University of Zurich[UZH]

Emulsion Detectors

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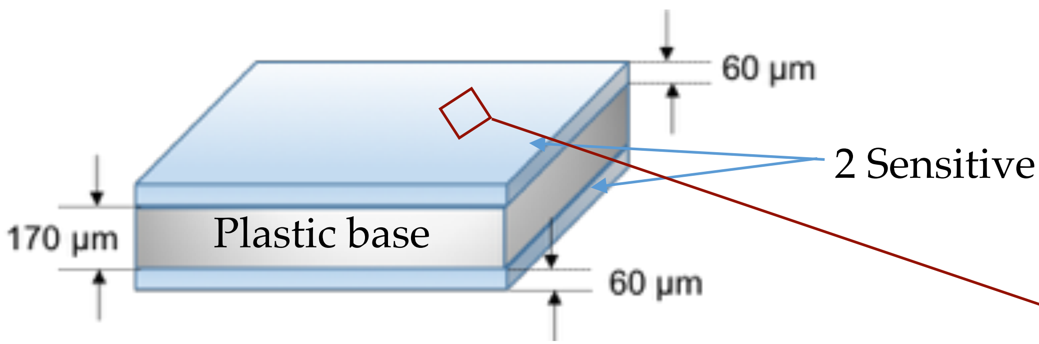
- Universität Zürich -

Guest Lecture in Particle Physics II

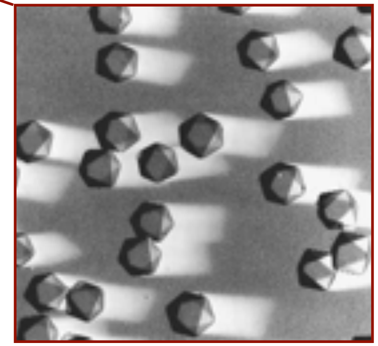
May 24, 2018

What are nuclear emulsions?

- Nuclear emulsions are 3D tracking detectors allowing to reconstruct the track of a charged particle with a resolution of the order of 1 μm or less in position and of 0.003 rad in angle

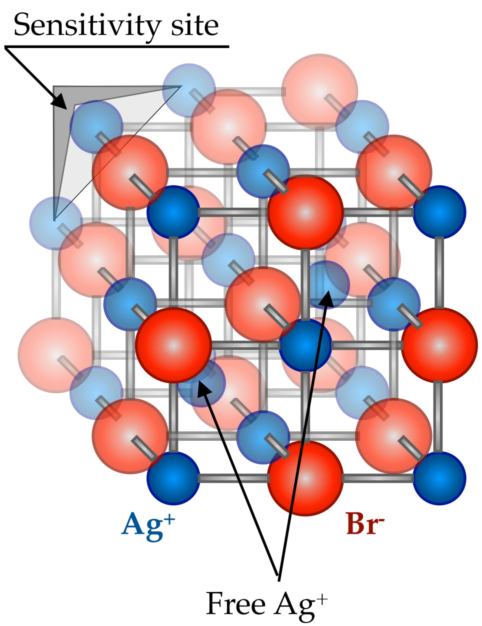


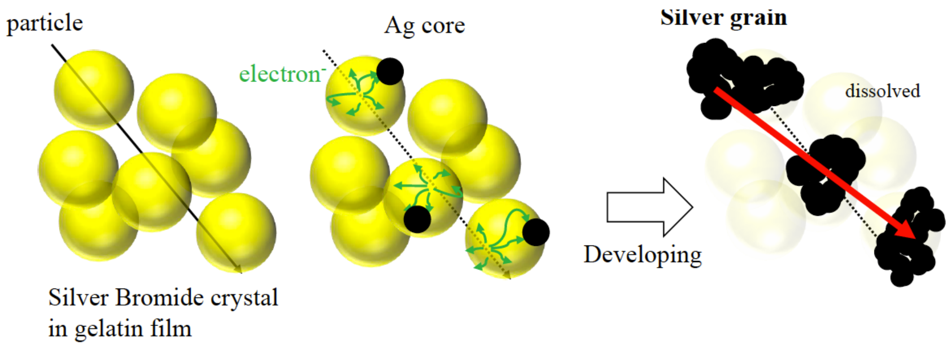
- **Basic detector**:
  - AgBr micro (~ 0.2 μm) crystal semiconductor (Band gap ~ 2.6eV) scattered in a gelatine binder
  - ~ 10^{13} "detectors" per film



How do emulsions work?

- In silver halide crystals Ag + Br atoms are arranged as in a face-centered cube.
- There are also free interstitial Ag^+ ions and areas of trace chemicals that form sensitivity site
- Exposure of the crystal to photons/charged particles results in the release of electron which travel to the sensitivity site → negatively charged → attract free Ag^+
- When the silver ions reach the sensitivity site, they acquire an electron and become neutral silver atoms.
- These silver atoms now constitute a ***latent image site***





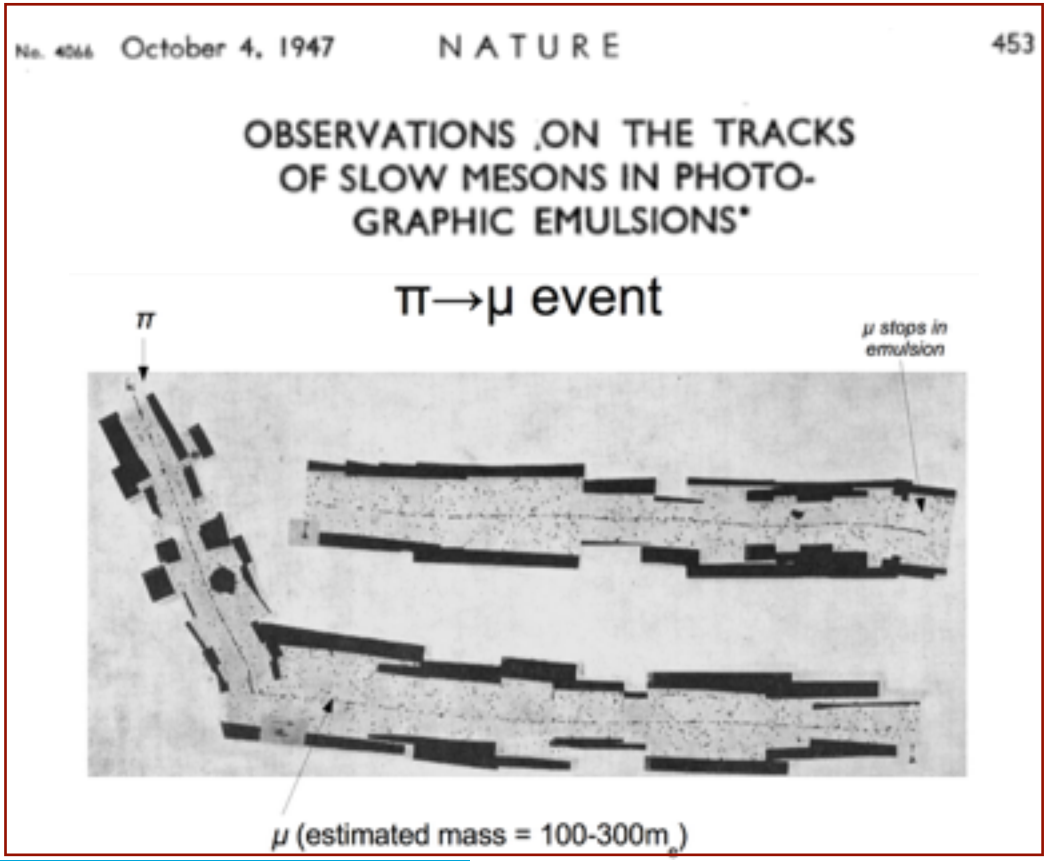
- During the development the Ag atoms initiate the conversion of Ag^+ in the crystal into one large grain of metallic silver

Emulsions VS Photographic films

- Main differences with respect to standard photographic films:
    1. The ratio of silver halide to gelatine ~ 8x larger in nuclear emulsions
    2. Emulsions are ~ 10 up to 100 times thicker
    3. Developed silver grains are smaller and more uniform

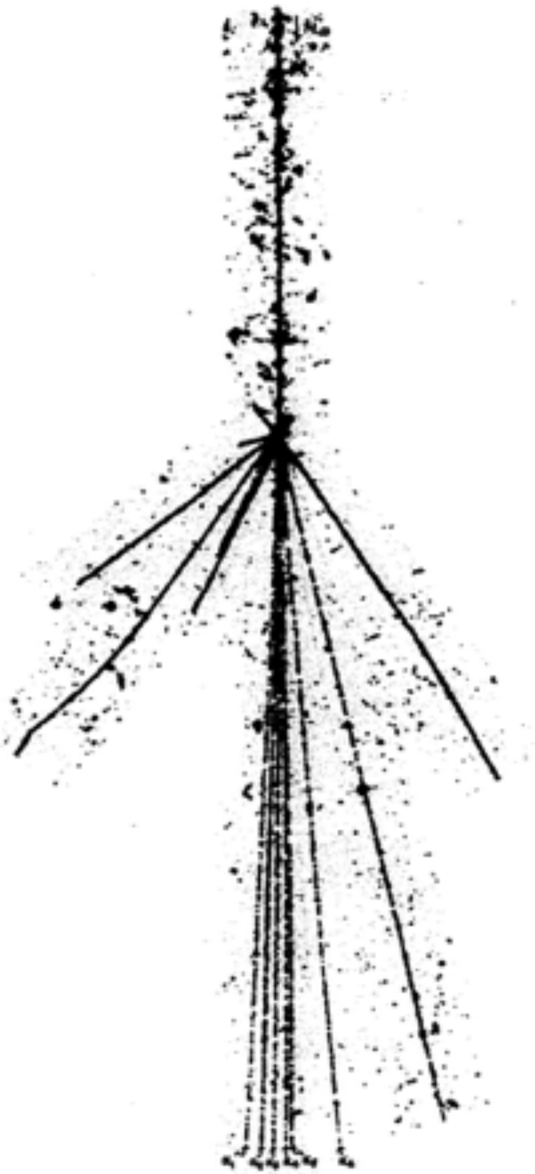
Some history …

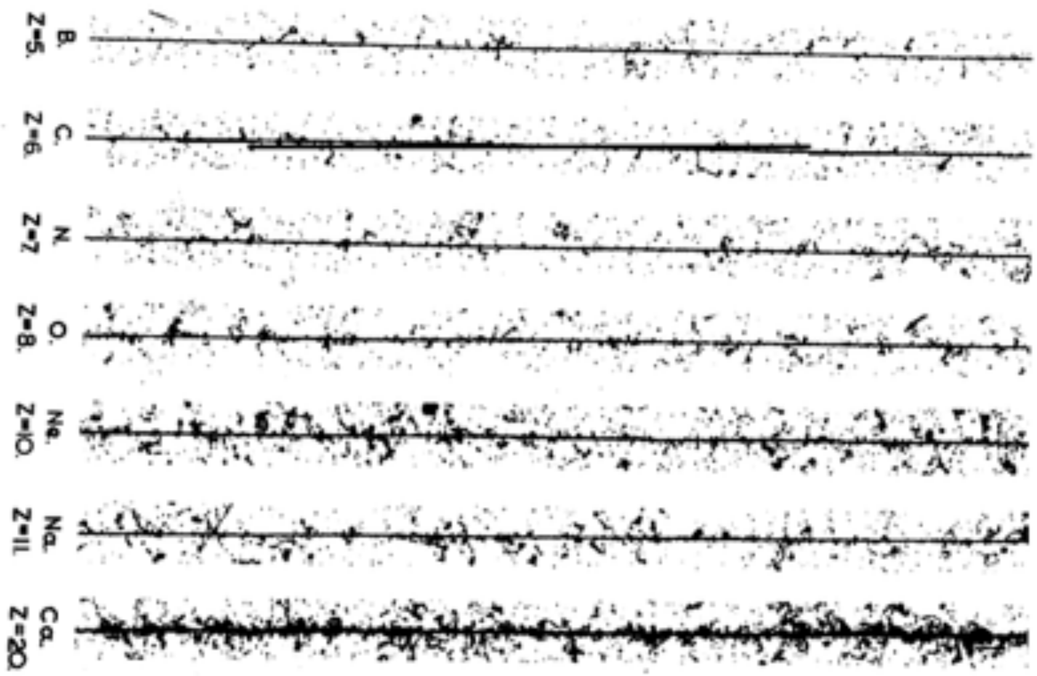
- In the **1930s-1940s**, emulsion films were used to investigate the cosmic radiation:
  - They could allow a direct and detailed insight into the physical processes which accompany the passage of charged particles through matter
- **1947:** C. Powell, G. Occhialini, C. Lattes publish:



- The meson π (with its subsequent decay in a μ) is observed in emulsions exposed on Mount Chacaltaya (~5600m) in the Bolivian Andes
- ***Powell*** was awarded the ***1950 Nobel Prize*** for his <u>development of the emulsion technique</u> and for the discovery of the pion

From C. Powell's Nobel Lecture in 1950



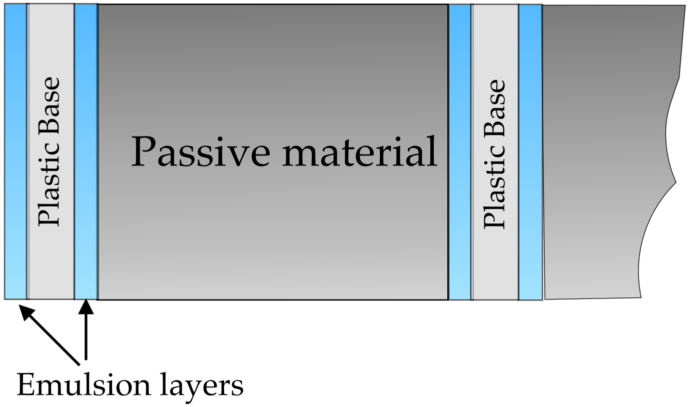


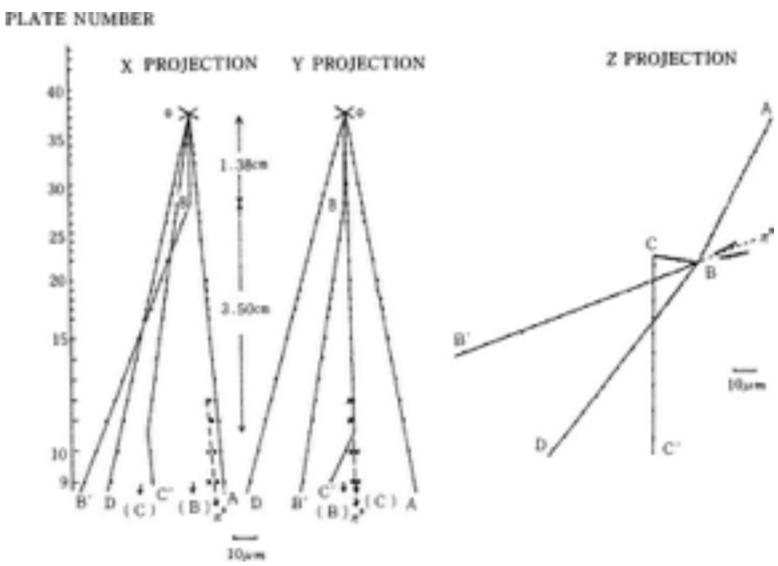
From C. Powell's Nobel Lecture in 1950

Photo-micrographs of four examples of the successive decay $\pi \to \mu \to e$ as recorded in photographic emulsions.

Some history …

- **1951:** Kaplon introduces the ***Emulsion Cloud Chamber (ECC) technique*** to study heavy primaries in cosmic ray radiation:
  - Emulsion films interleaved with passive material (plastic, metal, lead) plates
    - Spatial resolution reaches 1 μm
    - Possibility to reconstruct cascade showers in the detector
- **1971:** (K.Niu et al.) discover a pair of naked charm particles in a cosmic-ray interaction, three years prior to the discovery of the hidden charm particle, J/Ψ

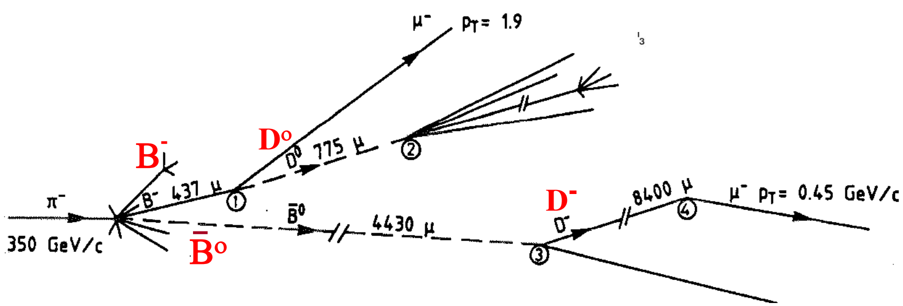


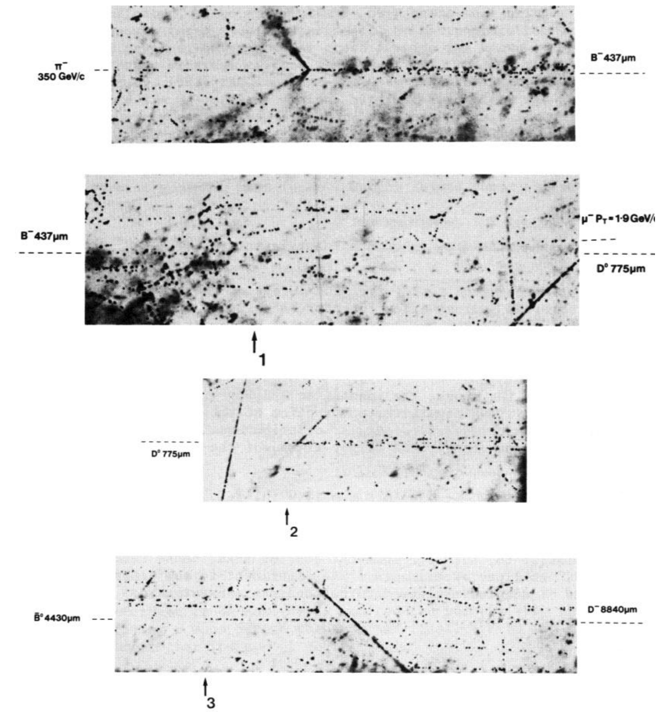


Some history…

- **1985:** Direct Observation of the Decay of Beauty Particles Into Charm Particles

