# Status and plans of ENUBET (NP06)

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

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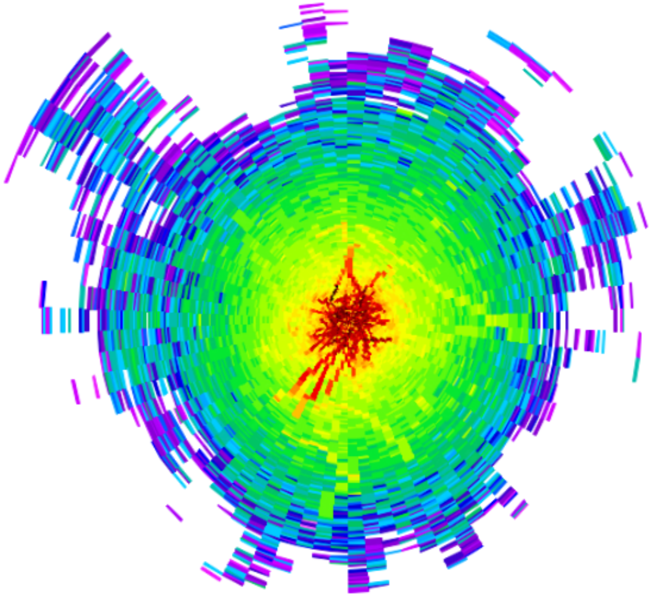
Padova Univ. and INFN

On behalf of the ENUBET coll.



145th meeting of the CERN-SPSC
12 April 2022

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

# The concept of monitored neutrino beams

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

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


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

# ENUBET / NP06

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

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

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

ENUBET: 60 physicists, 12 institutions

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

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

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

**pillars**

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

# The 2022 SPSC report

https://cds.cern.ch/record/2805716/files/SPSC-SR-310.pdf

NP06/ENUBET annual report 2022 for the SPSC

The ENUBET Collaboration

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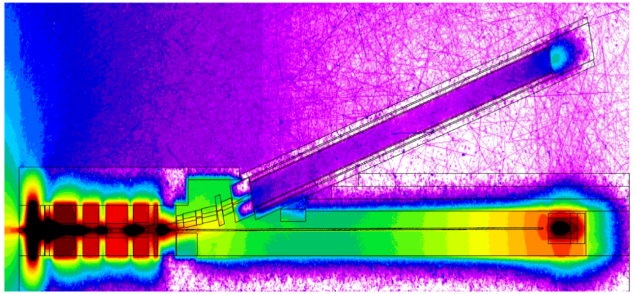
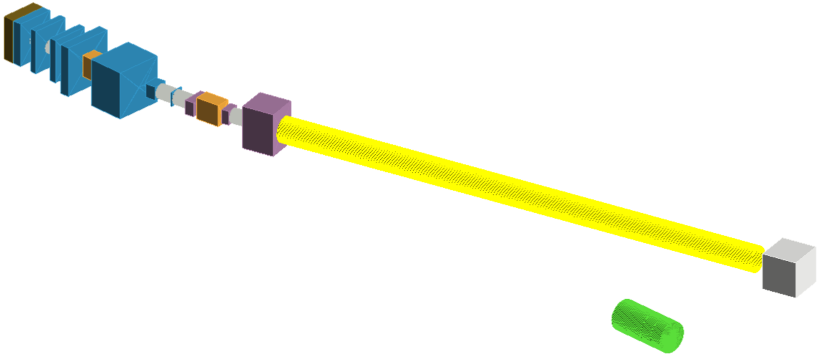
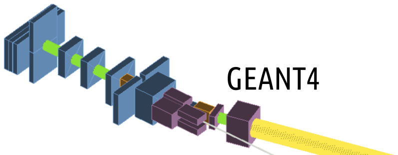
Last year has been a key period with substantial progress on the main open items:

- The **design of the beamline**
- The analysis of the reduction of **systematic errors** on the flux
- The construction of the **demonstrator** of the instrumented decay region
- Synergies with other projects



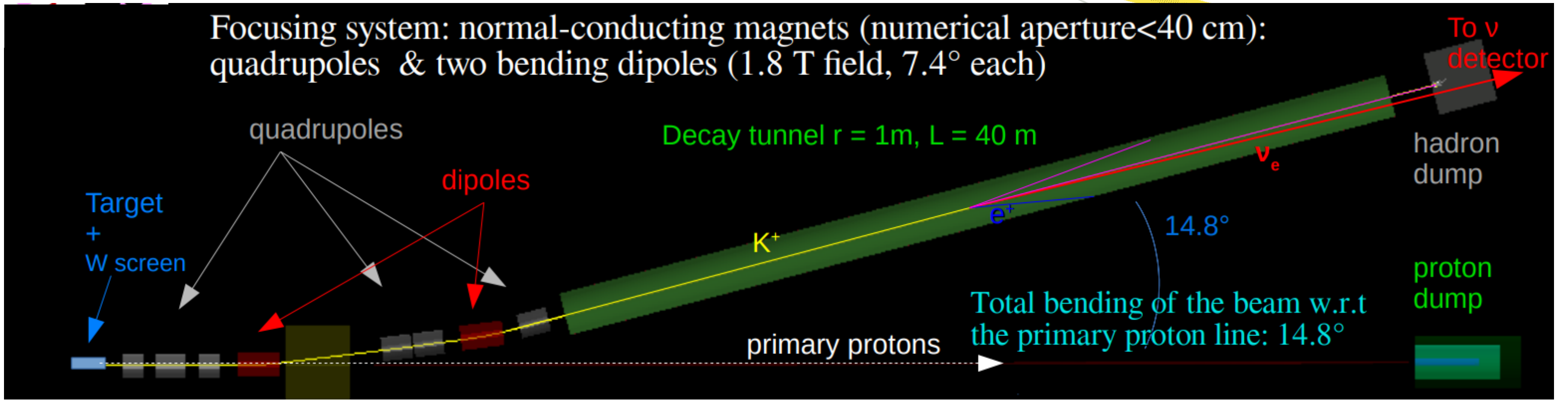


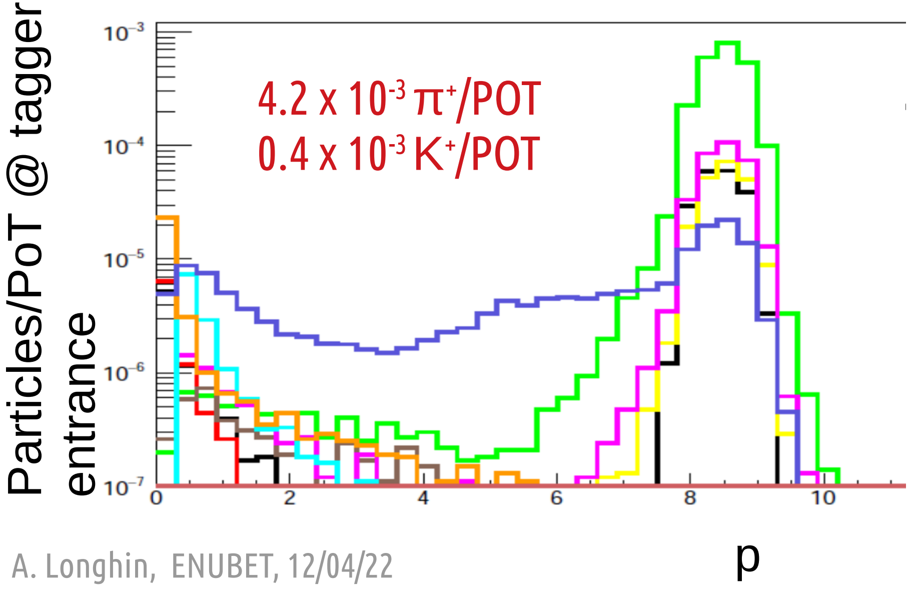
# The ENUBET hadron beamline

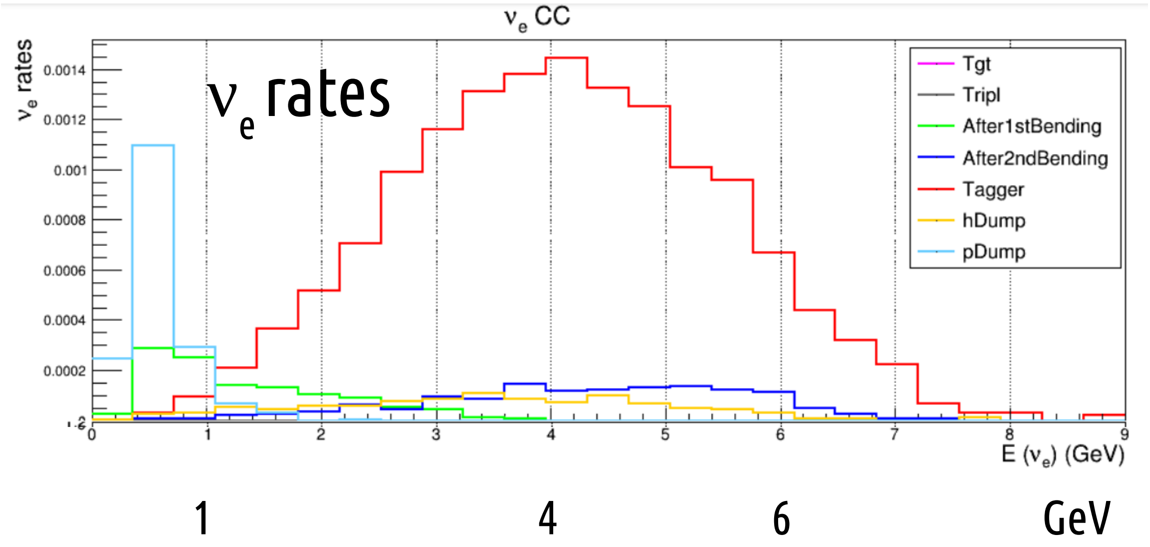



- Focuses 8.5 ± 5% GeV/c

$4.5\times10^{19}$ POT/y →
$10^4$ $\nu_e^{CC}$ on 500 t @ 100m
from target in ~ 2 years

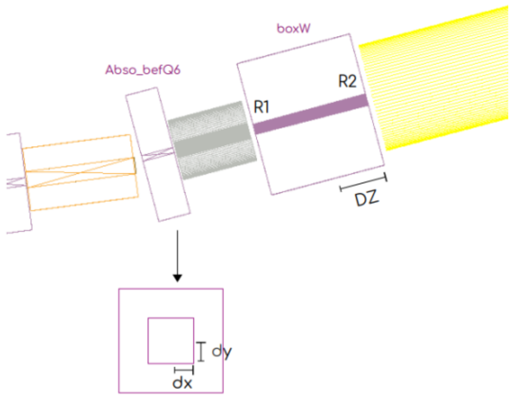


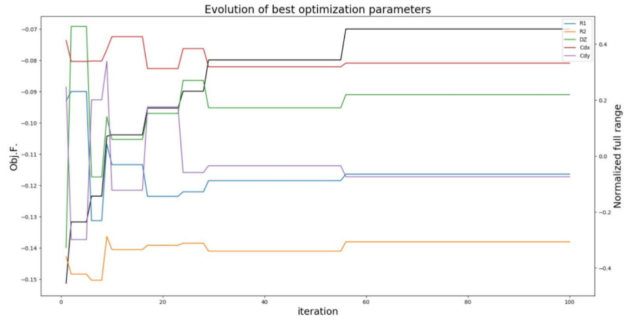



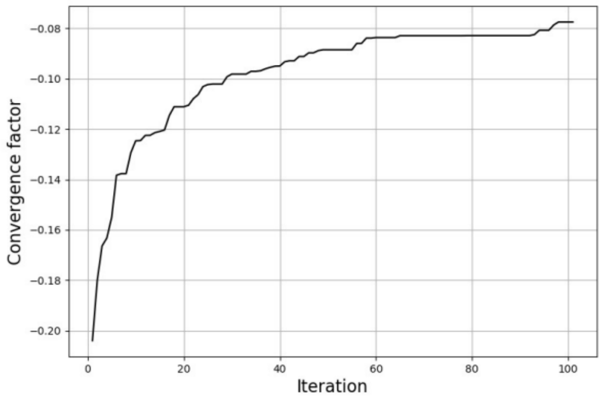



# Genetic beamline optimizer with G4

- A very **difficult optimization in a large parameter space** (geometry of magnets, collimators, fields …).
- **Crucial importance of beam backgrounds** and substantial **room for improvement** → a very **ambitious optimization campaign is worth** doing!
- GEANT4 simulation has been setup with a fully **parametric geometry** easily accessible with control cards (.mac)
- **Genetic opt. algorithm** developed for the horn ported to the full beamline.
- Figure of merit (FOM)
  - n. of background $e^+/\pi^+$ hitting tagger with respect to incoming $K^+$
- **Pilot run with 5 parameters**:
  - CC-IN2P3 cluster: 100 beamlines for each + 100 iterations (5-8 hours each)
- **Convergence** achievable in a reasonable amount of time.
- Led to a new configuration that improved the FOM of the initial configuration →

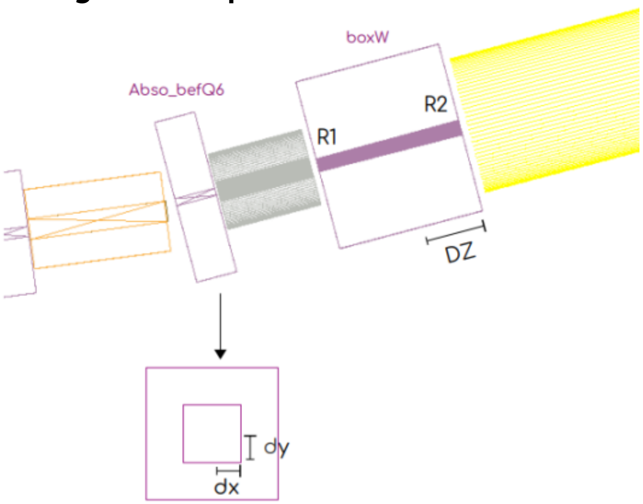


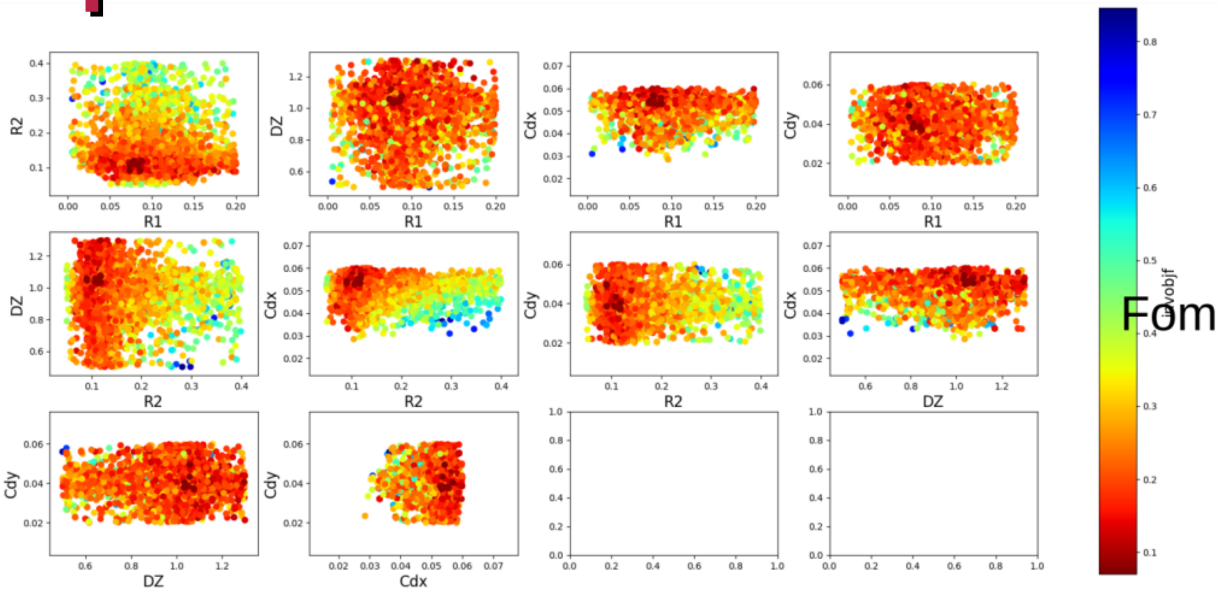



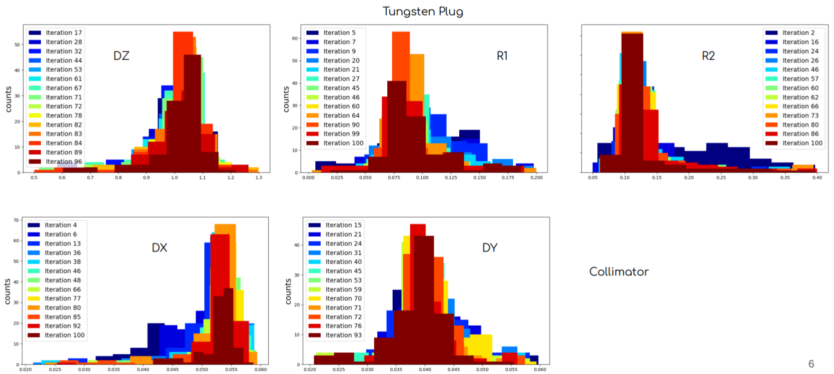



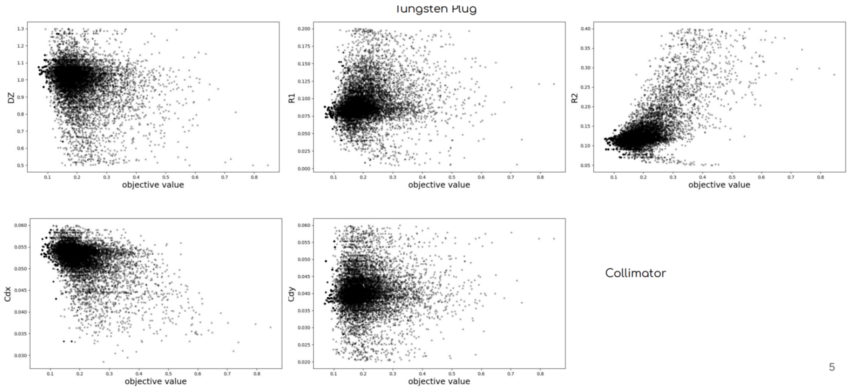
# Genetic beamline optimizer with G4

Diagnostics plots



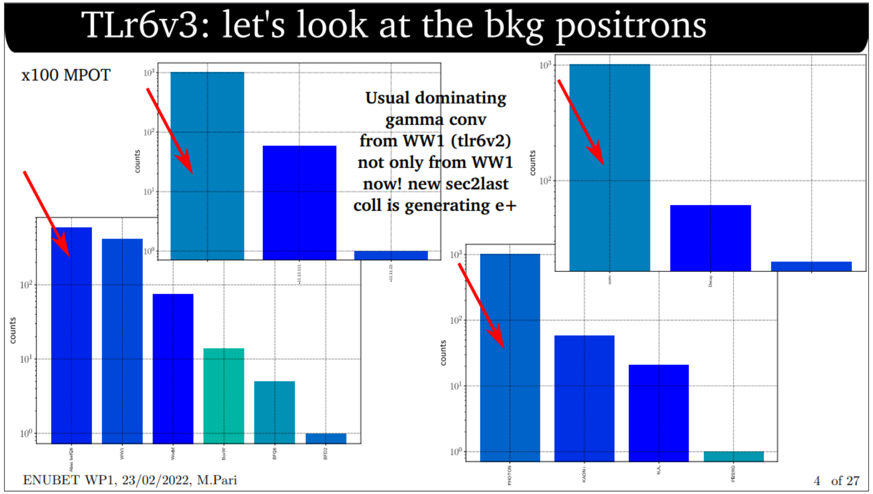



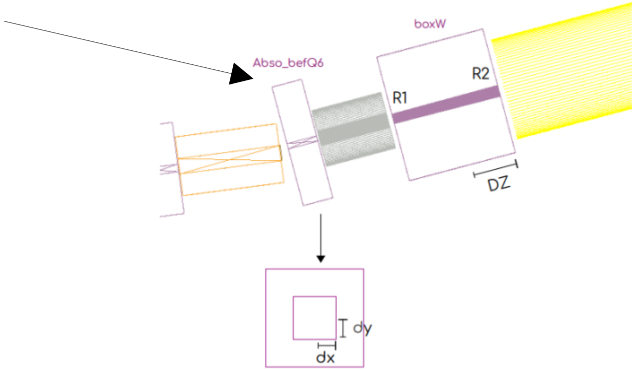



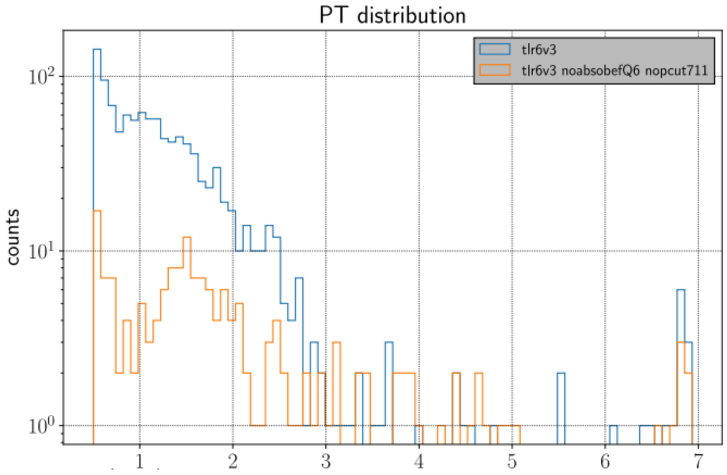
# Beamline optimization: lesson learnt

The **“integral” FOM might be not optimal**. The selected configuration was very promising in terms of background reduction but the **shapes** (in energy and impact point along the tagger) of signal and background were similar → less discriminating power for the multivariate analysis.

The **originating volume** of each component can be tracked → most of background **e⁺** was coming from a specific collimator whose range of variation was too small. **Removing the collimator reduced this background by a x 6 (!)**.



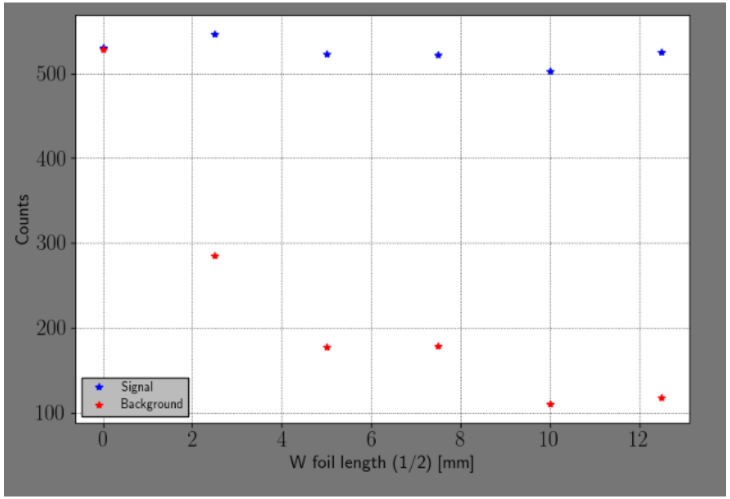
# Beamline optimization: ideas/prospects

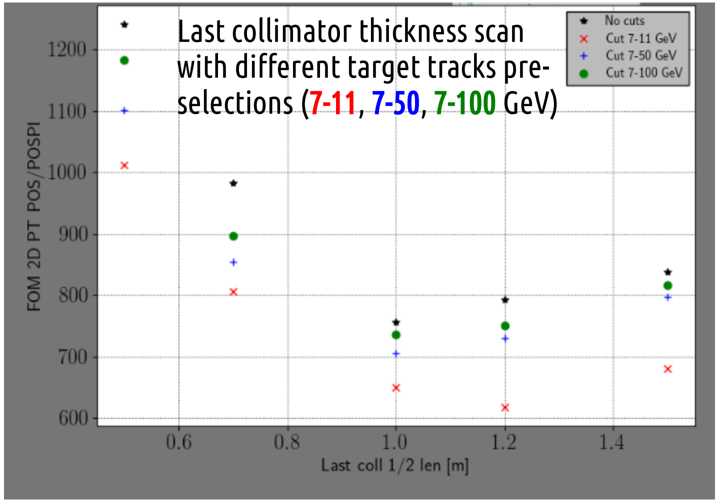
- We have taken the **optimal solution** from the algorithm and tried to **vary single parameters one at a time**.
  - i.e. W $e^+$ absorber foil. Not in the generic optimization, came from a previous study with G4BL → scan says 5 mm is still good
  - last collimator length. The same minimum as the one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

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

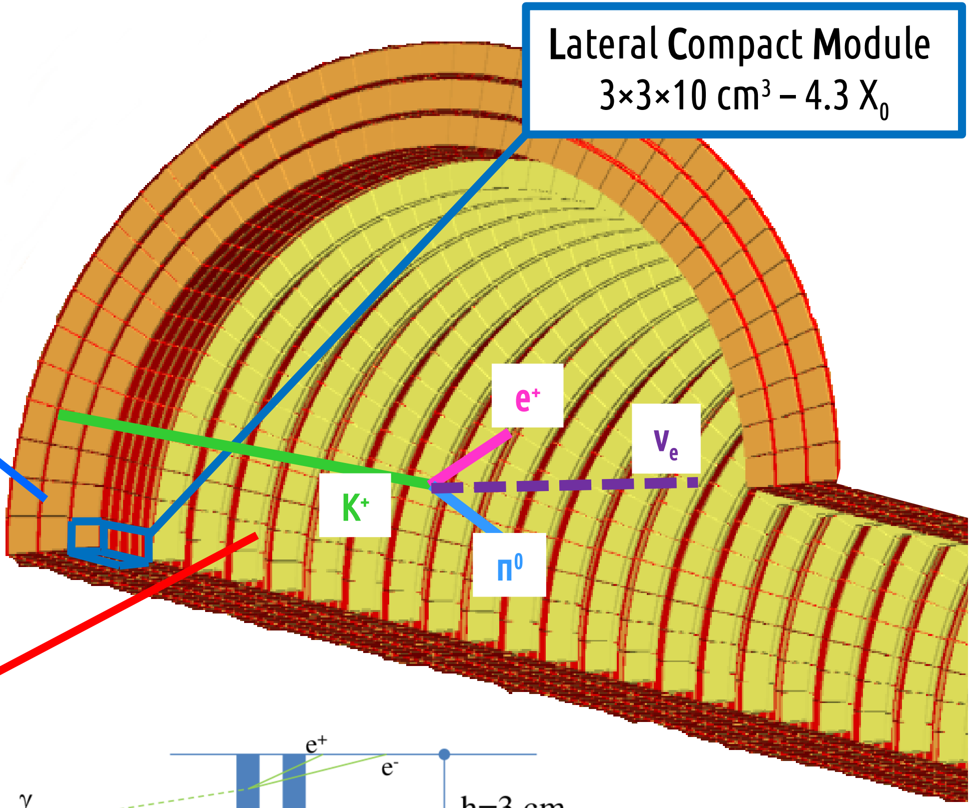
- Finally with this empowered tool we would like to explore the **parameters of the upstream part of the beamline**

W-foil thickness scan on the optimized conf.



