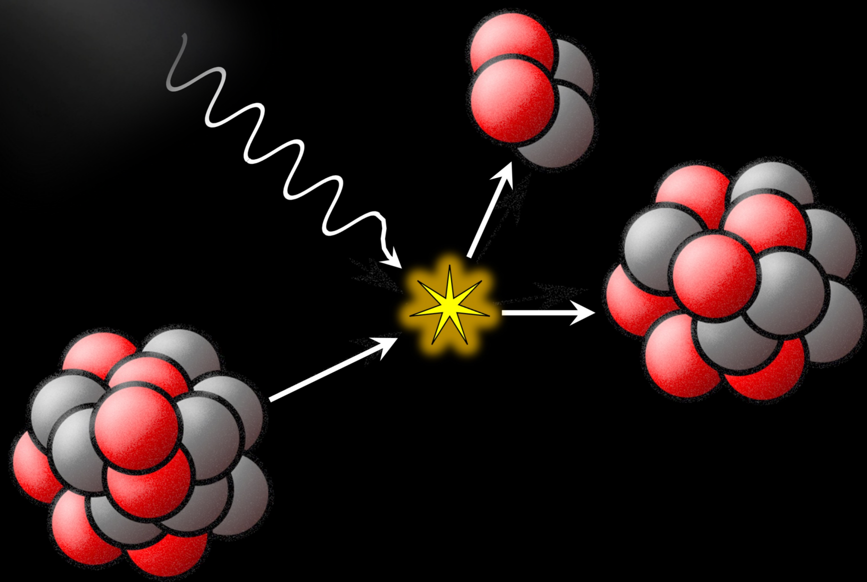
Shining a light on nuclear astrophysics with γ-beams at HIγS



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UK Nuclear Physics Community Meeting– 11th January 2023

Sheffield Hallam University

Overview

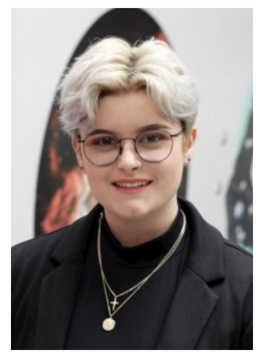
- Nuclear physics at Sheffield Hallam University
- Overview of HIγS facility
- Importance of $^{12}C(\alpha,\gamma)$ reaction in astrophysics
- Efforts to measure $^{12}C(\alpha,\gamma)$ using Optical TPC at HIγS
    - Published results and on-going analysis
- New measurements of $^{12}C(\alpha,\gamma)$ with a new electronic TPC
    - on-going analysis

Nuclear physics at Sheffield Hallam

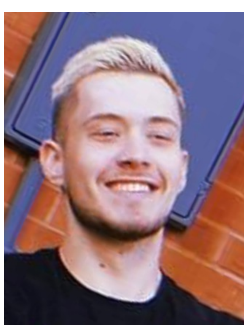
Robin Smith

Raed Dallal
New detector technologies

Ocean Wong
Neutron spectrum unfolding (UKAEA)



Olivia Tindle
Alpha particle clustering in light nuclei



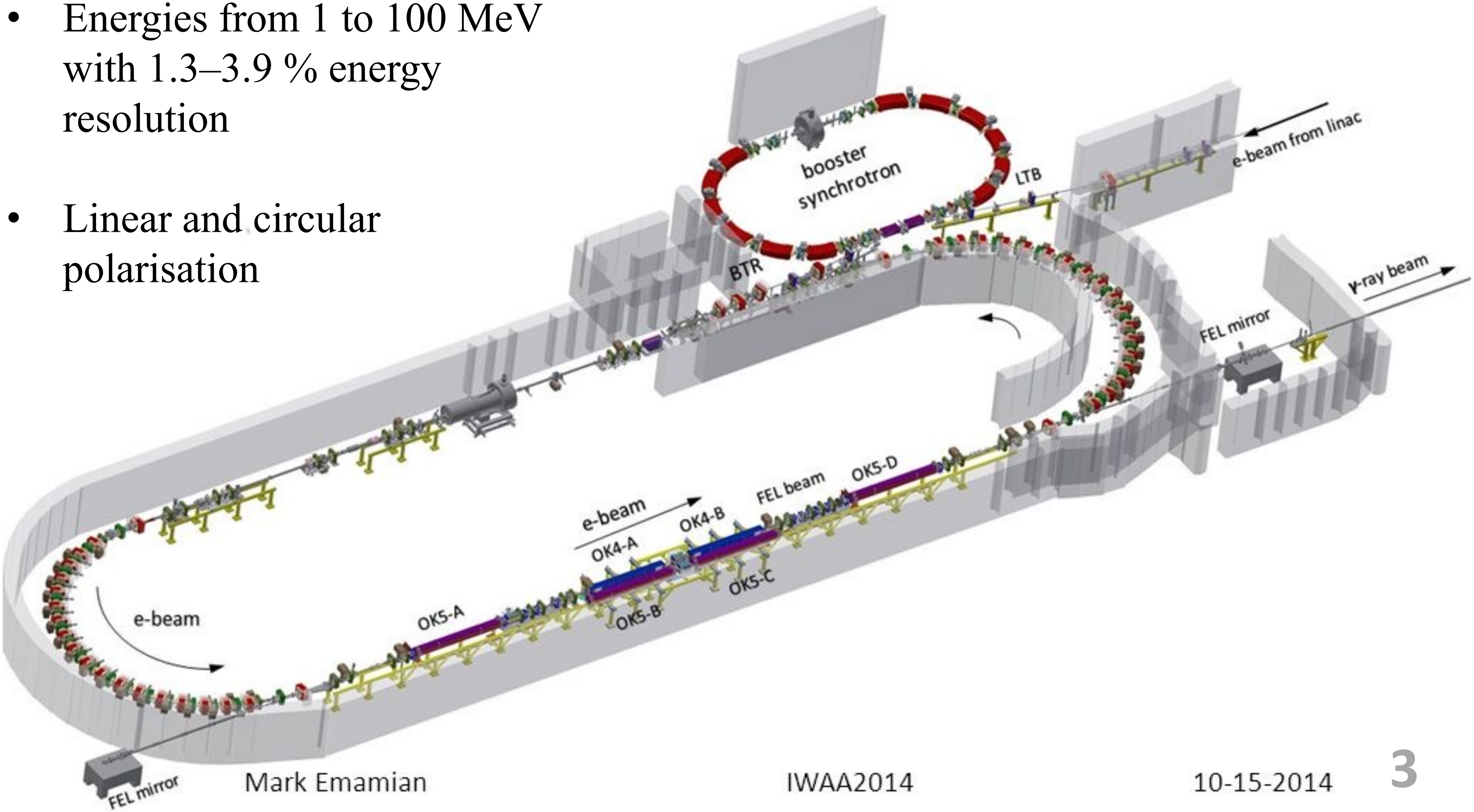
Kris Haverson
Nuclear structure & astrophysics with TPC detectors

Kimberley Lennon
Machine learning for improvements in gamma spectroscopy (UKAEA)

HIγS facility

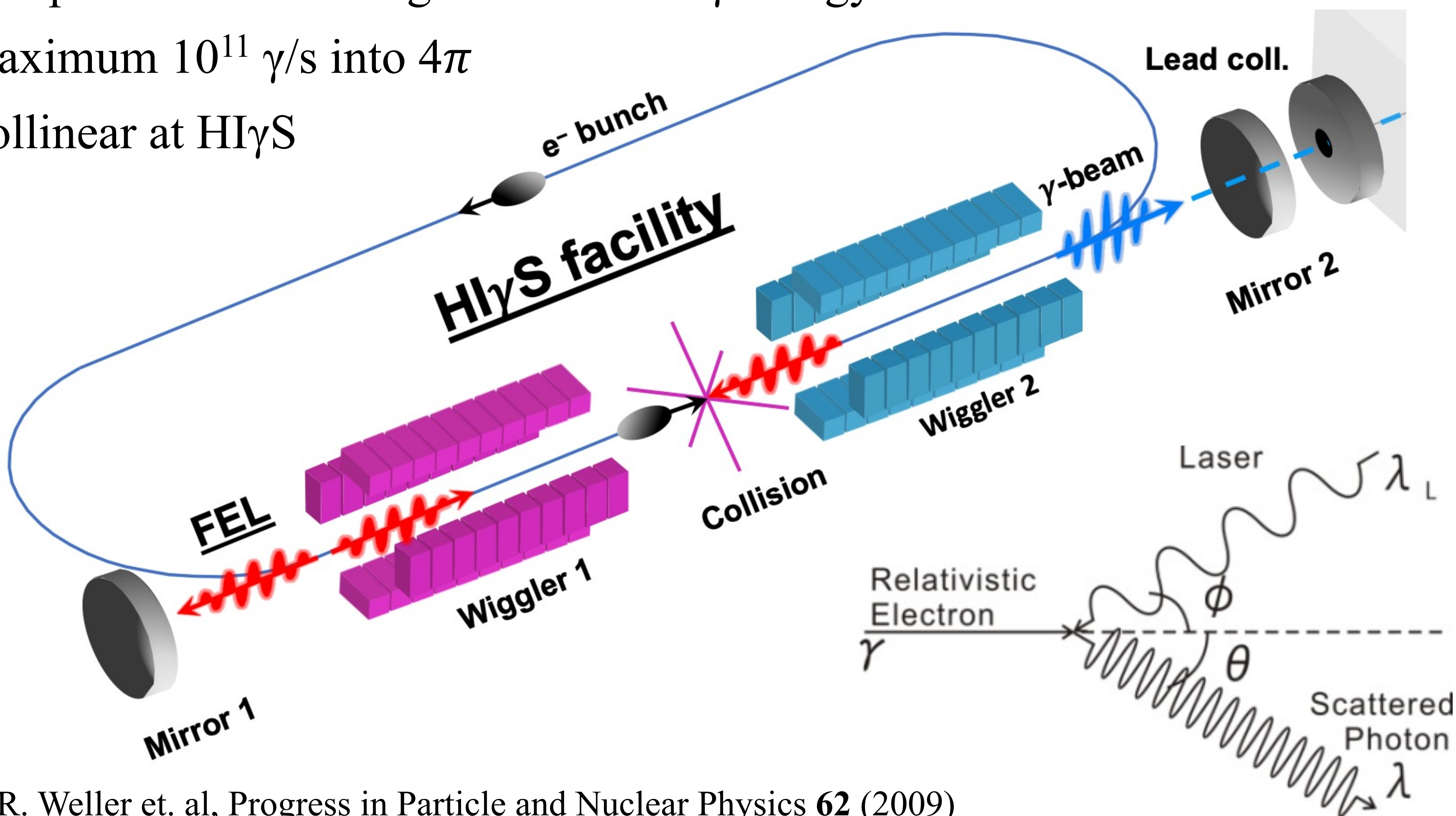
HIγS facility

- Quasi-monoenergetic γ-beams
- Energies from 1 to 100 MeV with 1.3–3.9 % energy resolution
- Linear and circular polarisation



