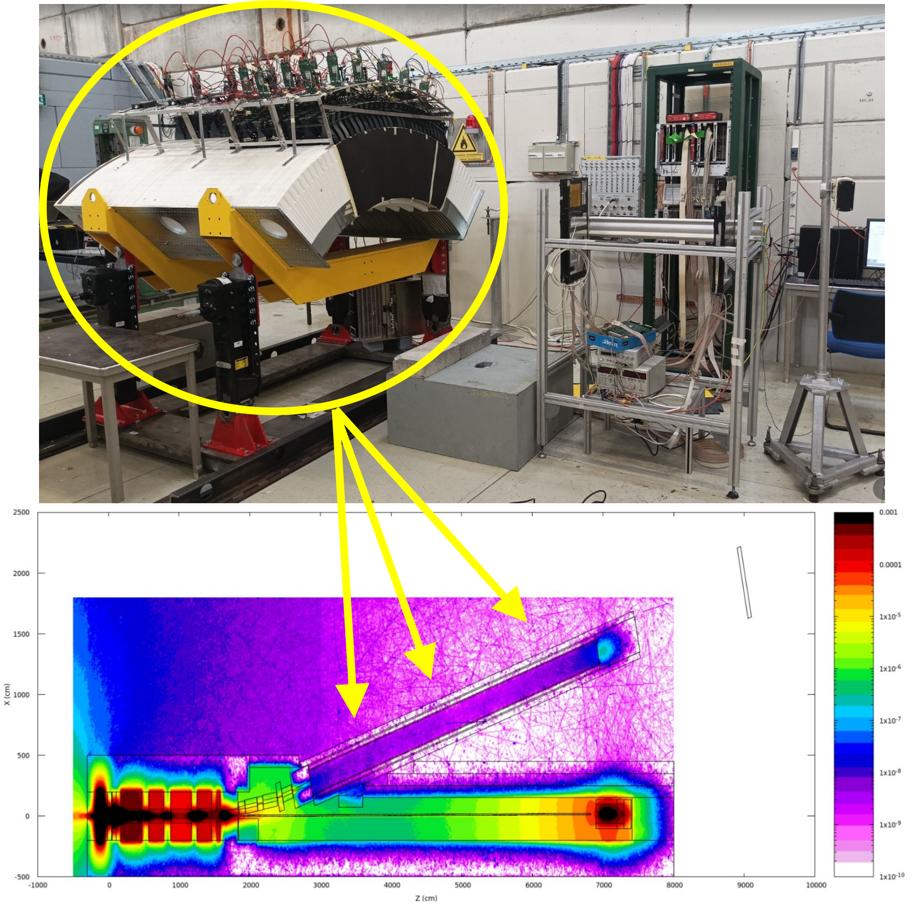
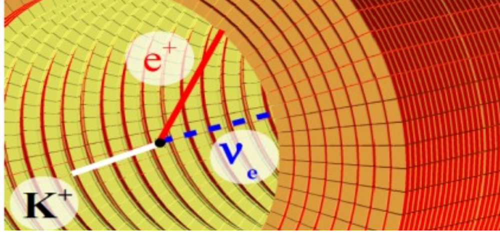
The ENUBET monitored neutrino beam

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

NuFact 2023, Seoul,
25 Aug 2023



ENUBET



- A dedicated short baseline neutrino beam with a 1% precision in ν_e and ν_μ fluxes aimed to a refined near detector
- Reduce the dominant systematics on flux → precise cross section measurements → consolidate the the long-baseline program with high quality experimental inputs

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

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**

erc

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

April 2019

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

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

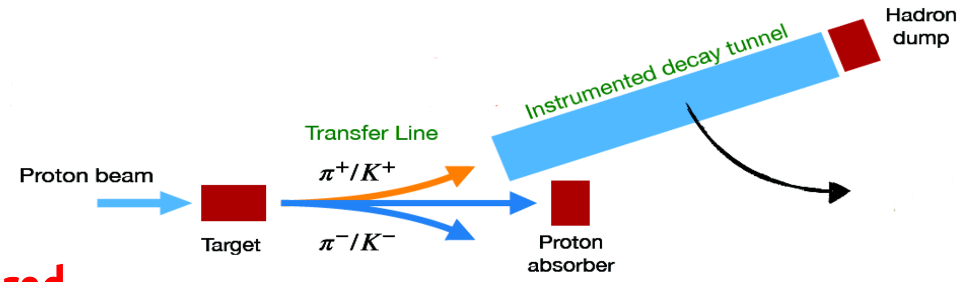
X @enubet

Present collaboration: 72 phys, 15 institutions

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

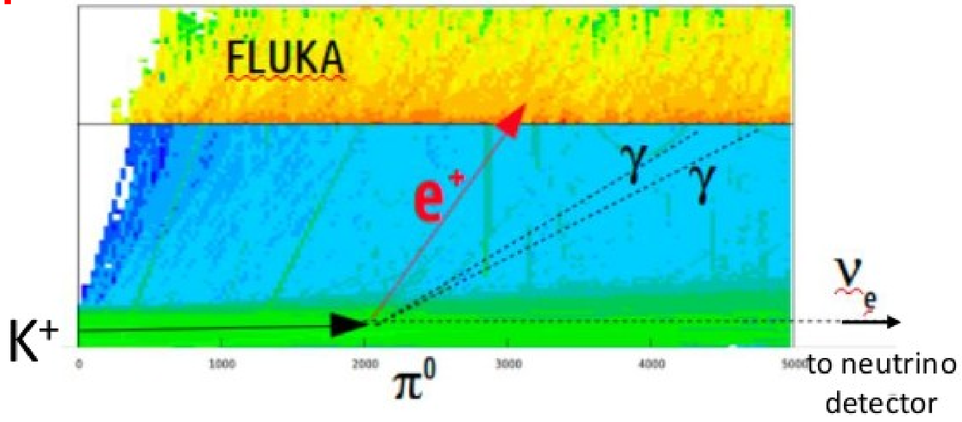
The underlying idea

ENUBET the first **"monitored neutrino beam"**:



the production of neutrino-associated leptons is monitored at single particle level in an instrumented decay region

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



- Needs a **collimated momentum-selected hadron beam** → only the decay products hit the tagger
  → manageable rates and irradiation in the detectors
- Needs a **"short", 40 m, decay region** : ~all ν_e from K, only ~1% ν_e from μ (large flight length)

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

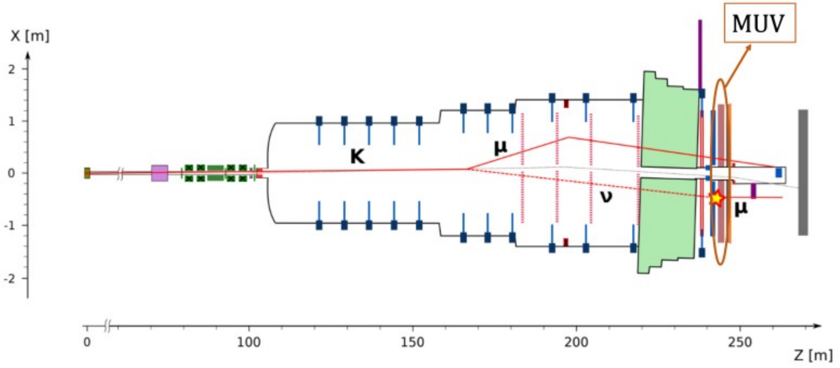
For the first time at this conference!   :-)

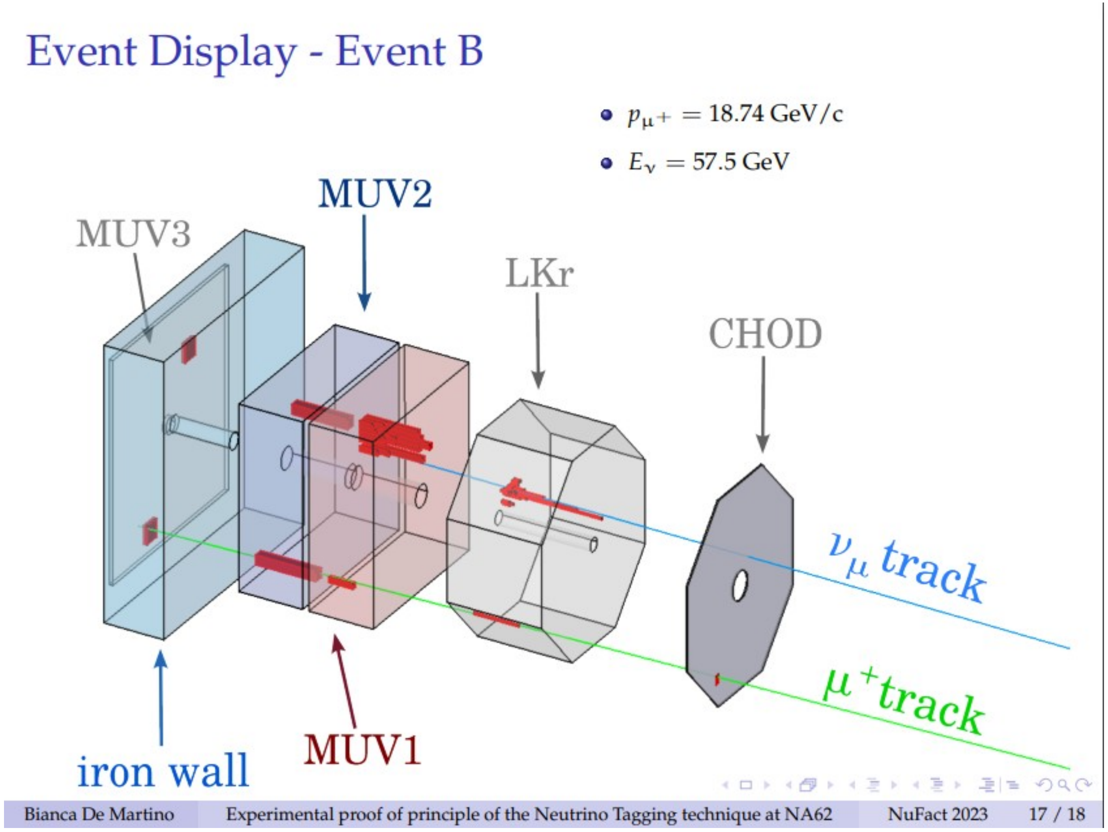
https://indico.cern.ch/event/1216905/contributions/5448754/attachments/2702123/4690877/NuFACT_NuTagging_DeMartino.pdf

Bianca De Martino (NA62)

S/B=5.5, 2 candidates

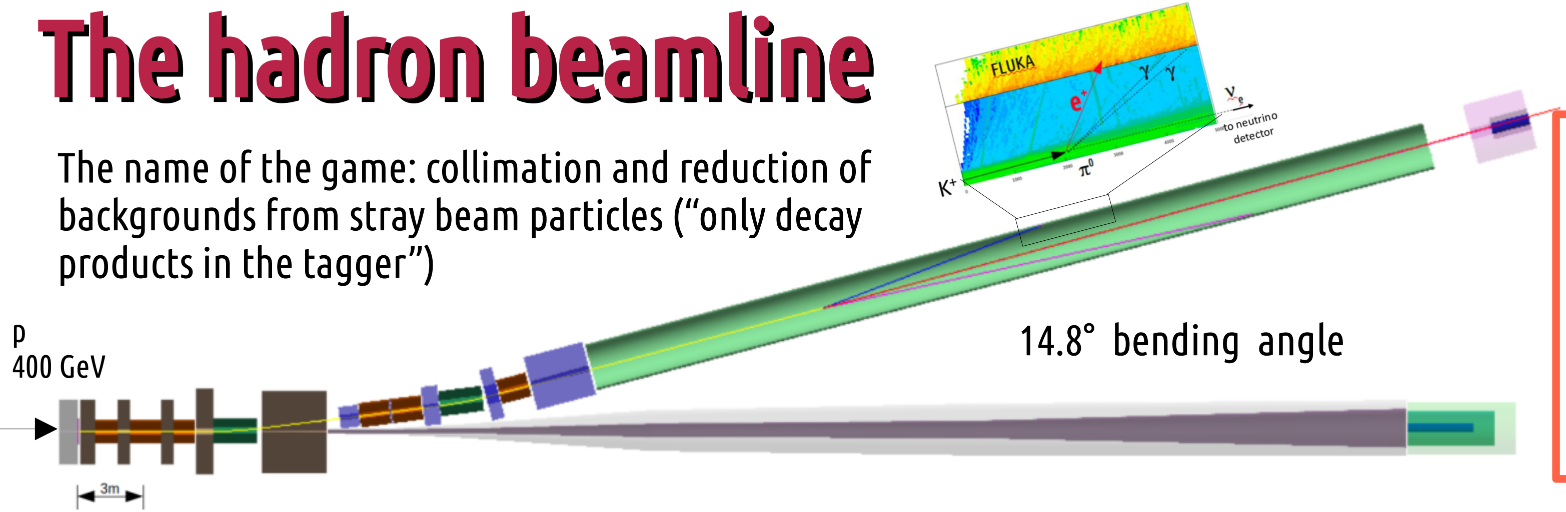
Muon from K decay + neutrino interaction in Xe calorimeter in an existing experiment!





The hadron beamline

The name of the game: collimation and reduction of backgrounds from stray beam particles (“only decay products in the tagger”)

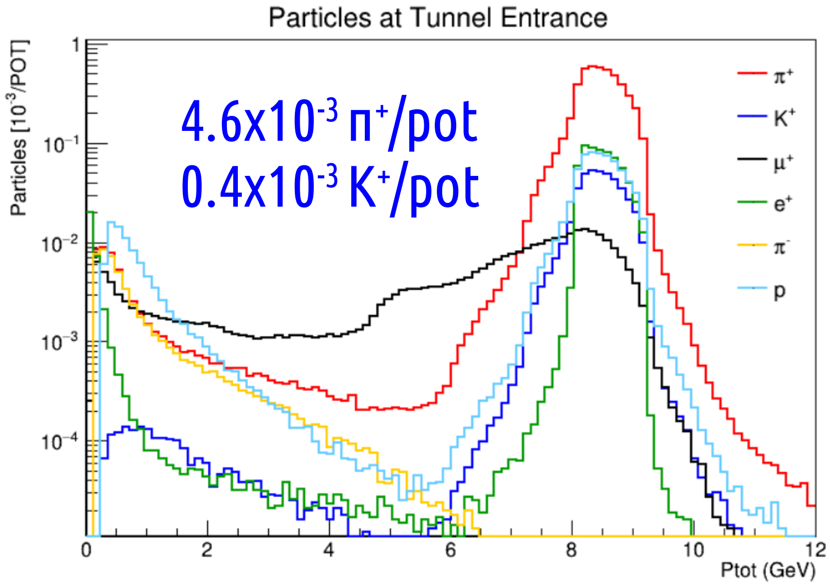


Design and performance of the ENUBET monitored neutrino beam

F. Acerbi[1], I. Angelis[21], L. Bomben[2,3], M. Bonesini[3], F. Bramati[3,4], A. Branca[3,4], C. Brizzolari[3,4], G. Brunetti[3,4], M. Calviani[6], S. Capelli[2,3], S. Carturan[7], M.G. Catanesi[8], S. Cecchini[9], N. Charitonidis[6], F. Cindolo[9], G. Cogo[10], G. Collazuol[5,10], F. Dal Corso[5], C. Delogu[5,10], G. De Rosa[11], A. Falcone[3,4], B. Goddard[6], A. Gola[1], D. Guffanti[3,4], L. Halić[20], F. Iacob[5,10], C. Jollet[16], V. Kain[6], A. Kallitsopoulou[24], B. Kliček[20], Y. Kudenko[13], Ch. Lampoudis[21], M. Laveder[5,10], P. Legou[24], A. Longhin[a,5,10], L. Ludovici[15], E. Lutsenko[2,3], L. Magaletti[8,14], G. Mandrioli[9], S. Marangoni[3,4], A. Margotti[9], V. Mascagna[22,23], N. Mauri[9,18], J. McElwee[16], L. Meazza[3,4], A. Meregaglia[16], M. Mezzetto[5], M. Nessi[6], A. Paoloni[17], M. Pari[5,10], T. Papaevangelou[24], E.G. Parozzi[4], L. Pasqualini[9,18], G. Paternoster[1], L. Patrizii[9], M. Pozzato[9], M. Prest[2,3], F. Pupilli[5], E. Radicioni[8], A.C. Ruggeri[11], G. Saibene[2,3], D. Sampsonidis[21], C. Scian[10], G. Sirri[9], M. Stipčević[20], M. Tenti[9], F. Terranova[3,4], M. Torti[3,4], S.E. Tzamarias[21], E. Vallazza[3], F. Velotti[6], L. Votano[17]

https://arxiv.org/pdf/2308.09402.pdf

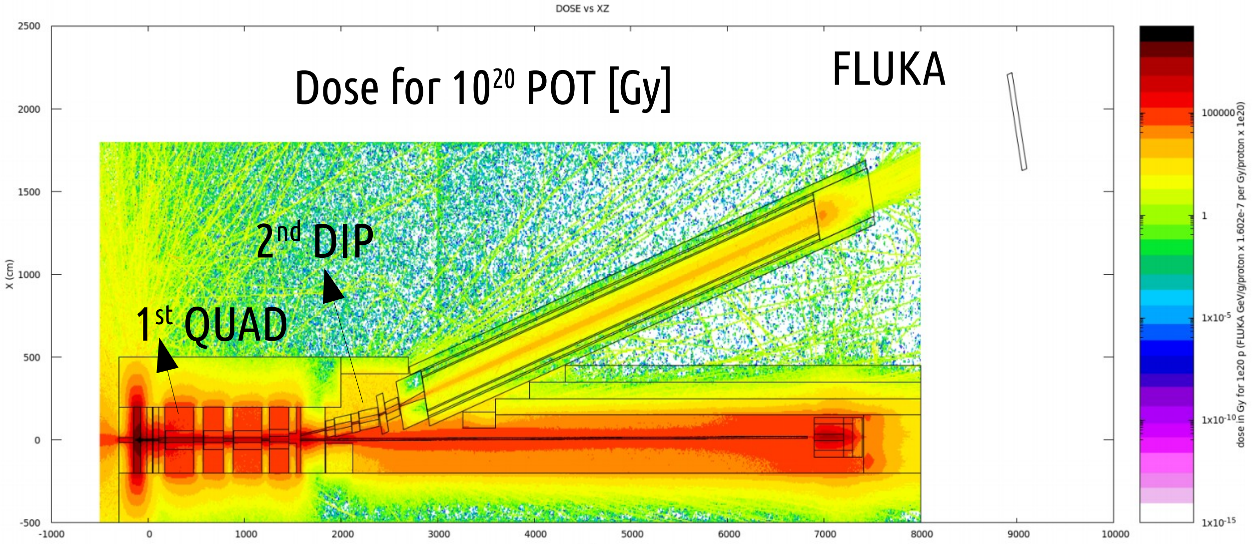
- Uses existing standard (warm) magnets
- Focuses **8.5 GeV +/- 10%** pions and kaons (drives the ν spectrum!)
- Target: graphite L = 70 cm, r = 3 cm (optimized)
- W foil: downstream of target to absorb background from e^+
- Inermet optimized absorber @ tagger entrance
- p-dump: three cyl. layers (graphite core → aluminum → iron)
- H-dump: ~ p-dump to reduce back-scattering in the tunnel
- Simulation: optics optimization (TRANSPORT). Particle transport, interactions: G4beamline. Irradiation (FLUKA). Systematics (GEANT4, fully parametric, access to particle history).

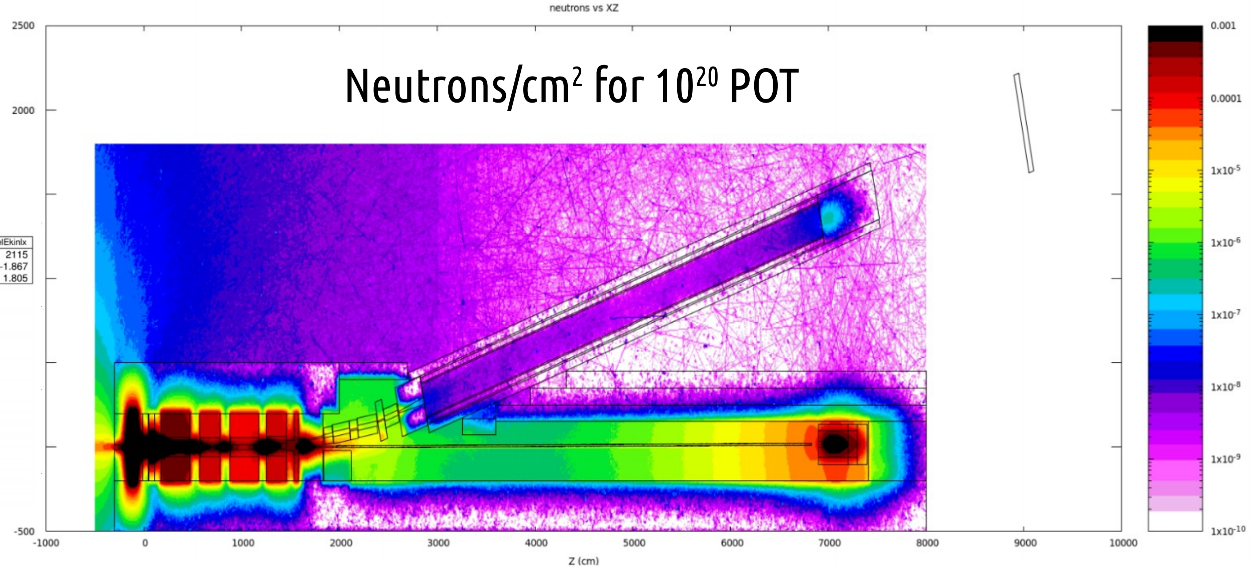


Irradiation/detectors

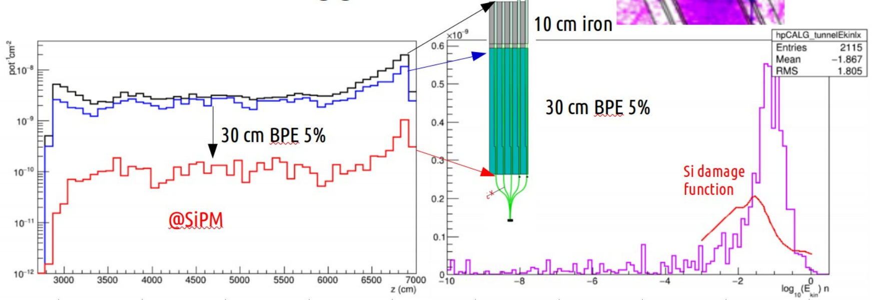
Dose is sustainable by magnets even in the hottest regions (<300 kGy/10^{20} pot).

