Status and plans of NP06/ENUBET

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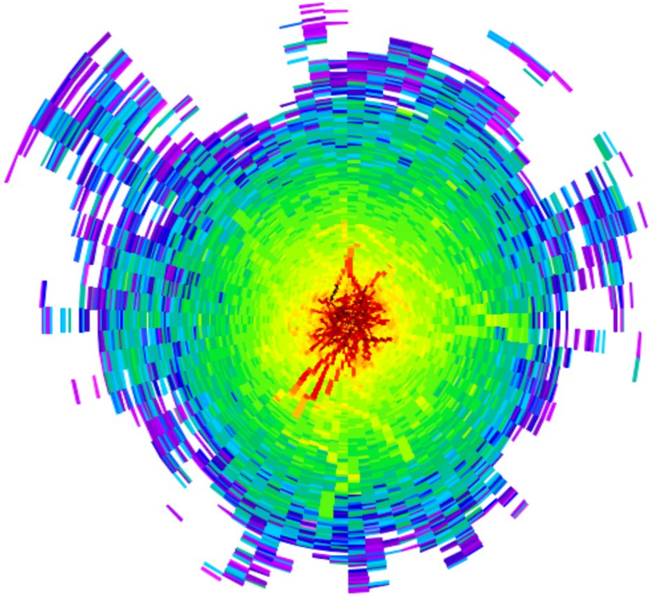
A. Longhin
Padova Univ. and INFN

On behalf of the ENUBET coll.

149th meeting of the CERN-SPSC
10 May 2023



The 2023 SPSC report

https://cds.cern.ch/record/2856999/files/SPSC-SR-327.pdf

Last year has been a key moment for ENUBET:
the ERC project deadline (Nov. 2022) brought substantial achievements:

- The finalization of the **optimization and design of the beamline**
- The analysis on **systematic errors** on the flux reached a level of maturity
- The construction of the **demonstrator** of the instrumented decay region was accomplished and test occurred at the CERN-PS in October 2022
- We are in the process of completing the documentation/paper writing
- Synergies with other projects

NP06/ENUBET annual report 2023 for the SPSC

The ENUBET Collaboration

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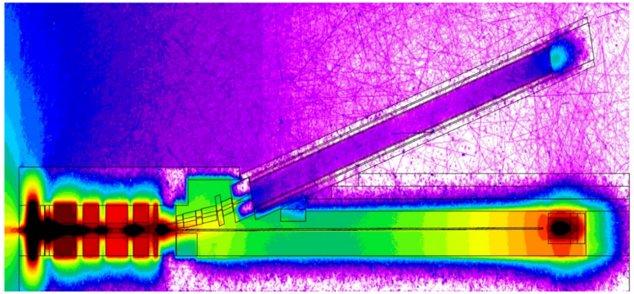
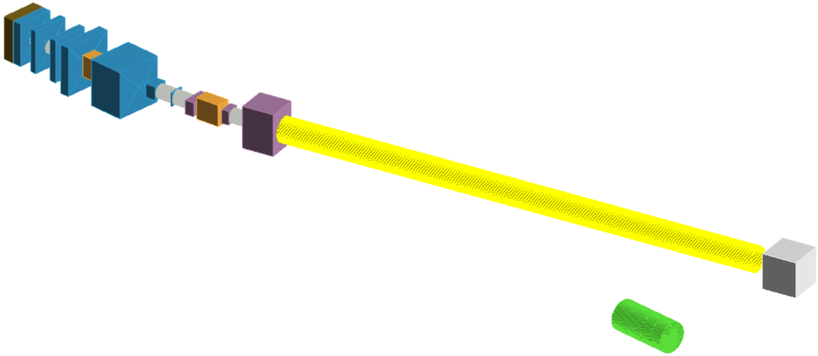
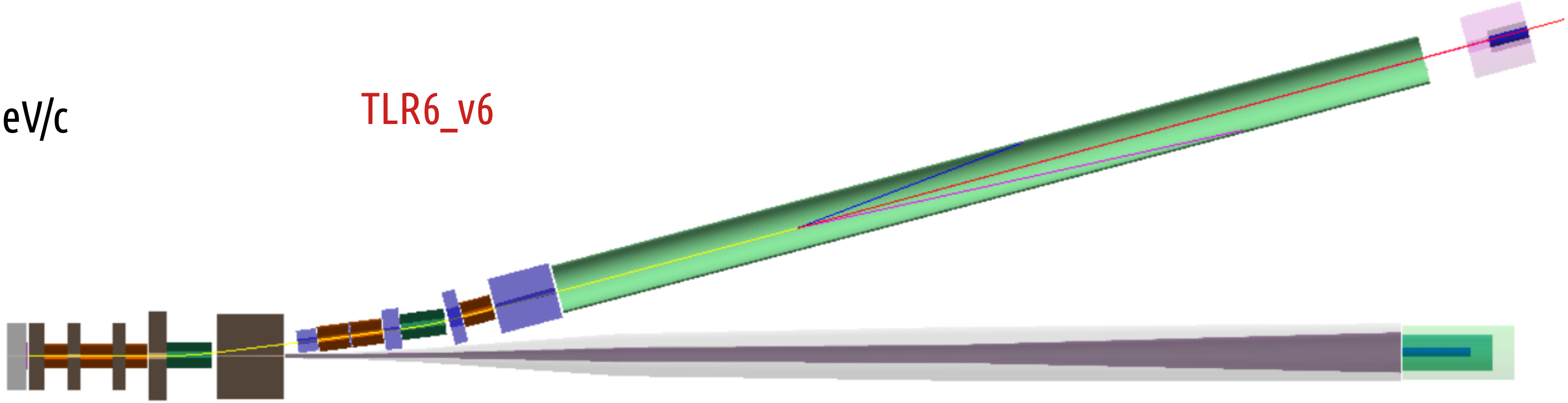




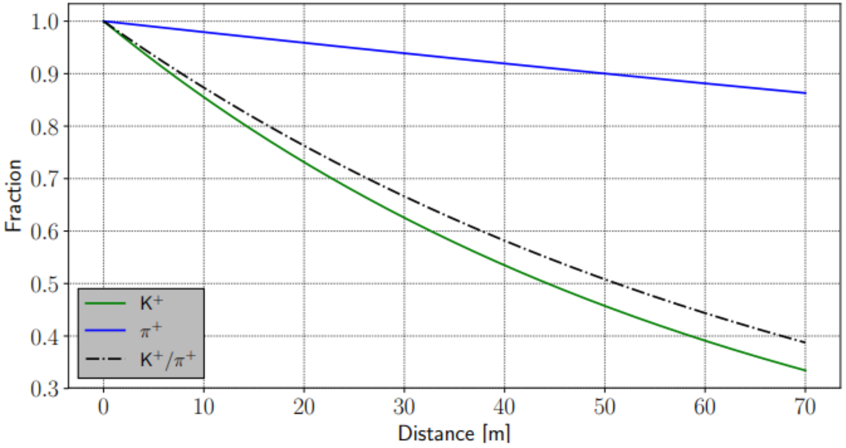
The ENUBET hadron beamline

- Focuses 8.5 ± 5% GeV/c

TLR6_v6



A short beamline



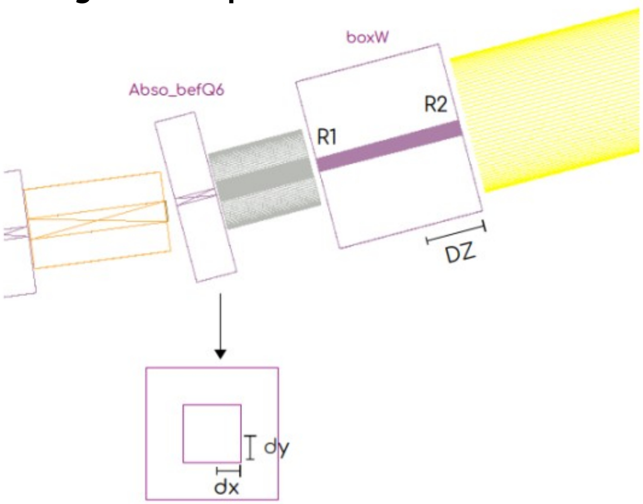
- Employing standard/existing warm magnets
- The optimization based on the genetic algorithm finalized.
- TLR6 v6: an evolution of the 2022 version.
- Comparison with other simulation programs (G4beamline).
- Tuning of single parts (W foil, hadron dump).
- We consider it our baseline →

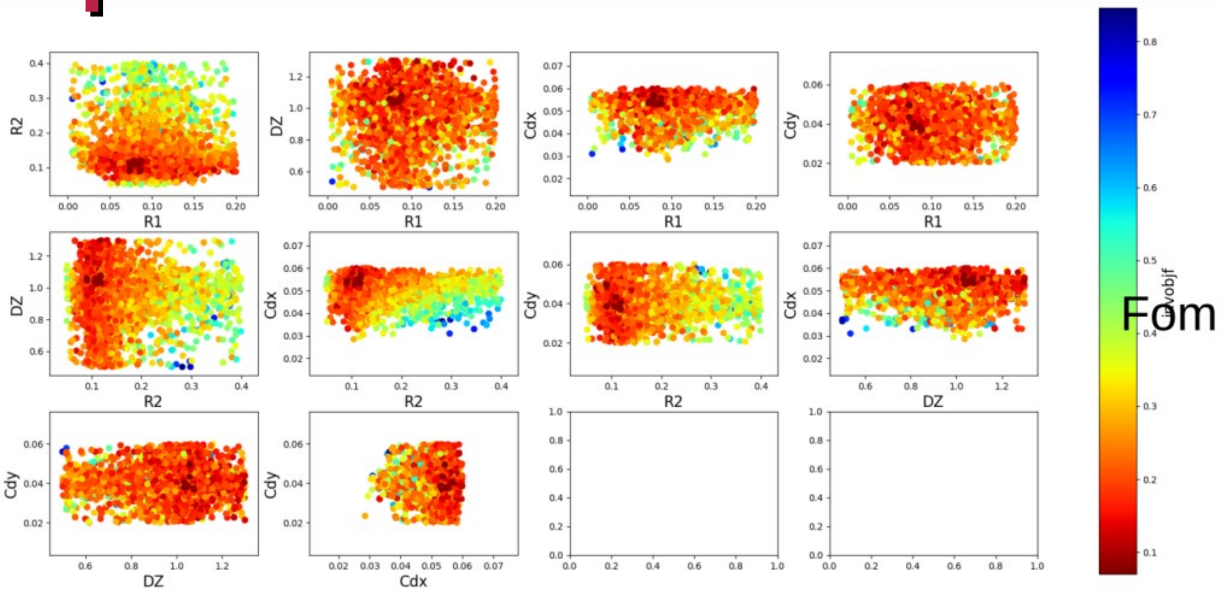
Design and performance of the ENUBET monitored neutrino beam*

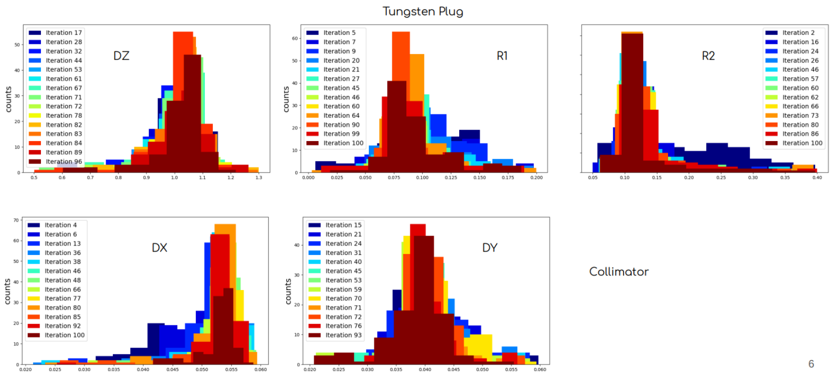
Publication almost ready for submission

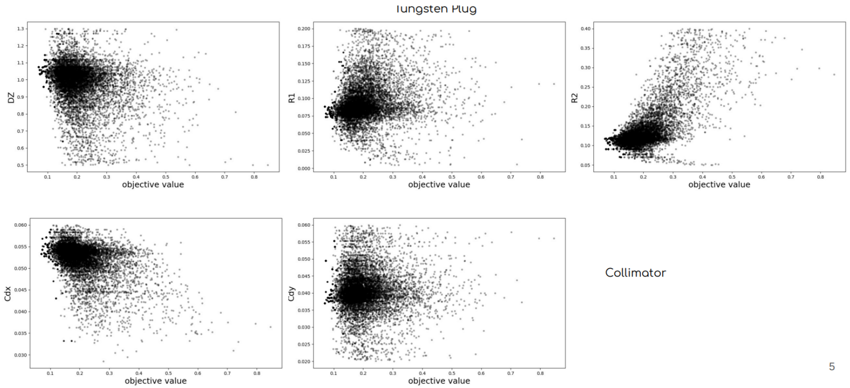
Genetic beamline optimizer with Geant4

Diagnostics plots





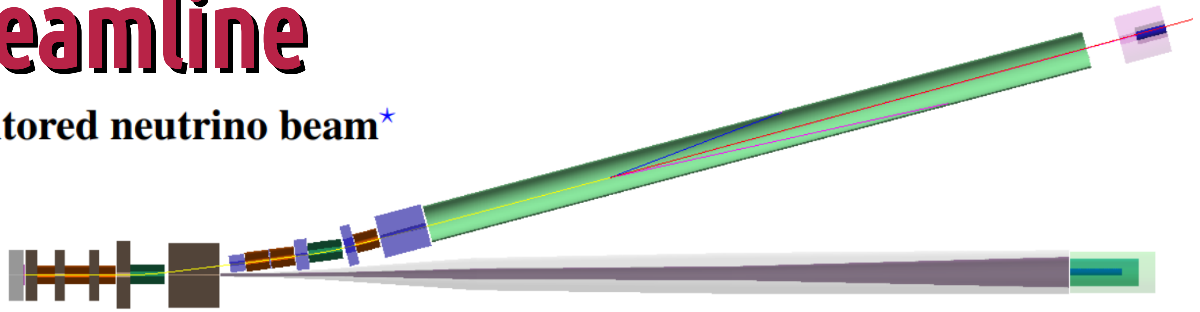




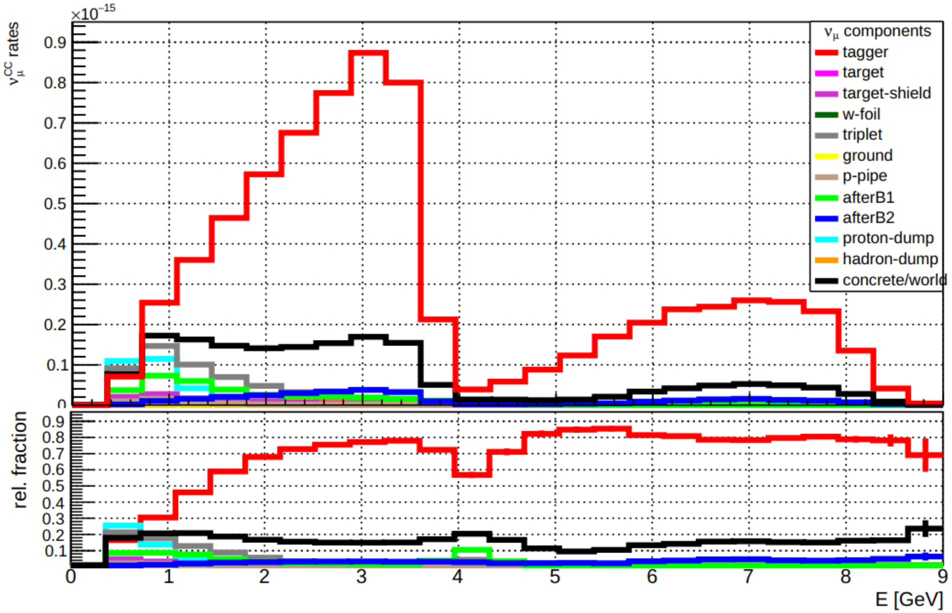
The ENUBET hadron beamline

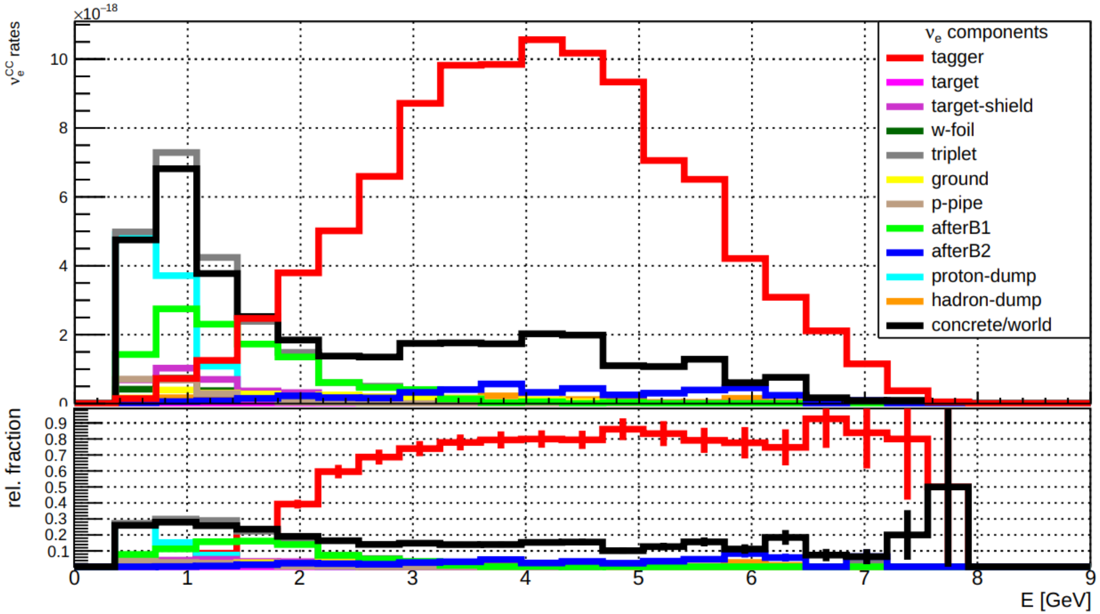
Design and performance of the ENUBET monitored neutrino beam*

- Focuses 8.5 ± 5% GeV/c

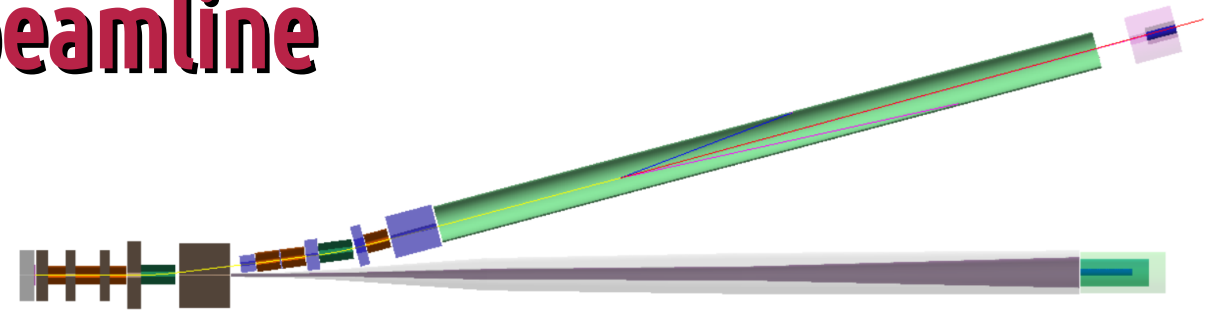


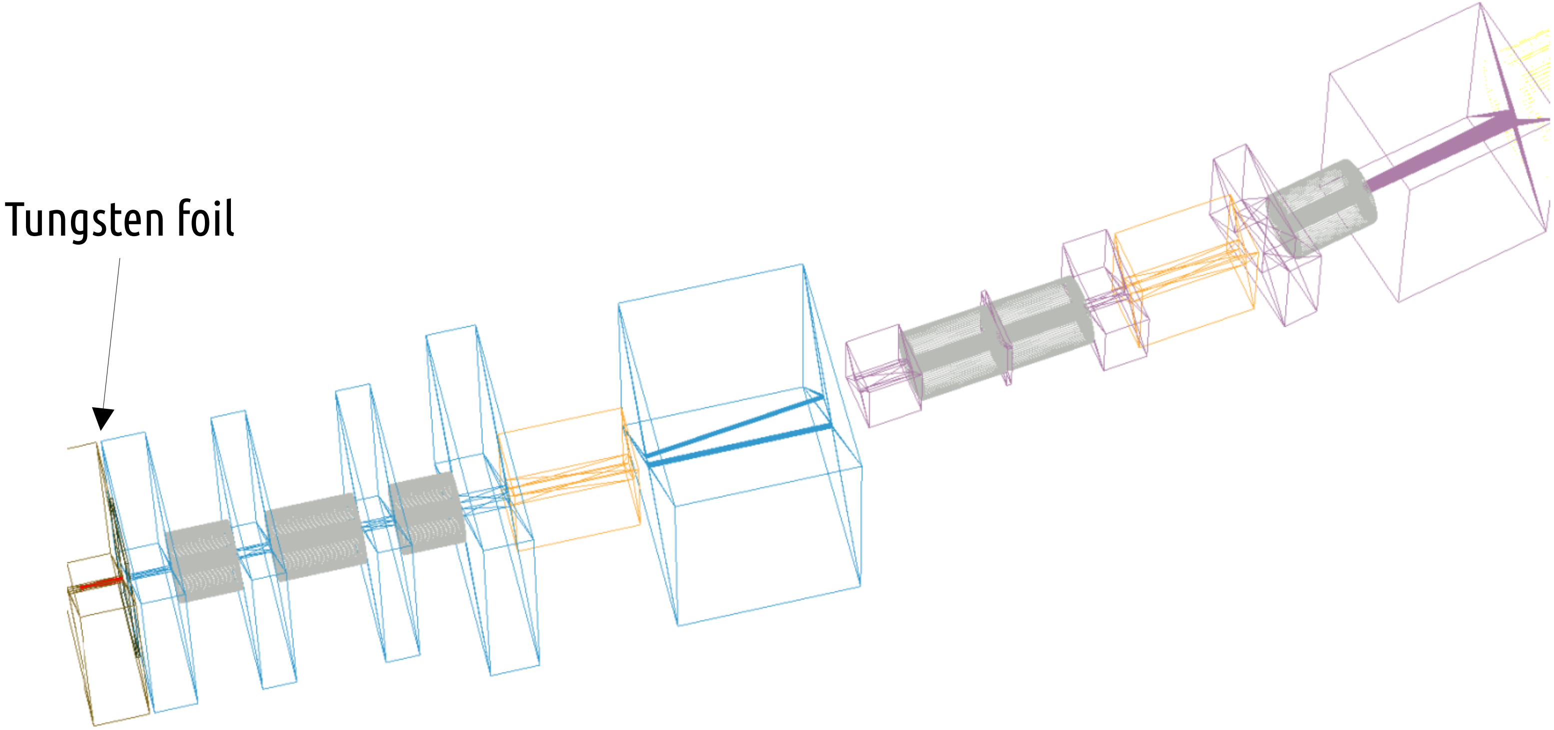
4.5×10^{19} POT/year on 500 t @ 100m from target: 10^4 ν_e^{CC} in 2.3 years, 10^5 ν_μ^{CC} in 1.1 years





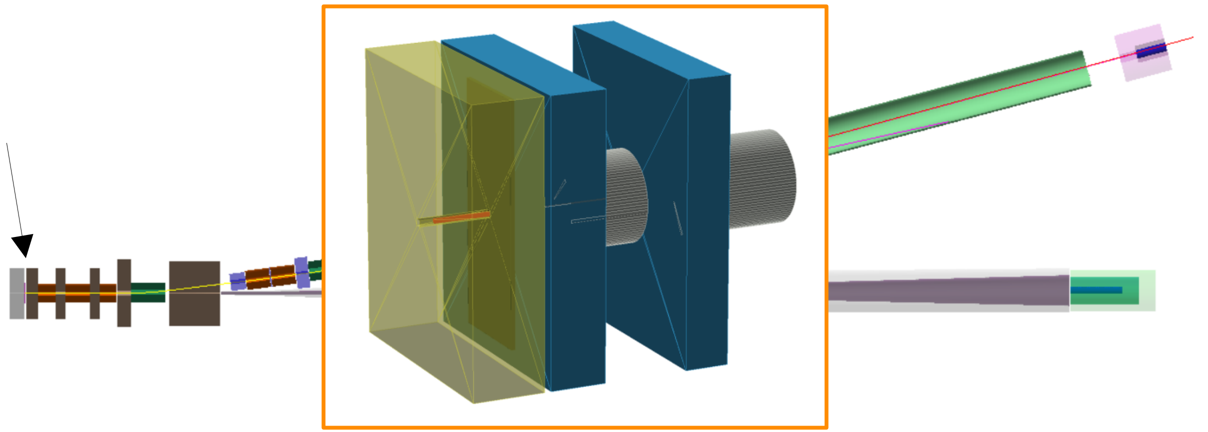
The ENUBET hadron beamline

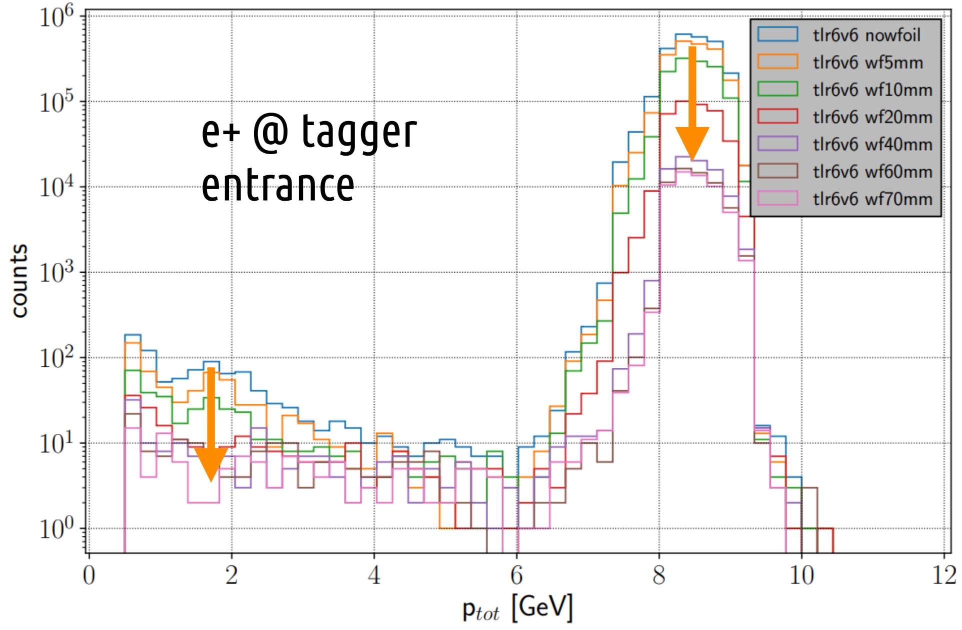


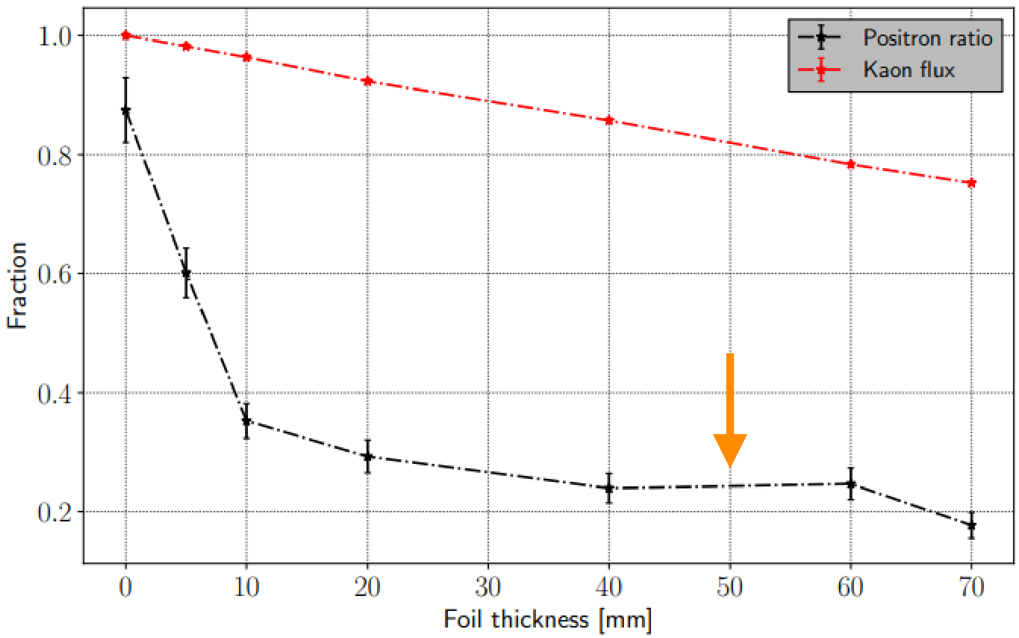


W foil optimization

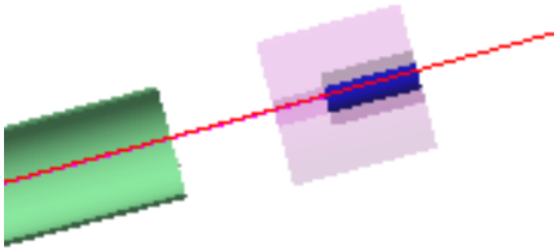
- We have optimized the thickness of the tungsten foil to suppress effectively the electron/positron background without losing too many Kaons

