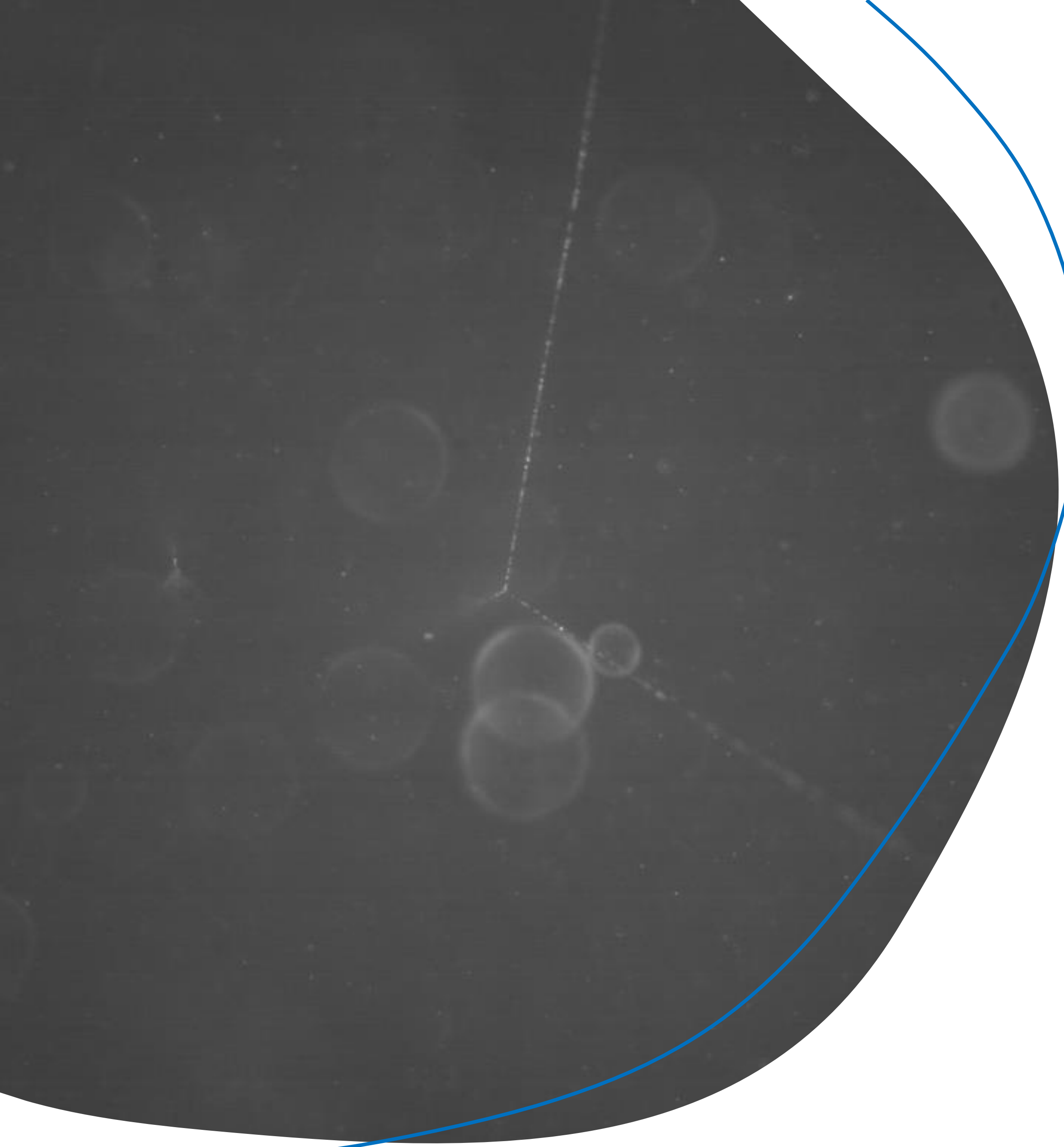

First Results from NIT Pilot Run

A. Alexandrov, T. Asada, V. Boccia, N. D'Ambrosio, A. Di Crescenzo, G. De Lellis, G. Galati, A. Iuliano, A. Lauria, M.C. Montesi, V. Tioukov (vincenzo.boccia@na.infn.it)

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XVI FOOT General Meeting, Napoli 26/6/2024

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Ministero dell'Università e della Ricerca
Italiadomani Piano Nazionale di Ripresa e Resilienza

Outline

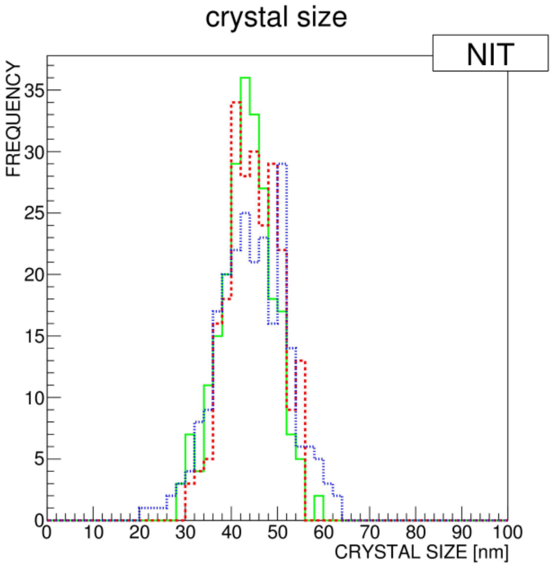
- Short summary of NIT activities so far
- Results from the test beam in CNAO
- Scanning of Pilot Run data and first results
- Application of the Super Resolution (SR) microscope: current status
- Next steps

Nano Imaging Trackers (NIT)

- **Nano Imaging Trackers** (**NIT**) are a novel kind of nanometric nuclear emulsion films that were designed to achieve a directional direct detection of WIMP-induced nuclear recoils
- The expected nuclear recoil track lengths in NIT are of the order of **100 nm** → extremely high spatial resolution required
- New production method: finer AgBr crystals (tunable from **20 nm to 80 nm**) and dedicated low temperature development
- NIT production facilities in Nagoya (Japan) and Gran Sasso (LNGS, Italy)

Undeveloped NIT sample

LNGS Gel Production Machine



From: Asada T. et al. Prog. Theor. Exp. Phys. 2015

DAMON: A new approach to Target Fragmentation

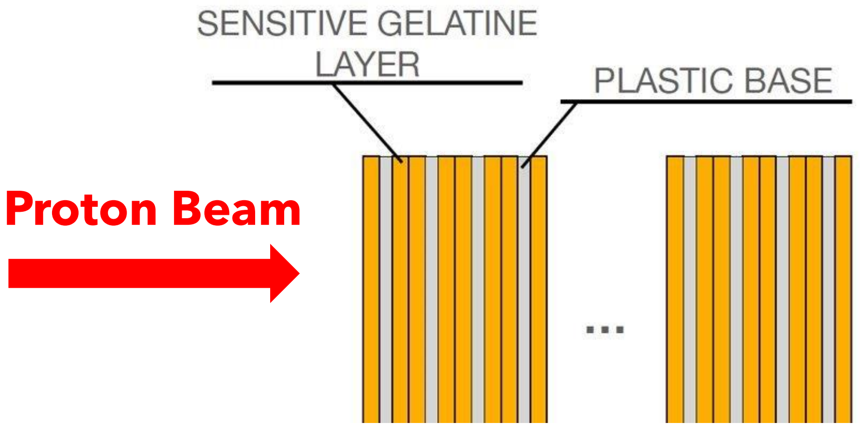
- The DAMON (Direct meAsureMent of target fragmentation) project (PRIN 2022) aims at measuring for the first time proton-induced target fragmentation in **direct kinematics**

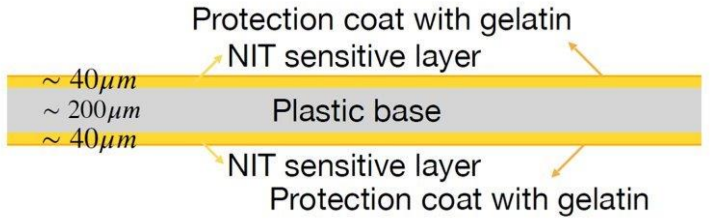
- Direct detection of short fragments made possible by NIT **acting both as target and tracking devices**

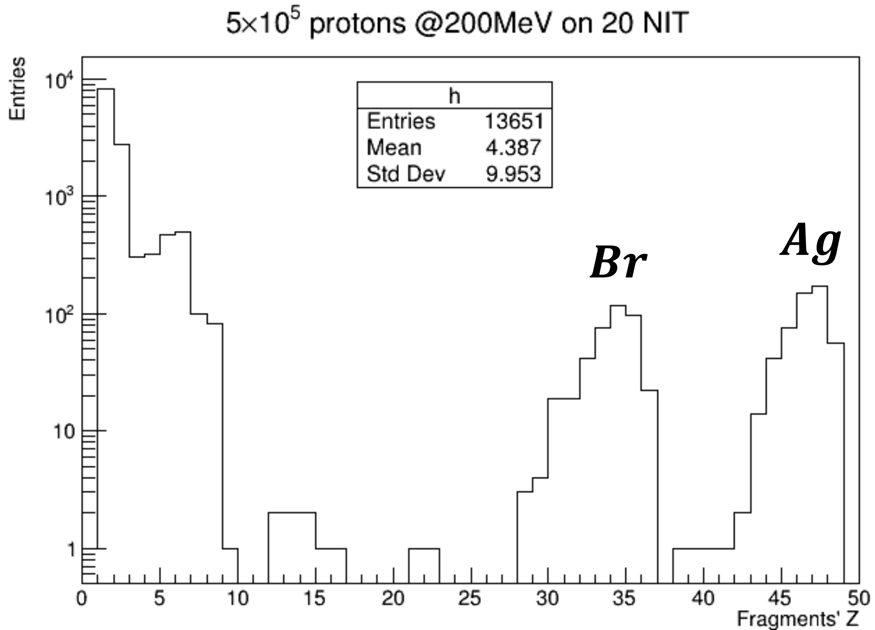
- The estimated interaction probability for 200 MeV protons in a detector with 20 NIT is ~ $\mathbf{1\%}$

- Among all interactions (Geant4 Simulation):
    - ~38 % occur in the emulsion gel (C, O, H, N, Ag, Br)
    - ~62% occur in the plastic support (Polystirene, $(C_8H_8)_n$)
    - Less than 10% of interactions on Ag, Br

- Typical energies of fragments, of the order of MeV, make them travel at least 300 nm → **detectable!**



