Progress on Fissile Actinides Evaluations: ^{233,235}U and ^{239}Pu

Marco T. Pigni, Travis Green, Kang Seog Kim
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Roberto Capote[(a)], Andrej Trkov[(b)]
(a) Nuclear Data Section, International Atomic Energy Agency, Vienna, Austria
(b) Jožef Stefan Institute, Slovenia

Nuclear Criticality Safety Program (NCSP) Technical Program Review (TPR) Meeting[1]
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[1] Hosted virtually.

OVERVIEW

- **^{233}U**
  - Motivation: underestimated reactivity for critical assemblies
  - Status (FY20): updates to PFNS, thermal constants, R-matrix improved subset of benchmarks (31 cases)[2]
  - Status (FY21): RRR extended up to 2.5 keV and improved validation including suite of 180 benchmarks
  - Future updates: inclusion of capture data recently measured at LANL and URR in the energy range 2.5–40 keV
- **^{235}U**
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  - Status (FY21): ^{238}U evaluation[3] affecting the burn-up trend and updated URR evaluation by including recently measured fission data
  - Future updates: define strategy to improve the low reactivity at high burnup among the interplay of four nuclides (^{16}O, ^{235,238}U, ^{239}Pu)
- **^{239}Pu**
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  - Status (<FY20): updates in TNC and PFNS with partial work to extend RRR up to 5 keV
  - Status (FY21): continuing with the extension updates and working on coupling RRR with neutron multiplicities
  - Future updates: to complete extension up to 5 keV and to resolve negative slope as a function of the temperature not understood yet (bias over 2σ lower than measured)

[2] Annals Nuclear Energy **163** (2021) 108595.
[3] Updated evaluation released within INDEN collaboration.

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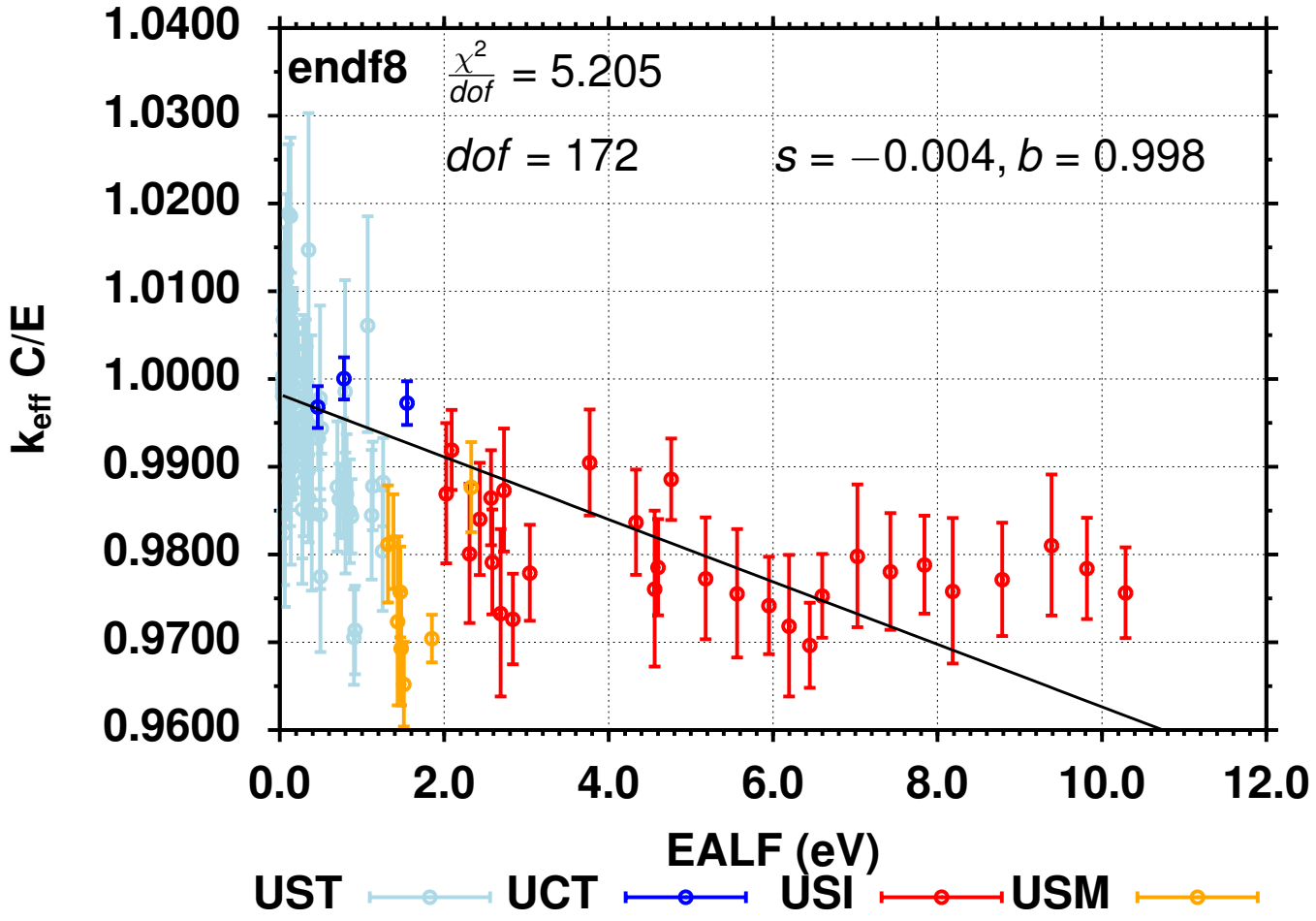
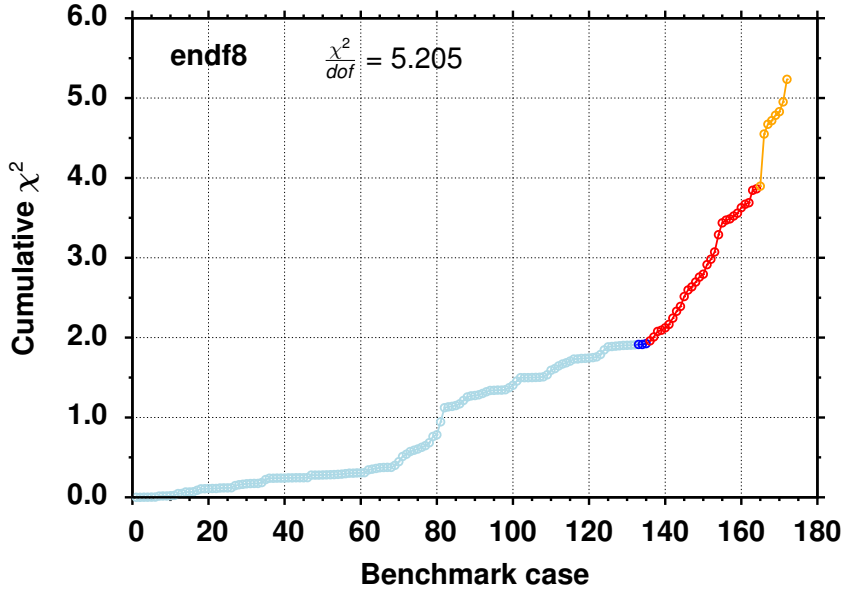
PERFORMANCE OF ^{233}U EVALUATION IN ENDF/B-VIII.0

- Focus on resolving strong negative gradient observed in ^{233}U suite of benchmarks (180 cases)[6]



