An Update on the FOOT Experiment

Programma anni futuri
Richieste 2025
Sblocchi SJ

M. Villa (INFN Bologna)

05 September 2024

The FOOT Collaboration (2025)

93+6 Authors, 33+2 Institutions

Italy, France, Germany, Japan, Cuba, +India

3 Continents (Europe, Asia, America)

INFN:

12 units (Ba, Bo, LNF, LNGS, Mi, Na, Pg, Pi, Rm1, Rm2, TIFPA, To)

66 researchers & 13 technologists

28.9 FTE (25.5 researchers, 3.4 technologists)

2025:

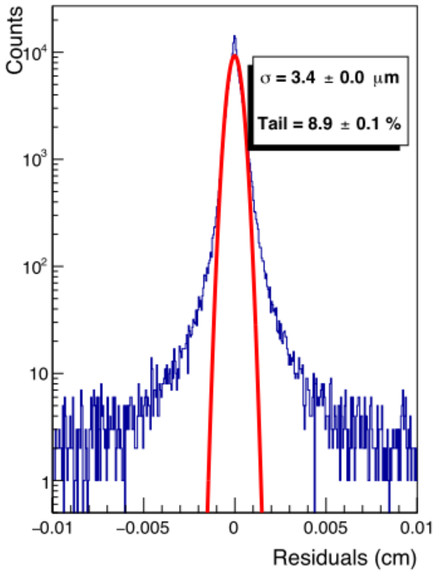
LNGS : Preparation/development of nuclear emulsions

Calicut University (Kerala, India): participation to the analysis
(MAECI - mobility of researchers)

Data taking campaigns already performed

Beam	Target	Energy MeV/u	Statistics (millions, electronic set-up only)	Integral Differential elemental	Integral Differential isotopic	direct	Inverse	Emul-sions	Campaign	Analysis status
O	C C2H4	200 400	0.06	angle	NO	YES	NO	Yes Yes	GSI 2019 GSI 2020	published
O	C C2H4 C C2H4	200 200 400 400	14.2 12.2 5.5 6.5	angle	NO	YES	NO	Yes	GSI 2021	In the pub phase
He	C	100 140 200 220	18.5 19.6 13.5 14.4	angle	NO	YES	NO	No	HEID 2022	Only detector calib
C	C	200	4.1	angle	NO	YES	NO		CNAO 2022	Det calib.
C	C C2H4	200 200	3.2 2.0	Angle Energy	YES	YES	YES	Yes	CNAO 2023	Started

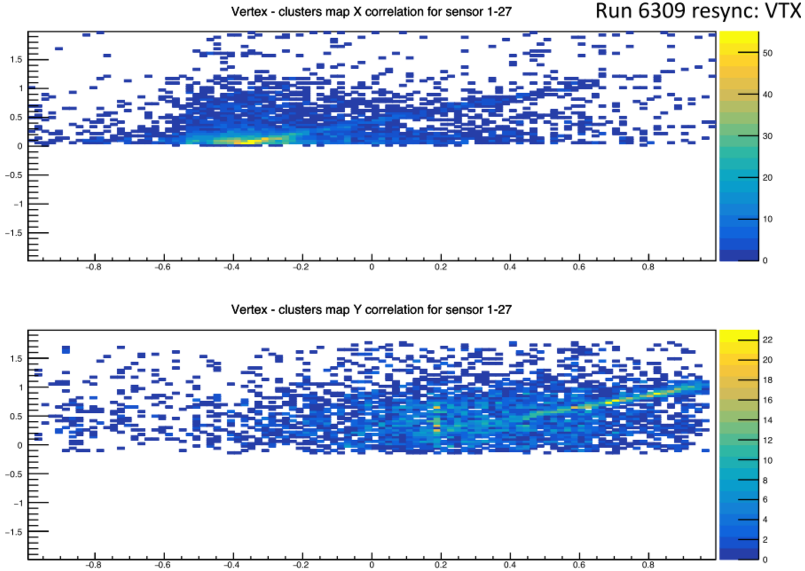
Vertex & Inner tracker – CNAO 2023



Vertex spatial resolutions

- Correlation position btw 1 VTX & 1 ITR sensor

Run 6309 resync: VTX

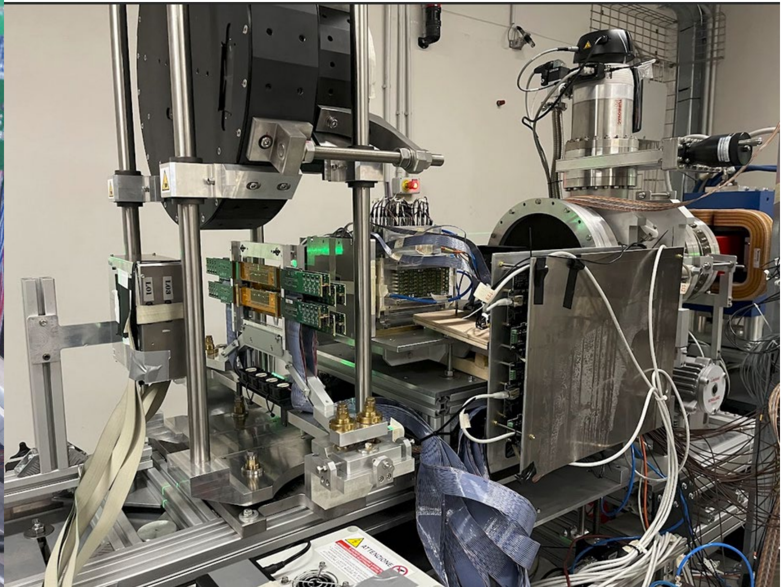


➡ Correlation btw one sensor of VTX with one of ITR (rear side)

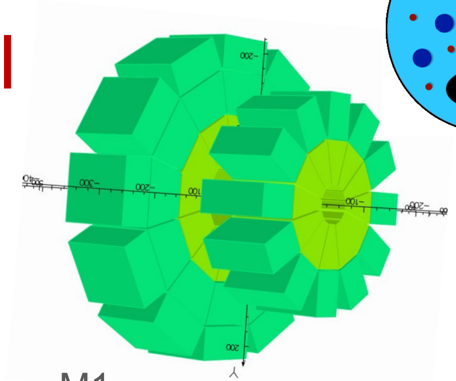
Magnet and Intermediate Tracker!

BTF test

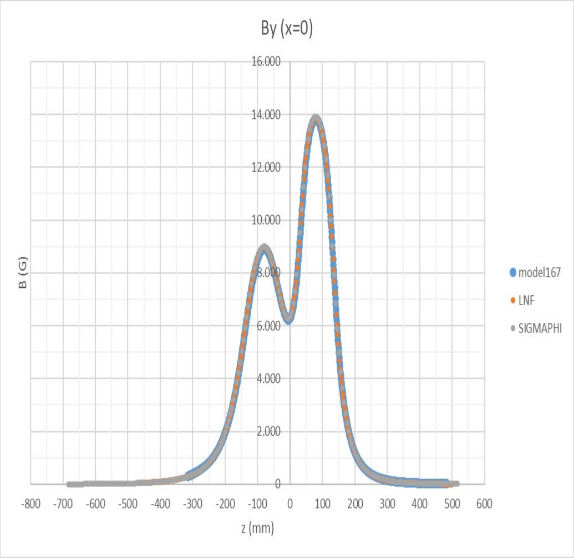
CNAO set-up

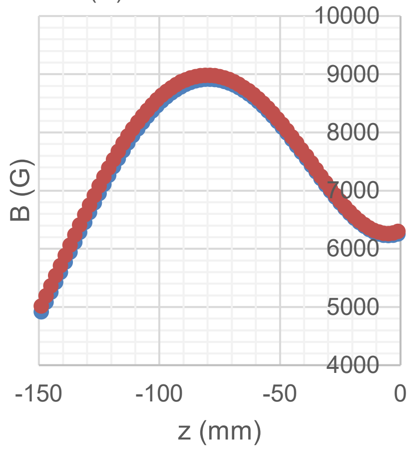


LNF measurements.
3D mechanical and magnetic model

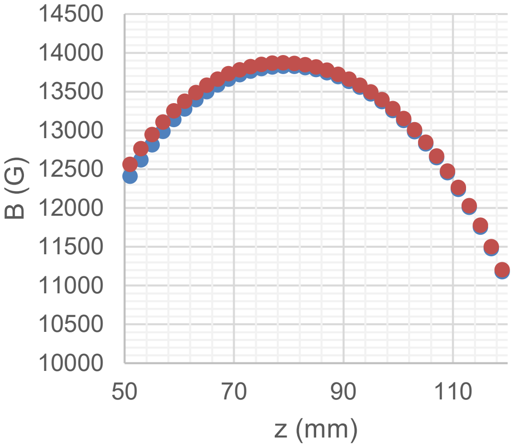


- Needed several iteration to get the real «as built»
- Several tests for different «real positions» of M1 & M2
- Permanent magnets BH curves from producer.





M2



M1

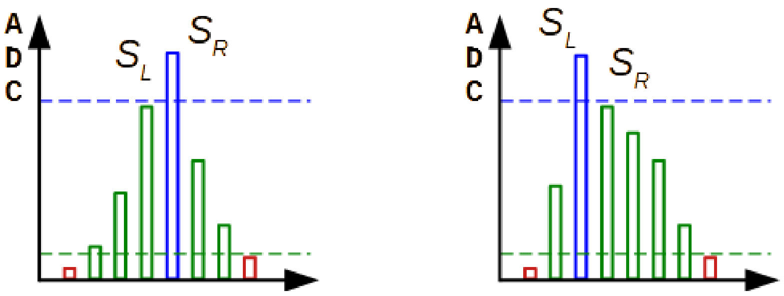
Max 2% disagreement.

<0.5% at B max

MSD status

A lot of effort to understand well the detector. W.r.t. the starting condition:

- Changes in firmware to reduce induced noise in the strips
- Optimized tracking of the pedestals (that might vary in a run)
- Updated definition of hit clusters with two thresholds (Seed, signal)
- Optimized spatial reconstruction, taking into account the eta-dependence
- Energy deposition calibrated w.r.t. the eta-dependence
- Checked all the samples from GSI 2021 to CNAO 2023



$$\eta = \frac{S_L}{S_L + S_R}$$

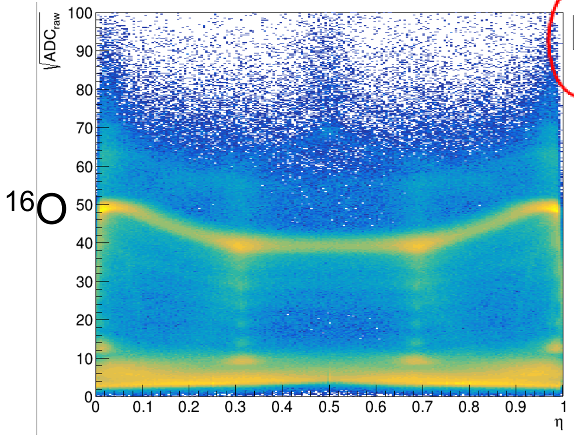
$S_{L/R}$ = two highest strips in cluster

η correction: application to the energy release

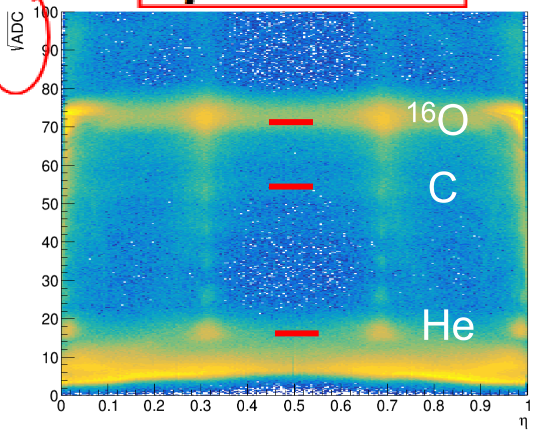
Apply η-correction → Sensor response correctly flattened!!

$$\sqrt{\Delta E\,(\mathrm{keV})} \propto Q$$

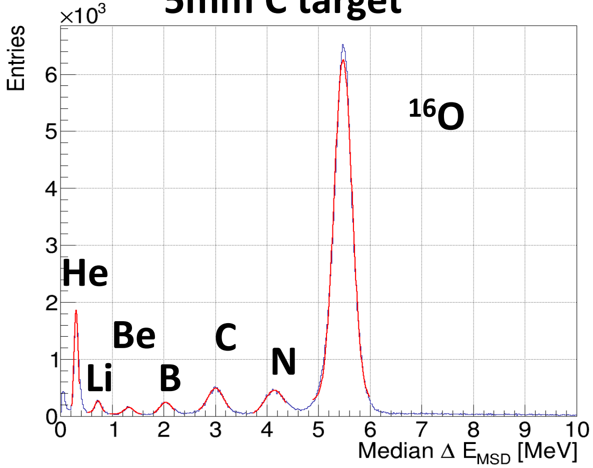
Un-calibrated



η-calibrated



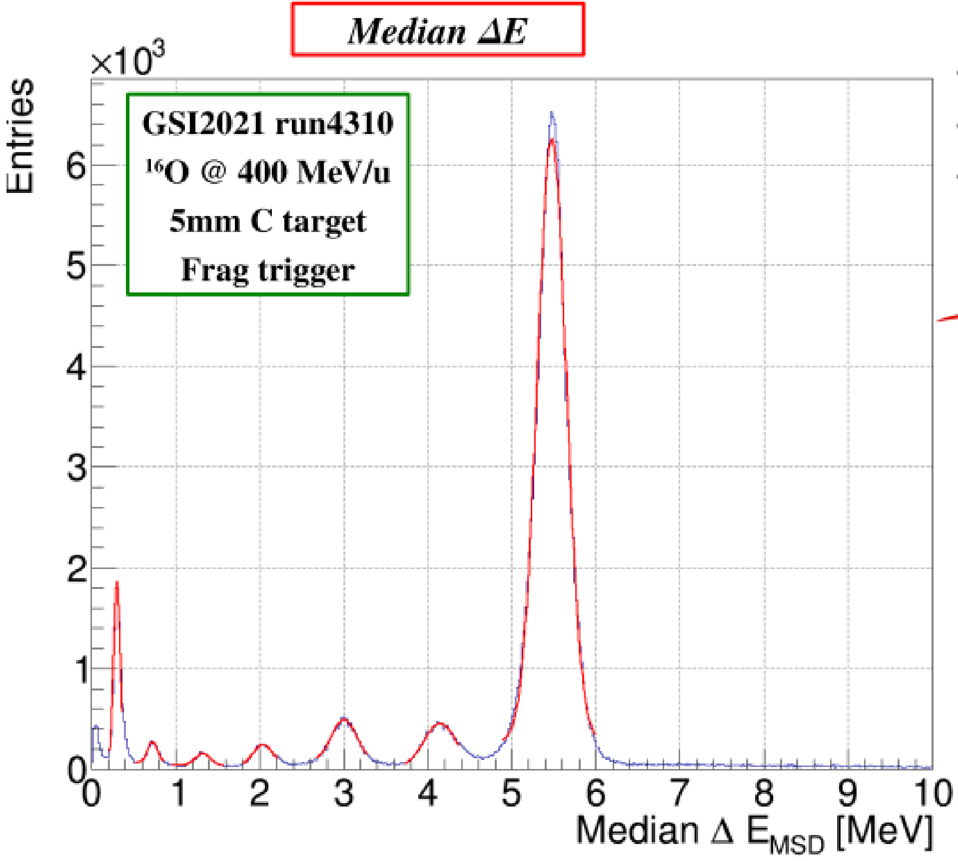
^{16}O @ 400 MeV/u
5mm C target



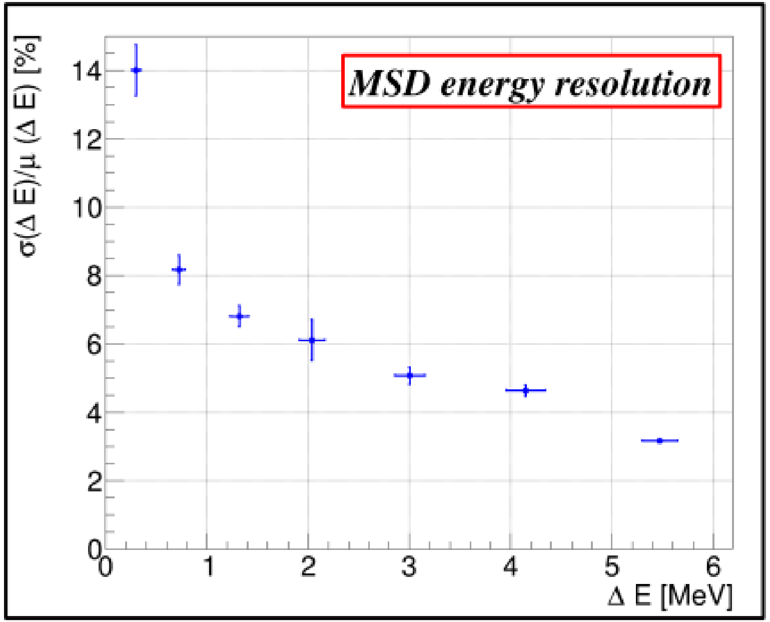
Median ΔE on a track

In-flight interations can be well identified if they happens after MSD

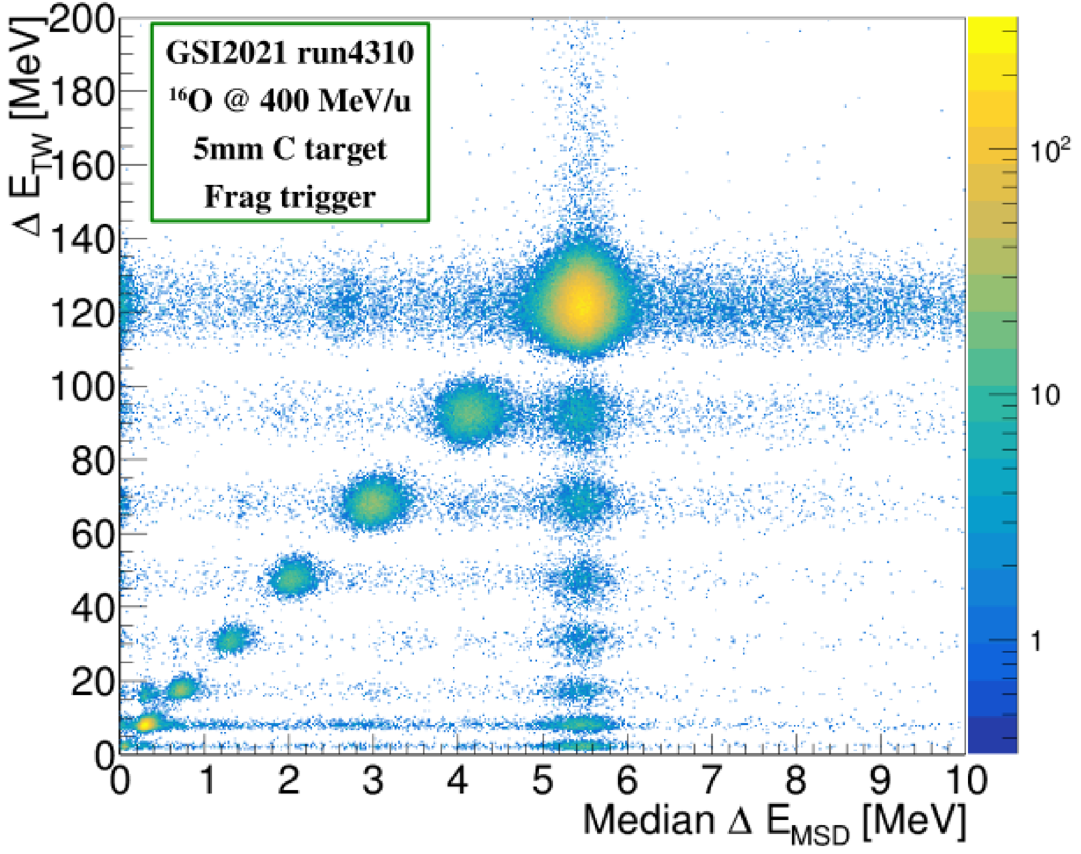
η correction: multi-sensor energy loss



- **Much better!!!**
- Get rid of artifacts
- Very good energy resolution!



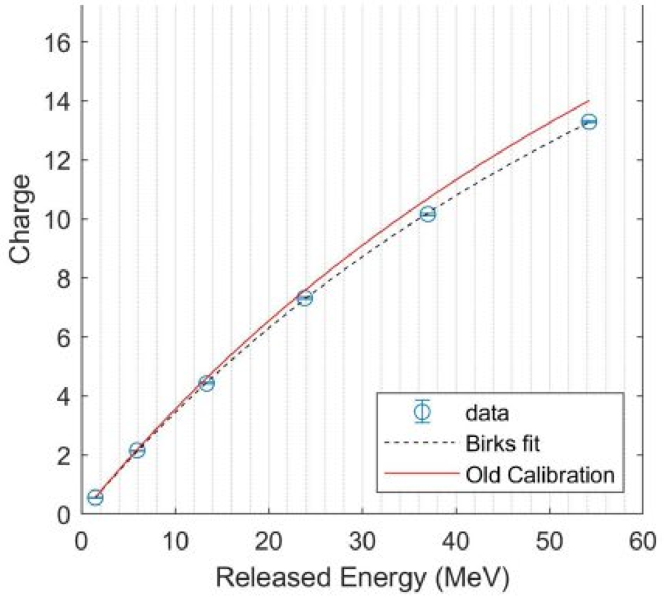
MSD-TW correlation

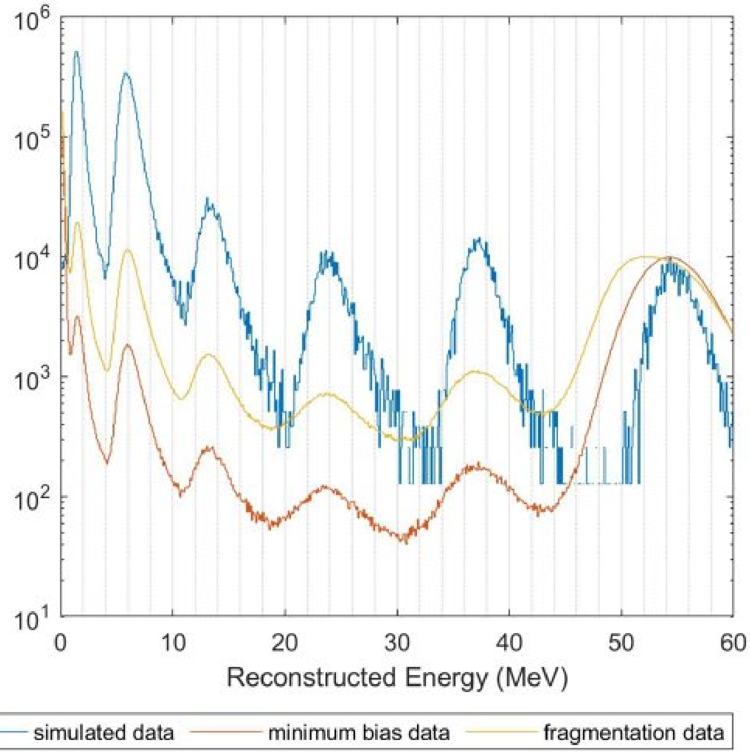


- **Very good MSD-TW correlation!**
- Possible to recognize many physics and reconstruction effects
  - Good correlation
  - Out-of-target fragmentation
  - 2-α pile-up
  - Noise artifacts
  - Event pile-up (?)

