Measurements of Prompt Neutron Emission from Photofission of ^{235}U, ^{238}U, and ^{239}Pu

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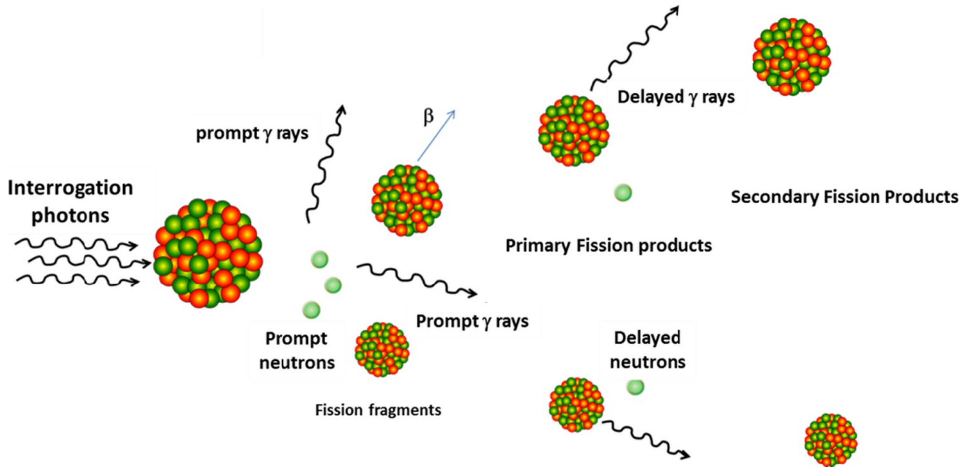


Outline

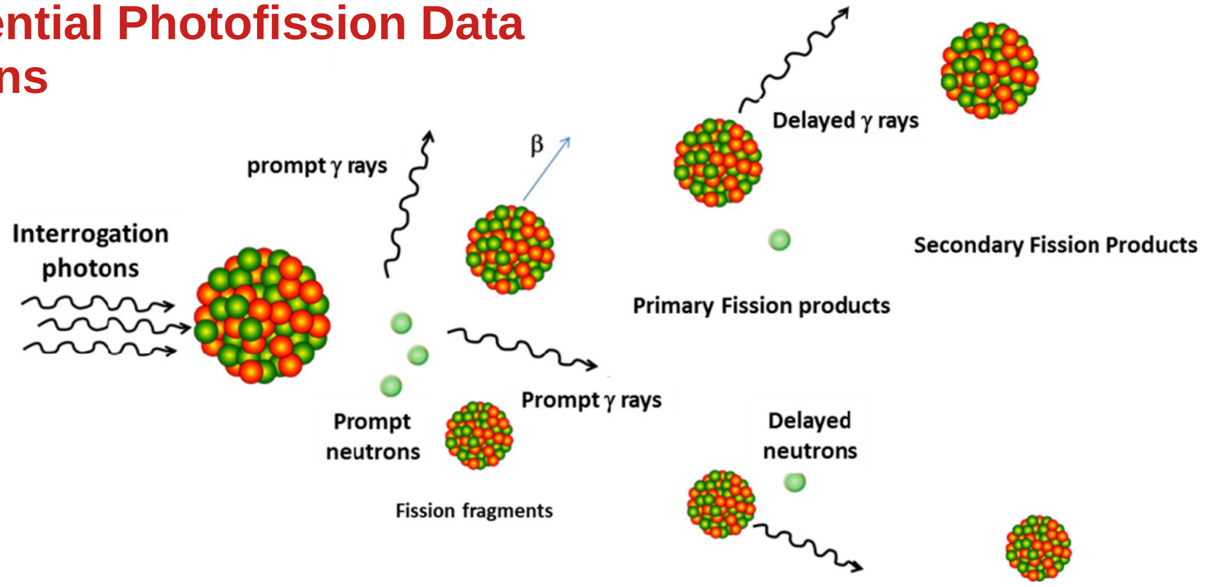
First Energy-Angle Differential Photofission Data w/ ~Monoenergetic Photons

- Brief intro, motivation

- Simulation and Supporting Measurements
  - GEANT4 simulation approach
  - ^{252}Cf active source measurements
  - Scintillator light output function measurements

- Measurements with E_γ <= 10 MeV
  - Measure outgoing neutrons above 1 MeV
    - Extrapolate to 0 with Maxwellian fits
  - Estimate (γ,n) neutron contribution with fits
  - Estimate balance of (γ,f) and <ν> using coincidence measurements
  -

- Active target measurements for E_γ = 10, 13.5, 16 MeV
  - Direct access to <ν>
  - Unambiguous removal of (γ,n) events



$$\frac{d\nu_n(\theta_n,\phi_n,E_n)}{d\Omega dE_n} = \frac{Y_n(\theta_n,\phi_n,E_n)}{N_f}\left(\frac{1}{d\Omega dE_n}\right)\frac{\epsilon_f}{\epsilon_n(E_n)}$$

$\nu_n \equiv$ Differential neutron multiplicity

$Y_n \equiv$ True coincidence yield for the detector

$N_f \equiv$ Number of fission events

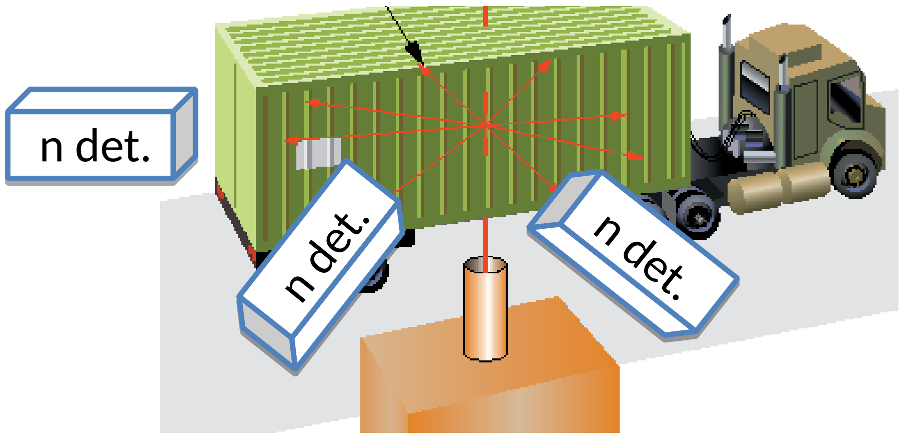
$\epsilon_n \equiv$ Neutron detection efficiency as function of E_n

$\epsilon_f \equiv$ Fission fragment detection efficiency

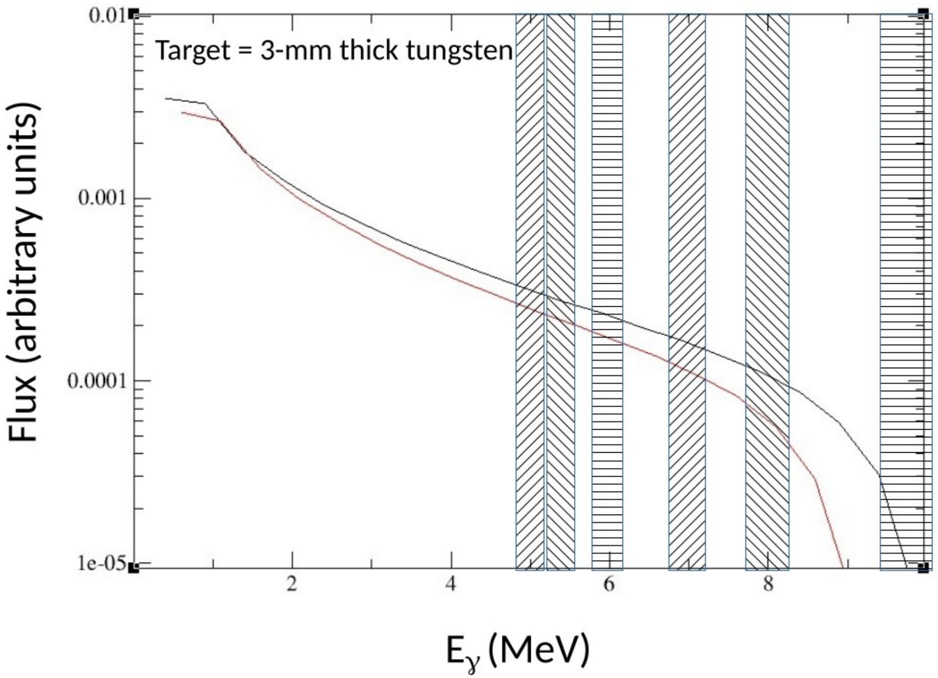
$d\Omega \equiv$ Detector solid angle

Motivation

- How does one efficiently scan for nuclear material?
- To look for fissionable materials, look for the signature of fission: neutrons
- Fission is most commonly initiated with neutrons, but neutrons also cause activation in other materials.
- Fissionable materials are unique in that they produce relatively large amounts of neutrons from <10 MeV photons.
  - The photofission cross section falls off quickly with energy
  - A realistic photon source would use Bremsstrahlung radiation
    - Most of the flux is at low energy where photofission cross sections are very low



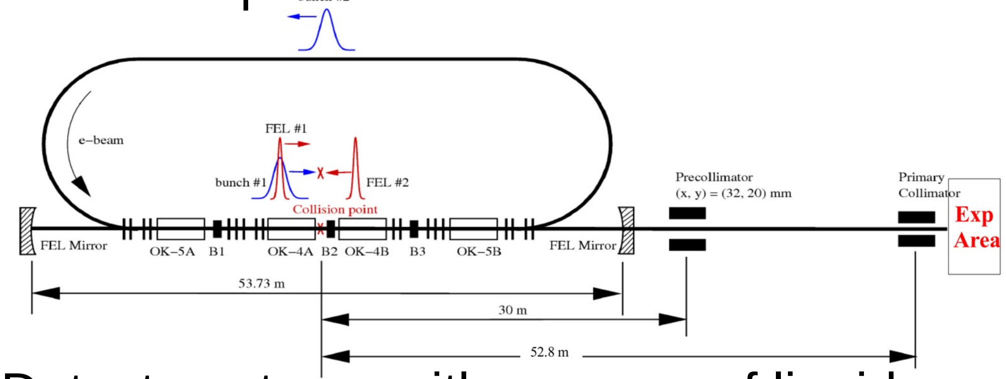
Bremsstrahlung distribution at 10 and 9 MeV



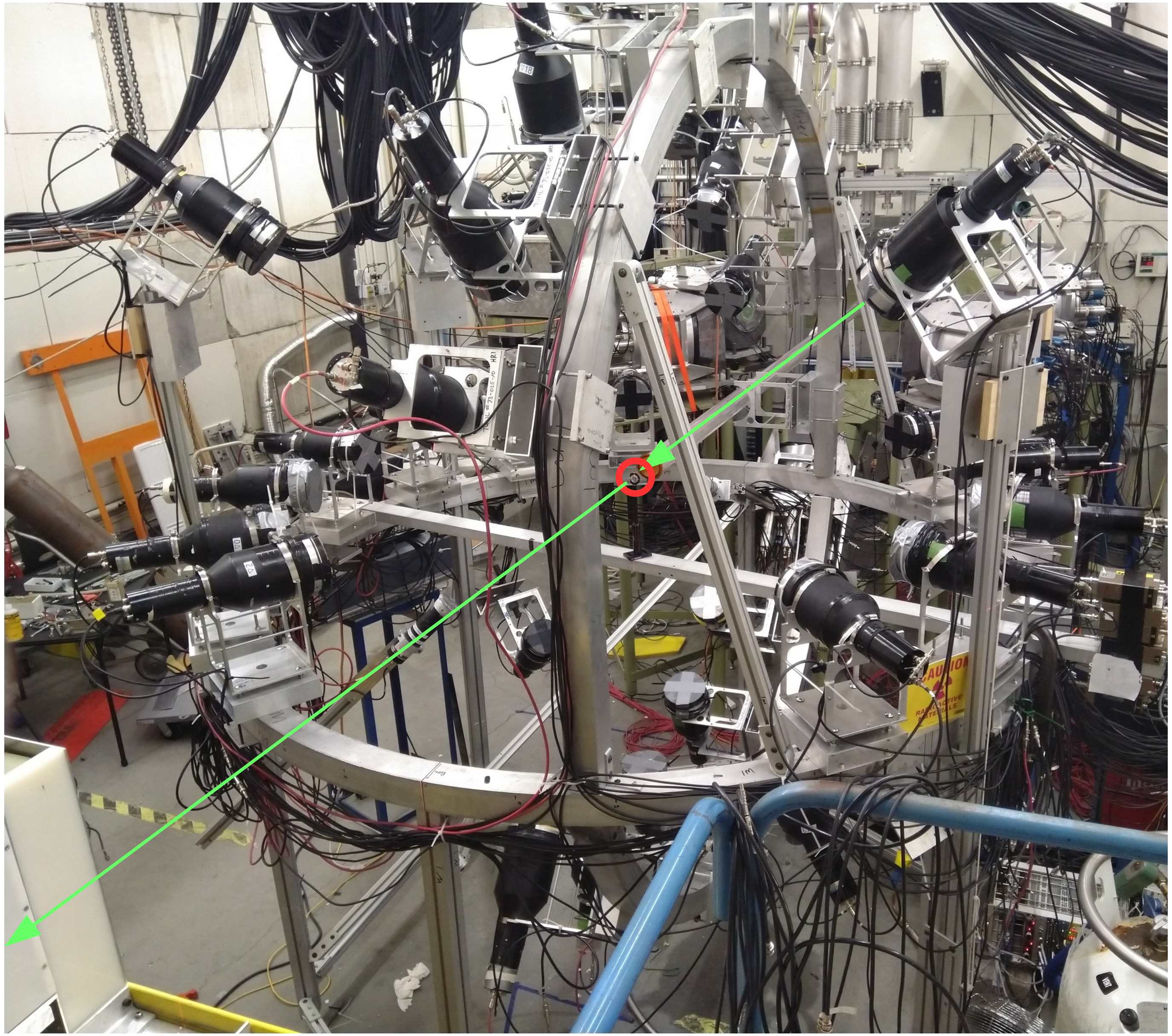
Figures adapted from talk by C.R. Howell

General Experimental Approach

- Produce incident gamma rays by inverse compton backscattering at the High Intensity Gamma Source (HIγS) facility at TUNL
  - Circular Polarization
  - Pulse period 179.22 ns

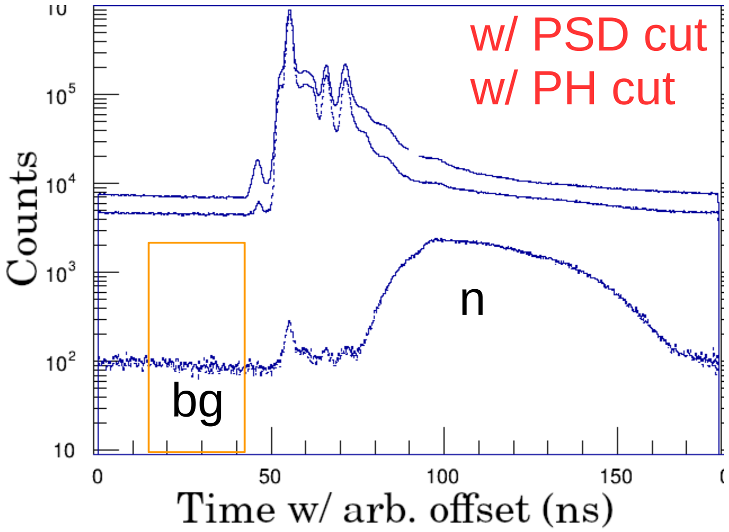


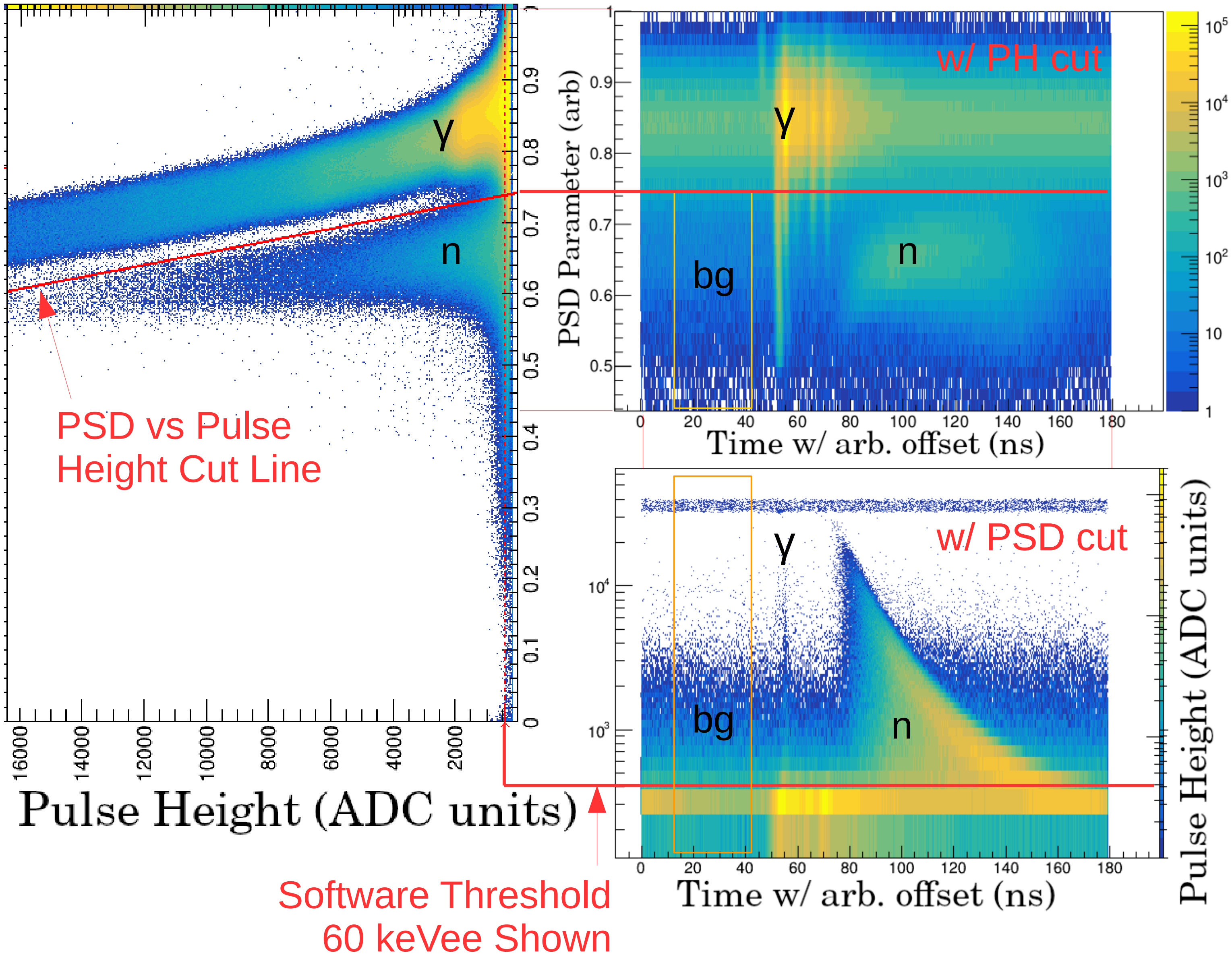
- Detect neutrons with an array of liquid scintillator (BC501A/EJ301) neutron detectors capable of pulse-shape-discrimination (PSD)
  - Shield with ~3mm of lead on front faces
  - Neutron energy by time-of-flight (TOF)
  - Digitize all signals
- Measure incident flux with the mirror paddle system and fission chambers where possible



Analysis Approach Part I

- Use PSD to tag neutrons on an event-by-event basis
  - Efficiency of the PSD cut as a function of pulse height is estimated using templating method with real data
- A time window before the beam arrival is used to estimate the constant background in the room for later subtraction

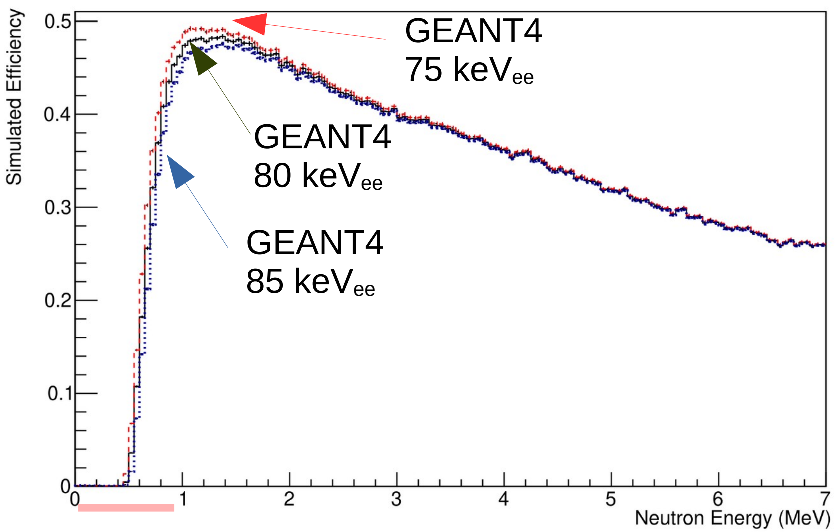


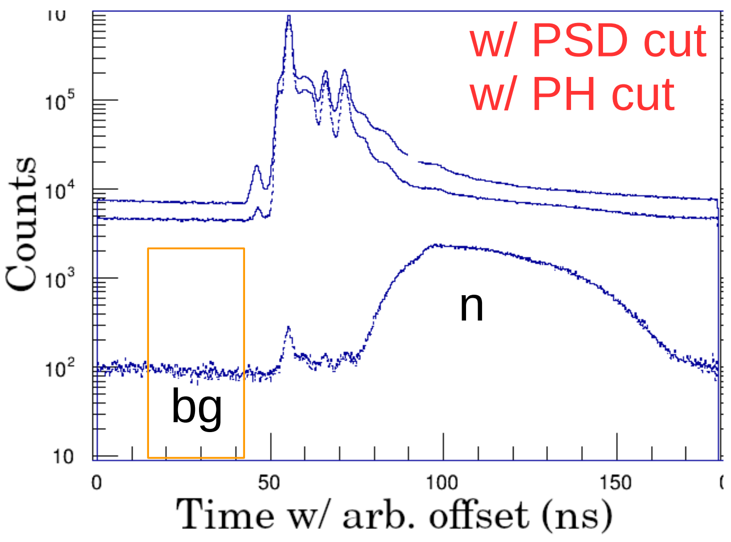


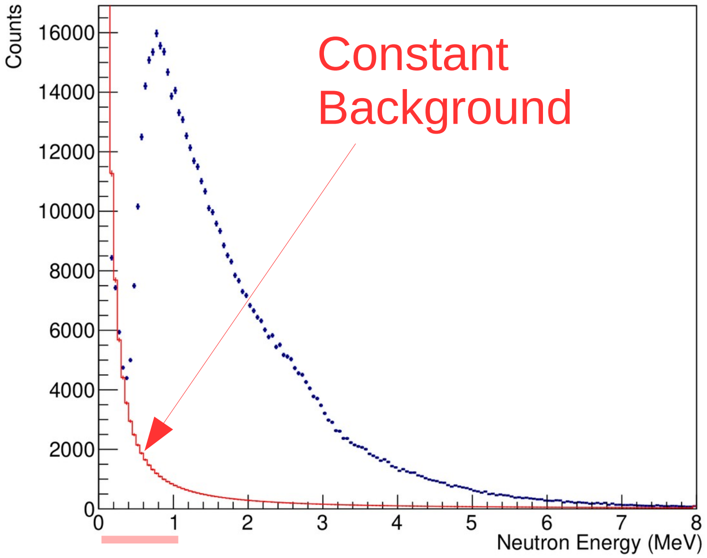
Data shown were taken by the detector on channel 22 at 10 MeV with 235U

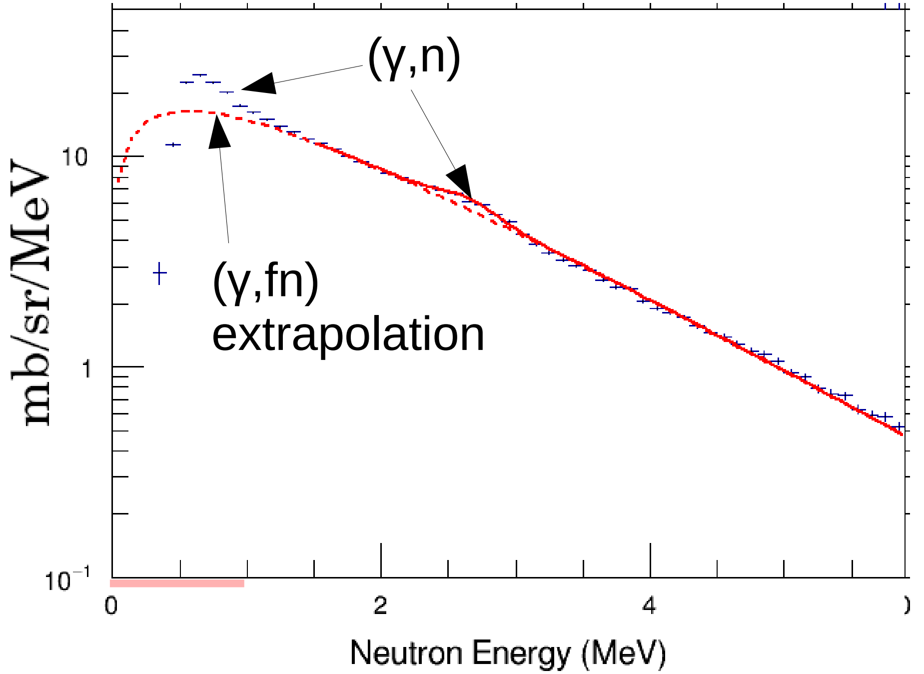
Analysis Approach Part II

- The detectors have an energy and threshold-dependent efficiency which must be undone
- The energy spectrum from each detector is processed independently and fit with a maxwellian spectrum
  - Depending on the (γ,n) contribution, a gaussian may be added to the fit
- We present neutron yields in units of cross section
  - For prompt photofission neutrons this is $\langle\nu\rangle\sigma_{(\gamma,f)}$
  - For photoneutrons this is $\sigma_{(\gamma,n)}$





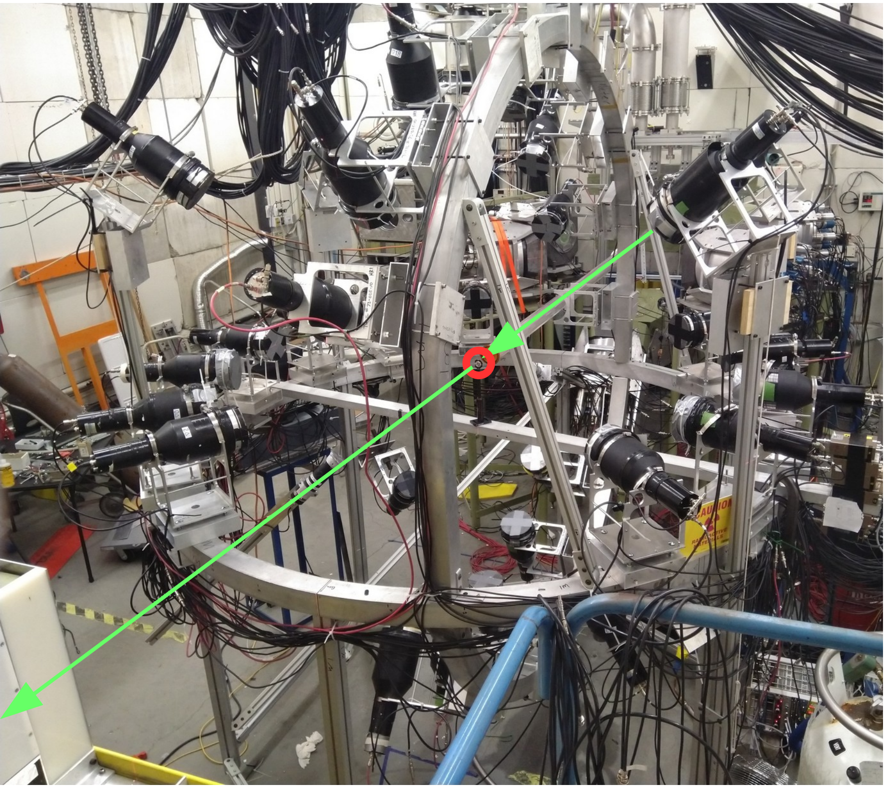




Data shown were taken by the detector on channel 22 at 10 MeV with 235U

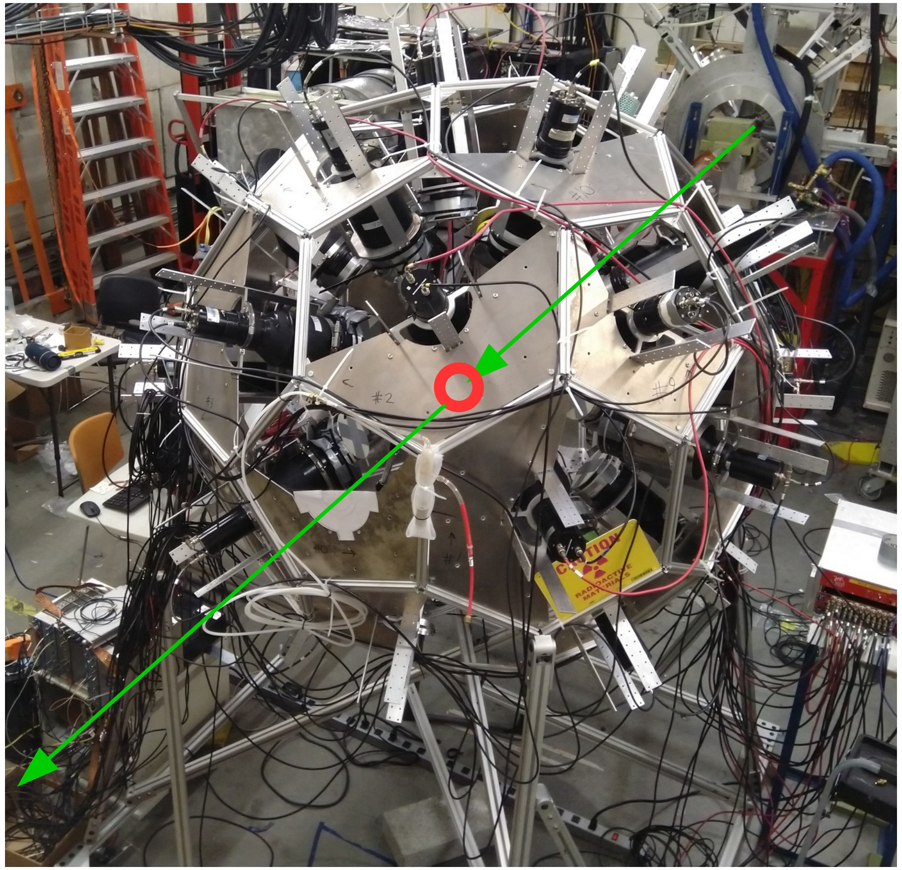
New Complimentary Detector Placement Capabilities

Round 1 Configuration

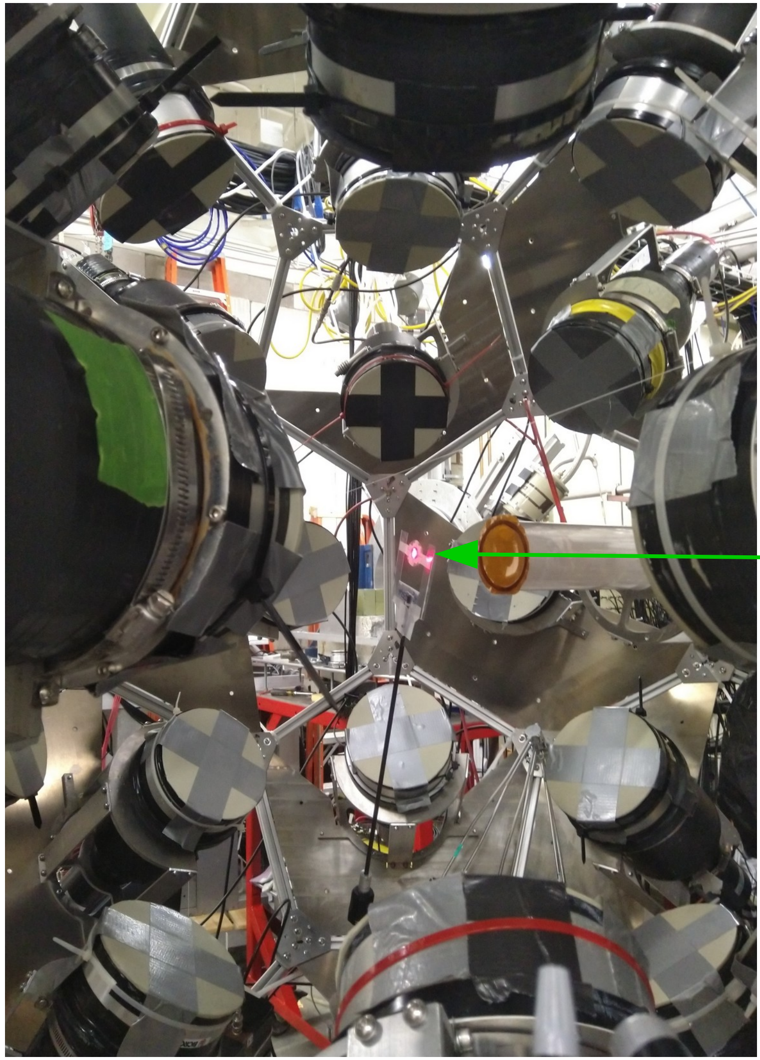


- ~100 cm neutron flight path
  - Very good energy resolution
  - Minimal multiple scattering effects
  - Original setup used before 2023

Round 2 "Soccer Ball" Configuration



- ~42 cm neutron flight path (adjusts 30-60 cm)
  - Large solid angle (~25% of 4π)
  - Attempt to measure multiplicity distribution
  - Linear distance between detectors similar
  - 32 Faces: up to 30 detectors (ran with 27)

