Spectrum Average Cross Sections (SACS) and its impact on evaluation of neutron standards

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Neutron Standards evaluation (2017)

TABLE II. Neutron Cross Section Standards.

Reaction	Standards Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1.4 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 0.15 MeV to 200 MeV, 7.8-11 eV
^{238}U(n,f)	2 MeV to 200 MeV

reference XS: ^{239}Pu(n,f) 0.15 MeV to 200 MeV

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Outline

- Introduction
- SACS: basic concepts and reference spectra
- STD evaluation issues
- Updated SACS-Cf experimental database
- Updated Mannhart SACS evaluation
  (based on measured SACS in Cf-252(sf) field)
- SACS-U5(nth,f) experimental database and
  Manhhart evaluation

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Basic concepts: SACS in spectrum
SACS-Cf = SACS in Cf-252(sf) PFNS

$$SACS = \frac{\int \sigma(E)\varphi(E)dE}{\int \varphi(E)dE} \qquad \int \varphi(E)dE \equiv 1$$

$$SACS = \int \sigma(E)\varphi(E)dE \cong \sum_{k=0}^{n} \varphi(k)\sigma(k)$$

$$\frac{\partial(SACS)}{\partial\sigma(k)} = \varphi(k)$$

SACS sensitivity to $\sigma(k)$ = spectral weight $\varphi(k)$ @ E_k

SACS are VERY CLEAN INTEGRAL DATA

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IRDFF validation of Cf(sf) and U5(nth,f) neutron fields ~ 40+ reactions

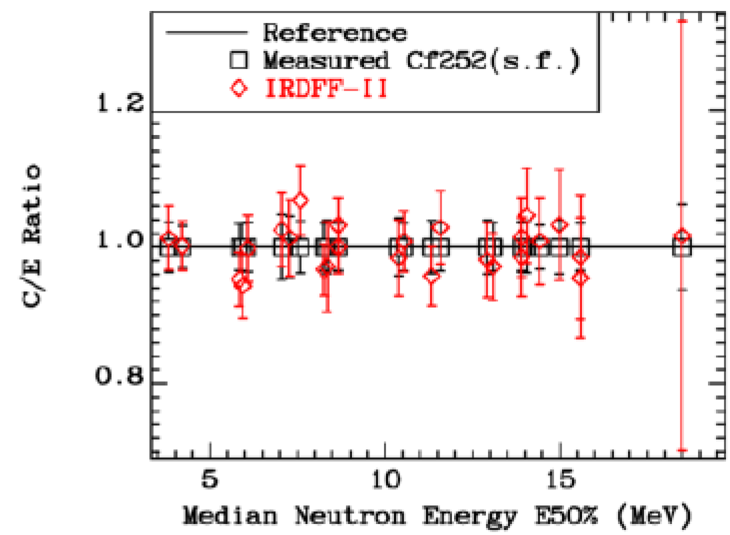

FIG. 123. (Color online) C/E relative to median energy $E_{50\%}$ for the IRDFF-II cross sections averaged in the ^{252}Cf(s.f.) neutron field measured at Řež near Prague. Plotted values are listed in Table 19.

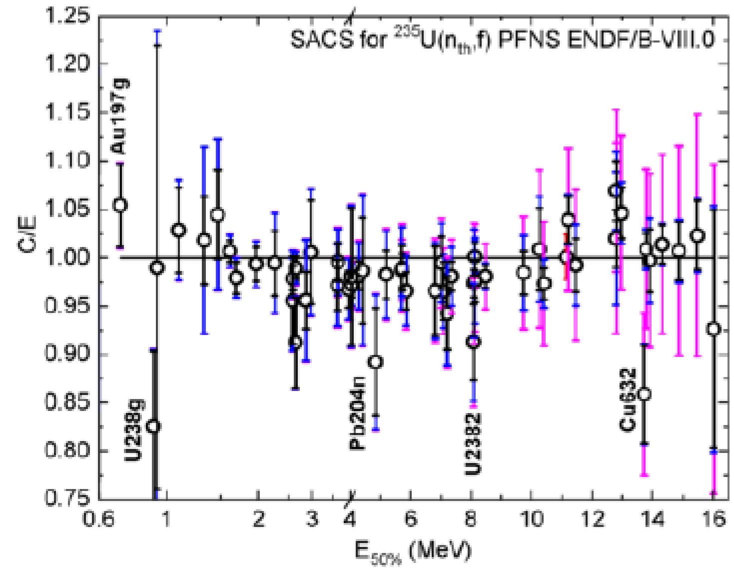

FIG. 124. (Color online) C/E as a function of median energy $E_{50\%}$ for the IRDFF-II cross sections averaged in the ^{235}U(n_{th},f) PFNS field are shown as circles. Uncertainty bars reflect a r.m.s. combination of uncertainty contributions from the measurement (black), IRDFF-II cross sections (blue) and spectra (pink). Plotted values are listed in Table 20. Only outlying C/E values are labelled with reaction IDs from Table 20.

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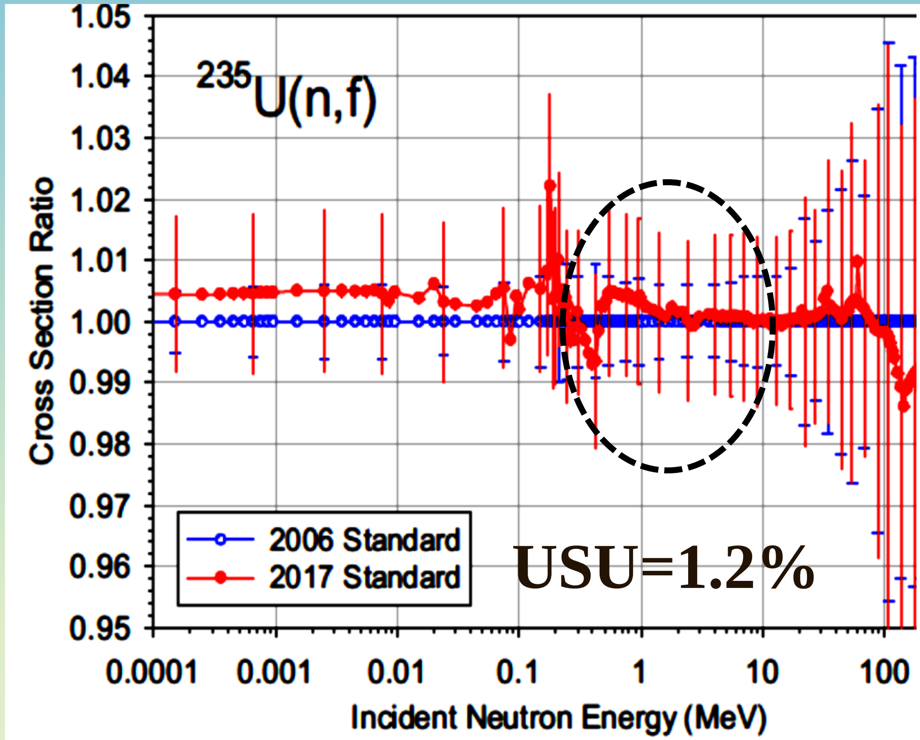
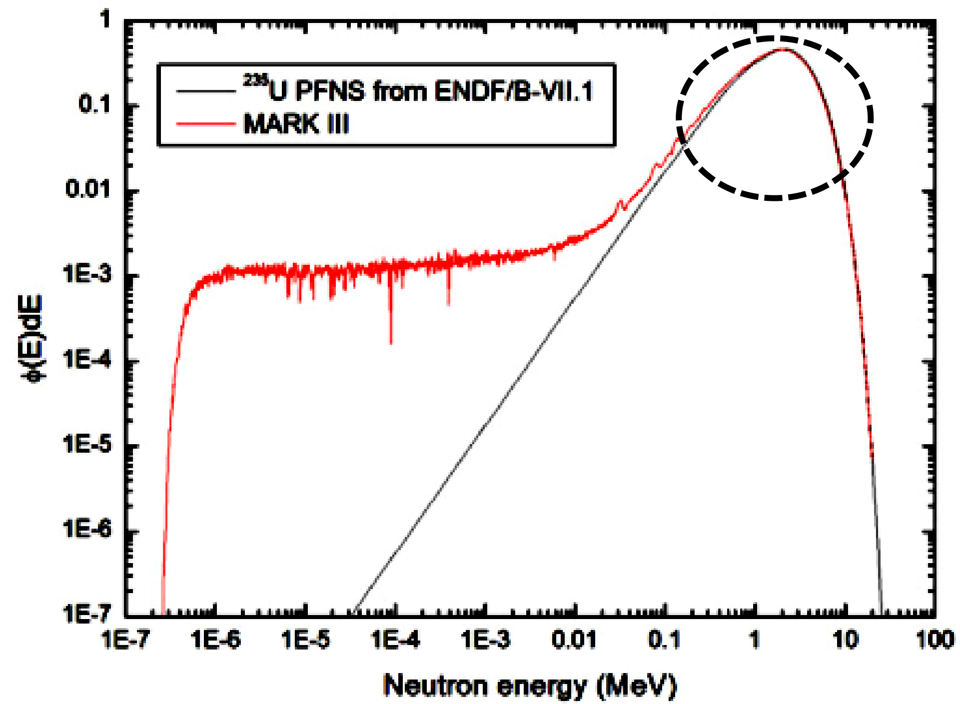
Neutron Standard & Reference (n,f) XS





