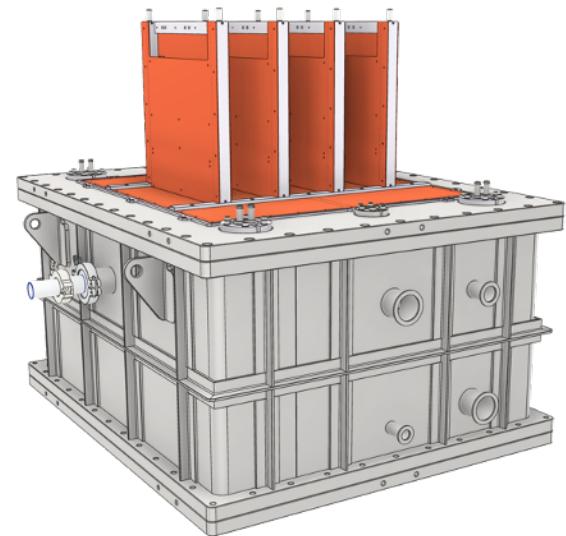


Warsaw Active-Target TPC: a new detector for photonuclear reactions studies at astrophysical energies



**FACULTY OF
PHYSICS**

Mikołaj Ćwiok
University of Warsaw



European Nuclear Physics Conference 2022

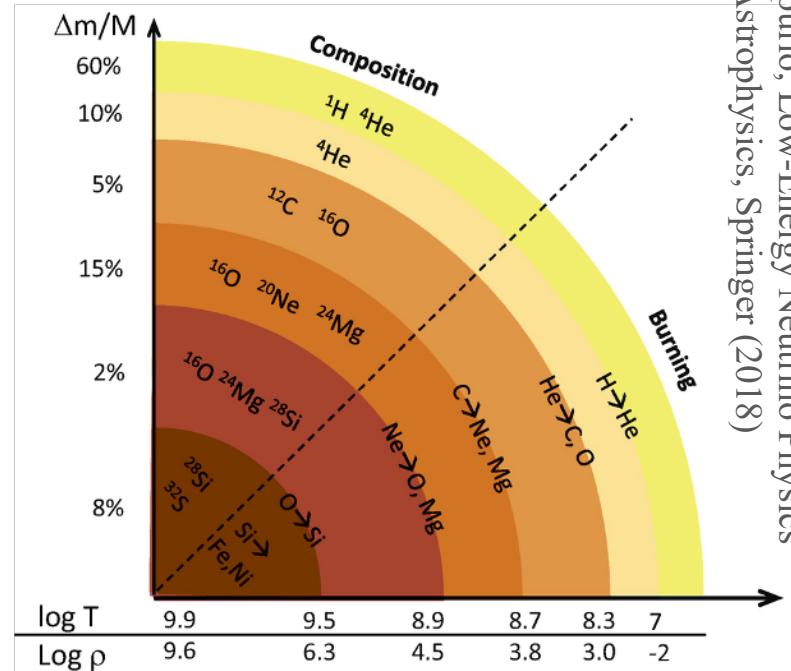
24-28 October 2022 – University of Santiago de Compostela, Spain

**Eu N
P C**

Nuclear Astrophysics with monochromatic γ -ray beams

Physics goals:

- Study (α,γ) and (p,γ) reactions of current astrophysical interest that:
 - burn He \rightarrow regulate C / O ratio
 - burn ^{18}O \rightarrow regulate $^{16}\text{O}/^{18}\text{O}$ ratio
- Particular focus on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction at $E_{\text{CM}} \gtrsim 1$ MeV



Nuclear Astrophysics with monochromatic γ -ray beams

Approach:

- **Photodisintegration** reactions instead of direct capture:

- detailed balance principle for time-reverse reactions
 - different systematics and experimental challenges

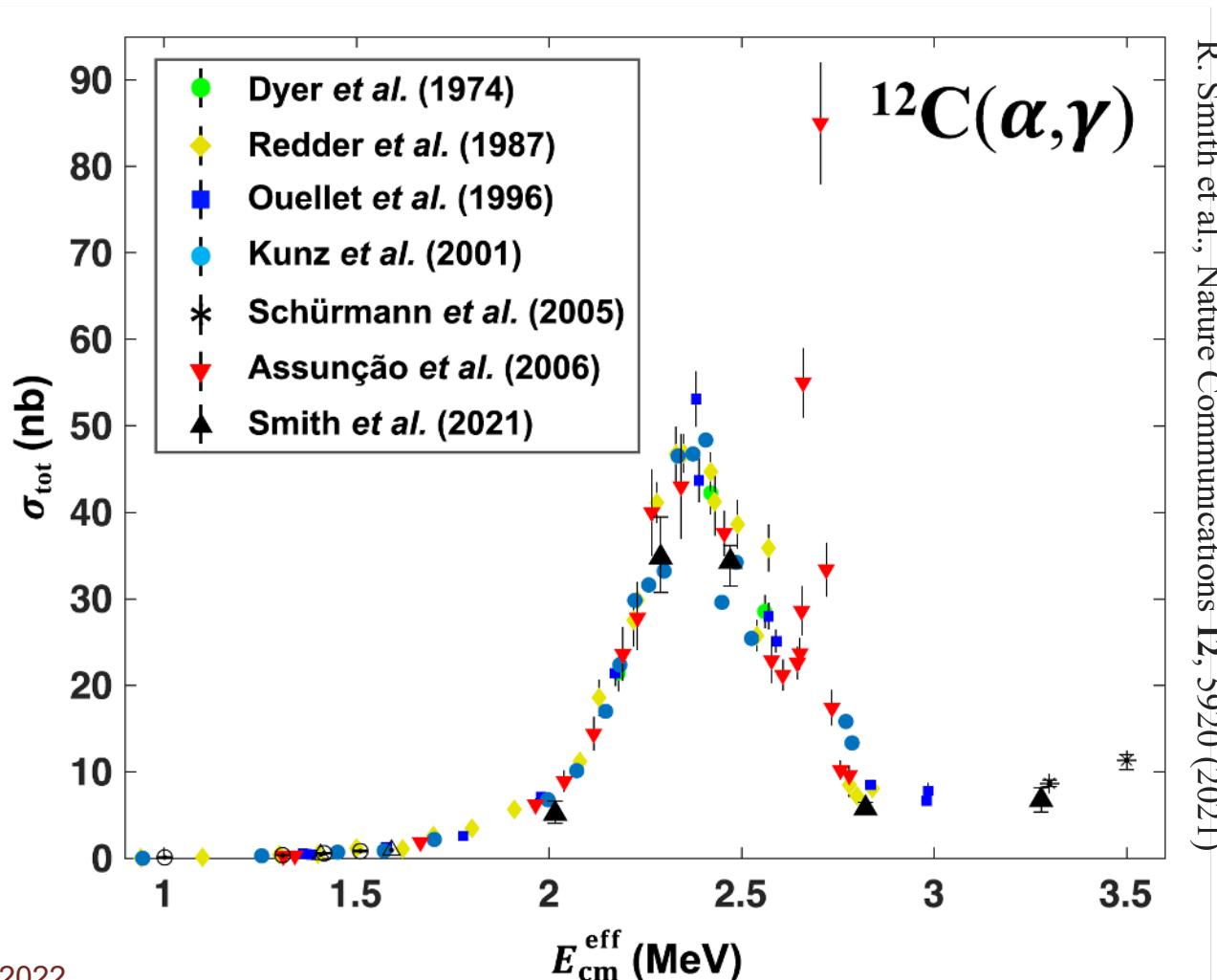
$$\mathbf{B}(b, \gamma)\mathbf{A} \leftrightharpoons \mathbf{A}(\gamma, b)\mathbf{B}$$

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

- Intense **monochromatic gamma-ray beams**:
 - H γ S, ELI-NP facilities
- Active-target **Time Projection Chamber**:
 - measure kinematics of low-energy charged particle products
 - obtain accurate values of E1 / E2 components

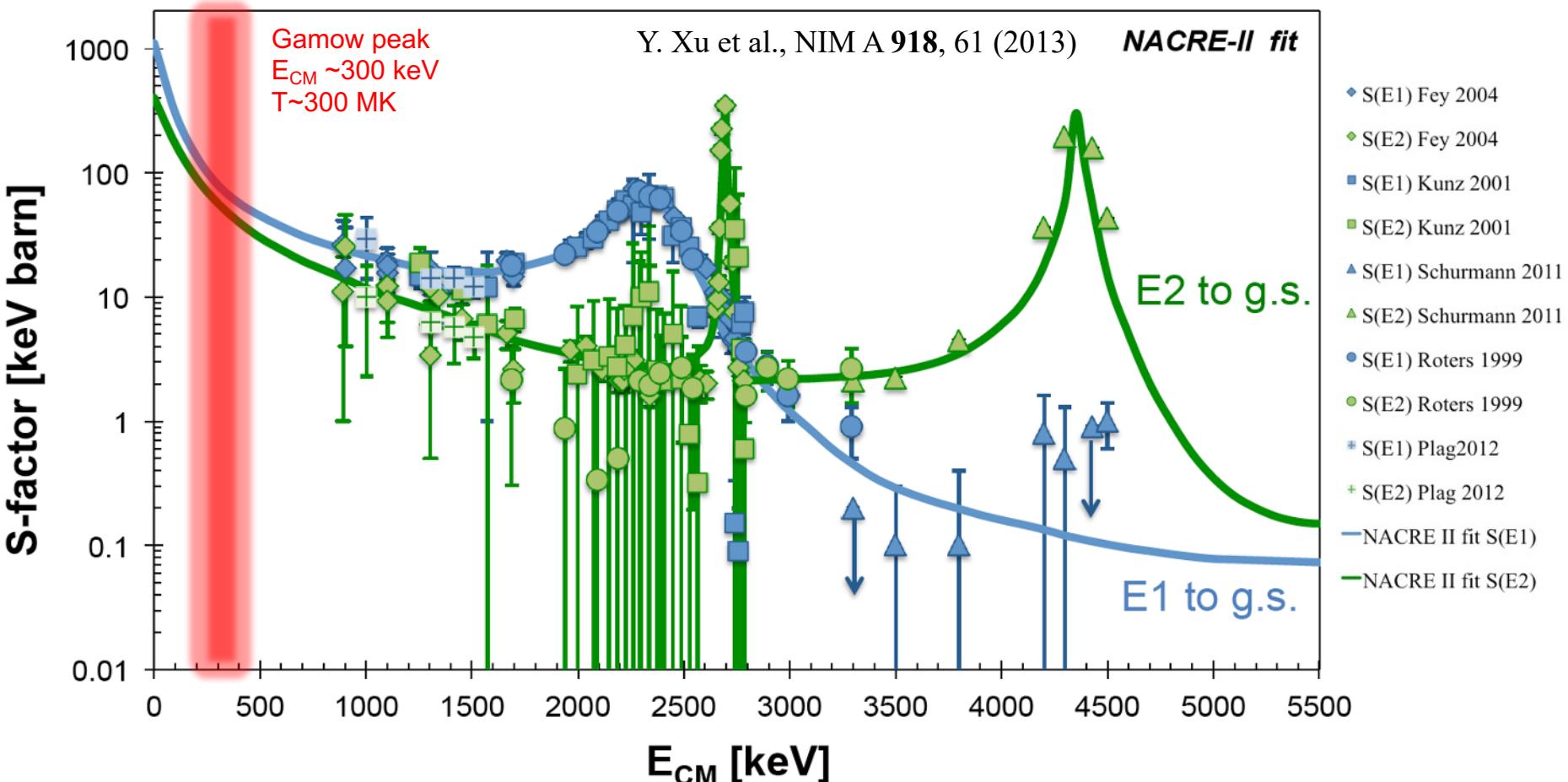
Experimental data on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Total cross section for $E_{\text{CM}} > 1$ MeV measured with charged particle beams (direct capture) and with gamma beams (photodisintegration) :



Experimental data on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

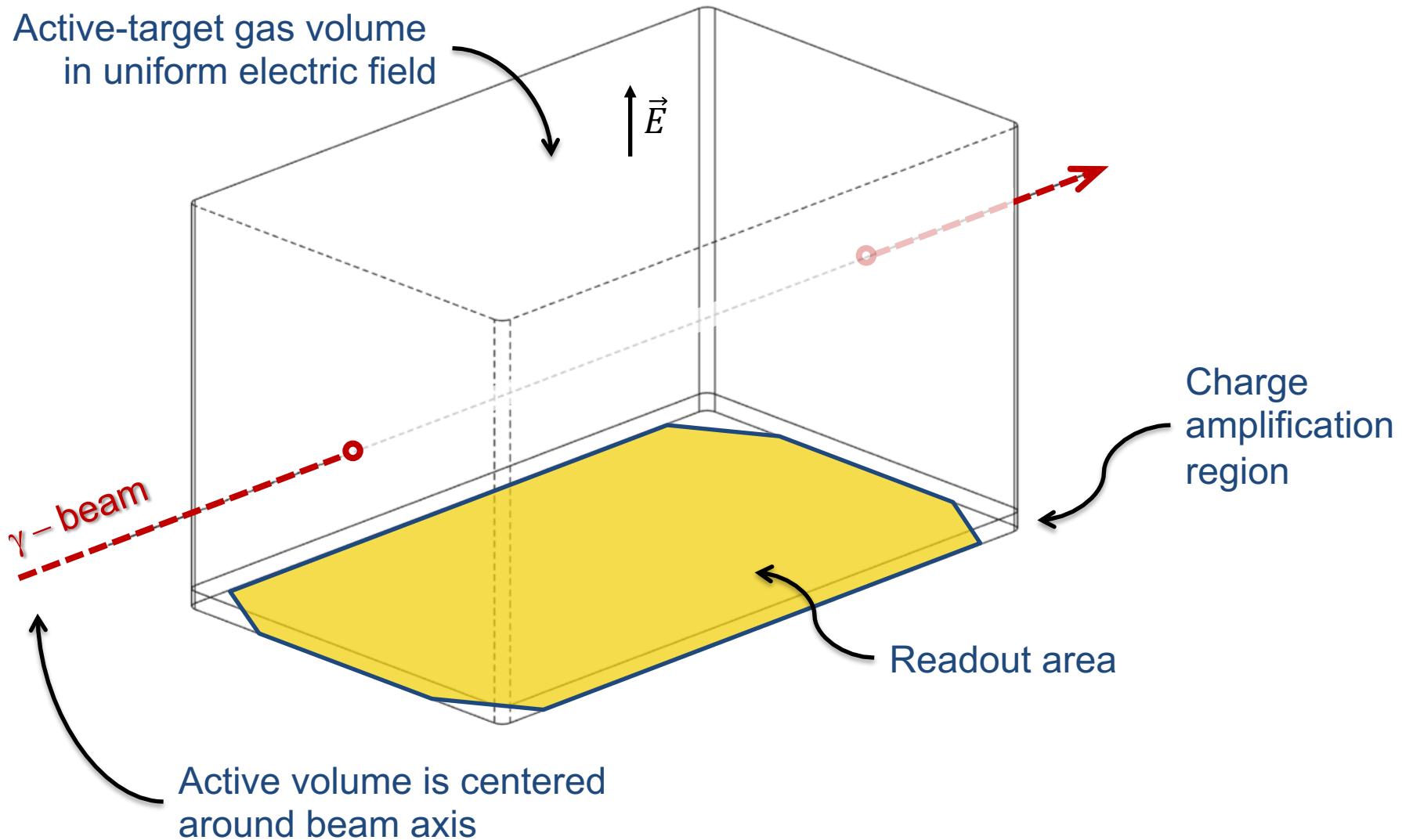
Extrapolated p-wave (E1) & d-wave (E2) astrophysical **S-factors** to the Gamow peak in red giant stars: **40 – 80% uncertainty**