TOF Wall – Energy calibration – CNAO 2023

Routine calibration at each data taking: check of timings and energy deposits





Calorimeter calibration

Set-up almost completed

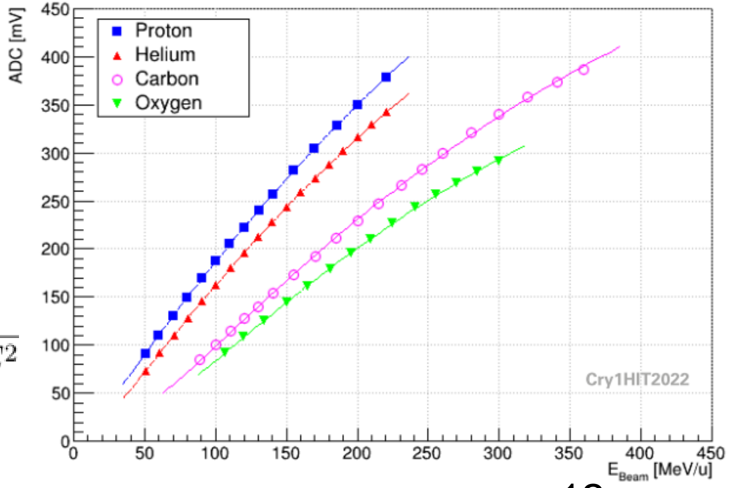
Module holding mechanics to be substituted

HIT2022: few modules calibrated with p, He, C, O

CNAO2023: all modules calibrated with p & C

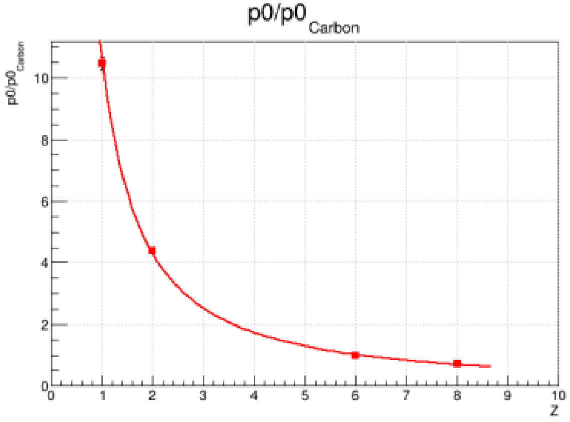
$$\frac{dS}{dx} = \frac{A \cdot dE/dx}{1 + k \cdot B \cdot dE/dx}$$

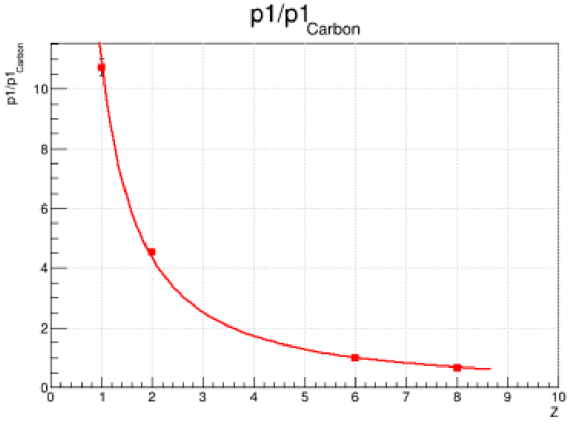
$$ADC(E) = \frac{P_0 E^2}{1 + P_1 E + P_2 E^2}$$

