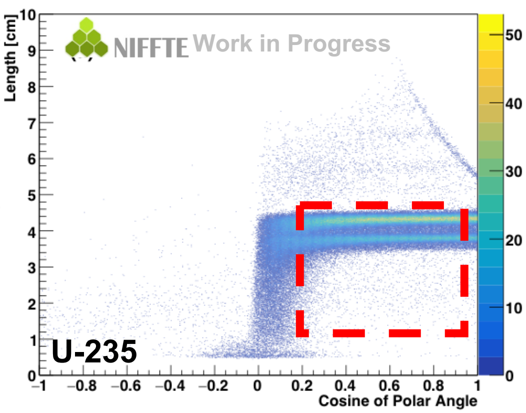
Measured using TPC, and a precision α-particle Counting System for validation

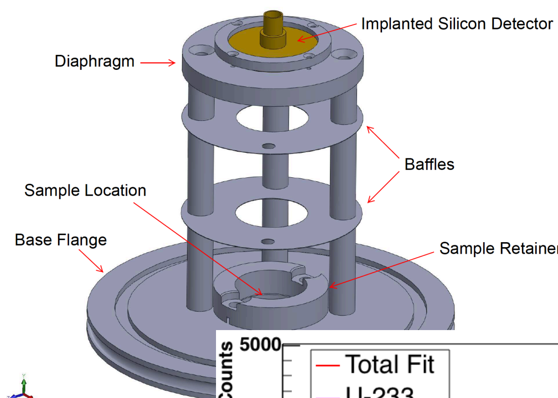
TPC Determination

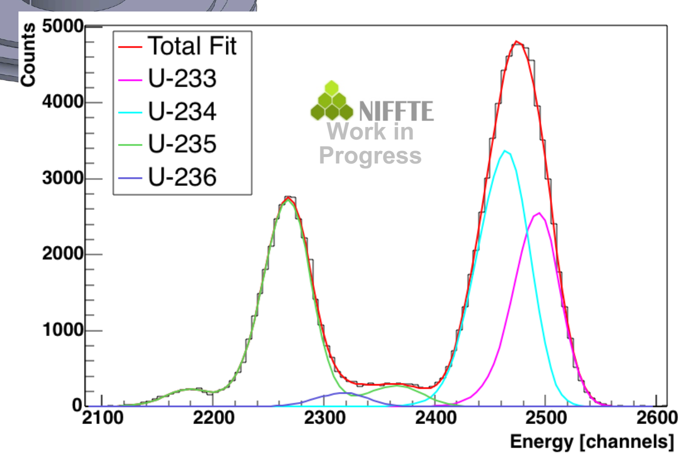
See K. Schmitt Poster

αCS Determination









- Select parameter regions, identical for each target, where reliable tracking has been demonstrated
  - Avoid regions with high straggling, higher energy daughter lines, …
- Correct for double counting and other tracking artifacts, esp. for Pu-239

- Counting setup defines identical & repeatable solid angle for actinide targets
- Mass Spec. results constrain isotope ratios in spectral fit

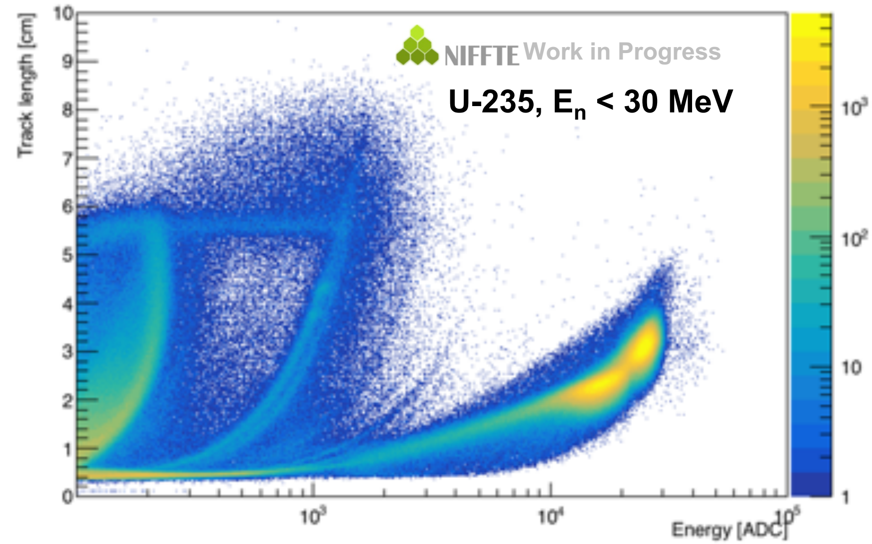
TPC Result: N_{U5}/N_{P9} = 1.759 +/- 0.011

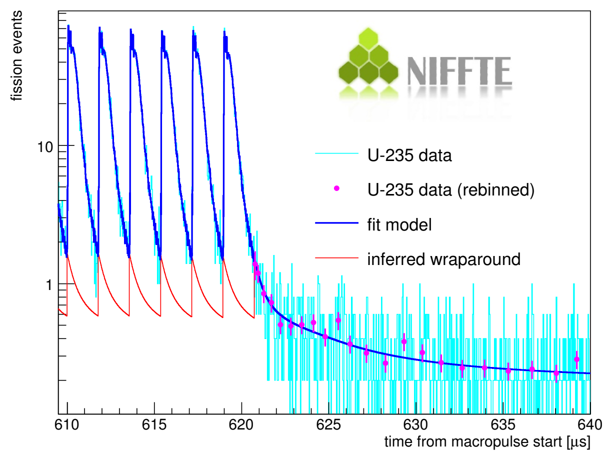
αCS Result: N_{U5}/N_{P9} = 1.760 +/- 0.010