# The lepton tagger



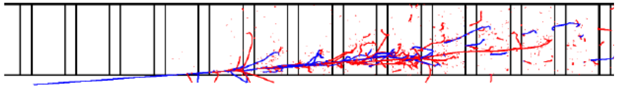

**Calorimeter**

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

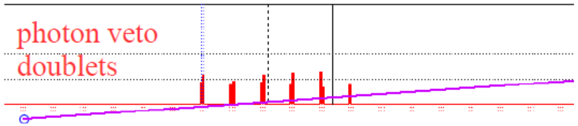
→ $e^+/\pi^\pm/\mu$ separation

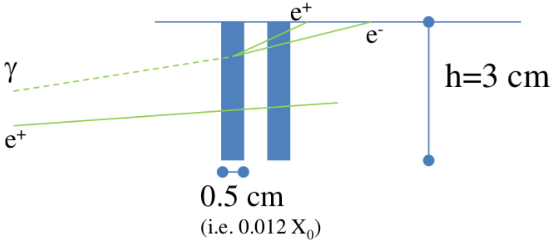


**Integrated photon veto**

- Plastic scintillators rings of $3\times3$ cm² pads

→ $\pi^0$ rejection




$e^+$ (signal) topology

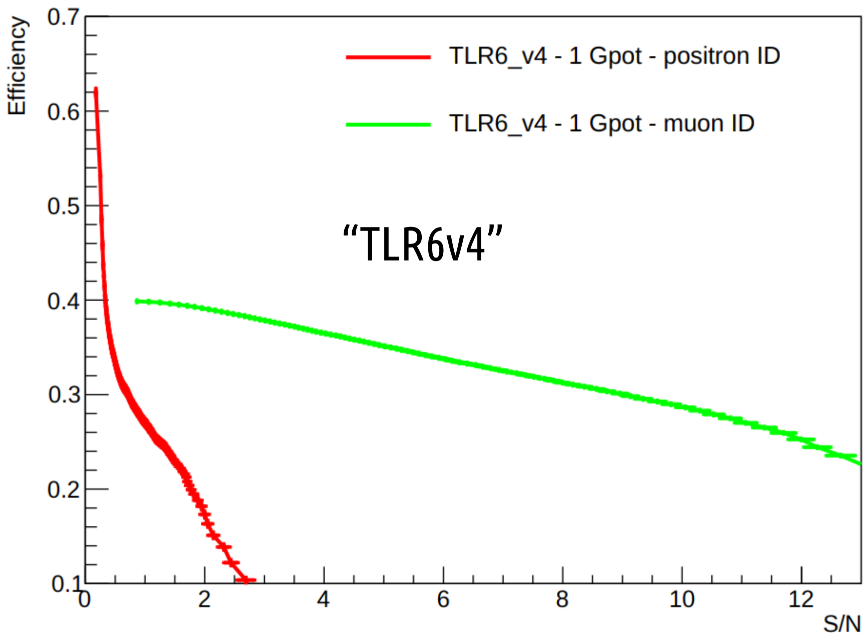
$\pi^0$ (background) topology

$\pi^+$ (background) topology

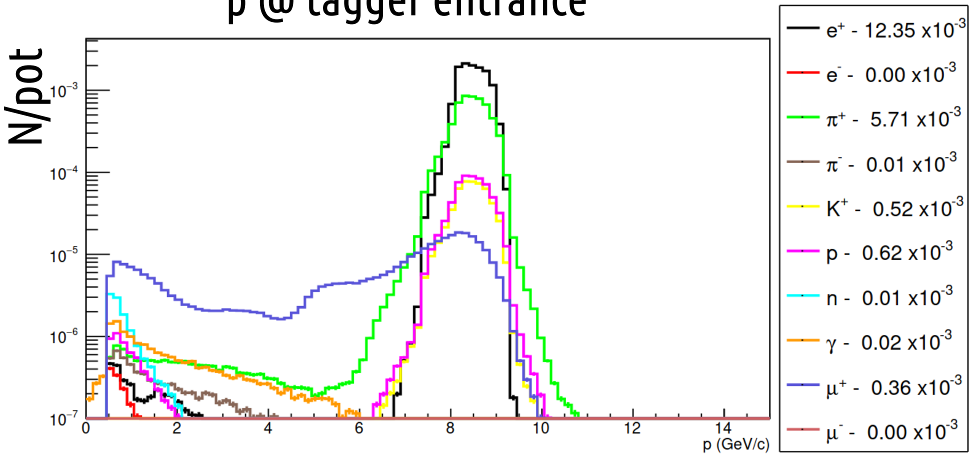
# Current optimum

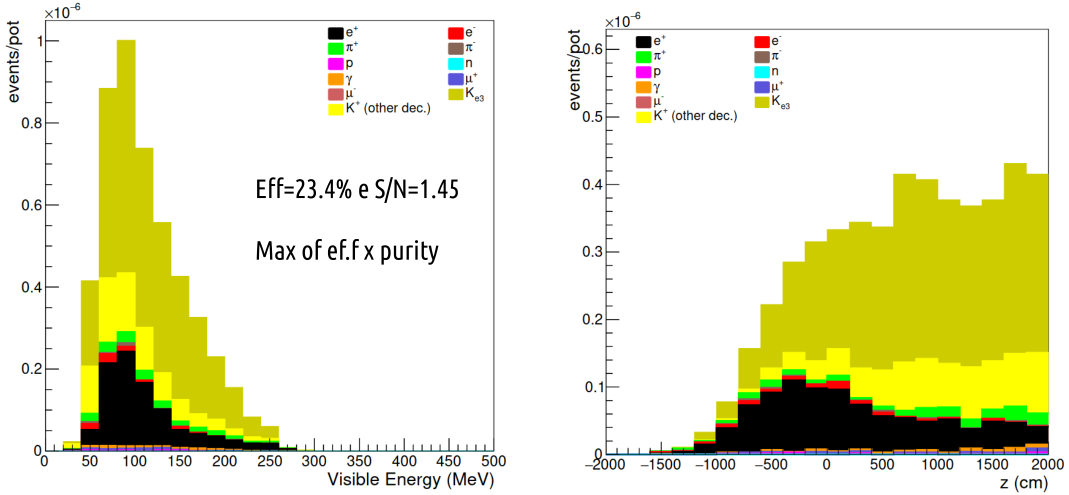
Current status: the present beamline is the result of the 5-dim search with some “manual” tweaking guided by our “diagnostic” tools.

The performances are similar to the ones that we had before but with a realistic implementation of background sources (G4) while several assumptions were present in the previous result based on G4Beamline.




p @ tagger entrance

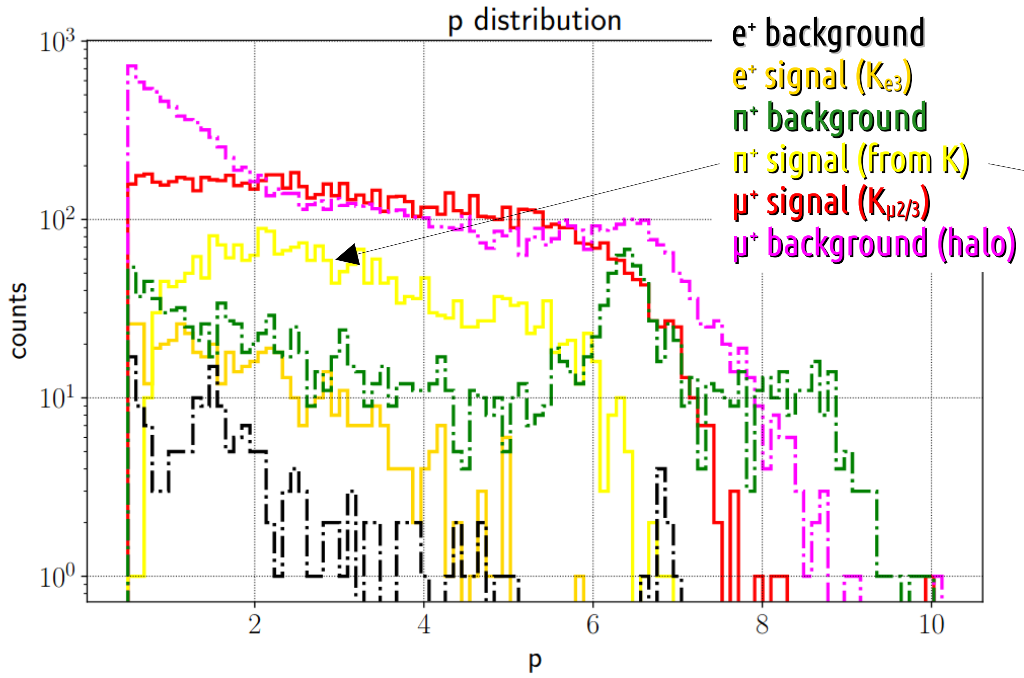


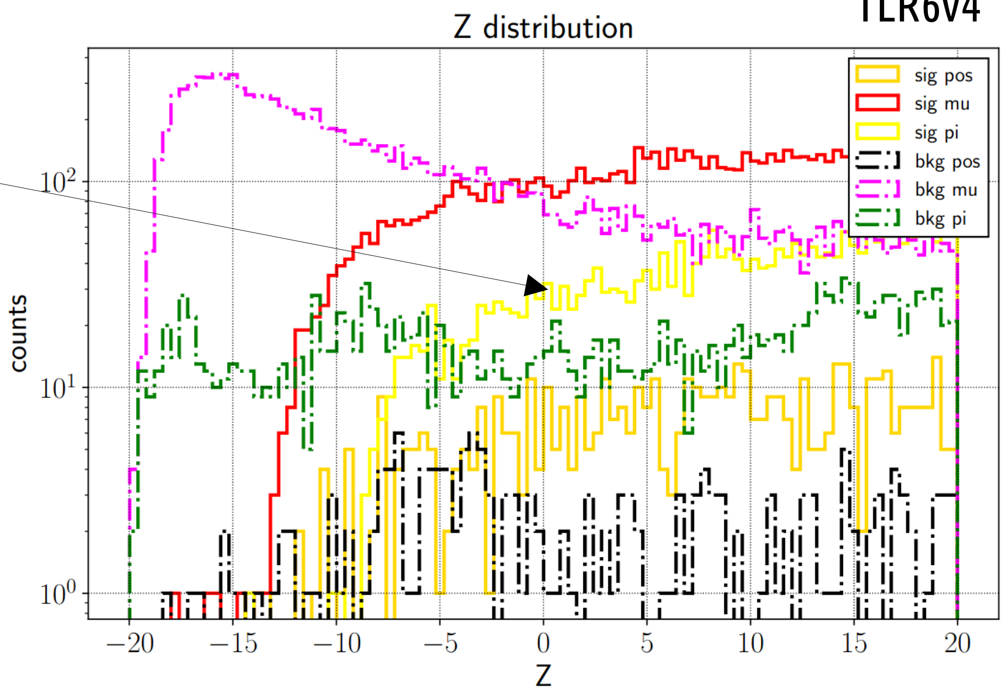



# Pion sample

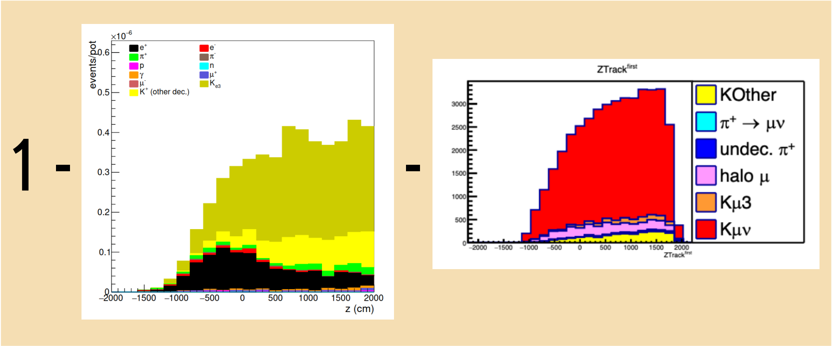
## Particles hitting the tagger at true level

TLR6v4



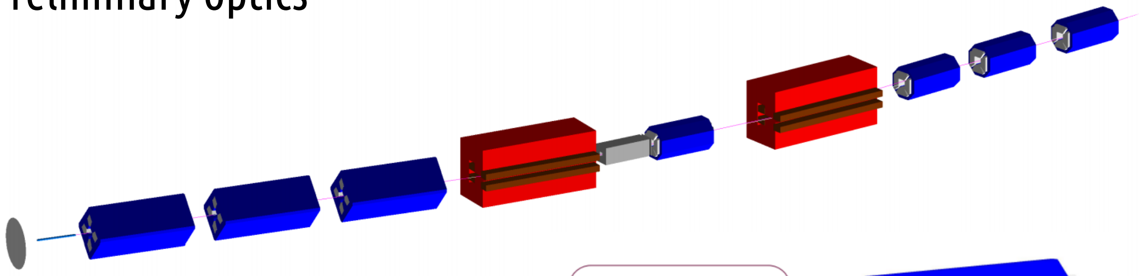

By selecting events not classified as e⁺ or muons (already available) we can access the sample of pions from kaon decays where S/B could be good (yellow component) and efficiency high (large B.R.) → independent constraint on the kaon yields → fluxes of $\nu_e$ and $\nu_\mu$. In the pipeline.



# “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.

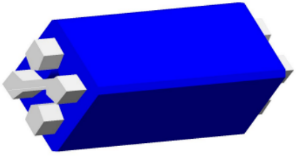
Preliminary optics



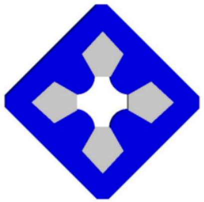
Realistic Q200 Magnet.

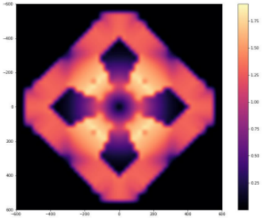
Lenght: 2 m (2.43 m)

Aperture diameter: 0.2 m

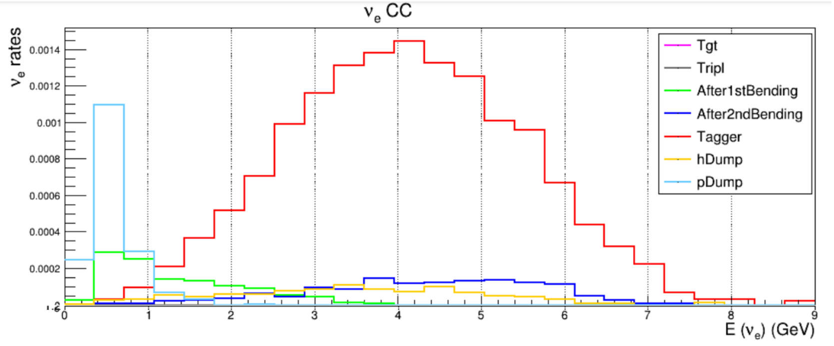


Focus on a detailed implementation of magnetic fields maps measured for existing magnets at CERN



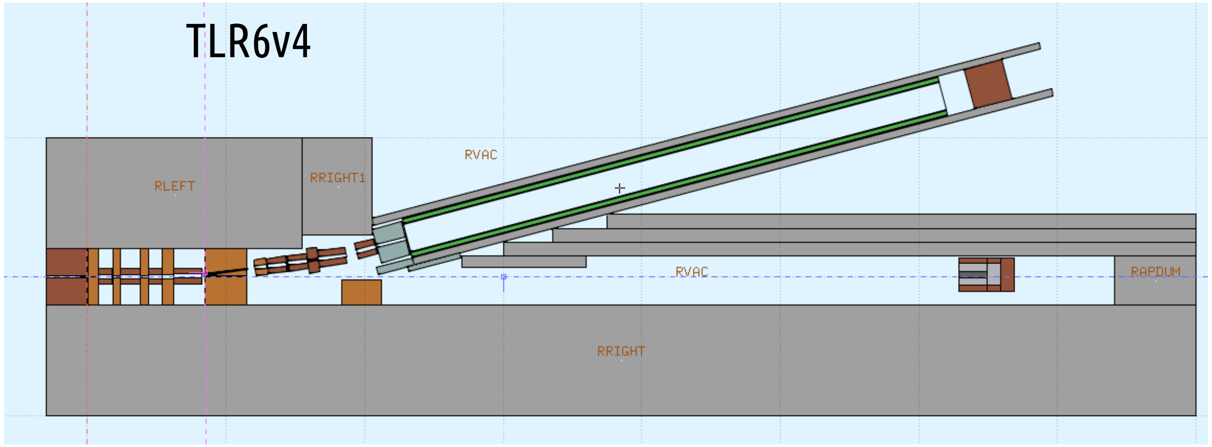


$\nu_e$ from **8.5** GeV/c secondaries (current baseline)

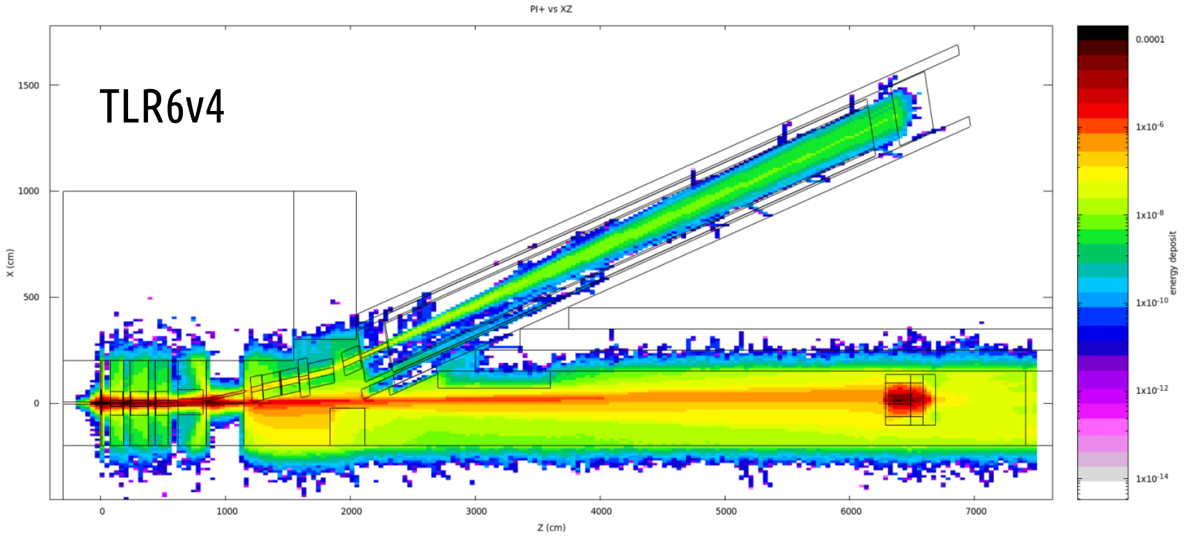



1 4 6 GeV

# FLUKA irradiation studies




Detailed FLUKA simulation of the setup replicated for the latest beamline (TLR6v4) in a semi-automatic way exploiting our G4 code.



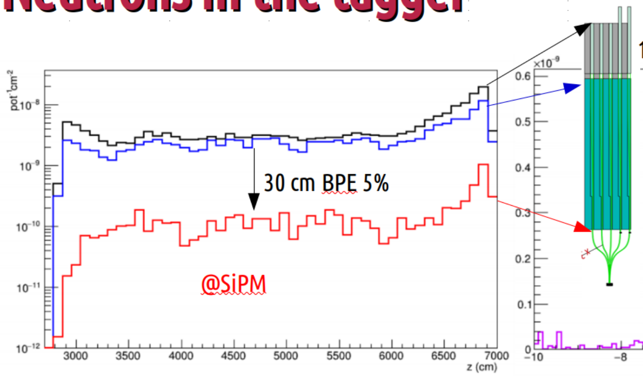

**π⁺ fluence**: gives an idea on the pion occupancy in the tagger and is a quick test for the correct implementation of magnetic fields.

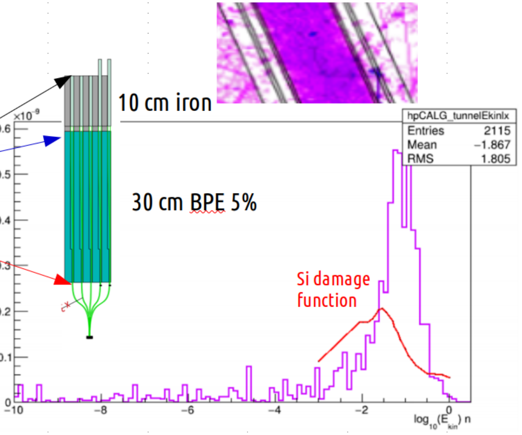
# FLUKA irradiation studies

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

From the point of view of irradiation the new beamline is in line with our previous baseline with two dipoles.

