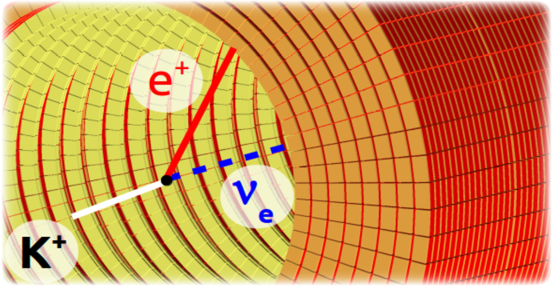


The Demonstrator: a large scale prototype of the instrumented decay tunnel for the ENUBET monitored neutrino beam

Valerio Mascagna

Università degli Studi di Brescia & INFN - PV

Siena, Sep. 25 – 29 – IPRD2023

European Research Council
Established by the European Commission

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647)

OUTLINE

- The ENUBET project
- The instrumented tunnel and the tagger
- Prototyping and testbeam results
- Conclusions and outlooks

Enhanced NeUtrino BEams from kaon Tagging

http://enubet.pd.infn.it

Project approved by the European Research Council (ERC)
5 years (ended in 2022)
overall budget: 2 MEUR

ERC-Consolidator Grant-2015, no 681647 (PE2)
P.I.: **A. Longhin**
Host Institution: **INFN**

Expression of Interest (CERN-SPSC, Oct. 2016)
CERN-SPSC-2016-036; SPSC-EOI-014

April 2019: CERN Neutrino Platform Experiment – **NP06/ENUBET**
Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna

74 physicists & **24 institutions**

Expression of Interest

Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project

A. Berra[a,b], M. Bonesini[b], C. Brizzolari[a,b], M. Calviani[m], M.G. Catanesi[l], S. Cecchini[c], F. Cindolo[c], G. Collazuol[k,j], E. Conti[j], F. Dal Corso[j], G. De Rosa[p,q], A. Gola[o], R.A. Intonti[l], C. Jollet[d], M. Laveder[k,j], A. Longhin[j(*)], P.F. Loverre[n,f], L. Ludovici[f], L. Magaletti[l], G. Mandrioli[c], A. Margotti[c], N. Mauri[c], A. Meregaglia[d], M. Mezzetto[j], M. Nessi[m], A. Paoloni[e], L. Pasqualini[c,g], G. Paternoster[o], L. Patrizii[c], C. Piemonte[o], M. Pozzato[c], M. Prest[a,b], F. Pupilli[e], E. Radicioni[l], C. Riccio[p,q], A.C. Ruggeri[p], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i], L. Votano[e], E. Wildner[m]

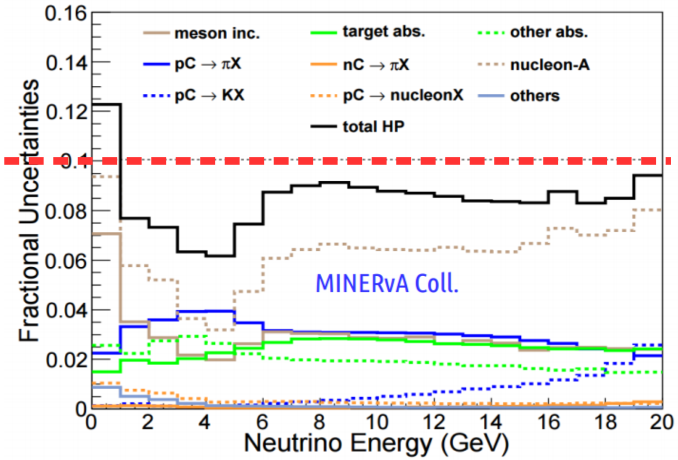
Flux uncertainty and $\nu_{e,}\ \nu_{\mu}$ cross sections

Last 10 years: knowledge of **$\sigma(\nu_\mu)$** improved enormously

MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA …

Nevertheless, the flux systematics **"wall"** is still there being typically the **dominant uncertainty** for cross section measurements

No absolute measurements below ~7-10%



In addition, for **$\sigma(\nu_e)$** we use the beam contamination (no intense/pure sources of GeV ν_e): data still sparse Gargamelle, T2K, NOvA, MINERvA

Poor knowledge of **$\sigma(\nu_e)$** can spoil :

- the **CPV discovery potential**
- the insight on the underlying physics (standard vs exotic)

→ Monitored beams

Monitored neutrino beams

The "holy grail" of neutrino physicists:

B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257

> The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$,

Based on **conventional technologies**, aiming for a 1% precision on the ν_e **flux**

protons → (K^+, π^+) → K decays → e^+ ν_e → neutrino detector

Monitor (~ inclusively) the decays in which ν are produced

→ "by-pass" of the hadro-production, beam-line efficiency uncertainties, …

K_{e3}

$\mu^+\nu_\mu$	(63.55 ±0.11) %
$\pi^0 e^+ \nu_e$	(5.07 ±0.04) %
$\pi^0 \mu^+ \nu_\mu$	(3.353±0.034) %
$\pi^+\pi^0$	(20.66 ±0.08) %
$\pi^+\pi^0\pi^0$	(1.761±0.022) %
$\pi^+\pi^+\pi^-$	(5.59 ±0.04) %

Traditional

- **Passive** decay region
- ν_e flux relies on **ab-initio simulations** of the full chain
- **large uncertainties**

↔

Monitored

- **Fully instrumented**

$K^+ \to e^+ \nu_e \pi^0 \to$ large angle e^+

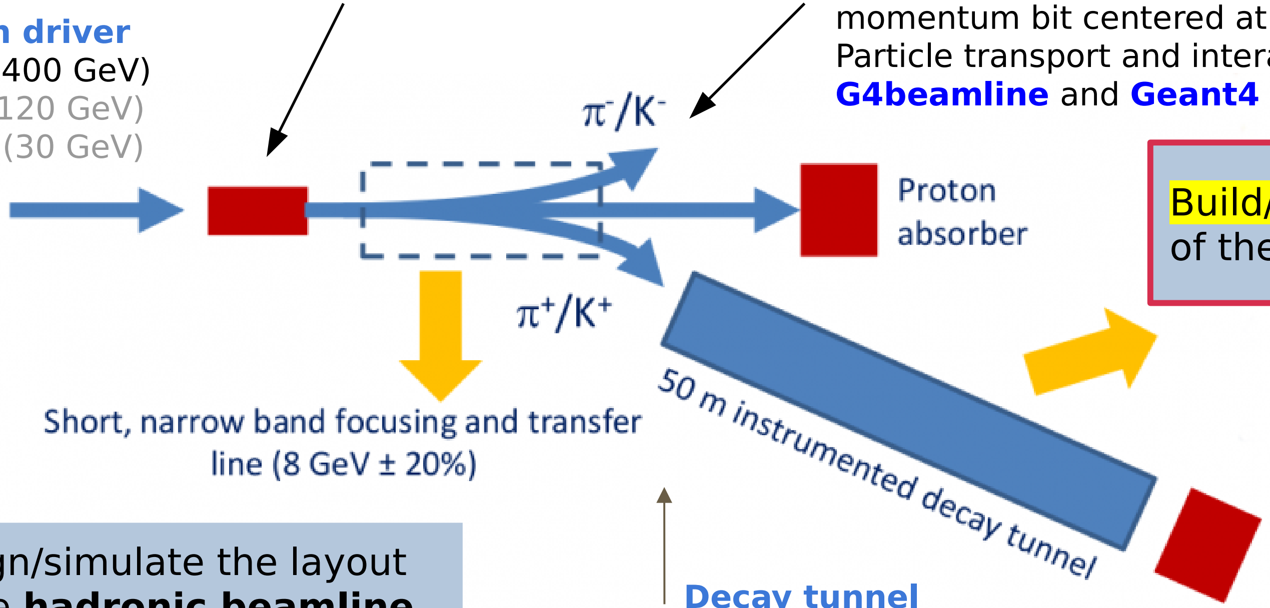
- ν_e **flux prediction =** e^+ **counting**

The ENUBET "facility"

Proton driver
CERN (400 GeV)
FNAL (120 GeV)
J-PARC (30 GeV)

Target
(Be, graphite. **FLUKA**)

Transfer Line
Horn vs **Static** focusing under study (tested at the **CERN SPS**)
TL kept short, optimized with **TRANSPORT** to a 10% momentum bit centered at 8.5 GeV/c
Particle transport and interaction: **full simulation** with **G4beamline** and **Geant4**



Build/test/simulate a **demonstrator** of the **instrumented decay tunnel**

Design/simulate the layout of the **hadronic beamline**

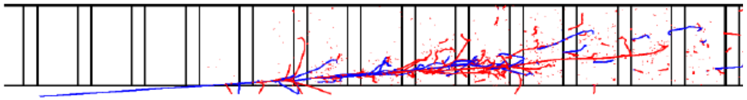
Decay tunnel
R = 1 m, L = 50 m

Hadron dump

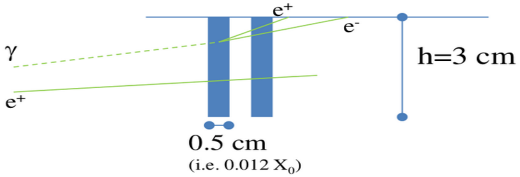
~500 T neutrino detector
100m from the target.
E.g. :
ProtoDUNE@CERN
ICARUS@FNAL
Water Cher @J-PARC

The ENUBET tagger

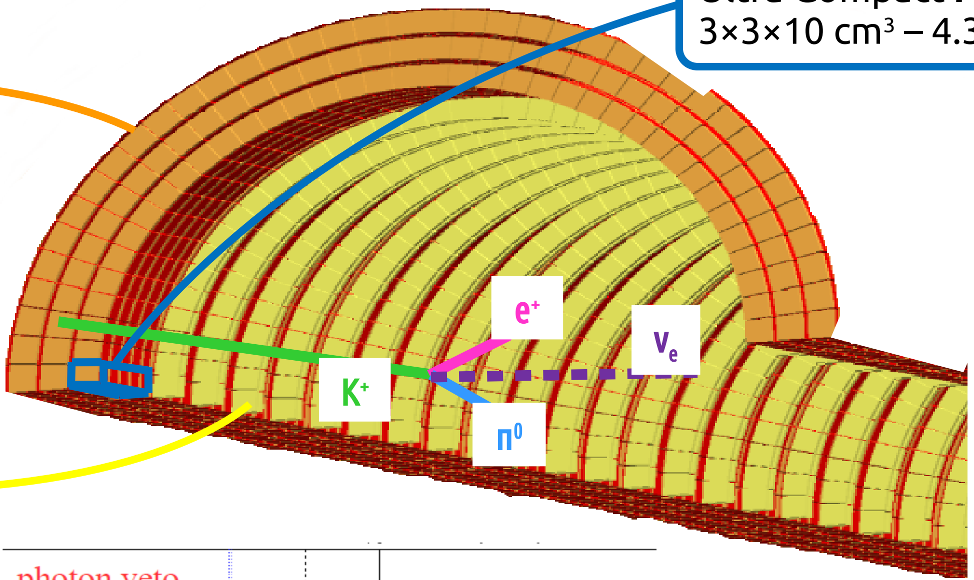
Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation

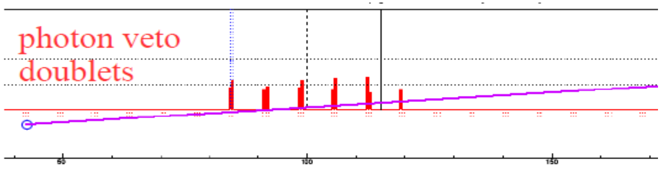


Integrated photon veto
Plastic scintillators, rings of 3×3 cm² pads
→ π^0 rejection



Ultra Compact Module
$3\times3\times10$ cm³ – 4.3 X_0



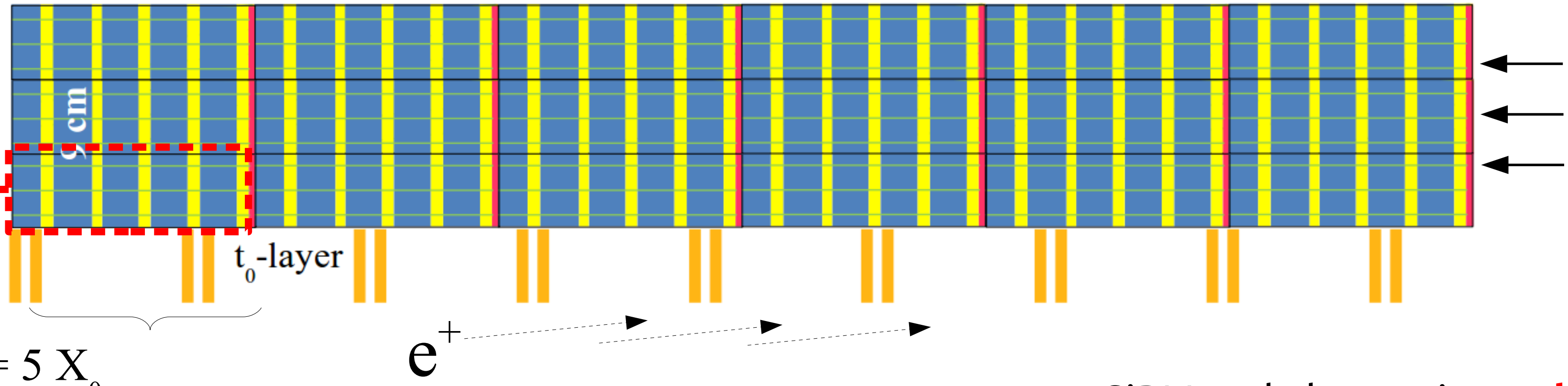


e^+ (signal) topology

π^0 (background) topology

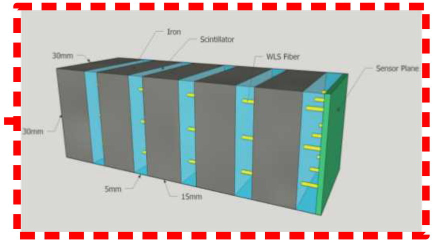
π^+ (background) topology

The shashlik prototype



10 cm = 5 X_0

UCM: ultra compact module.