HIγS facility

- Free electron laser – λ = 190 -1064 nm
- Compton backscattering increases the γ energy
- Maximum 10^{11} γ/s into 4π
- Collinear at HIγS



[1] H.R. Weller et. al, Progress in Particle and Nuclear Physics **62** (2009)
[2] A. Endo, Laser Pulses-Theory, Technology, and Applications. InTech, (2012)

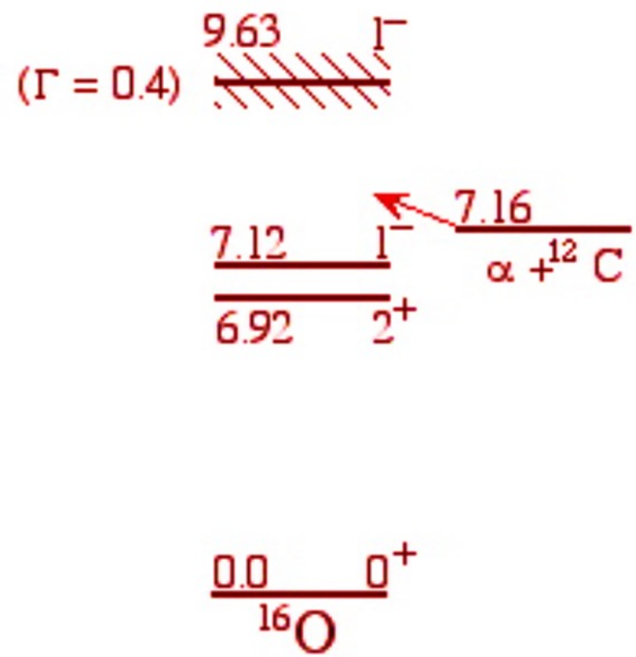
Stellar helium burning – $^{12}C(\alpha,\gamma)^{16}O$

- The ratio of carbon-to-oxygen after helium burning
  - Composition of White Dwarfs
  - Yield of intermediate-mass isotopes (C, Ne, O burning etc.)
  - Explosive burning – light curves of Type Ia supernovae
  - Final states of massive stars – Type II supernovae

Stellar helium burning – $^{12}C(\alpha,\gamma)^{16}O$

- The ratio of carbon-to-oxygen after helium burning
  - Cross sections for $3\alpha \rightarrow {}^{12}C$ and $^{12}C(\alpha,\gamma)^{16}O$

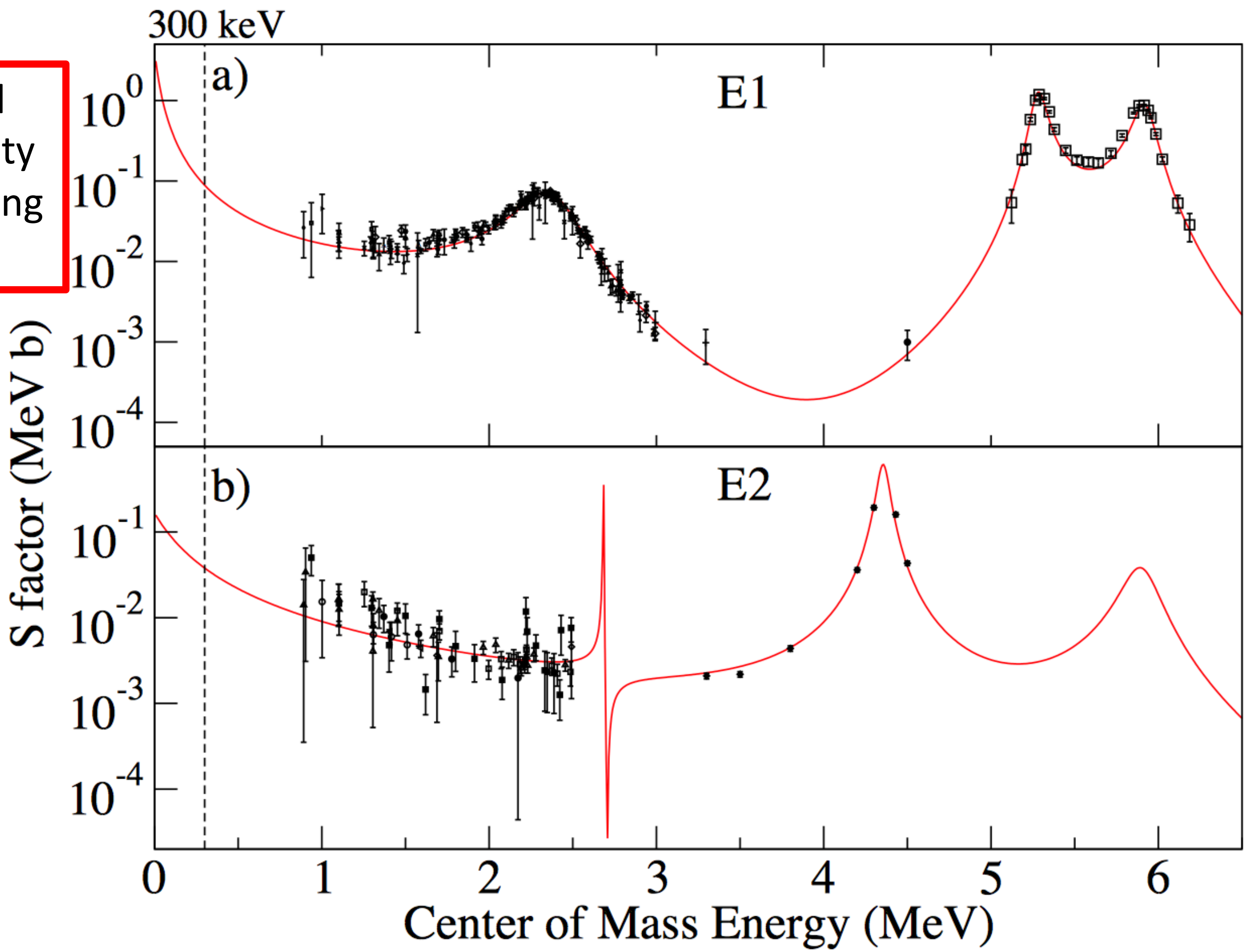
"The single most important nuclear physics uncertainty in astrophysics"



[3] W.A. Fowler, Rev. Mod. Phys. **56** (1984) 149.

Data evaluation efforts

Claimed uncertainty approaching 10%



[4] R. J. deBoer et. al, The $^{12}C(\alpha,\gamma)^{16}O$ reaction and its implications for stellar helium burning, Rev. Mod. Phys. **89** (2017)

New method: $^{16}O(\gamma,\alpha)^{12}C$

- Measure reverse process – photodissociation of ^{16}O inside active target detector

- The γ-beam excites ^{16}O target to a known energy

- Measure the angular distributions of the emitted ^{12}C and α from the break-up – Time Projection Chamber

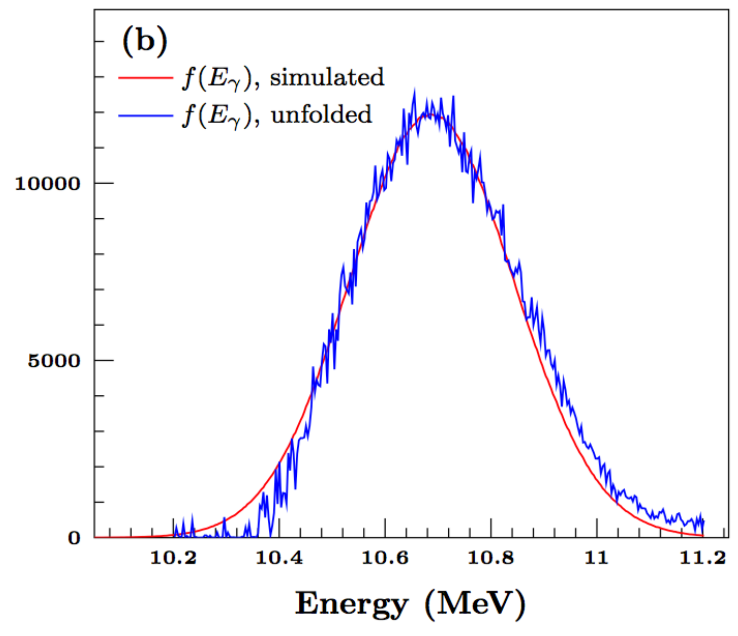
Method: $^{16}O(\gamma,\alpha)^{12}C$

- Advantages
  - Higher cross section – detailed balance
  - Ability to measure precise angular distributions with TPC

Method: $^{16}O(\gamma,\alpha)^{12}C$

- <u>Advantages</u>
  - Higher cross section – detailed balance
  - Ability to measure precise angular distributions with TPC