A.D.Carlson et al, Nucl. Data Sheets 148, 143 (2018) J. Wagemans et al, EPJ Web of Conferences 106, 06003 (2016)

SACS-Cf provide excellent normalization for many En energies: 0-10 MeV ~ 99% spectrum, lowest XS uncertainty

SACS-Cf provide better normalization than absol. fission XS/ratios measurements in quasi-monoenergetic beams (USU=1.2% spread)

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SACS–Cf evaluation – updated Mannhart

```
cf_dat.dat            Set 1
EXPERIMENT : Heaton + Grundl memo + Grundl-Gilliam + Schroeder + Davis/Knoll
10
 1  1  0 1.216E+3  1.6200    U235F         GRUNDL MEMO (Rev. Heaton 1976 ABSOL U-235f),indc(nds)-146, p.237
 2  1  2 3.73      1.2000    U235F/U238F   GRUNDL-GILLIAM indc(nds)-146, p.244, inverse = 0.2681
 3  1  3 0.666     0.9000    U235F/PU239F  GRUNDL-GILLIAM indc(nds)-146, p.244, inverse = 1.502 (0.9%)
 4  3  1 1.500E+0  1.6000    PU239F/U235F  Heaton 1976 ANL-76-90 60% ratio correl derived from common ratio uncert.
 5  2  1 0.2644    1.3200    U238F/U235F   Heaton 1976 ANL-76-90 60% ratio correl derived from common ratio uncert.
 6  2  1 0.269E+0  1.2000    U238F/U235F   Schroeder JANS 50(1985)154
 7  3  1 1.500E+0  0.8000    PU239F/U235F  Schroeder JANS 50(1985)154
 8  1  0 1.234E+3  1.4500    U235F         Schroeder JANS 50(1985)154
 9  1  0 1.215E+3  1.7900    U235F         Davis/Knoll ANE 5 (1978) 583
10  3  0 1.790E+3  2.2600    PU239F        Davis/Knoll ANE 5 (1978) 583
 100                                                                          1    Grundl memo ABS (rev. Heaton)
  23 100                                                                      2    Grundl/Gilliam ratio
  -9  36 100                                                                  3    Grundl/Gilliam ratio
   0   0   0 100                                                              4    Heaton ratio
   0   0   0  60 100                                                          5    Heaton ratio
   0   0   0   0   0 100                                                      6    Schroeder ratio
   0   0   0   0   0  77 100                                                  7    Schroeder ratio
   0   0   0   0   0   0   0 100                                              8    Schroeder ABS
   0   0   0   0   0   0   0   0 100                                          9    Davis/Knoll abs
   0   0   0   0   0   0   0   0  59 100                                      10   Davis/Knoll abs
                      Set 2
EXPERIMENT : ADAMOV
 2
 1  2  1 2.741E-1  1.6600    U238F/U235F    *1.0      ADAMOV
 2  3  1 1.475E+0  1.5000    PU239F/U235F   *1.0
 100
  29 100
                      Set 3
EXPERIMENT: NBS-VNC + SPIEGEL
 1
 1  2  1 2.491E-1  5.2200    U238F/U235F     *2.0
 100
```

SACS exp. data
13 sets

```
EVAL <SIGMA> in CF-252 (PRIOR VALUES)
 3
 1 1.205E+3 50.0000    U-235(N,F)
 2 3.180E+2 50.0000    U-238(N,F)
 3 1.807E+3 50.0000    PU-239(N,F)
 100
   0 100
   0    0 100
```

PRIOR (uninf.)

```
EVAL <SIGMA> - CF-252
 3
 1 1.221E+3  0.9065    U-235(N,F)
 2 3.264E+2  1.0577    U-238(N,F)
 3 1.825E+3  1.0122    PU-239(N,F)
 100
  81 100
  88  87 100
```

with new data
(13 datasets)

Pu9(n,f)/U5(n,f) SACS ratio	1.495 (1.8%) **Pu9f & U5f ind.**
U8(n,f)/U5(n,f) SACS ratio	0.267 (2.0%) **U8f & U5f ind.**

EVALUATION

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SACS–Cf eval. – Mannhart updated

Quantity	Mannhart updated SACS (b)	STD 2017 SACS (b)
U5(n,f) SACS	1.221 (0.9%)	1.2267 (1.21%)
Pu9(n,f) SACS	1.825 (1.0%)	1.7978 (1.25%)
U8(n,f) SACS	0.326 (1.1%)	0.3215 (1.3%)
Pu9(n,f)/U5(n,f) SACS ratio	1.495 (0.7%) **no corr:1.8%**	1.466 **(C/E=0.98)**
U8(n,f)/U5(n,f) SACS ratio	0.267 (1.0%) **no corr:2.0%**	0.262 **(C/E=0.98)**

EXPERIMENT

Pu9(n,f)/U5(n,f) Schroeder 1985	1.50 (1) (0.8%)
Pu9(n,f)/U5(n,f) Heaton 1976	1.50 (2) (1.6%)
Pu9(n,f)/U5(n,f) Grundl-Gilliam	1.50 (1) (0.9%)
U8(n,f)/U5(n,f) Grundl-Gilliam	0.268 (3) (1.2%)
U8(n,f)/U5(n,f) Schroeder	0.269 (3) (1.2%)
U8(n,f)/U5(n,f) Heaton 1976	0.264 (3) (1.3%)

Pu9(n,f)/U5(n,f) SACS ratio	1.495 (1.8%) **Pu9f & U5f ind.**
U8(n,f)/U5(n,f) SACS ratio	0.267 (2.0%) **U8f & U5f ind.**

```
EVAL <SIGMA> - CF-252
 3
 1 1.221E+3   0.9065     U-235(N,F)
 2 3.264E+2   1.0577     U-238(N,F)
 3 1.825E+3   1.0122     PU-239(N,F)
100
  81 100
  88  87 100
```

with new data (13 datasets)