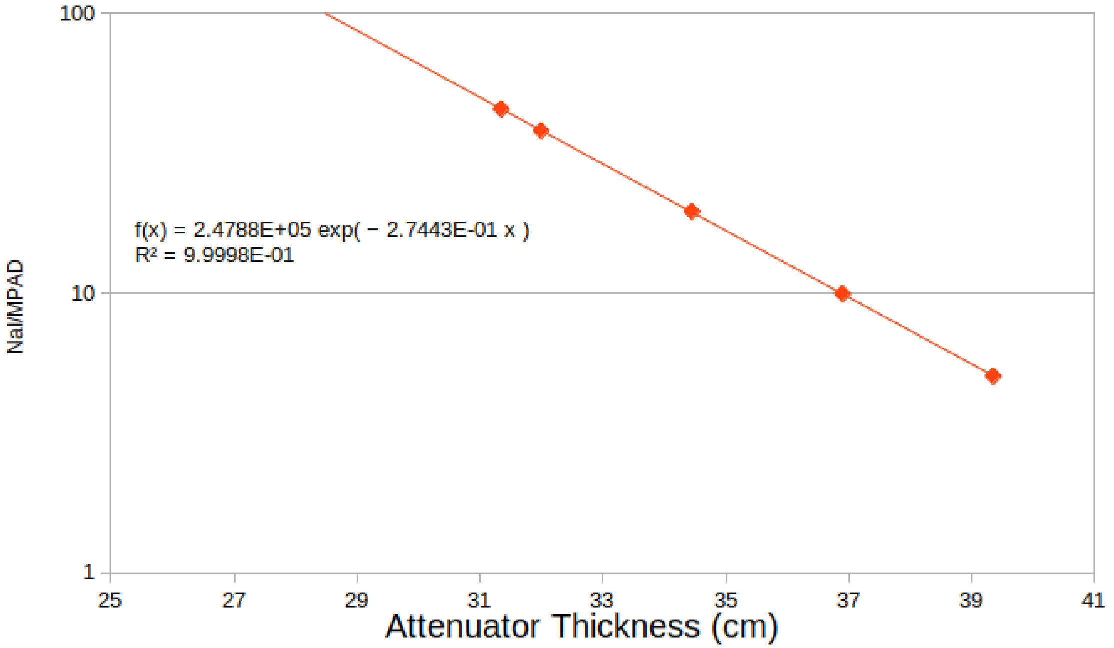


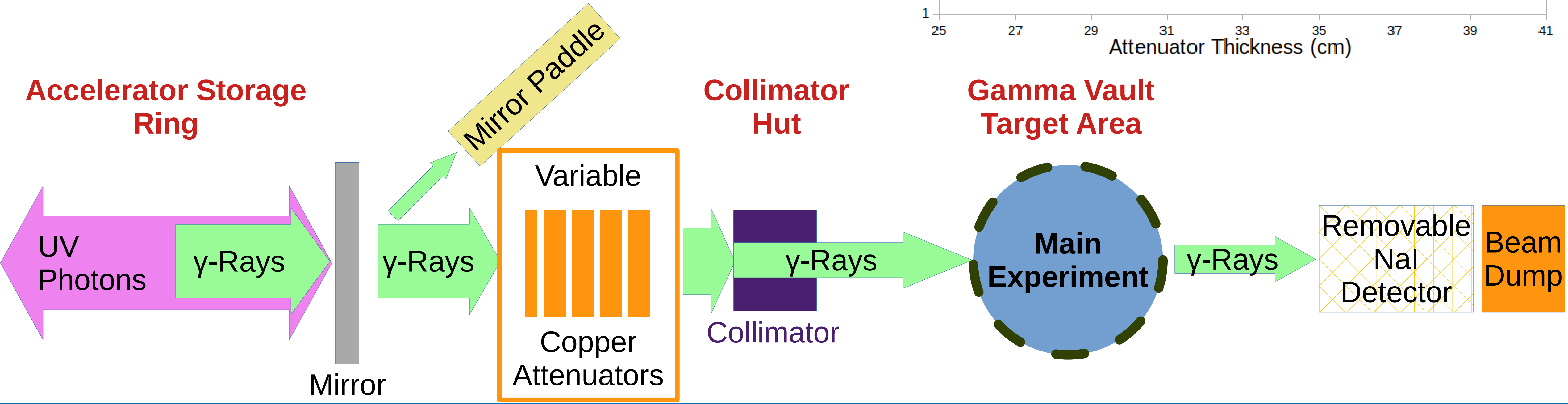
- Target in holder aligned with laser system

Flux Determination in Passive Target Experiments

Mirror Paddle:

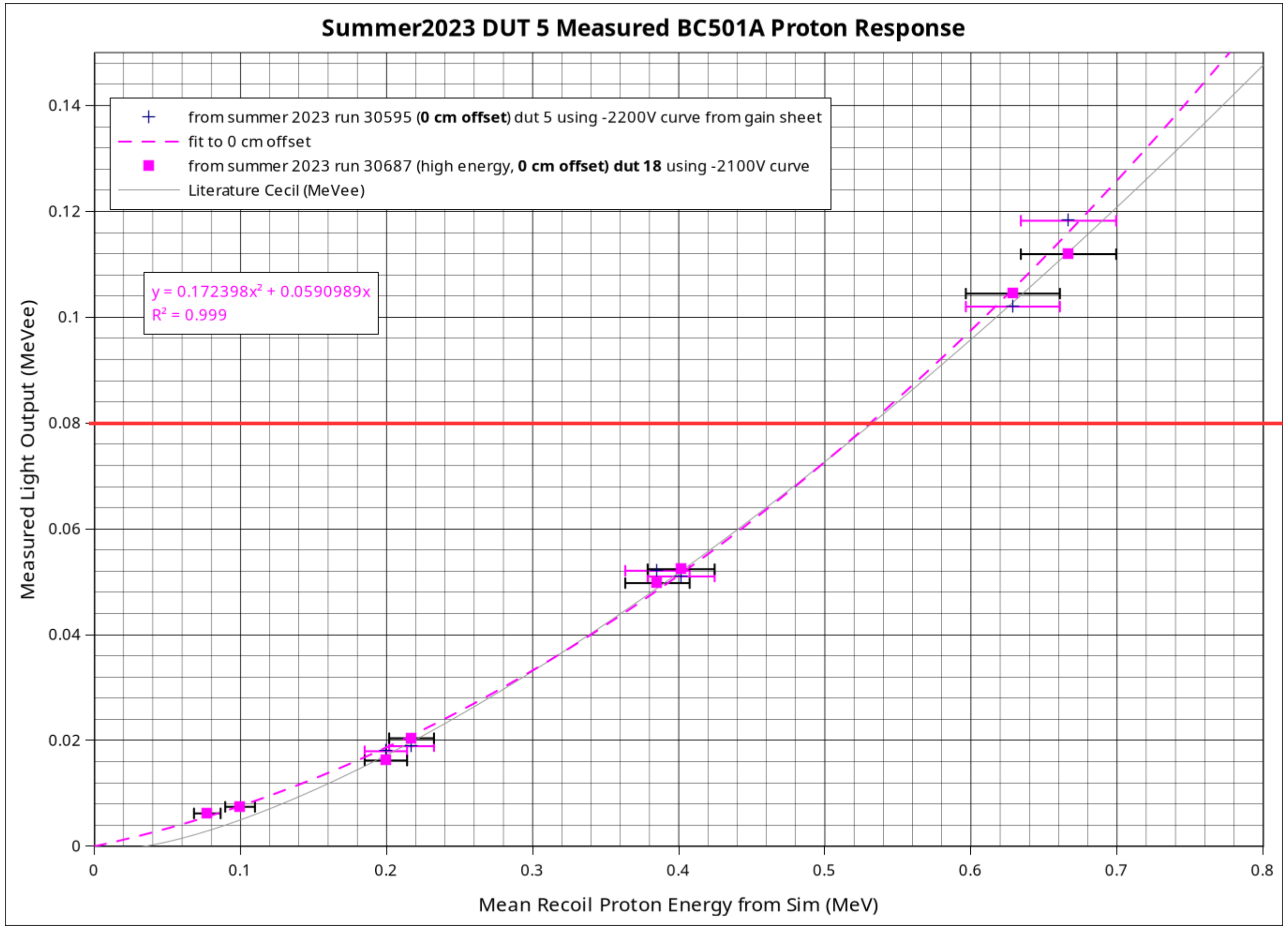
- Passively counts in proportion to beam delivered by the accelerator for a given mirror and configuration
- Vary the beam attenuation and measure the effect in downstream detector, determine copper attenuation coefficient
- Extrapolate backward to 0 attenuation to form a calibration factor with units of photons/MPAD counts

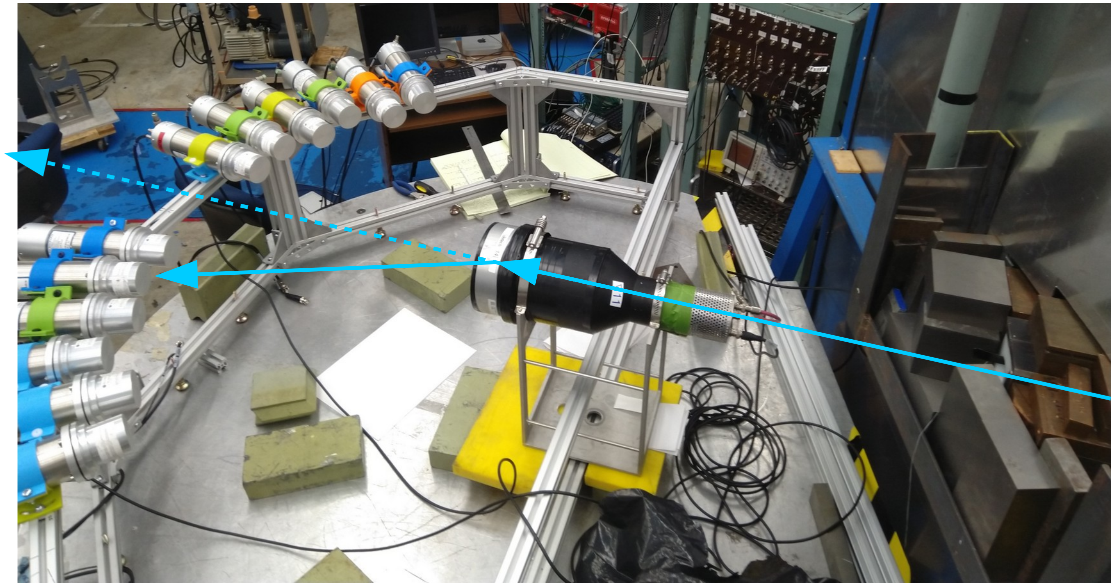




Scintillator Light Output Measurements at Low Energy

- A collimated neutron beam was scattered from a neutron detector at known angles
- Proton recoil energies were calculated from the angles of the scattered neutrons

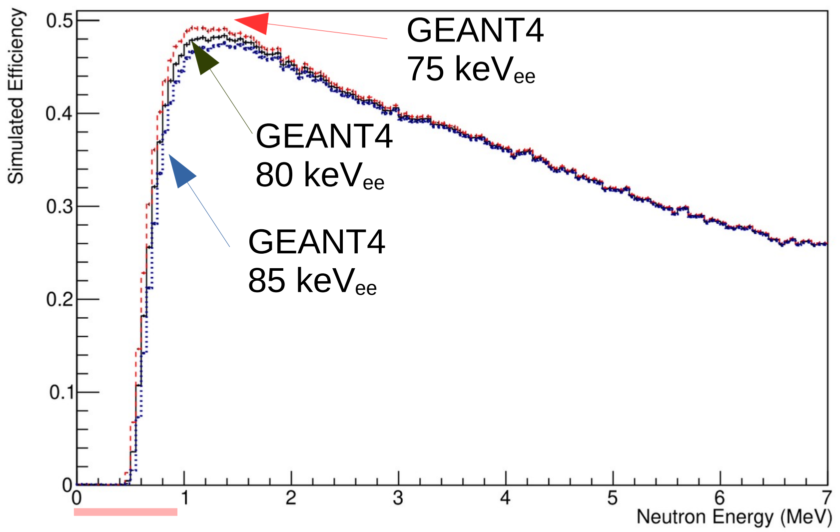




- **Use local Tandem Accelerator Facility**
- Light Output Functions for BC501A/EJ301/NE213 are not well-measured at low pulse heights
- Map out proton recoils < 1 MeV
- Measure light collection radial dependence
- Compare older and newer detectors
- Undergraduate student project of Michelle Riemann

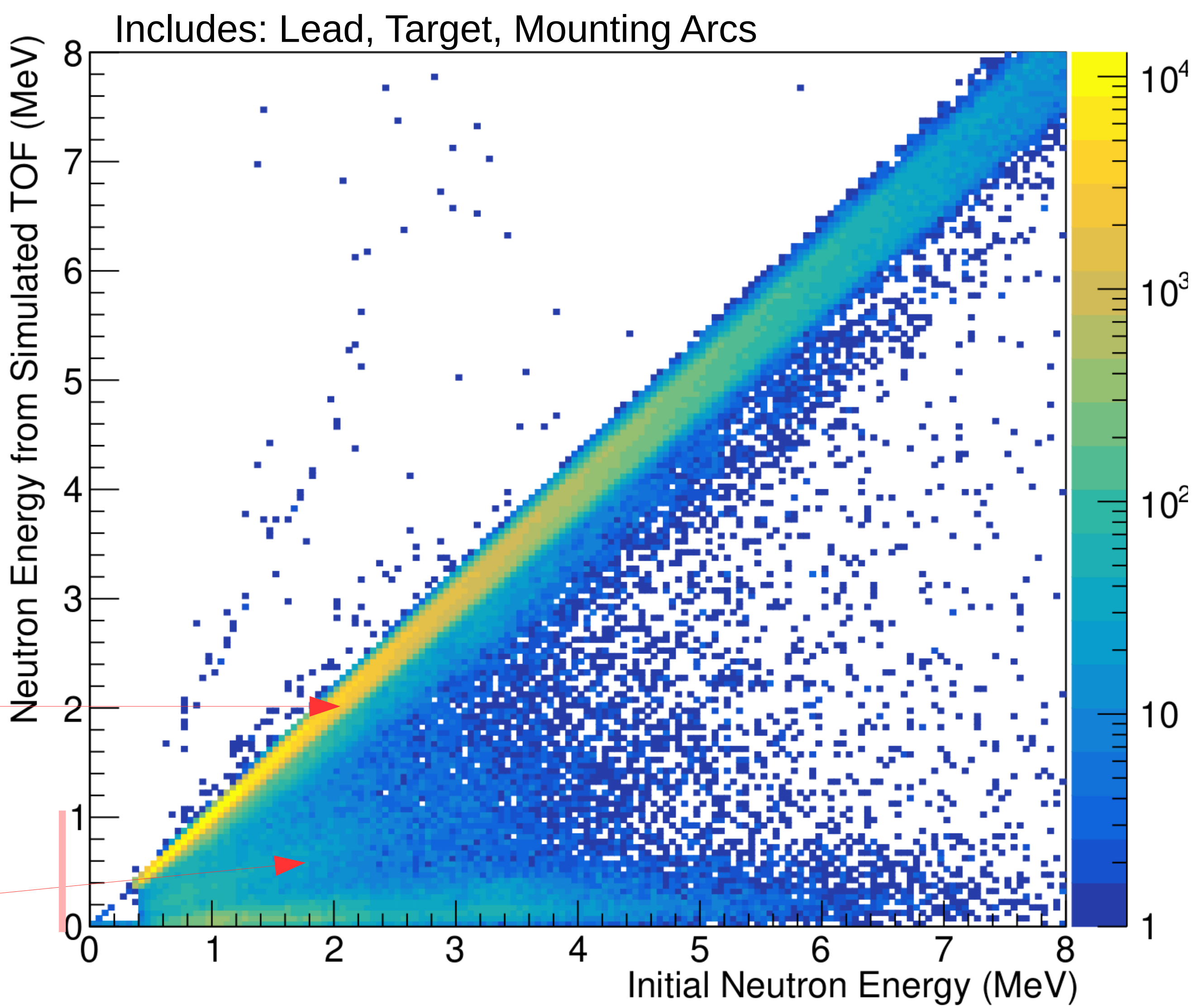
Simulation with FREYA and GEANT4

- GEANT4 simulation takes individual neutron events from FREYA grouped by fission
- Neutron interactions in the detectors are simulated
  - Recoil ions are fed through light output functions to reproduce detector response
    - We are currently re-measuring these functions for low energy recoil ions
    - Detector resolution is also modeled

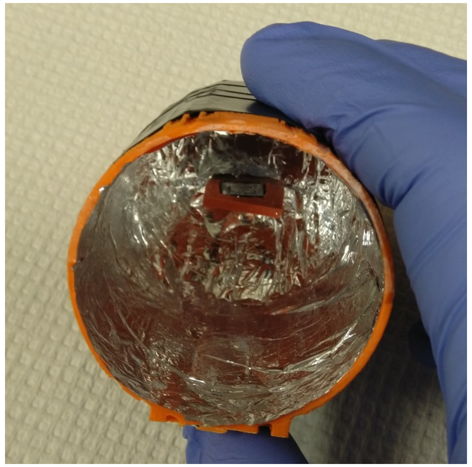


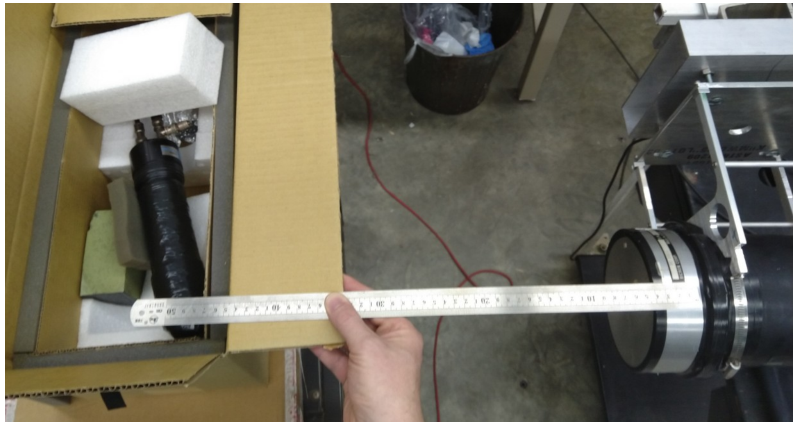
Spread from Geometry and Timing

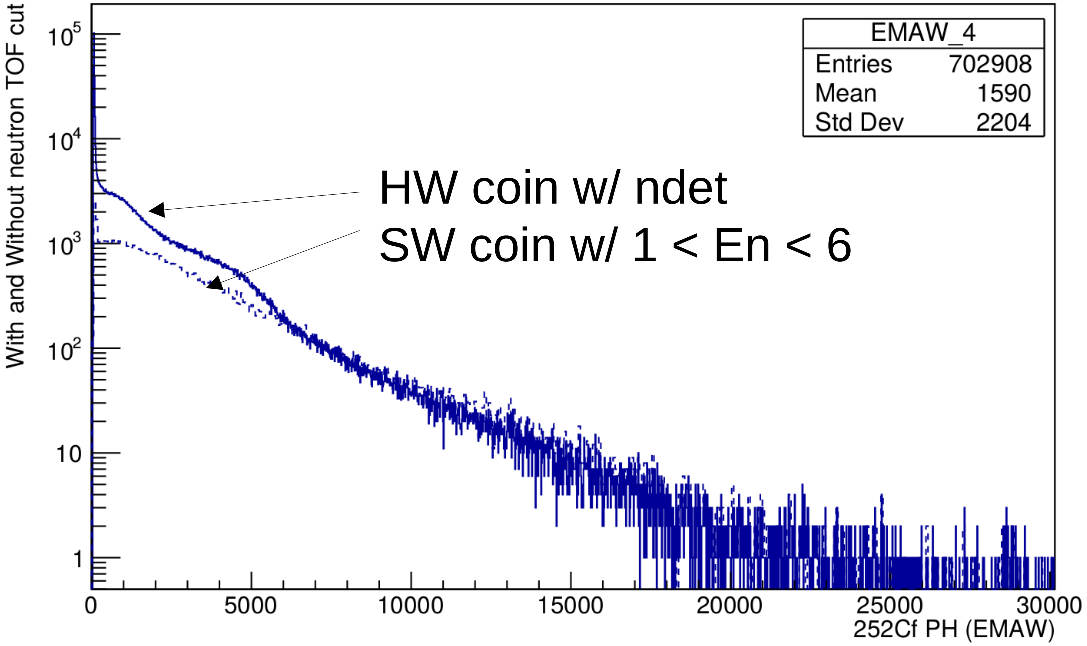
Intermediate Scattering

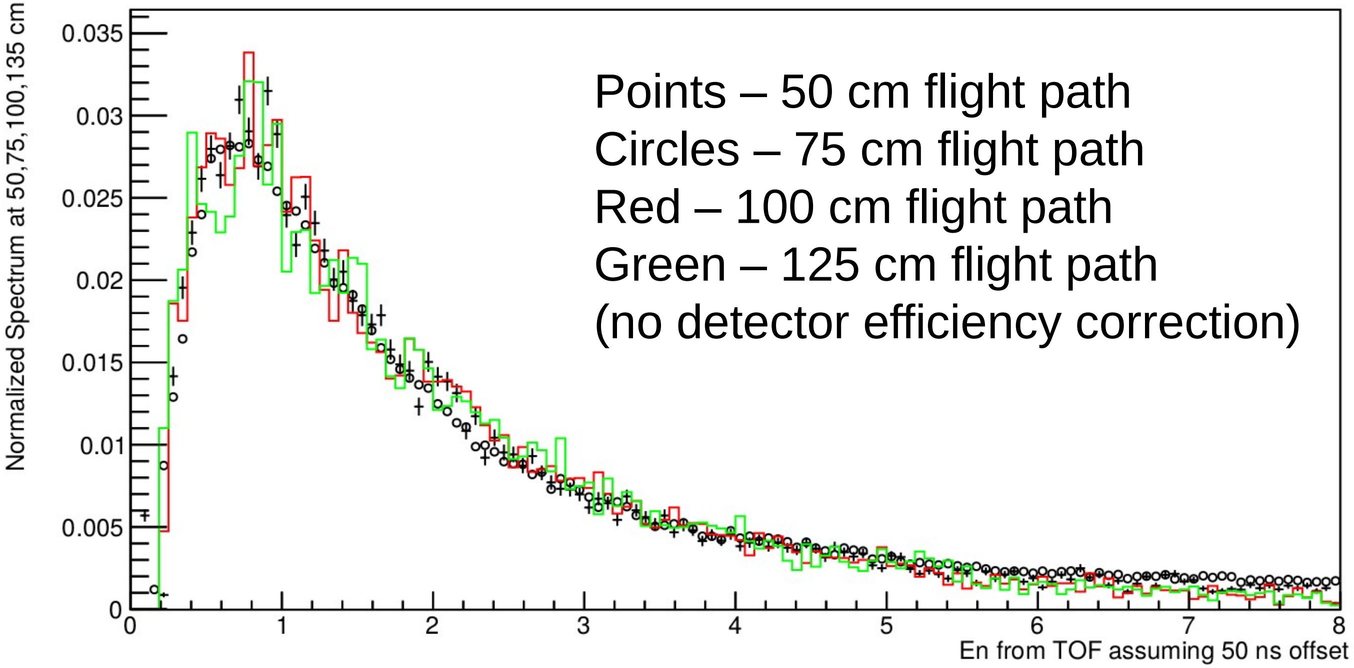


252Cf Active Target Updates – Tests w/ single PMT





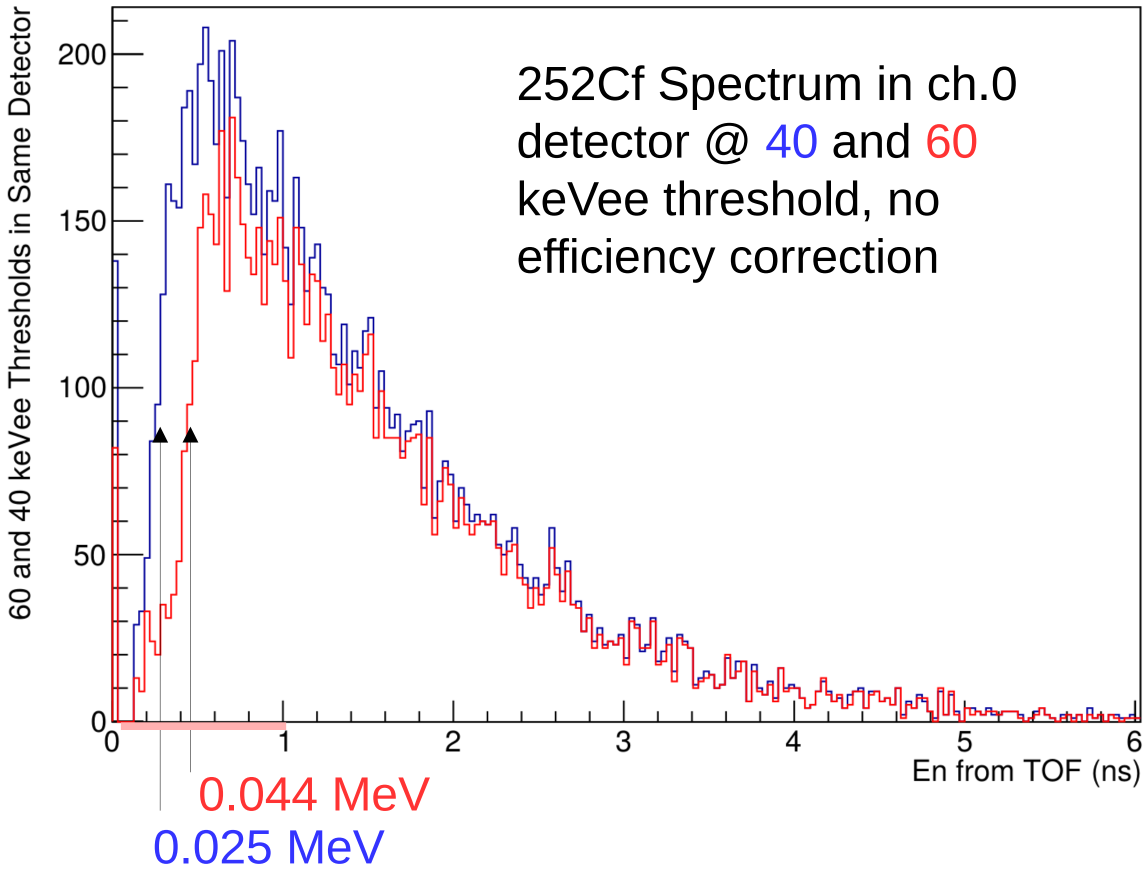


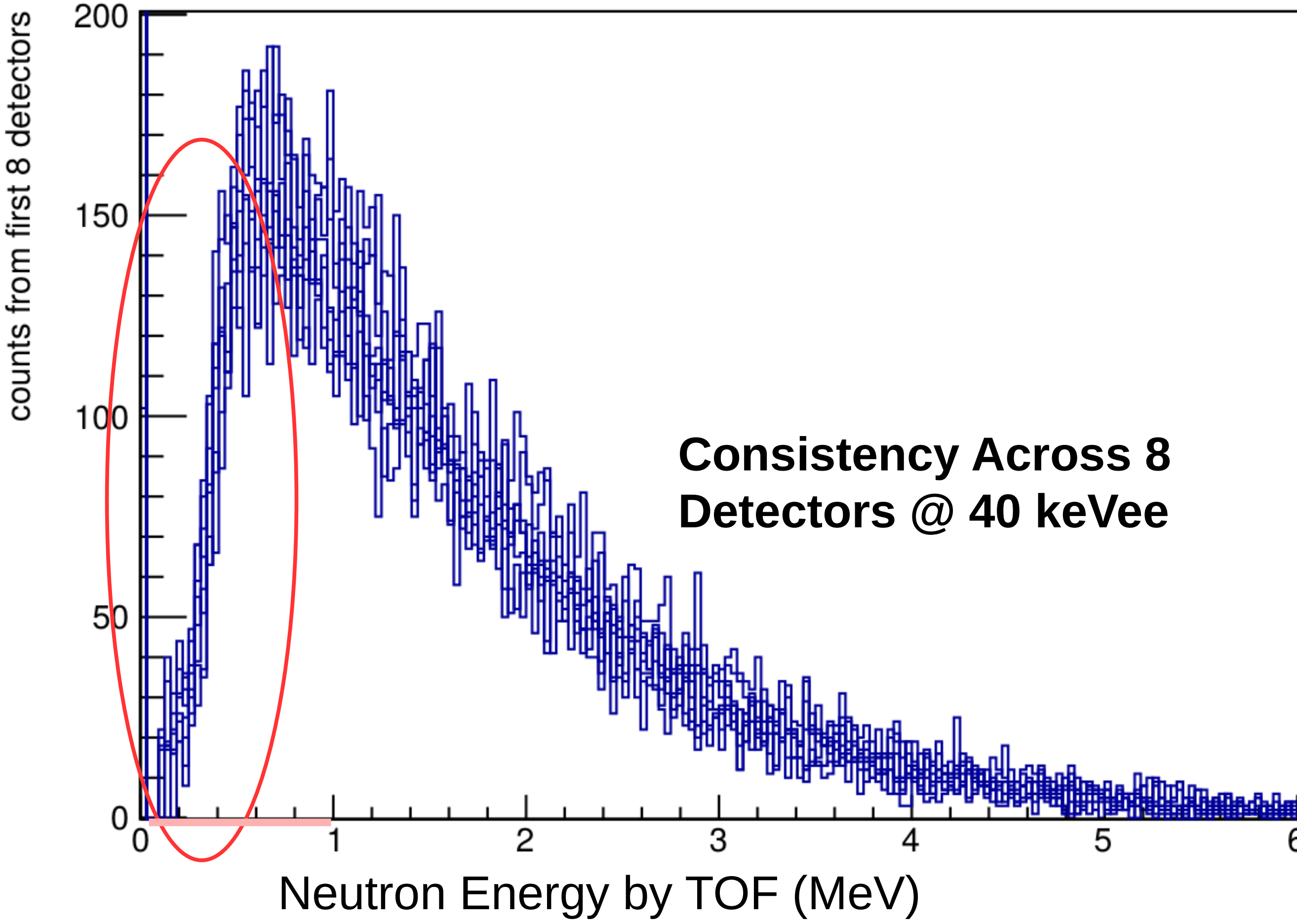


- Active ^{252}Cf neutron source was used to check self-consistency of measured energies at different flight paths
- Raw neutron TOF energy spectrum at different distances shows effect of changing flight path

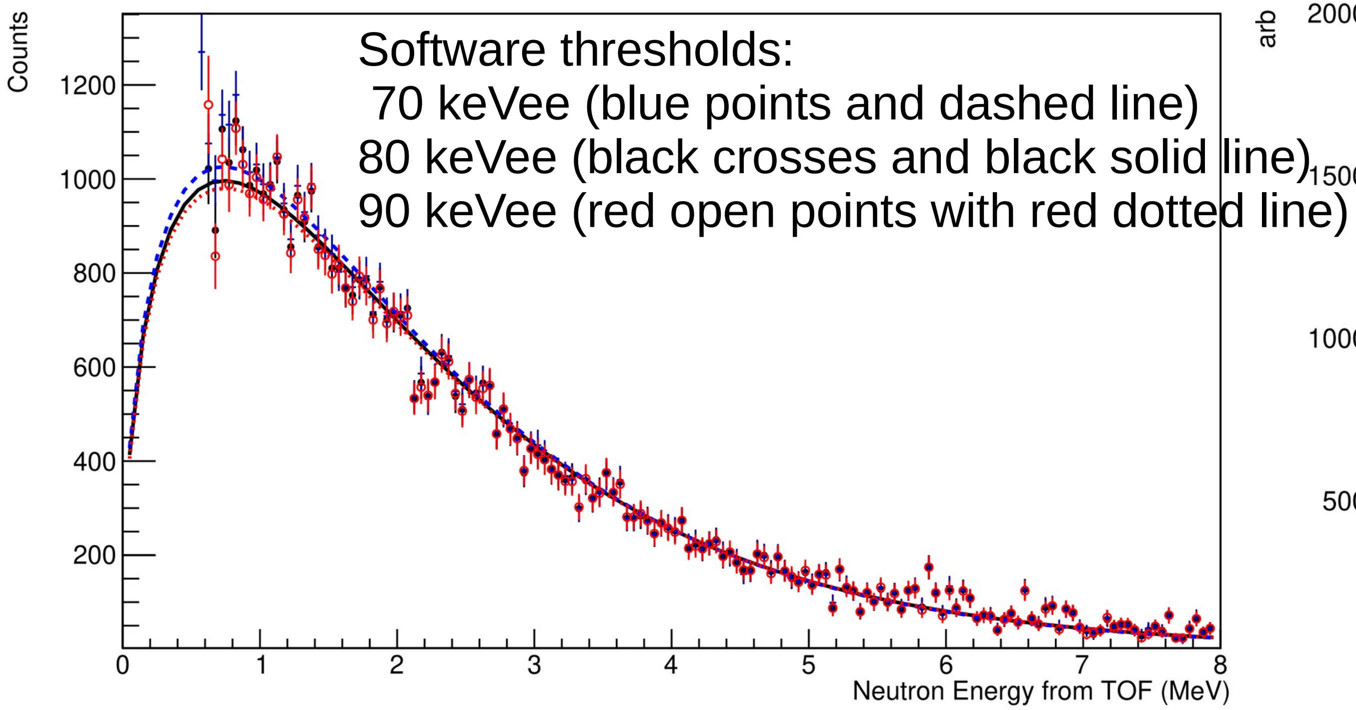
252Cf Active Target – Check of detector consistency