- <u>Disadvantages</u>
  - $\sigma = 130$ keV γ energy resolution
  - Uncertainty in beam flux
  - Rate in TPC



$^{16}O(\gamma,\alpha)^{12}C$ with an Optical TPC

- Proof-of-principle experiment
- Optical TPC operating with **$CO_2 + N_2$** gas mixture
- Focused on higher energy region $E_{cm} = 2 – 3.5$ MeV
  - cross section is higher and shapes of angular distributions vary significantly

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ARTICLE

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https://doi.org/10.1038/s41467-021-26179-x

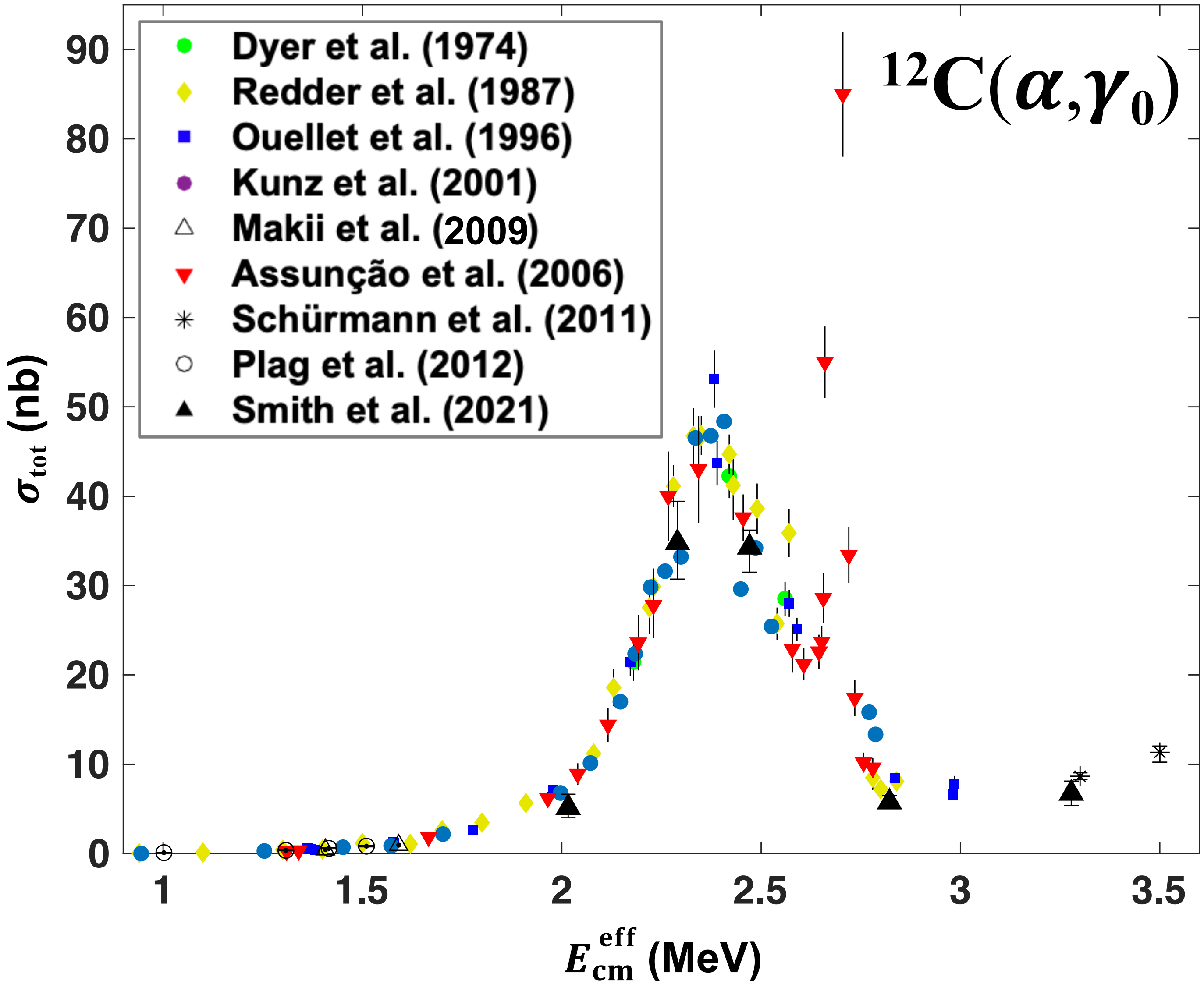
OPEN

Precision measurements on oxygen formation in stellar helium burning with gamma-ray beams and a Time Projection Chamber

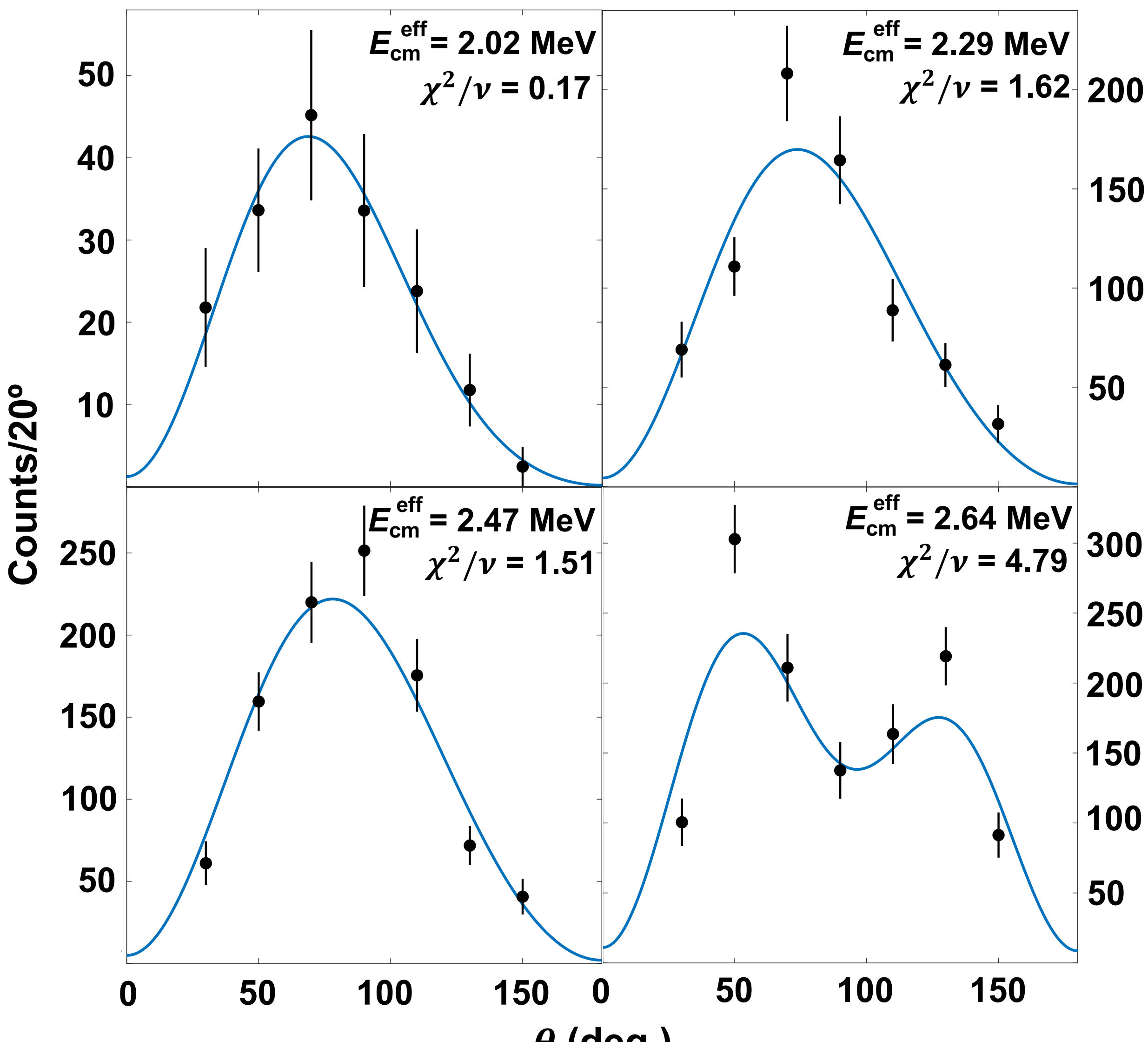
R. Smith[1,2]✉, M. Gai[2], S. R. Stern[2], D. K. Schweitzer[2] & M. W. Ahmed[3,4]

[5] R. Smith, M. Gai et al. Nature Communications 12, 5920 (2021).