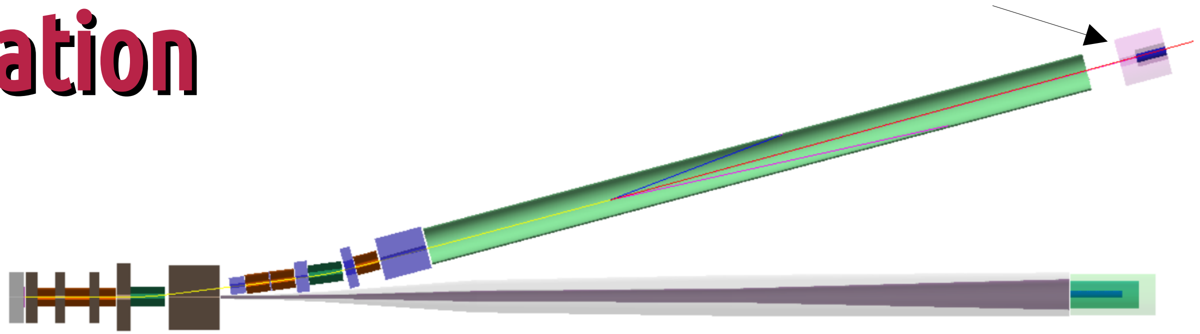




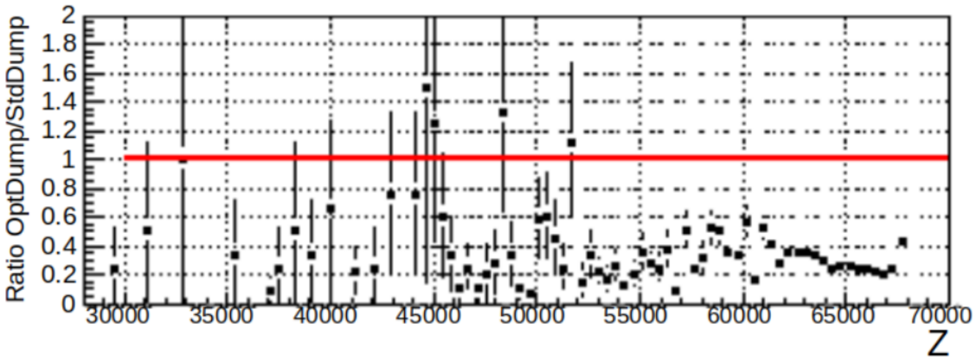


Hadron dump optimization





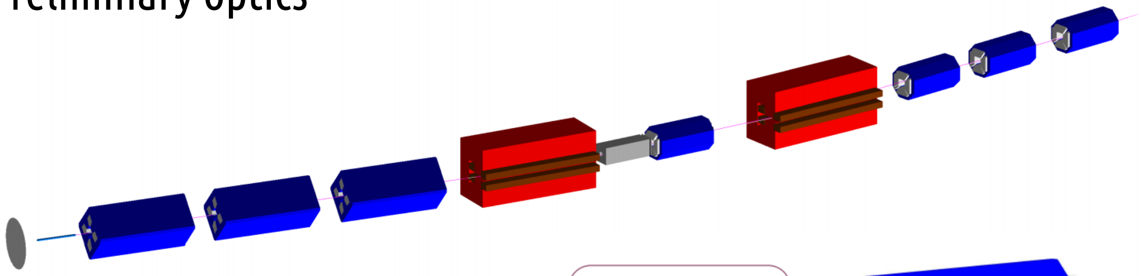
- Proton dump was already optimized→ hadron dump
- graphite core cylinder (50 cm Ø)
  - inside iron (1 m Ø)
    - inside borated concrete (4 m Ø).
- 1 m thick borated concrete in front
  - leaving an opening for the beam
- Factor 5 reduction in neutrons back-scattered on the tagger

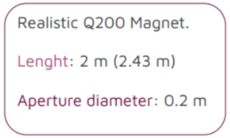


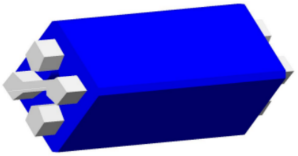
Alternative transferline (MMB)

- A parallel study ongoing for the hadron beamline to **add flexibility** and allow a set of **different neutrino spectra** spanning from the **"Hyper-K" to DUNE** regions of interest. Focus **8.5**, **6** or **4** GeV/c secondaries by changing the magnetic fields only.

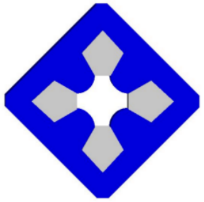
Preliminary optics

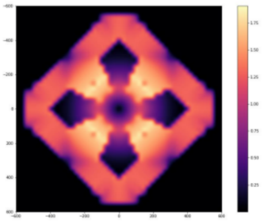




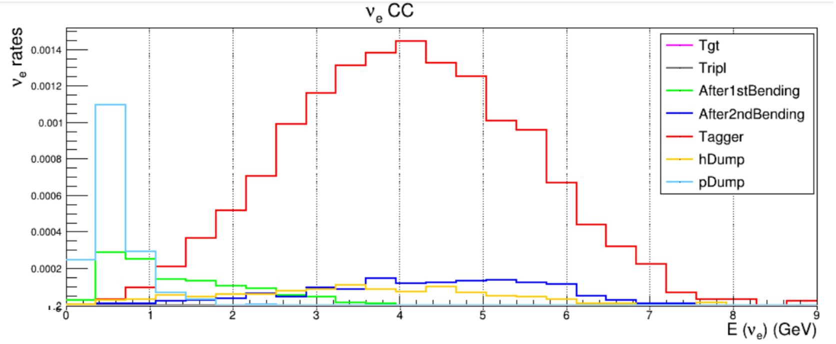


Focus on a detailed implementation of magnetic fields maps measured for existing magnets at CERN





ν_e from **8.5** GeV/c secondaries (current baseline)

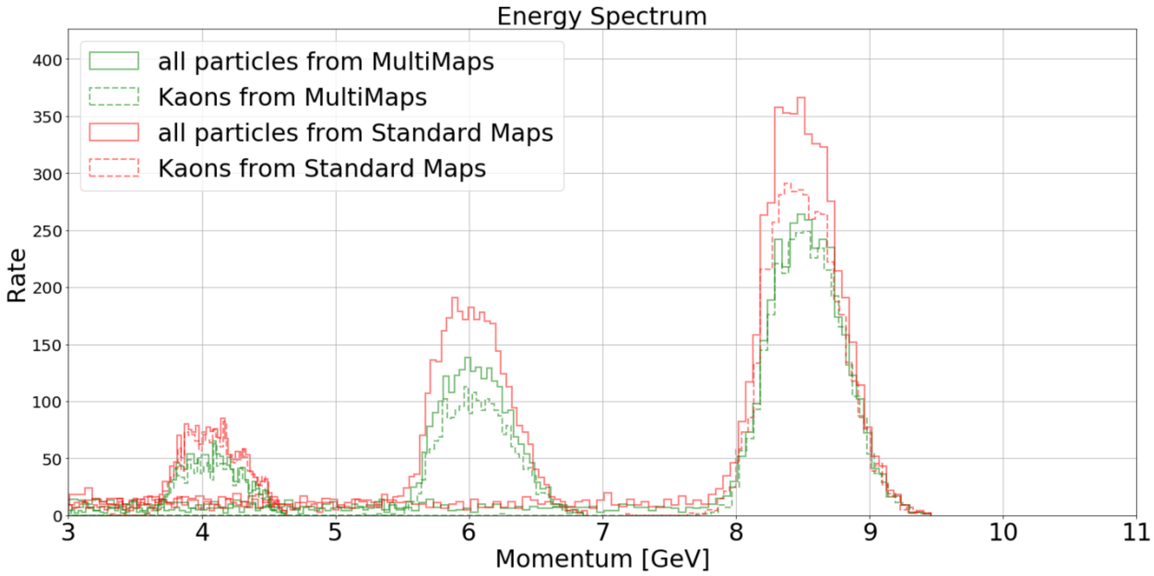


1 4 6 GeV

Alternative transferline (MMB)

Particle rates at tagger entrance:

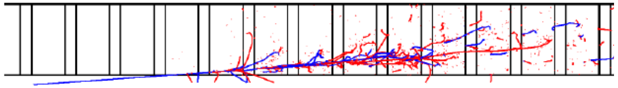
Particles [10^{-3}] PoT	8.5 GeV/c	6 GeV/c	4 GeV/c
MMB			
K^+ π^+	0.68 7.9	0.28 4.1	0.08 1.7
Baseline Beamline			
K^+ π^+	0.36 3.97	/ /	/ /



- This study has advanced a lot (CERN doct. PhD thesis, E. Parozzi, completed. Supervisor N. Charitonidis).
- Much high collection efficiency (x2 !!!) and backgrounds seem on a comparable level.
- Data are being included in the full simulation chain to assess the final performances.

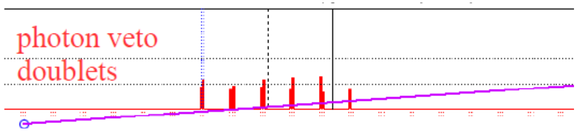
The lepton tagger

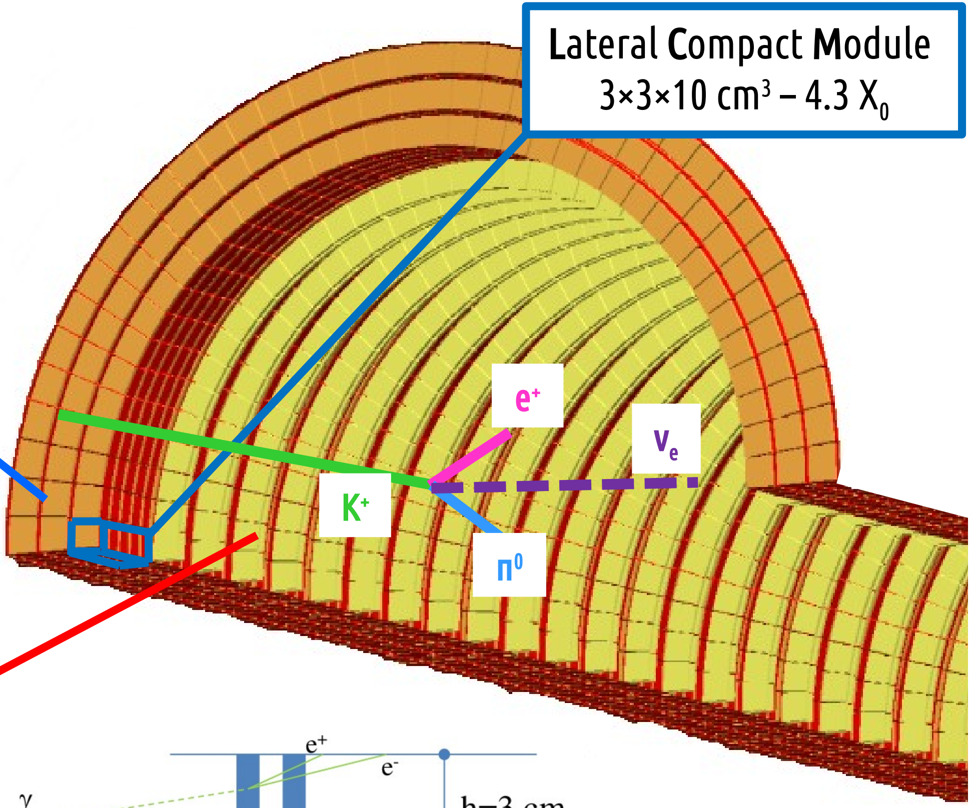
Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation

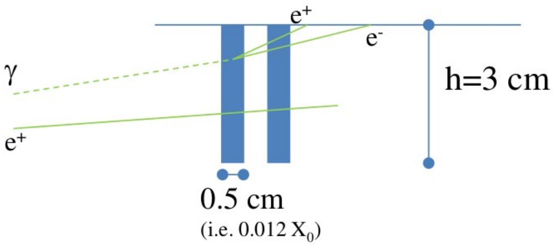


Integrated photon veto
- Plastic scintillators rings of 3×3 cm^2 pads

→ π^0 rejection





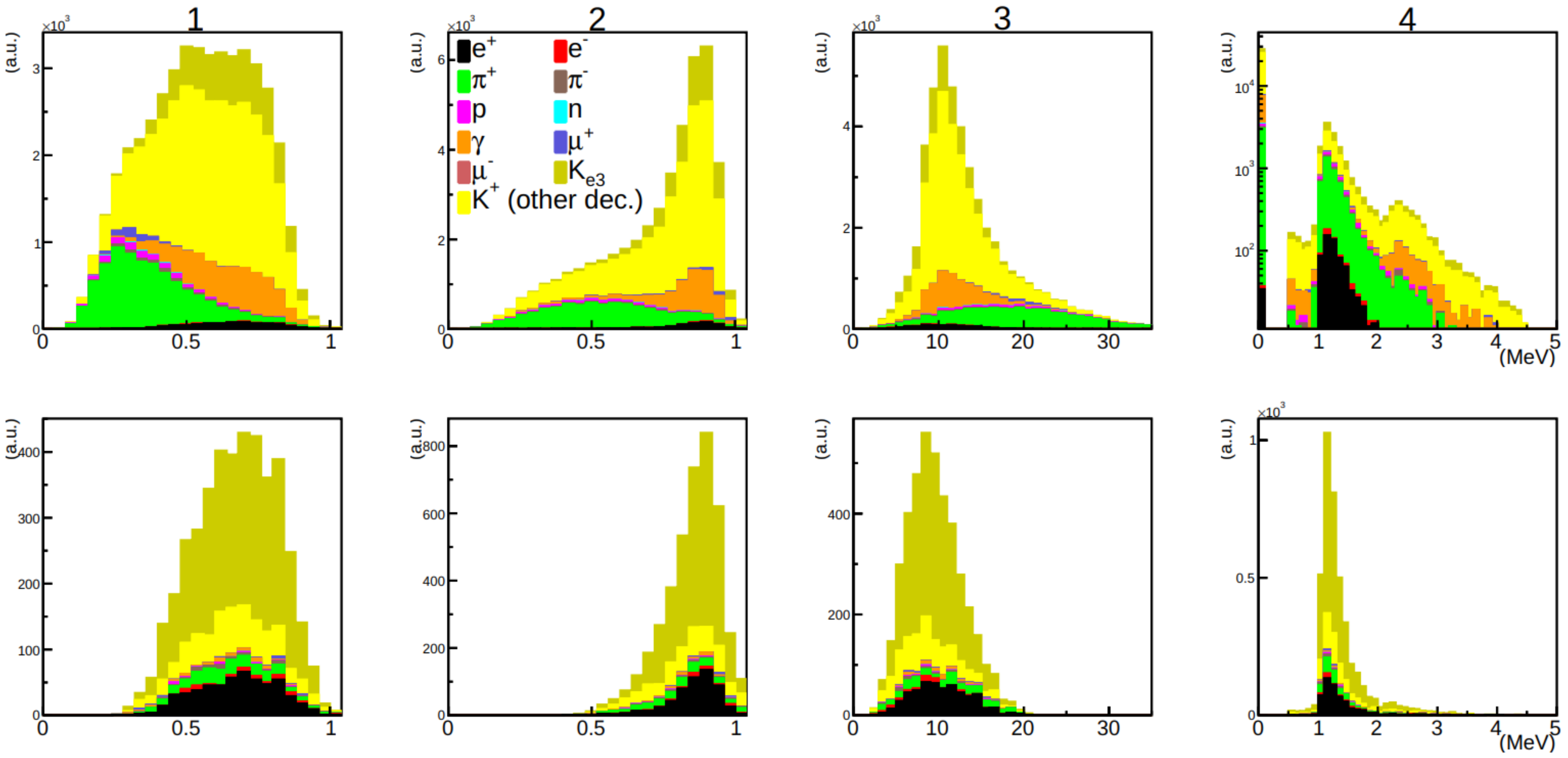


e^+ (signal) topology

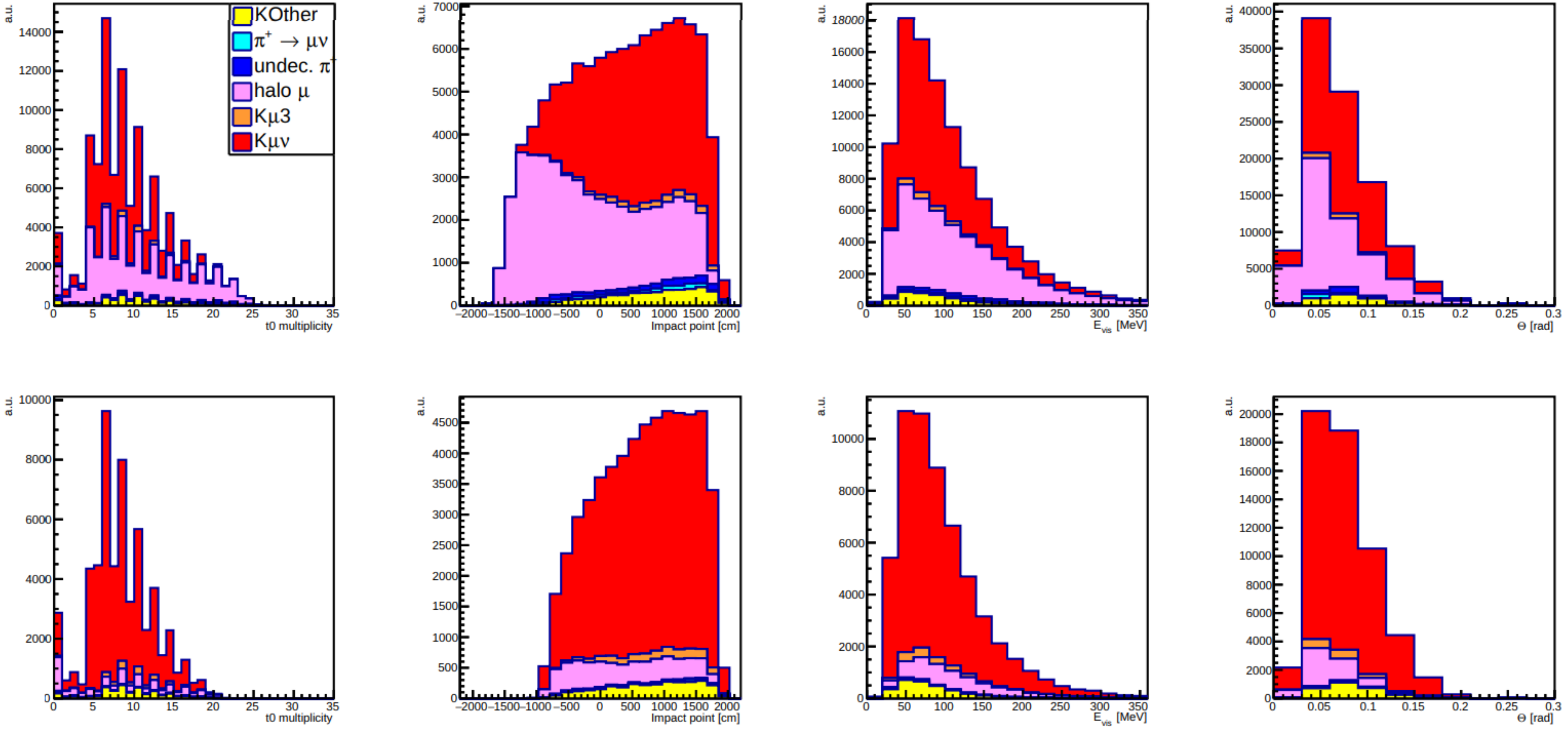
π^0 (background) topology

π^+ (background) topology

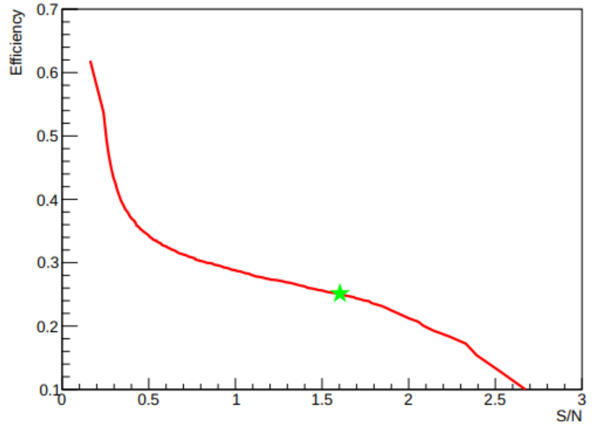
Positron selection

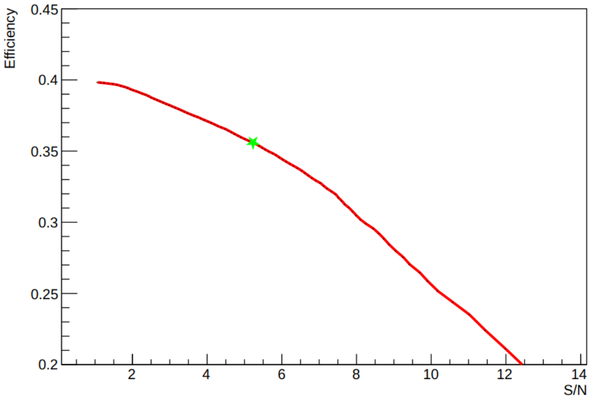


Muon selection

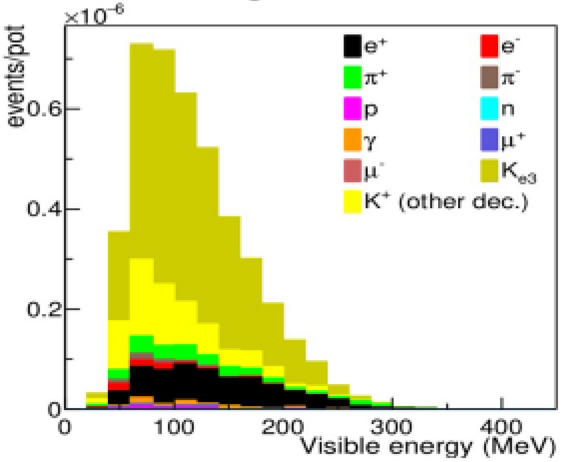


Overall lepton reconstruction performance in the tagger





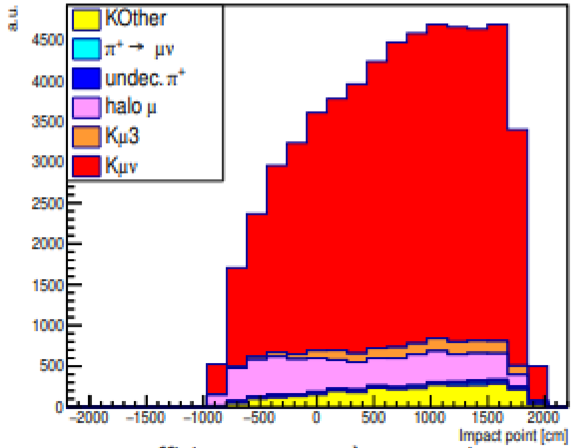
energia visibile e^+



Selezione e^+ da K_{e3} :

S/N = 2
ε = 22%

punto impatto μ^+ lungo il calorimetro



efficienza ε ~ metà geometrica

Selezione μ^+ da $K_{\mu\nu}$:

S/N = 5.2
ε = 35.6 %

Time-tagging with full simulation

Potentials for time-tagging with a 2s long spill and 4.5 x 10^{13} protons.

NEW Evaluated for the first time with a full simulation also taking into account the contributions of fake matches generated by wrong positron candidates and neutrinos produced in the tagger or outside of it.

Intrinsic spread related to the difference in path between the lepton and the neutrino (vertex position is assumed not constrained here): $\sigma_{\Delta t}$=134 ps

True e^+ + ν_e match (both from tagger region)
Fake e^+ + ν_e match (ν_e from tagger)
Fake e^+ + ν_e match (ν_e from outside tagger)

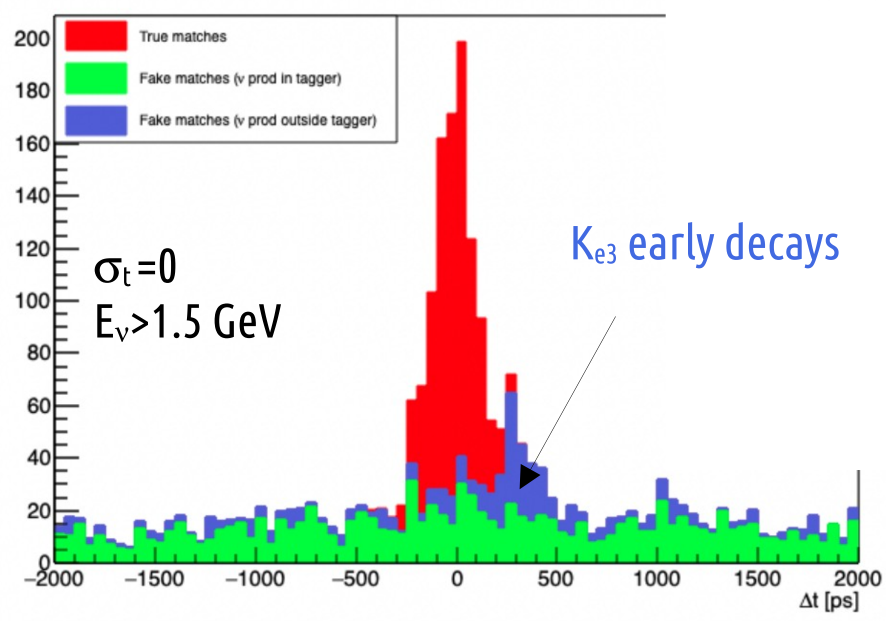
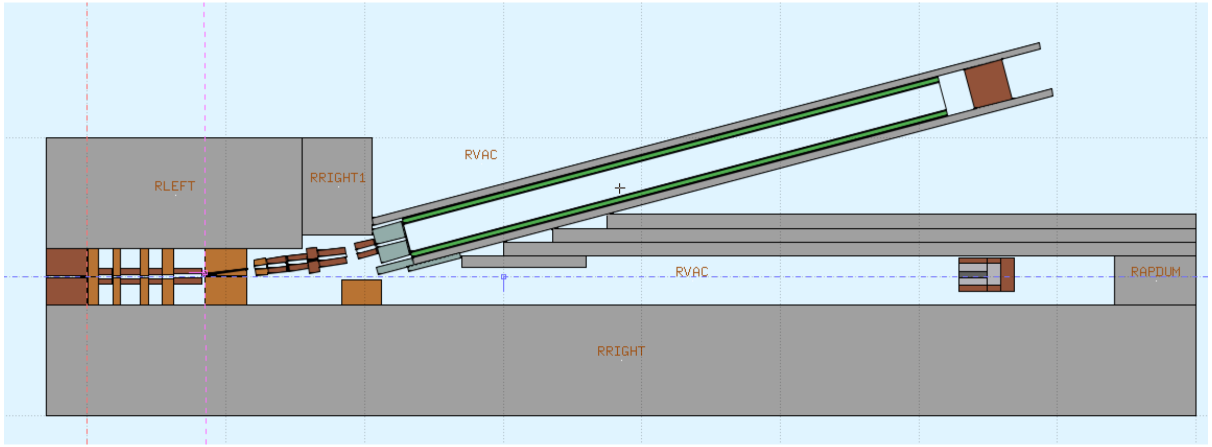


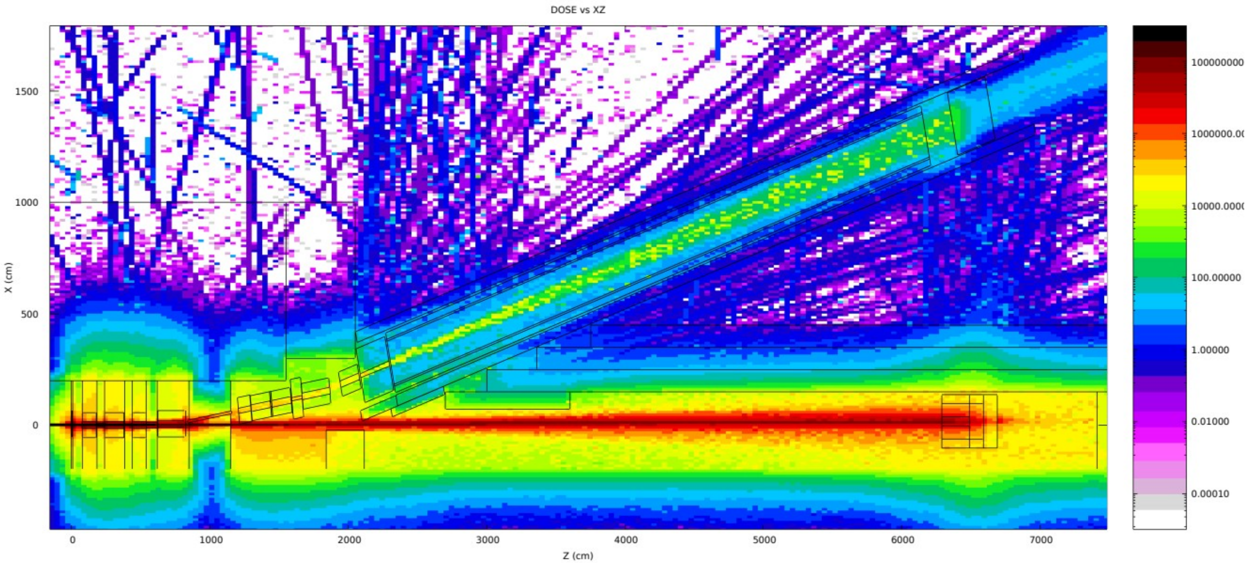
Fig. 24 Distribution of time differences between all time tagged pairs of ν_e^{CC} and positron events within a ±2 ns time window. True matches (red) are tagged pairs from the same K_{e3} decays, whereas fake matches are tagged pairs between unrelated candidate positrons and ν_e^{CC} where the neutrino is produced inside (green) or outside (blue) the tagger volume.