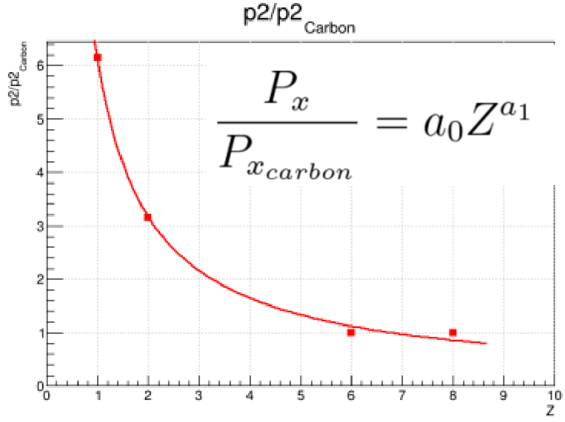


Charge dependence of the parametrization

HIT 2022

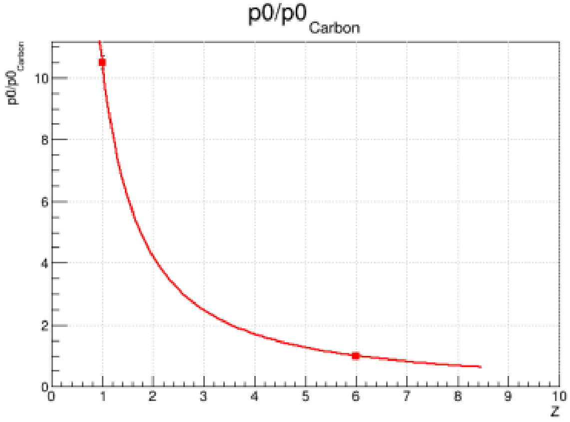


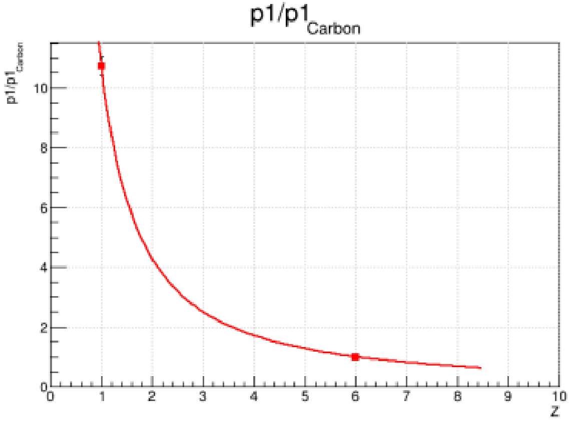


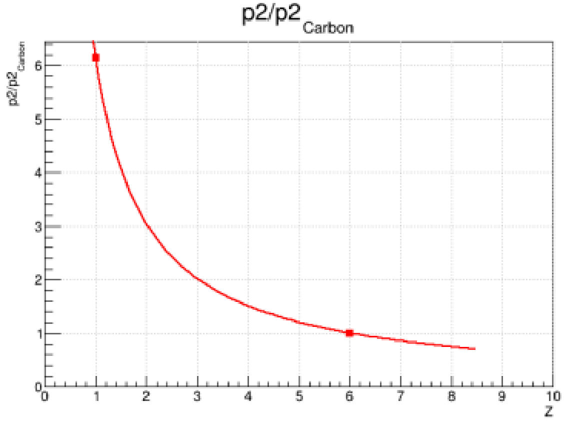


$$\frac{P_x}{P_{x_{carbon}}} = a_0 Z^{a_1}$$

CNAO 2023



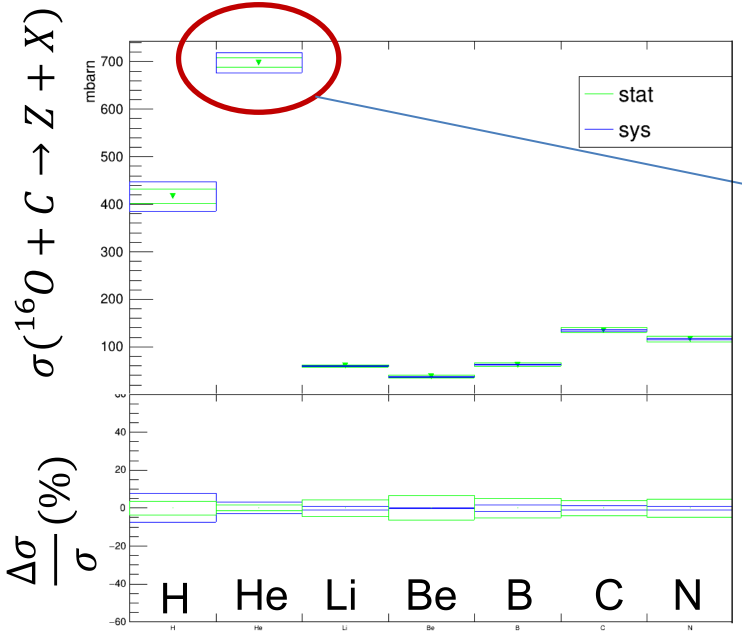


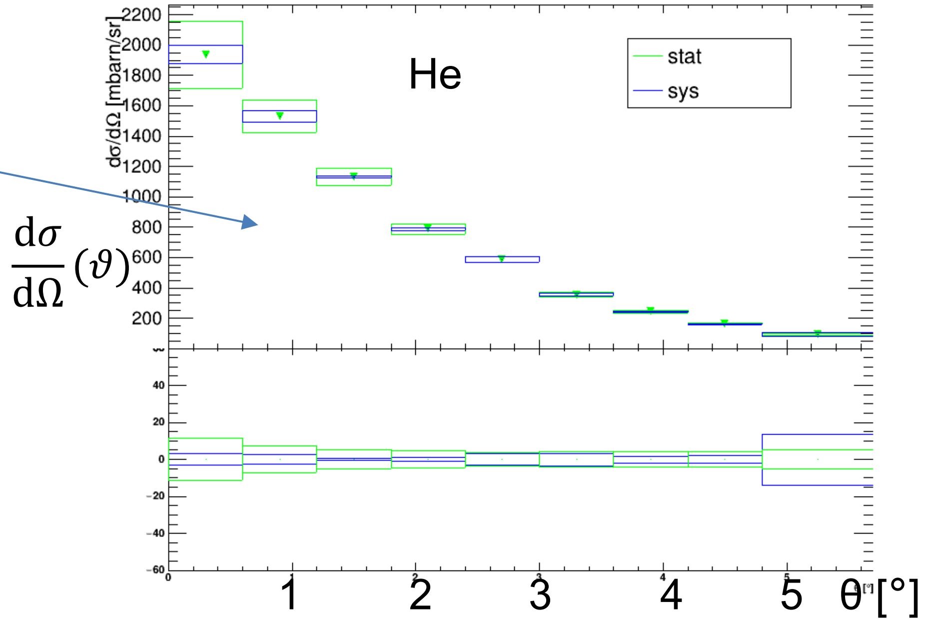


GSI 2021 analysis – electronic set-up – ^{16}O+C, 400 MeV/n

Few detector elements: SC, BM, TW (no VTX, ITR, MSD, CALO)
«high» background from in-flight interactions
Full analysis chain; MC closure test OK;
Efficiencies validated for each detector

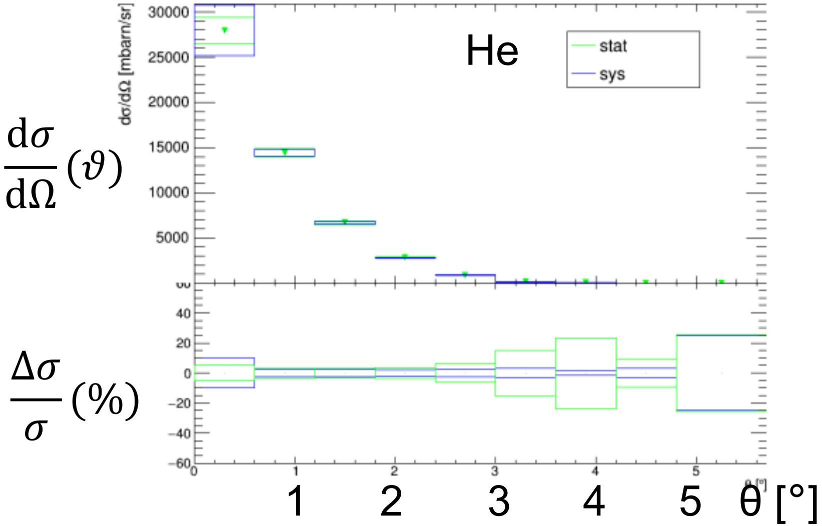
$$\frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta)}{N_{\mathrm{prim}} \cdot N_{\mathrm{TG}} \cdot \Delta\theta \cdot \varepsilon(Z,\theta)}$$

