Neutrino physics with ENUBET and T2K

Prof. Andrea Longhin

Per gli studenti di LT e LM in Fisica

DFA UniPD, 23/02/2024

1222·2022 800 ANNI
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The neutrino

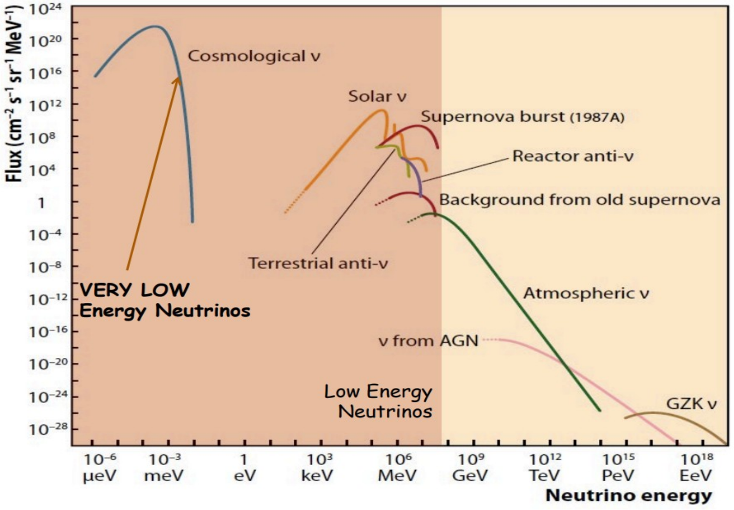
Hypothesis 1932 (Pauli), discovery 1957 (reactors, Reines-Cowan)

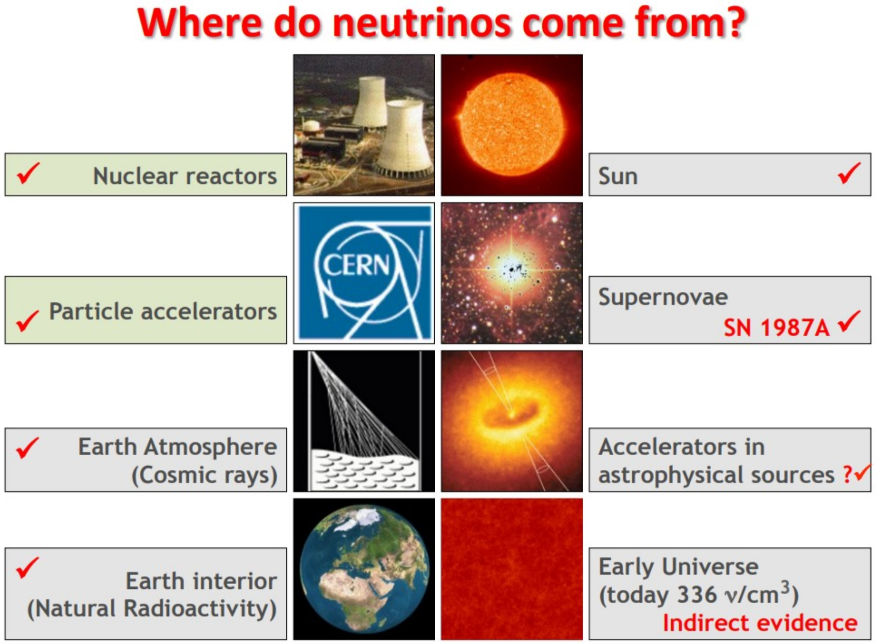
Extremely abundant:

the Sun → $6x10^{10}$/s/cm^2 !!!

the Early Universe → 336/cm^3 (indirect)

Many sources over ~20 orders of magnitude in energy →





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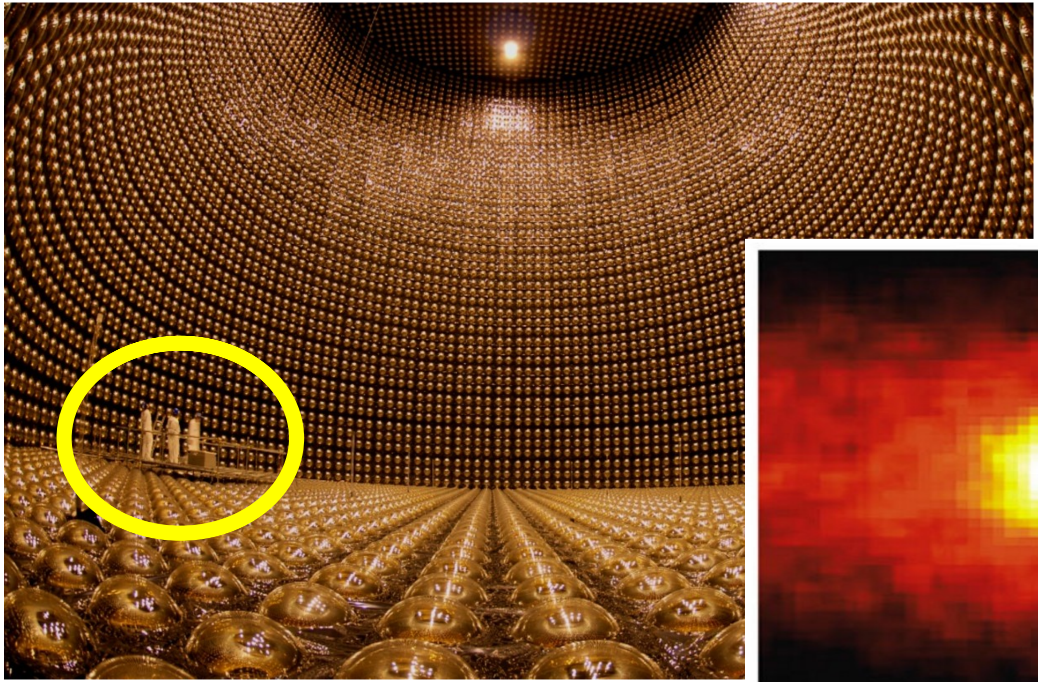
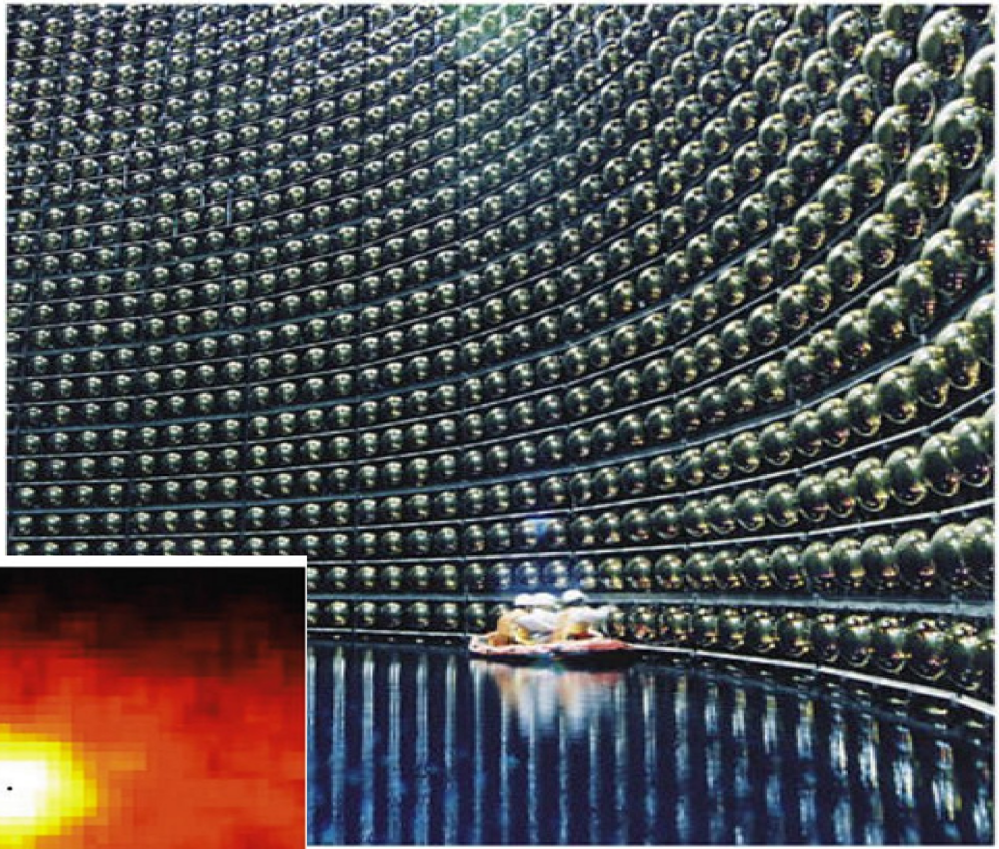
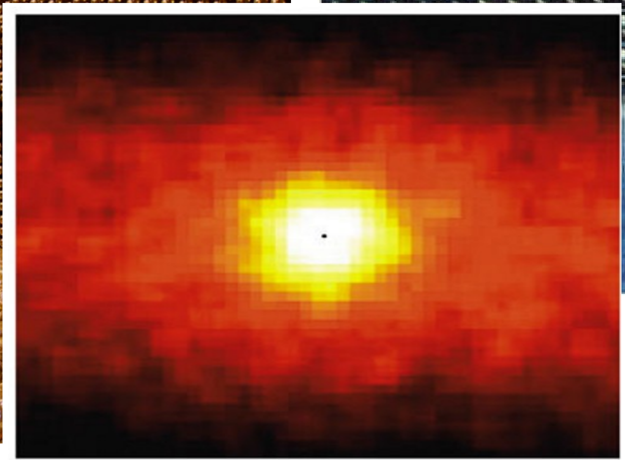
Weak interaction only

The only elementary particle with weak interaction only → gigantic and refined detectors