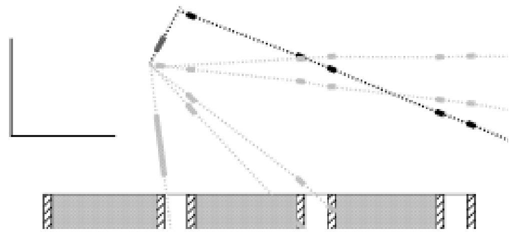
WA75 at CERN Phys. Lett. 158B (1985) 186





- **2001:** First observation of the ν_τ particle

F.L. = 280 μm
θ_{kink} = 90 mrad
$p = 4.6^{+1.6}_{-0.4}$ GeV/c
$p_T = 0.41^{+0.14}_{-0.08}$ GeV/c

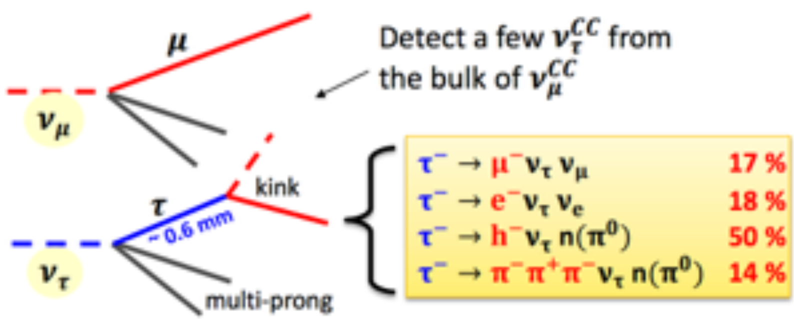


- **2015:** Discovery of the oscillation $\nu_\mu \rightarrow \nu_\tau$ in appearance mode **(OPERA)**

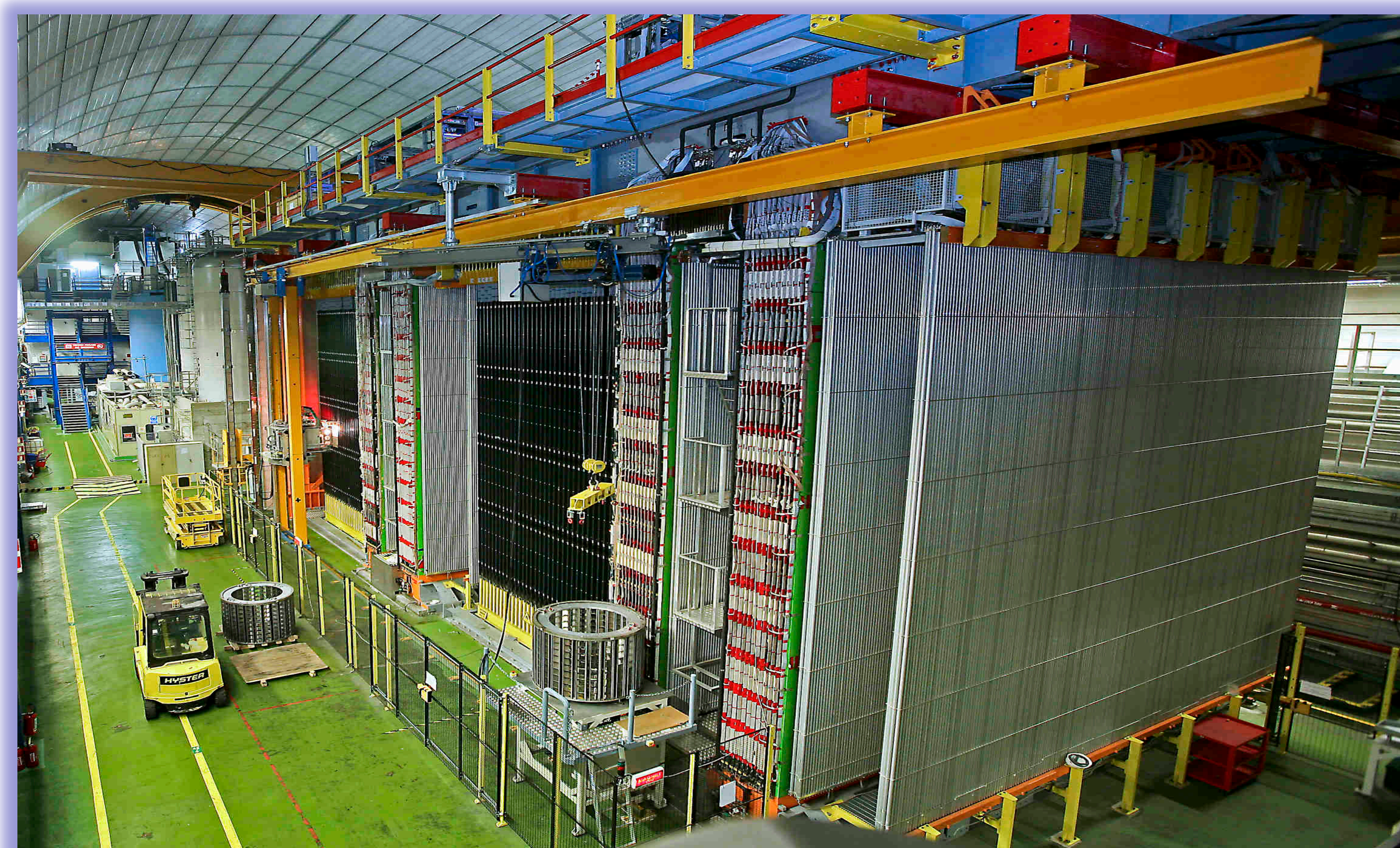
The OPERA experiment

The OPERA experiment

- **Aims:**
  - Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale.
  - ν_τ appearance event-by-event in an artificial ν_μ beam
- **Beam:**
  - ν_μ beam produced at CERN (<E> = 17 GeV)
- **Target:**
  - Detector at LNGS, 730 km from CERN

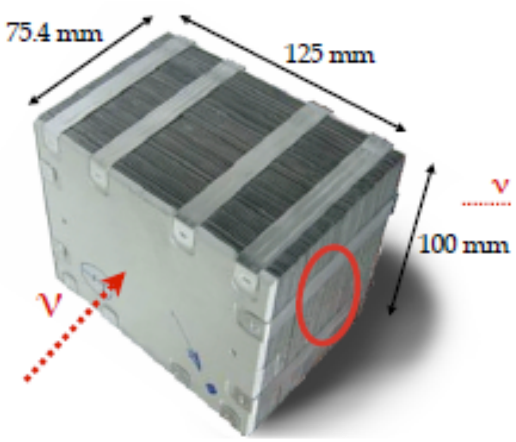


The OPERA detector

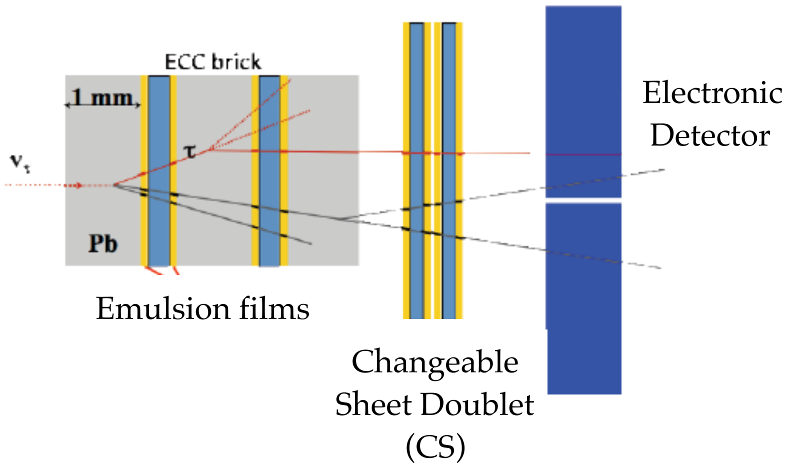


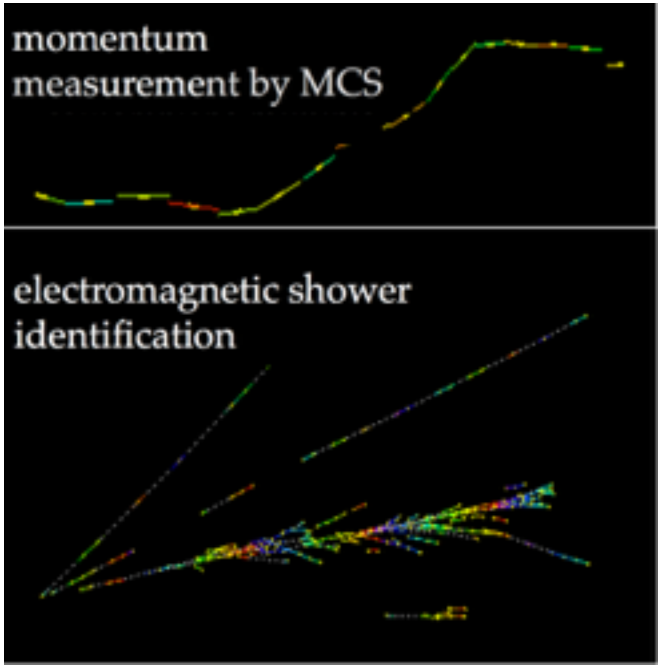
The target

Fundamental unit: the **Brick (~8.3 kg)**

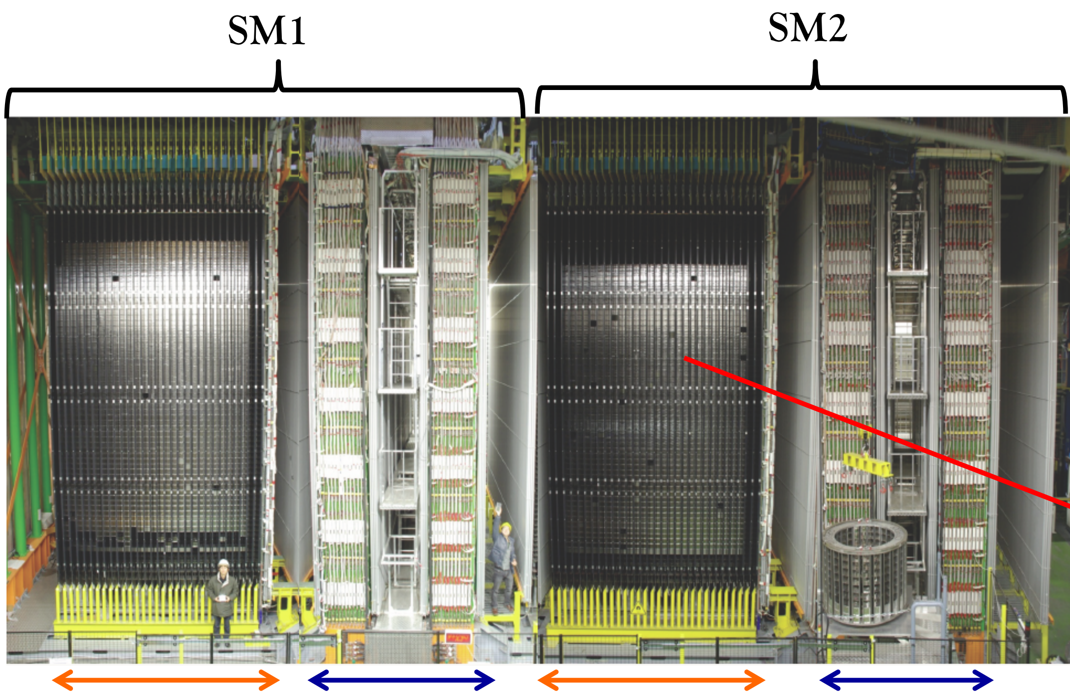


- Exploits the ECC technique:
  - 57 emulsion films → High res. tracking devices
  - 56 lead plates → Passive material for ν interaction
  - 1 changeable sheet doublet
  - 10 X_0

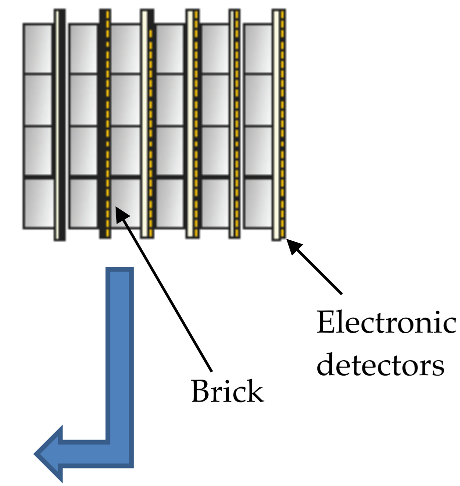


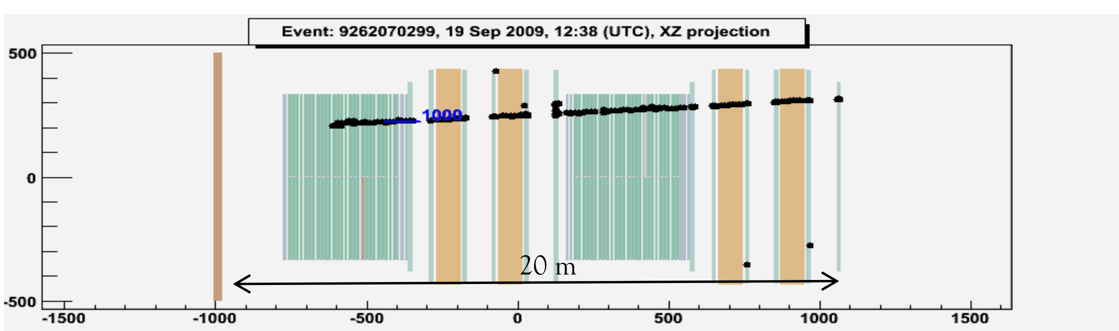


The OPERA apparatus



- 2 supermodules
- Target:
  - 53 walls
  - 31 planes of electronic detectors
  - 150000 bricks
  - Total mass ~1.2 kTon





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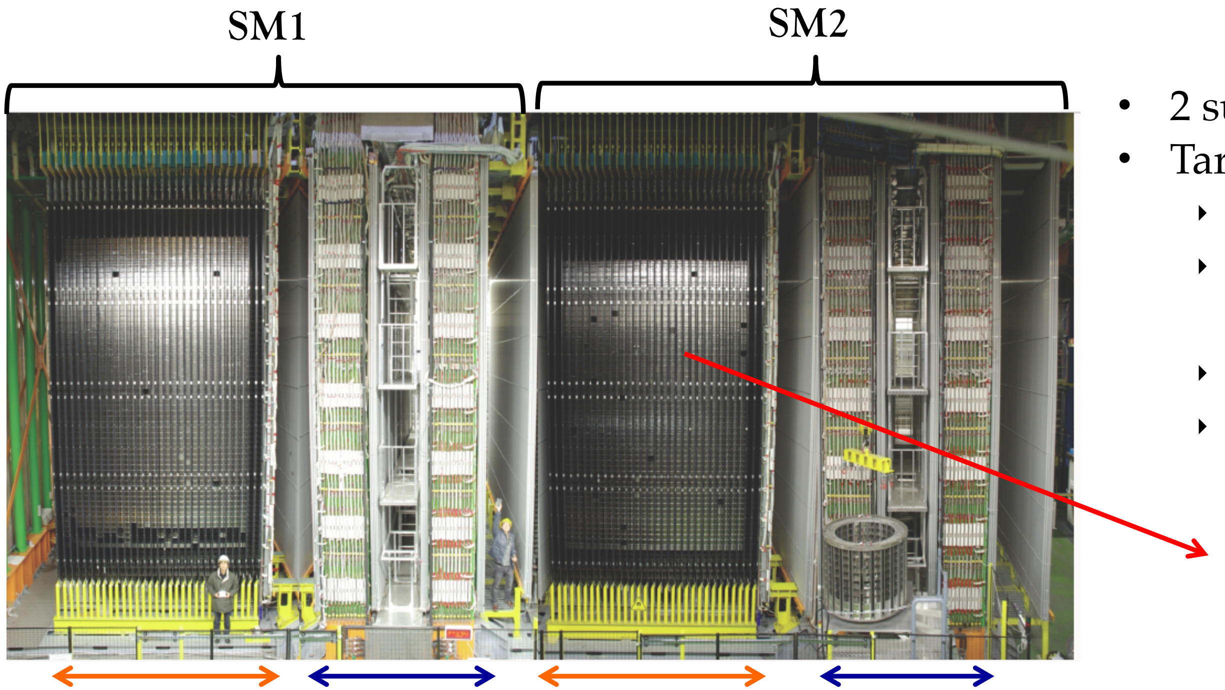

