UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

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The Demonstrator of the instrumented decay tunnel for the ENUBET monitored neutrino beam

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MILANO

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IEEE NUCLEAR SCIENCE SYMPOSIUM, MEDICAL IMAGING CONFERENCE AND ROOM TEMPERATURE SEMICONDUCTOR DETECTOR CONFERENCE

Overview

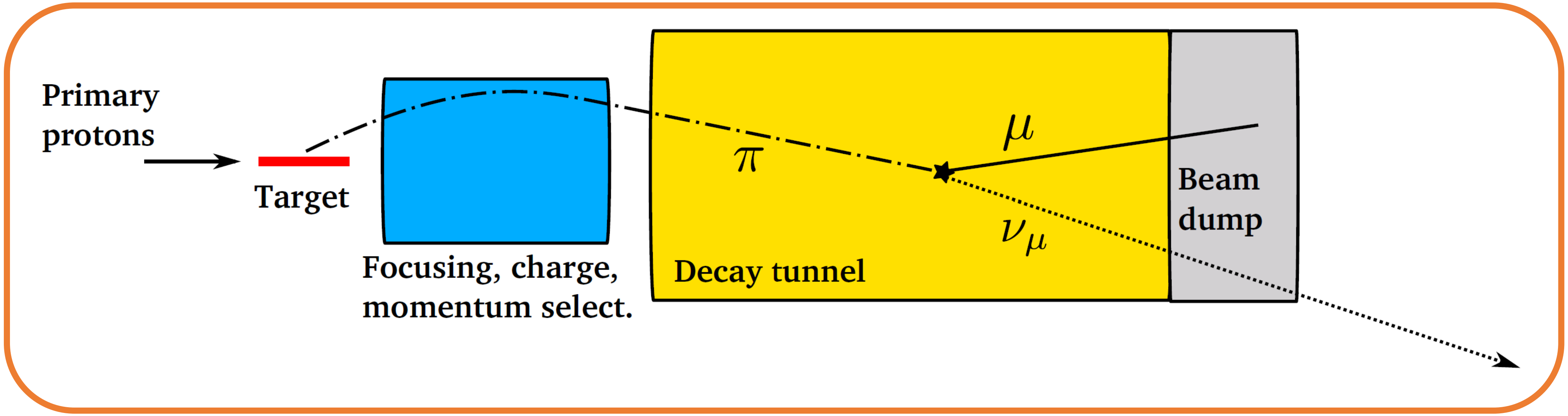
Particle accelerators are used to generate a controlled muon neutrino flux.

Advantages Unlike other neutrino sources:
- control of neutrino energy;
- control of source-detector distance.

Disadvantages
- Contaminations of ν_e poorly know;
- energy reconstruction based on products at the detector;
- overall flux uncertainty of ~ O(10%)

$$N_{\nu_e} = P_{\nu_e \to \nu_\mu} \, \sigma_{\nu_e} \, \phi_{\nu_\mu}$$

Possible approach:
monitored neutrino beams

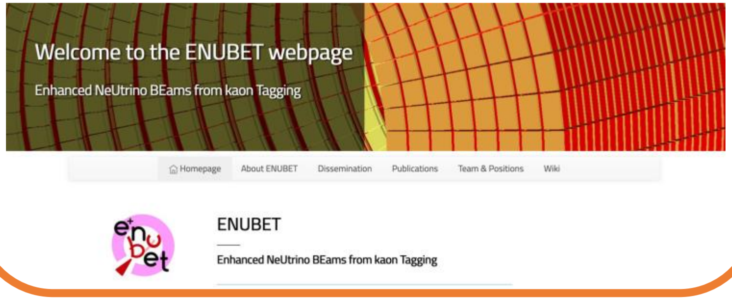


ENuBET project

ENUBET is the project for the realization of the first monitored neutrino beam, by developing a new beam in which the flux and flavor composition are known at 1% level, and the energy with O(10%) precision.

- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (COVID: extended to end 2022). PI: A. Longhin;
- Since April 2019: CERN Neutrino Platform Experiment – NP06/ENUBET– and part of Physics Beyond Colliders (PBS);
- Collaboration: 60 physicists & 13 institutions;
- Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna.

Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/



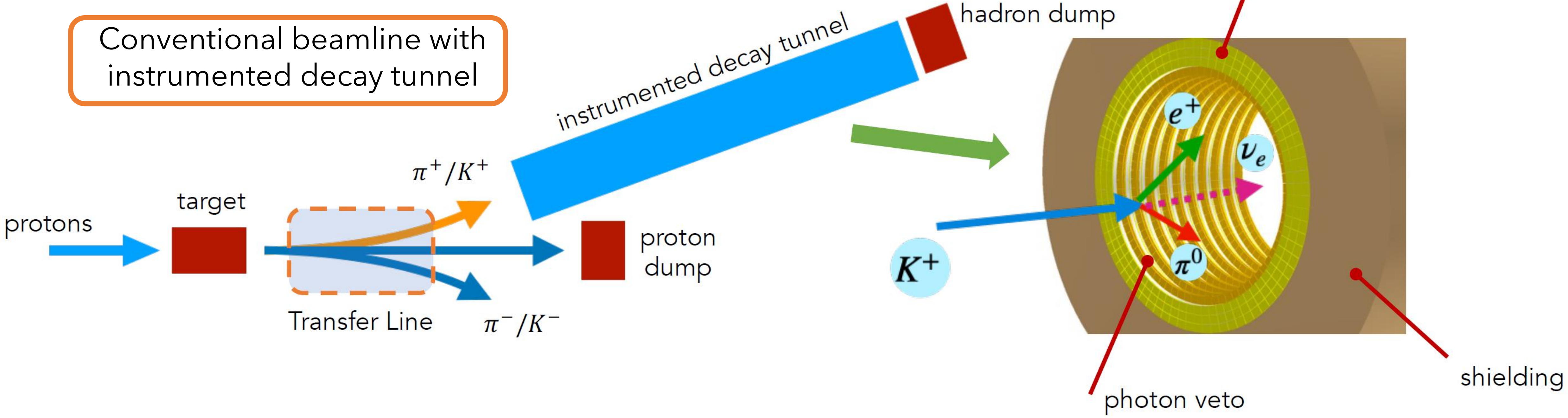
Present collaboration: 65 phys, 13 institutions

ENuBET: the first monitor neutrino beam

Monitored ν flux from narrow-band beam
measure rate of leptons ⟺monitor ν flux

Conventional beamline with instrumented decay tunnel

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155



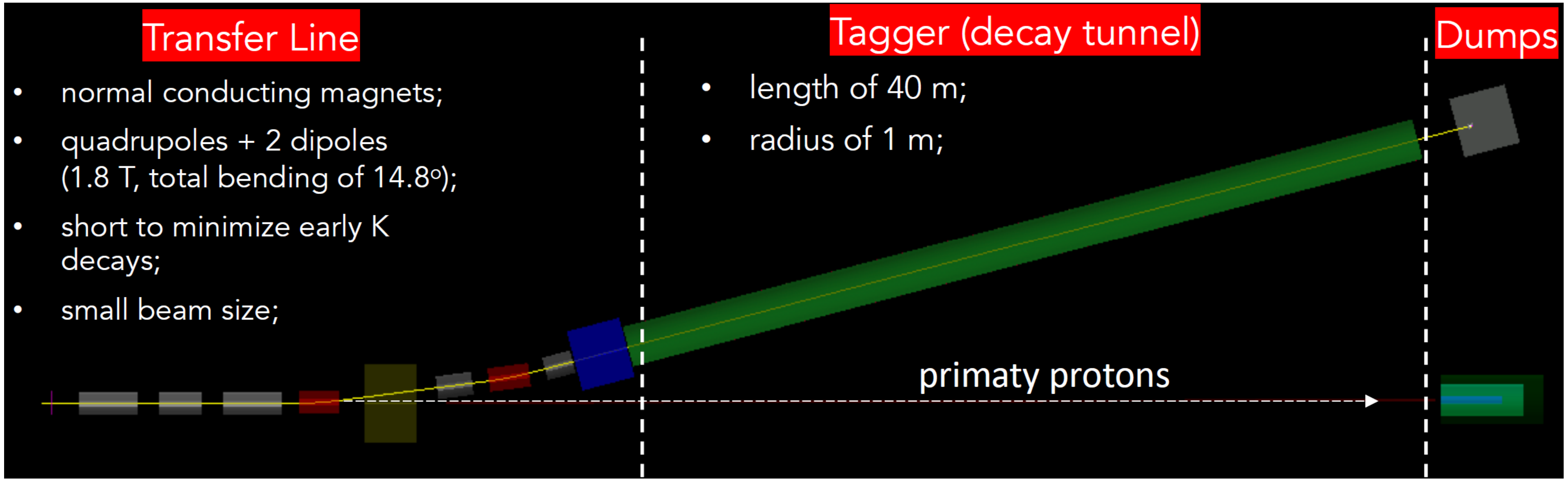
- ERC project focused on:

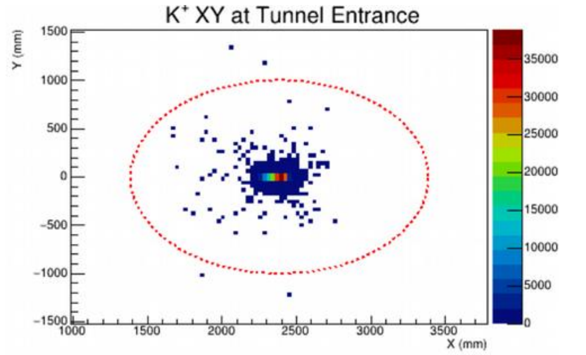
measure positrons (instrumented decay tunnel) from K_{e3} ⟹ determination of ν_e flux.

- As CERN NP06 project:

extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ ⟹ determination of ν_μ flux.

ENuBET beamline





Rates @ Tunnel entrance for 400 GeV POT

π^+[10^{-3}]/POT	K^+[10^{-3}]/POT
4.13	0.34

~1.5 X w.r.t. previous results!