FLUKA irradiation studies

Doses:

In Gy for 1e20 POT @ 400 GeV





The dose at the hottest point of the quadrupole closest to the target is < 300 kGy for 10^{20} pot.

Conventional magnets can be operated without risk in a monitored neutrino beam like ENUBET for the entire duration of the data taking

TLR6v4

FLUKA irradiation studies

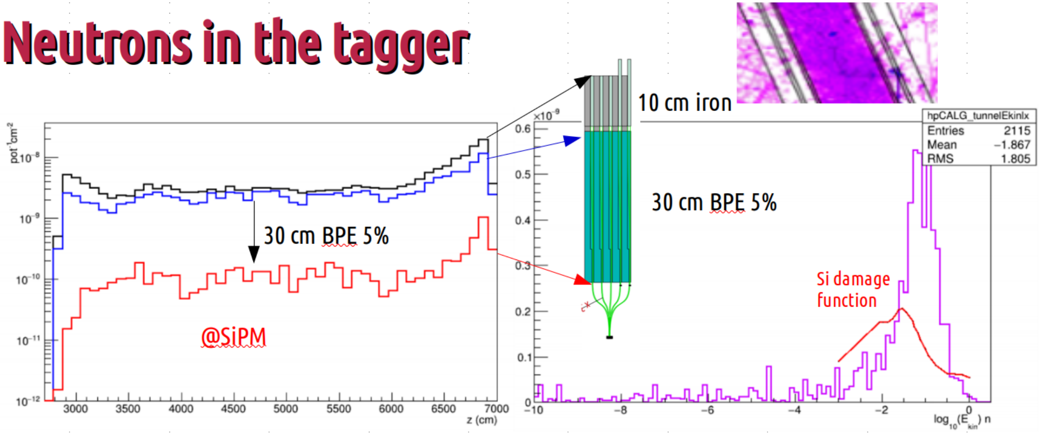
Neutrons: guided the design of the detector technology for the demonstrator (SiPM outside of the calorimeter) → instrumentation lifetime.

Modern SiPMs developed for collider physics can stand > 10^{12} neutrons/cm^2 and these sensors can be employed without risk in the ENUBET instrumented decay tunnel.

Commercial SiPMs with a radiation hardness similar to the photosensors employed in the ENUBET Demonstrator were irradiated up to 10^{11} neutrons/cm^2 in a dedicated campaign performed in 2018.

In ENUBET, these SiPMs retain sensitivity to minimum ionizing particles for neutron fluences that are > 3 times larger than the expected fluence in ENUBET.

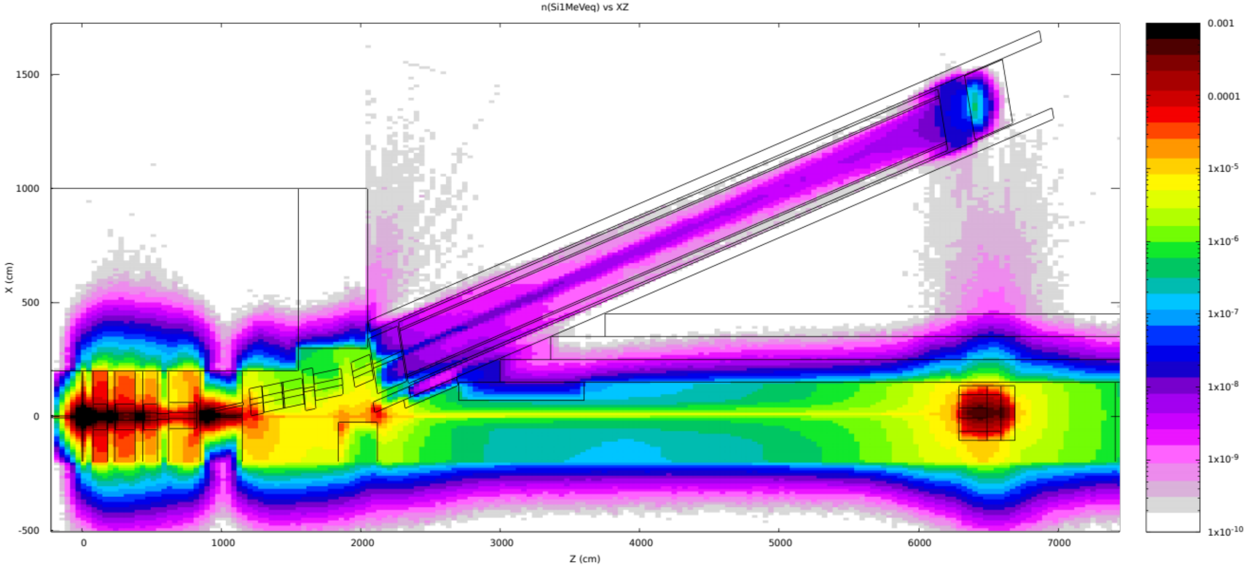
Neutrons in the tagger



BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7×10^{-11} n/POT/cm^2 **~ 10 x reduction**
(7×10^{9} n/cm^2 for 10^{20} POT)

E_{kin} of surviving neutrons is O(10-100) MeV

TLR6v4



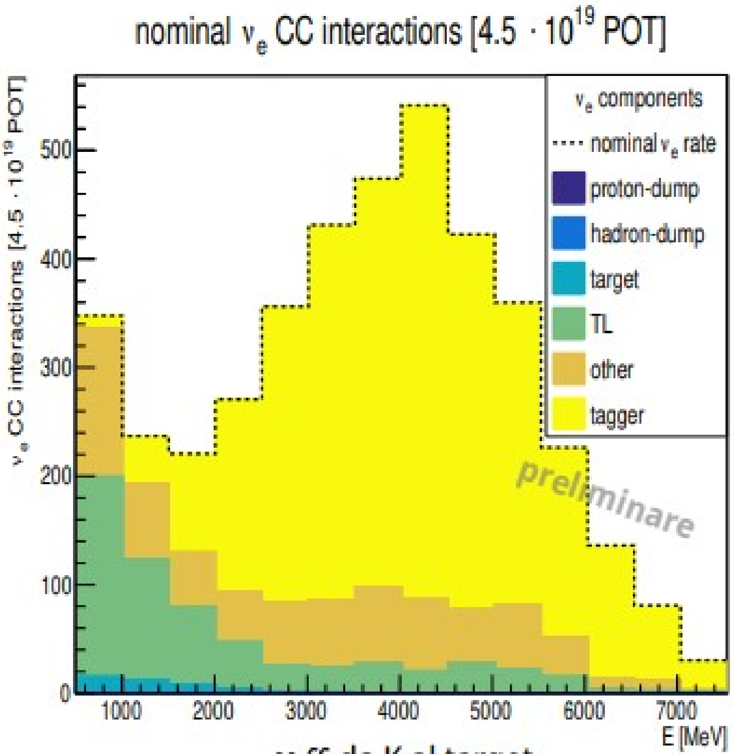
Flux constraint: reduction of hadro-prod. syst.

Employ hadro-production model fitted on NA56/SPY data

→ fit e+ rates to constraint the model hadro-production parameters

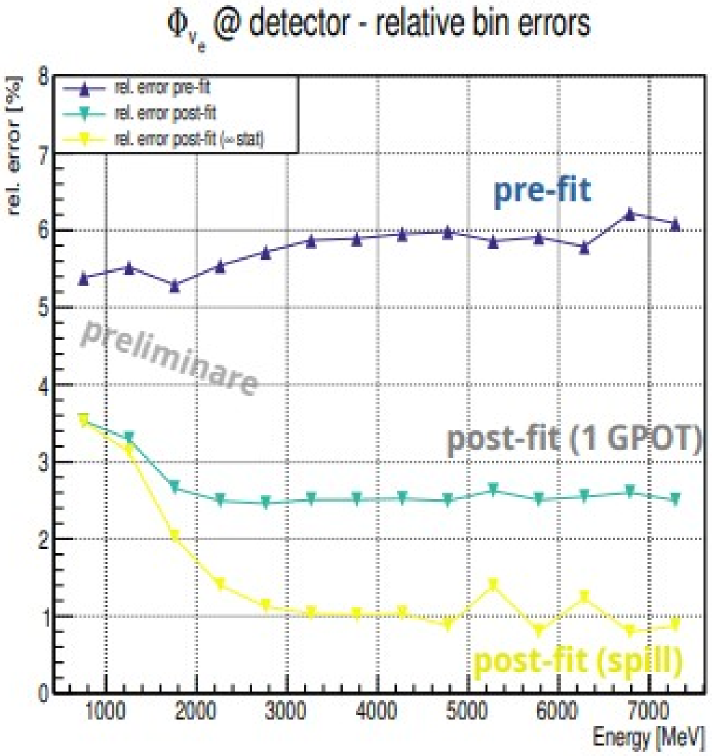
Reduction in the error envelope on the electron neutrino flux (6% → ~1%)

rate di interazione ν_e CC al rivelatore



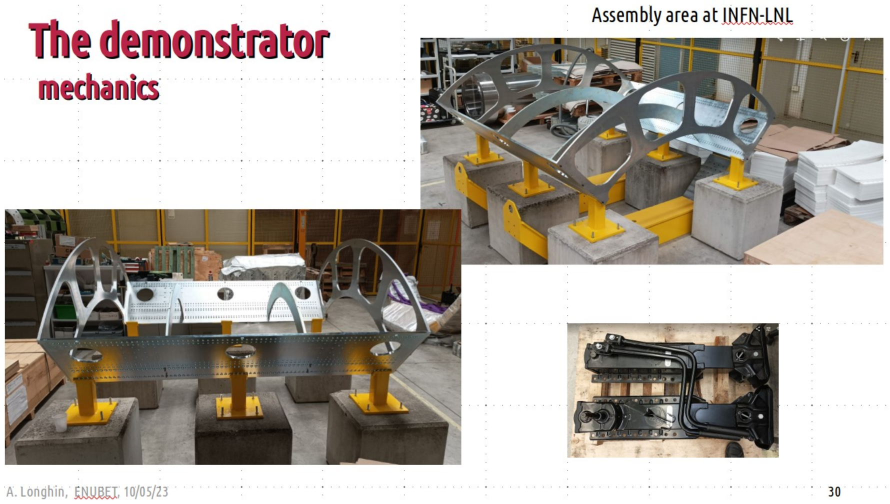
ν_e^{cc} da K al target

errori relativi su rate ν_e CC : pre e post-fit



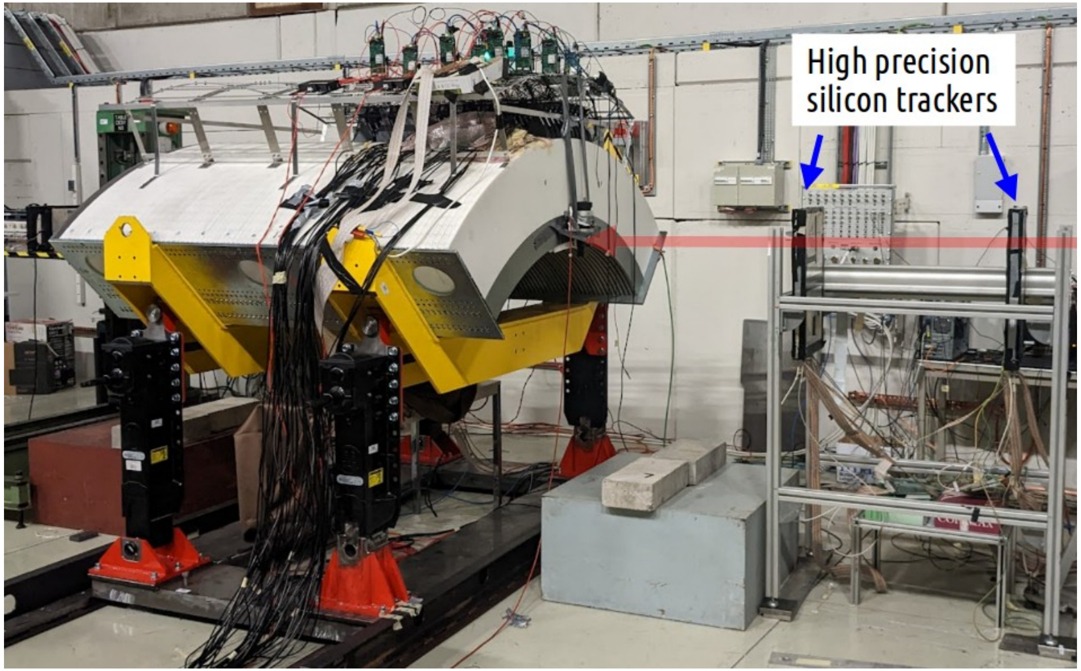
Progress on the demonstrator

April 2022



From the presentation at last year SPSC

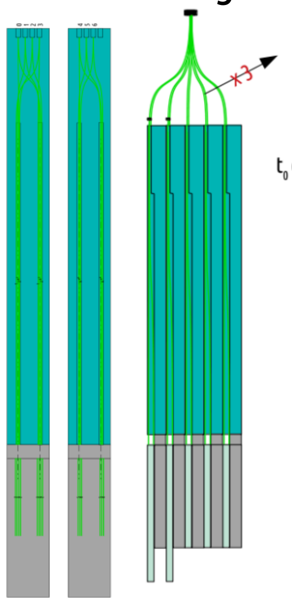
October 2022

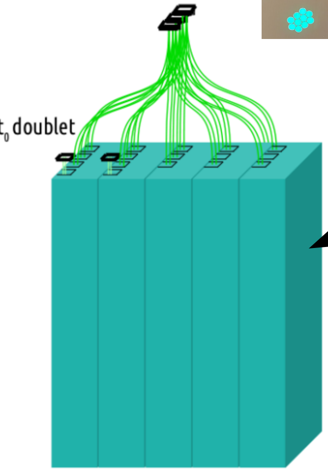


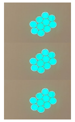
The demonstrator

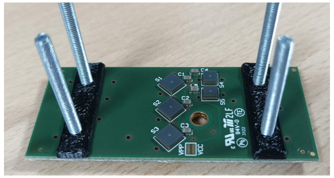
Demonstrate detector performance (PID, homogenity, eff.), scalability, cost effectivess…

WLS routing



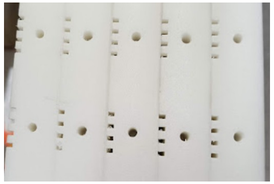




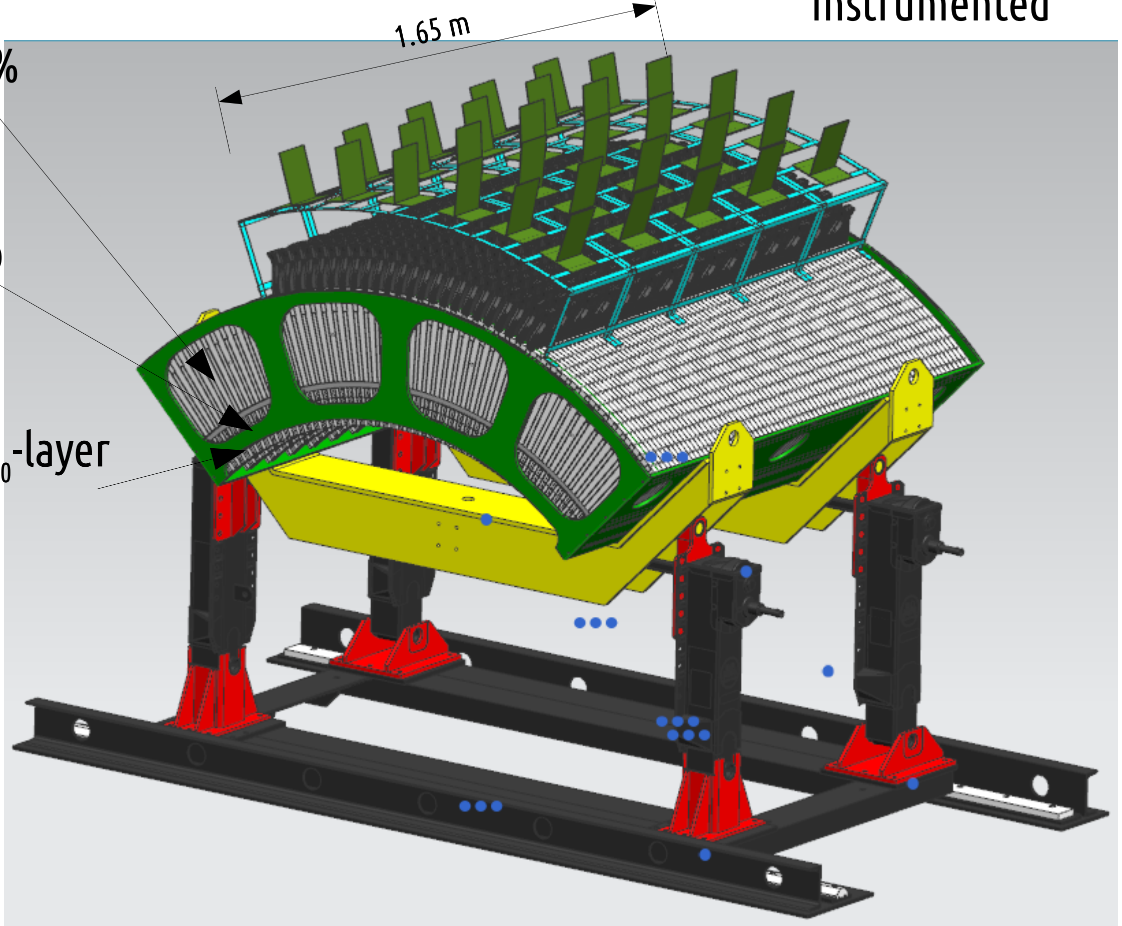


BPE 5%

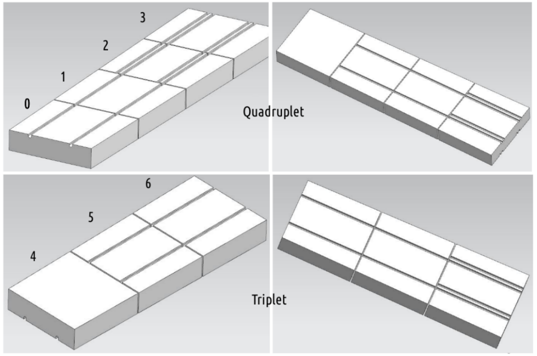
Sampling iron/scint calo

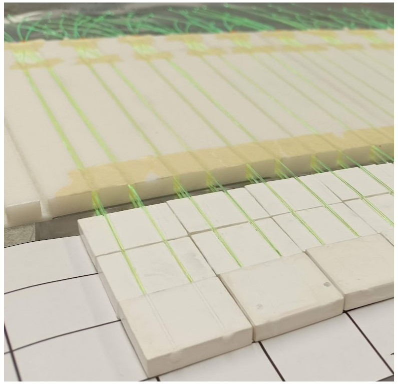


90°, partially instrumented



t_0-layer

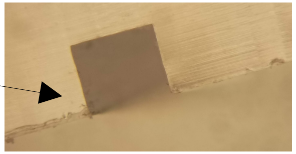


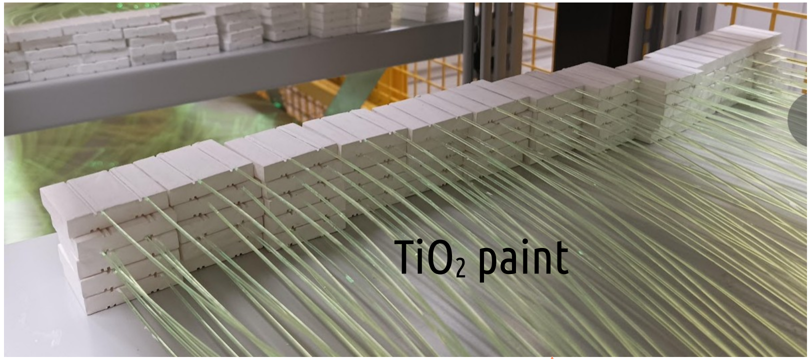


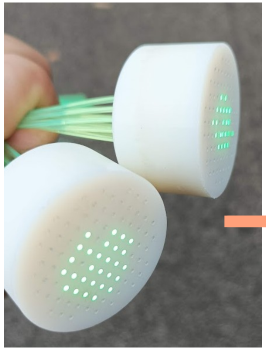
Scintillators + WLS light readout handling

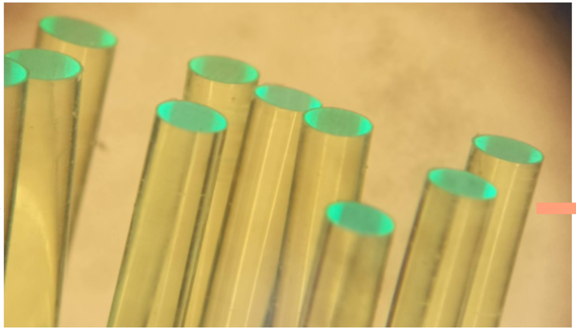
Summer 2022
@ INFN-LNL

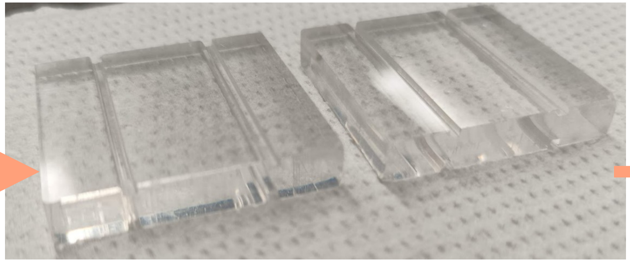
Injection molding INR could not be finalized → commercial scintillator slabs + cutting/milling in Italy.
Critical impact → polishing, fibre gluing, tiles painting **with personnel from the collaboration**.

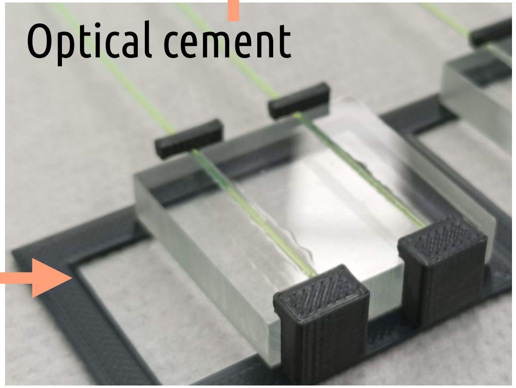






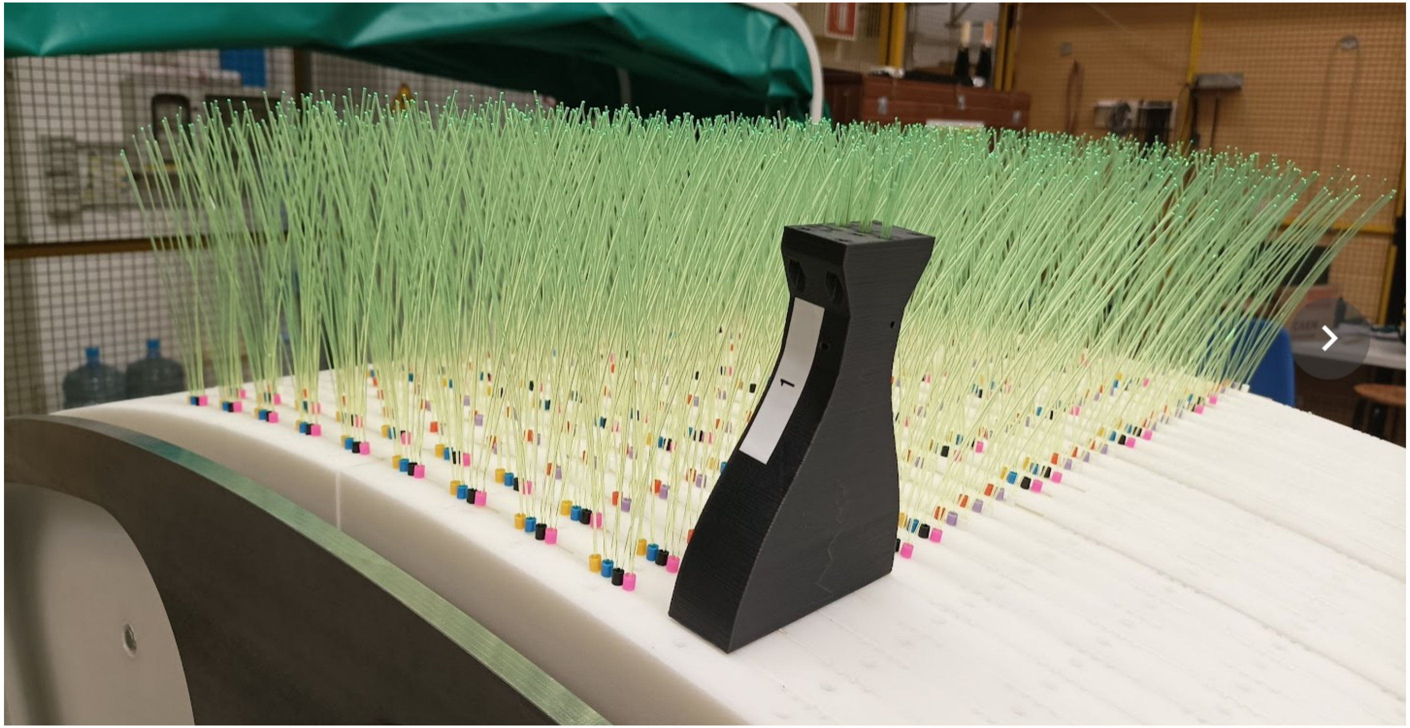


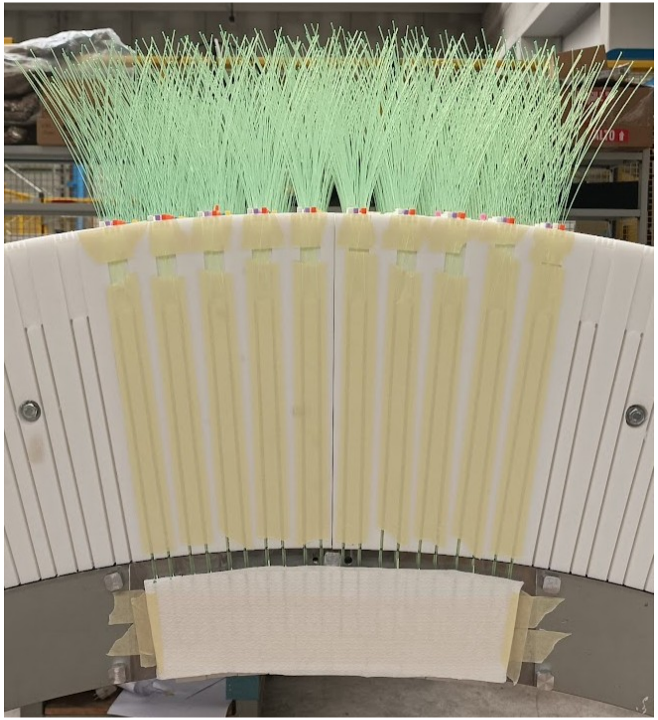




Assembly of the iron / scintillators/ BPE planes

Summer 2022 @ INFN-LNL

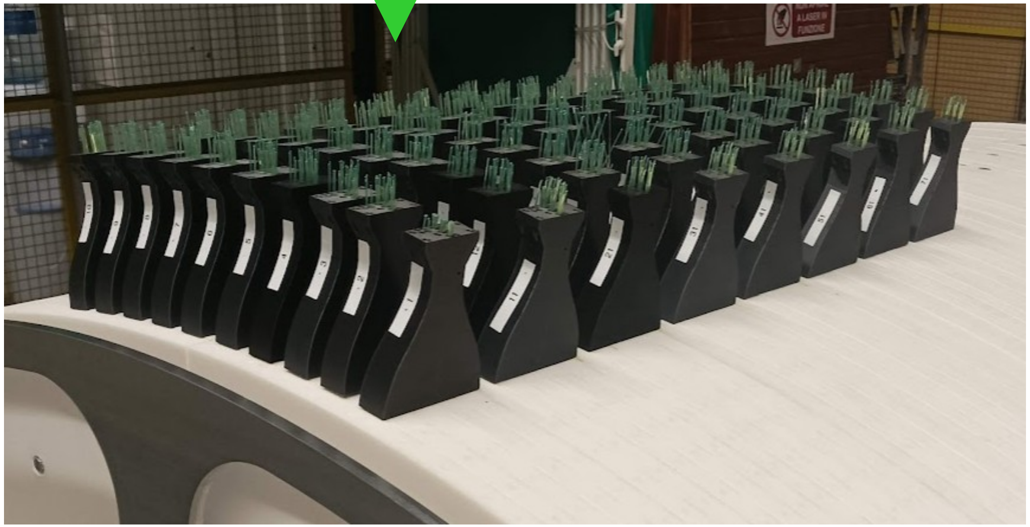


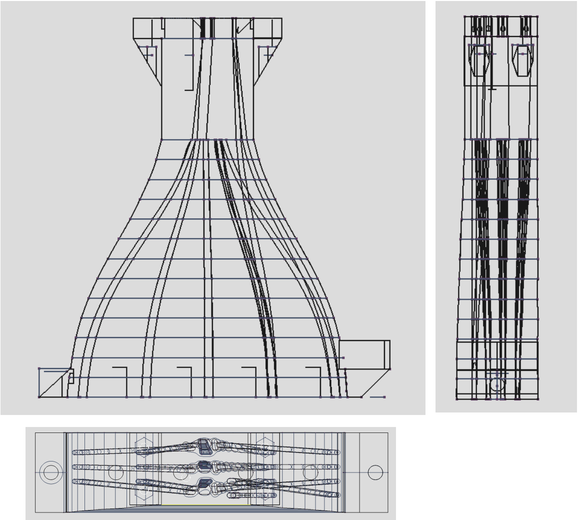


Fiber bundling with new “concentrators”