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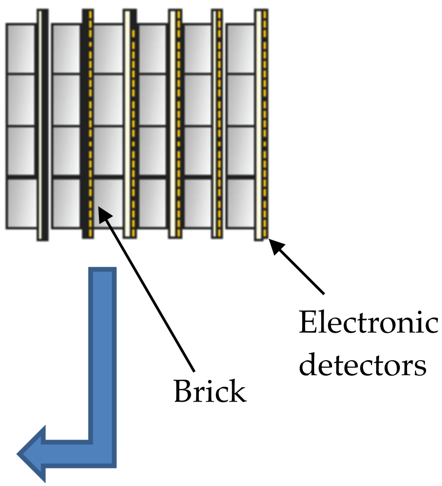
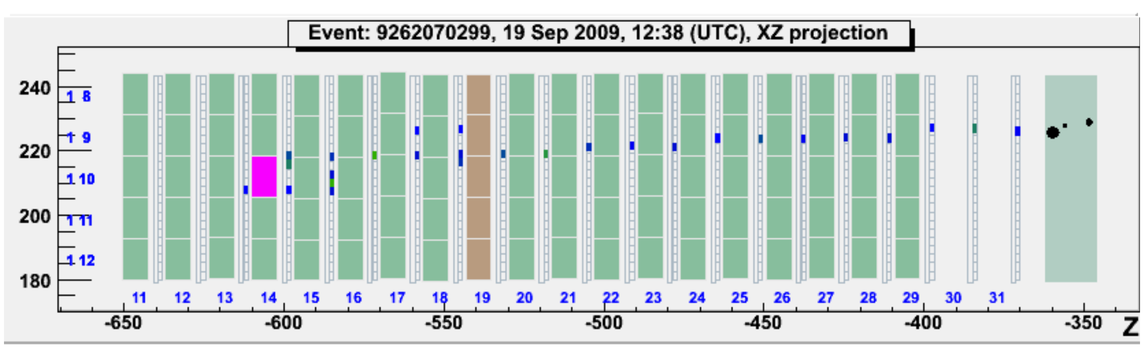
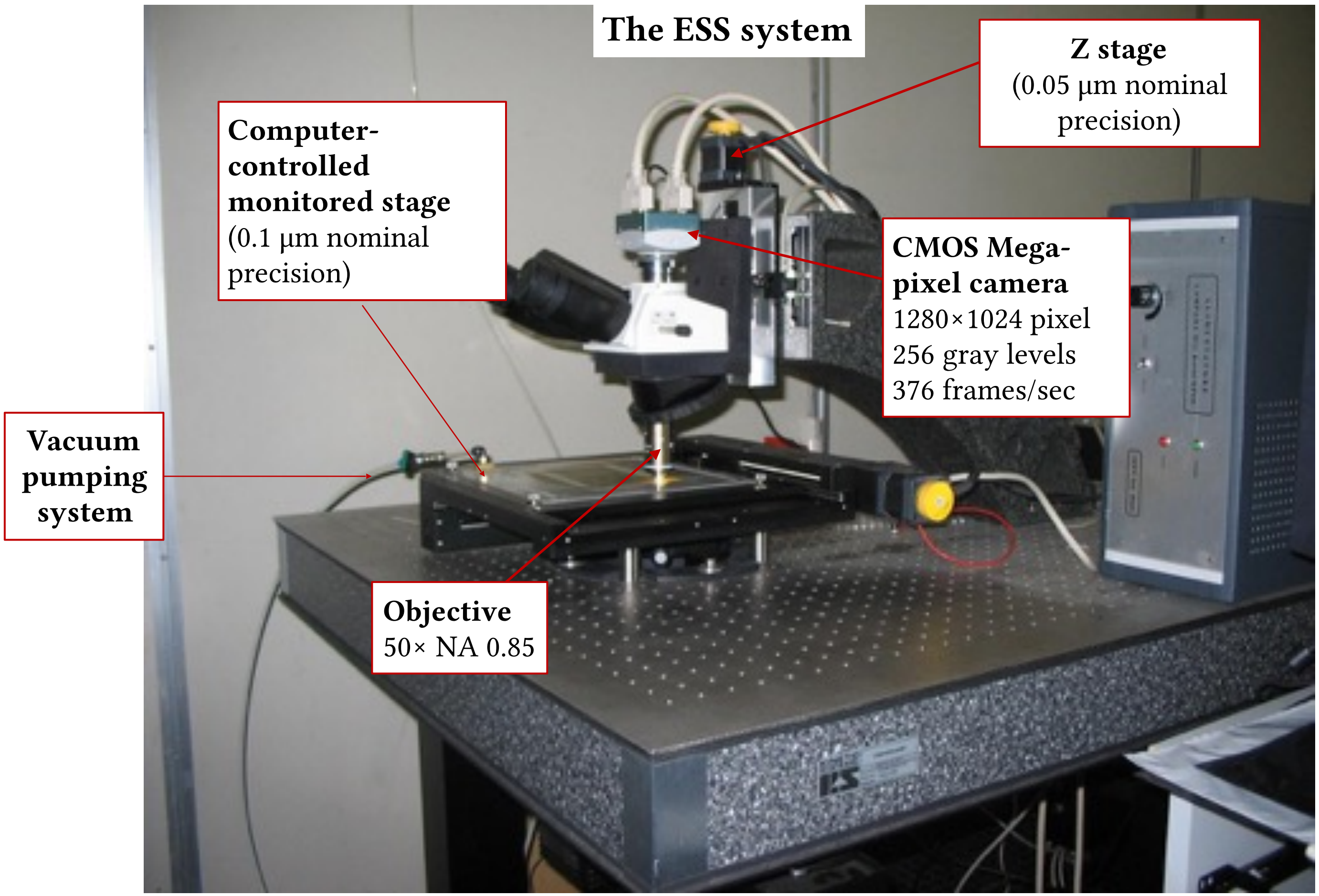


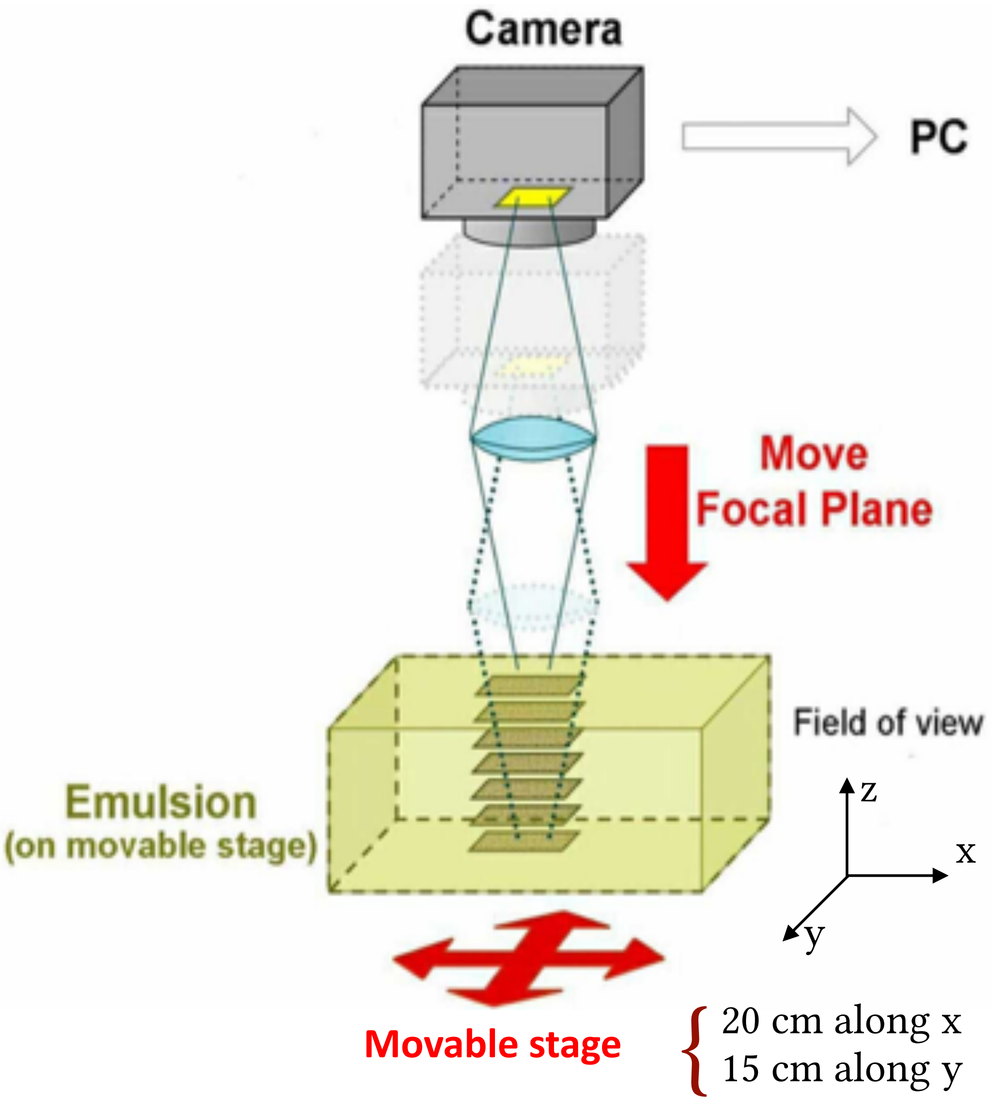


The OPERA European Scanning System (ESS)

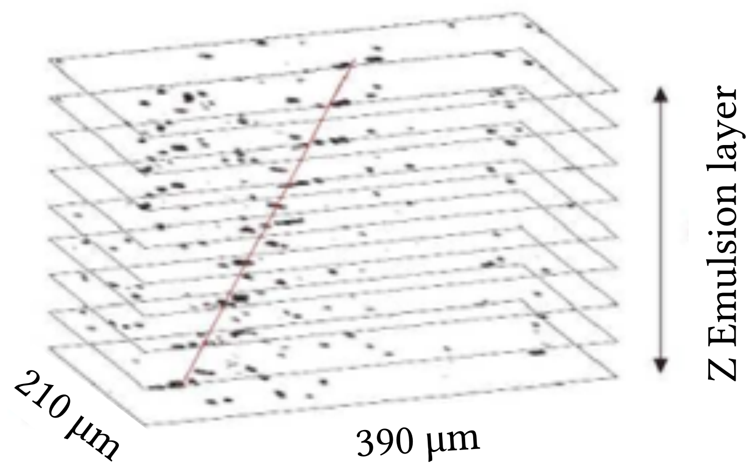
Fully automated optical microscope



Principle of automatic emulsion scanning

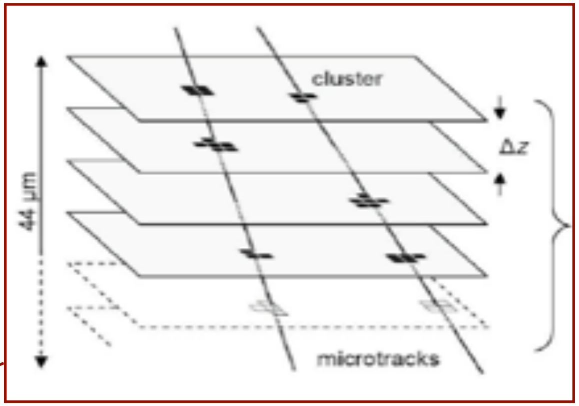


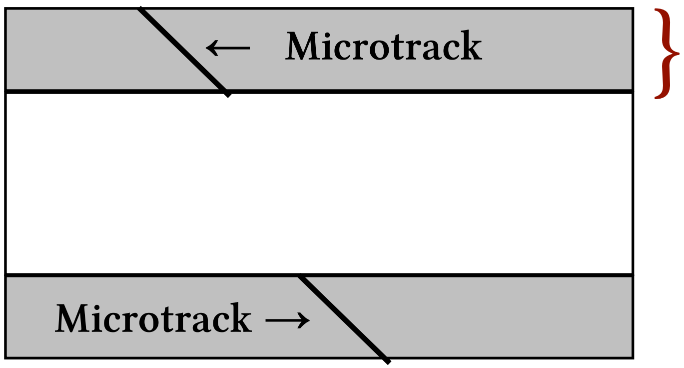
1. For each field of view (390 x 210 μm^2) several tomographic images of the emulsions are taken at equidistant depth (~2-3 μm) moving the focal plane
2. Images grabbed by digital camera with stop-and-go algorithm and processed by a vision multi-processor board



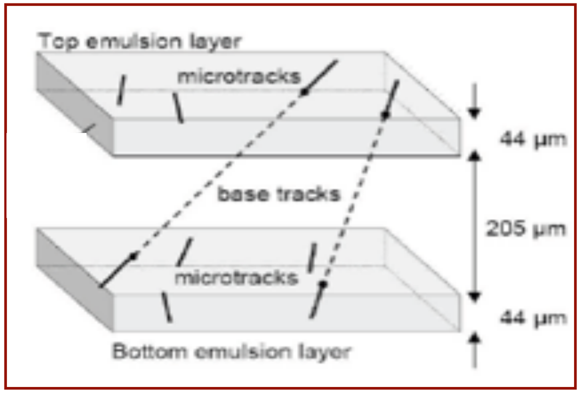
Principle of automatic emulsion scanning

3. 3D sequences of aligned clusters (grains) are recognised
4. Tracks are formed from sequence of grains in a single emulsion layer **(Microtracks, MT)**





3D view:

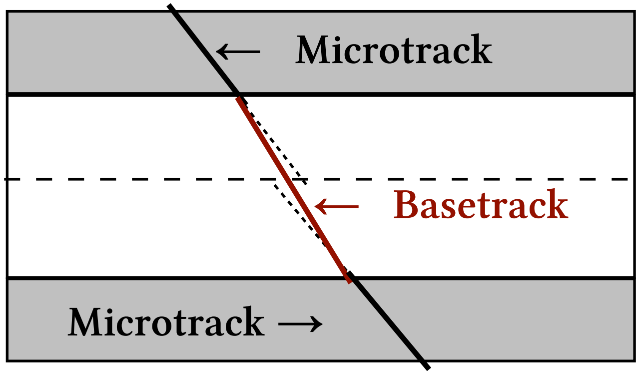


This is the output after emulsion scanning

Track reconstruction in emulsion films

Performed with a dedicated offline software (**FEDRA**[1]):

1. **Shrinkage correction:** correction for emulsion thickness reduction after development (dissolution of silver halide)
2. **Linking:** formation of ***basetracks (BT)*** ⟶ Background reduction from fake combinatorial alignments + minimisation of distortion effects

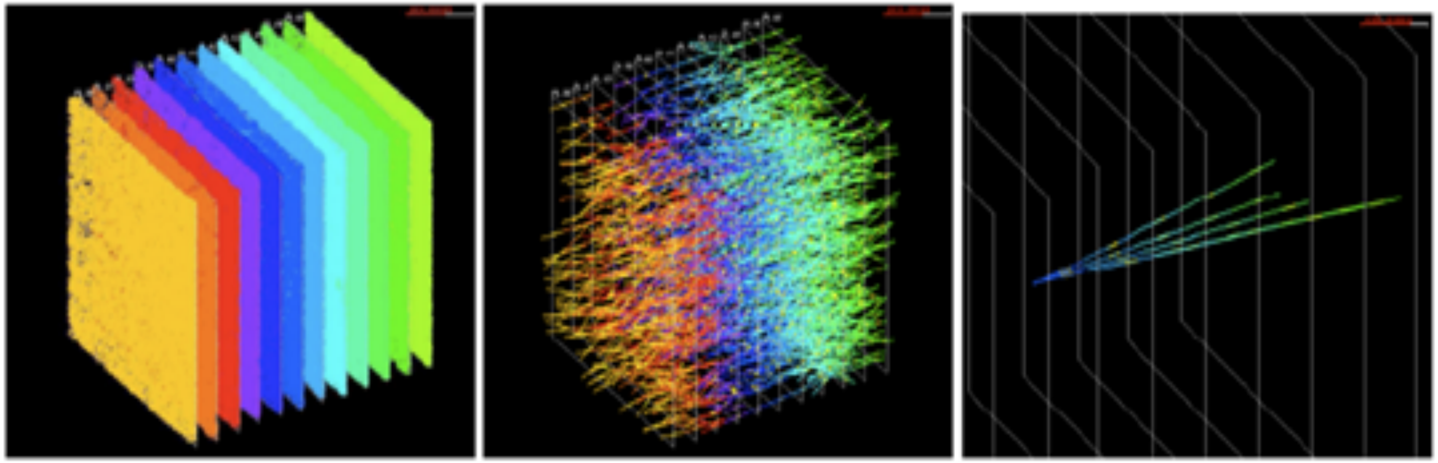


[1] Framework for Emulsion Data Reconstruction and Analysis

Track reconstruction in emulsion films

Performed with a dedicated offline software (**FEDRA**[1]):

1. **Shrinkage correction:** correction for emulsion thickness reduction after development (dissolution of silver halide)
2. **Linking:** formation of ***basetracks*** ⟶ Background reduction from fake combinatorial alignments + minimisation of distortion effects
3. **Alignment:** Definition of a *global reference system* for different emulsion plates ⟶ allows full-volume wide reconstruction of particle tracks
4. **Track reconstruction:** Connection of base tracks in consecutive emulsion films

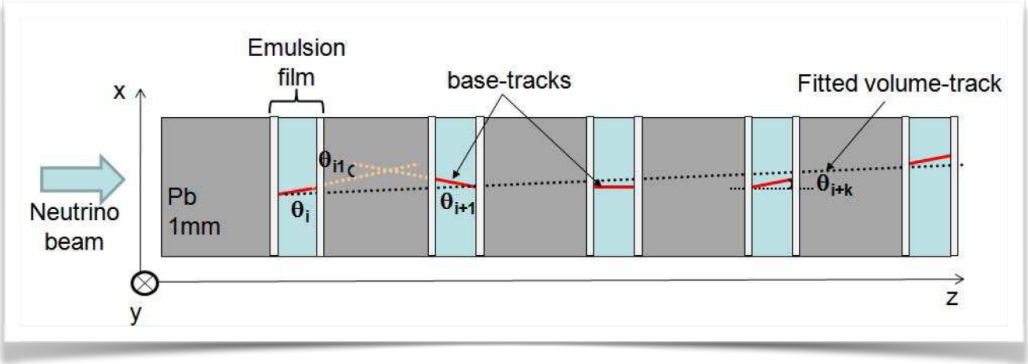


[1] Framework for Emulsion Data Reconstruction and Analysis

Momentum measurements with ECC

- Total length of a brick ~ 10 X_0 (X_0 = 5.6 mm).
- Scattering is dominated by the lead
- Momentum measurement by MCS can be carried out in 2 ways:
  - track position (coordinate method)
  - track angle (angular method)