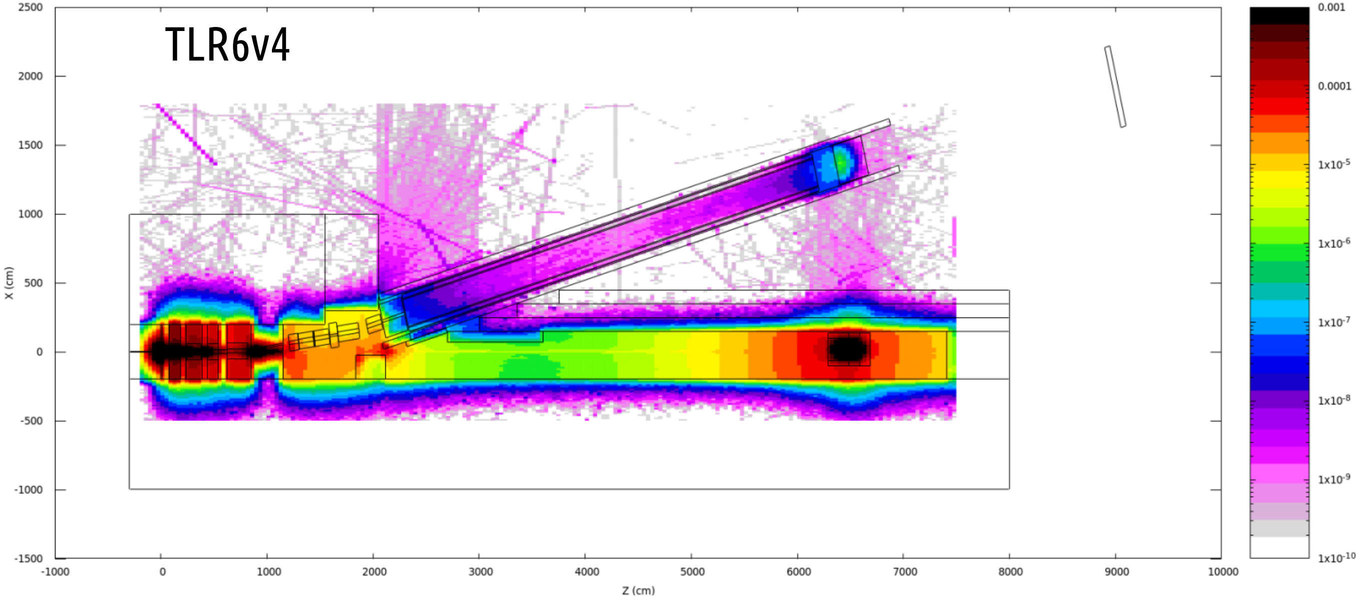
## Neutrons in the tagger



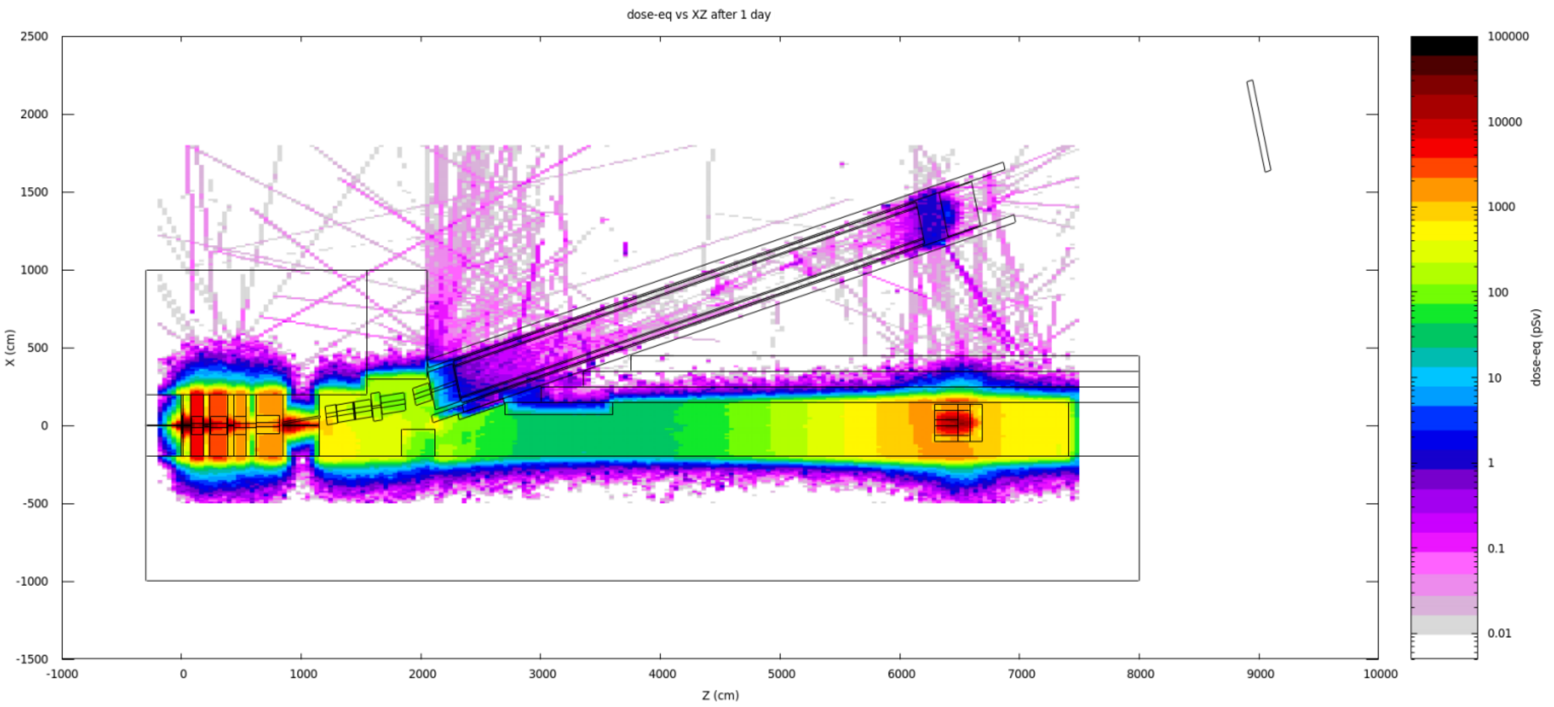

BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
$7 \times 10^{-11}$ n/POT/cm$^2$ **~ 10 x reduction**
($7 \times 10^{9}$ n/cm$^2$ for $10^{20}$ POT)

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



# FLUKA irradiation studies

We have also preliminary results (new) on the equivalent dose after a certain cool-down period (1h, 1 day, 1 month) to guide the shielding of the tagger instrumentation and evaluate accessibility.




In the tunnel, after 1d, ~0.05 pSv per primary proton

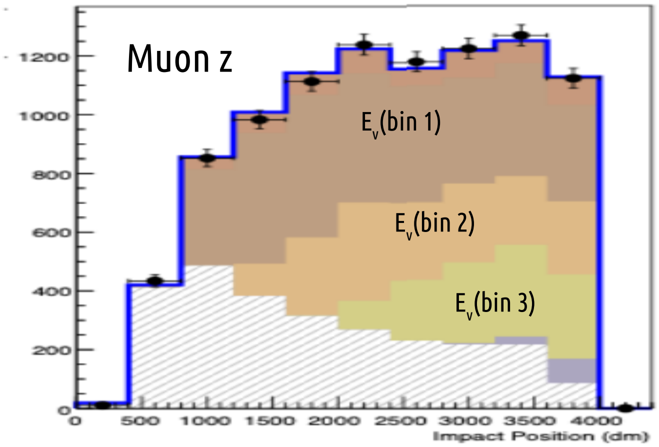
# ENUBET: flux constraint

Link: Talk at nuFact2021 (A. Branca)

**Uncertainty reduction on the flux**

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

Each histogram component corresponds to a bin in neutrino energy




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

$$\mathrm{PDF}_{\mathrm{Ext.}}(\mathrm{N}_{\mathrm{exp}}, \vec{\alpha}, \vec{\beta}) = \mathrm{N}_{\mathrm{S}}(\vec{\alpha}, \vec{\beta}) \cdot \mathrm{S}(\vec{\alpha}, \vec{\beta}) + \mathrm{N}_{\mathrm{B}}(\vec{\alpha}, \vec{\beta}) \cdot \mathrm{B}(\vec{\alpha}, \vec{\beta})$$

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

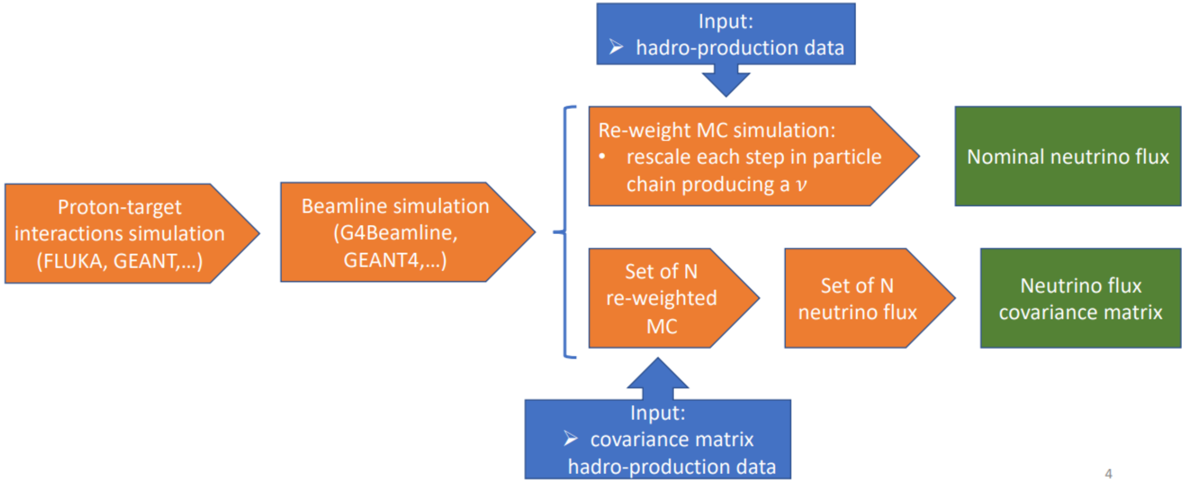
EML fit approach:

$$\mathrm{L}(\mathrm{N}|\mathrm{N}_{\mathrm{exp}}) = \mathrm{P}(\mathrm{N} \mid \mathrm{N}_{\mathrm{exp}}) \cdot \prod_{\mathrm{bins}} \mathrm{P}(\mathrm{N}_{\mathrm{i}} \mid \mathrm{PDF}_{\mathrm{Ext.}}(\mathrm{N}_{\mathrm{exp}}, \vec{\alpha}, \vec{\beta})_{\mathrm{i}}) \cdot \mathrm{pdf}_{\alpha}(\vec{\alpha} \mid 0,1) \cdot \mathrm{pdf}_{\beta}(\vec{\beta} \mid 0,1)$$

parameters are constrained by their pdfs

# ENUBET: flux constraint

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

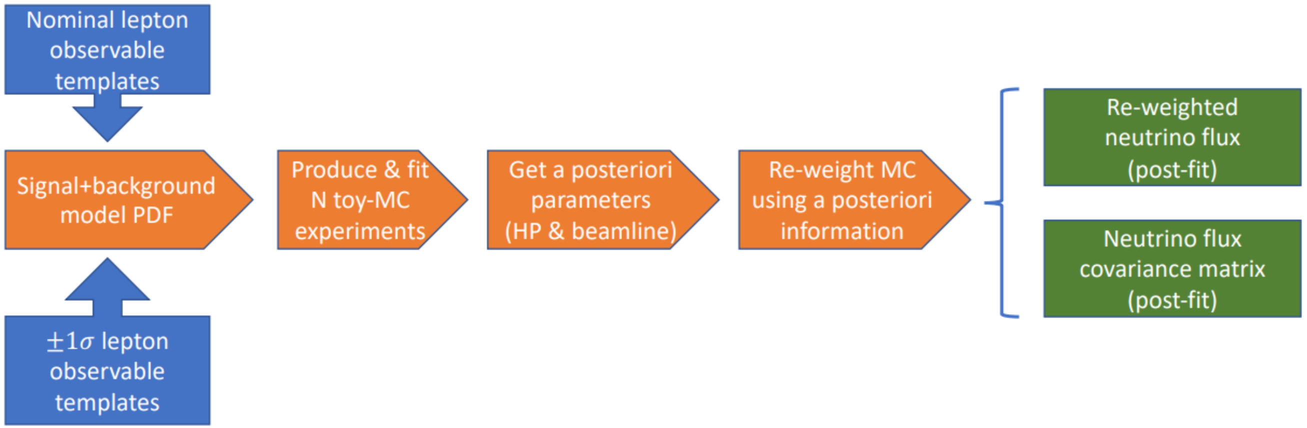



The hadroproduction model is a realistic one derived from a fit to real data obtained by the NA56/SPY experiment using 400 GeV proton interactions.



Flux systematic treatment including ENUBET information:

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



# Flux constraint on hadro-prod.

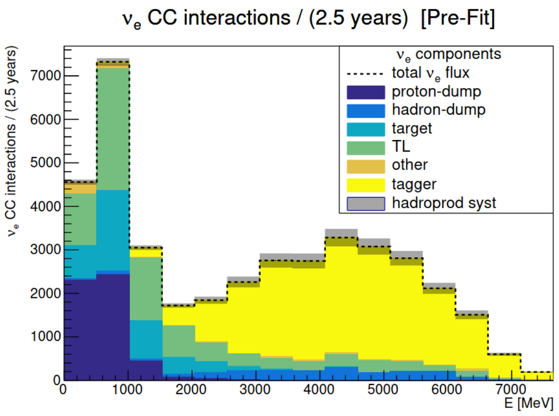
Link: Talk at nuFact2021 (A. Branca)

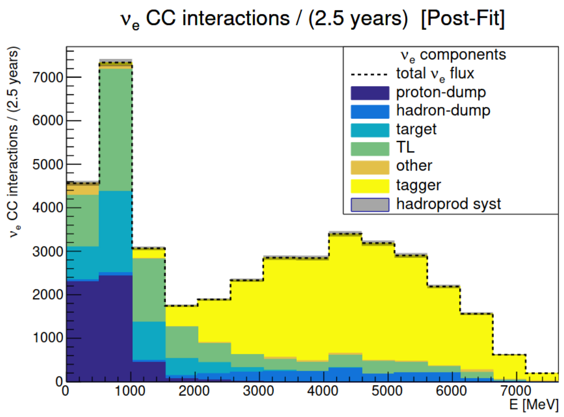
Previous report: machinery was using a toy MC (no bias, assessment of post-fit errors). We can now show the reduction of uncertainty introduced by the tagger constraint using the full G4 simulation →

Both $K_{e3}$ (for $\nu_e$) and $K_{\mu2}/K_{\mu3}$ (for $\nu_\mu$) data sample constraints have been implemented.

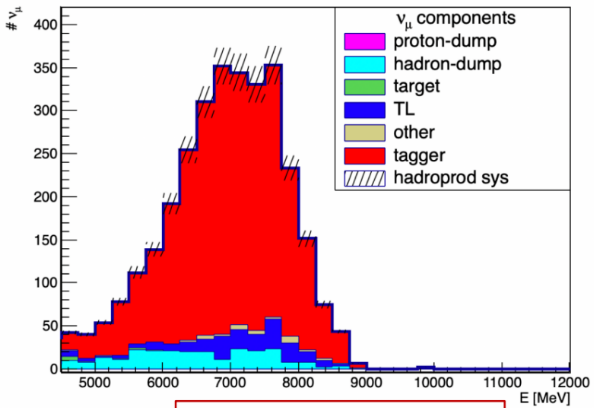
We can link the spectrum of measured leptons (muons and electrons in the tagger) to a reduction in the neutrino flux normalization →

We still cannot quote how precise we could finally be because we are still working in the limit where hadroproduction uncertainty can be completely eliminated with sufficient statistics. Next step is to use the same approach to include beam-line, detector and physics (BRs, decay kinematics) systematics → asymptotic value.

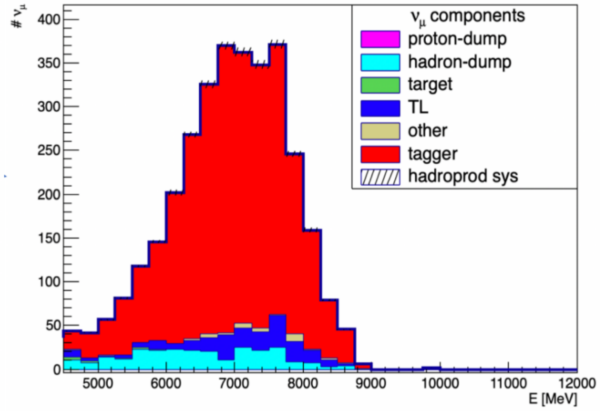



Pre-Fit (unconstrained)



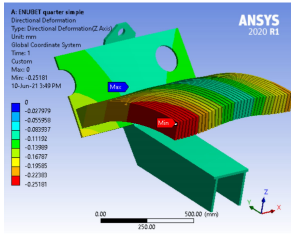

post-Fit (constrained)



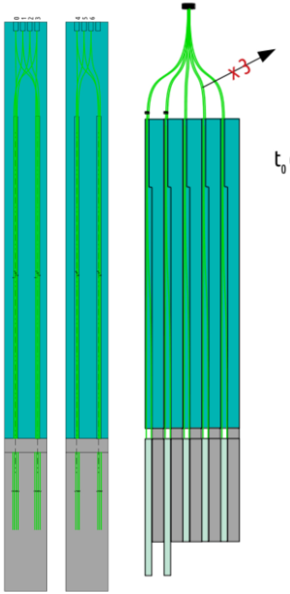
# The demonstrator

Custom digitizers @ 500 MS/s

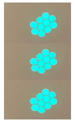
FE mech. studies

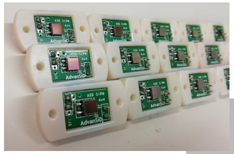



WLS routing

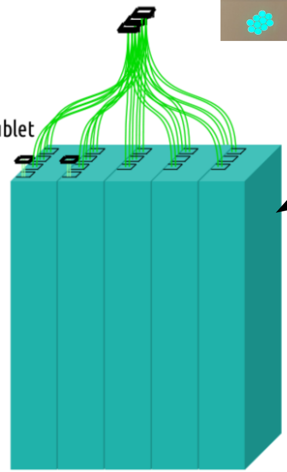



3 LCM





$t_0$ doublet



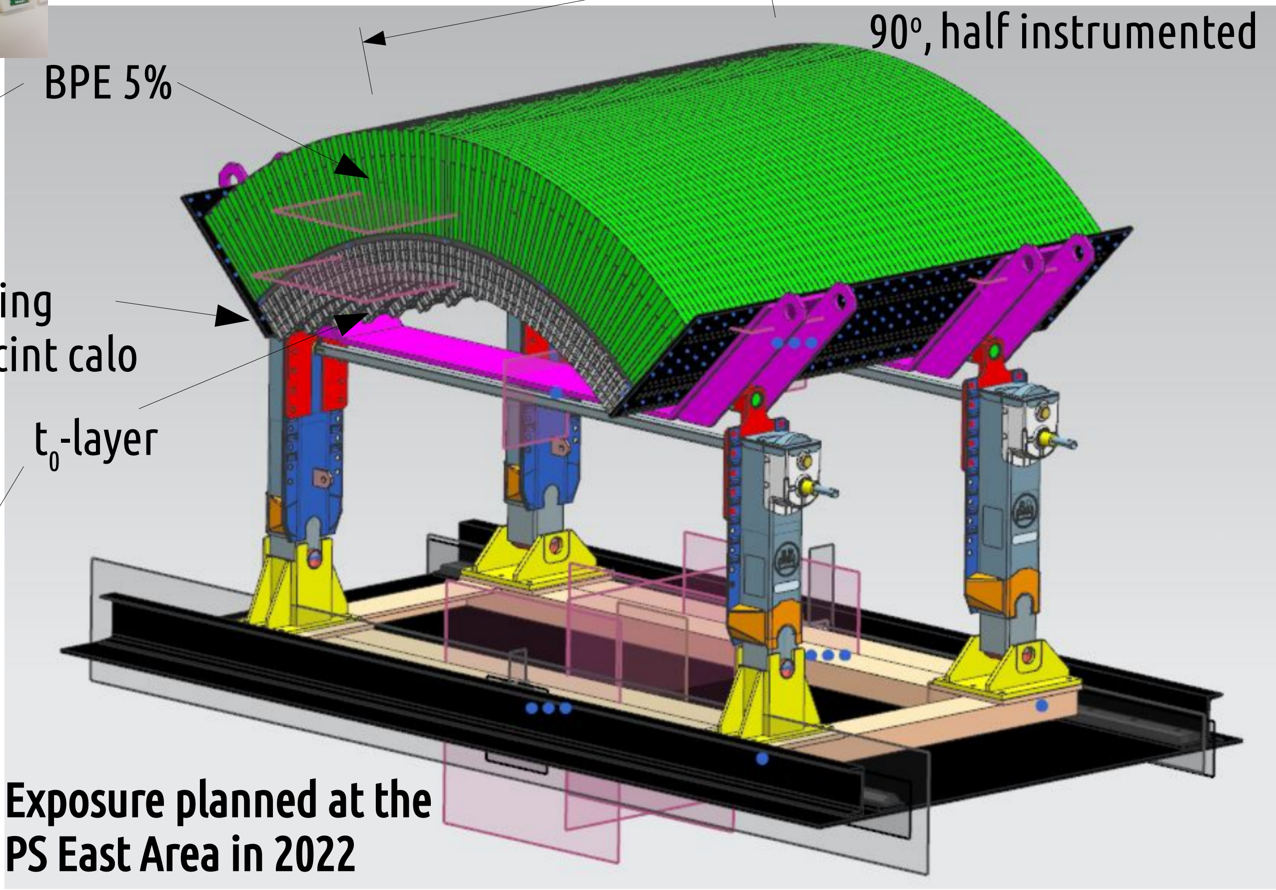
1.65 m

90°, half instrumented

BPE 5%

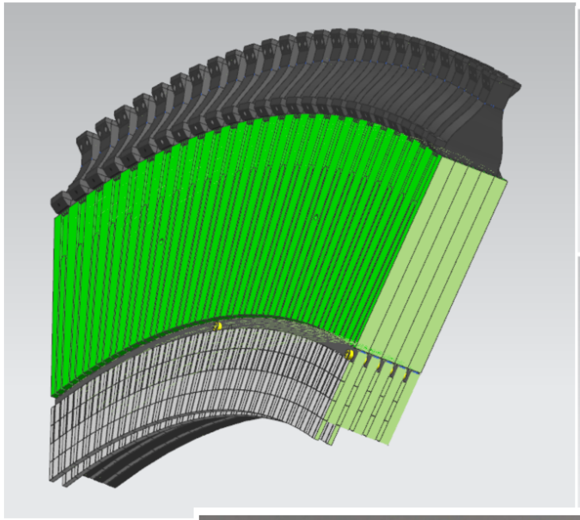
Sampling iron/scint calo

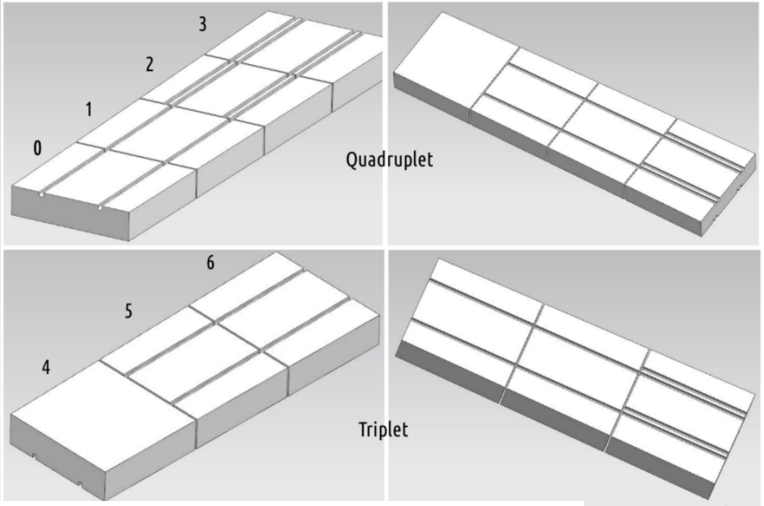
$t_0$-layer



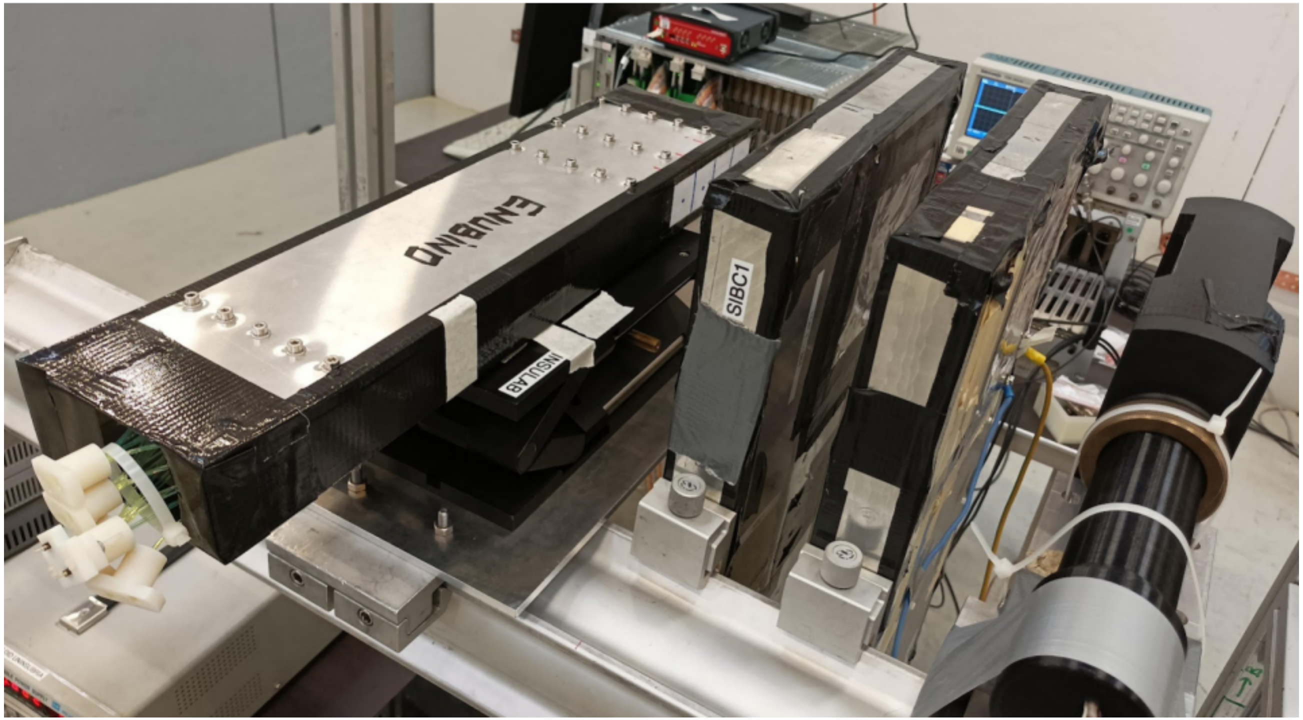
**Exposure planned at the PS East Area in 2022**