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- We used 7 data of U5 & Pu9 SACS-Cf (no ratios !) in STD 2017 evaluation (GMA)
- Mannhart used activation + 7 SACS fission data
- Updated GMA-py +13 data incl. precise ratios -> EVAL

```
EXPERIMENT : Heaton + Grundl memo + Grundl-Gilliam + Schroeder + Davis/Knoll
10
 1  1  0 1.216E+3  1.6200   U235F         GRUNDL MEMO (Rev. Heaton 1976 ABSOL U-235f),indc(nds)-146, p.237
 2  1  2 3.73      1.2000   U235F/U238F   GRUNDL-GILLIAM indc(nds)-146, p.244, inverse = 0.2681
 3  1  3 0.666     0.9000   U235F/PU239F  GRUNDL-GILLIAM indc(nds)-146, p.244, inverse = 1.502 (0.9%)
 4  3  1 1.500E+0  1.6000   PU239F/U235F  Heaton 1976 ANL-76-90 60% ratio correl derived from common ratio uncert.
 5  2  1 0.2644    1.3200   U238F/U235F   Heaton 1976 ANL-76-90 60% ratio correl derived from common ratio uncert.
 6  2  1 0.269E+0  1.2000   U238F/U235F   Schroeder JANS 50(1985)154
 7  3  1 1.500E+0  0.8000   PU239F/U235F  Schroeder JANS 50(1985)154
 8  1  0 1.234E+3  1.4500   U235F         Schroeder JANS 50(1985)154
 9  1  0 1.215E+3  1.7900   U235F         Davis/Knoll ANE 5 (1978) 583
10  3  0 1.790E+3  2.2600   PU239F        Davis/Knoll ANE 5 (1978) 583
```

3 abs. U5f, 10 ratios

```
                    Set 2
EXPERIMENT : ADAMOV
 2
 1  2  1 2.741E-1  1.6600   U238F/U235F    *1.0      ADAMOV
 2  3  1 1.475E+0  1.5000   PU239F/U235F   *1.0
 100
  29 100
                    Set 3
EXPERIMENT: NBS-VNC + SPIEGEL
 1
 1  2  1 2.491E-1  5.2200   U238F/U235F     *2.0
 100
```


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- ❑ **No U5(nth,f) SACS used in STD 2017 evaluation (GMA)**
- ❑ **Mannhart compiled 3 datasets**

```
EXPERIMENT : NBS Smolenice 1983 + Fabry(1978) EXFOR 20947   set_3.dat
 3
 1   1   0 1.216E+3   1.6100     U-235(n,f)                      NBS
 2   2   1 1.504E+0   1.6200     Pu-239(n,f) /U-235(n,f)        Fabry
 3   5   1 2.540E-1   2.6900     U-238(n,f)  /U-235(n,f)
 100
   0 100
   0   0 100
set_2.dat
EXPERIMENT : Fabry(1975) EXFOR 20946
 4
 1   1   5 3.940E+0   2.0000     U-235(n,f)  /U-238(n,f)      Fabry
 2   2   5 5.930E+0   2.1900     Pu-239(n,f) /U-238(n,f)
 100
   0 100
set_8.dat
EXPERIMENT : Grundl(1968) EXFOR 12193 + Leachman(1957) EXFOR 12448
 7
 1   5   0 3.109E+2   1.6300     U-238(n,f)              Leachman 1957 nu=2.4320
 2   1   5 3.850E+0   6.0000     U-235(n,f)  /U-238(n,f) Grundl    1968
 100
   0 100
```

SACS in $^{235}U(n_{th},f)$

2 abs. U5f,U8f
5 ratios

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SACS–U5(nth,f) eval. – Mannhart

Quantity	Mannhart 2008 eval SACS (b)	STD 2017 SACS (b)
U5(n,f) SACS	1.217 (1.1%)	1.2253 (1.21%)
Pu9(n,f) SACS	1.831 (1.7%)	1.7933 (1.25%)
U8(n,f) SACS	0.3094 (1.1%)	0.3062 (1.2%)
Pu9(n,f)/U5(n,f) SACS ratio	1.504 (~2.0%)	1.463 (C/E=0.973)
U8(n,f)/U5(n,f) SACS ratio	0.254 (~1.6%)	0.250 (C/E=0.98)

EXPERIMENT

Pu9(n,f)/U5(n,f) Fabry 1978	1.504 (1.6%)
U8(n,f)/U5(n,f) Fabry 1978	0.254 (2.7%)
U8(n,f)/U5(n,f) Fabry 1975	0.254 (2.0%)
Pu9(n,f)/U8(n,f) Fabry 1975	5.93 (2.2%)

```
 Chi**2 =    0.914  Data =   3  Iteration =   2

EVAL <sigma> - U-235
 1 1.217E+3  1.1226     U-235(n,f)
 2 1.831E+3  1.6541     Pu-239(n,f)
 5 3.094E+2  1.1325     U-238(n,f)

|  100
   59 100
   63   52   100
```

Mannhart SACS evaluation 2008

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SACS–Cf & SACS-U5(nth,f)

EXPERIMENT

Quantity	Mannhart 2008 eval [b] in U5(nth,f)	Mannhart updated SACS [b]
U5(n,f) SACS	1.217(1.1%) (U/Cf=1)	**1.221 (0.9%)**
Pu9(n,f) SACS	1.831(1.7%) (U/Cf=0.99)	**1.825 (1.0%)**
U8(n,f) SACS	0.3094(1.1%) (U/Cf=0.99)	**0.326 (1.1%)**
Pu9(n,f)/U5(n,f) SACS ratio	1.504(~1%) (U/Cf=1.006)	**1.495 (0.7%)**
U8(n,f)/U5(n,f) SACS ratio	0.254 **(U/Cf=0.95)**	**0.267 (1.0%)**

Cf

Pu9(n,f)/U5(n,f) Schroeder 1985	1.50 (1) (0.8%)
Pu9(n,f)/U5(n,f) Heaton 1976	1.50 (2) (1.6%)
Pu9(n,f)/U5(n,f) Grundl-Gilliam	1.50 (1) (0.9%)
U8(n,f)/U5(n,f) Grundl-Gilliam	0.268 (3) (1.2%)
U8(n,f)/U5(n,f) Schroeder	0.269 (3) (1.2%)
U8(n,f)/U5(n,f) Heaton 1976	0.264 (3) (1.3%)

U5

Pu9(n,f)/U5(n,f) Fabry 1978	1.504 (1.6%)
U8(n,f)/U5(n,f) Fabry 1978	0.254 (2.7%)
U8(n,f)/U5(n,f) Fabry 1975	0.254 (2.0%)
Pu9(n,f)/U8(n,f) Fabry 1975	5.93 (2.2%)

SACS-Cf and SACS-U5(nth,f) can be used for the STD fit

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SACS–Cf & SACS-U5(nth,f)

EXPERIMENT

Quantity	Mannhart 2008 SACS eval [b]	STD 2017 SACS (b)
U5(n,f) SACS	1.217 (1.1%)	1.2253 (1.26%) 0.36% sp 1.1% reac
Pu9(n,f) SACS	1.831 (1.7%)	1.7933 (1.30%) 0.37% sp 1.2% reac
U8(n,f) SACS	0.3094 (1.1%)	0.3062 (1.4%) 0.75% sp 1.2% reac

U5

Pu9(n,f)/U5(n,f) Fabry 1978	1.504 (1.6%)
U8(n,f)/U5(n,f) Fabry 1978	0.254 (2.7%)
U8(n,f)/U5(n,f) Fabry 1975	0.254 (2.0%)
Pu9(n,f)/U8(n,f) Fabry 1975	5.93 (2.2%)

Capote, R. and Trkov, A., "Predicting Spectrum Averaged Cross Sections in Prompt Fission Neutron Fields," *Reactor Dosimetry: 16th International Symposium, ASTM STP1608*, M. H. Sparks, K. R. DePriest, and D. W. Vehar, Eds., ASTM International, West Conshohocken, PA, 2018, pp. 117–123, http://dx.doi.org/10.1520/STP160820170114[2]