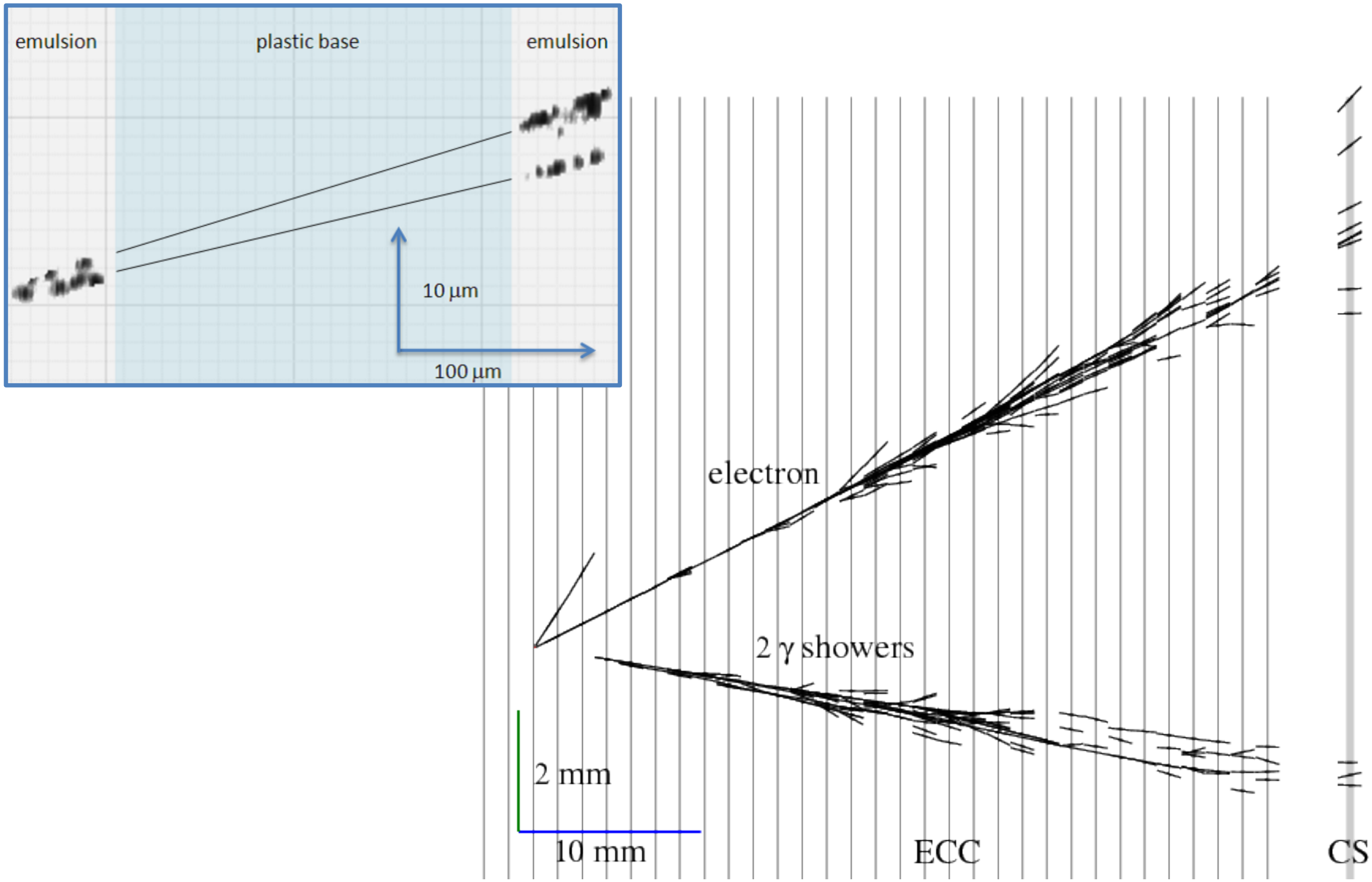
} Deviation of the trajectory from a straight line

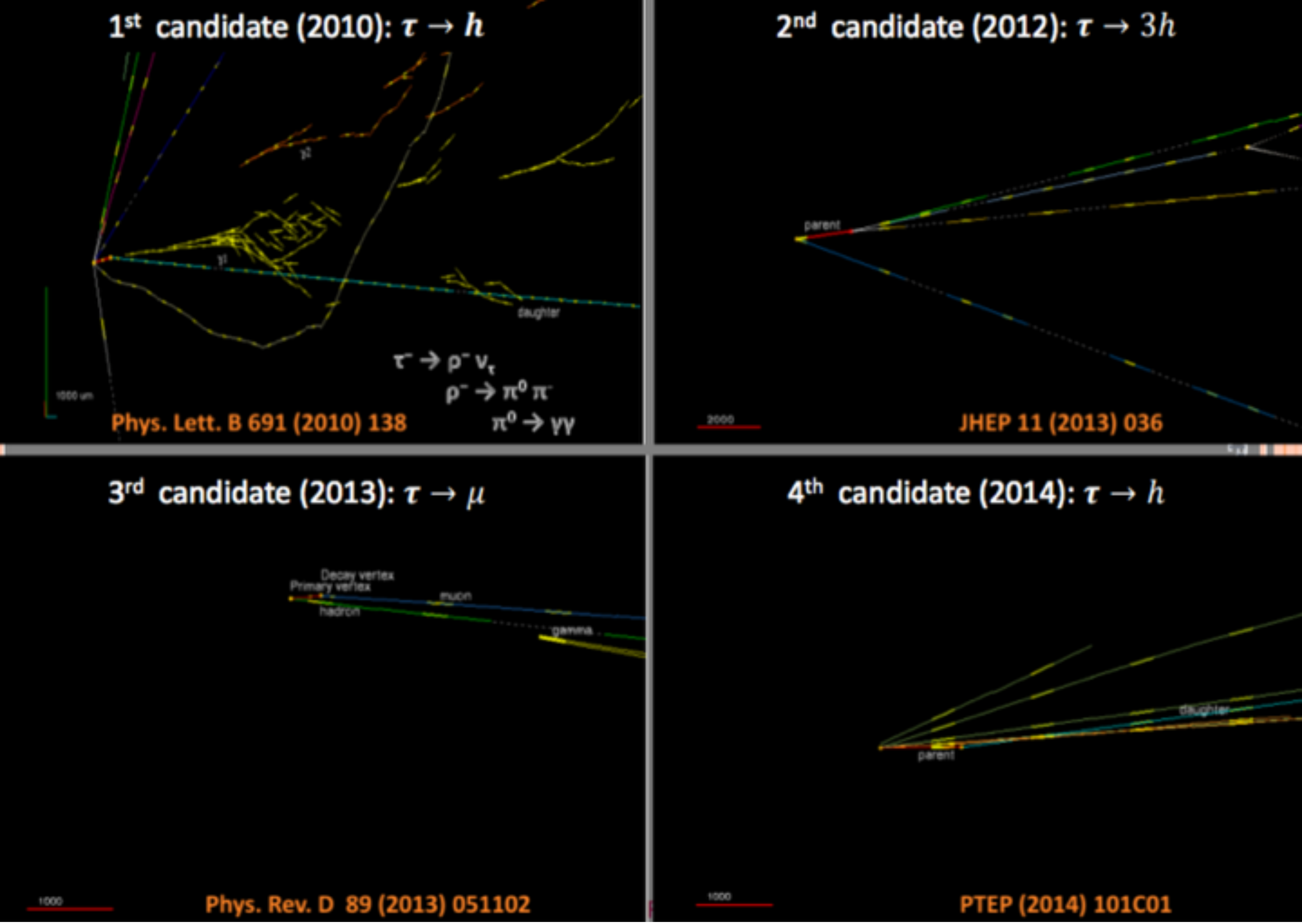


$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{x}{X_0}} \times \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

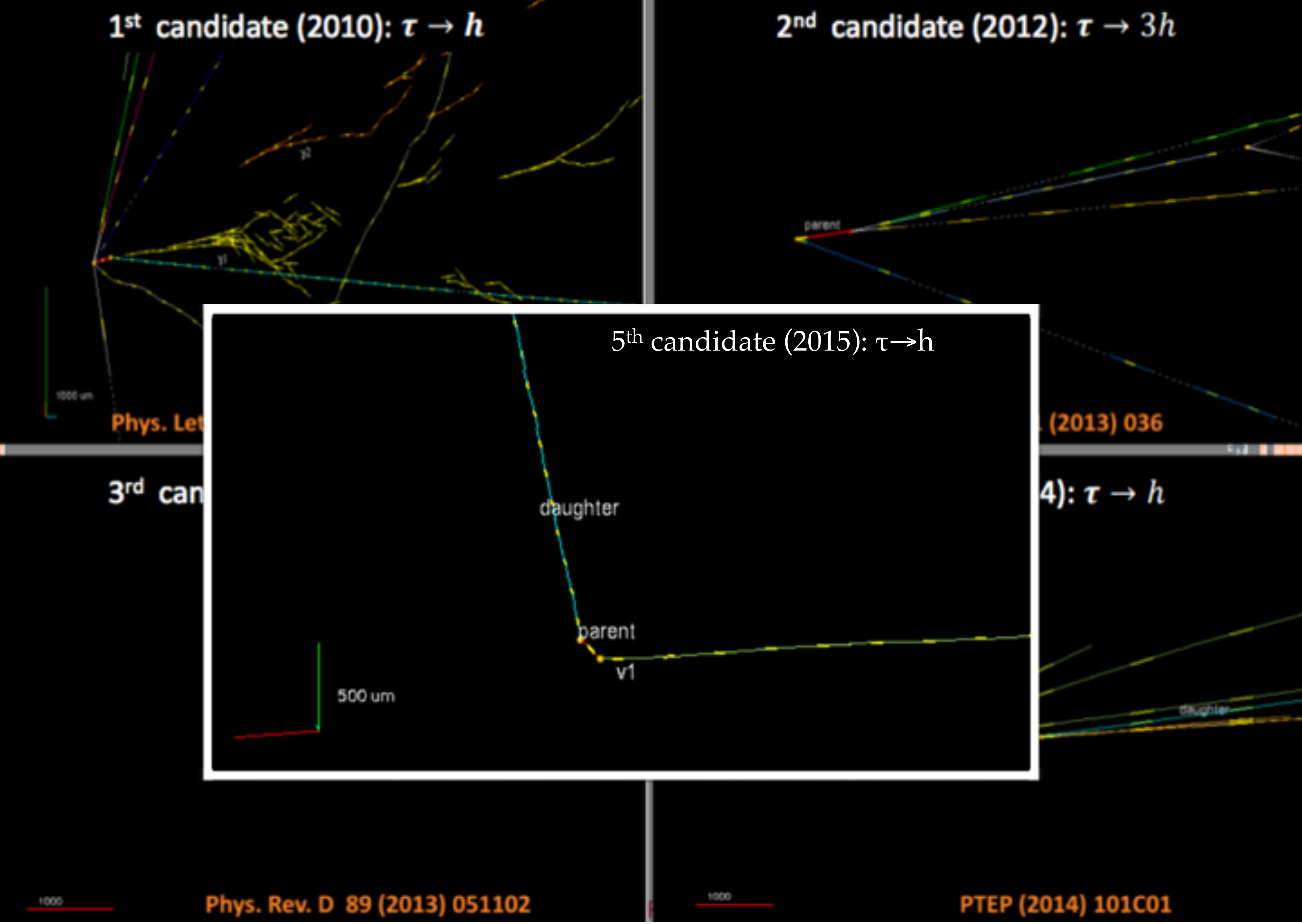
Momenta up to 8 GeV/c can be measured with a resolution better than 30%

Shower identification





1st candidate (2010): $\tau \to h$
$\tau^- \to \rho^- \nu_\tau$
$\rho^- \to \pi^0 \pi^-$
$\pi^0 \to \gamma\gamma$
daughter
Phys. Lett. B 691 (2010) 138
2nd candidate (2012): $\tau \to 3h$
parent
JHEP 11 (2013) 036
3rd candidate (2013): $\tau \to \mu$
Decay vertex
Primary vertex
muon
hadron
gamma
Phys. Rev. D 89 (2013) 051102
4th candidate (2014): $\tau \to h$
daughter
parent
PTEP (2014) 101C01



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3rd can
4): τ → h
5th candidate (2015): τ→h
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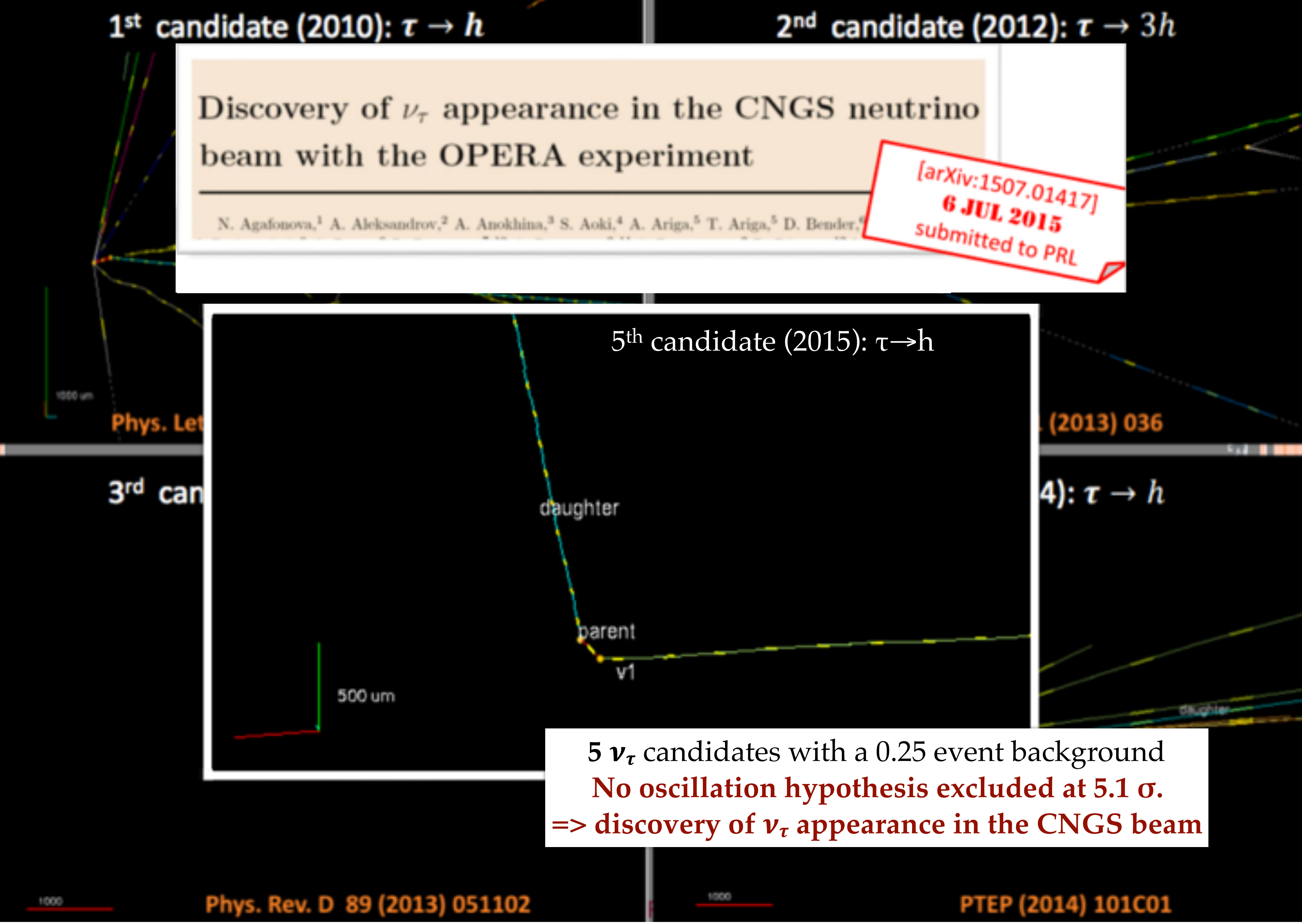
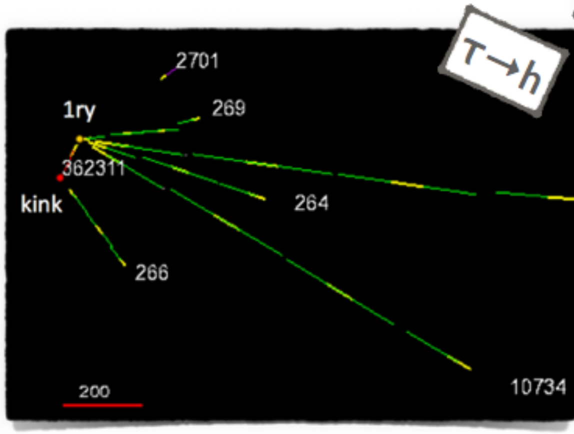


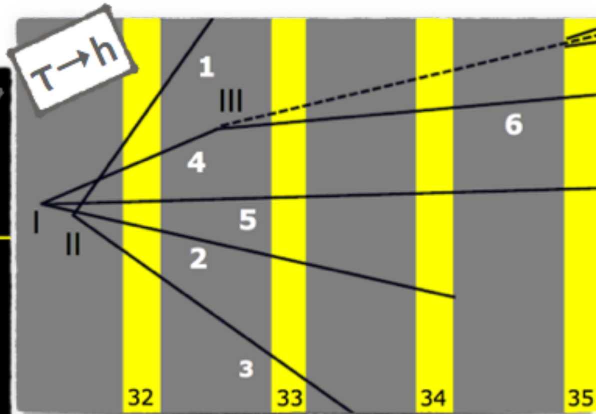
5 ν_τ candidates with a 0.25 event background

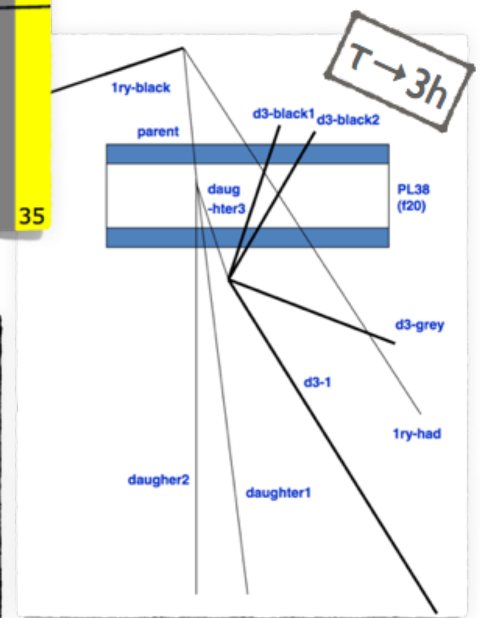
No oscillation hypothesis excluded at 5.1 σ.

