Cross sections with the ENUBET monitored neutrino beam

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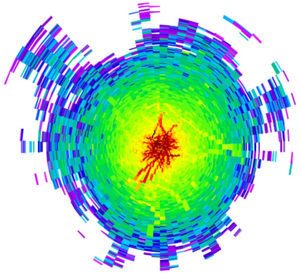
Padova Univ. and INFN
on behalf of the ENUBET Coll.

NUINT 2022, Seoul,
25 Oct 2022

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (G.A. n. 681647).



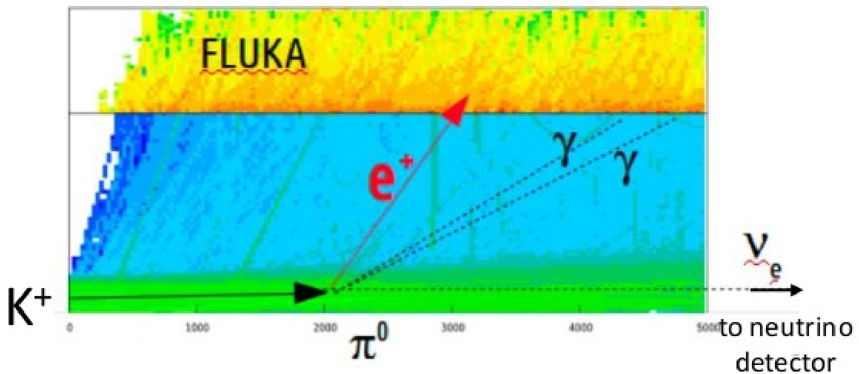
What is ENUBET ?

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

ENUBET aims at realizing the first monitored neutrino beam:

The production of associated leptons is monitored at single particle level in an instrumented decay region

- **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**



a **collimated momentum-selected hadron beam**
→ mainly **decay products hit the tagger → manageable rates**
a **"short", 40 m, tunnel** (~all ν_e from K, ~1% ν_e from μ)

NB: it requires a specialized beam, not a "pluggable" technology for existing super-beams

ERC project 6/2016- 12/2022

Enhanced **NeU**trino **BE**ams from kaon **T**agging ERC-CoG-2015, G.A. 681647,
PI A. Longhin, **Padova University, INFN**

https://www.pd.infn.it/eng/enubet/

Since April 2019

- **CERN Neutrino Platform: NP06/ENUBET**
- **Physics Beyond Colliders**

Present collaboration: 65 phys, 13 institutions

PI: A. Longhin, F. Terranova. Techn. Coord: V. Mascagna

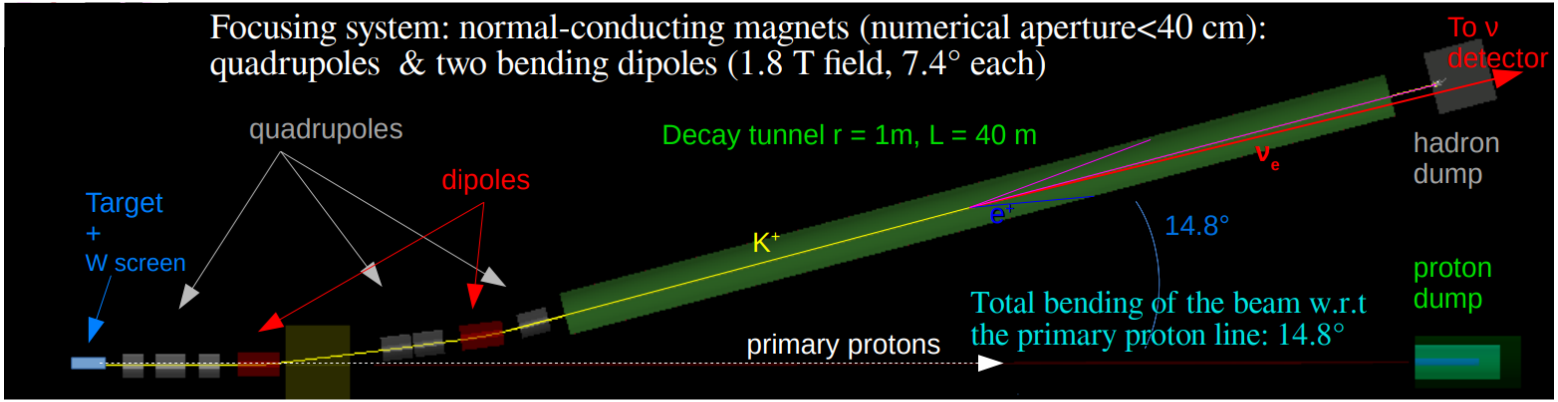
Wish list for a new generation cross-section facility

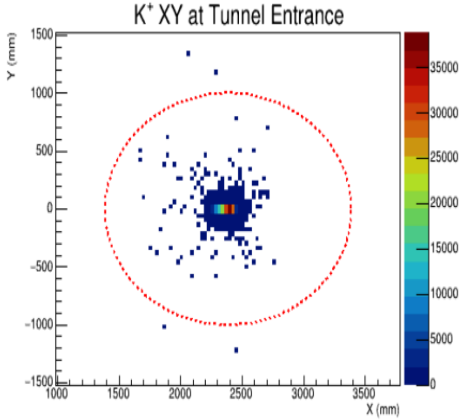
A dedicated short baseline beam for a precision <1% in ν_e and ν_μ fluxes

Symmetry 13 (2021) 9, 1625

- Reduce the dominant systematics on flux empowering existing mitigations:
  - Combine **hadro-production data** + **ν-e scattering** (5-10%). World record: arXiv:2209.05540 (3.3-4.7% !)
  - → Monitored neutrino beam (this talk) 0.5-1 %
  - Muon storage ring (nuSTORM) <1%
- Constrain E_ν without relying on the final state
  - Narrow band beams combined with movable detectors (rough approximation of a "monocromatic beam")
  - Monitored neutrino beam "Narrow band- off-axis technique" (this talk)
- Use the same target as far detectors (DUNE, Hyper-K) + **low Z target** (existing or new experiments)
  - **near detectors** do an excellent job but issues with **flux × cross-section deconvolution**
  - new experiments with existing or novel detectors and beam (following the success of exp like MINERvA)
- Large statistics (double differential cross sections)
  - Not an issue for ν_μ. $O(10^4)$ ν_e in conventional beams and monitored neutrino beams
  - $O(10^6)$ in all flavors using muon storage rings (nuSTORM)

The hadron beamline





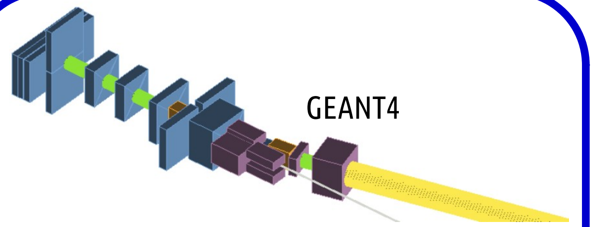
Large bending angle of 14.8°: better collimation + less μ background and ν_e from early decays. ~1.5 $\times$ gain in signal.

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 (see next →);
- optimized graphite target 70 cm long with 3 cm radius (optimized geometry, materials);
- W foil downstream target to suppress positron background;
- W alloy absorber @ tagger entrance to suppress backgrounds;

Dumps:

- Proton dump: three cylindrical layers (graphite core → aluminum → iron);
- Hadron dump: ~ proton dump to reduce backscattering flux in tunnel;



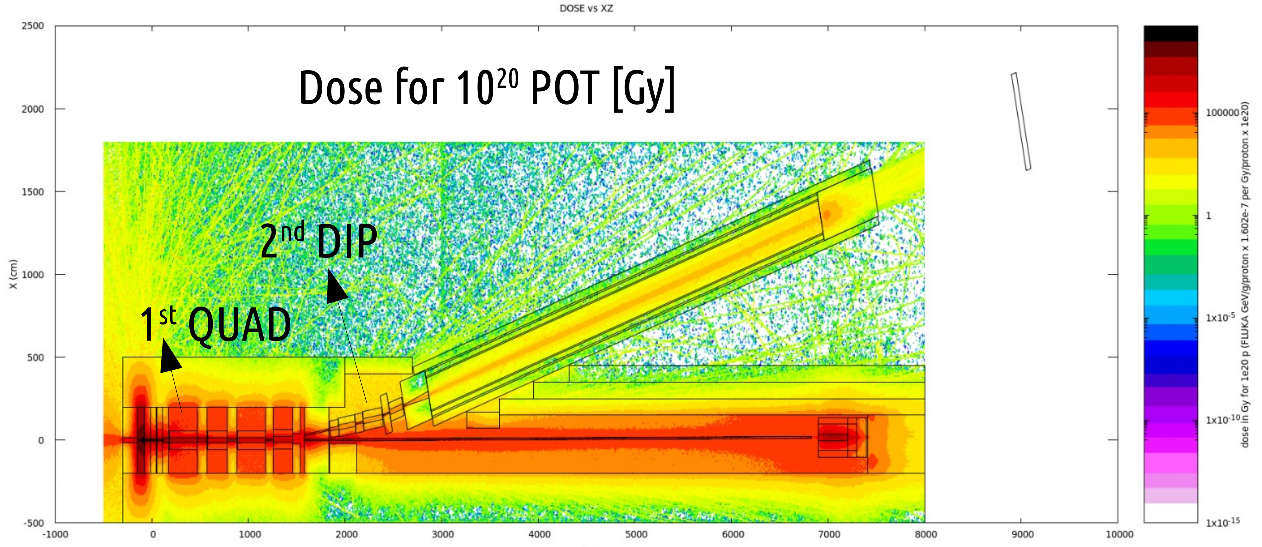
Full facility also implemented in GEANT4:
Easy control over all parameters;
Access to the particles histories;
assessment of the ν flux systematics

The beamline in FLUKA

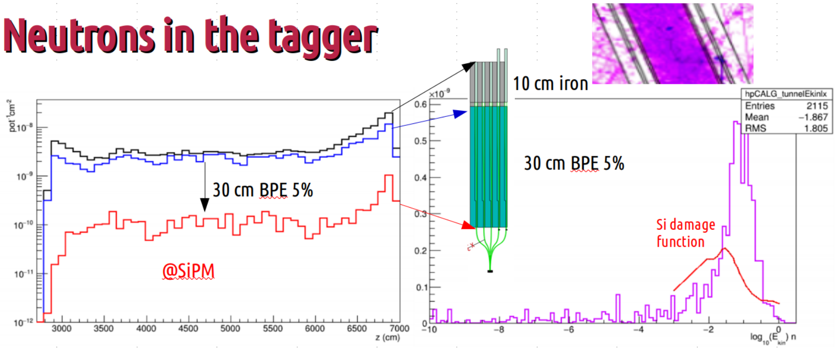
Detailed FLUKA simulation of the setup

Guided the design of the detector technology for the demonstrator

Good lifetime of instrumentation and focusing elements achieved.

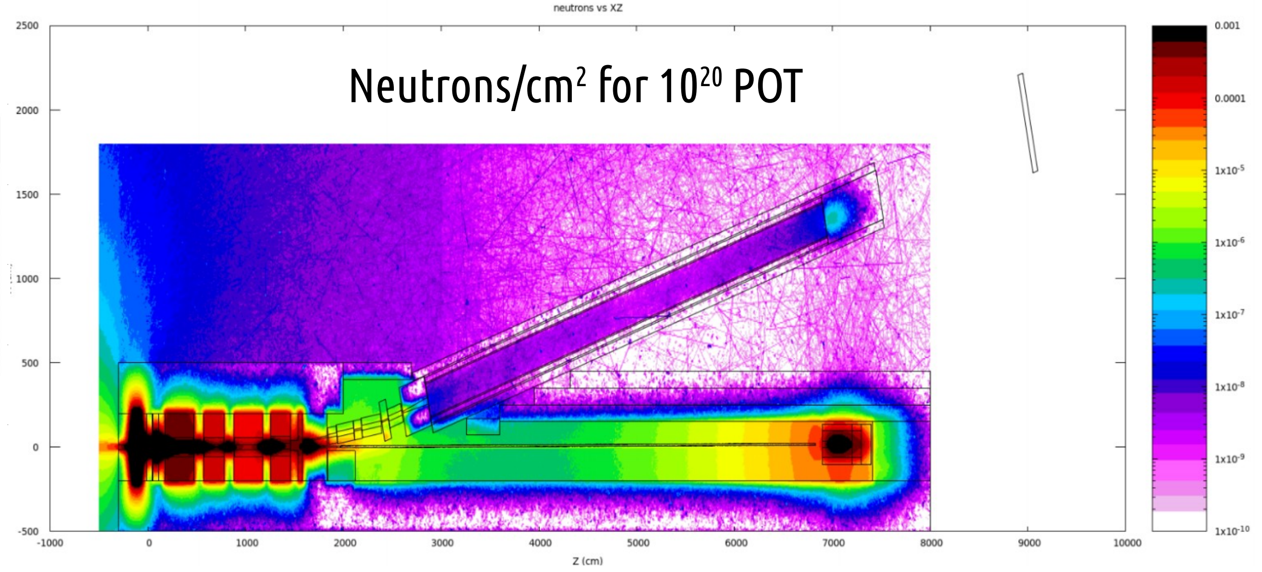


Neutrons in the tagger



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

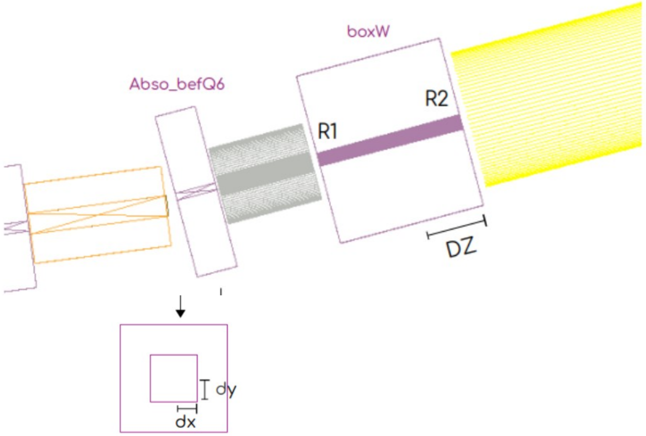
E_{kin} of surviving neutrons is O(10-100) MeV



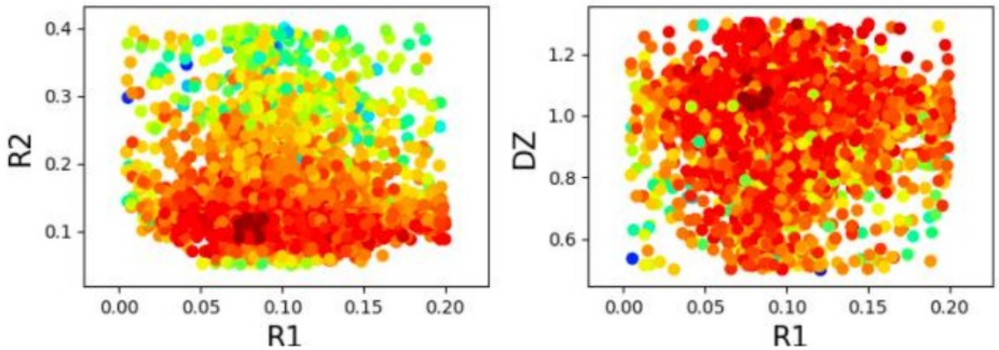
Optimization of the beamline

- FOM = signal/background
- Signal: π & K @ tagger entrance
- Background: e^+ & π hitting tunnel walls (excl. those from decays)

C. Delogu, PhD thesis



FOM dependence on opt. parameters



Systematic optimization campaign:

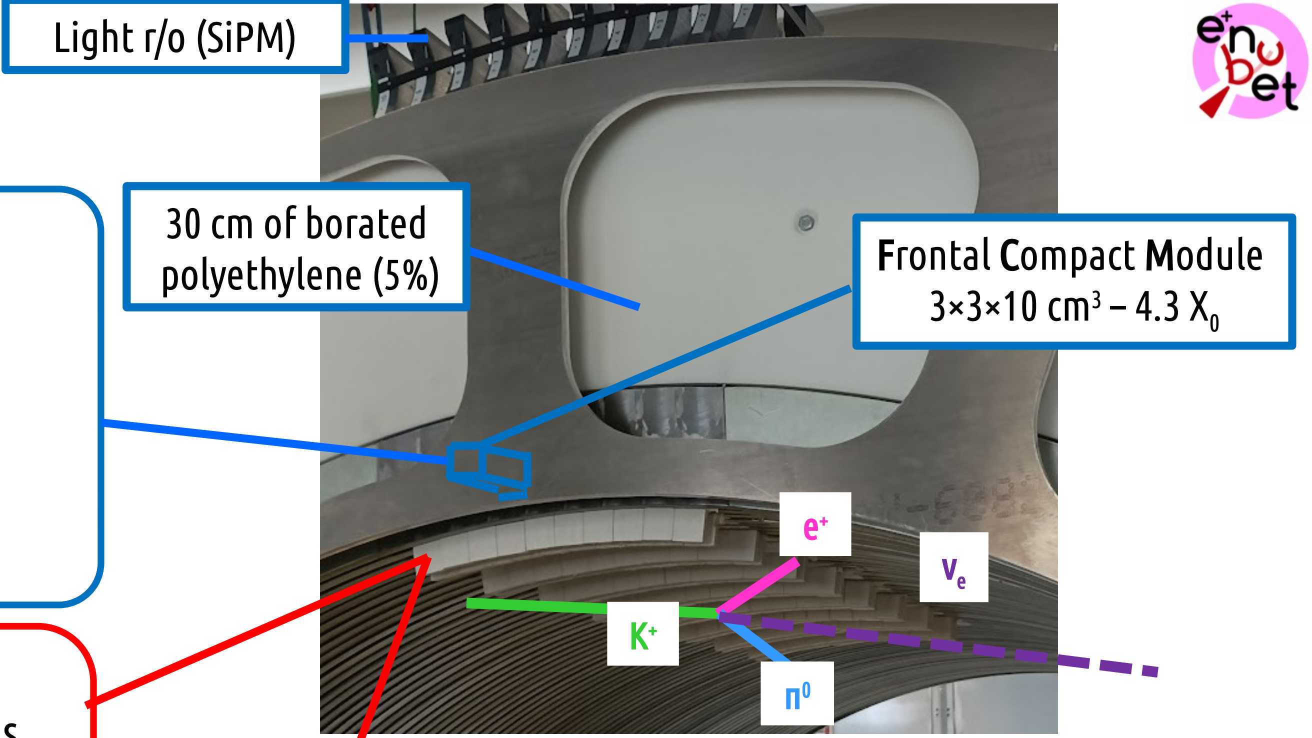
- increase the π/K input flux, decrease bckg
- fully in GEANT4 → control all pars with external cards
- explore multi-D parameters space to maximize FOM.
- Genetic algorithm run on a cluster (Lyon IN2P3)

	signal		backgrounds	
	π^+ /10^3 POT	K^+ /10^3 POT	e^+/K^+ 10^{-3}	π^+/K^+ 10^{-3}
Design	4.13	0.34	7	59
Optim.	**5.27**	**0.44**	**2**	**35**

→ next steps:
better FOM (include S/B shapes with improved execution speed)
extend the parameter space (now 5 pars. in the downstream part)
Updated results in Jan 2023.