SACS-Cf and SACS-U5(nth,f) can be used for the STD fit

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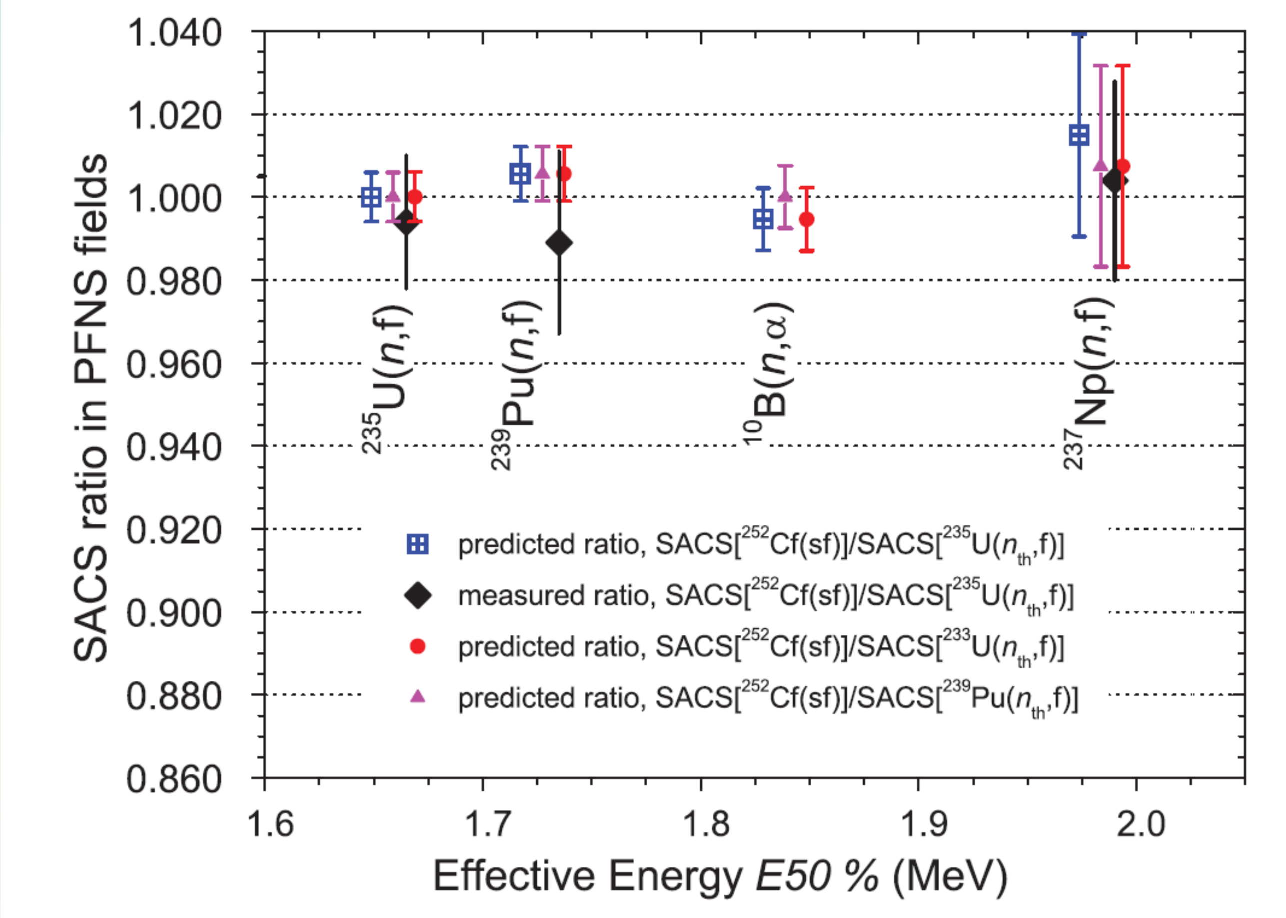
SACS(nf) independent of the PFNS

Capote, R. and Trkov, A., "Predicting Spectrum Averaged Cross Sections in Prompt Fission Neutron Fields," *Reactor Dosimetry: 16th International Symposium, ASTM STP1608*, M. H. Sparks, K. R. DePriest, and D. W. Vehar, Eds., ASTM International, West Conshohocken, PA, 2018, pp. 117–123, http://dx.doi.org/10.1520/STP160820170114[2]



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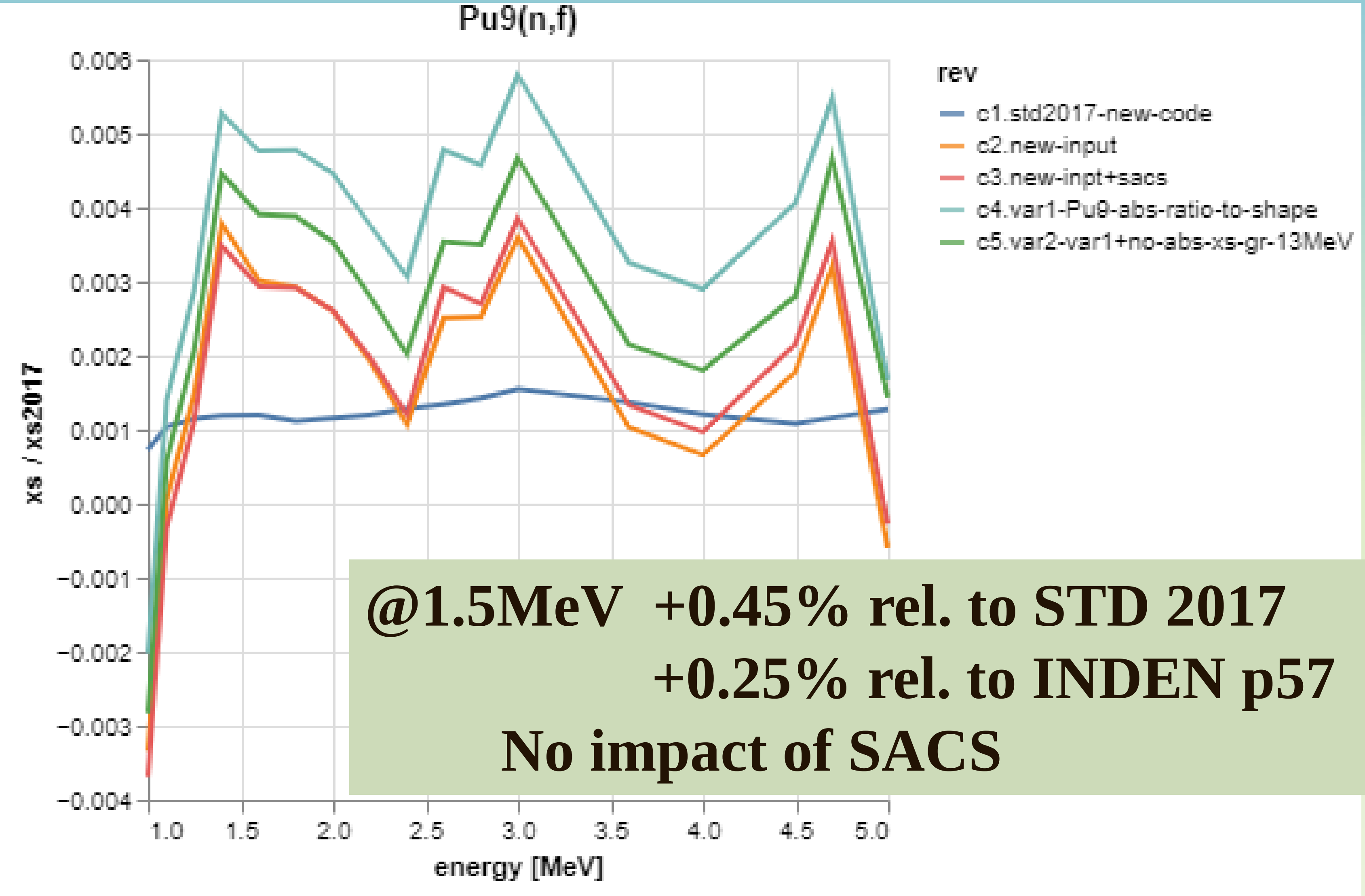
Pu9f reference: 2017 vs current – GMA-py



