

Warsaw active-target TPCs for studying astrophysical reactions



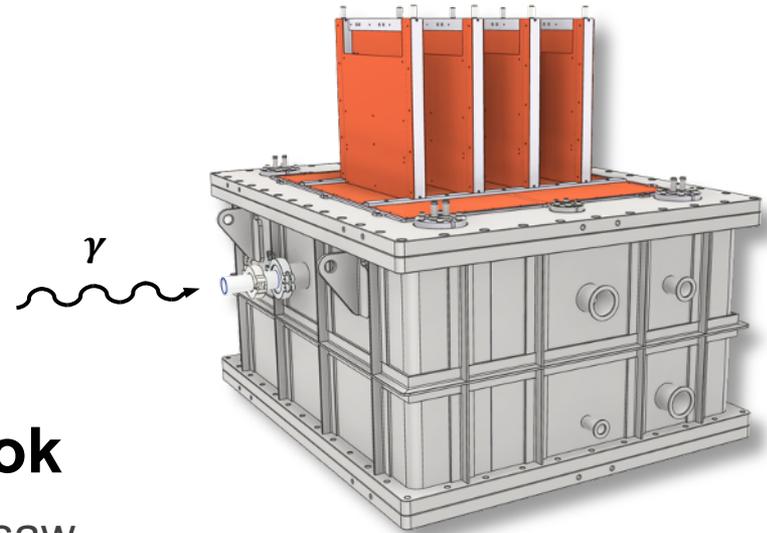
**FACULTY OF
PHYSICS**

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Faculty of Physics

Division of Particles and Fundamental Interactions



Particle Physics Seminar – University of Bonn

12 February 2026



Part – 1

TPCs for neutral beams

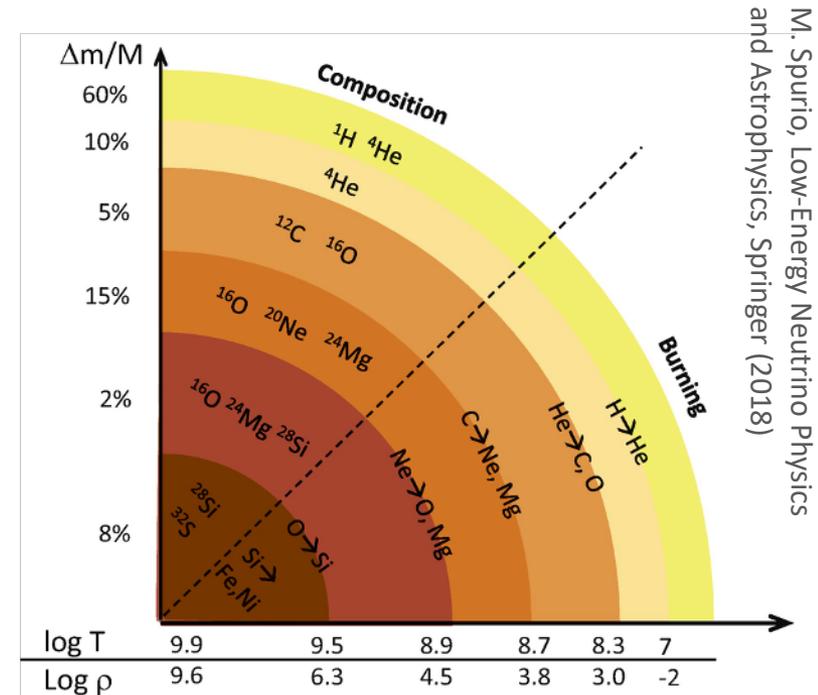
Nuclear Astrophysics with monochromatic γ -ray beams

Big Bang Nucleosynthesis – burning of: ${}^4\text{He}$, ${}^2\text{H}(\text{d})$, ${}^3\text{He}$, ${}^7\text{Li}$

Stellar Nucleosynthesis – burning of: H, He, C, Ne, O, Si + *supernovae explosions*

Physics goals:

- study (α, γ) and (p, γ) reactions of current astrophysical interest that:
 - burn **He** \rightarrow regulate **C / O** ratio (\mathcal{R})
 - stars $\mathcal{M} > 10 \mathcal{M}_{\odot}$: final \mathcal{R} determines fate of *red giant stars* (NS or BH)
 - stars $\mathcal{M} \approx 1.4 \mathcal{M}_{\odot}$: final \mathcal{R} affects light curves of *type Ia supernovae*
 - burn ${}^{18}\text{O}$ \rightarrow regulate ${}^{16}\text{O}/{}^{18}\text{O}$ ratio
- particular focus on ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction at $E_{\text{CM}} \gtrsim 1 \text{ MeV}$



Nuclear Astrophysics with monochromatic γ -ray beams

Experimental approach for (α, γ) and (p, γ) reactions:

- measure **photo-disintegration** instead of direct capture process:

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

- $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction: gain of factor 40 in cross section at $E_{CM} \sim 1$ MeV

- use quasi-monochromatic **intense gamma-ray beams**:

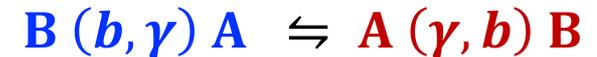
- facilities such as: HI γ S (USA), ELI-NP (Romania)

- use **active-target Time Projection Chamber**:

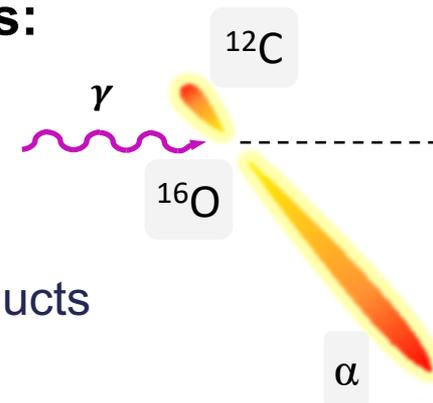
- measure kinematics of low-energy charged particle products
- obtain accurate values of E1 / E2 components

direct capture

photo-disintegration



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

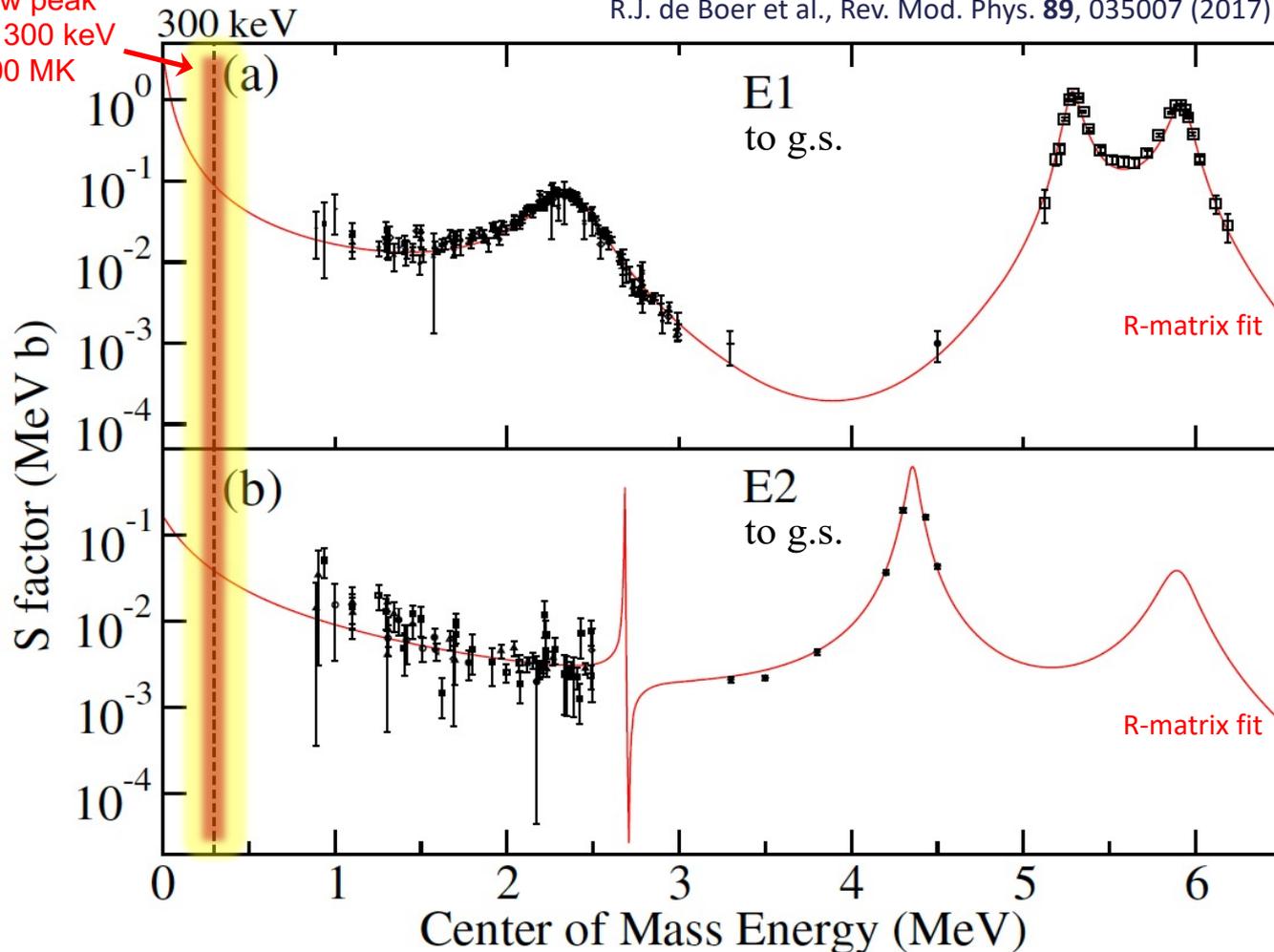


Experimental data on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

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

Gamow peak
 $E_{\text{CM}} \sim 300 \text{ keV}$
 $T \sim 300 \text{ MK}$

R.J. de Boer et al., Rev. Mod. Phys. **89**, 035007 (2017)



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

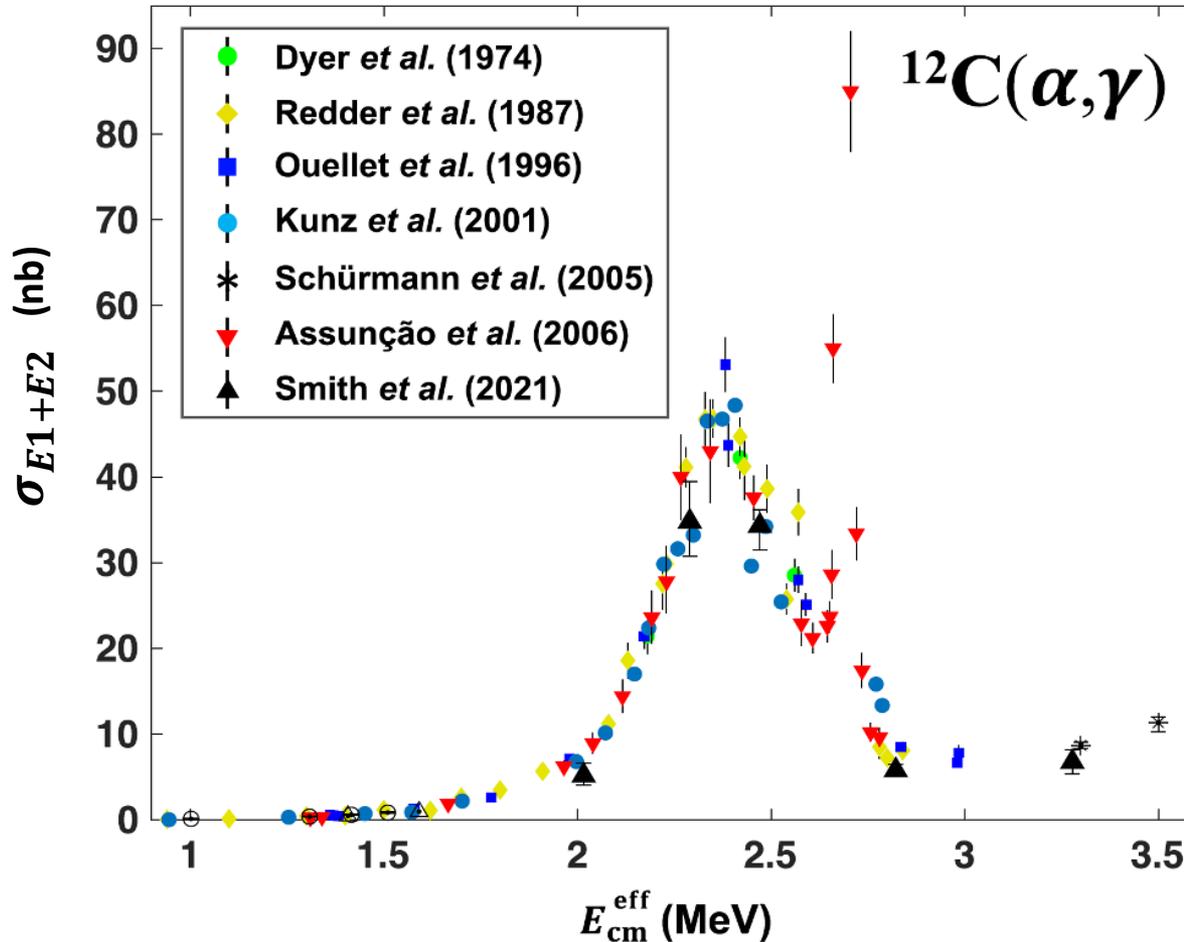
$$\eta = Z_1 Z_2 \frac{e^2}{\hbar} \sqrt{\mu_{12}/(2E)}$$

Brochard (1973)	E1
Dyer, Barnes (1974)	E1
Redder (1987)	E1, E2
Kremer (1988)	E1
Ouellet (1996)	E1, E2
Roters (1999)	E1, E2
Gialanella (2001)	E1
Kunz (2001)	E1, E2
Fey.(2004)	E1, E2
Assunção (2006)	E1, E2
Makii (2009)	E1, E2
Schürmann (2011)	E1, E2
Plag (2012)	E1, E2

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

Compilation of measured **E1+E2** cross sections for $E_{CM} \gtrsim 1$ MeV:

R. Smith et al., Nature Comm. 12, 5920 (2021)



- charged particle beams (direct capture)
- gamma beams (photo-disintegration)

TPC R&D timeline @ UW



Since 2004 – building & operating **TPCs with optical-readout (OTPC)**

for studying: *2p radioactivity, β -delayed emissions & rare decays* with radioactive ion beams

Since 2013 – developing GEM-based **active-target TPCs with UVW strip readout**

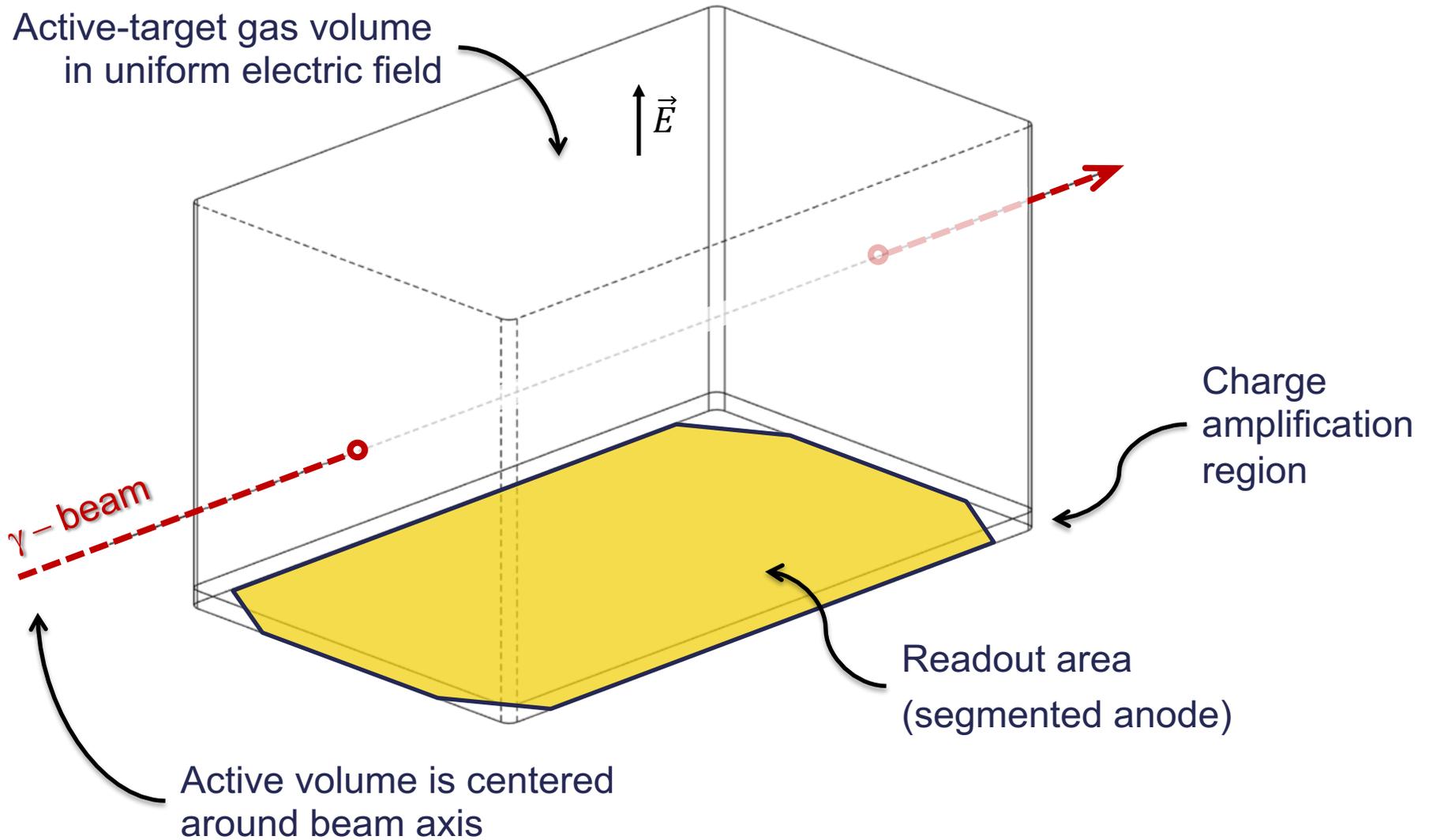
for studying *Nuclear Astrophysics reactions* with neutral beams (γ -rays, neutrons):

- TPC R&D partners: **ELI-NP / IFIN-HH** (Romania), **U. of Connecticut** (USA), **Sheffield Hallam U.** (UK)
- DAQ R&D partners: **GET collab.** (CEA/Saclay, CENBG/Bordeaux, GANIL/Caen, MSU/FRIB)
- 2015-2018 : low-pressure prototype **mini-TPC** with **256** readout channels
- 2019-2020 : low-pressure full scale **Warsaw TPC** with **1024** readout channels

2021-2022 – first experiments with the **Warsaw TPC**:

- 2021 : Institute for Nuclear Physics, Polish Academy of Science (IFJ-PAN), Cracow, Poland:
 - ✓ experiment with 13 MeV gamma source : $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
 - ✓ experiment with 14.1 MeV neutron source : $^{12}\text{C}(n,n')^{12}\text{C}(\text{Hoyle state})$
- 2022 : High Intensity Gamma-Ray Source (HIgS) / TUNL, Duke U., Durham, NC, USA:
 - ✓ experiment with 8.5 - 13.9 MeV gamma-ray beams : $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ and $^{12}\text{C}(\gamma,3\alpha)$

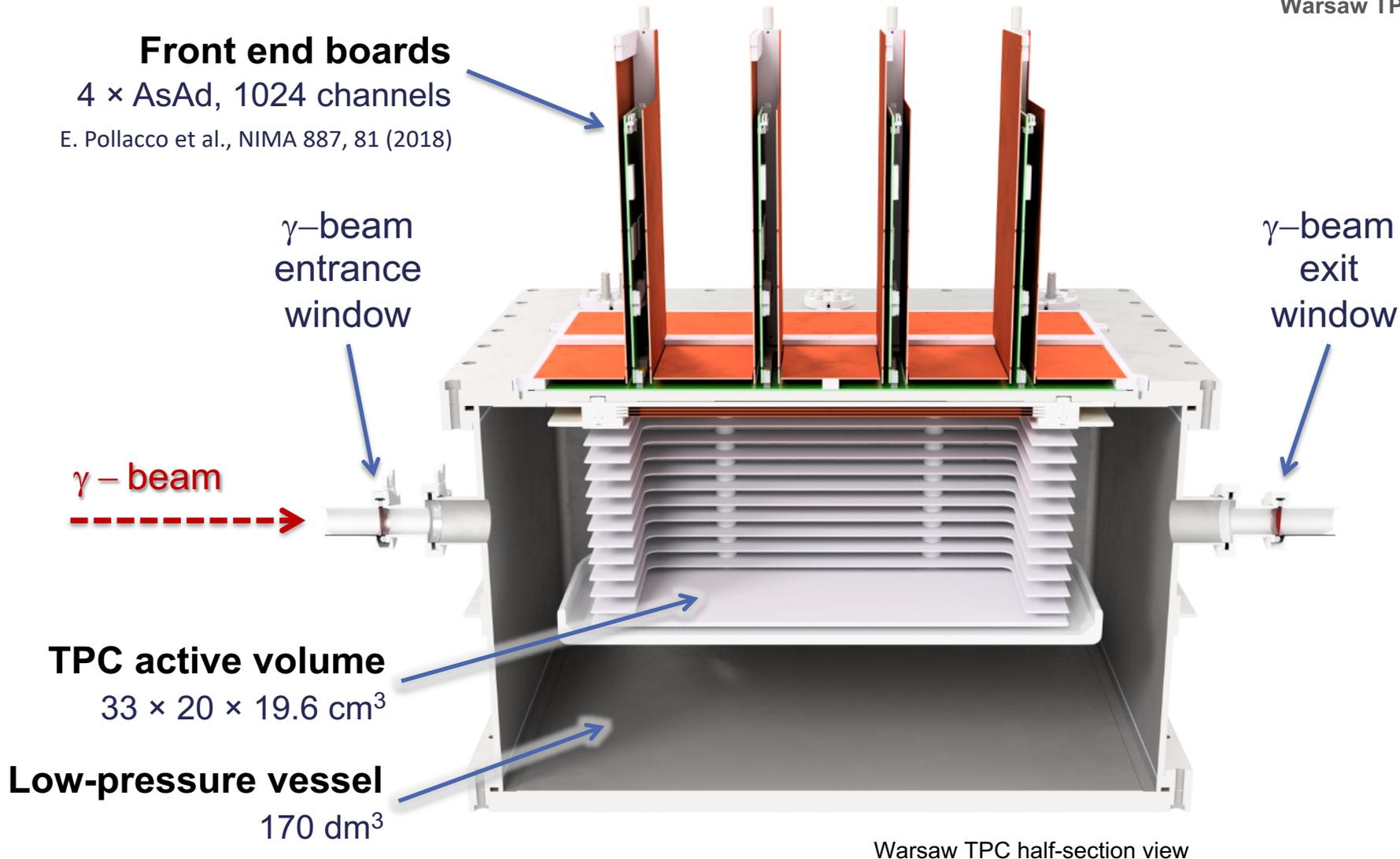
Active-target TPC for γ -ray beam



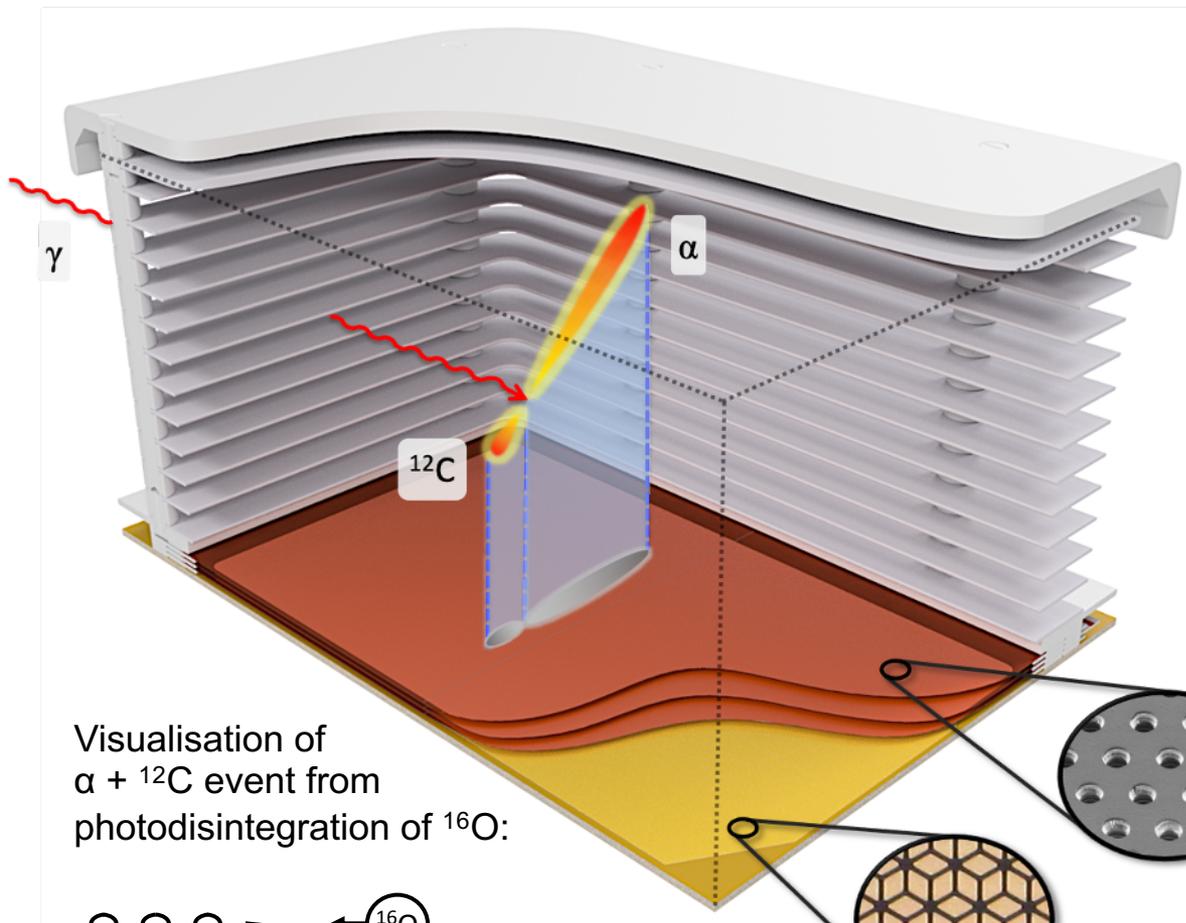
Warsaw TPC – internal structure



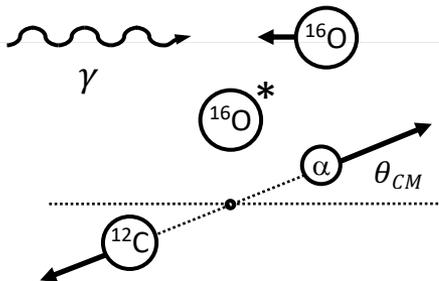
Warsaw TPC



Warsaw TPC – internal structure



Visualisation of $\alpha + {}^{12}\text{C}$ event from photodisintegration 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)
F.Sauli, NIMA 386, 531 (1997)

