Particle and Applied physics with nuclear emulsion in Europe

Giovanni De Lellis
University "Federico II" and INFN, Naples, Italy

A new era of the emulsion technology: from dark matter to particle therapy from archaeology to collider neutrinos

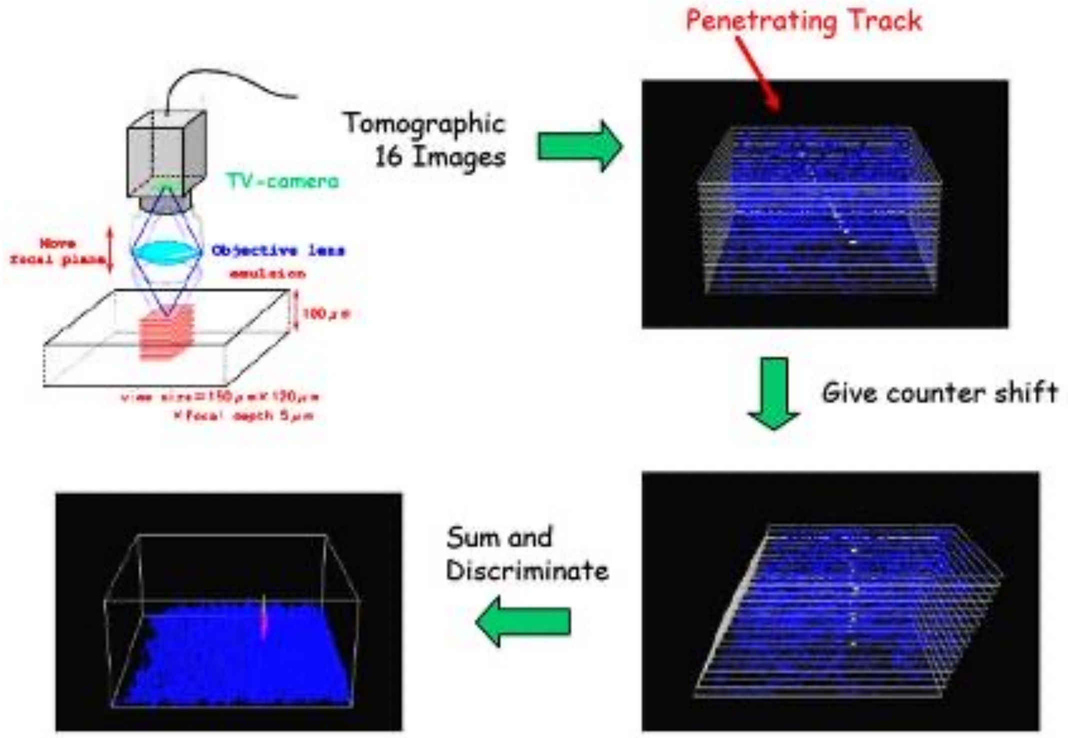
ICMaSS2023 Conference, Nagoya, December 2nd 2023

Birth of modern emulsion readout technology

- ***In 1974 Kimio Niwa: Track recognition by superimposing tomographic images from different focal planes***
- The first idea of automatic scanning
- Digital technology not yet ready since the first Digital Camera prototype from Kodak -1975
- Simple to implement, parallelizable
- Computing grows quickly with the track slope => limited angle

2004 Nishina Memorial Prize
2020 Bruno Pontecorvo Prize
2022 APS Panofsky Prize

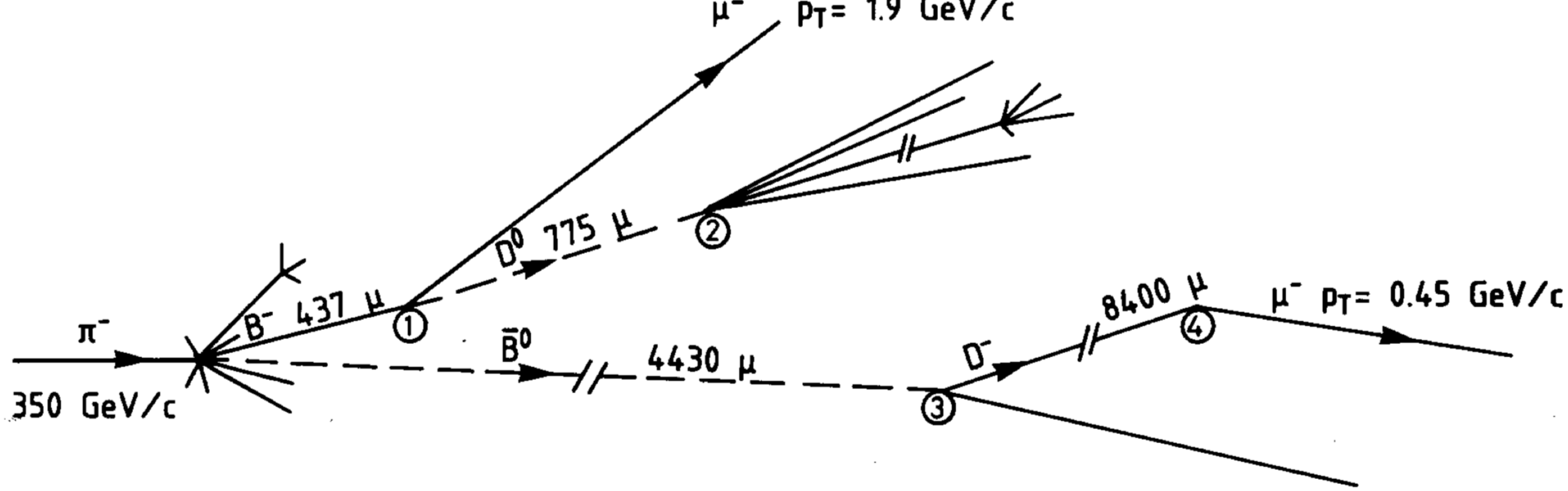
Prof. Kimio Niwa



First observation of “beauty” hadron decay

Volume 158B, number 2 PHYSICS LETTERS 8 August 1985

Important observation still based on “eye”/semi-automated scanning



$$L = \beta\gamma c\tau \sim \gamma c\tau$$

$$\gamma \sim \frac{1}{<\vartheta>}$$

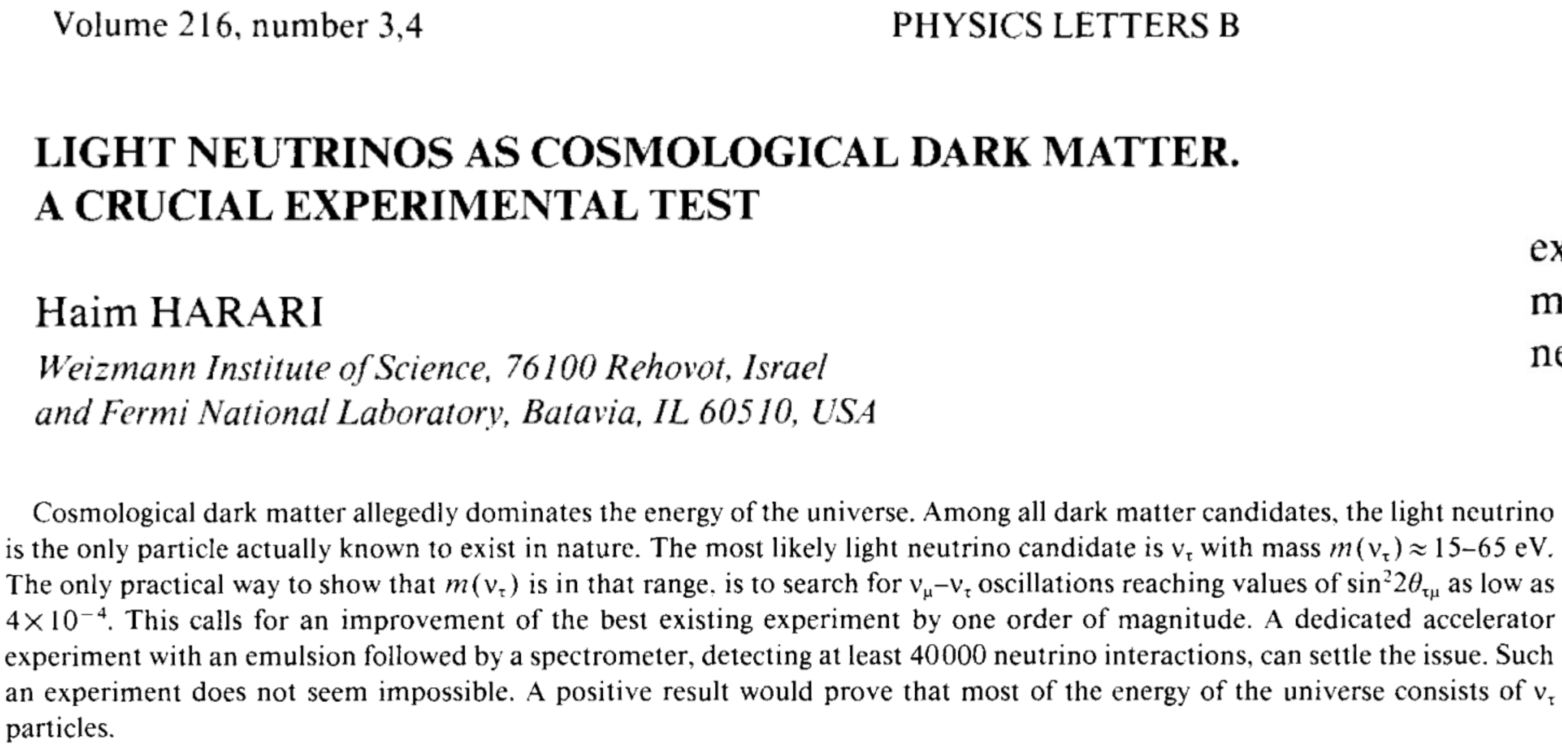
Petrera, Romano, NIM 174 (1980) 61

$$c\tau \sim L <\vartheta>$$

Two particles with “beauty” quark content are produced and decay (10^{-12} s) producing “charmed” particles that in turn decay

Direct Observation of the decay of Beauty particles into charm particles, PLB 158 (1985) 186
WA75 experiment at CERN

The dark matter problem: a proposed solution in 1989

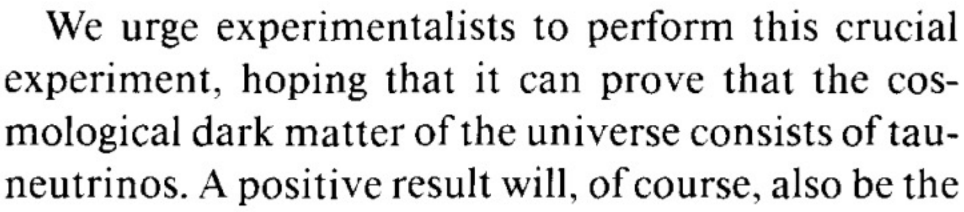


Volume 216, number 3,4 PHYSICS LETTERS B 12 January 1989

LIGHT NEUTRINOS AS COSMOLOGICAL DARK MATTER.
A CRUCIAL EXPERIMENTAL TEST

Haim HARARI
Weizmann Institute of Science, 76100 Rehovot, Israel
and Fermi National Laboratory, Batavia, IL 60510, USA

Cosmological dark matter allegedly dominates the energy of the universe. Among all dark matter candidates, the light neutrino is the only particle actually known to exist in nature. The most likely light neutrino candidate is ν_τ with mass $m(\nu_\tau) \approx 15$–65 eV. The only practical way to show that $m(\nu_\tau)$ is in that range, is to search for ν_μ–ν_τ oscillations reaching values of $\sin^2 2\theta_{\tau\mu}$ as low as 4×10^{-4}. This calls for an improvement of the best existing experiment by one order of magnitude. A dedicated accelerator experiment with an emulsion followed by a spectrometer, detecting at least 40000 neutrino interactions, can settle the issue. Such an experiment does not seem impossible. A positive result would prove that most of the energy of the universe consists of ν_τ particles.

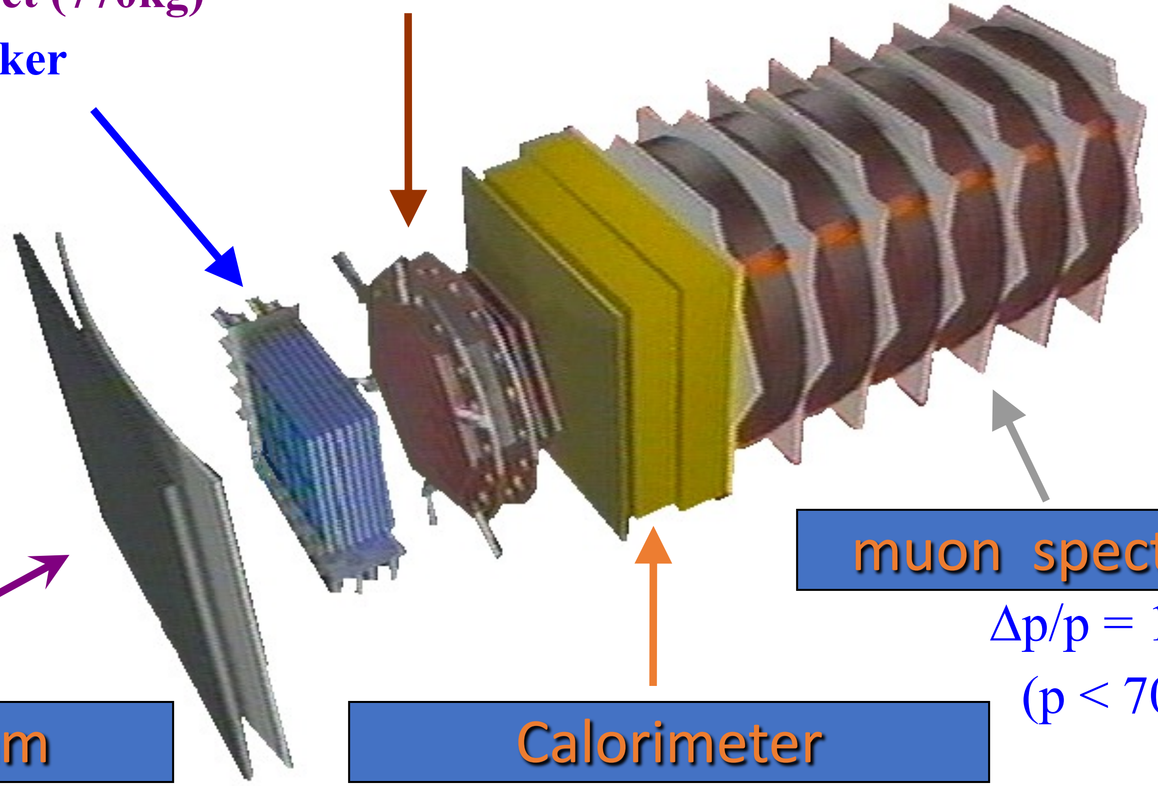


We urge experimentalists to perform this crucial experiment, hoping that it can prove that the cosmological dark matter of the universe consists of tau-neutrinos. A positive result will, of course, also be the

Assuming a “large” neutrino mass ($\Delta m^2 \sim 100$ eV^2)

ν_τ appearance in a ν_μ beam ($\nu_\mu \rightarrow \nu_\tau$ oscillation) with a short baseline (600 m) experiment

CHORUS (CERN Hybrid Oscillation Research Apparatus) detector



Active target

-nuclear emulsion target (770kg)

-scintillating fiber tracker

Air-core magnet

$\Delta p/p = 0.035\, p\, (\mathrm{GeV}/c) \oplus 0.22$

muon spectrometer

$\Delta p/p = 10 \div 15\%$

$(p < 70\ \mathrm{GeV}/c)$

Calorimeter

$\Delta E/E = 32\ \%/\sqrt{E}$ **(hadrons)**

$= 14\ \%/\sqrt{E}$ **(electrons)**

$\Delta\theta_h = 60$ **mrad @ 10 GeV**

ν

$E\nu \sim 27$ GeV

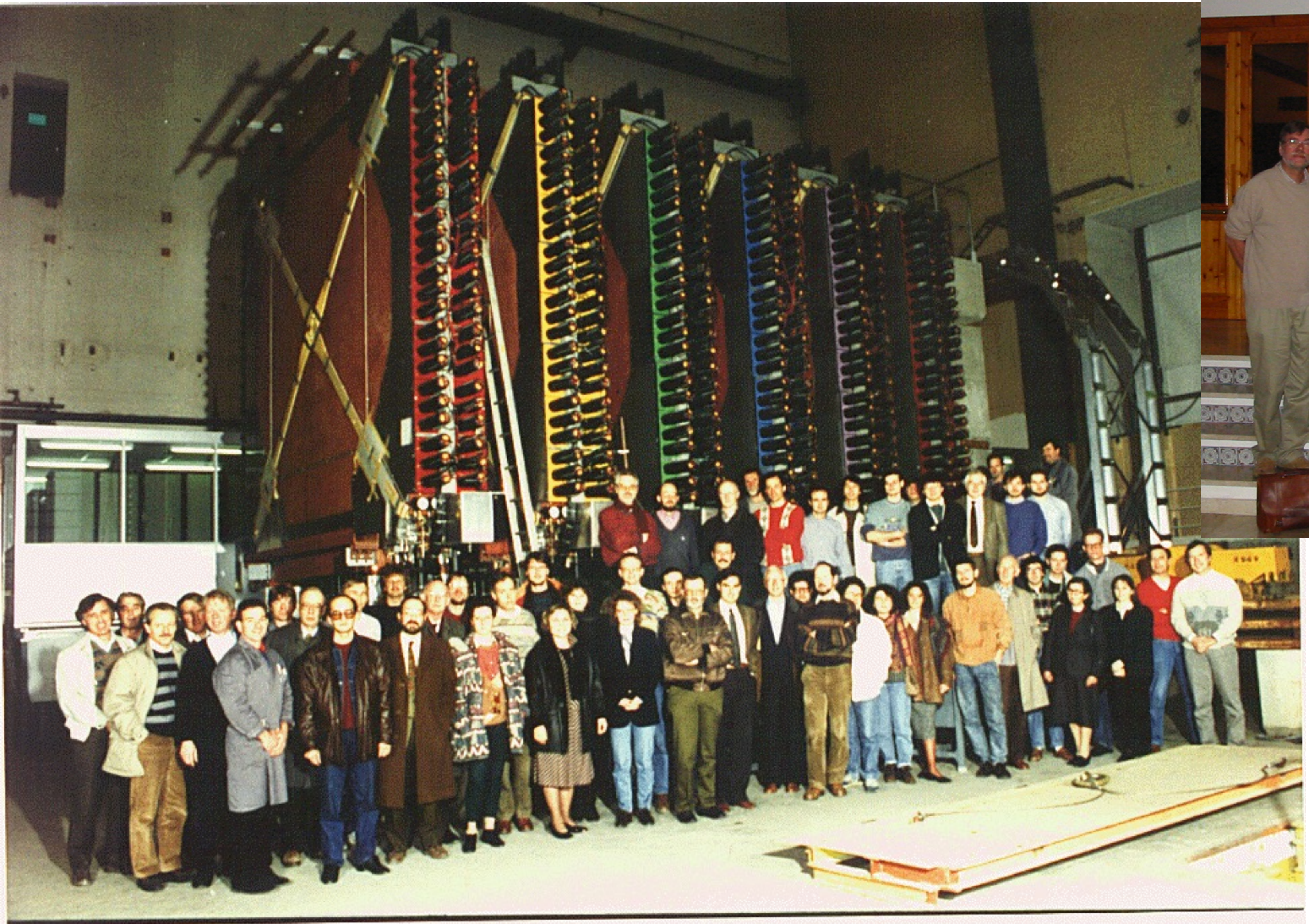
Neutrino beam

$\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e$

1.00 : 0.05 : 0.017 : 0.007

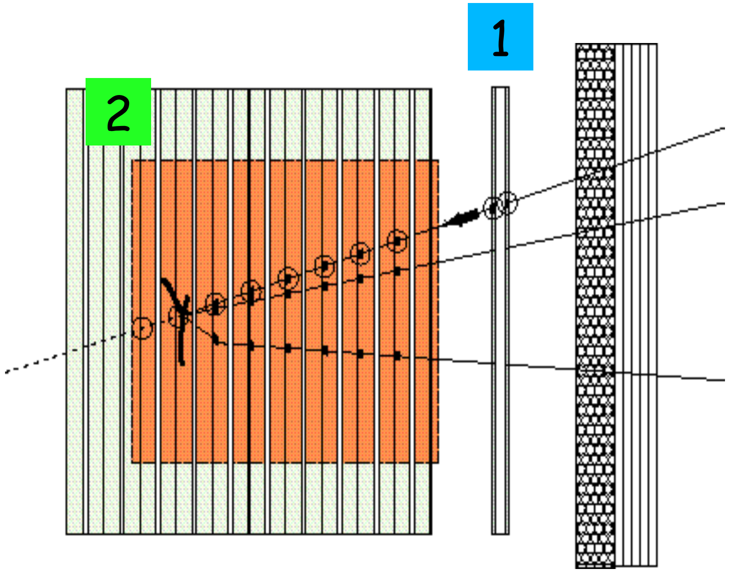
The CHORUS Collaboration at CERN

1994 at CERN



2002 at Chia Laguna, Sardinia

Automatic emulsion data acquisition (phase-II)



1 **Location of ν interaction vertex guided by electronic detectors**

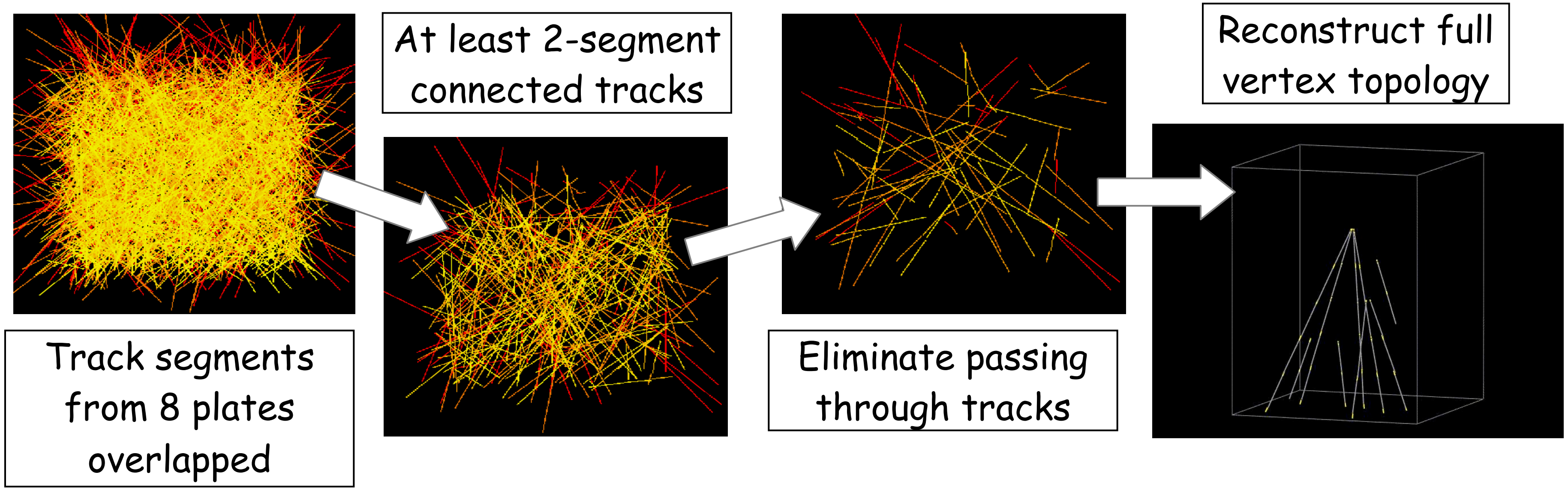
2 **Full data taking around ν interaction vertex**

Volume: 1.5 x 1.5 x 6.3 mm^3

Angular acceptance : 400 mrad

~ 11 minutes / event

3 **Offline tracking and vertex reconstruction**



Track segments from 8 plates overlapped

At least 2-segment connected tracks

Eliminate passing through tracks

Reconstruct full vertex topology

Our (ΛCDM) universe today

Heavy elements 0.03%

Stars 0.5%

?

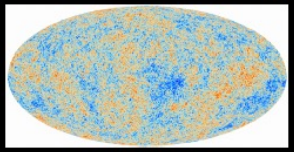
$0.1\% \lesssim$ Neutrinos $\lesssim 0.3\%$

Dark energy 70%

Hidrogen & Helium 4%

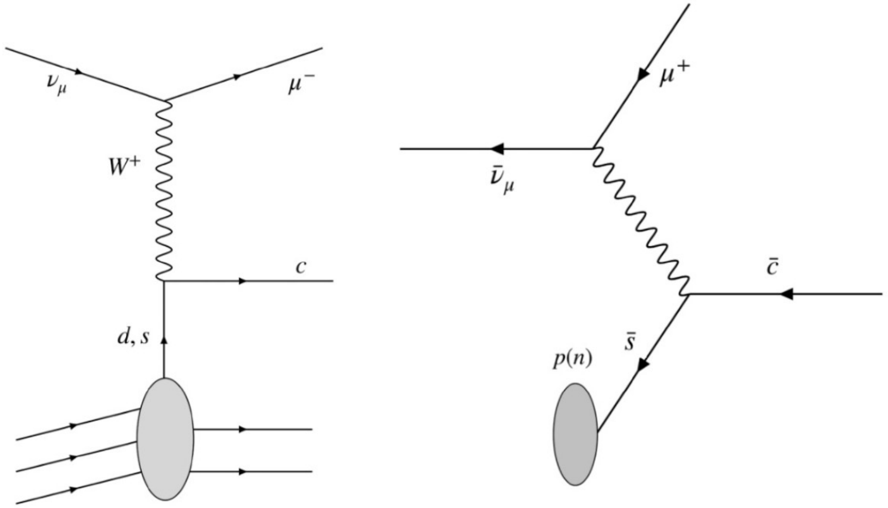
Dark matter 25%

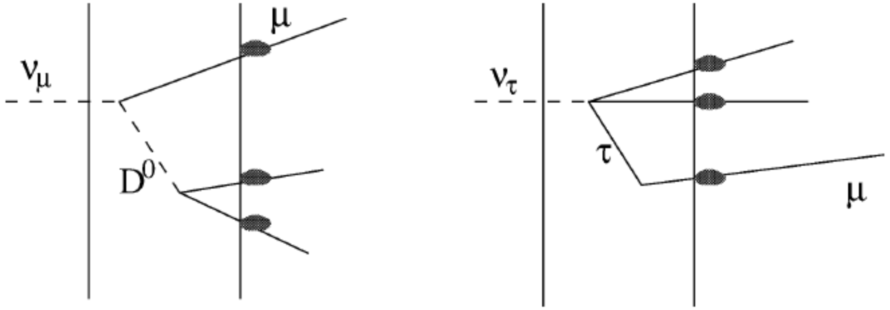
Cosmic Microwave Background 0.001%

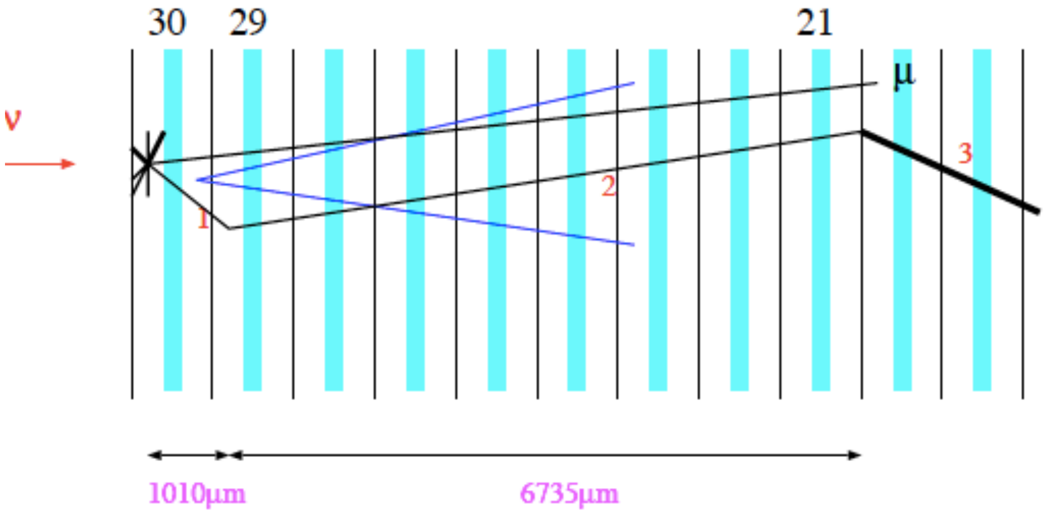


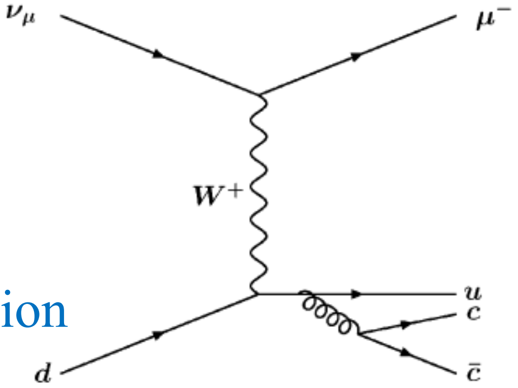
CHORUS studia fisica del charm

- At the Neutrino 1998 Conference in Takayama, Kajita-san reports Super-Kamiokande results → CHORUS is investigating the “wrong” parameter space ($\Delta m^2 > 100$ eV^2)
- CHORUS studies neutrino-induced charm production









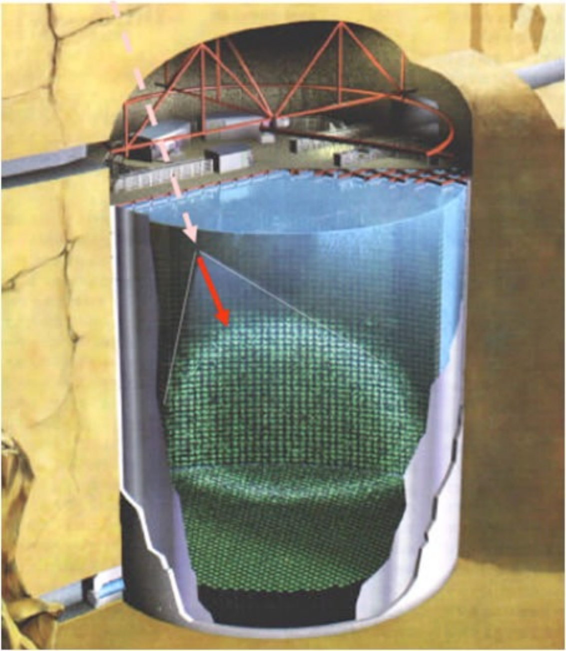
Associated charm production in neutrino scattering

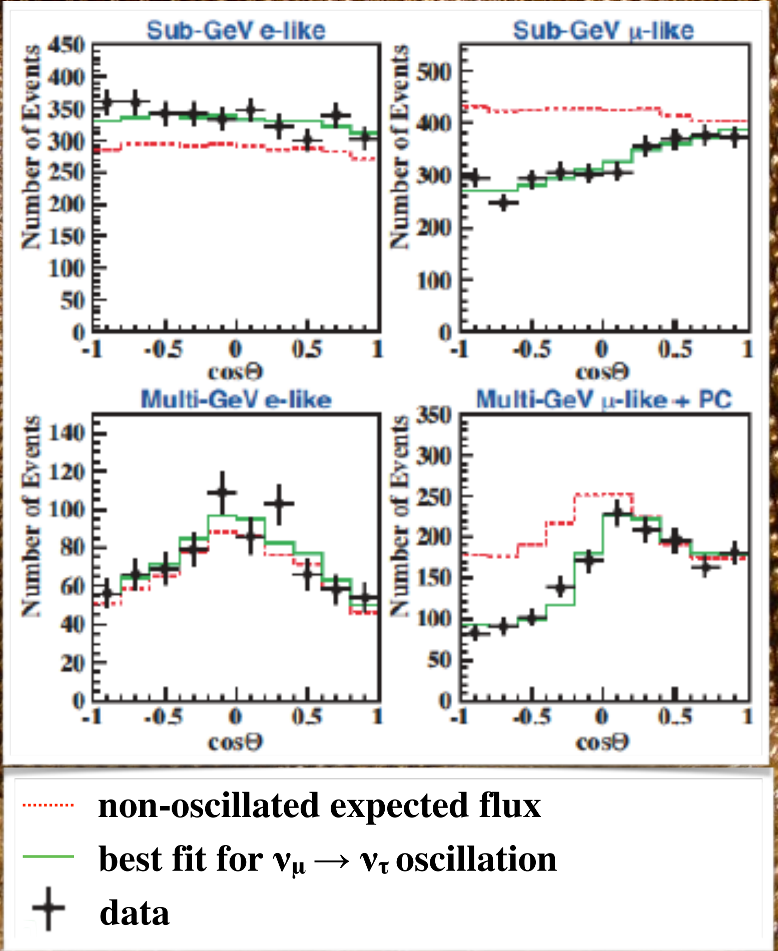
Super-Kamiokande in Japan

1000 m underground

50 kton pure water

13000 detectors



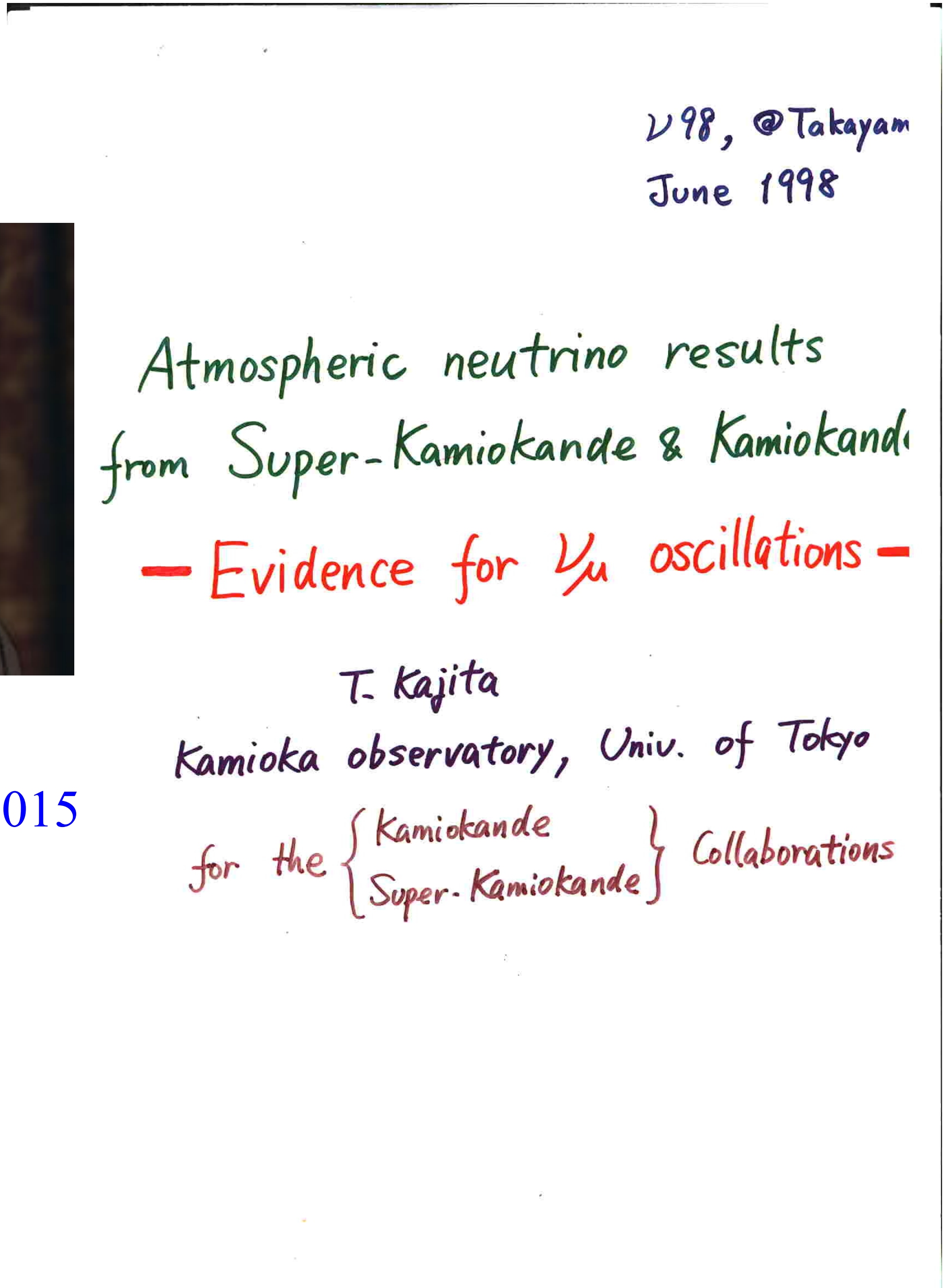


Yoji Totsuka (1942-2008) , Spokesperson

Data taking starts in 1996

Neutrino98, Takayama, Japan

Takaaki Kajita
Nobel Laureate 2015



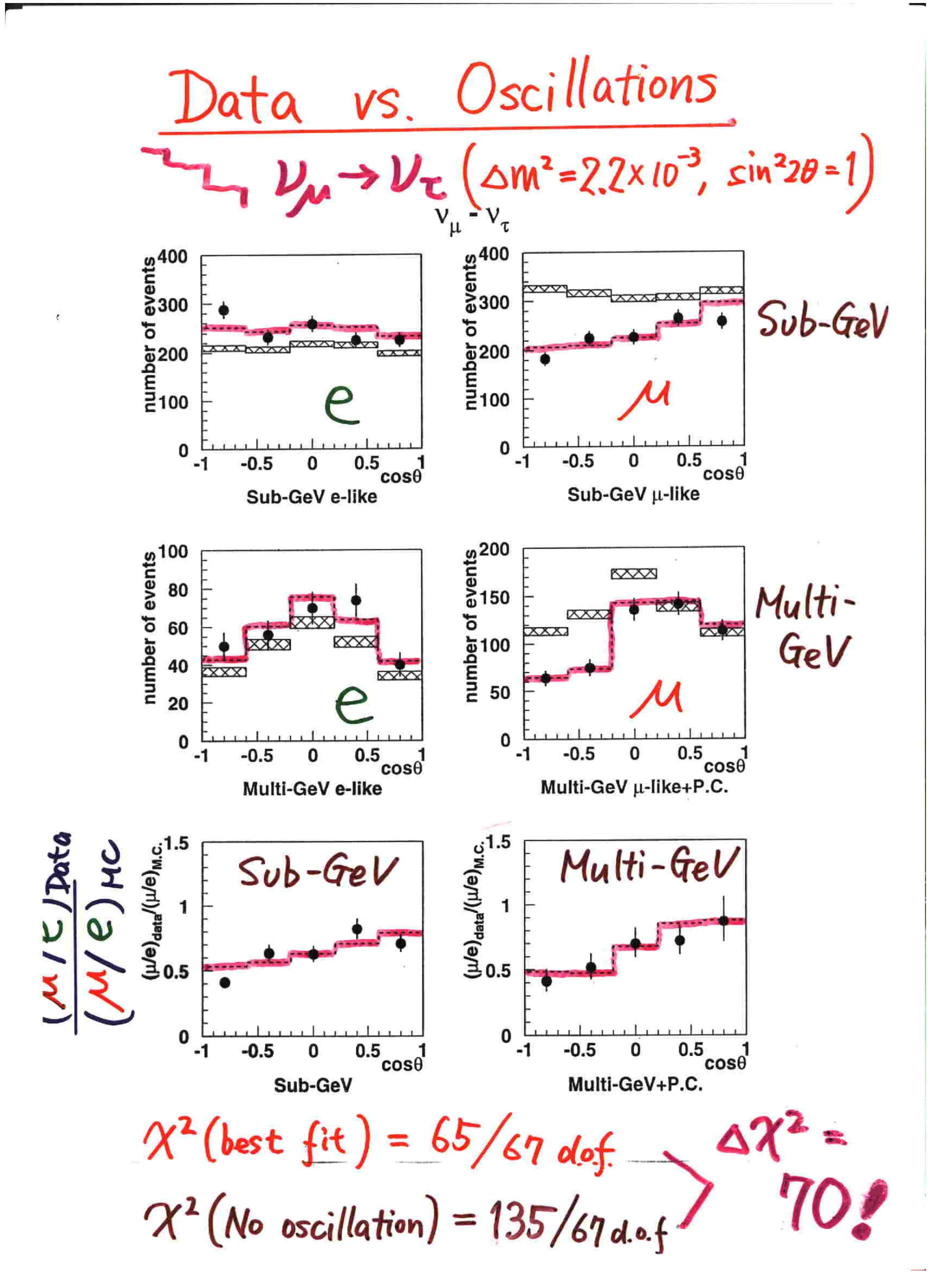
ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo

for the {Kamiokande / Super-Kamiokande} Collaborations



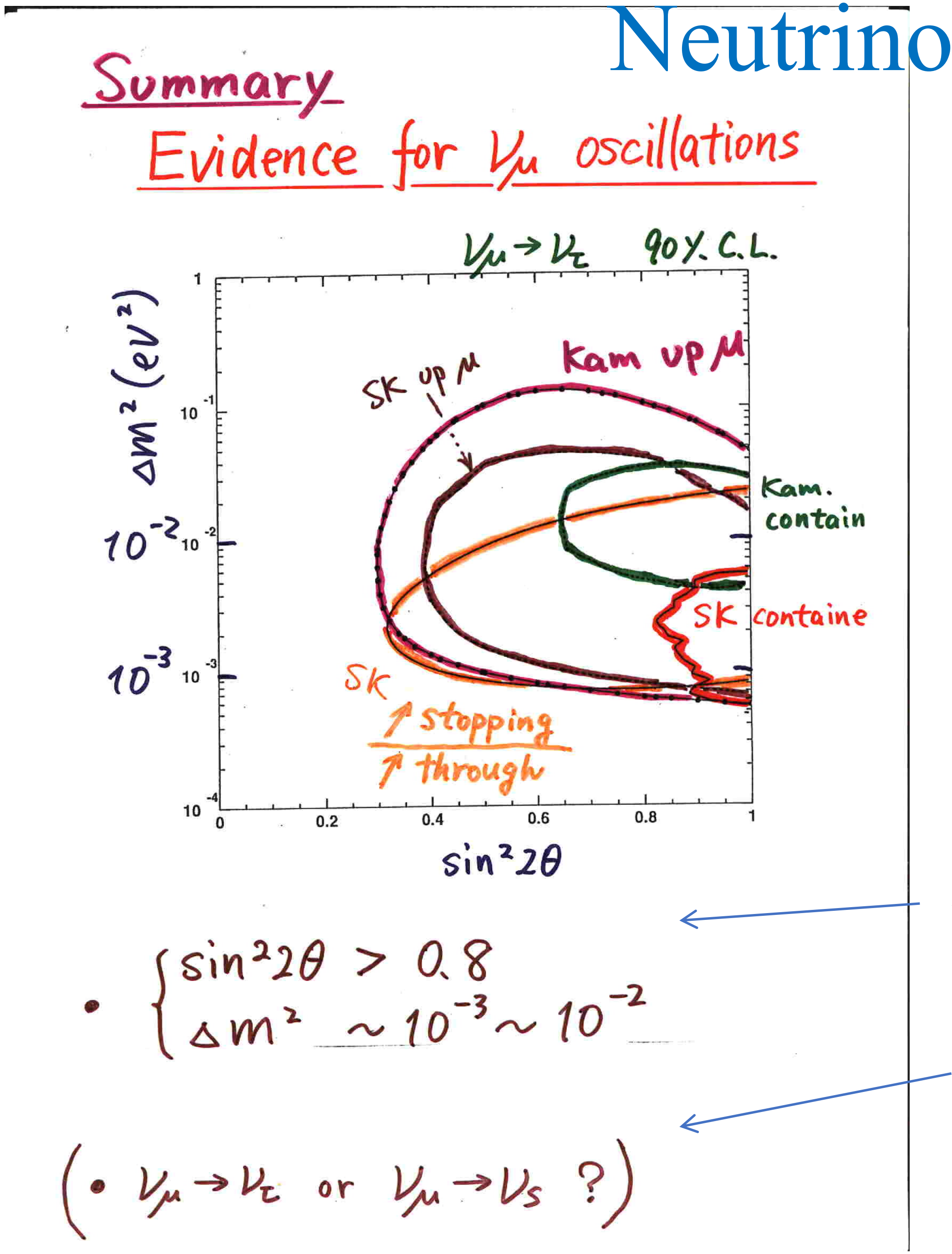
Data vs. Oscillations

$\nu_\mu \to \nu_\tau$ ($\Delta m^2 = 2.2\times10^{-3}$, $\sin^2 2\theta = 1$)

χ^2(best fit) = 65/67 d.o.f.
χ^2(No oscillation) = 135/67 d.o.f.

$\Delta\chi^2$ = 70!

Neutrino98, Takayama, Japan



Summary

Evidence for ν_μ oscillations

$\nu_\mu \to \nu_\tau$ 90% C.L.