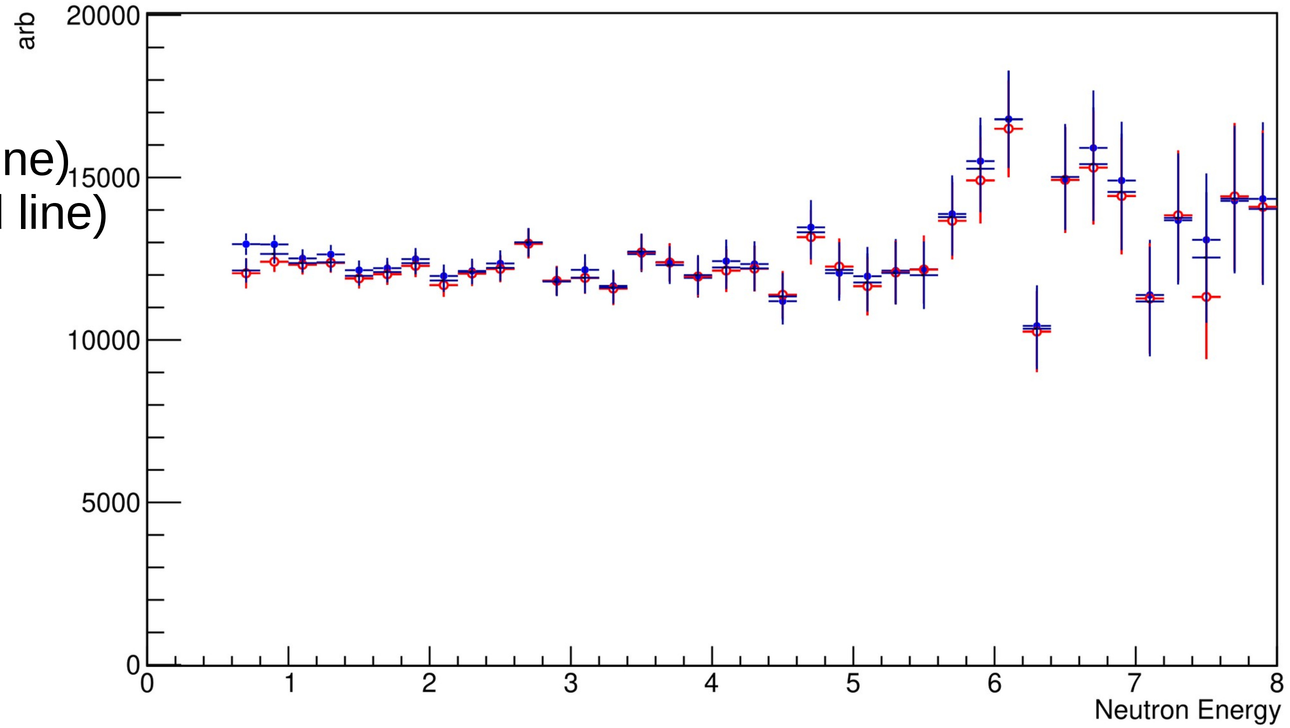
- Gain fits for neutron detectors use: ^{22}Na (0.341, 1.062 MeVee), ^{137}Cs (0.478 MeVee), ^{40}K (1.243 MeVee)
- ^{252}Cf is a common reference for fission experiments
- Consistency of measured spectra across different detectors at low threshold (40 keV$_{ee}$) confirms knowledge of gains and thresholds





^{252}Cf Active Target – Check of detector consistency



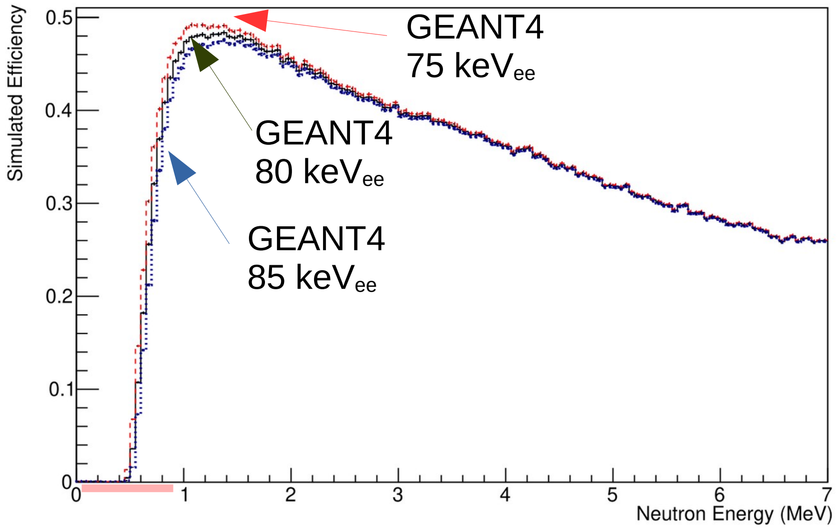


- ^{252}Cf in-situ in the soccerball configuration θ=116.6^{o}, φ=288^{o}, 2.4 mm thick Pb
- The maxwellian fit areas for the 70 and 90 keVee thresholds differed by about 3%
- The temperatures obtained at each threshold were in agreement with FREYA
- Strong indications that the neutron detector efficiency is well-understood

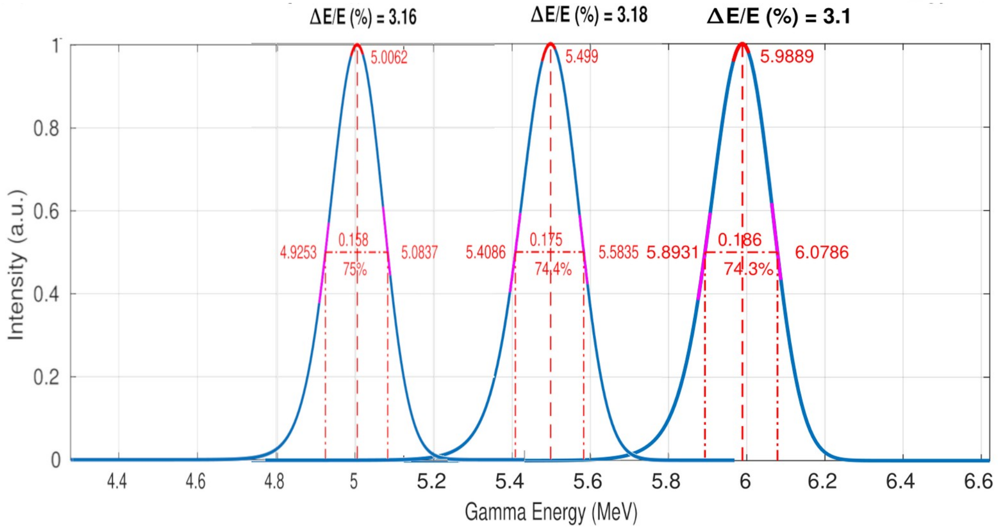
- Measured data at left divided by ^{252}Cf FREYA prediction (T=1.47 MeV, <ν>=3.75).
- The shape of the fission neutron spectrum is characterized with only basic corrections
- The y-axis does not have absolute units due to the active source having an unknown efficiency for fission fragment detection.

Systematics

- Error bars in plots are statistical
- Flux determination uncertainty was 3%
- A systematic of ~5% also effects each detector independently
  - Quantified as uncertainty on threshold (5 KeV_{ee}) and gain propagated to efficiency for fission spectrum
  - This detector systematic affects different targets in the same way
- Beam resolution as seen by target was 3.1% FWHM for runs at and below 6 MeV

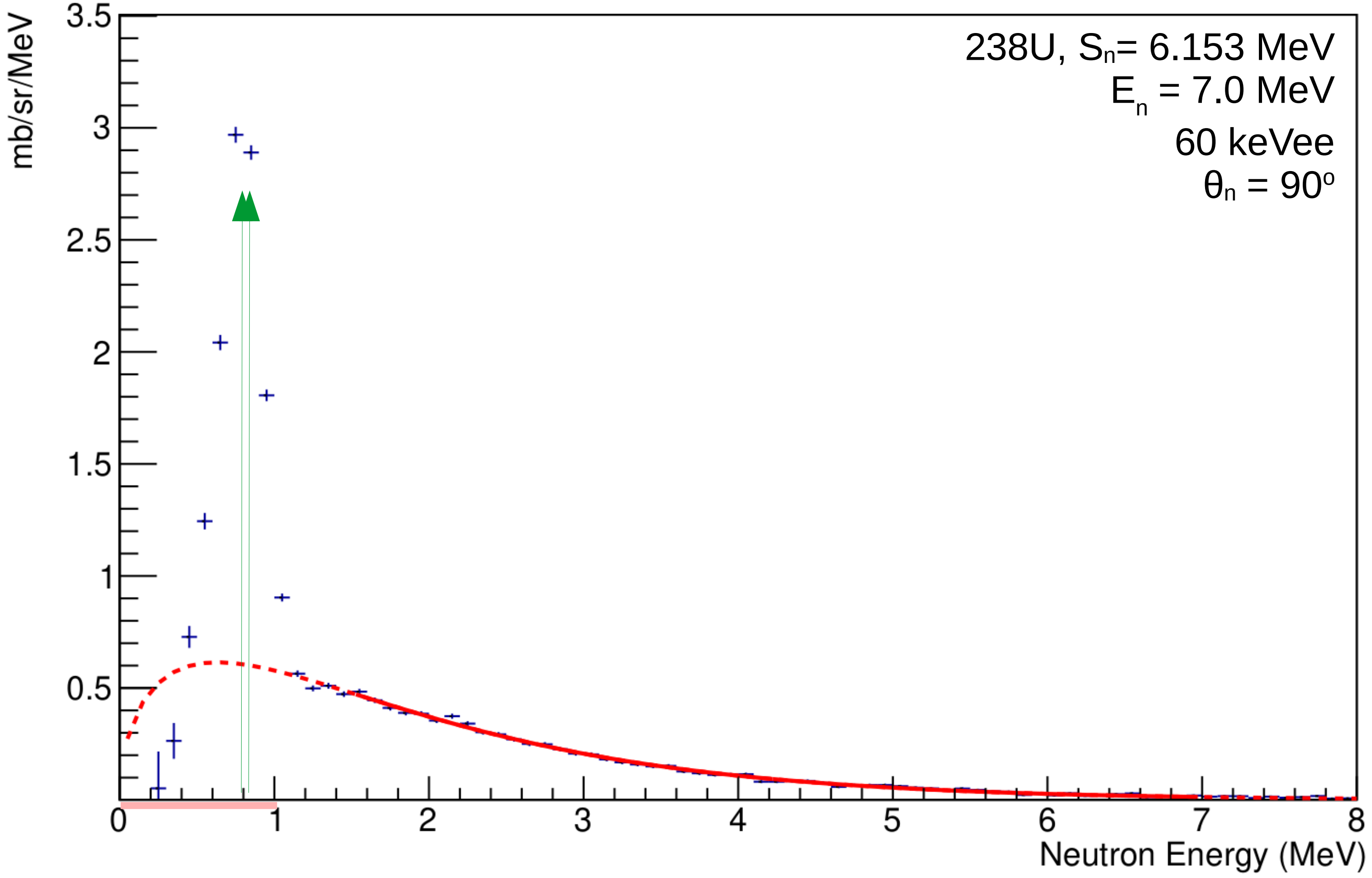


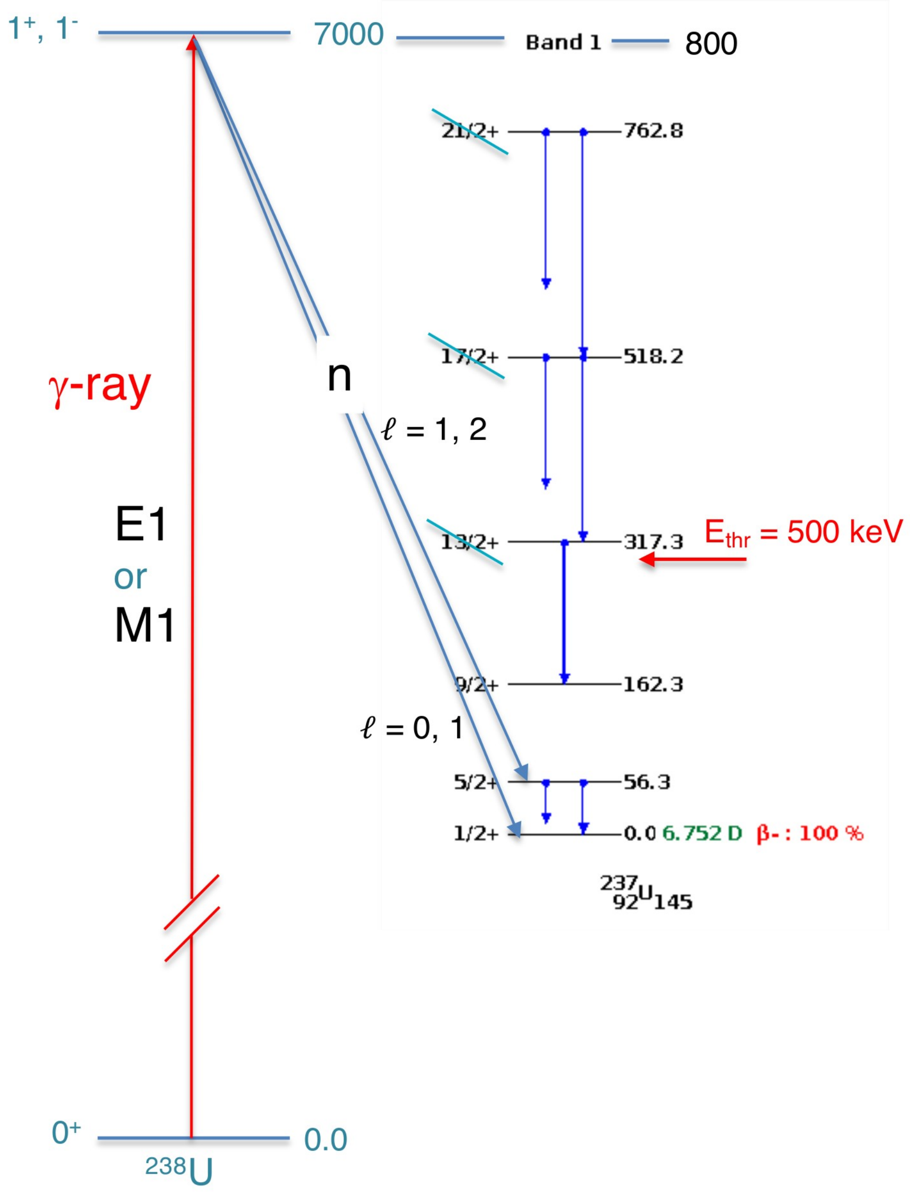
Source	Quantity	Systematic (stdev)
Luminosity ($N_\gamma \rho_t$)	$d\sigma_{(f,n)}/dE_n$ Magnitude	$\pm 5\%$
Detector Volume	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	+0.5% -2%
Detector Threshold (80 ± 5 keVee)	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	$\pm 2.5\%$
Detector Threshold (80 ± 5 keVee)	T_m	negligible
Beam Energy Resolution	E_γ Resolution	$\pm 1.3\%$ for $E_\gamma \leq 6$ MeV
Background and Bremsstrahlung	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	Comparable to Data at 5.0 Me
Intermediate Scattering	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	$\pm 2\%$
Timing Offset ± 0.5 ns for 1 m array	$\sigma_{(f,n)}$ Magnitude	$\pm 2\%$
Timing Offset ± 0.5 ns for 1 m array	T_m	±0.1 MeV
Timing Offset ± 0.5 ns for 0.42 m array	$\sigma_{(f,n)}$ Magnitude	$+4\% - 5\%$
Timing Offset ± 0.5 ns for 0.42 m array	T_m	±0.2 MeV
Isotopic Purity and Contaminant (γ,f) Uncertainty	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	Multiply total uncertainty by: ^{235}U: 1.07 ^{238}U: 1.001 ^{239}Pu: 1.02
Total for 1 m Array	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	$+6.3\% - 6.6\%$
Total for 0.42 m Array	$d\sigma_{(f,n)}/dE_n$ and $\sigma_{(f,n)}$ Magnitude	$+7.2\% - 8.0\%$



Example Data: 238U at 7 MeV

- 238U at 7 MeV with a 60 keVee detector threshold
  - Expect a neutron peak near 800 keV
    - Will not be included in (γ,n) lower bound (<1 MeV)

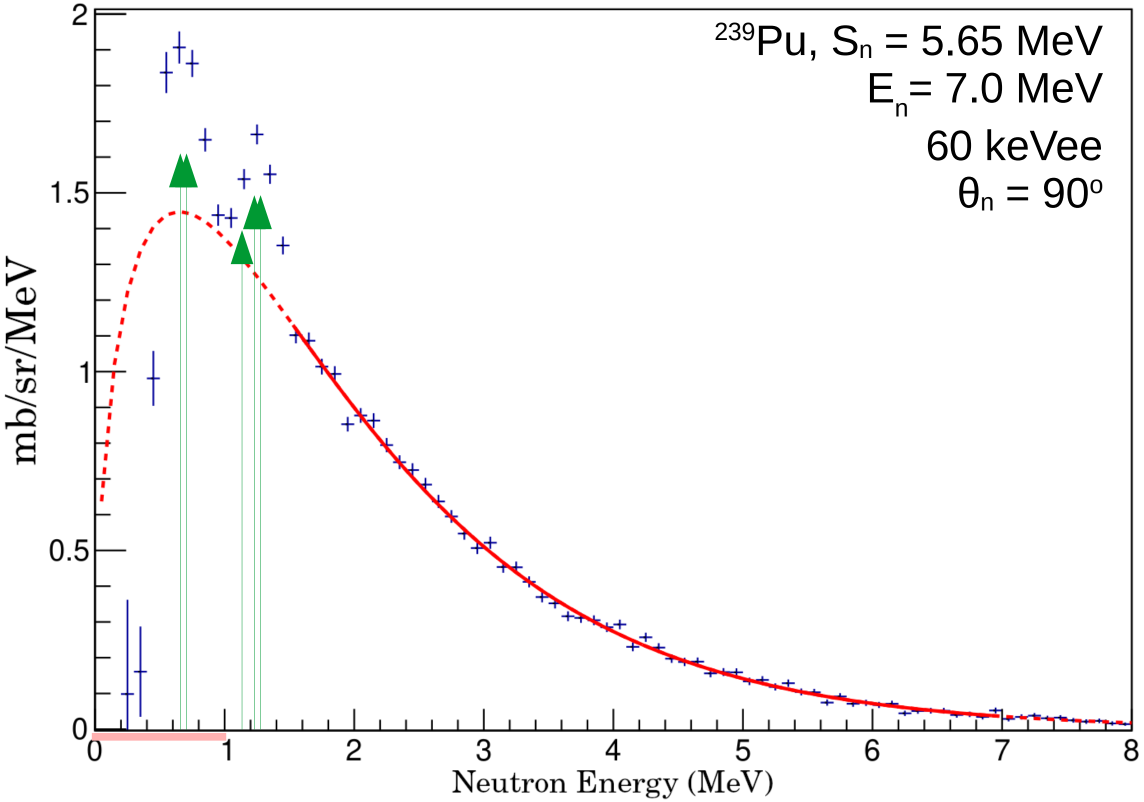


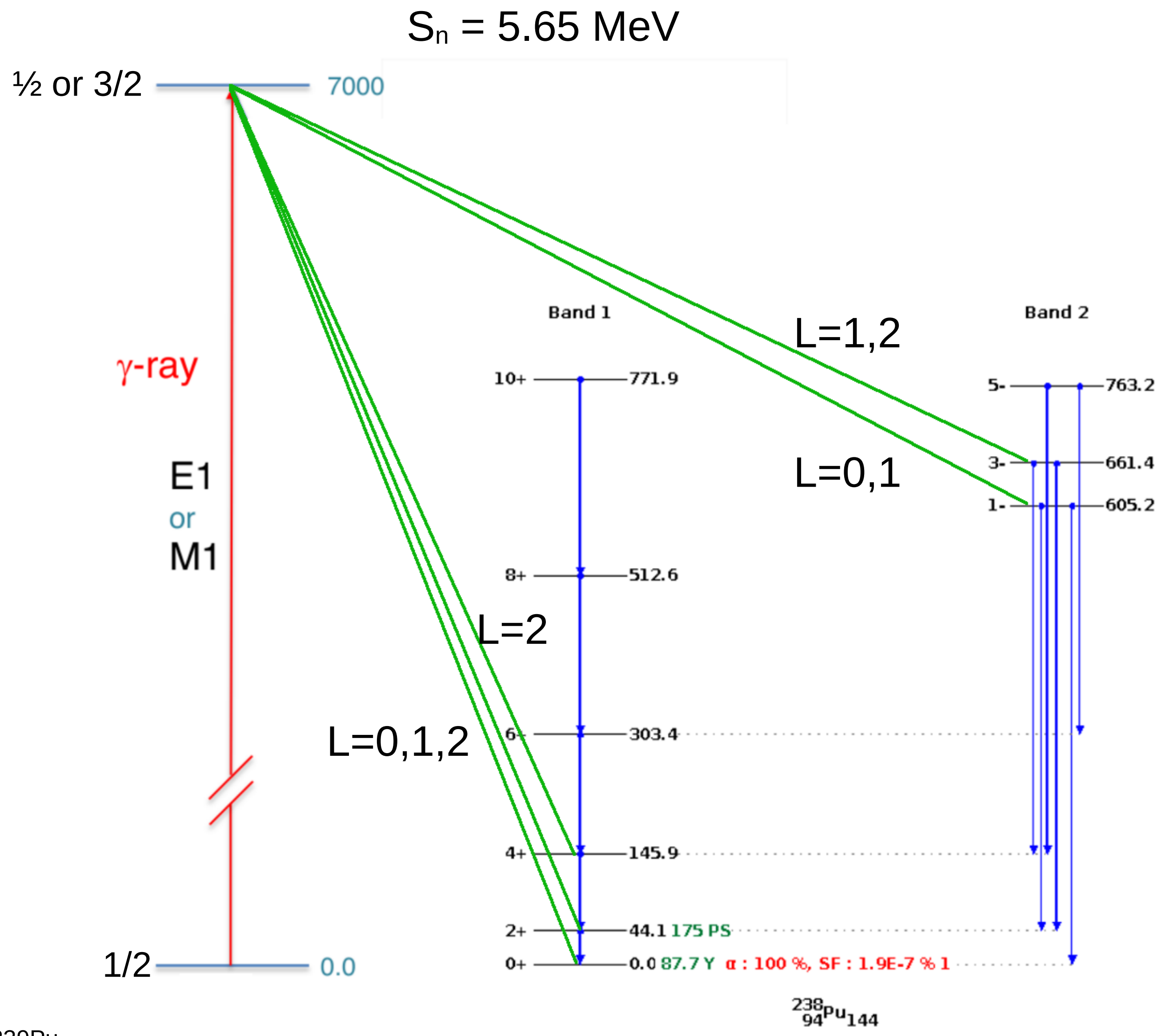


Rightmost figure from talk by C.R. Howell

Example Data: ^{239}Pu at 7 MeV

- Example for ^{239}Pu with 7 MeV incident photons:
  - ^{239}Pu can be moved into ½ or 3/2 excited state
  - Allowing for neutrons up to l=2, all possible neutrons above detection threshold are shown at right
    - Peak near 1.3 MeV is from decay(s) into band 1
    - Peak near 700 keV is from decay(s) into band 2

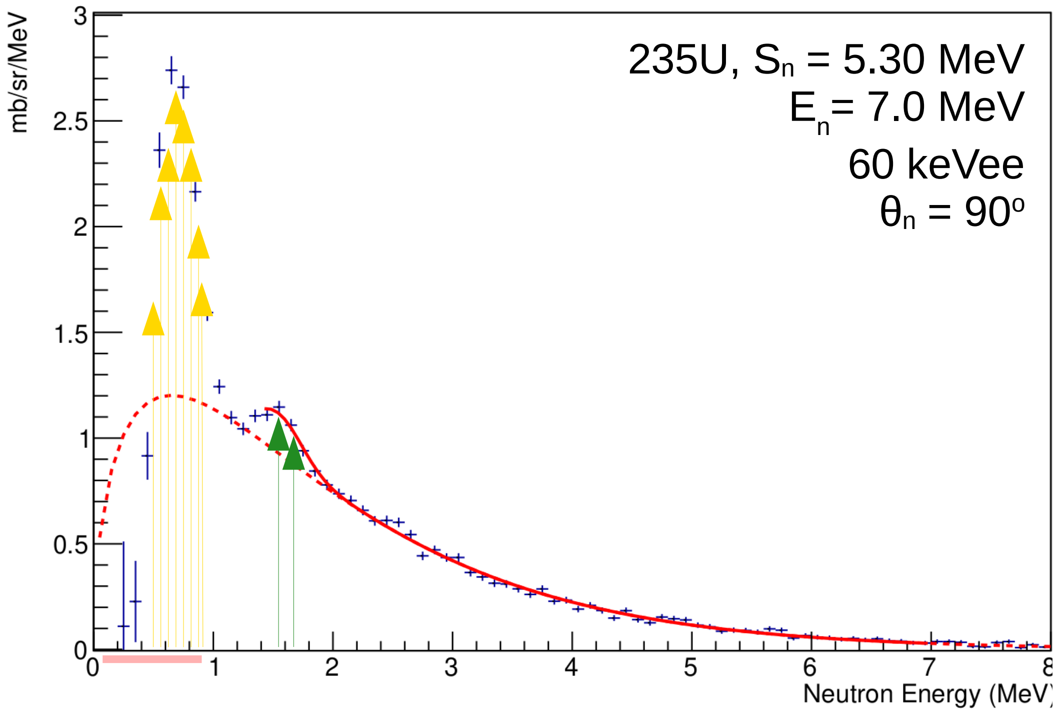


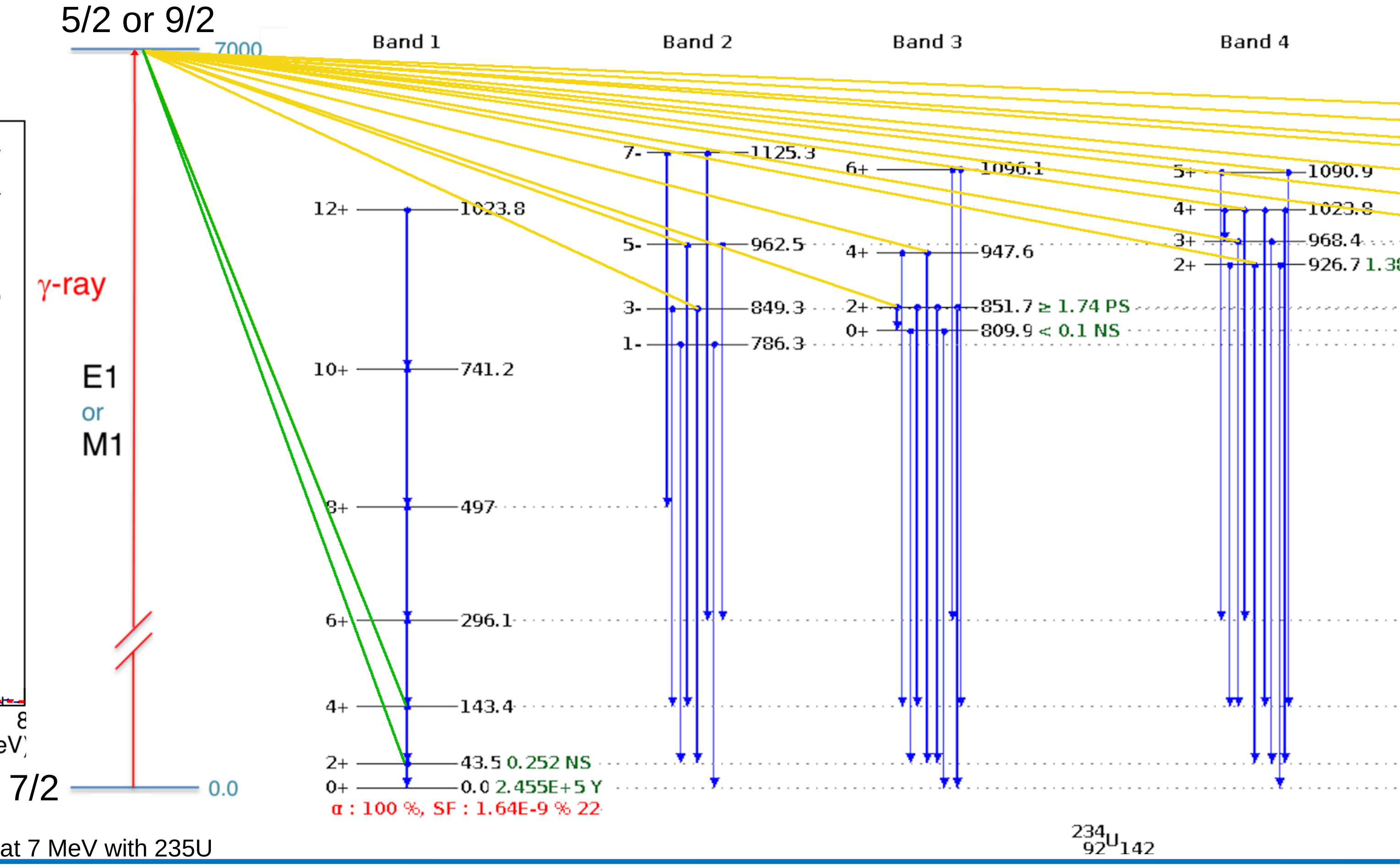


Data shown were taken by the detector on channel 22 (90 deg polar angle, upper arc) at 7 MeV with 239Pu

Example Data: 235U at 7 MeV

- Example for 235U with 7 MeV incident photons:
  - ^{235}U can be moved into 5/2 or 9/2 excited state
  - Possible l=0 neutrons above detection threshold are shown at right
    - Peak near 1.7 MeV is from decay(s) into 2+ or 4+ state in band 1 (green lines)
    - Peak near 700 keV could involve any of the orange lines
      - Additional possible states exist out to band 7
      - More possibilities if l=1 neutrons included





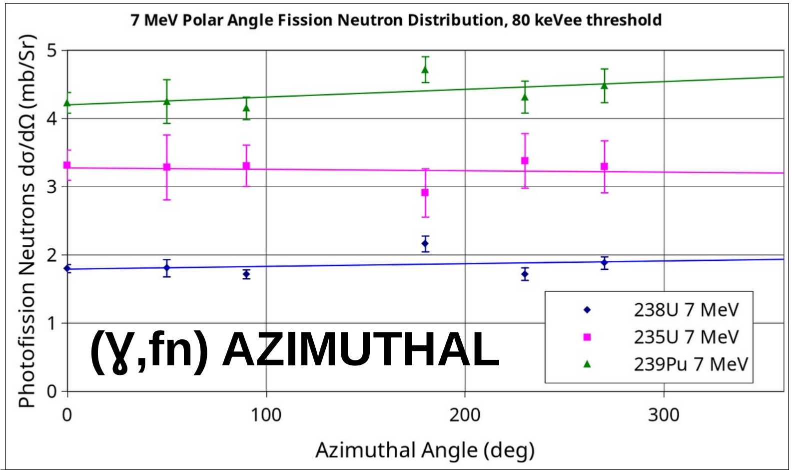
Data shown were taken by the detector on channel 22 (90 deg polar angle, upper arc) at 7 MeV with 235U

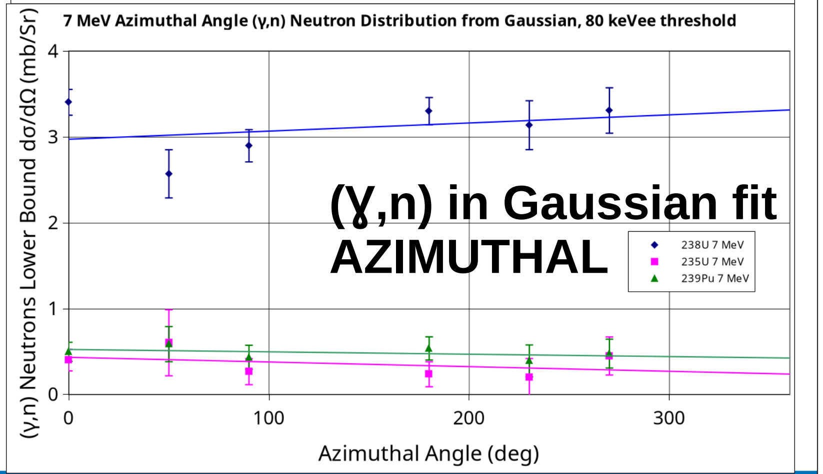
Example Data: 7 MeV

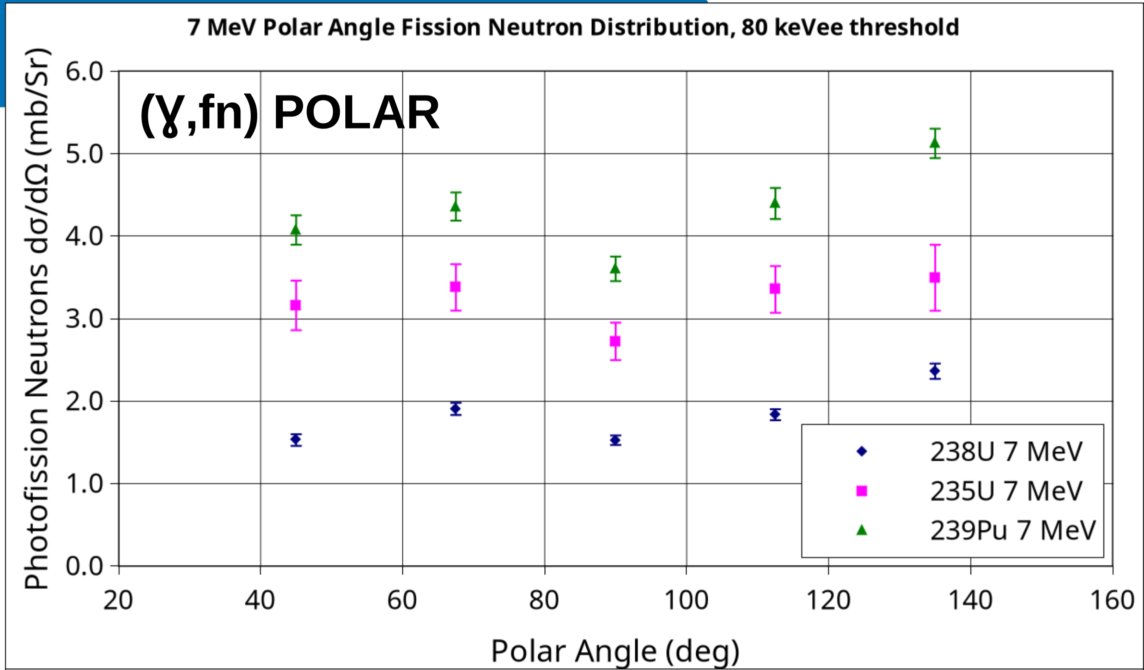
- Neutrons from (γ,n) are integrated from 0.8 to 3.5 MeV
- Data below show the integral of the (γ,n) gaussian ONLY
  - Consider this a lower bound. For higher $E_γ$ this can blend into the fission spectrum