Intermediate result: reduced backgrounds, but similar to signal shapes : 28% gain in flux → 2.4 y for 10^4 ν_e^{CC} (500 t @ 50m)

The lepton tagger



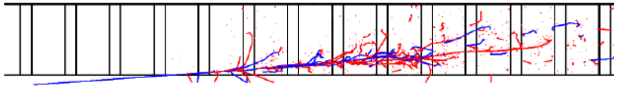
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

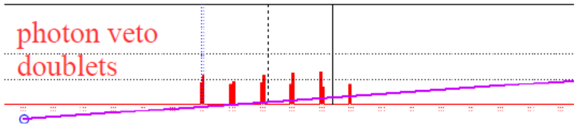
→ $e^+/\pi^\pm/\mu$ separation

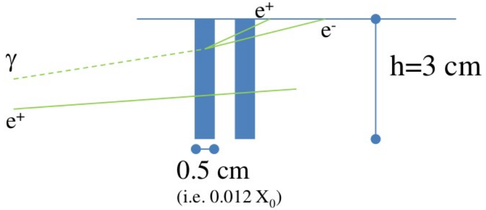


Integrated photon veto

- Plastic scintillators rings of 3×3 cm^2 pads

→ π^0 rejection





e^+ (signal) topology

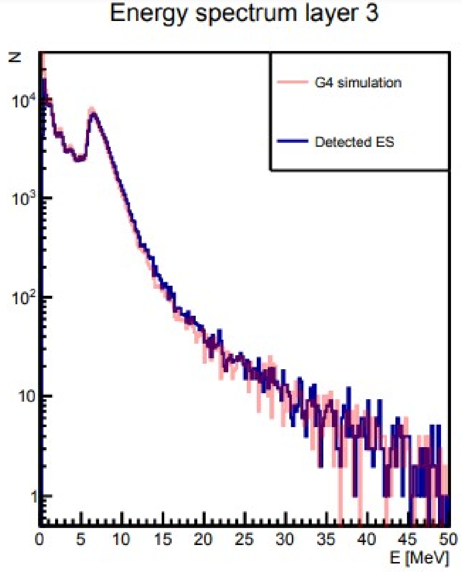
π^0 (background) topology

π^+ (background) topology

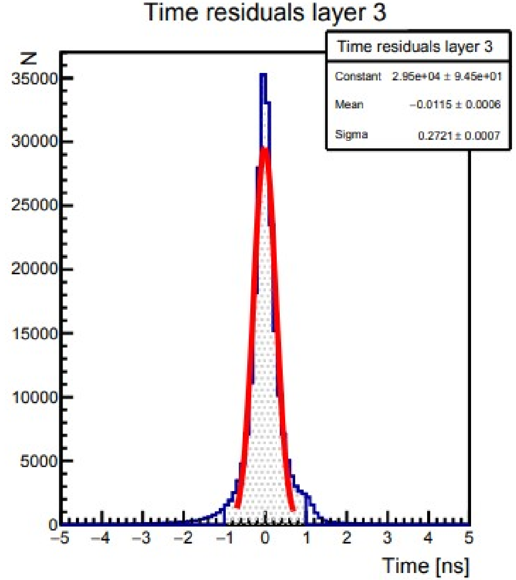
Event pile-up analysis

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 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

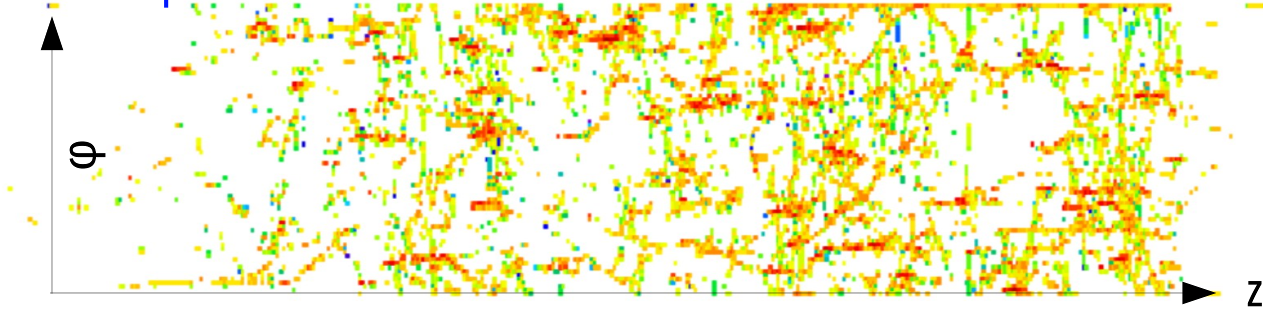
Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%

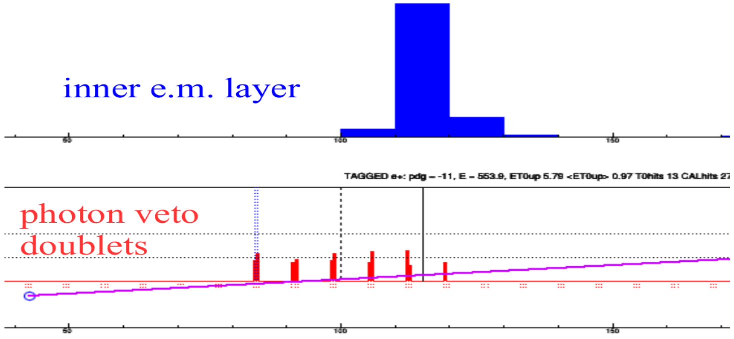
Lepton reconstruction

F. Pupilli et al., PoS NuFact2021 (2022) 025

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.

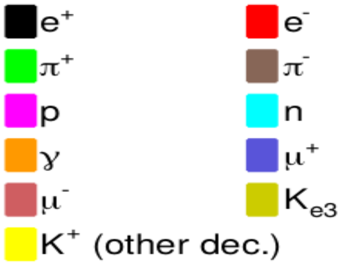
Hit map for e^+

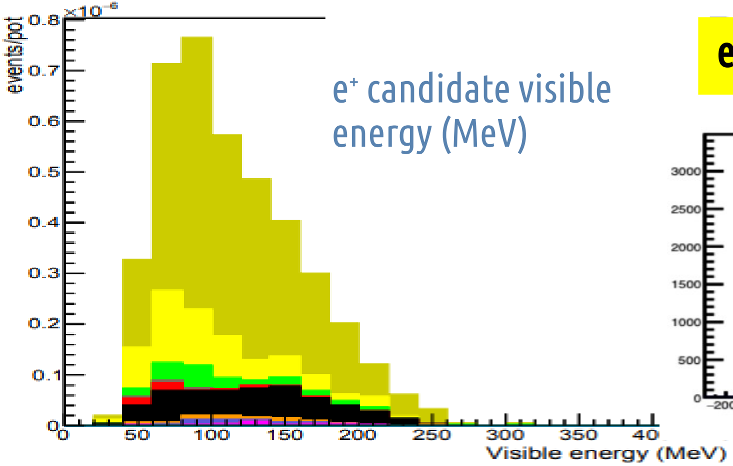




K_{e3} e+: Efficiency ~22%, S/N of ~2

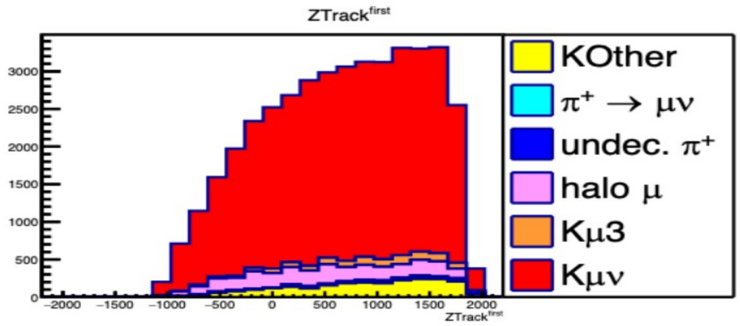
Half of efficiency loss is geometrical





e^+ candidate visible energy (MeV)

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



μ^+ candidate z coord (cm)

ν_e^{CC} spectra at detector

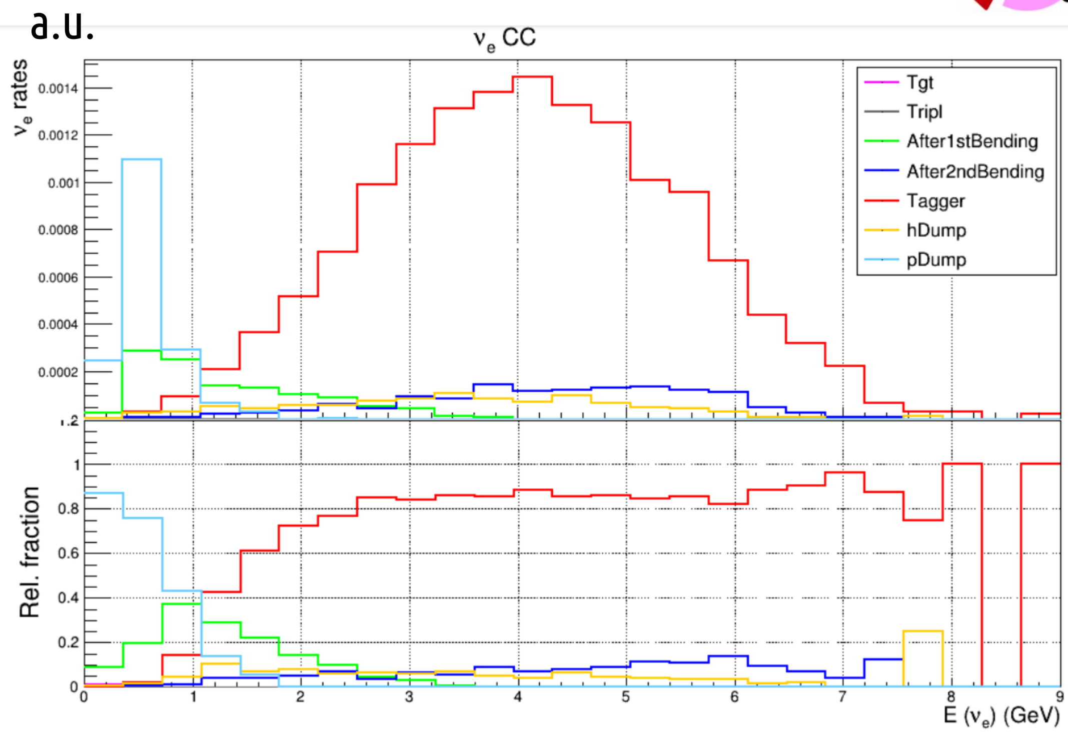
500t @ 50 m after the hadron dump
@ 400 GeV → 10^4 ν_e^{CC} with 9e19 POT

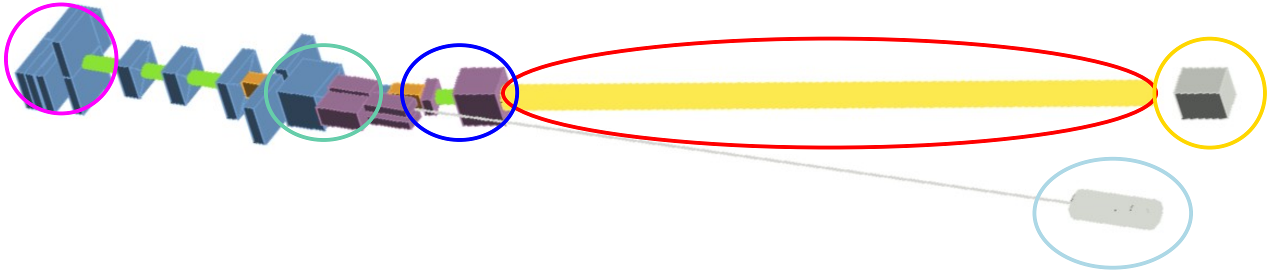
- ν_e from $K^{+/-}$ in the instrumented region
- ν_e from $K^{0+/-}$ in the proton/hadron dump

→ reduce by tuning the dump geometry/location

- ν_e from $K^{+/-}$ in front of the tagger

(after 1st bend/2nd bend) ~10% contamination → accounted for with simulation (~geometrical).





