Refining the low energy R-matrix fit of $^{13}C(\alpha,n)^{16}O$

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Technical Meeting on (alpha,n) Reaction Nuclear Data Evaluations and Data Needs, 27 November – 1 December, 2023 online

UNIVERSITY OF NOTRE DAME

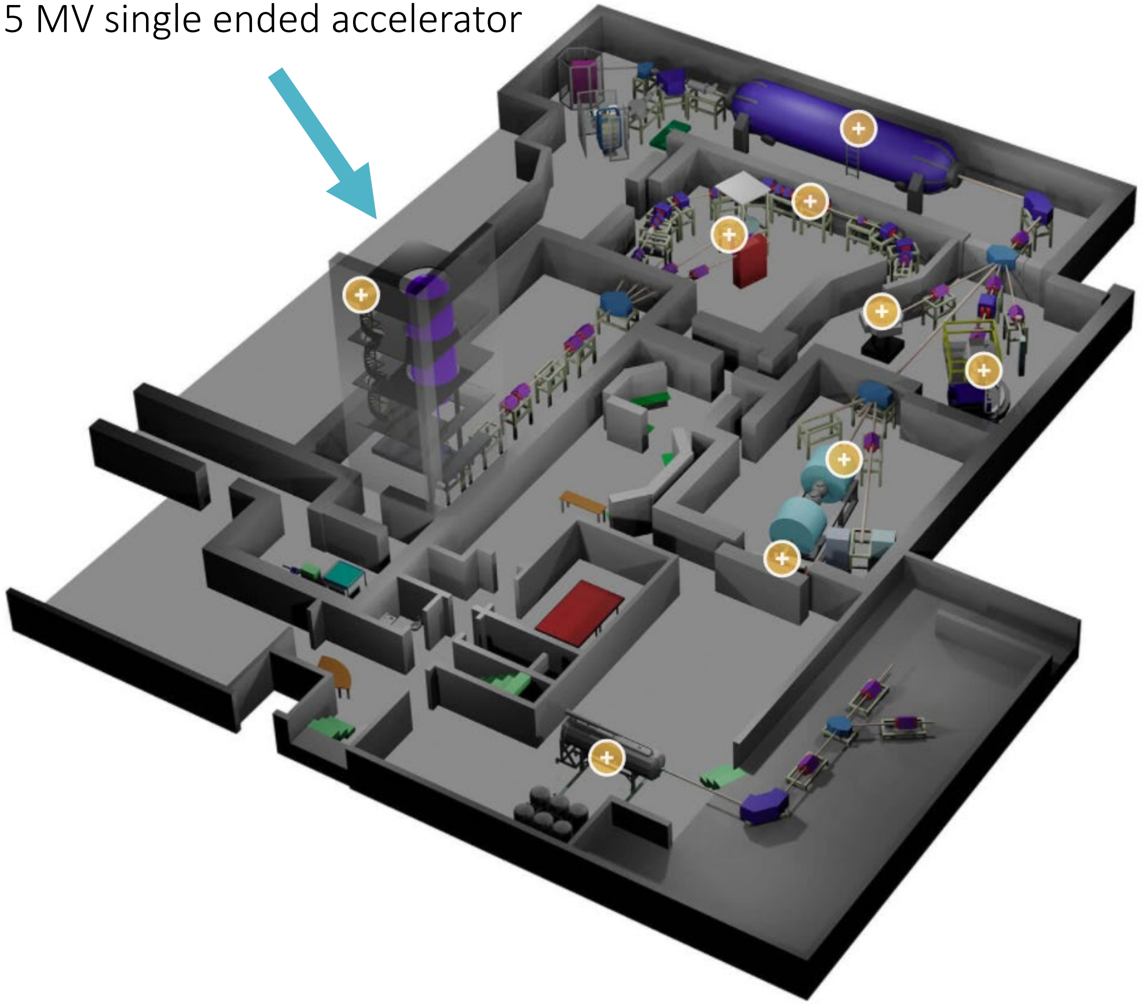
University of Notre Dame Nuclear Science Laboratory

Institute for Structure and Nuclear Astrophysics (isnap.nd.edu)

Three research accelerators

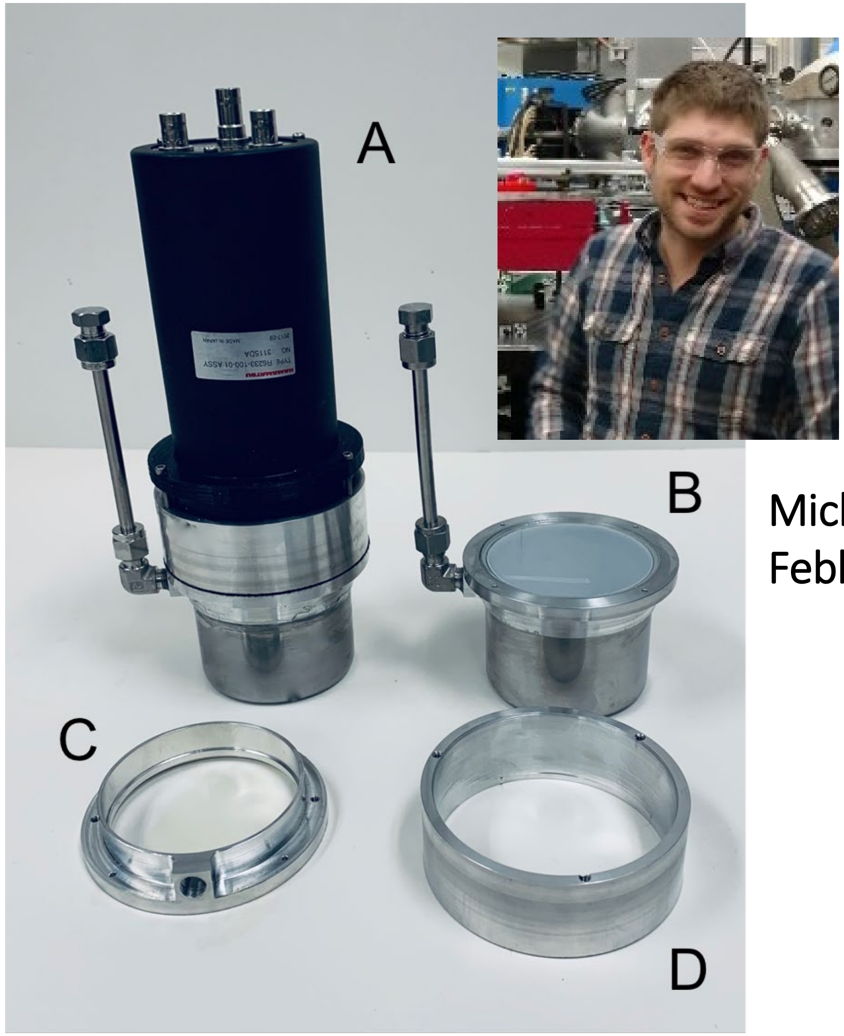
- 5 MV single ended
- High beam intensities of protons and alpha particles

5 MV single ended accelerator



Differential cross sections with ODeSA

- ORNL deuterated spectroscopic array (ODeSA)
- 9 **deuterated liquid scintillators** (one had issues)
- 1 EJ315
- 10’s of microamp beam intensity from ND 5U accelerator



Michael Febbraro

Spectrum unfolding

Experimentally determine detector response in separate calibration runs

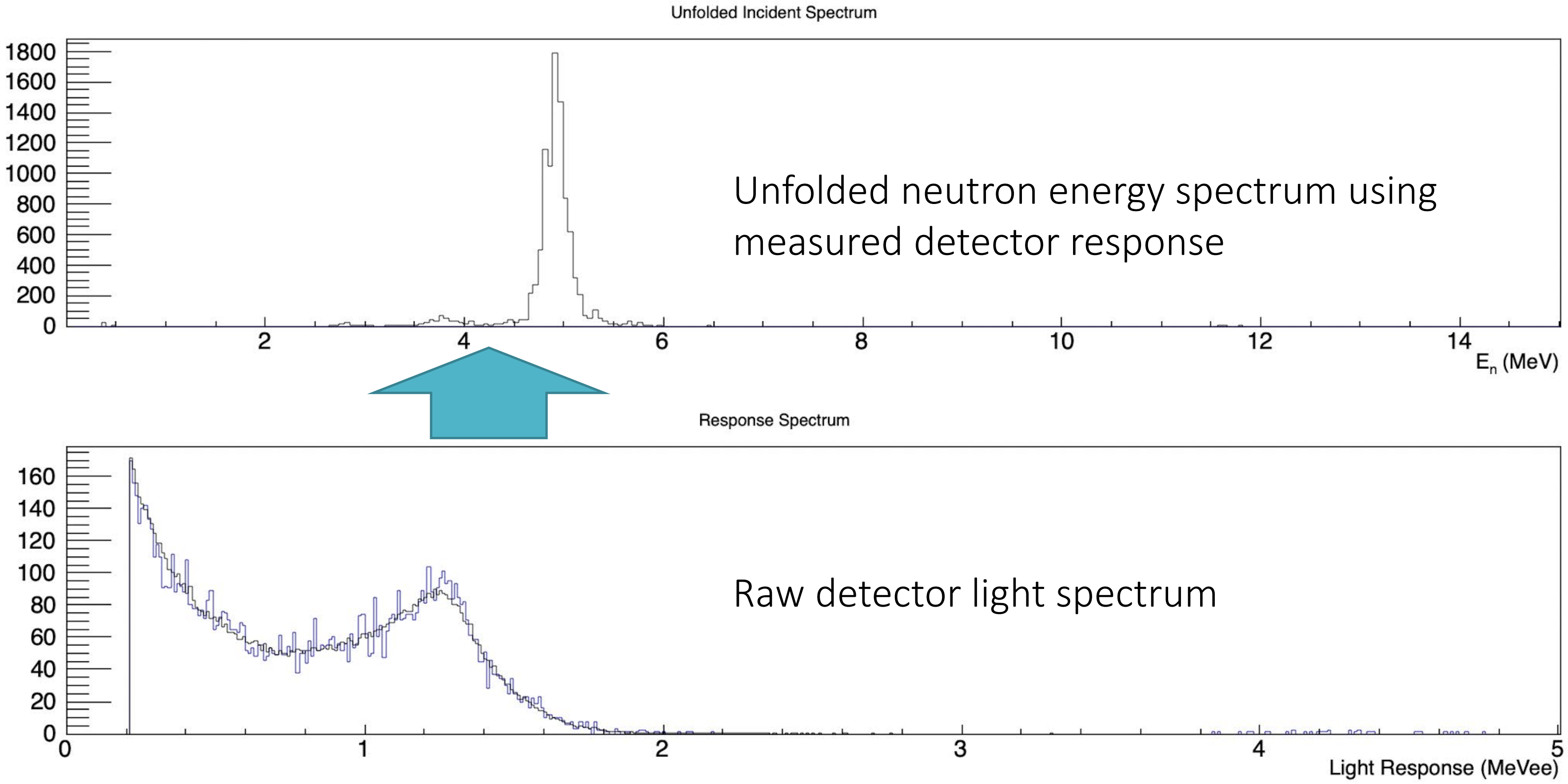
No time of flight information needed!