5 x (ABSORBER + SCINTI) → **~4 X_0**

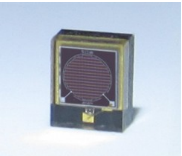
Fe-15mm + EJ200

TiO2 painting

WLS: Kuraray Y11 double clad, 1mm diameter

SiPM and electronics **embedded** in the shashlik calorimeter

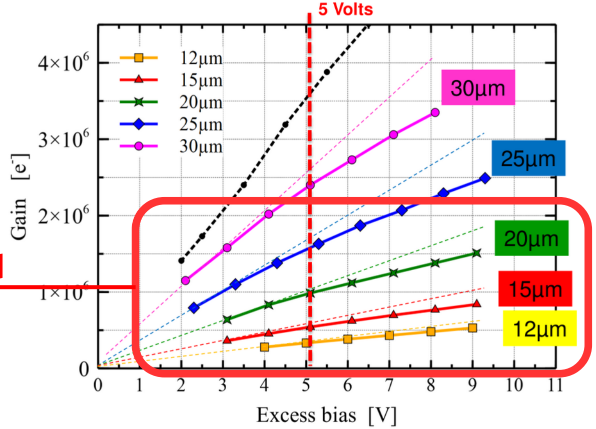
SiPMs: **FBK HD-RGB, 1mm²**



Required:
Fast ~10ns ← avoid pileup
Rad.hard (10^{12} n/cm²)

CS	FF	Cell Density
12 × 12 µm²	52 %	~7000 cells/mm²
15 × 15 µm²	62 %	~4444 cells/mm²
20 × 20 µm²	66 %	2500 cells/mm²
25 × 25 µm²	72 %	1600 cells/mm²
30 × 30 µm²	77 %	~1111 cells/mm²

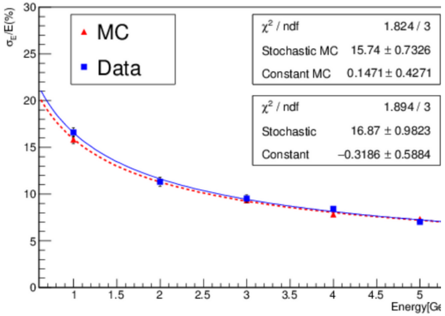
Tested

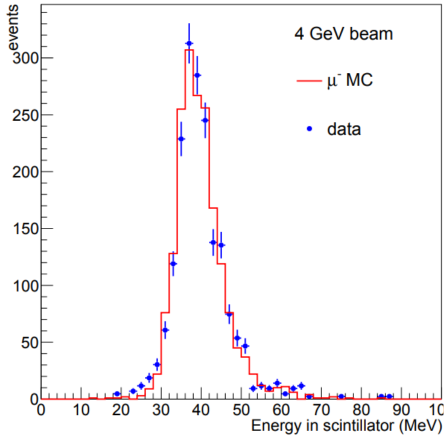


The shashlik prototype

Tested response to MIP, e and π$^-$

- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences

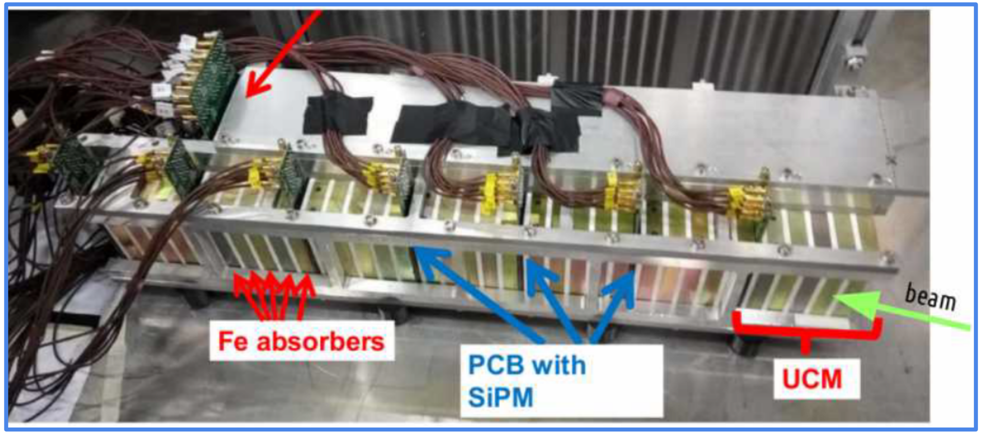


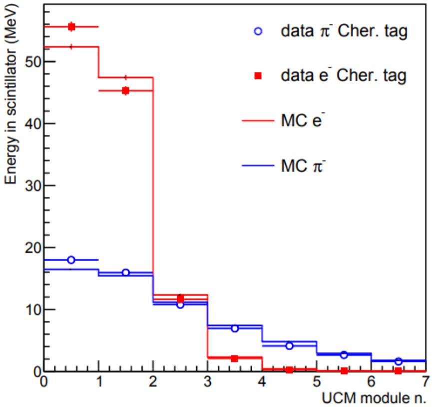


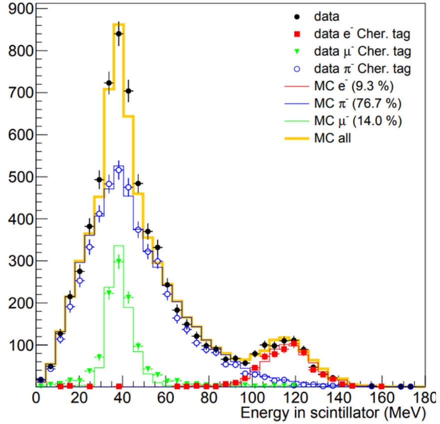
MC/data already in good agreement

Longitudinal profiles of partially contained π reproduced by MC @ 10% precision

CERN PS, Nov 2016 7x4x2 UCMs



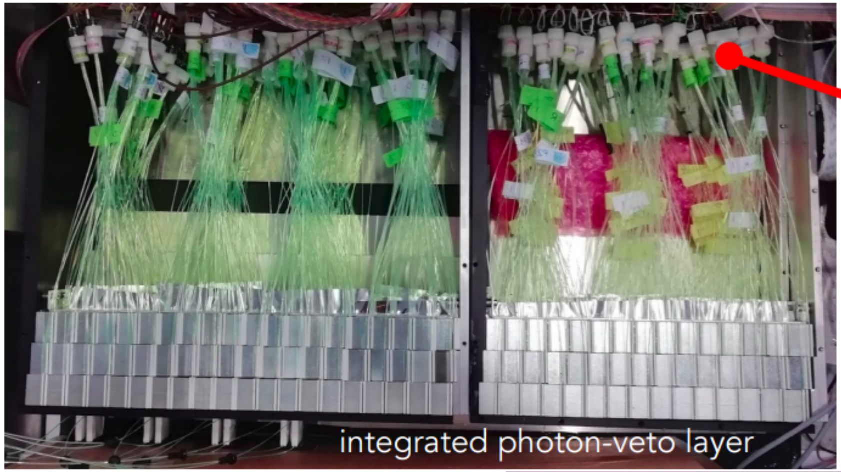




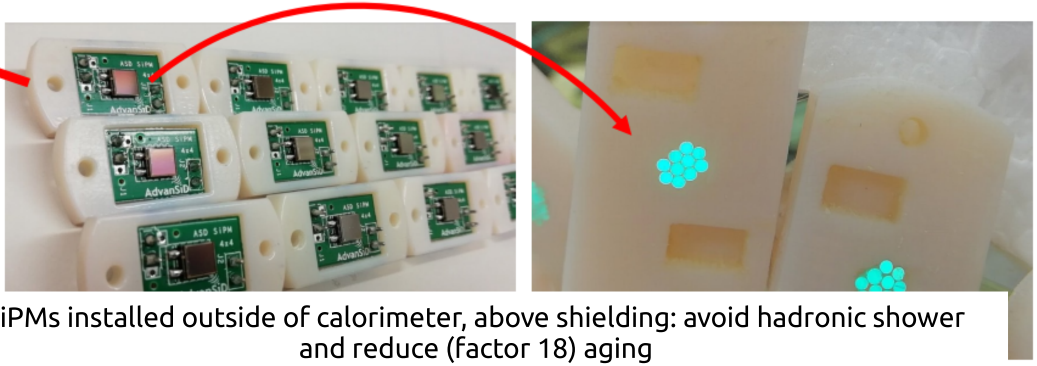
Ballerini et al., JINST 13 (2018) P01028

The lateral readout prototype

Lateral WLS-fibers for light collection

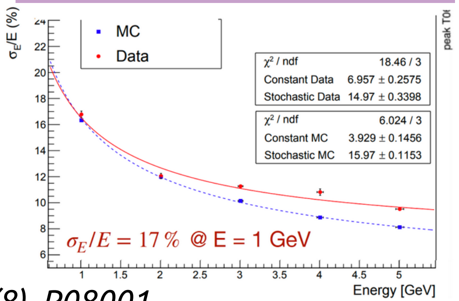


Large SiPM area (4x4 mm2) for 10 WLS readout (1 LCM)

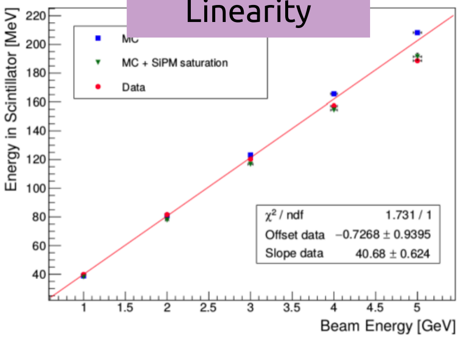


SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

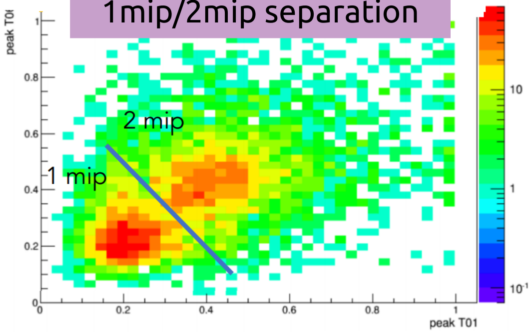
Electron energy resolution



Linearity



1mip/2mip separation

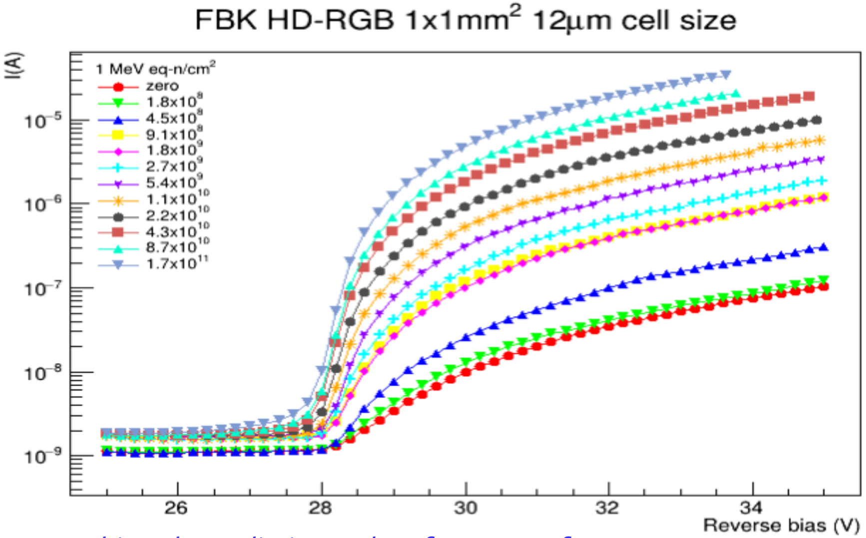


Test beam(s) 2017-2018
@ CERN PS T9 beamline

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

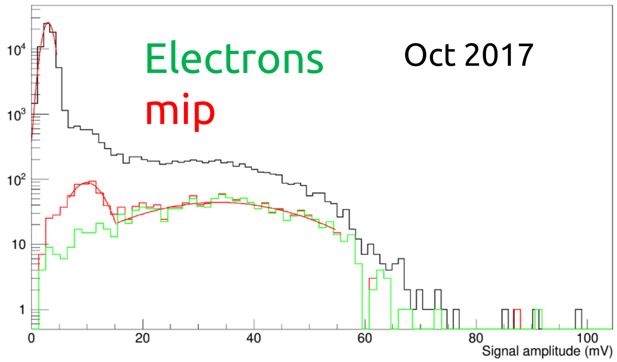
SiPM **irradiation** @ LNL

Dark current vs bias at increasing n fluences



F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

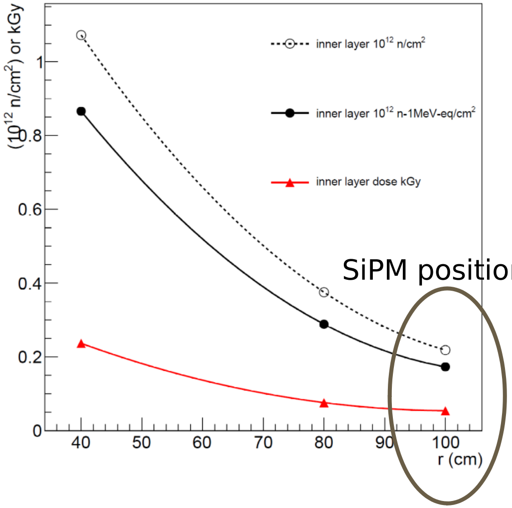
A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS



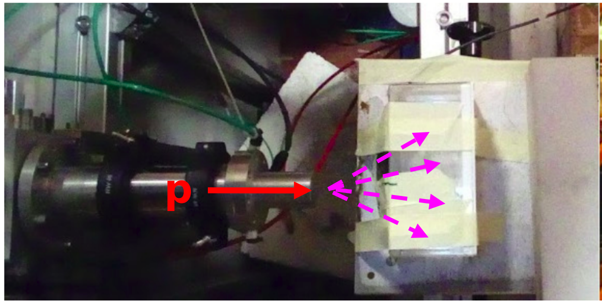
(FBK-HD-RB Advansid)

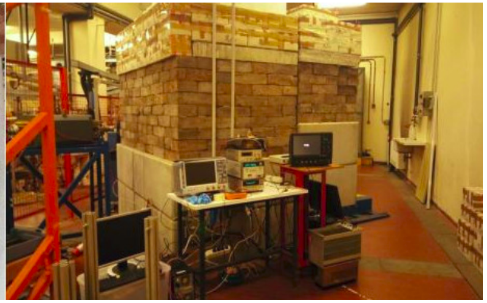
1.2 x 10^{11} n-1MeV-eq/cm^2

Expected 5-years neutron doses from K decays (**FLUKA**)



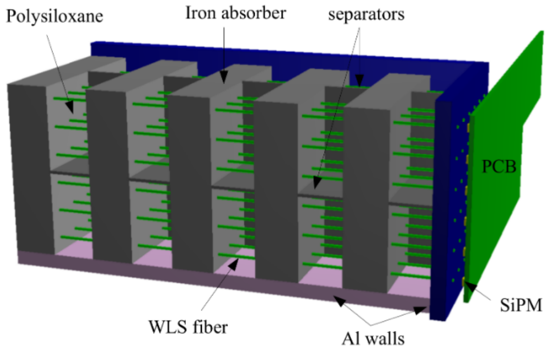
- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used from **channel-to-channel intercalibration** even after maximum irradiation.

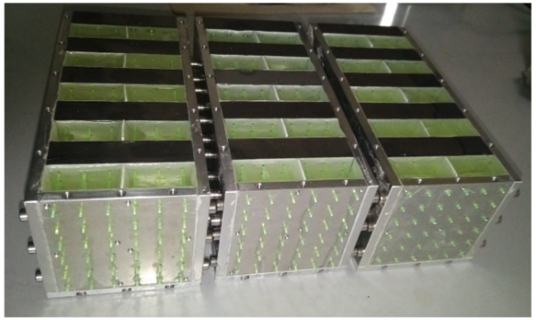


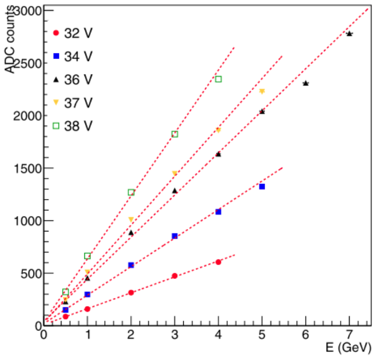


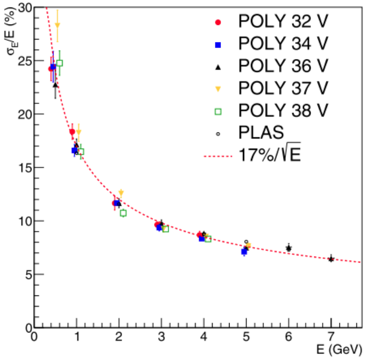
Test with polysiloxane scintillator

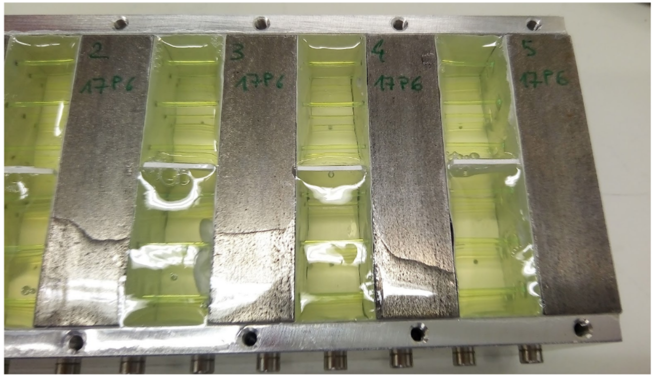
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)
A **$13X_0$ shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)

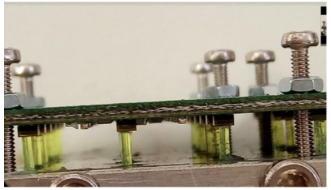


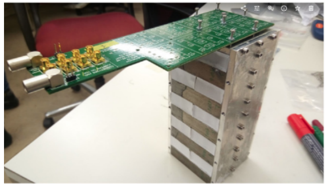


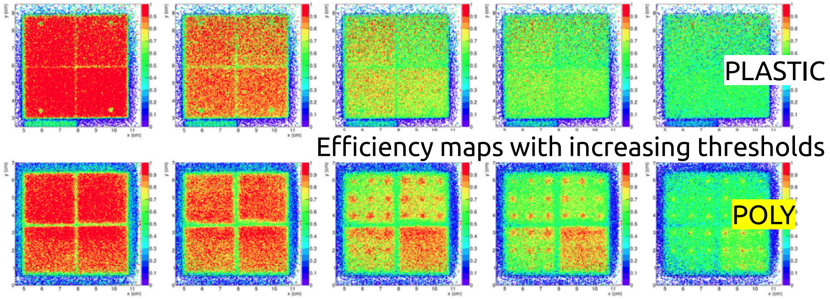








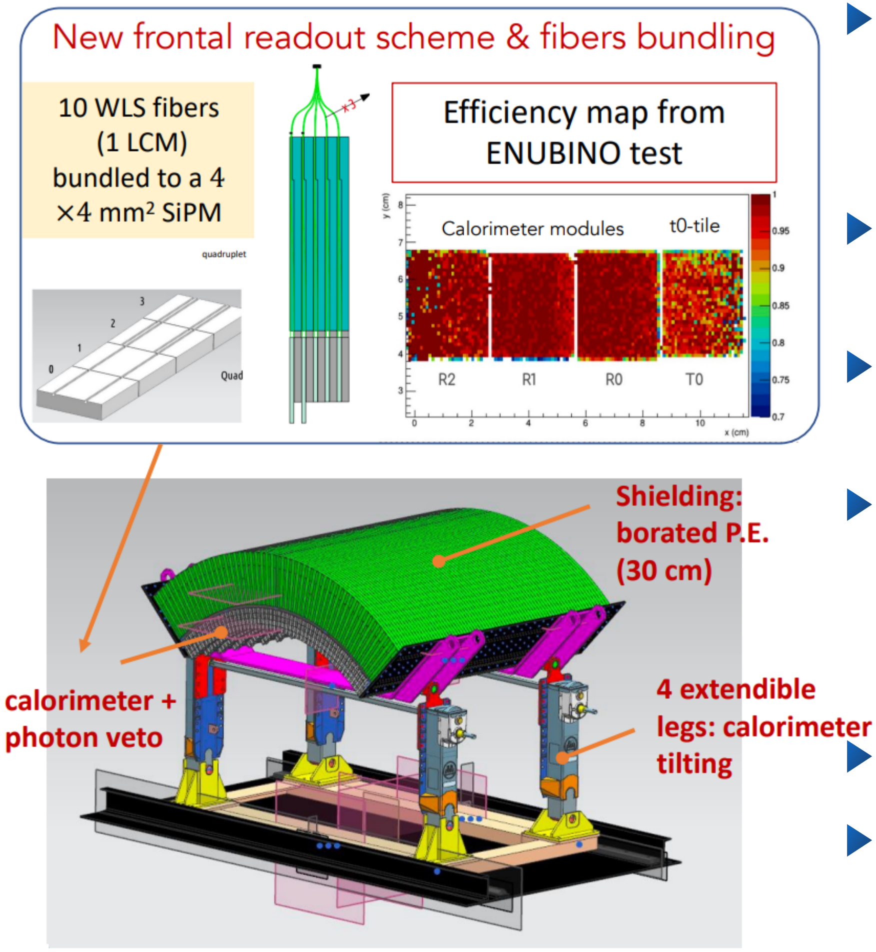




Cons: 15 mm thick scintillators
to compensate reduced light yields

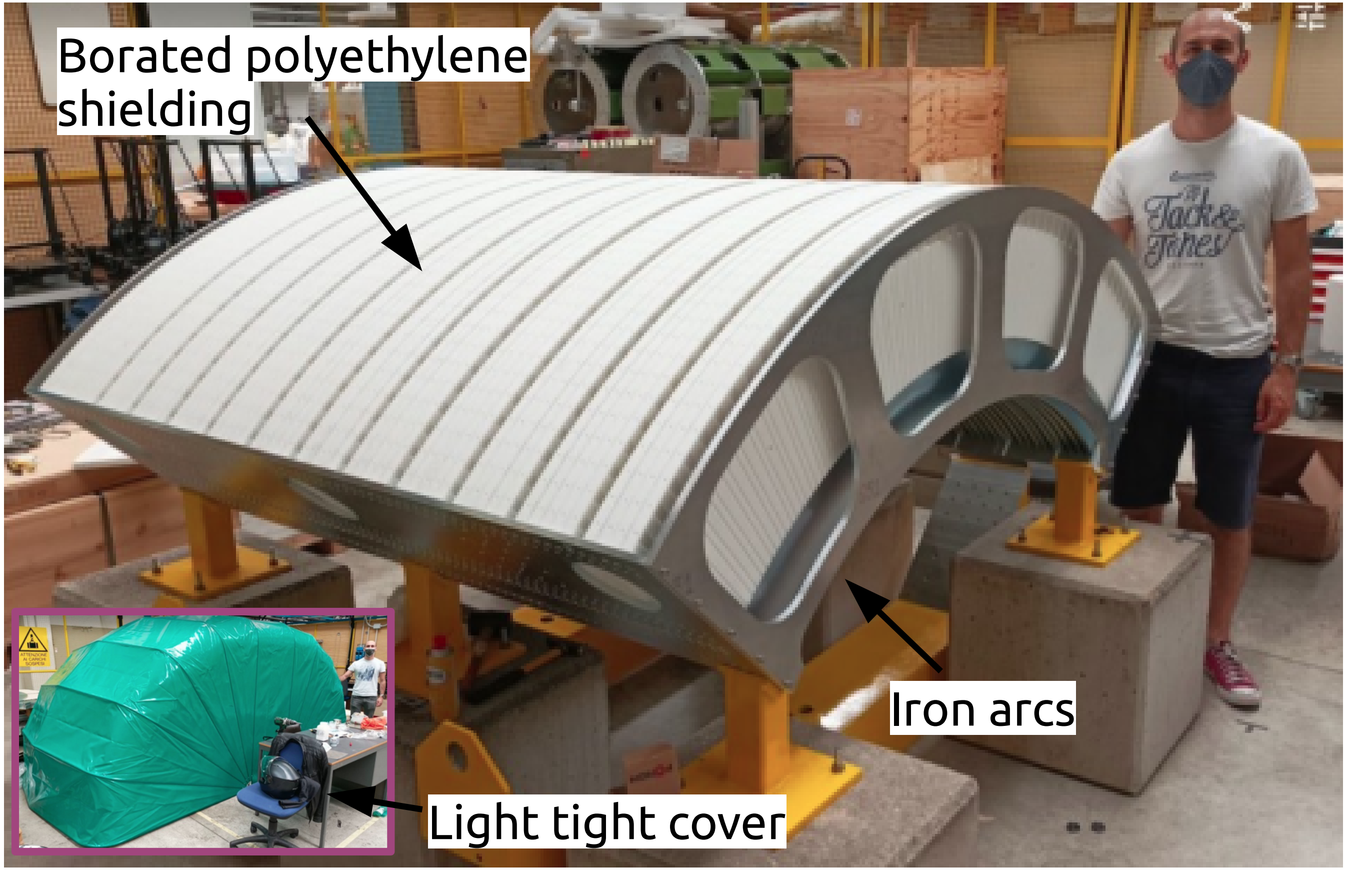
«Polysiloxane-based scintillators for shashlik calorimeters», NIM A 956 (2020)