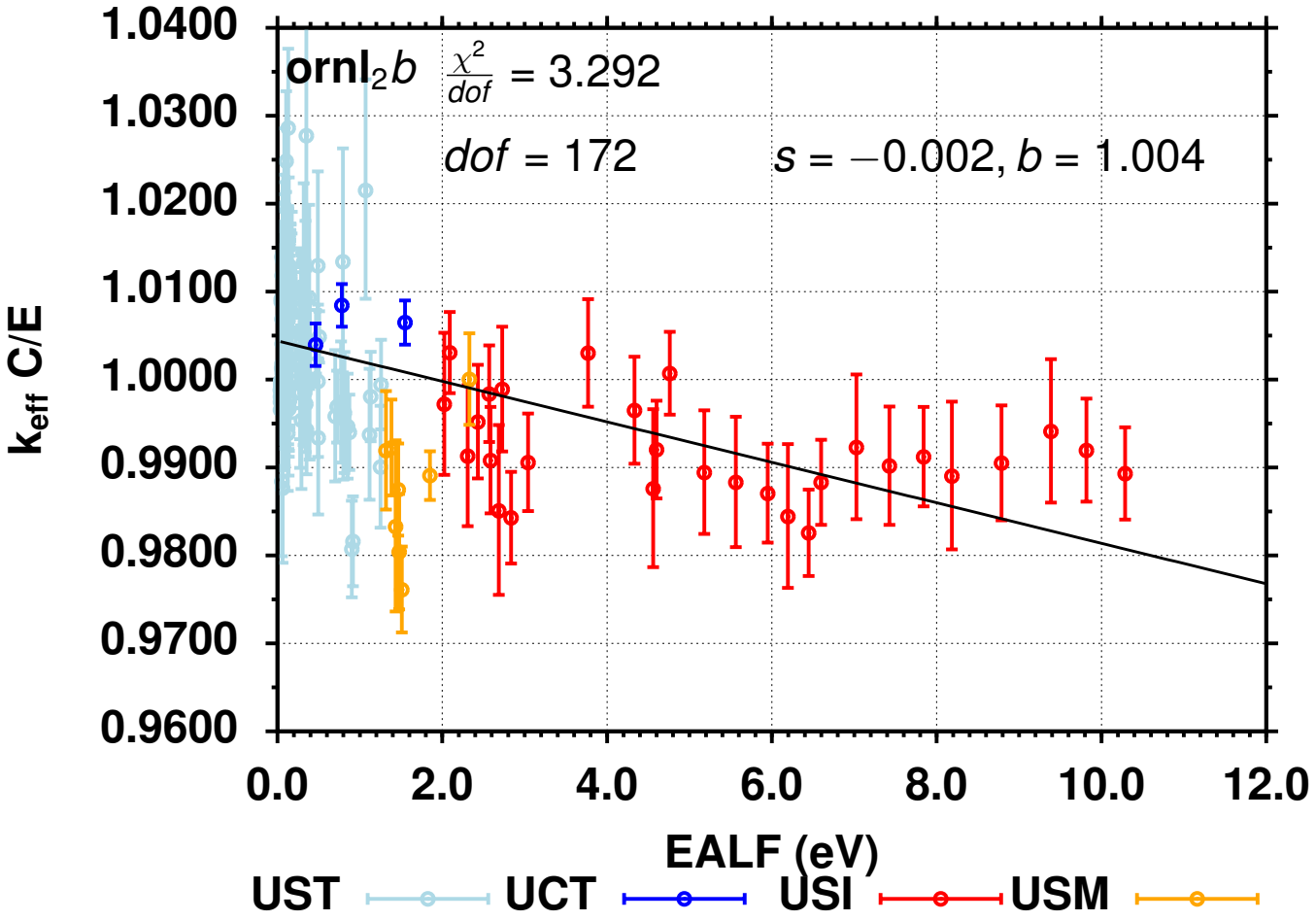


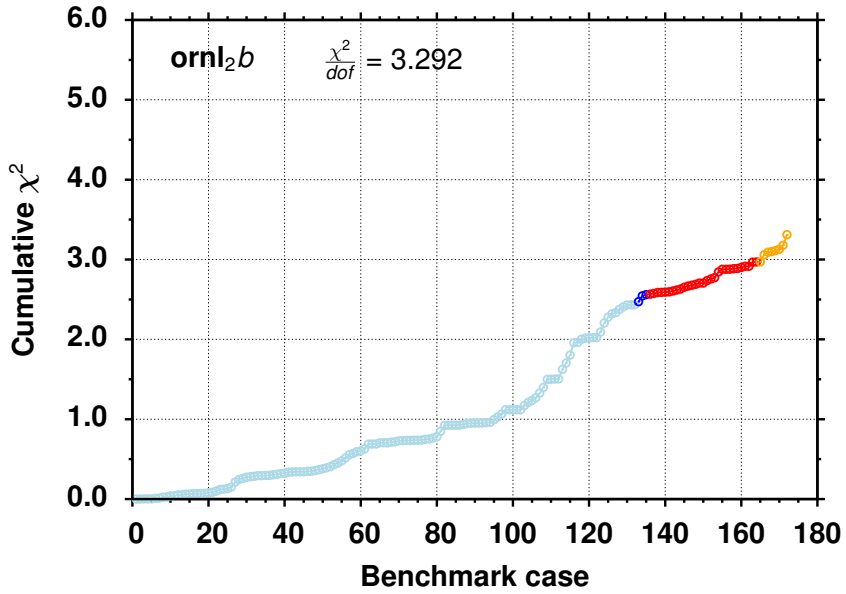
- Calculations performed with **SCALE/SHIFT**
- Model inputs for UST+UCT+USI+USM series of benchmarks validated by **Travis Green** (ORNL)

[6] 8 UST cases of the 012-00[1-8] series temporarily excluded in this work. Additional 10 UMF cases (EALF > 700 keV) not included.

PERFORMANCE OF ^{233}U EVALUATION (ORNL$_2$b)

- Remarkable increased criticality in the USI and USM series!





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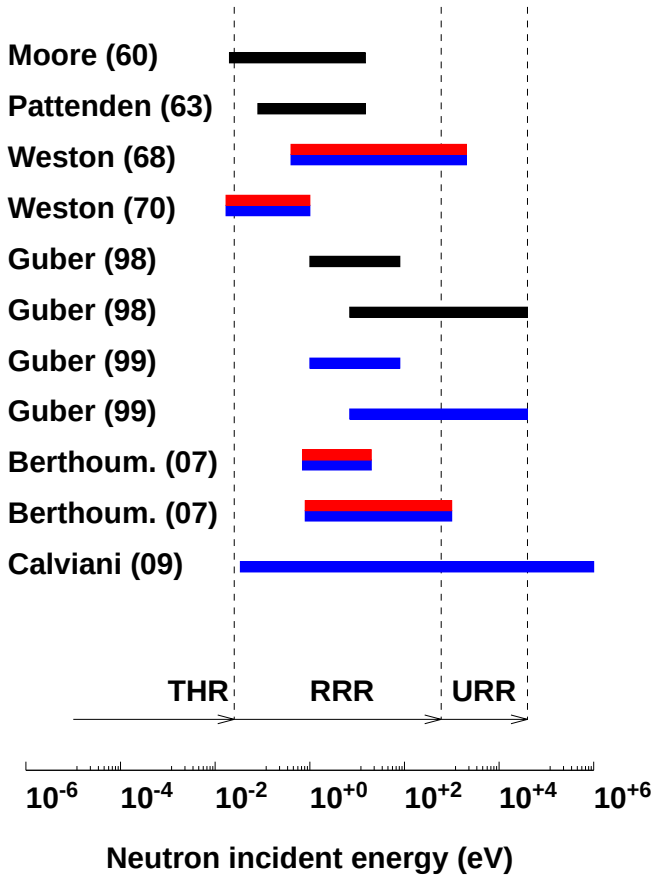
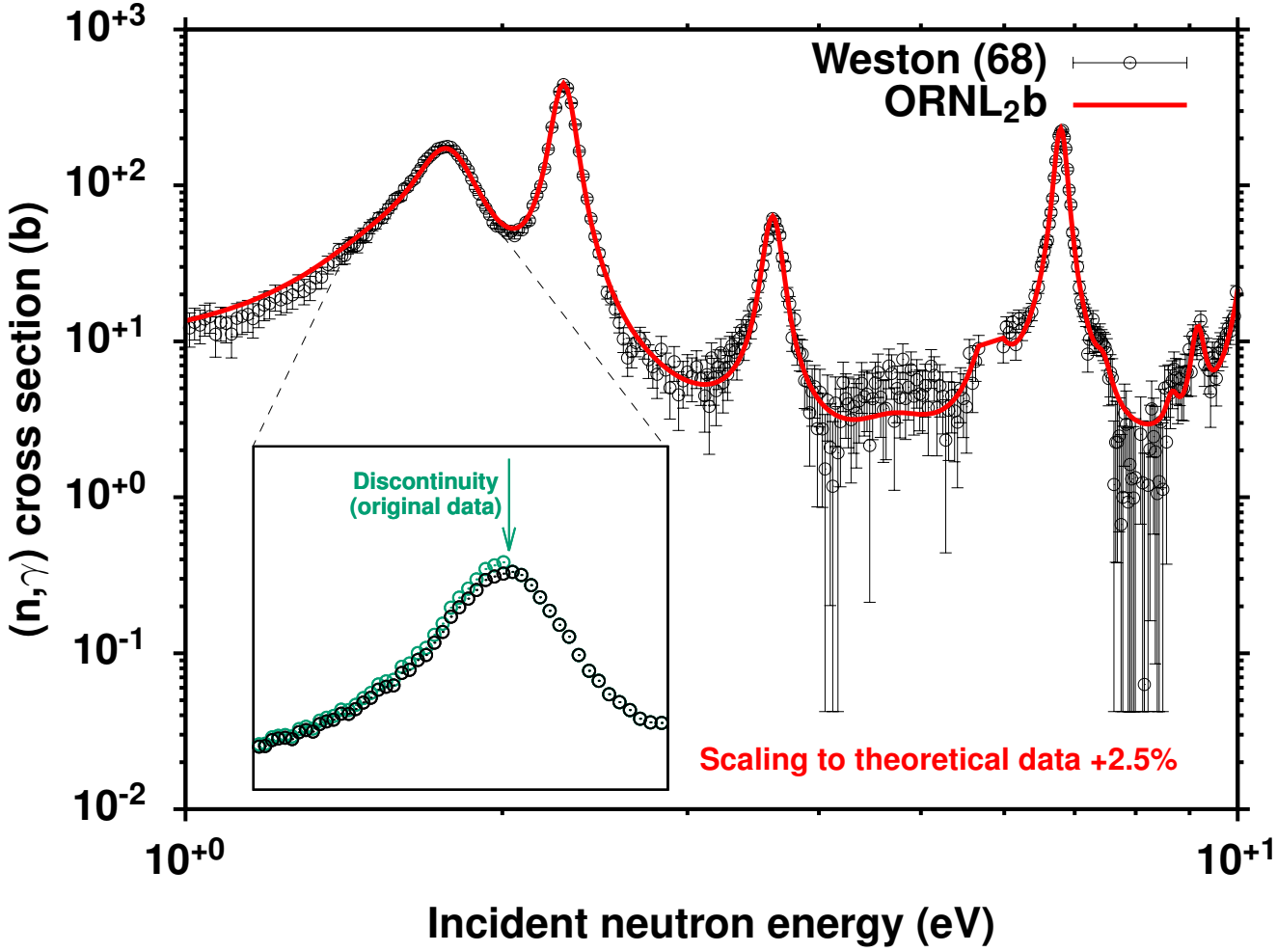
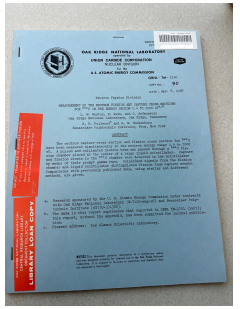
R-MATRIX UPDATES

