This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

ENUBET: the first monitored neutrino beam

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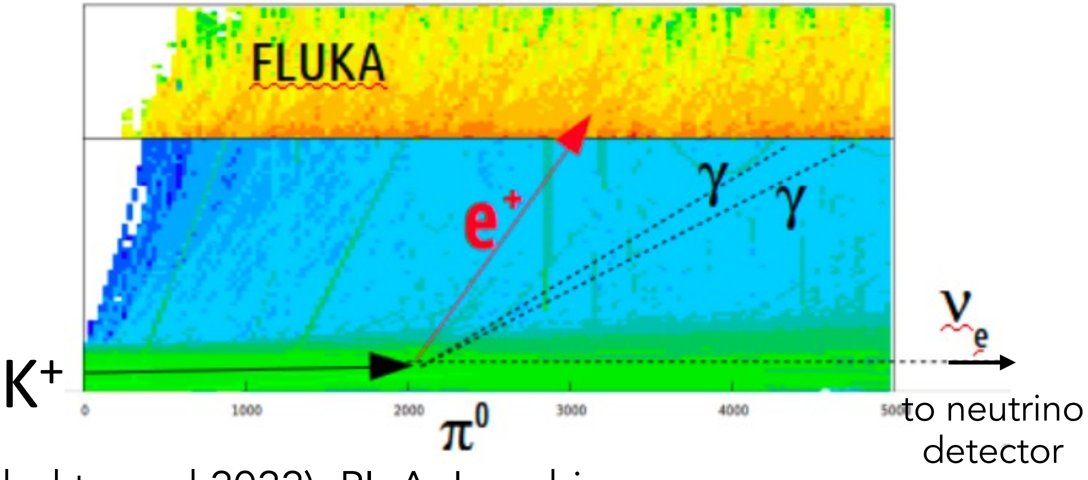
*on behalf of the ENUBET Collaboration

ICHEP 2022 - XLI International Conference on High Energy Physics

July 6-13, 2022 – Bologna, Italy

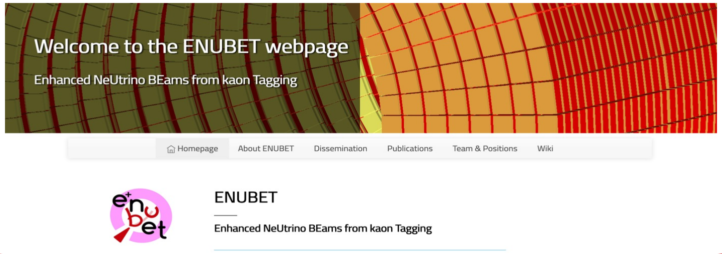
Outline

- ENUBET is the project for the realization of the first monitored neutrino beam.
  In the next slides:
  - Beamline final design and parameters fine tunning;
  - Chosen decay tunnel instrumentation;
  - Lepton reconstruction PID performance;
  - Hadroproduction systematics assessment;
  - Demonstrator status;



- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (COVID: extended to end 2022). PI: A. Longhin;
- Since April 2019: CERN Neutrino Platform Experiment – NP06/ENUBET – and part of Physics Beyond Colliders (PBS);
- Collaboration: 60 physicists & 13 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/



Systematics matter!

Next generation long-baseline experiments (DUNE & HyperK) conceived for precision ν-oscillation measurements:

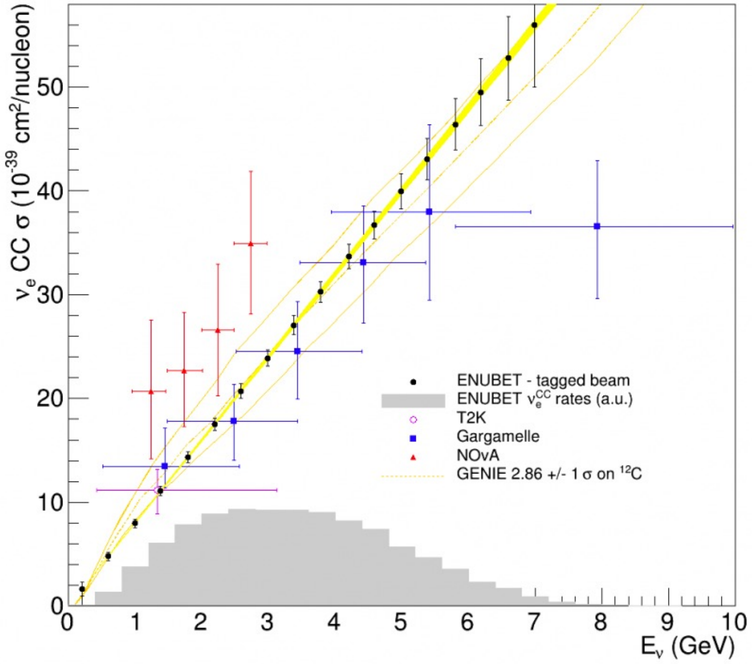
- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP asymmetry in the lepton sector;

$$N_{\nu_e}^{FAR} = P_{\nu_\mu \to \nu_e} \cdot \sigma_{\nu_e} \cdot \Phi_{\nu_\mu}^{FAR}$$

Very good knowledge needed!

Moreover ν-interaction models would benefit from improved precision on cross-sections measurements

ENUBET impact on σ_{ν_e}



The purpose of ENUBET: design a narrow-band neutrino beam to measure

- neutrino cross-section and flavor composition at 1% precision level;
- neutrino energy at 10% precision level;

From the **European Strategy for Particle Physics Deliberation document**:

To extract the most physics fromDUNE 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 first monitored neutrino beams

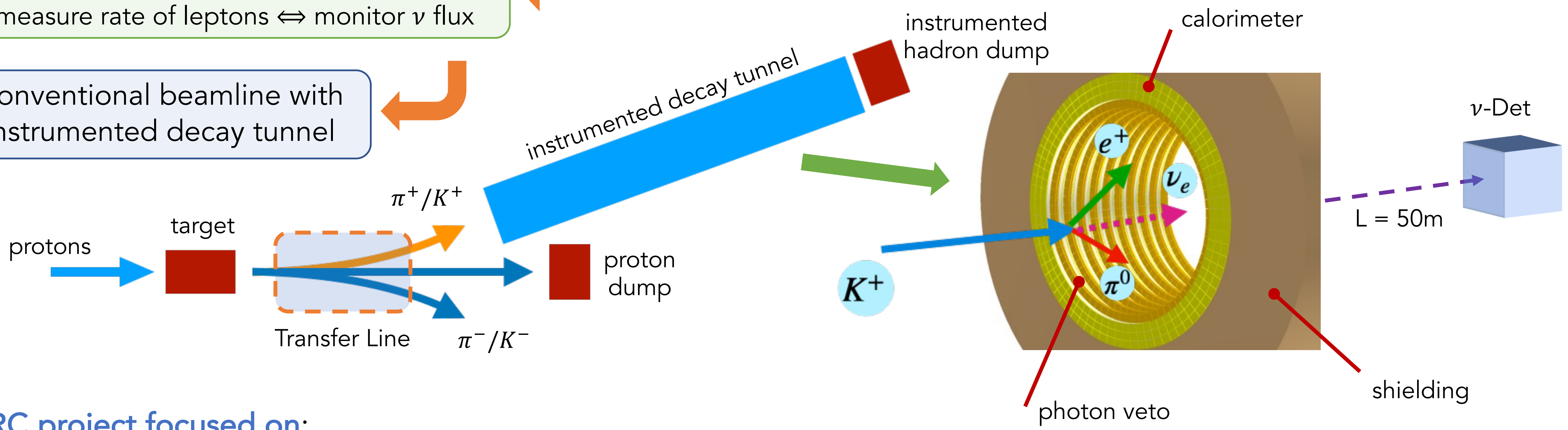
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam

measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

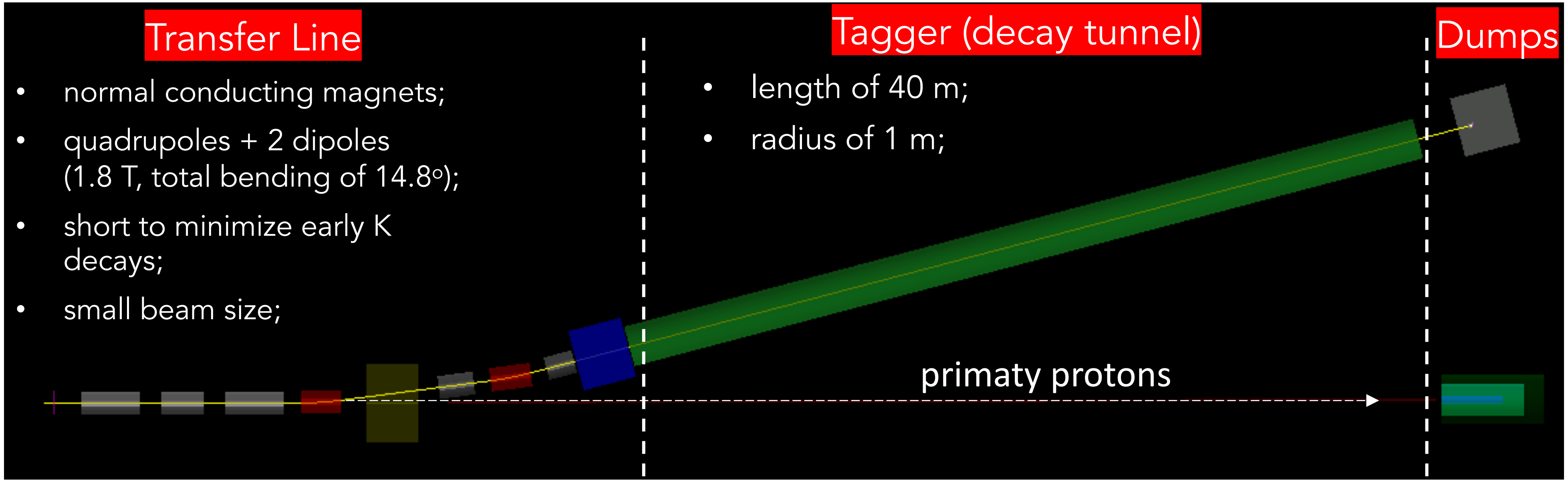
A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