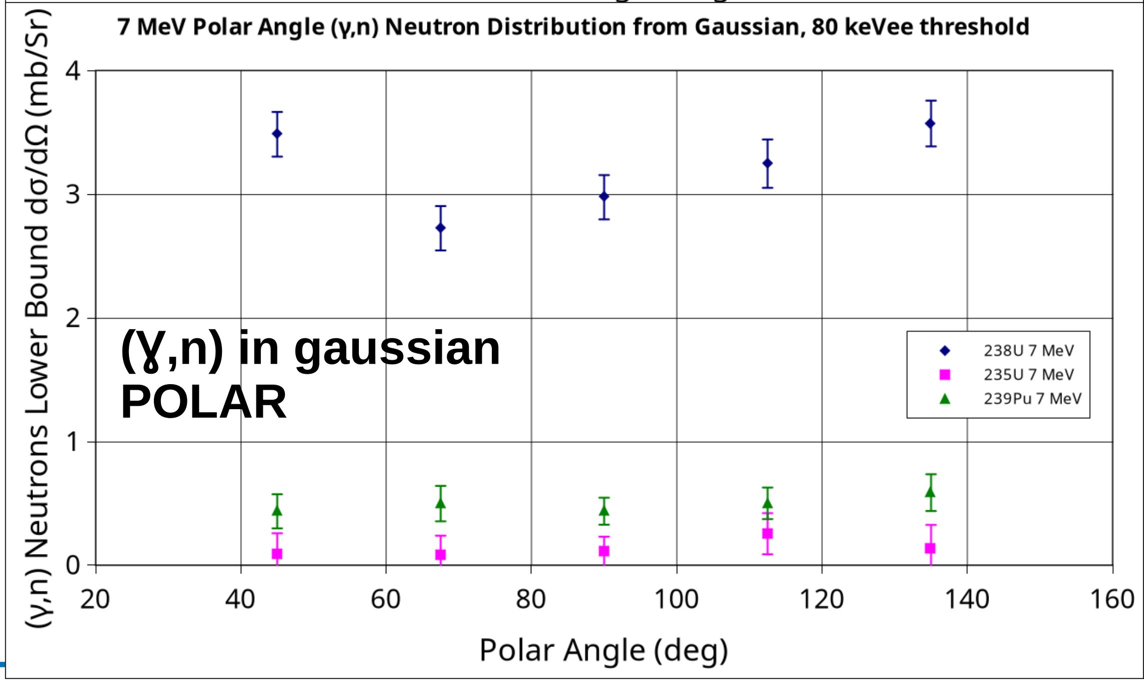
- ~1 m flight path
- Error bars statistical
- Possible self-shielding effect at 90 degrees due to target orientation

- Expect uniform azimuthal spectrum due to circular beam polarization



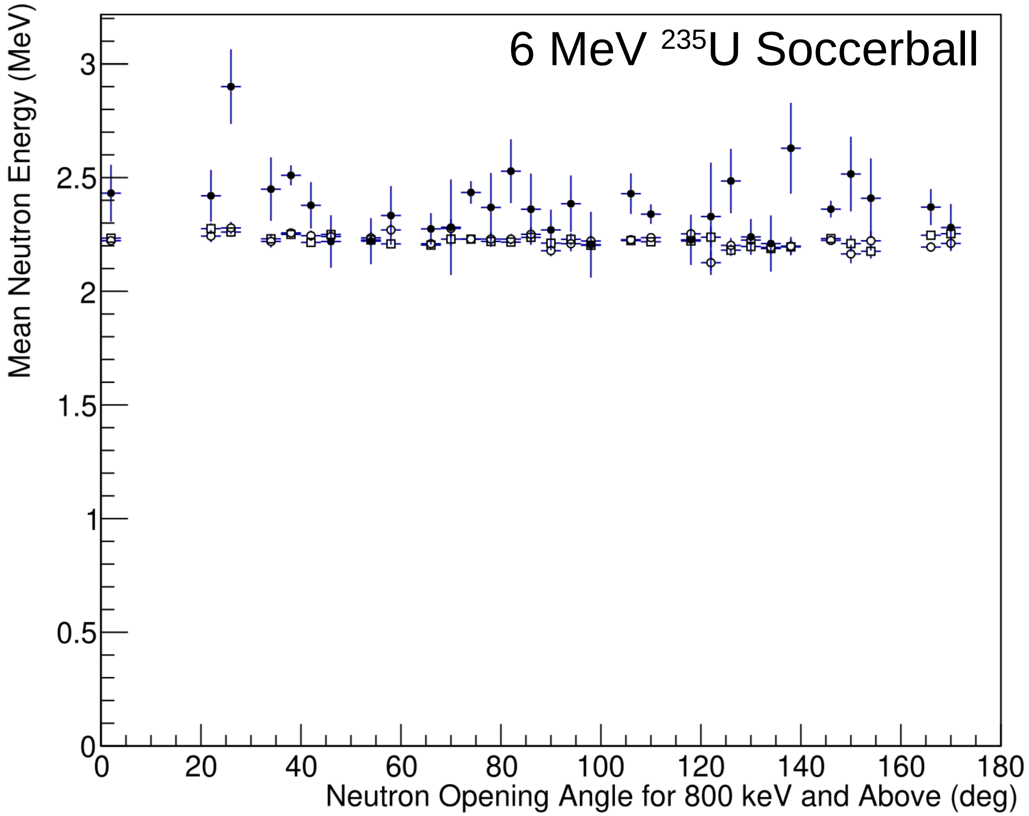


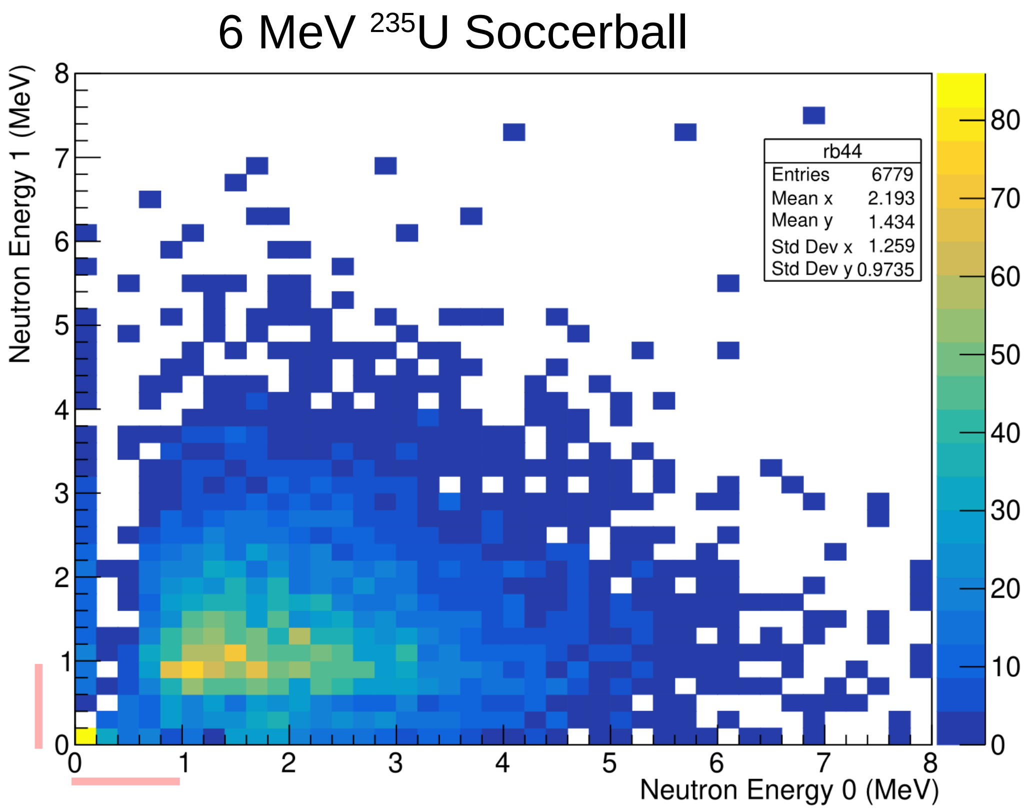


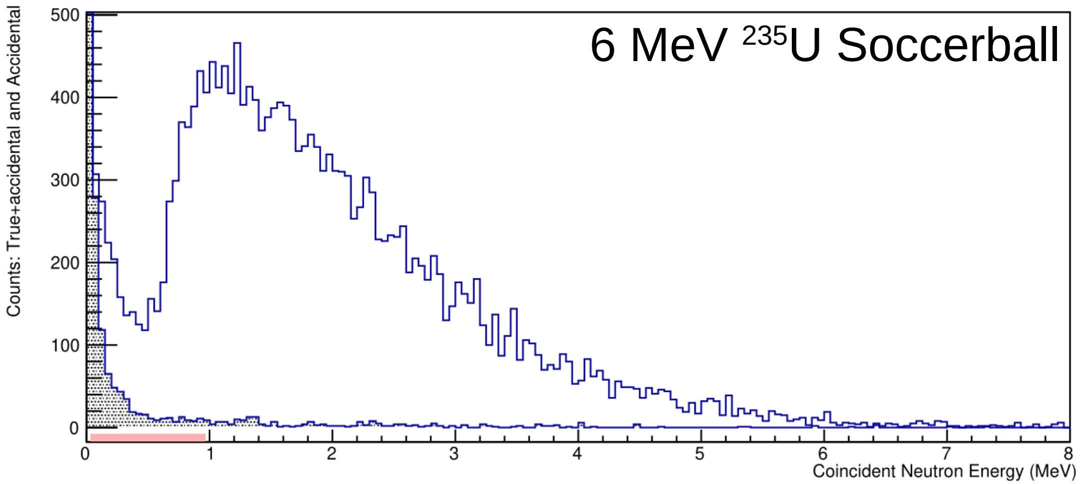


Neutron Coincidence Measurements

- Form neutron-neutron coincidences
  - Improve SNR for (Ɣ,fn) where ν>1
  - Search for evidence of correlations
  - Remove sensitivity to (Ɣ,n)
  - Gain sensitivity to <ν>
  - Investigate E_n dependence on ν

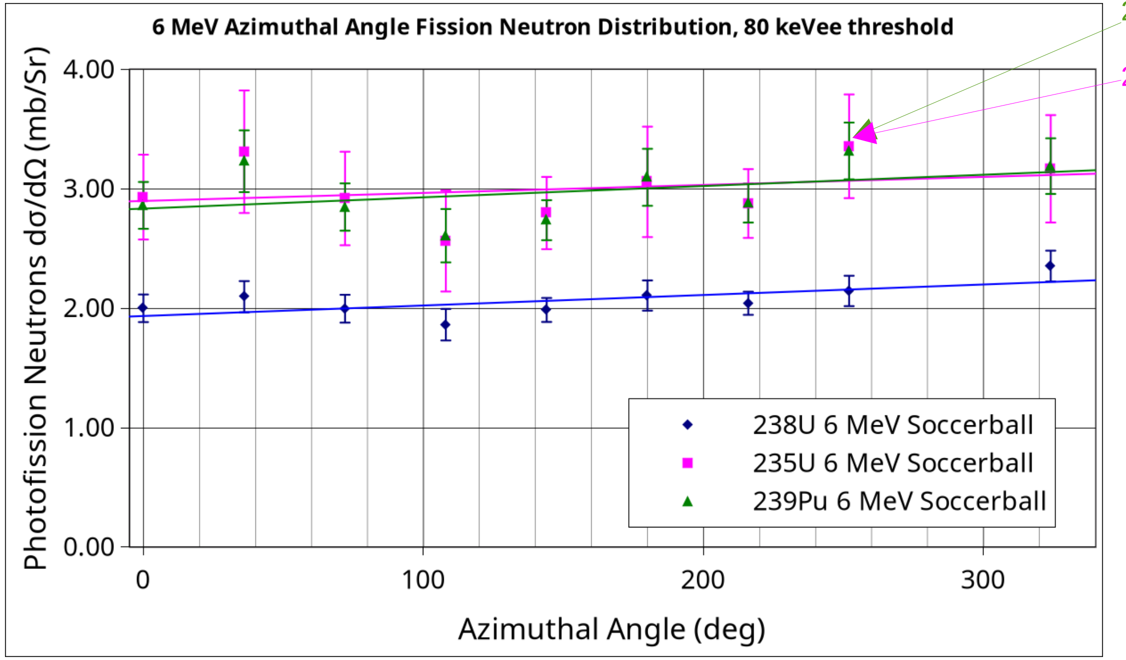






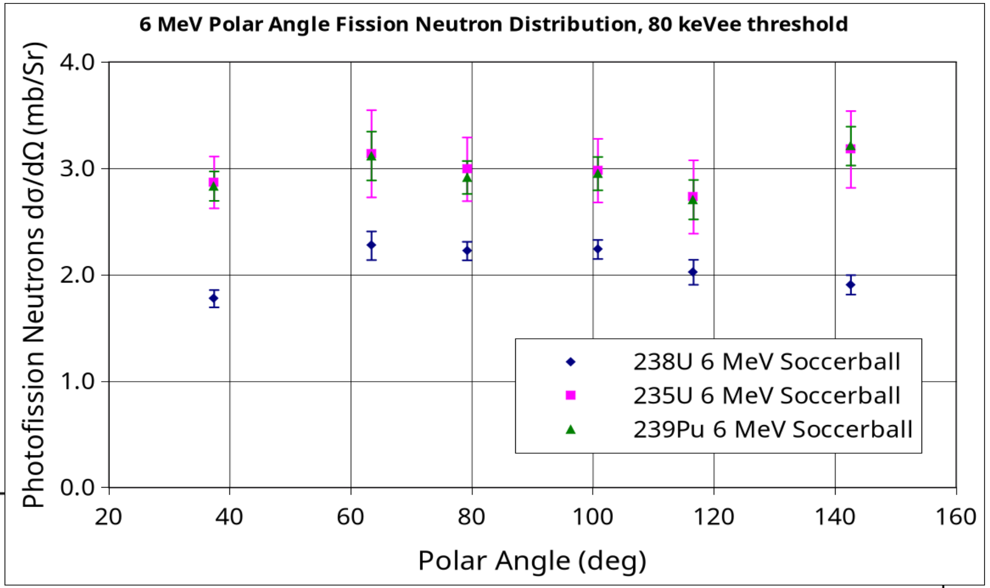
Example Data: 6 MeV

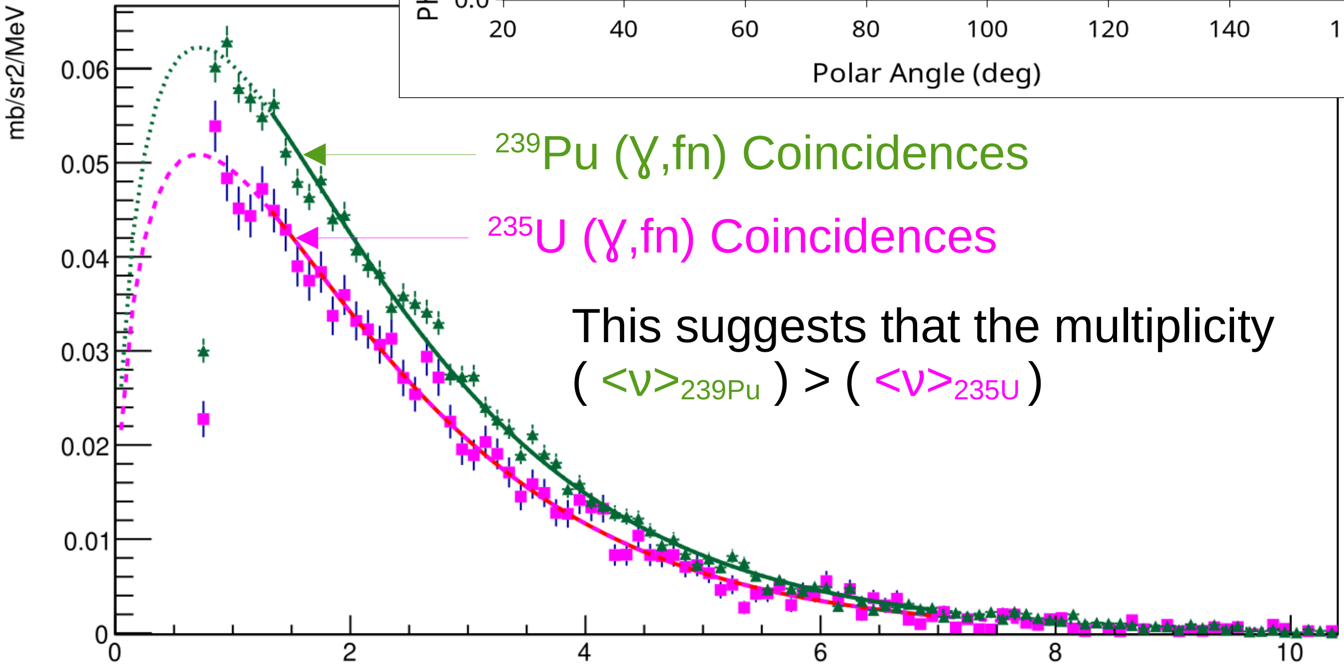
- Measured with the 42 cm flight path (soccerball) setup
- Error bars are statistical



^{239}Pu (ɣ,fn) Singles

^{235}U (ɣ,fn) Singles





^{239}Pu (ɣ,fn) Coincidences

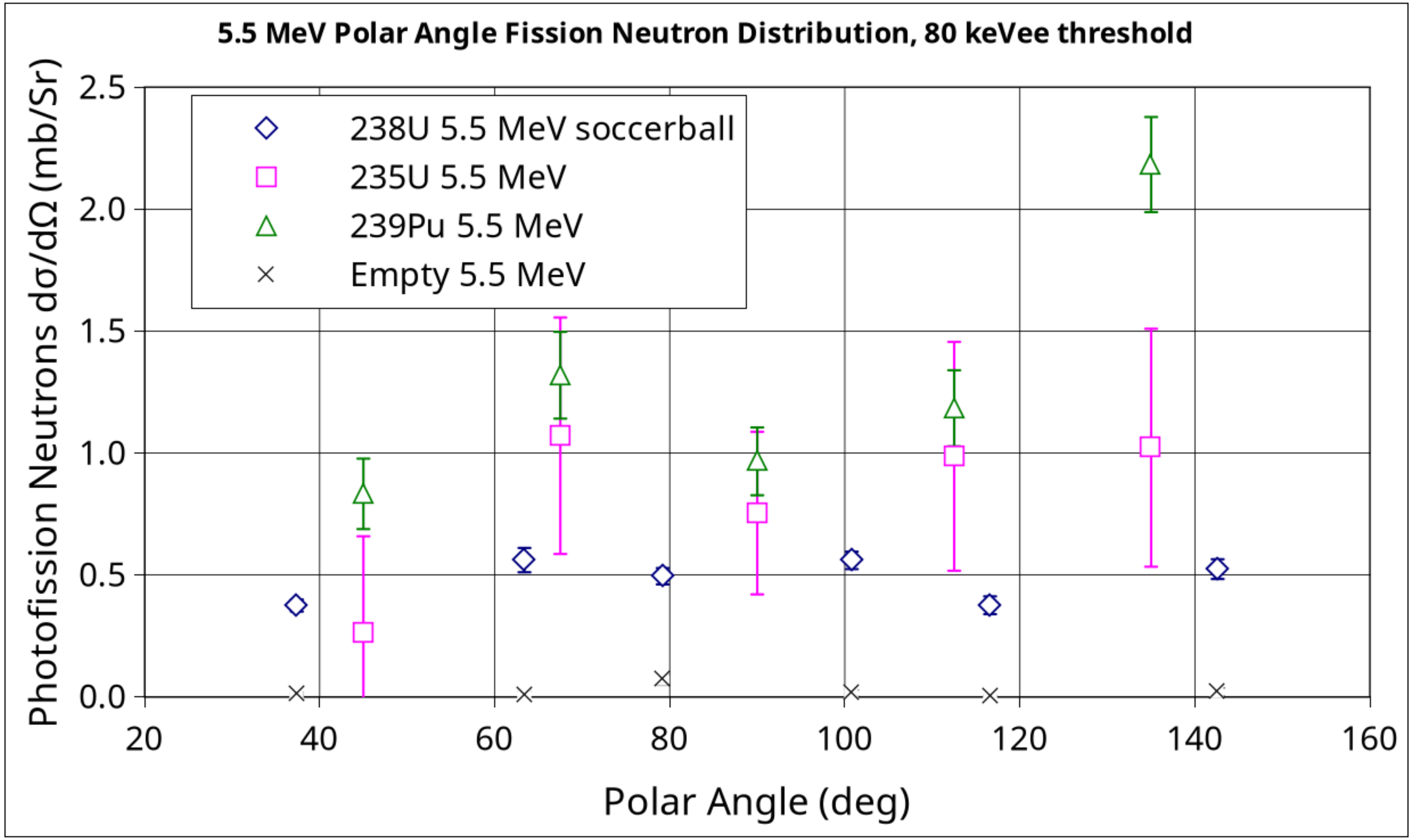
^{235}U (ɣ,fn) Coincidences

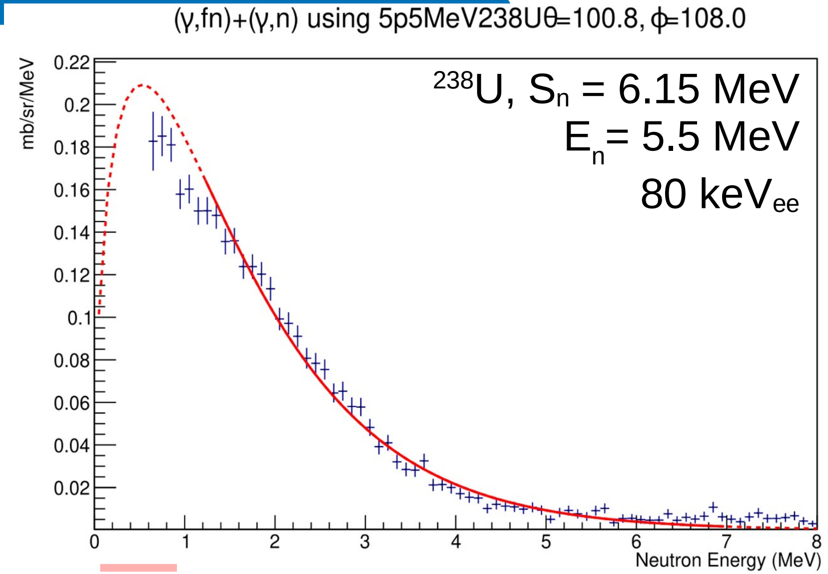
This suggests that the multiplicity ($\langle\nu\rangle_{239Pu}$) > ($\langle\nu\rangle_{235U}$)

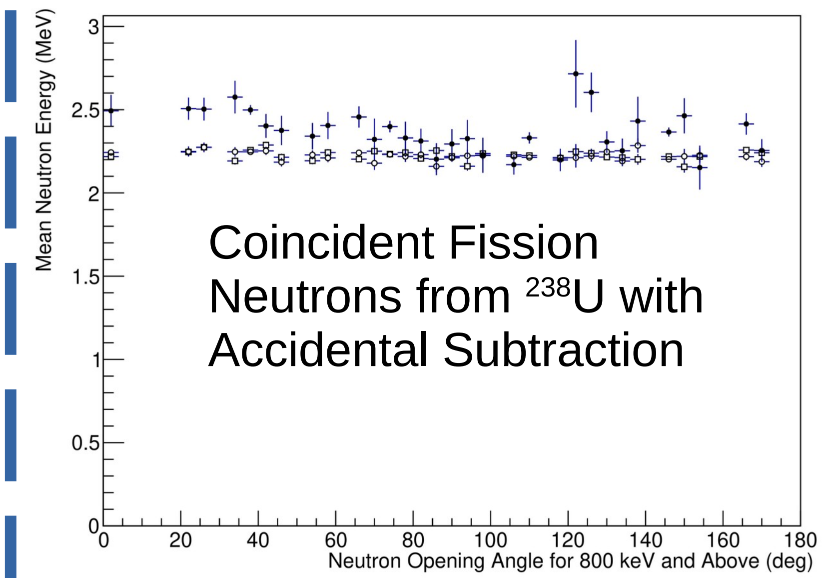
- At least 2 detectors per azimuthal point
  - Expect little variation due to circularly polarized beam

Example Data: 5.5 MeV

- Measured with the 42 cm flight path (soccerball) setup
- Error bars are statistical
- See unambiguous fission neutrons from all isotopes

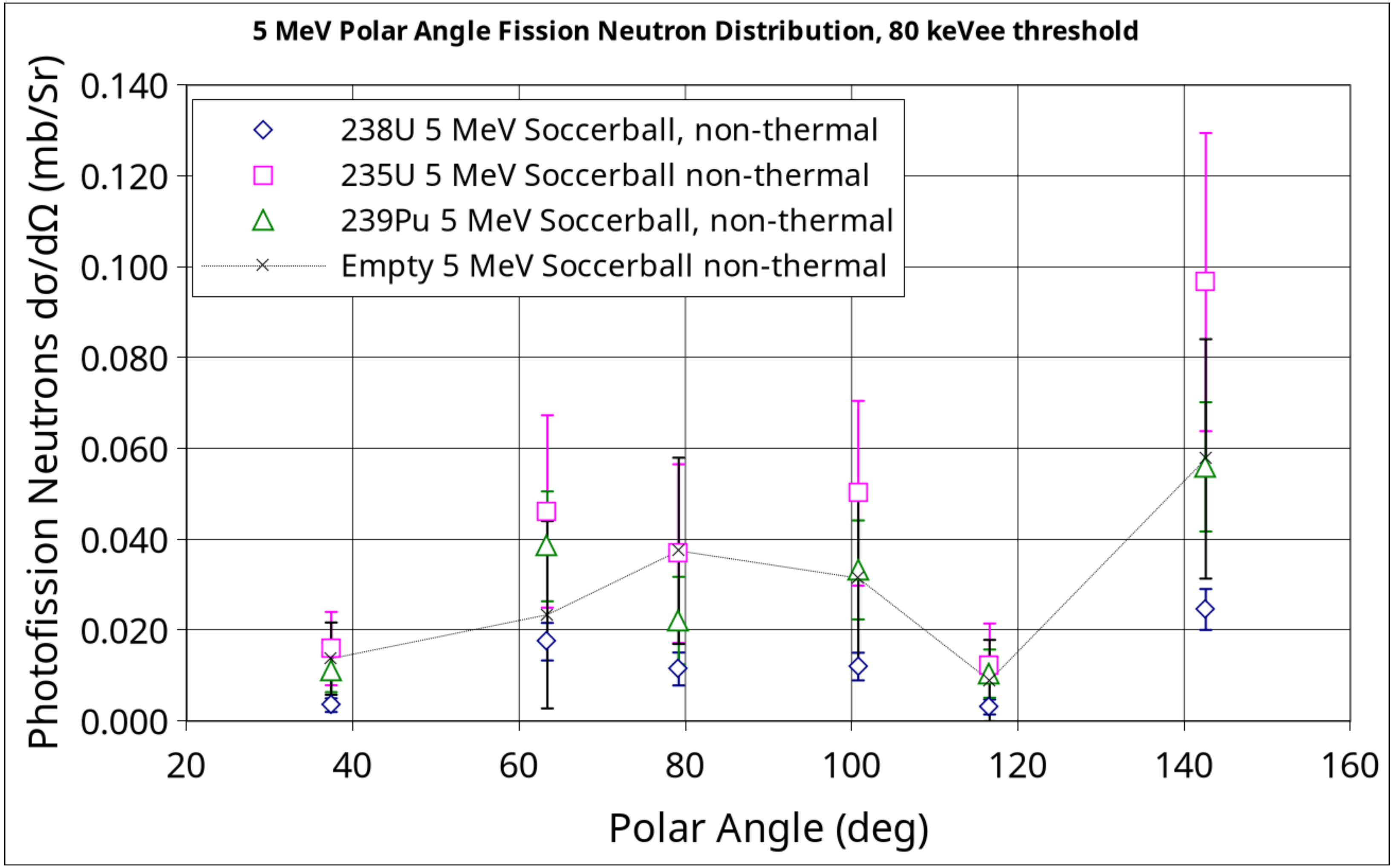


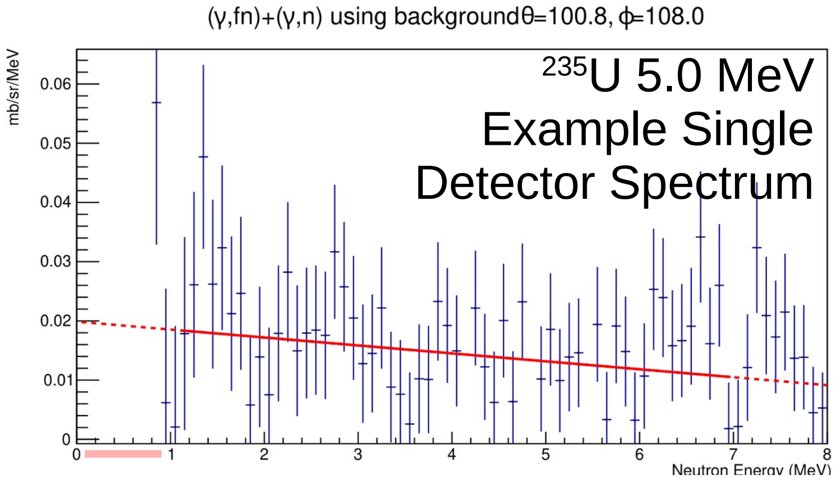


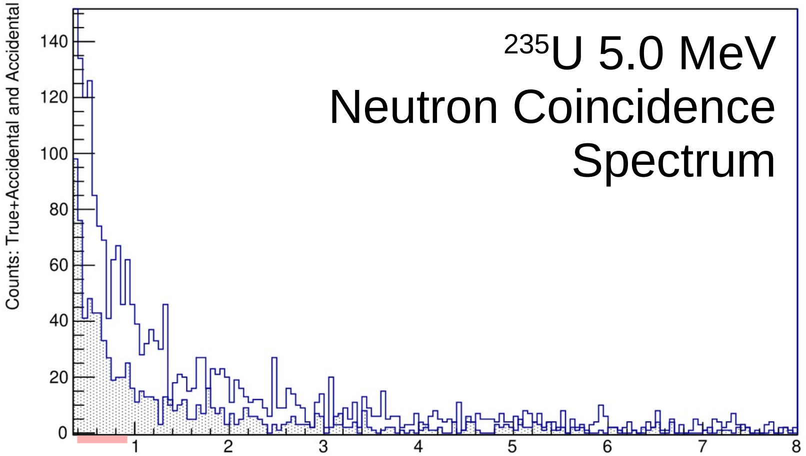


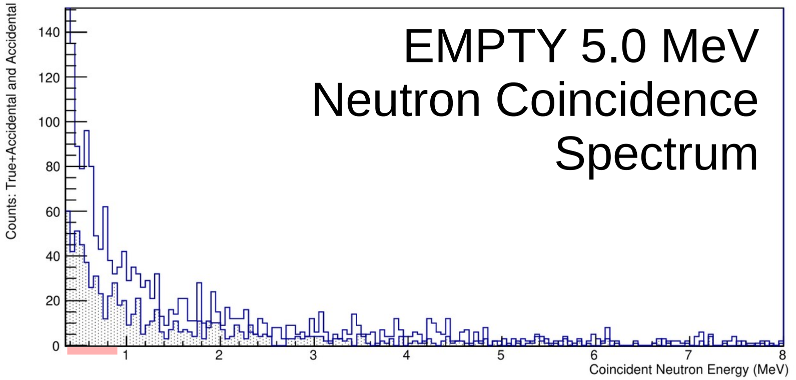
Example Data: 5.0 MeV – Measuring Zero

- Measured with the 42 cm flight path (soccerball) setup
- Helps constrain impact of higher energy Brem from accelerator
- **No indication of fission neutrons from any targets**