- No flight path distance restrictions

Very efficient measurements

Febbraro et al., NIM A **989**, 164824 (2021)

E_α = 2454 keV



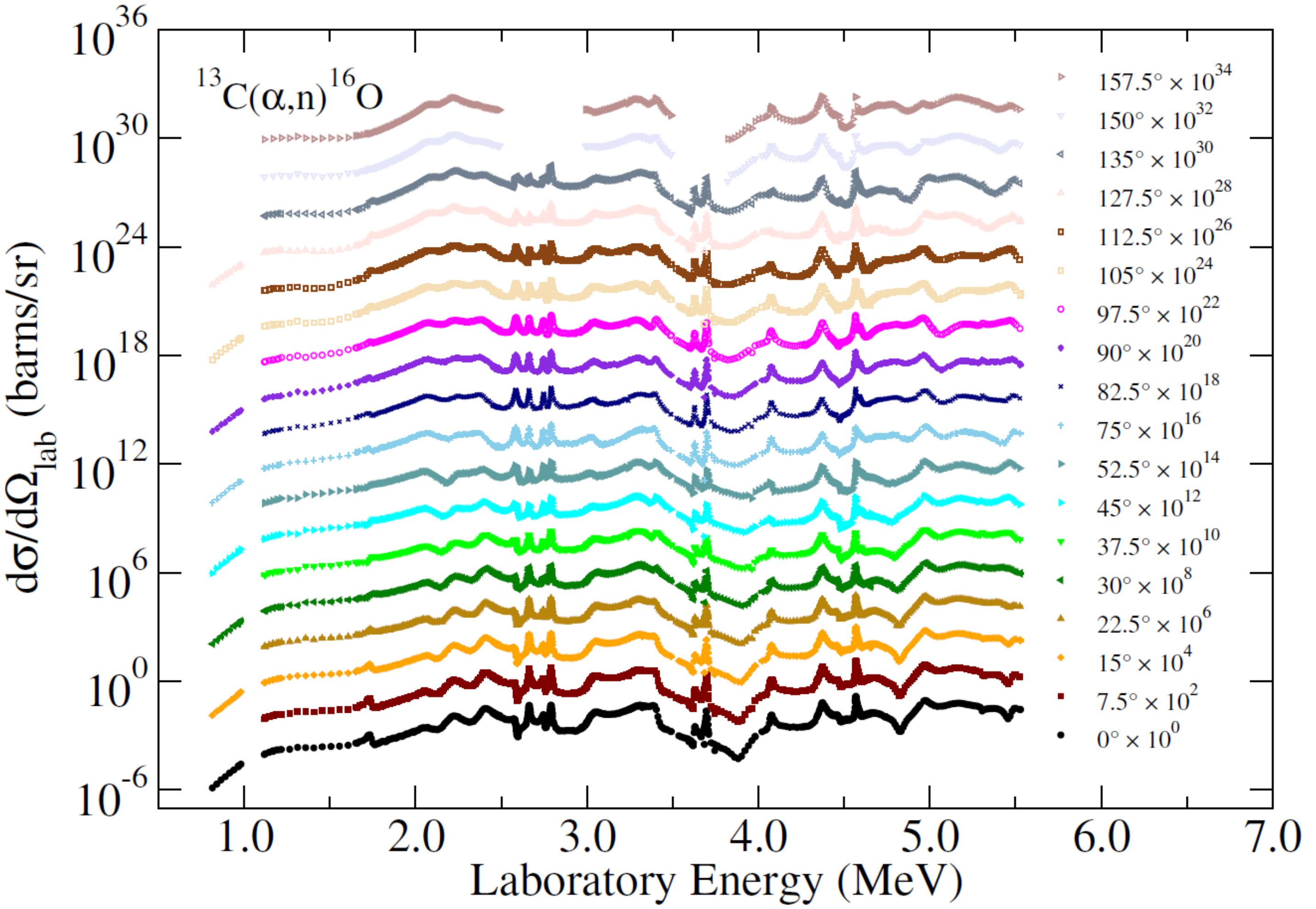
“Low energy” data set

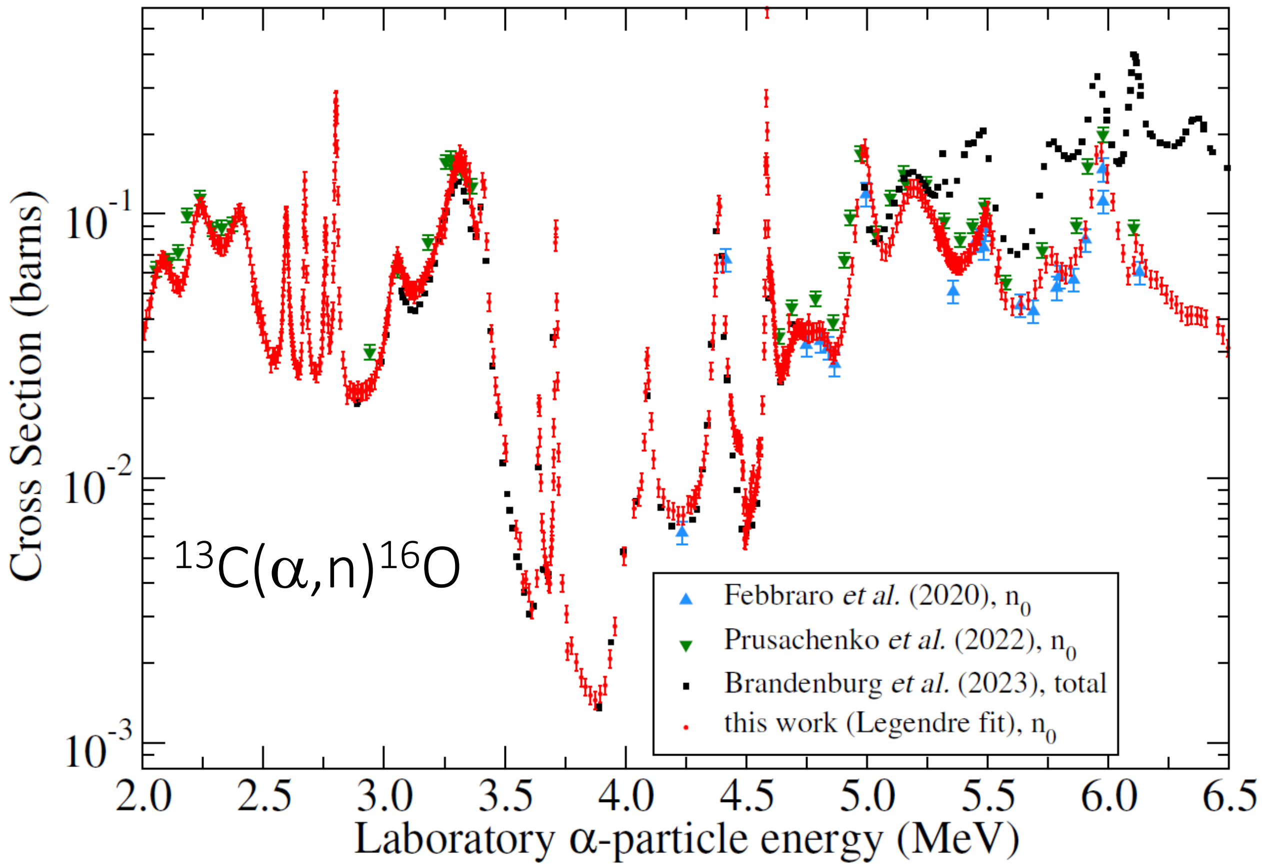
About 700 energies

18 point angular distributions for most of the data, 9 point for low energies below 1 MeV