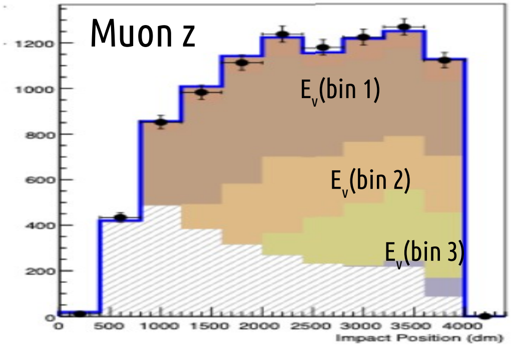
Flux constraint from lepton rates → systematics reduction

NUINT 2018

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

New! (March 22): for the first time we have managed to "put all the pieces together" and show the concept at work in a rigorous way

Flux constraint algorithm implementation

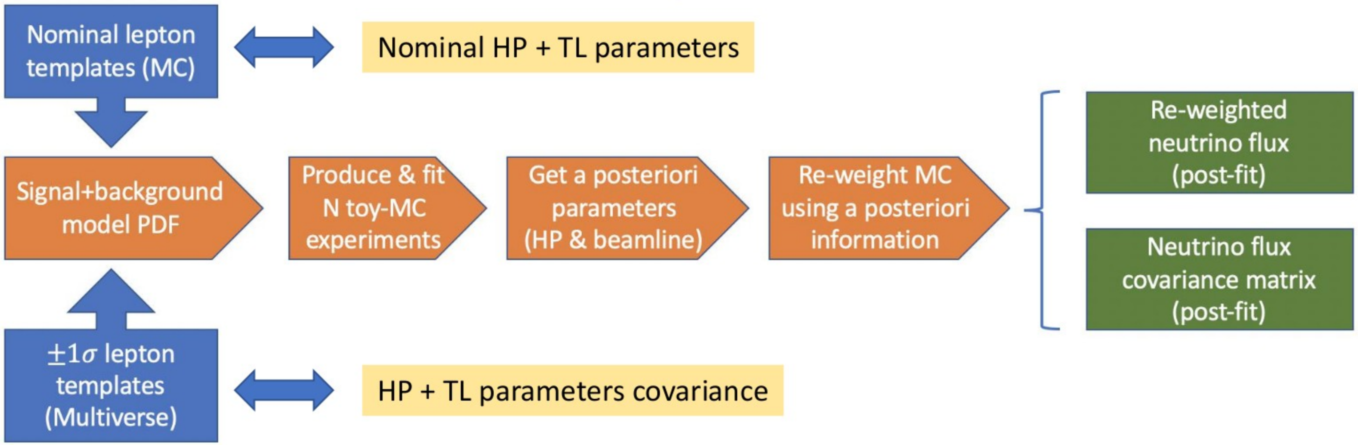


- build S+B model to fit lepton observables (2D in z and reco-energy)
- include hadro-production (HP) & transfer line (TL) systematics as nuisances

Extended Maximum Likelihood fit

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

Each histogram component corresponds to a bin in neutrino energy

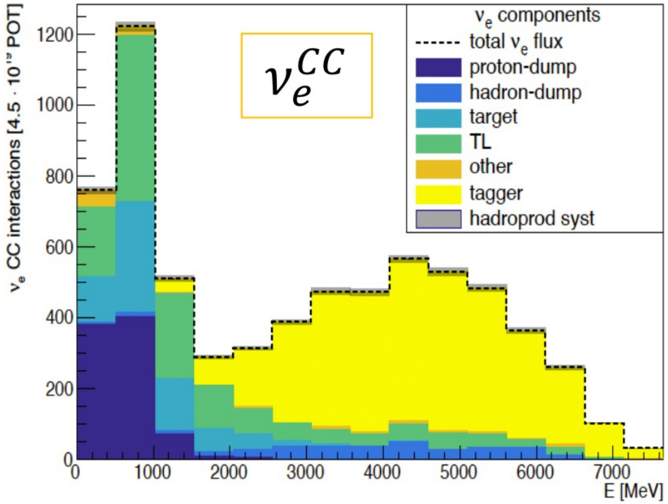


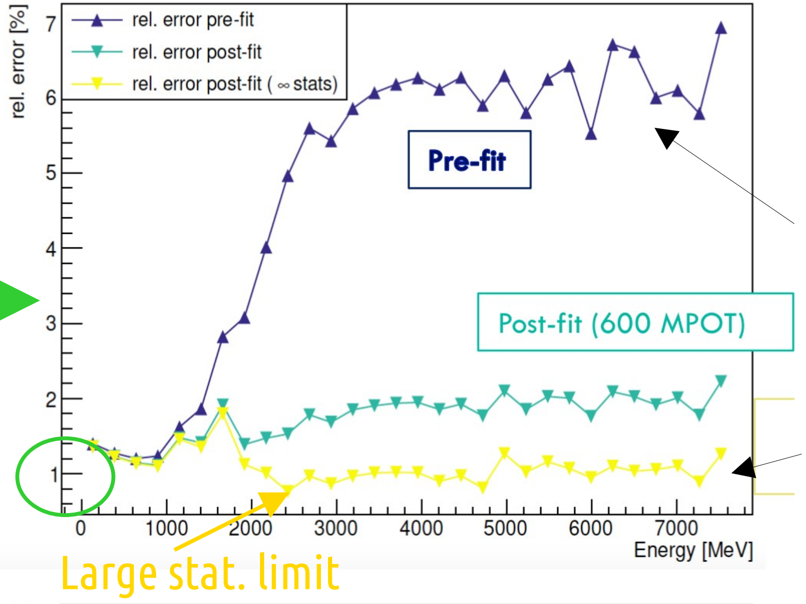
A. Branca et al, PoS NuFact2021 (2022), 030

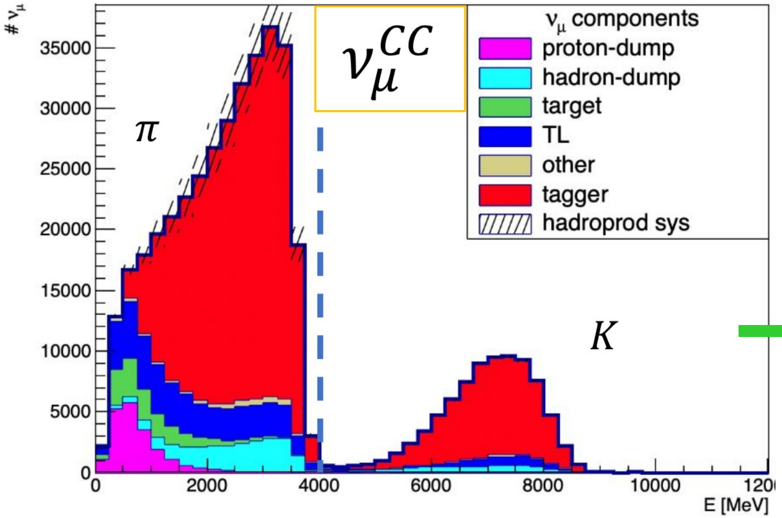
Used hadro-production data from **NA56/SPY experiment** to:

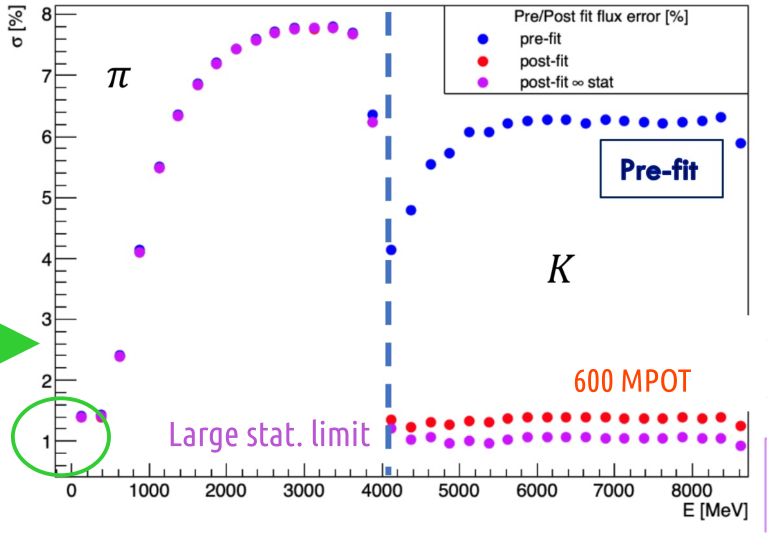
- reweight MC lepton templates and get their nominal distribution
- compute lepton templates variations ("envelopes") using multi-universe method ("toy exp")

Flux constraint results









Before constraint:

sys. budget from HP (NA56/SPY data): **~6%**

After constraint (fit to lepton rates measured by the tagger): Down to **~1%** !

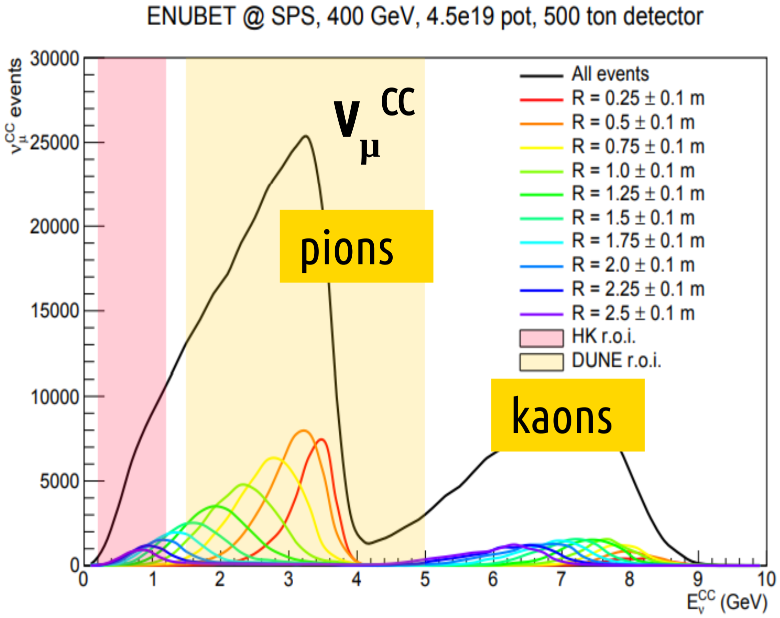
Original idea with a statistical analysis run on full simulation data (beamline, detector, reco.)

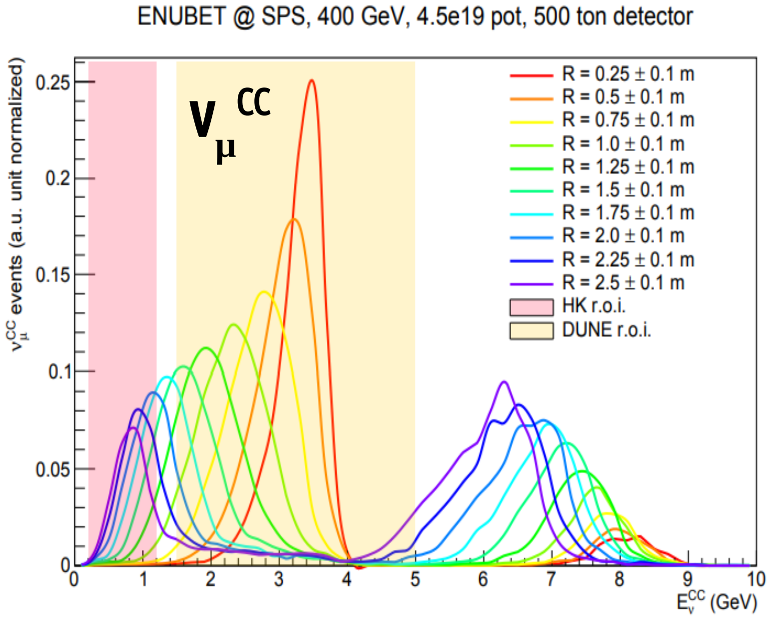
Works for both ν_e and ν_μ

TODO: include beamline, acceptance, detector, kinematics sys.

Fluxes decomposition: NBOA

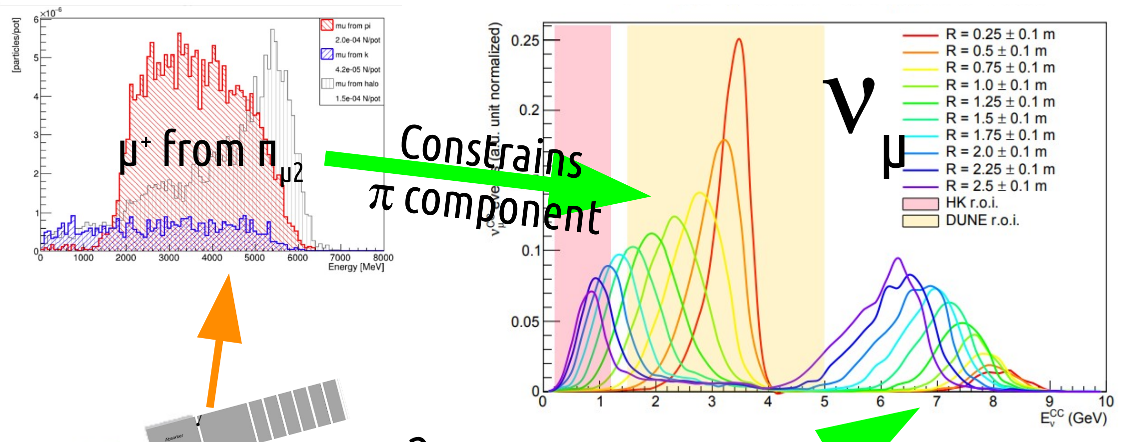
"Narrow-band off-axis technique" (NBOA): bins in the **radial distance from the center of the beam** → **single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable. A kind of "off-axis" but without having to move the detector (thanks to the small distance of the detector) !

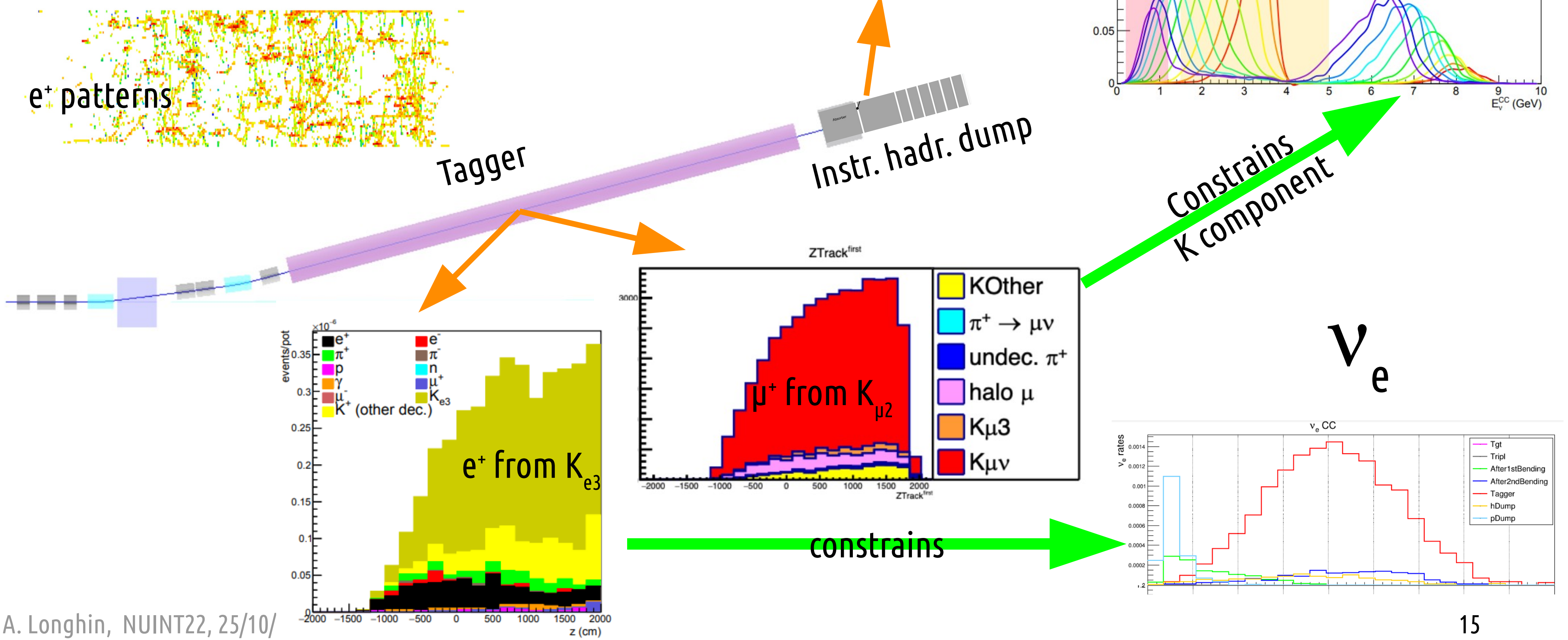




Oveview on lepton monitoring

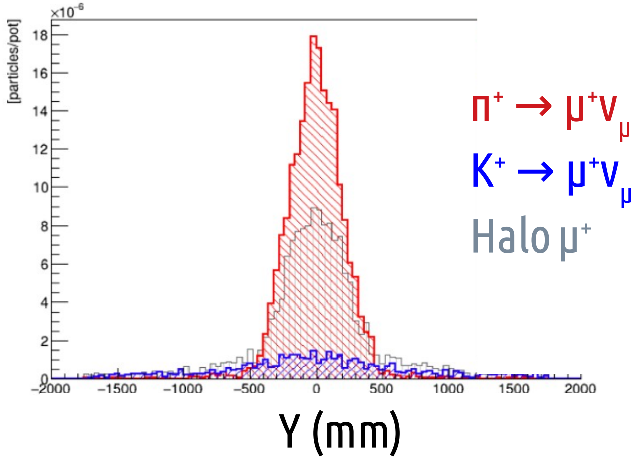
Tagger: leptons from K (ν_e and high-E ν_μ)
Hadron dump instr: μ from π (low-E ν_μ)

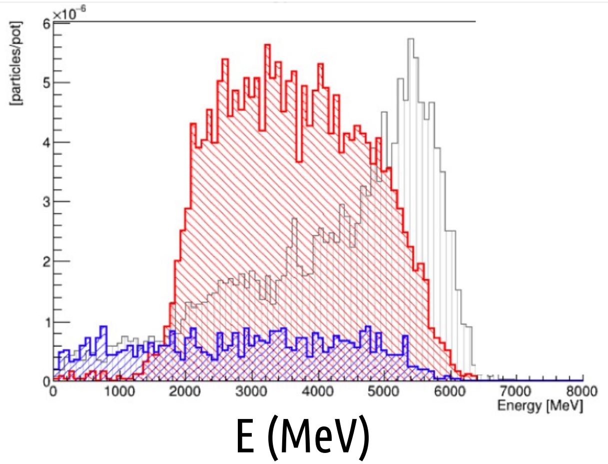


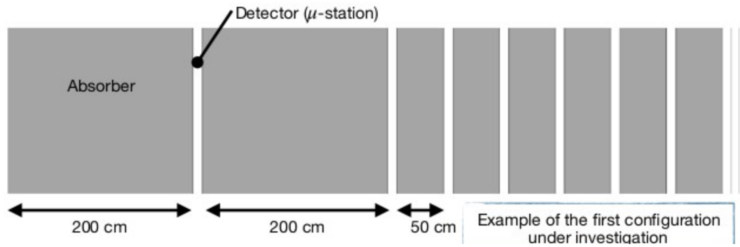


Forward region muons reconstruction

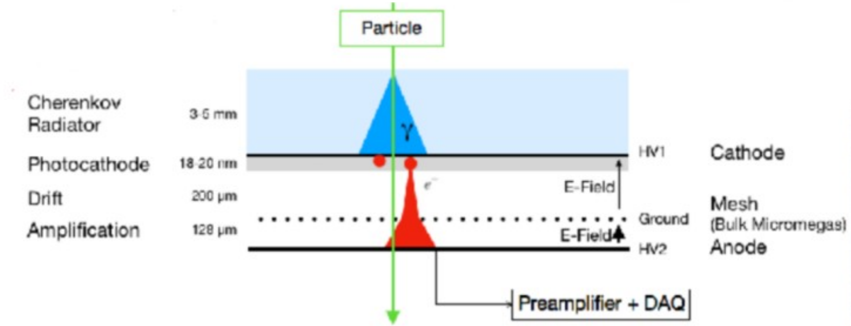
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.