UVW strip readout

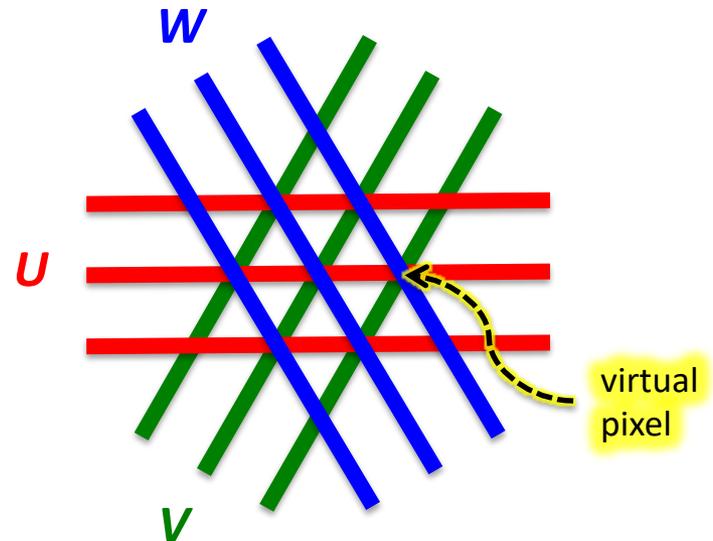
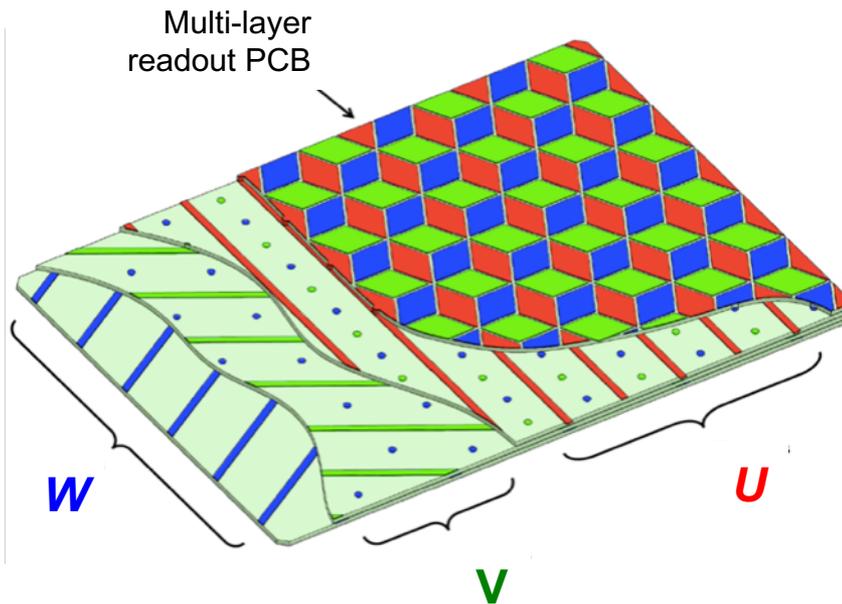
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

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



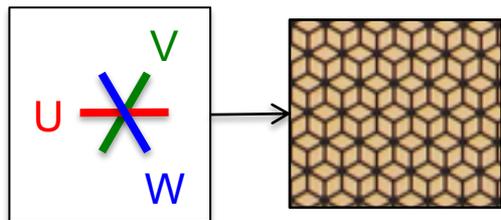
- [1] S. Bachmann et al., NIM A **478**, 104 (2002)
- [2] V. Ableev et al., NIM A **535**, 294 (2004)
- [3] J. Bihałowicz et al., Proc. of SPIE **9290**, 92902C (2014)
- [4] M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

Warsaw TPC – strip segmentation



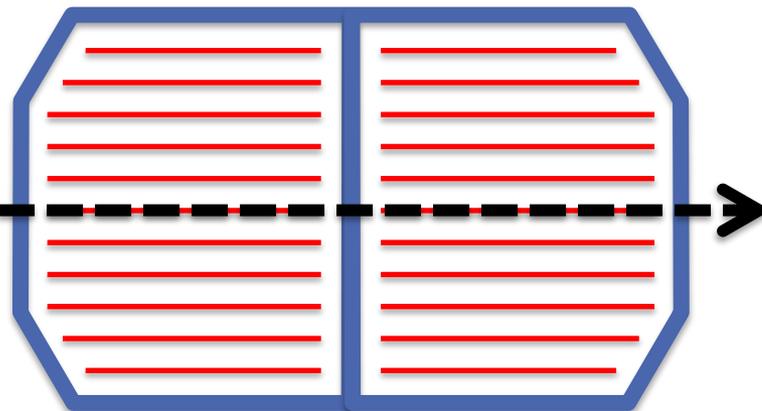
Warsaw TPC

- **1018 strips** in total
- 1.5 mm strip pitch (in each of U / V / W dirs.)

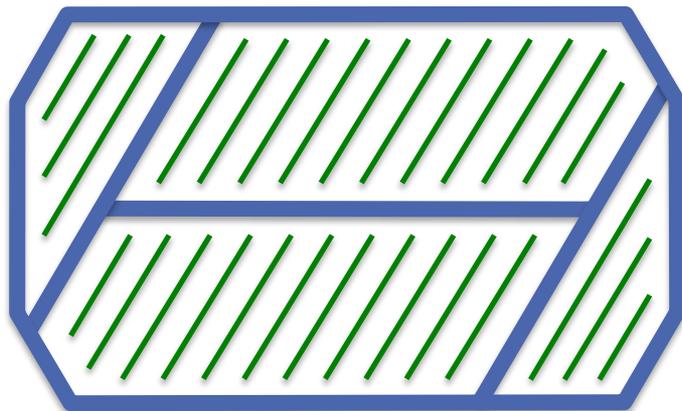


γ - beam

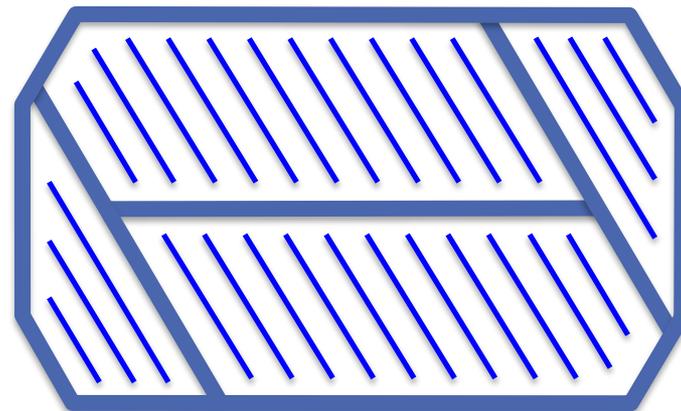
264 U-strips (2 sections)



376 V-strips (4 sections)



378 W-strips (4 sections)



Warsaw TPC – DAQ scheme



Commercial AsAd card
256-ch, 12-bit (GET collab.)

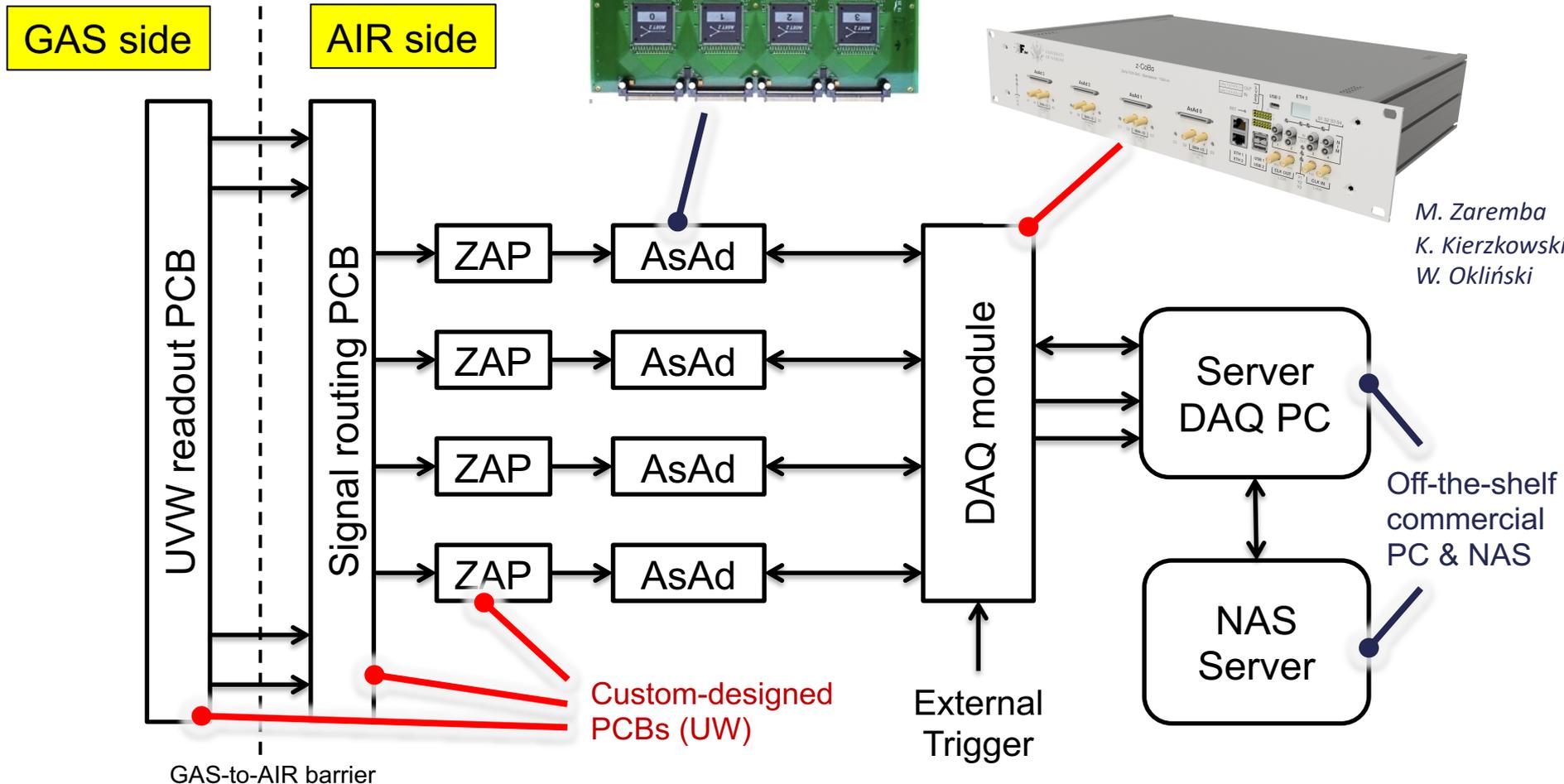
E. Pollacco et al., NIMA 887, 81 (2018)



Custom-designed FPGA-based
1024-ch DAQ module (UW)



M. Zaremba
K. Kierzkowski
W. Okliński



Warsaw TPC – custom FPGA module



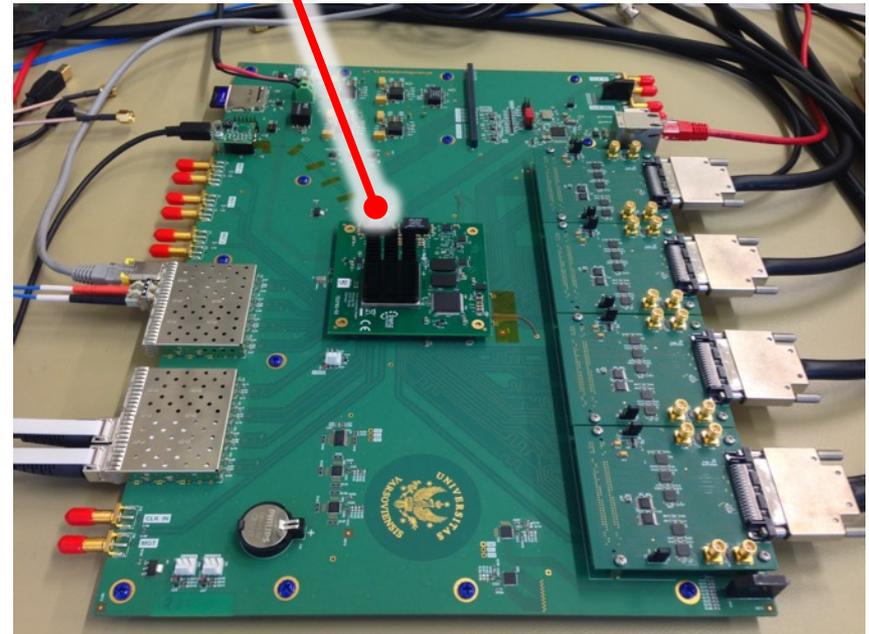
Warsaw TPC

- Commercial Xilinx Zynq-7000 SoC:
 - [Trenz TE-0782](#)
- Custom designed PCB & firmware:
 - **Reads 4 AsAd boards (1024 channels)**
 - Data output: up to 8 SFP+ ports (10 Gbit/s)
 - Internal or external trigger (NIM, TTL, LVDS or custom serial protocol)
 - Possibility of syncing 2-3 modules
- 19"-rack 2U chassis form-factor



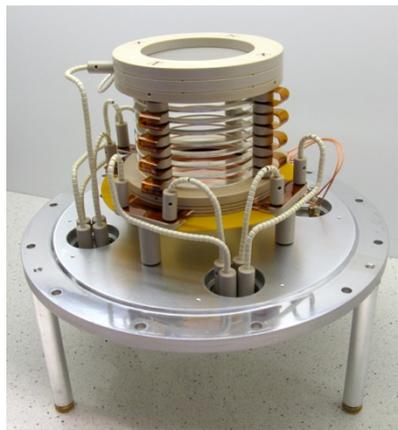
Commercial ZYNQ-7000 mezzanine

Custom DAQ main board



Chassis visualisation (front & rear)

Low-pressure GEM-based TPCs @ UW

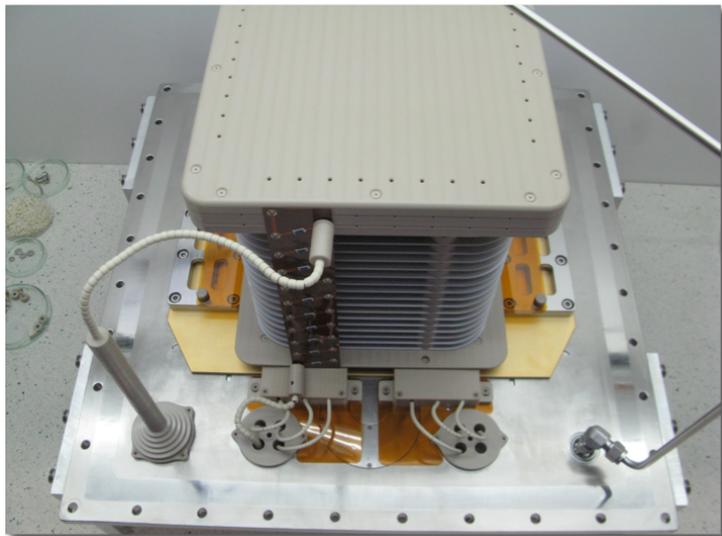


2-channel model detector

ϕ 5 cm (active area) \times 10 cm (drift)

256-channel mini-TPC

10 \times 10 cm² (active area) \times 20 cm (drift)



1024-channel Warsaw TPC

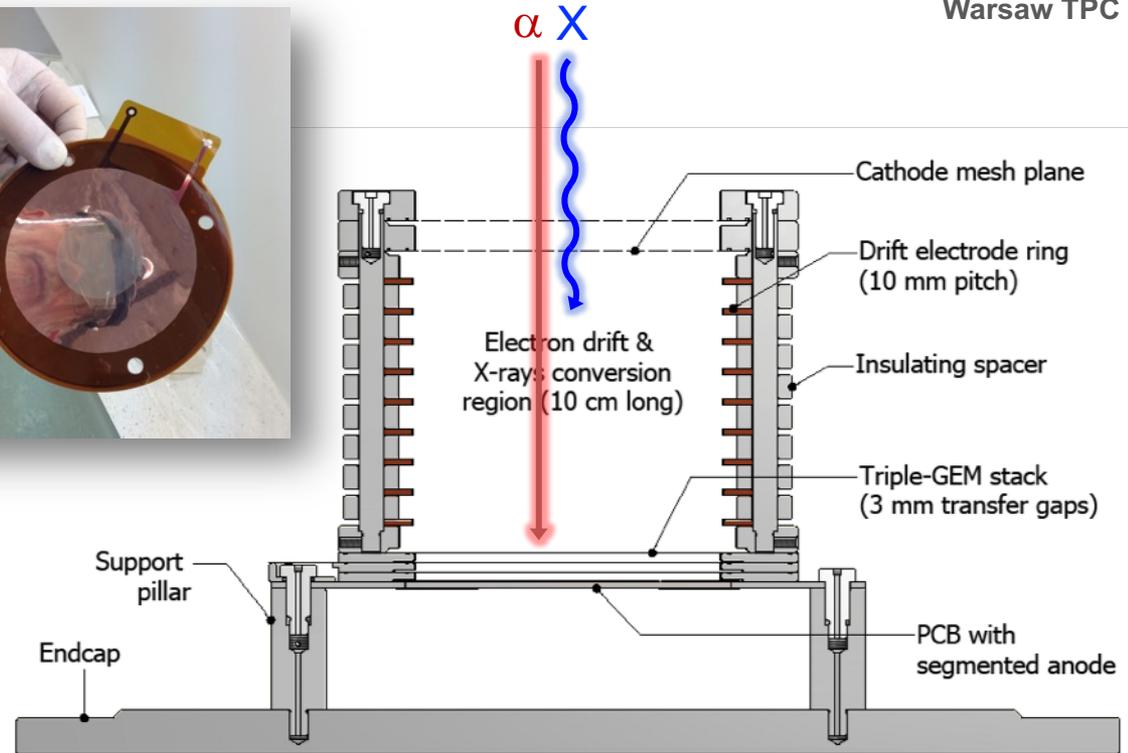
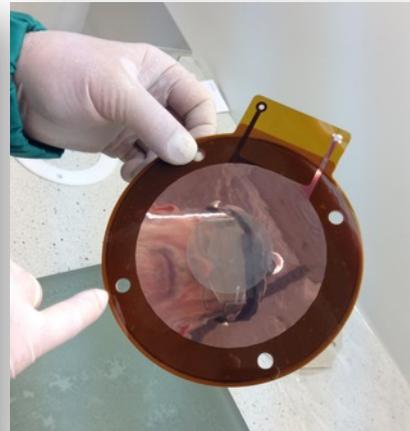
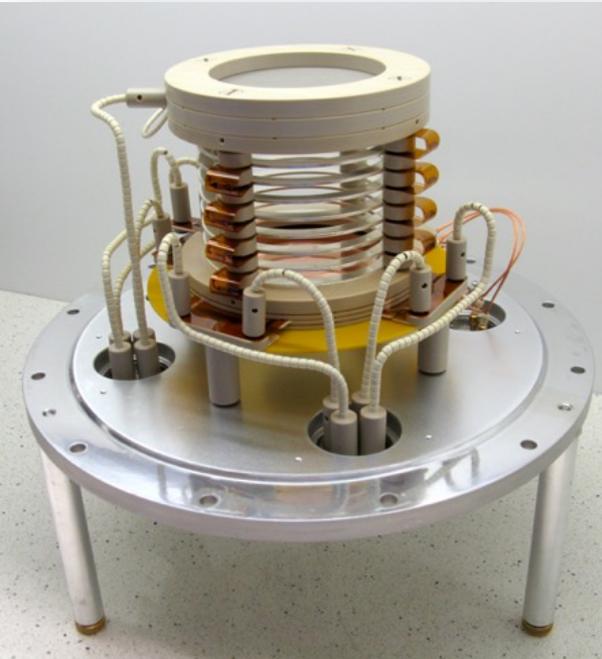
33 \times 20 cm² (active area) \times 19.6 cm (drift)



Test bench for GEM studies



Warsaw TPC



M. Ćwiok et al., Acta Phys. Pol. B **49**, 509 (2018)

- Low-pressure test bench:
 - model detector: 14 dm³ vessel, 3 or 2 GEM foils, $\phi 5$ cm {active area} \times 10 cm {drift}
 - GEM foil thickness: **50 μ m** (standard) or **125 μ m** (custom designed **thicker-GEM**)
 - soft X-rays (~ 5 keV) \Rightarrow **gas gain**, energy resolution
 - alpha-particle source (~ 5.5 MeV) \Rightarrow **electron drift velocity**, diffusion