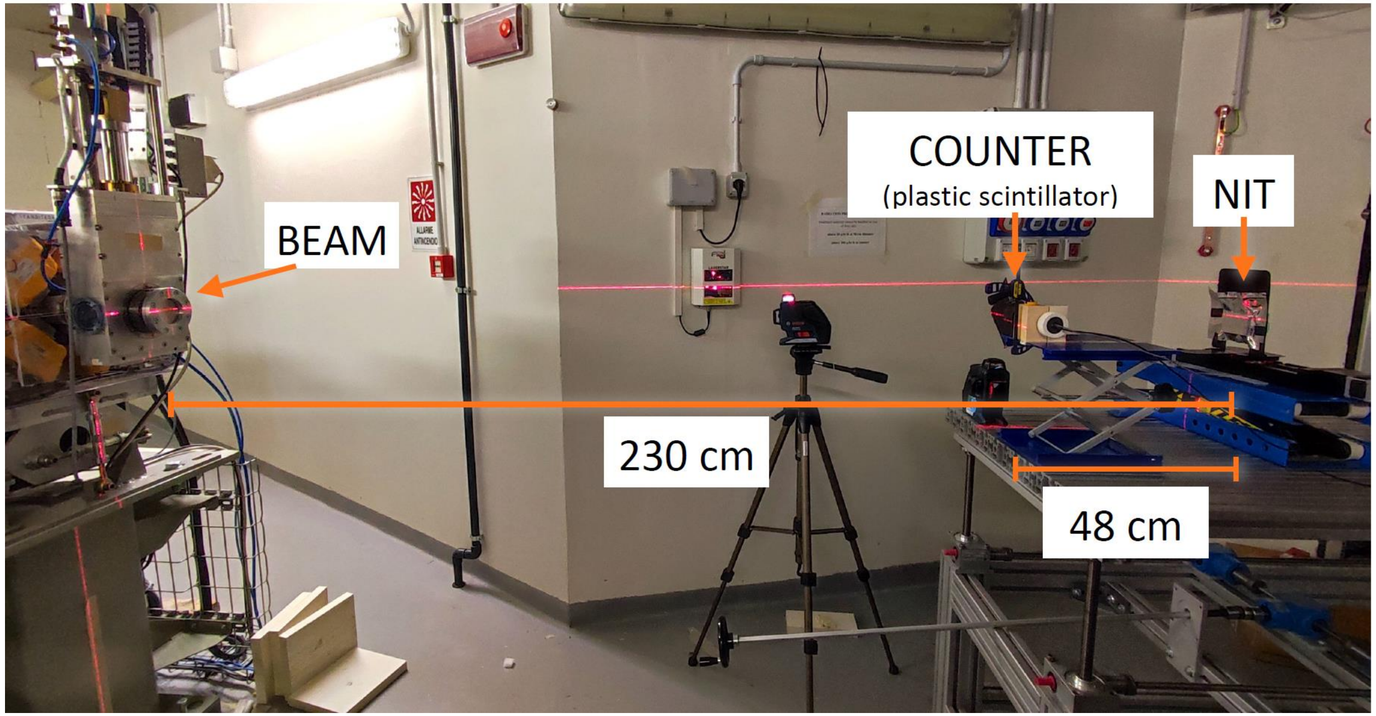


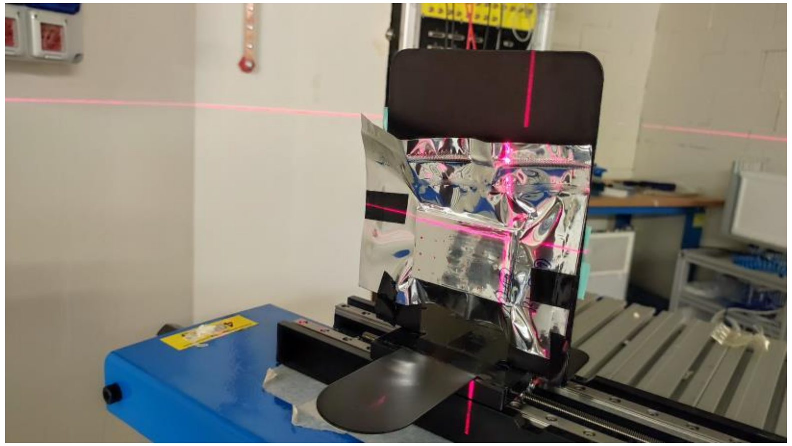


Data Taking in Trento (February 2023)

- 19 NIT films (~ 6.4x4 cm^2) for the brick, 1 film for sensitivity tests
- Fixed pencil beam @211 MeV (FWHM ~ 1.5 mm)
- 230 cm from beam exit window
- 6x4 grid for a uniform exposure of the NIT emulsions (about 11.000 protons per spot)

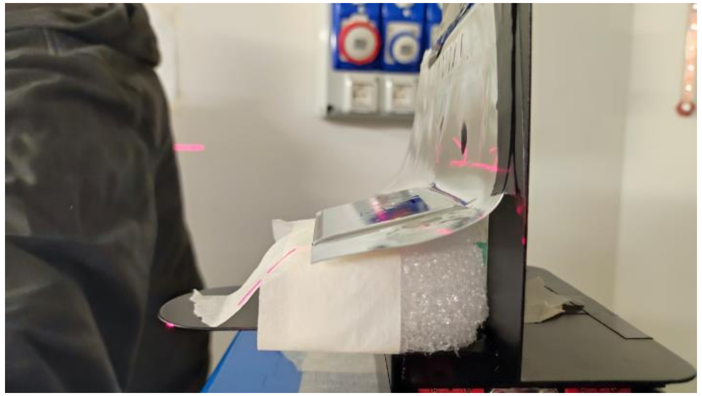
From Trento General Meeting





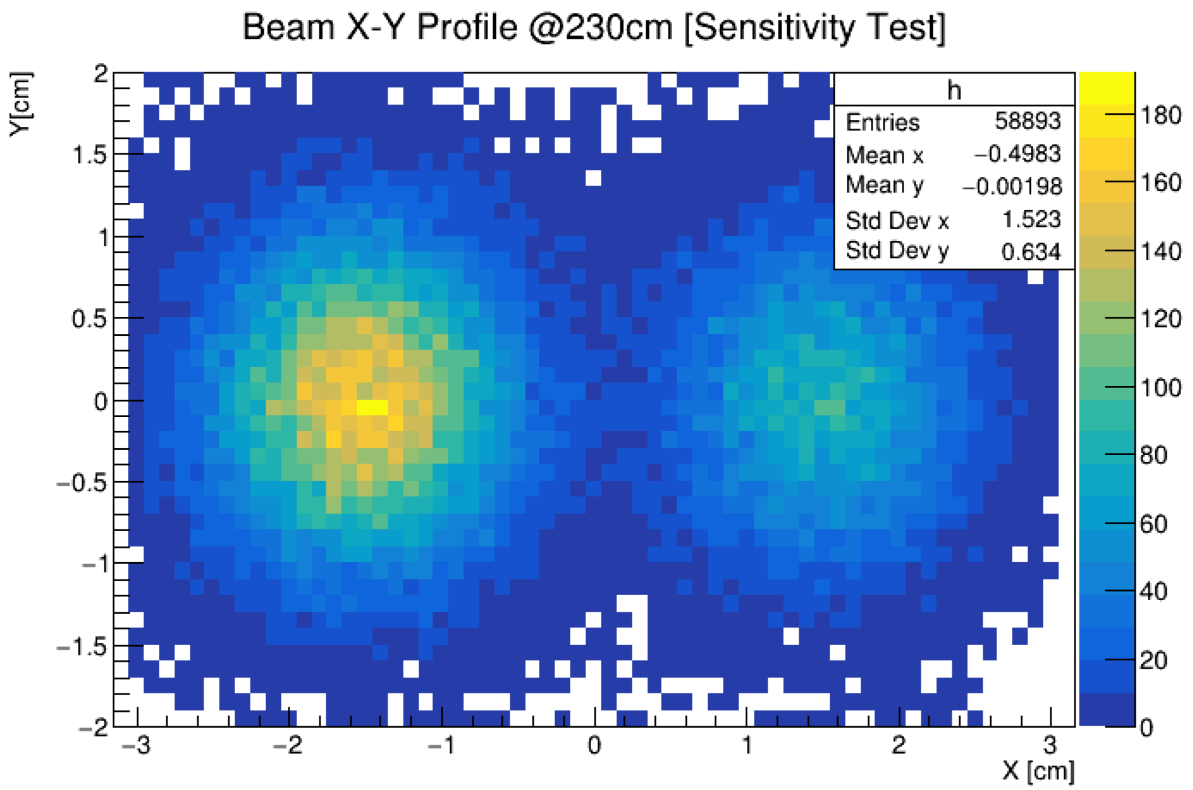
Brick Exposure

Sensitivity Test

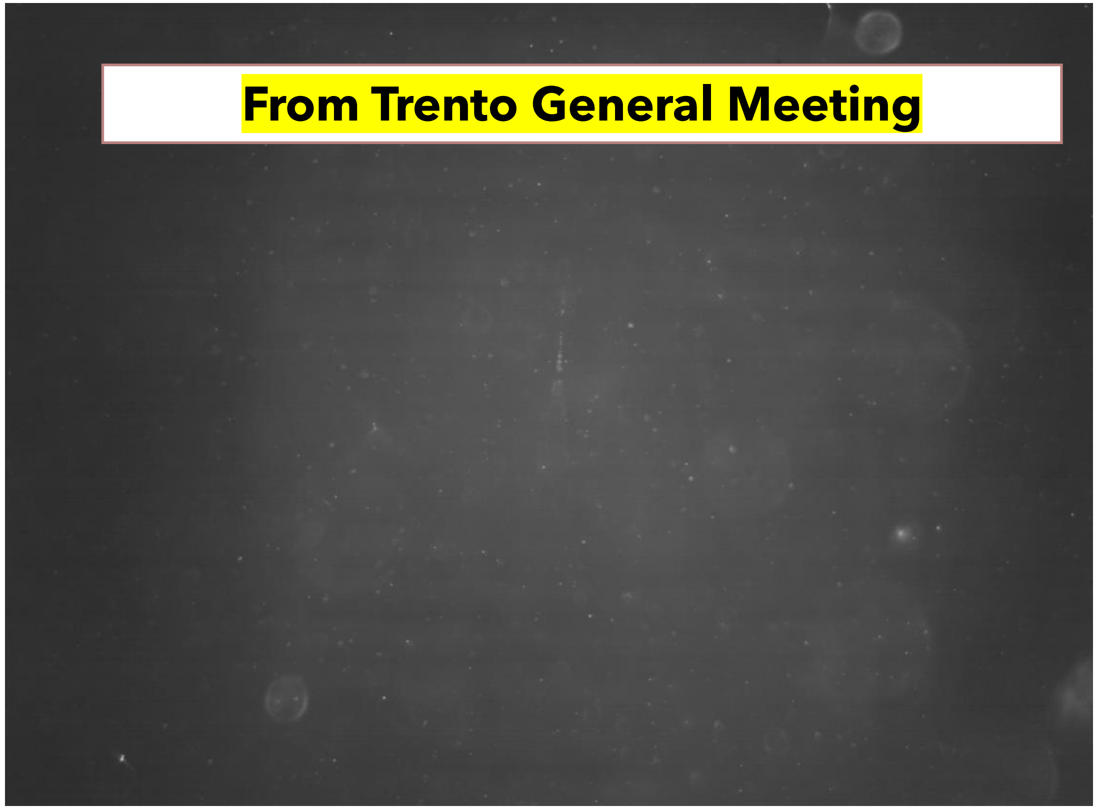


Sensitivity Issues: Test with Trento Data (1)

- The recorded sensitivity to primary protons (211 MeV) was extremely low
- The film was tilted by ~ 15° with respect to the beam direction so one expects approximately sin(15°)*(180)*0,12 ~ 6 protons per view (40x objective, 400x300 μm² views)



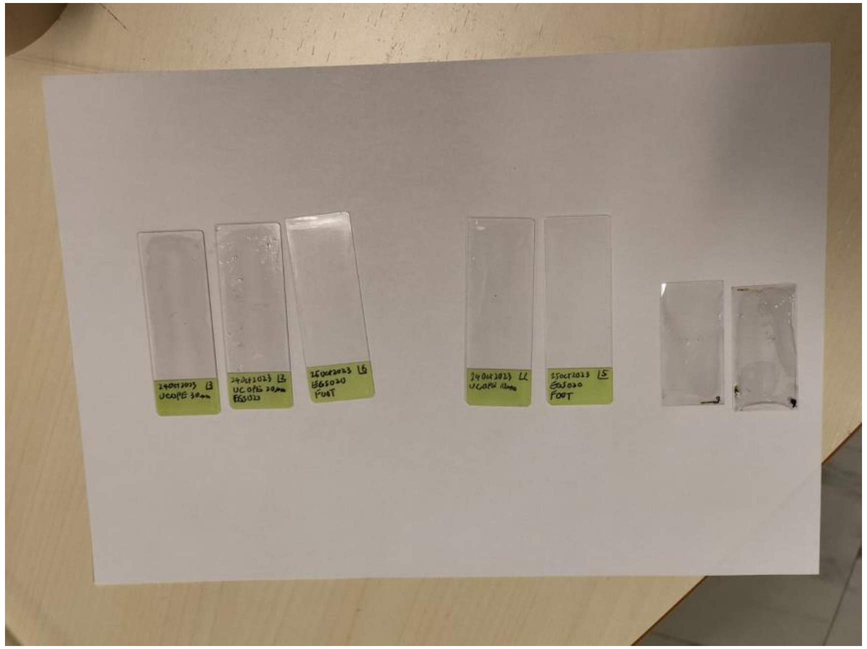
Simulated Beam Profile for Sensitivity Test



Most Views are Empty!