Neutrons simulations guided the design of the instrumentation → 30 cm of Borated PE (5%) added to protect the Silicon Photomultipliers. Good lifetime (7e9 n/cm^2/10^{20} pot). Accessible eventually.



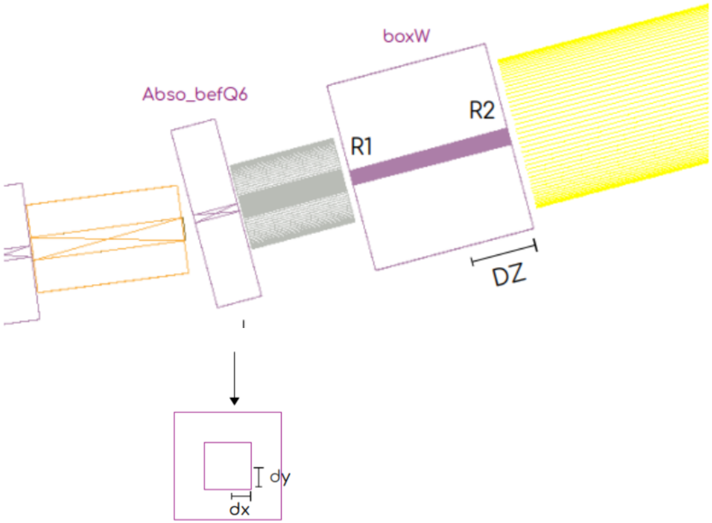


Neutrons in the tagger



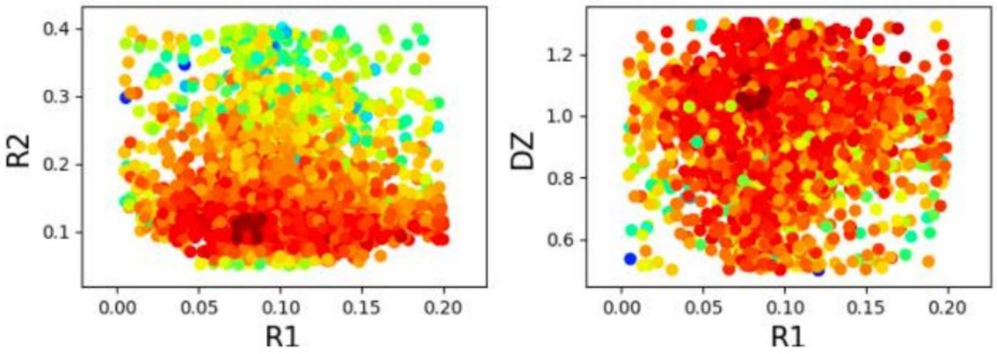
Optimization of the beamline

C. Delogu, PhD thesis
https://arxiv.org/pdf/2308.09402.pdf



- FOM = S/B
- S (signal):= π & K @ tagger entrance
- B(background):= e^{+} & π hitting tagger walls (excluding those from K_{e3} decays)

FOM dependence on parameters (example)

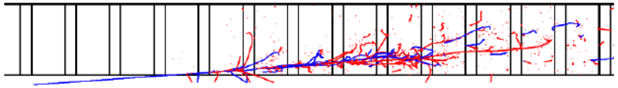


Ambitious optimization campaign:

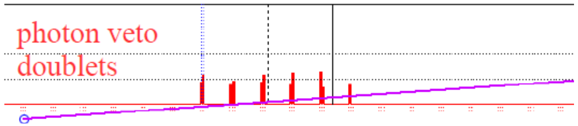
- fully in GEANT4 → control all pars with external cards
- explore multi-D parameters space to maximize FOM
- Genetic algorithm run on a cluster (Lyon IN2P3) with thousands of parallel jobs at each “generation”

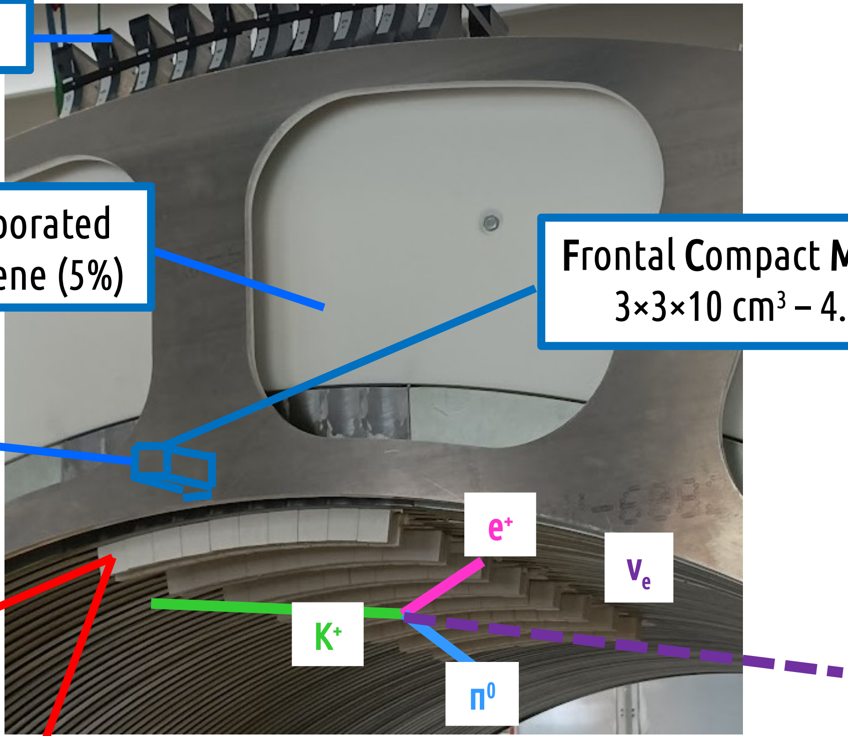
The lepton tagger

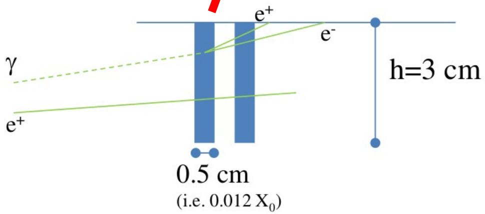
Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation



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







e^+ (signal) topology

π^0 (background) topology

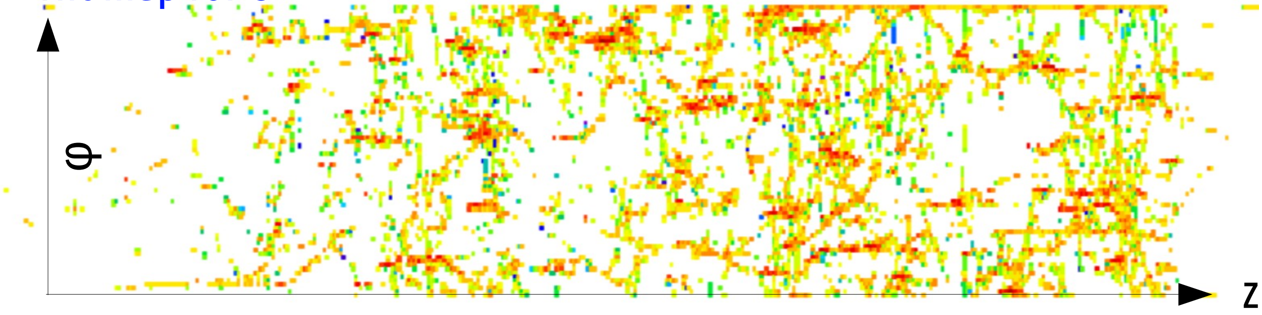
π^+ (background) topology

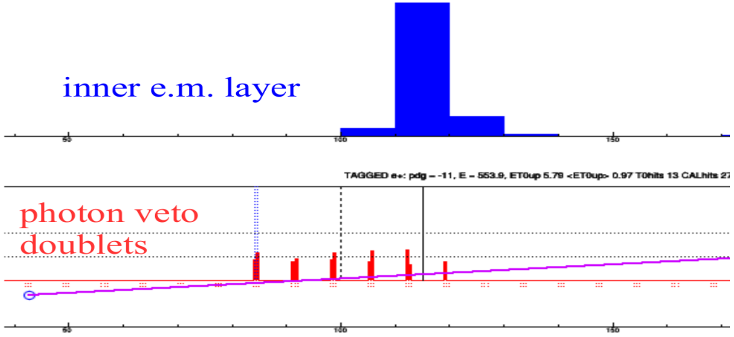
Lepton reconstruction in the tagger

F. Pupilli et al., PoS NuFact2021 (2022) 025
https://arxiv.org/pdf/2308.09402.pdf

GEANT4 simulation of the detector, validated by prototype tests at CERN since 2016.
Event building: clustering of cells in space and time (accounting for **pile-up**) → PID with a Multilayer Perceptron.

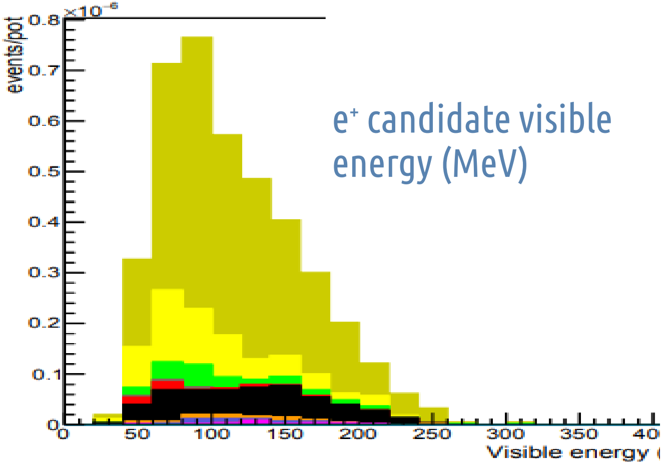
Hit map for e^+



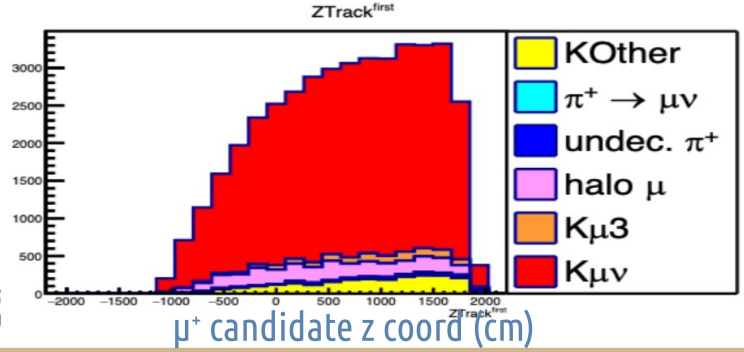


K_{e3} e+: Efficiency ~22%, S/N of ~2

Half of efficiency loss is geometrical



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



ν_e^{CC} spectra at detector

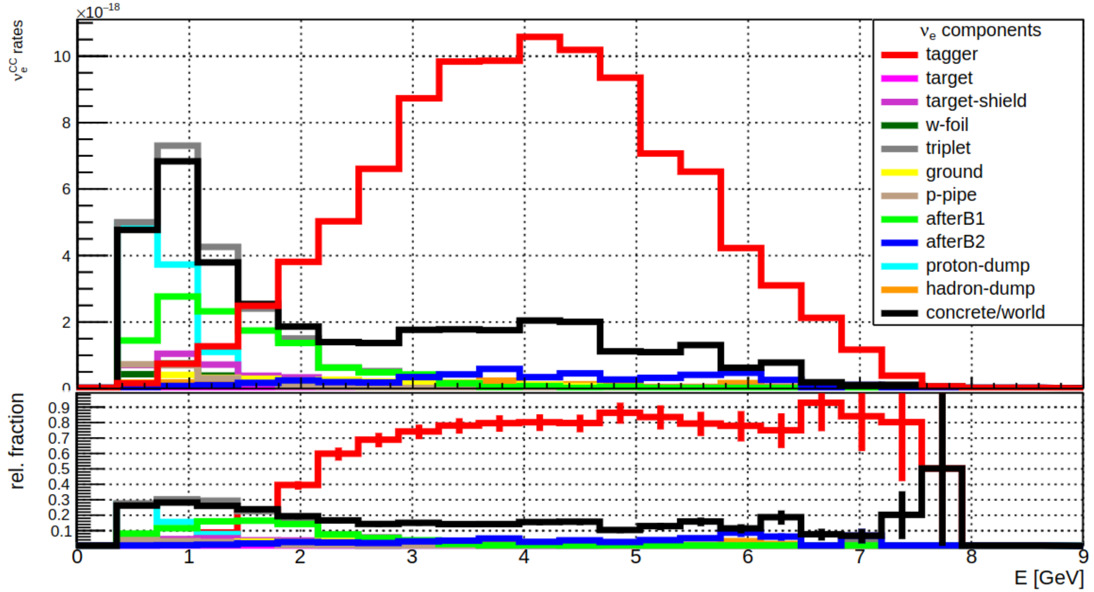
500t @ 50 m after the hadron dump
@ 400 GeV → **10000 ν_e^{CC}** with 9e19 POT (2-3 y)

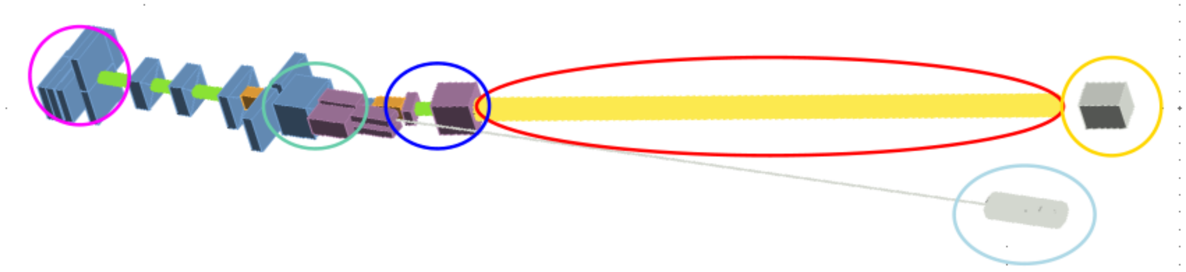
- ν_e from $K^{+/-}$ in the instrumented region
- ν_e from $K^{0+/-}$ in the proton/hadron dump

→ reduce by tuning the dump geometry/location

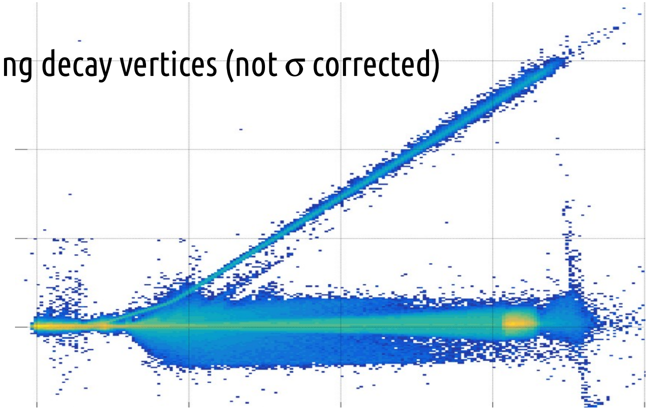
- ν_e from $K^{+/-}$ in front of the tagger

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



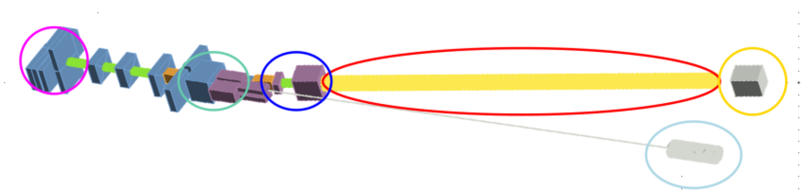


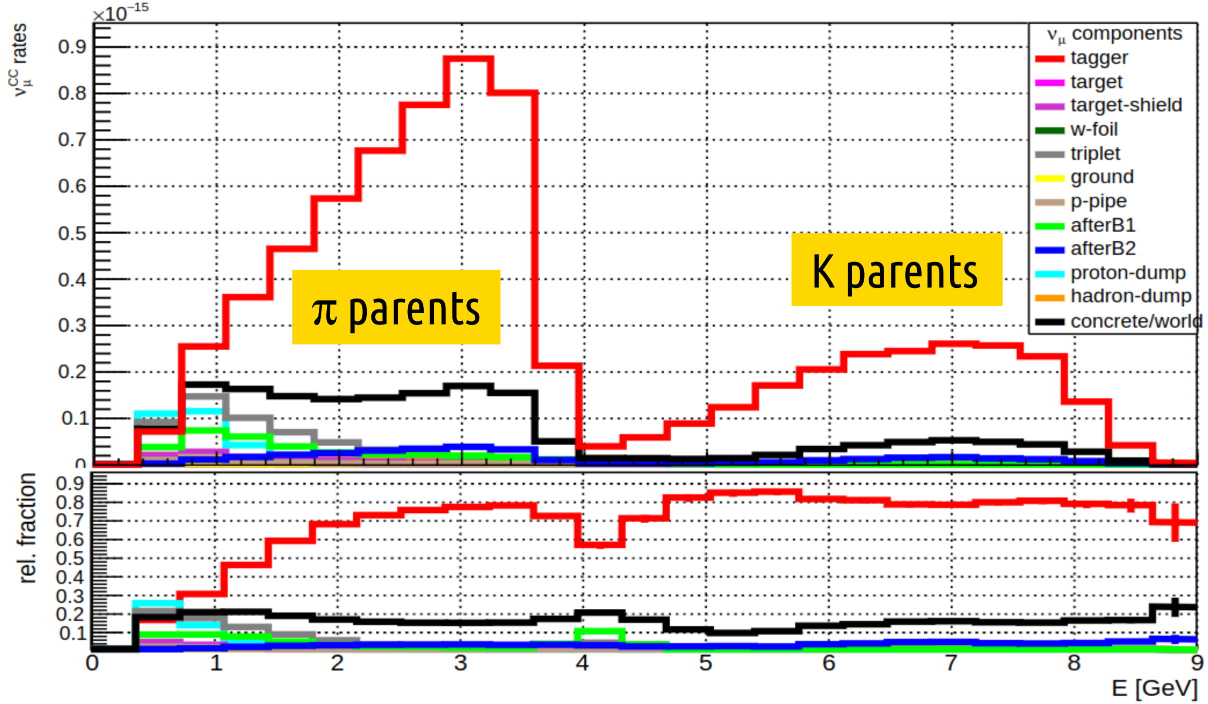
ν producing decay vertices (not σ corrected)



ν_μ^{CC} spectra at detector

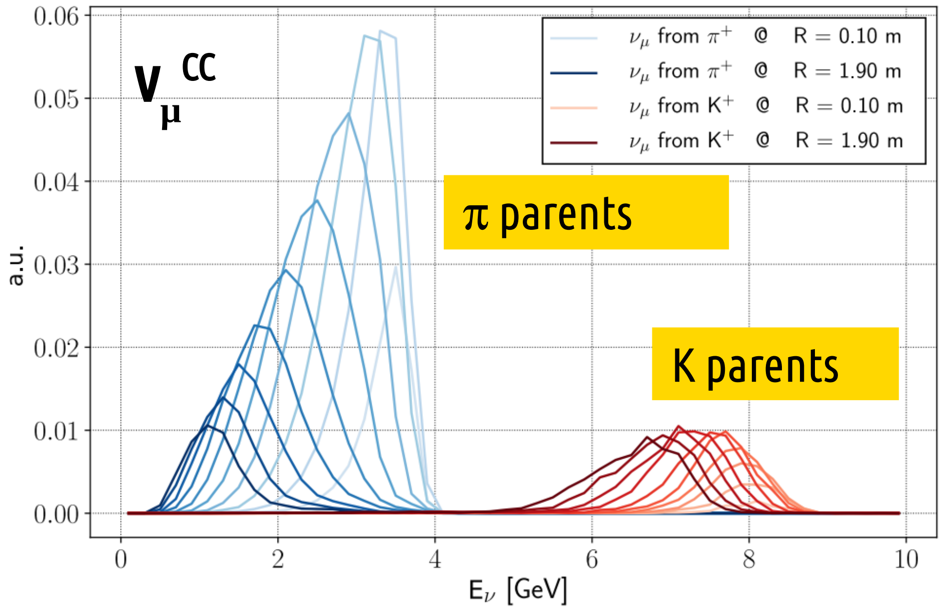
500t @ 50 m after the hadron dump
@ 400 GeV → **0.7 Mν_μ^{CC}** with 9e19 POT (2-3 y)

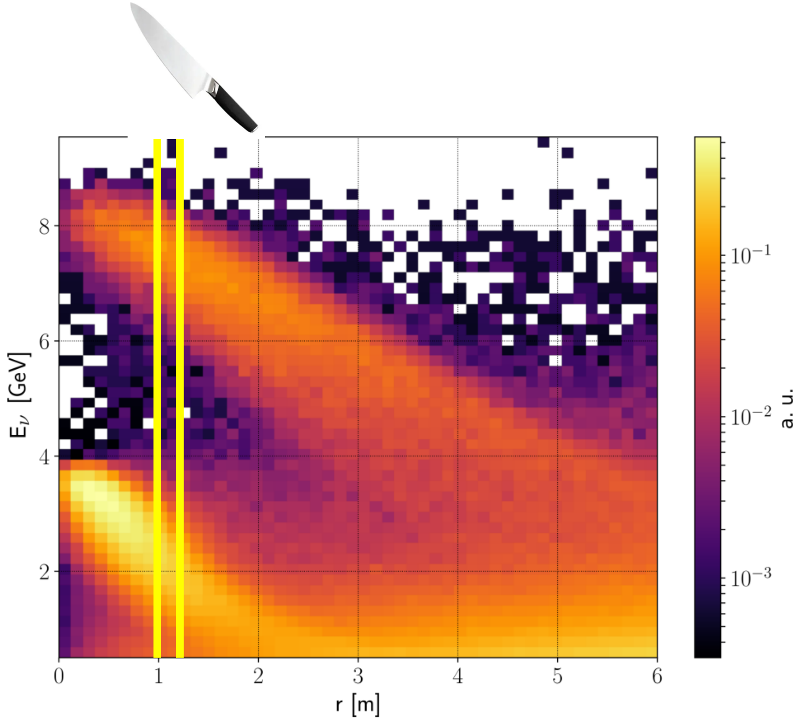




ν_μ fluxes decomposition: NBOA (~PRISM)

"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) !