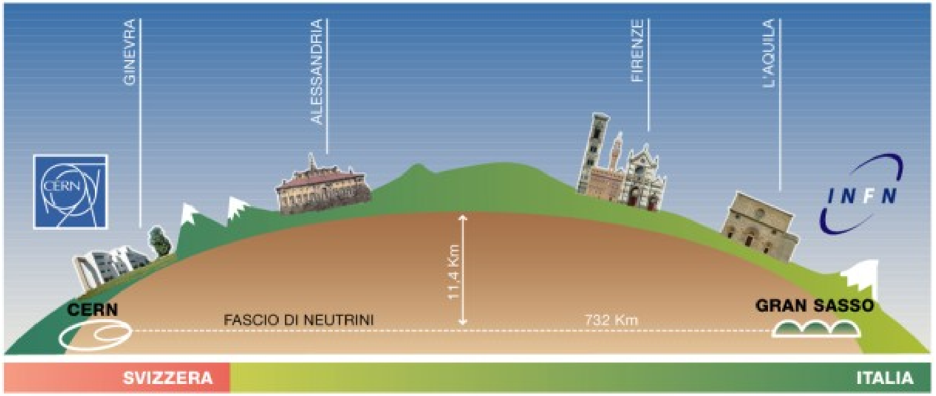


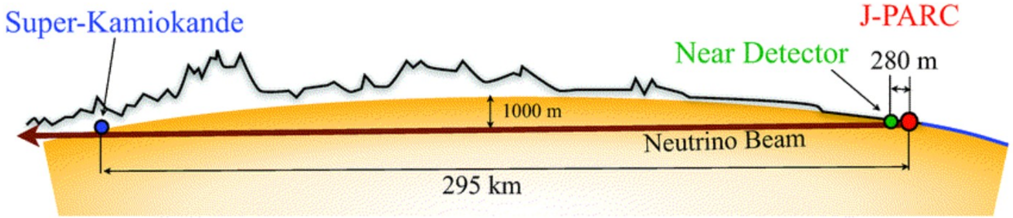


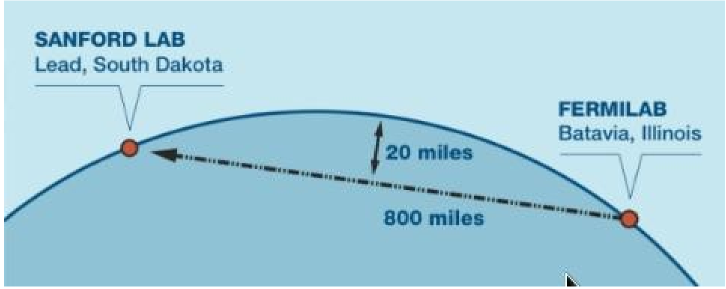
← The Sun neutrino-graphed by Super-Kamiokande

Tunnel? no thanks

Beams of O(100 km) or more feasible underground
→oscillation experiments (flavor transitions)







Light … but not too much

1998: discovery of neutrino oscillations → at least 2 out of the 3 neutrinos have a non-zero mass (< 1 eV) → Nobel 2015 (Kajita, McDonald)

Neutrinos are ~O(1 M) times lighter that the electron! why so unnaturally lighter than leptons (to which they are intimately related)?

Is it due to other undiscovered neutrinos at high-mass?
→ a ``portal'' towards physics beyond the standard model

Does neutrino masses arise from the Higgs mechanism?
Or are they intrinsically different particles? (``Majorana fermions'')

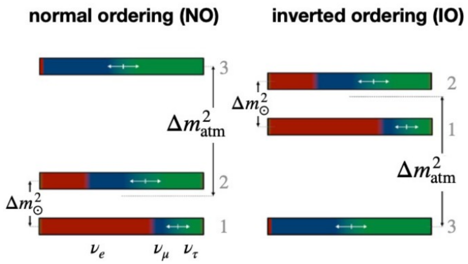
Open questions for new experiments

- Do neutrinos violate the CP symmetry as quarks?

Where does the matter-over antimatter asymmetry in the universe come from?

- Which is the mass of the lightest neutrino?

- Which is the mass ordering of the 3 mass states ?
  - We currently only now differences of mass^2 from oscillations.



- Are there "new" neutrinos beyond those with a standard lepton counterpart (sterile neutrinos)?

Experiments: how to progress?

Neutrinos are experimentally “**difficult**”

- Need to detect them far away + weak interactions → **large statistical uncertainties**
- production+interaction only described by models → **large systematic uncertainties**

Systematics are becoming the driving limitation
→ **Desperate need for high quality experimental inputs**

I will show 2 “directions” explored by our group:

- **1)** fully exploit the information from “near detectors”
  - Bayesian analysis of the T2K experiment data (“analysis”)
- **2)** new ideas to improve the source:
  - ENUBET demonstrator → a new concept neutrino source with 1% precision (“hardware”)

Experiments: how to progress?

Neutrinos are experimentally “**difficult**”

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… and more

- Spoiler of the talk of Prof. Collazuol here !!!!!
  - build brand new instrumentation for the near detector (Large angle TPC)
  - build a huge far detector (Hyper-Kamiokande)

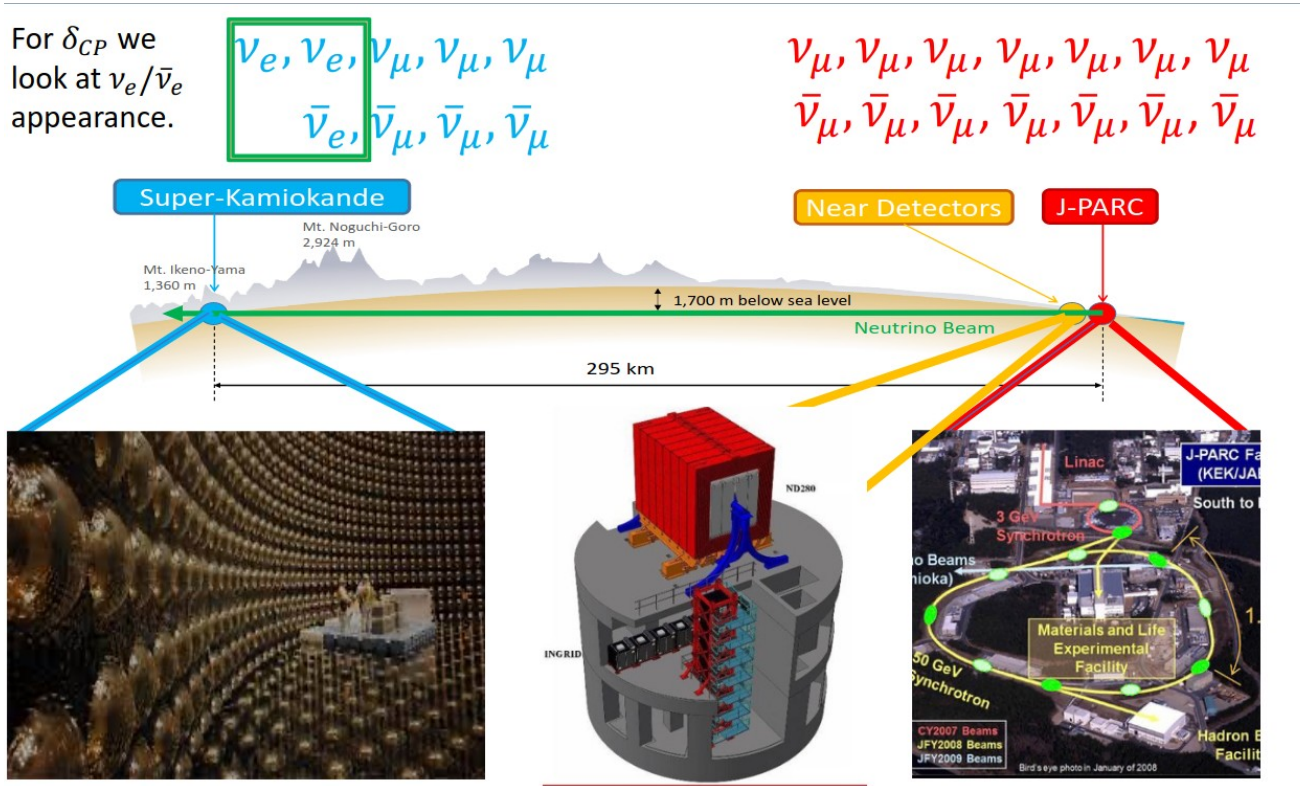
a (“analysis”)

the source:

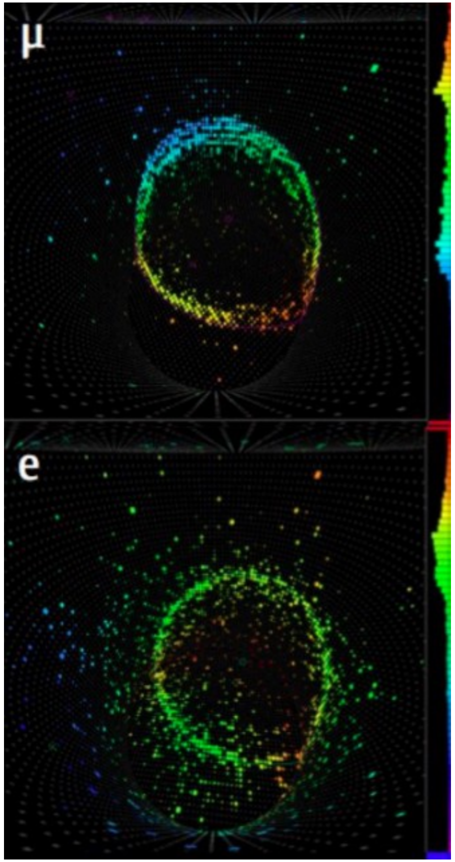
demonstrator → a new concept neutrino source with 1% precision (“hardware”)

1) Oscillation analysis with T2K

T2K uses difference in the process $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ to study the matter-antimatter asymmetry over a 295 km “travel”.