The demonstrator



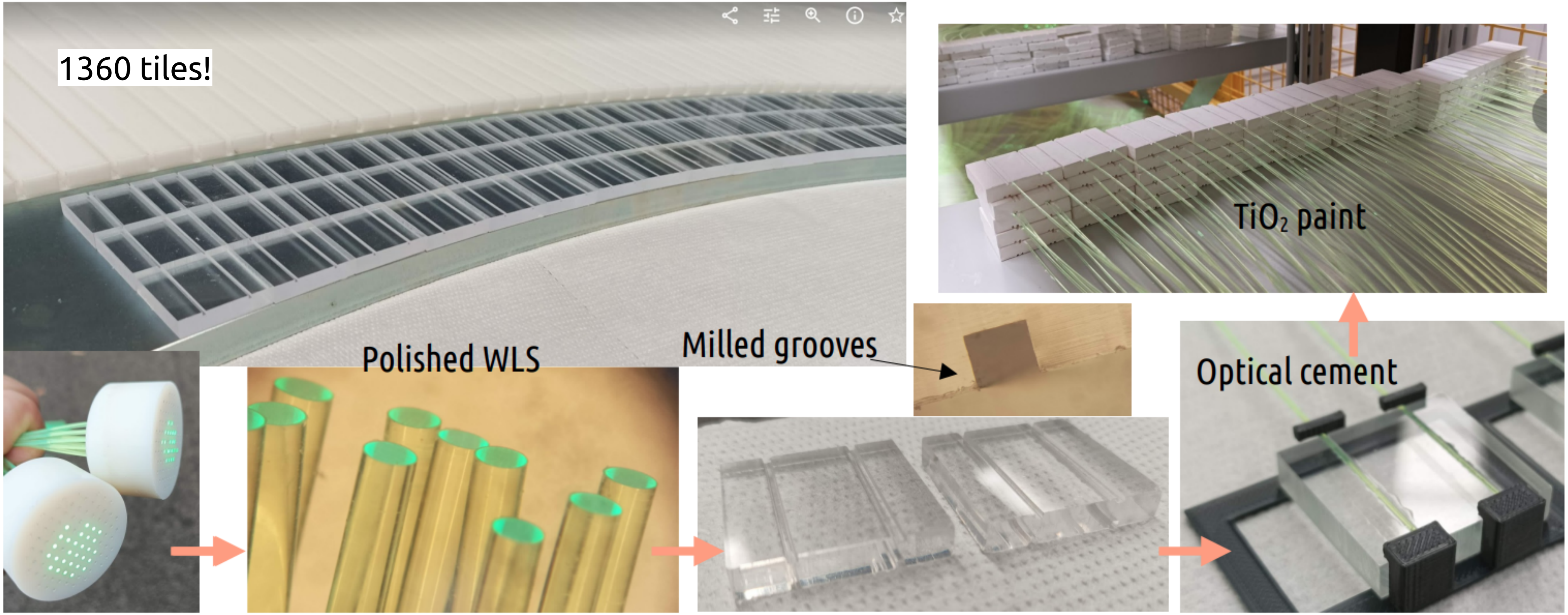
- Detector prototype tested @CERN in October 2022:
  - 1.65 m longitudinal & 90° in azimuth
  - 75 layers of: iron (1.5 mm thick) + scintillator (7 mm thick) => 12X3 LCMs (**L**ateral **C**ompact **M**odules)
- central 45° part instrumented: rest is kept for mechanical considerations
- modular design: 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 SCIONIX and milled by local Company
- ENUBINO: pre-demonstrator w/ 3 LCM tested @ CERN in November 2021 to study uniformity and efficiency

The demonstrator

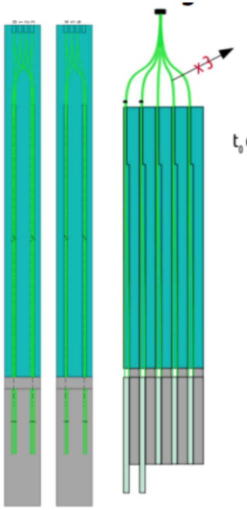


The demonstrator

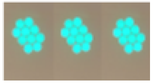
Commercial scintillator slabs + cutting/milling in Italy.
Polishing, fibre gluing, tiles painting with personnel from the collaboration @ INFN-LNL



The demonstrator



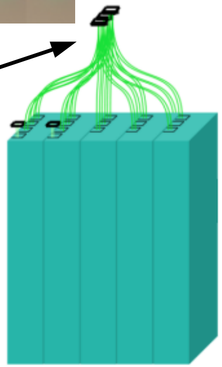
WLS routing and bundling

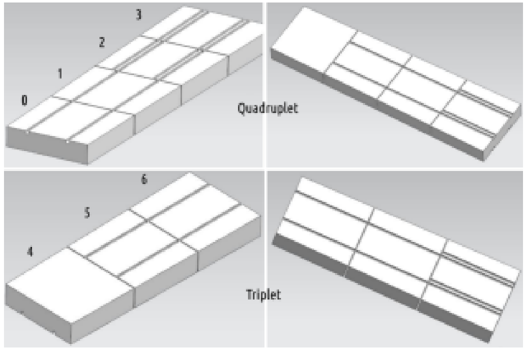


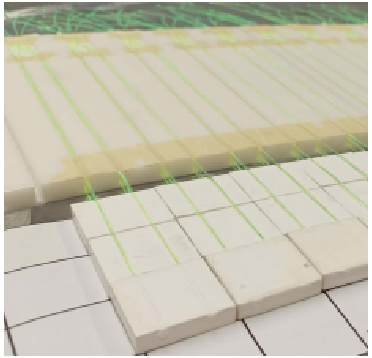
LCM (calorimeter layers)

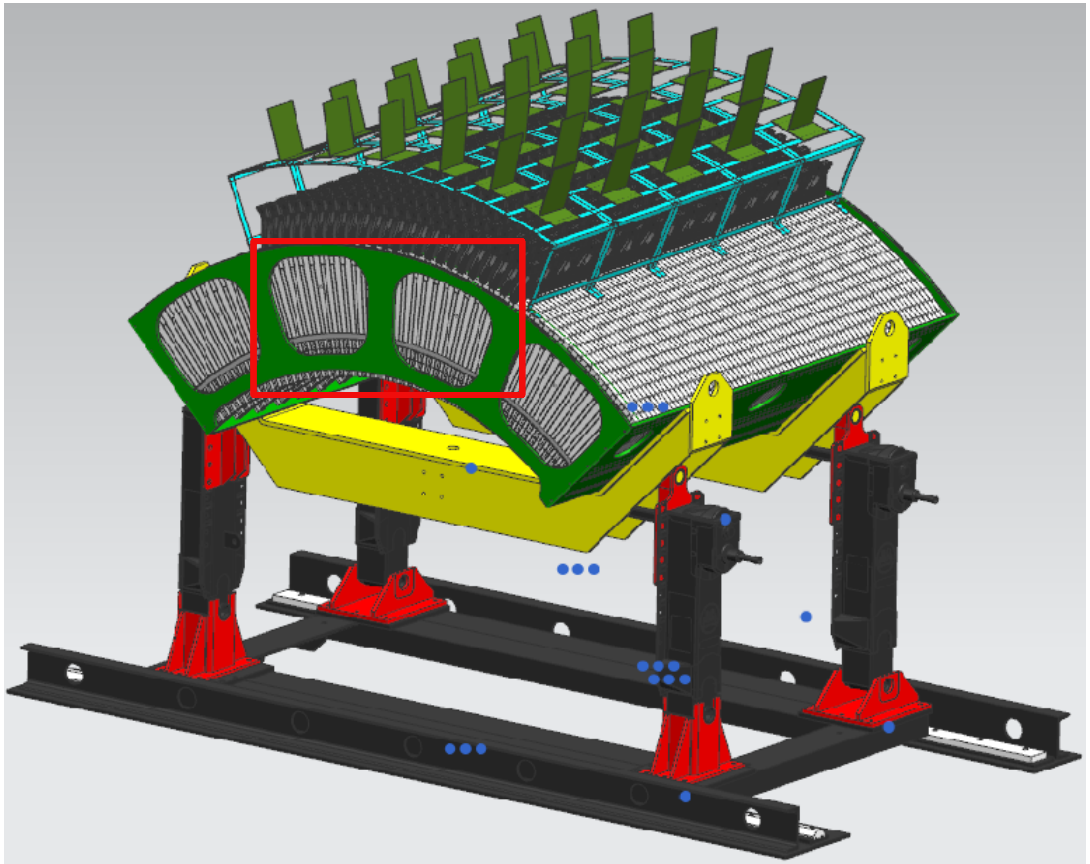
Doublets (t0-layer)

~1.5 km of WLS fibers







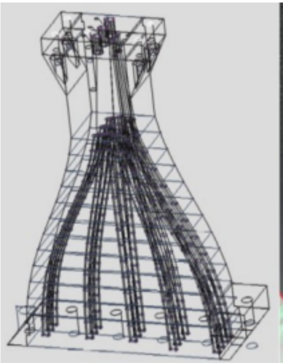


Light-collecting / passing grooves → no paint / paint

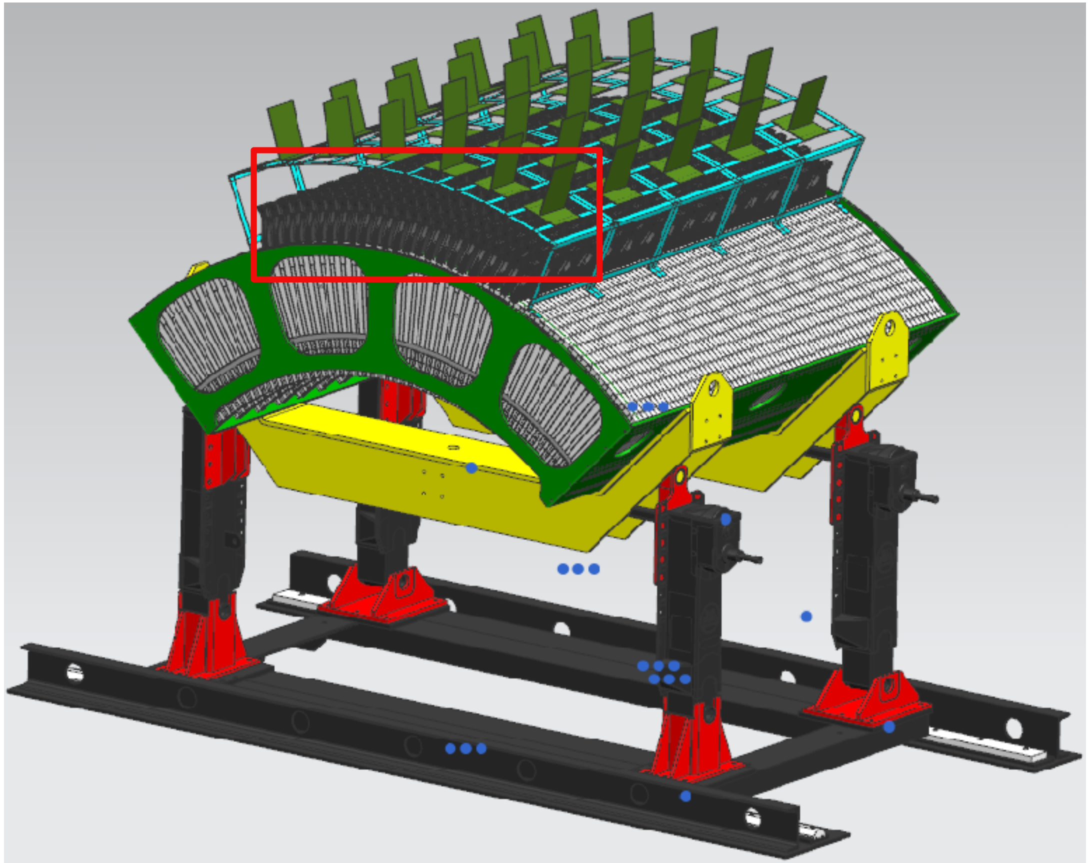
The demonstrator

WLS routing and bundling

Custom designed
3D printed
“concentrators”
(x **80**)

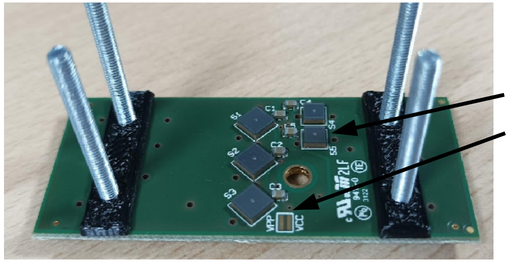


(commercial printers)