@1.5MeV +0.45% rel. to STD 2017
+0.25% rel. to INDEN p57
No impact of SACS

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Summary and conclusions

- ✓ SACS in ref. spectra -a key for STD (n,f) normalization
- ✓ STD 2017 show similar problems in both refer. spectra
- ✓ 13 SACS-Cf datasets identified and used
- ✓ Mannhart identified 7 SACS-U5(nth,f) data
- ✓ Use of SACS-U5 data planned
- ✓ Impact of the spectrum uncertainty on SACS(nf) very small

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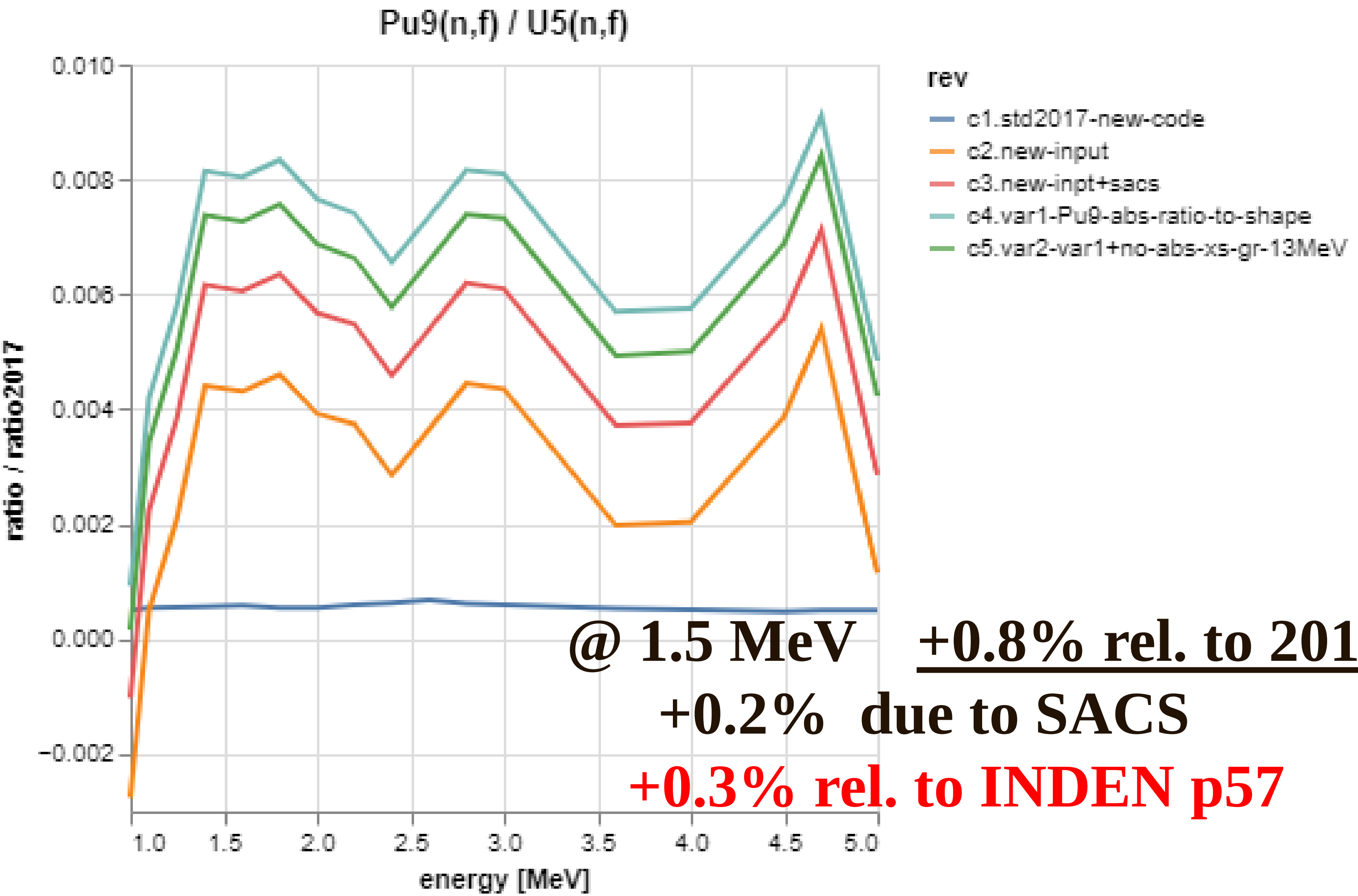
Pu9f/U5f: 2017 vs current – GMA-py



@ 1.5 MeV **<u>+0.8% rel. to 2017</u>**

+0.2% due to SACS

+0.3% rel. to INDEN p57

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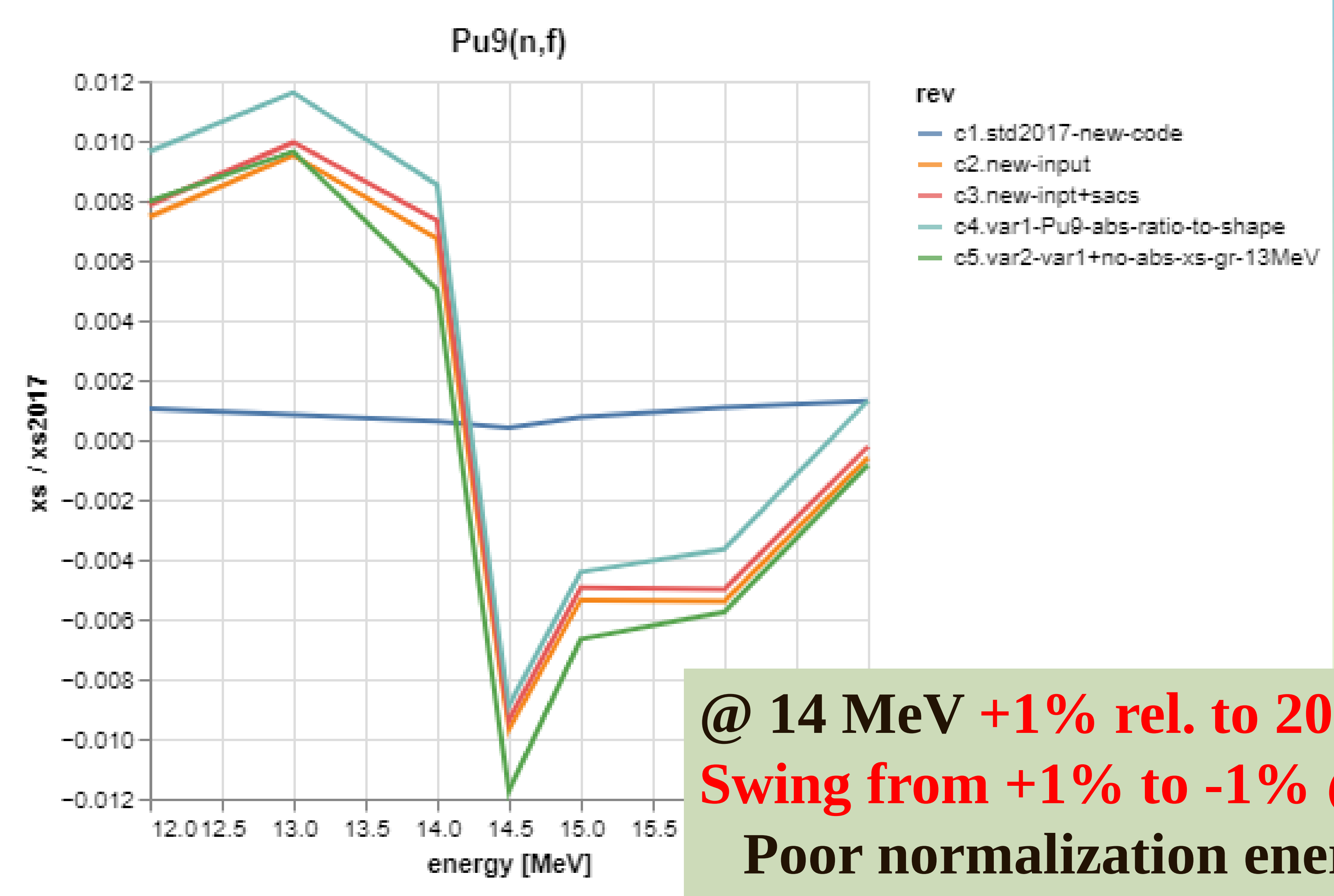
Pu9f/U5f: 2017 vs current – GMA-py