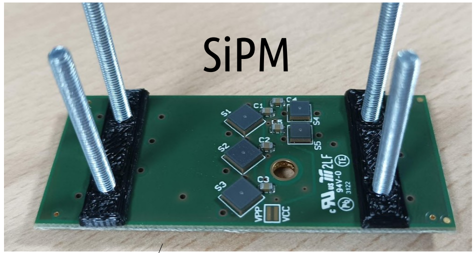
Summer 2022 @ INFN-LNL

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

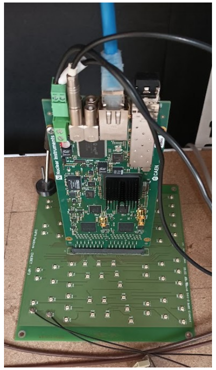


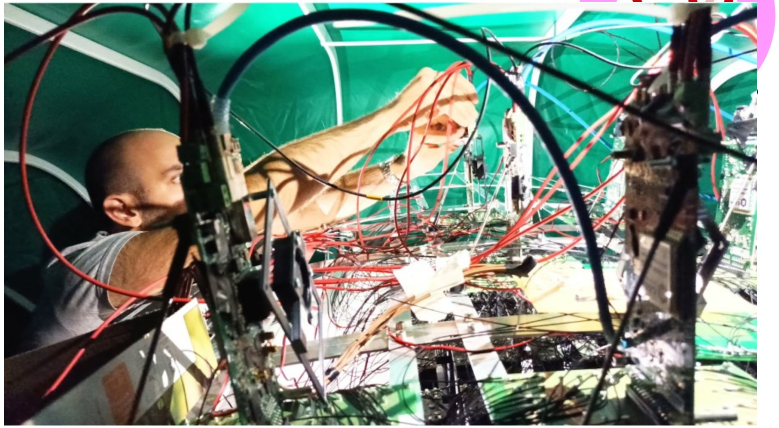


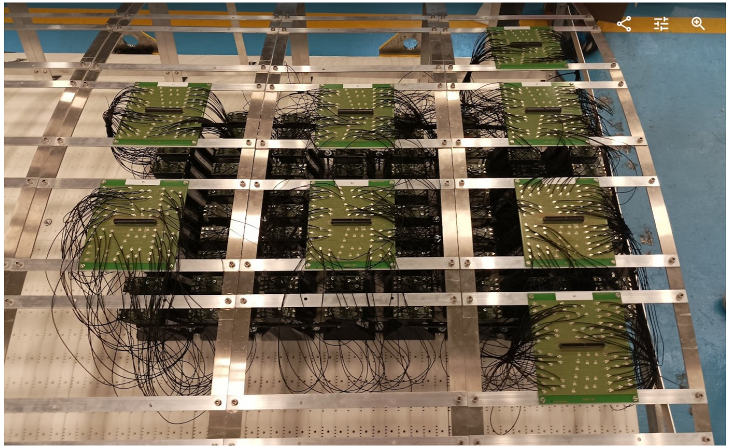
Readout electronics

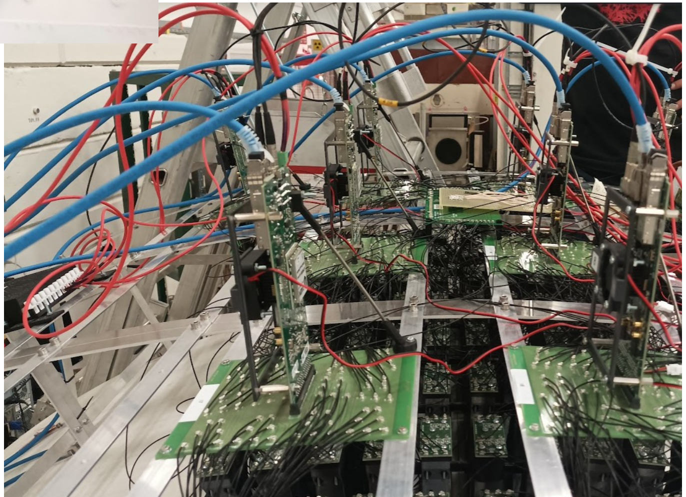


Oct 2022 @ CERN









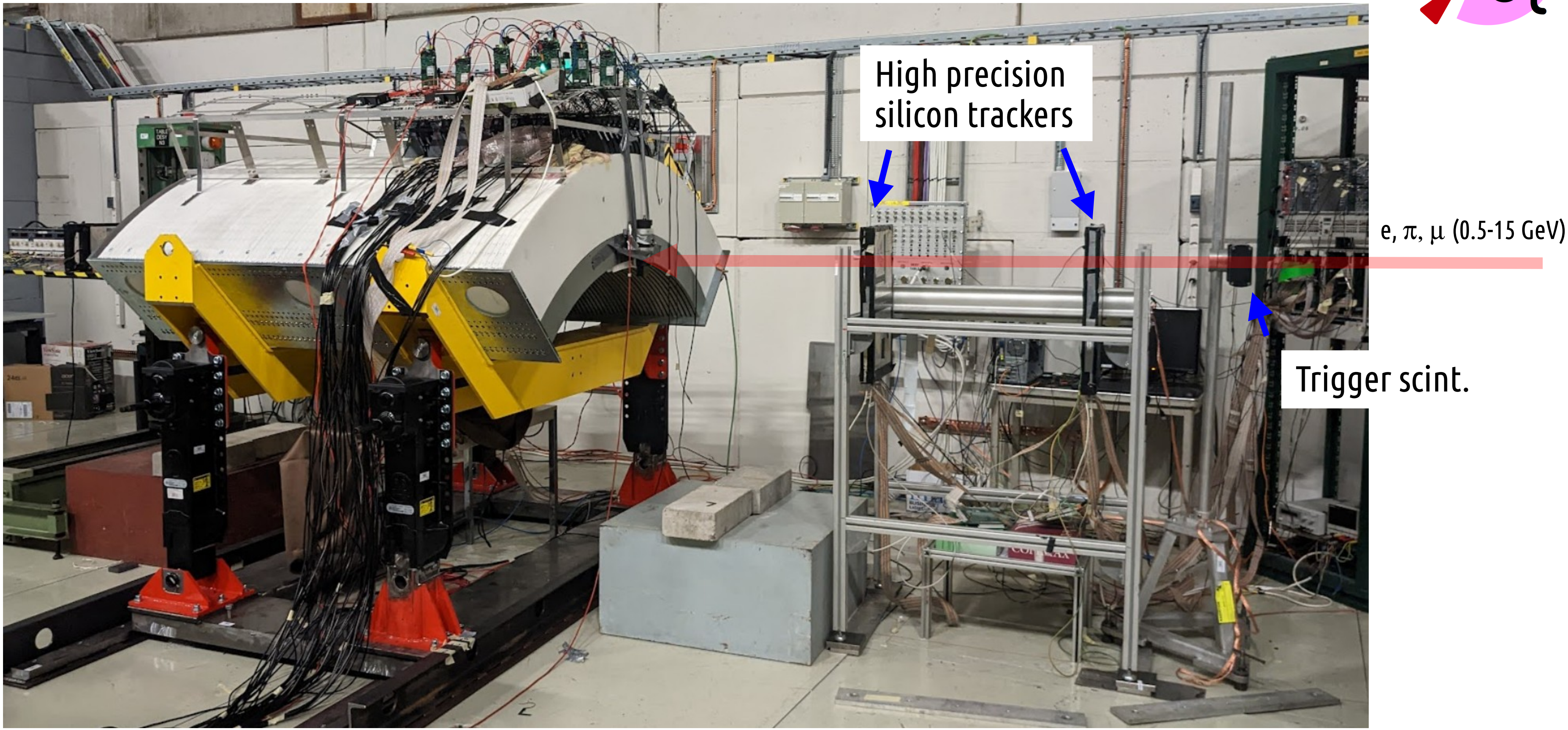
Launch …

3 Oct 2022 @ building 157, CERN Meyrin PS East Hall T9 area

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

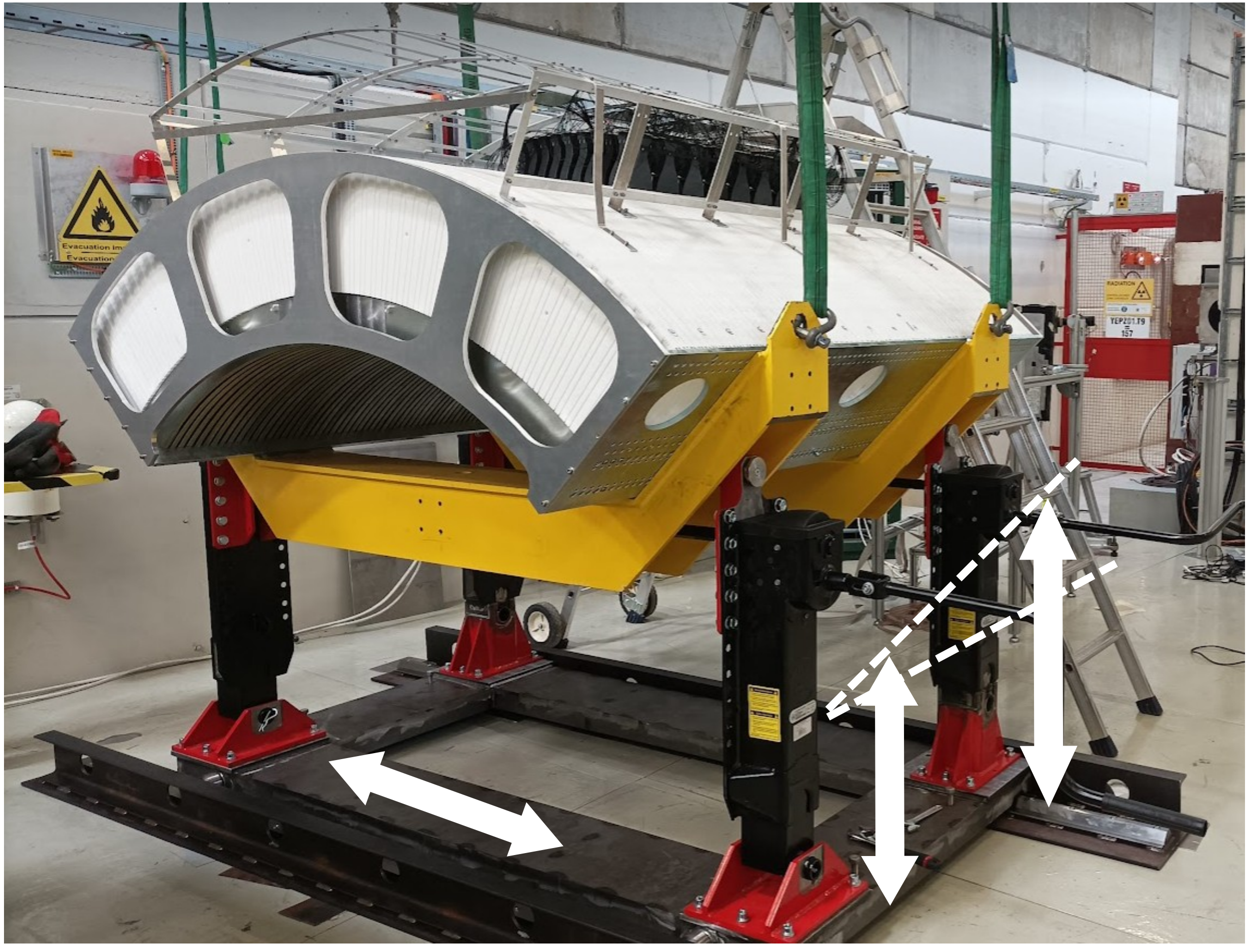
Landing at T9

Oct 2022 CERN-PS-T9



In numbers

- Scintillator tiles: **1360**
- WLS: ~ **1.5 km**
- Channels (SiPM): **400**
  - Hamamatsu **50 um** cell
    - **240** SiPM **4x4** mm^2 (calo)
    - **160** SiPM **3x3** mm^2 (t_0)
- 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**

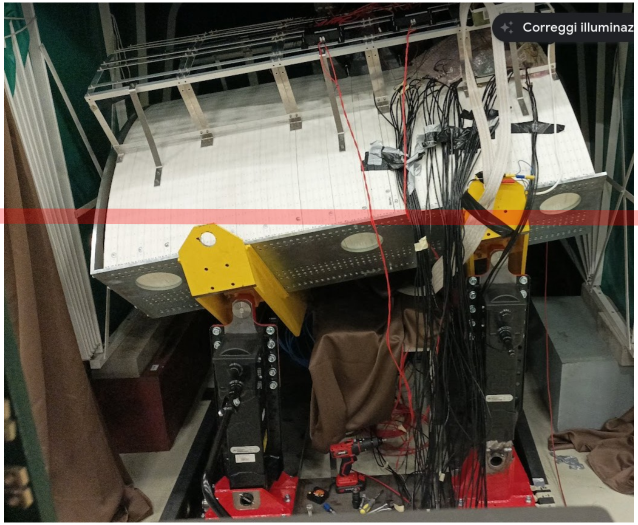


Data taking

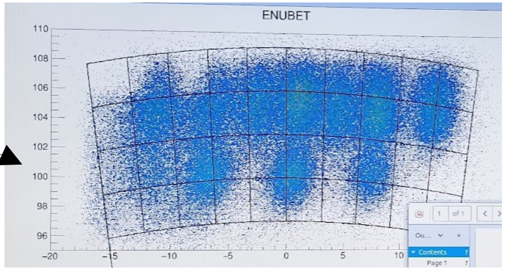
Oct 2022 CERN-PS-T9

horizontal run with darkening cover

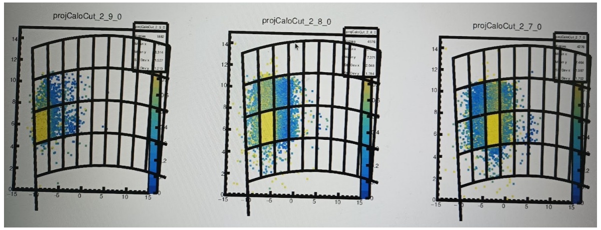
200 mrad tilt run



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



Efficiency maps



Highlights on test beam analysis

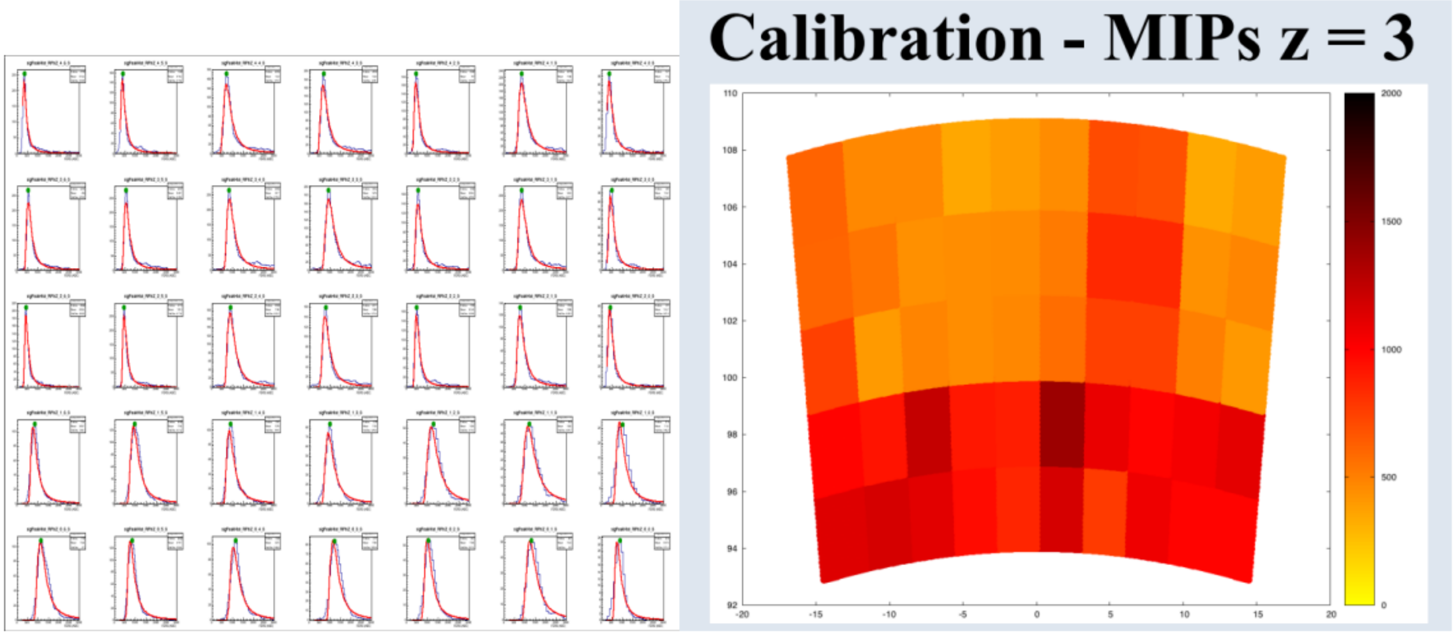


Figure 9: Calibration with m.i.p.s. Left: spectra of signals used to derive relative inter-calibration constants between different detector channels in the same z layer. Each column shows the spectra of calorimeter and t_0 channels in the same ϕ sector, while each row shows a calorimeter radial layer; 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.

Highlights on test beam analysis

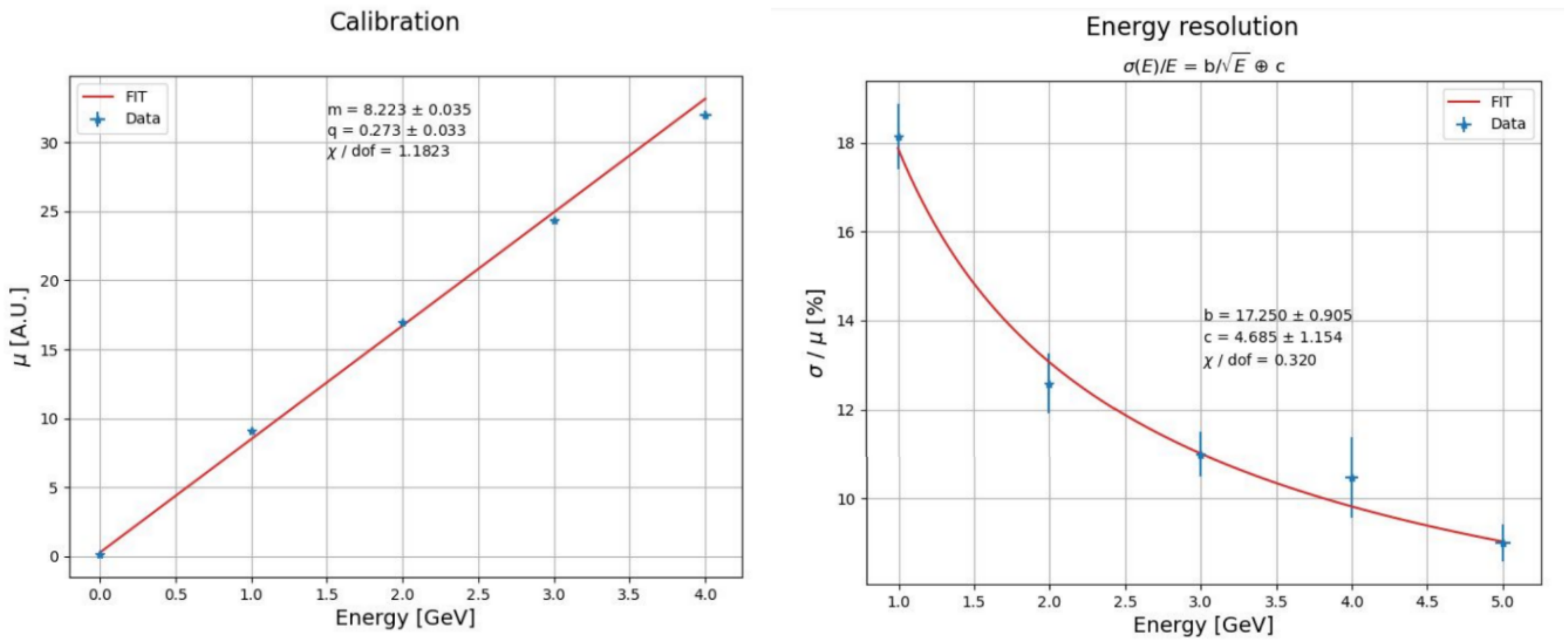


Figure 10: Linearity and energy resolution for electrons.

Simulation says expected resolution should be better by a few %.
Many checks done but still not nailed down → not too worrying. Work in progress.

Highlights on test beam analysis

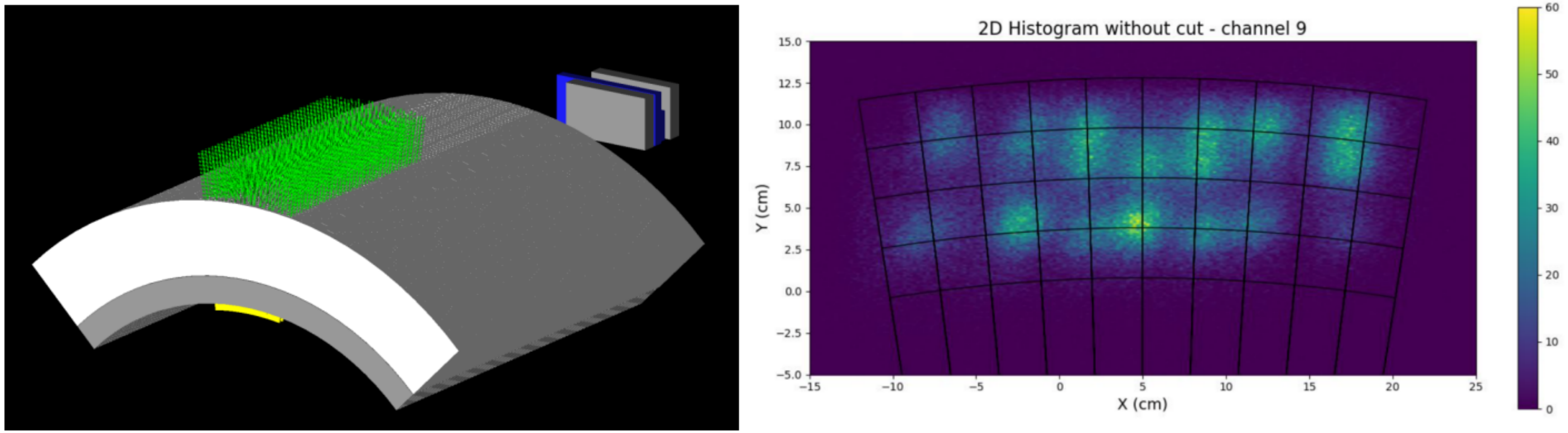


Figure 11: GEANT4 simulation of the demonstrator. Left: the geometry. Right: simulated beam profile at the upstream face. Each "island" corresponds to a run. The detector was moved in between runs to cover all tiles.

Improved GEANT4 simulation:

- the angular and spatial distributions of the beam as measured by Silicon tracking chambers;
- the calibration procedure with mips and the non-uniformity of light collection;
- the optical simulation (can be switched on);
- a model to describe photo-electron Poisson fluctuations;
- a model for the cross-talk between channels;

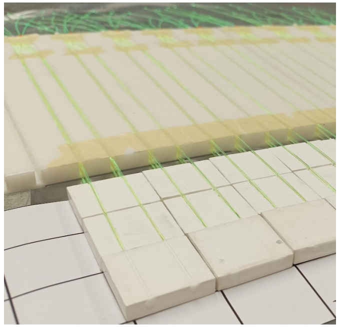
Highlights on test beam analysis

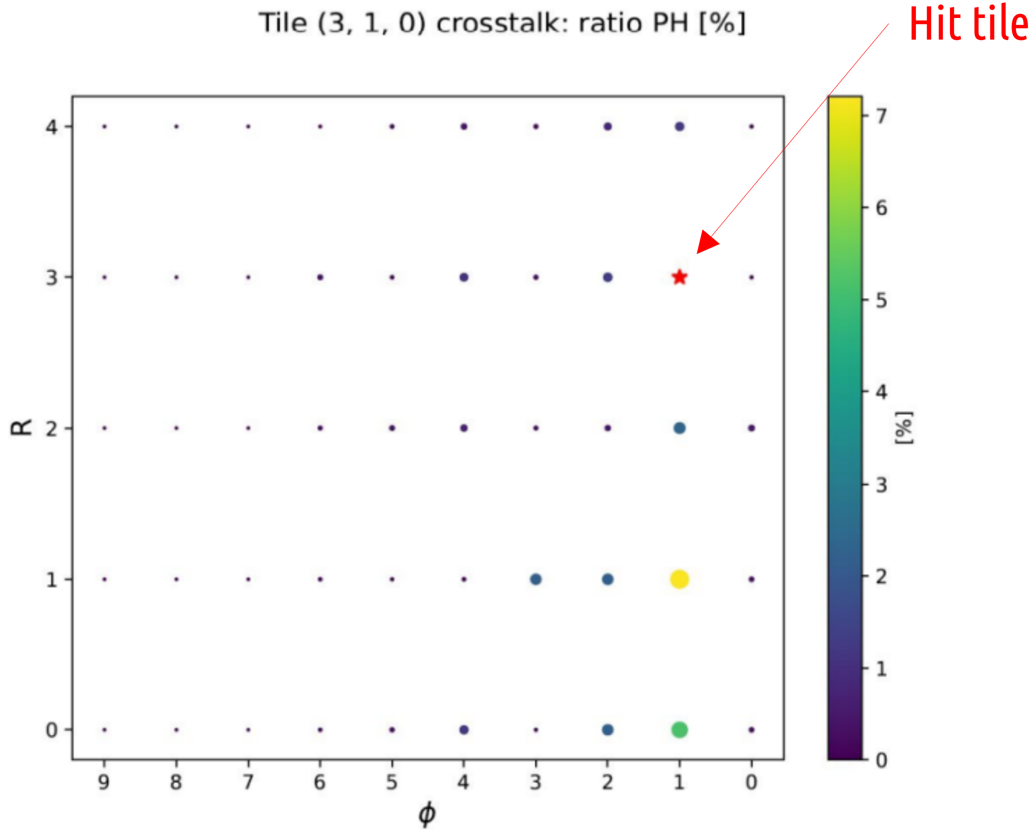
Cross-talk studies ongoing with muon samples

Seems present at a not too large level for some channels (~% level).