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

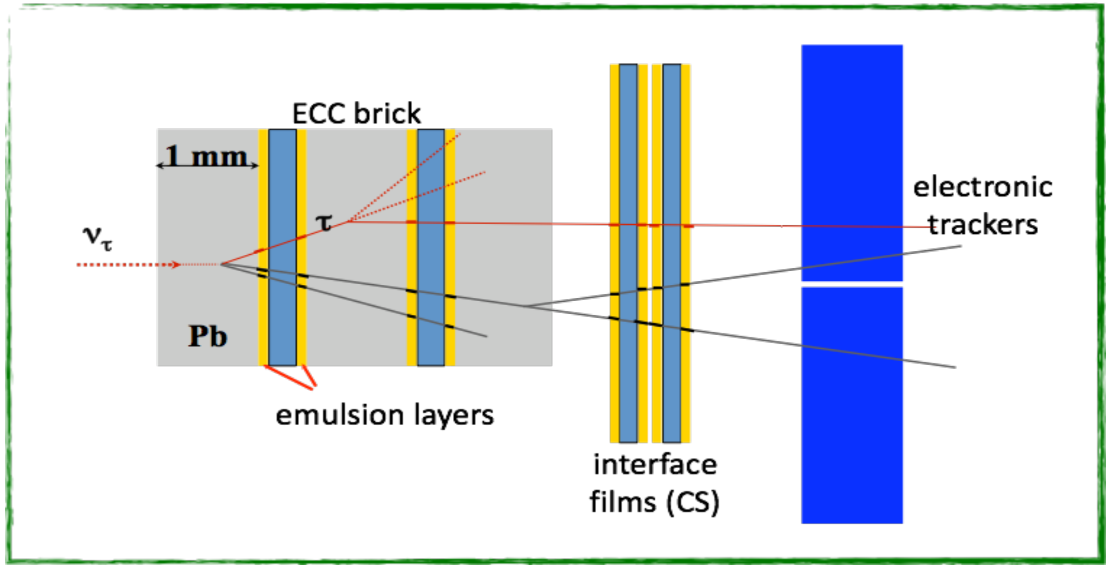
(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

$$P = \sin^2(2\vartheta)\sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

- ν_τ not yet seen in 1998!
- First indication of ν_τ in 2001 at Fermilab (DONUT)

The OPERA experiment

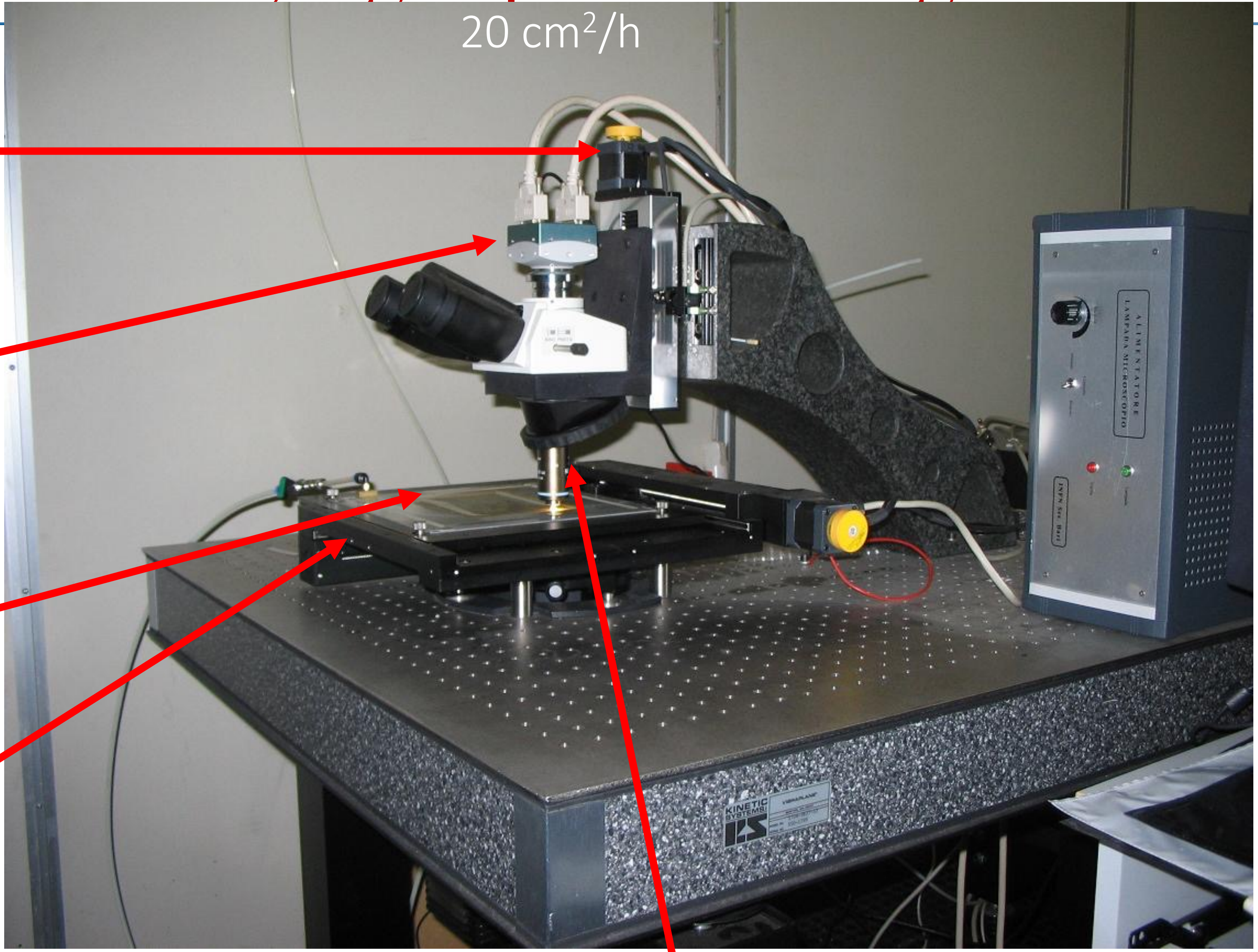
The largest emulsion detector for the proof of ν oscillation mechanism in appearance mode



2012 in Alushta

- Small neutrino cross-section and beam divergence: massive active target (~ 1.2 kton target with 30 ton emulsions)
- Detect τ-lepton production and decay: micrometric space resolution
- Underground location (10^6 reduction of cosmic ray flux)
- Electronic detectors to provide the "time stamp", preselect the interaction brick and reconstruct μ charge/momentum

First fully automated, high-speed scanning microscope in Europe: ESS



Z stage (Micos)
0.05 µm nominal
precision

CMOS camera
1280×1024 pixel
256 gray levels
376 frames/sec
(Mikrotron MC1310)

Emulsion Plate

XY stage (Micos)
0.1 µm nominal
precision

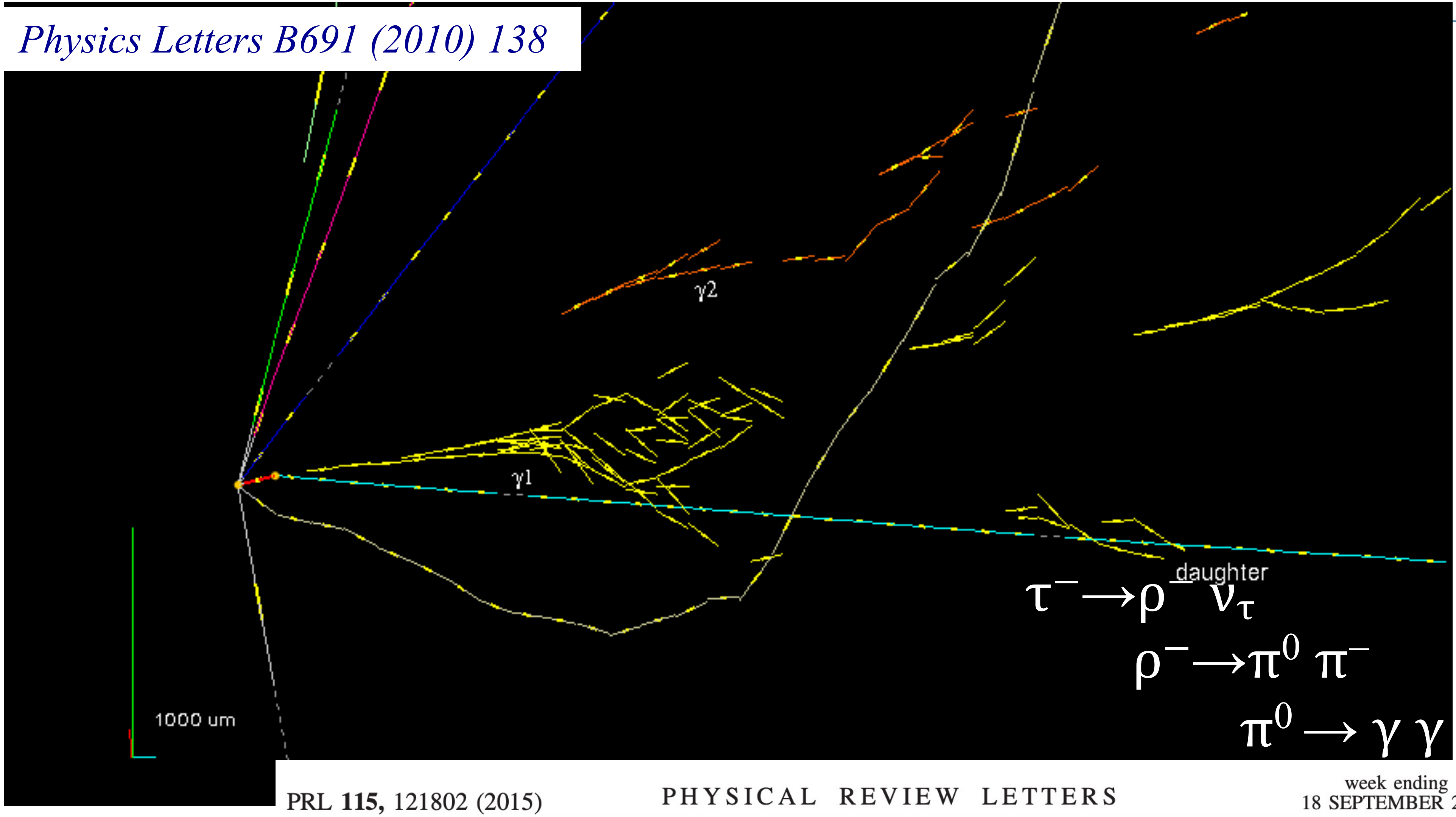
Illumination system, objective
(Oil 50× NA 0.85)
and optical tube (Nikon)

Essential contributions:
C. Bozza (software), Salerno
N. D'Ambrosio (hardware), Naples
V. Tioukov (reconstruction), Naples

2004, first prototype of the European Scanning System (ESS) operational in Naples, developed with other Italian groups (up to 20 cm^2/h)

NIM A551 (2005) 261-270
NIM A568 (2006) 578-587

THE FIRST ν_τ CANDIDATE AND THE ν_τ APPEARANCE



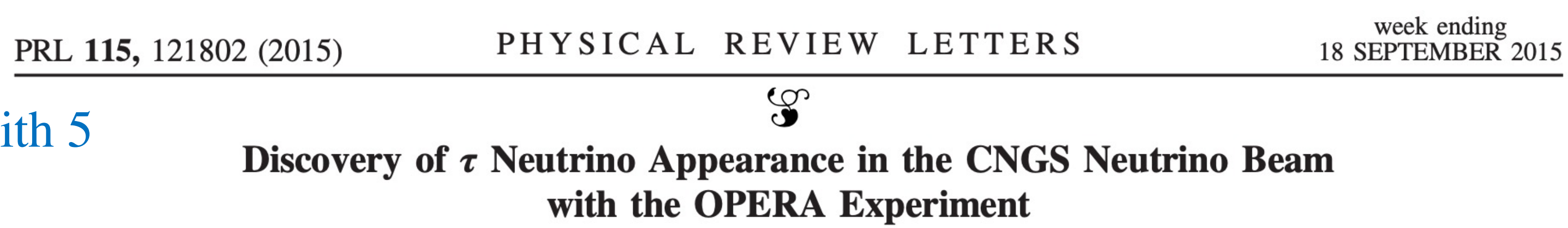
Physics Letters B691 (2010) 138

$\tau^- \rightarrow \rho^- \nu_\tau$

$\rho^- \rightarrow \pi^0 \pi^-$

$\pi^0 \rightarrow \gamma\, \gamma$

5.1 σ significance with 5 candidates

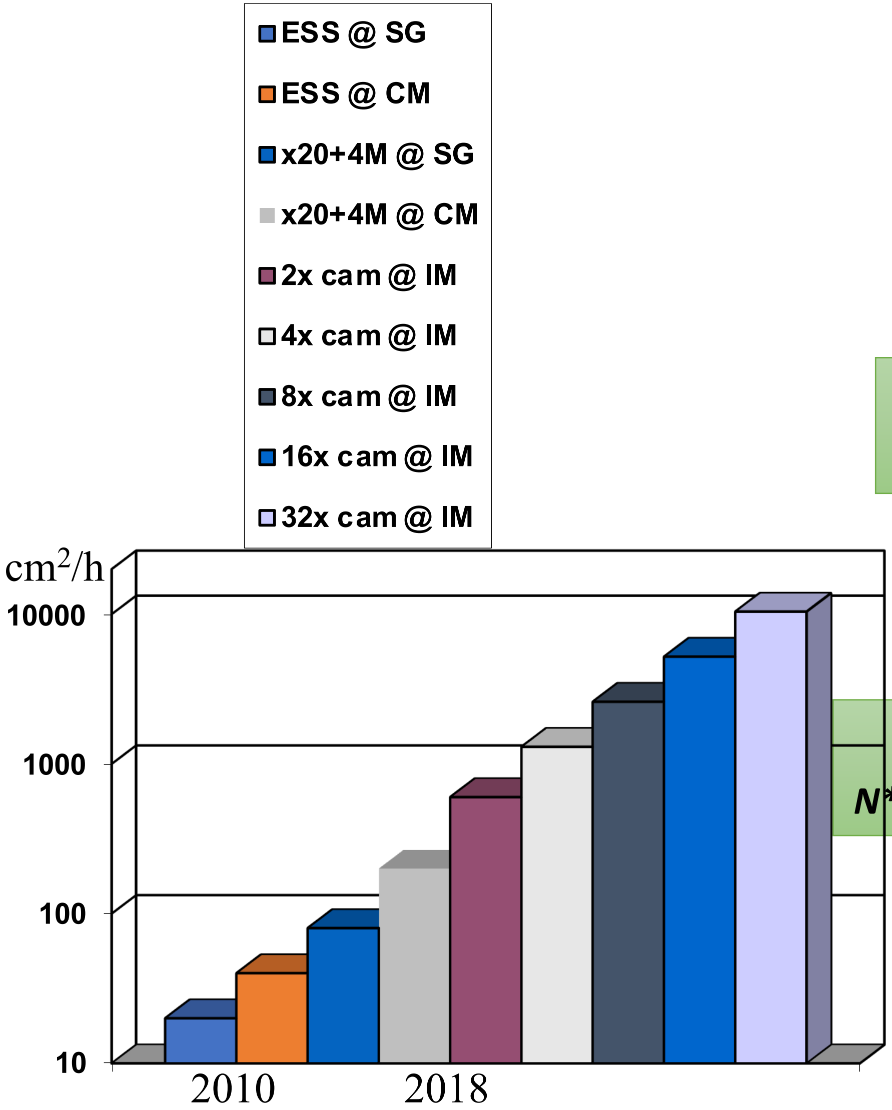


PRL **115,** 121802 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

Improvements in the scanning systems in Europe

A. Alexandrov (Naples)



2015
40 cm^2/h

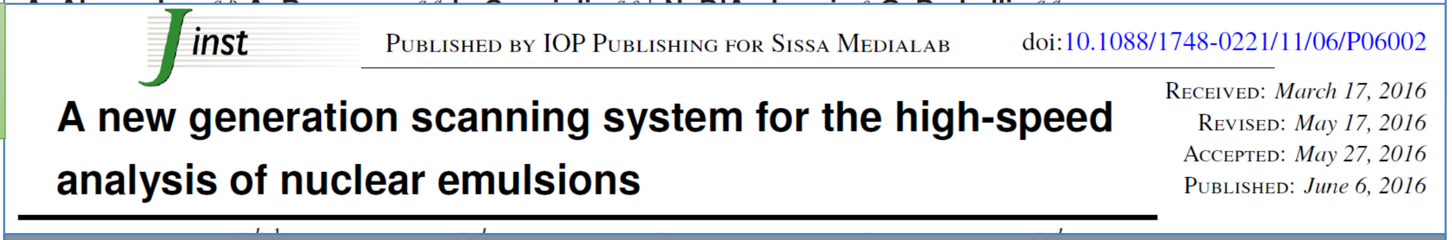

J inst
PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

doi:10.1088/1748-0221/10/11/P11006

RECEIVED: *July 24, 2015*
ACCEPTED: *October 19, 2015*
PUBLISHED: *November 12, 2015*

A new fast scanning system for the measurement of large angle tracks in nuclear emulsions

2016
80 cm^2/h

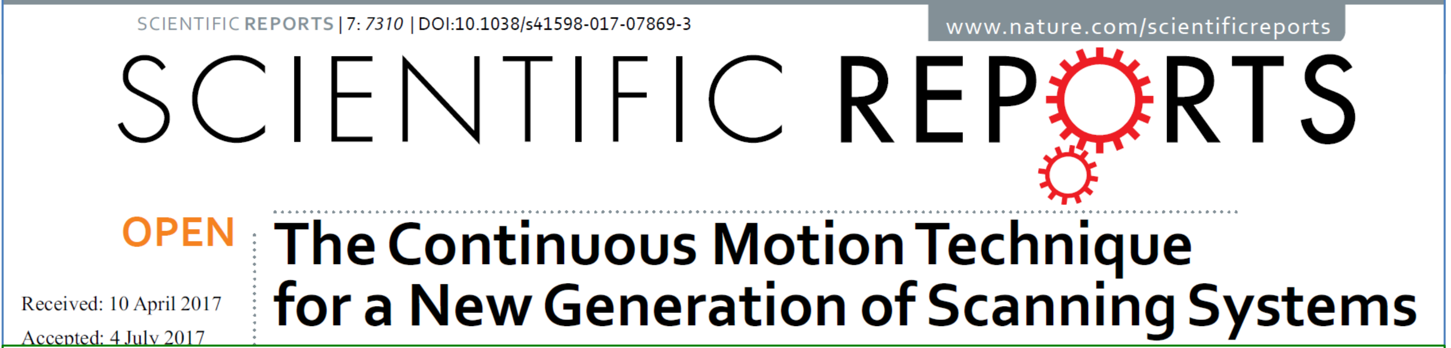

J inst
PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

doi:10.1088/1748-0221/11/06/P06002

RECEIVED: *March 17, 2016*
REVISED: *May 17, 2016*
ACCEPTED: *May 27, 2016*
PUBLISHED: *June 6, 2016*

A new generation scanning system for the high-speed analysis of nuclear emulsions

2017
200 cm^2/h


SCIENTIFIC REPORTS | 7: *7310* | DOI:10.1038/s41598-017-07869-3

www.nature.com/scientificreports

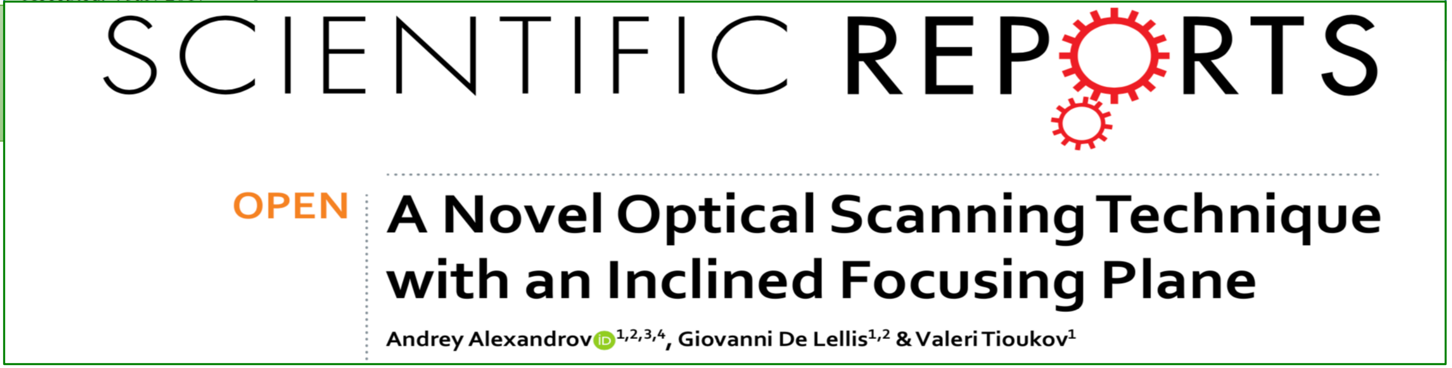
SCIENTIFIC REPORTS

OPEN

Received: 10 April 2017
Accepted: 4 July 2017

The Continuous Motion Technique for a New Generation of Scanning Systems

2019
*N*200 cm^2/h*


SCIENTIFIC REPORTS

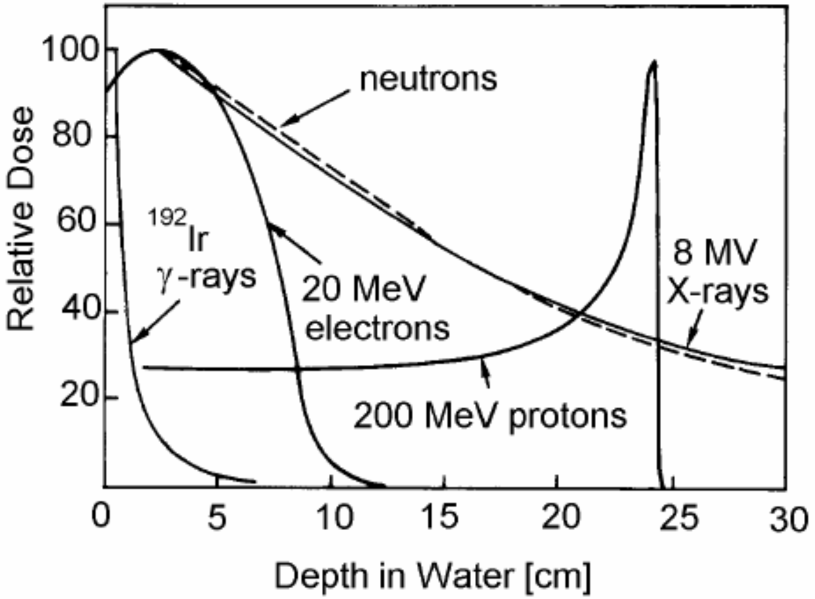
OPEN

A Novel Optical Scanning Technique with an Inclined Focusing Plane

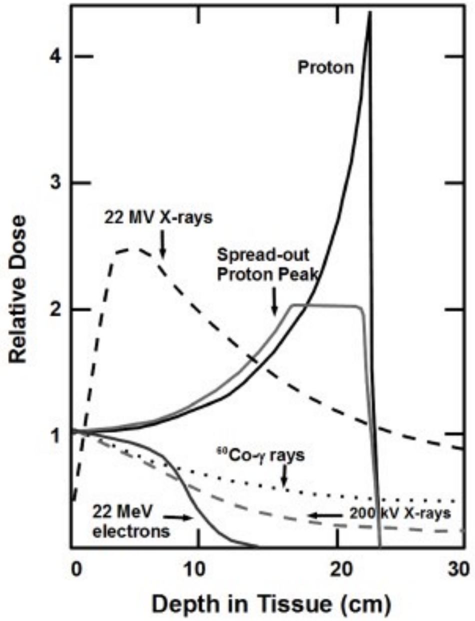
Andrey Alexandrov[1,2,3,4], Giovanni De Lellis[1,2] & Valeri Tioukov[1]

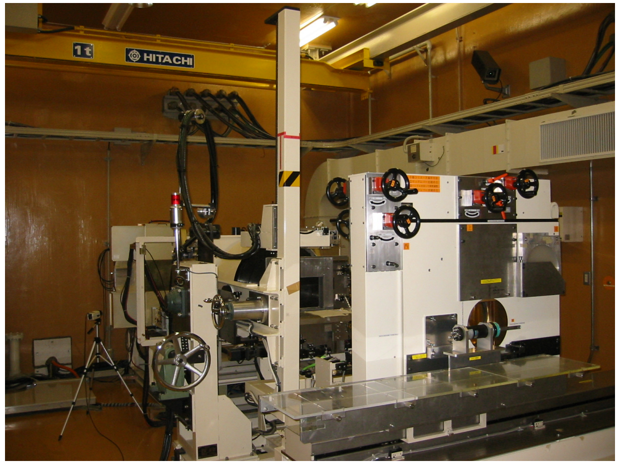
Applications beyond particle physics

New developments: application to hadron therapy



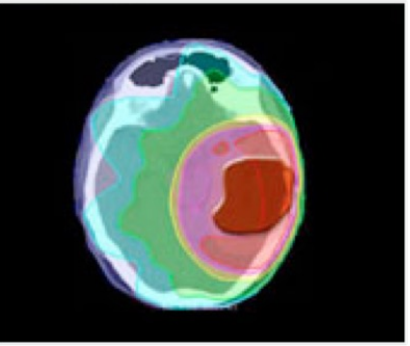
Protons and ions
used in hadron-
therapy
(Bragg peak)



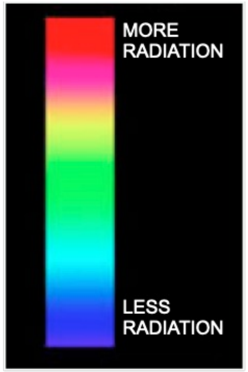


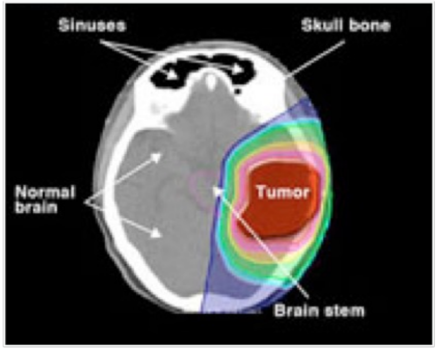
First exposure at HIMAC (Chiba)
October 2005

Scarce knowledge of the interaction along their path

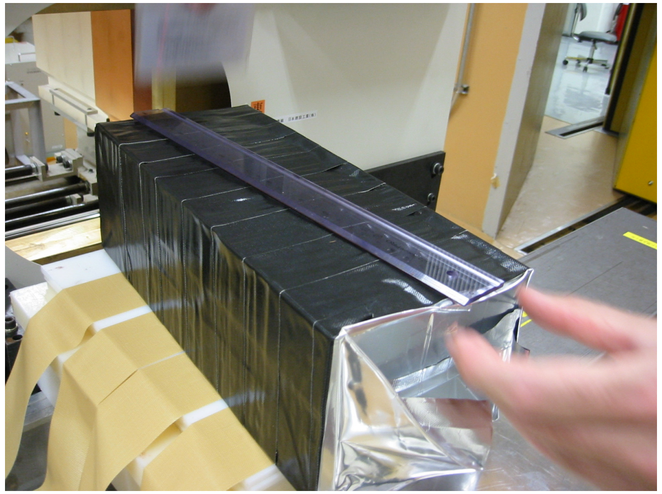


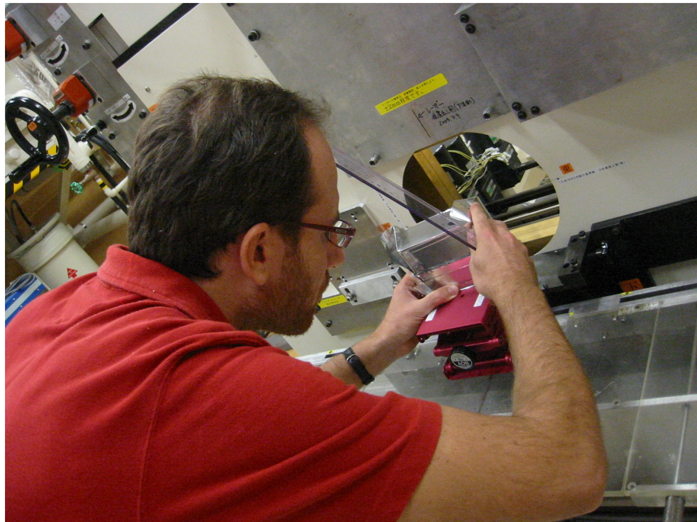
➡CONVENTIONAL
RADIOTHERAPY





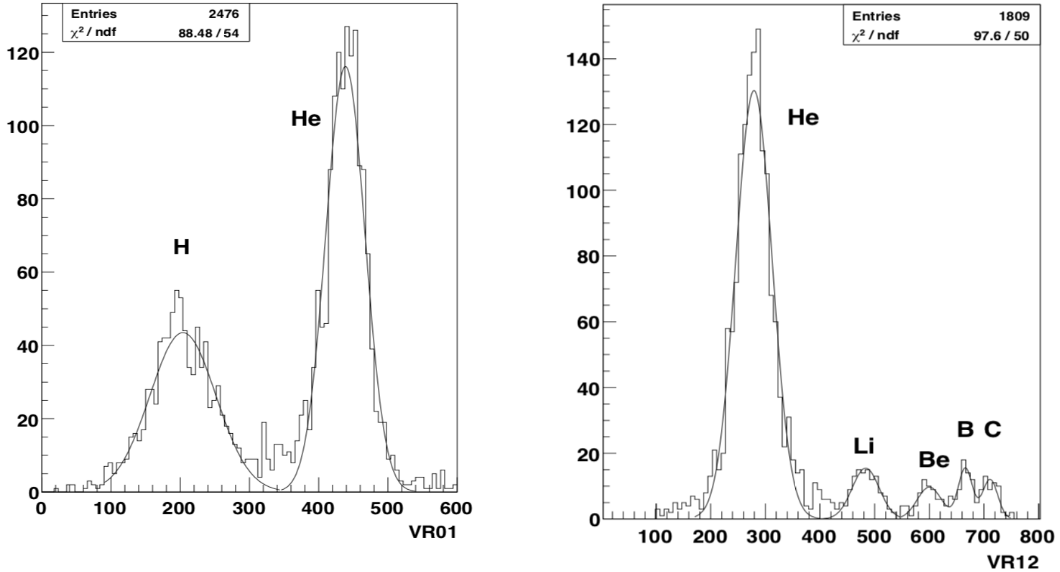
➡CHARGED PARTICLE
THERAPY





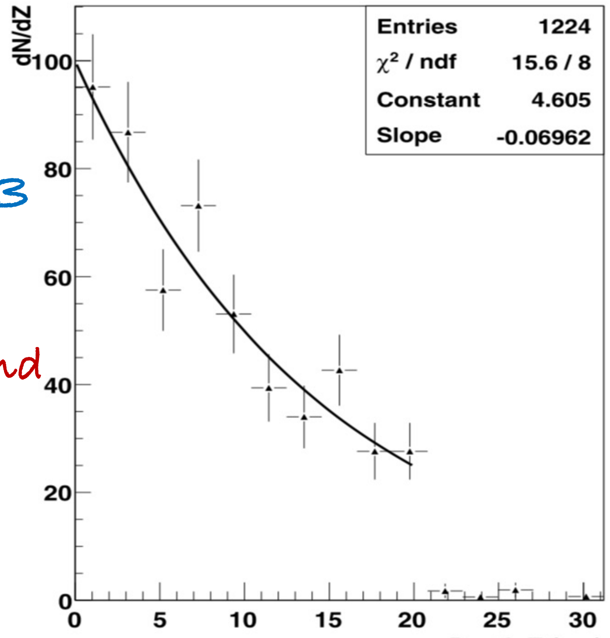
Charge identification and cross-section measurement

Identification of fragments through the measurement of



G. De Lellis et al., JINST 12 (2007) P08013

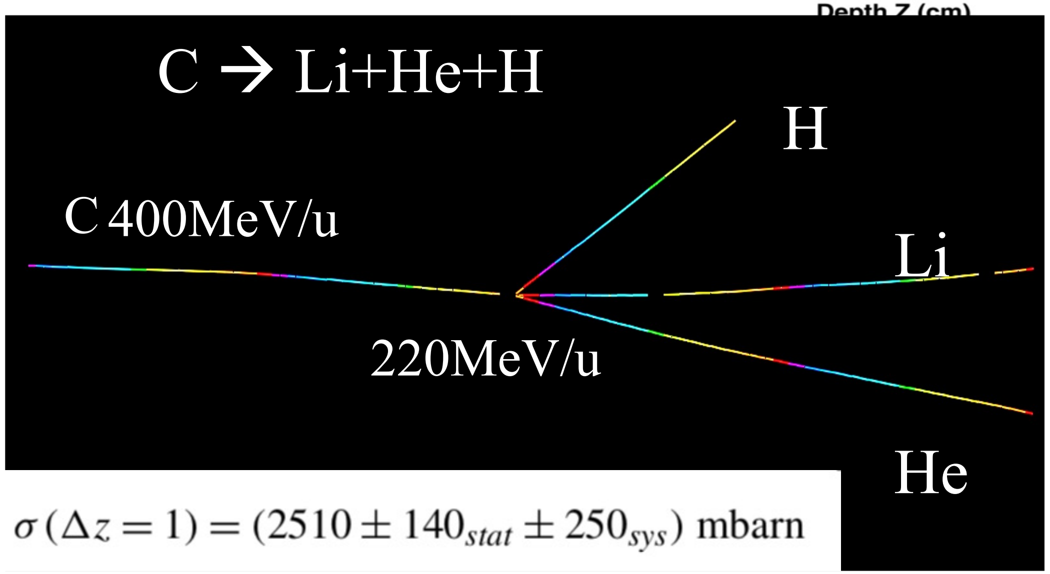
Using techniques of controlled fading of the latent image to expand dynamic range and overcome saturation



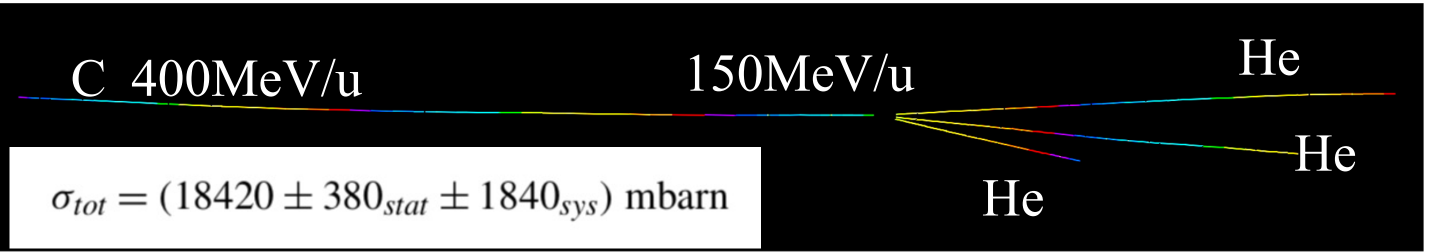
ECC structure: 219 OPERA-like emulsions and 219 Lexan sheets ($\rho = 1.15$ g/cm^3) 1 mm thick (73 consecutive "cells")

exposed to 400 Mev/u Carbon ions

- G. De Lellis et al., Nucl. Phys. A853 (2011) 124



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



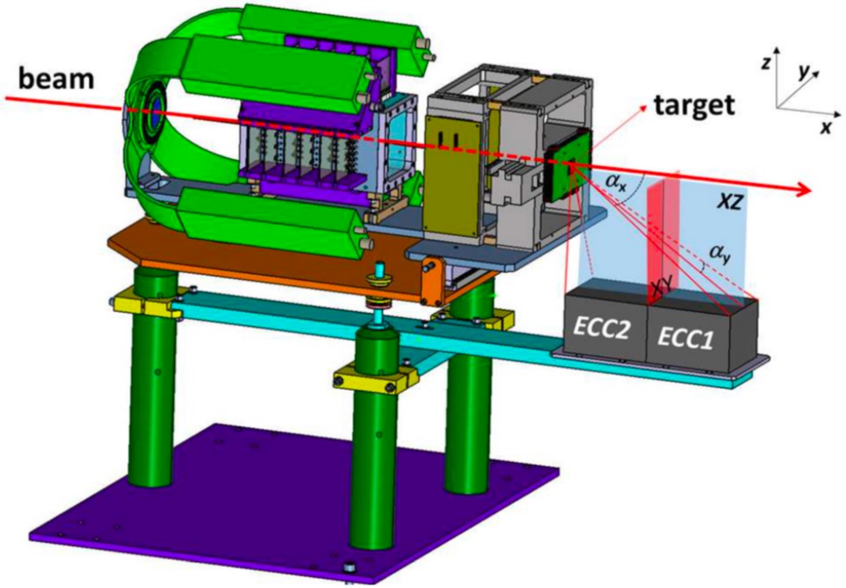
$\sigma_{tot} = (18420 \pm 380_{stat} \pm 1840_{sys})$ mbarn

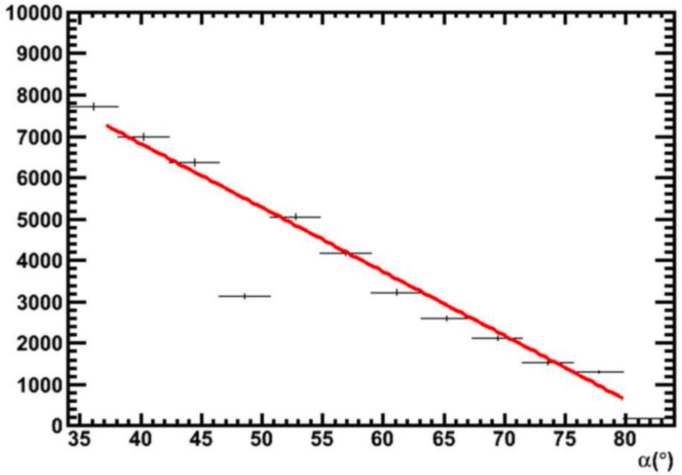
Momentum and angular distribution of fragments at GSI (Darmstadt)

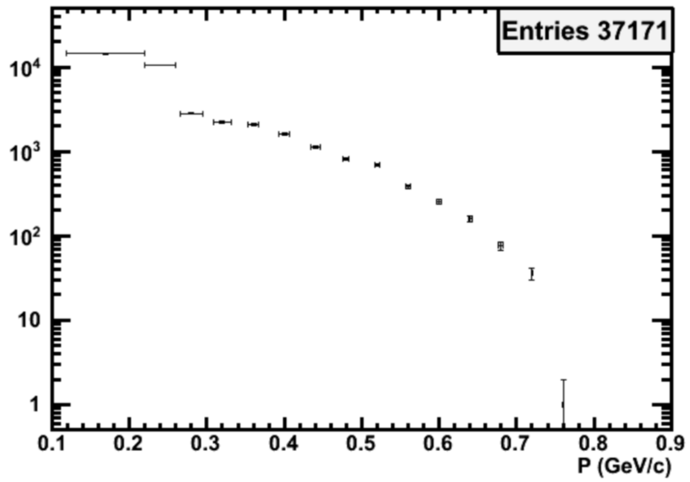
G. De Lellis et al., Meas. Sci. Technol. **26** (2015) 094001

G. De Lellis et al., JINST 12 (2017) P08013

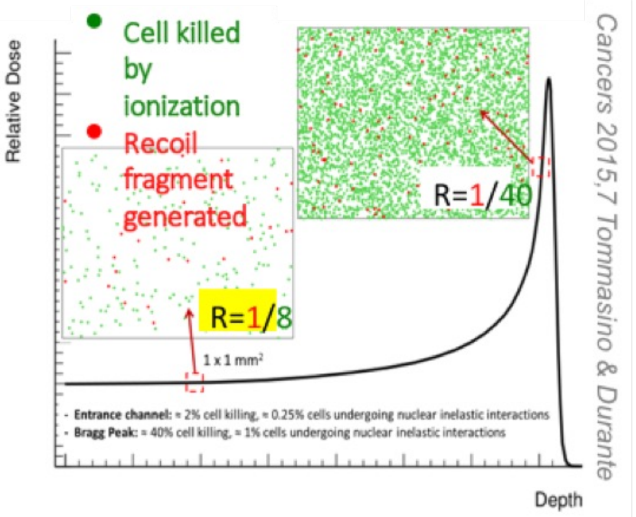
M. C. Montesi et al., Open Physics 17 (2019) 233.



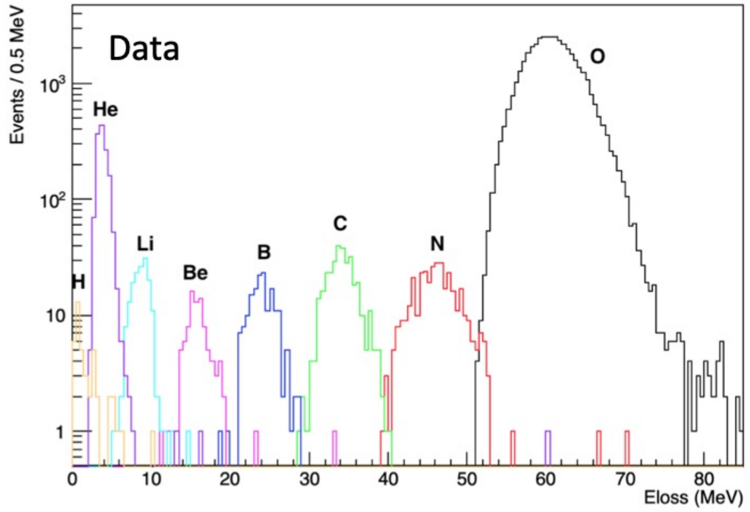


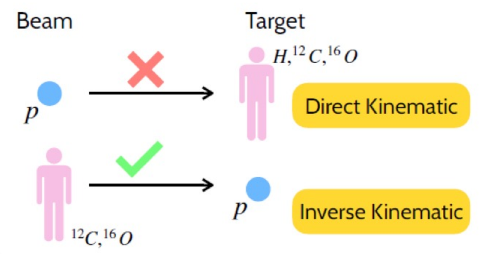


FOOT (FragmentatiOn of Target) experiment since 2017



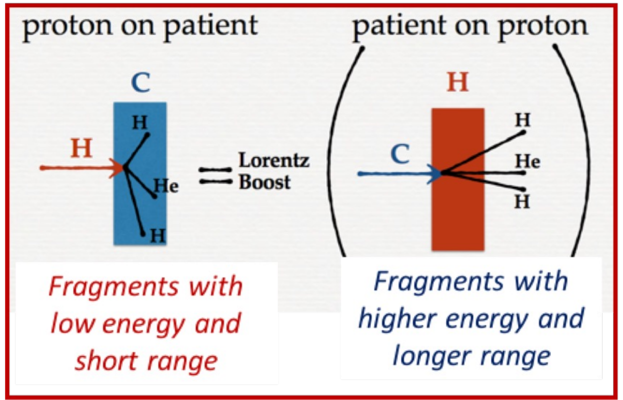
Cancers 2015,7 Tommasino & Durante

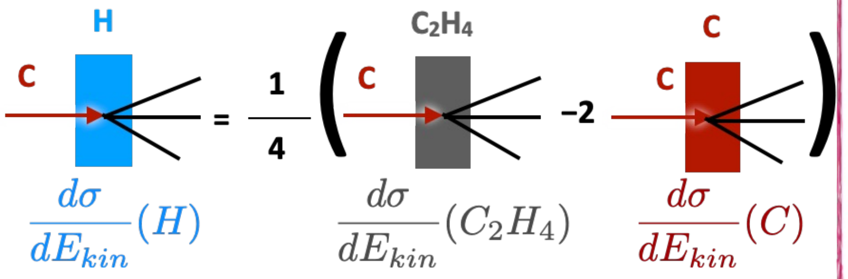




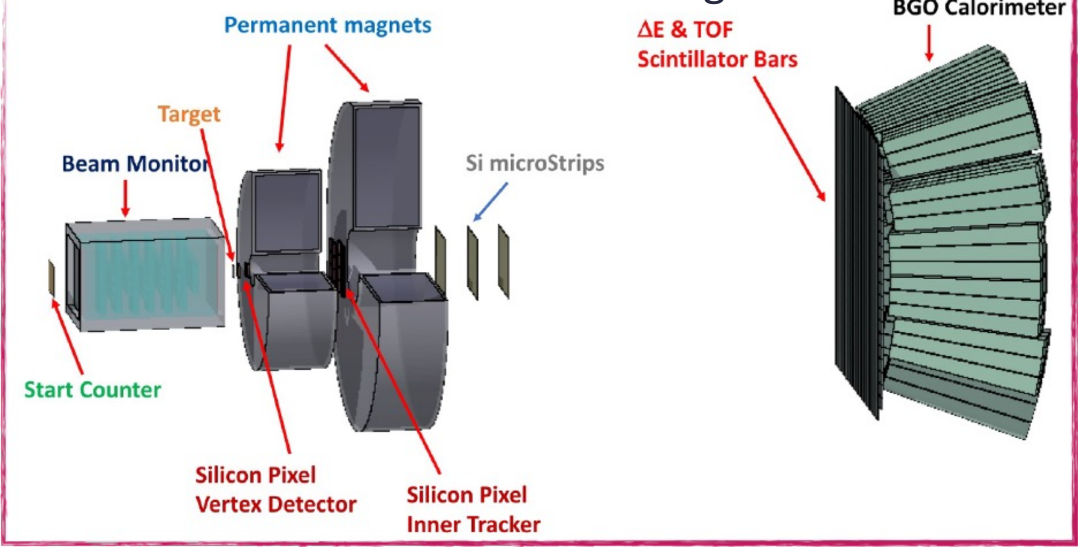
~ 100 members
10 INFN units, 15 Universities
3 laboratories: CNAO, GSI, IPHC

magnetic spectrometer with electronic detectors to measure Z ≥3 fragments

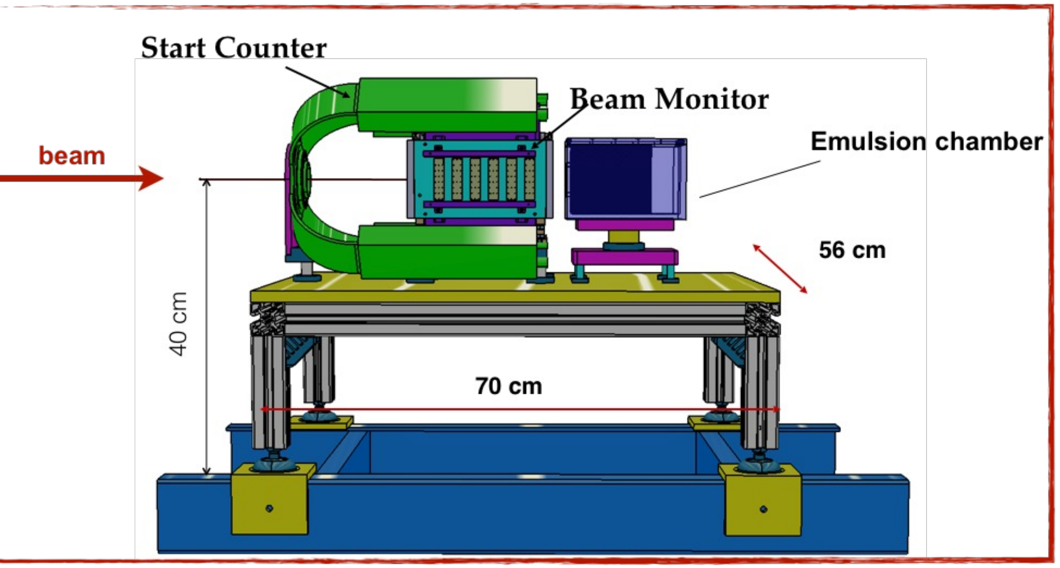


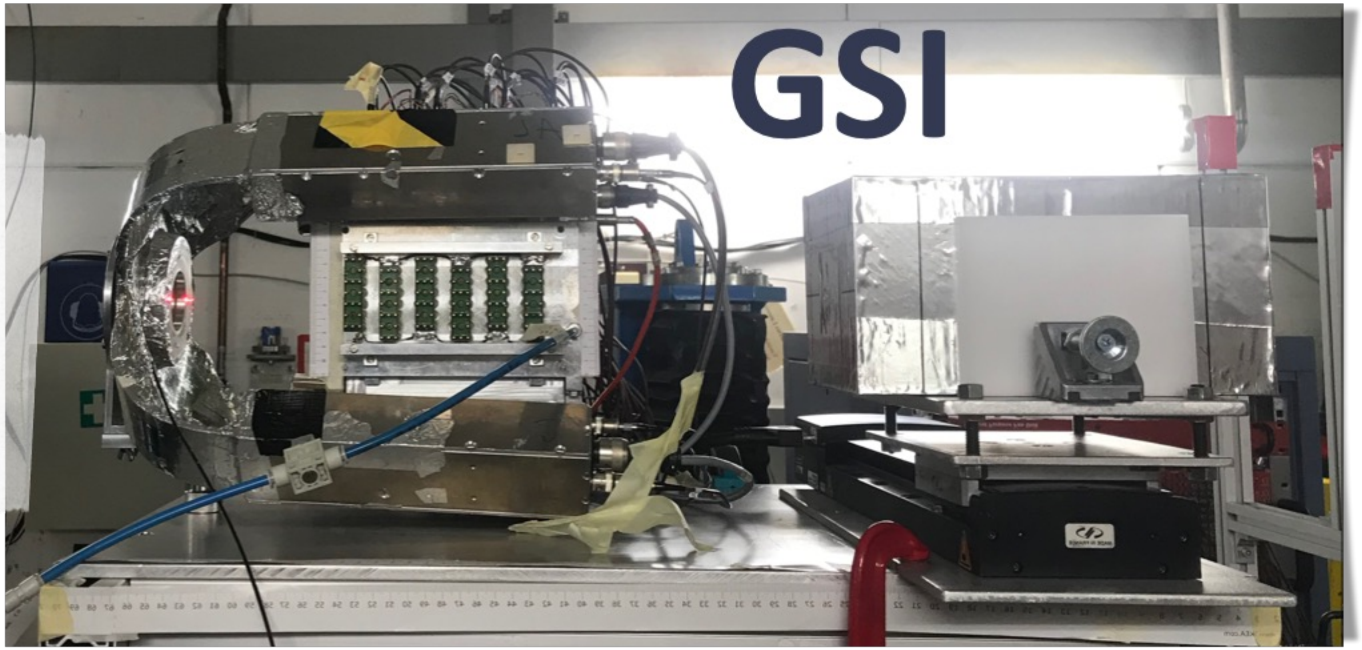


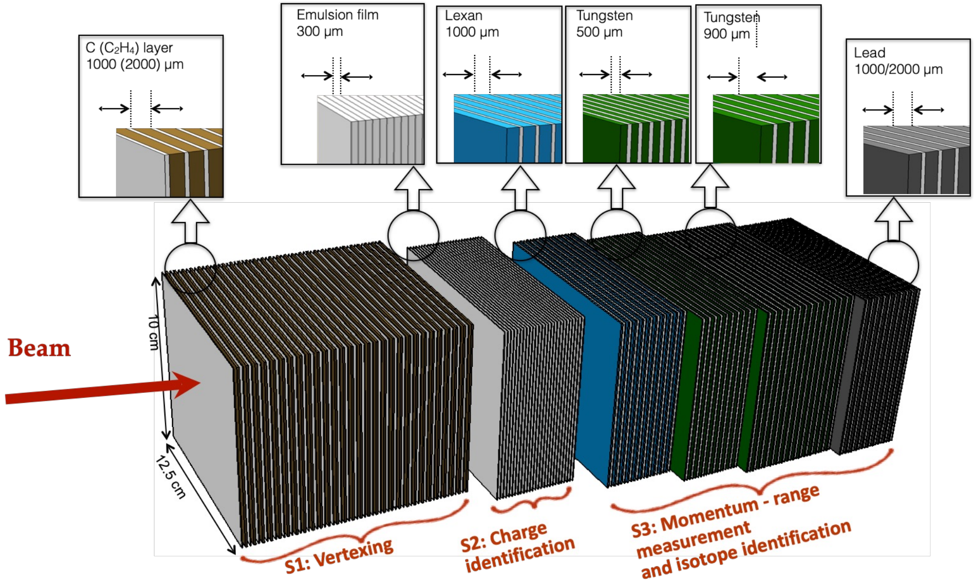
$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\,\frac{d\sigma}{dE_{kin}}(C)\right)$$



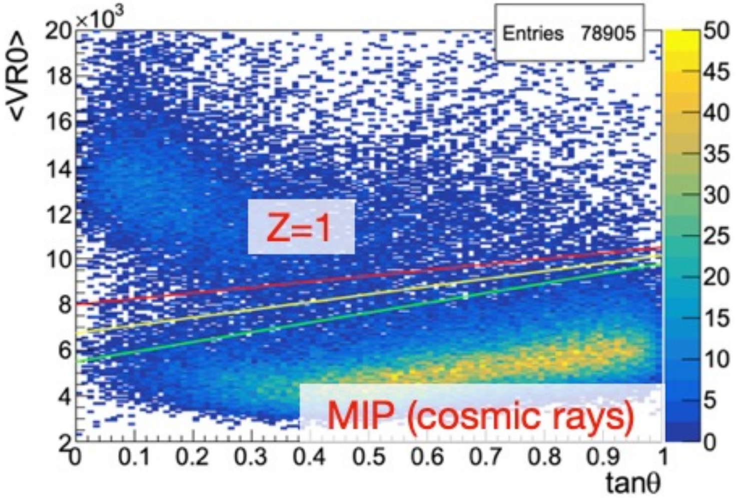
Nuclear emulsion spectrometer to measure Z≤3 fragments

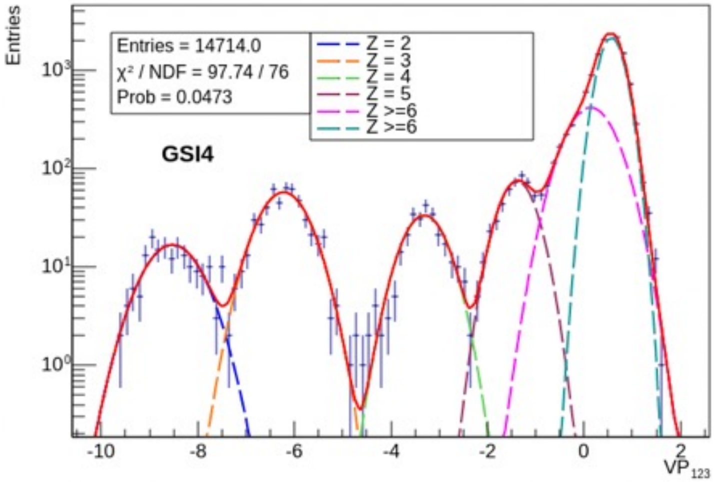




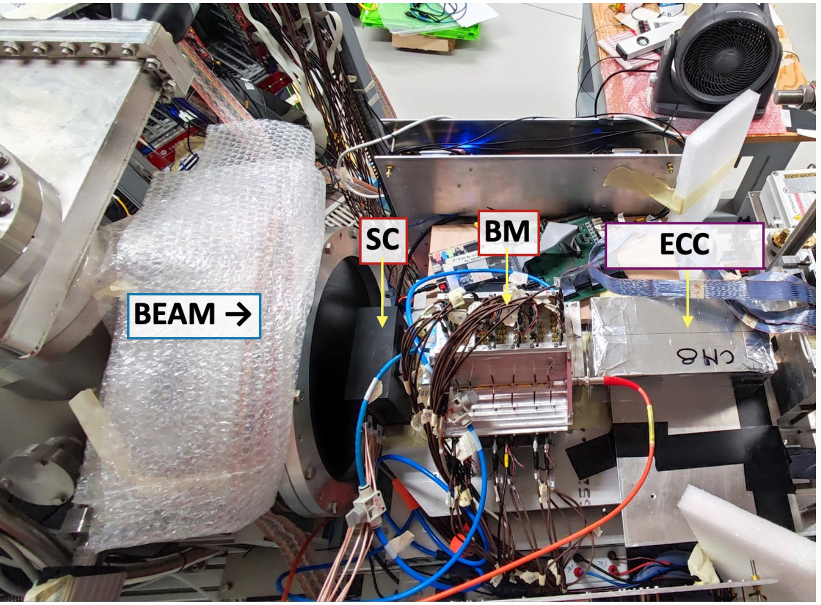


G. Galati et al., doi.org/10.1515/phys-2021-0032



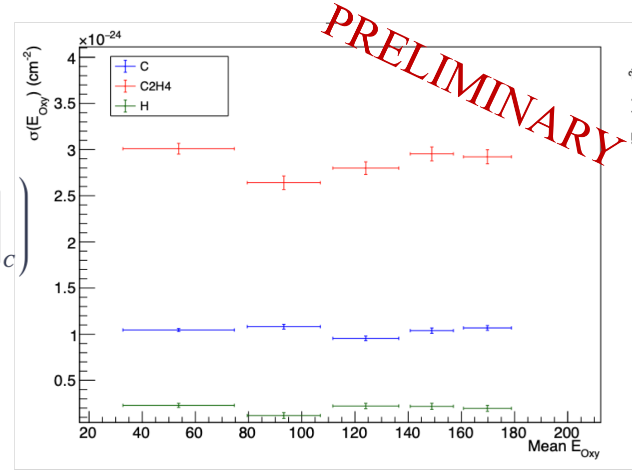


Cross-section measurement and direct detection

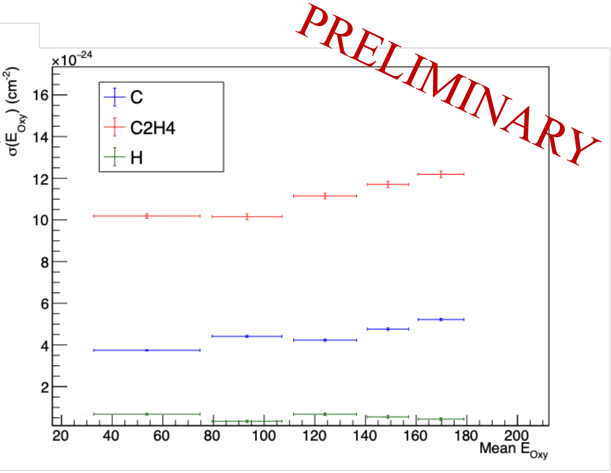


$$\left.\frac{d\sigma(x)}{dx}\right|_{C\ or\ C_2H_4} = \frac{Y_i(x)}{N_B N_{TG}\Delta x \epsilon^i_{reco}(x)}$$

$$\left.\frac{d\sigma(x)}{dx}\right|_{H} = \frac{1}{4}\left(\left.\frac{d\sigma(x)}{dx}\right|_{C_2H_4} - 2\left.\frac{d\sigma(x)}{dx}\right|_{C}\right)$$

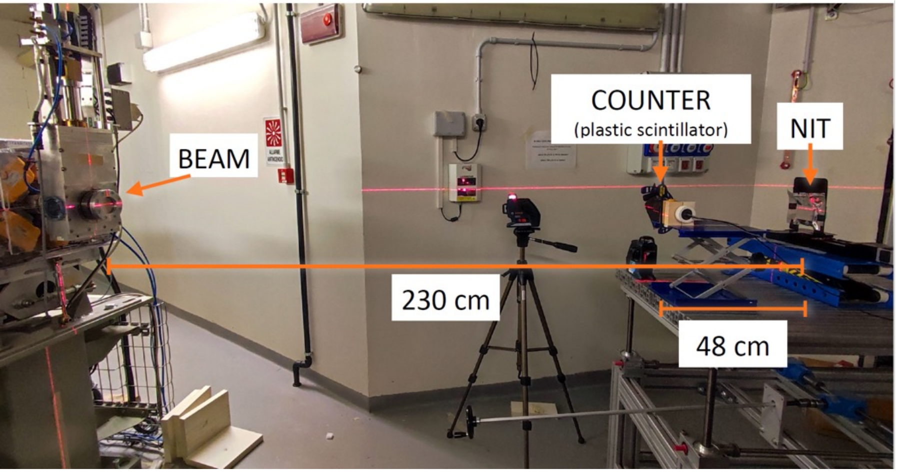


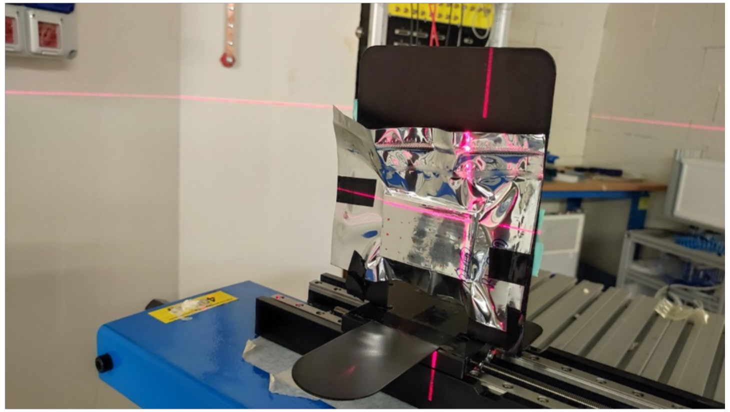
Total reaction cross section
($Y_i = \#$ of vertices)



Total production cross section
($Y_i = \#$ of fragments)

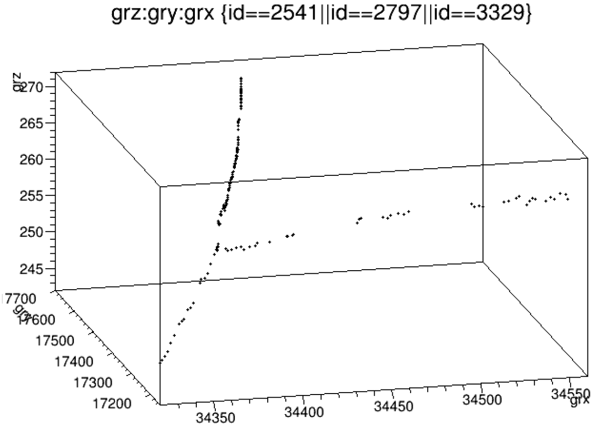
Project title: **DAMON: Direct meAsureMent of target fragmentatiON**





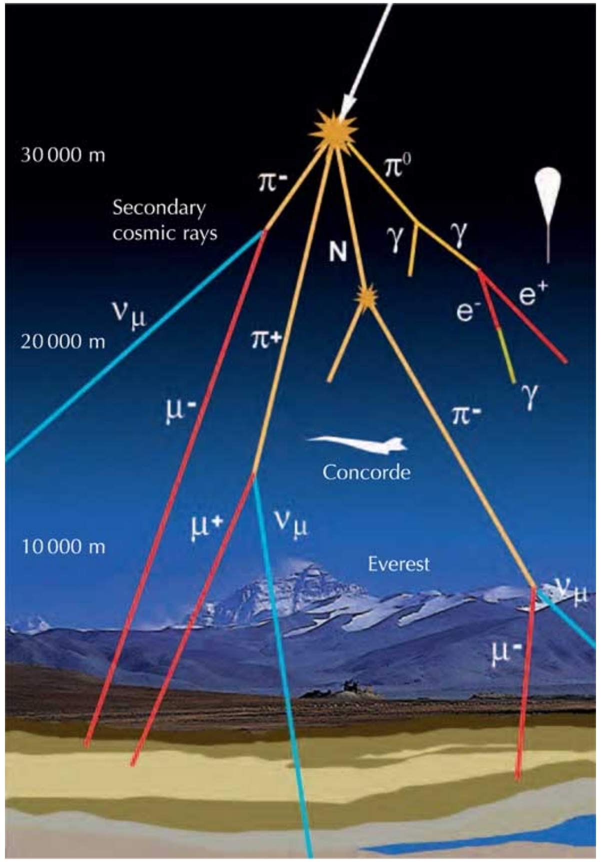
Using NIT (Nano Imaging Tracker) technology

First candidates



Investigation of volcanoes and archeological structures

Muons produced by protons coming from space in the upper layers of atmosphere



Muons are highly penetrating:
2TeV → ∽3 km w.e.