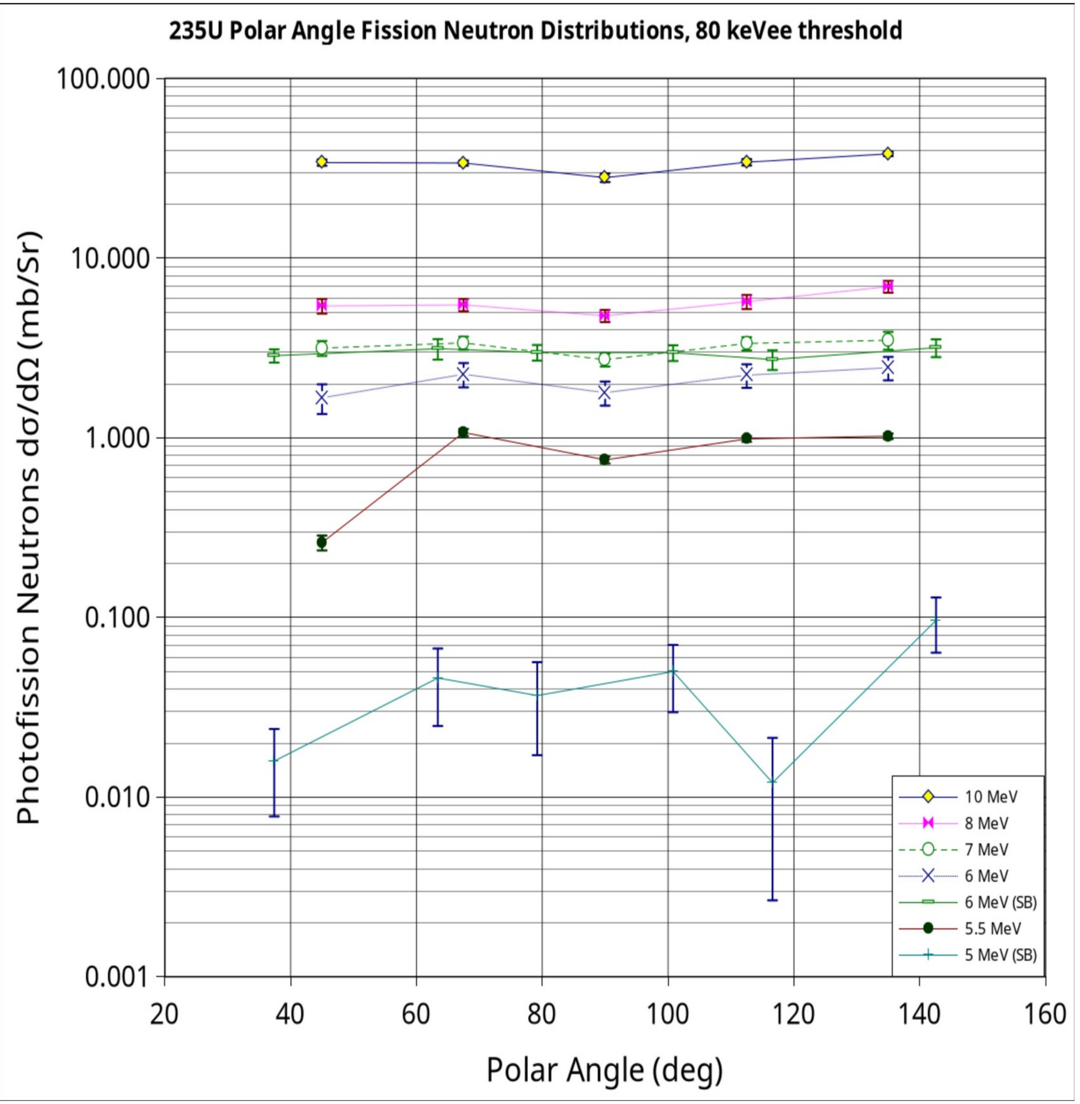


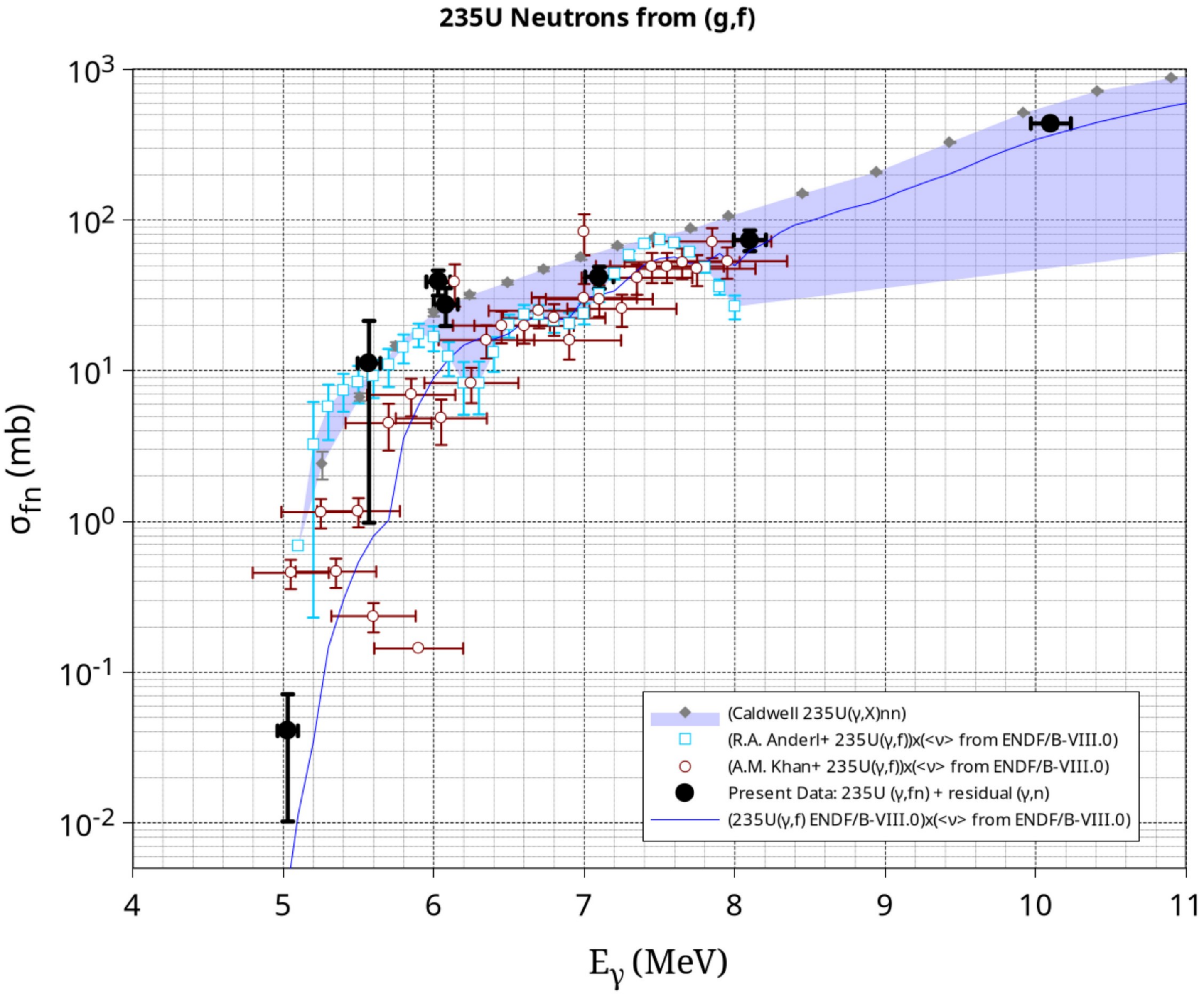




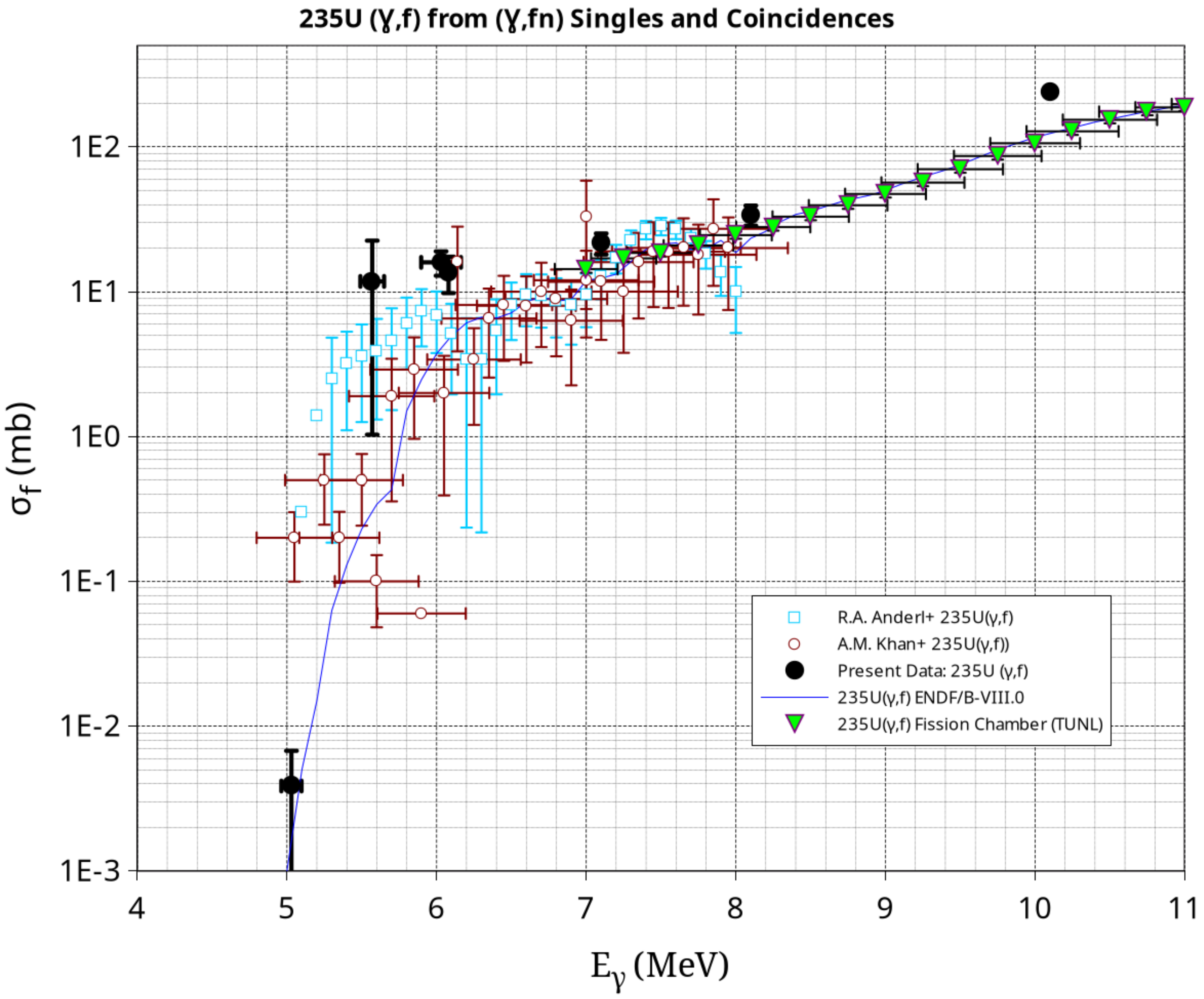


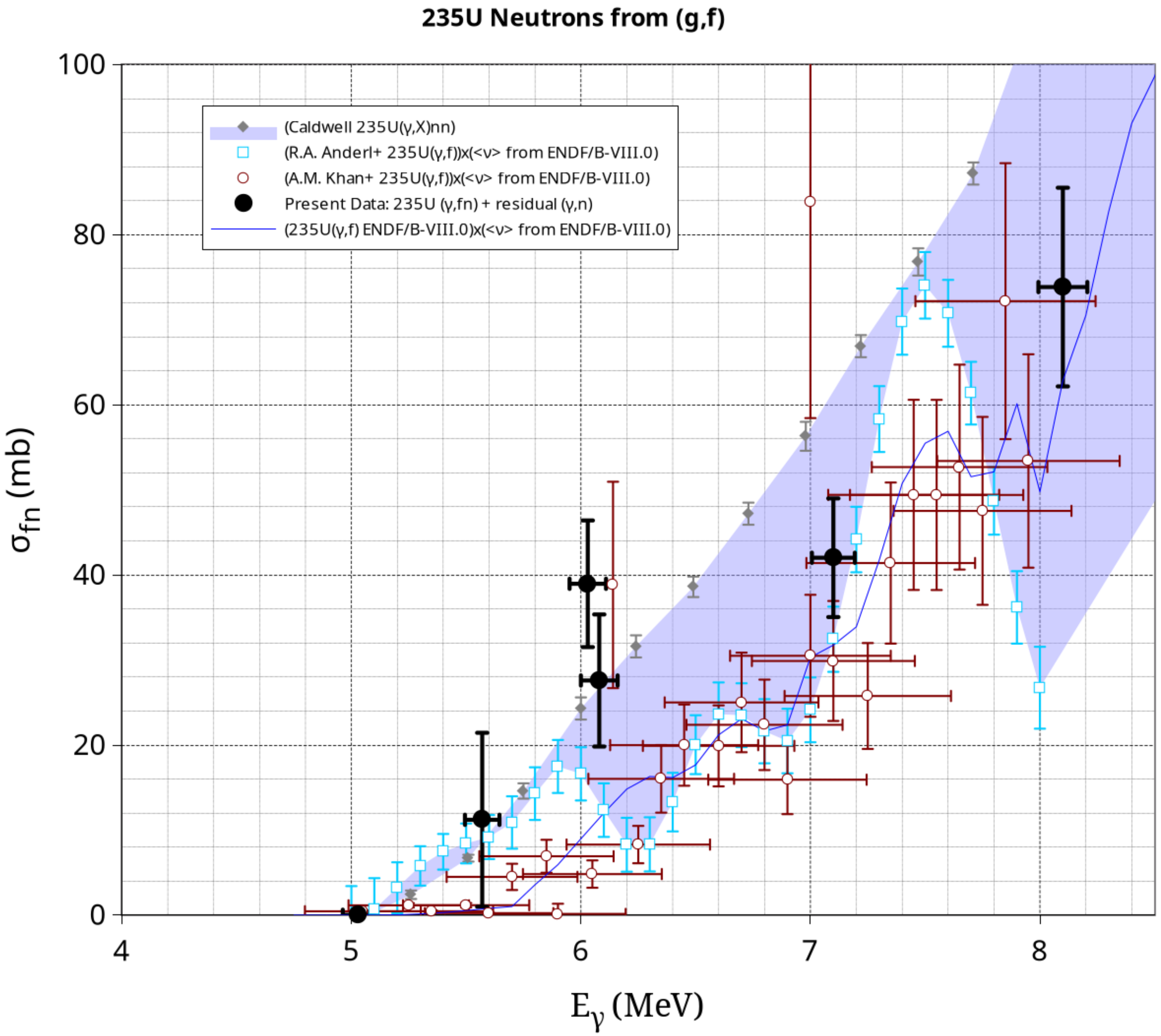
^{235}U Photofission



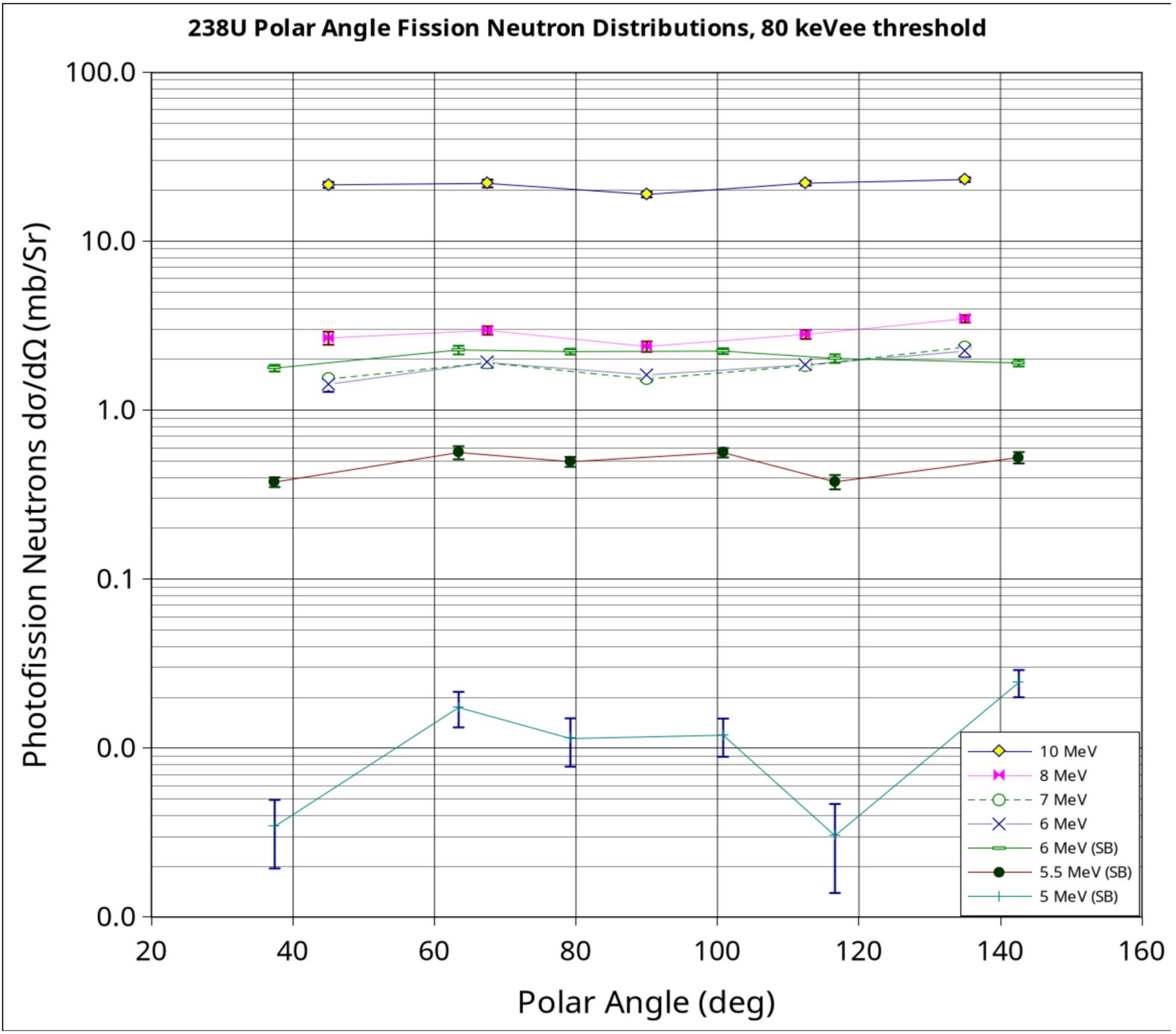


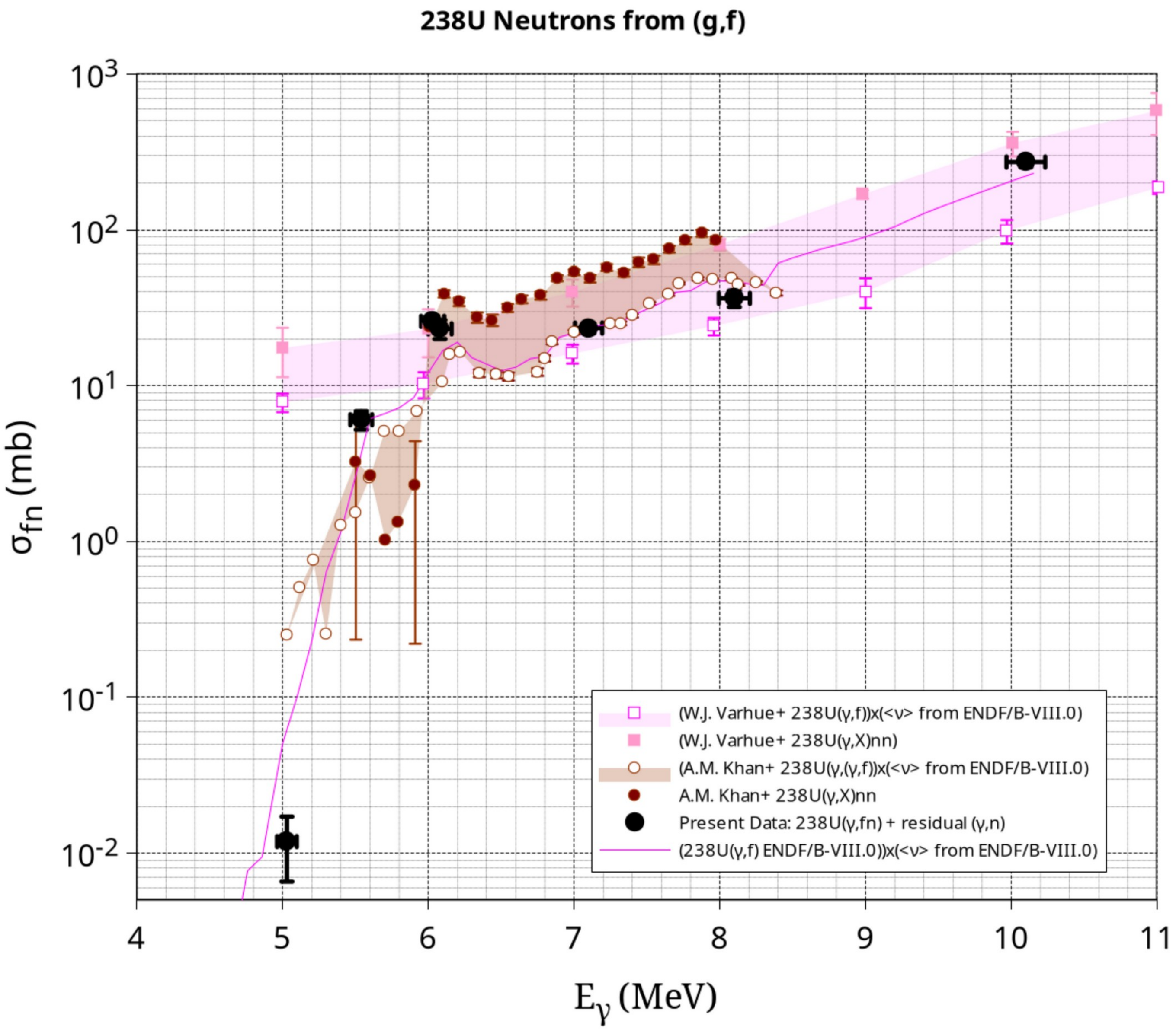
^{235}U Photofission



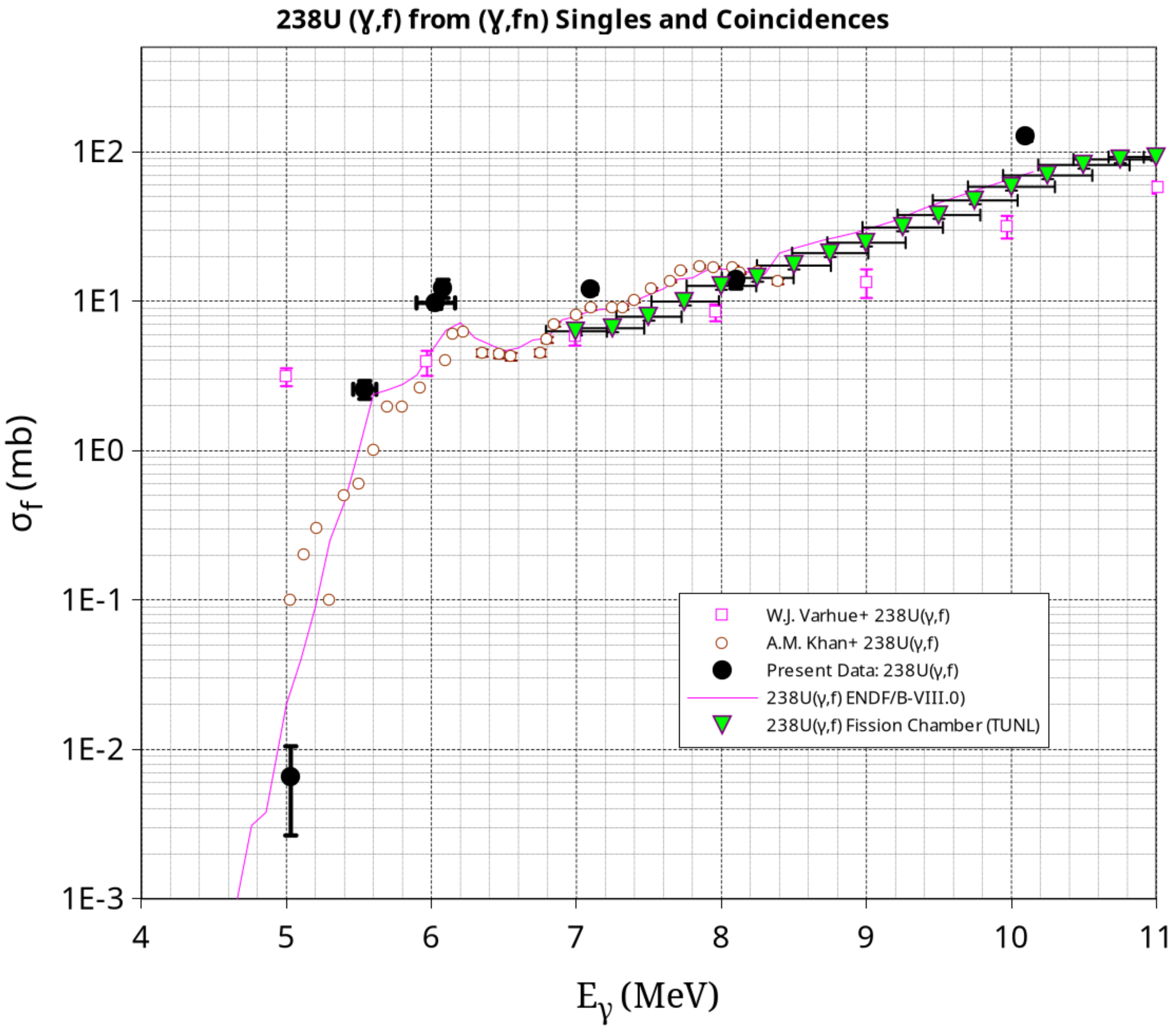


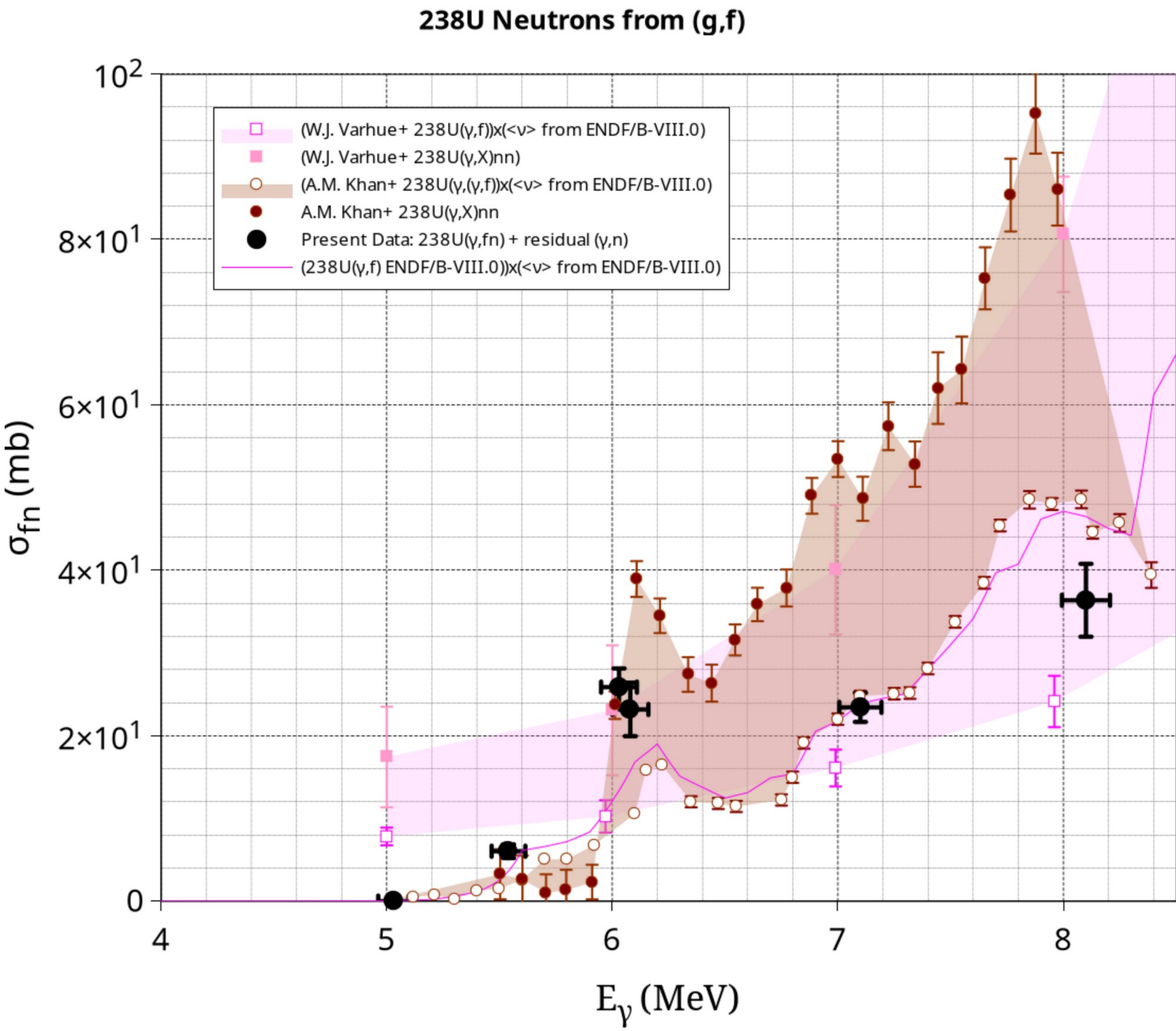
^{238}U Photofission



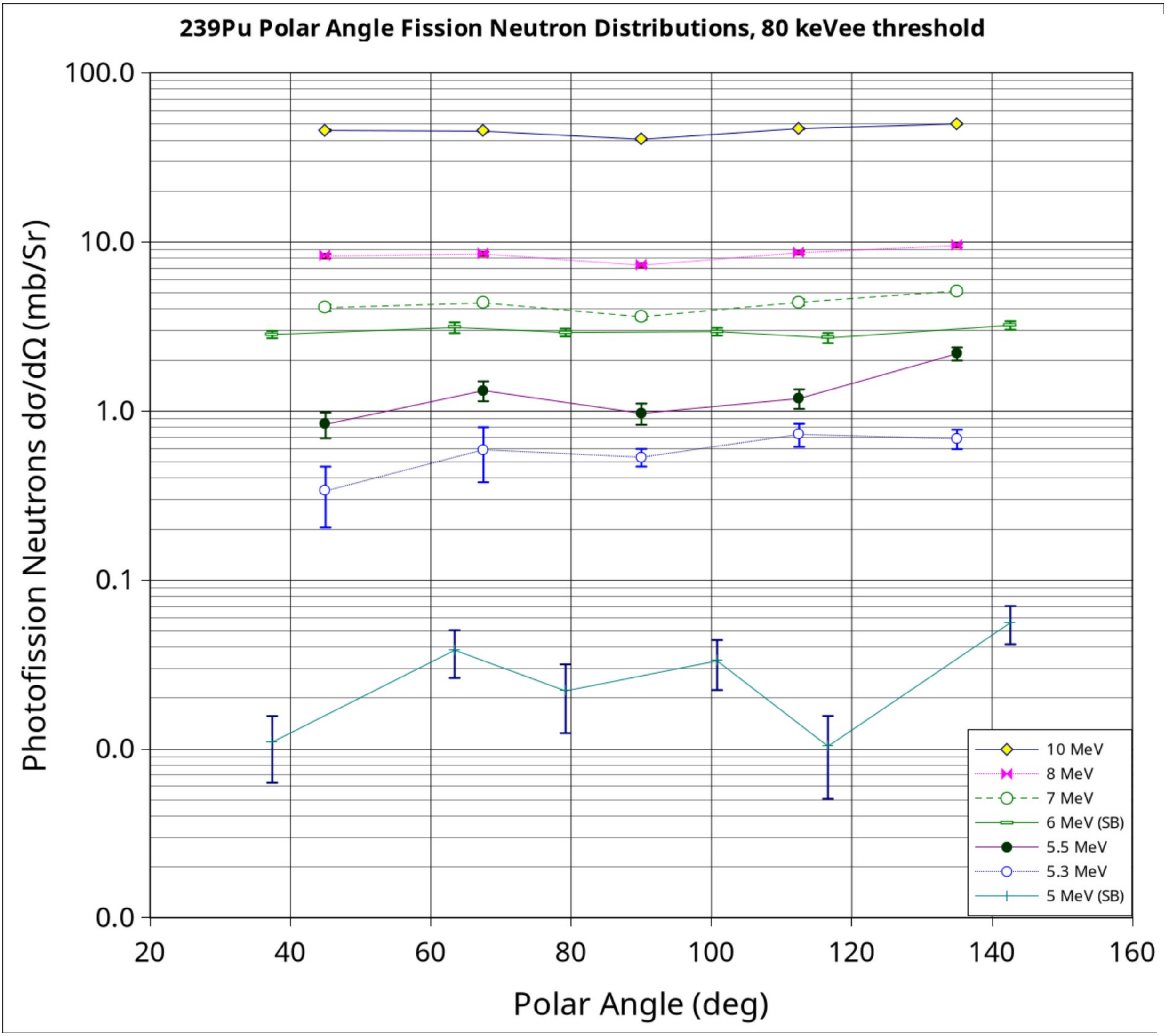


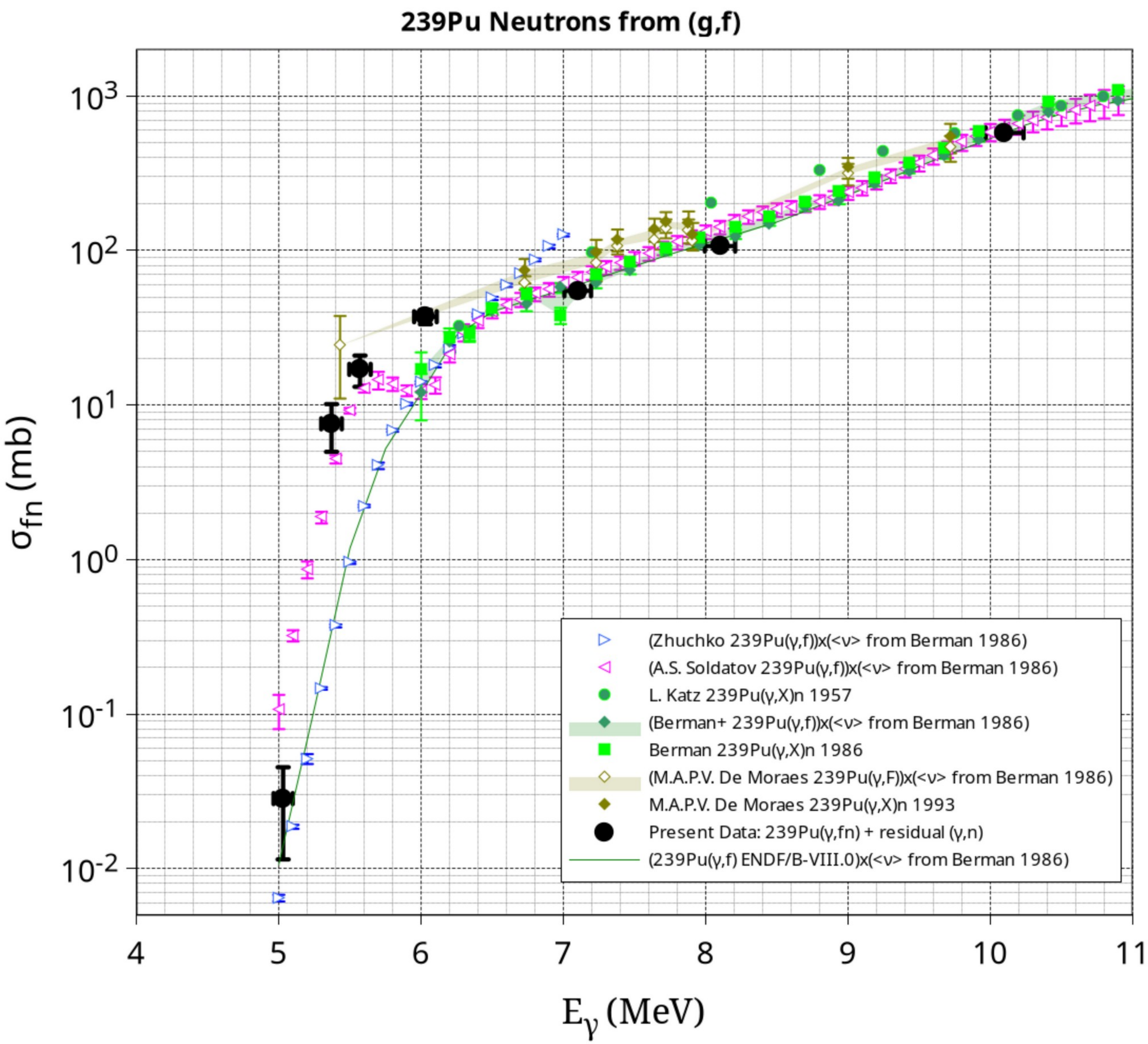
^{238}U Photofission



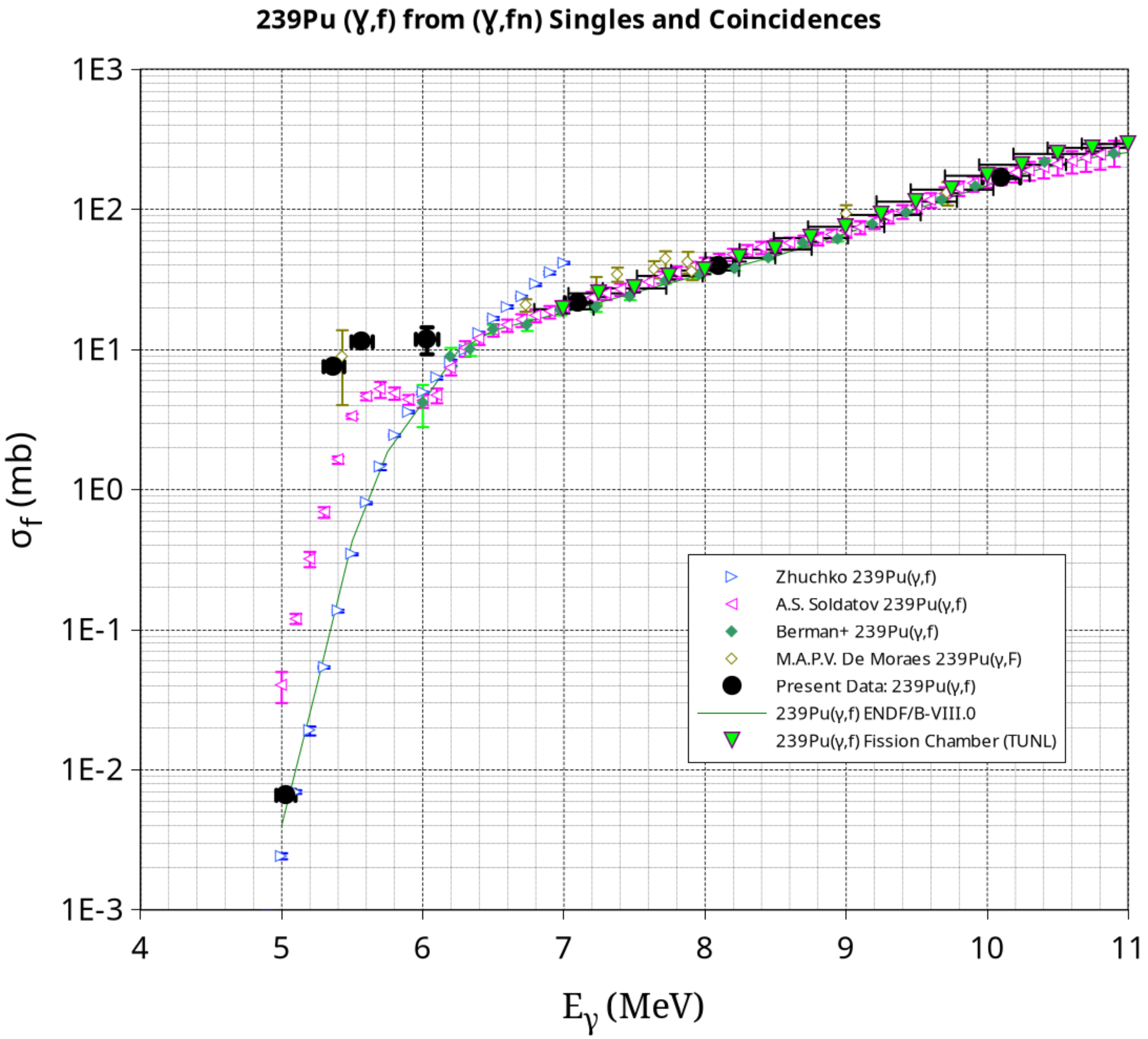


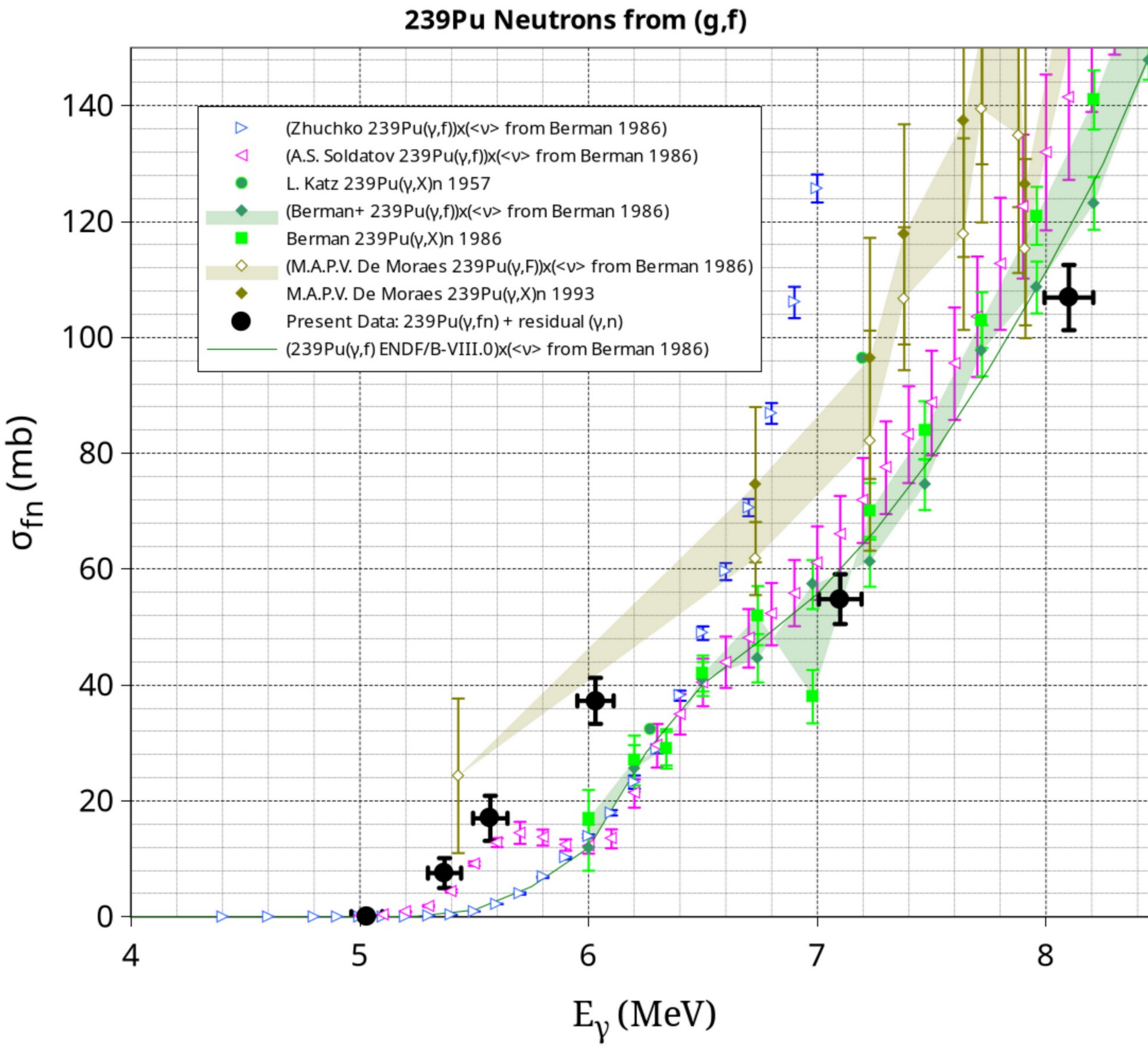
^{239}Pu Photofission





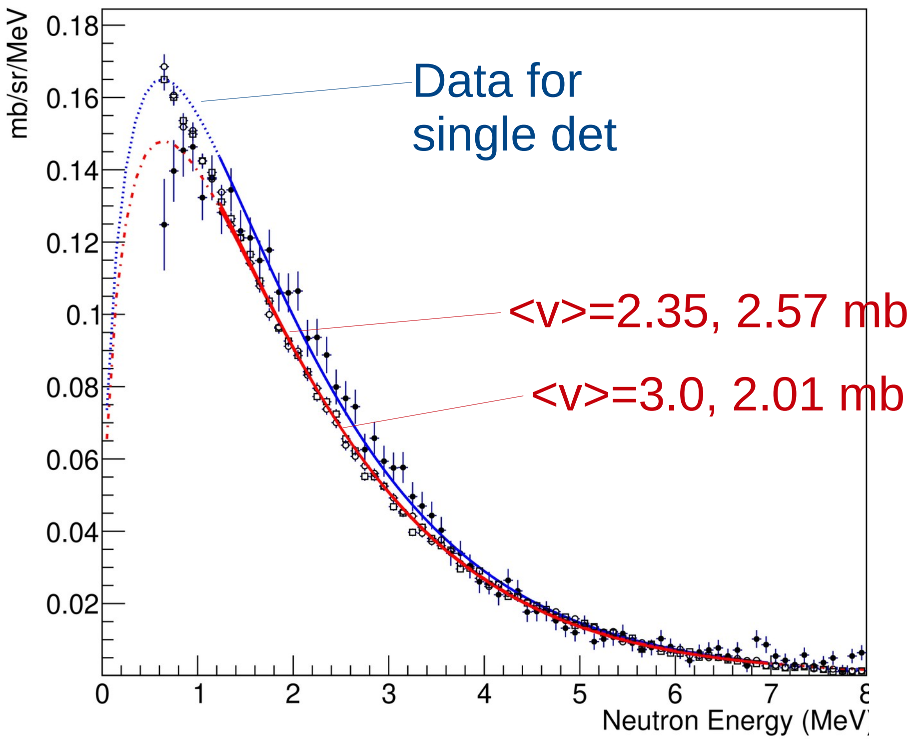
^{239}Pu Photofission

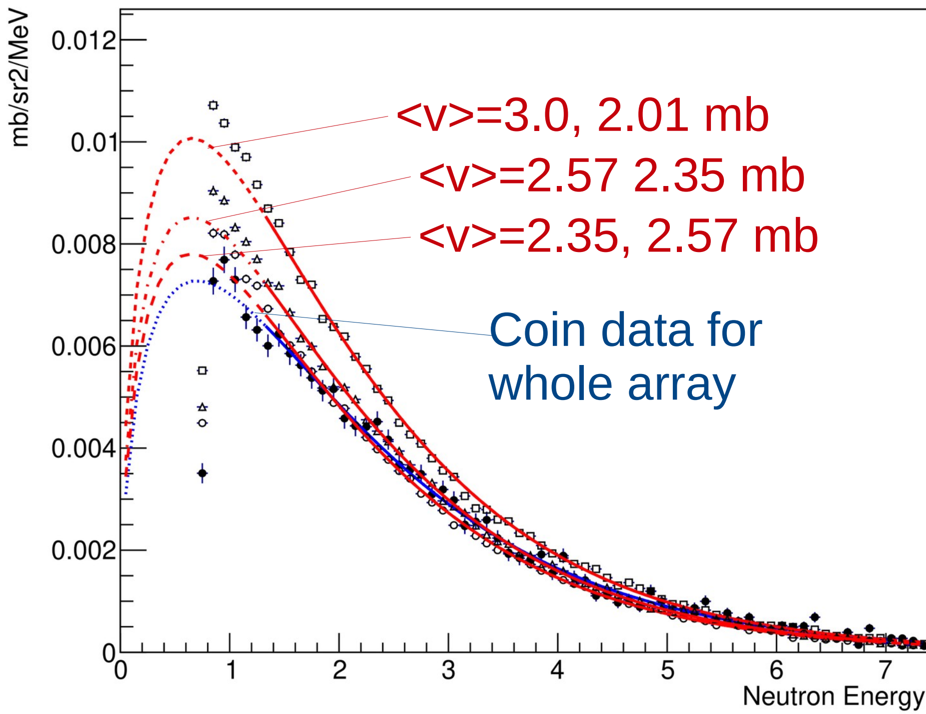


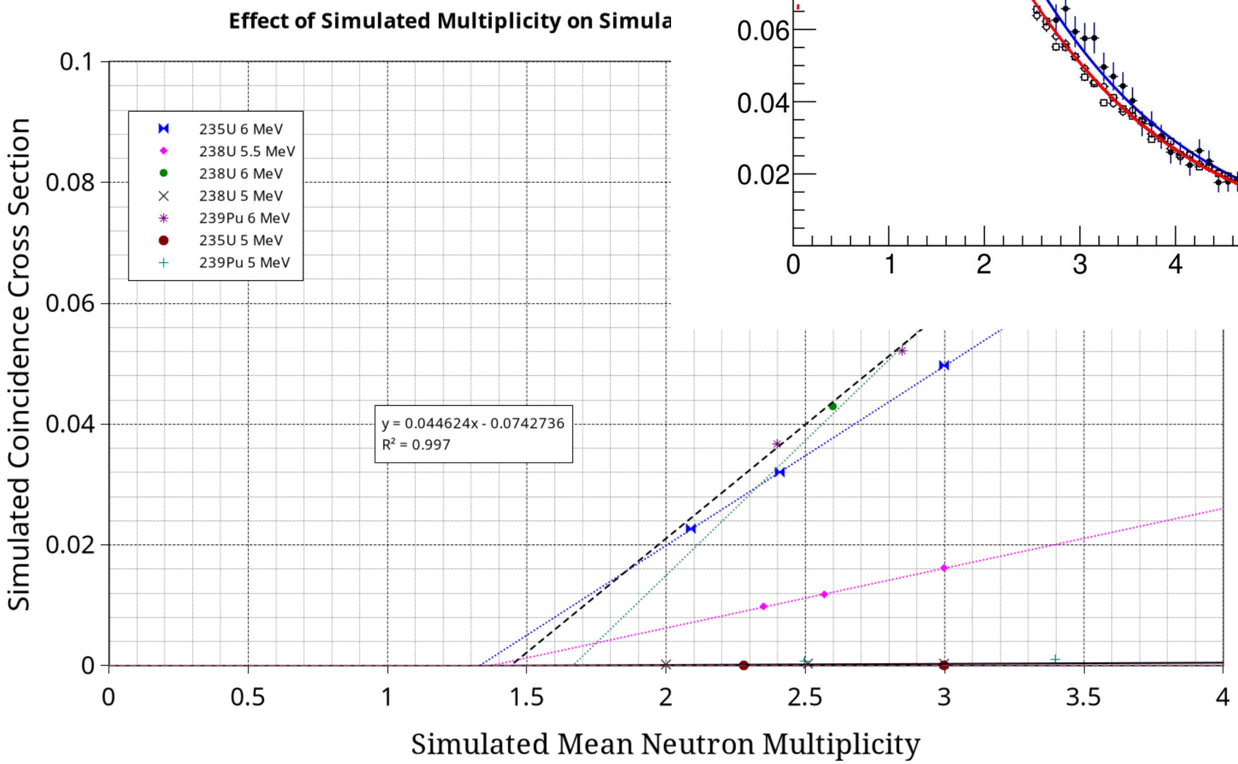


Estimating <ν> from coincidences and measured (ɣ,fn) singles

^{238}U 5.54 MeV
Soccerball
80 keVee SW threshold
0.8 MeV coin cutoff shown
1.1 MeV coin cutoff used for calculation

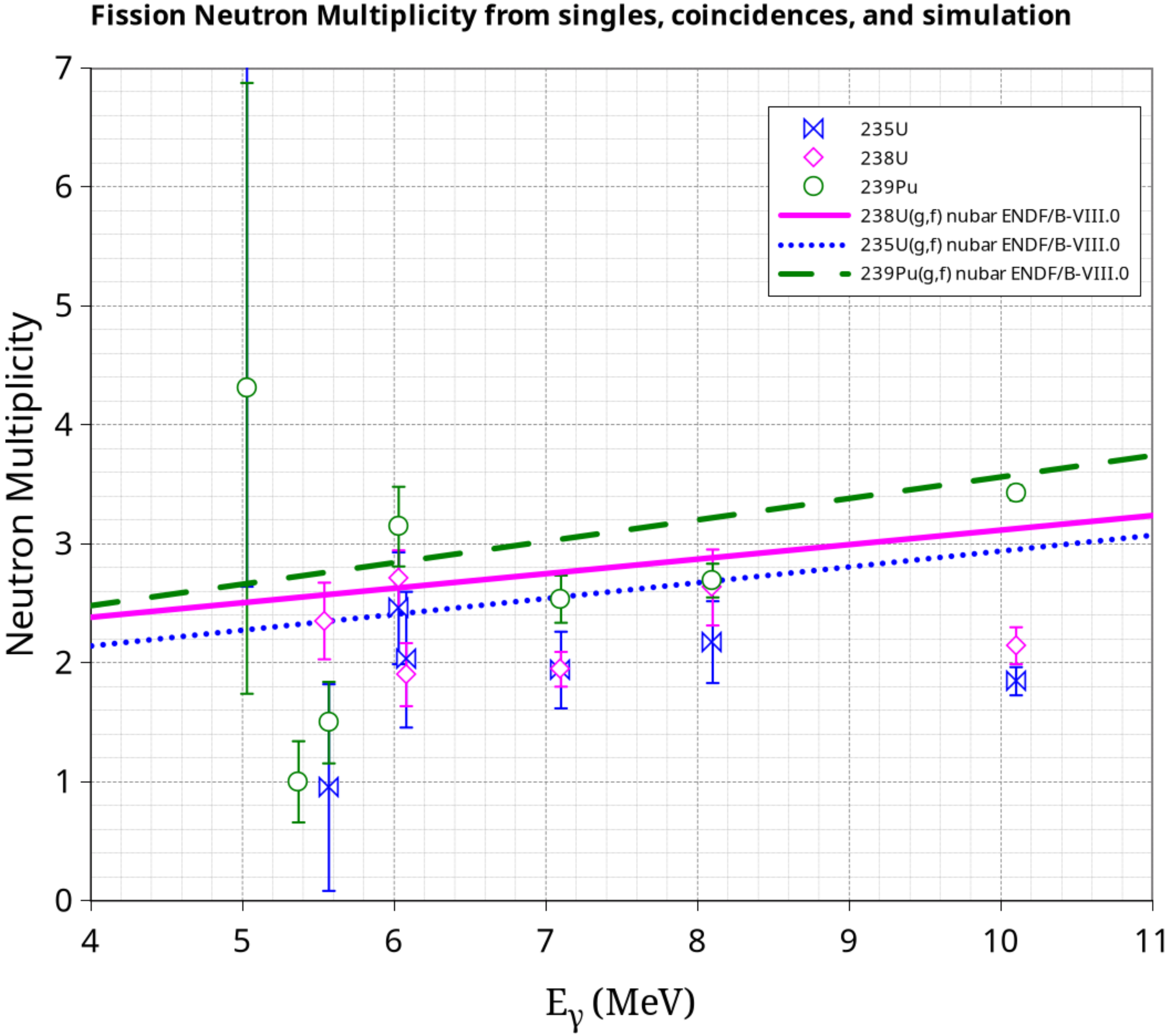


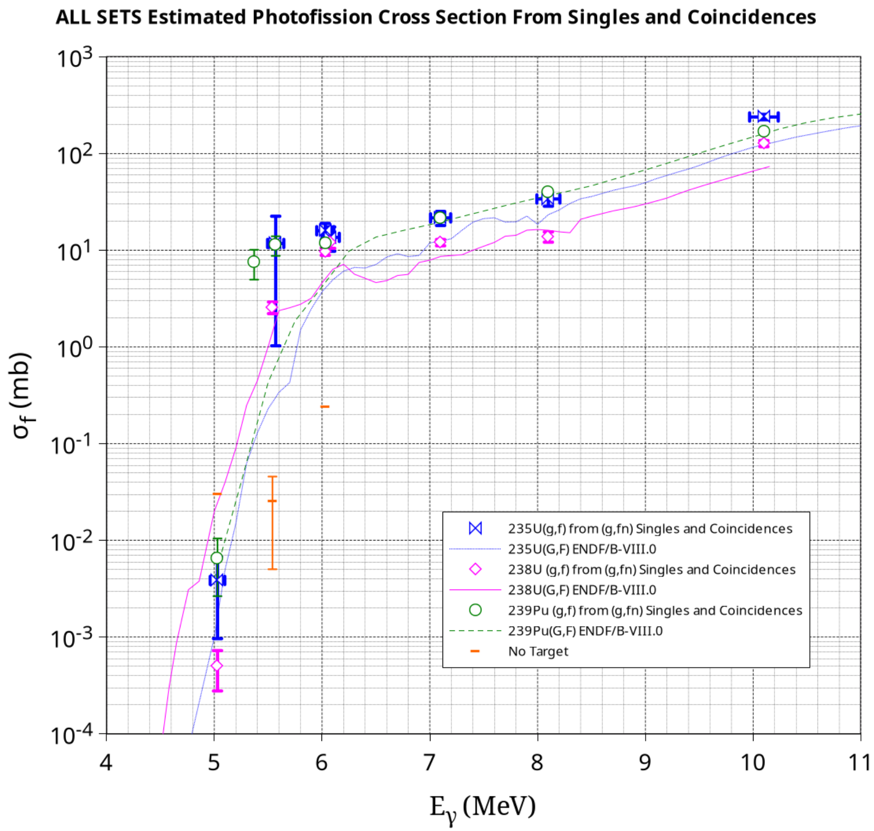




1. Compute (ɣ,fn) from data as usual from singles
2. Simulate the configuration with different <ν> such that