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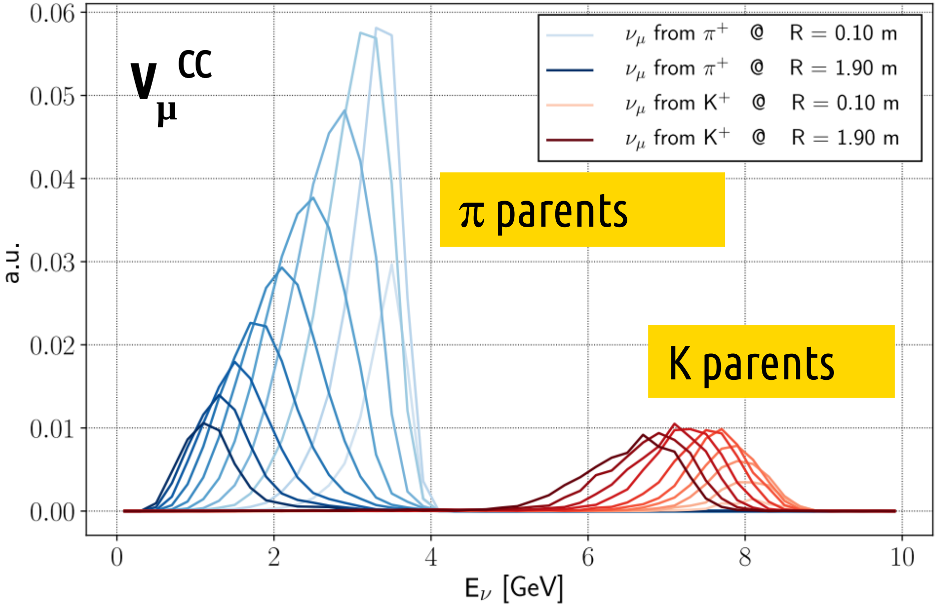
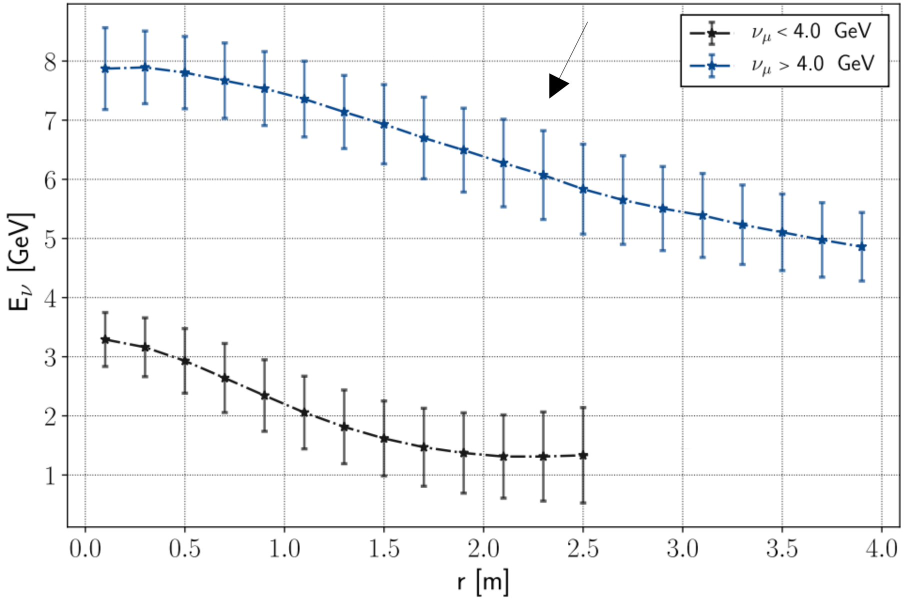
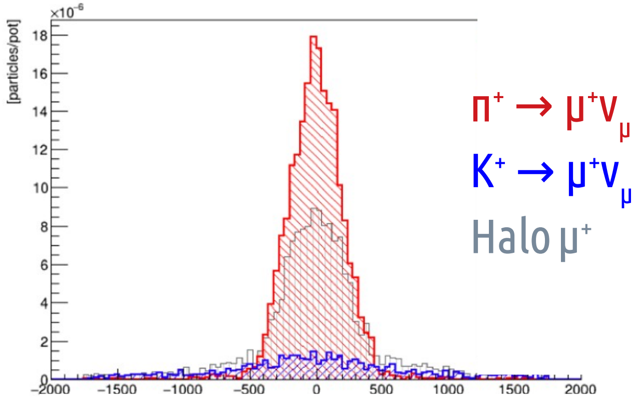


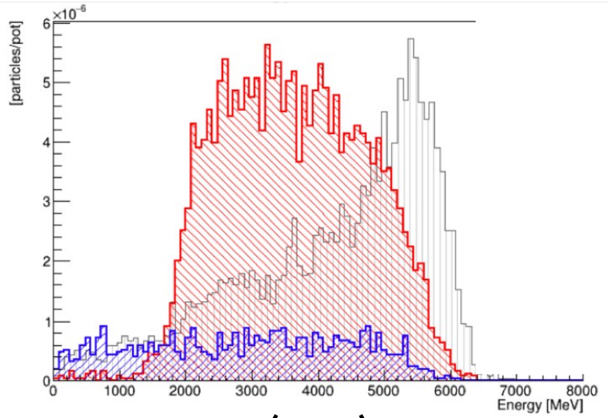
Error bands visualize the rms of the energy distributions

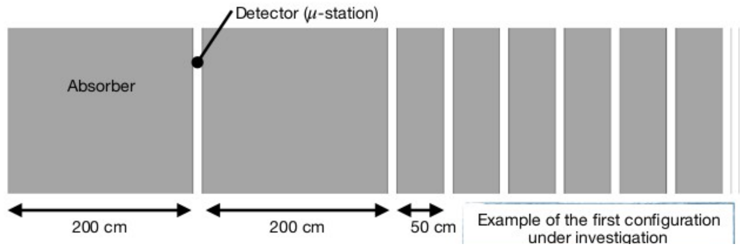


Forward region muons reconstruction

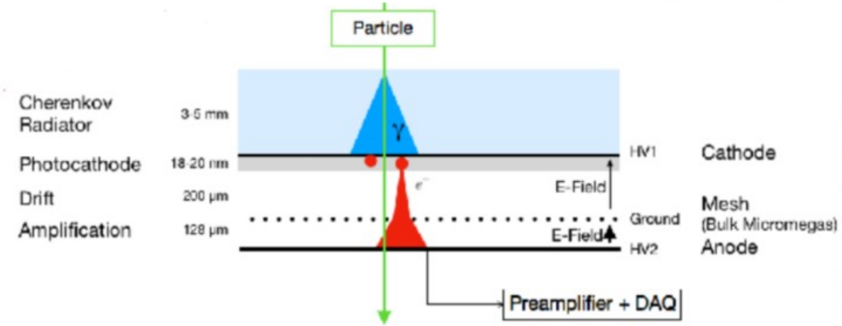
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu2}$ decays contributing to the low-E ν_μ.

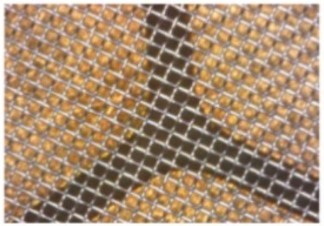






The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n$_{eq}$/cm^2.





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

→ PIMENT project ! →

PIMENT and ESSnuSB+

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

French ANR

PICOSEC **M**icrom**E**gas Detector for **ENUBET**

→

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)

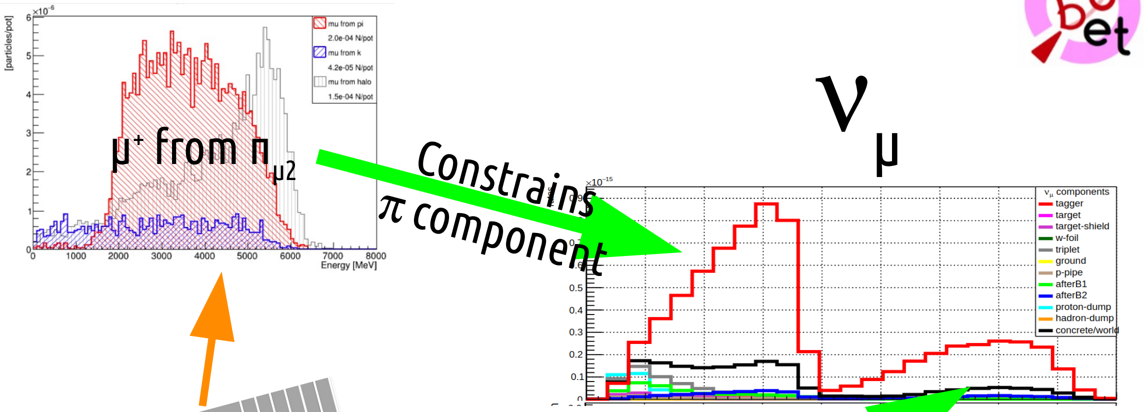
Funded by : RÉPUBLIQUE FRANÇAISE Liberté Égalité — anr agence nationale de la recherche

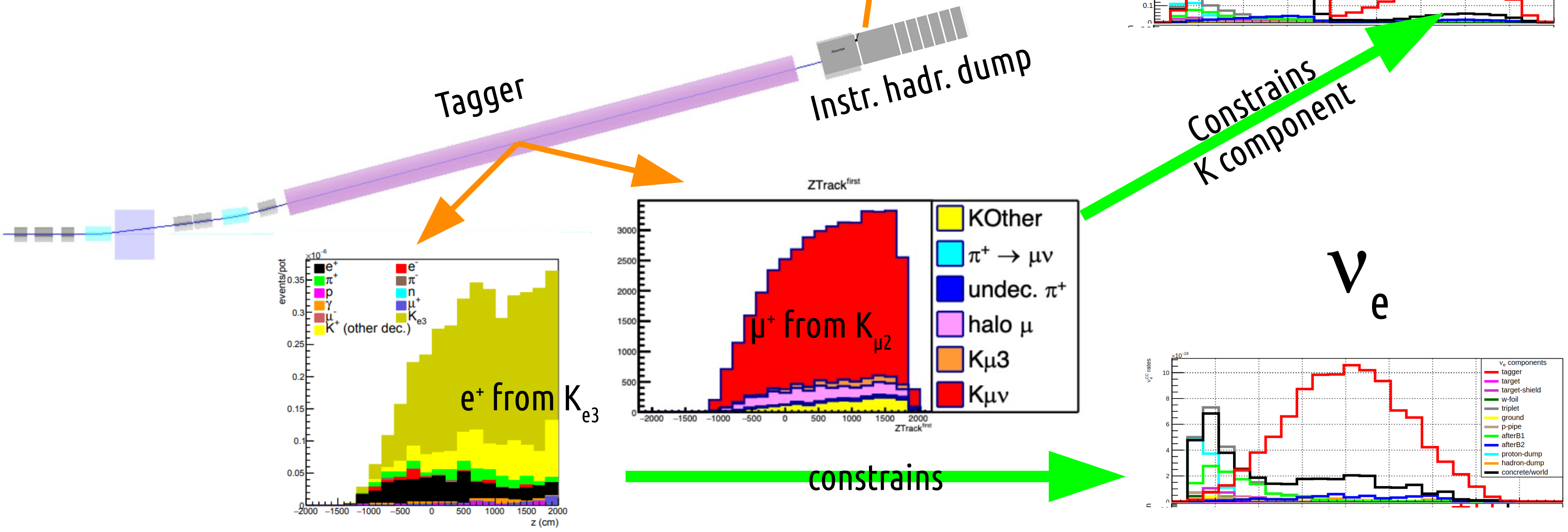
ESSnuSB+ WP6: could the idea of ENUBET be exploited also at the ESS proton driver using pions monitoring (E_{prot} = 2 GeV) ? See dedicated talk at the dedicated workshop here:

https://indico.cern.ch/event/1216905/contributions/5533277/attachments/2700208/4686626/LEMNB_WP6_NuFact2023_v2.pdf

Oveview on lepton monitoring at 400 GeV

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



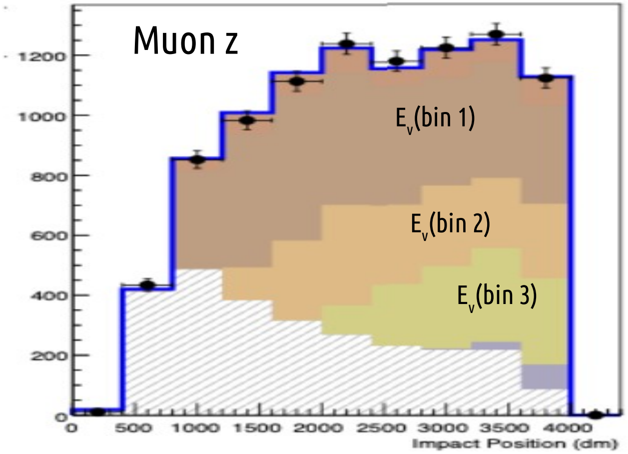


Flux constraint from lepton rates → systematics reduction

- build S+B model to fit lepton observables
  - 2D distributions in z(lepton) and reconstructed-energy
- include hadro-production (HP), transfer line (TL), detector systematics as nuisance parameters (α, β, ...)

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

→ Extended Maximum Likelihood fit

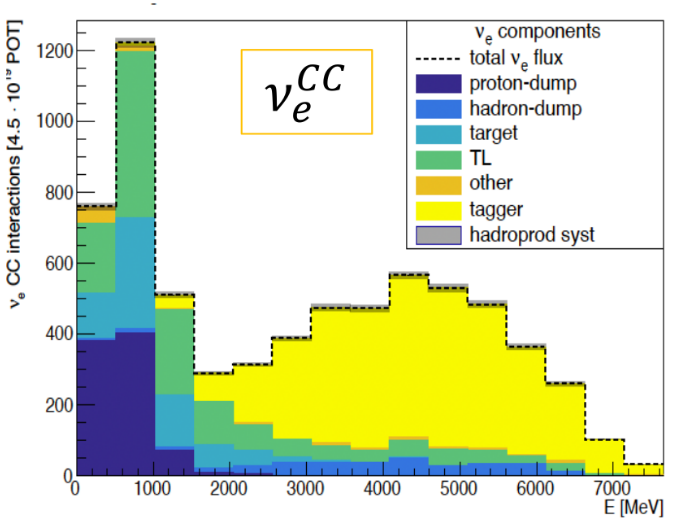


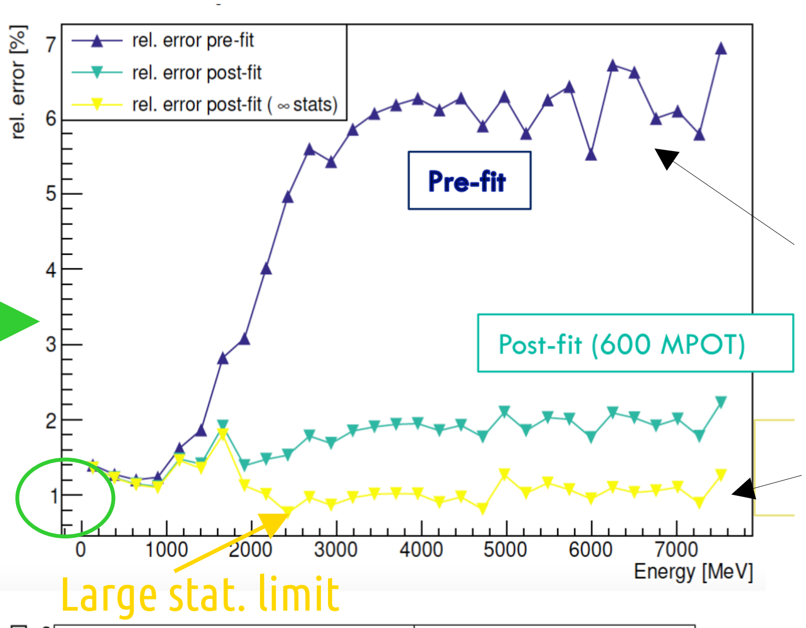
Each histogram component corresponds to a bin in E_ν

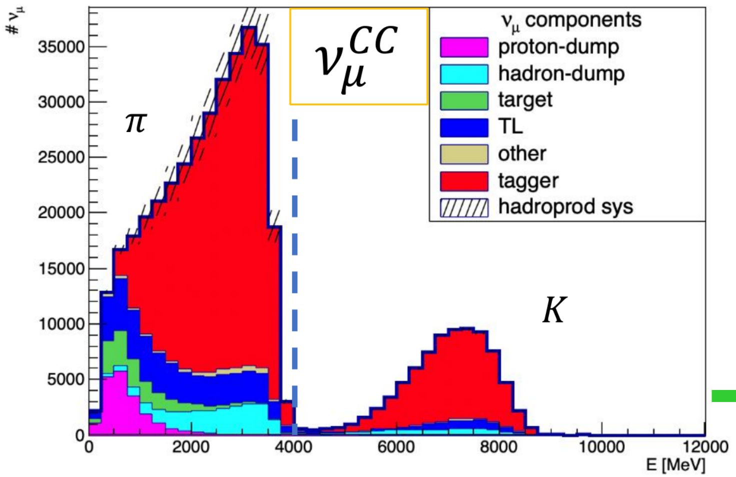
Use a parametric model fitted to hadro-production data from **NA56/SPY experiment**:

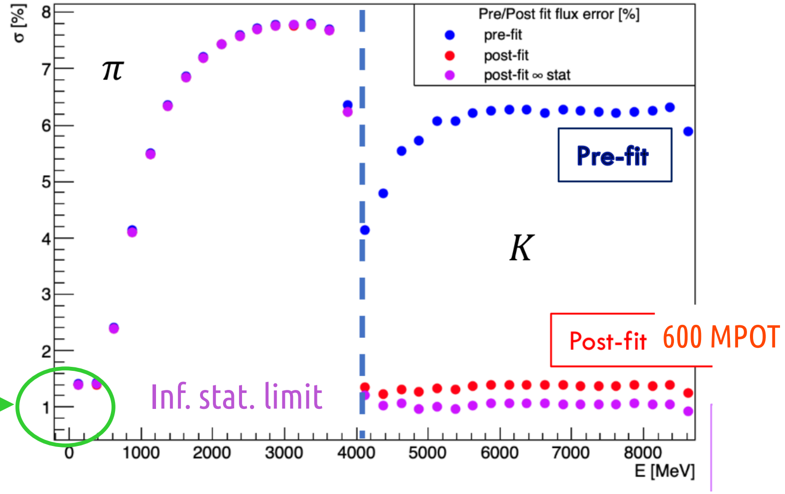
- compute variations ("envelopes") using multi-universe method ("toy exp") for the lepton observables and the flux of neutrinos
- evaluate "post-fit" variance of the expected flux

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.