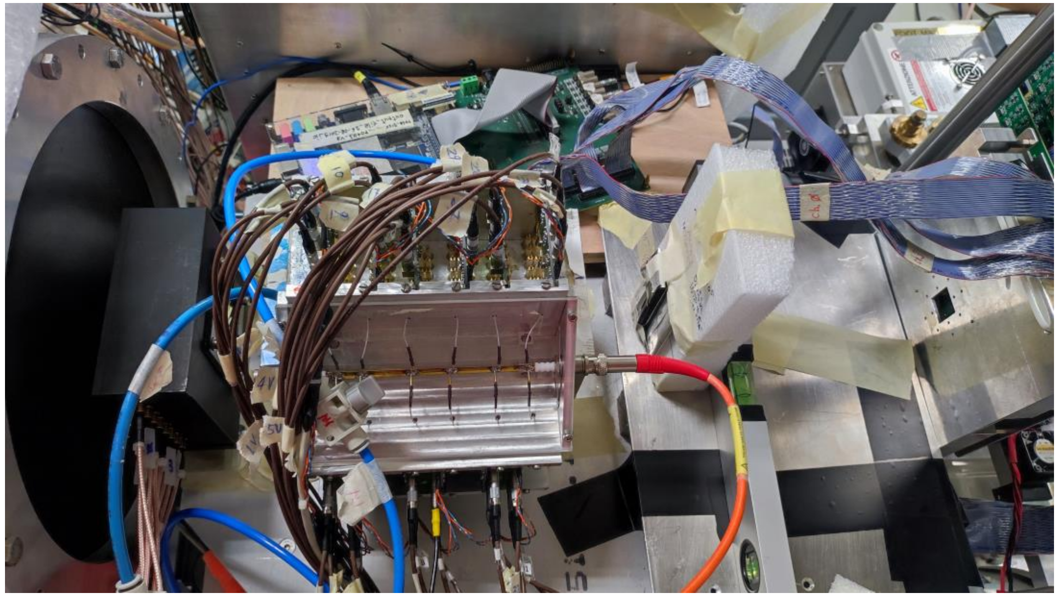
NIT Exposure at CNAO (November 2023)

- The samples exposed at CNAO are aimed at:
  - Testing NIT sensitivity to protons at 70 MeV (exposure with a single spot of 10^7 primaries)
  - Testing NIT-OPERA double coating and tracking with thin OPERA layers (exposure with a single spot with 10^5 primaries)
  - Mechanical test with double side pouring on 170 µm thick cover glasses
- For this purpose, NIT gel from two separate batches was poured on 2 mm thick slide-glasses
- The samples have been developed in LNGS and they need to be scanned (analysis on-going, more details will be given in future meetings)



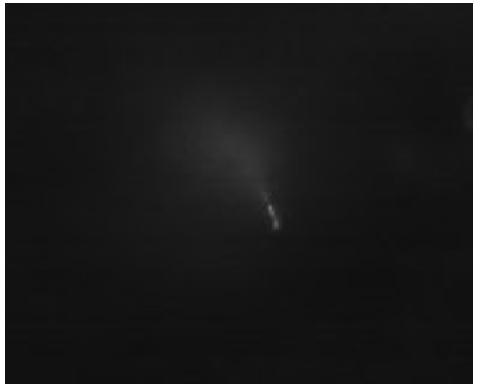
First Results from CNAO Test Beam

- For the sensitivity test, NIT films were exposed to a high intensity spot of 10^7 protons @70 MeV
- NIT samples were produced in LNGS and kept in a refrigerated box during transport to minimize thermal noise
- Usual NIT development was perfomed in LNGS and the samples have been brought to Naples

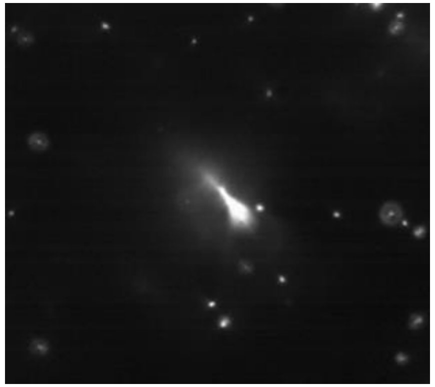


CNAO Exposure: single high intensity spot (10^7 protons)

- Current NIT (70 nm, MMA, HA sensitization) are **not sensitive enough to reconstruct primary protons** above $70\ MeV$!
- Possible to chemically develop OPERA-like and NIT layers together! More tests needed



NIT



OPERA-like

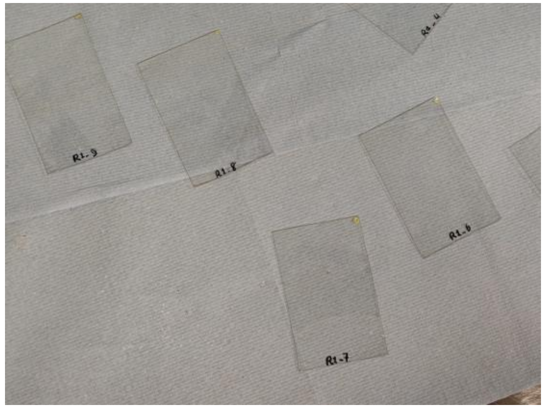
Pilot Run Readout

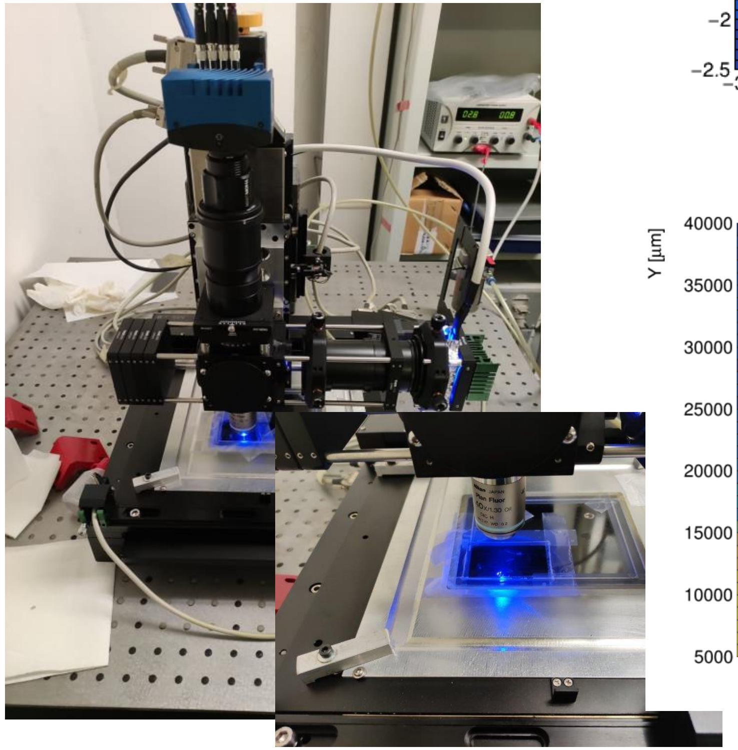
- Target density for the Pilot Run was 10^4 protons cm^{-2} → 5x5 grid for uniform exposure
- NIT size was $\sim 6x4\ cm^2$ with two sensitive gelatine layers ($\sim 60\ \mu m$) deposited on both sides of a polystyrene support ($\sim 200\ \mu m$)
- Two step readout: **fast scan** and **SR scan**

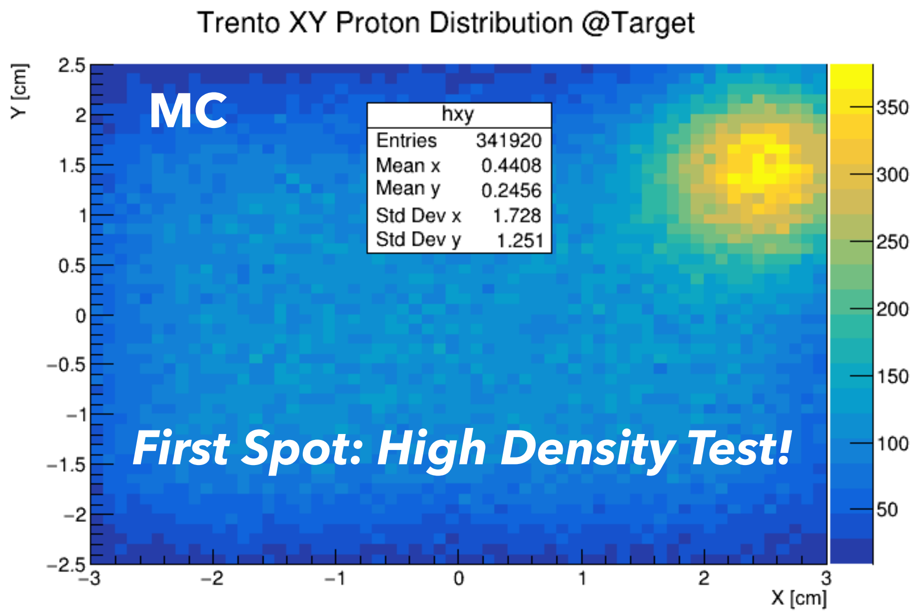
Fast Scan Features
(more details last GM)

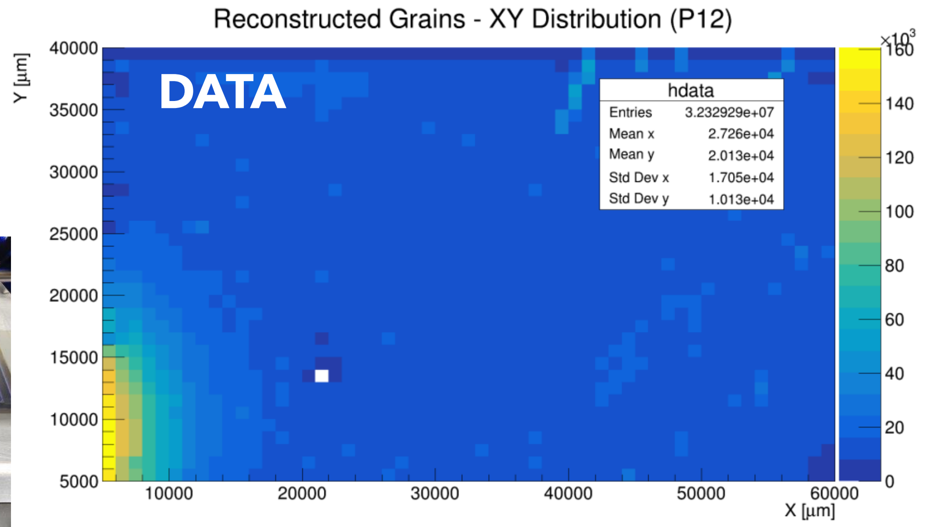
View Size	400x300 μm
Z step	0.75 μm
Scan Speed	$\sim 3\ cm^2/h$