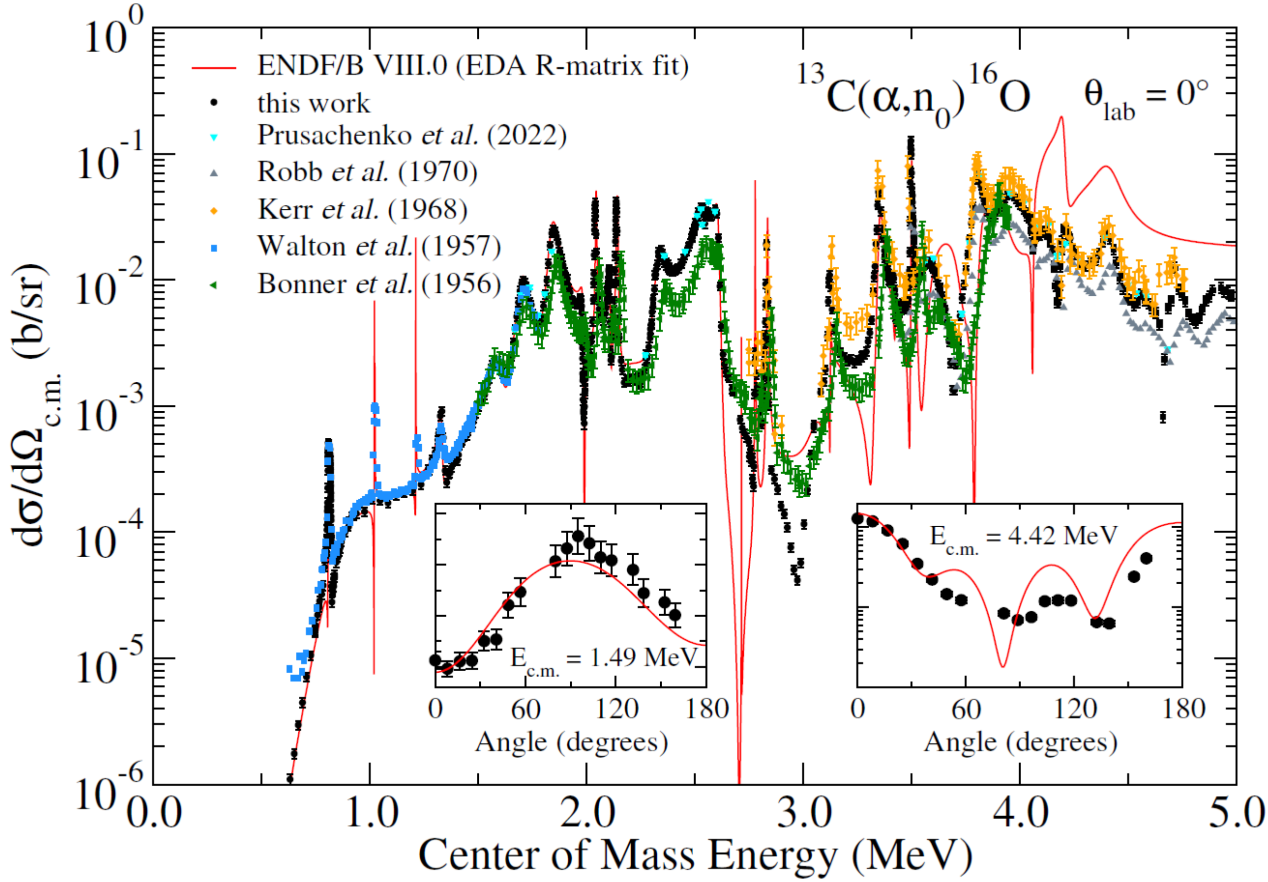
Measured at ND in 2020 and 2021

Currently under review



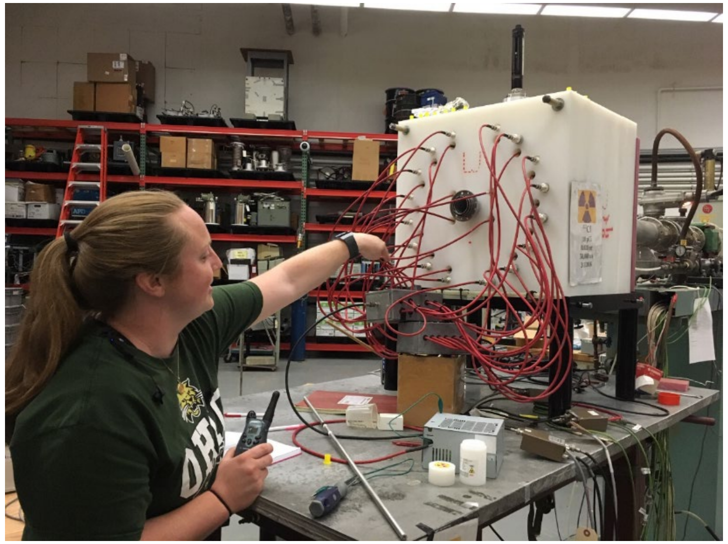


Cross Section (barns)
Laboratory α-particle energy (MeV)
13C(α,n)16O
Febbraro et al. (2020), n0
Prusachenko et al. (2022), n0
Brandenburg et al. (2023), total
this work (Legendre fit), n0

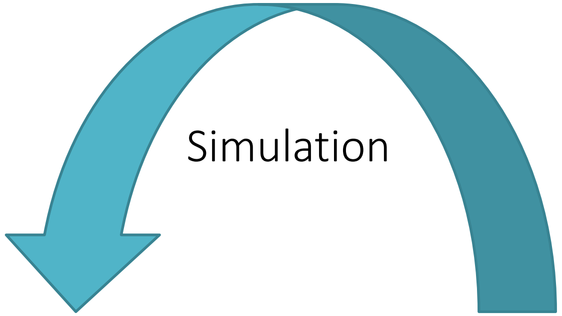


dσ/dΩc.m. (b/sr)
Center of Mass Energy (MeV)
13C(α,n0)16O
θlab = 0°
ENDF/B VIII.0 (EDA R-matrix fit)
this work
Prusachenko et al. (2022)
Robb et al. (1970)
Kerr et al. (1968)
Walton et al. (1957)
Bonner et al. (1956)
Ec.m. = 1.49 MeV
Ec.m. = 4.42 MeV
Angle (degrees)
Angle (degrees)

Problem: 4π doesn't really mean 4π



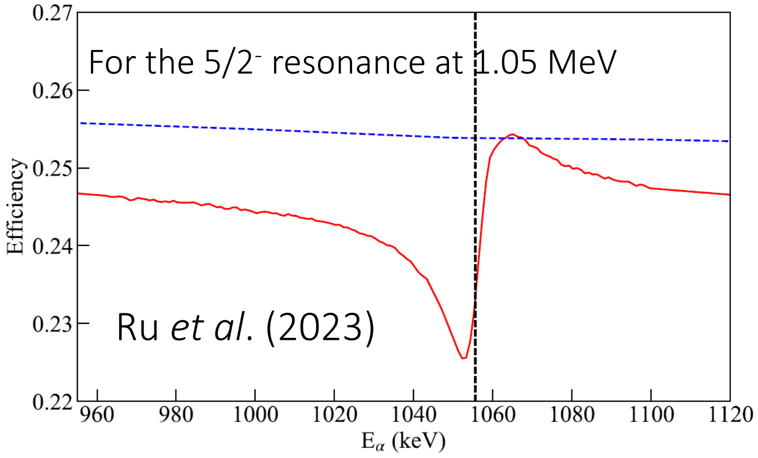
at Ohio University

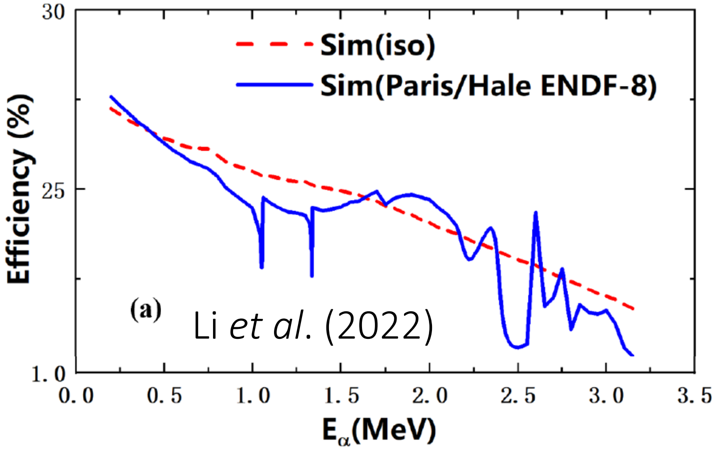


4π
measurements

Angular
distribution
measurements

10's of % deviations between isotropic and true angular distributions





From our last meeting, some problems

1) Energy calibration mismatch with n+^{16}O data

2) Large normalization factor (1.06) for the Cierjack's n+^{16}O total cross section data

3) Issues with data not being "low enough" in interference dip regions

4) Can't fit a narrow resonance in the n+^{16}O Cierjack's data

5) Uncertainties were not correct for the Bair and Haas data I was using!