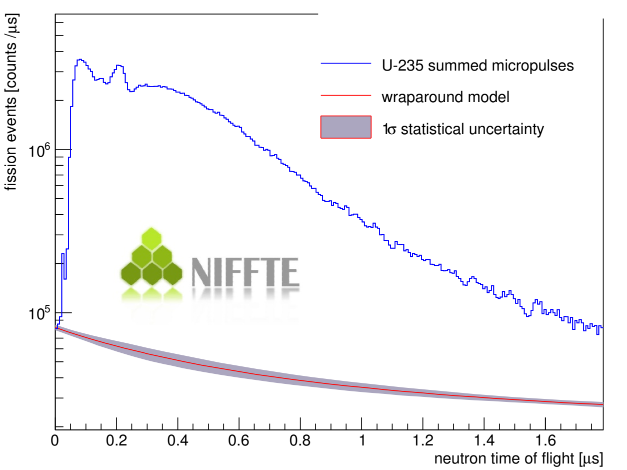
Background terms

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

- 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





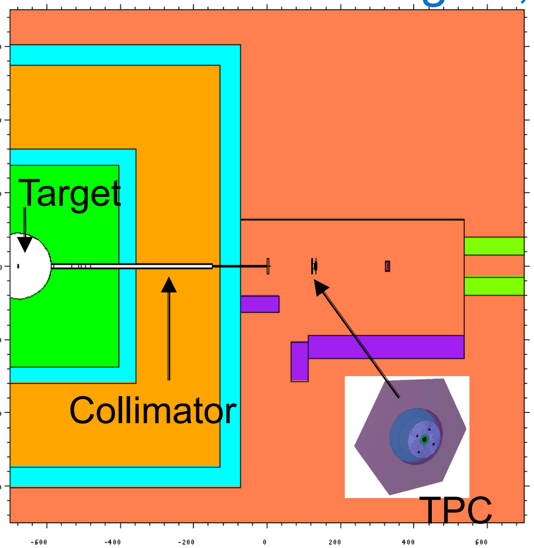


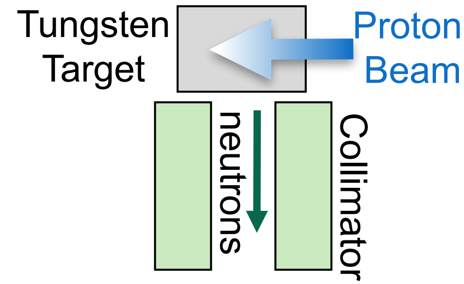
- Wrap-around correction (C_{bb}) represents low-energy tail in nToF spectrum, extending into following micropulses.
- Wrap-around shape is product of cross section & neutron flux transformed into nToF domain
  - ideally requires full simulation with free geometry/spallation physics
  - At present, a logarithmic spline is used
- Fit model for single-micropulse wraparound tail to whole-macropulse structure
  - Most significant constraint on wraparound is from tail of last micropulse

Neutron Flux Profile & Attenuation

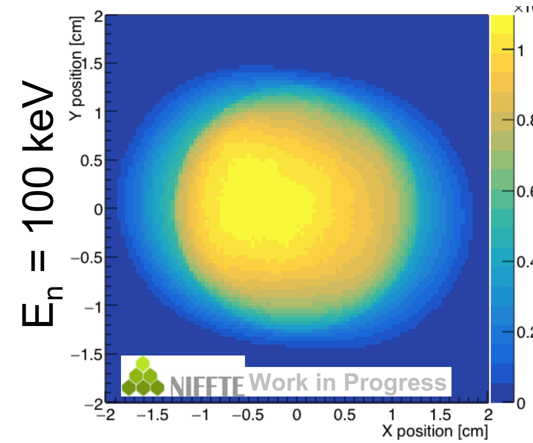
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i}\cdot n_{s,i})}{\sum_{XY}(\phi_{x,i}\cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff}-C^x_r-C^x_\alpha)-C^x_{bb}}{(C^s_{ff}-C^s_r-C^s_\alpha)-C^s_{bb}}$$

