First results on ^{16}O photo-disintegration studies at HIγS with the Warsaw TPC

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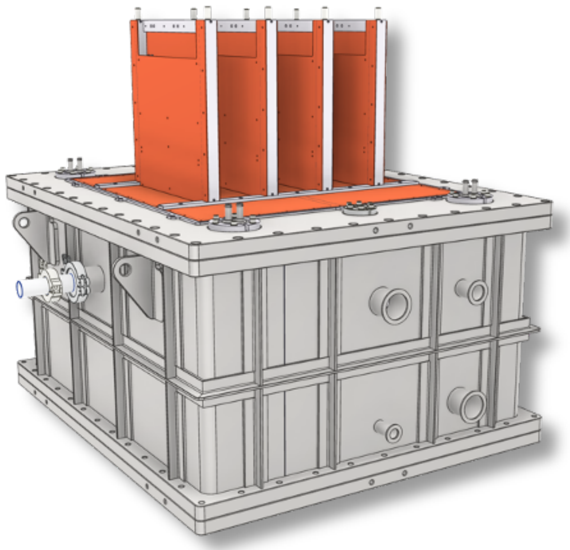
(on behalf of the Warsaw TPC collaboration)

UNIVERSITY OF WARSAW

FACULTY OF PHYSICS



ISNS 24

International Symposium on Nuclear Science

September 9-13, 2024 – Sofia, Bulgaria

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*

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

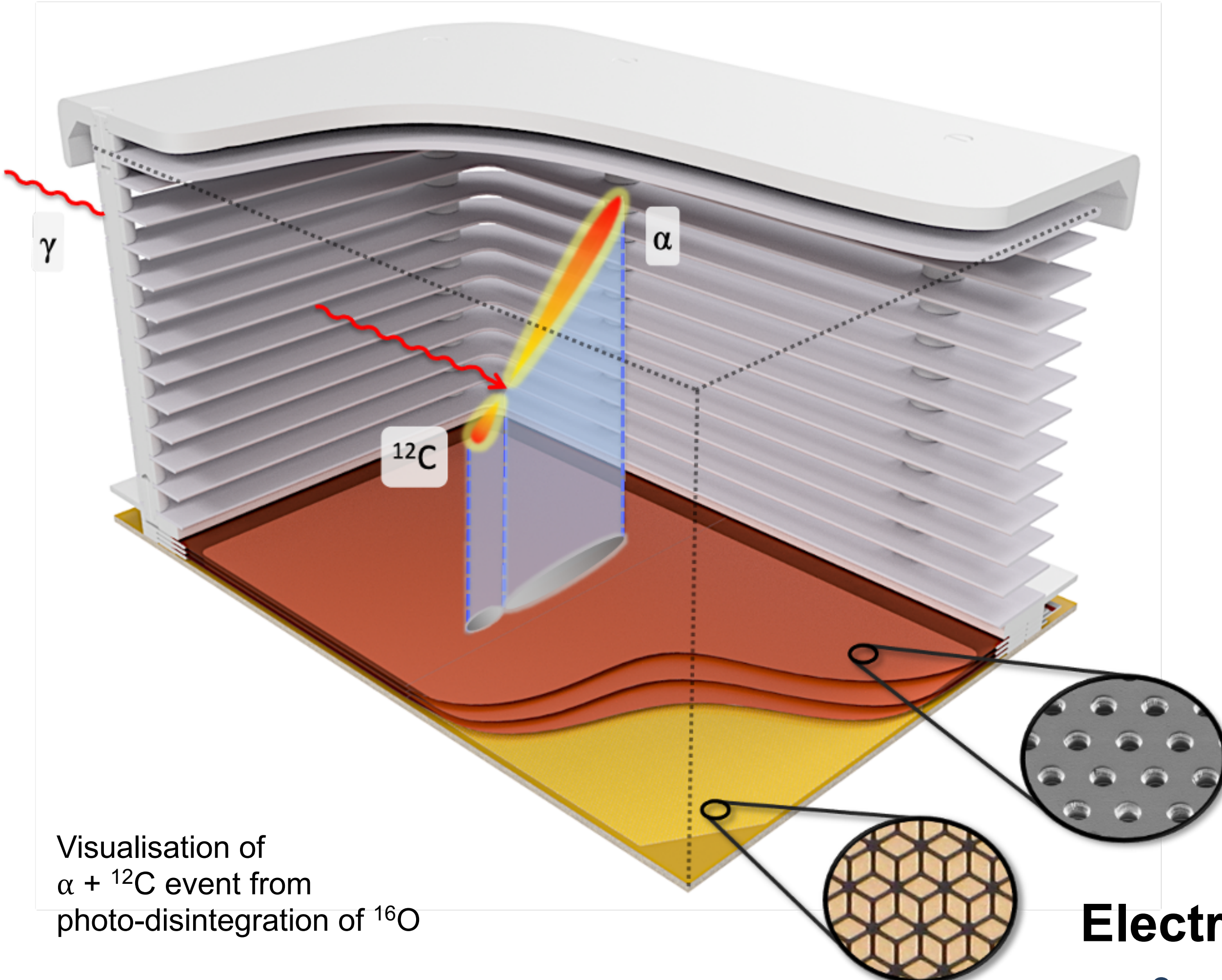
$$\sigma_{b\gamma} = \sigma_{\gamma b} \cdot \frac{g_{\gamma b}}{g_{b\gamma}} \cdot \frac{p_{\gamma b}^2}{p_{b\gamma}^2} =$$

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

- 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

Detection technique



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

EPJ Web of Conferences 290, 01004 (2023)

Active volume:

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

Charge amplification:

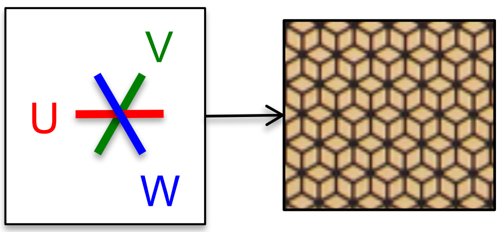
- Micro-Pattern Gas Detector
- 3 layers of 50-μm thick **Gas Electron Multiplier** foils (GEM)

Electronic readout:

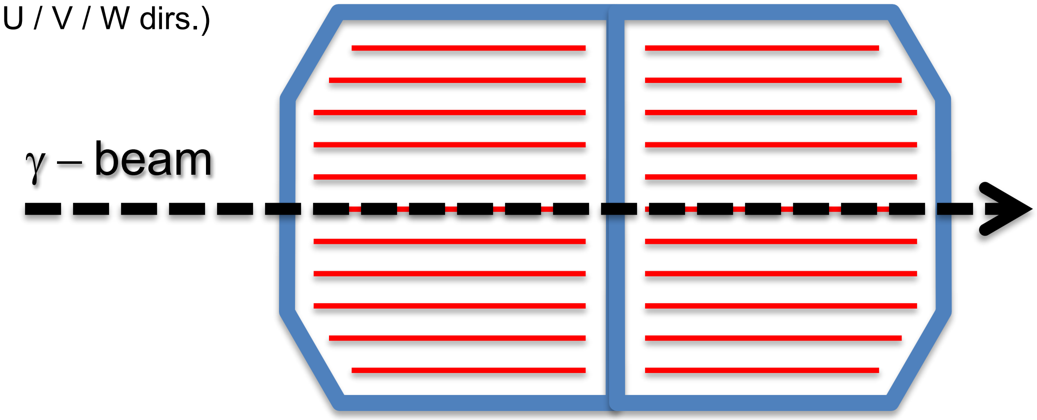
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

Detector readout concept

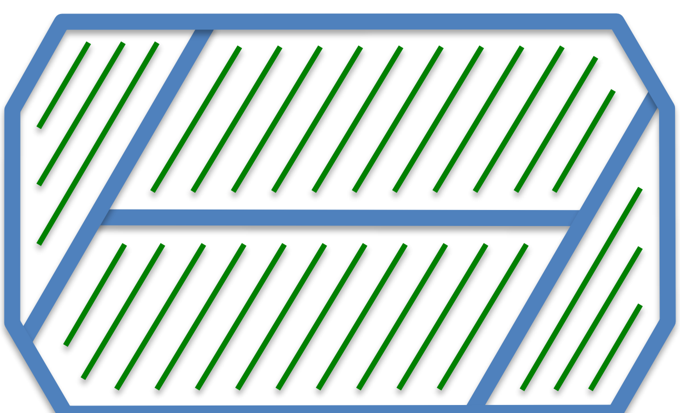
- **1018 strips** in total
- 1.5 mm strip pitch (in each of U / V / W dirs.)



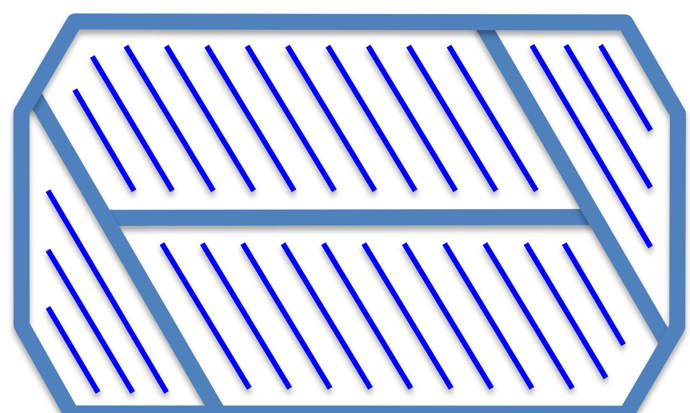
264 U-strips (2 sections)



376 V-strips (4 sections)



378 W-strips (4 sections)

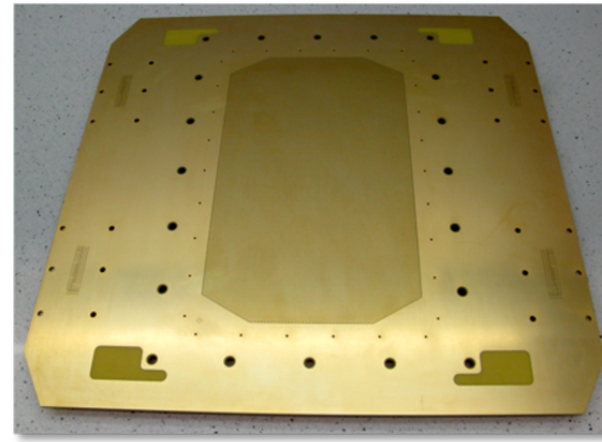


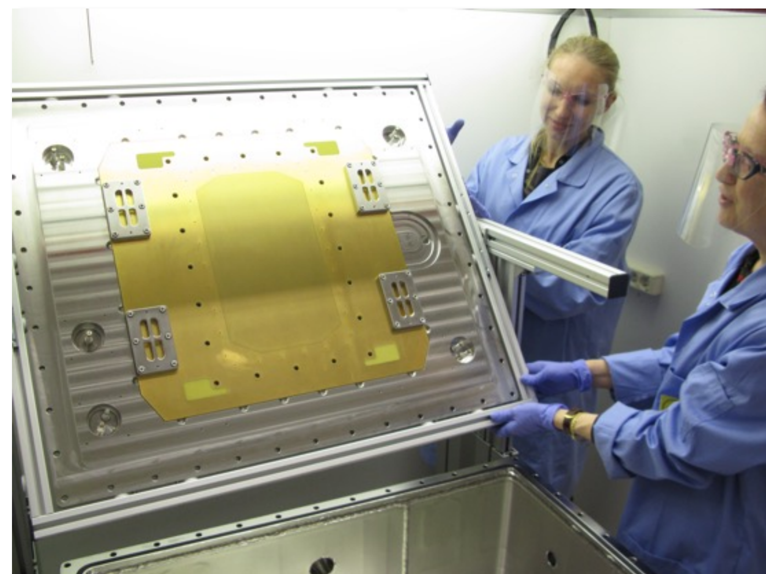
Warsaw TPC

Warsaw TPC detector

Warsaw TPC

- **2013:** started R&D programme on (γ,α) aimed at intense γ-ray beams from future ELI-NP facility
- **2020:** built full-scale demonstrator (Warsaw TPC)
- **2021:** first experiments with proton beam and neutron source @ INP PAS, Cracow, Poland

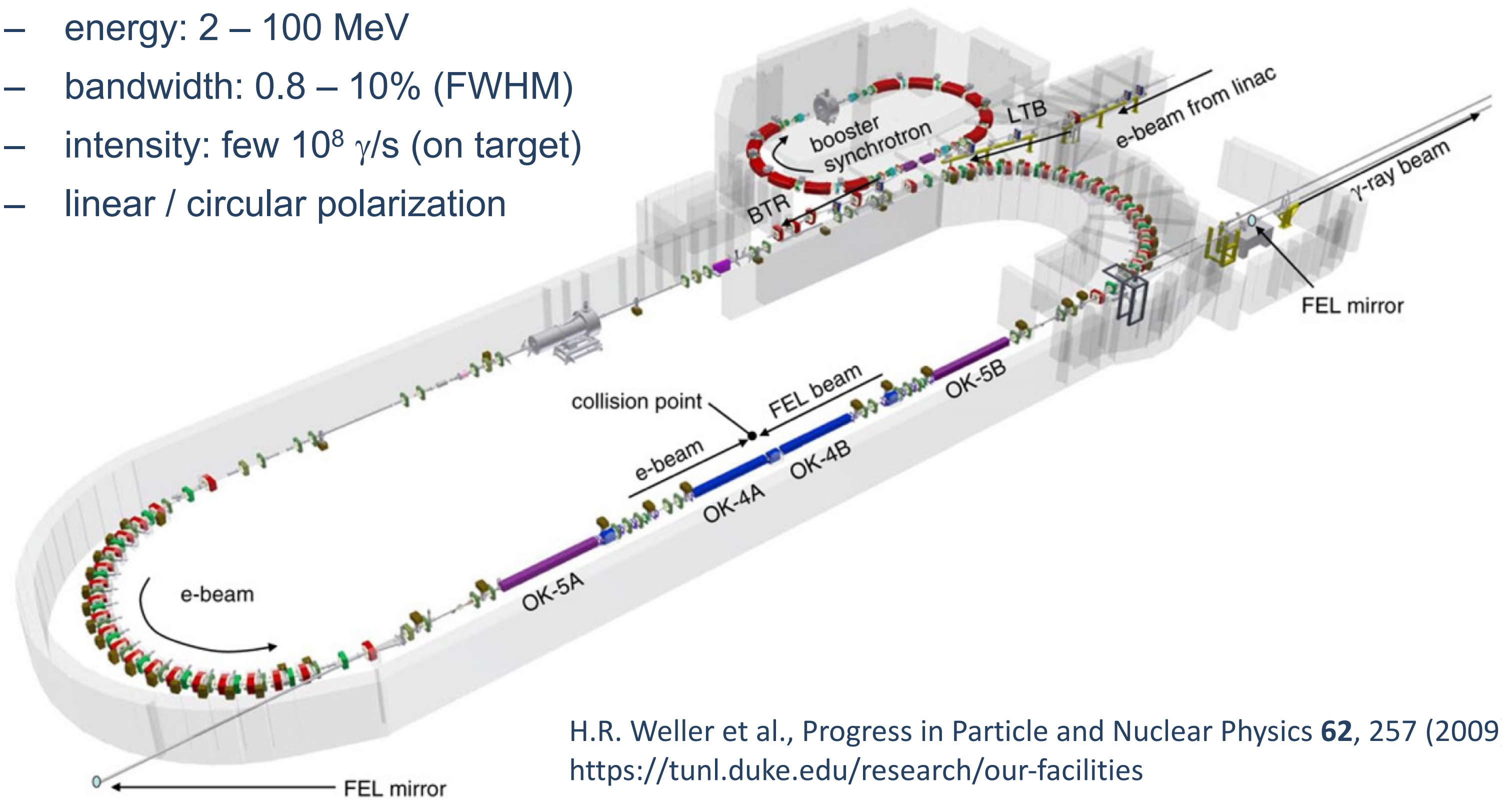




^{16}O photodisintegration experiment @ HIγS

(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)

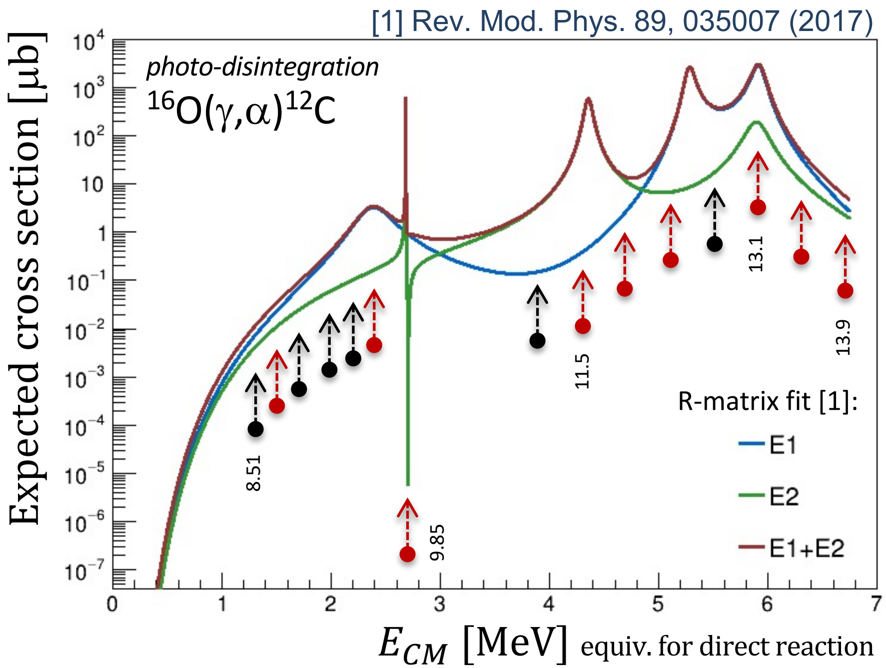
Warsaw TPC

- **Delivered γ-ray beams:**
  - 275 hours / 15 energy points
  - beam collimator: Ø10.5 mm
  - **E_γ nominal : 8.51 – 13.9 MeV**
    $\Leftrightarrow E_{CM}$: 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)**

Collected statistics

Warsaw TPC



Measured 15 beam energy points:

- 3 gas target densities (p_1 p_2 p_3)
- 3 resonant energies used for tuning reconstructed track energy scale (E)
- this talk covers partial statistics from 9 energy points (%)

Nominal E_γ [MeV]	8.51	8.66	8.86	9.16	9.36	9.56	9.85	11.1	11.5	11.9	12.3	12.7	13.1		13.5	13.9
Gas pressure [mbar]	130							190						250		
Events incl. bkg [$\times 10^3$]	55	239	187	64	58	34	88	160	248	168	254	314	201	412	568	528
Analysed fraction [%]	–	4	–	–	–	46	37	–	4	9	2	–	10	–	3	3

Analysis flow

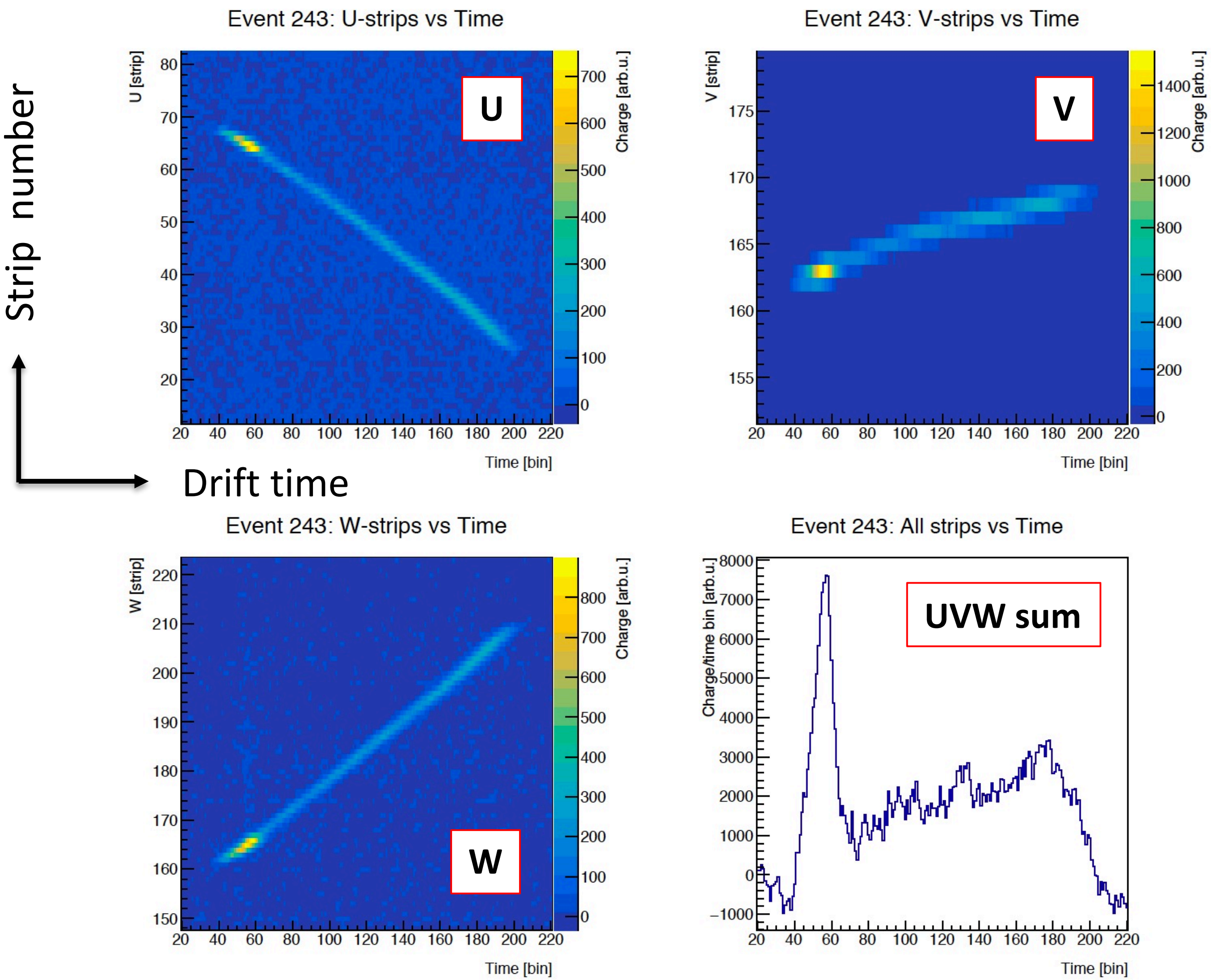
Warsaw TPC

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 events 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 momenta from LAB to CM frame
4. **Distributions in CM frame:** (corresponding to incident γ-ray beam energy profile)
   - 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}

Example raw data

Warsaw TPC

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



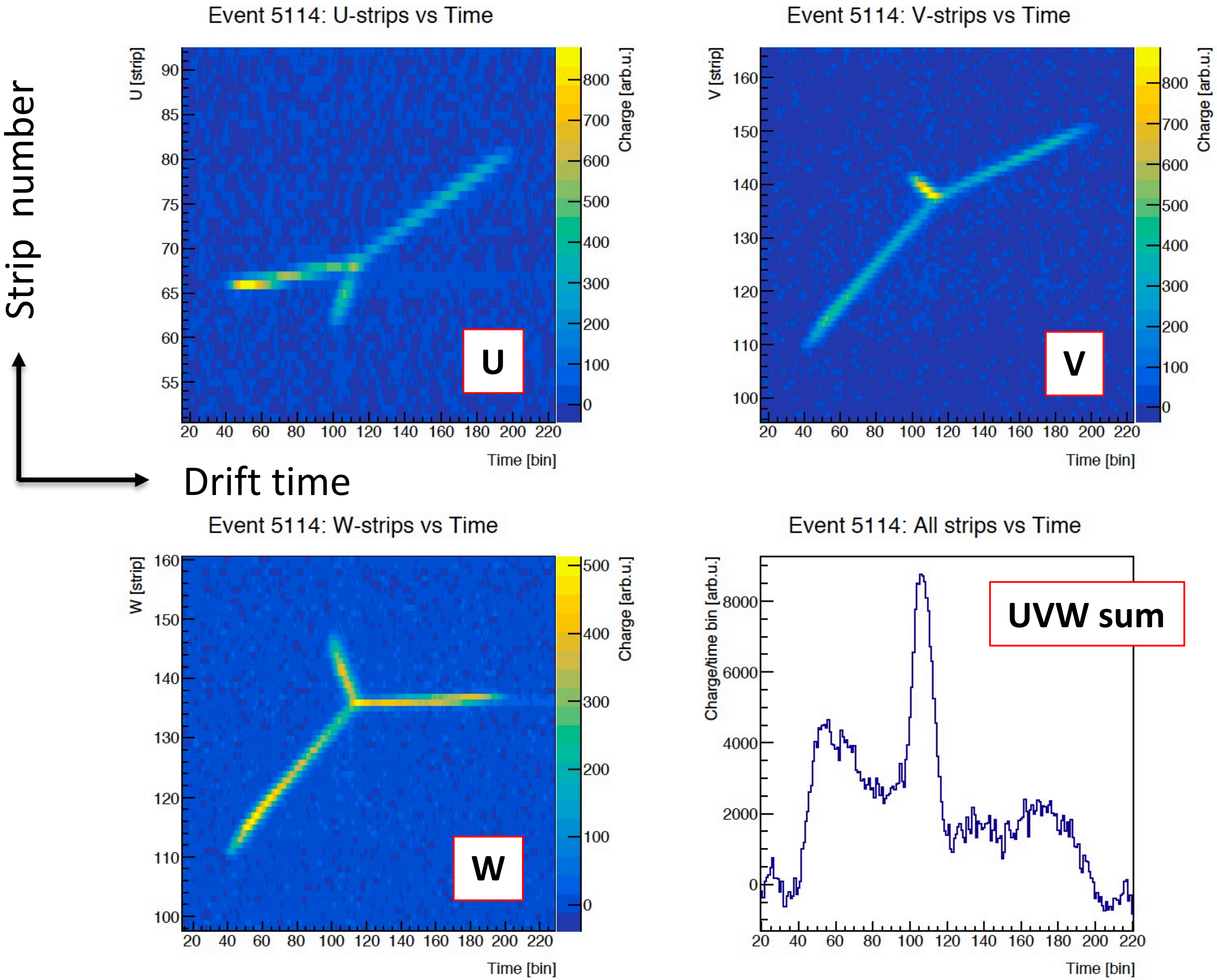
E_γ=13.9 MeV

- 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



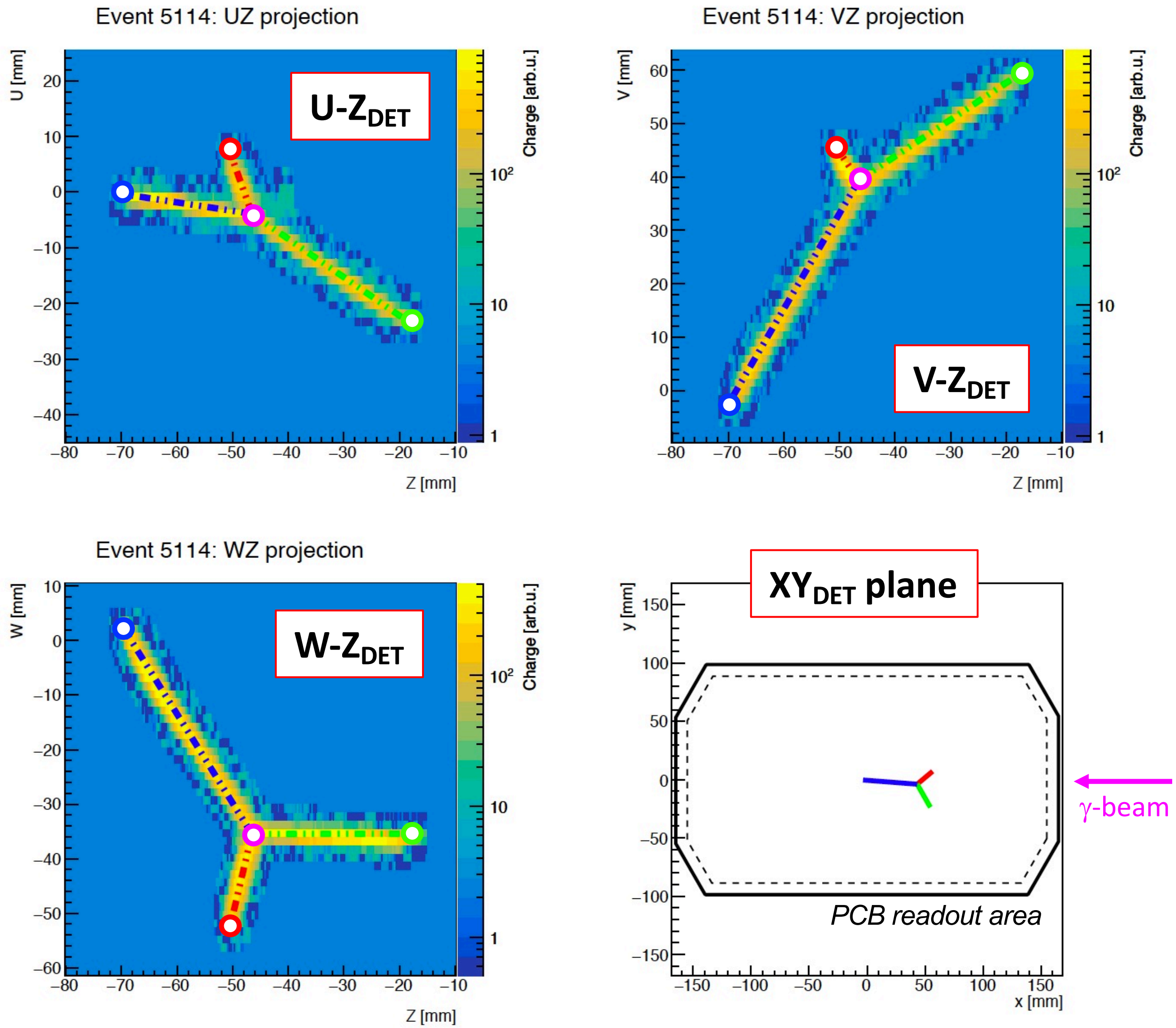
E_γ=13.9 MeV

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

Track finding

Warsaw TPC

3-particle topology: reconstructed α tracks in 3D



E_γ=13.9 MeV

- Pressure: 250 mbar
- Sampling: 12.5 MHz

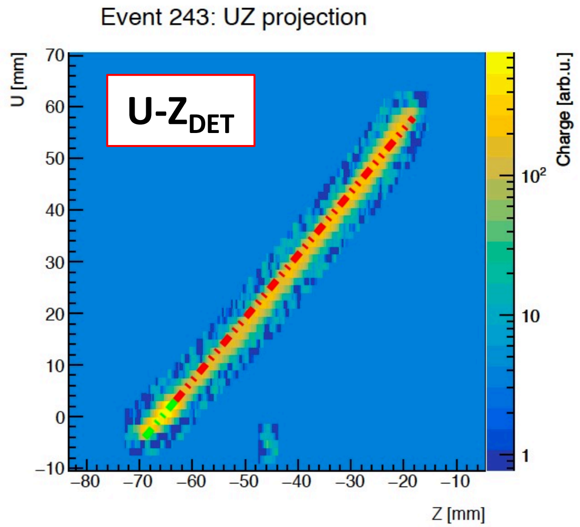
- Manual procedure for 1/2/3-particle topology *(current default)*
- Vertex & track ends selected by expert

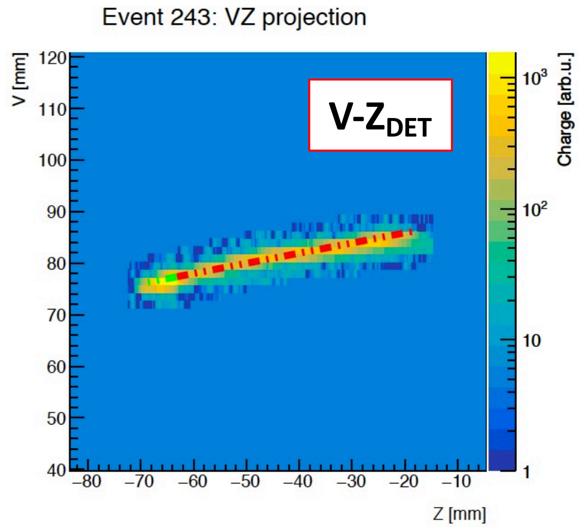
A. Kalinowski

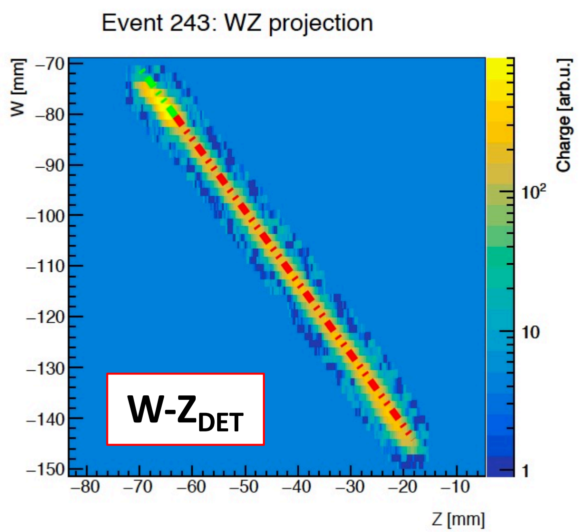
Track finding

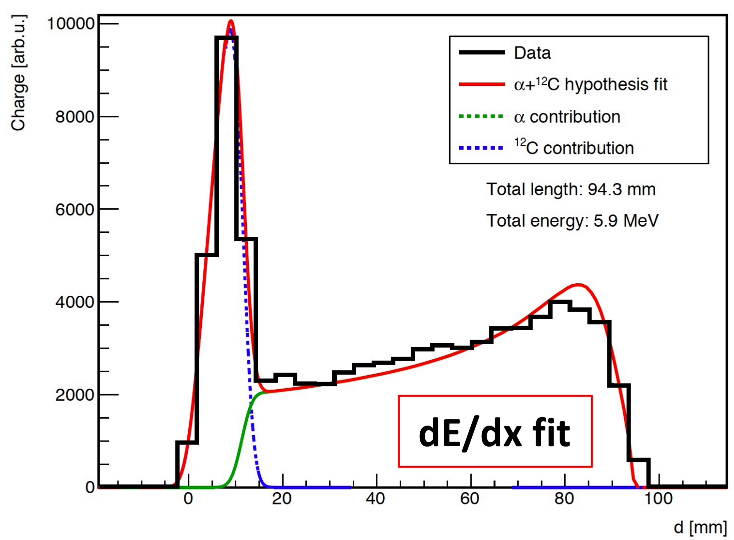
Warsaw TPC

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









E_γ=13.9 MeV

- Pressure: 250 mbar
- Sampling: 12.5 MHz

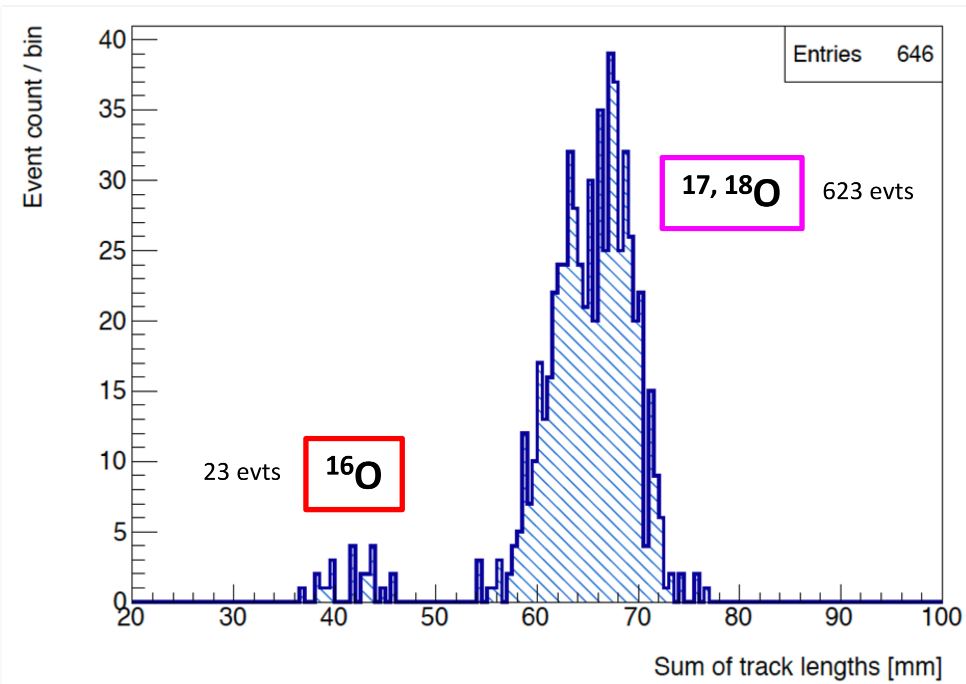
- Automatic procedure for 2-particle topology *(work in progress)*
- Clustered data fitted to dE/dx templates (SRIM + diffusion)

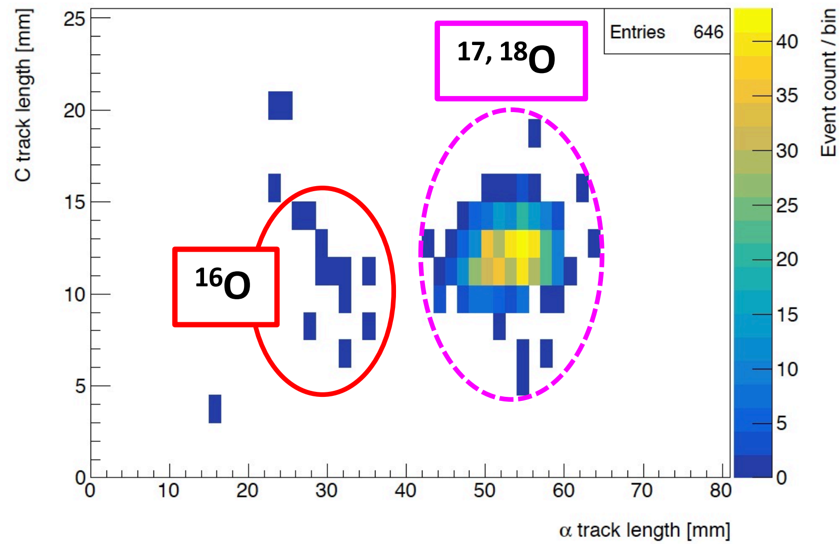
A. Kalinowski

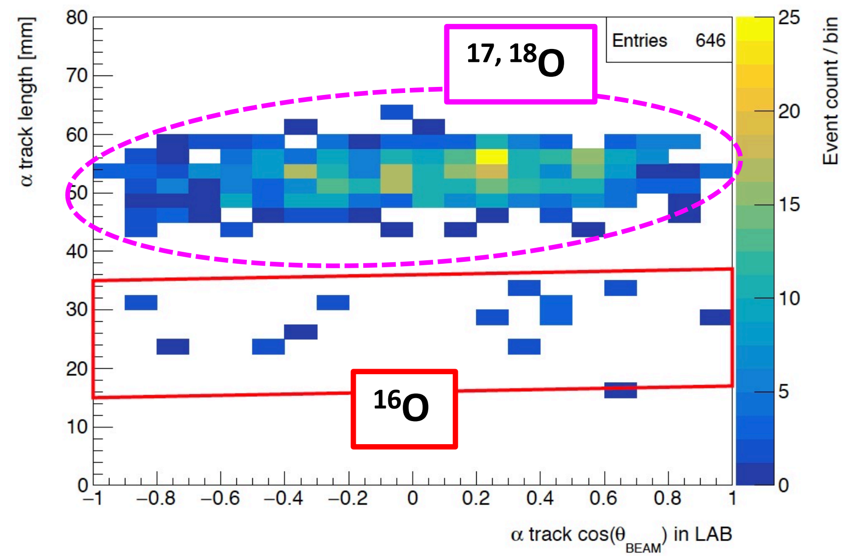
Reaction identification

Warsaw TPC

Various technical plots useful for
separating ^{16}O photo-disintegrations:







E_γ=8.66 MeV

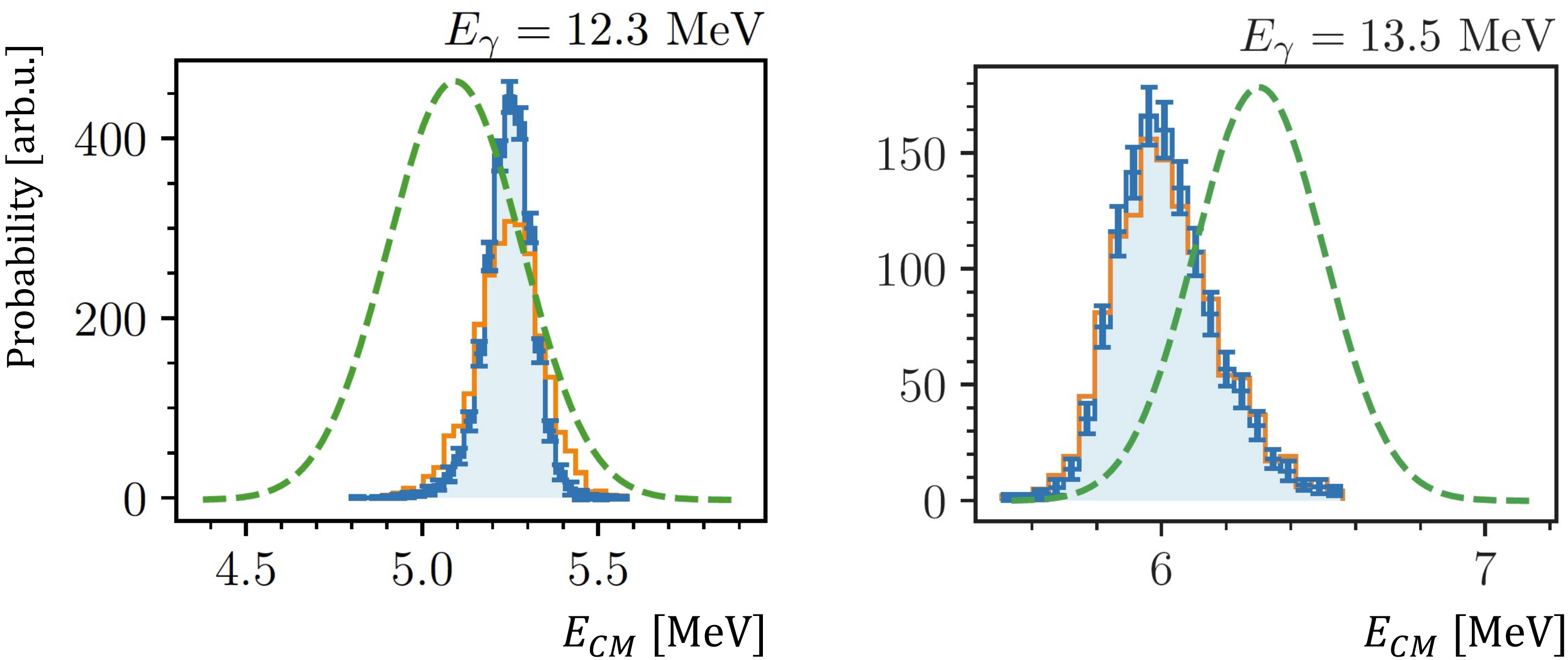
- Manual procedure
- 2-particle events
- Pressure: 130 mbar
- Sampling: 25 MHz

Energy distributions

Warsaw TPC

Distributions of center of mass energy E_{CM}: (equiv. to direct capture 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 with det. resol. $\sigma(E_{CM})$=67 keV

E_{CM} corresponding to unfolded E_γ spectrum from HPGe

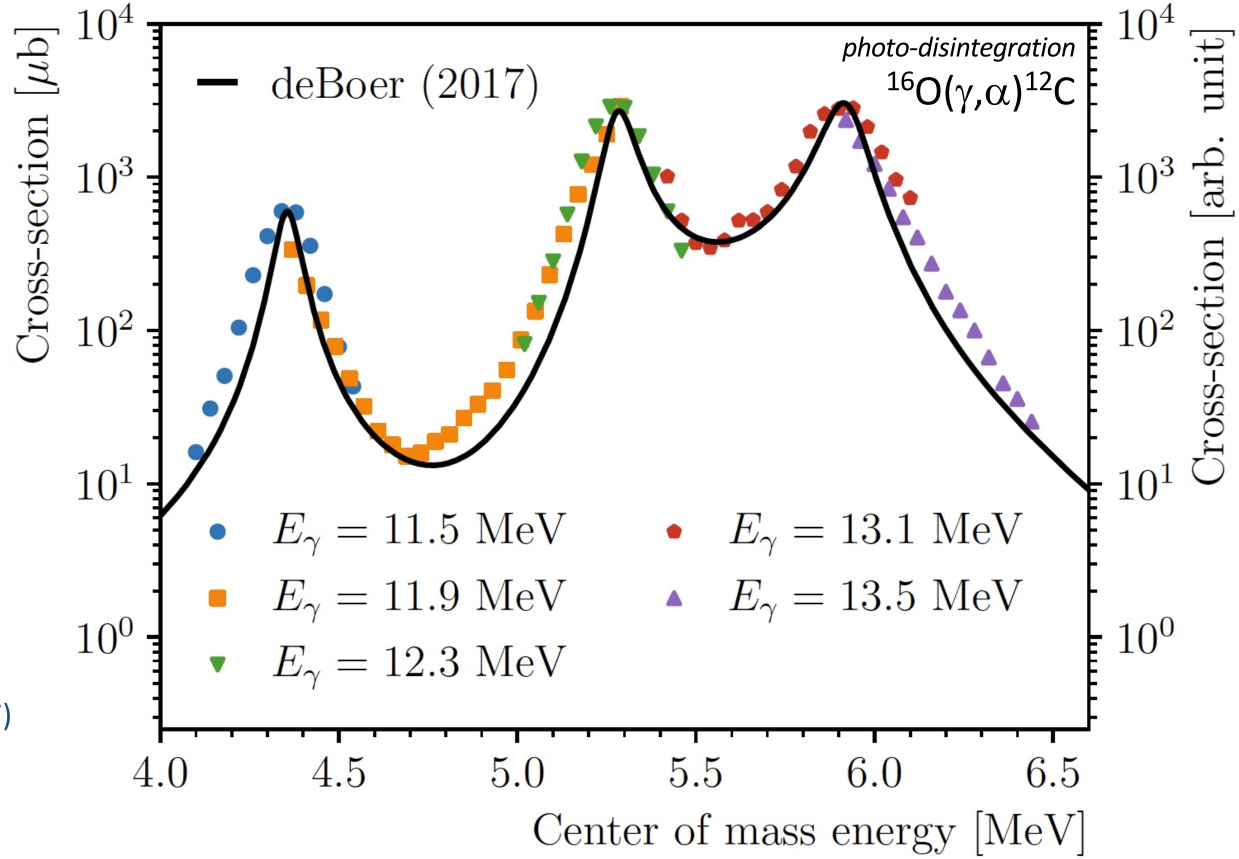
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

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



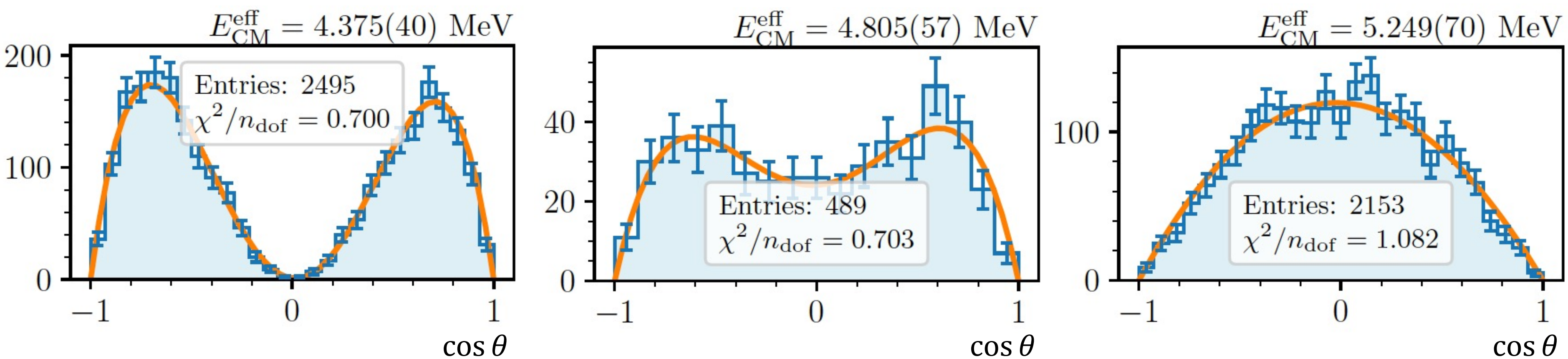
M. Fila, PhD thesis
(Univ. of Warsaw, 2024)

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

E1 / E2 multipolarity

- **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 $P_i(x)$

Warsaw TPC



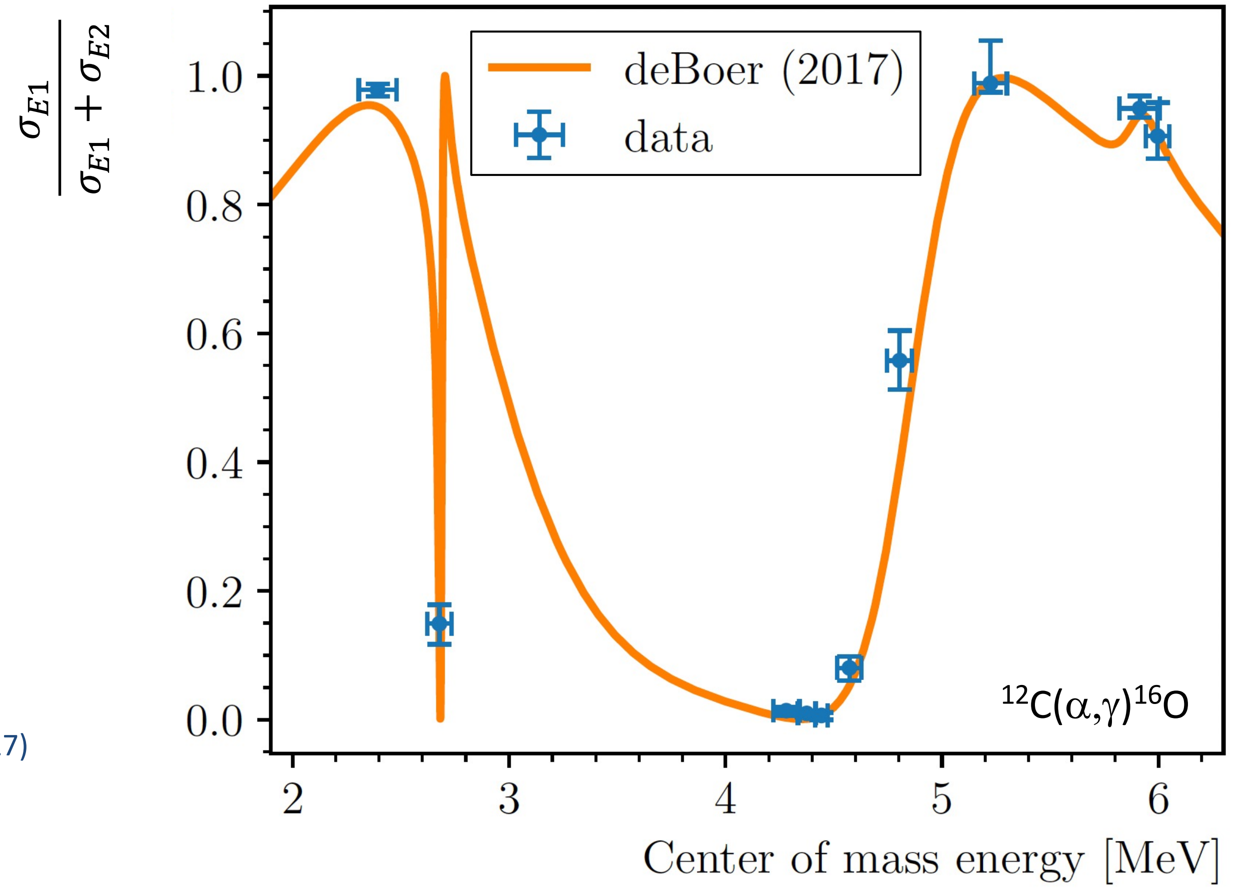
E^{eff}_{CM} [MeV]	E_{CM} bin [MeV]	Nom. E_γ [MeV]	σ_{E1}/σ_{E2}	φ_{12} [rad]
4.375	[4.30, 4.45]	11.5	$9.9\,^{+4.6}_{-6.2}\cdot 10^{-3}$	$1.95\,^{+0.17}_{-0.11}$
4.805	[4.70, 4.90]	11.9	$1.26\,^{+0.24}_{-0.23}$	$1.541\,^{+0.051}_{-0.051}$
5.249	[5.10, 5.40]	12.3	$85\,^{+489}_{-105}$	$1.4\,^{+0.1}_{-1.4}$

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

E1 / E2 multipolarity

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)

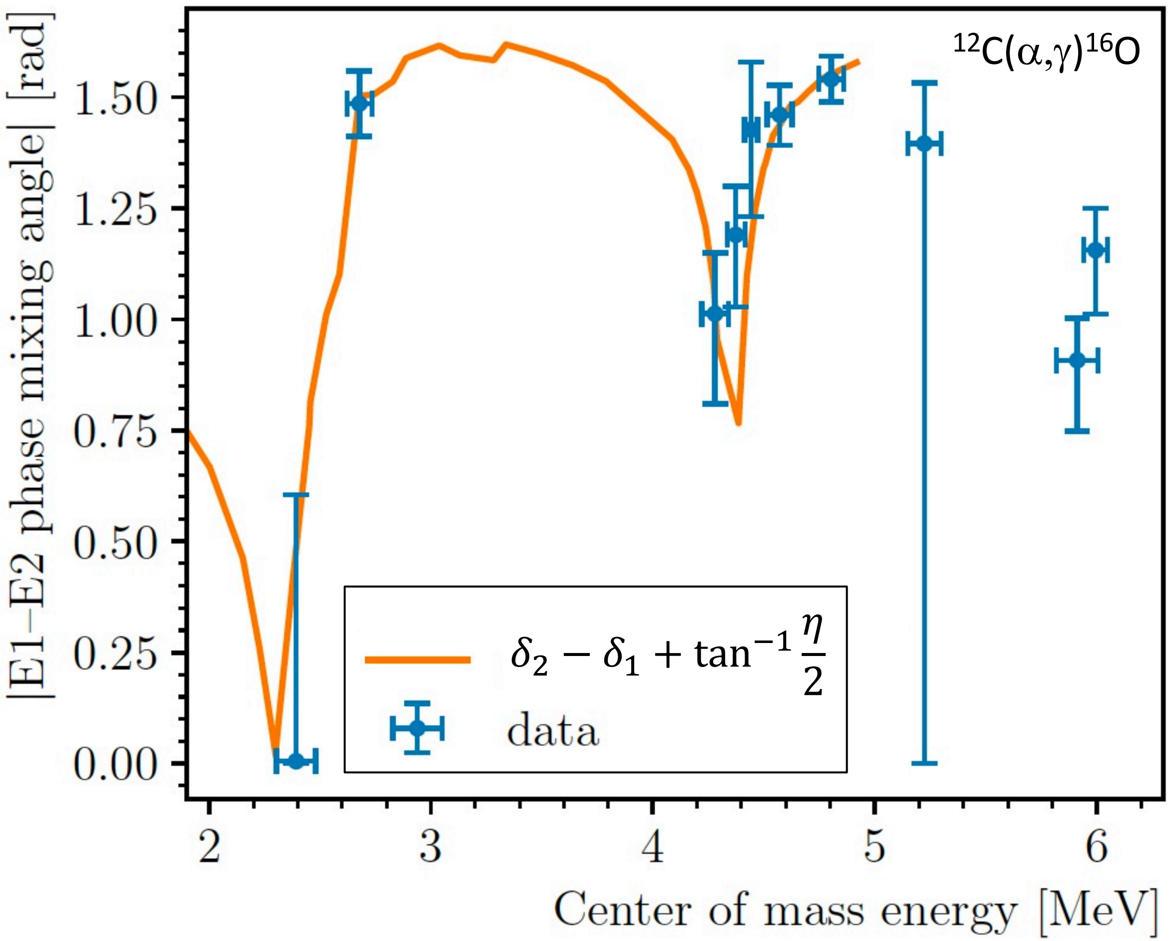
Warsaw TPC

E1 / E2 multipolarity

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)

Summary & outlook

Warsaw TPC

- First results from $^{16}O(\gamma,\alpha)$ photo-disintegration experiment at HIγS (NC, USA) using simple track reconstruction are encouraging:
  - publications: [1] EPJ Web of Conf. 279, 04002 (2023)
    [2] EPJ Web of Conf. 290, 01004 (2023)
  - one PhD thesis defended: Mateusz Fila (Univ. of Warsaw, 2024)
- Processing full statistics requires better automated reconstruction:
  - work is under way on improving automated track finding algorithms (UW, UConn, SHU)
  - new PhD student has joined UW team: Aneta Djakonow-Lichnowska
- Plans for 2025-26:
  - another measurement at HIγS using 8.5 MeV nominal E_γ energy to better explore E_{CM}~1 MeV region of $^{16}O(\gamma,\alpha)$ reaction
  - some upgrades to the HIγS facility are needed in order to reach 10^9 γ/s on target
  - need reliable methods to measure absolute beam intensity & beam energy spectra
- Longer term:
  - looking forward for more intense γ-ray source to be commissioned at the ELI-NP facility (Magurele, Romania)

Thank you for your attention !!!

Warsaw TPC

Experimental team – HIγS ’2022:

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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.

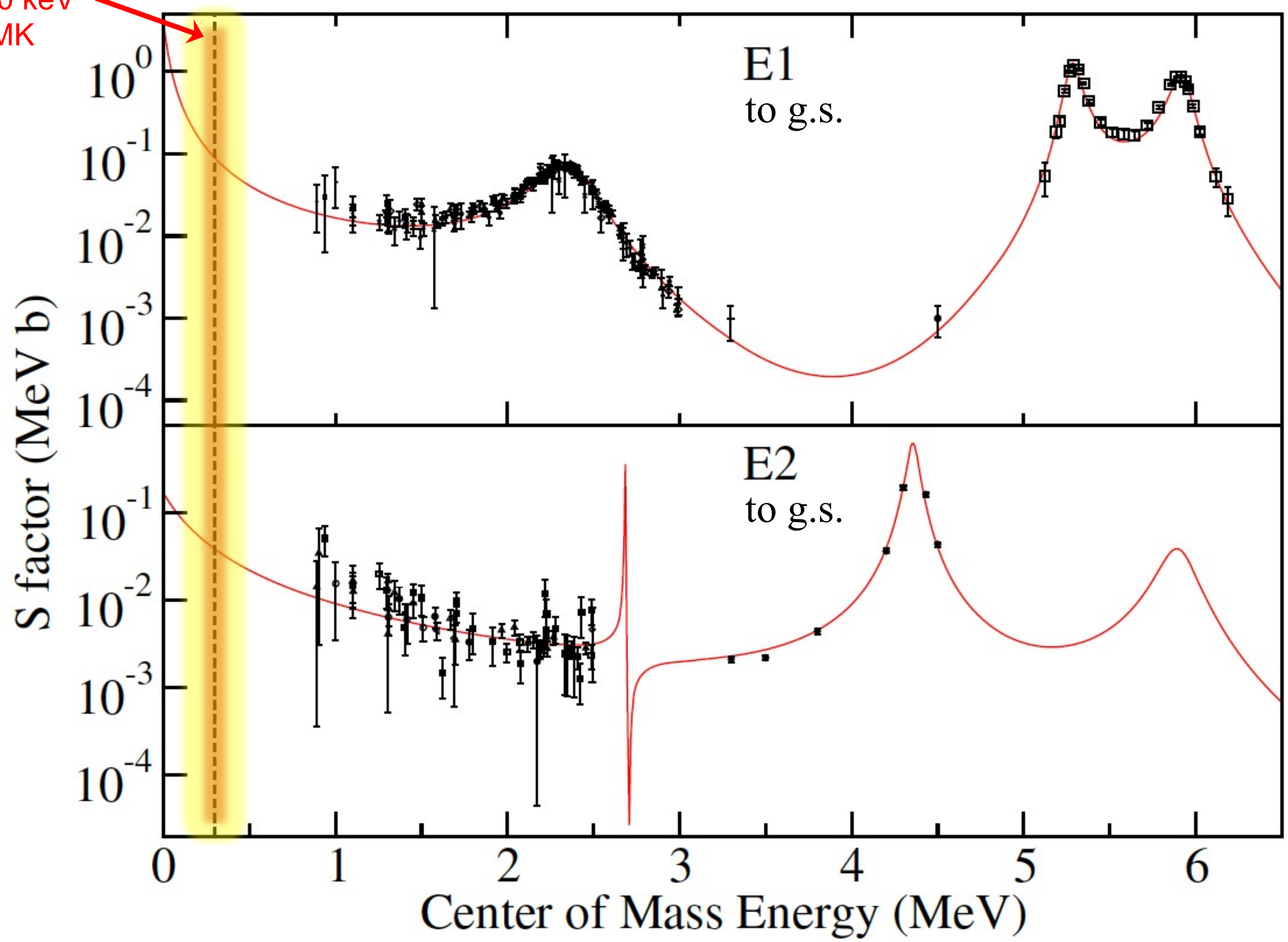
Backup slides

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)

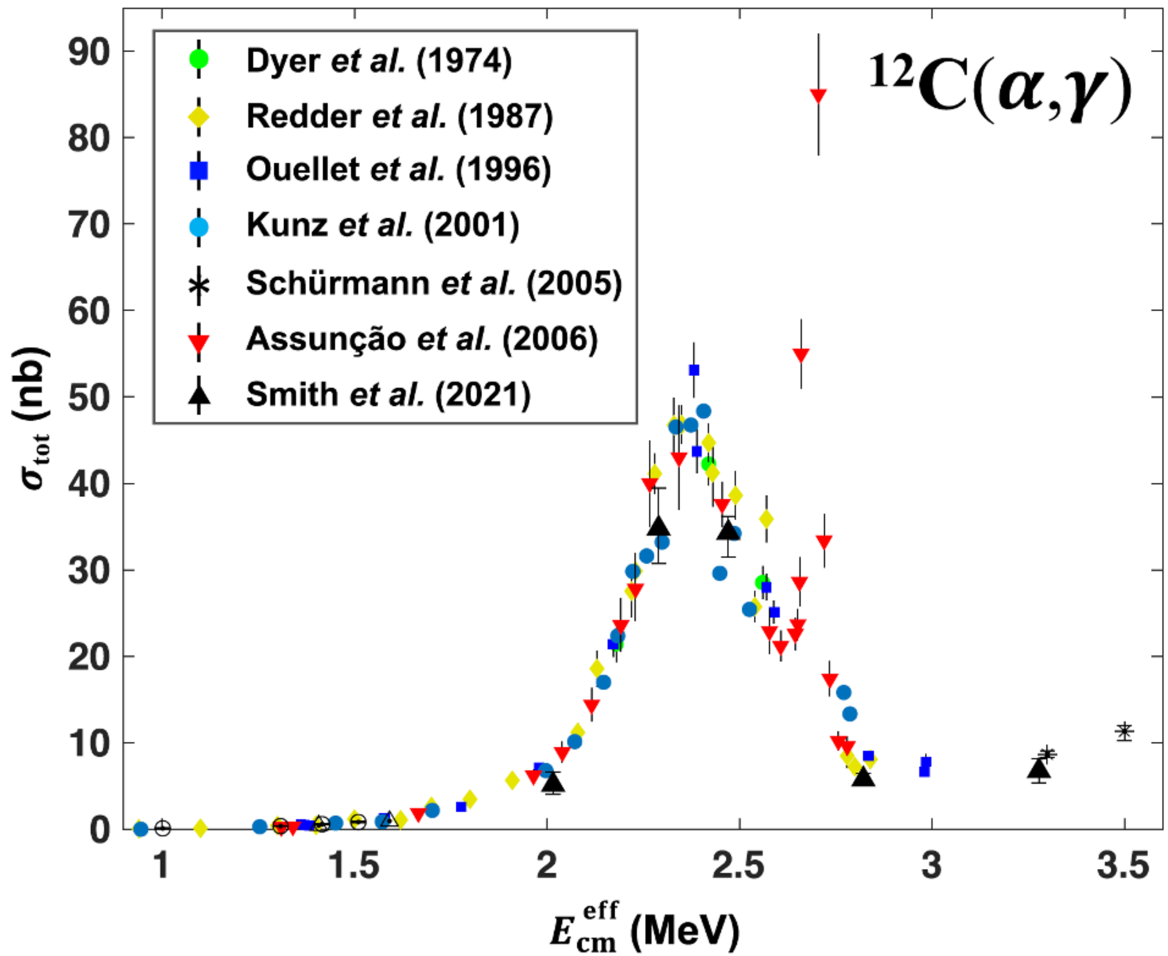


Brochard (1973)	E1
Dyer, Barnes (1974)	E1
Redder (1987)	E1, E2
Kremer (1988)	E1
Ouellet (1996)	E1, E2
Roters (1999)	E1, E2
Gialanella (2001)	E1
Kunz (2001)	E1, E2
Fey.(2004)	E1, E2
Assunção (2006)	E1, E2
Makii (2009)	E1, E2
Schürmann (2011)	E1, E2
Plag (2012)	E1, E2

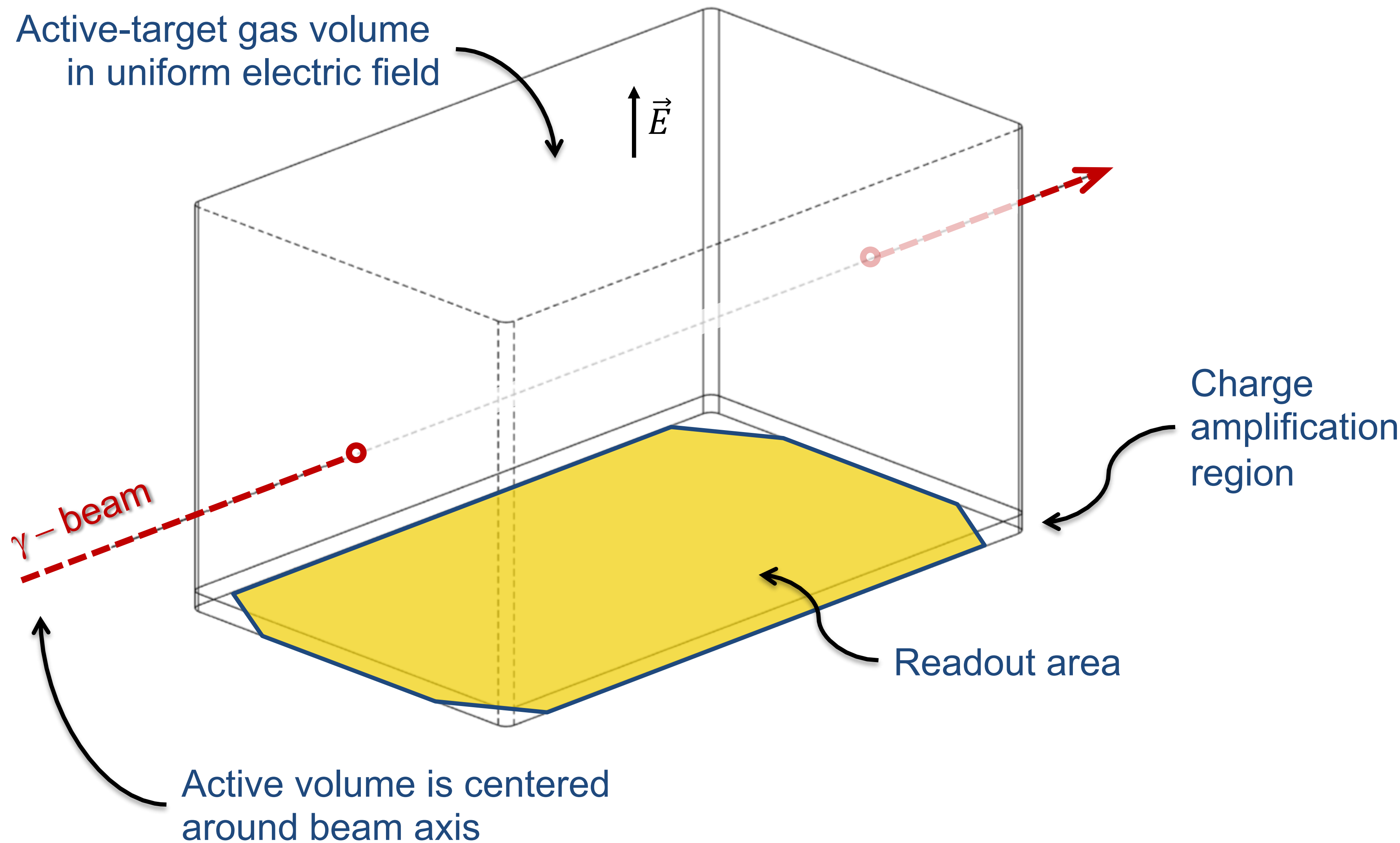
Experimental data on $^{12}C(\alpha,\gamma)^{16}O$

Total cross section for E_{CM}>1 MeV measured with charged particle beams (direct capture) and with gamma beams (photo-disintegration) :

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



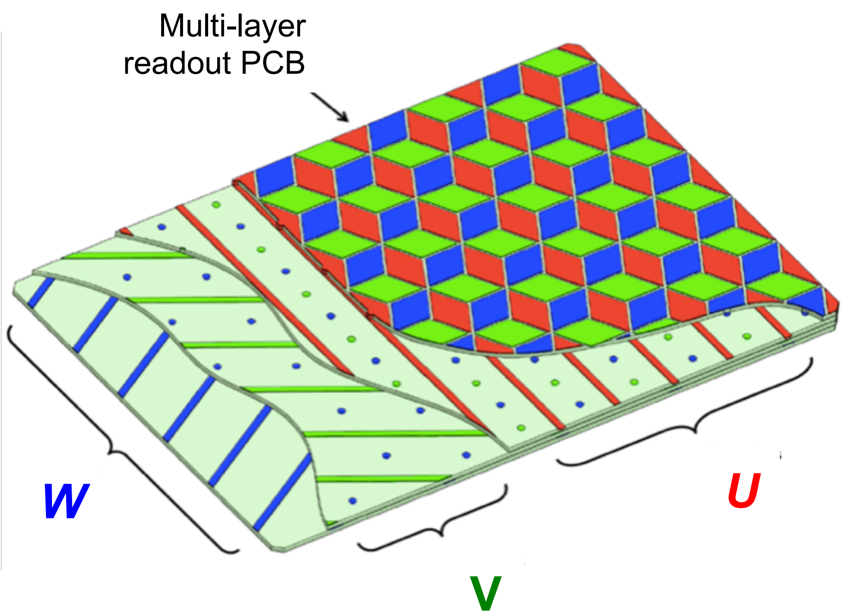
Concept – active-target TPC

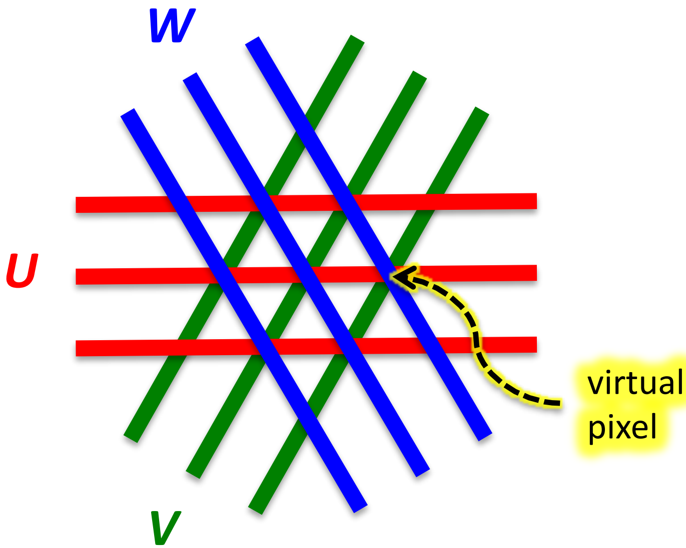


Concept – readout strips

3 grids of strips – crossed at 60° :

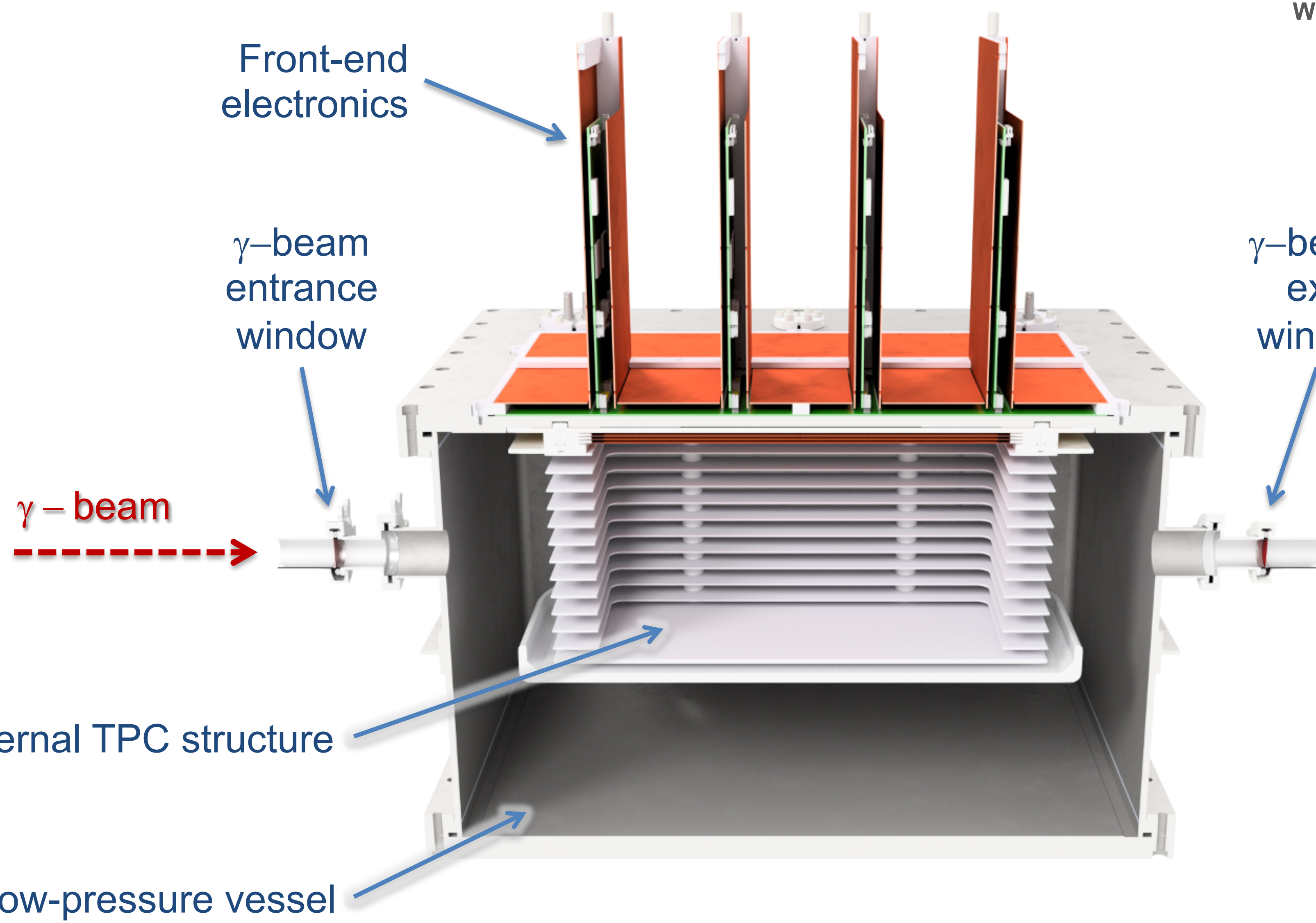
- 3-coordinate, planar, redundant strip readout, 1.5 mm strip pitch
- ***U-V-W*** strip arrays on XY plane + Z-coordinate from drift time → virtual 3D pixels
- Simple event topologies → expect only few tracks per event
- Moderate cost of electronics → only ***O*****(10^3)** channels are needed





[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)

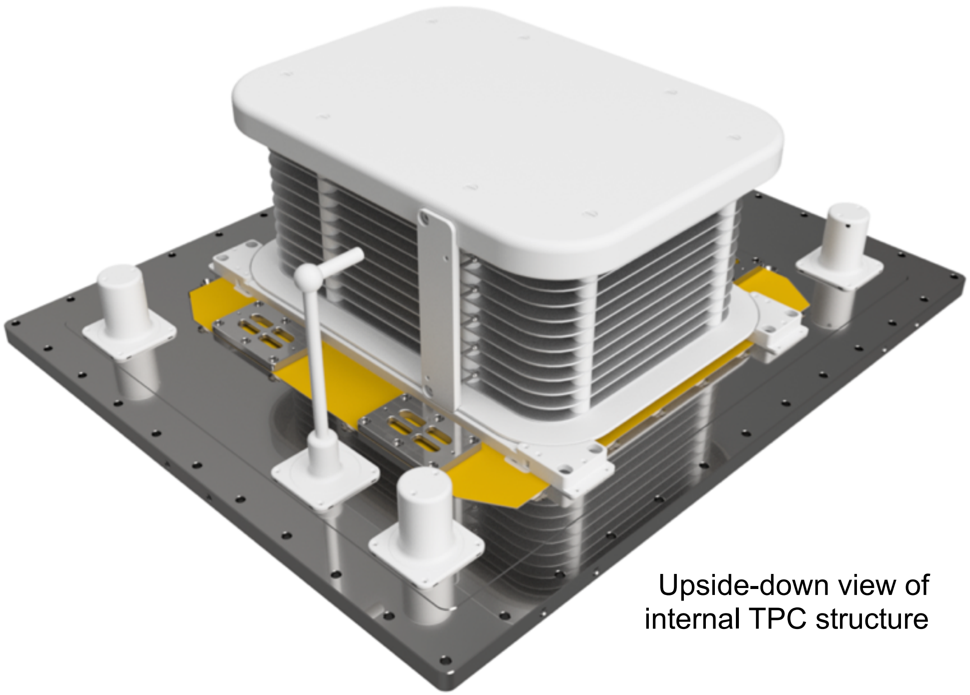
Detector design (1/2)



Detector design (2/2)

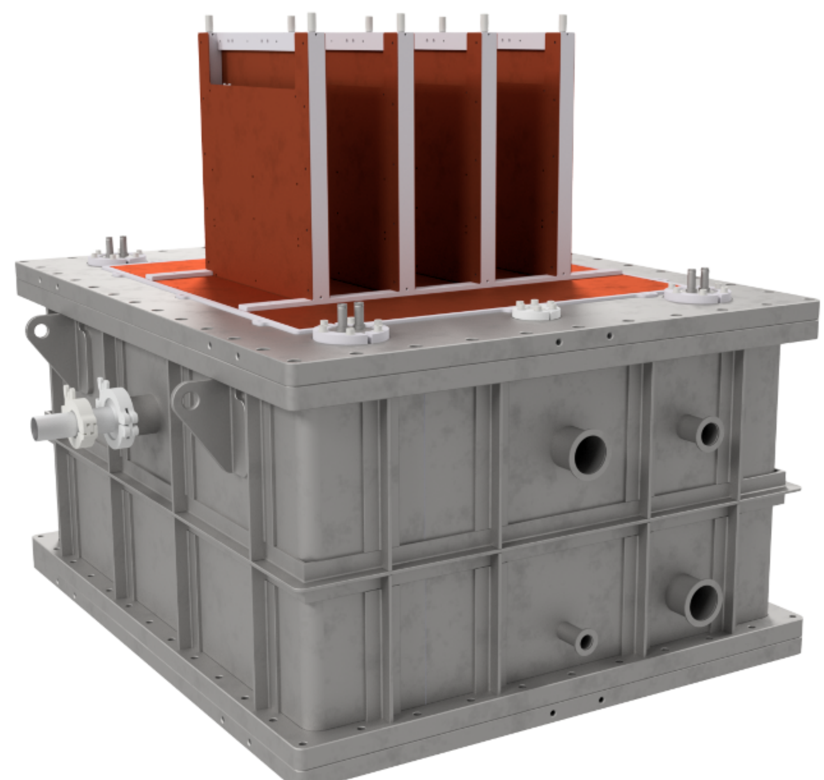
Warsaw TPC

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

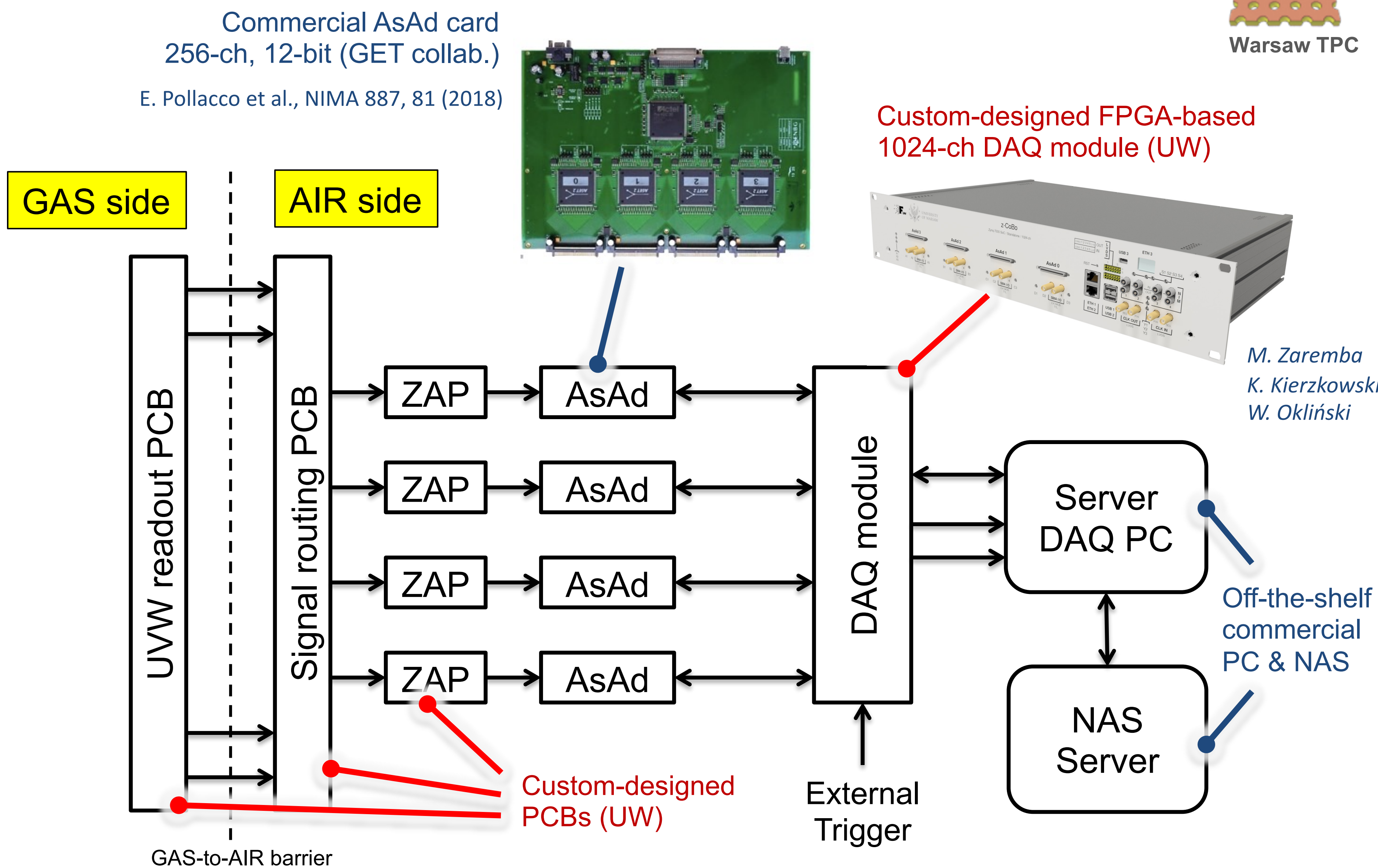


- Drift cage, triple GEM stack & readout PCB are fixed to the top endcap
- Aluminium field-shaping electrodes and cathode plate

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



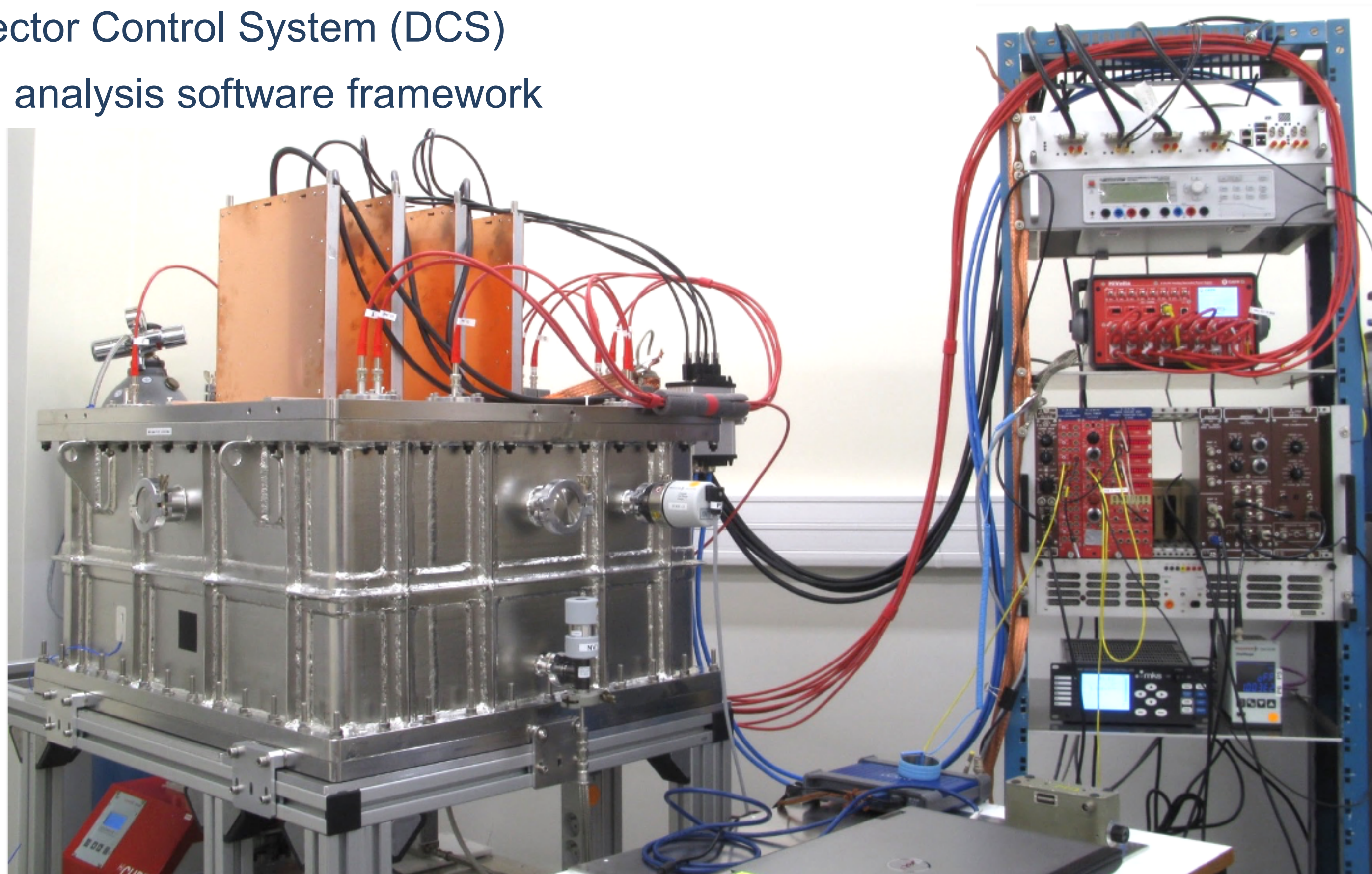
DAQ readout chain



Detector test bench

Warsaw TPC

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



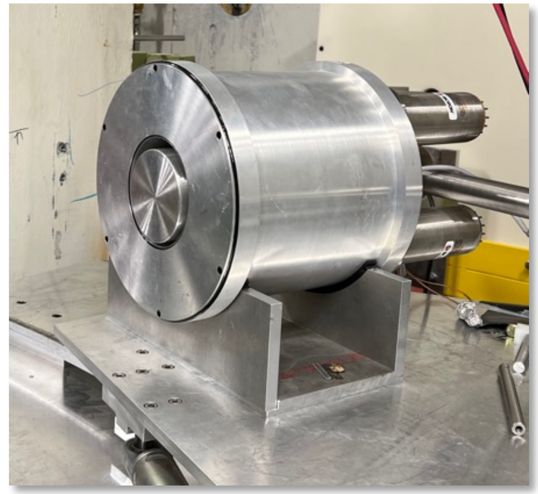
Beam monitoring & alignment

Warsaw TPC

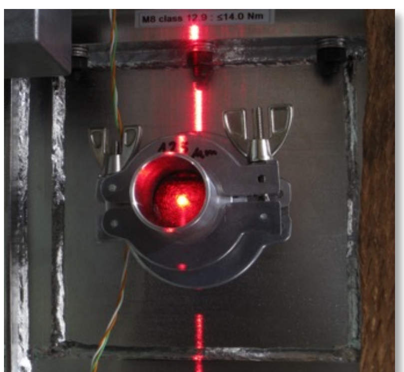
Collimator
ϕ =10.5 mm
(upstream)

Scintillators
(upstream)

HPGe (downstream)

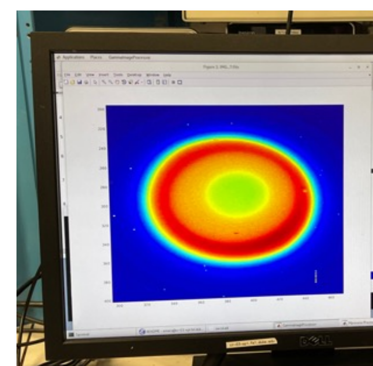


Au foil (downstream)



Alignment – laser

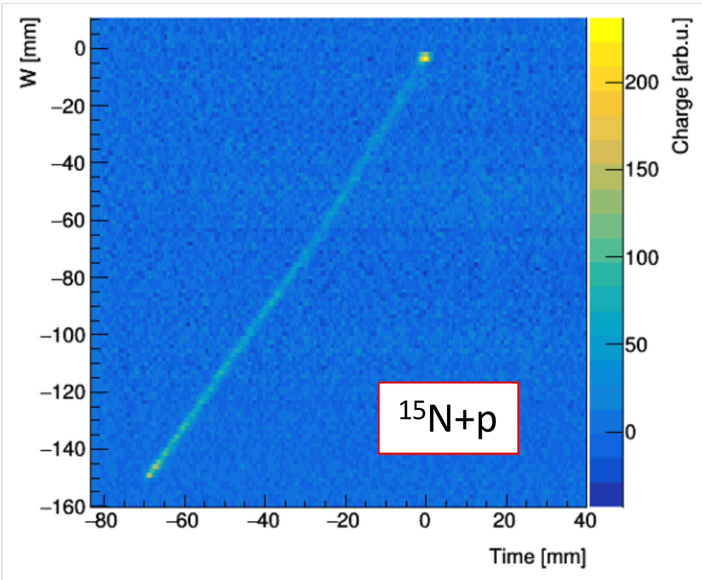
Alignment – CCD gamma camera + lead plugs:

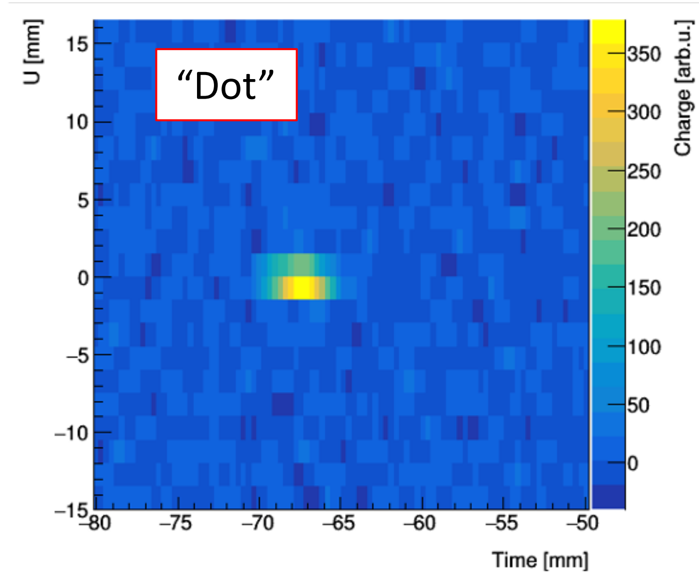


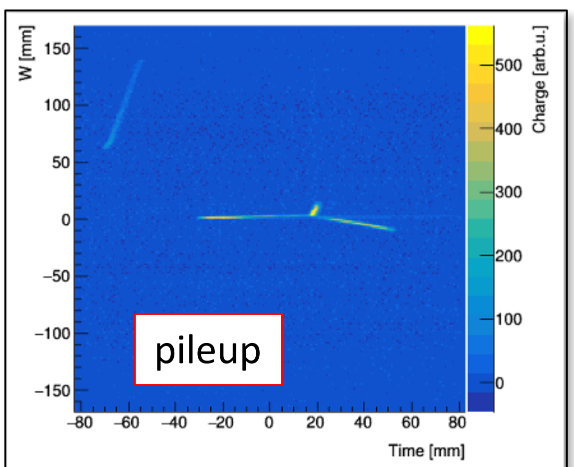
Example raw data - background

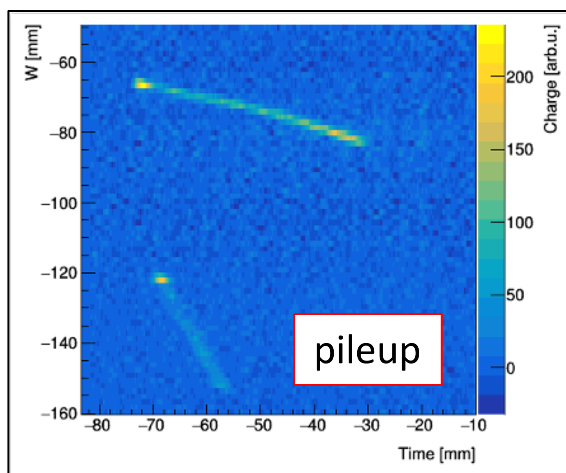
Warsaw TPC

- Examples of background & complex events:









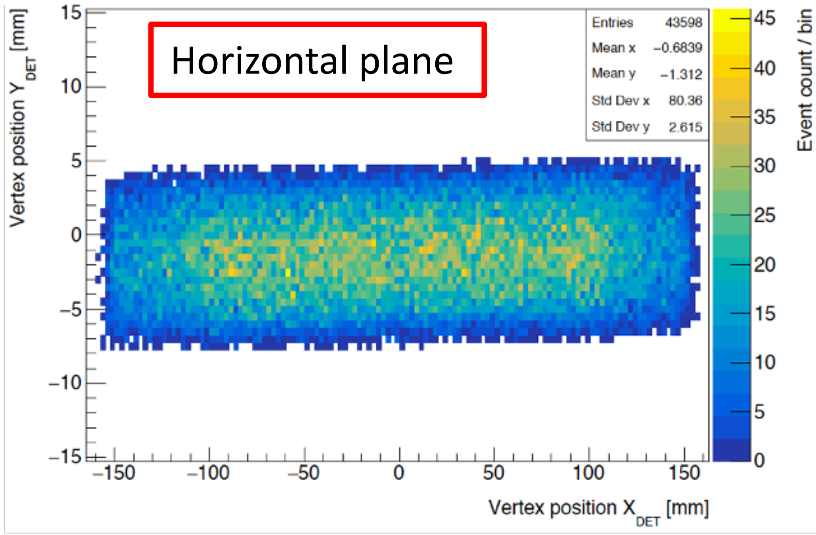
E_{γ}=13.9 MeV

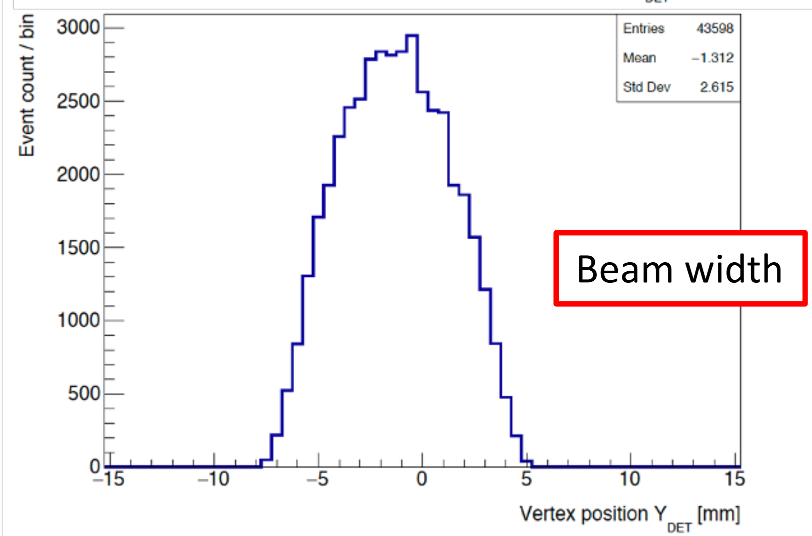
- Only 1 of 3 projections is shown for simplicity
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Beam mis-alignment

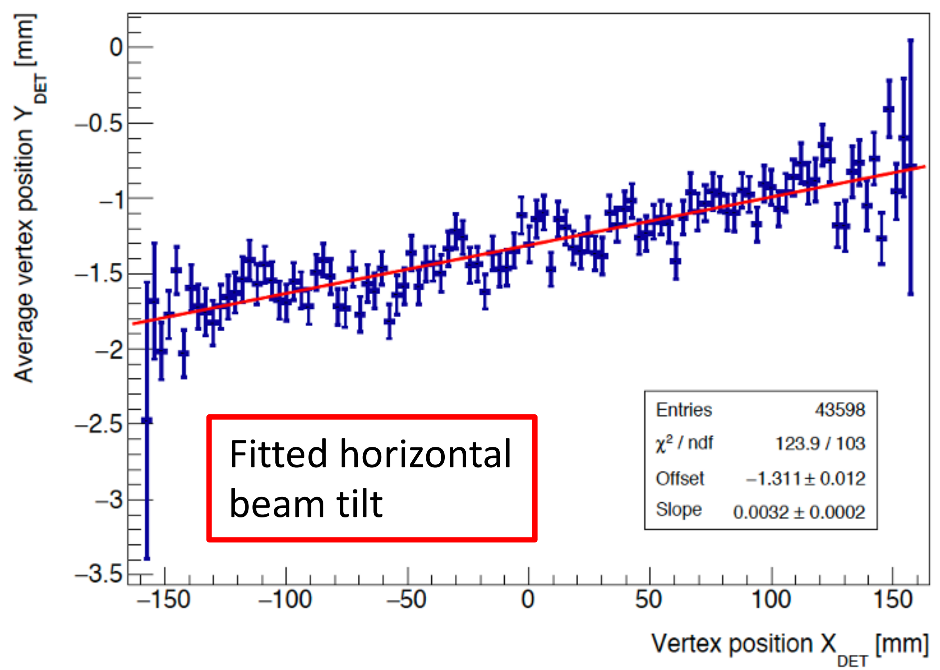
Warsaw TPC

- Automatic procedure, 2-particle reaction vertices:





E_γ=11.5 MeV

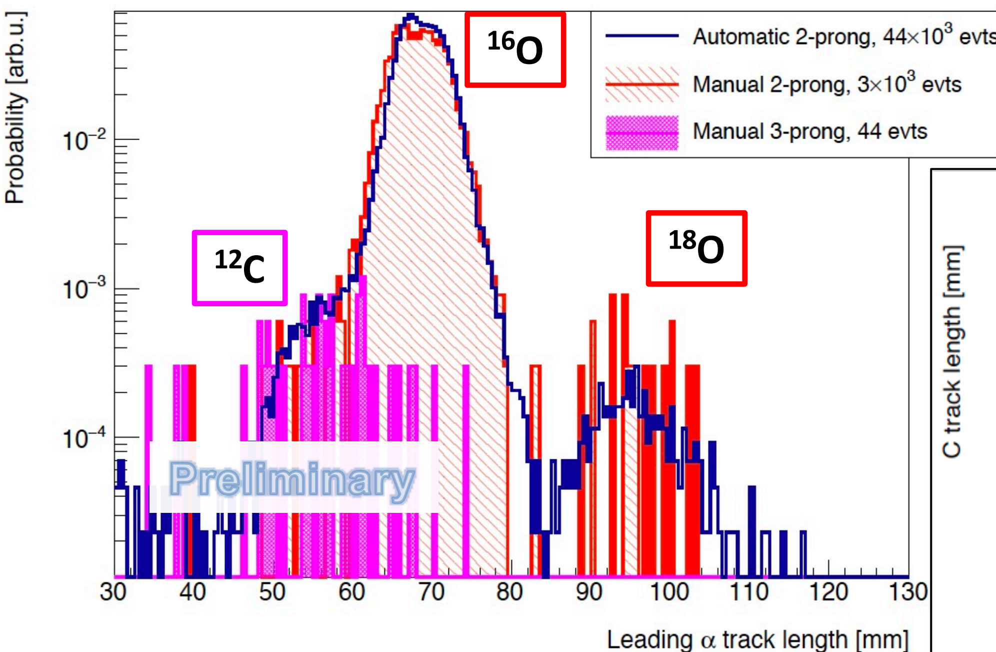


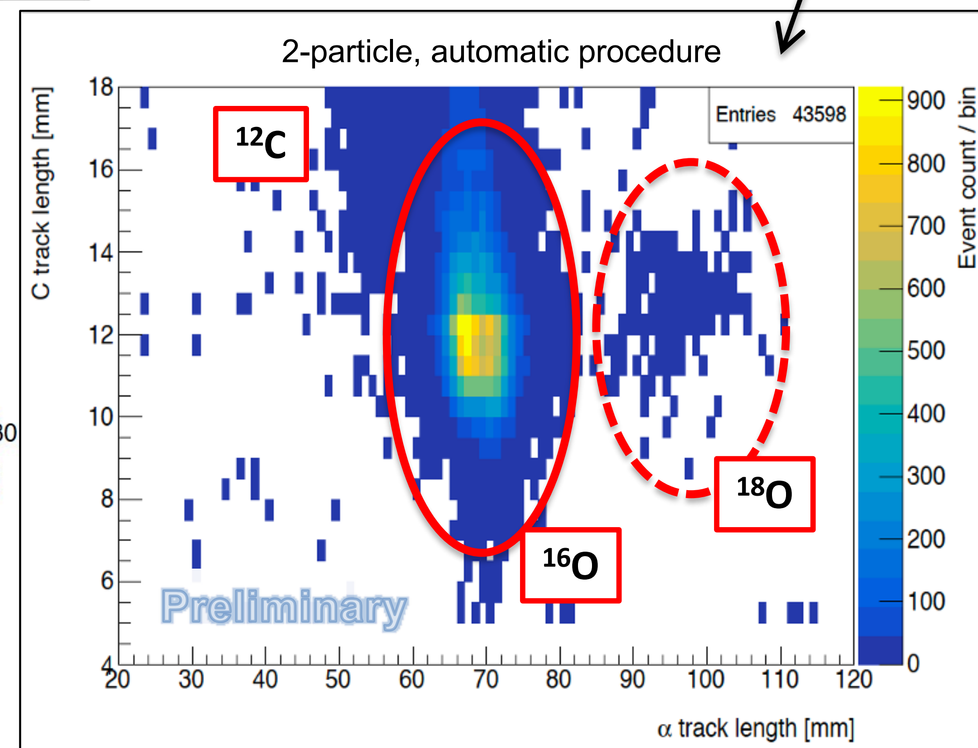
Event identification - automatic

Warsaw TPC

- Current automatic procedure reconstructs 1- and 2-particle events
- Mis-reconstructed 3-particle events can be rejected using 2D identification plots

2- and 3-particle, manual or automatic procedure





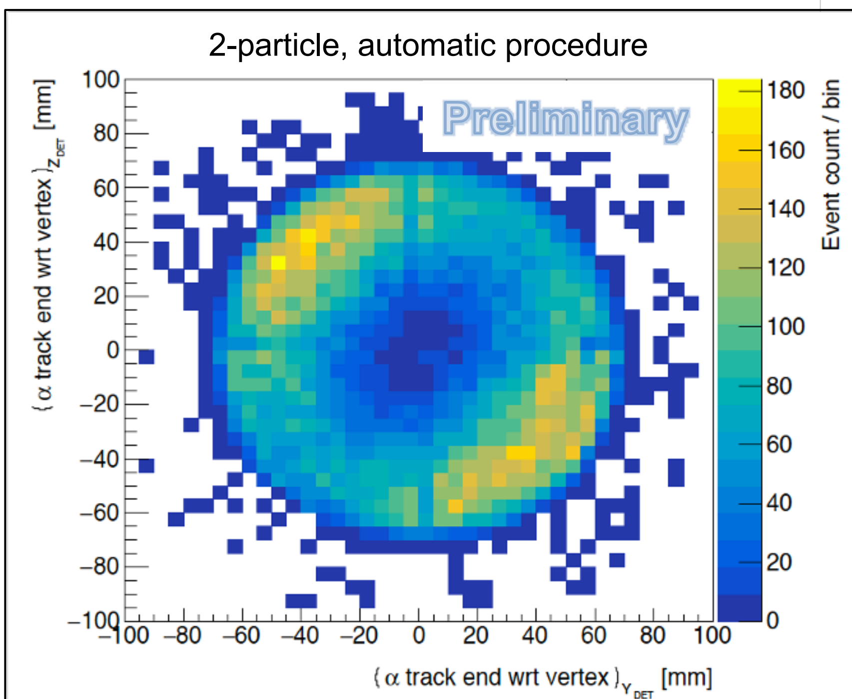
E_γ=11.5 MeV

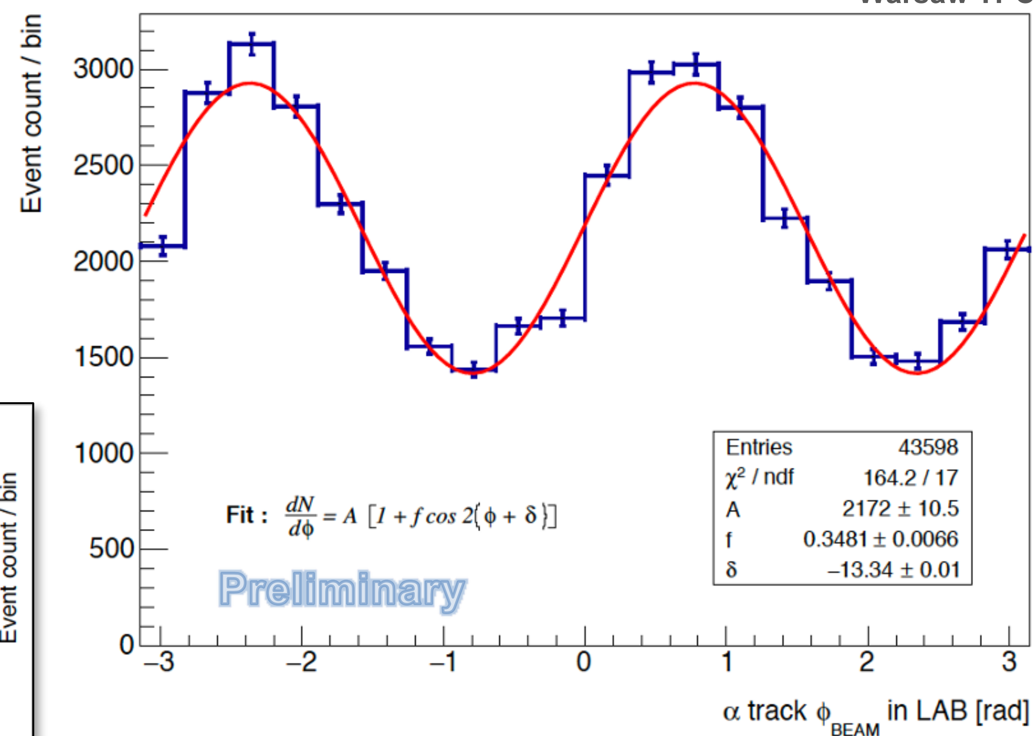
Angular distributions (1/3)

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 ($S_3 \approx 0.94$)

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

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

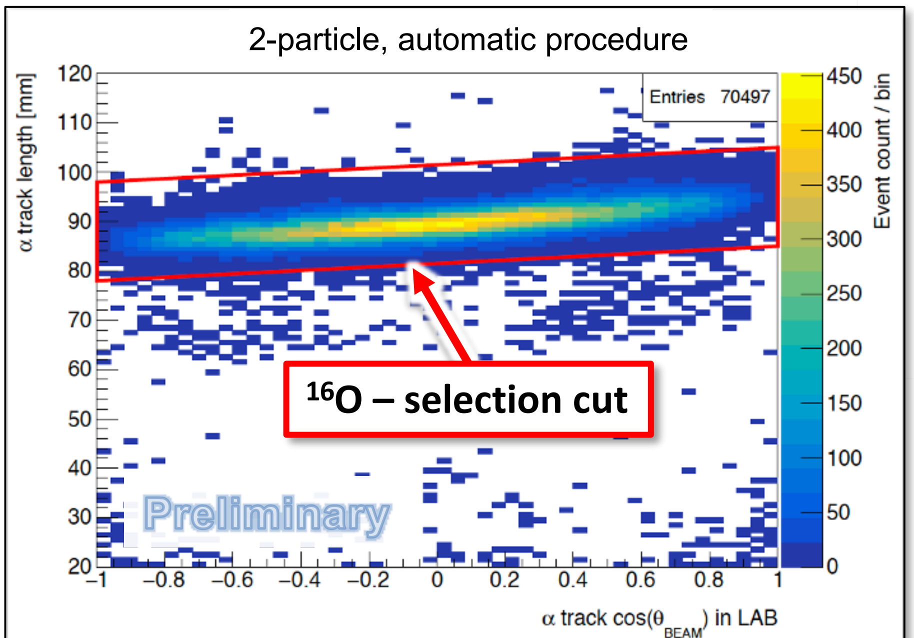
$$W(\phi) = 1 + f \cdot \cos 2(\phi + \delta)$$

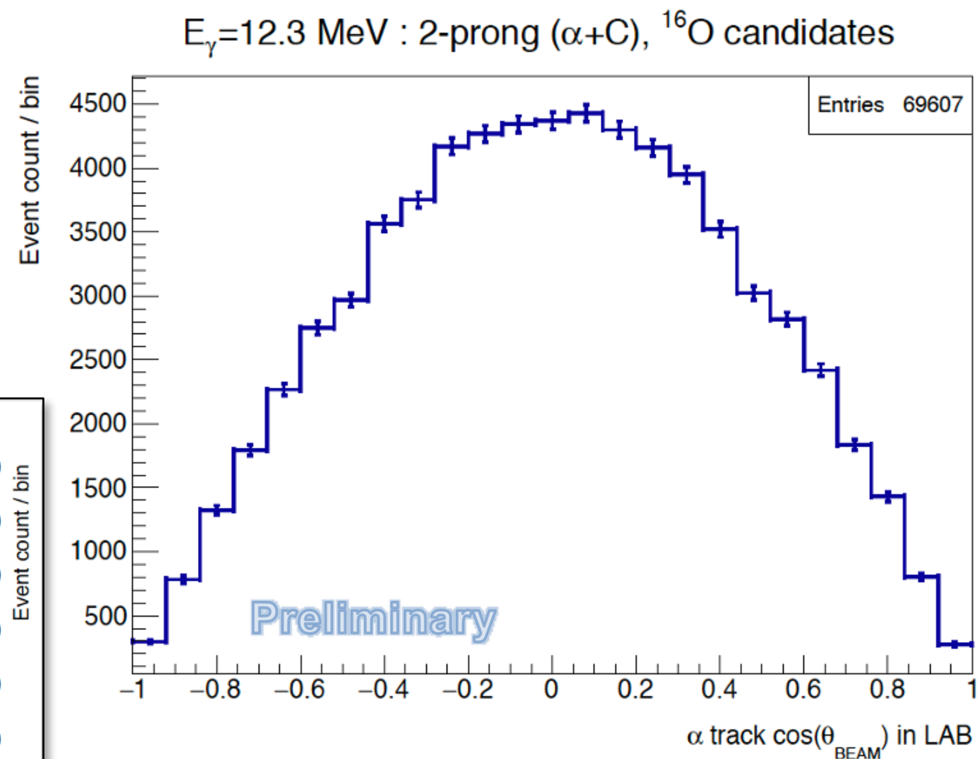
Angular distributions (2/3)

Warsaw TPC

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

E_γ=12.3 MeV





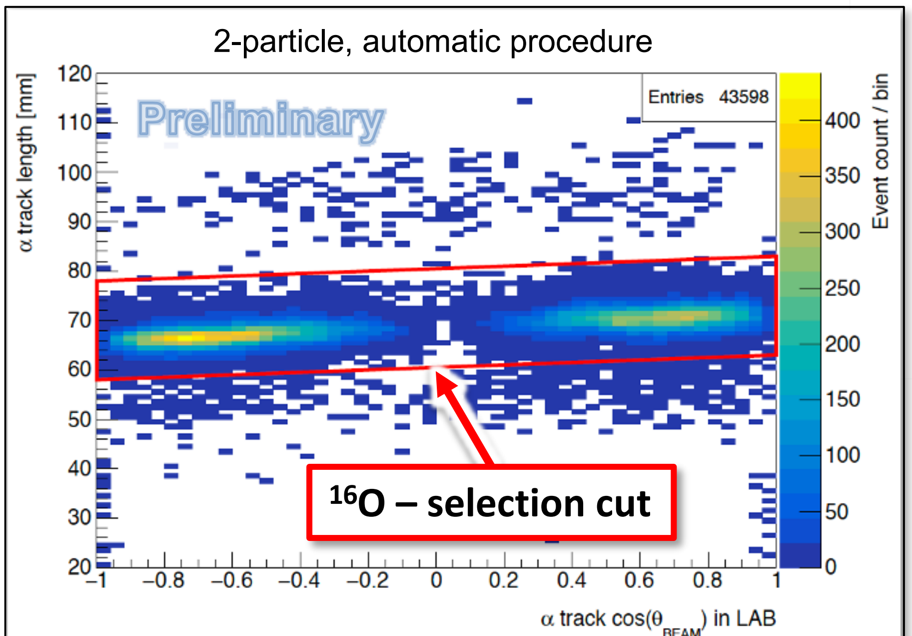
⇒ E1 shape

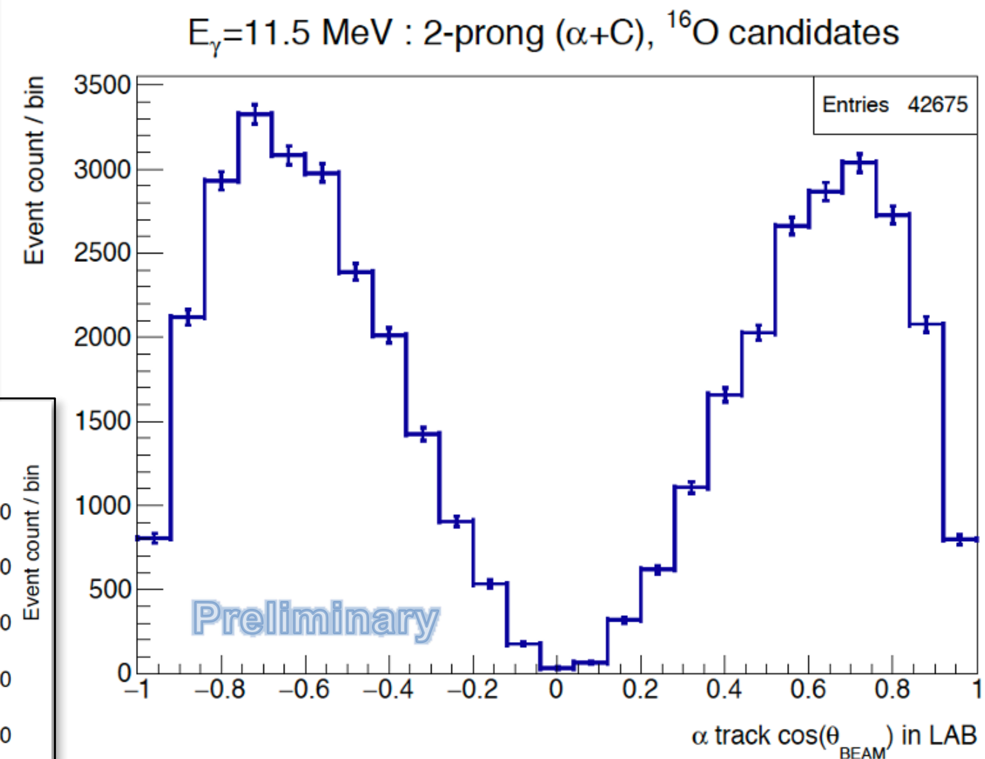
Angular distributions (3/3)

Warsaw TPC

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

E_γ=11.5 MeV



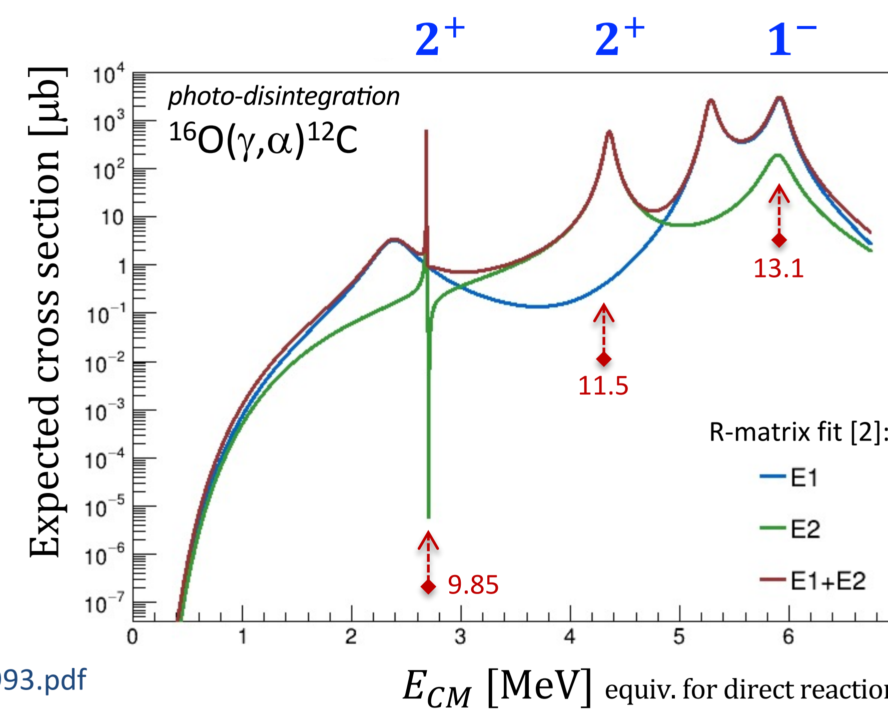


⇒ E2 shape

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 extracted from $Range(E)$ table or $\frac{dE}{dx}$ 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]:
    - $\mathbf{2^+}$: $E_x = 9.8445(5)$ MeV
    - $\mathbf{2^+}$: $E_x = 11.520(4)$ MeV
    - $\mathbf{1^-}$: $E_x = 13.090(8)$ MeV
  - measure 3 energy points with E_γ spectra centered at respective state
  - fit energy scale corrections separately for manual & automatic reconstruction



[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)

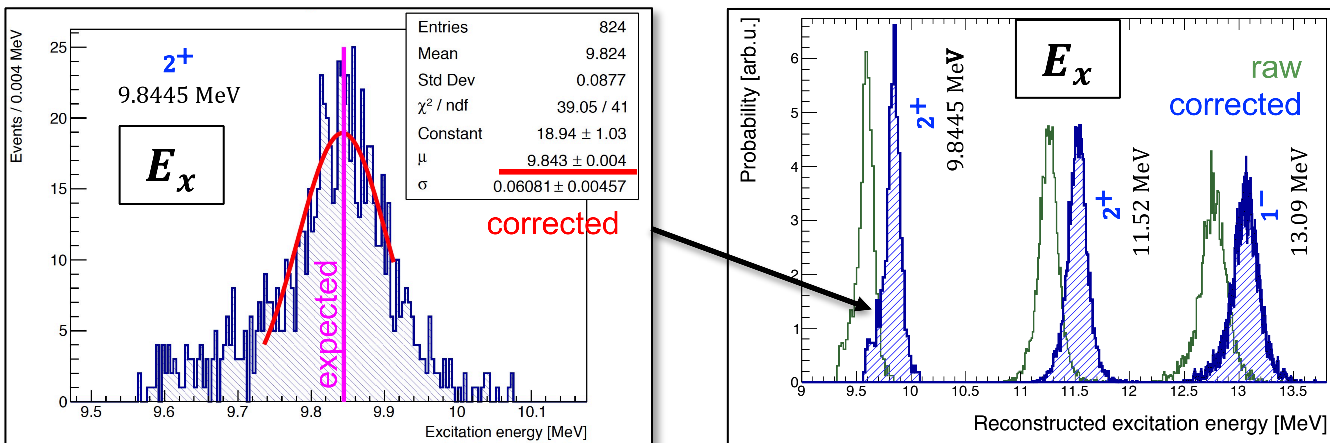
Energy scale calibration (2/3)

Warsaw TPC

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

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

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

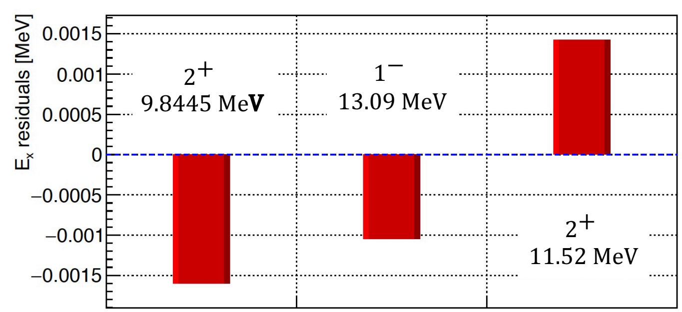


Manual reconstruction, ^{16}O candidate events

Fit residuals

RMS = 1.4 keV

|max-min| = 3.0 keV



Energy resolution

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

$\sigma(E_\alpha) \approx$ 45 keV @ E_α = 2 MeV

Energy scale

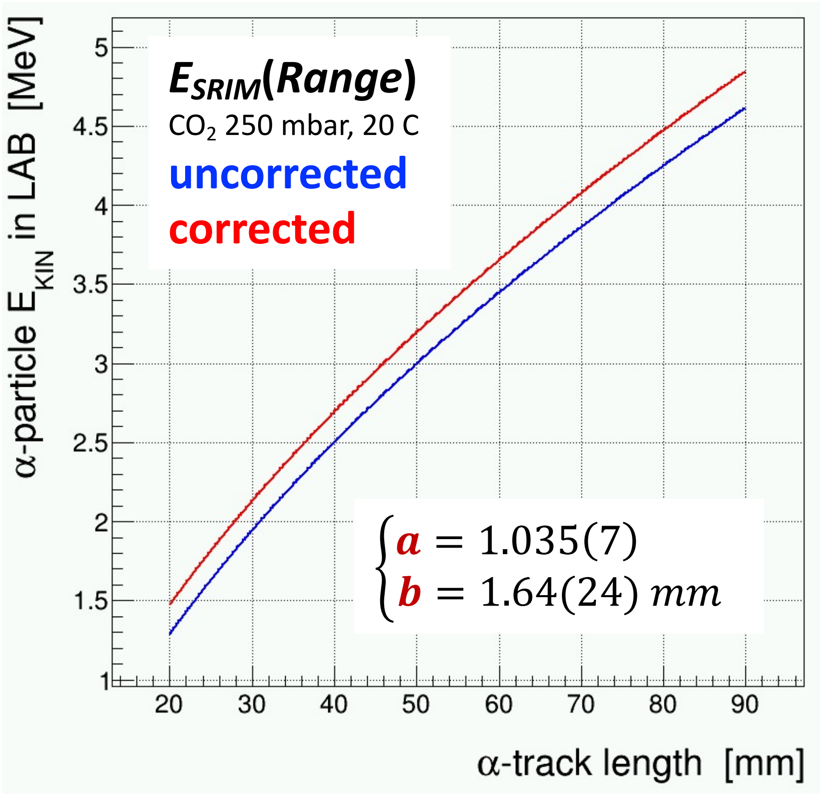
$$\begin{cases} a = 1.035(7) \\ b = 1.64(24)\ mm \end{cases}$$

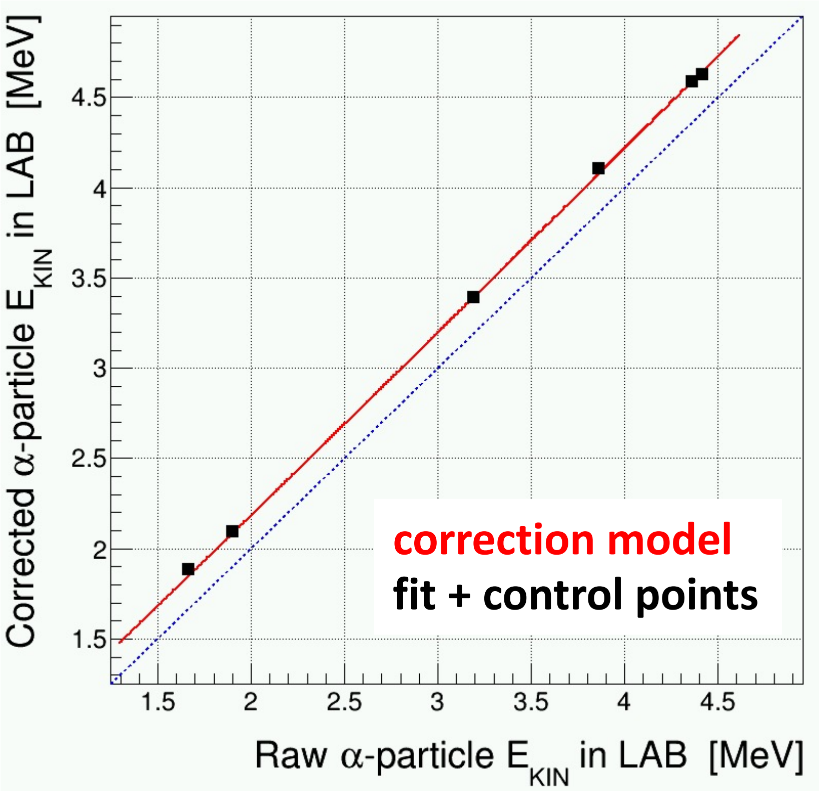
Energy scale calibration (3/3)

Warsaw TPC

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

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

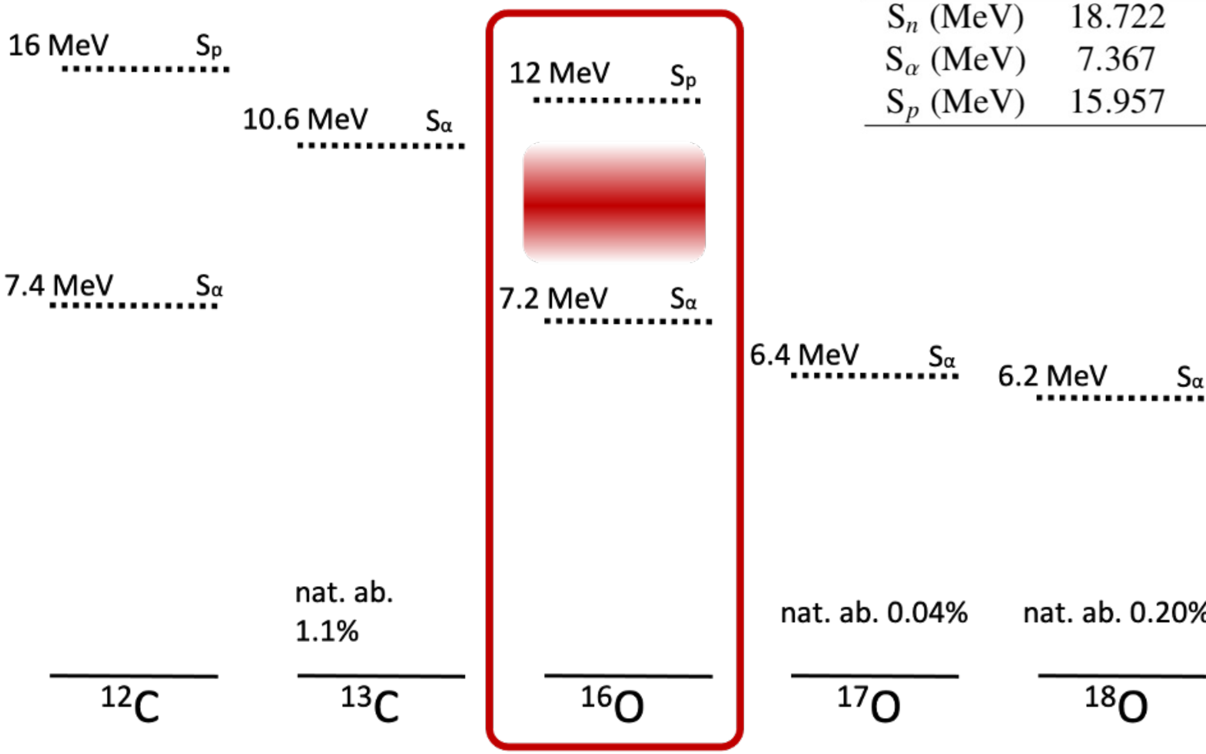




^{16}O photodisintegration experiment @ HIγS
(April-September, 2022)

Warsaw TPC

- **Possible reaction channels with gaseous 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