Residual pions can mimic cross-talk, cross talk effect very close to the noise → a delicate measurement (will collect more stat this summer!)

Seems not to degrade performances significantly (i.e. resolution)





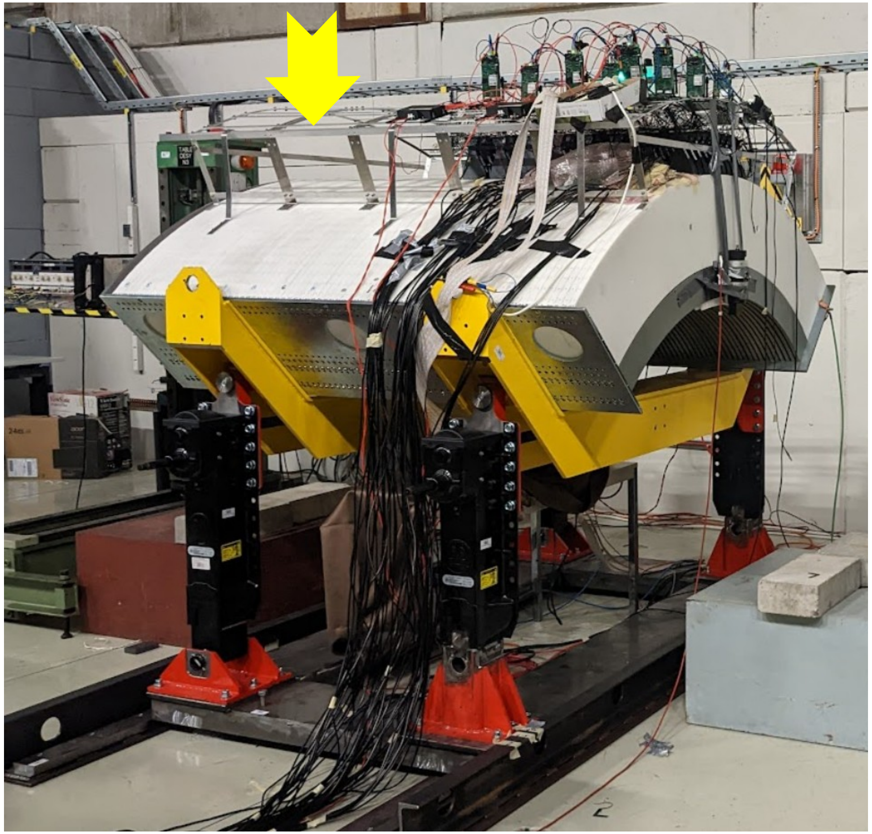
Demonstrator-22 → Demonstrator-23

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

2023:

- add 7 downstream z layers with 25 ϕ sectors
  - passing from 400 to 400+875 = **1275 channels**
- Possibly instrument a few channels with **custom digitizers**
- Larger acceptance:
  - we will take a run in “decay region” mode i.e. with the detector off-beam to try and detect K decay products

2023

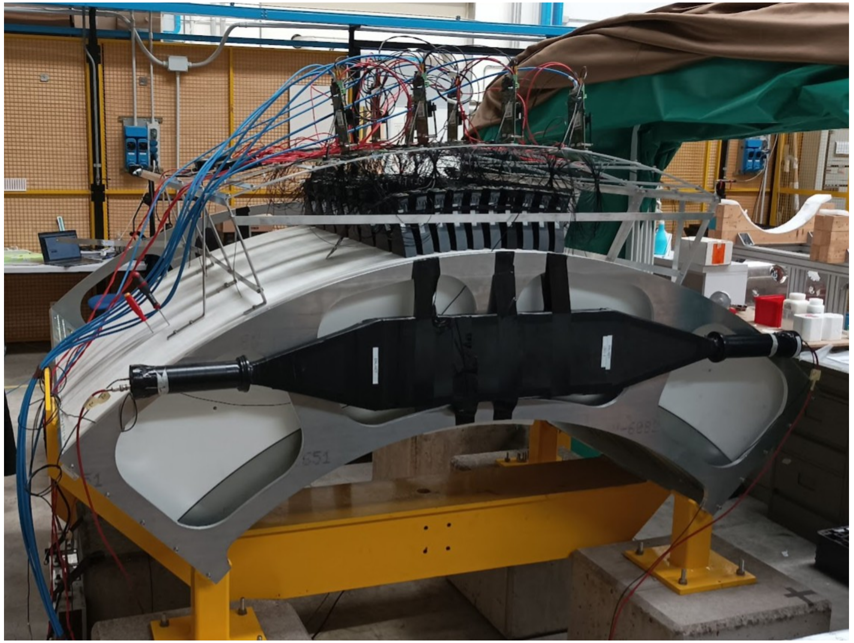


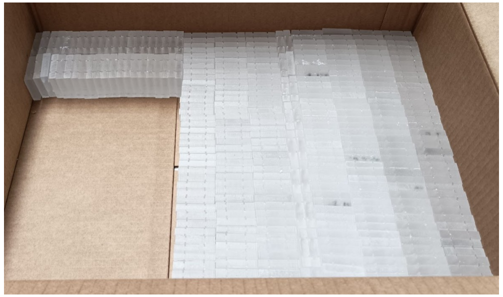
2022

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

Status @ INFN-LNL

- The downstream part has been dismounted and the new planes are being equipped
- In the meanwhile the instrumented half is collecting cosmic data (trigger on low-angle cosmic muons with a rate of ~ 0.5/min)
- DAQ is being refined:
  - integration between the silicon trackers and SiPM
- Scintillator thicknesses have been measured individually and are stored in a database to enable the possibility of applying corrections for non-uniformities





Conclusions and Outlook

ERC project completed. Established technique → **towards the completion of the NP06 program**:
- **Fully instrumented demonstrator** (Aug. 2023). Likely another test beam request in 2024.
- Finalization of the **alternative beamline** (plug into the full chain and check physics reach)

The successful R&D carried out in 2016-22 brought **new opportunities**:
- PIMENT (Picosecond MicroMegas for ENUBET). ANR funding 2022-24
- → Muon monitoring in instrumented hadron dump: constraint the ν_μ **flux from pions 2-body decays**.
- Participation in PBC (Physics Beyond Colliders):
  - In the "Conventional Neutrino Beams Group" in synergy with other users (NA62, NUTAG) and CERN experts
  - Soon: investigate the possibility of implementing ENUBET at CERN in parallel with the running of DUNE and Hyper-K, using the ProtoDUNEs (HD+VD) as neutrino detectors ?
- ESSvSB+ EU project
  - WP6: feasibility a monitored neutrino beam at the ESSource using the LINAC in its present configuration → access low energy cross sections
  - Post-doc positions openings. The instrumentation will be likely very "forward" and signal from pion decays → large synergies with the PIMENT (common working group: Athens, CNRS, INFN, Thessaloniki, Zagreb)

backup

Scintillators + WLS light readout handling

Summer 2022 @ INFN-LNL

From the report

2.1 Construction

The construction took place at INFN-LNL mainly during May-September 2022 with the contribution of shifters both local (Padova) or from Milano and Zagreb. The process involved a complex chain of operations involving several items:

- **Scintillators**. As already reported in the previous document the production and machining of the scintillators tiles was the most challenging and critical task. Scintillators had initially been produced by UNIPLAST (Moscow) in collaboration with the INR group using injection molding. Unfortunately, due to the war outbreak on 24 Feb. 2022, it was not possible to

finalize the procurement from Russia. The total number of needed tiles, 6375, in seven different shapes[2] were hence produced by an Italian company (STYLPLEX) in a very short time with critical deadlines. The machining was achieved using cutting and milling with numerical control machines in place of injection molding, starting from large scintillator sheets procured by SCIONIX. A view of one of the squared grooves is visible in Fig. 2 (center). Managing the preparation of scintillators without relying on the expertise and methods of INR/UNIPLAST has been a quite demanding task since all the operations were managed internally. In particular the collaboration took care of:

1. scintillators sand-papering for TiO_2 paint adhesion;
2. scintillators individual thickness measurement with caliper;
3. WLS cutting, polishing, WLS glueing to scintillators;
4. scintillators painting with $Ti0_2$;
5. assembly of scintillator planes on the iron arcs and mounting on the detector;
6. WLS fibers bundling with concentrators;
7. in situ cutting and polishing of WLS fibers bundles;
8. installation and cabling of front-end boards, interconnection boards and readout boards.

In Fig. 2 some of the various steps that led to the completion of the previous task are summarized and more details are provided in the caption. Figure 4 illustrates steps 5, 6 and Fig. 5 steps 6, 7. The installation of electronics and cabling are shown (8) are shown in Fig. 7.

- **WLS fibers**. We have used WLS fibers Y-11 double clad 1 mm diameter from Kuraray (JP). Fibers were cut in four different lenghts to account for the three calorimeter radial layer and for the t_0 layer and sandpapered/polished using some tools developed for the purpose (see Fig. 2).

- **Fiber concentrators**. We have developed and 3D printed fibers concentrators (FC) with a batch of five commercial 3D printers using PLA filaments. The concept proved to be completely successful and a very elegant solution to the complicated problem of routing the fibers in a tidy and reproducible manner: 34 fibers emerging from an area of about 3×11 cm^2 are collected into 3 bundles of 10 WLS (calorimetric modules) and 2 couples of 2 fibers (t_0) over an area of about 5×3 cm^2.

- **Photo-sensors**. We have used Hamamatsu models S14160-3050HS (3×3 mm^2) and S14160-4050HS (4×4 mm^2). The silicon photomultipliers and related electronic components were soldered on the PCB by the INFN-Padova electronics workshop, while the PCB production was outsourced;

- **Front-end boards**. The front-end boards are mounted and screwed on the FCs. Each hosts five SiPM as seen in Fig. 6. Large and small SiPMs can be powered with separate bias lines.

  Special boards were produced to be interfaced to CAEN digitizers to compare the output of CAEN A5202 boards. 9 modules were readout in this way for a fraction of the time during the test beam;

- **Interface boards**. The signals are sent from the FE boards to interface boards with host receptacles for many very thin coaxial cables by HIROSE which are used both for providing the HV to the SiPM and reading out the signals (Fig. 7).

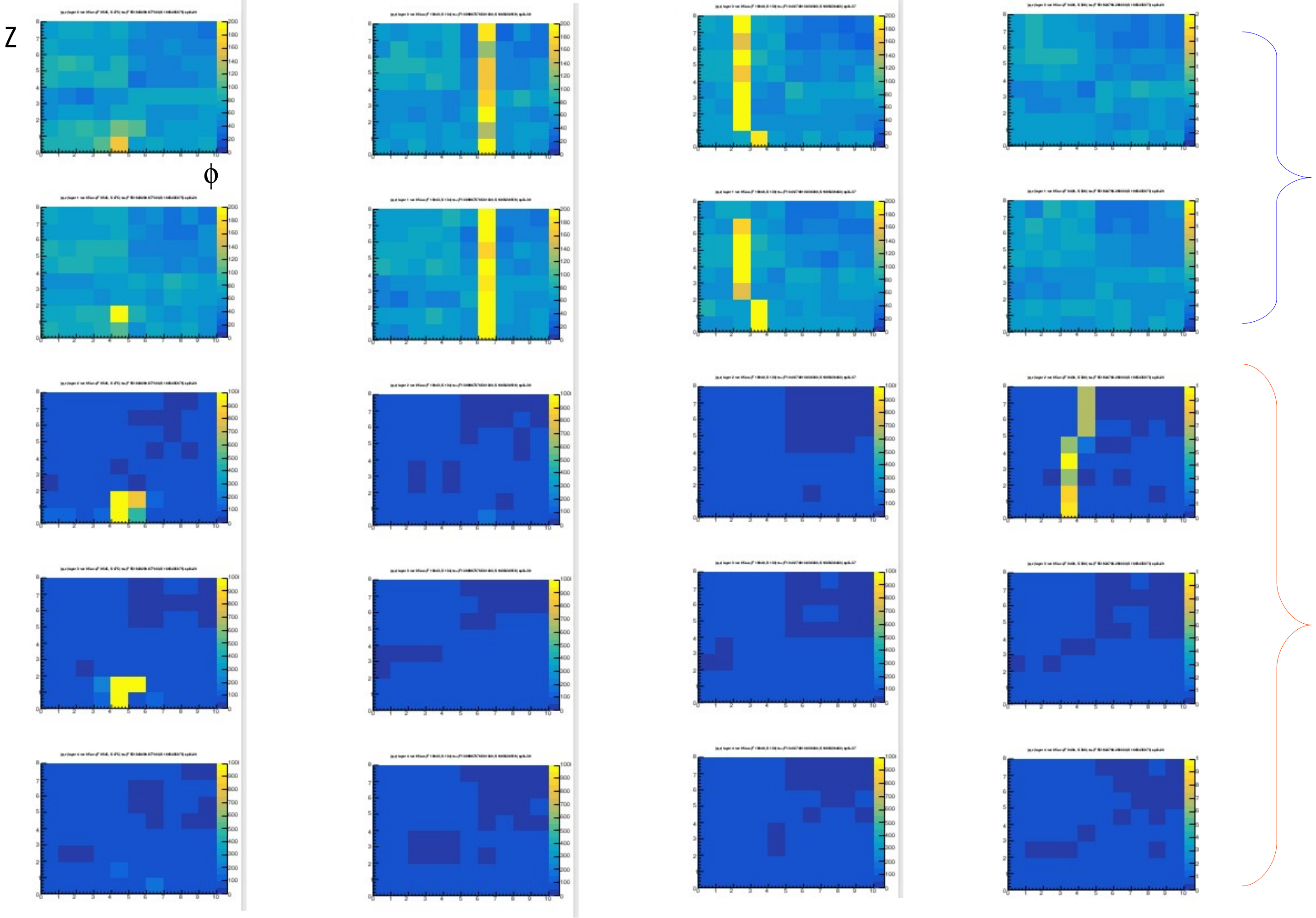
- **Readout boards**. We used a set of twenty 64-ch boards by CAEN (FERS, A5202) based on the WeeROC CitiROC-1A ASICs. They readout the signals' amplitudes and times for a total of 1280 channels (Fig. 7).

- **DAQ**. The JANUS program by CAEN was used. The system has been successfully synchronized offline with data from the silicon trackers and the Cherenkov counters during the test beam. Synchronization was achieved using a daisy-chain of LEMO cables connecting the FERS boards. An improved DAQ has been in the meantime been developed and it will be used in August 2023.

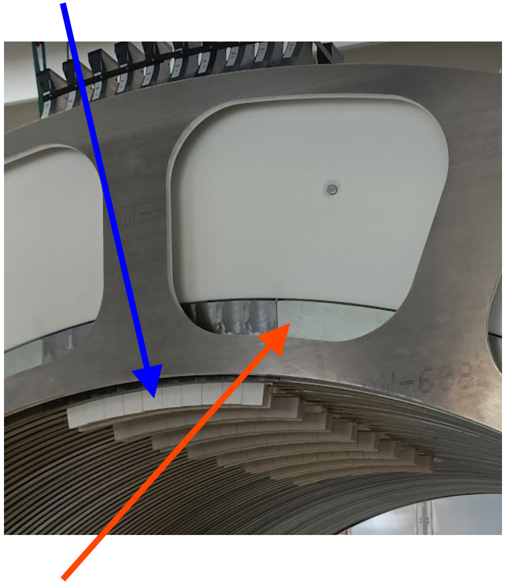
Event displays

Oct 2022 CERN-PS-T9

e-like	mip-like in t_0-layer	mip-like in t_0-layer	mip-like in 1 layer of calo



Tracker layers (“t_0”)



calorimeter layers

NB: channels not yet equalized with mips.

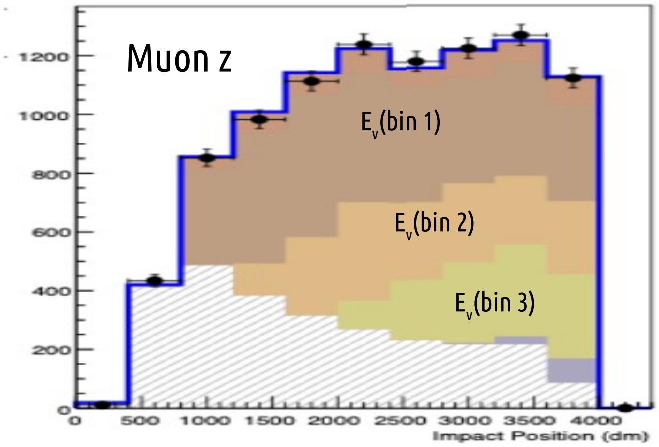
ENUBET: flux constraint

Link: Talk at nuFact2021 (A. Branca)

Uncertainty reduction on the flux

Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

Each histogram component corresponds to a bin in neutrino energy



Nominal and $\pm 1\sigma$ templates for the lepton observables are used to build the PDF:

$$PDF_{Ext.}(N_{exp}, \vec{\alpha}, \vec{\beta}) = N_S(\vec{\alpha}, \vec{\beta}) \cdot S(\vec{\alpha}, \vec{\beta}) + N_B(\vec{\alpha}, \vec{\beta}) \cdot B(\vec{\alpha}, \vec{\beta})$$

- $\vec{\alpha}$: set of hadro-production nuisance parameters (taking into account their correlations);
- $\vec{\beta}$: set of beamline nuisance parameters (uncorrelated);

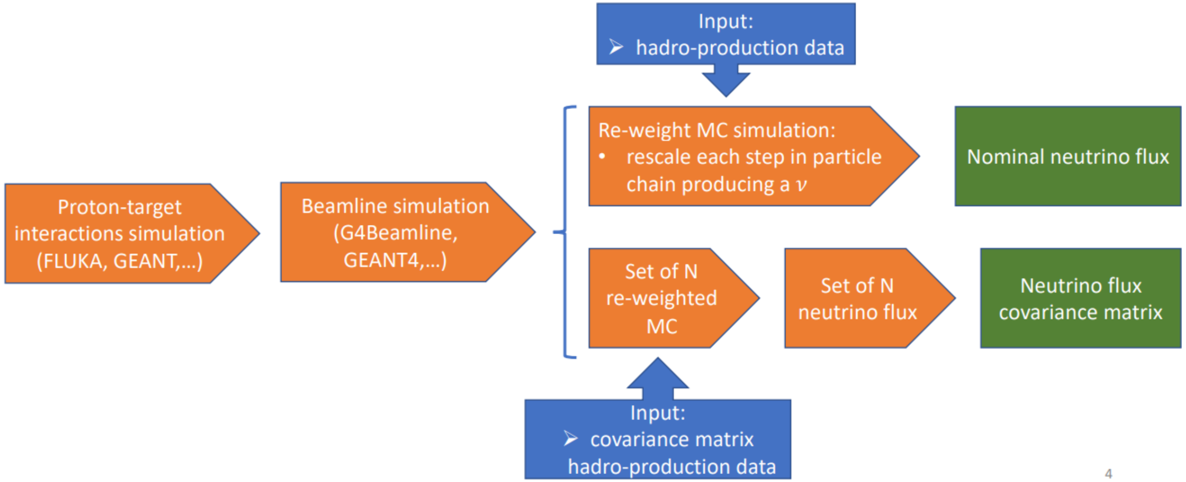
EML fit approach:

$$L(N|N_{exp}) = P(N \mid N_{exp}) \cdot \prod_{bins} P(N_i \mid PDF_{Ext.}(N_{exp}, \vec{\alpha}, \vec{\beta})_i) \cdot pdf_\alpha(\vec{\alpha} \mid 0,1) \cdot pdf_\beta(\vec{\beta} \mid 0,1)$$

parameters are constrained by their pdfs

ENUBET: flux constraint

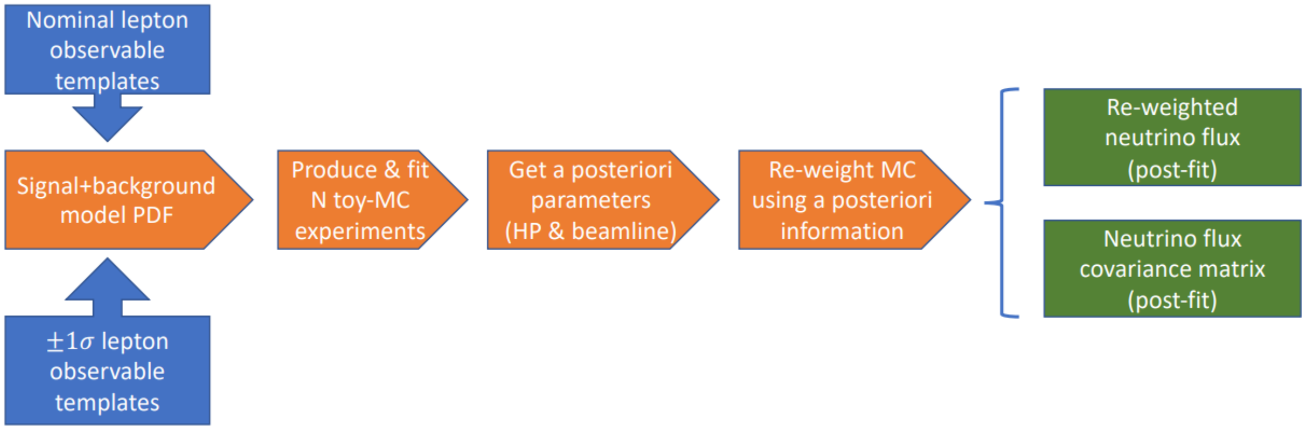
❖ Hadro-production: interaction of protons w/ target & hadrons produced inducing neutrinos



The hadroproduction model is a realistic one derived from a fit to real data obtained by the NA56/SPY experiment using 400 GeV proton interactions.

Flux systematic treatment including ENUBET information:

❖ build a model exploiting leptons templates in order to asses the impact on neutrino flux



Positron selection

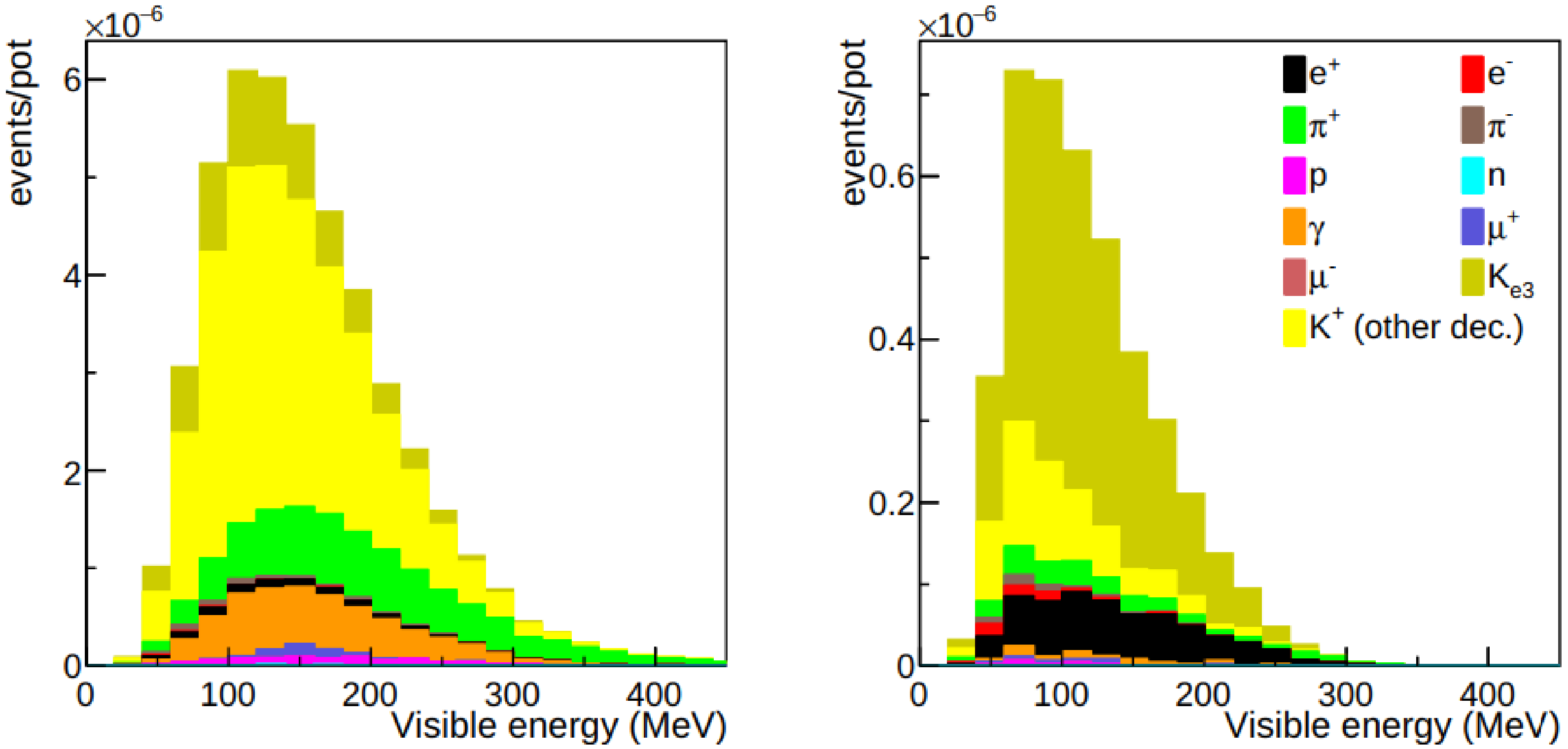


Fig. 19 Visible energy of the reconstructed events, before (left) and after (right) the cut on the NN classifier.

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

The concept of monitored neutrino beams

Conventional "meson-based" beam brought to a new standard → use a **narrow band beam** and shift the **monitoring at the level of decays** by instrumenting the decay tunnel (tag high-angle leptons)

An **ancillary facility** providing **physics input** to the long-baseline program

"By-pass" **hadro-production, protons on target, beam-line efficiency** uncertainties

ENUBET / NP06

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

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A. 681647, PI A. Longhin, **Padova University, INFN**

- **CERN Neutrino Platform: NP06**
- **Physics Beyond Colliders CERN study**

ENUBET: 60 physicists, 12 institutions

Aims at demonstrating the **feasibility** and **physics performance** of a neutrino beam where **lepton production is monitored at single particle level**

- **Instrumented decay region**
  - $K^+ \to e^+ \nu_e \pi^0 \to$ (large angle) e^+
  - $K^+ \to \mu^+ \nu_\mu \pi^0$ or $\to \mu^+ \nu_\mu \to$ (large angle) μ^+
- **ν_e and ν_μ flux prediction from e^+/μ^+ rates**

Requires a **collimated p-selected hadron beam**
→ **only decay products hit the tagger → manageable rates**
Requires a **"short", 40 m, tunnel** (~all ν_e from K, ~1% ν_e from μ)
→ **Bonus:** an **"a priori" constraint on the ν energy** by exploiting correlations between E_ν and the position of interactions in the detector (narrow band beams)

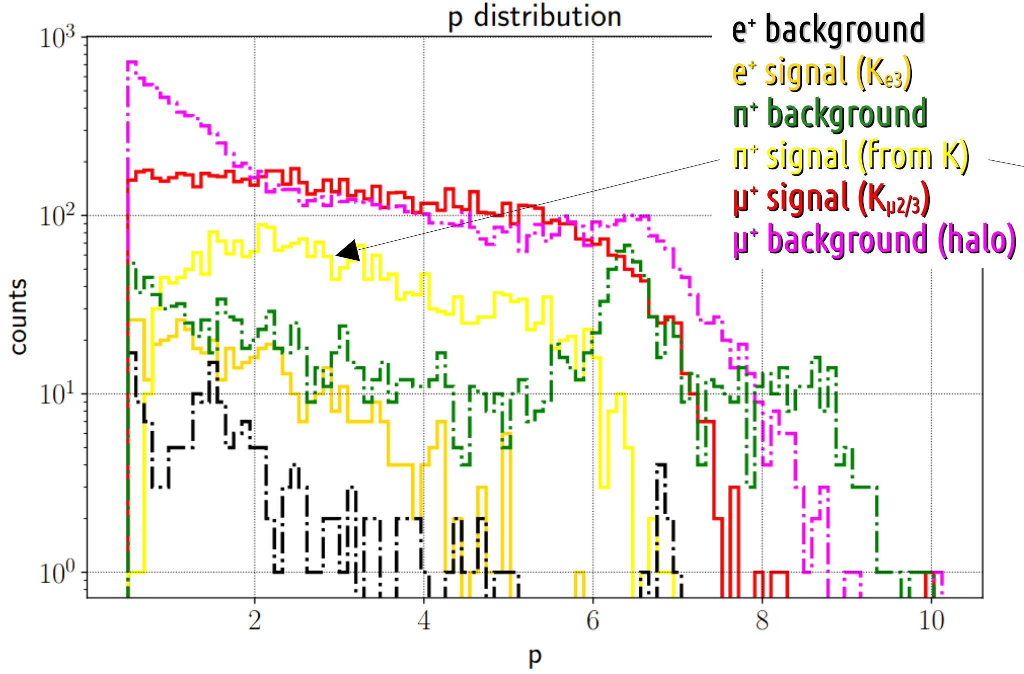
pillars

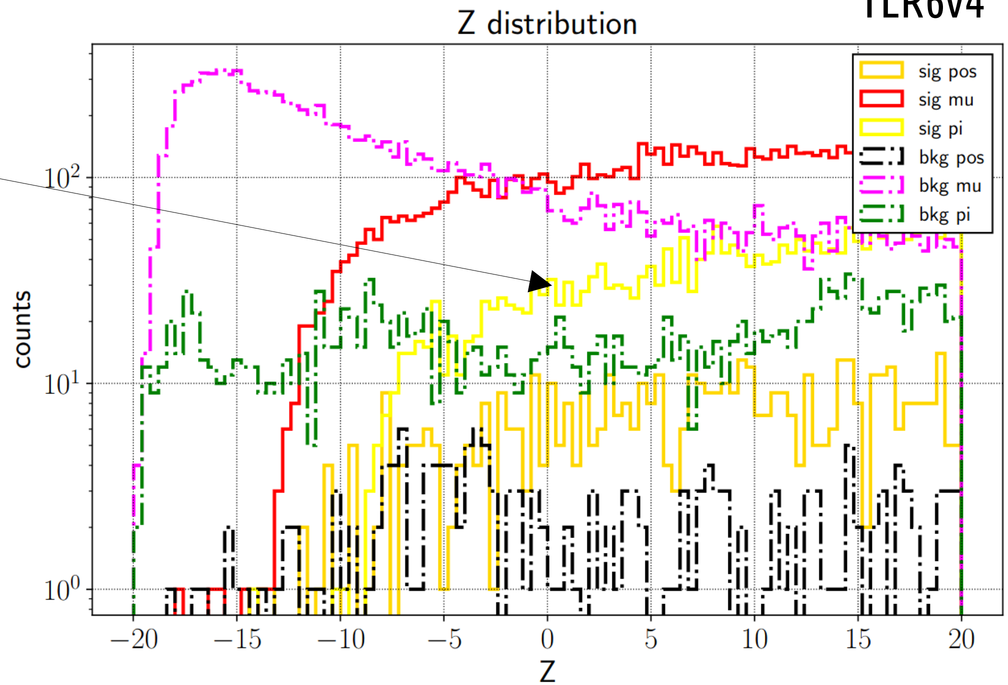
1) Design/simulate the layout of the **hadronic beamline**
2) Build/test a **demonstrator** of the instrumented decay tunnel

Pion sample

Particles hitting the tagger at true level

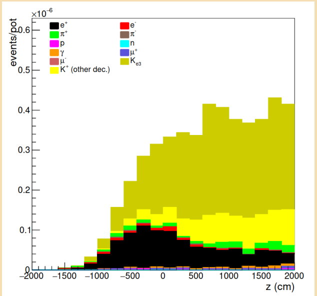
TLR6v4





By selecting events not classified as e⁺ or muons (already available) we can access the sample of pions from kaon decays where S/B could be good (yellow component) and efficiency high (large B.R.) → independent constraint on the kaon yields → fluxes of ν_e and ν_μ. In the pipeline.

1 -



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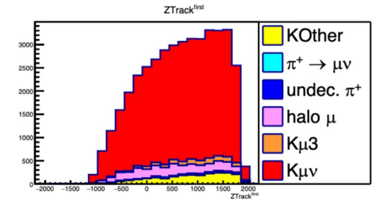


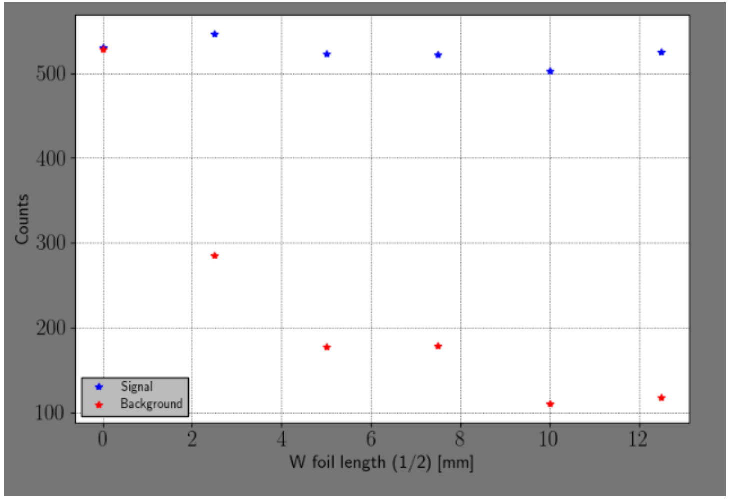
Beamline optimization: ideas/prospects

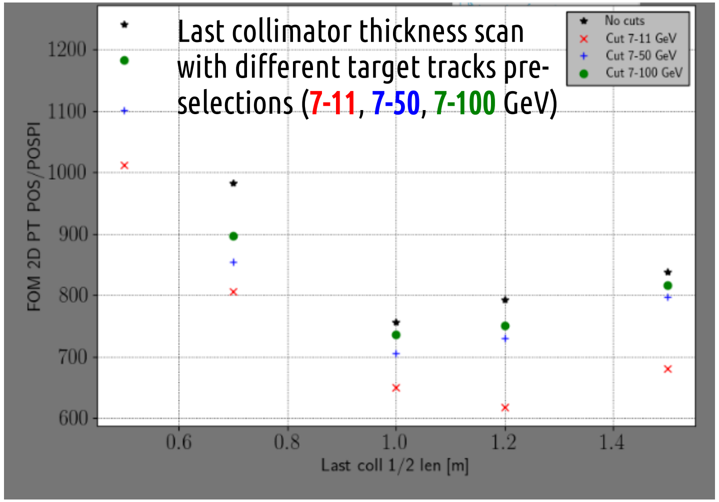
- We have taken the **optimal solution** from the algorithm and tried to **vary single parameters one at a time**.
  - i.e. W e^+ absorber foil. Not in the generic optimization, came from a previous study with G4BL → scan says 5 mm is still good
  - last collimator length. The same minimum as the one found by the multidimensional search ("sanity check" of the complex algorithm).

- A more refined **FOM** taking into account the **distributions of signal and background** implemented (E_{vis} vs Z_{impact}). More statistics is needed at constant CPU time so:
  - **Only track target particles in [7, 100] GeV** → CPU time down by x 3 with a limited reduction in the estimated background. Most importantly, the shape of the dependence of the FOM on parameters is preserved → "land" on the same minimum … but faster.
  - **Parametrize the variables of incoming background** to increase statistics and repeat simulation on parametrized pdfs.

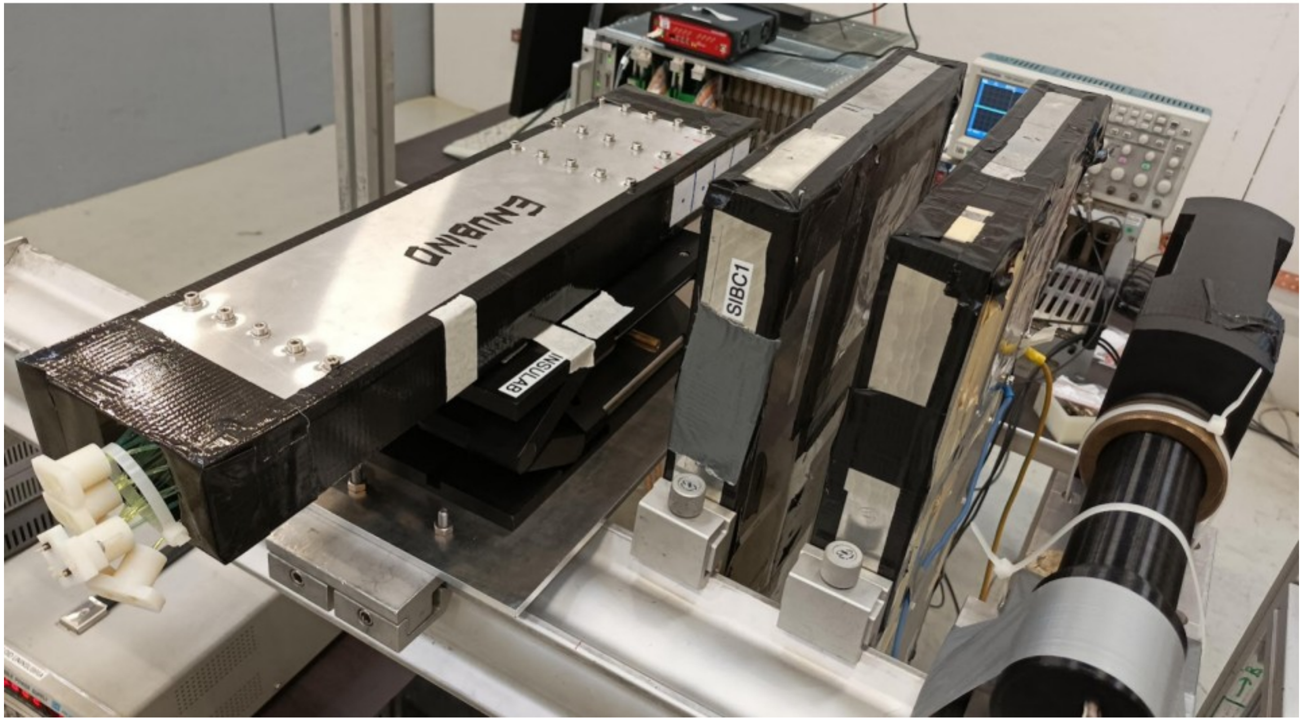
- Finally with this empowered tool we would like to explore the **parameters of the upstream part of the beamline**

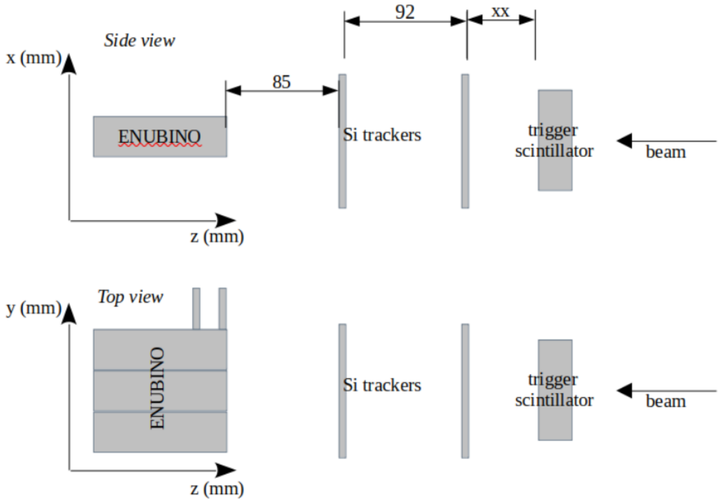
W-foil thickness scan on the optimized conf.

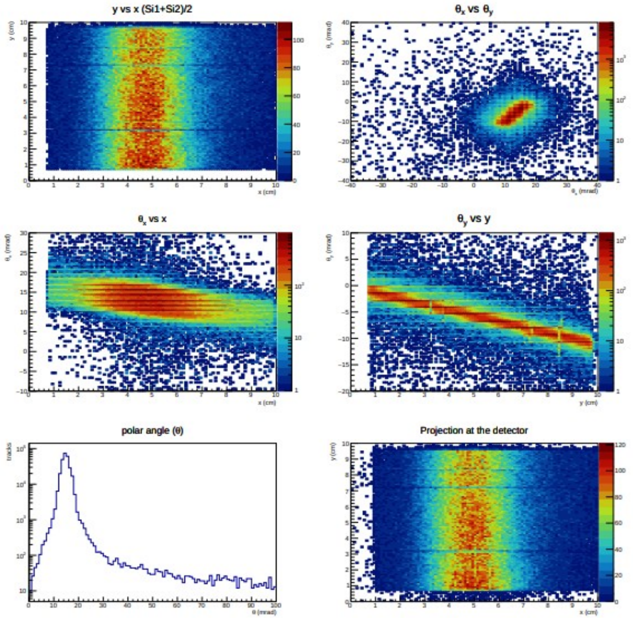




The Nov 2021 CERN-PS test beam

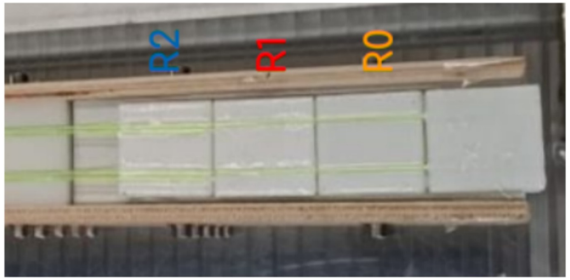






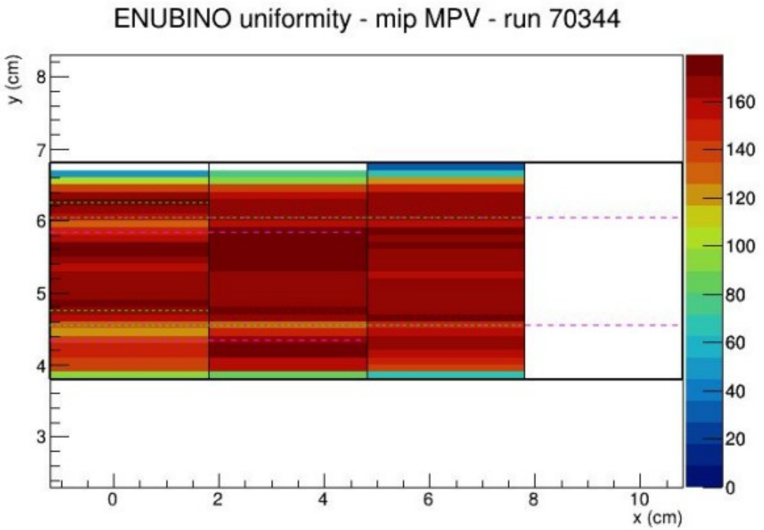
+15 GeV hadronic beam (parasitic to TOTEM)
Allowed to test the final configuration chosen for the demonstrator

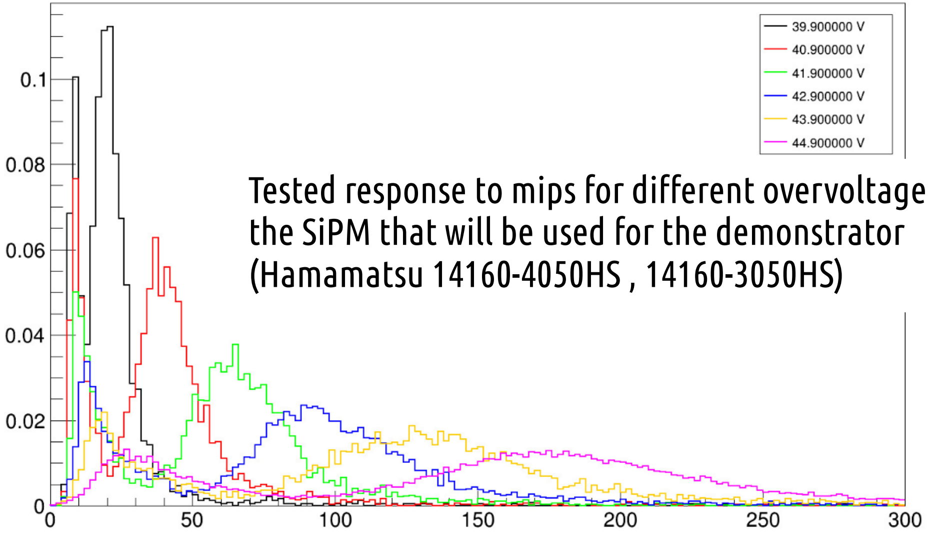
The Nov 2021 CERN-PS test beam



Light collection uniformity, response to mip, test of light readout scheme and SiPM choice.

More results soon (i.e. cross-talk)

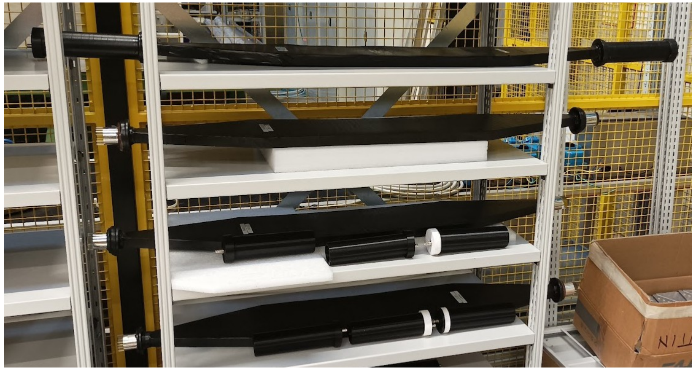


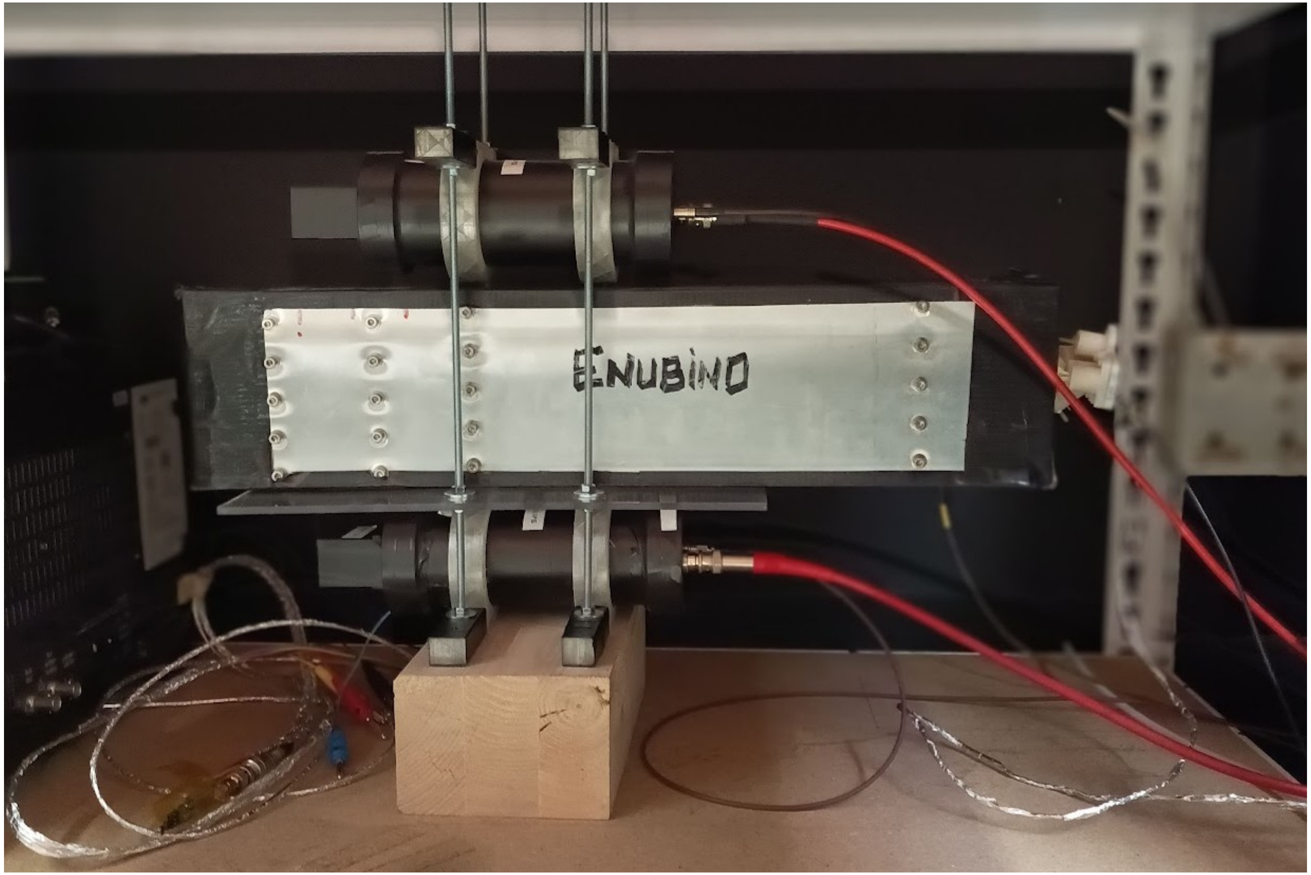


Tested response to mips for different overvoltage for the SiPM that will be used for the demonstrator (Hamamatsu 14160-4050HS , 14160-3050HS)

The Nov 2021 CERN-PS test beam

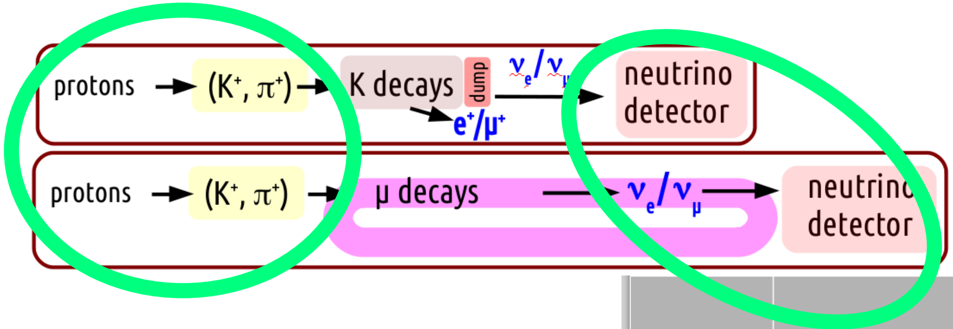
Caracterization continuing at LNL with cosmics





ENUBET-nuSTORM synergies

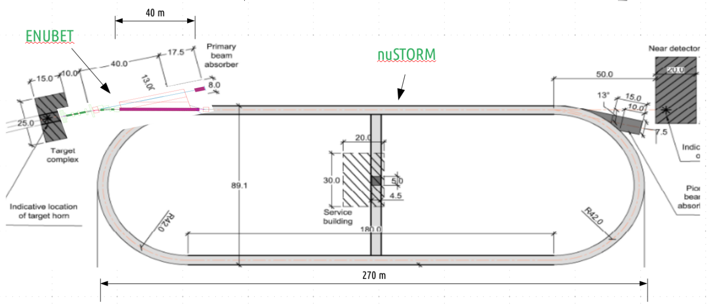
nuSTORM can be seen (simplistically) as an “ENUBET without a hadron dump” where pions and muons are channeled into a ring. Large room for smart ideas to match the requirements of the two experiments



- common points: **proton extraction line, target station, 1st stage of meson focusing, proton dump, neutrino detector (possibly)**

- But also significant differences (and scale)

	Decay region	Hadron dump	Proton extraction, energy, focusing	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps μ in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow extraction (+ quad triplets) “slow” in bursts (+horn) 400 GeV	similar	Similar but at ~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. μ kept: the most interesting flux parents.	Fast extraction (+horn) 100 GeV	similar	Similar but at > 300 m from target (ring straight section)



Engineering studies starting within Physics Beyond Colliders

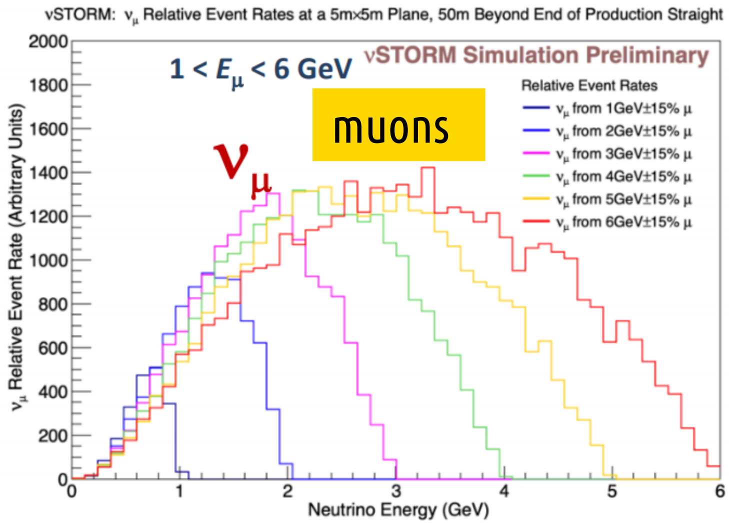
Fluxes decomposition

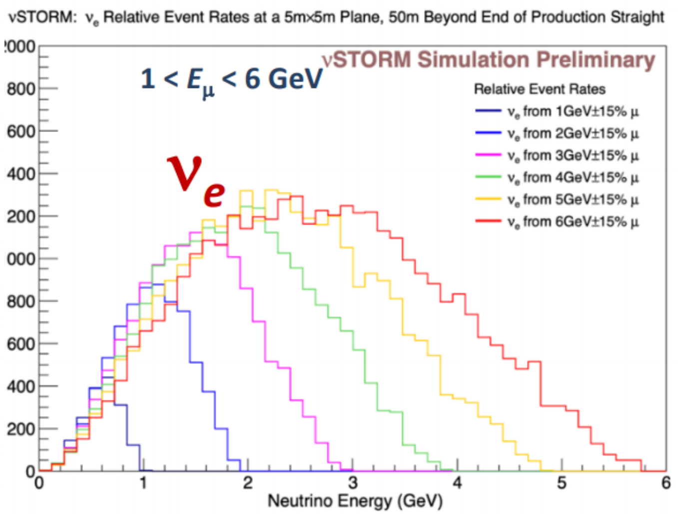
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

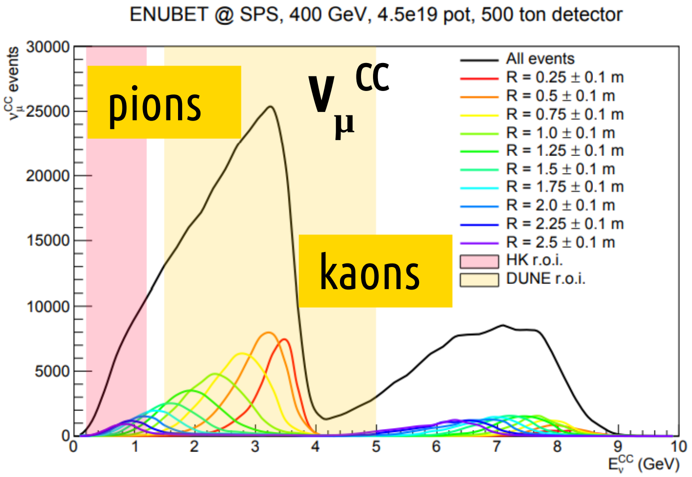
ENUBET narrow-band off-axis technique:

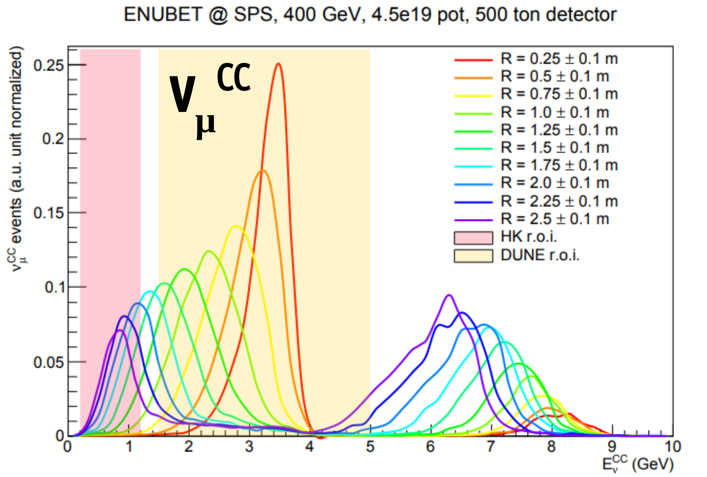
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable.

A kind of "off-axis" but without having to move the detector (thanks to the low distance of the detector) !



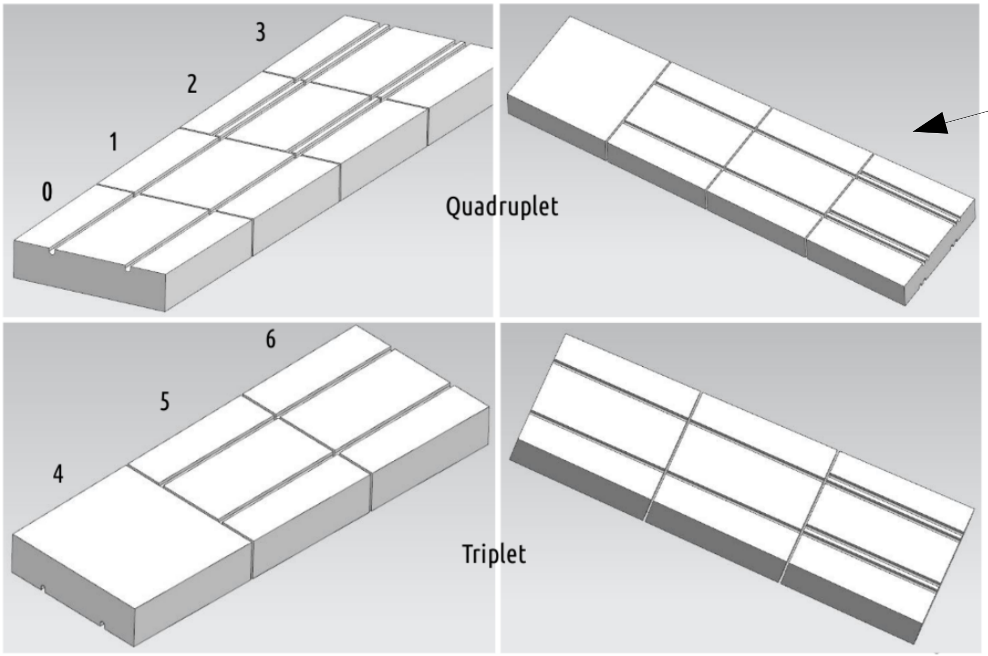




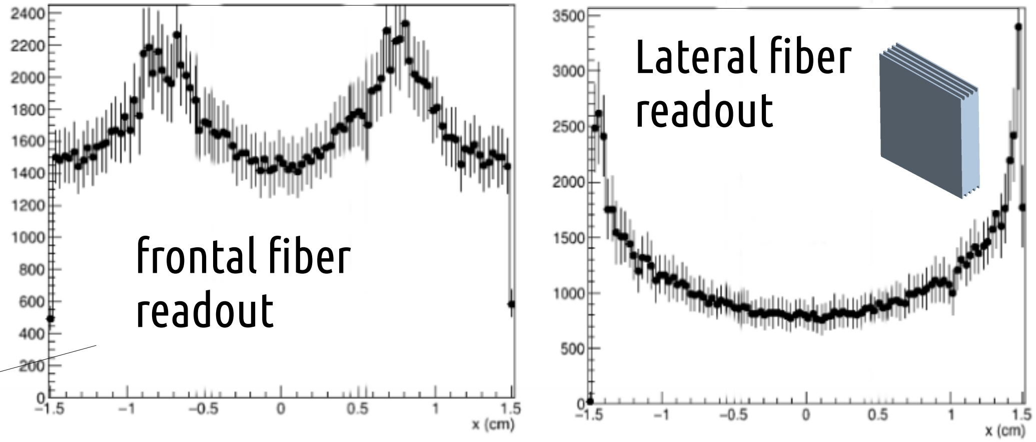


Updated light readout scheme

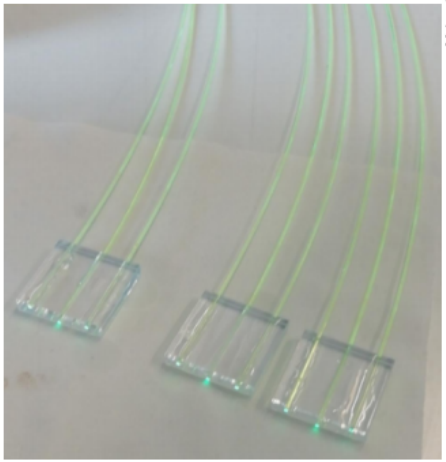
- From lateral to frontal light collection
- Safer for injection molding. More uniform, efficient.
- Each tile has readout grooves and “transit” grooves.
- Readout grooves on alternate sides.
- Staggering for the two tiles at larger r.

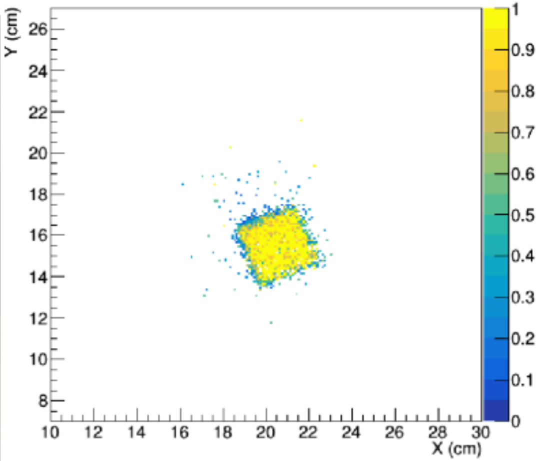


GEANT4 optical simulation



Uniformity tests with cosmic rays

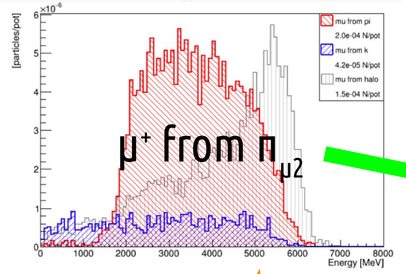


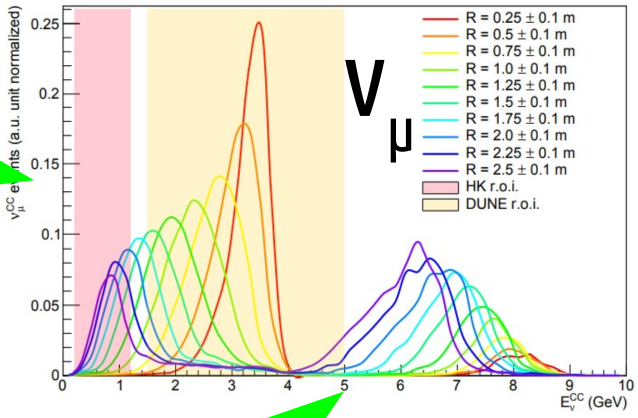


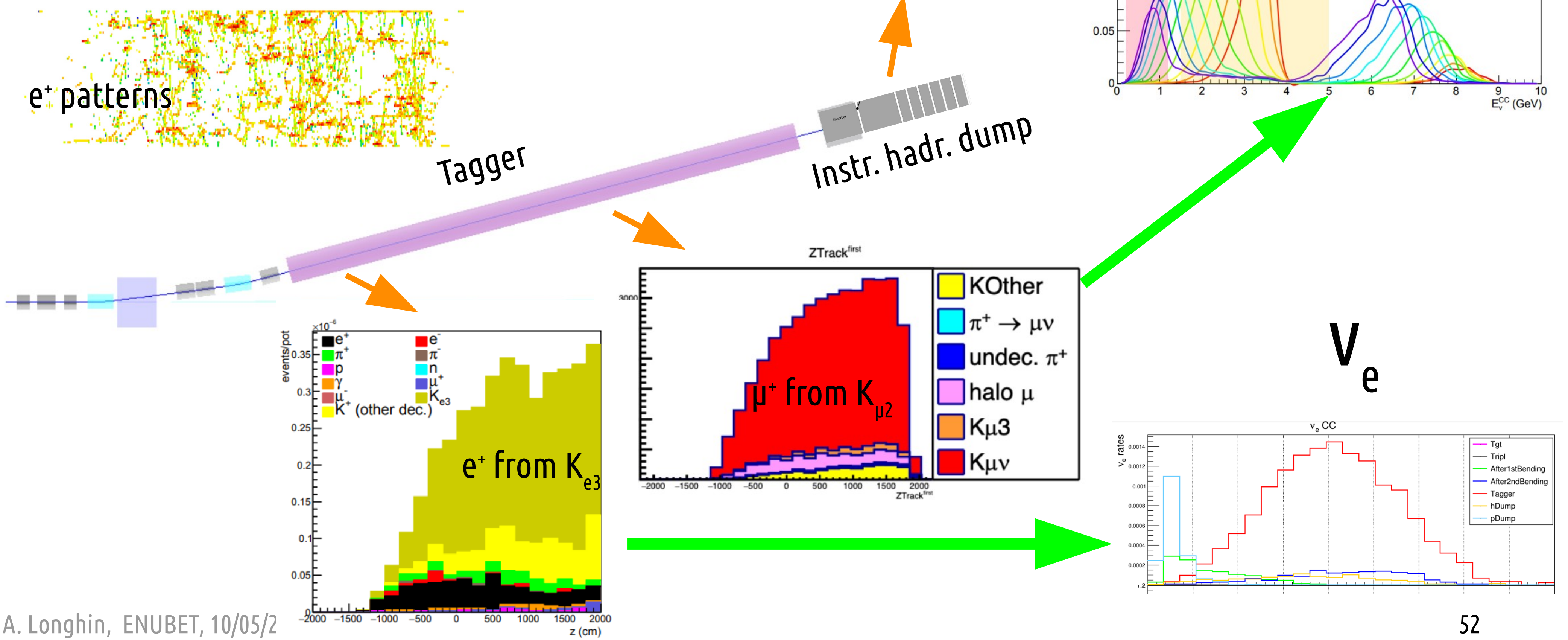
Lepton monitoring

Tagger: leptons from K (ν_e and high-E ν_μ)

Hadron dump instr: μ from π (low-E ν_μ)

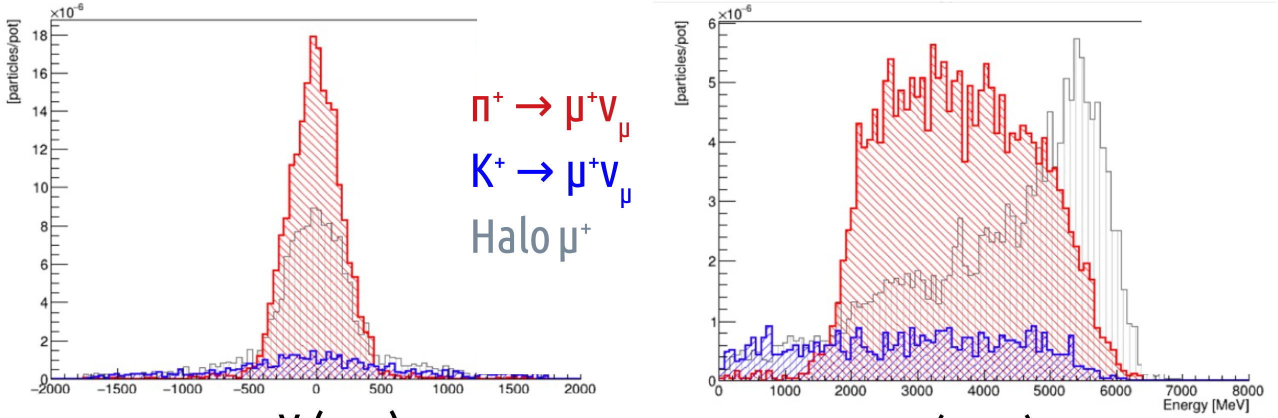






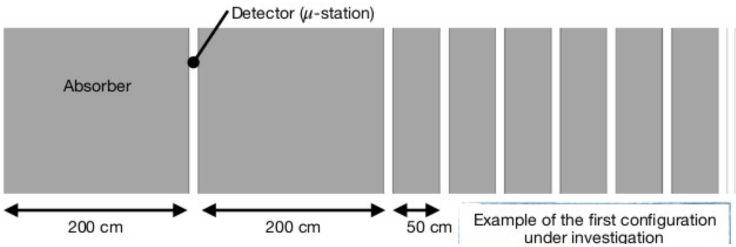
Forward region muons reconstruction

Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.



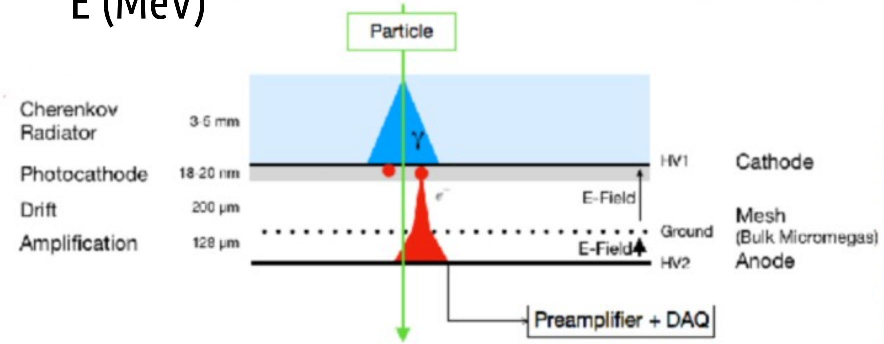
Y (mm)

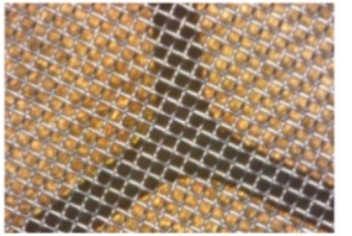
E (MeV)



The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n$_{eq}$/cm^2.

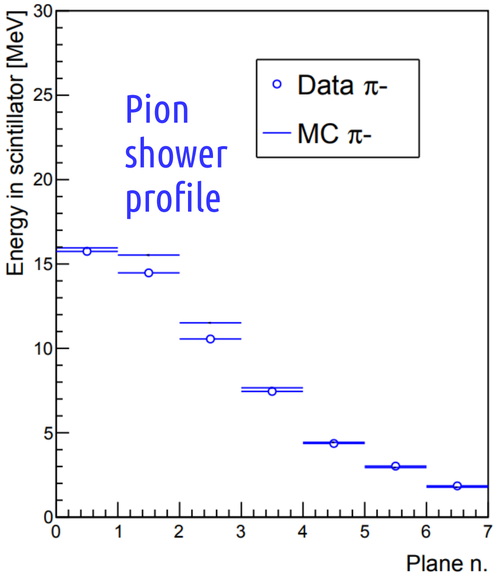
Design being defined. Possible candidate: fast Micromegas detectors employing Cherenkov radiators + thin drift gap (PIMENT). Bonus: excellent timing.





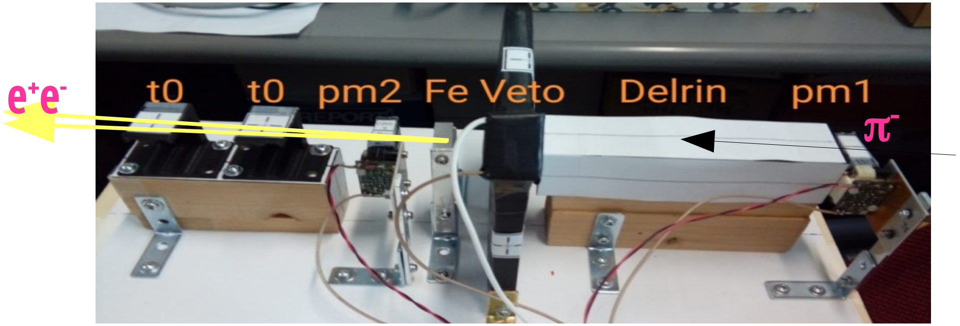
ENUBET: prototypes at the CERN-PS

JINST 15 (2020) 08, P08001

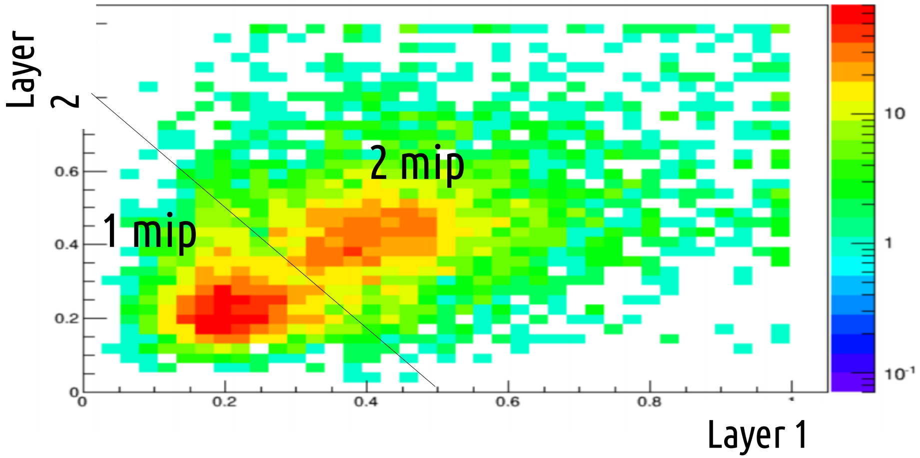


charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2



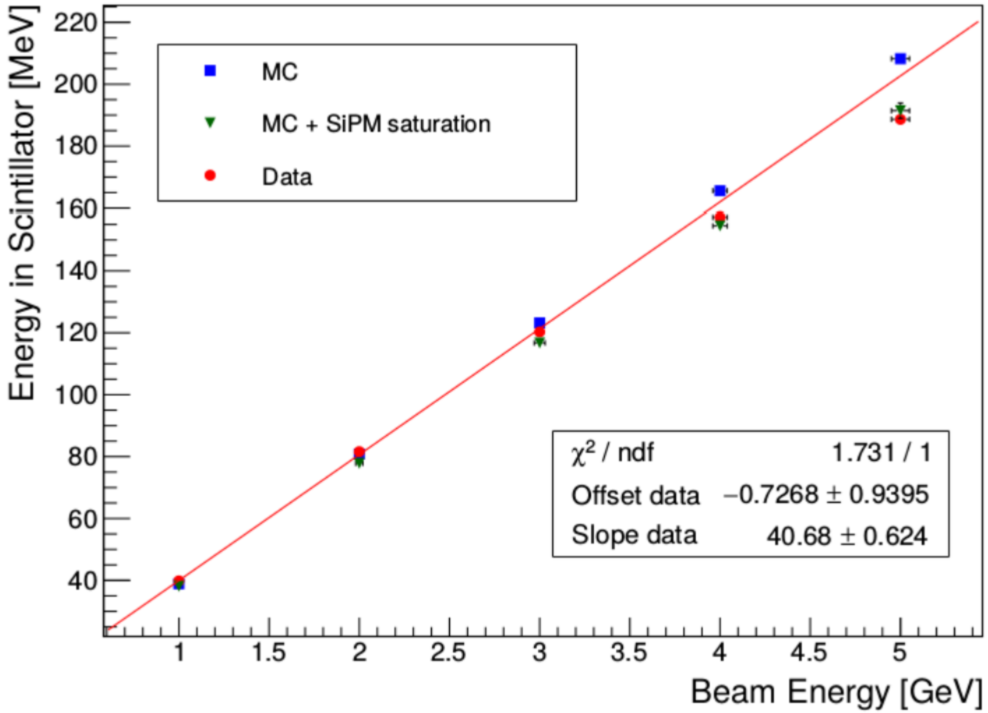
$\sigma_t \sim 400$ ps



JINST 15 (2020) 08, P08001

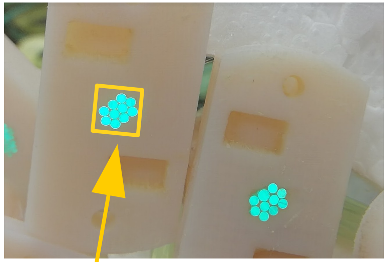
ENUBET: prototypes at the CERN-PS

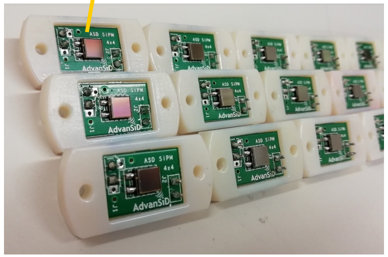
$$N_{\text{fired}} \simeq N_{\max}\left(1 - e^{-N_{\text{seed}}/N_{\max}}\right)$$



$$N_{\text{seed}} \equiv (1 + P_{x-talk}) \cdot N_{pe}$$

$$N_{\max} \simeq 5000 < 9340$$





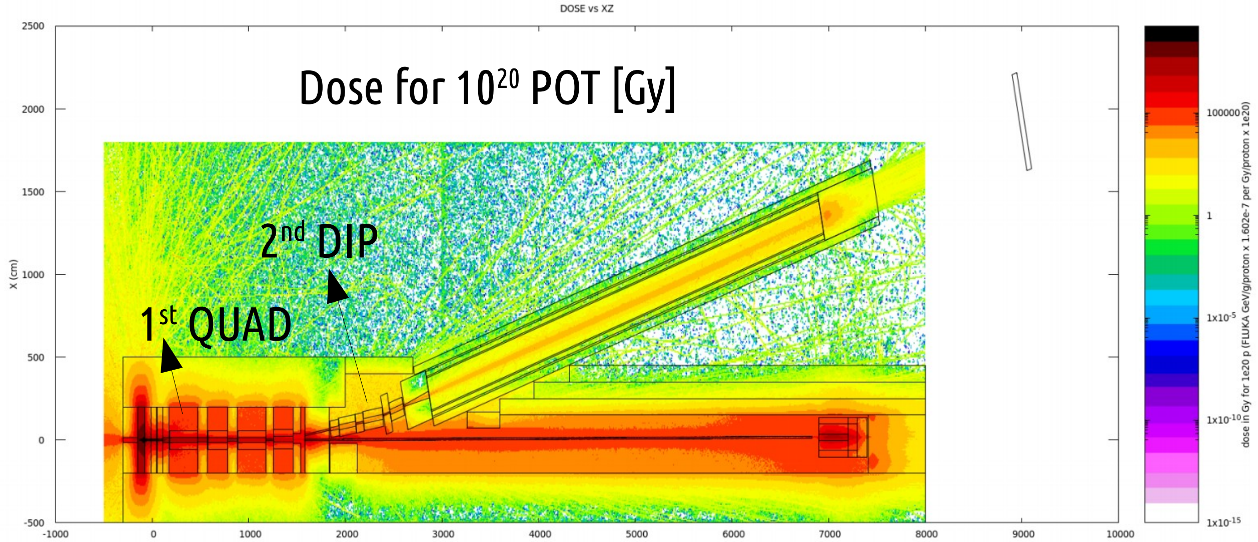
New SiPMs under test (NUV, RGB high density and low cross talk from FBK)

FLUKA irradiation studies

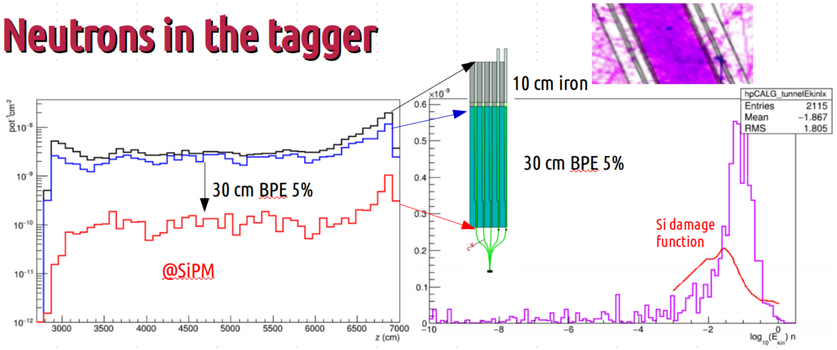
Detailed FLUKA simulation of the setup

Guided the design of the detector technology for the demonstrator

Good lifetime of instrumentation and focusing elements achieved.

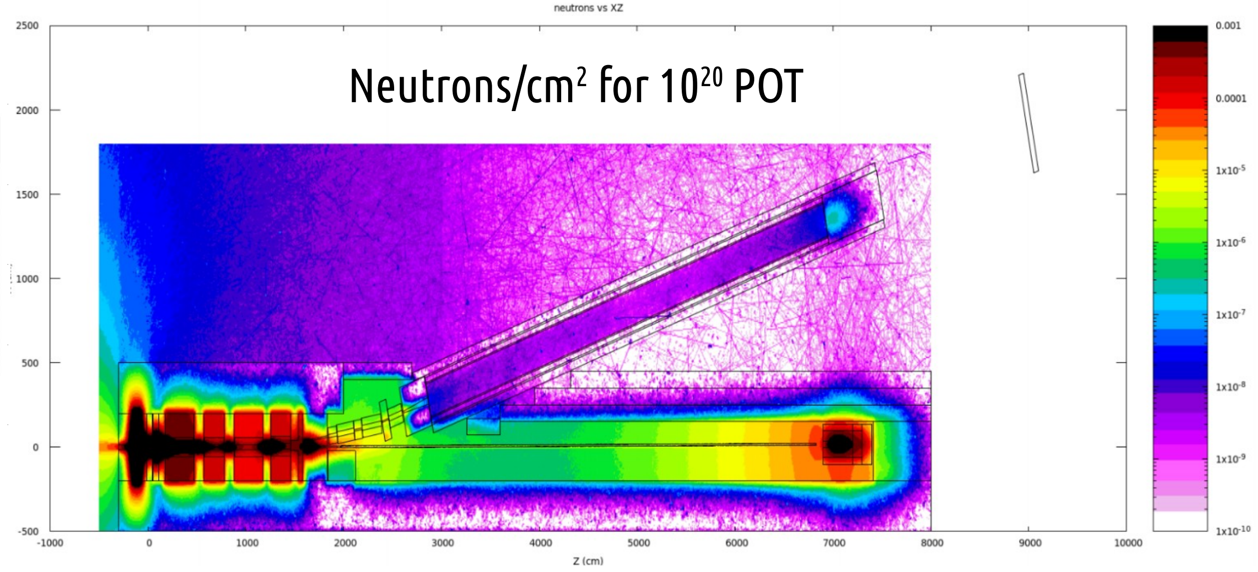


Neutrons in the tagger



BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7×10^{-11} n/POT/cm^2 ~ **10 x reduction**
(7×10^9 n/cm^2 for 10^{20} POT)

E_{kin} of surviving neutrons is O(10-100) MeV



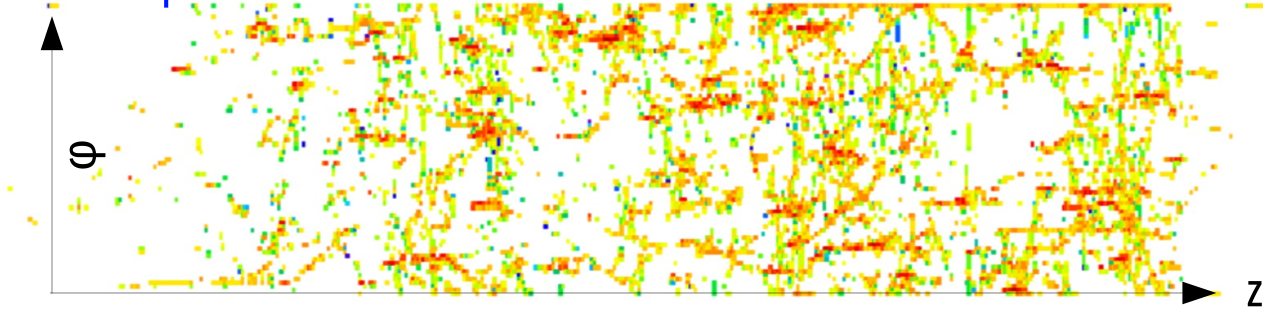
ENUBET: lepton reconstruction

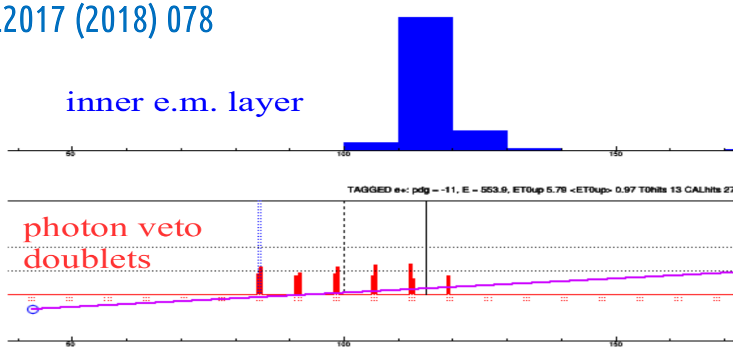
Talk by F. Pupilli

GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018.
Clustering of cells in space and time. Treat **pile-up** with waveform analysis. Multivariate analysis.

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

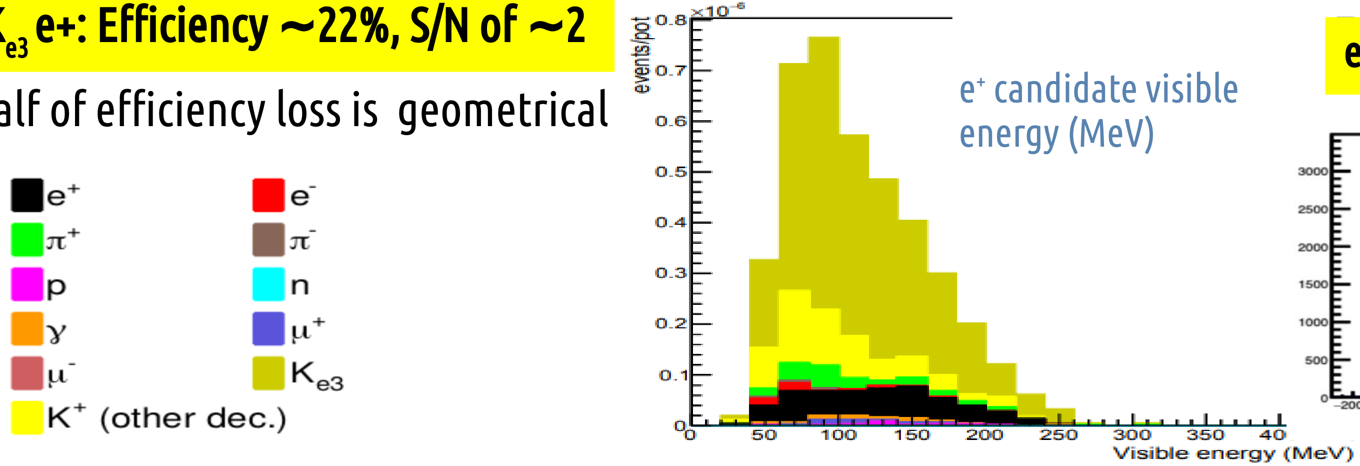
Hit map for e^+





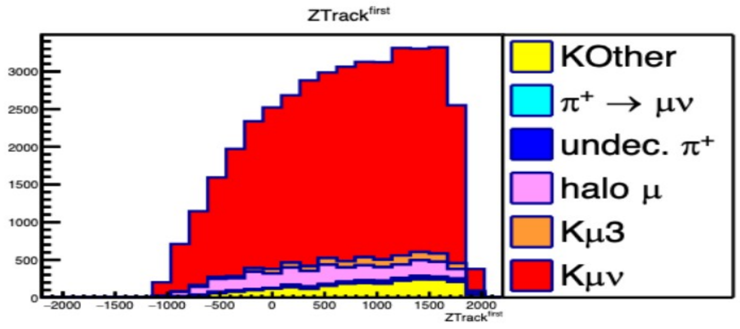
K_{e3} e+: Efficiency ~22%, S/N of ~2

Half of efficiency loss is geometrical



e^+ candidate visible energy (MeV)

efficiency 34% ($K_{\mu2}$) and 21% ($K_{\mu3}$) S/B ~ 6.1

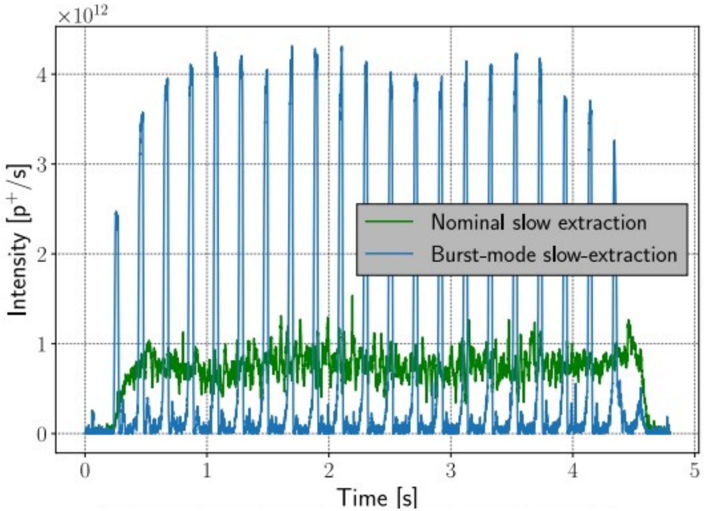


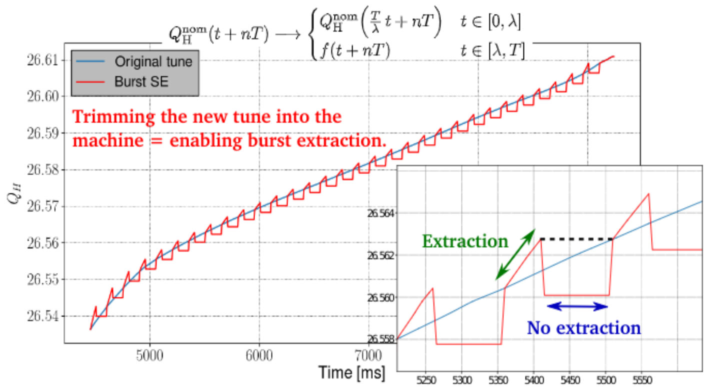
μ^+ candidate z coord (cm)

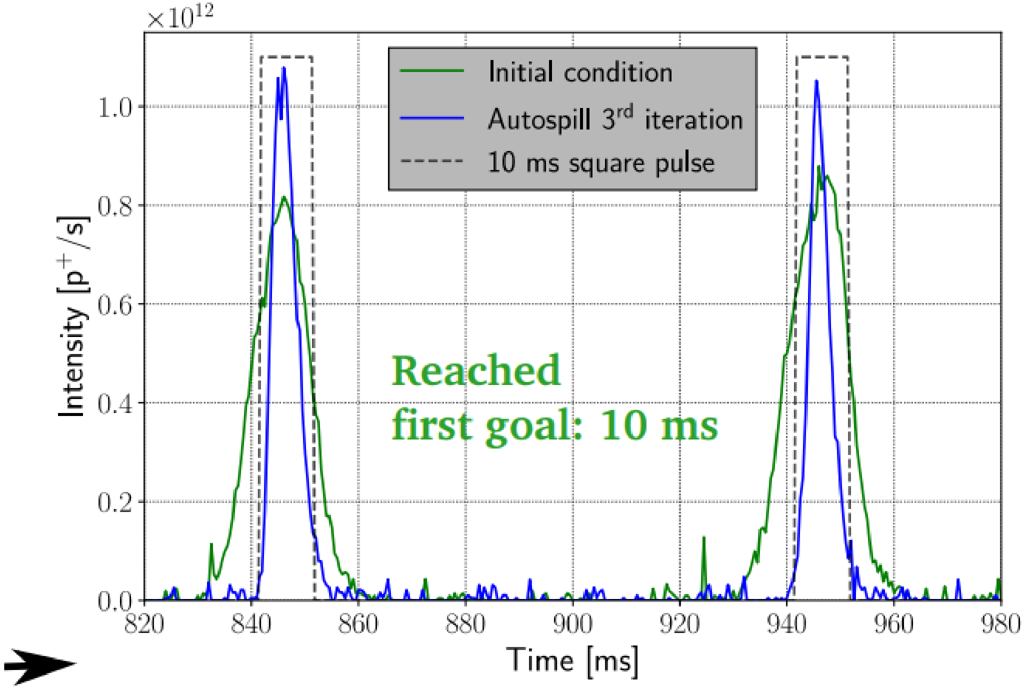
Proton extraction R&D for horn focusing

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

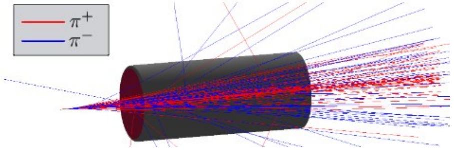




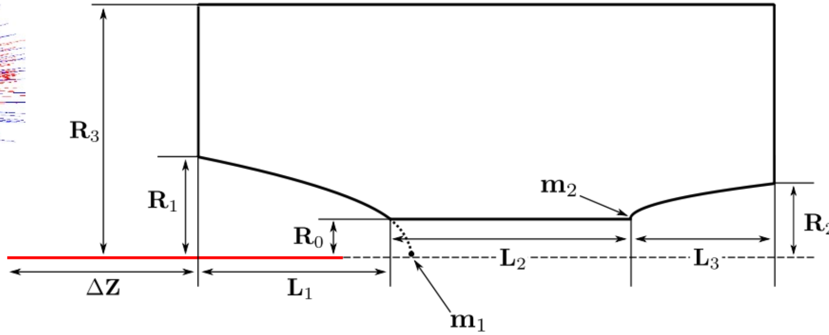


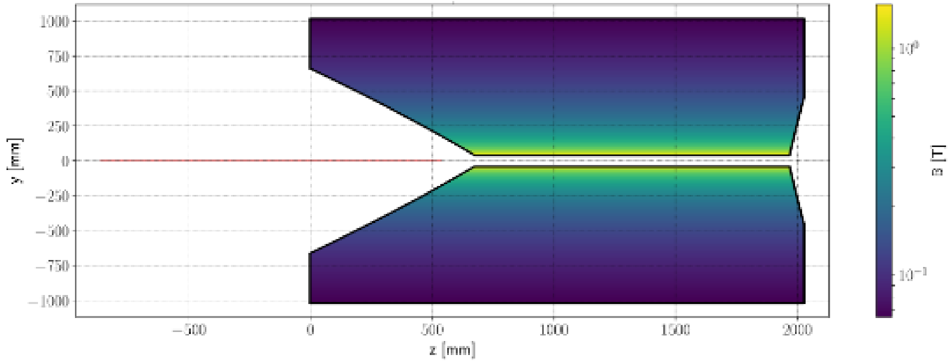
PhD thesis of M. Pari (UniPD + CERN doctoral).
Defended 23/2/21.

Horn optimization



- New **double-parabolic** geometry (formerly MiniBooNE-like)
- New **genetic algorithm** implemented successfully to sample the large space of parameters.
- FoM is ~ number of collimated K^+ with p ~8.5 GeV/c
- Convergence in O(100) iterations
- First candidate designs worked out

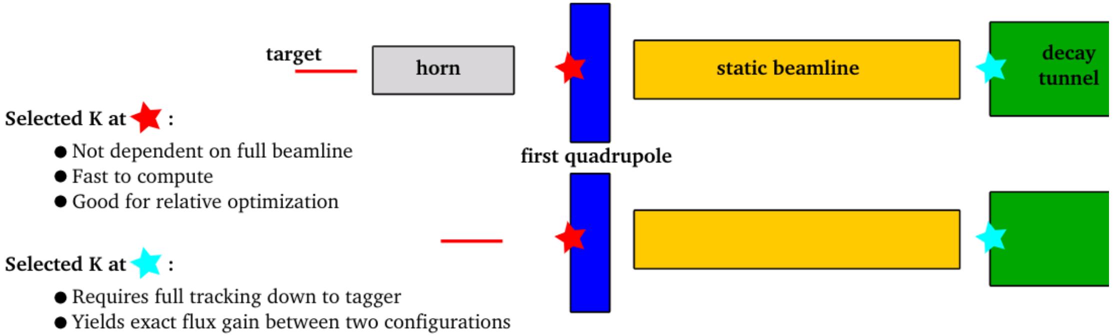




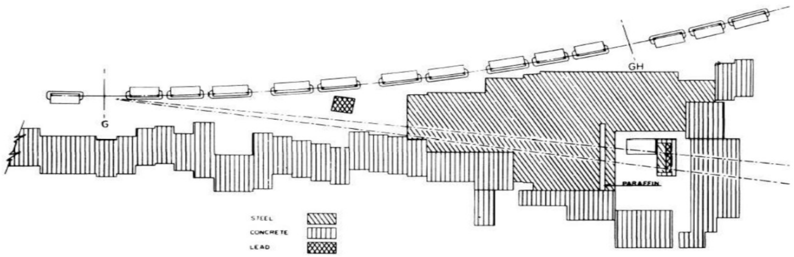
We were able to reach values of the **standalone FoM (★) of x 3 higher than the static case**. These results confirm an improvement w.r.t. early studies.

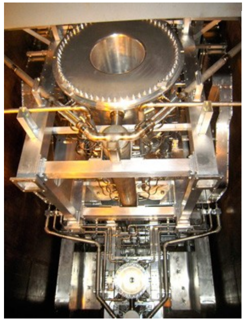
When plugged to the existing beamlines the gain factor reduces to only **x 1.5 → next step:** dedicated beamline optimization (★) to profit of the horn-option initial gain → larger apertures for initial quads.

Can extend the same systematic optimization tool.

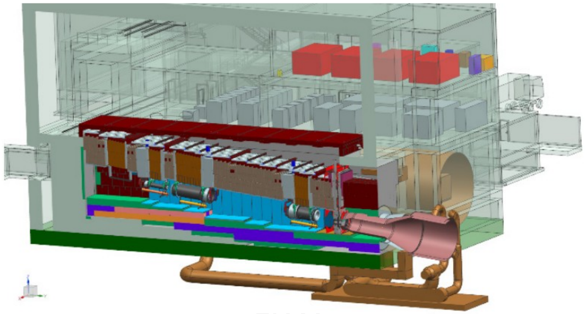


Accelerator based neutrino beams





J-PARC



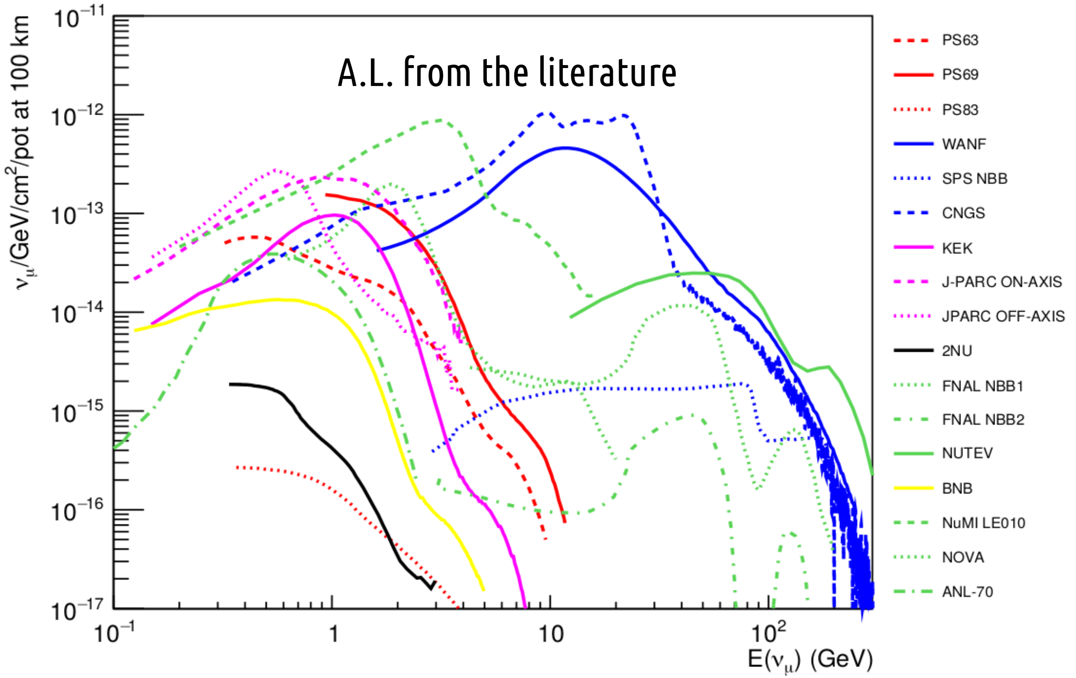
FNAL

Pion based neutrino beams have a **~60 y long history.** Lots of physics done at different energies.

Enormous **increase in intensity** → a leap in technology and complexity

More "**brute force**" than conceptual innovations. Still OK in the era of "statistical errors-dominance" and "large θ_{13}" but ...

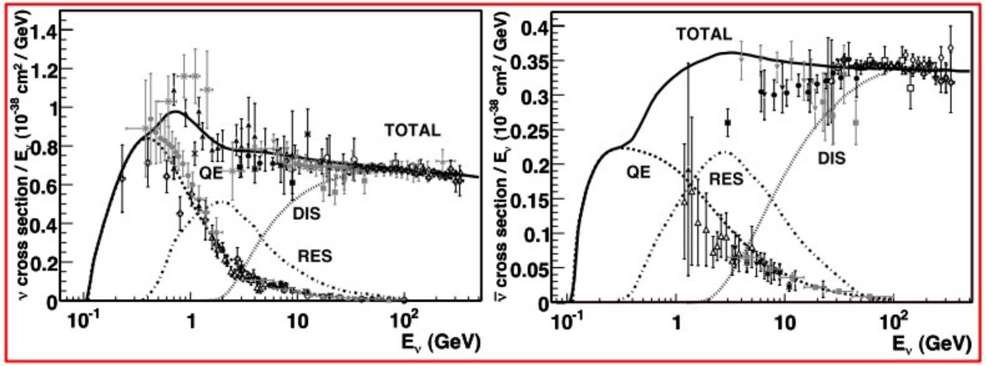
New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.

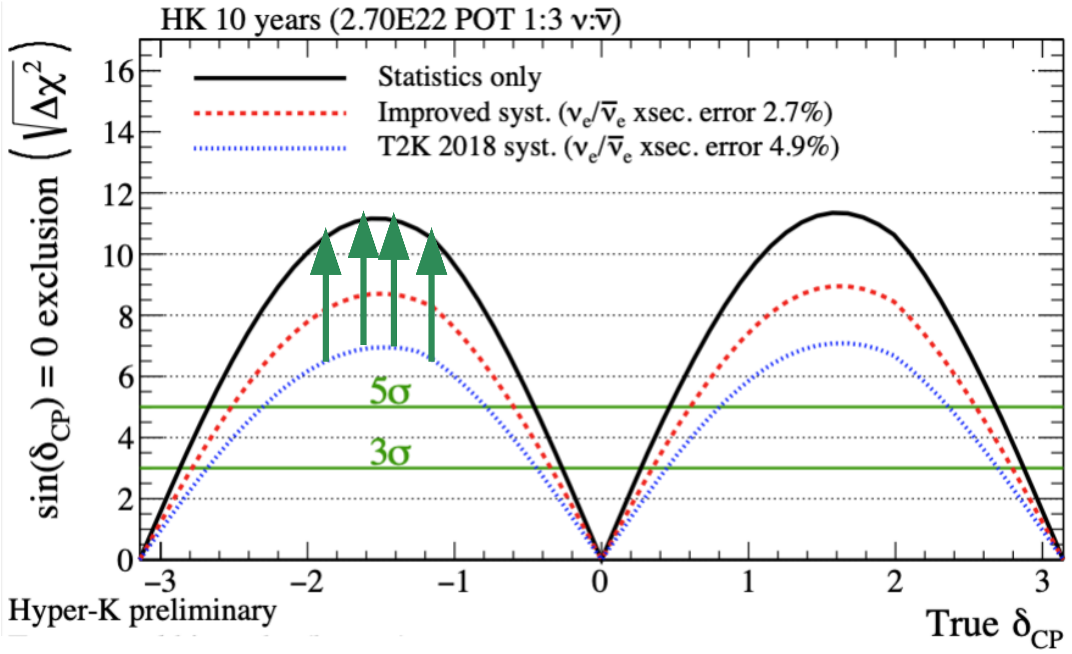


Precision for the Hyper-K/DUNE era

F. Di Lodovico, Neutrino Telescopes 2021

Improving the knowledge of (electron) neutrino and anti-neutrino cross sections in the GeV region strengthens significantly the physics reach of next generation Super-beams in construction





ENUBET and nuSTORM

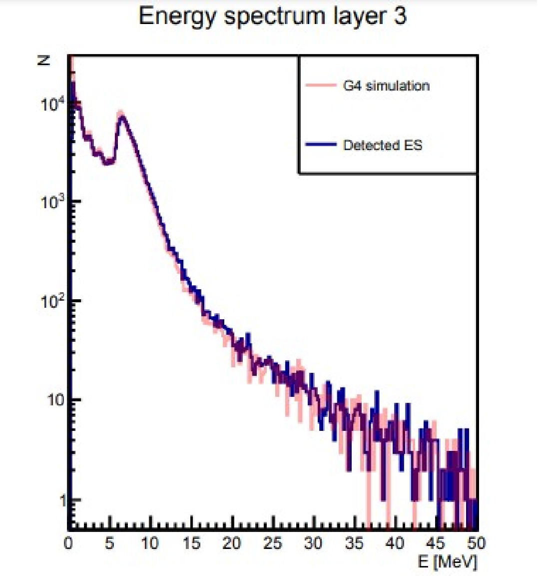
(see also the **European Strategy** Physics Briefbook, arXiv:1910.11775)

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

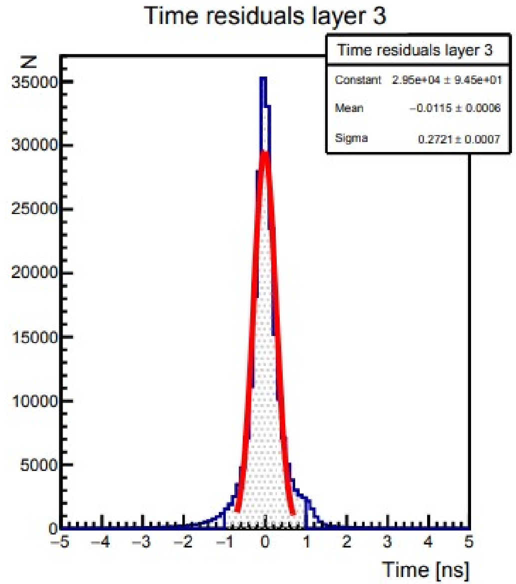
Waveform analysis

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.

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



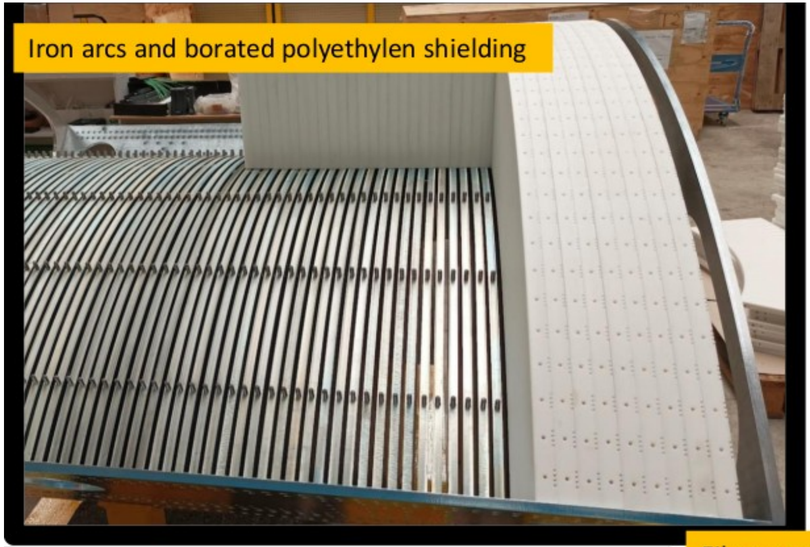
Matching between true and reconstructed time (500 MS/s). 270 ps.

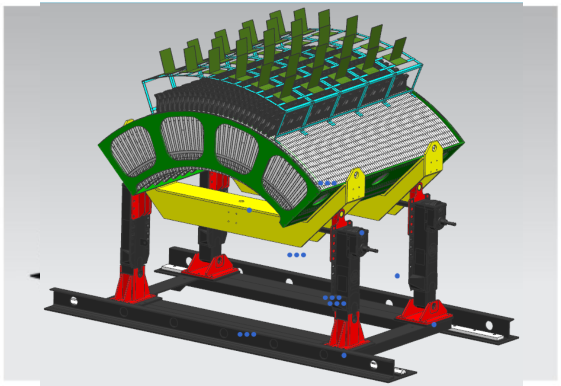


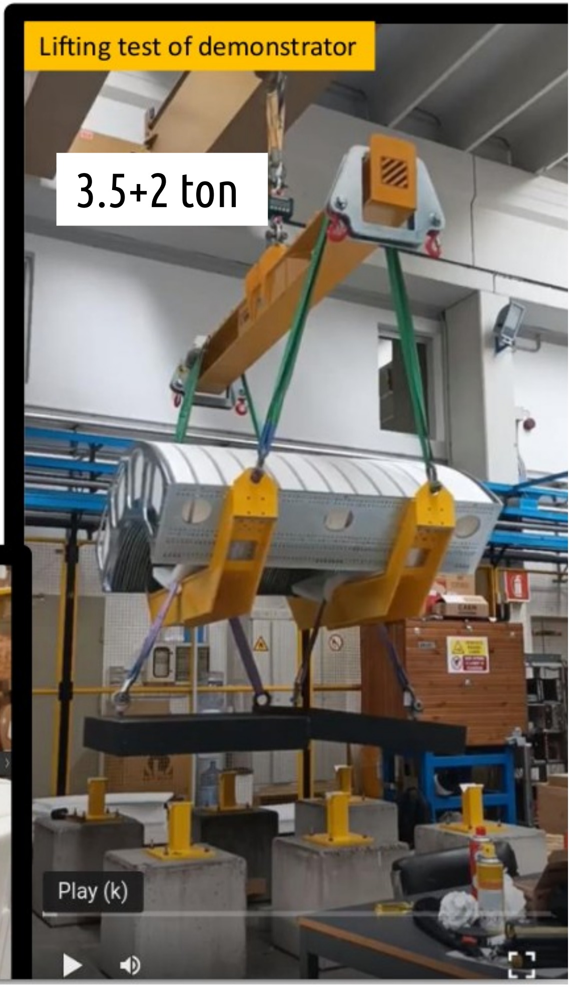
Peak finding efficiencies:
Slow ~ 4.5 x 10^{13} POT in 2s
Fast ~ horn ~ 10 x slow

Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%

Demonstrator construction at LNL-INFN labs





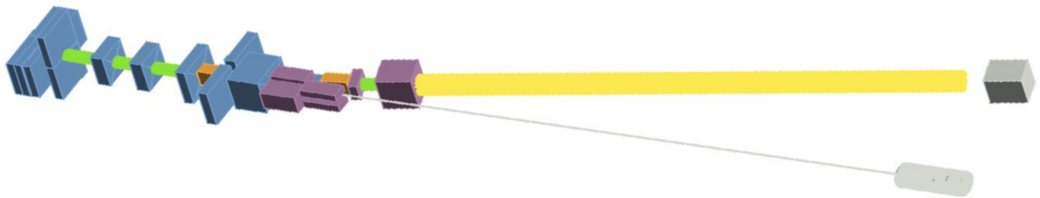


ENUBET: flux constraint

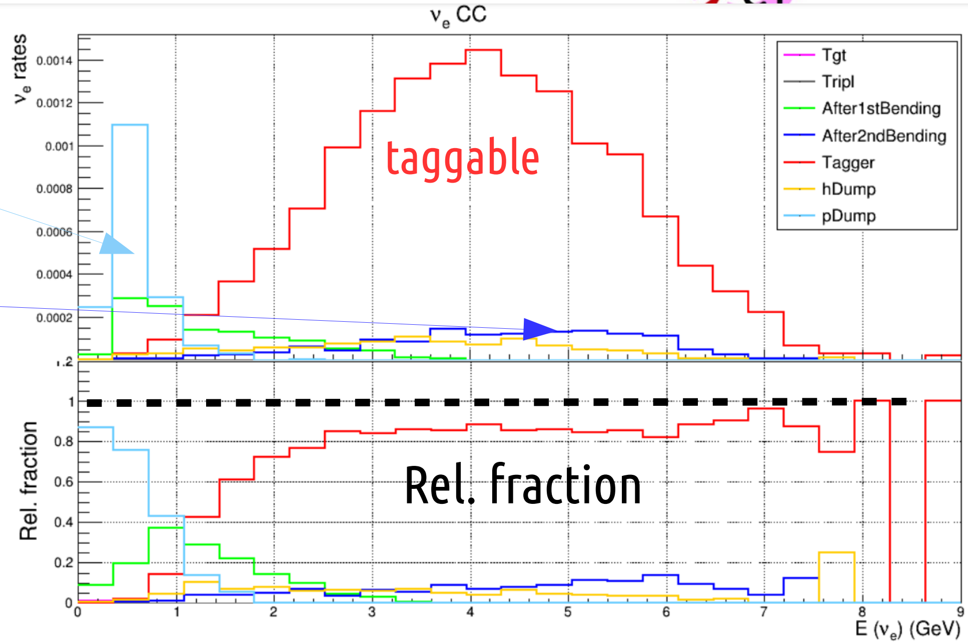
Not directly taggable components:

1) ν_e from $K^{0+/-}$ in the proton/hadron dump
→ reduce by tuning the dump geometry/location

2) ν_e from K^+ in front of the tagger
(after 1st bend/2nd bend) ~10% contamination → accounted for with simulation (~geometrical).



$\nu_{e\,CC}$ spectra



Uncertainty reduction for the tagged flux component

Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

An example:

Each histogram component corresponds to a bin in neutrino energy