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



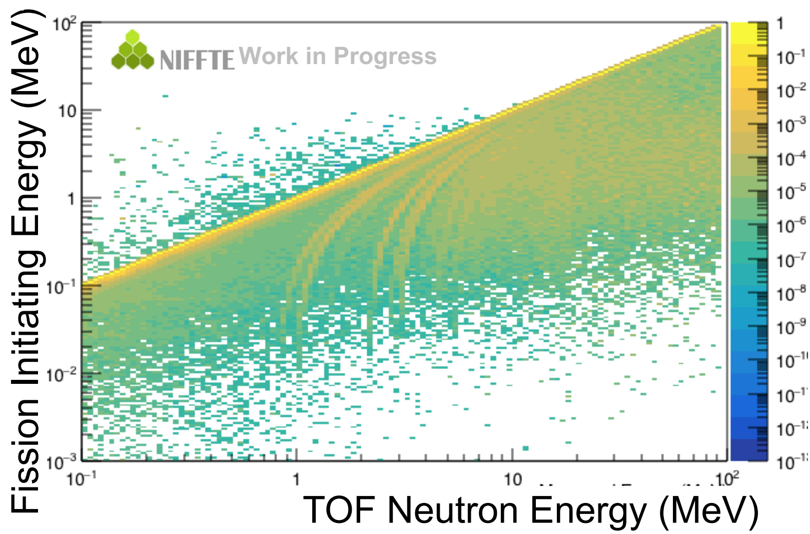


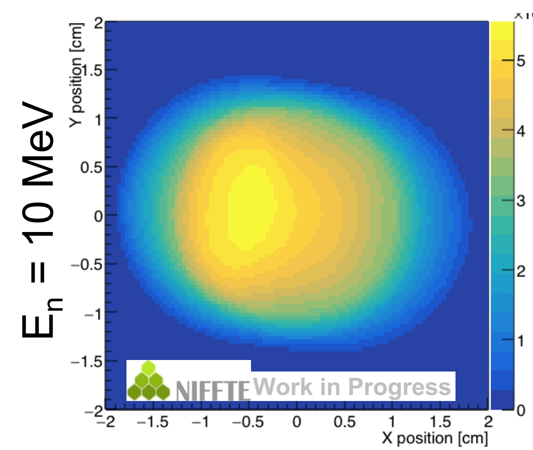
- Proton beam energy loss in the spallation target results in a non-uniform neutron beam profile
- Importantly, the spatial profile varies with neutron energy (at the TPC)



We use the MCNP model to account for:

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





Neutron Flux Profile & Target Overlap

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

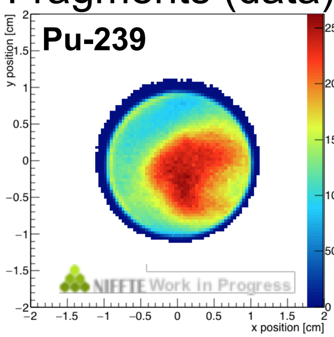
Correction required if beam *and* actinide target have spatial non-uniformity

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

'Fission/Alpha' distribution provides representation of neutron beam flux profile *at each energy*;

MCNP profile translated & scaled to match via fit to account for model/data discrepancies

Fragments (data)



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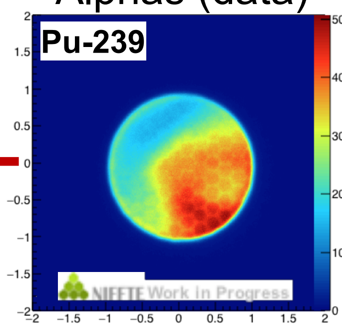
Alphas (data)



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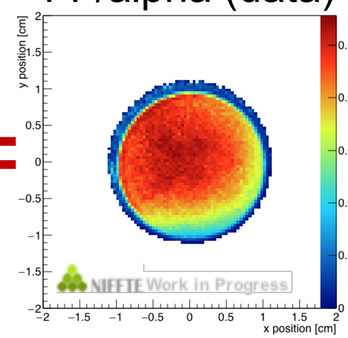
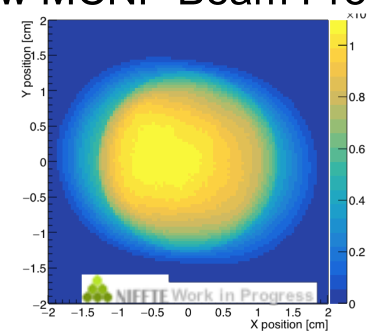
FF/alpha (data)

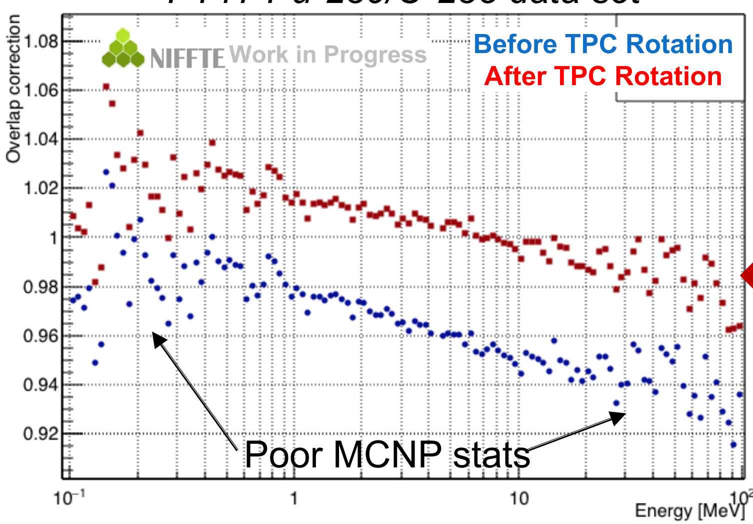


Fit

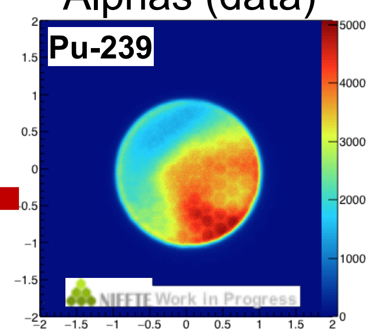
Raw MCNP Beam Profile



FY17 Pu-239/U-235 data set

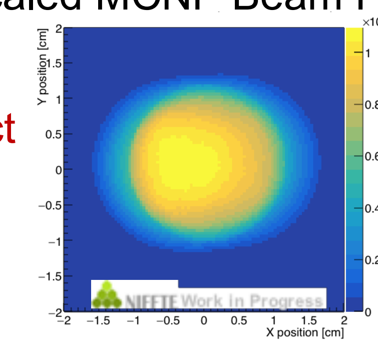


Alphas (data)