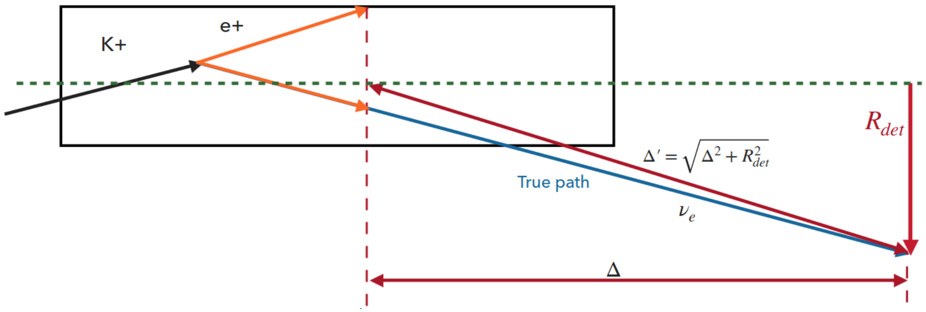
A bonus: time-tagging

https://arxiv.org/pdf/2308.09402.pdf

Goal of ENUBET: have a sample of associated leptons to constrain the flux. To do this an event-by-event information is needed. Timing has to be “just” good enough to limit the pileup (not too aggressive).

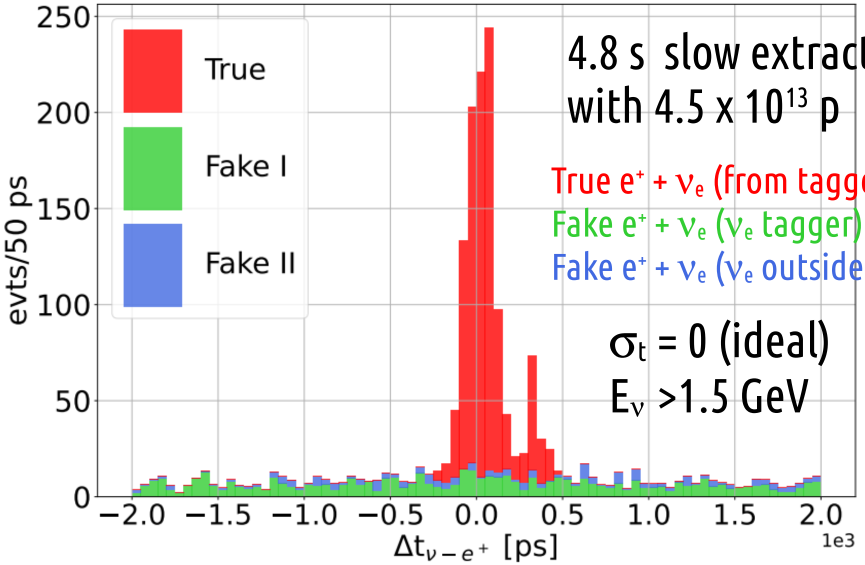
What could we do with an improved timing at tagger and ν-detector? →

NEW Time correlation btw K_{e3} e^+ and ν_e candidates.



$$\Delta t = t(\nu_e) - [t(e^+) + \Delta'/c]$$

Difference in path between the e^+ and ν_e (decay vertex position is unconstrained → we assume e^+ and ν_e to be collinear) → **“irreducible” time spread**: **$\sigma_{\Delta t}$ = 74 ps(*)**



4.8 s slow extraction with 4.5 x 10^{13} p

True e^+ + ν_e (from tagger)
Fake e^+ + ν_e (ν_e tagger)
Fake e^+ + ν_e (ν_e outside tagger)

σ_t = 0 (ideal)
E_ν >1.5 GeV

(*) already corrected for the position of the neutrino vertex
(**) could improve decreasing the tagger radius

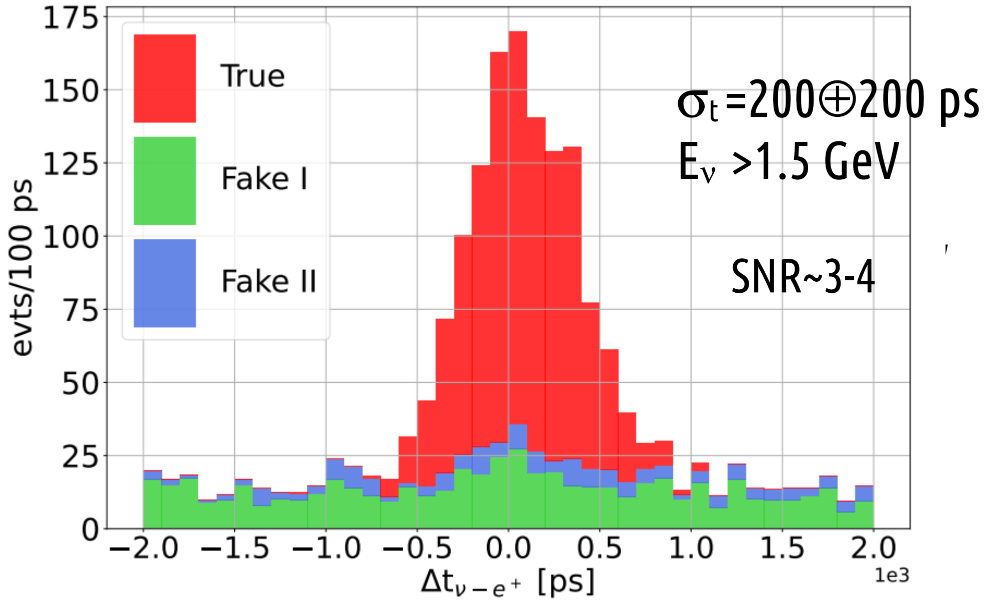
A bonus: time-tagging

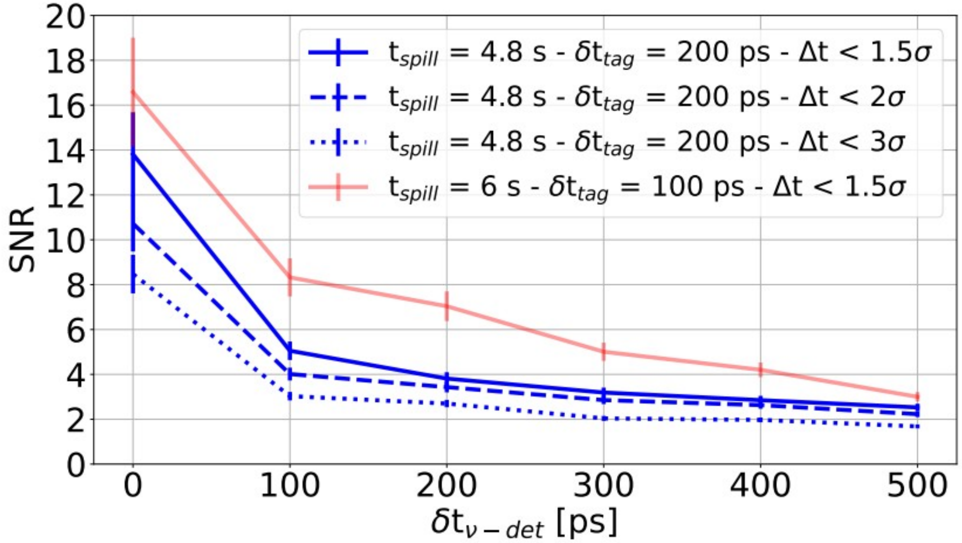
Dependence on timing resolution →

a broader peak but still we can exploit the time coincidences to improve the purity of the sample of associated positrons

Δt cut → signal-to- noise ratio (SNR) of the associated lepton sample can improve significantly the purity w.r.t. the untagged sample (SNR~2)

This of course only works for the subsample of the decays in which a neutrino is actually observed (a tiny fraction of all the reconstructed e^+).

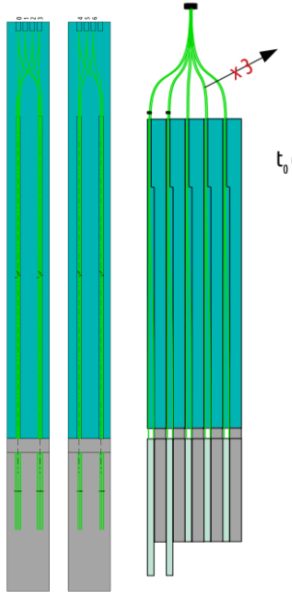


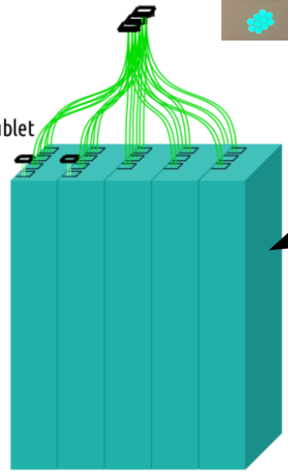


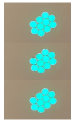
The demonstrator

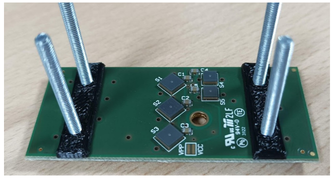
Demonstrate detector performance (PID, homogenity, eff.), scalability, cost effectivess...

WLS routing



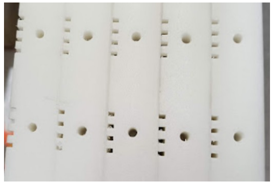






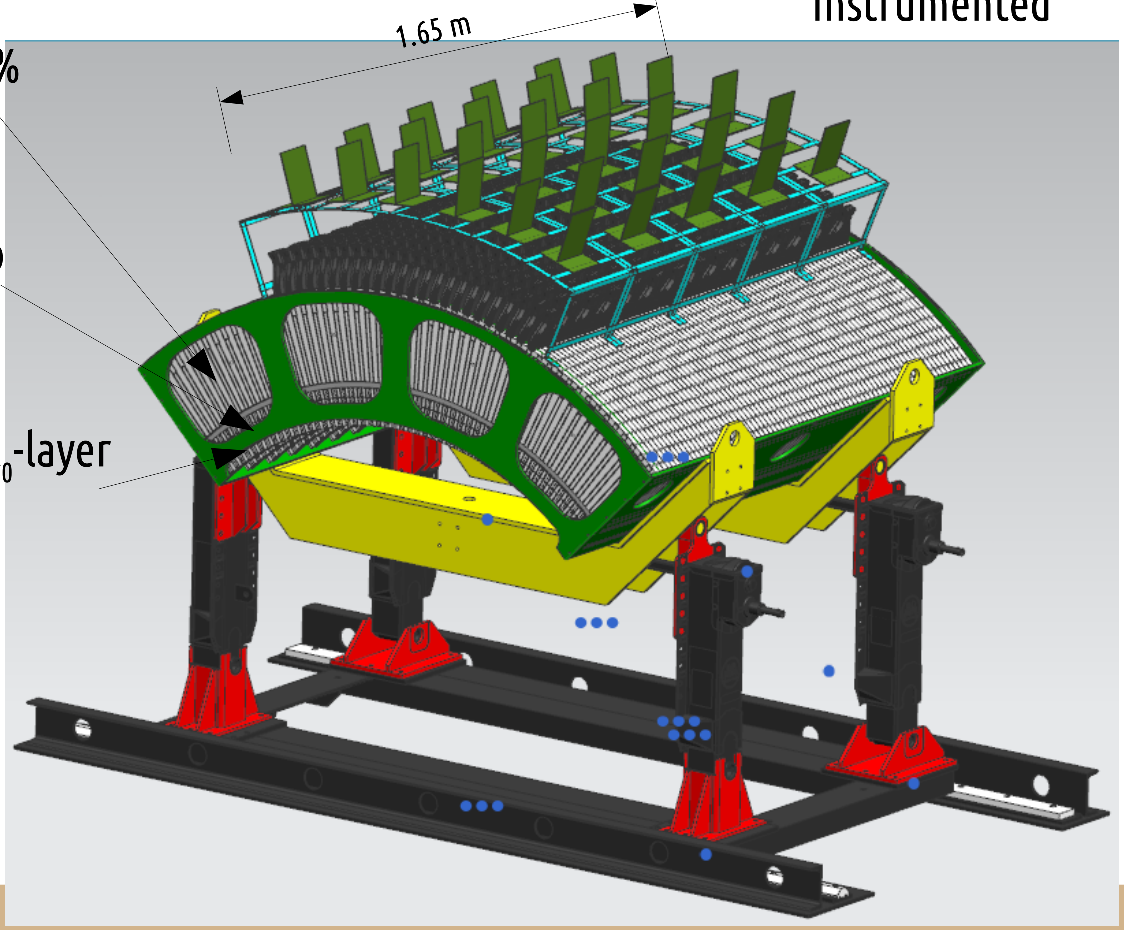
BPE 5%

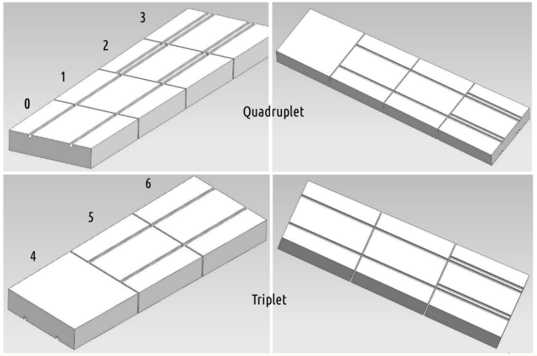
Sampling iron/scint calo

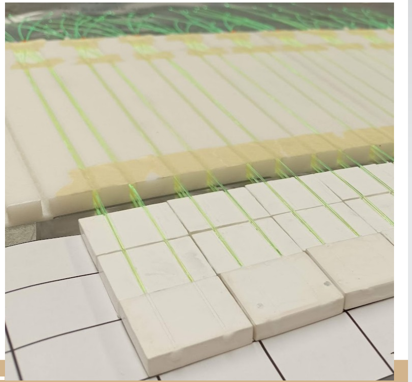


t_0-layer

90°, partially instrumented

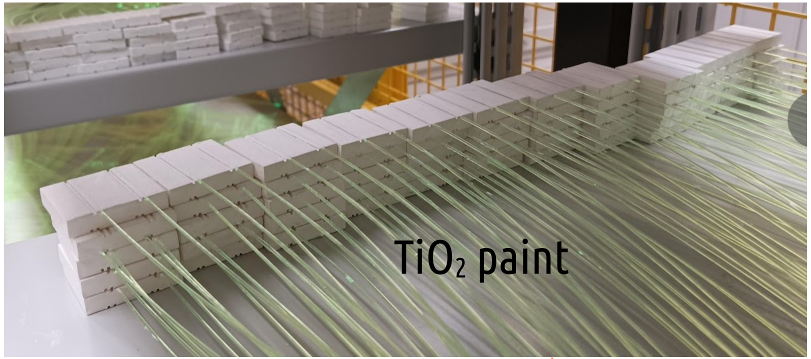


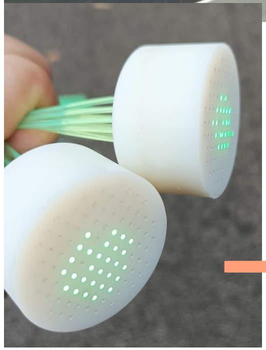


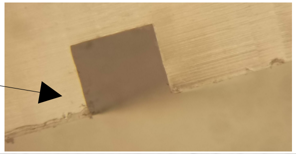


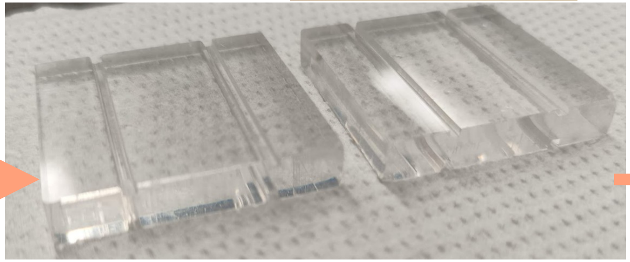
Scintillators + WLS light readout handling

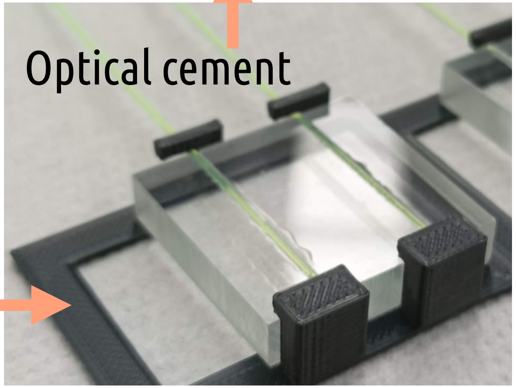
Commercial scintillator slabs + cutting/milling in Italy. Polishing, fibre gluing, tiles painting **with personnel from the collaboration @ INFN-LNL**





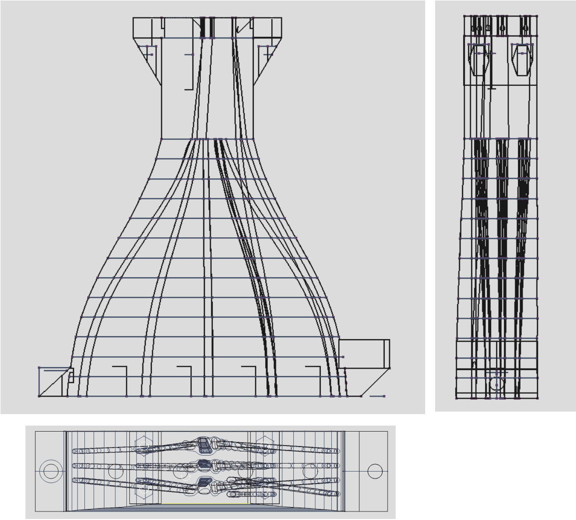




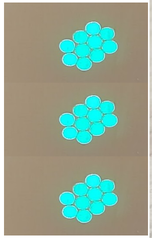


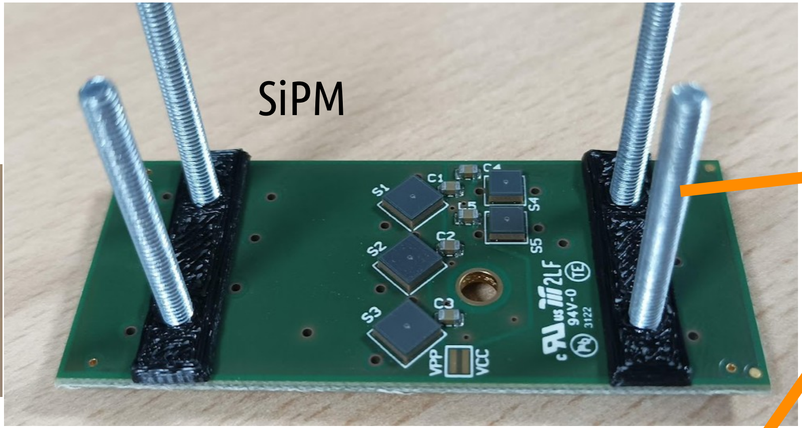
Fiber bundling with “concentrators”

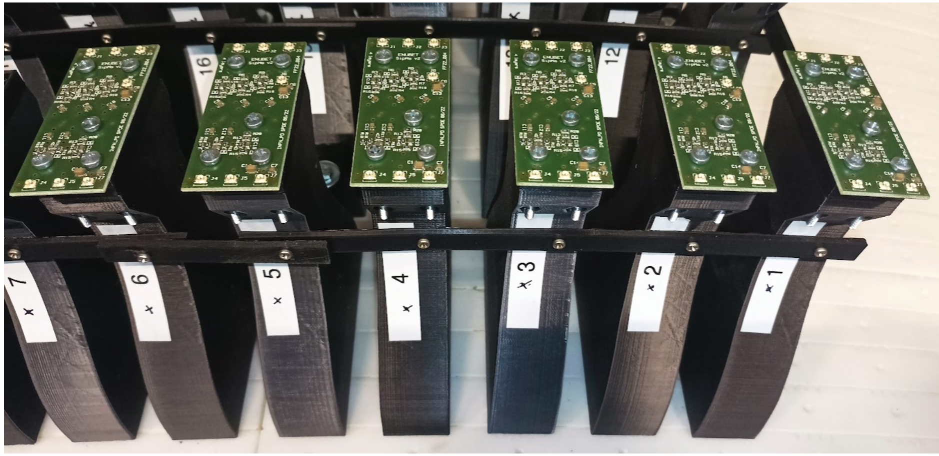
bundling of the WLS fibers with 3D printed “fiber concentrators”+ in situ polishing