Developed NIT samples



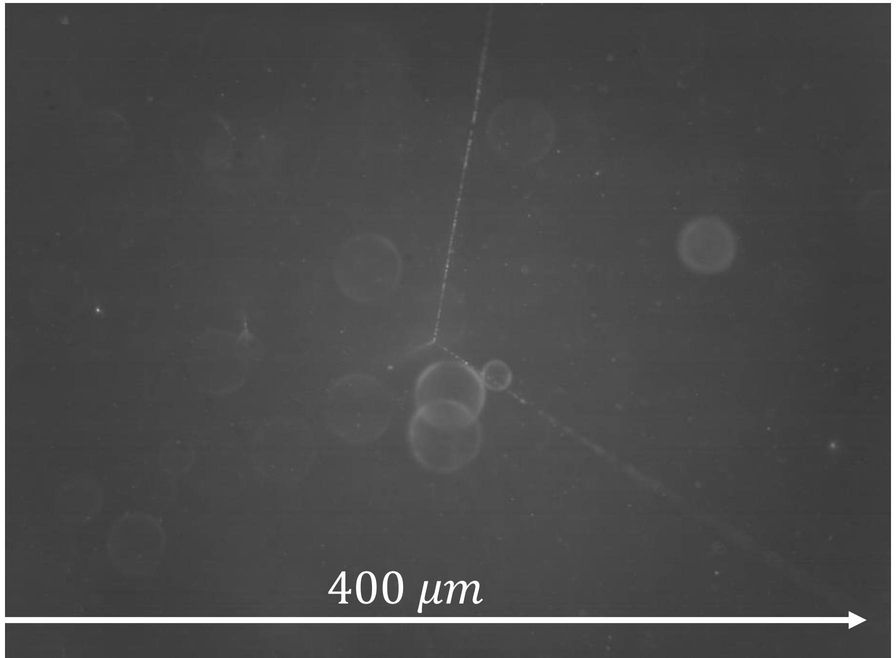




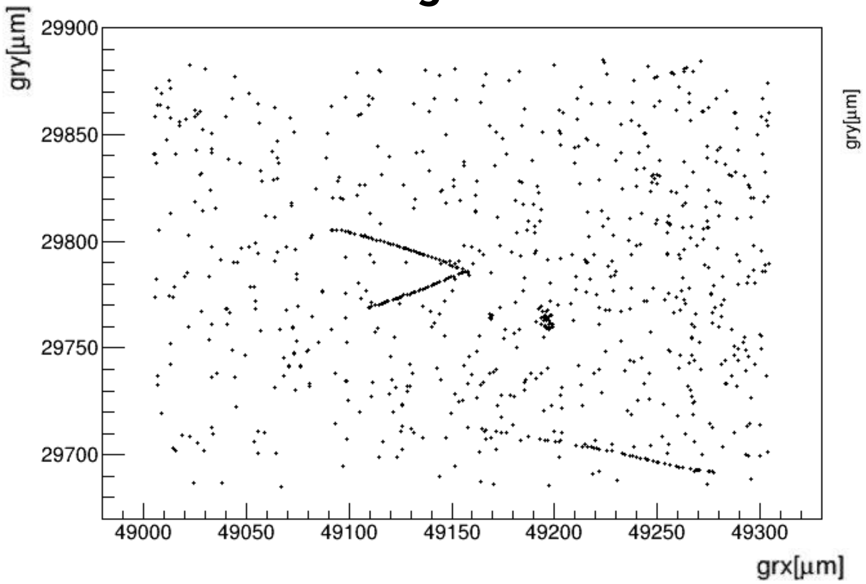


Offline Reconstruction Workflow

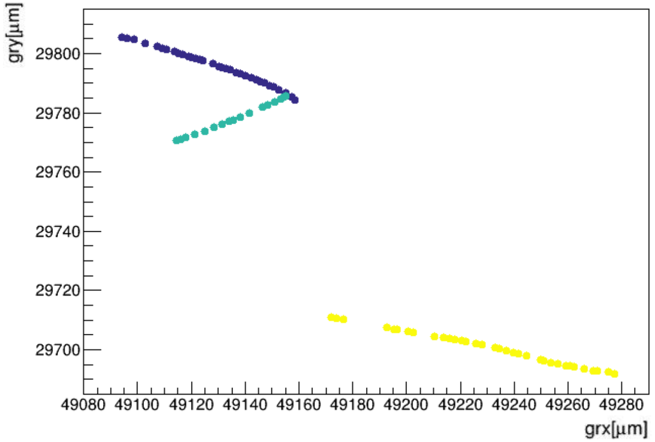
- After scanning, images are analyzed and clusters are merged to reconstuct **grains**
- Aligned grains are linked together to form segments in a single layer called **micro-tracks (MTs)**
- Background grains can be isolated (thermal noise…) or clustered (film damage, dust specks…)



MTs + Background Grains



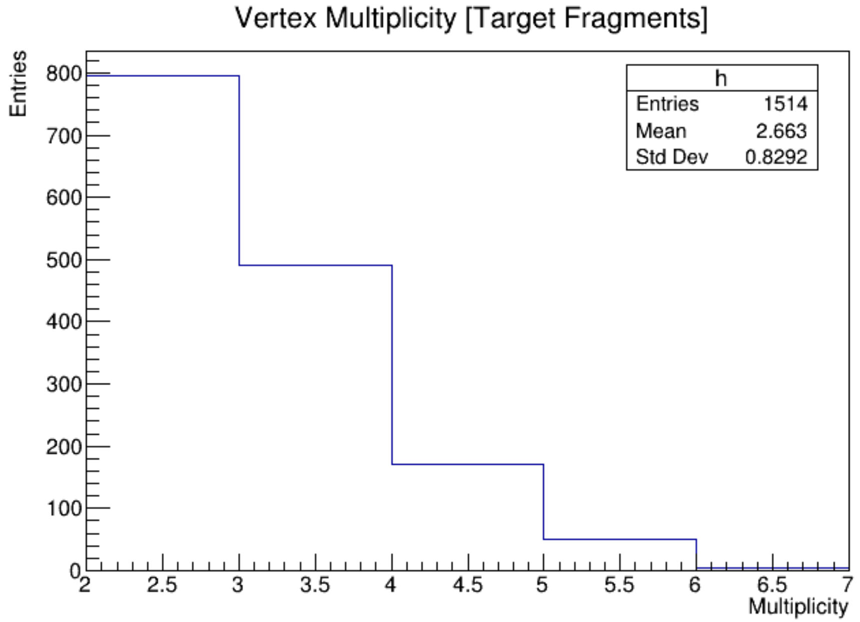
Linking + Cuts on Ngr

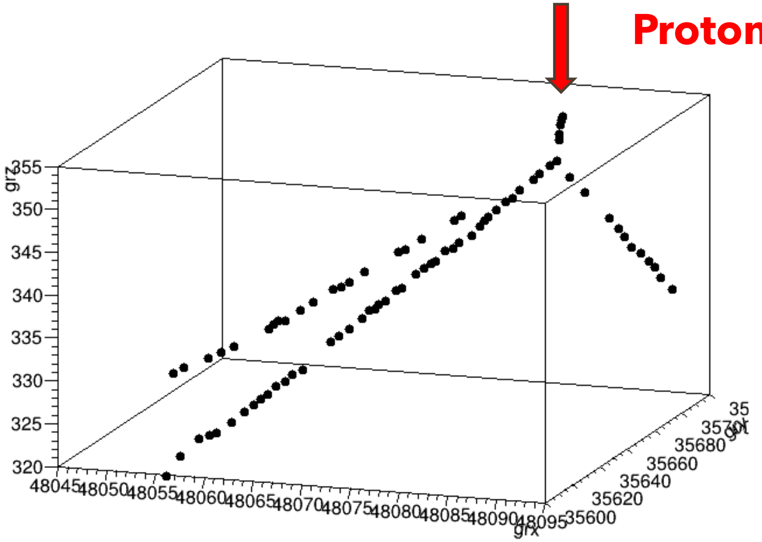


- Very **low background expected**:
  - Not sensitive to MIPs or primary protons
  - Environmental neutrons and radioactive nuclei (**mainly Radon** producing $\sim 20\ \mu m\ \alpha$ tracks and Uranium/Thorium producing α stars)
- Vertex search
  - At least one secondary track longer than 25 μm required (actually, little background expected below 10 μm)
  - Tracks shorter than 5 grains excluded to reduce background
  - Select only candidates with $IP < 5\ \mu m$

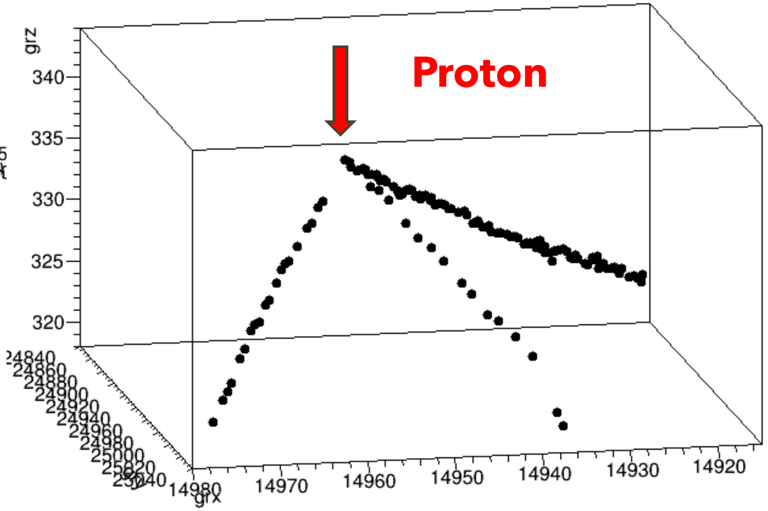
Results from Fast Scanning

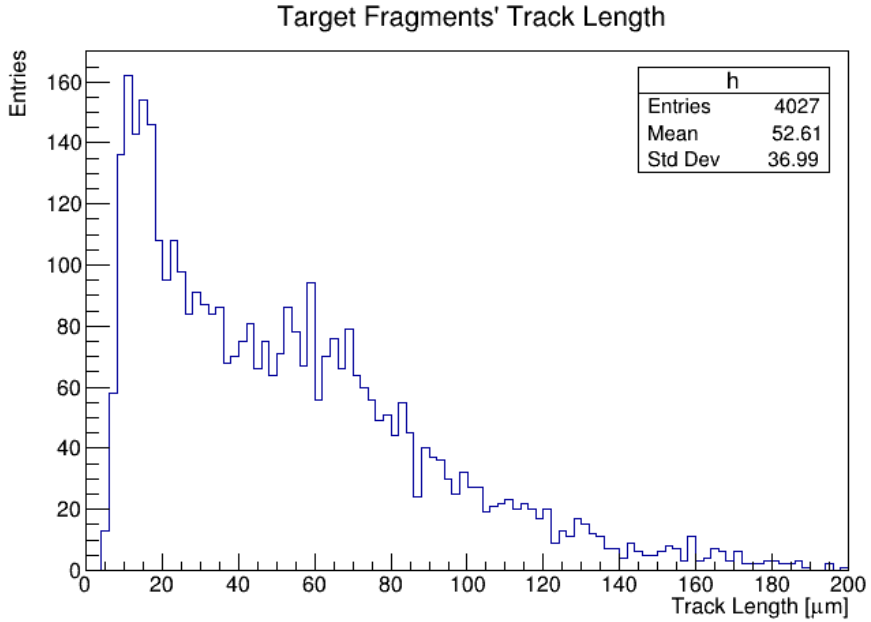
- After the Pilot Run, 18 films have been scanned
- Top-side scanning performed with fast optical microscope
- About **1500 reconstructed interactions**
- Currently on-going: scanning of these candidates with SR microscope