Dot product

Scaled MCNP Beam Profile



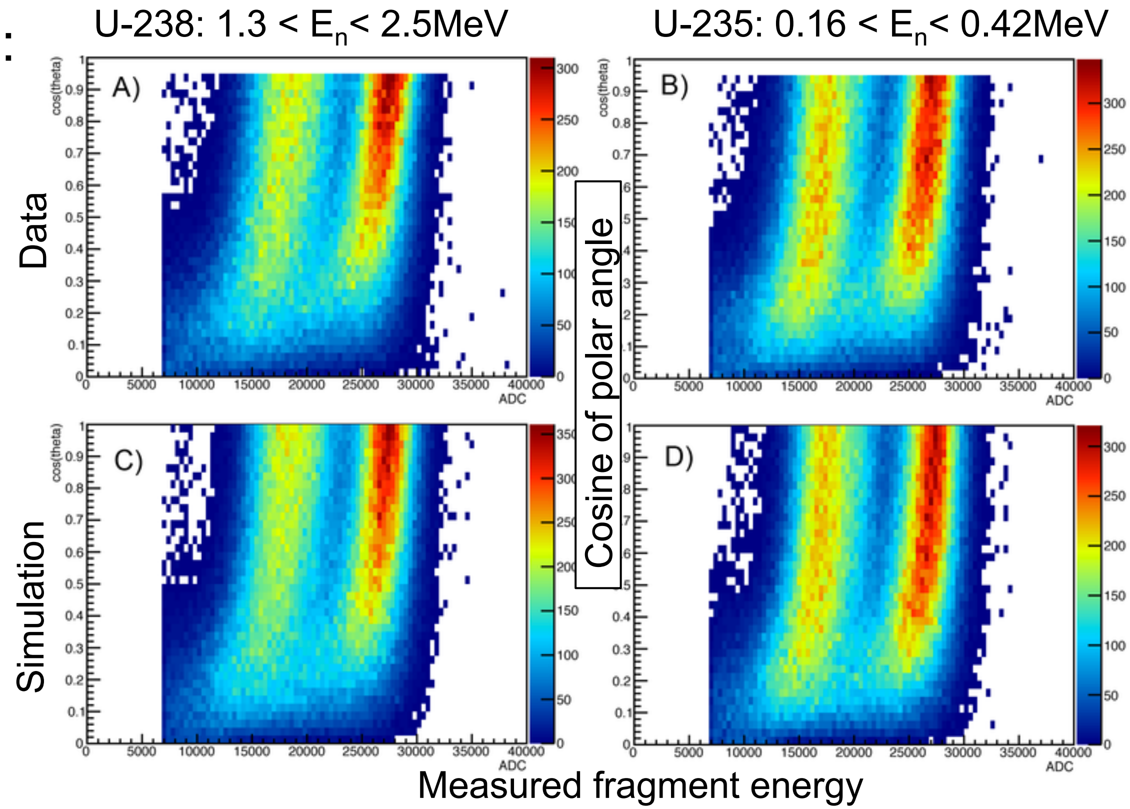
(these profiles do not cover same neutron energy range, but pictorially represent the procedure)

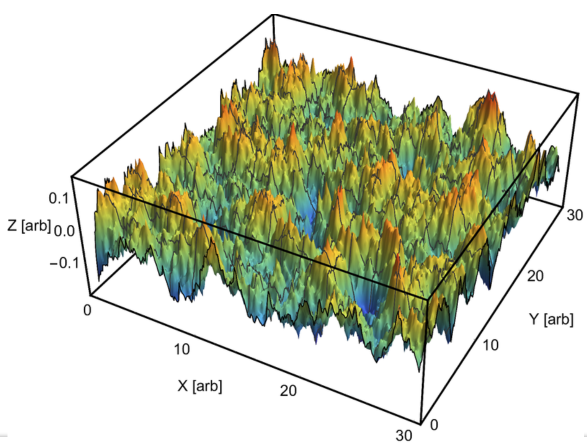
Fission Fragment Efficiency

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

Developed phenomenological model to describe fragment detection efficiency

- Incorporates myriad of effects:
  - fragment straggling in target
  - fission product yields
  - fragment stopping power
  - quantum and kinematic anisotropy
  - target thickness, composition, and surface roughness.
- Implemented via multi-parameter fit of observable distributions to Monte Carlo data realizations





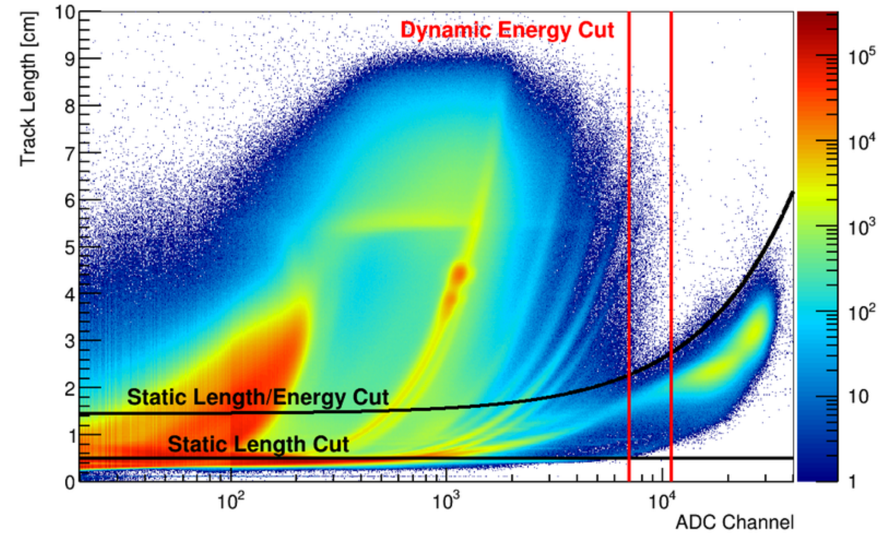
Fractal model of target surface roughness