- A systematic increase of the (n, f) cross sections confirmed in both ORELA and nTOF measurements might suggest a decrease of the (n, γ) reaction channel consistent with the underestimated reactivity
- Coupling between the (n, f) and (n, γ) for ratio measured data

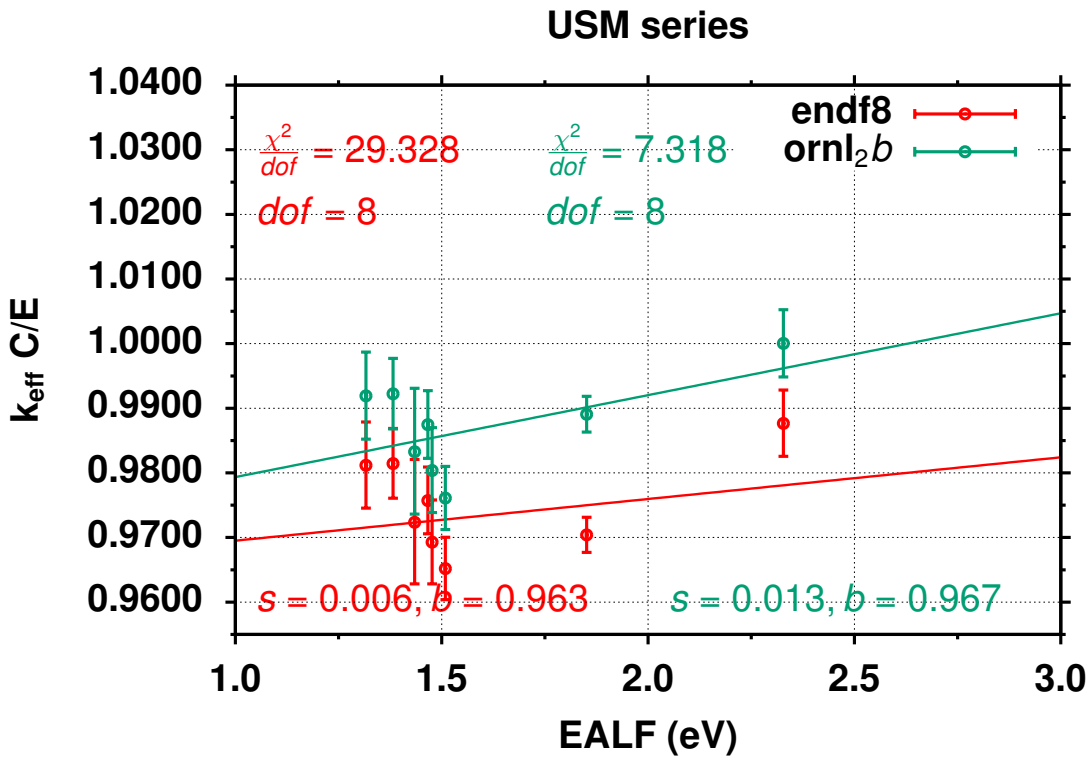


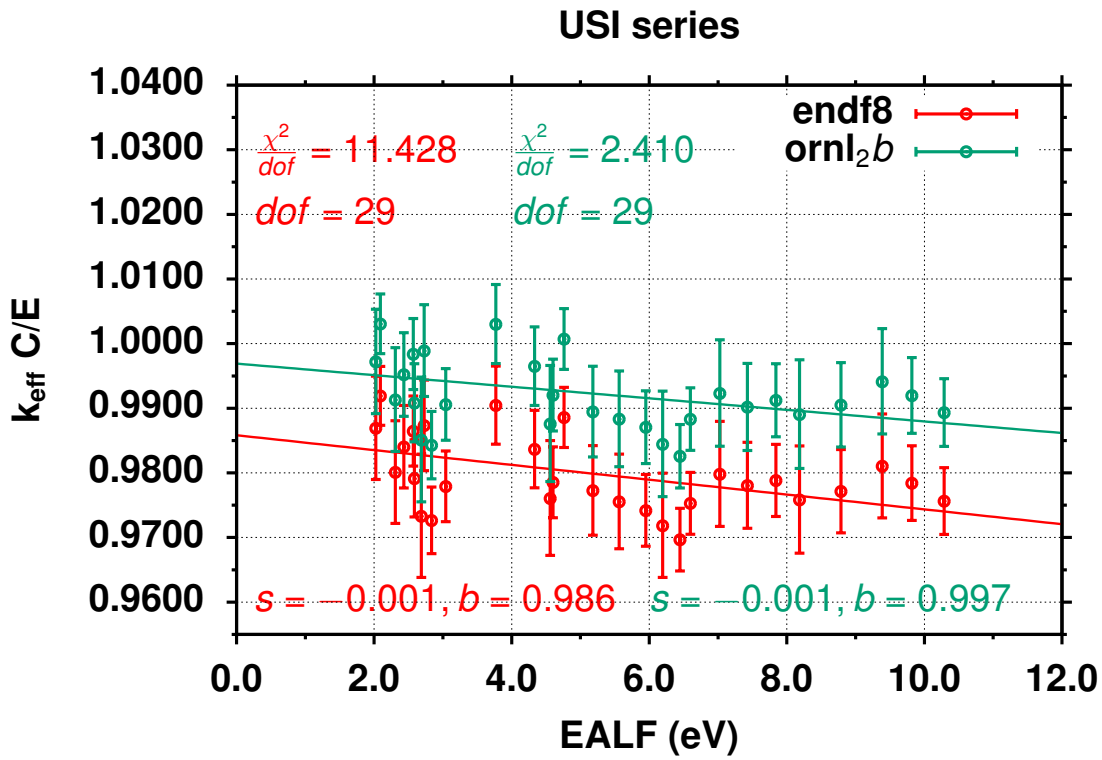




IMPACT OF R-MATRIX UPDATES ON USM/USI SERIES

- Improved χ^2 over ENDF/B-VIII.0 evaluation. However, underestimated reactivity particularly visible in particular EALF ranges: approaching reasonably good reactivity for 2 eV<EALF<3 eV, largely underestimated for EALF<2 eV and above 4 eV