   $(\gamma,fn)_{measured} = \langle\nu\rangle_{sim}(\gamma,f)_{sim}$
3. Use coincidence data to interpolate <ν>
4. Solve for $(\gamma,f)=(\gamma,fn)_{meas}/\langle\nu\rangle$

<ν> estimated from coincidences and measured (Ɣ,fn) singles



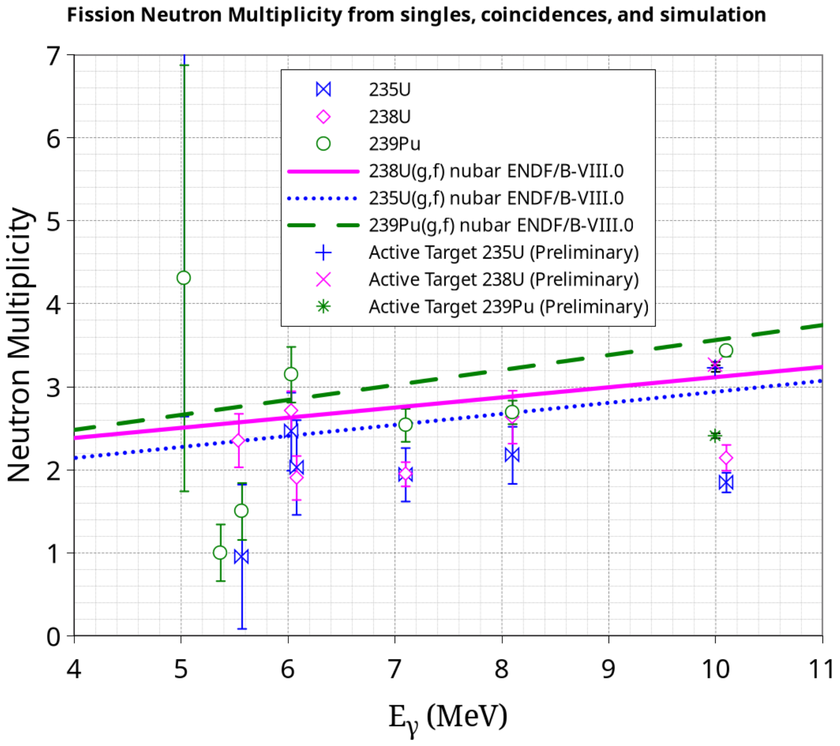


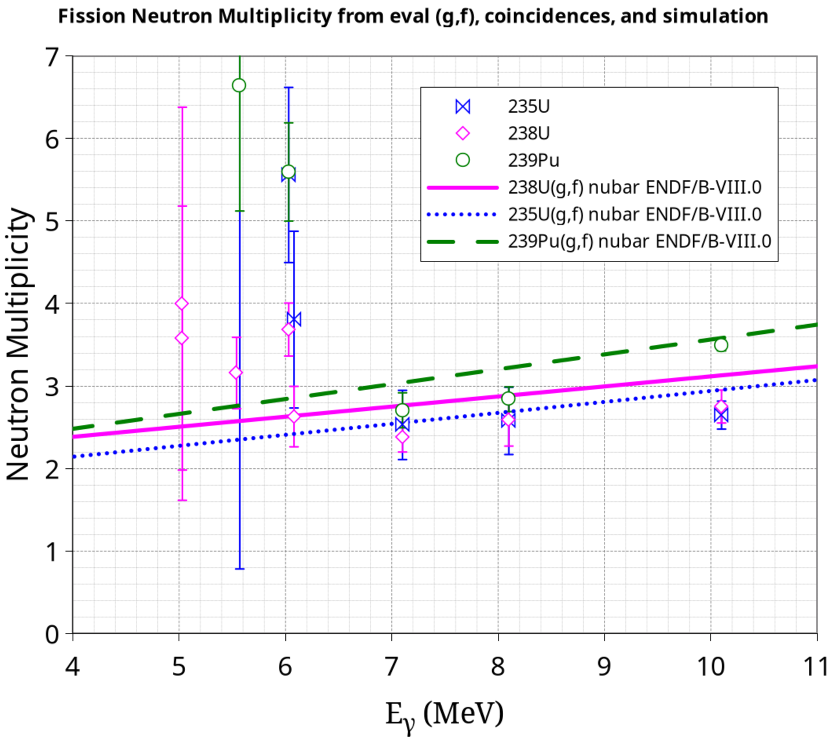
1. Compute (Ɣ,fn) from data as usual from singles
2. Simulate the configuration with different <ν> such that

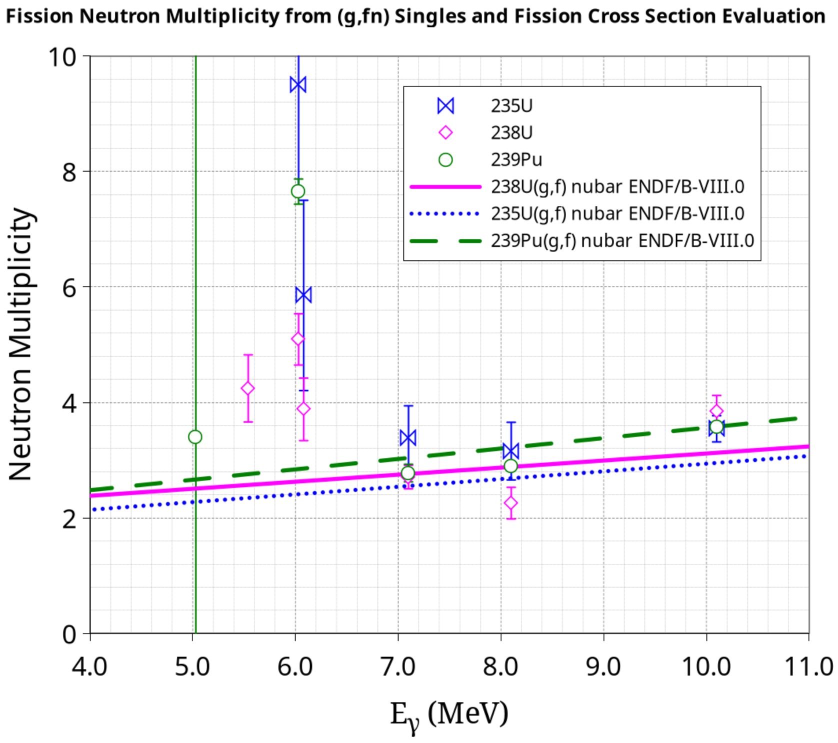
$$(\gamma,fn)_{measured} = \langle\nu\rangle_{sim}(\gamma,f)_{sim}$$

3. Use coincidence data to interpolate <ν>
4. Solve for $(\gamma,f)=(\gamma,fn)_{meas}/\langle\nu\rangle$

Comparing <ν> estimates using different methods







- Measured **(ɣ,fn) singles**
- Measured (ɣ,fn) **coincidences**
- Simulated (ɣ,fn) **coincidences**

- Estimates of (ɣ,f) and <ν> (covariant)
  - independent of evaluations

- Assume **evaluated (ɣ,f)** ENDF
- Measured (ɣ,fn) **coincidences**
- Simulated (ɣ,fn) **coincidences**

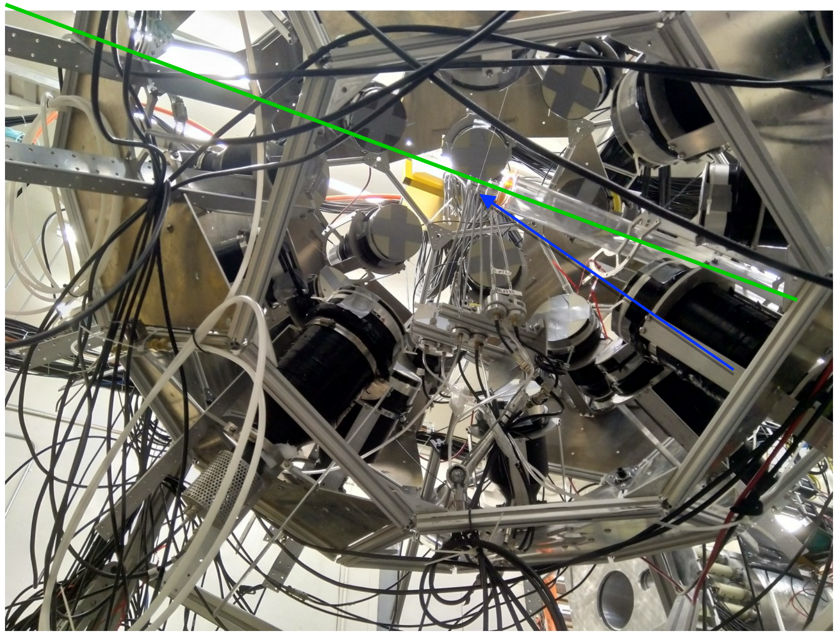
- Estimates <ν> assuming (ɣ,f) evaluation
  - Ignores singles data (better SNR)

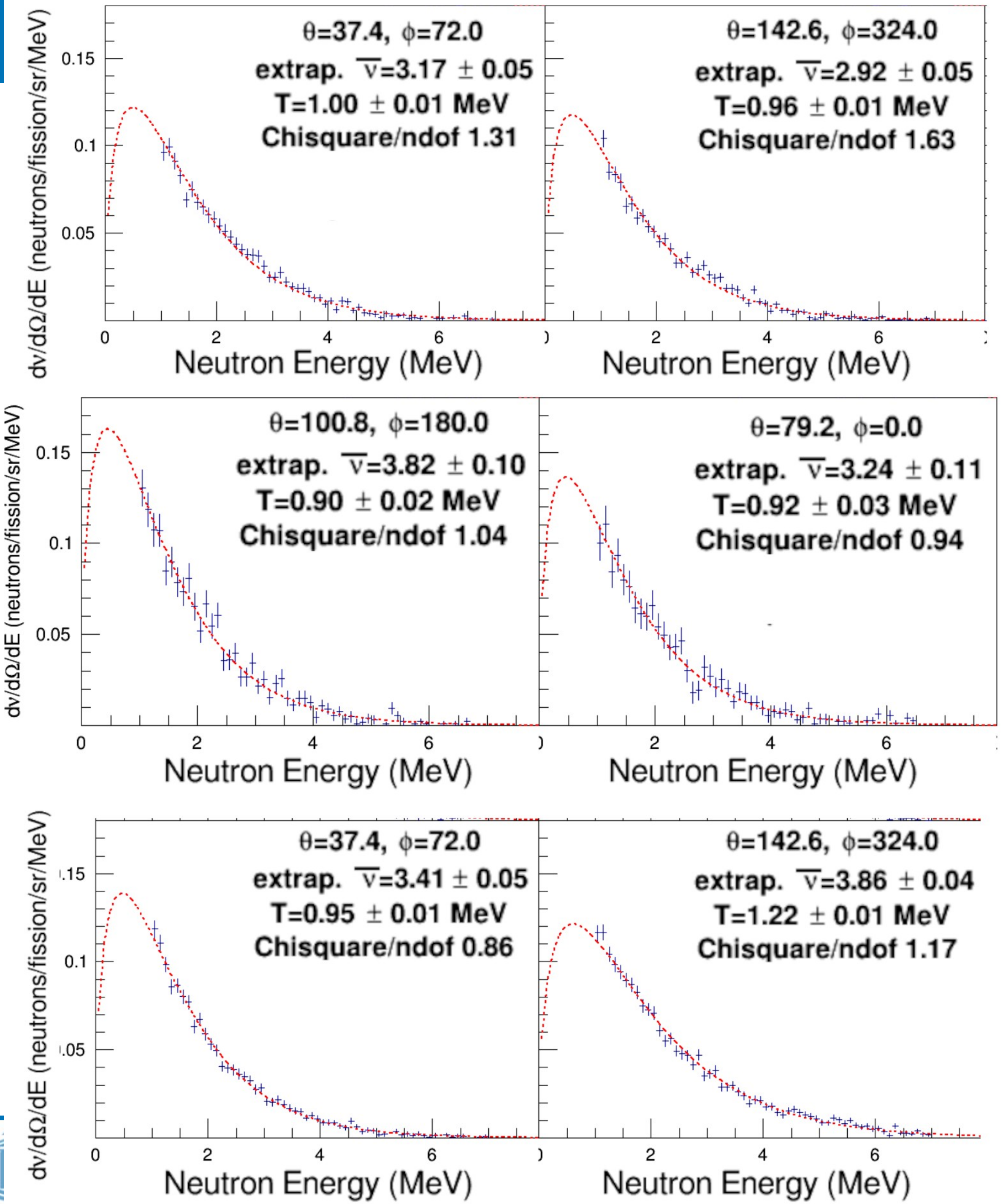
- Assume **evaluated (ɣ,f)** ENDF
- Measured (ɣ,fn) **singles**

