Oxygen photo-disintegration as a tool for studying $^{12}C(\alpha,\gamma)$ at astrophysical energies

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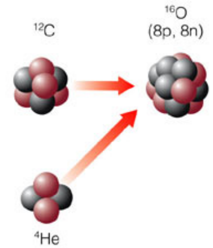
University of Warsaw

Bormio, January 23rd, 2023

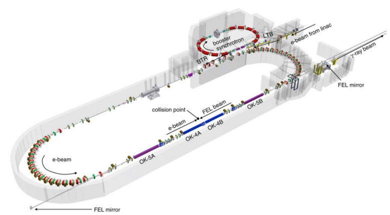
Overview

Warsaw TPC

- Physics motivations and goals



- Methodology



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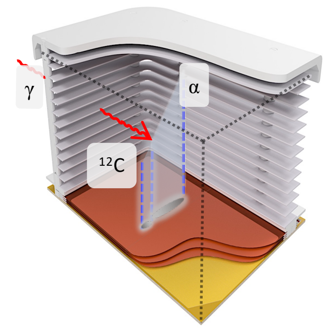
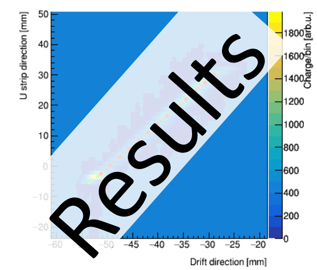
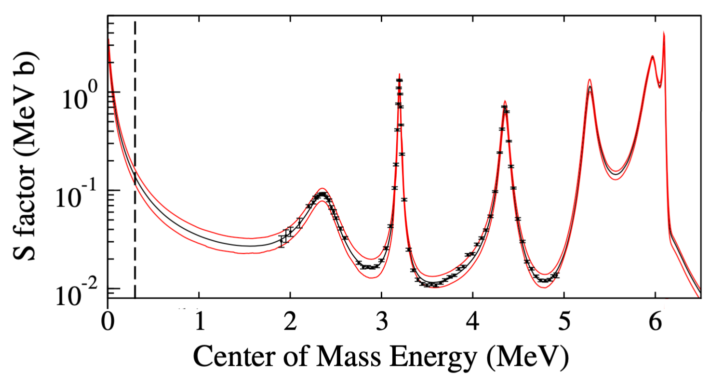


- Measurements and preliminary results



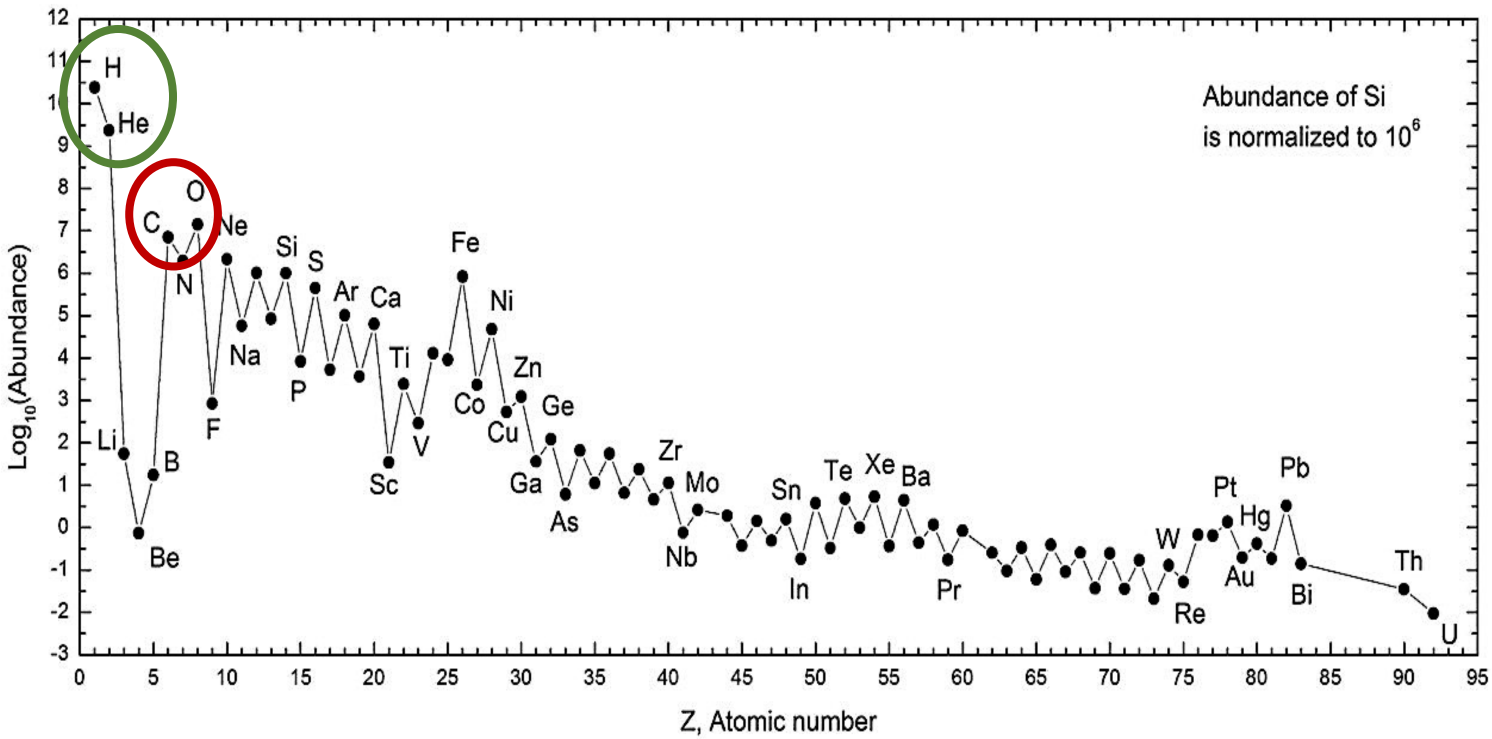
- Summary and outlook



Physics motivations and goals

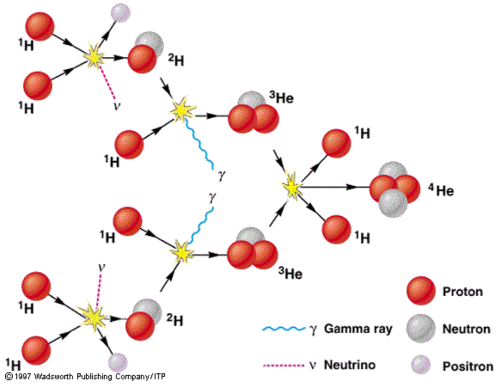
Physics motivations

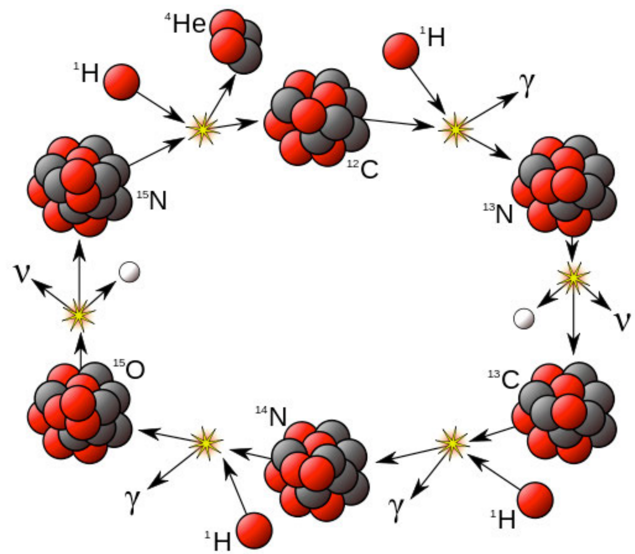
- Abundance of the elements in the Universe
  - in weight: H - 74%, He - 24%, O - 0.85%, C - 0.39%, …
- Abundance of the elements in the human body:
  - in weight: O - 65%, C - 18%, H - 10%, N - 3%, other 4%



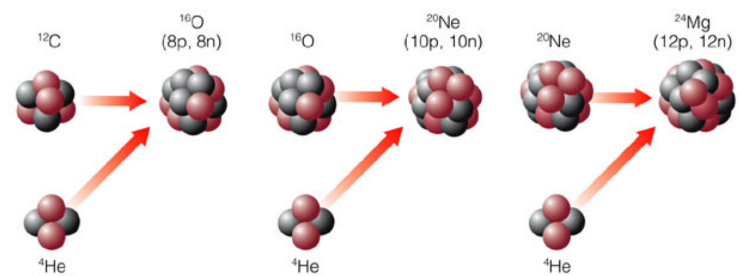
Physics motivations

- Synthesis of He in H-burning reactions
  - **pp-chain, CNO cycle**, hot-CNO, NeNa cycle, MgAl cycle, …
  - $4p \longrightarrow {}^{4}He + 2e^{+} + 2\nu$





- Synthesis of C, O, Ne in He-burning
  - $3\alpha \longrightarrow {}^{12}C$; $\mathbf{{}^{12}C(\alpha,\gamma){}^{16}O}$; ${}^{16}O(\alpha,\gamma){}^{20}Ne$



Cross-section measurement of (α,γ) and (p,γ) at astrophysical energies

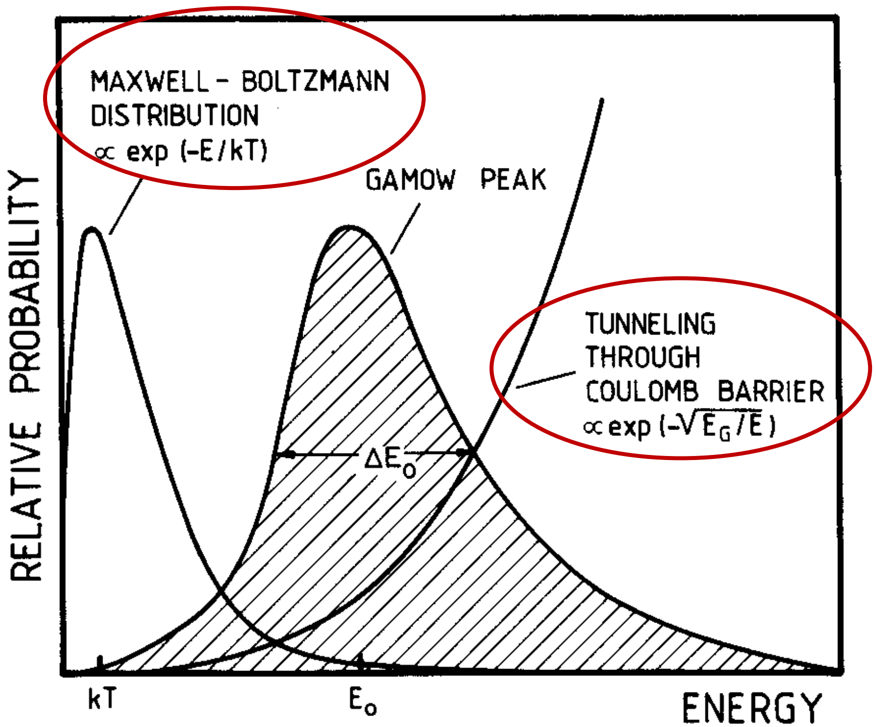
Nature's challenges: the issue of the Coulomb barrier