3D displays of reconstructed events

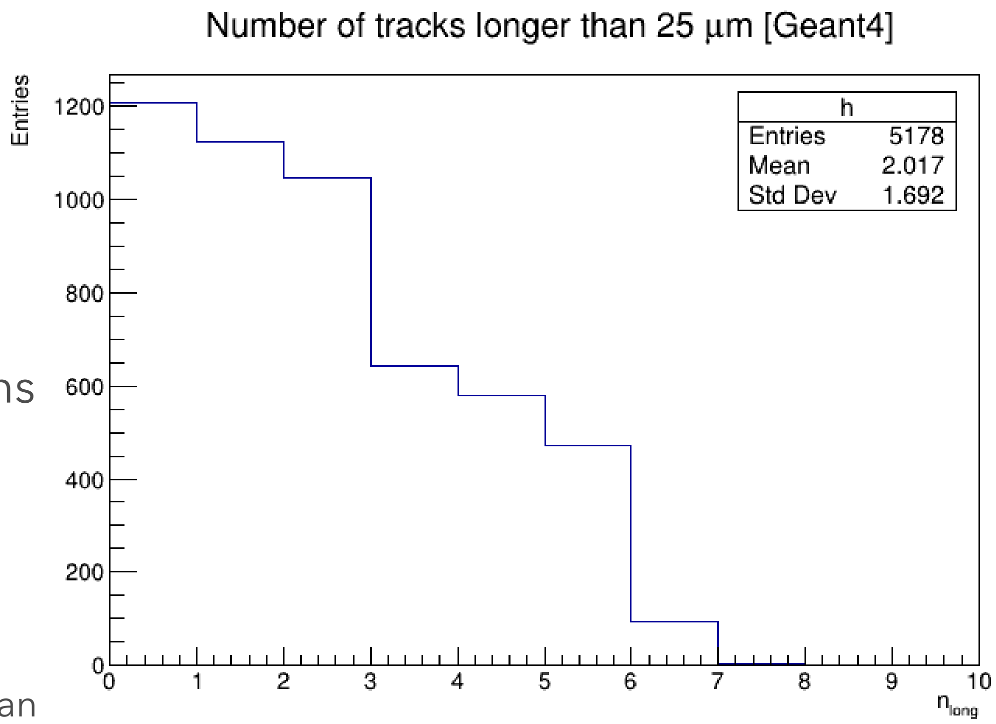


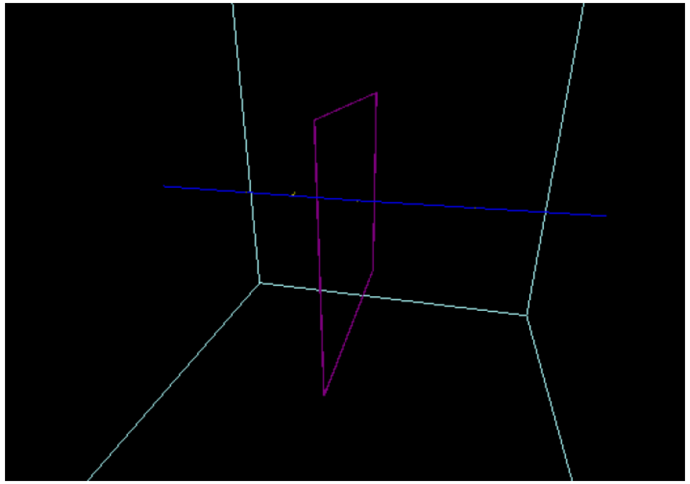


These results will be featured in the proceedings of the 2024 Pisa Meeting

MC Study of Proton Sensitivity

- The sensitivity of the detector for the Pilot Run is limited by two important factors:
  1. NIT sensitivity to protons
  2. Request of at least one track longer than 25 μm
- The most critical factor is the **energy threshold** at which protons become visible in NIT
- According to Geant4 MC
  - 77% of vertices have at least one track longer than 25 μm
  - 65% of vertices have at least one **visible** track longer than 25 μm assuming an energy threshold of 70 MeV
  - **45%** of vertices have at least one **visible** track longer than 25 μm assuming an energy threshold of 10 MeV
- If the energy deposit needed to sensitize a NIT grain is $2\ keV$ then the energy threshold is near 10 MeV (energy deposition by 10 MeV protons in AgBr ~2.2 $keV/70\ nm$)

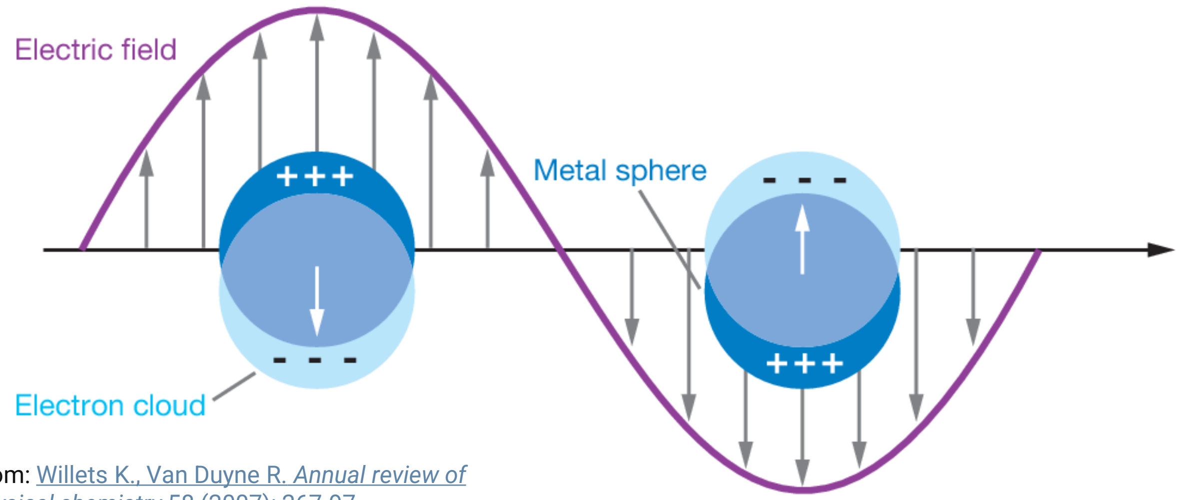




$10\ \mu m\ AgBr\ Box\ in\ Air$

Readout: Localized Surface Plasmon Resonance

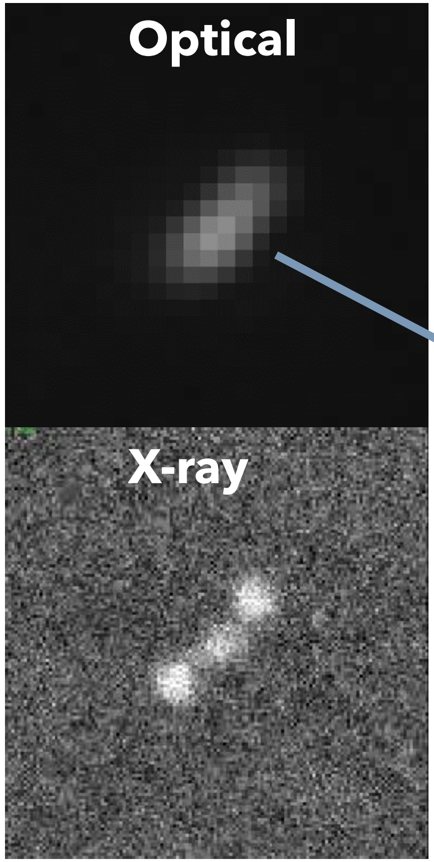
- **Super-resolution (SR)** is achieved by exploiting the **localized surface plasmonic resonance** (LSPR)
- Localized surface plasmons are non-propagating excitations of the conduction electrons of metallic nanostructures immersed in a dielectric → **silver grains in NIT exhibit LSPR at visible wavelengths**!



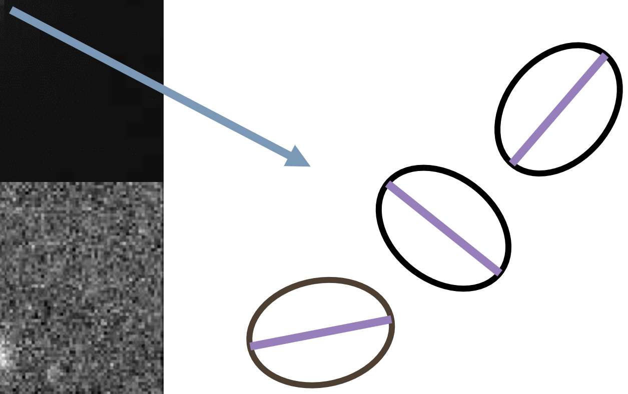
From: Willets K., Van Duyne R. *Annual review of physical chemistry* 58 (2007): 267-97

$$\alpha = 4\pi a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \rightarrow \varepsilon = -2\varepsilon_m$$

Resonance condition



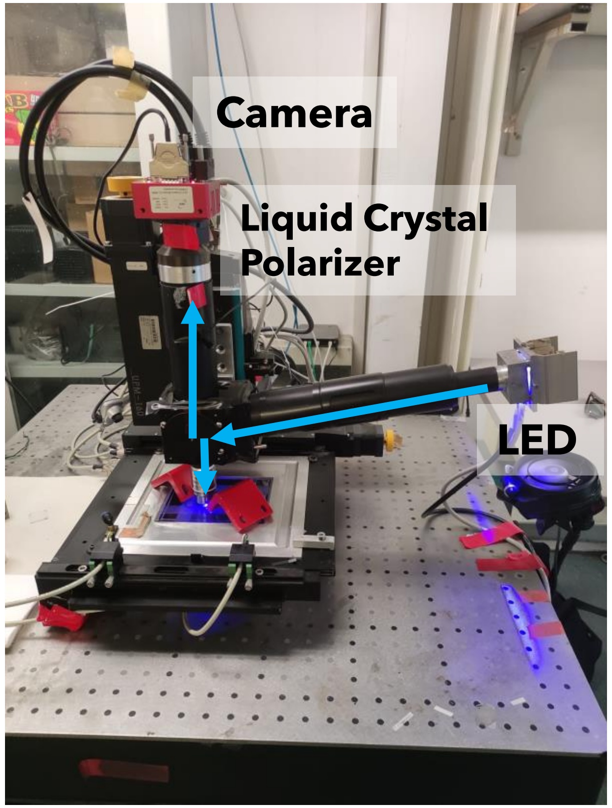
LSPR depends on the **shape** and **orientation** of the nanoparticle



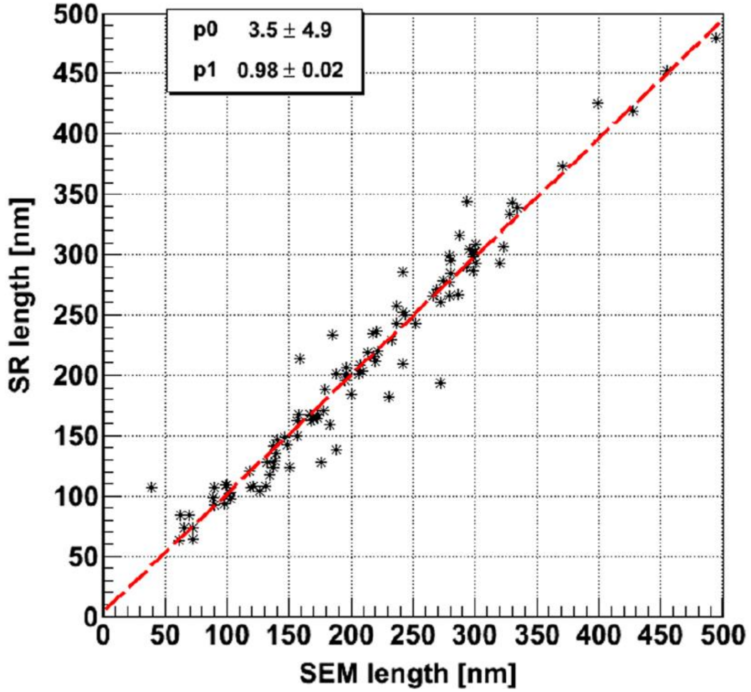
Maximum reflected light when E field is parallel to major axis → possible to resolve close structures!