Super-Kamiokande can separate ν_μ from ν_e

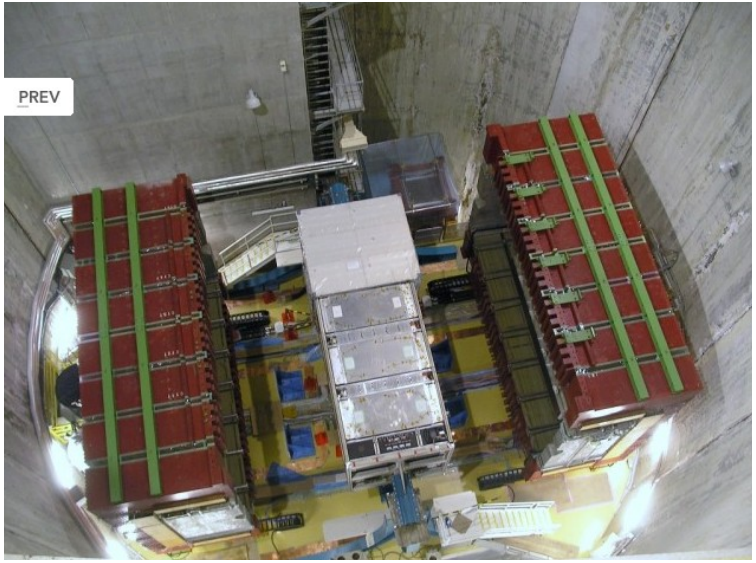


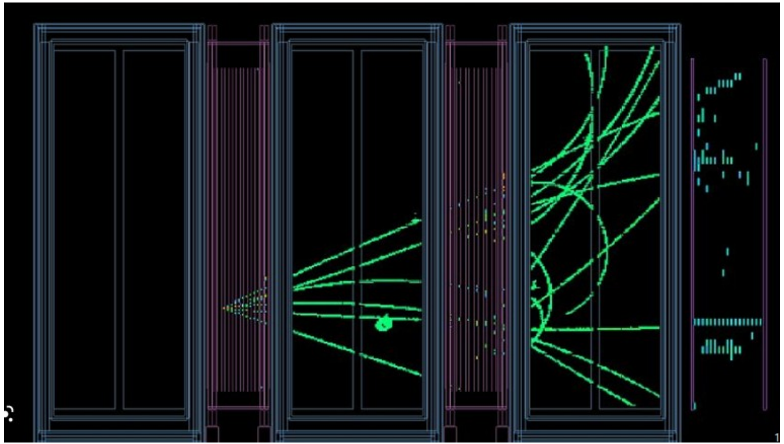
1) Oscillation analysis with T2K

Many unknowns:
- the neutrino flux (different between near and far)
- the neutrino interaction parameters (that depend on nuclear models, from the target composition)
- There are several different final states each with a different efficiency in the detectors.

The goal is to **predict as precisely as possible the number of neutrinos that we expect at the far detector** → the difference is due to oscillations (appearance of electron neutrinos, disappearance of muon neutrinos) that we can then study.

We use the data collected at the **near detector** (at only 280 m → high statistics) to get a constraint on unknown quantities ("nuisance parameters").





1) Oscillation analysis with T2K

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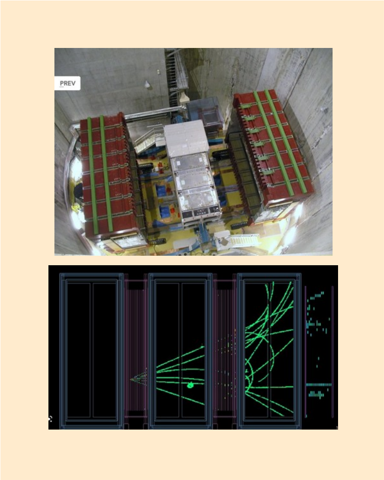
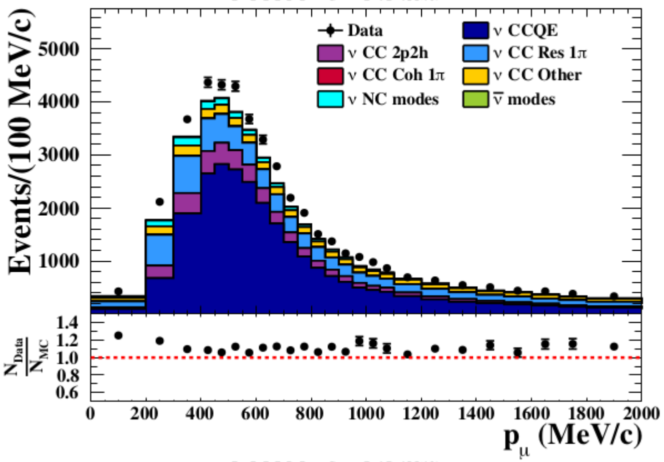
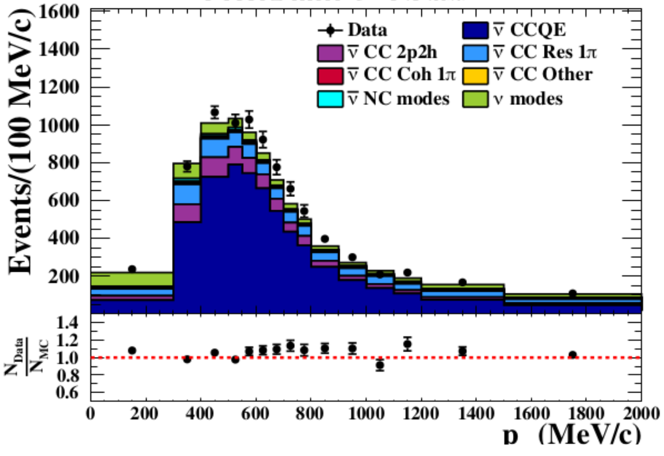
The “Near detector fit”

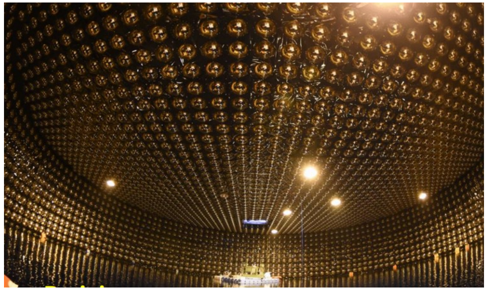


Near detector data BEFORE fit

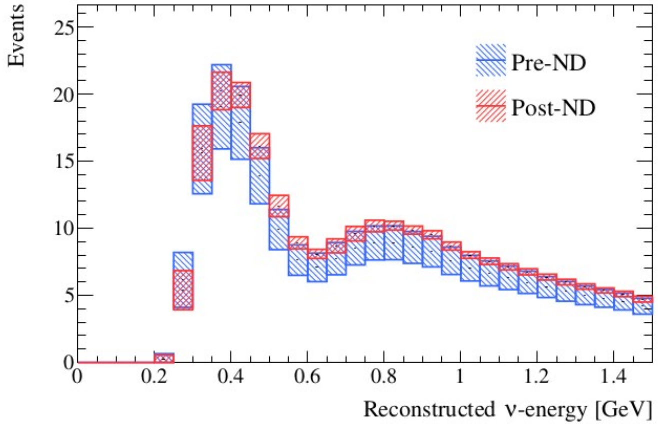


Near detector data AFTER fit



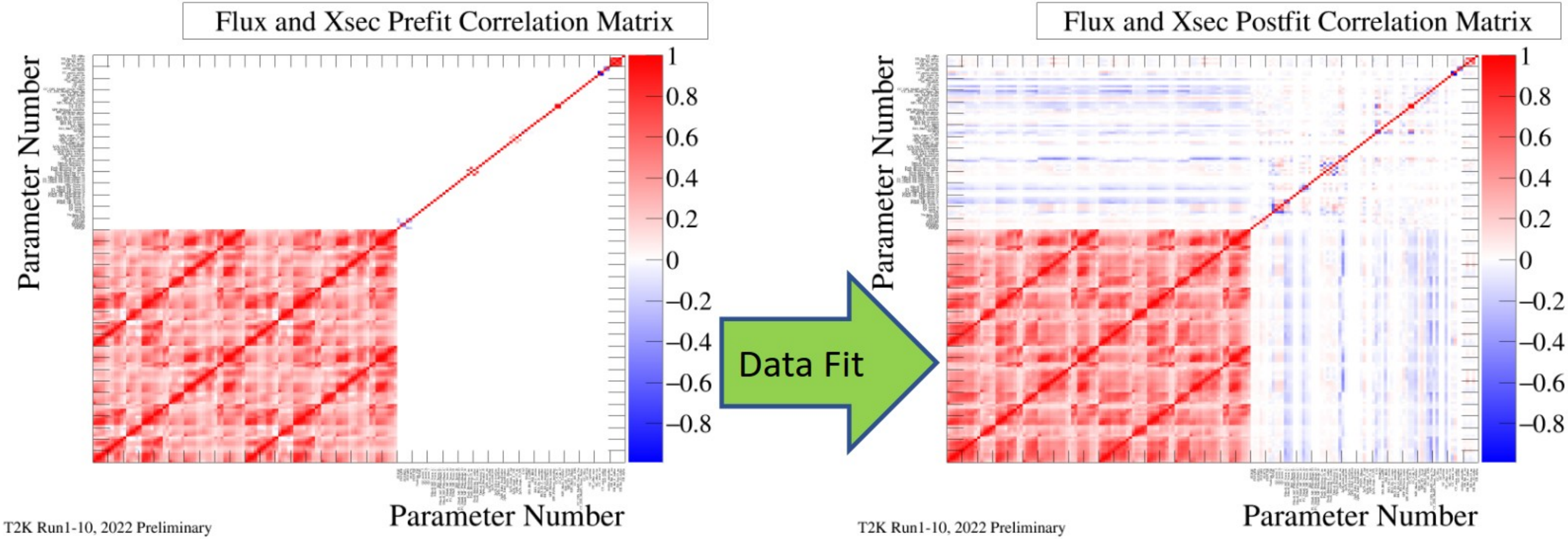


Uncertainty on the prediction at far BEFORE ad AFTER the near detector fit:



1) Oscillation analysis with T2K

The fit is very complex. Besides the oscillation parameters it involves **hundreds of unknown parameters** (“nuisance”) from uncertainties in nuclear models, final state interactions, flux, detector parameters. These are “fitted out” to finally access the interesting oscillation parameters (3).