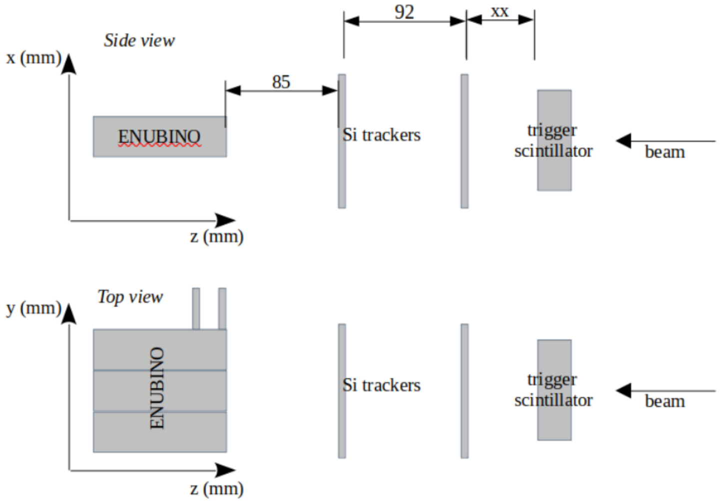
# The demonstrator

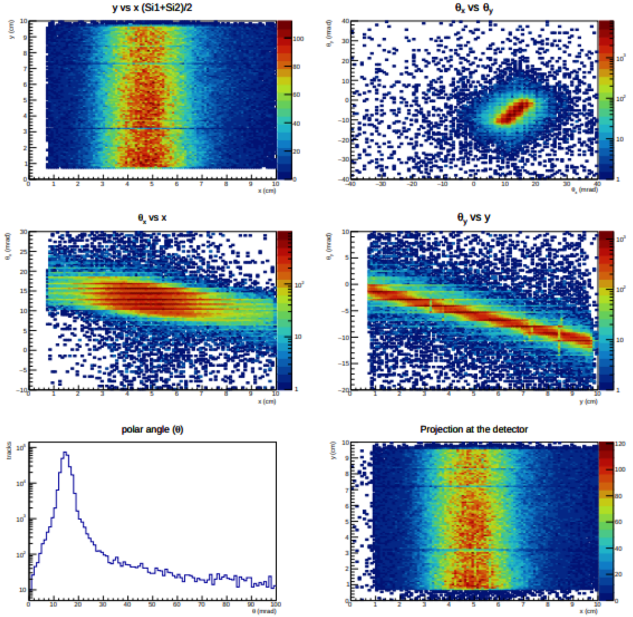





# The Nov 2021 CERN-PS test beam

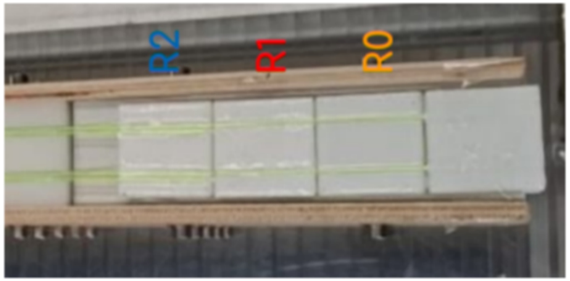


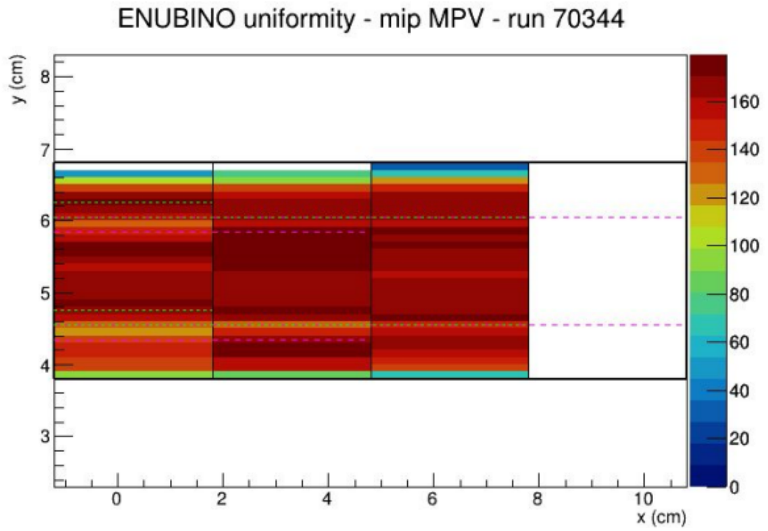

+15 GeV hadronic beam (parasitic to TOTEM)
Allowed to test the final configuration chosen for the demonstrator

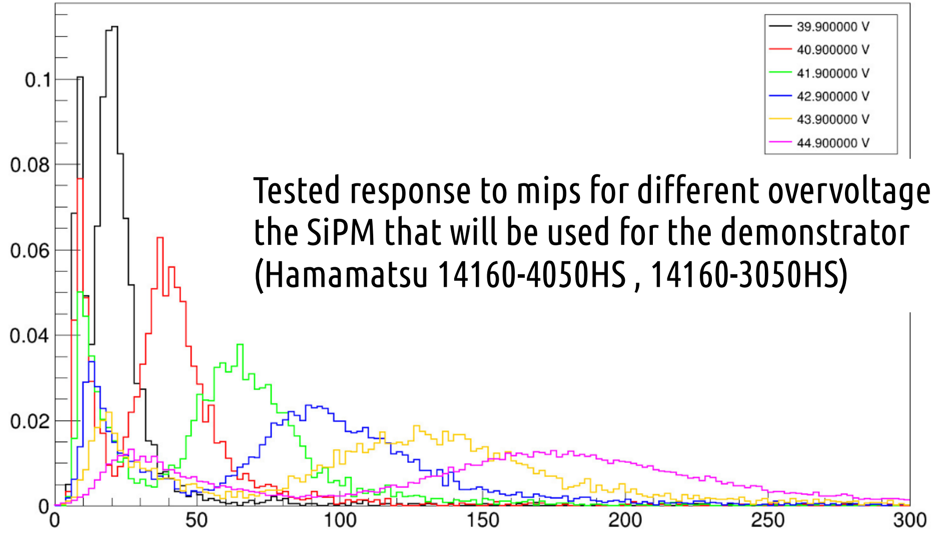
# The Nov 2021 CERN-PS test beam




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

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

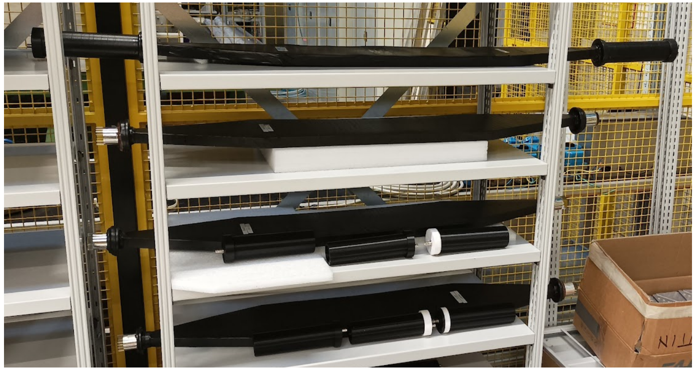


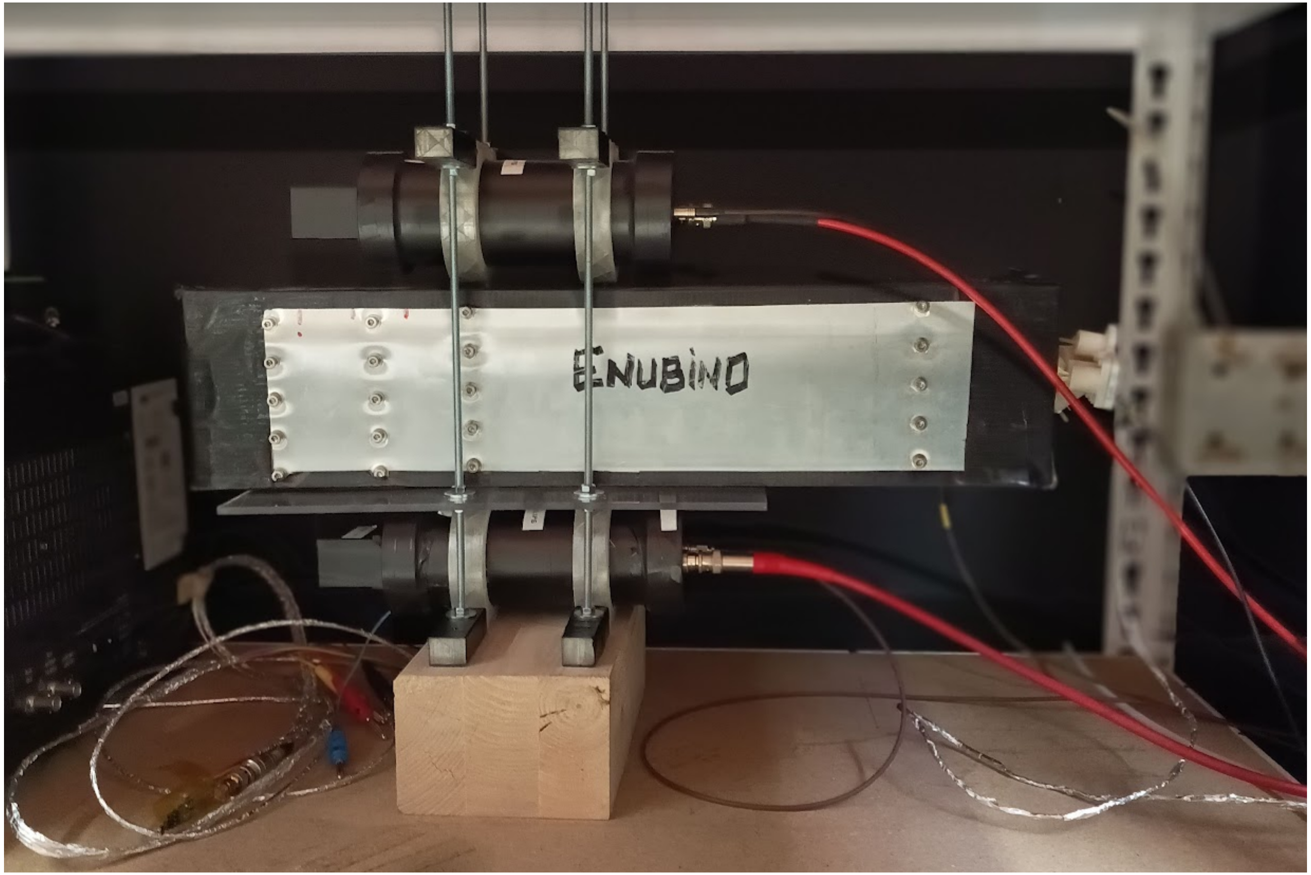




Tested response to mips for different overvoltage for the SiPM that will be used for the demonstrator (Hamamatsu 14160-4050HS , 14160-3050HS)

# The Nov 2021 CERN-PS test beam

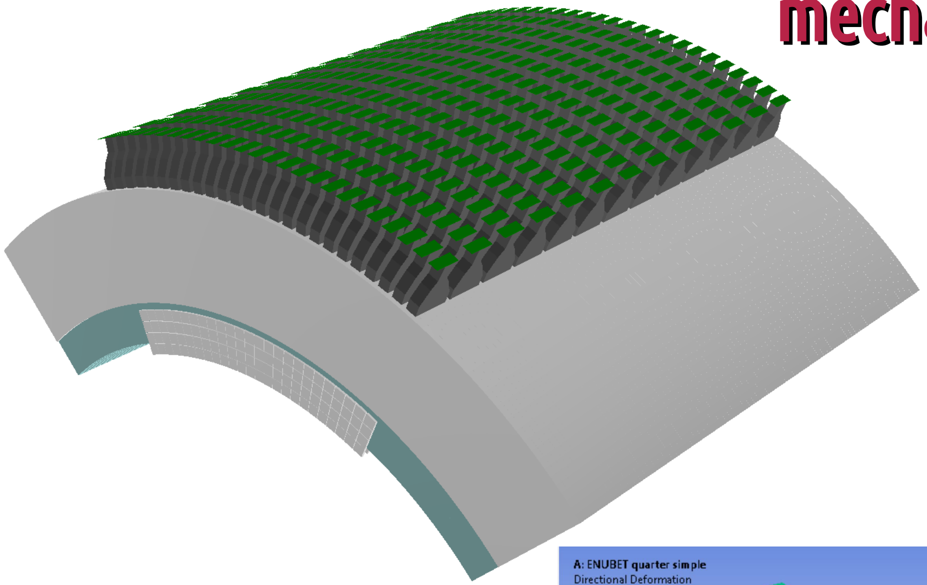
Caracterization continuing at LNL with cosmics



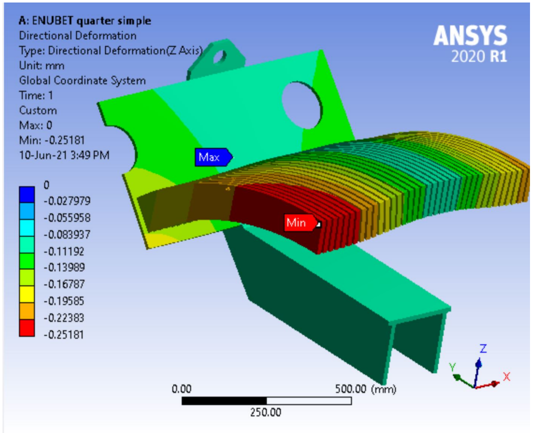


# The demonstrator

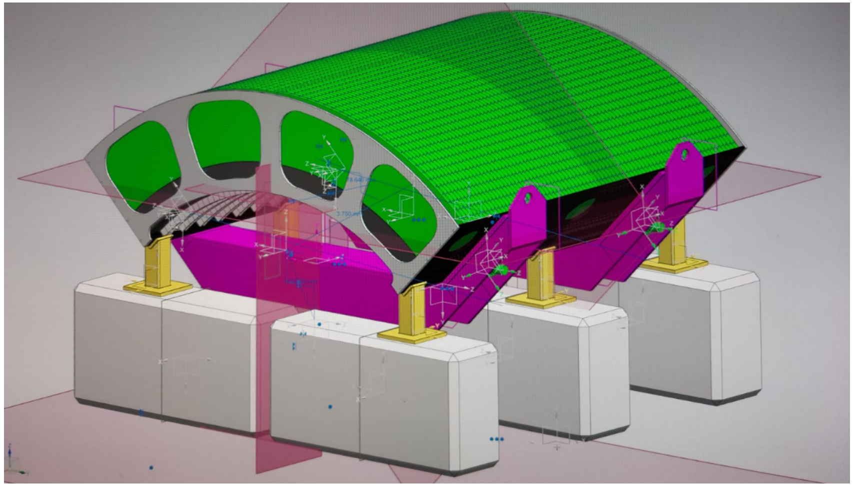
## mechanics

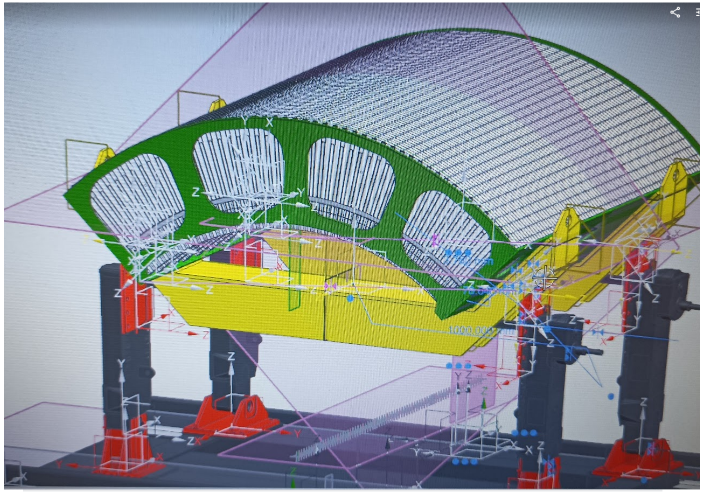


Weight ~ 7 t

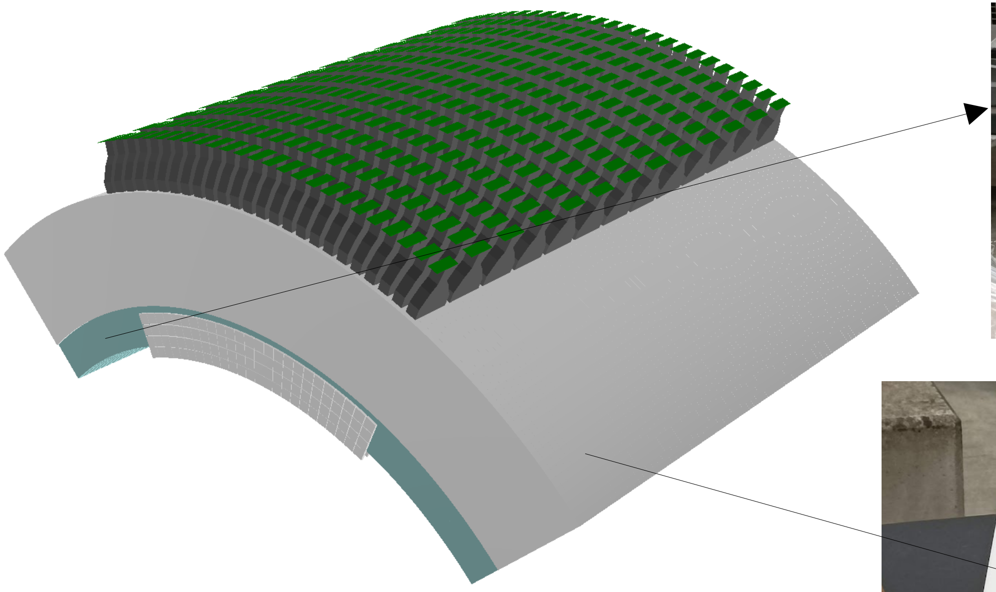


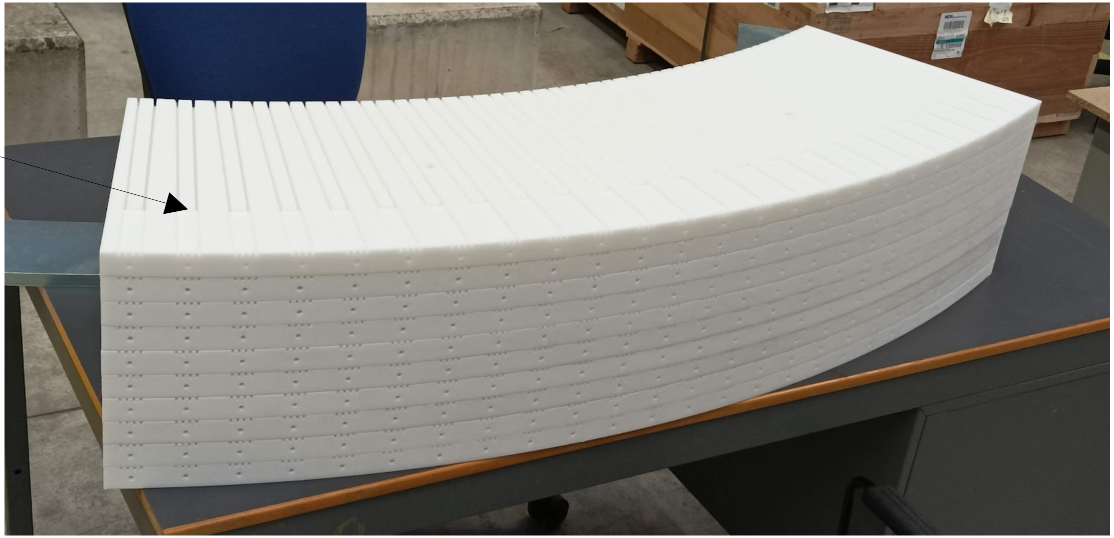

Assembly:





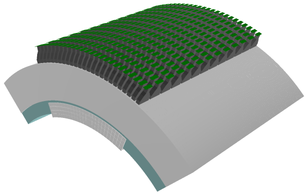
# The demonstrator building blocks

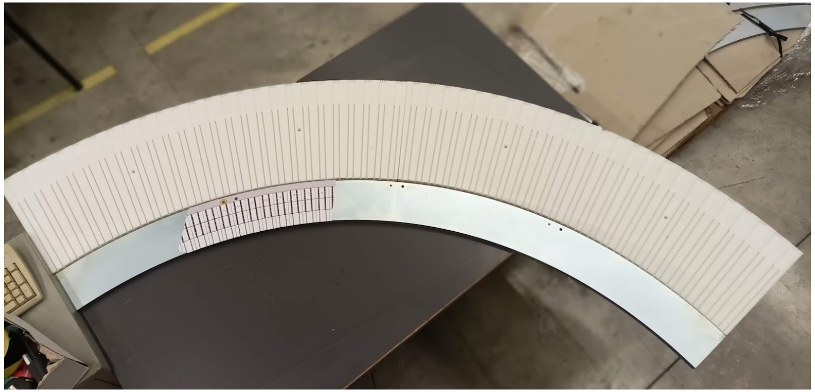


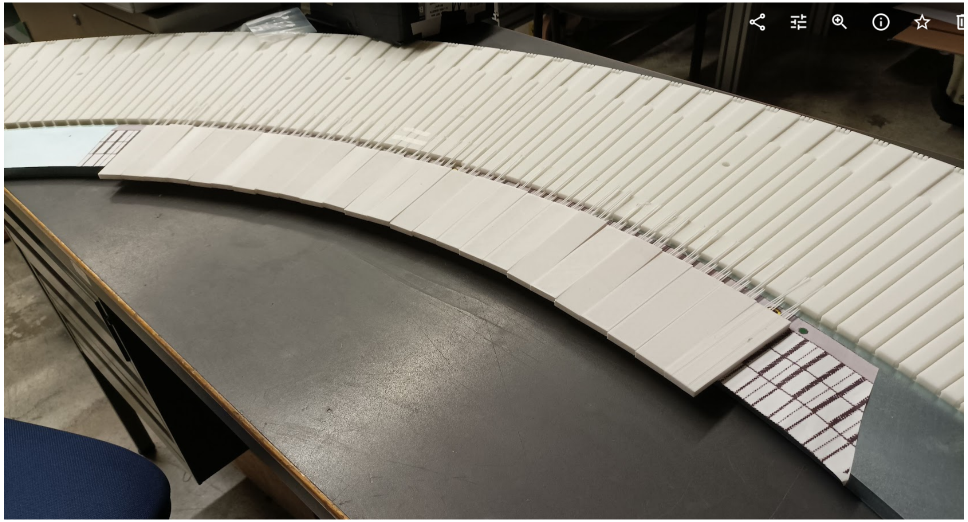


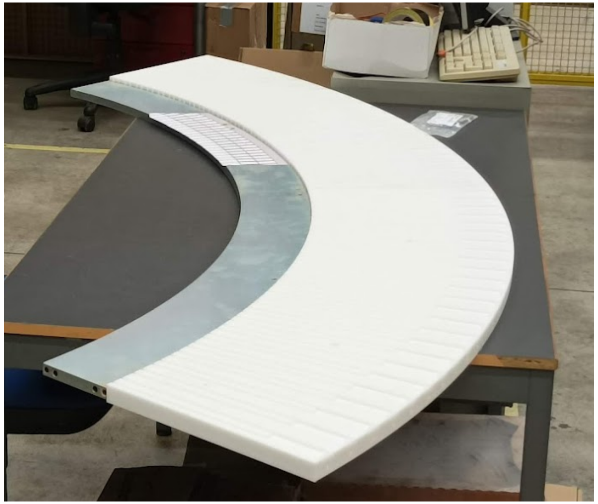
Basic building pieces have been delivered at INFN-Legnaro (near Padova): machined iron and 5% Borated Polyethylene arcs.