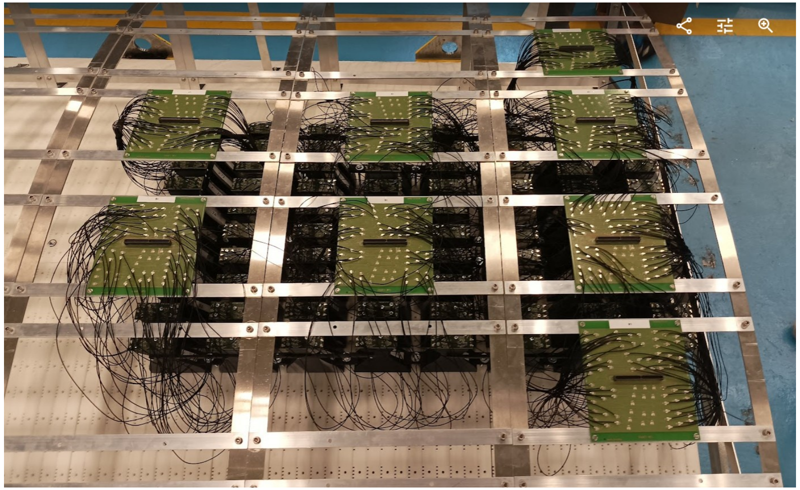


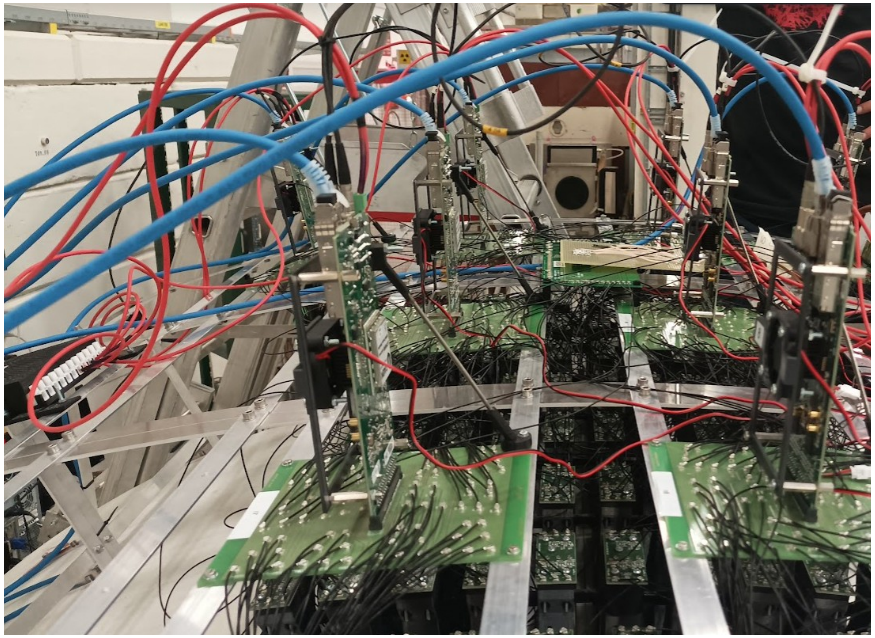
Readout scheme











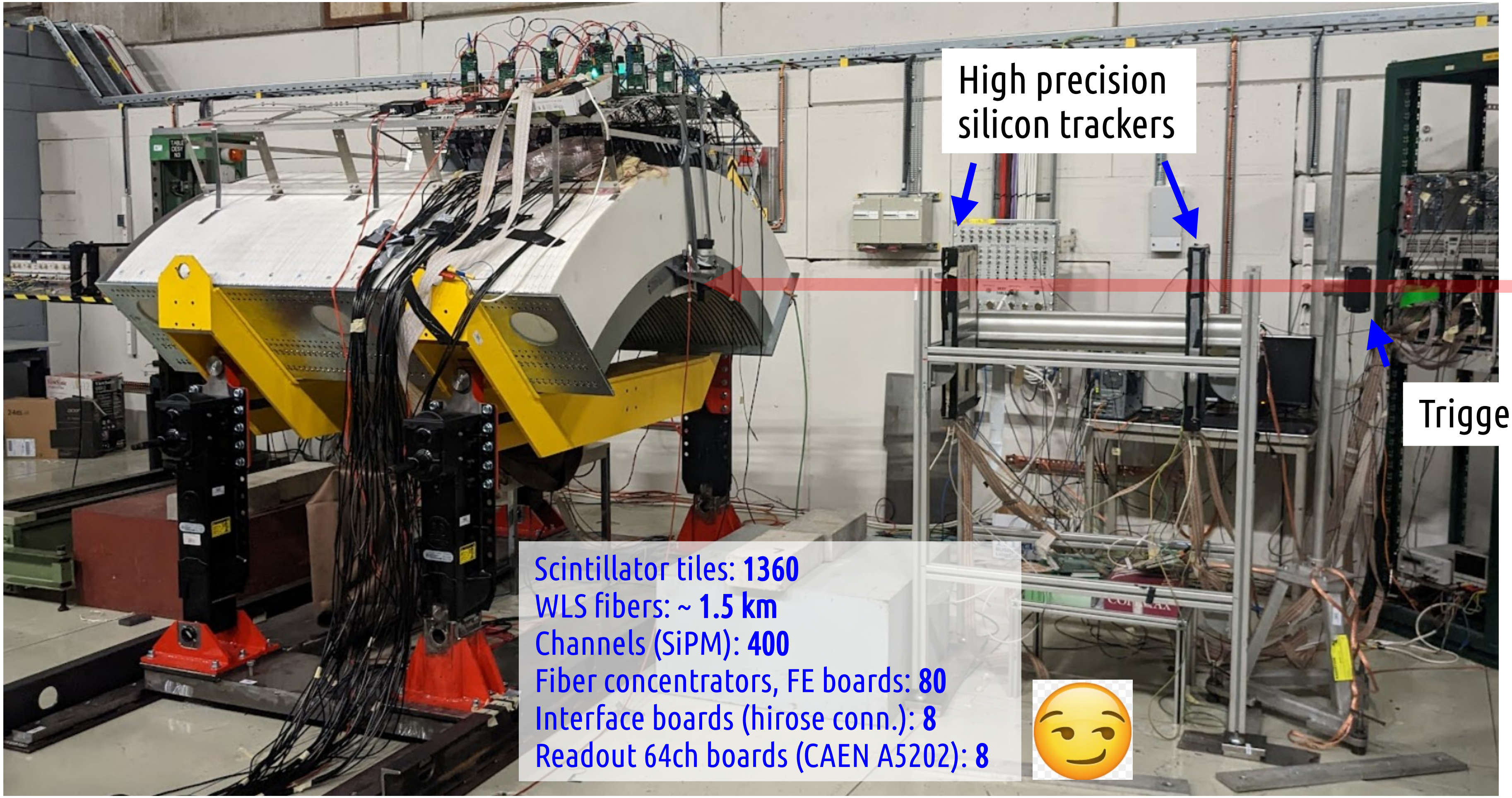
ENUBET demonstrator timeline

April 2022 INFN-LNL

Scintillator tiles: **0**
WLS fibers: ~ **0 km**
Channels (SiPM): **0**
Fiber concentrators, FE boards: **0**
Interface boards (hirose conn.): **0**
Readout 64ch boards (CAEN A5202): **0**

ENUBET demonstrator timeline

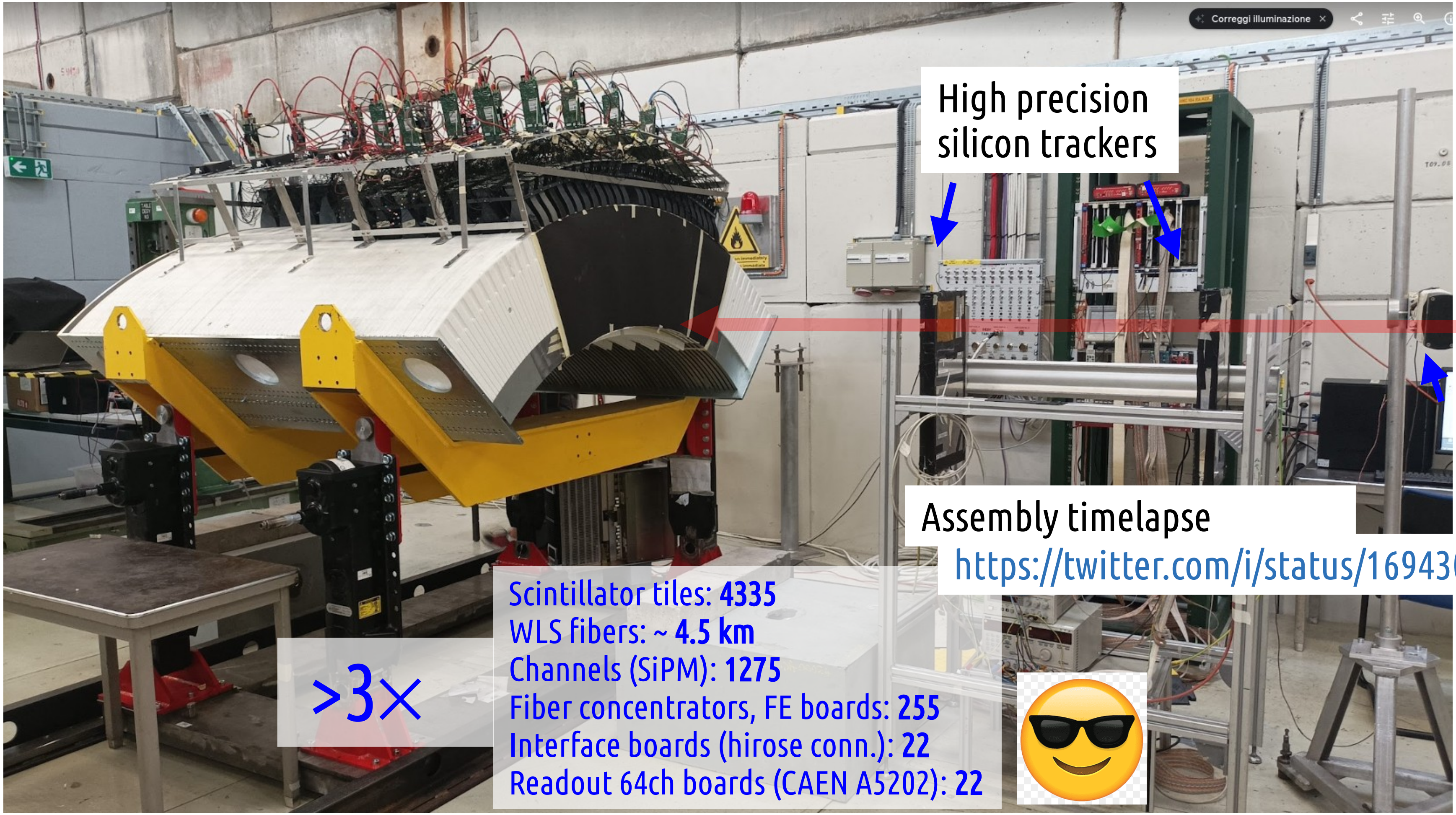
October 2022 CERN-PS-T9



- Scintillator tiles: **1360**
- WLS fibers: ~ **1.5 km**
- Channels (SiPM): **400**
- Fiber concentrators, FE boards: **80**
- Interface boards (hirose conn.): **8**
- Readout 64ch boards (CAEN A5202): **8**

ENUBET demonstrator timeline

August 2023 CERN-PS-T9



Assembly timelapse
https://twitter.com/i/status/1694308753514889350

>3×

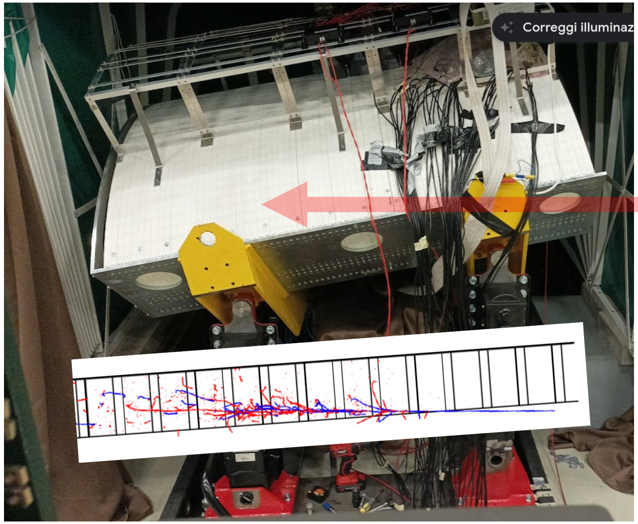
- Scintillator tiles: **4335**
- WLS fibers: ~ **4.5 km**
- Channels (SiPM): **1275**
- Fiber concentrators, FE boards: **255**
- Interface boards (hirose conn.): **22**
- Readout 64ch boards (CAEN A5202): **22**

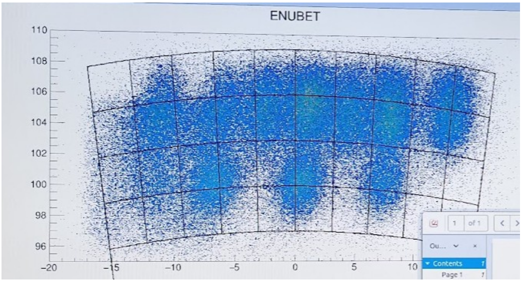
Data taking and early results

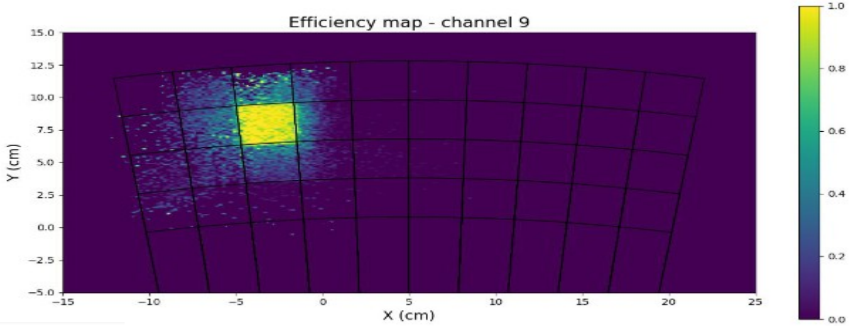
horizontal run with darkening cover

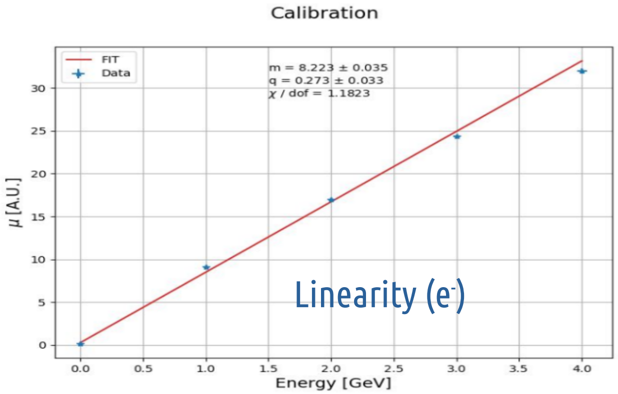
200 mrad tilt run

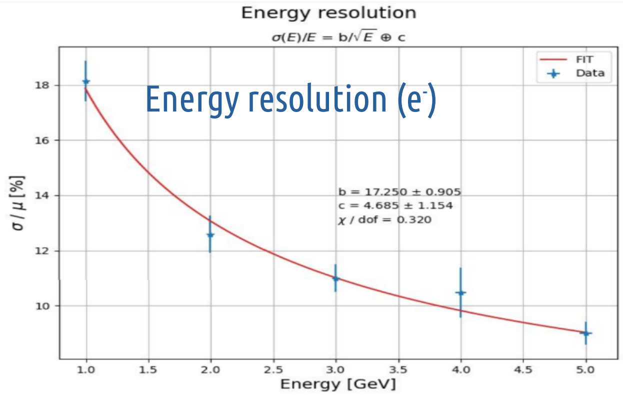
Beam spot at the detector upstream face after several runs illuminating different regions of the detector











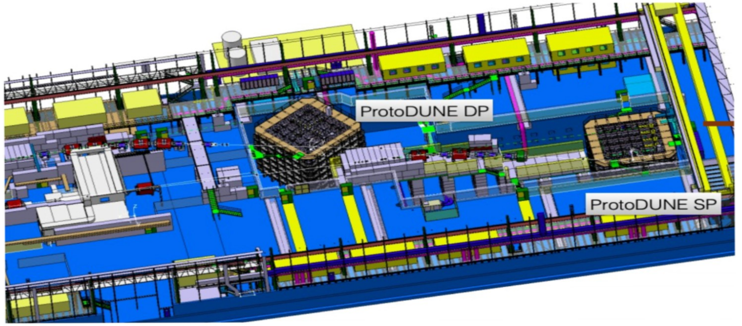
Preliminary

Publication in the pipeline with both 2022 and 2023 data

Implementation scenarios

- So far a very successful R&D!
- Next → deliver of a Conceptual Design Report
- Proposing a short baseline neutrino experiment @ CERN exploiting the SPS and the protoDUNE detectors
- Run tentatively after CERN LS3 (i.e. during DUNE and Hyper-K data taking)

- **The "cheap" scenario**: dedicated beamline extracted from the North Area to the PD
  - Maximum use of existing facilities
  - Slow extraction easily implemented
  - Strong interference with other experiments
  - Potential radiation issues
- **The "clean" one**: dedicated extraction line near the N.A. pointing to PD
  - less interference with experiments and existing facilities
  - radiation issues somewhat easier
  - Higher cost



Accelerator and civil engineering studies in the framework of Physics Beyond Colliders starting since October with dedicated personnel

Thank you!