The demonstrator

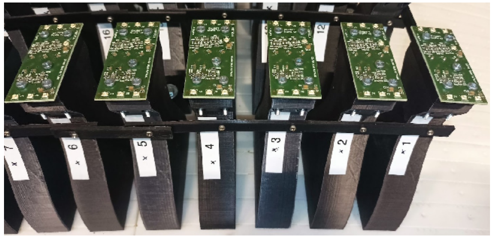
SiPM and frontend electronics

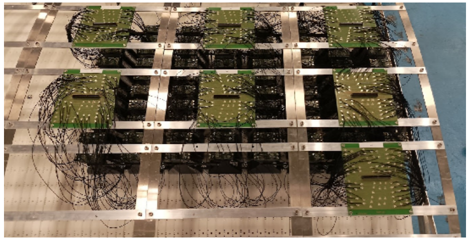


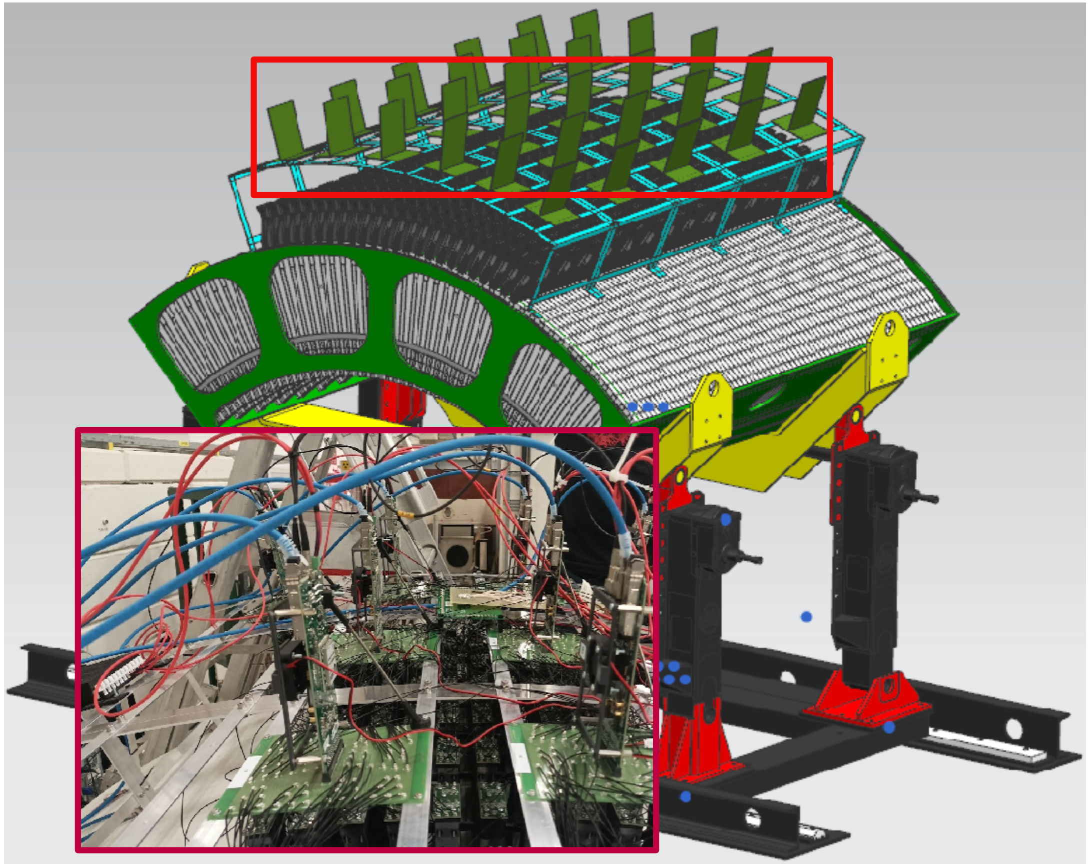
Frontend Board (FEB) equipped with:

Hamamatsu S14160 series
3050HS 3x3 mm² (t0-layer)
4050HS 4x4 mm² (calo)

Typ. no.	Number of channels (ch)	Effective photosensitive area/channel (mm²)	Pixel pitch (μm)	Number of pixels/channel	Package	Window	Window refractive index	Geometrical fill factor (%)
S14160-3050HS		3.0 × 3.0		3531				
S14160-4050HS	1	4.0 × 4.0		6331				
S14160-6050HS		6.0 × 6.0		14331				
S14161-3050HS-04	16 (4 × 4)	3.0 × 3.0	50	3531	Surface mount type	Silicone	1.57	74
S14161-3050HS-08	64 (8 × 8)	3.0 × 3.0		3531				
S14161-4050HS-06	36 (6 × 6)	4.0 × 4.0		6331				
S14161-6050HS-04	16 (4 × 4)	6.0 × 6.0		14331				

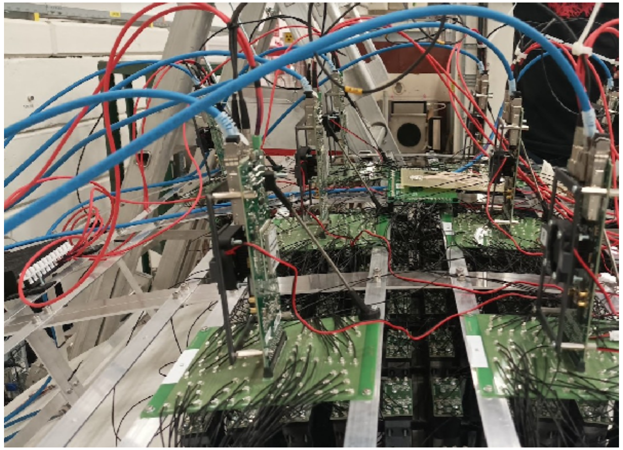


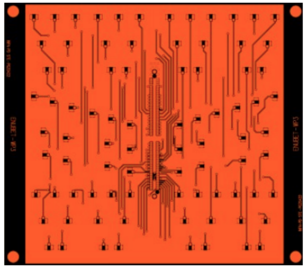




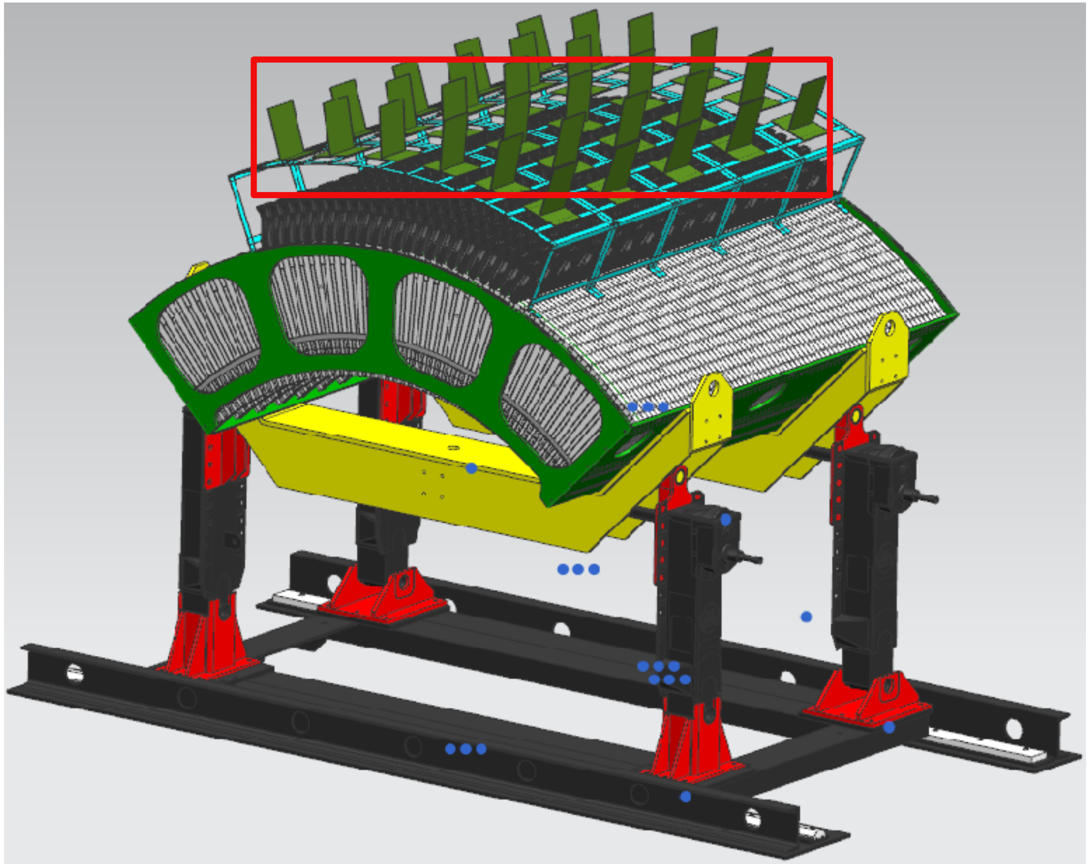
The demonstrator

SiPM and frontend electronics

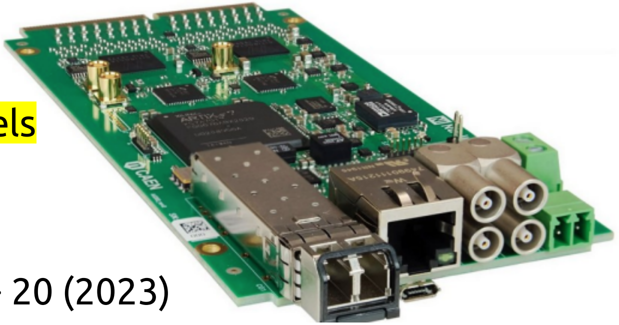




Custom interface board
to connect 5 FEB (60 ch)
to a A5252
8 boards



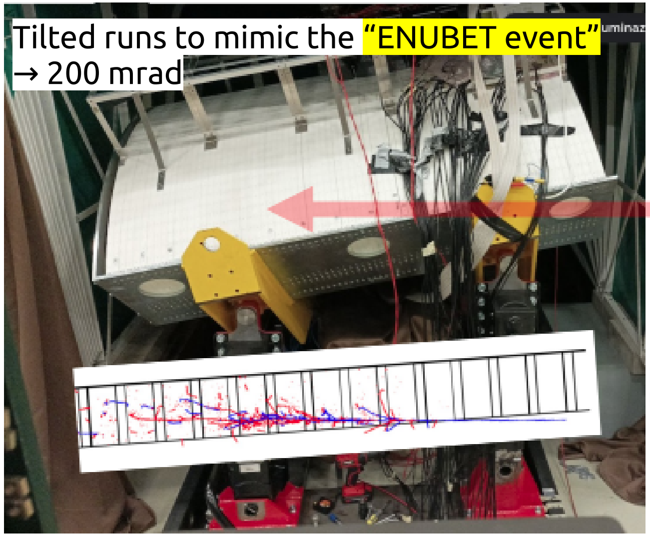
CAEN A5202
64 readout channels
2 Citiroc-1A ASICs
Peak sensing
Amplitude / ToT
8 boards (2022) → 20 (2023)

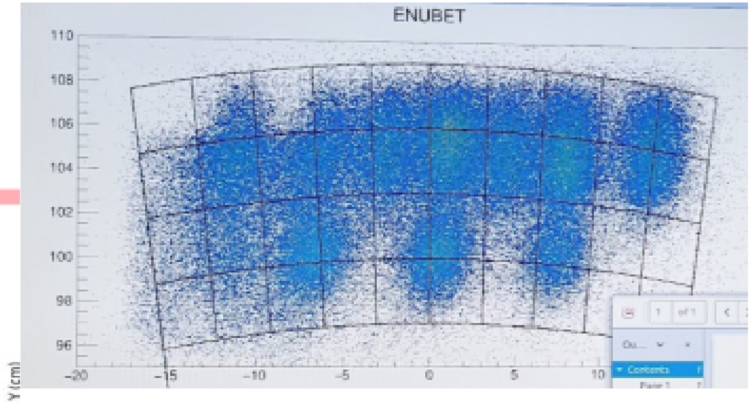


The demonstrator test @ CERN 2022

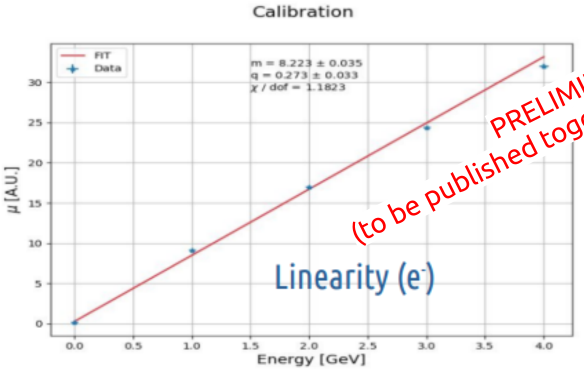
Horizontal run (calibration)

Tilted runs to mimic the "ENUBET event" → 200 mrad

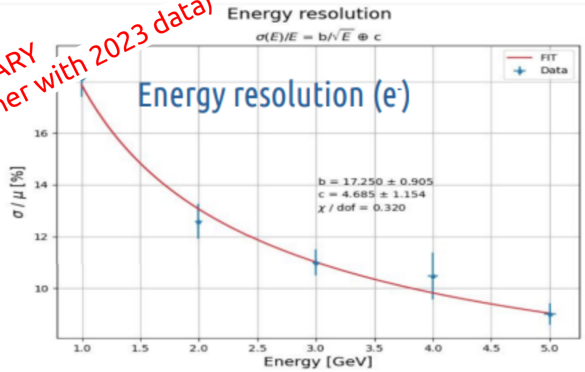




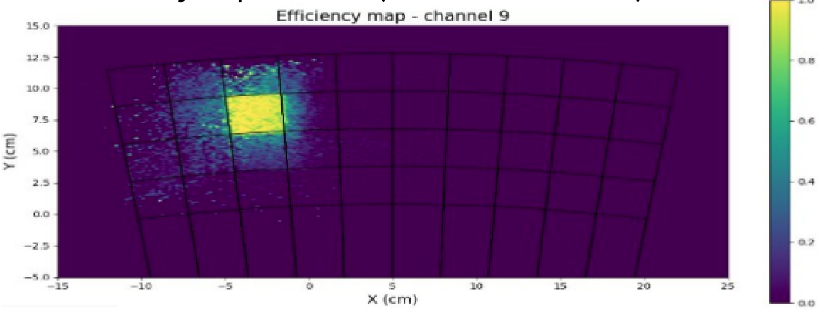
Beam spot at the detector face after several runs illuminating different region of the detector



PRELIMINARY
(to be published together with 2023 data)



Efficiency map of 1 LCM (calorimeter channel)



The demonstrator test @ CERN 2023

2022: 8 upstream z layers with 10 Φ sectors (400 ch)