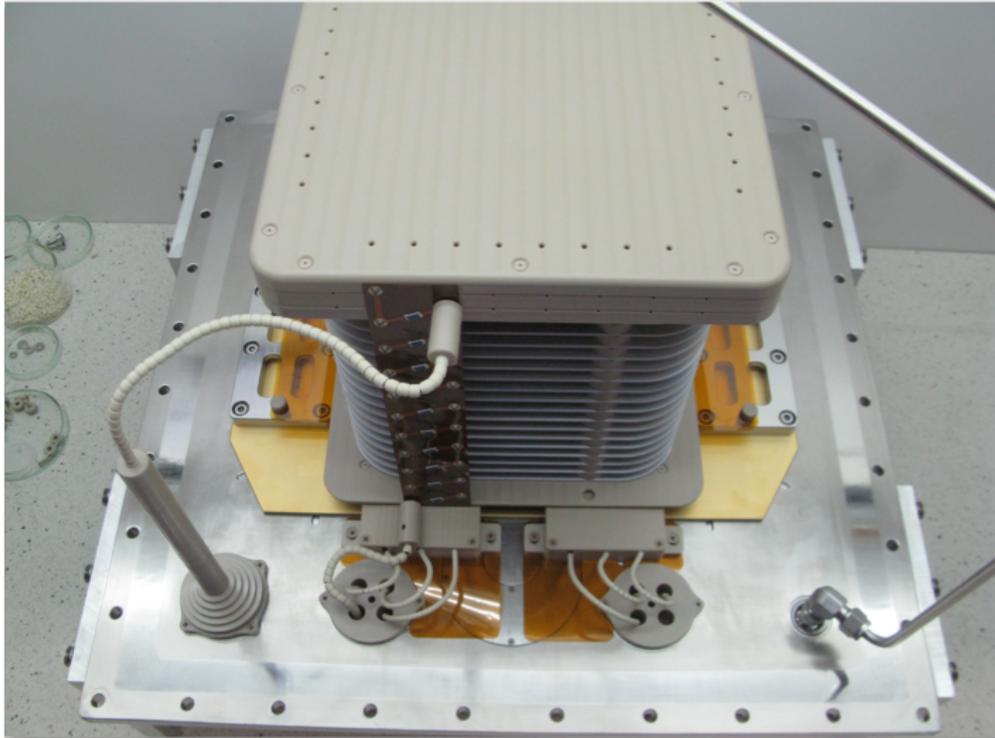
Mini-TPC demonstrator



- Readout area: **10 × 10 cm²**, drift length: **20 cm**
- Vacuum vessel (53 L) with low-pressure gas system
- GET electronics: **256 channels** (z-CoBo)

Vacuum vessel with 1 AsAd card

Assembled internal TPC structure



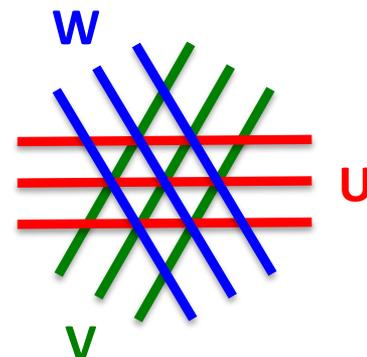
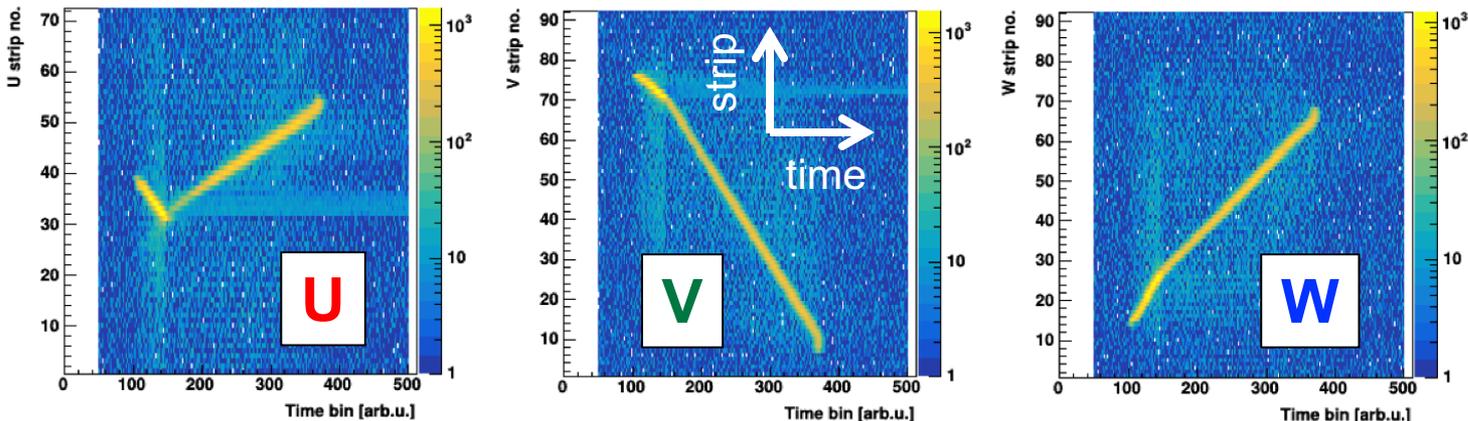
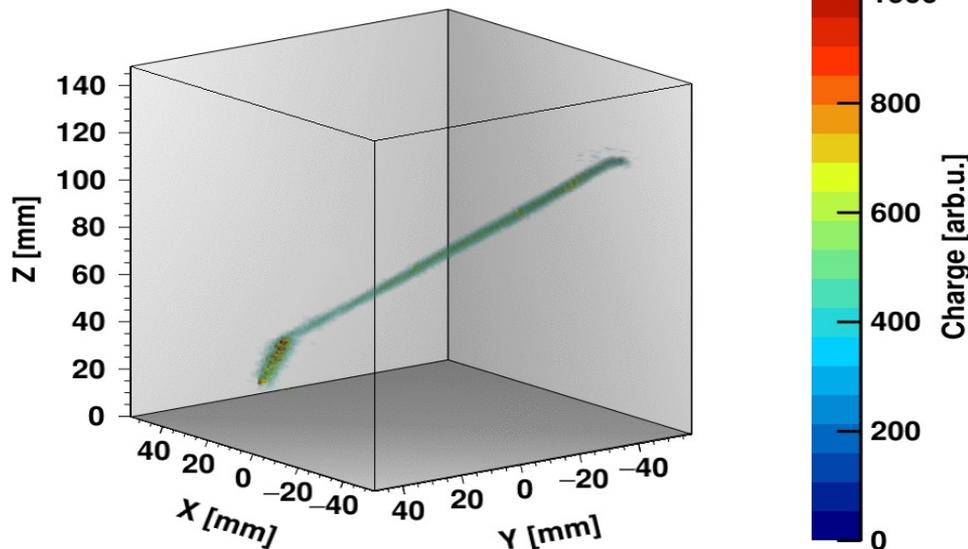
Mini-TPC demonstrator



Warsaw TPC

Example of neutron reacting with nuclei of CO₂ gas molecule

- **Neutron beam – June 2018:**
 - 3 MV Tandem facility at IFIN-HH, Bucharest, Romania
 - neutrons produced by 6.5 MeV α -particle beam on Be target
 - TPC operated with pure CO₂ @ 100 mbar
- Right: energy losses along tracks reconstructed in 3D
- Bottom: raw-data from U / V / W strips

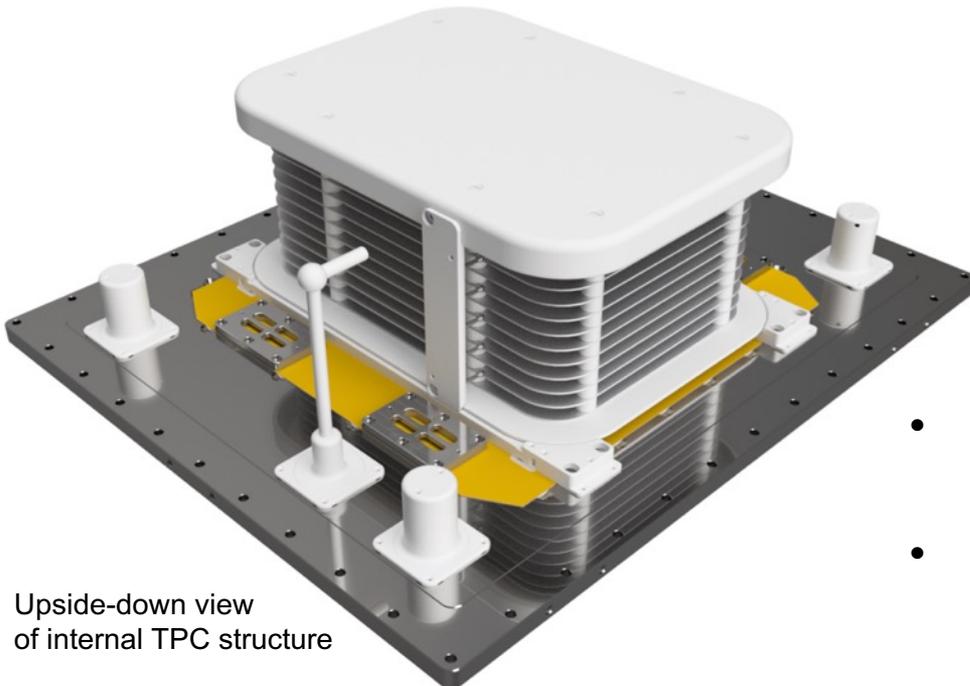
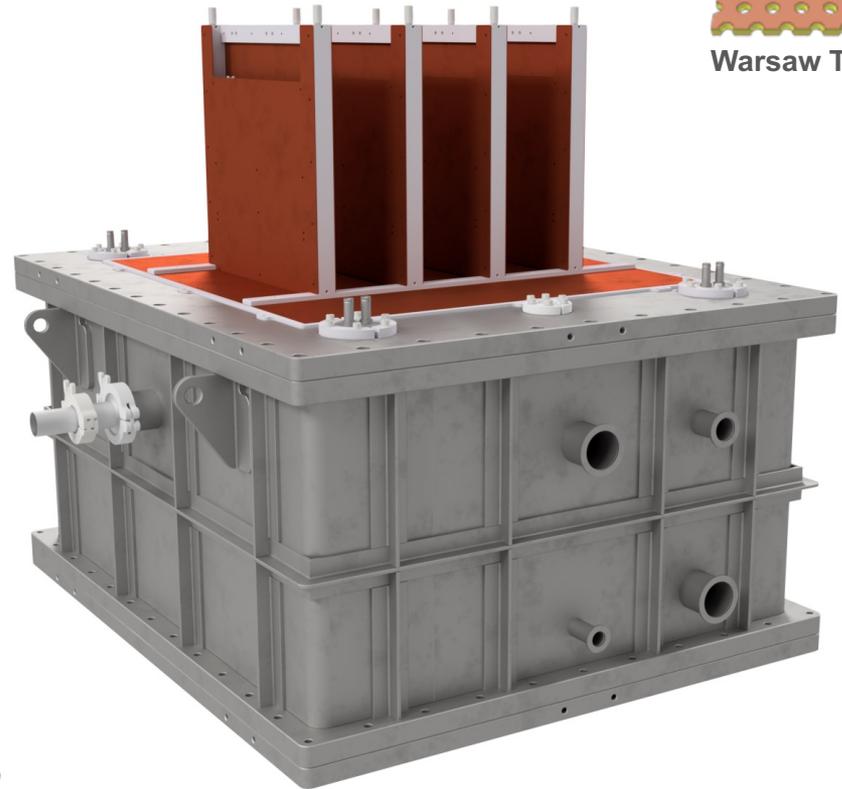


M. Gai et al.,
NIM A 954, 161779 (2020)

Full scale detector



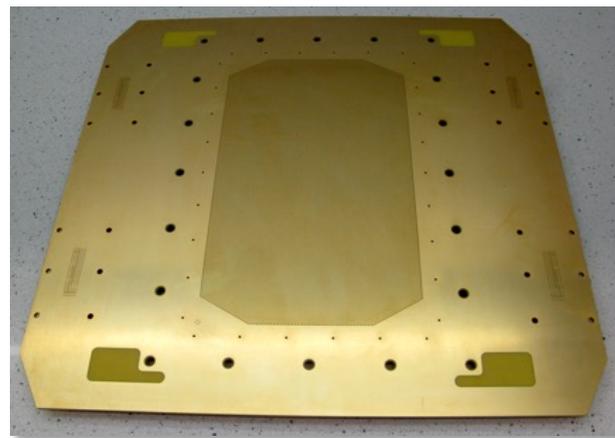
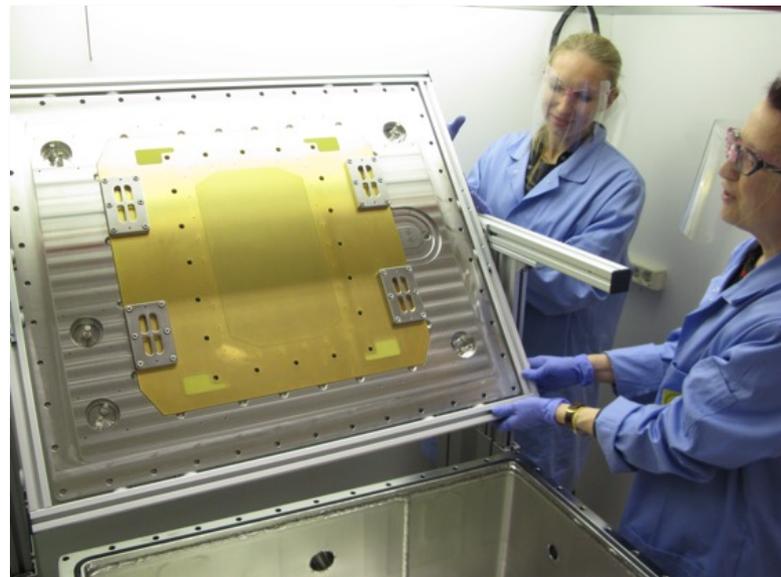
- Stainless steel vessel (170L)
- Barrel + 2 endcap plates
- Standard ISO-KF ports + 4 custom analogue signal ports



Upside-down view
of internal TPC structure

- Drift cage, GEM stack & readout PCB fixed to top endcap plate
- Aluminium, hollow field-shaping electrodes & solid plate cathode

Full scale detector

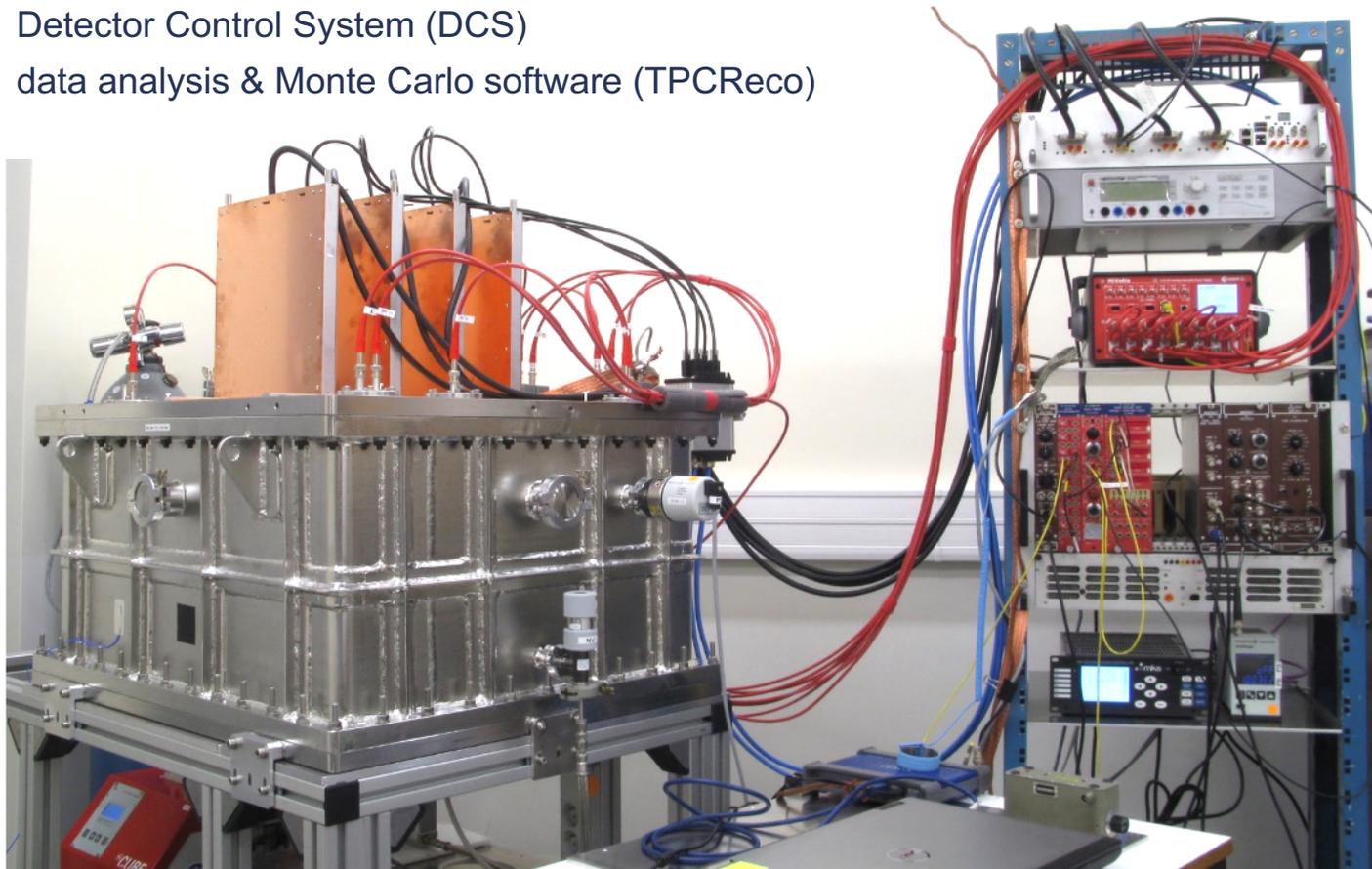


- Left: drift cage integrated with PCB
- Right: readout anode PCB with $20 \times 33 \text{ cm}^2$ active area

Full scale detector



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



Full scale detector



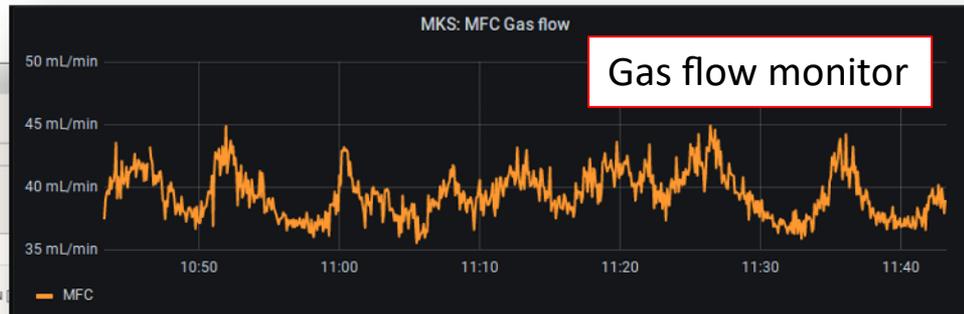
Warsaw TPC

- DCS interfaced with Grafana:

The screenshot shows the DT1415ET (GEM-HV) control interface. It displays the status of various channels (CH 0 to CH 7) and their associated components. The interface includes a table of channel parameters and a diagram of the detector structure.

Channel	Component	Status	Value	VSET [V]	IMON [uA]	Status
CH 0	TR1	ON	270.2	270.0		
CH 1	GEM1	ON	220.1	220.0		
CH 2	TR2	ON	270.3	270.0		
CH 3	GEM2	ON	220.1	220.0		
CH 4	TR3	ON	270.2	270.0		
CH 5	GEM3	ON	220.4	220.0	0.011	ON
CH 6	DRIFT1	ON	980.6	980.0	10.045	ON
CH 7	DRIFT2	ON	980.3	980.0	10.068	ON
TOTAL		ON	3432.2	3430.0		

The diagram on the left shows the detector structure with components: Anode strips (+), TR 1, GEM 1, TR 2, GEM 2, TR 3, GEM 3, DRIFT, and Cathode (-). A red box highlights the CH 0 section (DT1470ET NEG. POL.) and the DRIFT section (HiVolta NEG. POL.).



Pressure PID control

The interface shows the pressure PID control settings and measurements. The flow measurement is 3.79 E 01 sccm and the pressure measurement is 8.000 E 01 mbar. The interface includes buttons for 'Config channels', 'Connect', and 'Disconnect'.

HV control

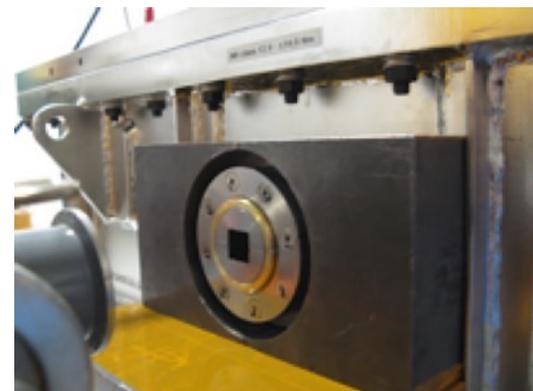
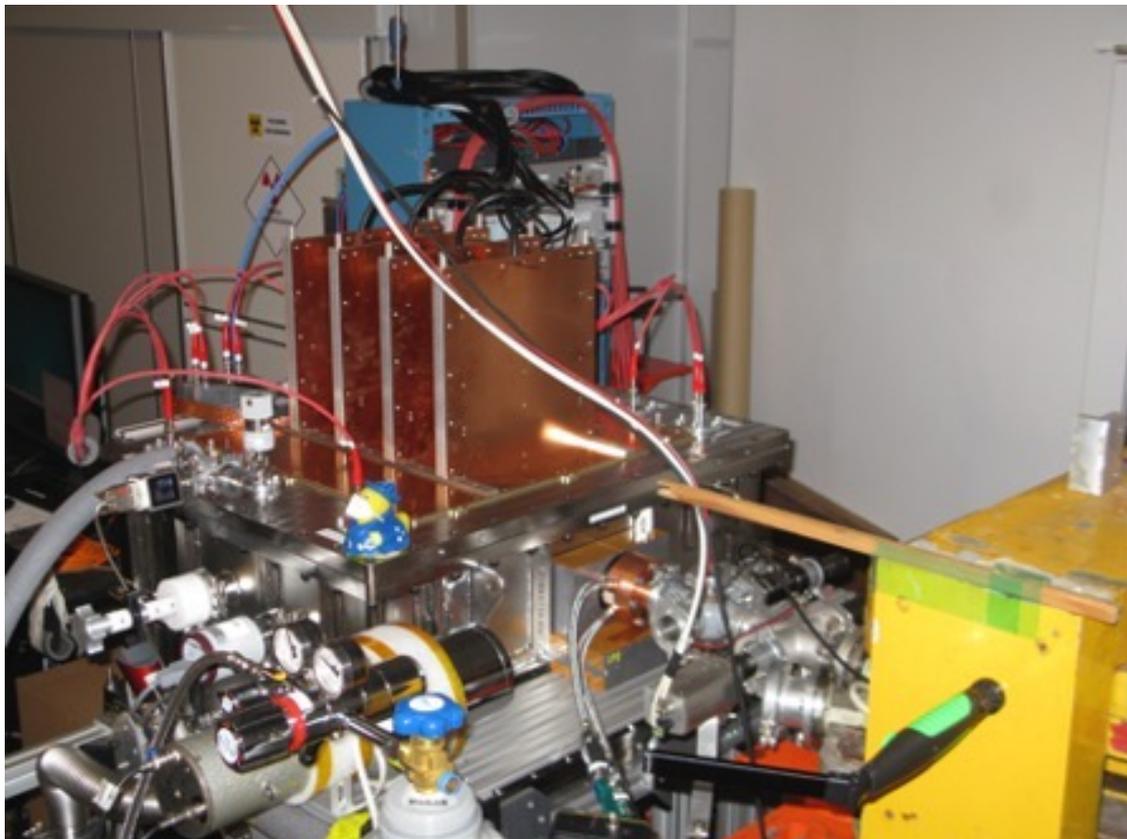
Pressure PID control