감사합니다

ENUBET @ CERN-PS –T9
16-29 Aug 2023

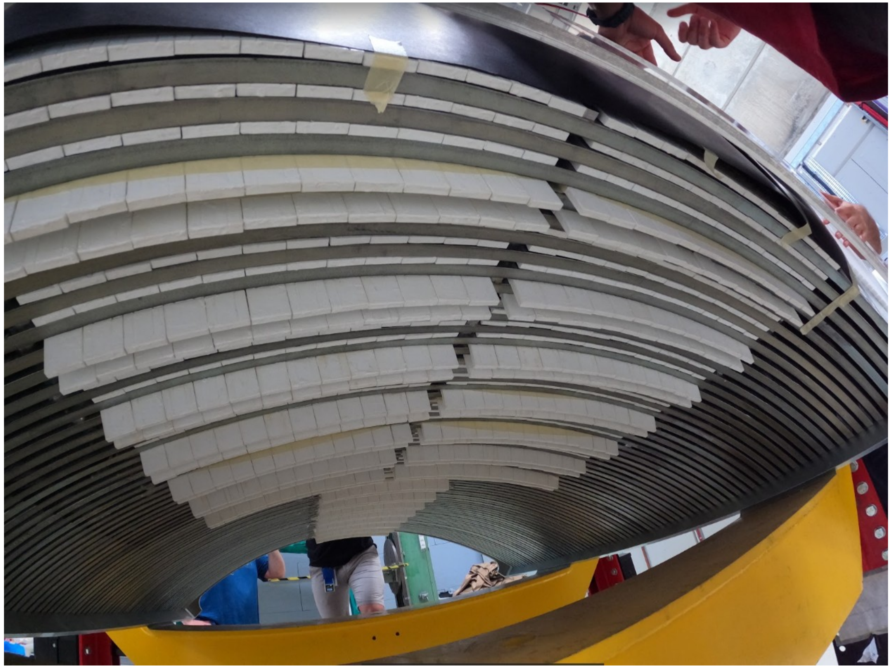
ENUBET @ NuFact23
21-26 Aug 2023

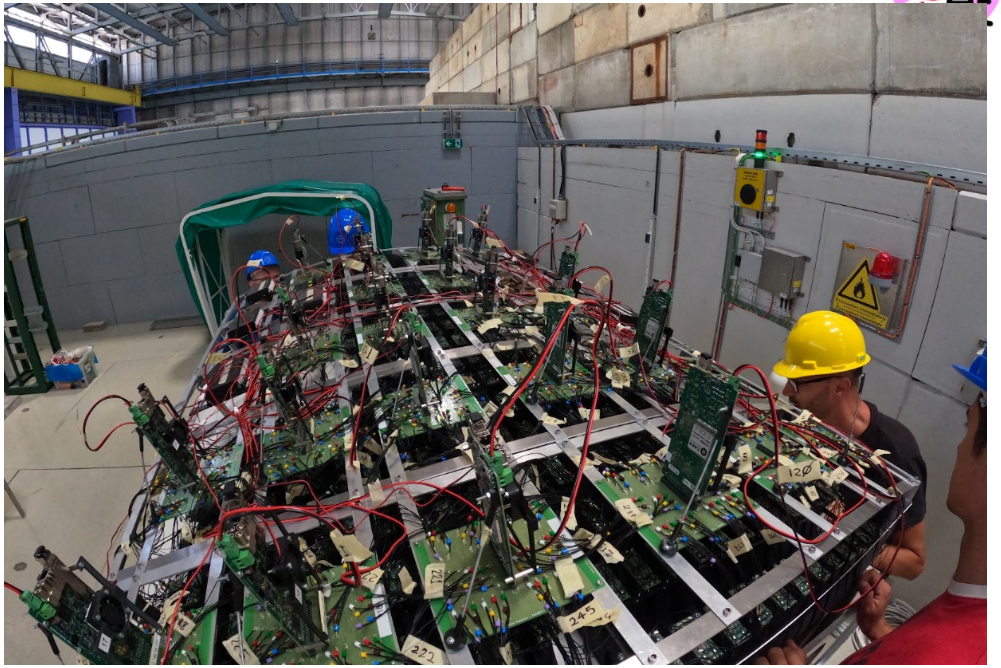
Backup

ENUBET: demonstrator

Assembly timelapse

https://twitter.com/i/status/1694308753514889350

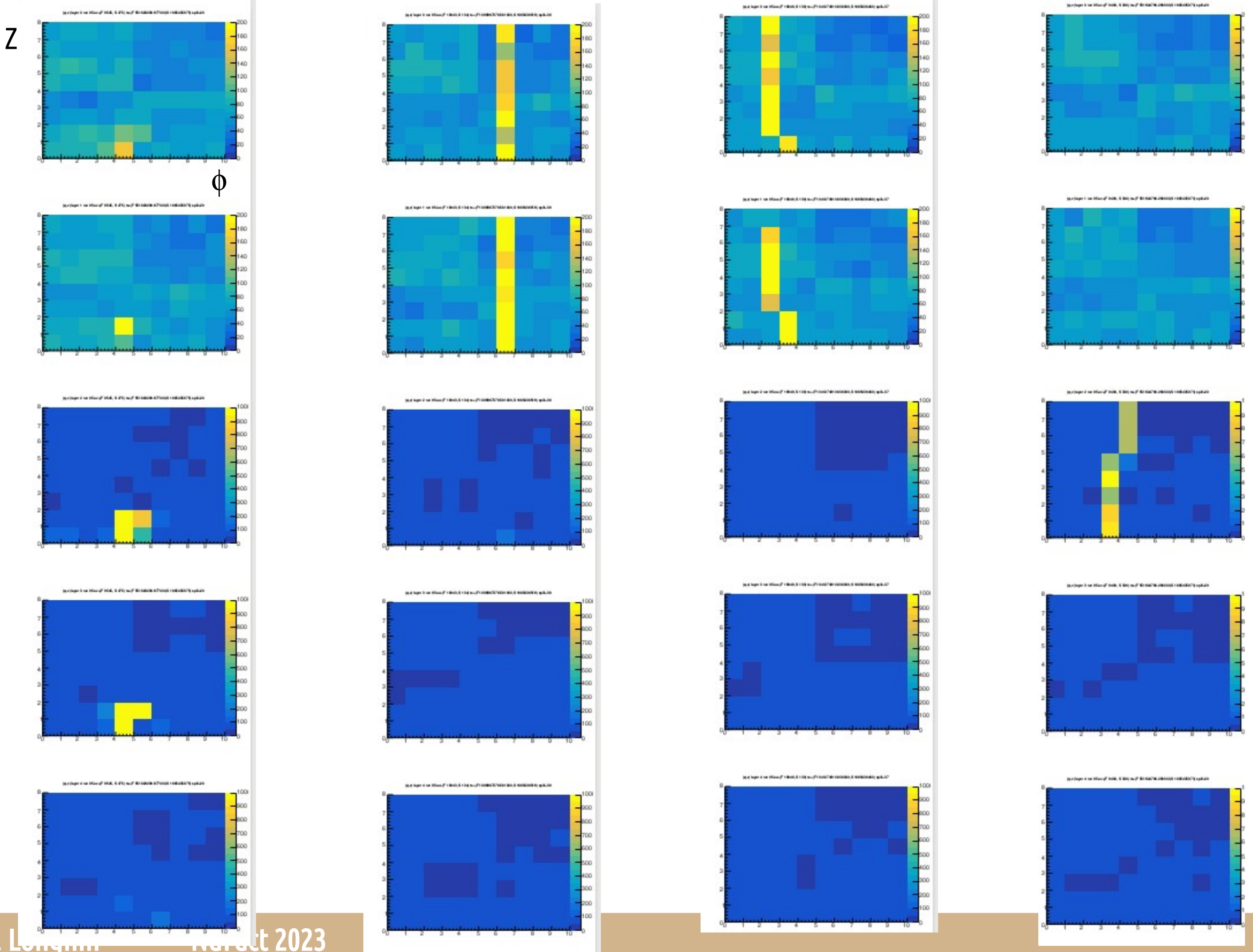




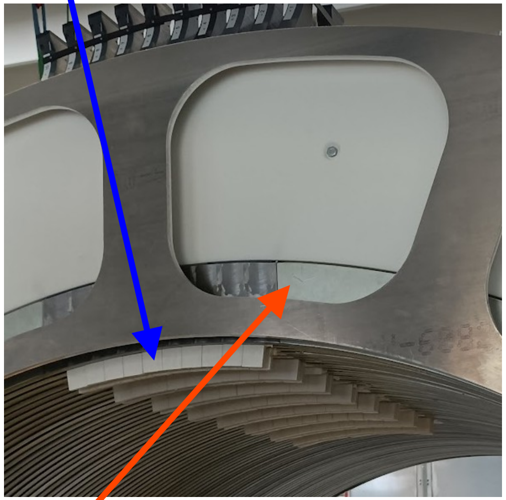
Event displays

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”)



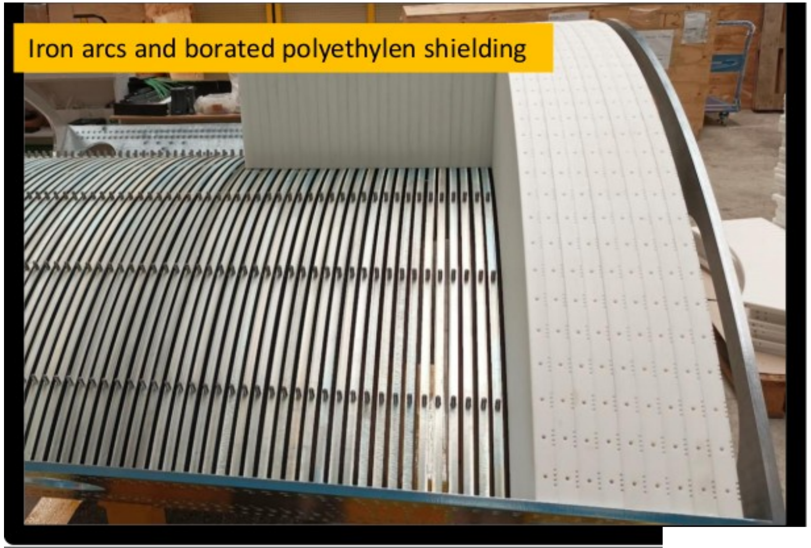
calorimeter layers

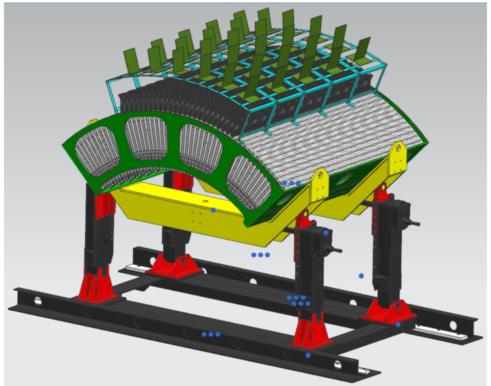
NB: channels not yet equalized with mips.

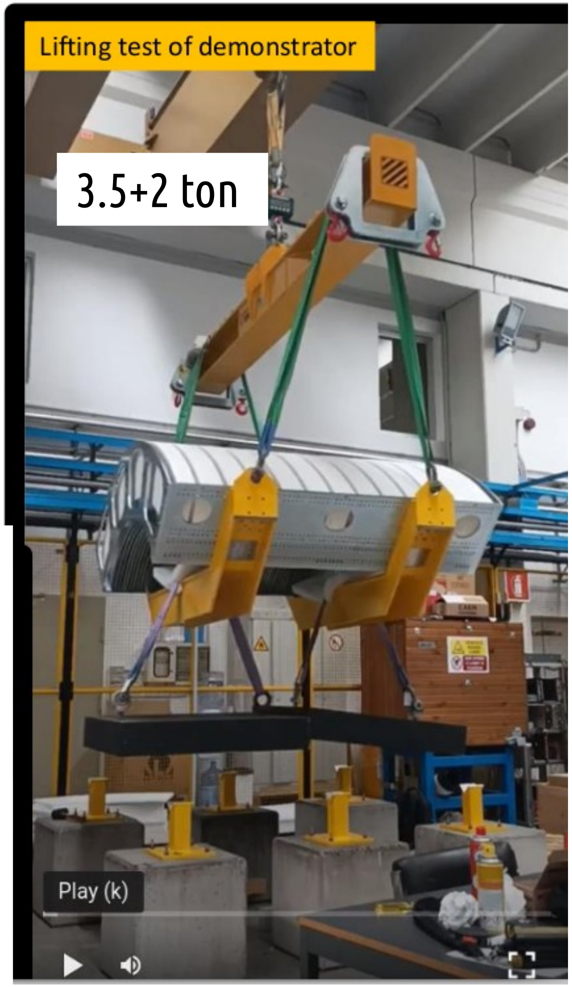
The ENUBET demonstrator in numbers

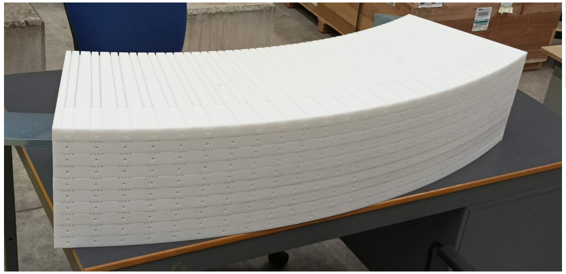
- Scintillator tiles: **1360**
- WLS: ~ **1.5 km**
- Channels (SiPM): **400**
  - Hamamatsu **50 um** cell
    - **240** SiPM **4x4** mm^2 (calo)
    - **160** SiPM **3x3** mm^2 (t_0)
- Fiber concentrators, FE boards: **80**
- Interface boards (hirose conn.): **8**
- Readout 64 ch boards (CAEN A5202): **8**
- Commercial digitizers: **45 ch**
- hor. movement ~**1m**
- tilt **>200 mrad**

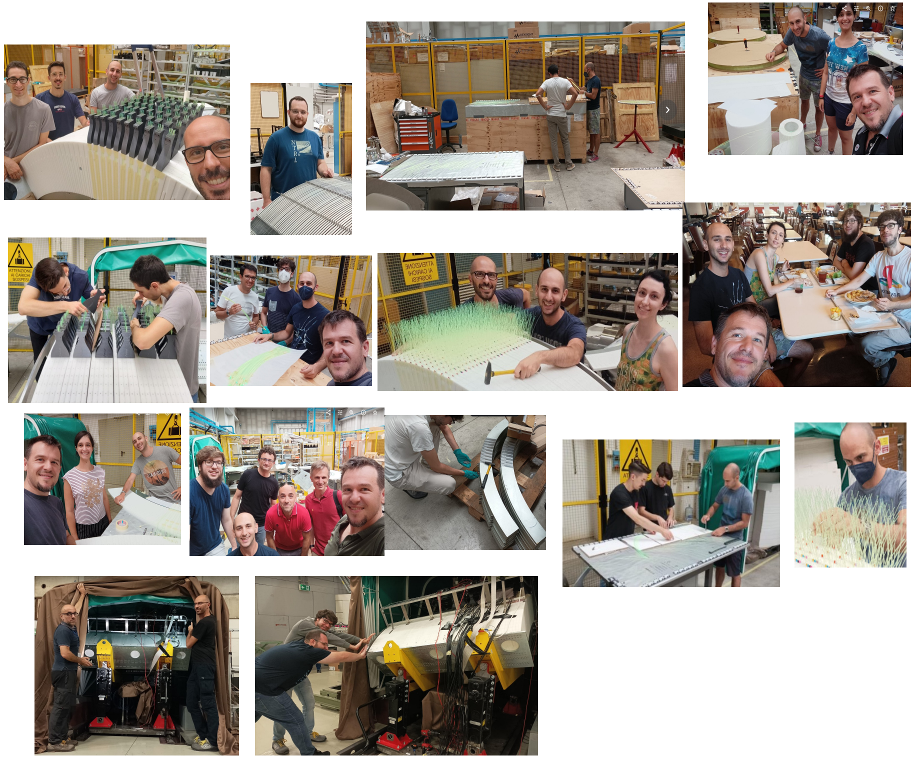
Demonstrator construction at LNL-INFN labs











ENUBET takes off !!!

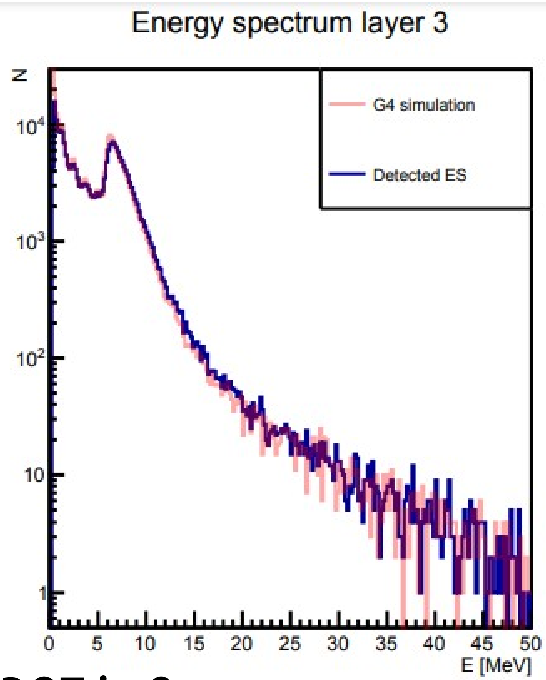
3 Oct 2022 @ building 157,
CERN Meyrin PS East Hall
T9 area

Movable platform "landing site" @ T9 test beam area.

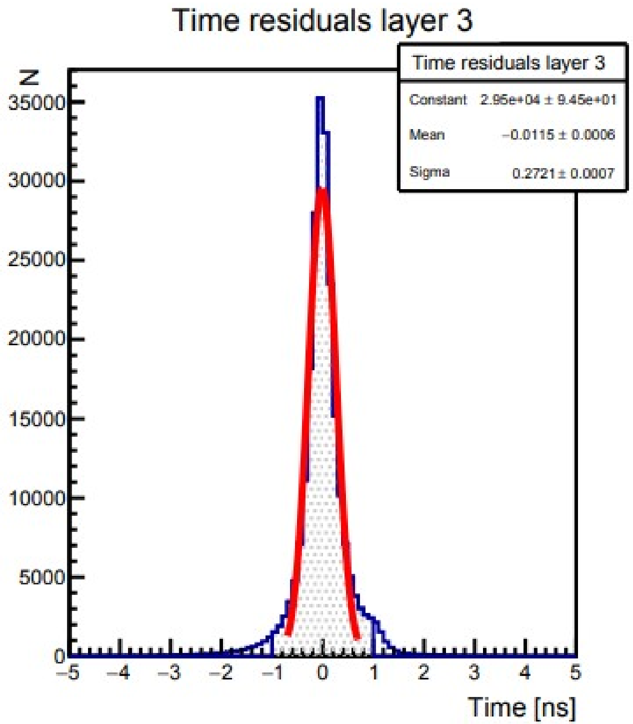
Event pile-up analysis

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

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



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



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

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

Highlights on test beam analysis

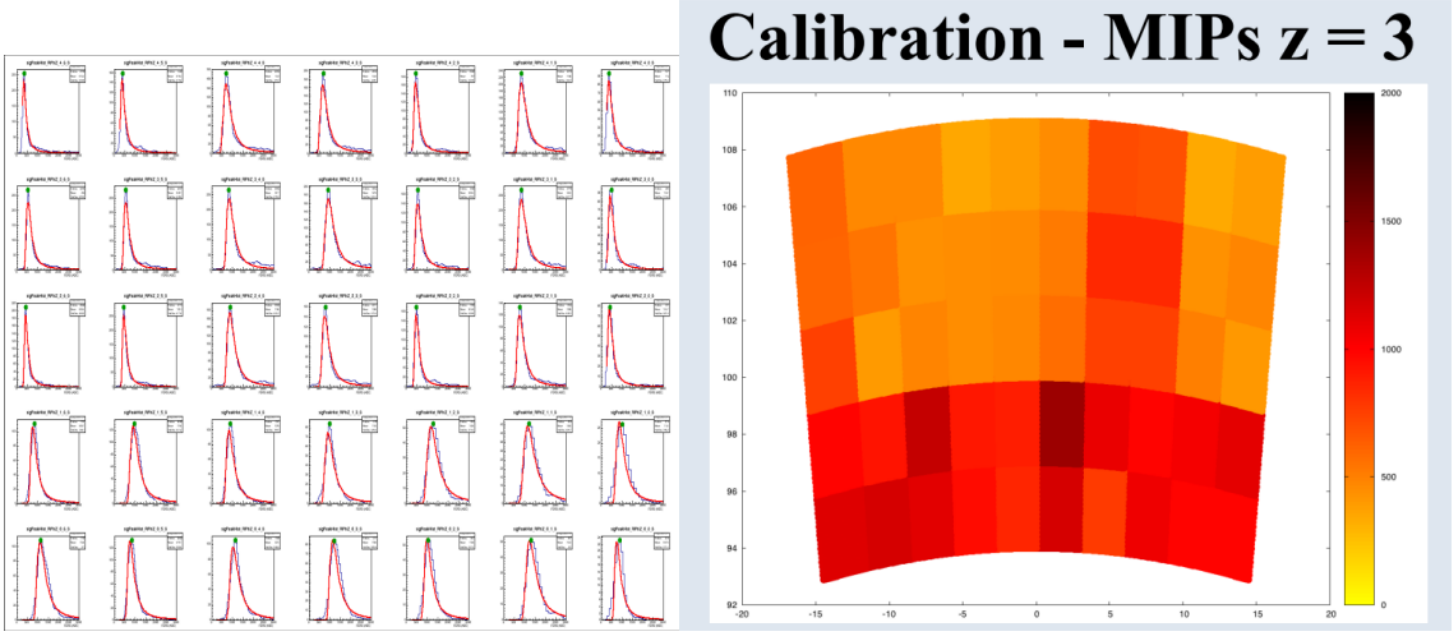


Figure 9: Calibration with m.i.p.s. Left: spectra of signals used to derive relative inter-calibration constants between different detector channels in the same z layer. Each column shows the spectra of calorimeter and t_0 channels in the same ϕ sector, while each row shows a calorimeter radial layer;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

Highlights on test beam analysis

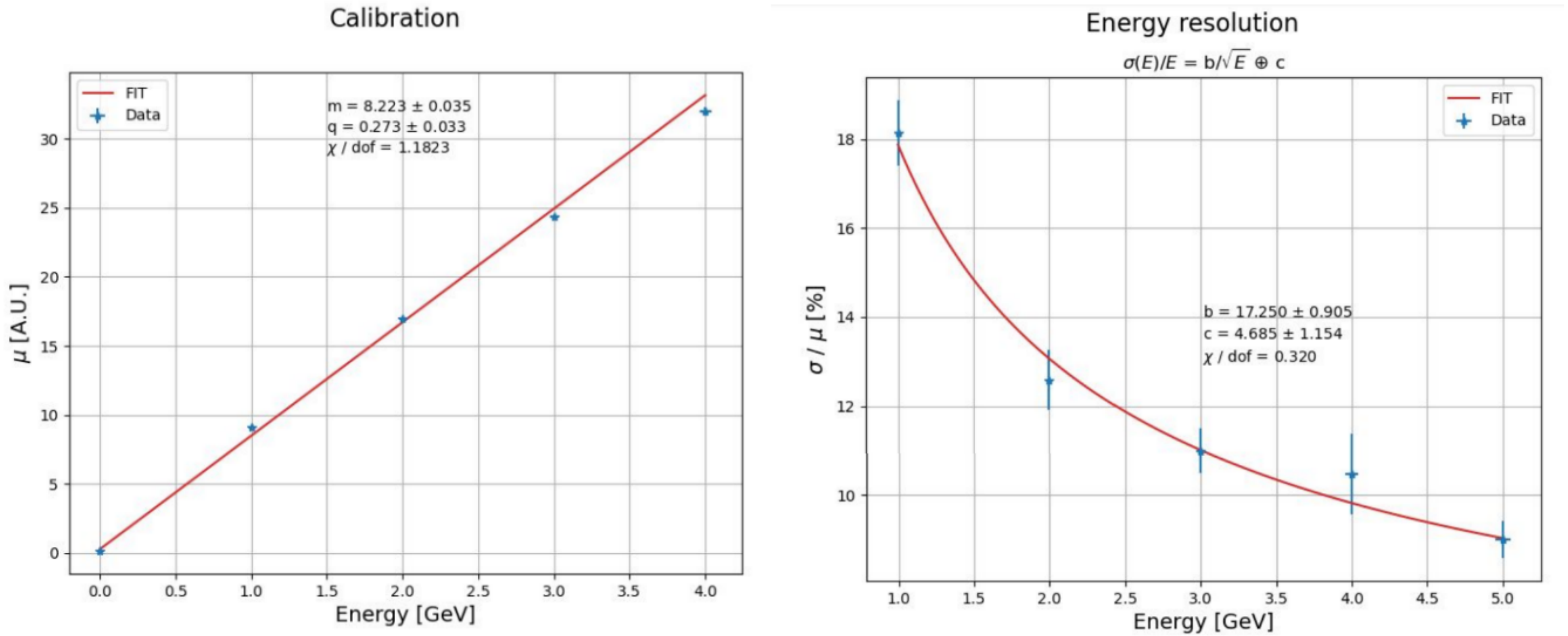


Figure 10: Linearity and energy resolution for electrons.