- The issue of the Coulomb barrier:
  at typical He-burning temperatures of T_6 ~ 300, **kT ~ 200 keV << E_{Coul}** (2- 8MeV)

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-31.29 \cdot Z_1 \cdot Z_2 \sqrt{\frac{\mu}{E}}\right)$$

Astrophysical factor

Gamow factor



Nuclear reactions that generate energy and synthesise elements take place inside the stars in a relatively narrow energy window: the Gamow peak

Gamow Energy for He-burning reactions: few hundreds keV

Science goals

- Accurate measurements of (very small) cross sections of (α,γ) and (p,γ) nuclear reactions

  → fundamental observable to determine reaction rates

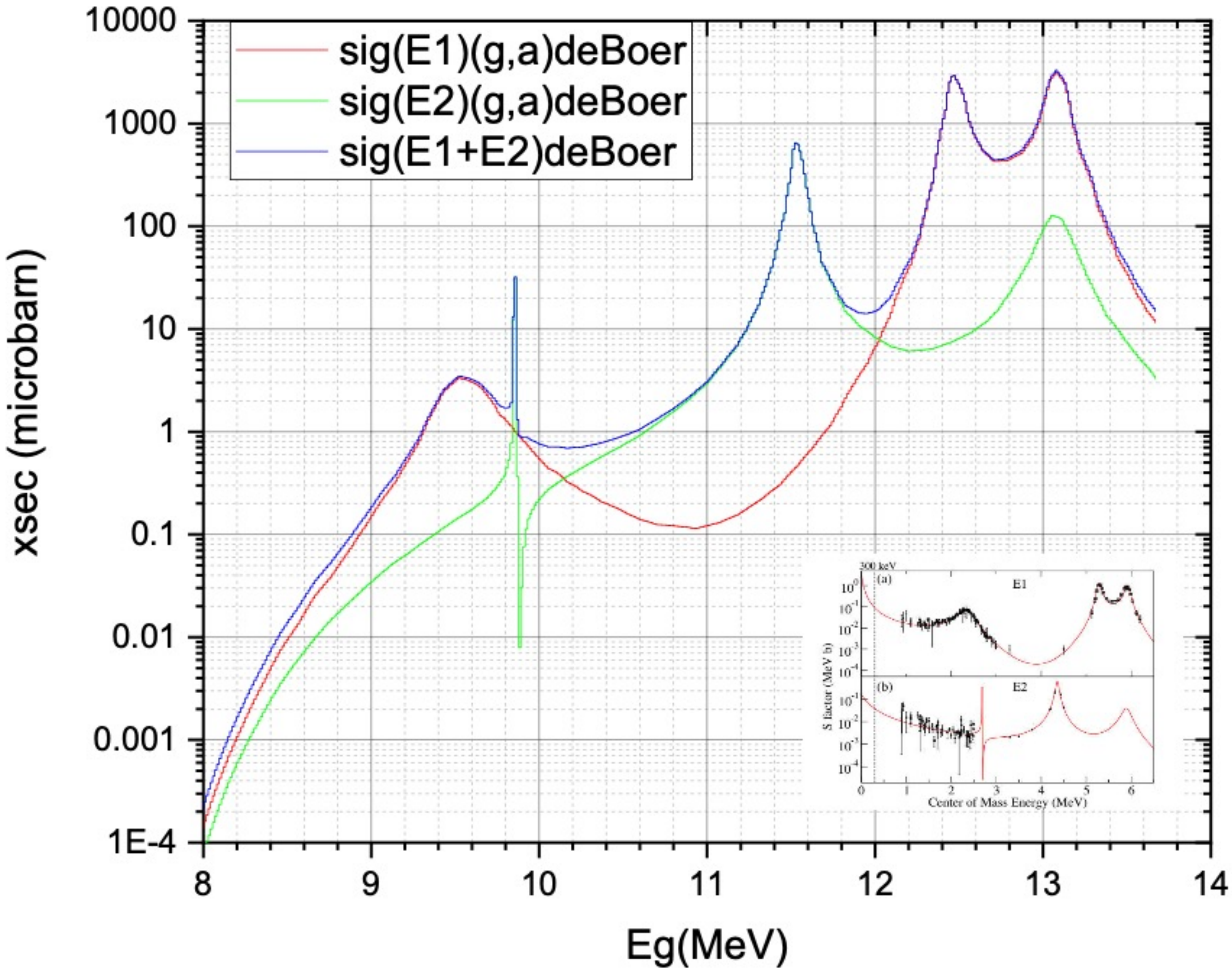
  → to be determined at the relevant energies (Gamow peak)

  → reaction rates as a function of the temperature/environmental condition are input for star evolution models

- Flagship reaction: $^{12}C(\alpha,\gamma)^{16}O$ at low energies

The flagship $^{12}C+\alpha$ --> $^{16}O+\gamma$: status of the experimental knowledge

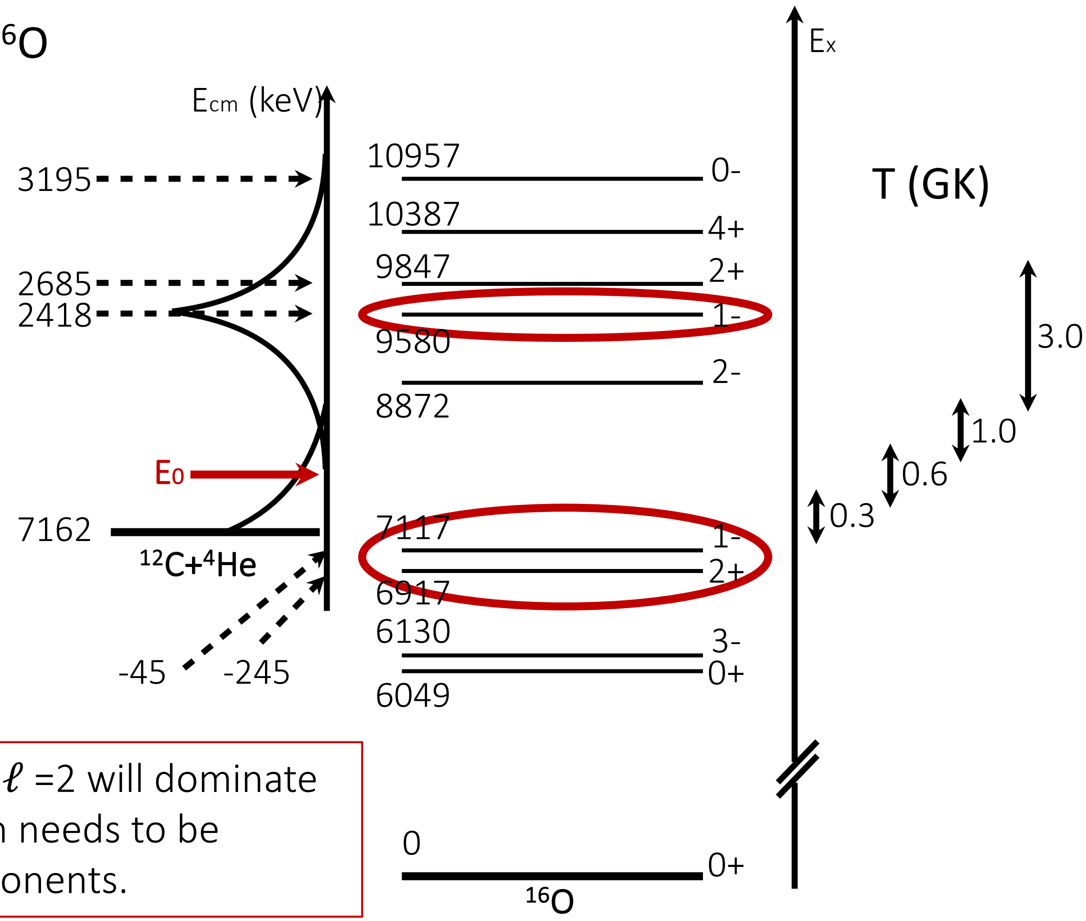
Total cross-section for $^{12}C(\alpha,\gamma_0)^{16}O$



Physics motivations: the flagship $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$

Survival of ^{12}C

- α-burning in the flagship $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$
- nuclear structure properties of ^{16}O



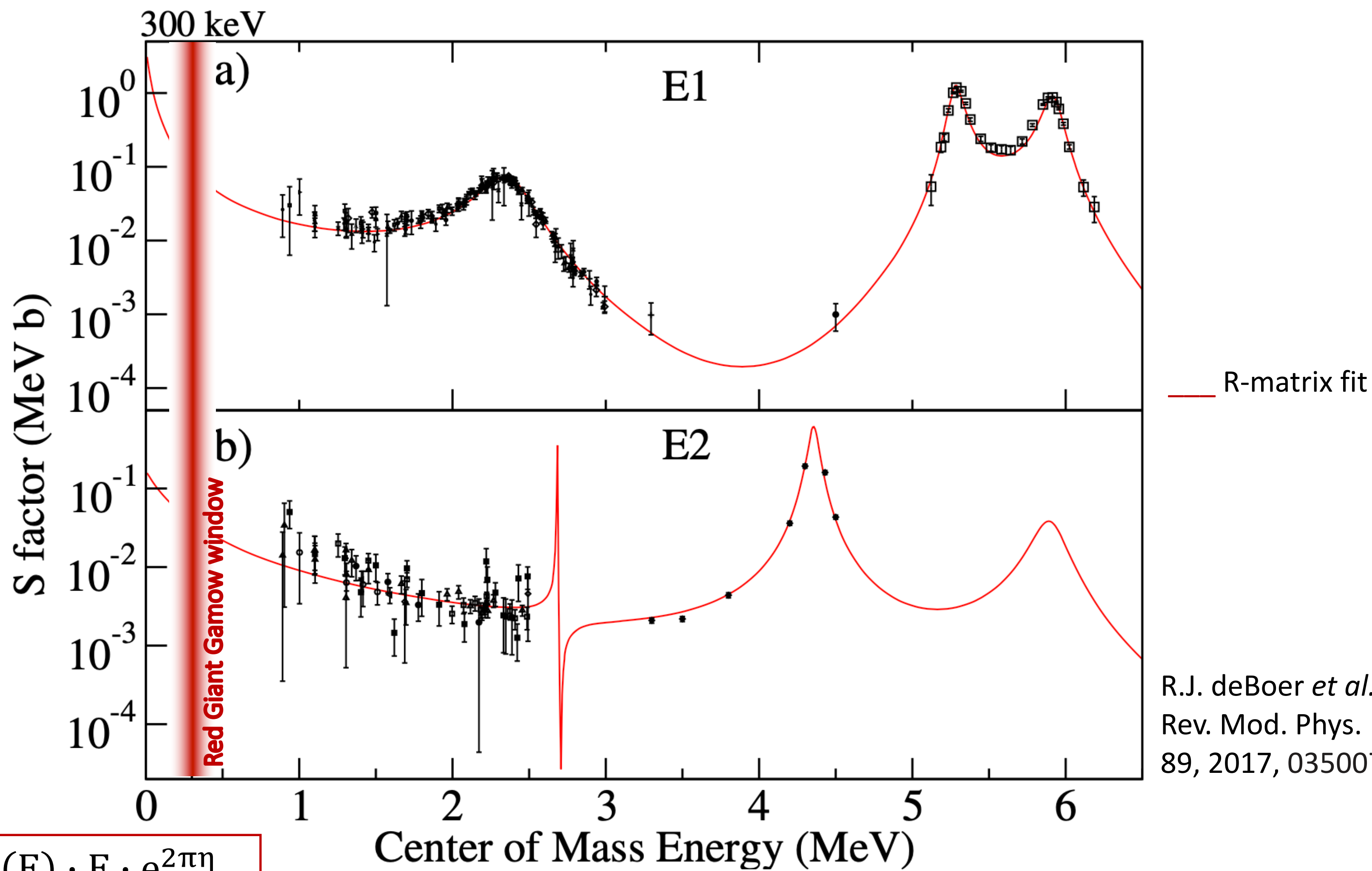
Two reaction mechanisms available

- non-resonant direct-capture
- non-resonant capture into the tails of nearby resonances