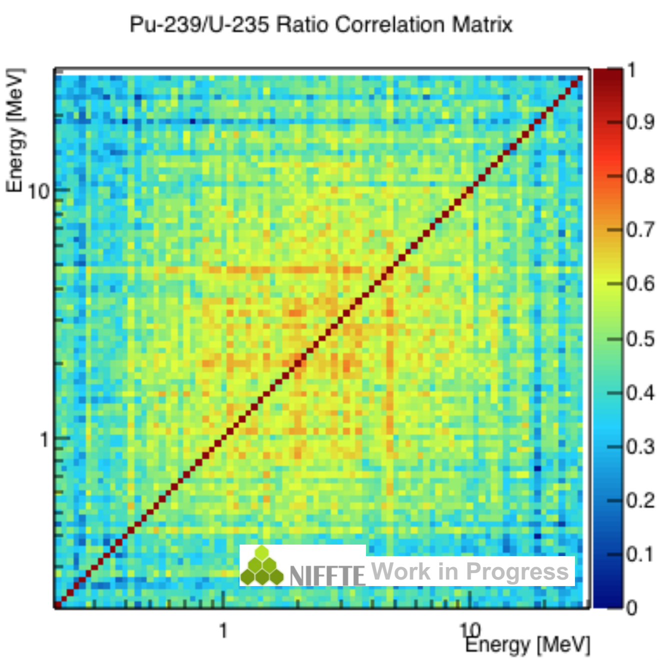
Figures from forthcoming U-238/U-235 ratio publication submitted to PRC

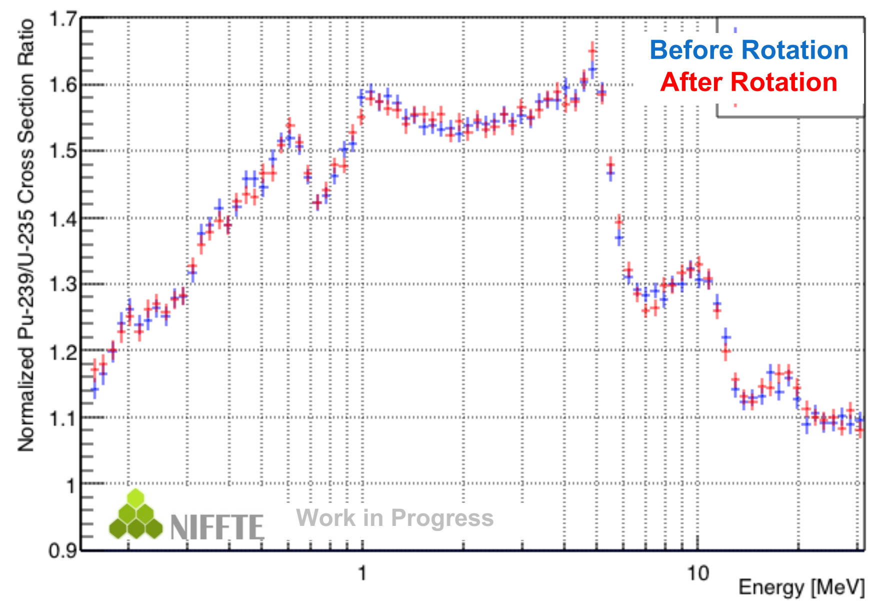
Uncertainty & Validation

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

- Residual (unaccounted for) systematic uncertainties estimated by ***cut variation***
- Uncertainty propagation & covariance performed by sampling fit parameter dists.
- Validations performed by ***TPC rotation*** and ***data set decimation***, e.g.:
  - Odd vs. Even run numbers
  - Morning vs. Night (time of day)
  - First vs. Last half of run