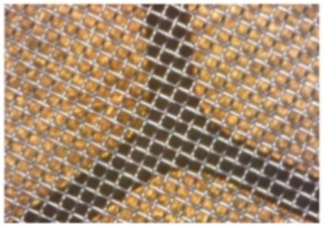






The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n$_{eq}$/cm^2.





Micromegas detectors employing Cherenkov radiators + thin drift gap ?
Bonus: cutting-edge timing (O(10) ps).

→ PIMENT project ! →

PIMENT and more...

New funding: **PIMENT (2022-25)**

French ANR

PICOSEC **M**icrom**E**gas Detector for E**N**UBE**T**

→

Development of a PICOSEC Micromegas Detector for ENUBET

Project Collaboration

- Partners:
  - Thomas Papaevangelou (CEA/DRF/IRFU)
  - Anselmo Meregaglia(CNRS/IP2I Bordeaux)
  - Dominique Breton (IN2P3/IJCLab)
  - Michal Pomorski (CEA/DRT/LIST)
- Duration: 36 months started from Jan 2022

- External Partners:
  - CERN (L. Ropelewski, E. Oliveri, F. Brunbauer, Rui d'Oliveira, A. Utrobičić, M.Lisowska)
  - University of Thessaloniki(S.Tzamarias, I.Angelis, D.Sampsonidis, K.Kordas, Ch.Lampoudis, A.Tsiamis)
  - USTC Hefei China (Zhou Yi)
  - ENUBET Collaboration (A.Longhin)

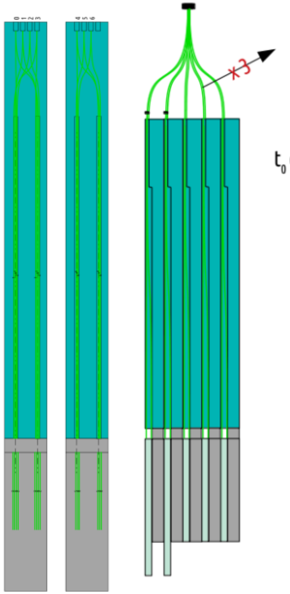
Funded by : RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité — anr agence nationale de la recherche

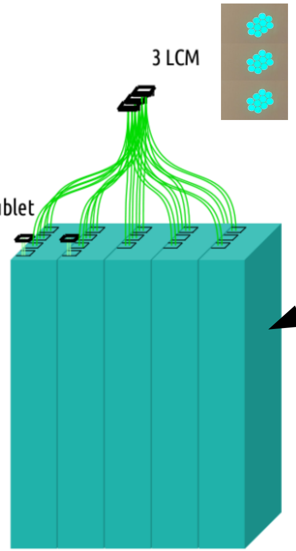
Italian groups also involved in the WP6 of the freshly approved **ESSnuSB+**: Could the idea of ENUBET be exploited also at the ESS proton driver using pions monitoring (E_{prot} = 2 GeV)?

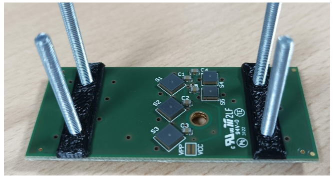
The demonstrator

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

WLS routing

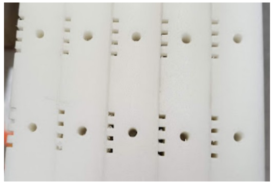






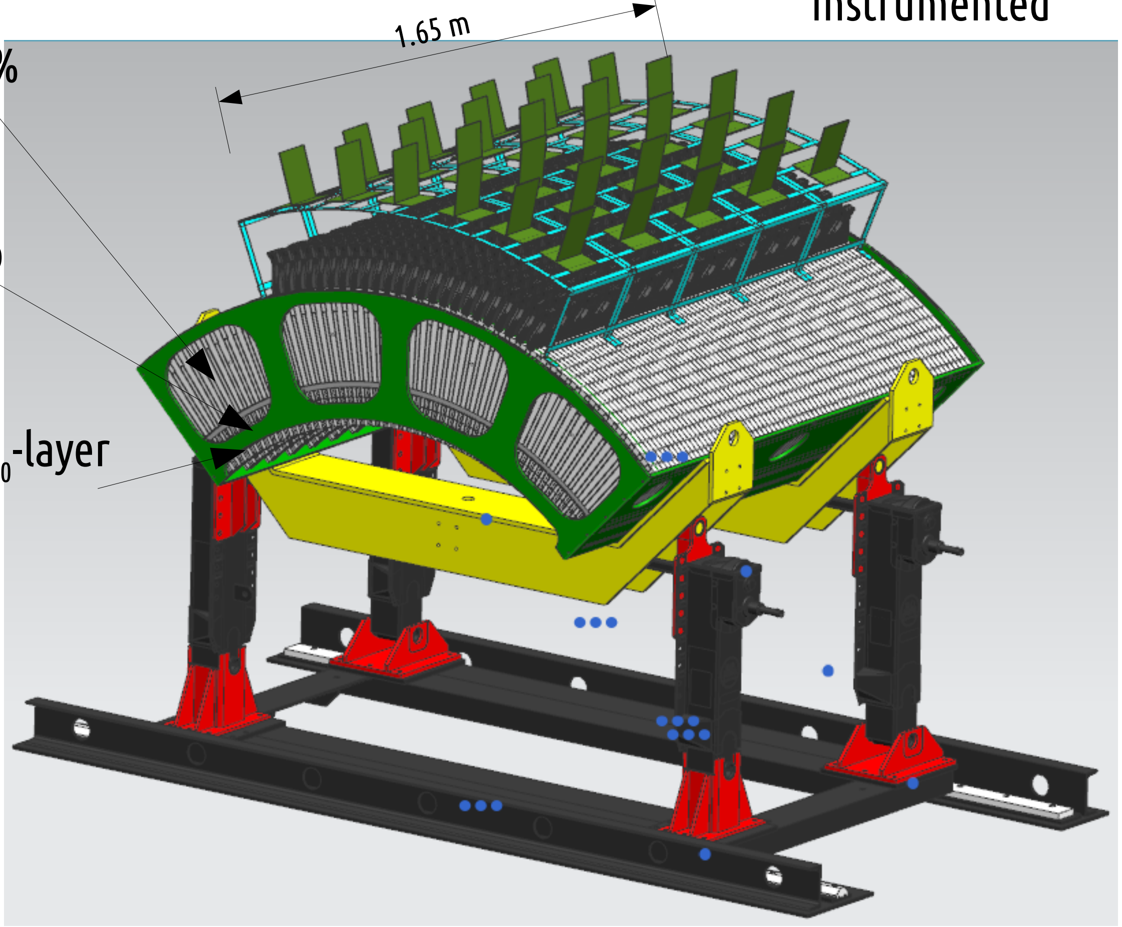
BPE 5%

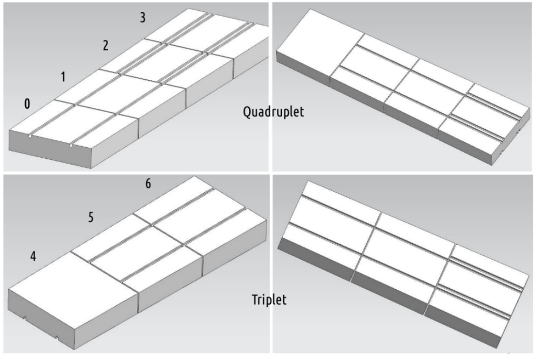
Sampling iron/scint calo

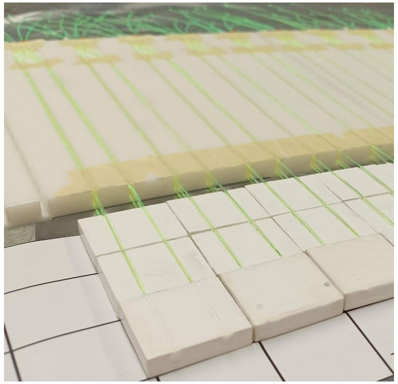


t_0-layer

90°, partially instrumented

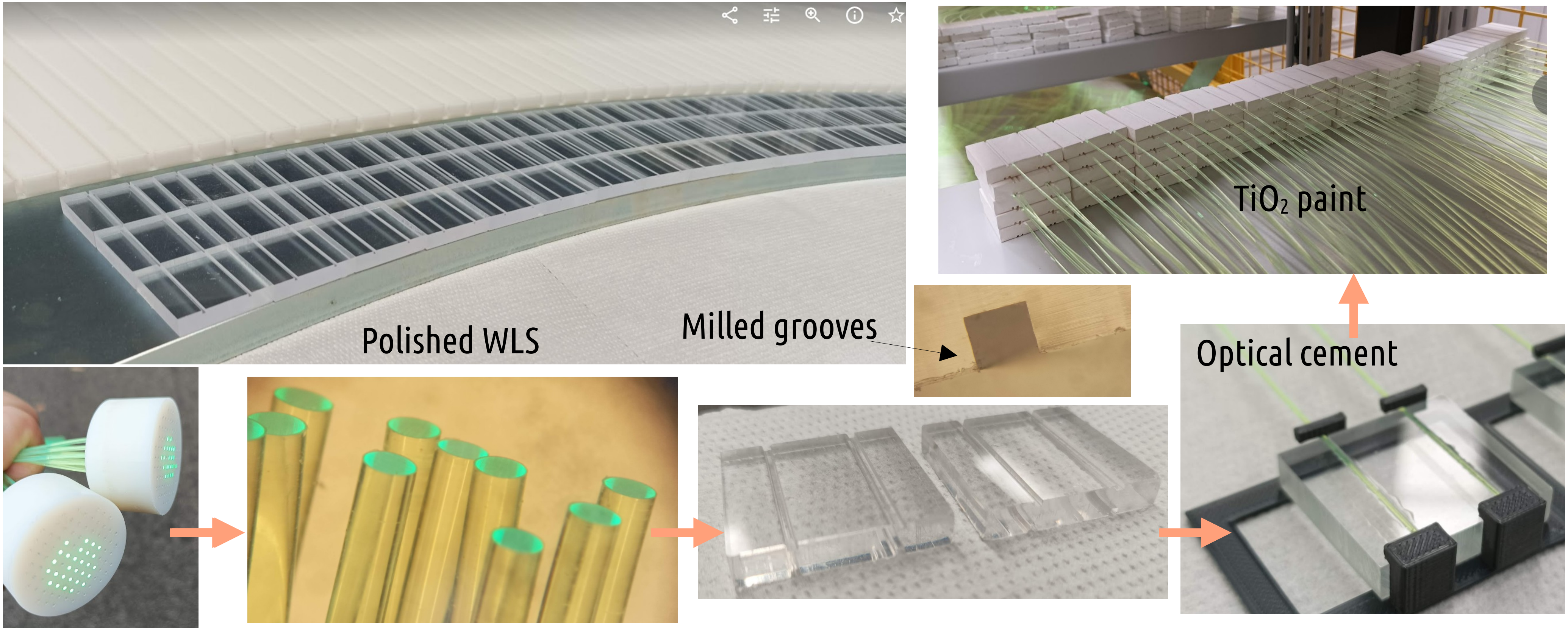




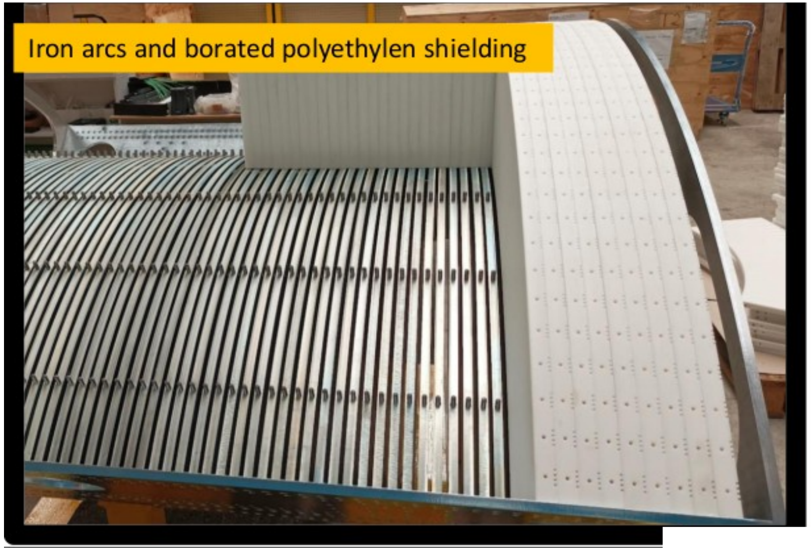


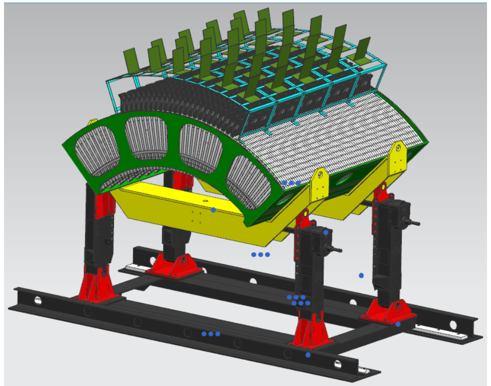
Scintillators + WLS light readout handling

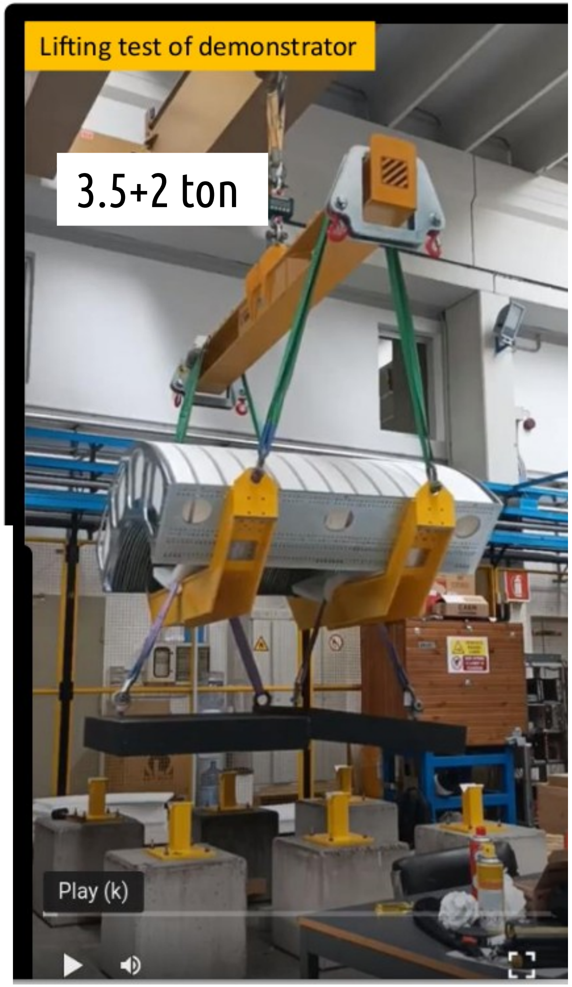
Pre-war scenario for scintillators = injection molding @Moskow: totally jeopardized → commercial scintillator slabs + cutting/milling in Italy. Critical impact → polishing, fibre gluing, tiles painting **with personnel from the collaboration**. “Titanic” effort concentrated in a few “hot” months.

