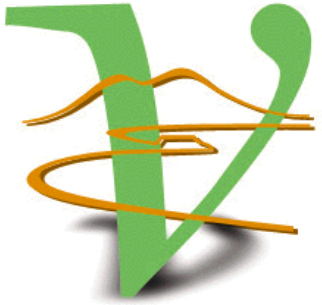
Measurement of the fragmentation of Carbon ions with nuclear emulsions for medical applications



Adele LAURIA

On the behalf of Naples emulsion group

University of Naples "Federico II", Italy

INFN, Naples

Outline

- Hadrontherapy motivation
- The ^{12}C fragmentation measurement with the Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- Measurements at GSI in the FIRST set-up
- Preliminary results
- Conclusion

Outline

- **Hadrontherapy motivation**
- The ^{12}C fragmentation measurement
- The Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- Measurements at GSI in the FIRST set-up
- Preliminary results
- Conclusion

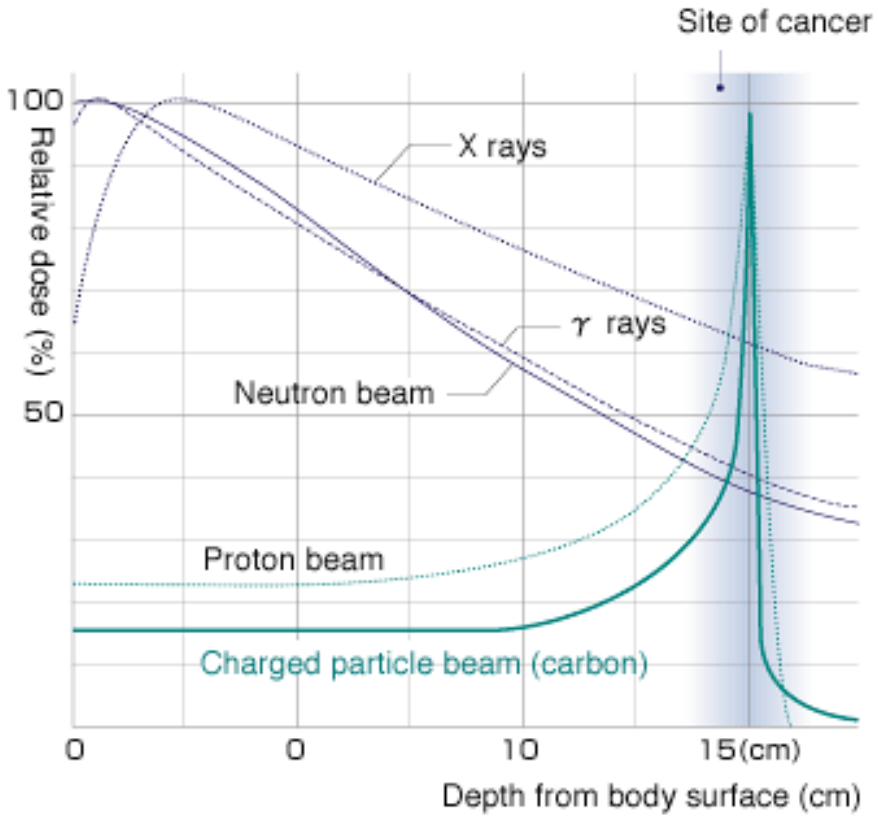
Hadrontherapy motivation

For hadrons (*compared to X and γ*):

- Energy deposited at the end of ionization range

For ^{12}C (*compared to protons*):

- Reduced lateral and longitudinal diffusion;
- Higher therapeutic effectiveness;
- Tissue thickness tunable by changing the nuclei energy;
- Less energy deposited to healthy neighboring tissues



Hadrontherapy

Facilities in Europe:

http://enlight.web.cern.ch/facilities

Patient Statistics (for facilities in operation at the end of 2012):

Patient Statistics (for facilities in operation end of 2012):

WHERE		PARTICLE	FIRST PATIENT	PATIENT TOTAL	DATE OF TOTAL	
Canada	Vancouver (TRIUMF)	p	1995	170	Dec-12	ocular tumors only
Czech Rep.	Prag (PTCCZ)	p	2012	1	Dec-12	
China	Wanjie (WPTC)	p	2004	1078	Dec-12	
China	Lanzhou	C ion	2006	194	Dec-12	
England	Clatterbridge	p	1989	2297	Dec-12	ocular tumors only
France	Nice (CAL)	p	1991	4692	Dec-12	ocular tumors only
France	Orsay (CPO)	p	1991	5949	Dec-12	4748 ocular tumors
Germany	Berlin (HMI)	p	1998	2084	Dec-12	ocular tumors only
Germany	Munich (RPTC)	p	2009	1377	Dec-12	
Germany	HIT, Heidelberg	C ion	2010	980	Dec-12	
Germany	HIT, Heidelberg	p	2010	252	Dec-12	
Italy	Catania (INFN-LNS)	p	2002	293	Nov-12	ocular tumors only
Italy	Pavia (CNAO)	p	2011	42	Dec-12	
Italy	Pavia (CNAO)	C ion	2012	3	Dec-12	
Japan	Chiba (HIMAC)	C ion	1994	7331	Jan-13	72 with scanning
Japan	Kashiwa (NCC)	p	1998	1226	Mar-13	
Japan	Hyogo (HIBMC)	p	2001	3198	Dec-11	
Japan	Hyogo (HIBMC)	C ion	2002	1271	Dec-11	
Japan	Tsukuba (PMRC, 2)	p	2001	2516	Dec-12	
Japan	Shizuoka	p	2003	1365	Dec-12	
Japan	Koriyama-City	p	2008	1812	Dec-12	
Japan	Gunma	C ion	2010	537	Dec-12	
Japan	Ibuzuki (MMRI)	p	2011	490	Dec-12	
Korea	Ilsan, Seoul	p	2007	1041	Dec-12	
Poland	Krakow	p	2011	15	Dec-12	ocular tumors only
Russia	Moscow (ITEP)	p	1969	4300	Dec-12	estimated
Russia	St. Petersburg	p	1975	1386	Dec-12	
Russia	Dubna (JINR, 2)	p	1999	922	Dec-12	
South Africa	iThemba LABS	p	1993	521	Dec-11	
Sweden	Uppsala (2)	p	1989	1267	Dec-12	
Switzerland	Villigen-PSI, incl OPTIS2	p	1996	1409	Dec-12	498 ocular tumors
USA, CA.	UCSF - CNL	p	1994	1515	Dec-12	ocular tumors only
USA, CA.	Loma Linda (LLUMC)	p	1990	16884	Dec-12	
USA, IN.	Bloomington (IU Health PTC)	p	2004	1688	Dec-12	
USA, MA.	Boston (NPTC)	p	2001	6550	Oct-12	
USA, TX.	Houston (MD Anderson)	p	2006	3909	Dec-12	
USA, FL.	Jacksonville (UFPTI)	p	2006	4272	Dec-12	
USA, OK.	Oklahoma City (ProCure PTC)	p	2009	1045	Dec-12	
USA, PA.	Philadelphia (UPenn)	p	2010	1100	Dec-12	
USA, NY.	New Jersey ProCure PTC)	p	2012	137	Dec-12	
USA, IL.	CDH Warrenville	p	2010	840	Dec-12	
USA, VA.	Hampton (HUPTI)	p	2010	489	Dec-12	
				88448	**Total**	
			thereof	10316	C-Ions	
				78132	protons	

Total for all facilities (in operation and out of operation):

2054	He
1100	pions
10756	C-ions
433	other ions
93895	protons
108238	**Grand Total**

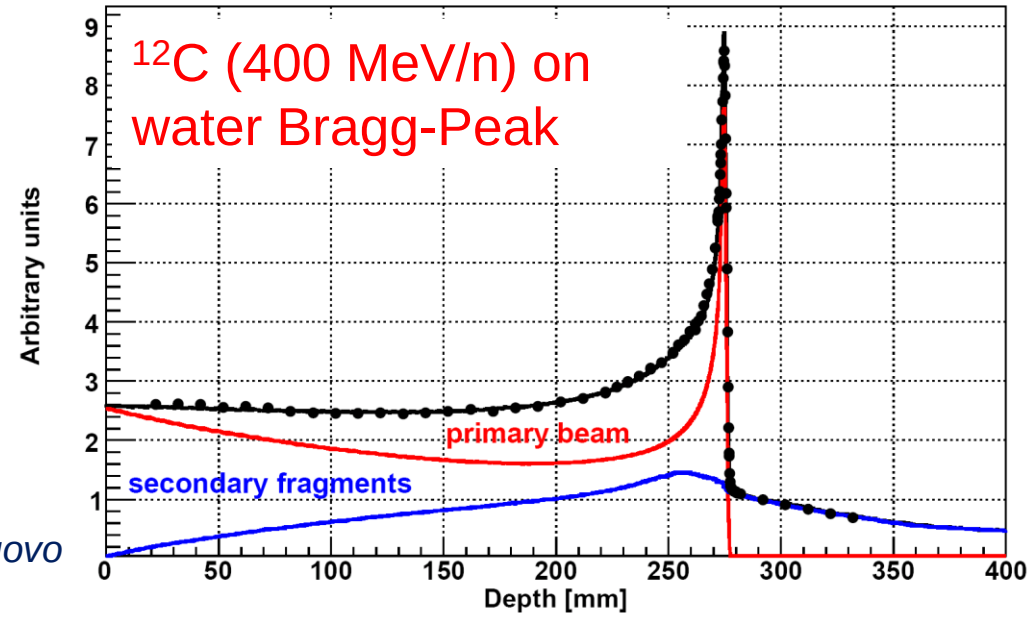
http://enlight.web.cern.ch

Fragmentation of ^{12}C

- Nuclear fragments are generated during the interaction inside the tissue
- Fragments have higher range and different direction with respect to primary ions
- Precise knowledge of fragments is necessary to predict the detailed irradiation of the neighboring tissues and, thereby, optimization of the therapy with higher effectiveness

What we need to know

- Kind of fragments
- Which energy?
- Which angle?

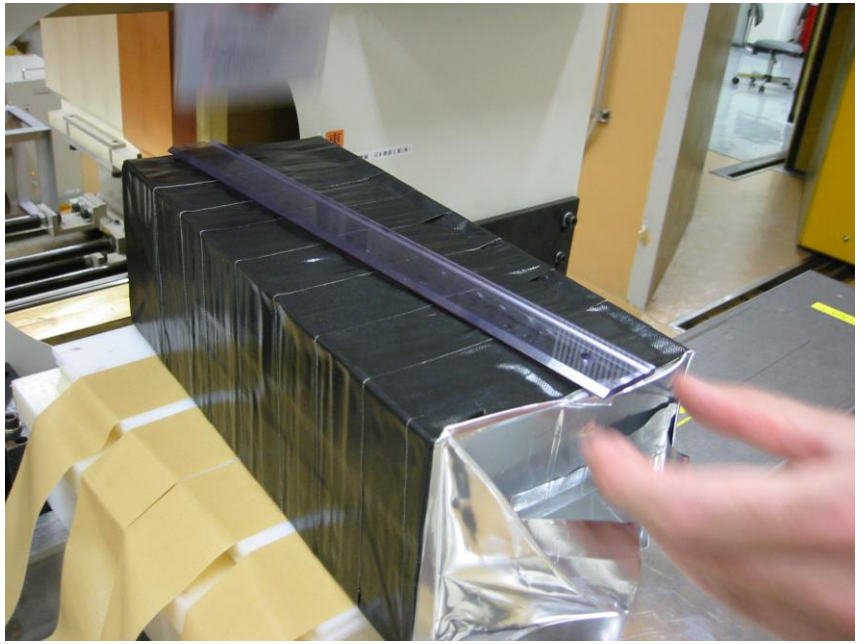


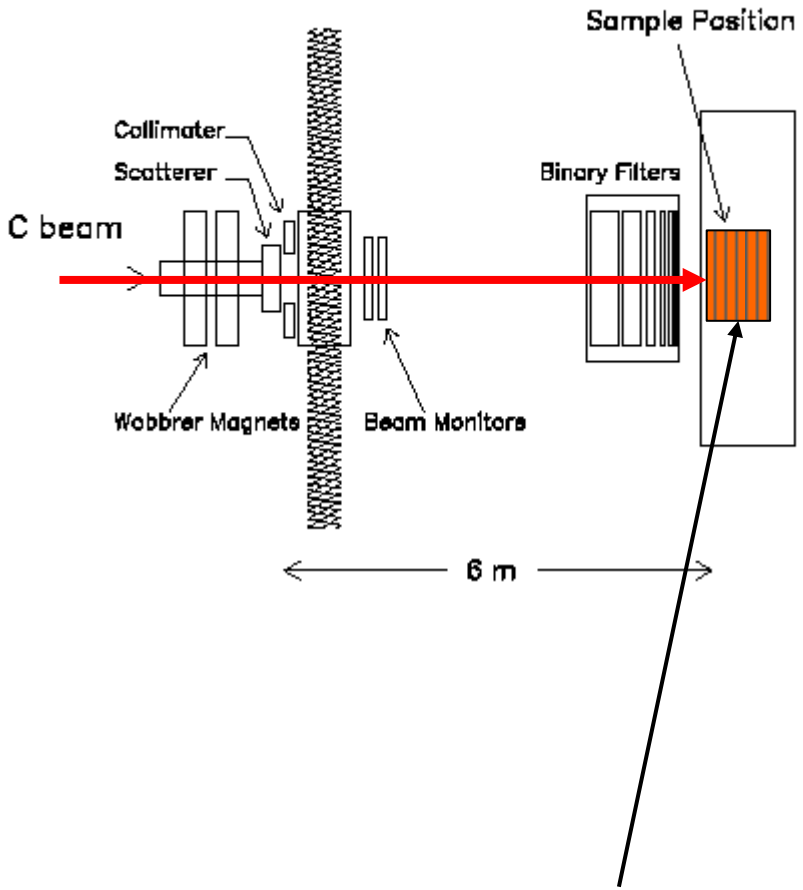
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Outline

- Hadrontherapy motivation
- The ^{12}C fragmentation measurement with the Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- Measurements at GSI in the FIRST set-up
- Preliminary results
- Conclusion

Carbon exposure at HIMAC* (NIRS**- Chiba(Japan))



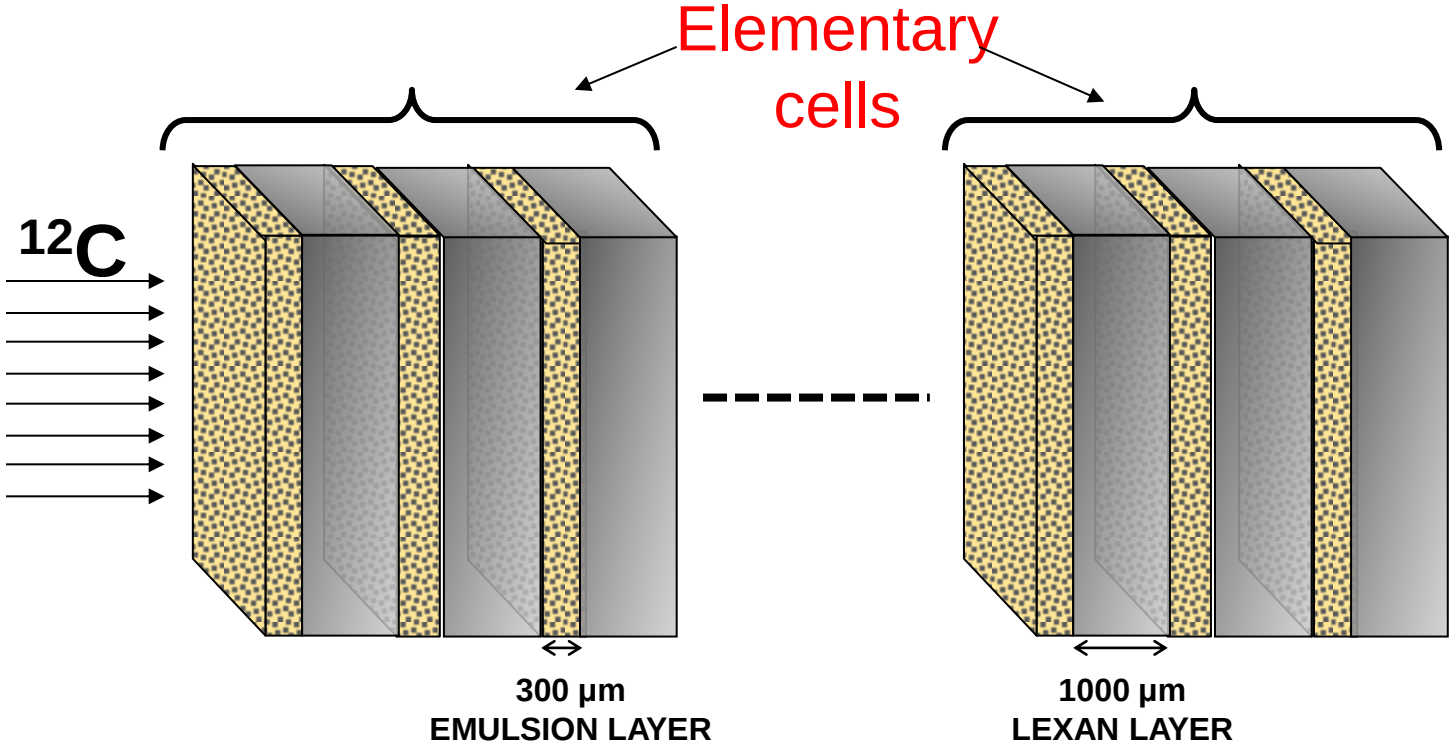


Emulsion Cloud Chamber (ECC)