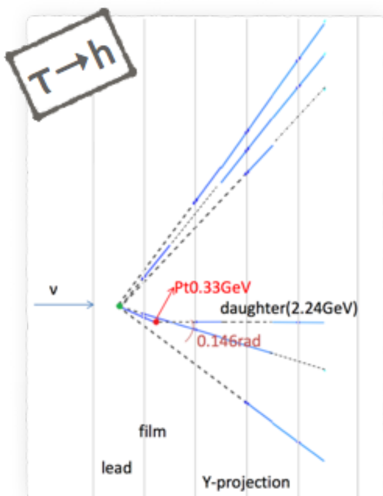
=> discovery of ν_τ appearance in the CNGS beam

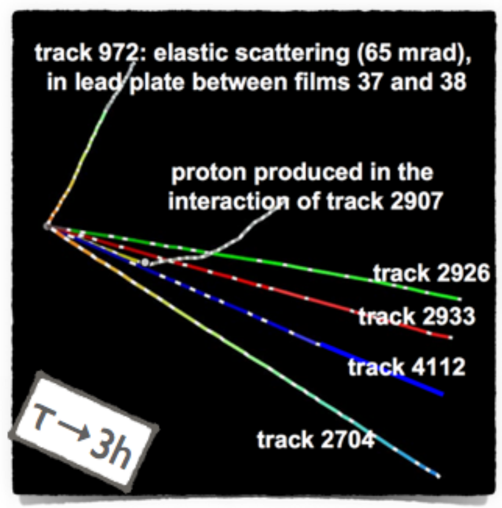
Five additional ν_τ candidates







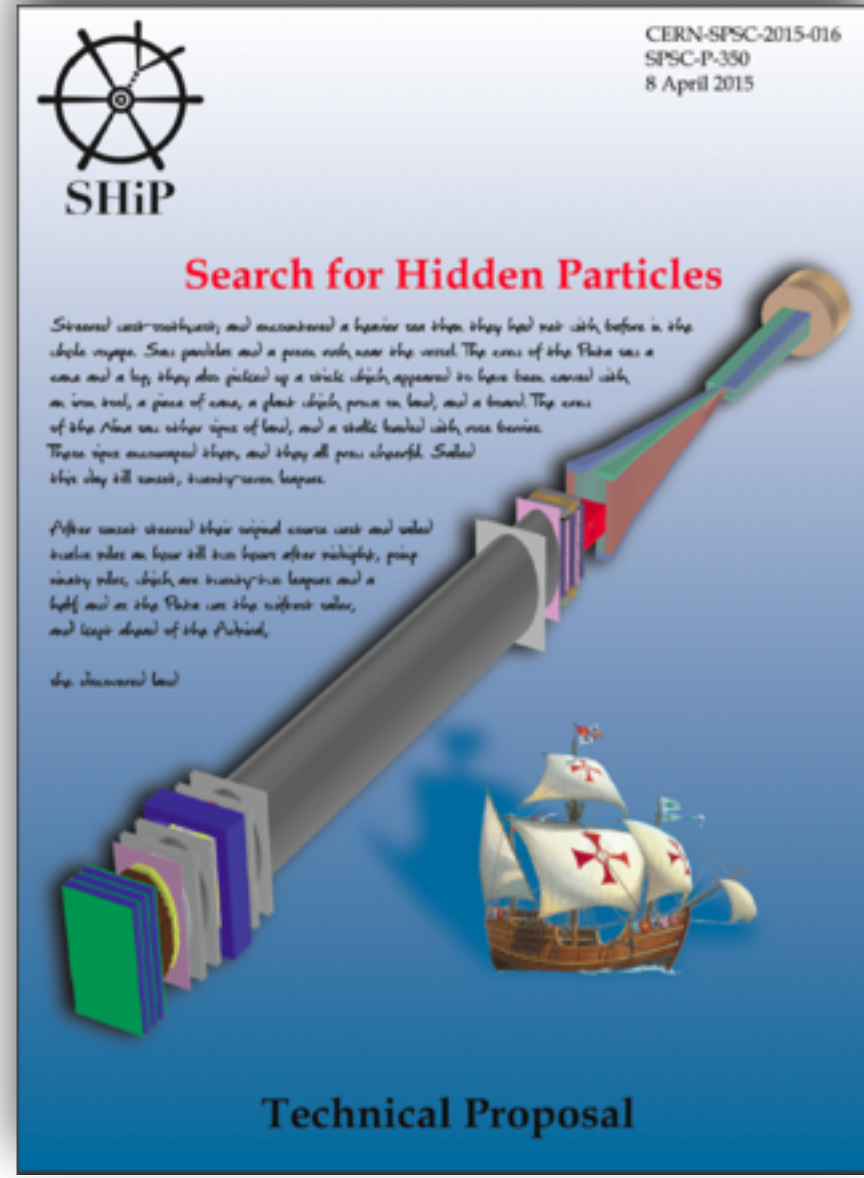




Final results of the OPERA experiment presented on May 22nd 2018

Other emulsion based detectors in Particle Physics

SHiP



- Expression of interest submitted in October 2013, Prof. N.Serra among the authors
- 1st SHiP Workshop organised in Zurich (2014)
- Technical Proposal submitted in April 2015 to CERN SPS Committee
- December 2018 deadline for submission of a Comprehensive Design Report

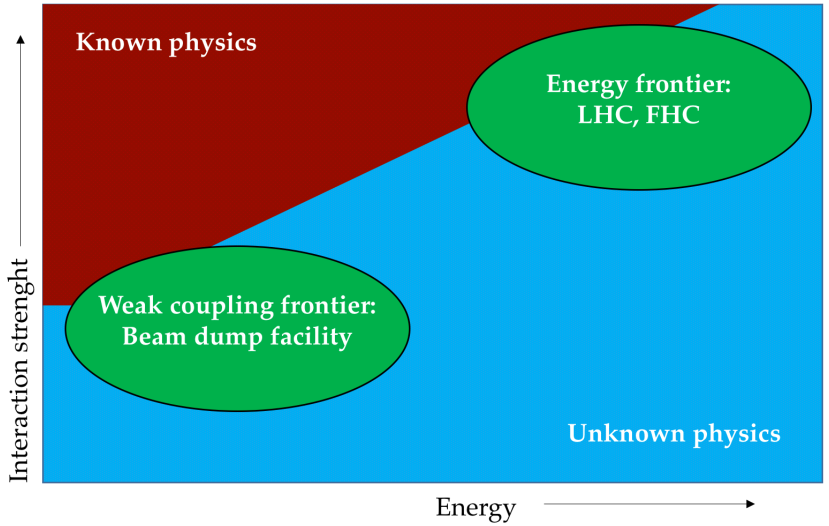
SHiP

➡ Physical Motivation

Hints for new physics come from inability of the Standard Model to describe:

- Neutrino masses
- Baryon Asymmetry in the Universe (BAU)
- Presence of Non-baryonic Dark Matter

Scale of new physics unknown



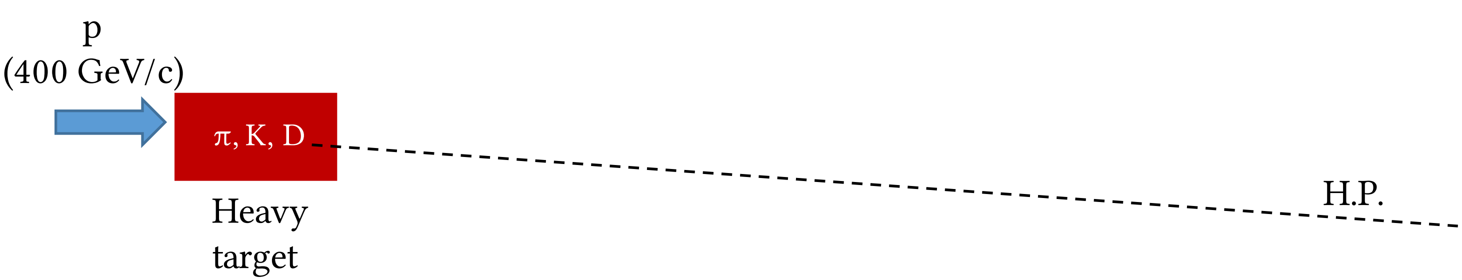
Long lived neutral (hidden) particles predicted in **many** BSM models.

→ Searched for in **intensity frontier** experiments

SHiP

➡ Experimental requirements

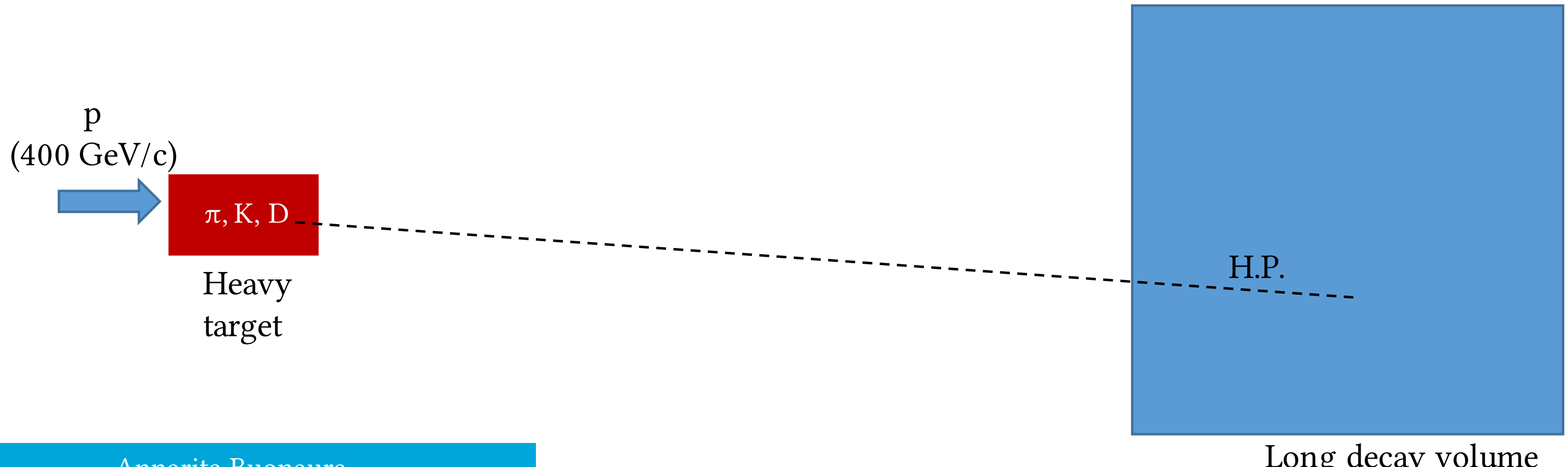
- Hidden particles with m(GeV) produced in heavy meson decays



SHiP

➡ **Experimental requirements**

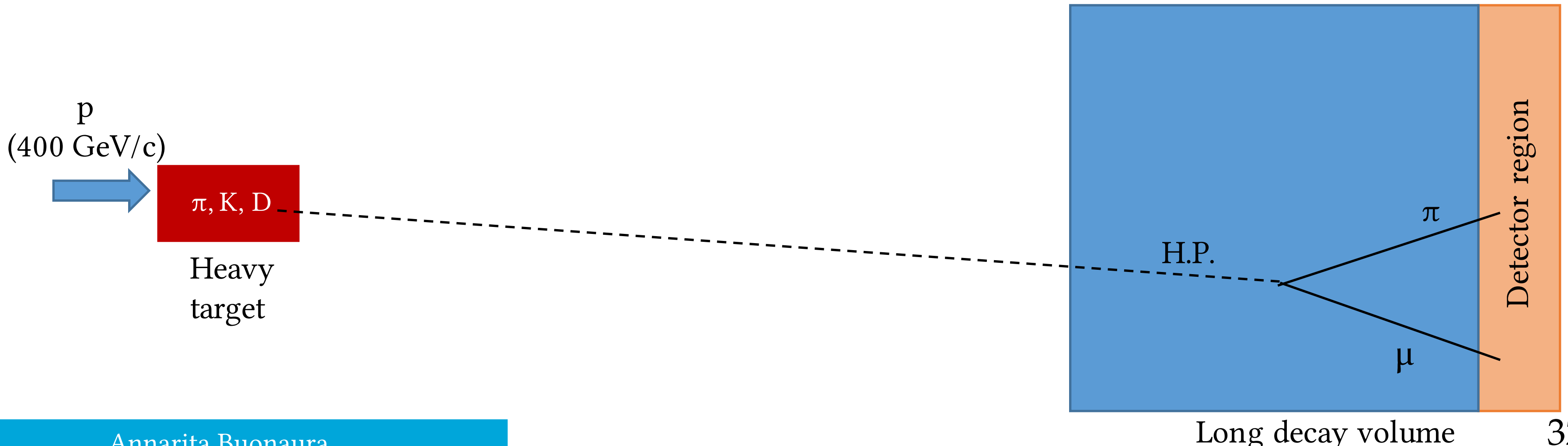
- Hidden particles with m(GeV) produced in heavy meson decays
  - Long life-time
  - Large transverse momentum



SHiP

➡ Experimental requirements

- Hidden particles with m(GeV) produced in heavy meson decays
  - Long life-time
  - Large transverse momentum
  - decay in SM particles

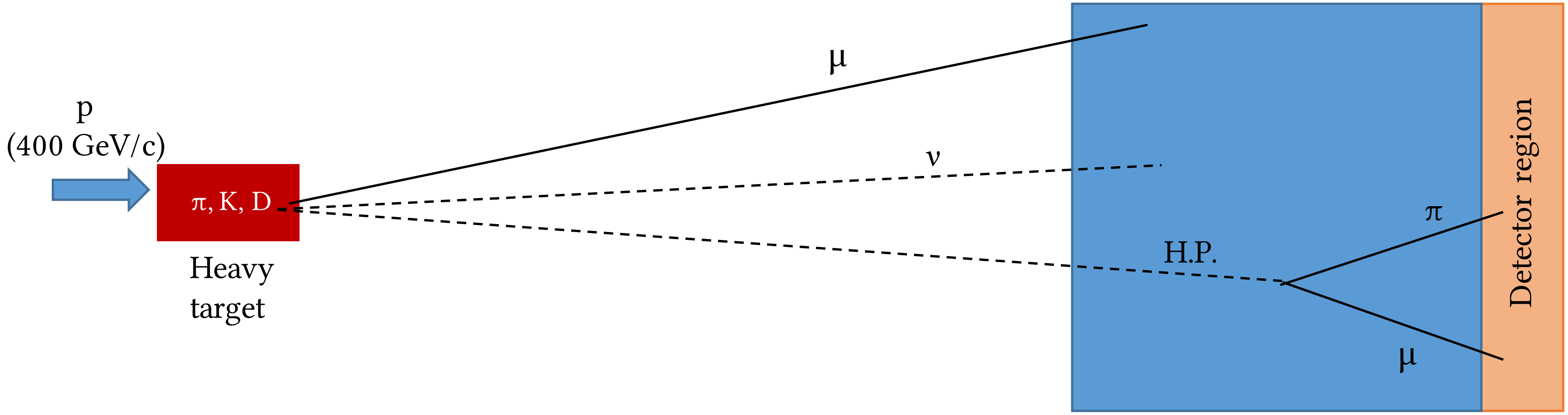


SHiP

➡ Experimental requirements

- Hidden particles with m(GeV) produced in heavy meson decays
  - Long life-time
  - Large transverse momentum
  - decay in SM particles
- Production and decay rates strongly suppressed

⟹ Background suppression (0 bkg experiment)



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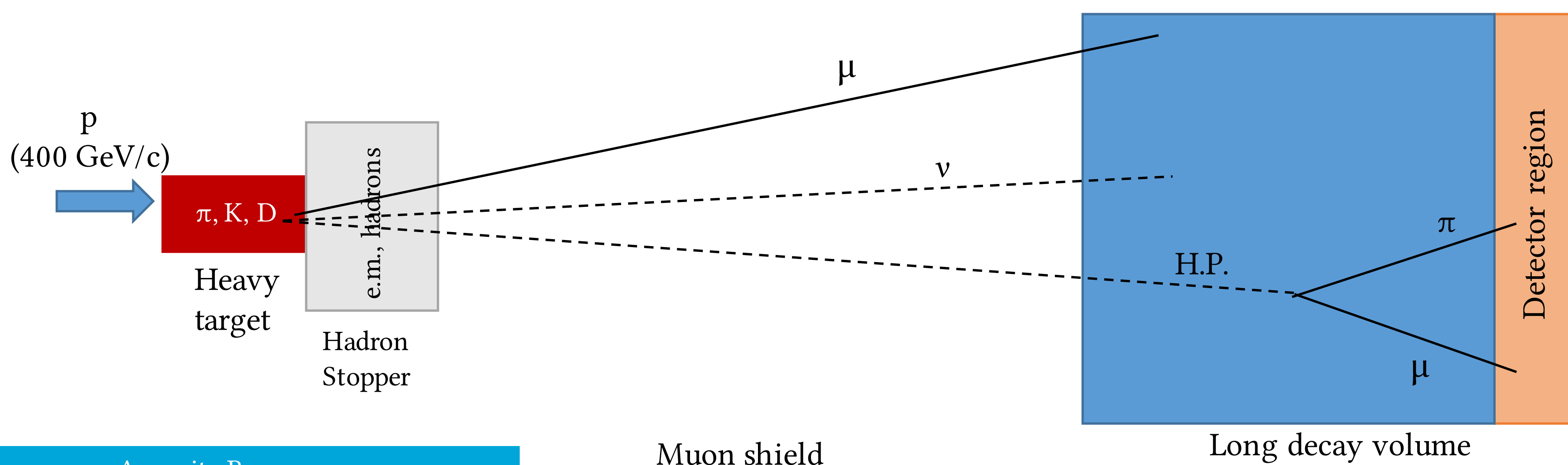
⟹ Background suppression (0 bkg experiment) } Hadron Stopper



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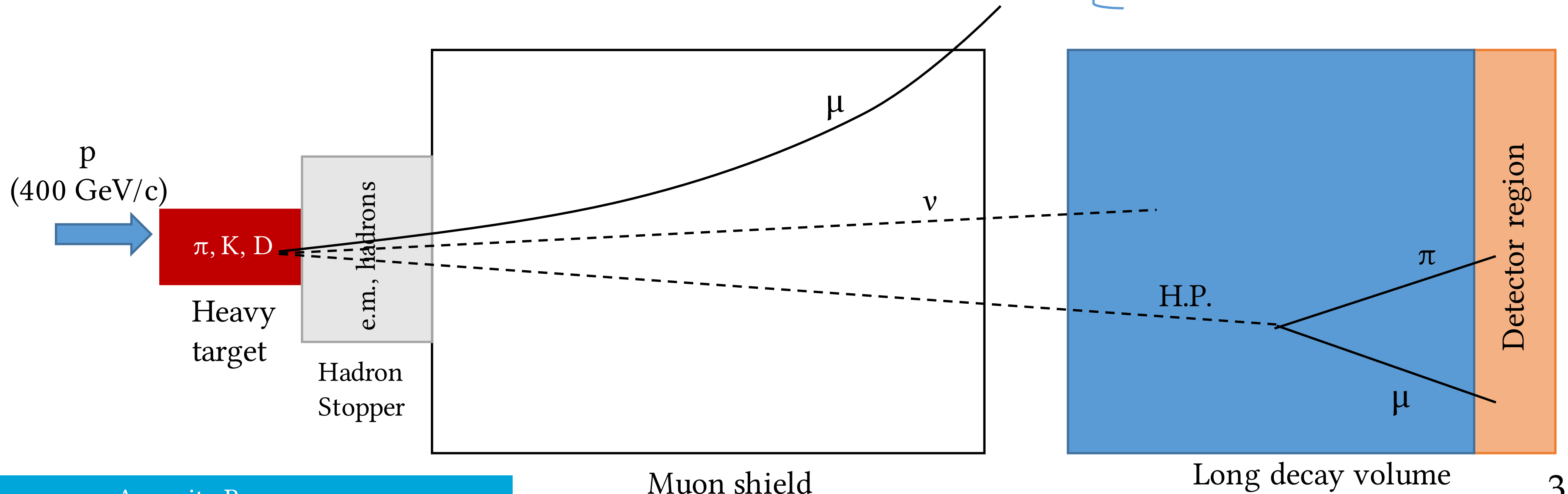
⟹ Background suppression (0 bkg experiment) { Hadron Stopper, Muon shield }



