Photo-disintegration of ^{16}O at astrophysical energies studied with the Warsaw TPC at the HIγS facility

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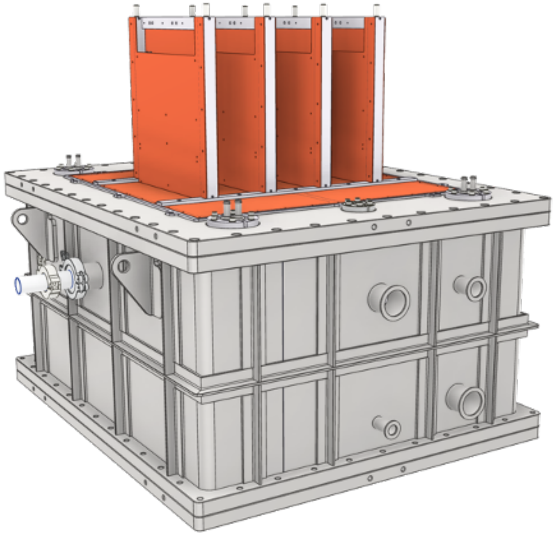


Nuclear Photonics 2023

September 11-15, 2023

Durham, NC, USA

Nuclear Astrophysics with monochromatic γ–ray beams

Experimental approach:

- Measure **photodisintegration** reactions instead of direct capture:
  - detailed balance principle for time-reverse reactions
  - different systematics and experimental challenges

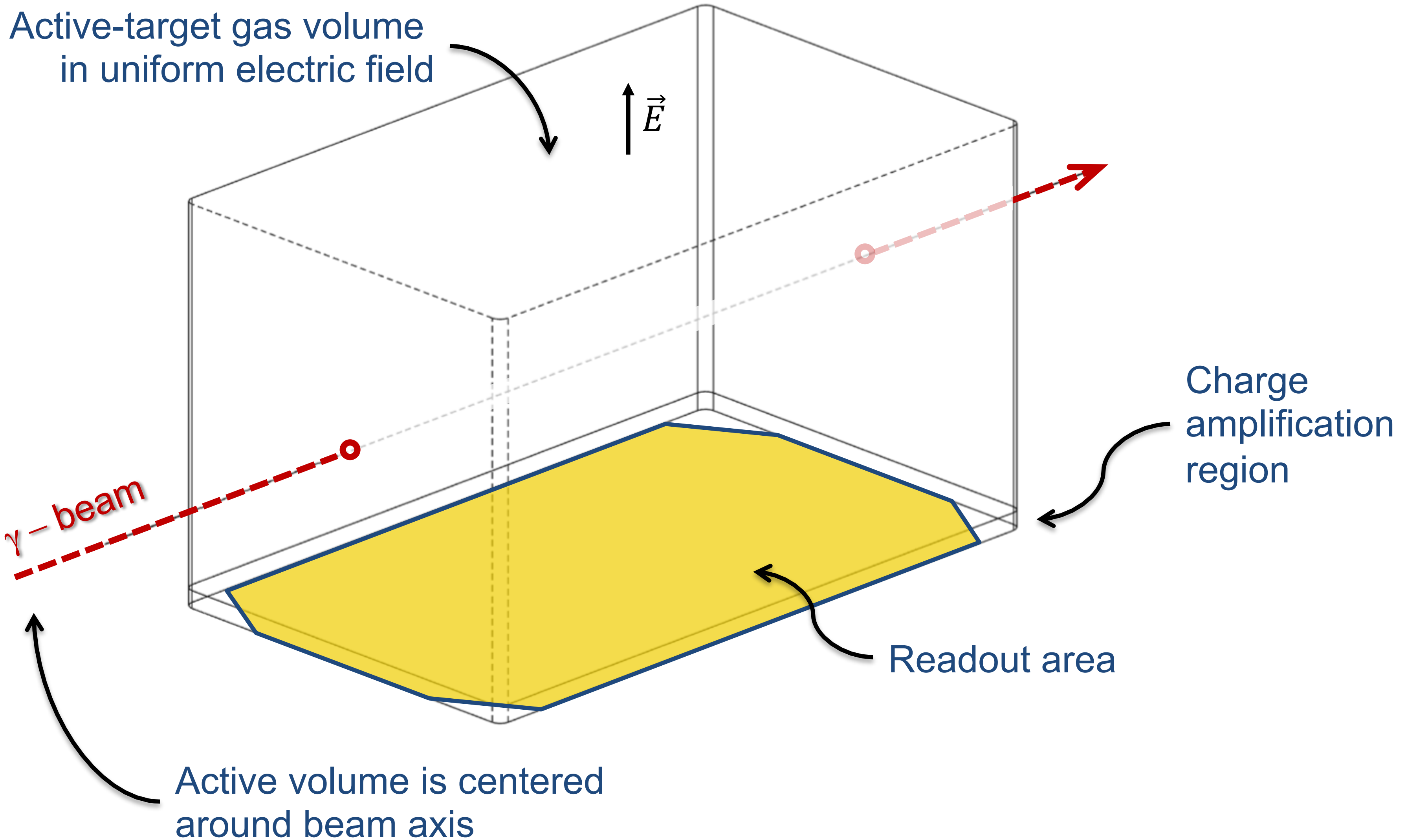
$$\mathbf{B}(\boldsymbol{b},\boldsymbol{\gamma})\mathbf{A} \leftrightharpoons \mathbf{A}(\boldsymbol{\gamma},\boldsymbol{b})\mathbf{B}$$

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

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

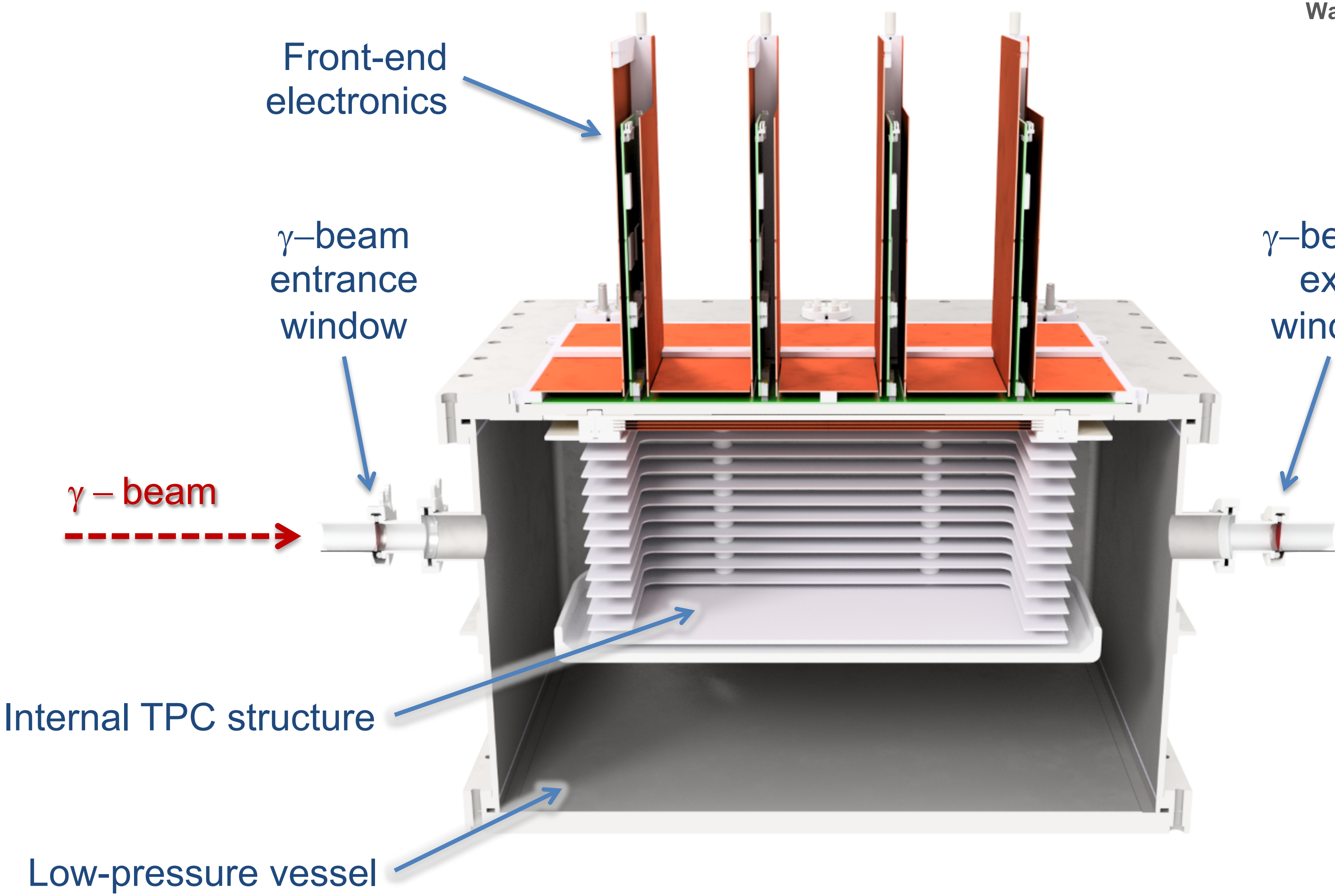
- Need quasi-monochromatic **intense gamma-ray beams:**
  - facilities such as: HIγS (USA), ELI-NP (Romania)
- Use **active-target** Time Projection Chamber technique**:**
  - measure kinematics of low-energy charged particle products
  - obtain accurate values of E1 / E2 components

Concept – active-target TPC



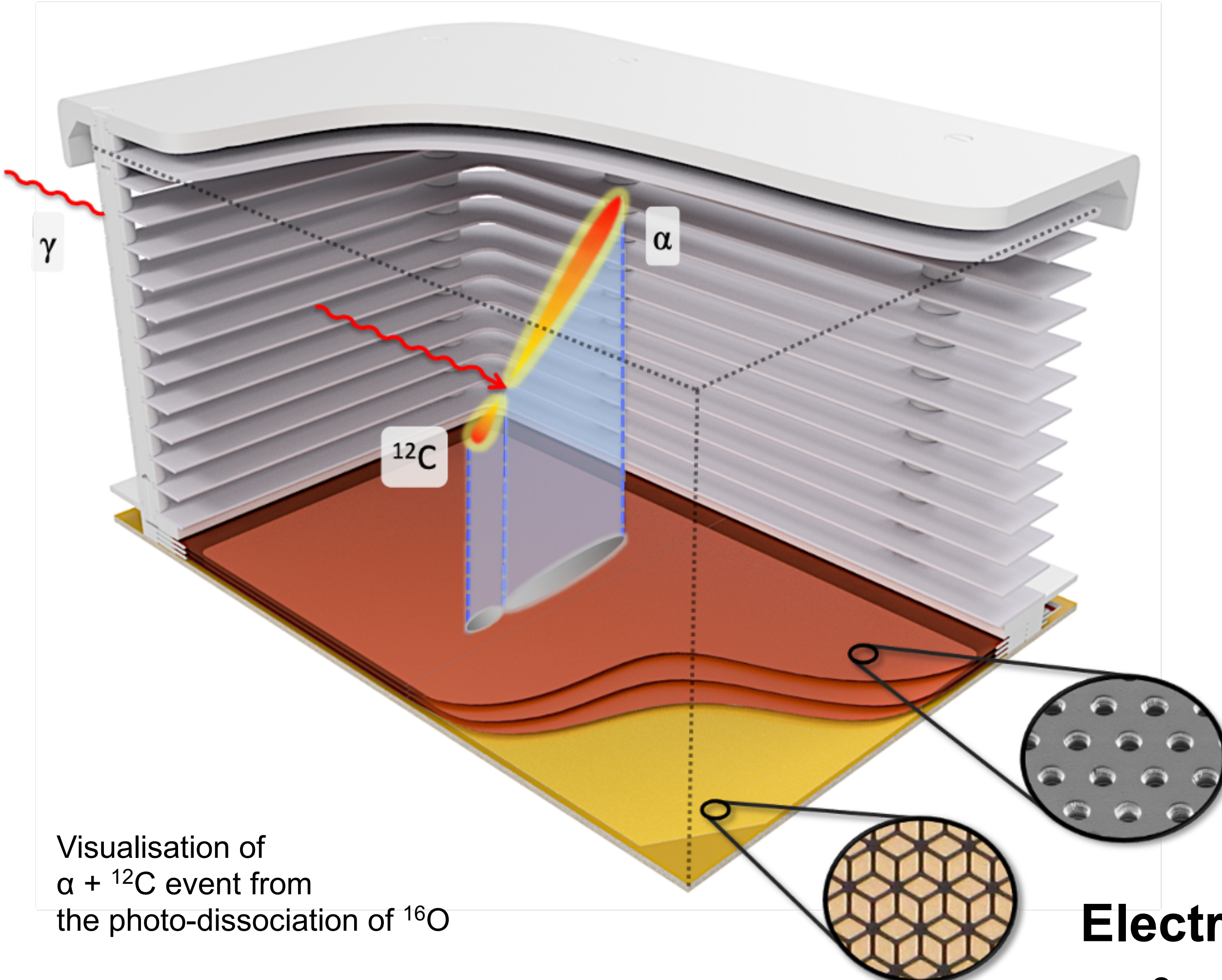
Concept – detector overview

Warsaw TPC



Concept – internal structure

Warsaw TPC



Visualisation of
α + ^{12}C event from
the photo-dissociation 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

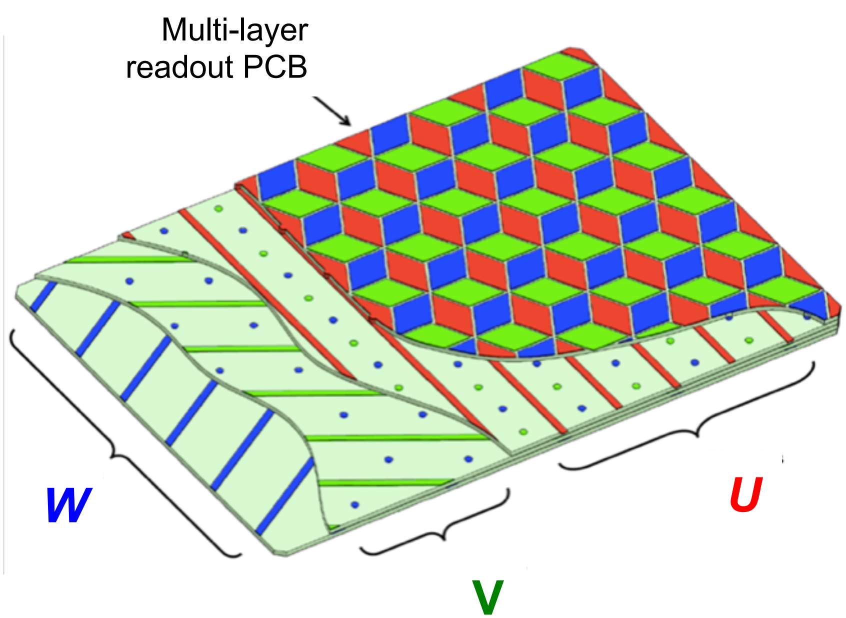
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