1) Oscillation analysis with T2K

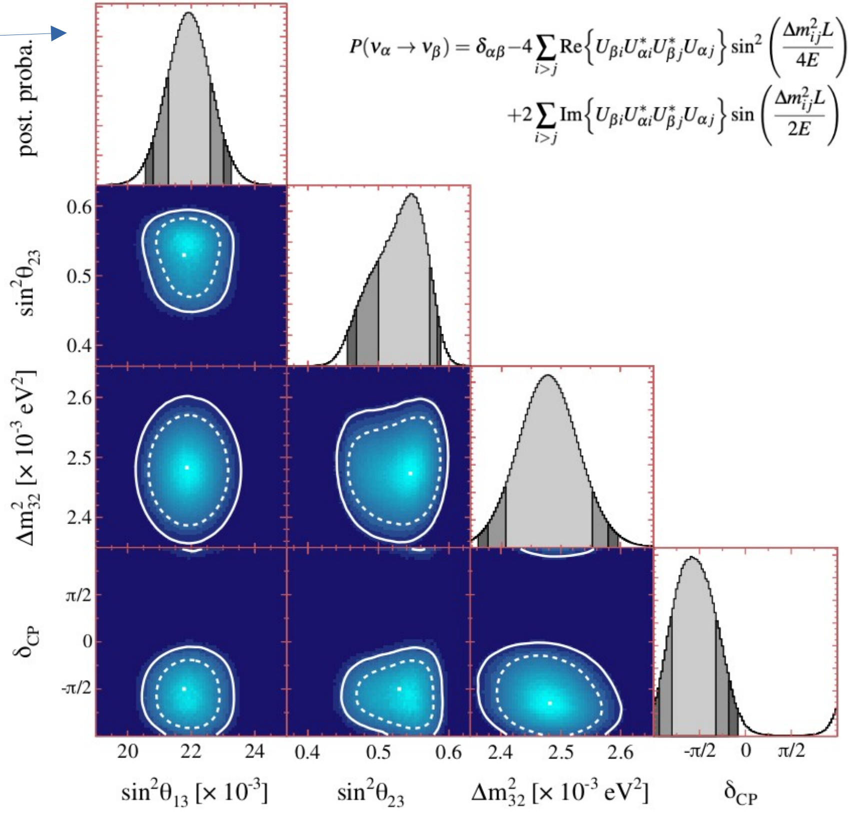
Bayesian statics → posterior probabilities on physical quantities.

The search of maxima in the complex multi-dim space of the likelihood function and marginalization of nuisance parameters is achieved with a **Metropolis-Hastings Markov-chain Monte Carlo**.

Plenty of room for students with a passion in **advanced analysis tools and statistics**.

Work would be in a **highly qualified international group** (in Padova A.L. convener of the oscillation analysis group)

$$
\begin{aligned}
-\ln(L) = & \sum_{i}^{ND280bins} N_i^p(\vec{b},\vec{x},\vec{f},\vec{d}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{f},\vec{d})] \\
& + \sum_{i}^{SK1R_\mu bins} N_i^p(\vec{b},\vec{x},s\vec{k}d) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},s\vec{k}d)] \\
& + \sum_{i}^{SK1R_e bins} N_i^p(\vec{b},\vec{x},s\vec{k}d) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},s\vec{k}d)] \\
& + \frac{1}{2}\sum_{i}^{E_\nu bins}\sum_{j}^{E_\nu bins} \Delta b_i (V_b^{-1})_{i,j} \Delta b_j \\
& + \frac{1}{2}\sum_{i}^{xsecpars}\sum_{j}^{xsecpars} \Delta x_i (V_x^{-1})_{i,j} \Delta x_j \\
& + \frac{1}{2}\sum_{i}^{fsipars}\sum_{j}^{fsipars} \Delta f_i (V_f^{-1})_{i,j} \Delta f_j \\
& + \frac{1}{2}\sum_{i}^{nd280det}\sum_{j}^{nd280det} \Delta d_i (V_d^{-1})_{i,j} \Delta d_j \\
& + \frac{1}{2}\sum_{i}^{skdet}\sum_{j}^{skdet} \Delta skd_i (V_{skd}^{-1})_{i,j} \Delta skd_j
\end{aligned}
$$



$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} & - 4\sum_{i>j} \mathrm{Re}\left\{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right\}\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \\
& + 2\sum_{i>j} \mathrm{Im}\left\{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right\}\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)
\end{aligned}
$$

2) monitored ν beams: ENUBET

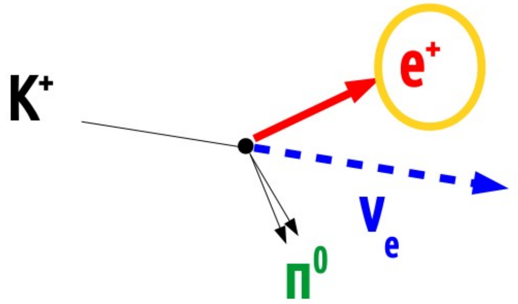
Reach a O(1 %) control on the flux → precise physics

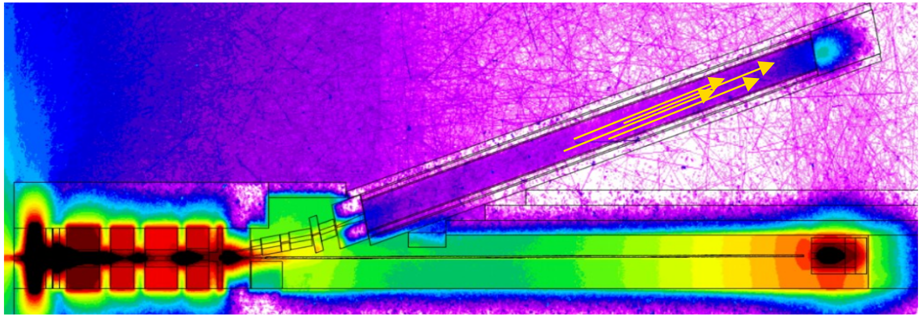
How ? “counting” positrons from kaon decays with a large/scalable detector

ENUBET → Enhanced NeUtrino Beams from kaon Tagging

European Research Council
Established by the European Commission

(1 e^+ = 1 neutrino)

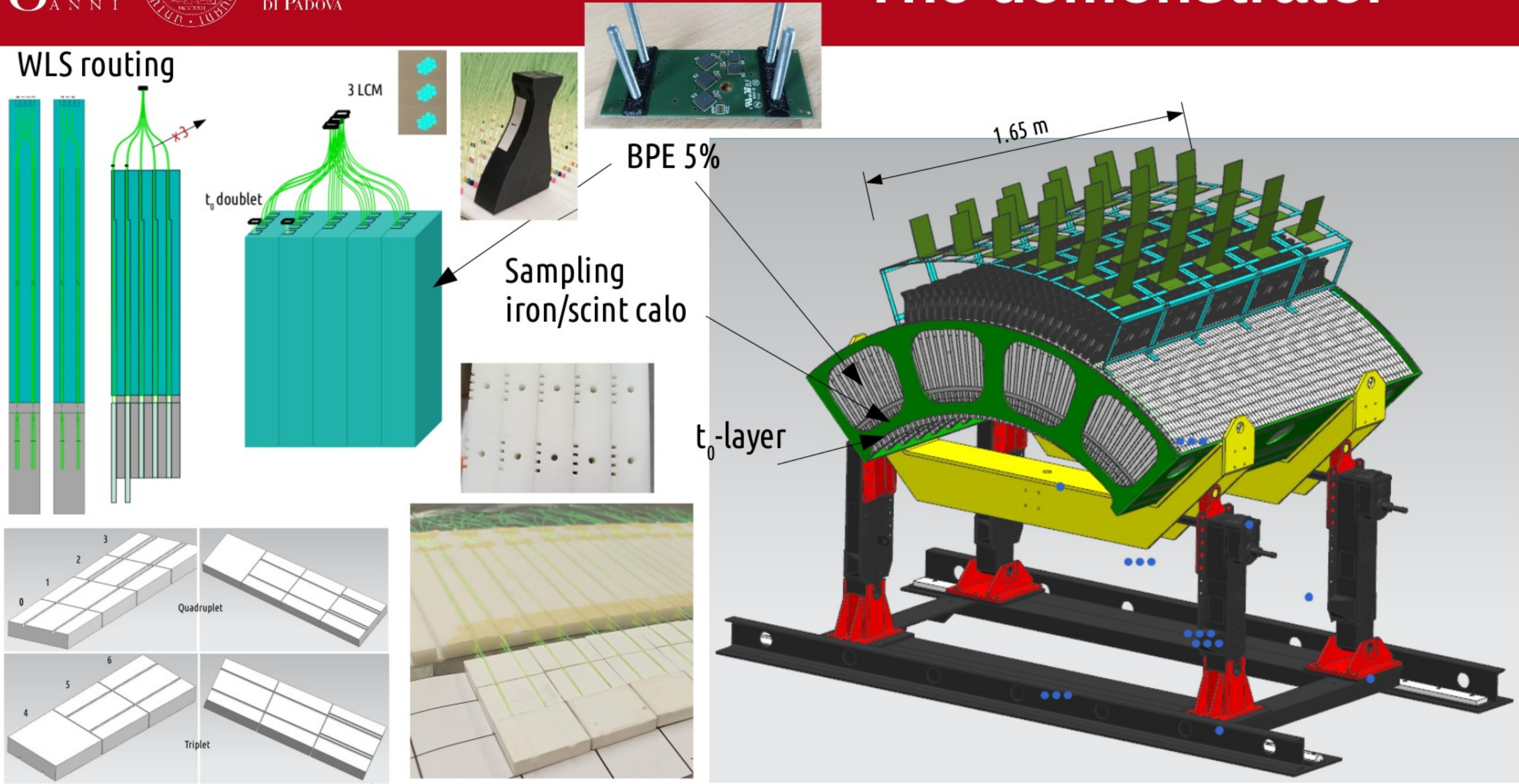




Challenges for the detector:

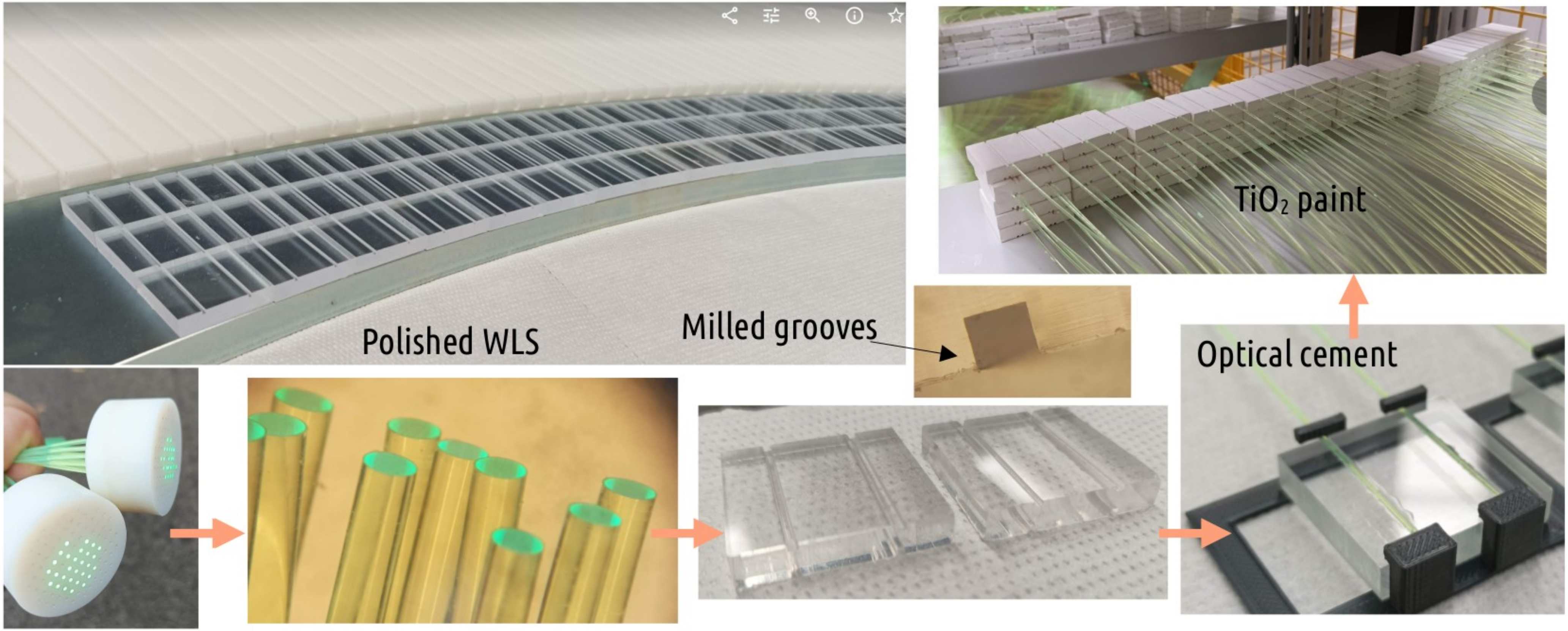
fast electronics / radiation tolerance / good particle identification with a cost-effective solution

The demonstrator



Construction of the ENUBET demonstrator

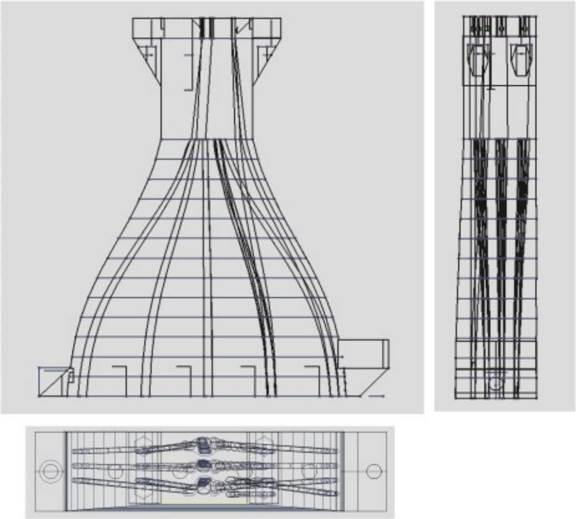
Summer 2022 @ INFN-LNL



Construction of the ENUBET demonstrator

Summer 2022 @ INFN-LNL

bundling of the WLS fibers with 3D printed "fiber concentrators"+ in situ polishing



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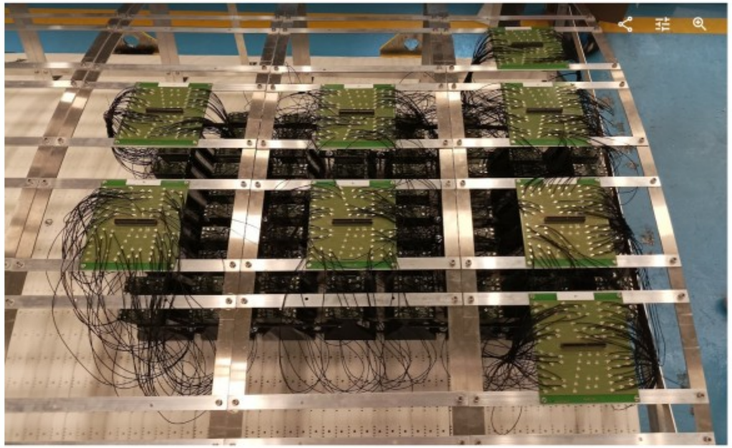
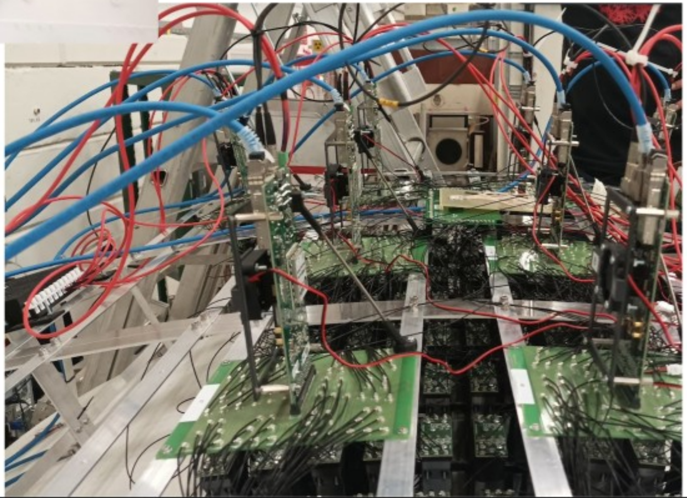
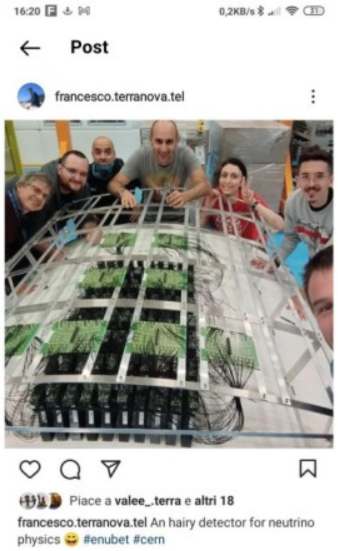
Readout electronics

Oct 2022 @ CERN







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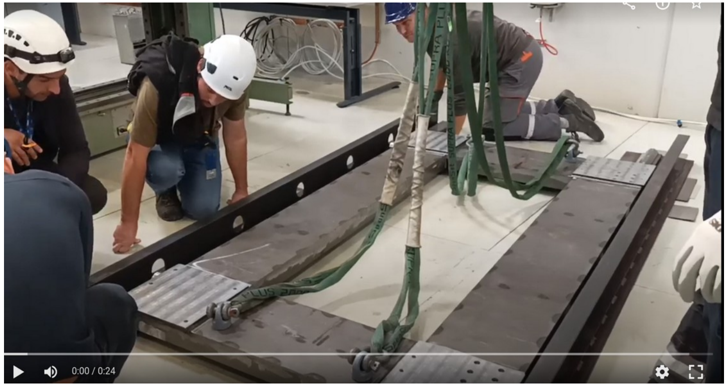
ENUBET takes off !!!

building 157, CERN
Meyrin PS East Hall
T9 area



Movable platform
“landing site” @ T9
test beam area.

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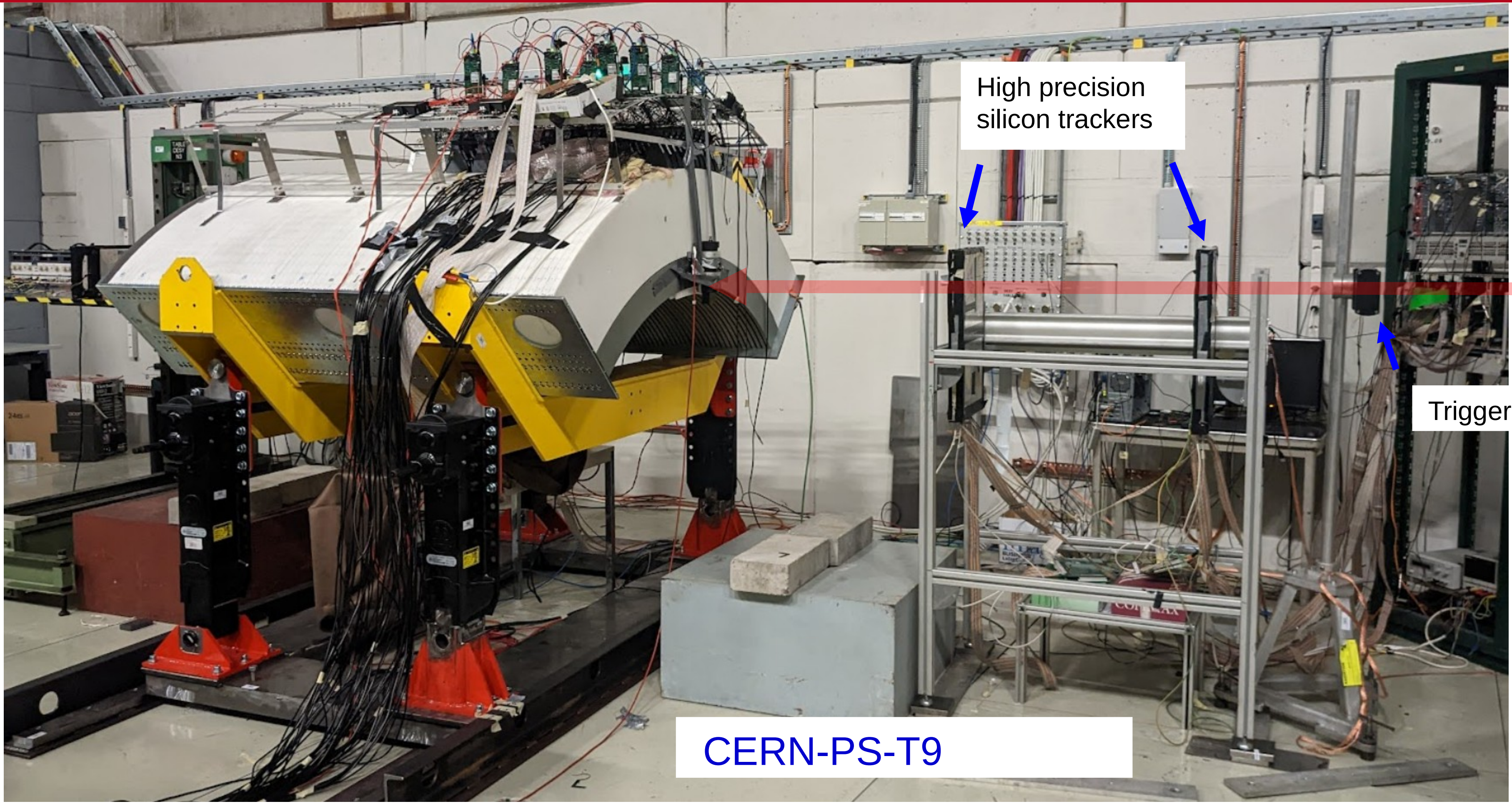
ENUBET “landed” at the PS-T9 area



e, π, μ (0.5-15 GeV)

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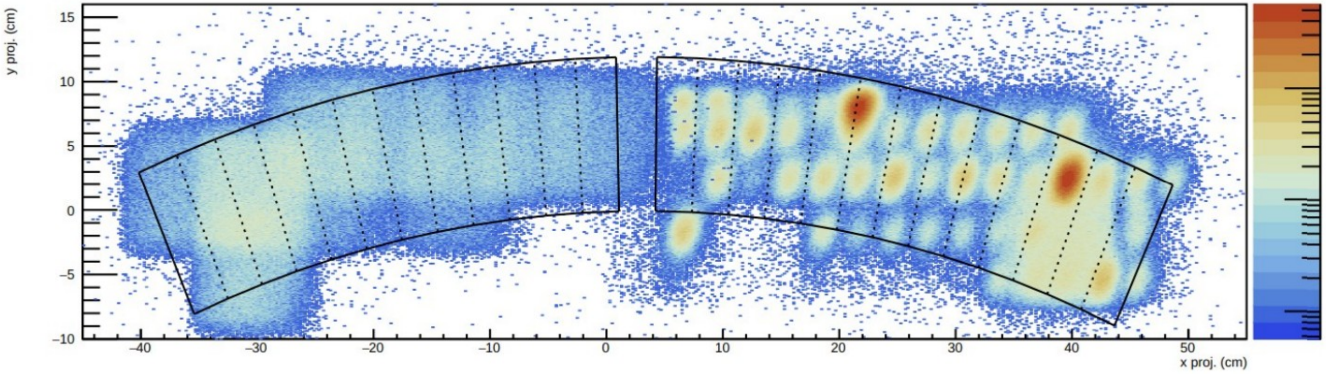
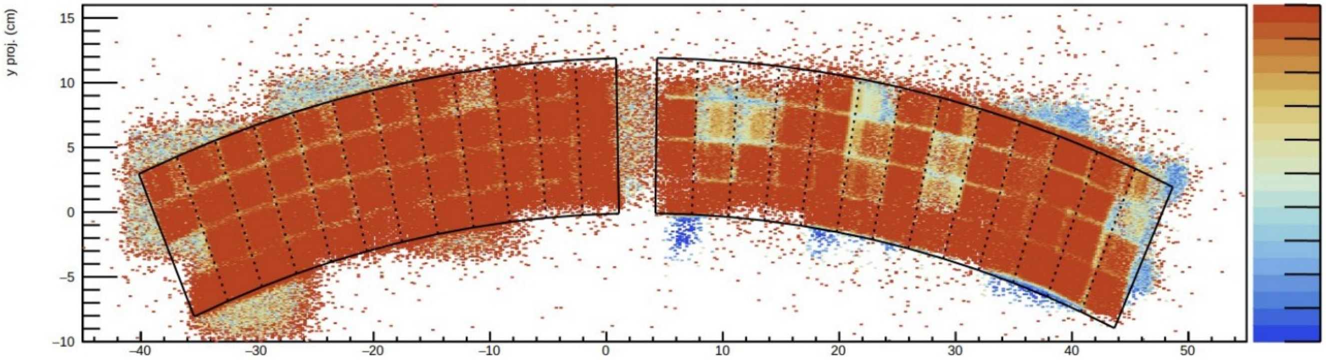
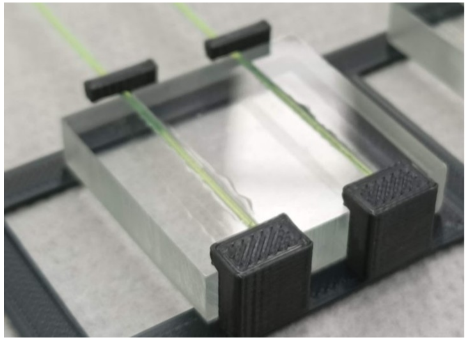
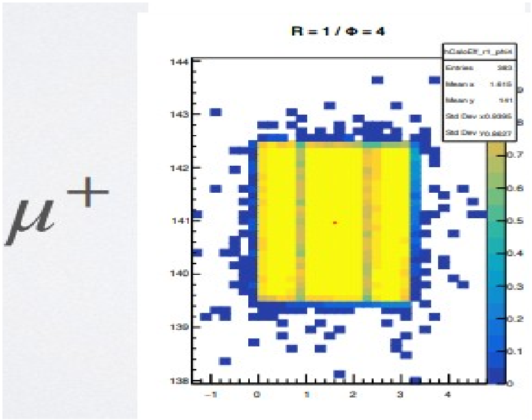
Simulation and data analysis of CERN data

Efficiency maps → “radiography” using muons









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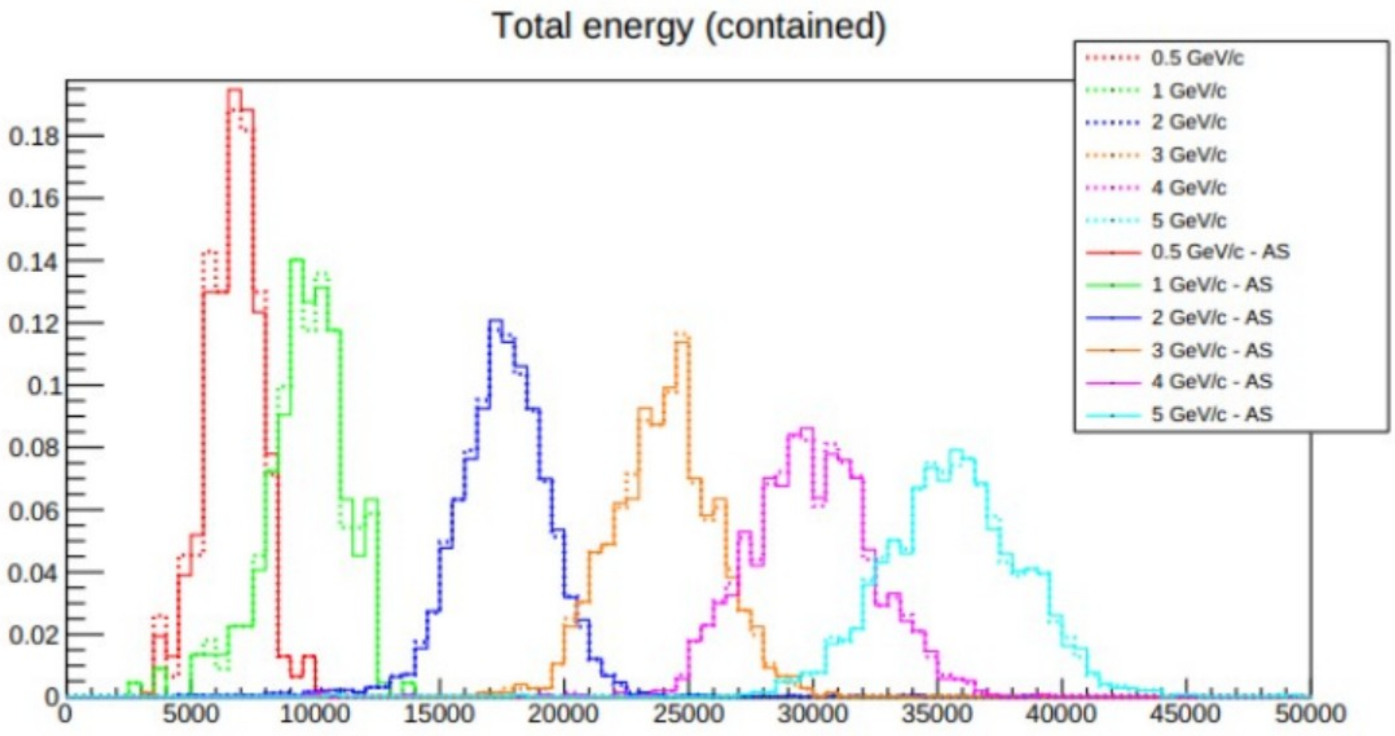
Simulation and data analysis of CERN data

