Development of Time Projection Chambers at the University of Warsaw for active-target & radioactive ion beam mode

UNIVERSITY OF WARSAW

FACULTY OF PHYSICS

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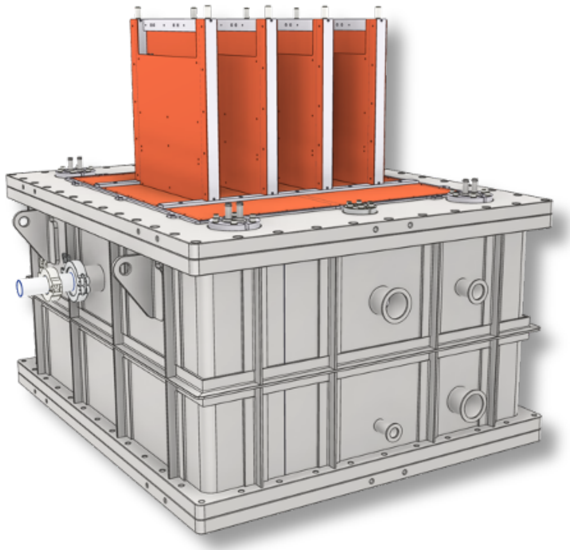


Nuclear Astrophysics Experiments with HIAF

September 3-5, 2025 – Institute of Modern Physics, China Academy of Science – Huizhou, Guangdong, China

Part – 1

TPCs for neutral beams

Nuclear Astrophysics with monochromatic γ-ray beams

__Experimental approach:__

- Measure **photo-disintegration** instead of direct capture process:
  - detailed balance principle for time-reverse reactions
  - different systematics and experimental challenges
  - $^{16}O(\gamma,\alpha)^{12}C$: gain of factor 40 in cross section at E_{CM}~1 MeV

direct capture *photo-disintegration*

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

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

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

- Use quasi-monochromatic **intense gamma-ray beams:**
  - facilities such as: HIγS (USA), ELI-NP (Romania)

- Use **active-target Time Projection Chamber** technique:
  - measure kinematics of low-energy charged particle products
  - obtain accurate values of E1 / E2 components

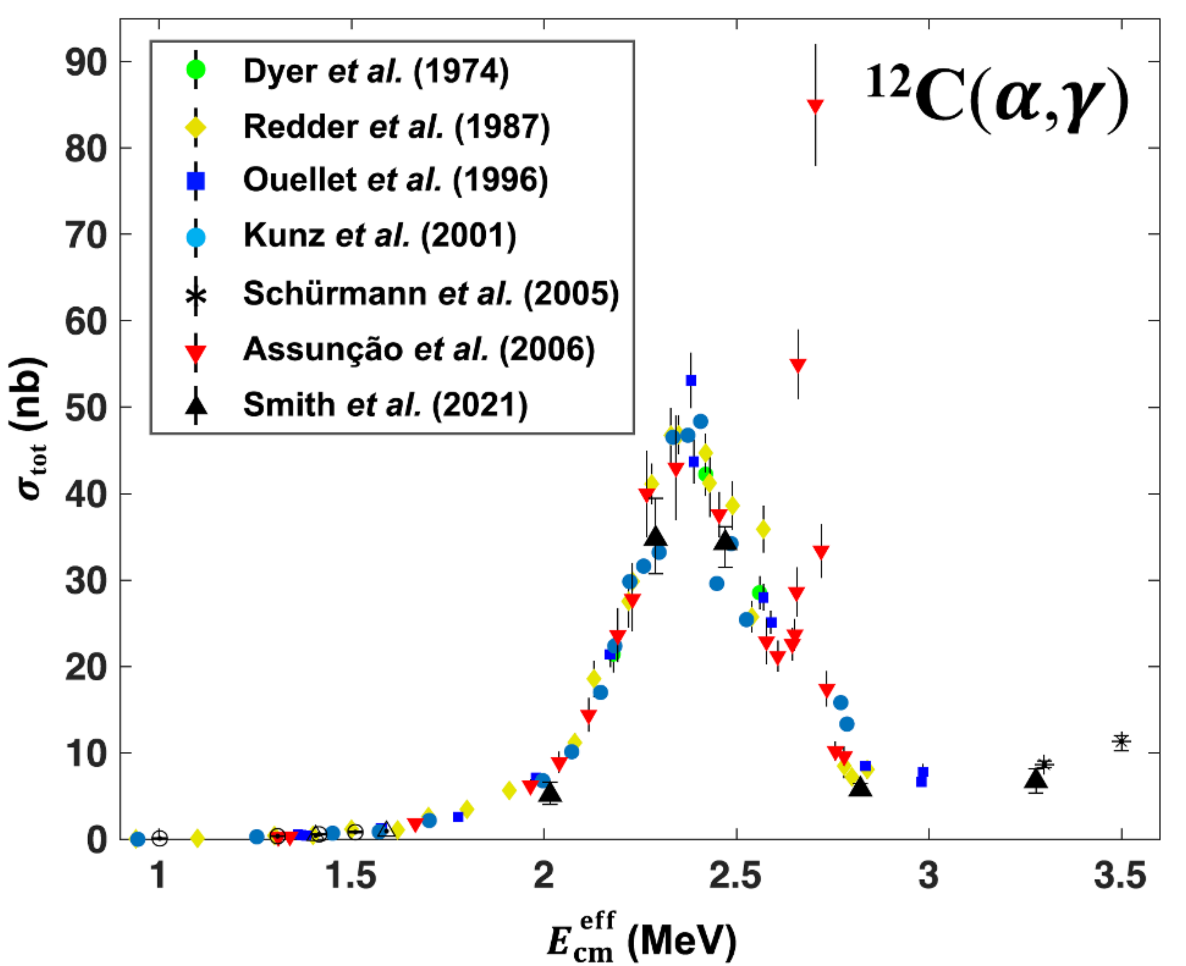
Warsaw TPC

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

Measured σ_{E1+E2} cross section for E_{CM}>1 MeV using:

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

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

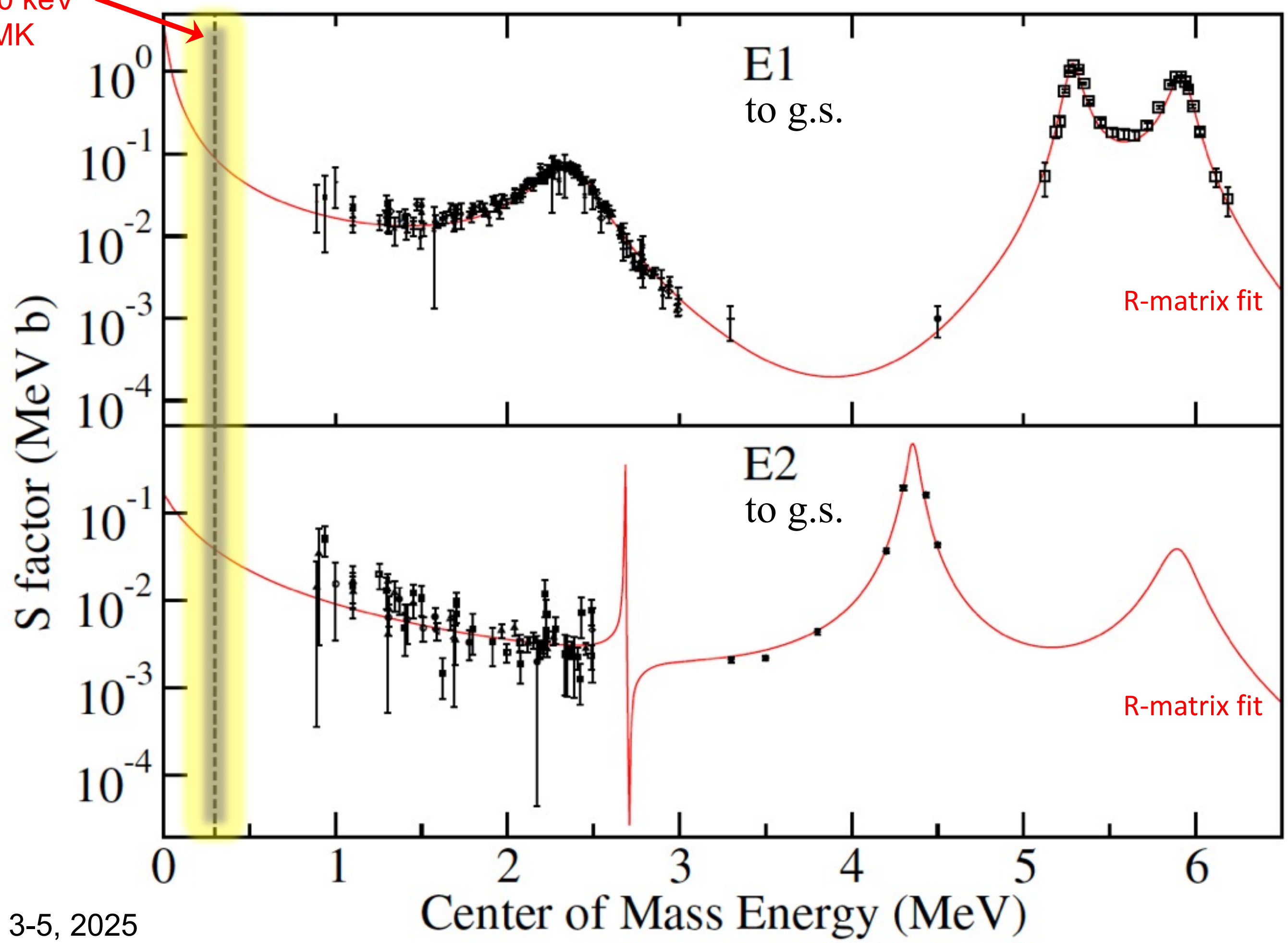


Experimental data on $^{12}C(\alpha,\gamma)^{16}O$

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

Gamow peak
E_{CM} ~ 300 keV
T ~ 300 MK

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



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

R&D timeline

Warsaw TPC

1. **Since 2004** – UW is building & operating **TPCs with optical-readout** (OTPC) for radioactive ion beam studies.

2. **Since 2013** – UW & partners are developing **active-target TPCs with strip readout:**
   - MoU with Extreme-Light Infrastructure Nuclear-Physics / IFIN-HH (ELI-NP), Romania
   - established ELITPC collaboration (U. of Warsaw, U. of Connecticut, ELI-NP/IFIN-HH, Sheffield Hallam U.)
   - joined GET Collaboration on electronics R&D (CEA/Saclay, CENBG/Bordeaux, GANIL/Caen, MSU/FRIB)

3. **2019-2020** – constructed active-target **Warsaw TPC** with 1K readout channels for reactions induced by neutral beams: γ–rays, neutrons.

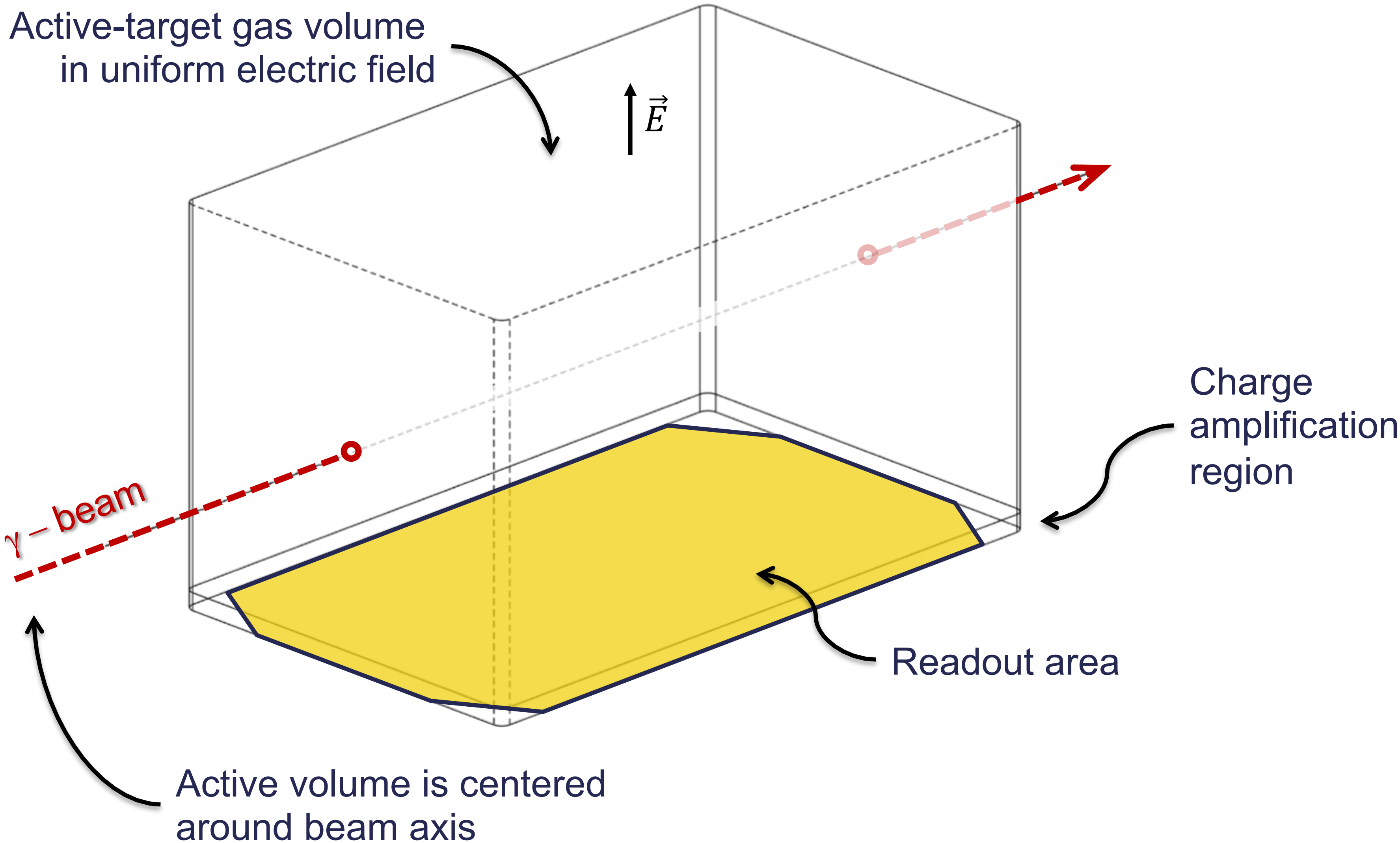
4. **2021** – first experiments at the Institute for Nuclear Physics, Polish Academy of Science (IFJ-PAN), Cracow, Poland:
   - gamma source 13 MeV : ^{16}**O(γ, α)**^{12}**C**
   - neutron source 14.1 MeV : ^{12}**C(n, n')**^{12}**C**$^{(HS)}$

5. **2022** – experiment at the High Intensity Gamma-Ray Source (HIγS), Durham, NC, USA:
   - gamma beams 8.5-13.9 MeV : ^{16}**O(γ, α)**^{12}**C** , ^{12}**C(γ, 3α)**

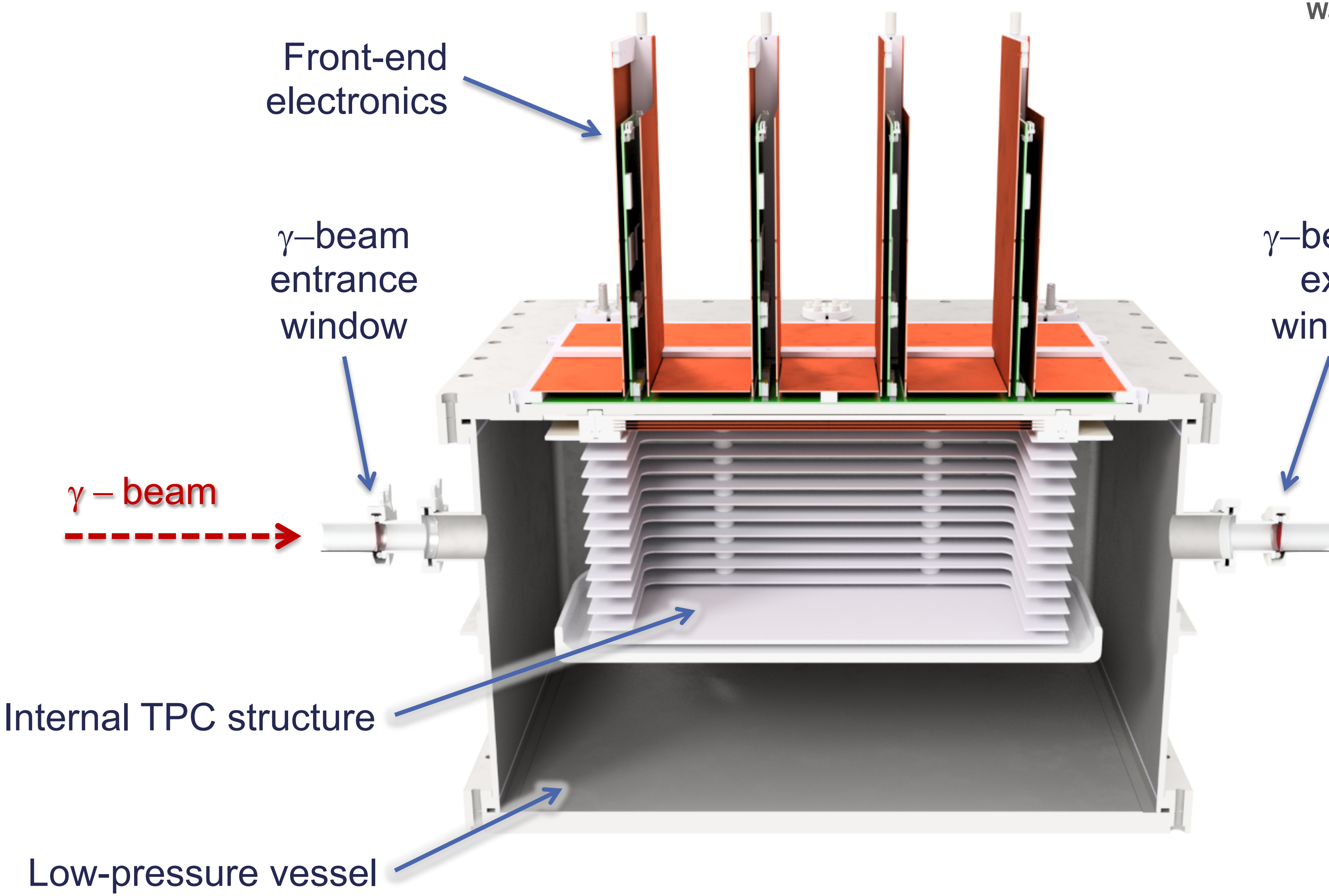
6. **Since 2023** – UW is developing next generation TPC with added ion-gating capability:
   - can be operated with both: neutral beams (active-target) & radioactive ion beams

Concept – active-target TPC

Warsaw TPC



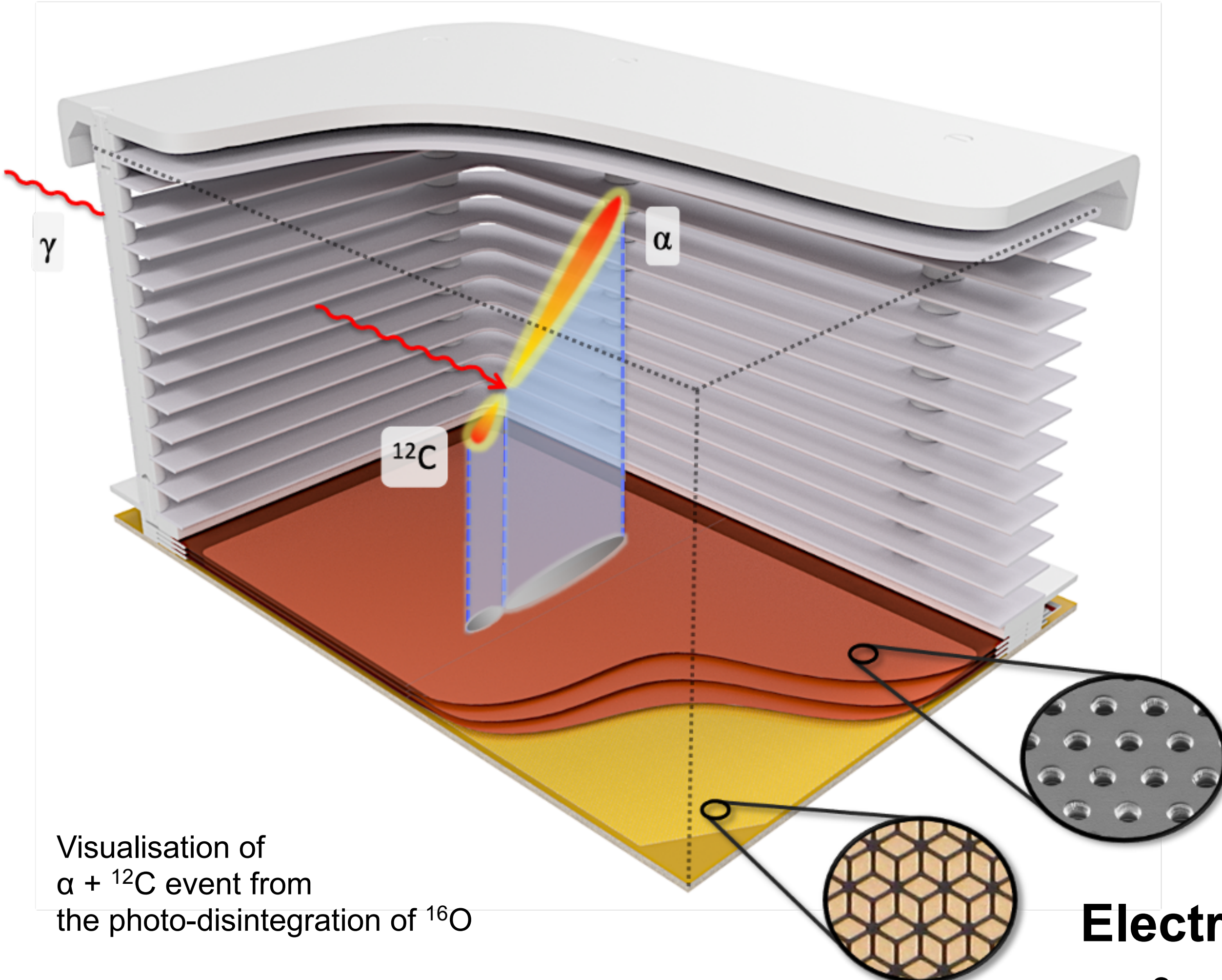
Concept – detector overview



Warsaw TPC

Concept – internal structure

Warsaw TPC



Visualisation of
α + ^{12}C event from
the photo-disintegration of ^{16}O

Active volume

- readout: **330 x 200 mm^2**
- drift length: **196 mm**
- gas: CO_2 @ 80-250 mbar