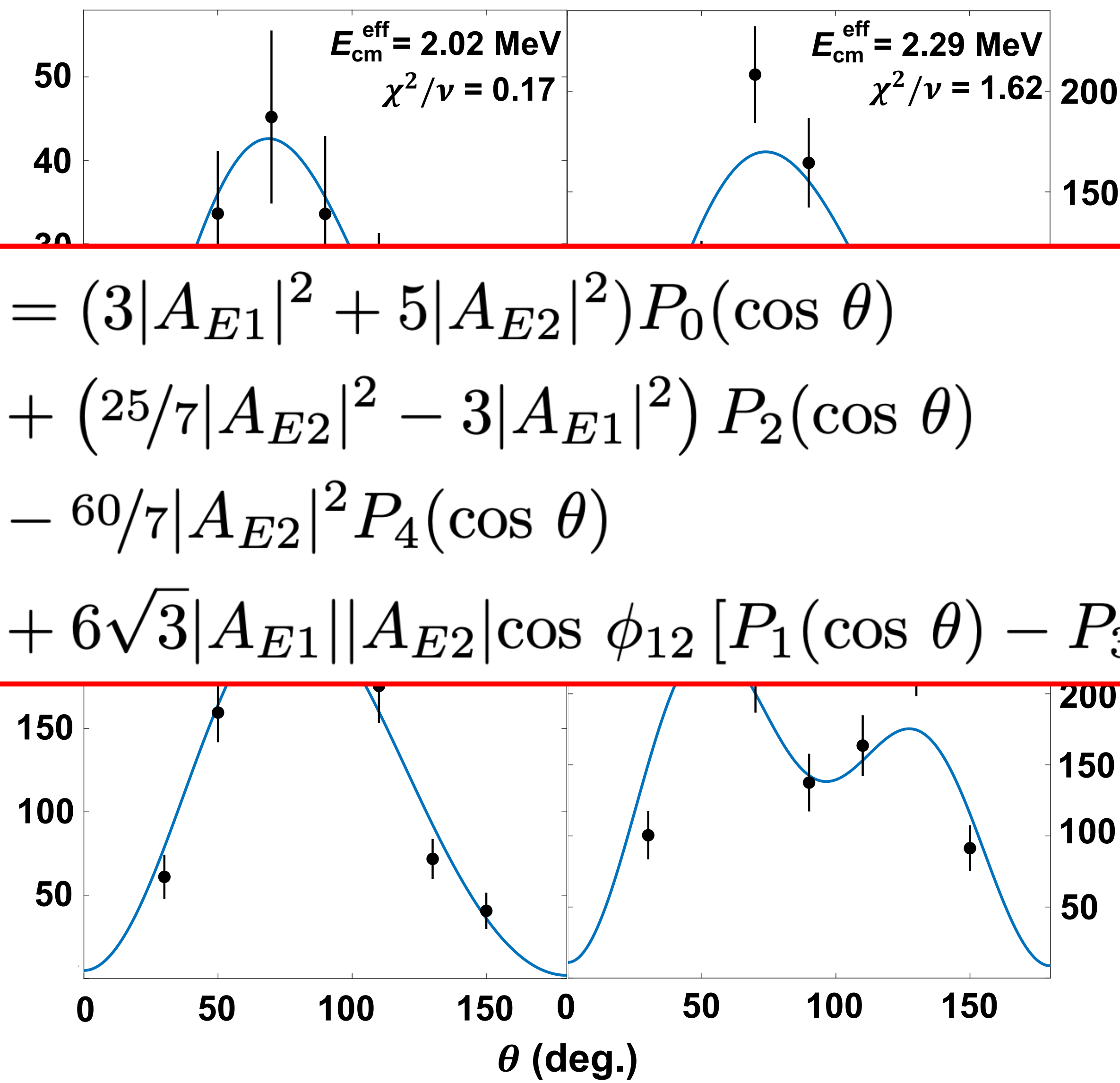
Total cross section



Angular distributions

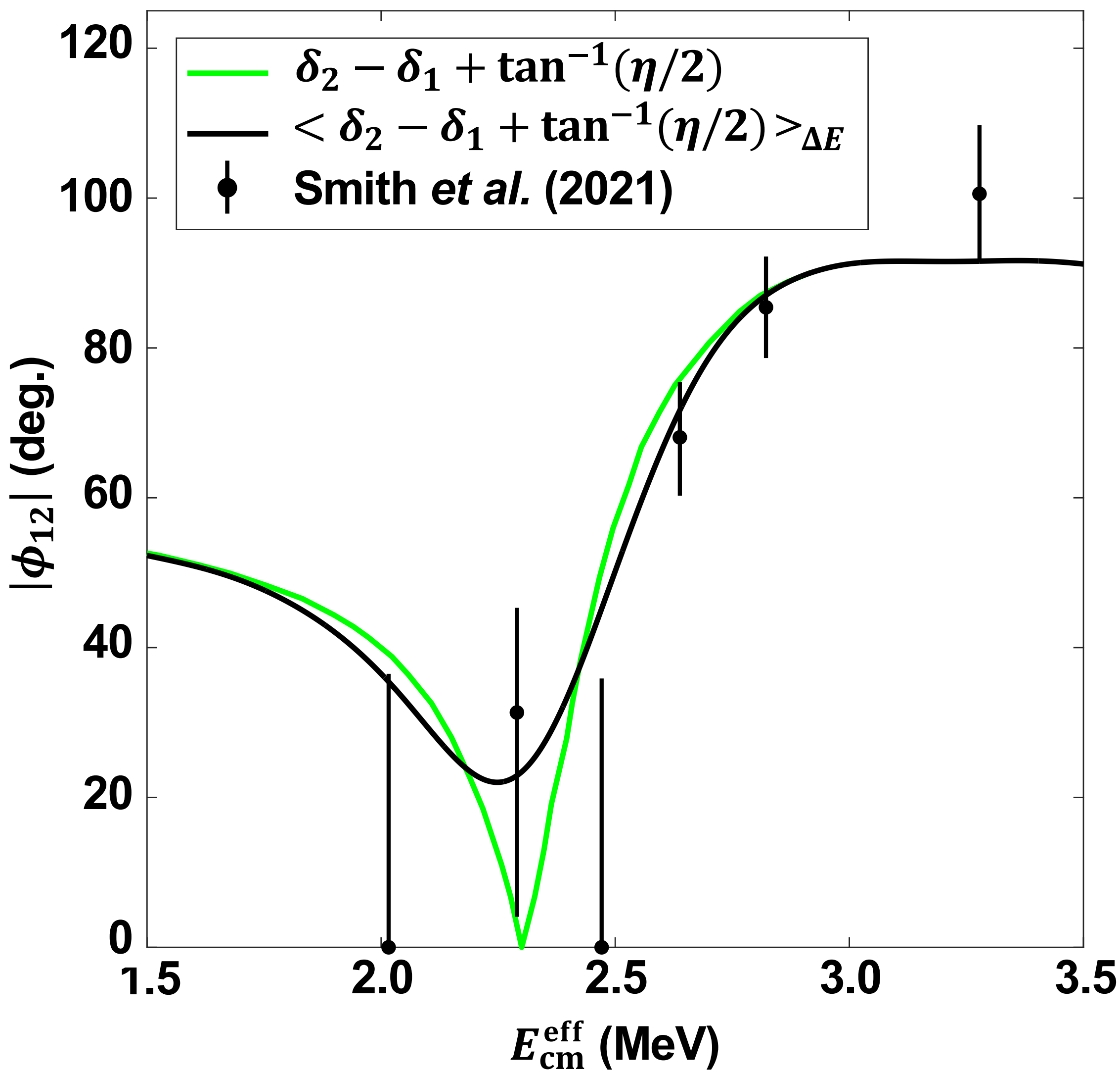


Angular distributions

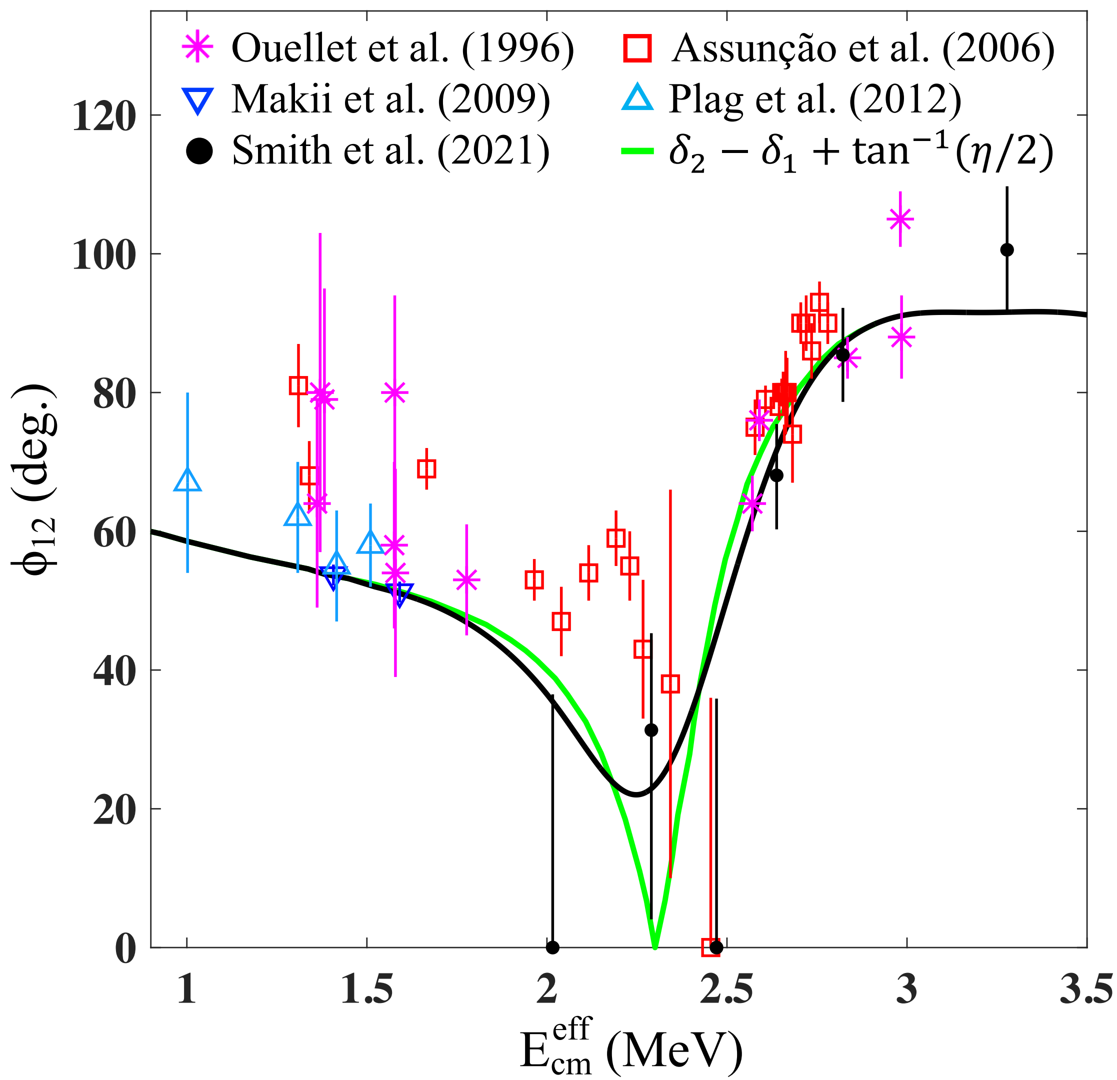


$$
\begin{aligned}
W(\theta) = {} & (3|A_{E1}|^2 + 5|A_{E2}|^2) P_0(\cos\,\theta) \\
& + \left({}^{25}\!/_{7} |A_{E2}|^2 - 3|A_{E1}|^2 \right) P_2(\cos\,\theta) \\
& - {}^{60}\!/_{7} |A_{E2}|^2 P_4(\cos\,\theta) \\
& + 6\sqrt{3} |A_{E1}||A_{E2}| \cos\,\phi_{12} \left[P_1(\cos\,\theta) - P_3(\cos\,\theta) \right]
\end{aligned}
$$