Electron energy resolution

A. Moro,
tesi triennale,
Dec. 2023



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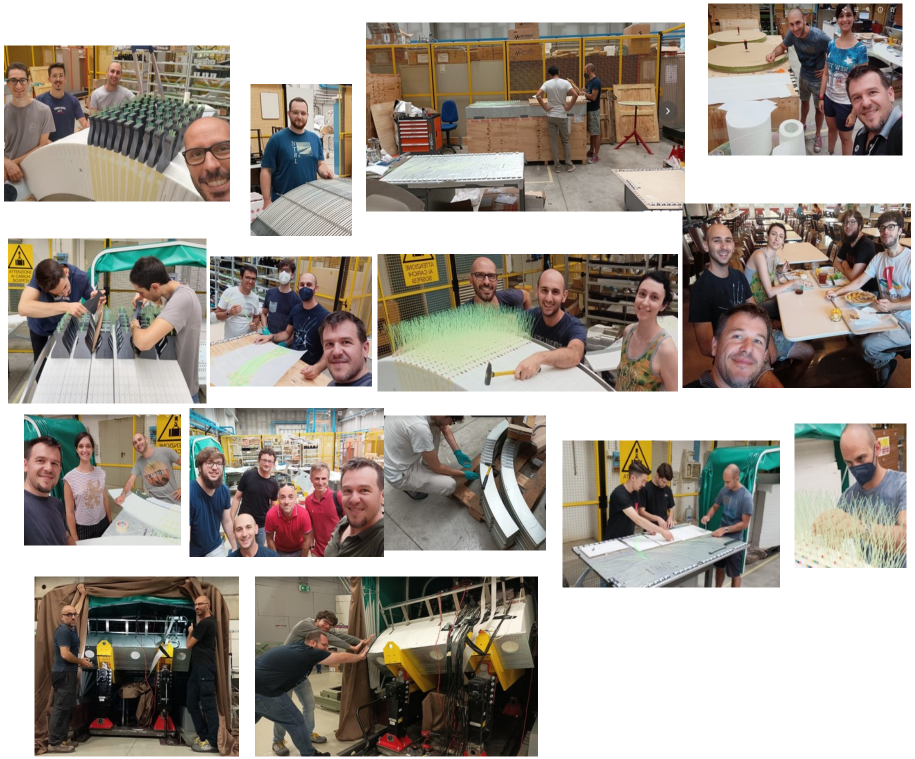
New horizons for ENUBET

We are currently upgrading the Data Acquisition system for a **new exposure at CERN in 2024.** Precious occasion for a thesis work with the possibility of participating to the construction (Legnaro) and testing (CERN) of a complex detector and analysis of the associated data.



Contacts

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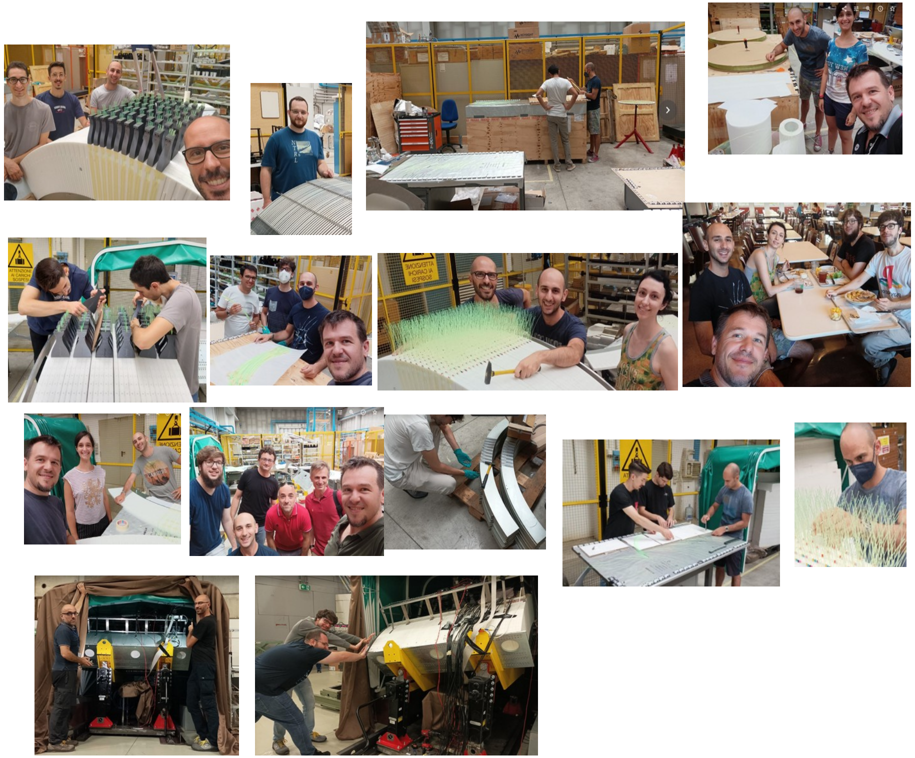
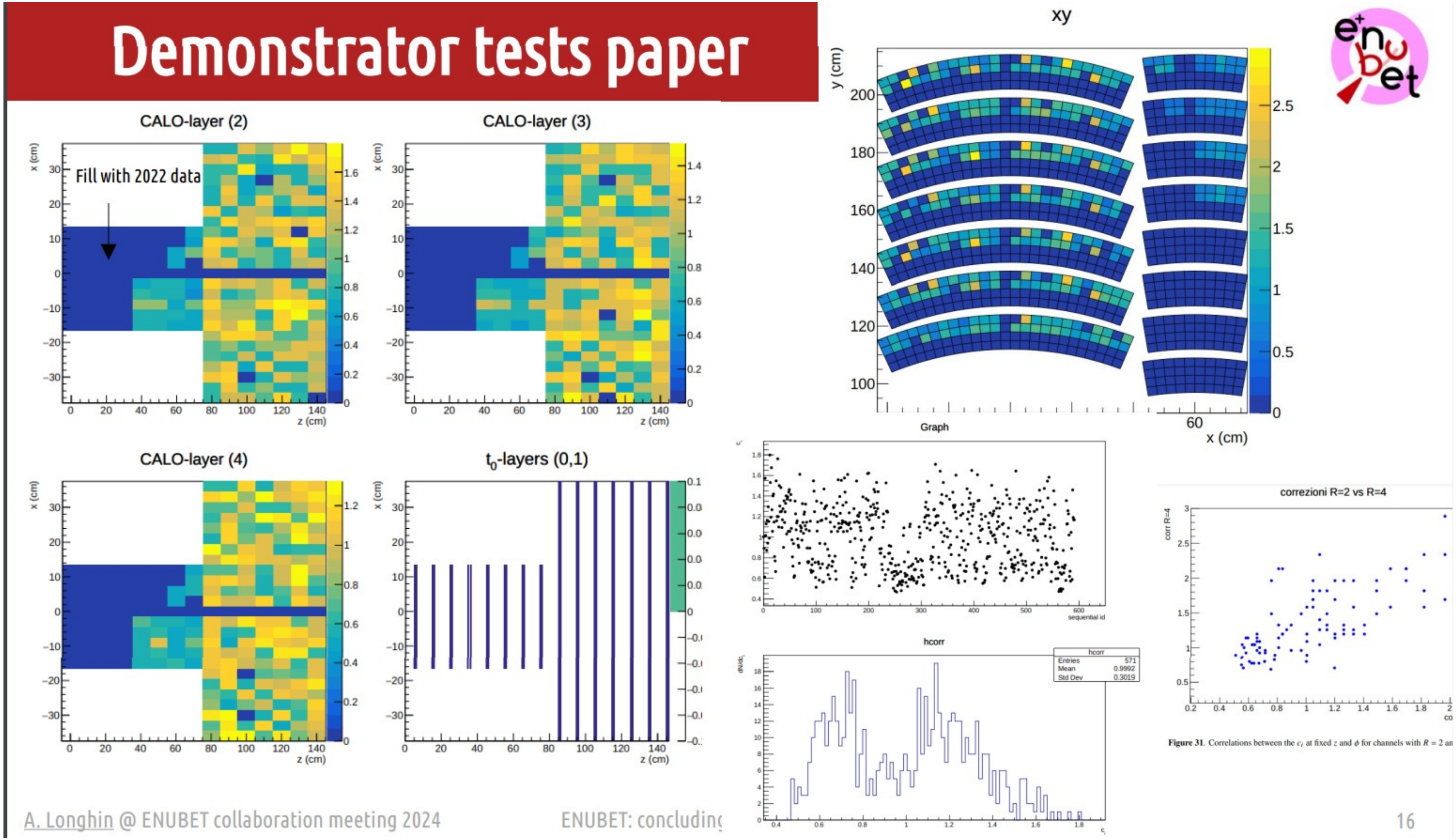
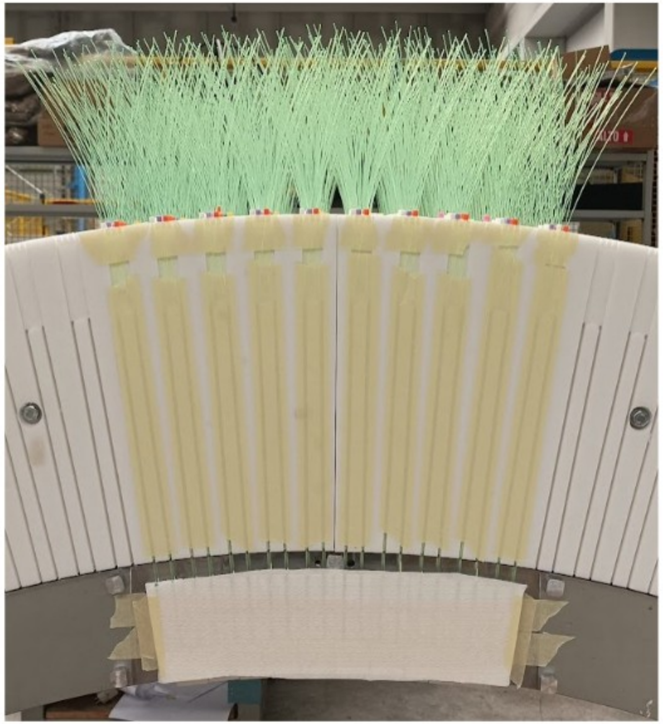