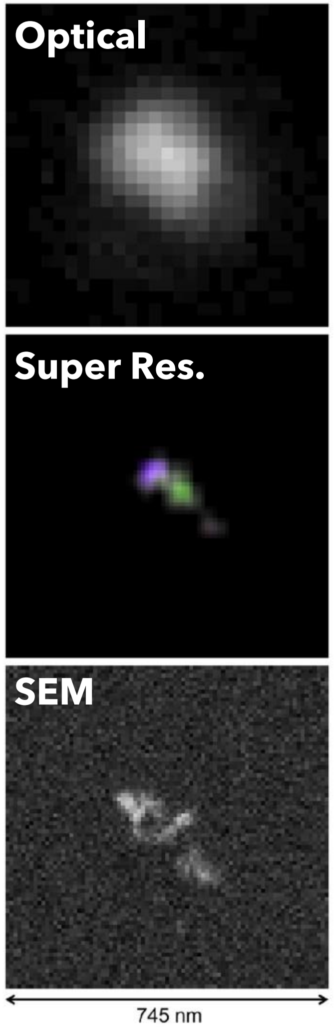
Super Resolution LSPR Optical Microscope

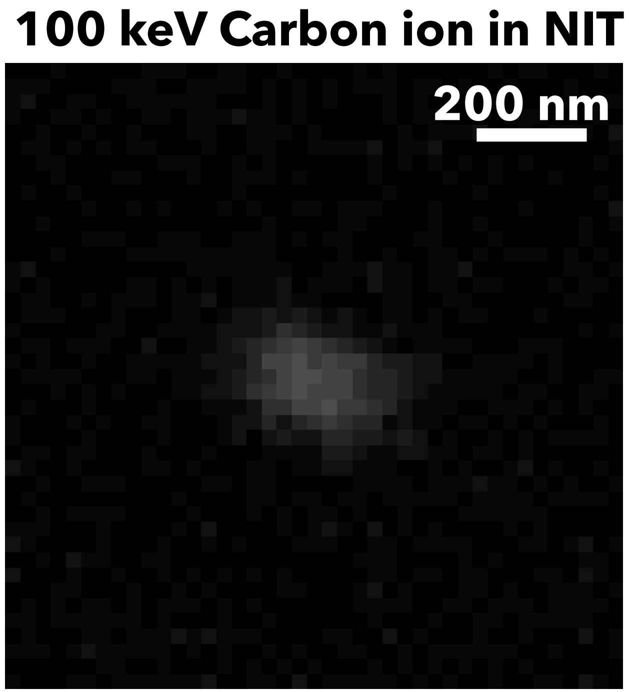
- 8x input images obtained with different polarizations (obtained with a liquid crystal polarizer)
- Tracks **down to 50 nm** have been reconstructed

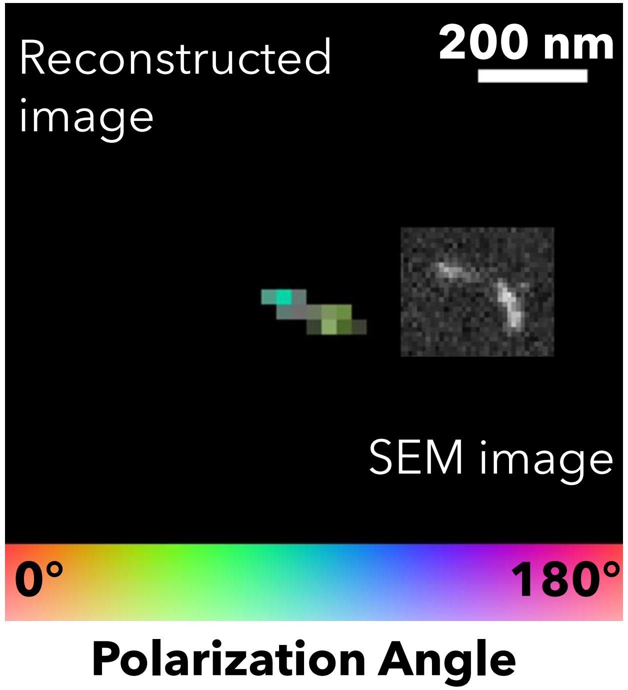


From: Alexandrov et al. Scientific Reports volume 13, Article number: 22813 (2023)





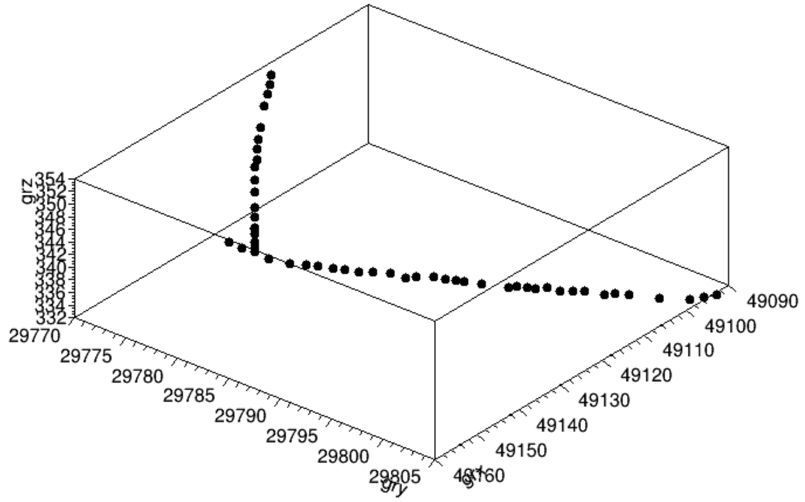


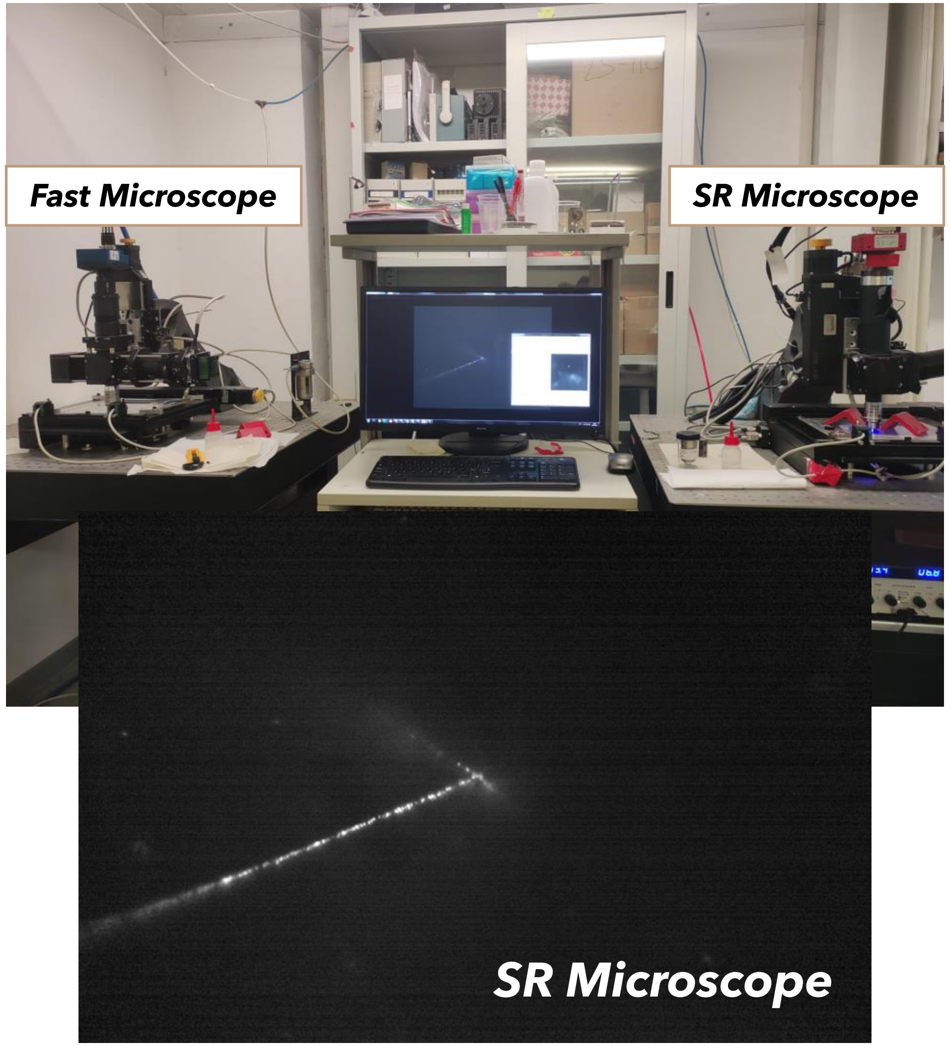


First Application of SR Microscope

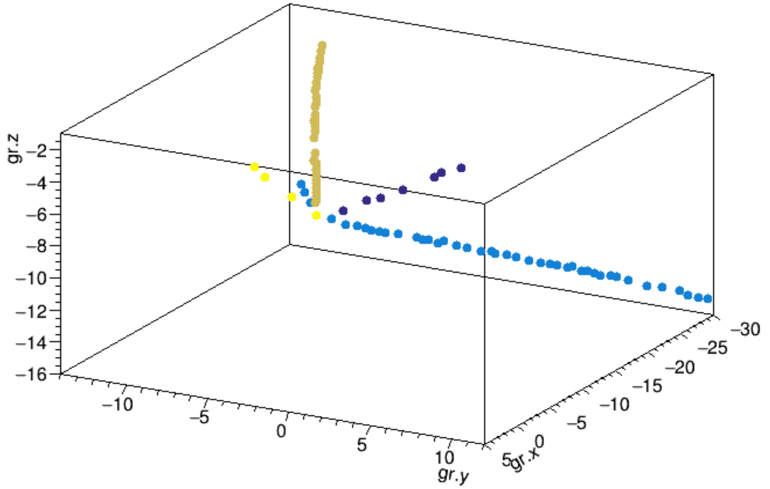
- Once a fragmentation interaction has been reconstructed, a second scan with SR mic can be performed
- Marks have been used as reference system

Reconstruction after fast scan



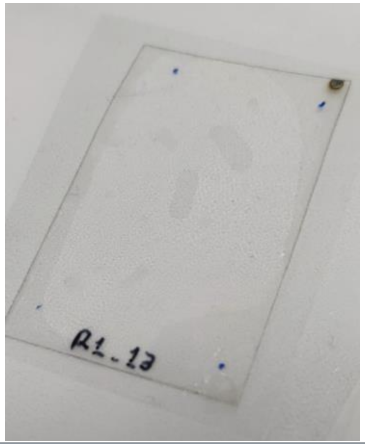


Reconstruction after second scan (no SR)

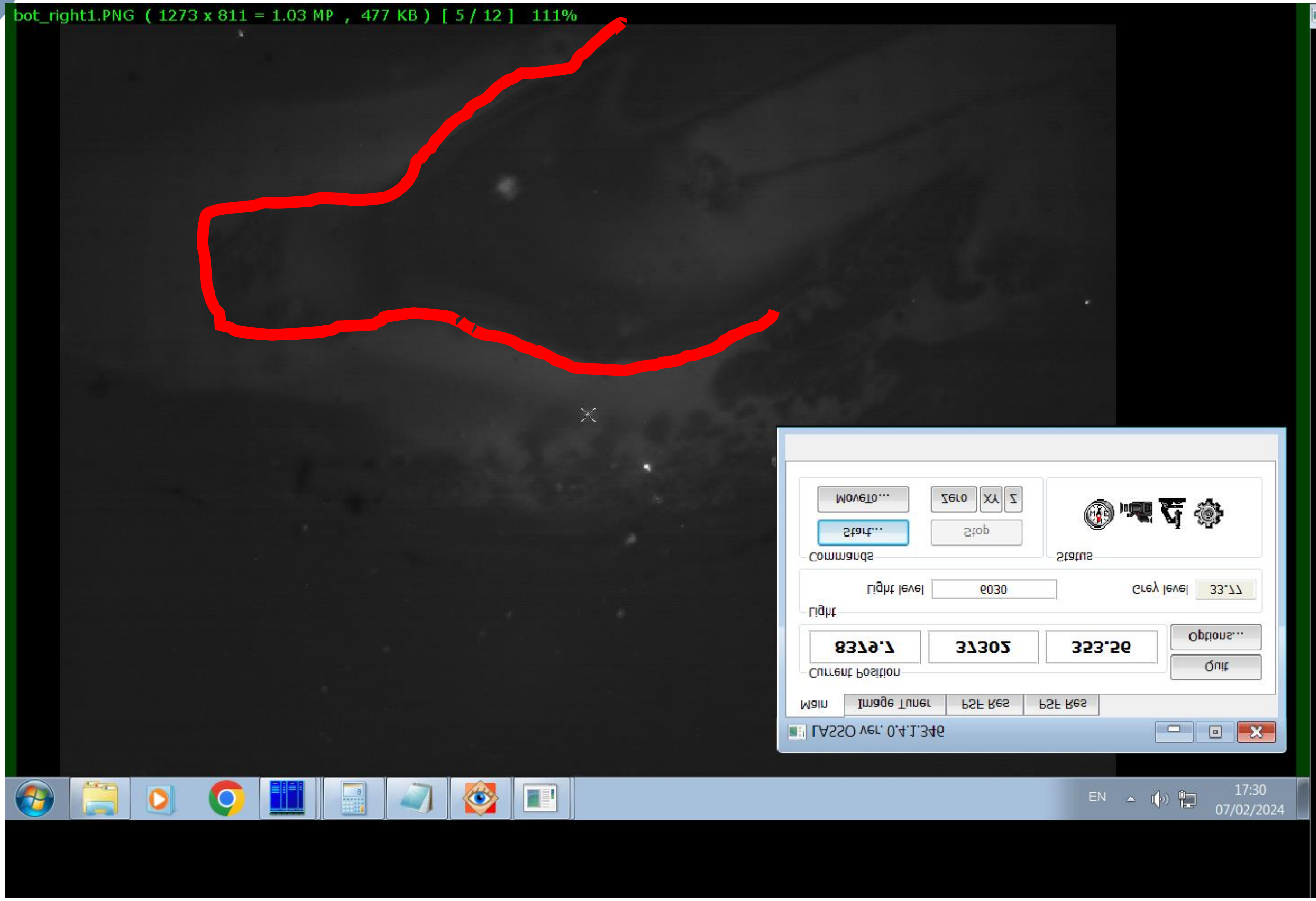


→ 3 shorter tracks are recovered during the second scan!

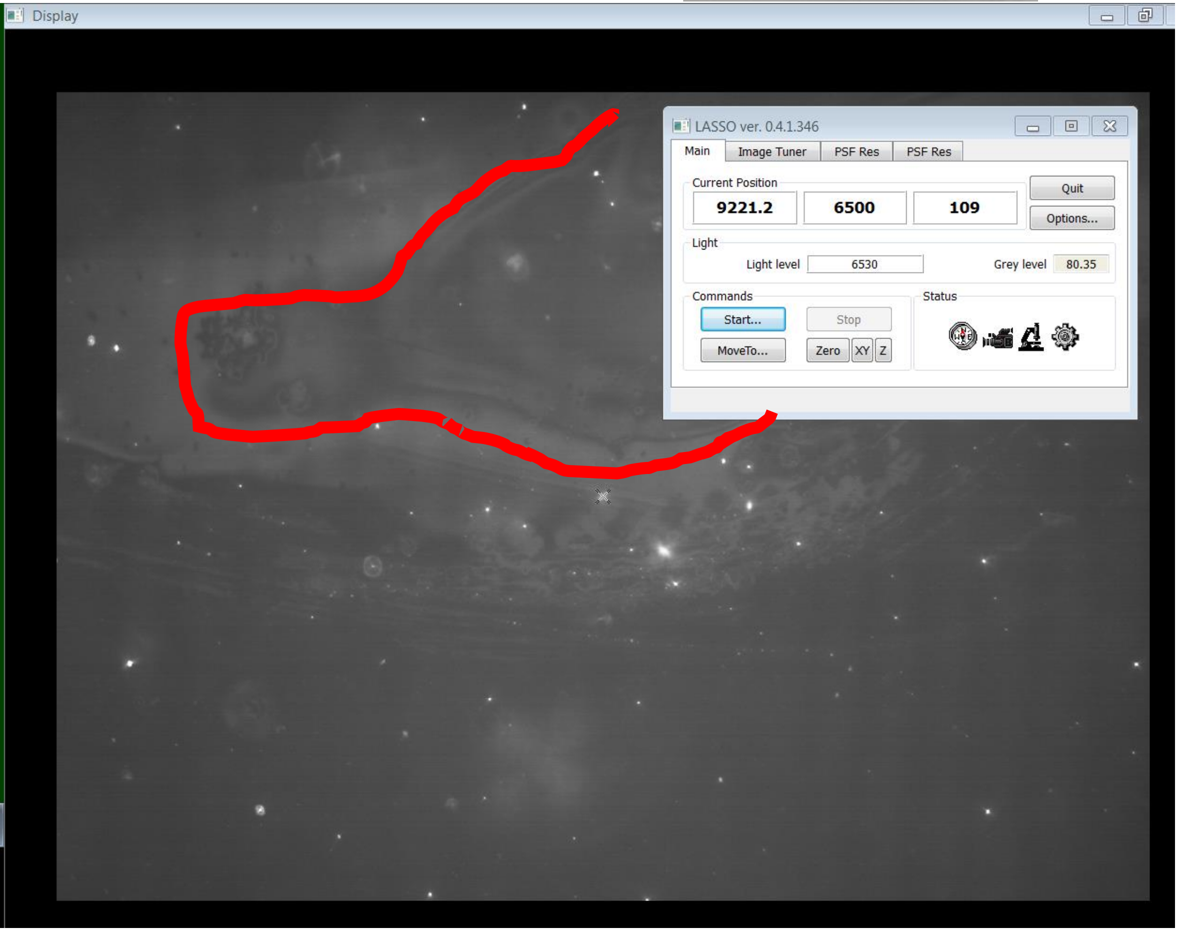
Reference System (1)



- Simple spots with a marker have been used to define a frame of reference for each emulsion
- Each spot has been found when scanning the emulsion from the bottom side