ϕ_{12} values



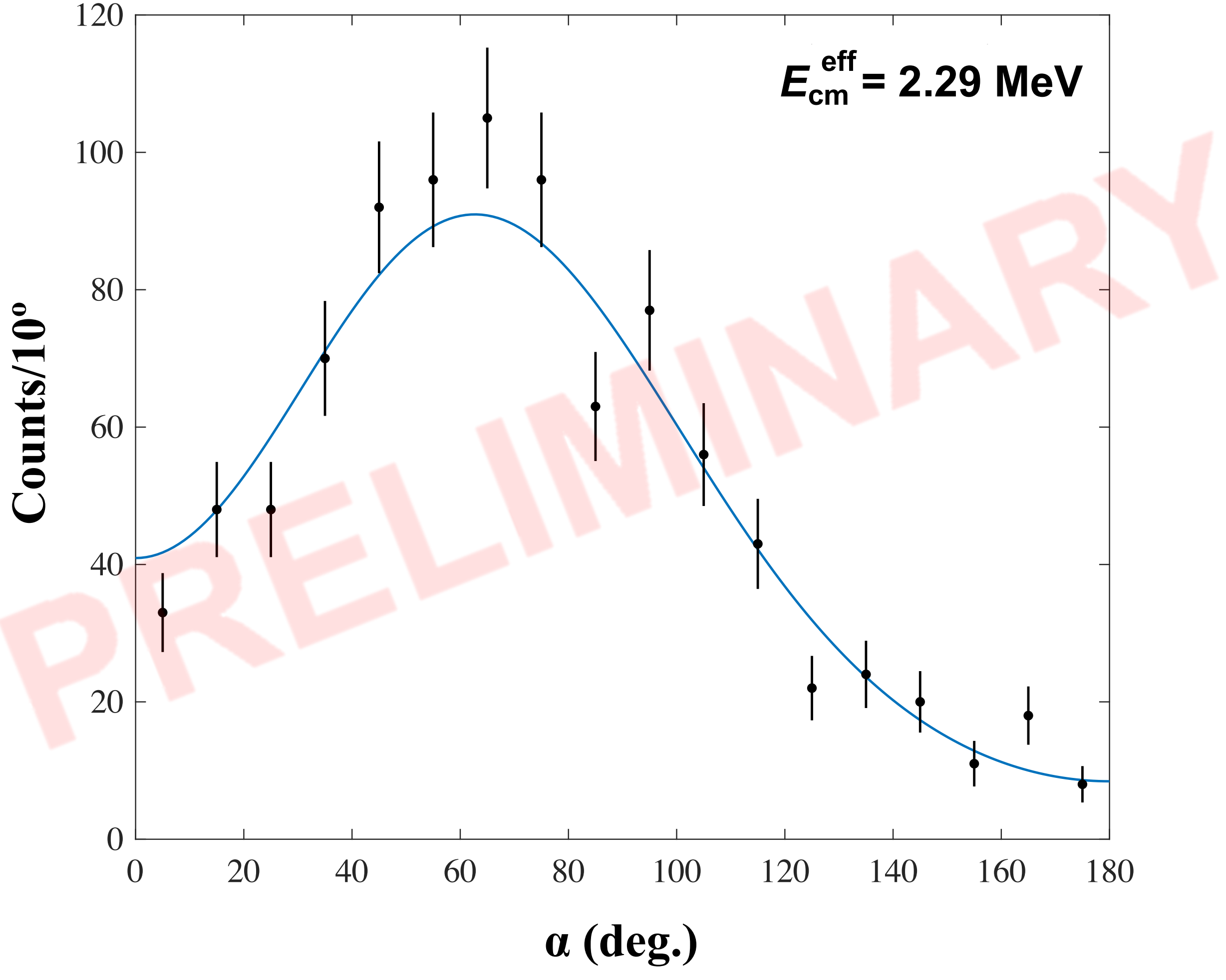
ϕ_{12} values



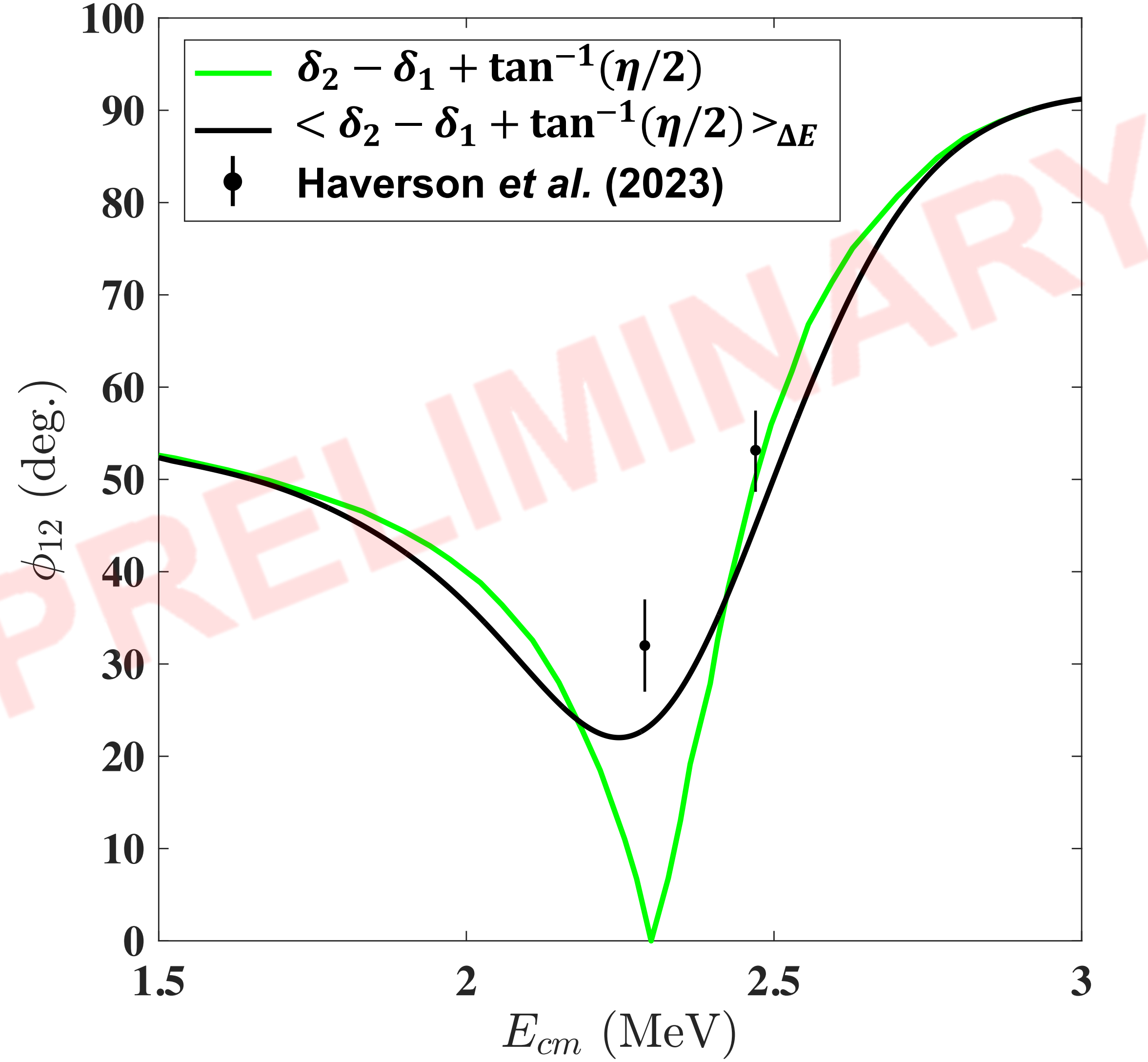
$^{16}O(\gamma,\alpha)^{12}C$ with an Optical TPC

- Later experiment performed – analysis by Kris Haverson (Ph.D. at Sheffield Hallam)
- Optical TPC operating with **$N_2O + N_2$** gas mixture
- Focused on high energy region E_{cm} = 2 – 3 MeV
- Higher statistics
- No carbon in the target – should permit simpler analysis