- Estimates <ν> assuming (ɣ,f) evaluation
- Does not use coincidence data or simulation of coincidences

Active Target Measurements

- Use Fission chambers as active targets
- Timing coincidences between chambers and neutron detectors
  - Eliminates (Ɣ,n) at high energy
- Provides a good <ν> estimate
- Example spectra for ^{238}U at right





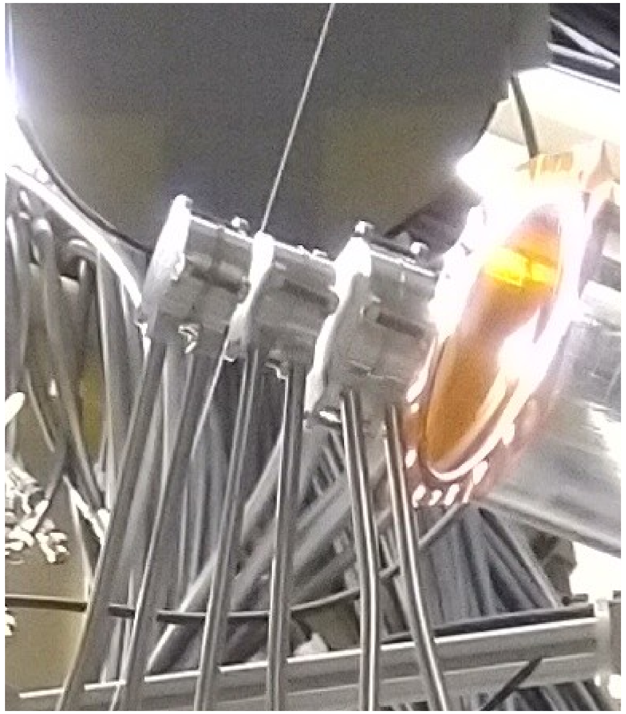
10 MeV (238U shown):
Date: Jan 2023
E_γ = 10.0 MeV
Targets: ^{238}U, ^{235}U, ^{239}Pu
Flight Path: ~42 cm
Beam Polarization: circular
Coll. Dia. = 0.75"
Beam Time: 66 hours

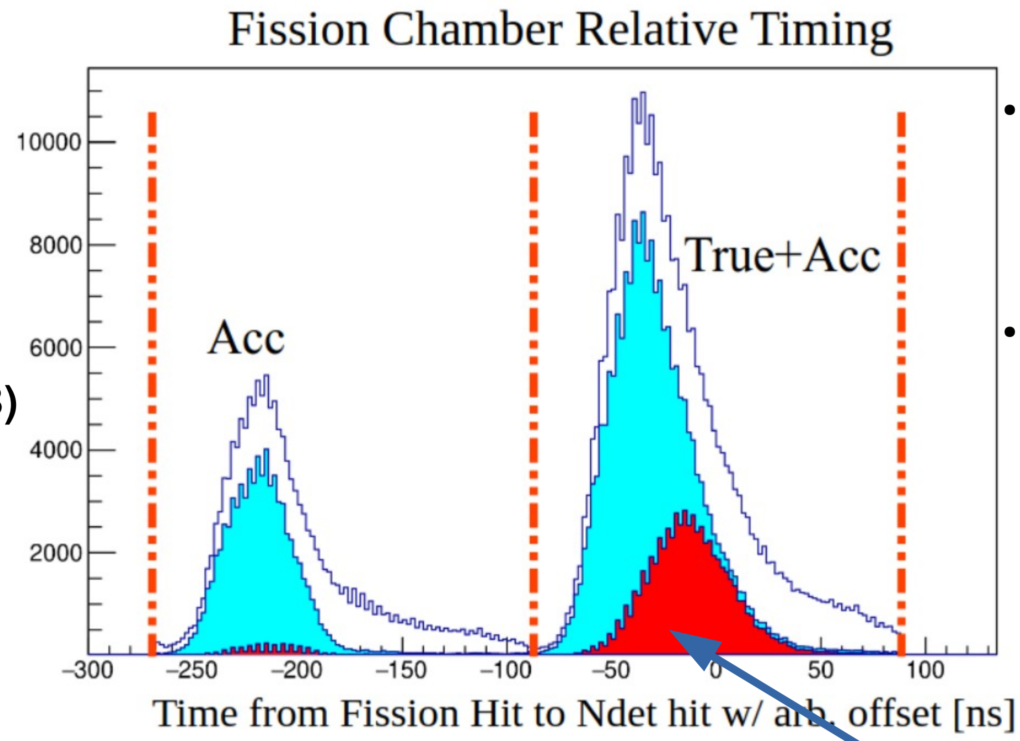
13.5 MeV (238U shown):
Date: Jan 2023
E_γ = 13.5 MeV
Targets: ^{235}U, ^{238}U, ^{239}Pu
Flight Path: ~42 cm
Beam Polarization: circular
Coll. Dia. = 0.75"
Threshold: 60 keVee shown

16.0 MeV (238U shown):
Date: May 2023
E_γ = 16.0 MeV
Targets: ^{238}U, ^{235}U, ^{239}Pu
Flight Path: ~42 cm
Beam Polarization: circular
Coll. Dia. = 0.75"
Threshold: 60 keVee shown

Active Target Measurements

Targets: ^{238}U, ^{235}U, ^{239}Pu
Beam Polarization: circular
Collimator. Dia. = 0.75”
f_γ = ~2 x 10^8 γ/s
10 MeV : **66 hours (Jan 2023 SB)**
11.2 MeV : **30 hours**
13.5 MeV : **35 hours**
13.5 MeV : **29 hours (Jan 2023 SB)**
16 MeV : **52 hours (May 2023 SB)**



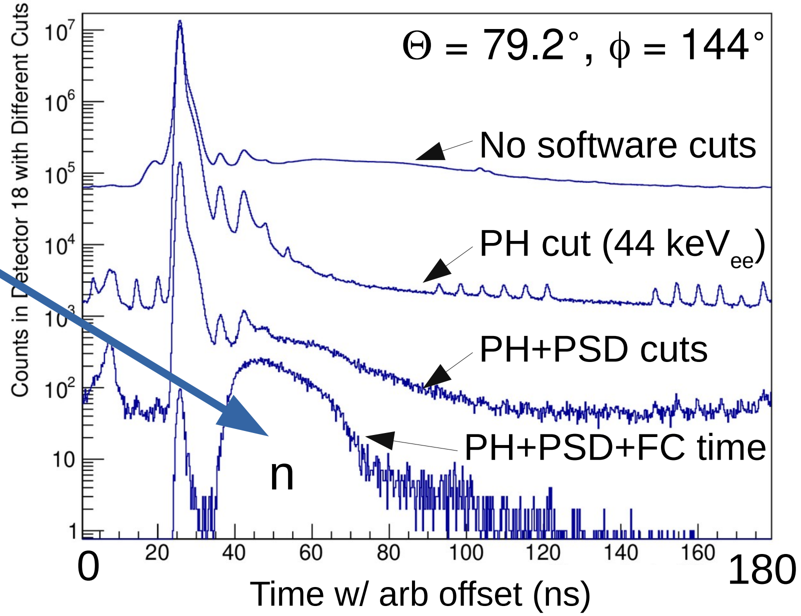


Hardware Timing Setup

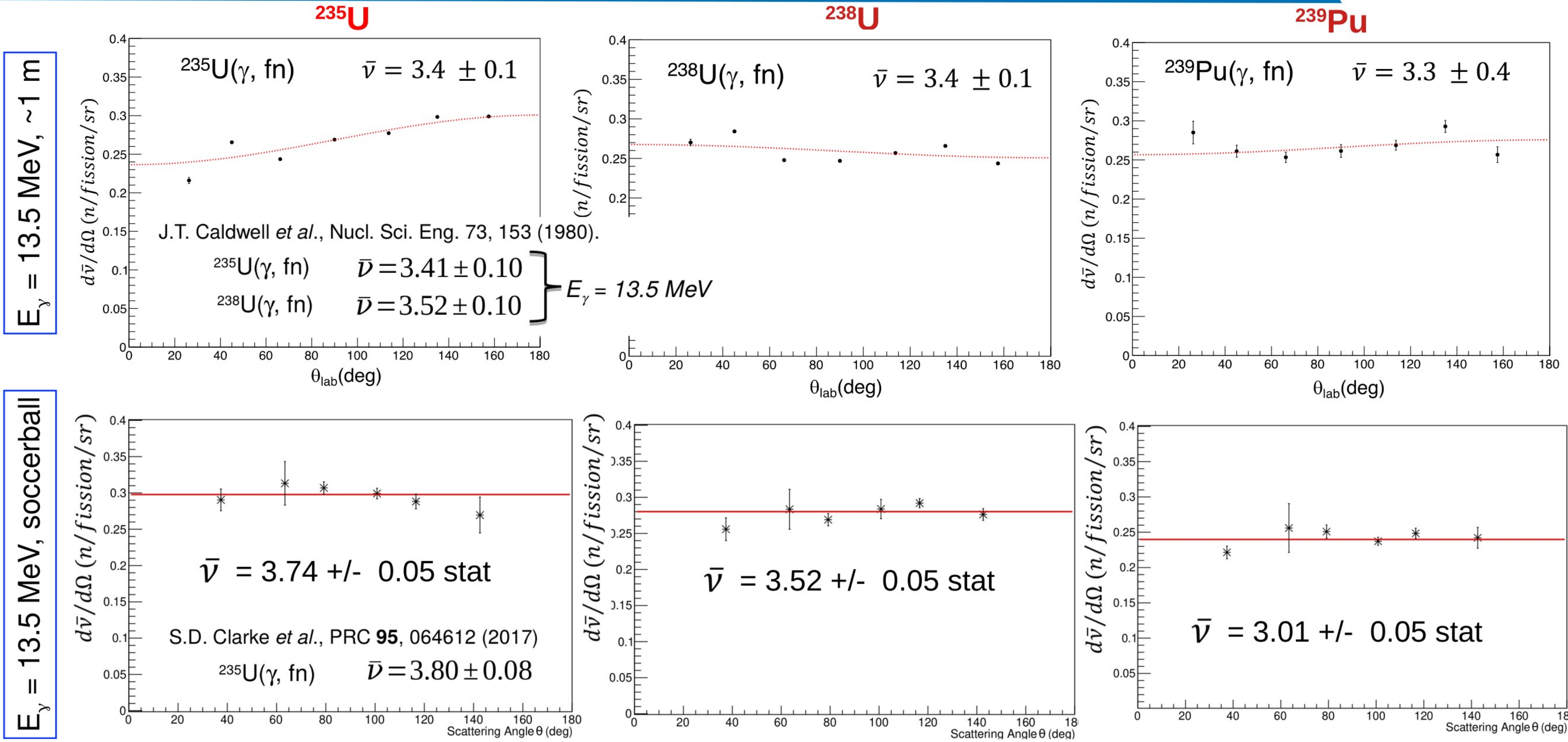
- All neutron detector channels are self-triggering
  - However, they are only allowed to self-trigger if a fission occurred within -400 ns to +10,000 ns

Software Timing Setup

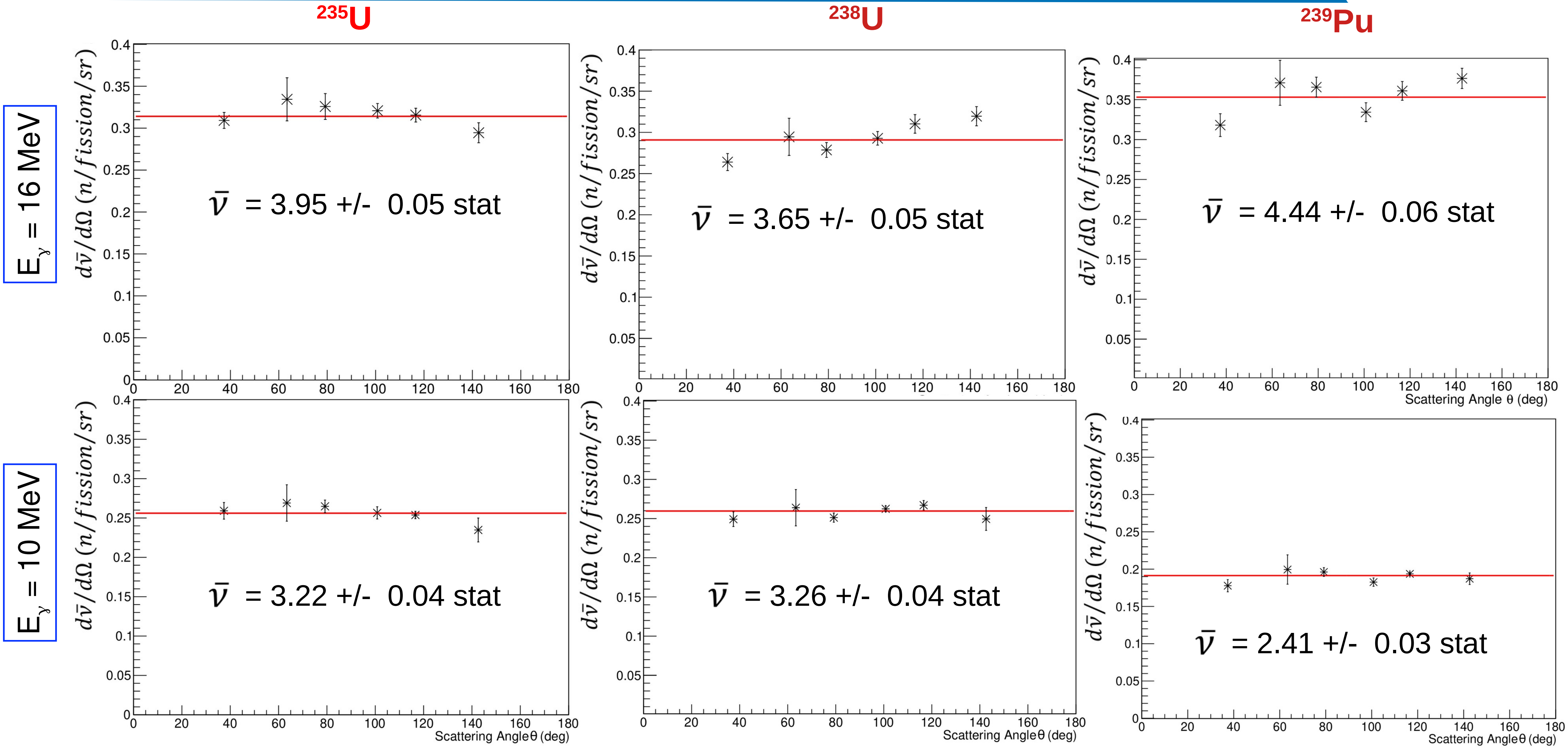
- Timing coincidences between neutron detectors and fission chambers are restricted to the same beam burst
  - An accidental coincidence builder is run in parallel
- Arrival of every beam burst is calculated by a software phase lock to the accelerator main oscillator



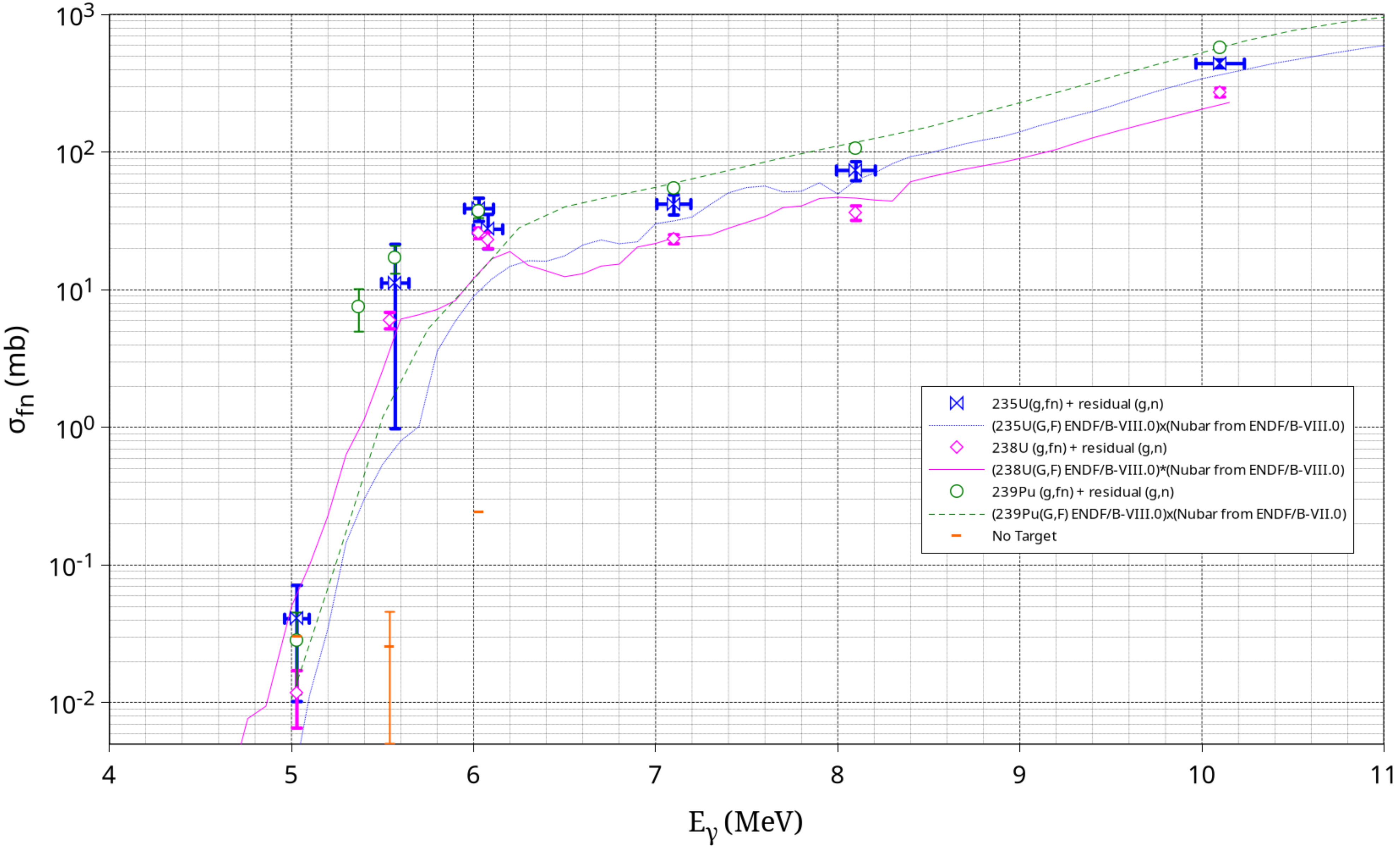
13.5 MeV Active Target Data from Different Geometries



16 and 10 MeV Active Target Data from Soccerball (~42 cm flight path)



Summary: Neutrons from Photofission at Low E_γ

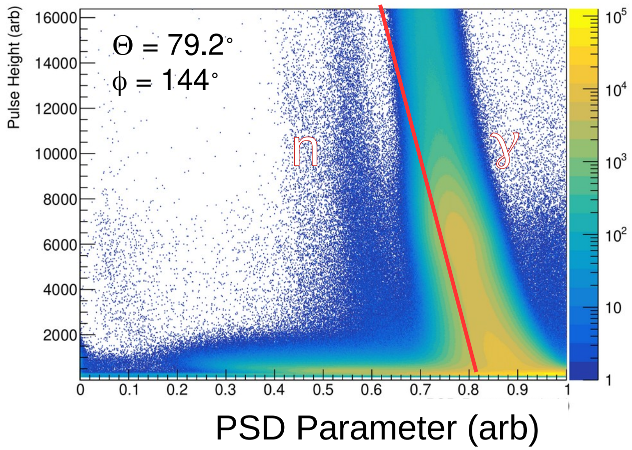


Begin Backup Slides

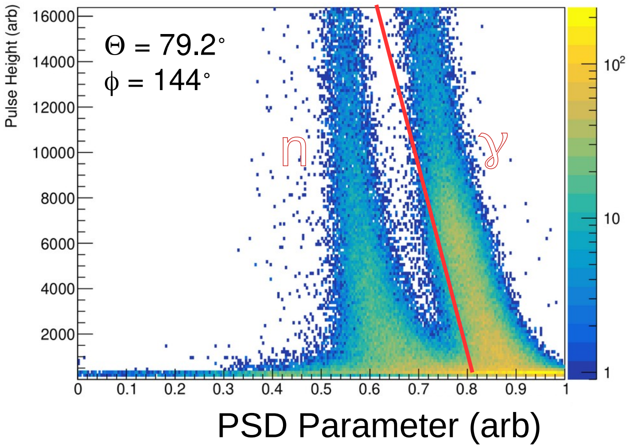
Thank You

Pulse Shape Discrimination in the Context of Photofission

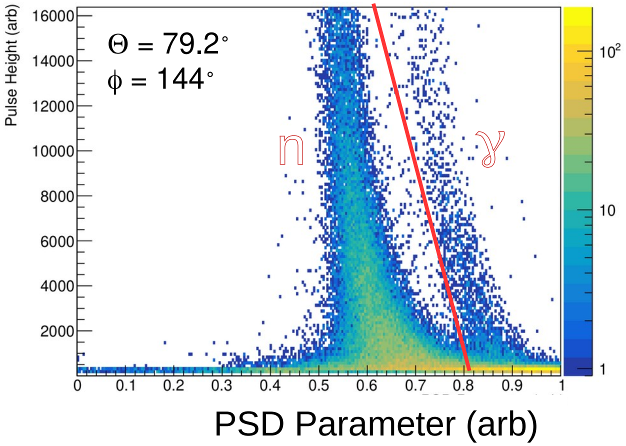
Hardware Timing Cuts Only



Neutron and Fission in same beam burst

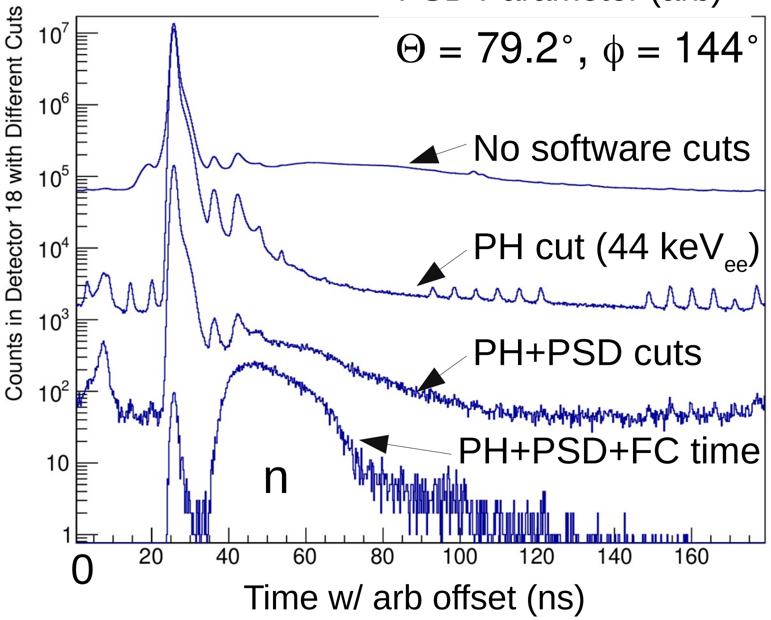


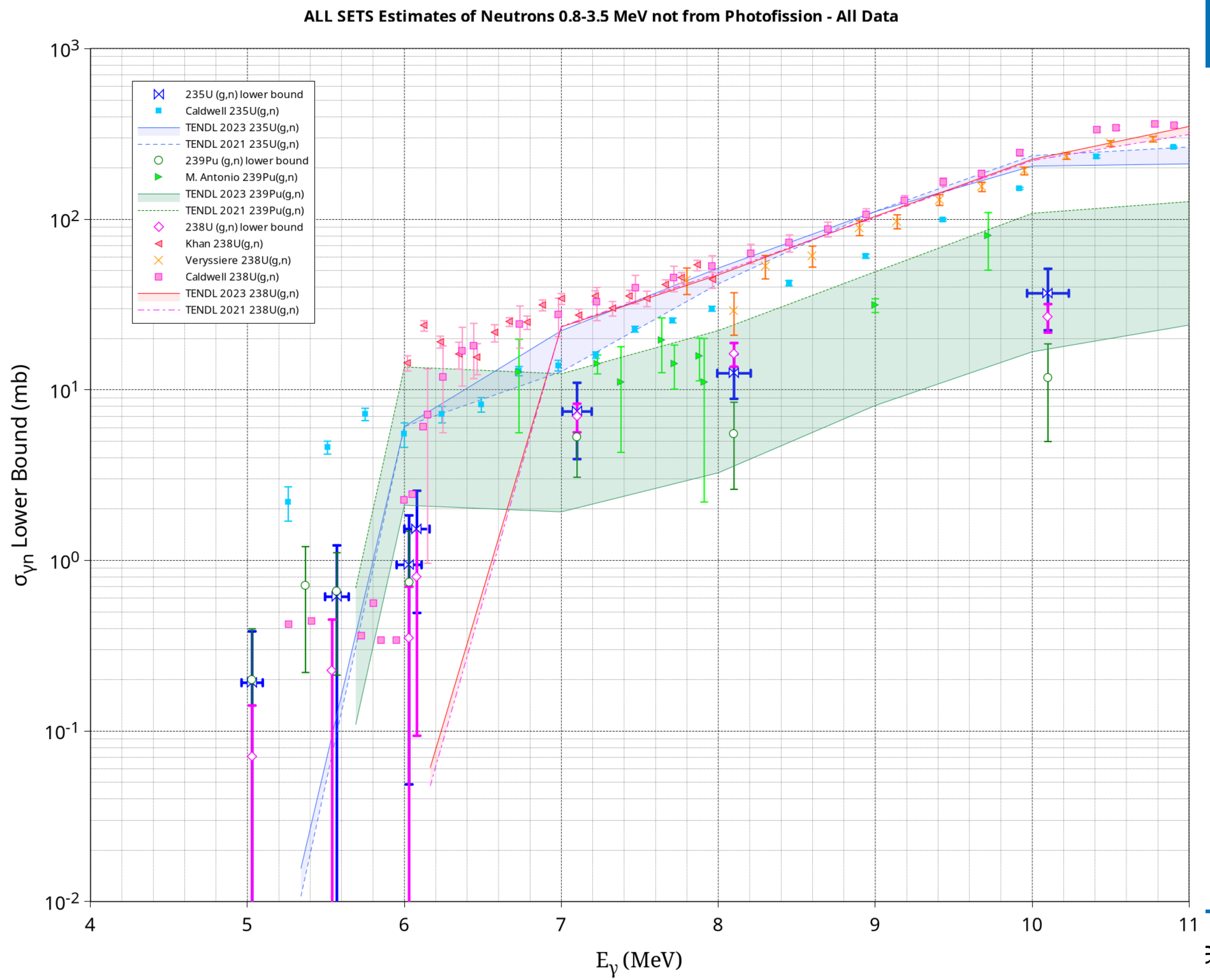
Neutron and Fission in same beam burst + neutron TOF cut



- **If Fission-ndet timing is set up well, PSD is not necessary**
  - **PSD hurts uncertainty due to inefficiency which must be undone for low thresholds**

- The effect of timing cuts on the SNR can be seen in the PSD plots above
- The PSD efficiency is also calculated as a function of pulse height for each channel using recorded waveforms:
  1) Neutron “templates” whose pulse height is sufficient for PSD to be unambiguous, are collected
  2) The templates are re-scaled and noise is added as appropriate to simulate neutron waveforms at any pulse height
  3) The generated neutron events are fed back through the PSD system

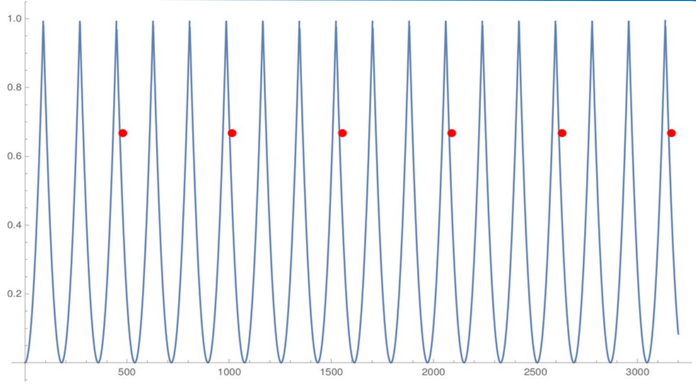



ALL SETS Estimates of Neutrons 0.8-3.5 MeV not from Photofission - All Data
235U (g,n) lower bound
Caldwell 235U(g,n)
TENDL 2023 235U(g,n)
TENDL 2021 235U(g,n)
239Pu (g,n) lower bound
M. Antonio 239Pu(g,n)
TENDL 2023 239Pu(g,n)
TENDL 2021 239Pu(g,n)
238U (g,n) lower bound
Khan 238U(g,n)
Veryssiere 238U(g,n)
Caldwell 238U(g,n)
TENDL 2023 238U(g,n)
TENDL 2021 238U(g,n)
$\sigma_{\gamma n}$ Lower Bound (mb)
E_γ (MeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
4
5
6
7
8
9
10
11

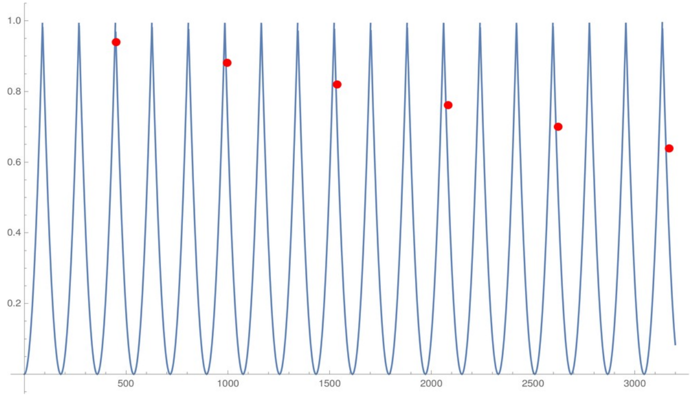
Target	Eγ (MeV)	Singles σ(γ,fn) (mb)	Stat and Fit stat Δσ(γ,fn) (mb)	systematic + σ(γ,fn) (mb)	systematic - σ(γ,fn) (mb)	Singles T (MeV)	Singles +/-T (MeV)	Coin T (MeV)
235U	*5.03**	0.04	*0.03*	0.003	0.003	*n/a*	*n/a*	1.98
235U	5.57	11.21	10.2	0.75	0.79	3.85	12.2	1.50
235U	6.08	27.59	7.8	1.85	1.94	1.70	0.8	1.17
235U	*6.03**	38.96	*7.4*	*2.98*	*3.31*	*1.51*	0.4	1.38
235U	7.1	42.02	7.0	2.82	2.95	1.74	0.4	1.24
235U	8.1	73.85	12	5.01	5.24	1.60	0.3	1.29
235U	10.1	441.23	28	29.72	31.13	1.25	0.0	1.26
238U	*5.03**	0.01	*0.01*	0.001	0.001	*n/a*	*n/a*	1.25
238U	*5.54**	6.04	*0.8*	0.44	0.48	*1.64*	*0.3*	*1.38*
238U	6.08	23.18	3.2	1.46	1.53	1.61	0.3	1.22
238U	*6.03**	25.88	*2.3*	1.87	2.07	*1.46*	*0.1*	*1.40*
238U	7.1	23.43	1.8	1.48	1.55	1.65	0.2	1.25
238U	8.1	36.37	4.4	2.29	2.40	1.61	0.2	1.26
238U	10.1	272.78	20	17.20	18.02	1.08	0.1	1.27
239Pu	*5.03**	0.03	*0.02*	0.002	0.002	*n/a*	*n/a*	*1.27*
239Pu	5.37	7.56	2.6	0.48	0.51	2.61	2.1	1.47
239Pu	5.57	17.01	3.9	1.09	0.26	2.12	0.8	1.23
239Pu	*6.03**	37.28	*4.0*	*2.73*	*3.03*	*1.53*	*0.2*	*1.42*
239Pu	7.1	54.84	4.3	3.52	3.69	1.67	0.2	1.37
239Pu	8.1	106.90	5.6	6.88	7.21	1.43	0.1	1.30
239Pu	10.1	577.59	11	38.32	40.14	1.33	0.02	1.31
EMPTY	*5.03*	0.03	*0.03*	*0.00*	*0.00*	*n/a*	*n/a*	*2.42*
EMPTY	*5.54*	0.03	*0.02*	*0.00*	*0.00*	*n/a*	*n/a*	*0.00*
EMPTY	*6.03*	0.24	*14.98*	*0.02*	*0.02*	*n/a*	*n/a*	*5.00*

Target	Eγ (MeV)	lower bound σ(γ,n) (mb)	Fits stdev +/- σ(γ,n) (mb)	σ(γ,n) + σ(γ,fn) (mb)	stat+syst Δσ (mb)	from coin, (ɣ,fn)meas, and sim <ν>	Δ<ν>	σ(γ,f) (mb)
235U	*5.03**	0.2	0.5	0.2	0.5	**10.55**	**7.91**	**0.0039**
235U	5.57	0.6	1.1	11.8	10.3	**0.95**	**0.87**	**11.8**
235U	6.08	1.5	1.0	29.1	8.1	**2.03**	**0.57**	**13.6**
235U	*6.03**	*0.9*	*0.9*	39.9	8.1	***2.46***	***0.47***	***15.9***
235U	7.1	7.5	3.5	49.5	8.3	**1.94**	**0.32**	**21.7**
235U	8.1	12.5	3.6	86.3	13.3	**2.17**	**0.34**	**33.9**
235U	10.1	36.8	14.5	478.0	44.0	**1.85**	**0.12**	**239.1**
238U	*5.03**	*0.1*	*0.4*	0.1	0.4	***23.54***	***10.51***	***0.0005***
238U	*5.54**	*0.2*	*0.4*	6.3	1.0	***2.35***	***0.32***	***2.6***
238U	6.08	0.8	0.7	24.0	3.6	**1.90**	**0.26**	**12.2**
238U	*6.03**	*0.4*	*0.7*	26.2	3.1	***2.71***	***0.24***	***9.7***
238U	7.1	7.0	1.3	30.4	2.7	**1.95**	**0.15**	**12.0**
238U	8.1	16.2	2.6	52.6	5.6	**2.63**	**0.32**	**13.8**
238U	10.1	26.7	5.1	299.5	27.0	**2.14**	**0.16**	**127.2**
239Pu	*5.03**	*0.2*	*0.7*	0.2	0.7	***4.31***	***2.57***	***0.0066***
239Pu	5.37	0.7	0.5	8.3	2.7	**1.00**	**0.34**	**7.6**
239Pu	5.57	0.7	0.4	17.7	4.0	**1.50**	**0.34**	**11.4**
239Pu	*6.03**	*0.7*	*0.9*	38.0	5.0	***3.15***	***0.33***	***11.9***
239Pu	7.1	5.3	2.2	60.1	6.0	**2.54**	**0.20**	**21.6**
239Pu	8.1	5.5	2.9	112.4	9.5	**2.69**	**0.14**	**39.7**
239Pu	10.1	11.8	6.8	589.4	41.2	**3.43**	**0.06**	**168.5**
EMPTY	*5.03*	*0.0*	*0.3*	0.1	0.3			
EMPTY	*5.54*	*0.1*	*0.2*	0.1	0.2			
EMPTY	*6.03*	*-0.4*	*0.3*	-0.1	15.0			

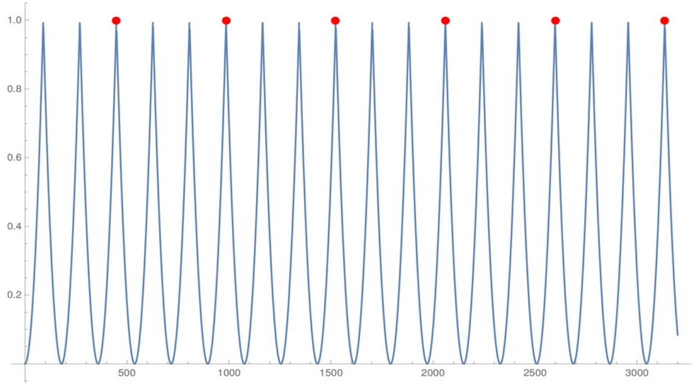
Backup: Software Beam Timing Lock



← Bad Phase

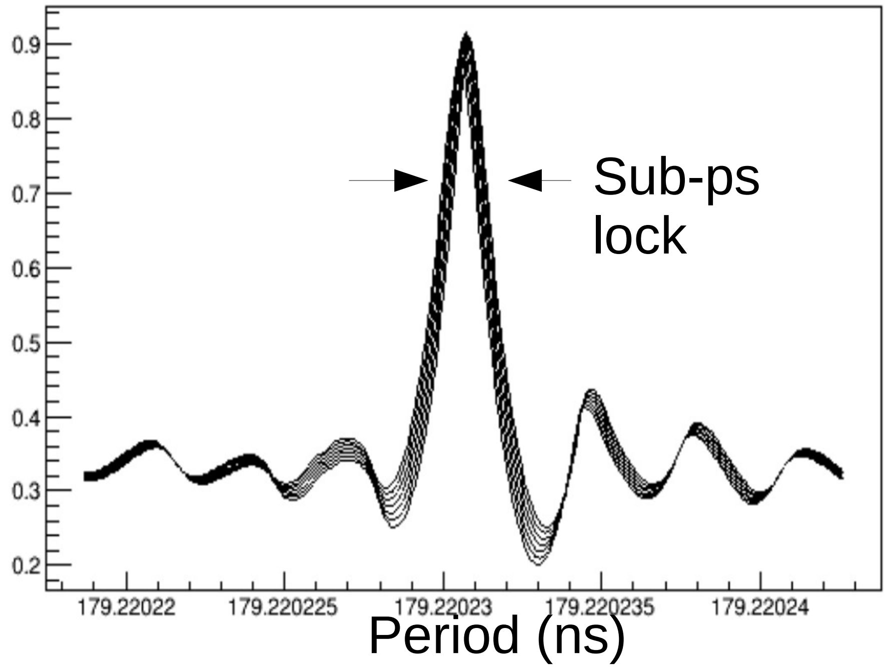


← Bad Freq.