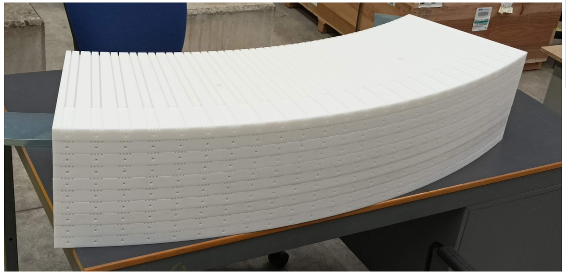


Demonstrator construction at LNL-INFN labs



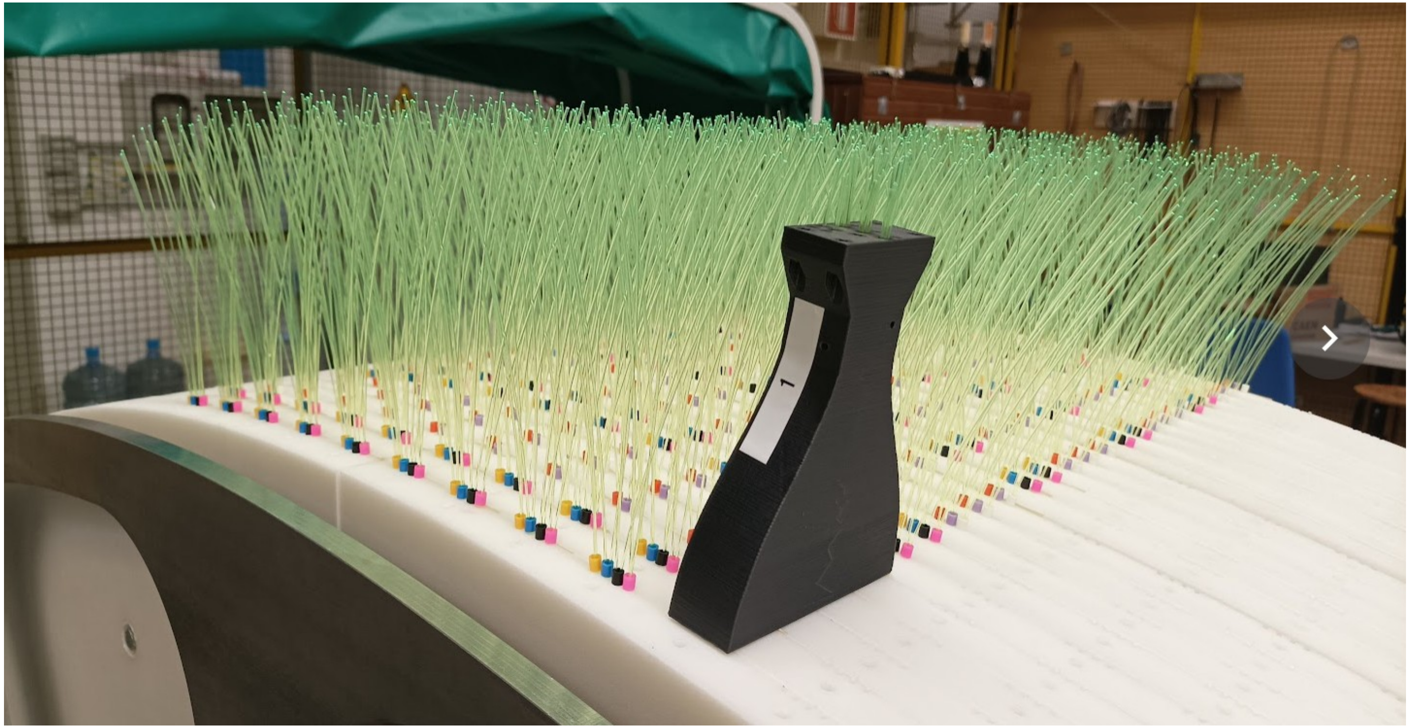


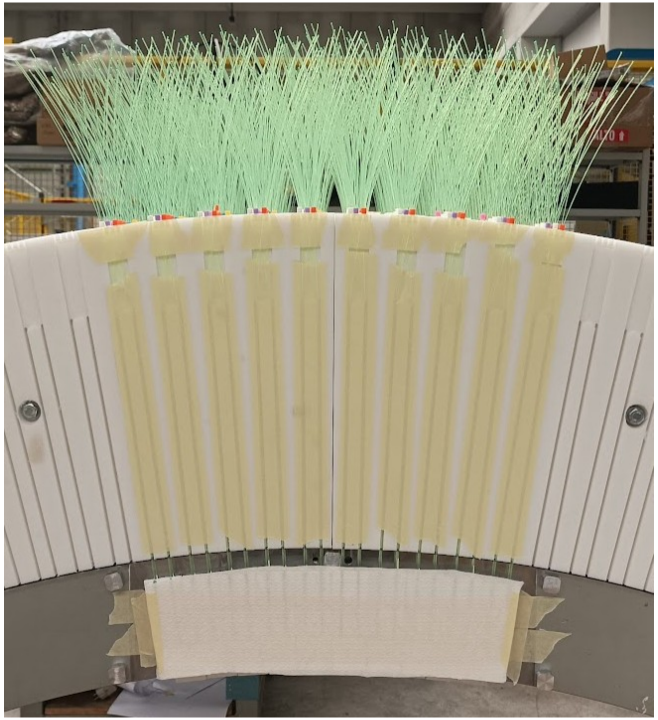




Assembly of the iron / scintillators/ BPE planes

Summer 2022 @ INFN-LNL

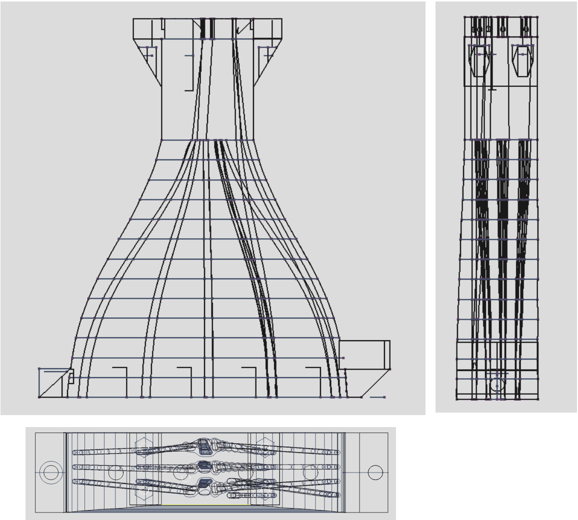




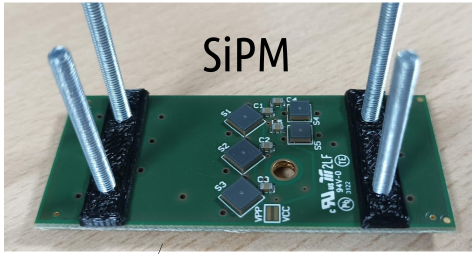
Fiber bundling with new “concentrators”

Summer 2022 @ INFN-LNL

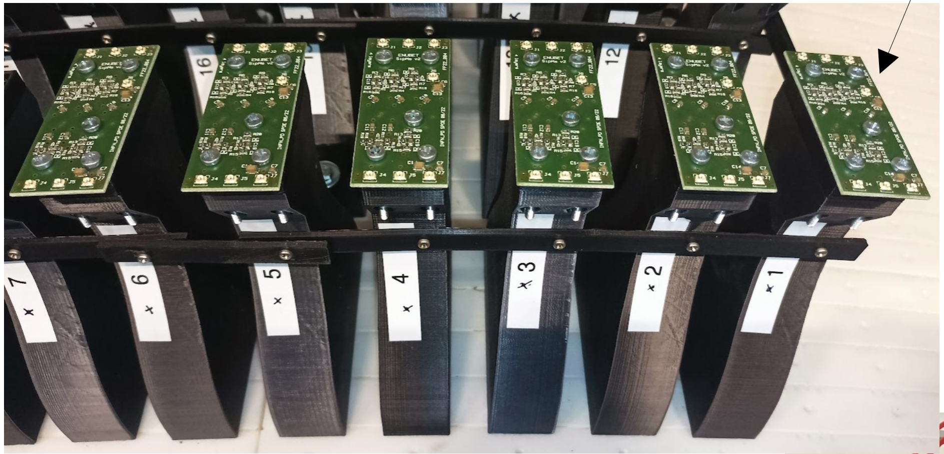
bundling of the WLS fibers with 3D printed “fiber concentrators”+ in situ polishing

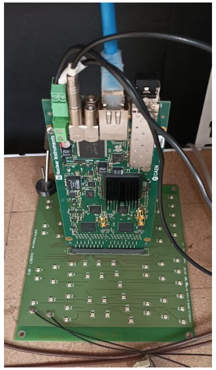


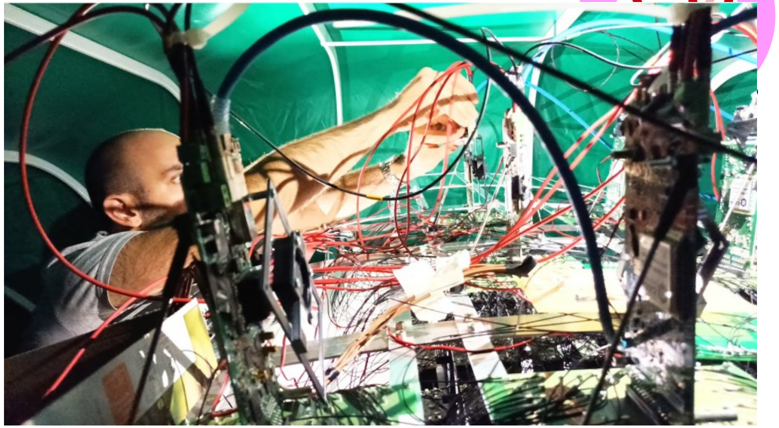
Readout electronics

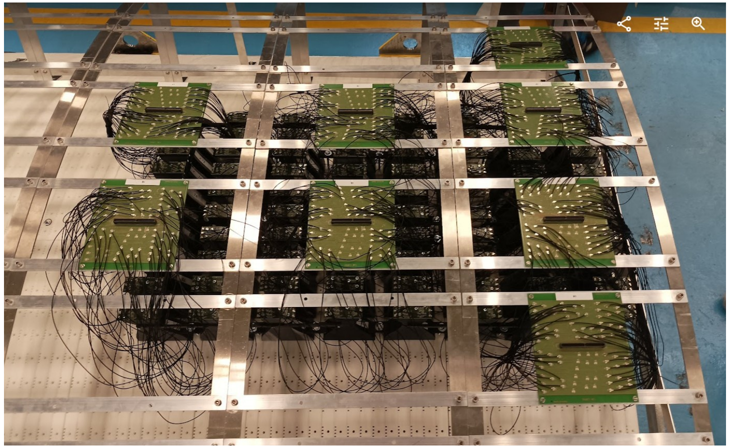


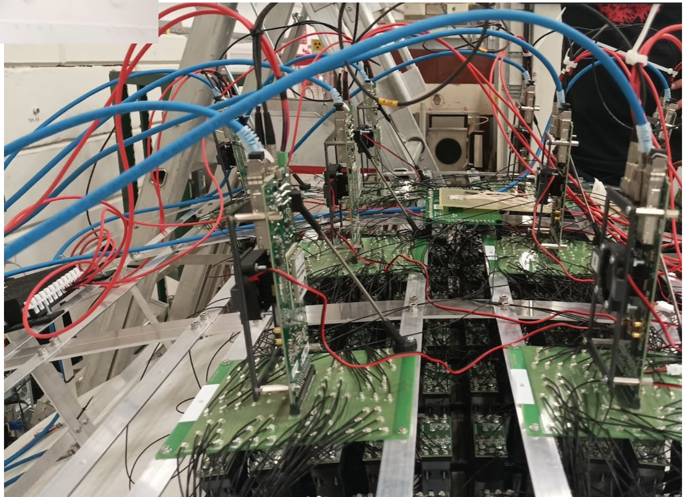
Oct 2022 @ CERN











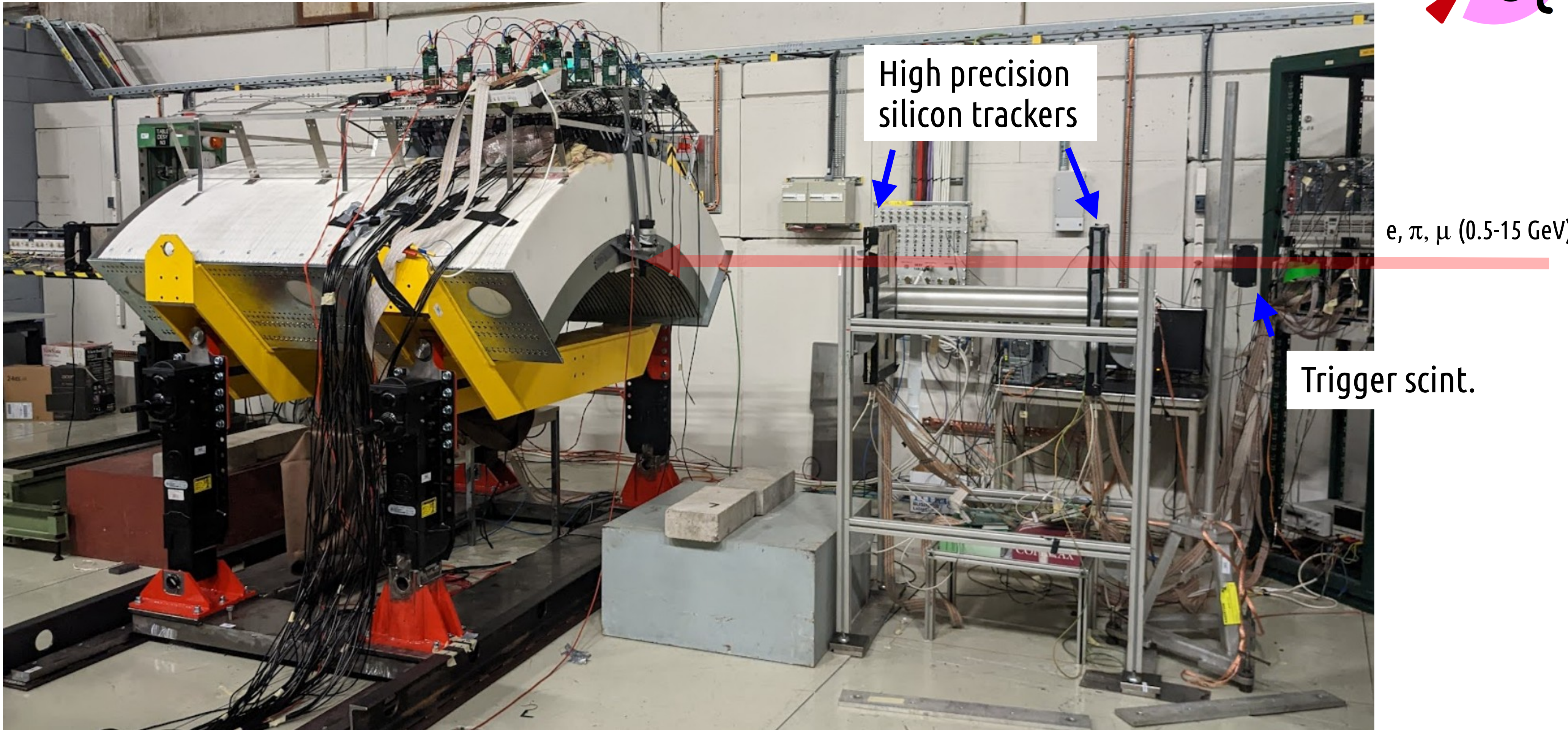
ENUBET takes off !!!