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Experimental requirements

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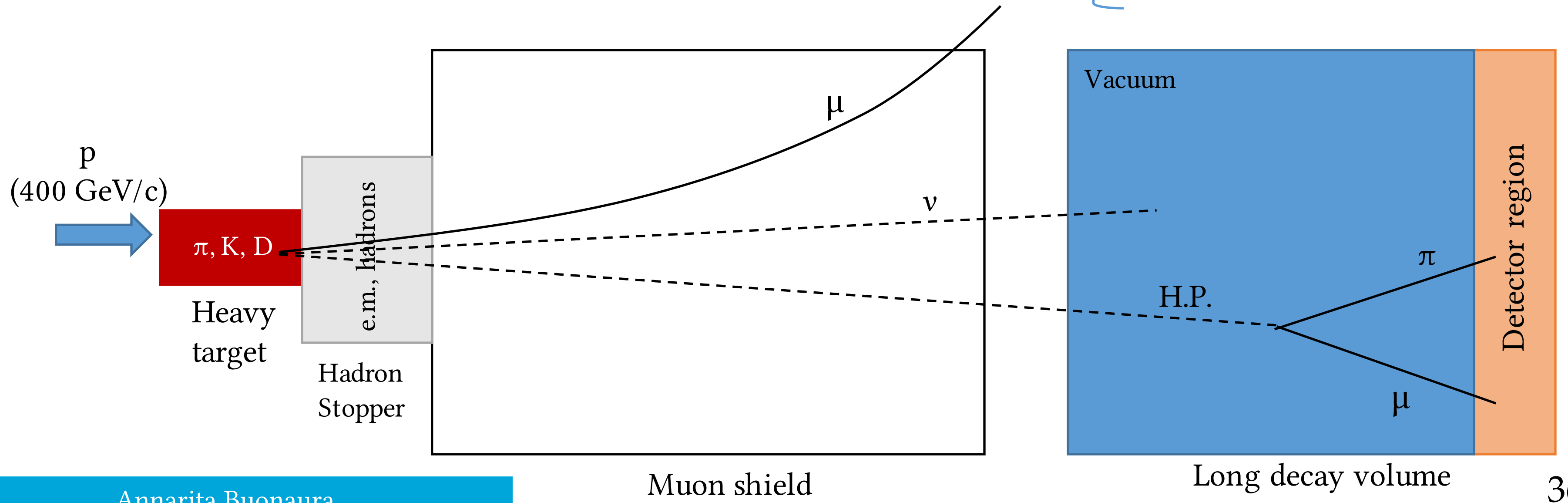
⟹ Background suppression (0 bkg experiment)
- Hadron Stopper
- Muon shield
- Vacuum decay vessel



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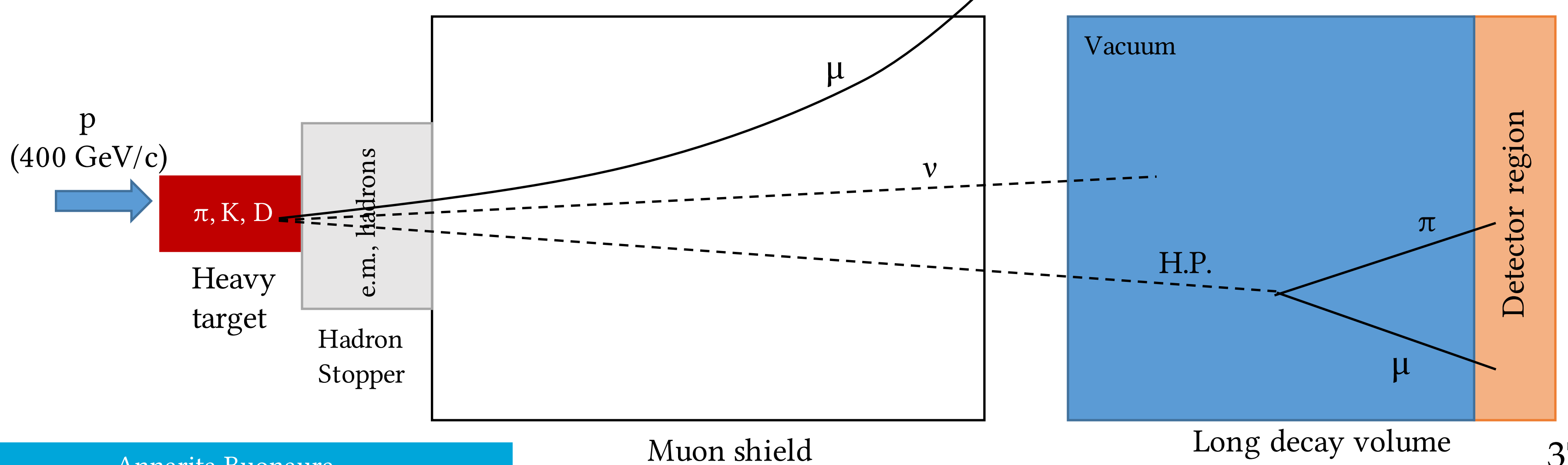
⟹ Background suppression (0 bkg experiment) — Hadron Stopper / Muon shield / Vacuum decay vessel

- Huge neutrino flux



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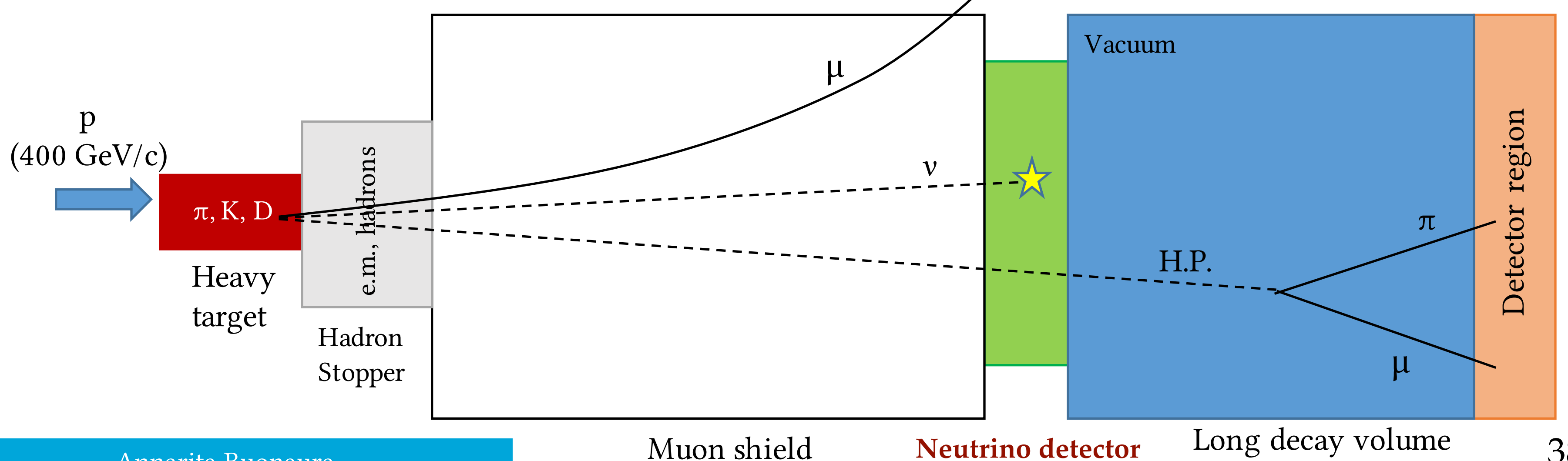
- Production and decay rates strongly suppressed

  ⟹ Background suppression (0 bkg experiment) — Hadron Stopper, Muon shield, Vacuum decay vessel

- Huge neutrino flux ⟹ Neutrino detector



SHiP

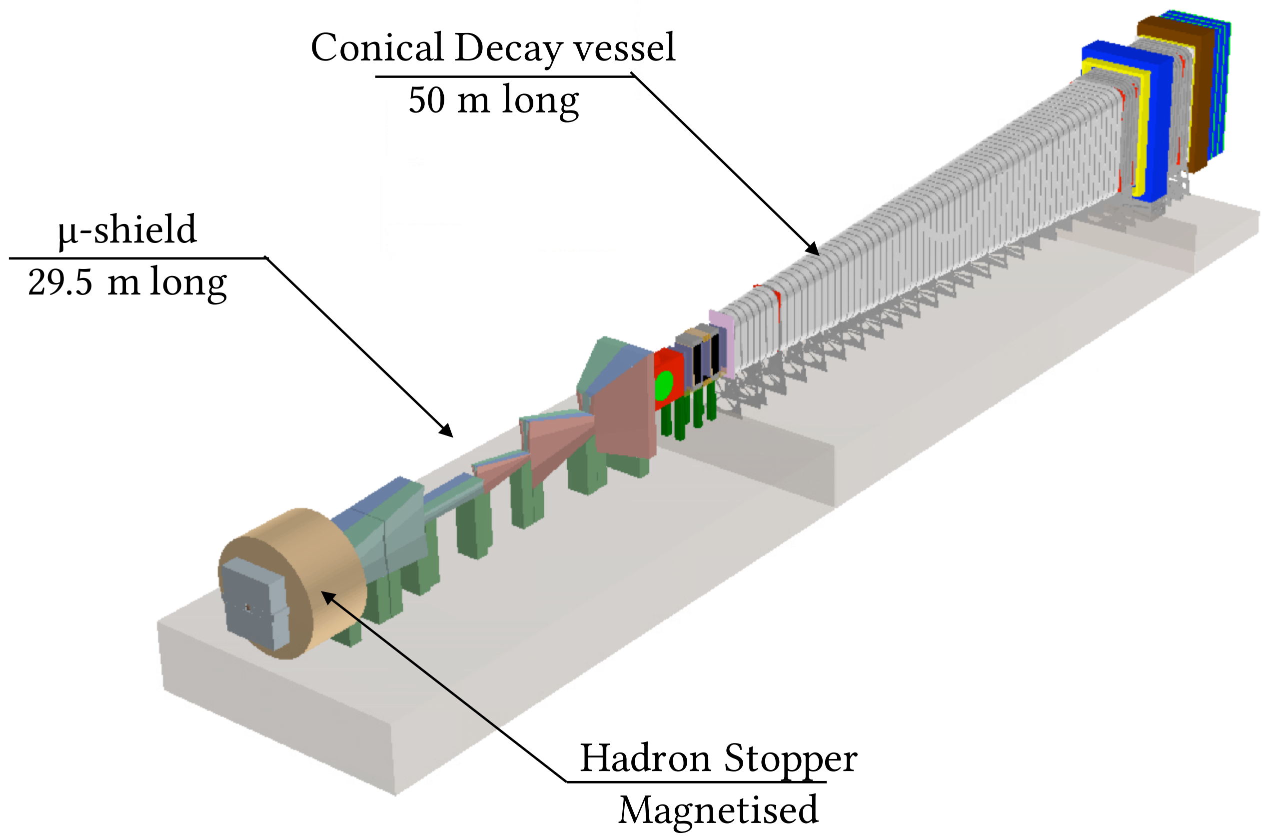
➡ Tau Neutrino physics

- **Motivation**
  - Less known particle in the SM
  - First observation by DONUT (2001)
  - 9 events (1.5 bkg) reported in 2008
  - 10 ν_τ candidates in OPERA with the discovery of ν_τ appearance in the CNGS neutrino beam (> 5 σ)
  - Anti- ν_τ never observed

- **Program**
  - ~30k expected ν_τ and ~20k anti-ν_τ interactions in the target
  - First observation of anti-ν_τ
  - Sufficient statistics to measure ν_τ and anti-ν_τ cross section.
  - First measurement of F_4 and F_5 in DIS ν-nucleon cross section

SHiP

➡ **Current Layout of the experiment**



SHiP

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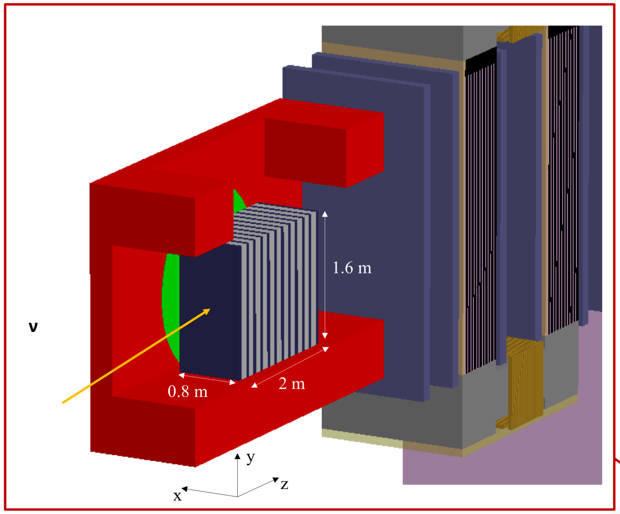
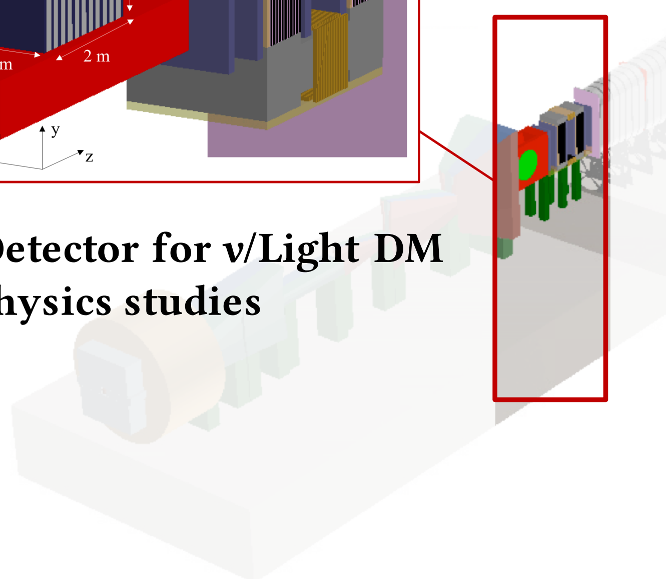


Neutrino Detector for ν/Light DM physics studies



Neutrino/LDM Target

- Dimensions: 0.8 x 2 x 1.6 m^3
- Number of ECC bricks: 924
- Total mass: ~7 tons
- Horizontal magnetic field

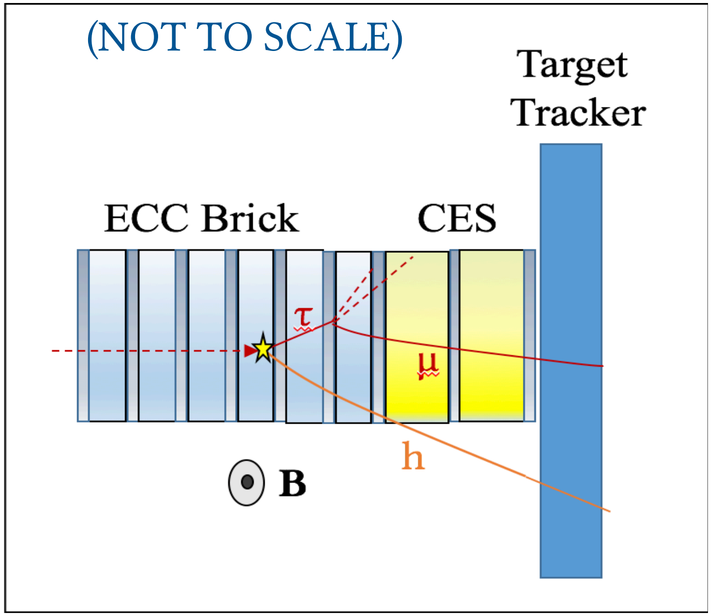
Muon Magnetic spectrometer

- Dipolar magnetic (1.5 T) spectrometer
  - 12 iron layers/arm (5 cm each)
  - 11 RPC layers/arm (2 cm each)
  - 6 Drift Tube Tracker Planes
- Momentum resolution better than 25%
- Charge measurement efficiency ~ 94%

➡ The neutrino target

ECC Brick (OPERA-like)

Lead plates (high density material for the interaction) interleaved with ***emulsion films*** (tracking devices with μm resolution)



Compact Emulsion Spectrometer (CES)

- 3 emulsion films interleaved with 2 light material layers 15-mm thick
- Allows measurement of hadron track curvature in magnetic field
  - Reconstruction of charge + momentum

Target Trackers

- Provide Time stamp
- Link muon track information in ν target to μ magnetic spectrometer

NEWSdm

(Nuclear Emulsion for Wimp Search - directional measurement)

- Dark matter is a kind of matter that doesn't interact with light => Cannot be detected in conventional ways.
- Evidences for the existence of DM come from:
  - Studies on galaxies rotation curves
  - Observation of Bullet Cluster (collision of 2 galaxies)
  - Cosmic Microwave Background
  - …
- But so far no hint of what is dark matter made of!
- One of the possible Dark Matter candidates: **Wimp = W**eakly **I**nteracting **M**assive **P**article

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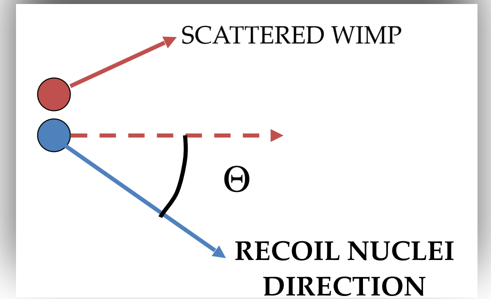
→ **Direct proof needed!**

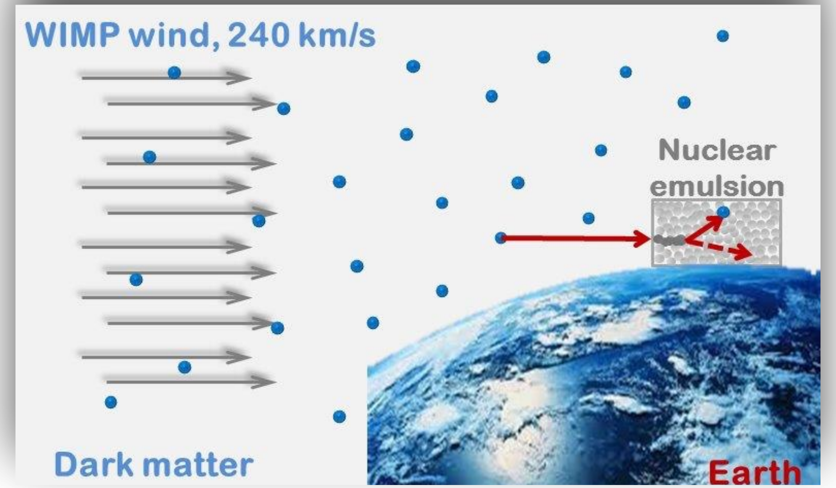
NEWSdm

(Nuclear Emulsion for Wimp Search - directional measurement)

➡ Experimental requirements

- Search for low-energy recoils (typically a few keVs) of nuclei induced by interactions with WIMPs, which are passing through the Earth
  - Large detector mass needed
  - Small recoil track O(100 nm) → very high resolution tracking detector





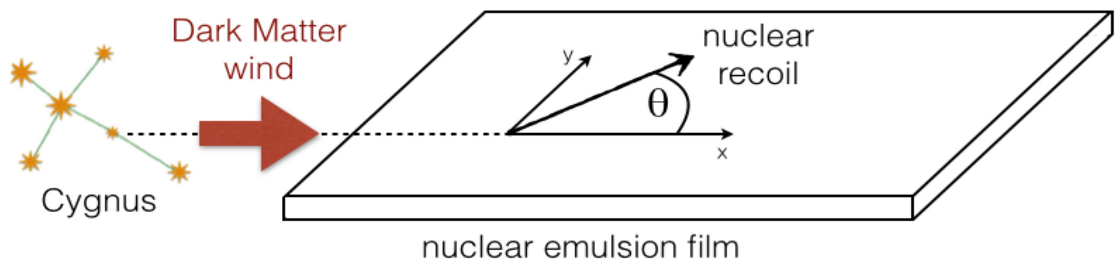
- Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy, i. e. from Cygnus Constellation
- Important to look also at the directionality of the impinging particle!