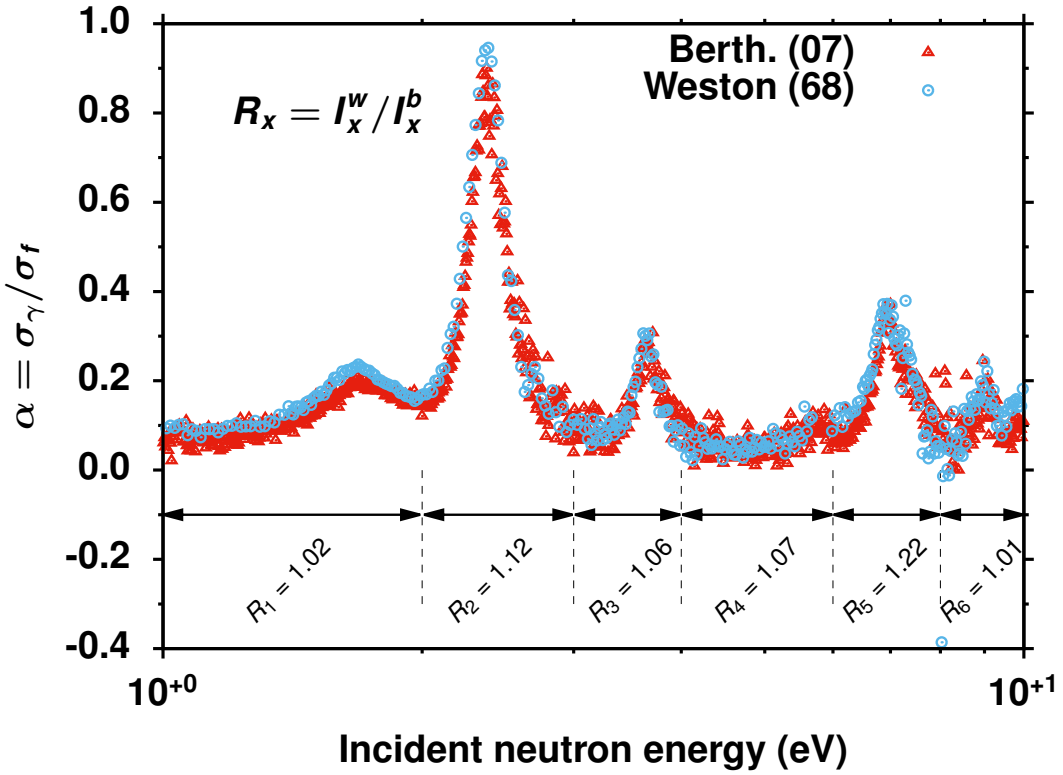


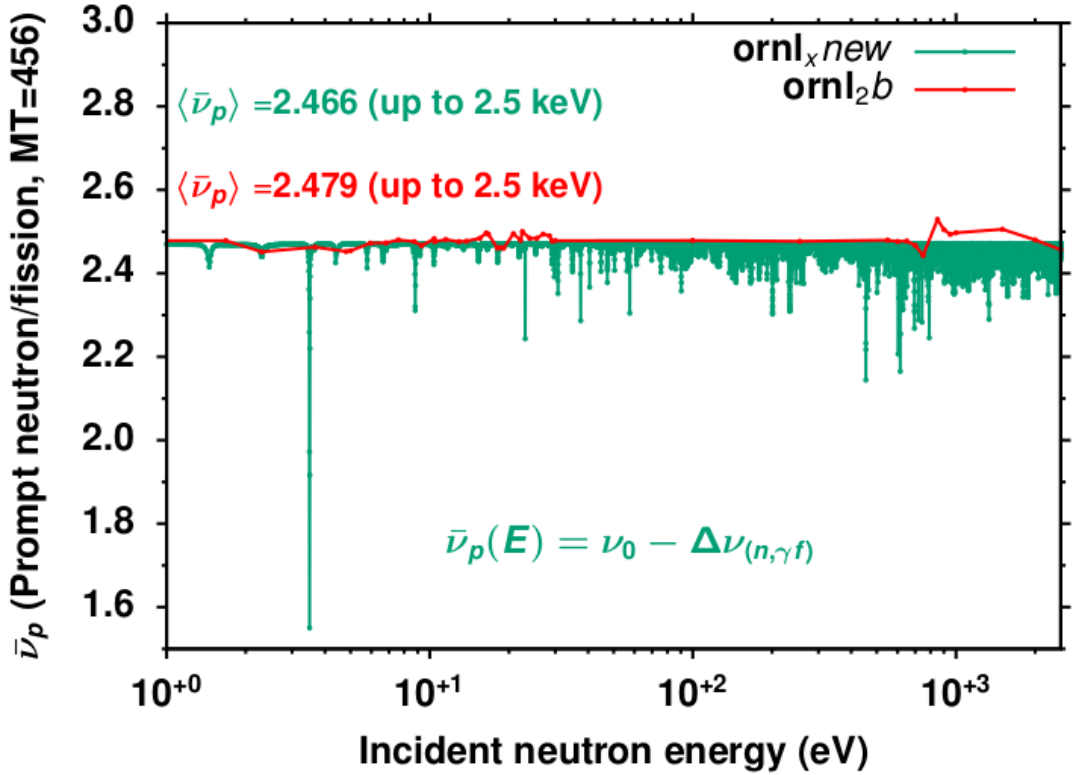


Increased criticality of the UST solutions (sensitive to energies <1 eV) can be addressed by decreasing prompt number of neutrons ($\bar{\nu}_p$)

INTEGRAL COMPARISON OF RATIO DATA AND $\bar{\nu}_p$

- Comparison of the ratio (capture to fission) measured data between Berthoumieux (07) and Weston (68)[78]
- Average discrepancy $\langle R \rangle$ over six intervals is about 8%



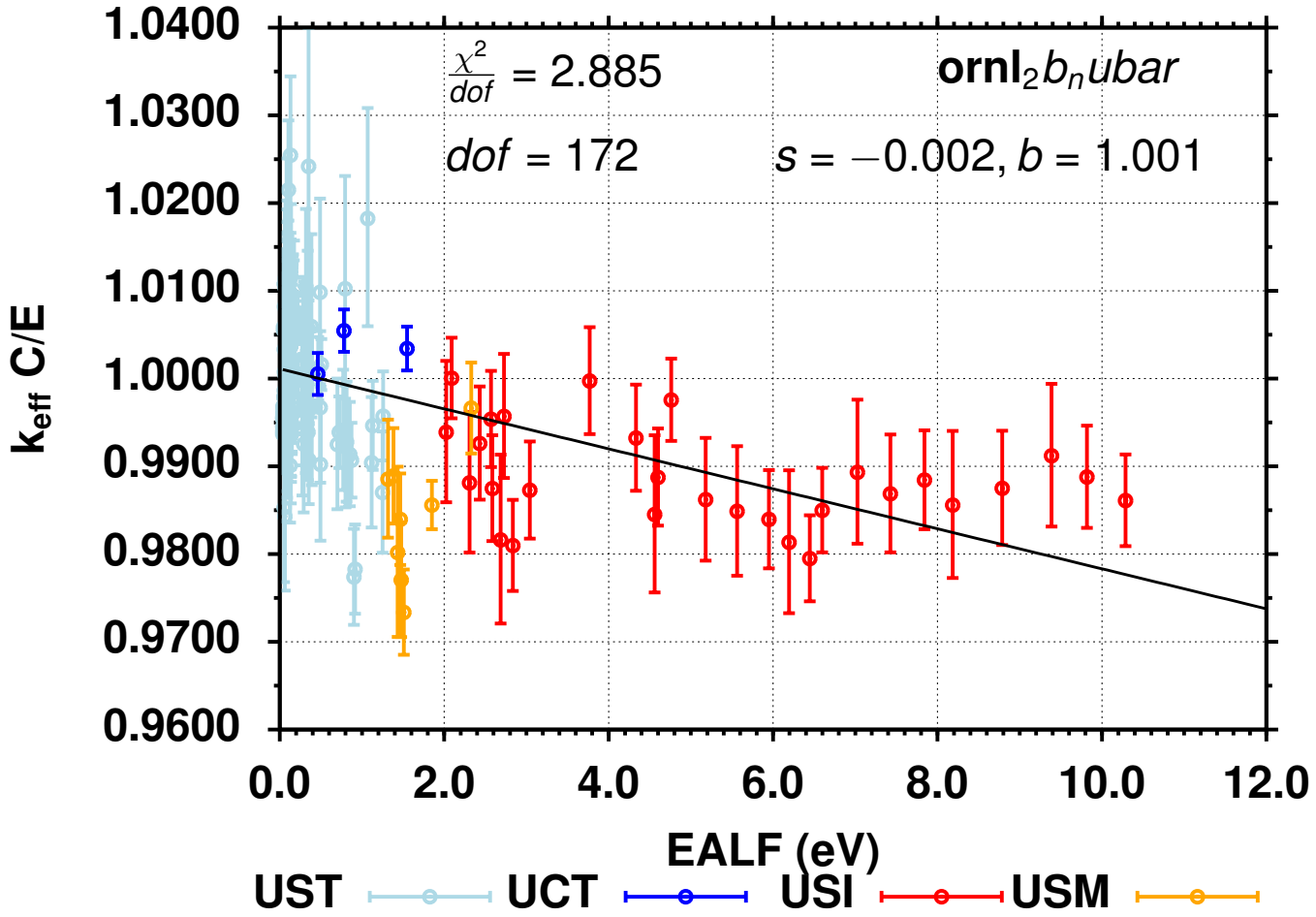


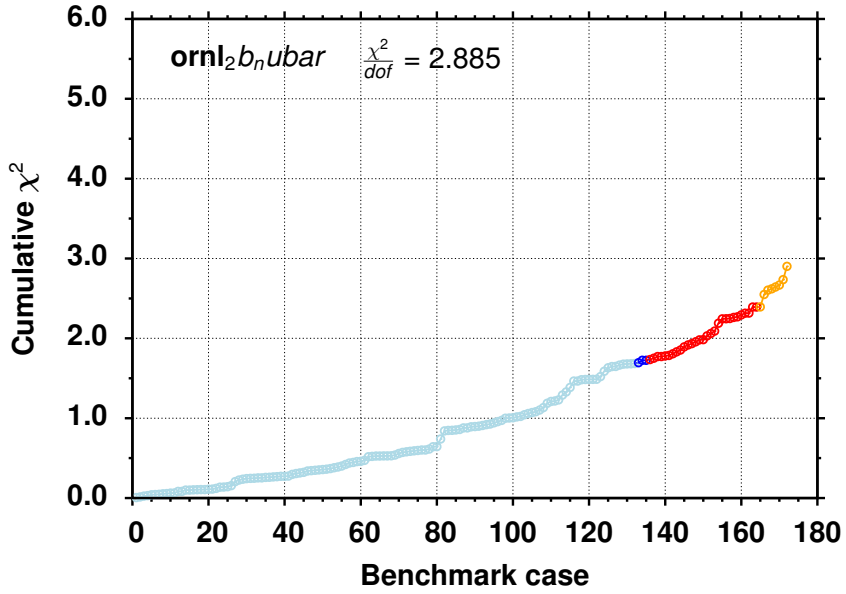
…testing a reduction of 0.5% (≈0.2% in fluctuations) in $\bar{\nu}_p$ with fluctuations due to (n,γf) channel

[7]The correction for sample abundances is about 1%.
[8]Integrated over energy intervals $I_x = \int_{\Delta_x} \alpha / E dE$.