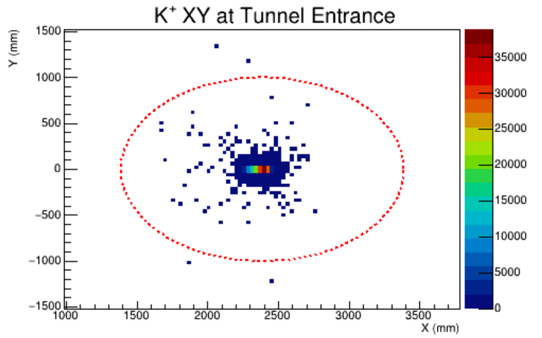


- **ERC project focused on**: measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**: extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

The ENUBET beamline: the final design





Rates @ Tunnel entrance for 400 GeV POT	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.13	0.34

~1.5X w.r.t. previous results

Large bending angle of 14.8°:

- better collimated beam + reduced muons background + reduced ν_e from early decays;

Transfer Line:

- optics optimization w/ **TRANSPORT** (5% momentum bite centered @ 8.5 GeV) **G4Beamline** for particle transport and interactions;
- **FLUKA** for irradiation studies, **absorbers and rock** volumes included in simulation (not shown above);
- **optimized graphite target** 70 cm long & 3 cm radius (dedicated studies, scan geometry and different materials);
- **tungsten foil downstream target** to suppress positron background;
- tungsten alloy **absorber @ tagger entrance** to suppress backgrounds;

Dumps:

- **Proton dump**: three cylindrical layers (graphite core -> aluminum layer -> iron layer);
- **Hadron dump**: same structure of the proton dump -> allows to reduce backscattering flux in tunnel;

Full facility implemented in GEANT4:

- Controll over all paramaters;
- Access to the paricles histories;

assessment of the nu flux systematics

ν_e^{CC} energy distribution @ detector

A total ν_e^{CC} statistics of 10^4 events in ~3 years

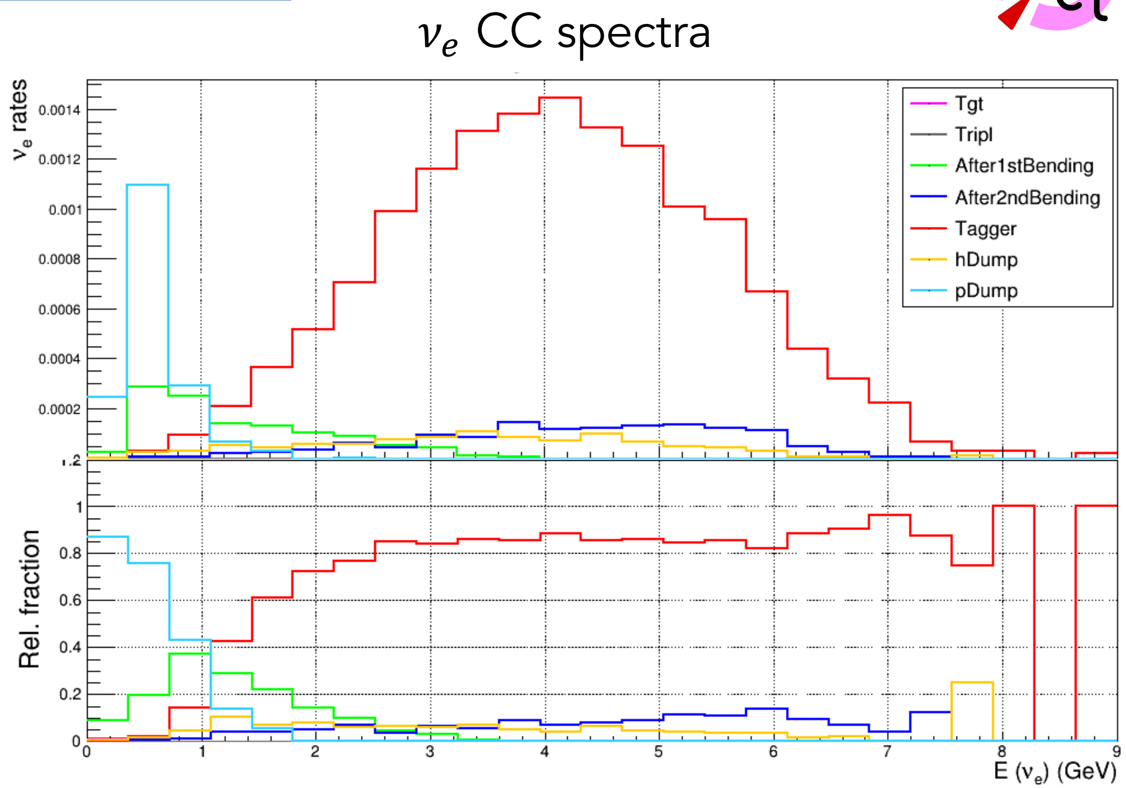
- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;

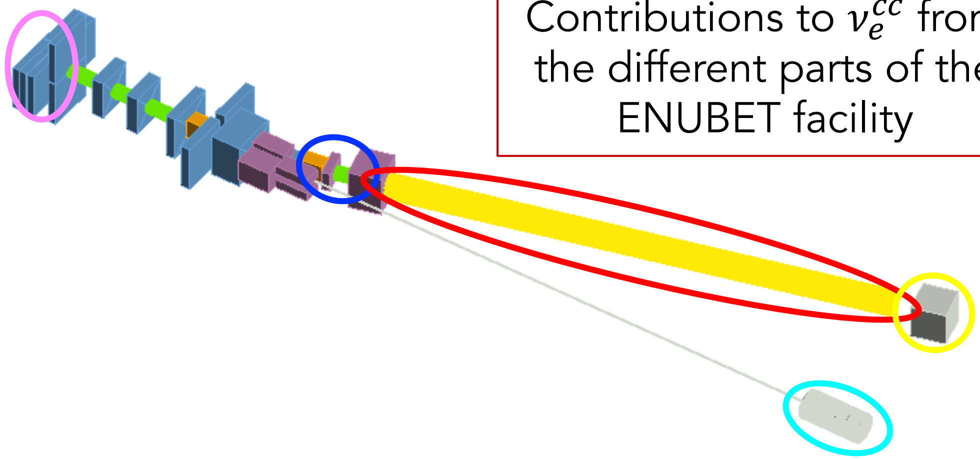
Taggable component

About 80% of total ν_e flux is produced by decays in the tunnel (above 1 GeV)

Non taggable components:

- **Below 1 GeV**: main component produced in p-dump
  - clear separation from taggable ones (energy cut);
  - further improvements in separation optimizing p-dump position;
- **Above 1 GeV**: contributions from straight section before tagger and hadron-dump;
  - rely on simulation for this component;





Contributions to ν_e^{CC} from the different parts of the ENUBET facility

ν_μ^{CC} energy distribution @ detector

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

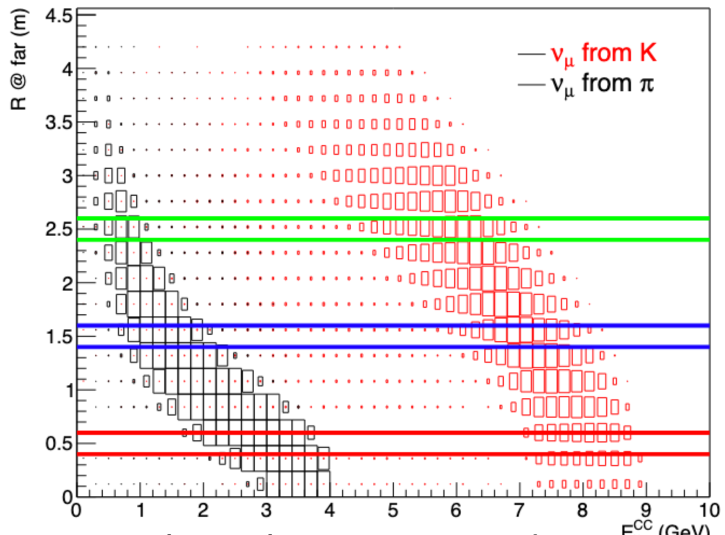
E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

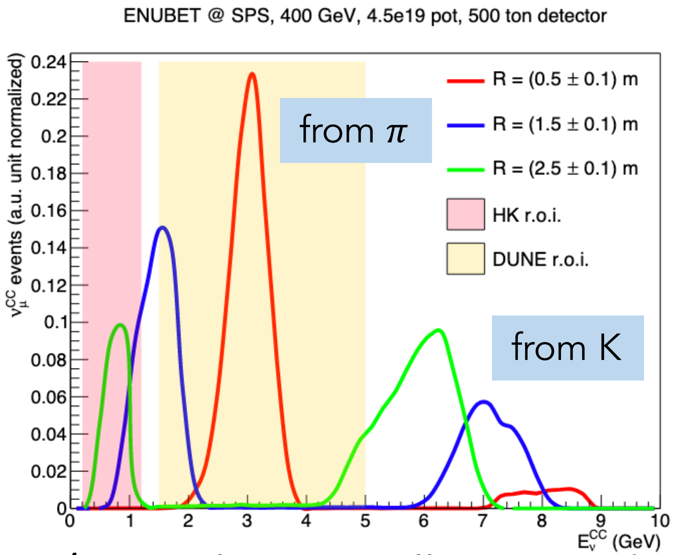
F. Acerbi et al., CERN-SPSC-2018-034

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

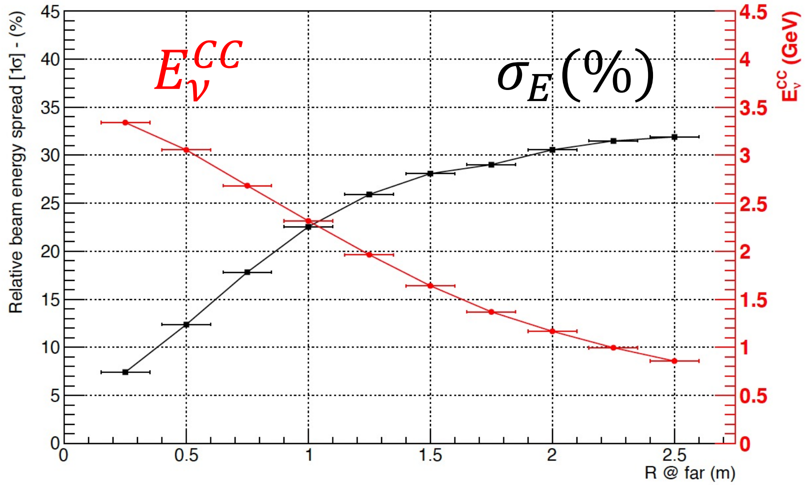
- 8-25% E_ν resolution from π in DUNE energy range;
- 30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):
  - ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