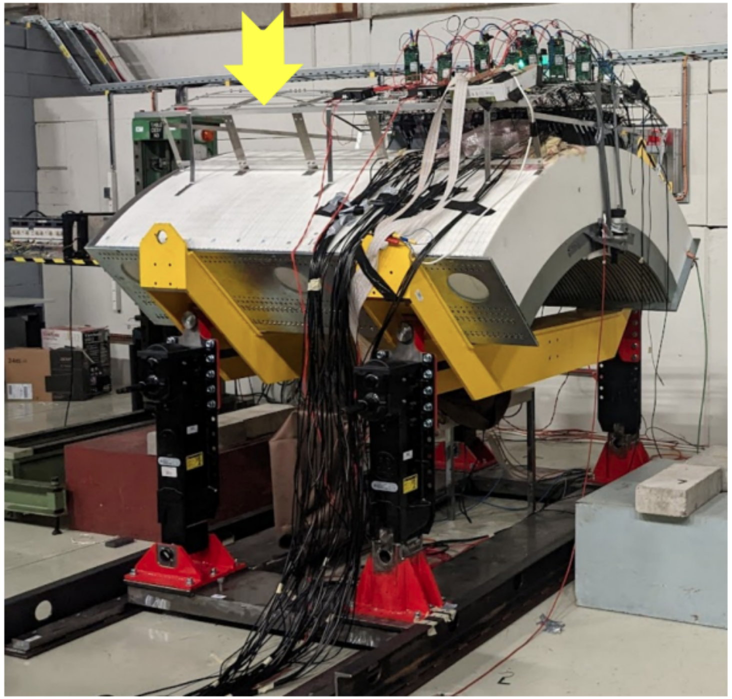
2023:
- add 7 downstream z layers with 25 Φ sectors
- from 400 to 400+875 = 1275 channels
- Larger acceptance → run in "decay region" mode i.e. with the detector off-beam to detect K decay products

Parameter	Quantity or range
Scintillator tiles (7 shapes)	1360
WLS	1.5 km
Channels (SiPM) Hamamatsu (50 μm cell)	400 240, 4×4 mm^2 - calo, 160 3×3 mm^2, t_0
Fiber concentrators (FE boards)	80
Interface boards	8
read-out boards (A5202)	8
CAEN digitizers	45 ch
horizonthal movement	$\sim$ 1 m
vertical tilt	up to $\sim$ 200 mrad

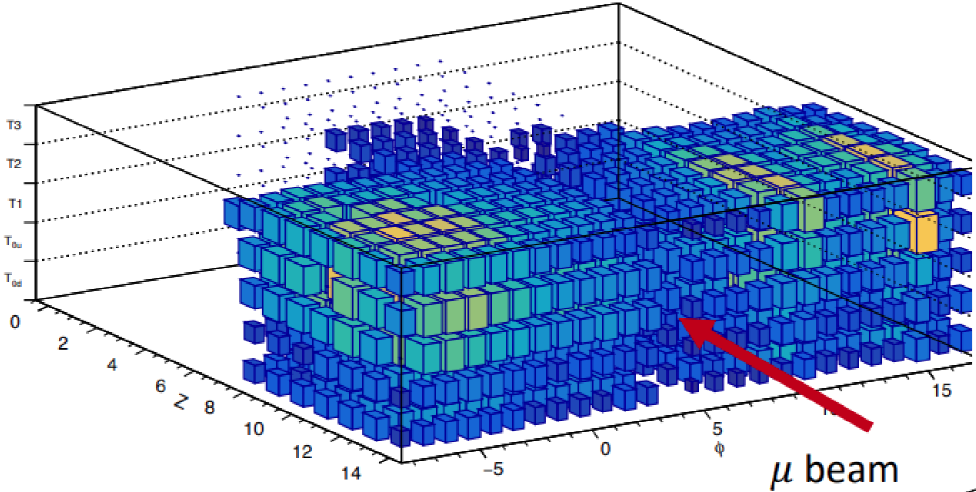
2022 demonstrator numbers

… x 3 !

2023



The demonstrator test @ CERN 2023

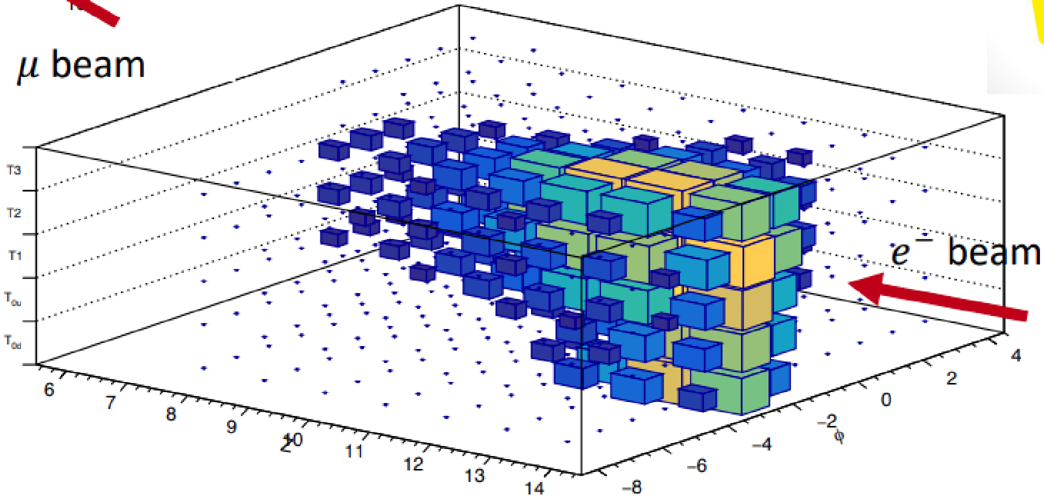


Calibration runs with 10 GeV muons

All channels have been covered by a large amount of statistics with MIPs → will allow good equalization of channels

Energy scan with electron beams at different energies for linearity and resultion studies

Example of shower profile from 5 GeV e- run



Conclusions and outlook

- Succesful 5 years R&D
- Final DEMONSTRATOR built and tested (+ test 2024?)
- Next: deliver of a Conceptual Design Report

→ Propose a short baseline neutrino experiment @ CERN exploiting the SPS and the protoDUNE detectors

→ Run tentatively after CERN LS3 (i.e. during DUNE and Hyper-K data taking

Cheapest option: dedicated beamline extracted from North Area to protoDUNE

Pro:
Maximum use of exisiting facilities
Slow extraction easily implemented

Cons:
Potential radiation issues
Interference with other experiment

Cleanest option: dedicated extraction line near the North Area toward protoDUNE

Pro:
Minor radiation issues
No interference with experiments and existing facilities

Cons:
Higher cost
Potential issues with the slow extraction

Thanks for your attention!

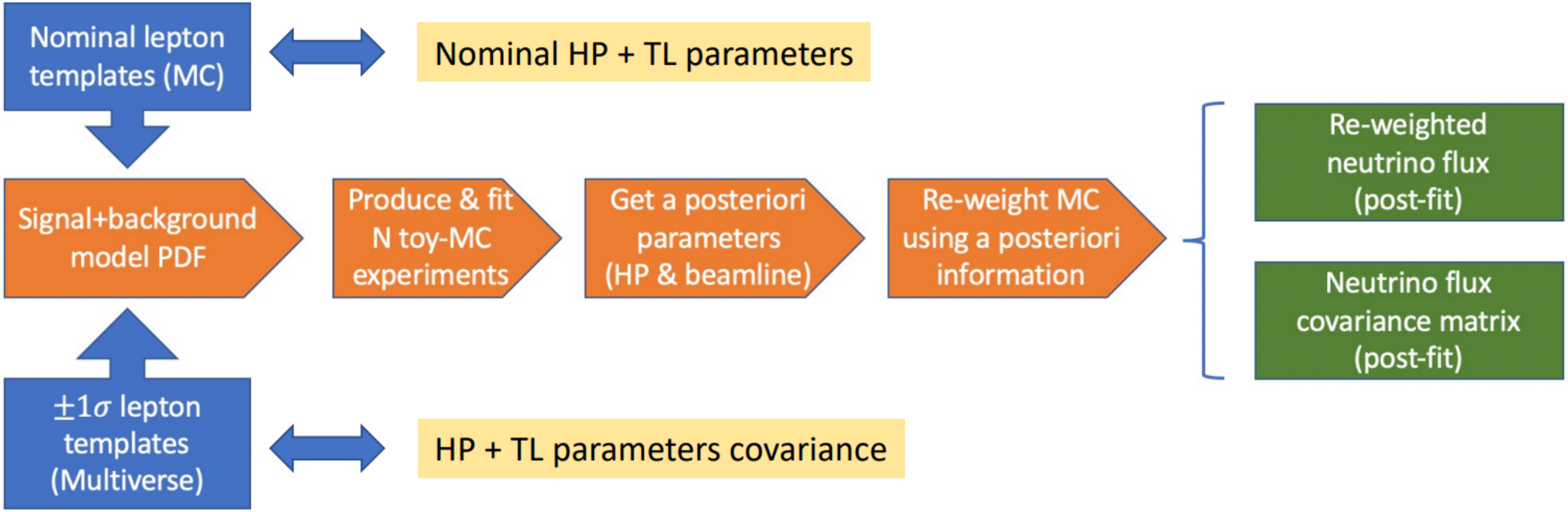
ENUBET testbeam @CERN – T9 beamline – 16-29 August 2023

Backup

ν-flux: assessment of systematics

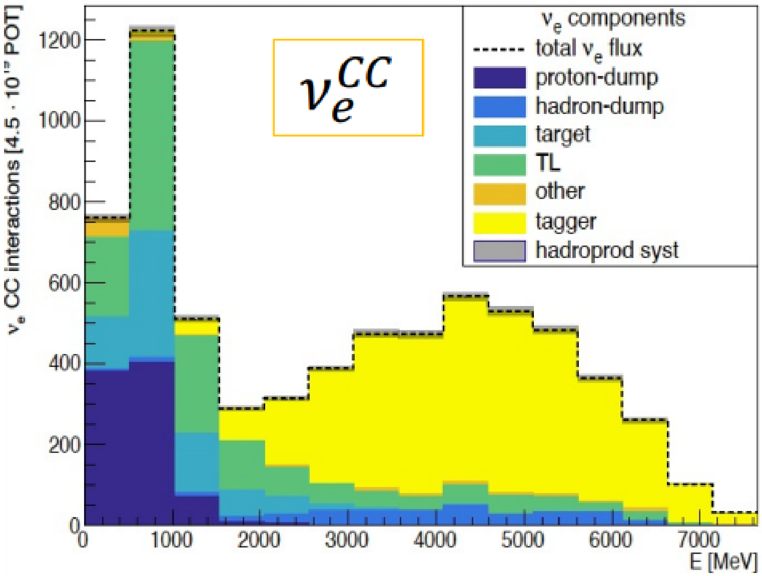
Monitored ν-flux from narrow-band beam: measure rate of leptons ⟺ monitor ν-flux

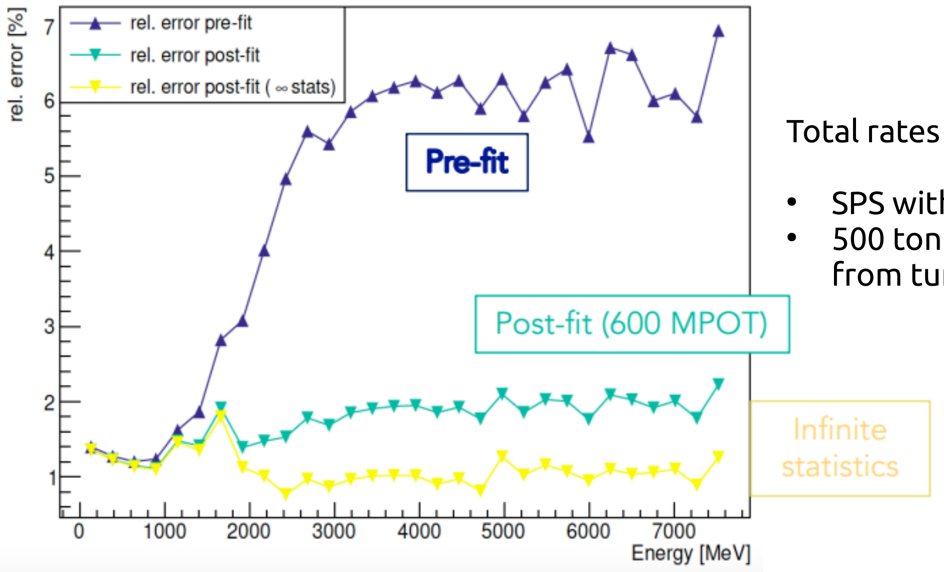
- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;



hadro-production data from NA56/SPY experiment to Reweight MC lepton templates, get their nominal distribution, compute lepton templates variations using multi-universe method

ν-flux: impact on hadro-production systematics





Total rates in 1 year:

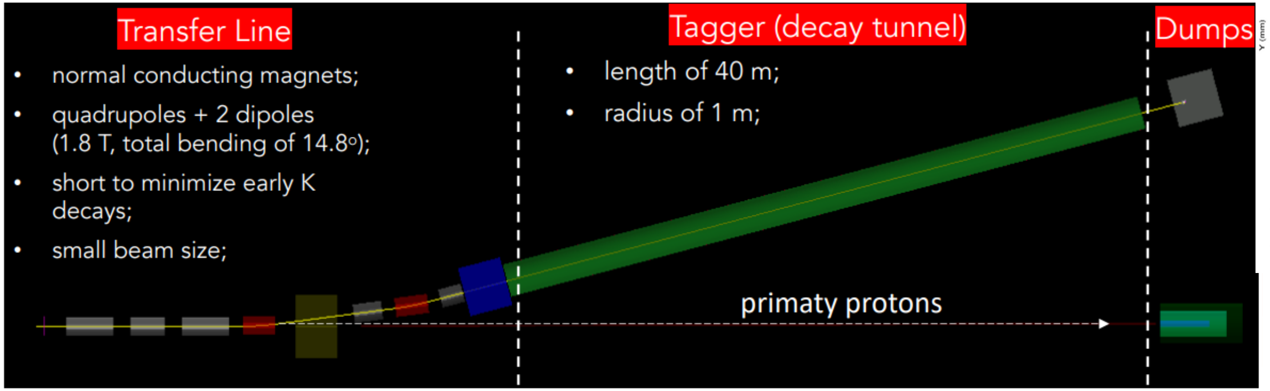
- SPS with 4.5E19 POTS/year
- 500 ton detector @50m from tunnel end

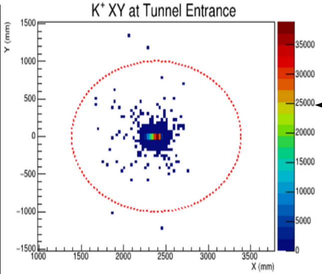
Before constraint
6% systematics due to hadro-production uncertainties

After constraint
1% from fit to lepto rates masured by tagger

Achieved ENUBET goal of 1% systematics from monitoring lepton rates

The ENUBET beamline: final design





Beam spot…

… and 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

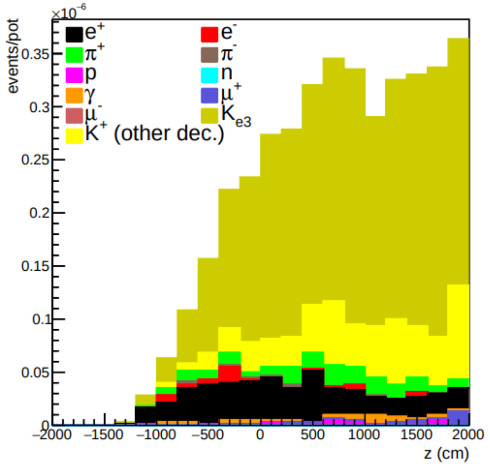
- **Dumps**
  - Proton dump: three cylindrical layers (graphite core → aluminum layer → iron layer)
  - Hadron dump: same structure of the proton dump → allows to reduce backscattering flux in tunnel

Lepton reconstruction

Full **GEANT4 simulation** of the detector:

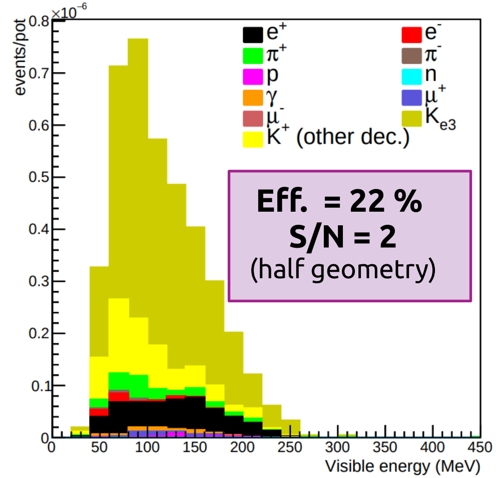
- **validated** by prototype tests at CERN in 2016-2018;
- hit-level detector response;
- pile-up effects included (waveform treatment in progress);
- event building and PID algorithms (2016-2020)

Reconstructed events



→ Large angle e+ and mu from kaon decays reconstructed searching for patterns in energy depositions in tagger

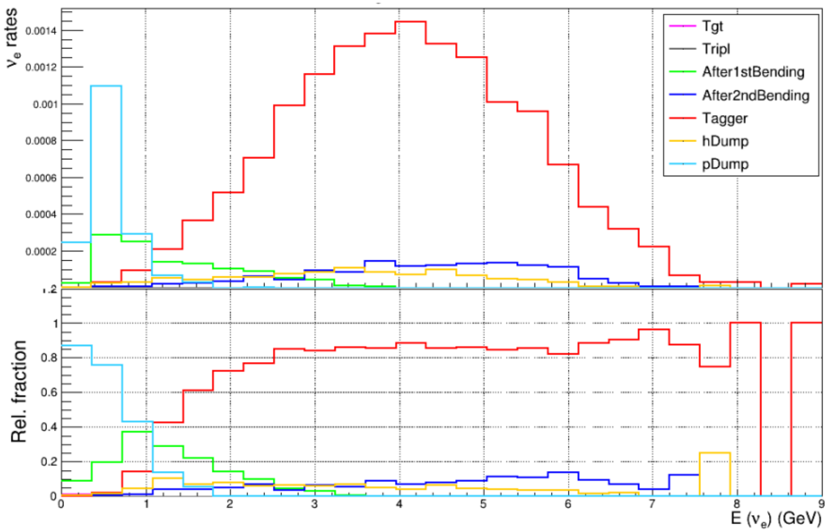
→ Signal identification done using a Neural Network trained on a set of discriminating variables

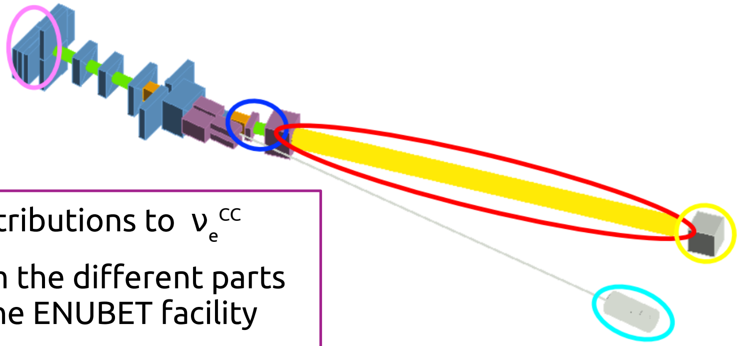


K_{e3} (BR ~5%) and K make ~5 – 10% of the beam composition

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

ν_e CC energy distribution @ detector





Contributions to ν_e^{CC} from the different parts of the ENUBET facility

A total ν_e^{CC} statistics of 10^4 events in ~3 years

- @ SPS with 4.5E19 POT/year
- 500 tons detector @ 50 m from tunnel end

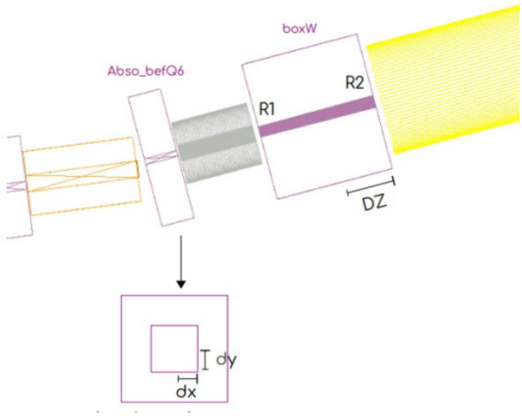
Taggable component (> 1 GeV)

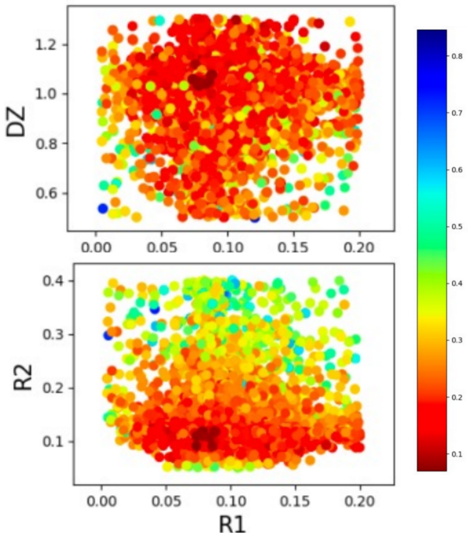
About 80% of total ν_e is produced by decays in the tunnel

Non taggable components

- 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

Beamline optimization studies





FOM dependence on optimization parameters

FOM = signal/background

Signal: π/*K* @ tagger entrance

Background: e+ and π hitting the tunnel walls

Rates @ tunnel entrance for 400 GeV POT	π^+ [10^{-3}]/POT	K^+ [10^{-3}]/POT
Design	4.13	0.34
Optimized	5.27	0.44

preliminary

Background hitting tunnel walls	e^+ [10^{-3}]/K^+	π^+ [10^{-3}]/K^+
Design	7	59
Optimized	2	35

preliminary

Optimization campaign is progress:

- **Goal**: further improvement of the π/*K* flux at tunnel entrance while keeping background level low;
- **Strategy**: scan parameters space of beamline to maximize FOM;
- **Tools**: full facility implemented in Geant4 → controll with external cards all parameters → systematic optimization with developed framework based on genetic algorithm;

preliminary

- About 28% gain in flux → 2.4 years to collect 10^4 ν_e^{CC} !
- Reduced backgrounds, but similar to signal shapes → next step: improve FOM definition (include sgn/bkg distributions)

ν_μ^{CC} energy distribution @ detector

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

E_ν = neutrino energy;

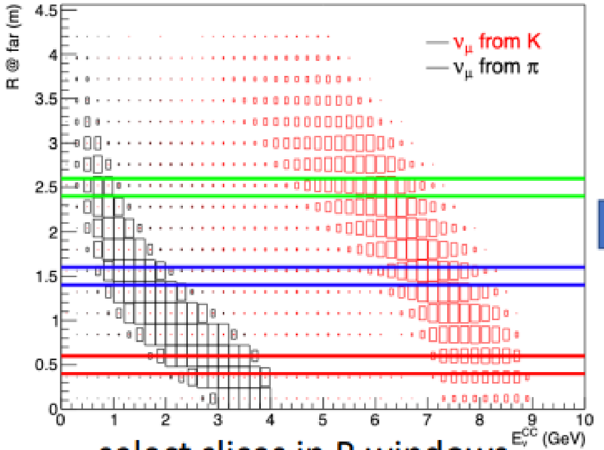
R = radial distance of interaction vertex from beam axis;

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

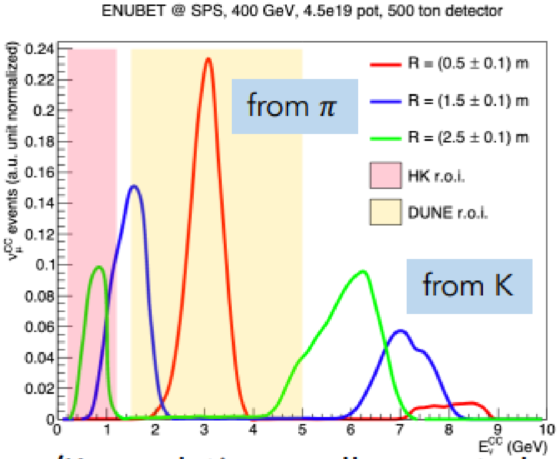
Precise determination of E_ν:

no need to rely on final state particles from ν_μ^{CC} interaction

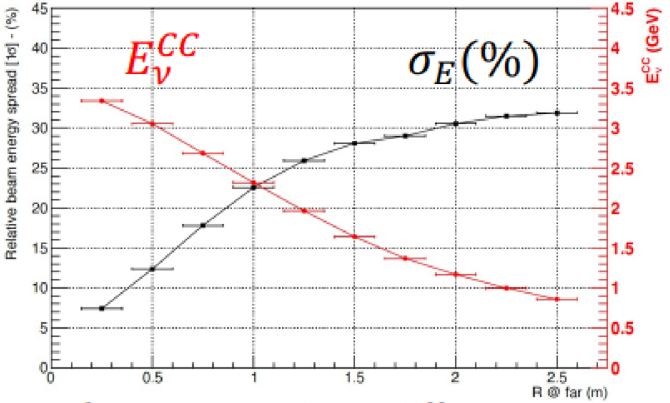
- 8-25% E_ν resolution from π in DUNE energy range;
- 30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):
  - ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



π/K populations well separated

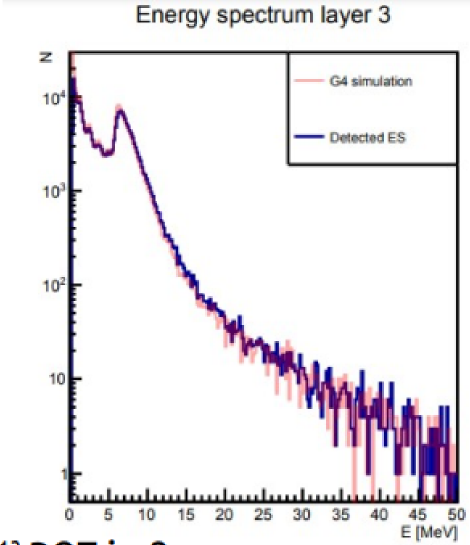


from pion peaks at different R

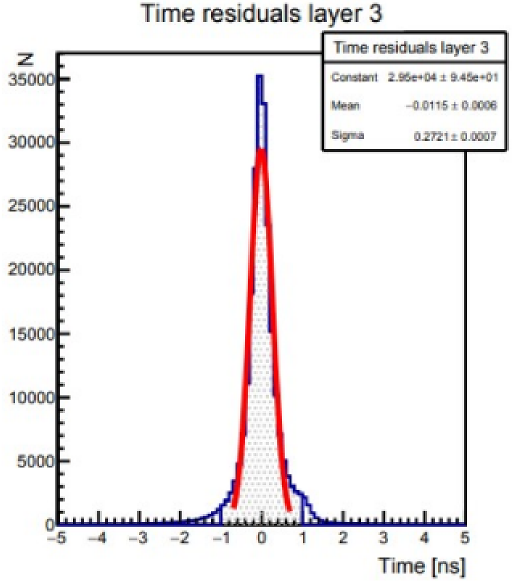
Event pile-up analysis

The energy is now reconstructed as it will happen for real data i.e. considering the **amplitudes digitally-sampled signals at 500 MS/s**. **Pile-up** effects treated rigorously by "fitting" superimposing waveforms.