PERFORMANCE OF ^{233}U EVALUATION (ORNL$_2$b with $\bar{\nu}_p$)

- Compared to ORNL$_2$b a decrease in $\bar{\nu}_p$ improved thermal solutions with little deviations in reactivity for EALF>1 eV





- Improved χ^2 with smooth cumulative trend
- Additional test with $\bar{\nu}_p$ decreased only by fluctuations: fluctuations physically (or by definition) decrease $\bar{\nu}_p$

U(nresolved) R(esonance) R(egion) ANALYSIS OF ^{235}U

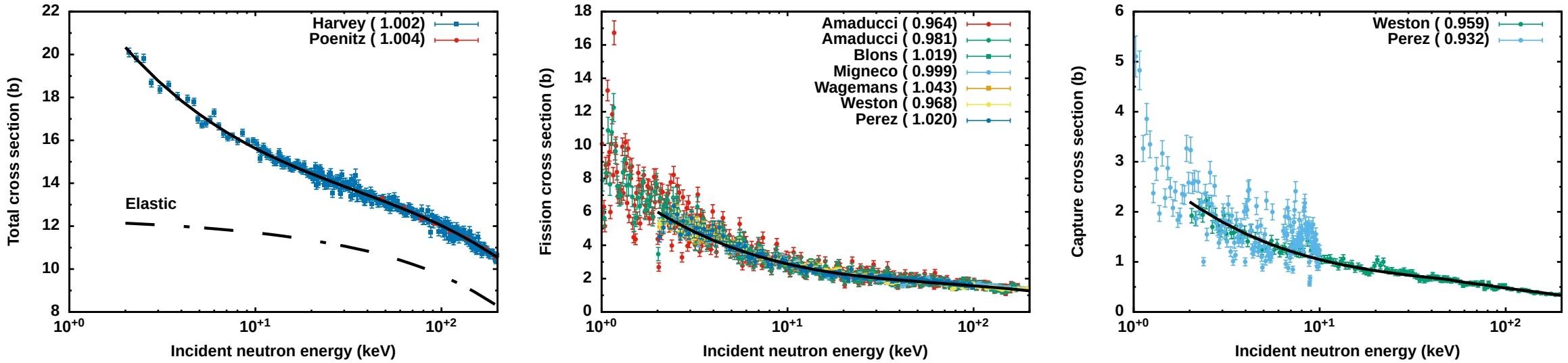


Figure 1: Preliminary SAMMY/FITACS fit of available total, fission, and capture data sets. Elastic channel computed by difference and inelastic channel parameterized by neutron strength functions and energy scaled penetrability factors.

- Except for the inelastic channel (11%), scaling factors ranging up to 6%
- Except for fluctuations, reasonable agreement with ENDF/B-VIII.0 (file 3)
- 20 keV is an acceptable upper energy limit for URR fit to account for self shielding effects

U(nresolved) R(esonance) R(egion) ANALYSIS OF ^{235}U

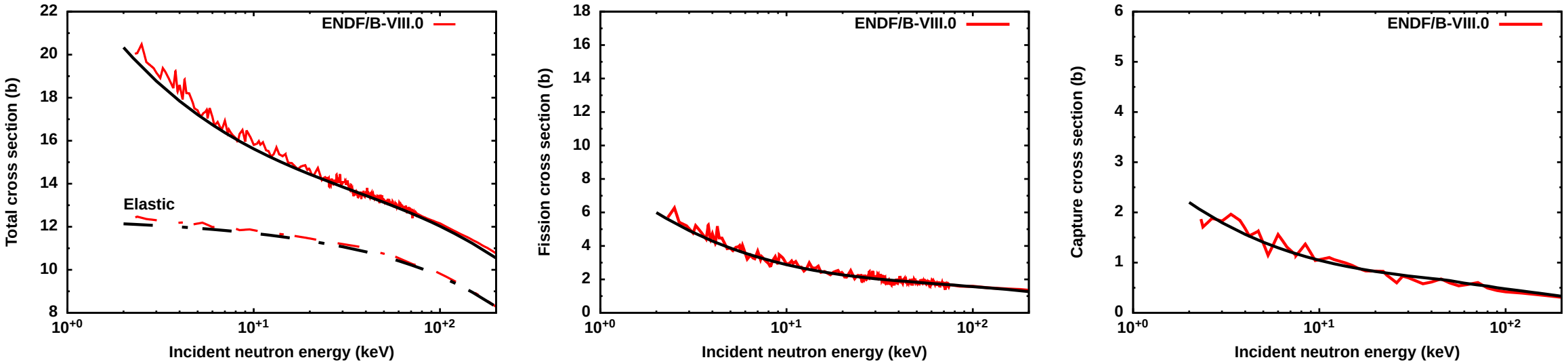


Figure 2: Preliminary SAMMY/FITACS fit compared to ENDF/B-VIII.0 evaluated data (file 3).

- ENDF/B-VIII.0 evaluated data show fluctuating behavior (to be checked if there is formal consistency between file 2 and file 3)

U(nresolved) R(esonance) R(egion) ANALYSIS OF ^{235}U

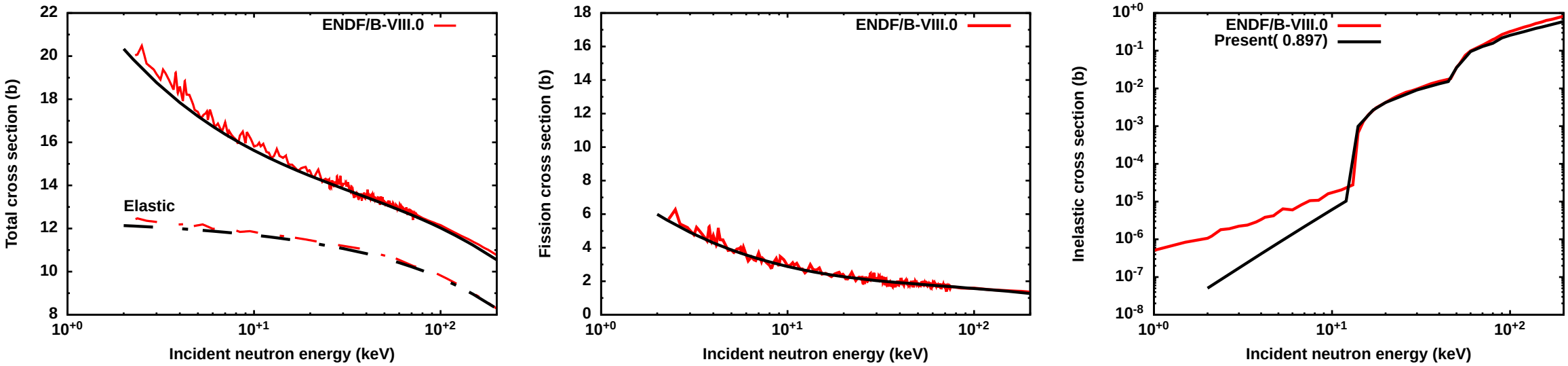
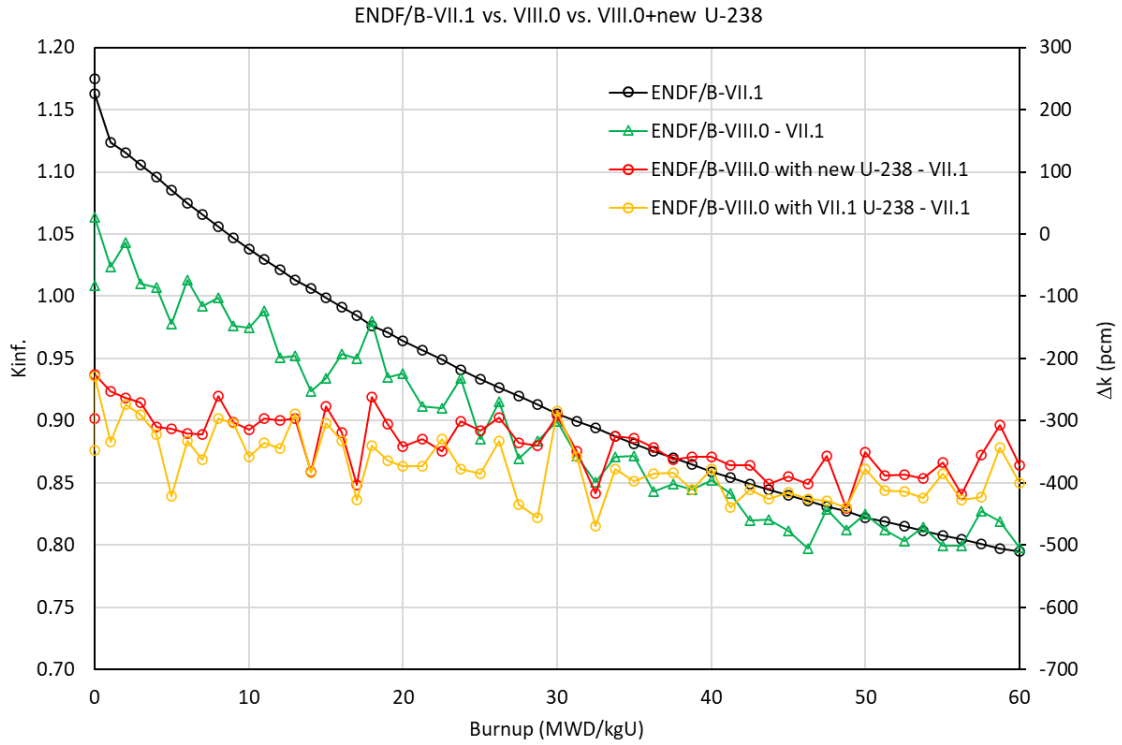