# The demonstrator



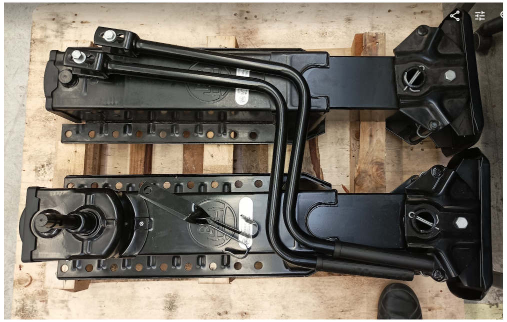




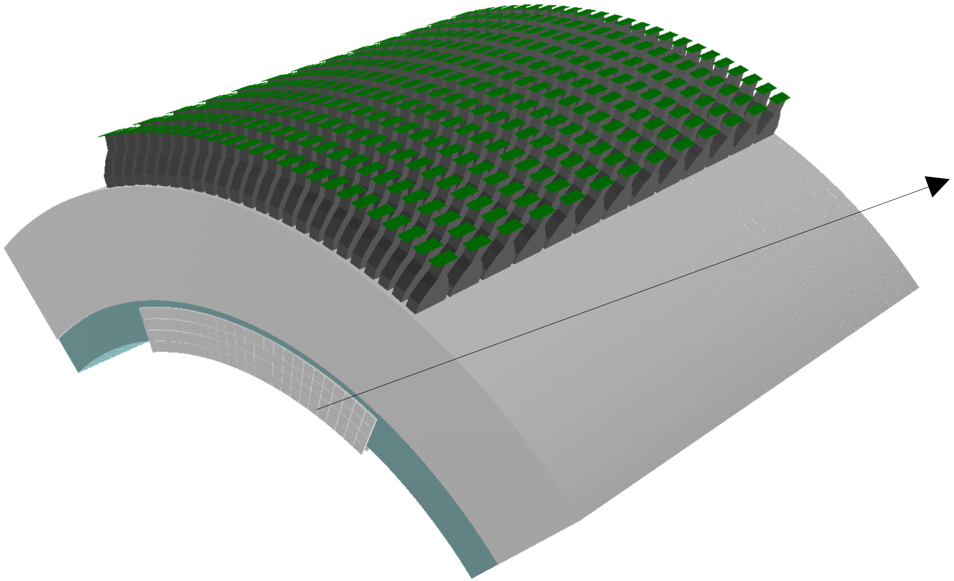


# The demonstrator
## mechanics

Assembly area at INFN-LNL



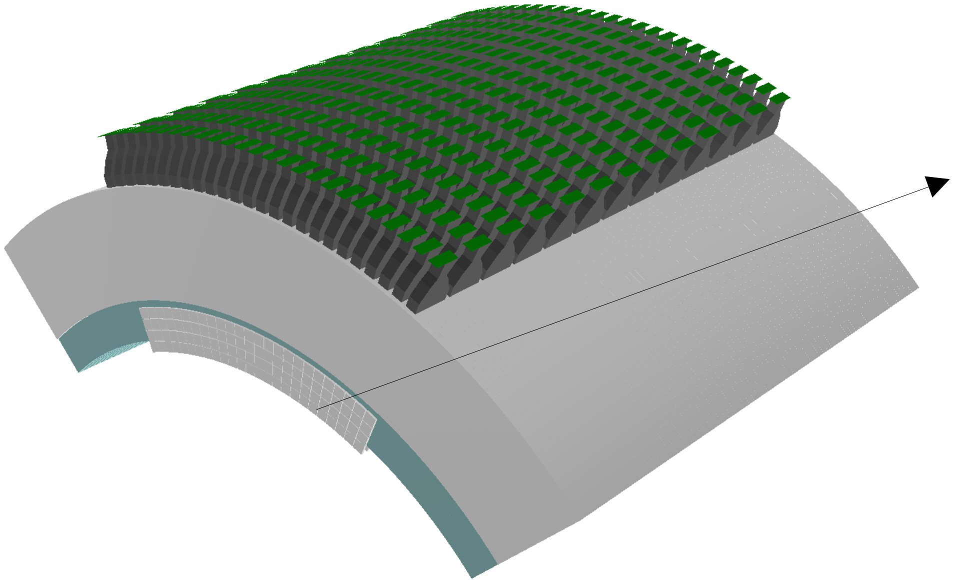
# The demonstrator scintillators



Scintillators being prepared at INR
(Y. Kudenko) with UNIPLAST

Press form for
injection molding

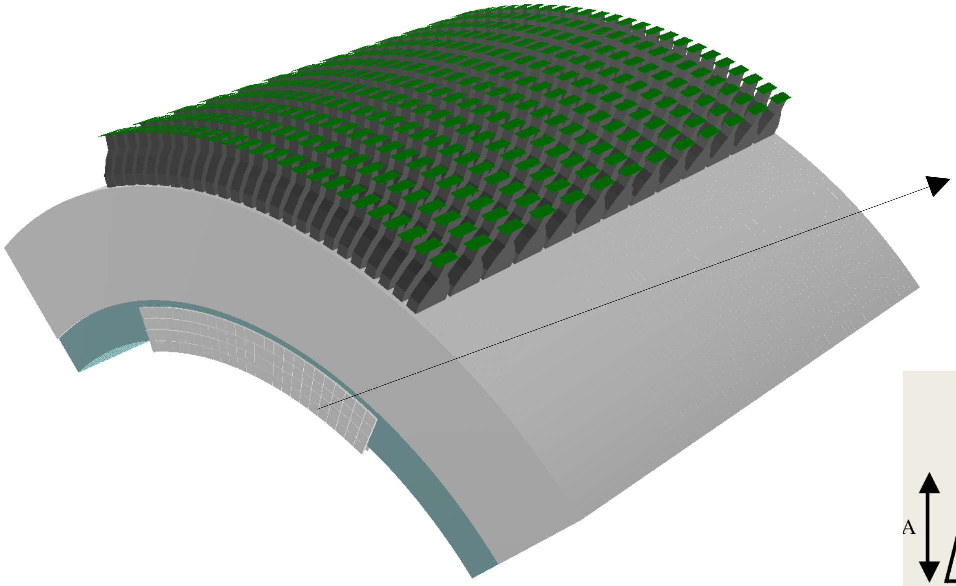
# The demonstrator scintillators



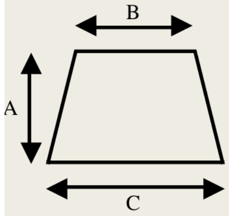
Dec 2021: first tile produced

Scintillators being prepared at INR (Y. Kudenko) with UNIPLAST

# The demonstrator    scintillators

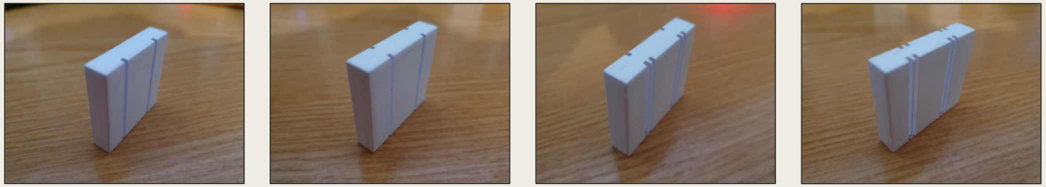


**Four types of tile sizes**




| Side | Size, mm | | | |
|---|---|---|---|---|
| A | 30.0 | 30.0 | 30.0 | 30.0 |
| B | 29.8 | 30.8 | 31.8 | 32.7 |
| C | 30.6 | 31.6 | 32.6 | 33.5 |

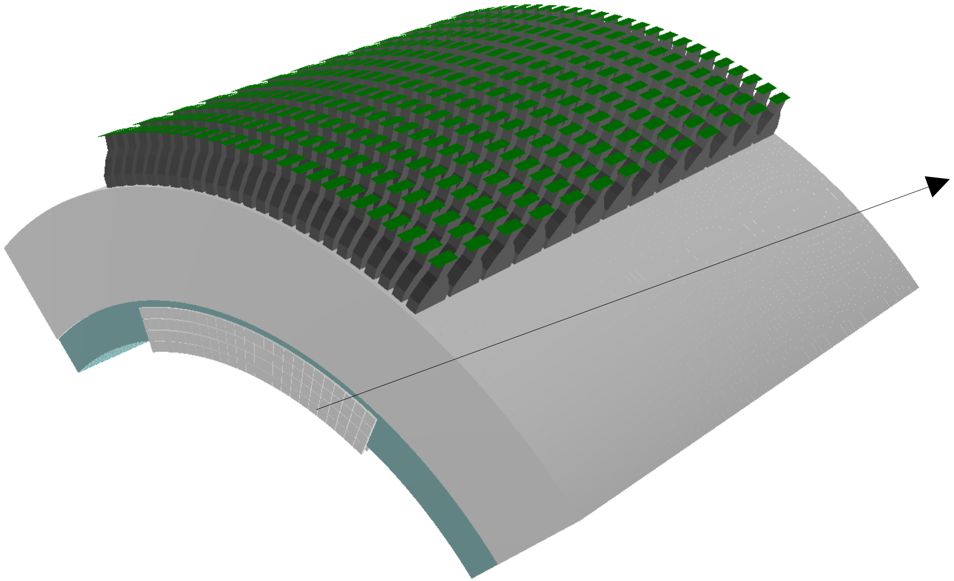
**Four types of grooves**

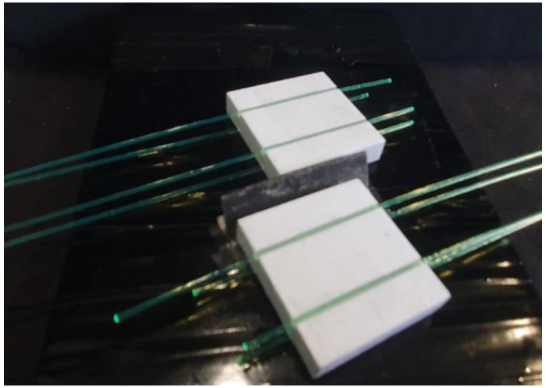


*Tested 7 different combination of size and grooves*

Scintillators being prepared at INR
(Y. Kudenko) with UNIPLAST

# The demonstrator scintillators

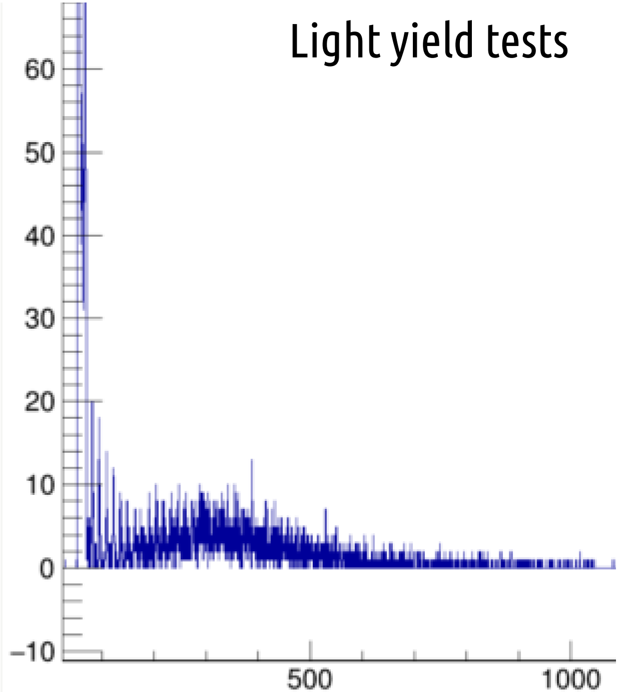




Scintillators being prepared at INR
(Y. Kudenko) with UNIPLAST

48 p.e./ mip

Light yield tests



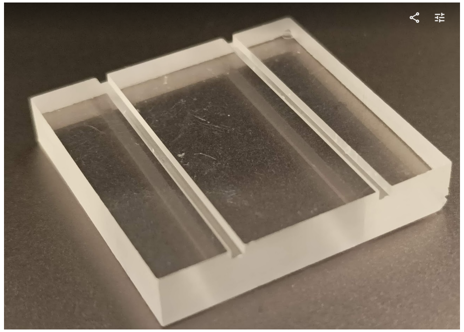
# The demonstrator scintillators

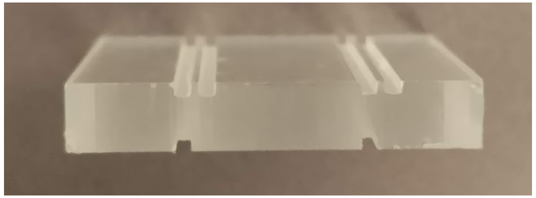
INR: the press form for the plastic injection molding has been finalized and a first set of some hundreds tiles produced and tested for light yield with very good results. The total number of needed tiles is 6375, in seven different shapes.

The delivery of materials and transactions are evidently critical due to the international situation.

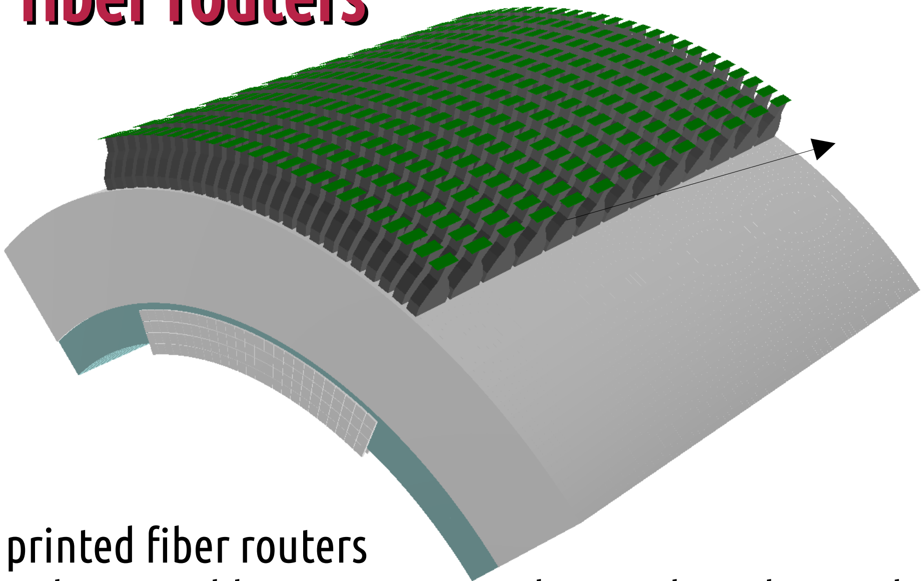
In view of the high probability of delays we have made contacts with a company that could likely perform the production with **milling** instead of using injection molding, starting on scintillator sheets that are being procured by SCIONIX. The first scintillator tiles specimen with this alternative plan became recently available. Some additional waste of material which is intrinsic in the milling procedure due to the size of the milling drive of a few mm. Tests in progress.

Contingency plan specimens

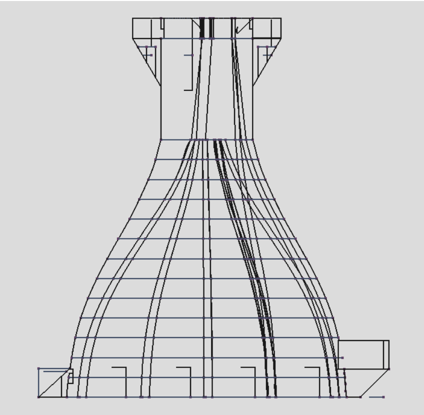


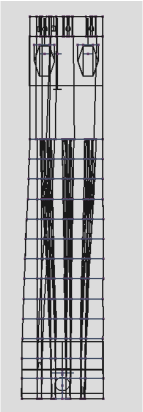


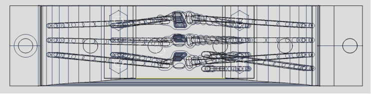
# The demonstrator
## fiber routers

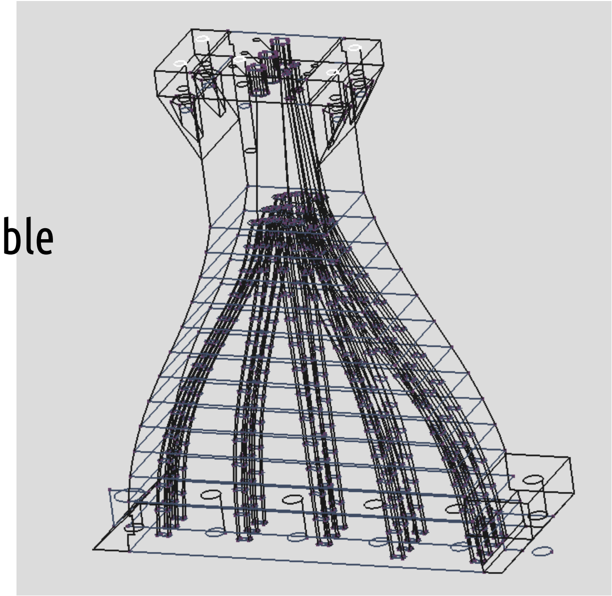


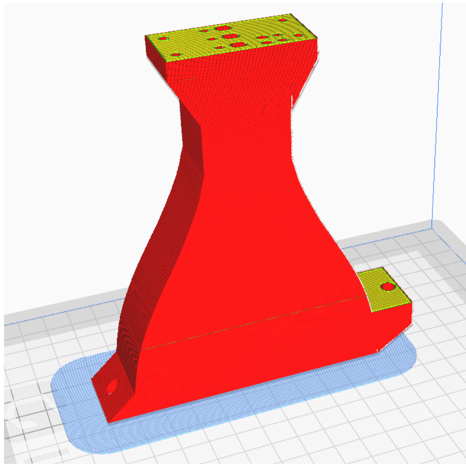
3D printed fiber routers
→ make assembly easier, more robust, tidy and reproducible



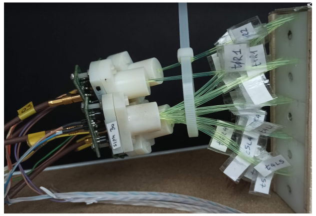




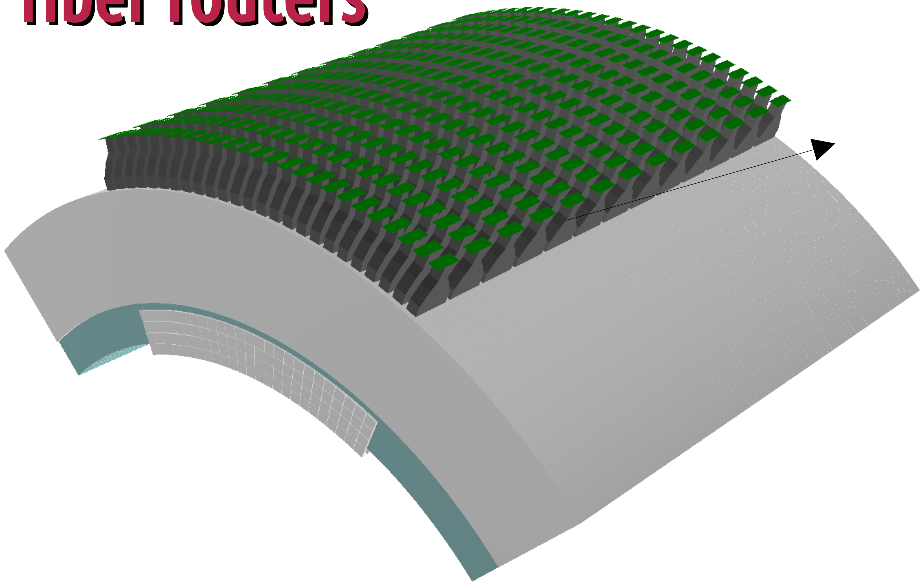


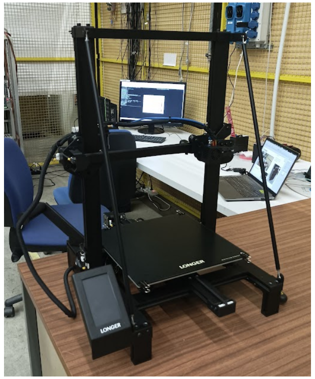


old

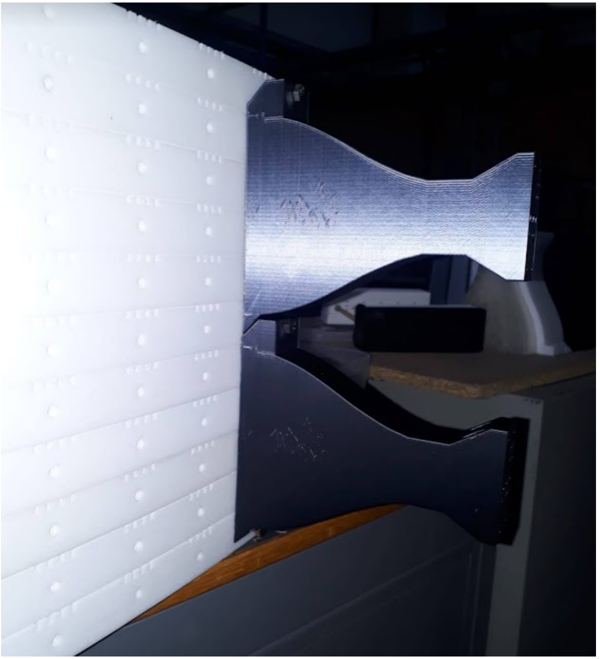


# The demonstrator
## fiber routers





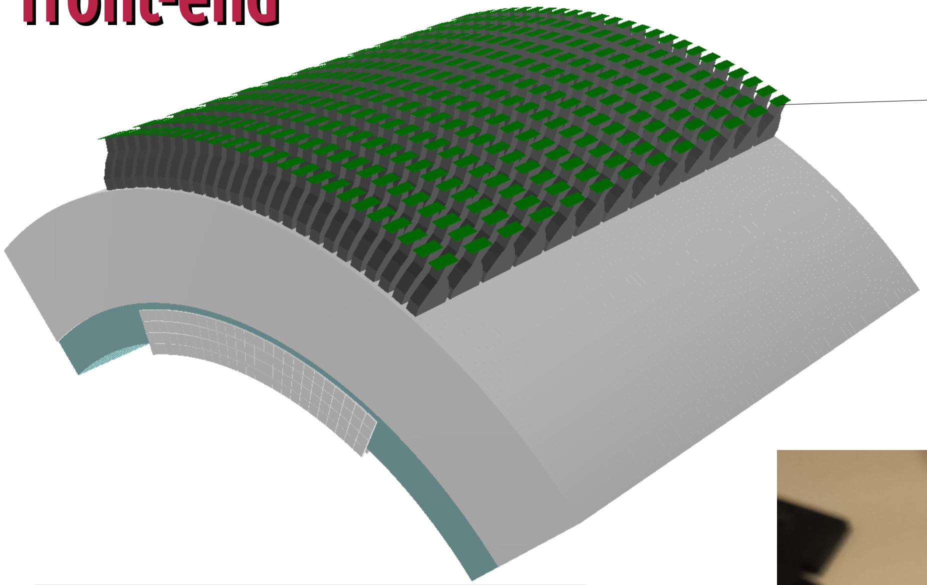
x5



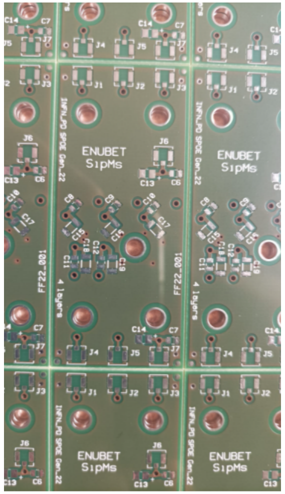
Produced with a battery of 5 consumer level 3D printers (~25% done).

Reliable and quick enough (10/day).