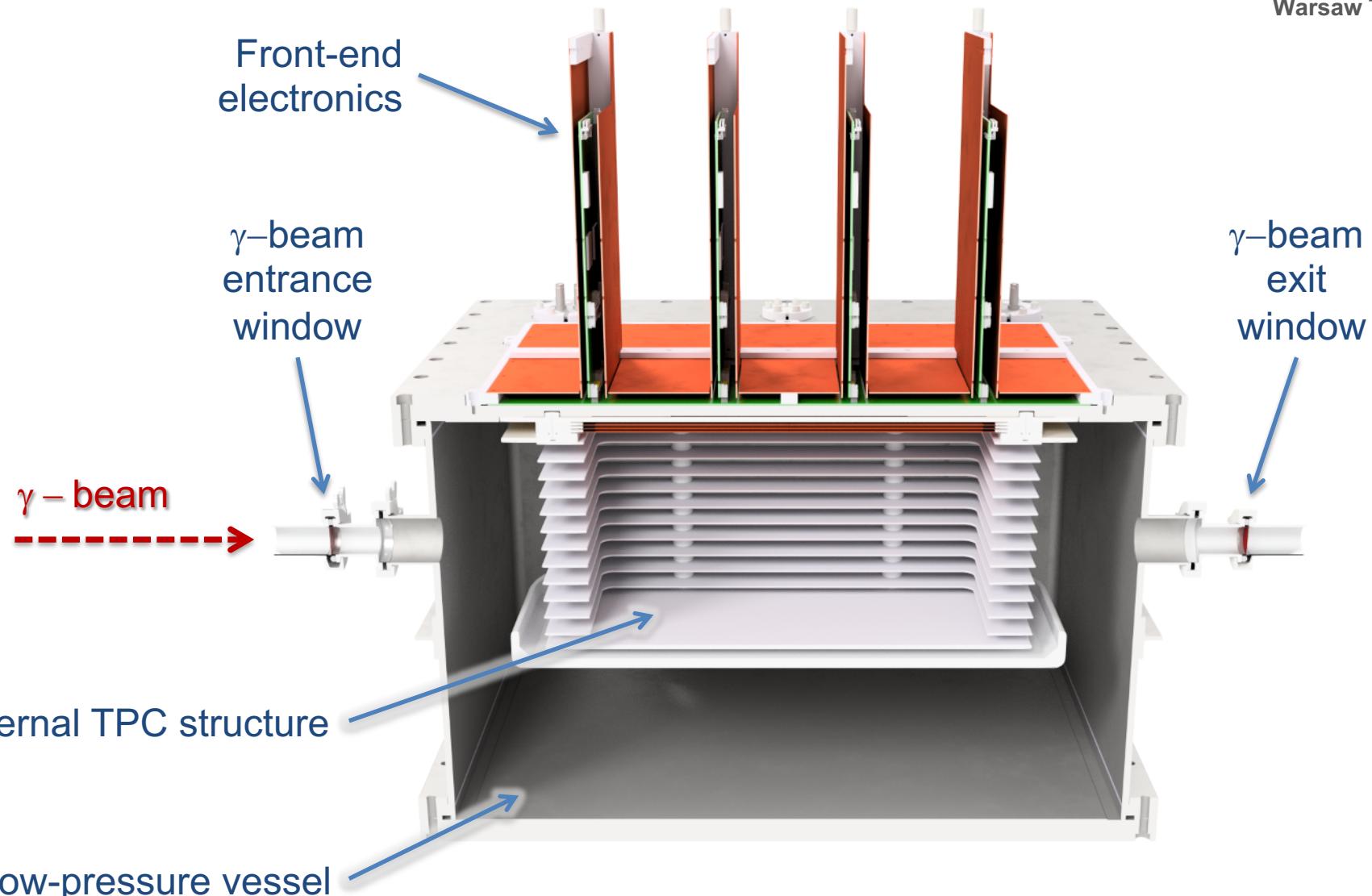
Concept – active-target TPC



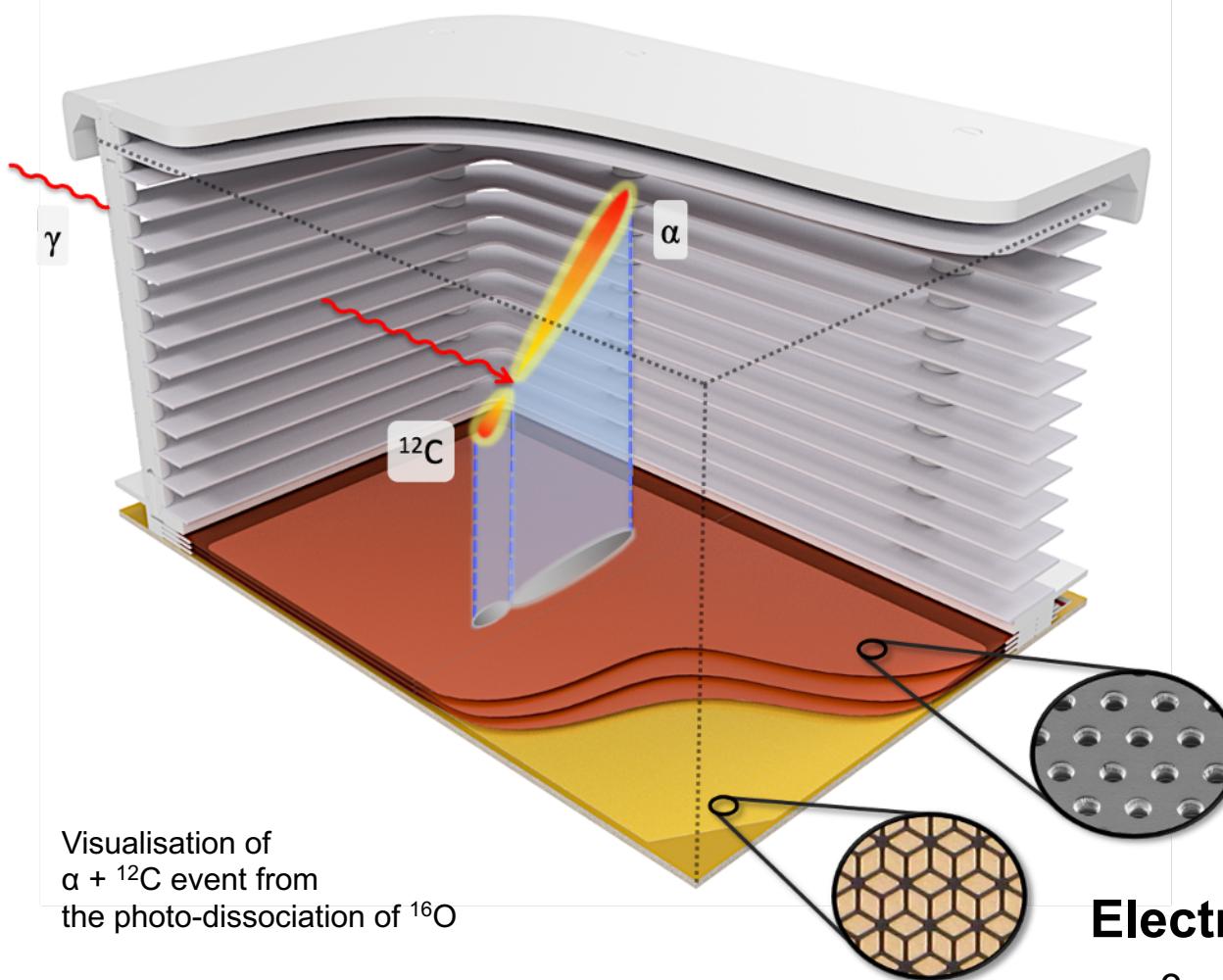
Active-target gas volume
in uniform electric field



Concept – detector overview



Concept – internal structure



Visualisation of
 $\alpha + {}^{12}\text{C}$ event from
the photo-dissociation of ${}^{16}\text{O}$

Active volume

- readout: **330 x 200 mm²**
- drift length: **196 mm**
- gas: CO₂ @ 80-250 mbar

Charge amplification

- Micro-Pattern Gas Detector
- 3 layers of 50-µm thick
Gas Electron Multiplier
foils (GEM)

Electronic readout

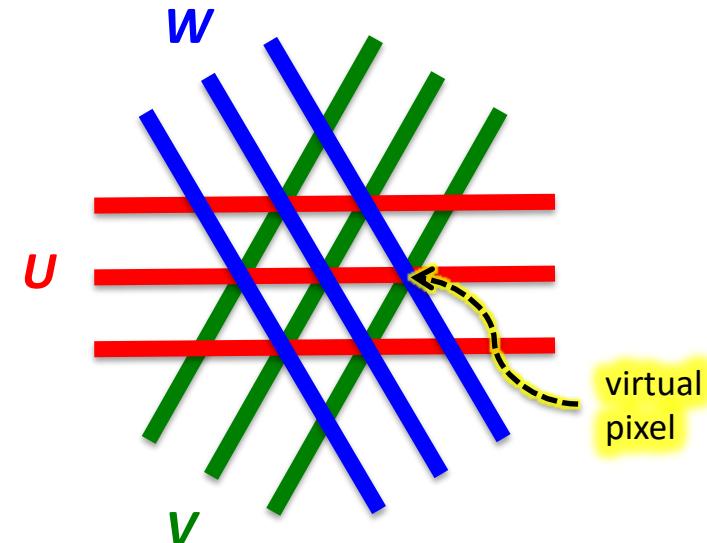
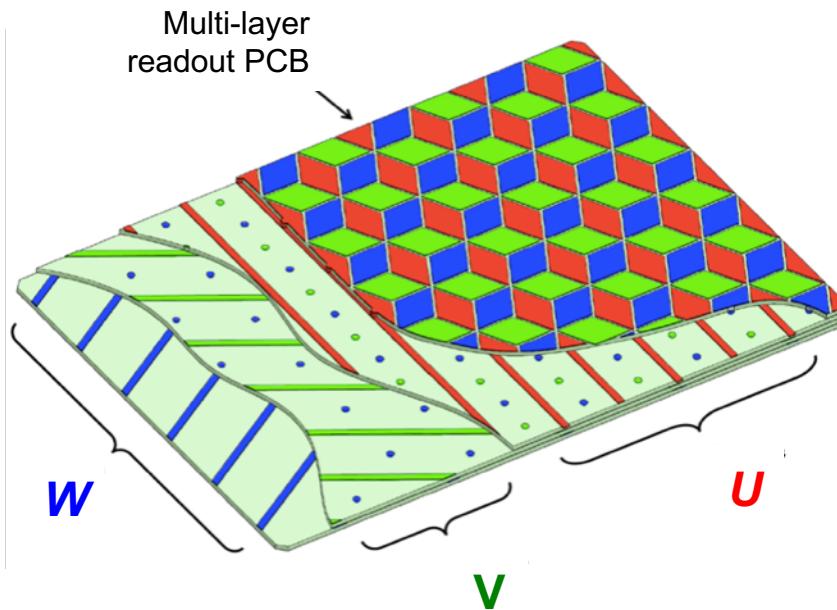
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

Concept – readout strips



3 grids of strips – crossed at 60° :

- 3-coordinate, planar, redundant strip readout, 1.5 mm strip pitch
- **U-V-W** strip arrays on XY plane + Z-coordinate from drift time → virtual 3D pixels
- Simple event topologies → expect only few tracks per event
- Moderate cost of electronics → only $O(10^3)$ channels are needed

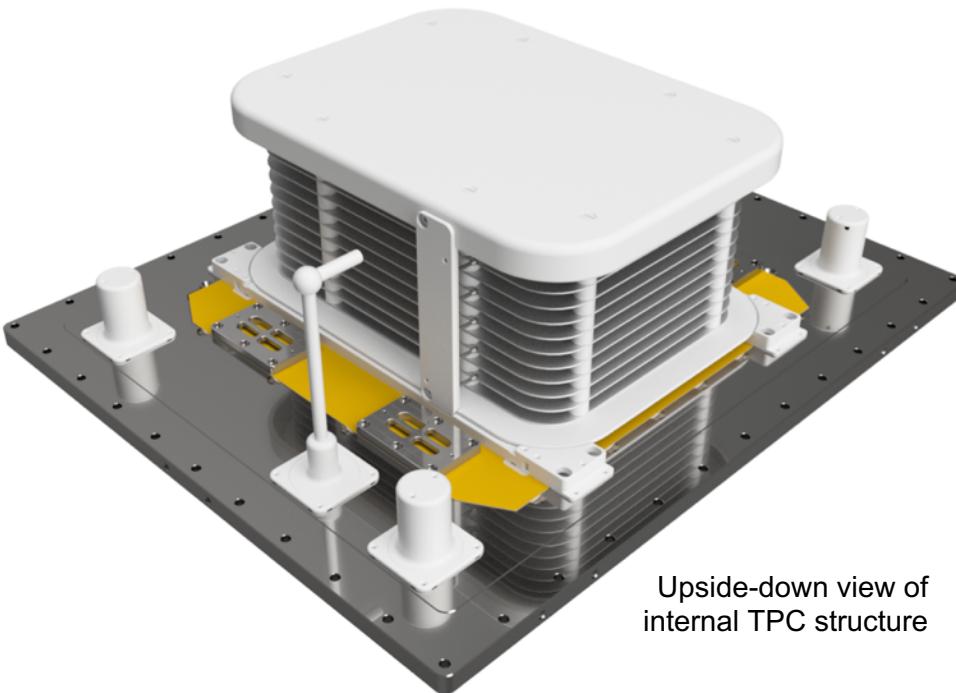


S. Bachmann et al., NIM A **478** (2002) 104
V. Ableev et al., NIM A **535** (2004) 294
J. Bihałowicz et al., Proc. of SPIE **9290** (2014) 92902C
M. Ćwiok, Acta Phys. Pol. B **47** (2016) 707

Detector design

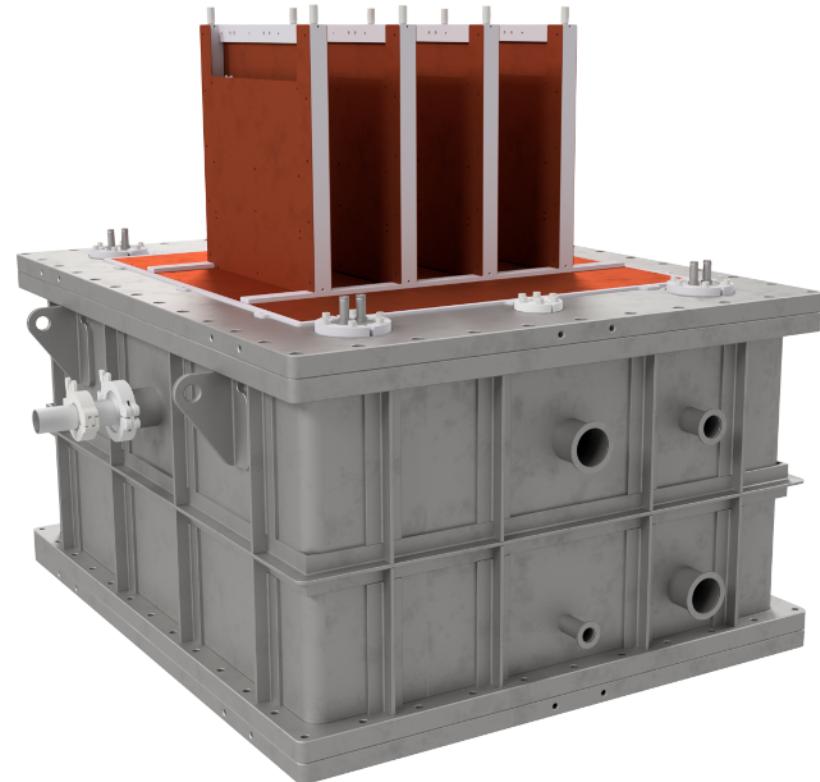


TPC with accompanying infrastructure designed and built at the Faculty of Physics, Univ. of Warsaw:



- Drift cage, triple GEM stack & readout PCB are fixed to the top endcap
- Aluminium field-shaping electrodes and cathode plate

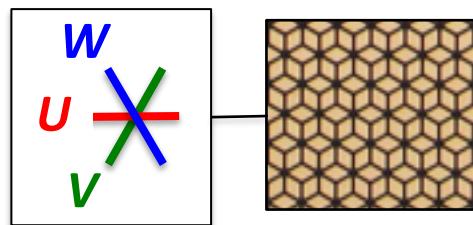
- Stainless steel vessel (170L)
- Barrel + two endcaps
- ISO-KF ports + custom signal ports



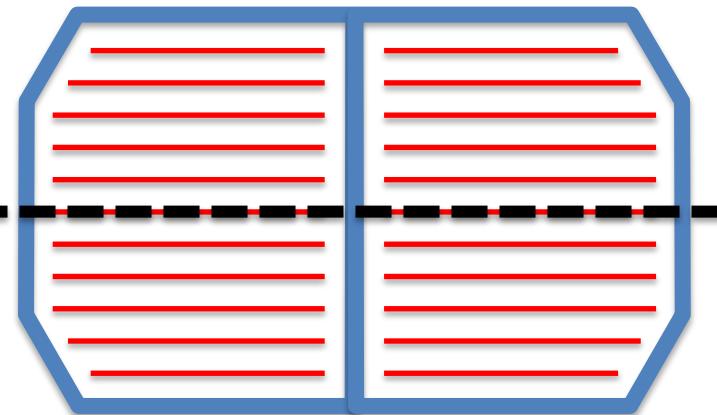
Readout PCB



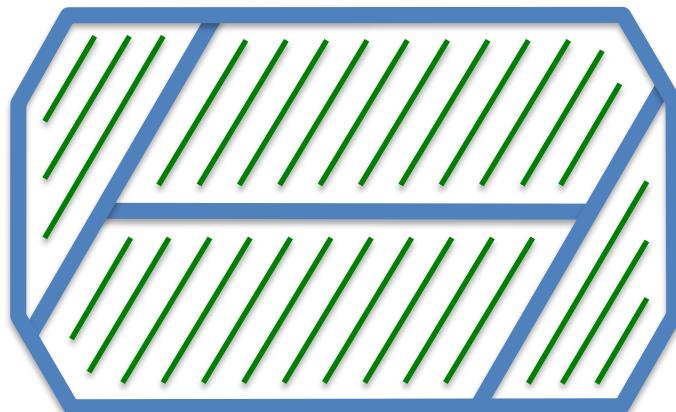
- 1018 strips (+6 spare channels for ext. analogue triggers)
- 1.5 mm strip pitch



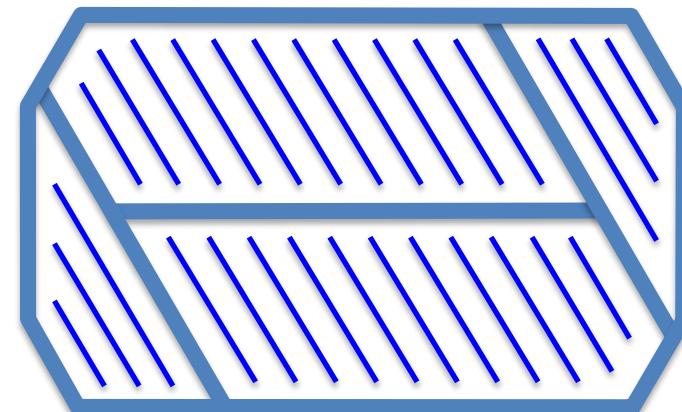
264 U-strips (2 sections)



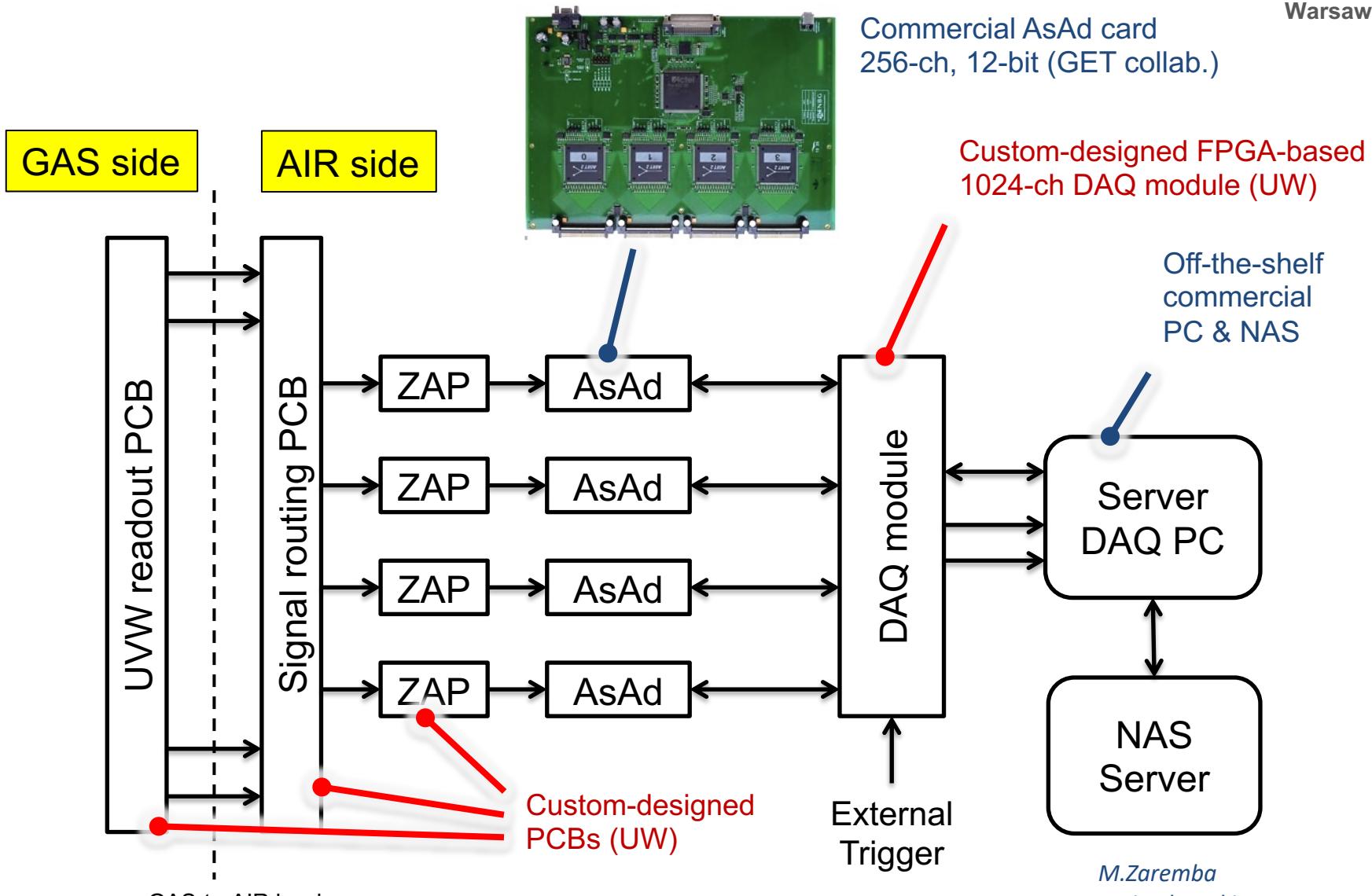
376 V-strips (4 sections)



378 W-strips (4 sections)



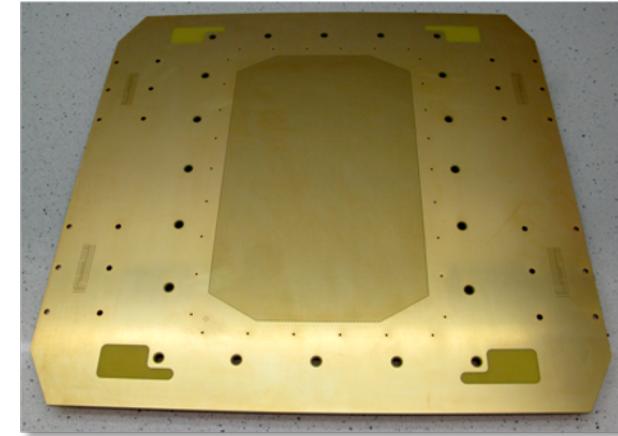
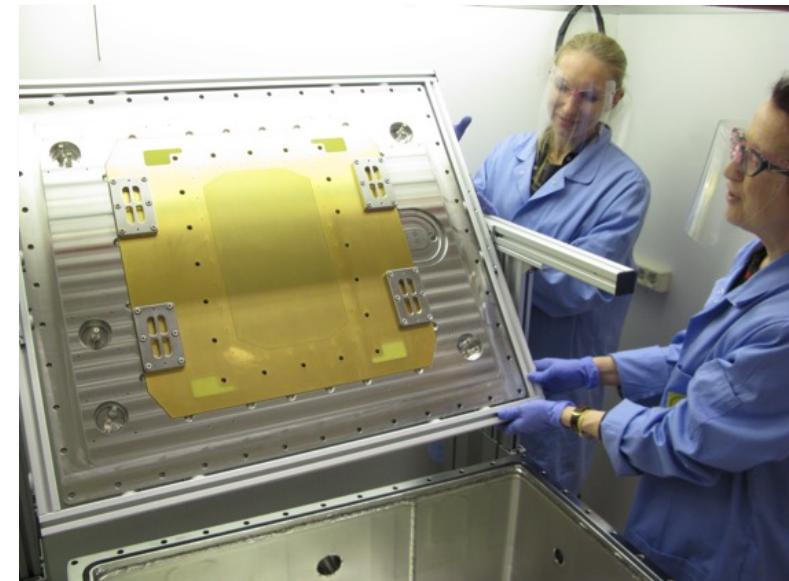
DAQ readout chain



Detector assembly



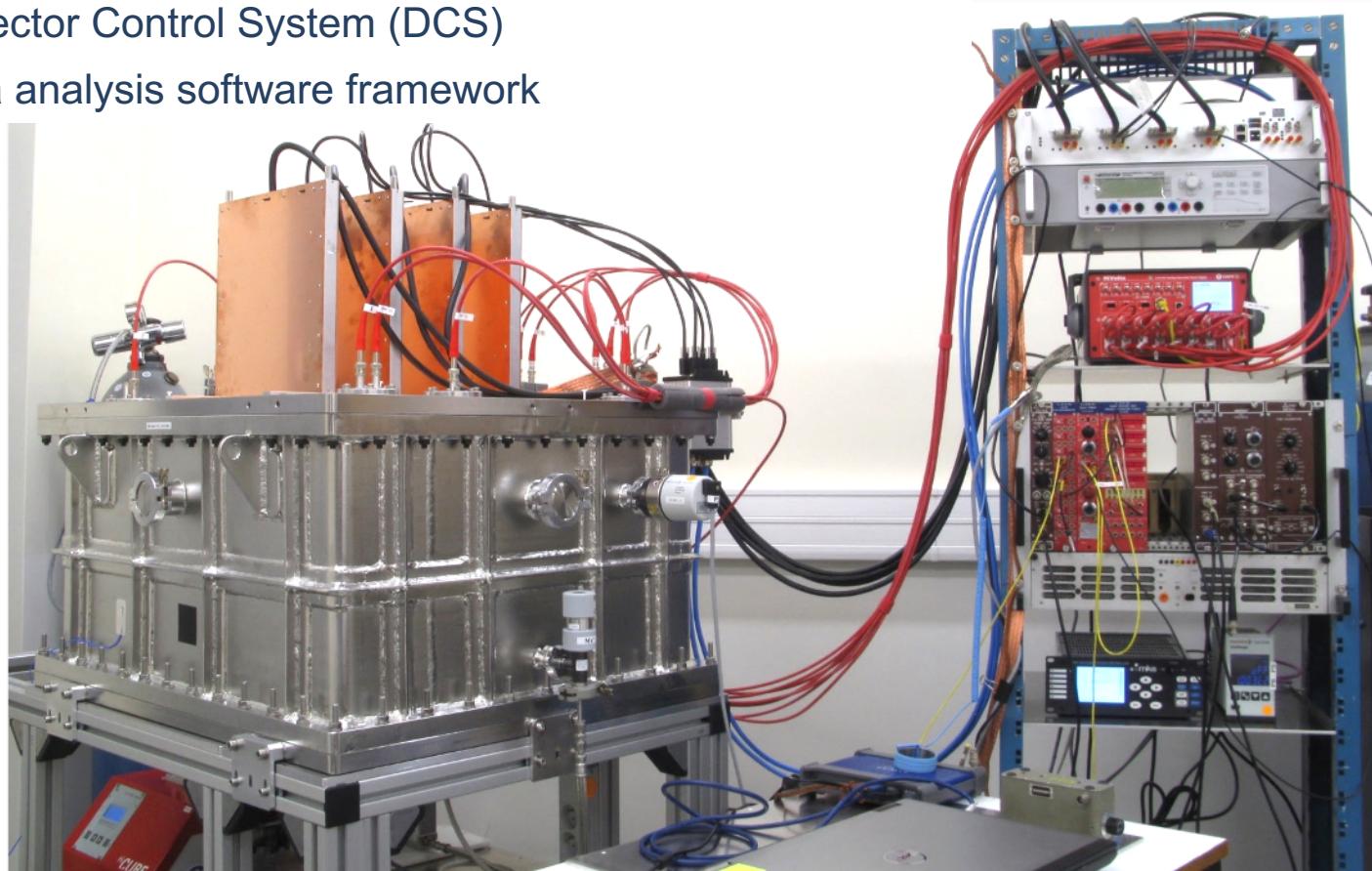
- Assembled TPC drift cage integrated with readout PCB & top endcap



Detector test bench



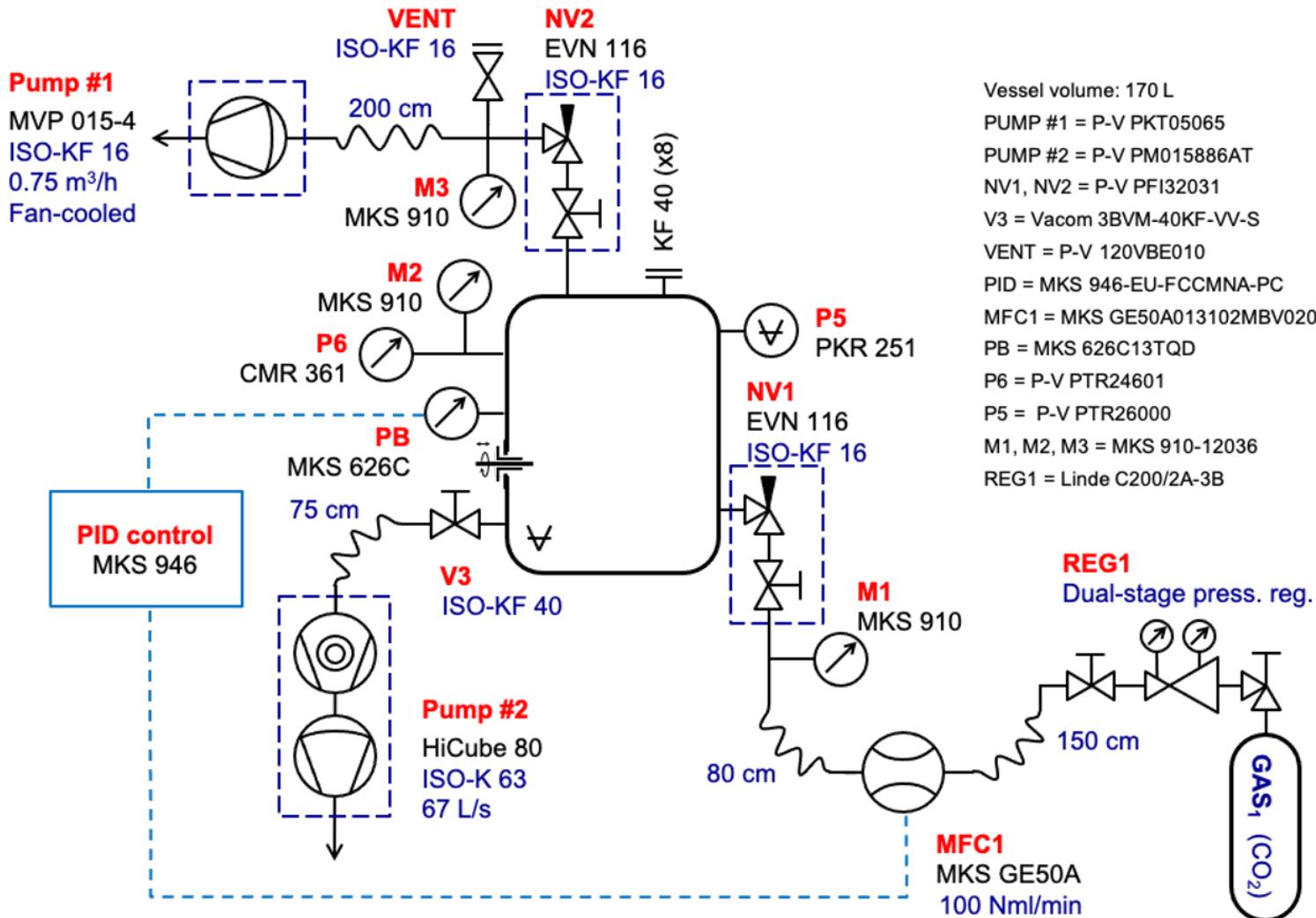
- **Warsaw TPC detector – operational since March 2020**
- Mobile low-pressure test stand is complemented with:
 - data acquisition and data storage systems
 - Detector Control System (DCS)
 - data analysis software framework



Detector test bench



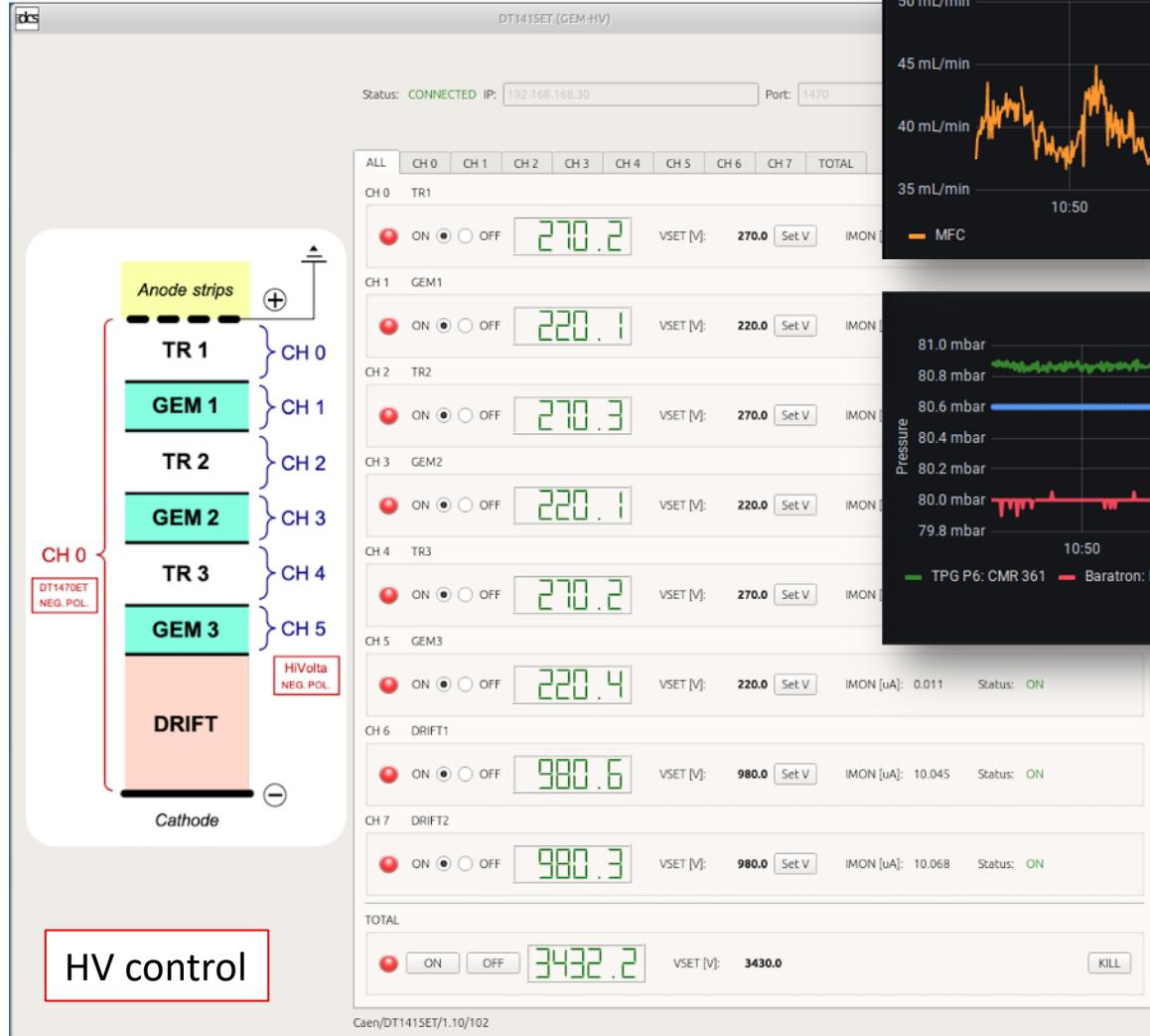
- Low-pressure gas system:



Detector test bench



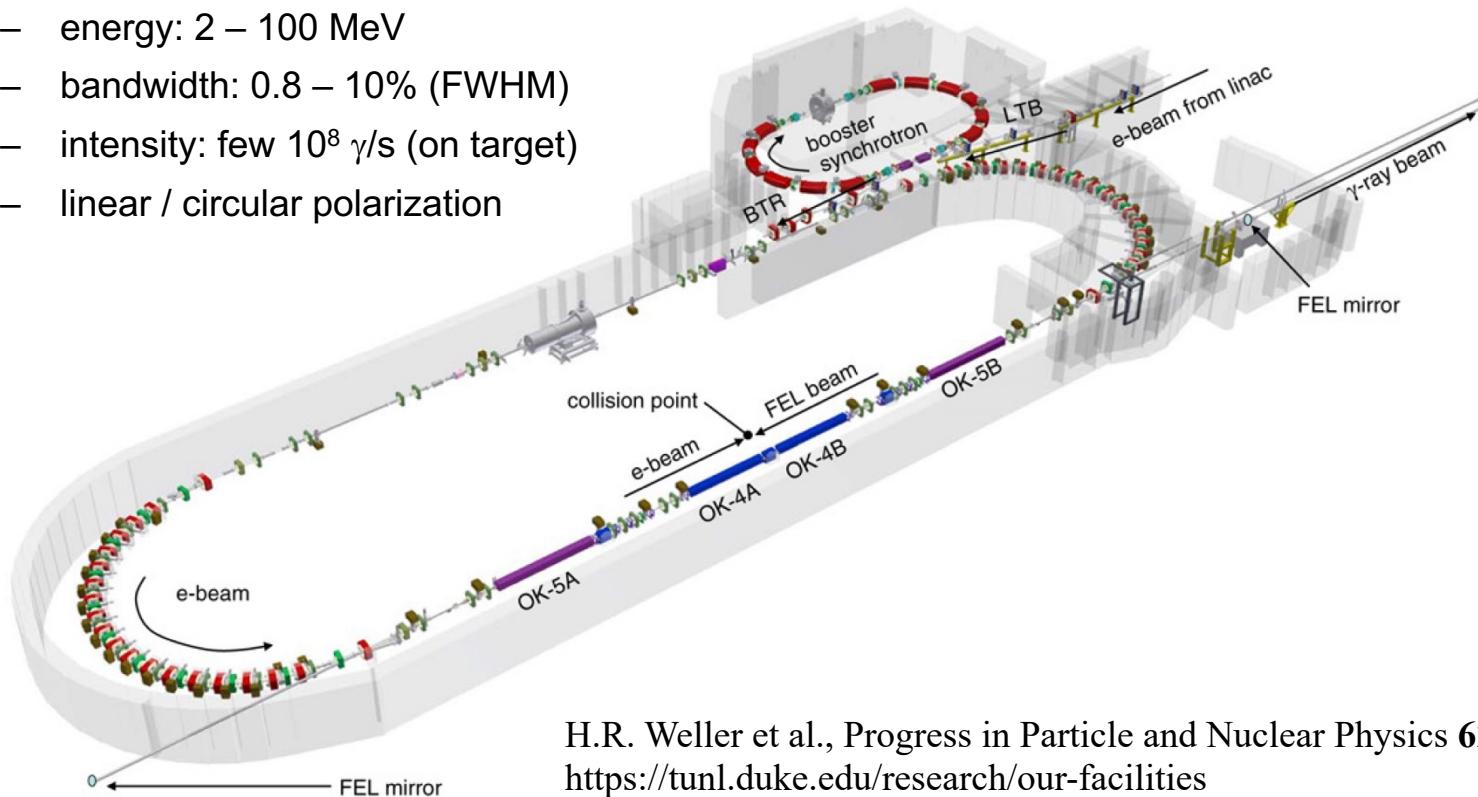
- DCS interfaced with Grafana:



^{16}O photodisintegration experiment @ HiS

(April-September, 2022)

- High Intensity γ -Ray Source (TUNL, Durham, NC, USA)
- Compton back scattering:
 - free-electron laser (FEL) beam collides with relativistic electron beam ($E_e=0.24\text{-}1.2 \text{ GeV}$)
- Gamma beams:
 - energy: 2 – 100 MeV
 - bandwidth: 0.8 – 10% (FWHM)
 - intensity: few $10^8 \gamma/\text{s}$ (on target)
 - linear / circular polarization



H.R. Weller et al., Progress in Particle and Nuclear Physics **62**, 257 (2009)
<https://tunl.duke.edu/research/our-facilities>

^{16}O photodisintegration experiment @ H γ S (April-September, 2022)



- **Monochromatic γ -ray beams:**
 - $E_\gamma = 8.51 - 13.9 \text{ MeV}$
 $E_{CM} = 1.35 - 6.7 \text{ MeV}$ $\Leftarrow ^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
 - $I_\gamma \geq 1.5 \cdot 10^8 \text{ } \gamma/\text{s}$
 - $FWHM : 350 \text{ keV} @ 8.51 \text{ MeV}$
 - 10.5 mm beam collimator
 - 275 hours / 15 energy points
- **Beam monitoring:**
 - E_γ spectrum from HPGe detector
 - I_γ from standard H γ S diagnostics (scintillators) + Au foil activation
- **TPC working points:**
 - pure CO_2 gas @ 130, 190 or 250 mbar
 - pressure, electron drift velocity, electronics sampling rate optimized for charged particle ranges in detector's active volume

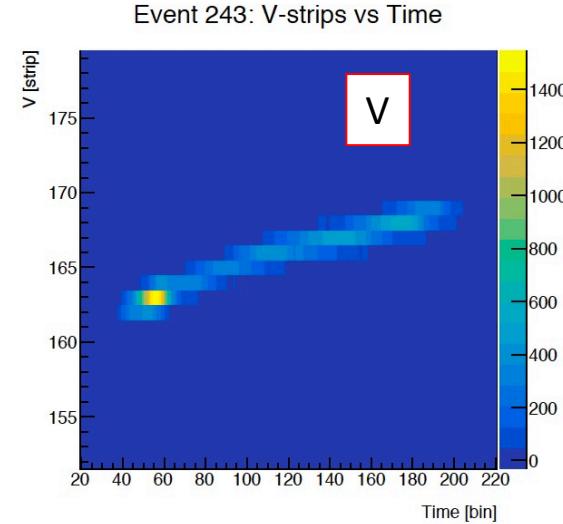
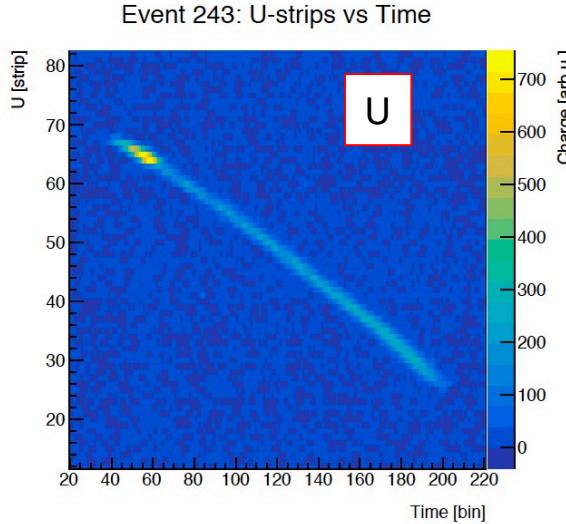


⇒ can study both $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ and $^{12}\text{C}(\gamma,3\alpha)$

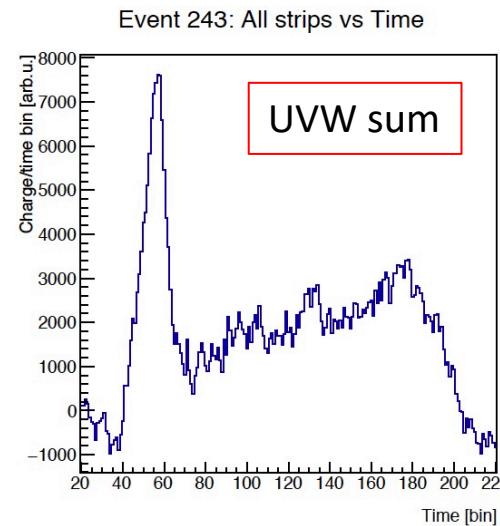
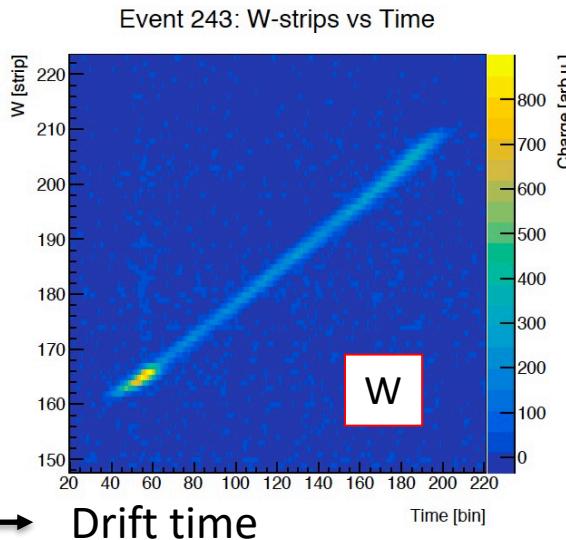
^{16}O photodisintegration experiment @ HIyS (April-September, 2022)



- Example 2-particle topology: raw data



$E_{\gamma} = 13.9 \text{ MeV}$



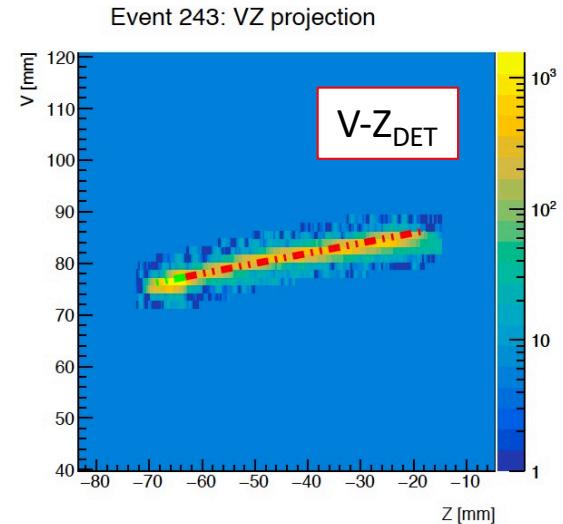
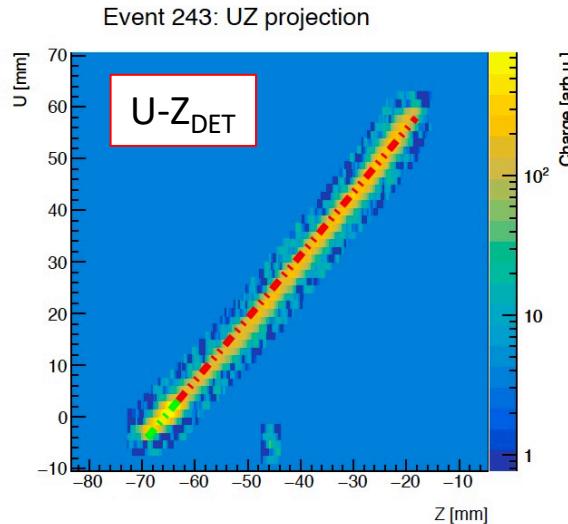
- Pressure: 250 mbar
- Sampling: 12.5 MHz

^{16}O photodisintegration experiment @ HIyS

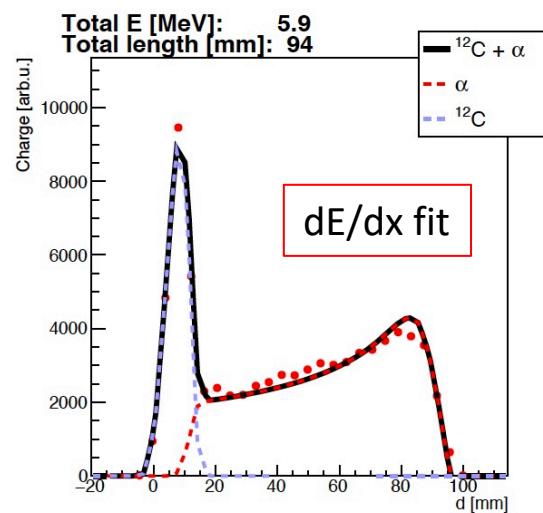
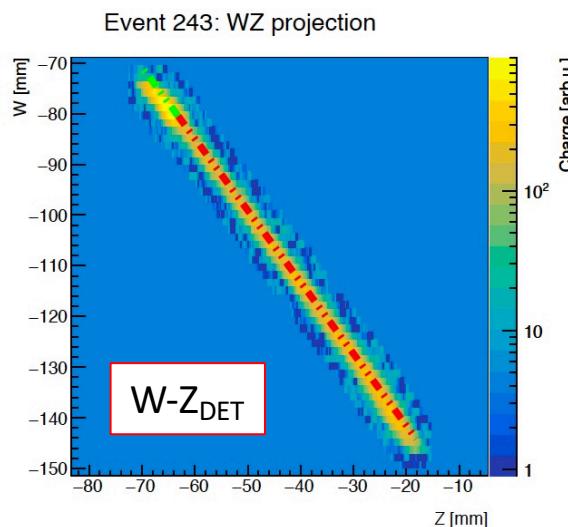
(April-September, 2022)



- Example 2-particle topology: reconstructed $\alpha + \text{C}$ tracks in 3D



$$E_{\gamma} = 13.9 \text{ MeV}$$



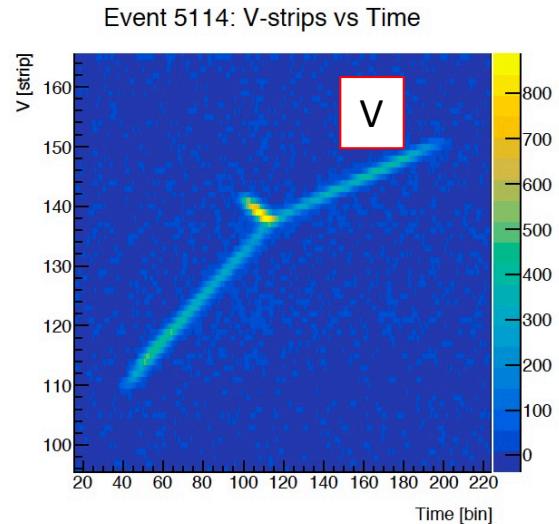
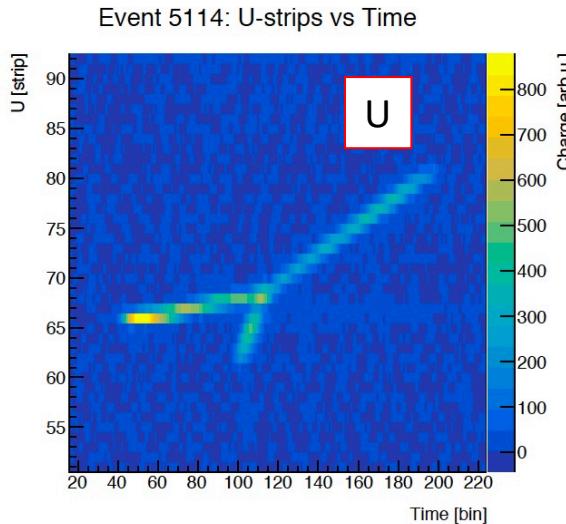
- Pressure: 250 mbar
- Sampling: 12.5 MHz
- Automatic procedure
- Clustered data fitted to smeared dE/dx templates (SRIM + diffusion)

A.Kalinowski
M.Fila

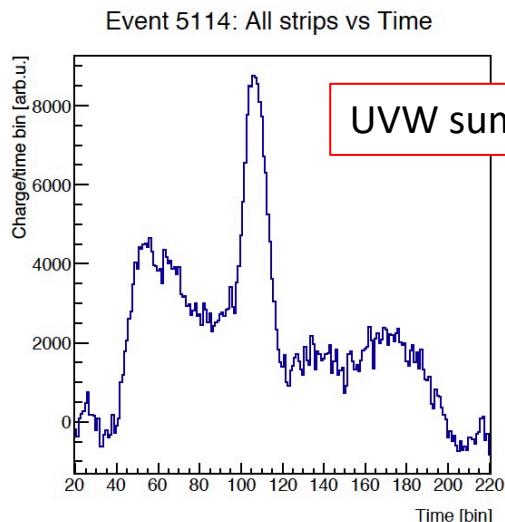
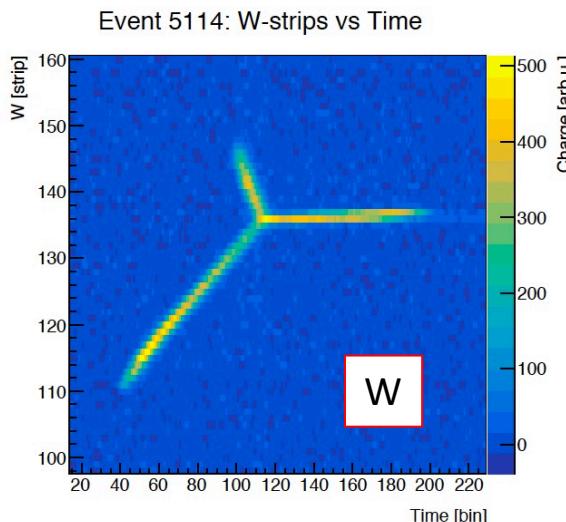
^{16}O photodisintegration experiment @ HI γ S (April-September, 2022)



- Example 3-particle topology: raw data



$E_{\gamma} = 13.9 \text{ MeV}$

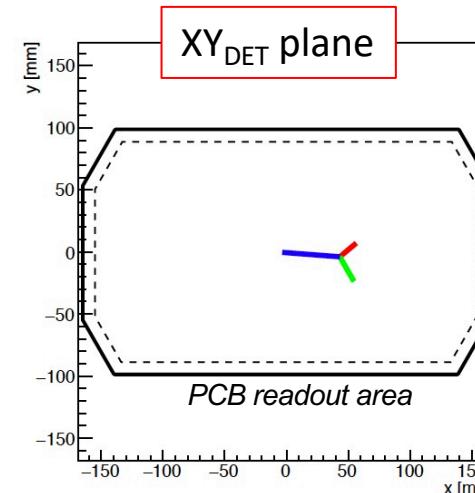
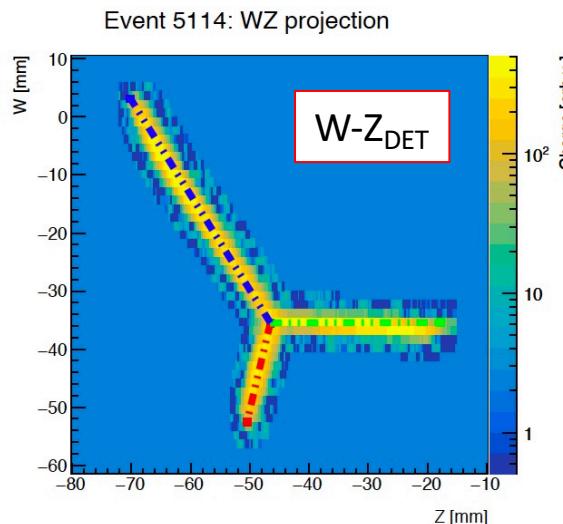
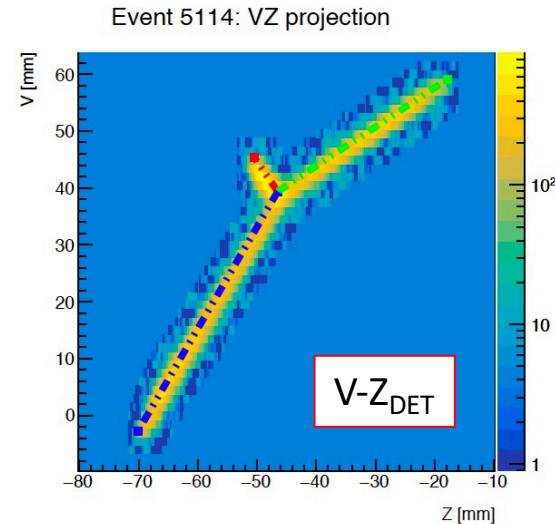
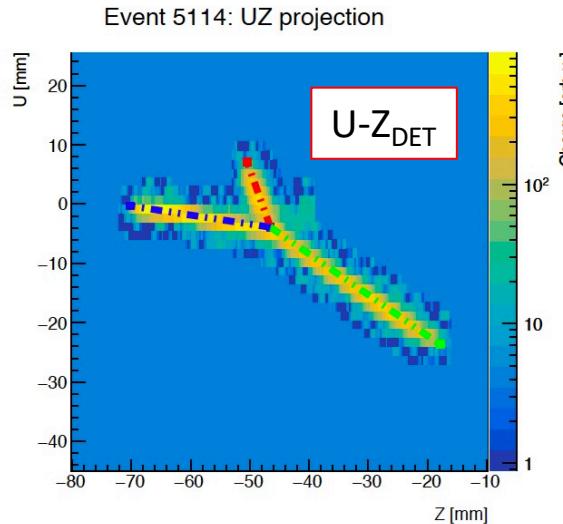


- Pressure: 250 mbar
- Sampling: 12.5 MHz

^{16}O photodisintegration experiment @ Hl γ S (April-September, 2022)



- Example 3-particle topology: reconstructed α tracks in 3D



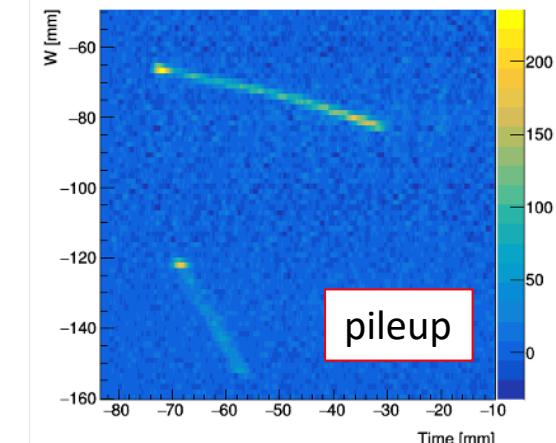
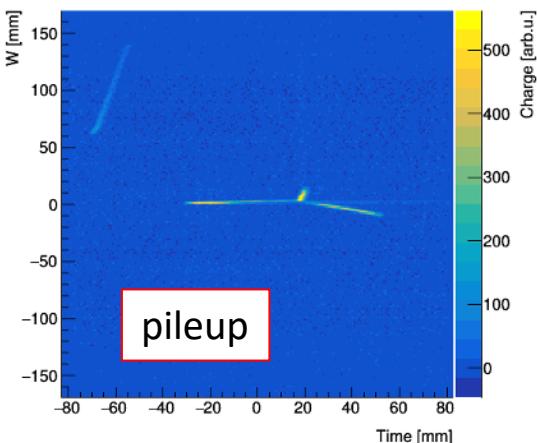
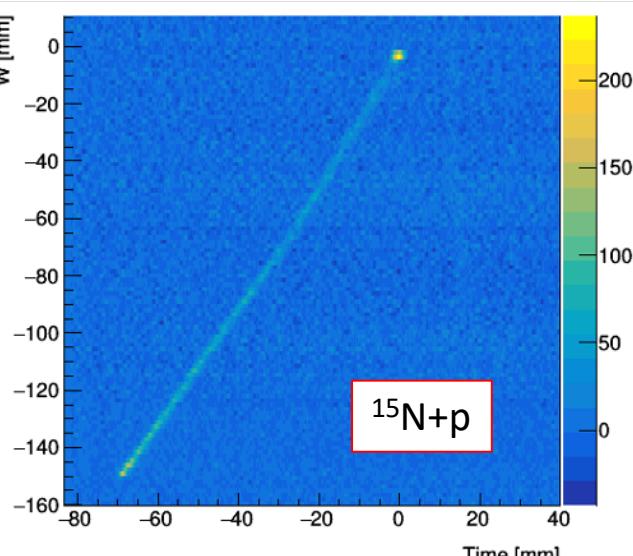
$$E_{\gamma} = 13.9 \text{ MeV}$$

- Pressure: 250 mbar
- Sampling: 12.5 MHz
- Manual procedure
- Clustered data fitted by eye

^{16}O photodisintegration experiment @ HIyS (April-September, 2022)



- Examples of background & complex events:



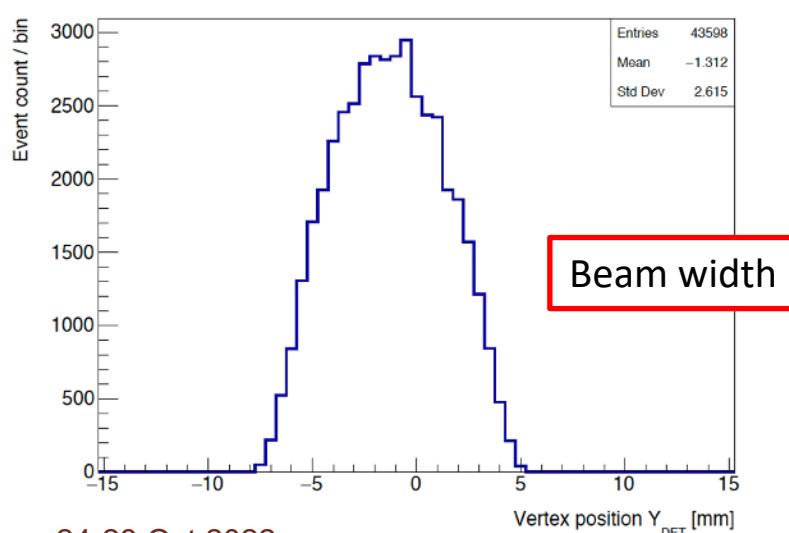
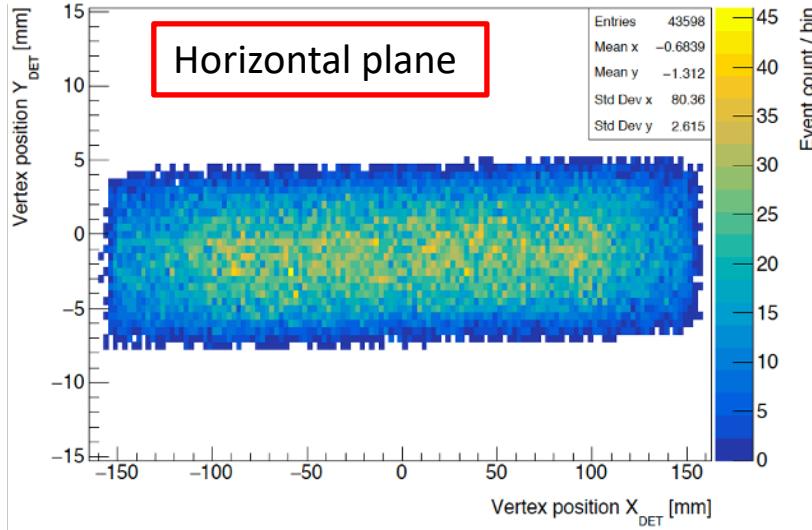
$E_{\gamma} = 13.9 \text{ MeV}$

^{16}O photodisintegration experiment @ HIγS

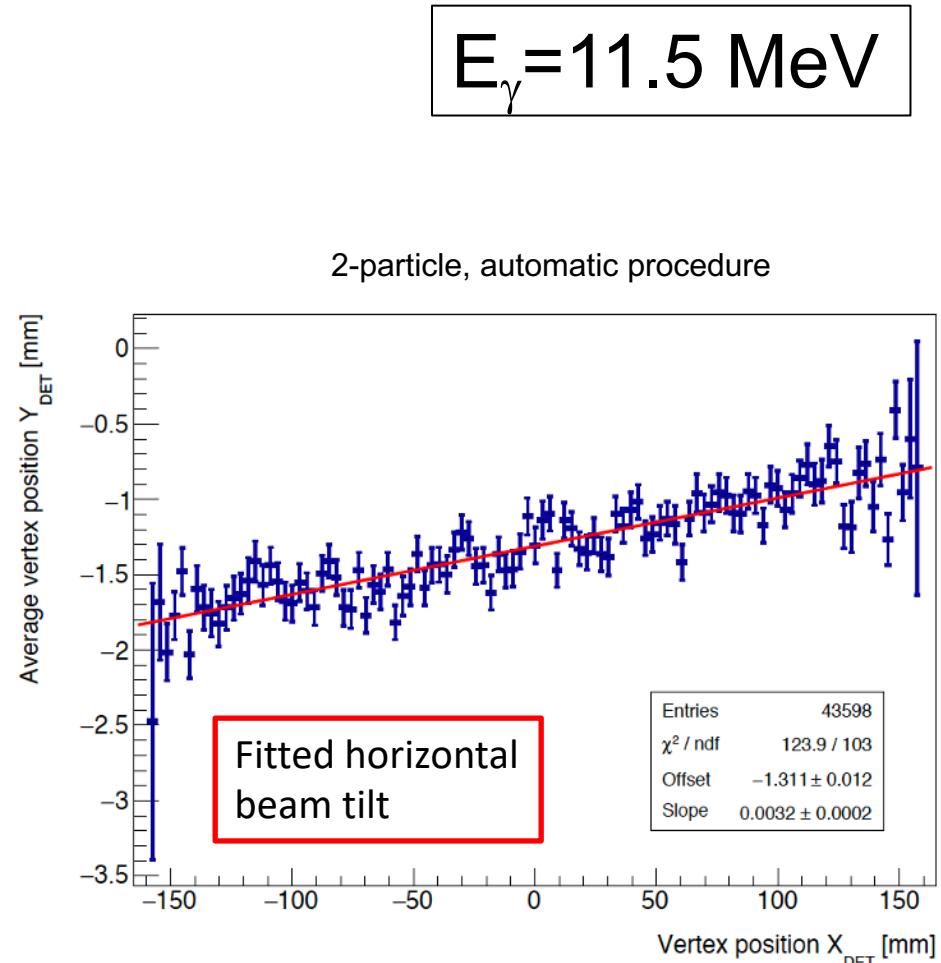
(April-September, 2022)



- Beam alignment from reconstructed 2-particle reaction vertices:



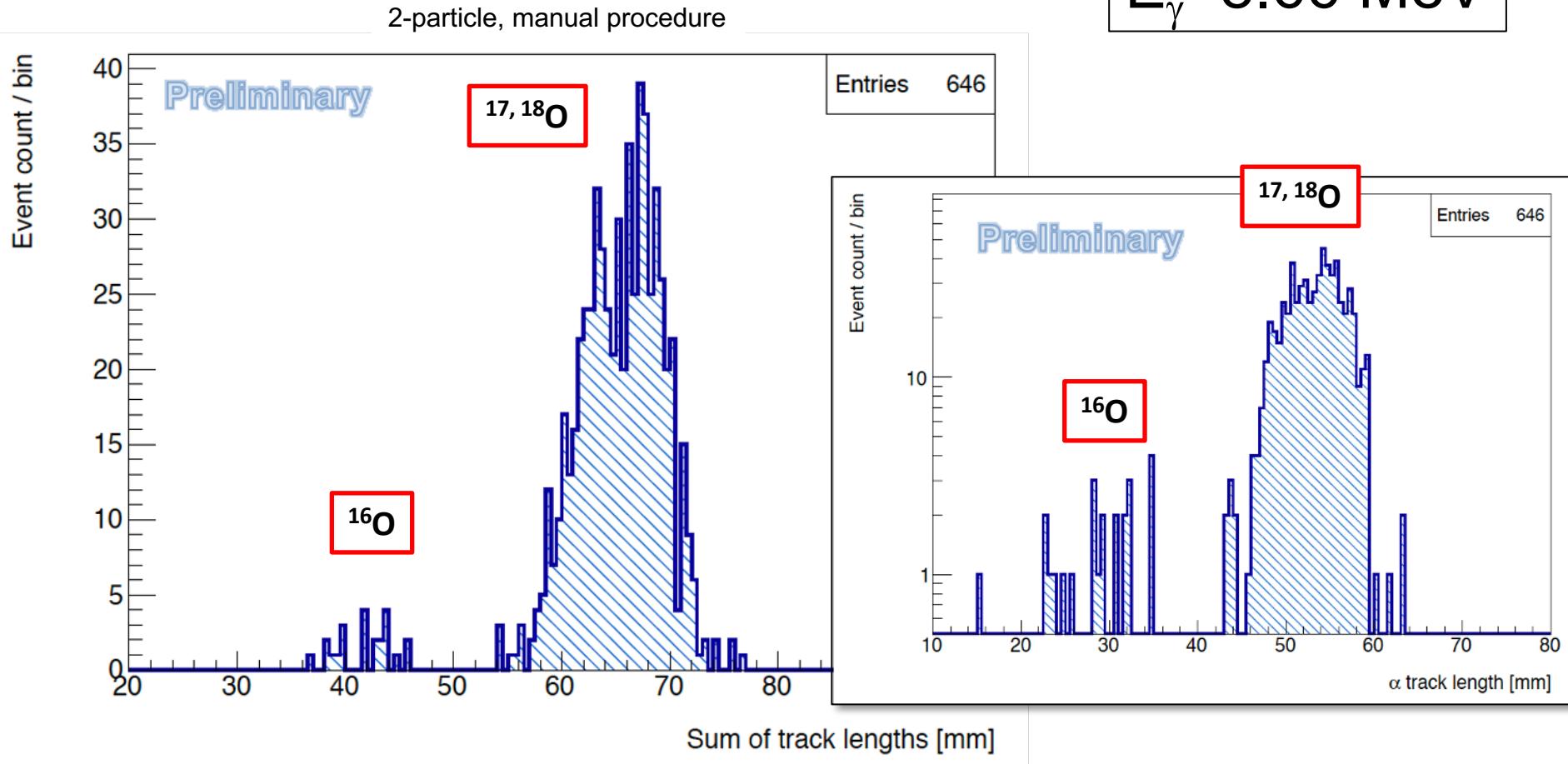
$E_{\gamma} = 11.5 \text{ MeV}$



^{16}O photodisintegration experiment @ HIγS (April-September, 2022)



- Event identification

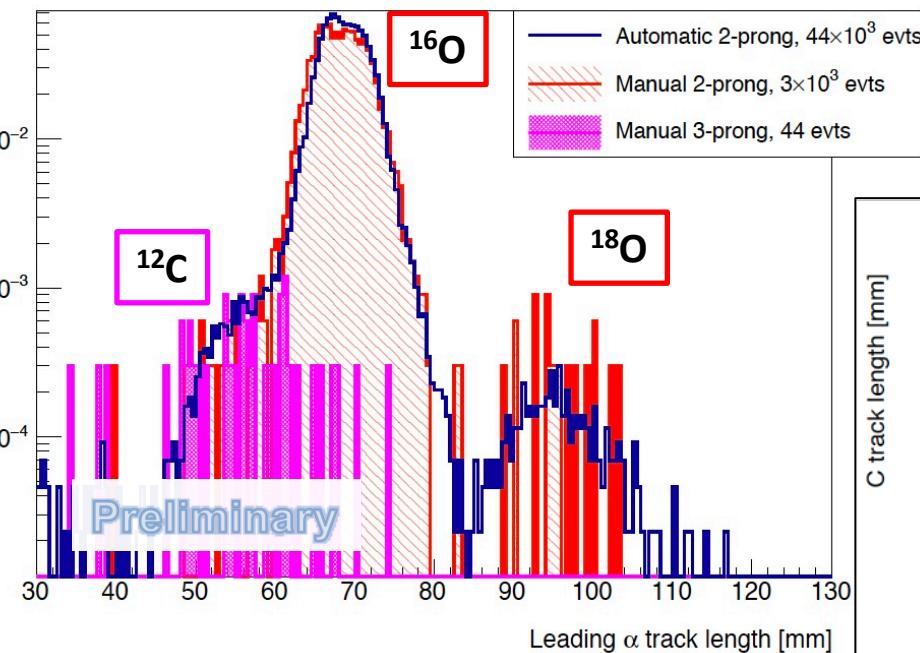


^{16}O photodisintegration experiment @ HIγS (April-September, 2022)

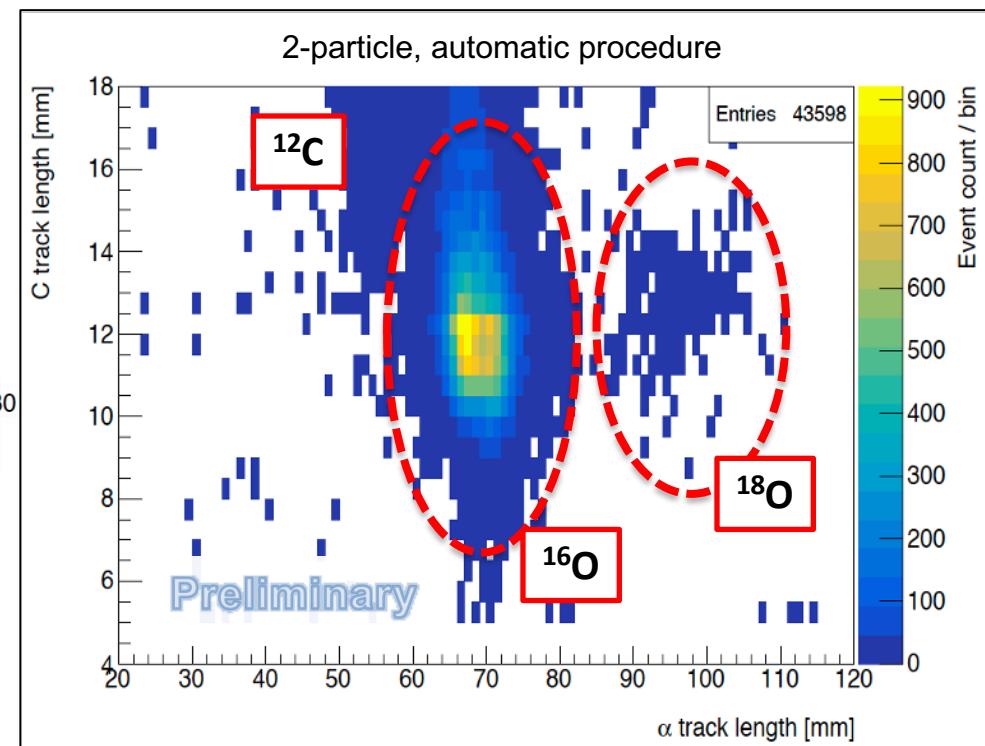


- Event identification

2- and 3-particle, manual or automatic procedure



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

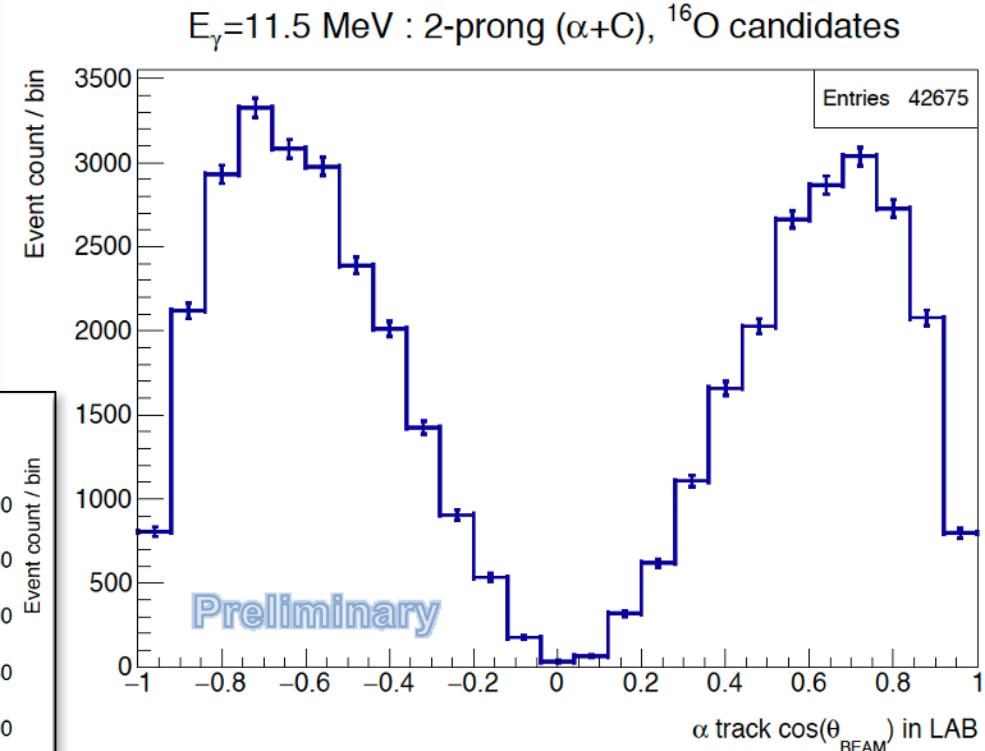
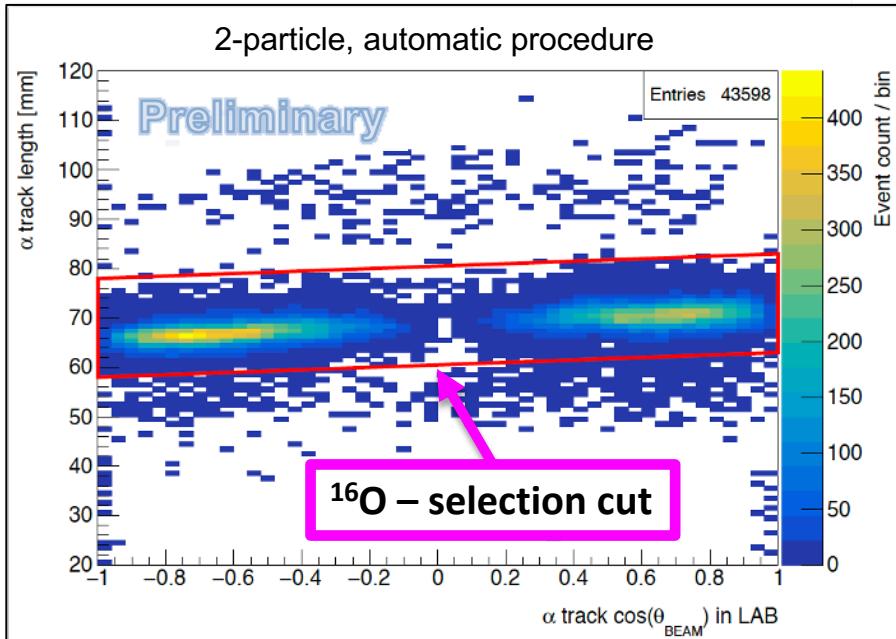


^{16}O photodisintegration experiment @ HIyS (April-September, 2022)



- Polar θ angle of $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ candidate events

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



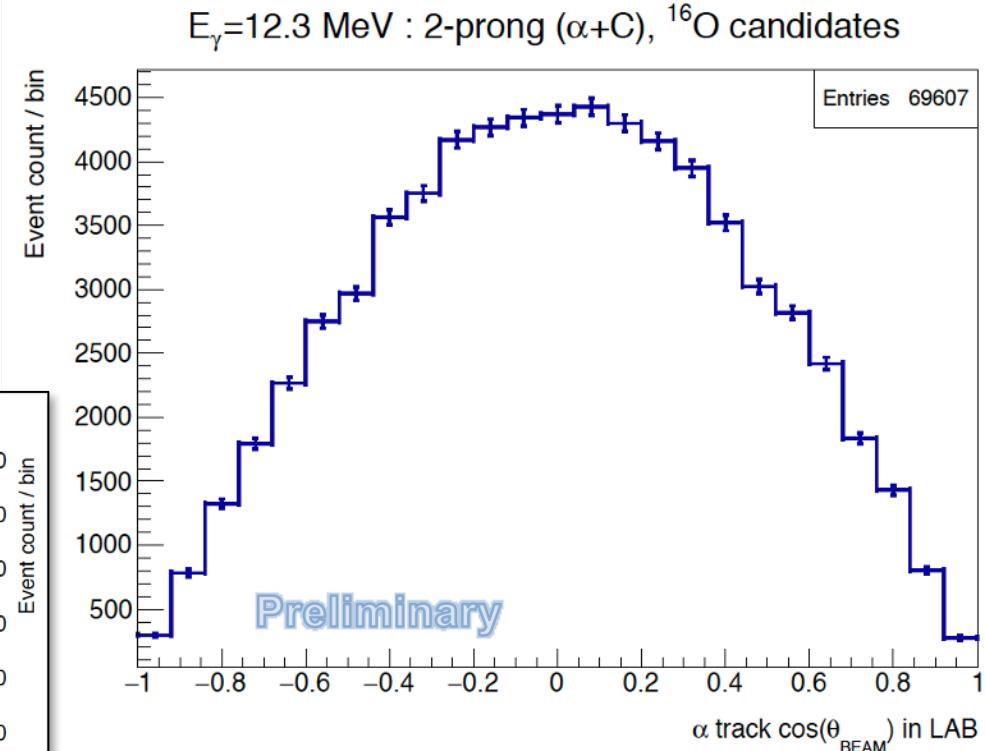
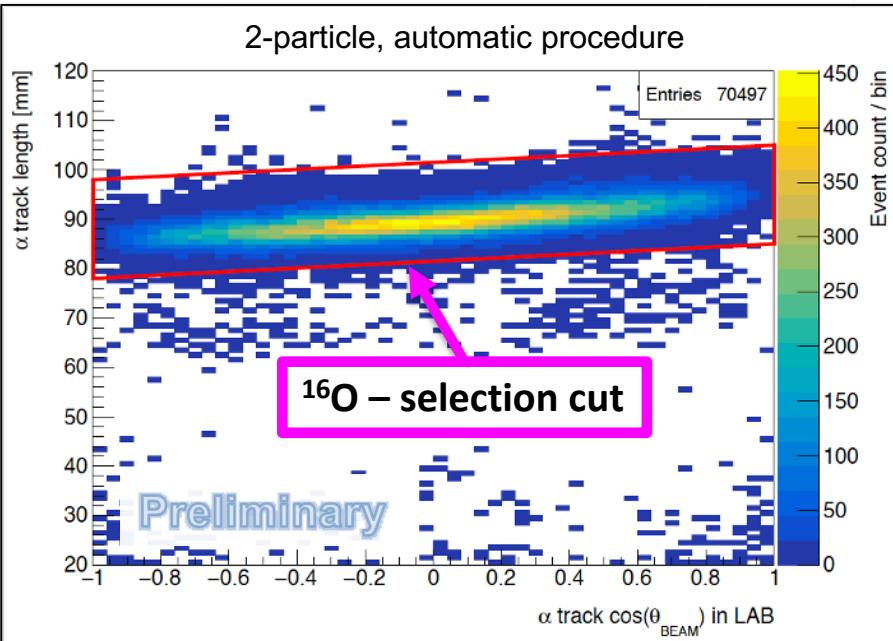
⇒ E2 shape

^{16}O photodisintegration experiment @ HIγS (April-September, 2022)



- Polar θ angle of $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ candidate events

$E_\gamma = 12.3 \text{ MeV}$



⇒ E1 shape

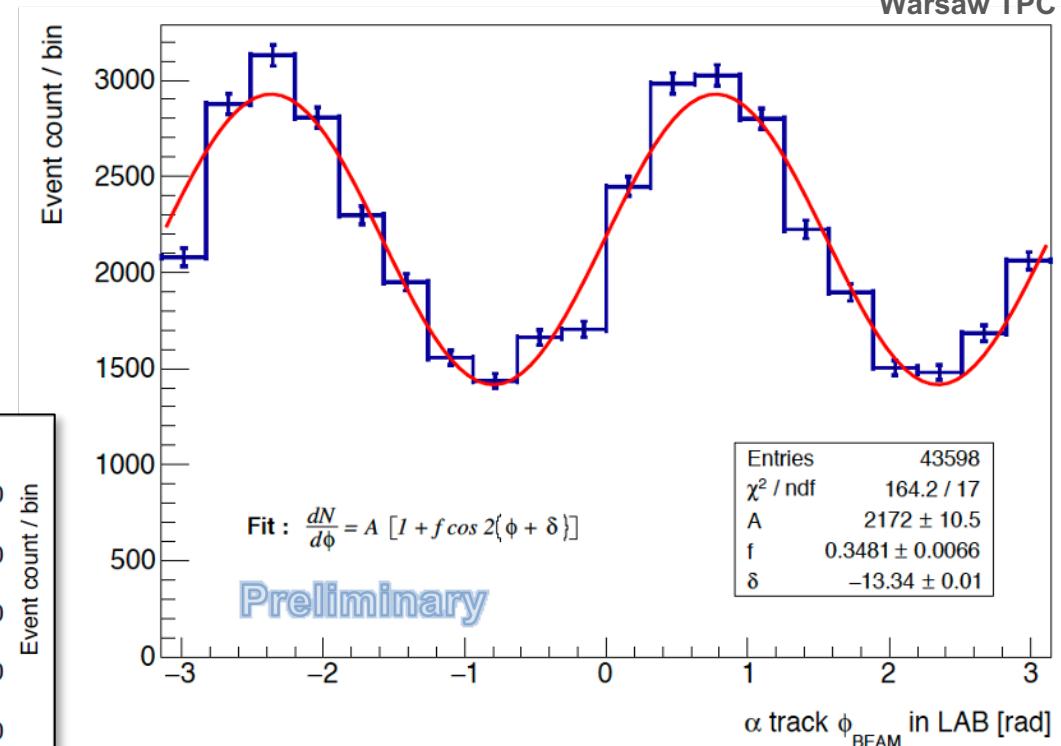
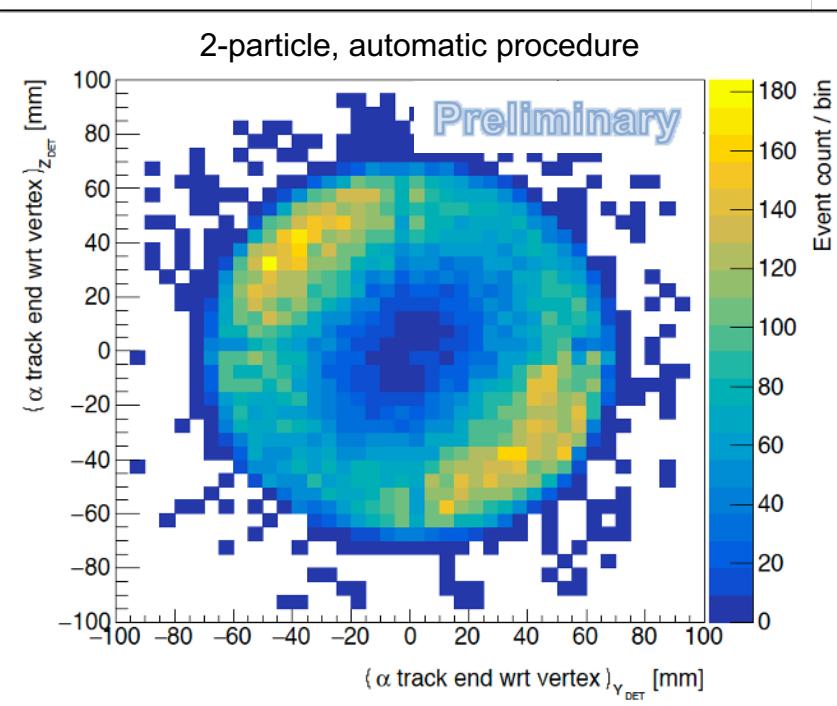
^{16}O photodisintegration experiment @ HIyS

(April-September, 2022)



- Azimuthal ϕ angle of 2-particle events

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



→ degree of circular polarization in good agreement with direct measurement ($S_3 \approx 0.94$)

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

$$S_1 = \frac{W(0) - W\left(\frac{\pi}{2}\right)}{W(0) + W\left(\frac{\pi}{2}\right)}$$

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

$$S_2 = \frac{W\left(\frac{\pi}{4}\right) - W\left(-\frac{\pi}{4}\right)}{W\left(\frac{\pi}{4}\right) + W\left(-\frac{\pi}{4}\right)}$$

$$W(\phi) = 1 + f \cdot \cos 2(\phi + \delta)$$

Summary & plans



✓ R&D phase:

- **2014-2020:** verification of materials, production & assembly techniques, low-pressure technique, LV & HV power supplies, customized FPGA DAQ readout, prototype tests

✓ First experiments:

- **June-September 2021:** first runs with gamma- and neutron beams at the Institute for Nuclear Physics, Polish Academy of Science (IFJ-PAN, Cracow, Poland)
- **April-September 2022:** measurements of $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ at $E_\gamma = 8.51 \div 13.9 \text{ MeV}$ at the High Intensity γ -Ray Source – HI γ S (TUNL, Durham, NC, USA)

✓ Future plans:

- **2024:** exploring lower E_{CM} energies for $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ and $^{12}\text{C}(\gamma,3\alpha)$ at the HI γ S facility – pending increase of gamma beam intensity
- **After 2023:** delivering similar detector (ELITPC) dedicated for the new Variable Energy Gamma system – VEGA (ELI-NP, Romania)

Thank you for your attention !!!



Team members:

M. Ćwiok, W. Dominik, A. Fijałkowska, M. Fila, Z. Janas,
A. Kalinowski, K. Kierzkowski, M. Kuich, C. Mazzocchi,
W. Okliński, M. Zaremba

Faculty of Physics, University of Warsaw, Poland

M. Gai, S. Stern, D. Schweitzer

LNS at Avery Point, University of Connecticut, CT, USA

D. Balabanski

IFIN-HH / ELI-NP, Romania



Acknowledgements:

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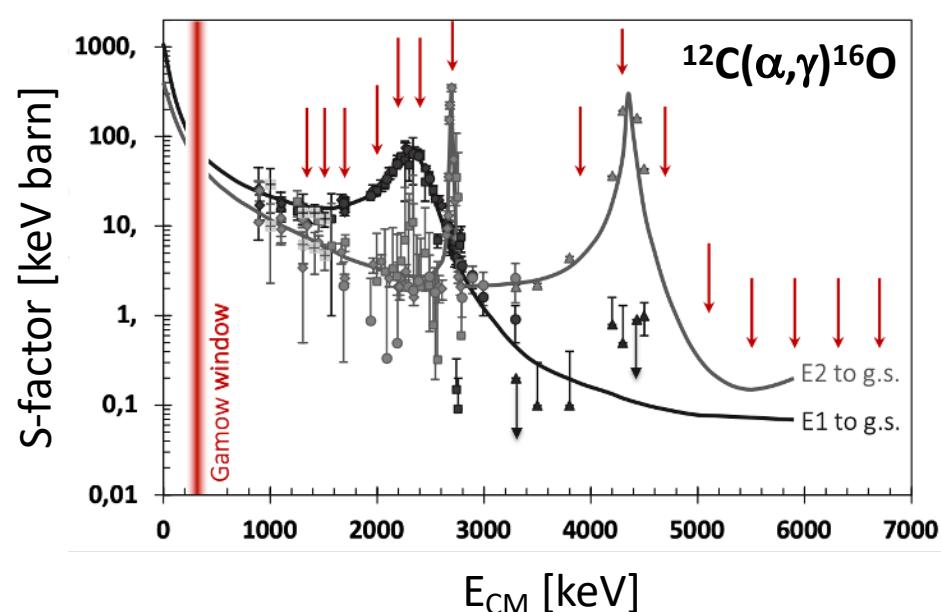
Backup slides

^{16}O photodisintegration experiment @ HIγS (April-September, 2022)



- Measured energy points:

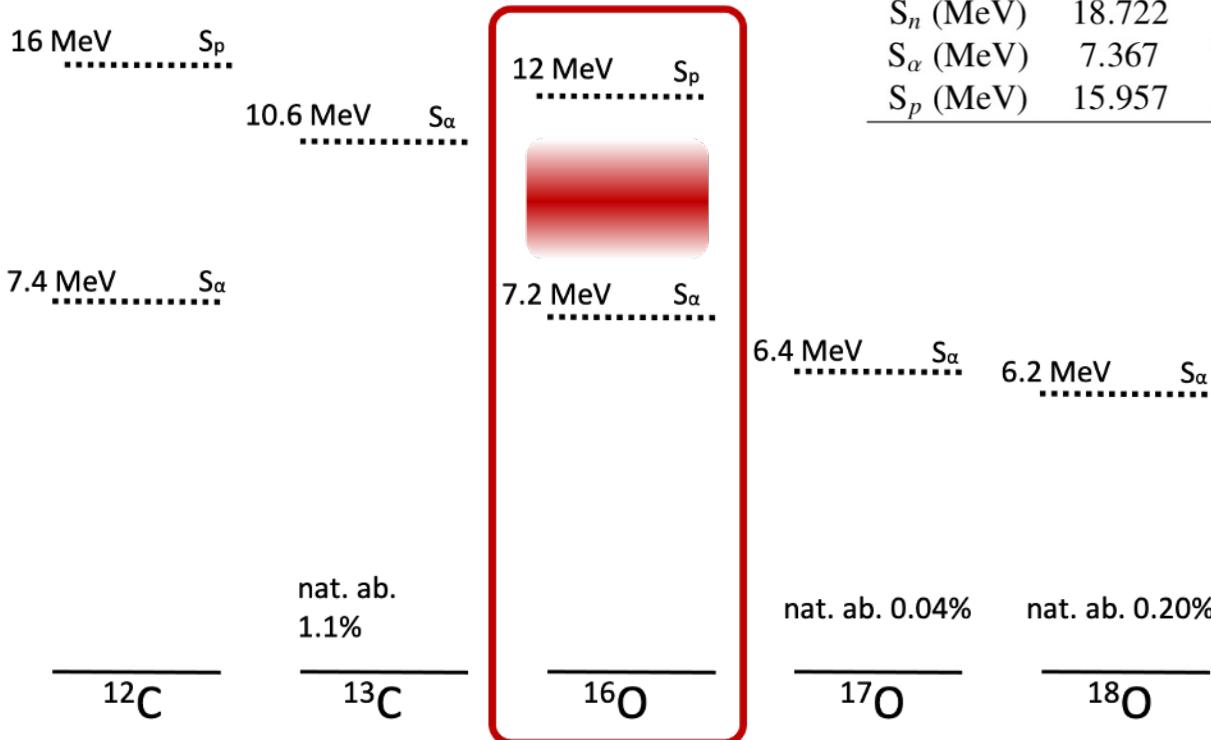
E_γ (MeV)	8.51	8.66	8.86	9.16	9.36	9.56	9.85	11.1	11.5	11.9	12.3	12.7	13.1	13.5	13.9
p (mbar)	130	130	130	130	130	130	130	190	190	190	190	190	250	250	250



^{16}O photodisintegration experiment @ HLyS (April-September, 2022)



- Possible reaction channels for CO_2 gas target:



Separation energies for neutrons, protons and alpha particles in $^{12,13}\text{C}$ and $^{16,17,18}\text{O}$ isotopes

	^{12}C	^{13}C	^{16}O	^{17}O	^{18}O
S_n (MeV)	18.722	4.946	15.664	4.144	8.044
S_α (MeV)	7.367	10.648	7.162	6.359	6.227
S_p (MeV)	15.957	17.533	12.128	13.780	15.942