➡ Nuclear emulsion based detector perfectly suited for this job!

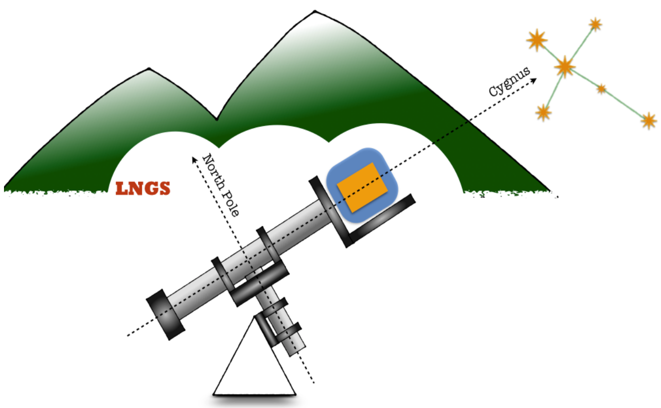
NEWSdm

(Nuclear Emulsion for Wimp Search - directional measurement)

➡ **NEWSdm principle**



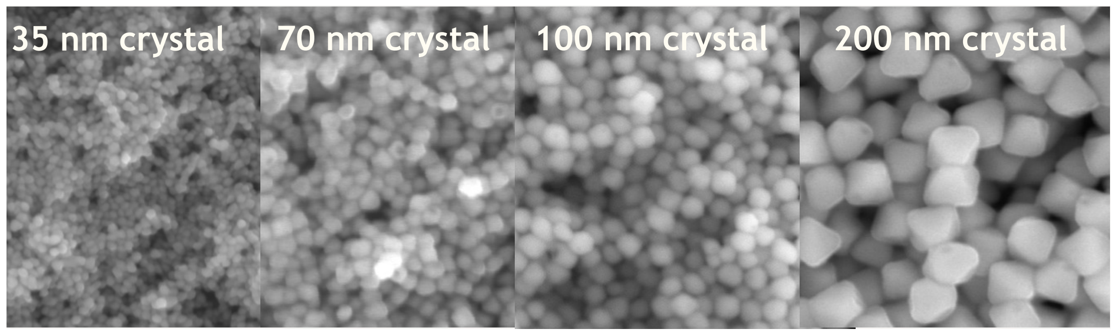
- **Aim**: detect the direction of **nuclear recoils** produced in WIMP interactions
- **Target**: **nanometric nuclear emulsions acting both as target and tracking detector**
- **Background reduction:** neutron **shied** surrounding the target
- **Fixed pointing**: target mounted on **equatorial telescope** constantly pointing to the Cygnus Constellation
- **Location**: Gran Sasso Underground Laboratory



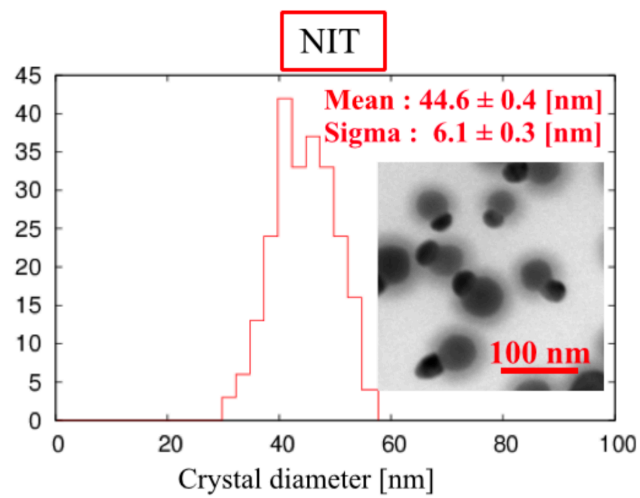
NEWSdm

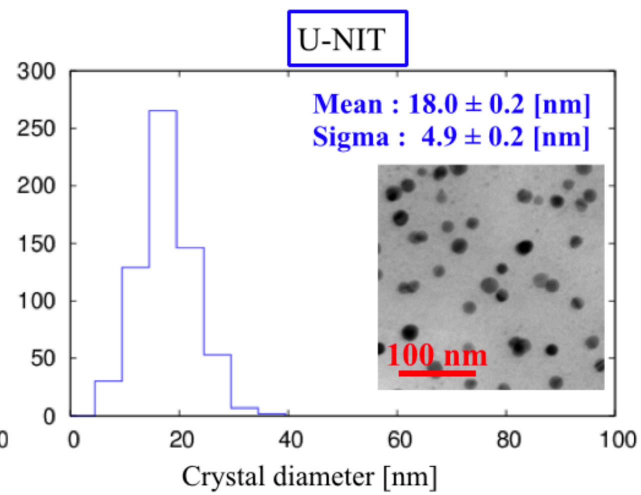
(Nuclear Emulsion for Wimp Search - directional measurement)

➡ A special type of Emulsions: NIT



Technological development ← → **Size**



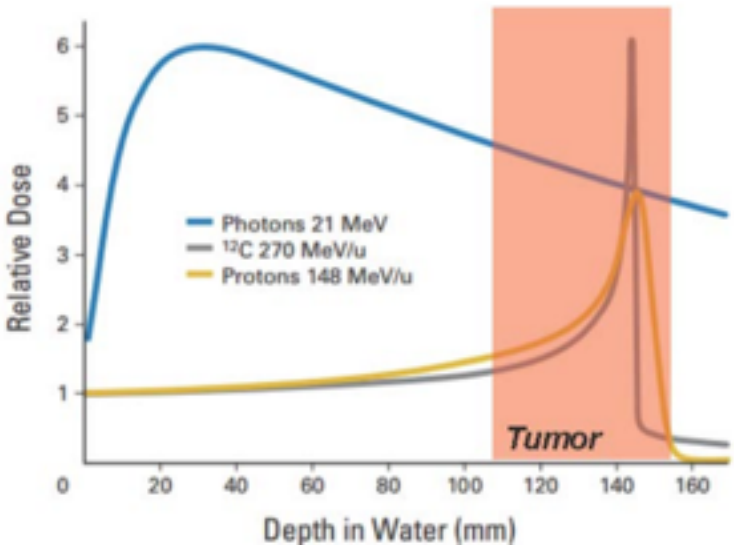


Other applications of emulsion detectors

Medical Physics

➡ FOOT: FragmentatiOn On Target

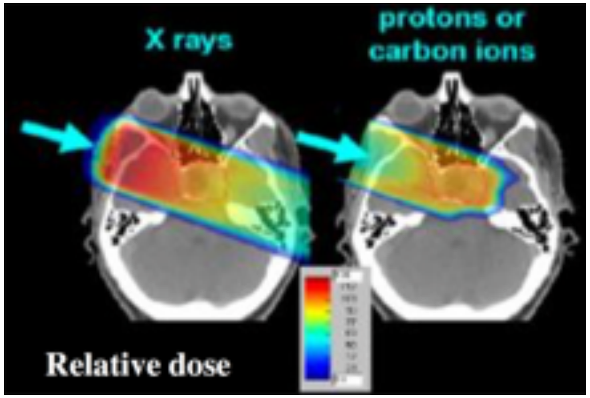
- Experiment for measuring nuclear fragmentation cross sections for Particle Therapy



Schulz-Ertner et al. *J. Clin. Oncol.* (2007)

- **Charged Particle Therapy vs “Conventional” radiotherapy (photons)**
  - Peak of dose released at the **end of the track**, allowing sparing the normal tissue
  - Beam penetration function of beam energy

Hadrons hit the tutor with minimal unwanted damage!

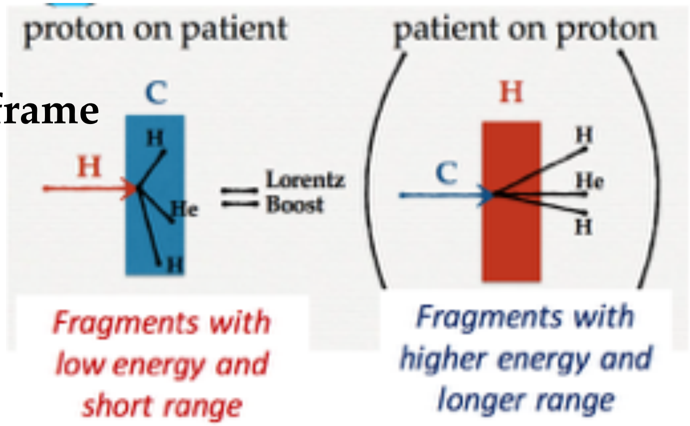


Medical Physics

➡ **FOOT: FragmentatiOn On Target**

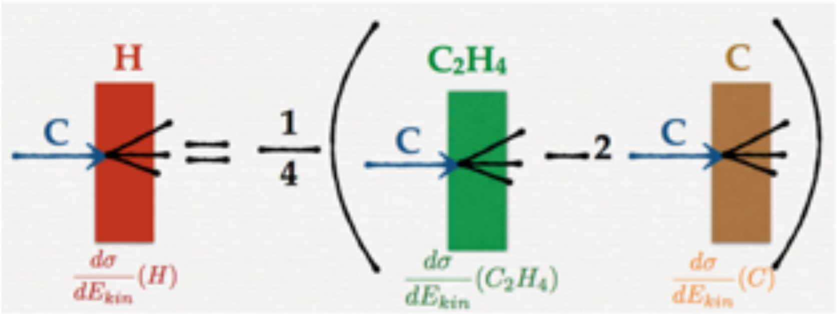
- Important to know the fragments cross section produced by proton on carbon or oxygen, the most common nuclei in tissue
- Inverse kinematic approach used:

Lab frame



Protons @ Ekin= 200 MeV (β~0.6) on a "patient" (98% C, O, and H nuclei) replaced by ^{16}O, ^{12}C ion beams impinging on a target made of protons

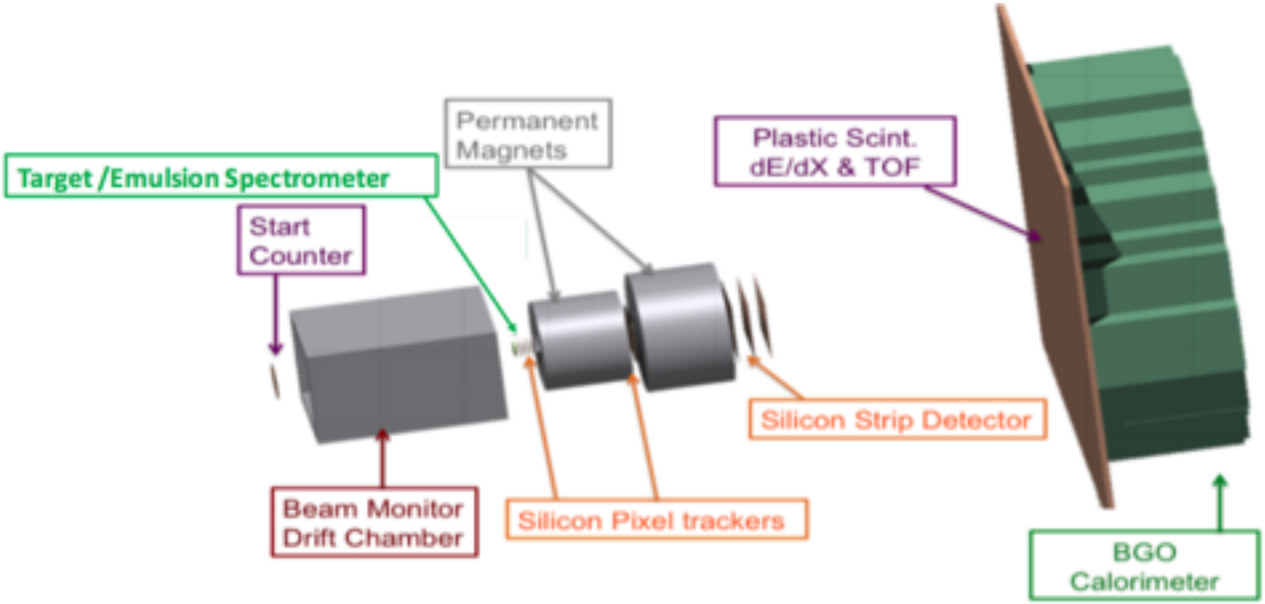
- C→H cross-section can be estimated by C→C_2H_4 and C→C cross-section:



- Major challenge is to identify particles produced in the interaction

Medical Physics

➡ **FOOT: FragmentatiOn On Target**



Medical Physics

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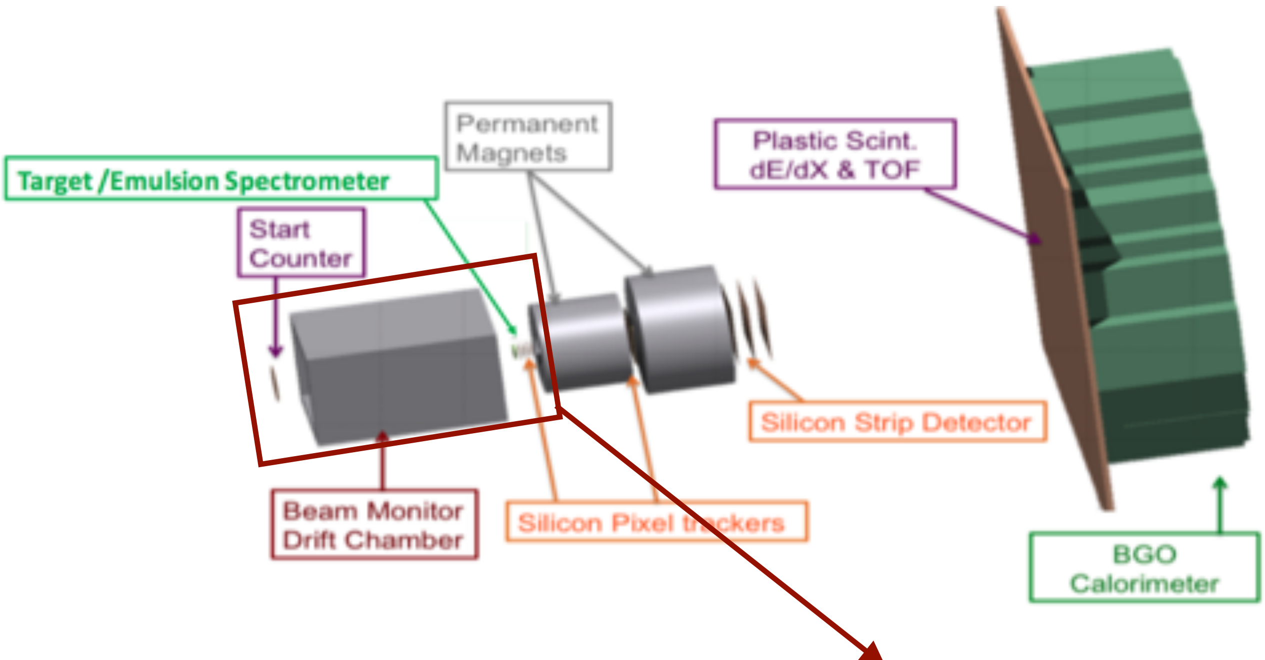
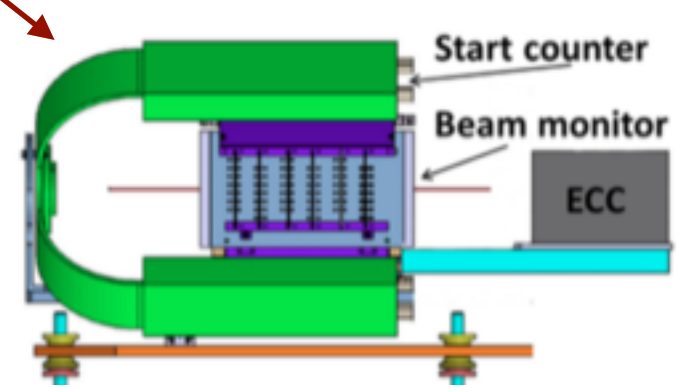