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

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

ENUBET "landed" at the PS-T9 area

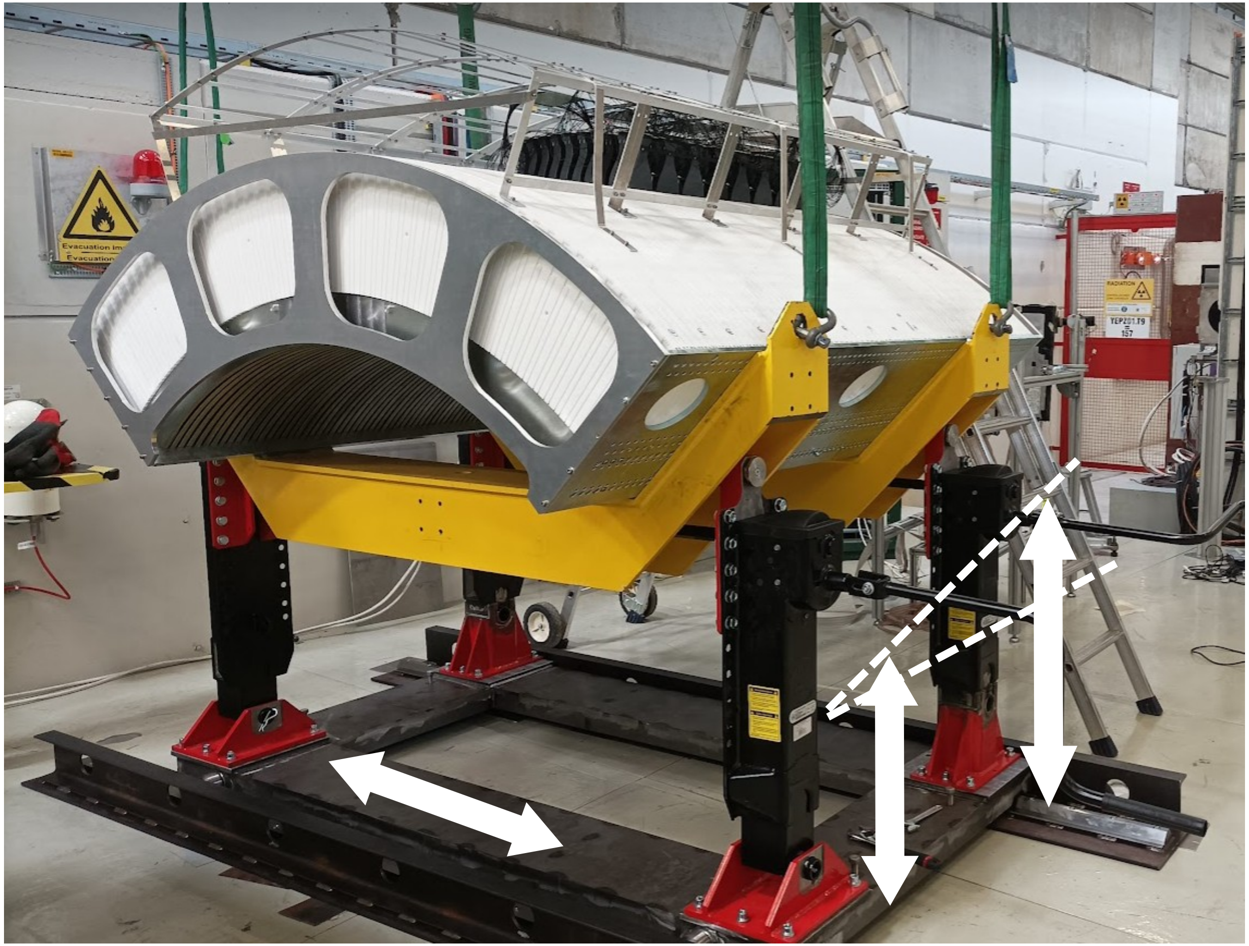
Oct 2022 CERN-PS-T9



The ENUBET demonstrator 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**

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

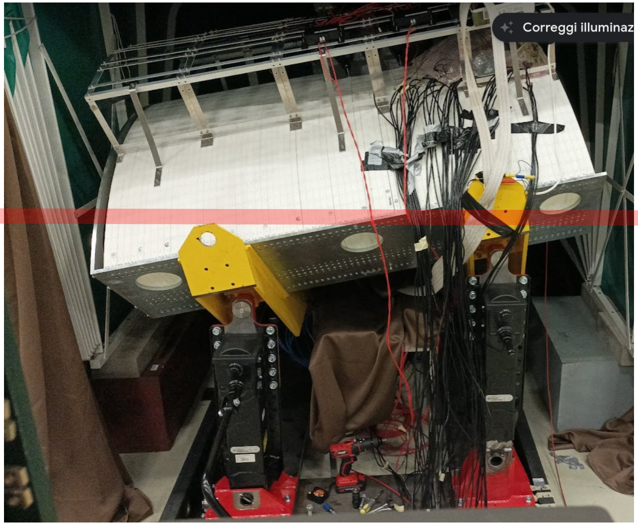


Data taking with the demonstrator

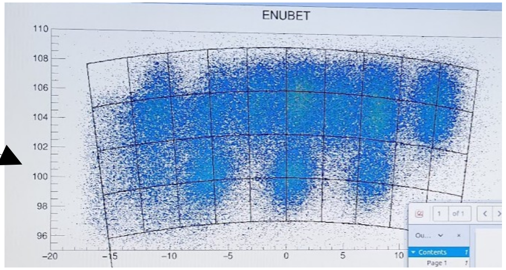
Oct 2022 CERN-PS-T9

horizontal run with darkening cover

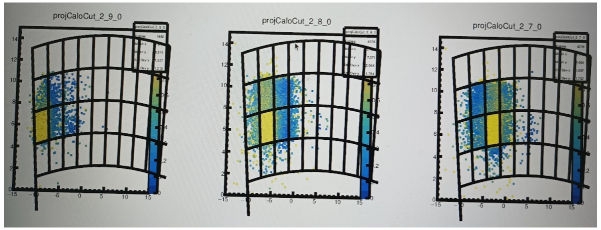
200 mrad tilt run



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



Efficiency maps

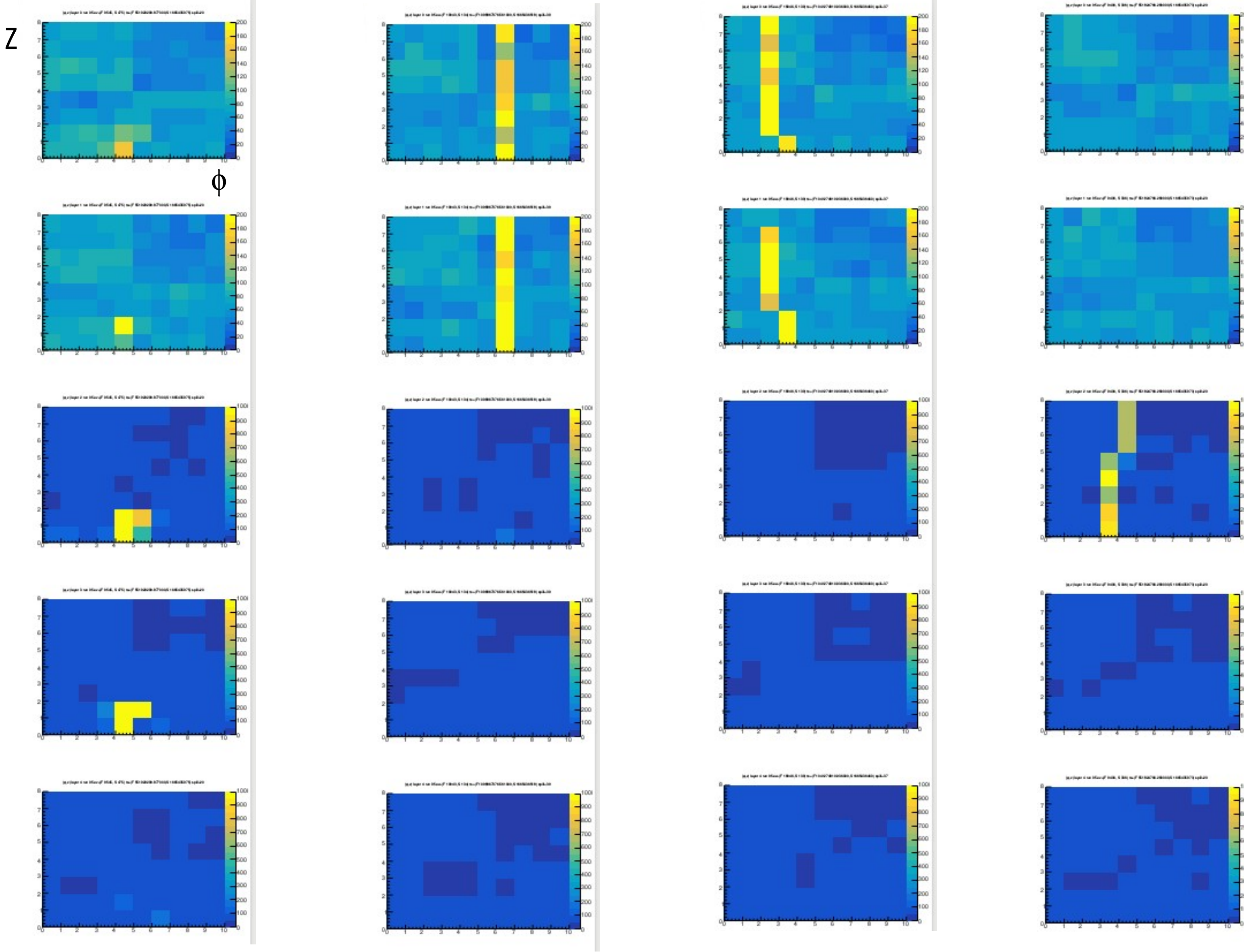


Data look good! Complete analysis in progress (test finished ~1 week ago).

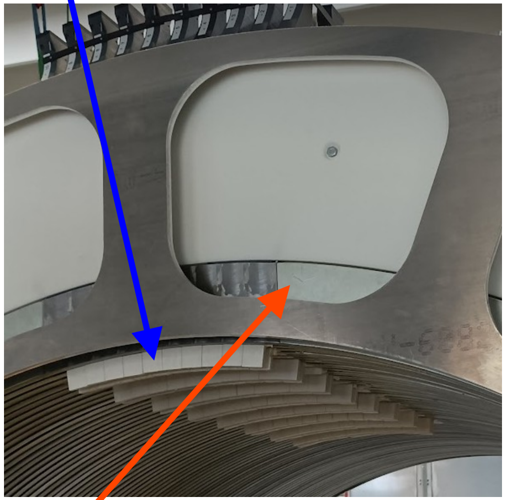
Event displays

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.

Steps towards a real experiment

- **A successful R&D** is **not enough to propose a SBL neutrino beam** at CERN in 2029 (Run 4 of LHC, in parallel with DUNE and Hyper-K).

We need:

- to create **consensus in the neutrino community**. → Detail the physics case + detector requirements
- to be realistic as regards the site implementation. We need 5-9x10^{19} pot in 2-5 years and a location that can fit a suite of detectors, possibly including ProtoDUNEs.
- transform a generic interest into **a real proposal by 2025**

Framework:

- we are carrying on the beam optimization (**pot reduction**, energy measurement) and site-dependent study in the **framework of Physics Beyond Collider at CERN**
- we are detailing the physics case with **nuSTORM** because many items are in common
- ENUBET physicists are involved in both DUNE and Hyper-K and they are aware of the **needs of these experiments and complementarity with the Near Detector measurements**

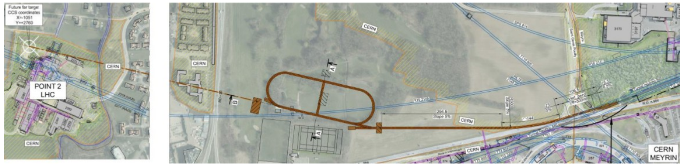
Implementation scenarios

- **The cheapest**: dedicated beamline extracted from the North Area to the ProtoDUNEs
  - Maximum use of existing facilities
  - Slow extraction easily implemented
  - Strong interference with other experiments
  - Potential radiation issues

- **The cleanest**: a dedicated extraction line near the North area pointing to ProtoDUNE
  - No interference with experiments and existing facilities
  - radiation issues somewhat easier
  - Slow extraction
  - Higher cost

M. Antonello et al., CERN-SPSC-2012-010

- **The nuSTORM-like extraction line**
  - Relatively cheap
  - Incompatible with ProtoDUNE in their current position
  - Potential issues with the slow extraction



Ahida et al., CERN-PBC-REPORT-2019-003, TT60 existing extr. line

Studies/discussions starting within Physics Beyond Colliders

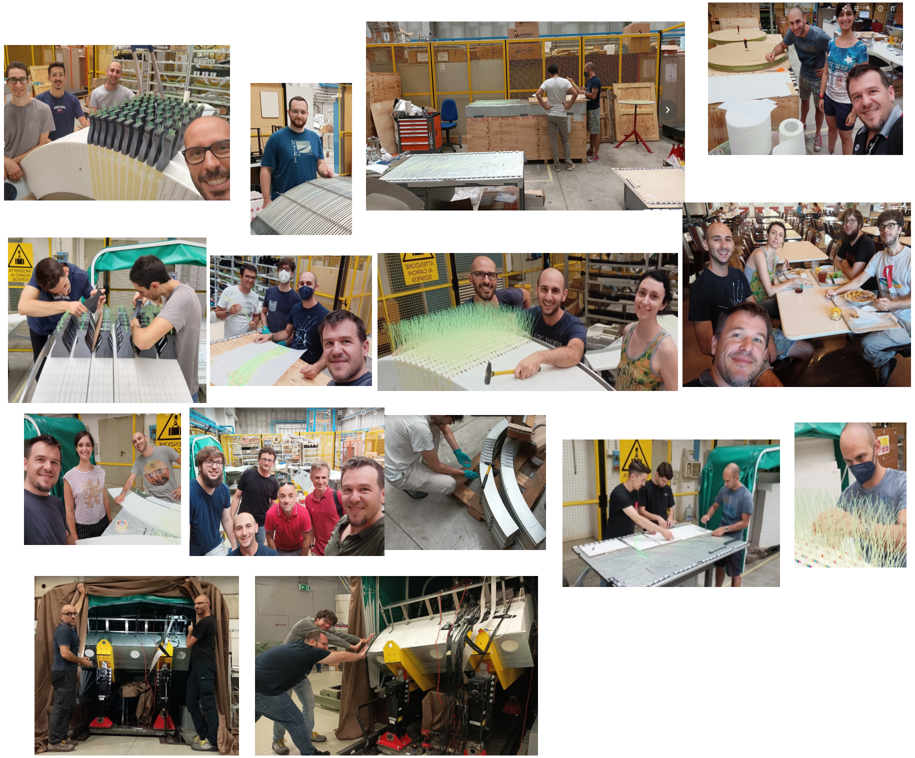
Conclusions and outlook

- **Monitored neutrino beam**: all features needed for **a new generation of cross-section experiments**
- Not anymore just an “interesting idea”: the **proof-of-concept is nearly complete** and NP06/ENUBET has proven it both by **simulations and an experimental validation**
- The final ENUBET results will appear in **journals (3-4 papers) in 2023**.
- We have started the process of **addressing the real implementation** at CERN and aim at a proposal in 2024-2025 to be in data taking for LHC Run IV (2029)

- This is **a major effort** that requires:
  - Careful assessment of physics performance
  - Assets and limitations for the use of ProtoDUNE (e.g. cosmic rejection in a slow extraction, kinematic reconstruction of final states, etc.)
  - Optimal location at CERN to exploit the SPS slow extraction, radioprotection constraints

We look forward to your suggestions for a design fulfilling the needs of the ν and nuclear physicists to have such an experiment up and running in // with DUNE/HK

감사합니다

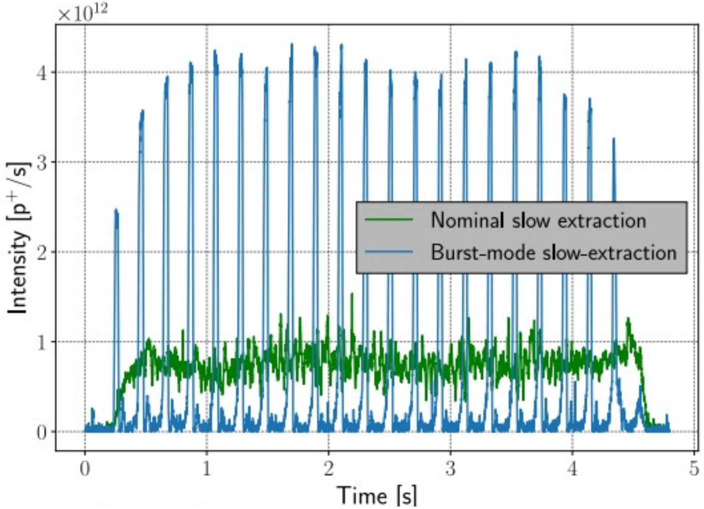


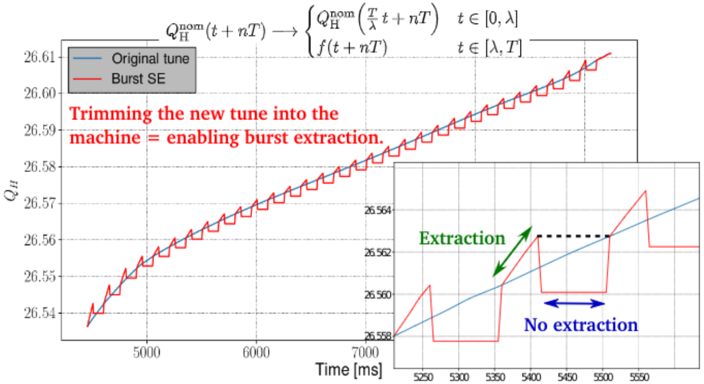
Backup

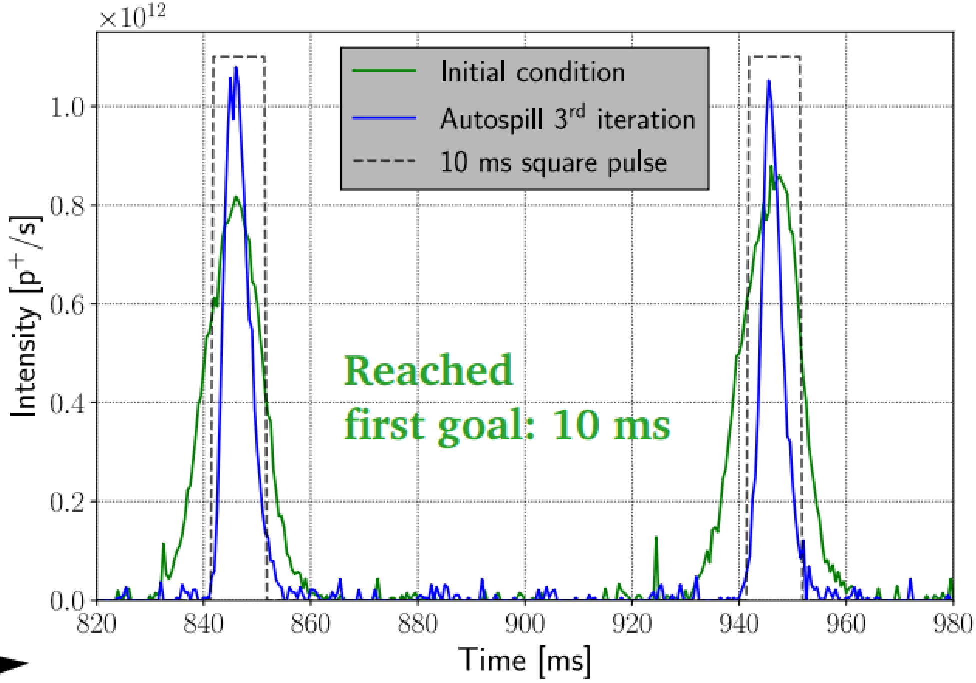
Proton extraction R&D for horn focusing

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.

