Investigating photodisintegration reactions with the Warsaw TPC

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on behalf of the Warsaw TPC group

Seminar “Physics of Atomic Nucleus”, 15.06.23

William Fowler,
Nobel Foundation archive

“It is little wonder that the determination of the ratio $^{12}C/^{16}O$ produced in helium burning is a problem of paramount importance in Nuclear Astrophysics.”

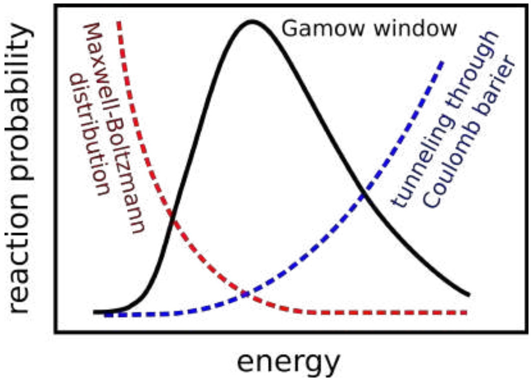
W. A. Fowler, Rev. Mod. Phys. **56**, 149 (1984)

C/O ratio importance

- stellar evolution modelling
- Ia supernova (Standard candles) light curves modelling
- influences the gap in black-hole mass distribution

C/O ratio

Stellar nuclear reactions occur within narrow energy windows



The ^{12}C/^{16}O ratio depends on the relative rates of the reactions:

$$3\alpha \rightarrow {}^{12}\mathrm{C}$$

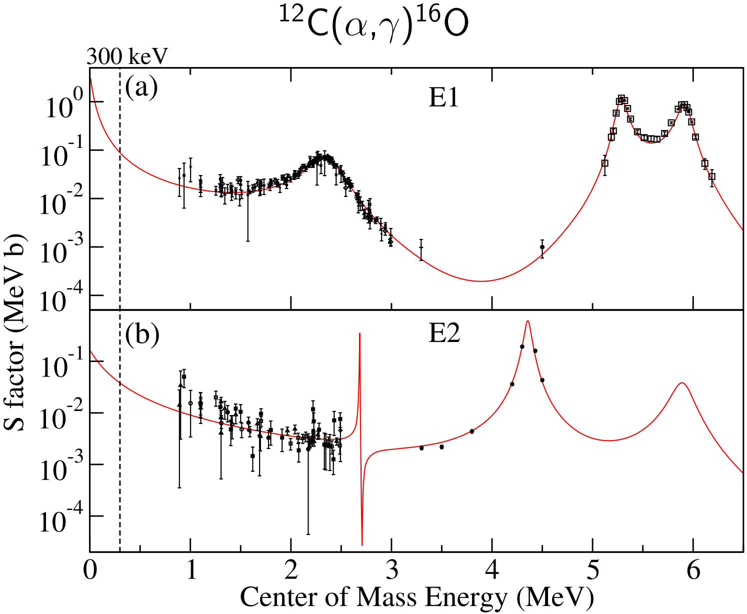
$$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$$

Experimental data

- R-matrix fits to extrapolate at Gamow energy
- cross sections need to be measured at as-low-as-possible
- measurements are challenging below 2 MeV in c.o.m.

$$S(E) = \frac{E}{\exp\left(-2\pi\eta\right)}\sigma(E)$$

$$\eta = \frac{Z_1 Z_2 \alpha}{\beta}$$



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

The detailed balance principle

$$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O} \rightleftharpoons {}^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$$

direct capture photodisintegration

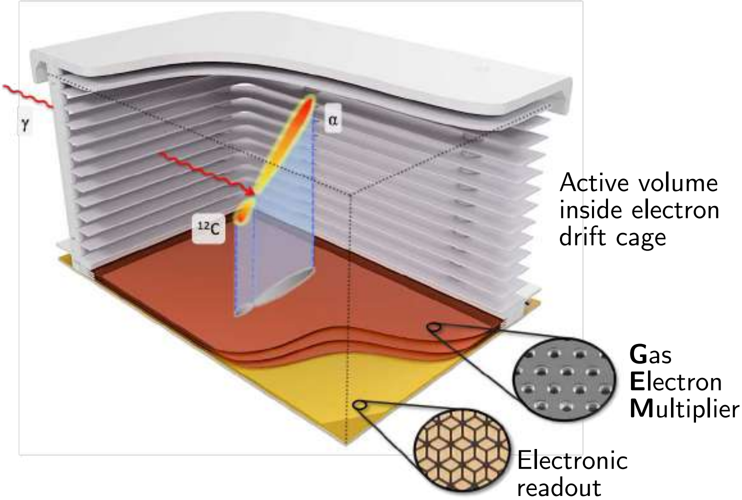
Photodisintegration vs direct capture:

- low background measurement,
- different systematic uncertainty,
- higher cross-section

$$\sigma_{\alpha,\gamma}(1\ \mathrm{MeV}) \approx 50\ \mathrm{pb}$$

$$\sigma_{\gamma,\alpha}(1\ \mathrm{MeV}) \approx 2000\ \mathrm{pb}$$

Active-target Time Projection Chamber with electronic readout



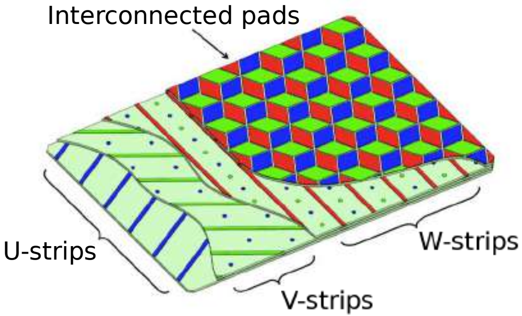
- active volume: 33x20x20 cm^3
- under-pressured (80-250 mbar CO_2)
- charge amplification with 3 GEM foils
- custom readout