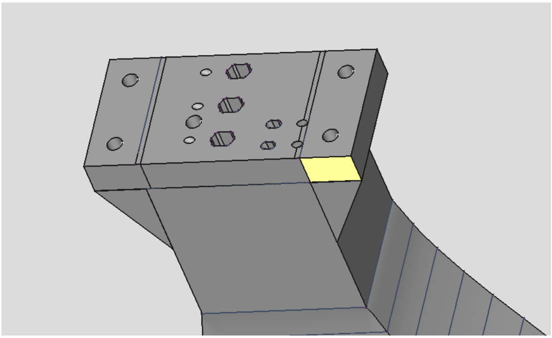
# The demonstrator
## front-end

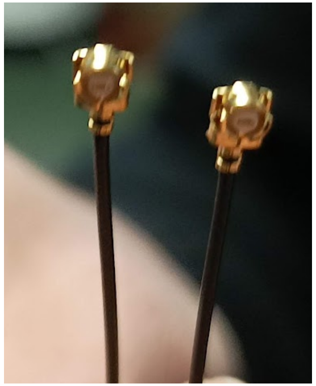


In production

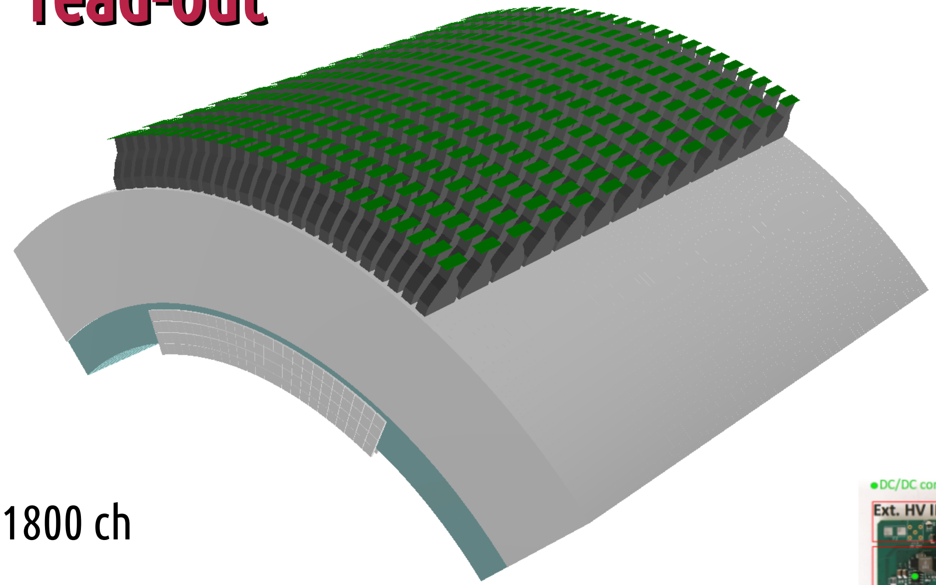


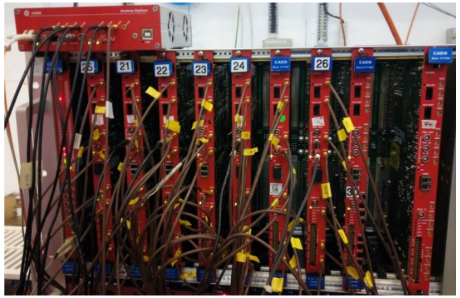

SiPM: Hamamatsu, already procured (14160-4050-HS and 14160-3050-HS)





# The demonstrator
## read-out

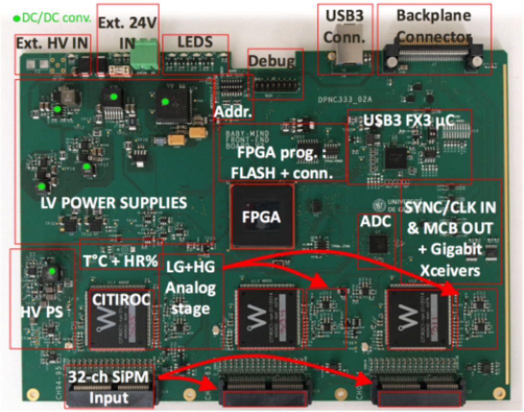


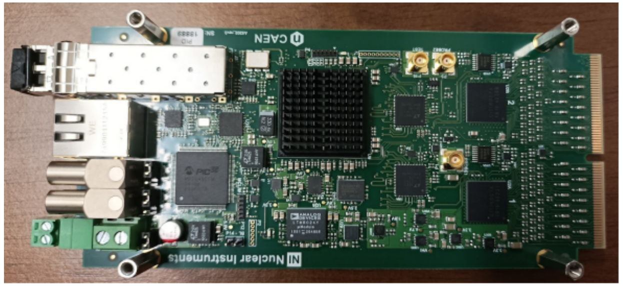


~1800 ch

Hybrid system

- Custom digitizers
- Commercial CAEN digitizers
- BabyMIND (peak+time, Citiroc ASIC 96 ch)
- CAEN FERS A5202 (Weeroc Citiroc-1A, peak+time, 64 ch)



# More activities, news … miscellanea

- **ERC** further extended up to November 2022 (COVID pandemic).
- **Physics Beyond Colliders**. We have been actively participating to the workpackage on conventional neutrino beams with regular presentations on the beamline development with useful interactions with other users (NA62, NUTAG) and CERN experts. Contributing to the workpackage on searches for new physics.
- **The nuSTORM/ENUBET workshop in Cagliari**. A special joint plenary session with nuSTORM was organised on 9/9/2021. It was an important occasion to get a broad visibility and discuss possible scenarios in which both experiments could be fed by mesons produced in a common target station. A scenario involving a siting at the muon colliders test facility at the PS was discussed.
- Recently submitted the ENUBET physics case to the **Snowmass 2021** DPF Community Planning Exercise [10].
- We started a collaboration with the **PIMENT** project, funded by the French ANR for the next 3 years with Thomas Papaevangelou from CEA-Saclay as PI. It will deal with the possibility of **upgrading the ENUBET $t_0$-layer with a detector based on the PICOSEC thin gap Micromegas** detector to achieve sub-100 ps time resolutions on large areas.
- **Two new PhD students** from Thessaloniki University (advisor Prof. S. Tzamarias) will start working in ENUBET on waveform reconstruction and the identification of forward muons from pion decays.

# Final considerations and outlook

1) a very flexible and powerful **optimization framework based on genetic algorithms** implemented for the beamline → final design from improved FOM/statistics/par. space.

2) a working **framework to constrain the flux** from the lepton observables. Realistic simulation of the beamline and the detector and algorithms → next: final systematics budget.

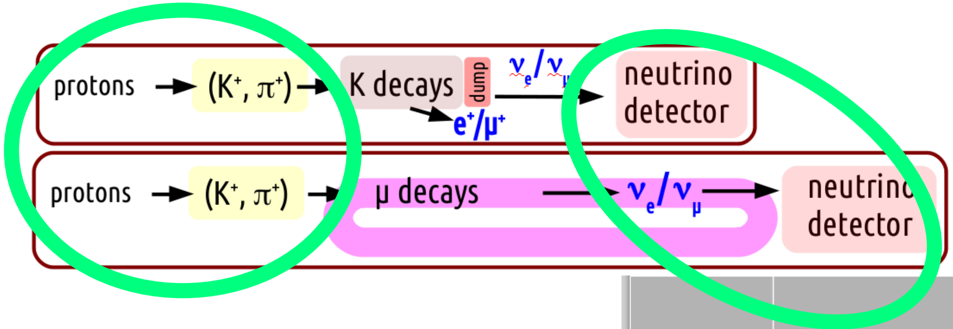
3) **demonstrator:** tight schedule ahead but feasible (main bottleneck scintillators)

4) publication of the ENUBET baseline (CDR) expected by end 2022

# backup

# ENUBET-nuSTORM synergies

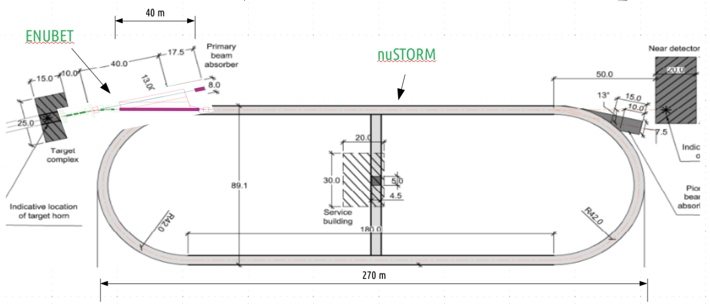
nuSTORM can be seen (simplistically) as an "ENUBET without a hadron dump" where pions and muons are channeled into a ring. Large room for smart ideas to match the requirements of the two experiments




- 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) $\nu_e$ pollution to $K_{e3}$ - $\nu_e$ | Slow extraction (+ quad triplets) "slow" in bursts (+horn) 400 GeV | similar | Similar but at ~100 m (some flexibility) |
| nuSTORM | Replaced by straight section of the ring (180 m). | No. μ kept: the most interesting flux parents. | Fast extraction (+horn) 100 GeV | similar | Similar but at > 300 m from target (ring straight section) |




Engineering studies starting within Physics Beyond Colliders

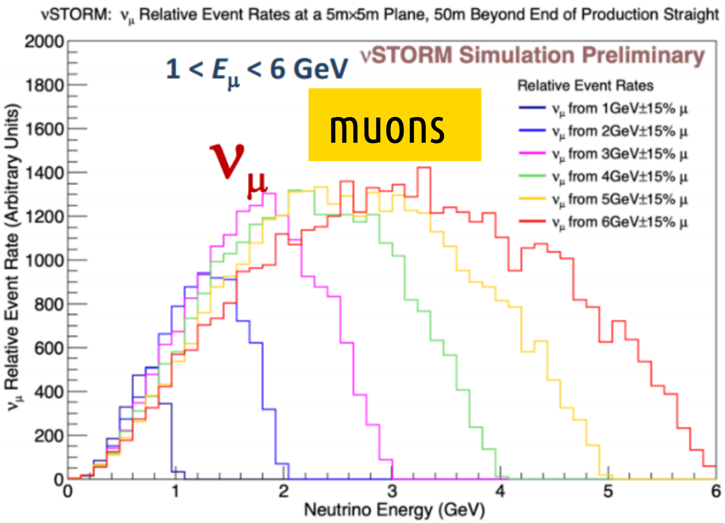
# Fluxes decomposition

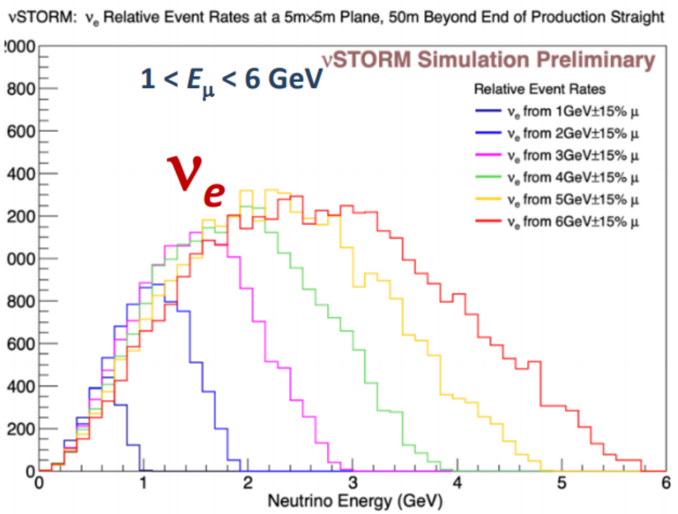
**nuSTORM**: vary the channeled muon energy from 1 to 6 GeV/c

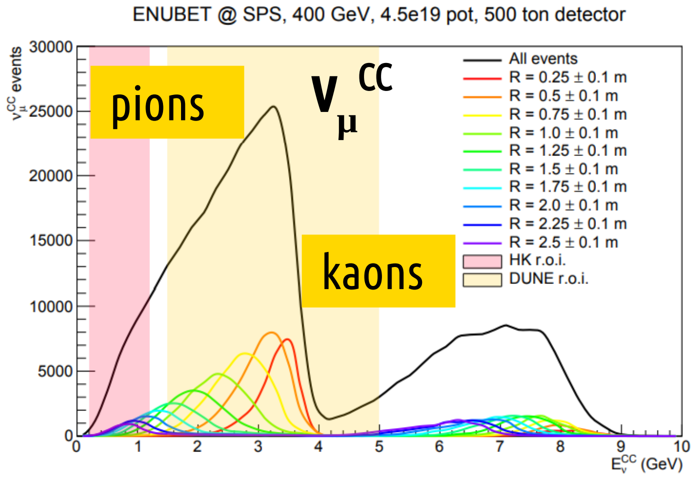
**ENUBET** narrow-band off-axis technique:

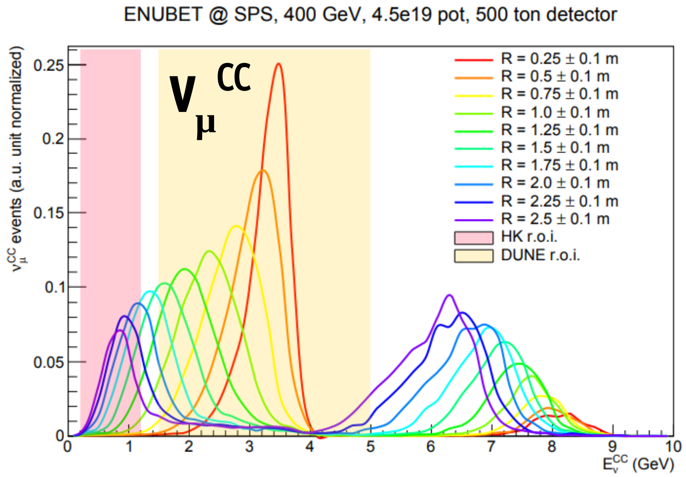
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. “Easy” rec. variable.

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



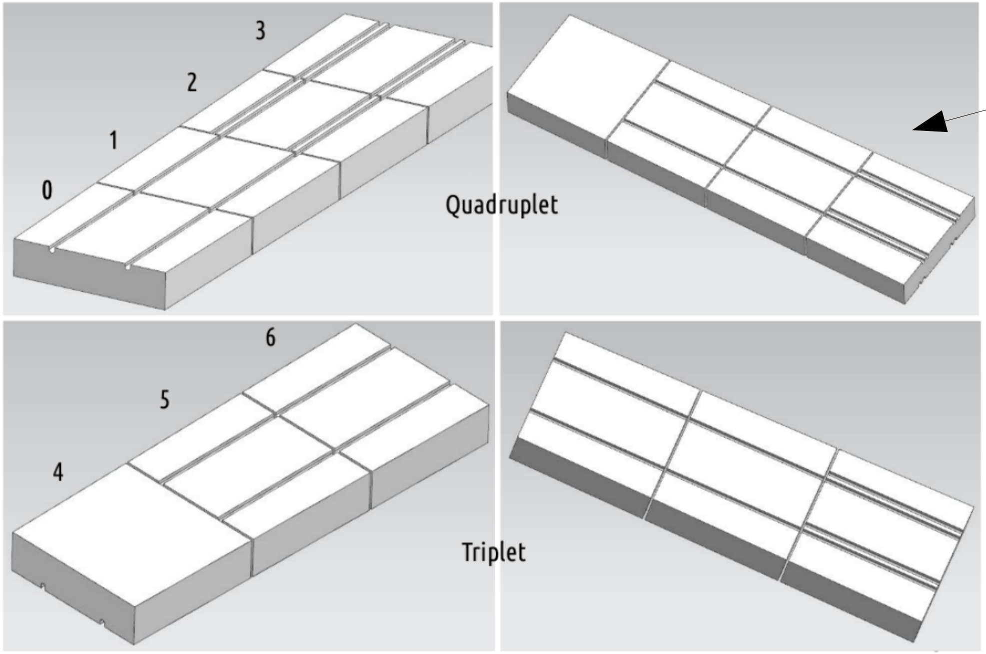



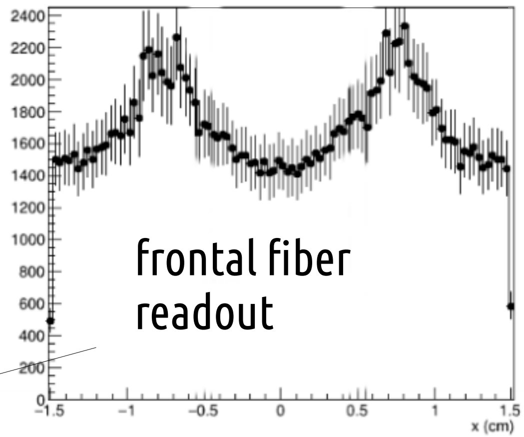



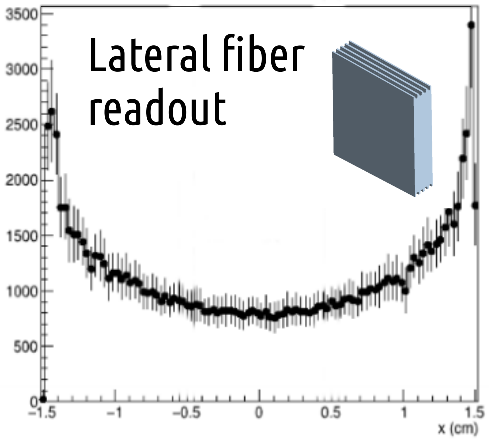
# Updated light readout scheme

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

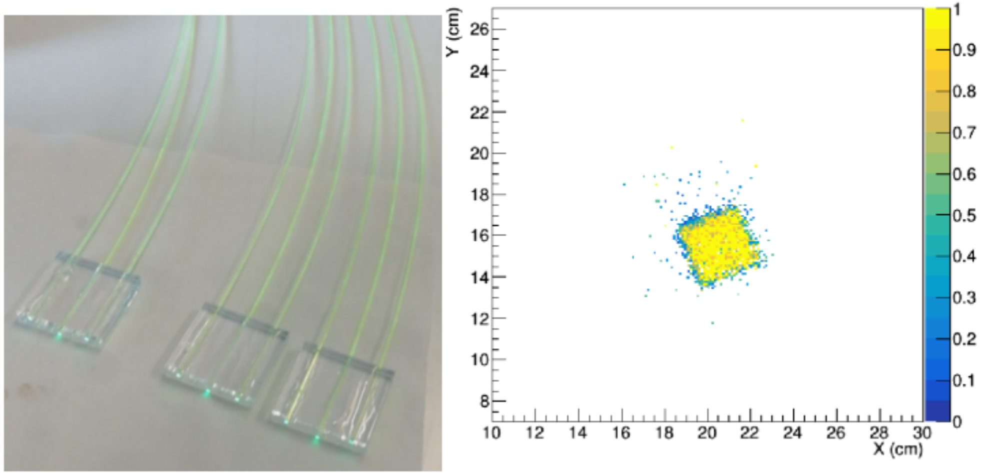



GEANT4 optical simulation



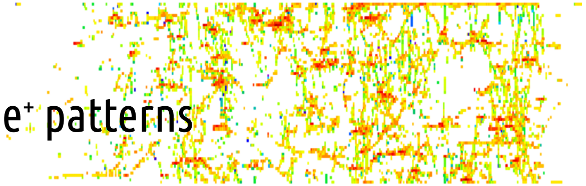

Uniformity tests with cosmic rays

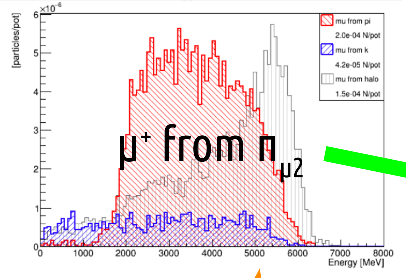


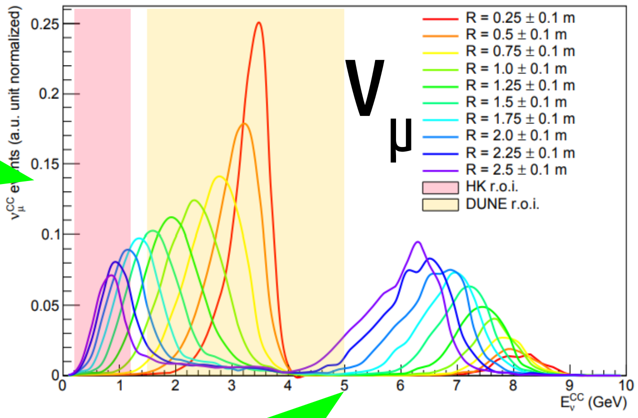
# Lepton monitoring

Tagger: leptons from K ($\nu_e$ and high-E $\nu_\mu$)

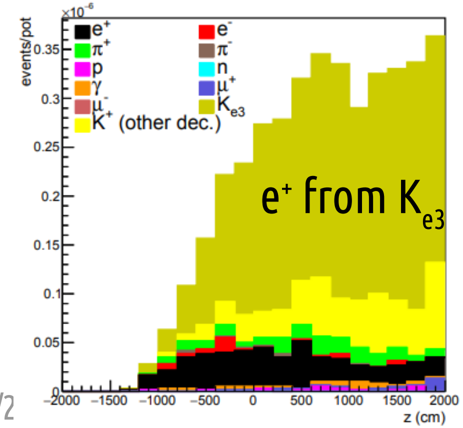
Hadron dump instr: μ from π (low-E $\nu_\mu$)

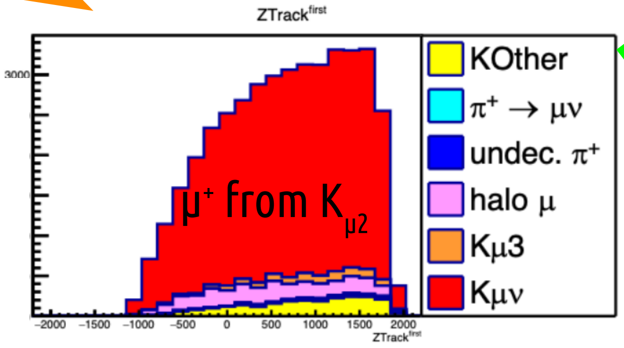


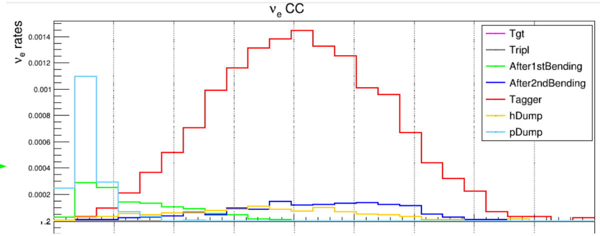





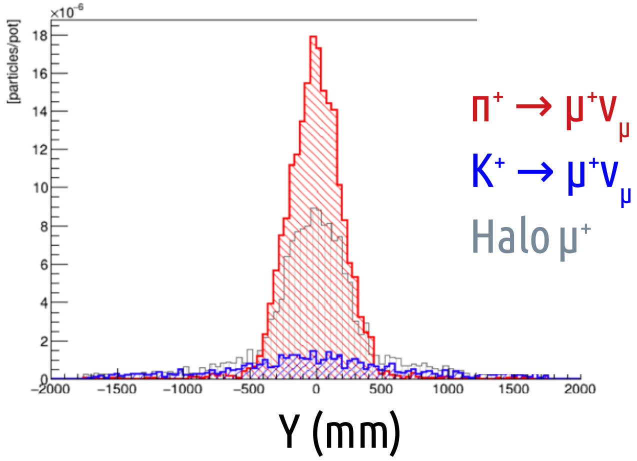


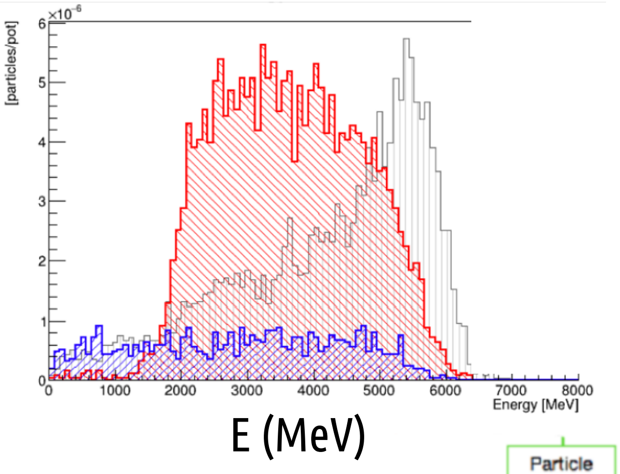



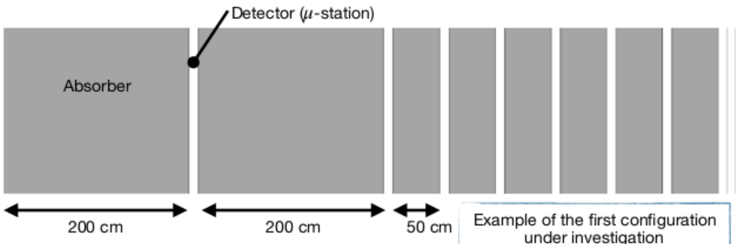



# Forward region muons reconstruction

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 $\nu_\mu$.

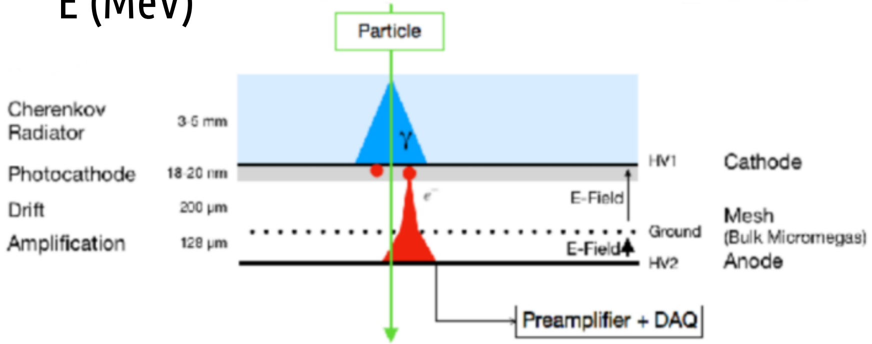


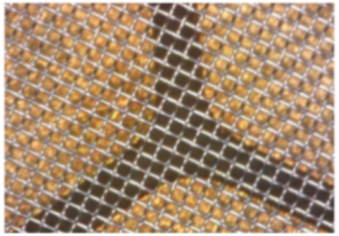




The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm$^2$ and about $10^{12}$ 1 MeV-n$_{eq}$/cm$^2$.