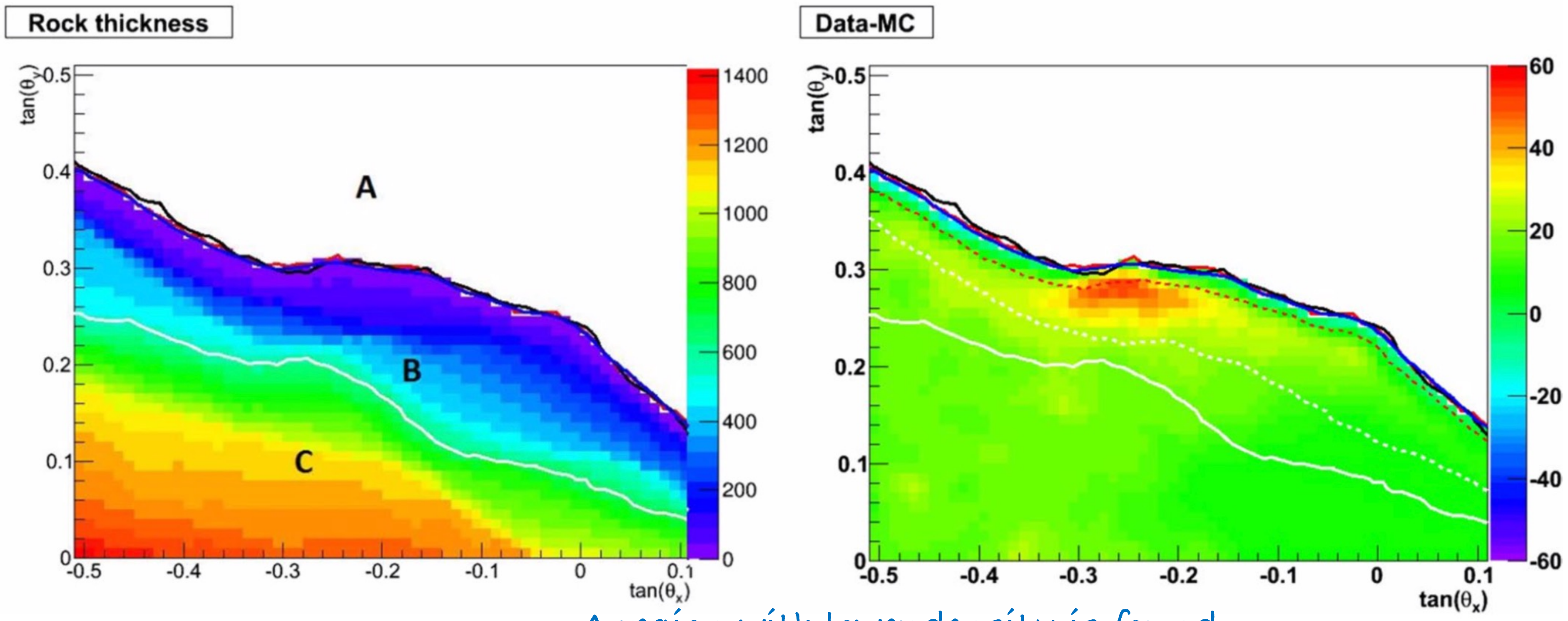

Stromboli, Italy

Results of the investigation of Stromboli volcano

Scientific **Reports 9 (2019) 6695**
https://doi.org/10.1038/s41598-019-43131-8

SCIENTIFIC **REPORTS**

OPEN **First muography of Stromboli**

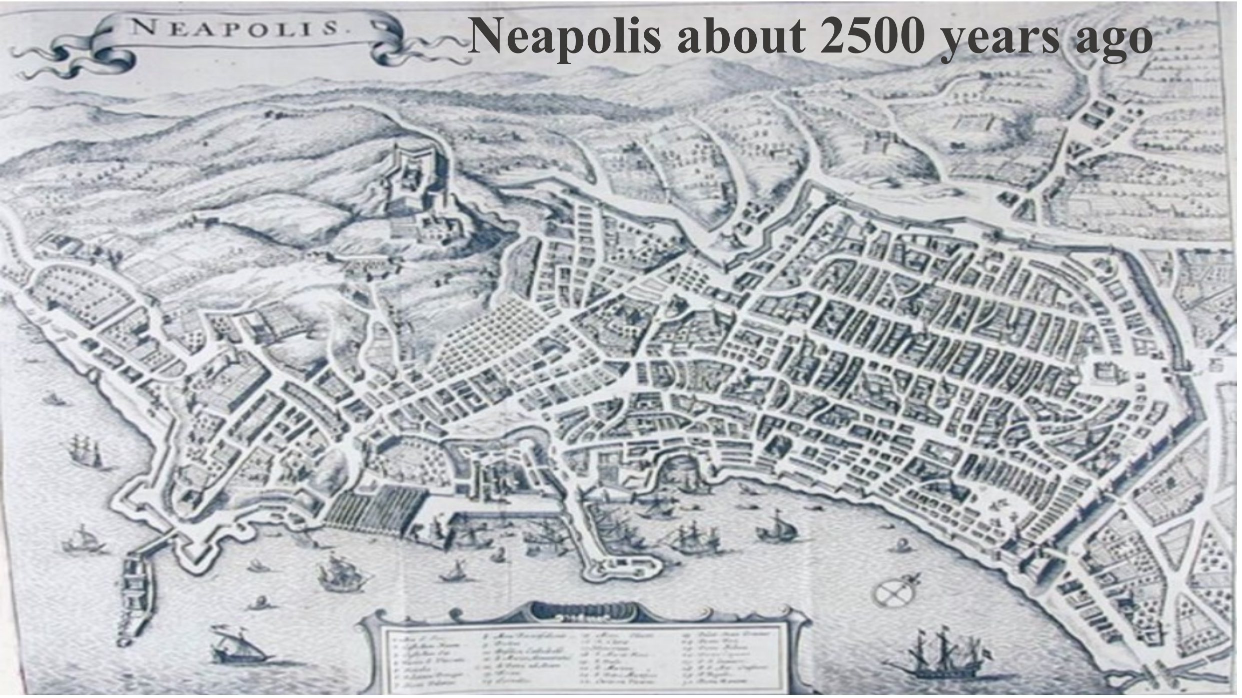


A region with lower density is found

A. Alexandrov, G. De Lellis, V. Tioukov et al., Scientific Reports 9 (2019) 6695

The region is within 50 and 200m below the crater and the density is ranging between 1.4 and 2.2 g/cm^3

Investigation of the underground Naples



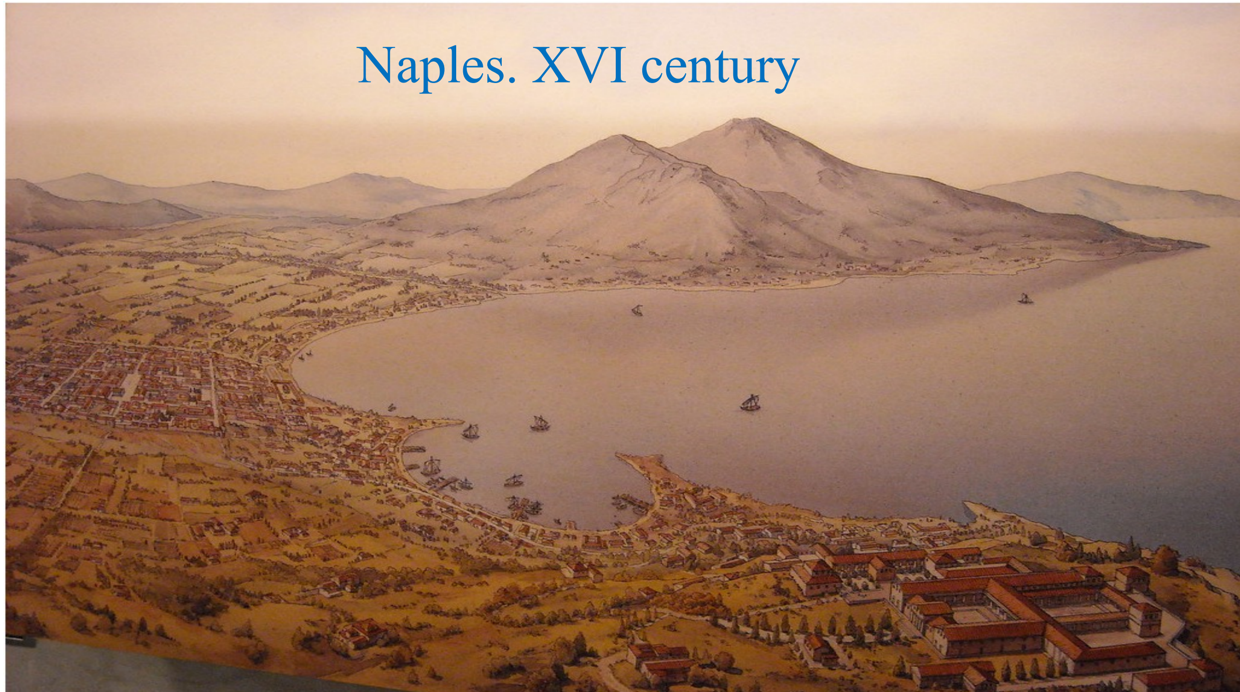
Neapolis about 2500 years ago

Ancient Greek and Roman cultural layer of Neapolis was covered later by eruptions and alluvions and completely forgotten

Starting from XVI century, active urbanization started in this region and some Greek and Roman constructions were accidentally revealed

Next 1000 years – Roman period

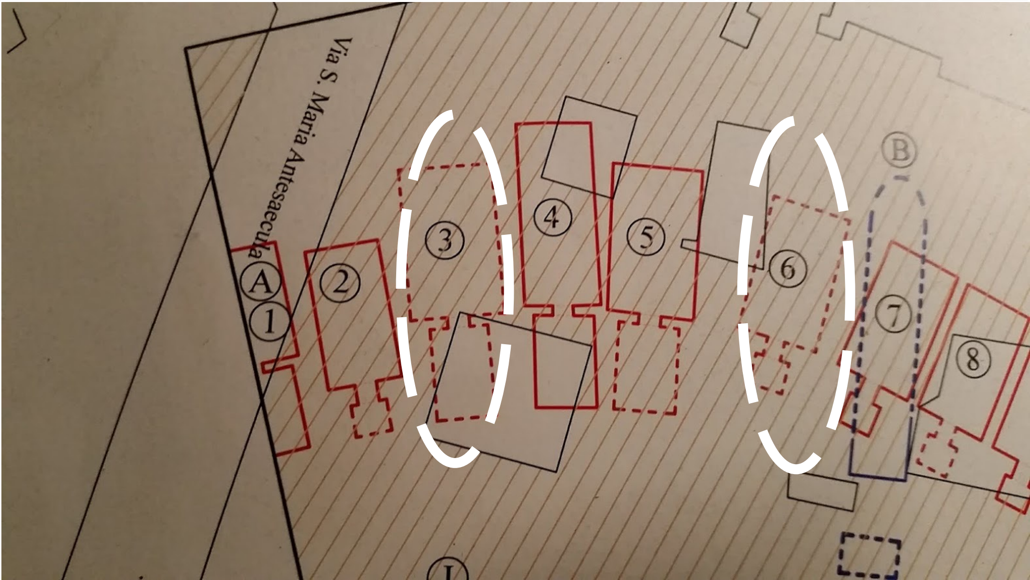
Roman aqueduct Serino



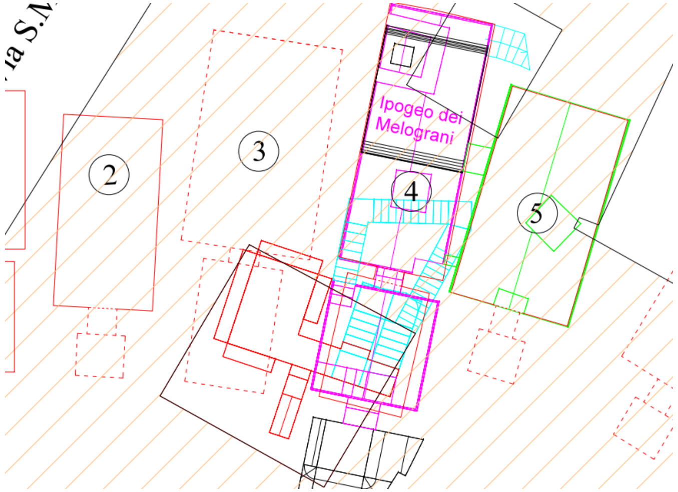
Naples. XVI century

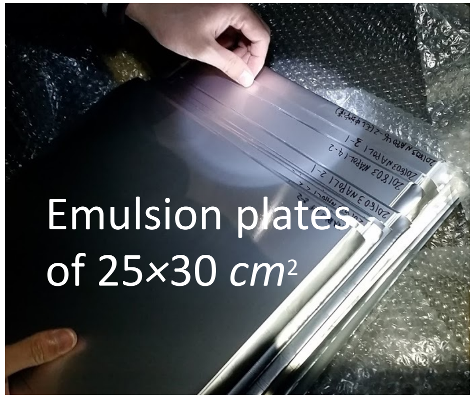
Investigation of Hellenistic Neapolis in the Sanità district

Today, Greek and Roman layers are about 10 m underground, in highly populated districts of the city



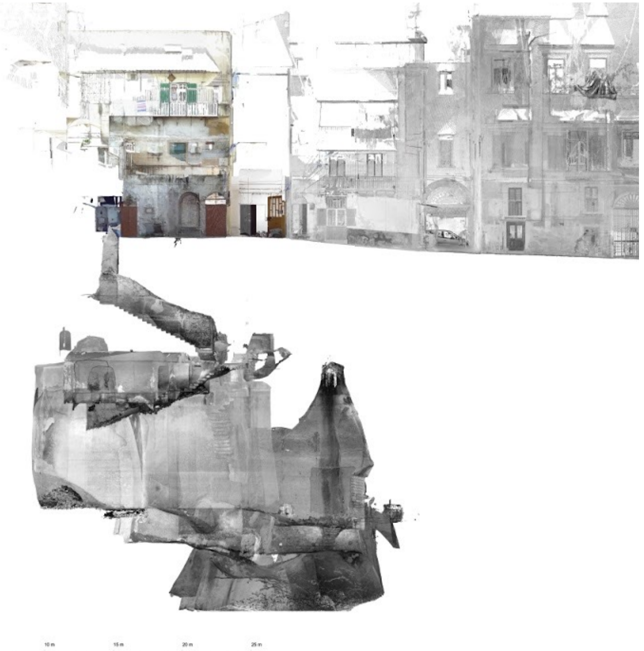
Investigation of Hellenistic Neapolis in the Sanità district

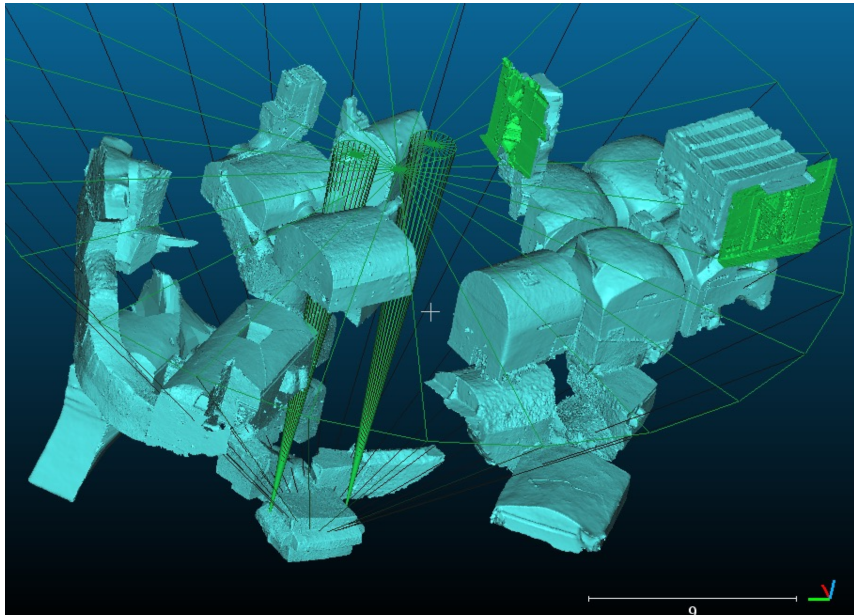



Emulsion plates of 25×30 cm^2

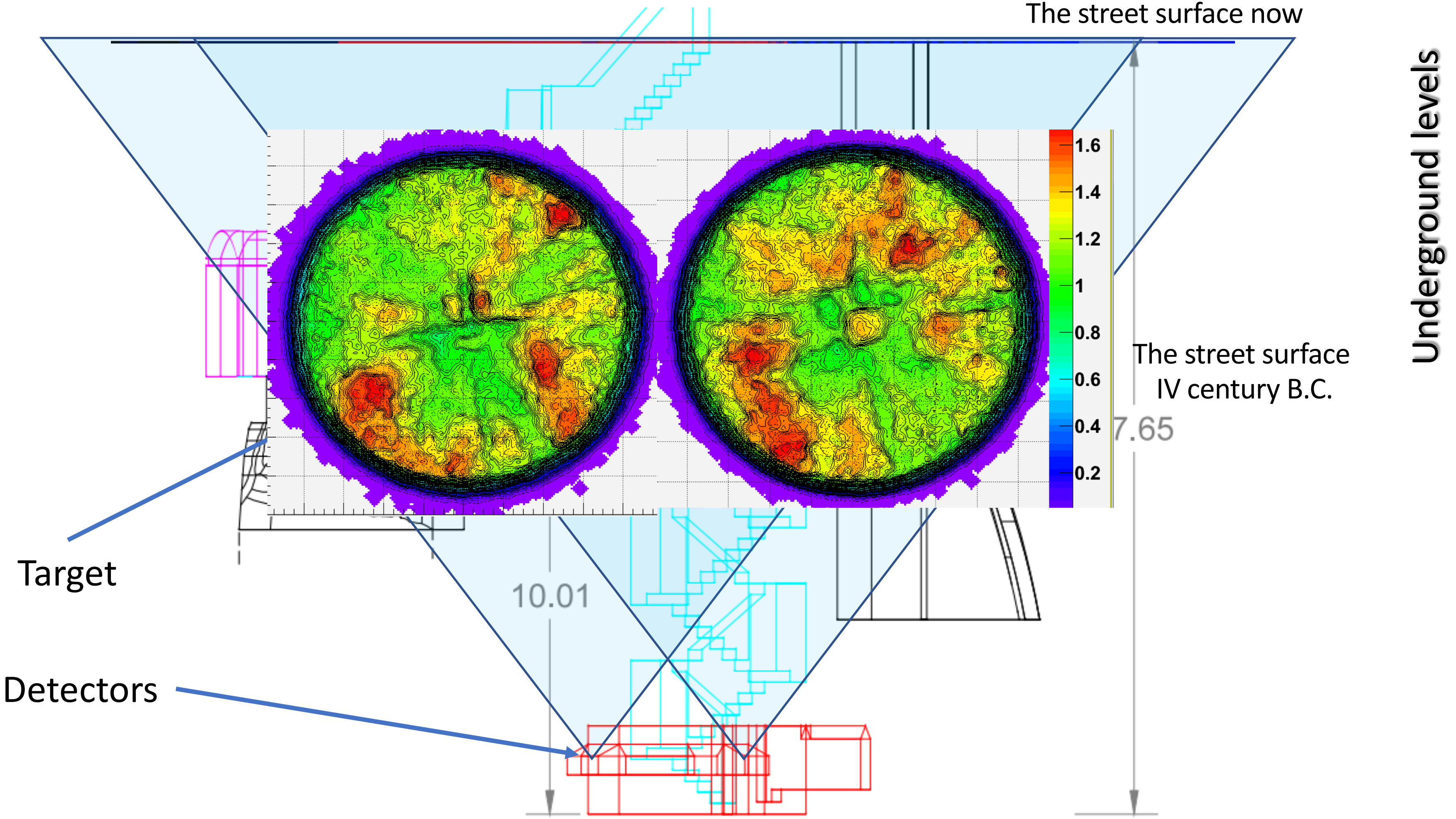

Napoli - Via Santa Maria Antesaecula, 126.
Ipogeo dei "Melograni" Camera inferiore - Parete est
Associazione Culturale Celanapoli

unique choice for a harsh or hard-to-access sites



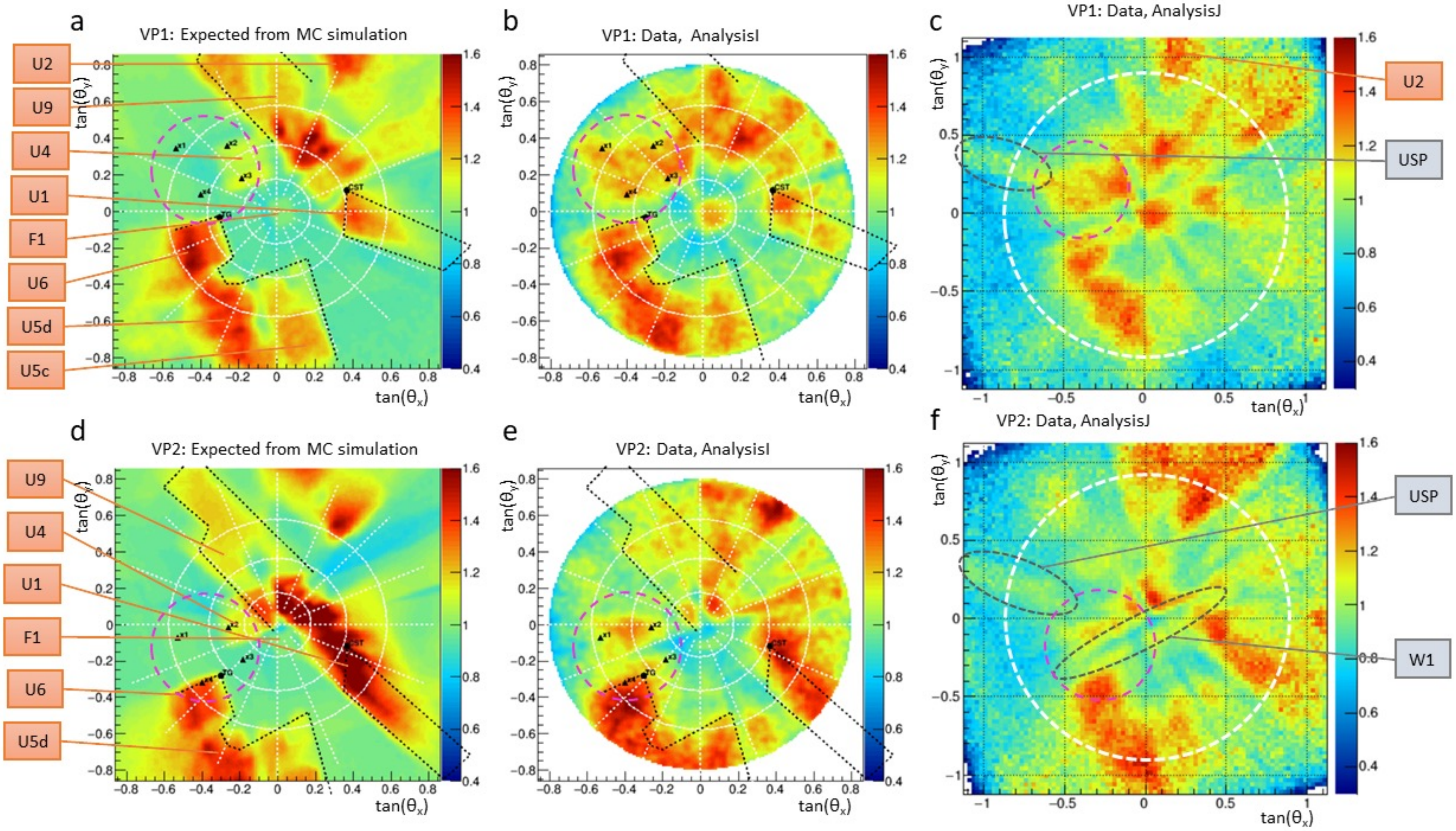


Investigation of Hellenistic Neapolis in the Sanità district

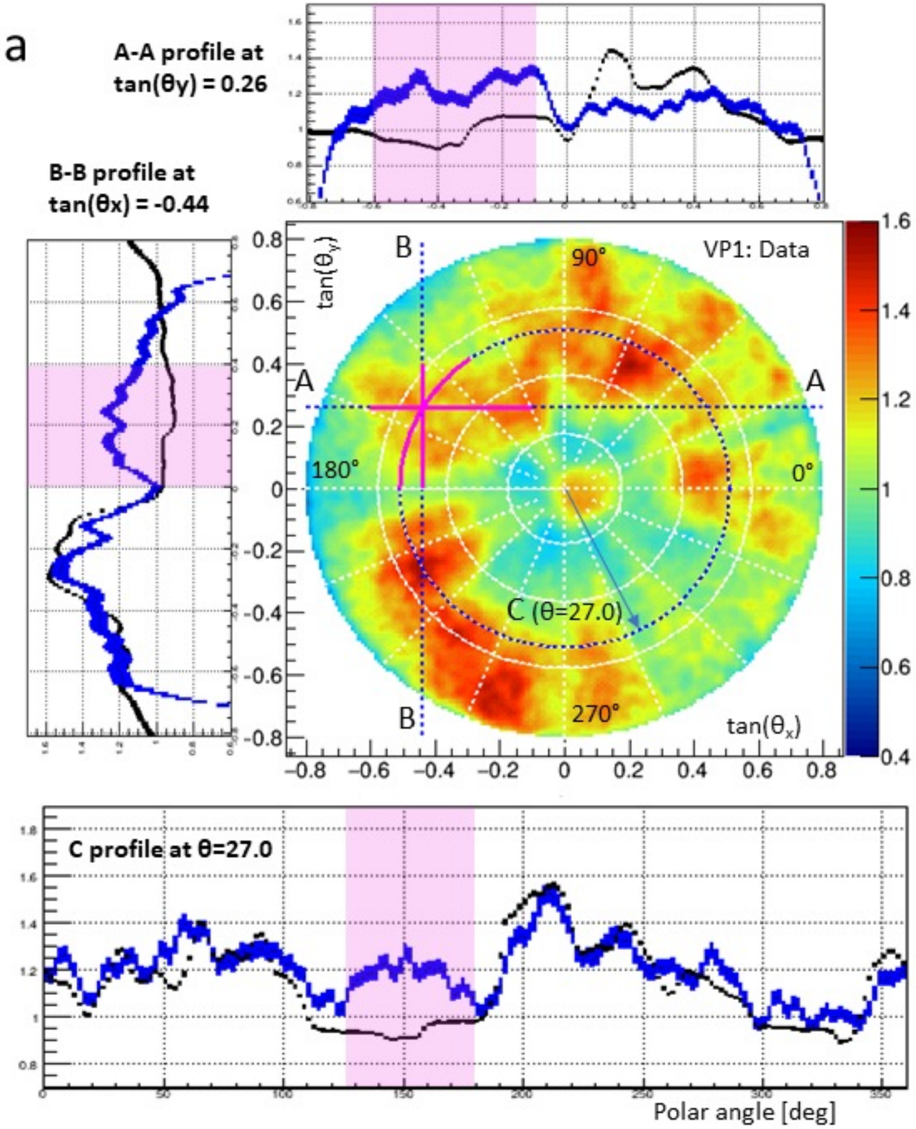


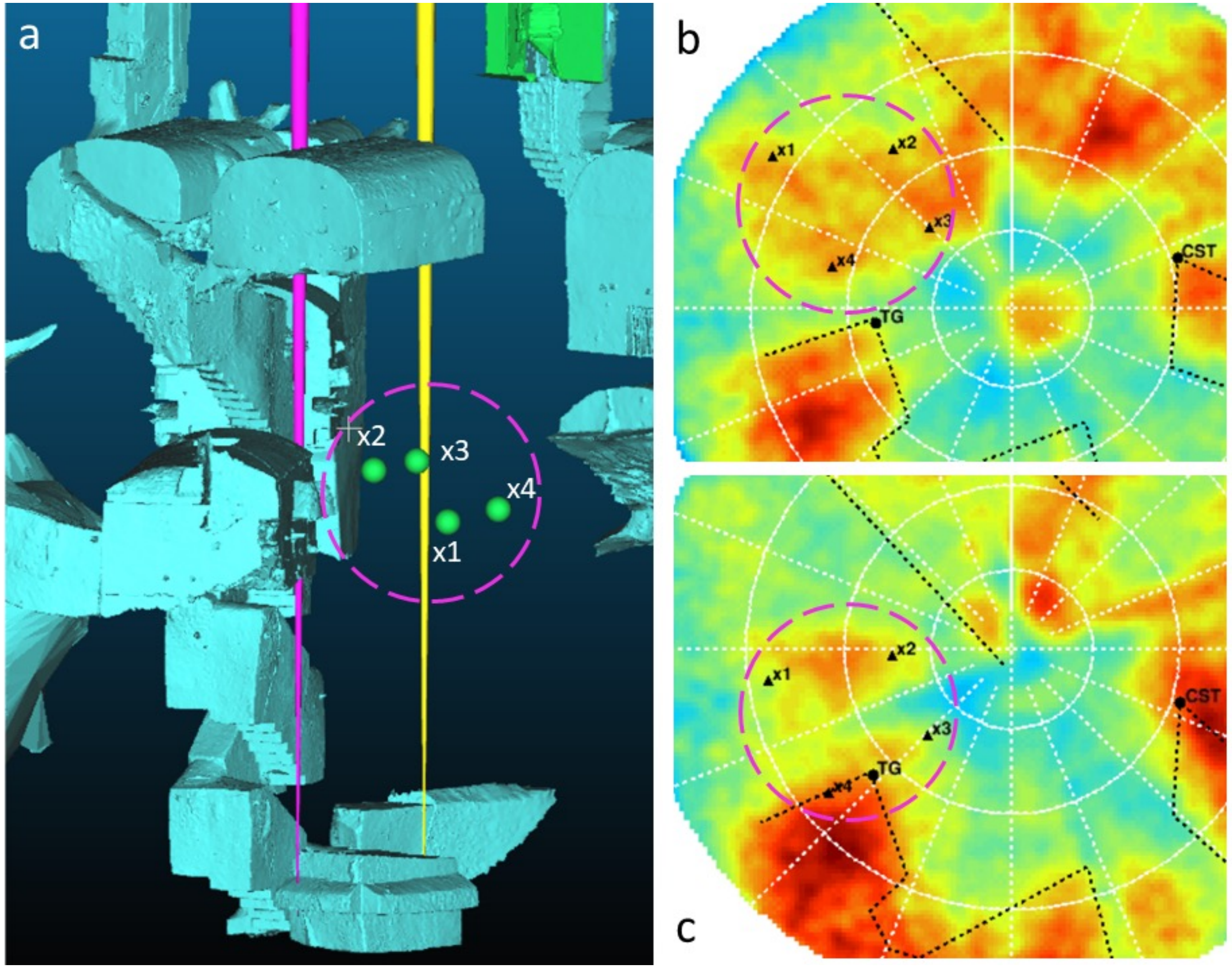
28 days data accumulation
Two 0.15 m^2 detectors

Hidden chamber discovery in the Sanità district



Hidden chamber discovery in the Sanità district





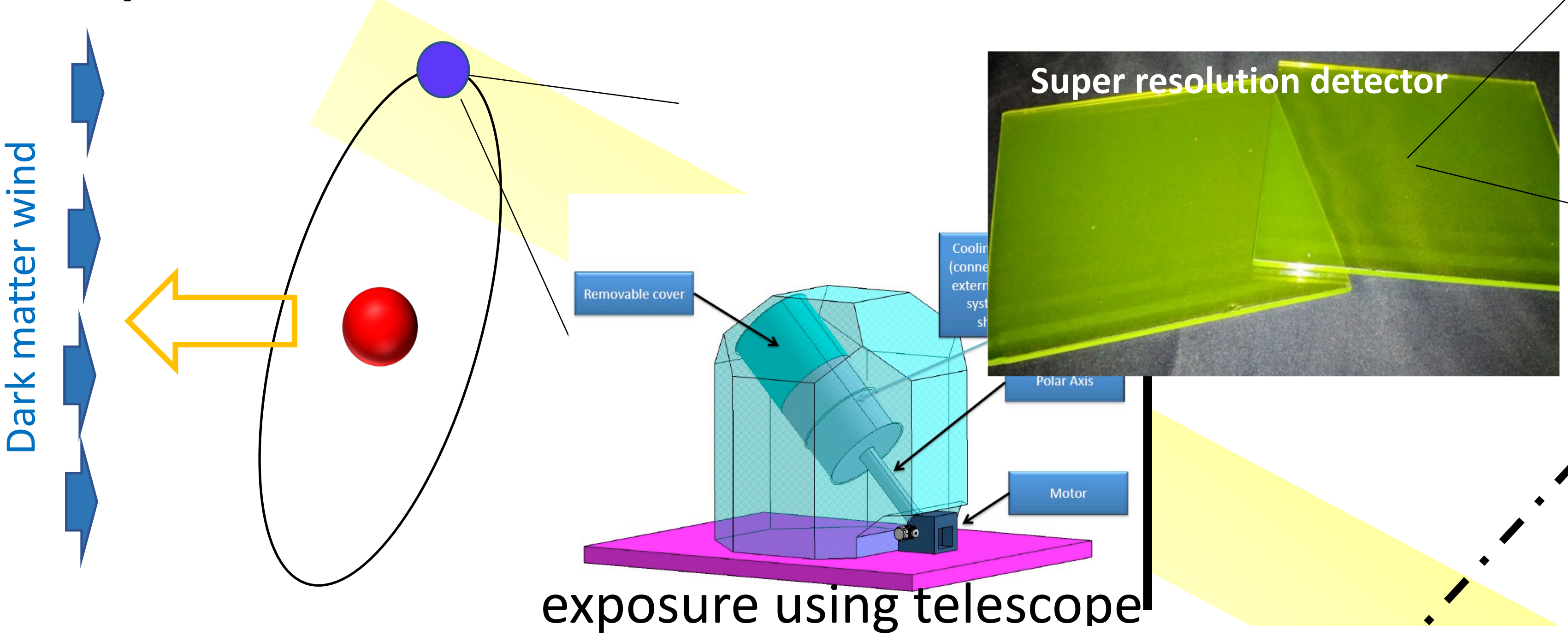
https://doi.org/10.1038/s41598-023-32626-0 Scientific Reports (2023) 13:5438

Valeri Tioukov[1]✉, Kunihiro Morishima[5], Carlo Leggieri[3], Federico Capriuoli[4], Nobuko Kitagawa[5], Mitsuaki Kuno[5], Yuta Manabe[5], Akira Nishio[5], Andrey Alexandrov[1,2], Valerio Gentile[1,2], Antonio Iuliano[1,2] & Giovanni De Lellis[1,2]

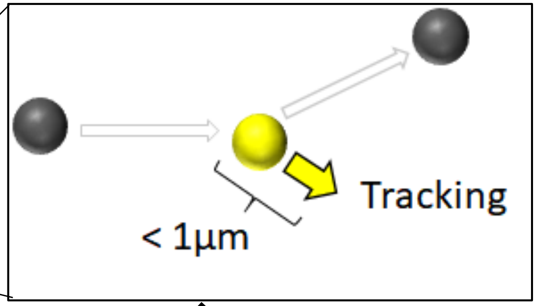
Back to fundamental science: the dark matter problem

NEWSdm experiment concept

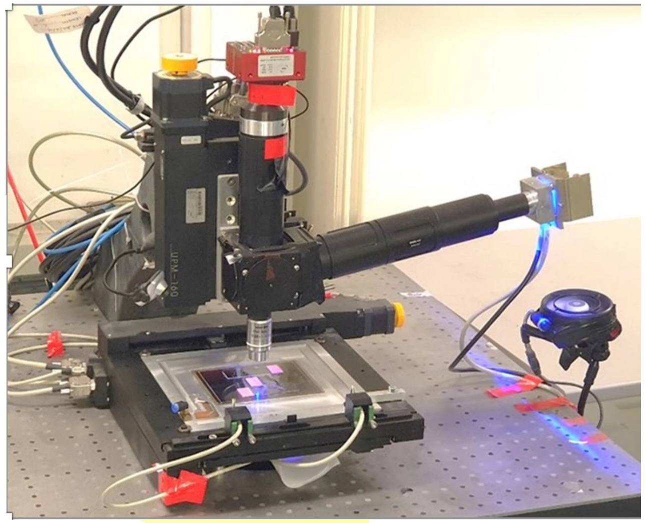
Direction sensitive dark matter search with nano-tracking technologies for super resolution nuclear emulsion



exposure using telescope



Optical image readout



Underground laboratory
Gran Sasso (LNGS)

80 physicists in 5 Countries

ITALY
LNGS
INFN e Univ. Napoli
INFN Roma

TURKEY
METU Ankara

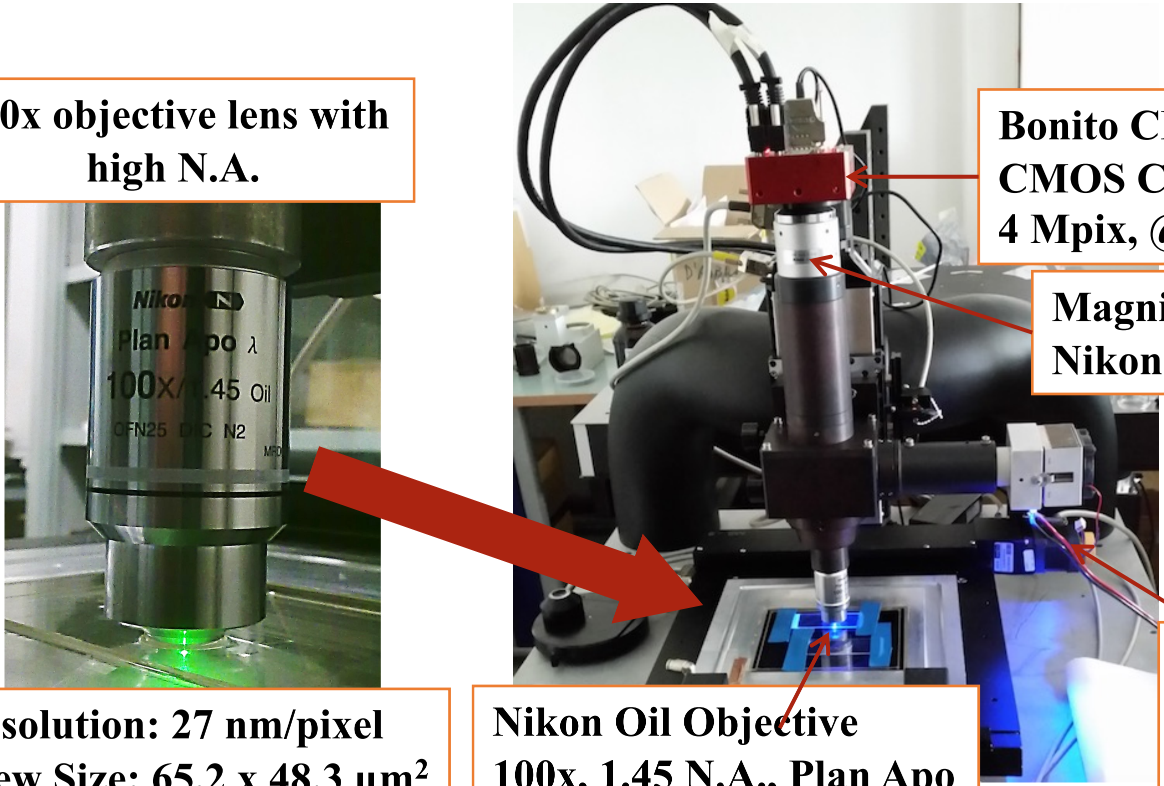
SOUTH KOREA
Gyeongsang

RUSSIA
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
MISiS
Yandex School of Data Analysis

JAPAN
Nagoya
Chiba
Toho

NIT technology developed at Nagoya University

OPTICAL MICROSCOPE READ-OUT: STEP 1



100x objective lens with high N.A.

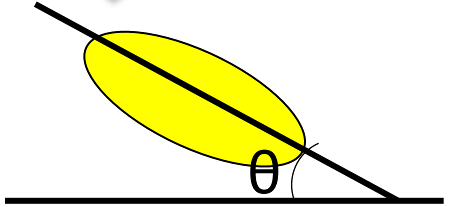
Bonito CL/CMC-4000 CMOS Camera 4 Mpix, @100 fps

Magnifying lens, Nikon VM C-2.5x

100W Halogen Lamp

Resolution: 27 nm/pixel
View Size: 65.2 x 48.3 μm²

Nikon Oil Objective 100x, 1.45 N.A., Plan Apo

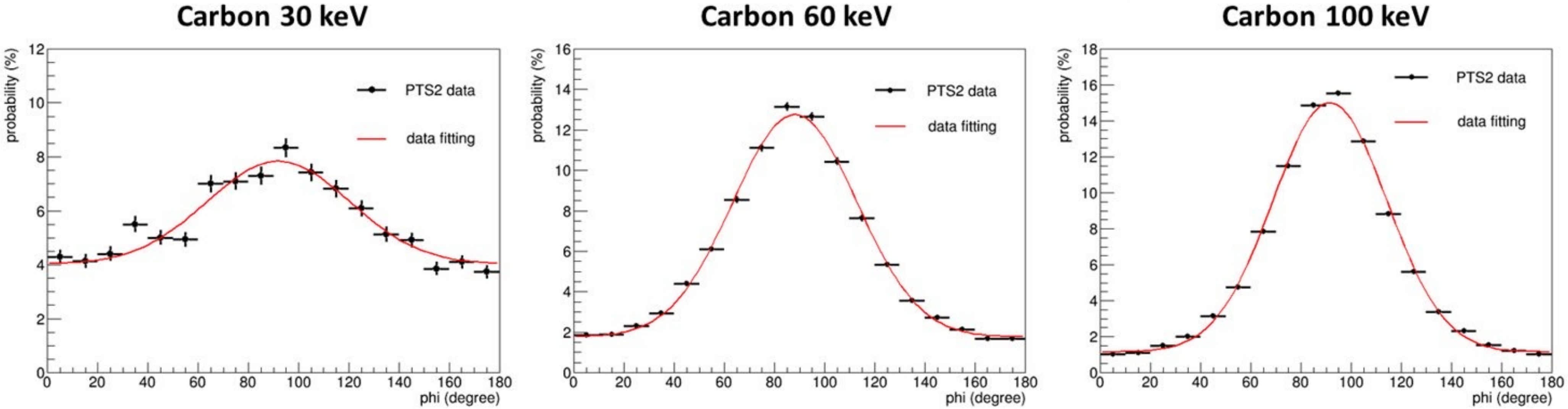


Direction detected!