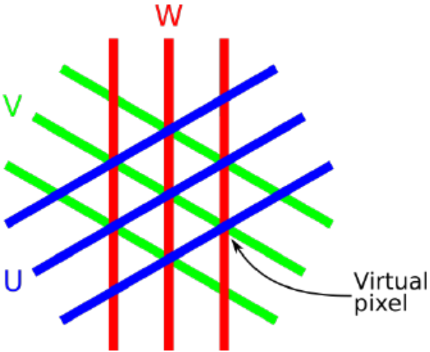
Strip readout

XY plane: $\sim$ 1000 channels (U,V,W),
Three coordinates
Redundant coordinate for hit disambiguation

$$\begin{pmatrix} u \\ v \\ w \\ t \end{pmatrix} = \begin{pmatrix} \cos(0) & \sin(0) & 0 \\ \cos\left(-\frac{2\pi}{3}\right) & \sin\left(-\frac{2\pi}{3}\right) & 0 \\ \cos\left(-\frac{\pi}{3}\right) & \sin\left(-\frac{\pi}{3}\right) & 0 \\ 0 & 0 & \frac{1}{v_d} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Z axis: drift time



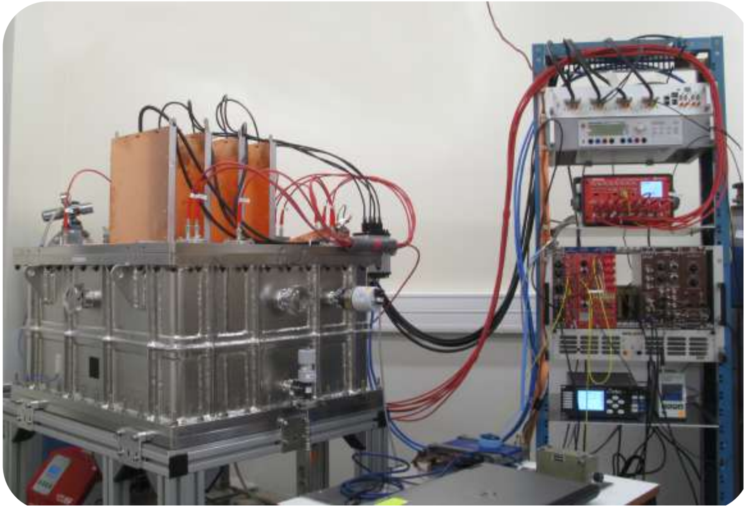


M. Ćwiok, Acta Phys.Pol. B **47** (2016)

Detector operational since March 2020

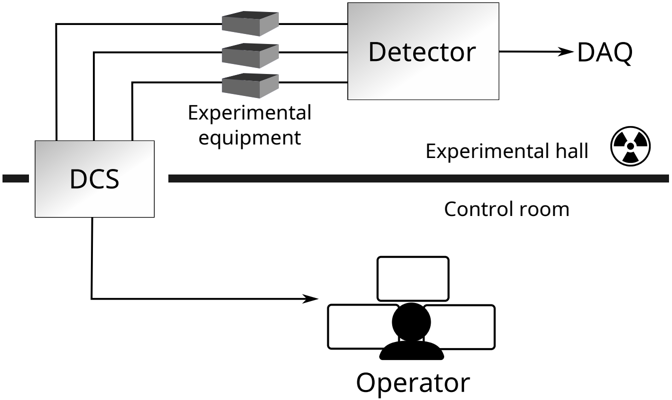
The detector is accompanied by:

- Detector Control System,
- data acquisition and data storage systems,
- simulation framework,
- data analysis software framework.



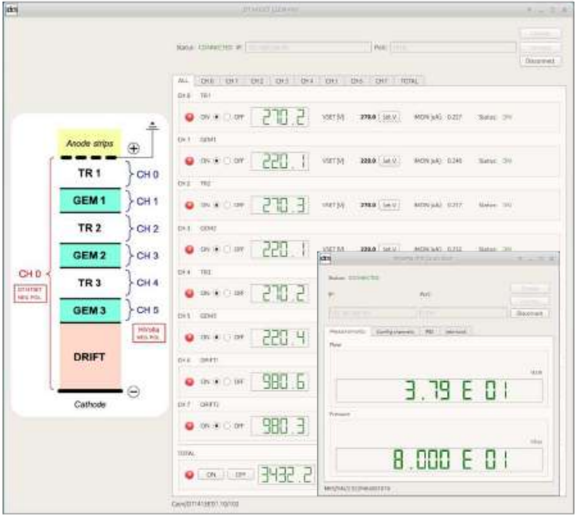
Detector Control System

- monitoring
- device control
- historical data
- alarms
- access restriction

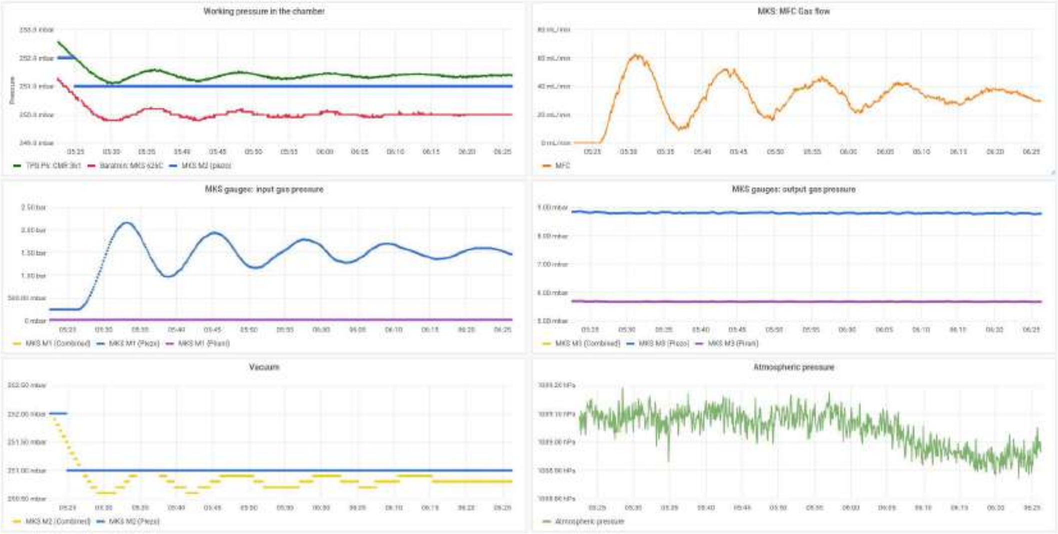


DCS

- Based on OPC UA open standard
- Qt5 control panel
- InfluxDb time-series database
- Grafana dashboards