Simulation and data analysis of CERN data



Construction of the ENUBET demonstrator

Summer 2022 @ INFN-LNL



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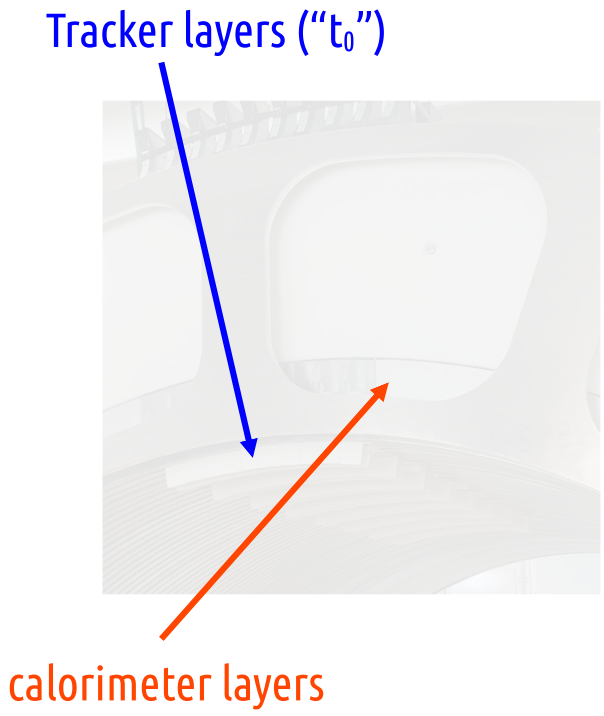
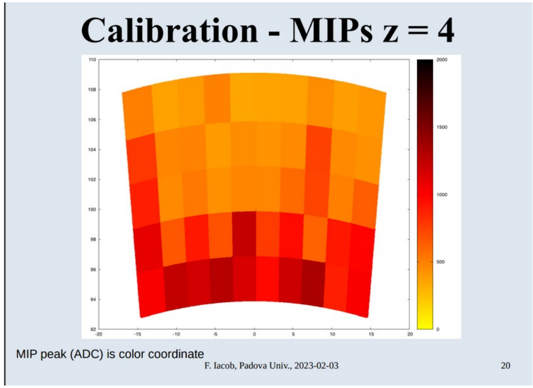
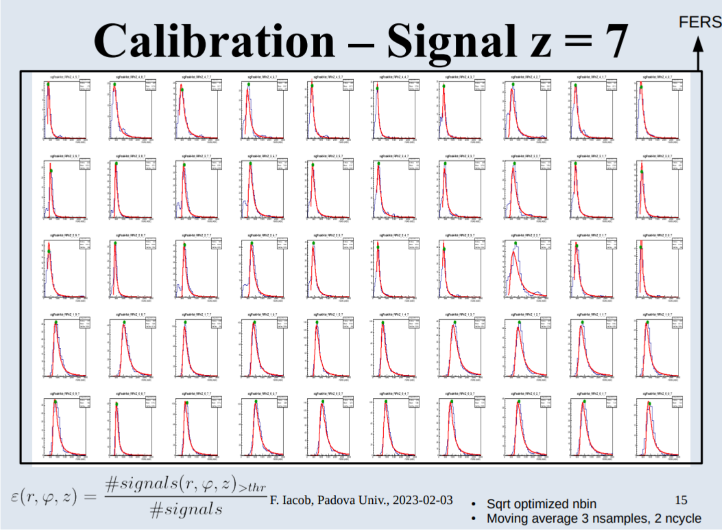
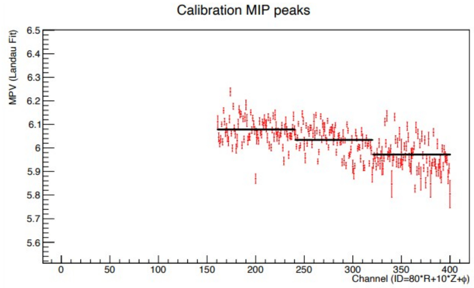
Event displays

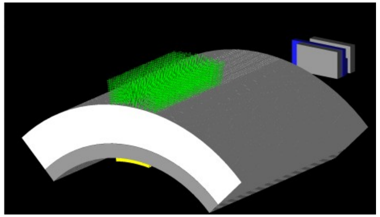


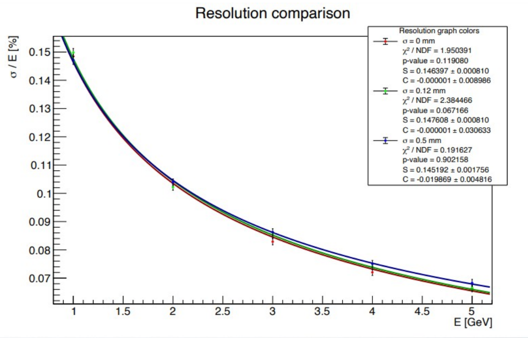
Simulation and data analysis of CERN data

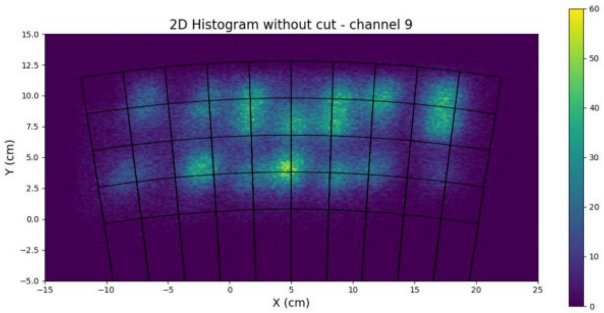


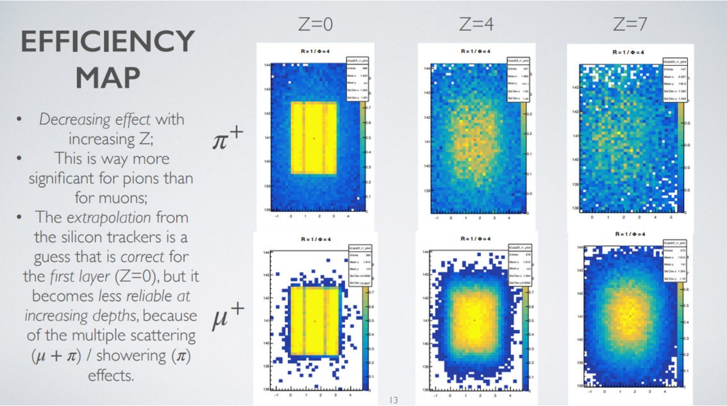












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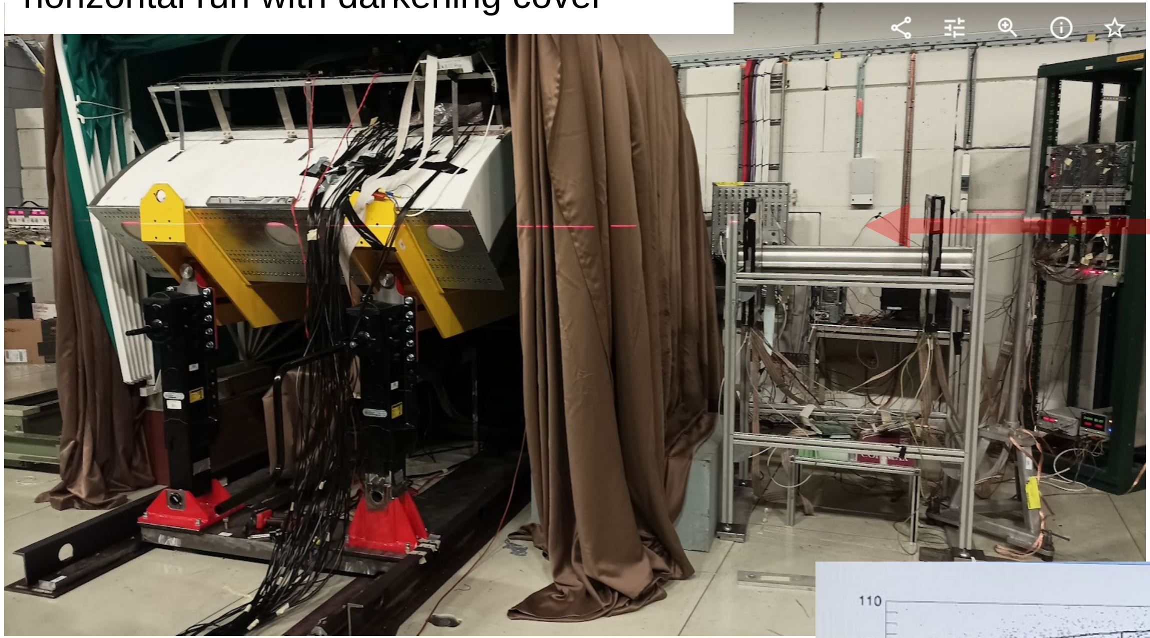
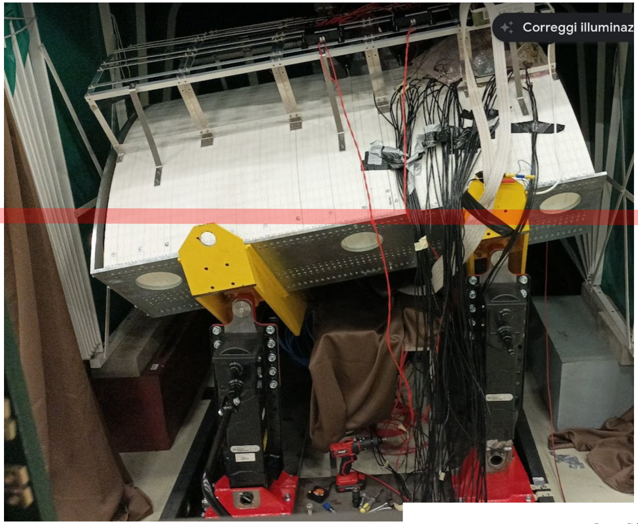
Data taking with the demonstrator

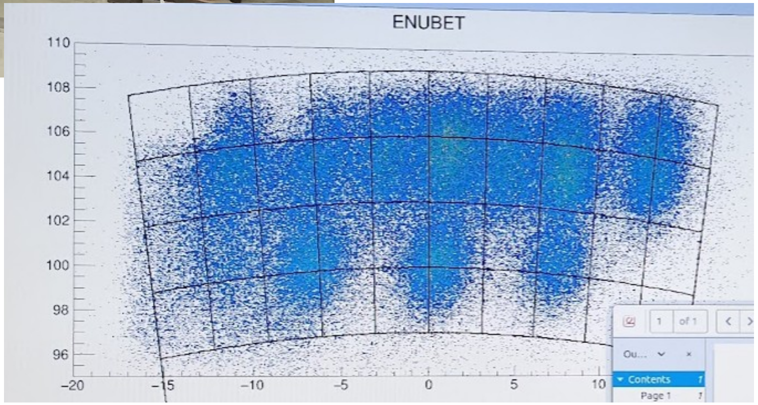
horizontal run with darkening cover





200 mrad tilt run

Beam spot at the detector upstream face after several runs illuminating different regions of the detector



Oct 2022 CERN-PS-T9