Matching between true level energy deposits from GEANT4 and fully reconstructed waveforms



Matching between true and rec. time (500 MS/s). 270 ps.



With 4.5 x 10^{13} POT in 2s

- 1.1 MHz rate in the hottest channels
- Peak finding efficiency = 97.4 %

Highlights on test beam analysis

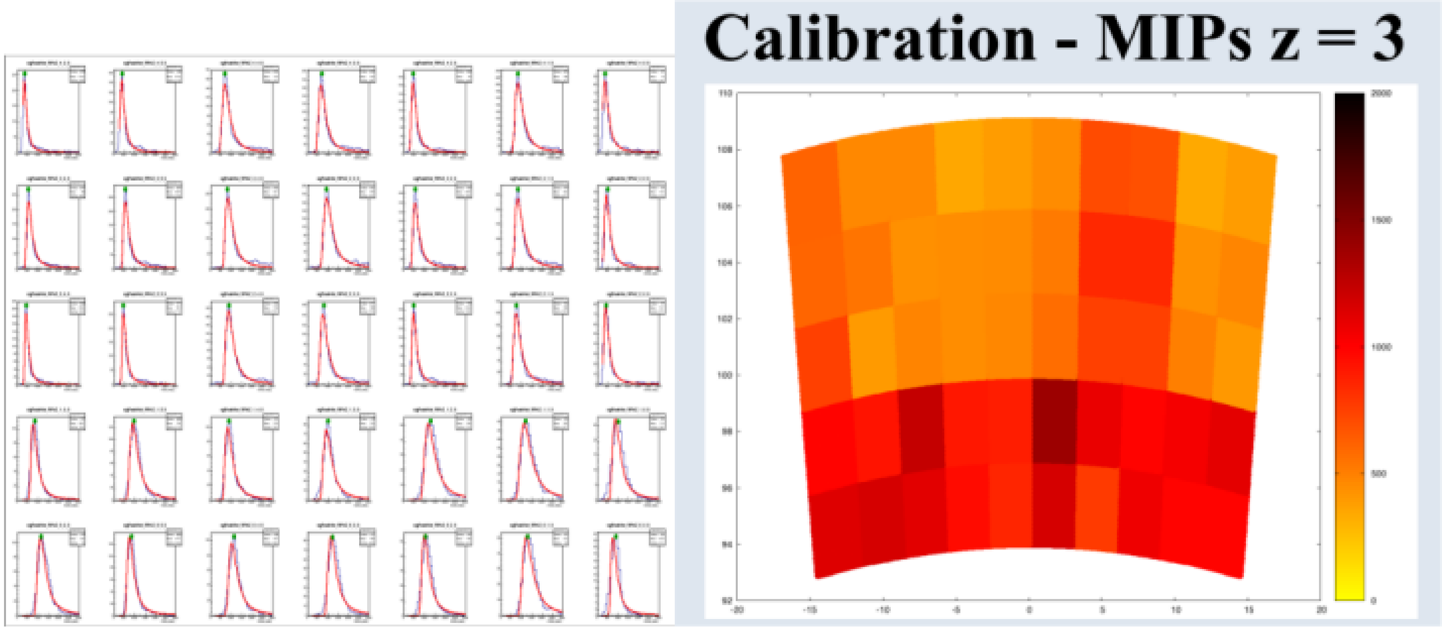
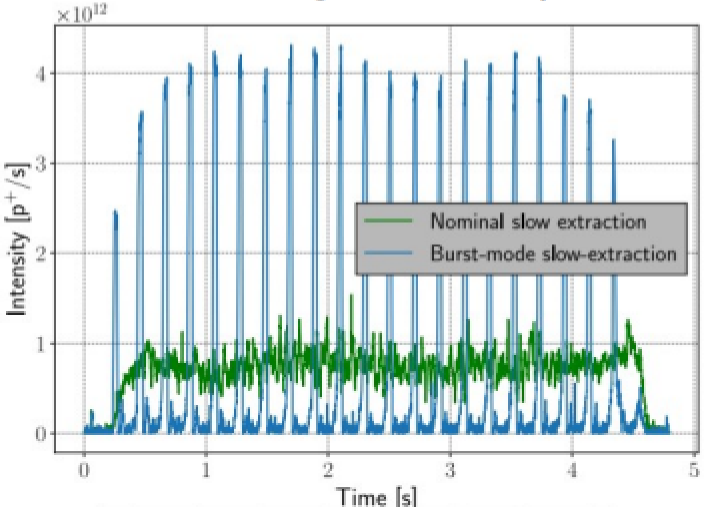


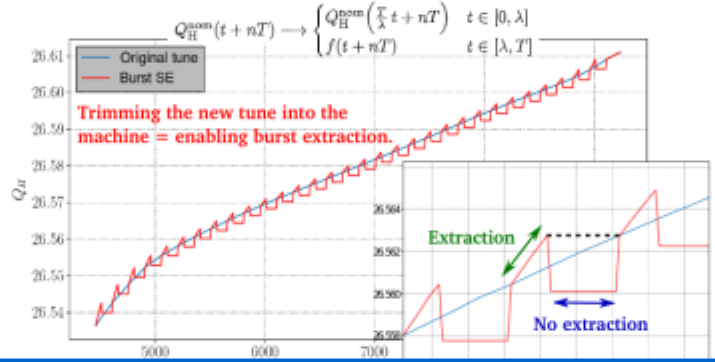
Figure 9: Calibration with m.i.p.s. Left: spectra of signals used to derive relative inter-calibration constants between different detector channels in the same z layer. Each column shows the spectra of calorimeter and t_0 channels in the same ϕ sector, while each row shows a calorimeter radial layer; the bottom rows refer to the two t_0 channels of each ϕ module. Landau fits are superimposed (red). Right: example of normalization constants derived from the mip calibration for z layer 3.

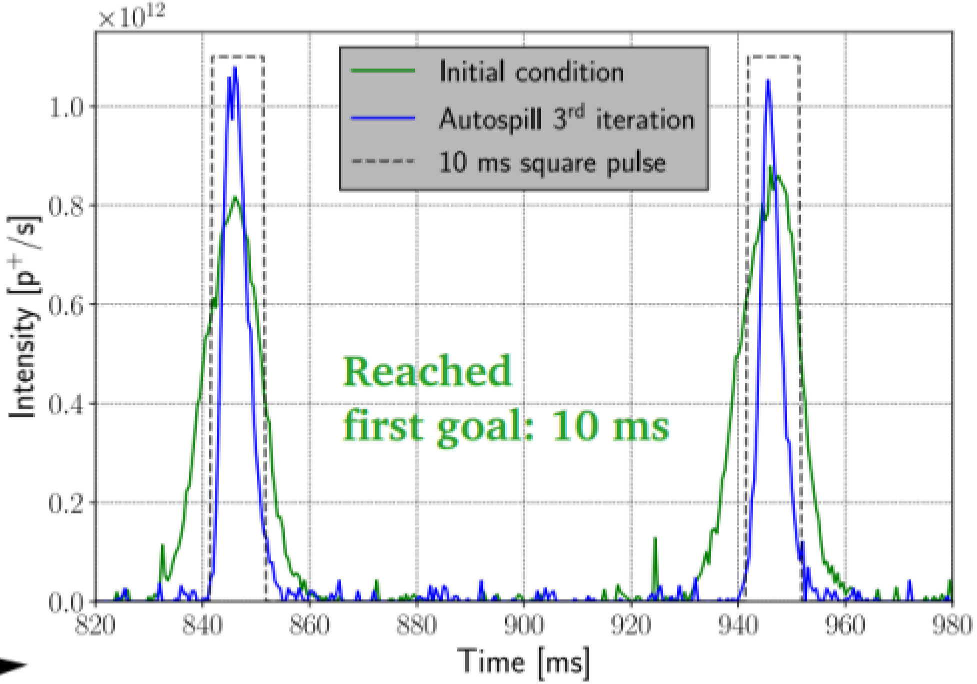
Proton extraction R&D for horn focusing

CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

before LS2: burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa

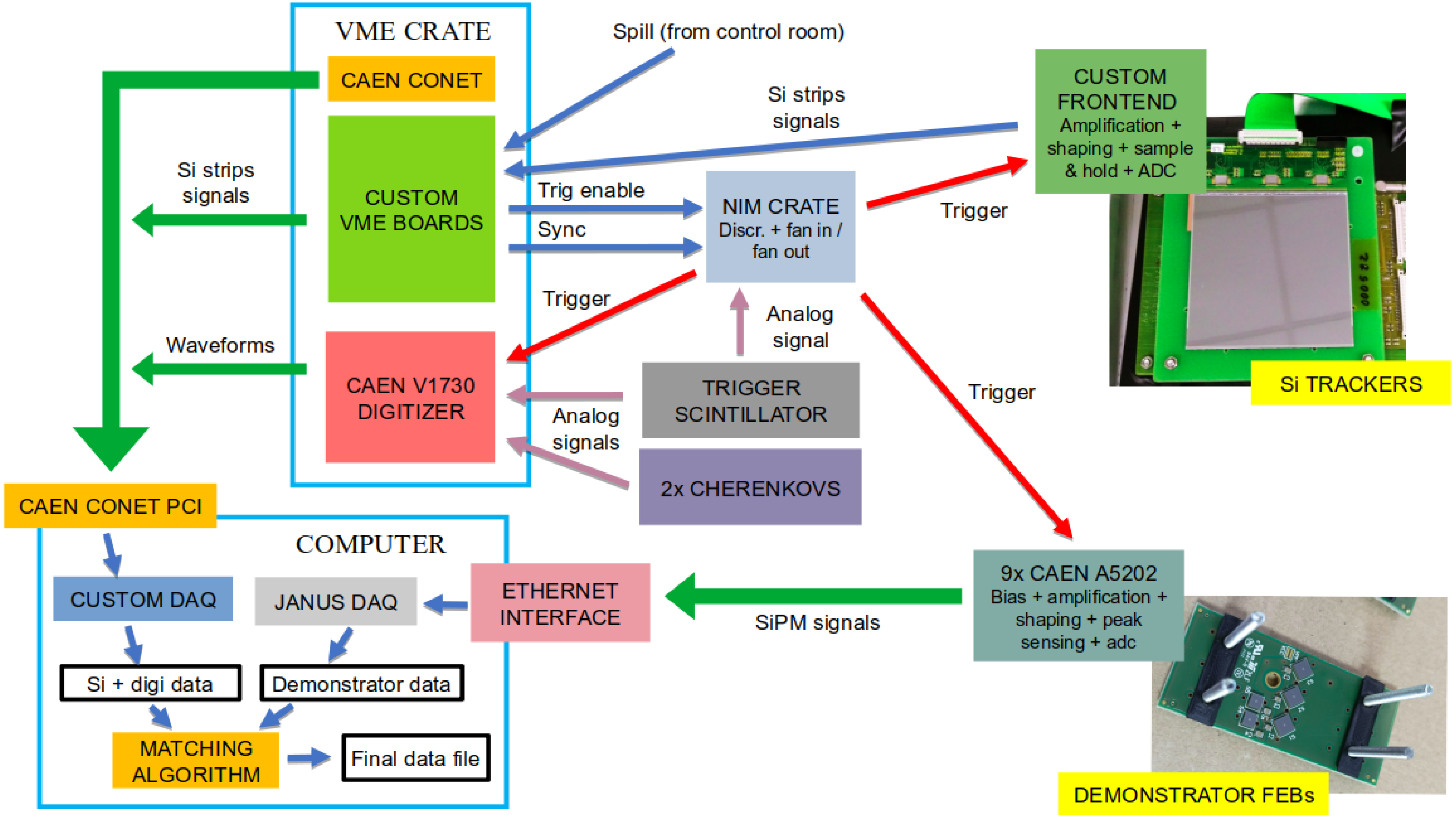






PhD thesis of M. Pari (UniPD + CERN doctoral). Defended 23/2/21.

DAQ



VME CRATE
CAEN CONET
CUSTOM VME BOARDS
CAEN V1730 DIGITIZER
Spill (from control room)
Si strips signals
Si strips signals
Waveforms
Trig enable
Sync
Trigger
NIM CRATE Discr. + fan in / fan out
Trigger
Trigger
CUSTOM FRONTEND Amplification + shaping + sample & hold + ADC
Si TRACKERS
Analog signal
Analog signals
TRIGGER SCINTILLATOR
2x CHERENKOVS
CAEN CONET PCI
COMPUTER
CUSTOM DAQ
JANUS DAQ
ETHERNET INTERFACE
Si + digi data
Demonstrator data
MATCHING ALGORITHM
Final data file
SiPM signals
9x CAEN A5202 Bias + amplification + shaping + peak sensing + adc
DEMONSTRATOR FEBs