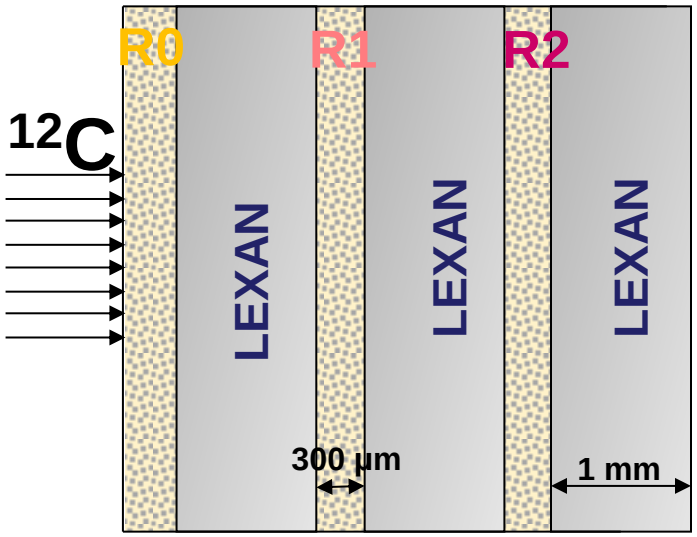
**Heavy Ion Medical Accelerator*
***National Institute of Radiological Sciences*

The structure of the Emulsion Cloud Chamber

- ECC structure:
  - “OPERA” type: alternate passive and sensitive material
  - High resolution tracking device: nuclear emulsion (300 μm thick)
  - Passive material: lexan plates 1 mm thick
  - 73 consecutive “cells”: 219 alternate nuclear and lexan layers
- Lexan: ρ=1.15 g/cm^3 and electron density=3.6·10^{23}/cm^3 (water: 3.3·10^{23}/cm^3)



The cell structure of the Emulsion Cloud Chamber

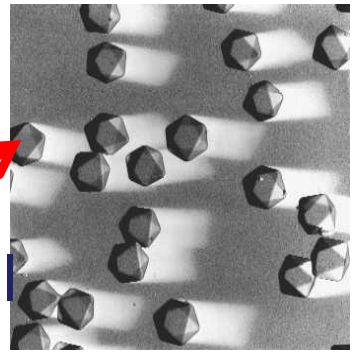


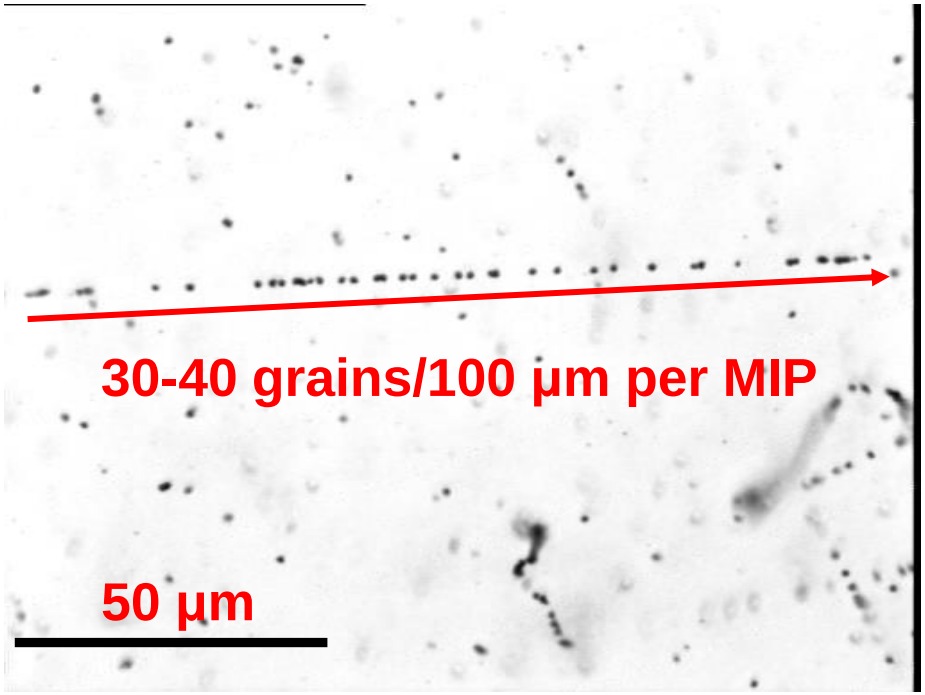
Emulsion were differently treated after the exposure and before the chemical treatment according to their position in the elementary cell (**0**, **1**, **2**)

- **R0:**
  - Not refreshed
  - Developed soon after the exposure
  - **Sensitive to m.i.p.**
- **R1:**
  - 3 day refreshing at 98% relative humidity at 30° C
  - Insensitive to m.i.p.
  - **Sensitive to protons**
- **R2:**
  - 3 day refreshing at 98% relative humidity at 38° C
  - **Sensitive to He**

Nuclear emulsion

- Charged particle detector
- First kind of detector for ionizing radiation
- AgBr crystal (0.2 μm) is the elementary detection cell
- The particle tracking is registered from the AgBr grains along its path





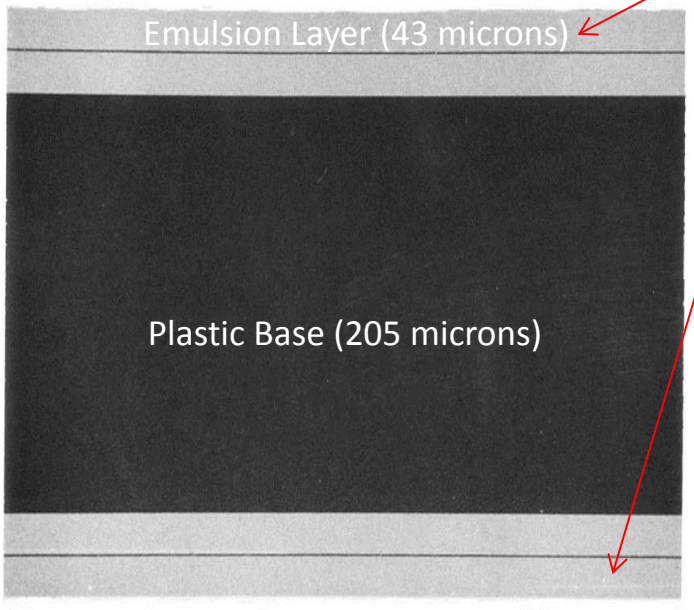
Microscope image

OPERA emulsions

OPERA industrial emulsions from FujiFilm

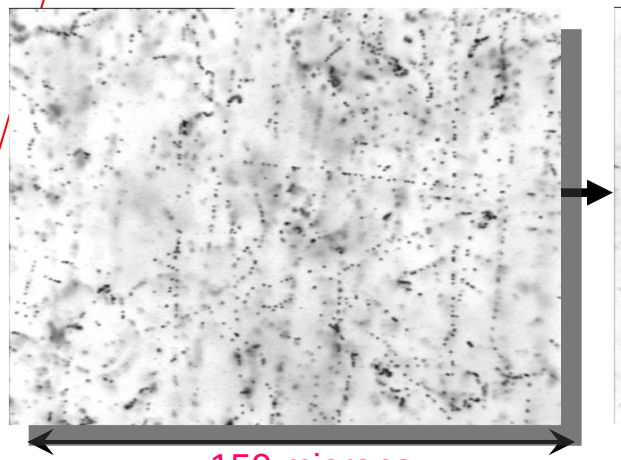
- The AgBr density in the OPERA emulsions is higher in respect to the commercial films

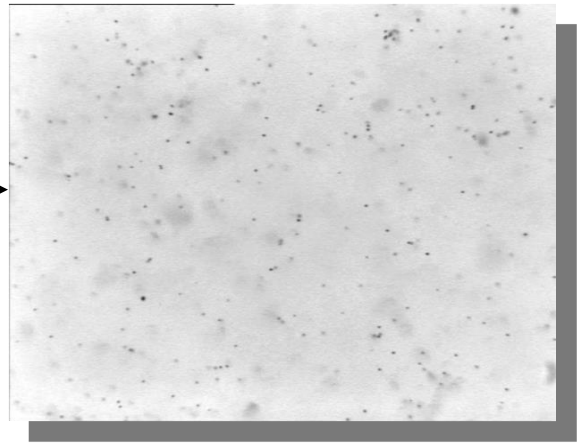
- Special R&D for OPERA: the double pouring procedure



Before refreshing
>30 tracks/mm^2

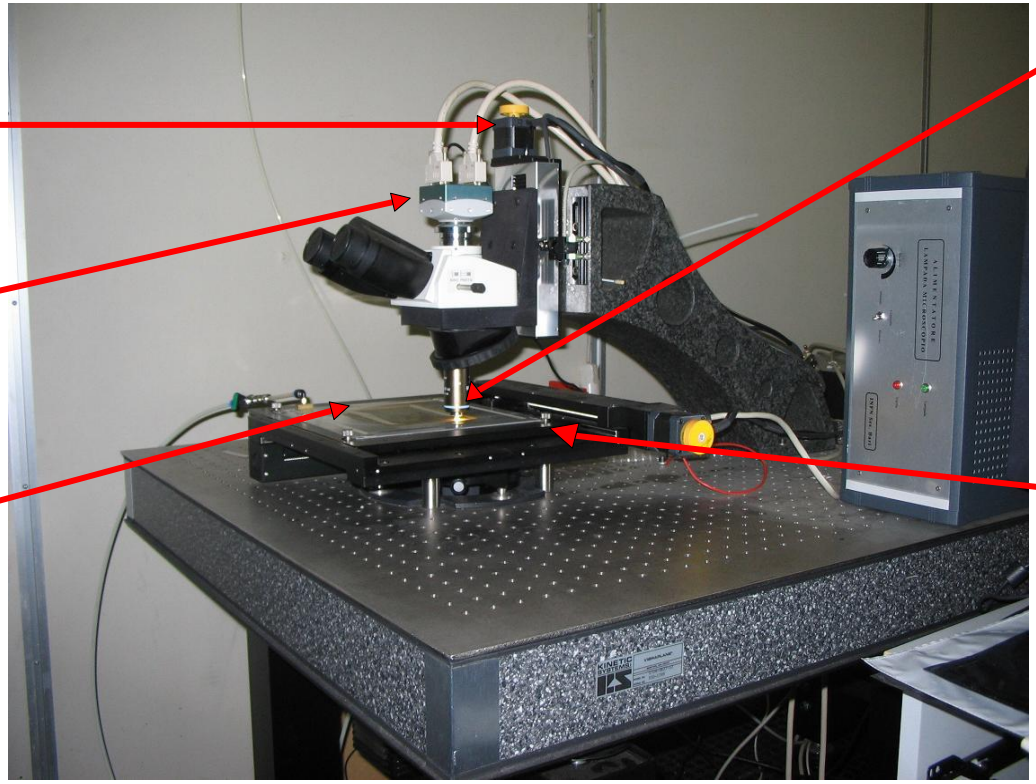
After refreshing
~1 tracks/mm^2



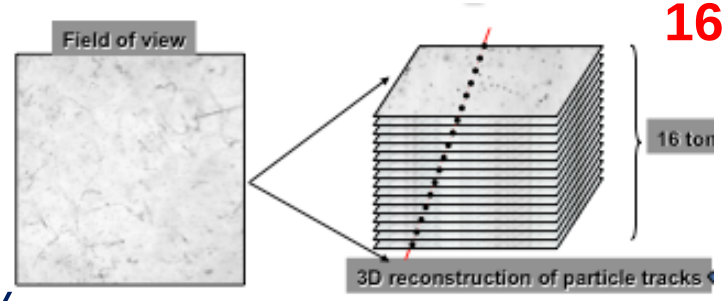


Emulsions are continuously sensitive detector ALL charged particle: cosmic rays, natural radioactivity etc recorded as a latent images. They can be partially erased by a “refreshing” procedure applied just before the detector assembling.

Emulsion scanning system

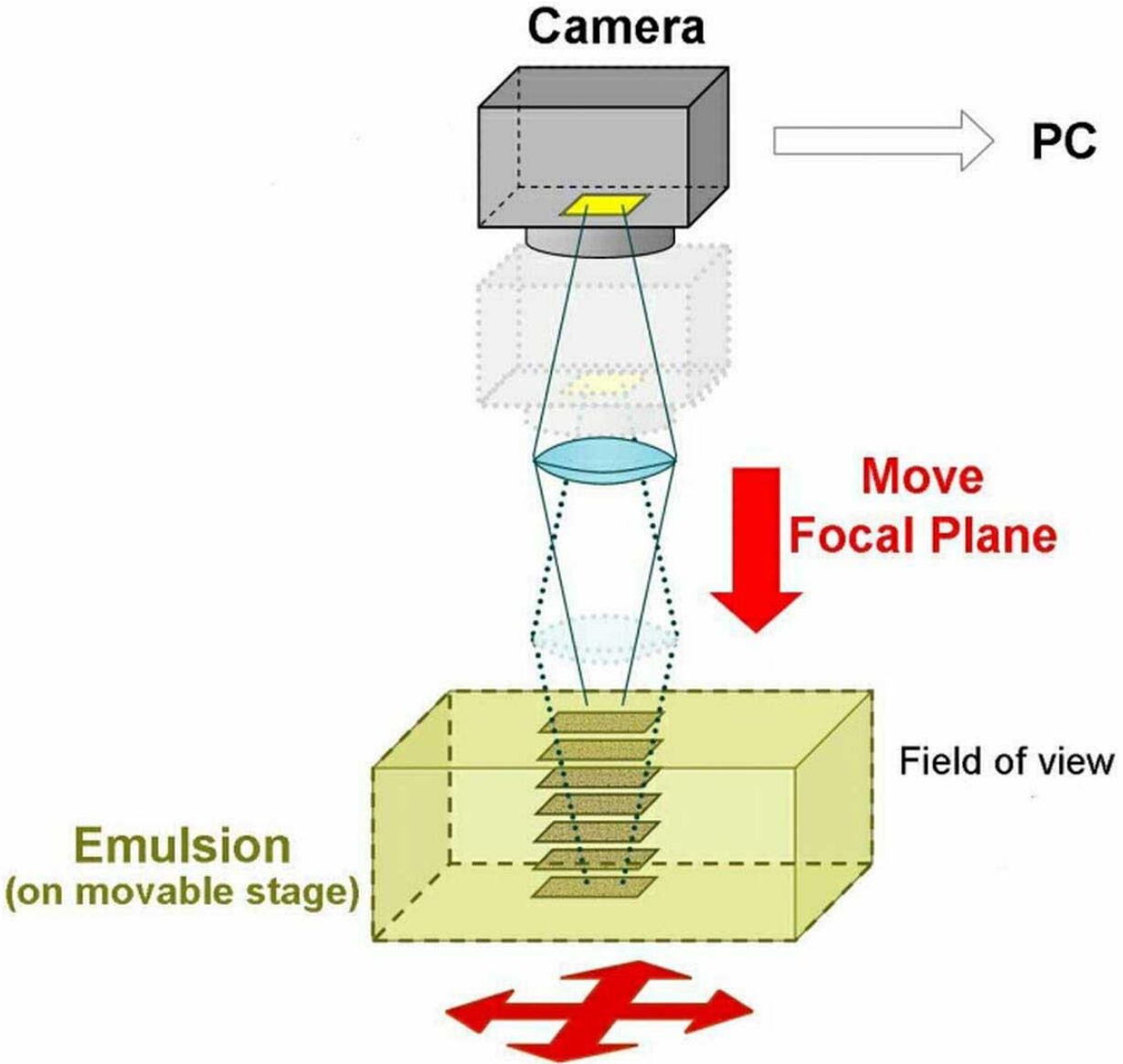


- OPERA expertise in scanning
- 3d track reconstruction
- Scanning speed: 20 cm^2/h
- Spatial resolution: ~0.3 μm
- Angular resolution: ~2 mrad
- Detection efficiency of the tracks: ~95%