Large bending angle of 14.8°:
- better collimated beam + reduced muons background + reduced ν_e from early decays;

Transfer Line:
- optics optimization w/ TRANSPORT (5% momentum bite centered @ 8.5 GeV) G4Beamline for particle transport and interactions;
- FLUKA for irradiation studies, absorbers and rock volumes included in simulation (not shown above);
- optimized graphite target 70 cm long & 3 cm radius (dedicated studies, scan geometry and different materials);
- tungsten foil downstream target to suppress positron background;
- tungsten alloy absorber @ tagger entrance to suppress backgrounds.

Dumps:
- Proton dump: three cylindrical layers (graphite core -> aluminum layer -> iron layer);
- Hadron dump: same structure of the proton dump -> allows to reduce backscattering in tunnel.

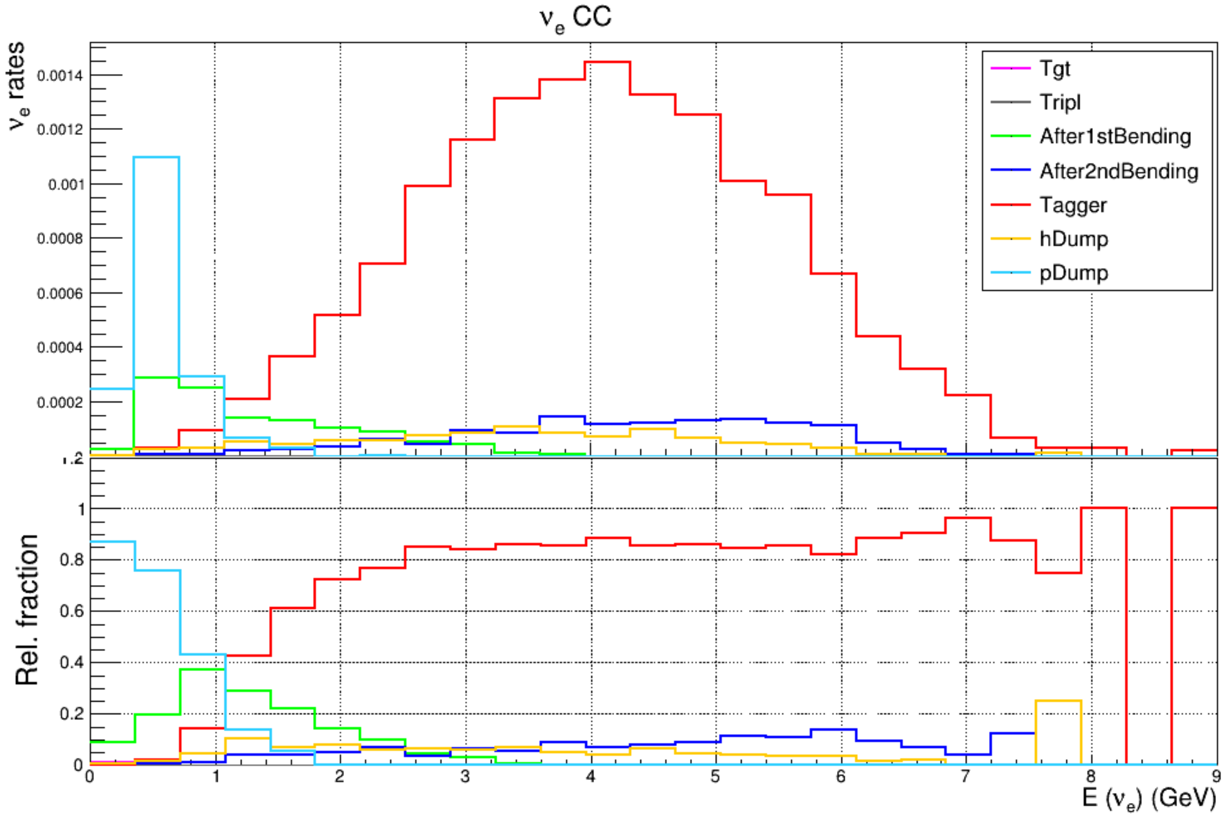
ν_μ CC energy distribution at the detector

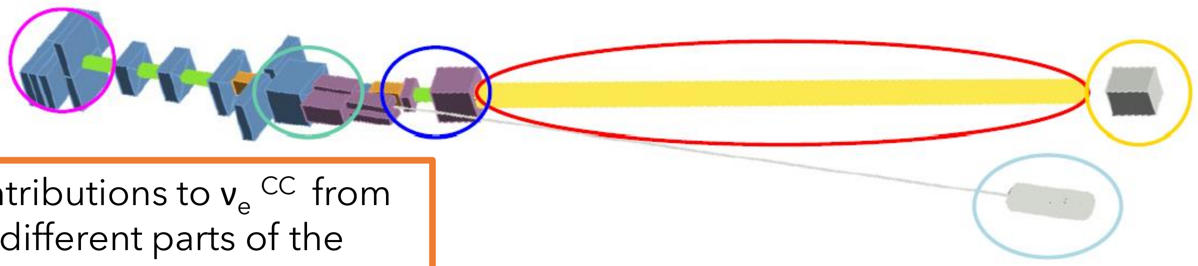
A total ν_e CC statistics of 10^4 events in ~3 years
- @ SPS with 4.5 x 10^{19} POT/year;
- 500 ton detector @ 50 m from tunnel end.

Taggable component
About 80% of total ν_e flux is produced by decays in the tunnel (above 1 GeV).

Non taggable component
Below 1 GeV: main component produced in p-dump
- clear separation from taggable ones (energy cut);
- further improvements in separation optimizing p-dump position.

Above 1 GeV: contributions from straight section before tagger and hadron-dump
- rely on simulation for this component.





Contributions to ν_e CC from the different parts of the ENUBET facility

ν_μ CC energy distribution at the detector

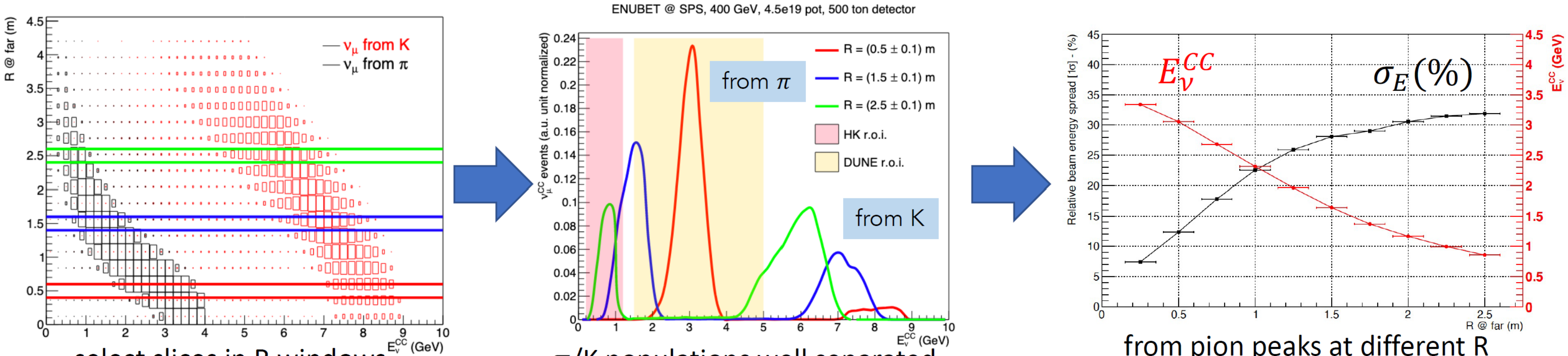
Narrow-band off-axis Technique
Narrow momentum beam O(5-10%)
(E_ν,R) are strongly correlated
E_ν = neutrino energy;
R = radial distance of interaction vertex from beam axis.

F. Acerbi et al., CERN-SPSC-2018-034

Precise determination of E_ν: no need to rely on final state particles from ν_μ^{CC} interaction;

- 8-25% E_ν resolution from π in DUNE energy range (1.5-5 GeV);
- 30% E_ν resolution from π in HyperK energy range (<1.2 GeV);
- ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV)

=> HyperK & DUNE optimized.



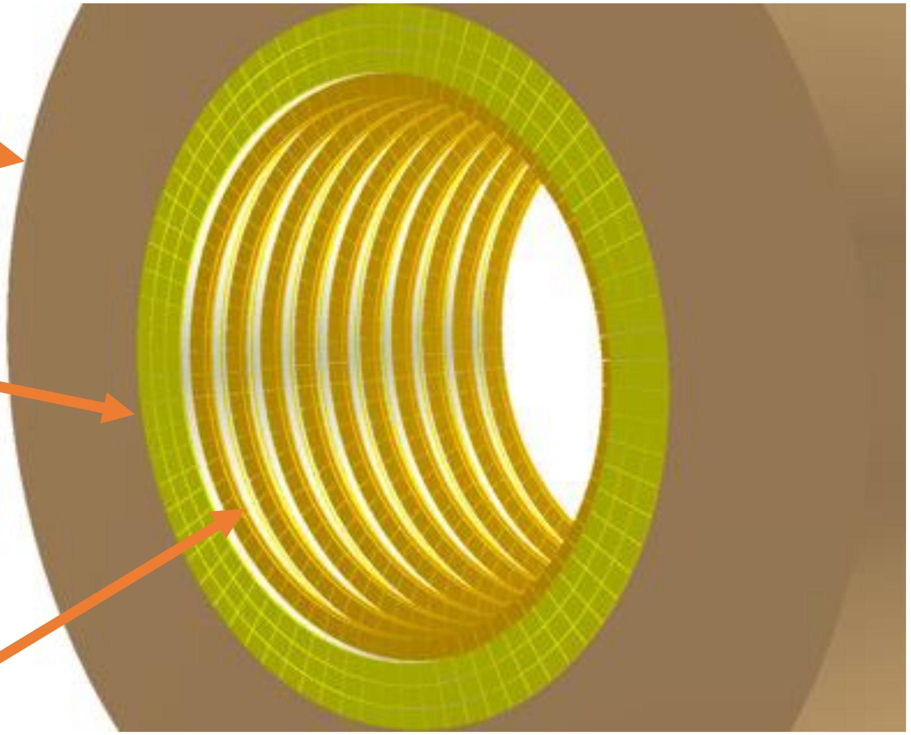
select slices in R windows — π/K populations well separated — from pion peaks at different R

Decay tunnel instrumentation

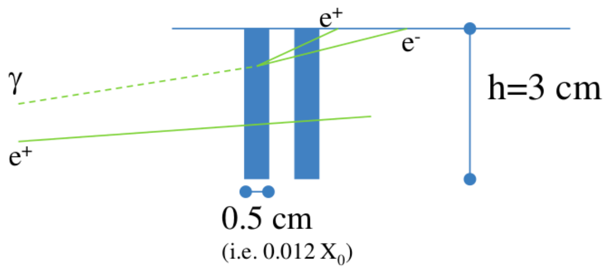
Shielding
- 30 cm of borated polyethylene;
- SiPMs installed on top -> factor 18 reduction in neutron fluence.