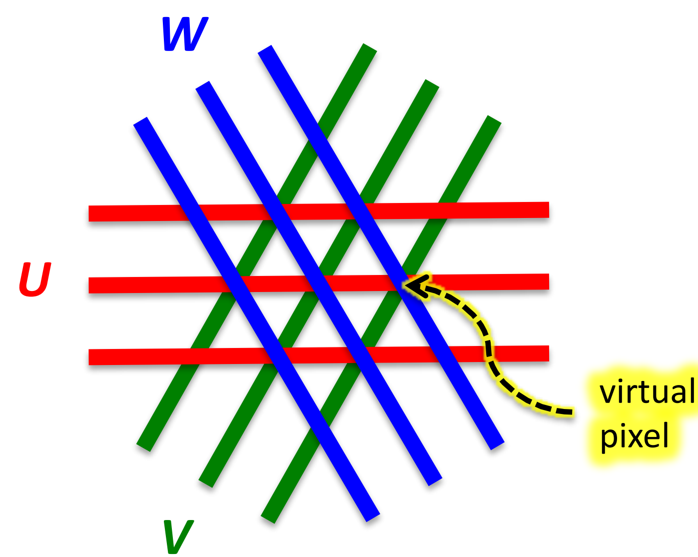
Concept – readout strips

Warsaw TPC

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



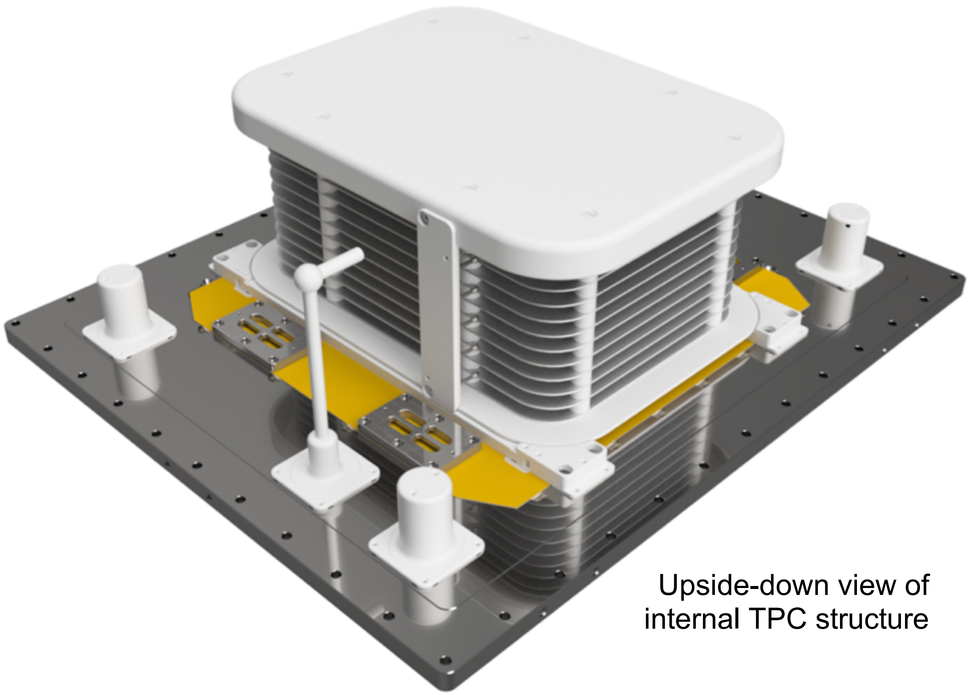


[1] S. Bachmann et al., NIM A **478**, 104 (2002)
[2] V. Ableev et al., NIM A **535**, 294 (2004)
[3] J. Bihałowicz et al., Proc. of SPIE **9290**, 92902C (2014)
[4] M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

Detector design

Warsaw TPC

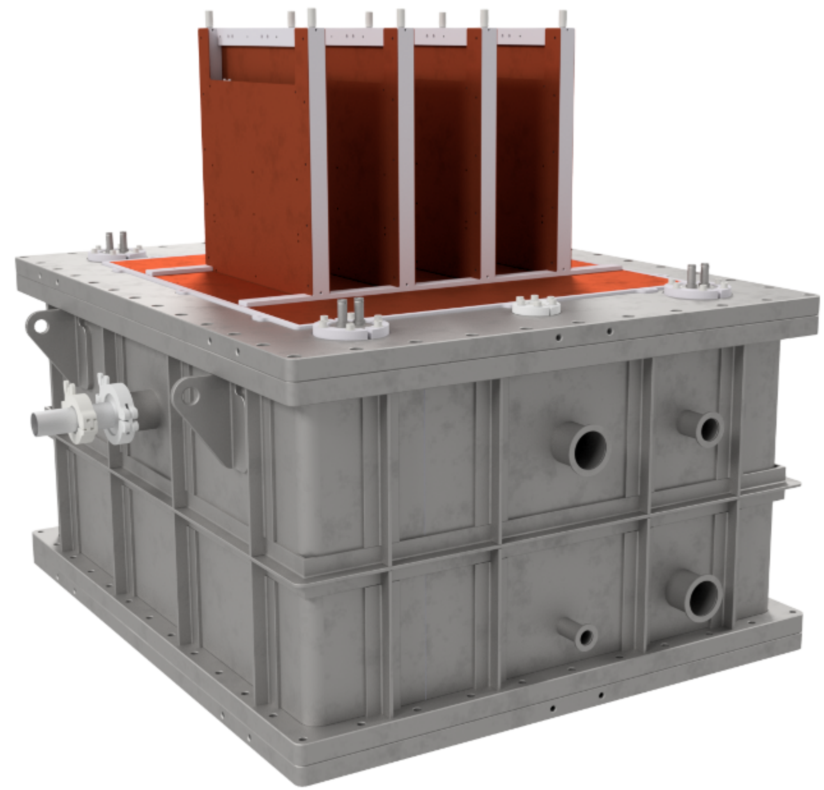
TPC with accompanying infrastructure designed and built at the Faculty of Physics, Univ. of Warsaw:



Upside-down view of internal TPC structure

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

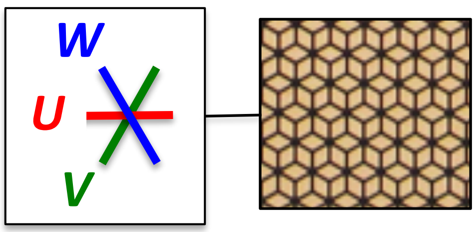
- Stainless steel vessel (170L)
- Barrel + two endcaps
- ISO-KF ports + custom signal ports



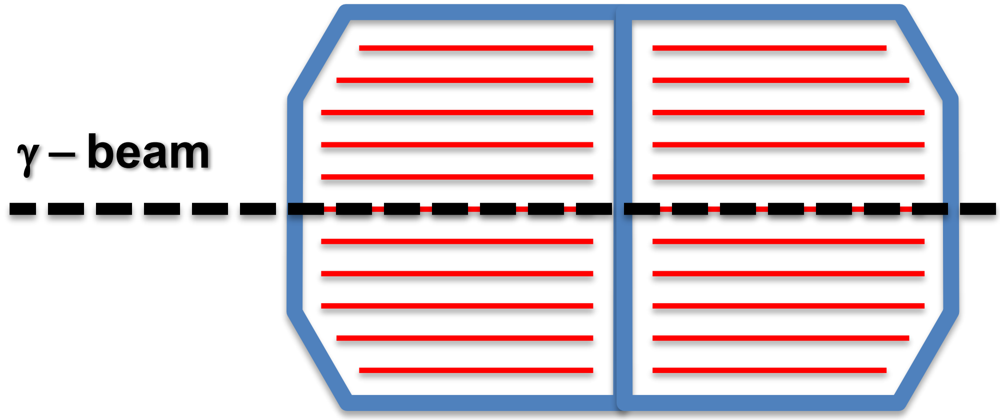
Readout PCB

Warsaw TPC

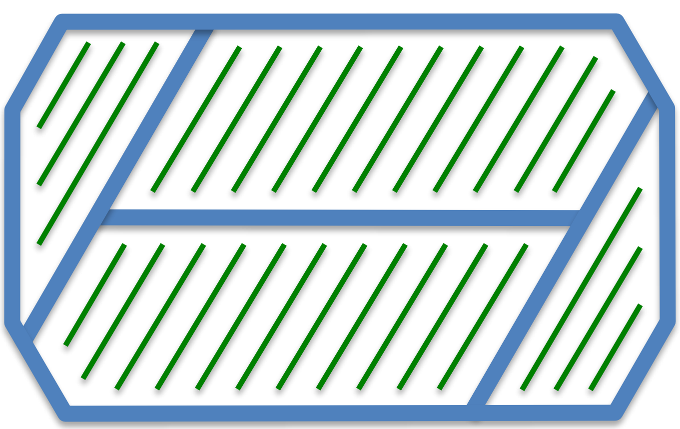
- 1018 strips (+6 spare channels for ext. analogue triggers)
- 1.5 mm strip pitch



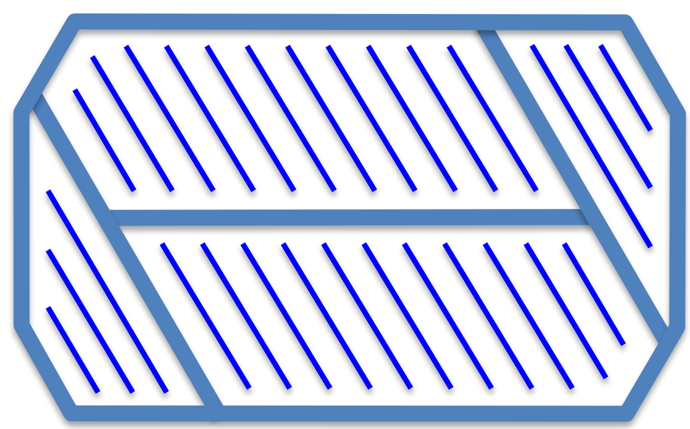
264 U-strips (2 sections)