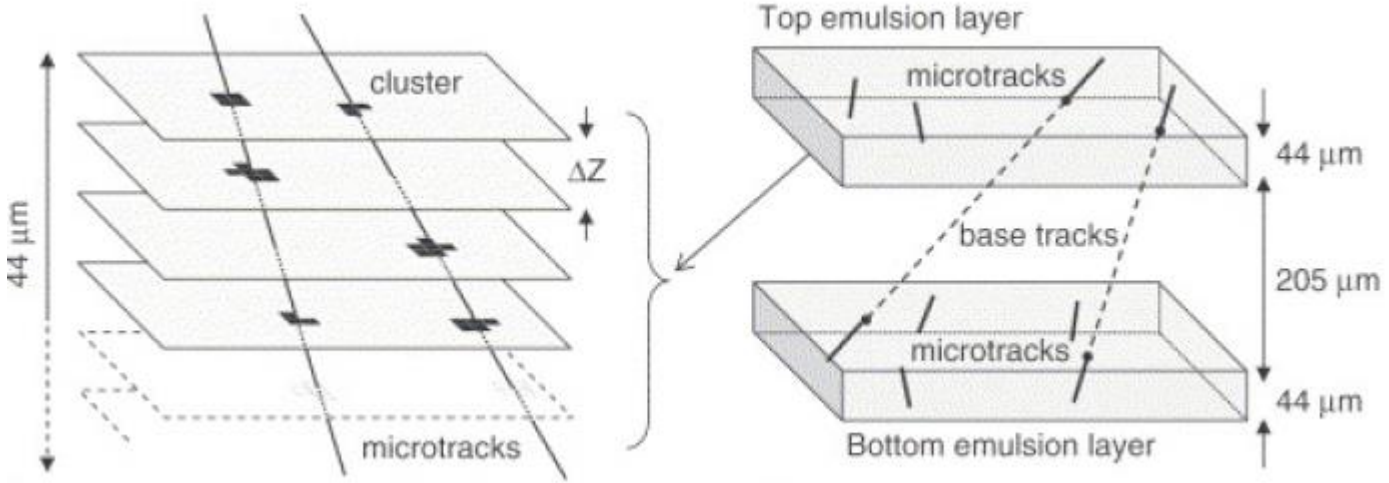
Principle of scanning emulsion

16 images taken through 44-micron emulsion layer



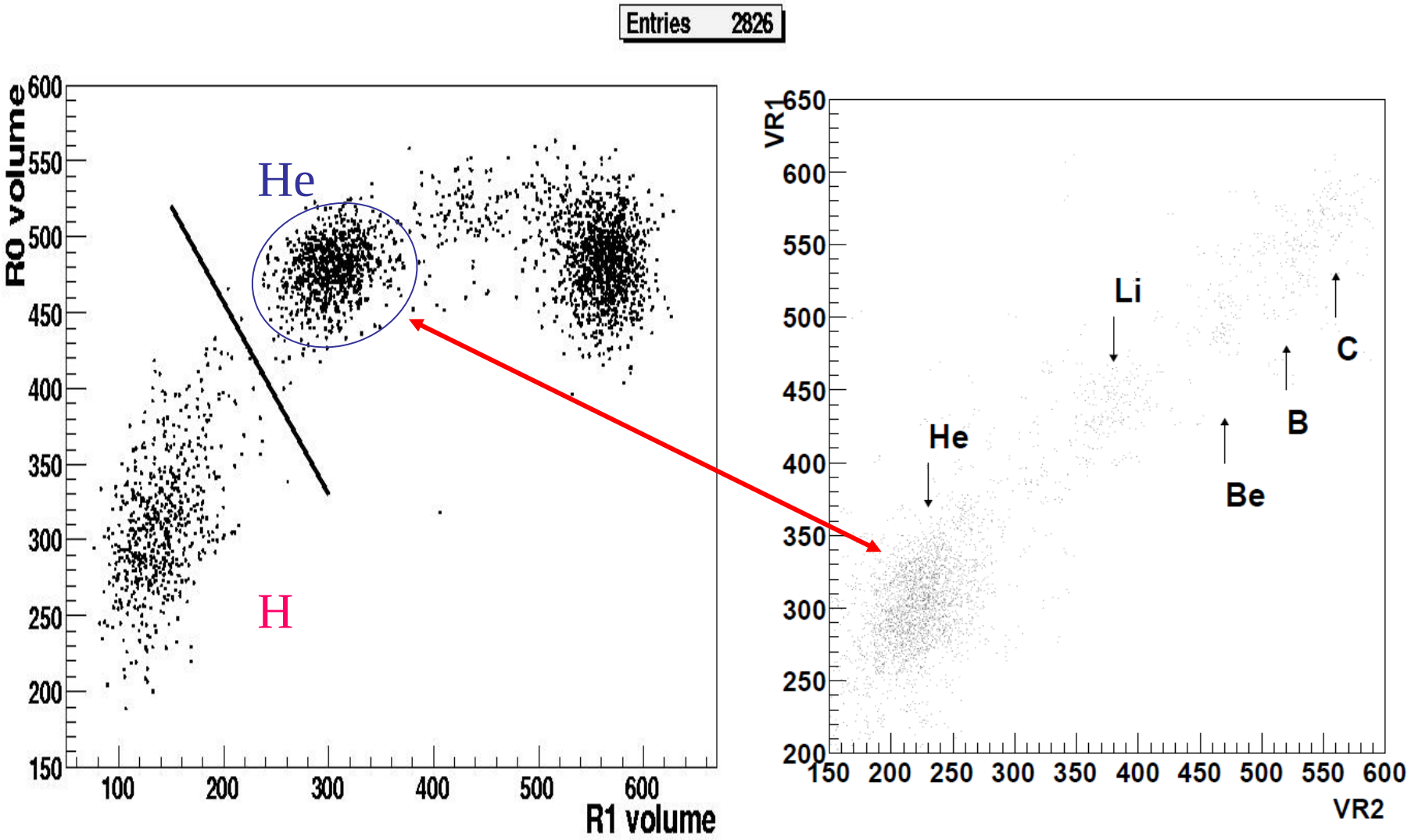
Automatic scanning system

- Micro-track reconstruction in one emulsion layer by combining clusters belonging to images at different levels.
- Micro-tacks are connected across the plastic base to form a base-tracks.



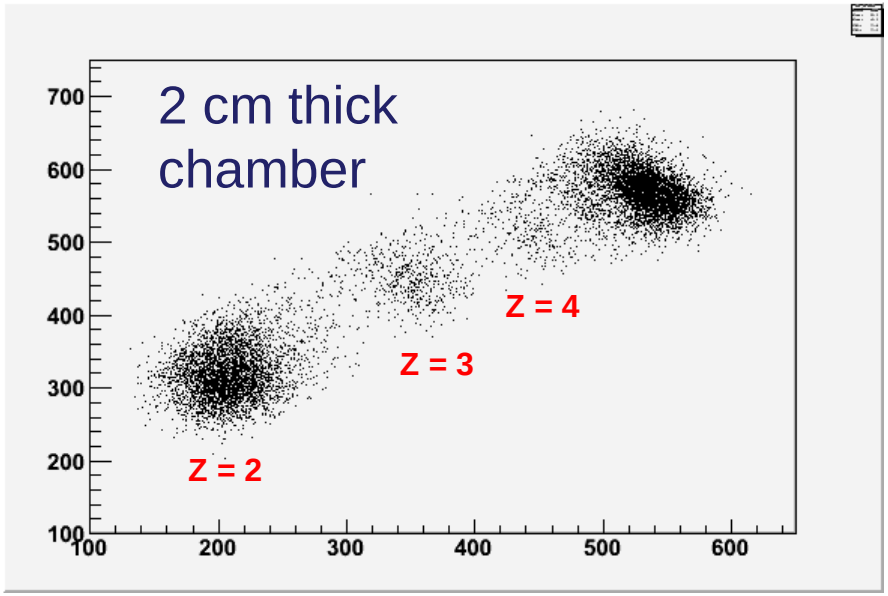
Results

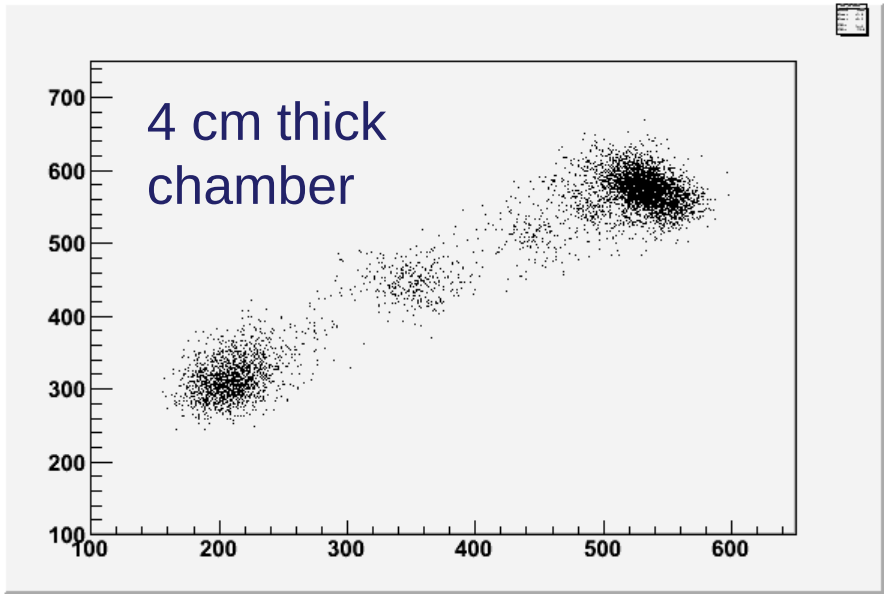
Combining the information on consecutive films to get rid of the saturation effect R0 vs R1 and R1 vs R2 scatter plot

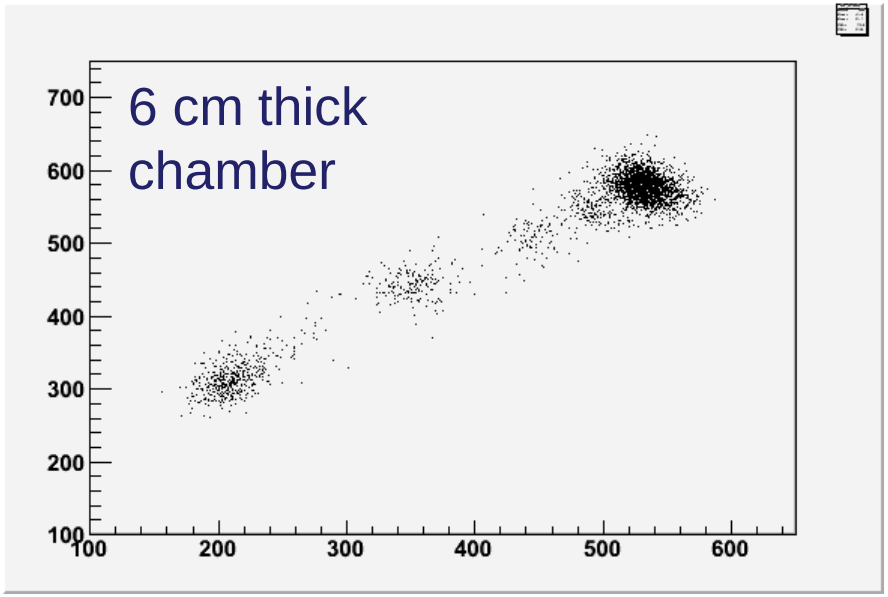


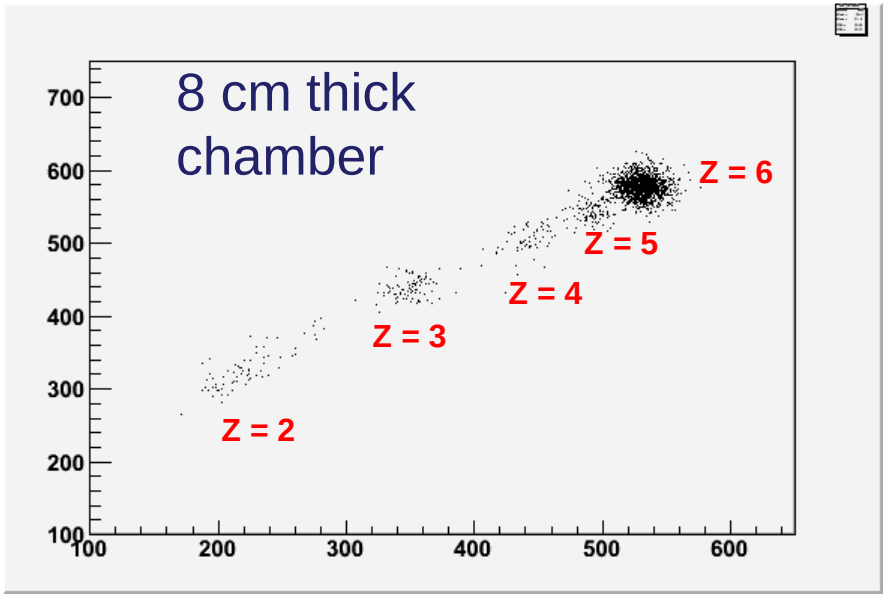
Journal of Instrumentation 2 (2007) P06004