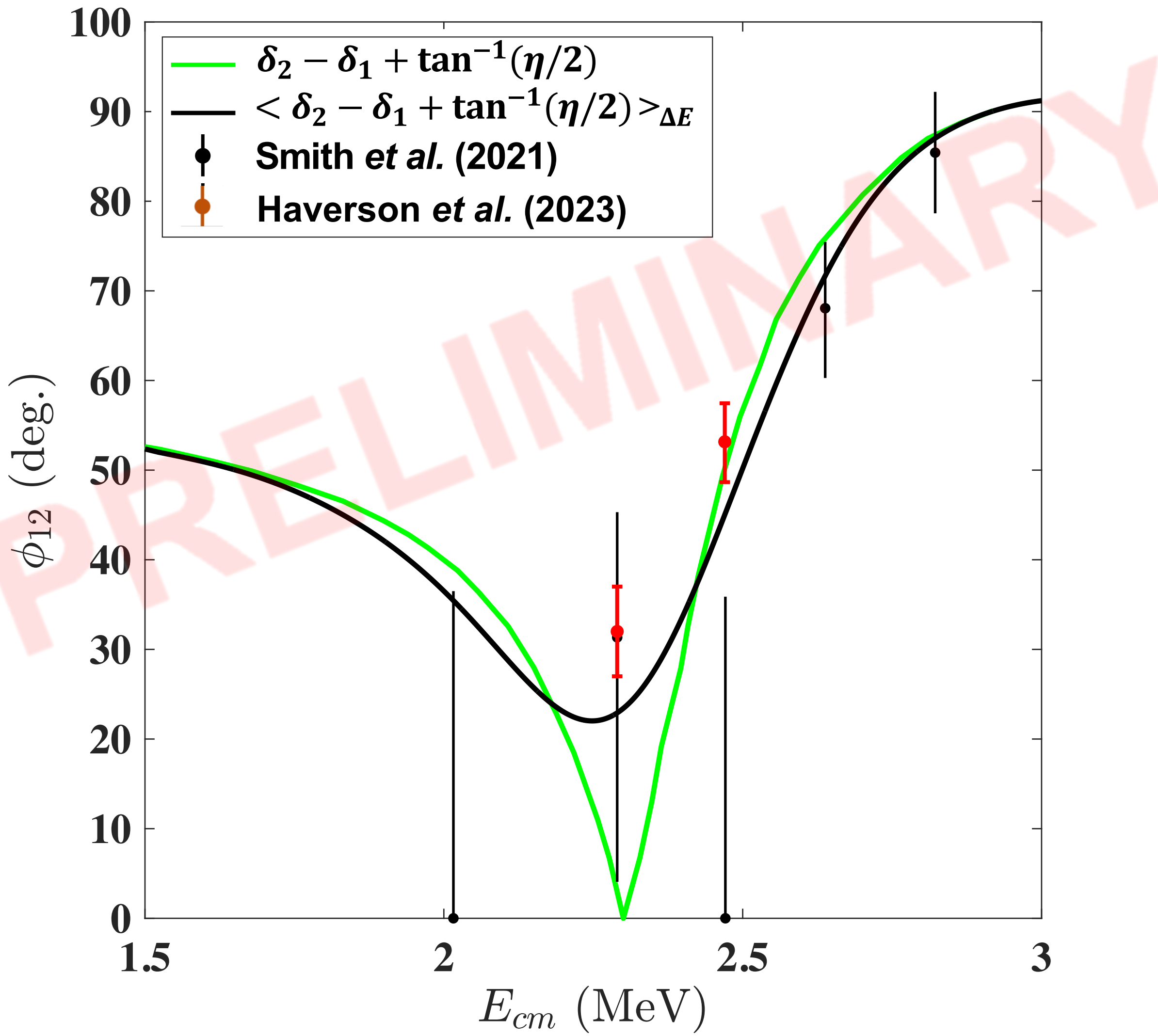
Angular distribution



ϕ_{12} values



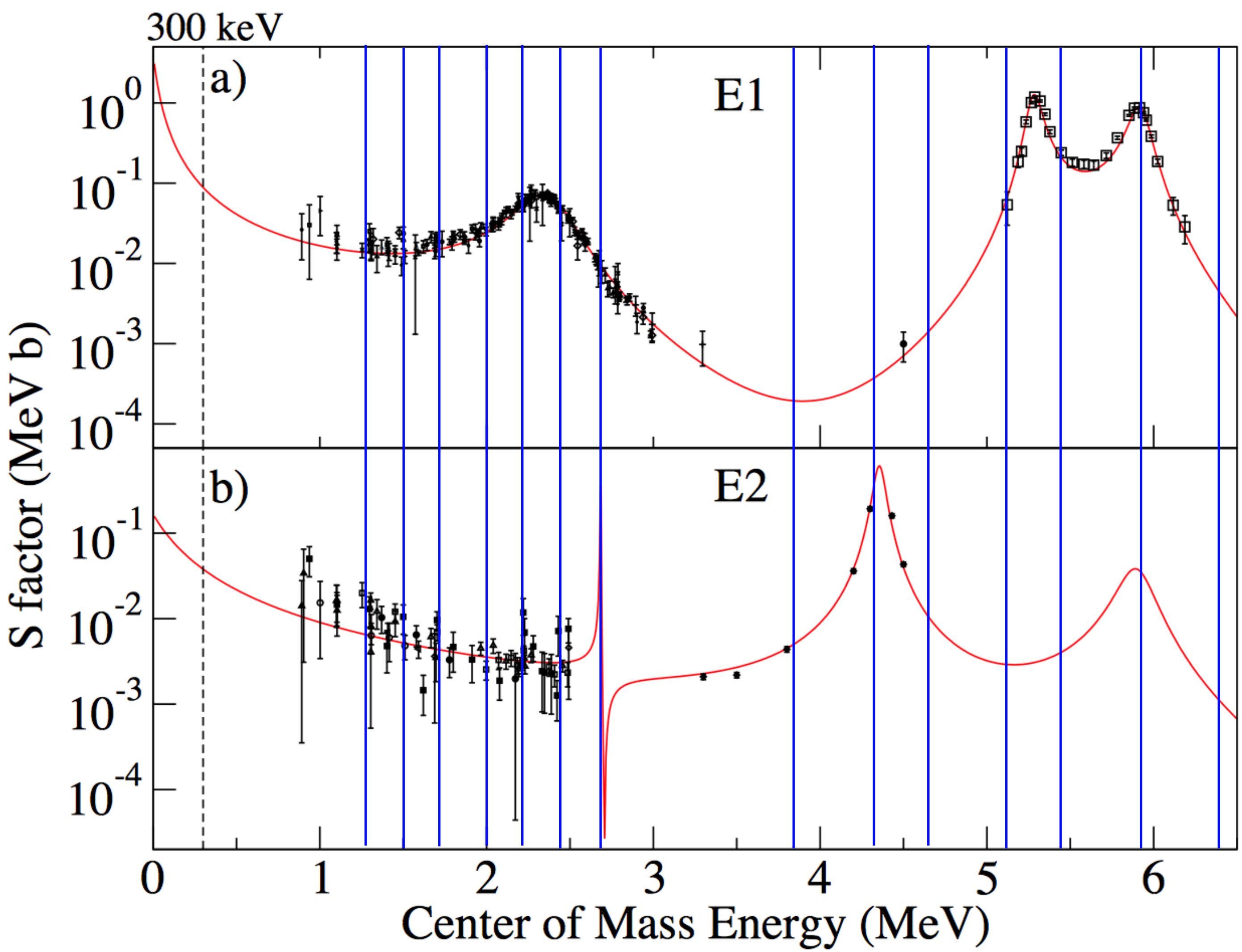
ϕ_{12} values



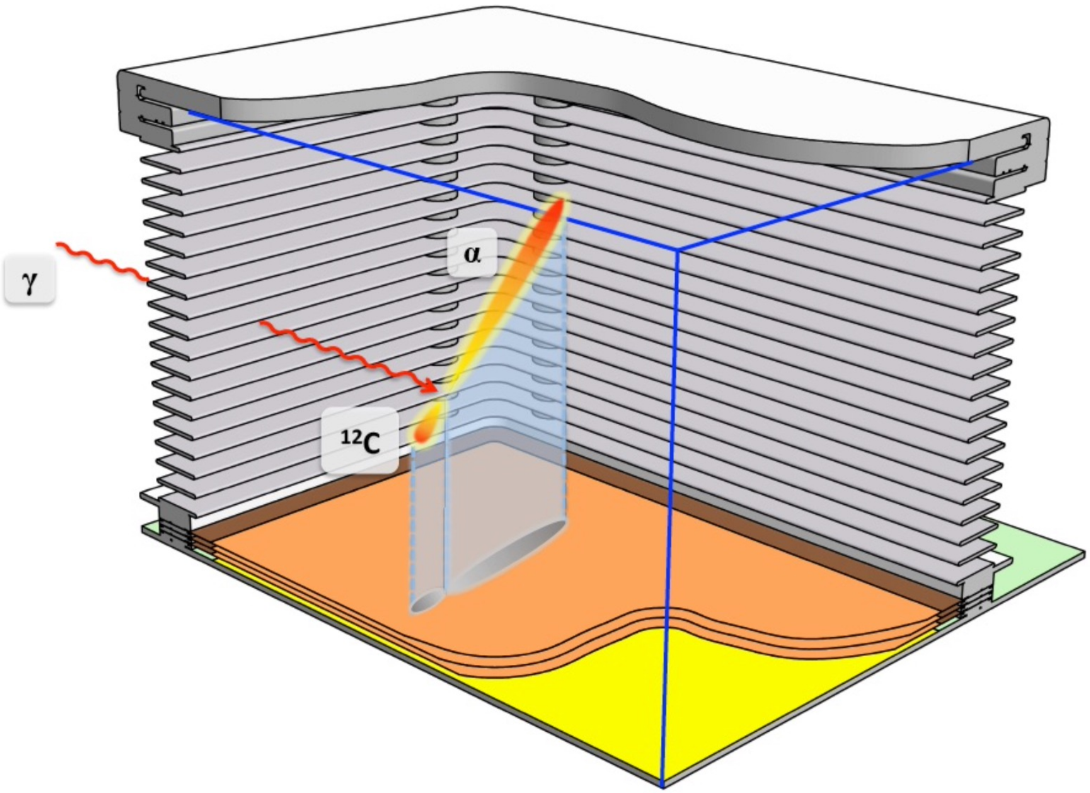
$^{16}O(\gamma,\alpha)^{12}C$ with an electronic TPC