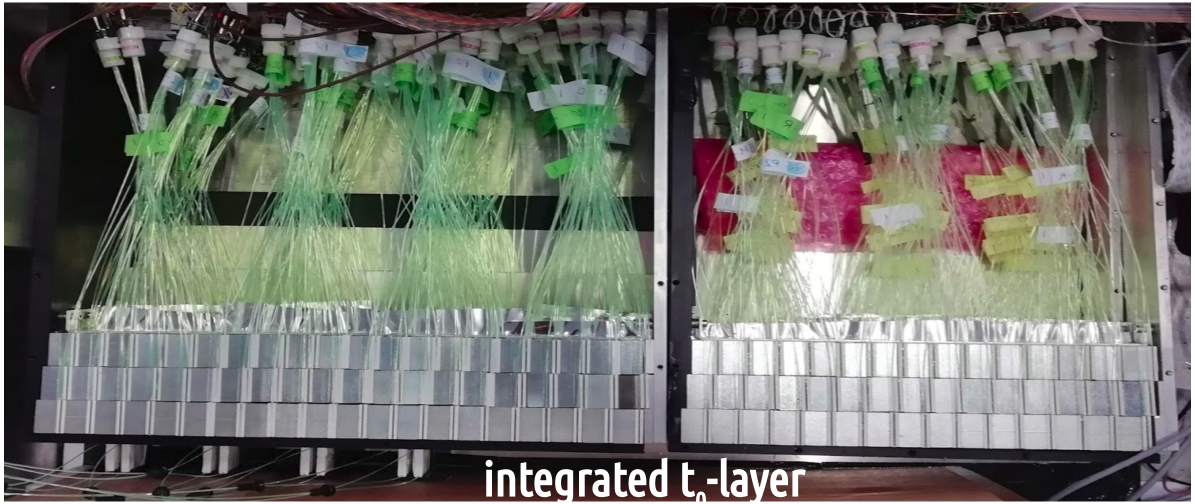
Design being defined. Possible candidate: fast Micromegas detectors employing Cherenkov radiators + thin drift gap (PIMENT). Bonus: excellent timing.

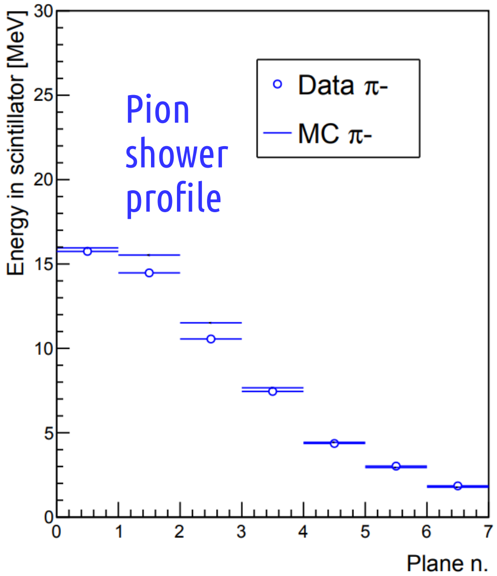


JINST 15 (2020) 08, P08001

# ENUBET: prototypes at the CERN-PS

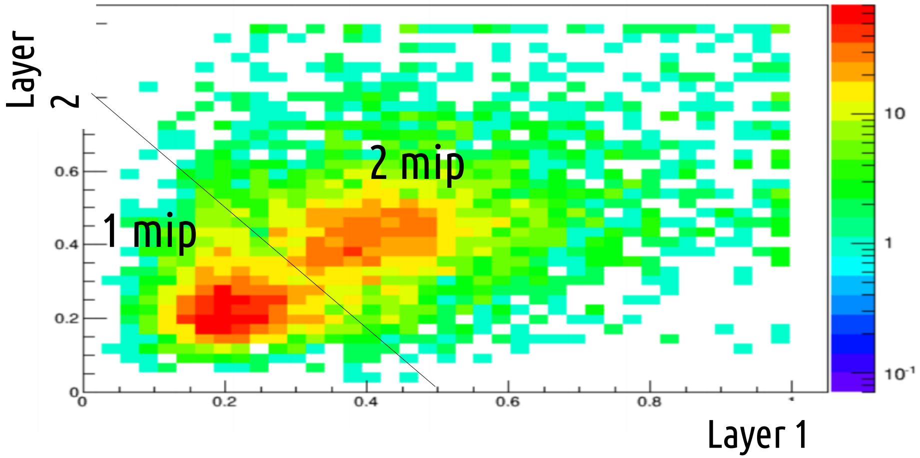



charge exchange: $\pi^- p \rightarrow n\, \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2

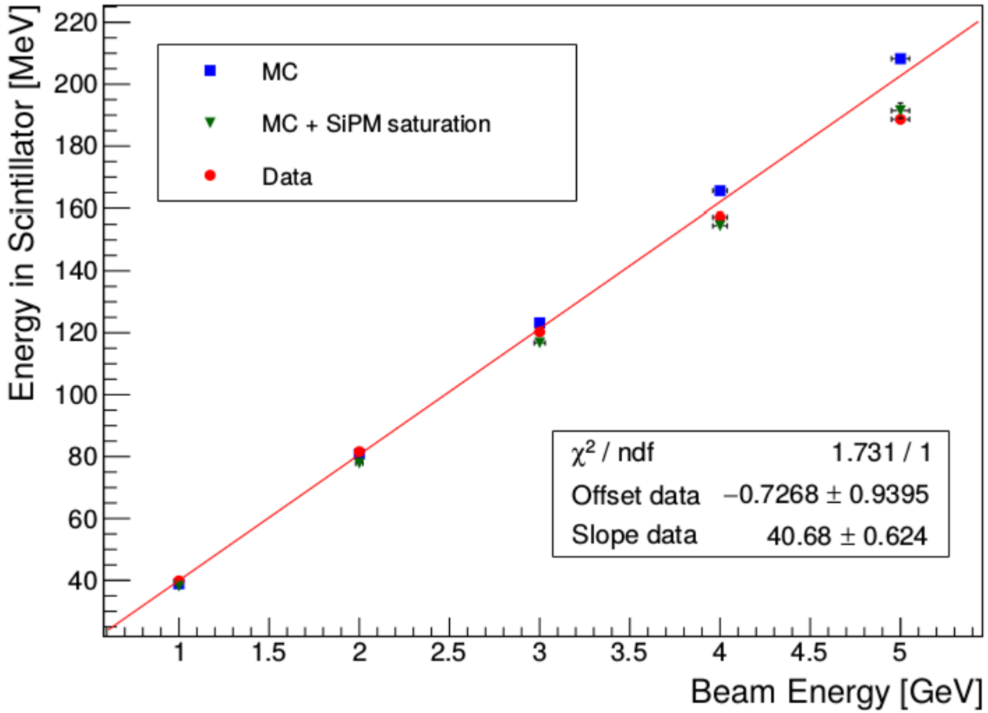

$\sigma_t \sim 400$ ps



JINST 15 (2020) 08, P08001

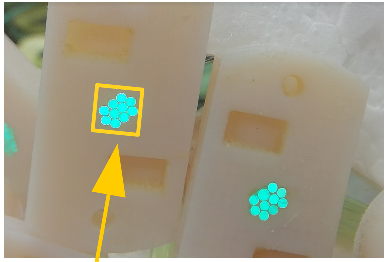
# ENUBET: prototypes at the CERN-PS

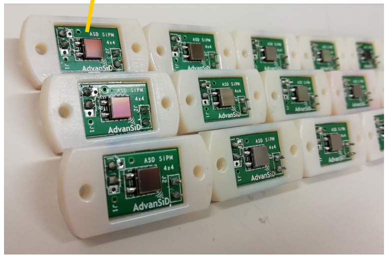
$$N_{\text{fired}} \simeq N_{\max}\left(1 - e^{-N_{\text{seed}}/N_{\max}}\right)$$




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

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





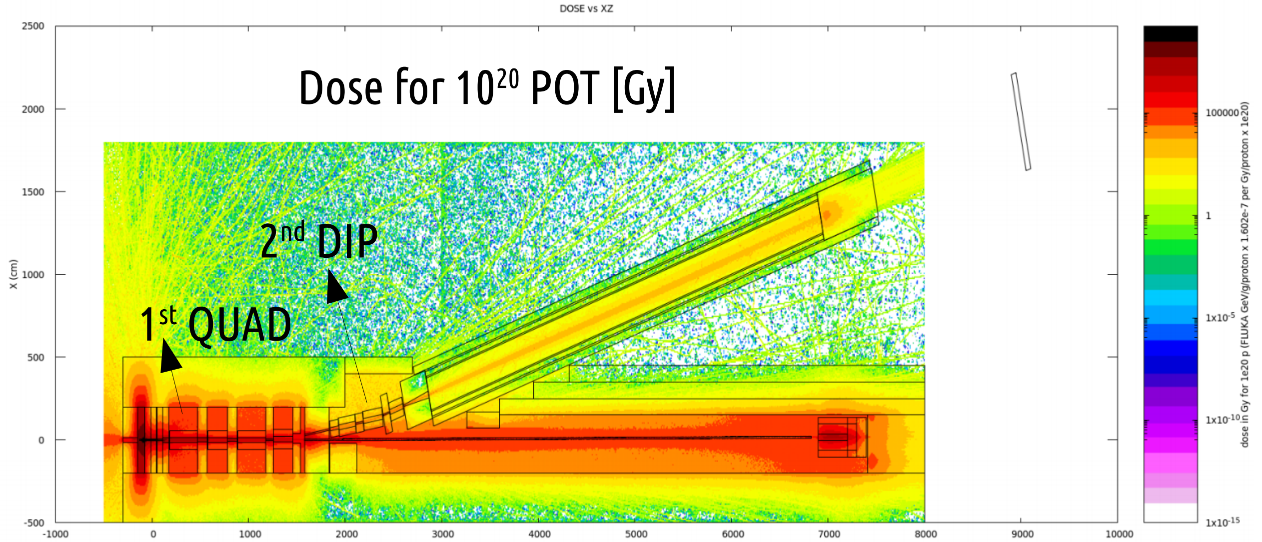
New SiPMs under test (NUV, RGB high density and low cross talk from FBK)

# FLUKA irradiation studies

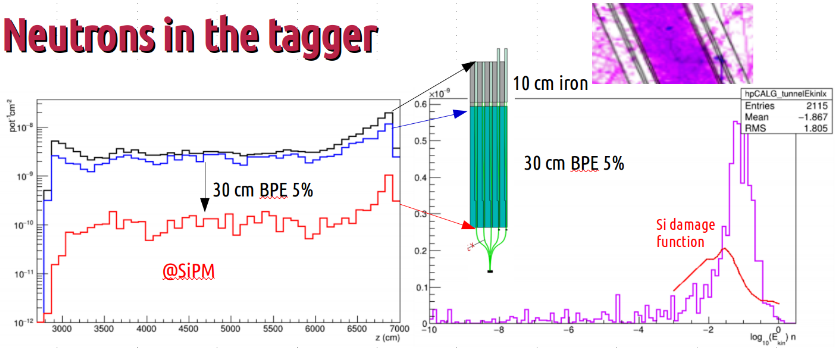
Detailed FLUKA simulation of the setup

Guided the design of the detector technology for the demonstrator

Good lifetime of instrumentation and focusing elements achieved.

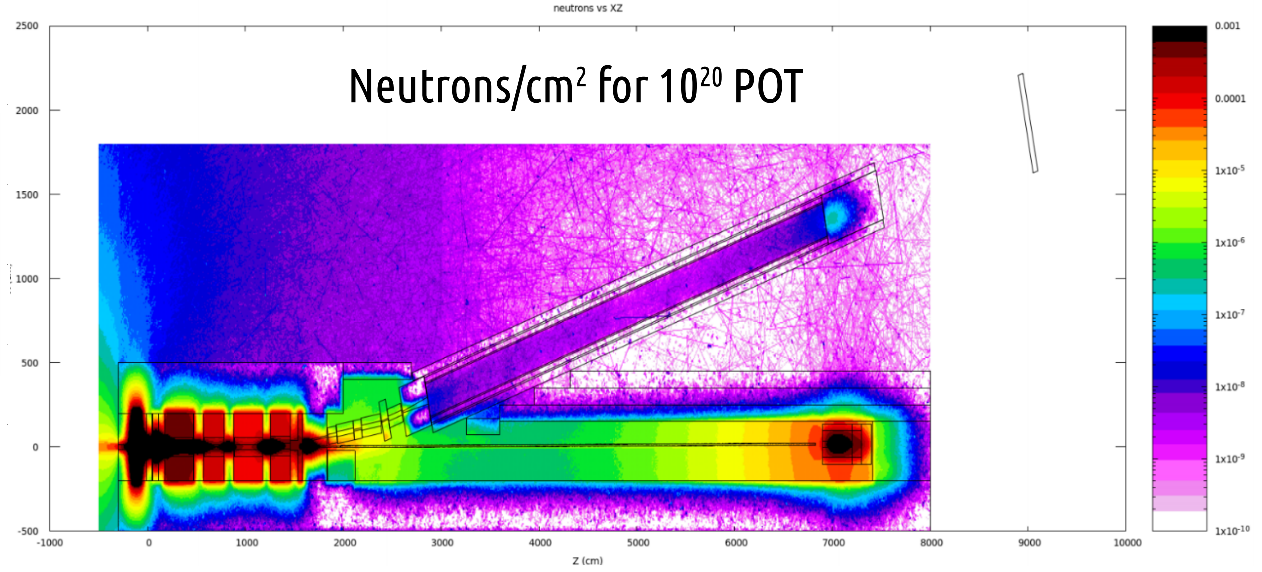



## Neutrons in the tagger




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

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



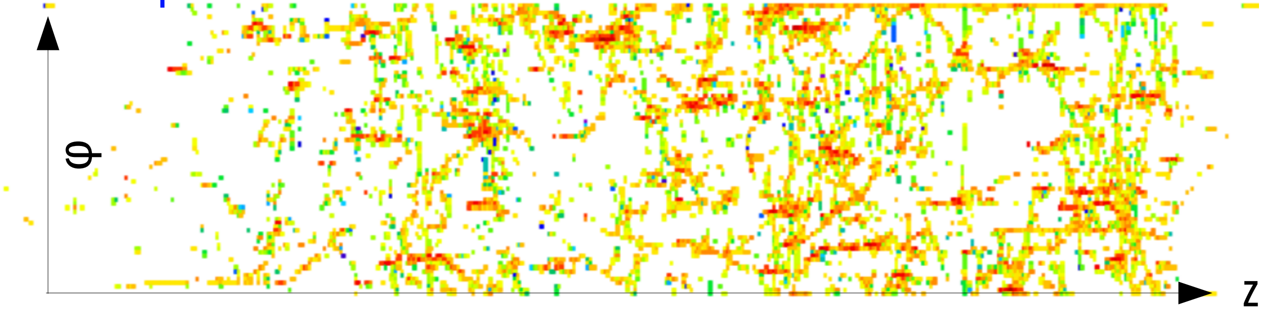
# ENUBET: lepton reconstruction

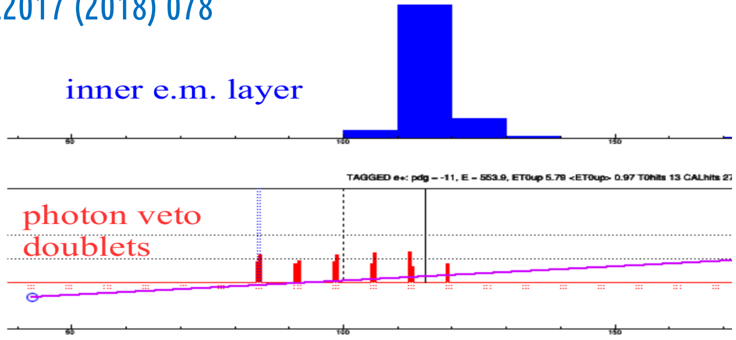
Talk by F. Pupilli

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

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

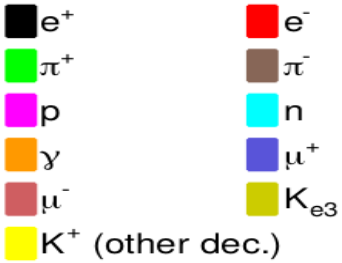
Hit map for $e^+$

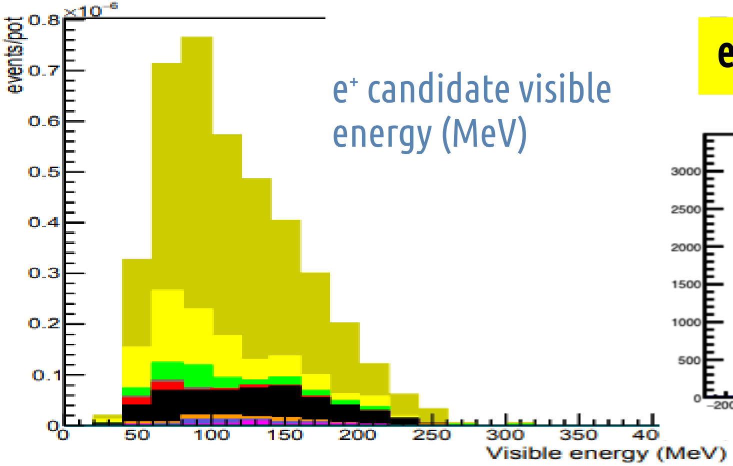



**$K_{e3}$ e+: Efficiency ~22%, S/N of ~2**

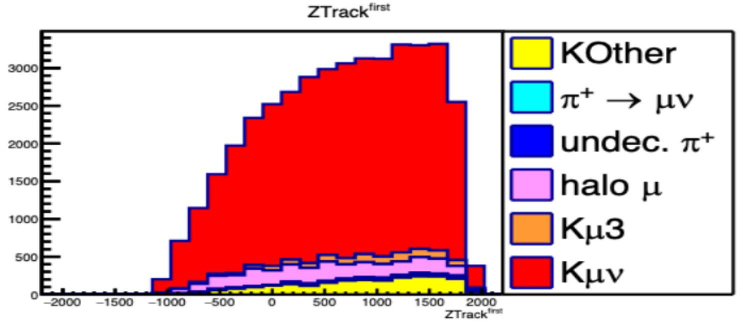
Half of efficiency loss is geometrical




$e^+$ candidate visible energy (MeV)

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

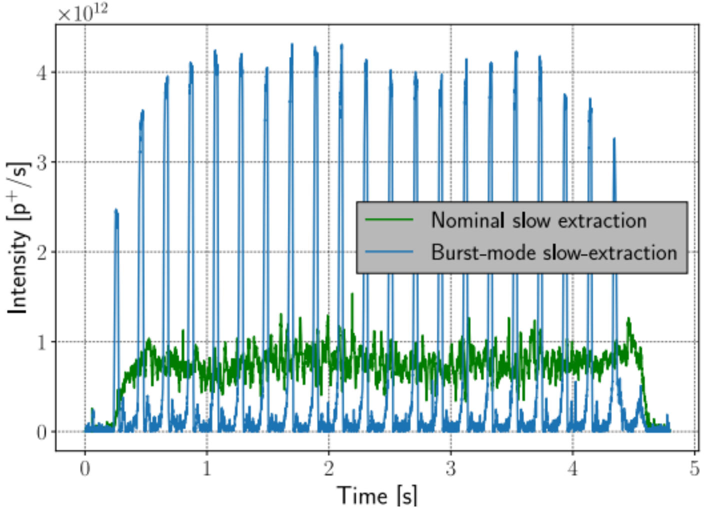


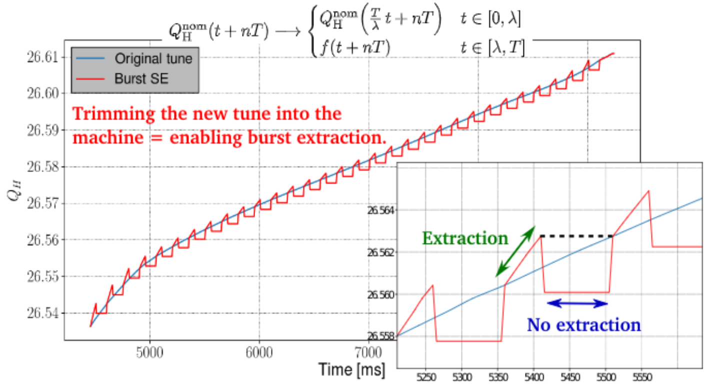

$\mu^+$ candidate z coord (cm)

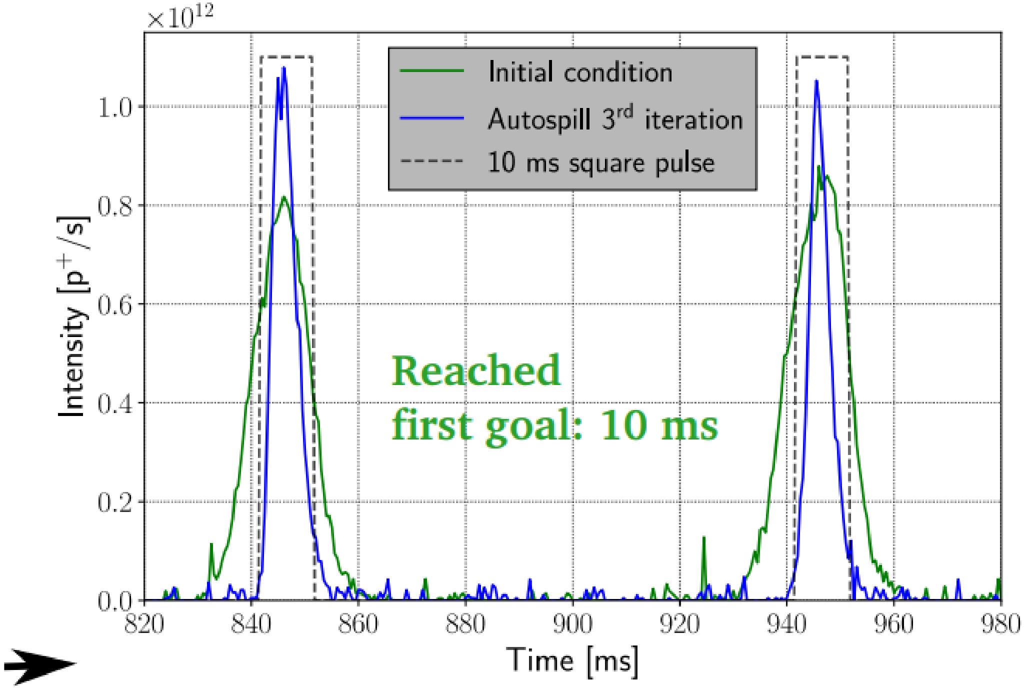
# Proton extraction R&D for horn focusing

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

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

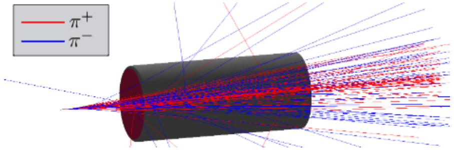


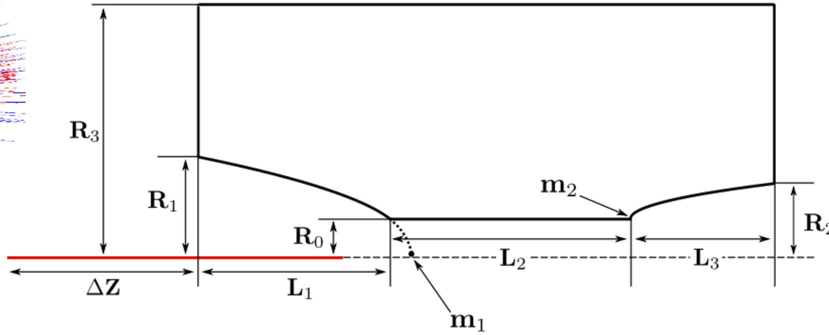



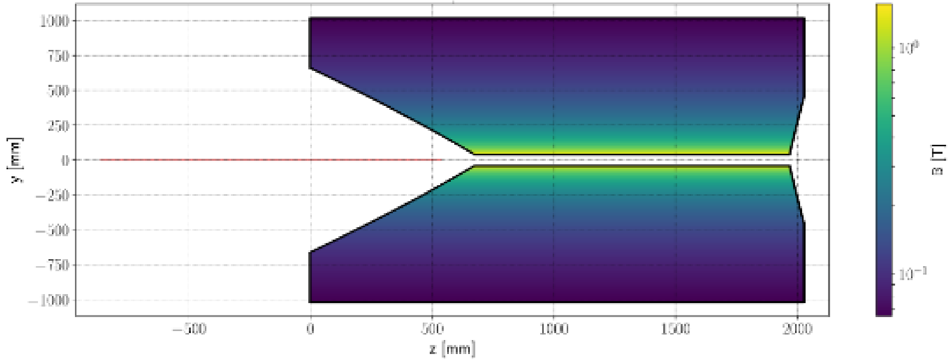

PhD thesis of M. Pari (UniPD + CERN doctoral).
Defended 23/2/21.