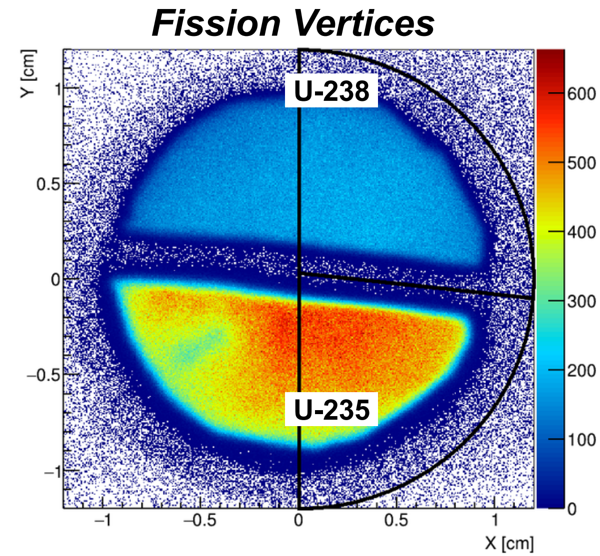


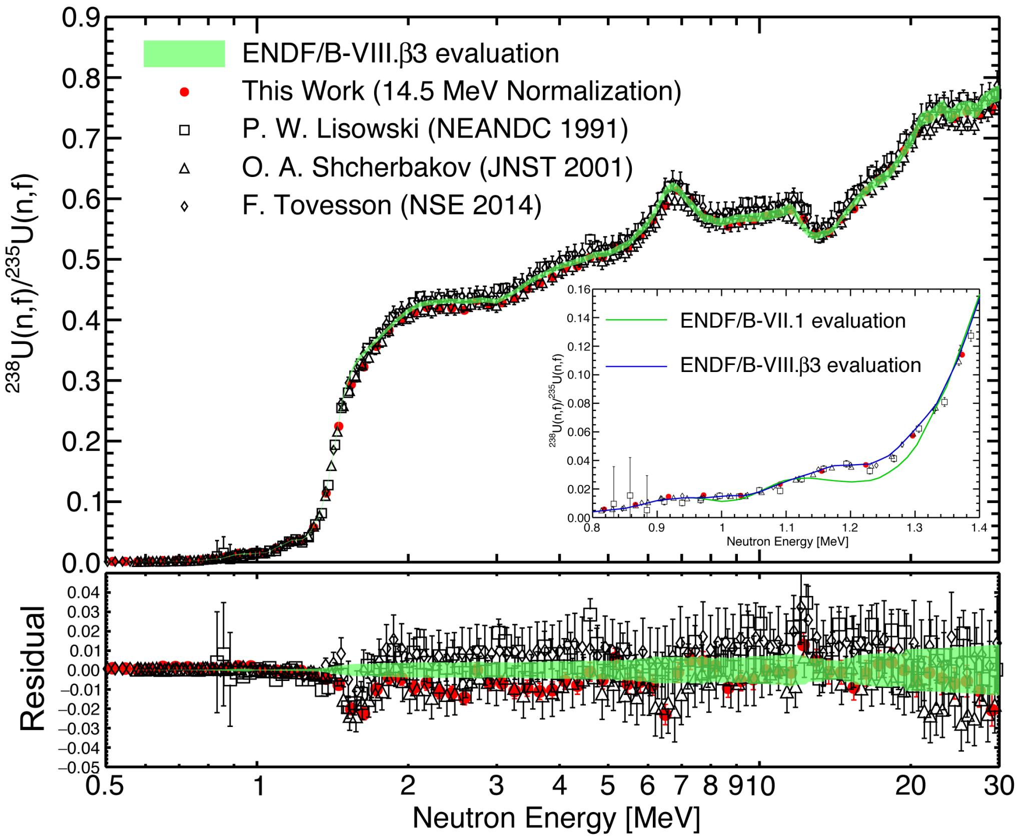


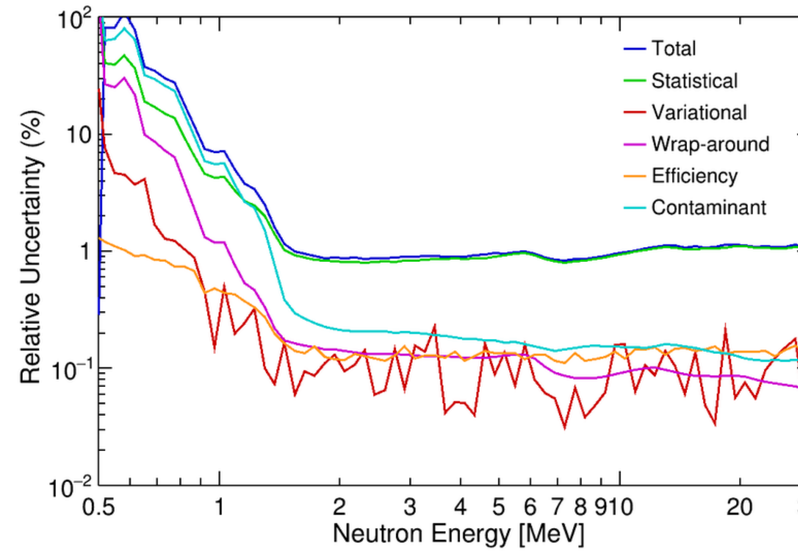


U-238/U-235 Fission Cross Section Ratio

- Used ‘half moon’ actinide deposits on thin backing
- Unable to normalize neutron flux using recoil protons due to gain non-uniformity, energy dependent spatial variation (acceptance) and possible TPC tilt
- Therefore, ***normalized to ENDF/B-VIII.β3 at 14.5 MeV***