@ 14 MeV +1% rel. to 2017
Swing from +1% to -1% @14.5
Poor normalization energy !!

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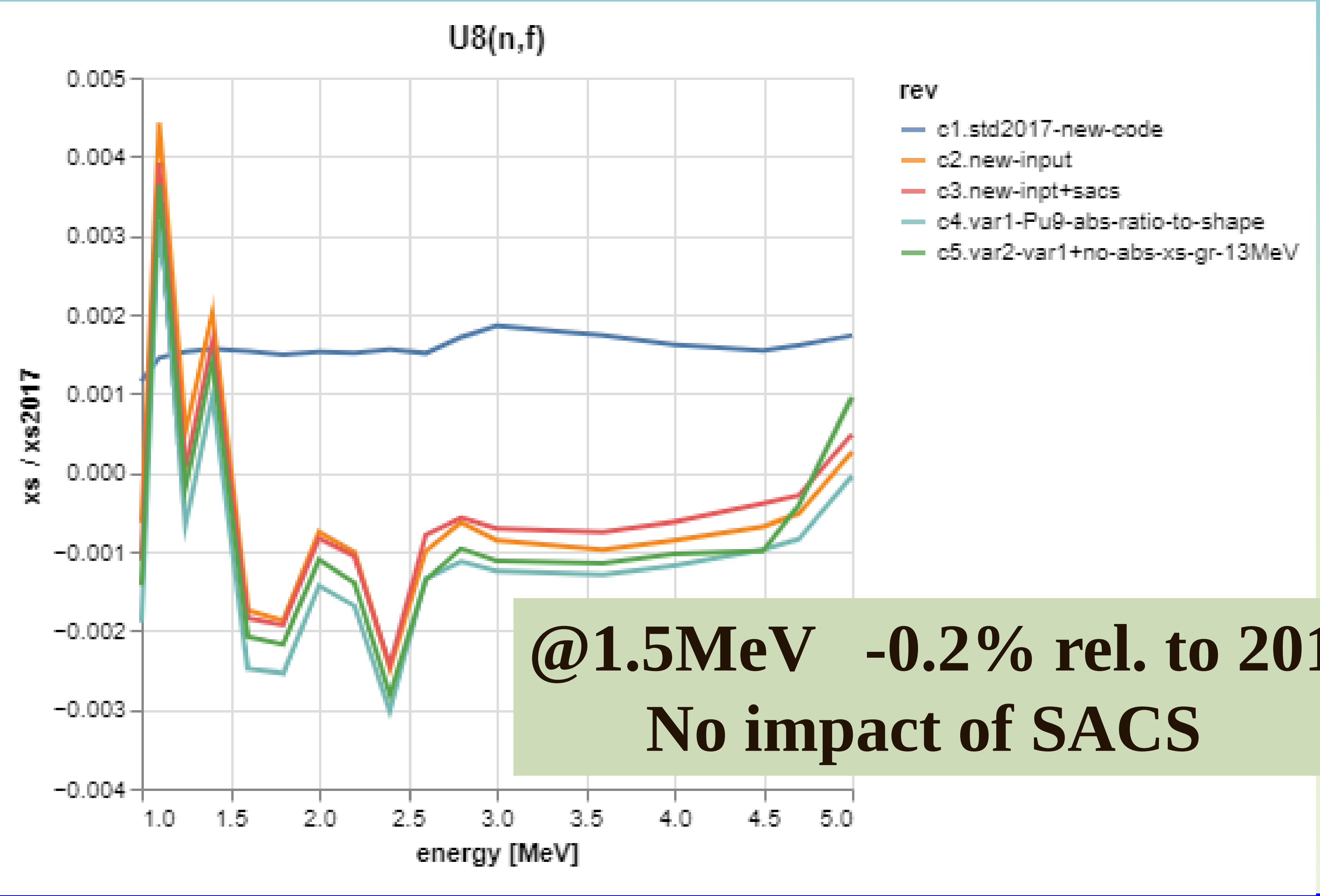
U8f standard: 2017 vs current – GMA-py



@1.5MeV -0.2% rel. to 2017
No impact of SACS

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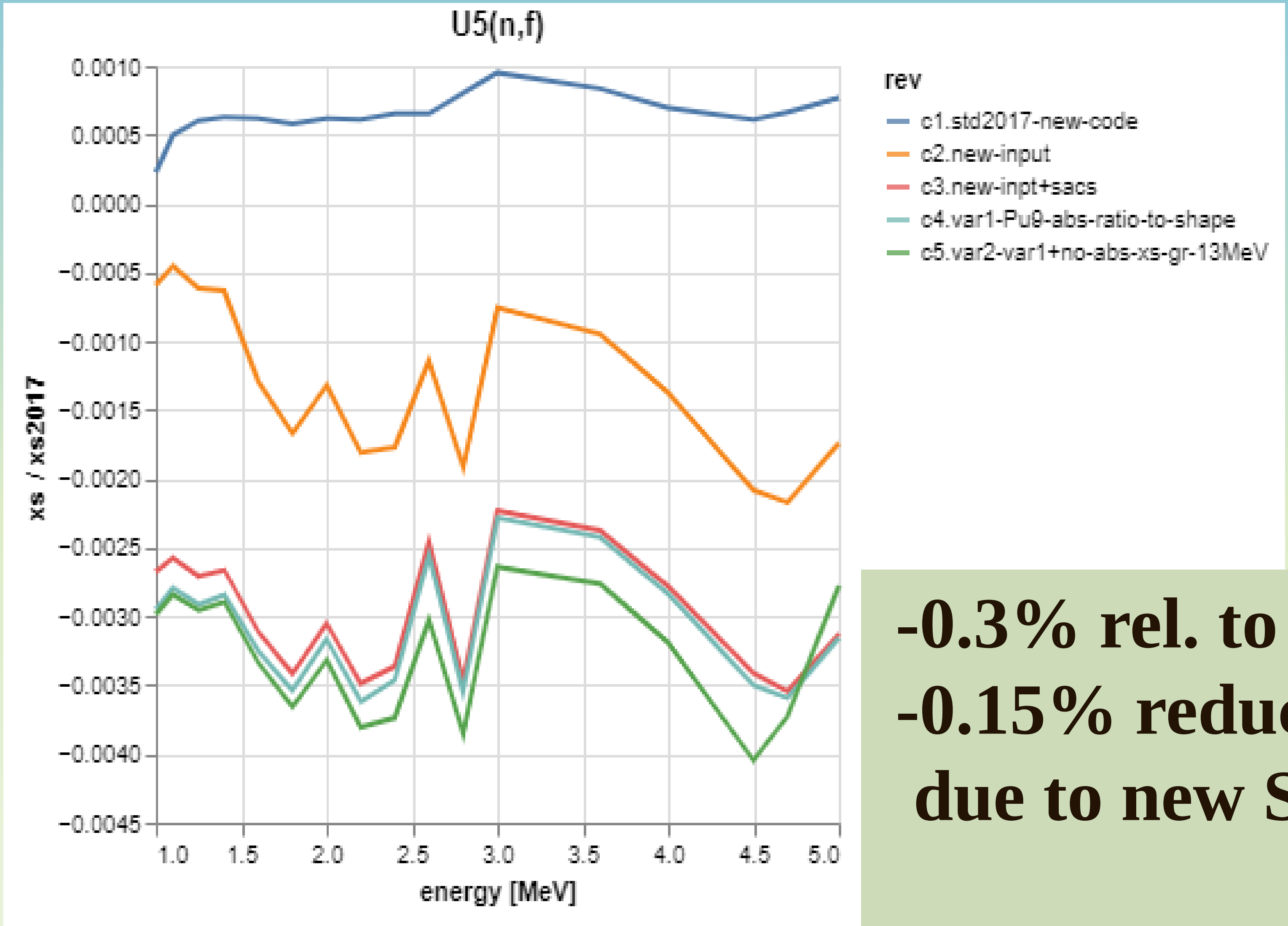
U5f standard: 2017 vs current – GMA-py