M.Fila
M.Kuich

First experiments



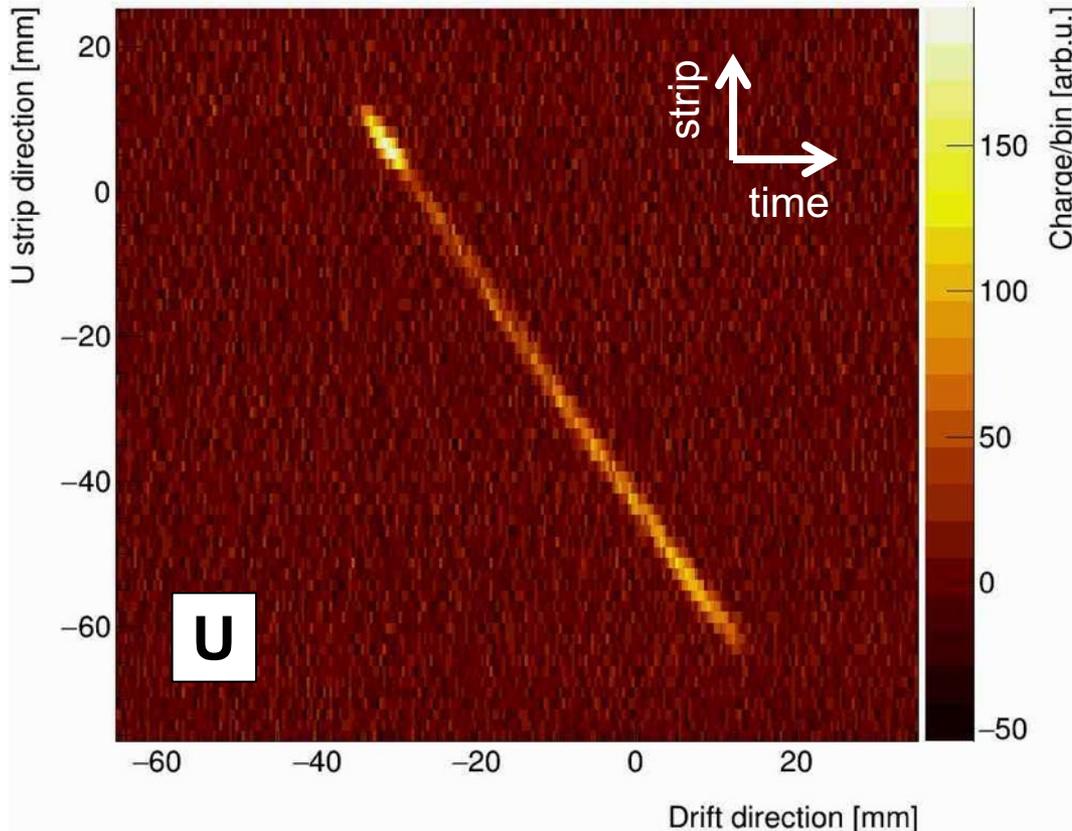
- **Gamma source** – June 2021:
 - Van de Graaff accelerator (IFJ-PAN, Cracow, Poland): 1.03 MeV proton beam on $^{15}\text{N}\text{Cr}$ target produced **13 MeV γ -rays** in $^{15}\text{N}(p, \gamma)^{16}\text{O}$ reaction
 - TPC operated with pure **CO_2 @ 250 mbar**



First experiments



- **Gamma source** – June 2021:
 - Van de Graaff accelerator (IFJ-PAN, Cracow, Poland) : **13 MeV γ -rays** in $^{15}\text{N}(p, \gamma)^{16}\text{O}$ reaction
 - TPC operated with pure **CO_2 @ 250 mbar**



Candidate event for
 $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction

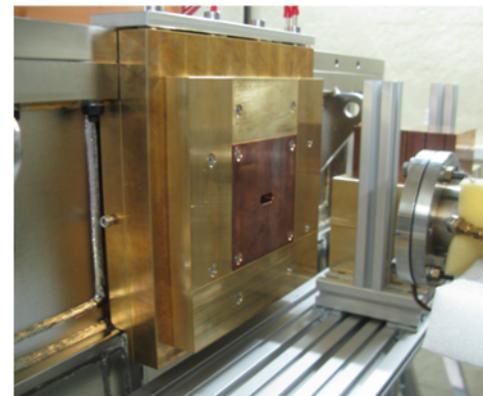
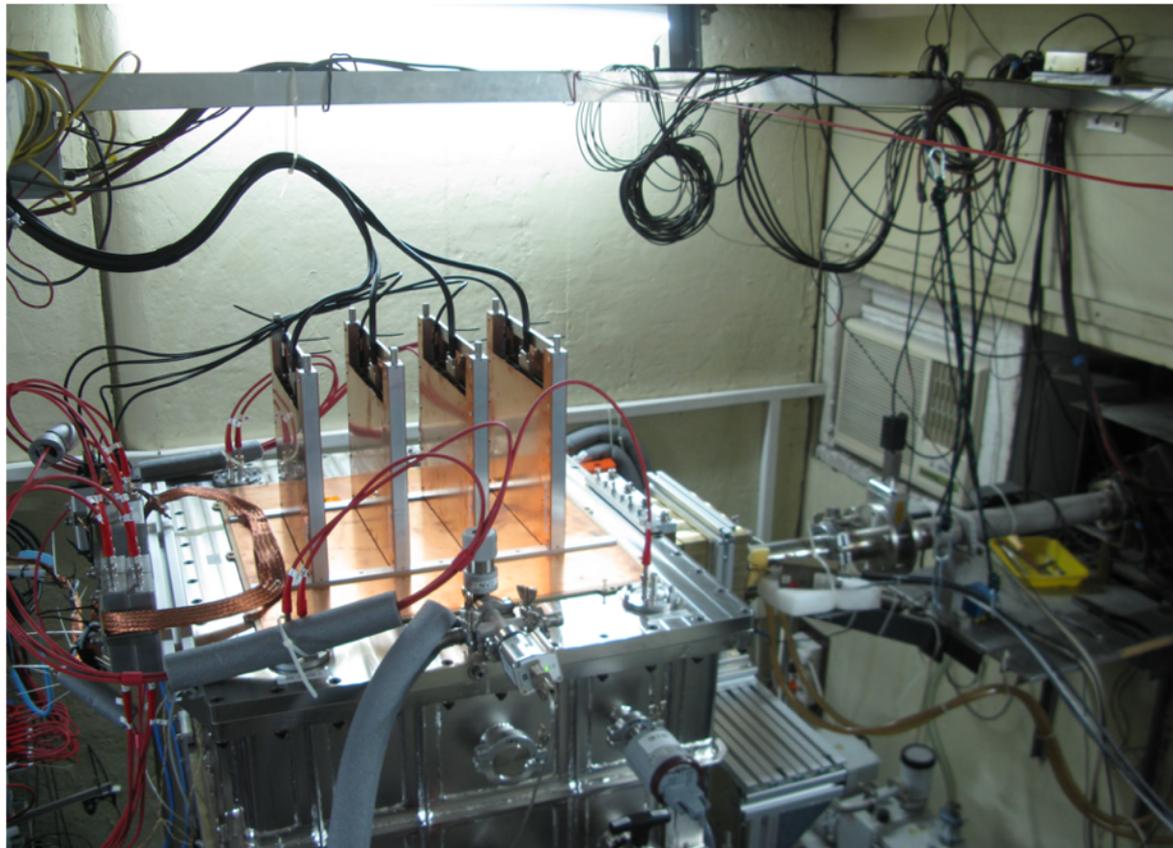
- Only 1 out of 3 projections is shown for simplicity
- Zoomed area: 100 mm x 100 mm

M. Kuich et al., Acta Phys. Pol. B
Proc. Suppl. **16**, 4-A17 (2023)

First experiments



- **Neutron source** – July / September 2021:
 - IGN-14 pulsed neutron generator (IFJ-PAN, Cracow, Poland) : **14.1 MeV neutrons** from $T(d, n)\alpha$ reaction
 - TPC operated with pure **CO₂ @ 80 mbar**



First experiments



- **Neutron source** – July / September 2021:
 - IGN-14 pulsed neutron generator (IFJ-PAN, Cracow, Poland) : **14.1 MeV neutrons** from T(d, n) α reaction
 - TPC operated with pure **CO₂ @ 80 mbar**

Example of candidate event for $^{12}\text{C}(n,n')^{12}\text{C}^{\text{(HS)}}$ reaction:

$$E_{\alpha 1} = 145 \text{ keV}$$

$$E_{\alpha 2} = 108 \text{ keV}$$

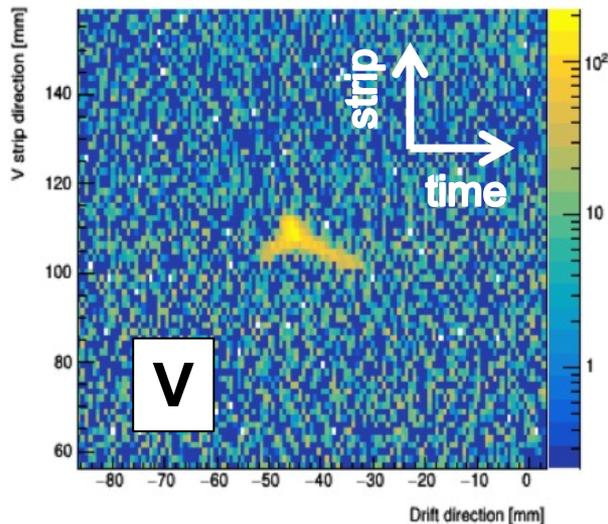
$$E_{\alpha 3} = 60 \text{ keV}$$

$$E_x(^{12}\text{C}) = 7.60 \text{ MeV}$$

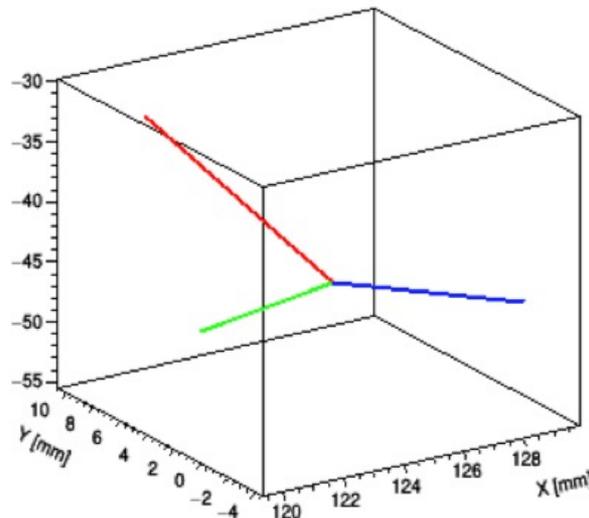
Also observed:

- 3-particle events from: $^{12}\text{C}(n, n')^{12}\text{C}$
- 2-particle events from: $^{12}\text{C}(n, \alpha)^9\text{Be}$

Event-903: Raw signals from V strips



- Left: only 1 out of 3 projections is shown for simplicity
- Right: reconstructed track lengths in 3D

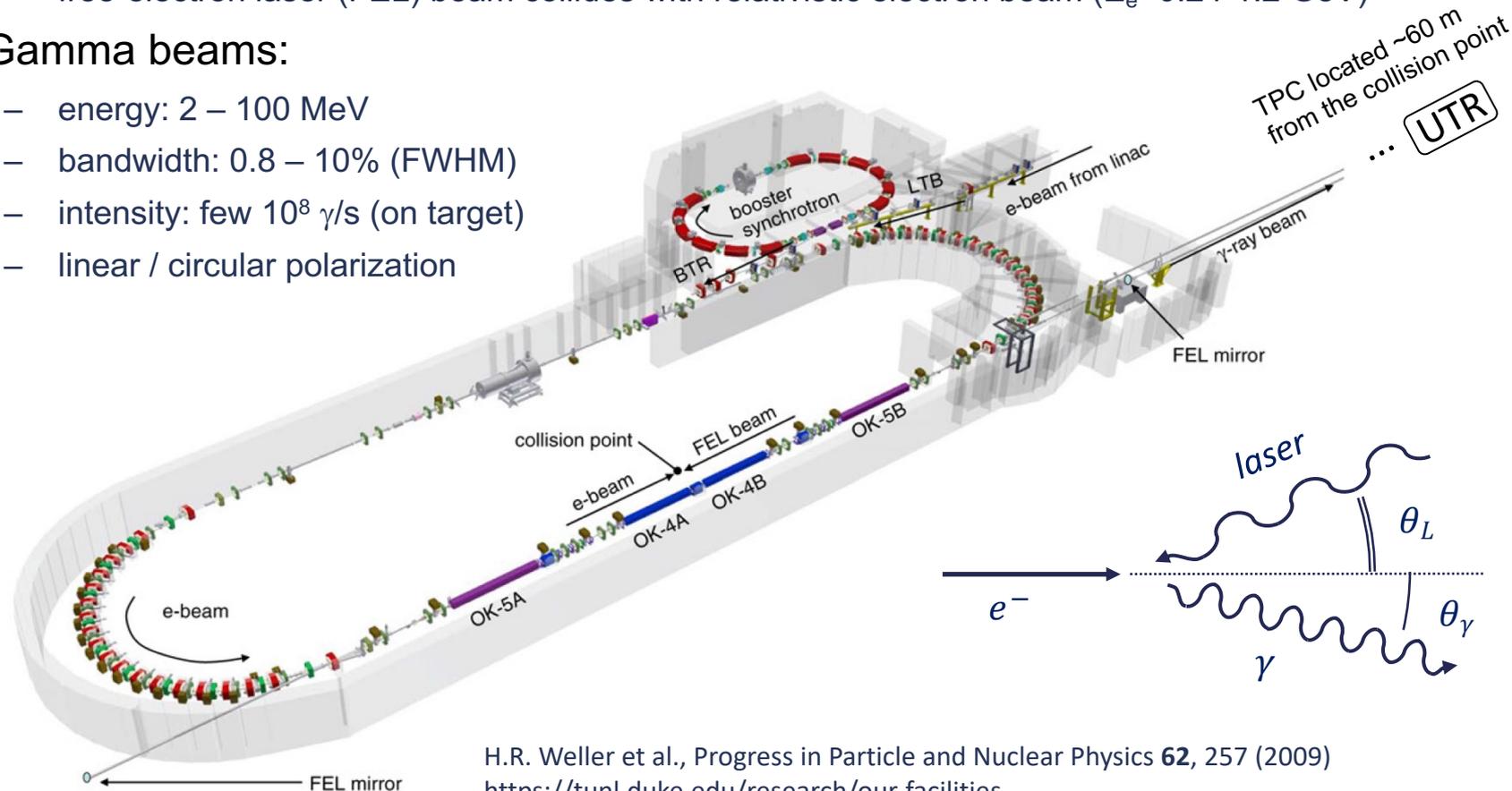


M. Kuich et al., Acta Phys. Pol. B
Proc. Suppl. **16**, 4-A17 (2023)

^{16}O photodisintegration experiment @ HI γ S

(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)



Warsaw TPC

- **Delivered γ -ray beams:**

- 275 hours / 15 energy points
- beam collimator: $\varnothing 10.5$ mm
- E_γ nominal : **8.51 – 13.9 MeV**
 $\Leftrightarrow E_{CM}$: 1.35 – 6.7 MeV of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
- E_γ fwhm : 350 keV @ 8.51 MeV
- I_γ on target : **(1.5 – 5) $\times 10^8$ γ/s**

- **Beam monitoring:**

- E_γ spectra : from HPGe detector
- relative $I_\gamma(t)$: from scintillators
- absolute $\int I_\gamma(t)dt$: from activation of Au foils from (γ,n)

- **Active-target TPC working points:**

- **pure CO_2 gas @ 130 / 190 / 250 mbar**
- gas density, electron drift velocity, electronics sampling rate optimized for charged particle ranges in detector's active volume



Warsaw TPC in the User Target Room (UTR)
~60 m from the collision point

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

Beam monitoring & alignment



Collimator
 $\phi = 10.5 \text{ mm}$
(upstream)



Scintillators
(upstream)

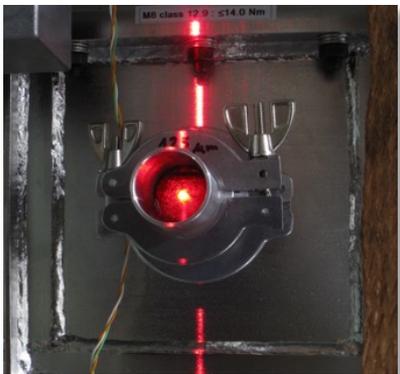
HPGe
(downstream)



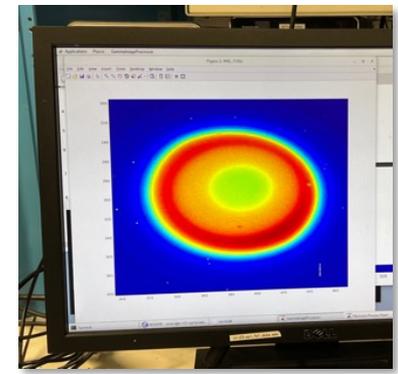
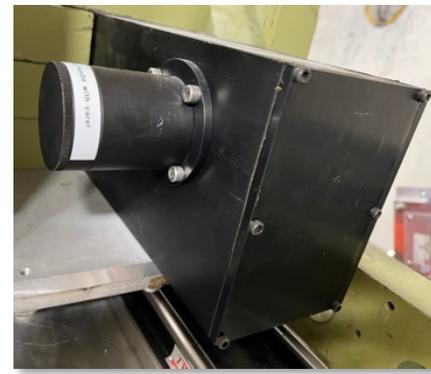
Au foil activation
(downstream)



Alignment – laser



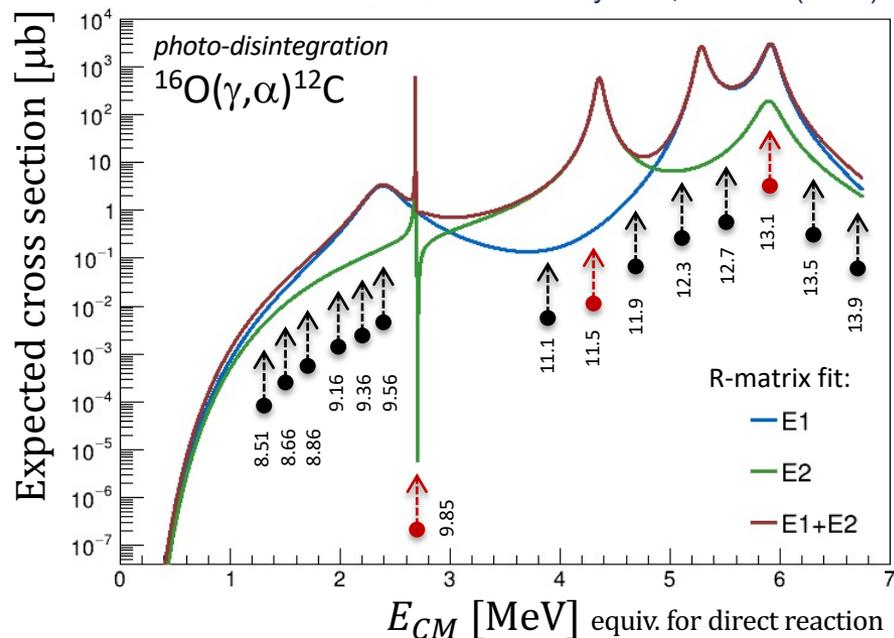
Alignment – BGO CCD gamma camera & lead plugs:



Energy scans

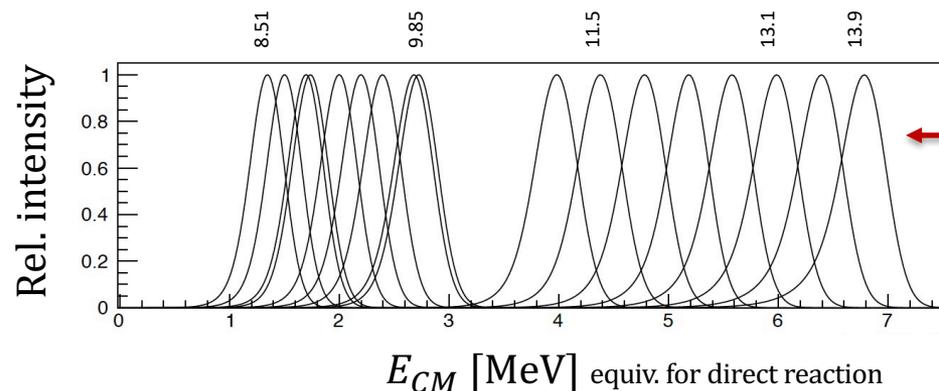


R-matrix fit from: Rev. Mod. Phys. 89, 035007 (2017)



Overview of experimental conditions:

- scanned **15** nominal E_γ energy points split into two data-taking periods
- **3** resonant energies used for *in situ* tuning of α -track energy scale
- several TPC working points:
 - 3 gas target densities
 - 2 front-end electronics sampling rates
 - 7 electron drift velocities



typical shapes of γ -beam spectra on target (TPC volume) for all studied nominal energy points

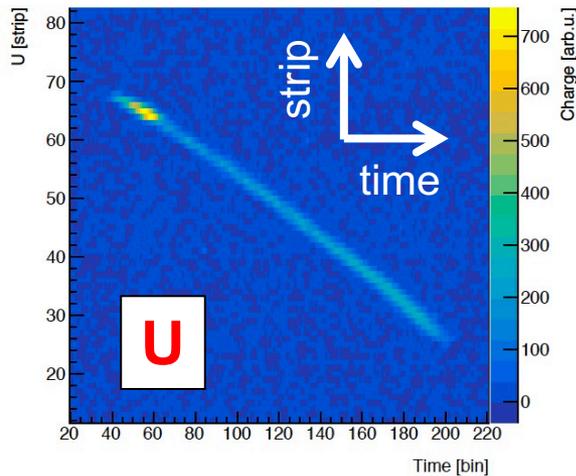
(courtesy of prof. Y. Wu, HIGS/TUNL)

Example raw data

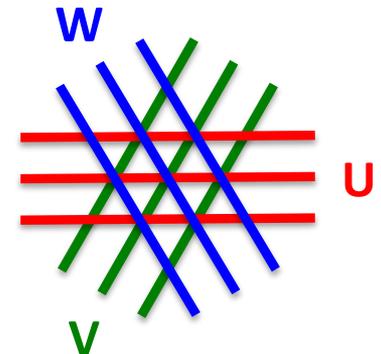
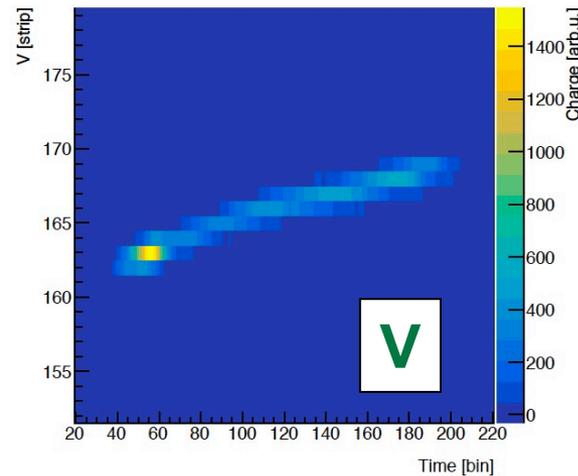


2-particle topology: $^{16}\text{O}(\gamma, \alpha)$ candidate event

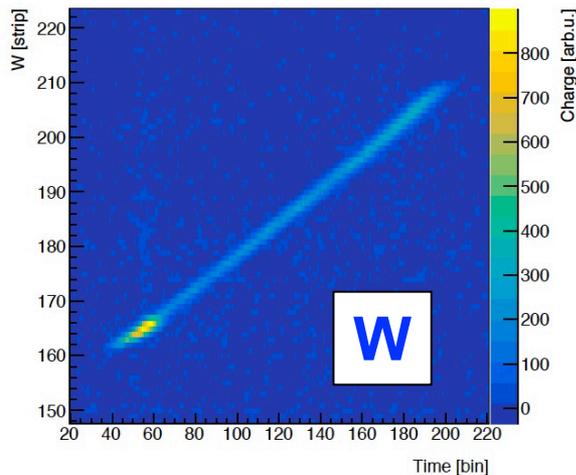
Event 243: U-strips vs Time



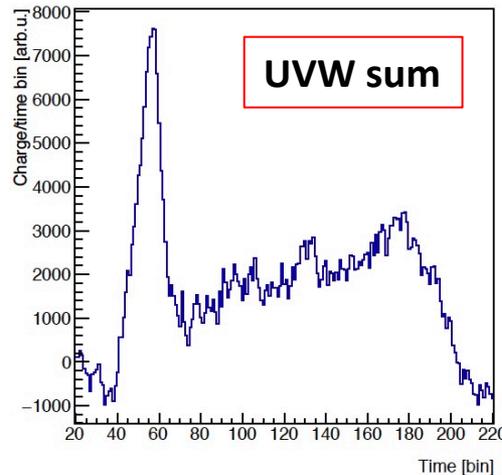
Event 243: V-strips vs Time



Event 243: W-strips vs Time



Event 243: All strips vs Time



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

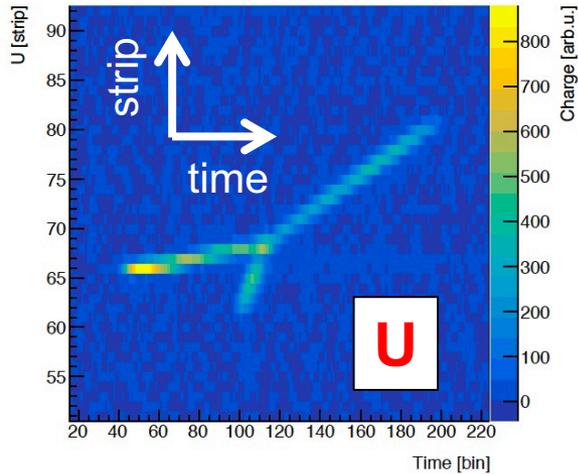
- Zoomed region of interest
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Example raw data

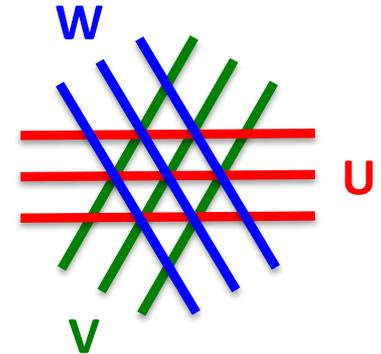
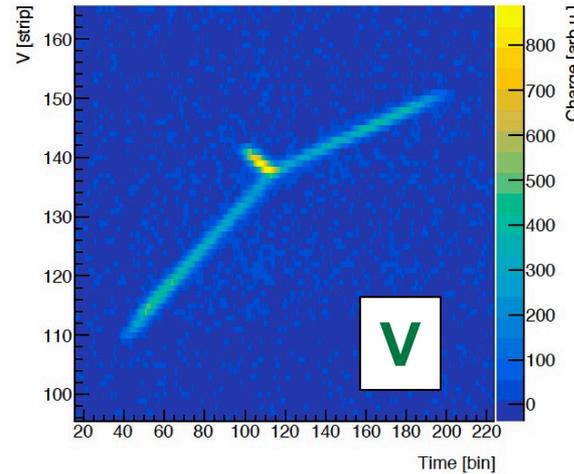


3-particle topology: $^{12}\text{C}(\gamma, 3\alpha)$ candidate event

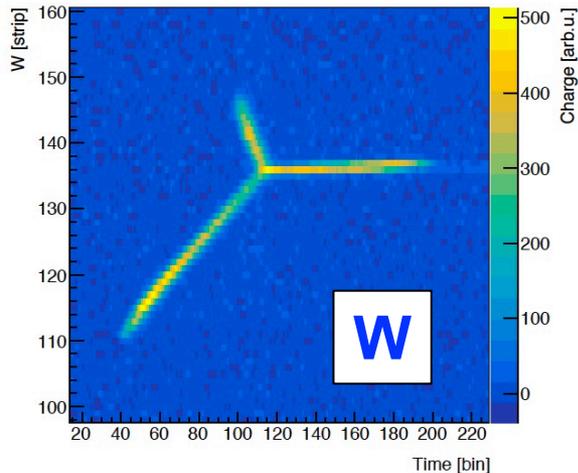
Event 5114: U-strips vs Time



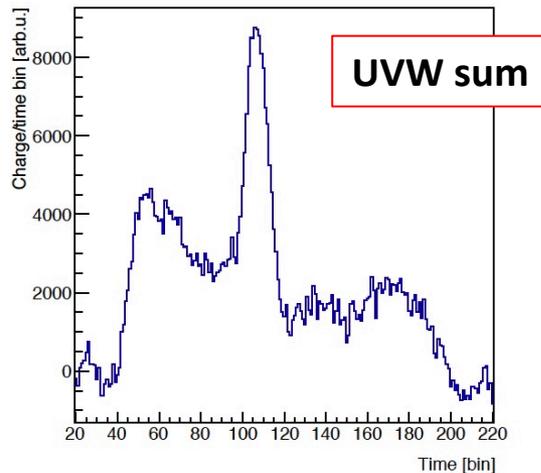
Event 5114: V-strips vs Time



Event 5114: W-strips vs Time



Event 5114: All strips vs Time



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

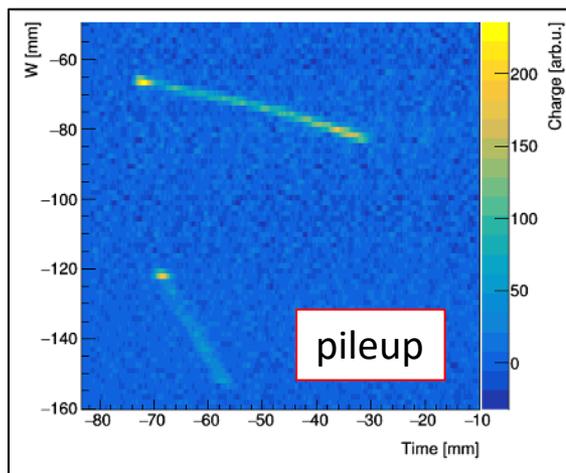
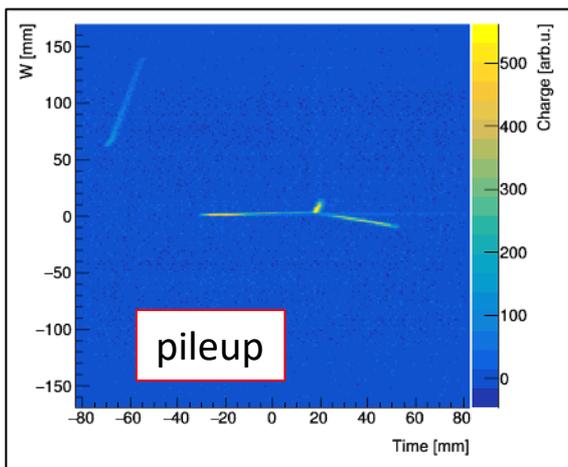
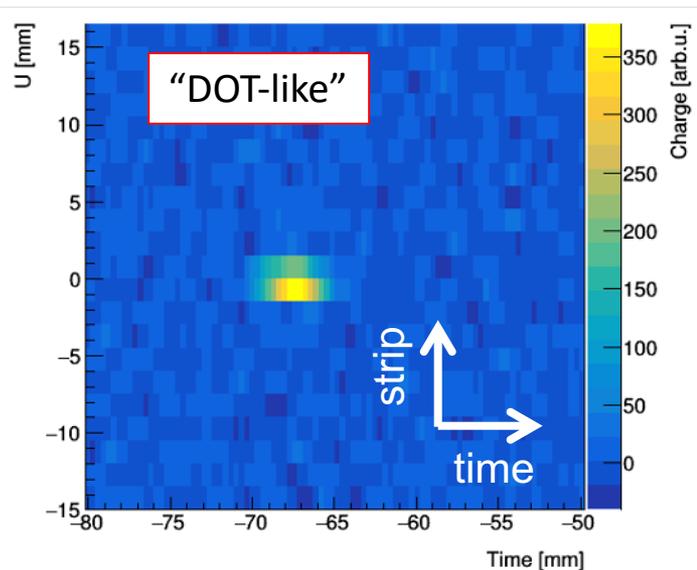
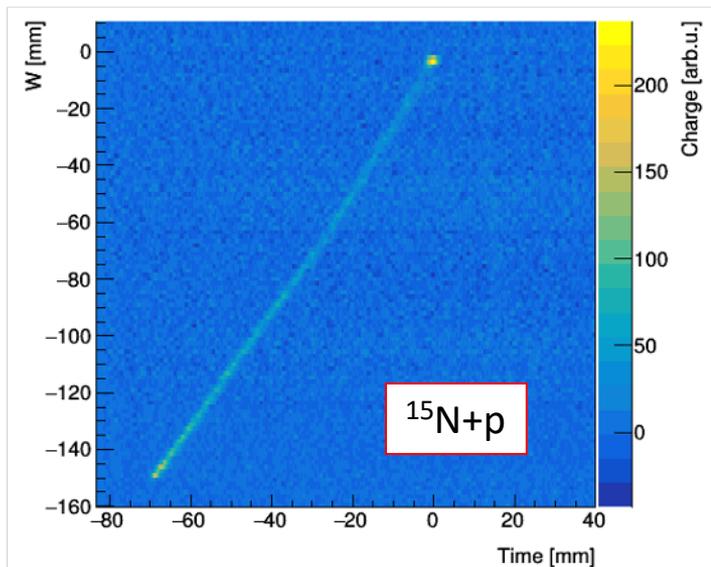
- Zoomed region of interest
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Example raw data - background



Warsaw TPC

Examples of background & more complex events:



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

- Only 1 out of 3 projections is shown for simplicity
- Pressure: 250 mbar
- Sampling: 12.5 MHz

TPC data analysis flow



1. Event-by-event classification:

- 1, 2 or 3 charged particles, “dots”, e-m interactions
(visual inspection, or cuts in {max. charge} × {integrated charge} phase space)

2. Find tracks:

- interaction vertex in 3D
- lengths & directions of all tracks in 3D

3. For “2-particle” event category apply:

- detector fiducial cuts
- range-to-energy conversion (with α -particle energy scale calibrated from real data)
- Lorentz boost of particle momenta from LAB to CM frame
- 1D and 2D $^{16}\text{O}(\gamma, \alpha)$ reaction identification cuts

4. Construct distributions in CM frame: (corresponding to incident γ -ray spectra)

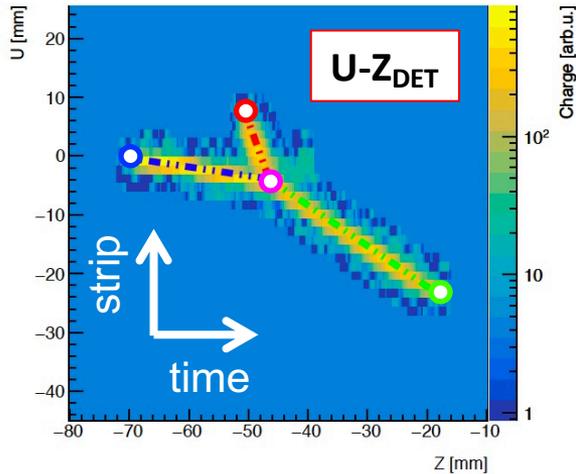
- observed spectra : T_α, E_x, E_{CM} (corrected for TPC energy resolution)
- α -particle polar angle θ_{CM}
- α -particle azimuthal angle φ_{CM}

Track finding

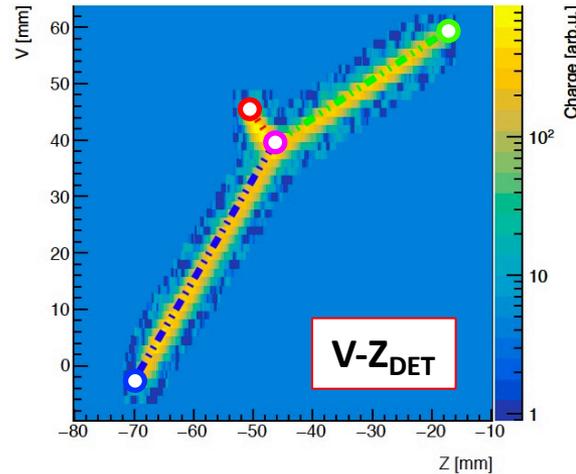


3-particle topology: reconstructed α tracks in 3D

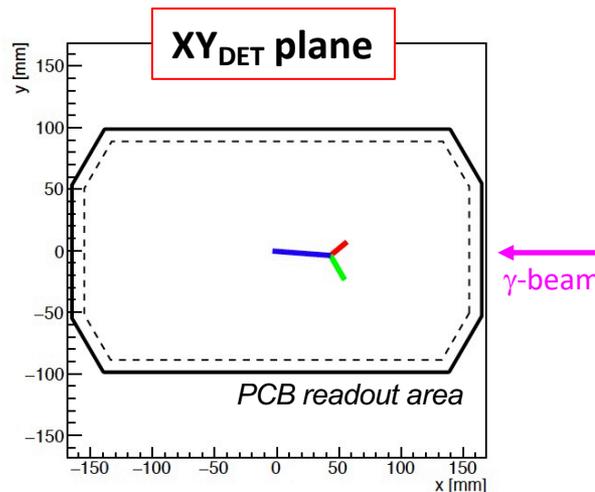
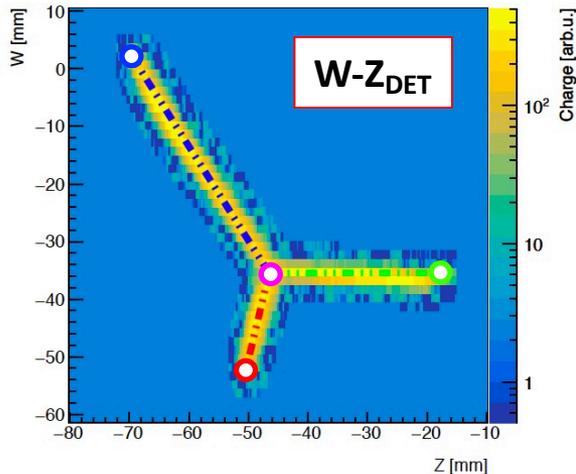
Event 5114: UZ projection



Event 5114: VZ projection



Event 5114: WZ projection



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

- Pressure: 250 mbar
- Sampling: 12.5 MHz
- **Manual procedure** for 1/2/3-particle topology (*current default*)
- Vertex & track ends selected by expert

A. Kalinowski

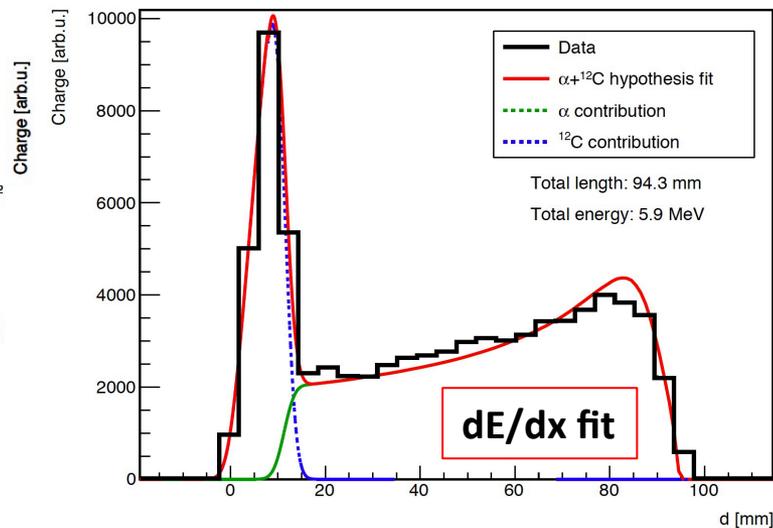
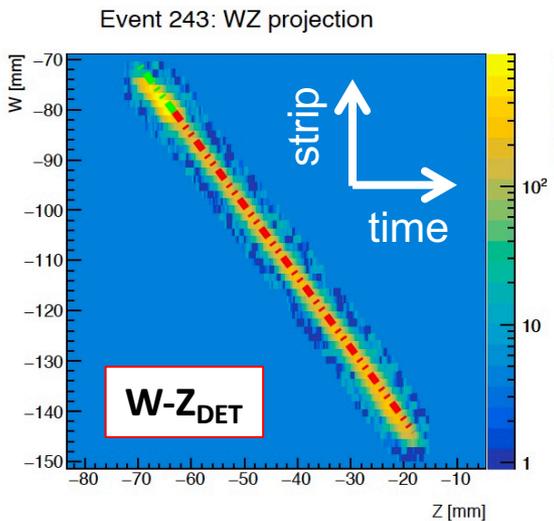
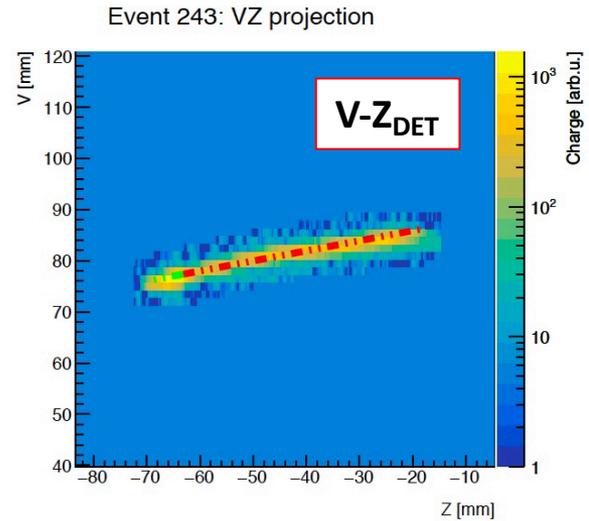
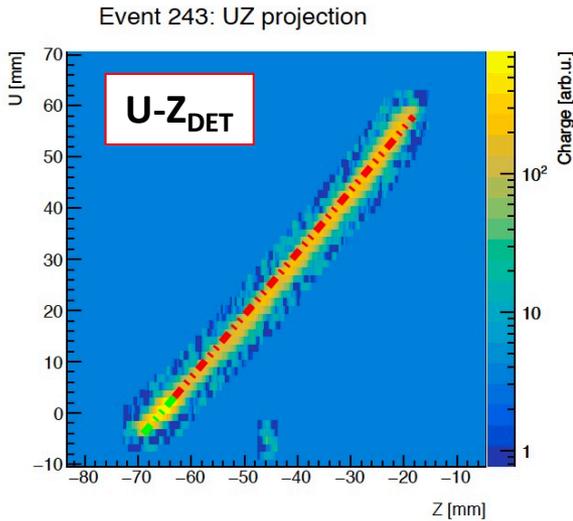
Track finding



2-particle topology: reconstructed α + carbon track in 3D

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

- Pressure: 250 mbar
- Sampling: 12.5 MHz
- **Automatic procedure** for 2-particle topology (*work in progress*)
- Clustered data fitted to dE/dx templates (SRIM + diffusion)



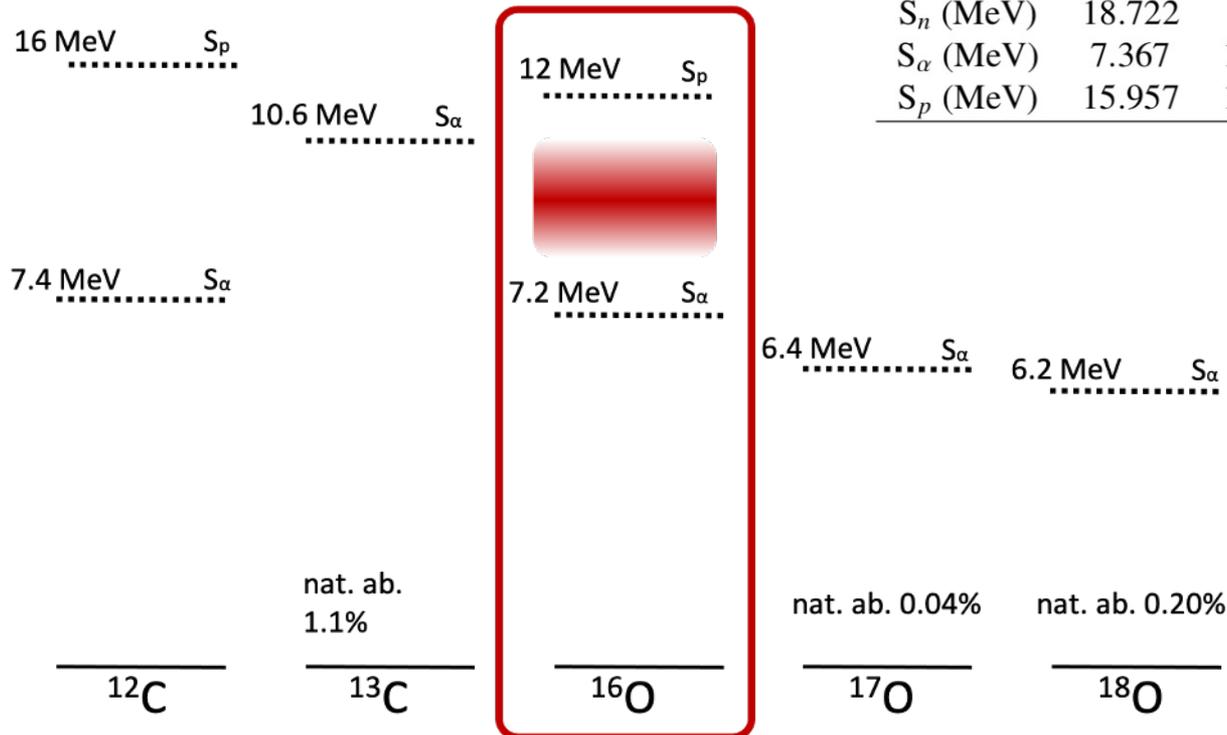
Reaction identification (1/2)



Possible reaction channels with gaseous CO_2 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

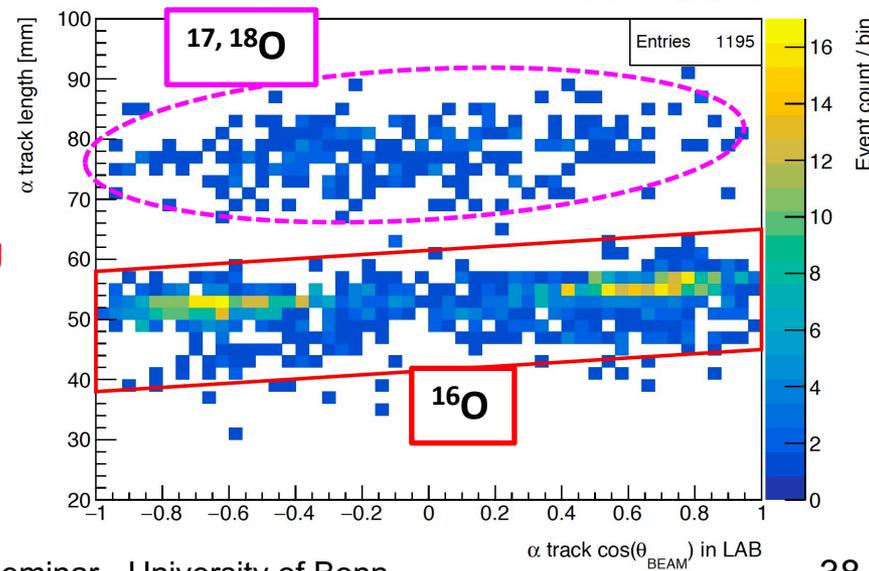
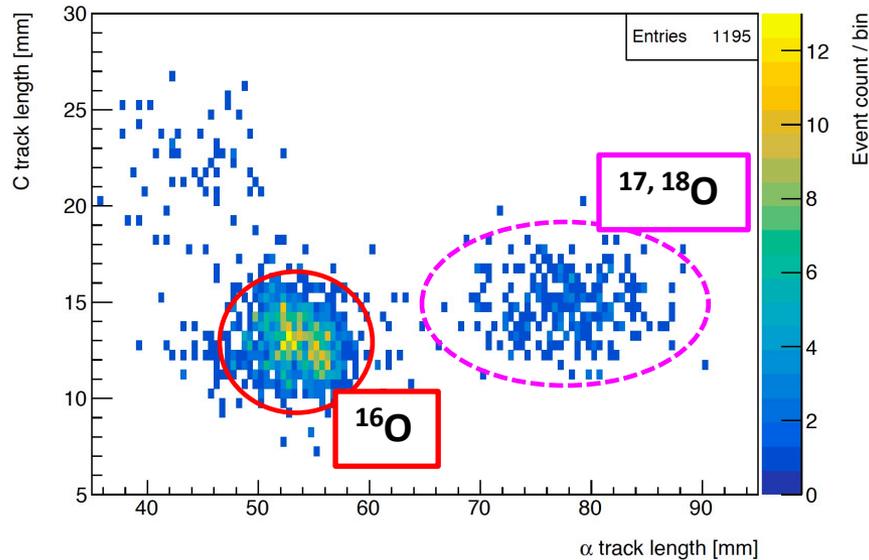
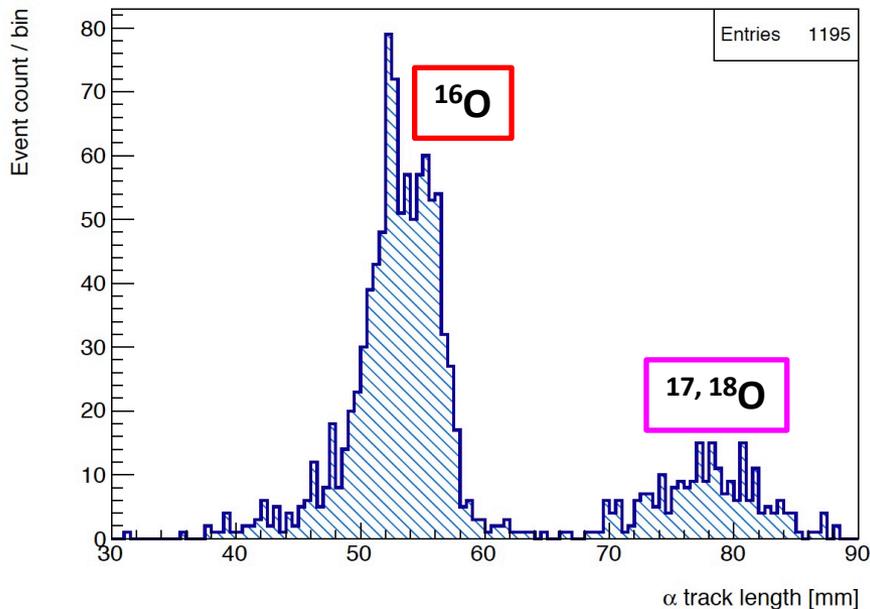


Reaction identification (2/2)



Warsaw TPC

Separation of ^{16}O photo-disintegrations based on track length:



$$E_\gamma = 9.85 \text{ MeV}$$

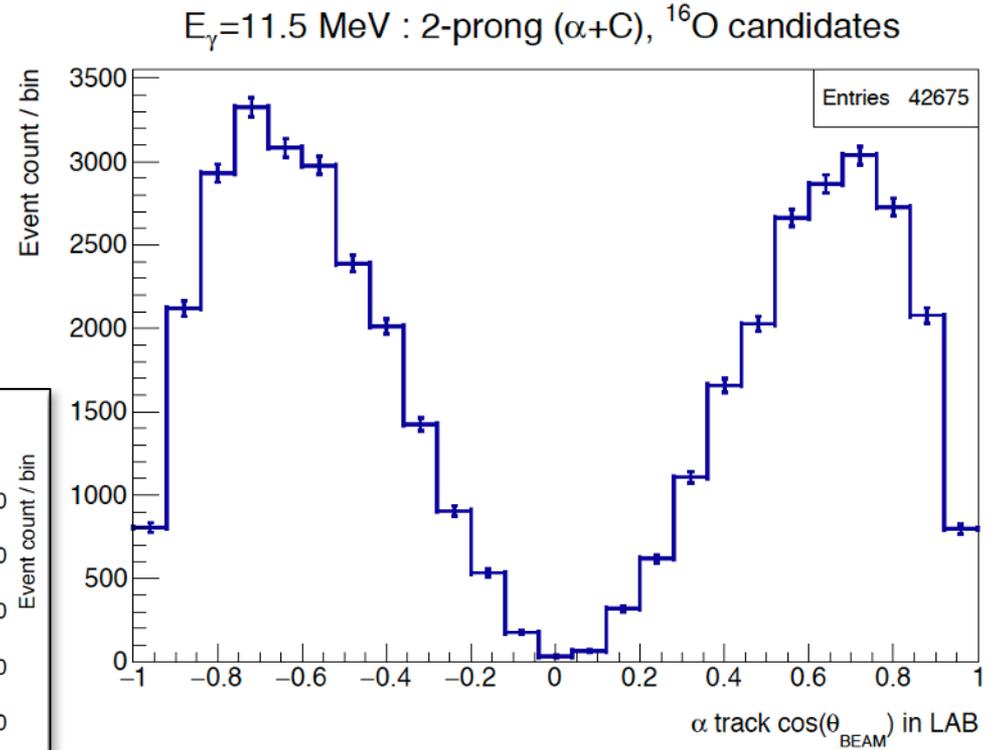
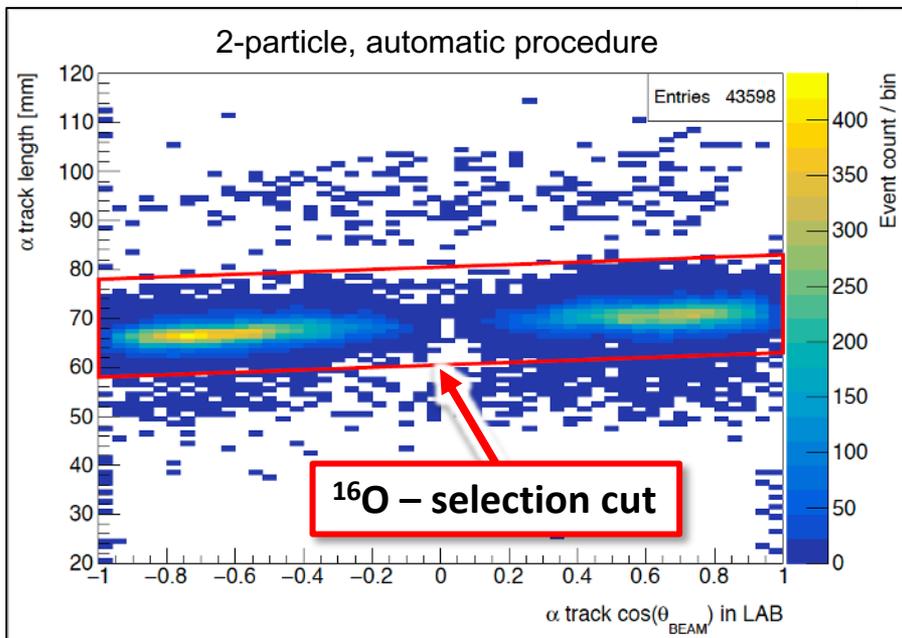
- Manual track finding
- 2-particle events
- Pressure: 130 mbar
- Sampling: 25 MHz

Angular distributions (1/3)



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

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



⇒ E2 shape

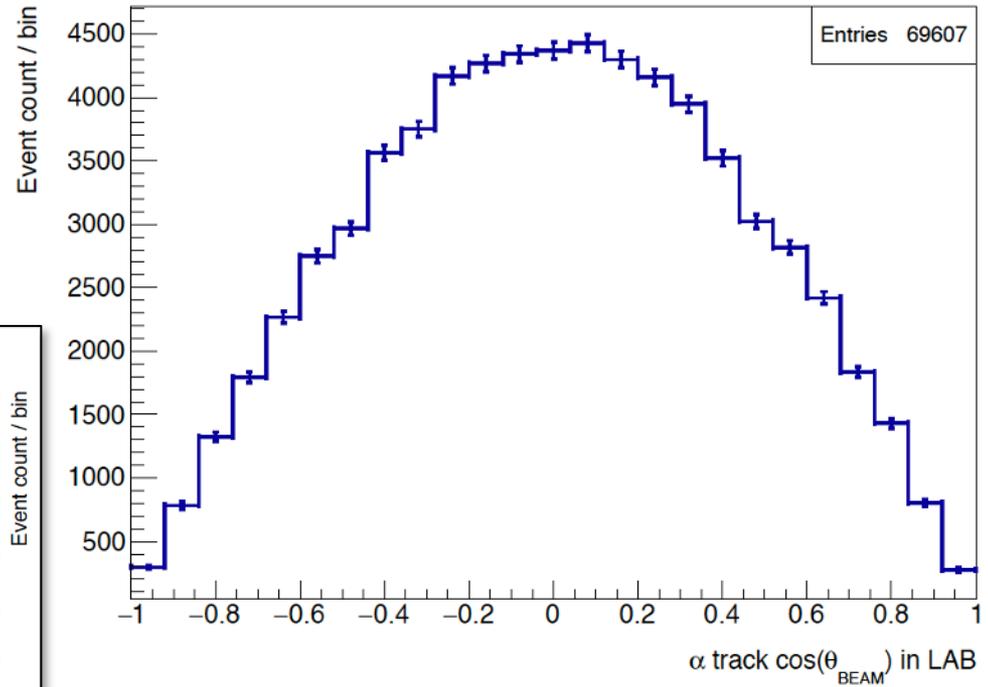
Angular distributions (2/3)



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

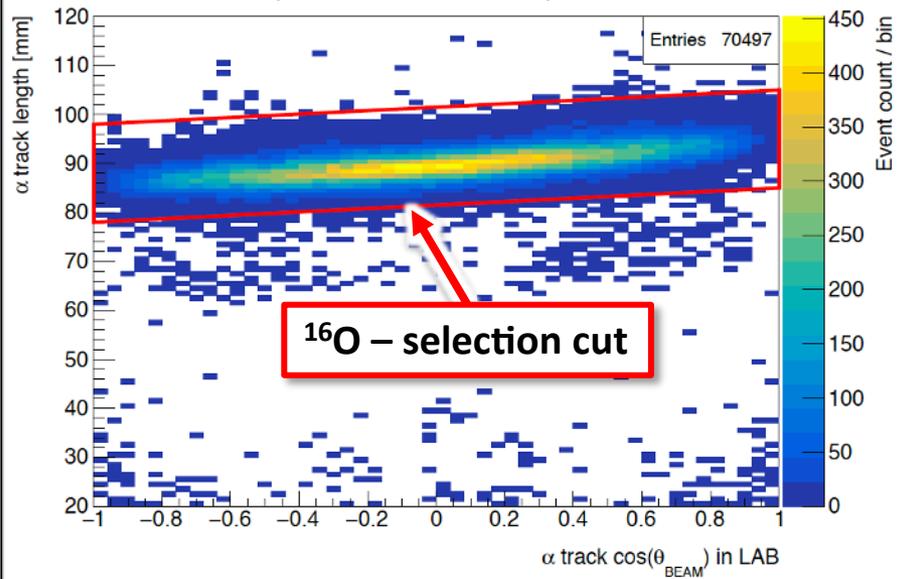
$$E_\gamma = 12.3 \text{ MeV}$$

$E_\gamma = 12.3 \text{ MeV}$: 2-prong ($\alpha + \text{C}$), ^{16}O candidates



⇒ E1 shape

2-particle, automatic procedure



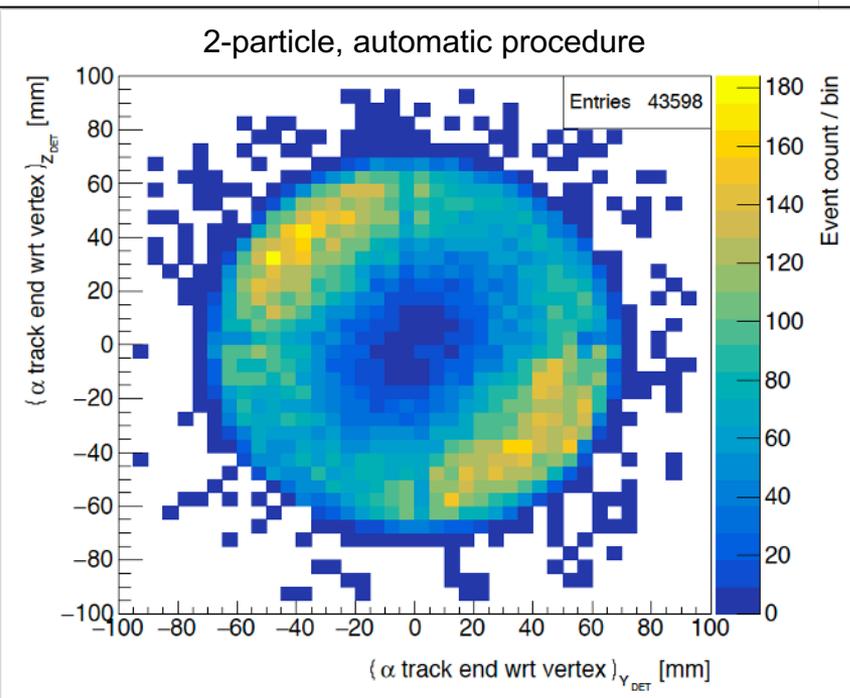
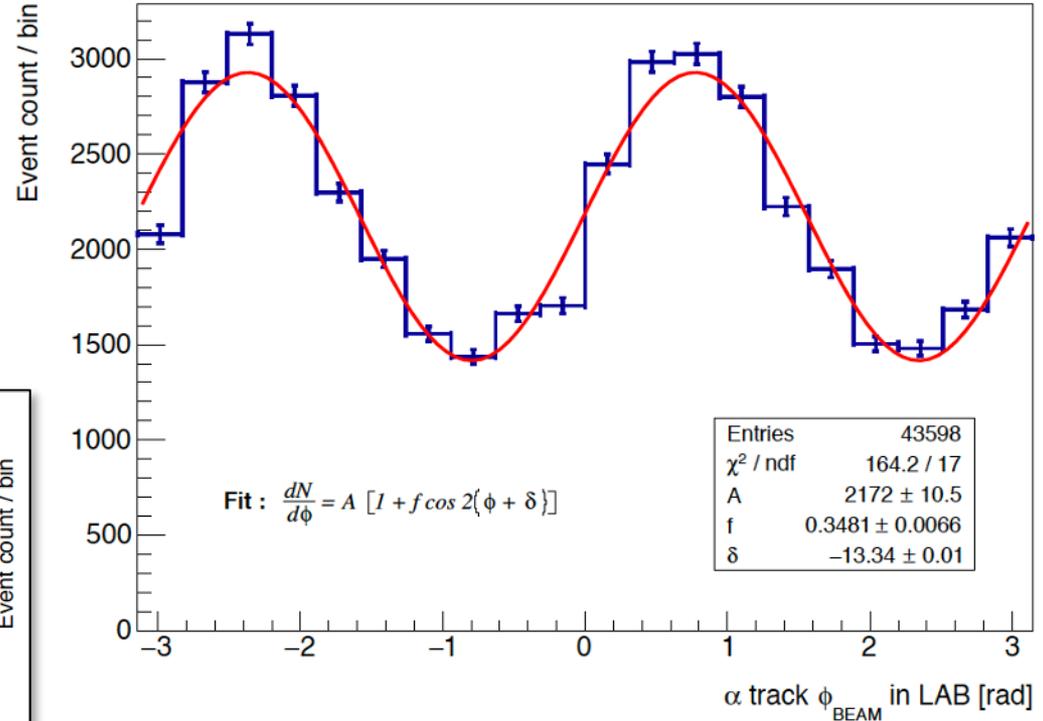
Angular distributions (3/3)



Warsaw TPC

- Azimuthal angle φ of 2-particle events
- **Automatic track finding**

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



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

$$\vec{S} = (1, S_1, S_2, S_3)^T \quad S_3 = \sqrt{1 - S_1^2 - S_2^2}$$

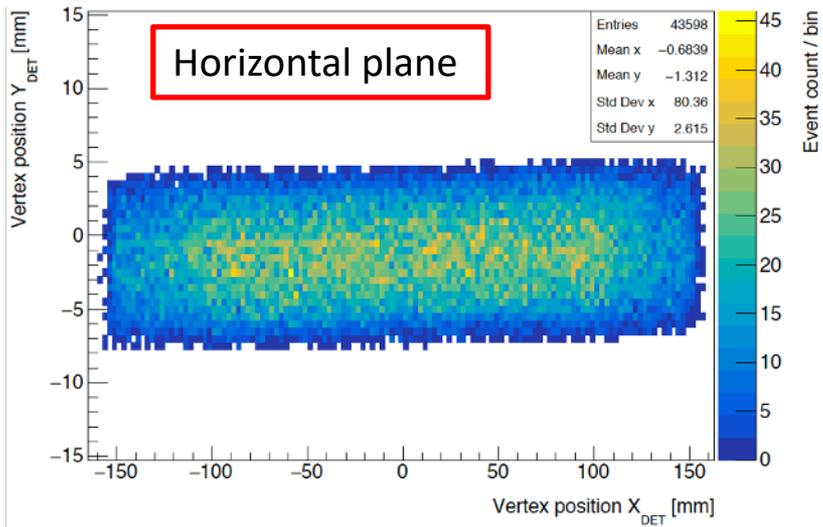
$$S_1 = \frac{W(0) - W(\frac{\pi}{2})}{W(0) + W(\frac{\pi}{2})} \quad S_2 = \frac{W(\frac{\pi}{4}) - W(-\frac{\pi}{4})}{W(\frac{\pi}{4}) + W(-\frac{\pi}{4})}$$

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

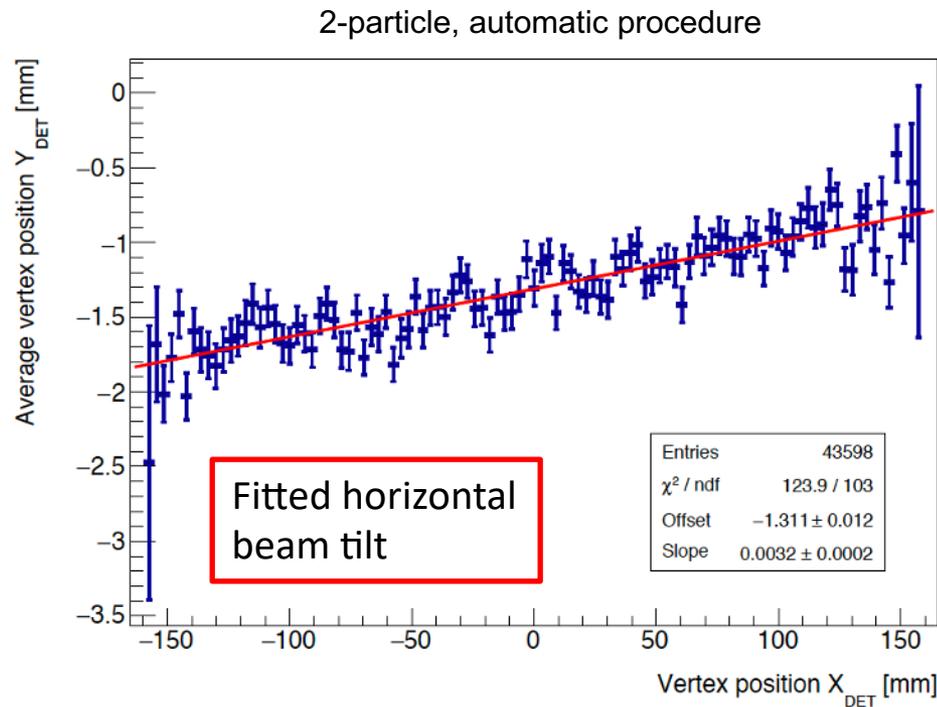
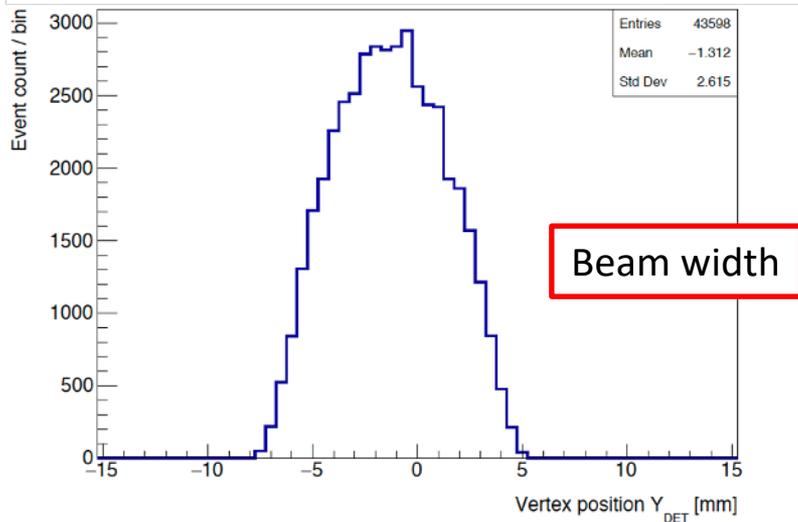
Beam mis-alignment



- Automatic track finding, distributions of 2-particle reaction vertices:



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

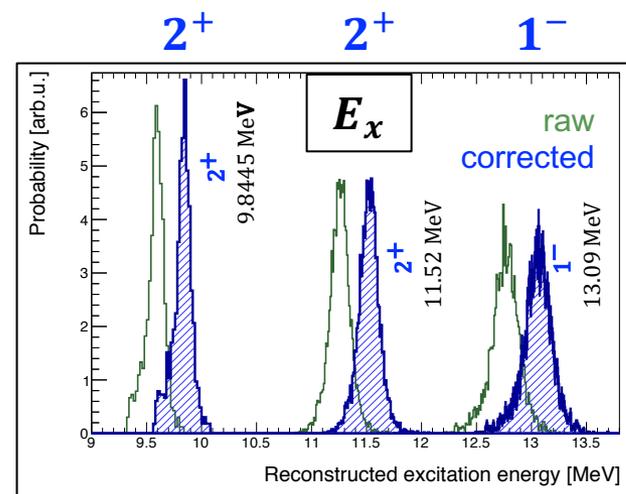
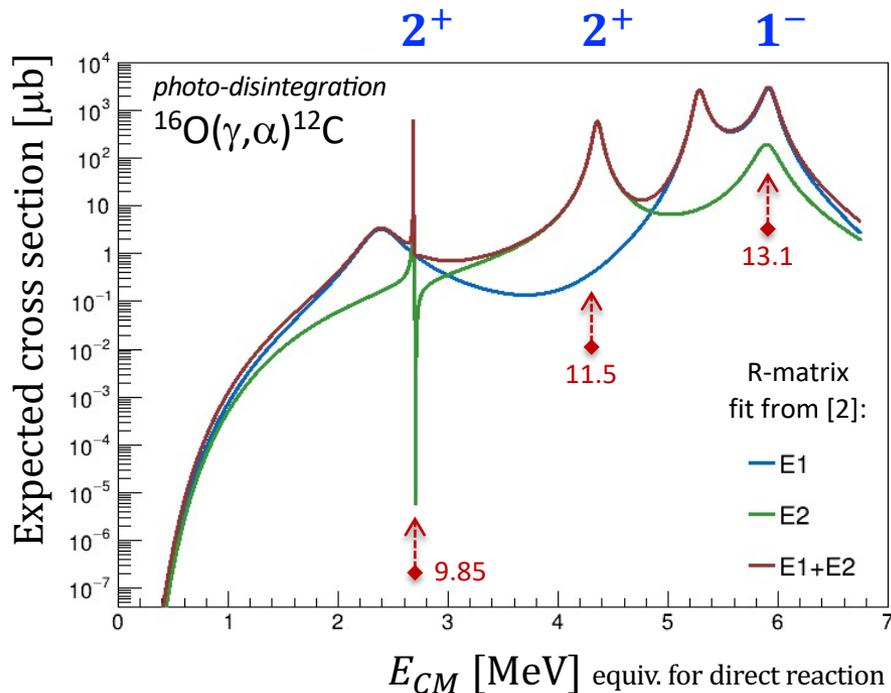


Energy scale calibration



Warsaw TPC

- For $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ it is sufficient to measure kinematics of α -particle only
- Kinetic energy T_α extracted from predicted $Range(E)$ tables or $\frac{dE}{dx}$ Bragg curves
- Energy scale needs fine-tuning from data using known [1] resonant states:
 2^+ ($E_x = 9.8445(5)$ MeV) / 2^+ ($E_x = 11.520(4)$ MeV) / 1^- ($E_x = 13.090(8)$ MeV)



Energy resolution

$$\sigma(E_x) \approx 60 \text{ keV} @ E_x = 9.85 \text{ MeV}$$

$$\sigma(T_\alpha) \approx 45 \text{ keV} @ T_\alpha = 2 \text{ MeV}$$

– manual track finding

[1] TUNL compilation data for ^{16}O levels:

https://nucldata.tunl.duke.edu/nucldata/HTML/A=16/16_13_1993.pdf

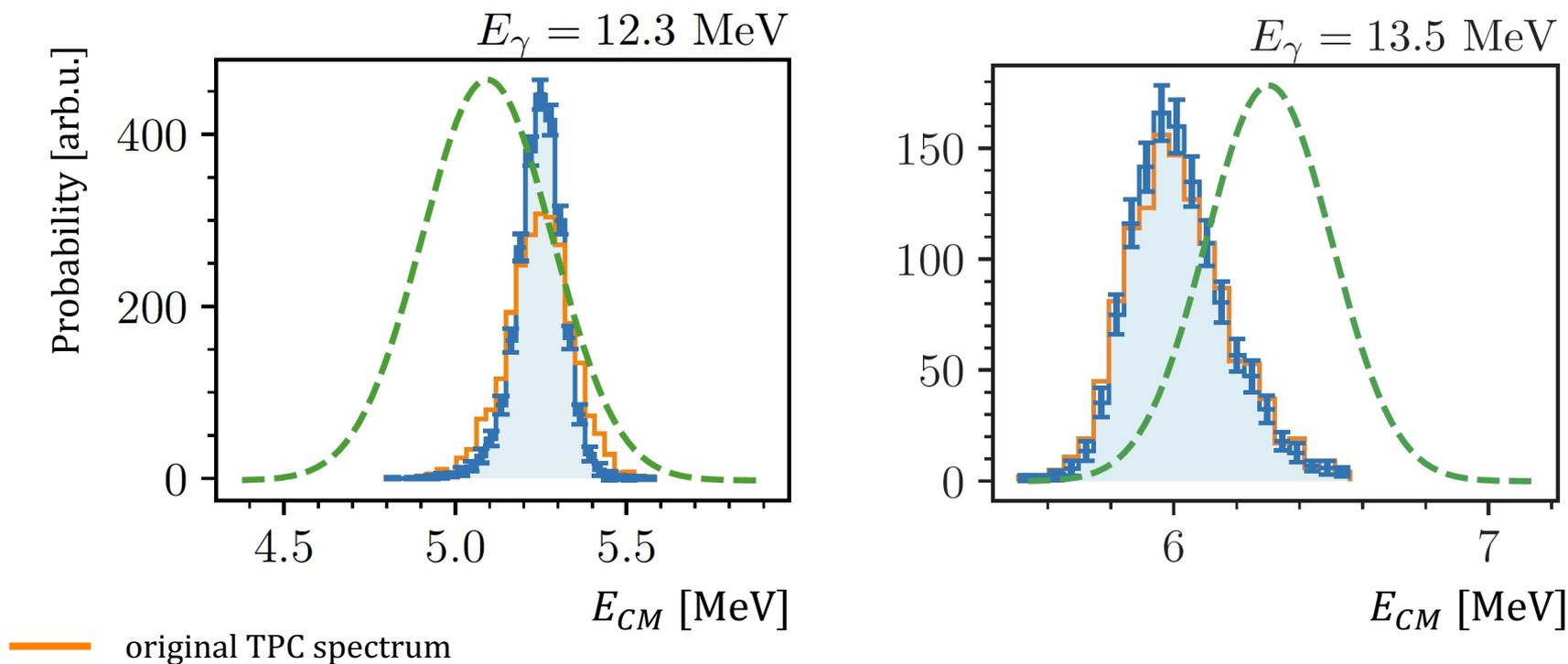
[2] R. J. deBoer et al., Rev. Mod. Phys. **89**, 035007 (2017)

Unfolded energy distributions



Energy distributions of α -particles in LAB converted to distributions of reconstructed E_{CM} : (E_{CM} corresponds to direct reaction)

- **manual track finding**, $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events
- analyzed 9 beam energy runs (results for 2 runs are shown below)



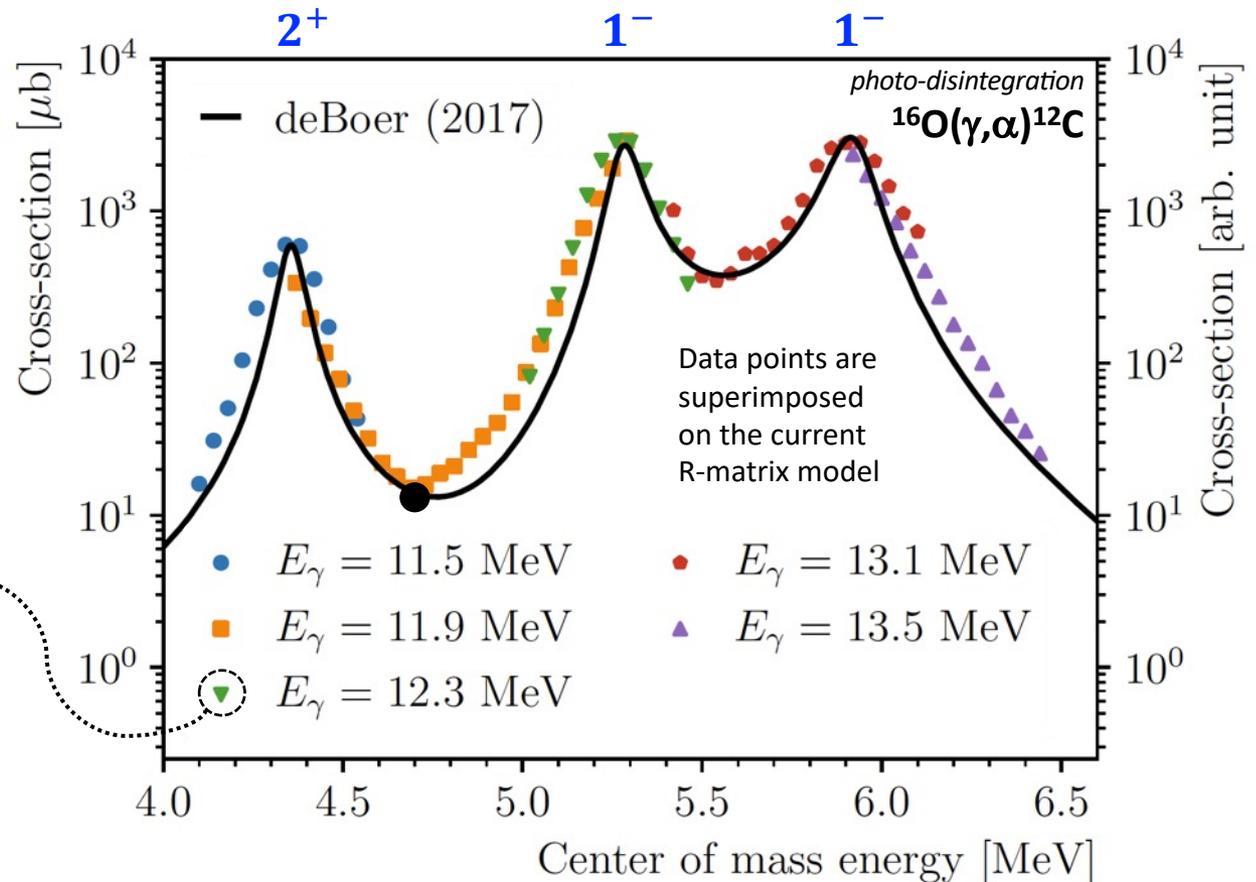
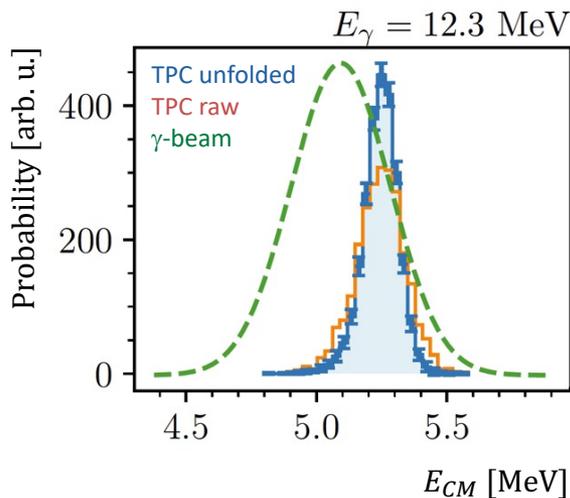
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

Relative E1+E2 cross section



Unfolded TPC spectra divided by γ -beam spectra:

- **manual track finding**, $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events, assumed $\sigma(E_{CM})=67$ keV
- combined 5 beam energy runs using overlapping E_{CM} energy bins
- resulting stitched curve normalized to R-matrix model at a single point (●)
- information about absolute γ -beam intensity is not used



M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

R-matrix fit for E1+E2:
Rev. Mod. Phys. 89, 035007 (2017)

E1 / E2 multipolarity (1/3)

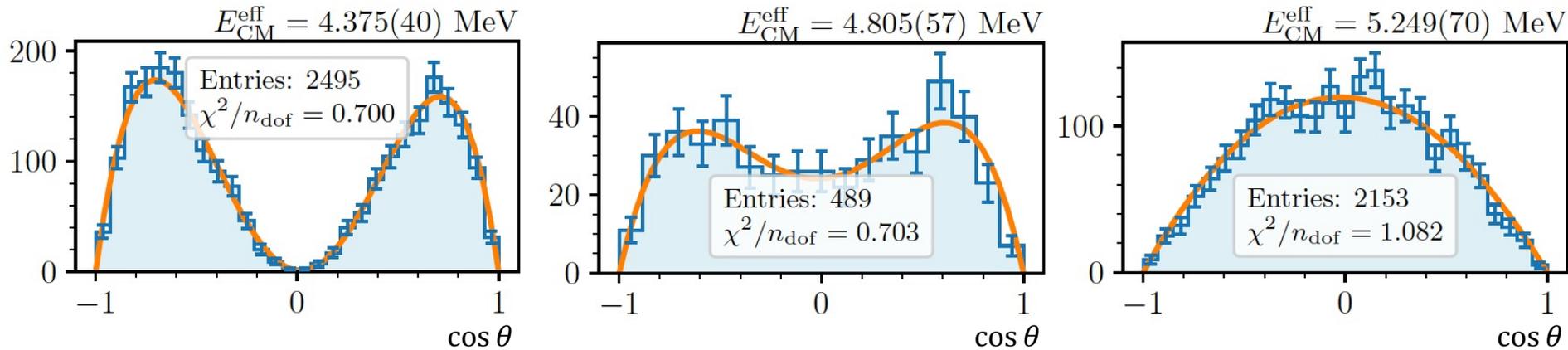


- **Distributions of polar angle θ_{CM} of α -particles:**

- **manual track finding**, $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ candidate events
- corresponding to effective energy of 10 arbitrary E_{CM} bins (results for 3 example bins are shown below)

- **Fit:**
$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \left\{ \sigma_{E1} W_{E1}(\cos\theta) + \sigma_{E2} W_{E2}(\cos\theta) + \sqrt{\sigma_{E1}\sigma_{E2}} \cos\varphi_{12} W_{12}(\cos\theta) \right\}$$

- $W_{E1}, W_{E2}, W_{12}(x)$ expressed by Legendre polynomials $P_i(x)$



E_{CM}^{eff} [MeV]	E_{CM} bin [MeV]	Nom. E_γ [MeV]	σ_{E1}/σ_{E2}	φ_{12} [rad]
4.375	[4.30, 4.45]	11.5	$9.9^{+4.6}_{-6.2} \cdot 10^{-3}$	$1.95^{+0.17}_{-0.11}$
4.805	[4.70, 4.90]	11.9	$1.26^{+0.24}_{-0.23}$	$1.541^{+0.051}_{-0.051}$
5.249	[5.10, 5.40]	12.3	85^{+489}_{-105}	$1.4^{+0.1}_{-1.4}$

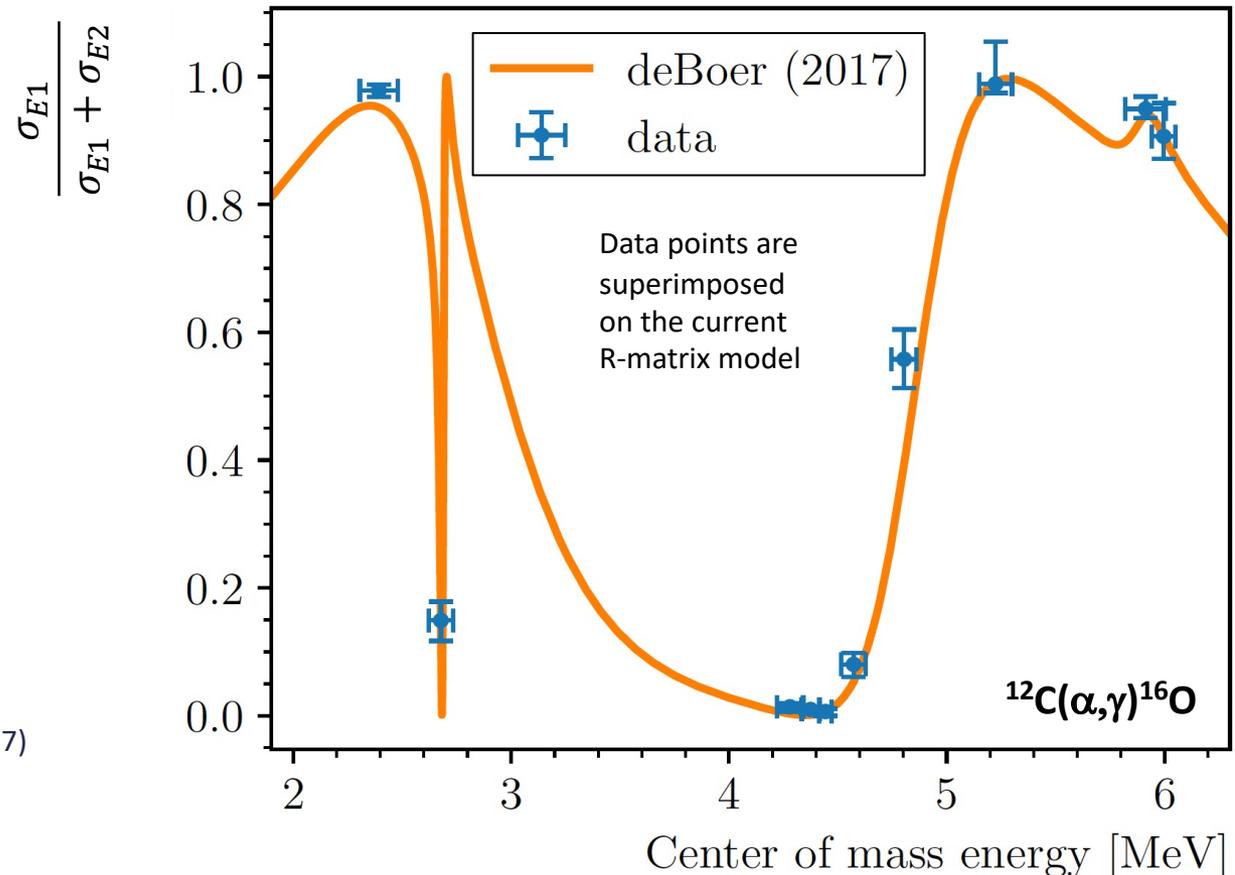
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

E1 / E2 multipolarity (2/3)



Evolution of $\sigma_{E1}/(\sigma_{E1} + \sigma_{E2})$ ratio:

- **manual track finding**, $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events
- corresponding to effective energy of 10 arbitrary E_{CM} bins



M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

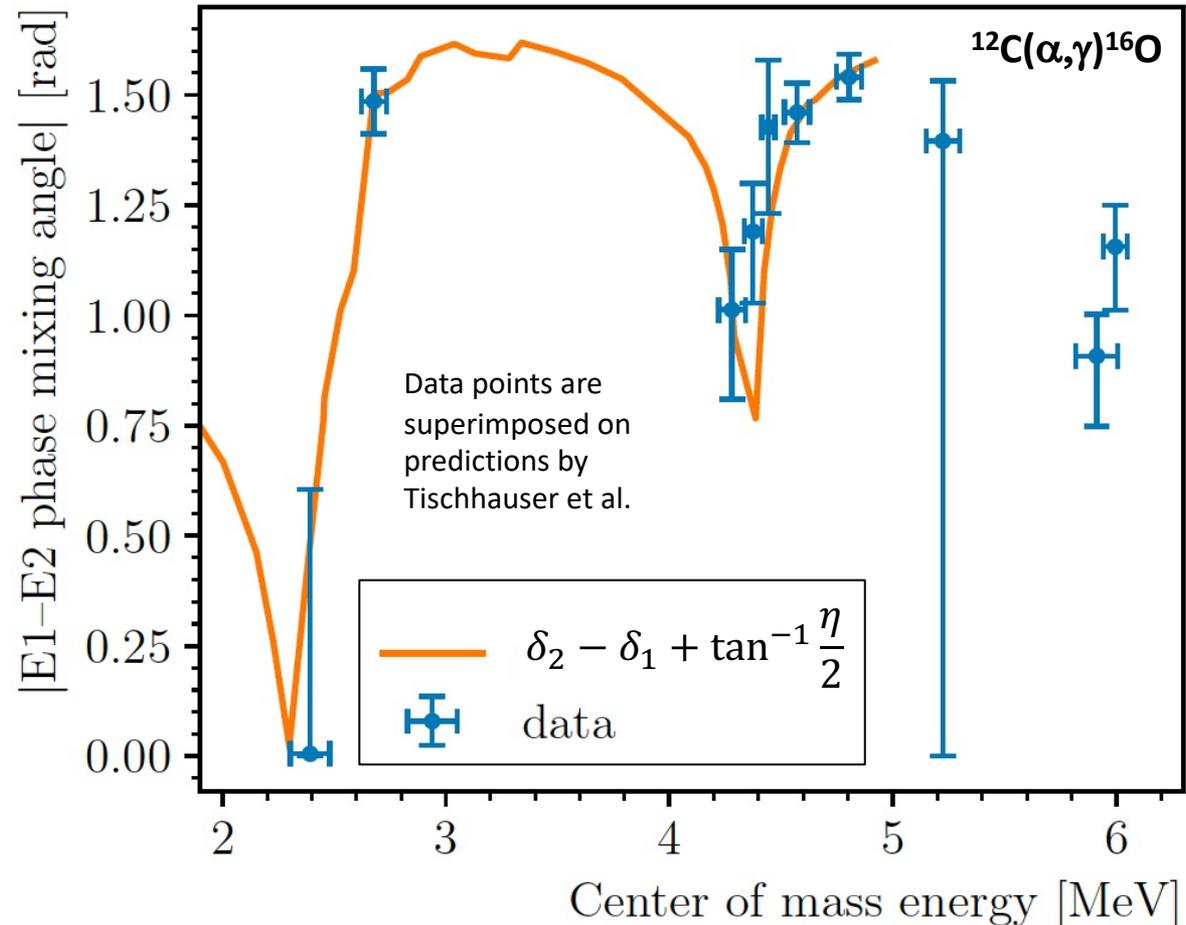
R-matrix fit:
Rev. Mod. Phys. 89, 035007 (2017)

E1 / E2 multipolarity (3/3)



Evolution of E1 – E2 mixing phase angle φ_{12} : (normalized to $[0, \frac{\pi}{2}]$)

- **manual track finding**, $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ candidate events
- corresponding to effective energy of 10 arbitrary E_{CM} bins



M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

Model curve:
Phys. Rev. C 79, 055803 (2009)
Nuclear Physics A 465, 291 (1987)
Nuovo Cimento A 27, 1 (1975)

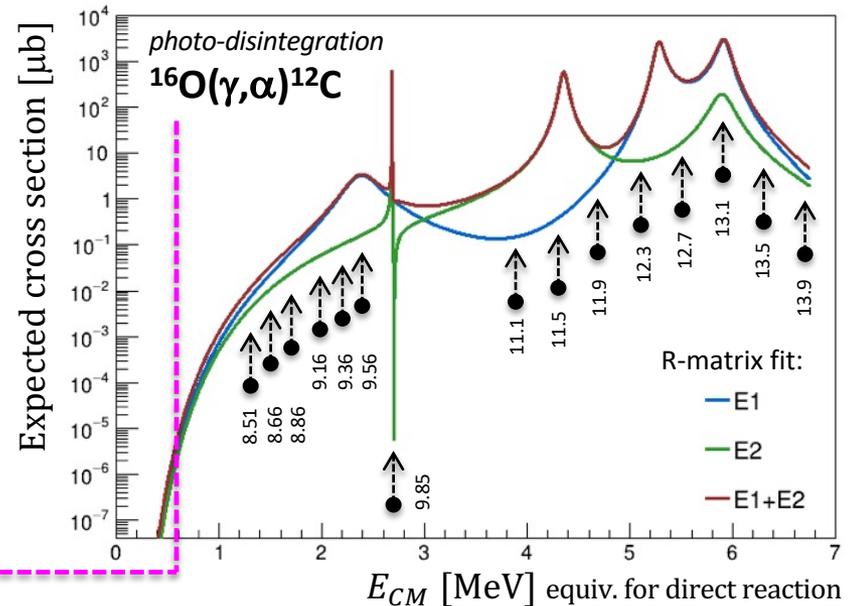
Part 1 : Summary & Outlook



- ✓ Active-target TPCs commissioned with successful experiments using γ -ray beams & neutron sources
 - 2 PhD thesis defended: Mateusz Fila (UW, 2024), Kristian Haverson (SHU, 2025)
- ✓ Working on improved automated track finding algorithms
 - testing classic (human invented) & Machine Learning approaches

Future plans:

- **Summer 2026** : next experiment approved by the HI γ S PAC
 - $E_{CM} \sim 1$ MeV region of $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction
 - increased beam intensity
- Looking forward for even more intense γ -ray source in the ELI-NP facility (Bucharest-Magurele, Romania)
 - move closer to the Gamow region at $E_{CM} \sim 300$ keV



Part 1 : List of publications



- [1] K.C.Z. Haverson *et al.*, *Il Nuovo Cimento* **48 C**, 17 (2025)
- [2] M. Ćwiok *et al.*, *EPJ Web Conf.* **290**, 01004 (2023)
- [3] M. Ćwiok *et al.*, *EPJ Web Conf.* **279**, 04002 (2023)
- [4] C.R. Brune, C. Matei, S.D. Pain and R. Smith, *Eur. Phys. J. A* **59**, 165 (2023)
- [5] M. Kuich *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **16**, 4-A17 (2023)
- [6] M. Gai *et al.*, *NIM A* **954**, 161779 (2020)
- [7] M. Ćwiok *et al.*, *Acta Phys. Pol. B* **49**, 509 (2018)
- [8] M. Ćwiok, *Acta Phys. Pol. B* **47**, 707 (2016)
- [9] O. Tesileanu *et al.*, *Romanian Rep. in Phys.* **68** Supplement, S699 (2016)

Doctoral theses:

- [10] K.C.Z. Haverson (SHU, 2025); <https://shura.shu.ac.uk/36824>
- [11] M. Fila (UW, 2024); <https://repozytorium.uw.edu.pl/entities/publication/7c43c2bd-a5c0-4933-95dd-cb54bdad7b8d>

Part 1 : Collaboration



Experimental team – H_lS '2022:

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Part – 2

TPC for radioactive-ion (RI) beams

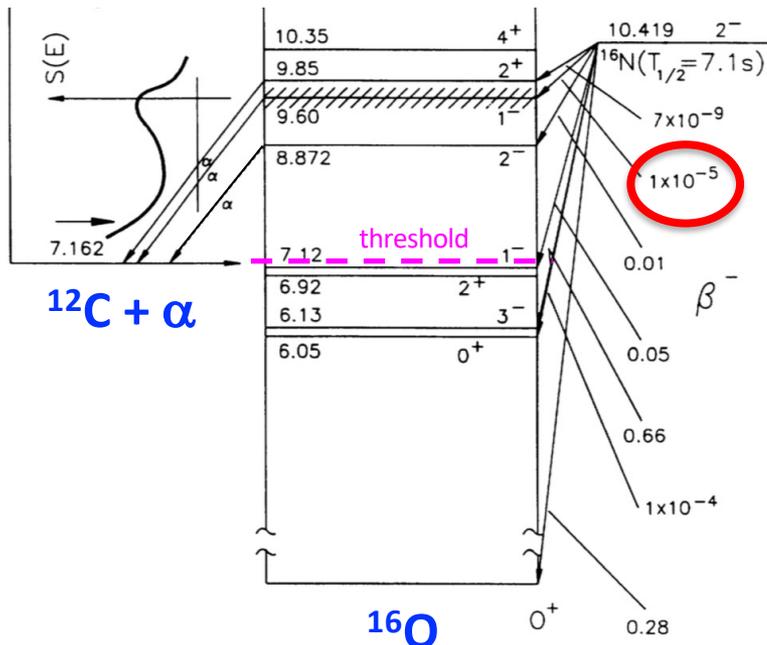
Nuclear Astrophysics with RI beams

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction can be also probed via β -delayed α decay of ^{16}N :

$^{16}\text{N}(\beta,\alpha)^{12}\text{C}$

^{16}N

$T_{1/2}=7.1\text{ s}$



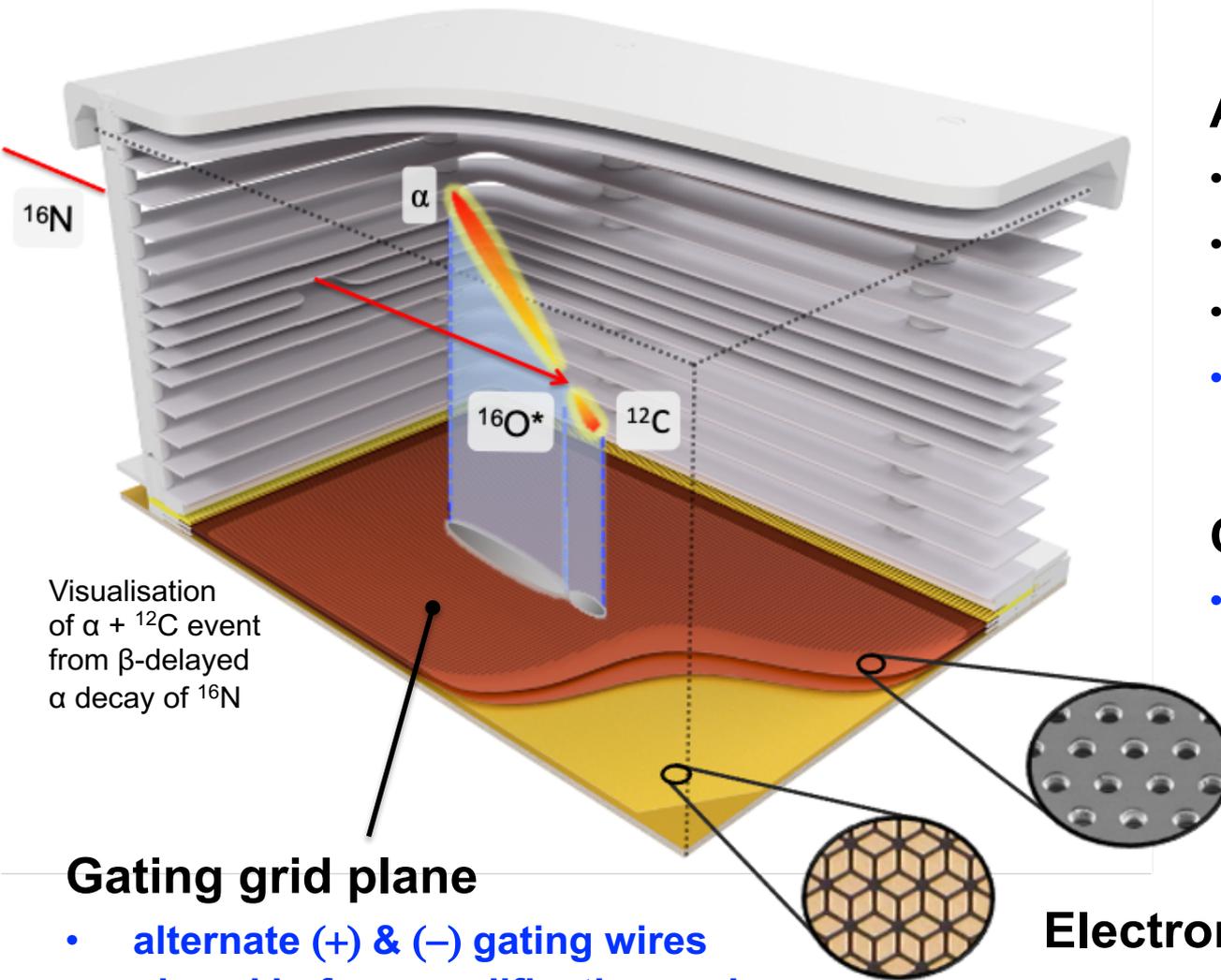
Experimental approach:

- Use TPC as a stopping gas cell:
 - reconstruct kinematics of α -particles from $^{12}\text{C} + \alpha$ events (BR = 10^{-5})
 - operate below electron detection threshold
 - β -delayed α spectra constrain $E1$ component at low E_{CM} region
- Use pulsed **radioactive ion beam**:
 - stop & accumulate some ^{16}N ions in the gas, then switch TPC from **blocked** to **active** mode

R. Azuma et al., Phys. Rev. C **50**, 1194 (1994)

X. Tang et al. Phys. Rev. C **81**, 045809 (2010)

Adaptations for RI beam



Visualisation of $\alpha + {}^{12}\text{C}$ event from β -delayed α decay of ${}^{16}\text{N}$

Gating grid plane

- **alternate (+) & (-) gating wires placed before amplification region**
- fast HV pulser

Active volume

- readout: **330 x 200 mm²**
- drift length: **200 mm**
- low-pressure gas: TBD
- **larger central opening for incoming RI beam**

Charge amplification

- **2 layers of 125- μm thick GEM foils**

Electronic readout

- same UVW segmentation
- same GET front-end electronics

Adaptations for RI beam



- Stainless steel & aluminium vessel (250L)
- All walls are removable for easy access
- Larger ISO-K 63 ports for beam entrance



Section view of internal TPC structure

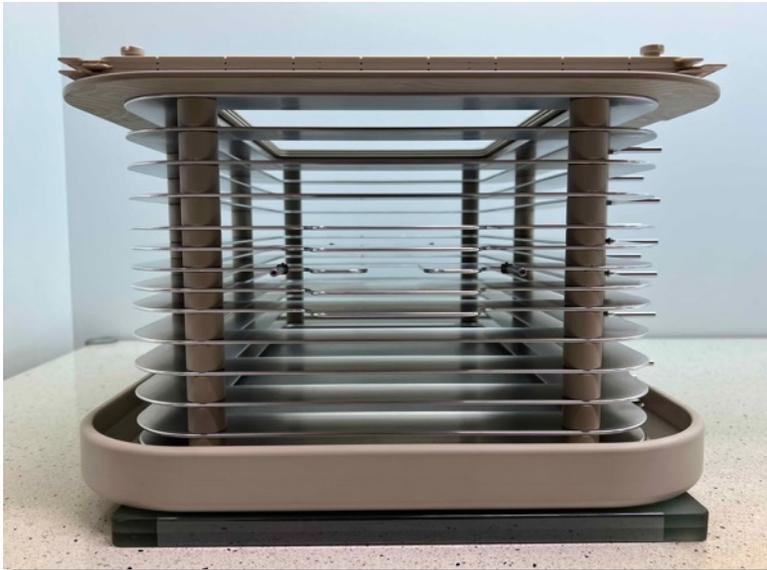
- Drift cage accepts beam spots up to $28 \times 18 \text{ mm}^2$
- Aluminium hollow field-shaping electrodes & solid plate cathode

Progress of TPC assembly

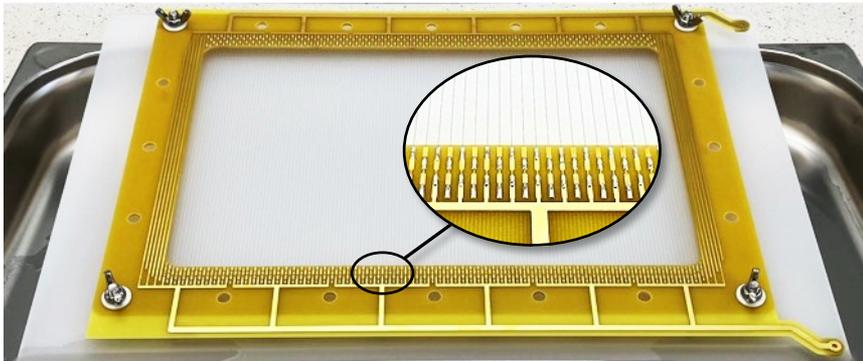


- Details of new TPC with thicker-GEMs (125 μm) and gating grid

TPC drift cage dry assembly test



Vacuum vessel (250 dm³) with removable endcaps & side walls

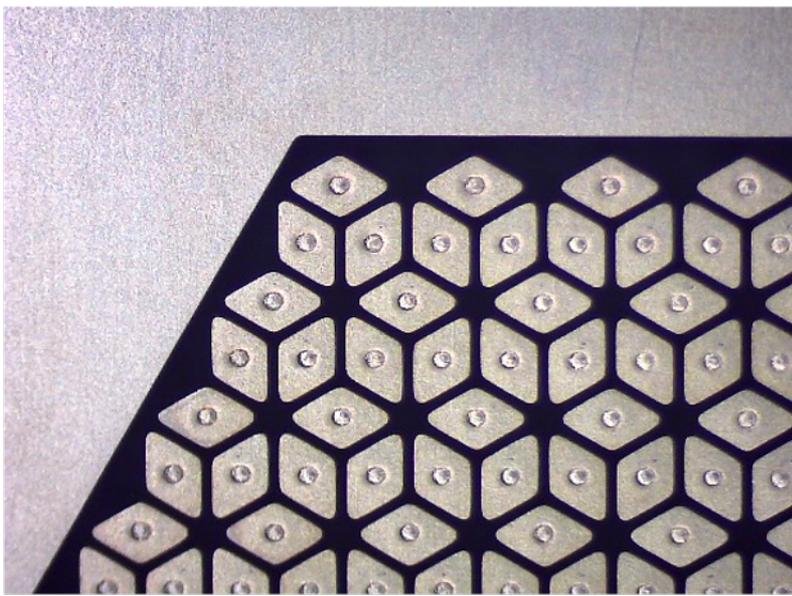


Gating grid frame with 50 μm wires, 2.5 mm wire pitch

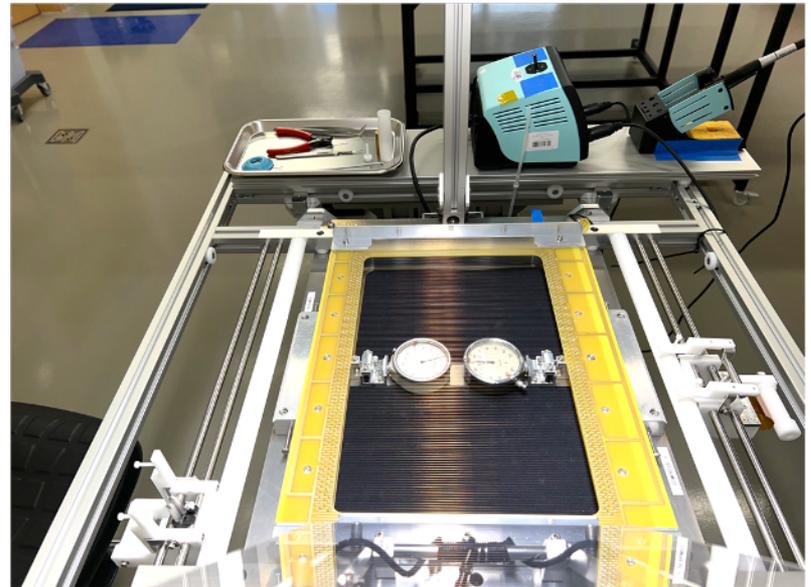
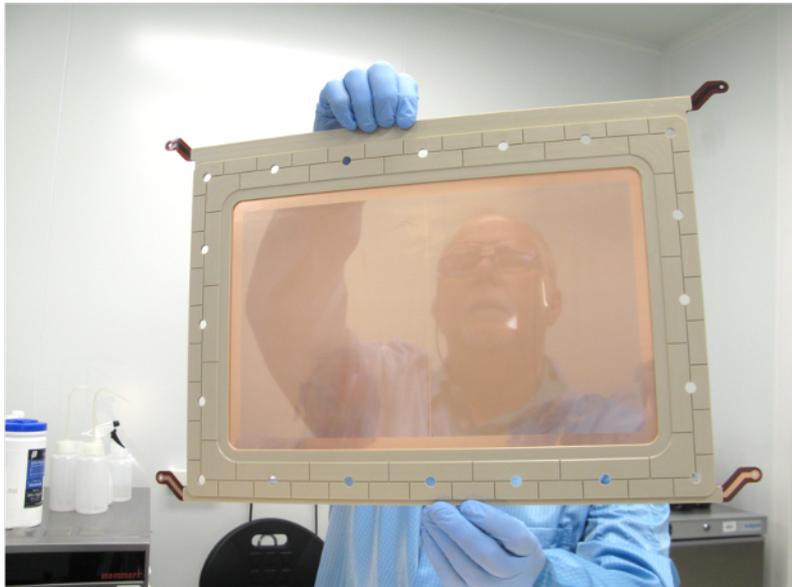
Part 2 : Summary & Outlook



- ✓ Since 2023 : developing multi-purpose low-pressure TPC:
 - acronym **WING TPC** (**W**arsaw **I**on **N**eutron **G**amma **T**PC)
 - can work with neutral beams (as active-target) & radioactive ion beams
 - added ion gating capability
 - replaced 3-stage standard GEMs with 2-stage thicker GEMs
 - same UVW readout structure for compatibility with existing analysis & MC software
- ✓ New vacuum vessel & all detector parts are ready for the final assembly in our clean room
- **Future plans:**
 - perform laboratory tests with radioactive sources
 - prepare grant application for studying $^{12}\text{C}(\alpha,\gamma)$ via β -delayed α decay of ^{16}N (radioactive-ion beam mode) using next generation **WING TPC**



Thank you for your attention !!!

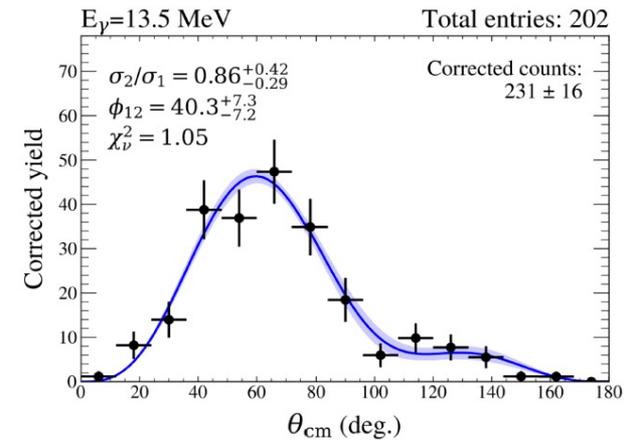
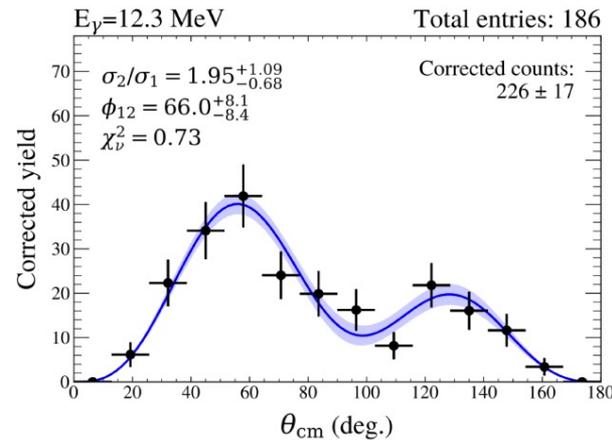
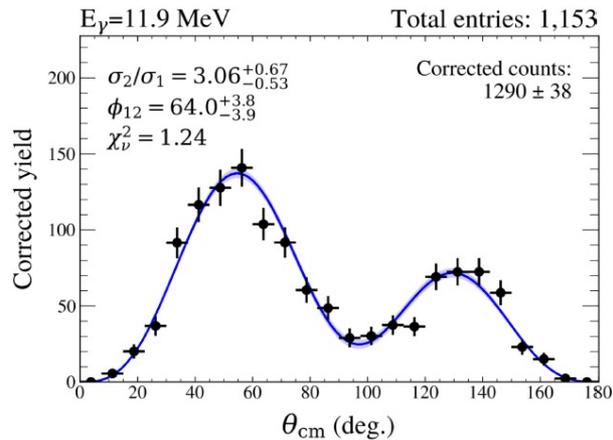
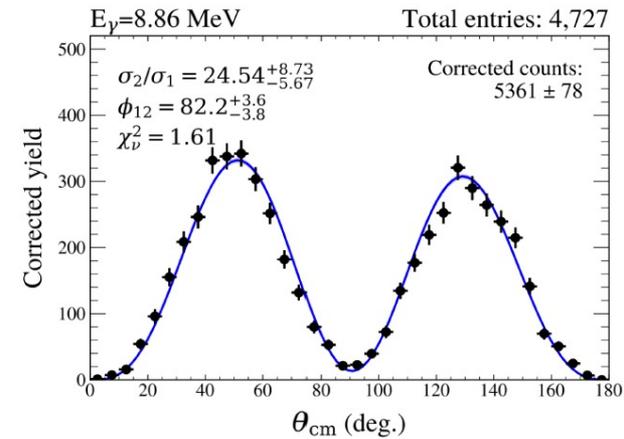
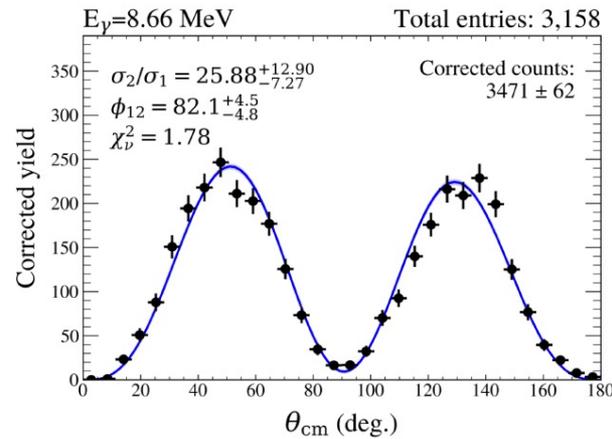
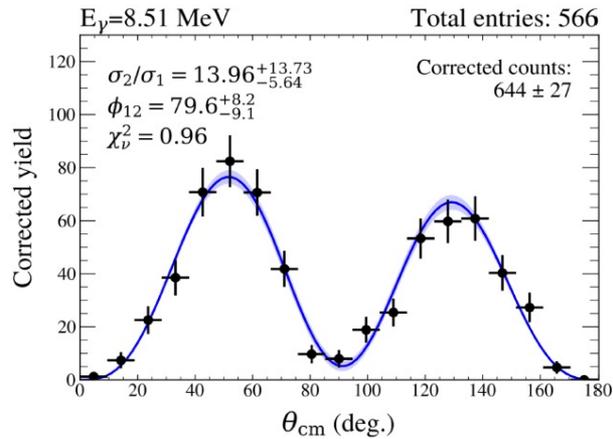


E1 / E2 multipolarity – NEW (1/3)



- **Distributions of polar angle θ_{CM} of α -particles:**

- $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events, full run statistics, 12 bins of E_{CM} (only 6 out of 12 are shown)
- **automatic track finding** (T_α from *track length*) **K. Haverson, PhD thesis (SHU, 2025)**

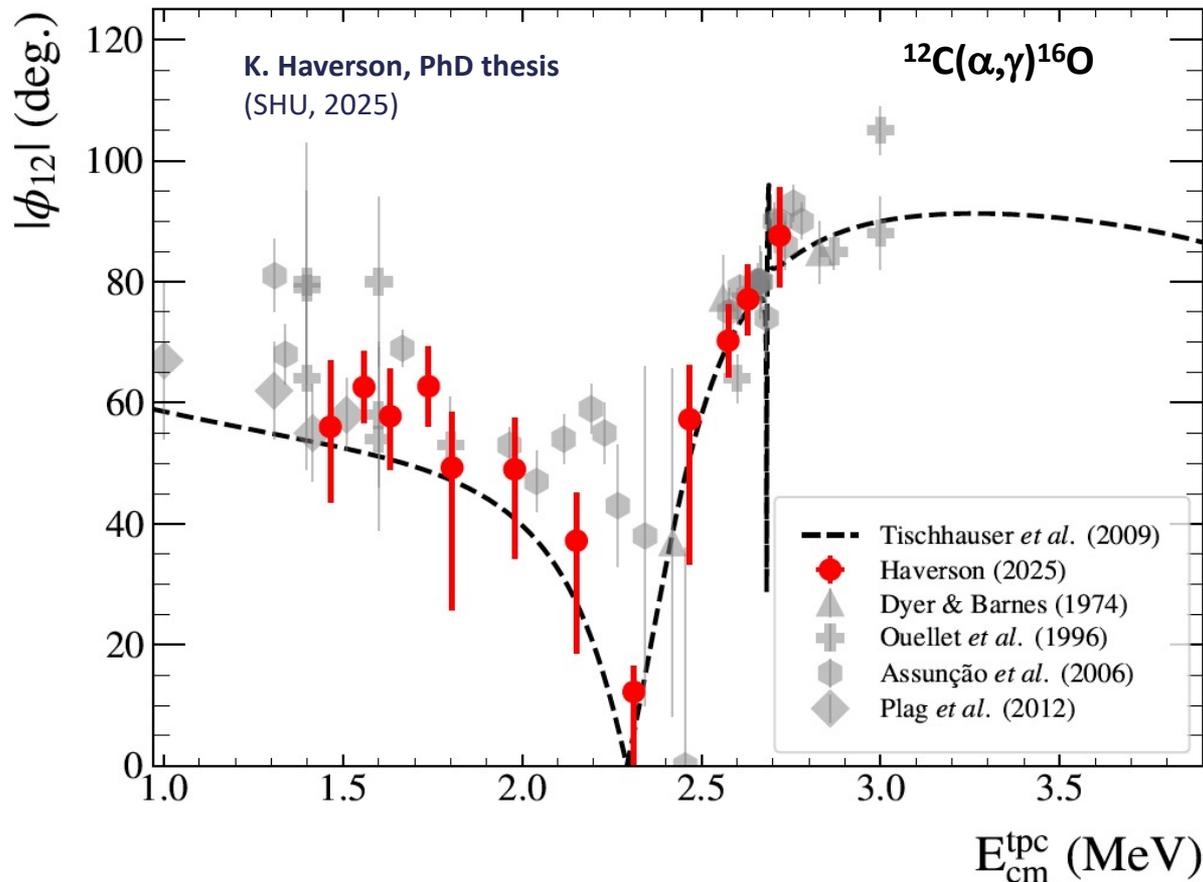


E1 / E2 multipolarity – NEW (2/3)



Warsaw TPC

- Evolution of E1 – E2 mixing phase angle φ_{12} :
 - $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events, full run statistics
 - **automatic track finding** (T_α from *track length*)



E1 / E2 multipolarity – NEW (3/3)



Warsaw TPC

- Evolution of σ_{E2}/σ_{E1} ratio:
 - $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ candidate events, full run statistics
 - **automatic track finding** (T_α from *track length*)