Charge identification

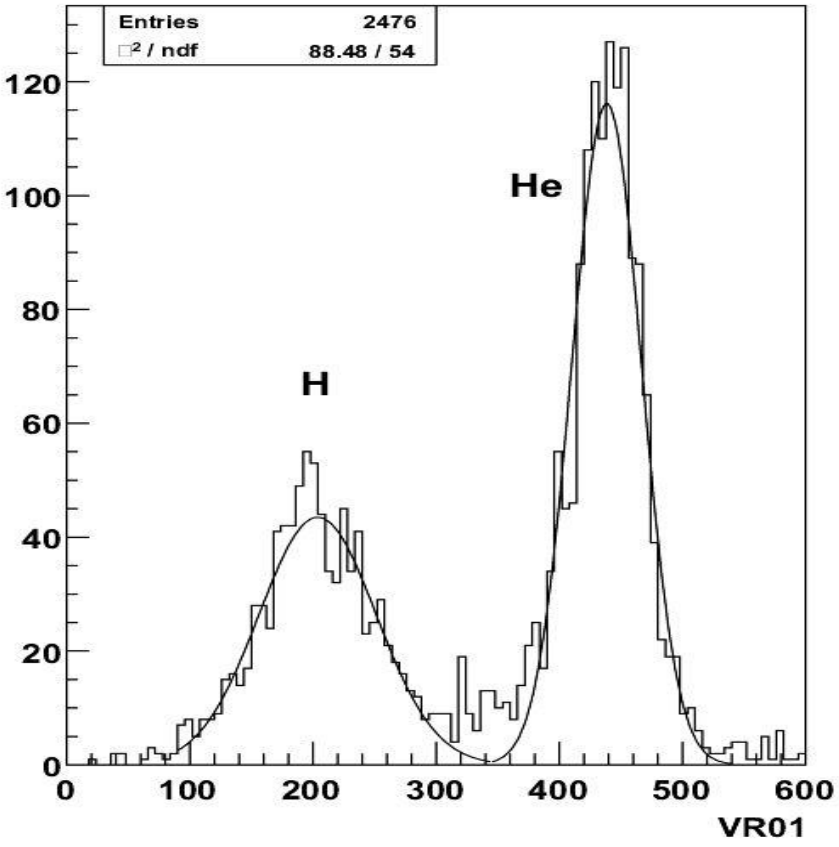


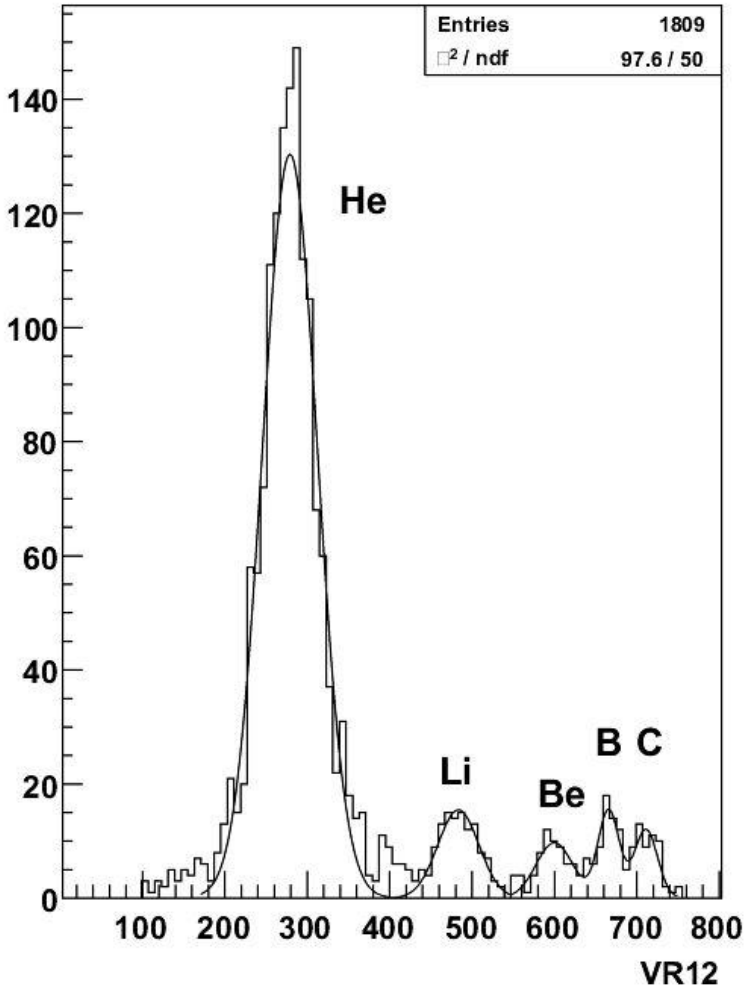






Charge separation

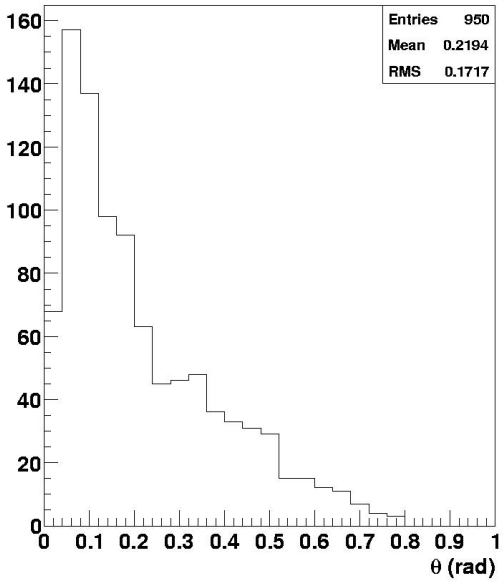




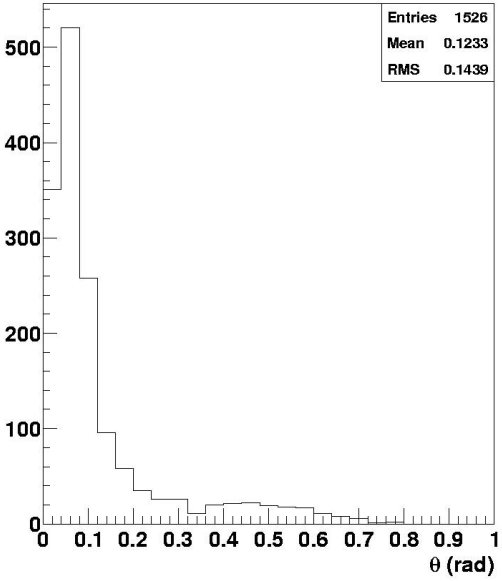
Journal of Instrumentation 2 (2007) P06004

Scattering angle of emitted particles

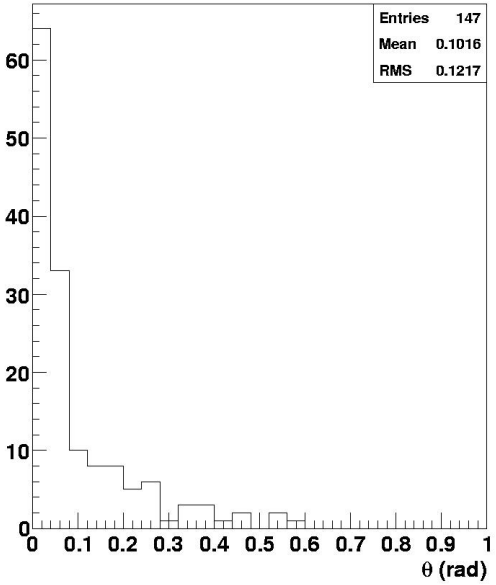
Hydrogen



Helium



Lithium



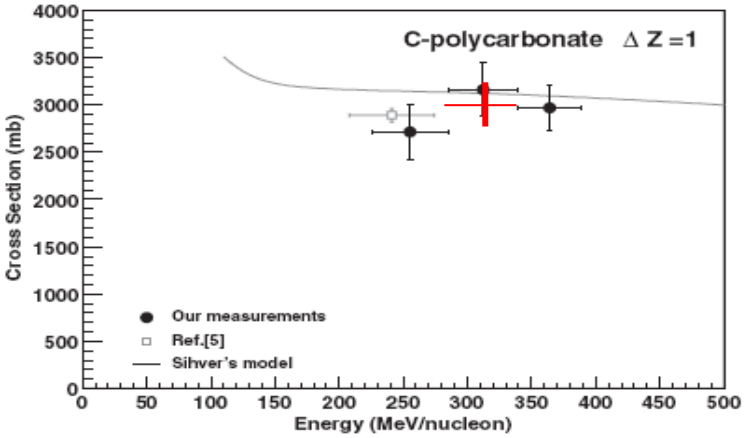
Cross-section measurement

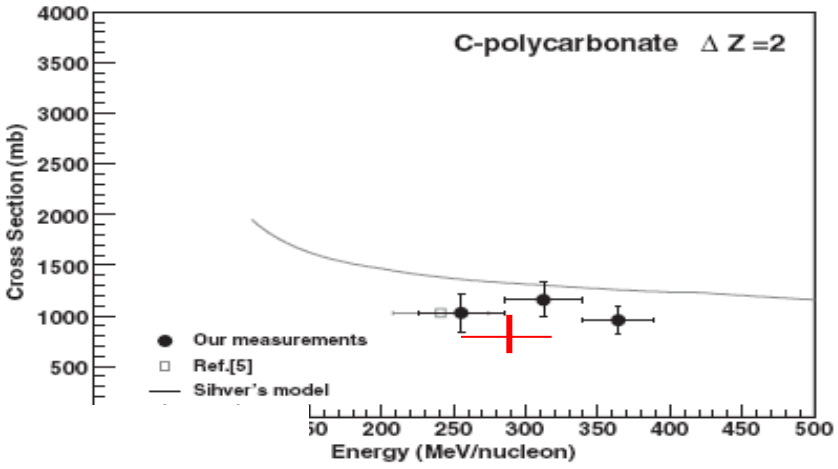
- A volume of about 24 cm^3 analyzed
- Average energy of the Carbon beam: 315 MeV/n
- Counting the events with Lithium ($\Delta z = 3$), Beryllium ($\Delta z = 2$) and Boron ($\Delta z = 1$) as the heaviest particle in the final state

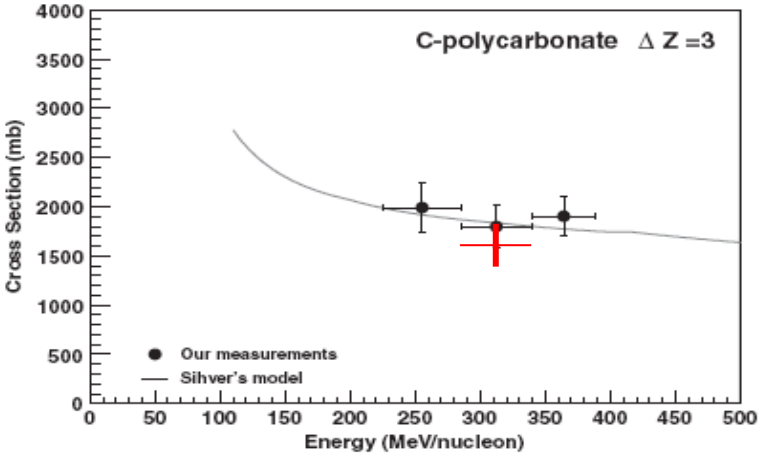
$$\sigma(\Delta z = 1) = (2510 \pm 140_{stat} \pm 250_{sys})\text{mbarn}$$

$$\sigma(\Delta z = 2) = (1170 \pm 90_{stat} \pm 120_{sys})\text{mbarn}$$

$$\sigma(\Delta z = 3) = (1460 \pm 105_{stat} \pm 150_{sys})\text{mbarn}$$



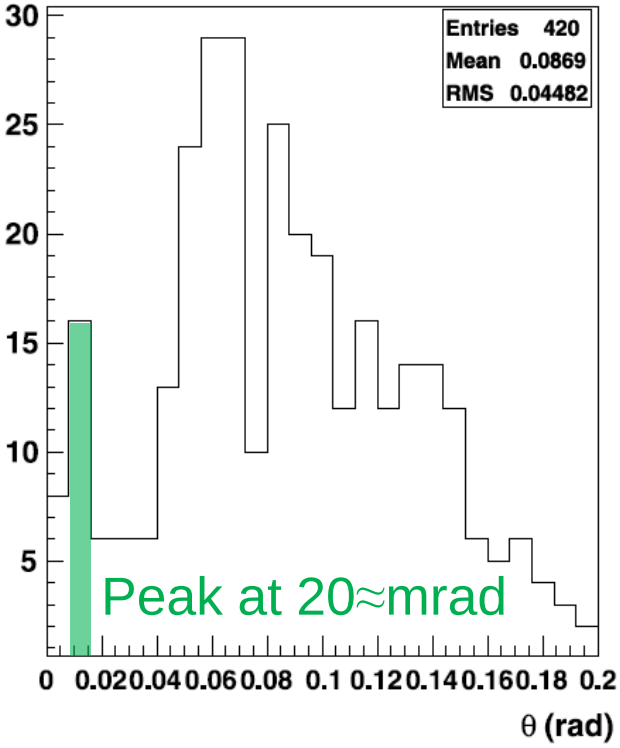


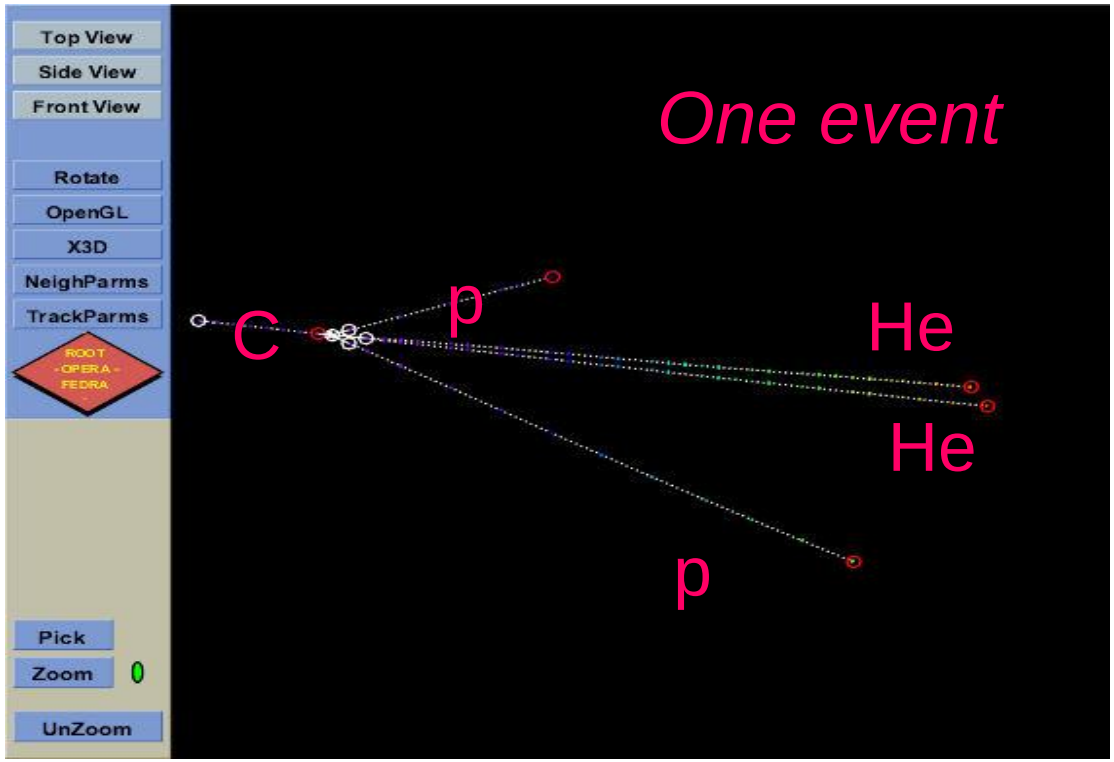


Black points: Phys.Rev.C75 (2007) 054606

^{8}Be production Cross Section

- ^{8}Be → He + He (10^{-16} s)
- Q value 90 keV → small opening angle
- Opening angle between pairs of reconstructed Helium tracks





$$\sigma(C \rightarrow 8Be) = (190 \pm 40)\text{mbarn}$$

Outline

- Hadrontherapy motivation
- The ^{12}C fragmentation measurement with the Emulsion Cloud Chamber (ECC) detector
- **The FIRST detector**
- Measurements at GSI in the FIRST set-up
- Preliminary results
- Conclusion

FIRST experiment

- FIRST: Fragmentation of Ions Relevants for Space and Therapy
- Aim:
  - ✓ Production yelds of Z=0, 1, 2 ,3 ,4 ,5 fragments
  - ✓ Measurement of cross section wrt angle and energy, with large angular acceptance
- A collaboration among:

INFN: Cagliari, LNF, LNS, Milano, Napoli, Roma3,Torino;

DSM/IRFU/SPhN CEA Saclay, IN2P3 Caen, Strasbourg, Lyon;

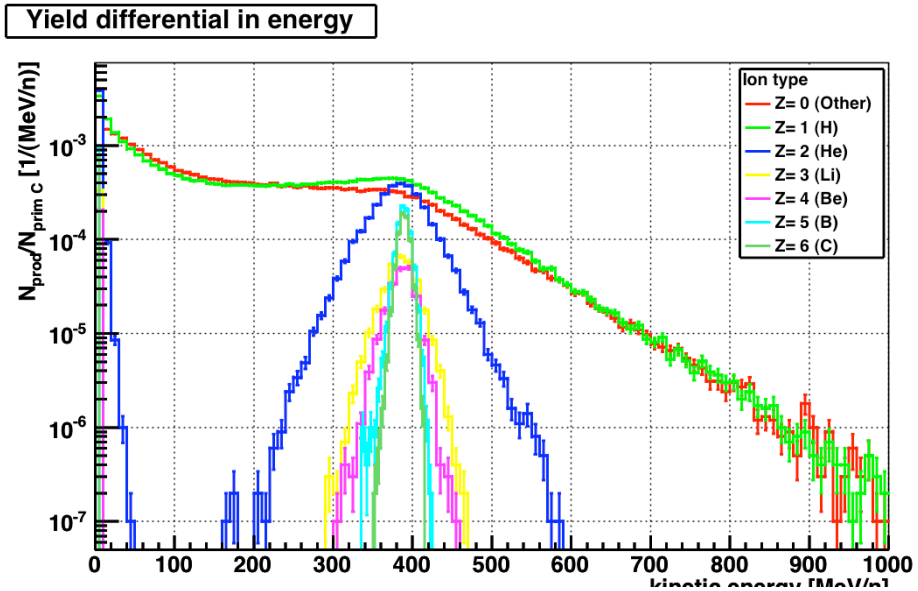
GSI:

- ✓ Therapeutical beam of ^{12}C @ 200-400 MeV/n available
- ✓ Existing setup designed for higher E and Z fragments: Dipole magnet, Large Volume TPC, TOF Wall, low angle Neutron detector.

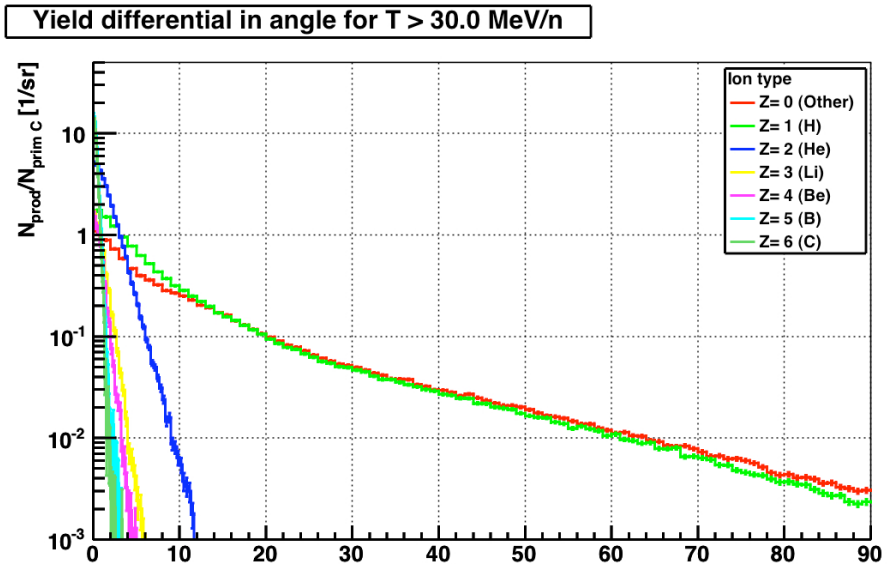
ESA, CERN

What do we expect from MC (FLUKA)?

- The Z>2 produced fragments approximately have the same velocity of the ^{12}C beam projectiles and are collimated in the forward direction
- The protons are the most abundant fragments with a wide angular distribution and a kinetic energy spectrum up to 1 Gev/n
- The Z=2 fragment are emitted within 20° of angular aperture



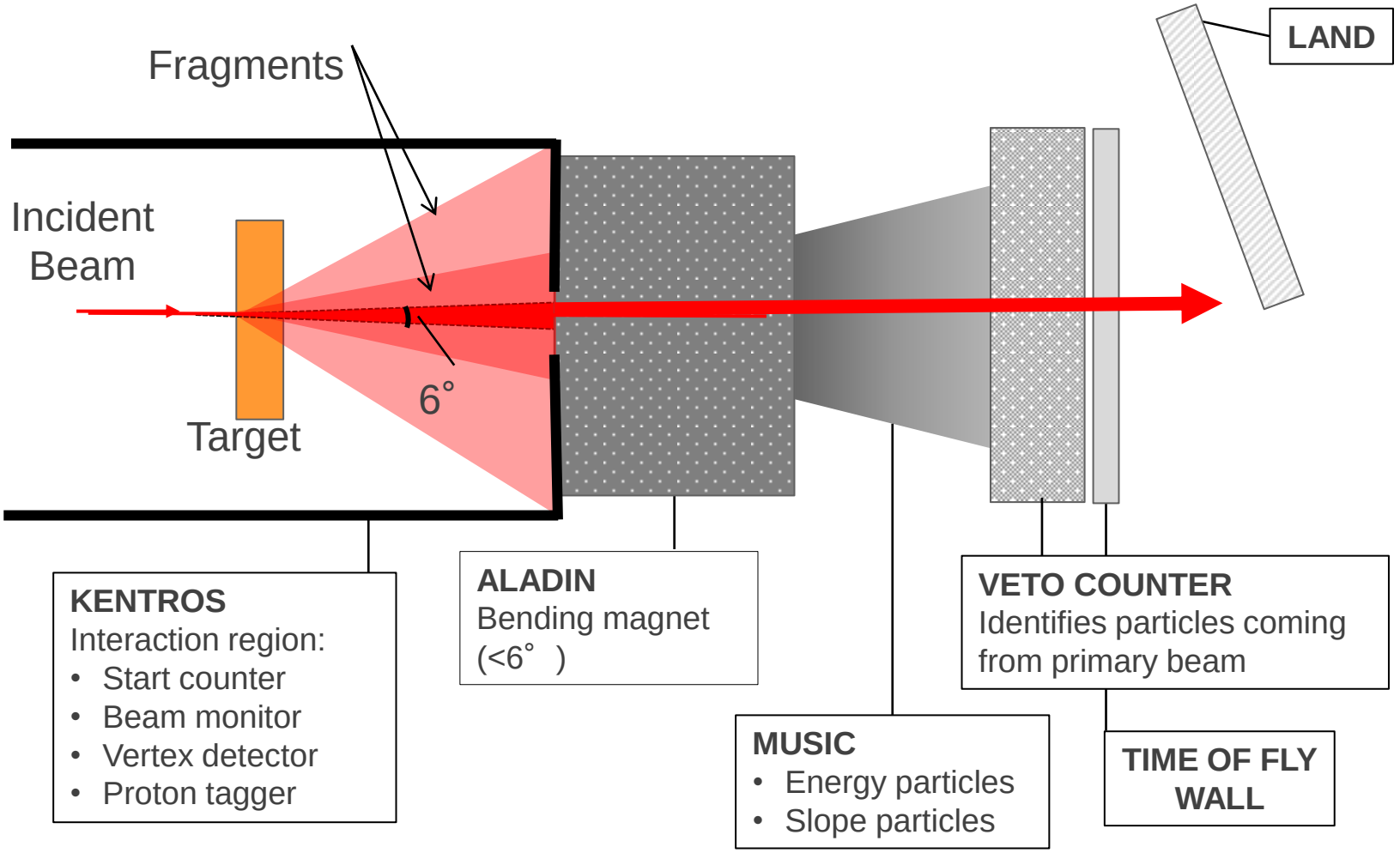
Kinetic energy (MeV/nucl)



Emission angle (deg)

FIRST set up

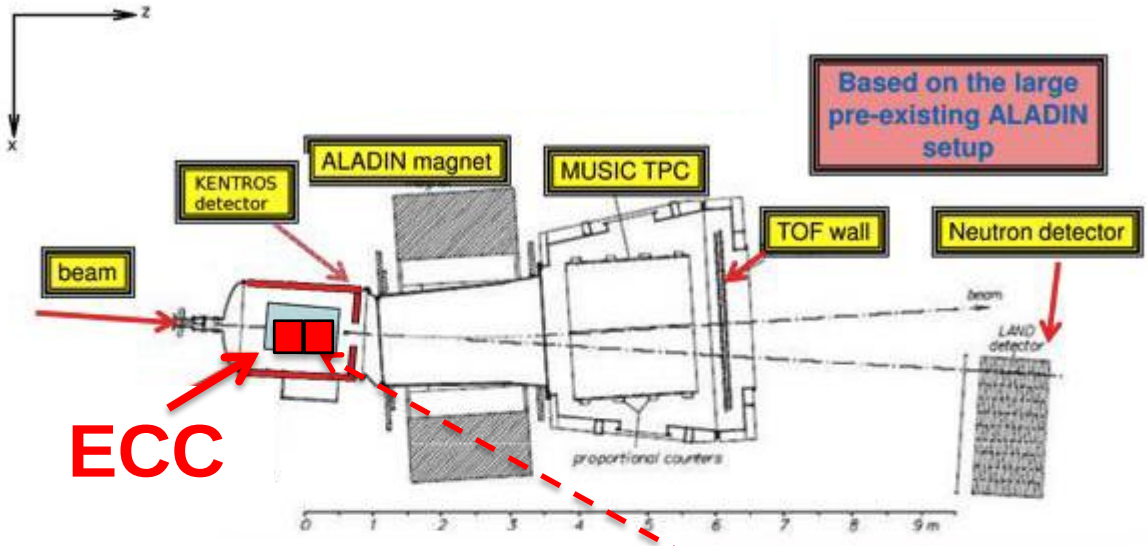
The measurements were performed at the GSI facilities, where a therapeutical beam of ^{12}C @ 200-400 MeV/n is available

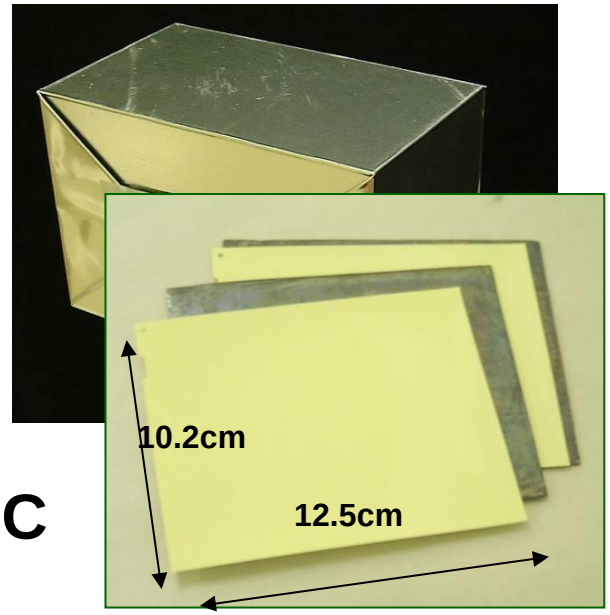


Outline

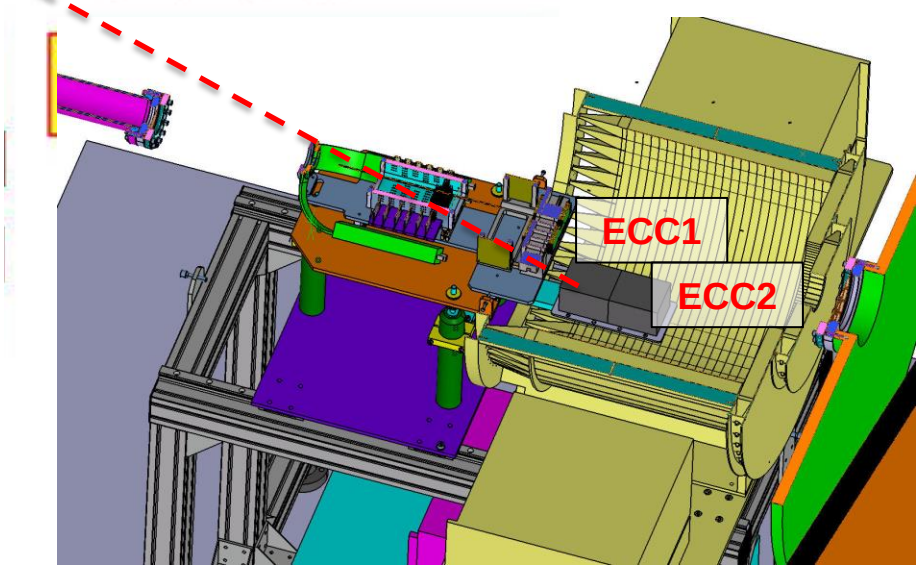
- Hadrontherapy motivation
- The ^{12}C fragmentation measurement with the Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- **Measurements at GSI in the FIRST set-up**
- Preliminary results
- Conclusion

The FIRST set-up





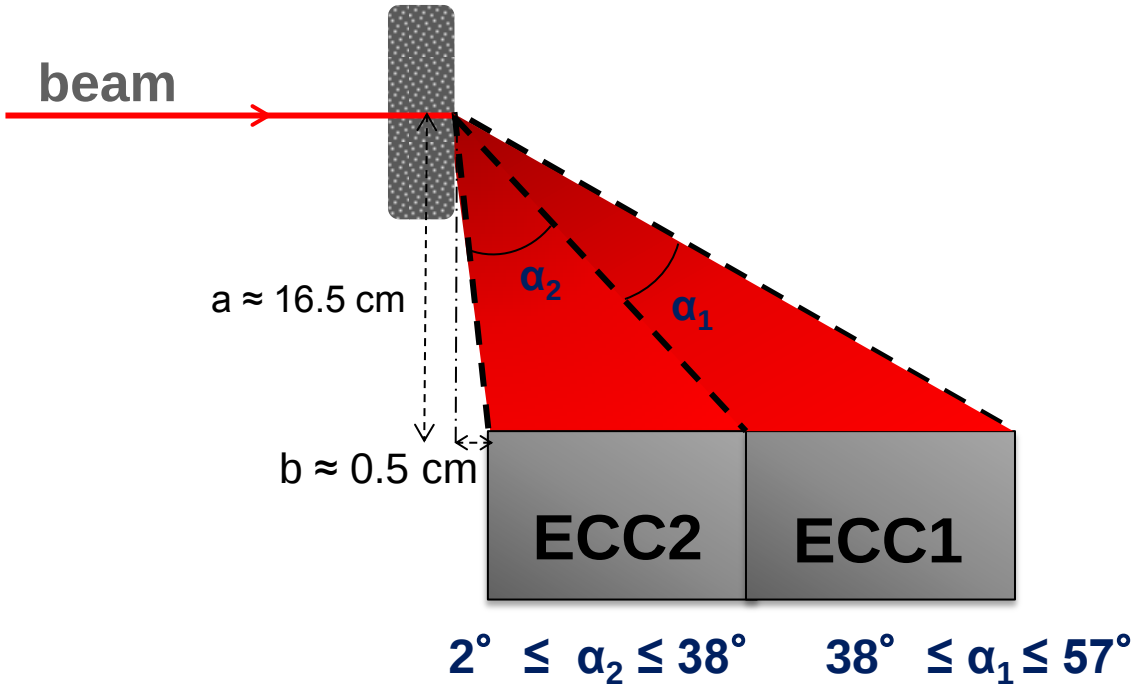
ECC



"FIRST experiment: Fragmentation of Ions Relevant for Space and Therapy"
Journal of Physics: Conference Series ***420*** *(2013) 012061 doi:10.1088/1742-6596/420/1/012061*

Beam exposure of ECC

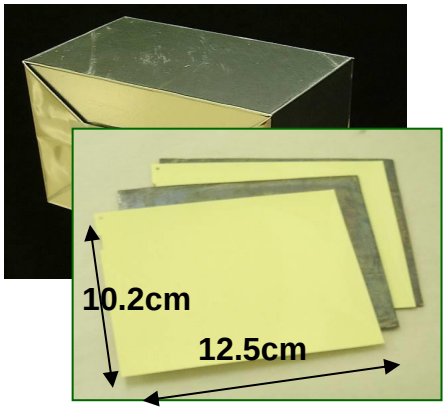
- ^{12}C beam with 400 MeV/n
- Carbon target (8 mm thick)
- Two ECC were collocated inside the detector FIRST
- Dedicated study on large angle track detection

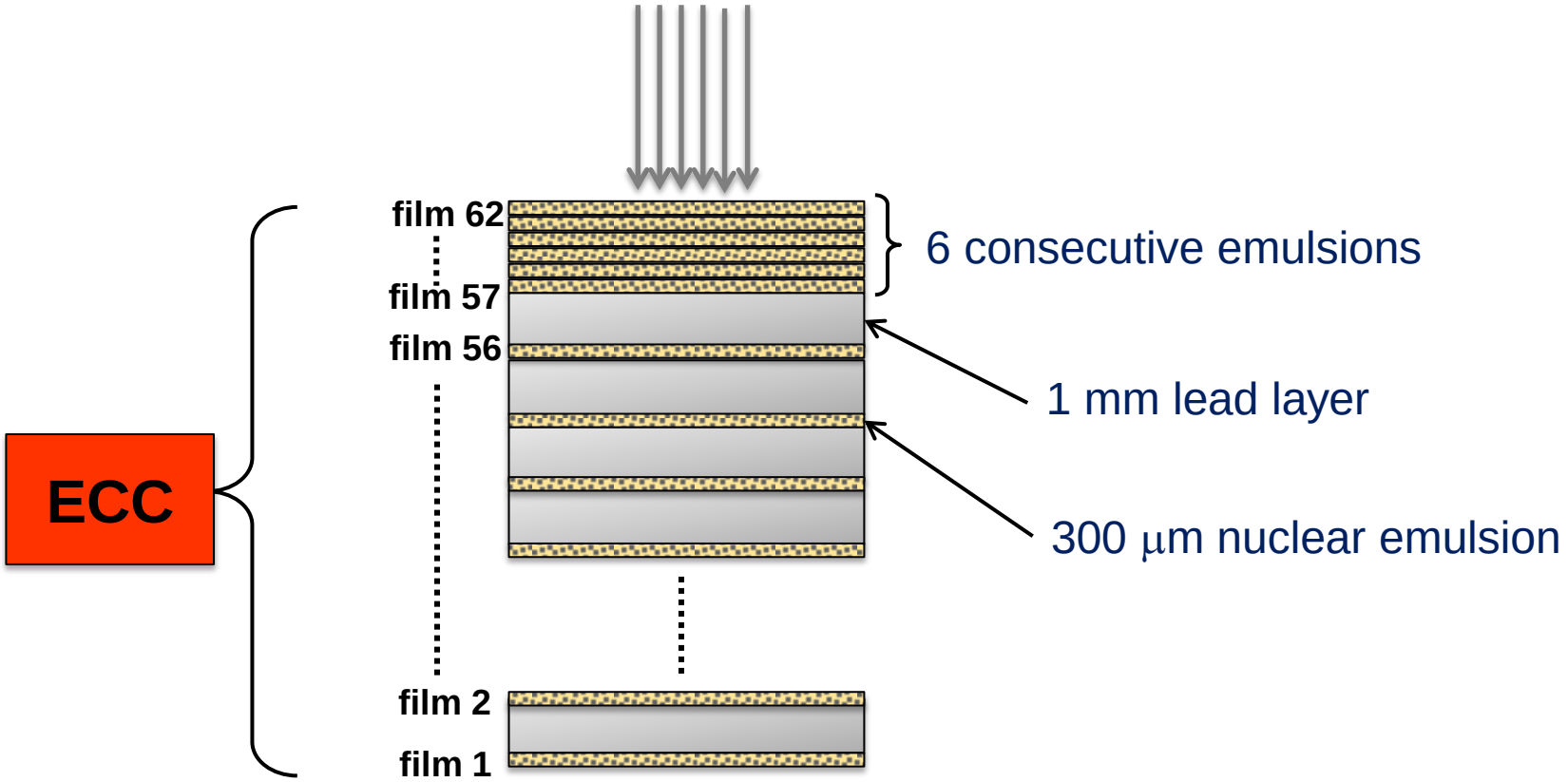


ECC strucutre

ECC structure:

- Not homogeneous structure
- 6 consecutive emulsion films
- 56 nuclear emulsion layers (300 μm) interleaved with 56 lead plates (1 mm)

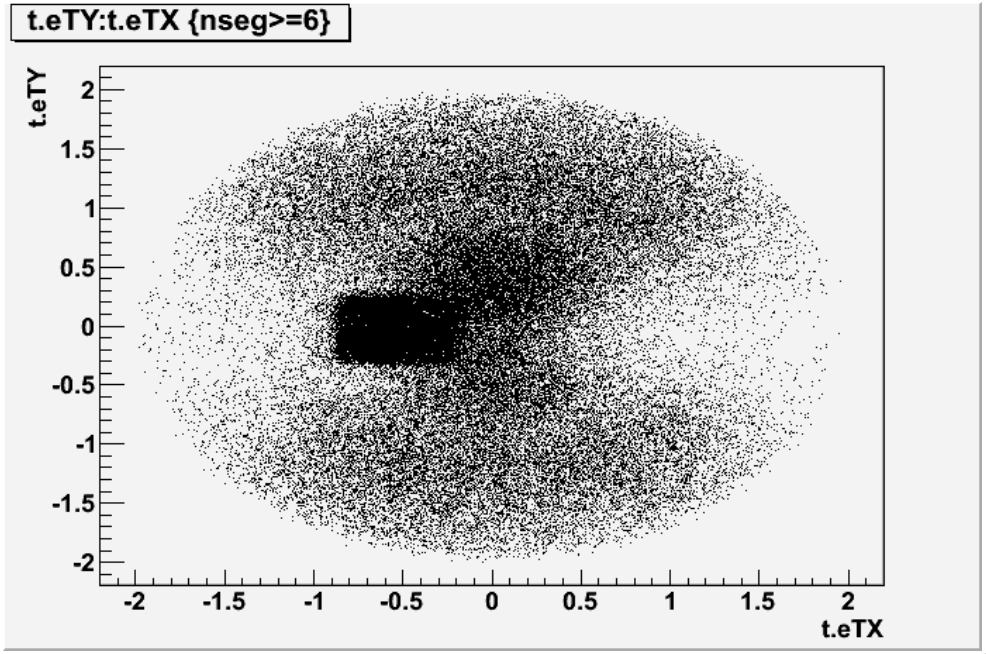




Outline

- Hadrontherapy motivation
- The ^{12}C fragmentation measurement
- The Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- Measurements at GSI in the FIRST set-up
- **Preliminary results**
- Conclusion

ECC 2: Tracks angular distribution



Signal and cosmic rays

- 20 emulsions were scanned (6 consecutive emulsions and 14 emulsions interleaved with lead)
- Data were scanned and processed up to tg $\theta \leq 2$

Signal cut:

$-0.9 \leq \text{tg}\,\Theta_x \leq -0.1$

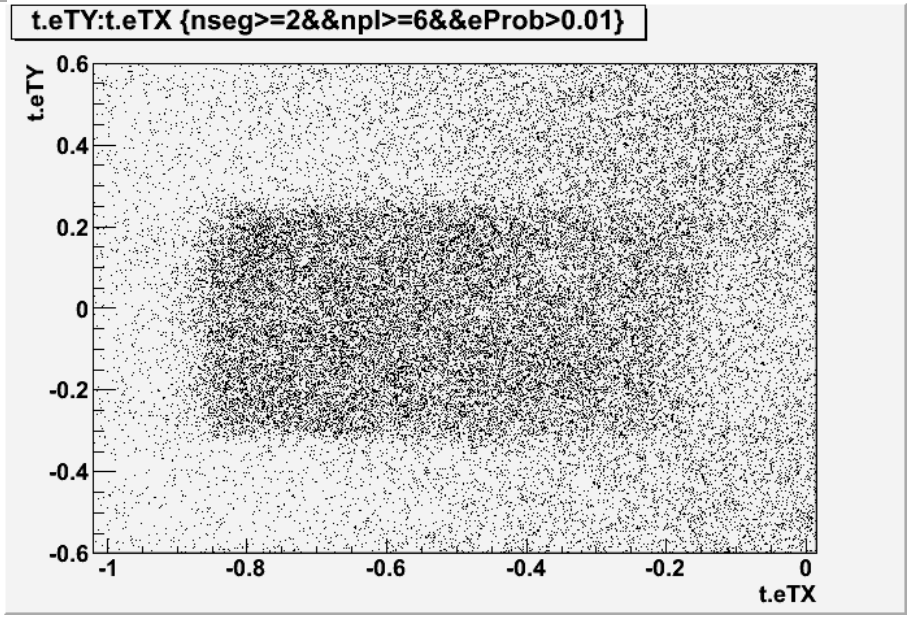
$-0.3 \leq \text{tg}\,\Theta_y \leq 0.28)$

Signal is effectively measured at:

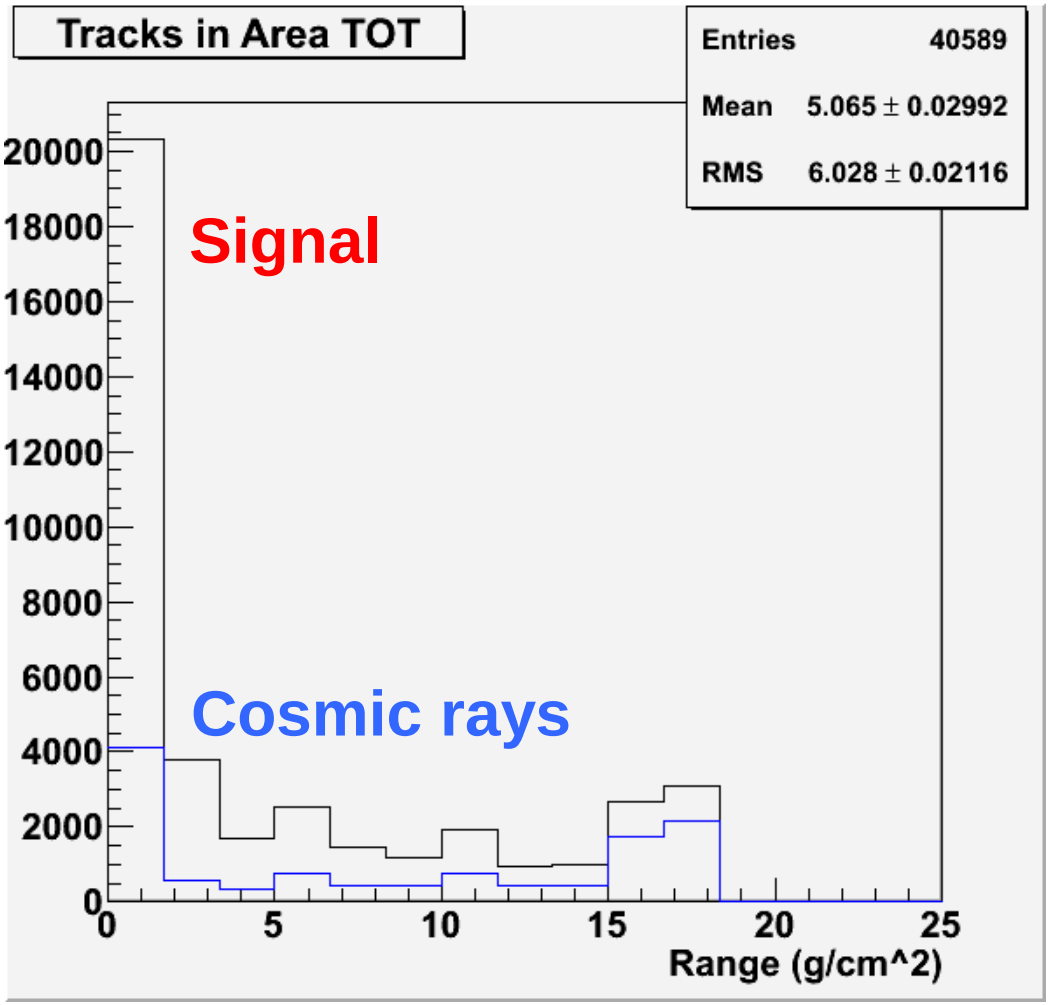
$3^\circ \leq \theta \leq 40^\circ$ (*for ECC2*)

$40^\circ \leq \theta \leq 60^\circ$ (*for ECC1*)

as it was expected from the exposition geometry

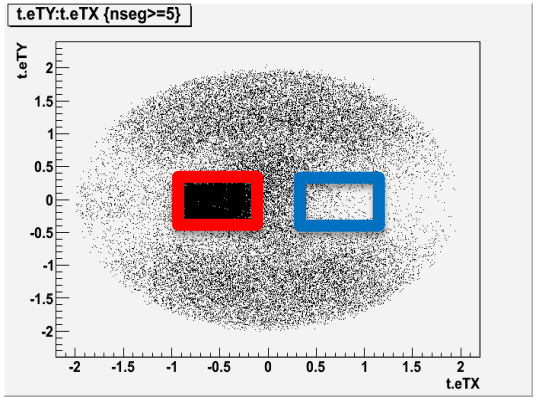


Signal and cosmic ray range distribution



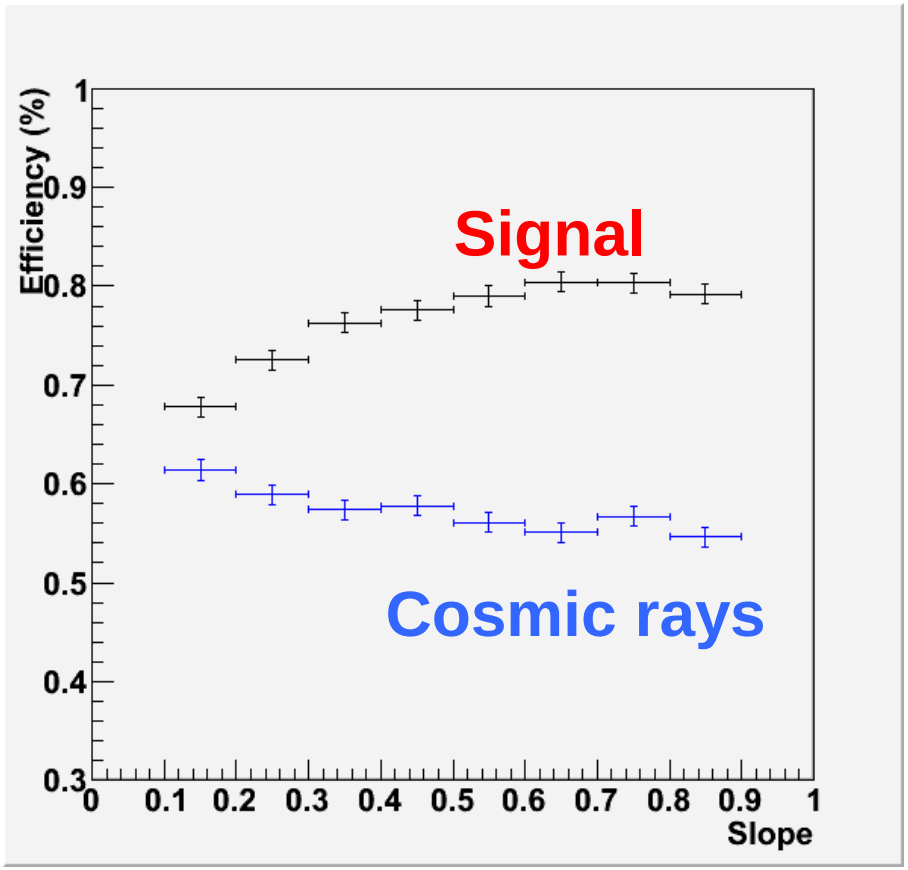
Tracks selected:

- $-0.9 \leq \mathrm{tg}\,\Theta_x \leq -0.1$
- $-0.3 \leq \mathrm{tg}\,\Theta_y \leq 0.28$
- number of segments ≥ 2

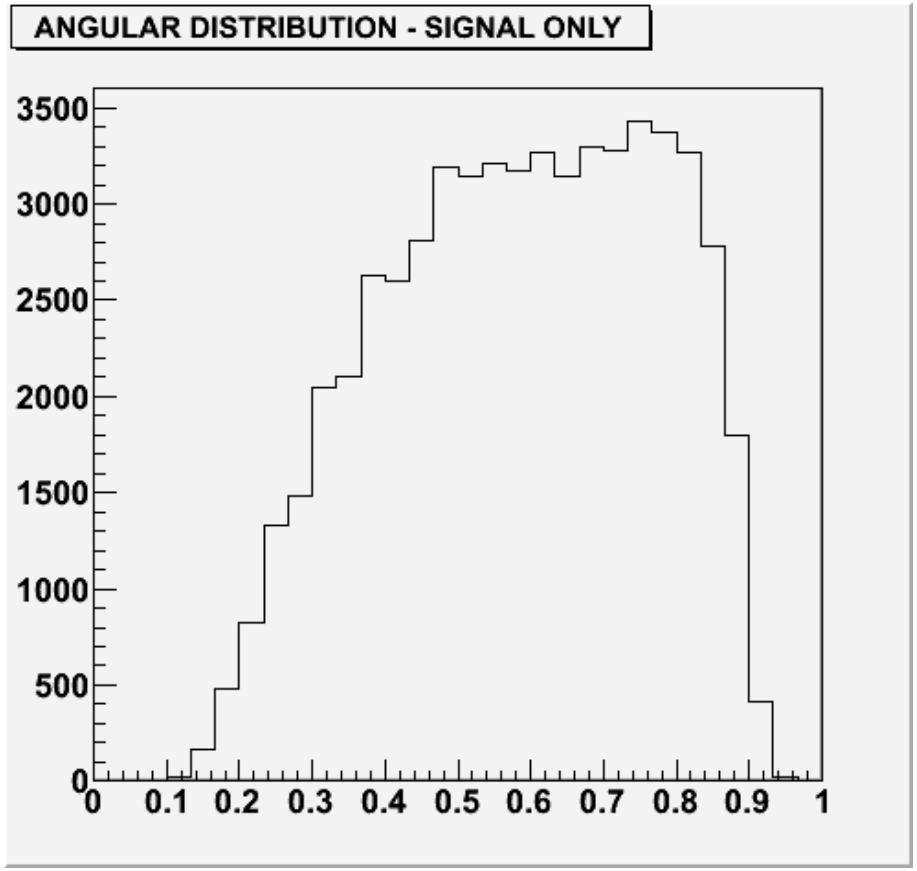


preliminary results

Reconstruction efficiency



Efficiency vs tracks slope



Angular distribution of only signal corrected by efficiency

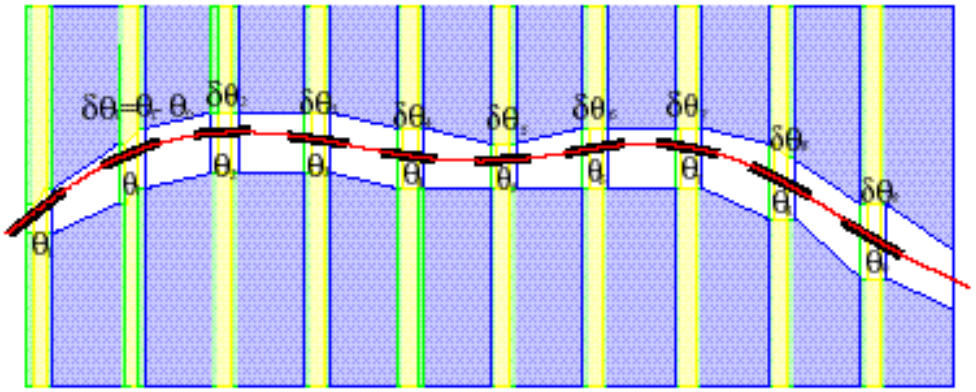
CR/(S+CR)=24.4%

preliminary results

Kinematical measurements

1. Momentum measurement by multiple coulomb scattering (MCS)

[Angle Method]