Calorimeter with $e/\pi/\mu$ separation capabilities:
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout.

Photon-Veto allows π^+ rejection and timing:
- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of ~400 ps.



LCM: Lateral Compact Module
5 x Lead+Scint - $3 \times 3 \times 10$ cm^3 - 4.3 X_0



Lepton reconstruction and identification performance

Full GEANT4 simulation of the detector:

- validated by prototype tests at CERN in 2016-2018;
- hit-level detector response;
- pile-up effects included (waveform treatment in progress);
- event building and PID algorithms (2016-2020).

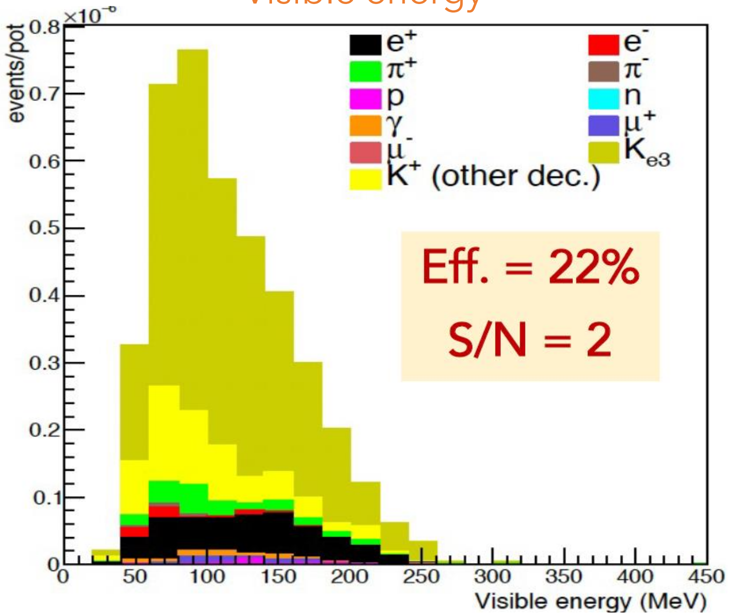
- Large angle positrons and muons from kaon decays reconstructed searching for patterns in energy depositions in tagger.

- Signal identification done using a Neural Network trained on a set of discriminating variables.

- K_{e3} (BR ~5%) and K make ~5 – 10% of the beam composition.

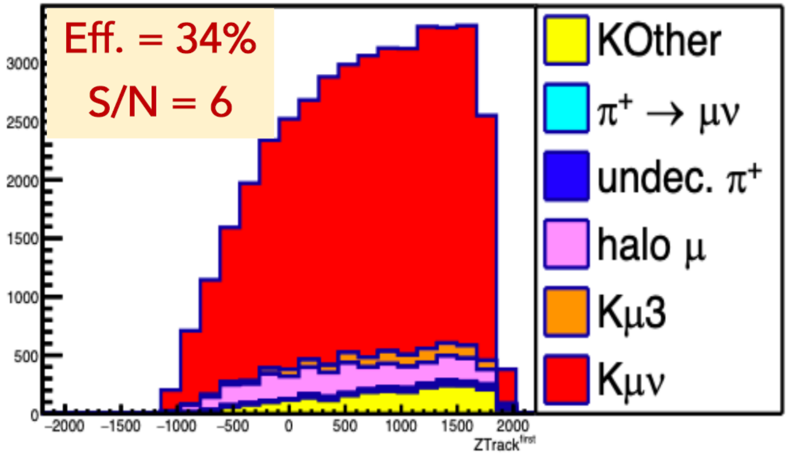
F. Pupilli et al., PoS NEUTEL2017 (2018), 078

Visible energy



K_{e3} positrons -> constrain ν_e
Efficiency ~half geometrical

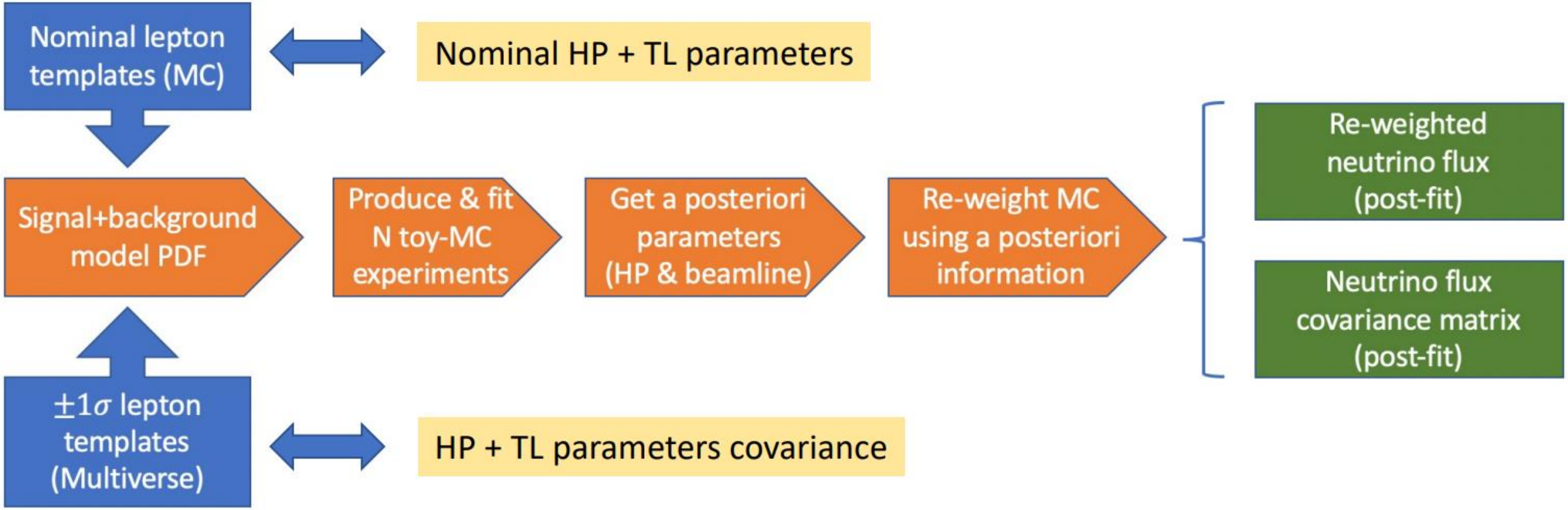
Tagger impact point



$K_{\mu 2}$ muons -> constrain ν_μ
Efficiency ~half geometrical

ν flux: assessment of systematics

Monitored ν-flux from narrow-band beam: measure rate of leptons ⇔ monitor ν-flux
- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances.

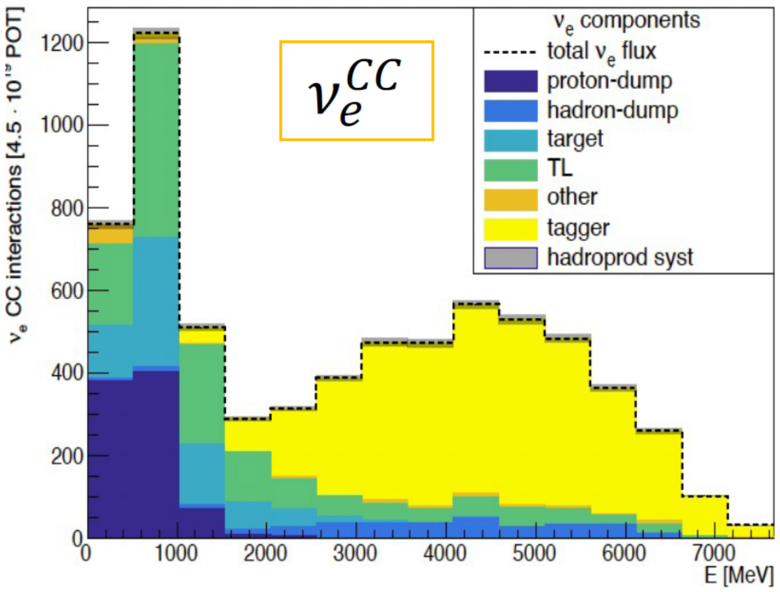


Used hadro-production data from NA56/SPY experiment to:
- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method.