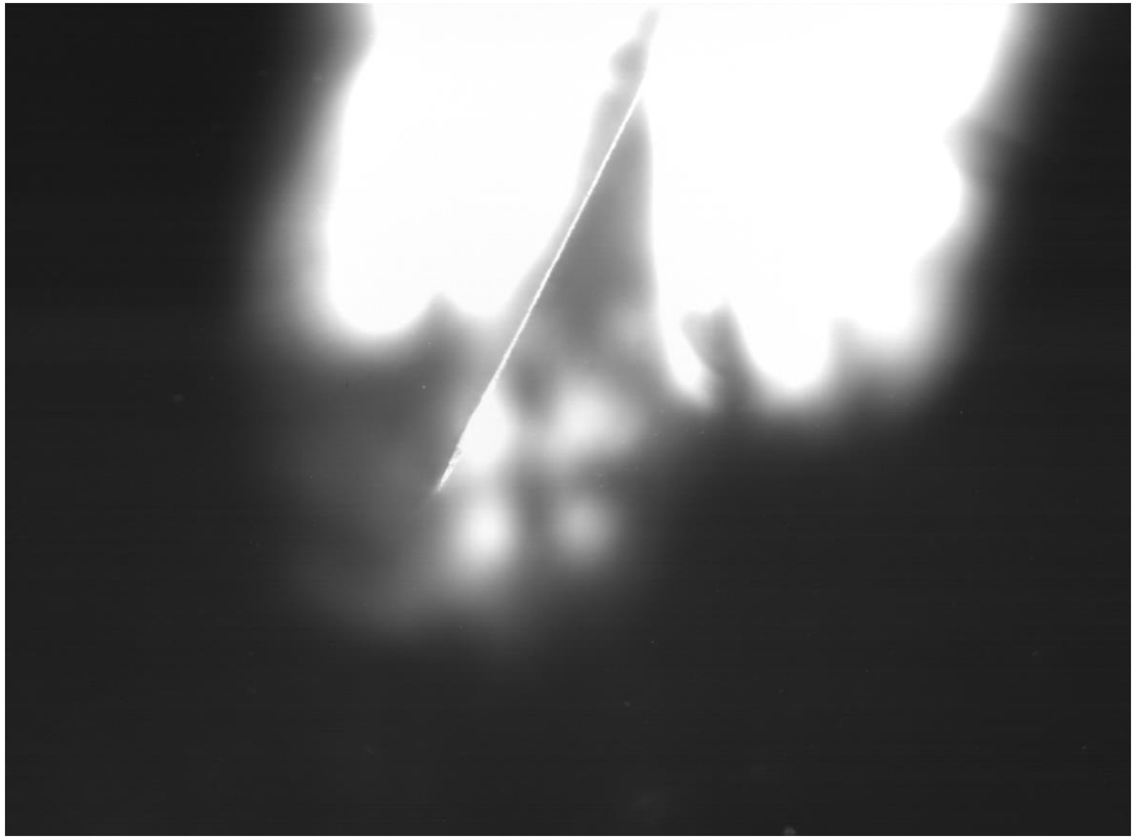
Bot Side Scan



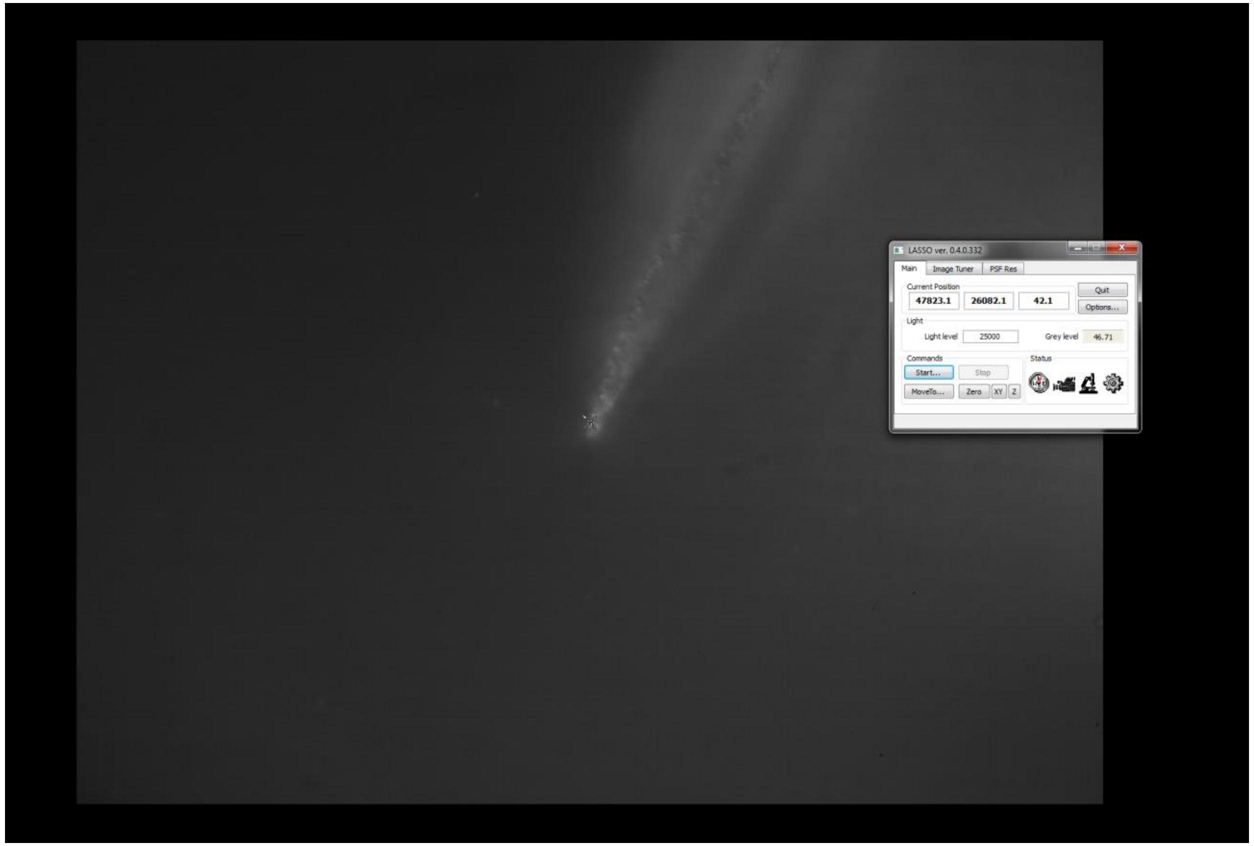
Top Side Scan

Reference System (2)

- Finding the same spot with a different microscope (higher magnification) has proven to be difficult
- For the first tests, a crack in one of the emulsions has been used
- A possible solution could be to add Ag nanoparticles on top of the emulsion films (to be tested)

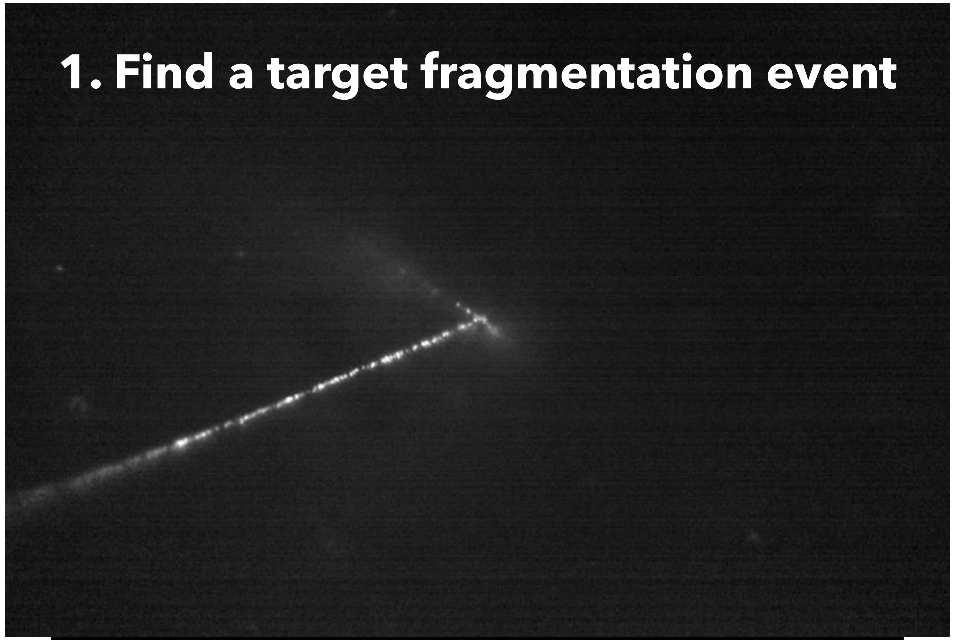


Mic8 (fast optical microscope)

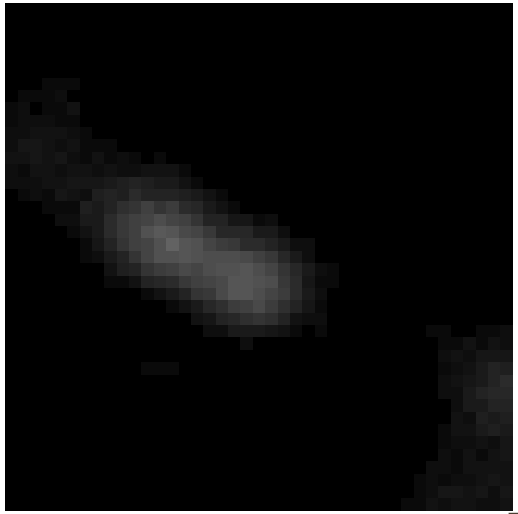


Mic6 (SR microscope)

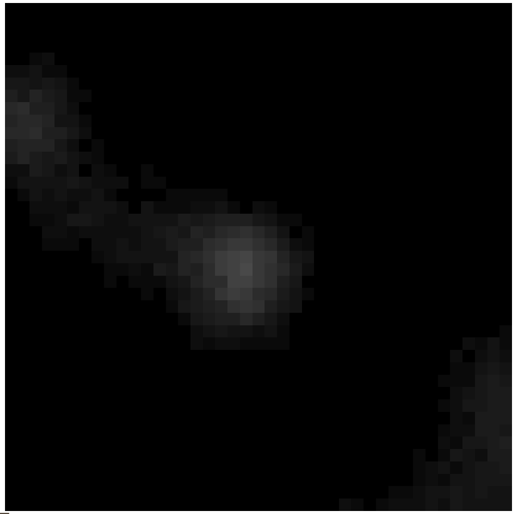
SR Workflow



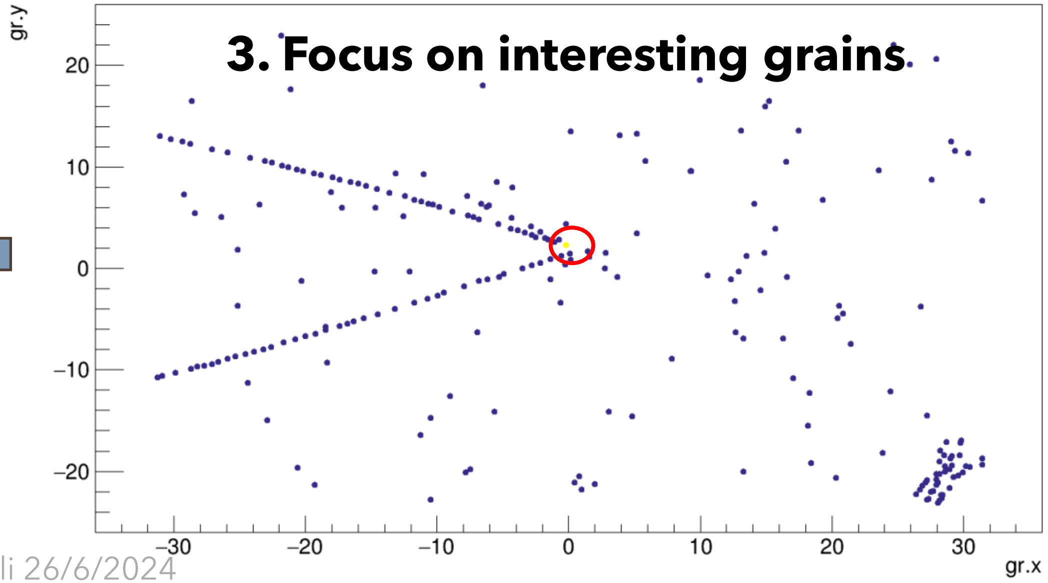
2. Perform scanning with 8 polarizations

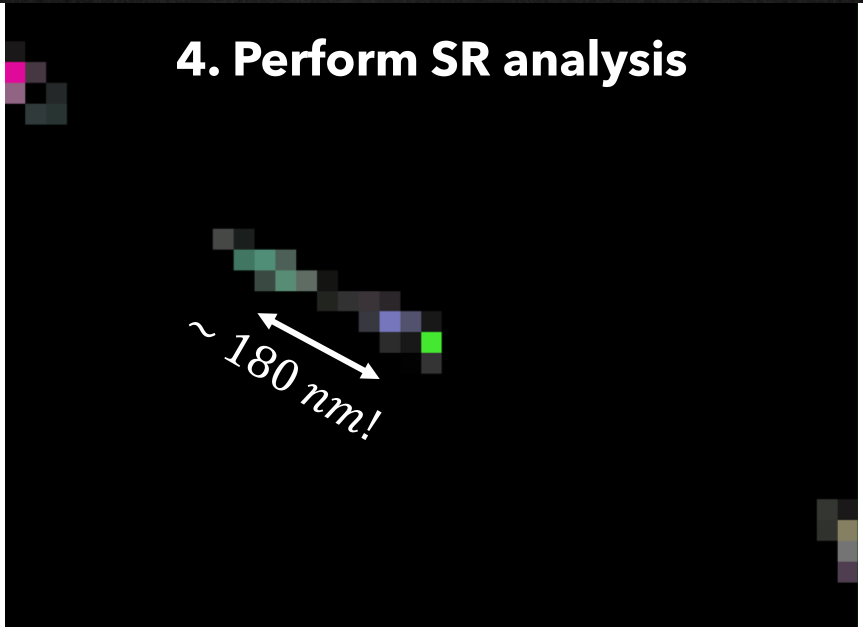


Polarization Angle **= $112.5°$**



Polarization Angle **= $180°$**





Conclusions

- CNAO test beam confirmed that the current NIT sample is not sensitive to protons @70 MeV and above
- Top side scanning of all the emulsions from the Pilot Run has been completed
- Analysis of the Pilot Run: more than 1500 interactions identified via fast scanning!
- On-going
  - Optimization of SR system for current NIT sample
  - SR scanning of reconstructed interactions and study of grain density for charge ID

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Ministero dell'Università e della Ricerca
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