From the slope measurements along the particle track of the same particle obtained from the ECC it is possible to calculate the particle impulse in the range: 200 MeV/c ÷ 2 GeV/c

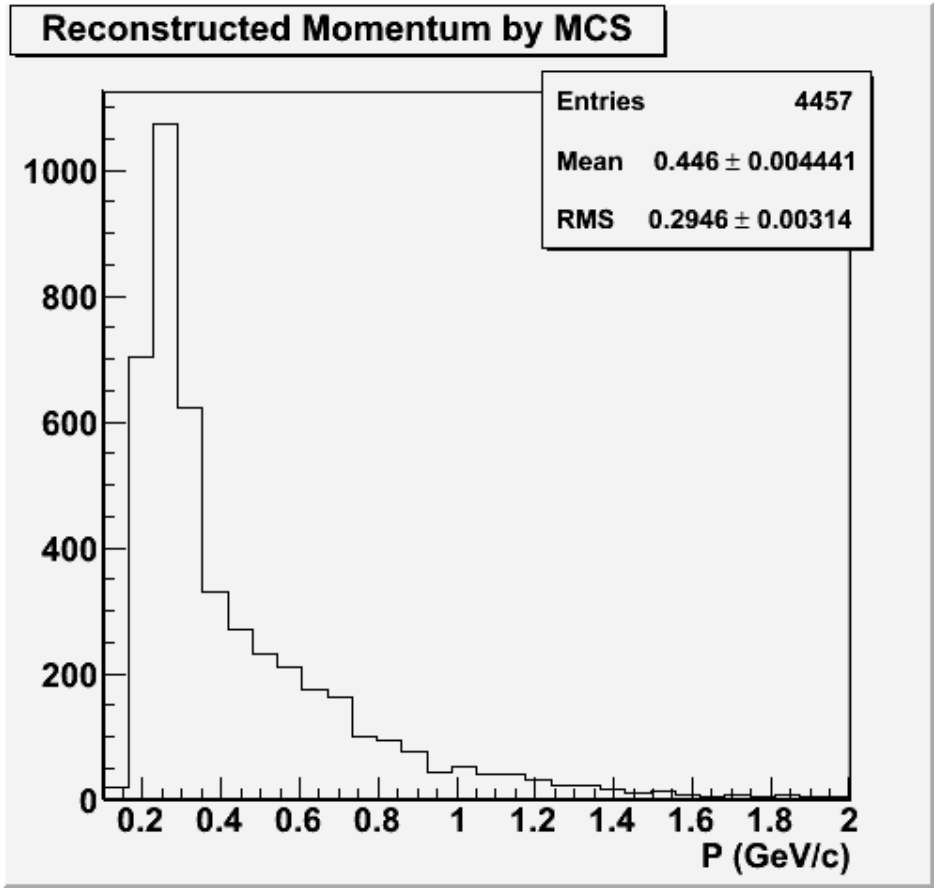
The algorithm was used for OPERA experiment and is based on:

$$p\ (MeV/c) = \frac{13.6}{\beta\ \delta\theta\ (mrad)}\sqrt{\frac{x}{X_0}}$$

"Momentum measurement by the angular method in the Emulsion Cloud Chamber", Nuclear Instruments and Methods in Physics Research A 512 (2003) 539–545

Kinematical measurements

1.Momentum measurement by MCS



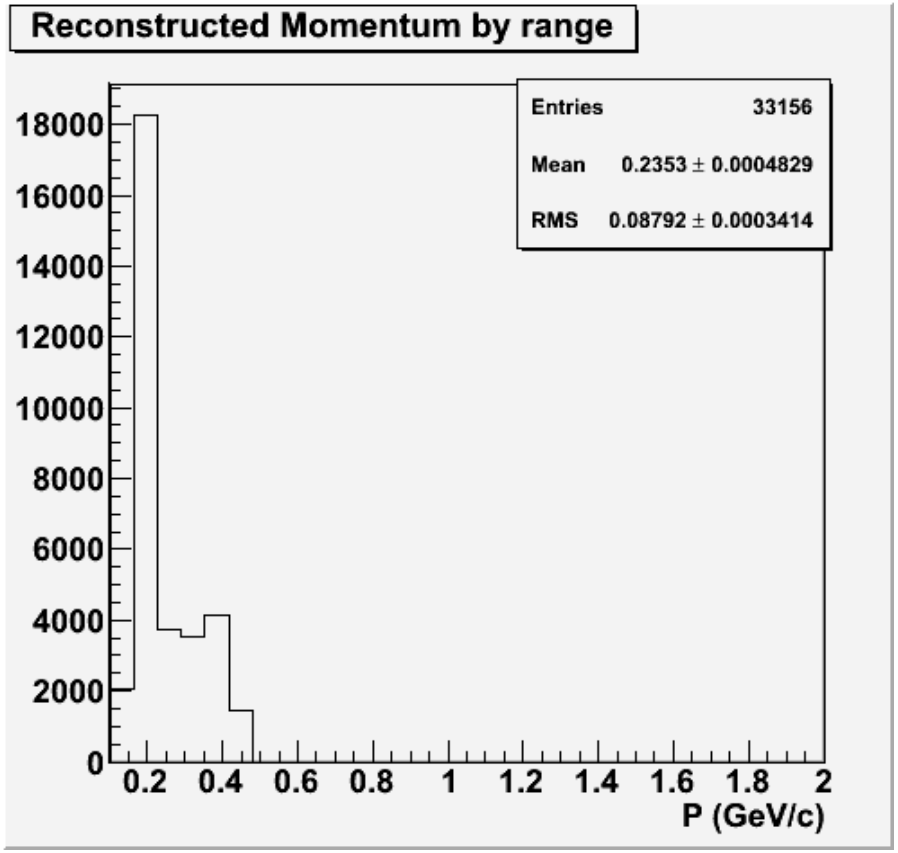
- Tracks behind the first 6 emulsions
- Tracks with at least 3 segments passing through

11 % of the total tracks of the sample

preliminary results

Kinematical measurements

2. Momentum measurement by range



- Tracks for which it is not possible the measurement by the MCS method
- Tracks stopped in the first 6 emulsions
- Tracks not stopped inside the considered volume (20 layers)

82 % of the total tracks of the sample

preliminary results

Outline

- Hadrontherapy motivation
- The ^{12}C fragmentation measurement with the Emulsion Cloud Chamber (ECC) detector
- The FIRST detector
- Measurements at GSI in the FIRST set-up
- Preliminary results
- **Conclusion**

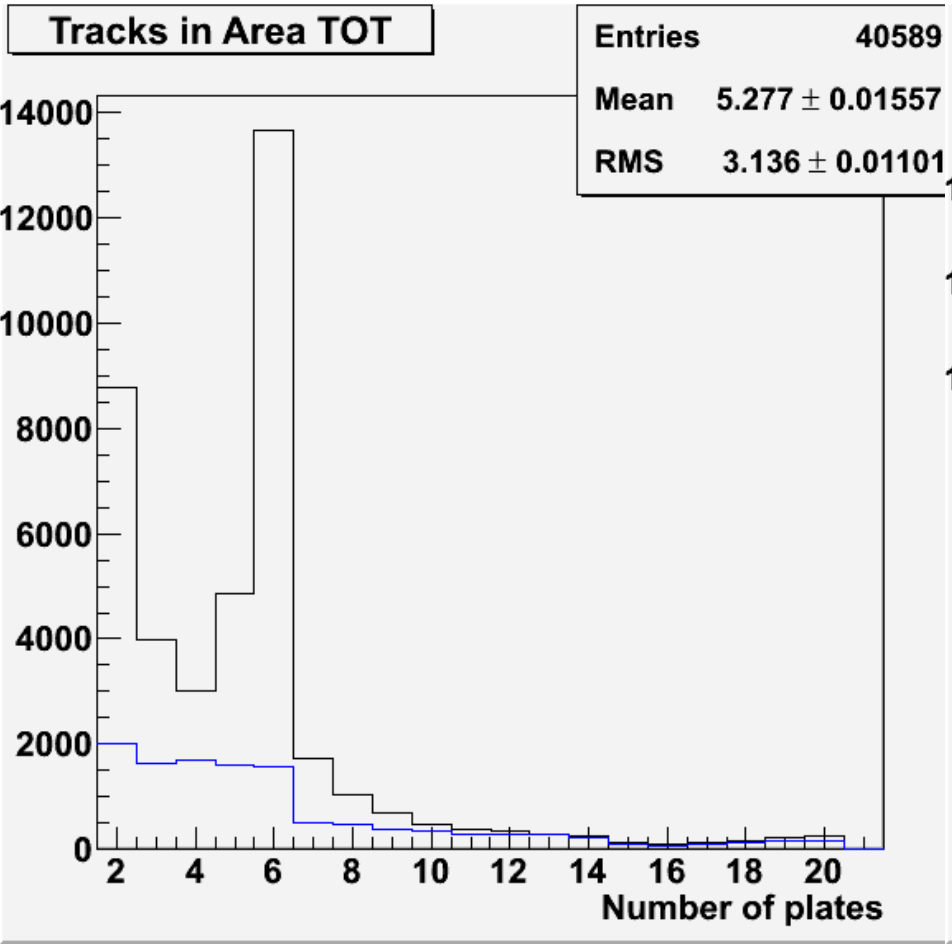
Conclusions

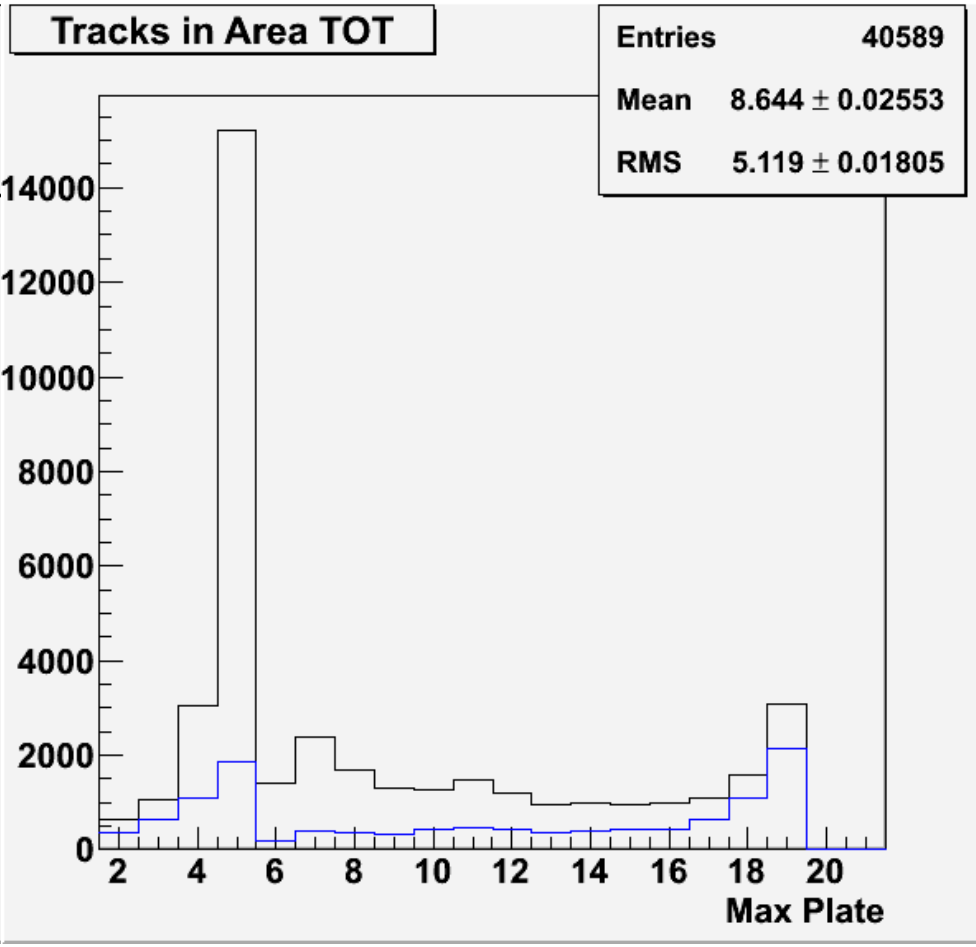
- Emulsion Cloud Chamber technique used to study the fragmentation of Carbon ions
  1. Homogeneous ECC used as target and detector
  2. Not Homogeneous ECC used as detector

From these studies:

- Discrimination of produced fragments in Z
- Charge-changing cross-section measured
- Moment measurement with MCS algorithm and range method

Backup slides

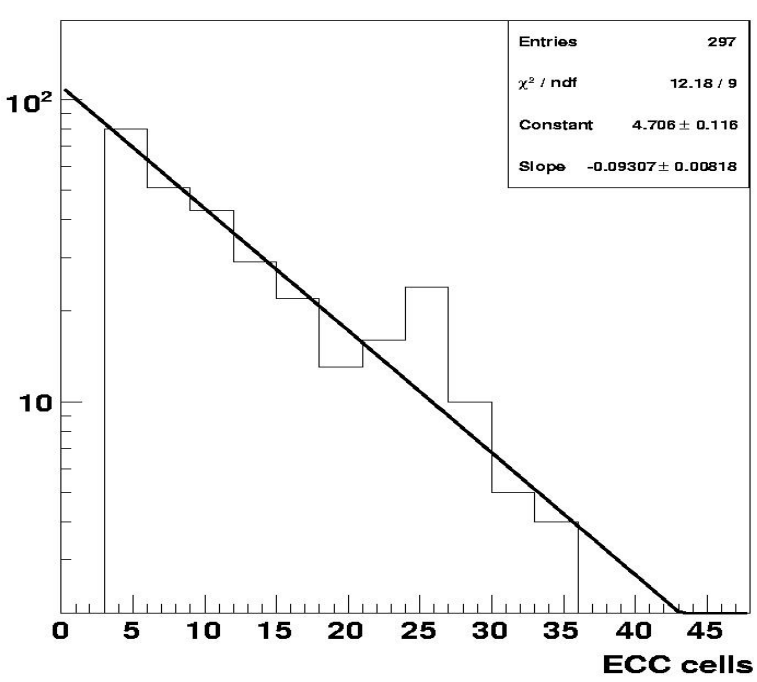


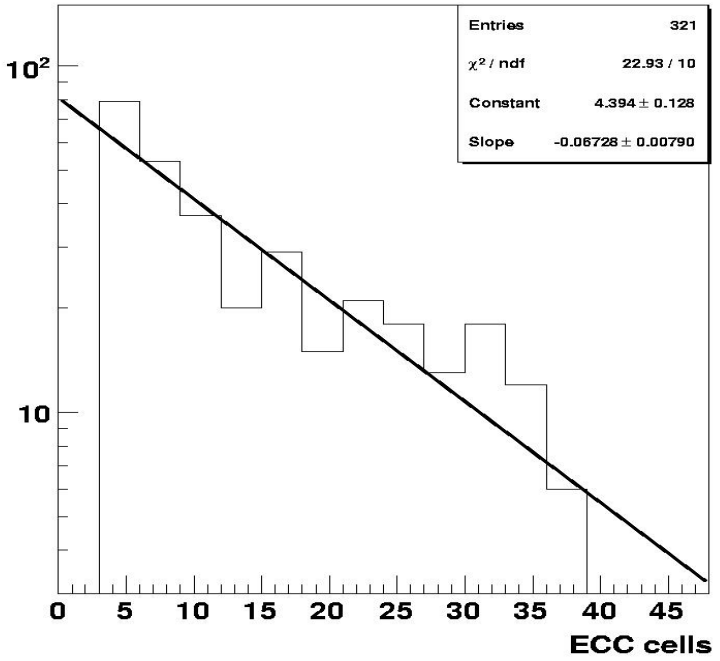


Interaction length of secondary ions

$\lambda_H = 14.0 \pm 1.2 mm$

$\lambda_{He} = 19.3 \pm 2.3 mm$





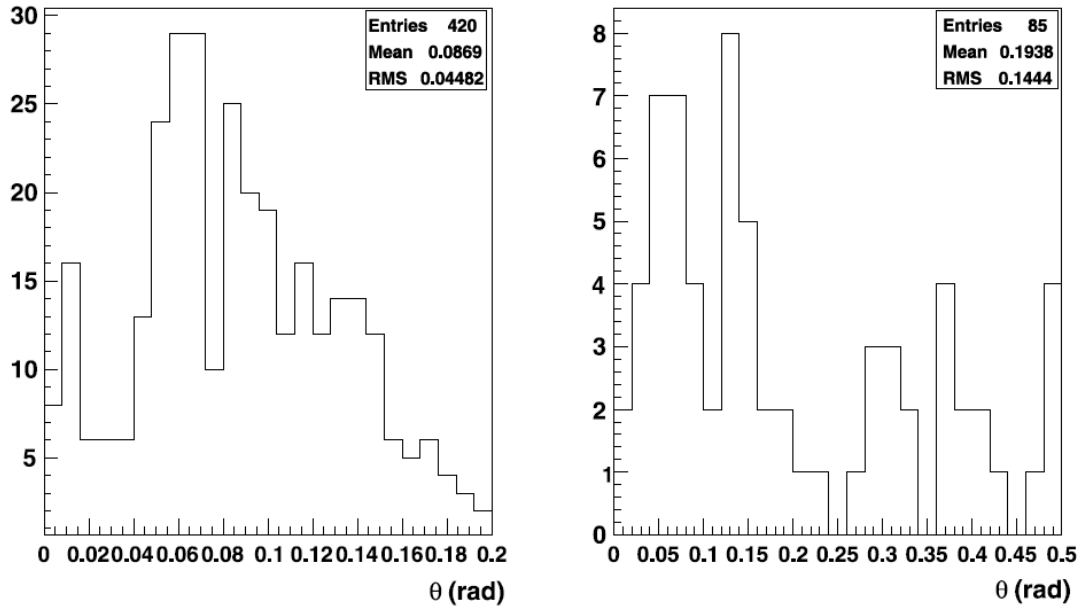


Fig. 9. Opening angle between pairs of reconstructed Helium tracks (left). A peak is visible below 20 mrad. No peak is visible in the distribution of the opening angles between Helium and Hydrogen (right). Note the different horizontal scales of the histograms.