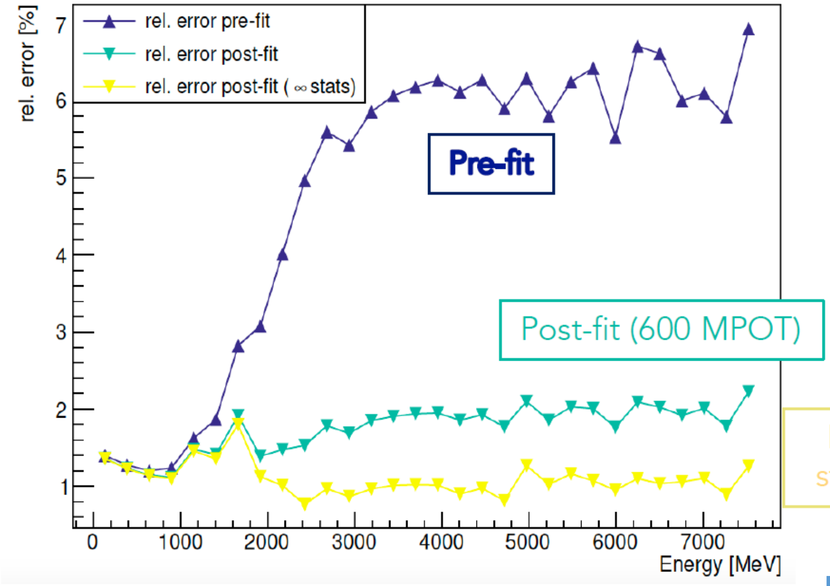
ν flux: impact on hadro production systematics

A. Branca et al., PoS NuFact2021 (2022) 030

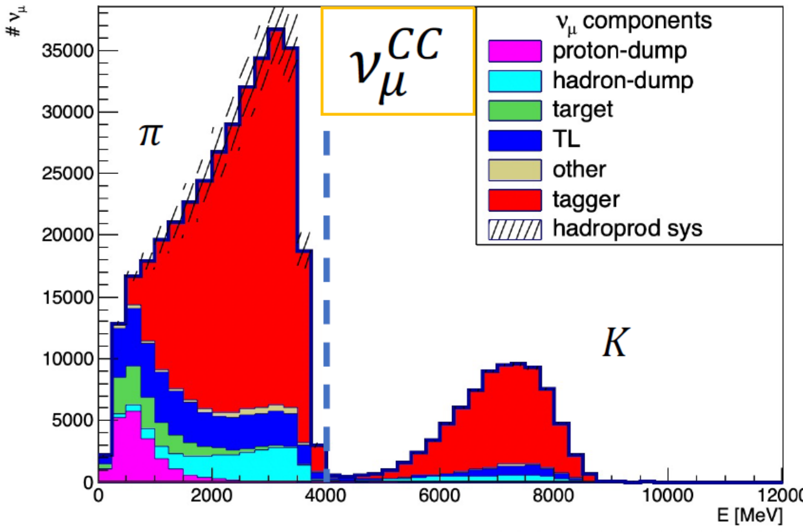
Neutrino interaction rates @ detector

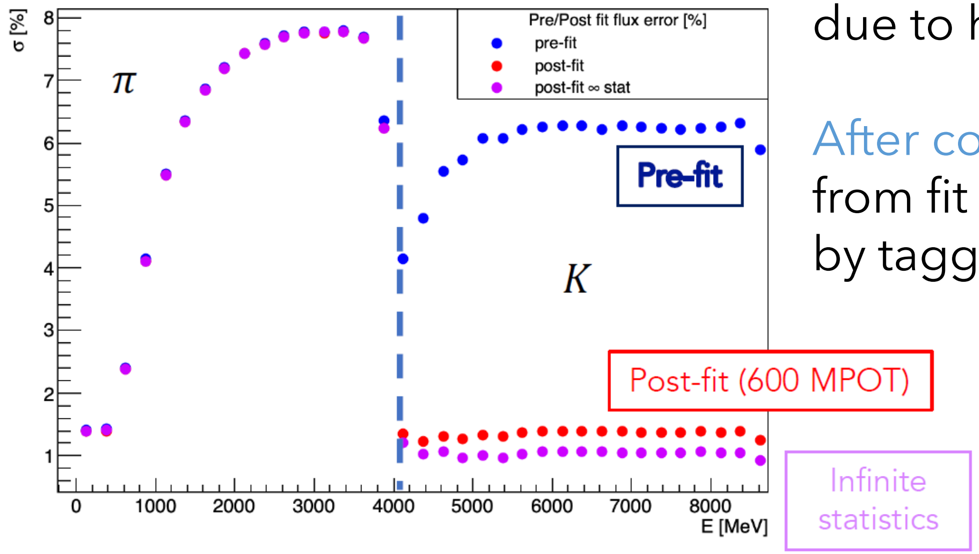


Pre & Post fit relative errors on rates



Total rates in 1 year of data taking
- @ SPS with 4.5 x 10^{19} POT/year;
- 500 ton detector @ 50 m from tunnel end.





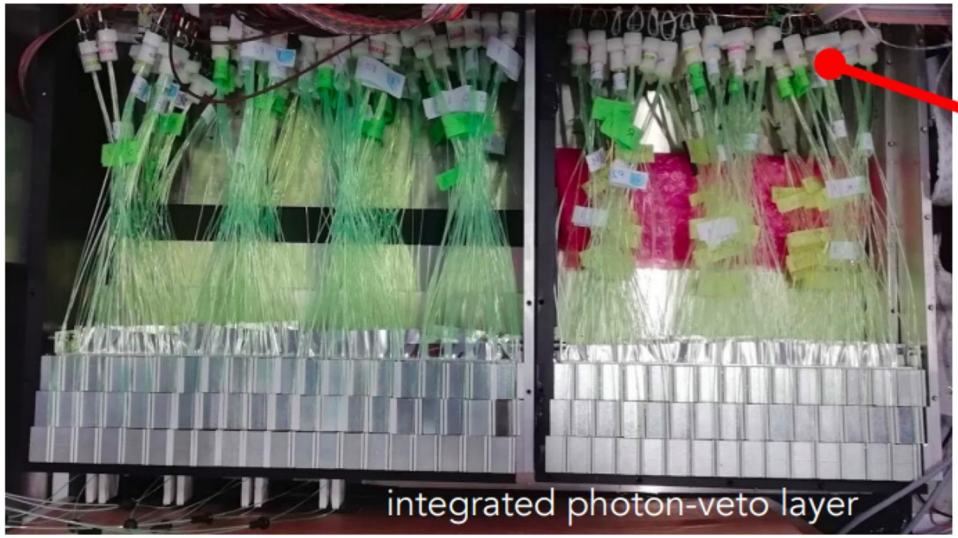
Before constraint: 6% systematics due to hadroproduction uncertainties.

After constraint: 1% systematics from fit to lepton rates measured by tagger.

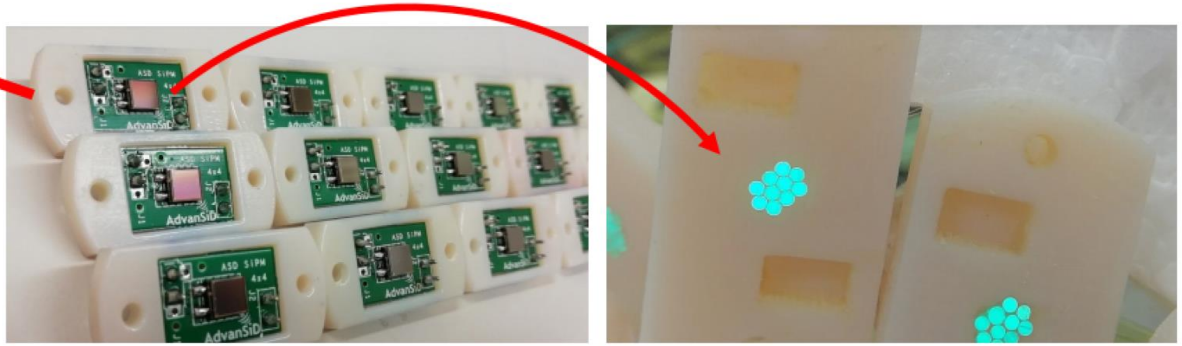
Achieved ENUBET goal of 1% systematics from monitoring lepton rate

Prototypes and tests

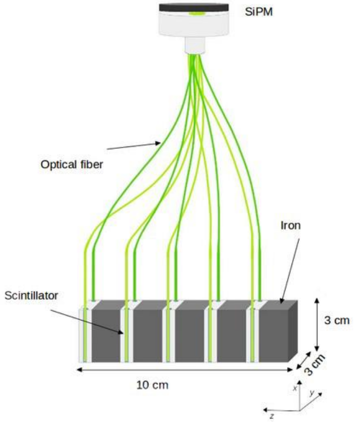
Tested during 2018 test beams runs @ CERN-PS: Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection



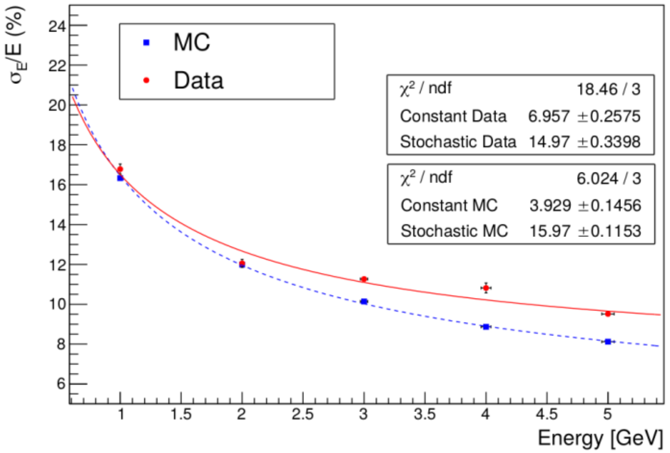
Large SiPM area (4x4 mm2) for 10 WLS readout (1 LCM)



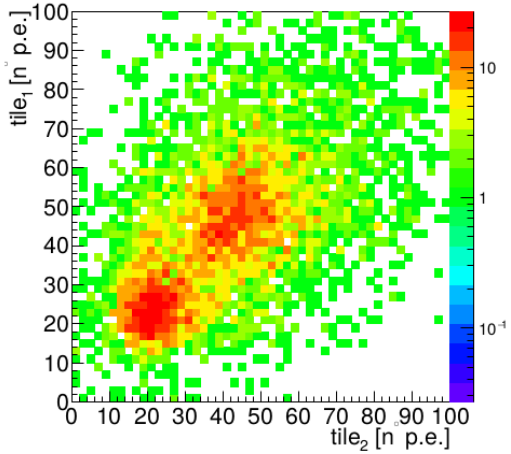
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging



Electron energy resolution



1/2 mip separation



F. Acerbi et al., JINST (2020), 15(8), P08001

Status of calorimeter:

- ➢ longitudinally segmented calorimeter prototype successfully tested;
- ➢ photon veto successfully tested.

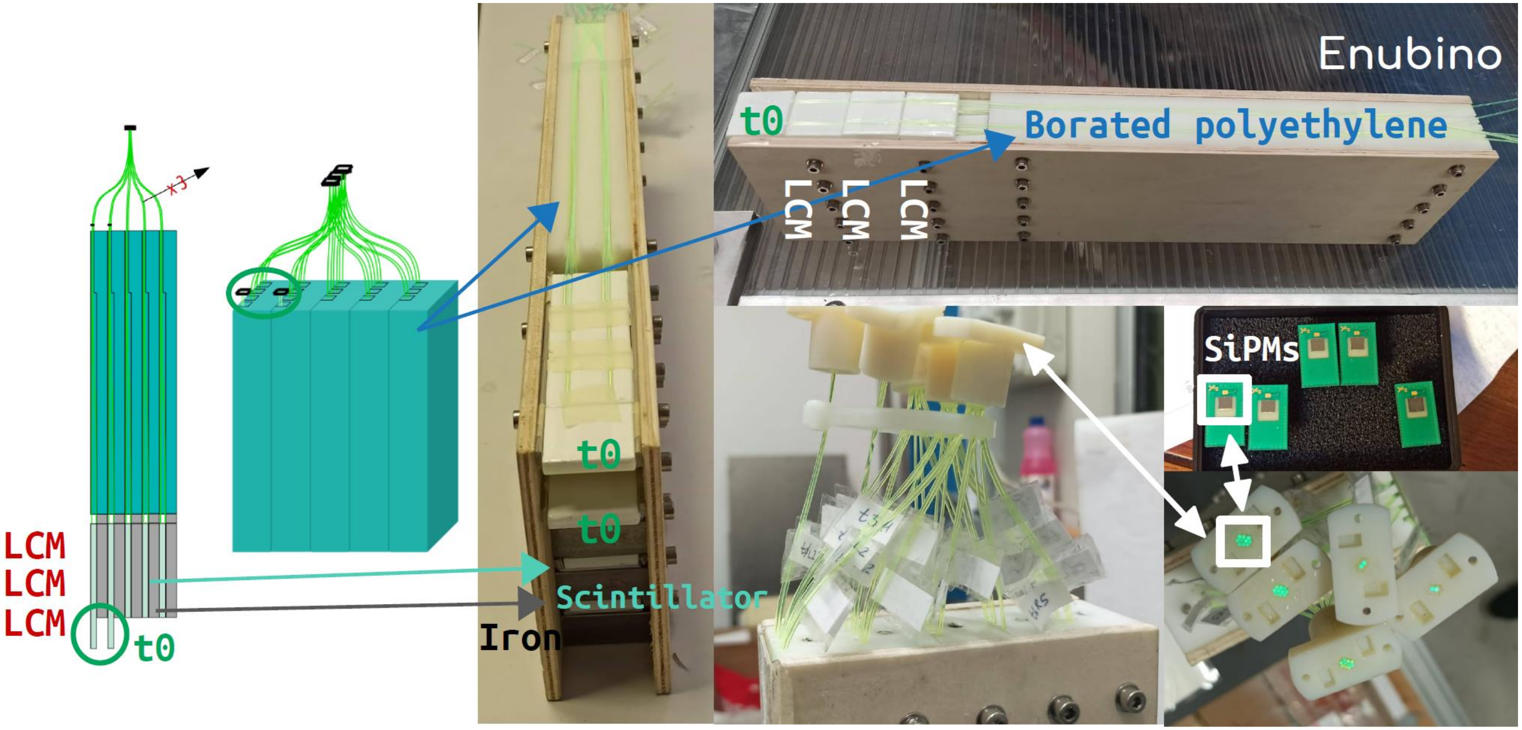
Choise of technology: finalized and cost-effective!

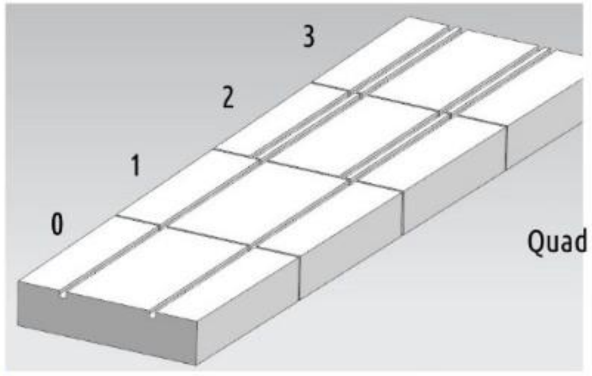
Prototypes and tests - Enubino

2021 test beam @ CERN-PS:

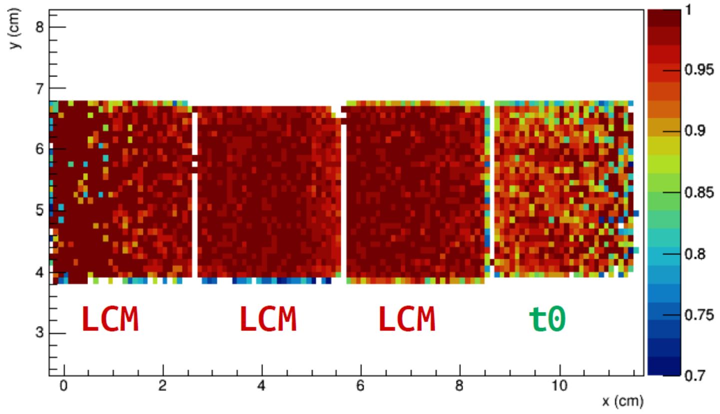
- Sampling calorimeter: plastic scintillator + iron absorber + BPE.
- Fibers collect the scintillation light frontally
- Uniform light collection.
- Fiber routing through BPE to SIPMs.

New frontal readout scheme & fibers bundling, again with 1 LCM bundled to a 4x4 mm^2 SiPM.

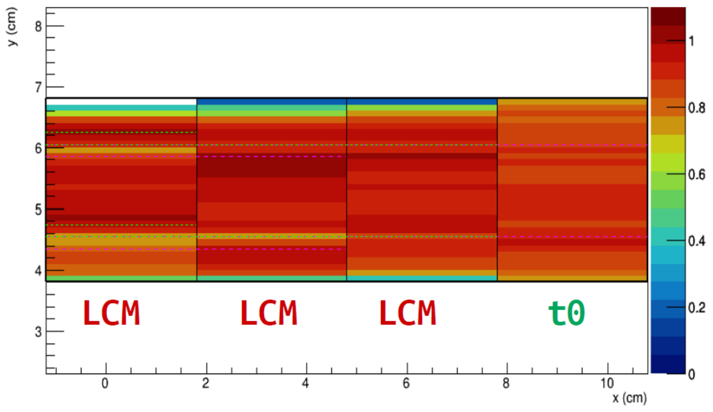




Efficiency map

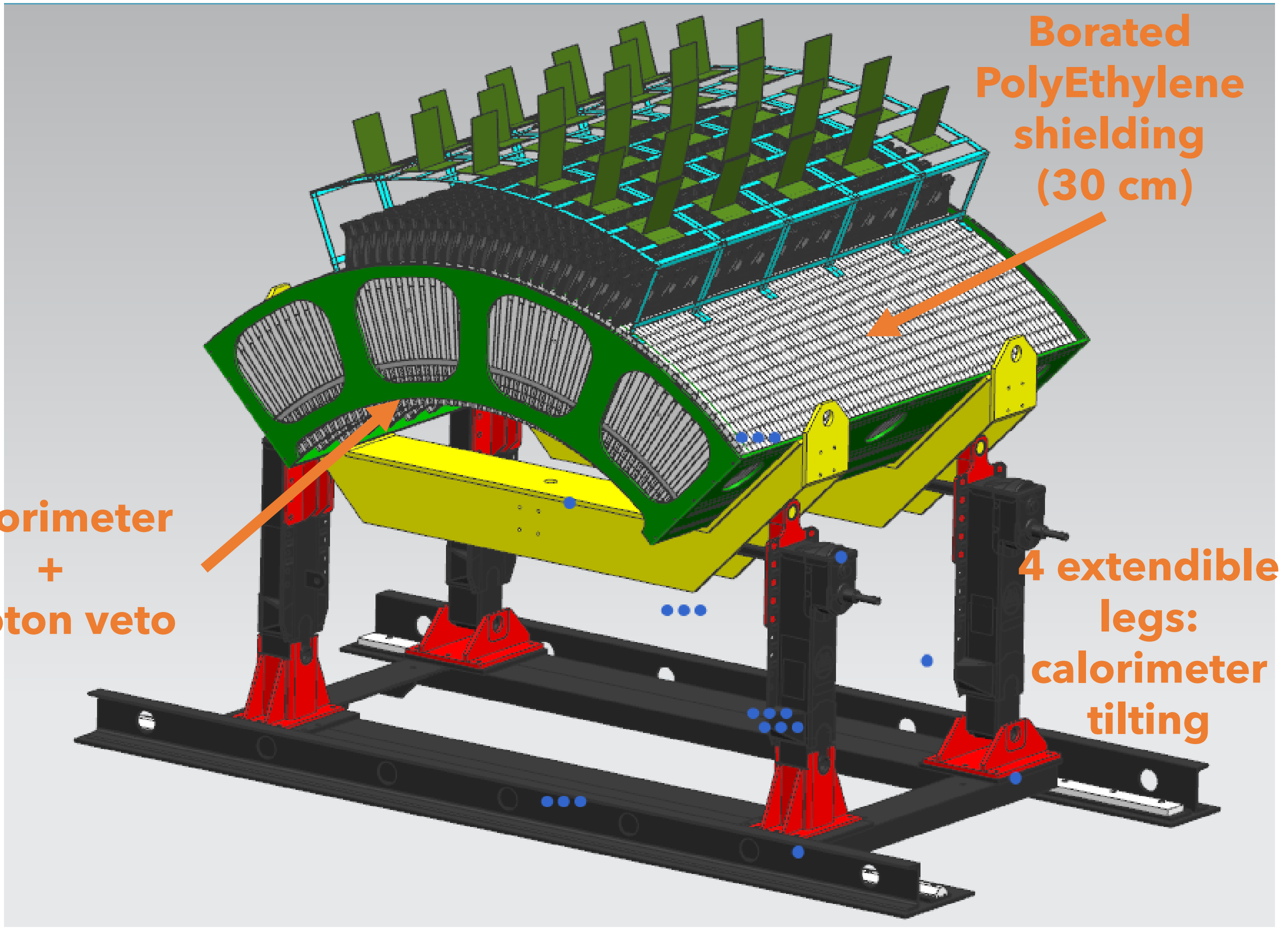


Uniformity

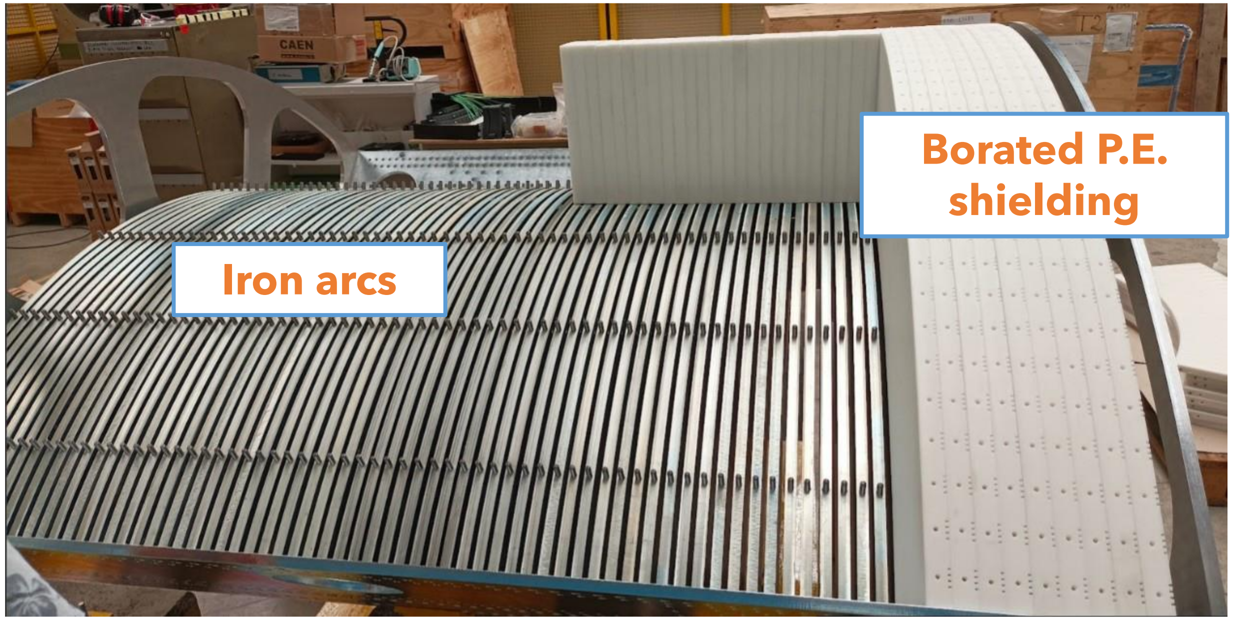


The tagger demonstrator

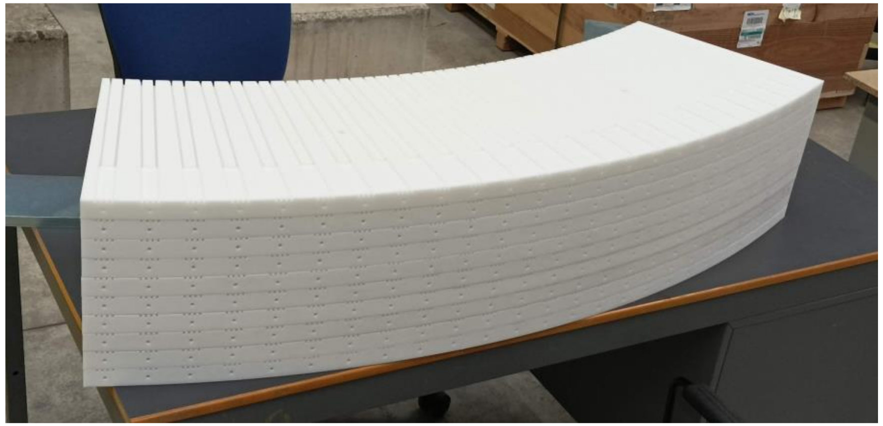
- Detector prototype to demonstrate performance / scalability / cost-effectiveness:
  - 1.65 m longitudinal & 90° in azimuth;
  - 75 layers of: iron (1.5 mm thick) + scintillator (7 mm thick) => 12x3 LCMs.
- Central 45° part instrumented: rest is kept for mechanical considerations;
- Modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions);
- New light readout scheme with frontal grooves instead of lateral grooves:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection;
  - performed GEANT4 optical simulation validation.
- Scintillators: produced by SCONIX and milled by local company.



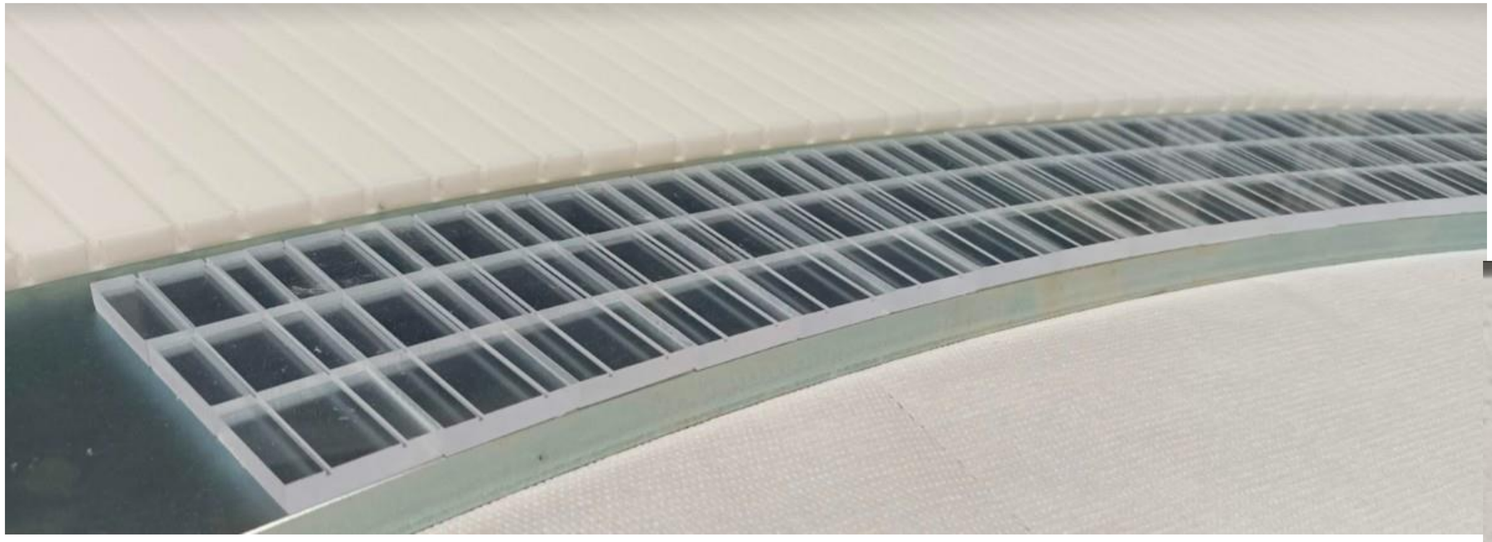
The tagger demonstrator: mechanical stracture



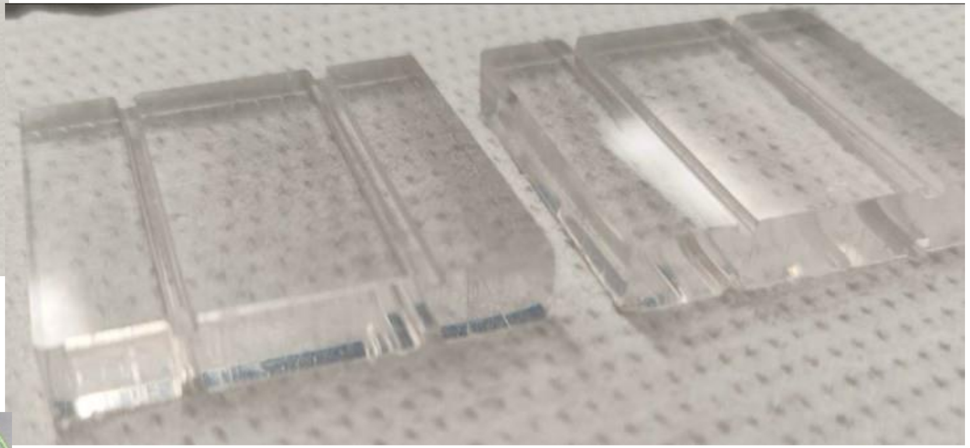
Lifting test with additional 2 tons (prototype weight ~3.2 tons)

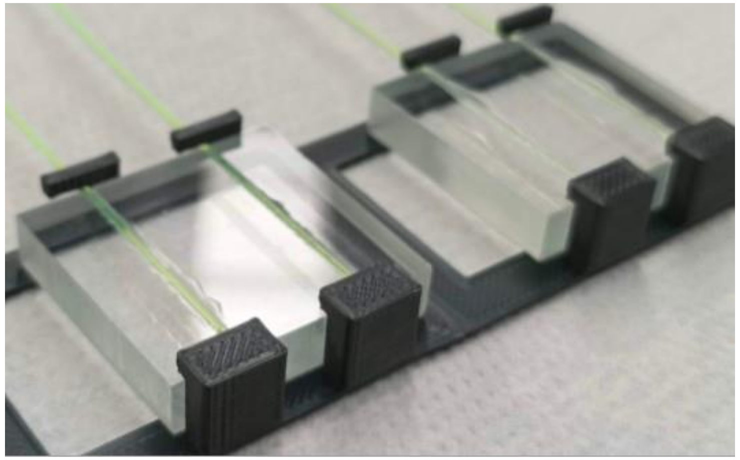


The tagger demonstrator: scintillator tiles



EJ-204 scintillator tiles
(3x3 cm^2)
with grooves for WLS fibers

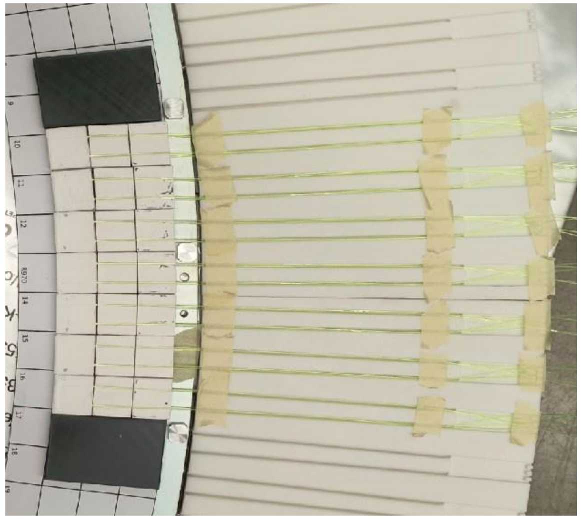




Fiber gluing
(EJ-500 optical cement)

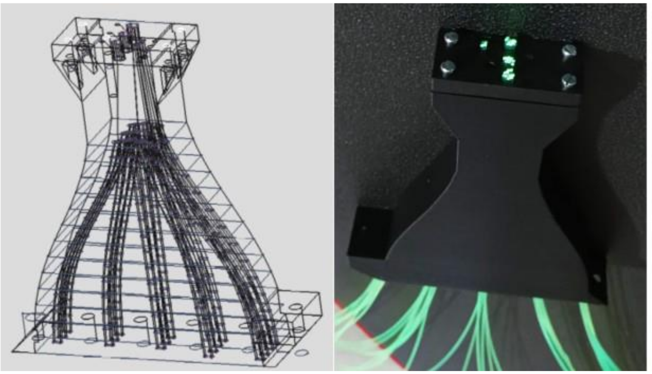
Tile painting
(EJ-510 TiO_2 reflecting painting)

Tile assembling on arcs and fiber routing



The tagger demonstrator: fiber routing

Fiber concentrators for bundling and routing to SiPMs

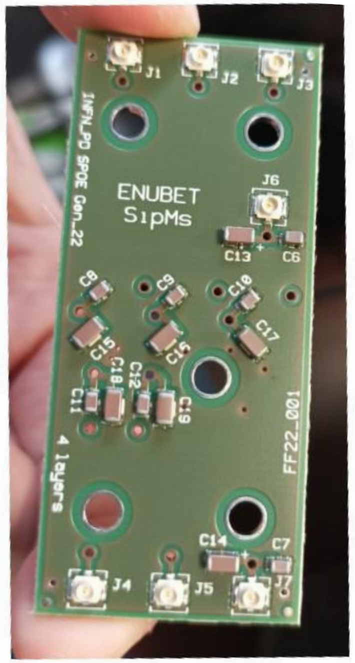


Custom design

Produced with 5 consumer level 3D printers

The tagger demonstrator: electronics

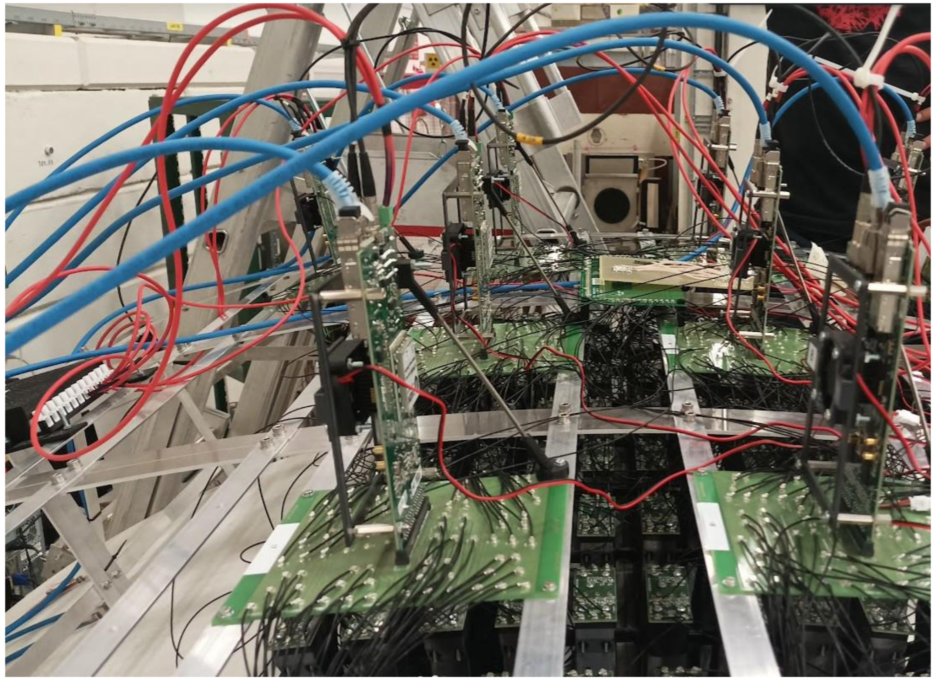
Custom + Commercial electronics



Front-End Board (SiPMs + Low V)

Commercial read-out board (CAEN A5202)

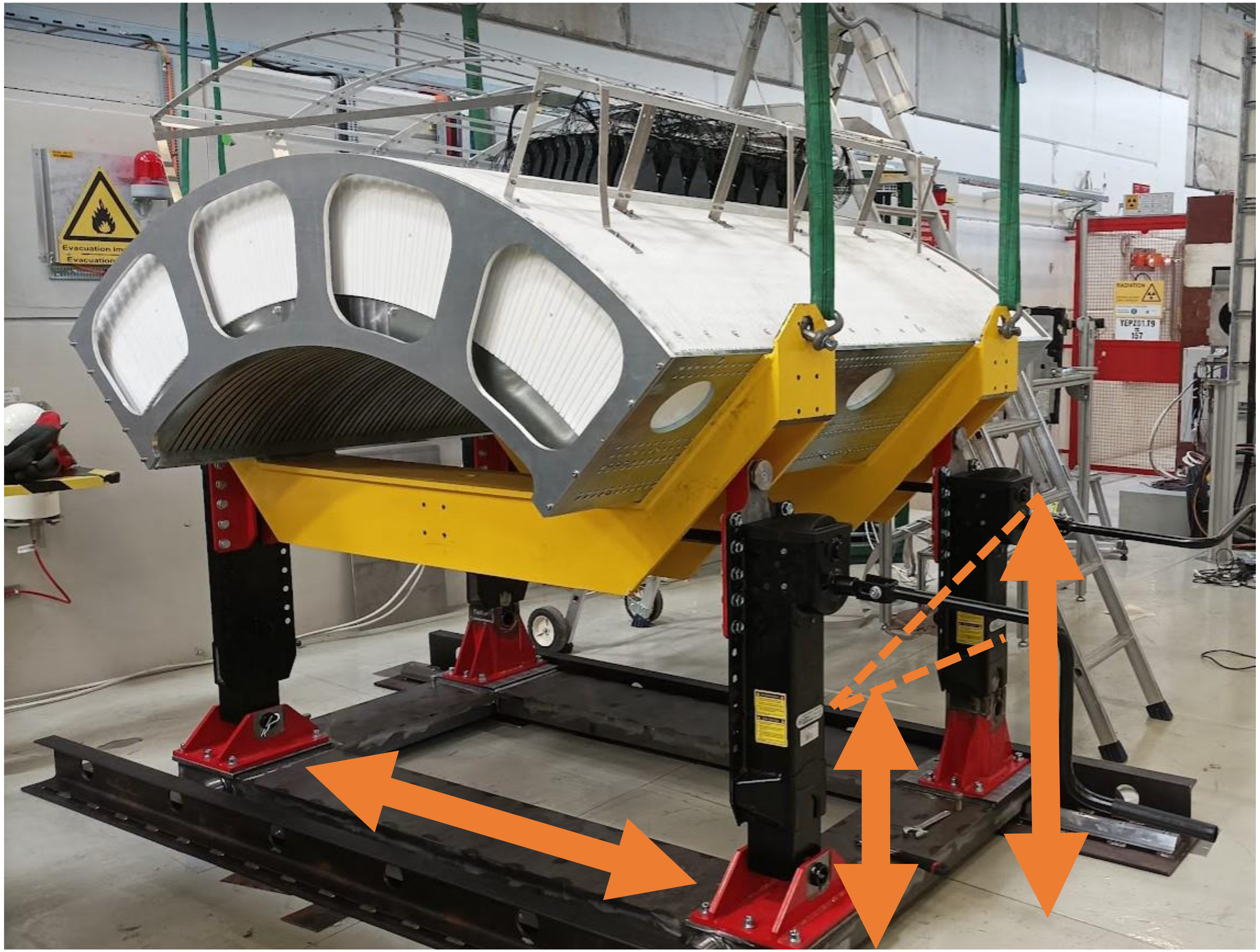
Custom interface board to connect 5 FEB (60 ch) to 1 A5202 (64 ch)



The tagger demonstrator at CERN

- Scintillator tiles: 1360
- WLS: ~ 1.5 km
- Channels (SiPM): 400
  - Hamamatsu 50 um cell
  - 240 SiPM 4x4 mm2 (calo)
  - 160 SiPM 3x3 mm2 (t0)
- Fiber concentrators, FE boards: 80
- Interface boards (hirose conn.): 8
- Readout 64 ch boards (CAEN A5202): 8
- Commercial digitizers: 45 ch
- Hor. movement ~1m
- Tilt >200 mrad

- Instrumented fraction can be extended (> x2) in the future with already available materials (with more time for an exposure next year).