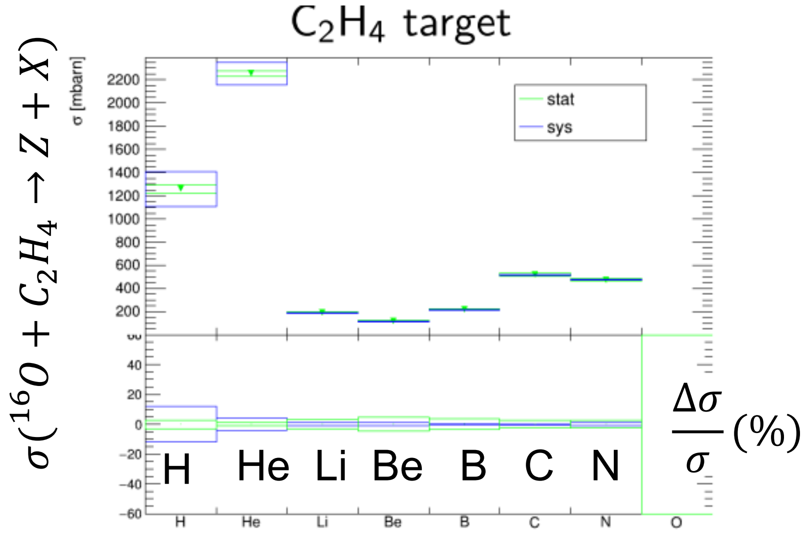


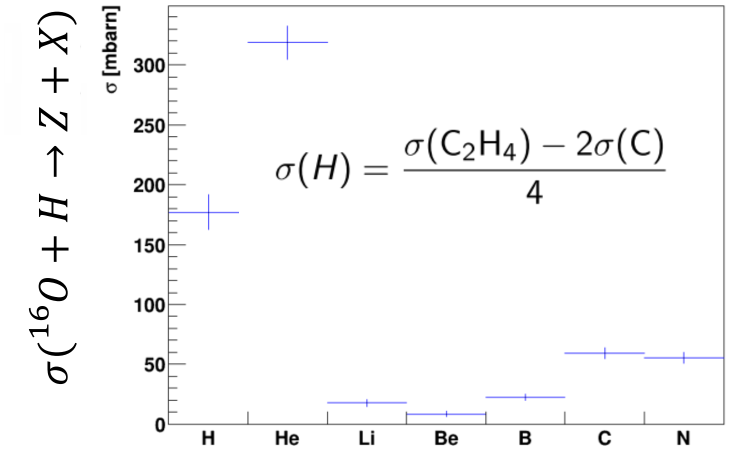


GSI 2021 analysis – electronic set-up – $^{16}O+C_2H_4$, 400 MeV/n

Ongoing analysis of C2H4
Preliminary results

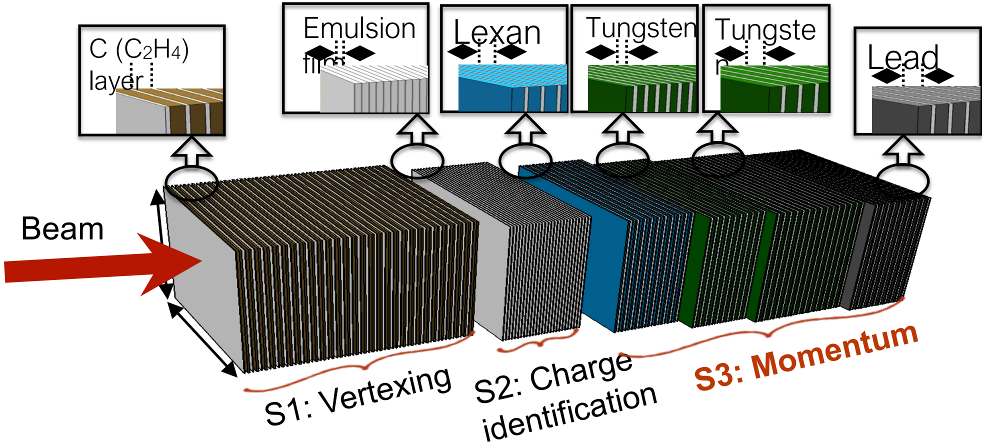


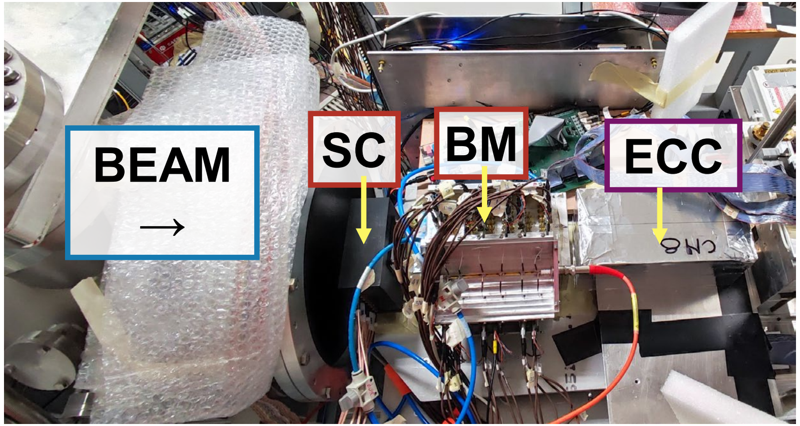


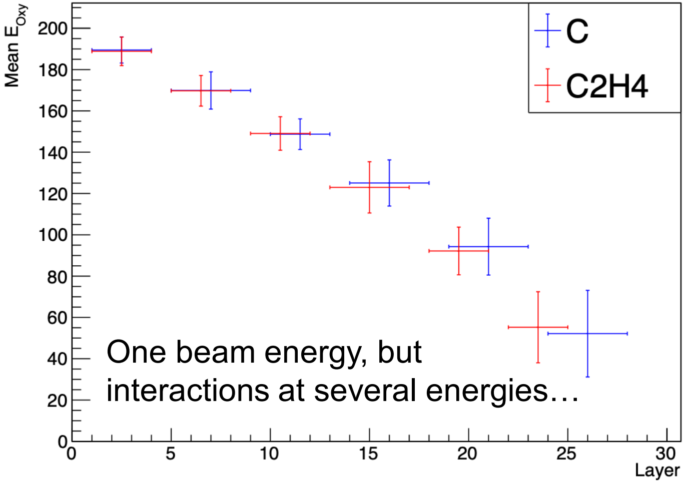


Emulsions: data analysis and cross section measurement

- Analysis of ^{16}O @ 200 MeV/n on C and C_2H_4 targets almost completed:
  - Improvements in data-driven effects added on Monte Carlo reconstruction (background, misalignments, local distortion due to chemical development…)
  - Evaluation of total and reaction cross sections
  - Evaluation of systematics effects by data-driven methods
- Paper on cross section measurements with ^{16}O at 200 MeV/n on C, C_2H_4 and H **in preparation**