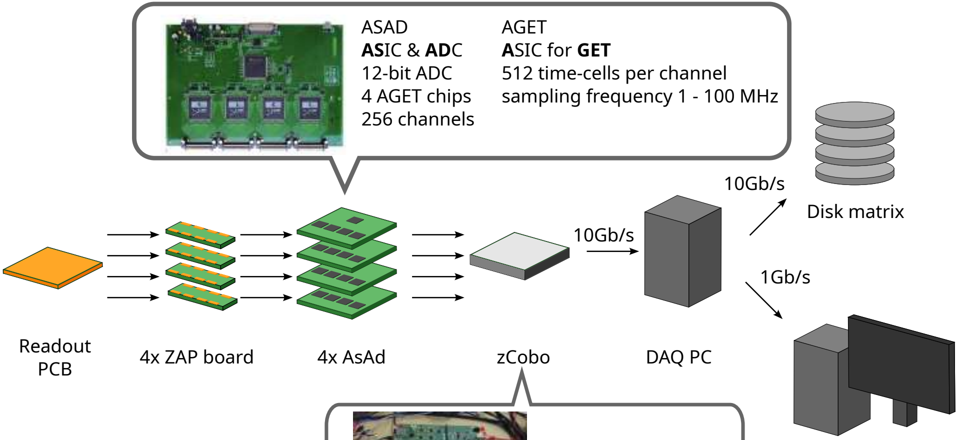
DCS historical data

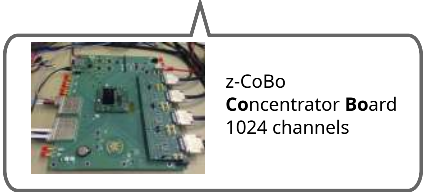


DAQ chain based on GET

Generic **E**lectronics for **T**PCs

(CEA/IRFU, CENBG, GANIL, MSU/NSL)





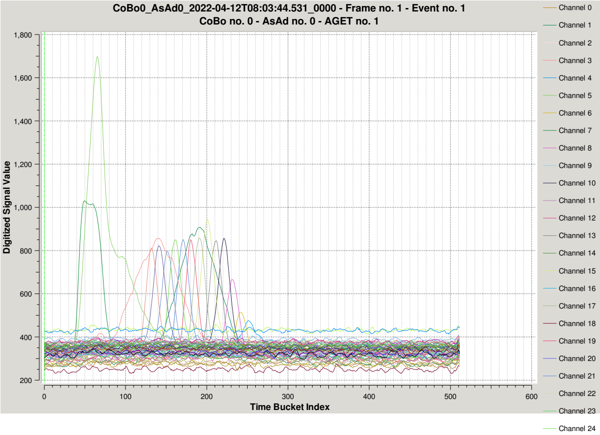
Control room PC

Readout PCB, ZAP boards and z-CoBo developed at UW

M. Zaremba
K. Kierzkowski
W. Okliński

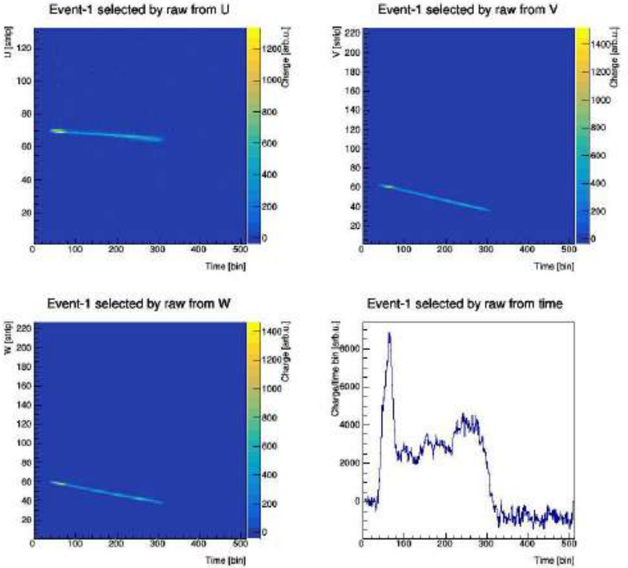
Event waveform

- ∼1000 electronic channels
- 512 time bins



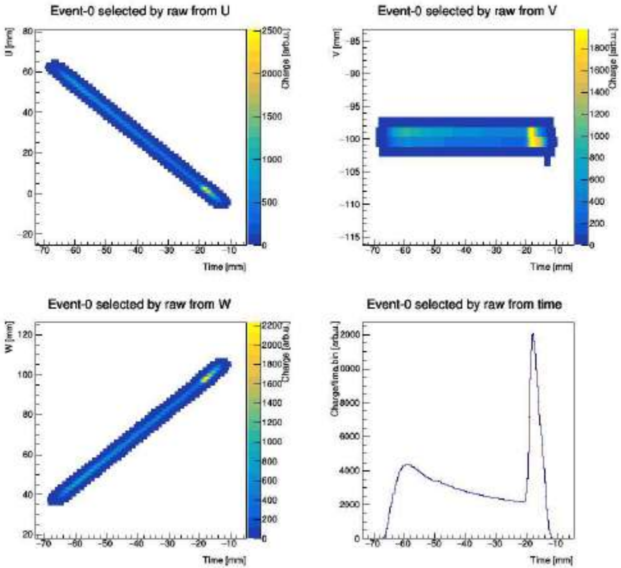
Event representation

- Electronic channels mapping
- 3x 2D projection on strip direction (U, V, W)