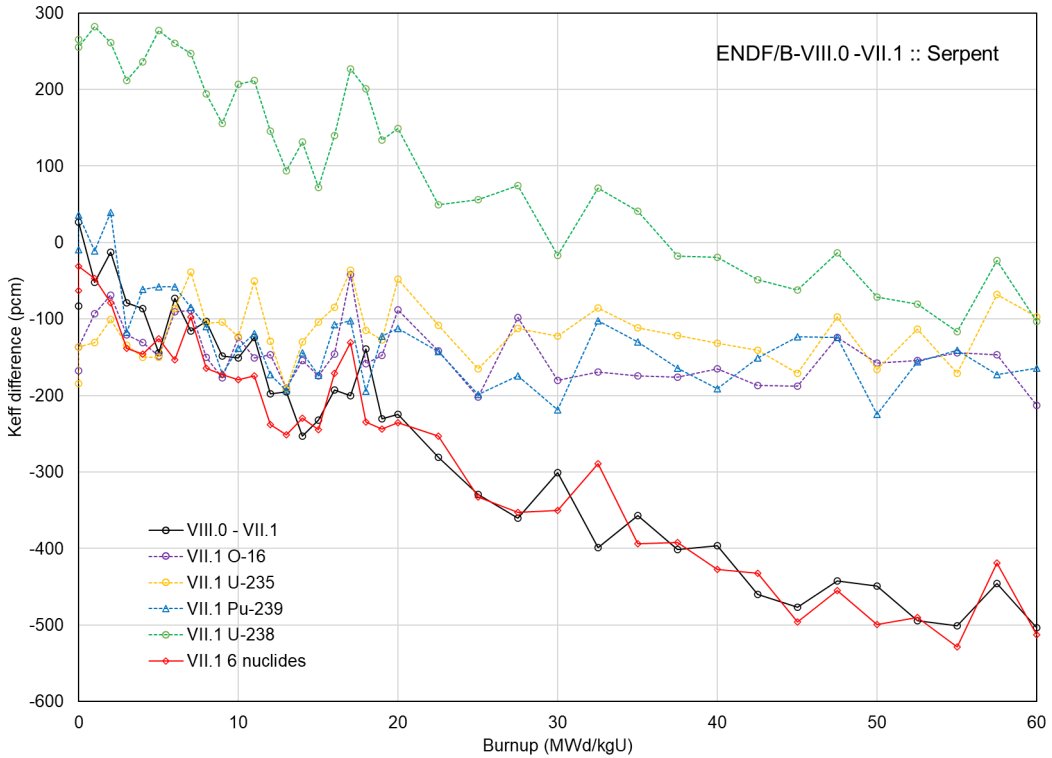
Figure 3: Preliminary SAMMY/FITACS fit compared to ENDF/B-VIII.0 evaluated data (file 3).

- Inelastic channel deviates from ENDF/B-VIII.0 below ≈10 keV
- μbarn should have no impact on criticality!
- Next step is the inclusion of fluctuations! (Resonance parameters ⇒ fit ⇒ effective/theoretical cross sections)

STATUS OF DEPLETION VS CRITICALITY

- Focus on resolving reactivity rates in VERA Depletion benchmark results[9]
- Four nuclides, i.e. ^{239}Pu, ^{235}U, ^{16}O and ^{238}U, contribute in the low reactivity at high burnup points





[9]Kang Seog Kim et al., CSEWG2019

NEUTRON MULTIPLICITIES OF ^{239}Pu

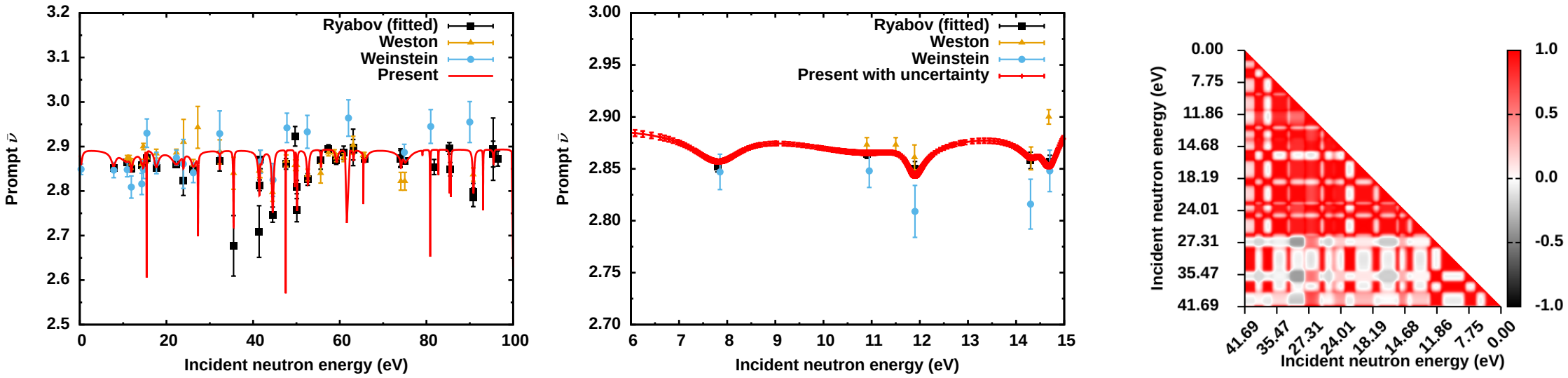


Figure 4: Preliminary fit of neutron multiplicities with available measured data and related covariance matrix.

- Measured data with different resolutions. Ryabov seems the most comprehensive and consistent in absolute normalization
- As expected the correlation matrix reflects the $\bar{\nu}$ fluctuating behavior
- To reduce size of covariance matrix, energy grid properly defined around each energy level
- Calculated uncertainty is about $\leq$0.3%

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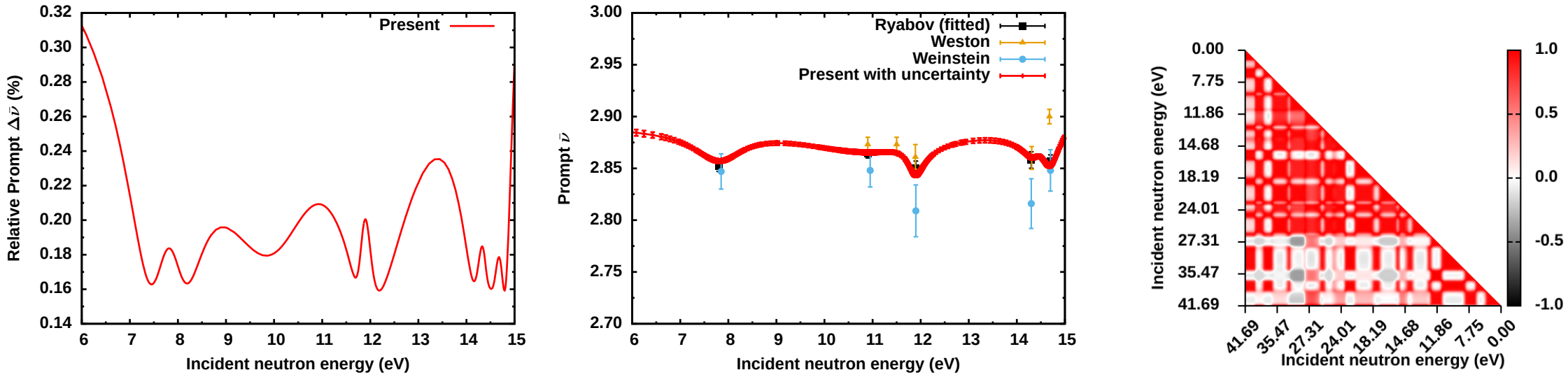

Figure 5: Preliminary fit of neutron multiplicities with available measured data and related covariance matrix.