Stellar environments: capture via ℓ=1 or ℓ =2 will dominate --> not only the total E1+E2 cross section needs to be determined, but also its E1 and E2 components.

The flagship $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$: status of the experimental knowledge

Extrapolated S-factor for p-wave (E1) & d-wave (E2) ^{12}C+ α capture for Gamow peak in red giants (300 MK)



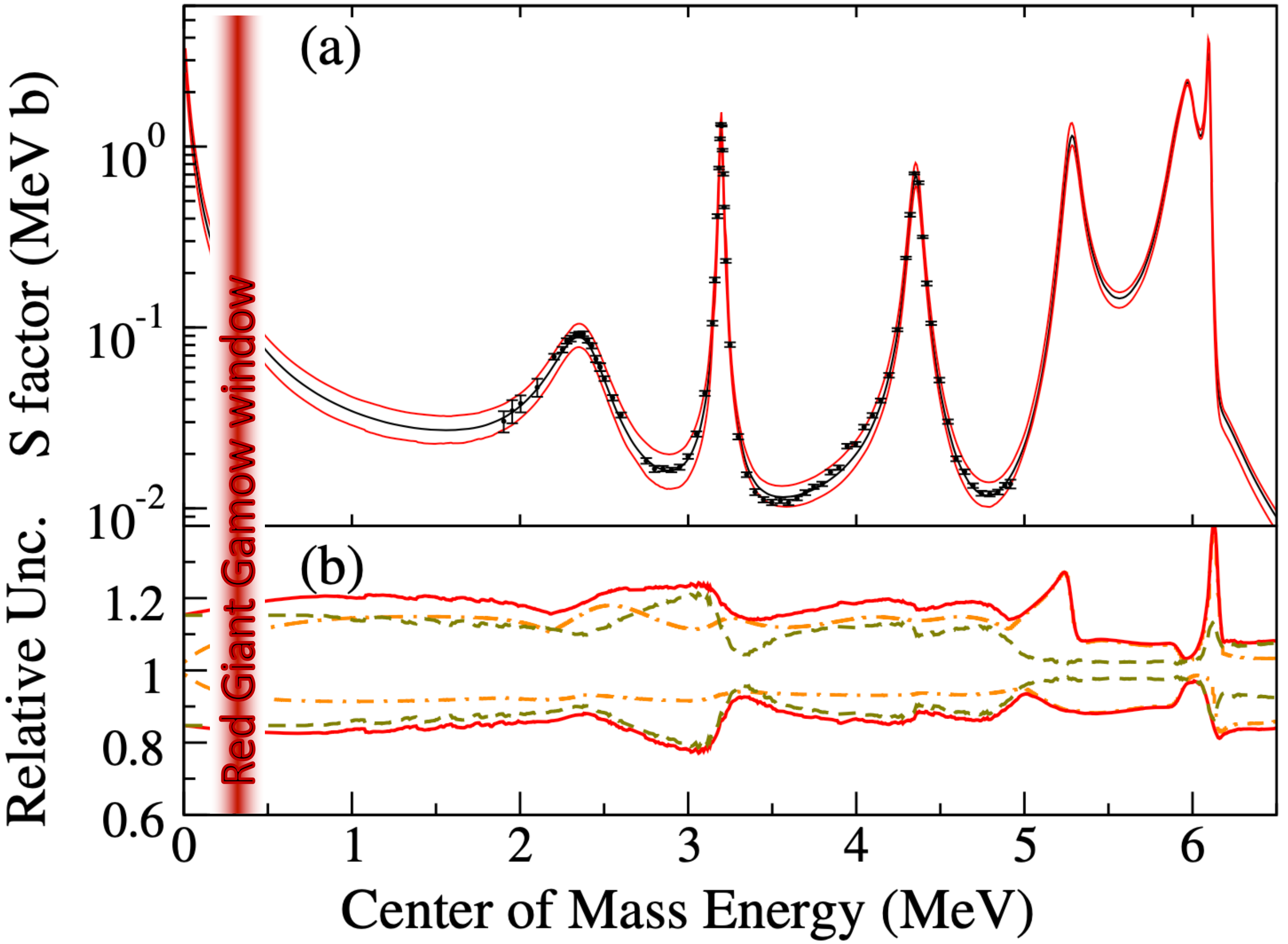
R.J. deBoer *et al.*, Rev. Mod. Phys. 89, 2017, 035007

$$S(E) = \sigma(E) \cdot E \cdot e^{2\pi\eta}$$

$$2\pi\eta = 31.29 \cdot Z_1 \cdot Z_2\sqrt{\mu/E_{cm}}$$

The flagship $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$: status of the experimental knowledge

Uncertainties: R.J. deBoer et al., Rev. Mod. Phys. 89, 2017, 035007



Uncertainty in the S factor (model+MC analysis). Data from Schürmann et al. (2005)

Uncertainties relative to the best fit value for the Monte Carlo analysis

Uncertainties derived from the model

Total uncertainty

$$S(E) = \sigma(E) \cdot E \cdot e^{2\pi\eta}$$

$$2\pi\eta = 31.29 \cdot Z_1 \cdot Z_2\sqrt{\mu/E_{cm}}$$

Methodology of choice

Low-pressure Active-Target TPC coupled to monochromatic γ-ray beams

Experimental challenges

- Measurement of $^{12}C(\alpha,\gamma)^{16}O$ cross section at the Gamow peak beyond the current experimental reach
    - R-matrix fits to extrapolate at Gamow energy
    - cross sections need to be measured at as-low-as-possible c.o.m. energies to constrain the fit
    - measurements are challenging below 2 MeV in c.o.m.:
        * Limited beam intensity and target thickness
        * Beam-induced background from contaminant reactions ($^{13}C(\alpha,n)^{16}O$)

Experimental challenges : how to meet the challenge and improve the accuracy

- Measuring the cross section for the p- and α-capture reactions by means of the inverse photo-disintegration reaction

  - Strong and e.m. interactions invariant with respect to time reversal

  - photo-disintegration vs capture reaction

$$B(b,\gamma)A \rightleftharpoons A(\gamma,b)B$$

  - principle of detailed balance in nuclear reactions:

$$\sigma_{b\gamma} \cdot g_{b\gamma} \cdot p_{b\gamma}^{2} = \sigma_{\gamma b} \cdot g_{\gamma b} \cdot p_{\gamma b}^{2}$$

$g_{b\gamma}$, $g_{\gamma b}$ = spin factors

$$\sigma_{b\gamma} = \sigma_{\gamma b} \cdot \frac{g_{\gamma b}}{g_{b\gamma}} \cdot \frac{p_{\gamma b}^{2}}{p_{b\gamma}^{2}} = \sigma_{\gamma b} \frac{2J_{CN}+1}{(2J_b+1)(2J_B+1)} \cdot \frac{E_\gamma^2}{E_{CM}} \cdot \frac{1}{\mu_{bB}c^2}$$

Experimental challenges : how to meet the challenge and improve the accuracy

- Measuring the cross section for the p- and α-capture reactions by means of the inverse photo-disintegration reaction
- Advantages
  - direct capture vs photo-disintegration reaction (at Ecm = 1.0 MeV):

$$^{12}C + \alpha \dashrightarrow {}^{16}O + \gamma \Longrightarrow \sigma = 50 \text{ pb}$$

$$^{16}O + \gamma \dashrightarrow {}^{12}C + \alpha \Longrightarrow \sigma = 2000 \text{ pb}$$

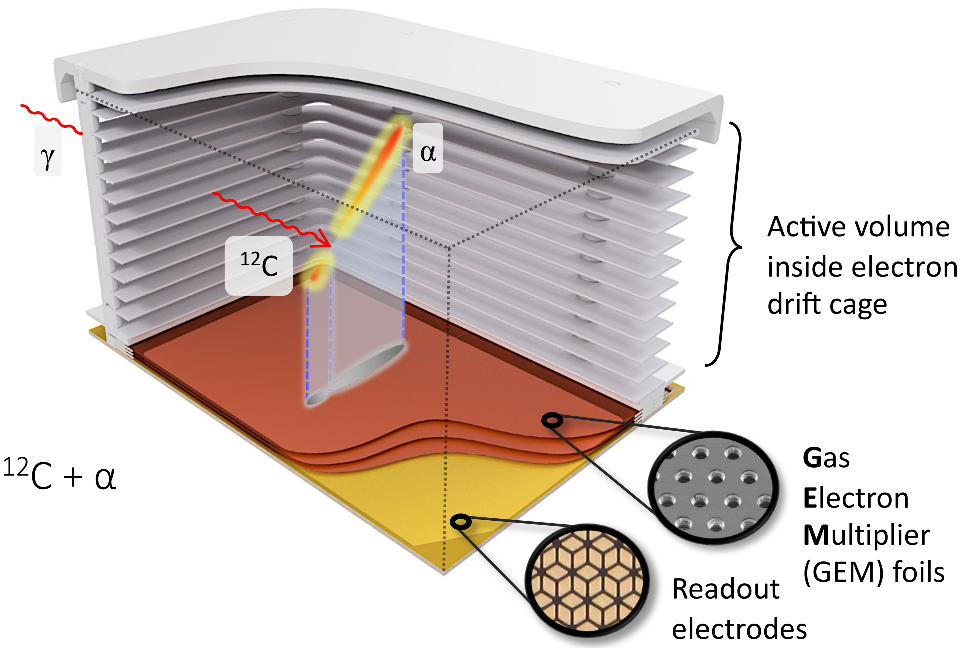
factor 40!!