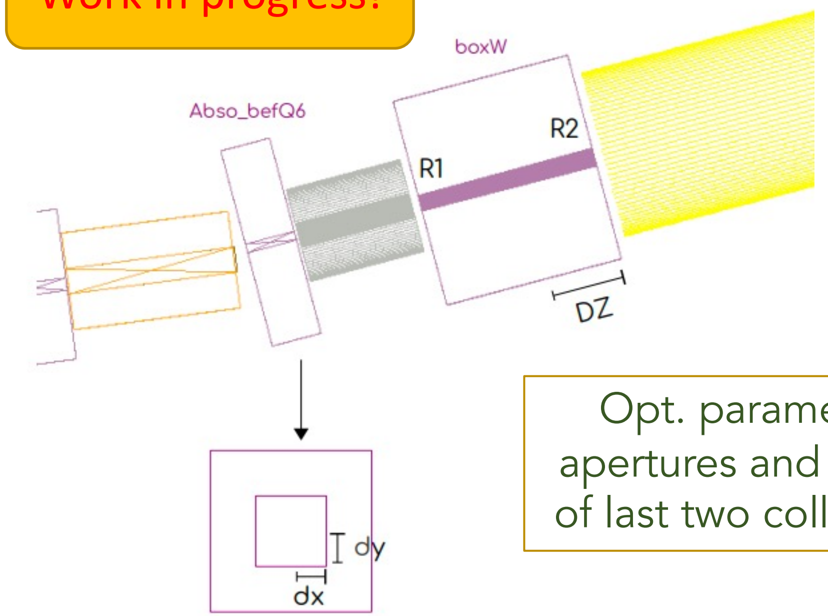
π/K populations well separated



from pion peaks at different R

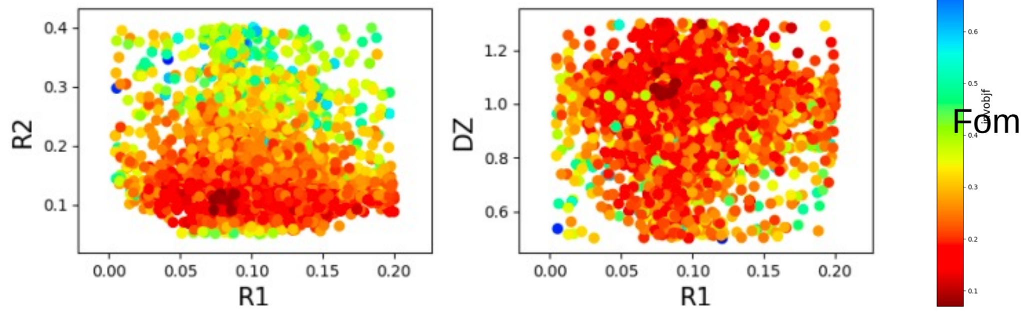
The ENUBET beamline: optimization studies

Work in progress!



Opt. parameters: apertures and shapes of last two collimators

FOM dependence on opt. parameters



FOM = signal/background

Signal: π & K @ tagger enterance

Background: e^{+}& π hitting tunnel walls

Rates @ Tunnel entrance for 400 GeV POT	π^{+} $[10^{-3}]$/POT	K^{+} $[10^{-3}]$/POT
Design	4.13	0.34
Optimized	5.27	0.44

Preliminary

Background hitting tunnel walls	$e^{+}[10^{-3}]/K^{+}$	$\pi^{+}[10^{-3}]/K^{+}$
Design	7	59
Optimized	2	35

Preliminary

An optimization campain is ongoing:

- **Goal**: further improvement of the π/K flux at tunnel entrance while keeping background level low;
- **Strategy**: scan parameters space of beamline to maximize FOM;
- **Tools**: full facility implemented in Geant4 -> controll with external cards all parameters -> systematic optimization with developed framework based on genetic algorithm;

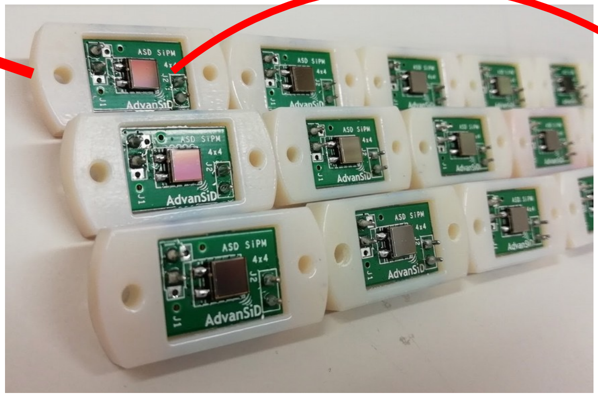
- About 28% gain in flux -> 2.4 years to collect 10^4 ν_e^{CC};
- Reduced backgrounds, but similar to signal shapes -> next step: improve FOM definition (include sgn/bkg distributions);

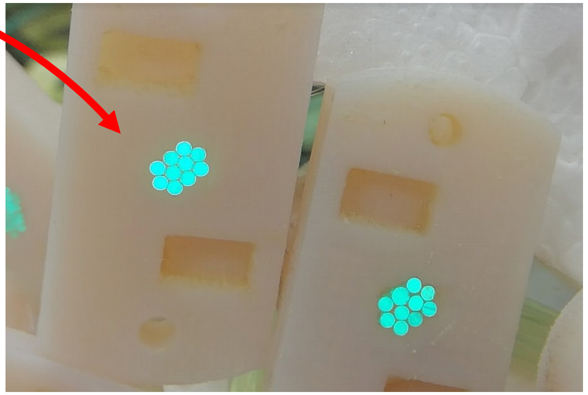
Preliminary

Decay tunnel instrumentation prototype & tests

Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection

Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)

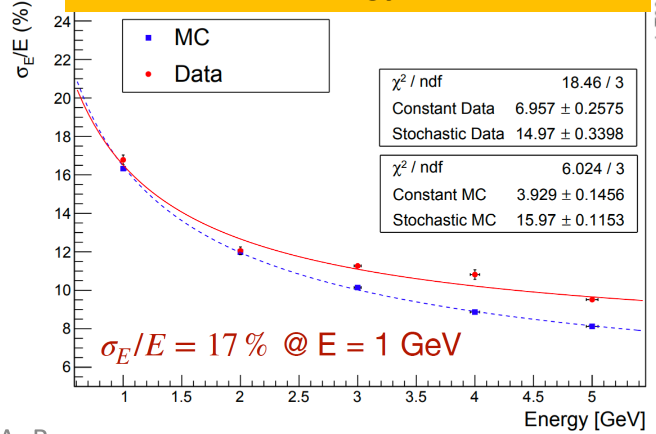




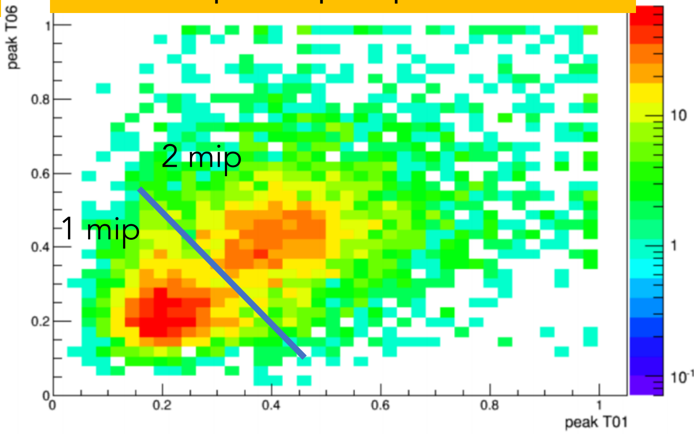
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution



1mip/2mip separation



Status of calorimeter:

- ✓ longitudinally segmented calorimeter prototype successfully tested;
- ✓ photon veto successfully tested;
- ➢ custom digitizers: in progress;

Choise of technology: finalized and cost-effective!

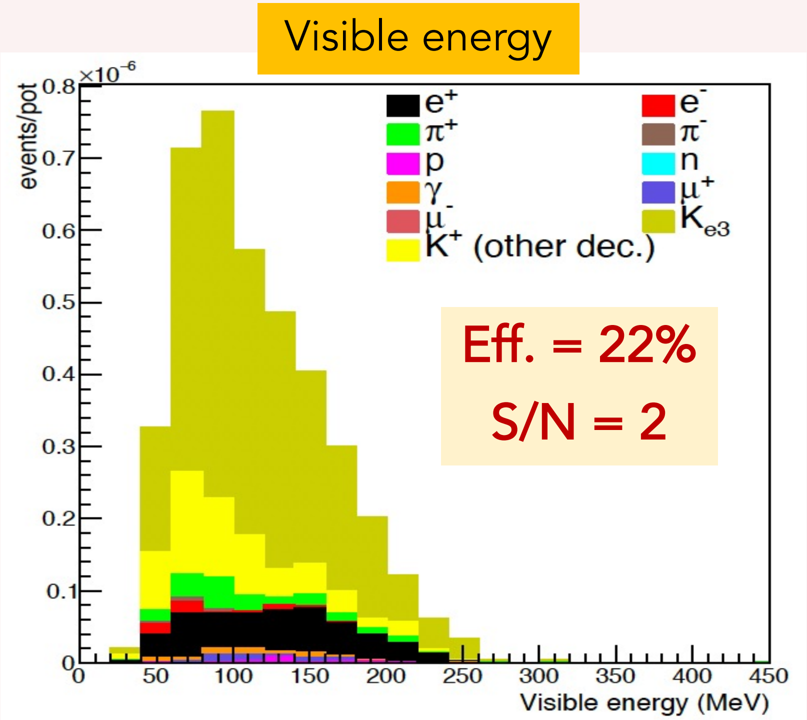
F. Acerbi et al, JINST (2020), 15(8), P08001

Lepton reconstruction and identification performance

✓ **Full GEANT4 simulation of the detector**: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects included (waveform treatment in progress); event building and PID algorithms (2016-2020);

- Large angle positrons and muons from kaon decays reconstructed searching for patterns in energy depositions in tagger;
- Signal identification done using a Neural Network trained on a set of discriminating variables;

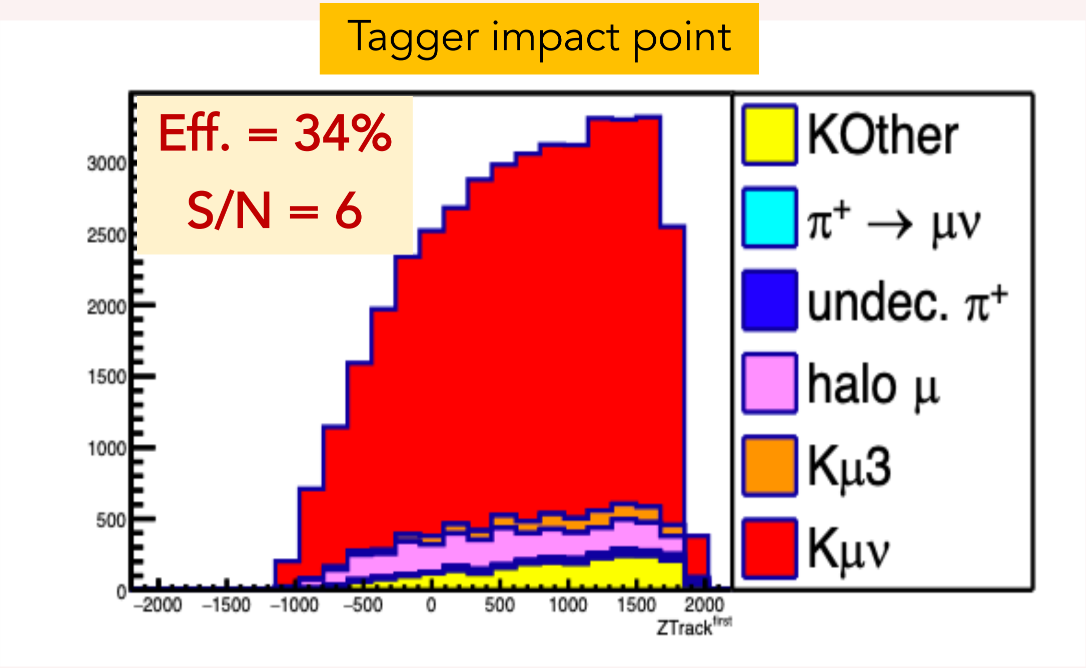
K_{e3} positrons -> constrain ν_e



Efficiency ~half geometrical

K_{e3} BR ~5% and K make ~$5-10\%$ of beam composition

$K_{\mu 2}$ muons -> constrain ν_μ



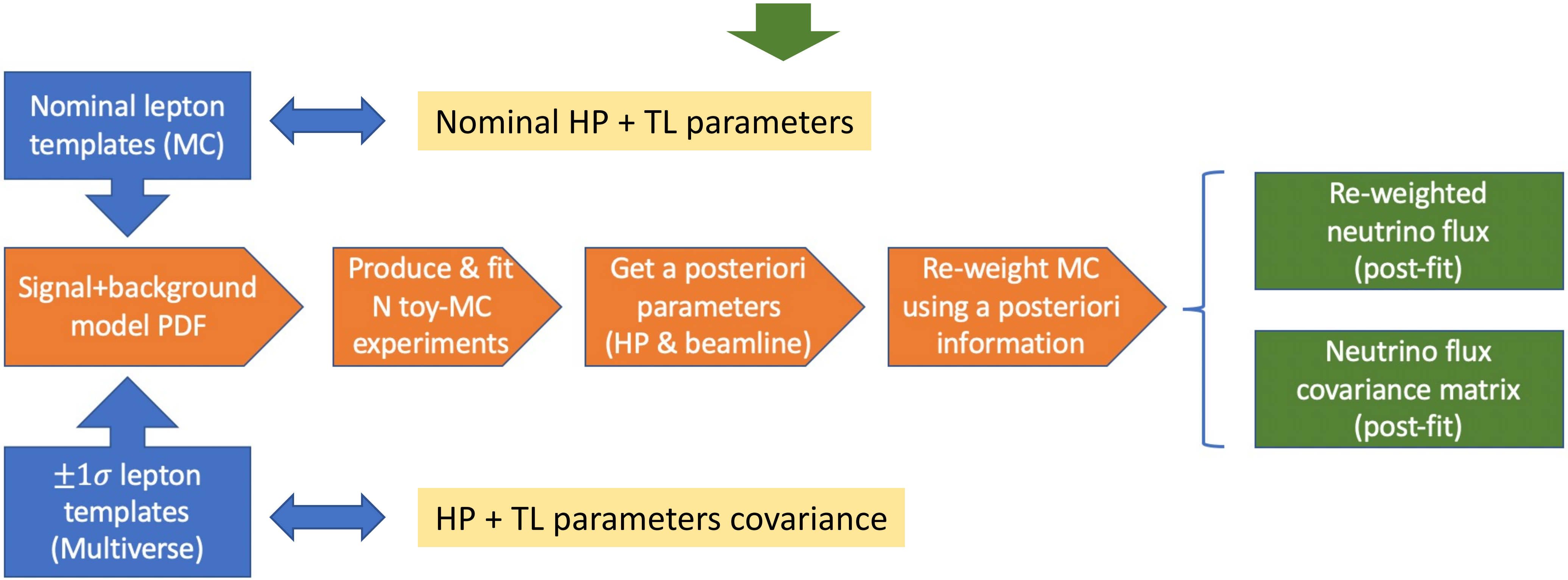
Efficiency ~half geometrical

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

ν-Flux: assessment of systematics

Monitored ν flux from narrow-band beam: measure rate of leptons $\Leftrightarrow$ monitor ν flux

- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;



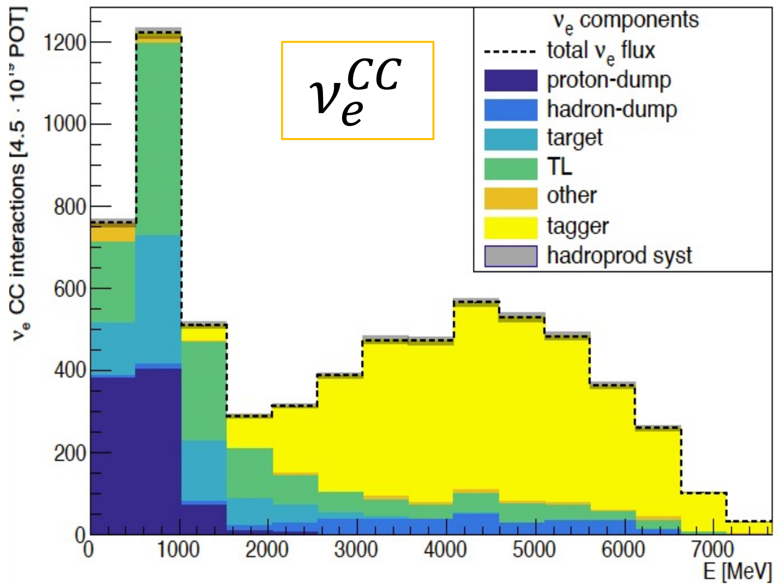
Used hadro-production data from NA56/SPY experiment to:

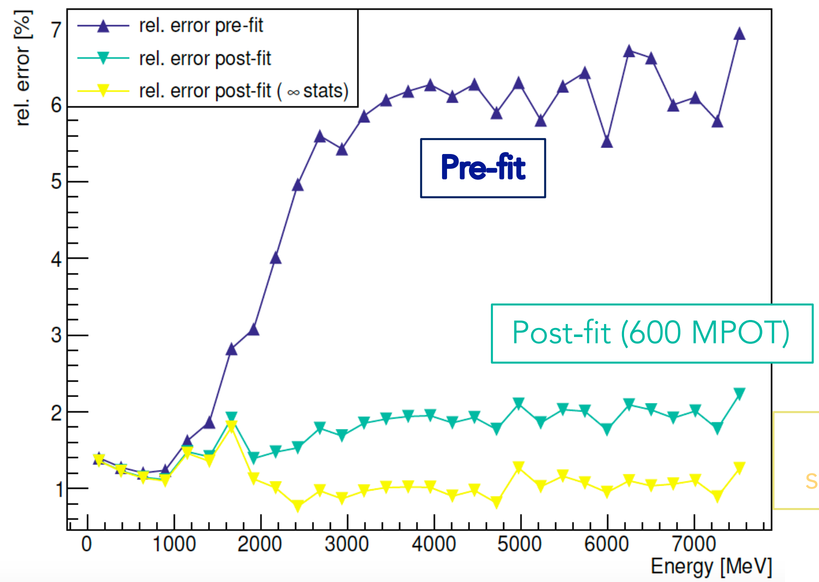
- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

ν-Flux: impact of hadro-production systematics

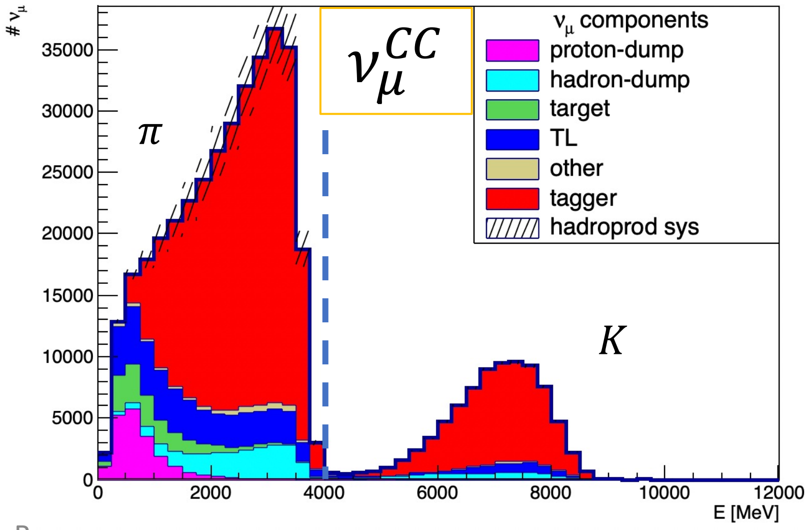
Neutrino interaction rates @ detector

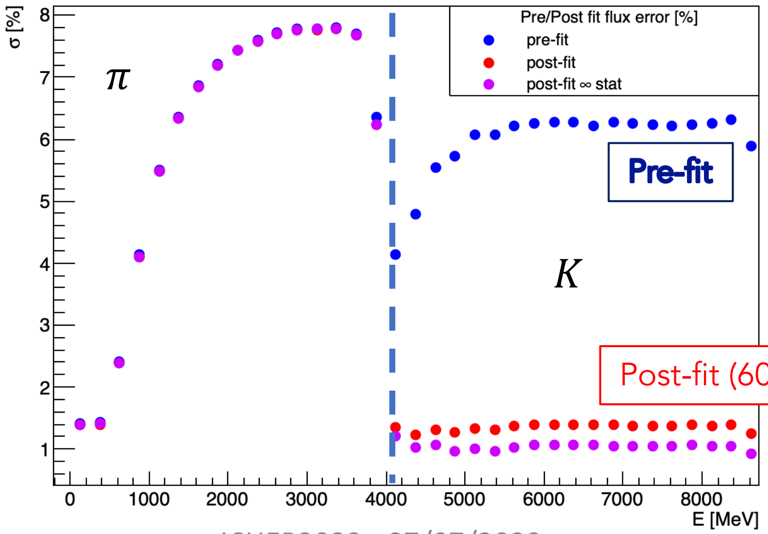
Pre & Post fit relative errors on rates





Infinite statistics





Post-fit (600 MPOT)

Infinite statistics

Total rates in 1 year of data taking

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 ton detector @ 50 m from tunnel end;

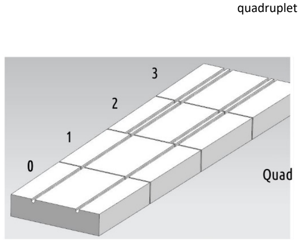
- **Before constraint**: 6% systematics due to hadro-production uncertainties;
- **After constraint**: 1% systematics from fit to lepton rates measured by tagger;

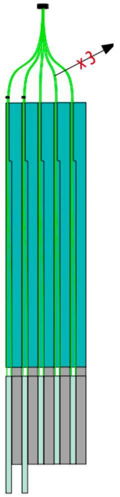
Achieved ENUBET goal of 1% systematics from monitoring lepton rates

The demonstrator

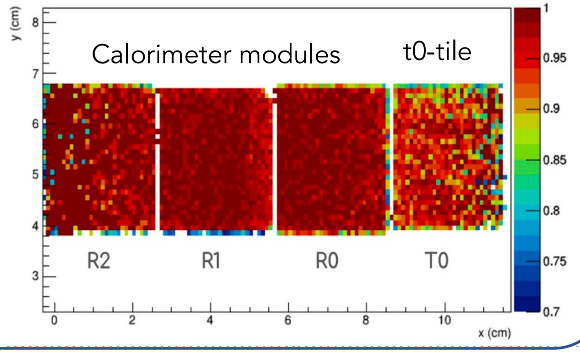
New frontal readout scheme & fibers bundling

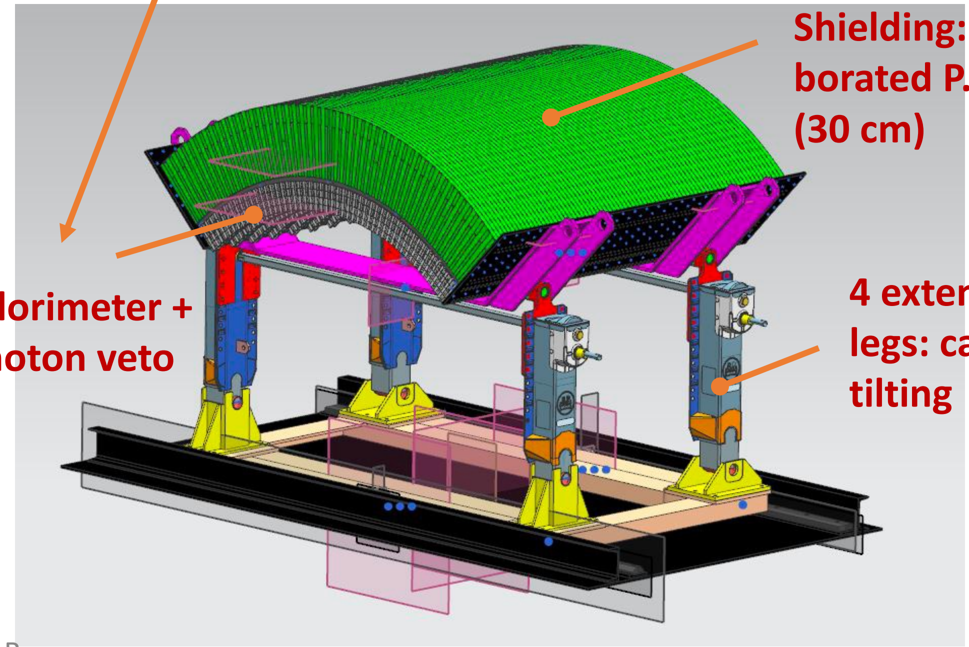
10 WLS fibers (1 LCM) bundled to a 4 ×4 mm² SiPM





Efficiency map from ENUBINO test





Shielding: borated P.E. (30 cm)

calorimeter + photon veto

4 extendible legs: calorimeter tilting

- Detector prototype under construction, to demonstrate:
  - Performance / scalability / cost-effectiveness;

Test-beam @ CERN in October 2022

  - ➢ 1.65 m longitudinal & 90° in azimuth;
  - ➢ 75 layers of: iron (1.5 mm thick) + shintillator (7 mm thick) => 12X3 LCMs;
- central 45° part instrumented: rest is kept for mechanical considerations;
- modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions);
- new light readout scheme with frontal grooves instead of lateral grooves:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection;
  - performed GEANT4 optical simulation validation;
- scintillators: produced by SCONIX and milled by local company;
- ENUBINO: pre-demonstrator w/ 3 LCM tested @ CERN in November 2021 to study uniformity and efficiency;

The demonstrator

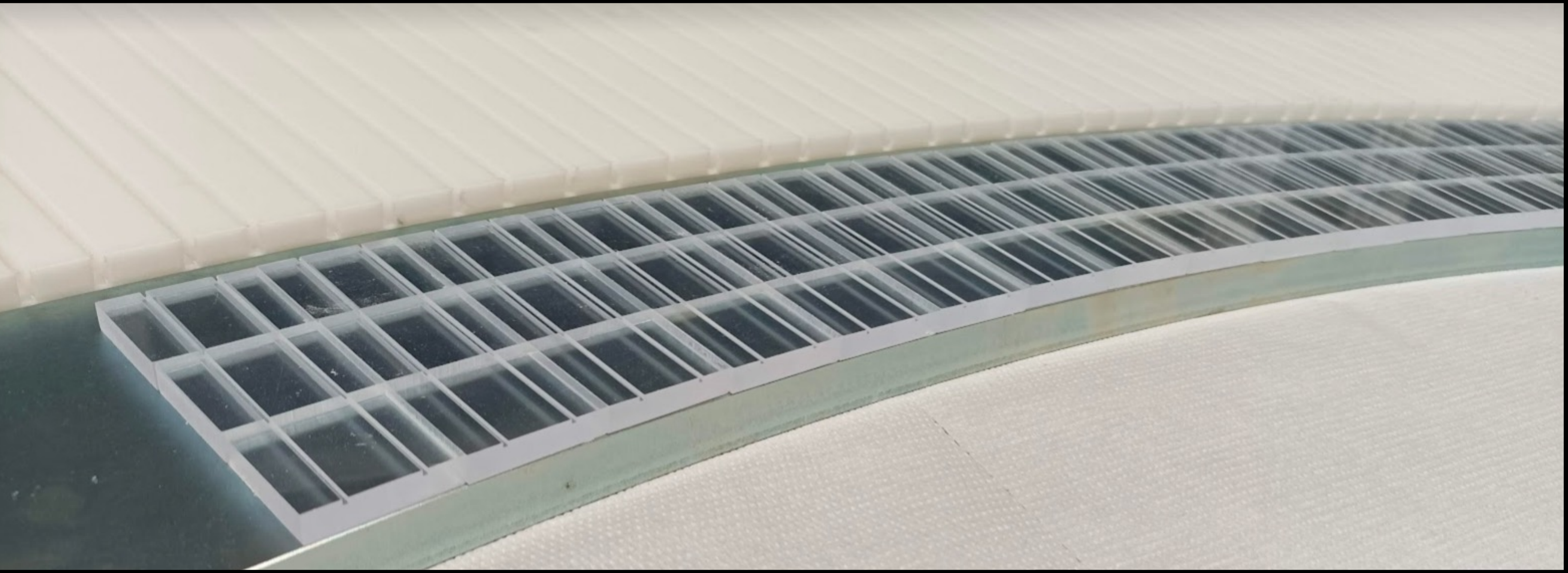
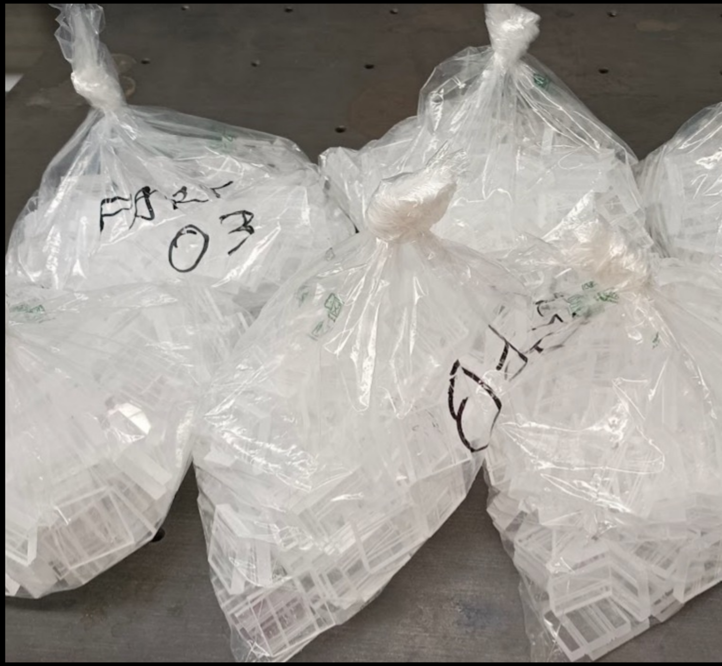
Construction @ LNL-INFN Labs

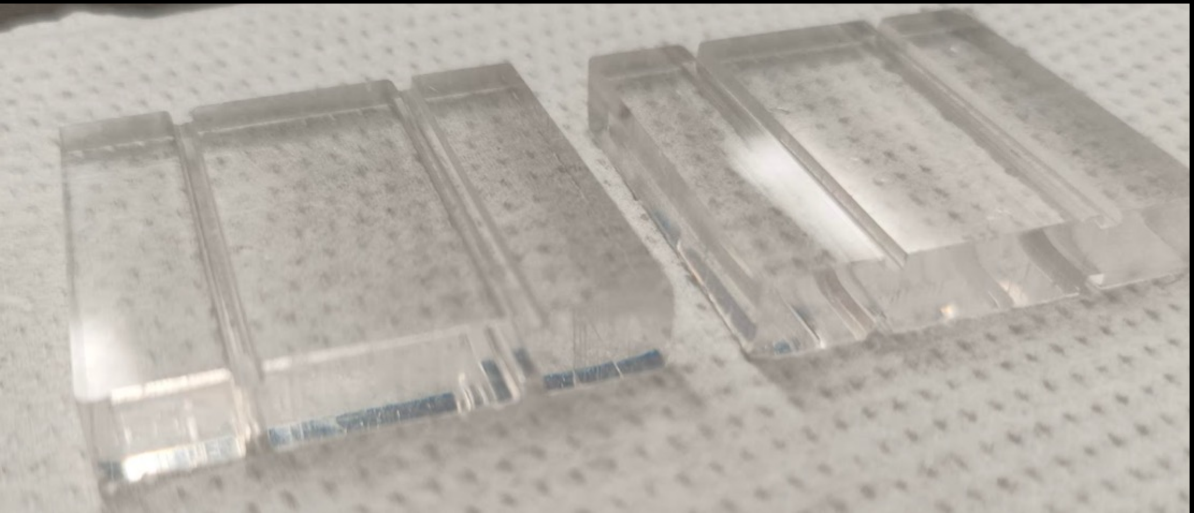
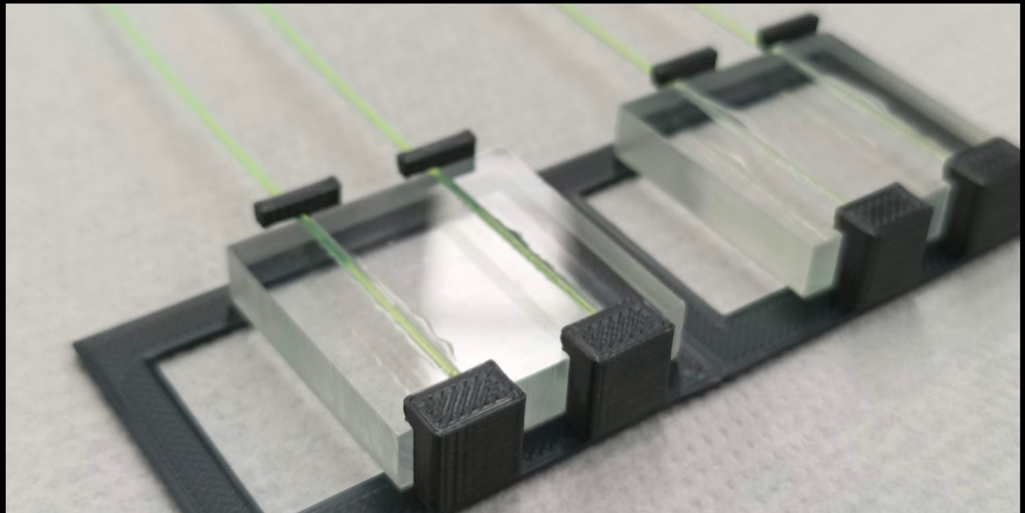
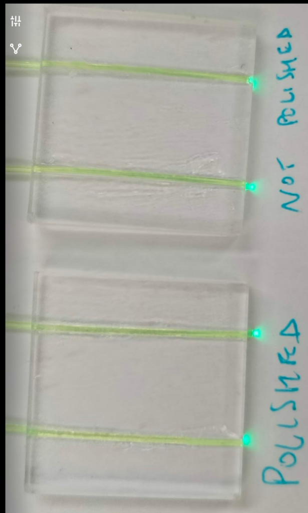
- 15 mins lift test with additional 2 tonnes (total 5.2 tonnes)

The demonstrator

Construction @ LNL-INFN Labs

- The scintillator tiles

Conclusions and next steps

- **ENUBET goal: first monitored neutrino beam for neutrino cross-section measurements @ O(1%):**
  - ERC project started in 2016;
  - CERN experiment (NP06) within Neutrino-Platform in 2019;
  - part of Physics Beyond Collider framework;
- **Final design of beam transfer line in place, fine-tunning parameters:**
  - static transfer line: 10^4 ν_e^{CC} events in ~3 years (@ SPS);
  - ongoing optimization of transfer line parameters w/ dedicated framework;
  - multi-momentum beamline ongoing R&D: DUNE & HyperK optimized;
- **Design of decay tunnel instrumentation finalized:**
  - prototypes test-beams @ CERN: technology validation;
  - building final demonstrator to be tested @ PS East Hall in 2022;
- **Detector simulation and PID studies done:**
  - developed full GEANT4 simulation of calorimeter;
  - finalizing waveform to fully assess the pile-up effects;
  - very good PID performance achieved on both positron and muon reconstruction;
- **Systematics: hadroproduction and next steps:**
  - achieved 1% systematic goal due to hadroproduction with lepton monitoring;
  - assess systematics due to detector effects and beamline parameters;

ERC project is on schedule and in the last stage

CERN site-dependent implementation within NP06/ENUBET in PBS framework

2023-2024 delivery of Conceptual Design Report with physics and costs definition

Experimental proposal expected in 2024

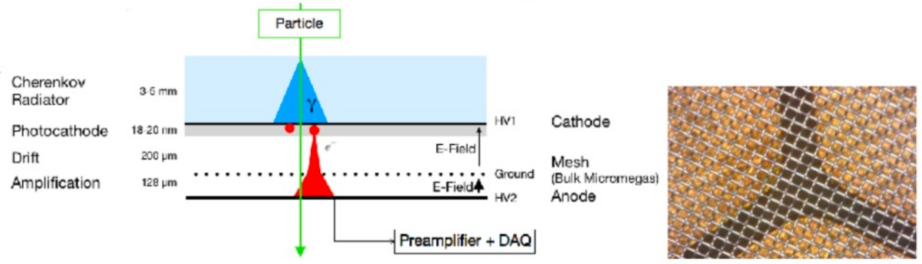
Thank you for your attention!

Additional Material

Lepton reconstruction and identification:

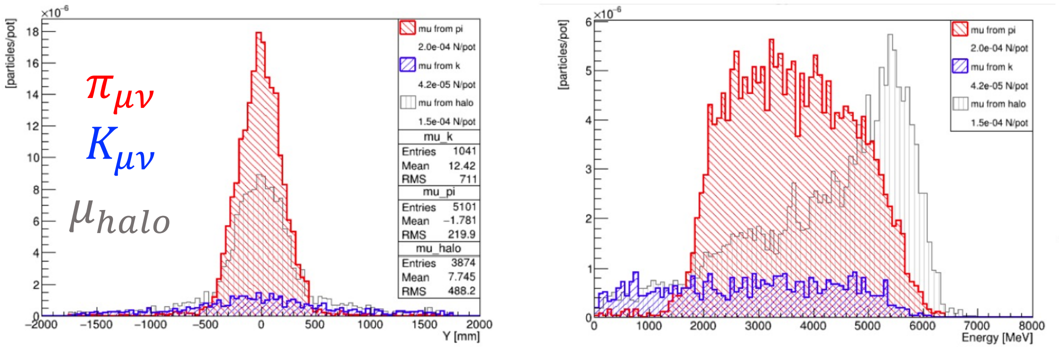
$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

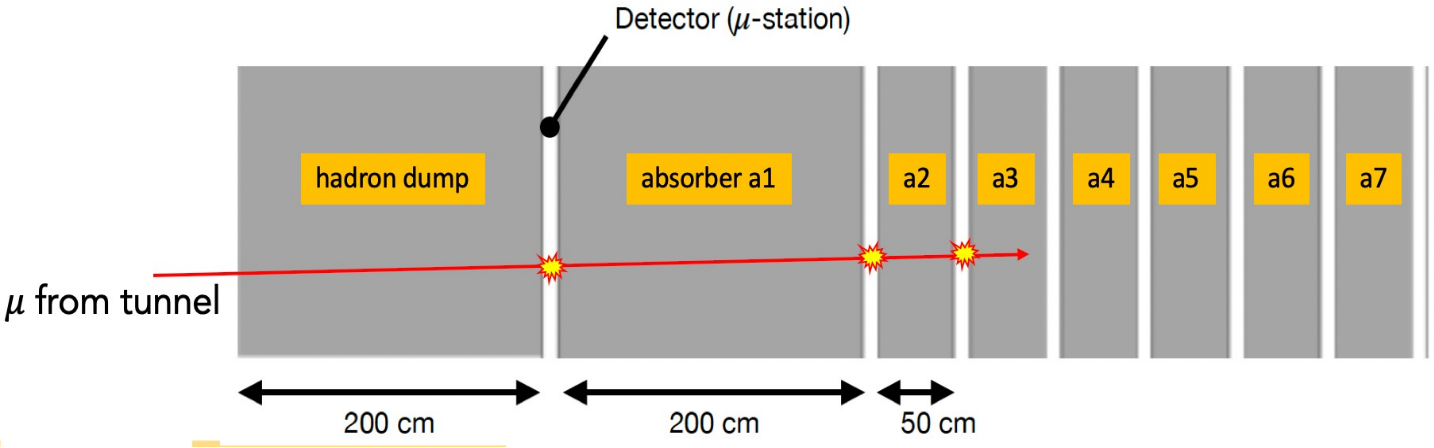
✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump

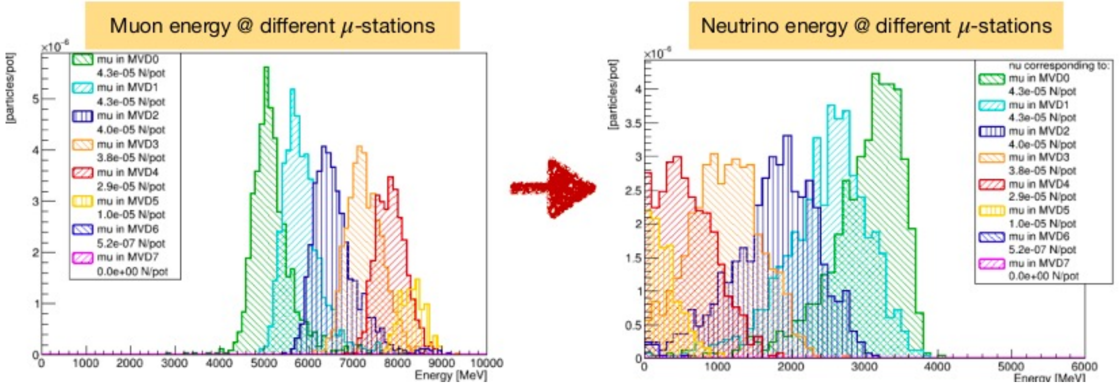


Possible candidates: fast Micromega detectors with Cherenkov radiators (PIMENT project)

Exploit differences in distributions to disentangle components







Hottest detector (upstream station): cope with ~2 MHz/cm^2 muon rate and ~10^{12} 1 MeV-n$_{eq}$/cm^2

Exploit:

- correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- difference in distribution to disentangle signal from halo-muons;

Detector technology: constrained by muon and neutron rates;

Systematics: punch through, non uniformity, efficiency, halo-μ;

Waveform simulation & pile-up

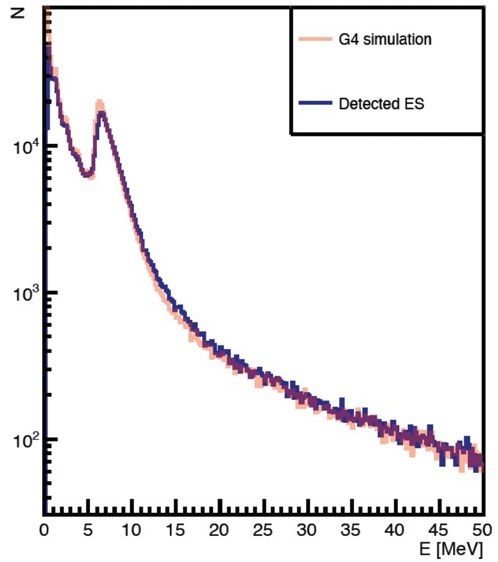
Implementation of waveform generation in the full simulation: as in real data (digitally sampled signals @ 500 MS/s) -> real pile-up treatment

- GEANT4 hit-level energy deposits are converted into photons hitting SiPMs (~15 phe/MeV, from test-beams & cosmic rays measurements);
- SiPM response simulated using GoSiP software: fine control on all sensor parameters;
- waveforms are processed with a pulse-detection algorithm: time and energy information are evaluated;
- results is used as input for event building;

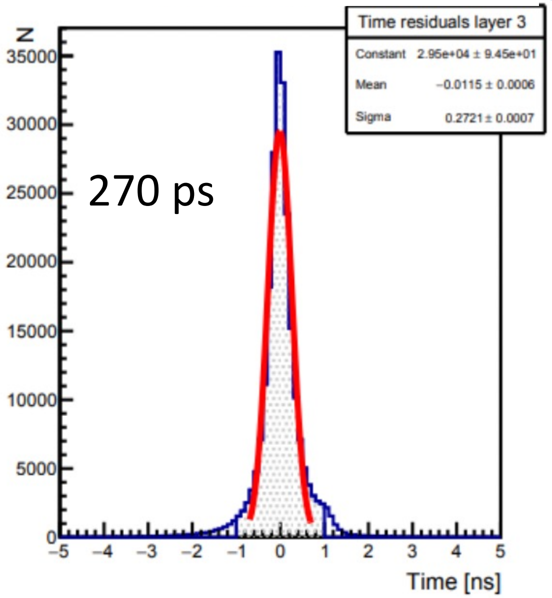
Complete assessment of pile-up effects on detector performance

pulse-detection algorithm optimized for faithful energy evaluation, high efficiency, and accurate time resolution

Geant4 energy/WF reco energy



Residuals: G4 true-time/WF reco



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%

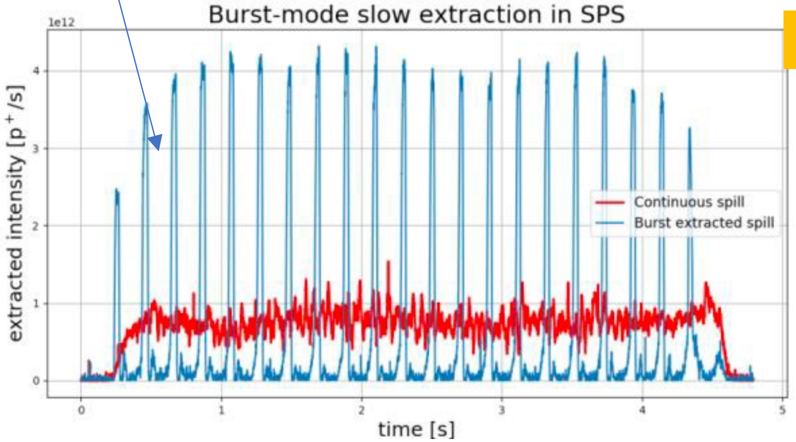
Slow extraction = 4.5×10^{13} POT in 2 s;
Fast extraction (horn) = 10× slow extraction;

Horn based focusing

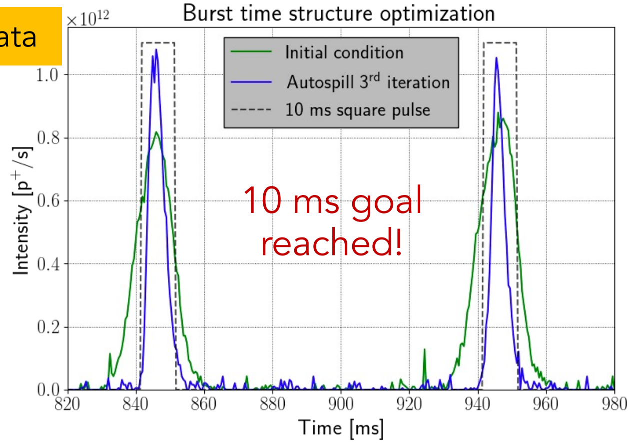
M.Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

Boosting the neutrino flux → Employ magnetic Horn → Overkilling pile-up @ tunnel

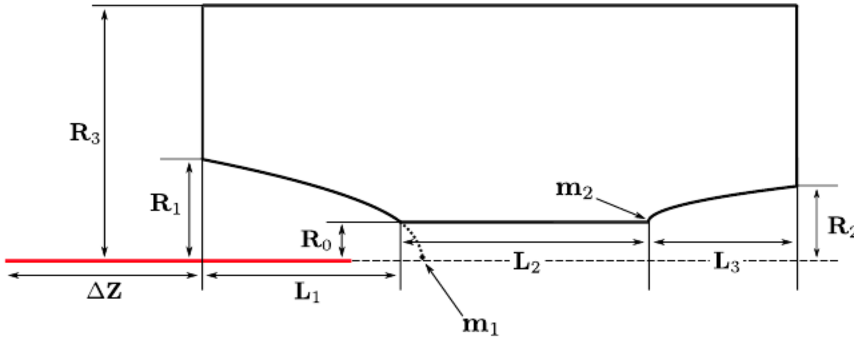
Burst mode slow extraction: multiple ms-long pulses slow-extracted during flat-top → compatible with Horn and pile-up @ tunnel



from real data



New double parabolic geometry implemented



Dedicated tests at CERN-SPS:

- successfully implemented;
- optimized down to 10 ms length @ 10 Hz;

From simulation studies:

- 3 to 10 ms pulse length can be reached;

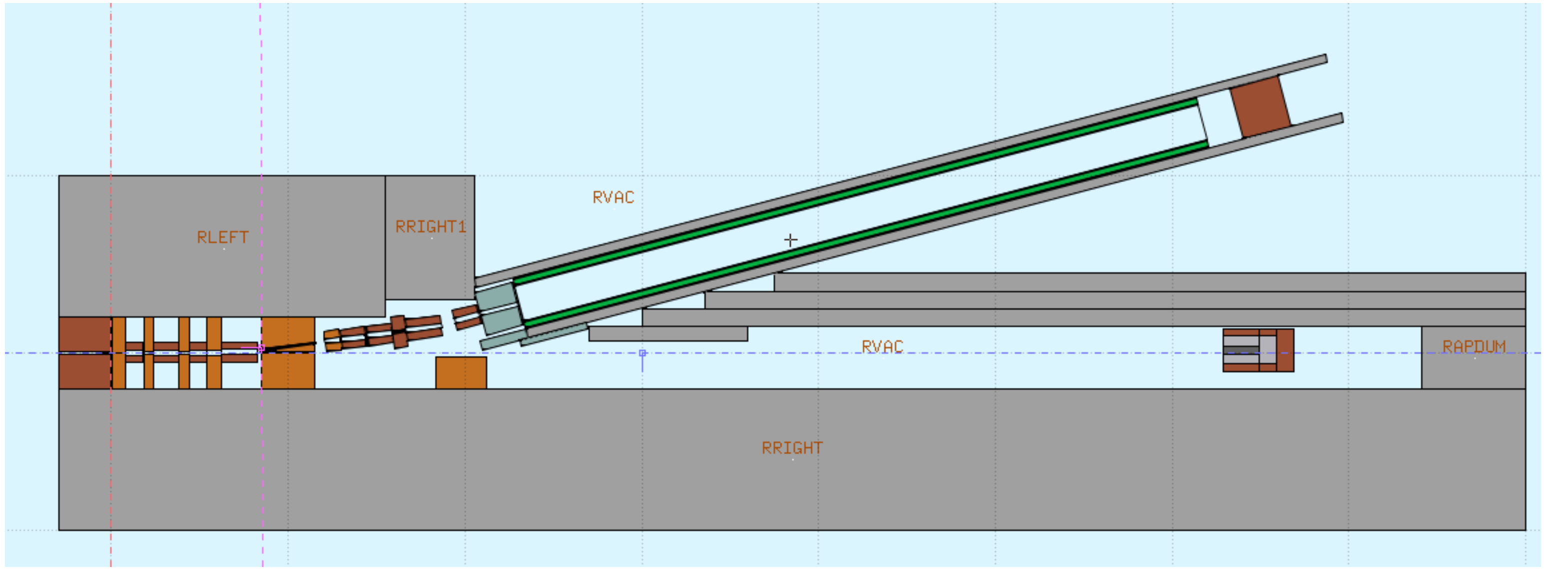
Horn optimization: search for best shape & current values to maximize flux

- developed a dedicated optimization algorithm based on Genetic Algorithm;
- tests show that a FOM* 3x static beamline can be achieved;
- NEXT: further studies on dedicated beamline fine-tuned for horn;

*FOM = # of K^+ within momentum bite focused at first quadrupole after the horn => beamline independent