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

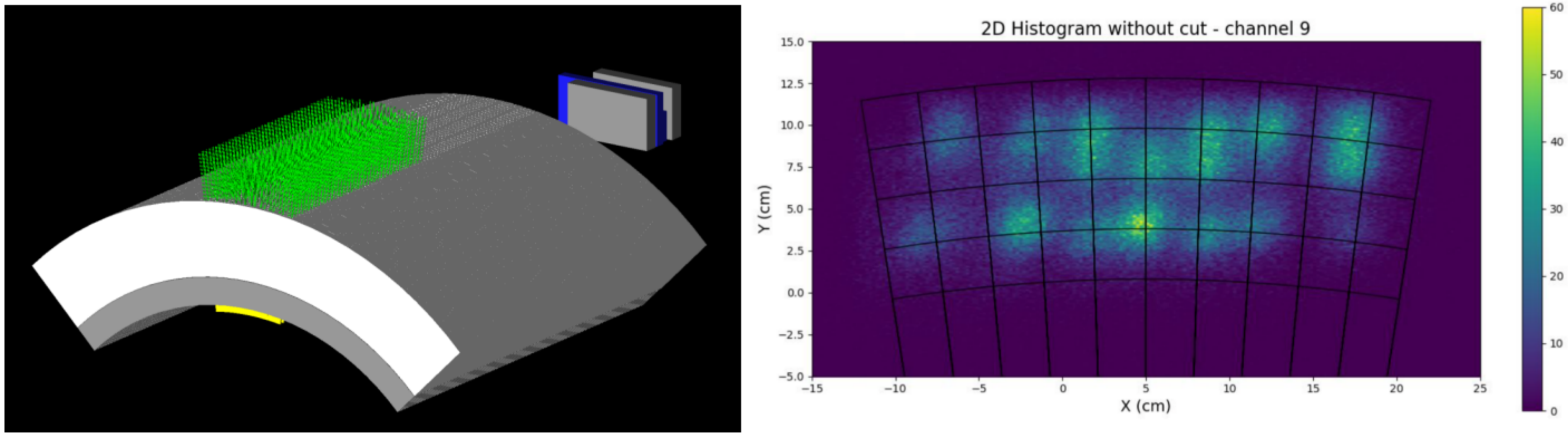


Figure 11: GEANT4 simulation of the demonstrator. Left: the geometry. Right: simulated beam profile at the upstream face. Each "island" corresponds to a run. The detector was moved in between runs to cover all tiles.

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;

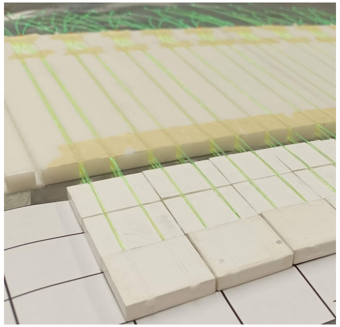
Highlights on test beam analysis

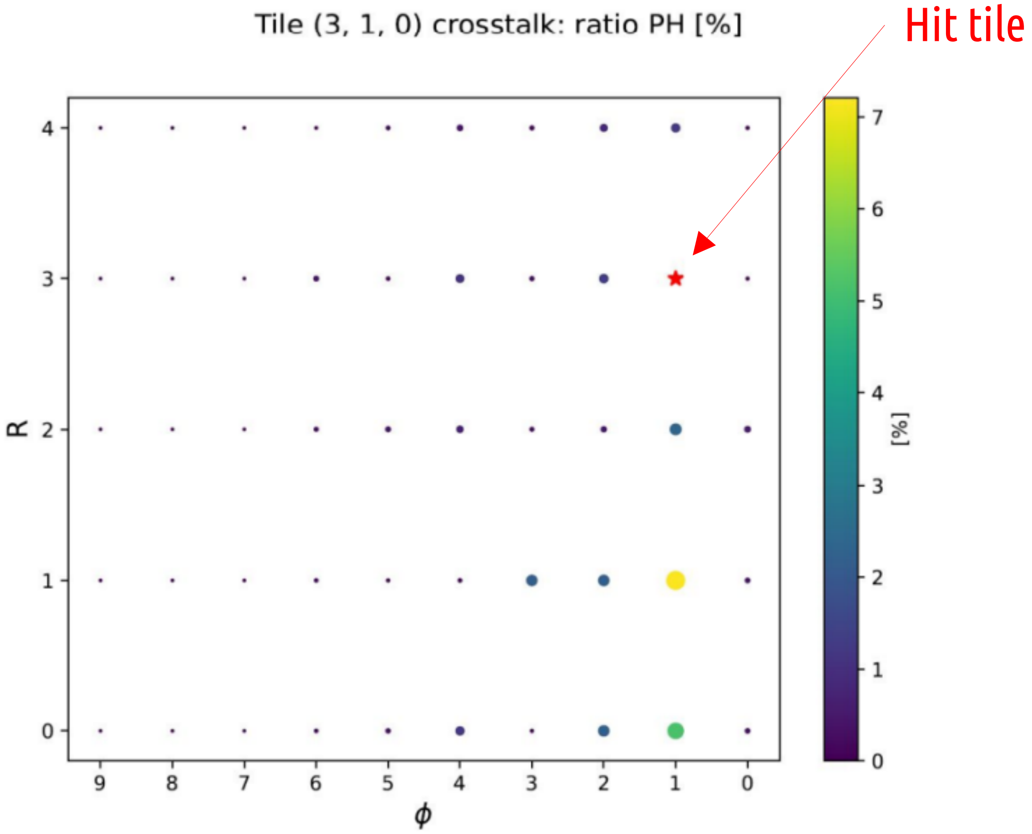
Cross-talk studies ongoing with muon samples

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

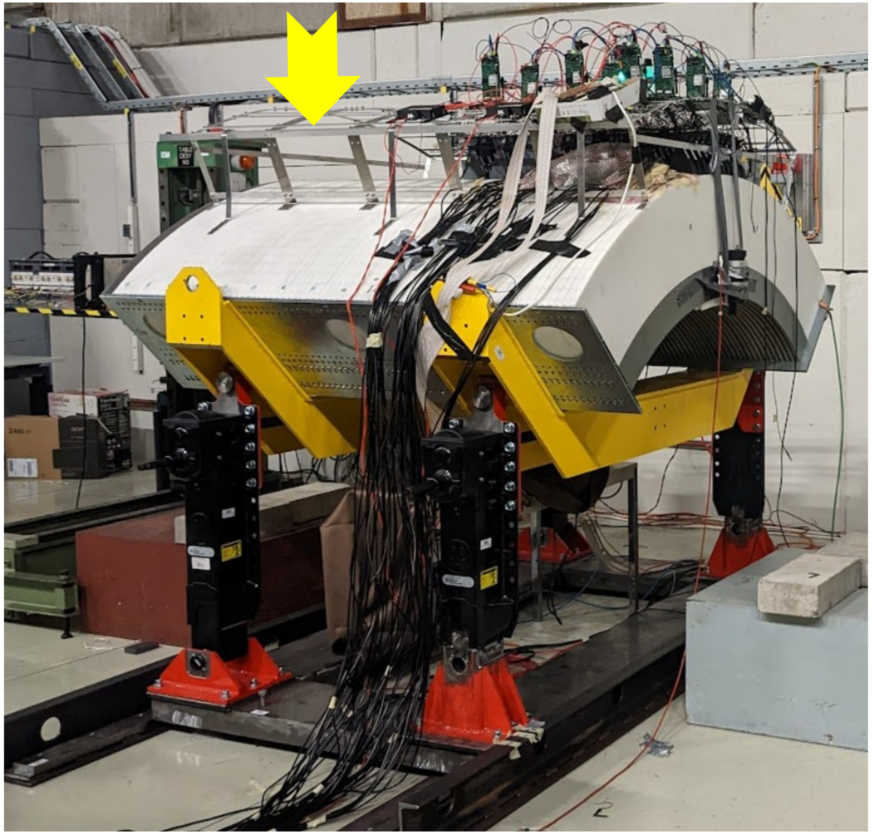
2022: 8 upstream z layers with 10 ϕ sectors (400 ch)
2023:
- add 7 downstream z layers with 25 ϕ sectors
  - passing from 400 to 400+875 = **1275 channels**

- 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

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

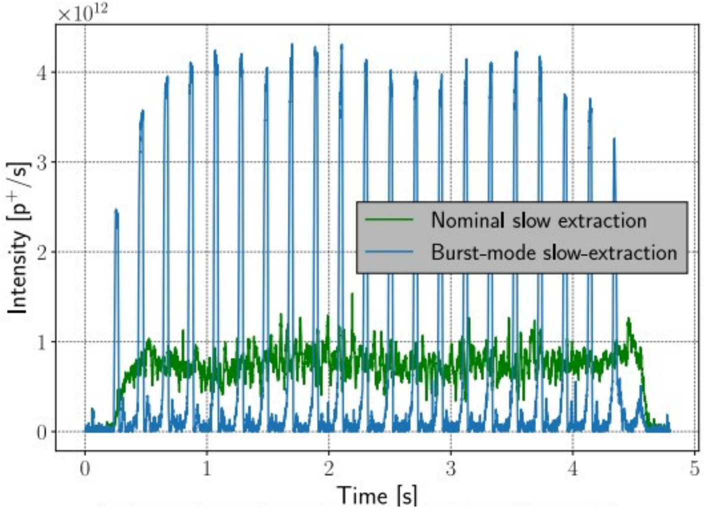
2023

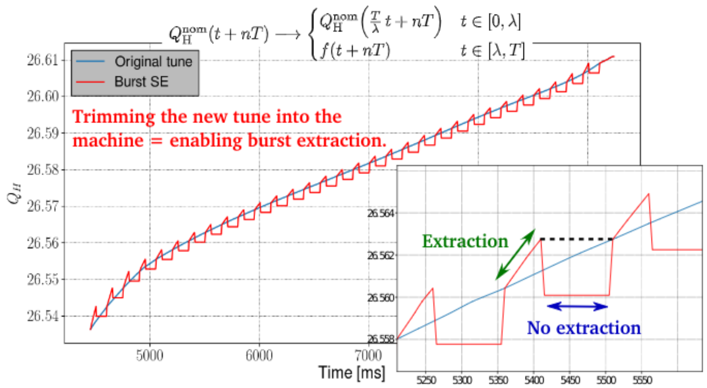


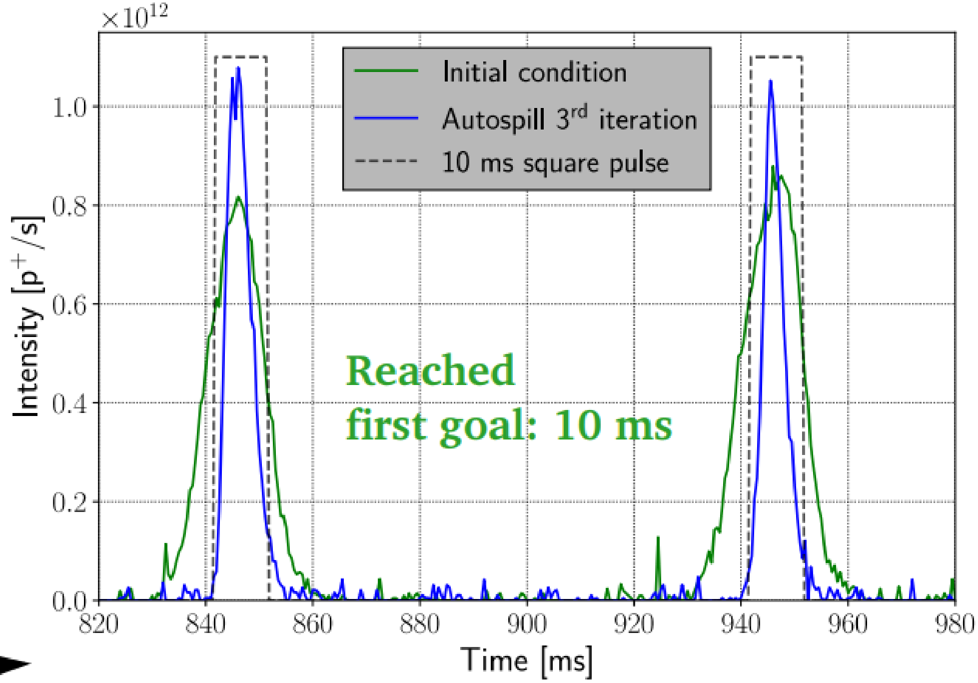
Proton extraction R&D for horn focusing

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

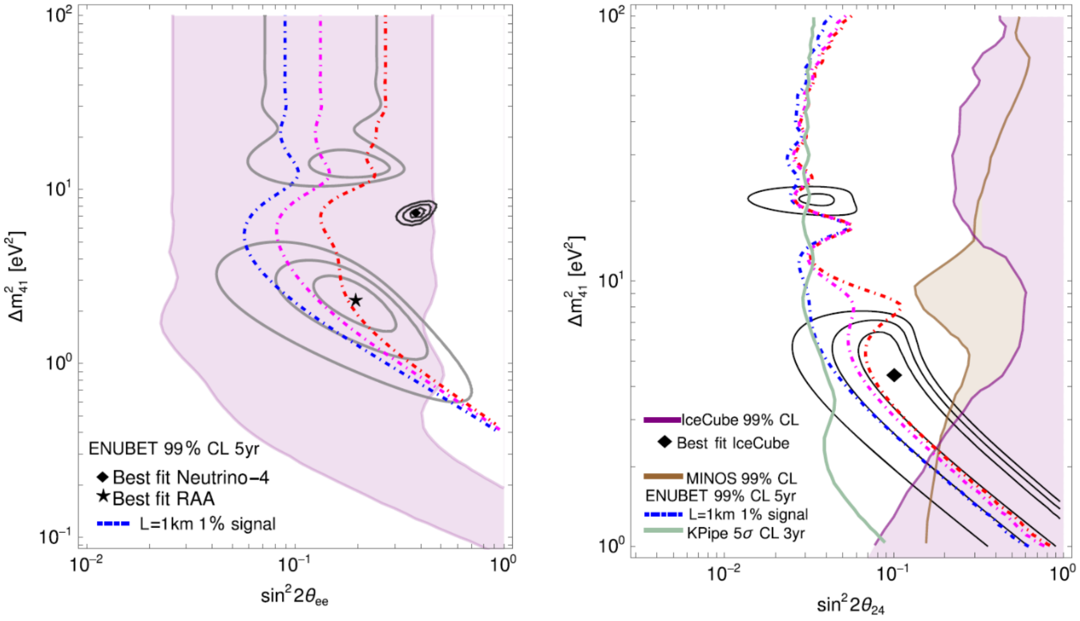






PhD thesis of M. Pari (UniPD + CERN doctoral). Defended 23/2/21.

BSM



Sterile neutrinos: some results already available

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

Instrumented proton and hadron dump:

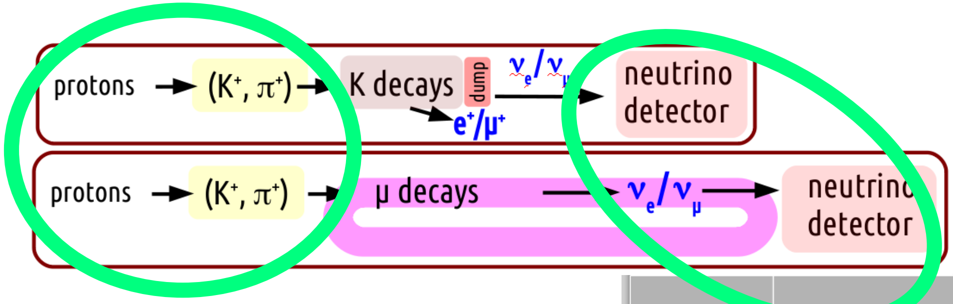
P. S. Bhupal Dev, Doojin Kim, K. Sinha, Yongchao Zhang, Phys. Rev. D 104, 035037 [ALP]
J. Spitz, Phys. Rev. D 89 (2014) 073007 [KDAR]

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

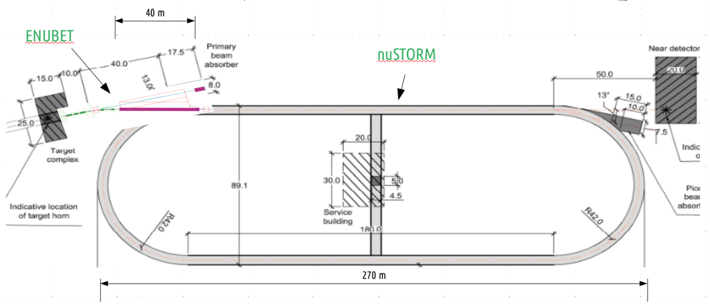
nuSTORM can be seen (simplistically) as an “ENUBET without a hadron dump” where pions and muons are channeled into a ring. Large room for smart ideas to match the requirements of the two experiments



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

- But also significant differences (and scale)

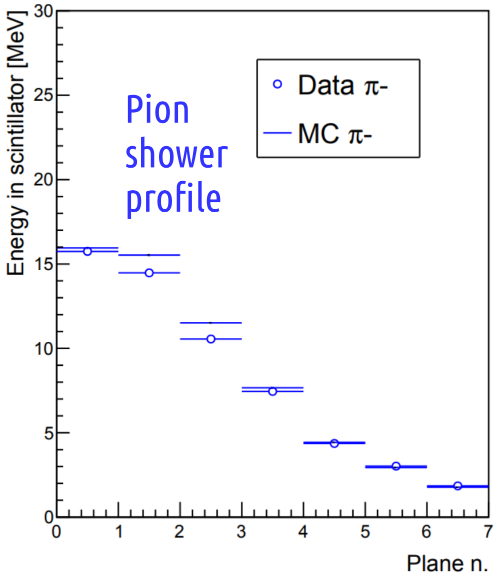
	Decay region	Hadron dump	Proton extraction, energy, focusing	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps μ in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow extraction (+ quad triplets) “slow” in bursts (+horn) 400 GeV	similar	Similar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

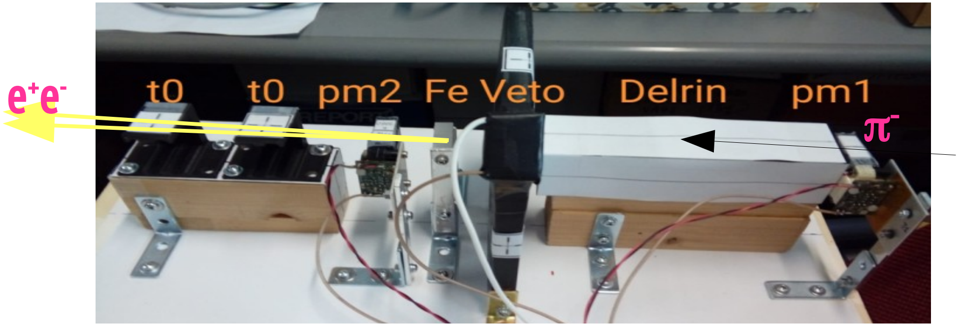
JINST 15 (2020) 08, P08001

ENUBET: prototypes at the CERN-PS

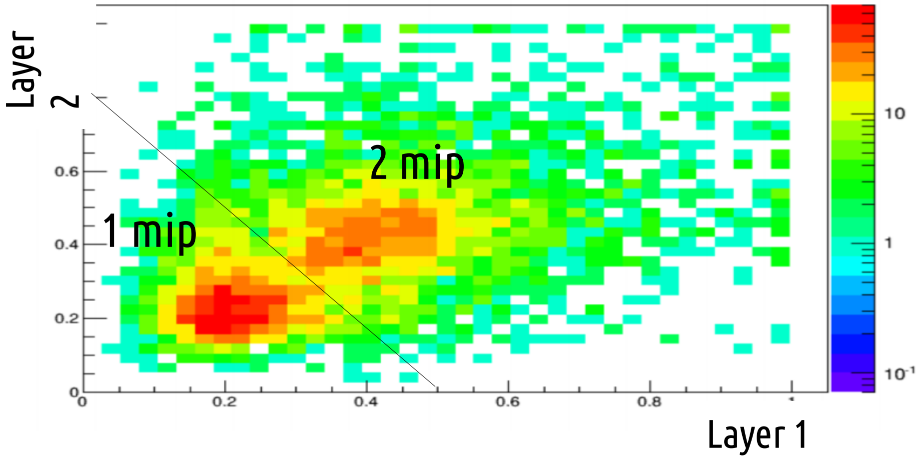


charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2



$\sigma_t \sim 400$ ps



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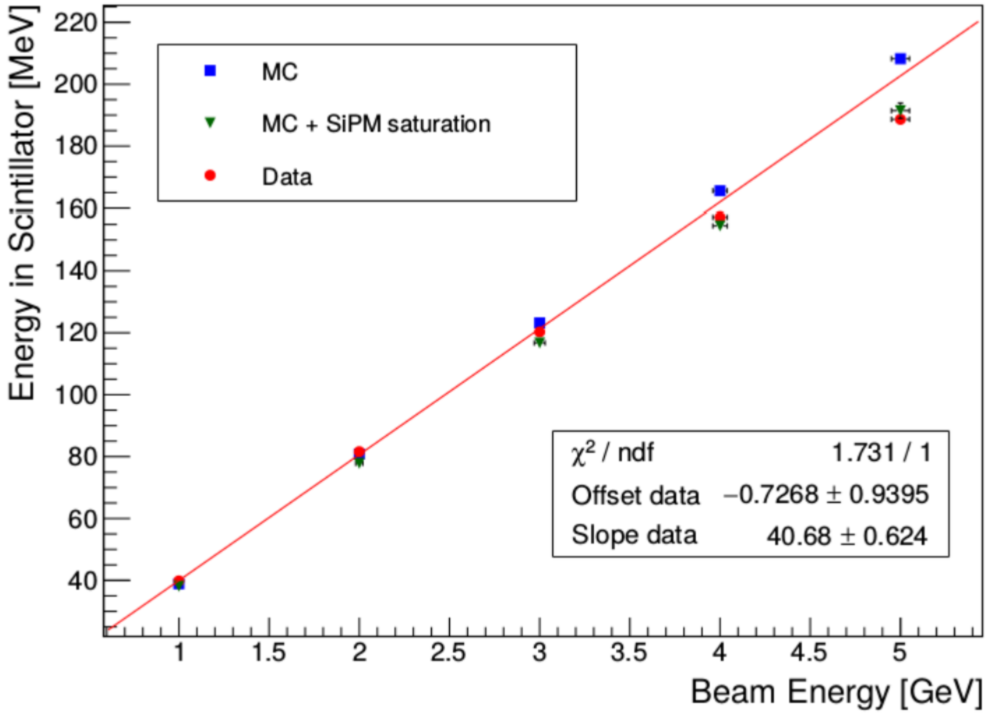
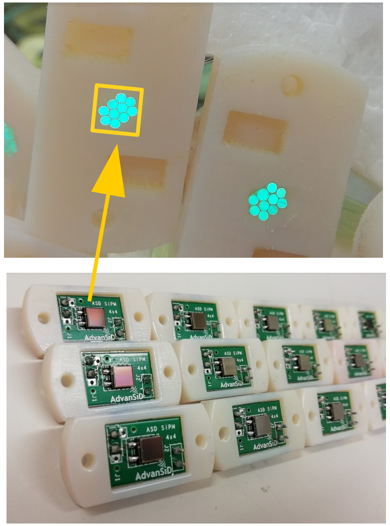
ENUBET: prototypes at the CERN-PS