  - inherently low background measurements
  - different systematic uncertainty w.r.t. charged-particle induced reactions at low energies
    - * target and its deterioration
    - * (effective) beam energy definition
- only ground-state branch measured
- intense monochromatic and focussed γ-ray beams

Warsaw active target TPC

✓ An active-target TPC to study reaction cross-sections of astrophysical interest where the reaction products are charged particles

—> full unambiguous reconstruction of multiple-particle events is possible

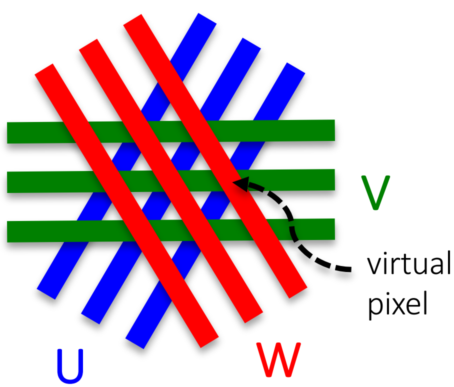


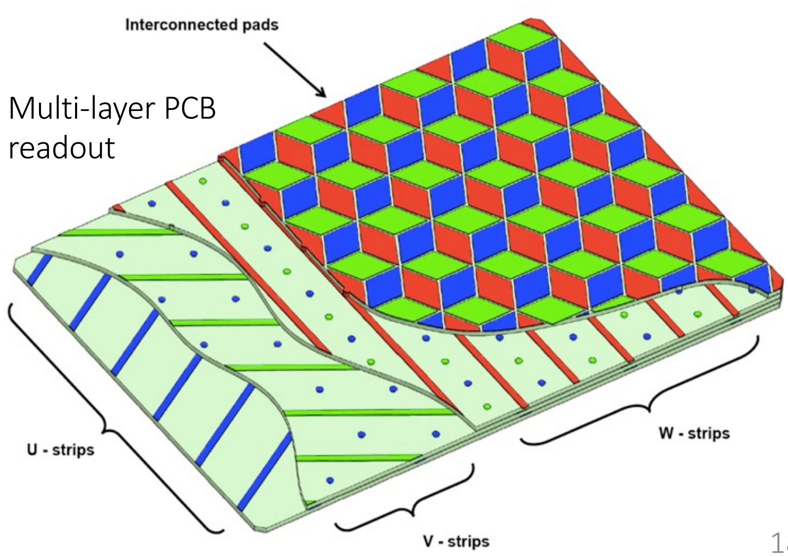
Example:
$^{16}O + \gamma \rightarrow {}^{12}C + \alpha$

- active volume: 33 cm x 20 cm x 20 cm
- under-pressured (100-250 mbar of CO_2): low-energy particles!
- charge amplification: 3 GEM structures

Warsaw active target TPC: detector concept

- Read-out:
  - 3-coordinate, planar, redundant electronic readout: 3 independent linear sets of strips (u-v-w): 1.5 mm pitch
  - needs only ~1000 channels —> moderate cost of electronics
  - u-v-w strip arrays for hit disambiguation in 2D —> virtual pixels
  - z-coordinate from timing information
  - aimed for relatively simple event topologies —> few tracks per event
  - General Electronics for TPCs (GET) for signal amplification & digitization:
    - flexible sampling frequency: 1-100 MHz
    - adjustable gain & filtering per channel
  - both external- and self-trigger possible



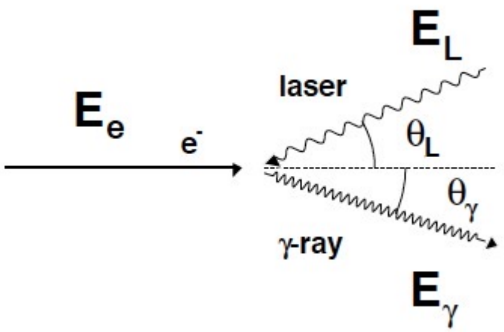


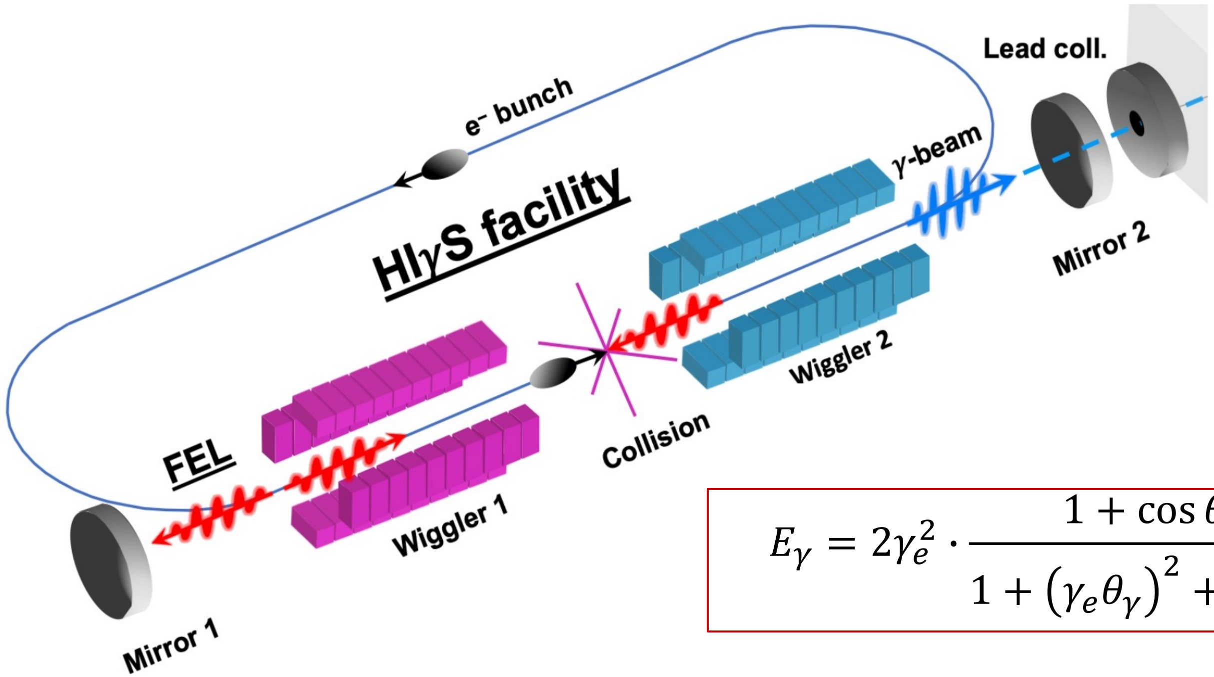
Measurements and preliminary results

HIγS facility: monochromatic γ-ray beams

HIγS facility (TUNL, Durham, NC)

- quasi-monoenergetic γ beams
- energies: 1 to 100 MeV with ~3% FWHM
- linear and circular polarisation
- Production of monochromatic γ-ray beams:
  - Compton Back Scattering of photons on ultra-relativistic electrons (the most efficient frequency amp.)
  - FEL: λ = 400 nm - 193 nm



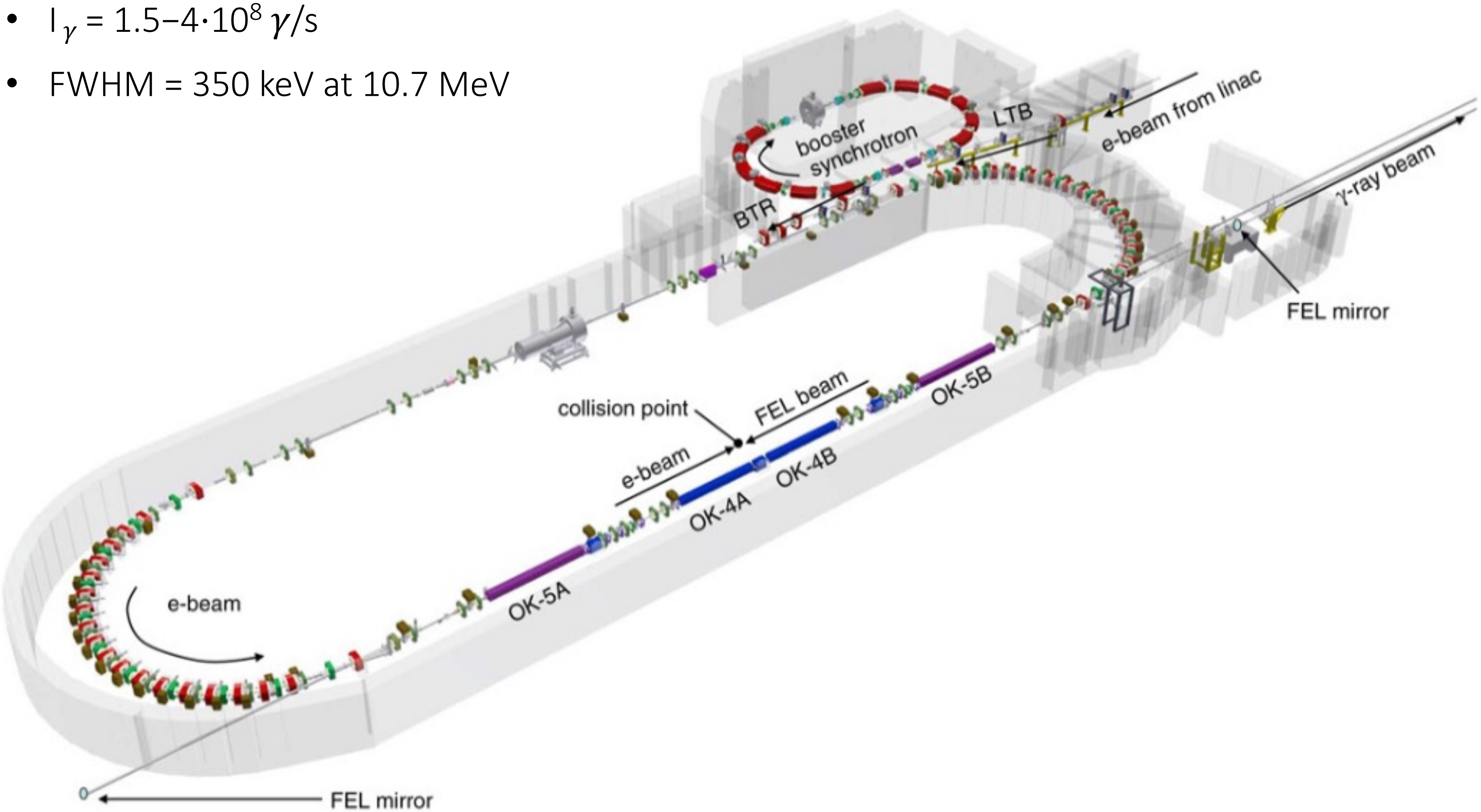


$$E_\gamma = 2\gamma_e^2 \cdot \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L \approx 4\gamma_e^2 E_L$$

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

^{16}O photo-disintegration experiment

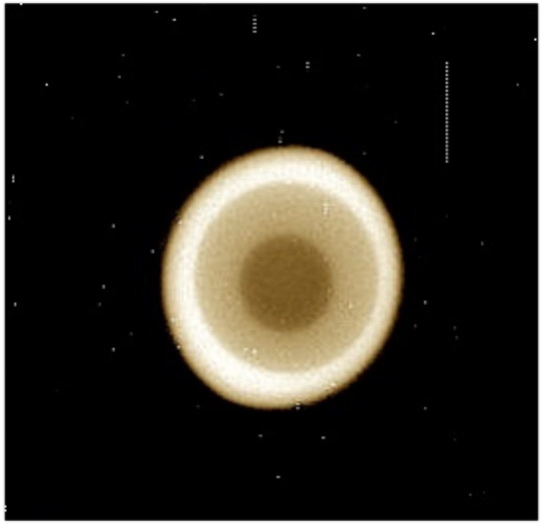
- Measurement conducted in April and August/September 2022 at the HIγS facility (TUNL, Durham, NC)
- Monochromatic γ-ray beams produced with
  - E_γ = 8.51 to 13.9 MeV)
  - I_γ = 1.5–4·10^8 γ/s
  - FWHM = 350 keV at 10.7 MeV



H.R. Weller et. al, Progress in Particle and Nuclear Physics **62** (2009)

^{16}O photo-disintegration experiment: beam monitoring

- Beam monitoring:
  - energy determined by HPGe detector
  - intensity as a function of time monitored by means of scintillation counters
  - absolute calibration of the scintillation detectors event rate: (γ,n) activation measurements on ^{197}Au targets synchronous with data taking
  - beam alignment:
    - laser beam collinear with γ beam + collimator 10.5 mm
    - Attenuated beam and gamma-camera



^{16}O photo-disintegration experiment: Warsaw active-target TPC

- Active gas: CO_2

  - 130 mbar for $E_\gamma < 10$ MeV

  - 190 mbar for 11 MeV $< E_\gamma \leq 13.1$ MeV

  - 250 mbar for $E_\gamma \geq 13.1$ MeV

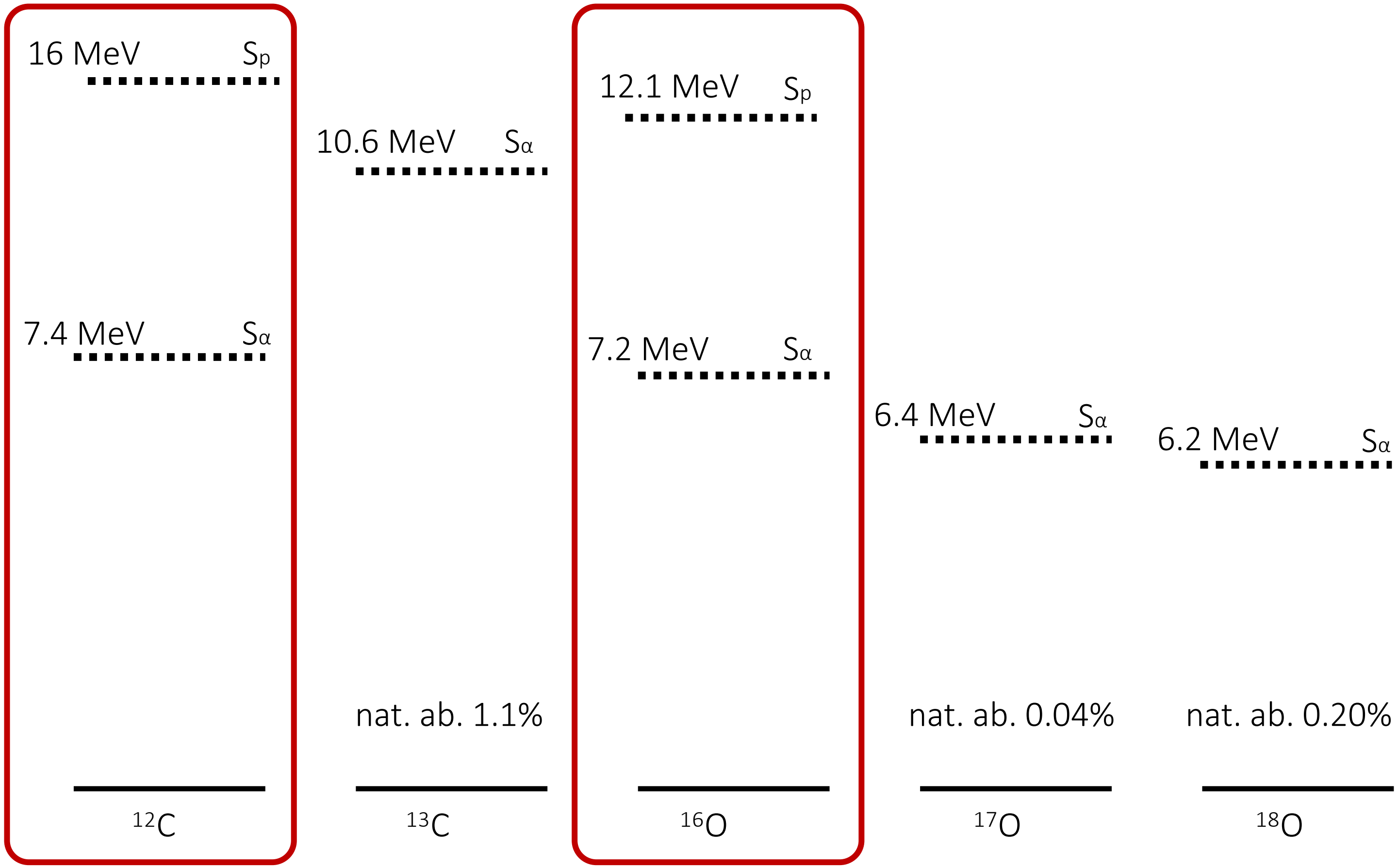
- Charged reaction-products detected

^{16}O photo-disintegration experiment: background

- CO_2 gas: natural isotopic composition

  → reactions on ^{12}C and ^{16}O – goal of the experiment | discriminant: topology

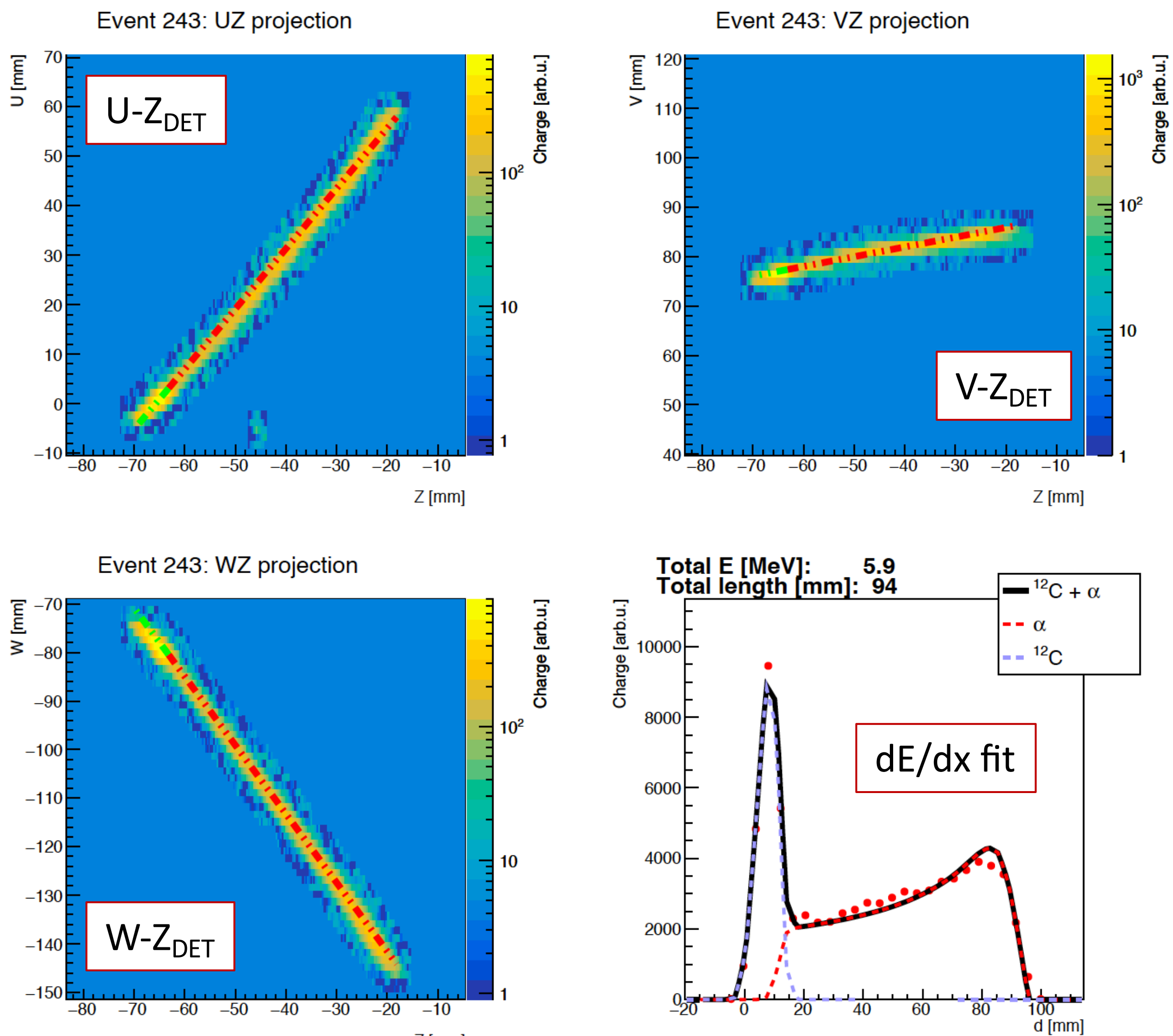
  → reactions on $^{17,18}O$ and ^{13}C – beam-induced background | discriminant: Q-value



Preliminary(!) results: $^{16}O(\gamma,\alpha)$

Warsaw TPC

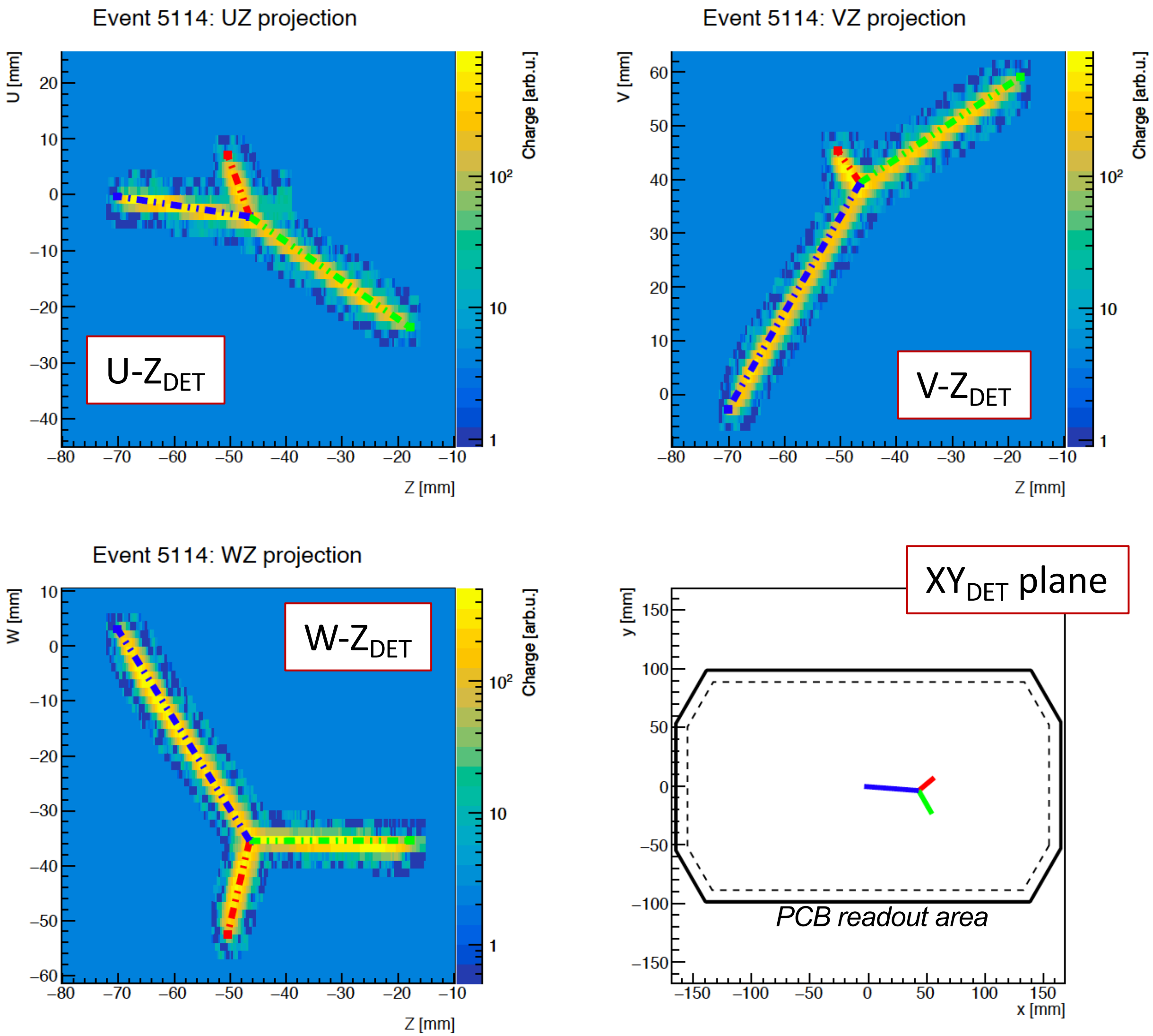
$E_{\gamma} = 13.9$ MeV



Preliminary(!) results: $^{12}C(\gamma,3\alpha)$

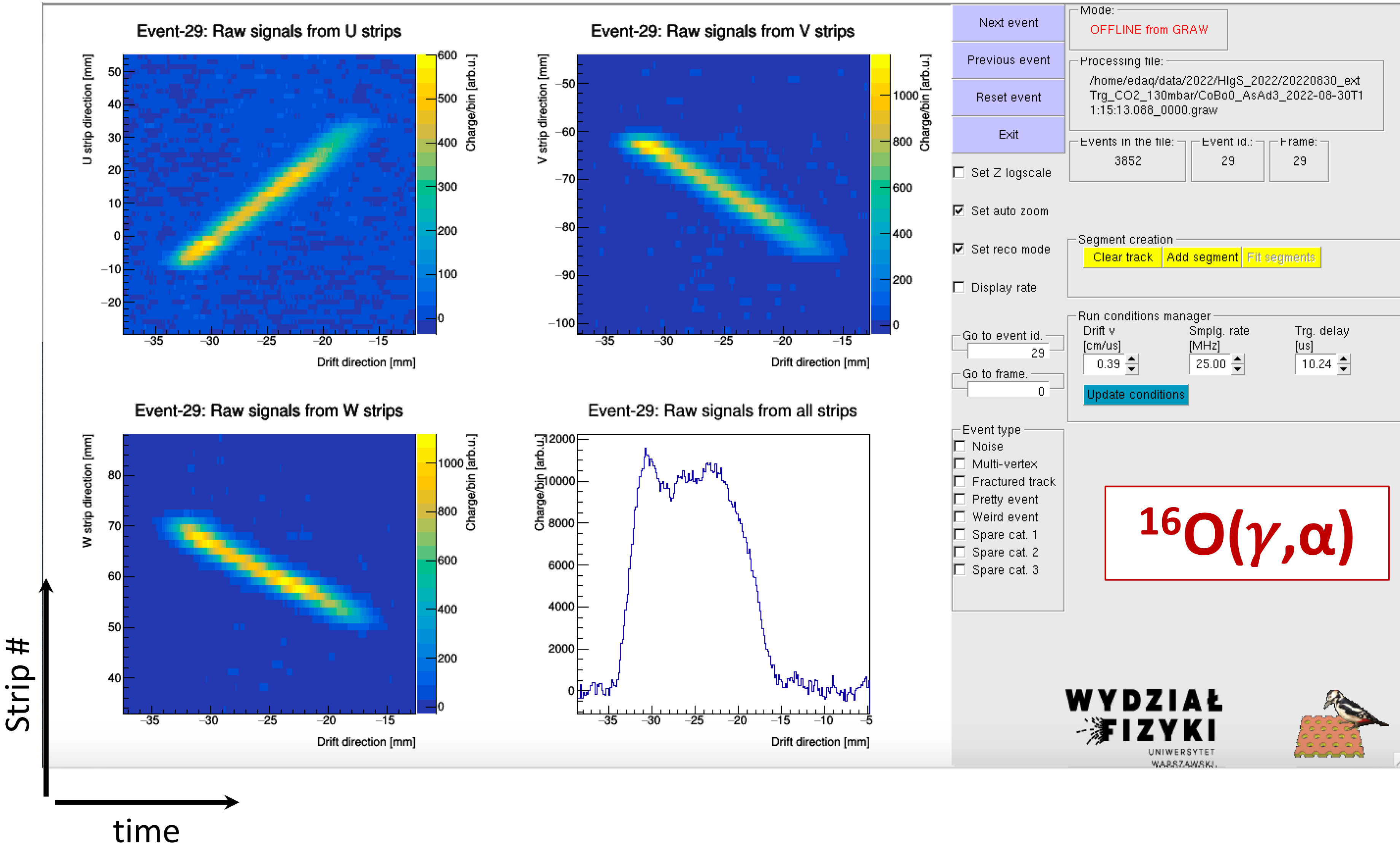
Warsaw TPC

E_γ = 13.9 MeV



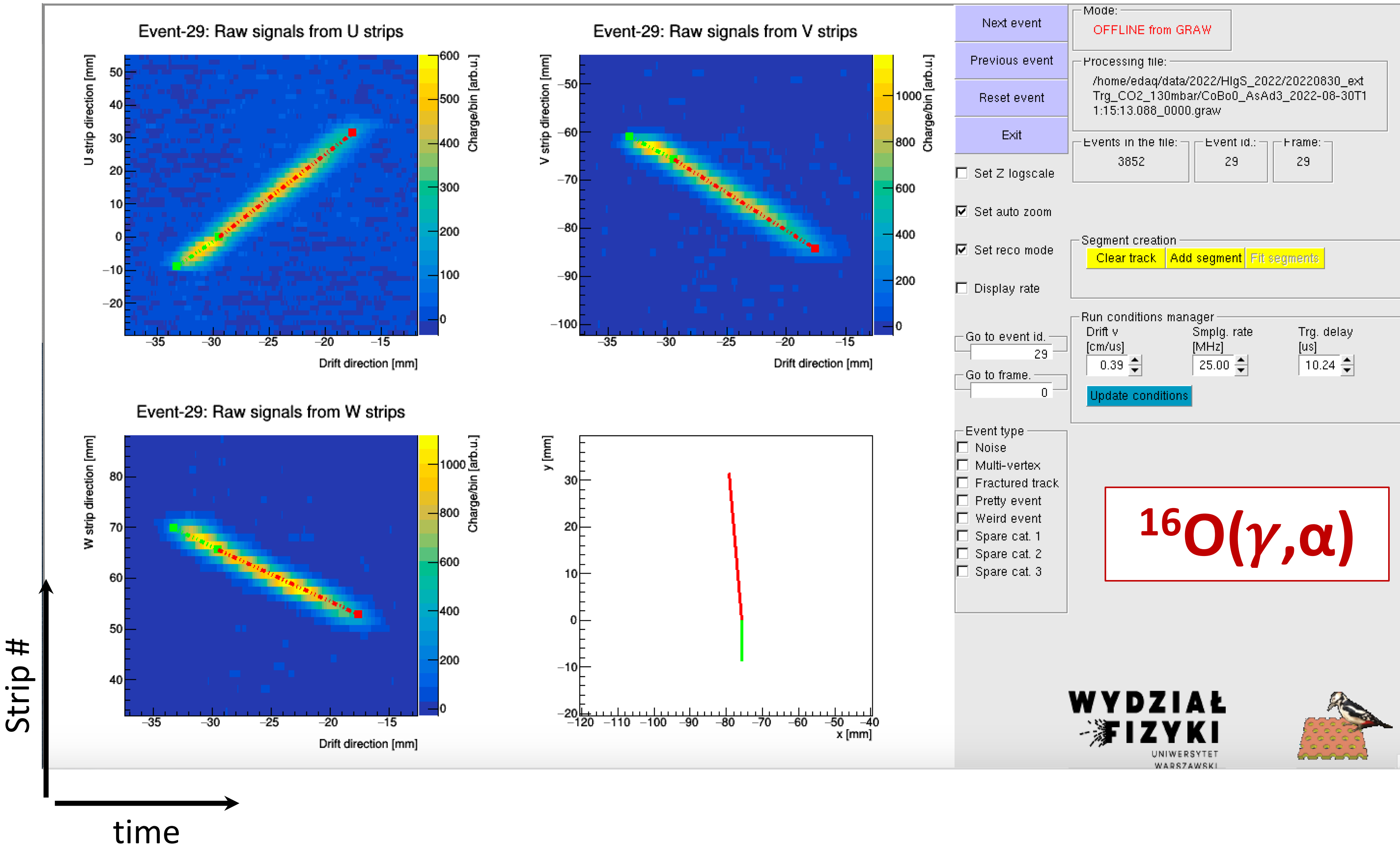
Preliminary(!) results: $^{16}O(\gamma,\alpha)$

$E_\gamma = 8.66$ MeV

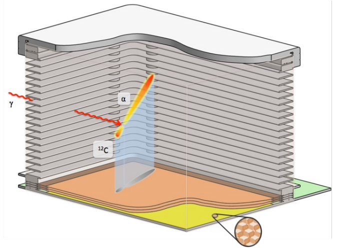


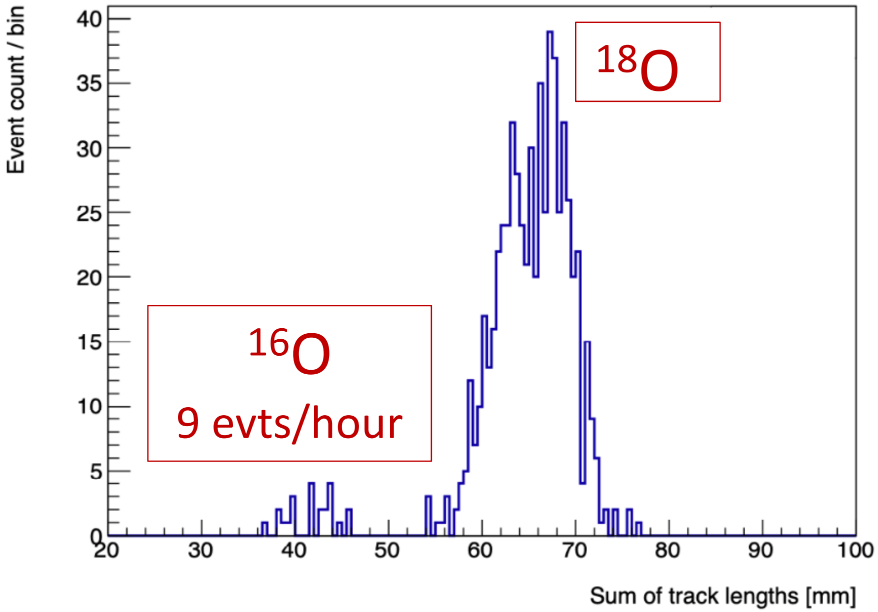
Preliminary(!) results: $^{16}O(\gamma,\alpha)$

$E_\gamma = 8.66$ MeV



Event identification

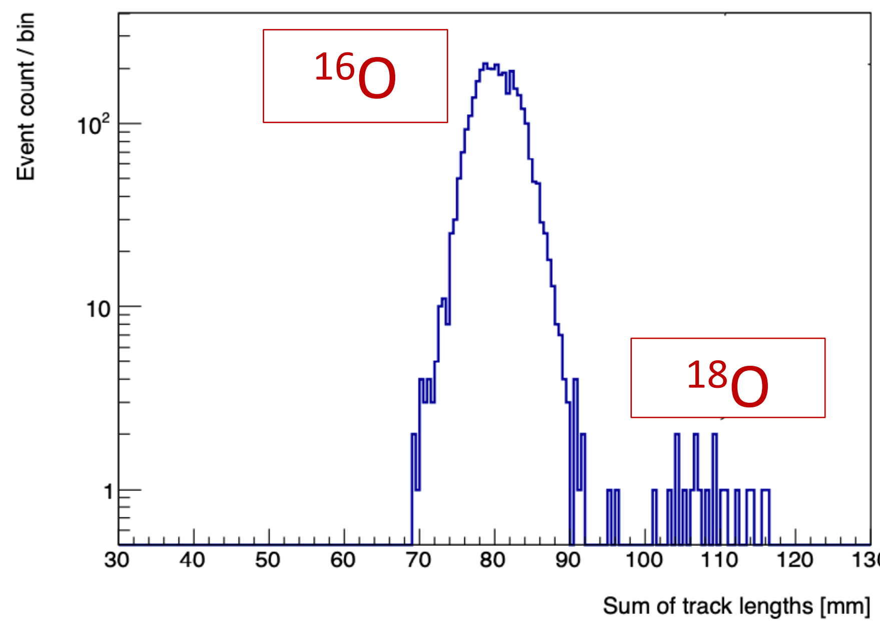




E_γ = 8.66 MeV

Preliminary!

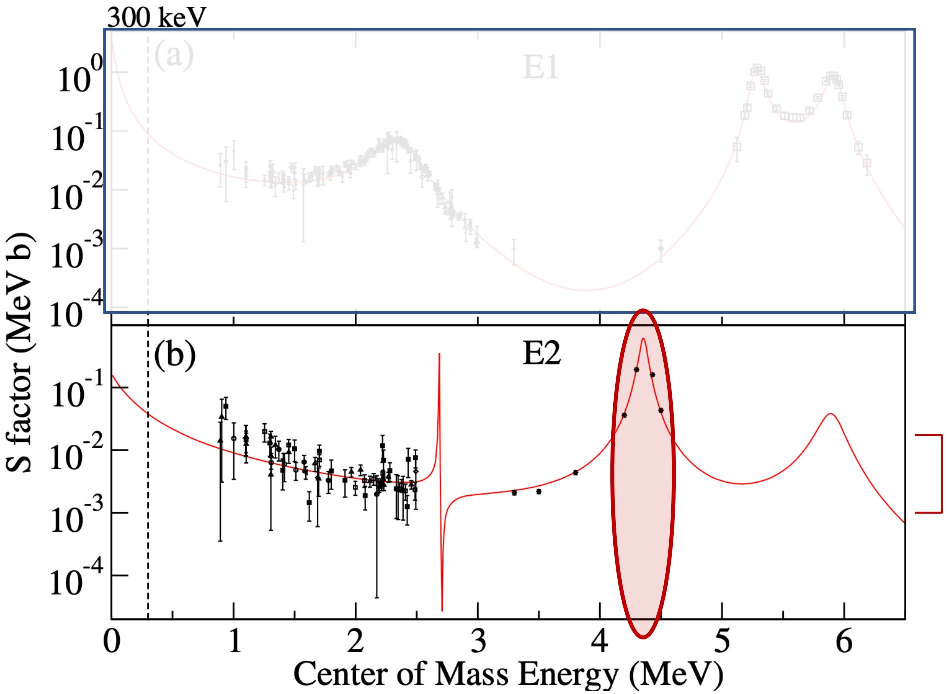
E_γ = 11.5MeV



Topology:
2-particle events

LAB ref. system

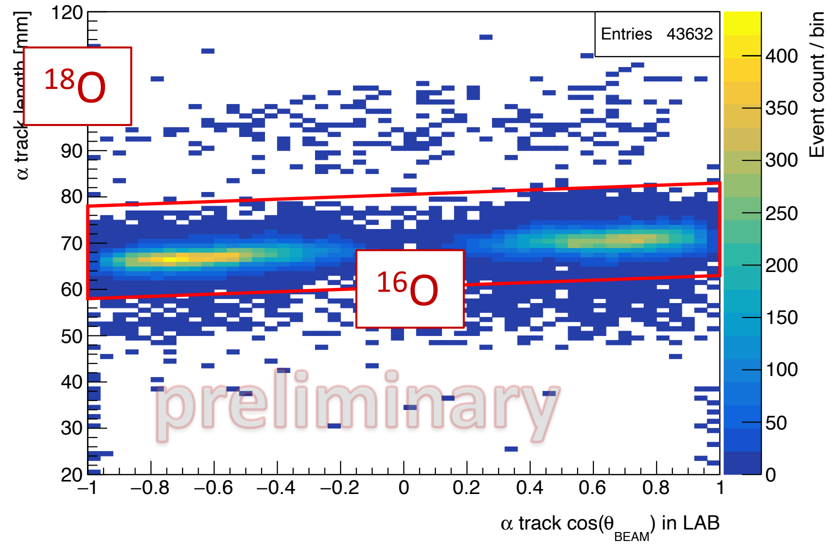
Angular distribution (polar, θ)--> multipolarity

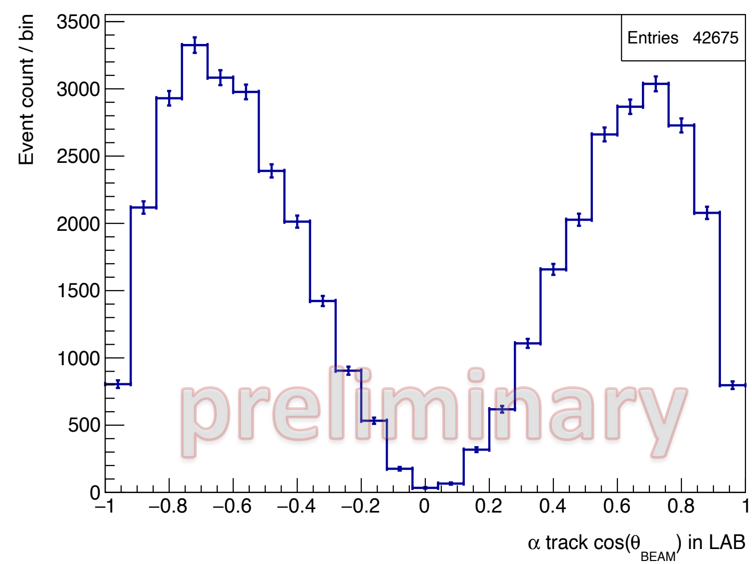


$E_\gamma = 11.5\text{MeV}$

$^{16}O \rightarrow ^{12}C + \alpha$

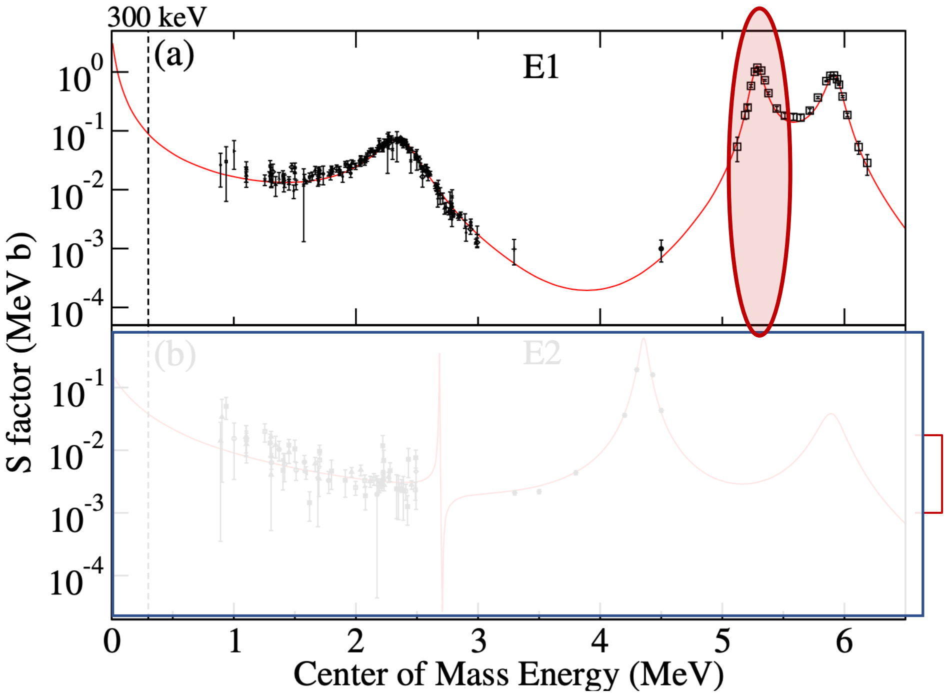
Topology:
2-particle events



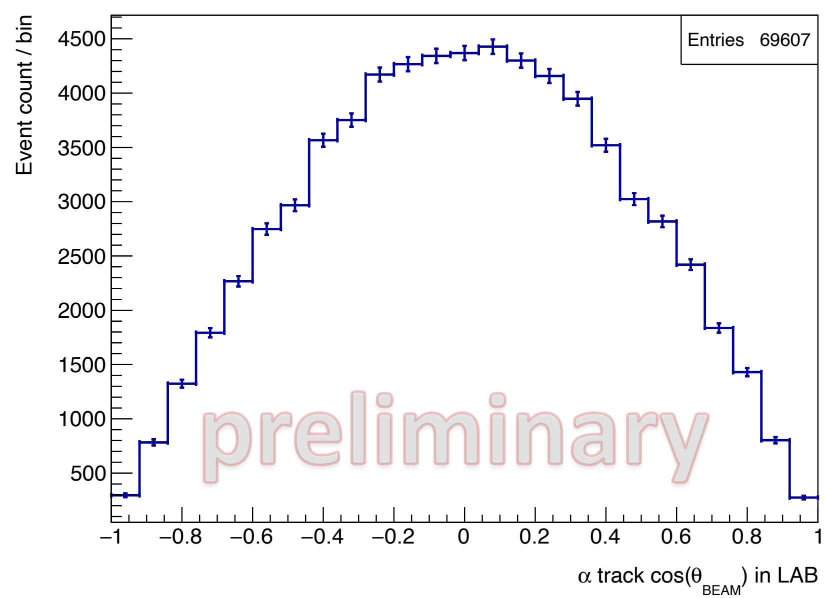


LAB ref. system

Angular distribution (polar, θ) --> multipolarity



Topology:
2-particle events



E_{γ} = 12.3 MeV

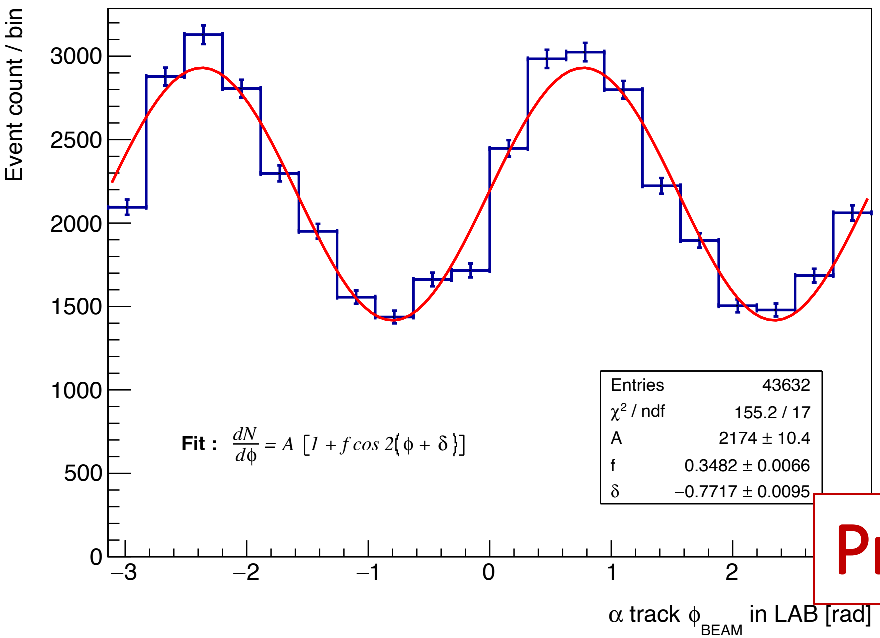
$^{16}O \rightarrow ^{12}C+\alpha$

Topology:
2-particle events

LAB ref. system

Angular distribution (azimuthal, ϕ) --> beam characterization

E_γ = 11.5MeV



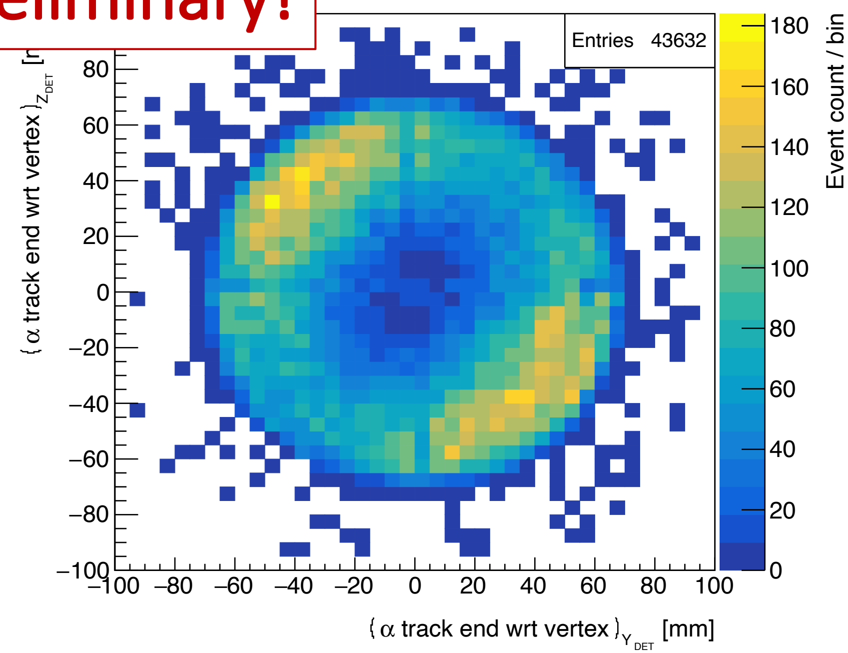
Degree of circular polarization

- direct measurment of γ beam polariz.

$$S_3 = 0.9374$$

- direct measurement of linear polariz. of laser beam (Y.K. Wu, 2021, priv. comm.), values in very good agreement

Preliminary!



Polarization --> Stokes vector

$$\vec{S} = (1, S_1, S_2, S_3)^T$$

$$W(\phi) = 1 + f \cdot cos(\phi - \phi_0)$$

$$S_1 = \frac{W(0°) - W(^{\pi}/_{2})}{W(0°) + W(^{\pi}/_{2})}$$

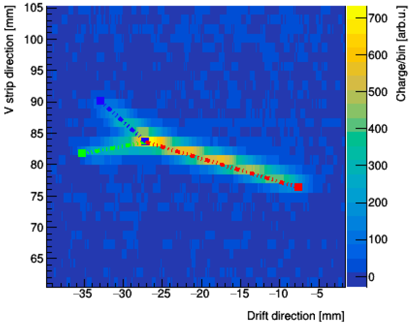
$$S_2 = \frac{W(^{\pi}/_{4}) - W(-^{\pi}/_{4})}{W(^{\pi}/_{4}) + W(-^{\pi}/_{4})}$$

$$\boldsymbol{S_3} = \sqrt{\boldsymbol{1 - S_1^2 - S_2^2}}$$

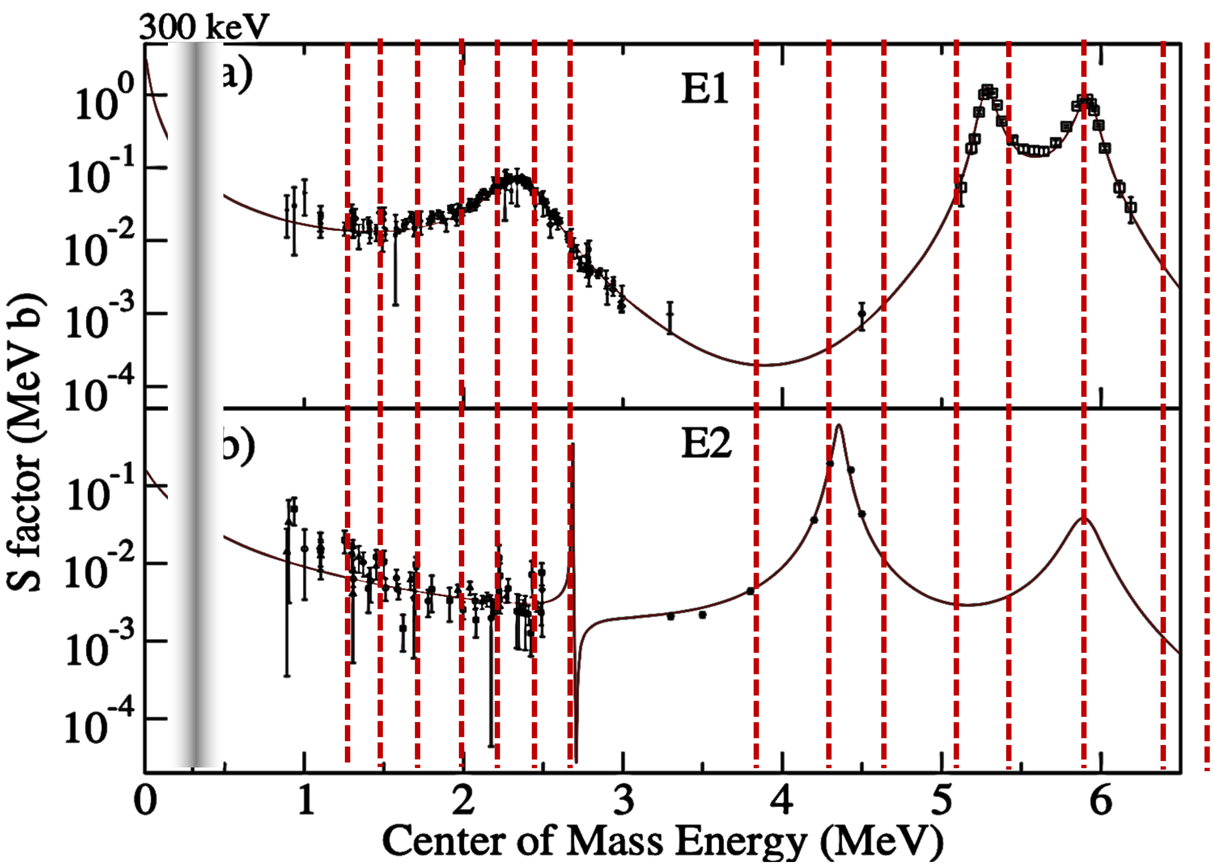
Summary and Outlook

- First experiments with the Warsaw active target TPC to measure $^{16}O(\gamma,\alpha)$ and $^{12}C(\gamma,3\alpha)$ at E_{γ} = 8.51 – 13.9 MeV in April and Aug./Sep. 2022 at HIγS@TUNL

- Data under analysis, more to come…



… STAY TUNED!



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