Scanning with **optical microscope** and **shape analysis**

$\sigma^2 = \sigma^2_{intrinsic}+\sigma^2_{scattering}$

$\sigma_{int} \sim 13$ degrees

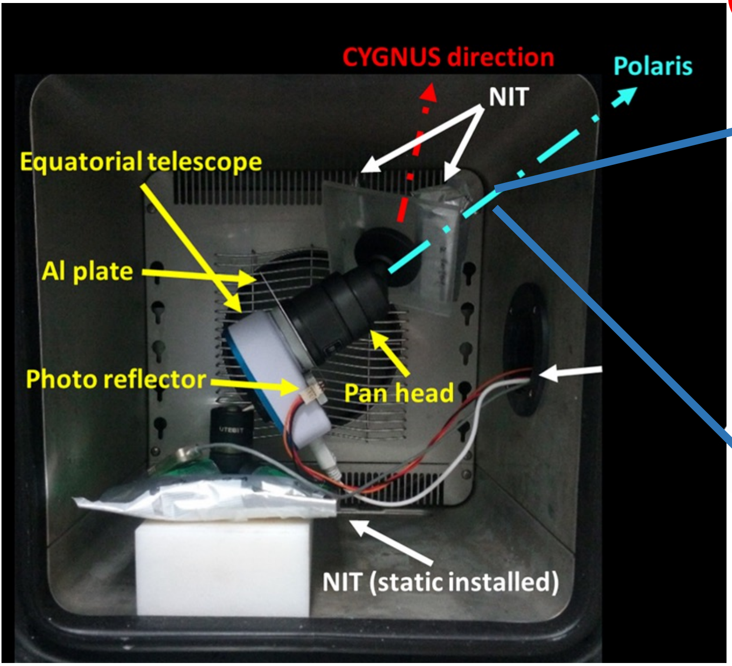

Carbon 30 keV

Carbon 60 keV

Carbon 100 keV

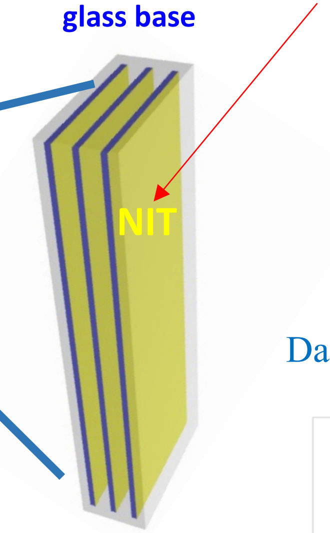
Demonstration of directional dark matter search exposure on the surface without shield

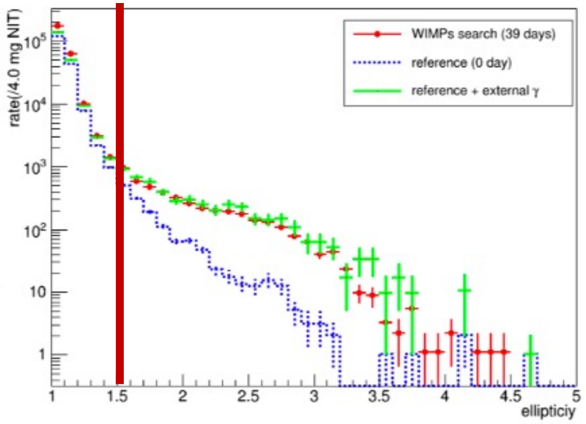
Technical test



Keeping the orientation to Cygnus

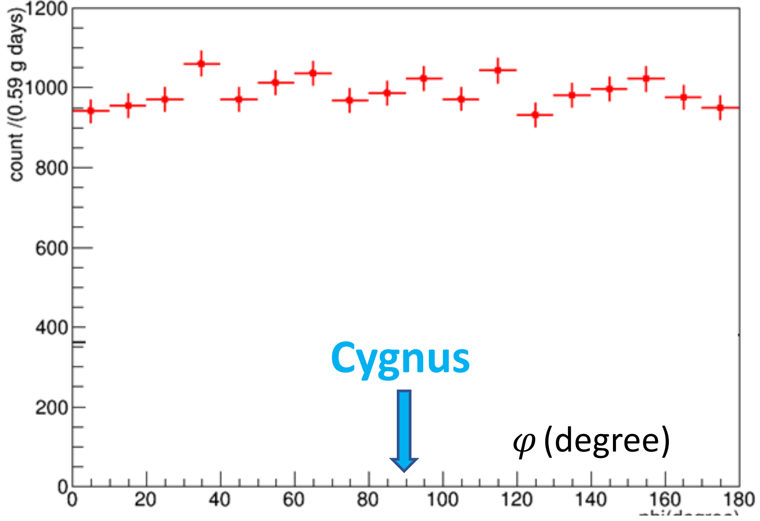
CYGNUS (parallel to x axis)
glass base



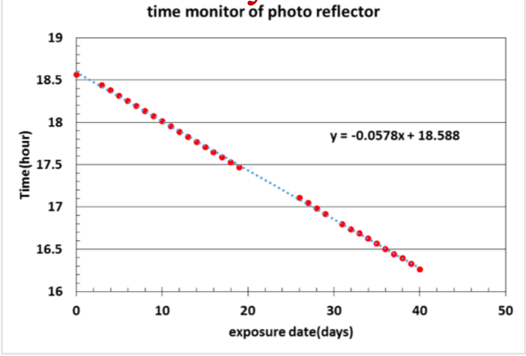


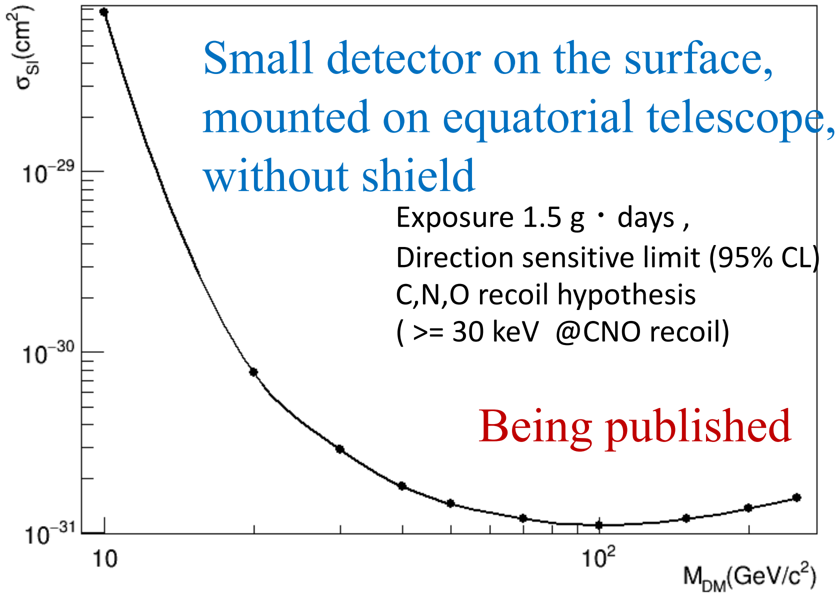
Data well described by the background model

φ distribution (ellipticity≧1.5)



Sidereal day: 23h 56' 4s"





Small detector on the surface, mounted on equatorial telescope, without shield

Exposure 1.5 g・days ,
Direction sensitive limit (95% CL)
C,N,O recoil hypothesis
(>= 30 keV @CNO recoil)

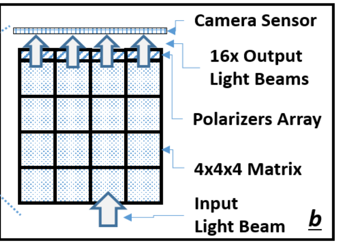
Being published

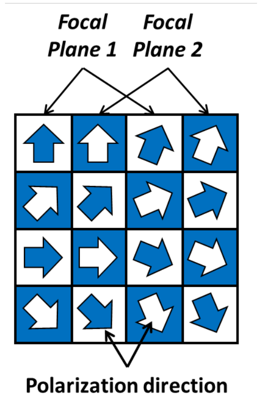
- **First demonstration of tracking analysis with a solid detector**
- **First directional search in the ~10 GeV/c^2 region**

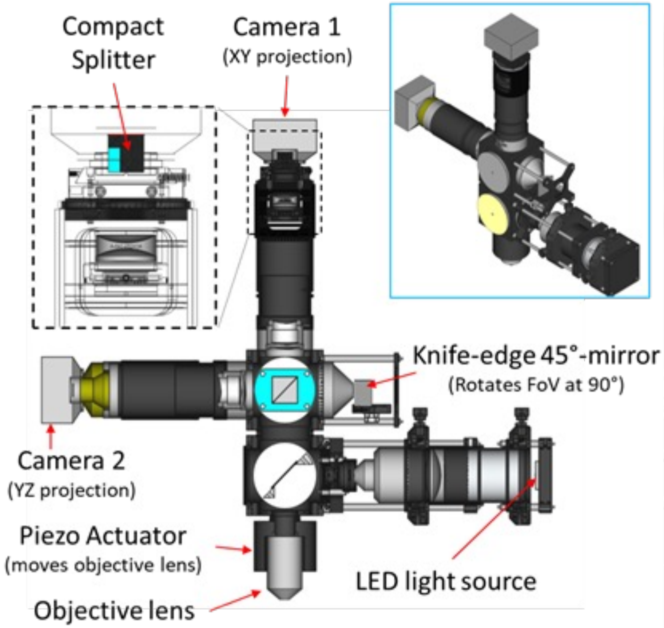
SUPER RESOLUTION MICROSCOPE WITH 3D RECONSTRUCTION

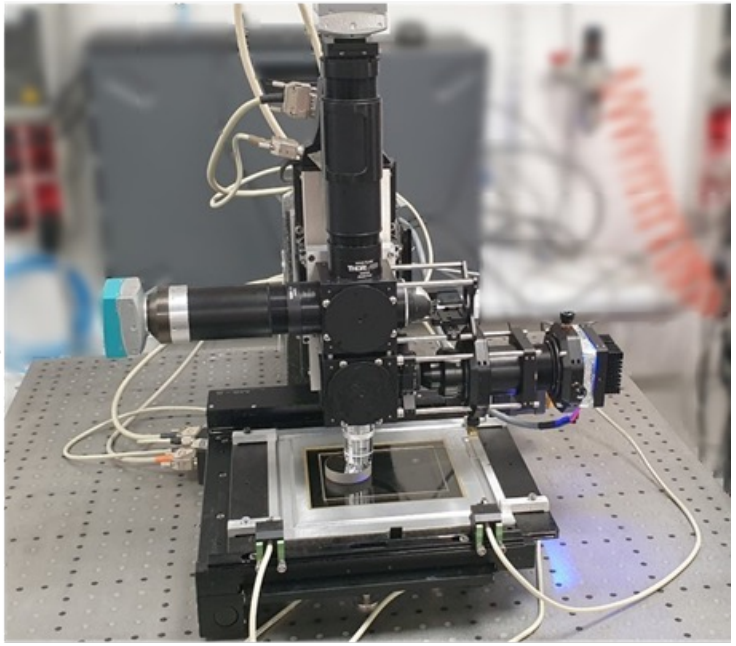
A. Alexandrov, GDL, V. Tioukov, N. D'Ambrosio

Breakthrough

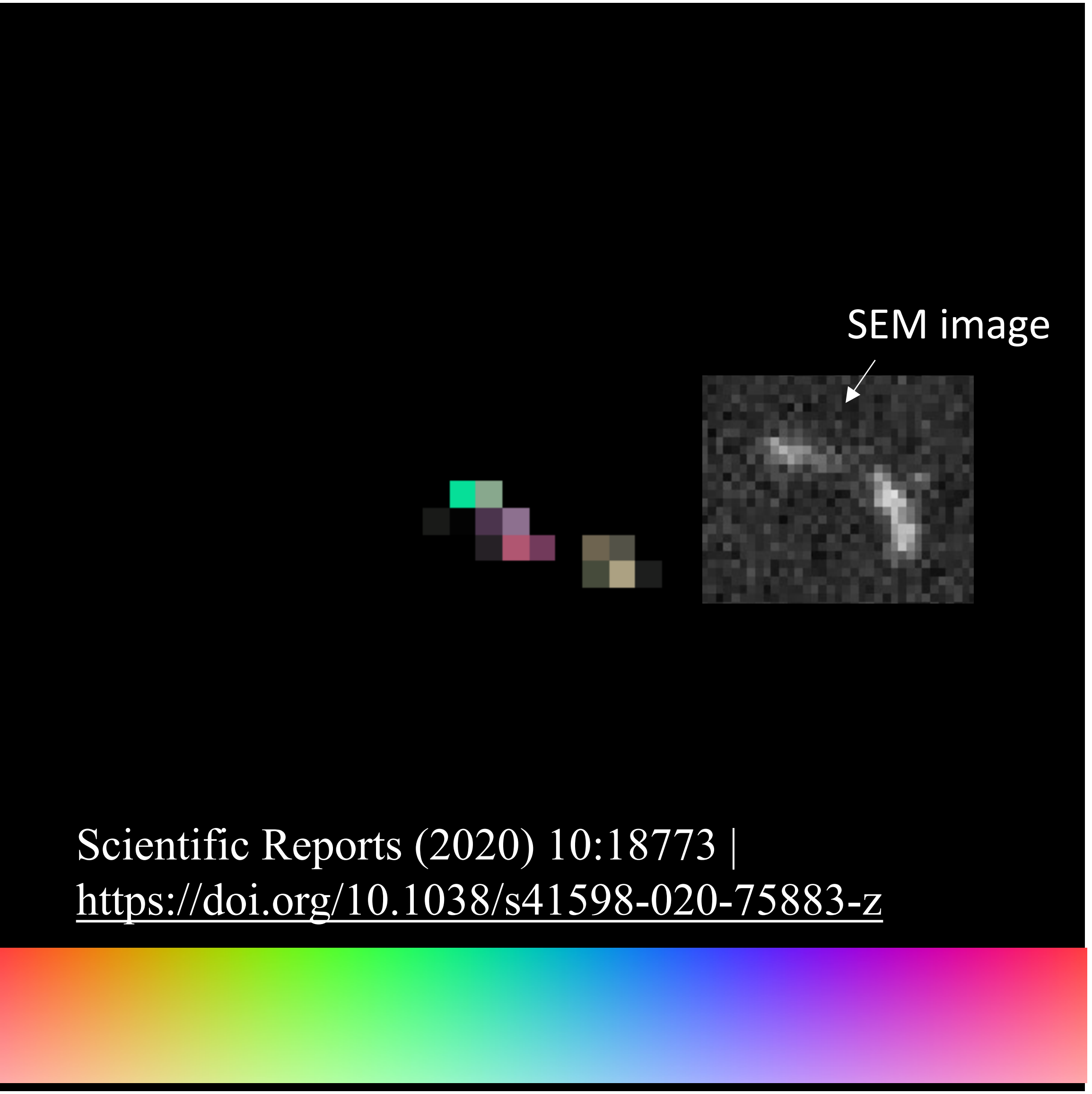








Super-resolution imaging (plasmon resonance) for low-energy ion tracking in NIT



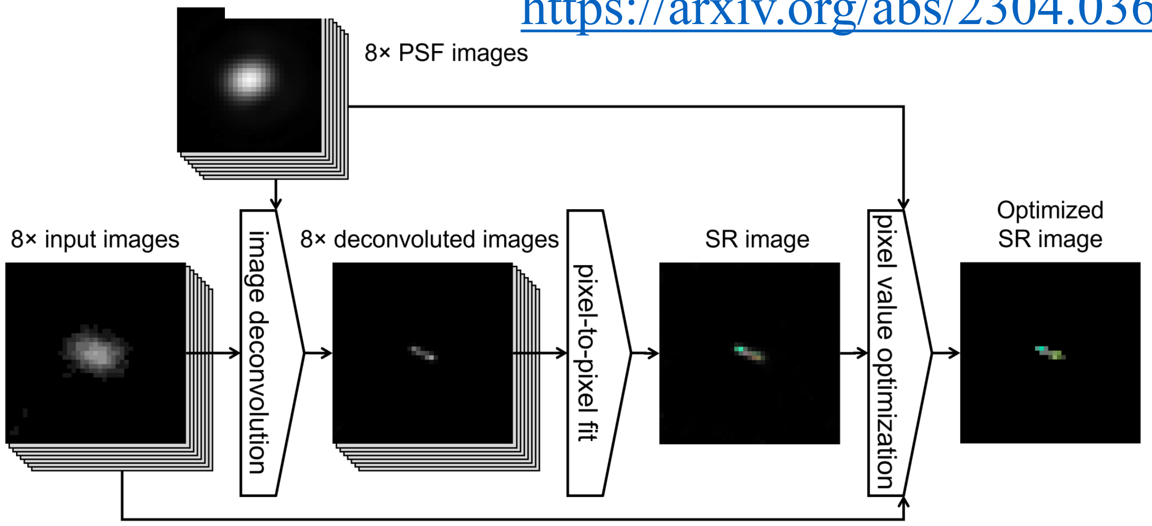
Scientific Reports (2020) 10:18773 | https://doi.org/10.1038/s41598-020-75883-z

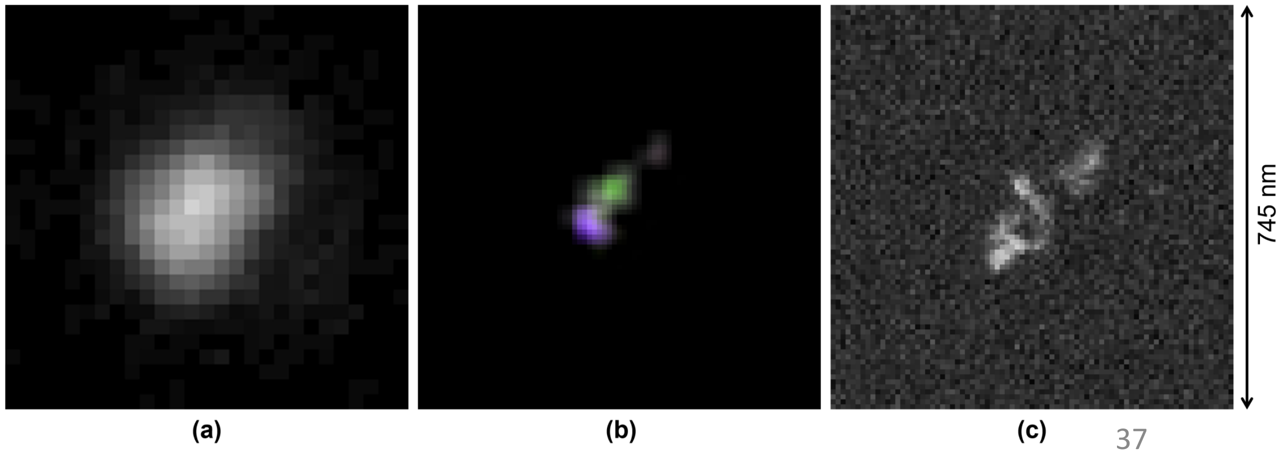

Prepared for submission to Scientific Reports

Super-resolution imaging for the detection of low-energy ion tracks in fine-grained nuclear emulsions

Andrey ALEXANDROV[1,2,*], Takashi ASADA[1,2], Fabio BORBONE[1], Valeri TIOUKOV[2], and Giovanni DE LELLIS[1,2]

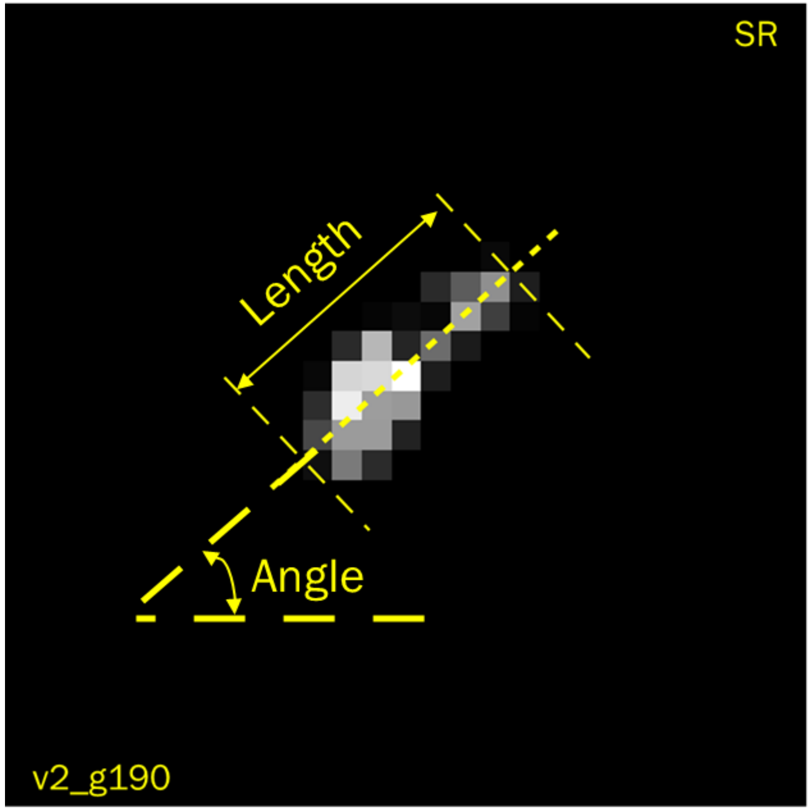
https://arxiv.org/abs/2304.03645

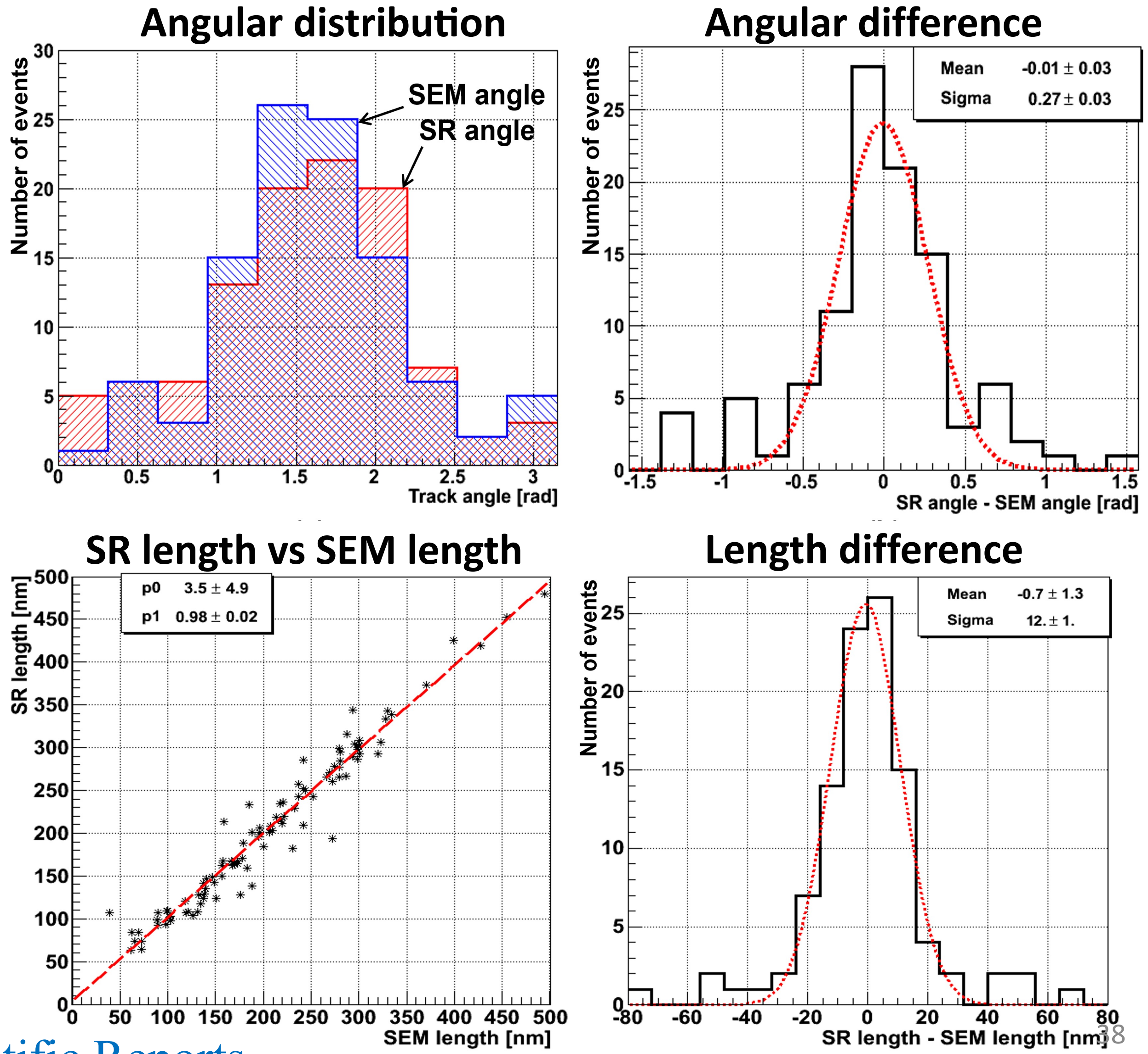




Optical mic. SR image SEM

Super-resolution imaging for the detection of low-energy ion tracks in fine-grained nuclear emulsions





Angular resolution: 270 ± 30 mrad

Length accuracy: 12 ± 1 nm

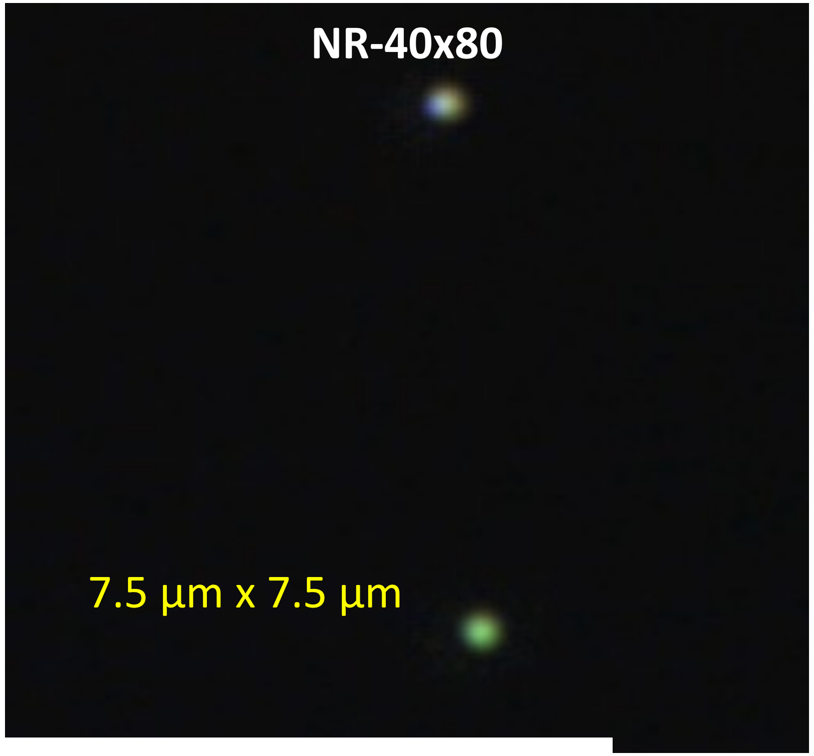
Spatial resolution: ~ 60 nm

NIT granularity: 71 nm

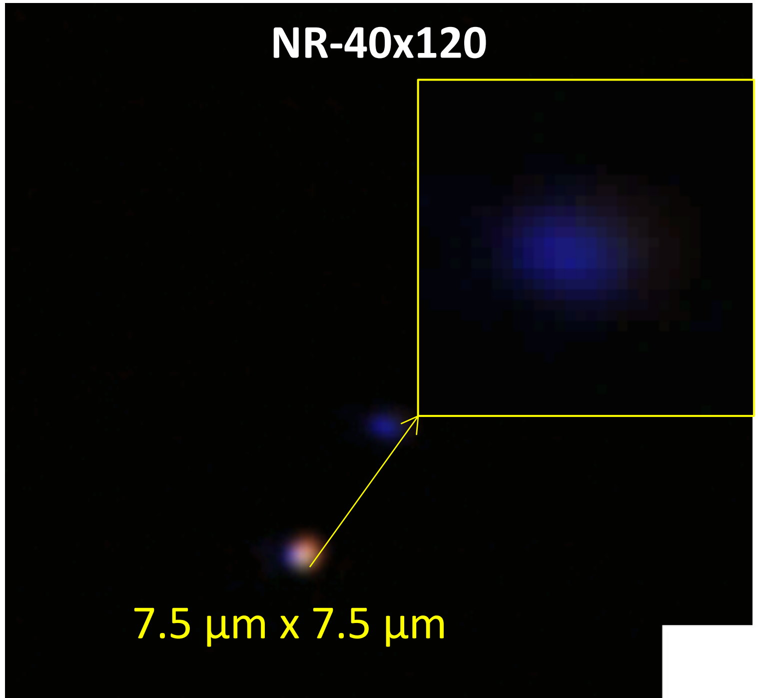
https://arxiv.org/abs/2304.03645 Scientific Reports

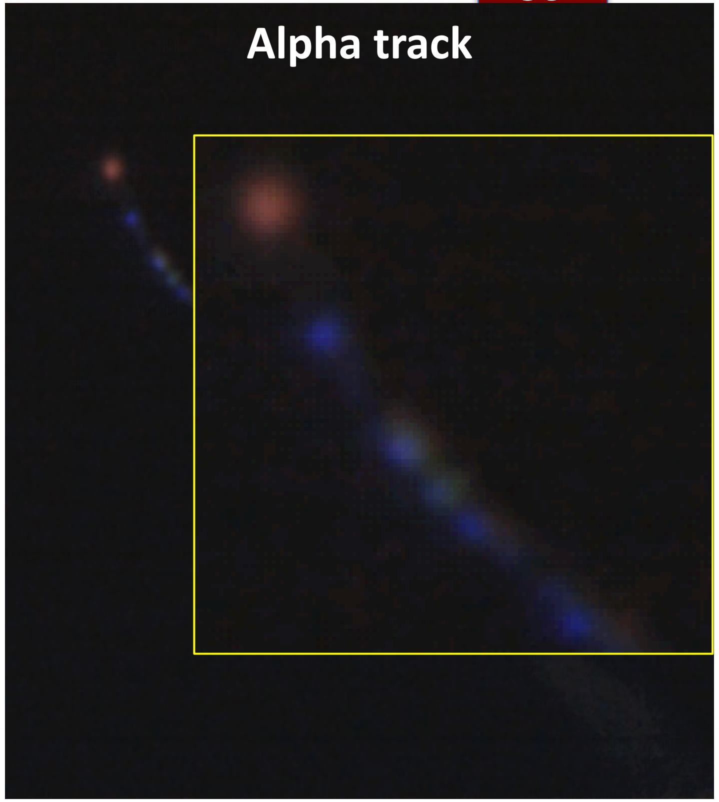
Plasmon wavelength response: silver nanorods for calibration

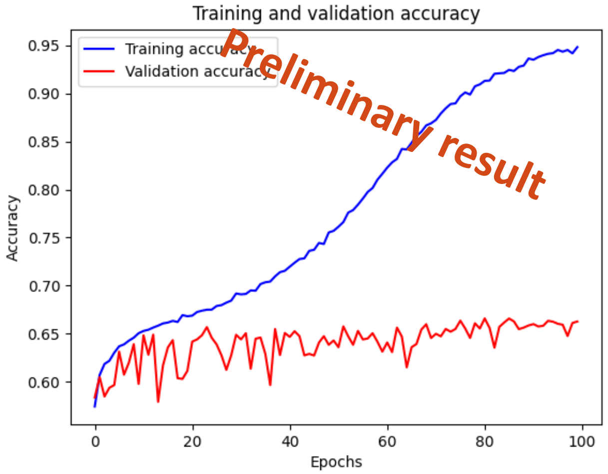
40 nm diameter, 80 nm height



40 nm diameter, 120 nm height



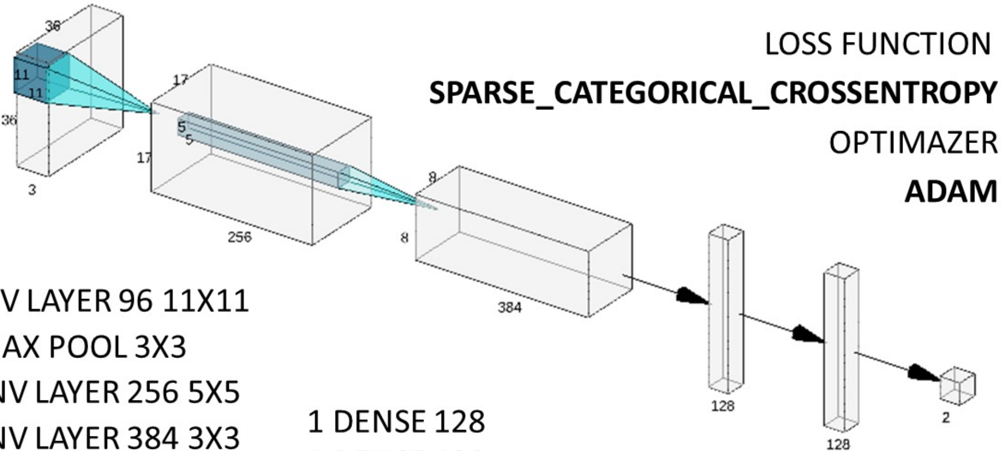




Machine learning technique for head-tail sense recognition

Sense prediction accuracy = 65%

Only the colour information used, polarization to be included



LOSS FUNCTION

SPARSE_CATEGORICAL_CROSSENTROPY

OPTIMAZER

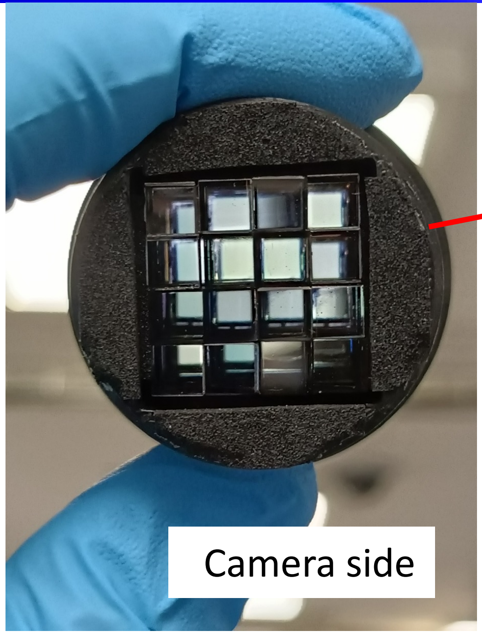
ADAM

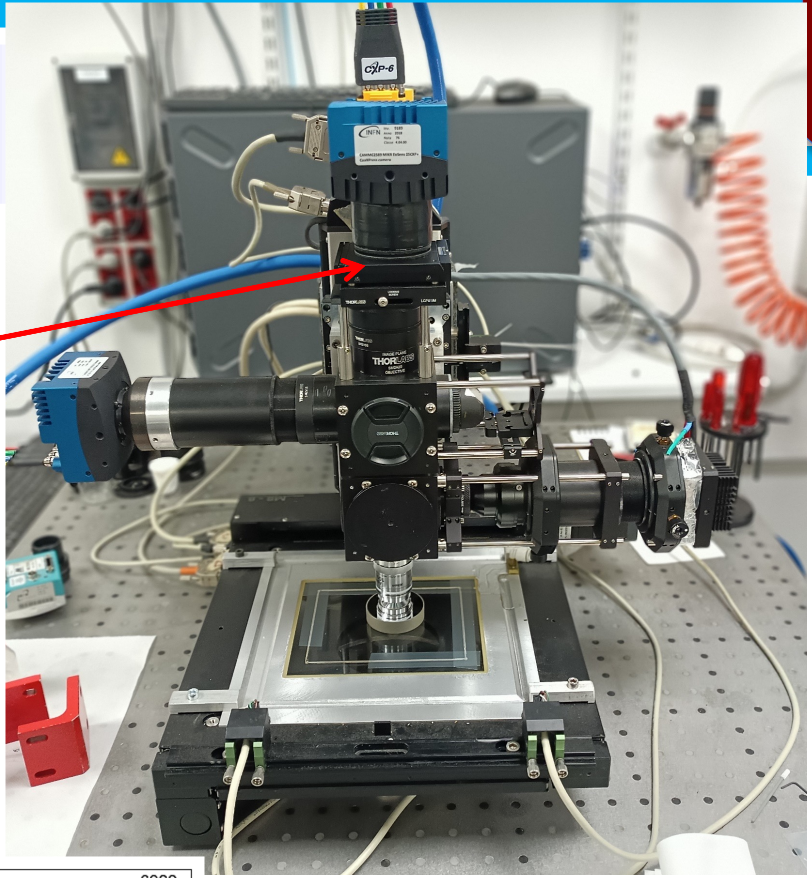
1 CONV LAYER 96 11X11
MAX POOL 3X3
2 CONV LAYER 256 5X5
3 CONV LAYER 384 3X3
MAX POOL 3X3

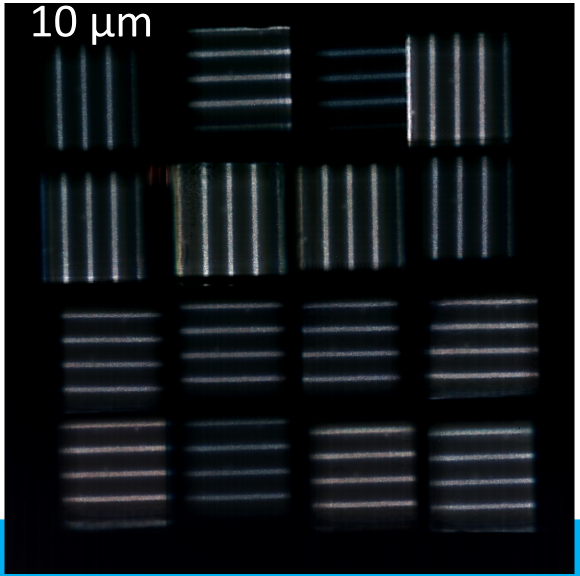
1 DENSE 128
1 DENSE 128
1 DENSE 2

New device: 16x Splitter for 3D nanometric readout


16 output windows (at the opposite side)


Camera side

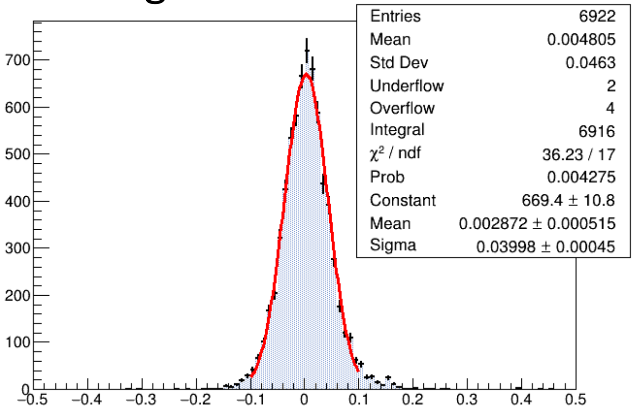


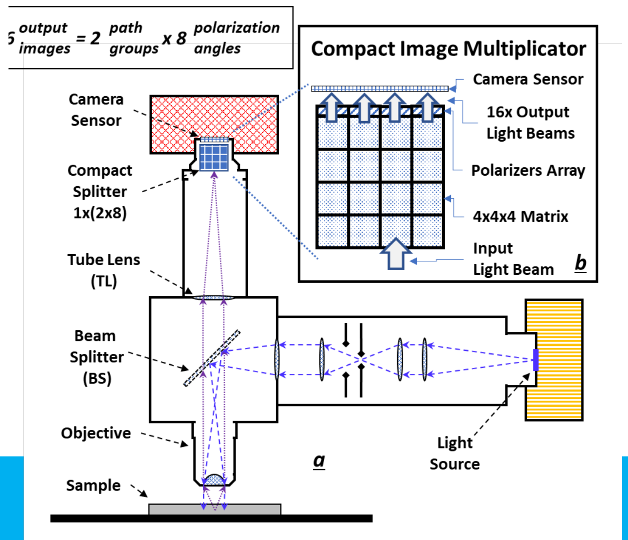


100×
45 nm/pixel
27 µm × 27 µm

~22% sensor surface
5.5/25 Mpixel

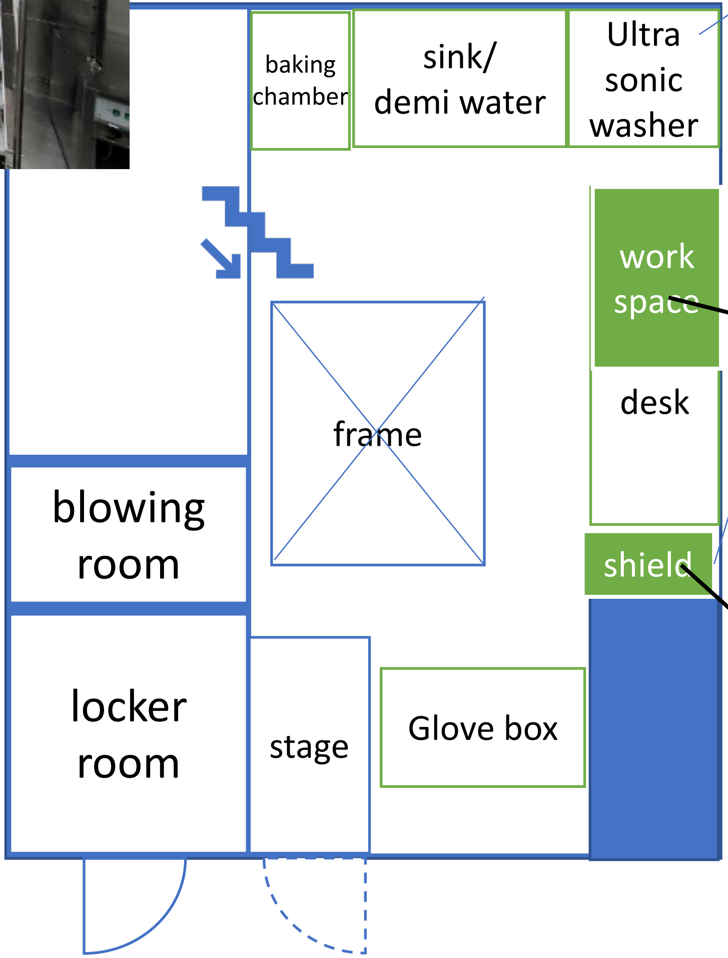
along Z ~40 nm





Another patent according to the INFN office

CR1


baking chamber

sink/ demi water

Ultra sonic washer

work space

desk

frame

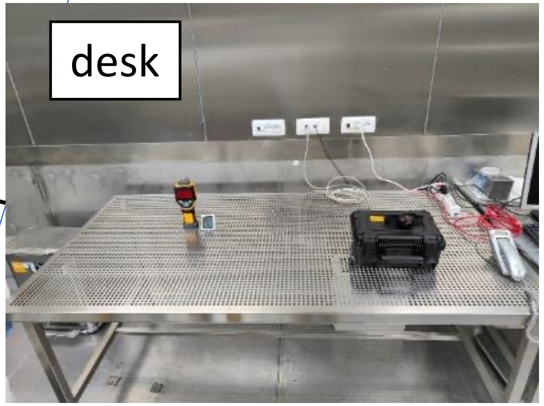
shield

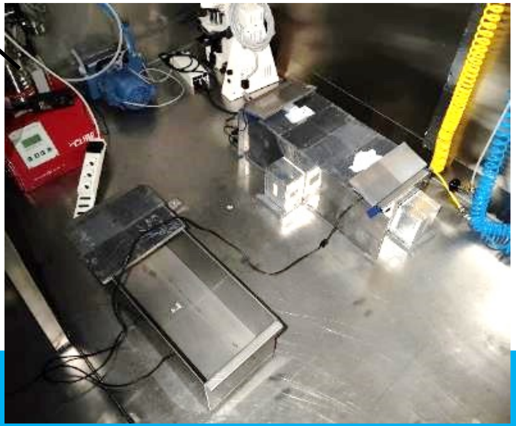
blowing room

locker room

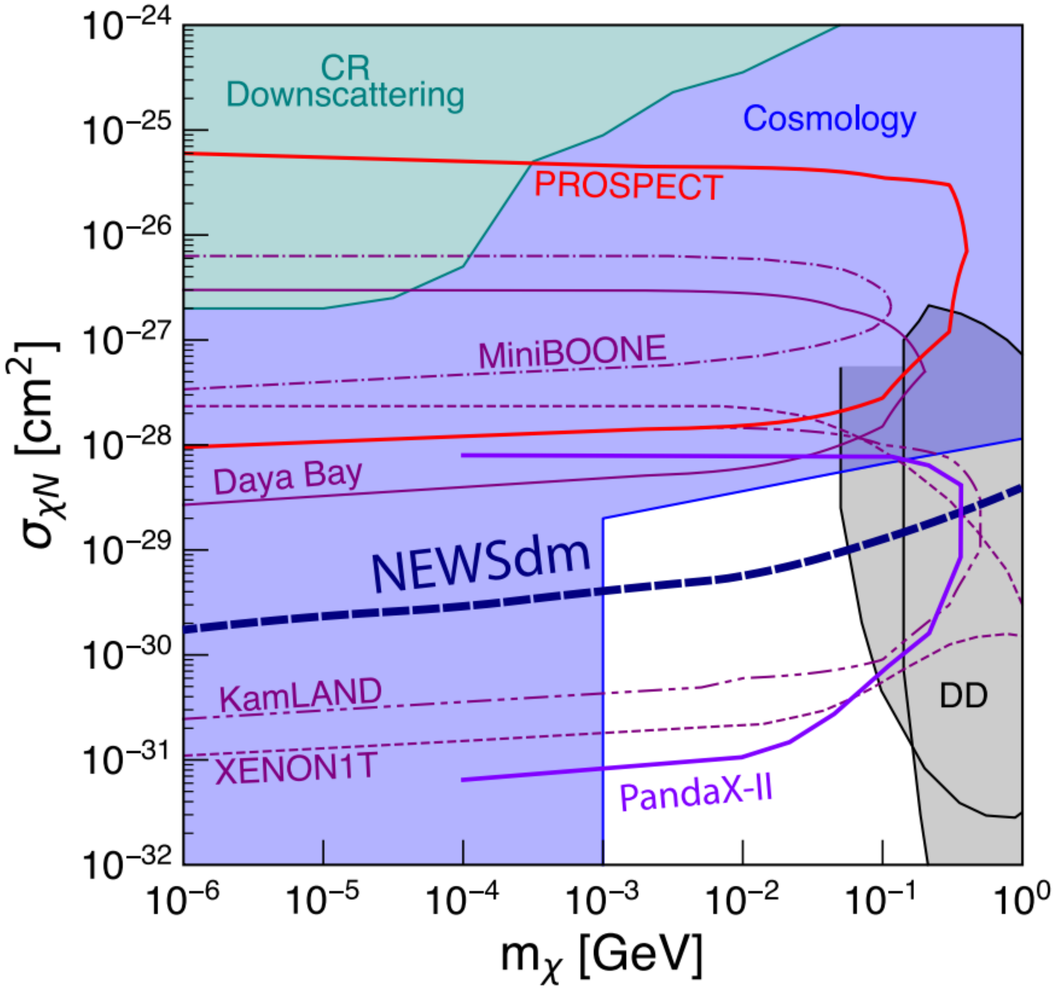
stage

Glove box





Sensitivity of a 10kg year emulsion detector to BDM



https://iopscience.iop.org/article/10.1088/1475-7516/2023/07/067/pdf JCAP 07 (2023) 067

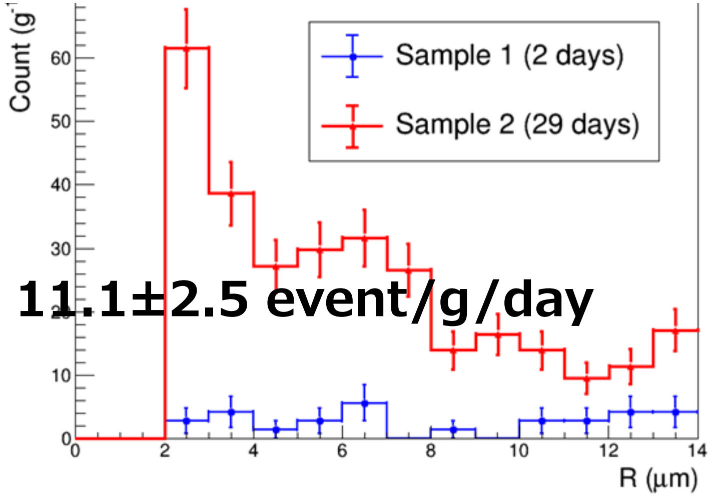
- NEWSdm sensitivity curve: operate a 10 kg year detector on the surface. Detector mass much smaller than other detectors
- Most of the limits (Daya Bay, KamLAND, MiniBOONE and XENON1T) obtained by theorists who recomputed the sensitivity. Only PROSPECT and PandaX-II have done their own analysis.
- XENON1T, PandaX-II, Kamland and Daya Bay are located deep underground
- PROSPECT and MiniBOONE are similar to NEWSdm from the operation point of view.

Surface exposure possible thanks to the long track lengths. The measurement of sub-MeV energy neutrons on the surface laboratory with a NIT detector has demonstrated this concept

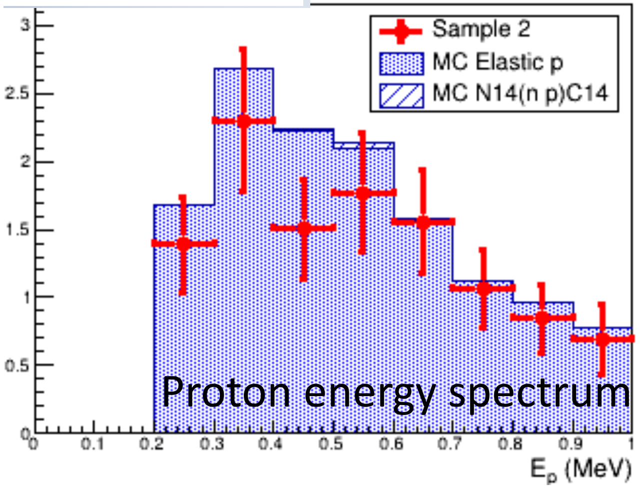
First directional and sub-MeV neutron measurement at LNGS

Environmental sub-MeV neutron measurement at the Gran Sasso surface laboratory with a super-fine-grained nuclear emulsion detector

T. Shiraishi,[1, a)] S. Akamatsu,[1] T. Naka,[1,2] T. Asada,[3,4] G. De Lellis,[3,4] V. Tioukov,[4] G. Rosa,[5] R. Kobayashi,[6]
N. D'Ambrosio,[7] A. Alexandrov,[3,4] and O. Sato[8]

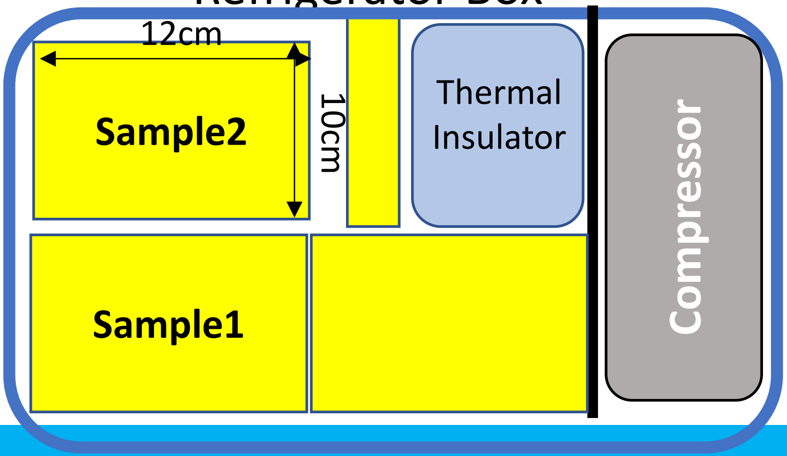


11.1±2.5 event/g/day



Proton energy spectrum

Refrigerator Box

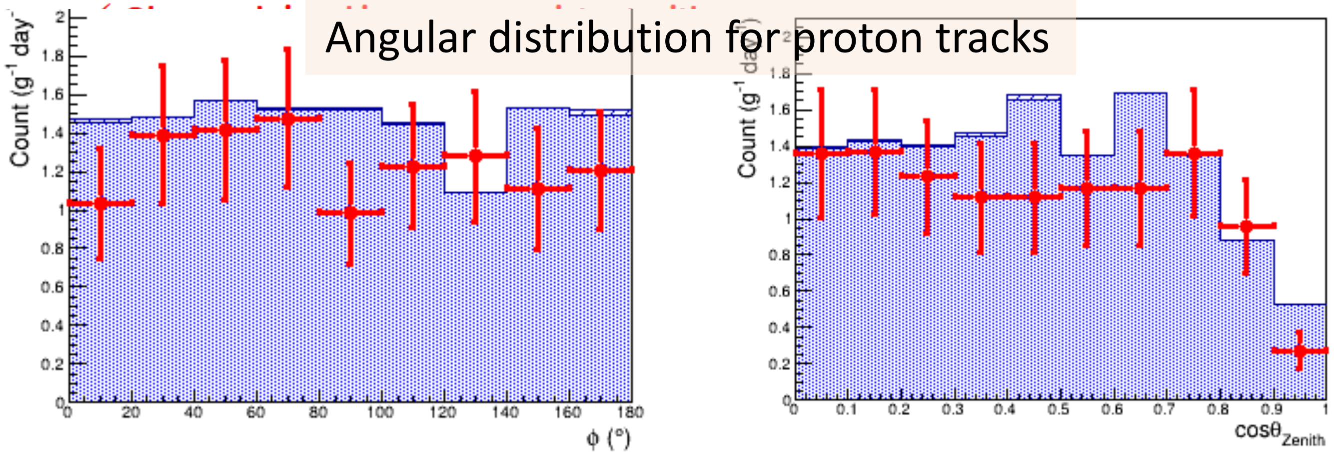


Sample2

Thermal Insulator

Sample1

Compressor



Angular distribution for proton tracks

Neutron Flux @0.25-10 MeV :
$(7.6 \pm 1.7) \times 10^{-3}$n cm^{-2} s^{-1}

First measurement of sub-MeV neutron with direction information

Phys. Rev. C 107, 014608 (2023)

Neutrino physics at CERN

Future plans at the SPS: SHiP

Search for Feebly Interacting Particles and study νs

Accelerator schedule	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC	Run 3				LS3			Run 4				LS4
SPS (North Area)	🟩	🟩	🟩	🟩	🟥	🟥	🟥🟧🟩	🟩	🟩	🟩	🟩	🟥
BDF / SHiP	Study	Design and prototyping				Production / Construction / Installation				Operation		🟥

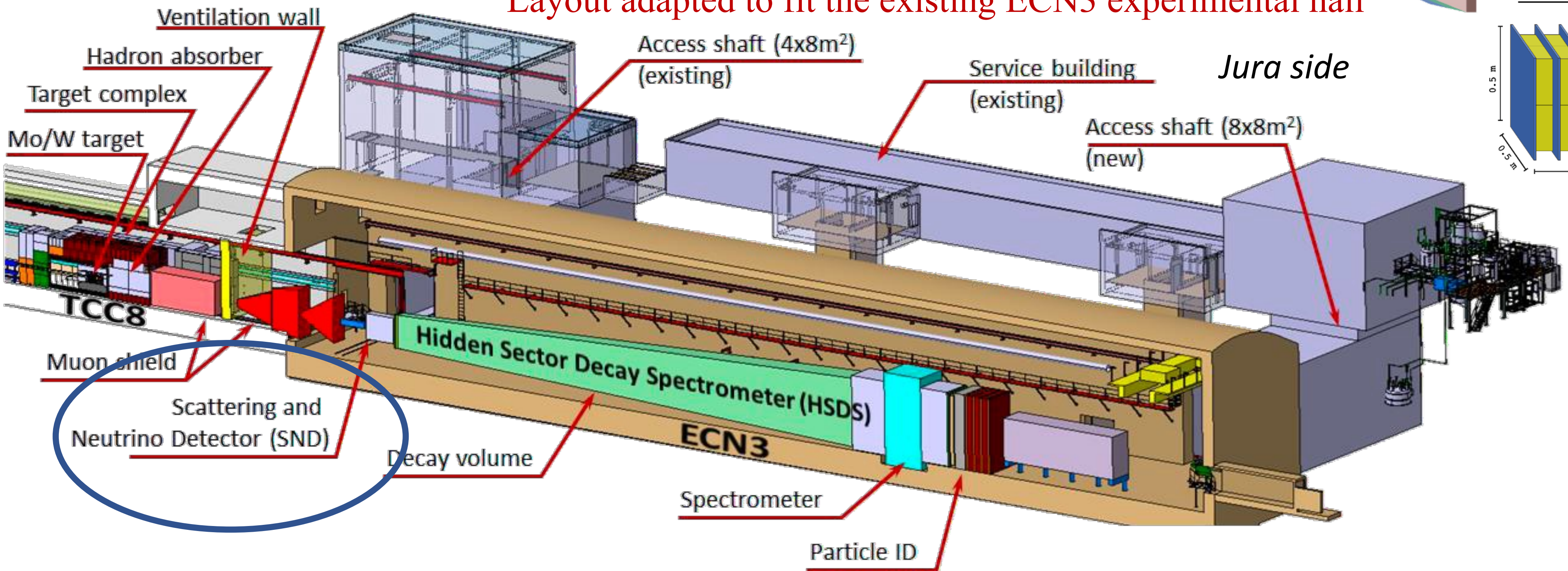
Beam Dump Facility

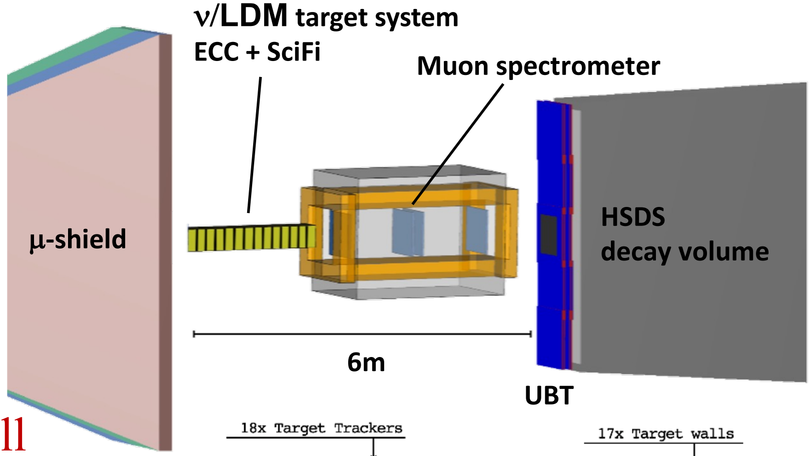
Very thick → use full beam and secondary interactions (12 λ)