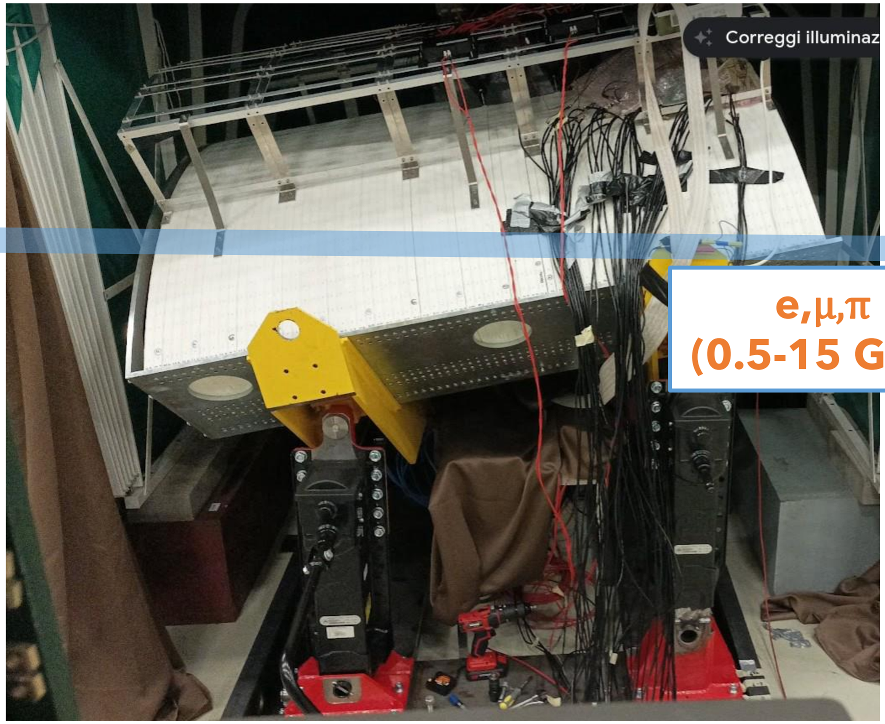
ENUBET at CERN PS-T9 area

October 2022 CERN-PS-T9

ENUBET at CERN PS-T9 area

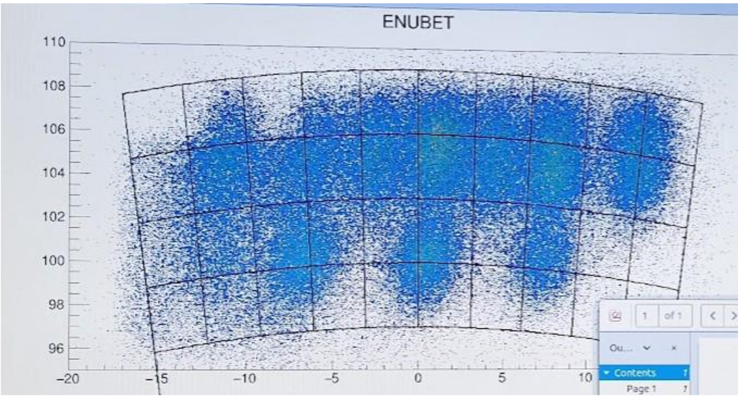
horizontal run with darkening cover

200 mrad tilt run

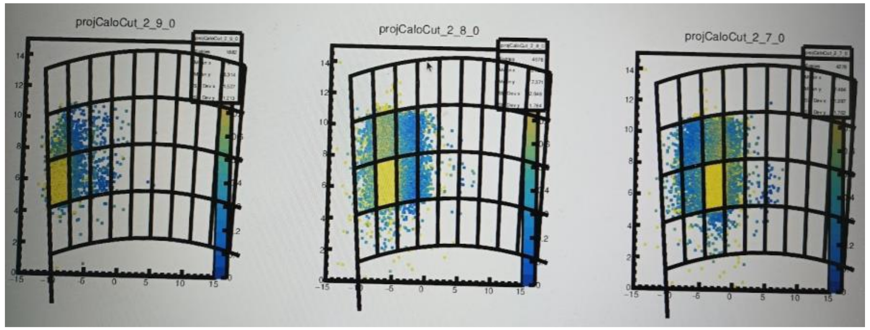


e,μ,π (0.5-15 GeV)

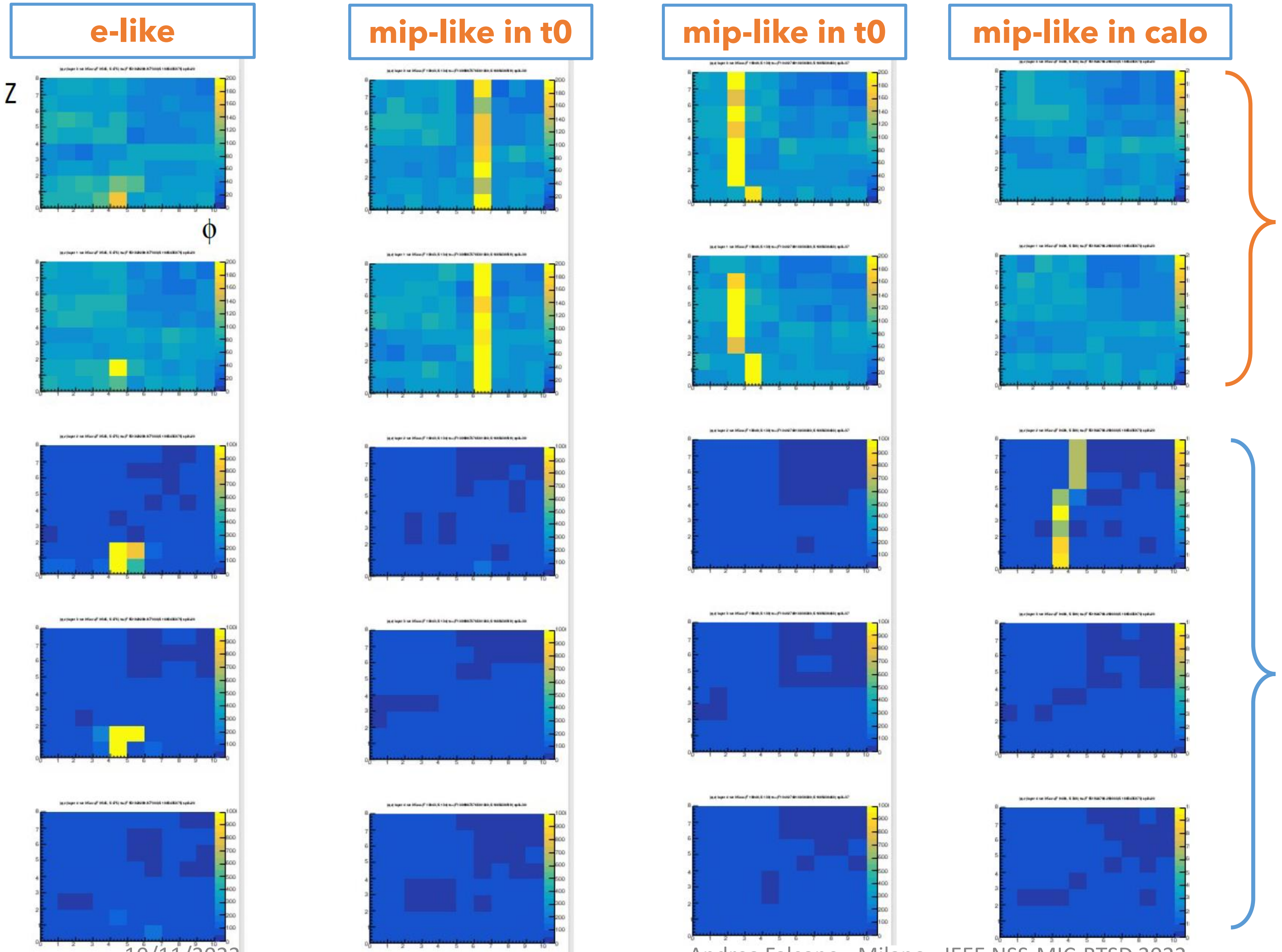
Beam spot at the detector upstream face after several runs illuminating different regions of the detector



Efficiency maps



Event display



Tracker layer "t0"

Calorimeter layer

NB: channels not yet equalized with mips.

Conclusions and outlooks

ENUBET goal: first monitored neutrino beam for neutrino cross-section measurements @ O(1%):

- ERC project started in 2016
- CERN experiment (NP06) within Neutrino-Platform in 2019
- part of Physics Beyond Collider framework

Final design of beam transfer line in place, fine-tunning parameters:

- static transfer line: 104 events in ~3 years (@ SPS)
- ongoing optimization of transfer line parameters w/ dedicated framework
- multi-momentum beamline ongoing R&D: DUNE & HyperK optimize

Design of decay tunnel instrumentation finalized:

- prototypes test-beams @ CERN: technology validation;
- final demonstrator tested @ PS East Hall in October 2022 -> results coming soon!

Detector simulation and PID studies done:

- developed full GEANT4 simulation of calorimeter
- finalizing waveform to fully assess the pile-up effects
- very good PID performance achieved (both positron and muon reconstruction)

Systematics, hadroproduction and next steps:

- achieved 1% systematic goal due to hadroproduction with lepton monitoring
- assess systematics due to detector effects and beamline parameters