Narrow band off axis

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;

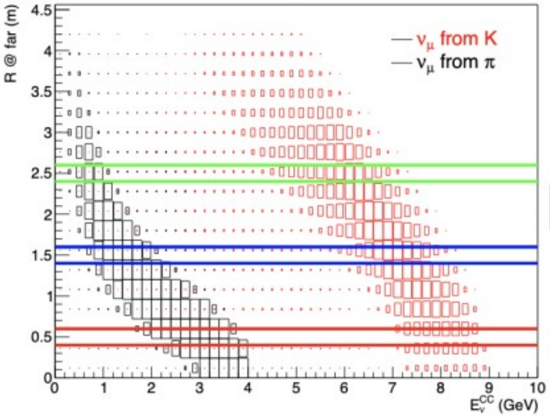
F. Acerbi et al., CERN-SPSC-2018-034

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

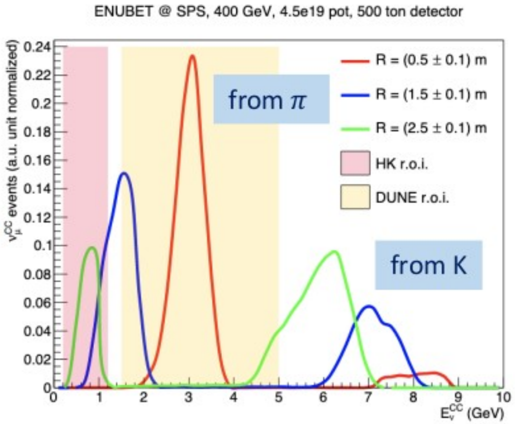
8-25% E_ν resolution from π in the DUNE energy range

30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):

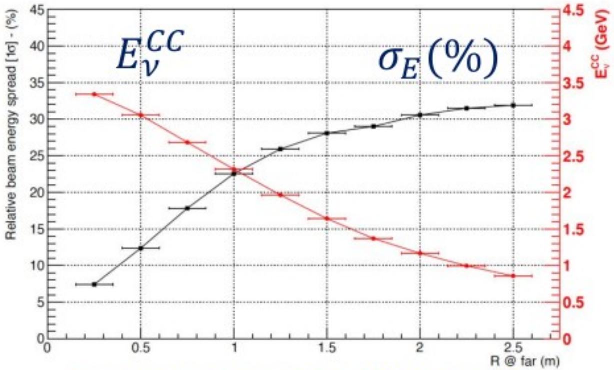
- ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



π/K populations well separated

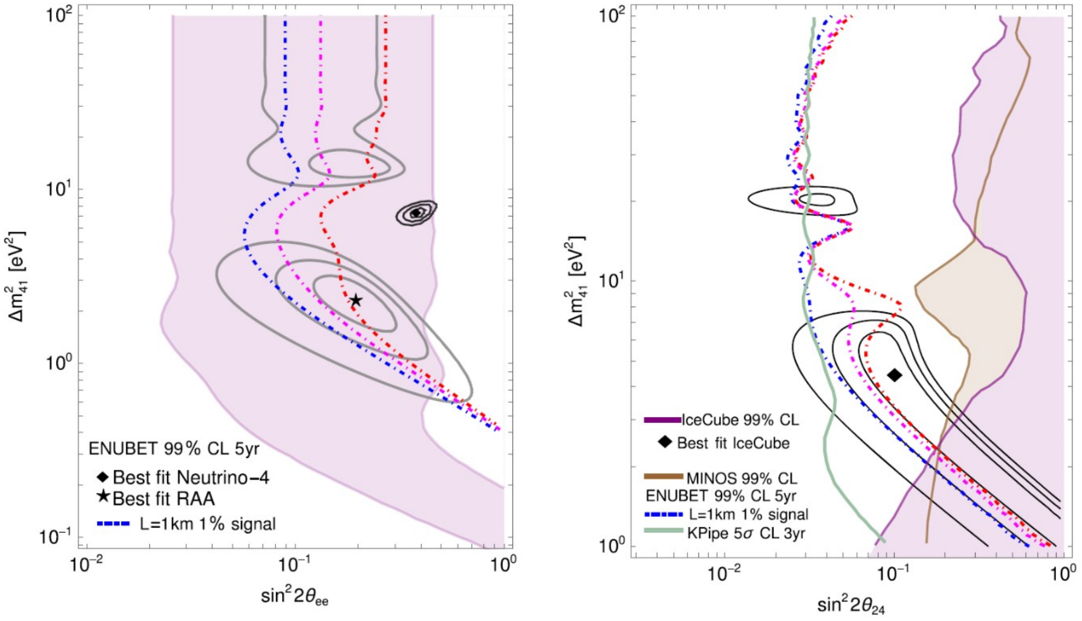


from pion peaks at different R

BSM

Sterile neutrinos: some results already available

L.A. Delgadillo, P. Huber, PRD 103 (2021) 035018



Instrumented proton and hadron dump:

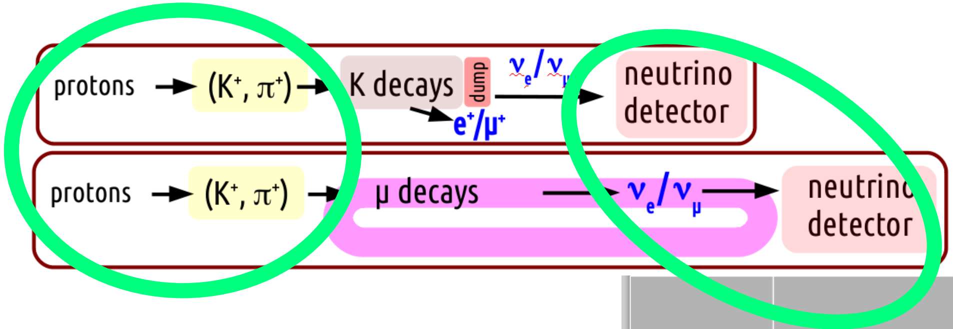
P. S. Bhupal Dev, Doojin Kim, K. Sinha, Yongchao Zhang, Phys. Rev. D 104, 035037 [ALP]
J. Spitz, Phys. Rev. D 89 (2014) 073007 [KDAR]

Work ongoing for studies of **Dark Sector** and **non-standard neutrino interactions** to assess potential of SBL versus Near detectors:

- Pros: energy control of the incoming flux. Outstanding precision on flux and flavor
- Cons: limited statistics

ENUBET-nuSTORM synergies

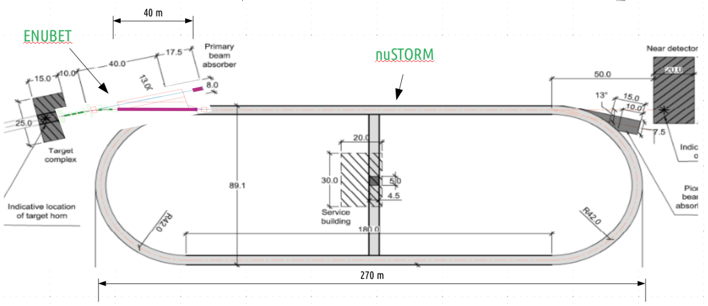
nuSTORM can be seen (simplistically) as an “ENUBET without a hadron dump” where pions and muons are channeled into a ring. Large room for smart ideas to match the requirements of the two experiments



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

- But also significant differences (and scale)

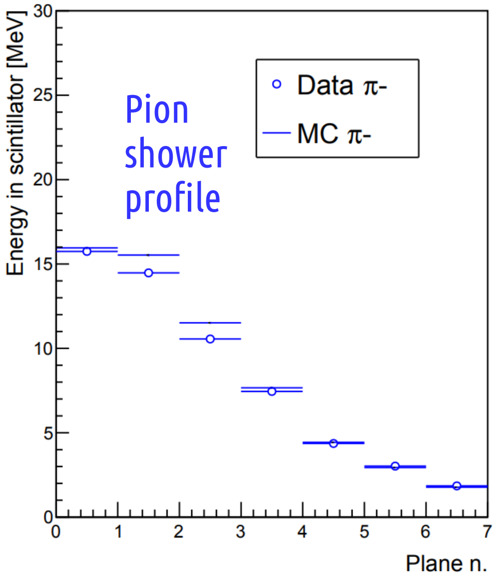
	Decay region	Hadron dump	Proton extraction, energy, focusing	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps μ in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow extraction (+ quad triplets) “slow” in bursts (+horn) 400 GeV	similar	Similar 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

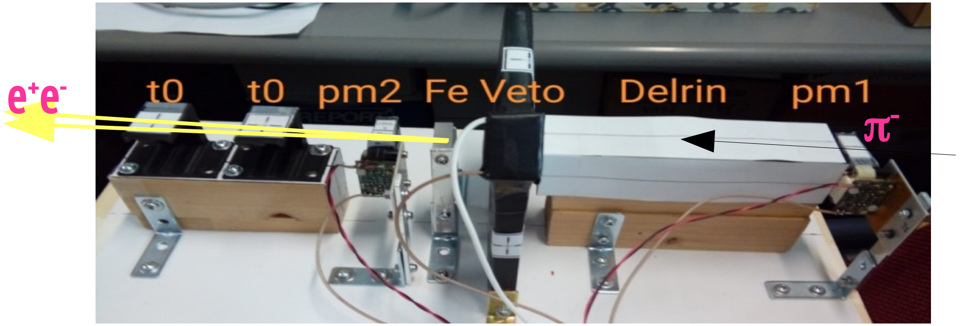
JINST 15 (2020) 08, P08001

ENUBET: prototypes at the CERN-PS

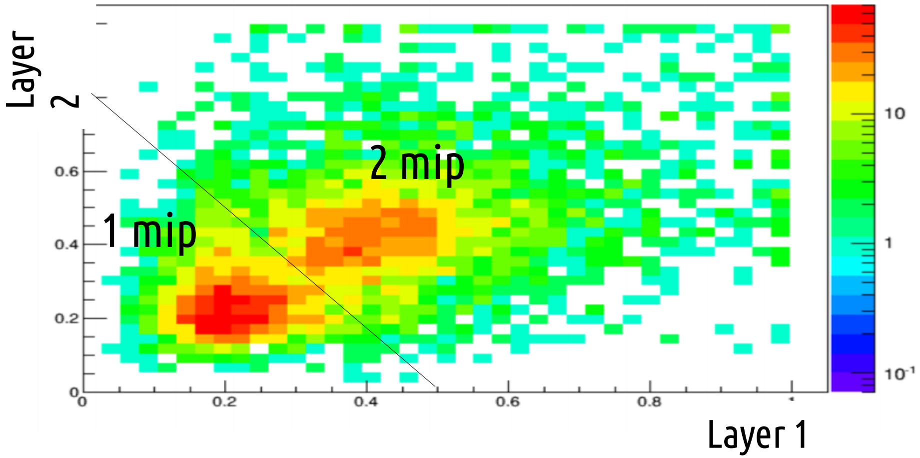


charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2



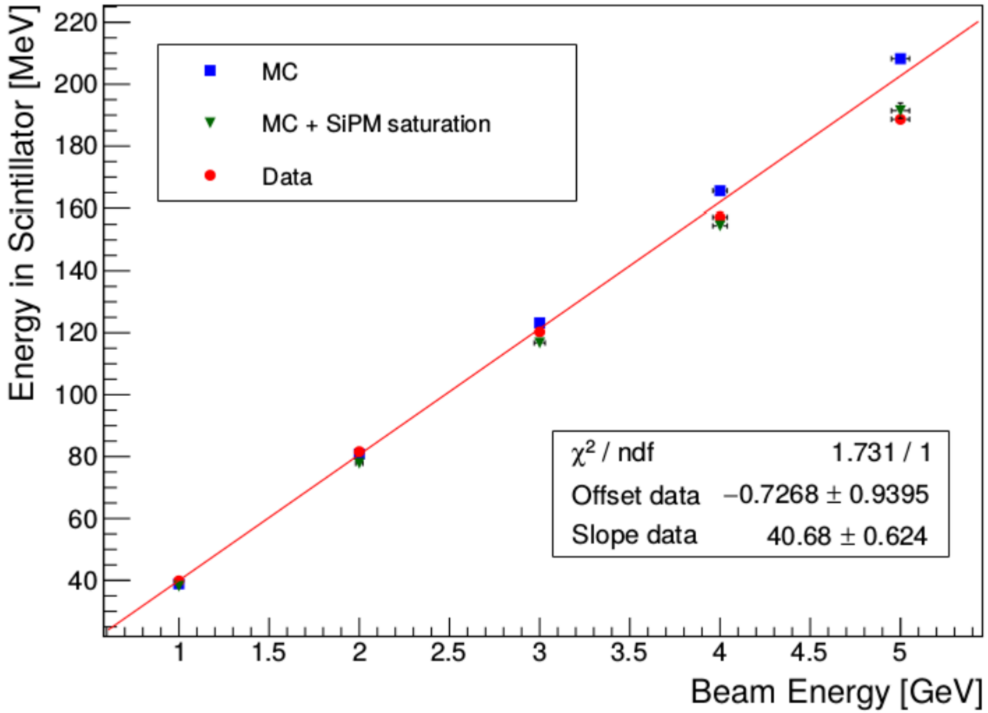
$\sigma_t \sim 400$ ps



JINST 15 (2020) 08, P08001

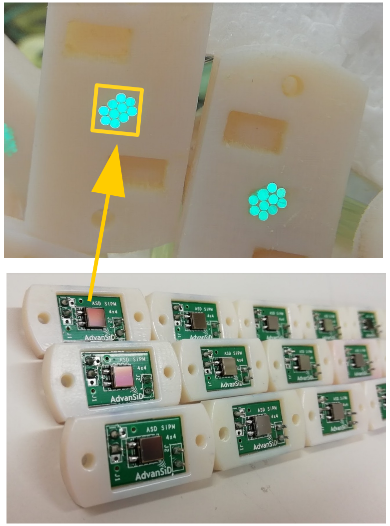
ENUBET: prototypes at the CERN-PS

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



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

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



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

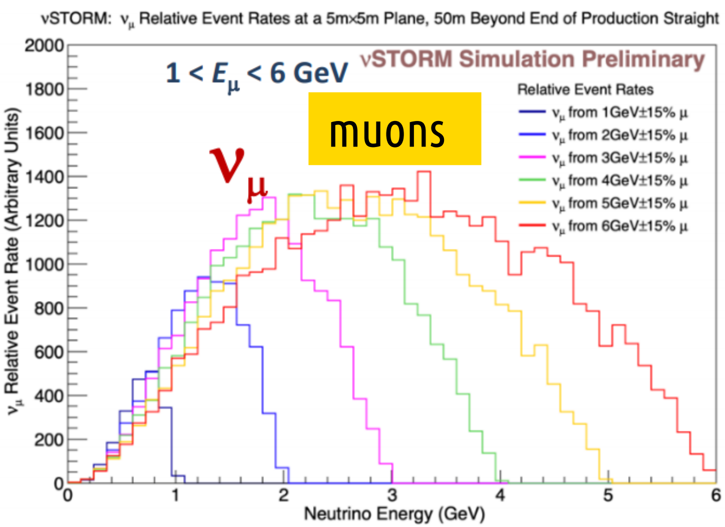
Fluxes decomposition

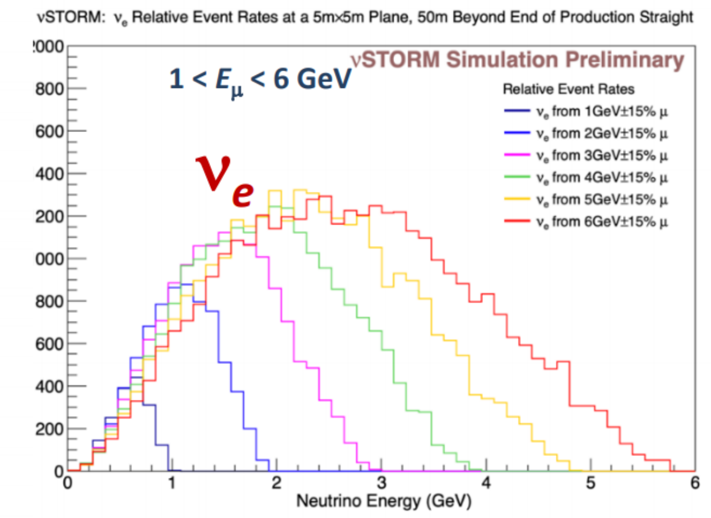
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