376 V-strips (4 sections)

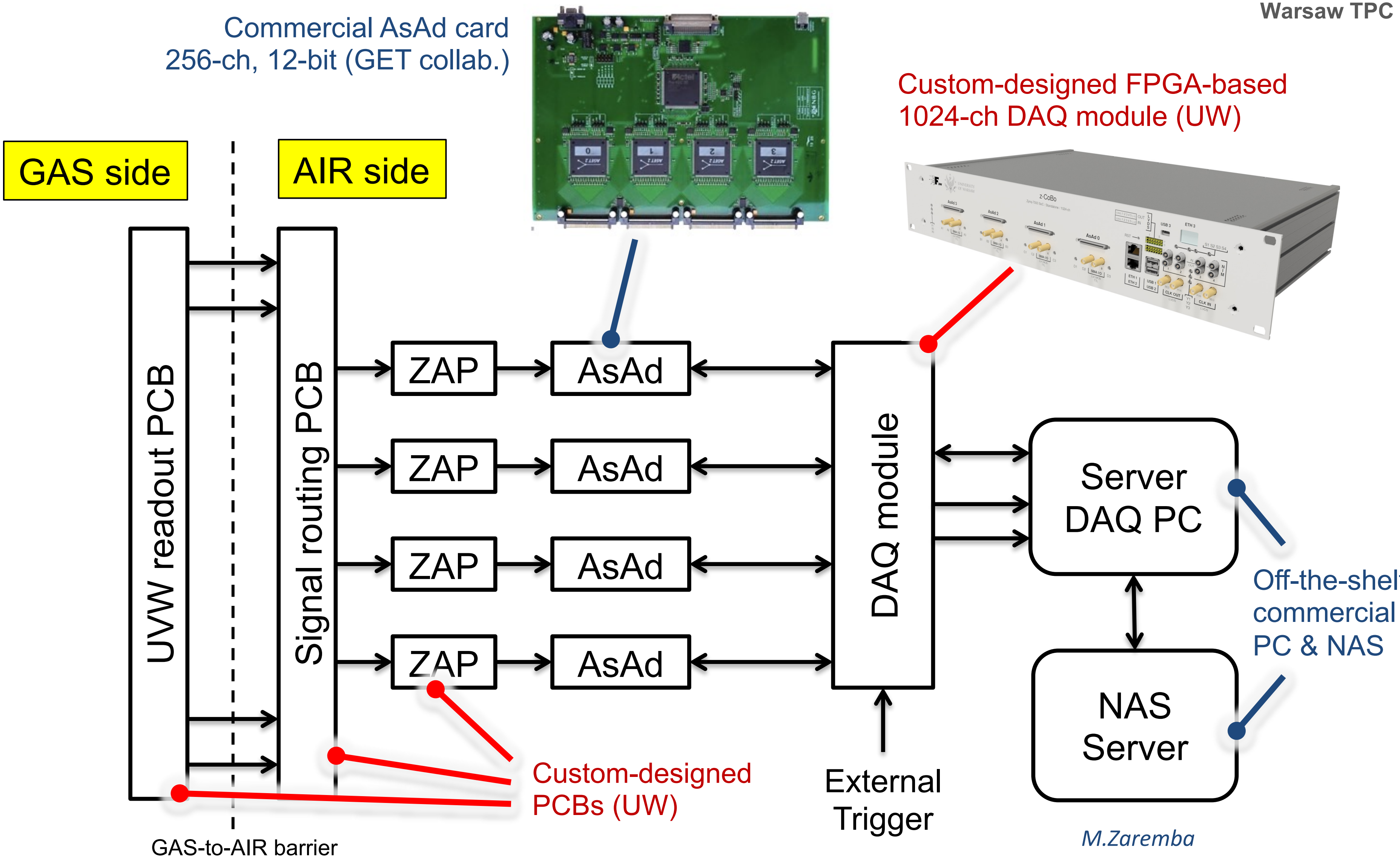


378 W-strips (4 sections)



DAQ readout chain

Warsaw TPC

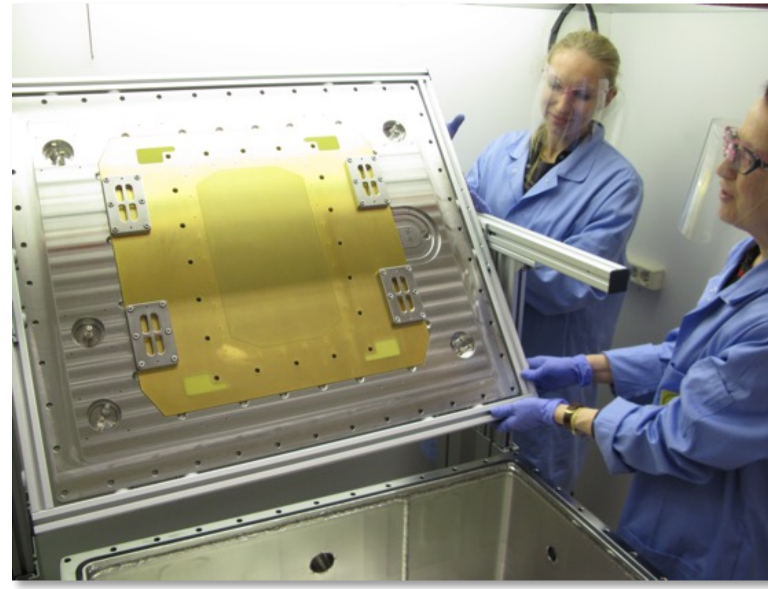


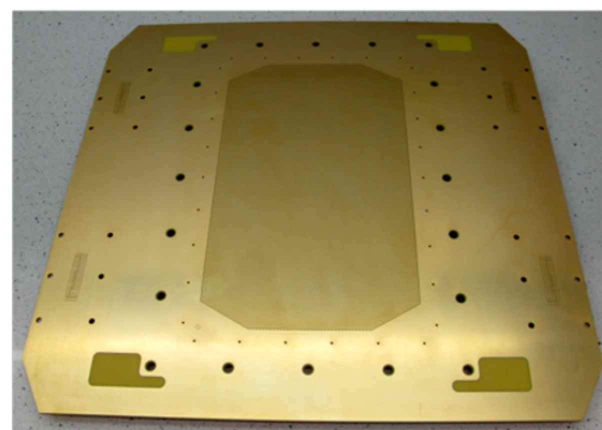
M.Zaremba
K.Kierzkowski
W.Okliński

Detector assembly

Warsaw TPC

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

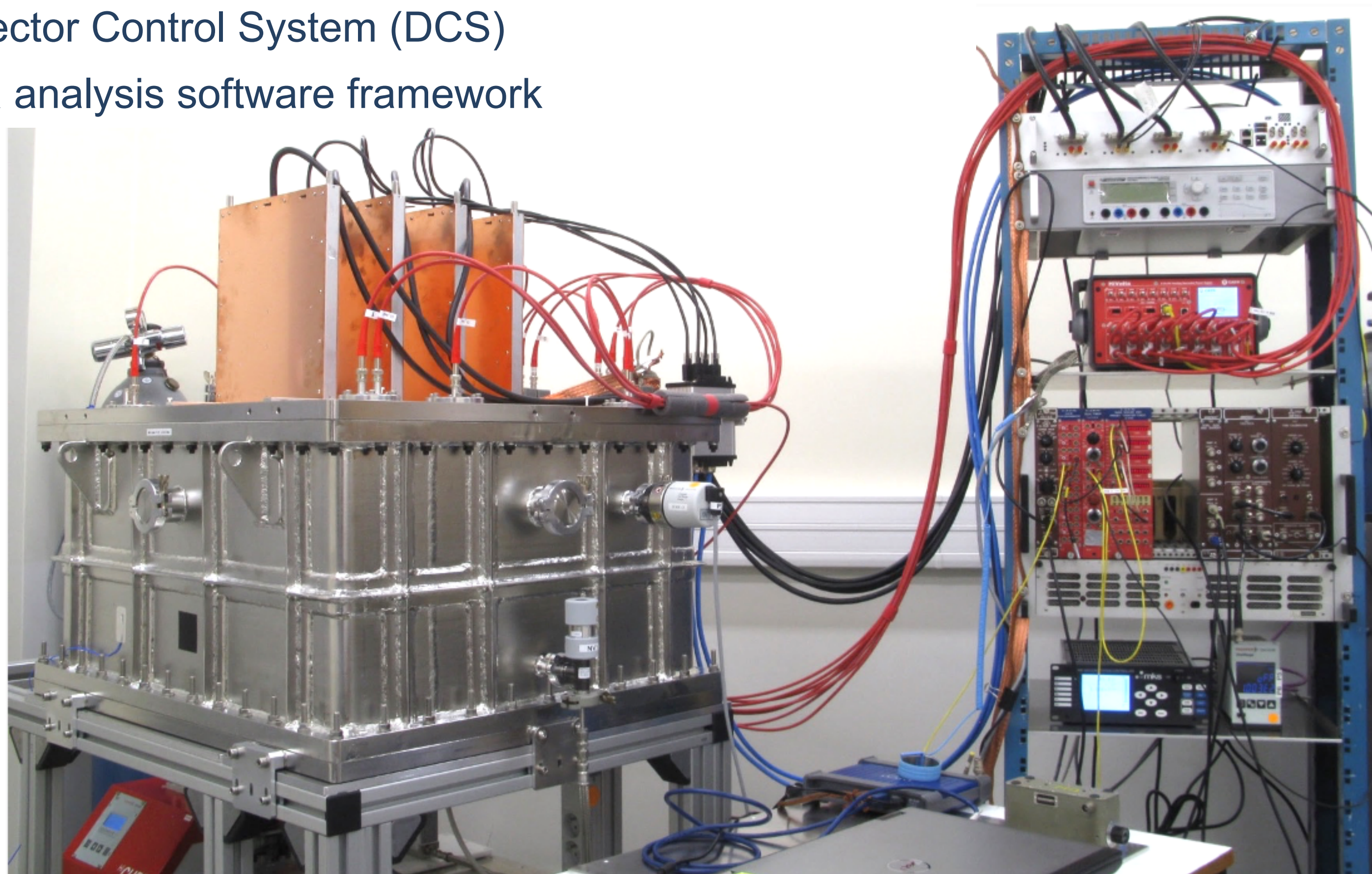




Detector test bench

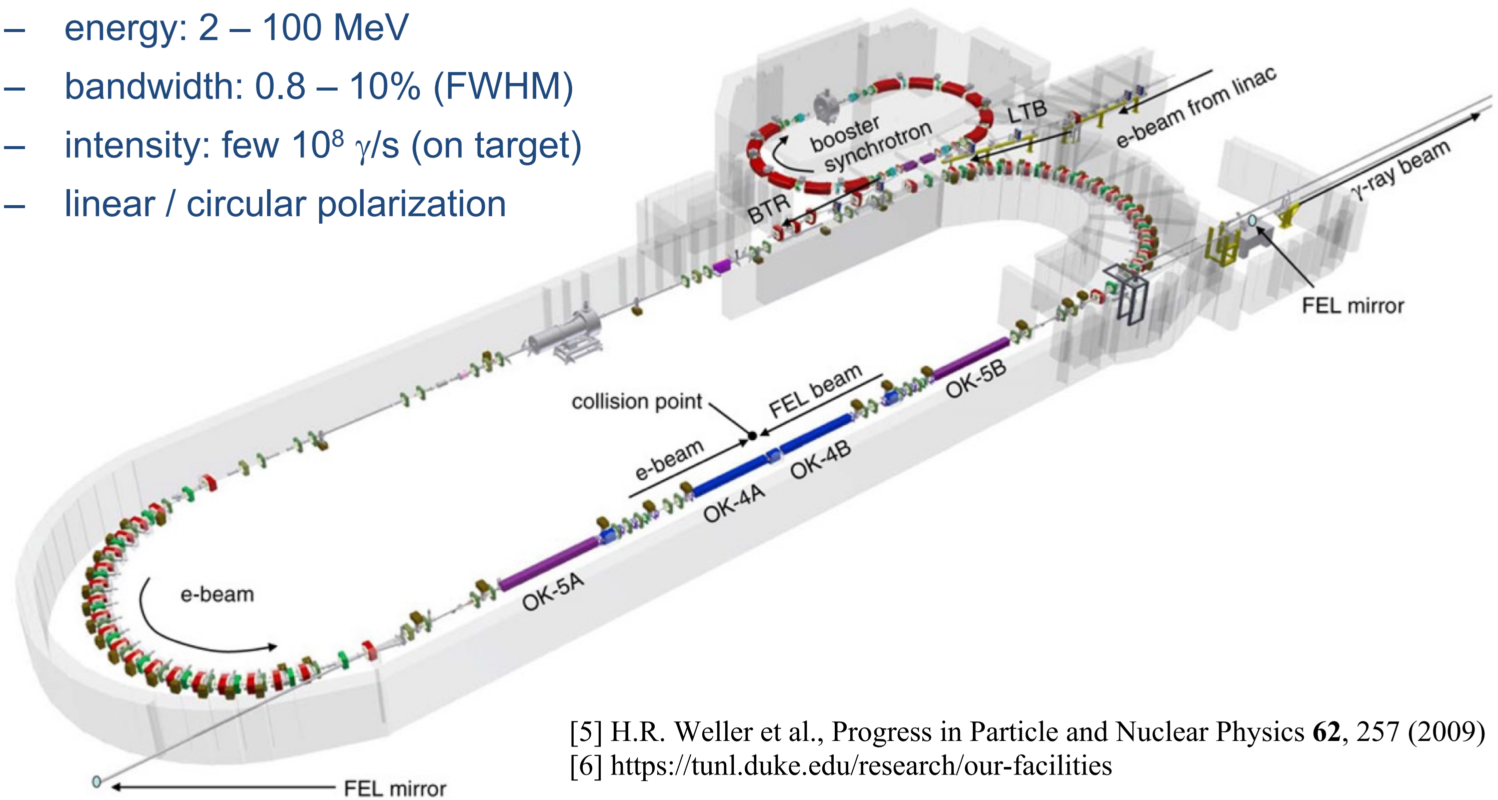
Warsaw TPC

- **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



^{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



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

^{16}O photodisintegration experiment @ HIγS

(April-September, 2022)

Warsaw TPC

- **Delivered γ-ray beams:**
  - E_{γ} = **8.51 – 13.9 MeV**
    E_{CM} = **1.35 – 6.7 MeV** ⇐ **^{12}C(α,γ)^{16}O**
  - I_{γ} = **(1.5 – 5)·10^{8} γ/s** on target
  - *FWHM* : 350 keV @ 8.51 MeV
  - ϕ =10.5 mm beam collimator
  - 275 hours / 15 energy points

- **Beam monitoring:**
  - E_{γ} : from HPGe detector
  - $I_{\gamma}(t)$: from scintillators
  - $\int I_{\gamma}(t)dt$: from activation of Au foils from (γ,n)

- **TPC working points:**
  - **pure CO_2 gas** @ 130, 190 or 250 mbar
  - pressure, electron drift velocity, electronics sampling rate optimized for charged particle ranges in detector's active volume

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

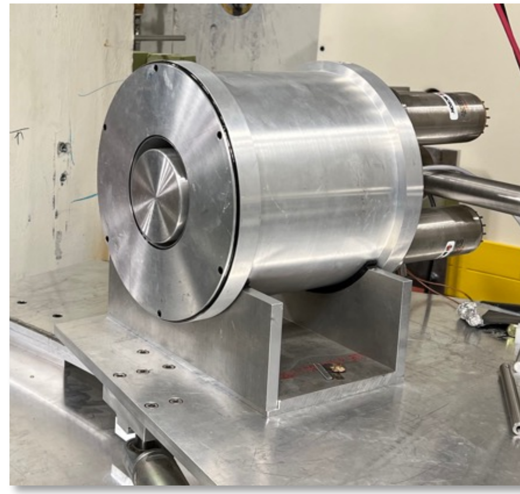
Beam monitoring & alignment

Warsaw TPC

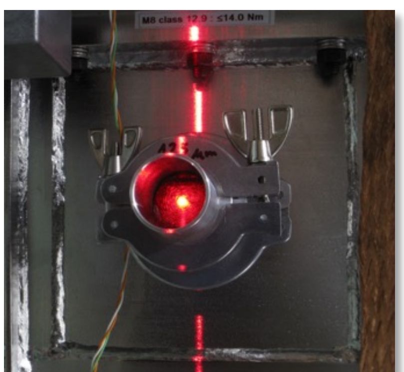
Collimator
ϕ =10.5 mm

Scintillators

HPGe (rear)

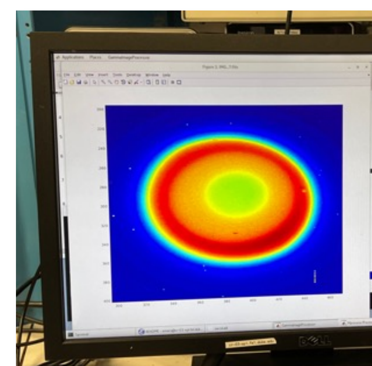


Au foil (rear)

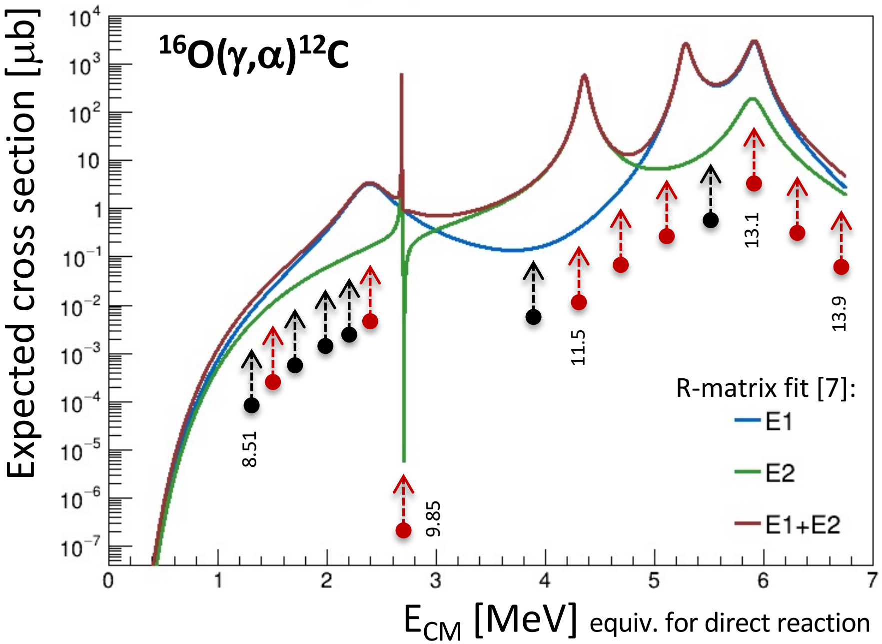


Alignment – laser

Alignment – CCD gamma camera + lead plugs:



Collected statistics



Warsaw TPC

- **Processed 9 out of 15 measured beam energy points:** %
  - 3 gas target densities p_1 p_2 p_3
  - 3 resonant energies used for tuning track energy scale E