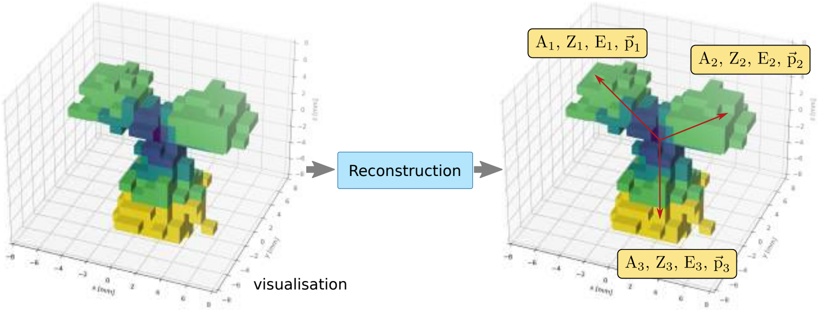
Simulation framework

- Event generator
- Ionization simulation with Geant4 or SRIM
- Electronics response
- Trigger effects
- Signal digitizer

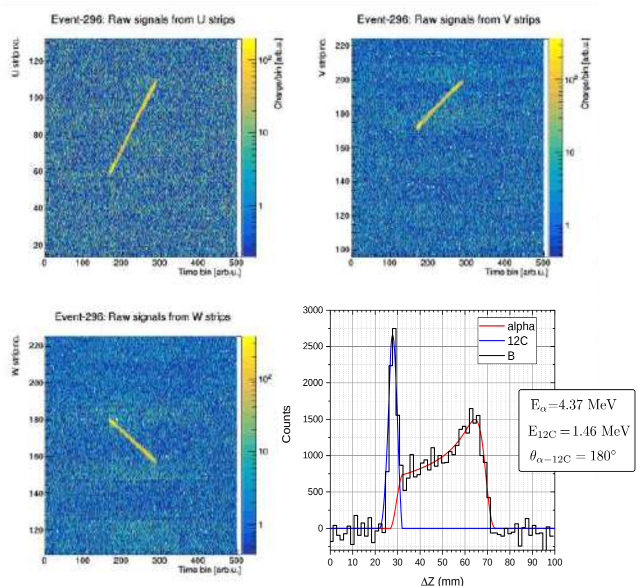


Event reconstruction

Concept:



Kinematic reconstruction

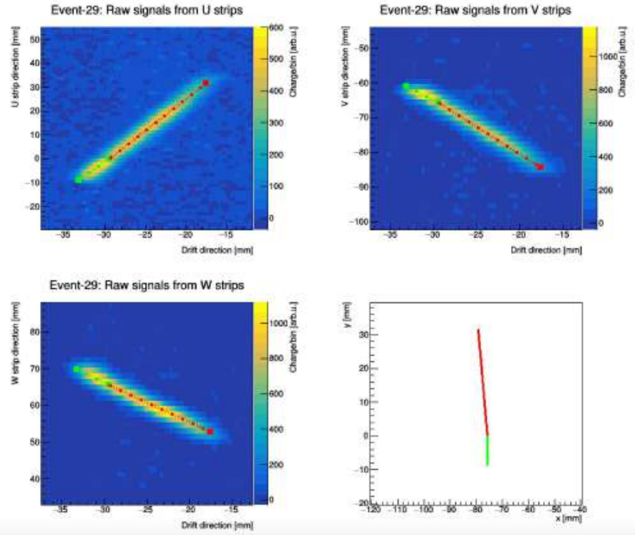


Particle identification, energy and momentum can be obtained from:

- track length (range in medium)
- ionization along the track (Bragg curve)

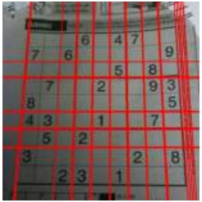
Manual reconstruction

- Vertex and endpoints marked by a human
- Strip coordinates converted to Cartesian coordinates using chosen two strip directions



Line detection in the wild

Hough, P. V. C., Conf. Proc. C 590914 (1959)



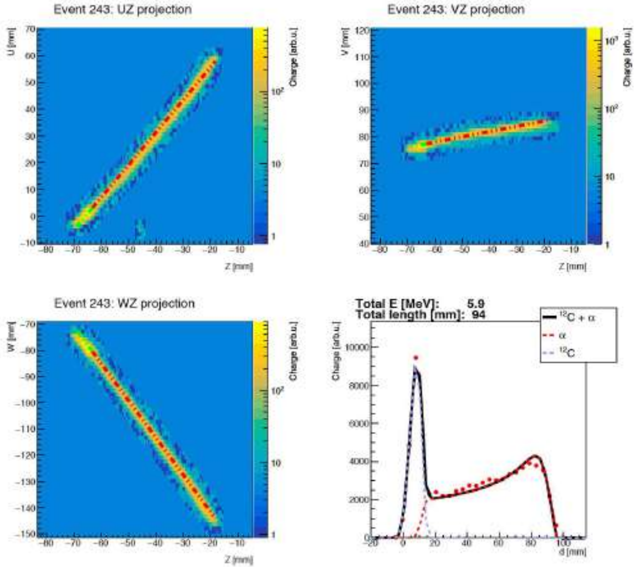
OpenCV tutorial

https://github.com/gchlebus/tennis-court-detection

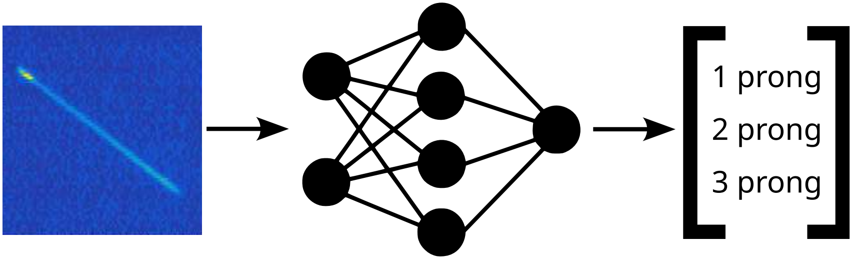
road line detection example

Automatic reconstruction

- Hough line detection
- 3D line fitting
- Bragg curve fit to the ionization along the track