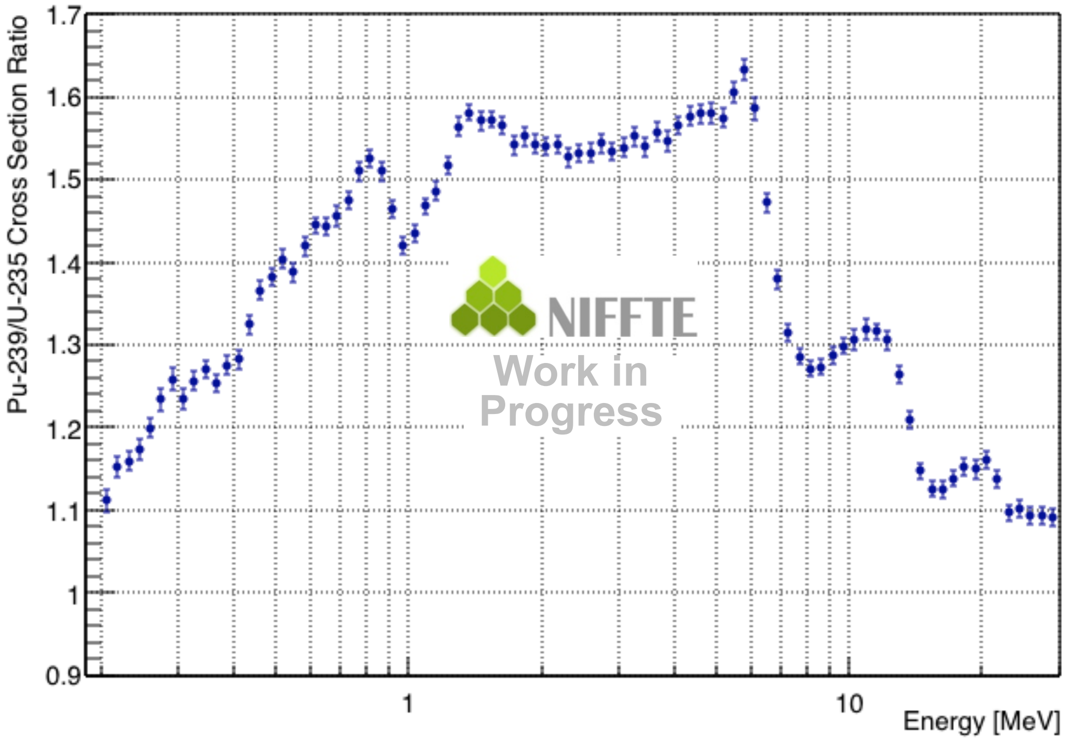


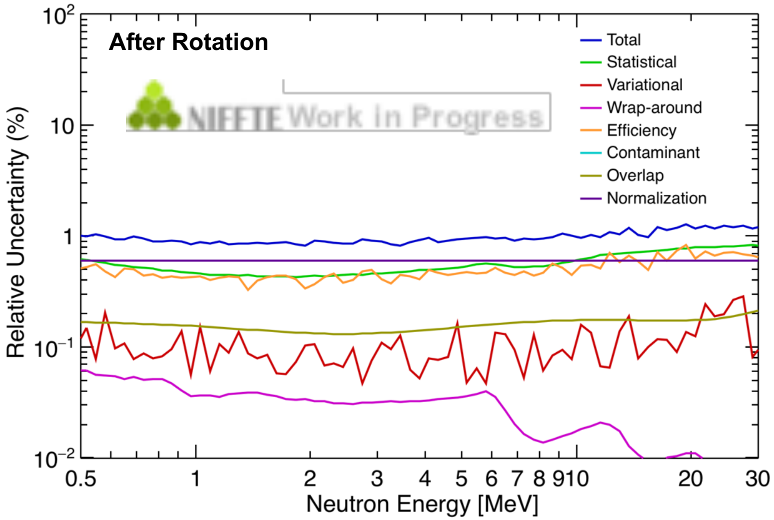


Figures from forthcoming U-238/U-235 ratio publication submitted to PRC

Pu-239/U-235 Fission Cross Section Ratio

- Used back-back deposits on thick backing – x-y overlap allows neutron flux normalization as described earlier
- Performing final validations of efficiency model, including TPC rotation
- Preliminary ratio presented here
  - Approaching 1% relative uncertainty goal, with primary contributions coming from normalization, efficiency model, and event statistics





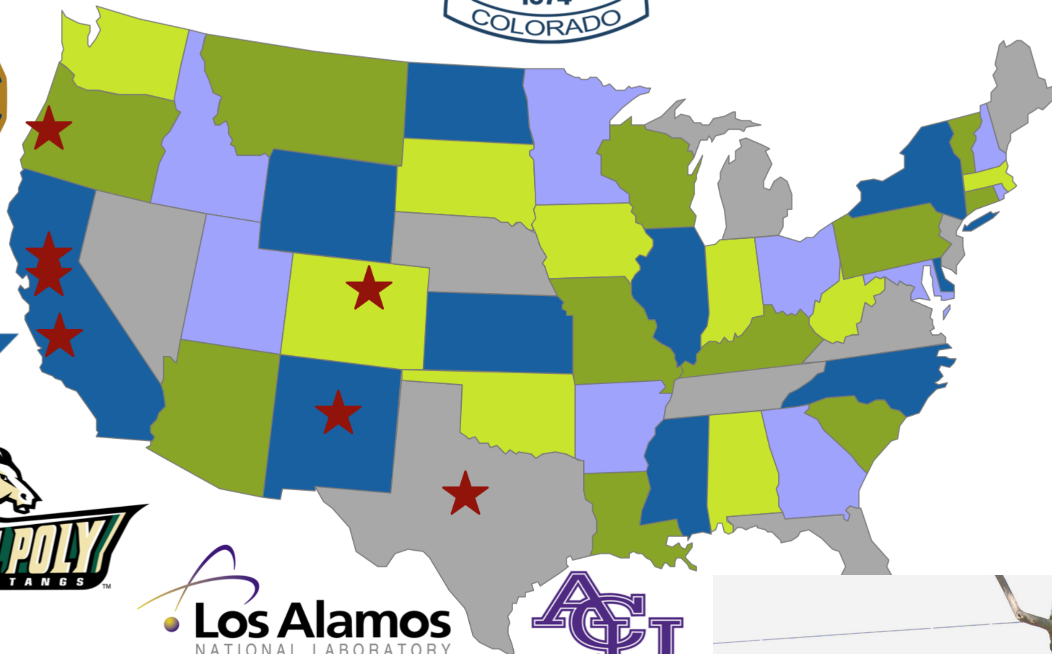
Aim to submit Pu-239/U-235 ratio publication before end of 2017