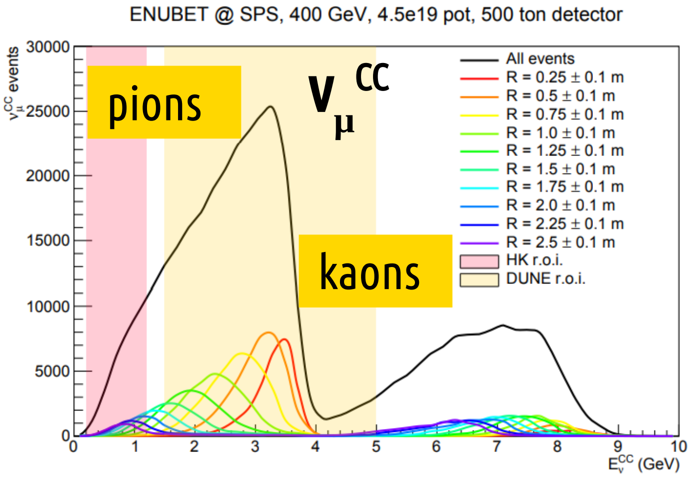
ENUBET narrow-band off-axis technique:

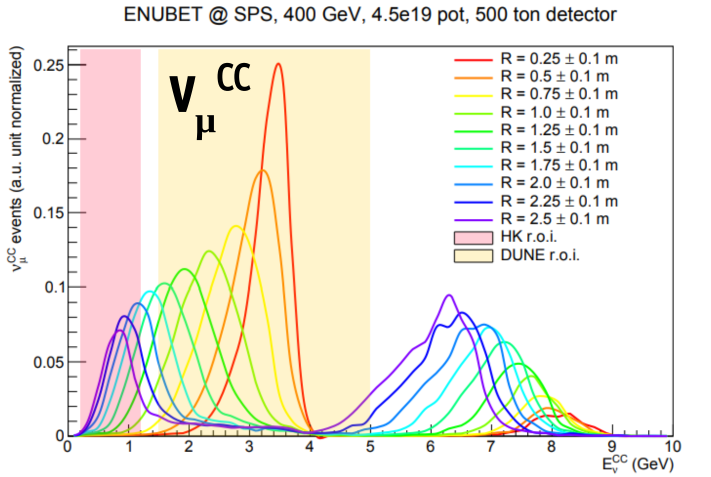
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable.

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







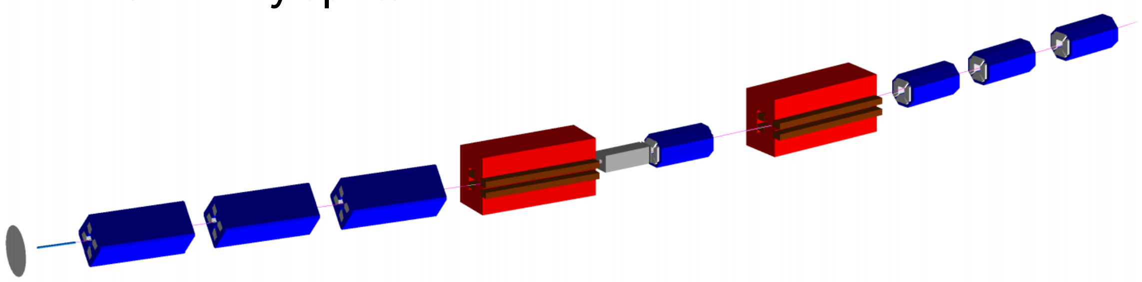


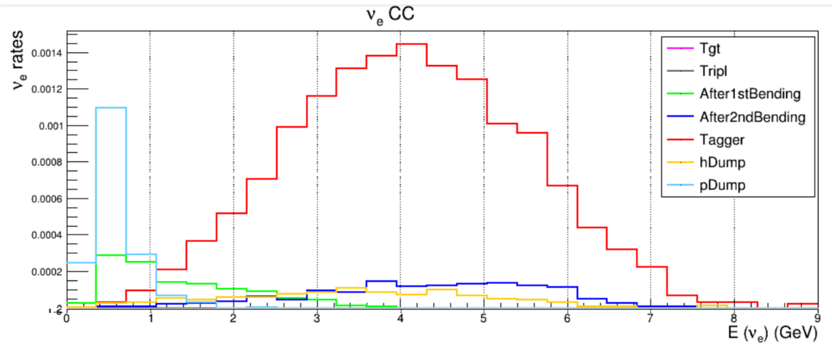
ENUBET multi-momentum transferline

- 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.

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

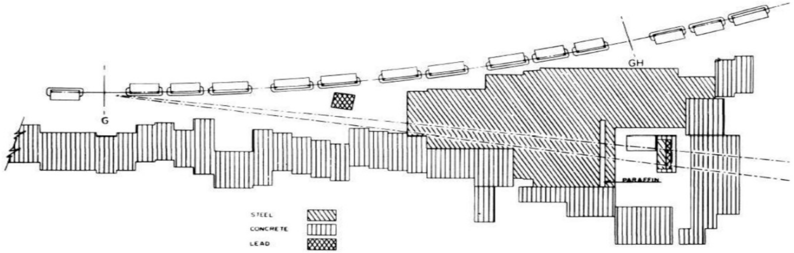
Preliminary optics

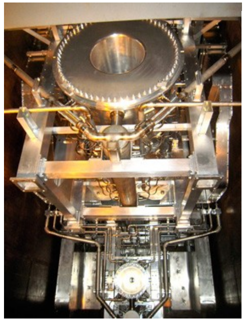




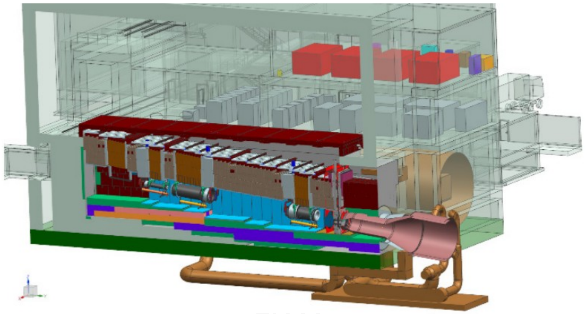
1 4 6 GeV

Accelerator based neutrino beams





J-PARC



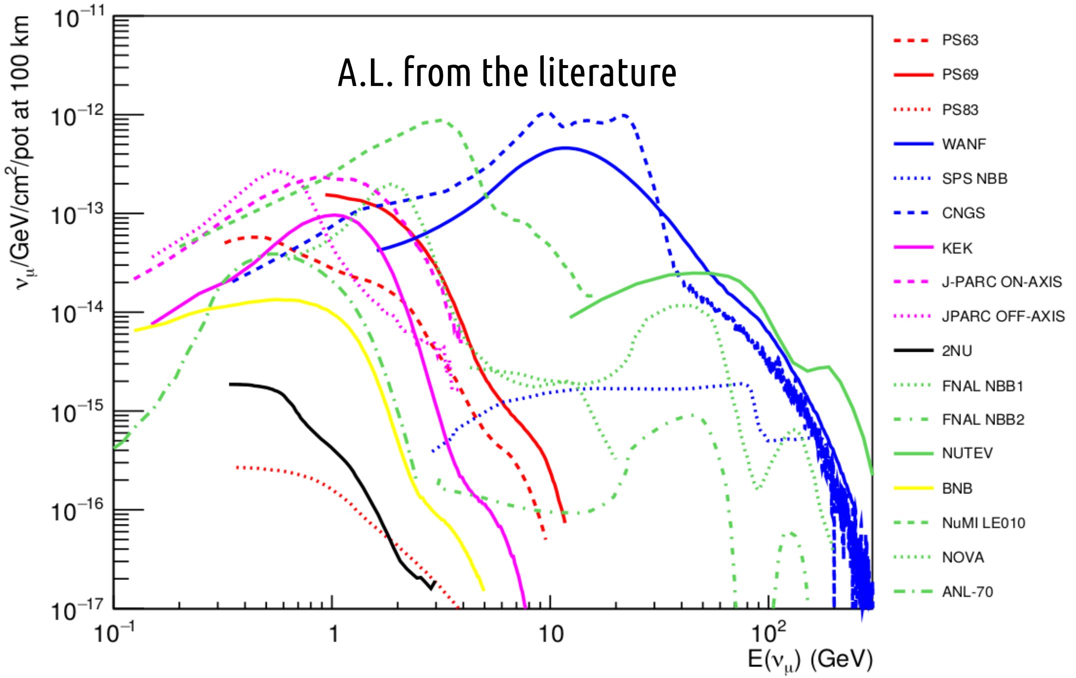
FNAL

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 ...

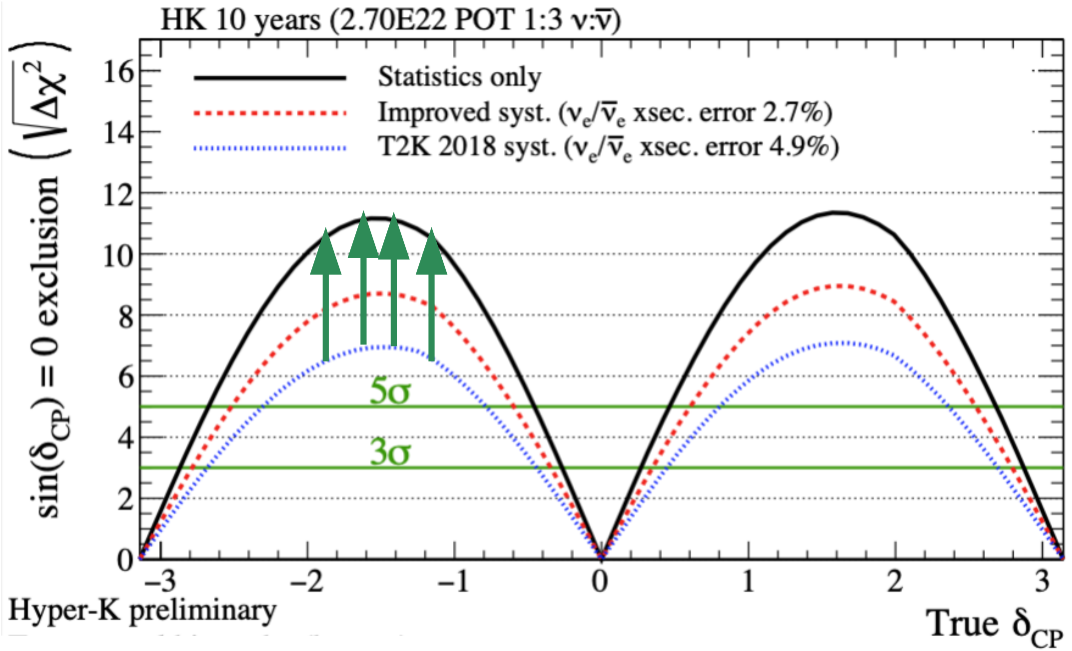
New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.



Precision for the Hyper-K/DUNE era

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

F. Di Lodovico, Neutrino Telescopes 2021



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.

Full simuation with true-level electrons

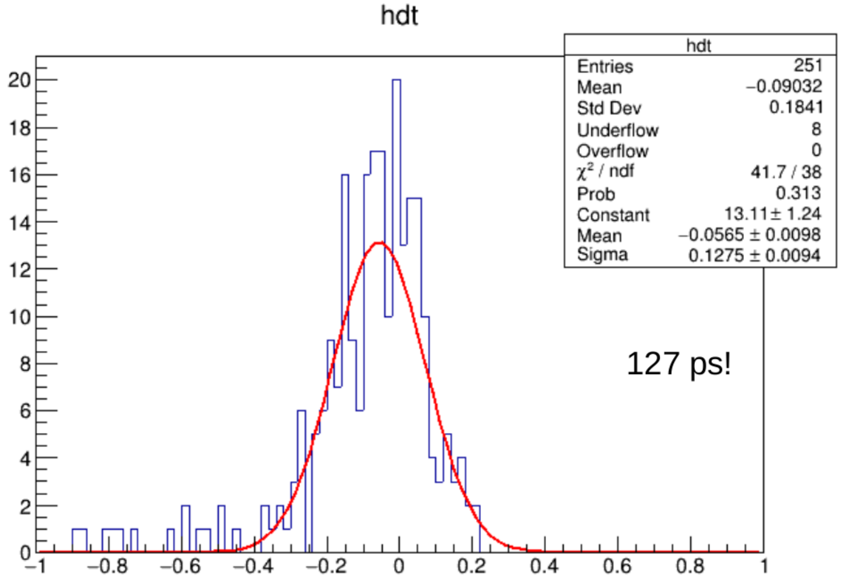
Based on GEANT4. Estimates the spread due to the non collinearity of products
(no contribution from experimental smearing of time measurements)

Ke3 selection based on the G4/G4TAG shared data structure

14/2/21

Time coincidences

Spread is consistent with estimates from the 2015 paper (difference in paths btw lepton and neutrino)



A. Longhin, ENUBET-WP5, 14/2/21 17

The concept of monitored neutrino beams

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

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)

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

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

The lepton tagger

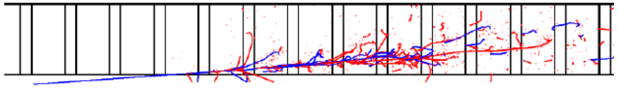
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

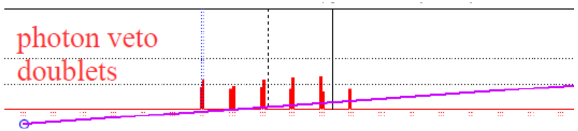
→ $e^+/\pi^\pm/\mu$ separation

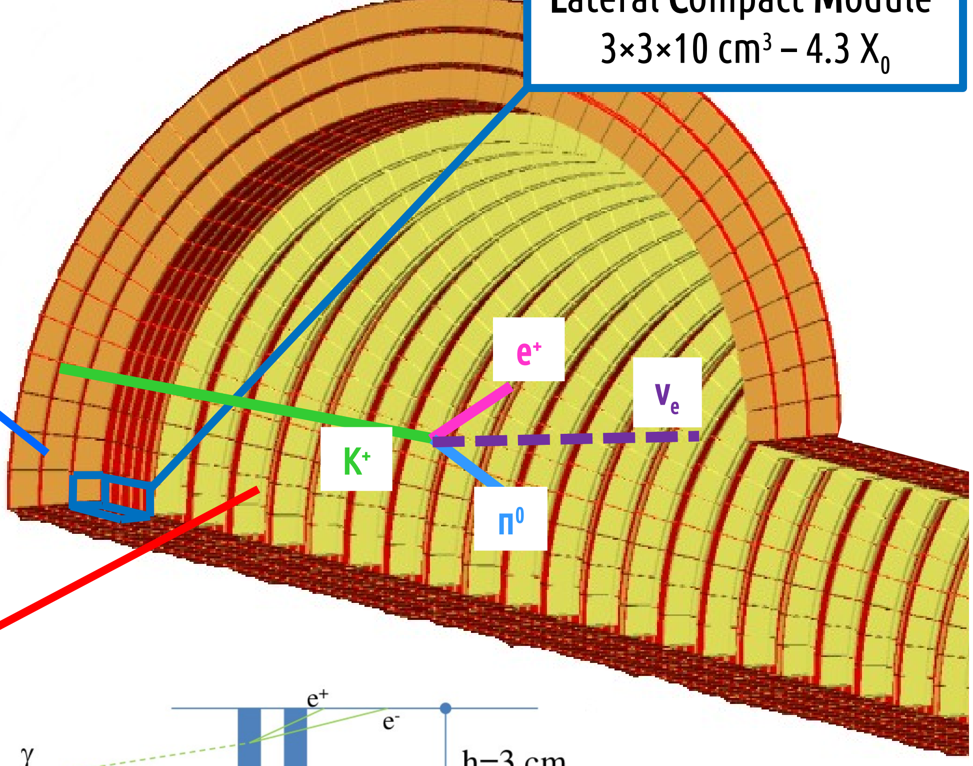


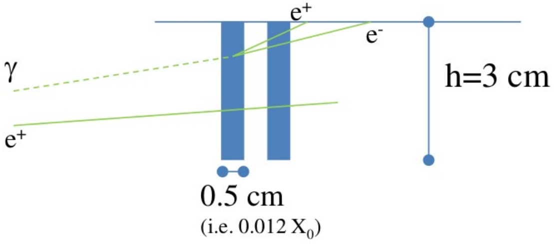
Integrated photon veto

- Plastic scintillators rings of 3×3 cm^2 pads

→ π^0 rejection







e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology