ENUBET

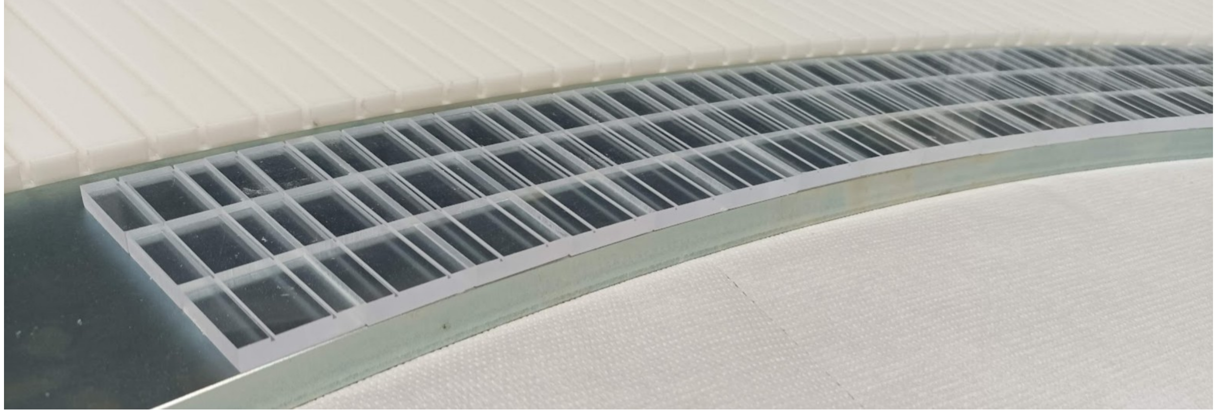
fasci di neutrino monitorati al CERN

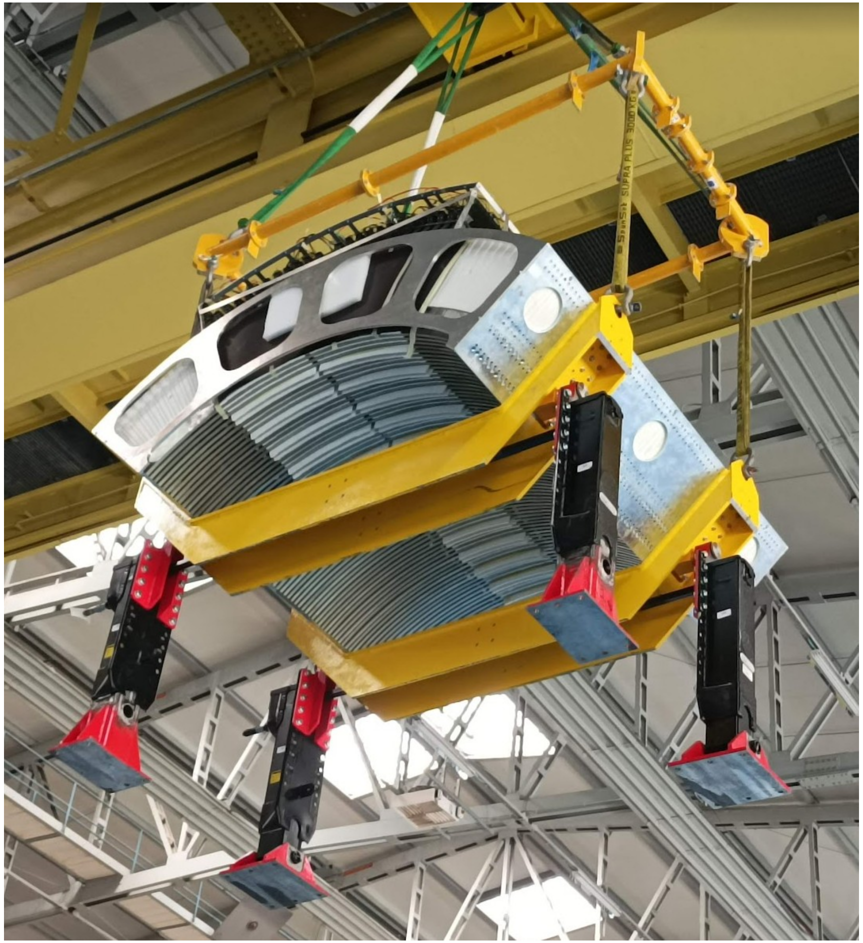
A. Longhin
Padova Univ. and INFN
on behalf of the ENUBET Coll.

Inputs EU strategy update 2025
INFN-PD 25/10/2024

HORIZON 2020

Istituto Nazionale di Fisica Nucleare





EU strategy 2020

EU strategy document (19 June 2020):

"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**".

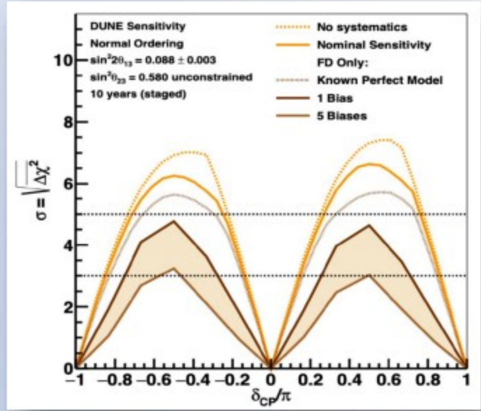
ENUBET

The rationale of ENUBET

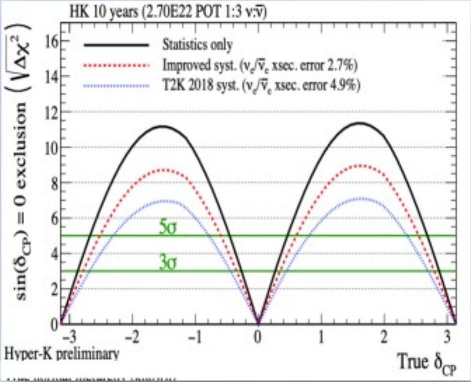
The knowledge of neutrino cross-section is stuck at 10-30 % level and the needs of the neutrino community are at 1% level because:

- Leading systematics for long-baseline experiments → Neutrino Oscillation Physics
- Limited possibility to validate nuclear electroweak effects ("nucleus and nuclear correction") → Electroweak physics
- Neutrino generators based on different approaches still provide results with >50% discrepancies → Nuclear Physics

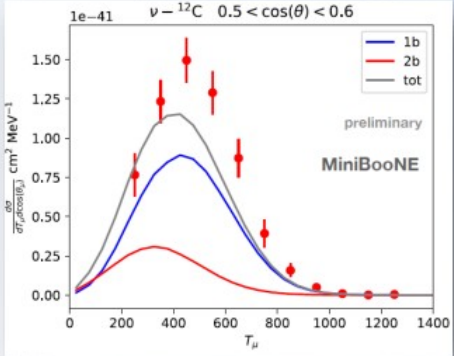
DUNE



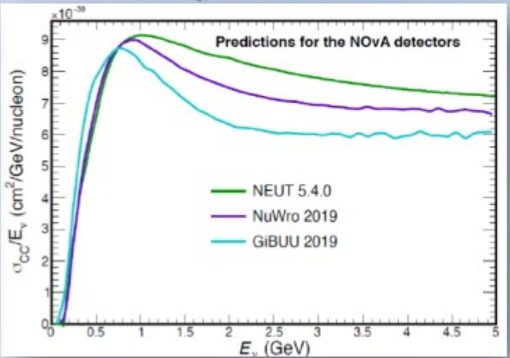
HyperKamiokande



N. Rocco, Nufact2022

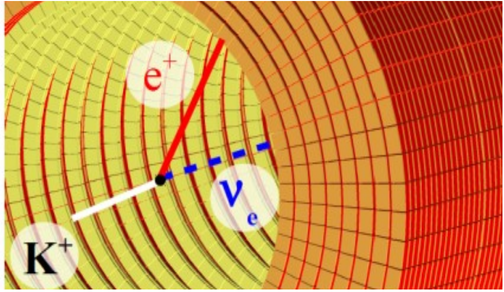


J. Paley, Nufact2022



21/06/2024 Giulia Brunetti | Neutrino2024 2

NP06/ENUBET development



- 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 long-baseline program with high quality experimental inputs

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

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

@enubet

ERC project 6/2016- 12/2022

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

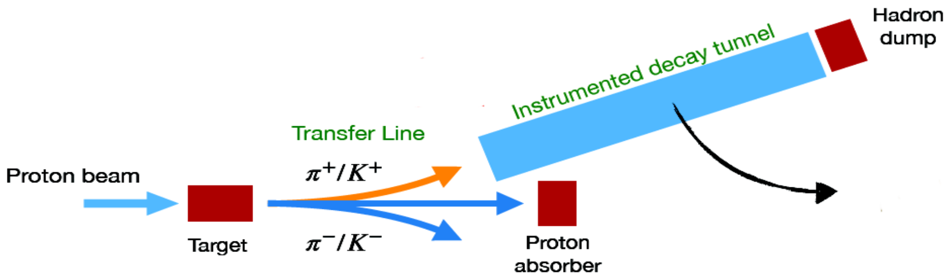
Enhanced **N**e**U**trino **BE**ams from kaon **T**agging ERC-CoG-2015, G.A. 681647, PI A. Longhin, **Padova University, INFN**

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

Present collaboration: 74 auth, 17 institutions

ENUBET

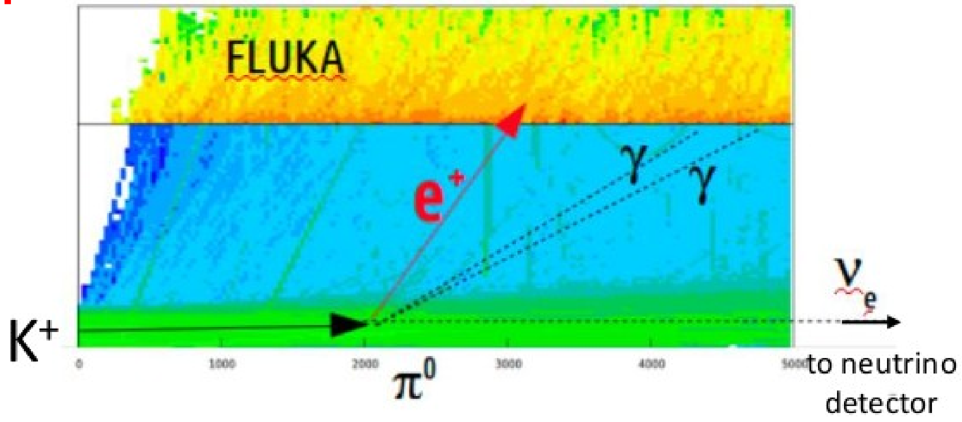
… the first **"monitored neutrino beam"**:



production of neutrino-associated leptons monitored at single particle level in an 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**

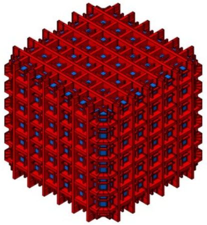


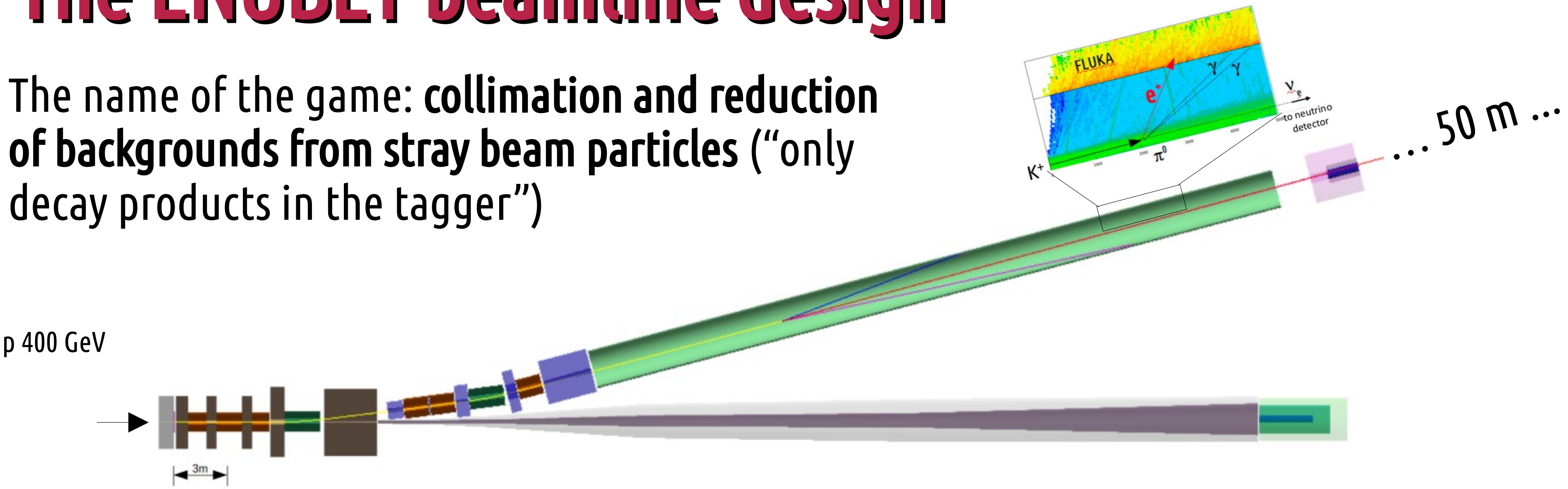
- Needs a **collimated mom-selected hadron beam** → **only the decay products hit the tagger**
  → manageable rates and irradiation in the detectors
- Needs a **"short" decay region** : ~all ν_e from K, only ~1% ν_e from μ (large flight length)

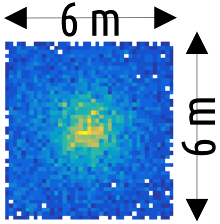
NB: it requires a **specialized beam**, not a "pluggable" technology for existing super-beams (unfortunately!)

The ENUBET beamline design

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







- Focuses **8.5 GeV +/- 10%** **mesons** (ν spectrum ROI ~ DUNE)
  - Length: 26 m
  - Tagger length: 40 m
  - Neutrino detector (500 t) 50 m after the hadron dump
  - 14.8° bending angle
- documented in **EPJ-C 83, 964, 2023**

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

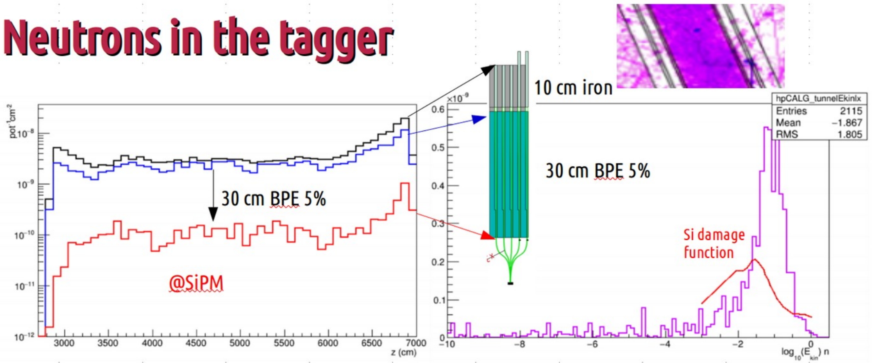
https://link.springer.com/article/10.1140/epjc/s10052-023-12116-3

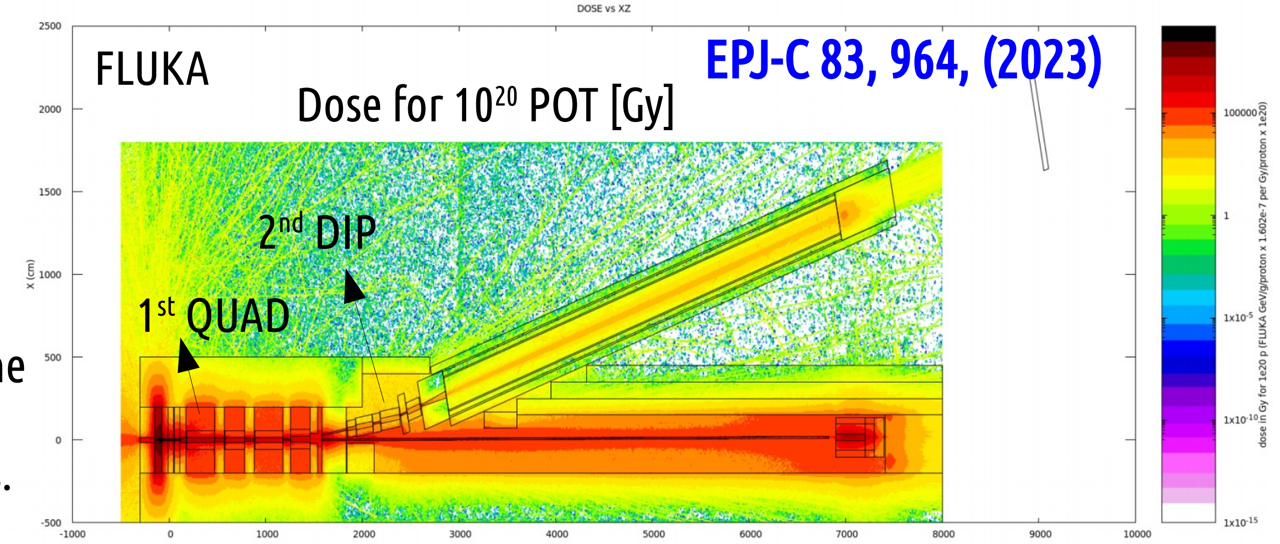
Irradiation levels

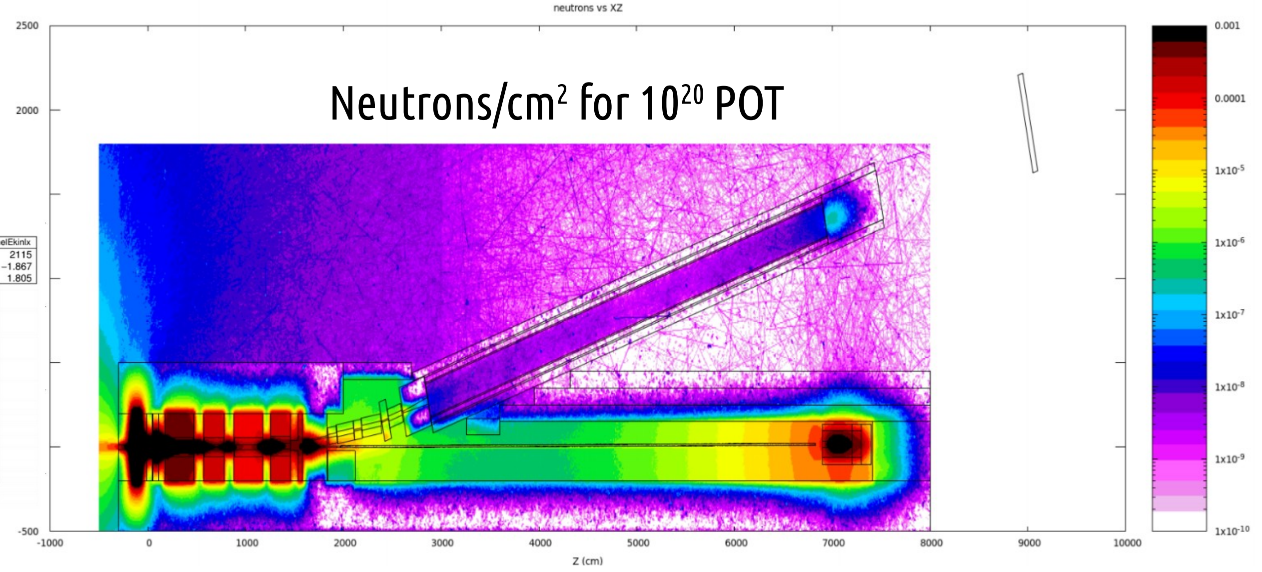
Dose is sustainable by magnets even in the hottest regions (<300 kGy/10^{20} pot).

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







Particle budget and rates

Entering the tagger:

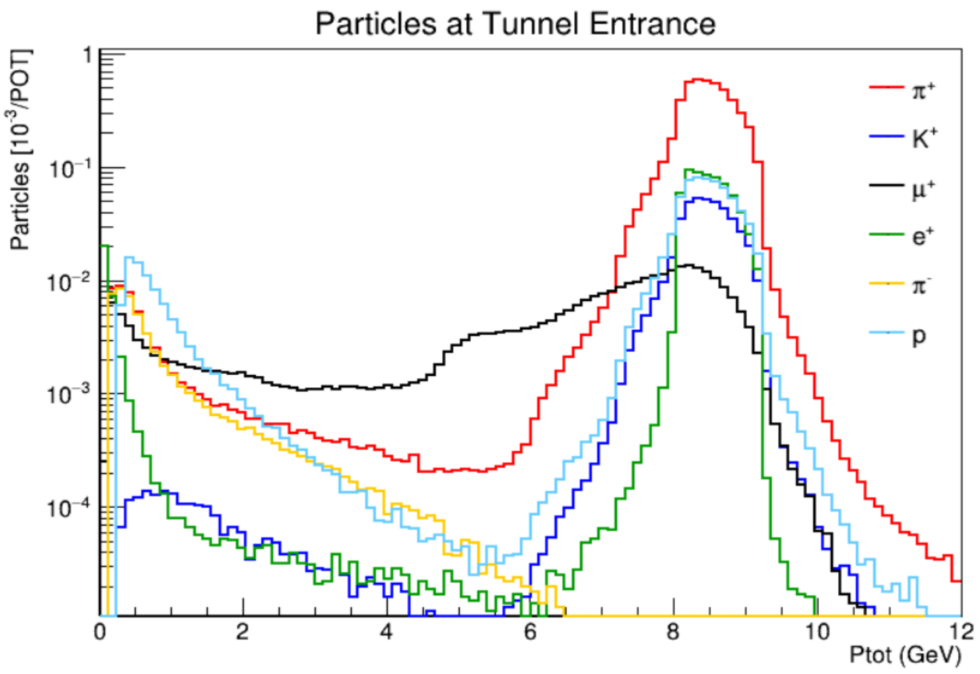
$4.6 \times 10^{-3}\ \pi^{+}$/pot

$0.4 \times 10^{-3}\ K^{+}$/pot

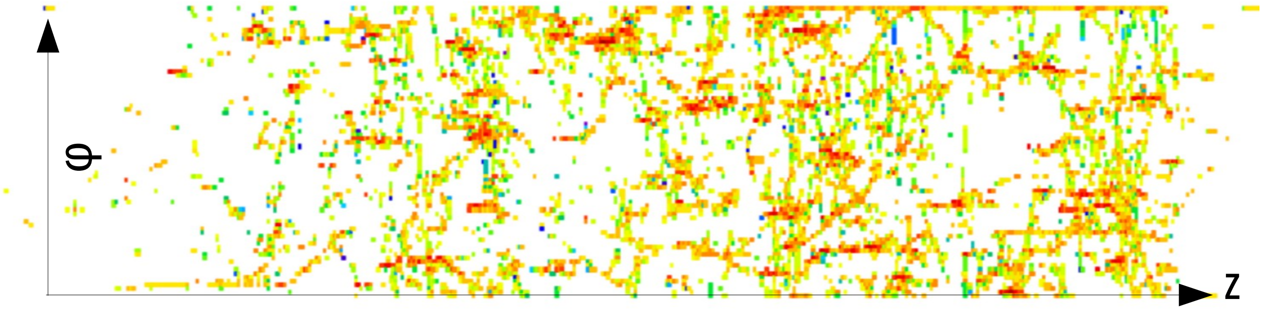
The hottest regions of the tagger see ~ 500 kHz/cm^2 with 2.5×10^{13} pot/2.4 s (slow extraction)

Pile-up mostly non critical but has to be treated.

→ the detector has to be fast enough, radiation hard, cost-effective (large area)



Hit map for e^{+} in a few ns

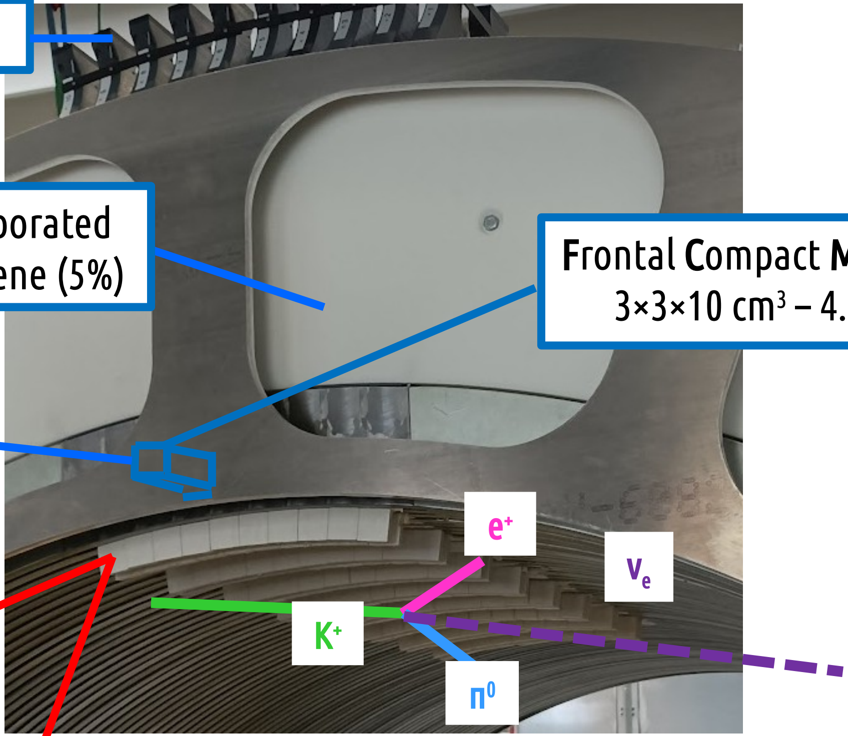


The lepton tagger

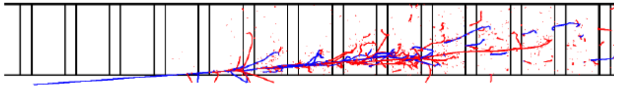
Light r/o (SiPM)

30 cm of borated polyethylene (5%)

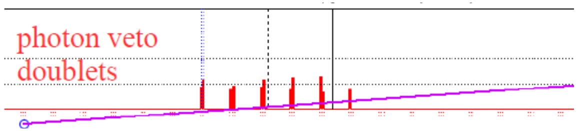
Frontal Compact Module
$3{\times}3{\times}10$ cm^3 – 4.3 X_0

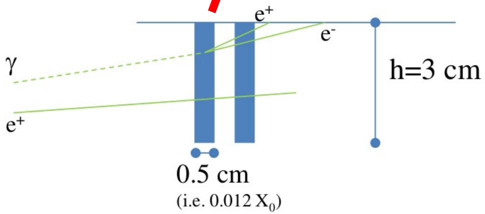


Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation



Integrated photon veto
Plastic scintillators rings of $3{\times}3$ cm^2 pads
→ π^0 rejection





e^+ (signal) topology

π^0 (background) topology

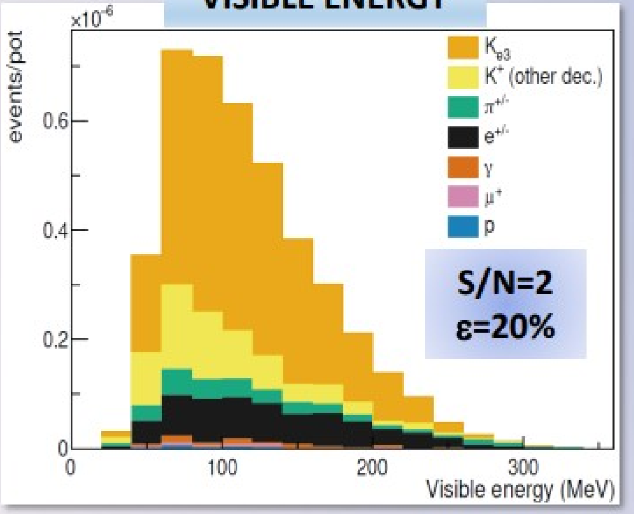
π^+ (background) topology

Lepton event by event reconstruction

GEANT4 simulation. Event building: clustering of cells in space and time (accounting for **pile-up**) → PID with a Multilayer Perceptron

K_{e3} positrons → constrain ν_e

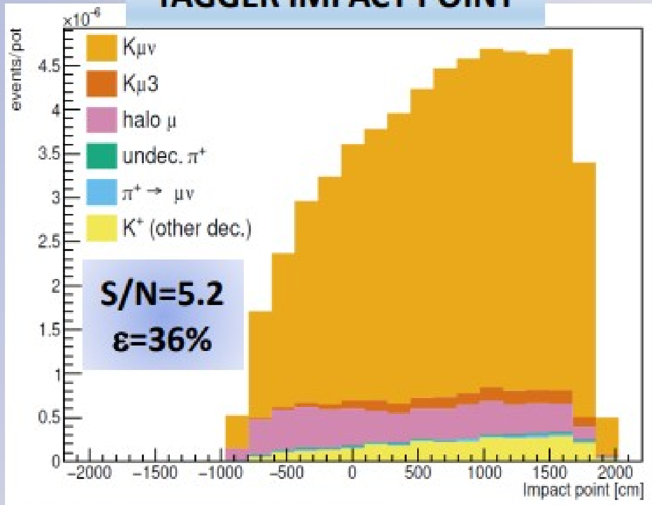
VISIBLE ENERGY



Efficiency ~half geometrical

$K_{\mu 2}$ muons → constrain ν_μ

TAGGER IMPACT POINT

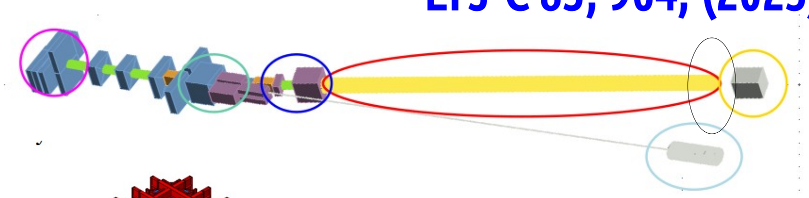


Efficiency ~half geometrical

See EPJ C 83 (2023) 964

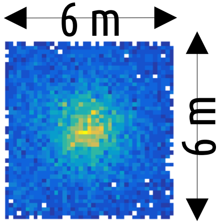
$\nu_{\mu/e}$ CC spectra at detector

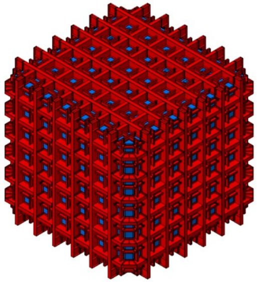
EPJ-C 83, 964, (2023)



500t @ 50 m after the hadron dump @ 400 GeV → **0.7 Mν_μ**^{CC} with 1e20 POT

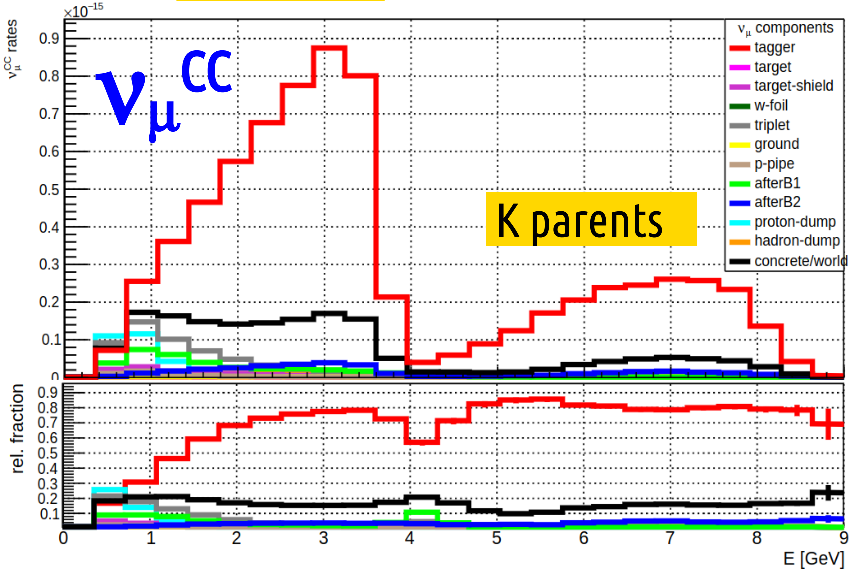
→ **10000 ν_e**^{CC} with ~1e20 POT

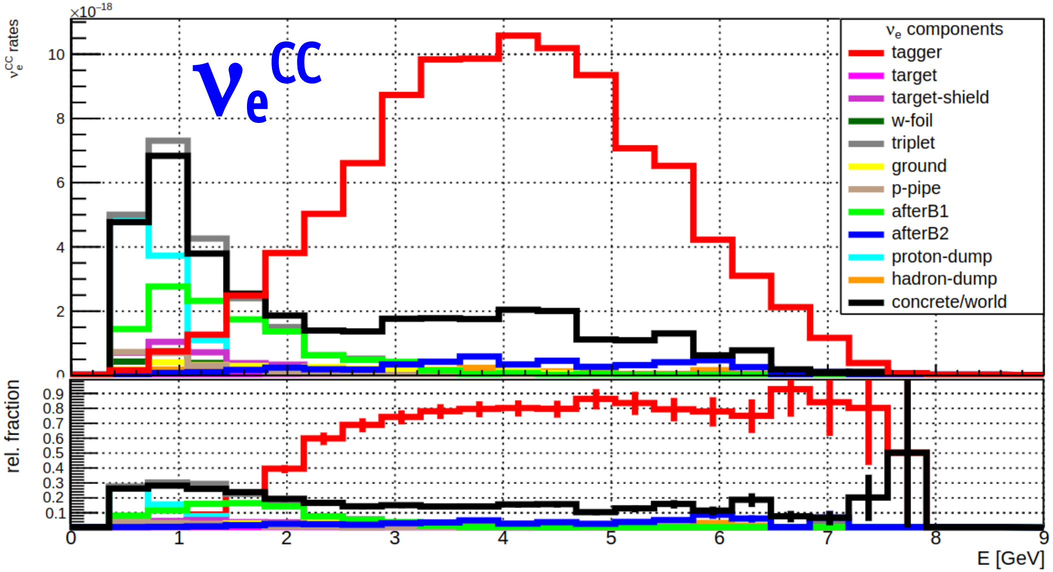




The protoDUNE(s) could be such a detector (an evident asset for a possible siting at CERN)

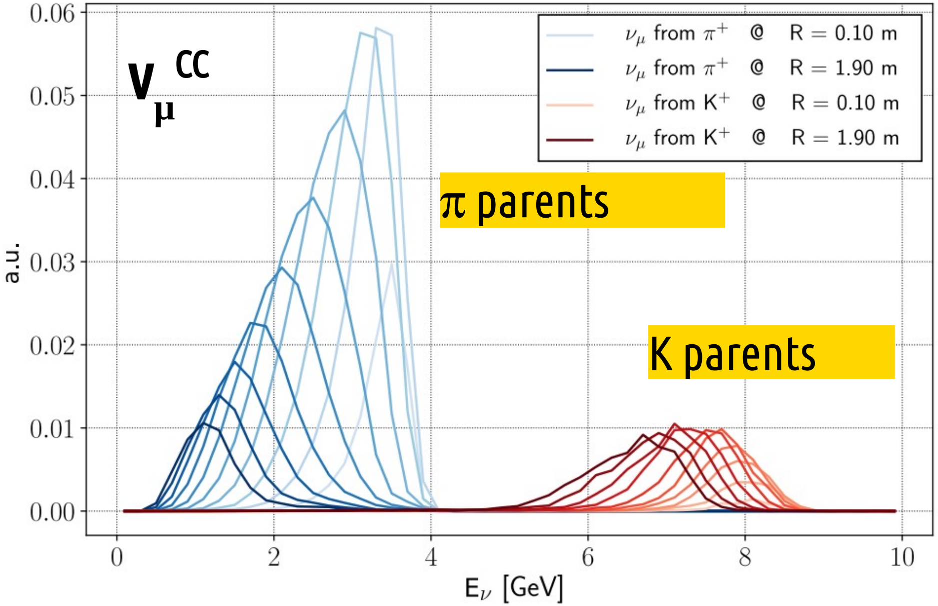
π parents

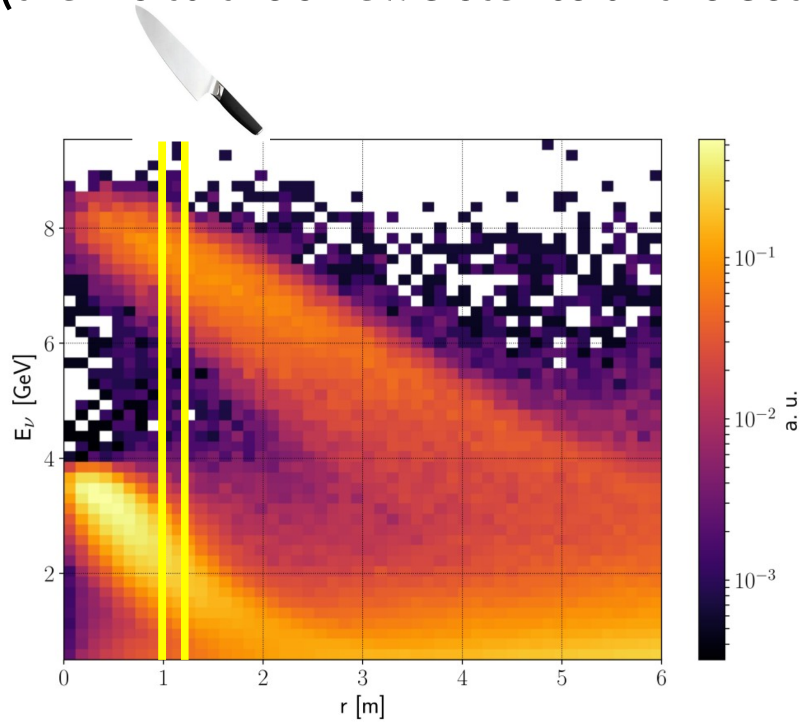




ν_μ fluxes decomposition: NBOA (~PRISM)

"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) !





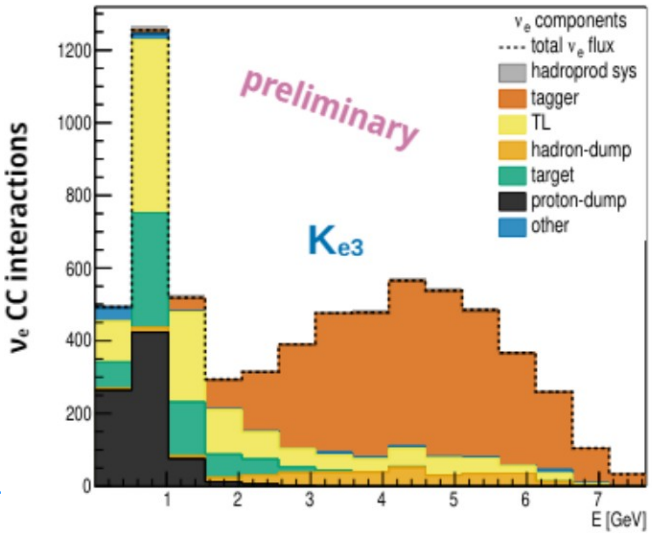
Precision on the neutrino flux

• considered the dominant sys. (hadroproduction) extracted from hadroproduction experiments at the SPS (NA56/SPY), which gives a 6% uncertainty on flux
• added as an additional prior the rate, position and energy distributions of positrons from K decay reconstructed in the tagger

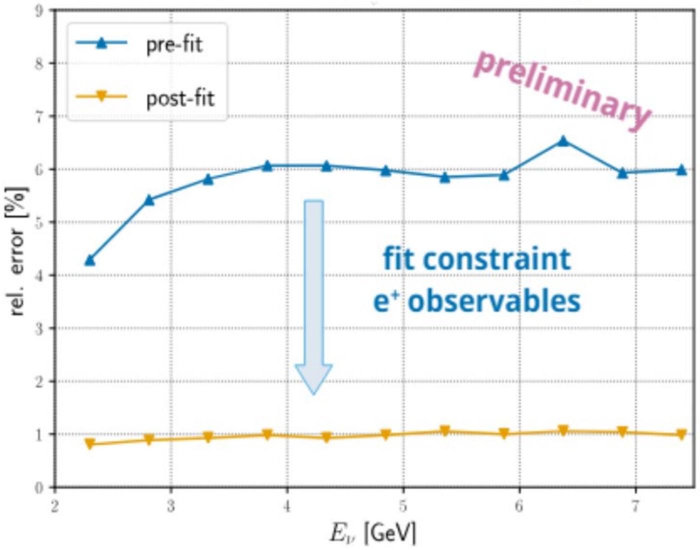
Flux uncertainty for ν_μ and ν_e drops from 6% to 1% using positrons only. Further improvements expected by adding the reco. muons

[F. Bramati poster at Neutrino2024]

ν_e CC rate



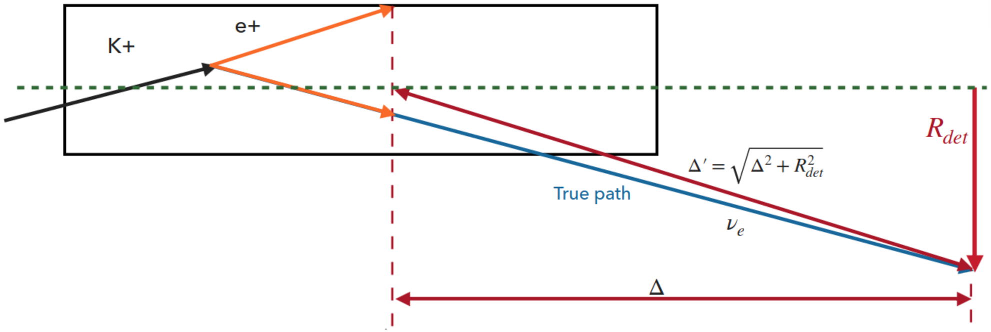
relative error on ν_e CC rate : pre and post-fit



In progress: add detector effects, magnet currents, beam component, material budget uncertainty, and exploit the additional constraints from reconstructed muons (paper in preparation)

t-tagging for interacting ν

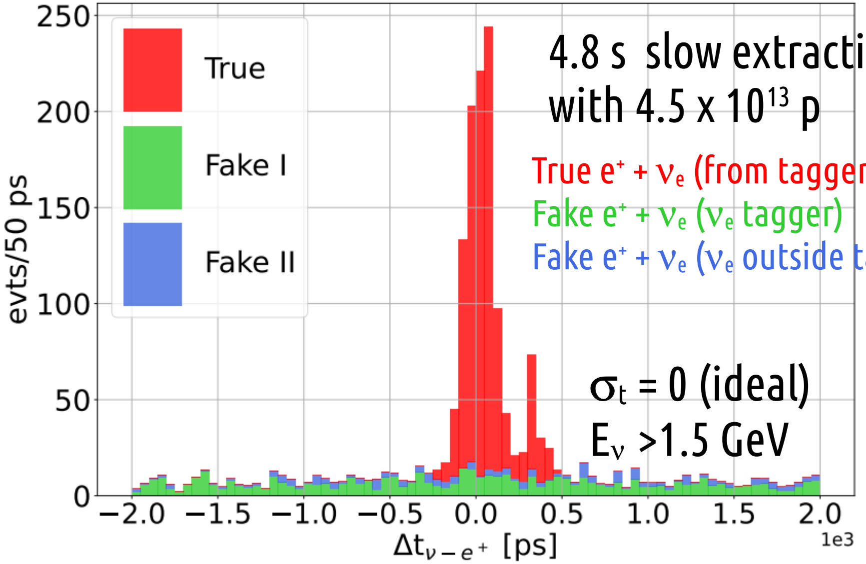
EPJ-C 83, 964, (2023)



The goal of ENUBET (monitored beam): get 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).

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

→ Time correlation btw K_{e3} e^+ and ν_e candidates with the full simulation (reconstruction, backgrounds) →



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

True $e^+ + \nu_e$ (from tagger)
Fake $e^+ + \nu_e$ (ν_e tagger)
Fake $e^+ + \nu_e$ (ν_e outside tagger)

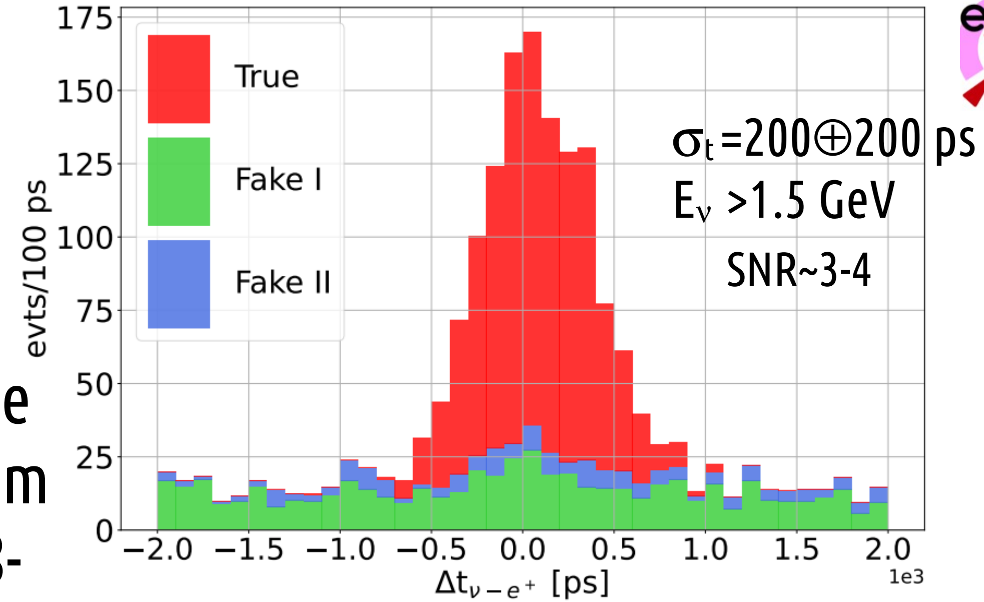
$\sigma_t = 0$ (ideal)
E_ν >1.5 GeV

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(*)**

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

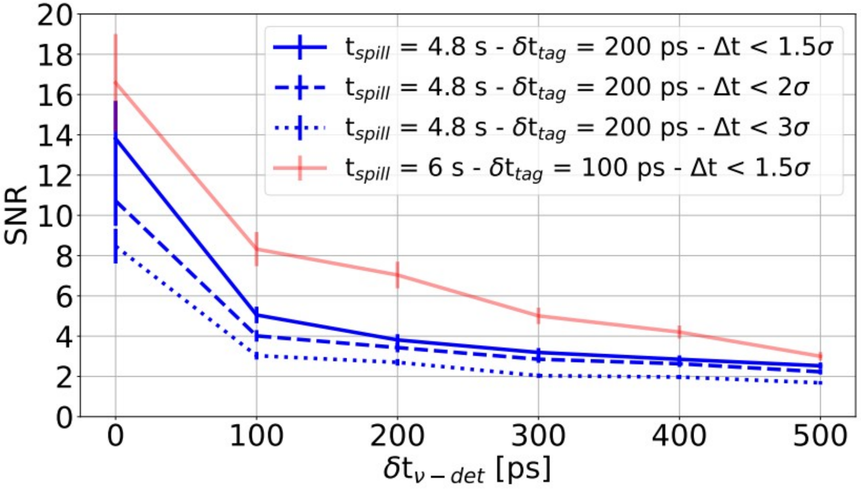
ENUBET & time-tagging

EPJ-C 83, 964, (2023)



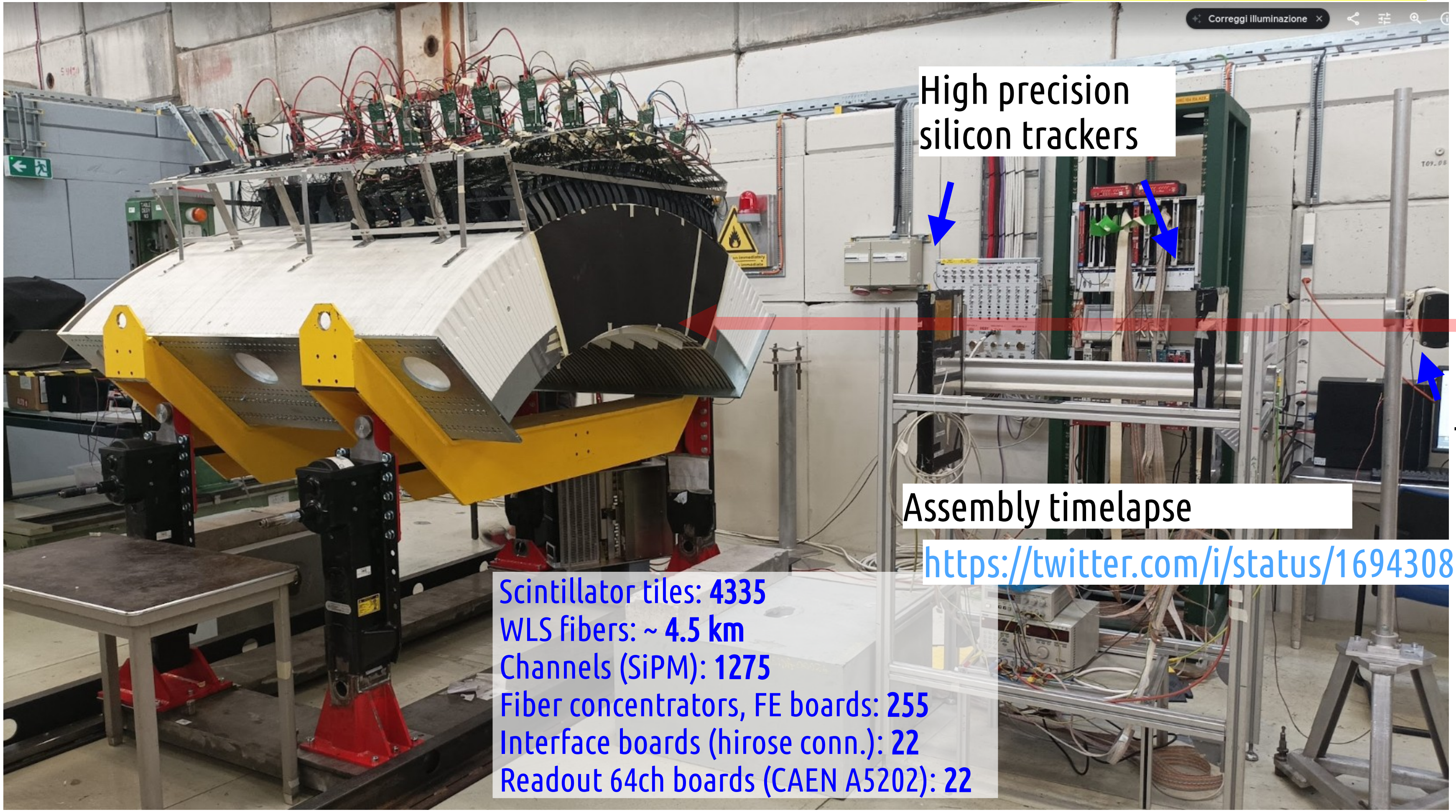
By applying a cut on the Δt bewteen the ν_e and e^+ candidates the SNR passes from ~2 (for the inclusive e^+ sample) up to ~8-10 for neutrino-associated e^+

Precise value depends on σ_t of tagger and neutrino detector and the slow extraction spill duration



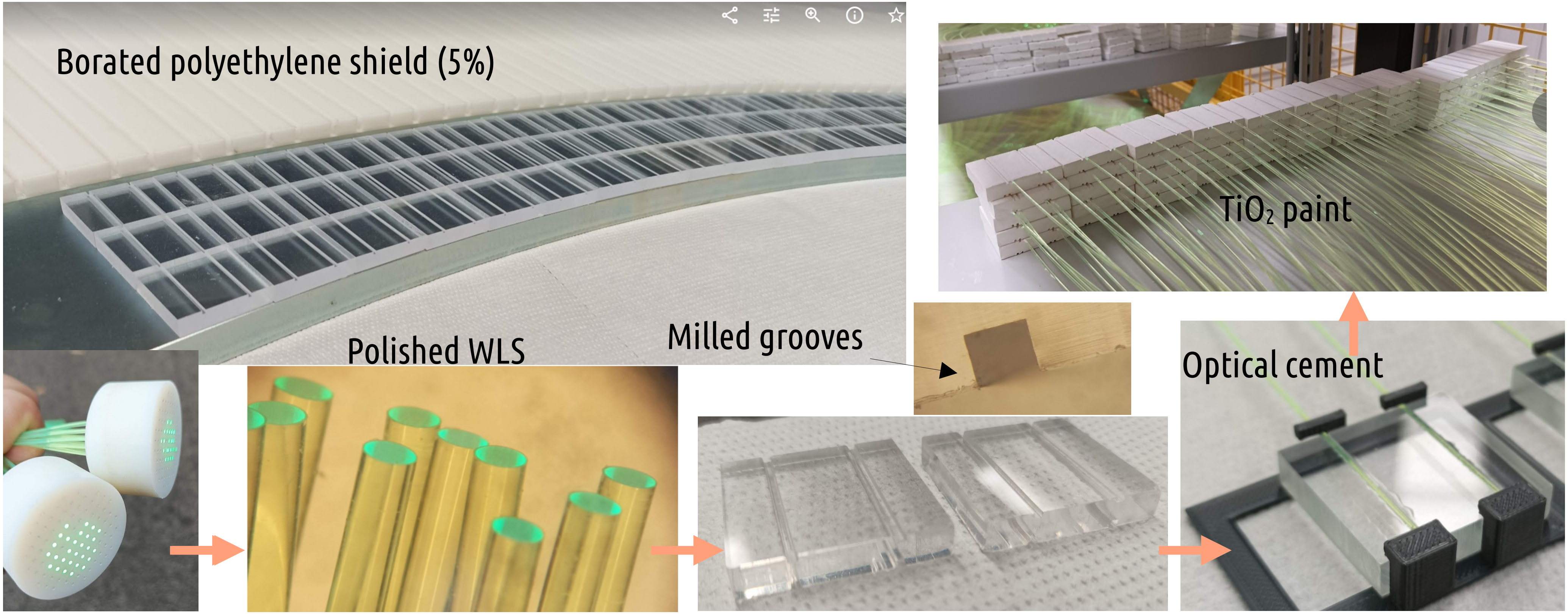
The demonstrator

10/22 + 08/23 + 08/24 @ CERN-PS-T9



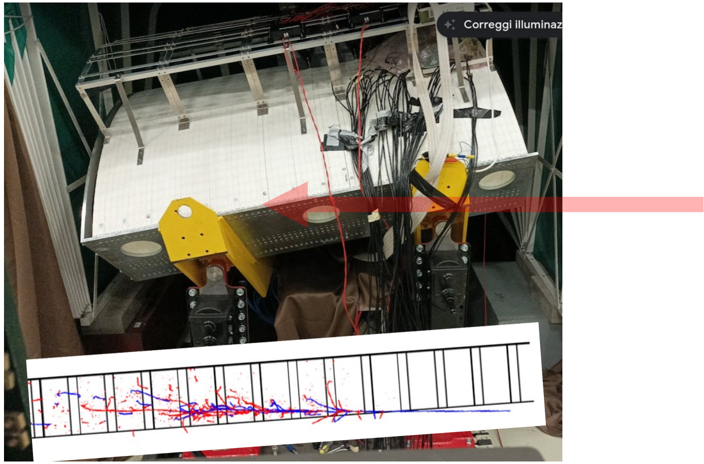
Scintillator tiles: **4335**
WLS fibers: ~ **4.5 km**
Channels (SiPM): **1275**
Fiber concentrators, FE boards: **255**
Interface boards (hirose conn.): **22**
Readout 64ch boards (CAEN A5202): **22**

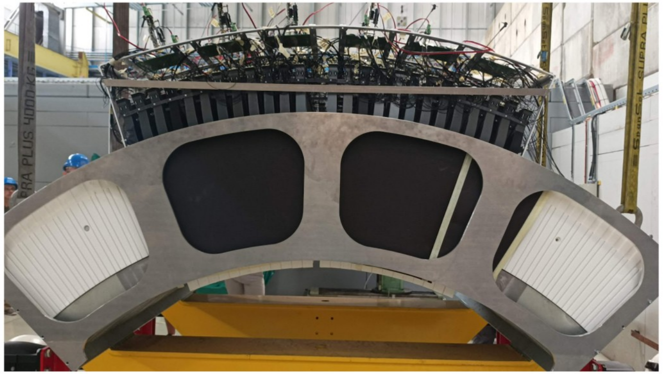
The demonstrator detector technology



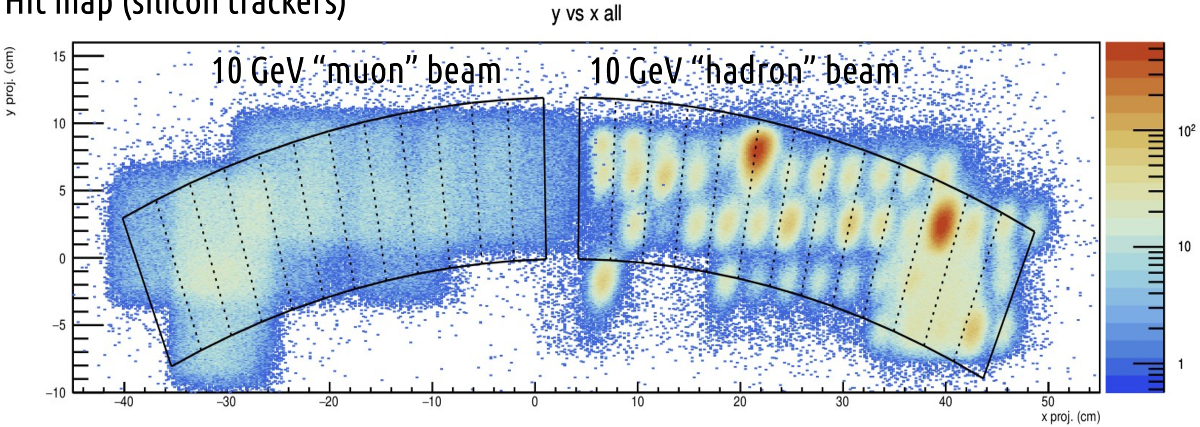
Inclined and calibration runs

200 mrad tilt run

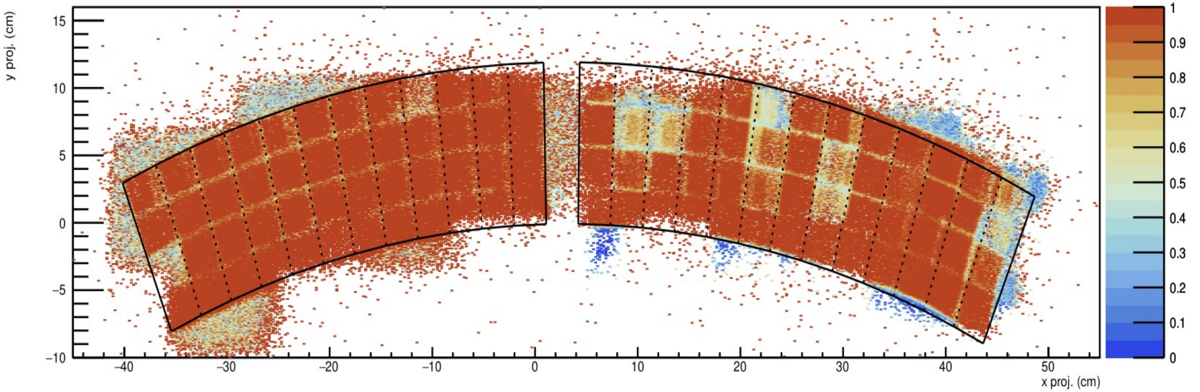




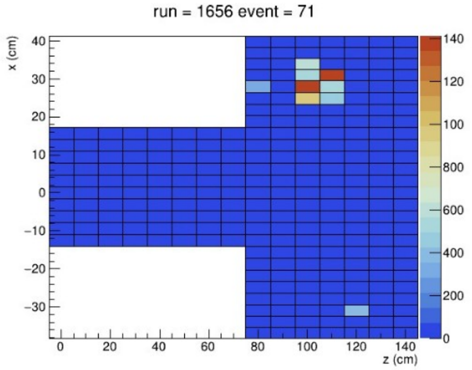
Hit map (silicon trackers)

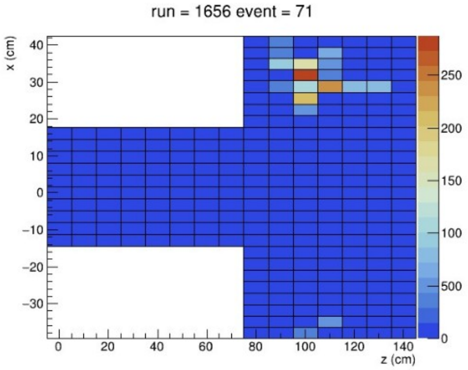


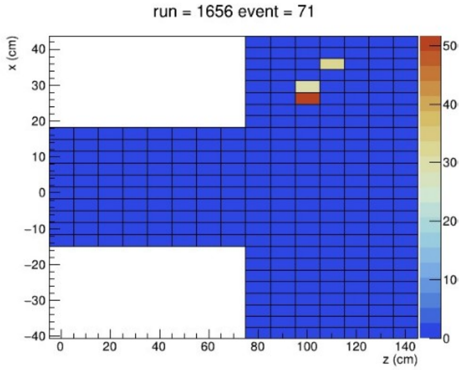
Efficiency map

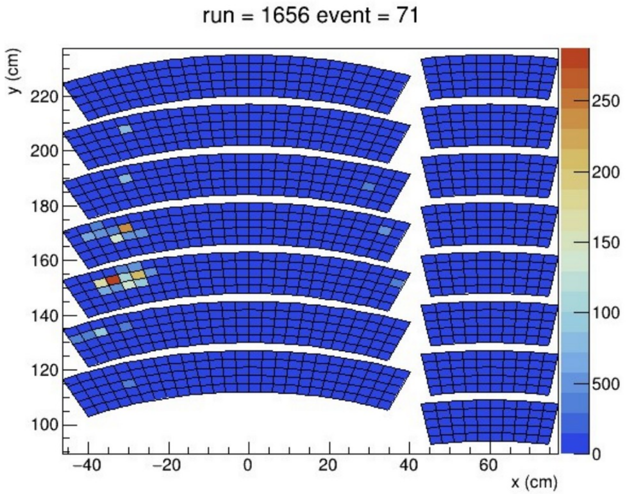


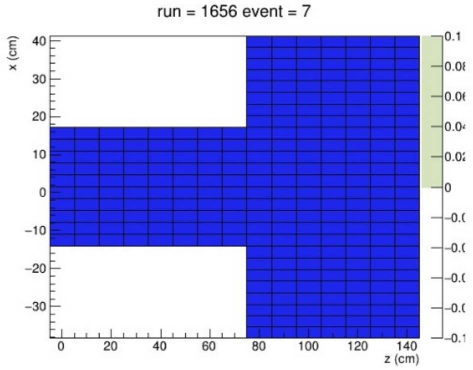
Event displays (mu, had 10 GeV)

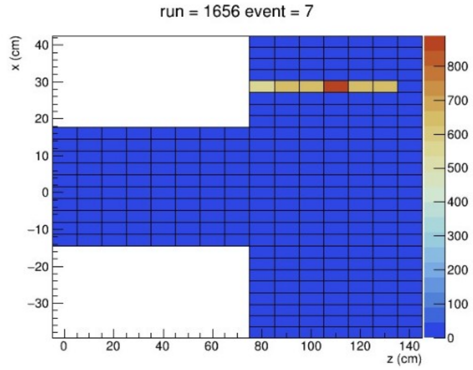


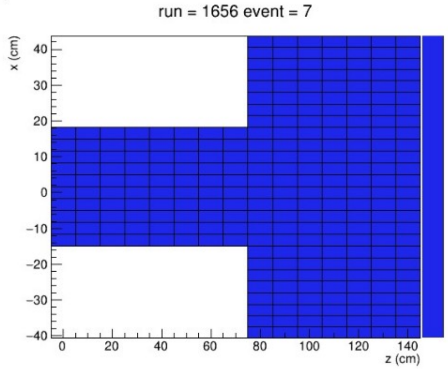


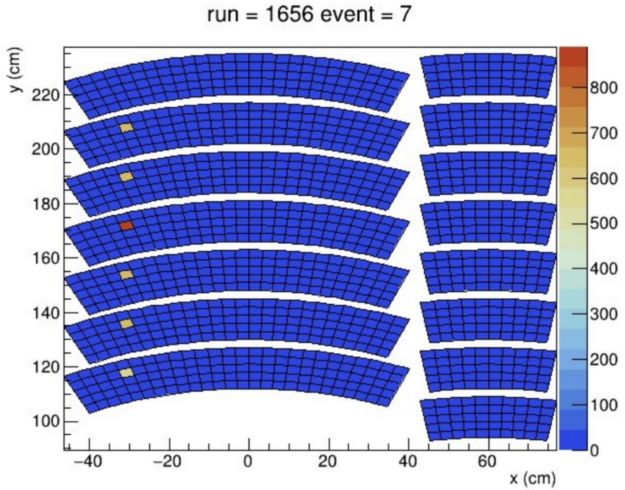




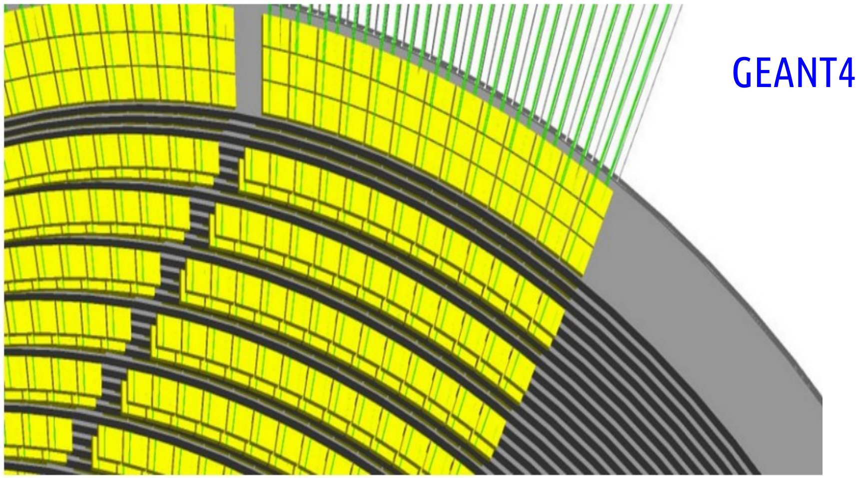


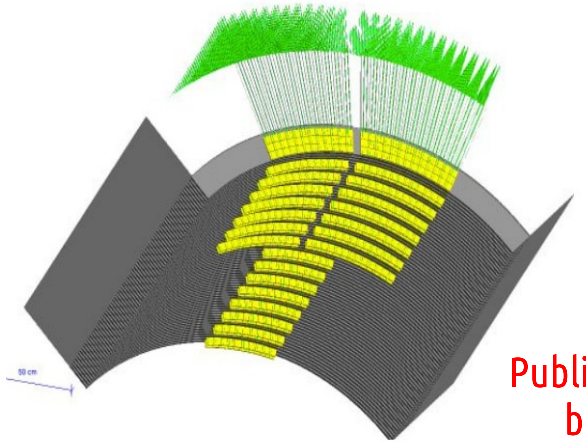


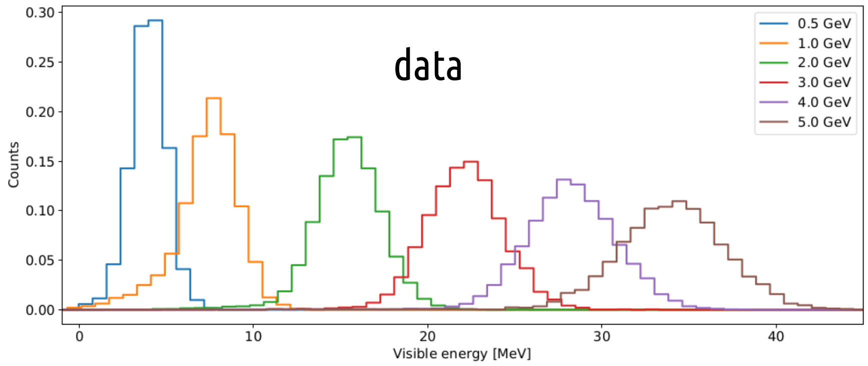


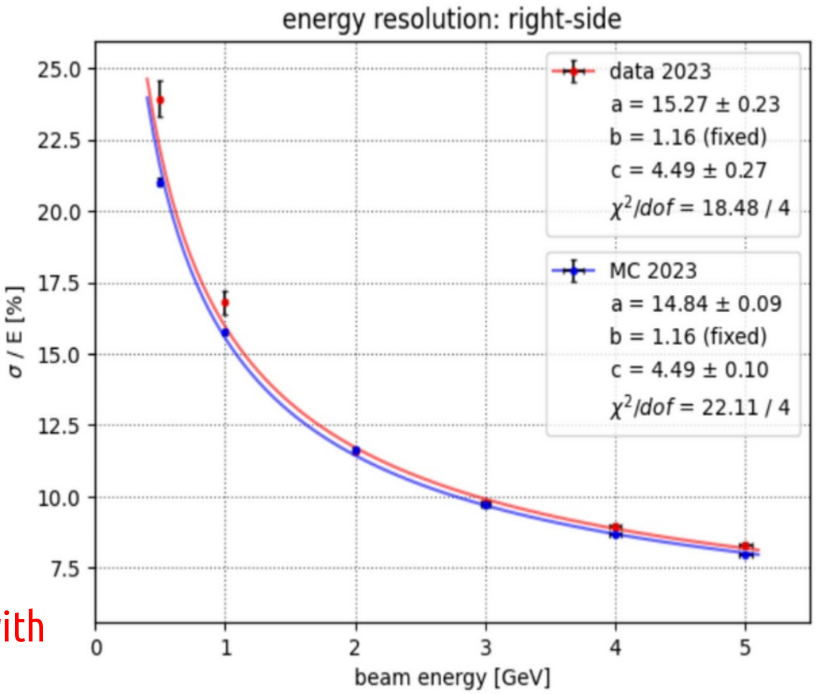


Electron E resolution



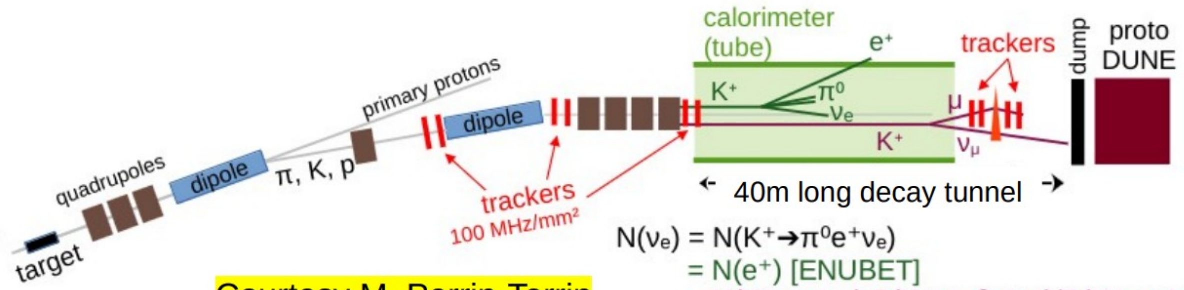






Publication in the pipeline with both 2022 and 2023 data

NuTAG: pushing on σ_t(tagger) and $\sigma(E_\nu)$



$N(\nu_e) = N(K^+ \to \pi^0 e^+ \nu_e)$
$= N(e^+)$ [ENUBET]
$= N(K^+ \to \mu^+ \nu_\mu)\ B(K^+ \to \pi^0 e^+ \nu_e)/B(K^+ \to \mu^+ \nu_\mu)$ [NuTAG]

Courtesy M. Perrin-Terrin

NuTAG: state-of-the-art silicon trackers with excellent timing ("4D")
→ **tag the parent of the decay**

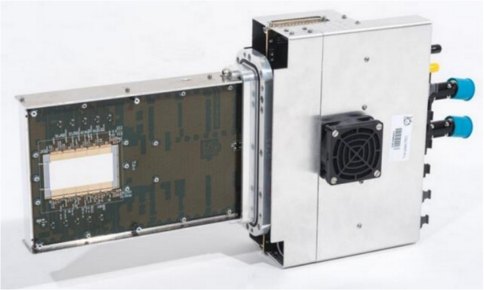
	Available	Max. Radiation	Max. Flux
NA62-GTK	since 2015	$10^{14}\ n_{eq}/cm^2$	2 MHz/mm²
HL-LHC	before 2028	$10^{16-17}\ n_{eq}/cm^2$	10-100 MHz/mm²

Ideal for 2-body decays ($\pi_{\mu 2}$, $K_{\mu 2}$) to reconstruct E_ν

$p_{\pi/K}$ (parent momentum): tracking before and after a dipole

θ_ν (with the interaction vertex in the detector)

$$E_\nu = \frac{(1 - m_\mu^2/m_\pi^2)\, p_\pi}{1 + \gamma^2 \theta_\nu^2}$$



Large BR statistics: low-intensity runs.
Flux of ν_e: inferred from knowledge of B.R.($K_{\mu 2}$)/B.R.(K_{e3})
If μ can also be tracked: predict the ν position -> Relax time matching

Could provide E_ν resolutions at the % level. Studies progressing.
Challenges: upgrade of NA62 GigaTracker, reconstruction.

A. Baratto-Roldan et al. arXiv: 2401.17068

PBC-SBN

CERN Physics Beyond Colliders short baseline neutrino (PBC-SBN)

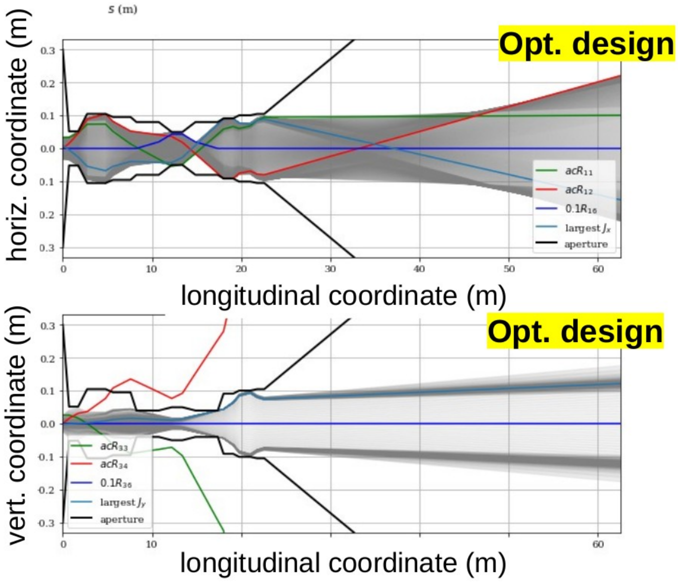
M. Jebramcik
link to talk @ PBC annual meeting
link to Neutrino2024 poster

4 directions:

- Improved design. Compatible with **ENUBET & NuTAG** — worked out
- **Compatible with the CERN fixed target programme** (more ν with less p) — worked out
- with fluxes down to **O(1) GeV → Hyper-Kamiokande** — being studied
- **Conceptual level feasibility study at CERN**: siting constraints, costs — being studied

The new design uses moderately "bolder" assumptions on the quads apertures (very conservative for NP06/ENUBET) → multi-objective optimization, CNGS-like target, shorter line →

1.4 × 10^{-3} K^+/pot → 3.5 × higher Large gain! → physics performances of ENUBET with this beamline is in progress (~ similar S/B).



PBC-SBN perspectives

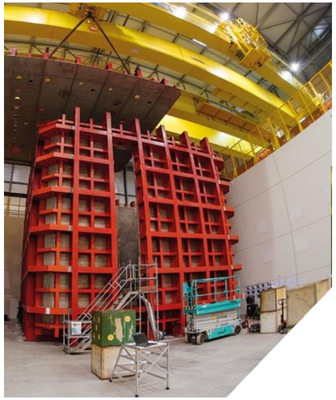
These recent studies shows that **~ 10^4 ν_e ^{CC} and 5×10^5 ν_μ ^{CC}, with a flux normalization at 1%, over ~ 5 years in a detector of similar size to the ProtoDUNEs are feasible**.

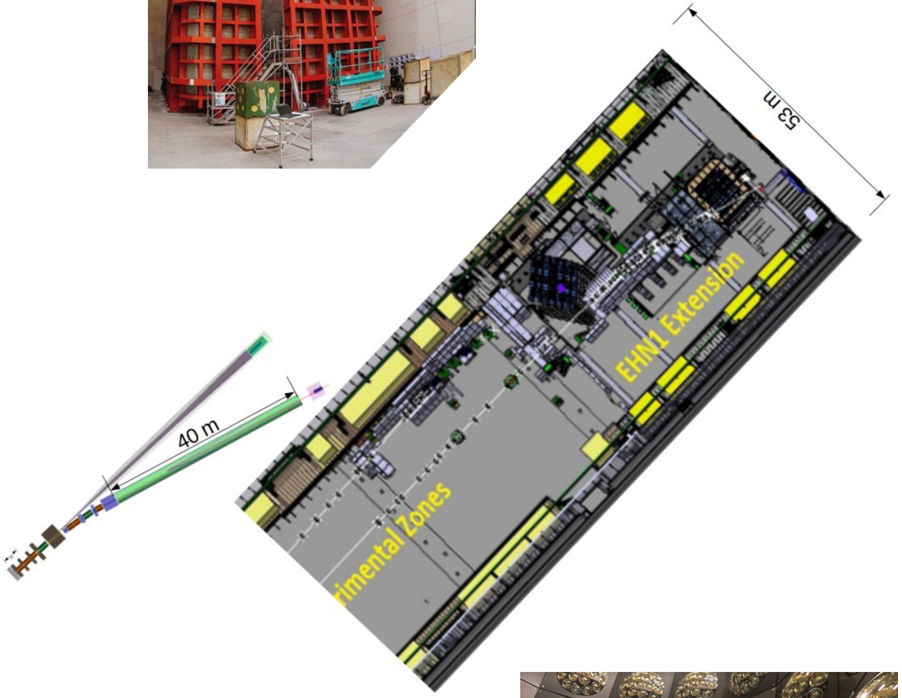
~0.3e19 POT/year (SHiP asks 4.0e19/year)

Studies about possible **siting at CERN** are in progress.

Shooting on the **protoDUNEs** at the North-Area would be an ideal optimization of resources → checking feasibility/costs in practice

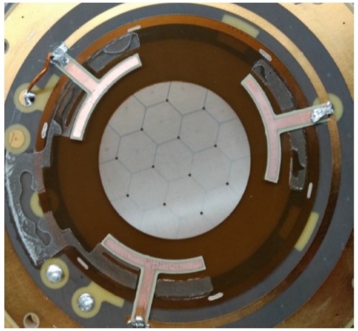
Other areas capable of accommodating detectors of similar size are being considered (also a WCh. detector ~ "**WCTE++**" would be extremely interesting)





Forward monitoring with PICOSEC Micromegas

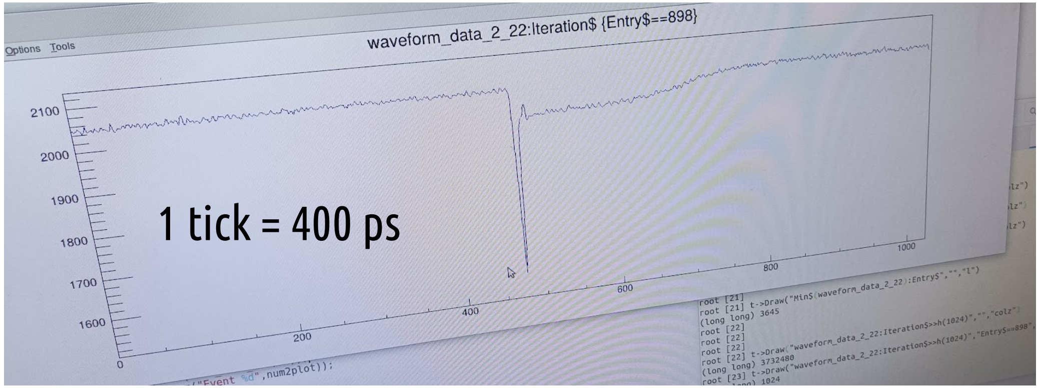
- **Instrument also the forward region**: observe μ from π decays → constrain low-E ν_μ component
- Instrumented hadron dump PIMENT (**PI**cosecond **M**icrom**E**gas for e**N**ube**T**), ANR2022-25
- Prototype tested with the ENUBET demonstrator **at T9** in Aug. 2024 → few 10s of ps resolutions achieved
- Athens, CNRS, INFN, Thessaloniki, Zagreb

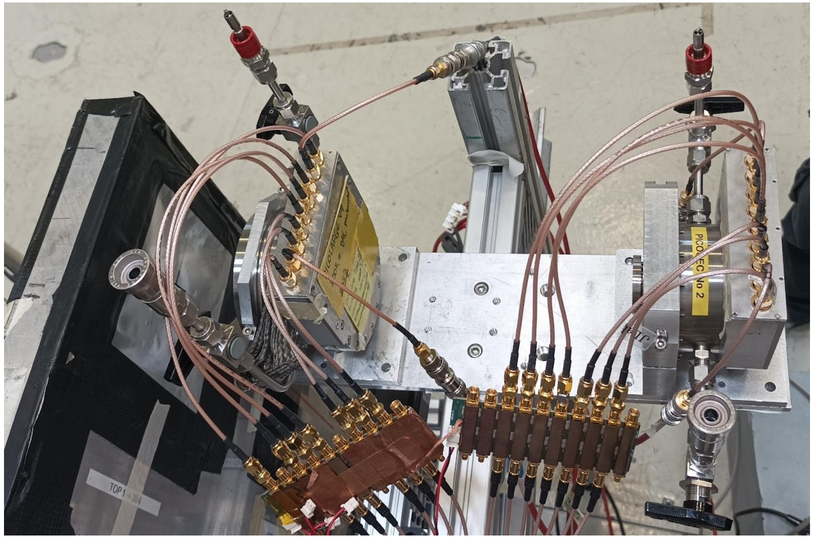


19 channel anode ⬡ 1 cm

https://doi.org/10.1016/j.nima.2018.04.033

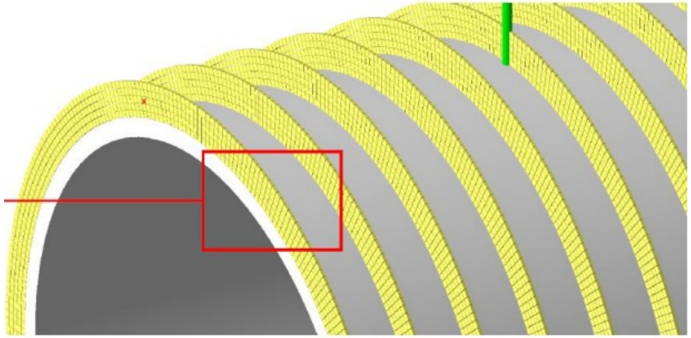
CERN Aug. 2024



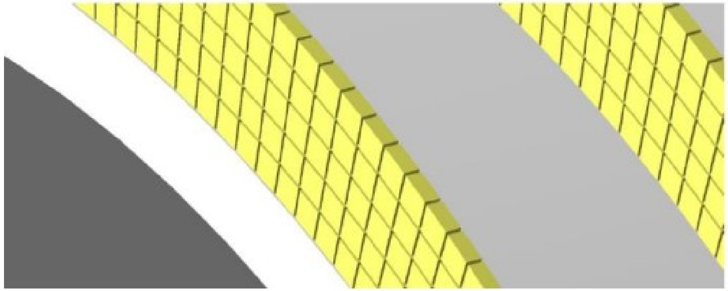


A low-E_ν monitored beam at ESS ?

- MNB@ESS WP6 of the ESSnuSB
  - previous talk by Tamer Tolba
- **E_p = 2 GeV**. No K and π multiplicity very low. Mitigated by a very LARGE intensity.
- Must **monitor muons**. They are not as forward as for ENUBET due to lower boost → cyl. geom. still OK.
- Design based on (PICOSEC) MicroMegas
- The spill structure (2.86 ms) makes **pileup** more delicate than for ENUBET (→ finer granularity 1cm^2)
- Use only a **fraction of the extracted protons**
- → Constrain on the flux **seems feasible**
- with a **sufficient statistics of neutrinos**
- End-to-end studies as for ENUBET being carried on



A. Branca link

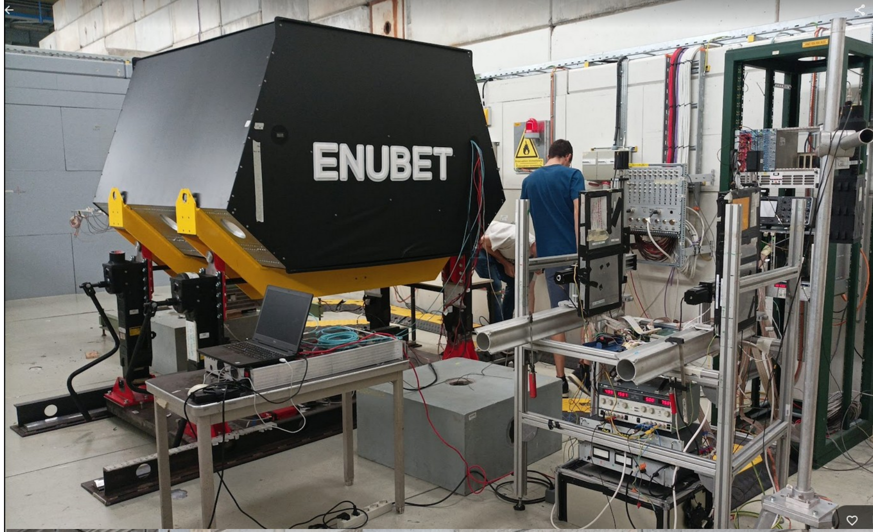


	ENUBET@CERN	MNB@ESS	Notes
Proton driver	400 GeV/c	2 GeV	At ESS we exploit pion decays and muon decays in flight [no K]
Secondaries	8.5 GeV/c	About 1-2 GeV	
Proton extraction	2 s	2.86 ms	This is a key item WP6 has assessed in 2023
Decay in flight of muons	Negligible	It is the main source of ν_e at the ESS	

7

Conclusions

CERN Aug. 2024 →

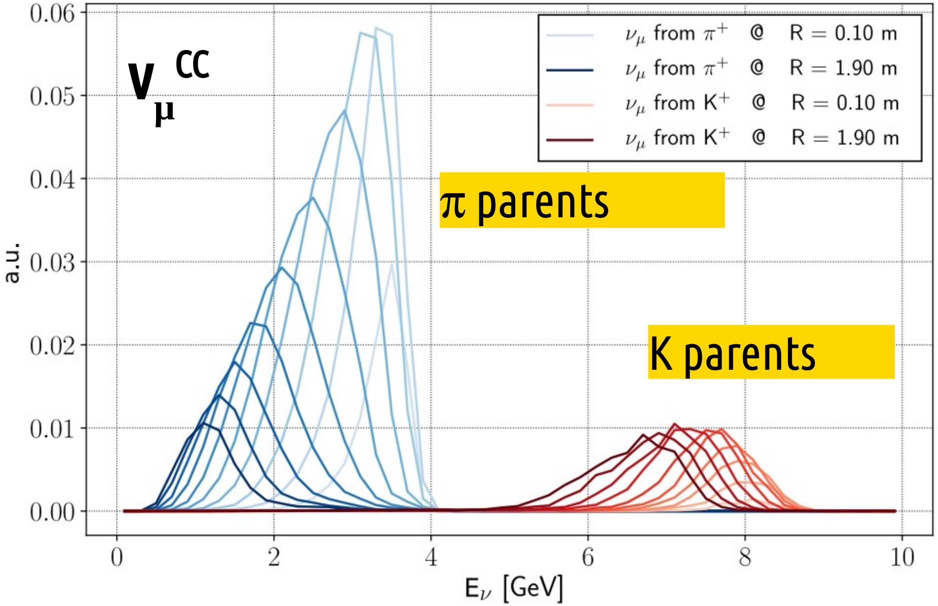


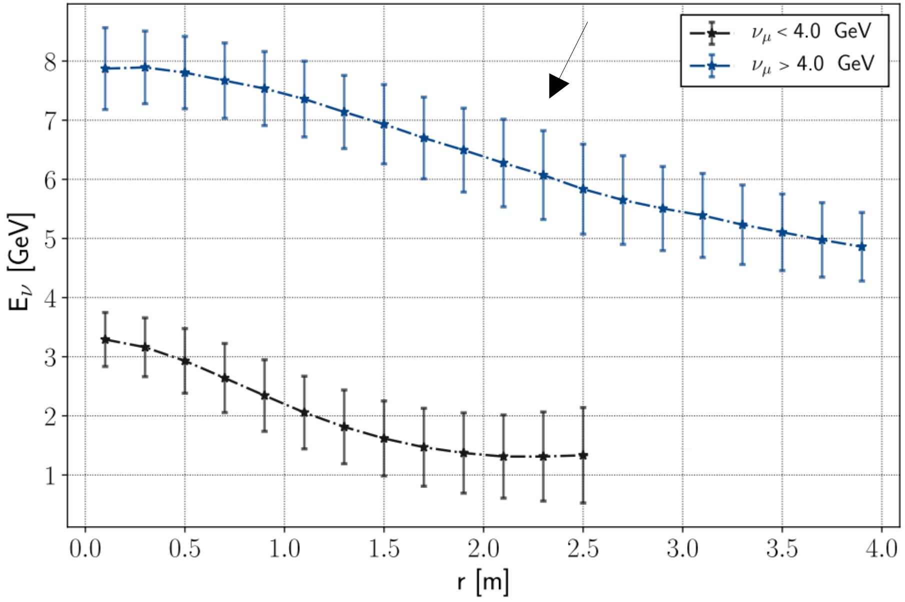
- Next two years will be crucial NP06/ENUBET
- Preparing for a dedicated **workshop Neutrinos@CERN** organized by PBC/Neutrino Platform at CERN in 23-24 January 2025
- and a **contribution to the ESPPU** process starting in spring 2025 ("European Strategy for Particle Physics Update").
- The importance of the inclusion of an **even larger community** does not need to be emphasized!
- Thanks!

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) !

Error bands visualize the rms of the energy distributions



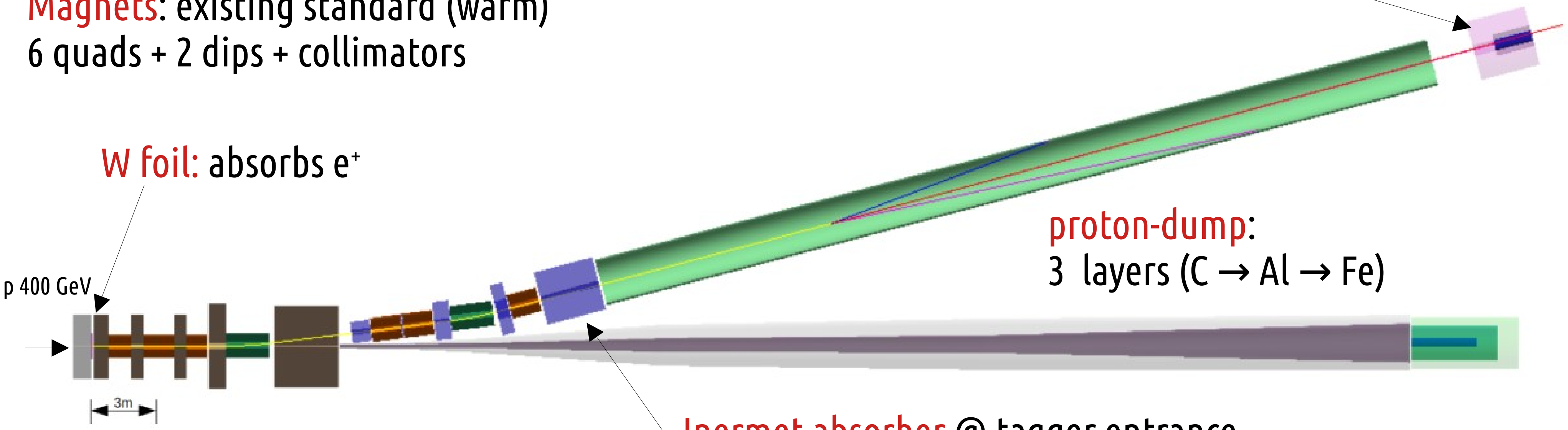


… a closer look

hadron-dump: ~
optimized to reduce back-scattering in the tunnel &
fraction of not-monitored flux

Magnets: existing standard (warm)
6 quads + 2 dips + collimators

W foil: absorbs e^+



proton-dump:
3 layers (C → Al → Fe)

Inermet absorber @ tagger entrance
with conical channel

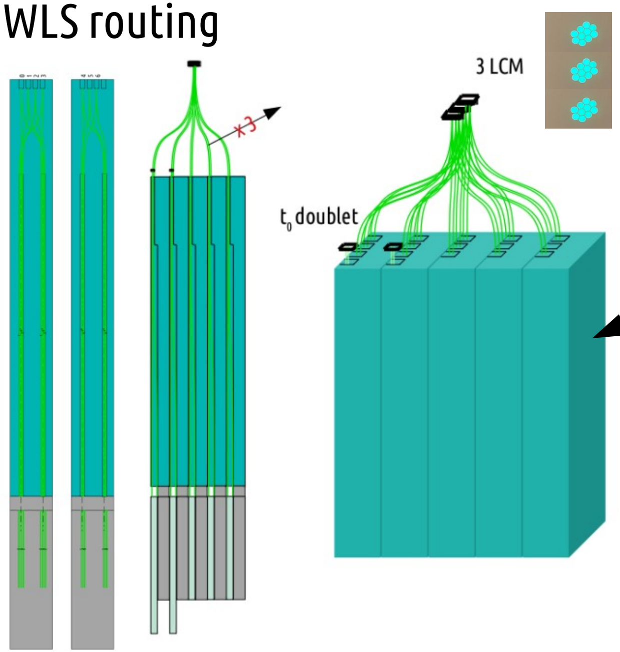
Target: graphite L = 70 cm, r = 3 cm

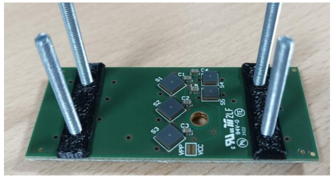
Simulation: optics optimization (TRANSPORT). Design: G4beamline.
Irradiation (FLUKA). Systematics (GEANT4, fully parametric, access to particle history).

The demonstrator

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

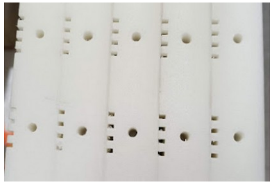
WLS routing





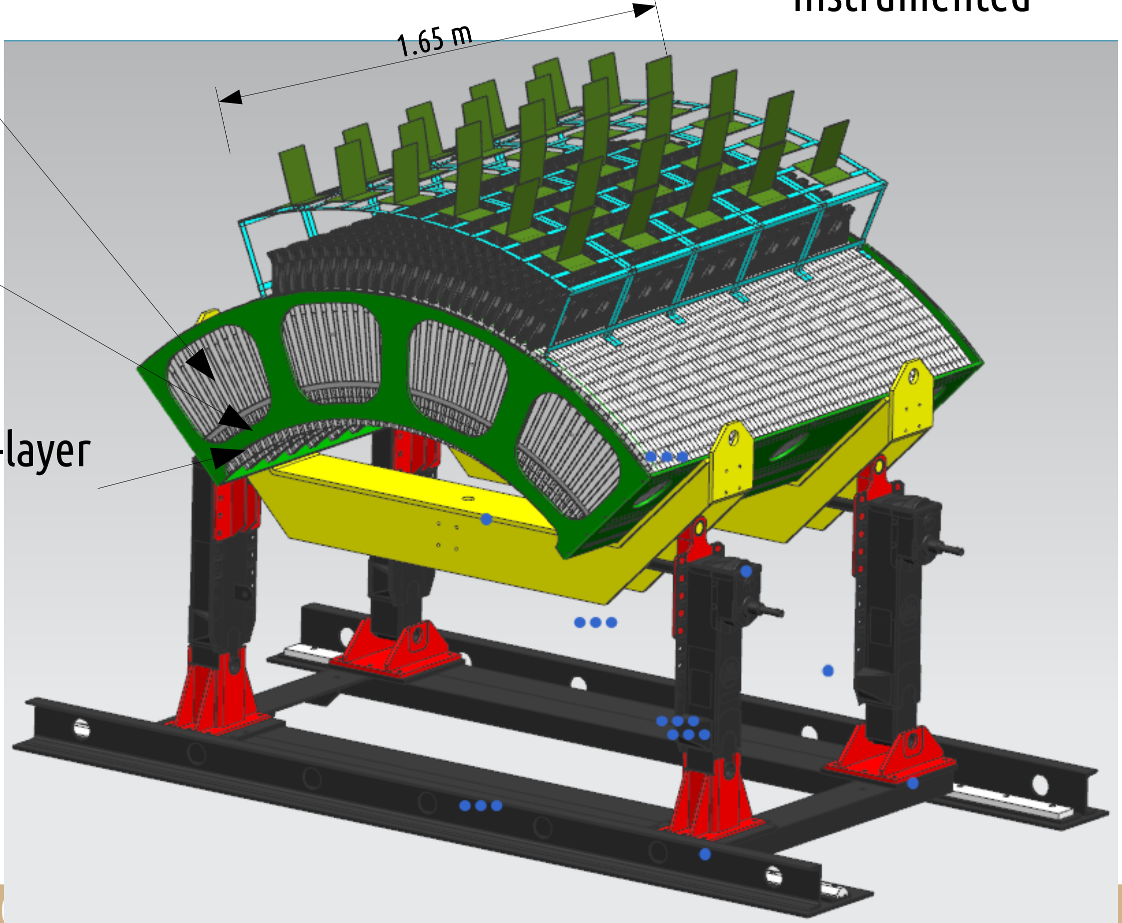
BPE 5%

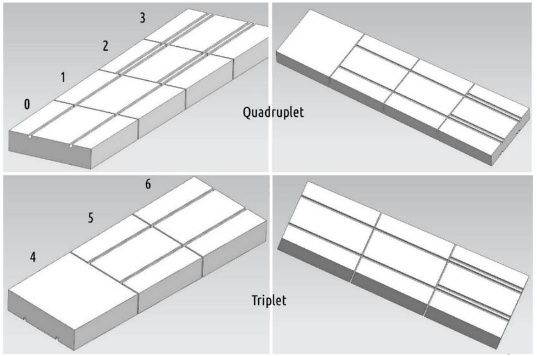
Sampling iron/scint calo

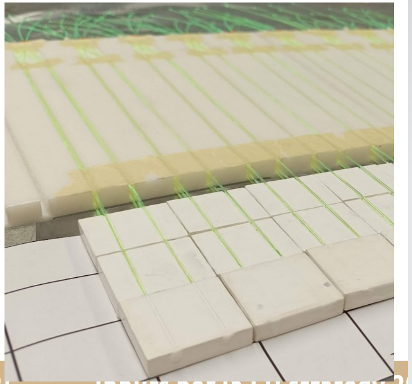


t_0-layer

90°, partially instrumented

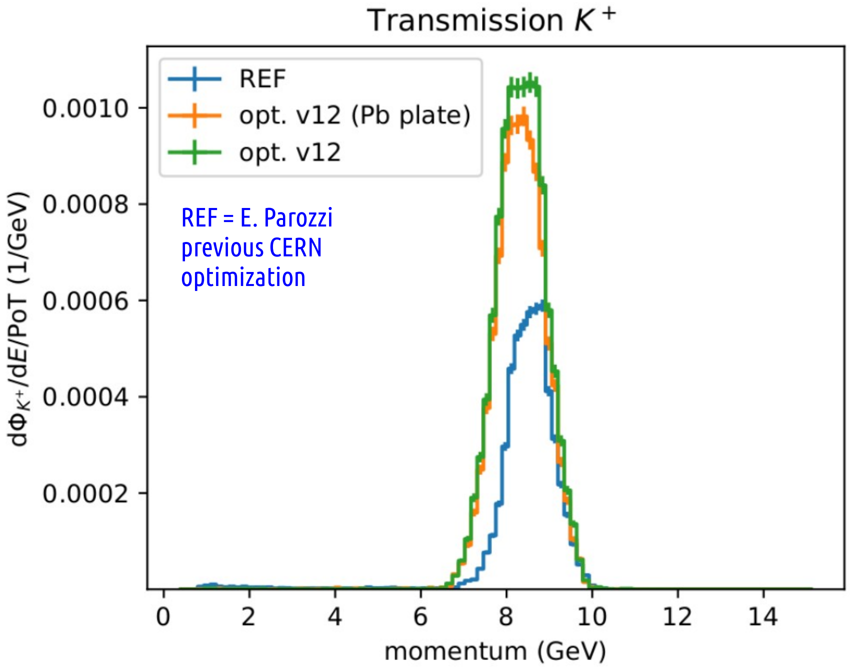


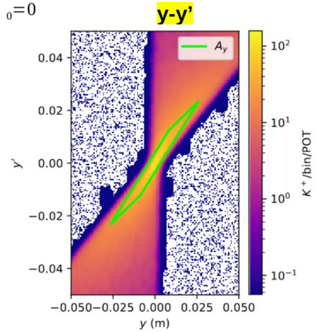


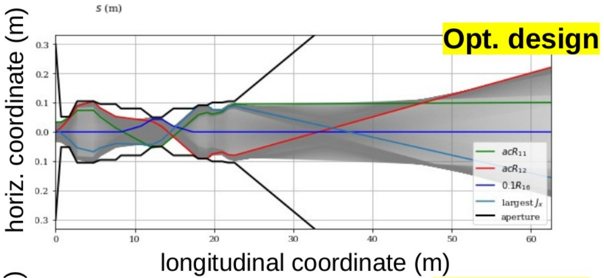


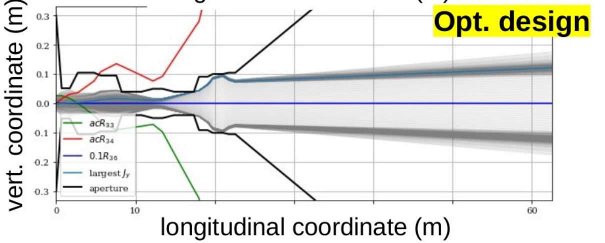
The PBC-SBN beamline optimization

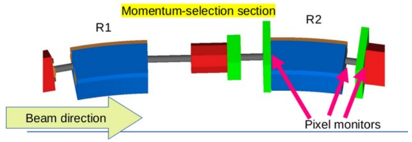
- link to the talk at the PBC annual meeting by M. Jebramcik 26/03/24
- Analyzed 16 targets, 7 drift spaces, 18 quad. parameters (6 magnets with different length, aperture, gradient) → **26 free parameters**
- **Multiple (3) objectives**: K+ & π+ transmission as possible and the beam size has to be as small as possible in the momentum selection and the decay tunnel
- 1) Linear optimization with **multi-objective genetic algorithm (MOGA)**
- 2) Verification with a start-to-end BDSIM simulation
- Optimized beamline **7 m shorter** (from 30 to 23 m). Uses a CNGS-like target
- 1.2 cm lead foil in the middle of momentum selection to suppress e^+
- **1.41×10^{-3} K^+/pot → 3.5x improvement. Huge gain! → tuning of backgrounds with the full chain is in progress (→ iteration)**

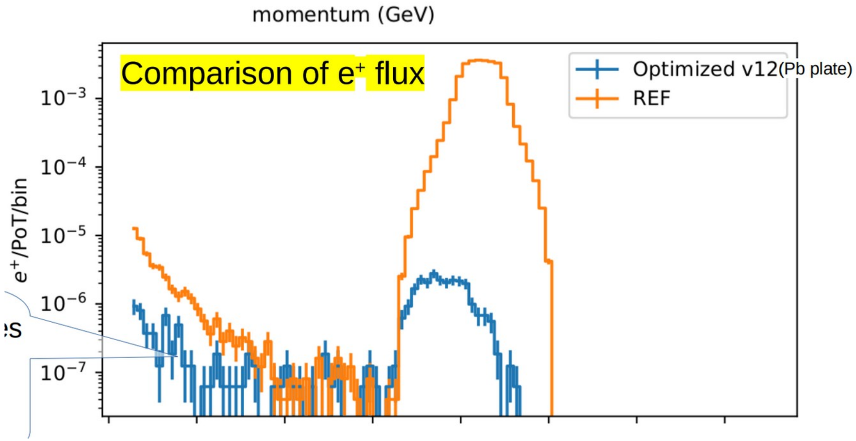








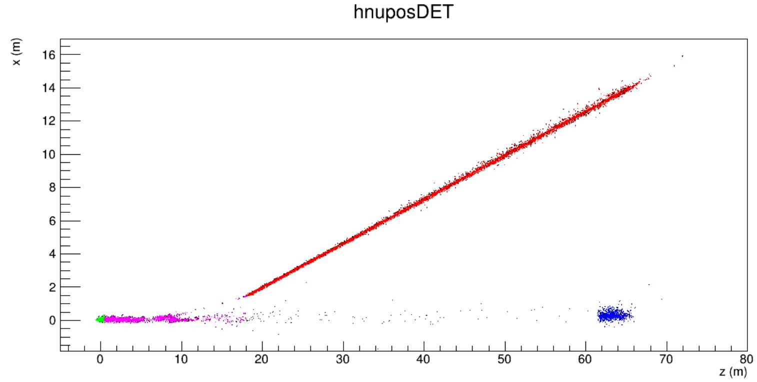


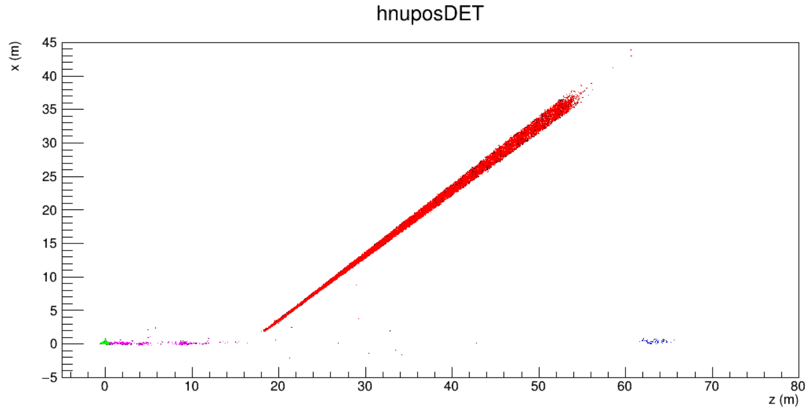


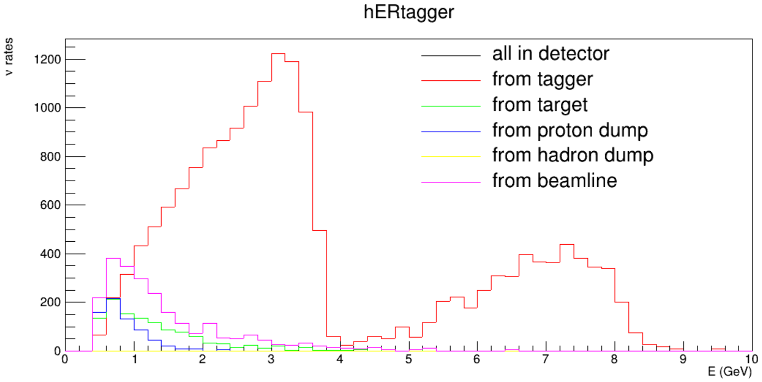
ν_μ^{CC} spectra at detector

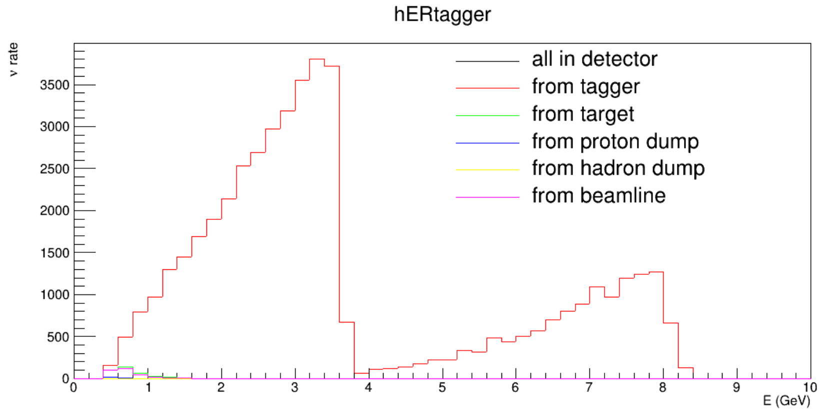
tlr6v6

With a SC second dipole





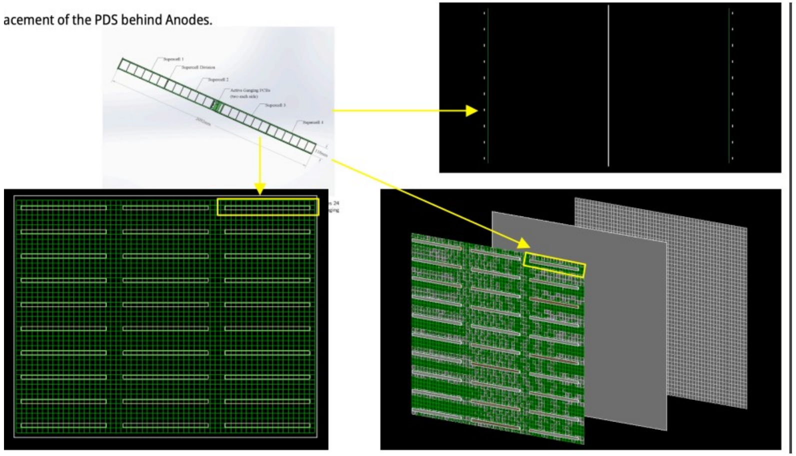


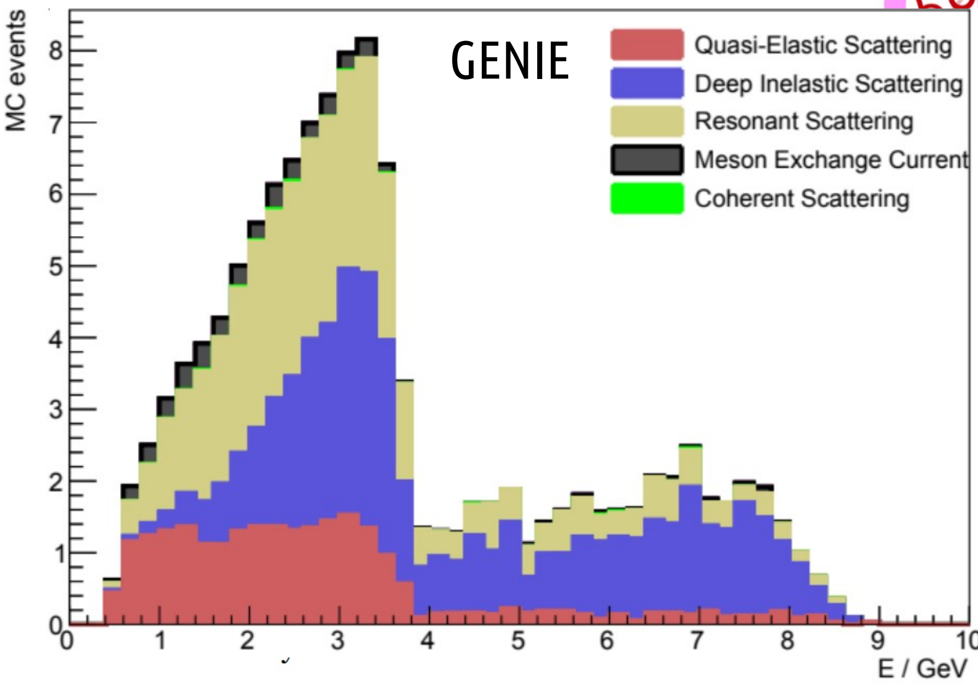


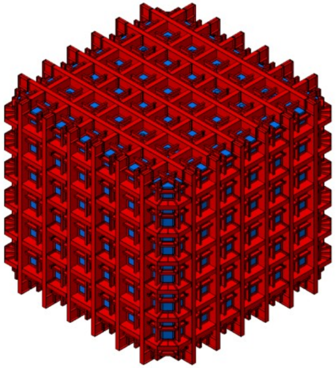
ν detector studies (ENUDET)

This R&D is being pursued by ENUBET together with the DUNE-SoLAR coll. and is instrumental in **exploiting liquid Argon in a tagged neutrino beam**. A dedicated task force is addressing:

- The **achievable σ_t of ProtoDUNE** overhauled for DUNE Phase II. It will be equipped with an **enhanced photon detection system**. The corresponding light yield will improve time resolution for GeV neutrinos below 1 ns.
- **Simulation of neutrino interactions (GENIE)** and **reconstruction effects** (i.e. role of **cosmic rays** background) to **assess the physics reach on the cross section for specific channels**

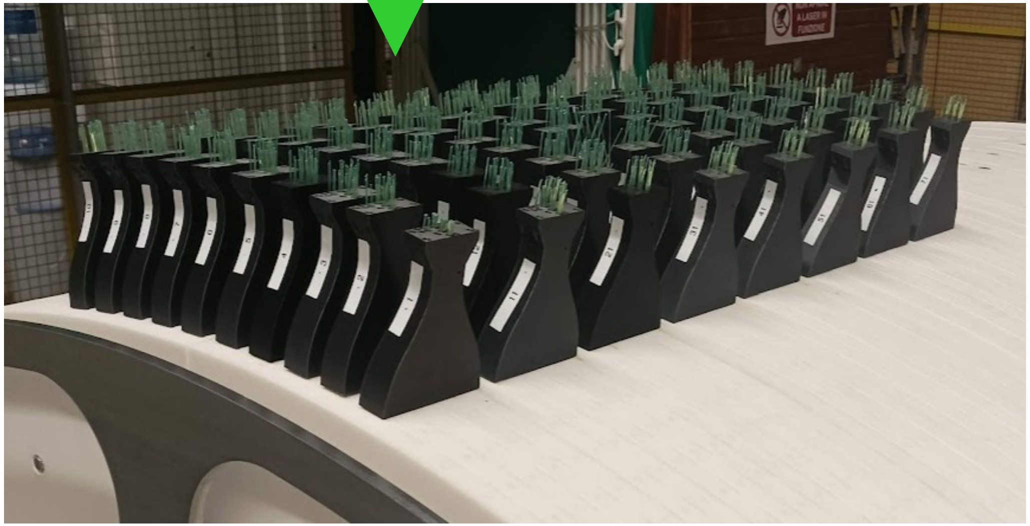


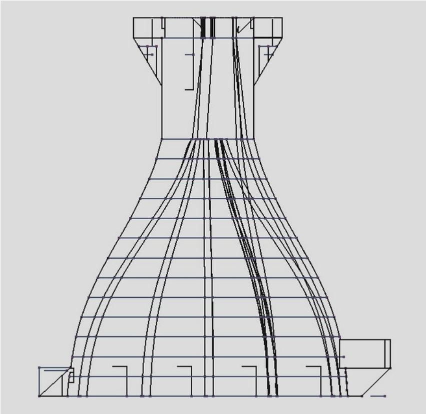


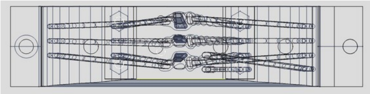


Fiber bundling with “concentrators”

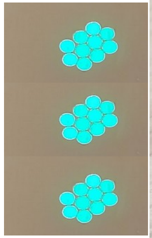
bundling of the WLS fibers with 3D printed “fiber concentrators”+ in situ polishing

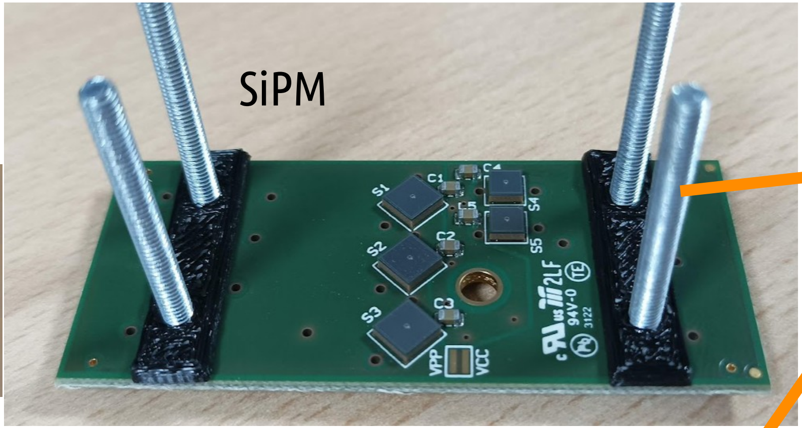


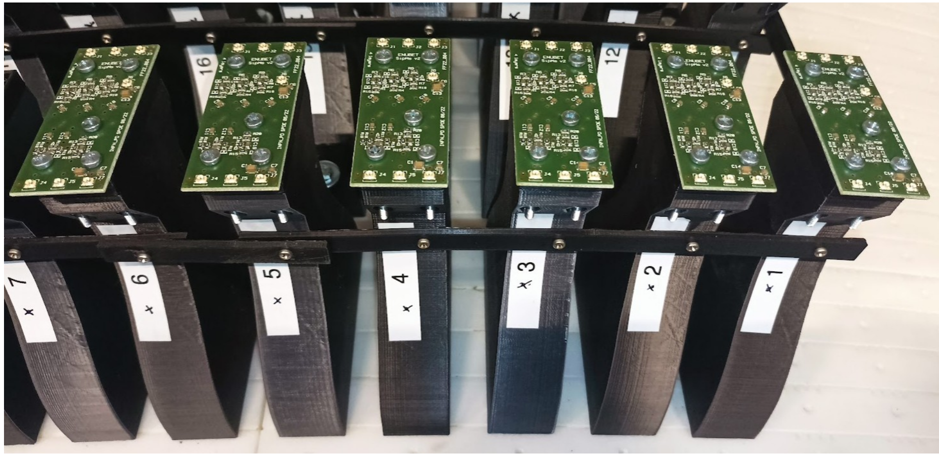


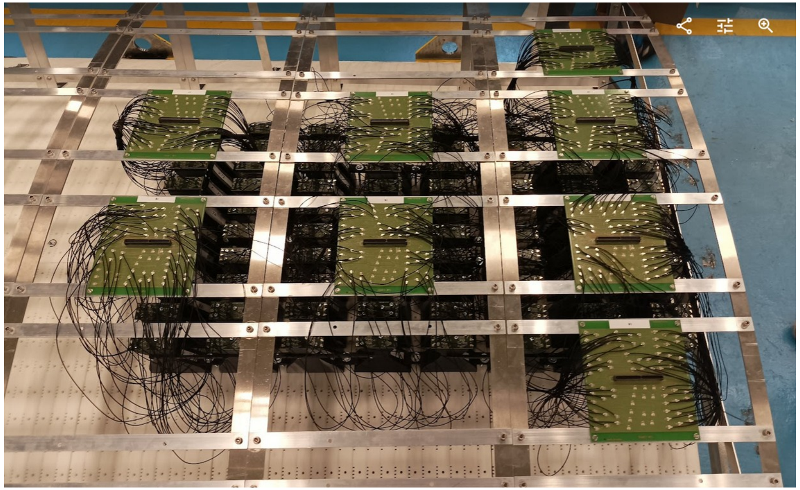


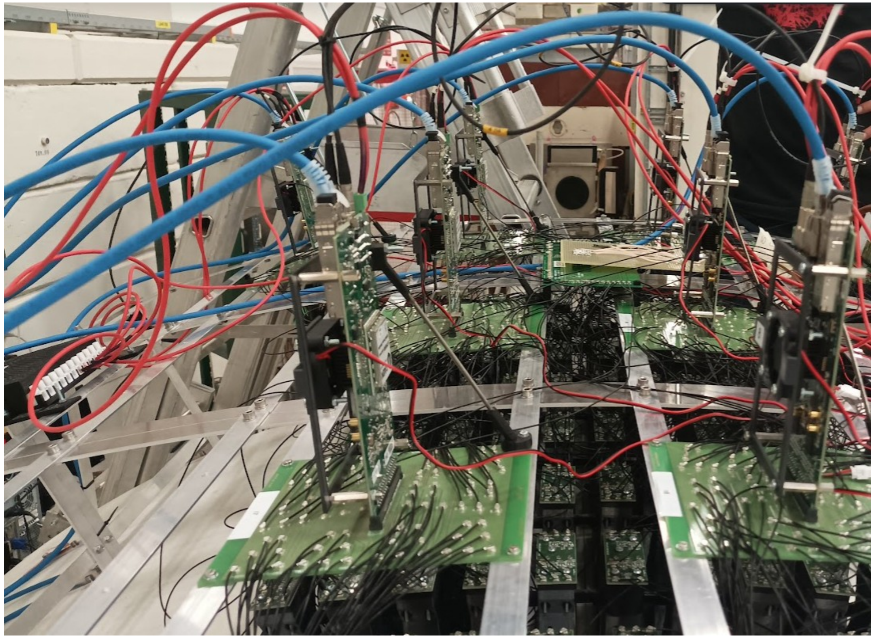
Readout scheme





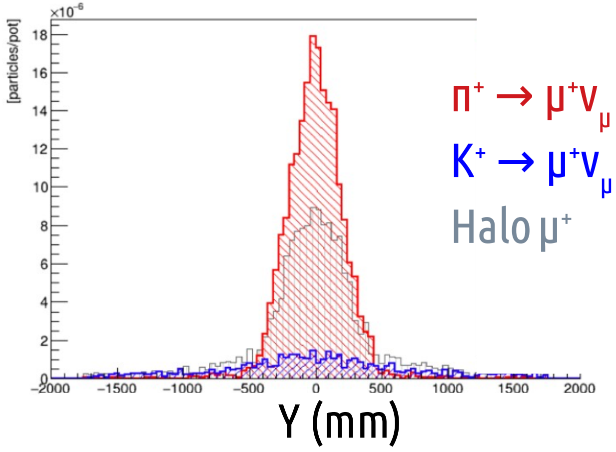


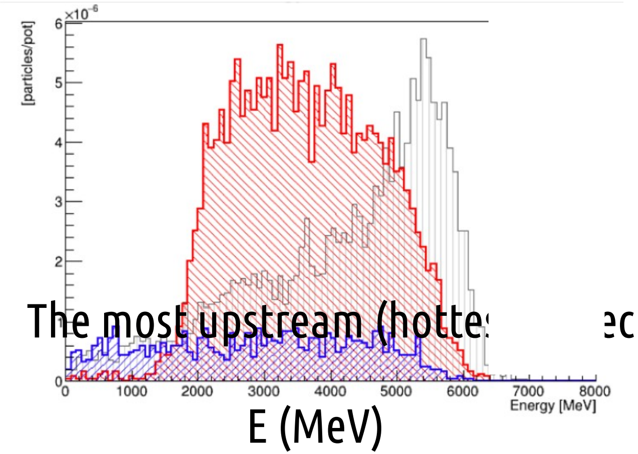


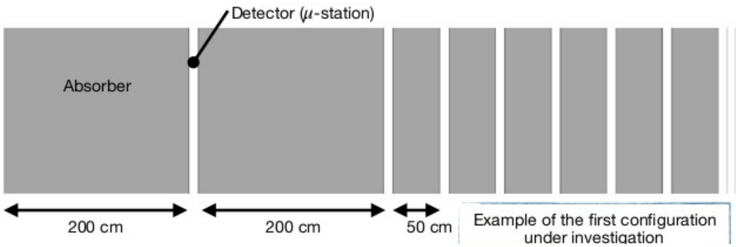


Forward region muons reconstruction

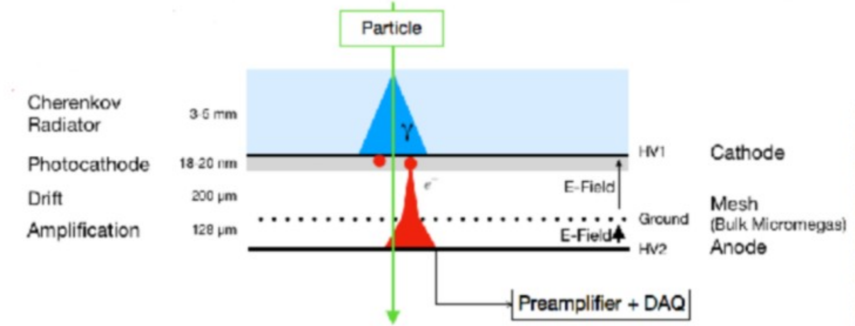
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.

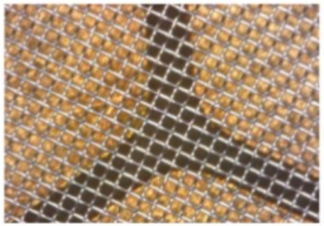






The most upstream (hottes ector needs to cope with a muon rate of ~ 2 MH





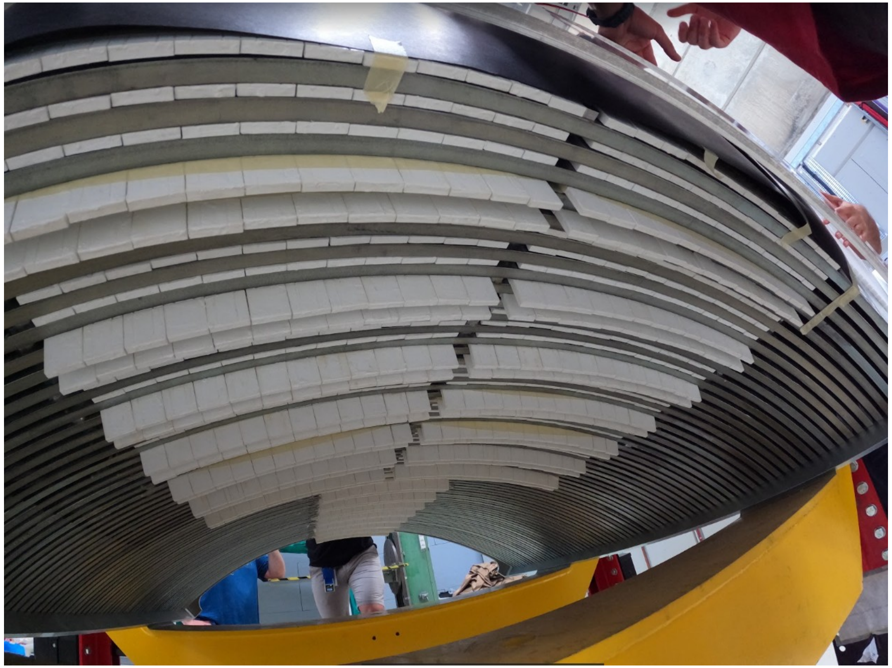
Micromegas detectors employing Cherenkov radiators + thin drift gap ?
Bonus: cutting-edge timing (O(10) ps).

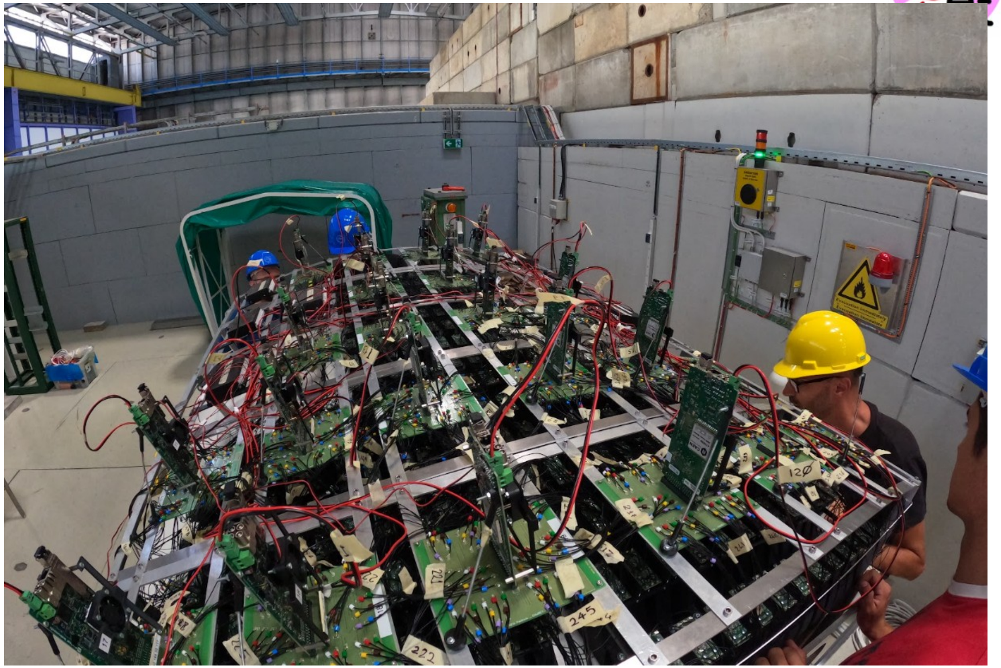
→ PIMENT project ! →

ENUBET: demonstrator

Assembly timelapse

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

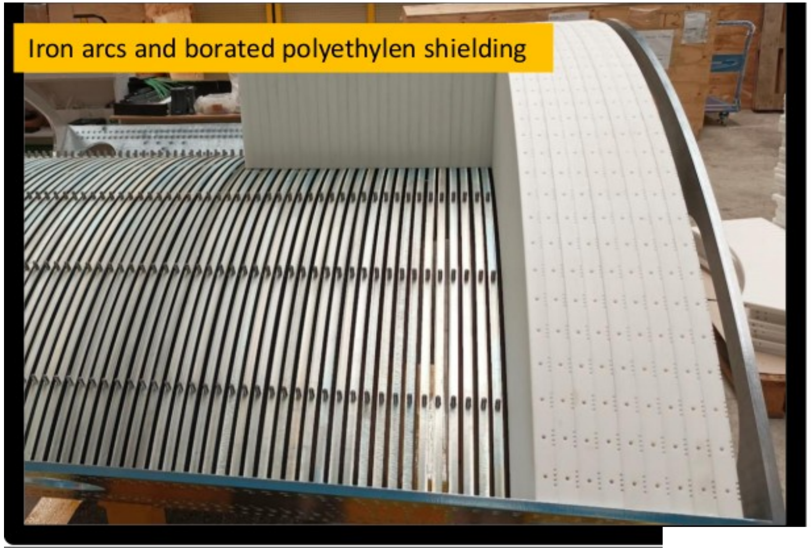


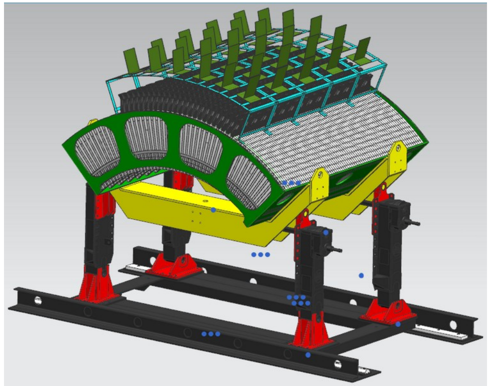


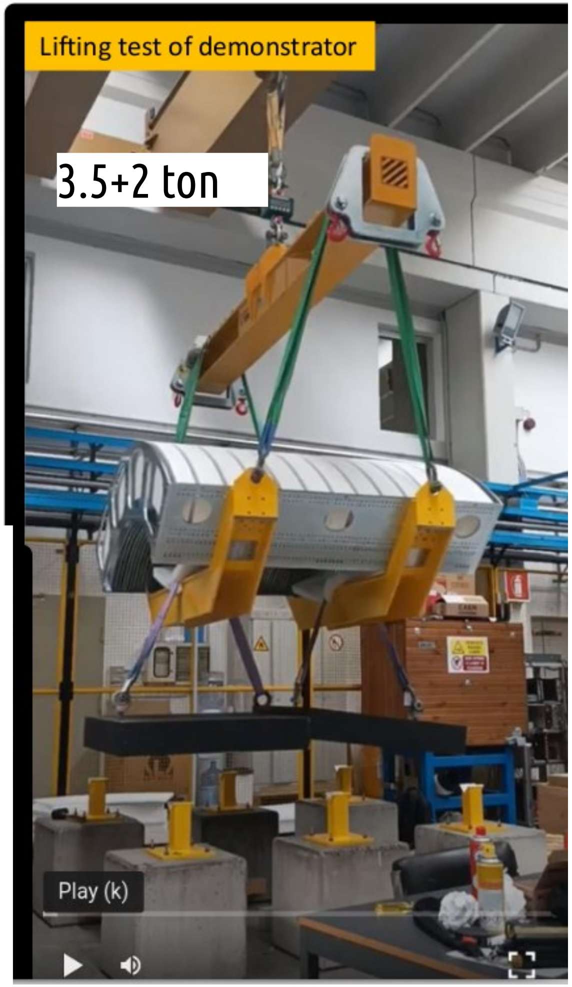
The ENUBET demonstrator in numbers

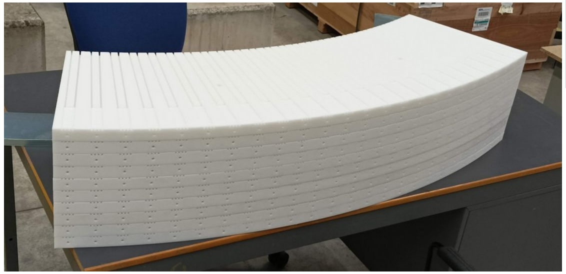
- Scintillator tiles: **1360**
- WLS: ~ **1.5 km**
- Channels (SiPM): **400**
  - Hamamatsu **50 um** cell
    - **240** SiPM **4x4** mm^2 (calo)
    - **160** SiPM **3x3** mm^2 (t_0)
- Fiber concentrators, FE boards: **80**
- Interface boards (hirose conn.): **8**
- Readout 64 ch boards (CAEN A5202):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

Demonstrator construction at LNL-INFN labs



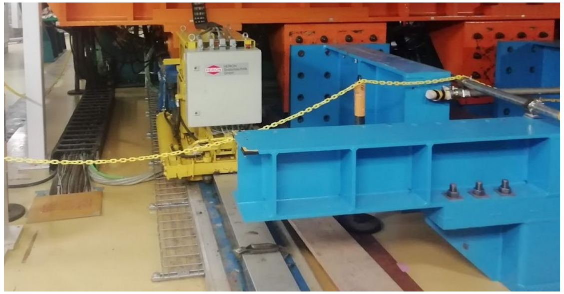




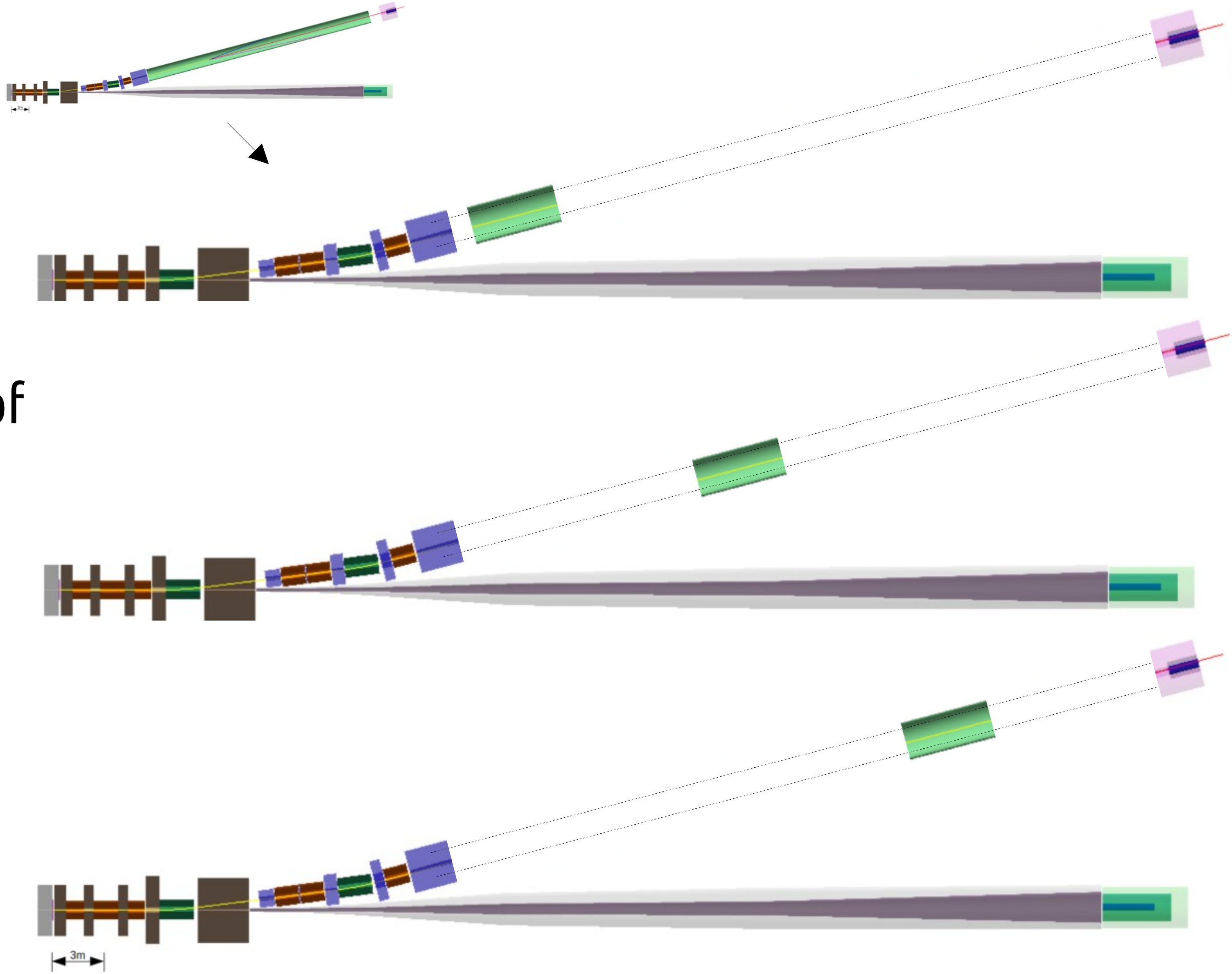


An option?

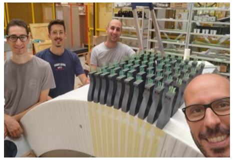
Study the systematics introduced but a partial “instantaneous” coverage of the full decay region



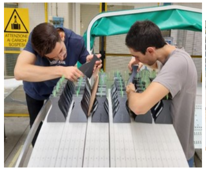
UA1/NOMAD/T2K magnet rail system

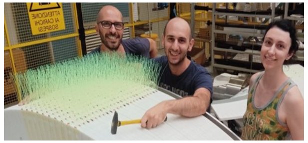


Group pictures

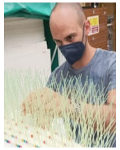


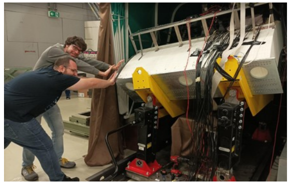








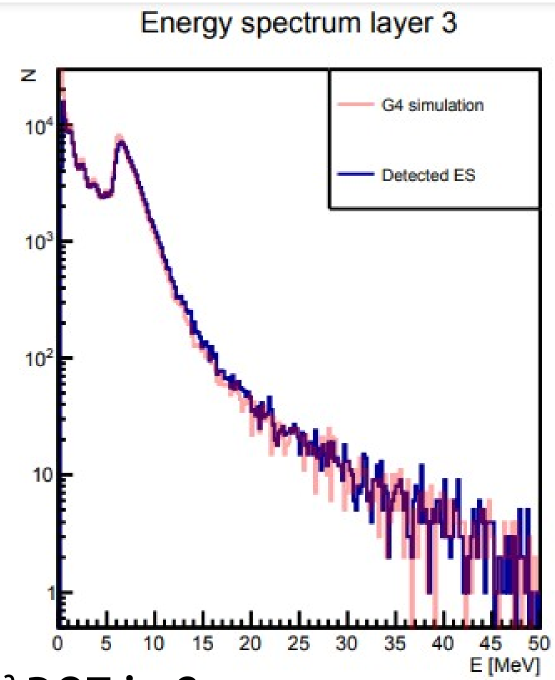




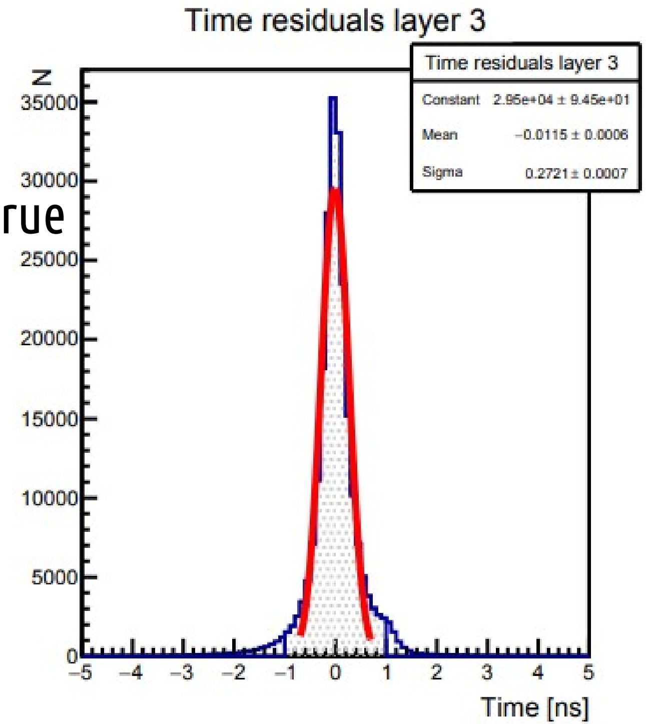
Event pile-up analysis

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.



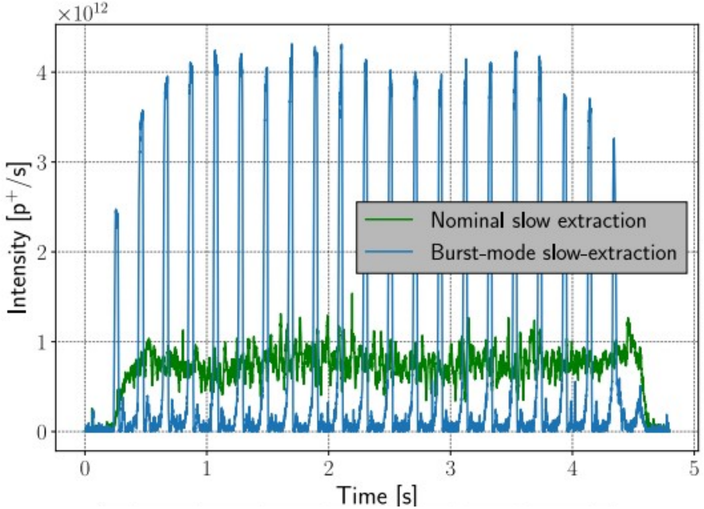
With 4.5 x 10^{13} POT in 2s

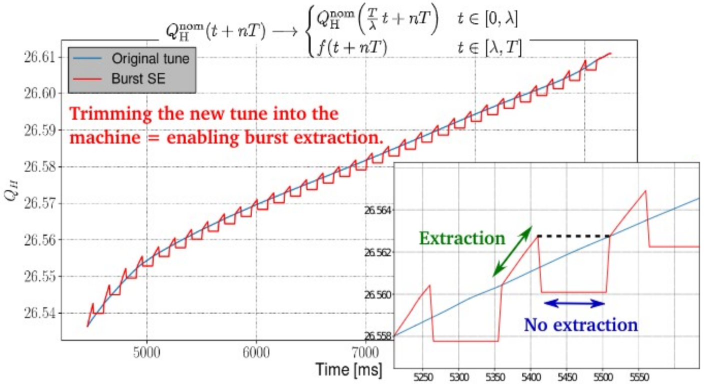
- 1.1 MHz rate in the hottest channels
- Peak finding efficiency = 97.4 %

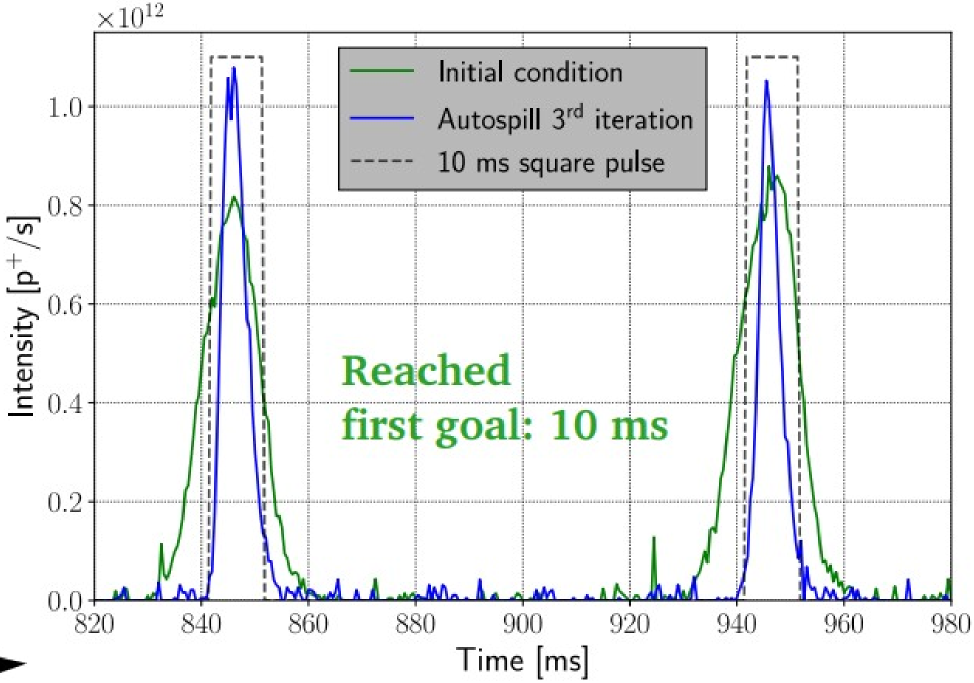
Proton extraction R&D for horn focusing

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

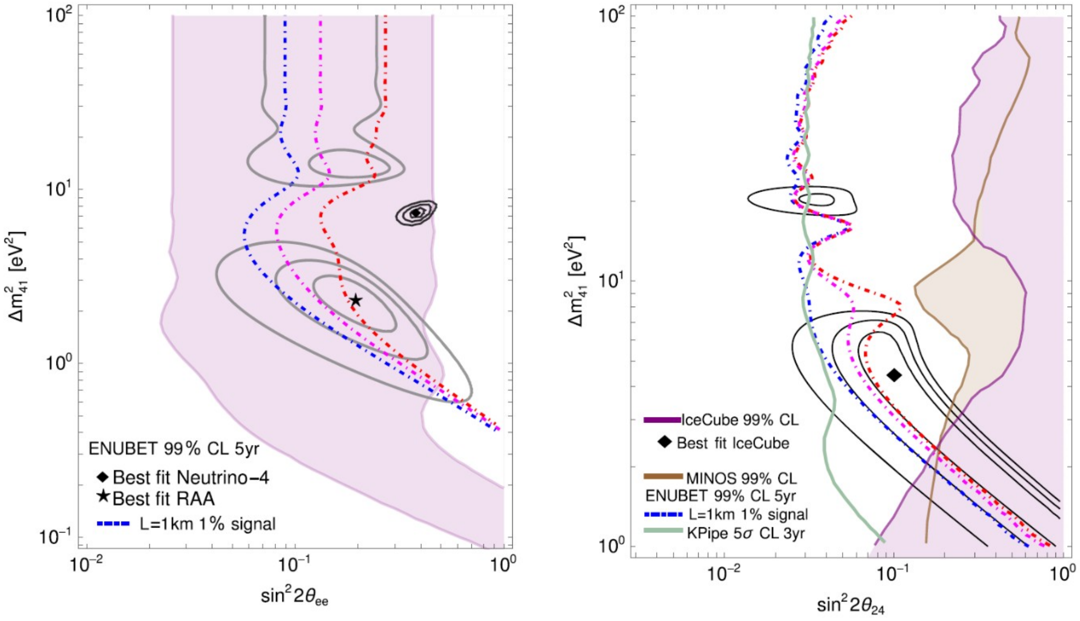






PhD thesis of M. Pari (UniPD + CERN doctoral).
Defended 23/2/21.

BSM



Sterile neutrinos: some results already available

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

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

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]

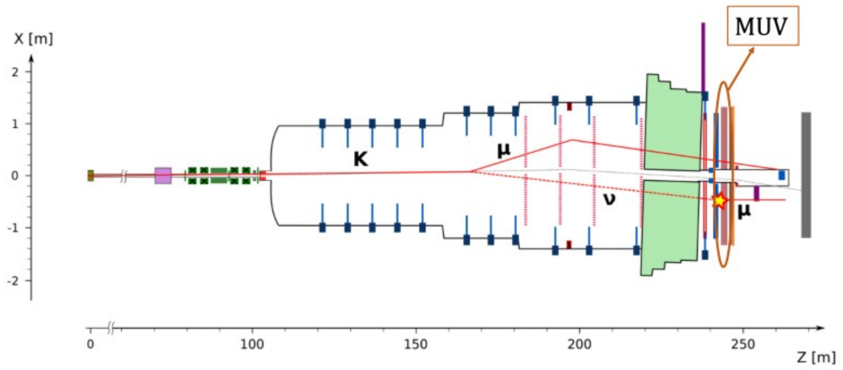
For the first time at nufact2023

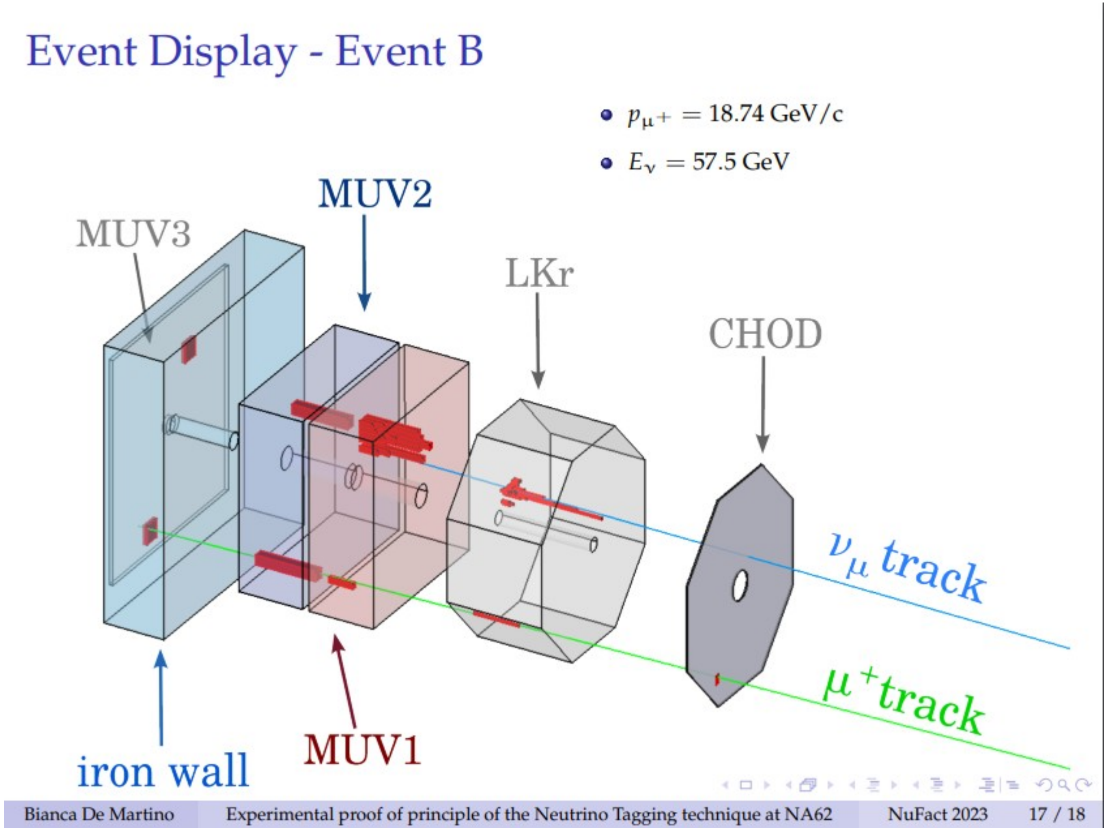
https://indico.cern.ch/event/1216905/contributions/5448754/attachments/2702123/4690877/NuFACT_NuTagging_DeMartino.pdf

Bianca De Martino (NA62)

S/B=5.5, 2 candidates

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





Lepton reconstruction

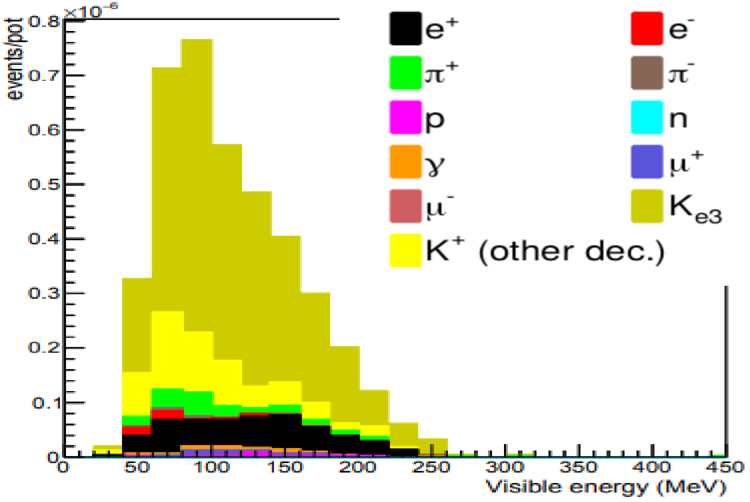
F. Pupilli et al., PoS NuFact2021 (2022) 025
https://arxiv.org/pdf/2308.09402.pdf

GEANT4 simulation. Event building: clustering of cells in space and time (accounting for **pile-up**) → PID with a Multilayer Perceptron

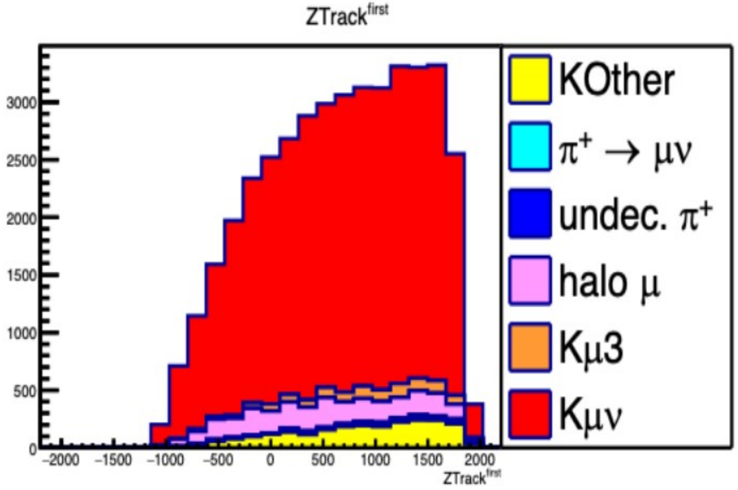
Half of efficiency loss is geometrical

K_{e3} eff. ~22% S/N ~2

$K_{\mu2}$ eff. 34% S/N ~ 6
$K_{\mu3}$ eff. 21% ($K_{\mu3}$) S/N ~ 6



e⁺ candidate visible energy (MeV)



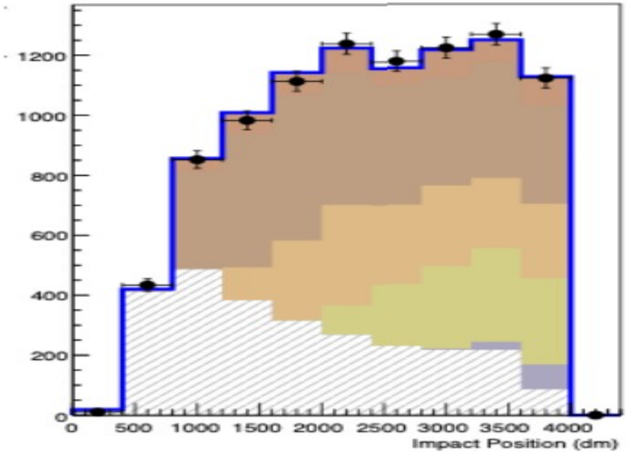
μ⁺ candidate z coord (cm)

Constraint from lepton rates → flux 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, ...)

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

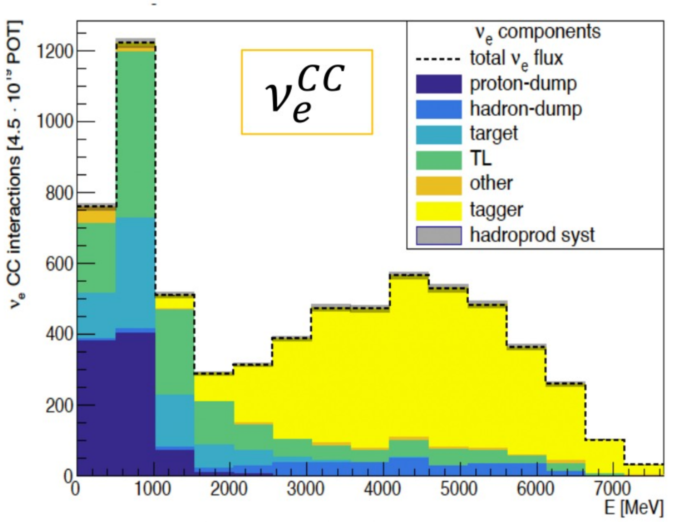
→ Extended Maximum Likelihood fit

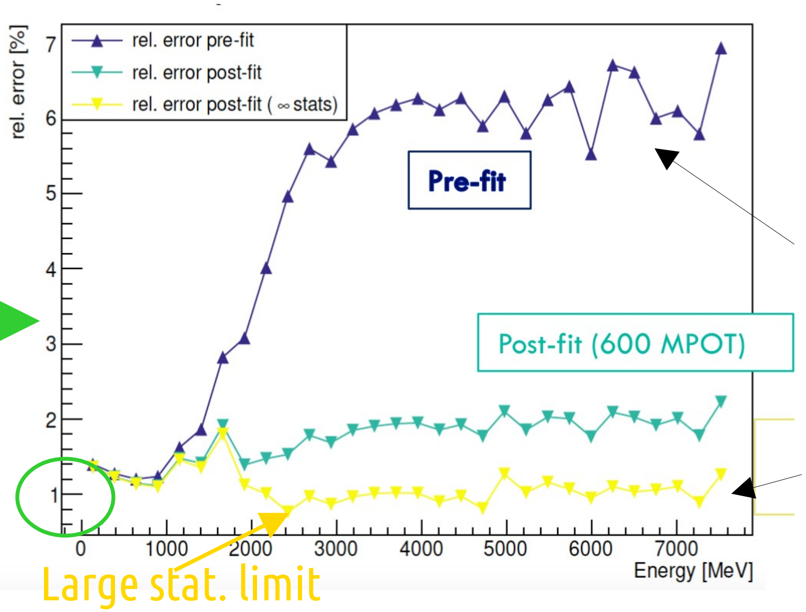


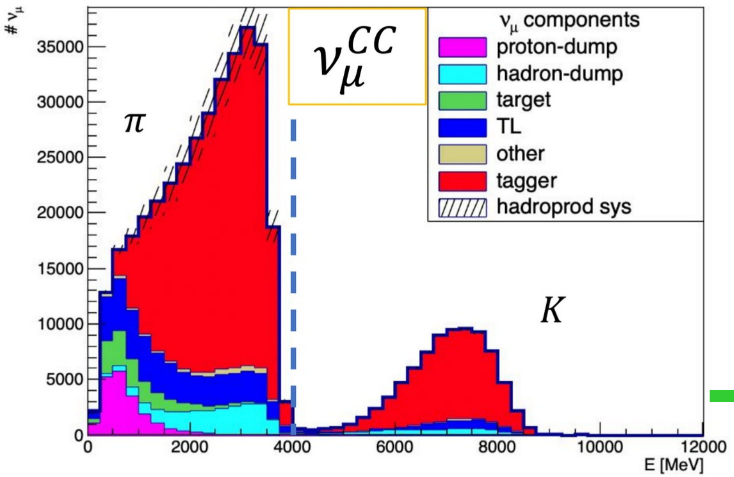
Each histogram component corresponds to a bin in E_ν

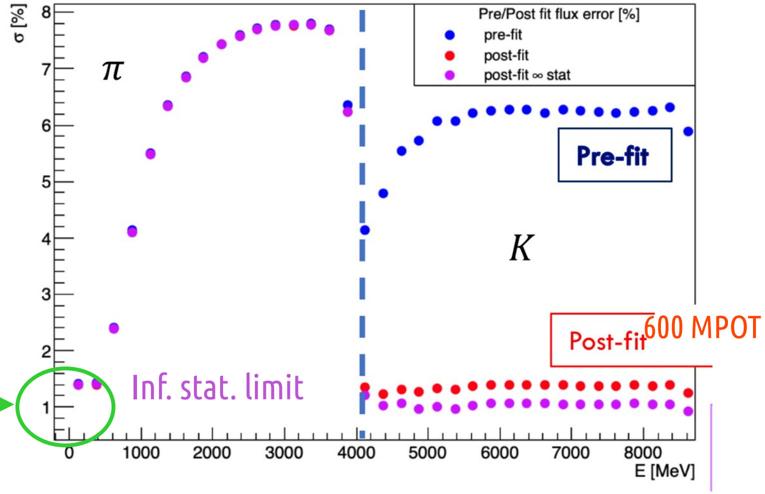
Use a parametric model fitted to hadro-production data from **NA56/SPY experiment**:
- compute variations (“envelopes”) using multi-universe method (“toy exp”) for the lepton observables and the flux of neutrinos
- evaluate “post-fit” variance of the expected flux

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%** !

Full simulation data (beamline, detector, reconstruction)

Works for both ν_e and ν_μ

Finalizing the analysis to include detector effects, publication in preparation

- **NP06/ENUBET: a monitored beam at 400 GeV (meas. decay products)**

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  - **Beamline design and performance**

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- **MNB@ESS**

Tagger particle budget at true level