The histogram on the left of Fig. 9 shows the opening angle of two Helium nuclei: an excess of events is visible below 20 mrad. On the contrary, no peak is visible when the opening angle of H–He is plotted (histogram on the right). Note the different scale of the two histograms. The background comes essentially from accidental He–He combinations. Their distribution appears to be compatible with that shown by H–He opening angle. We thus subtract from the He–He distribution a background having the shape of the H–He opening angle distribution. We obtain an excess of 25 ± 5 events corresponding to the ^{8}Be signal. From the observed excess of events, we get the cross-section of the ^{8}Be production:

$$\sigma\left(^{8}\mathrm{Be}\right) = 190 \pm 40 \text{ mbarn} \tag{6}$$

The histogram on the left of Fig. 9 shows the opening angle of two Helium nuclei: an excess of events is visible below 20 mrad. On the contrary, no peak is visible when the opening angle of H–He is plotted (histogram on the right). Note the different scale of the two histograms. The background comes essentially from accidental He–He combinations. Their distribution appears

to be compatible with that shown by H–He opening angle. We thus subtract from the He–He distribution a background having the shape of the H–He opening angle distribution. We obtain an excess of 25 ± 5 events corresponding to the ^{8}Be signal. From the observed excess of events, we get the cross-section of the ^{8}Be production:

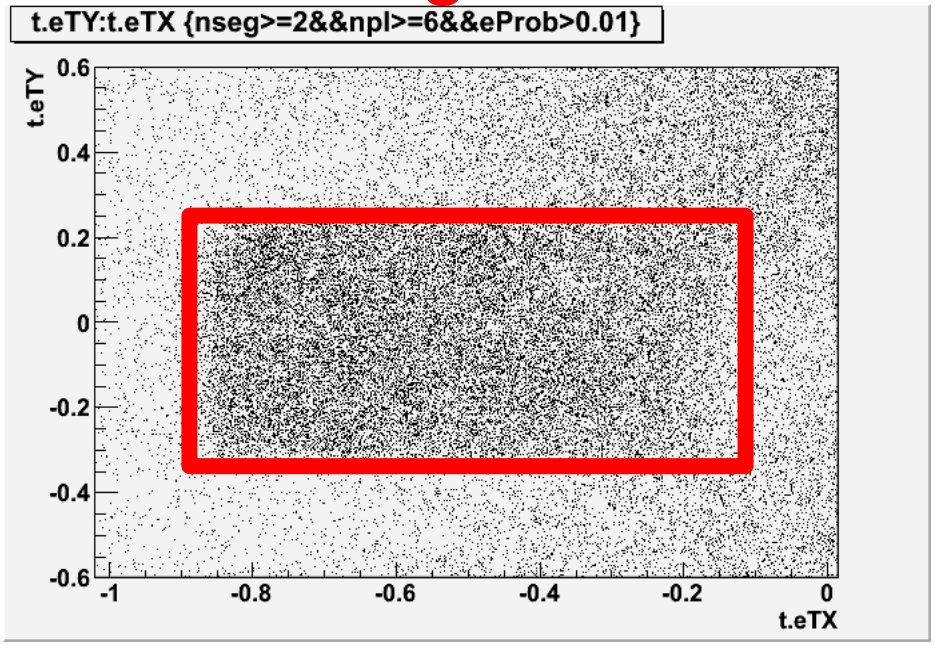
$$\sigma\left(^{8}\mathrm{Be}\right) = 190 \pm 40 \text{ mbarn} \tag{6}$$

Reconstruction efficiency

Tracks selected:

- angle selection
- number of segments ≥ 2
- Number of plates ≥ 6

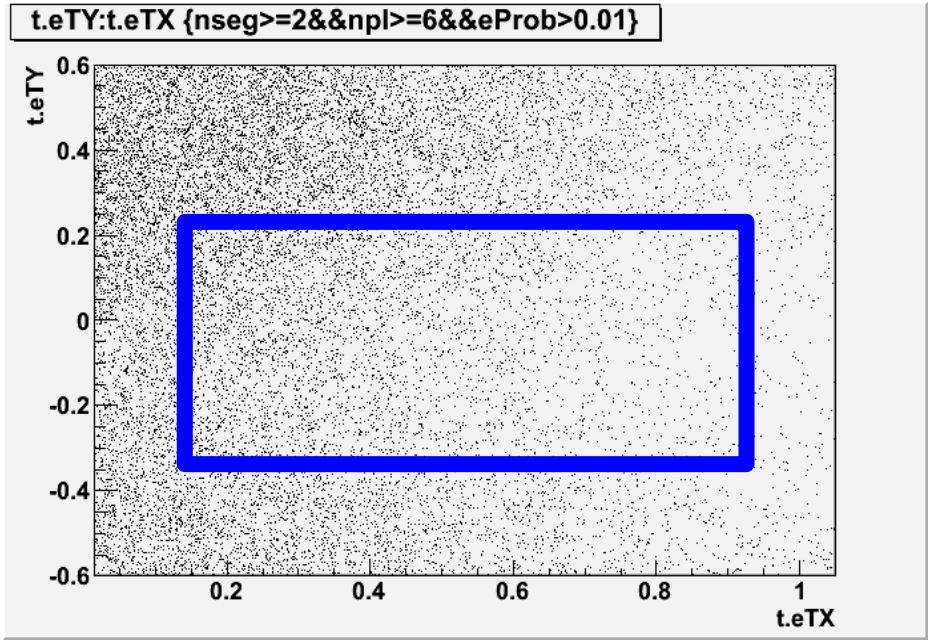
Signal



$-0.9 \leq \text{tg}\,\Theta_x \leq -0.1$

$-0.3 \leq \text{tg}\,\Theta_y \leq 0.28$

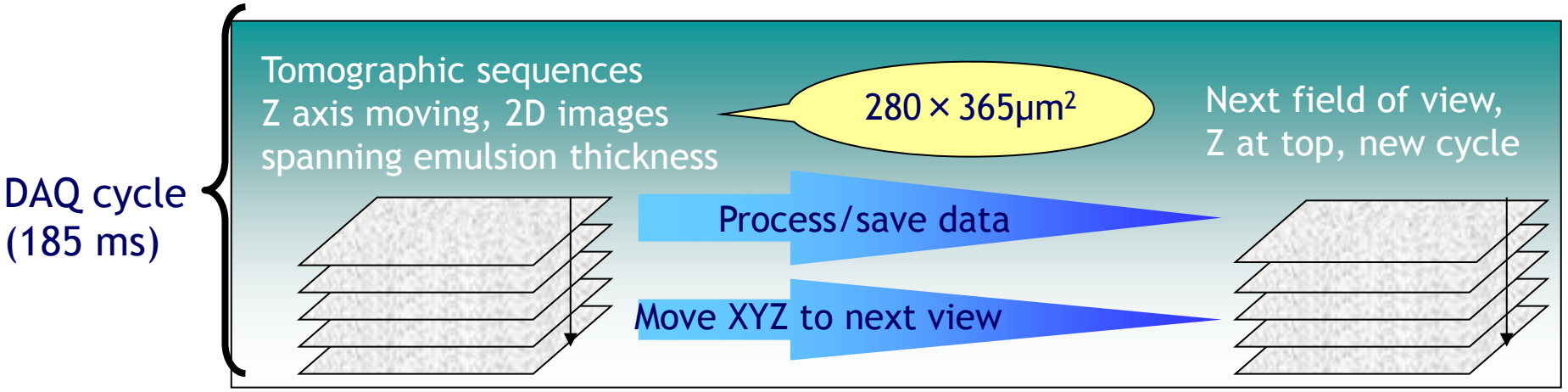
Cosmic rays

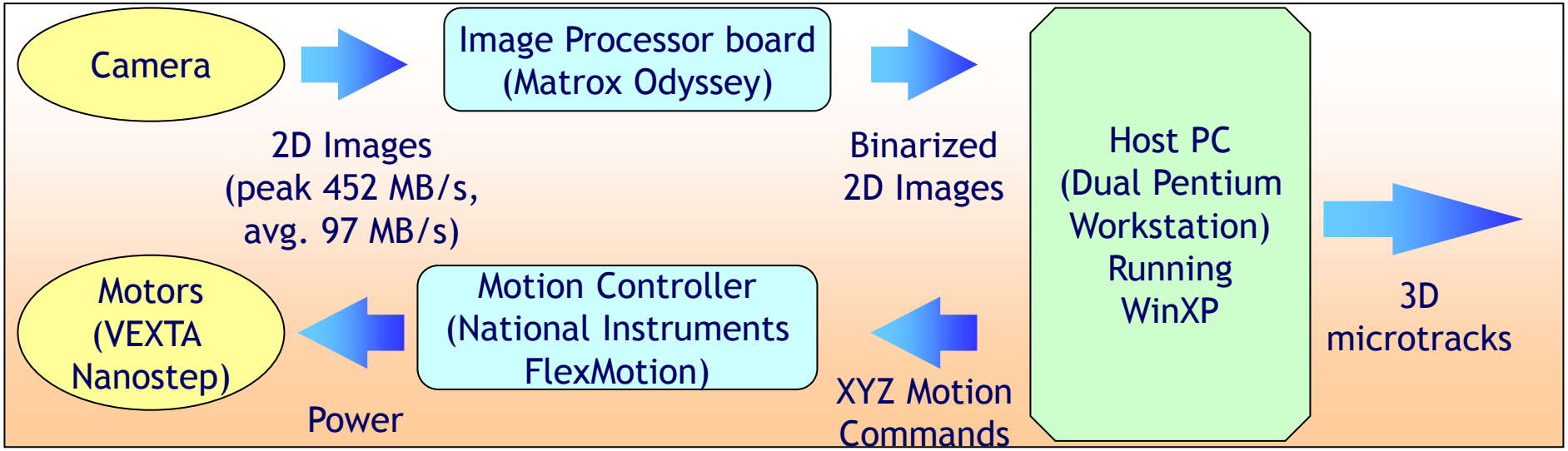


$0.1 \leq \text{tg}\,\Theta_x \leq 0.9$

$-0.3 \leq \text{tg}\,\Theta_y \leq 0.28)$

Data (images) processing and motion control flow in the ESS

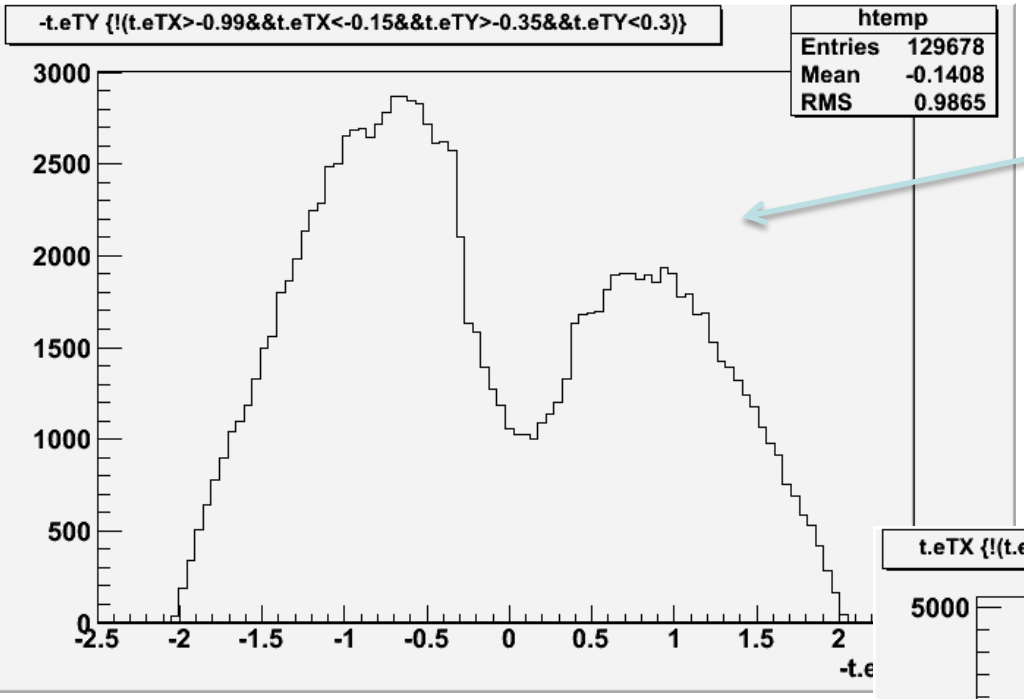


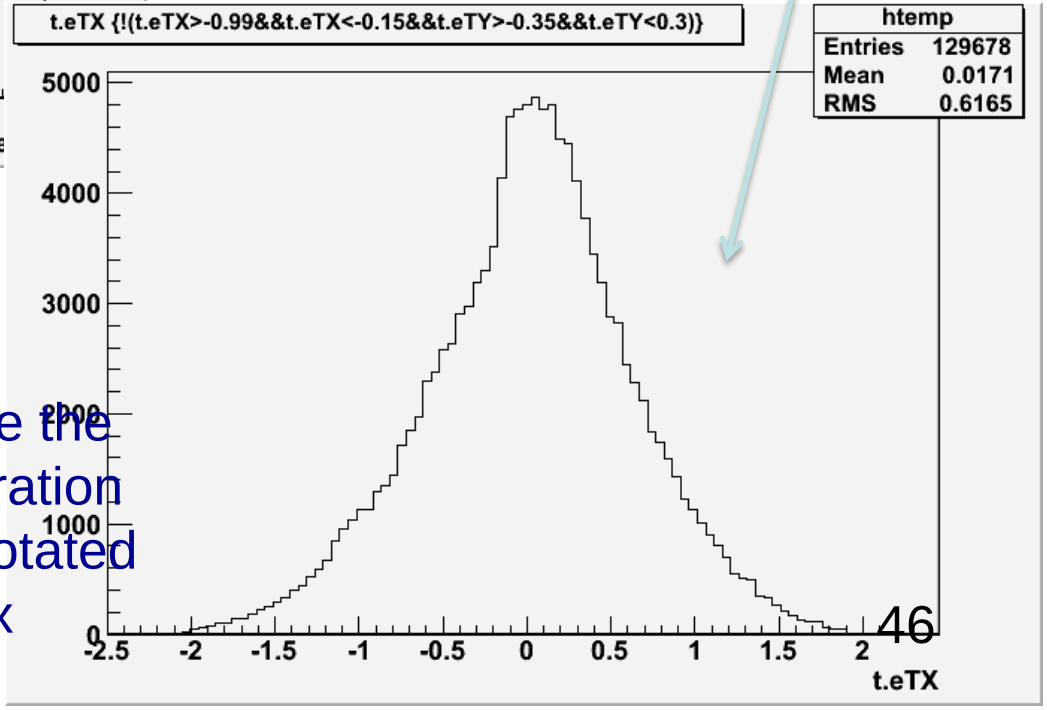


Functional blocks

Cosmic-ray angular distribution

- Films transported from Gran Sasso to CERN
- Brick assembled at CERN
- Cosmic-ray integrated during the transportation of the brick from CERN to GSI and from GSI to Gran Sasso
- Brick disassembled and film developed at Gran Sasso





Cosmic-rays taken with the films inside the brick in the same geometrical configuration as for the beam at GSI, with the brick rotated by 90 degrees to minimize the flux