-0.3% rel. to STD 2017
-0.15% reduction due to new SACS

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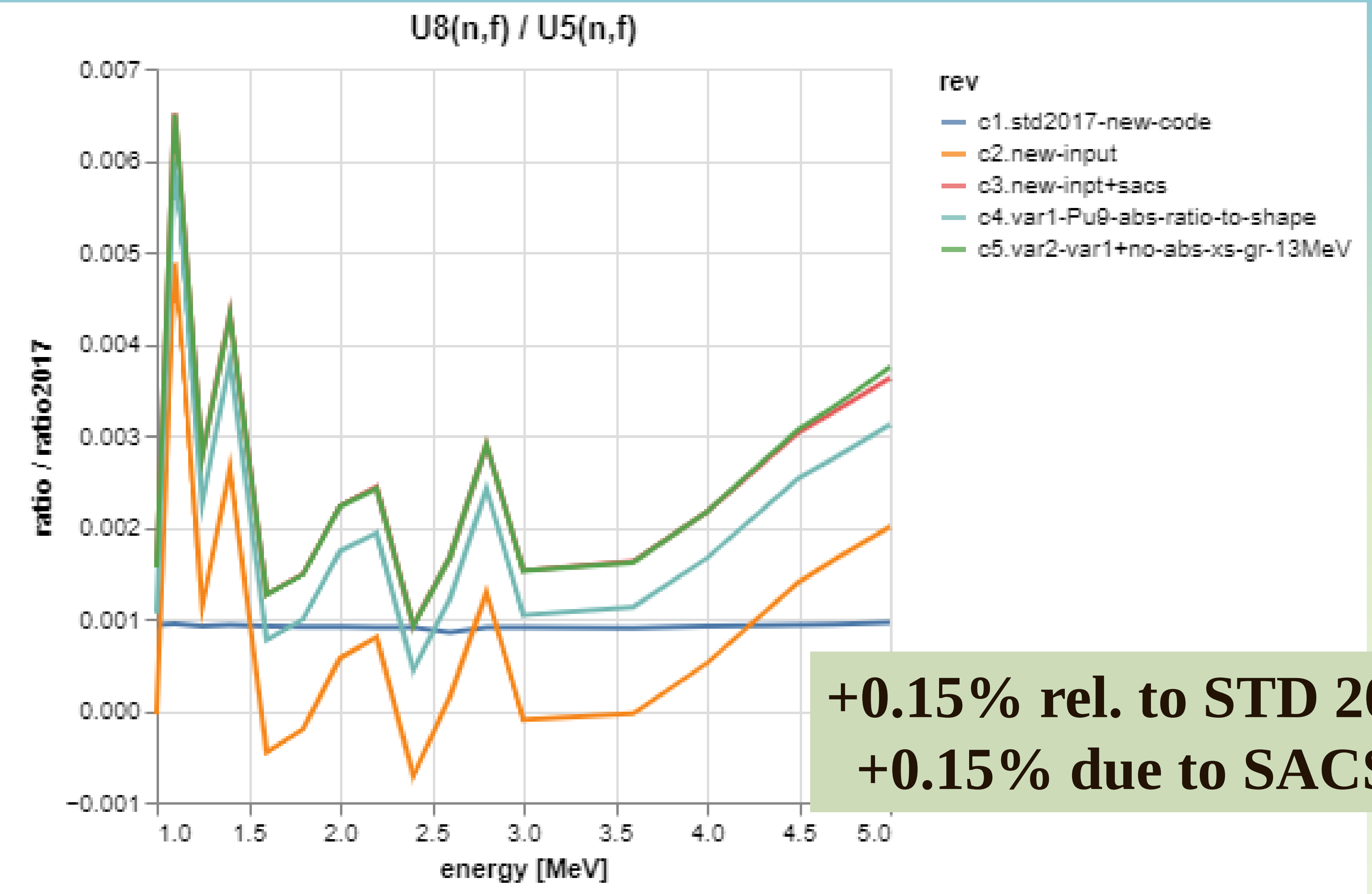
U8f/U5f: 2017 vs current – GMA-py