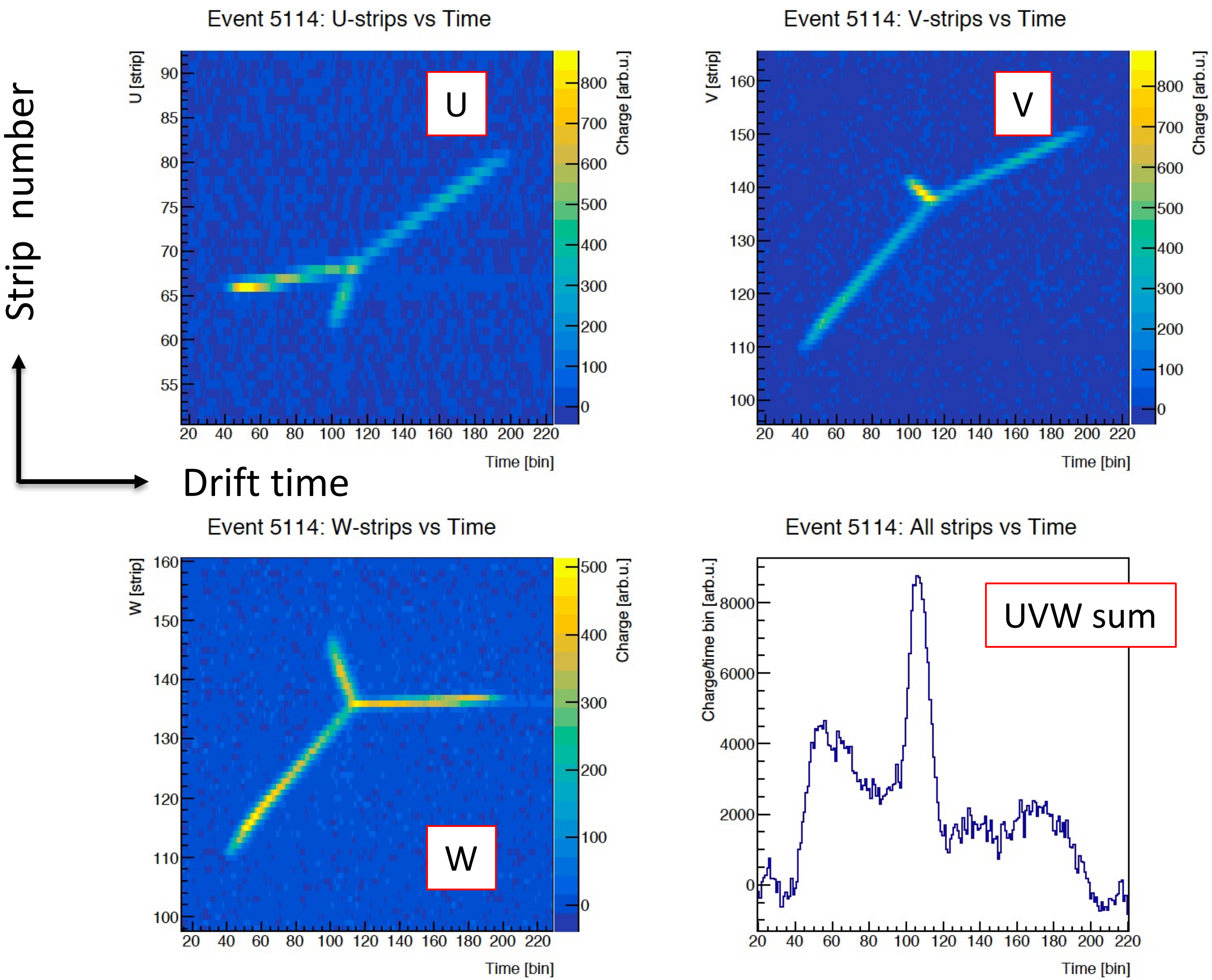
[7] R. J. deBoer et al., Rev. Mod. Phys. **89**, 035007 (2017)

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		
Beam time [h]	28.5	89	60.9	13	4	2.5	10.4	6	4	4.2	1.4	2	1.7	3	3.6	4.4
Events incl. bkg [× 10^3]	55	239	187	64	58	34	88	160	248	168	254	314	201	412	568	528
Analysed [%] MANUALLY	–	4	–	–	–	11	37	–	4	9	2	–	10	–	3	3
AUTO	–	–	–	–	–	–	–	–	30	–	38	–	–	–	–	–

Track reconstruction (1/5)

Warsaw TPC

- **Example 3-particle topology:** raw data



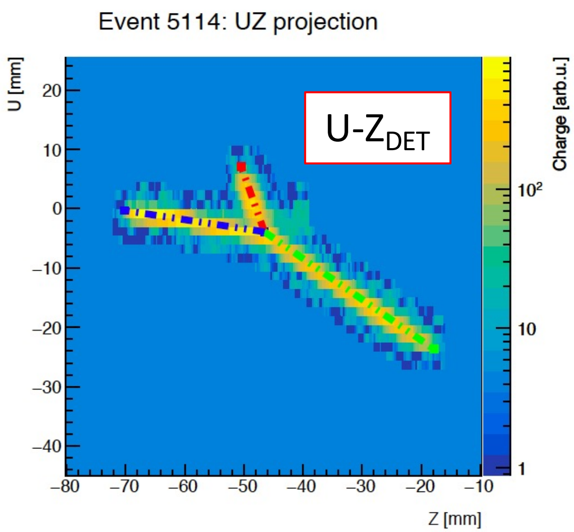
E_γ=13.9 MeV

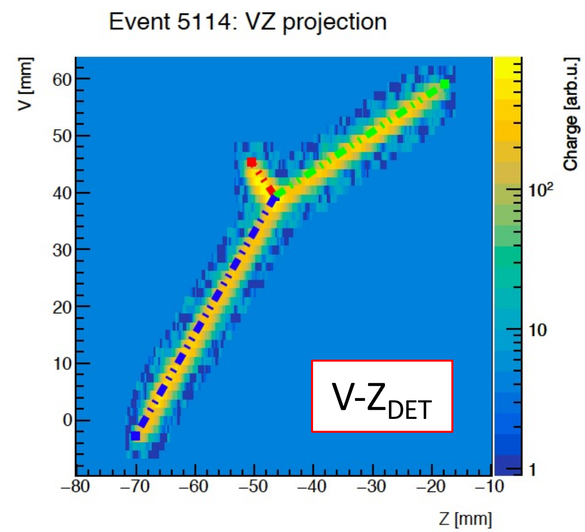
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Track reconstruction (2/5)

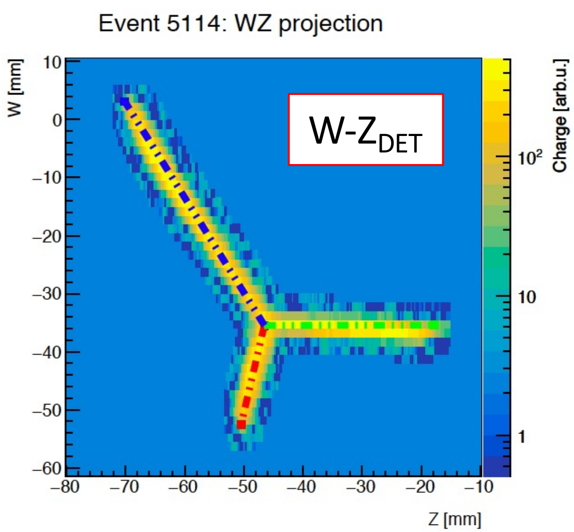
Warsaw TPC

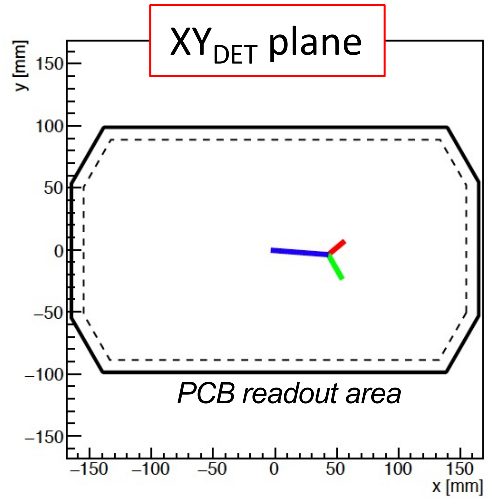
- **Example 3-particle topology:** reconstructed α tracks in 3D





E_γ=13.9 MeV

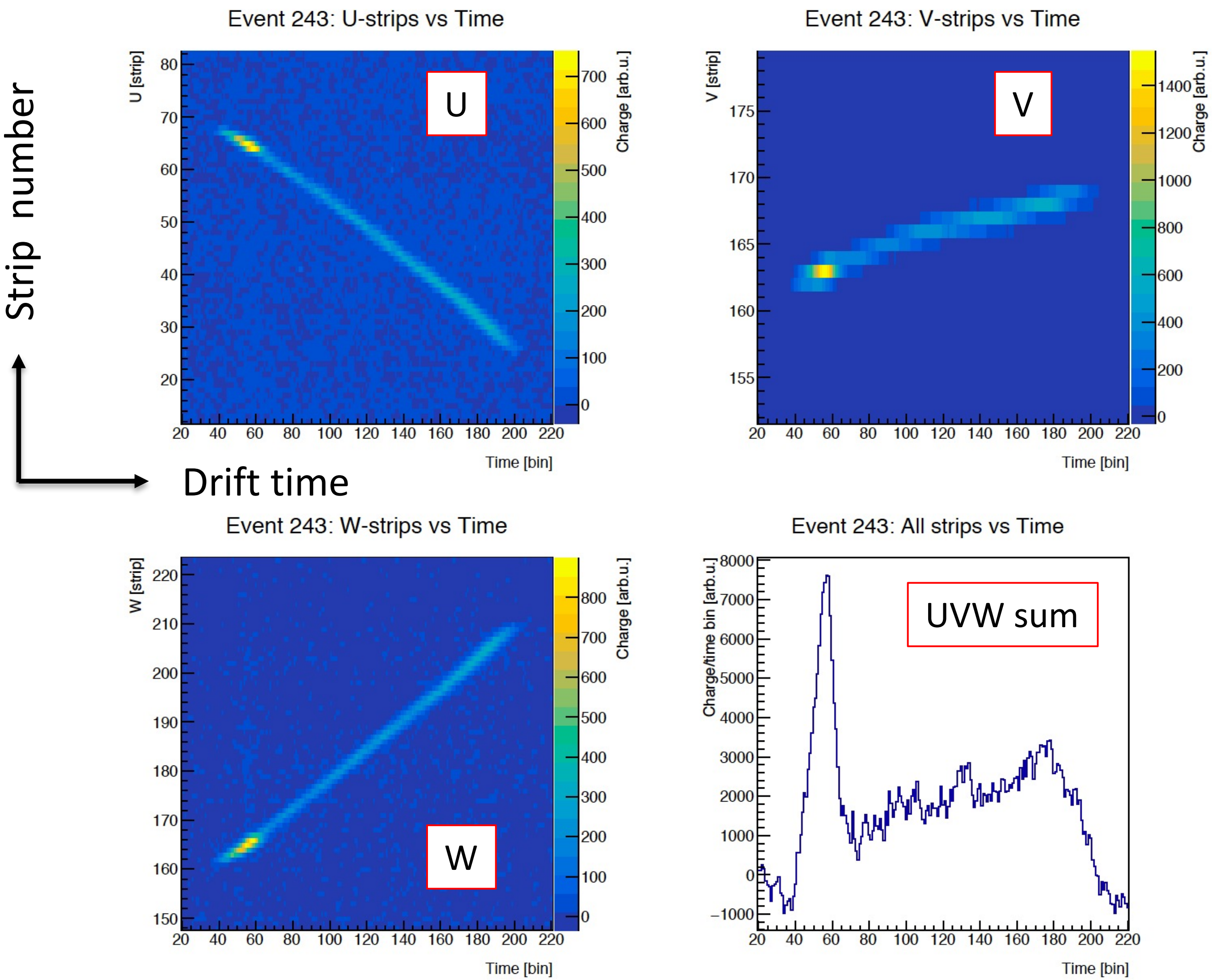




- Manual procedure
- Clustered data fitted by eye
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Track reconstruction (3/5)

- **Example 2-particle topology:** raw data



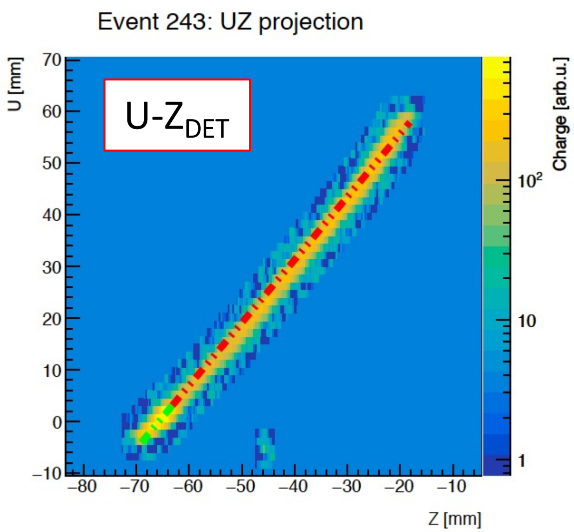
E_γ=13.9 MeV

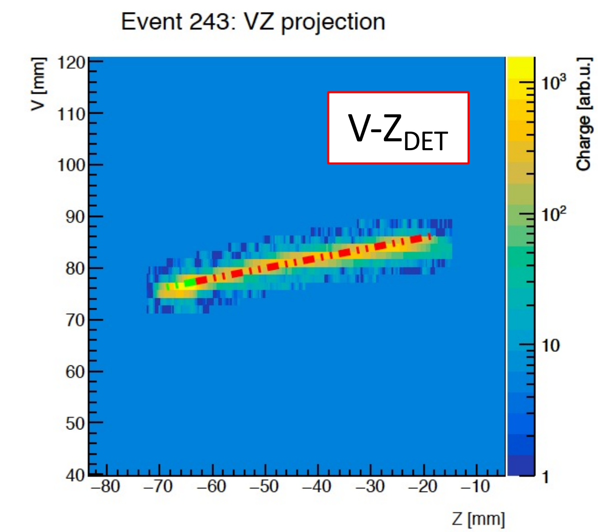
- Pressure: 250 mbar
- Sampling: 12.5 MHz

Track reconstruction (4/5)

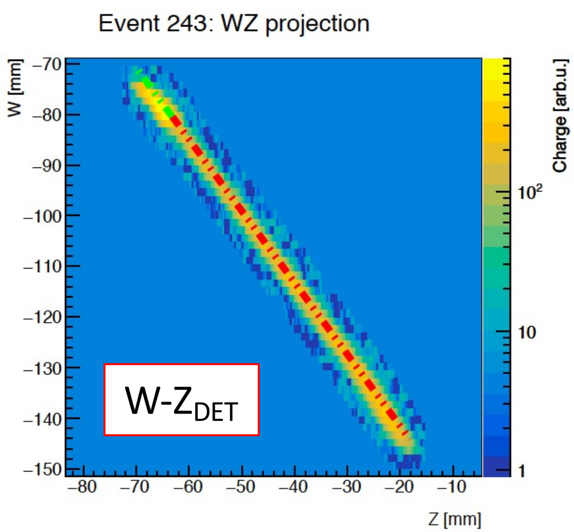
Warsaw TPC

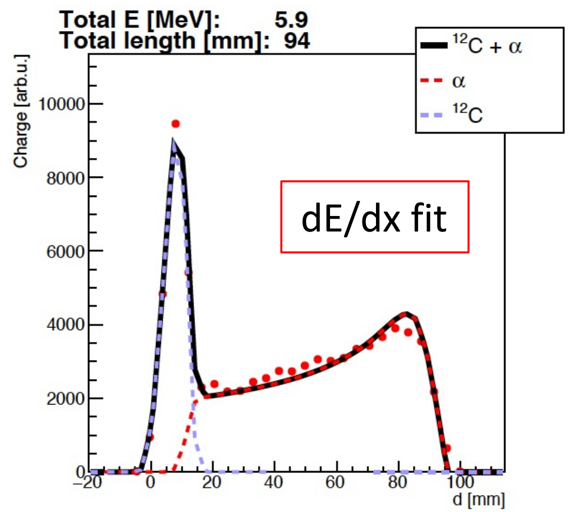
- **Example 2-particle topology:** reconstructed **α** + **C** tracks in 3D





E_γ=13.9 MeV





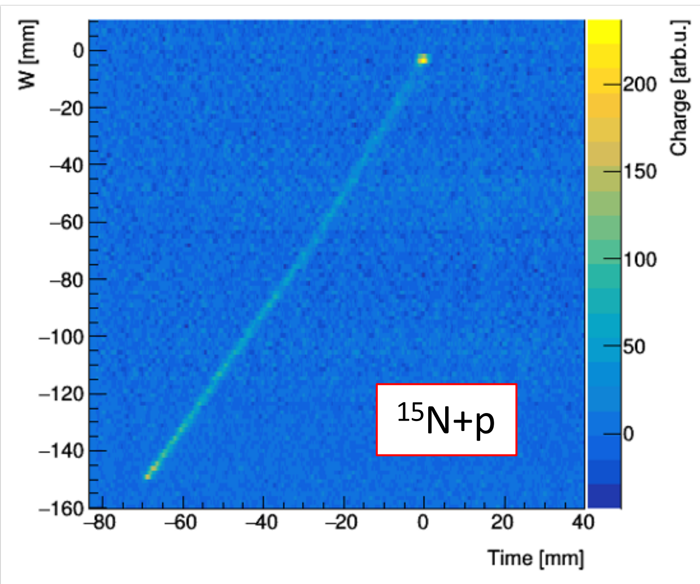
- Automatic procedure
- Clustered data fitted to smeared dE/dx templates (SRIM + diffusion)
- Pressure: 250 mbar
- Sampling: 12.5 MHz

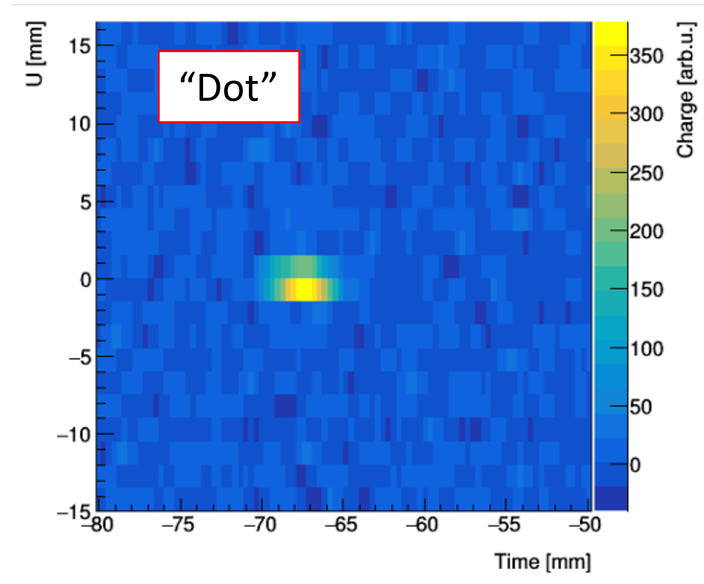
A.Kalinowski
M.Fila

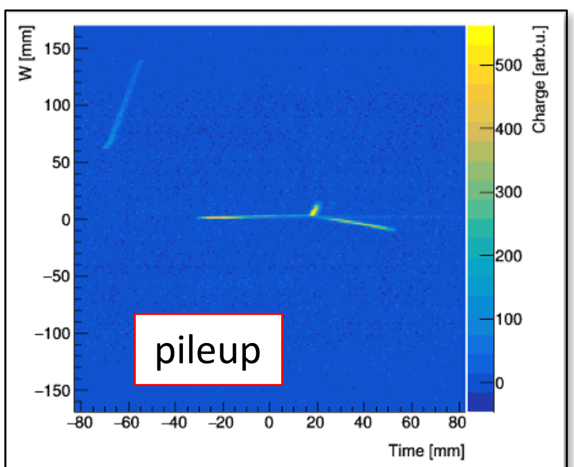
Track reconstruction (5/5)

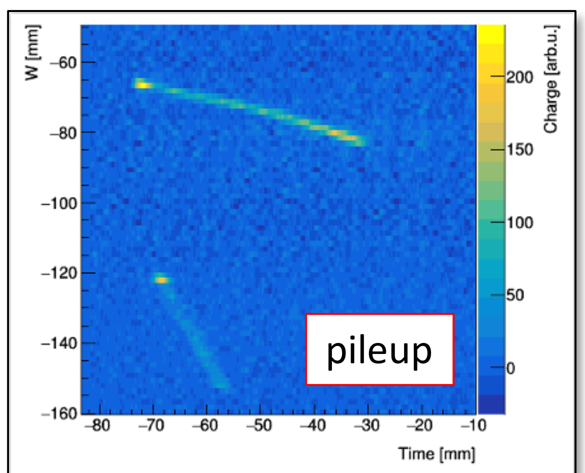
Warsaw TPC

- Examples of background & complex events:









E_{γ}=13.9 MeV

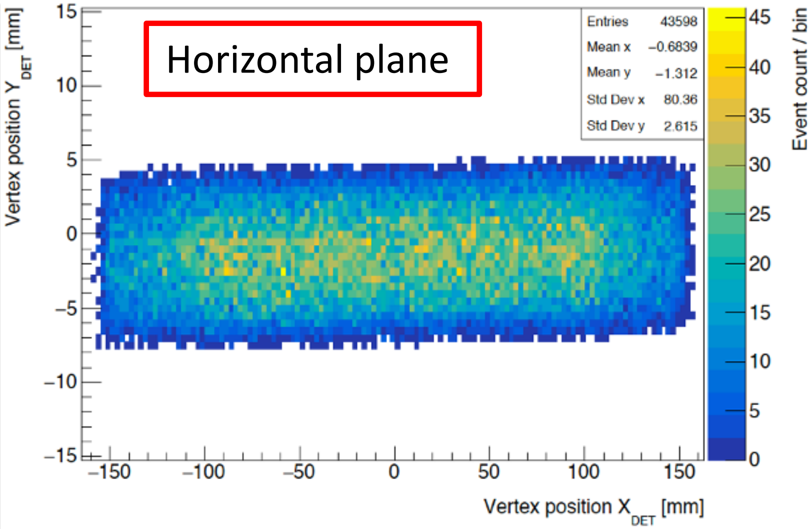
- Only 1 of 3 projections is shown for simplicity
- Pressure: 250 mbar
- Sampling: 12.5 MHz

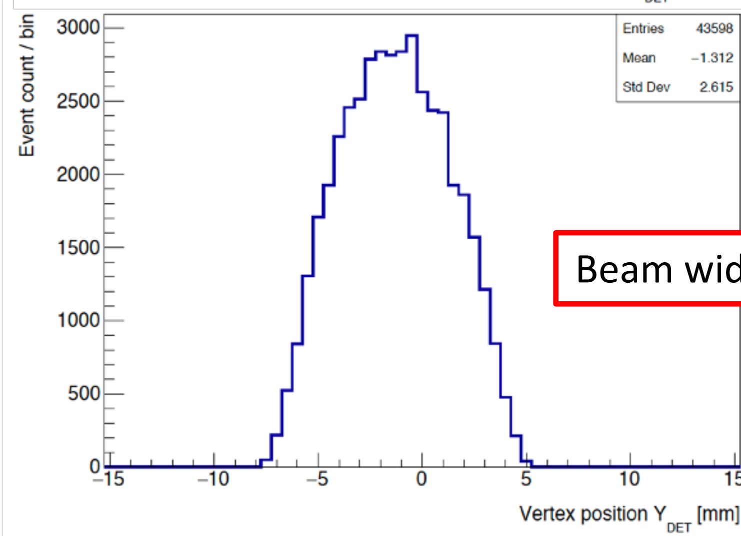
Beam mis-alignment

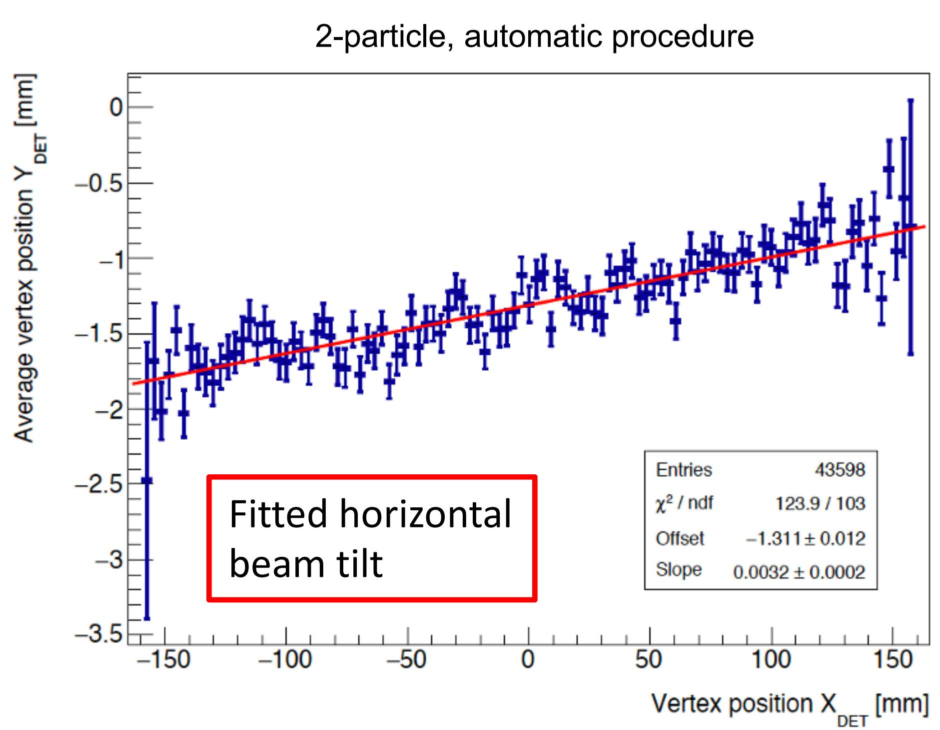
Warsaw TPC

- Automatic procedure, 2-particle reaction vertices:

E_γ=11.5 MeV





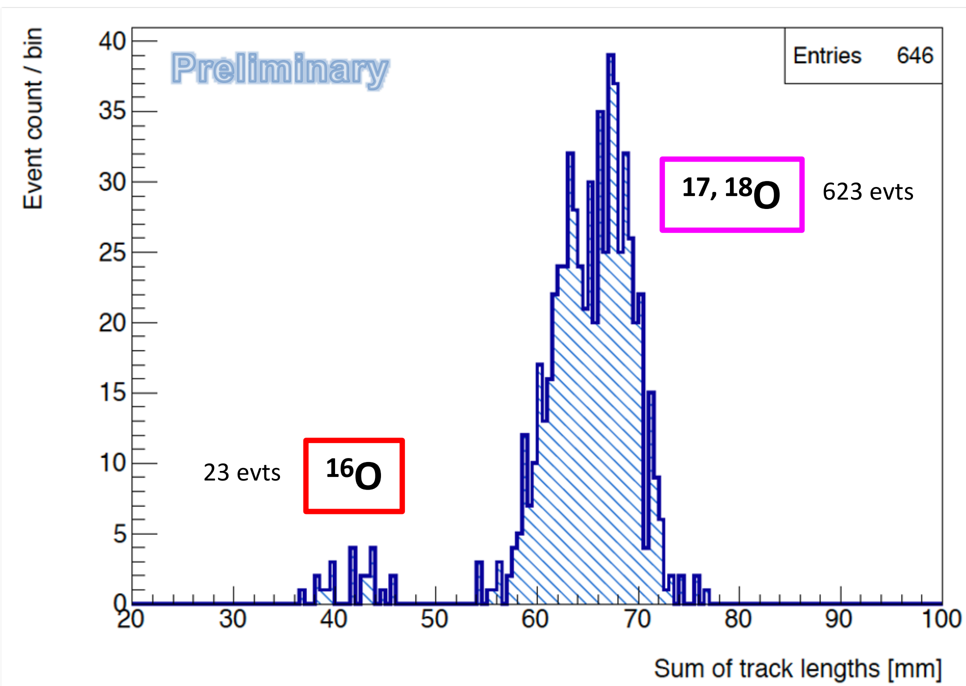


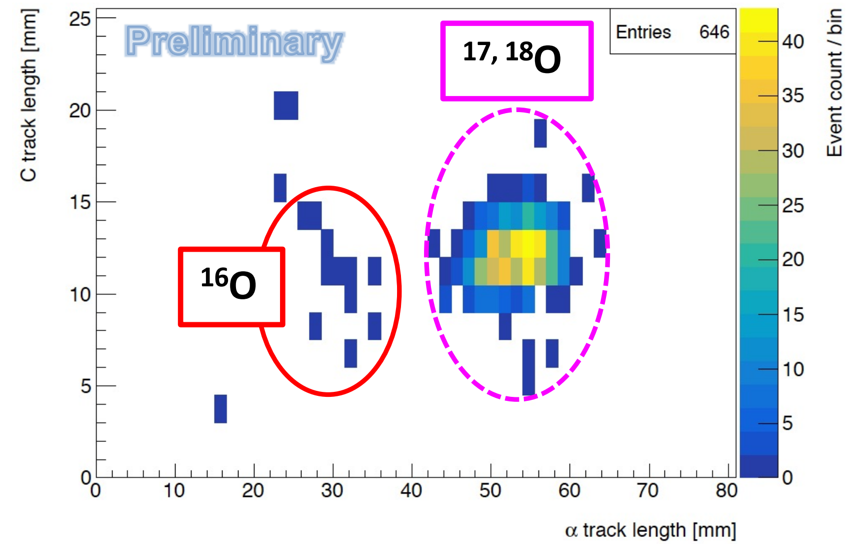
Event identification

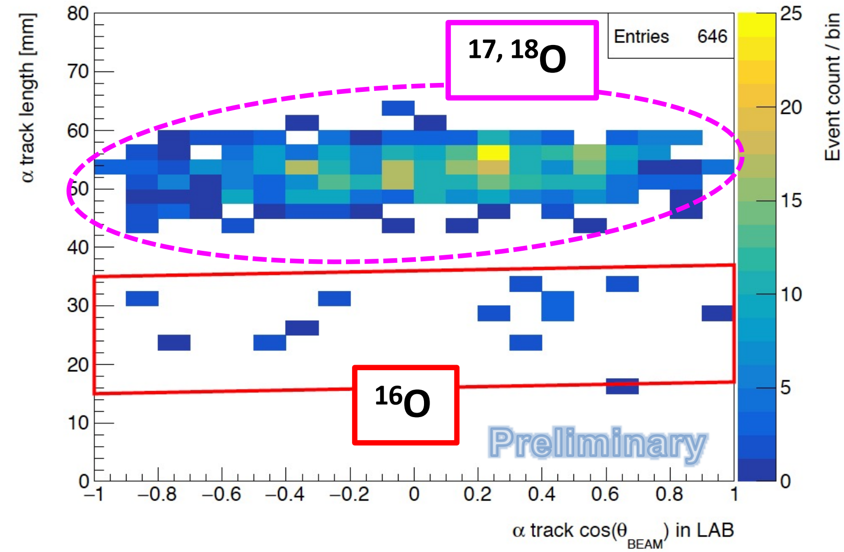
Warsaw TPC

- Example technical plots to identify ^{16}O candidate events
- Manual procedure, 2-particle events

E_γ=8.66 MeV





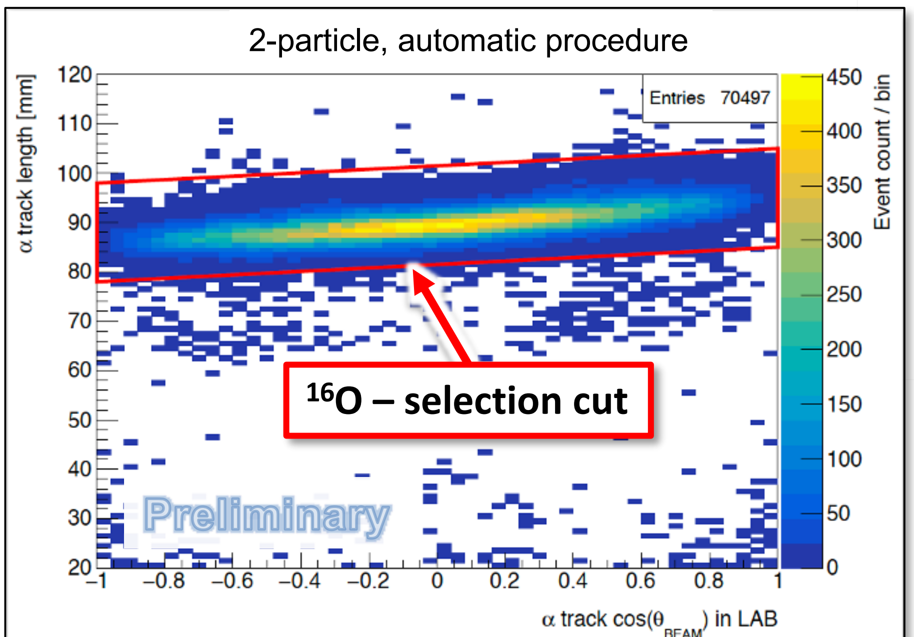


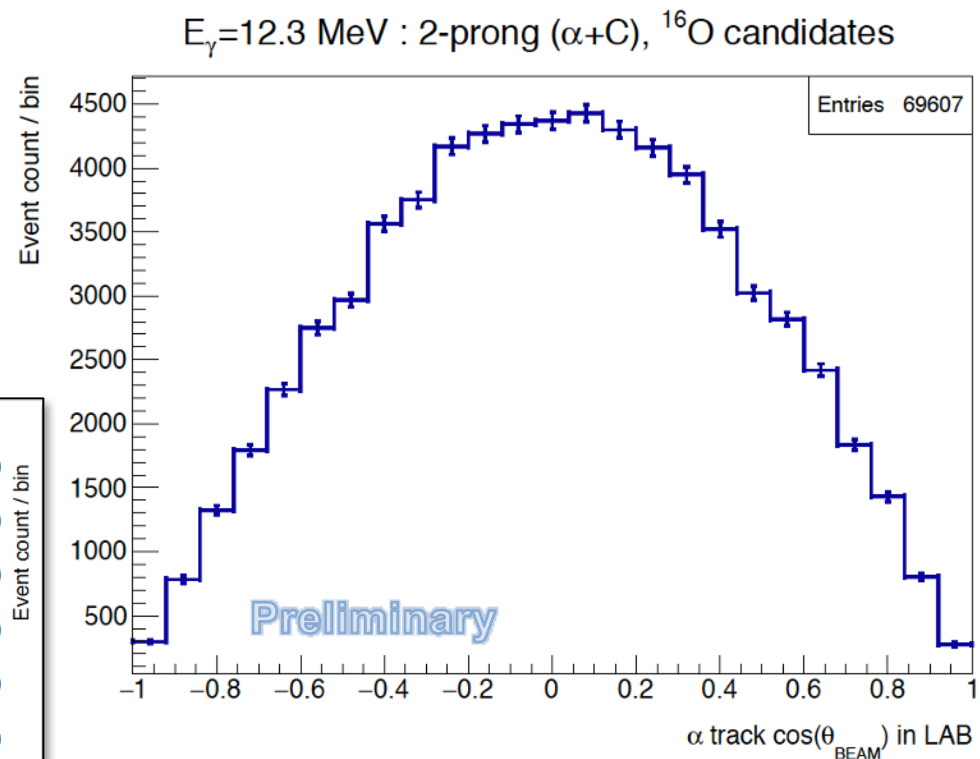
Angular distributions (1/3)

Warsaw TPC

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

E_γ=12.3 MeV





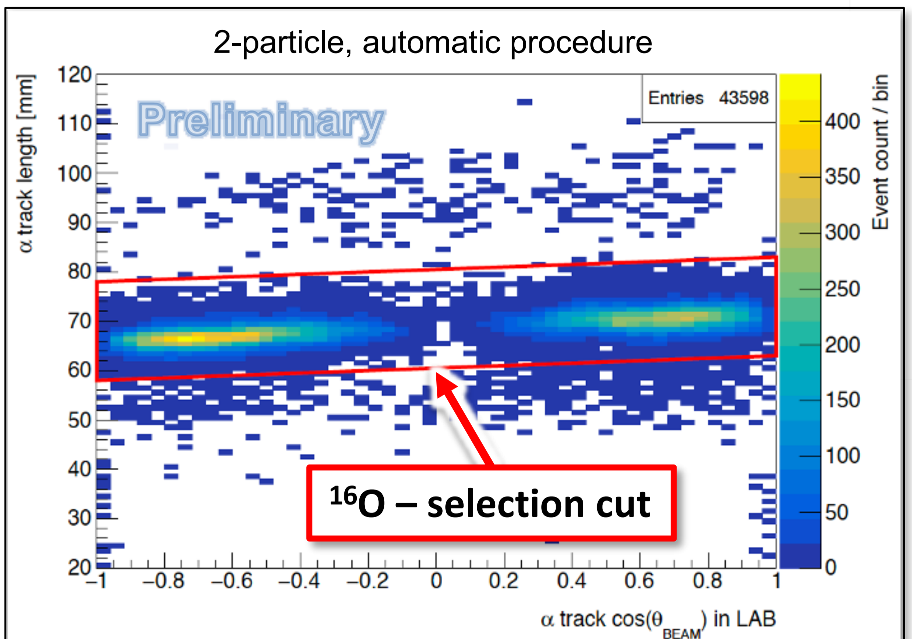
⇒ E1 shape

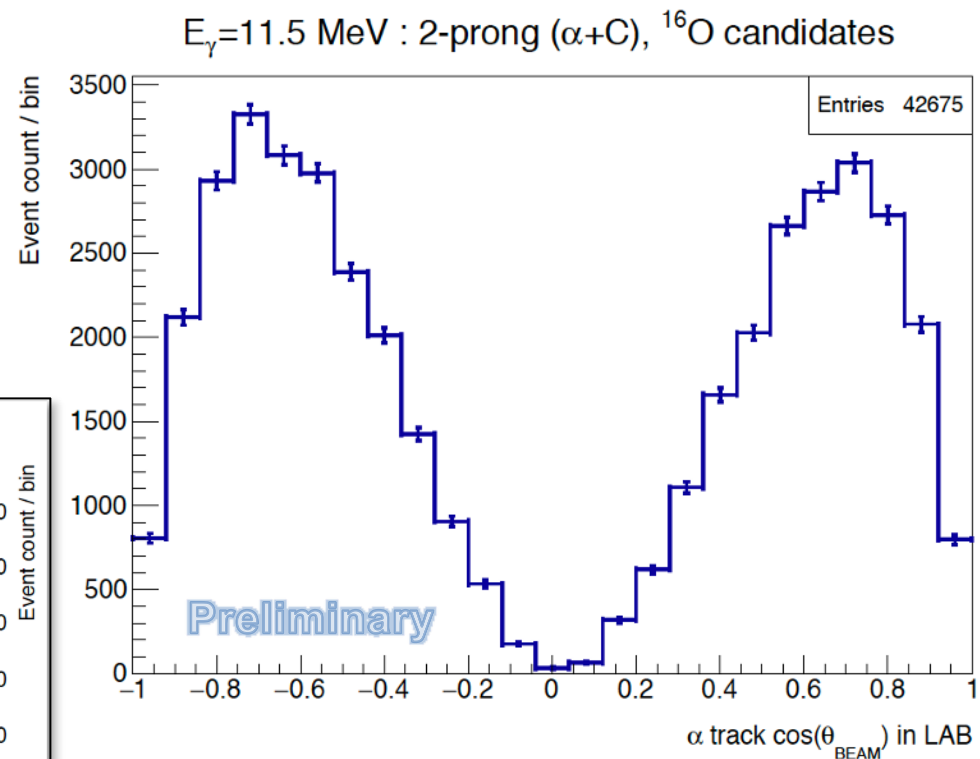
Angular distributions (2/3)

Warsaw TPC

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

E_γ=11.5 MeV





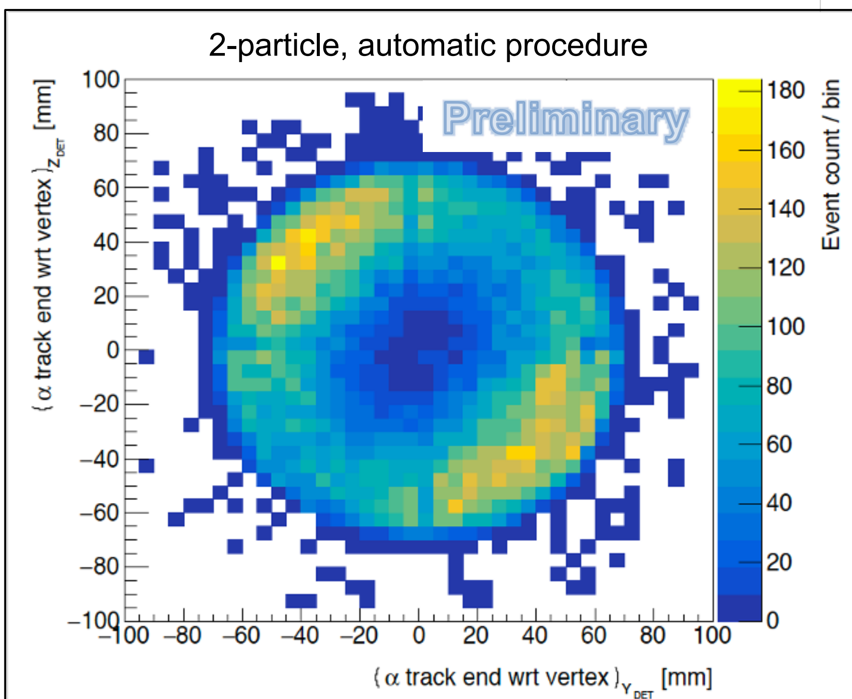
⇒ E2 shape

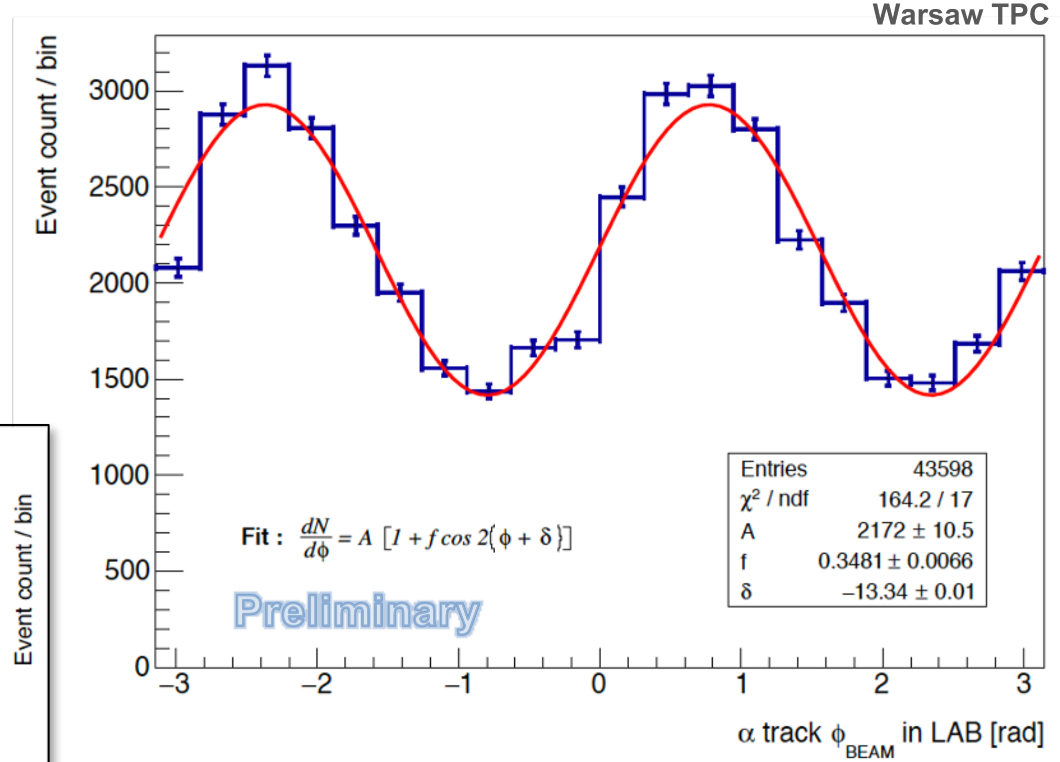
Angular distributions (3/3)

Warsaw TPC

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

E_γ=11.5 MeV





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

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

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

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

Energy scale calibration (1/2)

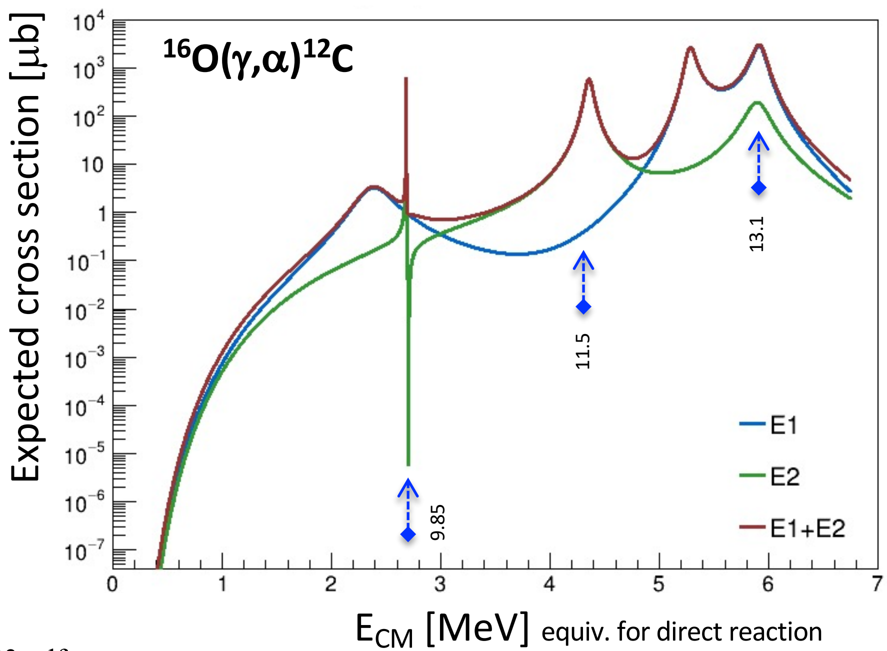
Warsaw TPC

- For $^{16}O(\gamma,\alpha)^{12}C$ it is enough to measure kinematics of α-particle track
- Particle energy from $Range(E)$ table or $\frac{dE}{dx}$ Bragg curve
  - predictions of SRIM and GEANT slightly differ
- 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 [8]:

    $\mathbf{2^+}$: $E_x = 9.8445 \pm 0.0005$ MeV

    $\mathbf{2^+}$: $E_x = 11.520 \pm 0.004$ MeV

    $\mathbf{1^-}$: $E_x = 13.090 \pm 0.008$ MeV
  - use 3 energy points with E_γ spectra centred at respective E_x
  - separate calibrations needed for manual- and automatic reconstruction



[8] TUNL compilation data for ^{16}O levels: https://nucldata.tunl.duke.edu/nucldata/HTML/A=16/16_13_1993.pdf

Energy scale calibration (2/2)

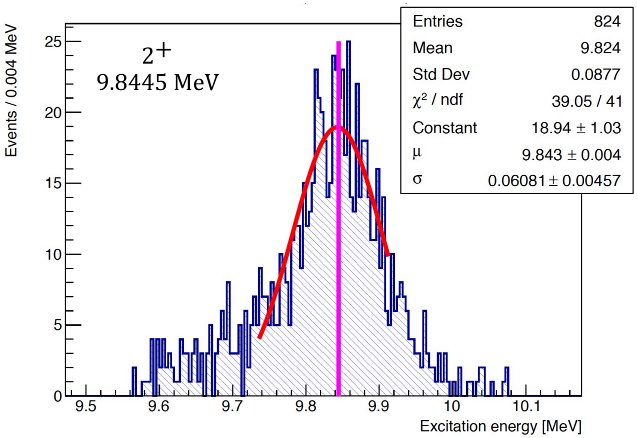
Warsaw TPC

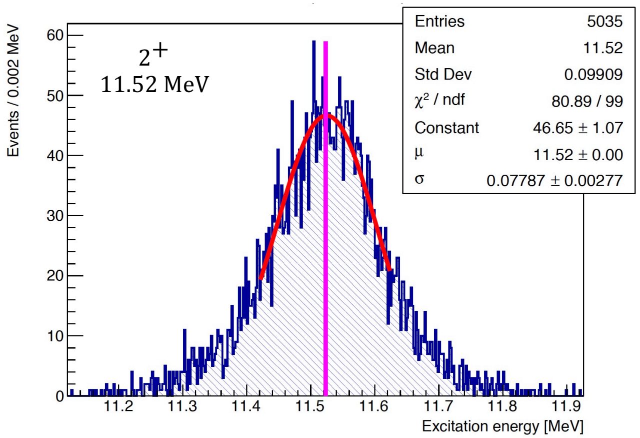
- Tested several 2-parametric models for correcting α-particle energy, e.g.:

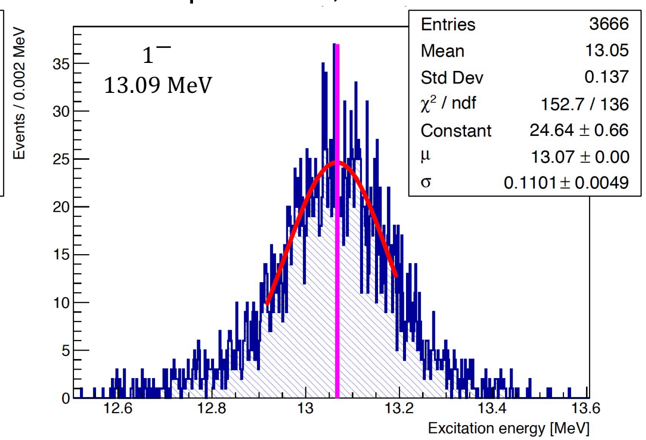
$$E_{corr}^{LAB}(R_{meas}) = a \cdot E_{SRIM}\left(R = R_{meas} \cdot \frac{p}{p_0} \cdot \frac{T_0}{T} + b\right)\Bigg|_{p_0\,,\,T_0}$$ where: a = scale, b = offset

- Fit for best agreement between **reconstructed** and **expected** peak position of the **Excitation Energy (E_x)** spectrum in CM frame

Manual procedure, ^{16}O candidates



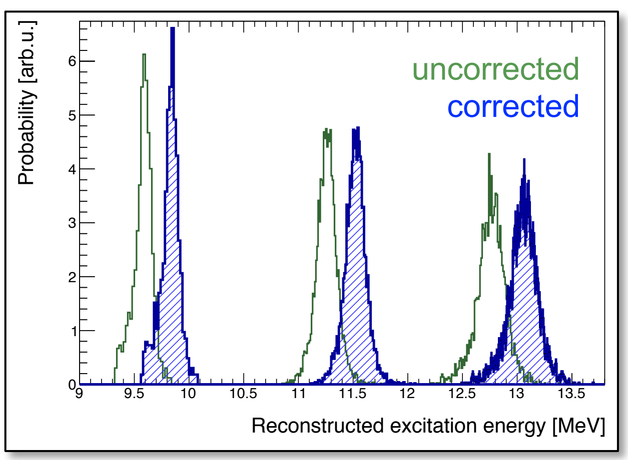


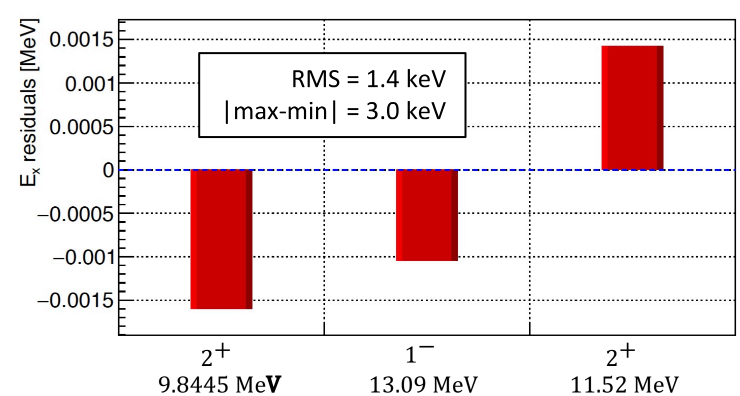


$$\begin{cases} a = 1.035(7) \\ b = 1.64(24)\ mm \end{cases}$$

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

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





Beam energy characterisation

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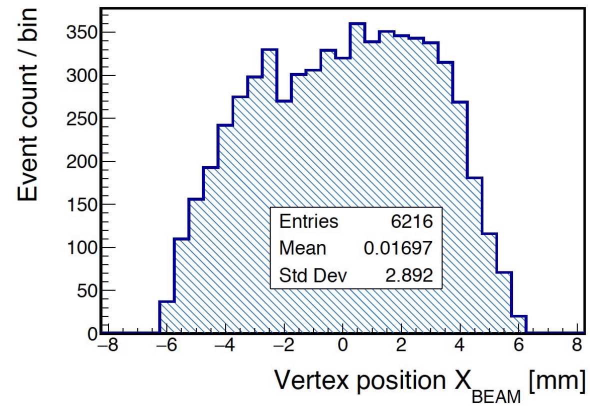
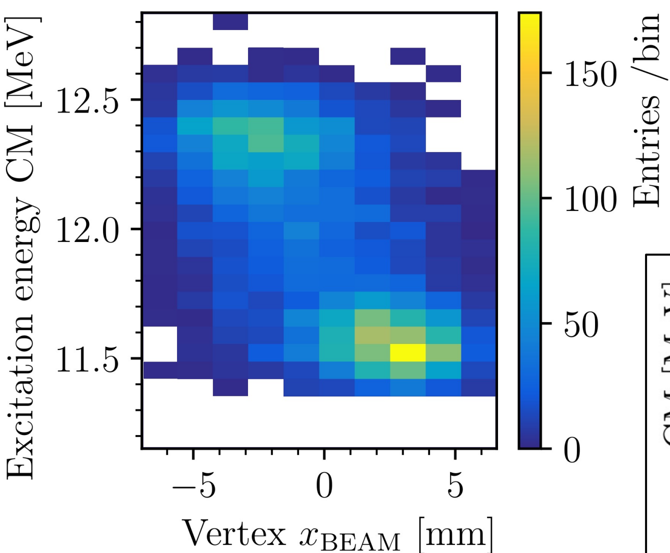
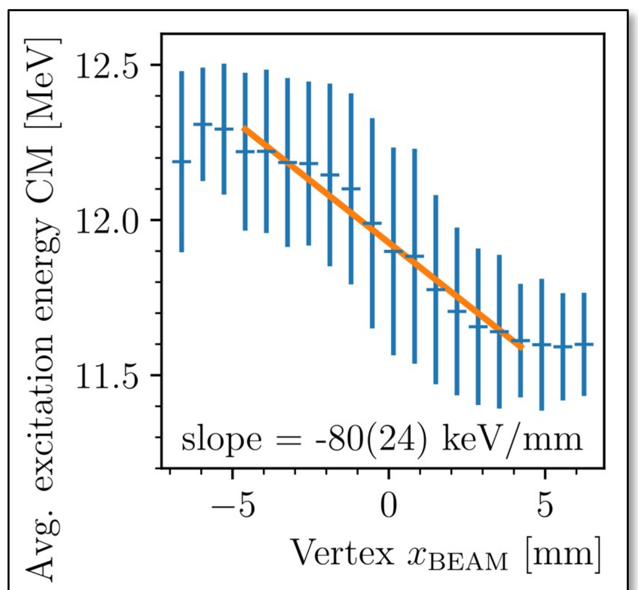
- Beam energy point @ 11.9 MeV excites two nearby resonant states: E_x =11.52 MeV (E2) and E_x =12.44 MeV (E1)
- <u>Observation</u>: reconstructed $\langle E_x \rangle$ & $\langle E_\gamma \rangle$ depend on the lateral beam position x_{BEAM} inside front γ-ray collimator

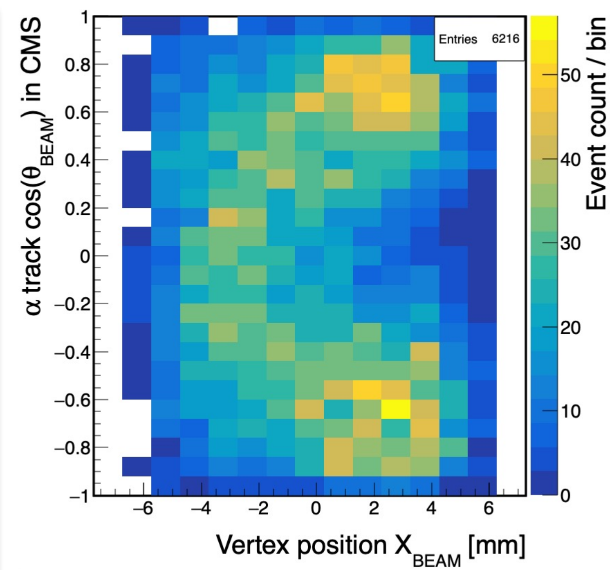




E_γ=11.9 MeV

Manual procedure, ^{16}O candidates





⇒ different E_γ spectra can be analyzed by slicing vertex pos.

⇒ narrower collimator should reduce E_γ spread on target

Conclusions

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✓ First experiments:

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

✓ Plans:

- improve automated track finding algorithms (e.g. with help of Machine Learning)
- improve energy scale calibration method
- unfold absolute beam intensity for cross-section measurement
- process full statistics with automated reconstruction
- **2024:** explore lower E_{CM} energies for $^{16}O(\gamma,\alpha)^{12}C$ and $^{12}C(\gamma,3\alpha)$ at the HIγS facility – pending increase of gamma beam intensity
- **After 2023:** deliver similar detector (ELITPC) dedicated for the new Variable Energy Gamma system – VEGA (ELI-NP, Romania)

Thank you for your attention !!!

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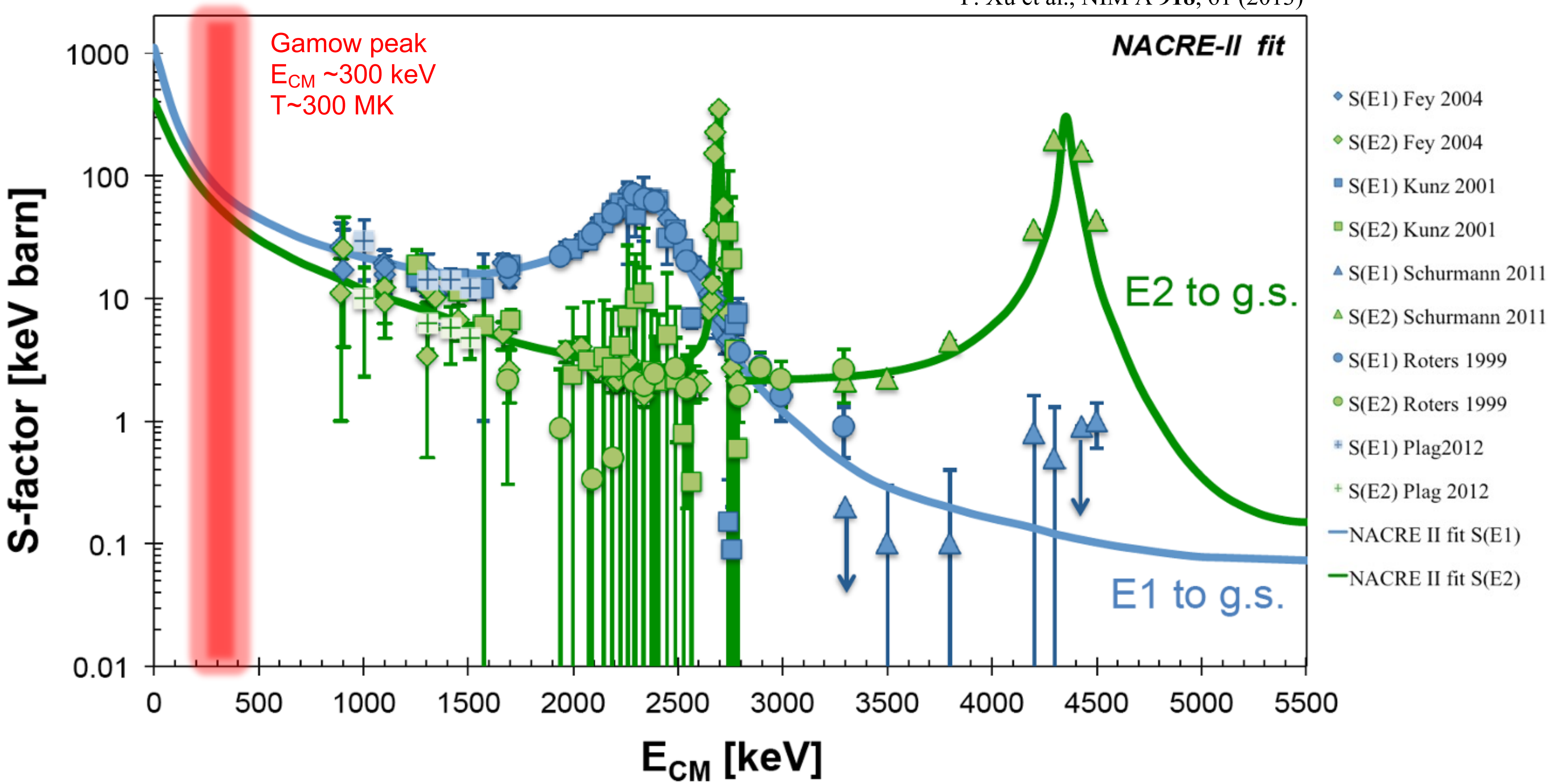
Backup slides

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**

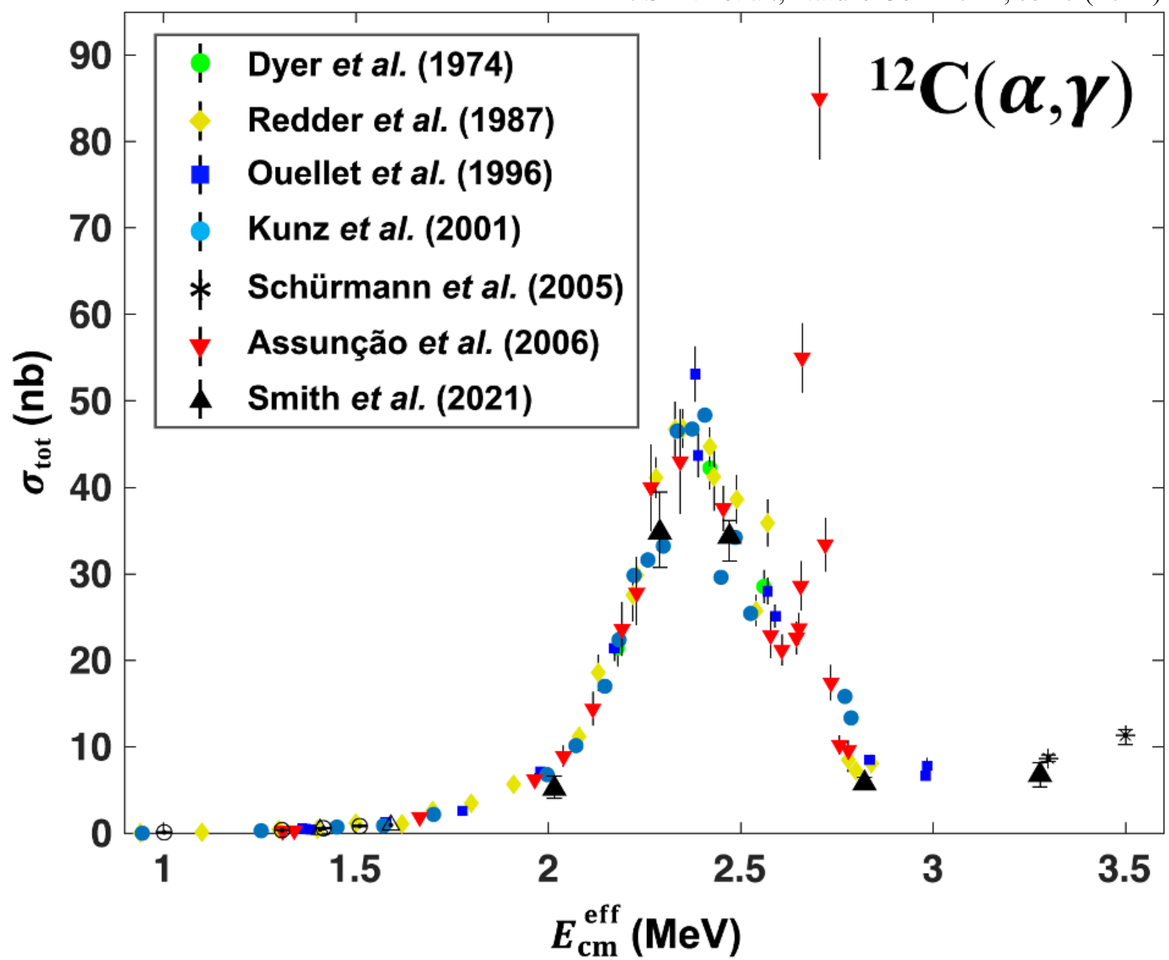
Y. Xu et al., NIM A **918**, 61 (2013)



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 (photodisintegration) :

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



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

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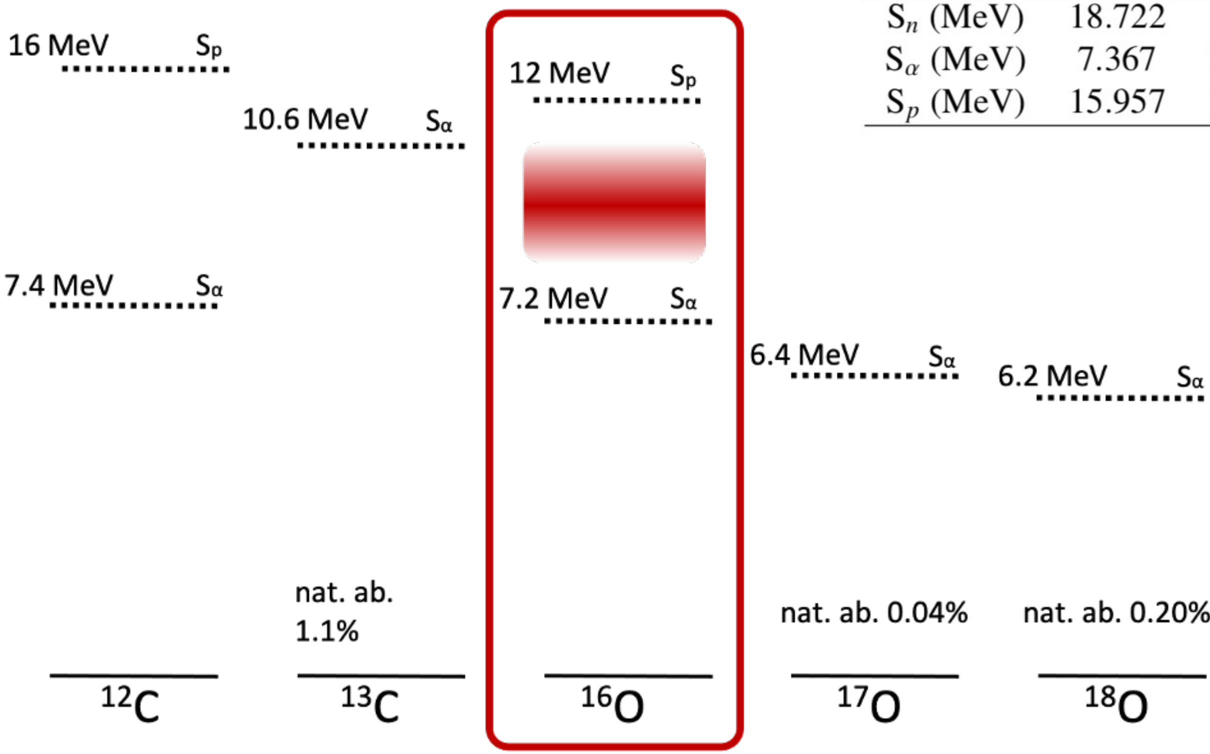
- **Possible reaction channels for CO_2 gas target:**

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

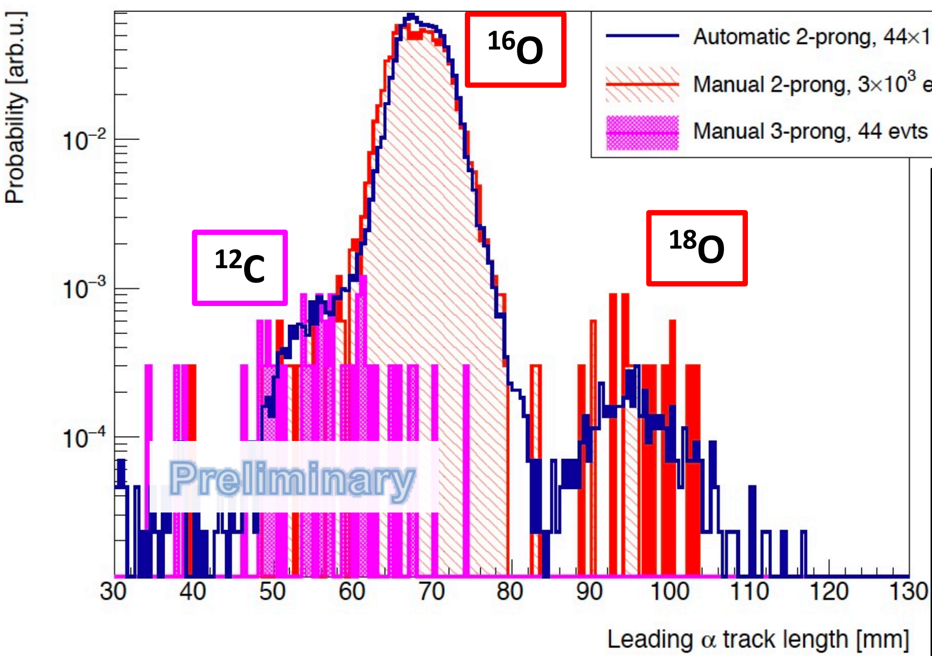
	^{12}C	^{13}C	^{16}O	^{17}O	^{18}O
S_n (MeV)	18.722	4.946	15.664	4.144	8.044
S_α (MeV)	7.367	10.648	7.162	6.359	6.227
S_p (MeV)	15.957	17.533	12.128	13.780	15.942



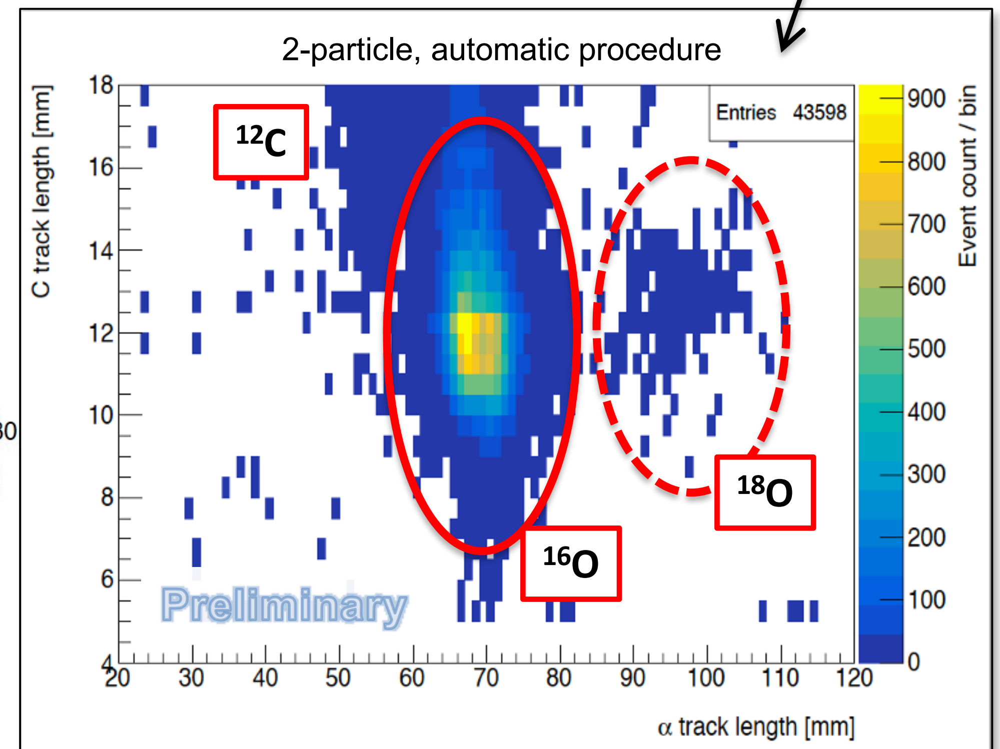
Event identification - automatic

- 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



2-particle, automatic procedure



E_γ=11.5 MeV

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Energy scale calibration – details (1/2)

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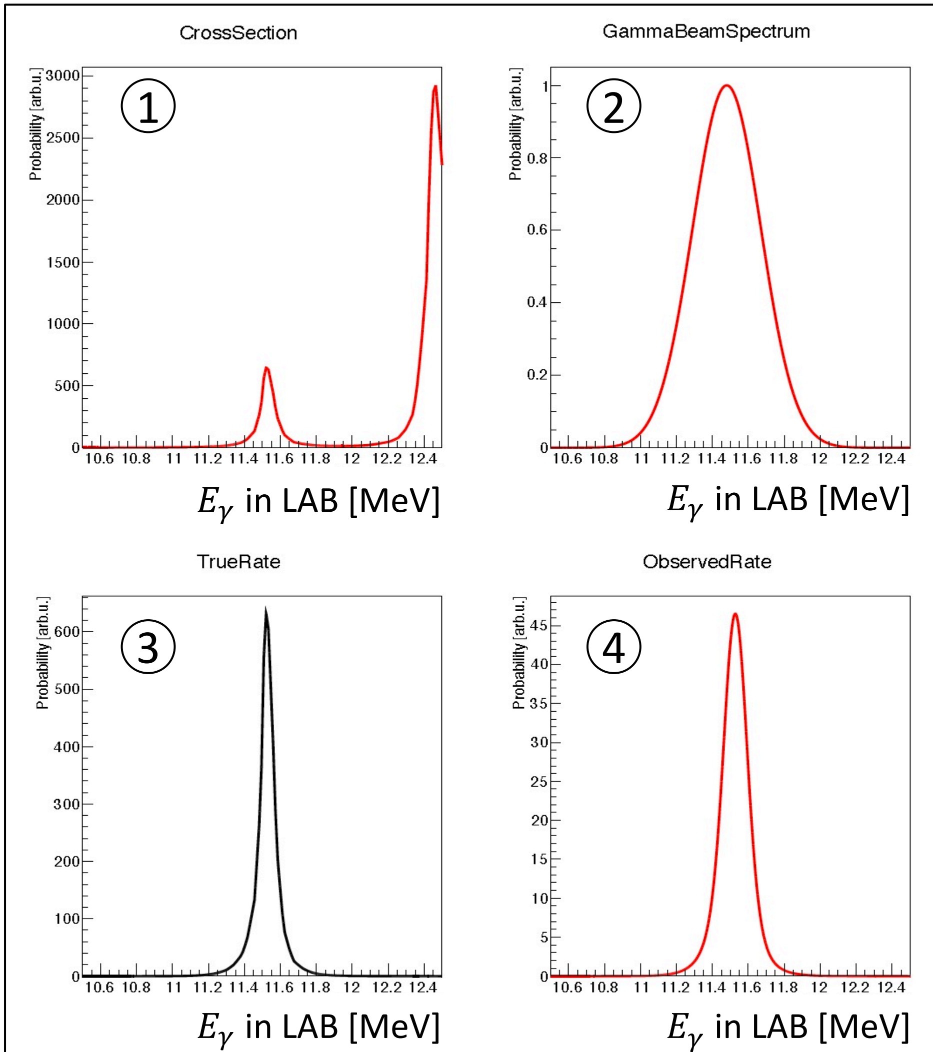
- Expected peak position of broad 2^+ state @ E_x=11.52 MeV (Γ=71 keV)

Expected x-sec from literature data

Unfolded E_γ spectrum from HPGe for the nominal beam energy of E_γ=11.5 MeV



Expected reconstructed spectrum of E_γ^{LAB} assuming perfect TPC resolution

$\sigma_{det} = 0$ keV

Expected reconstructed spectrum of E_γ^{LAB} assuming finite TPC resolution

$\sigma_{det} = 50$ keV

Energy scale calibration – details (2/2)

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

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

where: $\boldsymbol{a}$ = scale, $\boldsymbol{b}$ = offset