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CONCLUSIONS

- (^{233}U) Improved agreement with the benchmarks[10] and RRR extension to 2.5 keV completed
  - Additional investigation on EALF-dependent reactivity
  - Possible interplay between PFNS, TNC, RRR, and neutron multiplicities ($\bar{\nu}_p$)
  - Work on URR (up to 40 keV) in progress
  - Inclusion of LANL experimental ratio (capture/fission) data when data are available
- (^{235}U) Progress on understanding reactivity rates related to depletion calculations
  - Improved agreement with measured (capture) data for ^{235}U is quite insensitive to resolve the negative slope
  - Updates to ^{238}U evaluation restore ENDF/B-VII.1 trend
  - ^{239}Pu may be most impactful nucleus to increase reactivity rates
- (^{239}Pu) Coupling between R-matrix analysis and neutron multiplicities

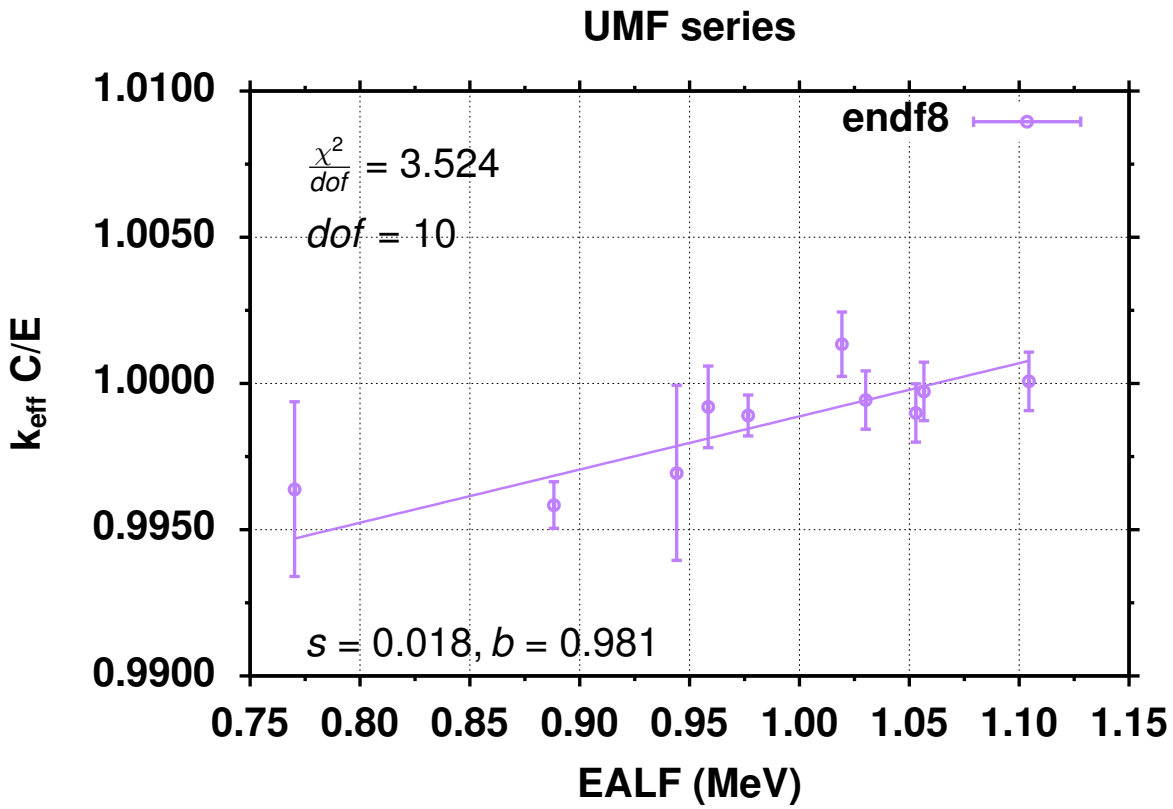
[10] 95% of benchmark cases (180≡UST+UCT+USI+USM) are sensitive to Thermal+RRR. Remaining 5% of the benchmark cases (10≡UMF) are sensitive to neutron energies >40 keV.

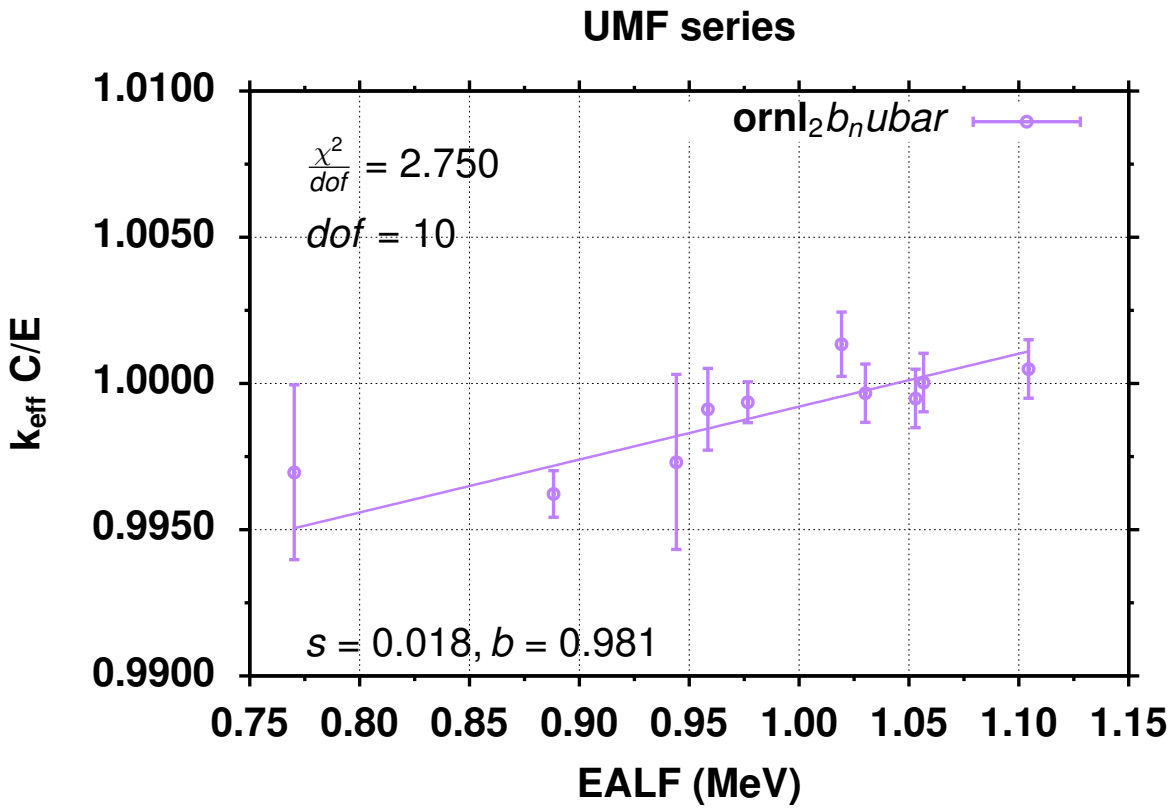
ACRONYMS

EALF	Energy of Average neutron Lethargy causing Fission
ENDF	Evaluated Nuclear Data File
IAEA	International Atomic Energy Agency
INDEN	International Nuclear Data Evaluation Network
LANL	Los Alamos National Laboratory
NCSP	Nuclear Criticality Safety Program
nTOF	neutron Time-of-Flight
ORELA	Oak Ridge Electron Linear Accelerator
ORNL	Oak Ridge National Laboratory
PFNS	Prompt Fission Nuclear Spectrum
RRR	Resolved Resonance Region
TNC	Thermal Nuclear Constant
URR	Unresolved Resonance Region

- UST ≡ U(ranium) S(olution) T(hermal), EALF<1.6 eV (140 cases)
- UCT ≡ U(ranium) C(omposition) T(hermal), 0.6<EALF<1.8 eV (3 cases)
- USM ≡ U(ranium) S(olution) M(ixed), 1.2<EALF<2.5 eV (8 cases)
- USI ≡ U(ranium) S(olution) I(ntermediate), 2<EALF<10.4 eV (29 cases)
- UMF ≡ U(ranium) M(etal) F(ast), EALF>700 keV (10 cases)