+0.15% rel. to STD 2017
+0.15% due to SACS

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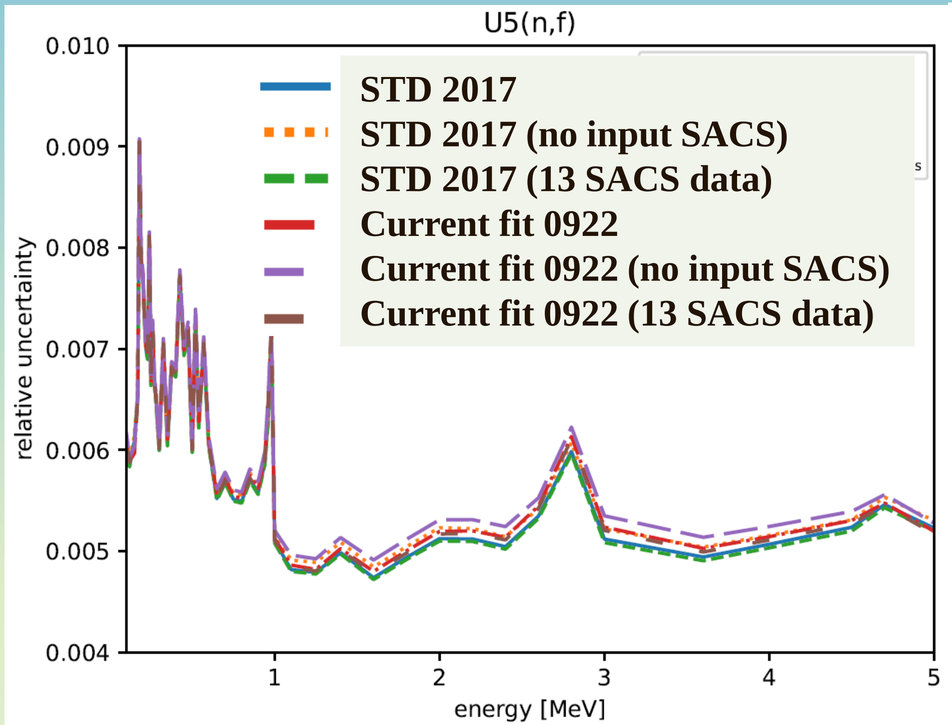
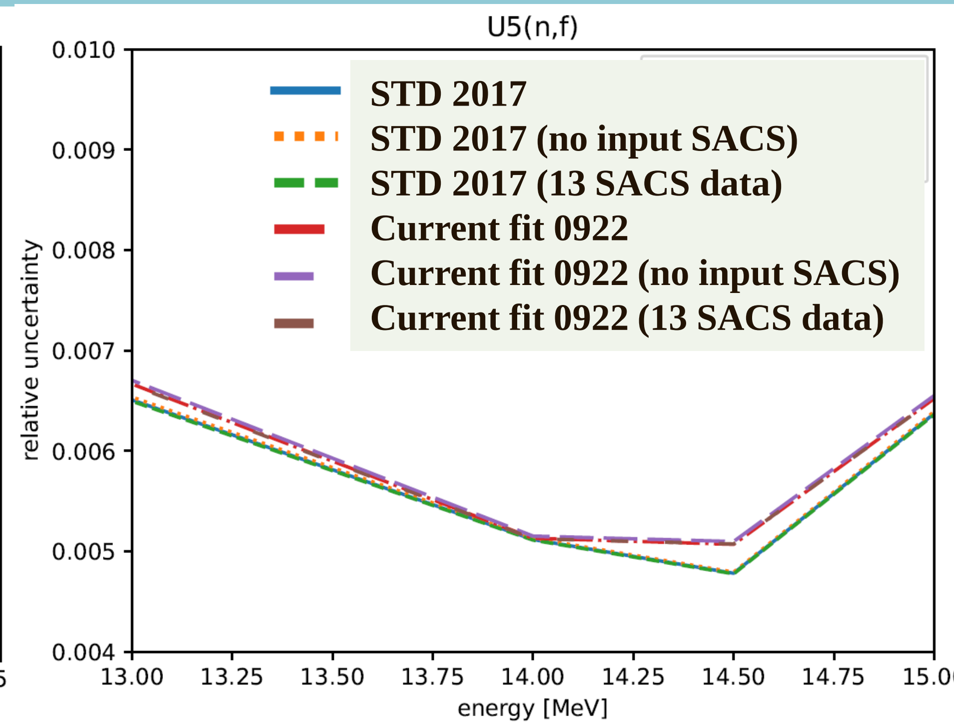
U5f uncert.: 2017 vs current – GMA-py





Last unc. 0.5-5 MeV ~0.5%-0.55% **Last unc. 13-15MeV ~0.5%-0.65%**

U5f uncert. at ~1.5 and ~14 MeV very similar

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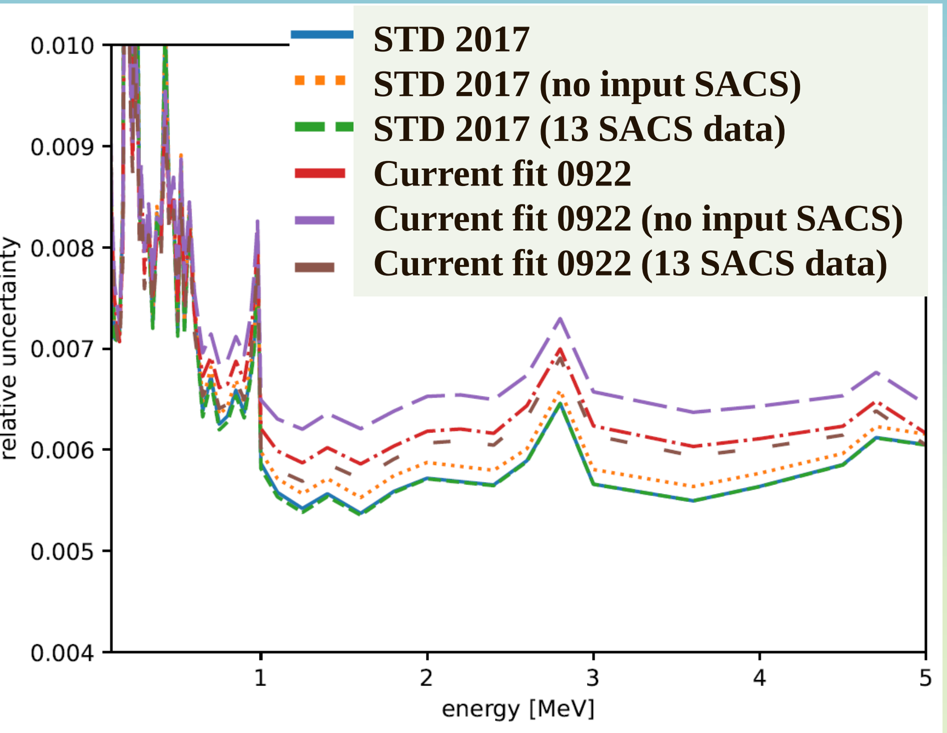
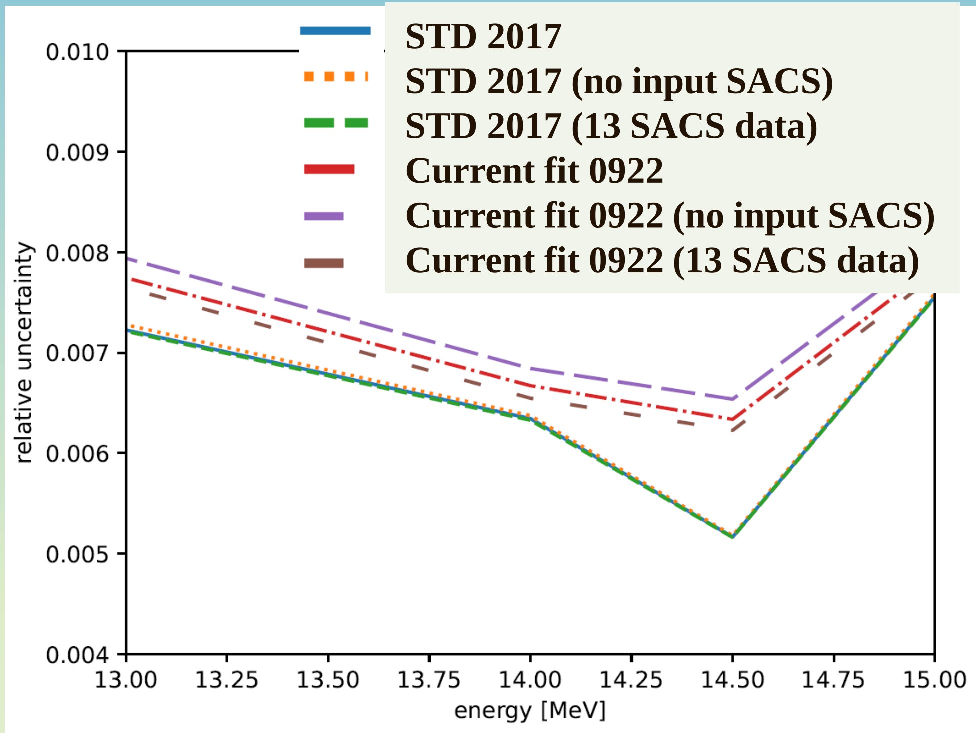
Pu9f uncert.: 2017 vs current – GMA-py





Last unc. 0.5-5 MeV ~0.6%-0.7%

Last unc. 13-15MeV ~0.7%-0.8%

Pu9f uncert. at ~1.5 slightly lower than at 14 MeV

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