- New experiment performed at HIγS in 2022
- Electronic TPC operating with pure **CO_2** gas
- TPC built by University of Warsaw
- $^{16}O(\gamma,\alpha)^{12}C$ measured at nominal E_{cm} = 1.35 – 6.7 MeV
- 275 hours of beamtime during 2022

$^{16}O(\gamma,\alpha)^{12}C$ with an electronic TPC



$^{16}O(\gamma,\alpha)^{12}C$ with an electronic TPC

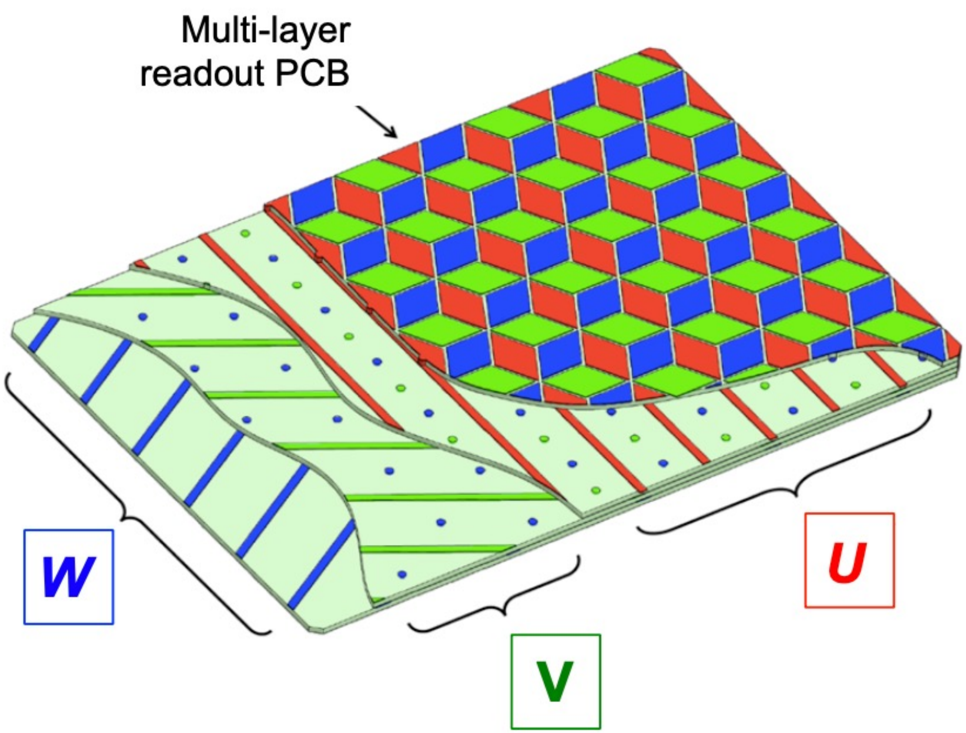


Active volume
33 x 20 cm^2 (readout) x 20 cm (drift)

Charge amplification
Gas Electron Multiplier (GEM) structures

Readout
Planar, 3-coordinate, redundant strip arrays, ~1000 channels
GET electronics

$^{16}O(\gamma,\alpha)^{12}C$ with an electronic TPC



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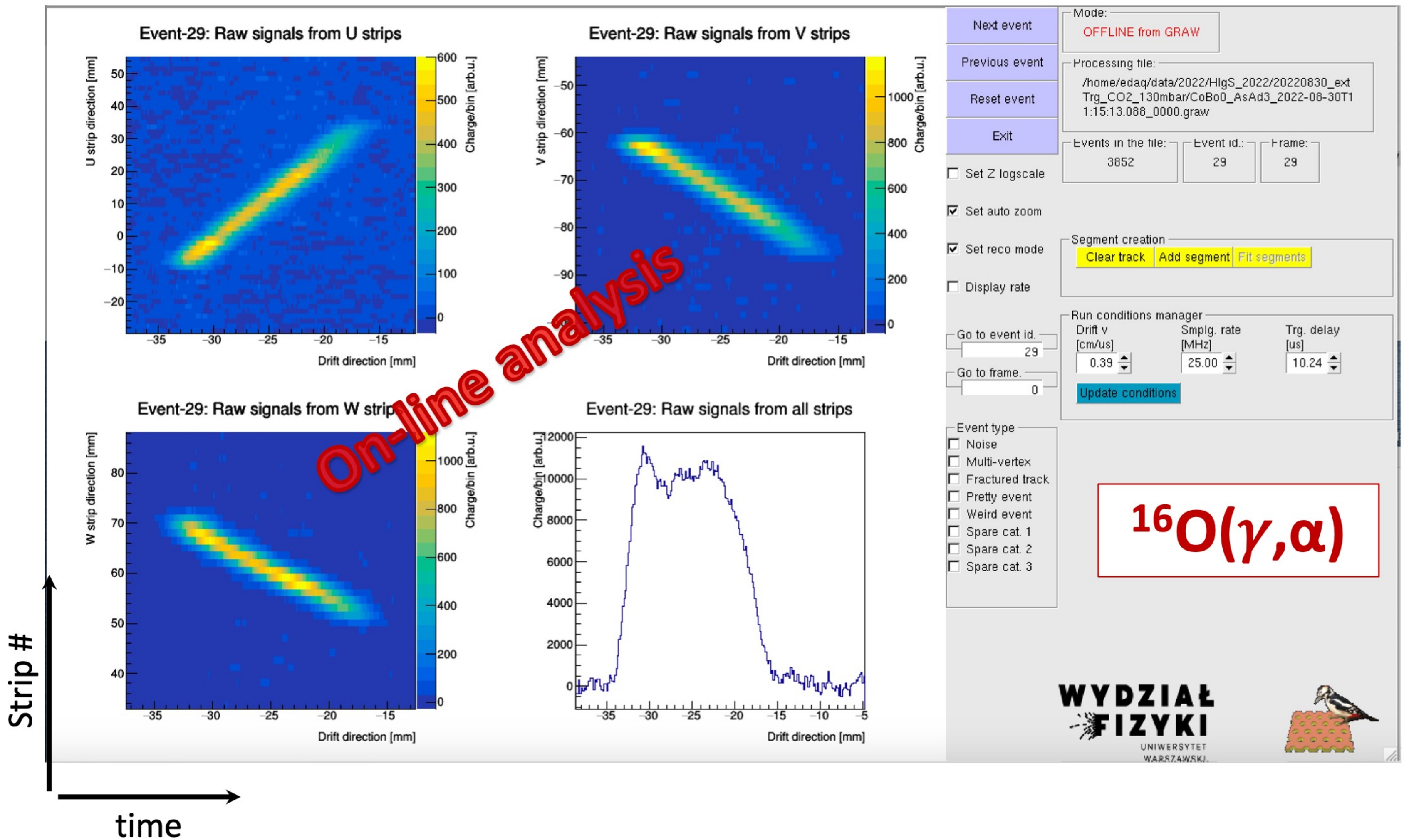
$^{16}O(\gamma,\alpha)^{12}C$ preliminary results

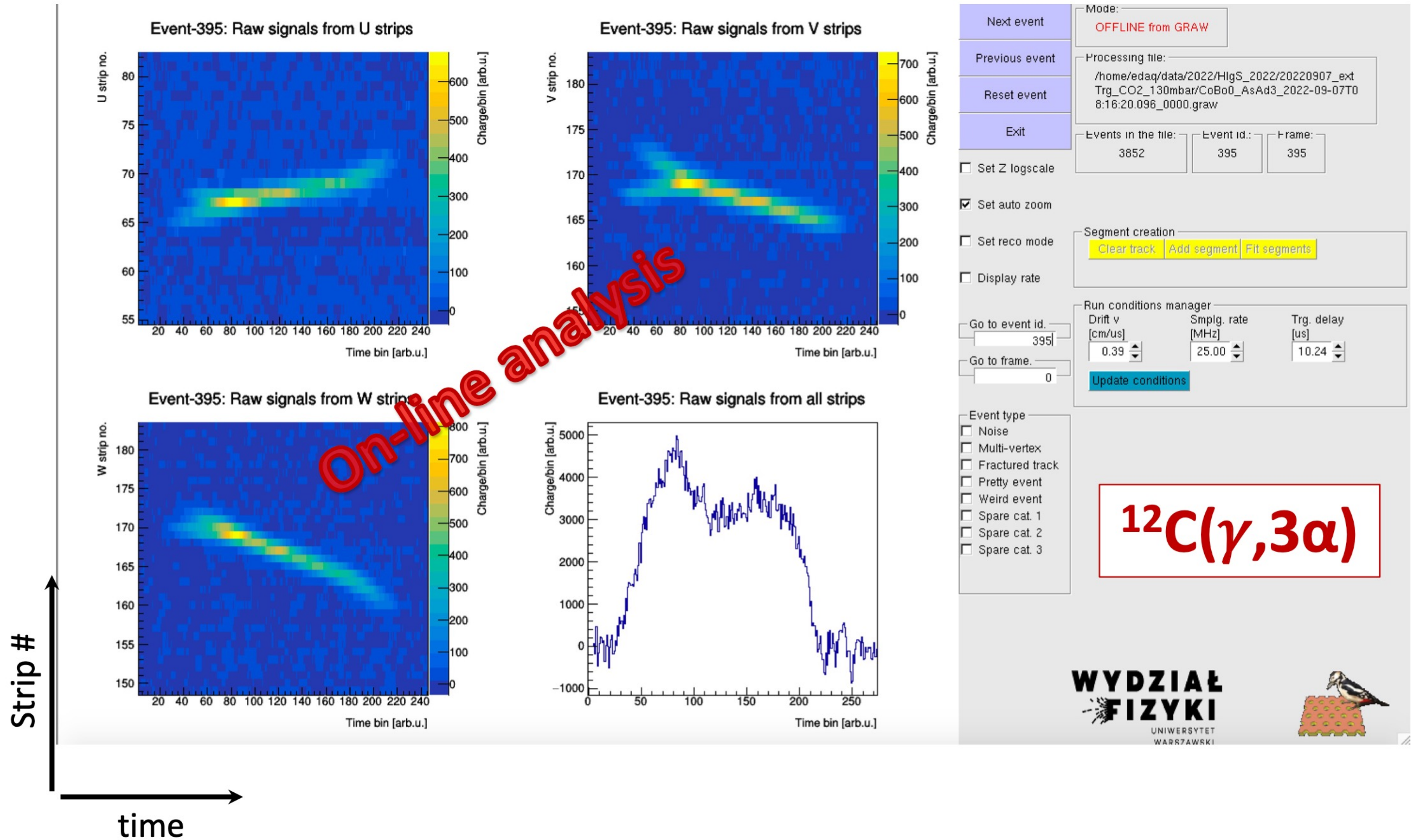
E_γ = 8.66 MeV (**E_{cm} = 1.5 MeV**)



[6] Mazzocchi, C.: Studies of photonuclear reactions at astrophysical energies with an active- target TPC. Paper presented at the 10th Nuclear Physics in Astrophysics Conference, CERN, 4–9 September 2022 (2022)

$^{12}C(\gamma,3\alpha)$ preliminary results

E_{γ} = 8.51 MeV (**E_{cm} = 1.35 MeV**)



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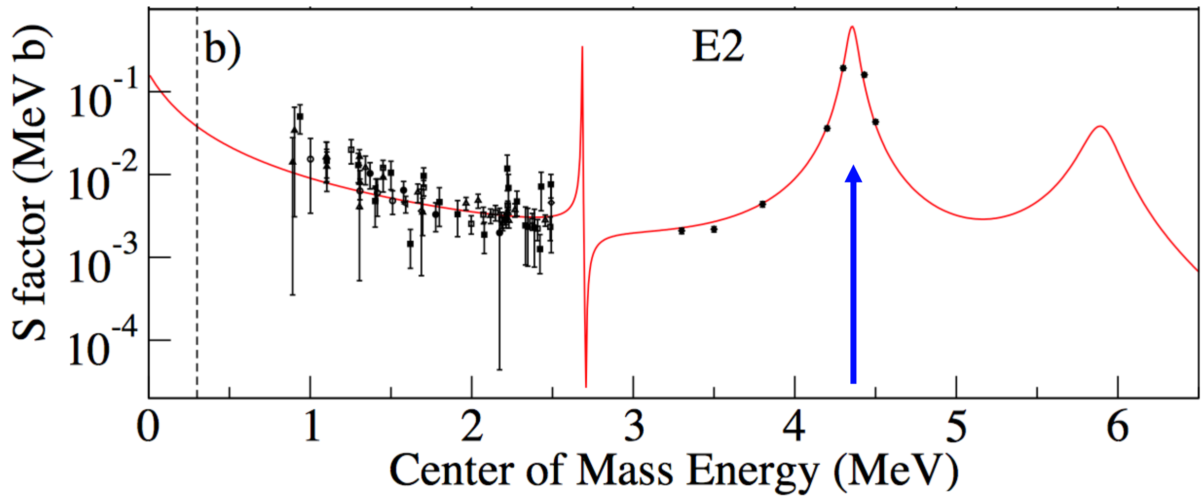
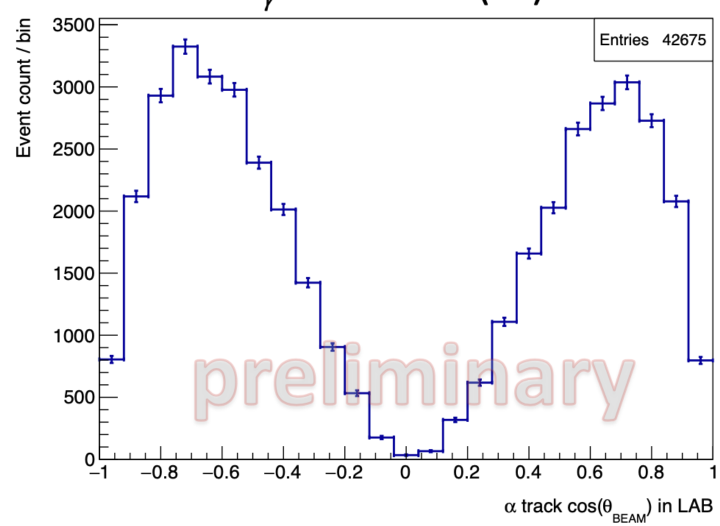
^{16}O(γ,α) prelim. ang. distributions



E_γ = 11.5MeV (E2)



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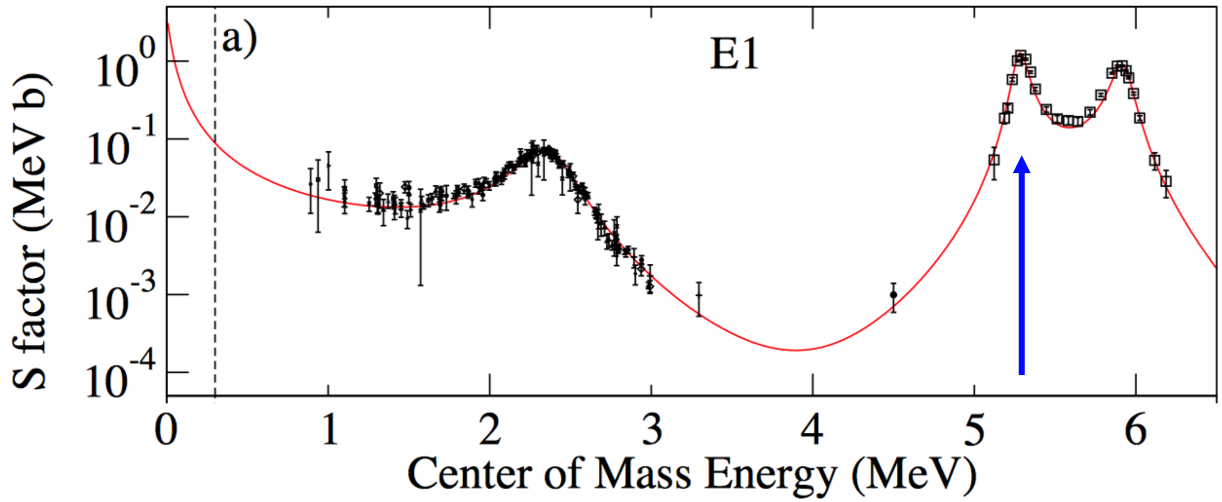
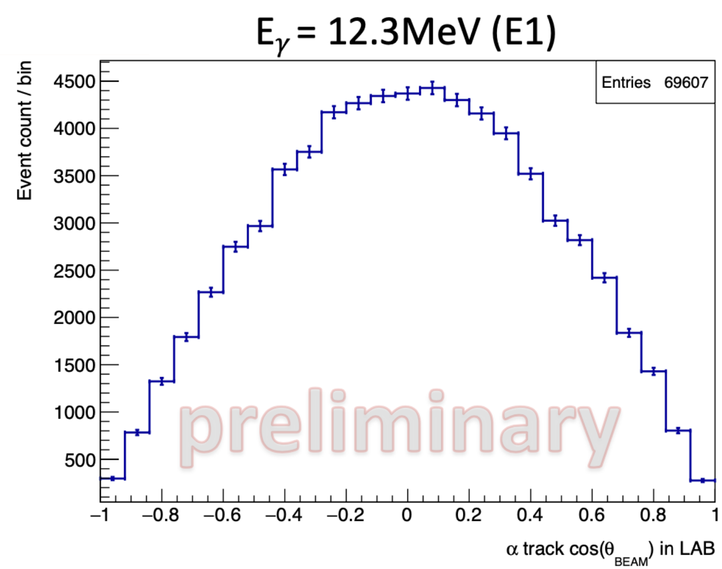
$^{16}O(\gamma,\alpha)$ prelim. ang. distributions





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Summary

Sheffield Hallam University

- Sheffield Hallam involved in several exciting studies in nuclear astrophysics using γ-beams and TPC detectors
  - Leading analysis of existing data
  - New experiments at HIγS
- Publication: R. Smith et al. Nature Communications 12, 5920 (2021).
  - Viability of γ-beam experiments for measuring $^{12}C(\alpha,\gamma)$ using TPCs
  - Newer Optical TPC data with N_2O gas mixture are promising
- State-of-the-art electronic TPC data are undergoing analysis
  - Data analysis led by Warsaw with contributions from SHU and UConn
- Nuclear structure studies on carbon-12 – $^{12}C(\gamma,\alpha)$

Collaborators

Mikołaj Ćwiok[1], *Wojciech* Dominik[1], *Aleksandra* Fijałkowska[1], *Mateusz* Fila[1], *Zenon* Janas[1], *Artur* Kalinowski[1], *Krzysztof* Kierzkowski[1], *Magdalena* Kuich[1], *Chiara* Mazzocchi[1,*], *Wojciech* Okliński[1], *Marcin* Zaremba[1], *Moshe* Gai[2], *Deran K.* Schweitzer[2], *Sarah R.* Stern[2], *Sean* Finch[3,4], *Udo* Friman-Gayer[3,4,**], *Samantha R.* Johnson[5,4], *Tyler M.* Kowalewski[5,4], *Dimiter L.* Balabanski[6], *Catalin* Matei[6], *Adrian* Rotaru[6], *Kristian C.Z.* Haverson[7], *Robin* Smith[7], *Ross A.M.* Allen[8], *Mark R.* Griffiths[8], *Stuart* Pirrie[8], and *Pedro* Santa Rita Alcibia[8]

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