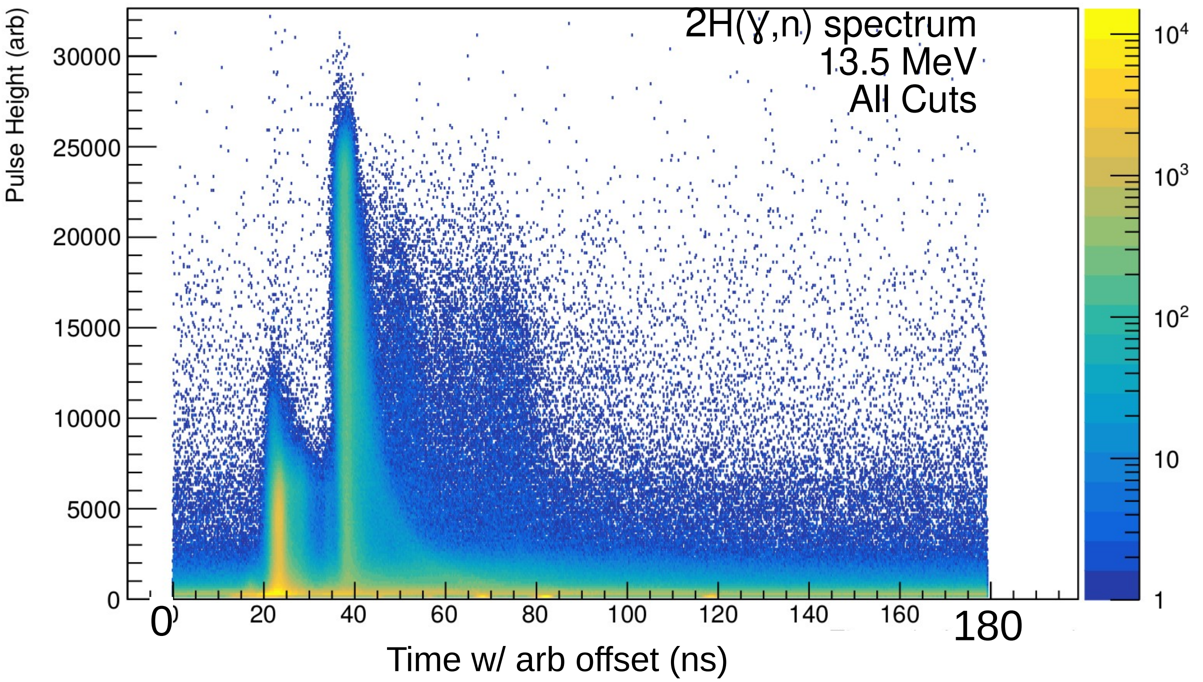


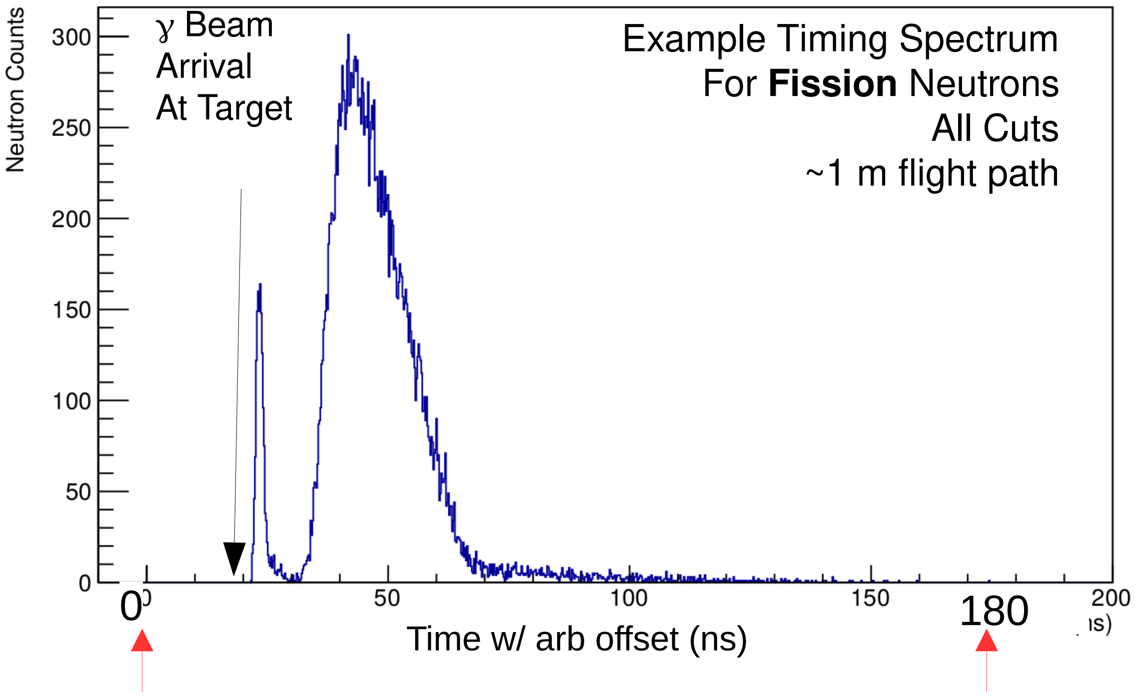
- Need to calculate neutron TOF with a reasonable beam pickof sampling rate
- Accelerator timing pulse is divided down (~700x) and digitize
- Division factor of 3 illustrated at left
- Timing precision better than traditional TDC/TAC approach
  - Resolution determined entirely by the detector

Good Lock



Timing Calibration In-Situ

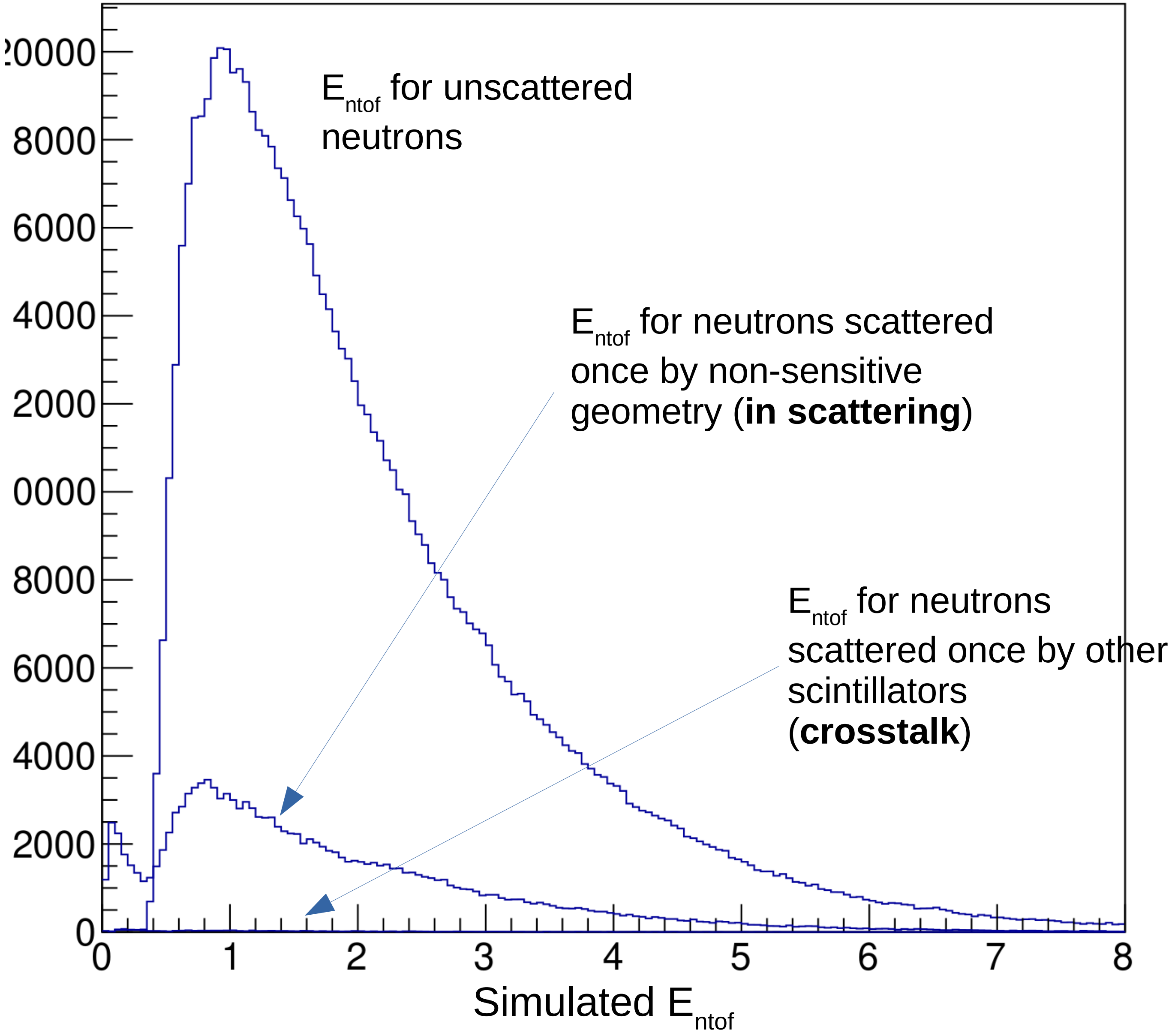


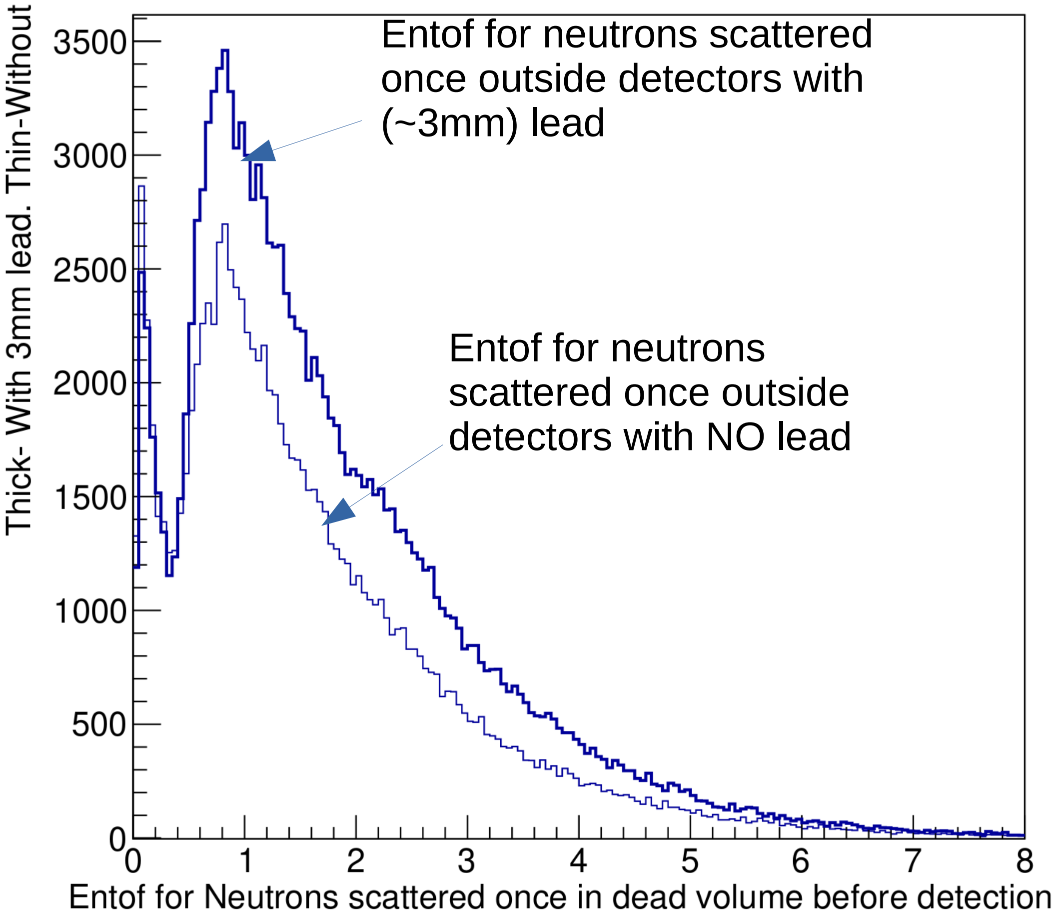


- Calibrate time offsets for all detectors:
  1) Measure detector flight paths
  2) Use ^{2}H(γ,n) to produce monoenergetic neutrons at the highest available beam energy
  3) Calculate the beam arrival time at target for all detectors

- Each detector has its own offset relative to the accelerator master oscillator
- The accelerator oscillator is divided by a large arbitrary number and digitized
  - Software phase lock interpolates all beam pulse arrivals at target with negligible uncertainty
  - Slow drift between accelerator and digitizer clocks is monitored with a phase factor

Multiple Scattering Effects for 1m Flight Path





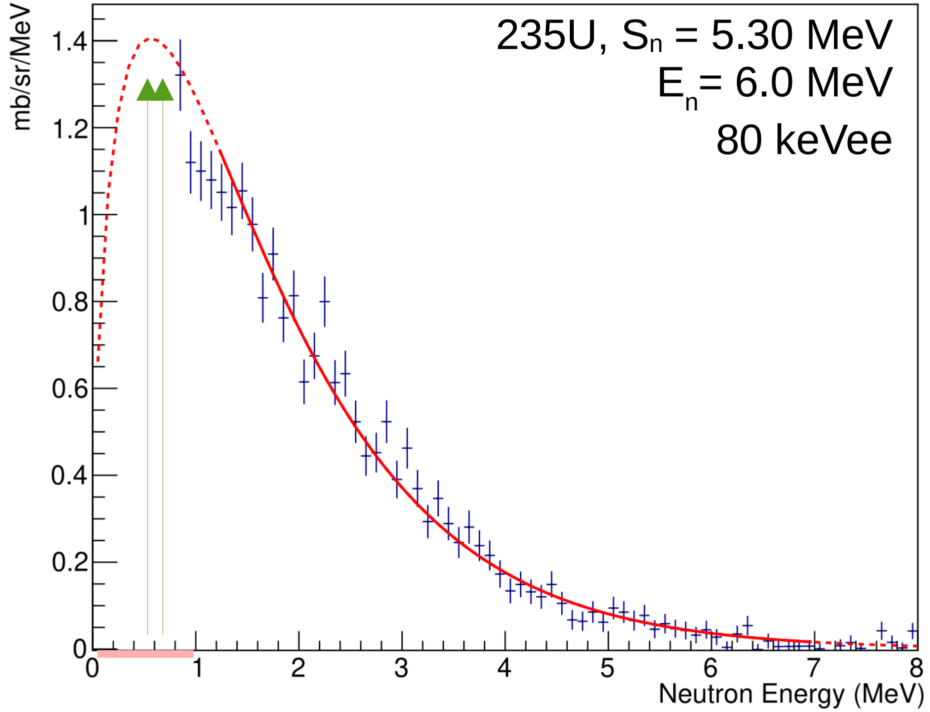
- Lead shielding on front of detectors does scatter neutrons, but the impact on the measurement is small

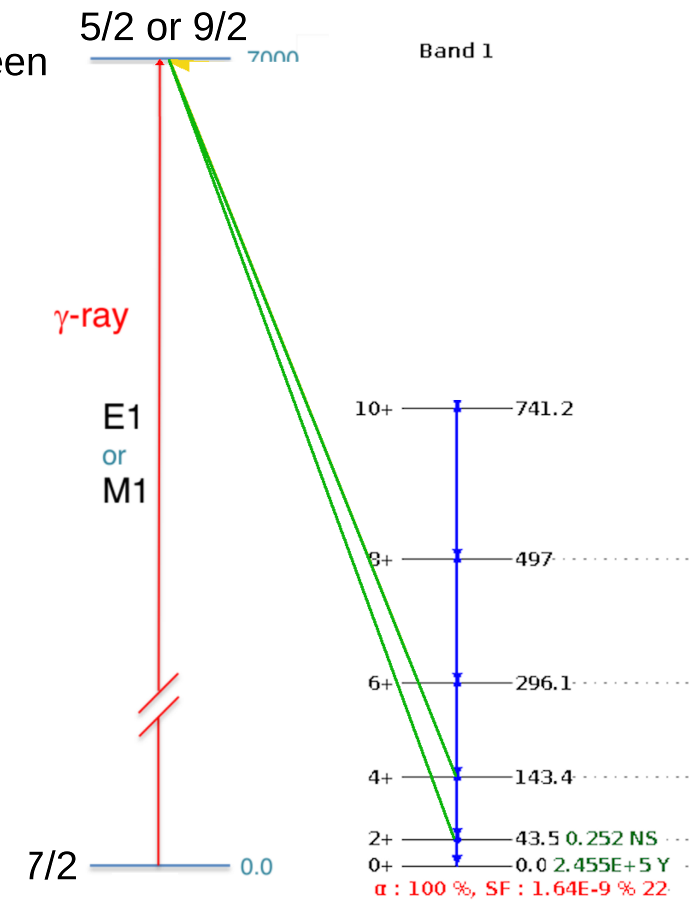
Backup: Negligible Systematics

- Intermediate scattering effects from lead on detector faces is negligible according to simulation
- The overall timing offset determination for the array has a 0.5 ns systematic uncertainty
  - Negligible effect on multiplicity
- Empty target spectra are a negligible fraction of the total for all measurements except 5.0 MeV

Example Data: 235U at 6 MeV

- Example for 235U with 6 MeV incident photons:
  - ^{235}U can be moved into 5/2 or 9/2 excited state
  - Possible l=0 neutrons above detection threshold are shown at right
    - There could be a peak near 0.7 MeV from decay(s) into 2+ or 4+ state in band 1 (green lines)





Data shown were taken by the detector on channel 22 (37 deg polar angle, upper hemisphere) at 6 MeV with 235U

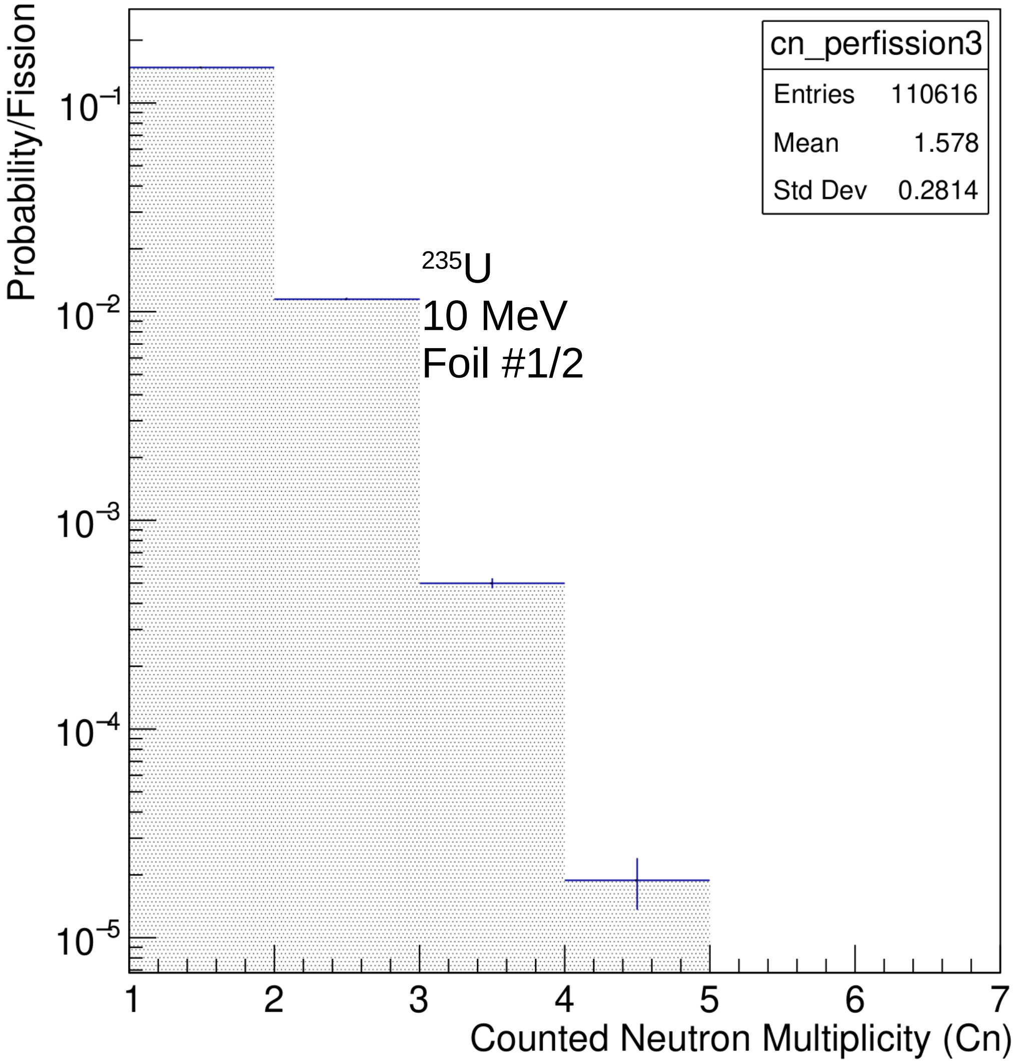
Backup: Evaluation Info

for 238U
FILE 3 (MF=3: NEUTRON CROSS SECTIONS) 9237 1451 140
9237 1451 141
MT=3 - Sum of MT=5,16,17,18. 9237 1451 142
9237 1451 143
MT=5 - (Ɣ,n) cross section, based on the Blokhin [Bl98] 9237 1451 144
evaluation of experimental data, especially the measurements of 9237 1451 145
Caldwell [Ca80]. 9237 1451 146
9237 1451 147
MT=16,17 - (g,xn) cross sections are taken from the evaluation 9237 1451 148
of Blokhin [Bl98]. 9237 1451 149
9237 1451 150
MT=18 - (Ɣ,f) cross sections obtained from the evaluation of 9237 1451 151
Blokhin [Bl98], which were optimized to the experimental data 9237 1451 152
evaluation of Varlamov [Va87]. 9237 1451 153

for 235U
FILE 3 (MF=3: NEUTRON CROSS SECTIONS) 9228 1451 133
9228 1451 134
MT=3 - Sum of MT=5,16,18. 9228 1451 135
9228 1451 136
MT=5 - (Ɣ,n) cross section from evaluation of Blokhin [Bl92], 9228 1451 137
based on experimental data, especially data of Caldwell [Ca80]. 9228 1451 138
9228 1451 139
MT=16 - (g,2n) cross sections are taken from the evaluation of 9228 1451 140
Blokhin [Bl92]. 9228 1451 141
9228 1451 142
MT=18 - (Ɣ,f) cross sections obtained from the evaluation of 9228 1451 143
Blokhin [Bl92], which were optimized to the experimental data of 9228 1451 144
Caldwell [Ca80] and Varlamov [Va87]. 9228 1451 145

for 239Pu
FILE 3 (MF=3: NEUTRON CROSS SECTIONS) 9437 1451 130
9437 1451 131
MT=3 - Sum of MT=5,16,17 and 18. 9437 1451 132
9437 1451 133
MT=5 - Taken from the GNASH calculation, with a small 9437 1451 134
modification at threshold. 9437 1451 135
9437 1451 136
MT=16,17 - (g,xn) cross sections are taken from the GNASH 9437 1451 137
analysis. 9437 1451 138
9437 1451 139
MT=18 - (Ɣ,f) cross sections obtained from evaluation of the 9437 1451 140
experimental data of Berman [Be86] and Moreas [Mo93] below 10 MeV,9437 1451 141
and from the GNASH analysis at higher energies. 9437 1451 142

Backup: The traditional Paradigm for Measuring the Multiplicity Distribution



$$P_\nu = \sum_{n=\nu}^{N} \frac{n!}{\nu!(n-\nu)!}\left(1-\frac{1}{\varepsilon}\right)^{n-\nu}\left(\frac{1}{\varepsilon}\right)^{\nu} C_n.$$

This relation gives the probability of emitting ν neutrons P_ν, based on the probability of observing C_n multiples of order n and the detection efficiency of the system ε.

From Simulation

- Goal is to turn measured coincidence into emitted multiplicity distribution
- The assumption in the above equation is that the system efficiency is >~90%
  - Ours is ~10%
- Can we use Bayes' Theorem instead?

$$P_\nu = \frac{P(\text{emit } \nu|\text{detect } k)}{P(\text{detect } k|\text{emit } \nu)} C_k$$

Top Equation and caption from PRC95.064612

Backup: New Approach to Fission Multiplicity Distribution

Setup:

C_k is the probability of **measuring** n neutron coincidences per fission. We get this from the experiment. Want to know probability the sample **emitted ν** neutrons per fission **P_ν**

Proposed Solution:

Use Bayes' Theorem to convert the measured C_k distribution to P_ν determining the conditional probabilities through simulation.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

$$P(B|A) = \frac{P(B \cap A)}{P(A)}$$

Hardest to think about

$$P_\nu = \frac{P(\text{emit } \nu|\text{detect } k)}{P(\text{detect } k|\text{emit } \nu)} C_k$$

$$P(\text{emit}\nu|\text{detect}k) = \frac{P(\text{emit } \nu \cap \text{detect } k)}{P(\text{detect } k)}$$

Easier to think about (given simplifying assumptions)

Get from simulation by correlating Input ← → output

Get from simulation by correlating Input ← → output

Backup: Obtaining the Conditional Probabilities from Simulation

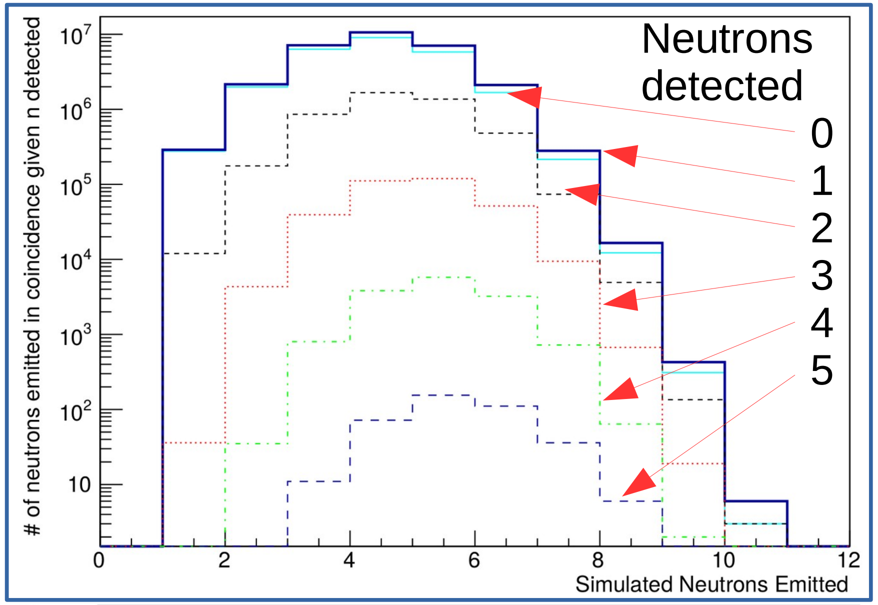
Simulation setup:

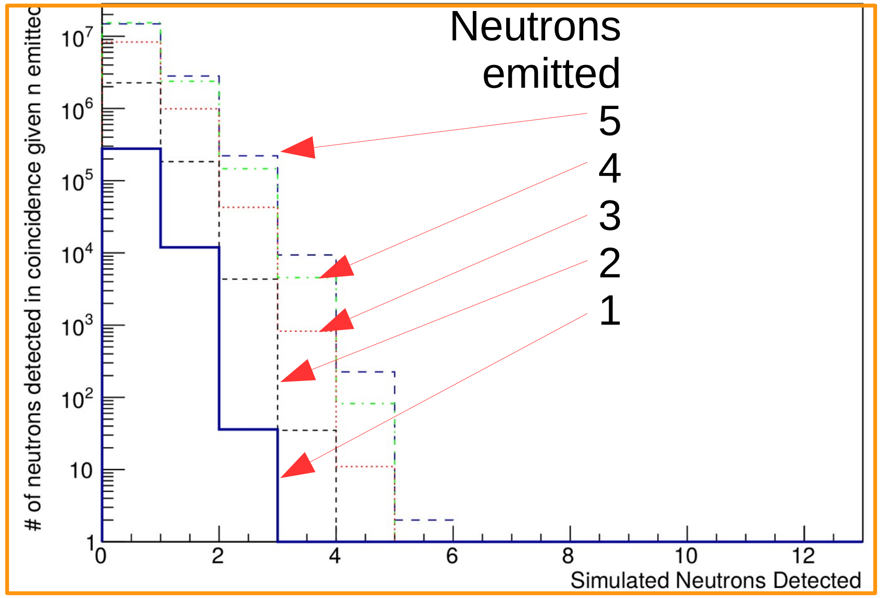
- Input events come from FREYA and are distributed reasonably*
- Every neutron is associated with a particular fission index and is tracked individually.
- Detector resolution and thresholds are modeled.
  1) For fissions with n emitted neutrons, we know the distribution of how many neutrons v are detected in coincidence
     a) The simulation output provides P(detect k)

$$P(\text{emit}\nu|\text{detect}k) = \frac{P(\text{emit }\nu \cap \text{detect }k)}{P(\text{detect }k)}$$

  2) For fissions where we detect v neutrons, we know the distribution of how many neutrons n were emitted
     a) We know the simulated multiplicity distribution P(emit v) from the simulation input

$$P(\text{detect}k|\text{emit}\nu) = \frac{P(\text{emit }\nu \cap \text{detect }k)}{P(\text{emit }\nu)}$$





Backup: Backup information