Thanks to Gerry Hale for pointing out most of these issues

The 8.465 MeV state

TUNL nuclear data compilation says this may be a 9/2+ state

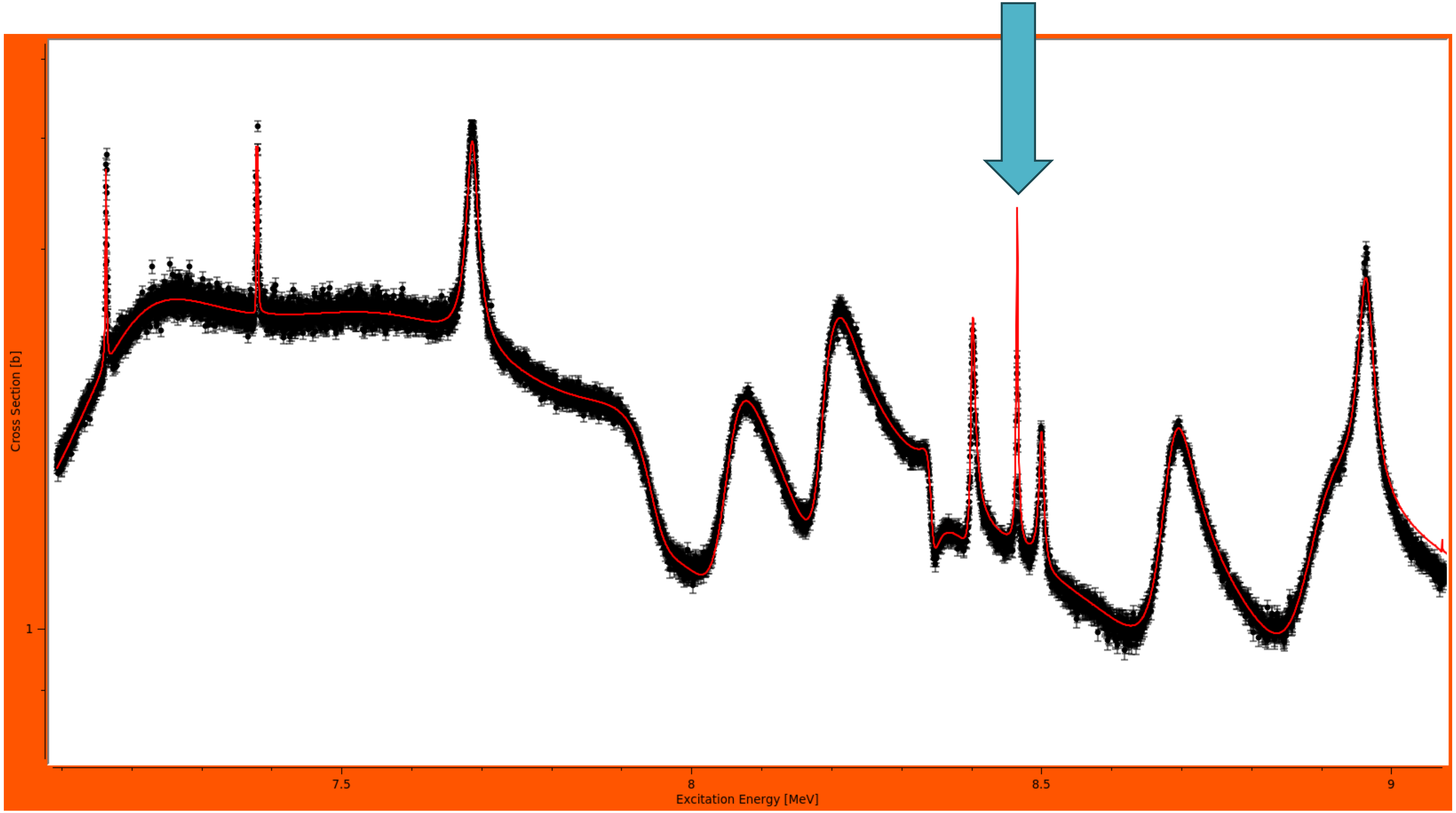
Issues

1) TUNL compilation only lists one state, but there are actually two.
2) 9/2+ gives a peak that is much too large
3) (a,n) data constrains this state to have a very small Γ_α

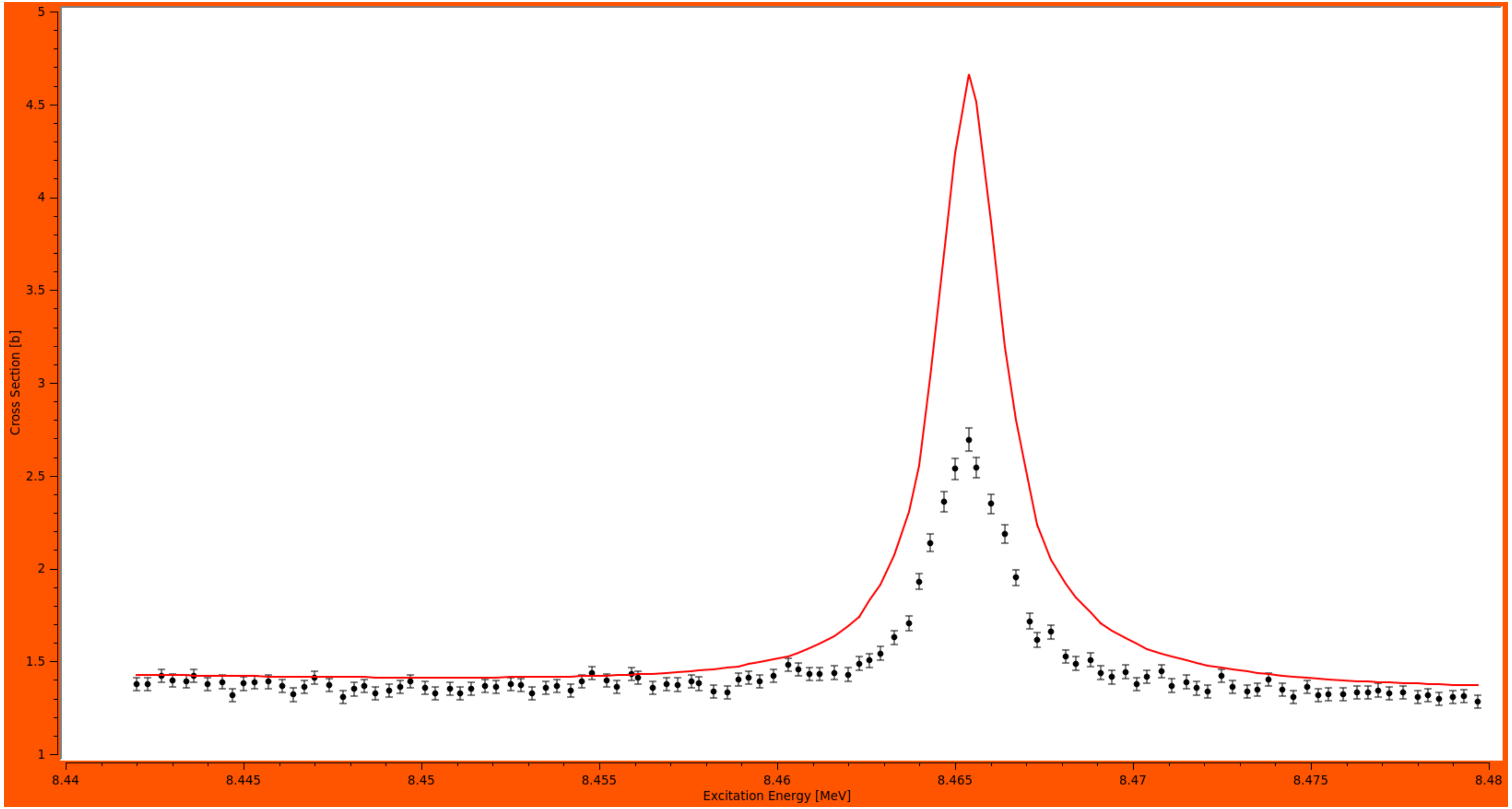
Table 17.10 from (1993TI07): Energy levels of ^{17}O (continued)

E_x in ^{17}O (MeV ± keV)	$J^\pi; T$	τ_m or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
8.070 ± 10	$\frac{3}{2}^+$	85 ± 9	n, α	12, 28, 32, 35
8.200 ± 7	$\frac{3}{2}^-$	60	γ, n, α	12, 20, 28, 32, 35, 41, 54
8.3424 ± 0.9	$\frac{1}{2}^+$	11.4 ± 0.5	γ, n, α	12, 28, 32, 35, 42
8.4023 ± 0.8	$\frac{5}{2}^+$	6.17 ± 0.13	γ, n, α	8, 12, 13, 14, 28, 32, 35, 42
8.4660 ± 0.8	$(\frac{9}{2}^+)$ [f]	2.13 ± 0.11	(γ), n, α	7, 8, 12, 13, 14, 28, 32, 35, 42, 54
8.5007 ± 0.8	$\frac{5}{2}^-$	6.89 ± 0.22	γ, n, α	8, 12, 13, 14, 28, 32, 35, 41, 42
8.6870 ± 1.0	$\frac{3}{2}^-$	55.3 ± 0.6	γ, n, α	12, 28, 32, 35, 41, 54
8.885 ± 14 [b]	$\frac{7}{2}^-, \frac{9}{2}^-$	6	γ	42
8.897 ± 8	$\frac{3}{2}^+$	101 ± 3	n, α	8, 12, 13, 14, 28, 29, 32, 35, 42

The wider energy range



Zoom in



Cross Section [b]
5
4.5
4
3.5
3
2.5
2
1.5
1
8.44
8.445
8.45
8.455
8.46
8.465
8.47
8.475
8.48
Excitation Energy [MeV]

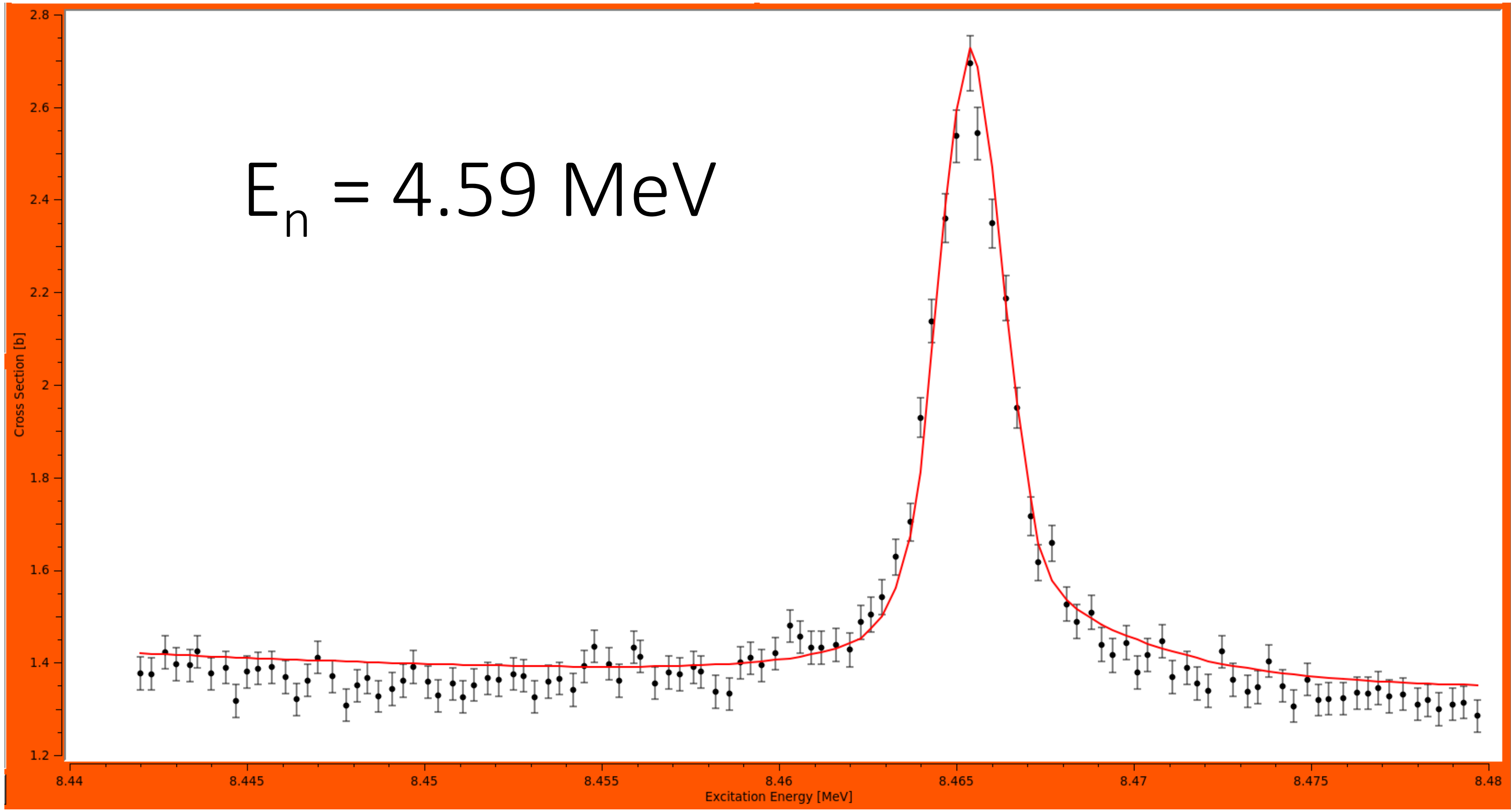
Resolution solution?

Decrease Γ_n from 2130 to 650 eV

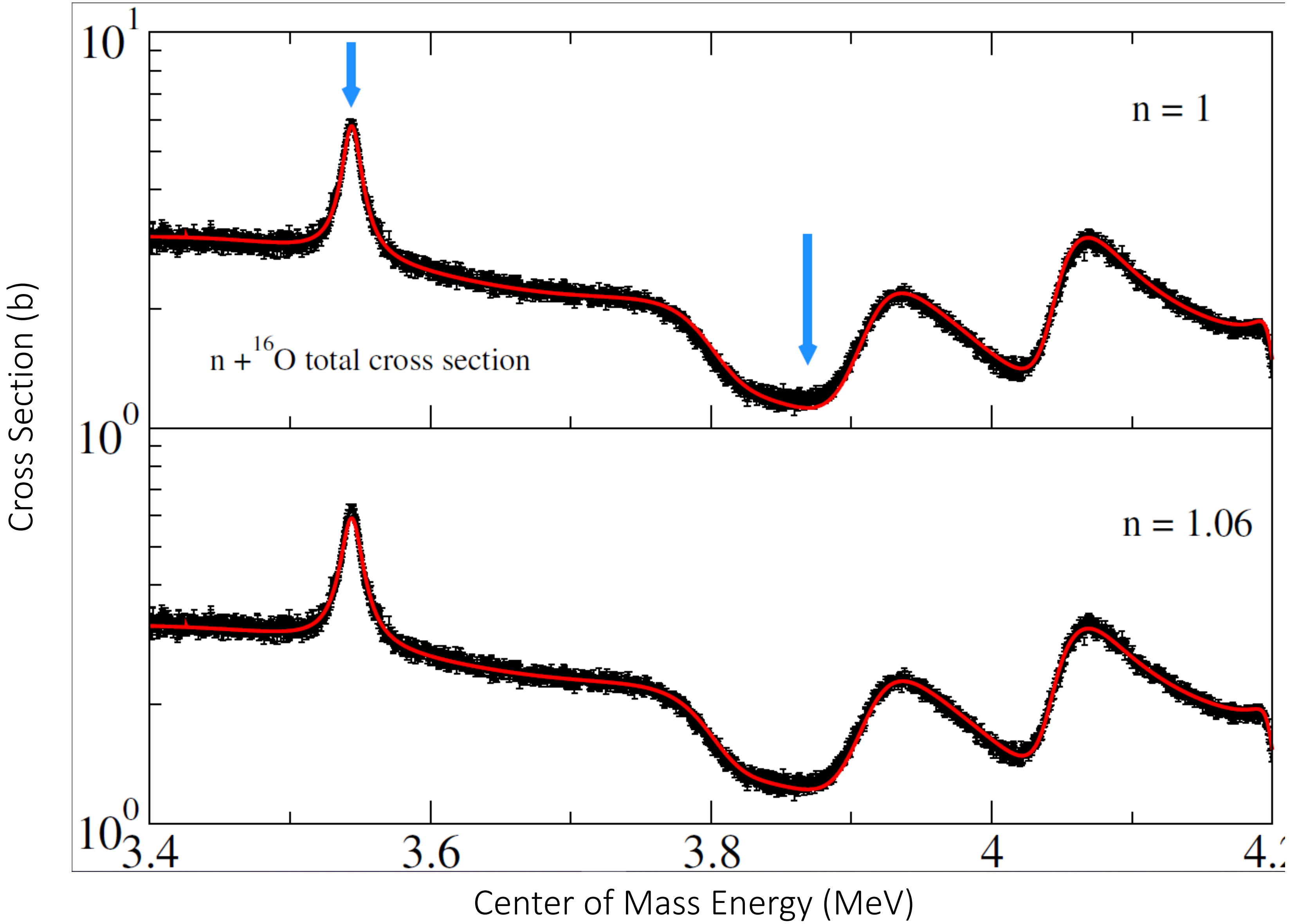
Convolute with a Gaussian resolution function with a sigma of 850 eV

From Cierjacks, dE (1sigma) = 630 eV @3 MeV

(right ball park)



Total cross section fitting issue



EDA compromise is 1.03

Total cross section fitting issues

If I fix the total cross section in the fit to its nominal normalization value, it results in a 10% larger overall all normalization for the $^{13}C(\alpha,n)^{16}O$ data than if I let it vary in the fit and go to a value of 1.06

This requires the ND data to be normalized up by about 10%, which is fine, well within their 13% systematic uncertainty

I think that the n+^{16}O data are probably correct but I don’t know why the fit is a bit off in this off-resonance region then

LANL uses a normalization of 1.03, which I also find to be some kind of compromise as well between the fit of the $^{16}O(n,\text{total})$ and $^{13}C(\alpha,n)^{16}O$ data

Energy calibration mismatch

Previously I had found an energy mismatch between the new ND $^{13}C(\alpha,n)^{16}O$ data and the Cierjack's $n+^{16}O$ data of 7 keV

I thought the ND energy calibration was correct, but I found that it was not!

Technical problem: new NMR probes in analyzing magnet

Talking with Xiaodong Tang I also found that their new $^{13}C(\alpha,n)$ data are in good agreement energy wise with the Cierjack's data

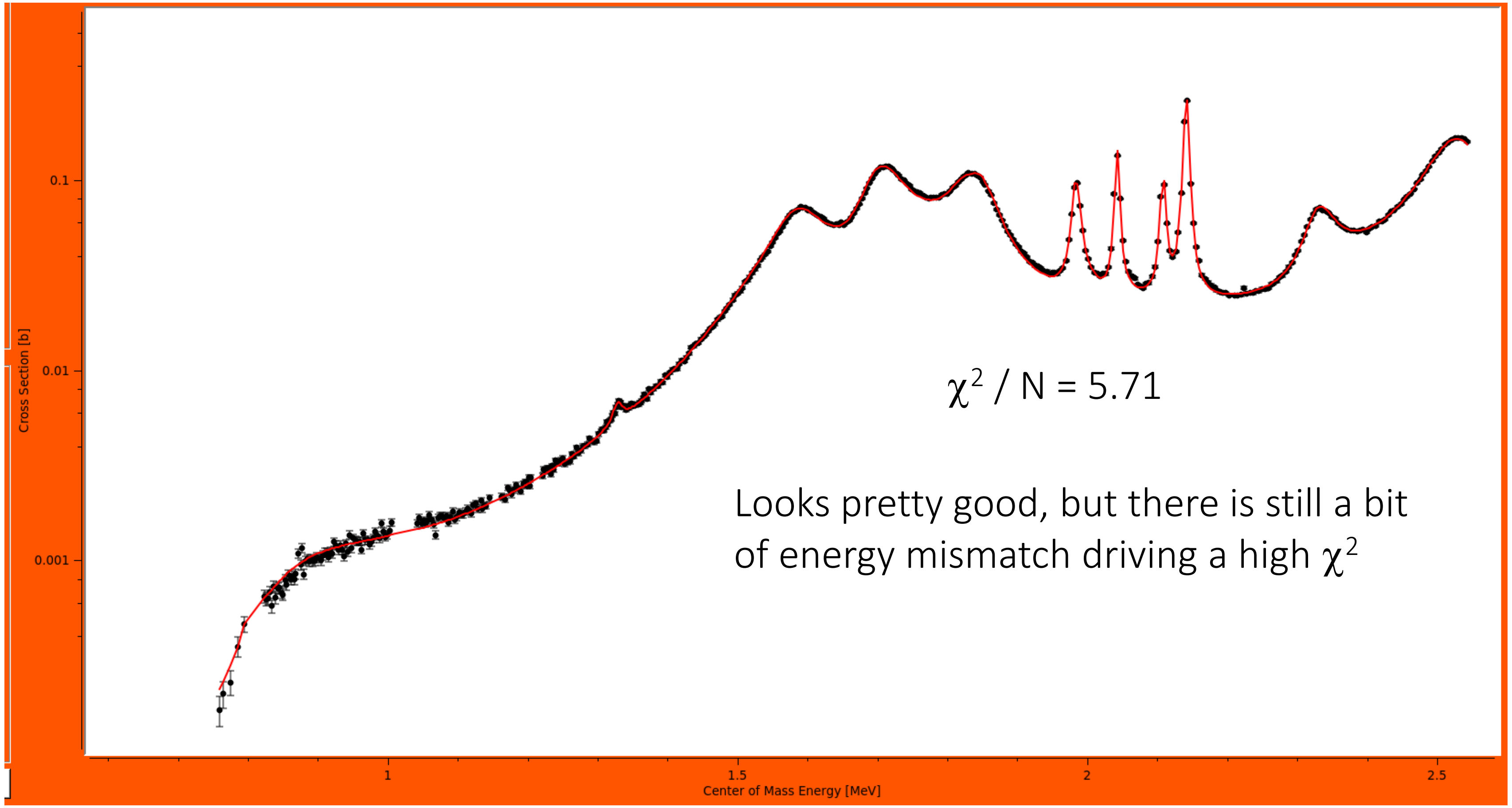
ND data have been recalibrated using narrow resonances in the Cierjack's data

Ended up being a shift of around 5 keV actually

Bair and Haas data

I had accidently included the systematic uncertainty in the point to point errors!

With the new energy calibration and a small energy shift, I get a pretty good fit to Bair and Haas



Bair and Haas uncertainties

Are they realistic?

Uncertainties are sub 1% over some energy ranges

Recent simulations of 4π neutron counters seem to indicate significant corrections could be needed

However, no one has simulated the ORNL large carbon moderator detector to my knowledge

A simple test of uncertainty inflation

- 1% → 2.71 χ^2/N
- 2% → 1.51 χ^2/N
- 3% → 0.93 χ^2/N

Minimum uncertainties of between 2 and 3% do not seem unreasonable given recent simulation studies

Total cross section effect on low energy $^{13}C(\alpha,n)^{16}O$ fit

The fit changes quite a bit

Cierjacks, 1.39 → 1.90

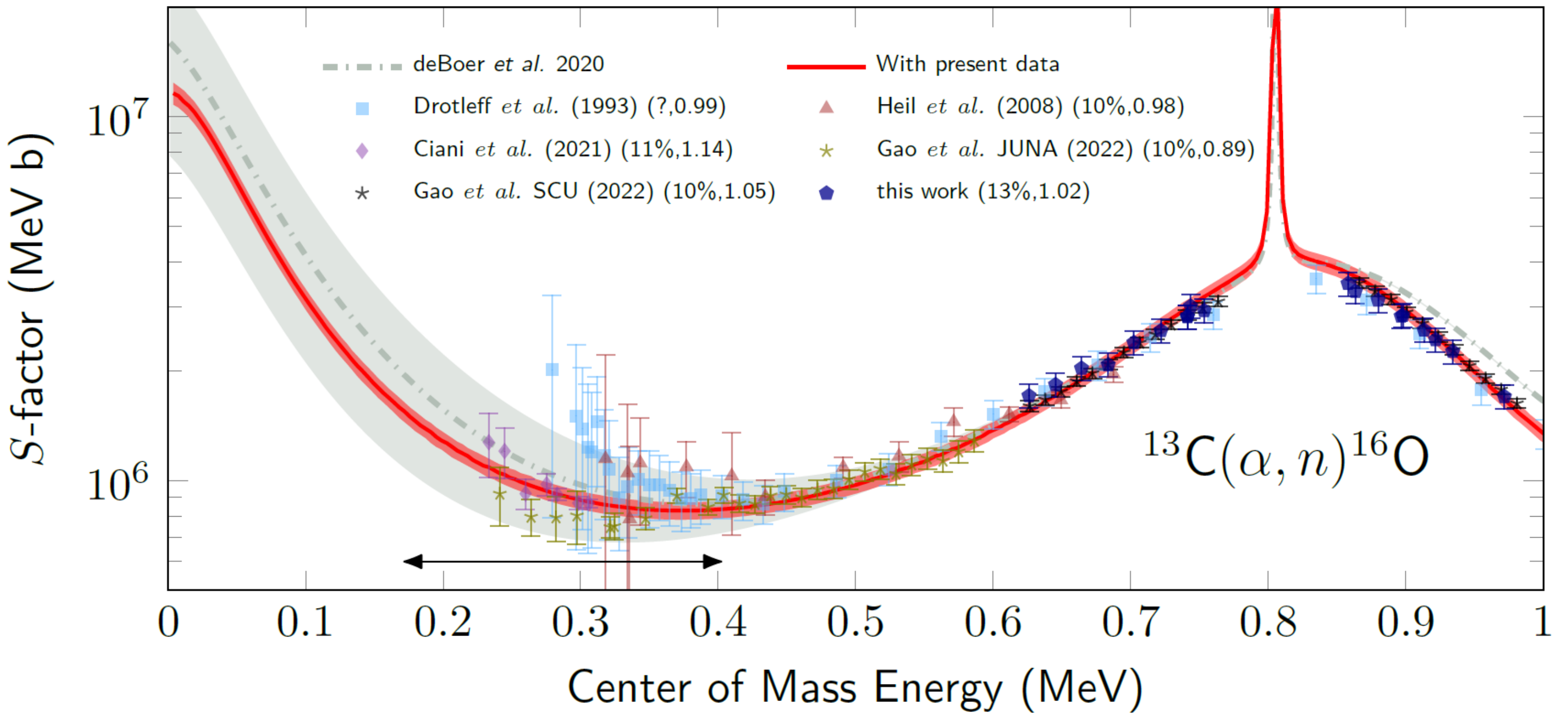
Drotleff, 0.85 → 1.69

Heil *et al.*, 1.24 → 1.64

Gao *et al.* (JUNA) 1.25 → 1.22

Gao *et al.* (SCU) 2.97 → 2.18

Ciani *et al.* (LUNA) 3.02 → 2.71



Some fits get better and some get worse…

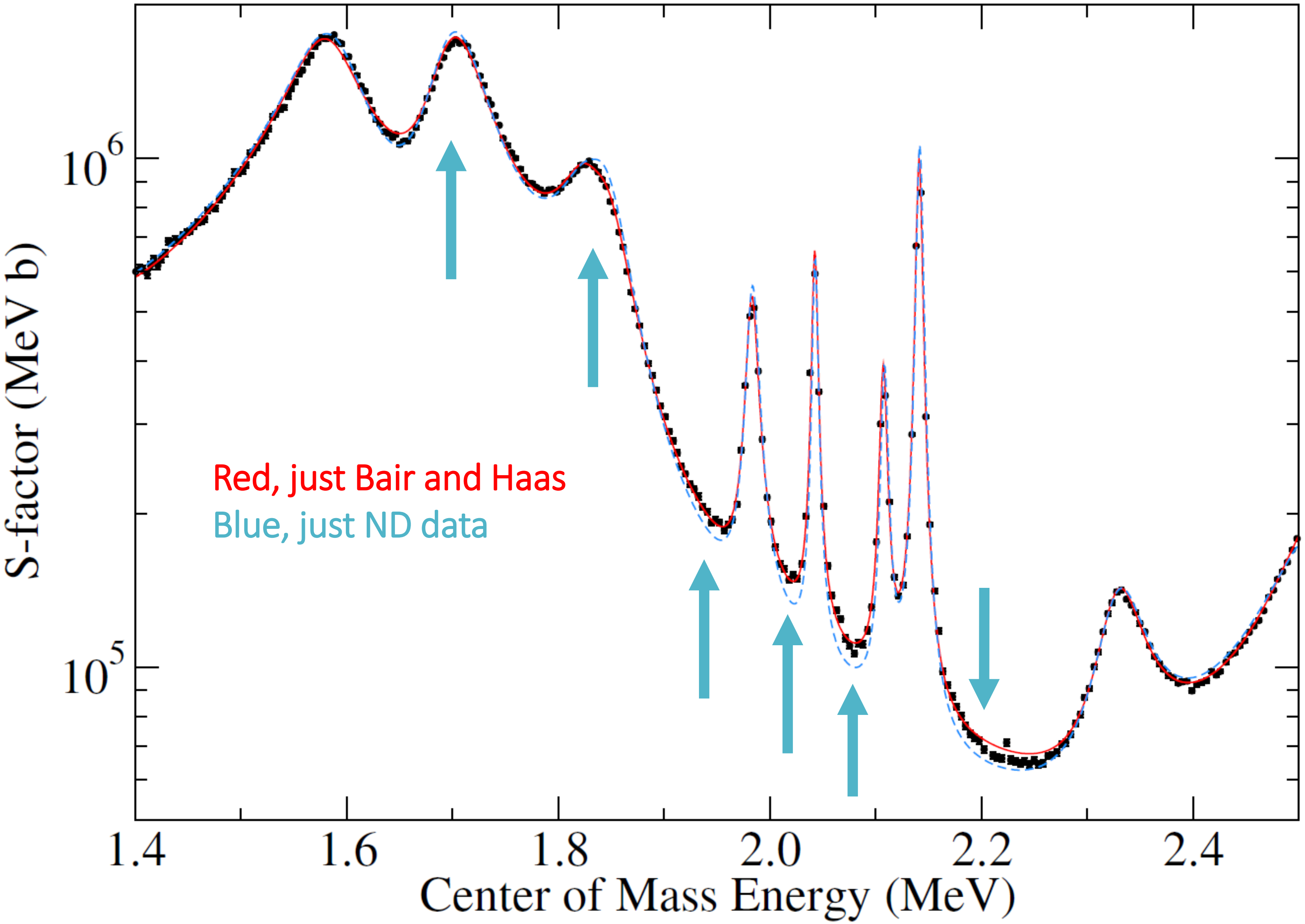
Since different data sets cover different energy ranges. This seems to point to a change in the energy dependence of the fit

Bair and Haas causes a lot of tension

ND data

No B&H → B&H 3% → B&H as is

2.45 → 2.88 → 3.24
2.23 → 2.48 → 2.86
1.07 → 1.34 → 1.69
1.97 → 2.09 → 2.34
1.11 → 1.14 → 1.39
2.23 → 1.92 → 2.02
1.18 → 1.14 → 1.46
1.76 → 1.33 → 1.55
1.31 → 1.01 → 1.16
2.02 → 1.91 → 2.11
1.46 → 1.46 → 1.66
1.53 → 1.51 → 1.65
0.99 → 0.87 → 0.84
1.70 → 1.91 → 1.94
1.28 → 1.39 → 1.35
1.85 → 2.03 → 2.07
0.941 → 1.29 → 1.32
1.60 → 2.06 → 2.28



ANGULAR DISTRIBUTION EFFECTS

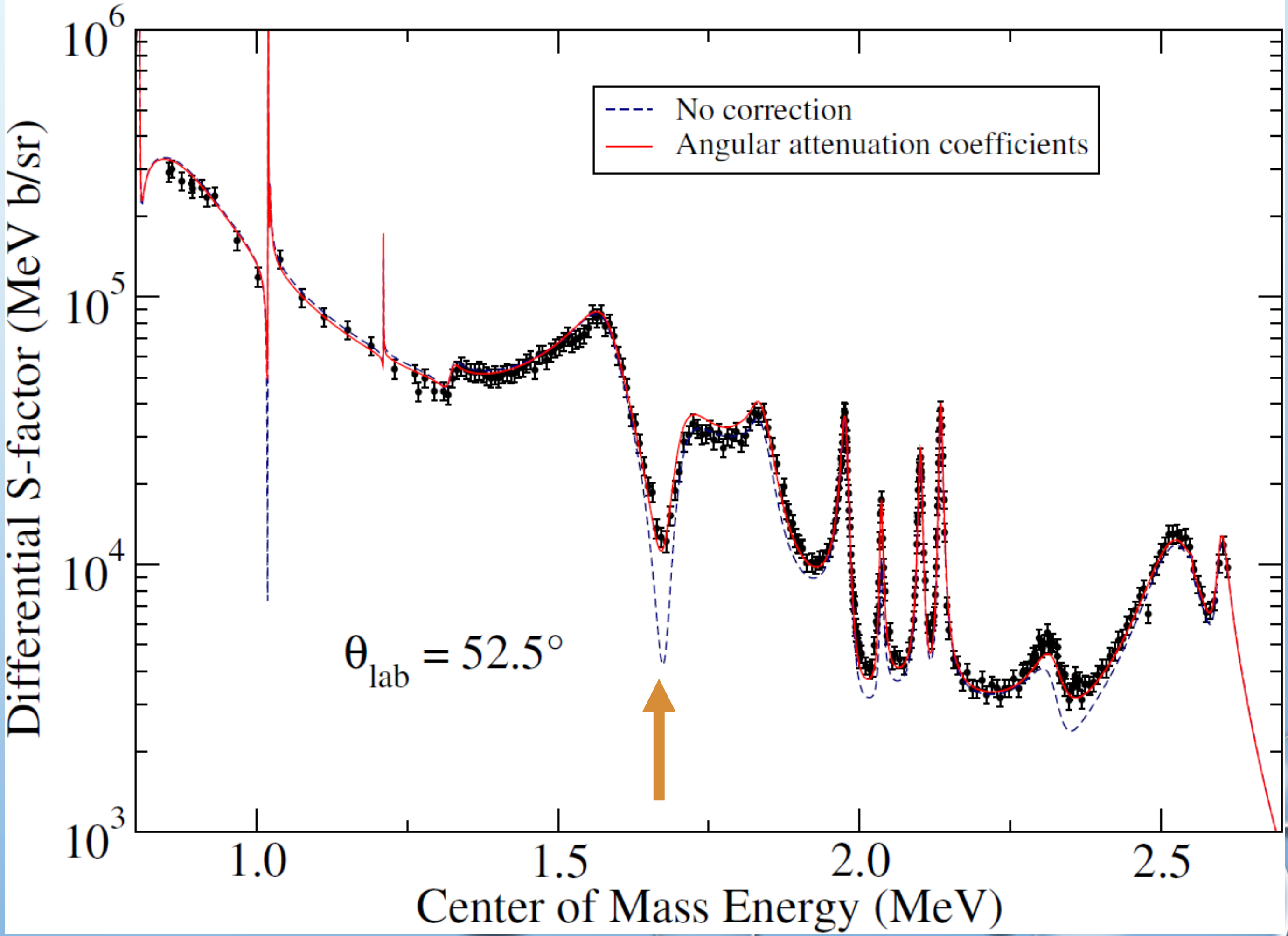
- EACH DETECTOR COVERS ABOUT 7 DEGREES (3 IN DIAMETER, 2 FEET FROM TARGET)

- THIS SEEMS TO BE QUITE SIGNIFICANT BECAUSE THERE ARE PLACES WHERE THE CROSS SECTION CHANGES VERY RAPIDLY WITH ANGLE

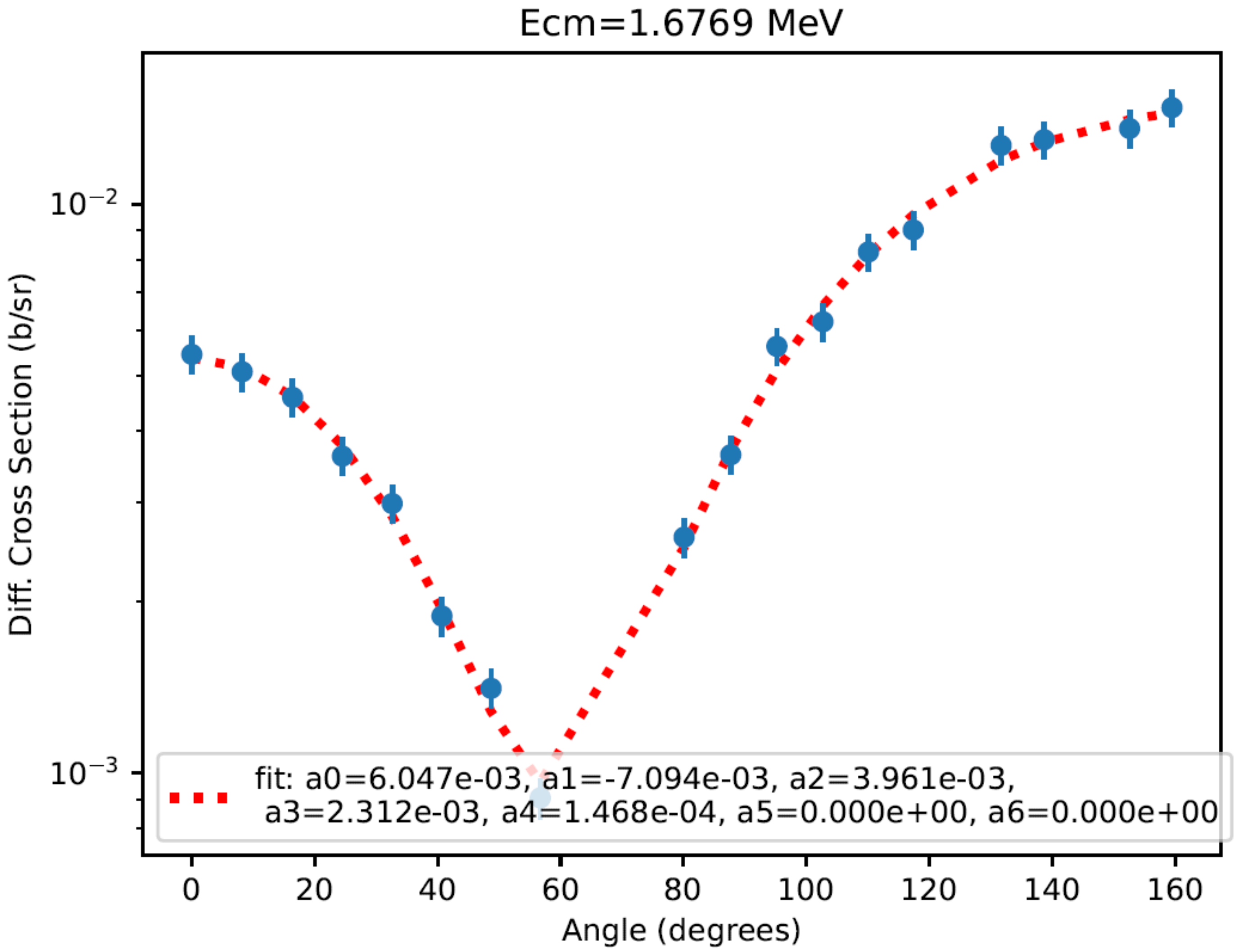
$$W(\theta) = \sum_i a_i Q_i P_i(\cos(\theta))$$

Angular attenuation coefficients

$a_i = 1,\ 0 < a_i < 1,\ a_i > a_{i+1}$



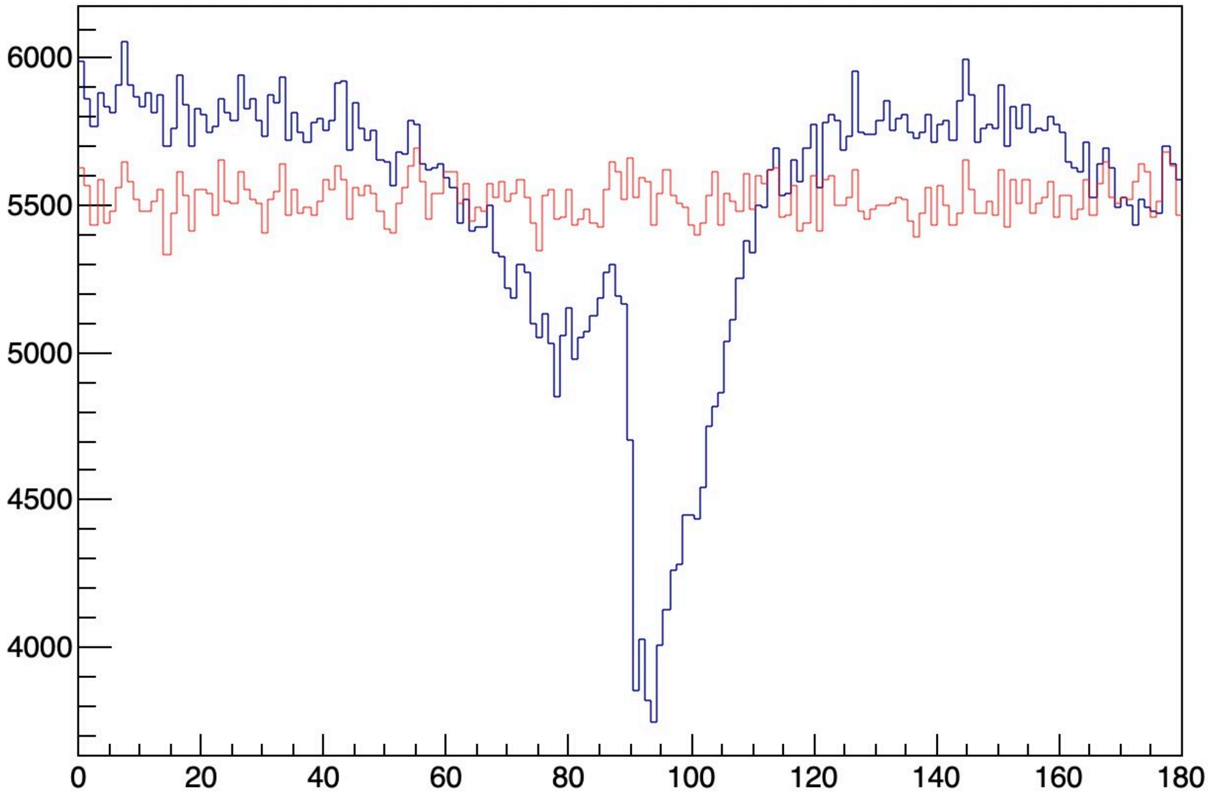
Angular distribution



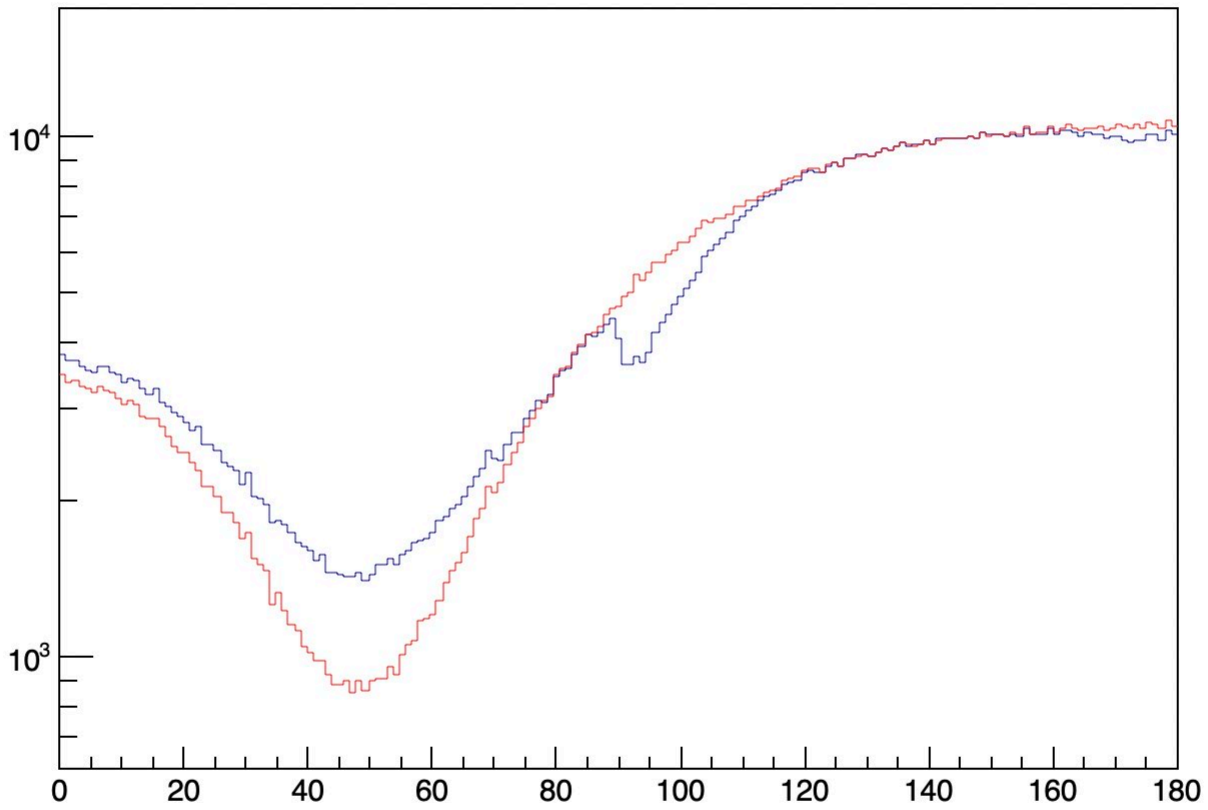
MCMP simulations

Blue, with target holder

Red, without target holder



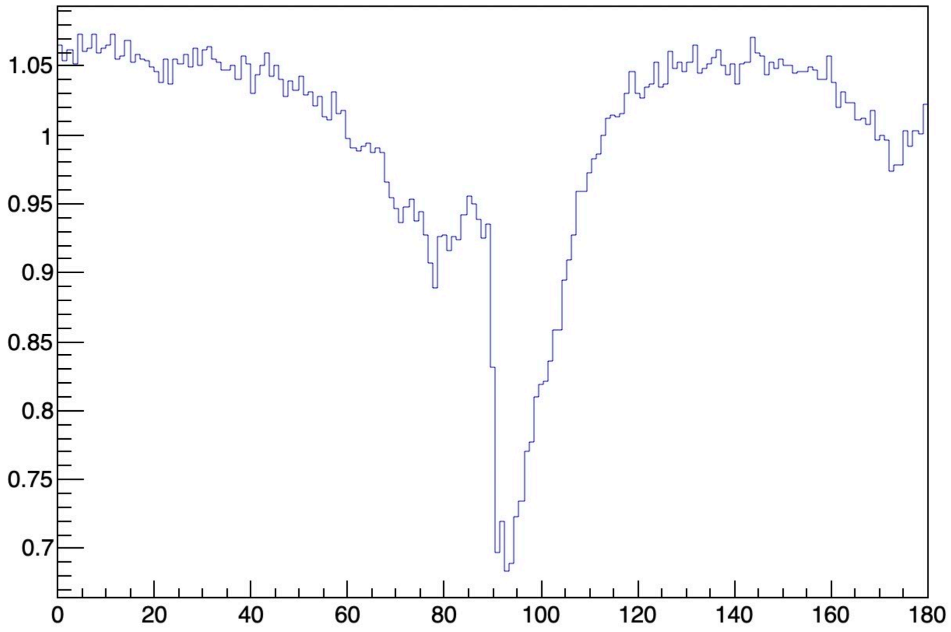
Isotropic distribution



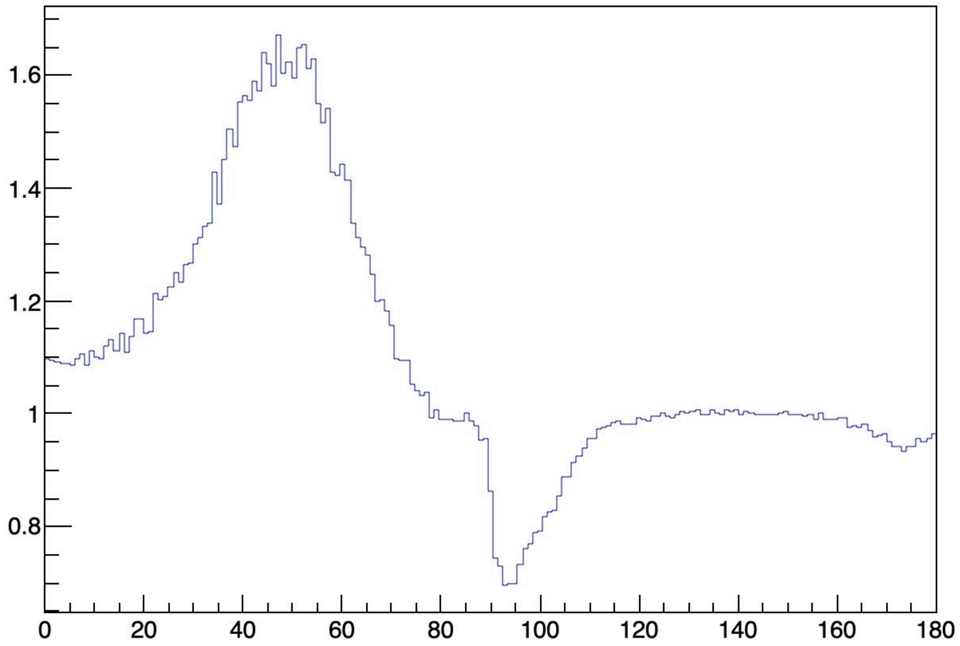
anisotropic distribution from R-matrix w/o attenuation

Neutron scattering

MCNP, isotropic distribution



MCNP, anisotropic distribution



Conclusions

I'm still getting a lot of tension between Bair and Haas' $^{13}C(\alpha,n)^{16}O$ data and the Cierjack's total neutron cross section data

However, this tension exists because of the really small error bars assigned to these data sets. The tension is GREATLY alleviated if uncertainties are inflated to the 3% level

There is a strange energy dependence inconsistency as well between the $^{13}C(\alpha,n)^{16}O$ data and the ^{16}O(n,total) data. This inconsistency happens both on and off-resonance, making the source of the issue harder to understand for me.

The ND data seems to be in agreement with B&H on the 2-3% level, but not on the sub 1% level. This doesn't seem surprising to me at all considering the sensitivity of the B&H data to angular distributions and multiple scatting corrections for the ND differential data.

The ND has very significant effects from neutron scattering over some regions. I don't see how this can be "fixed", but we may be able to look at the angular distributions and then increase the uncertainties over low cross section regions.

In the (not so) long term we will go back and redo these measurements but with a lower mass target holder and chamber to reduce these effects (see Hye Young's talk).