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



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

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



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

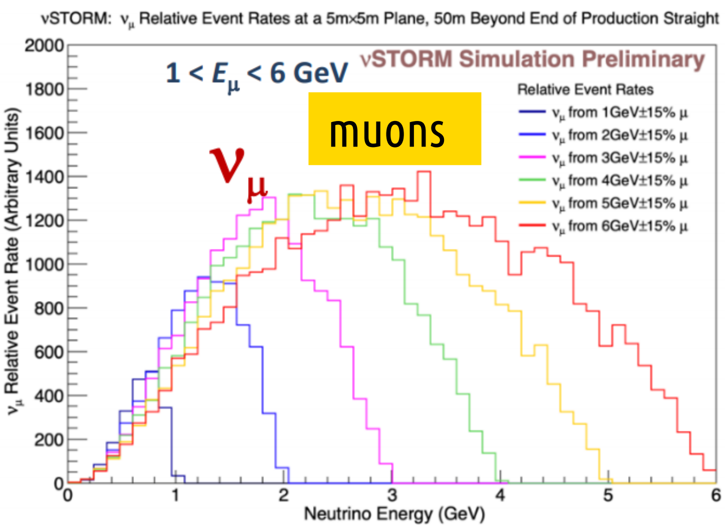
Fluxes decomposition

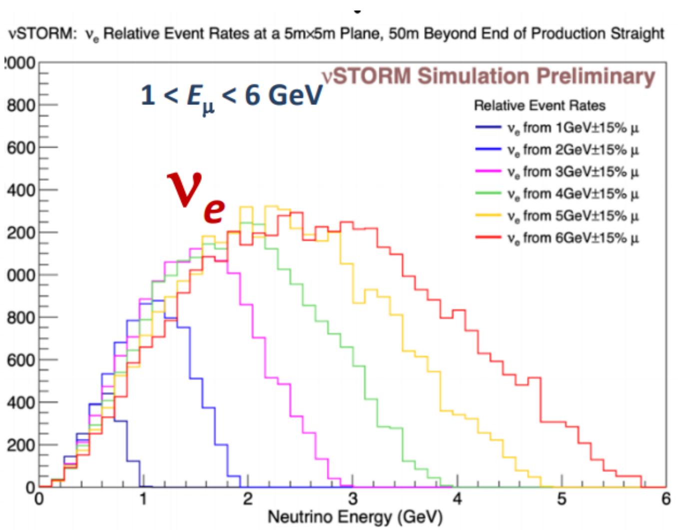
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

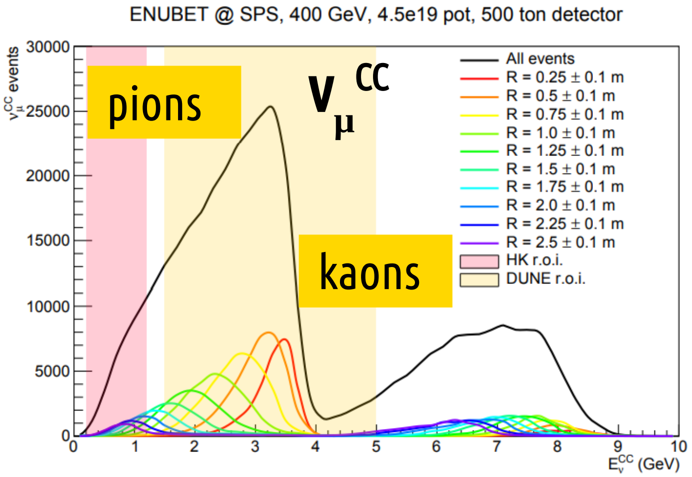
ENUBET narrow-band off-axis technique:

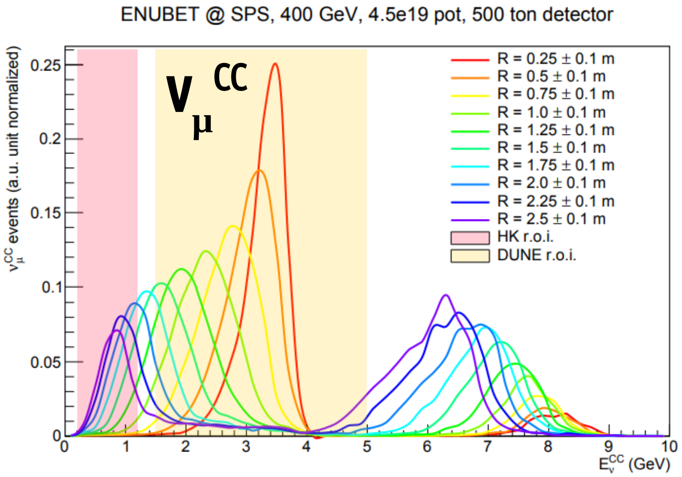
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable.

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





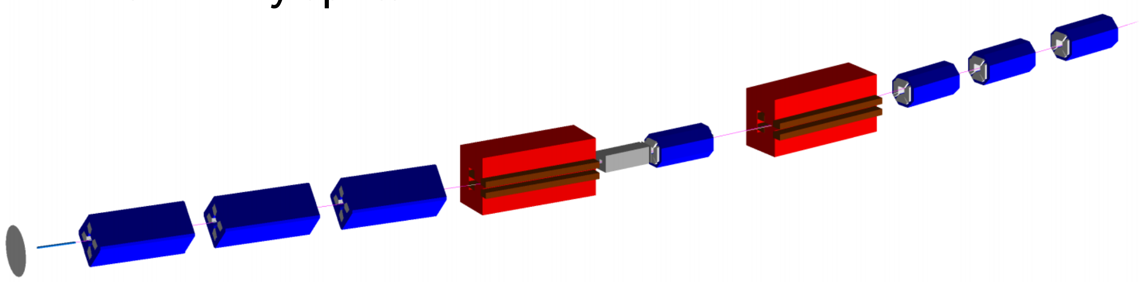




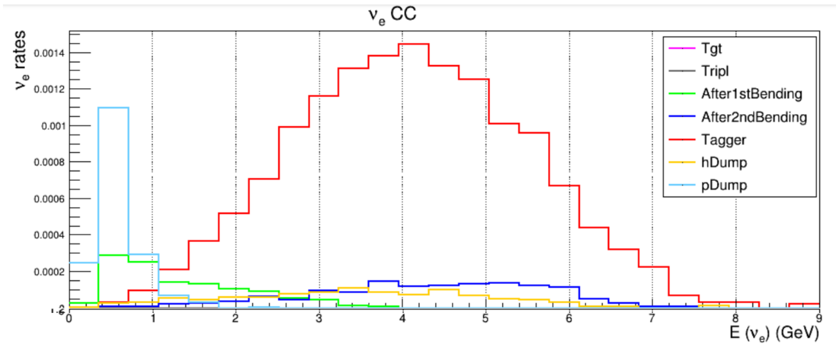
ENUBET multi-momentum transferline

- 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.

Preliminary optics

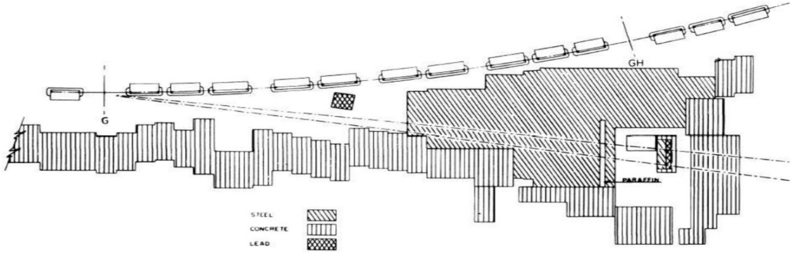


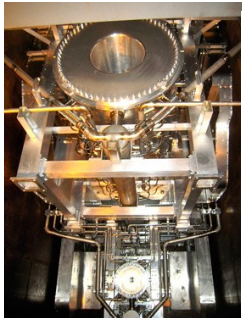
ν_e from **8.5** GeV/c secondaries (current baseline)



1 4 6 GeV

Accelerator based neutrino beams





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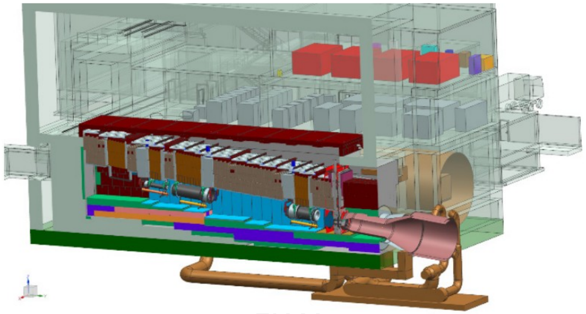


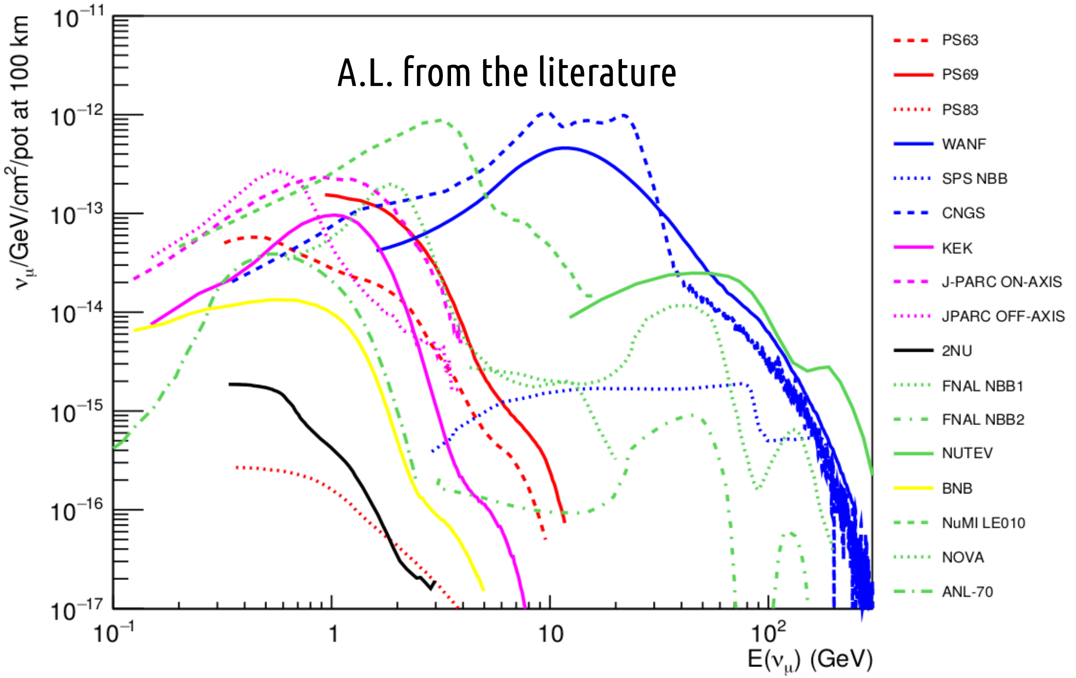
FNAL

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 ...

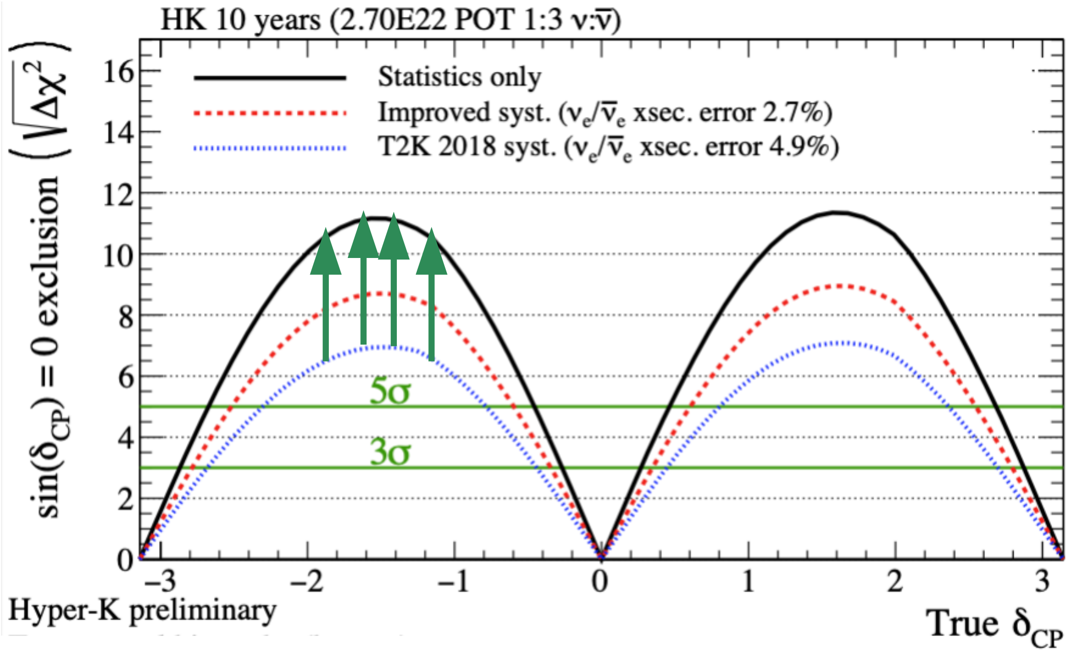
New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.



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.

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)

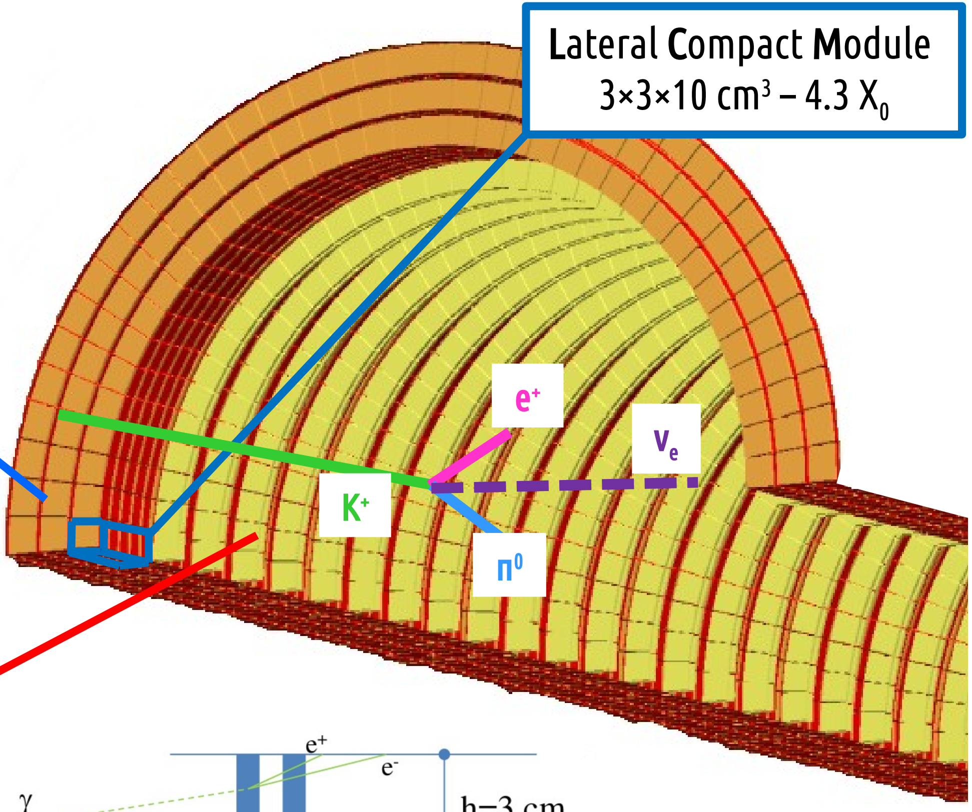
The concept of monitored neutrino beams

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)

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



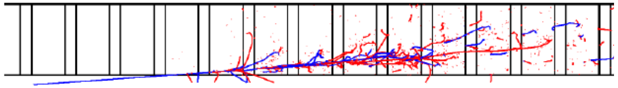
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

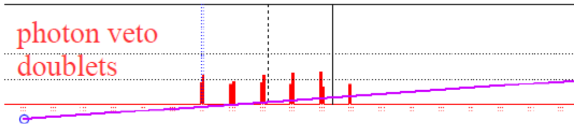
→ $e^+/\pi^\pm/\mu$ separation

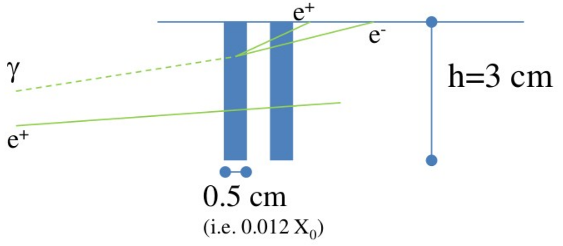


Integrated photon veto

- Plastic scintillators rings of 3×3 cm² pads

→ π^0 rejection



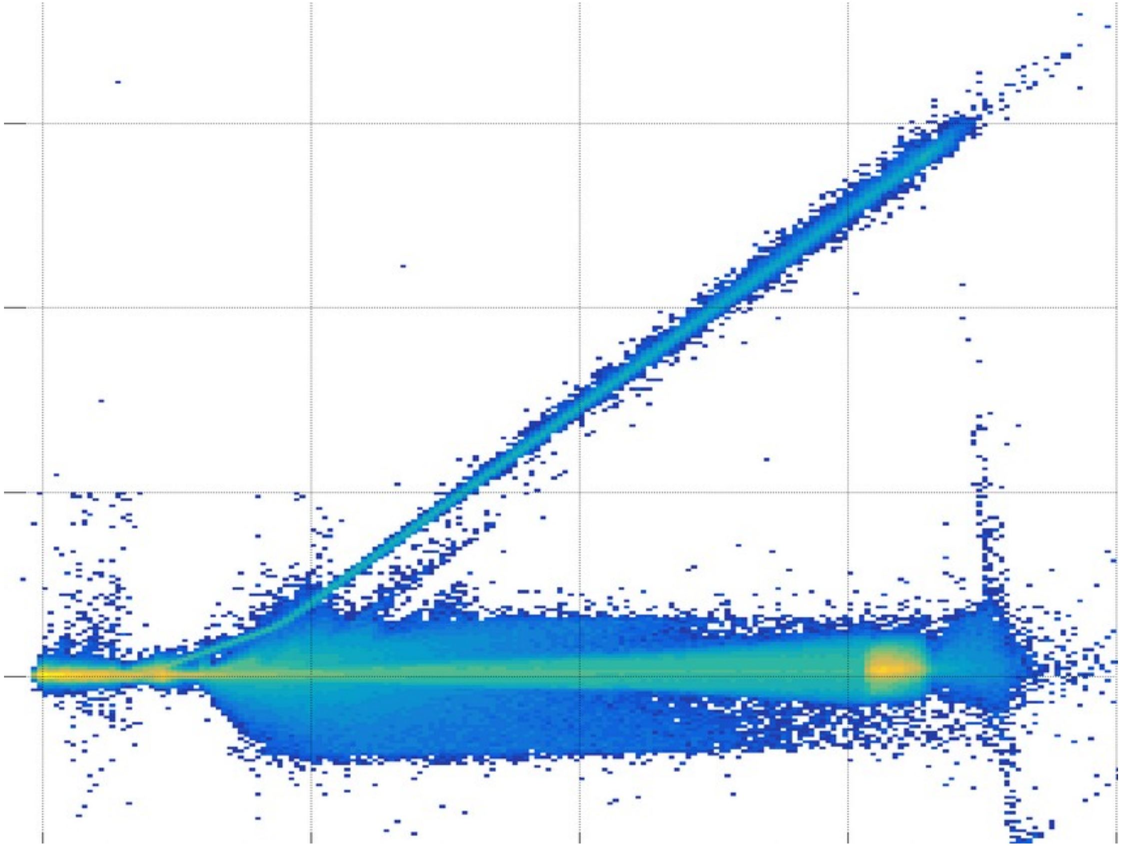


e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology

Neutrino creation points



Neutrino origin