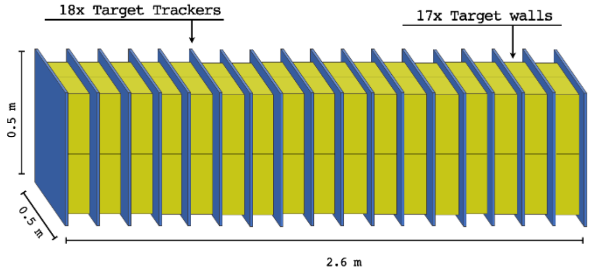
High-A&Z → maximise production cross-sections (Mo/W)

Short l (high density) → stop π/kaons before decay

Layout adapted to fit the existing ECN3 experimental hall



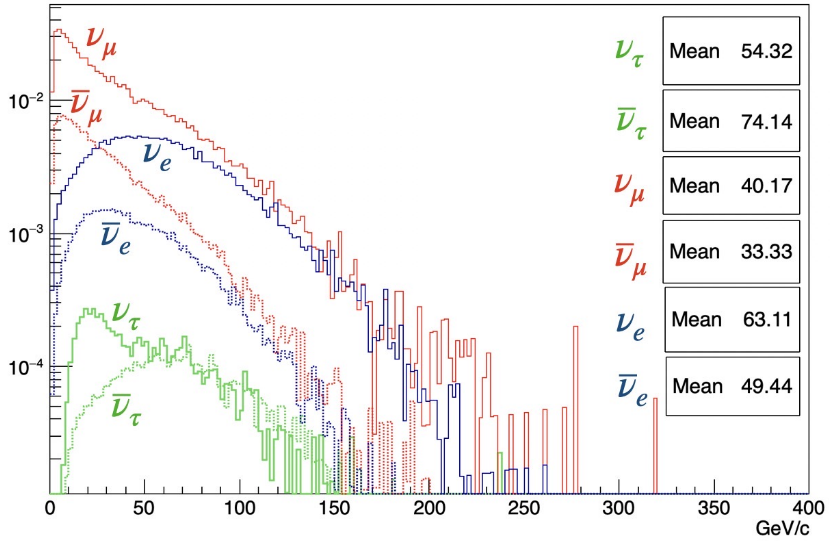




Assume 6×10^{20} pot

	<E> [GeV]	CC DIS interactions
ν_e	63	2.8×10^6
ν_μ	40	8.0×10^6
ν_τ	54	8.8×10^4
$\bar{\nu}_e$	49	5.9×10^5
$\bar{\nu}_\mu$	33	1.8×10^6
$\bar{\nu}_\tau$	74	6.1×10^4

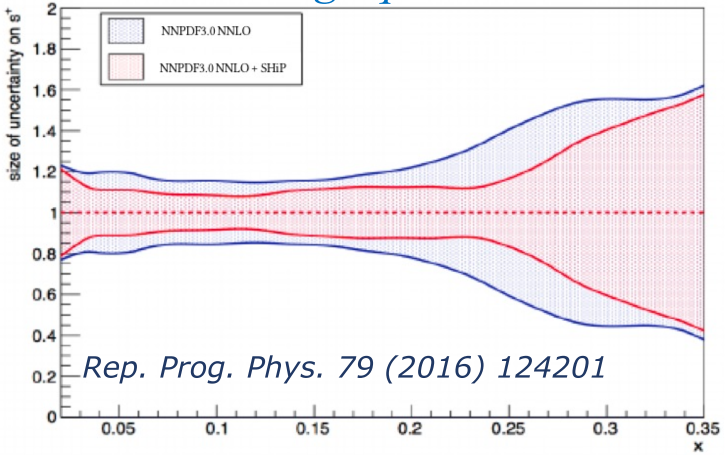
ν_τ cross-section, ν-induced charm, structure functions, …



Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

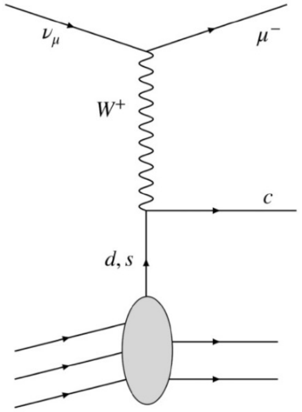
Complementary energy region to the LHC measurements

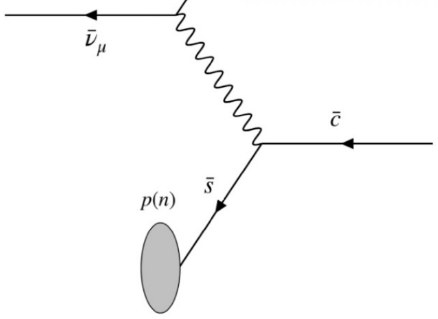
Strange quark distribution



Rep. Prog. Phys. 79 (2016) 124201

ν-induced charm





F4, F5 structure functions

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}\boxed{F_4} - \frac{m_\tau^2}{E_\nu M}\boxed{F_5}\right),$$

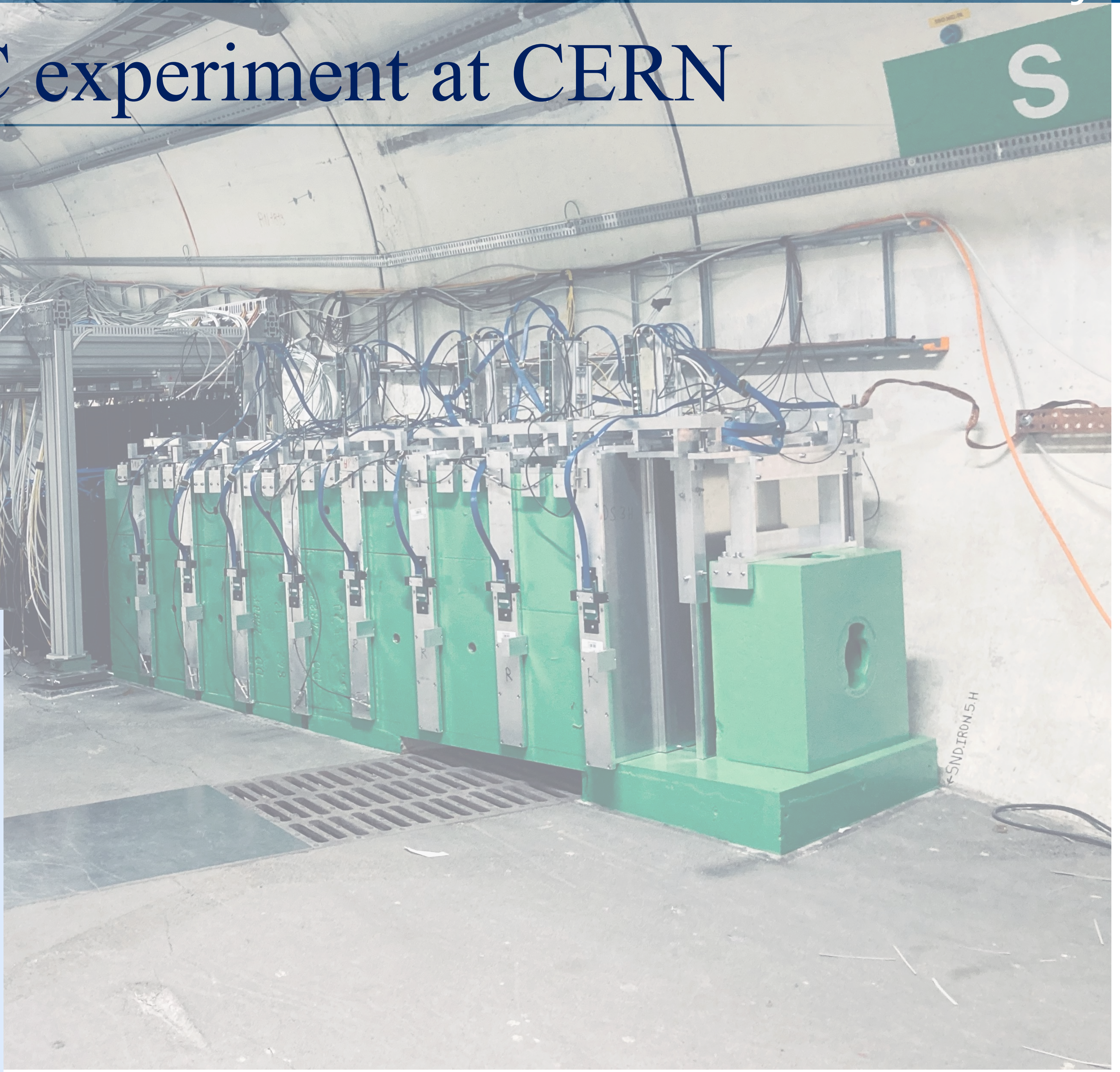
At LO $F_4 = 0$, $2xF_5 = F_2$
At NLO $F_4 \sim 1\%$ at 10 GeV

	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

Neutrino physics with the LHC

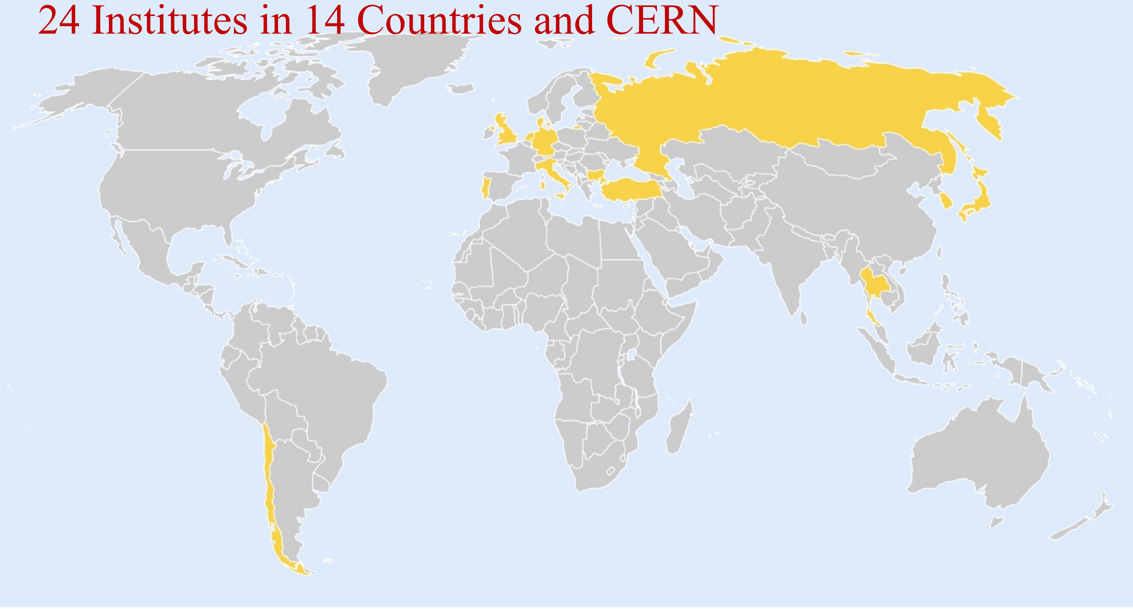
Scattering and Neutrino Detector
at the LHC

The SND@LHC experiment at CERN



Collaboration: 150 members

24 Institutes in 14 Countries and CERN



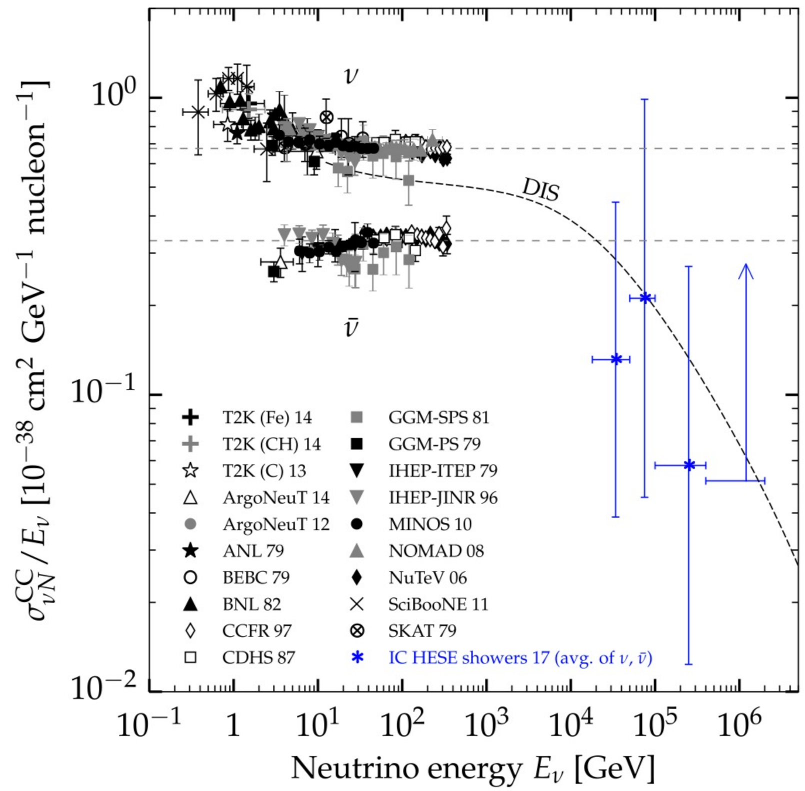
Neutrino physics at the LHC: motivation

LHC

Scattering and Neutrino Detector
at the LHC

- A. De Rujula and R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators, CERN-TH-3892/84
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- F. Vannucci, 1993, neutrino physics at the LHC
- http://arxiv.org/abs/1804.04413 April 12th 2018, First paper on feasibility of studying neutrinos at LHC

PRL 122 (2019) 041101



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IOP Publishing

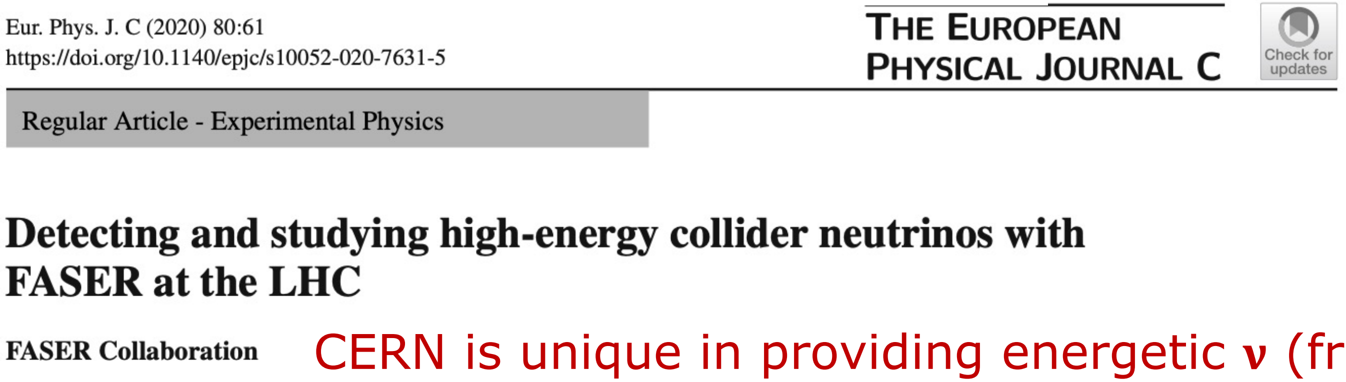
Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp)

https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

N Beni[1], M Brucoli[2], S Buontempo[5], V Cafaro[4],
G M Dallavalle[4,8], S Danzeca[2], G De Lellis[2,3,5],
A Di Crescenzo[3,5], V Giordano[4], C Guandalini[4], D Lazic[6],
S Lo Meo[7], F L Navarria[4] and Z Szillasi[1,2]



Eur. Phys. J. C (2020) 80:61
https://doi.org/10.1140/epjc/s10052-020-7631-5

THE EUROPEAN
PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Detecting and studying high-energy collider neutrinos with FASER at the LHC

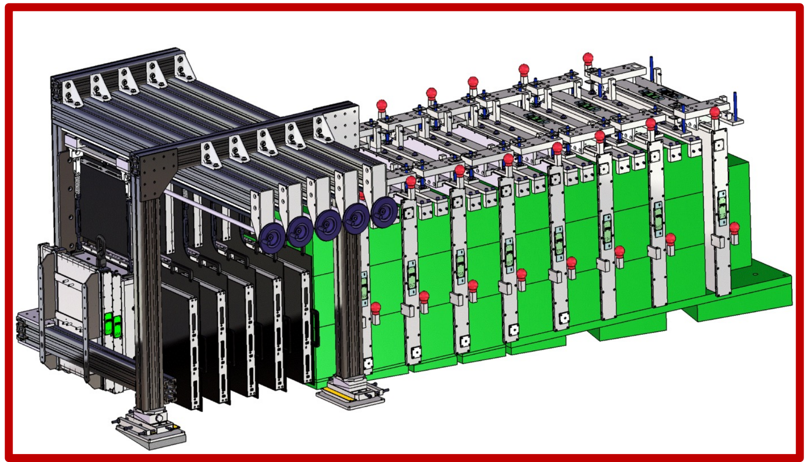
FASER Collaboration

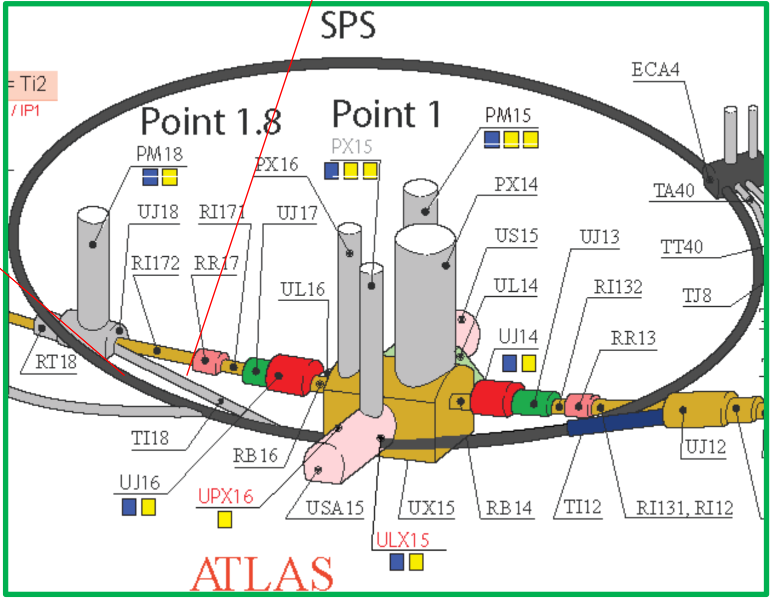
CERN is unique in providing energetic **ν** (from LHC)
and measure pp → **ν**X in an unexplored domain

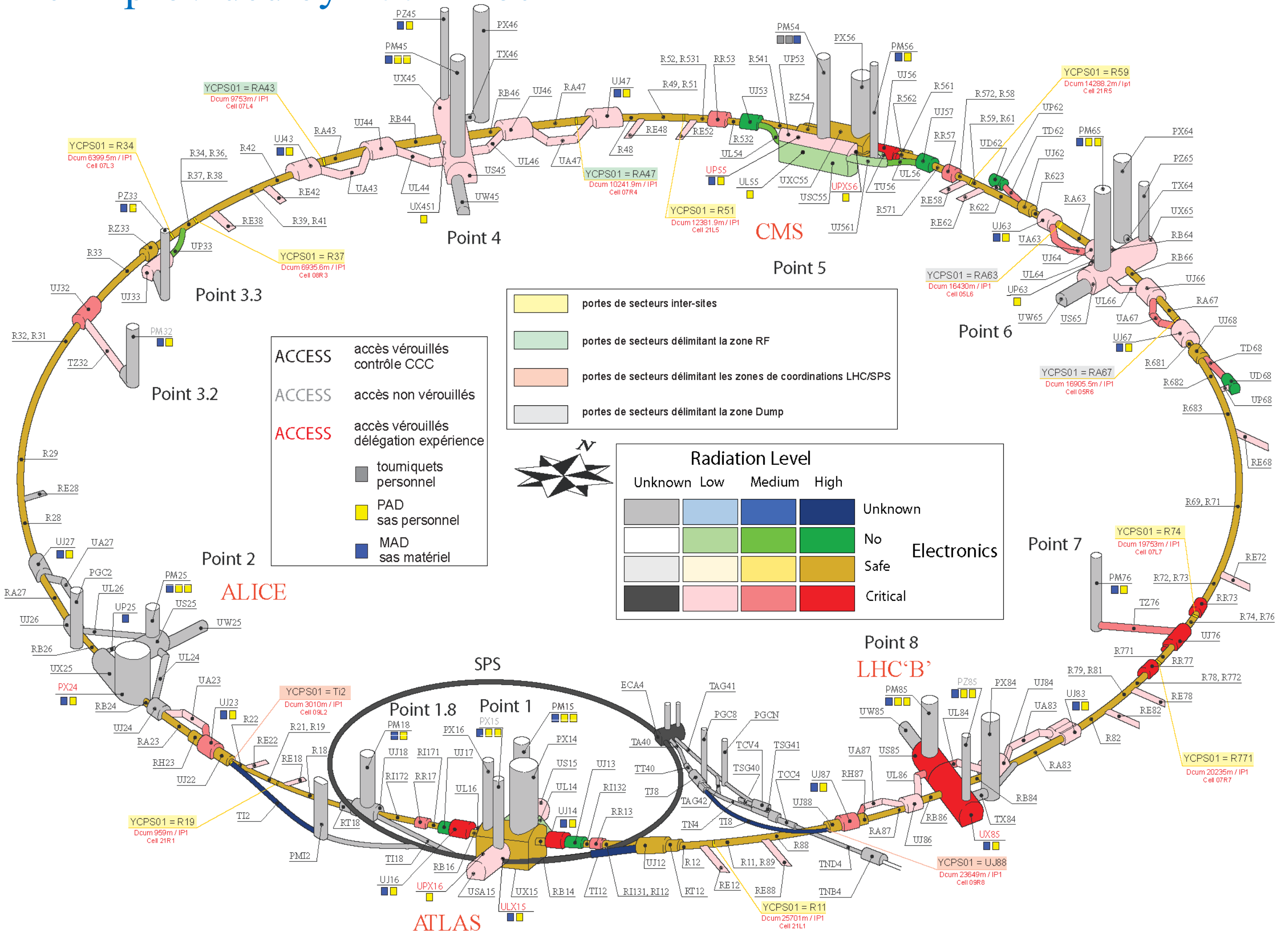
Location: TI18, transfer tunnel connecting SPS to LEP

LHC
Scattering and Neutrino Detector
at the LHC

- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock







The TI18 tunnel at the end of 2020

The tunnel

The LHC seen from the tunnel

Letter of intent presented on August 27th 2020
Technical Proposal presented in January 2021
Experiment approved in March 2021

Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

VETO PLANE:
tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:

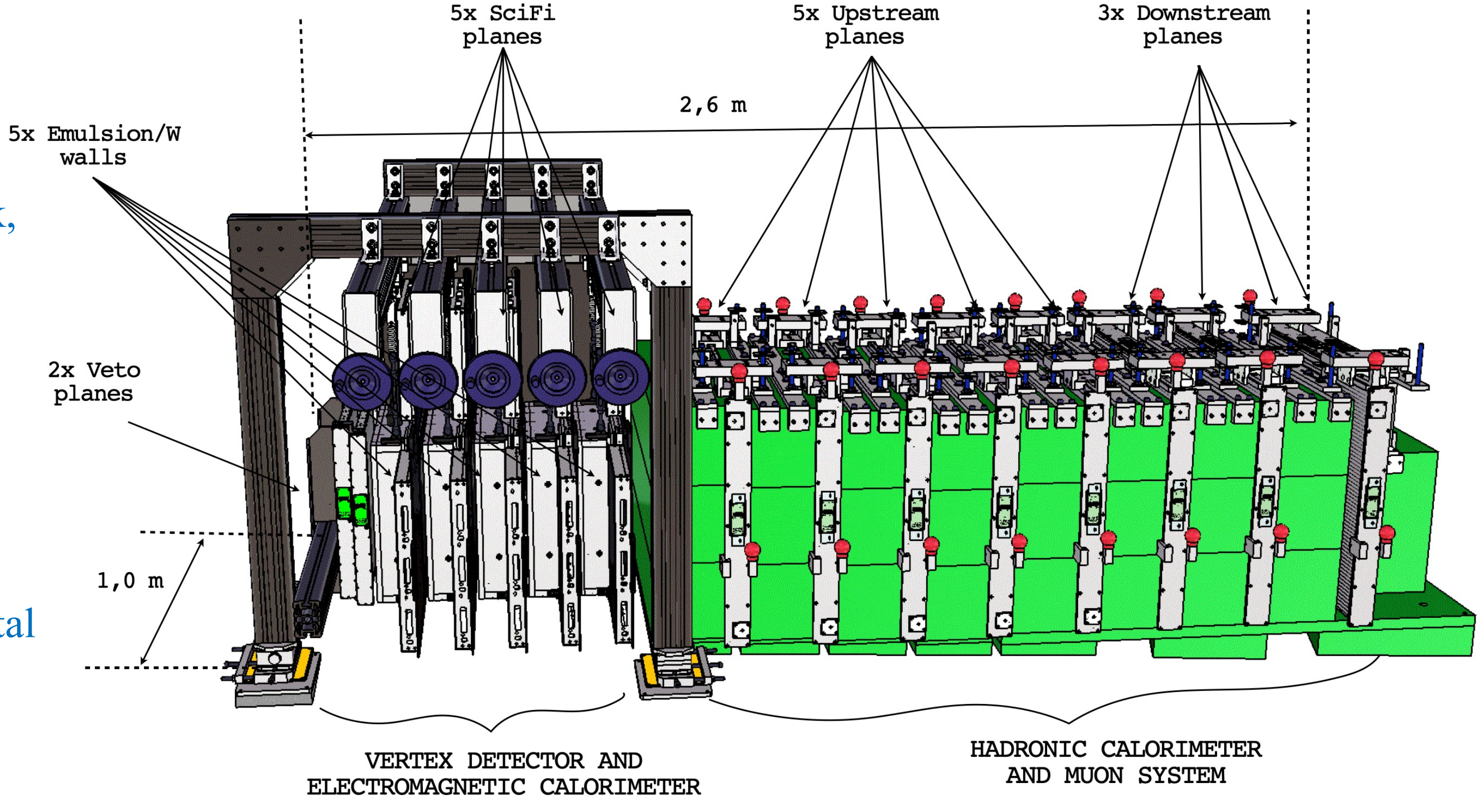
- Emulsion cloud chambers (60 emulsion films, 300μm thick, interleaved by 1mm thick tungsten plates)

E.M. CAL

- 250μm Scintillating fibres for timing information and e.m. energy measurement

HADRONIC CALO:
iron walls interleaved with plastic scintillator planes for a total of about 11 λ

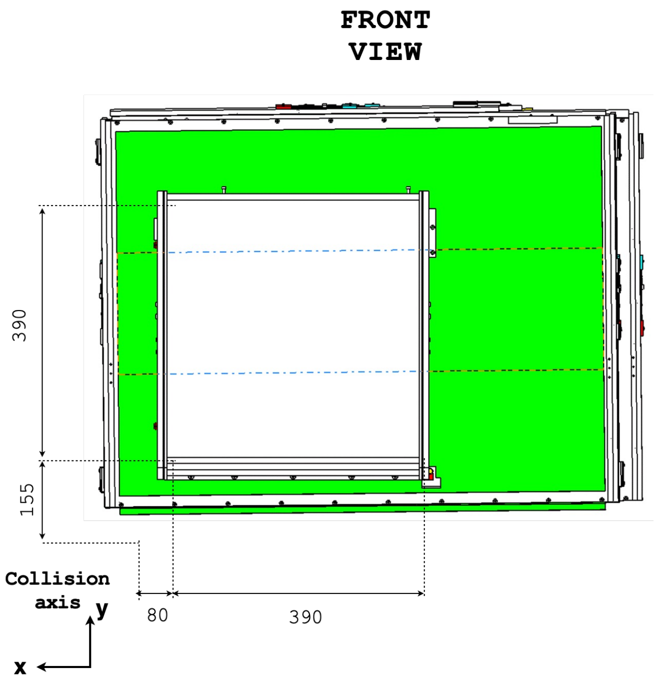
MUON IDENTIFICATION SYSTEM:
3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking



Detector layout

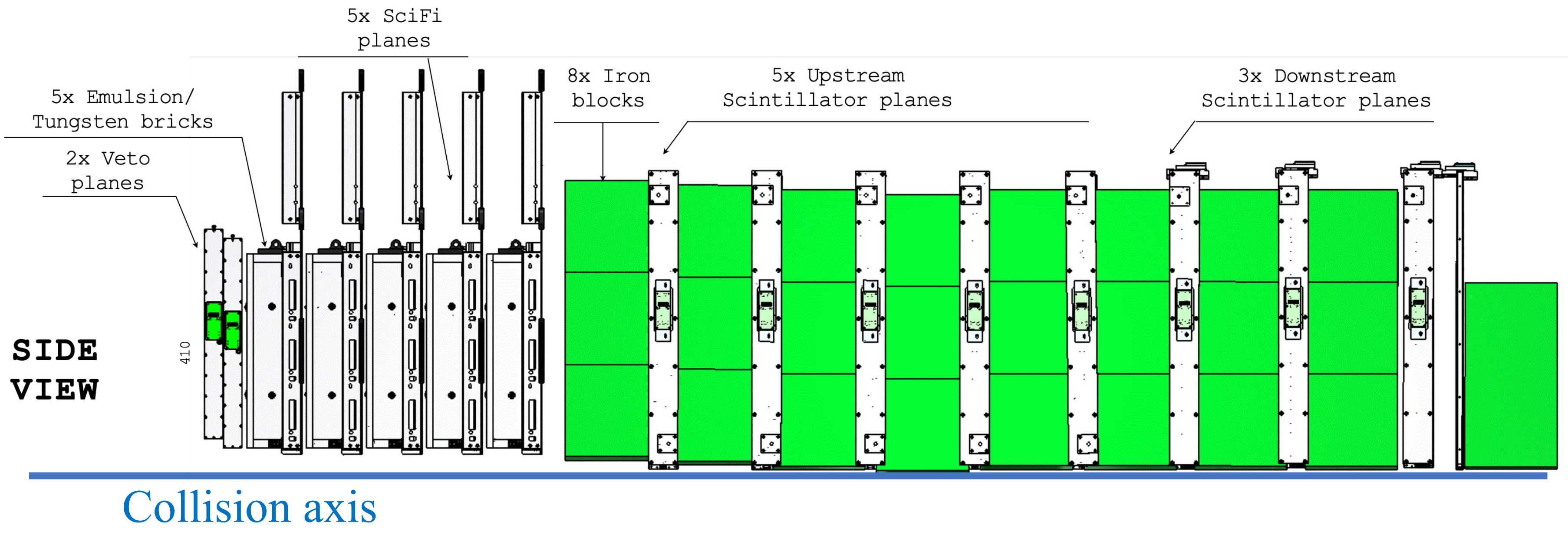
- Angular acceptance: $7.2< \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location

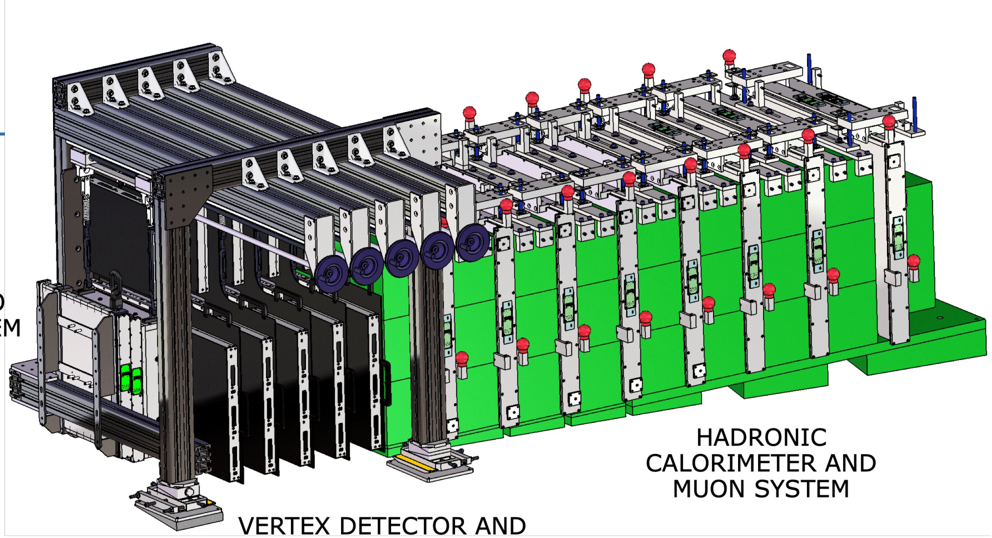


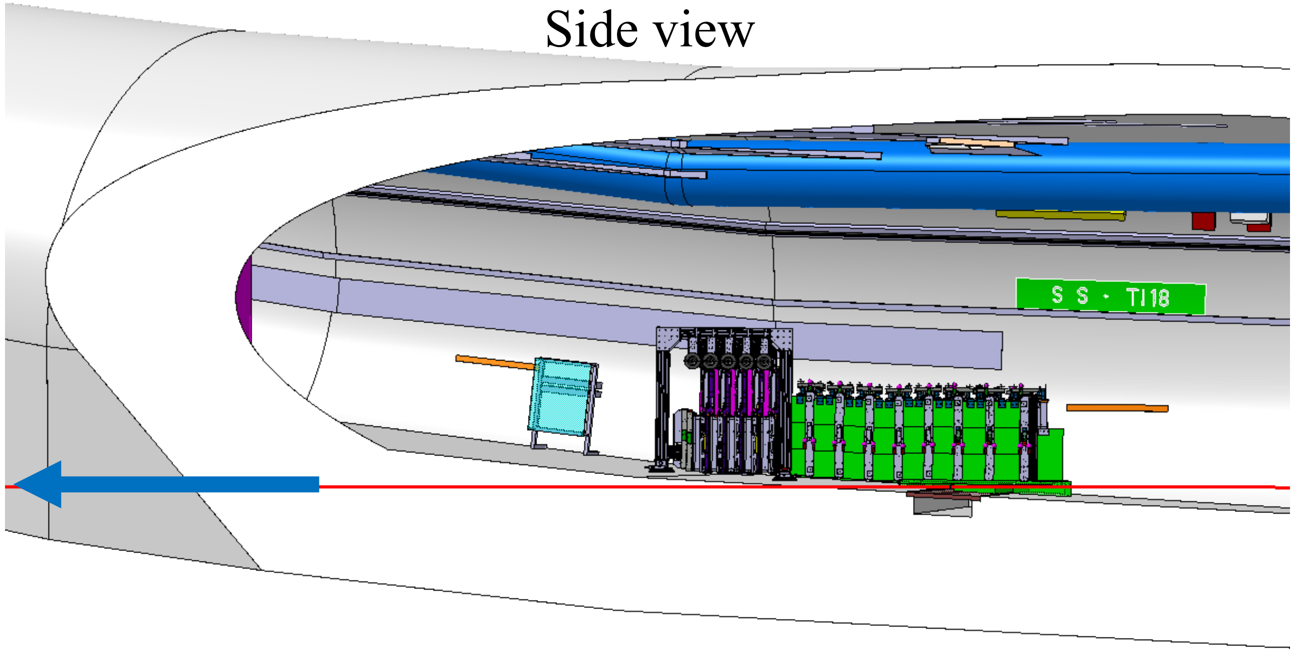
Electromagnetic calorimeter
~40 X_0

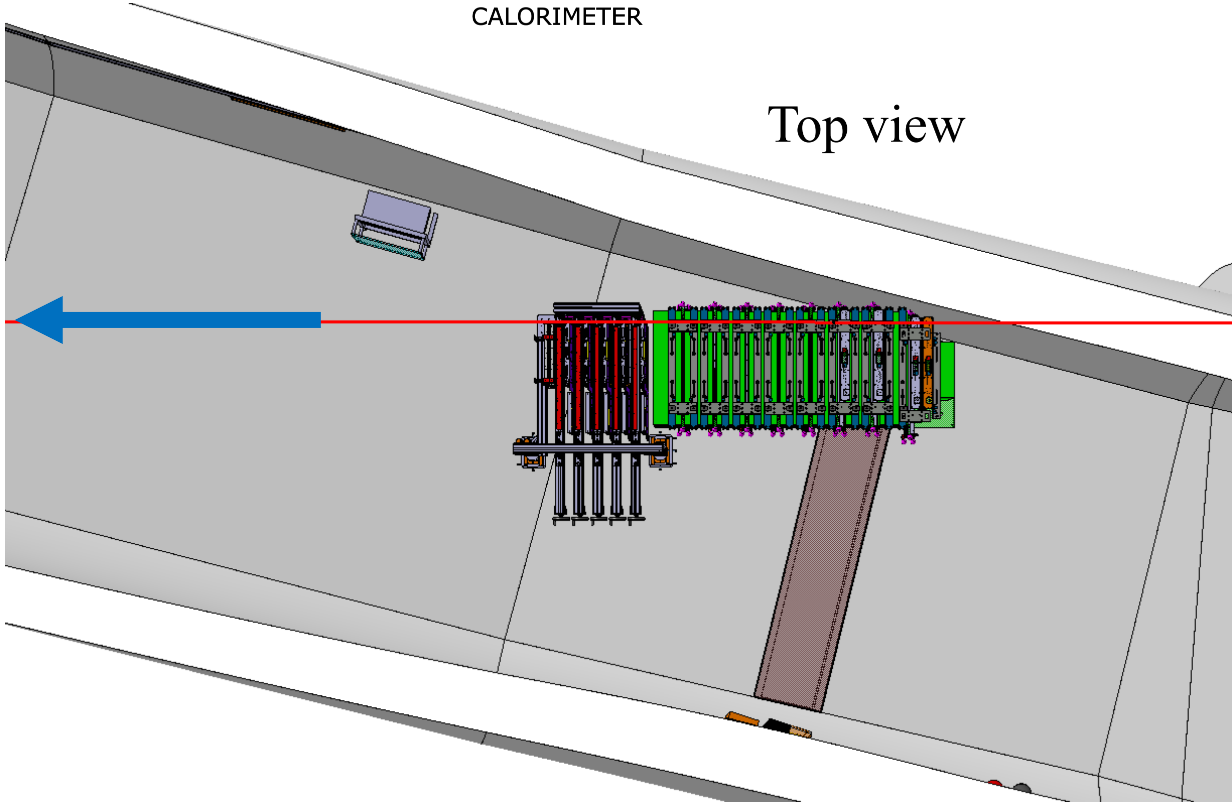
Hadronic calorimeter
~11 λ



SND@LHC in the TI18 cavern




Side view

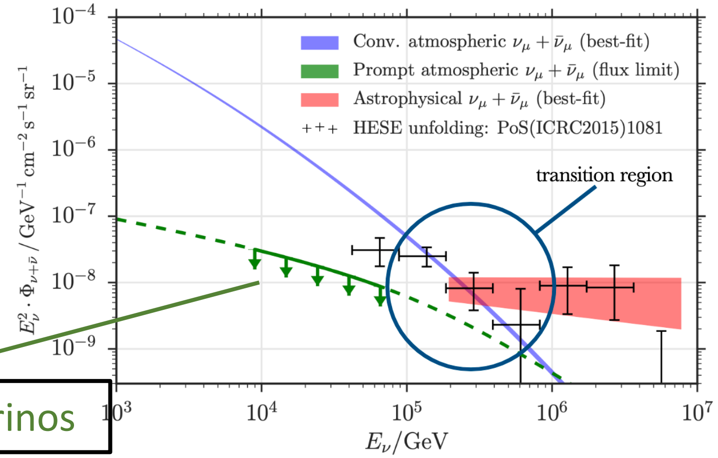

Top view

Physics goals

- Study neutrino interactions (cross-section, LFU, ..) in a new energy domain
- Systematic uncertainty on the cross-section measurement dominated by the uncertainty on the neutrino flux
- Studying the neutrino source, i.e. using neutrinos as probes → measuring charm production in pp collisions in the forward region using ν_e
- Manyfold interest for the charm measurement in pp collision at high η
- Charm production within the acceptance of FCC detectors
- Prediction of very high-energy neutrinos produced in cosmic-ray interactions → experiments also acting as a bridge between accelerator and astroparticle physics

IceCube Collaboration, six years data, Astrophysics J. 833 (2016) 3, https://iopscience.iop.org/article/10.3847/0004-637X/833/1/3/pdf

7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

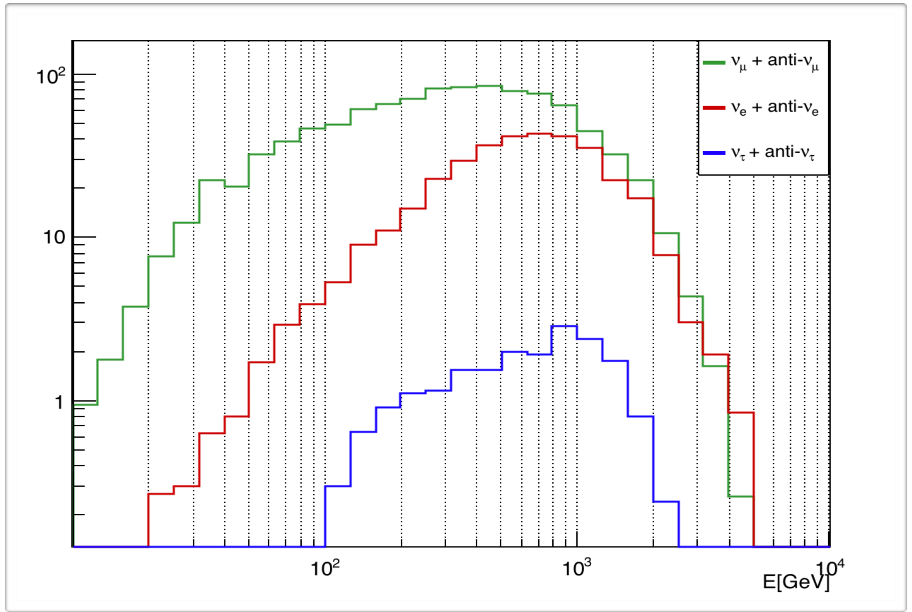


prompt atmospheric neutrinos

NEUTRINO DIS INTERACTIONS

$7.2 < \eta < 8.4,\ 0.4 < \vartheta < 1.5$ mrad

- **DPMJET3** embedded in FLUKA for neutrino production @ LHC
- Particle propagation towards the detector through the LHC **FLUKA** model
- **GENIE** used to simulate neutrino interactions in the detector target



Interacting Neutrinos

- Expectations in 290 fb^{-1} (43/57 upward/downward crossing angle)

	CC neutrino interactions		NC neutrino interactions	
Flavour	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

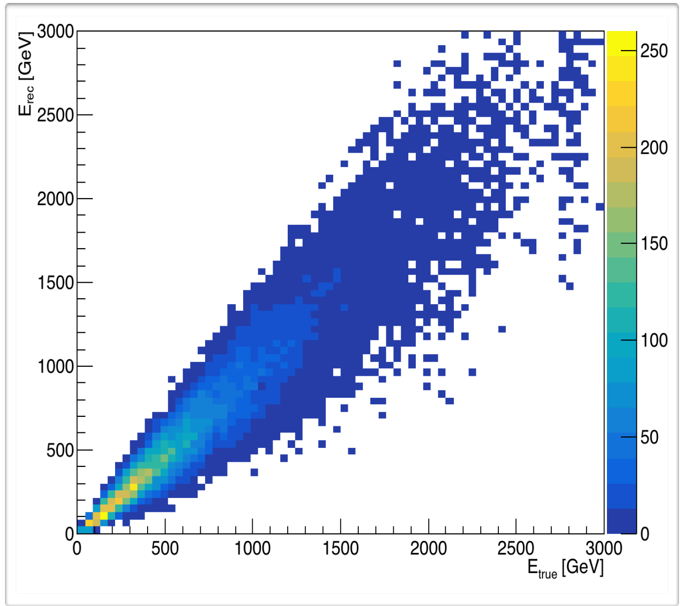
$\sim 30\ \nu_\tau$ CC interactions expected

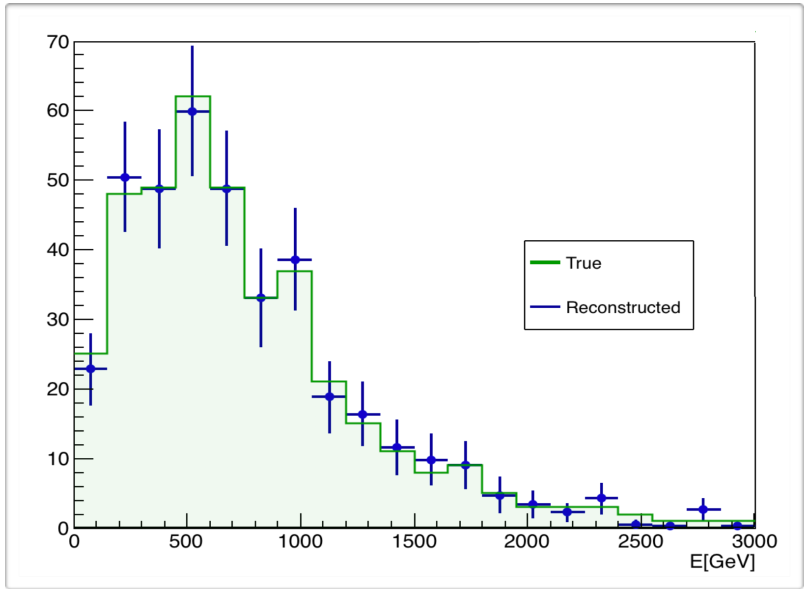
NEUTRINO PHYSICS PROGRAMME

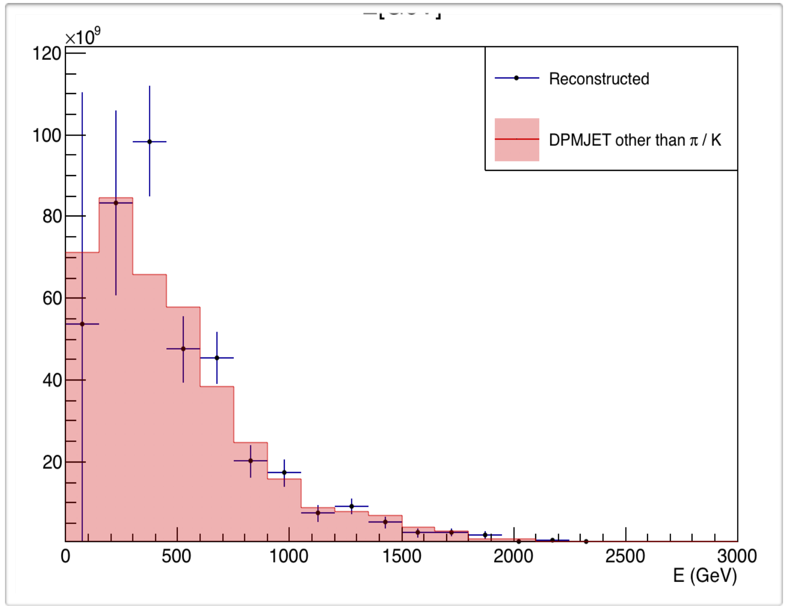
1. Measurement of the $pp \longrightarrow \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions
4. Measurement of the NC/CC ratio as a control sample

1. Measurement of pp$\longrightarrow\nu_e$X cross-section and charm

- 90% ν_e & anti-ν_e from the decay of charmed hadrons
- ν_e as a probe of charm production in this *η* range after unfolding instrumental effects
- Unfolding the *measured* energy spectrum to retrieve the *true* energy, deconvolution of ν (SM) cross-section (**15%**)
- Subtract kaon component dominates at low energies (E<200 GeV), different event generators up to a factor 2
- Procedure introduces an additional systematic uncertainty of **~20%** on the overall yield

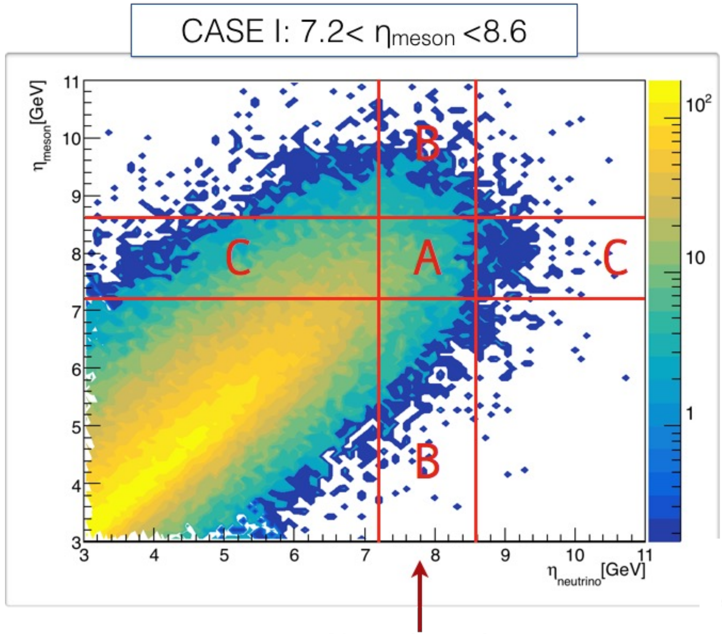






2. CHARMED HADRON PRODUCTION

- Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron
- Evaluation of the migration by defining regions in the pseudo-rapidity correlation plot



Neutrinos in SND@LHC acceptance

N_A/N_{A+B}

$$N(c\text{−mesons}) = N(\nu_e+\overline{\nu}_e)^{\text{charm}} \times \frac{f_{AB}}{f_{AC}} \times \frac{1}{Br(c\rightarrow\nu_e)}$$

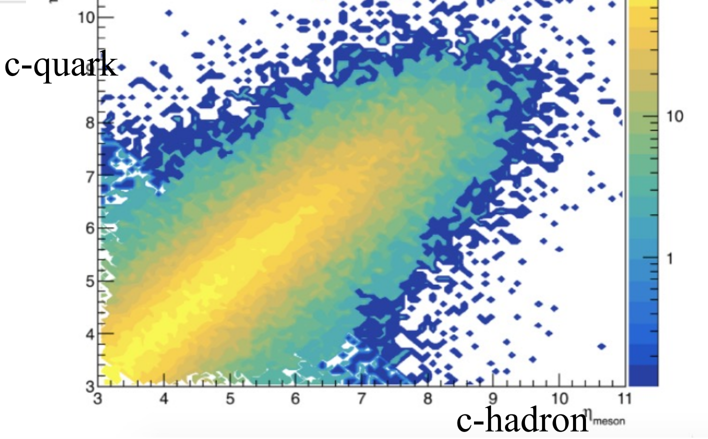
N_A/N_{A+C}

Branching ratio of charmed mesons to ν_e

- Fractions f_{AB} and f_{AC} evaluated using leading order computations+Pythia8 parameters for cc-bar production at 13 TeV
- Variation of parameters that describe charm production and hadronisation show that the ratio f_{AB}/f_{AC} is stable within **20-30%**

Statistical uncertainty ~5%

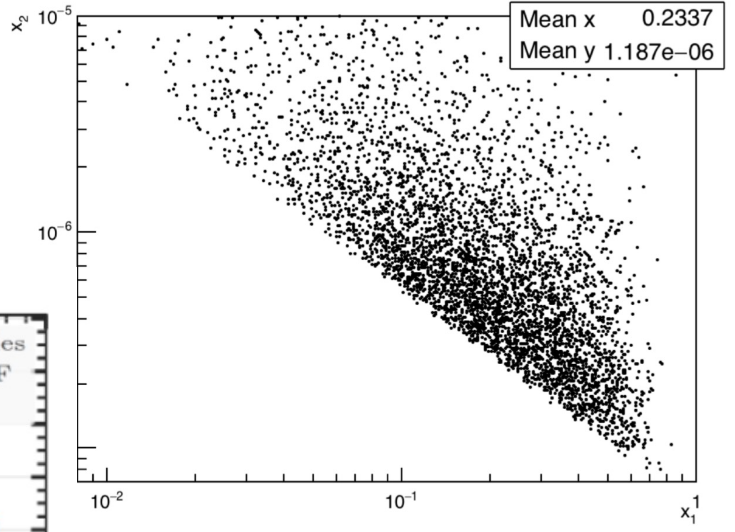
Systematic uncertainty ~35%

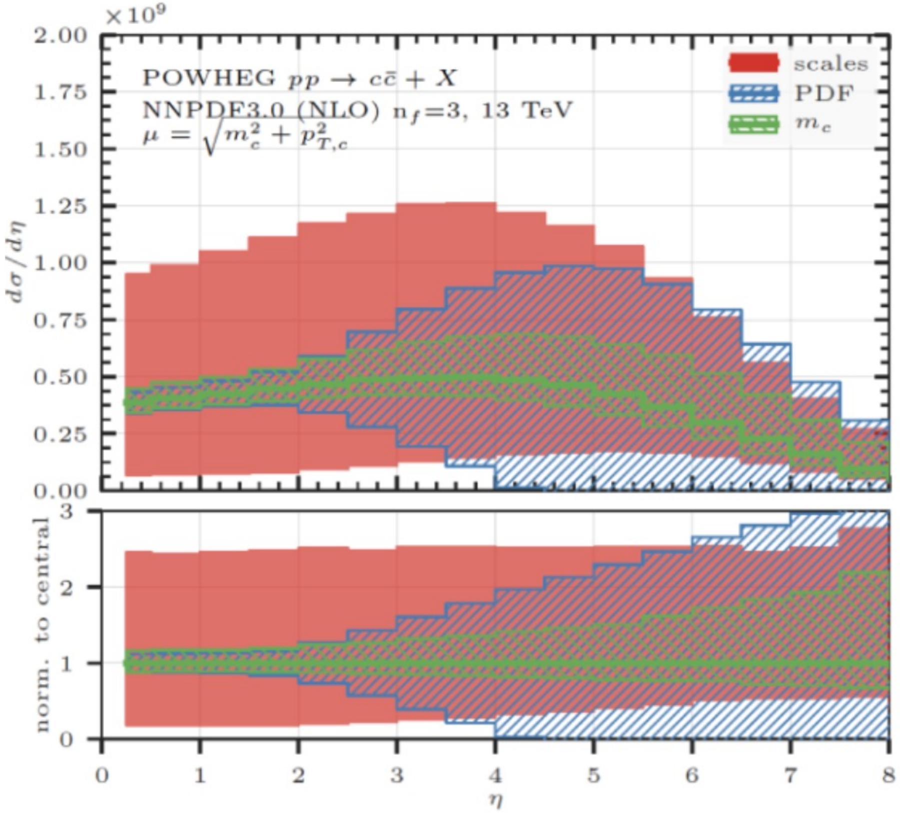


The measurement of charmed hadrons can be translated into a measurement of the corresponding open charm production in the same pseudo-rapidity range given the straight correlation between the hadron and its parent charm quark

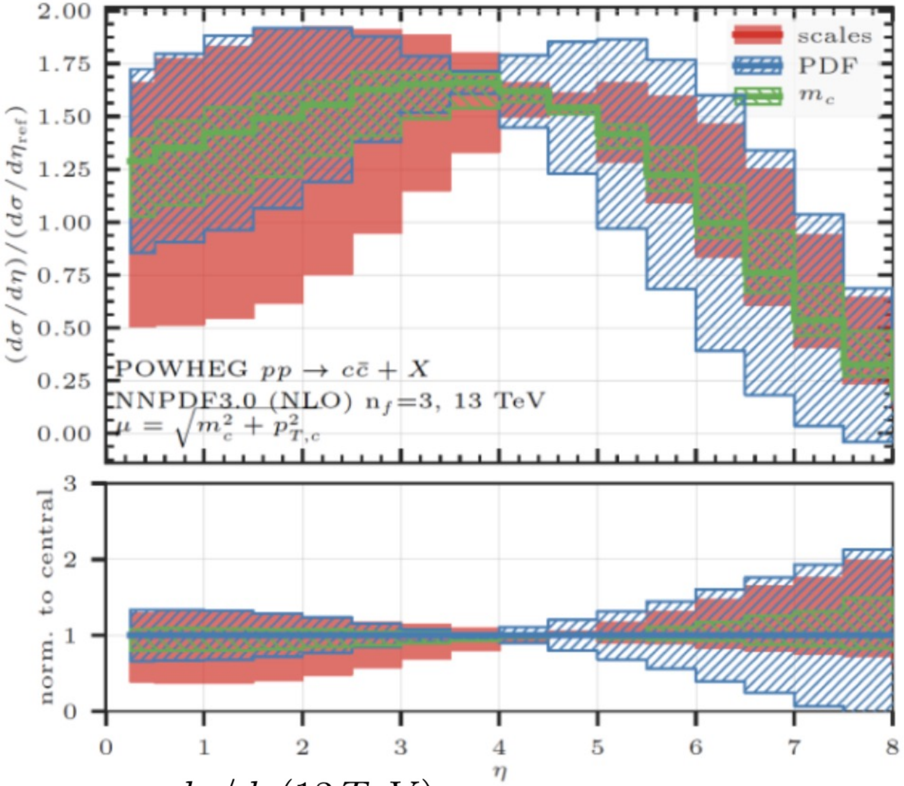
Extraction of the gluon PDF

- Dominant partonic process: gluon-gluon scattering
- SND@LHC data to constraint the gluon PDF in the very-small x region





$d\sigma/d\eta$ at 13 TeV

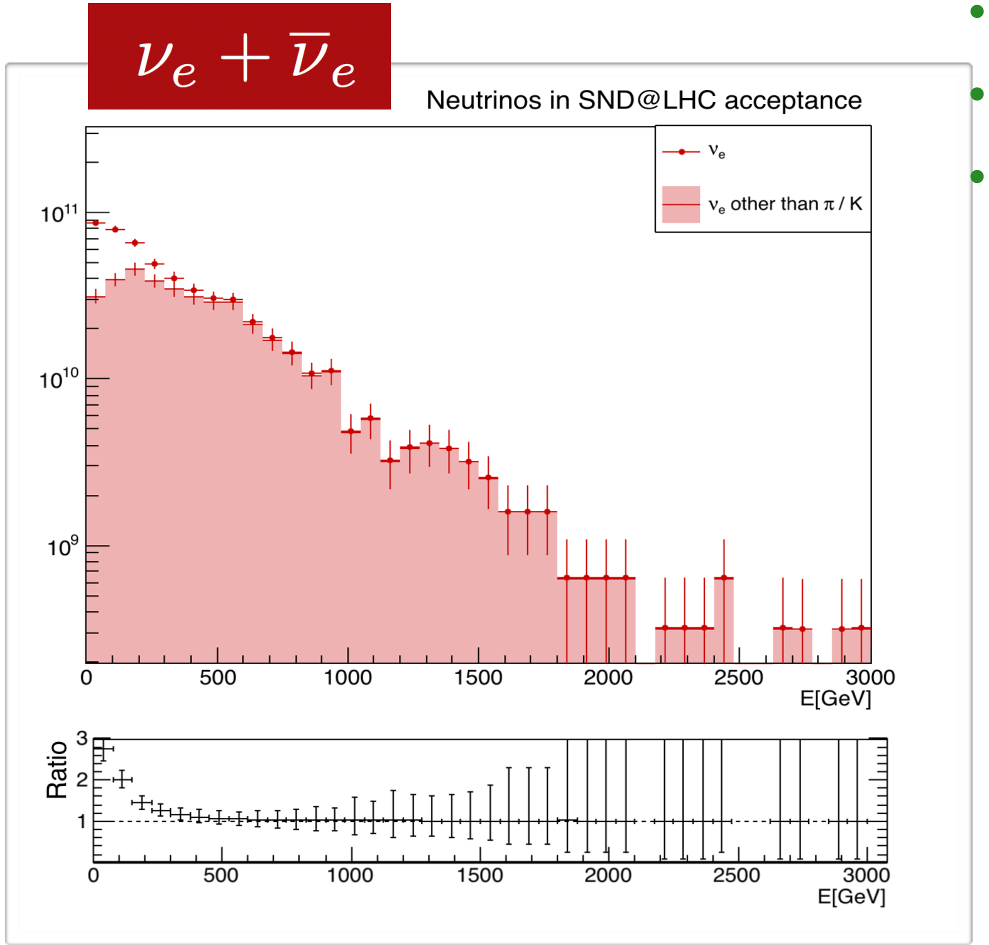


$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

$\eta_{ref} = [4, 4.5]$

3. Lepton flavour universality test in ν interactions

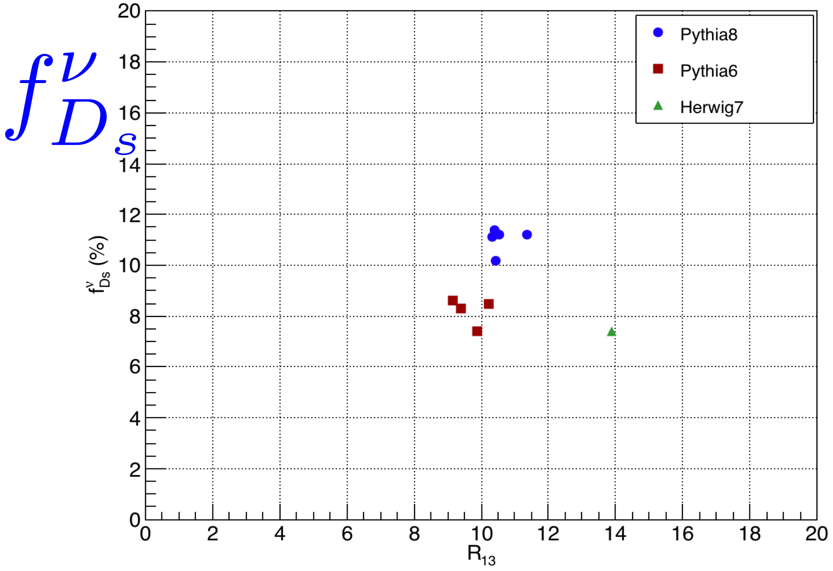
- The identification of 3 ν flavours offers a unique possibility to test LFU in ν interactions
  - ν_τs produced essentially only in D_s decays
  - ν_es produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
  - The ratio depends only on charm hadronisation fractions
  - Sensitive to ν-nucleon cross-section ratio



$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **20%** error due to ν_τ statistics



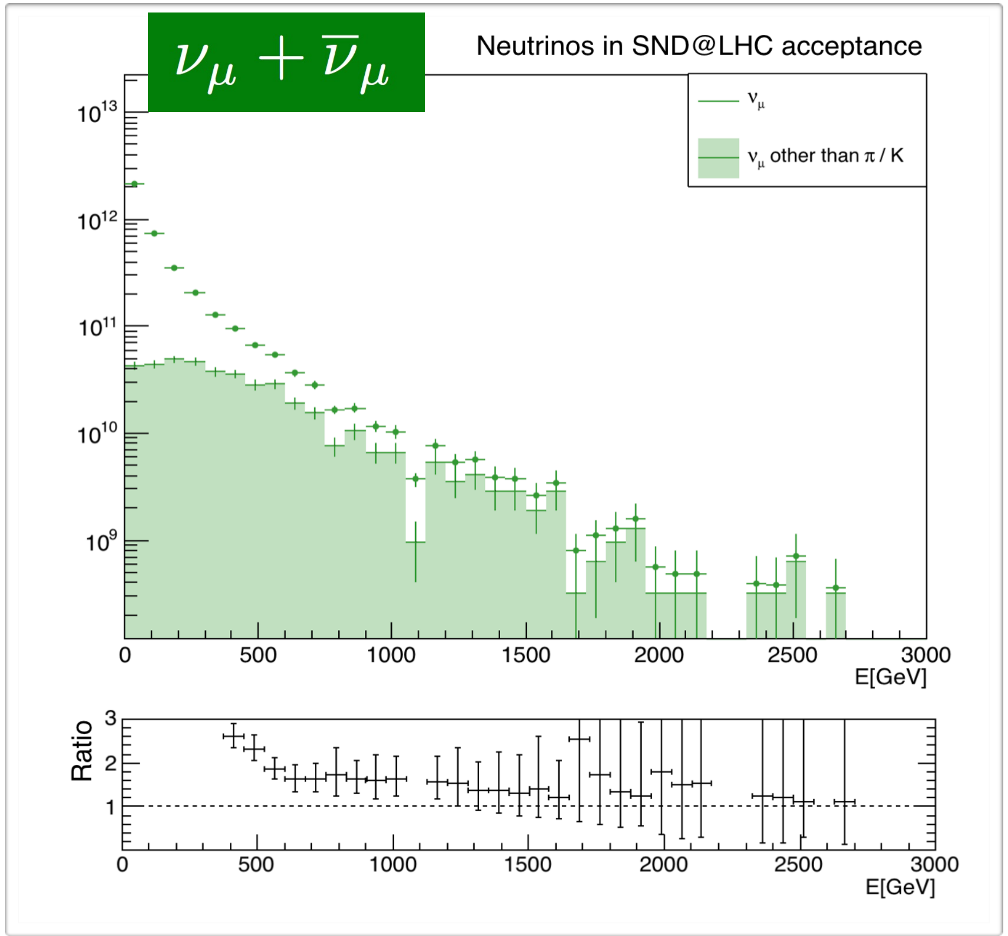
3. Lepton flavour universality test in ν interactions

- ν_μ spectrum at low energies dominated by neutrinos produced in π/k decays
- For E>600 GeV the contamination of neutrinos from π/k keeps constant (~35%) with the energy

$$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\,GeV] = 294$$ in 150 fb^{-1}

$$N(\nu_e + \overline{\nu}_e)[E > 600\,GeV] = 191$$ in 150 fb^{-1}

$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

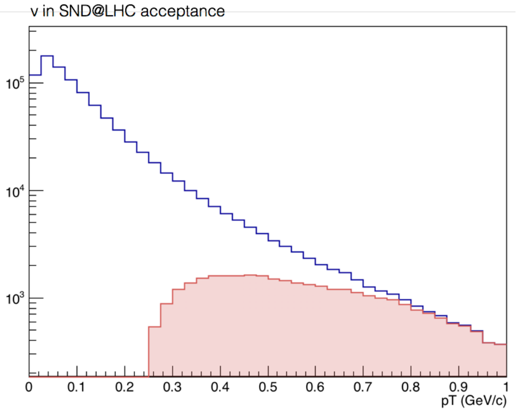


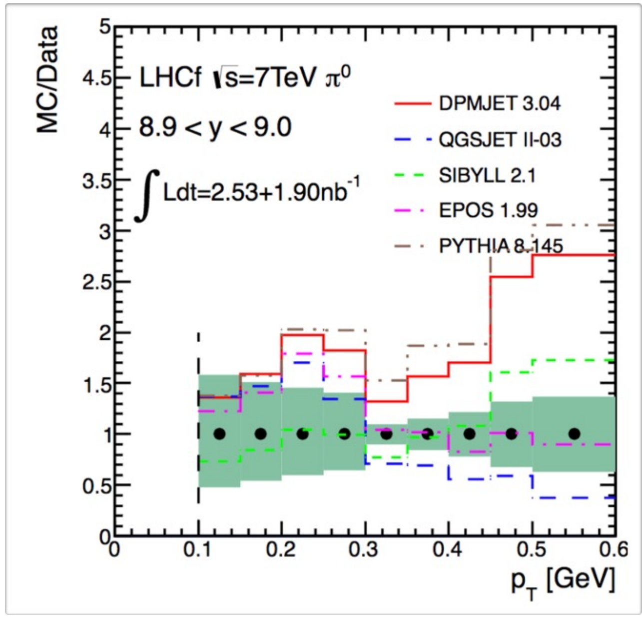
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and *Br*) since charmed hadrons decay almost equally in ν_μ and ν_e

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

contamination from π/k

- Statistcal error: **10%**
- Systematic uncertainty from the knowledge of π/k contamination: **10%**





Phys. Rev. D 86, 092001 (2012)

4. The NC/CC RATIO as a consistency check

- Lepton identification allows to distinguish between CC and NC interactions
- If differential ν and anti-ν fluxes are equal, the NC/CC ratio can be written as

$$P = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}}$$

- For DIS, P can be written as

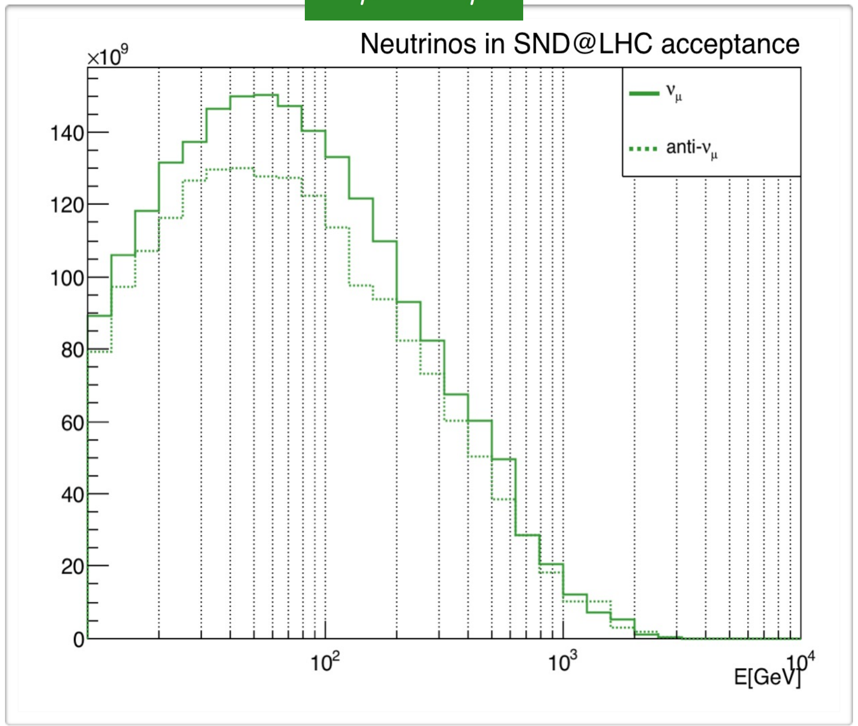
$$P = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda(1 - 2\sin^2\theta_W)\sin^2\theta_W\right\}$$

- where λ originates from the non-isoscalarity of the target, a correction factor of ~1%

- For a Tungsten target λ=0.04

- **Statistical** uncertainty given by the number of observed CC and NC interactions: **5%**
- **Systematic** uncertainty:
- asymmetry between ν and anti-ν spectra mainly in the ν_μ spectrum at low energies. Contribution to the error **<2%**
- CC to NC migration and neutron background subtraction: **10%**

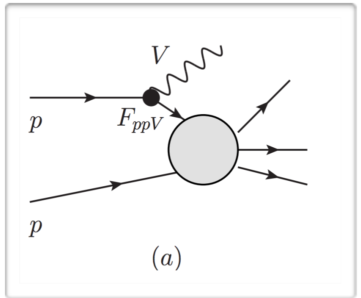
ν_μ vs $\overline{\nu}_\mu$



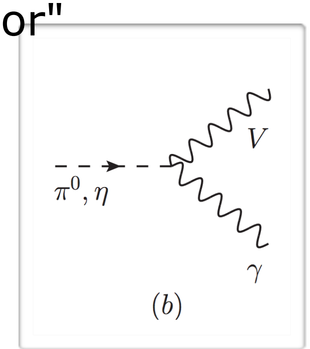
Important internal consistency test

FEEBLY INTERACTING PARTICLES

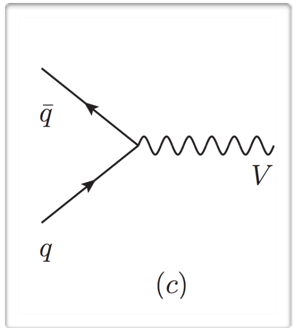
- SND@LHC can explore a large variety of BSM scenarios within the "Hidden Sector"



Proton bremsstrahlung



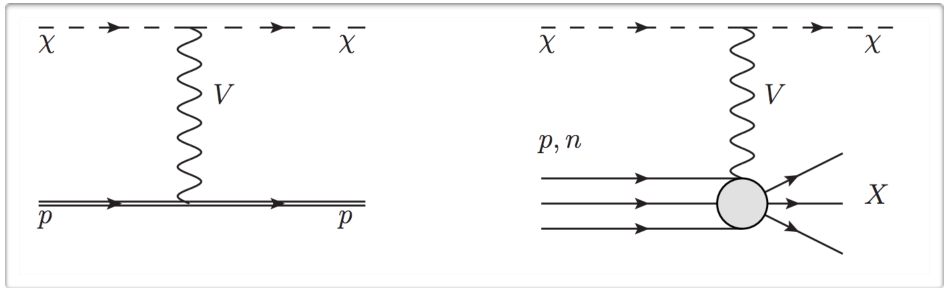
Meson decay

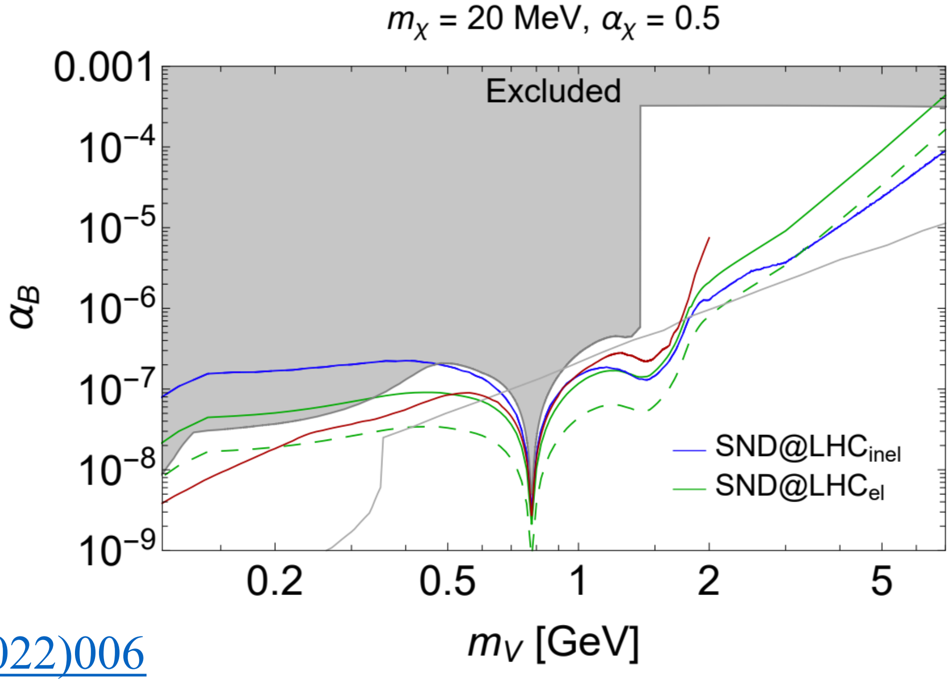


Drell-Yan process

Production: we consider a scalar χ particle coupled to the Standard Model via a leptophobic portal

Detection: χ elastic/inelastic scattering off target nucleons





https://link.springer.com/article/10.1007/JHEP03(2022)006

Detector installation in TI18

- Started on November 1st 2021
- Electronic detector completed on December 3rd 2021
- Neutron shield completed on March 15th 2022
- First emulsion films in the target on April 7th 2022


September 2021


December 2021


March 2022

Fully installed detector pointing to the IP

LHC
Scattering and Neutrino Detector
at the LHC

View of the machine towards the IP1 (left) and of the detector in TI18 (right)

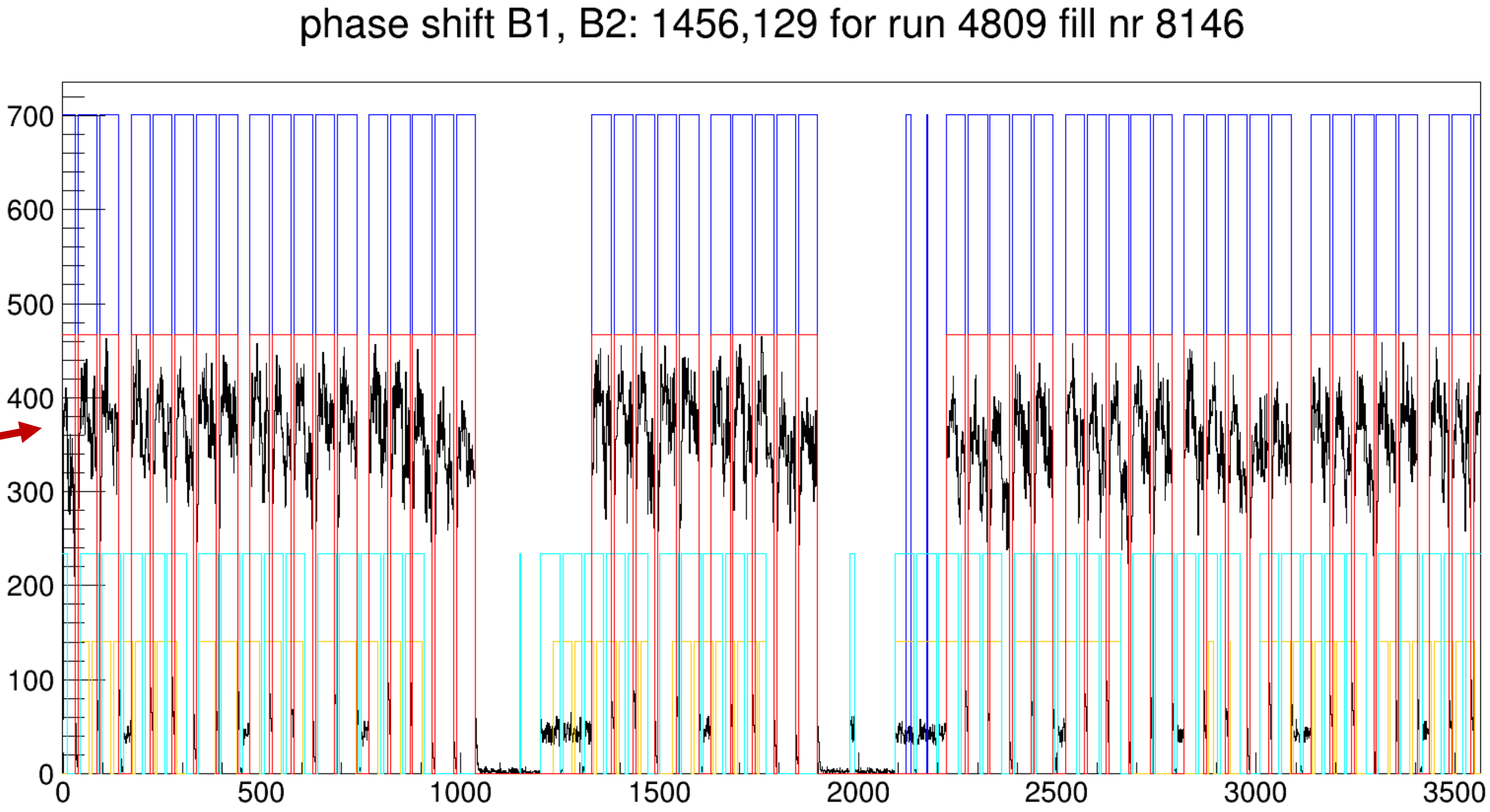
Start of data taking during LHC Commissioning

SND@LHC observed bunch structure overlaid with the LHC filling scheme with phase shift adjusted

Colour coding:
blue Beam1,

red IP1 xing,
cyan Beam2,
yellow IP2 xing

Most of the events from interactions in IP1

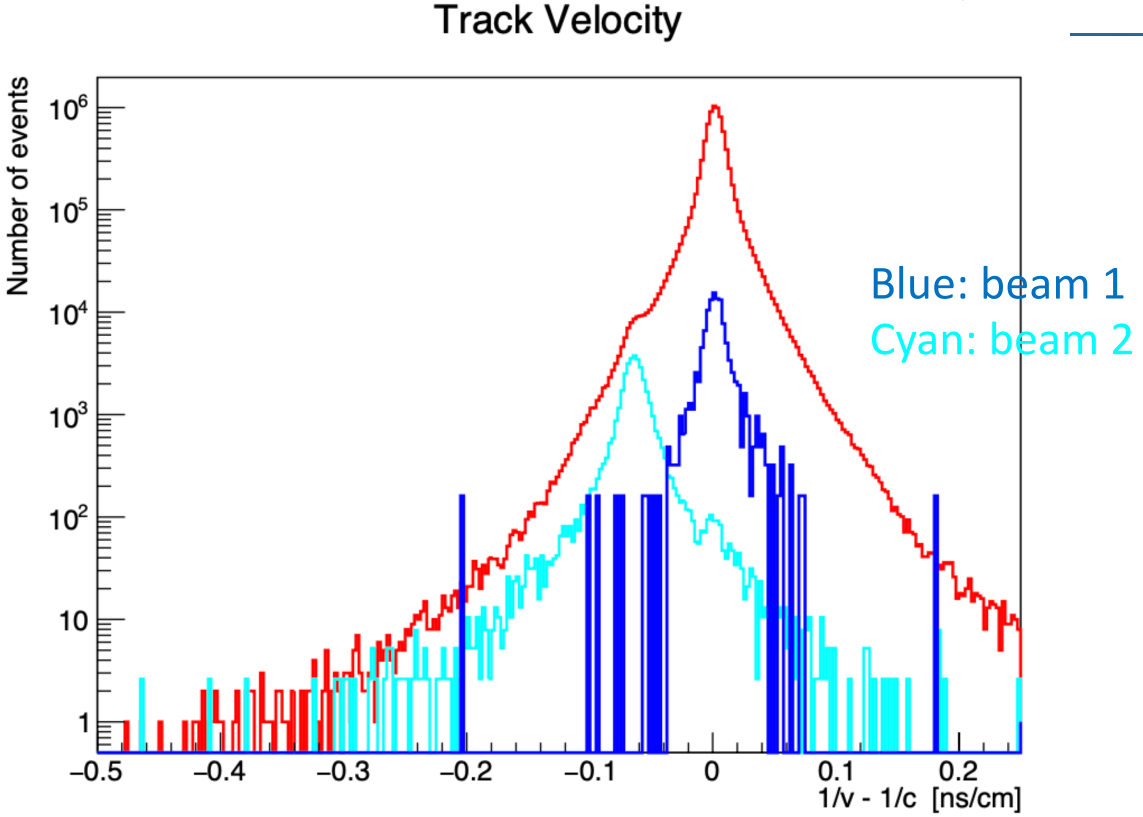


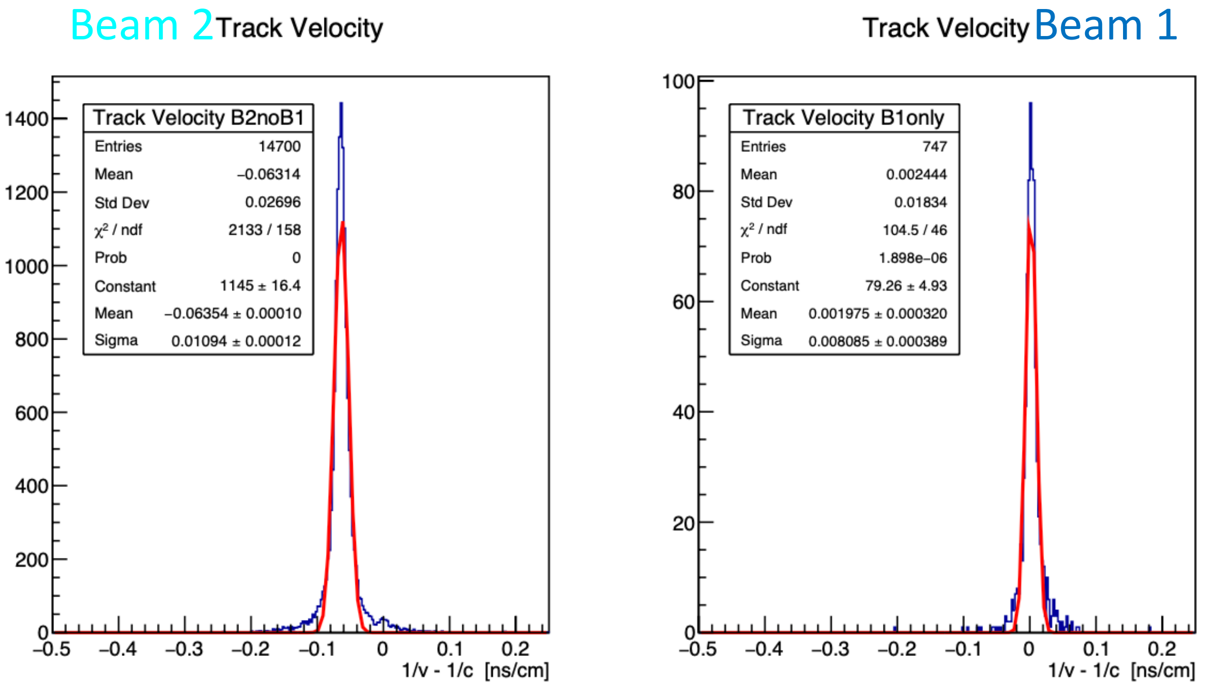
Bunch number

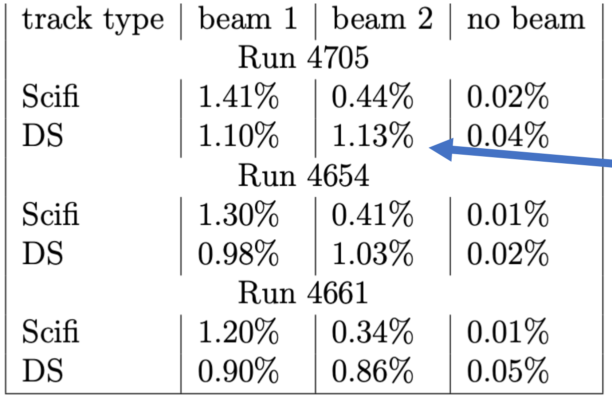
Phase shift of B2 relative to B1 of 129 clock (25ns) cycles is also a measurement of the distance of SND@LHC from IP1:

$$2\times\frac{482\ m}{0.3\,\frac{m}{ns}\times 25\ ns} = 128.6$$

Use bunch structure to study event features: the track direction





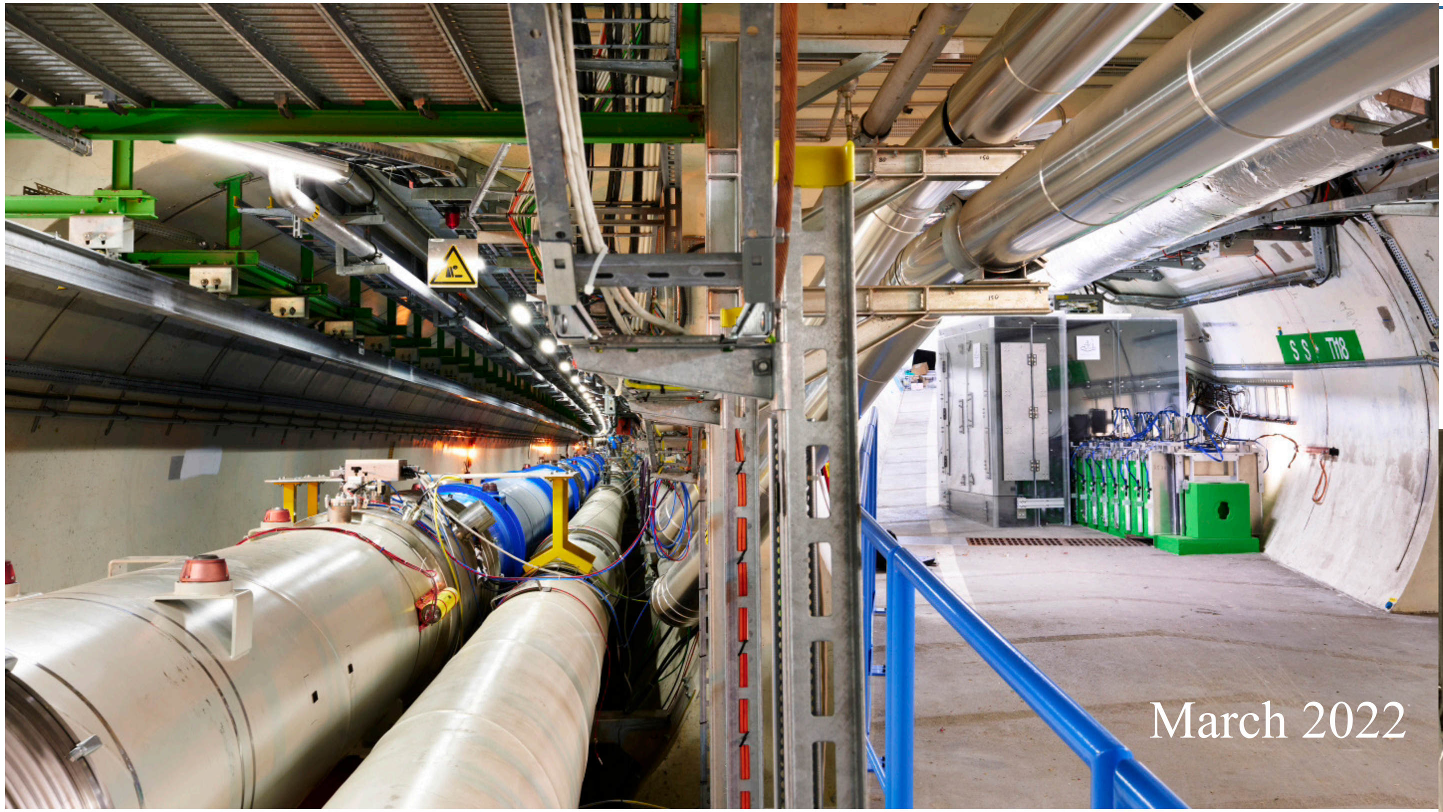


track type	beam 1	beam 2	no beam
Run 4705			
Scifi	1.41%	0.44%	0.02%
DS	1.10%	1.13%	0.04%
Run 4654			
Scifi	1.30%	0.41%	0.01%
DS	0.98%	1.03%	0.02%
Run 4661			
Scifi	1.20%	0.34%	0.01%
DS	0.90%	0.86%	0.05%

Table 1: Background rates for different runs.

Background on target tracks < 2%

Detector view in 2022 and in 2023



March 2022

LoI: August 2020
Technical Proposal: Jan 2021
Approval in March 2021
Ready to take data in April 2022 when Run 3 started

March 2023

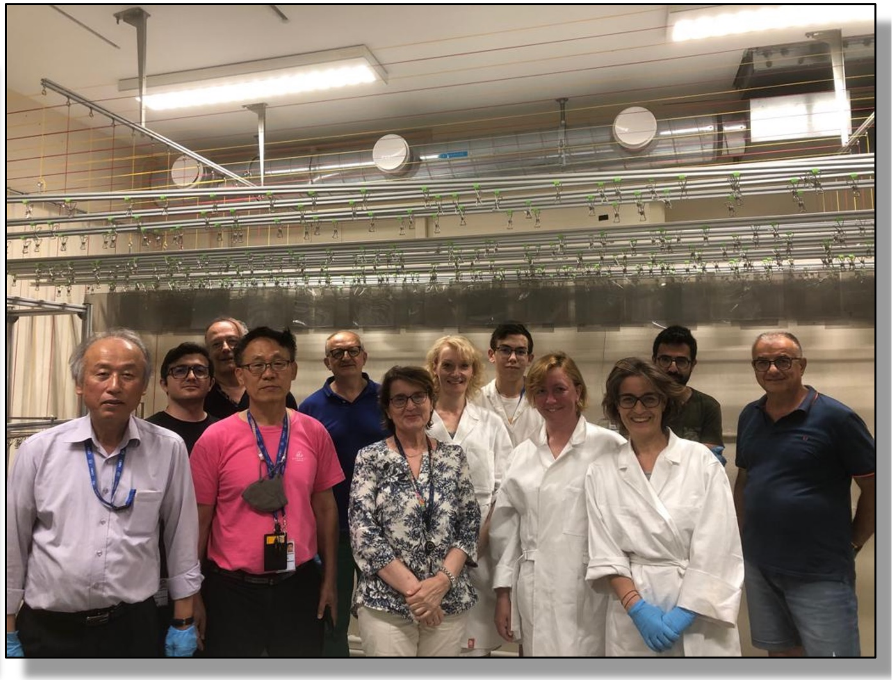
Emulsion replacements in 2023

- Mass of target #4: **797 kg**
- **1158** films (70% Nagoya+30% Slavich)
- Assembly: March 16th-19th
- Installation: **March 20th**
- Extraction: **June 23rd**
- Emulsion development: July 4th-17°
- Time for underground operation: 4 hours

- Mass of target #5: **784 kg**
- **1140** films (100% Nagoya)
- Assembly: March 16th-19th
- Installation: **June 23rd**
- Extraction: **July 27th**
- Emulsion development: August 12th-25th
- Time for underground operation: 4 hours

Target assembly

Target installation

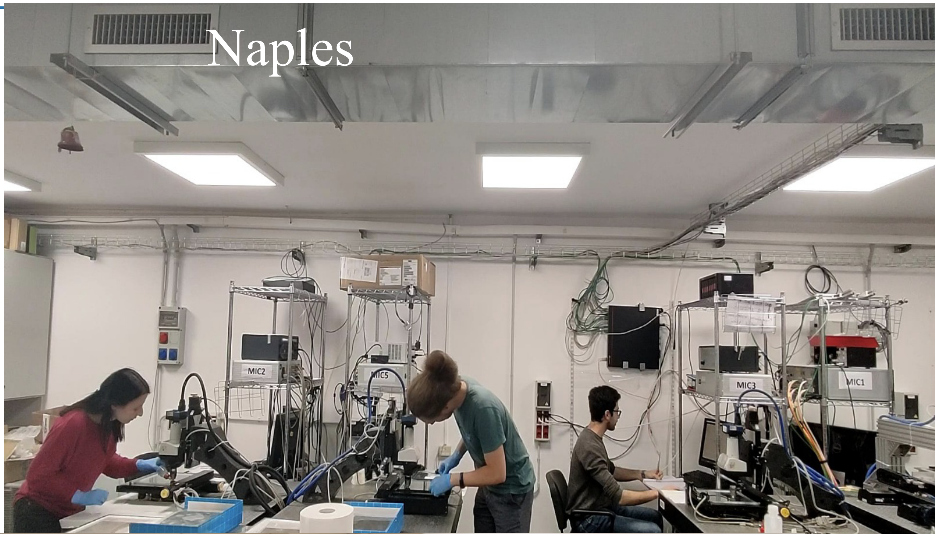


Emulsion development

Strengthening the scanning station power


Bologna

Bologna: 2 systems
Napoli: 2 systems
CERN: 2 systems + 2 upgrades
operational in Dec

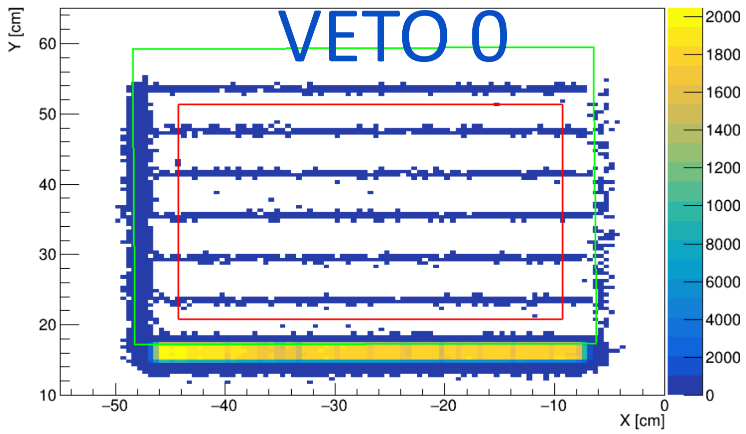

Naples

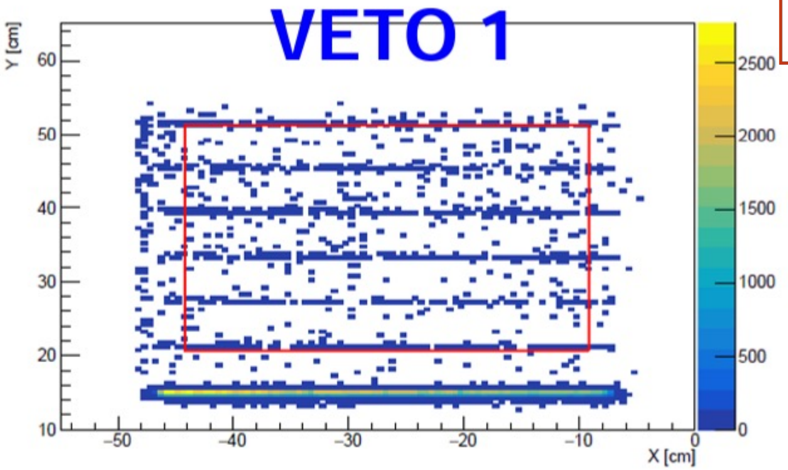

CERN

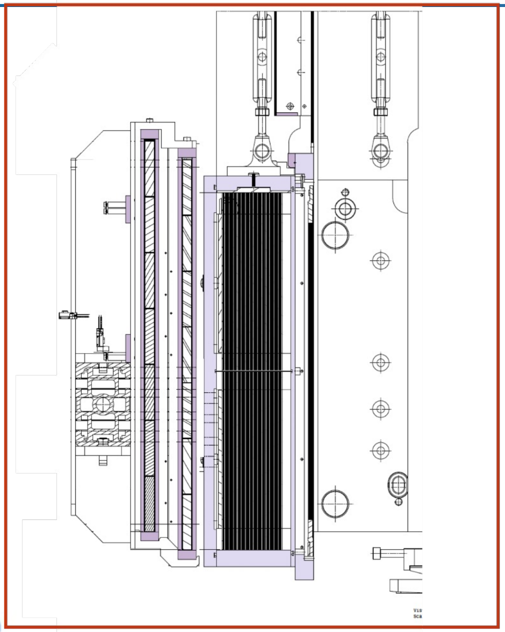

End of July 2023
CERN

Upgrade of the veto system during next YETS

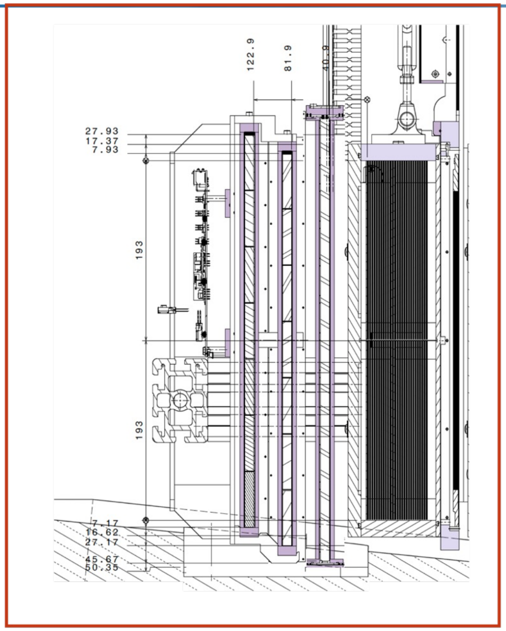
Extrapolated SciFi track position when no signal in Veto 0 or 1



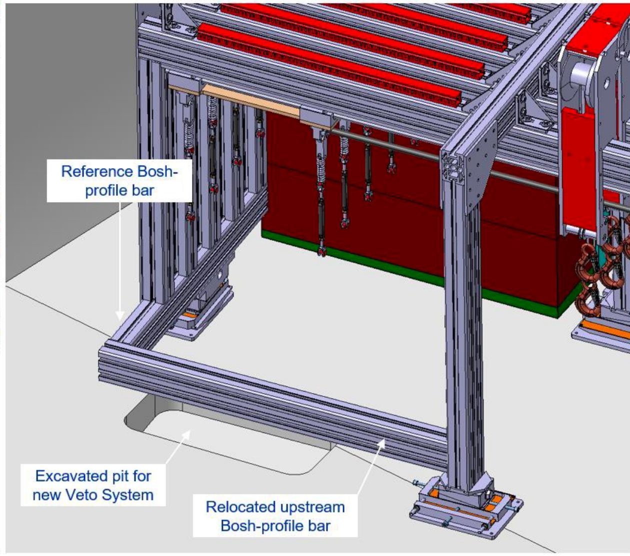




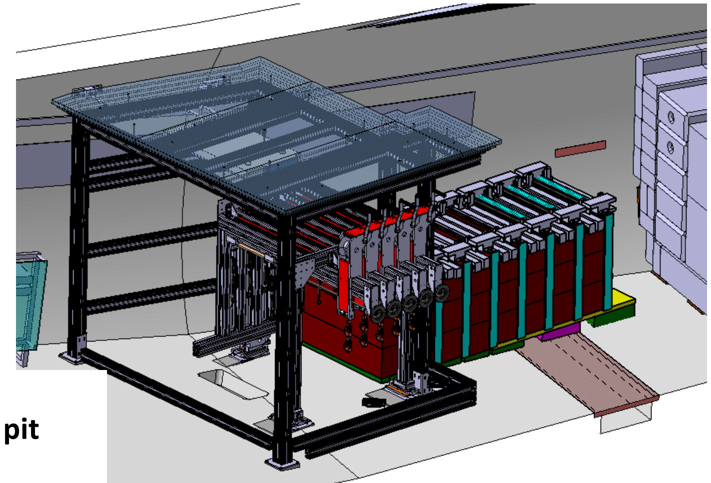
Current layout: two planes with H bars



Upgraded layout: third plane with vertical bars



3D integration model (YETS 2023/2024)



Excavated pit

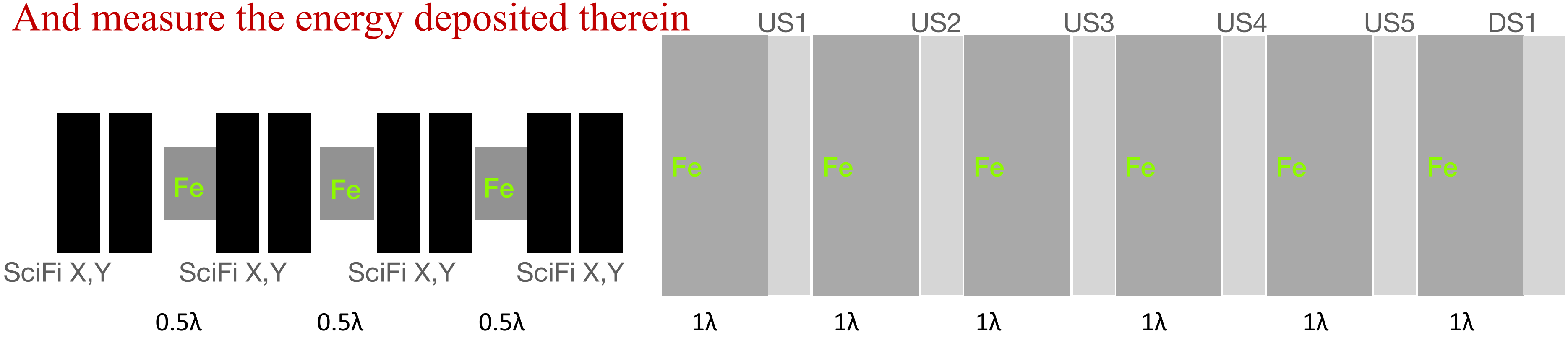
Recover fiducial volume, both longitudinally and in the transverse plane

Add a third layer to avoid loosing the first target wall and lower their position to cover the full transverse plane

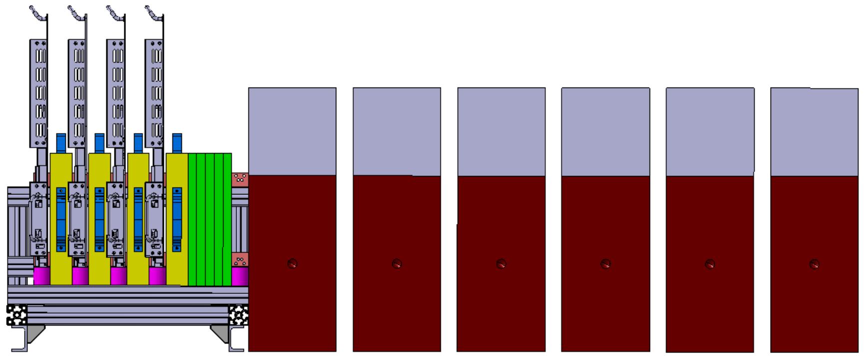
Towards energy calibration

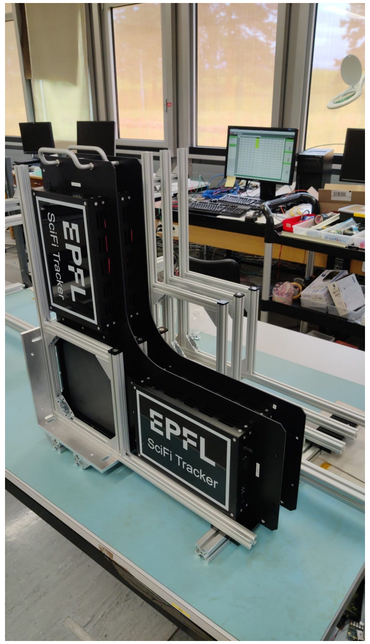
Target instrumented with SciFi stations to get the shower origin
And measure the energy deposited therein

All 5 US stations and 1 DS



Successful data taking in H8 in August

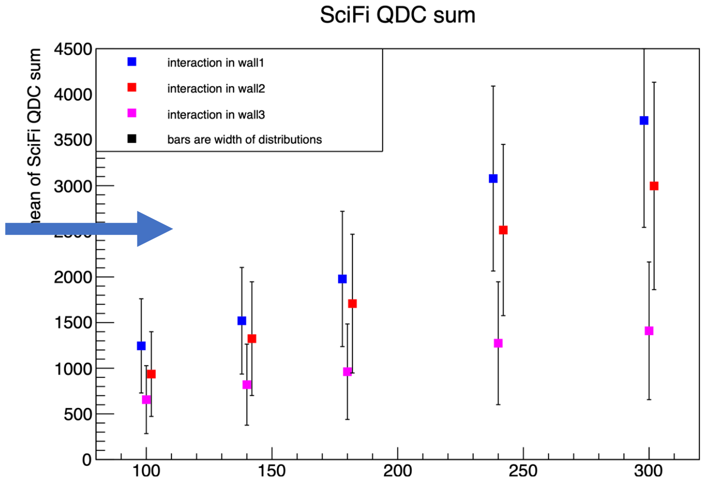


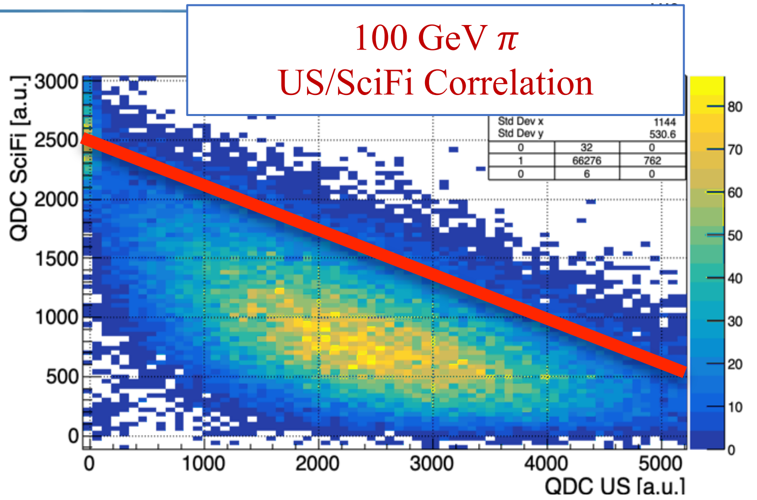


Preliminary calibration studies and energy resolution

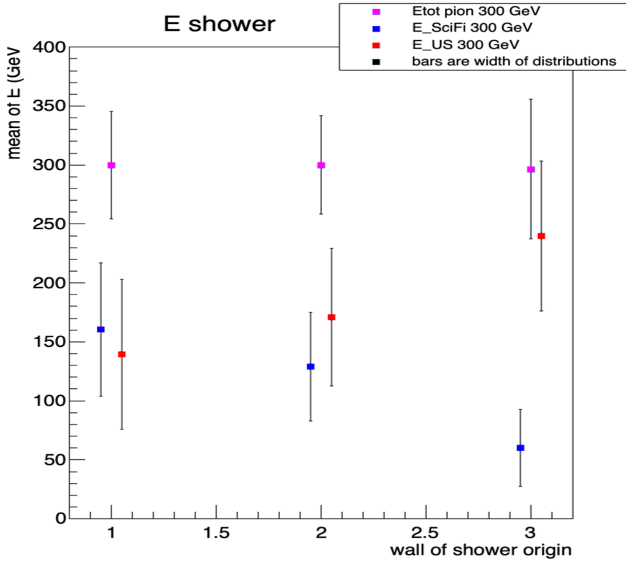
Reconstruction of the total energy requires the estimate of the fraction lost in the target region. SciFi accomplishing also this task

- Good proportionality of SciFi response to the particle energy
- Different calibration curves according to the (longitudinal) shower origin in the target

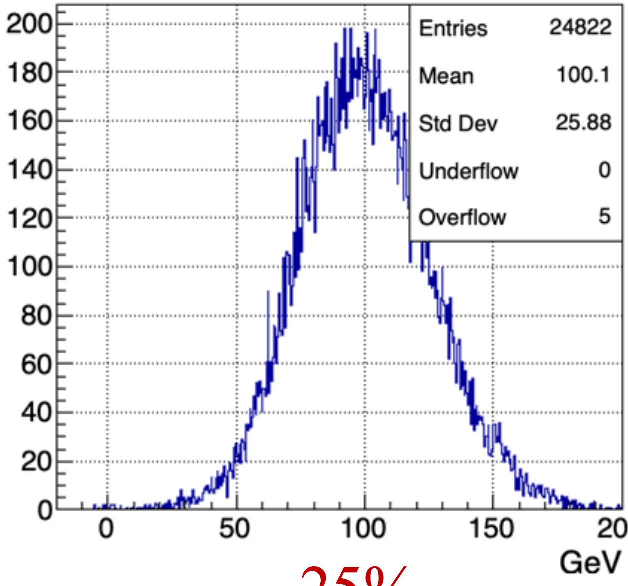



100 GeV π
US/SciFi Correlation

300 GeV π: energy sharing between SciFi and Upstream Station

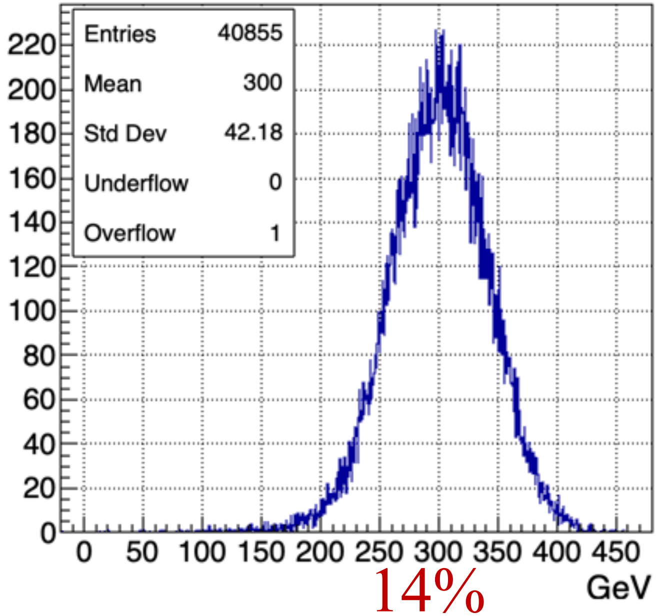


Reconstructed energy for 100 GeV π



25%

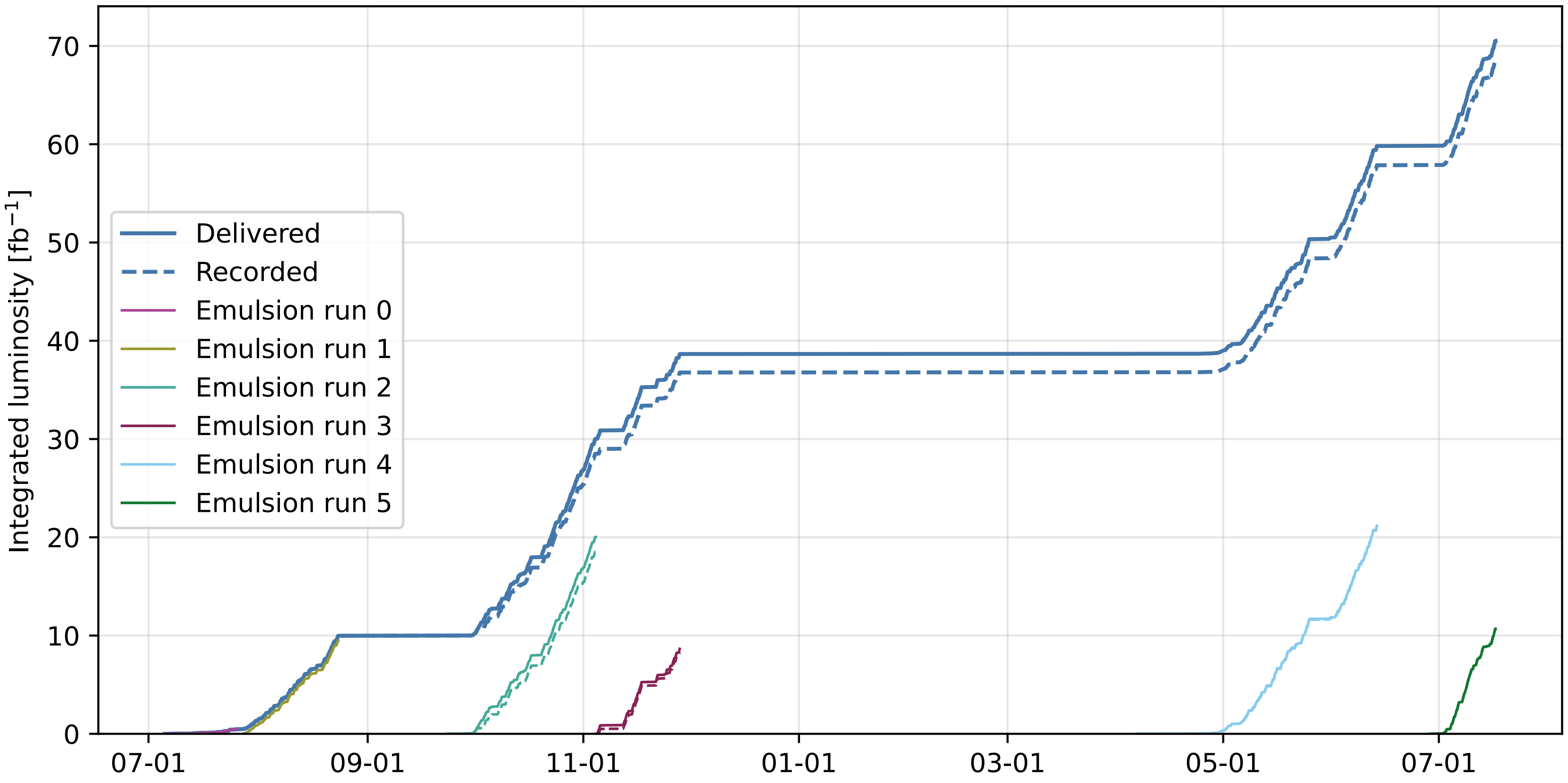
Reconstructed energy for 300 GeV π



14%

Data analysis

Integrated luminosity



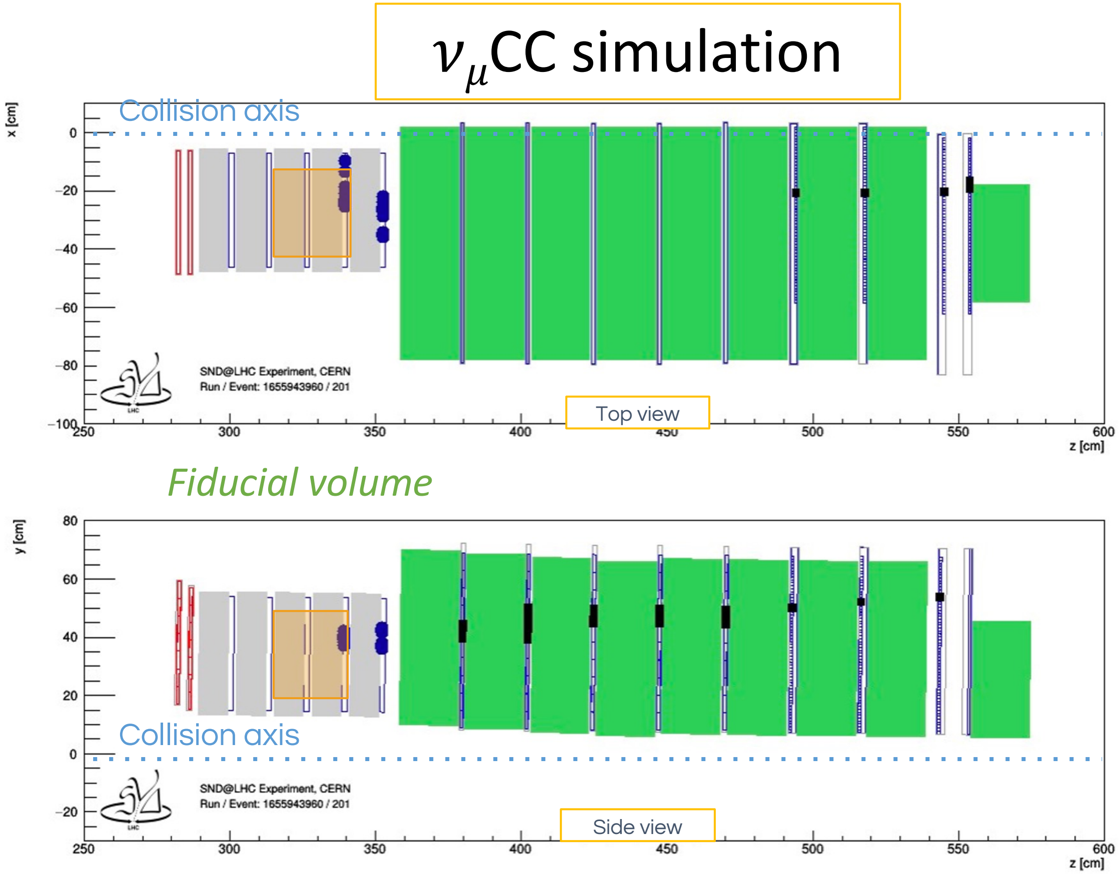
Integrated luminosity: 70.5 fb^{-1}

Recorded efficiency 97.3% (2022 95%, 2023 99.7%)

Neutrino observation with electronic detectors

- Analysis strategy:
  - Full Run 3 **2022 dataset**: recorded luminosity of 36.8 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach: initial S/N ~ 10^{-8} down to 100
  - ~10^9 muon events: **strong rejection power** to reach negligible background level

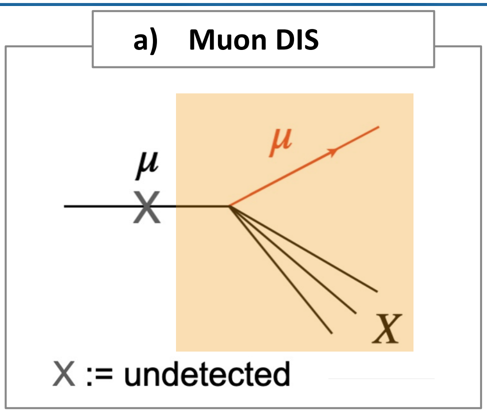
- Signal selection:
  - **Fiducial Volume (1, 2)** cuts
    - **Neutral vertex**, located in the 3rd or 4th target wall
    - Select fiducial cross-sectional area to reject background entering from the side
  - **Neutrino ID** cuts
    - Require "large" E.M. (SciFi) and hadronic activity (HCAL)
    - Event produced upstream (timing)
    - **Muon** reconstructed and **isolated** in the Muon system

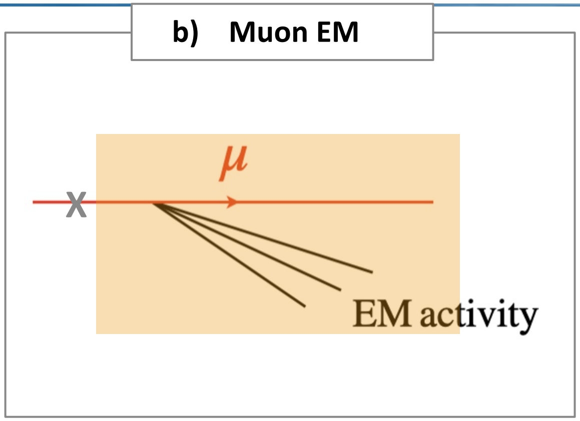


ν_μCC simulation

Fiducial volume

Background evaluation


a) Muon DIS

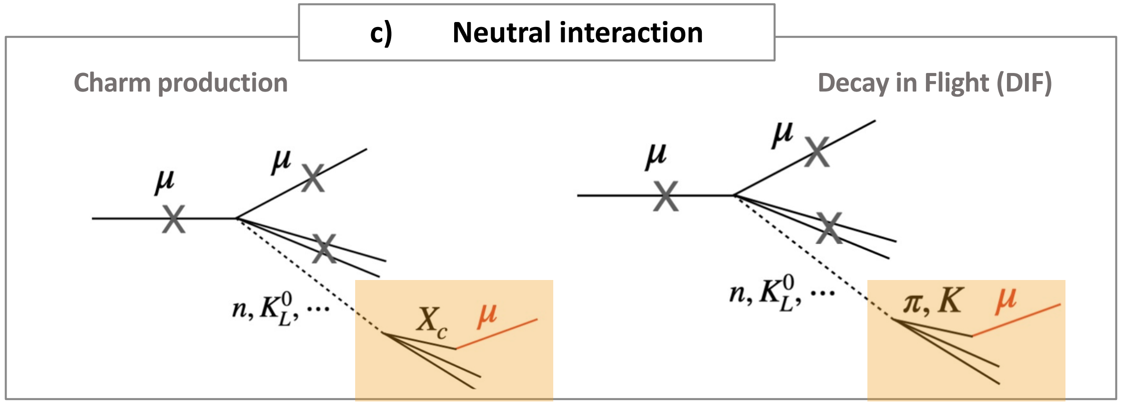

b) Muon EM

- Muon induced background: undetected muons entering the target (2022 Run3 data)

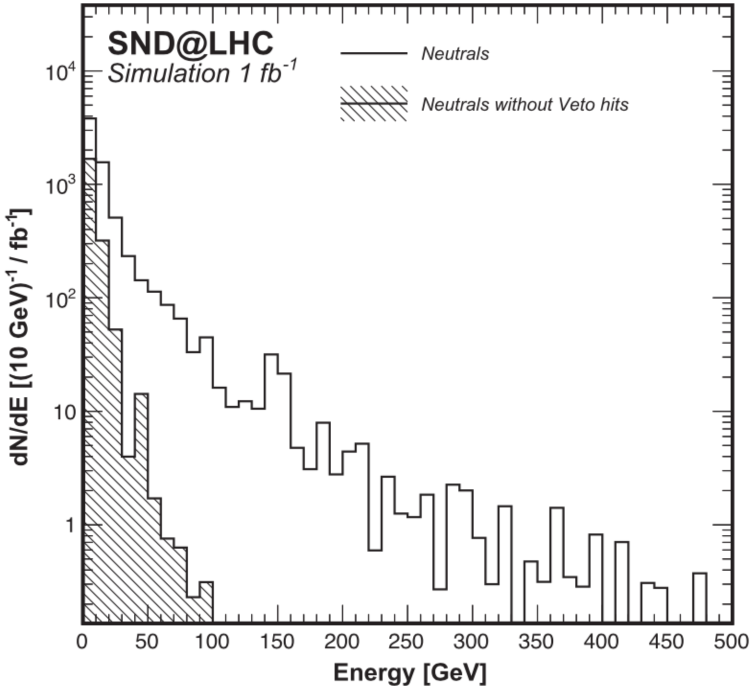
$$N_{bkg} = N_{\mu}\left(1-\varepsilon_{veto}\right) \times \left(1-\varepsilon_{SciFi1}\right) \times \left(1-\varepsilon_{SciFi2}\right) = 5.3 \times 10^{-12} N_{\mu}$$

$$N_{\mu} = 1.2 \times 10^{9}$$

Totally negligible


c) Neutral interaction

🟧 within SND@LHC acceptance

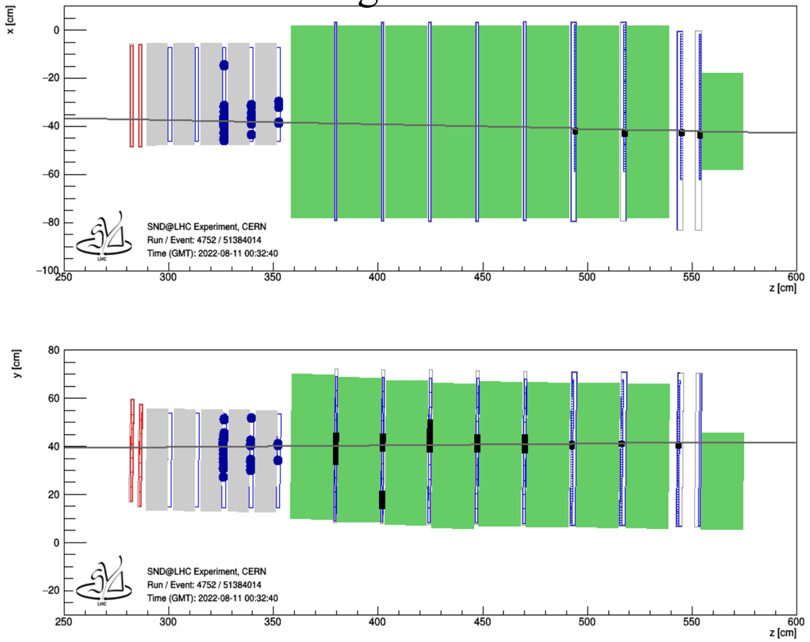


- Muon-induced neutral interactions

$$N^{\text{bkg}}_{\text{neutrals}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}} = (8.6 \pm 3.8) \times 10^{-2}$$

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



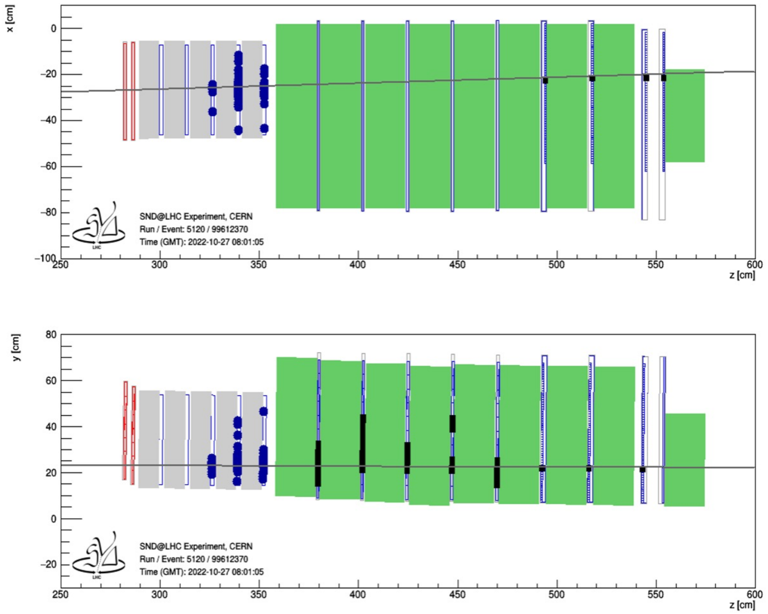
Editors' Suggestion

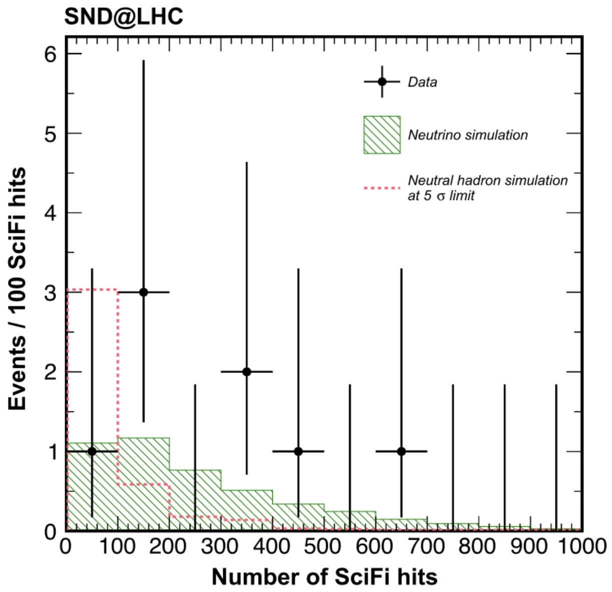
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)

Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023

Oct 27th 2022





Distribution of SciFi hits for ν_μ candidates with the MC expectation for ν events and background (augmented to the 5 sigma level)

8 observed events and an expected background

$$(8.6 \pm 3.8) \times 10^{-2}$$

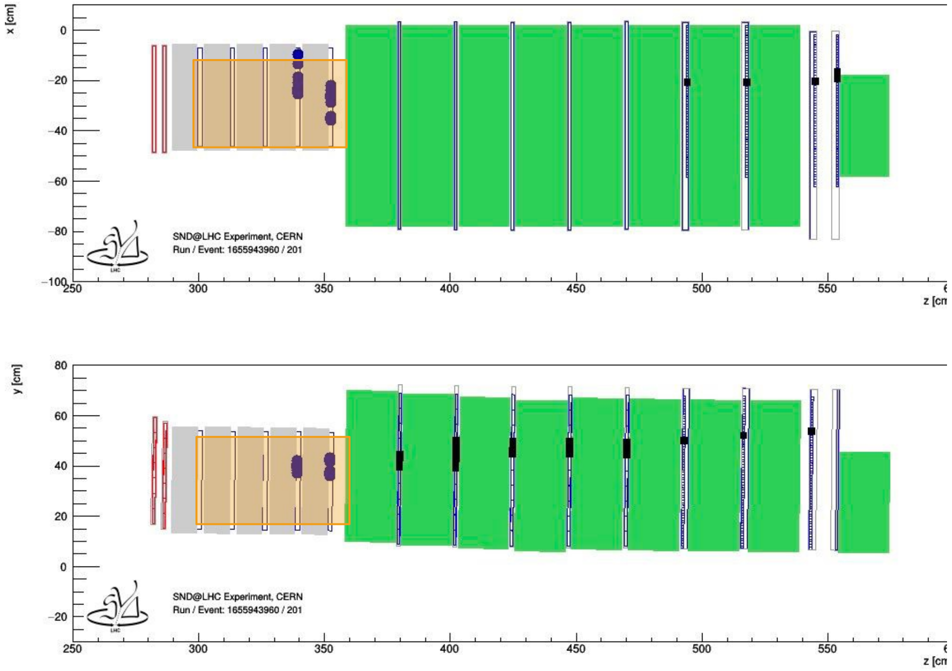
Background only hypothesis probability:

$$P = 7.15 \times 10^{-12}$$

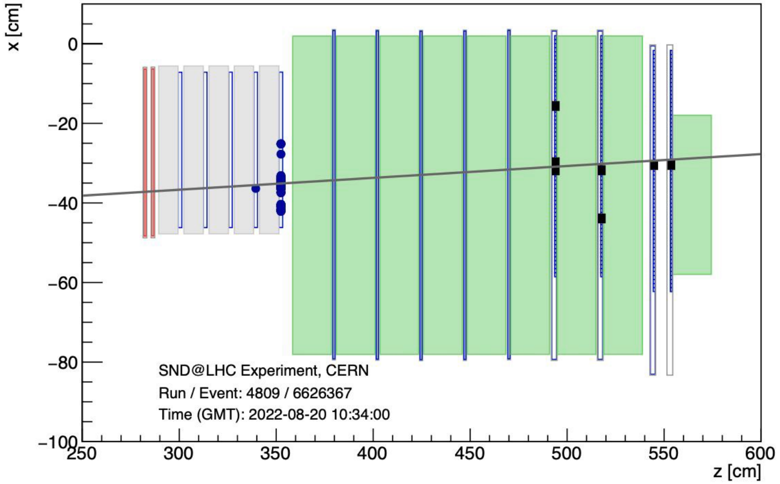
6.8 σ observation

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

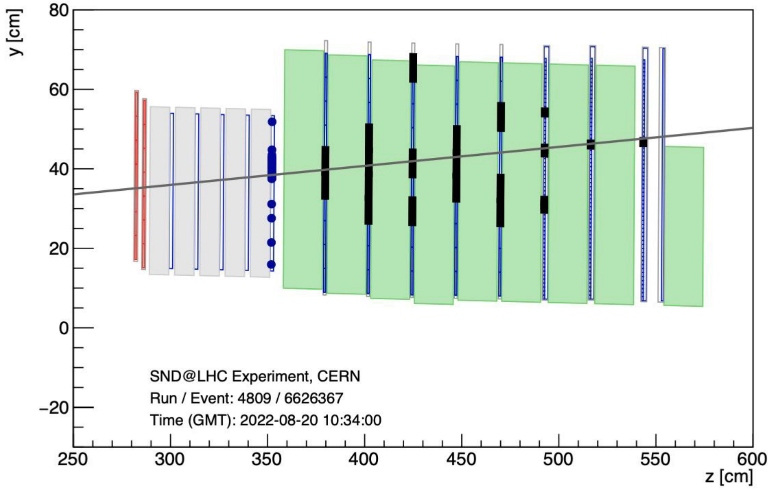
Muon neutrino selection with 2022-2023 data in an extended volume (wall 2 and 5 included)

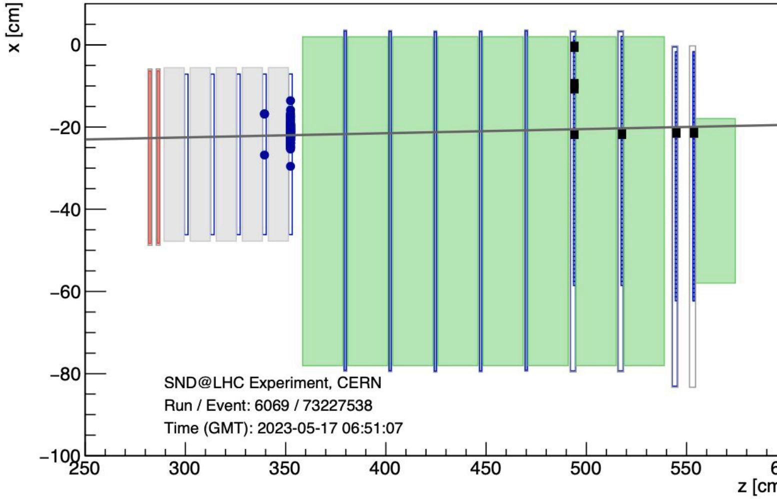


33 events: 16 in 2022 and 17 in 2023

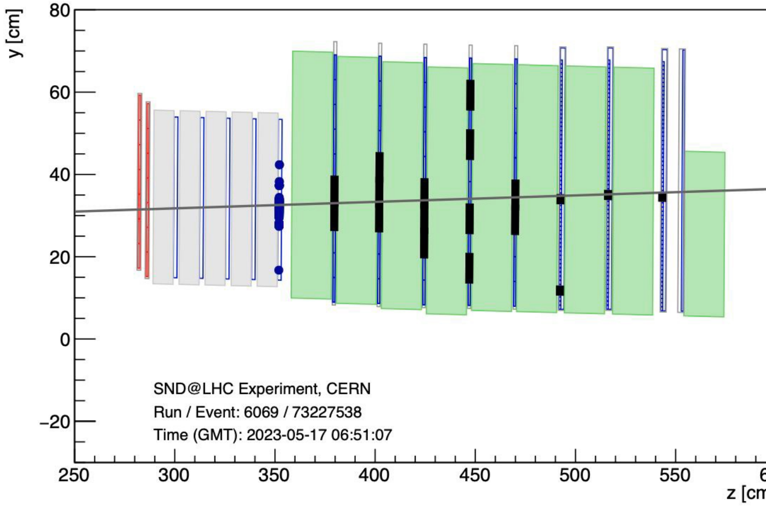


New 2022 event

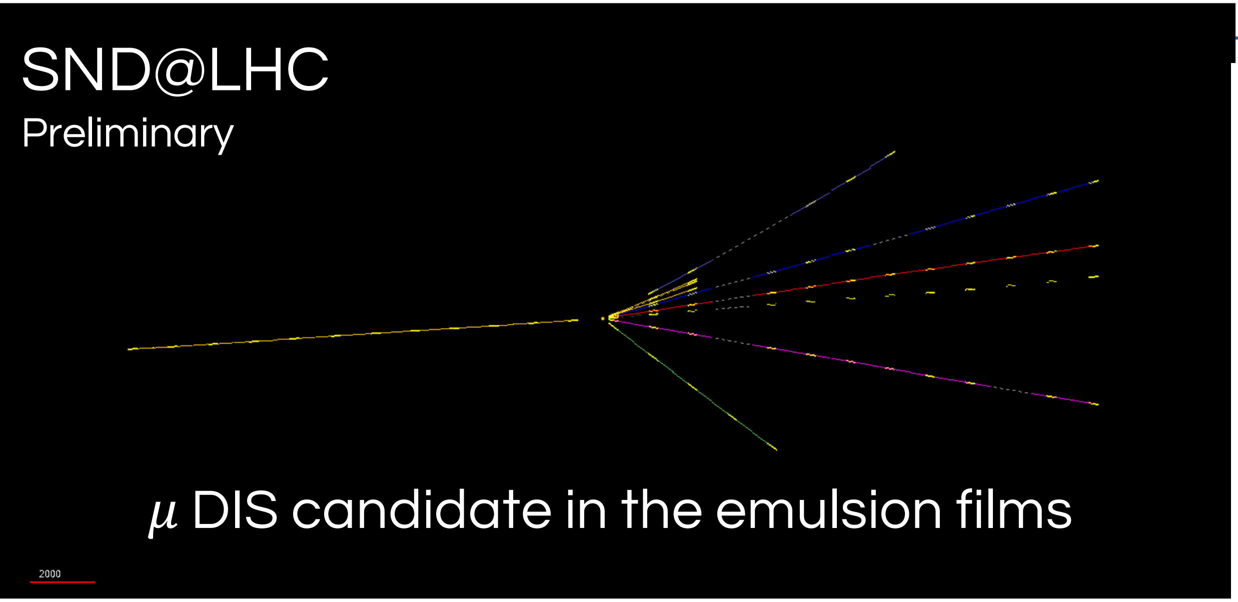




2023 event

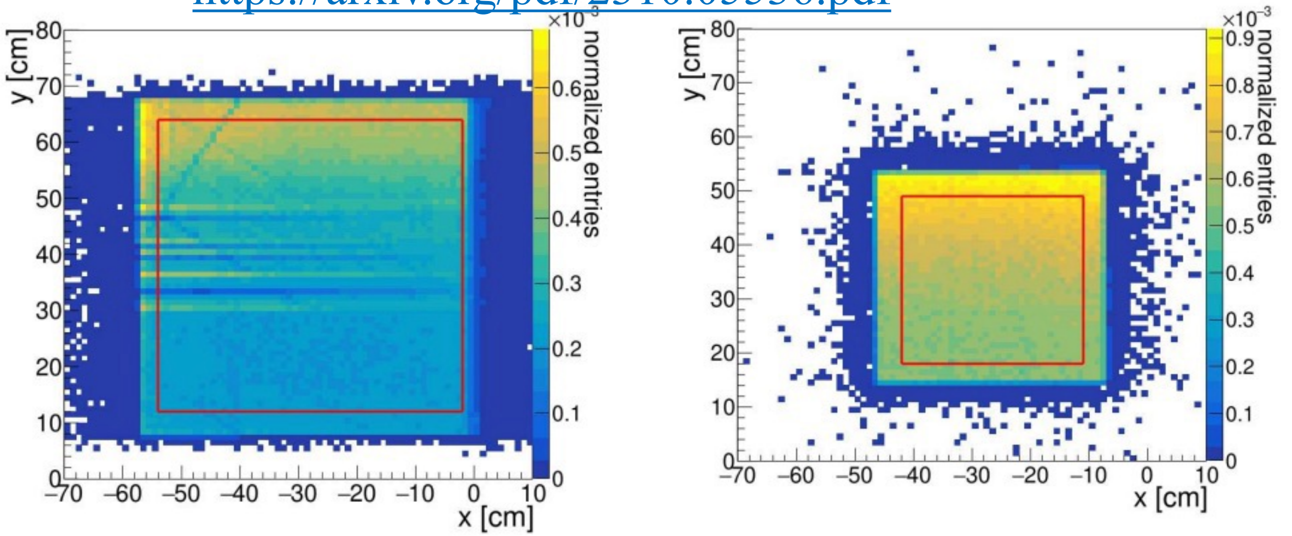


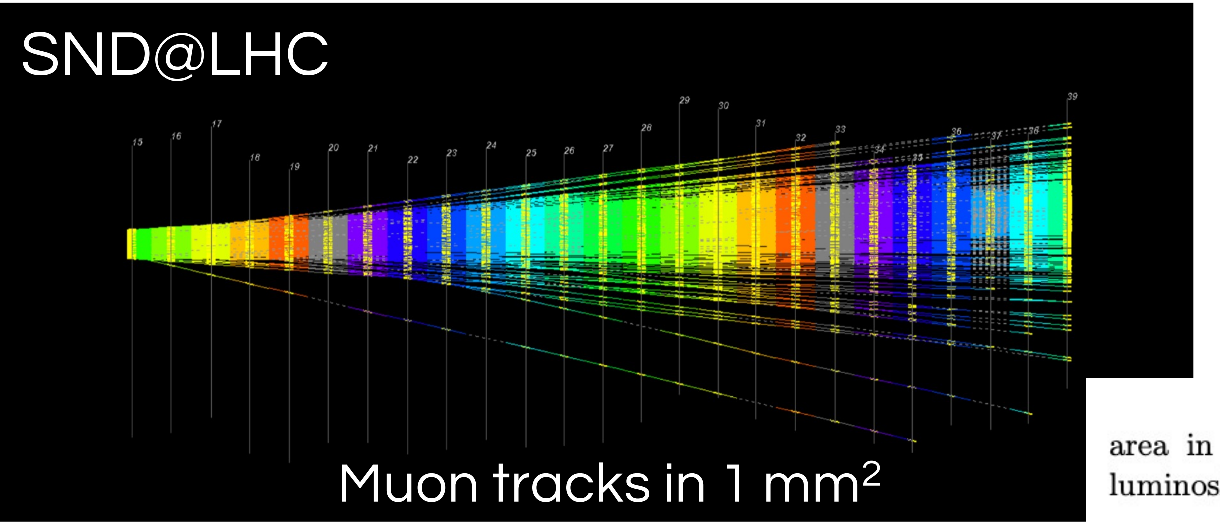
Muon flux measurement and emulsion analysis



μ DIS candidate in the emulsion films

https://arxiv.org/pdf/2310.05536.pdf





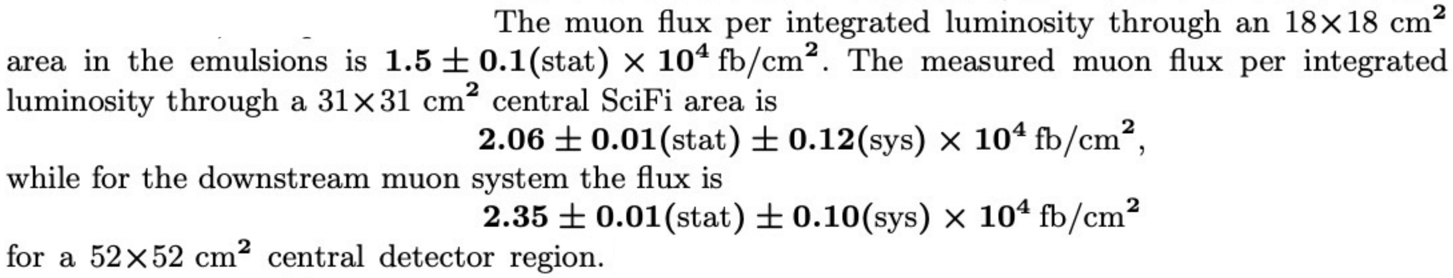
Muon tracks in 1 mm^2

10^5 tracks/cm^2 in 10 fb^{-1} exposure

SND@LHC measure muon flux in 3 different detector systems (emulsion, SciFi and Muon System).

Flux seen to increase with vertical distance from LOS.

FLUKA simulation estimate of flux ~20-25% lower than measurement.



The muon flux per integrated luminosity through an 18×18 cm^2 area in the emulsions is $\mathbf{1.5 \pm 0.1}$(stat) $\times$ $\mathbf{10^4}$ fb/cm^2. The measured muon flux per integrated luminosity through a 31×31 cm^2 central SciFi area is

$$\mathbf{2.06 \pm 0.01}(\text{stat}) \pm \mathbf{0.12}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2,$$

while for the downstream muon system the flux is

$$\mathbf{2.35 \pm 0.01}(\text{stat}) \pm \mathbf{0.10}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2$$

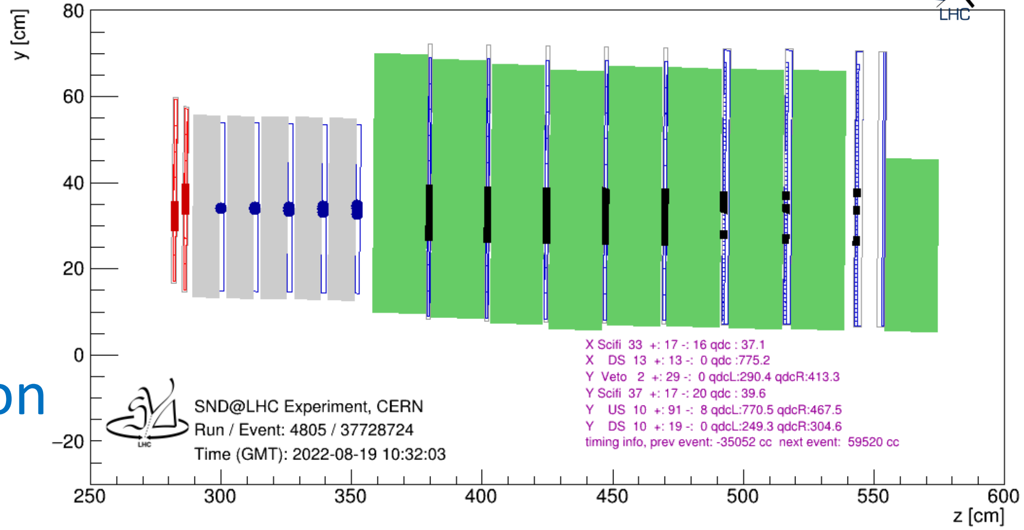
for a 52×52 cm^2 central detector region.

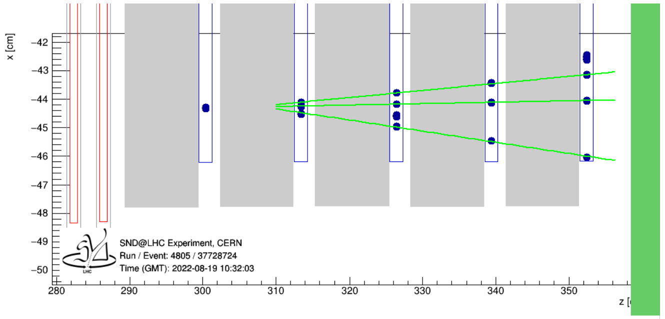
Trident process in the neutrino target

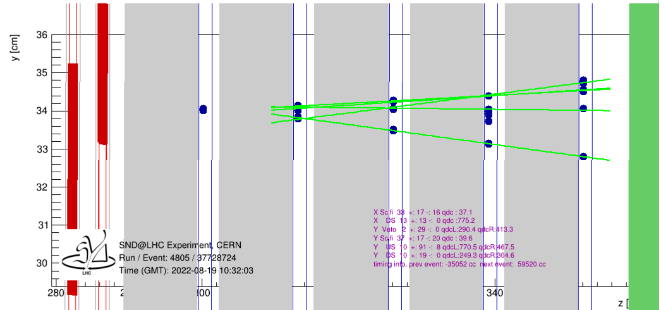
- $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
  - Studied in the 60's and 70's, Muon Tridents, J.D. Bjorken(SLAC), M.C. Chen, Observation of Muon Trident Production in Lead and the Statistics of the Muon
  - Due to identical muons, sensitive to Fermi statistics
  - With 10 GeV muon beam, measured 60 nb per lead nucleon
- "Background": bremsstrahlung followed by γ-conversion

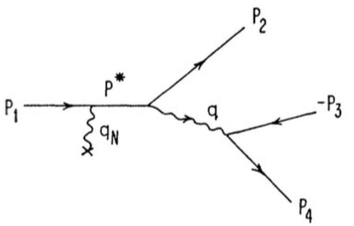
$$\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma, \gamma + N \rightarrow N + \mu^{+}\mu^{-}$$

- Process introduced in GEANT4 in 2022
- In 2022 data, 137 events observed with 3 tracks and 1 vertex
- Expect from simulation 85 events (2/3 due to γ-conversion and 1/3 genuine trident)

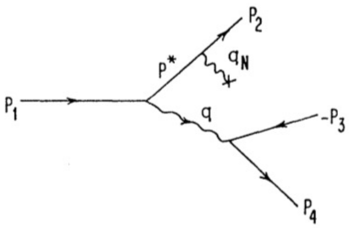




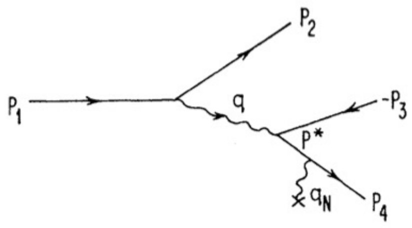




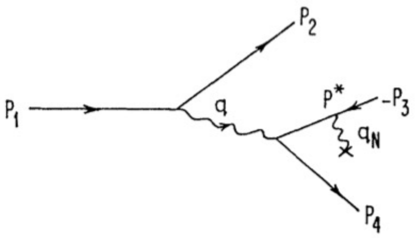
(a) q TIMELIKE
P* TIMELIKE



(b) q TIMELIKE
P* SPACELIKE



(c) q AND P* SPACELIKE

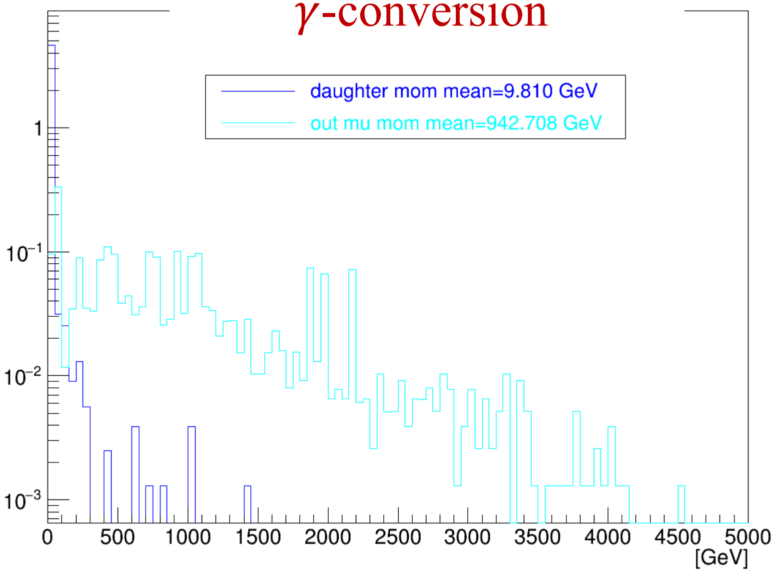


(d) q AND P* SPACELIKE

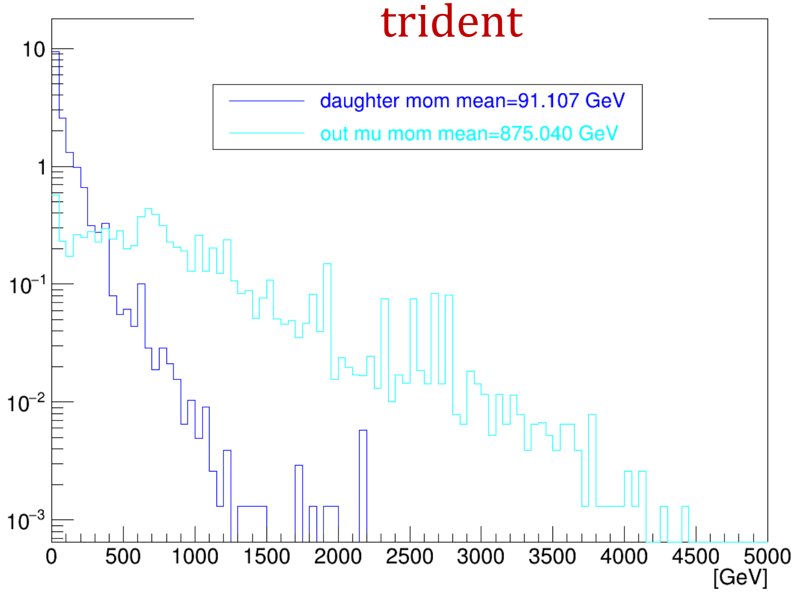
Trident events induced in the upstream rock

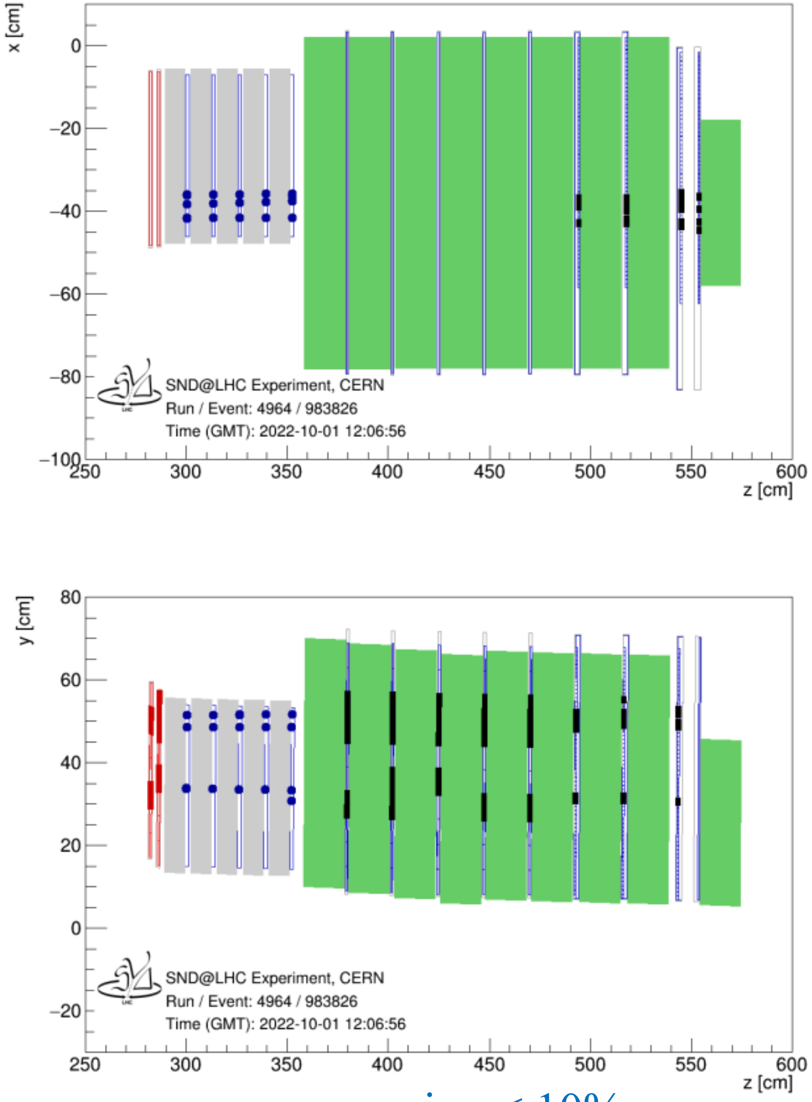
439 candidates in 2022 data
1032 expected from MC