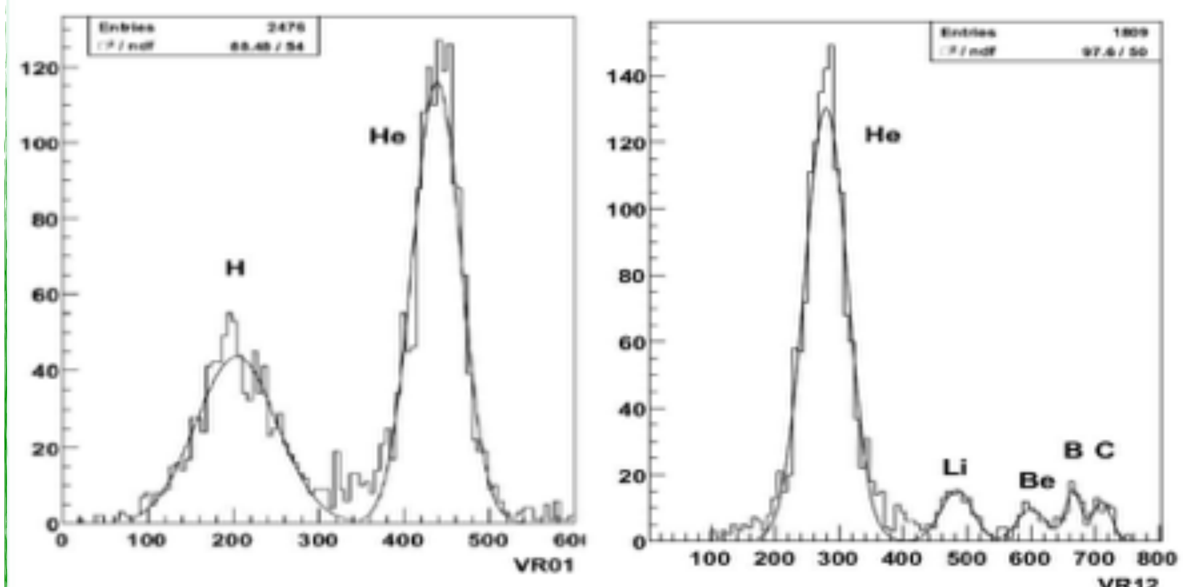


- Emulsion spectrometer used to measure the production of light charged fragments (protons, deuterons, ^{4}He and Li) up to ~70°

Medical Physics

➡ **FOOT: FragmentatiOn On Target**

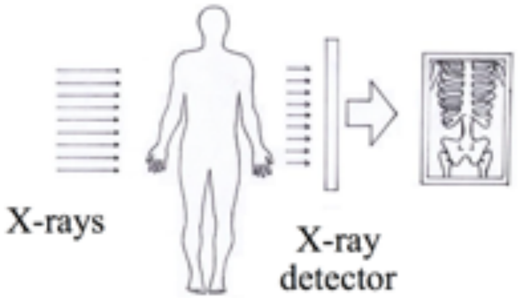
- Emulsion technique already exploited in the early 2000's to study the fragmentation of C ions in polycarbonate: identification of the secondary nuclei produced by fragmentation of 400 MeV/n ^{12}C can be achieved with high significance



G. De Lellis et al. JINST 2, 2007, P06004

Muon radiography

- **Main idea:** study muon absorption in matter depending on its density to see the "invisible"
- Different applications:



1. **Radiography of volcanoes**

- Reconstruct muon trajectories by a "muon telescope"
- Measure the muon flux absorption as a function of the muon direction
- Draw a map (in projective geometry) of the average rock density

Can help computer models in predicting "how" an eruption could develop

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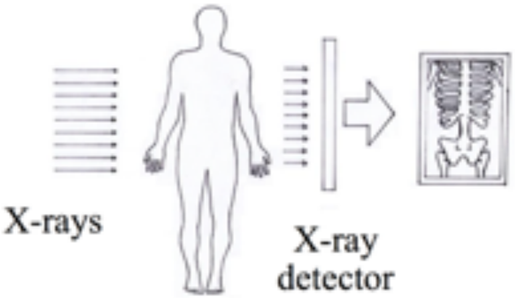


1. **Radiography of volcanoes**

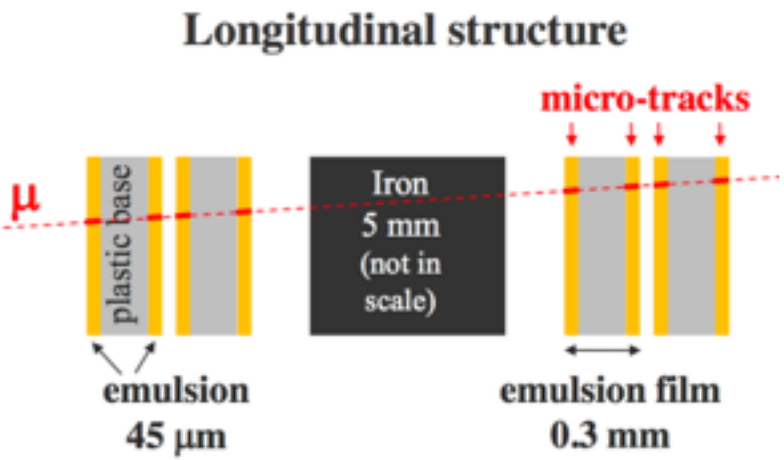
   - Emulsion target placed on Stromboli (Italy) and Unzen () volcanoes

4 emulsion films

1 iron plate

Very compact

Precise and redundant tracking (1 micro-track / em. film)



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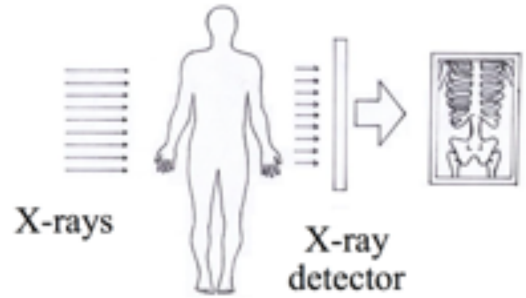

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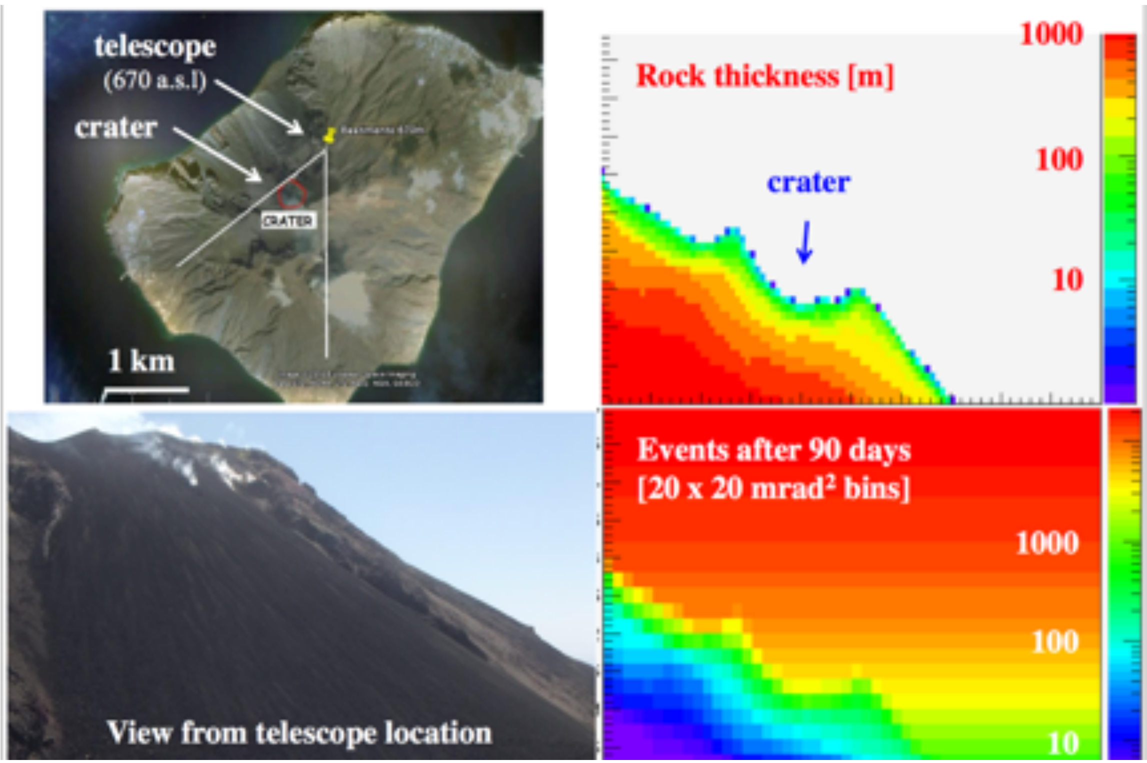

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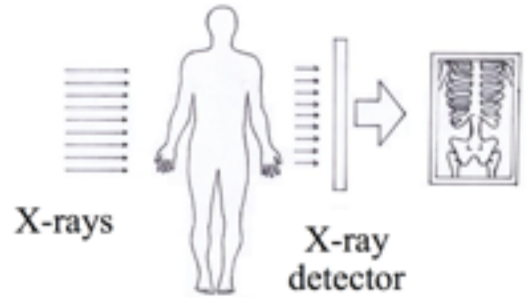
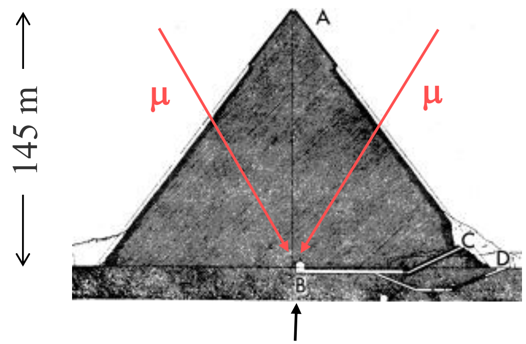


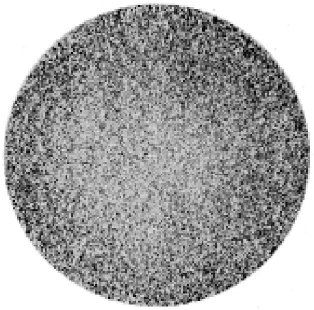
2. **Search for Hidden Chambers in Pyramids**

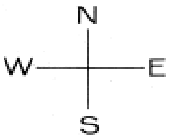
In late '60s L.W. Alvarez et al. searched for hidden chambers in Chephren's pyramid



Telescope in Belzoni chamber

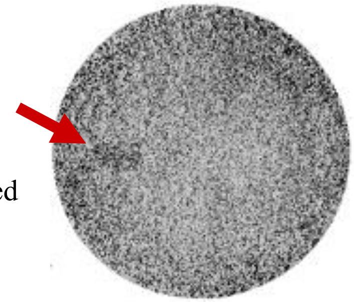
Data





Data and simulation are corrected for pyramid structure and telescope acceptance

Simulation with Hidden Chamber



No hidden chamber found!

L.W. Alvarez et al. Science 167 (1970) 832

Muon radiography

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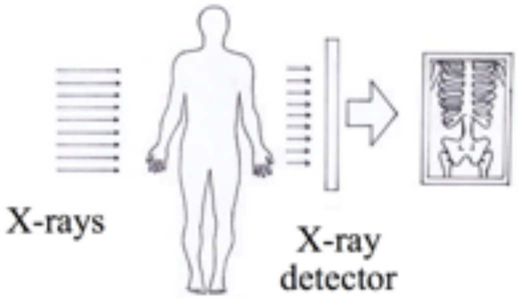
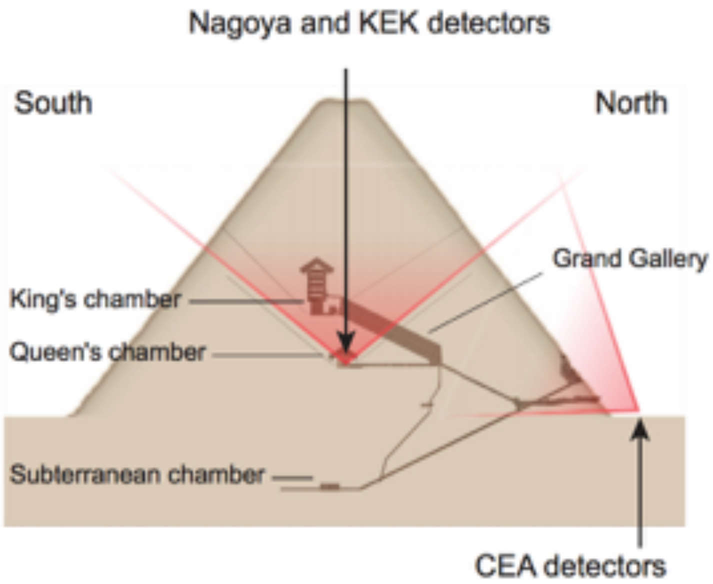
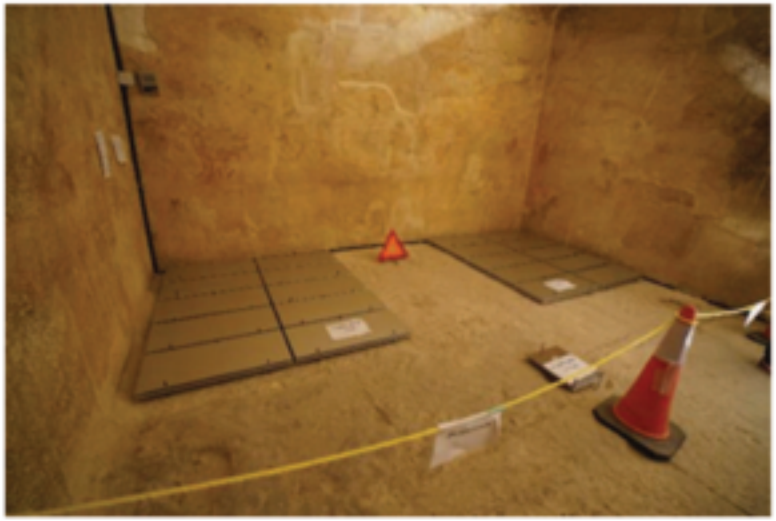


2. <u>Search for Hidden Chambers in Pyramids</u>

- New studies on Khufu's Pyramid performed from Nagoya-University (Japan)

Nature 552 (2017) no.7685, 386-390





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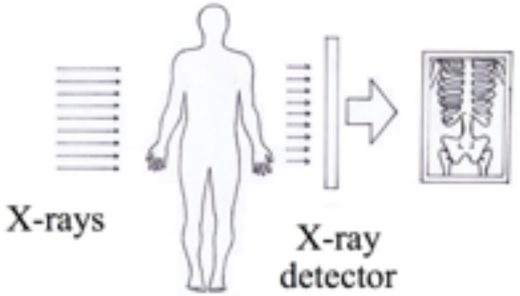

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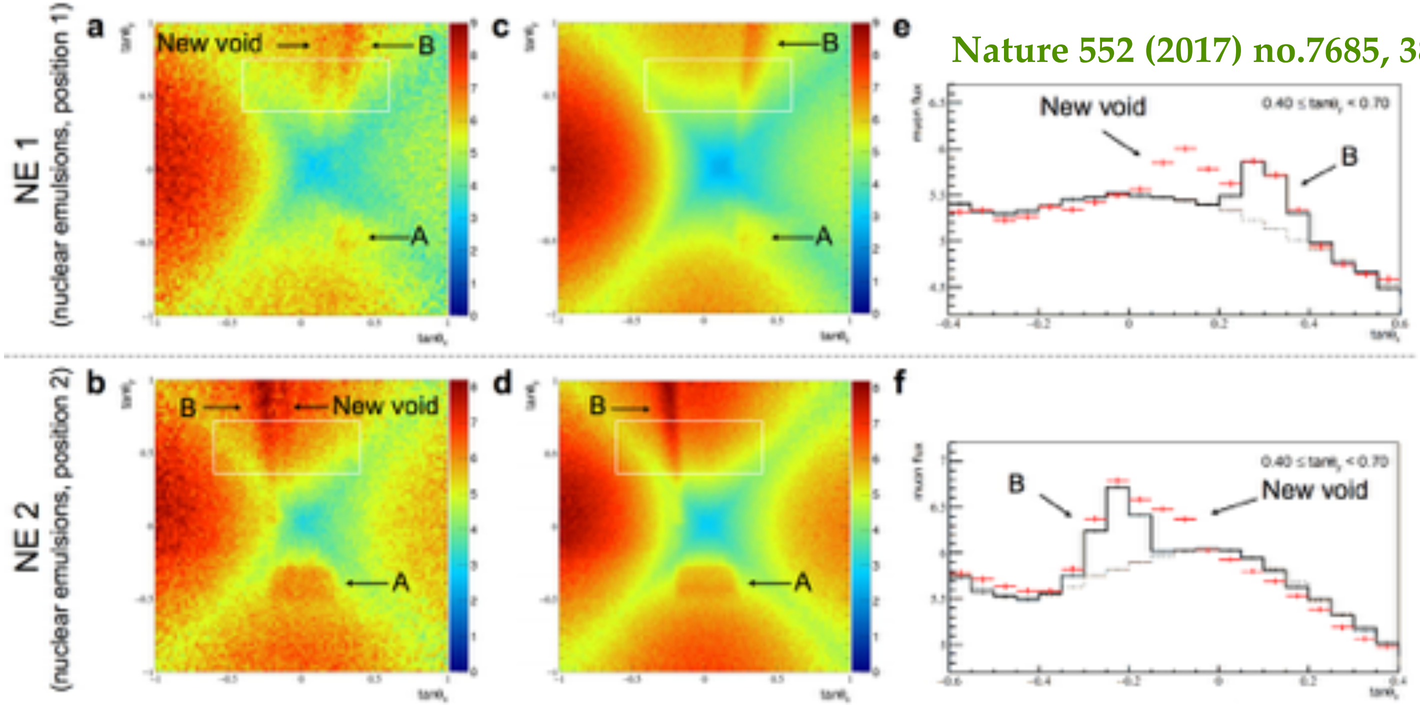


Thank you for
your attention!