NIFFTE

OREGON STATE

SCHOOL OF MINES 1874 COLORADO

UC DAVIS AGGIES



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Conclusion

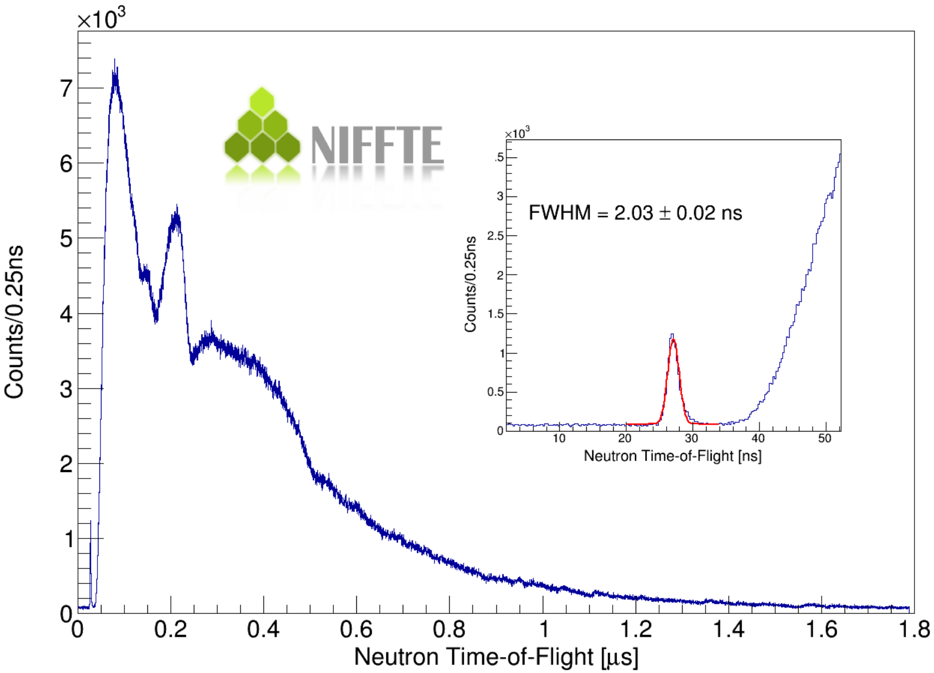
- The NIFFTE fissionTPC can probe systematic uncertainties in fission cross-section measurements
- The fully instrumented TPC has been operating since 2013
- Instrument performance has been being characterized through a broad range of measurements & detailed simulation studies
- ^{239}Pu(n,f)/^{235}U(n,f) & ^{238}U(n,f)/^{235}U(n,f) cross section ratio, ^{235}U Fission Anisotropy measurements nearing publication
- ^{239}Pu(n,f)/^{1}H(n,el) measurements will be the focus of future data taking periods

Backup Slides

FissionTPC Time-of-Flight

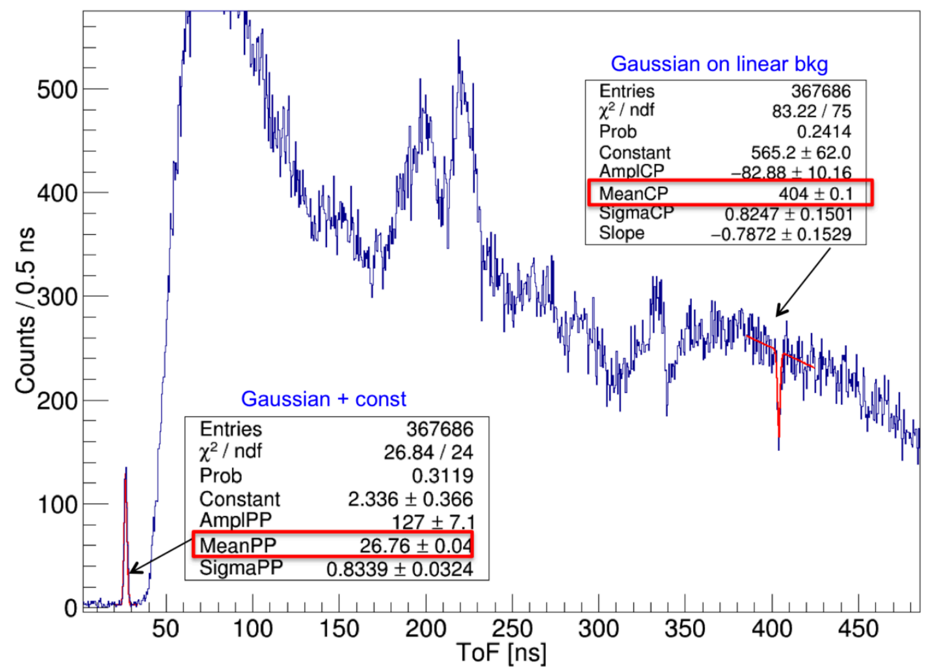
$$\frac{\sigma_x}{\sigma_s} = \frac{\epsilon^s_{ff}}{\epsilon^x_{ff}} \cdot \frac{\Phi_s}{\Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY}(\phi_{s,i} \cdot n_{s,i})}{\sum_{XY}(\phi_{x,i} \cdot n_{x,i})} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{(C^x_{ff} - C^x_r - C^x_\alpha) - C^x_{bb}}{(C^s_{ff}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

U238 & U-235 ToF Distribution



- Timing resolution = 2.03 ns FWHM
- Better or comparable to fission chamber

Flight Path Length Measurement



- Carbon-filter technique
- Flight Path = 8059 ± 3 (stat) ± 1 (syst) mm
- Validated with auxiliary fission chamber data and physical measurements