Charge amplification

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

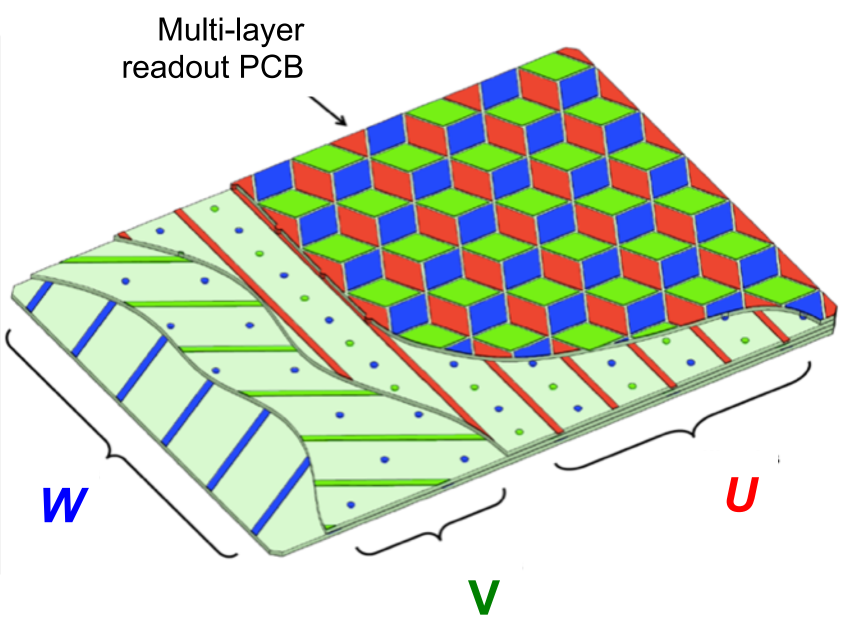
Electronic readout

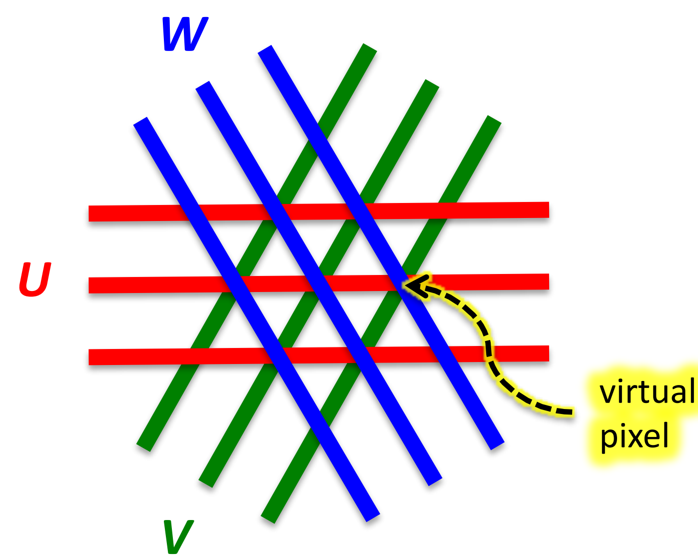
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

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*(10³)** channels are needed



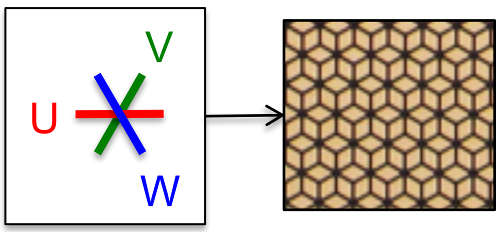


[1] S. Bachmann et al., NIM A **478**, 104 (2002)
[2] V. Ableev et al., NIM A **535**, 294 (2004)
[3] J. Bihałowicz et al., Proc. of SPIE **9290**, 92902C (2014)
[4] M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

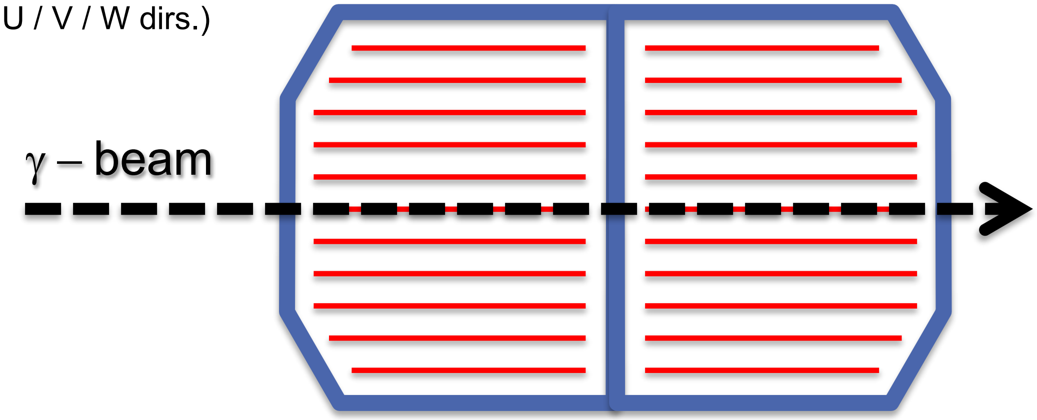
Detector readout concept

Warsaw TPC

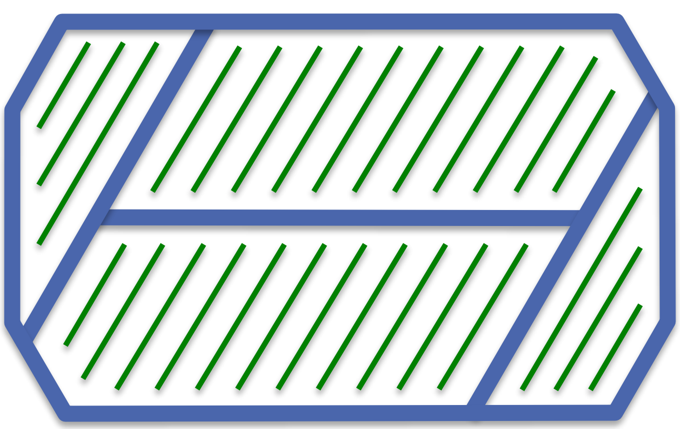
- **1018 strips** in total
- 1.5 mm strip pitch (in each of U / V / W dirs.)



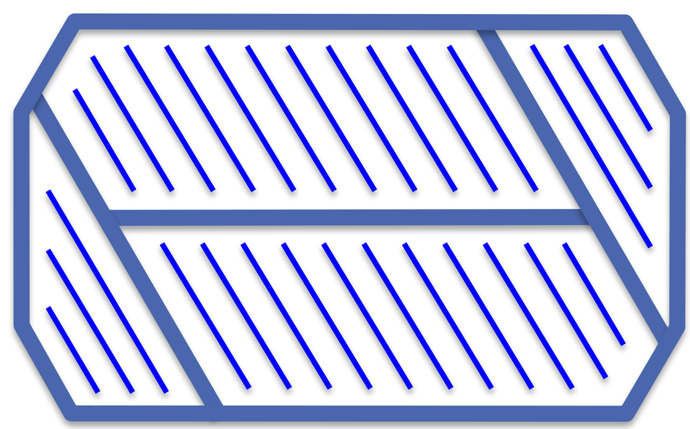
264 U-strips (2 sections)



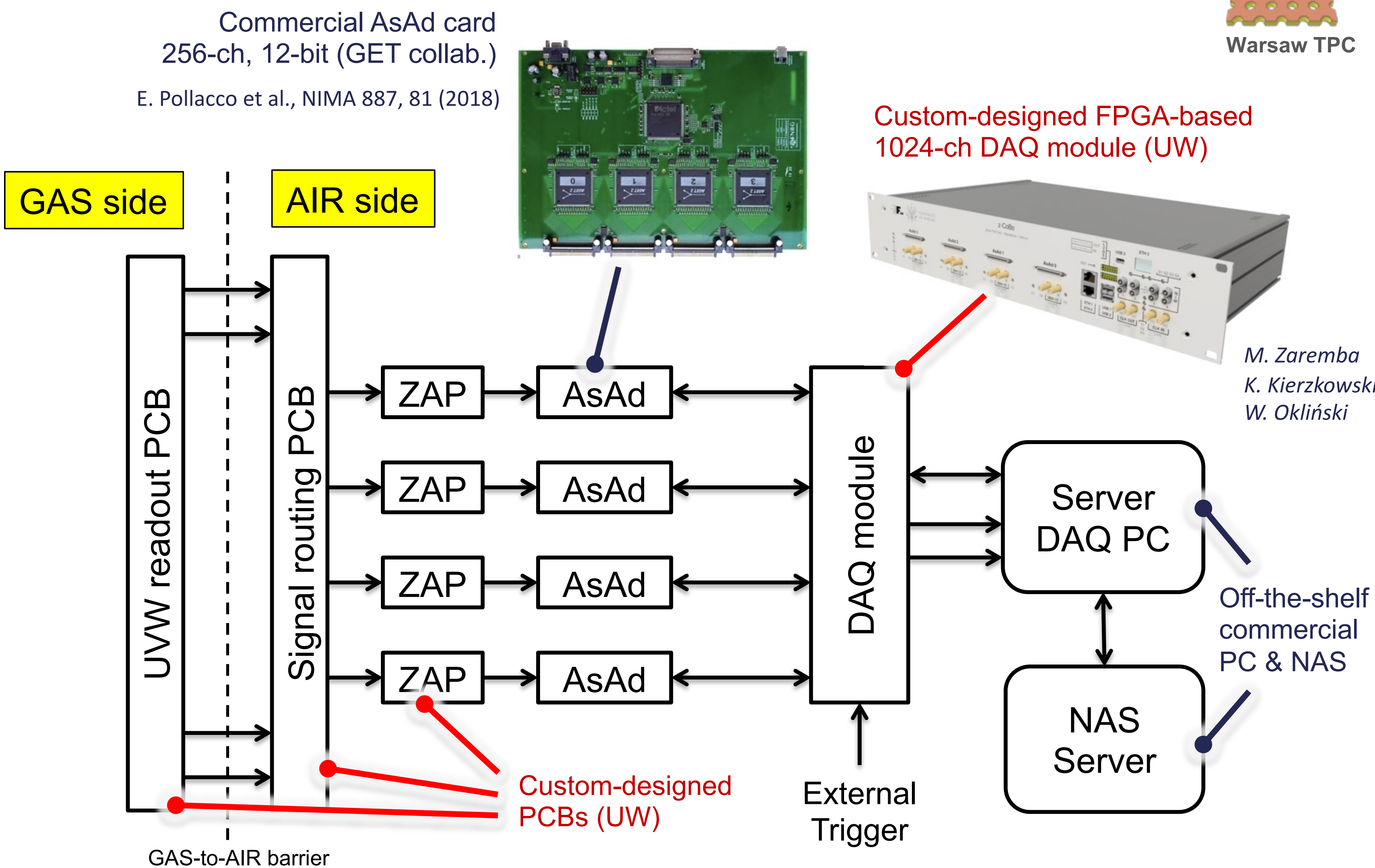
376 V-strips (4 sections)



378 W-strips (4 sections)



DAQ readout chain



Warsaw TPC

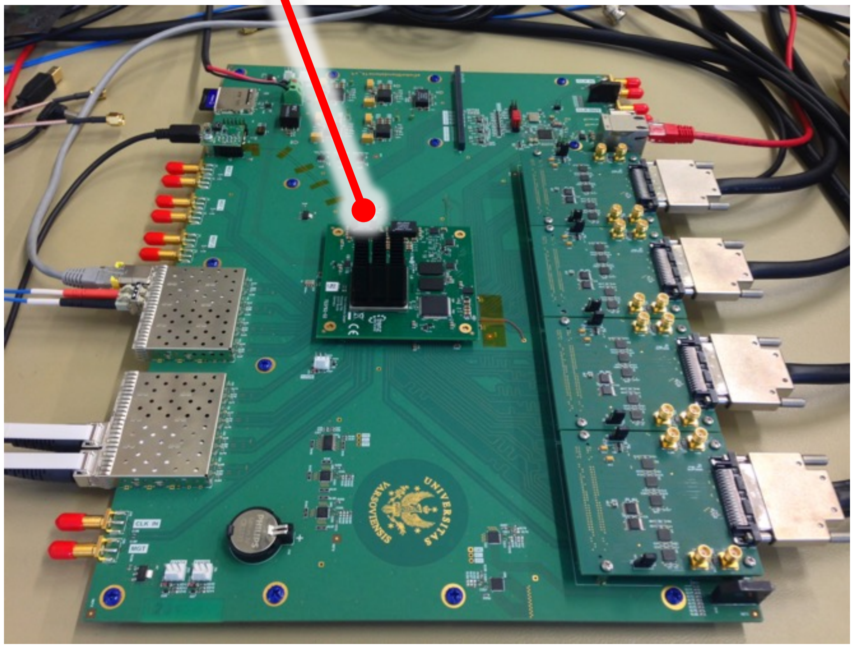
Custom FPGA DAQ module

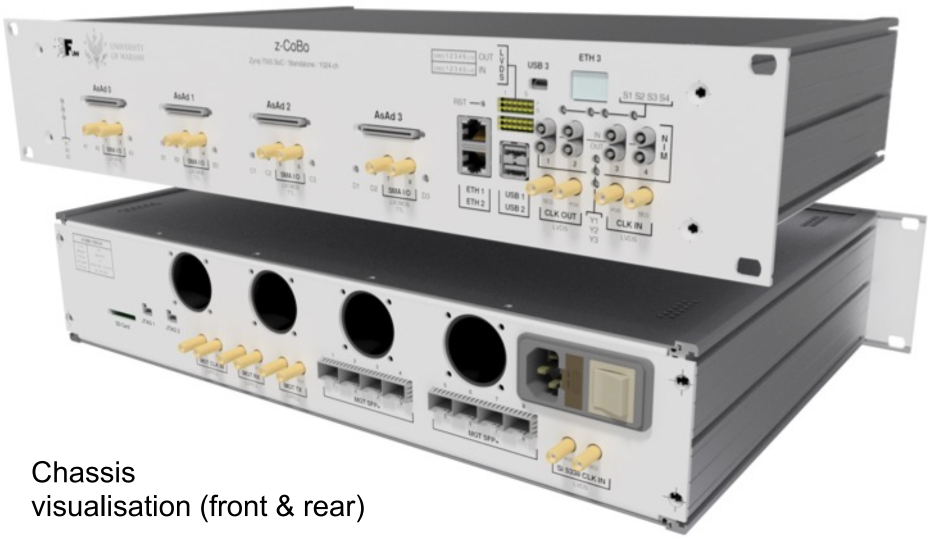
Warsaw TPC

- Commercial Xilinx Zynq-7000 SoC:
  - Trenz TE-0782
- Custom designed PCB:
  - **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

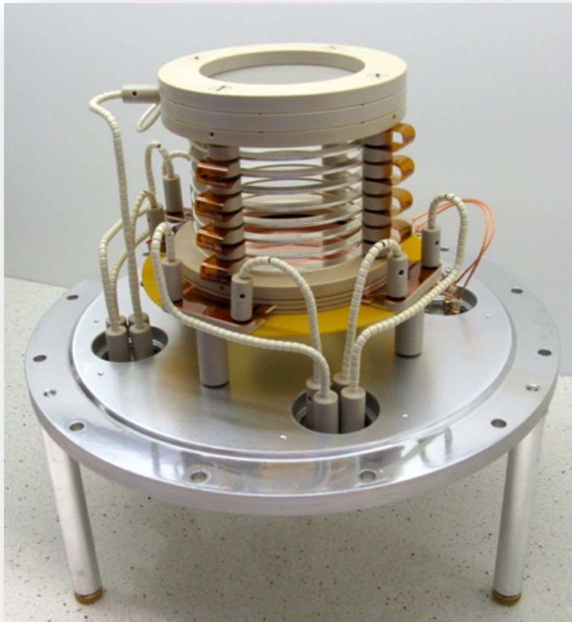


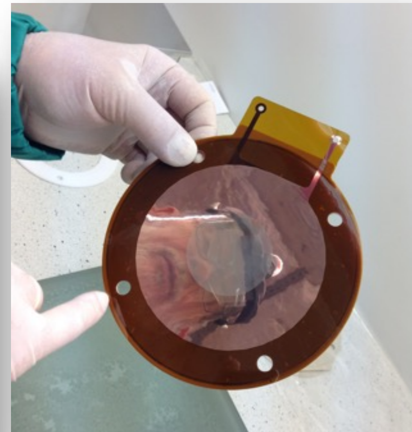


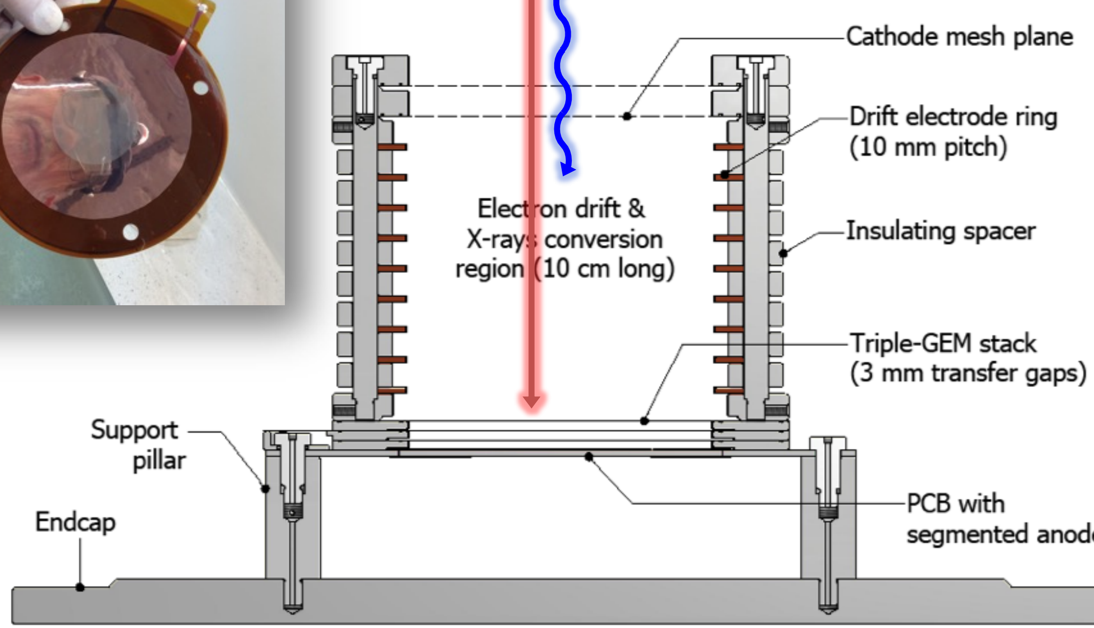
Chassis visualisation (front & rear)

Test bench for GEM studies

Warsaw TPC







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

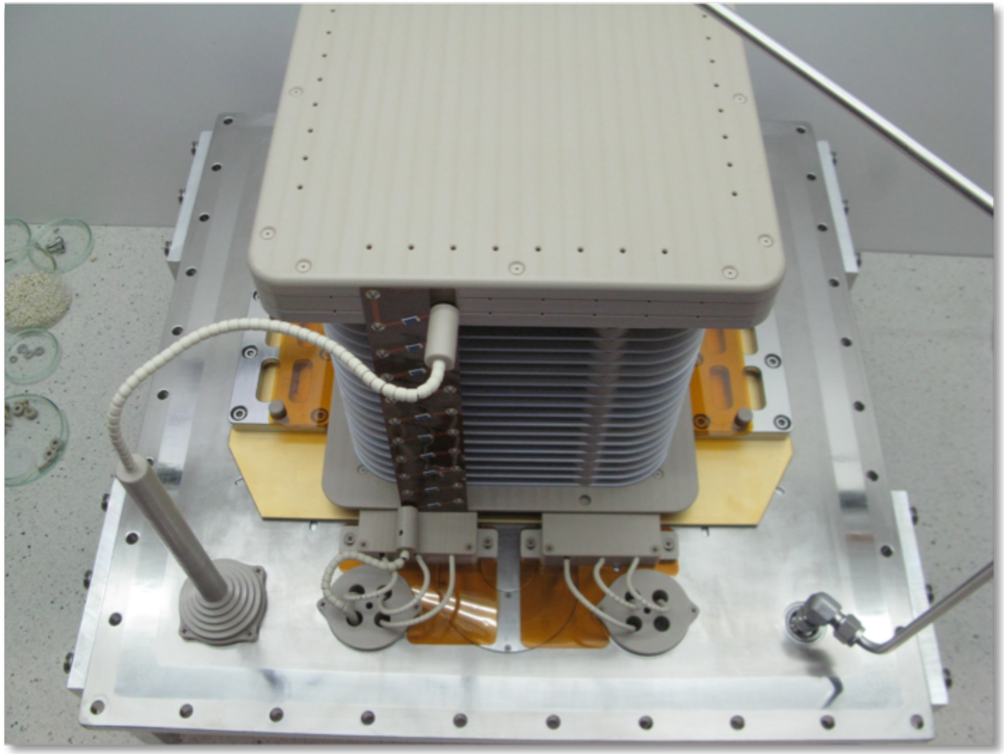
- Low-pressure test bench:
  - Model detector: 14 dm^3 vessel, 3 or 2 GEM foils, ϕ5 cm {active area} × 10 cm {drift}
  - GEM foil thickness: **50 µm** (standard) or **125 µm**
  - Soft X-rays (~5 keV) ⇒ **gas gain**, energy resolution
  - Alpha-particle source (~5.5 MeV) ⇒ **electron drift velocity**, diffusion