# Horn optimization



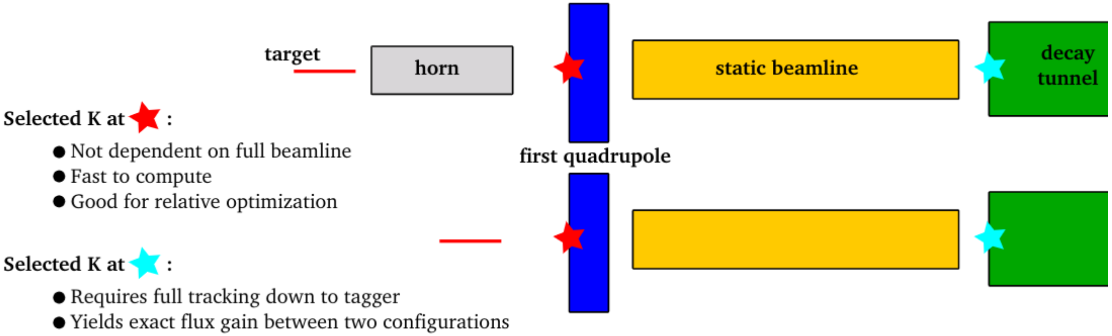

- New **double-parabolic** geometry (formerly MiniBooNE-like)
- New **genetic algorithm** implemented successfully to sample the large space of parameters.
- FoM is ~ number of collimated $K^+$ with p ~8.5 GeV/c
- Convergence in O(100) iterations
- First candidate designs worked out



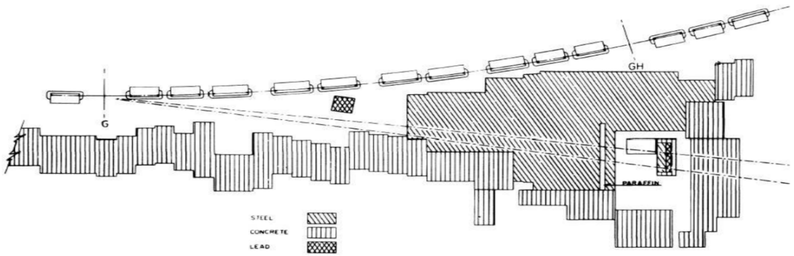

We were able to reach values of the **standalone FoM (★) of x 3 higher than the static case**. These results confirm an improvement w.r.t. early studies.

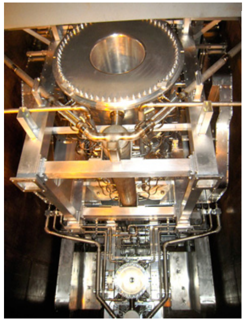
When plugged to the existing beamlines the gain factor reduces to only **x 1.5 → next step:** dedicated beamline optimization (★) to profit of the horn-option initial gain → larger apertures for initial quads.

Can extend the same systematic optimization tool.

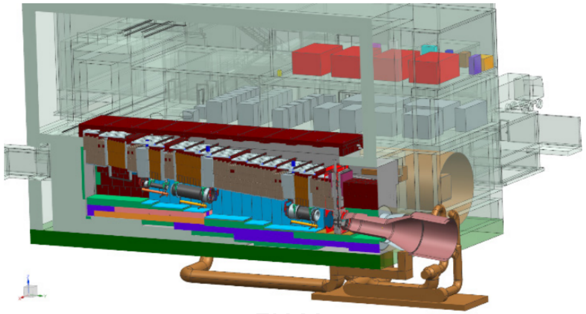


# Accelerator based neutrino beams



J-PARC



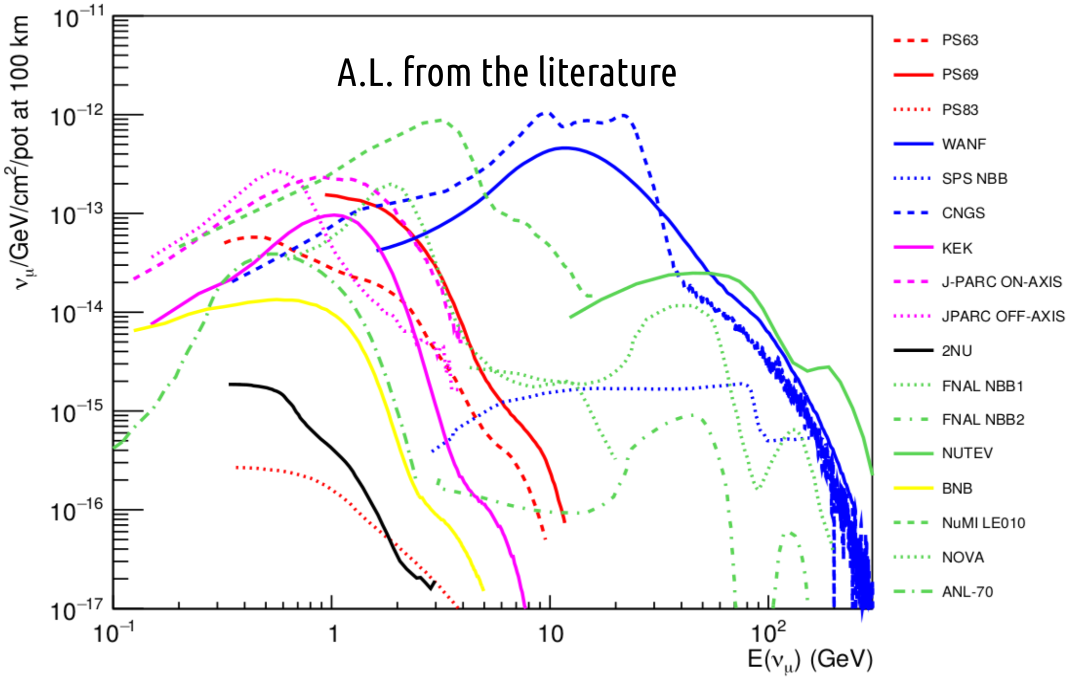
FNAL

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

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

More “**brute force**” than conceptual innovations. Still OK in the era of “statistical errors-dominance” and “large $\theta_{13}$” but ...

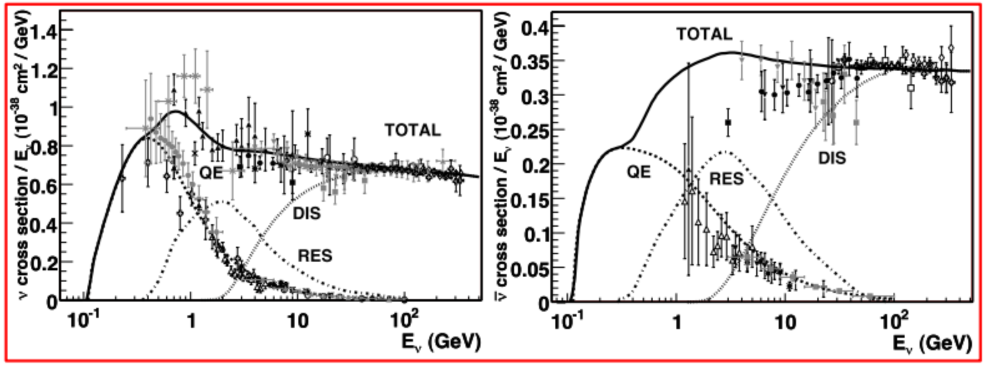
New future challenges ($\delta_{CP}$, searches) require timely **changes** or at least **“adjustments”** in this strategy.

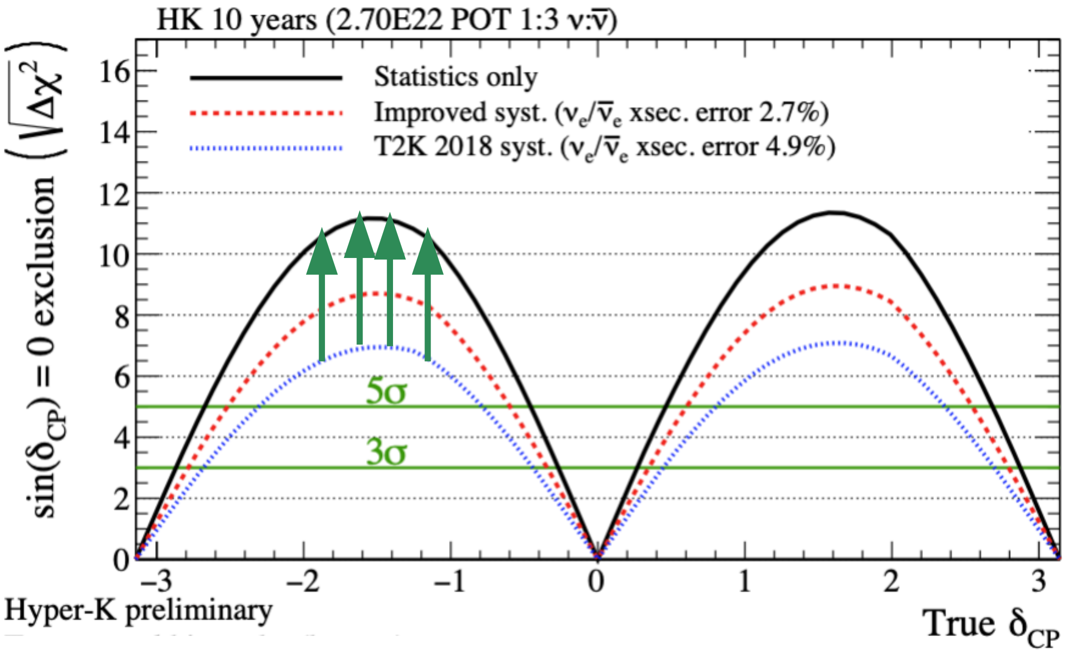


# Precision for the Hyper-K/DUNE era

F. Di Lodovico, Neutrino Telescopes 2021

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




ENUBET and nuSTORM

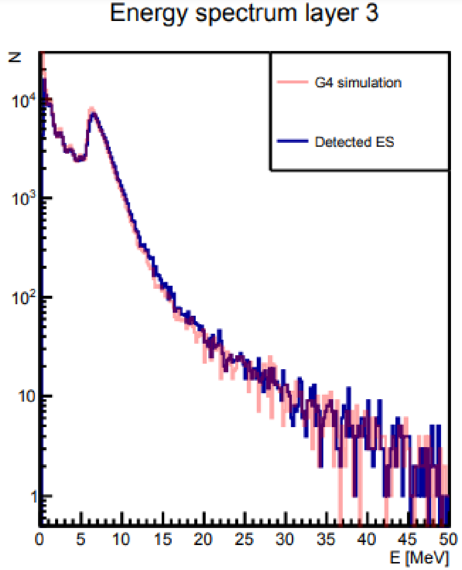
(see also the **European Strategy** Physics Briefbook, arXiv:1910.11775)

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

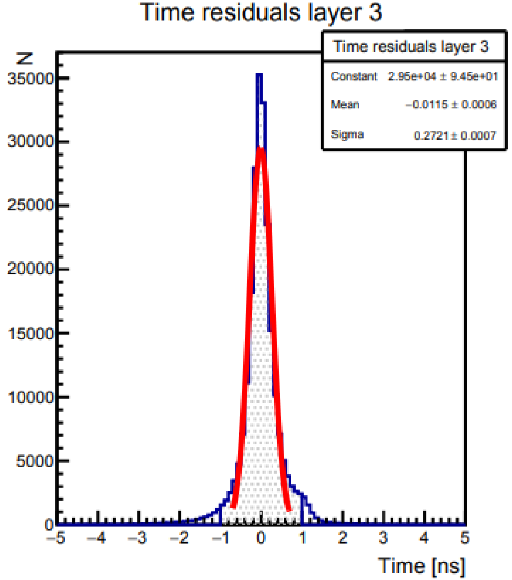
# Waveform analysis

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

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




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




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

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

# Tagged neutrino beams

Profit of advances/affordability of excellent **timing capabilities over large areas →**

**→ time coincidences of $\nu_e$ and $e^+$**

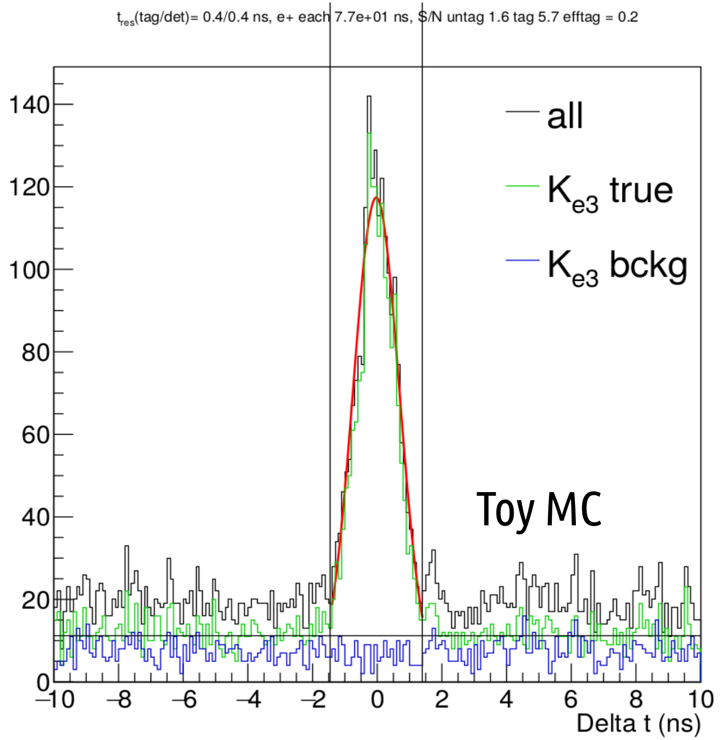
**Example with reconstructed $e^+$**
**$2.5\times10^{13}$ pot / 2s with 20% eff. S/N 1.6**

genuine $K_{e3}$ cand. : → **1 every ~ 77 ns**
background $K_{e3}$ cand. ~ 0.6 x → 1 cand / ~ 130 ns

Assumed time resolution: $0.4 \oplus 0.4$ ns

Flavour and energy determination at **interaction level** are enriched by information at the **decay level**.

Distance corrected Δt between tagged leptons and neutrino interactions



# Toy simulation

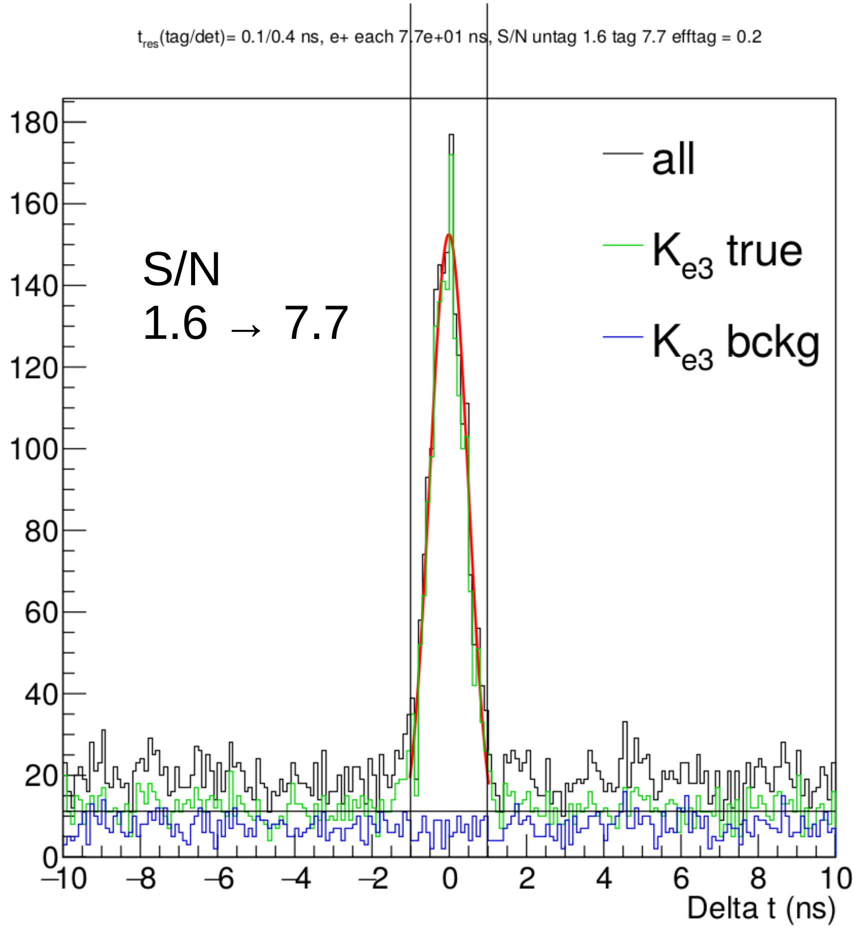
**Parameters:**

**Timing res of tagger/detector**
**Reconstruction eff (inc. acceptance)**
**S/N of reconstructed leptons**

**TODO:**

**Use information from the reconstructed lepton candidates to cross check and refine**

**Show distributions of leptons after timing cut (improvement in purity)**



# Full simuation with true-level electrons

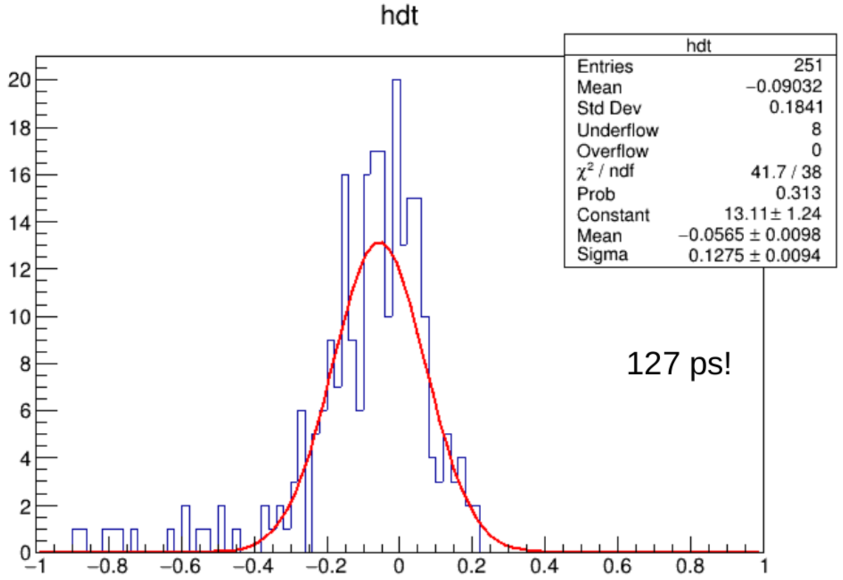
Based on GEANT4. Estimates the spread due to the non collinearity of products
(no contribution from experimental smearing of time measurements)

## Ke3 selection based on the G4/G4TAG shared data structure

14/2/21

Time coincidences

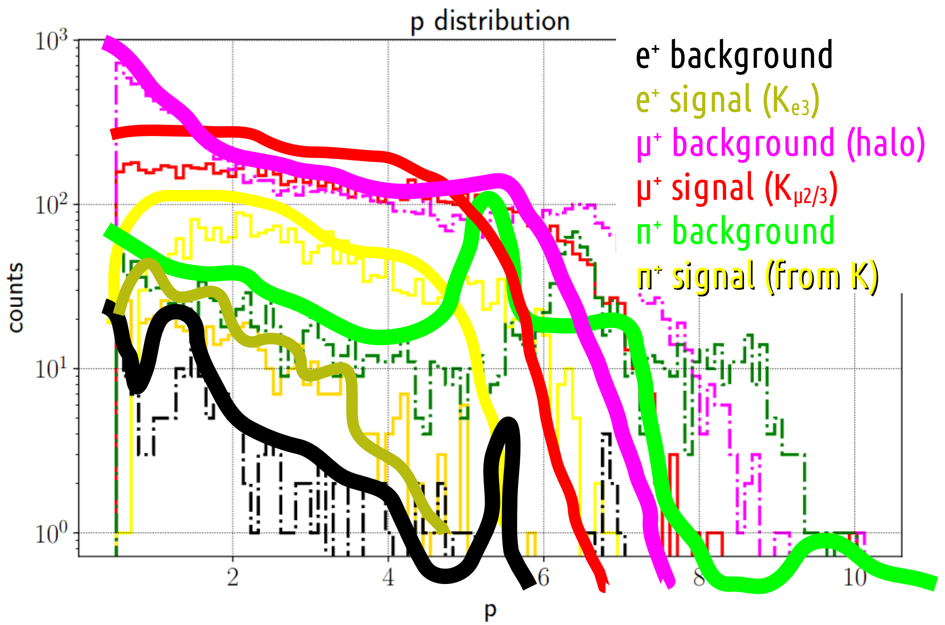
Spread is consistent with estimates from the 2015 paper (difference in paths btw lepton and neutrino)

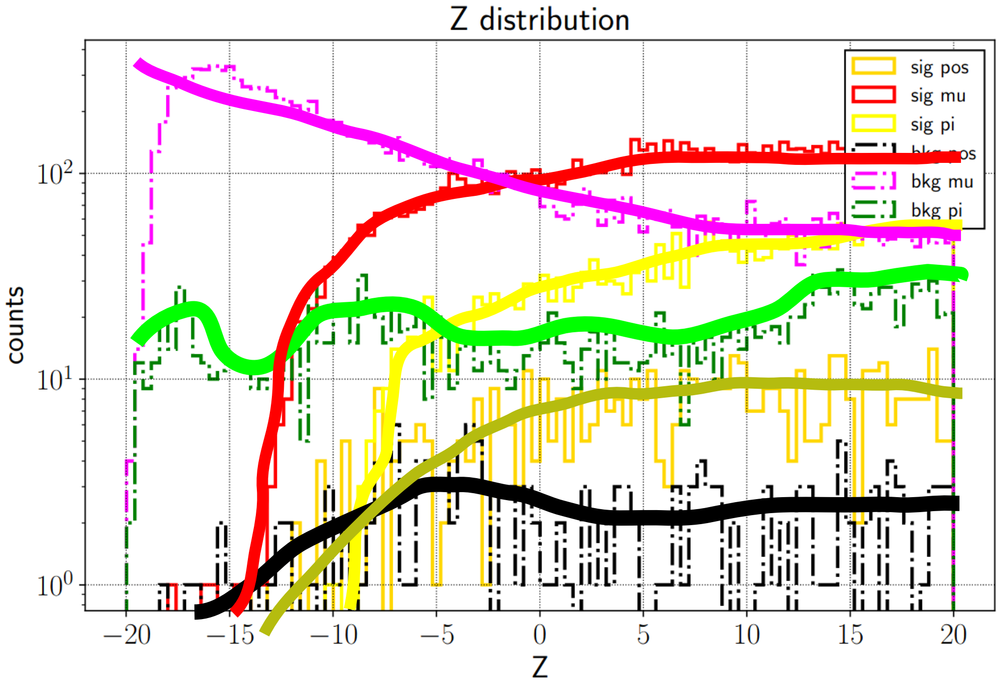


# Pion sample

TLR6v4

Particles hitting the tagger at true level




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

# ENUBET: flux constraint

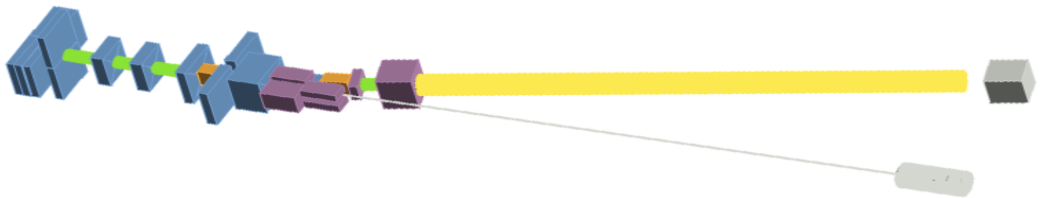
Not directly taggable components:

1) $\nu_e$ from $K^{0+/-}$ in the proton/hadron dump

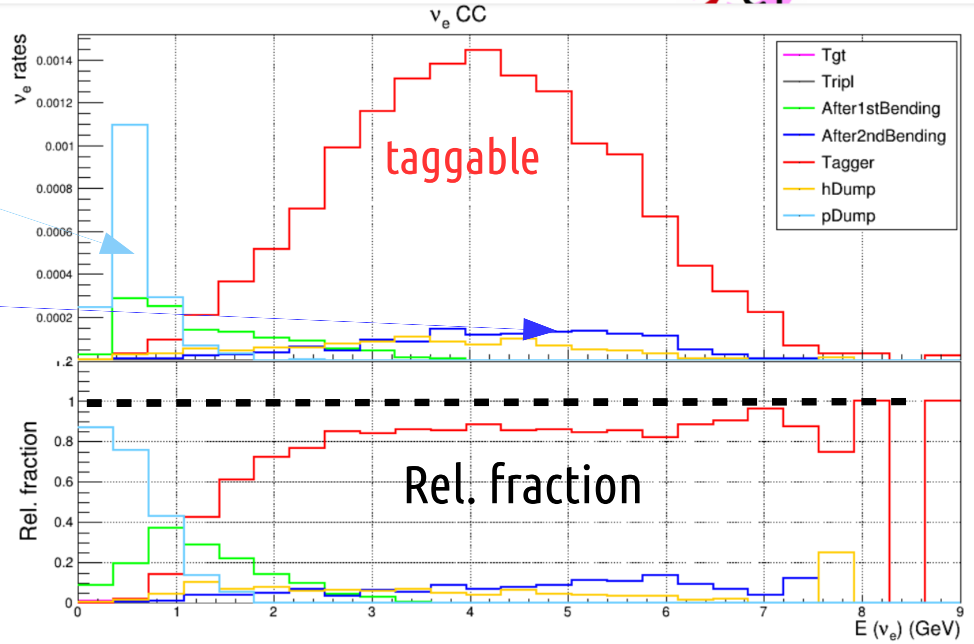
→ reduce by tuning the dump geometry/location

2) $\nu_e$ from $K^+$ in front of the tagger

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



$\nu_{e\,CC}$ spectra




**Uncertainty reduction for the tagged flux component**

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

**An example:**

Each histogram component corresponds to a bin in neutrino energy