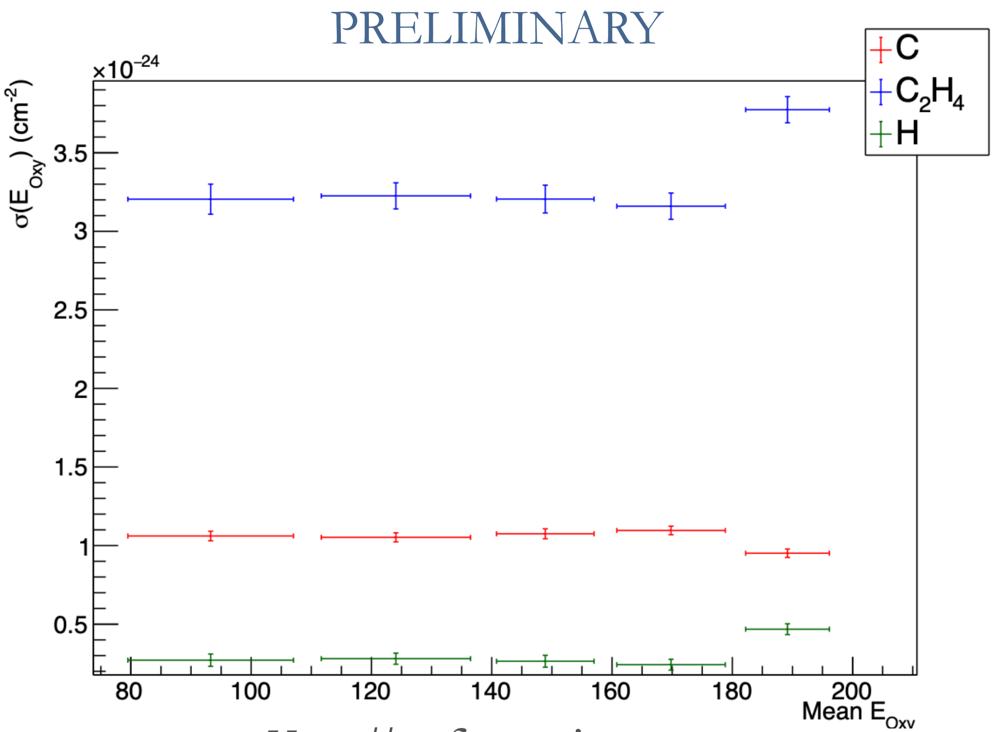






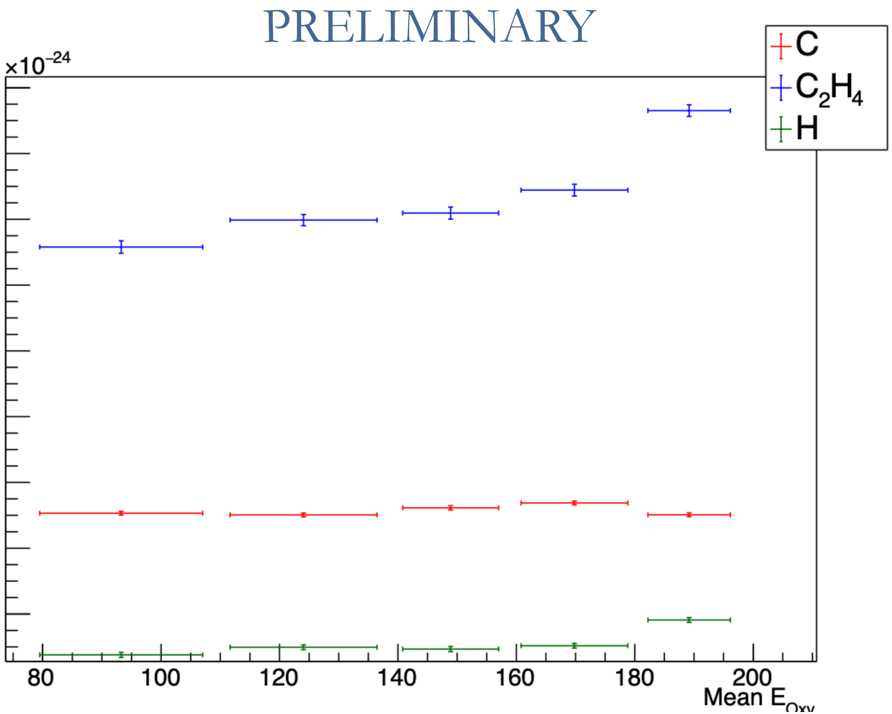
Integrated cross section H

Total reaction cross section



Y_i =# of vertices

Total production cross section



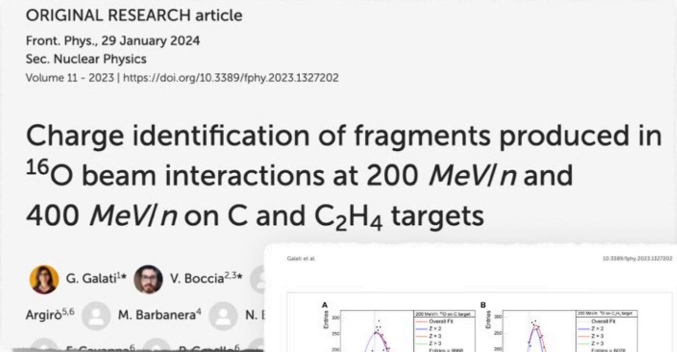
Y_i =# of fragments

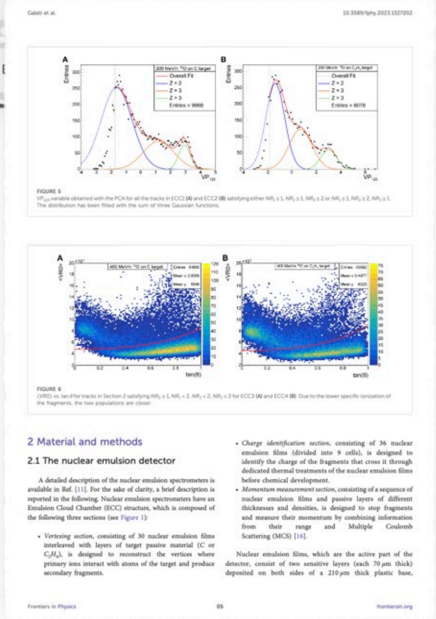
Publications and papers in preparation (emulsions)

- Paper **published** on Charge identification of fragments produced in ^{16}O at 200 MeV/n and 400 MeV/n on C and C_2H_4 targets

- Paper on cross section measurements with ^{16}O at 200 MeV/n on C, C_2H_4 and H **in preparation**

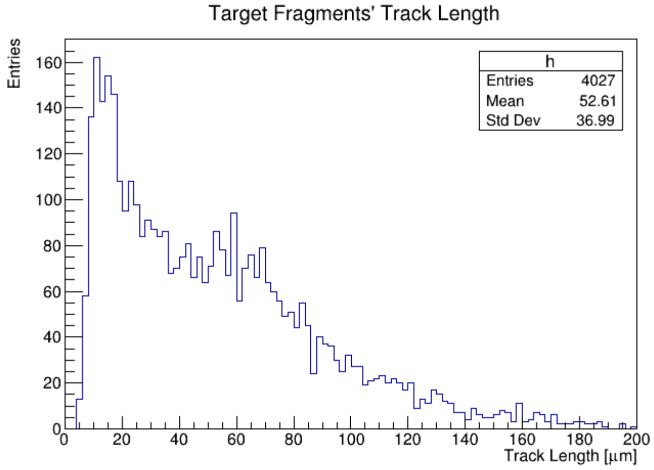
doi.org/10.3389/fphy.2023.1327202



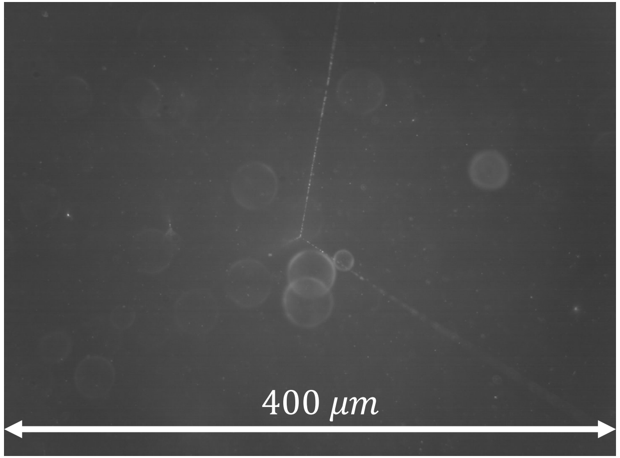


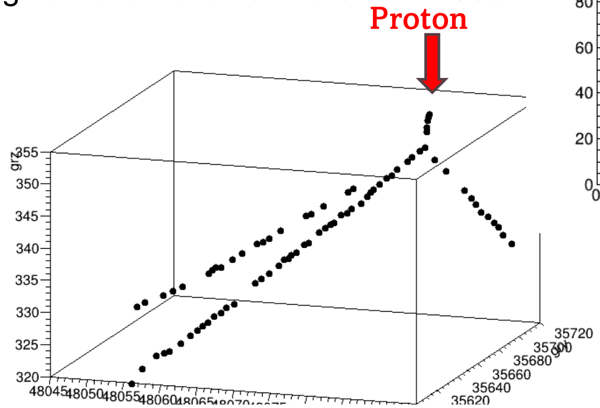
NIT emulsions first results

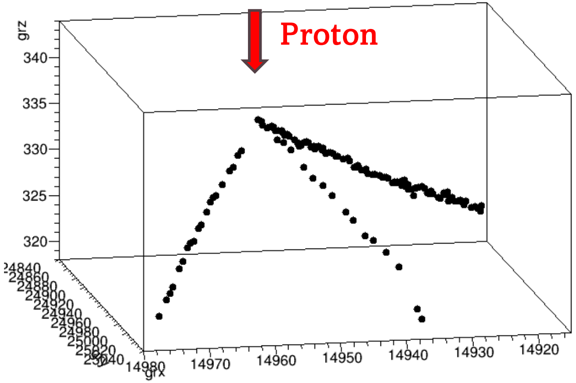
- Access to the direct kinematics of p+C fragmentation cross sections
- All the emulsions from the Pilot test have been scanned with the fast optical microscope
- Developed a strategy to identify target fragmentation events: more than 1500 events reconstructed so far



3D displays of reconstructed events





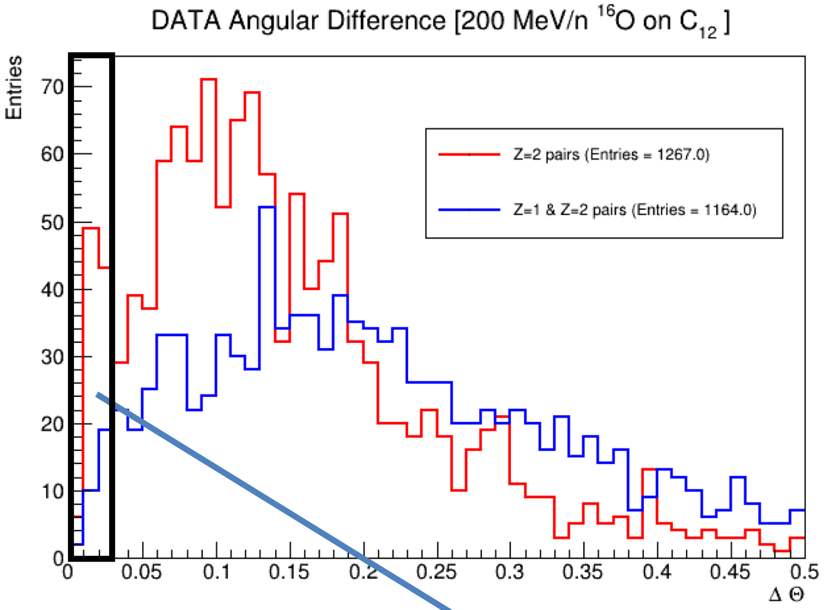


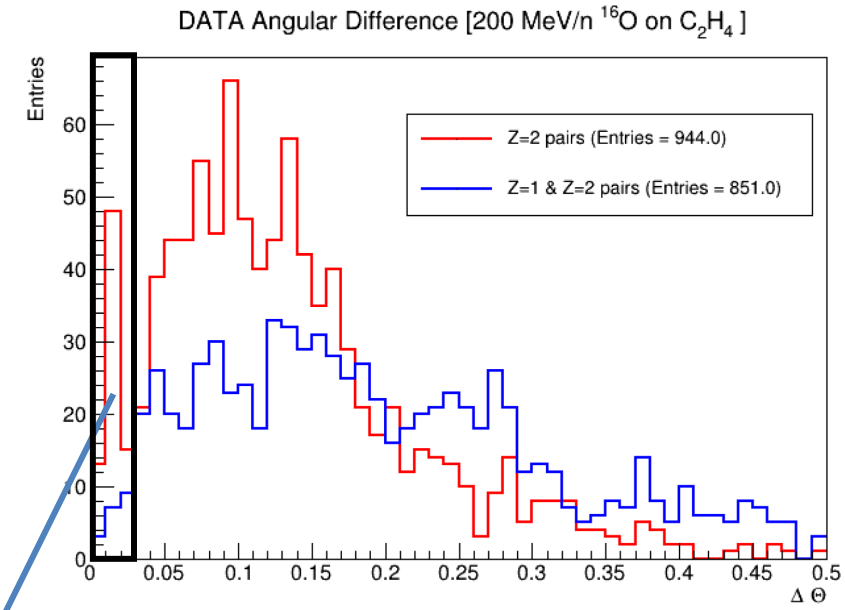
Developments/problems:

- Improved optics for the scanning microscopes
- Tracks and interactions are clearly seen
- Vertices can be easily reconstructed
- Impinging proton track is weak
- Emulsion preparation and development to be studied carefully

α clustering physics with nuclear emulsions

- Nuclear cluster structures can be probed by studying preferential dissociation channels (such as ${}^{16}O \rightarrow 4\,\alpha$)
- α clustering has not been thoroughly explored in the energy regime accessed by FOOT
- Analysis on-going with 2019 FOOT emulsion DATA (${}^{16}O$ @ $200\ \mathrm{MeV/n}$ on carbon and polyethylene targets)
- The detection of correlated He pairs (relative angle $< 25\ mrad$) is used to measure the production of ${}^{8}\boldsymbol{Be}_{g.s.}$ in the fragmentation of the oxygen nucleus





Observed Production of ${}^{8}\boldsymbol{Be}_{g.s.}$ in DATA

Future: 2025-2027

- At the moment there is no portable competing experiment with FOOT → no external improvements on cross section measurements.
- We are still working towards differential cross sections for hadrontherapy
- C+C, C+C2H4, O+C, O+C2H4 in different conditions at Ekin < 400 MeV/n
-A lot of interest also for higher energies for radioprotection (O+C, O+C2H4 at > 500 MeV/n)
-At CNAO there is a broad interest on 4He: both for therapy and for diagnostics

Far Future (>2027)

- O-O cross section (for space radioprotection) and Ca+C cross sections (for hadrontherapy) are also very interesting in their fields

Foreseen data taking campaigns

Beam	Target	Energy MeV/u	Integral Differential elemental	Integral Differential isotopic	Direct	inverse	Emul-sions	Campaign
C	C C2H4	100-200	Angle Energy	YES	YES	YES	YES (NIT?)	CNAO 2025
O	C	500-700 (?)	Angle Energy	YES	YES	YES	YES	GSI 2026
C	C C2H4	200-300	Angle Energy	YES	YES	YES	-	CNAO 2026
P	C	100-220	Angle Energy	YES	YES	-	NIT	CNAO 2026
C	C C2H4 PMMA	320-400	Angle Energy	YES	YES	YES	YES	CNAO 2027
He	C C2H4 PMMA	200-400(?)	Angle Energy	YES	YES	YES	YES	CNAO 2027

Richieste finanziarie 2025

Capitolo	Richieste (k€)	Voci principali
Inventariabile	0	*Finanziati su PRIN/MAECI o altro*
Consumo	47	NA: chim x emulsioni, LNF: mecc+schede,
Apparati	0	*Finanziati su PRIN/MAECI o altro*
Trasporti	5	BO, LNGS, MI, PI
Missioni	144	Tutti: prese dati a CNAO, meeting di collaborazione, tests, calibrazioni. NO GSI
Pubblicazioni	0	*Finanziati su MAECI, principalmente*
Totale	**195**	per una spesa pro capite di 6.7 k€/FTE

Storico richieste: 2017: 274 k€, 2018: 815k€, 2019: 868 k€, 2020: 545 k€, 2021: 389 k€
2022: 434 k€, 2023: 317 k€, 2024: 286 k€

Algoritmo missioni

- Viaggio ITA (AR): 220€, viaggio EU (AR): 440€
- Giorno ITA, giorno EU: 180€
- 2 Meeting di collaborazione ITA (per molti)
- Presa dati 1-4 persone per sede
- Trasporti per BO, LNF, MI, PI, TO (>1 m^3, >200 kg, sicurezza)

Richieste consumo 2025

Sede	Richieste (k€)	Voci principali
BO, LNF, MI, PI, RM1, RM2, TIPFA, TO	17	Metabolismi laboratorio (2 k€/sede in media)
LNGS	5	Prodotti chimici per emulsioni / smaltimento
BO, LNF	8	Schede elettroniche (DAQ, Nuovo VTX)
LNF	5	Sensori MIMOSA di riserva
NA	11,5	Emulsioni e reagenti chimici
Totale	**46,5**	

Richieste addizionali & sblocchi

Nessuna richiesta addizionale! → In caso di necessità ci aiuteremo tra le sezioni

Prossime prese dati: CNAO – Novembre 2024 – (+BTF prenotata per fine novembre)

SJ totali: 70 k€ - Richieste sblocco 48 k€, restituzione di 22 k€

Richieste di sblocco	Richieste (k€)	Sezione/voci principali
SJ missioni x CNAO	23.0	Varie sedi coinvolte (non tutte)
SJ Bonus dottorandi	24.5	BO (da usare per il CNAO)

Milestones

Milestone	Data	
Proceeding/articolo con risultati preliminari campagna 2023 set-up elettronico	31-dic-2025	
Proceeding/articolo con risultati preliminari emulsioni 2023	31-dic-2025	
Test su fascio del nuovo rivelatore di vertice	31-dic-2025	
Test su fascio di un prototipo di nuovo TofWall	31-dic-2025	
Sottomissione lavoro strumentale FOOT	31-dic-2025	
Proceeding/articolo R&D su emulsioni NIT per FOOT	31-dic-2025	

Grazie per l’attenzione!