Momentum distribution
γ-conversion

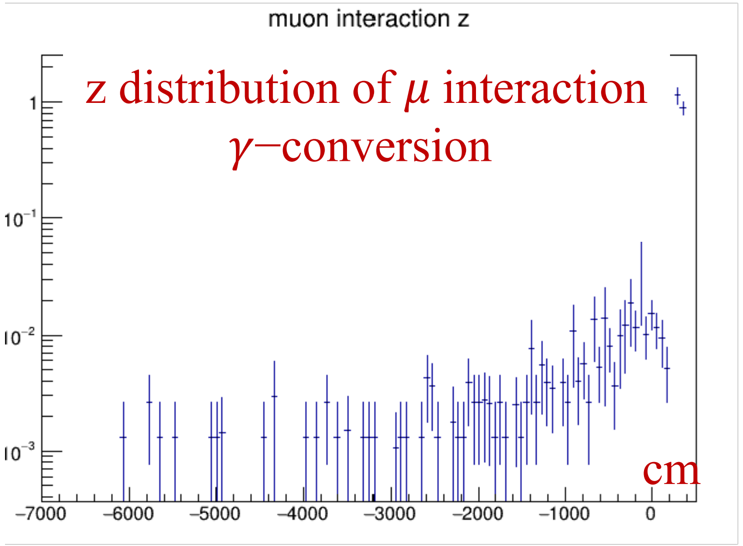


Momentum distribution
trident

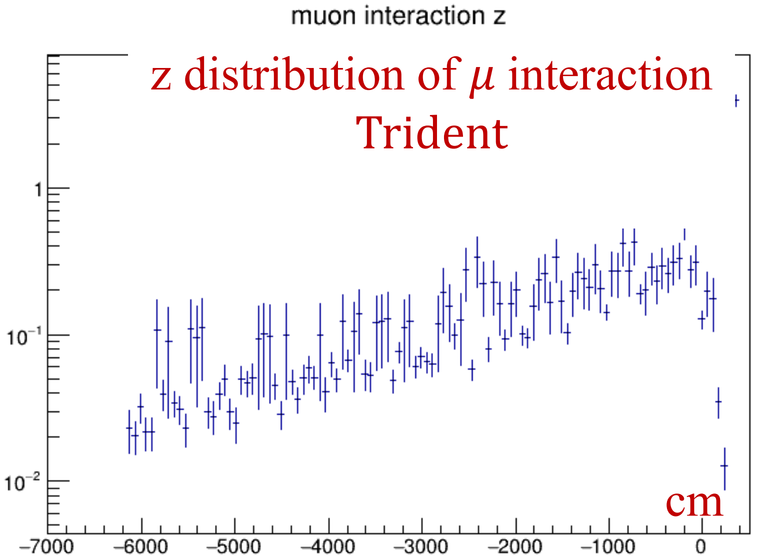




z distribution of μ interaction
γ−conversion



z distribution of μ interaction
Trident



γ−conversion < 10%

SND@LHC UPGRADE TOWARDS HL-LHC

LHC

Scattering and Neutrino Detector
at the LHC

Detector(s) concept to extend the physics case in HL-LHC

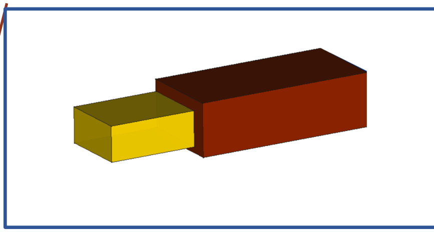
AdvSND-Far in TI18

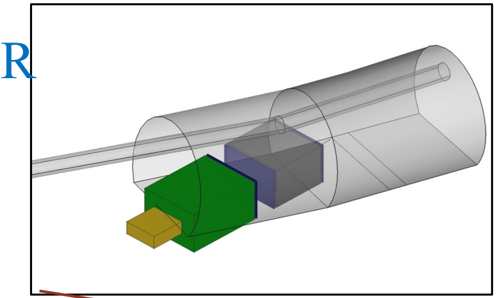
- Improve statistics, reduce systematics
- Separate ν from ν-bar
- Charm production measurements
- LFU

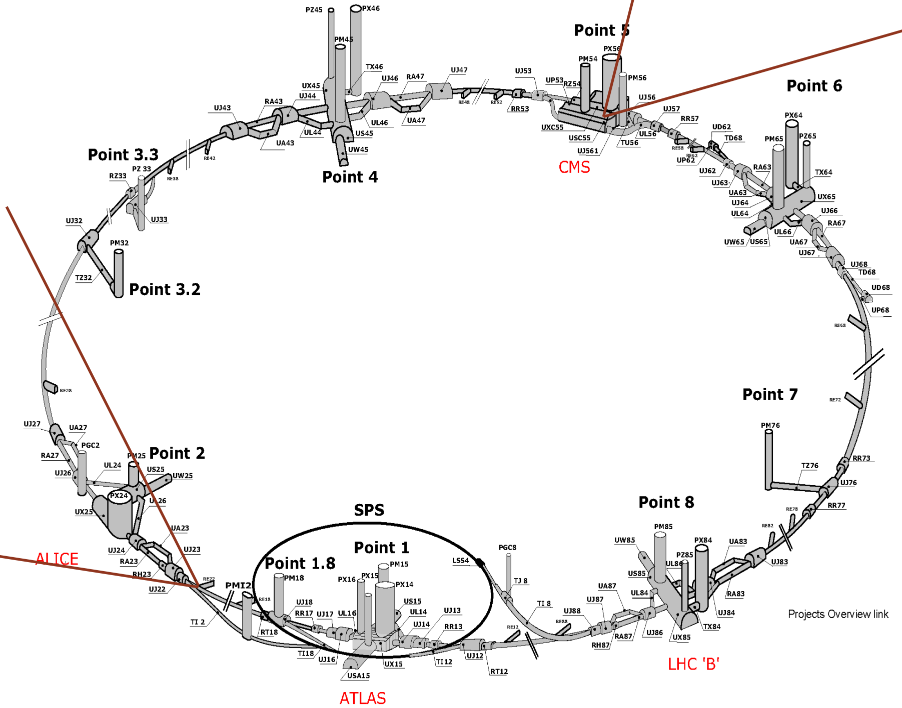
AdvSND-Near in UJ57 close to IP5

- Overlap with LHCb η where c/b measured
- Reduce sys uncertainties for the FAR
- ν cross-section

AdvSND-Near: $4.0 < \eta < 4.5$

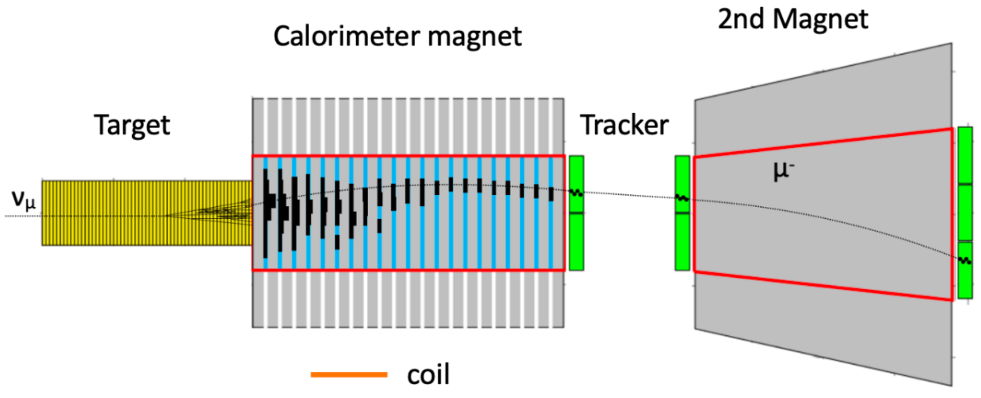


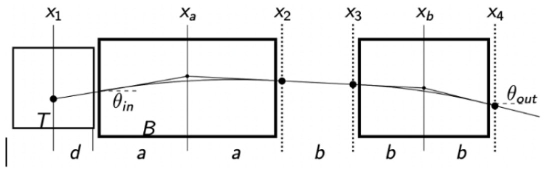


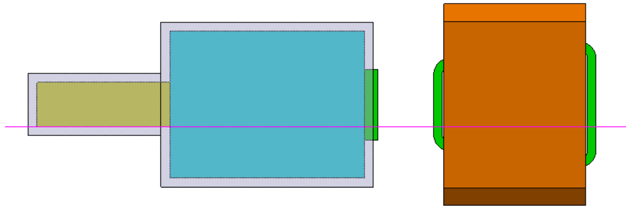


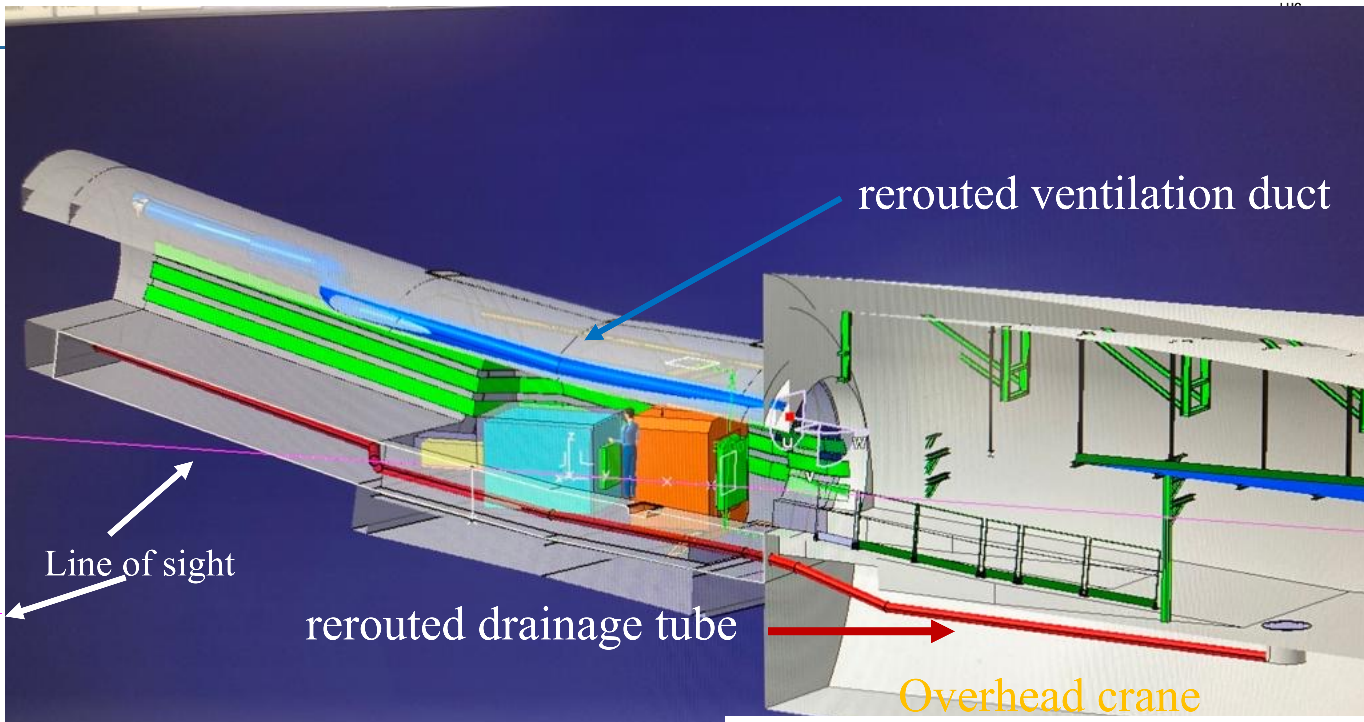
AdvSND-Far: $\eta > 7.4$

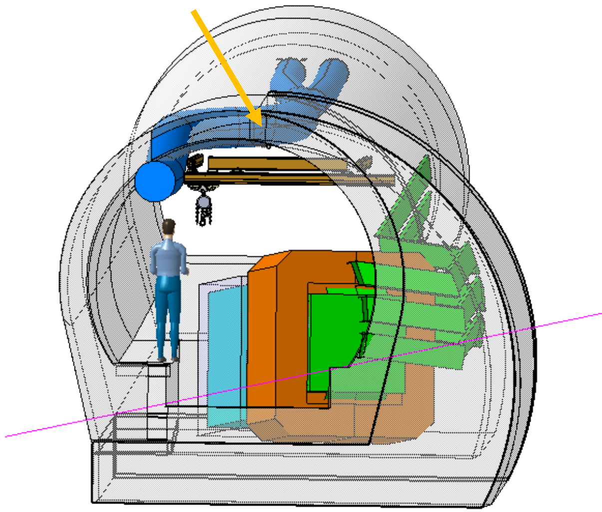
Adding a magnet for *ν*/*ν*bar separation and improved energy resolution



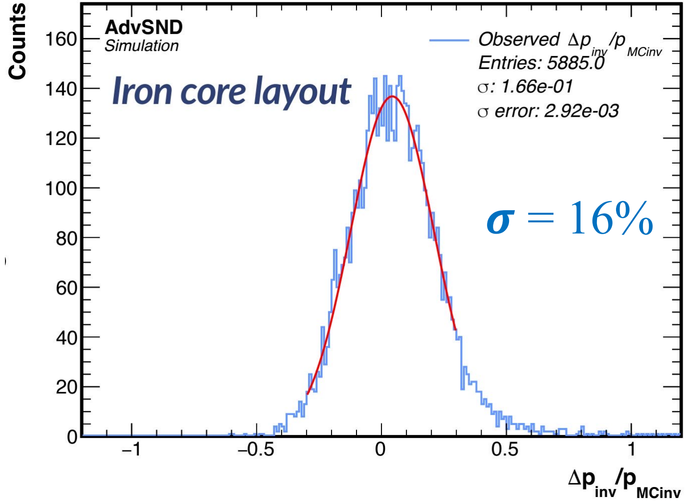




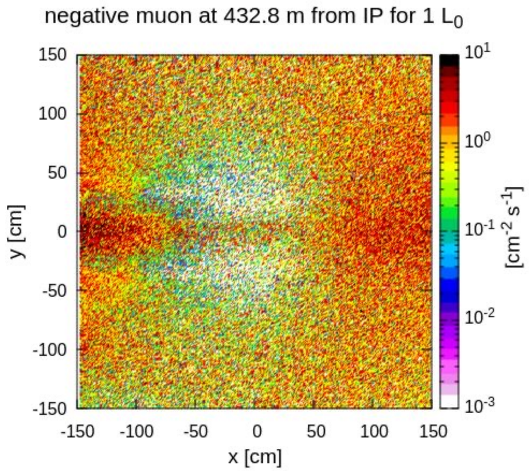


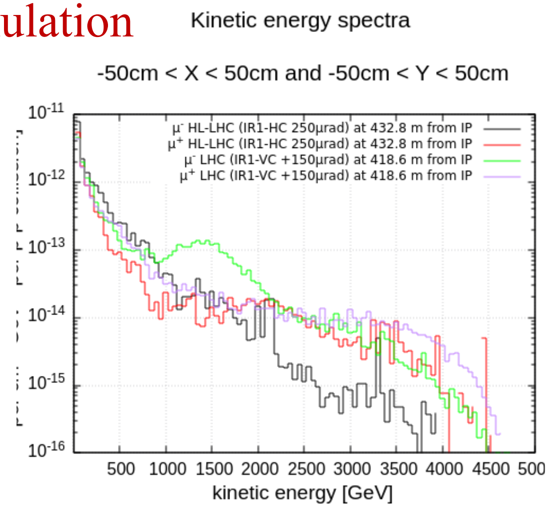


μ momentum resolution

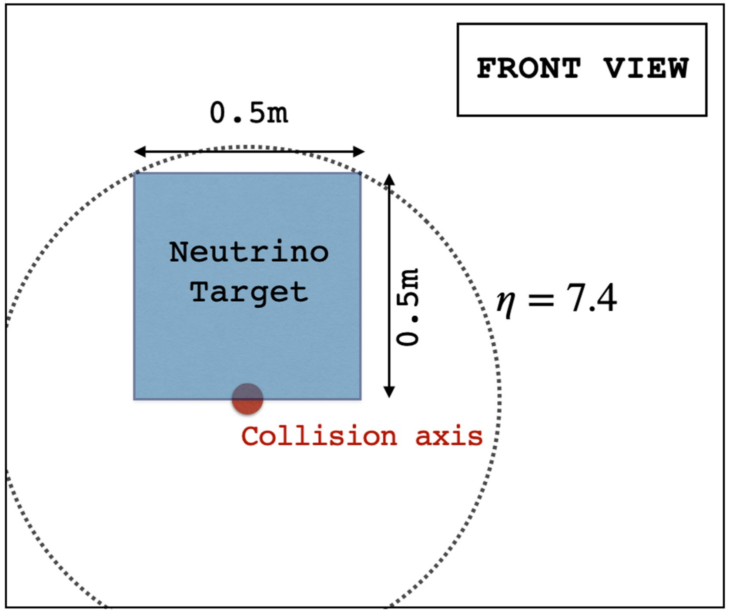


FLUKA HL simulation





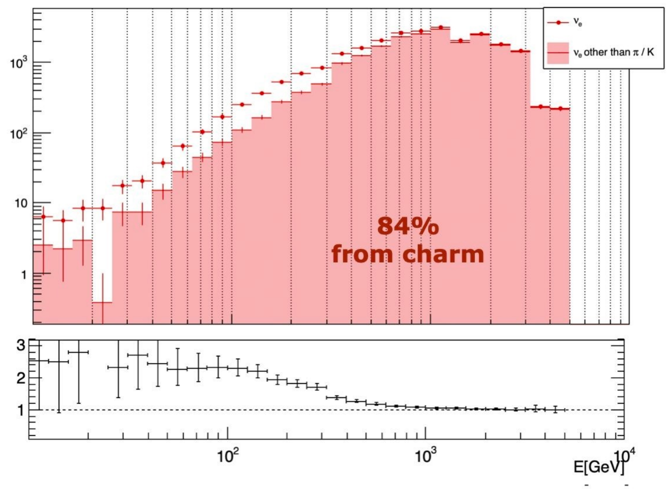
Off-axis configuration

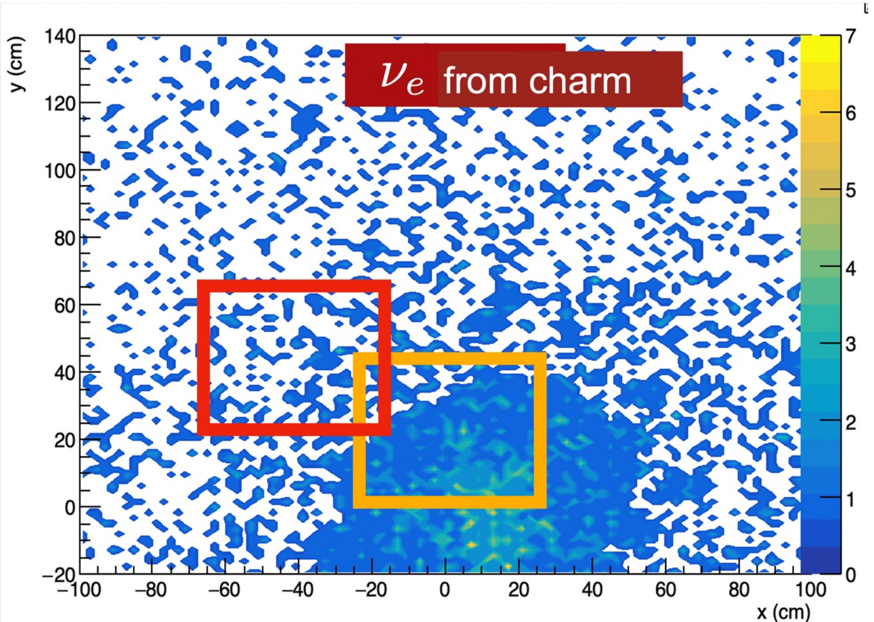


Flavour	CC neutrino interactions Yield	NC neutrino interactions Yield
ν_μ	6.9×10^4	2.0×10^4
$\bar{\nu}_\mu$	2.5×10^4	9.0×10^3
ν_e	2.1×10^4	6.5×10^3
$\bar{\nu}_e$	1.0×10^4	4.0×10^3
ν_τ	950	300
$\bar{\nu}_\tau$	580	240
TOT	1.3×10^5	4.1×10^4

Active surface: ~50 × 50 cm^2
Tungsten mass ~ 2 tons

Neutrino interactions in AdvSDN-Far
DPMJET+FLUKA total 3000 fb^{-1}

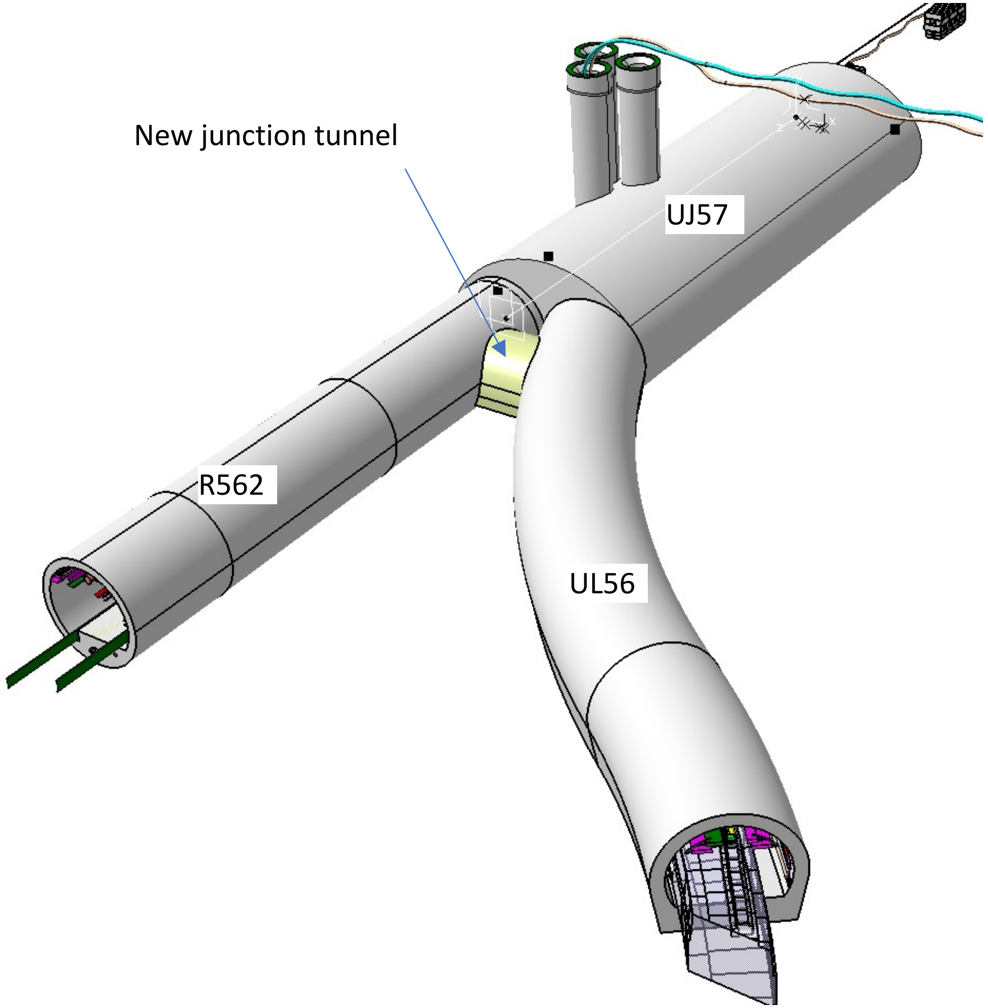


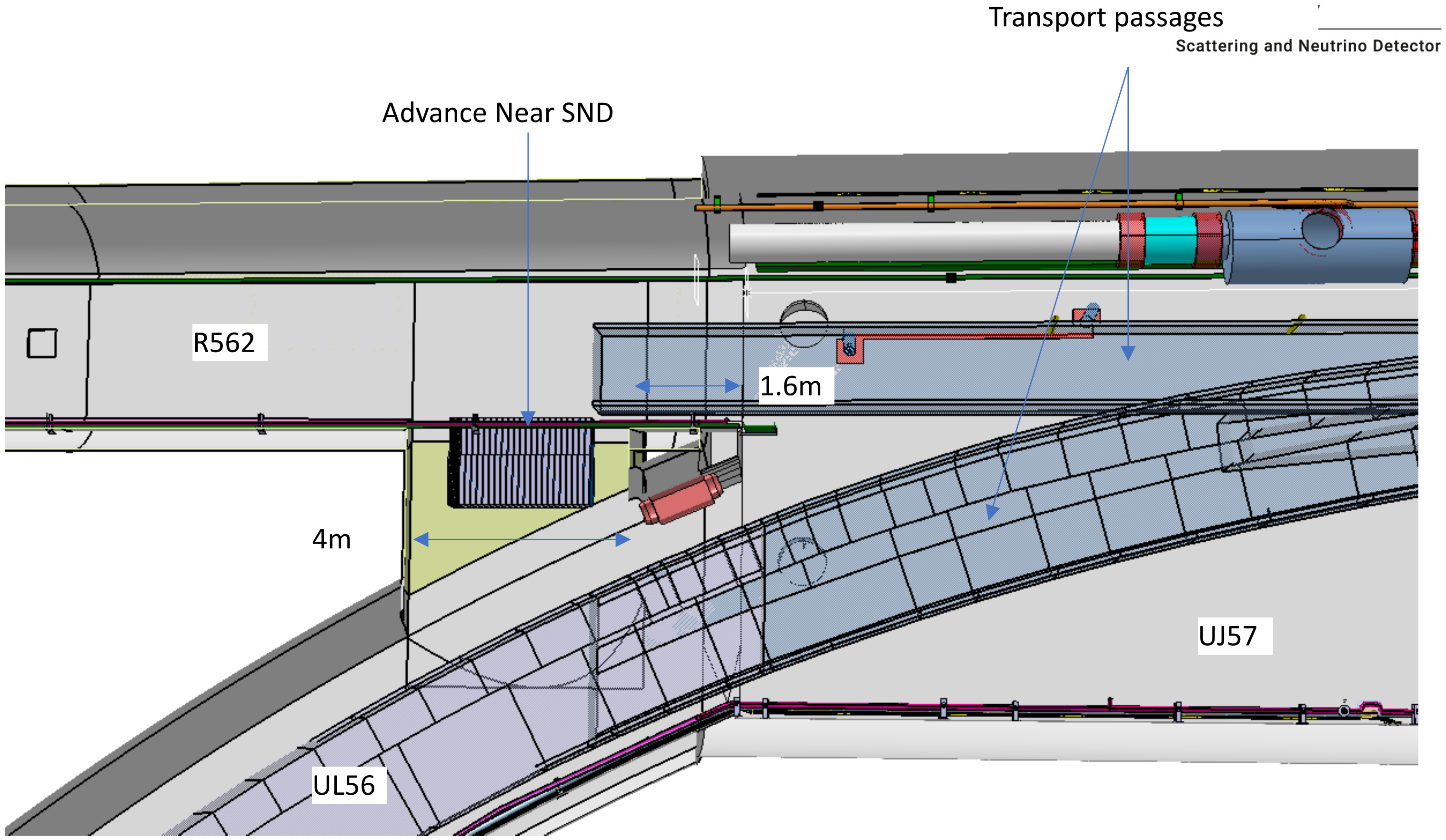


Lowered by ~15 cm
Partial overlap with FASER useful for data comparison/systematics
Gain in statistics × 4 w.r.t. current location for equal luminosity
> 150k ν interactions

Ongoing studies on optimal configuration of vertex detector and e/π^0 separation performance

Studies for Advanced NEAR

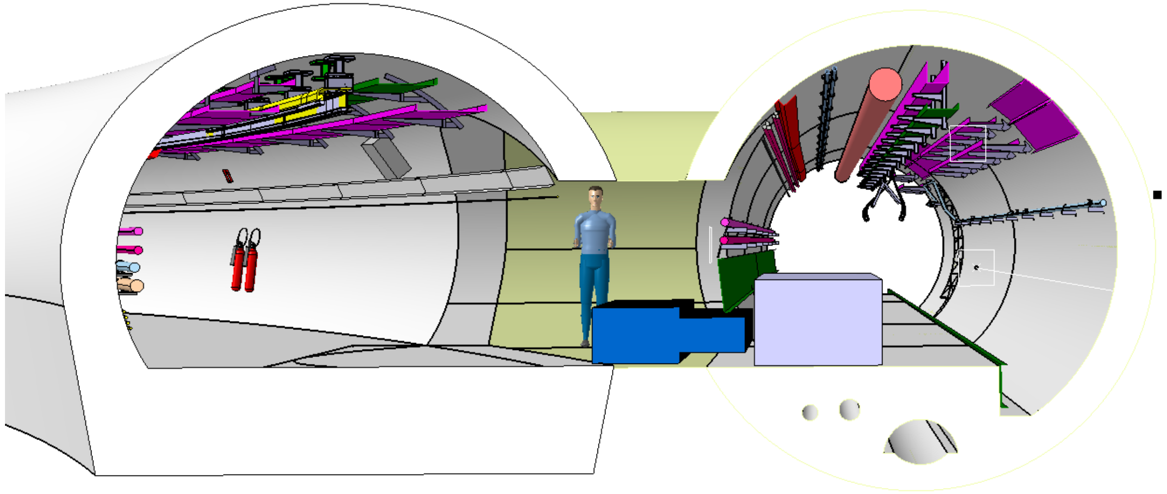


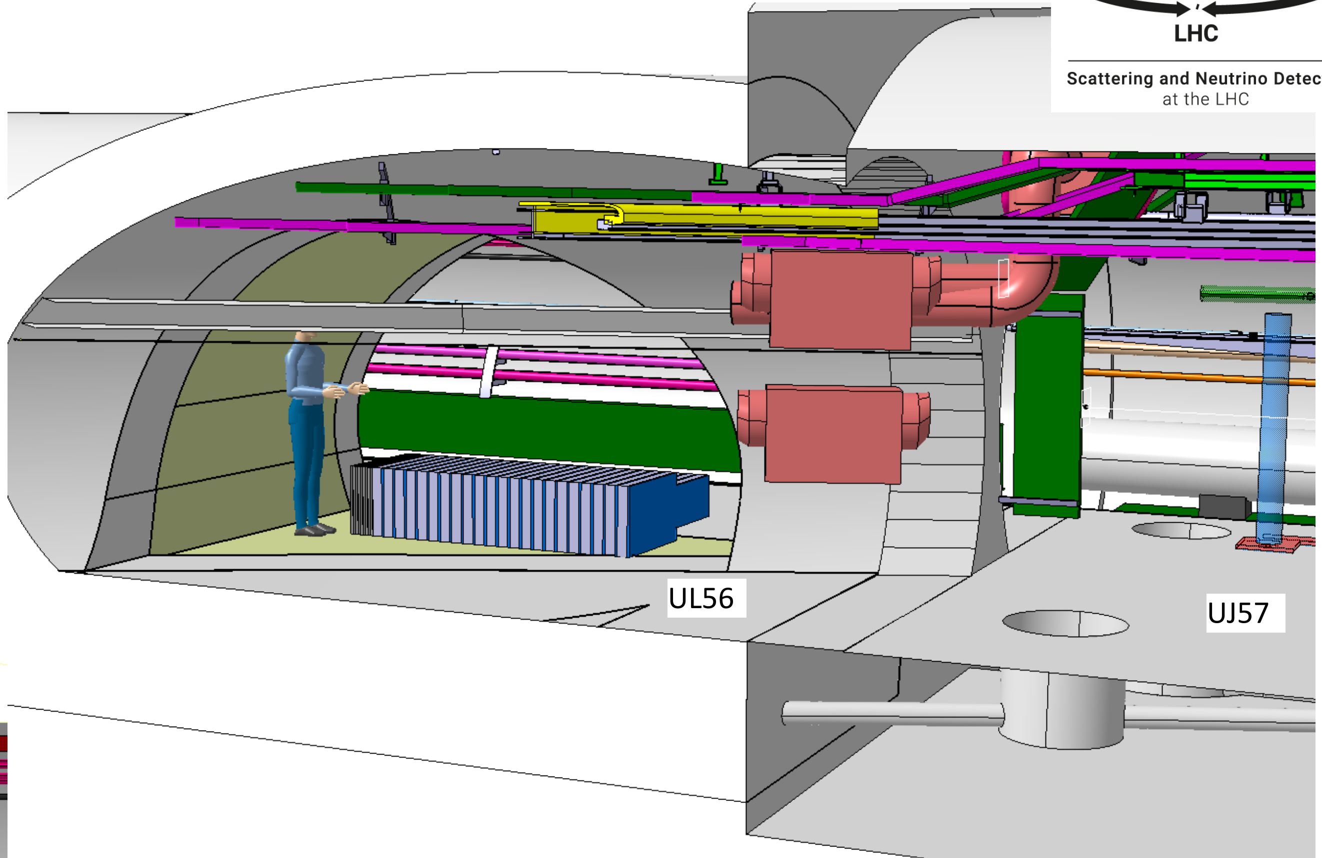


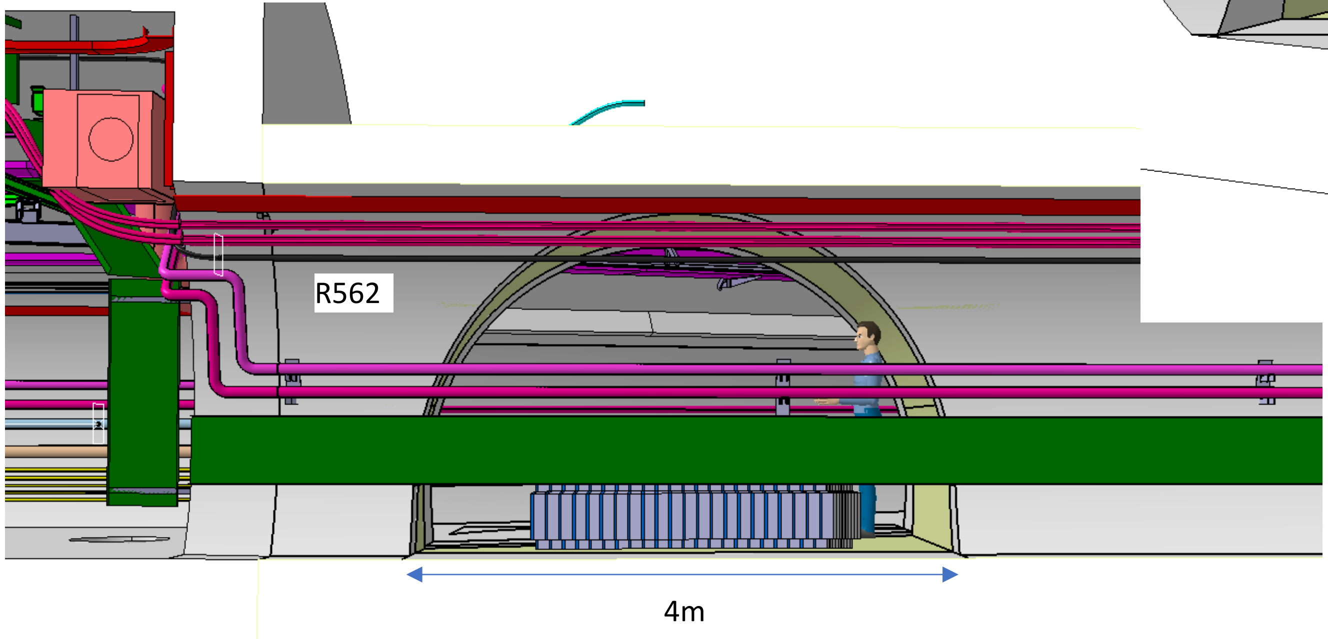
2.0m transversally (95mm clearence between ADV SND and transport volume in R562)

5m longitudinally towards CMS

Location for Advanced NEAR







Advanced NEAR: neutrino expectation

LHC
Scattering and Neutrino Detector
at the LHC

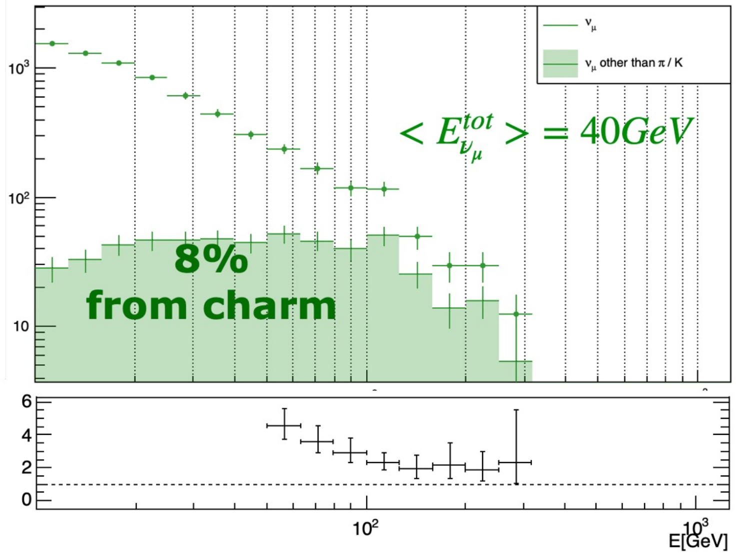
AdvSND-Near

η	[4.0, 4.62]
φ	3.5 %
mass (ton)	5
surface (cm^2)	147x53.5
distance (m)	87.2

Expectations in **3000 fb^{-1}**

	CC DIS Interactions			
Flavour	**total (DPMJET)**	**cc-bar (DPMJET)**	**cc-bar (PYTHIA8)**	**bb-bar (PYTHIA8)**
$\nu_\mu + \bar{\nu}_\mu$	17500	1025	950	47
$\nu_e + \bar{\nu}_e$	1800	1100	975	50
$\nu_\tau + \bar{\nu}_\tau$	75	75	75	10
Total	**19375**	**2200**	**2000**	**107**

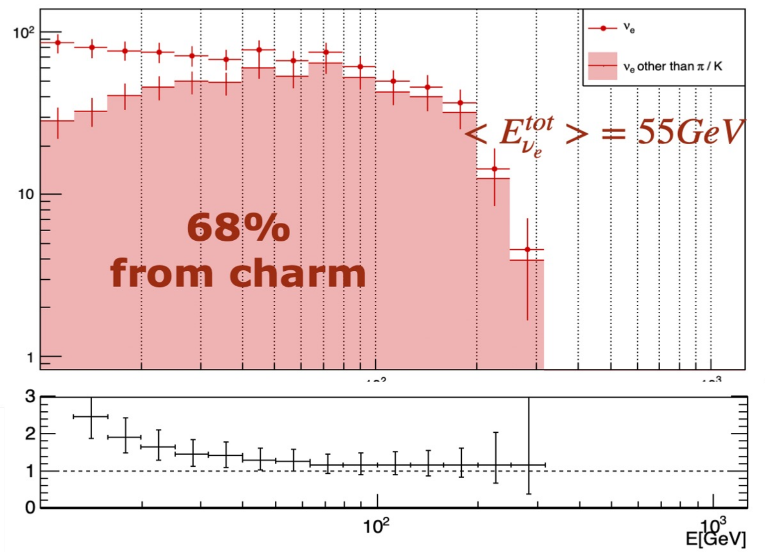
Neutrino interactions in AdvSDN-Near
DPMJET total 3000 fb^{-1}



$< E^{tot}_{\nu_\mu} > = 40GeV$

8% from charm

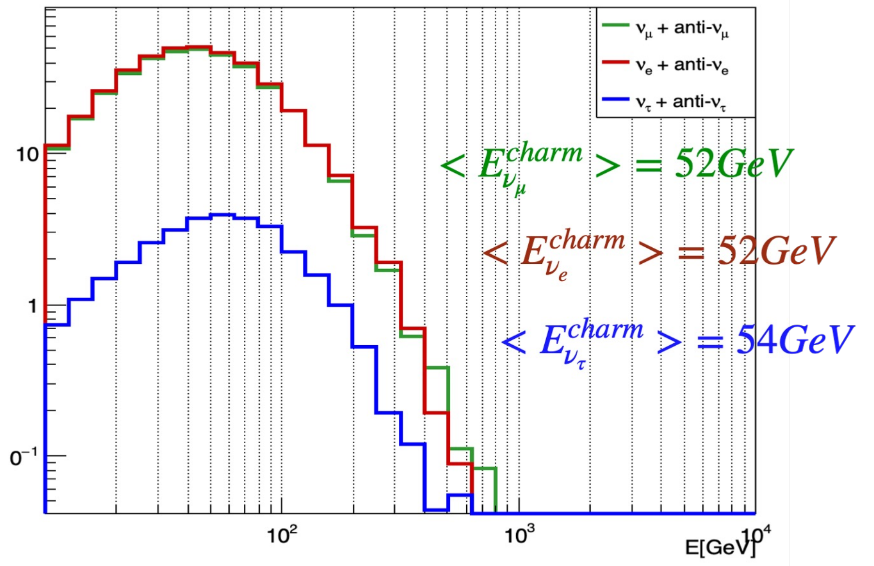
Neutrino interactions in AdvSDN-Near
DPMJET total 3000 fb^{-1}



$< E^{tot}_{\nu_e} > = 55GeV$

68% from charm

Neutrino interactions in AdvSDN-Near
PYTHIA8 cc-bar 3000 fb^{-1}



$< E^{charm}_{\nu_\mu} > = 52GeV$

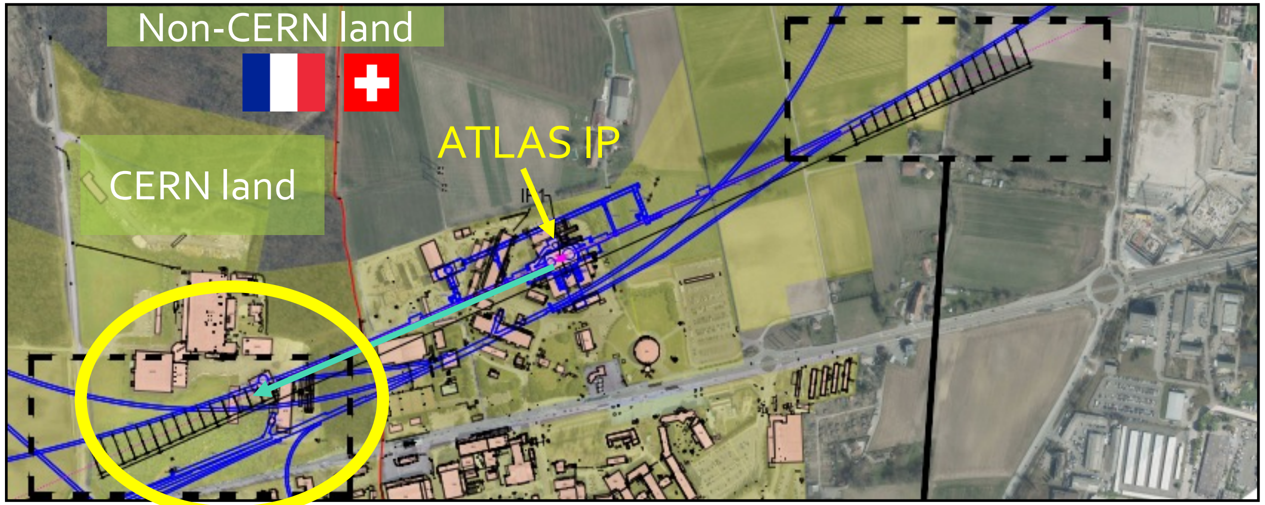
$< E^{charm}_{\nu_e} > = 52GeV$

$< E^{charm}_{\nu_\tau} > = 54GeV$

LHCb ~ 180k charmed hadrons https://link.springer.com/article/10.1007/JHEP05(2017)074 in the 4 to 4.5 η range → ~ 18k ν_e

Beyond Run 4: Forward Physics Facility

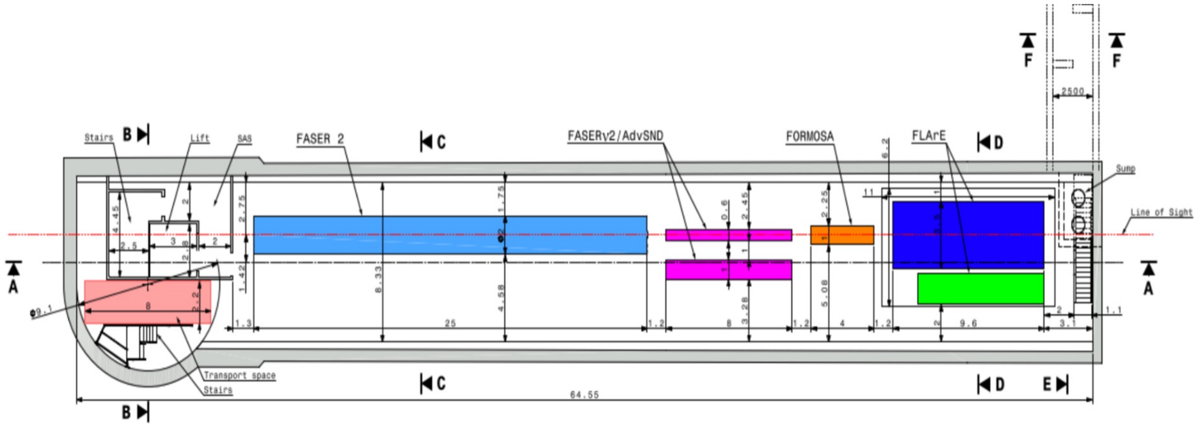
FASERν2 and AdvSND

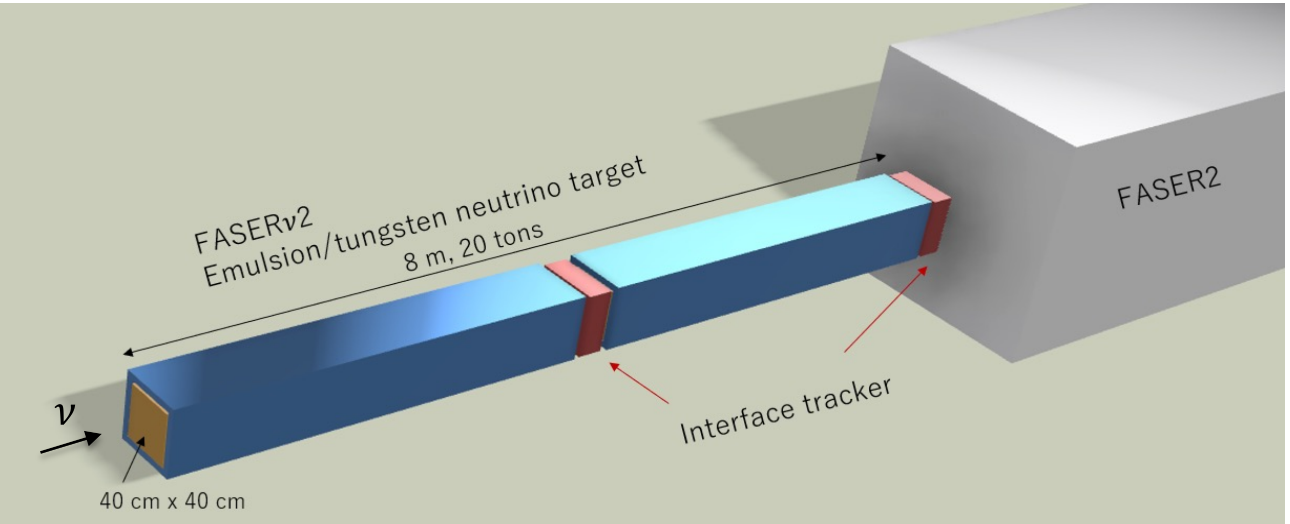


FPF White paper: *J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501*

https://iopscience.iop.org/article/10.1088/1361-6471/ac865e/pdf

- FPF proposed to house a suite of experiments to for BSM physics searches, neutrino physics and QCD.
- FASERν2 designed to carry out precision ν_τ measurements and heavy flavour physics studies
  - ~2300 (SIBYLL) / ~20000 (DPMJET) ν_τ interactions are expected
- AdvSND with two off-axis forward detectors
  - SND1: $\eta \sim$ 8 Reduce systematic uncertainties
  - SND2: $\eta \sim$ 4.5 link to LHCb measurements & high-energy ν physics
- FLArE with an on-axis LArTPC with ~10 ton LAr mass
  - neutrino and light DM detector





New era of collider neutrinos started!

https://cerncourier.com/a/collider-neutrinos-on-the-horizon/

LHC
Scattering and Neutrino Detector
at the LHC

CERNCOURIER | Reporting on international high-energy physics

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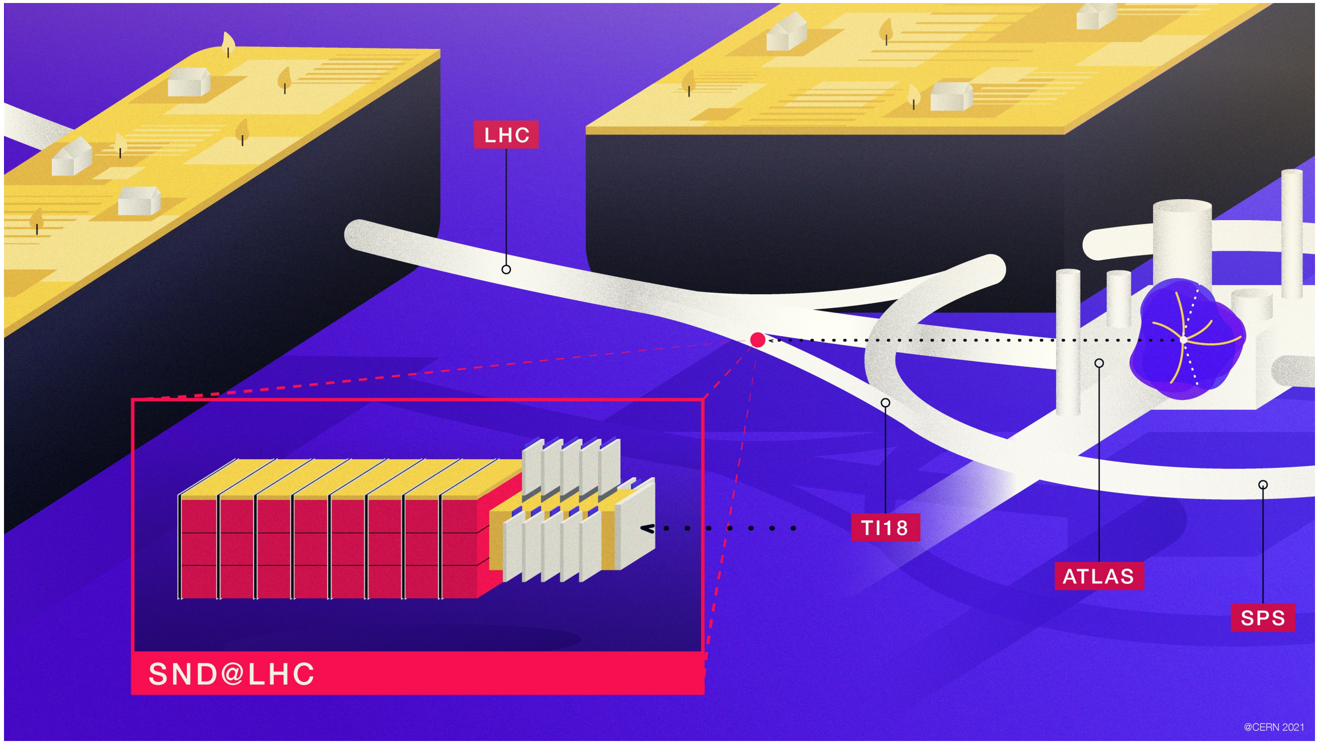
NEUTRINOS | NEWS

Collider neutrinos on the horizon

2 June 2021



Stay tuned! Data taking just started!
LHC Run3: 2022-2025
and beyond!