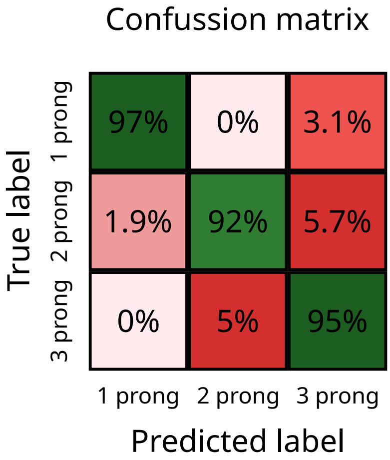


Neural network classification



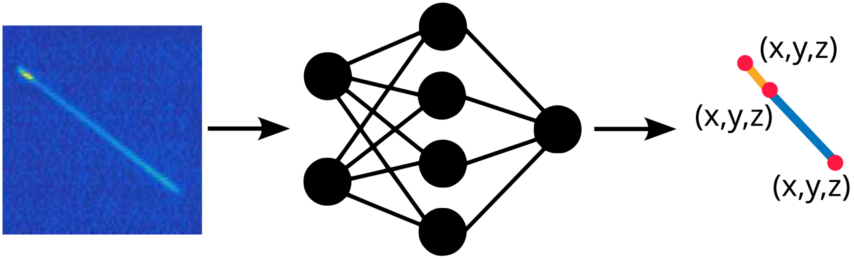
Neural network classification

- ResNet architecture
- Trained and evaluated on data manually labeled by experts



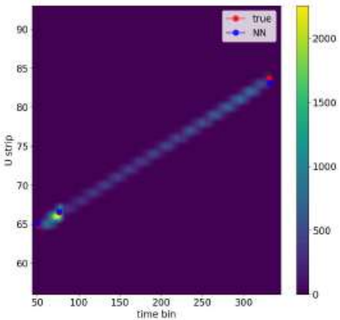
K. Haverson, R. Smith

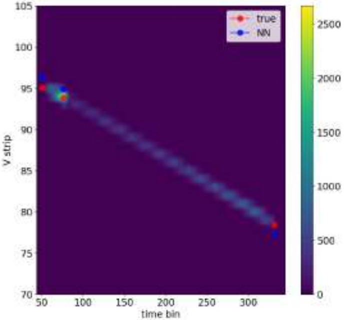
Neural network regression

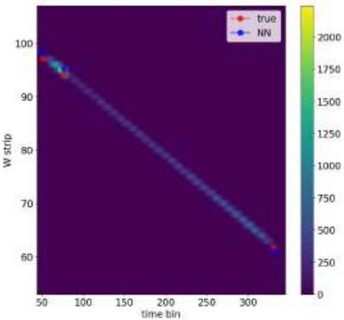


Neural network regression

Convolutional neural network trained and evaluated on simulation data







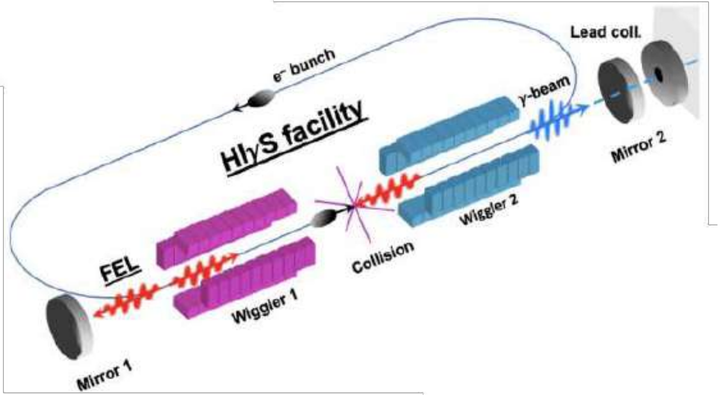
γ-beam facilities

- HIγS (**H**igh **I**ntensity **G**amma-Ray **S**ource, USA)
  $10^8\ \gamma/s, 3\%$ FWHM
- NewSUBARU (Japan)
  $10^5\ \gamma/s, 1.2\%$ FWHM
- ELI-NP (**E**xtreme **L**ight **I**nfrastructure **N**uclear **P**hysics, Romania, under construction)
  $10^9\ \gamma/s, 0.5\%$ RMS

HIγS facility

TUNL, Durham, USA

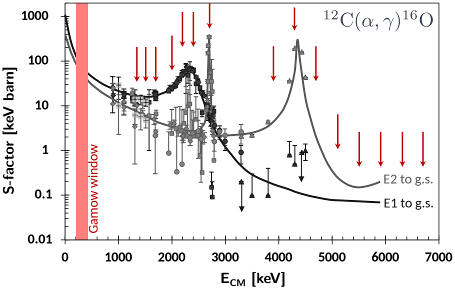
- quasi-monoenergetic γ-beams
- energies: 1 to 100 MeV with $\sim$3% FWHM
- linear and circular polarization
- beam produced in Compton back-scattering of laser photons on ultra-relativistic electrons



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

Experiment at HIγS

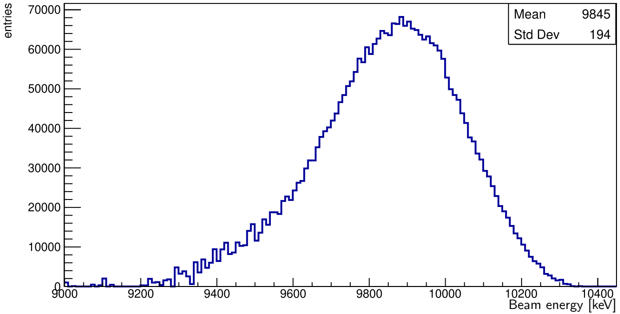
- April and August/September 2022 at the HIγS facility
- Monochromatic γ-beam:
  $E_\gamma = 8.5 - 13.9$ MeV
  $I_\gamma > 1.3 \cdot 10^8\ \gamma/s$
  FWHM(8.5 MeV) $= 350$ keV



- Chamber filled with pure CO_2 at 130, 190, 250 mbar
- Measurements of $^{16}O(\gamma,\alpha)^{12}C$ and $^{12}C(\gamma,3\alpha)$

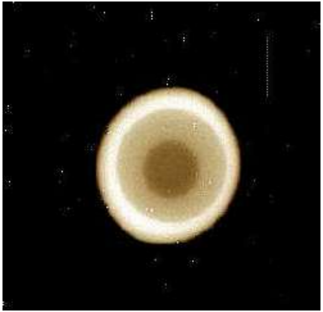
Beam monitoring

- energy determined by HPGe
- intensity time evolution monitored by scintillation counters
- absolute intensity calibrated by (γ, n) activation on ^{197}Au target



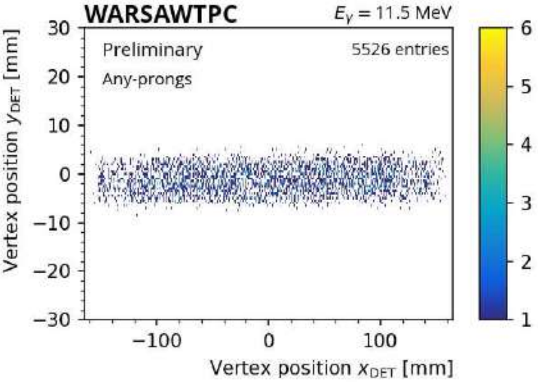
Beam alignment

- laser beam collinear with γ-beam + collimator 10.5 mm
- attenuated beam and gamma-camera

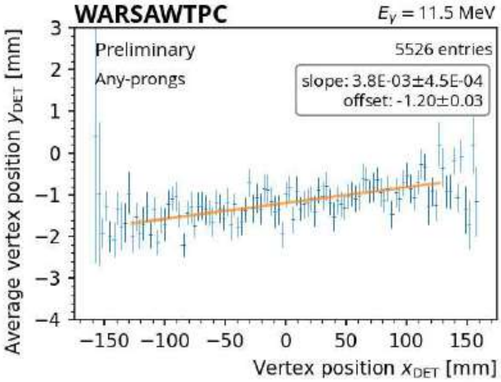


Beam alignment with TPC

Vertex on the detector plane

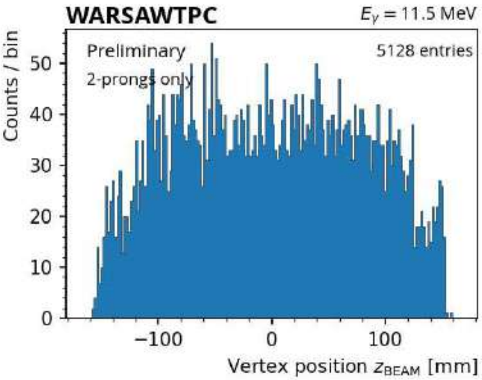


Beam misalignment

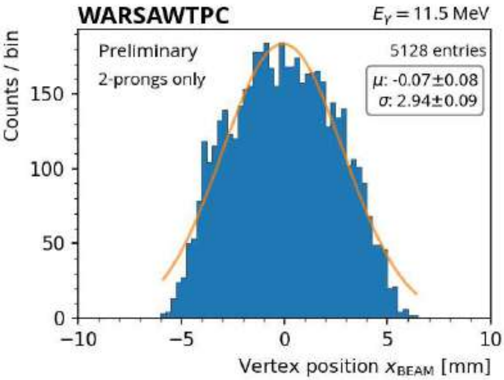


Beam alignment with TPC

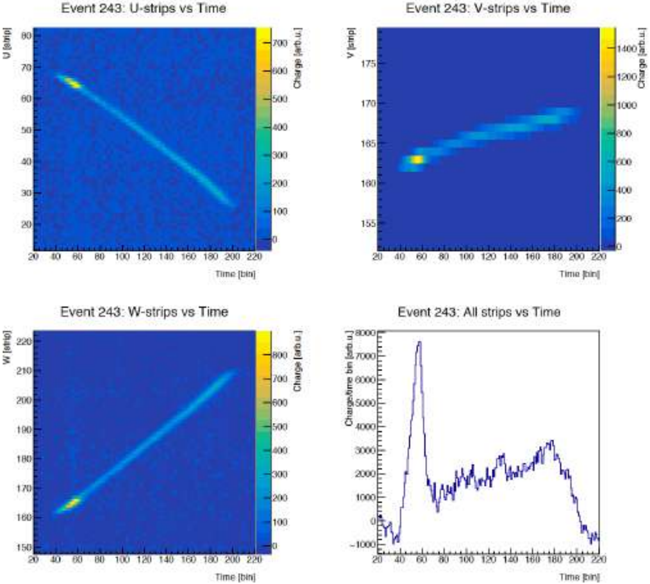
Counts along beam



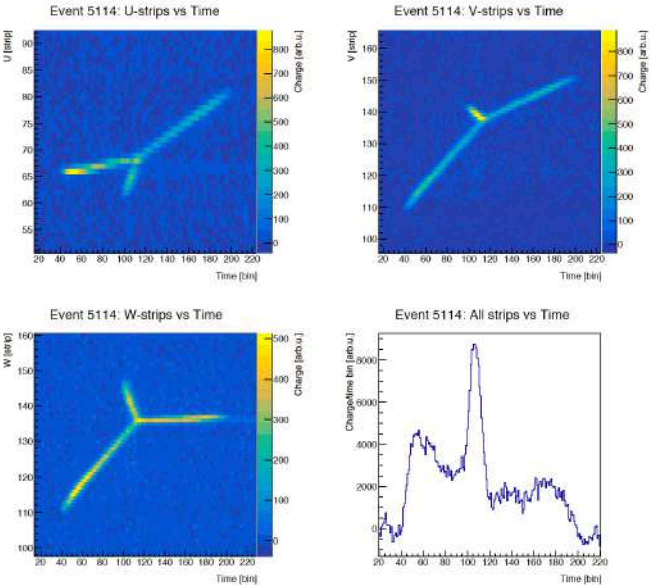
Beam shape

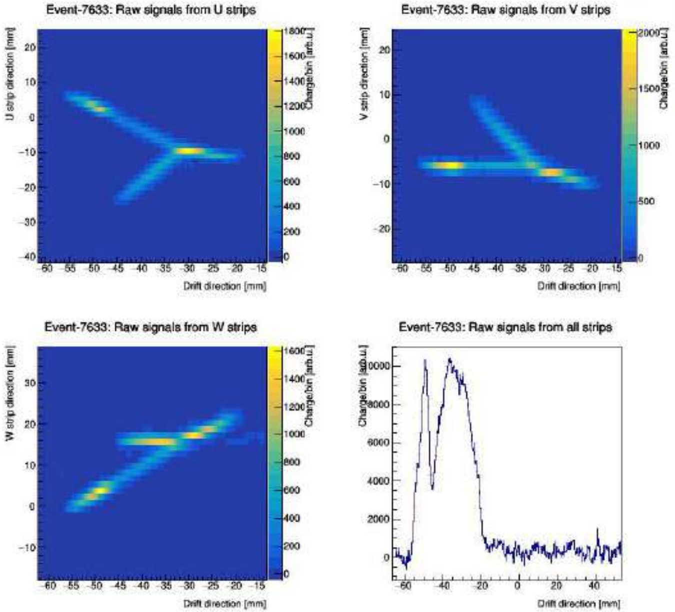


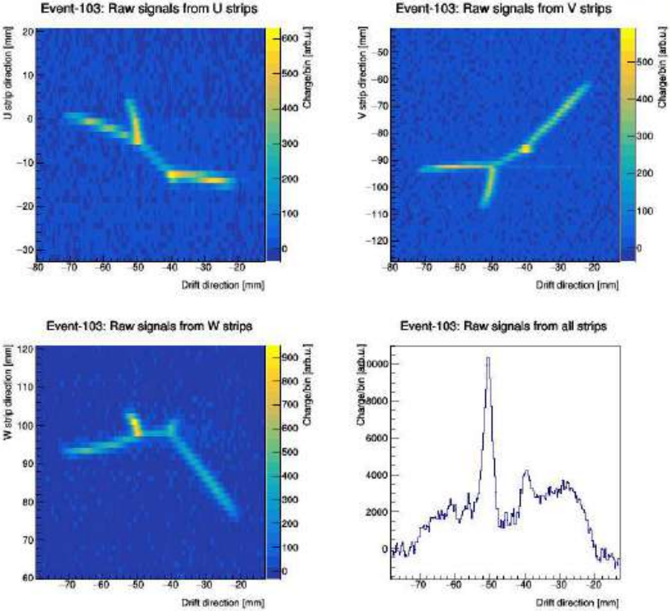
2-prong example, $^{16}O(\gamma,\alpha)^{12}C$ candidate

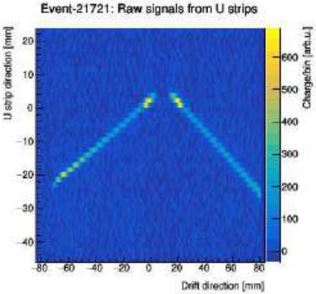


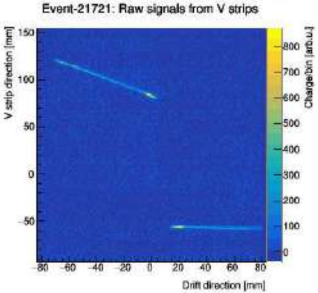
3-prong example, ^{12}C(γ,3α) candidate

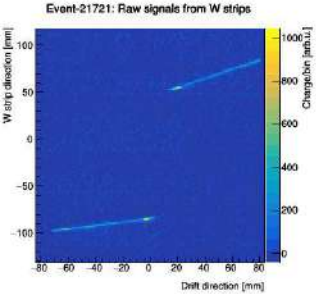


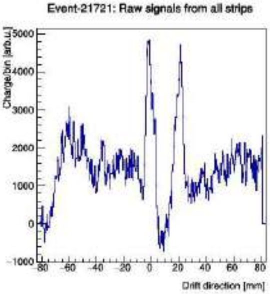

Event-7633: Raw signals from U strips
U strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]
Event-7633: Raw signals from V strips
V strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]
Event-7633: Raw signals from W strips
W strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]
Event-7633: Raw signals from all strips
Charge/bin [arb.u.]
Drift direction [mm]


Event-103: Raw signals from U strips
U strip direction [mm]
Charge/bin [arb.u.]
Drift direction [mm]
Event-103: Raw signals from V strips
V strip direction [mm]
Charge/bin [arb.u.]
Drift direction [mm]
Event-103: Raw signals from W strips
W strip direction [mm]
Charge/bin [arb.u.]
Drift direction [mm]
Event-103: Raw signals from all strips
Charge/bin [arb.u.]
Drift direction [mm]

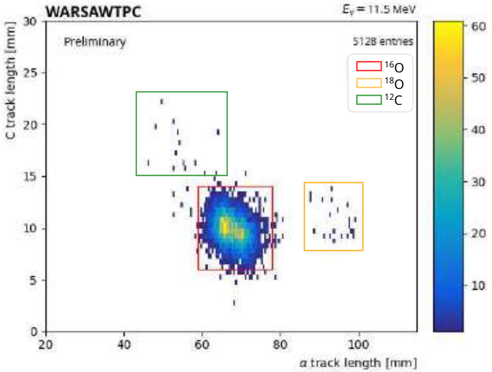

Event-21721: Raw signals from U strips
U strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]

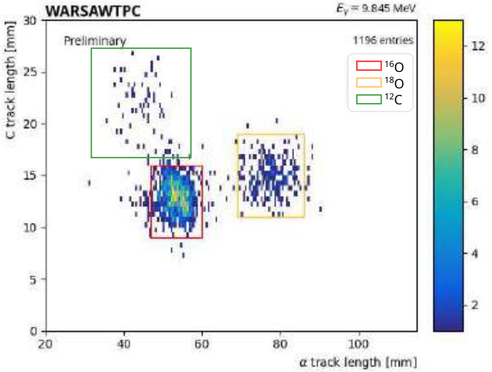

Event-21721: Raw signals from V strips
V strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]


Event-21721: Raw signals from W strips
W strip direction [mm]
Drift direction [mm]
Charge/bin [arb.u.]

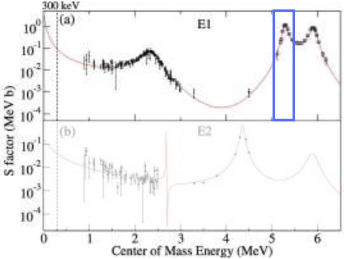

Event-21721: Raw signals from all strips
Charge/bin [arb.u.]
Drift direction [mm]

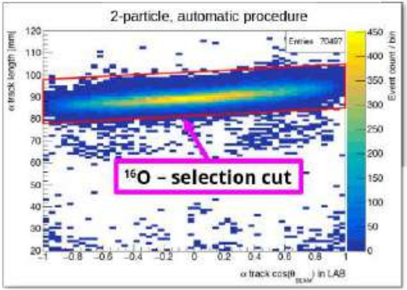
Event selection

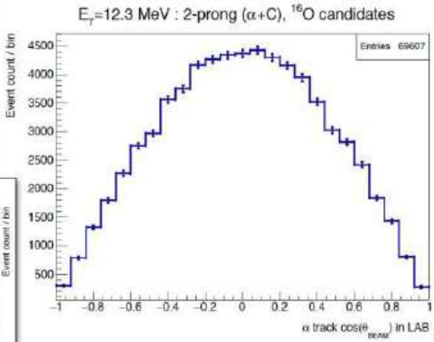




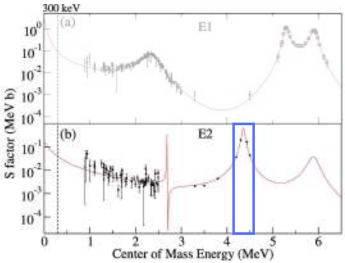
Preliminary results - 12.3 MeV

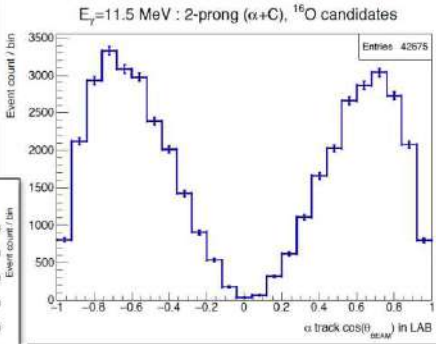


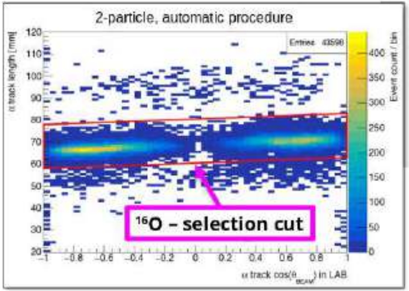




Preliminary results - 11.5 MeV

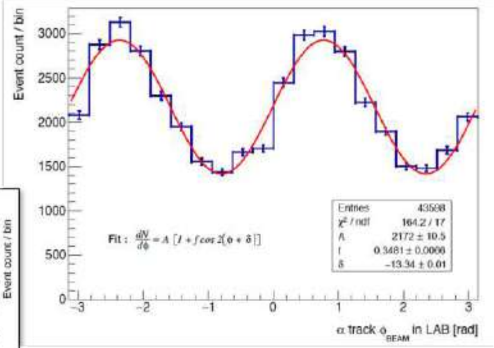


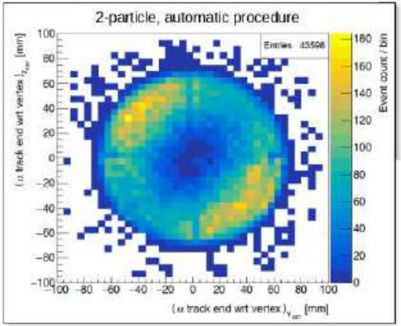




Preliminary results - 11.5 MeV

Azimuthal angle of 2-prong events





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

Summary

- An active-target TPC with electronic readout suited for studying photonuclear reactions has been developed at the University of Warsaw
- The first experiments with the detector to measure ^{16}O and ^{12}C photodisintegration were conducted in April and Aug./Sep. 2022 at the HIγS facility
- Ongoing data analysis

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