Mini-TPC demonstrator

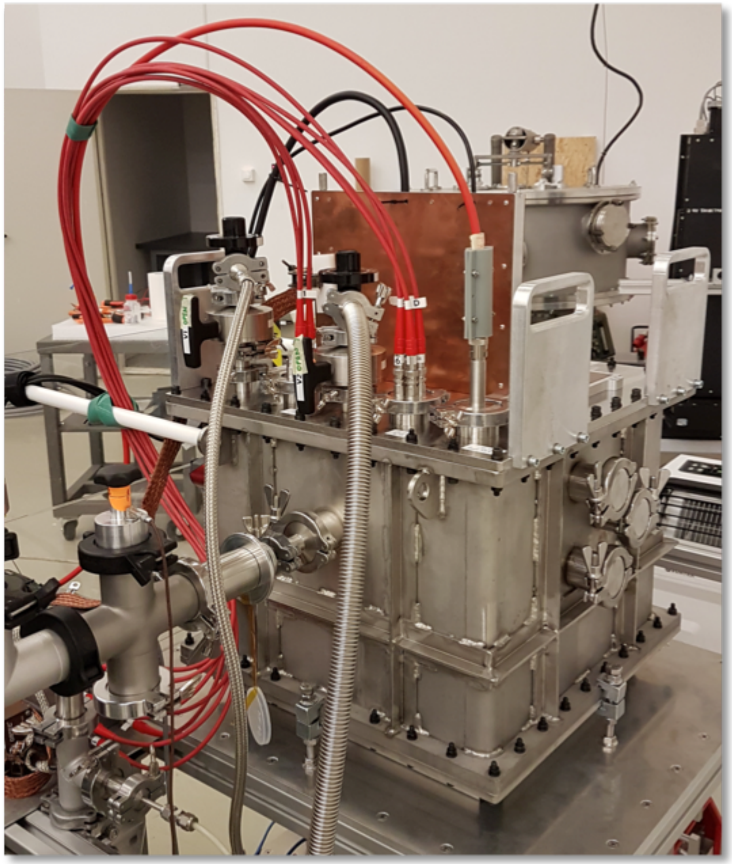
Warsaw TPC

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

Assembled internal TPC structure



Vacuum vessel with 1 AsAd card



M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

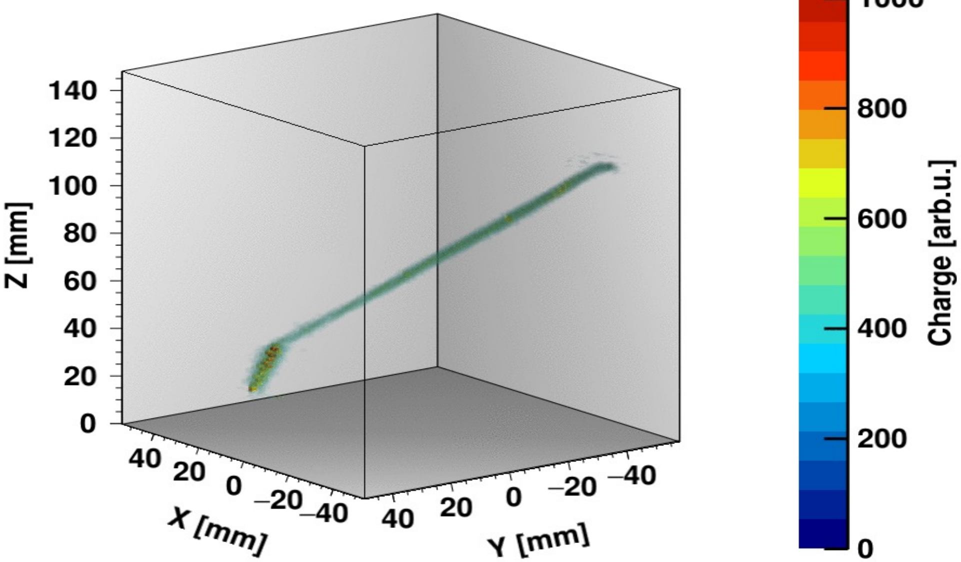
Mini-TPC demonstrator

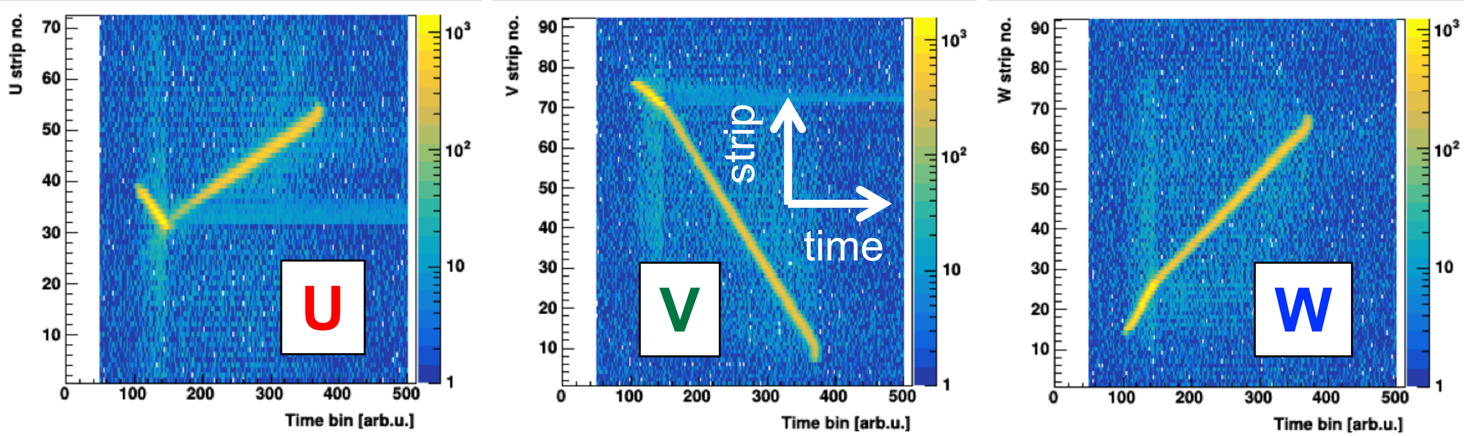
Warsaw TPC

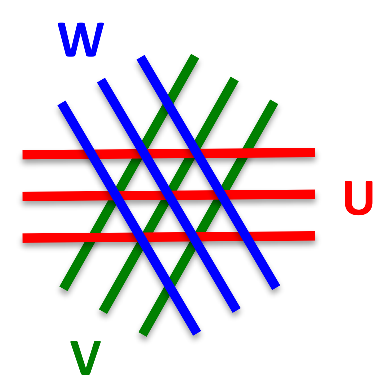
- **Neutron beam** – June 2018:
  - 3 MV Tandem facility at IFIN-HH, Bucharest, Romania
  - neutrons produced by 6.5 MeV α-particle beam on Be target
  - TPC operated with pure CO_2 @ 100 mbar

- Right: energy losses along tracks reconstructed in 3D
- Bottom: raw-data from U / V / W strips

Example of neutron reacting with nuclei of CO_2 gas molecule





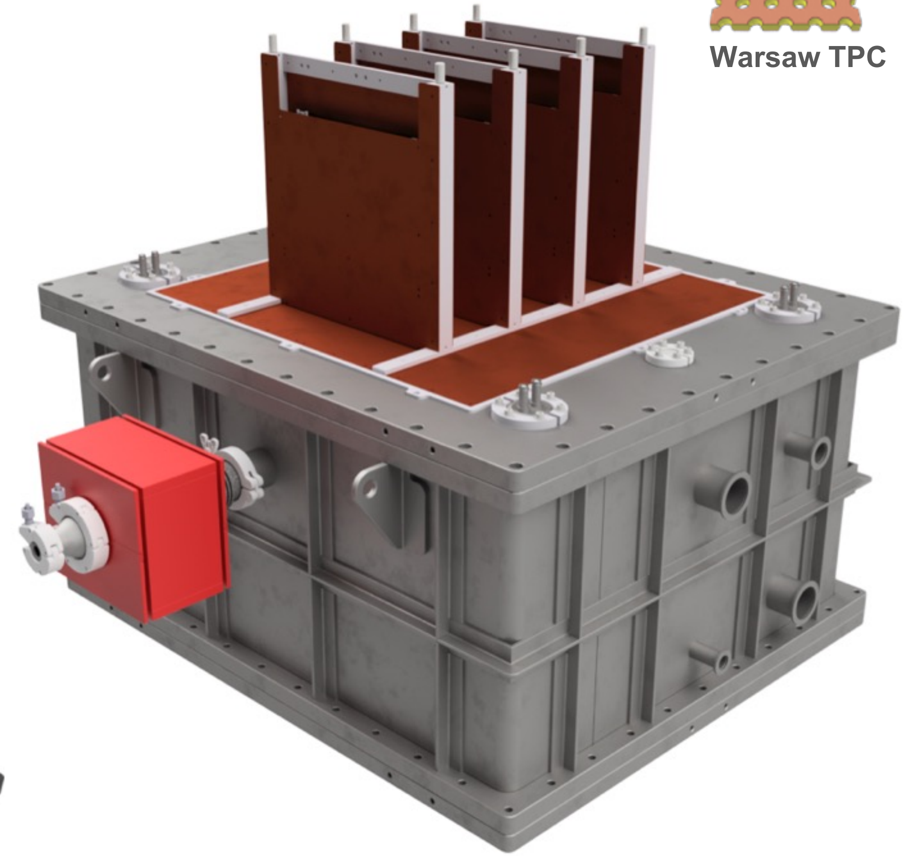


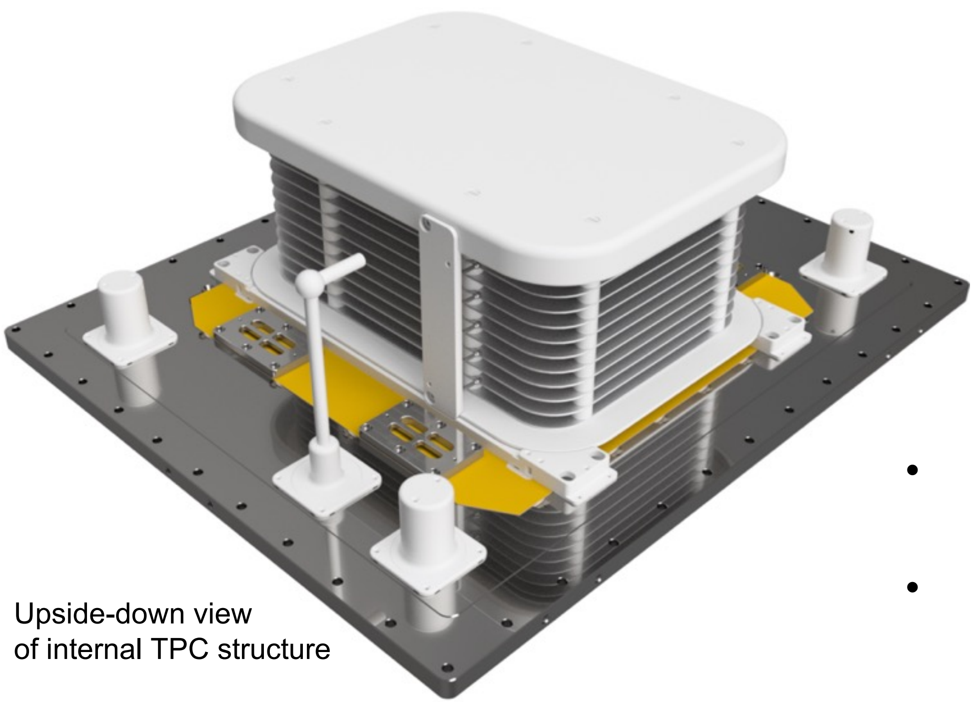
M. Gai et al., NIM A **954**, 161779 (2020)

Full scale detector

Warsaw TPC

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



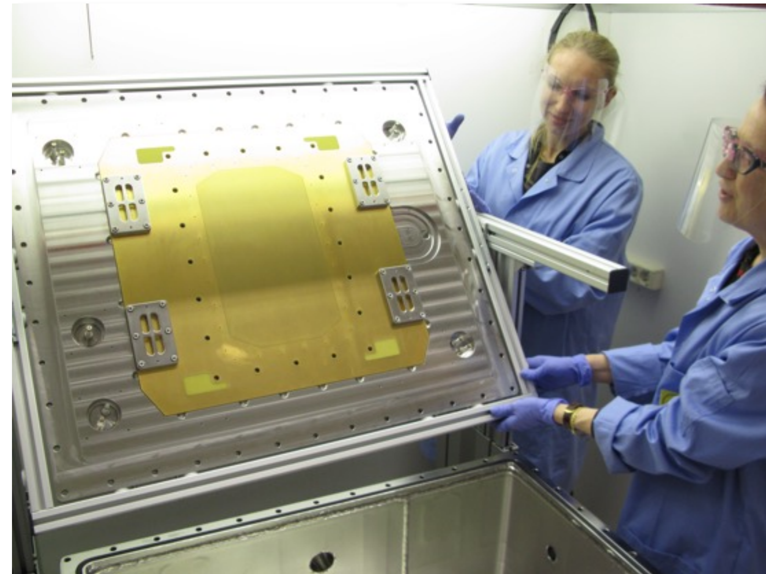


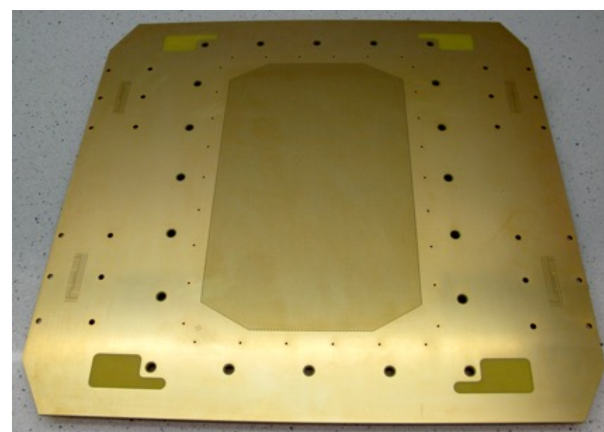
Upside-down view
of internal TPC structure

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

Full scale detector

Warsaw TPC



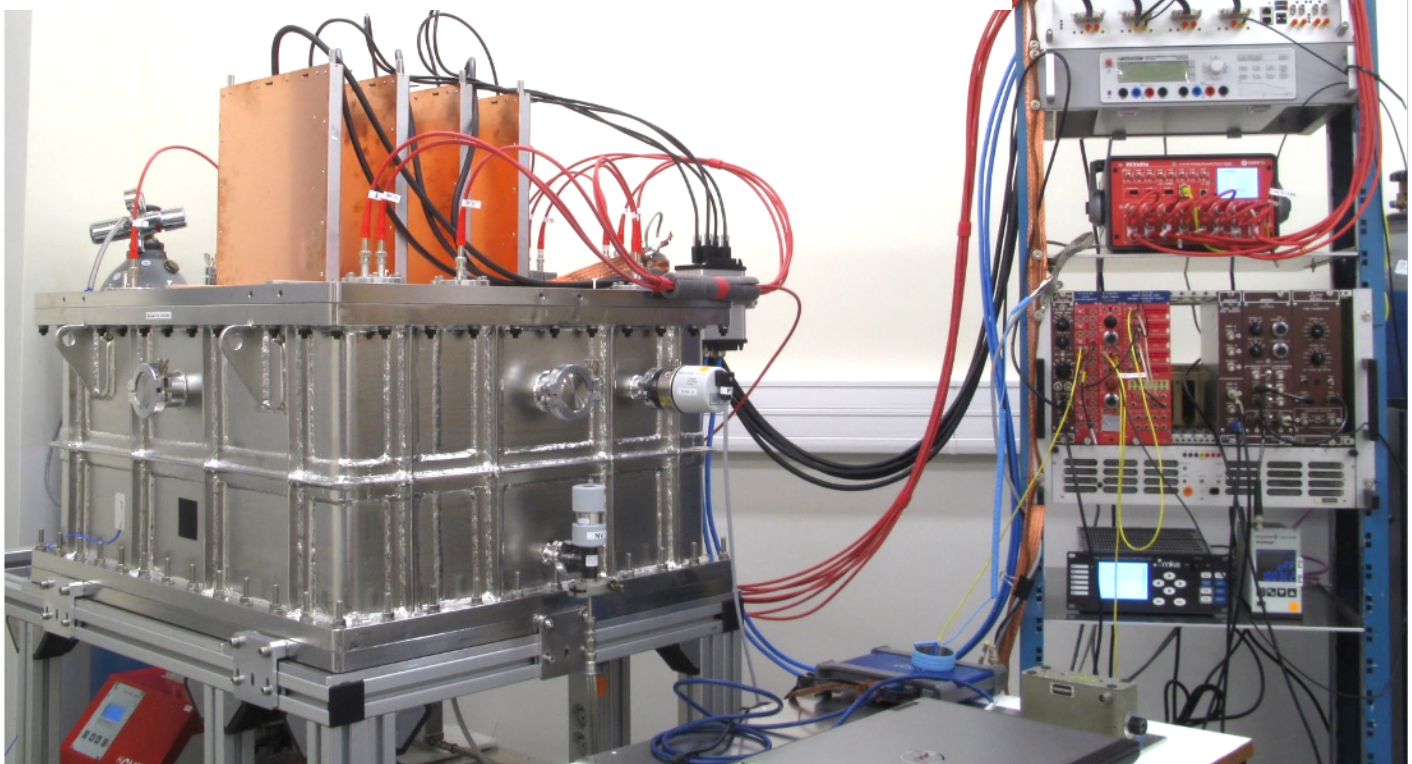


- Left: drift cage integrated with PCB
- Right: readout anode PCB with 20 x 33 cm^2 active area

Full scale detector

Warsaw TPC

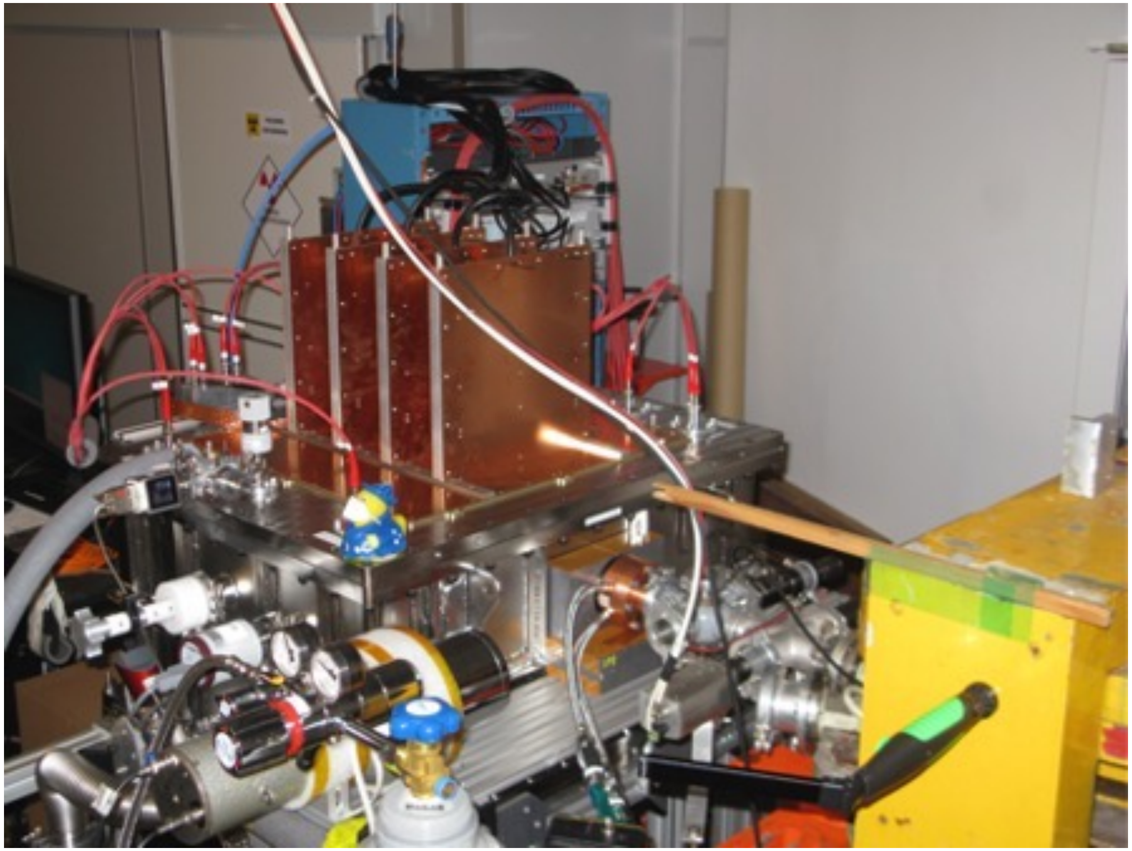
- **Warsaw TPC detector – operational since March 2020**
- Mobile low-pressure test stand is complemented with:
  - data acquisition & data storage systems
  - Detector Control System (DCS)
  - data analysis & Monte Carlo software framework

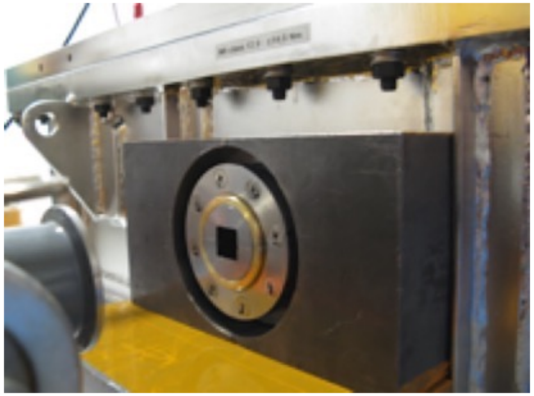


First experiments

Warsaw TPC

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





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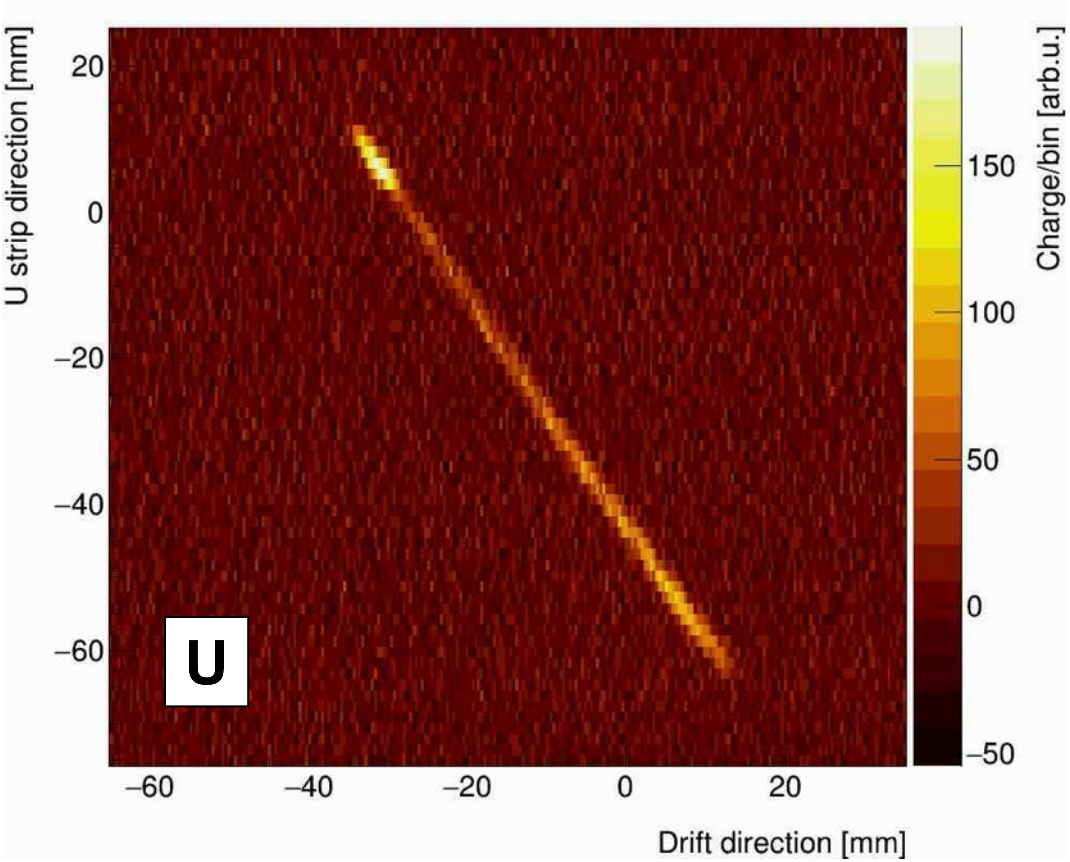


Candidate event for **$^{16}O(\gamma, \alpha)^{12}C$** reaction

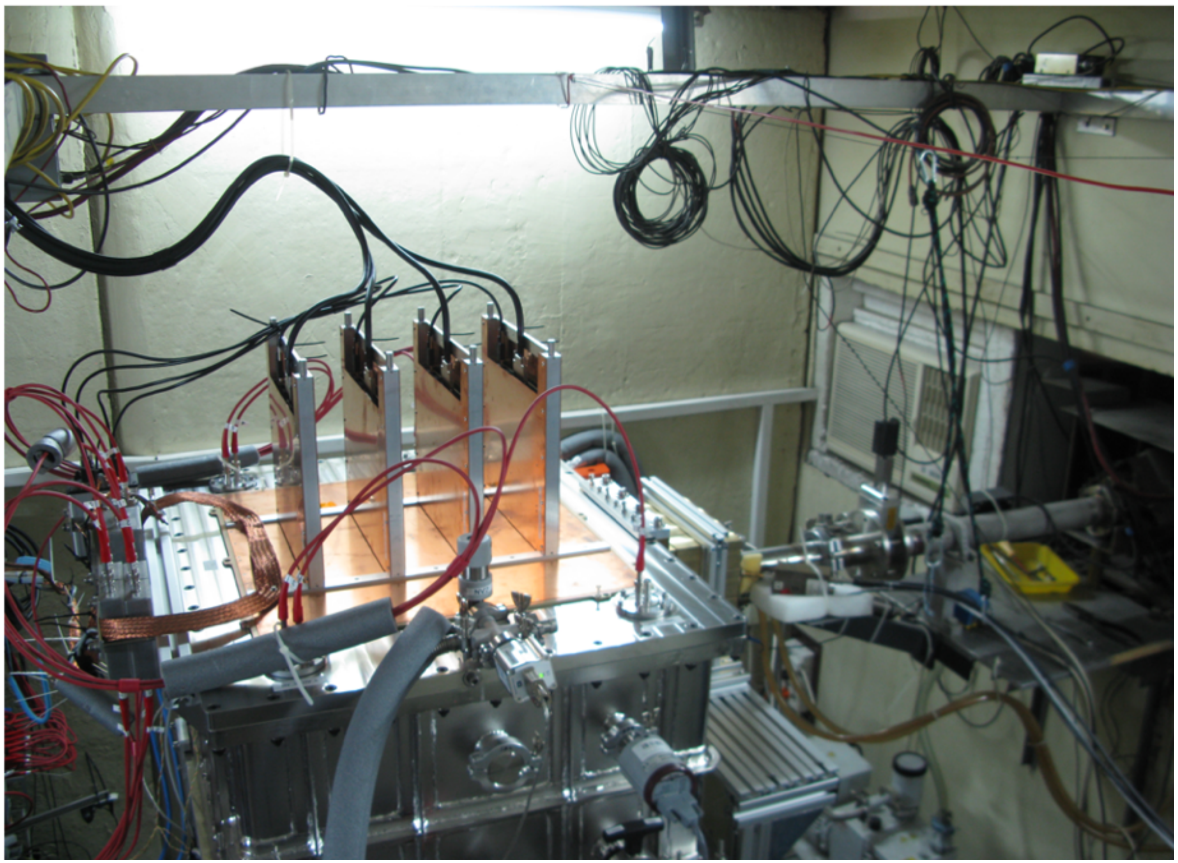
- Only raw-data from U strip direction is shown for simplicity
- Zoomed area: 100 mm x 100 mm

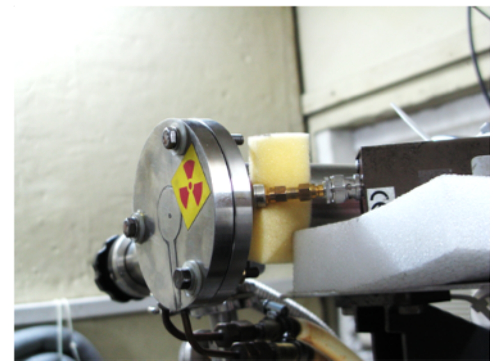
M. Kuich et al., Acta Phys. Pol. B Proc. Suppl. **16**, 4-A17 (2023)

First experiments

Warsaw TPC

- **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 CO_2 @ 80 mbar





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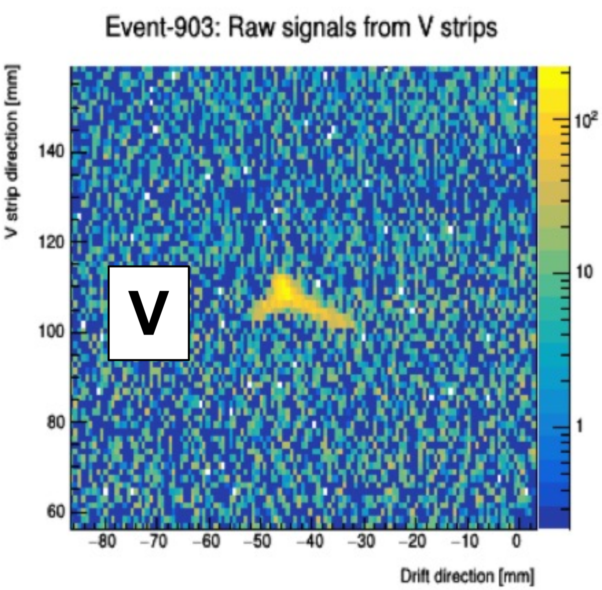
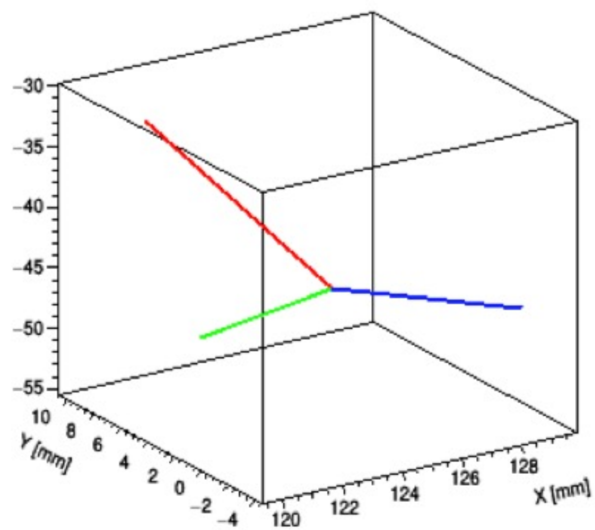


- Left: only raw-data from V strips is shown for simplicity
- Right: reconstructed track lengths in 3D



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

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

$E_{\alpha 1}$ = 145 keV

$E_{\alpha 2}$ = 108 keV

$E_{\alpha 3}$ = 60 keV

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

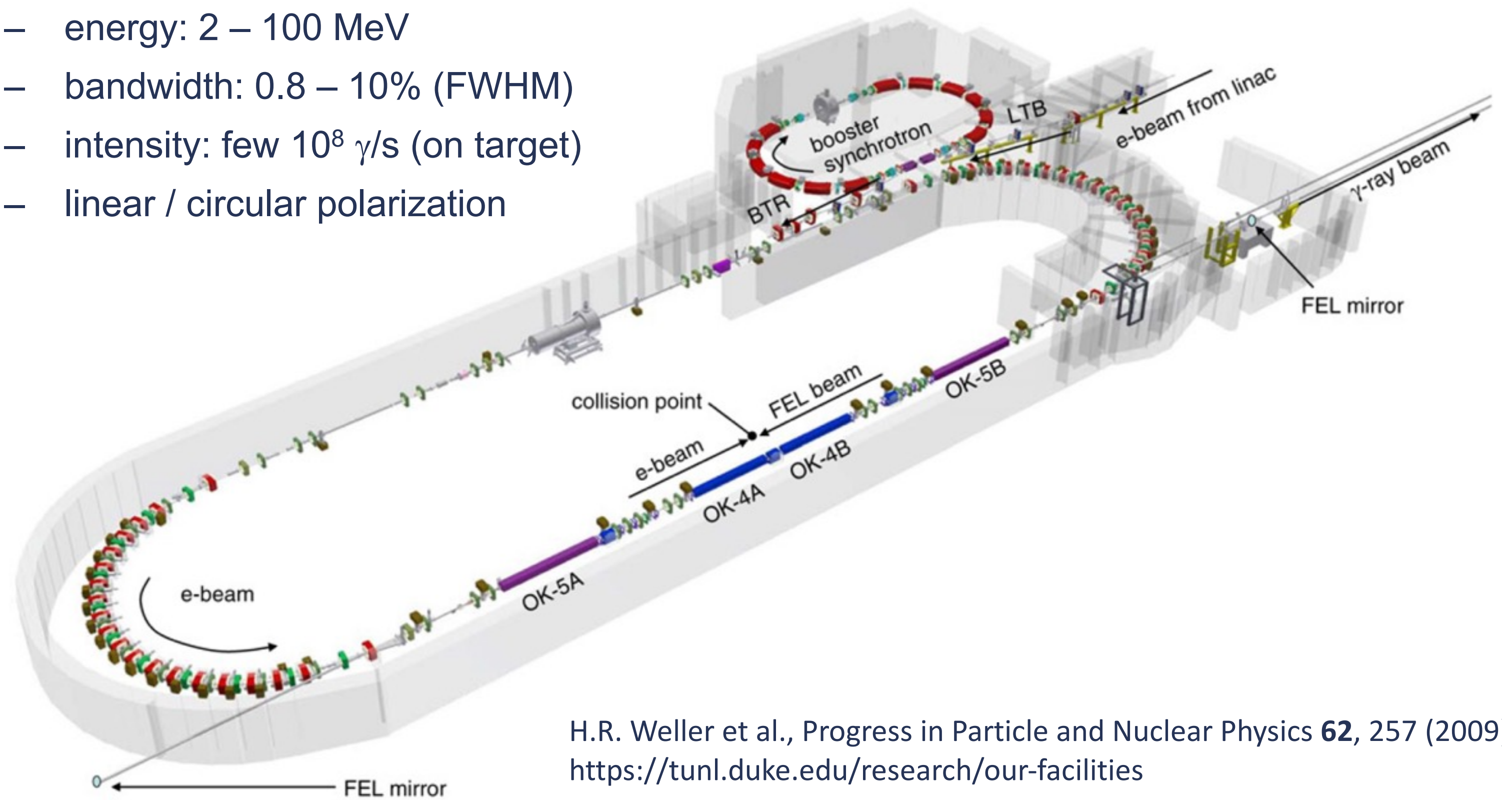
Also observed:

- 3-particle events from: ^{12}C(n, n')^{12}C
- 2-paticle events from: ^{12}C(n, α)^{9}Be

^{16}O photodisintegration experiment @ HIγS

(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=0.24-1.2 GeV)
- Gamma beams:
  - energy: 2 – 100 MeV
  - bandwidth: 0.8 – 10% (FWHM)
  - intensity: few 10^8 γ/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 @ HIγS
(April-September, 2022)

Warsaw TPC

- **Delivered γ-ray beams:**
  - 275 hours / 15 energy points
  - beam collimator: ∅10.5 mm
  - E_γ **nominal : 8.51 – 13.9 MeV**
    ⇔ E_{CM} : 1.35 – 6.7 MeV of ^{12}C(α,γ)^{16}O
  - E_γ fwhm : 350 keV @ 8.51 MeV
  - I_γ **on target : (1.5 – 5) x 10^8 γ/s**
- **Beam monitoring:**
  - E_γ spectra : from HPGe detector
  - relative $I_\gamma(\mathrm{t})$: 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

⇒ can study **^{16}O(γ,α)^{12}C** and **^{12}C(γ,3α)**

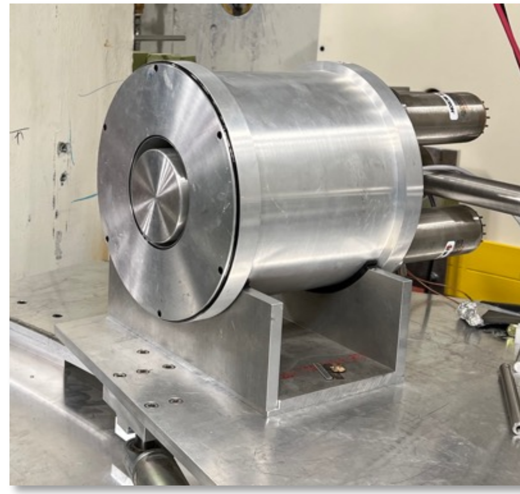
Beam monitoring & alignment

Warsaw TPC

Collimator
ϕ =10.5 mm
(upstream)

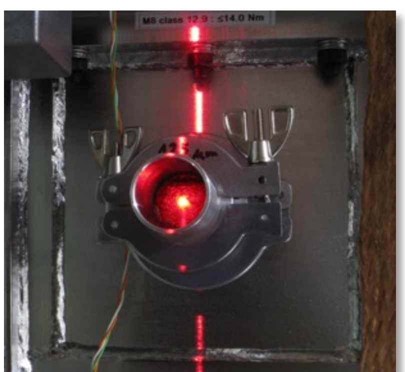
Scintillators
(upstream)

HPGe
(downstream)

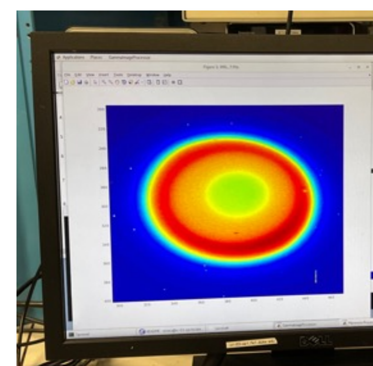


Au foil activation
(downstream)

Alignment – laser



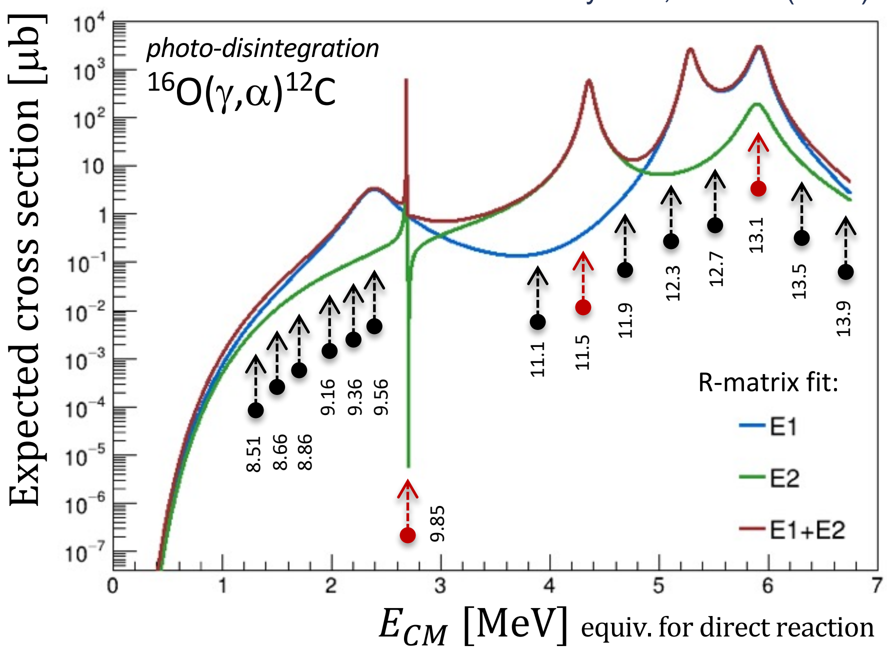
Alignment – BGO CCD gamma camera & lead plugs:



Energy scans

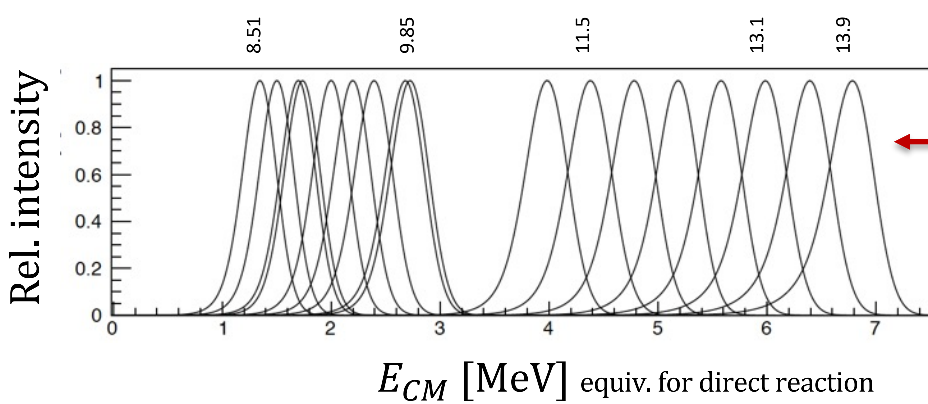
Warsaw TPC

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



Overview of experimental conditions:

- scanned 15 nominal 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



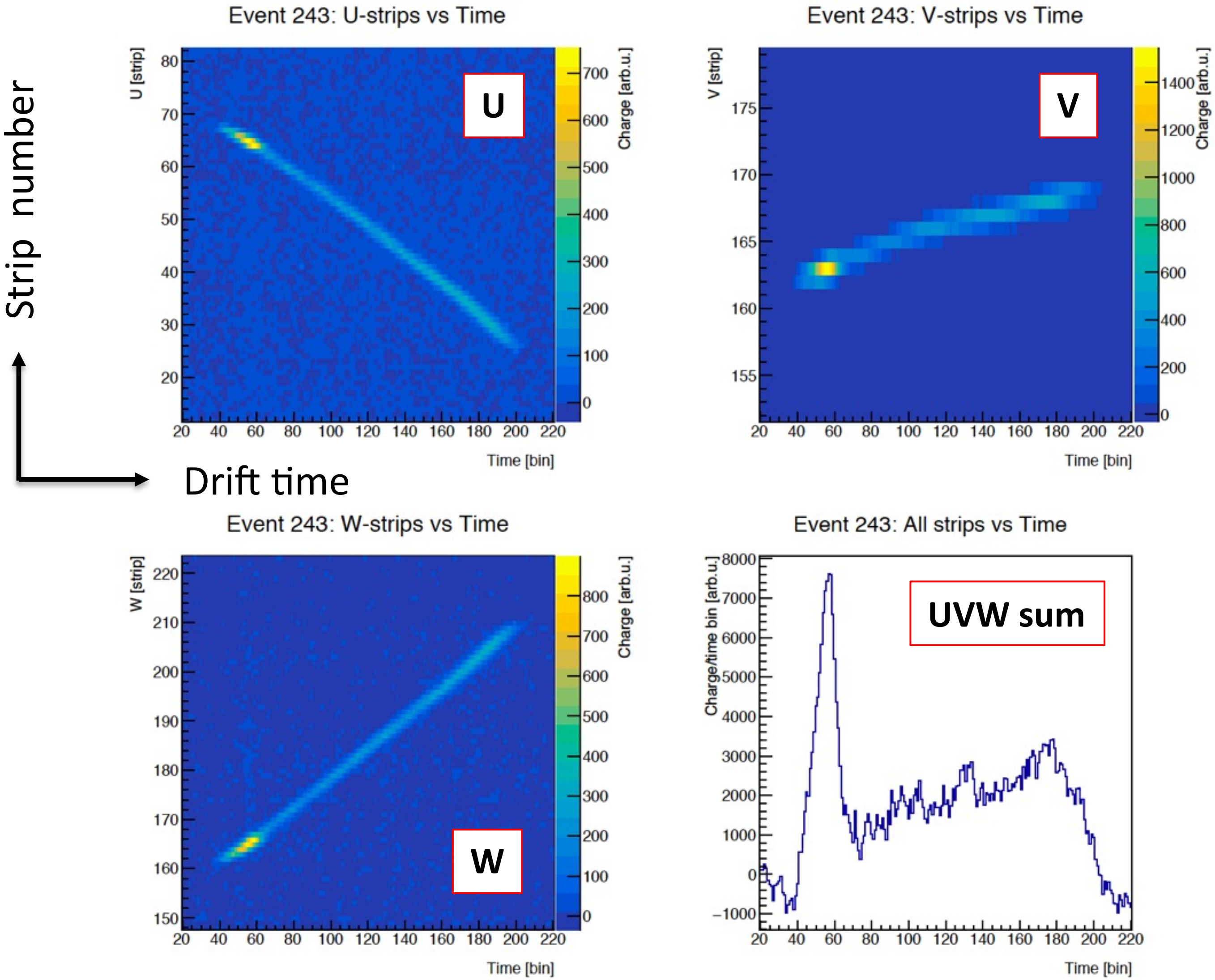
typical shapes of γ-beam spectra on target (TPC volume) for all studied nominal energy points

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

Example raw data

Warsaw TPC

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



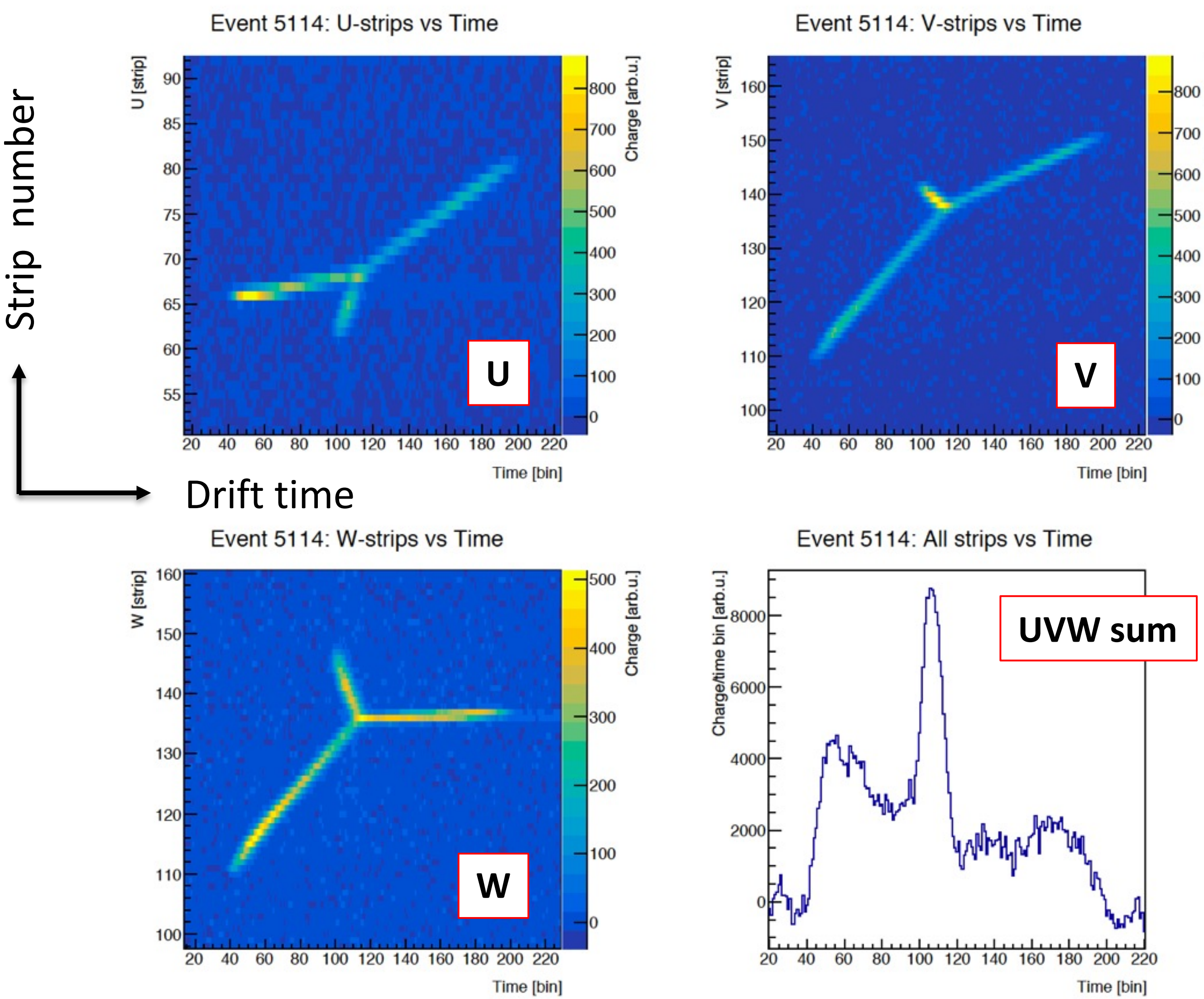
E_γ=13.9 MeV

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

Example raw data

Warsaw TPC

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



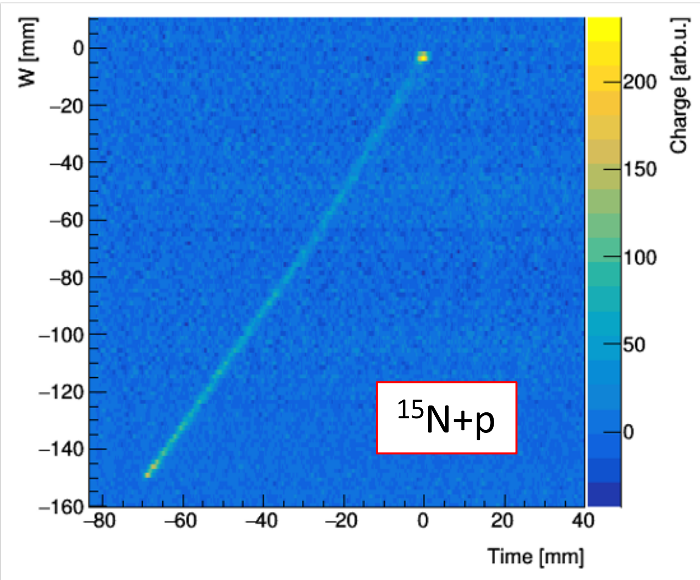
$E_\gamma = 13.9$ MeV

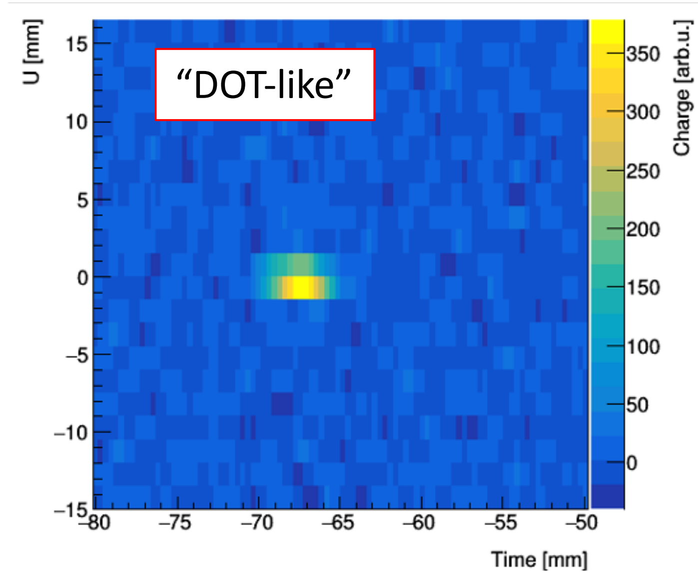
- Zoomed region of interest
- Pressure: 250 mbar
- Sampling: 12.5 MHz

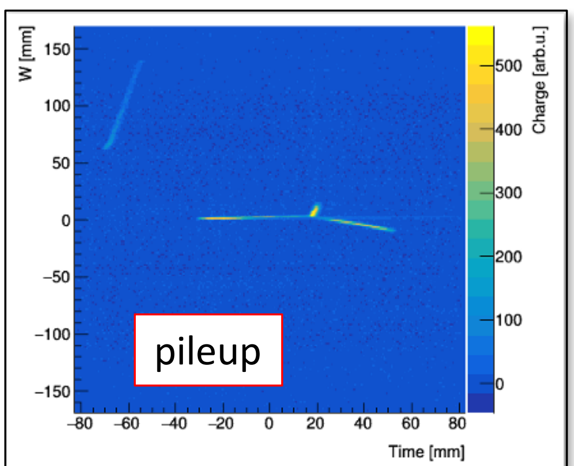
Example raw data - background

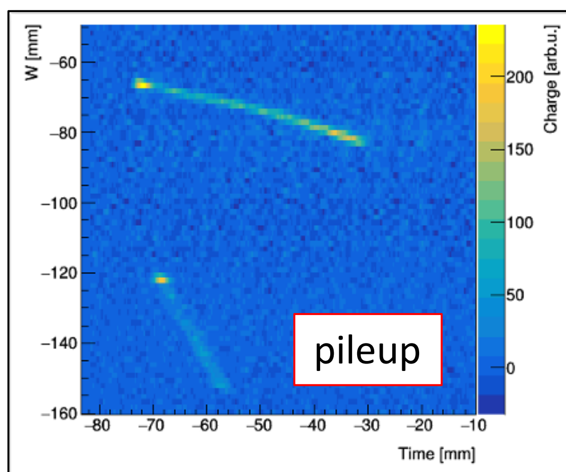
Warsaw TPC

Examples of background & more complex events:









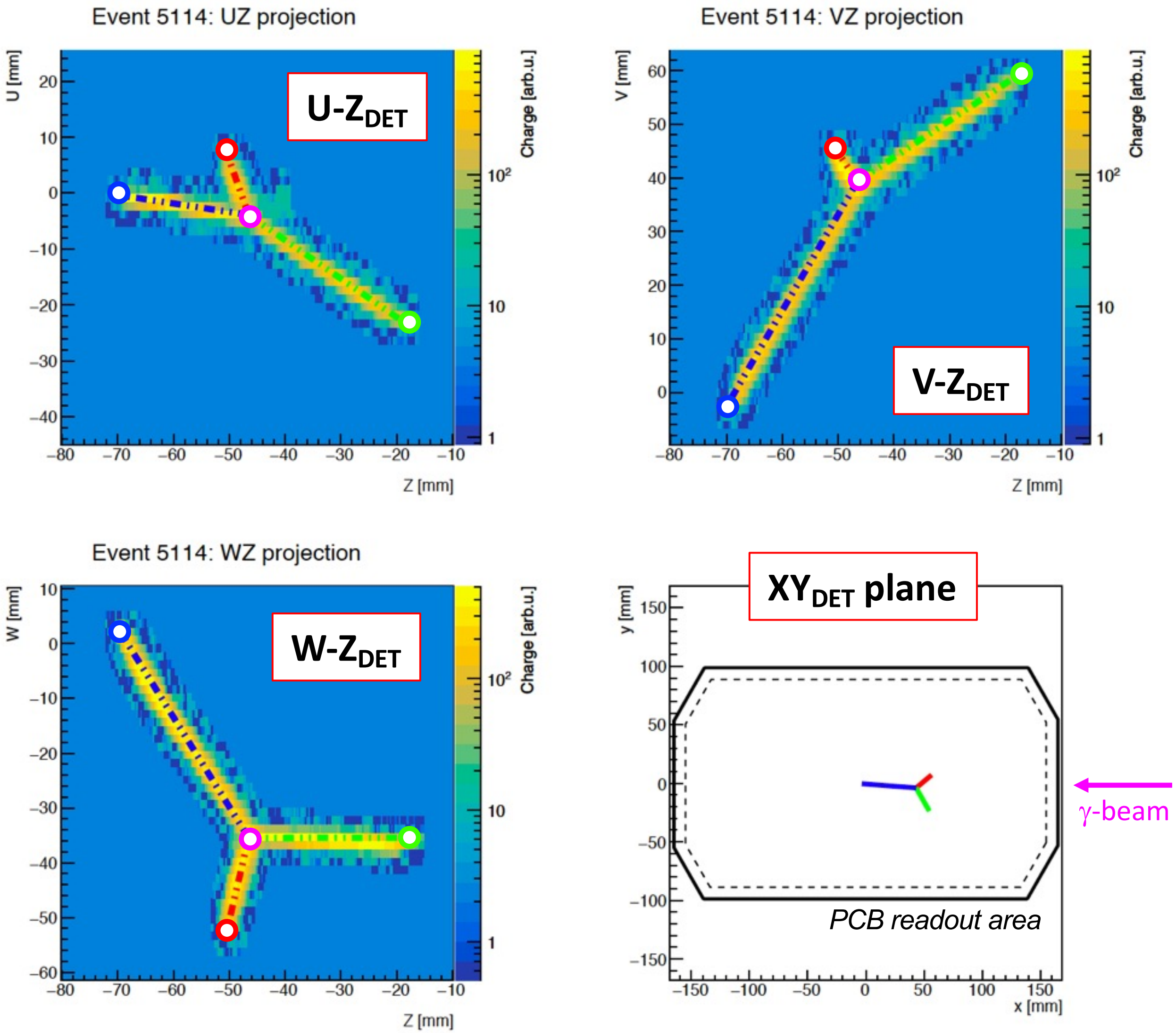
E_γ=13.9 MeV

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

Track finding

Warsaw TPC

3-particle topology: reconstructed α tracks in 3D



$E_\gamma = 13.9$ MeV

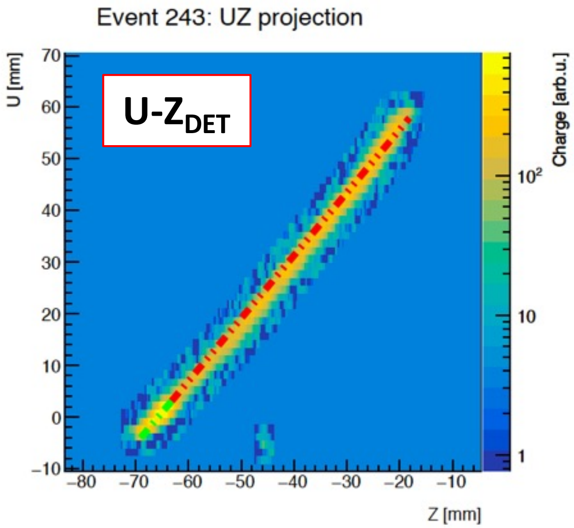
- Pressure: 250 mbar
- Sampling: 12.5 MHz
- **Manual procedure** for 1/2/3-particle topology *(current default)*
- Vertex & track ends selected by expert

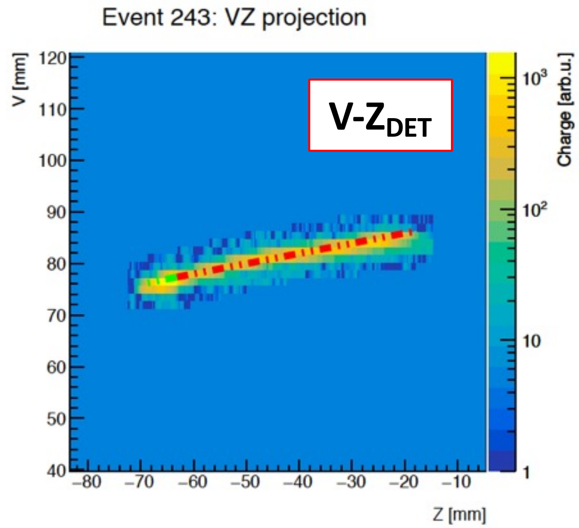
A. Kalinowski

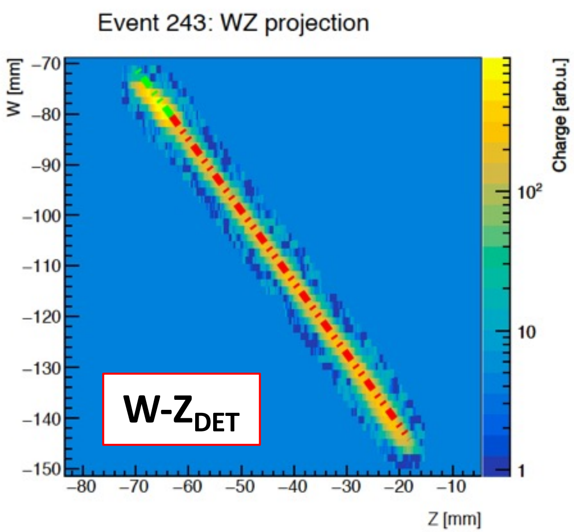
Track finding

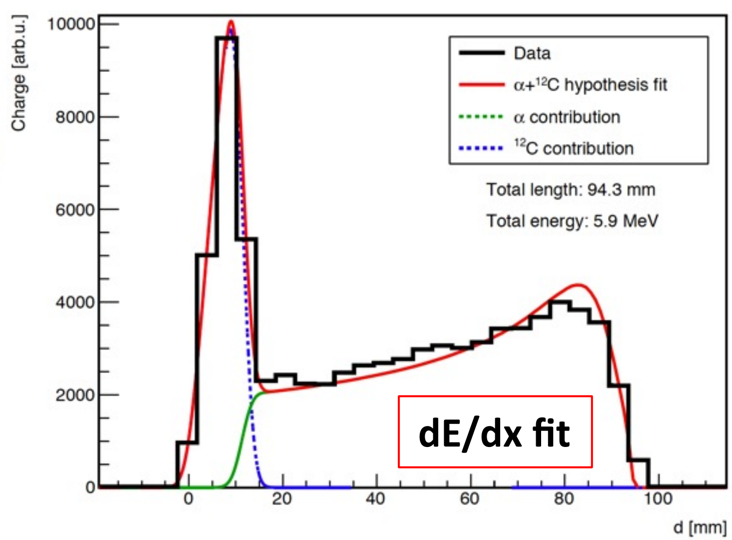
Warsaw TPC

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









E_γ=13.9 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)

A. Kalinowski

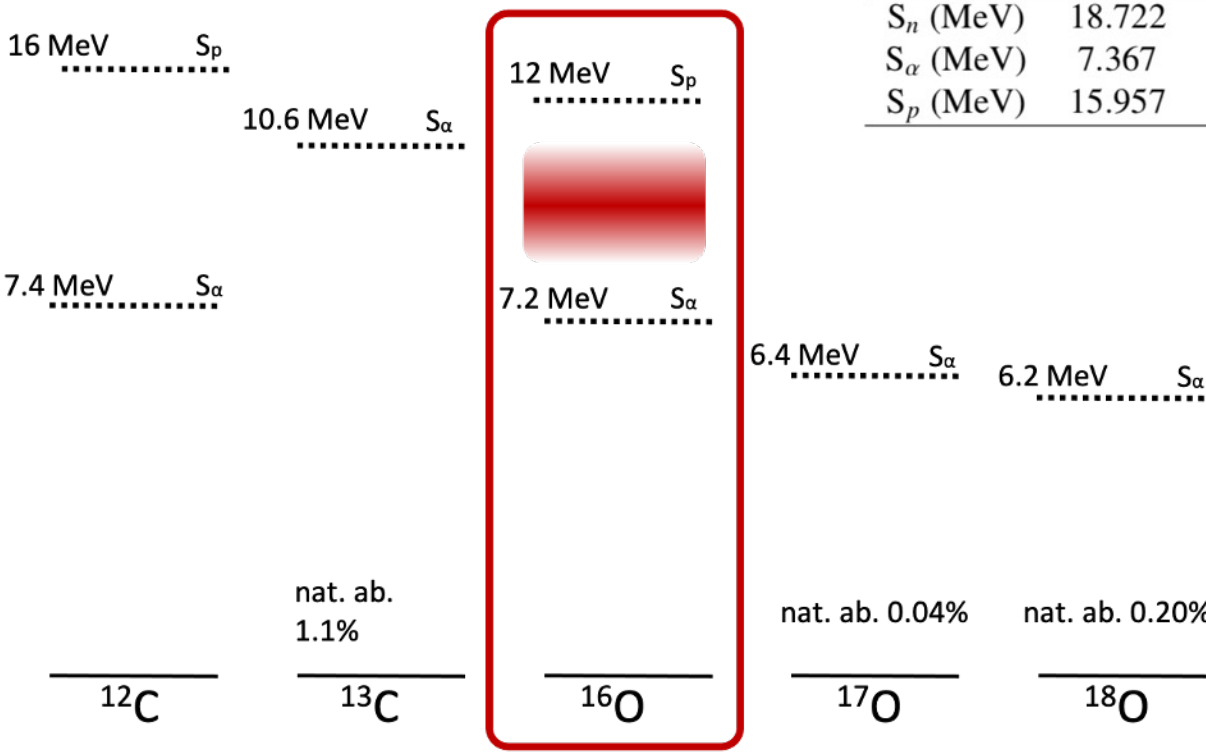
Reaction identification (1/2)

Warsaw TPC

Possible **reaction channels** with gaseous $\mathbf{CO_2}$ **target:**

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

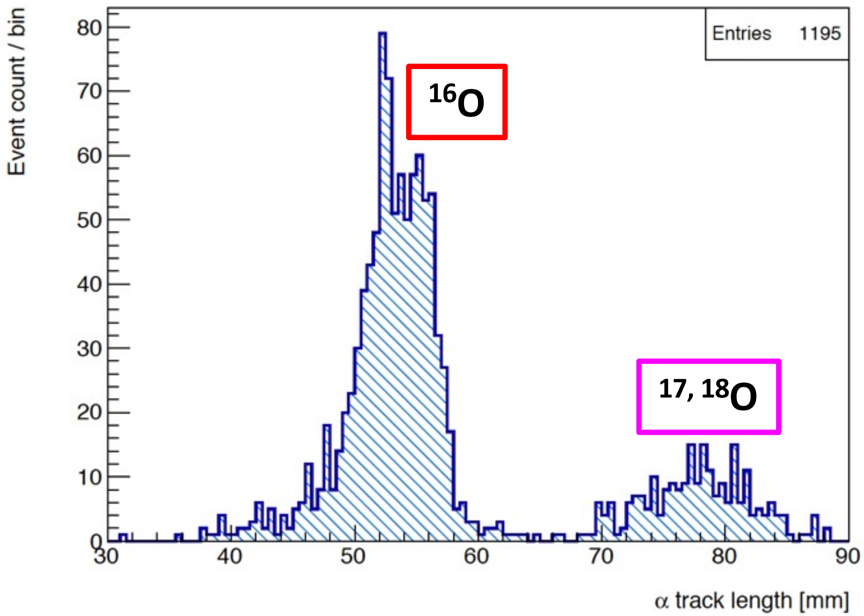
	^{12}C	^{13}C	^{16}O	^{17}O	^{18}O
S_n (MeV)	18.722	4.946	15.664	4.144	8.044
S_α (MeV)	7.367	10.648	7.162	6.359	6.227
S_p (MeV)	15.957	17.533	12.128	13.780	15.942

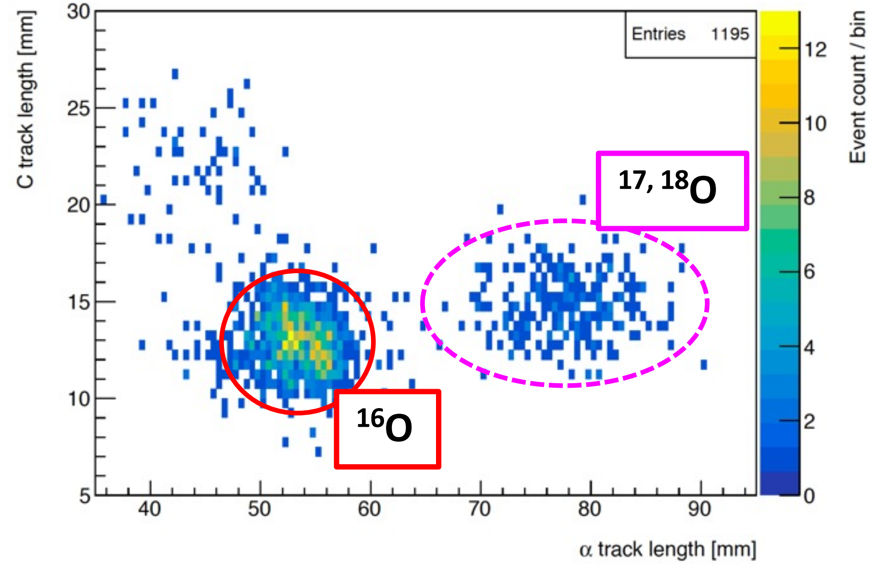


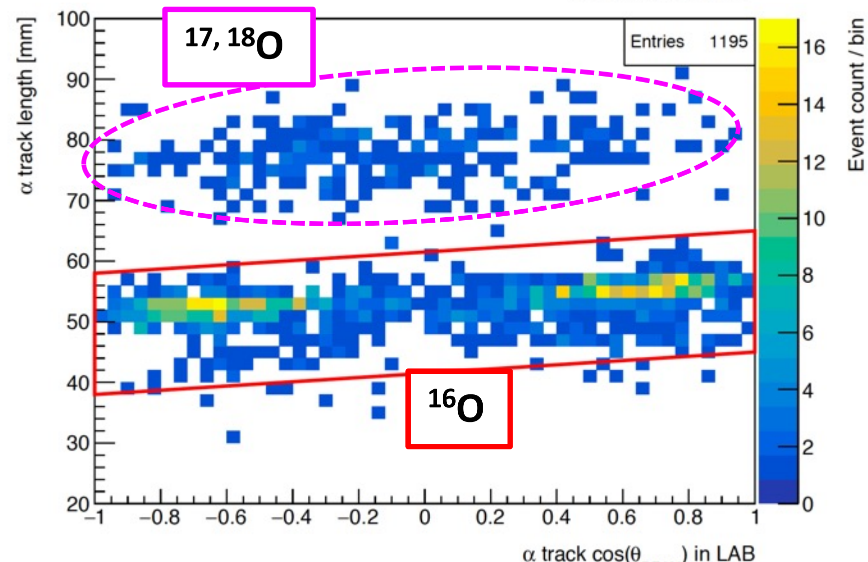
Reaction identification (2/2)

Warsaw TPC

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







E_γ=9.85 MeV

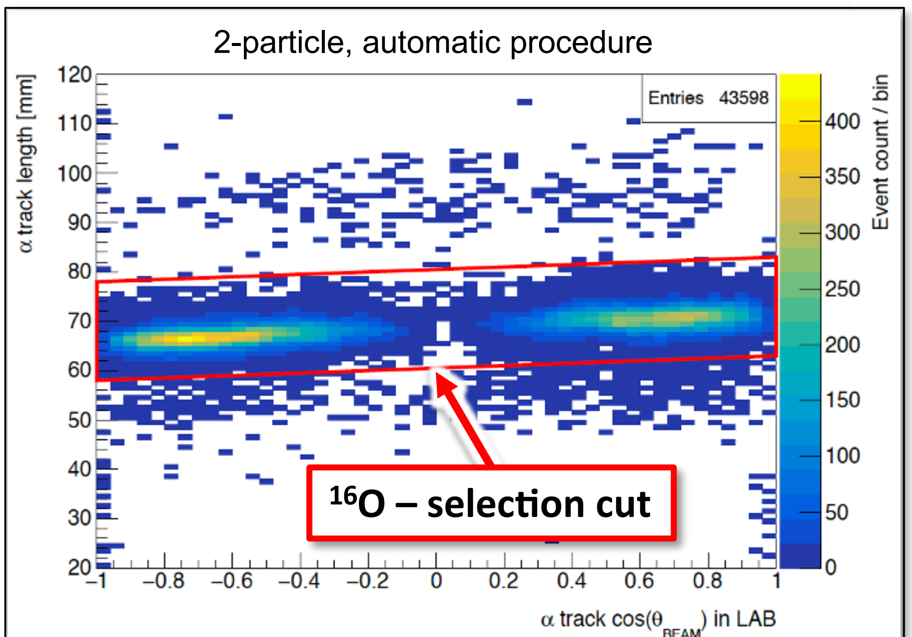
- **Manual procedure**
- 2-particle events
- Pressure: 130 mbar
- Sampling: 25 MHz

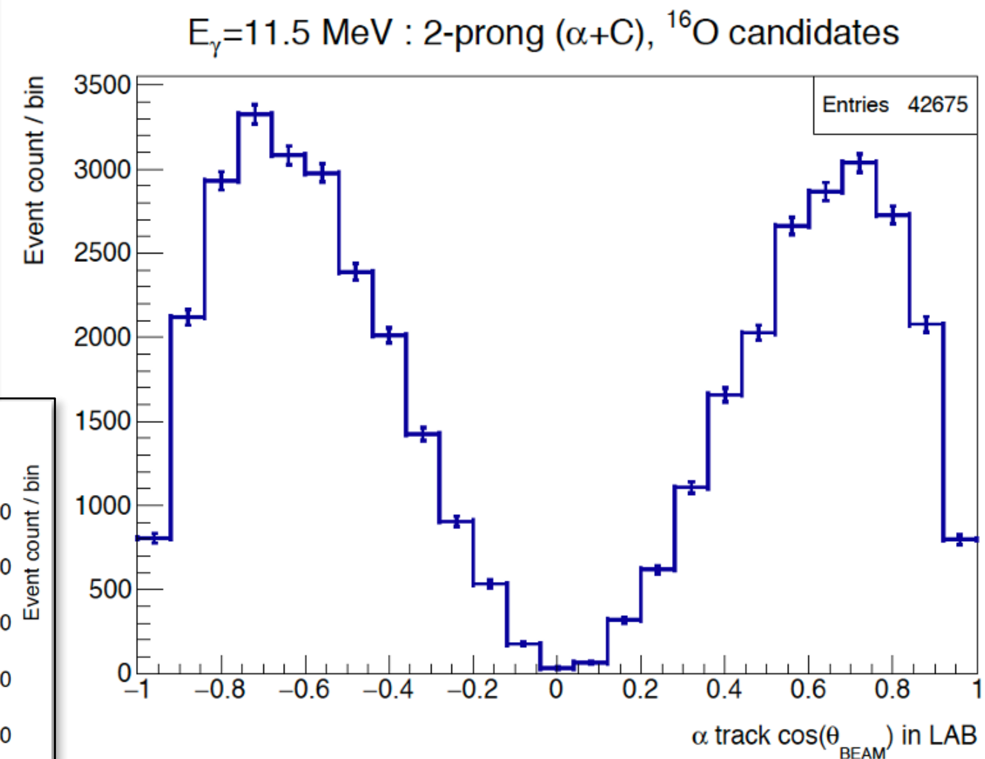
Angular distributions (1/3)

Warsaw TPC

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

E_γ=11.5 MeV



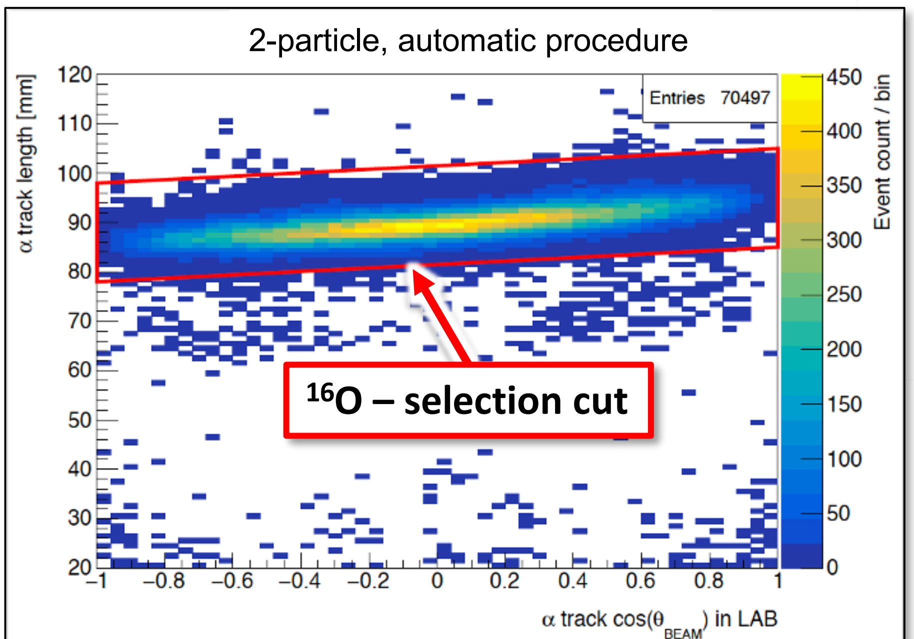


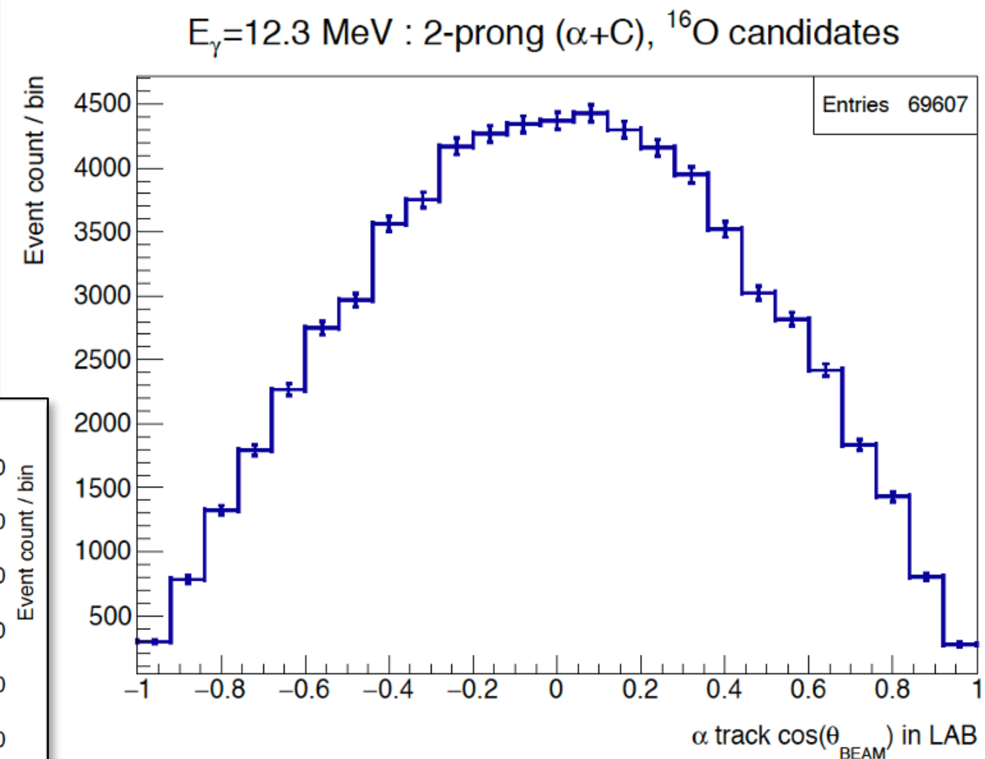
⇒ E2 shape

Angular distributions (2/3)

- Polar angle θ of ^{16}O(γ,α)^{12}C candidate events
- **Automatic procedure**

E_γ=12.3 MeV





⇒ E1 shape

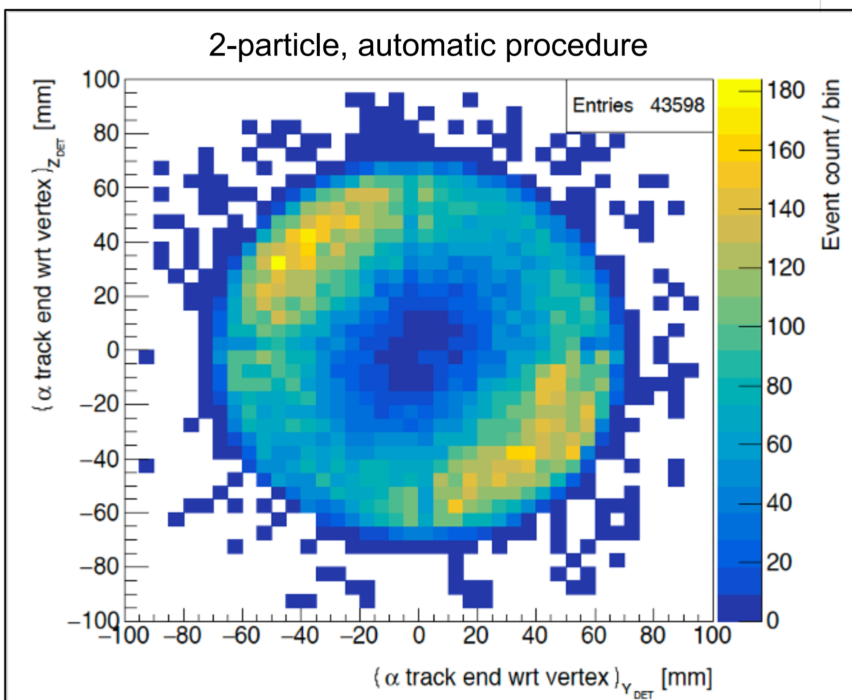
Warsaw TPC

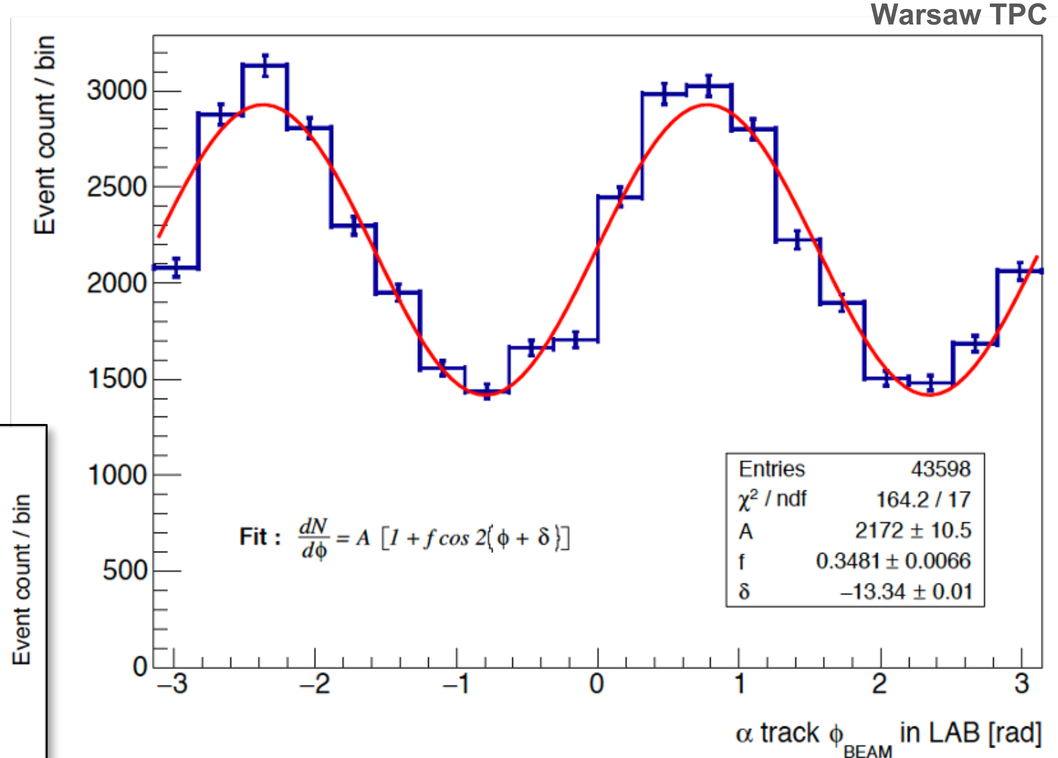
Angular distributions (3/3)

Warsaw TPC

- Azimuthal angle φ of 2-particle events
- **Automatic procedure**

E_γ=11.5 MeV





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

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

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

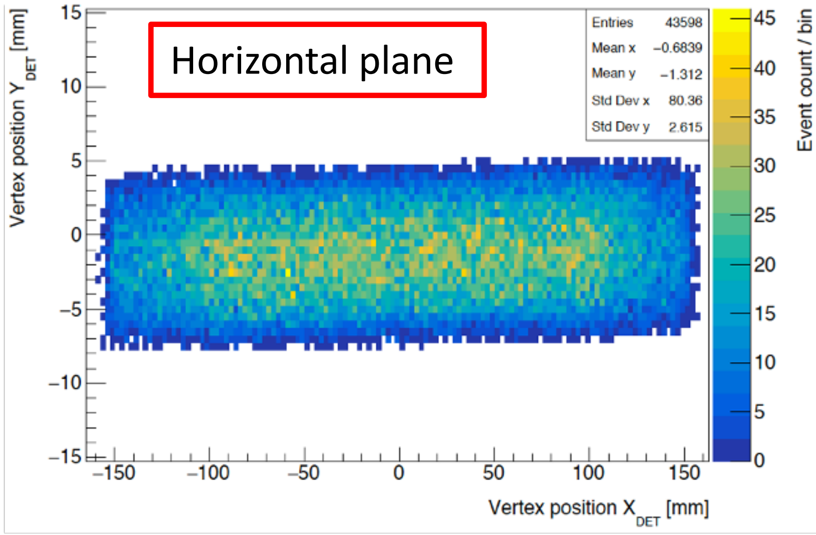
$$W(\phi) = 1 + f \cdot \cos 2(\phi + \delta)$$

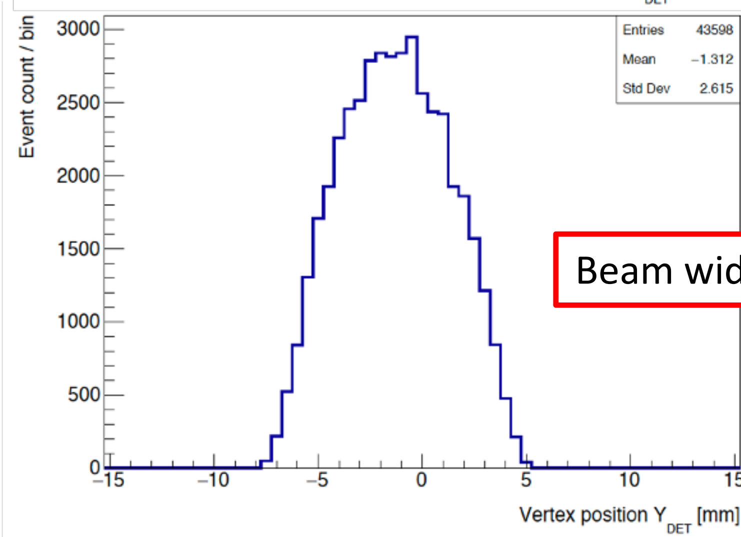
Beam mis-alignment

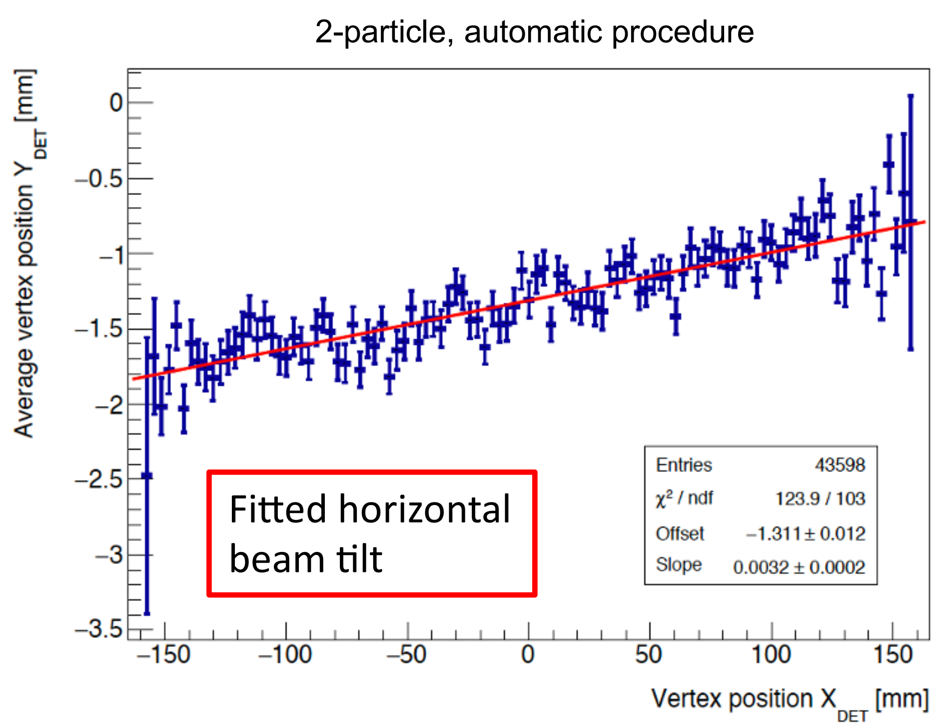
Warsaw TPC

- **Automatic procedure**, distributions of 2-particle reaction vertices:

E_γ=11.5 MeV



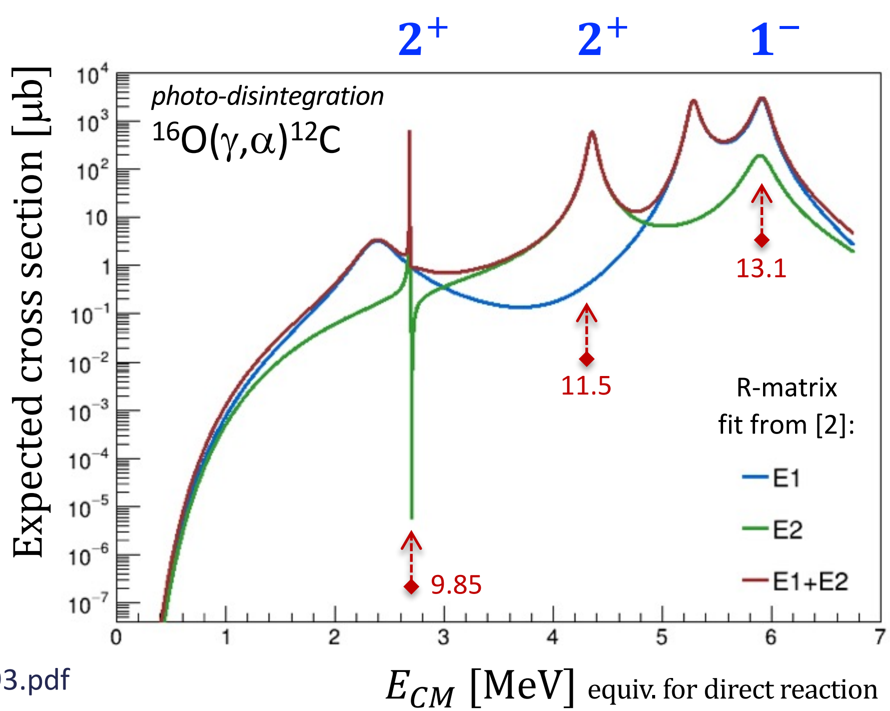




Energy scale calibration (1/3)

Warsaw TPC

- For **$^{16}O(\gamma,\alpha)^{12}C$** it is sufficient to measure kinematics of α-particle only
  - energy can be extracted from $Range(E)$ table or from fitting $\frac{dE}{dx}$ Bragg curve
- Residual biases due to: dE/dx modelling, charge diffusion & vertex/endpoint finding require **fine-tuning of α-particle energy scale** from data:
  - use 3 known resonant states [1]:
    - $2^+ : E_x = 9.8445(5)$ MeV
    - $2^+ : E_x = 11.520(4)$ MeV
    - $1^- : E_x = 13.090(8)$ MeV
  - measure 3 energy points with E_γ spectra <u>centered at</u> respective states
  - separate energy scale corrections are then fitted for manual & automatic reconstruction methods



[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)

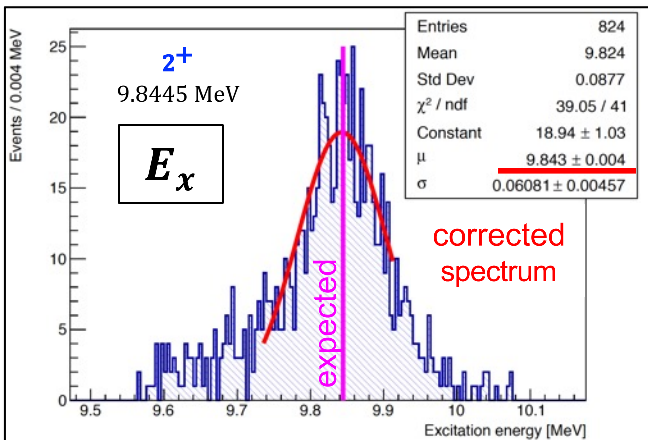
Energy scale calibration (2/3)

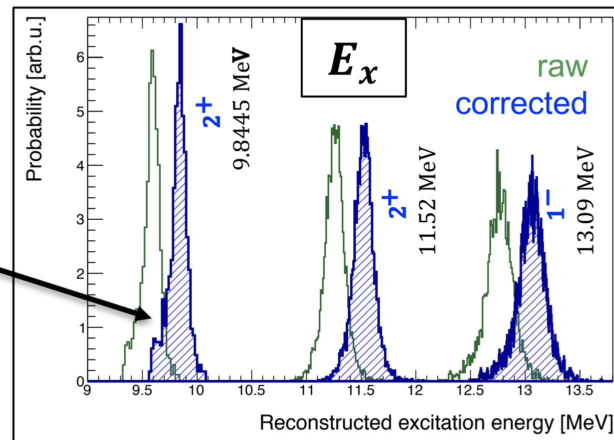
Warsaw TPC

- One of possible parameterizations to correct α-particle energy scale:

$$E_{corr}^{LAB}(\boldsymbol{R_{meas}}) = \boldsymbol{a} \cdot E_{SRIM}\left(R = \left[\boldsymbol{R_{meas}} \cdot \frac{p}{p_0} \cdot \frac{T_0}{T} + \boldsymbol{b}\right]\right)\Big|_{p_0\,,\,T_0}$$

  - where: $\boldsymbol{a}$ = energy scale, $\boldsymbol{b}$ = range offset, $\boldsymbol{R_{meas}}$ = measured α−particle range at given (p, T)
  - $\{\boldsymbol{a}, \boldsymbol{b}\}$ are fitted for best agreement between **expected** and **reconstructed** peak position for **excitation energy ($\boldsymbol{E_x}$)** spectra in CM frame



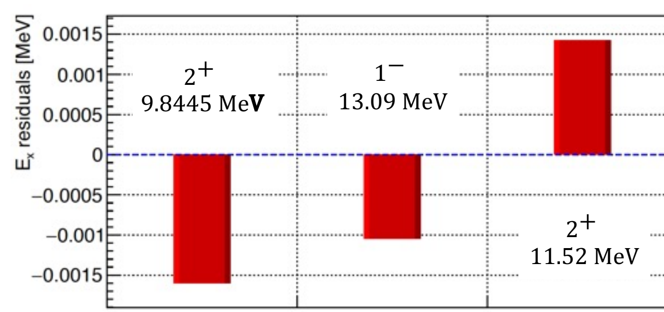


- **Manual procedure**
- ^{16}O candidate events

Fit residuals

RMS = 1.4 keV

|max-min| = 3.0 keV



Energy resolution

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

$\sigma(T_\alpha) \approx$ 45 keV @ T_α = 2 MeV

Energy scale

$$\begin{cases} \boldsymbol{a} = 1.035(7) \\ \boldsymbol{b} = 1.64(24)\ mm \end{cases}$$

Energy scale calibration (3/3)

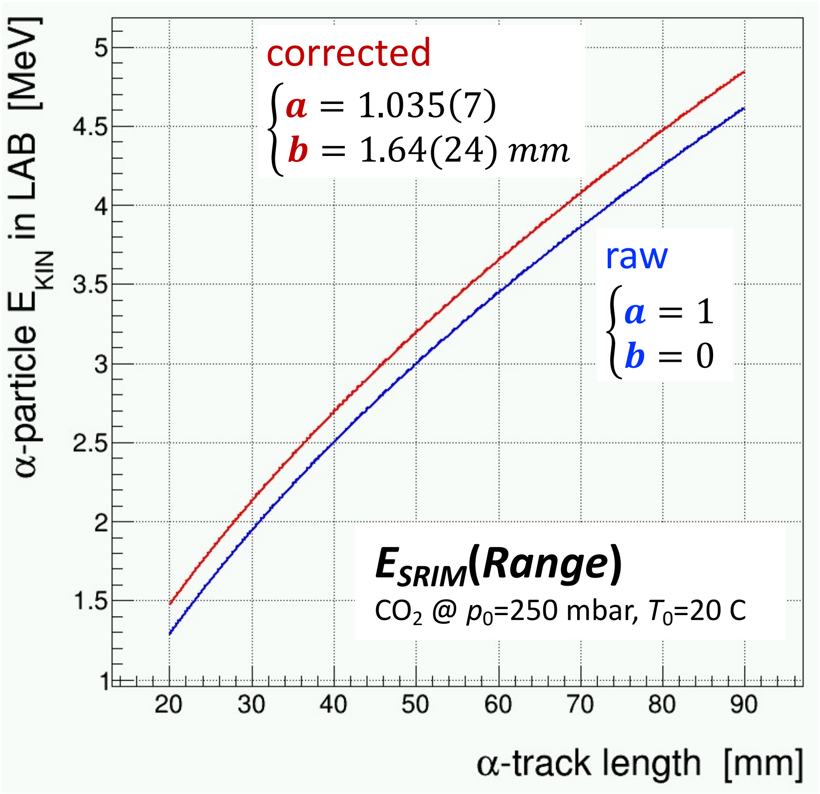
Warsaw TPC

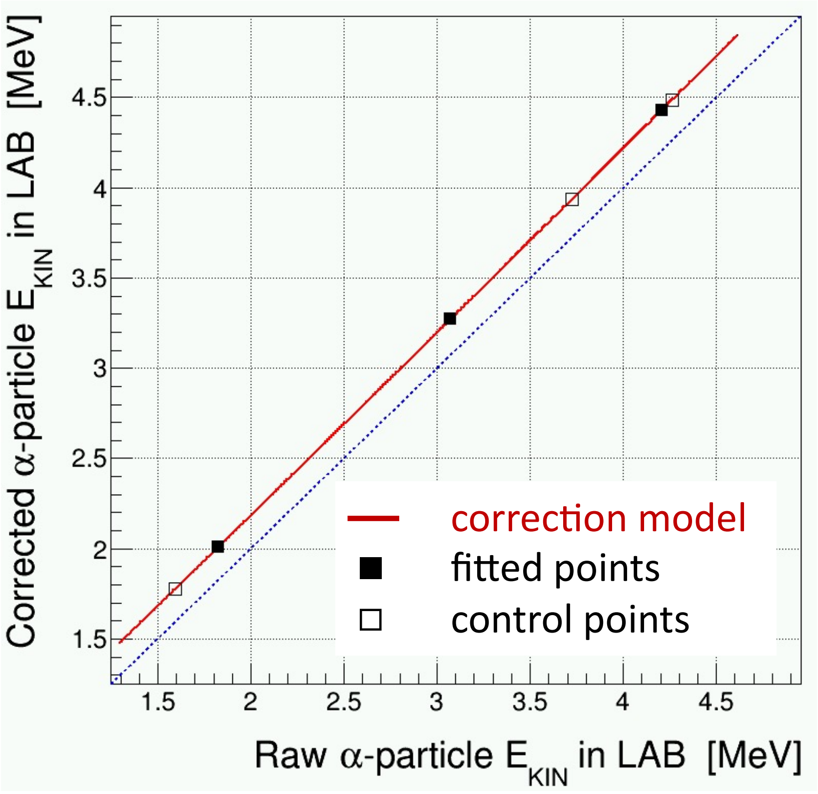
- 2-parameter correction model for α-particle energy from SRIM range:

$$E_{corr}^{LAB}(R_{meas}) = a \cdot E_{SRIM}\left(R = \left[R_{meas} \cdot \frac{p}{p_0} \cdot \frac{T_0}{T} + b\right]\right)\Big|_{p_0, T_0}$$

where: a = energy scale, b = range offset,
R_{meas} = measured α−particle range at given (p, T)

- **Manual procedure**
- ^{16}O candidate events





Data analysis flow

Warsaw TPC

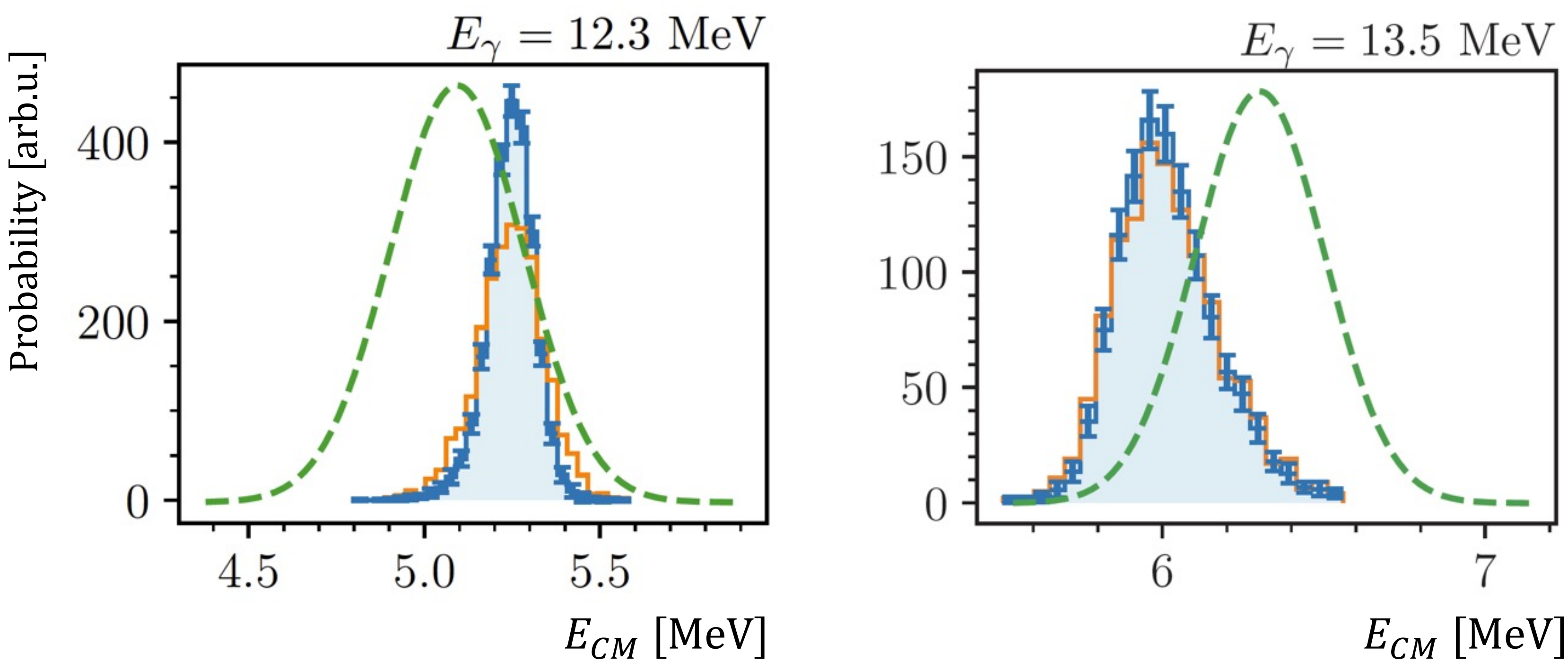
1. **Event-by-event classification:**
   - 1, 2 or 3 charged particles, "dots", e-m interactions
2. **Track finding:**
   - interaction vertex in 3D
   - lengths & directions of all tracks in 3D
3. **For "2-particle" event category apply:**
   - detector fiducial cuts
   - $^{16}O(\gamma,\alpha)$ identification cuts
   - range-to-energy conversion (with α-particle energy scale calibrated from real data)
   - Lorentz boost of particle momenta from LAB to CM frame
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}

Unfolded energy distributions

Warsaw TPC

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

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



original TPC spectrum

unfolded TPC spectrum assuming resolution of $\sigma(E_{CM})$=67 keV

E_{CM} corresponding to unfolded E_γ spectrum from HPGe

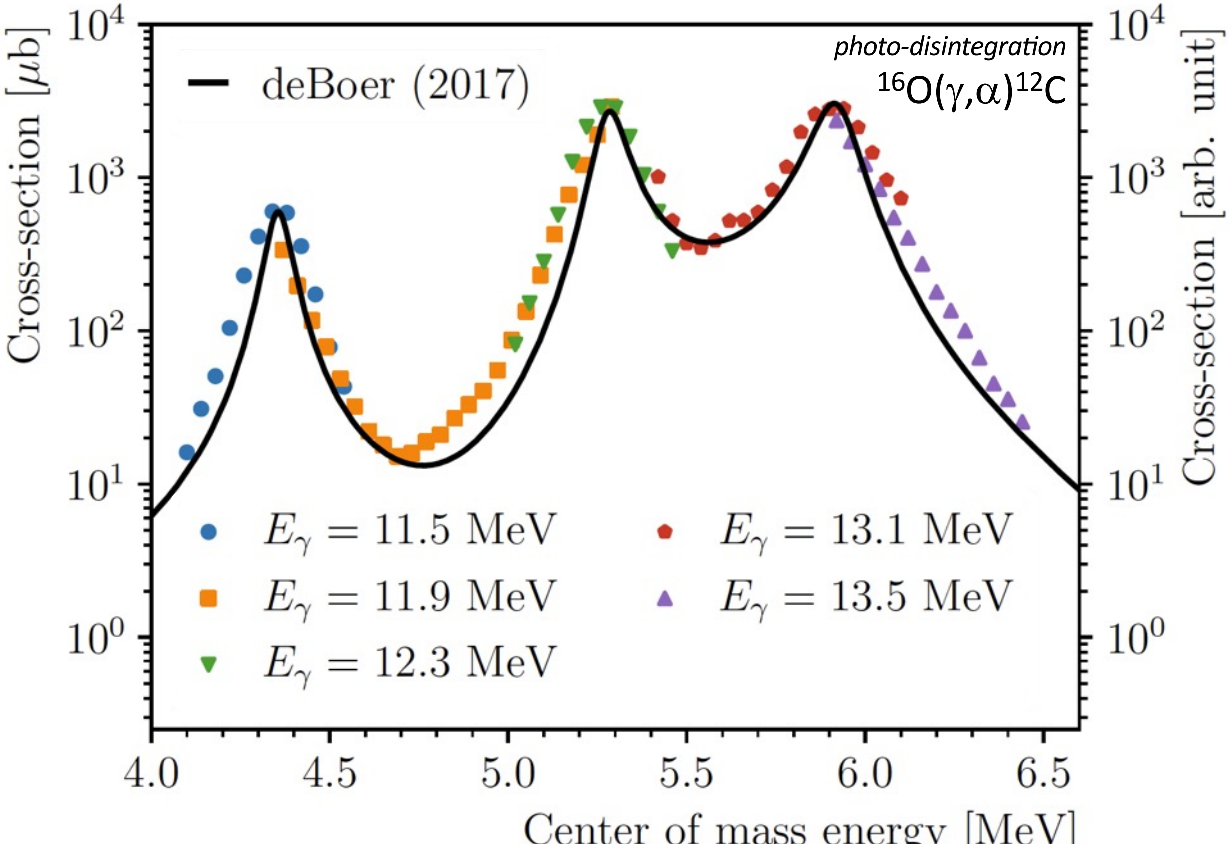
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

Relative E1+E2 cross section

Warsaw TPC

Unfolded TPC spectrum divided by γ-ray beam spectrum:

- **manual procedure**, $^{16}O(\gamma,\alpha)^{12}C$ candidate events
- combined 5 beam energy runs using overlapping energy bins
- resulting stitched curve normalized to R-matrix prediction at single point
- information about absolute γ-beam intensity is not used



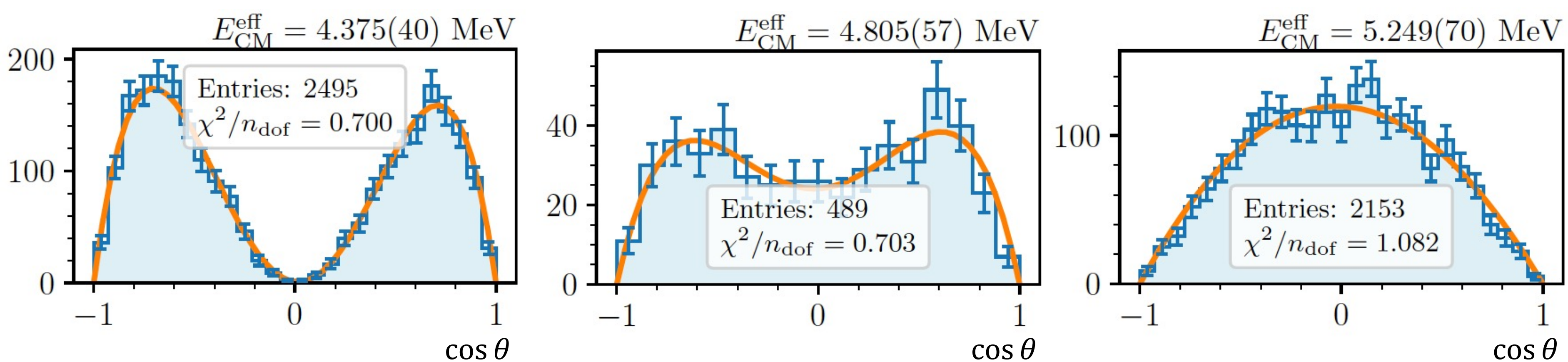
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

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

E1 / E2 multipolarity (1/3)

Warsaw TPC

- **Distributions of polar angle θ_{CM} of α-particles:**
  - **manual procedure**, $^{16}O(\gamma,\alpha)^{12}C$ candidate events
  - corresponding to effective energy of 10 arbitrary E_{CM} bins (results for 3 bins are shown below)
- **Fit:** $\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}\{\sigma_{E1}W_{E1}(\cos\theta) + \sigma_{E2}W_{E2}(\cos\theta) + \sqrt{\sigma_{E1}\sigma_{E2}}\cos\varphi_{12}\,W_{12}(\cos\theta)\}$
  - W_{E1}, W_{E2}, $W_{12}(x)$ expressed by Legandre 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}	$1.4^{+0.1}_{-1.4}$

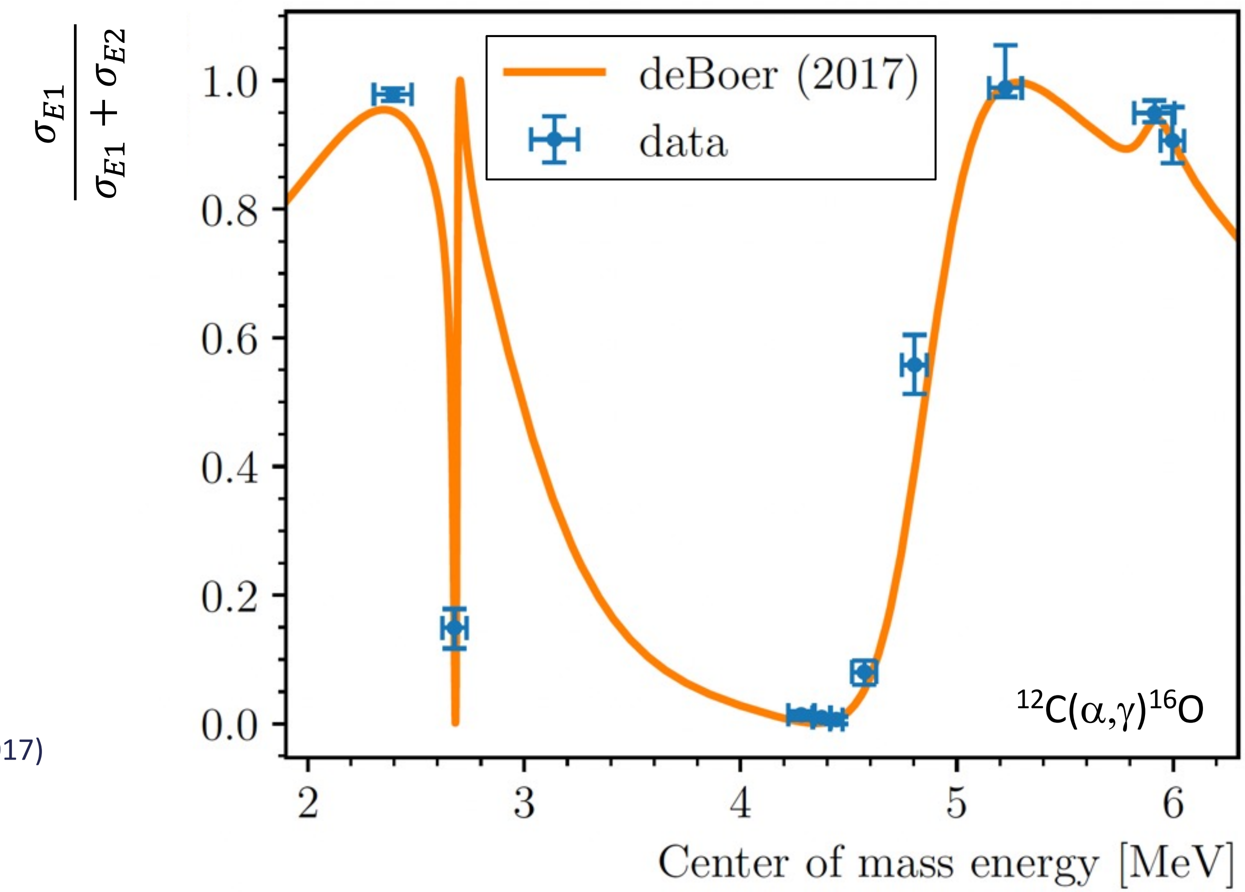
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

E1 / E2 multipolarity (2/3)

Warsaw TPC

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

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



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

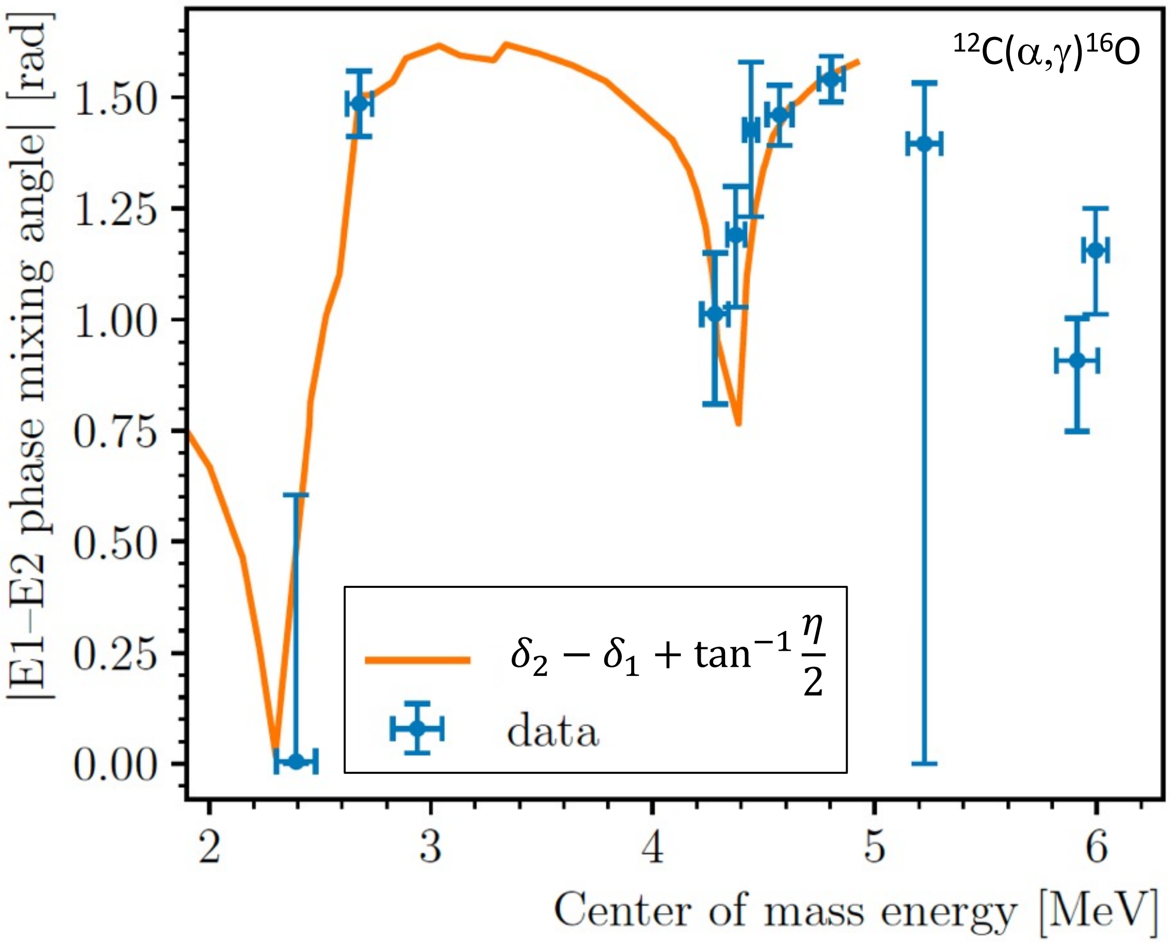
R-matrix fit:
Rev. Mod. Phys. 89, 035007 (2017)

E1 / E2 multipolarity (3/3)

Warsaw TPC

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

- **manual procedure**, $^{16}O(\gamma,\alpha)^{12}C$ 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

Warsaw TPC

- First results from $^{16}O(\gamma,\alpha)$ photo-disintegration experiment at HIγS:
  - recent publications: EPJ Web of Conf. **279**, 04002 (2023), EPJ Web of Conf. **290**, 01004 (2023), Il Nuovo Cimento **48 C**, 17 (2025)
  - 1 PhD thesis defended: Mateusz Fila (Univ. of Warsaw, 2024)
  - 3 PhD dissertations in preparation (expected by end of 2025)
  - processing full statistics requires better automated reconstruction:
    - work is under way on improving automated track finding algorithms & better physics analysis tools (UW, UConn, SHU)
    - also trying Machine Learning approach for event categorization & track finding

- Future plans:
  - summer 2026: next experiment at HIγS has been approved by the PAC using Warsaw TPC & increased gamma beam intensity
    - explore E_{CM}~1 MeV region of $^{16}O(\gamma,\alpha)$ reaction
  - looking forward for even more intense γ-ray source in the ELI-NP facility (Magurele, Romania)

Part 1 : List of publications

Warsaw TPC

[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)

Part 1 : Collaboration

Warsaw TPC

Experimental team – HIγS '2022:

M. Ćwiok, W. Dominik, A. Fijałkowska, M. Fila, Z. Janas, A. Kalinowski, K. Kierzkowski, M. Kuich, C. Mazzocchi, W. Okliński, P. Podlaski, M. Zaremba, R. Dąbrowski, H. Czyrkowski

Faculty of Physics, University of Warsaw, Poland

M. Gai, S. Stern, D. Schweitzer

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

D.L. Balabanski, C. Matei, A. Rotaru

IFIN-HH / ELI-NP, Bucharest-Magurele, Romania

K. Haverson, R. Smith

Sheffield Hallam University, UK

R. Allen, M.R. Griffiths, S. Pirrie, P. Santa Rita Alcibia

University of Birmingham, School of Physics and Astronomy, UK

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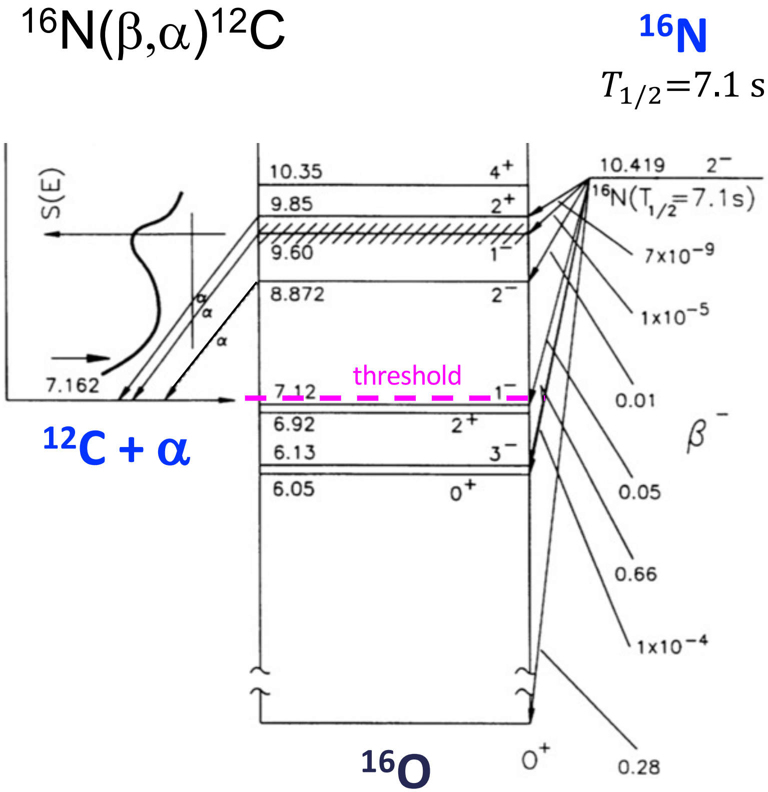
Special thanks to teams from Duke University and University of North Carolina at Chapel Hill.

Part – 2

TPC for radioactive-ion (RI) beams

Nuclear Astrophysics with RI beams

- ^{12}**C(α,γ)**^{16}**O** reaction can probed via **β-delayed α decay of** ^{16}**N**



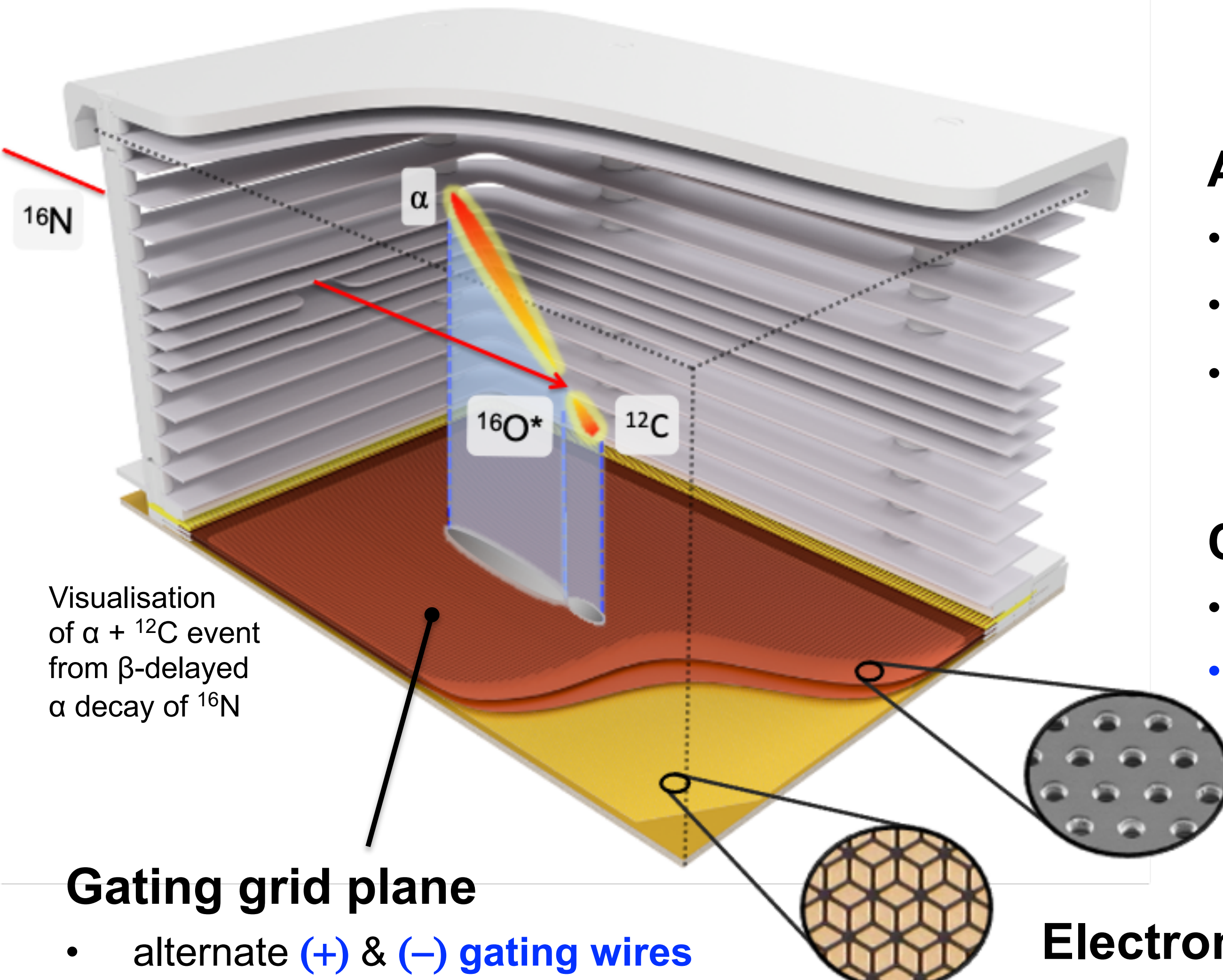
R. Azuma et al., Phys. Rev. C **50**, 1194 (1994)

Experimental approach:

- Use TPC as a stopping cell:
  - operate below electron detection threshold
  - reconstruct kinematics of α-particles from ^{12}C + α events
  - 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 before switching TPC from "blocked" to "active" mode

Adaptations for RI beam

Warsaw TPC



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

Active volume

- readout: **330 x 200 mm^2**
- drift length: **200 mm**
- low-pressure gas: TBD

Charge amplification

- 2-stage only
- **thicker 125-μm GEMs**

Gating grid plane

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

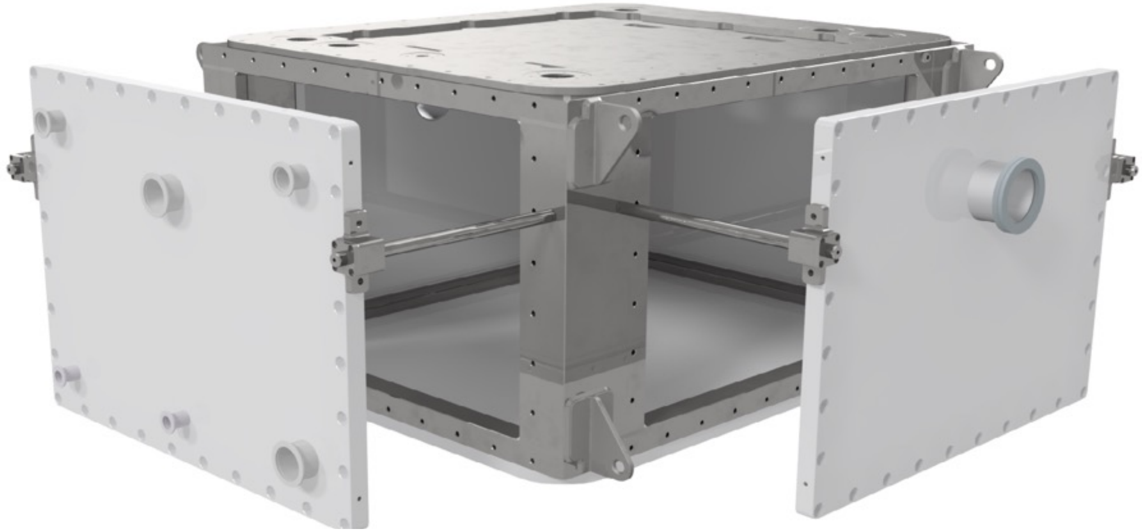
Electronic readout

- same UVW segmentation
- same GET front-end electronics

Adaptations for RI beam

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

Warsaw TPC

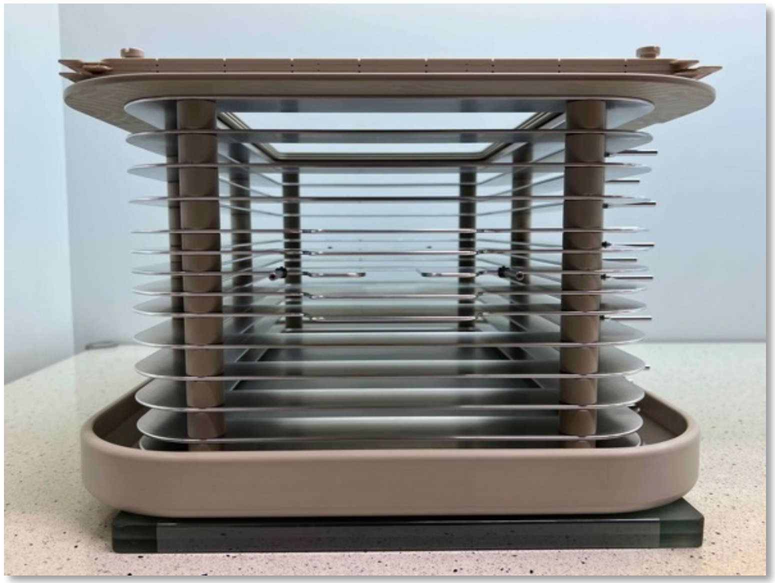


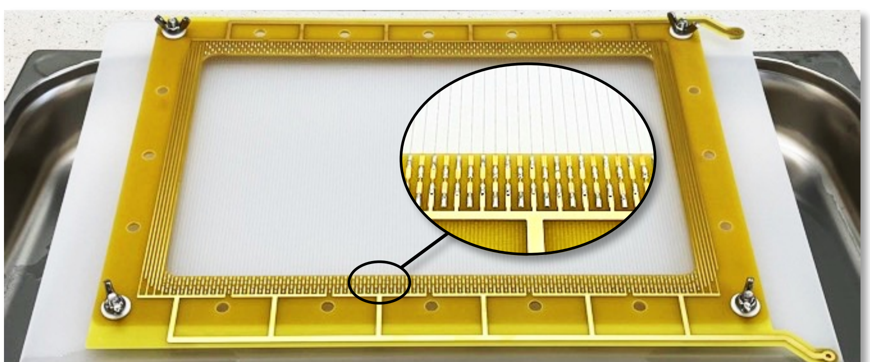
Section view of internal TPC structure

- Drift cage accepts beam spots up to 28 x 18 mm^2
- Aluminium hollow field-shaping electrodes & solid plate cathode

Status of assembly

Warsaw TPC





- Left: components of TPC internal structure
- Right: vacuum vessel with removed top lid

Part 2 : Summary & Outlook

Warsaw TPC

- Working on the next generation TPC detector optimized for, both, neutral- and radioactive ion beams:
  - acronym **WING TPC** (**W**arsaw **I**on **N**eutron **G**amma **TPC**)
  - to be equipped with:
    - two–stage amplification with thicker GEMs
    - gating grid with HV pulser
    - same UVW readout structure (can use existing analysis & Monte Carlo framework)
  - currently performing final integration tests & cleaning before final assembling

- Future plans:
  - preparing grant application for studying $^{12}C(\alpha,\gamma)$ via β-delayed α decay of ^{16}N (radioactive-ion beam mode) using next generation **WING TPC**

Thank you for your attention !!!