APPENDIX: UMF SERIES (EALF>700 keV)

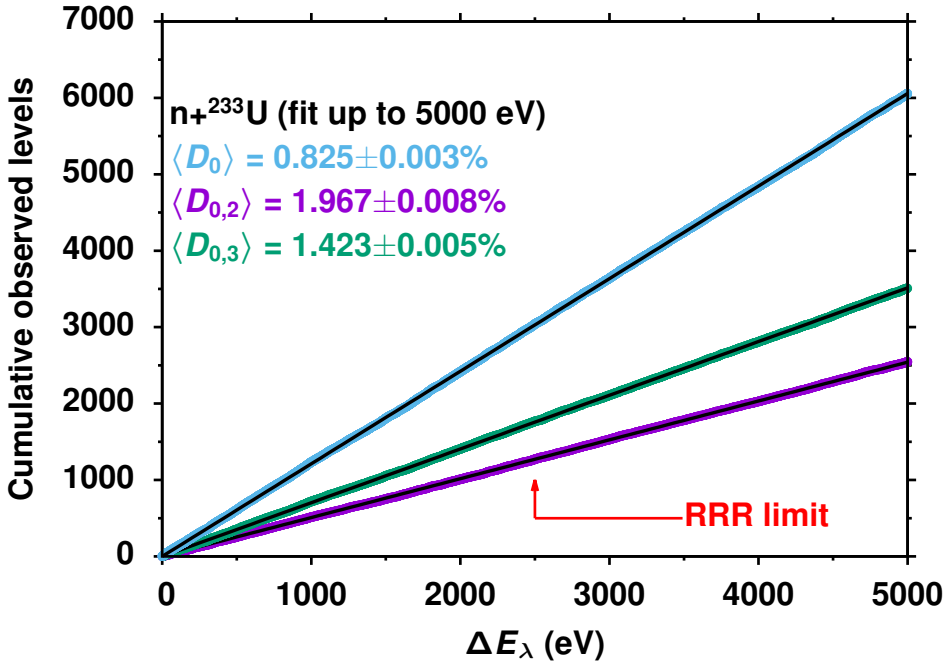


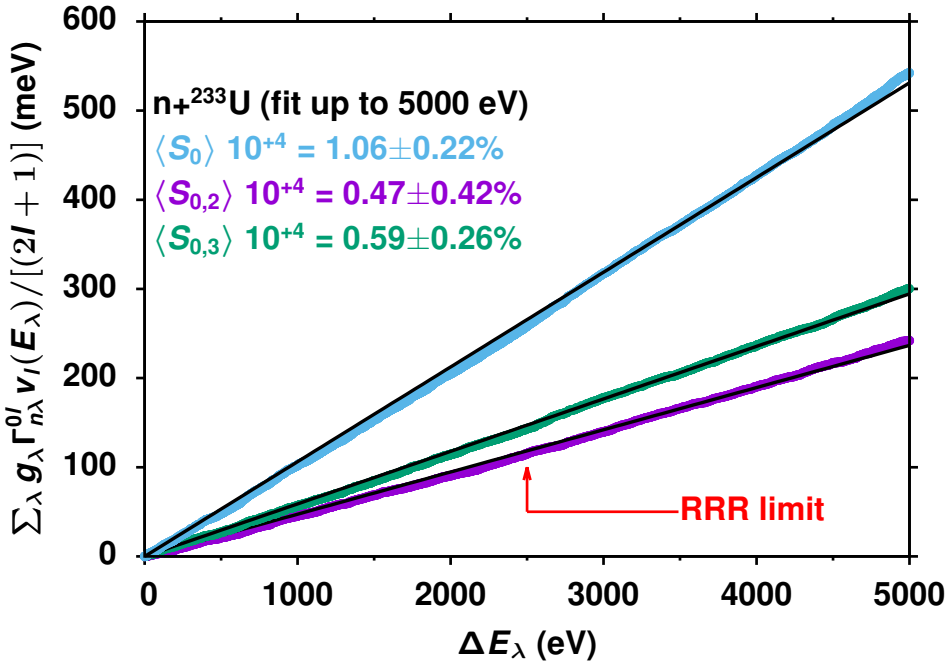


- UMF series of benchmarks are slightly affected by the changes in the RRR. These changes might due only to the updated PFNS.
- In the current validation suite there are no benchmarks sensitive to neutron energies in the 1–300 keV range to validate LANL measured data

APPENDIX: STATISTICS OF ^{233}U DATA UP TO 2.5 keV

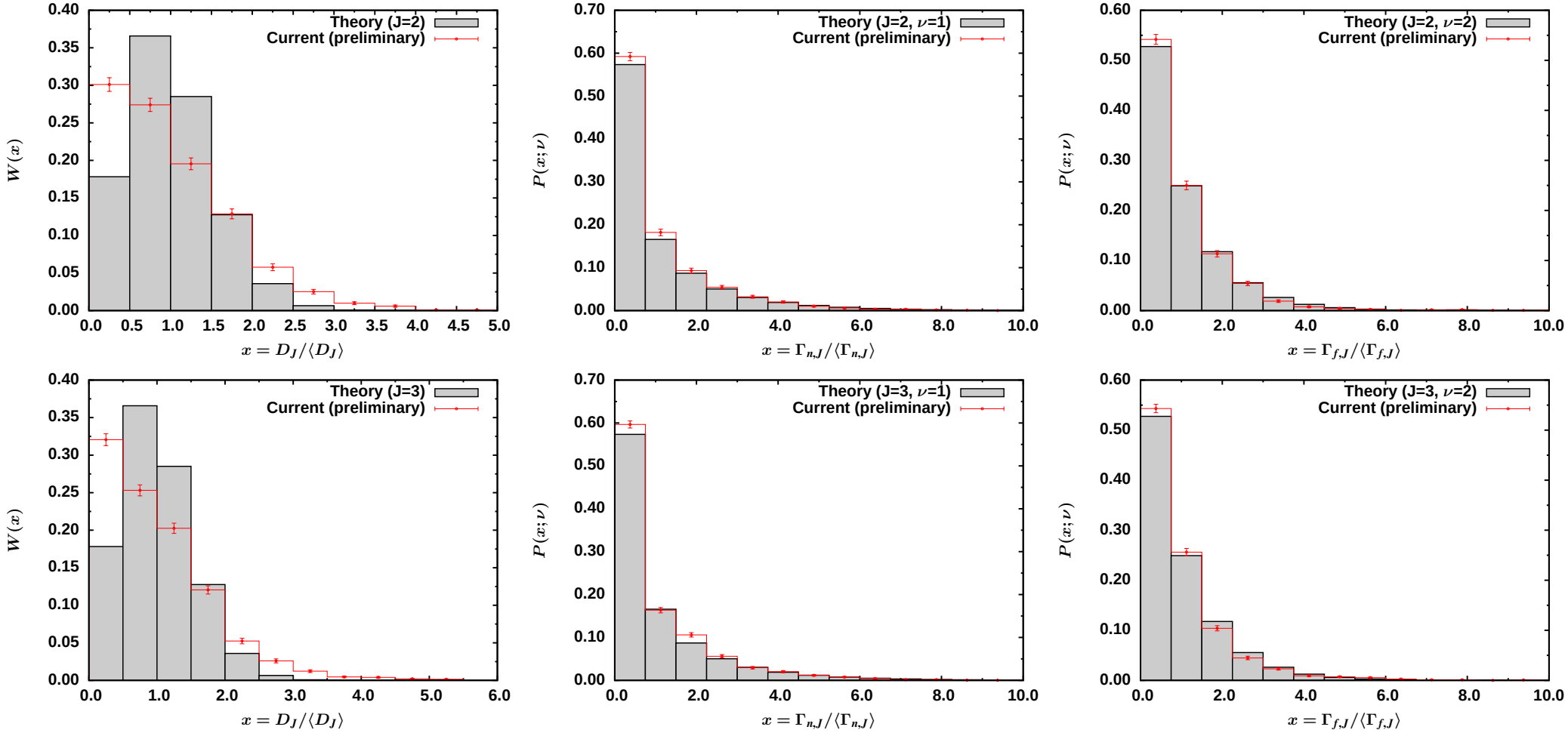
- RRR extended up to 2.5 keV with resonance parameters stored in the ENDF up to 5 keV





- URR up 40 keV in progress based on transmission and fission ORNL data sets

APPENDIX: STATISTICS OF ^{233}U DATA UP TO 2.5 keV[11]



[11] Plotted distributions (in red) are related to the posterior resonance parameters (energy and widths).

ACKNOWLEDGMENTS

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ORNL TEAM: D. Wiarda, J. McDonnell, A. Holcomb, K. Guber, C. Chapman, J. Brown, G. Arbanas

EXTERNAL COLLABORATORS: Esther Leal Cidoncha (LANL), Aaron J. Couture (LANL), and Luiz C. Leal (IRSN)

Thank you!