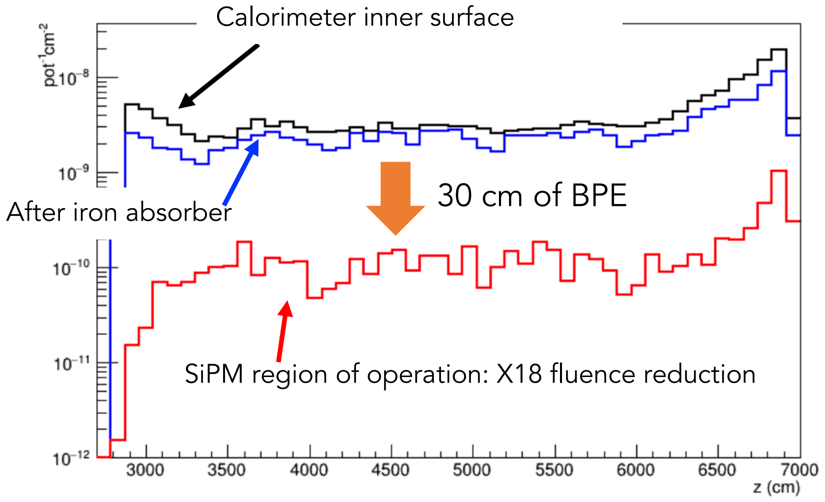
FLUKA irradiation studies

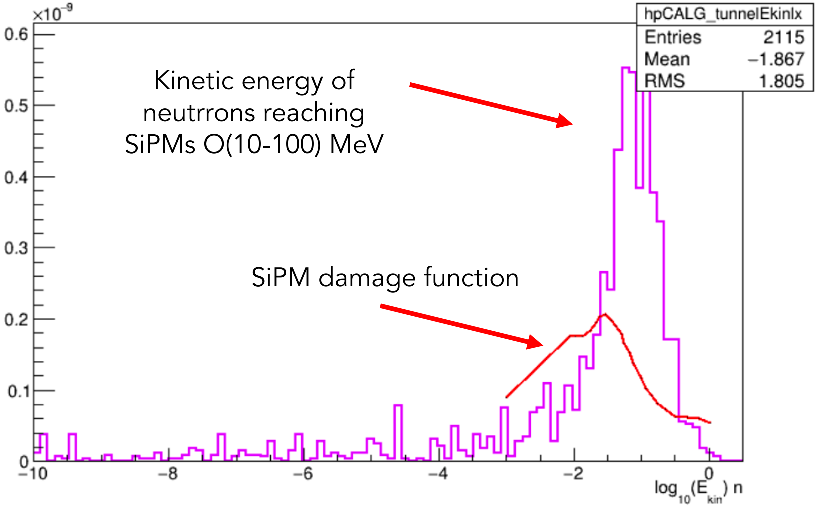
A detailed FLUKA simulation of the setup has been implemented (includes proper shielding around the magnetic elements)



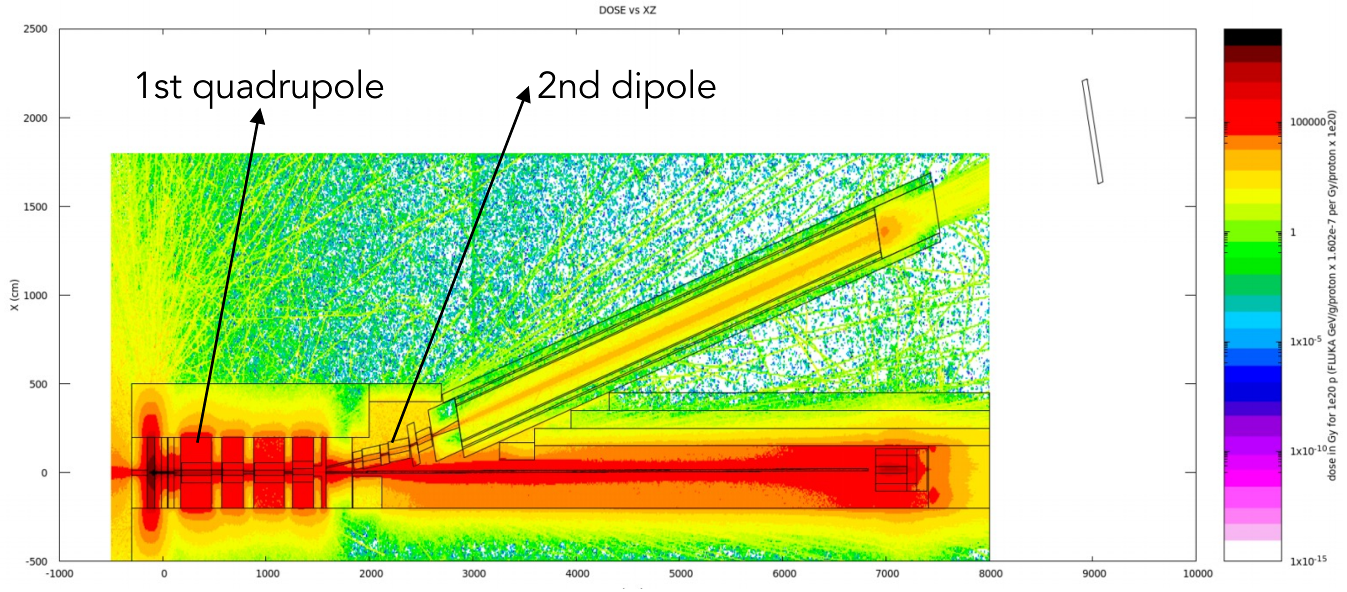
Neutron fluence provided by FLUKA guided the design of the detector tecnology for tagger:

-> SiPMs outside of the calorimeter





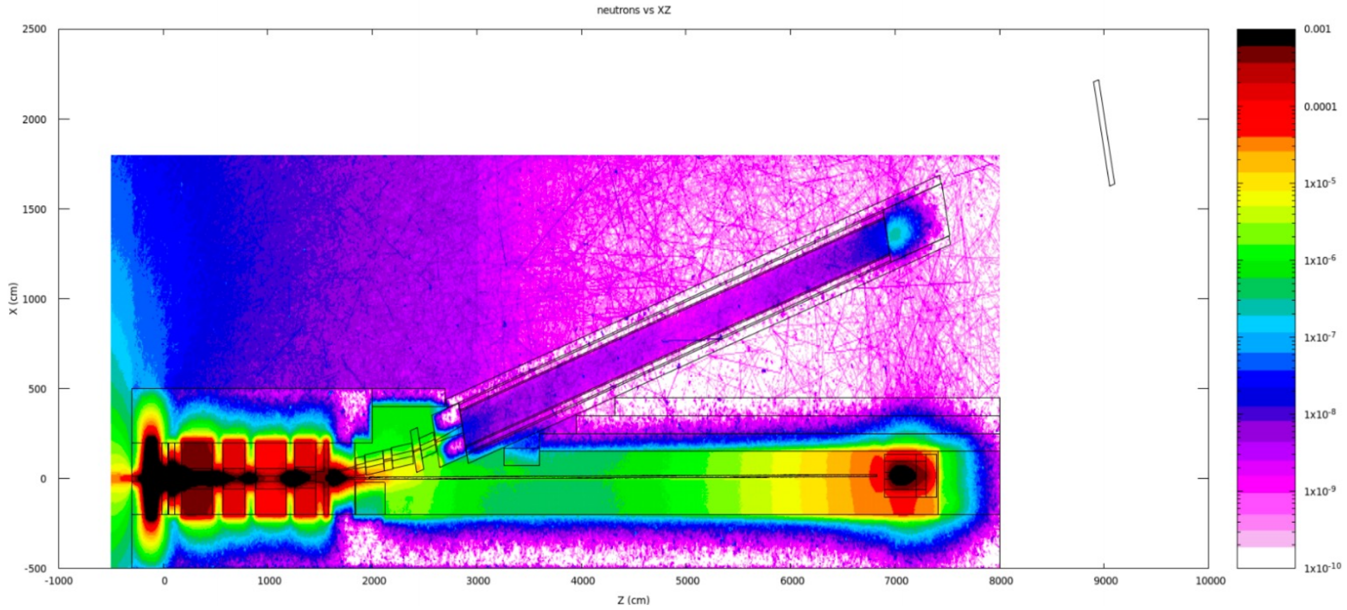
FLUKA irradiation studies



Dose for 10^{20} POT [Gy]

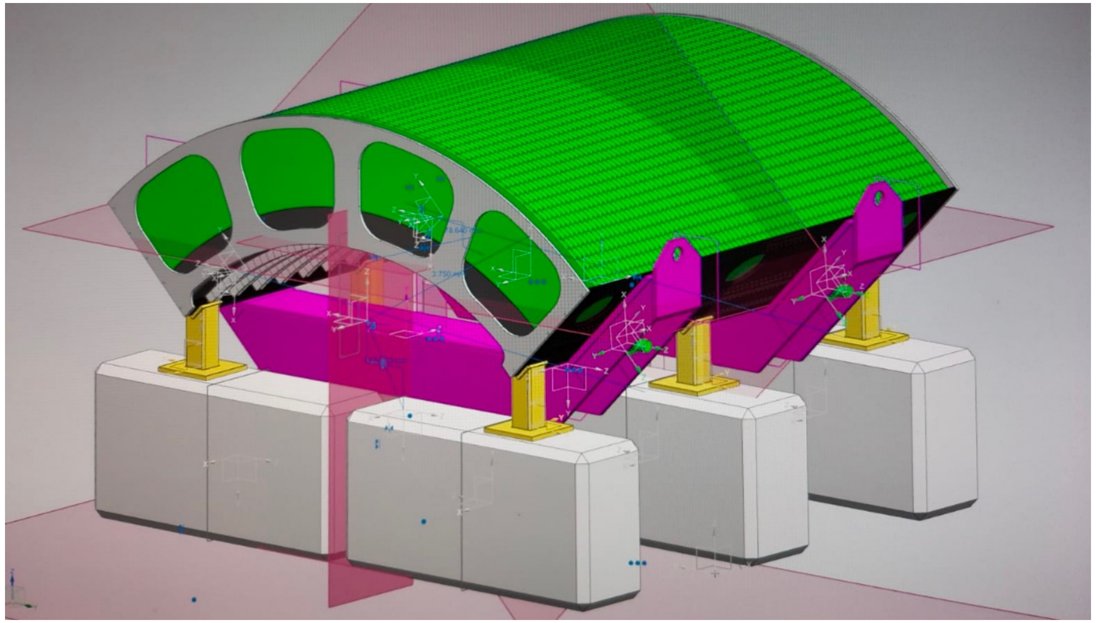
Hottest point -> quadrupole closest to target O(100-300 kGy): acceptable value for operations

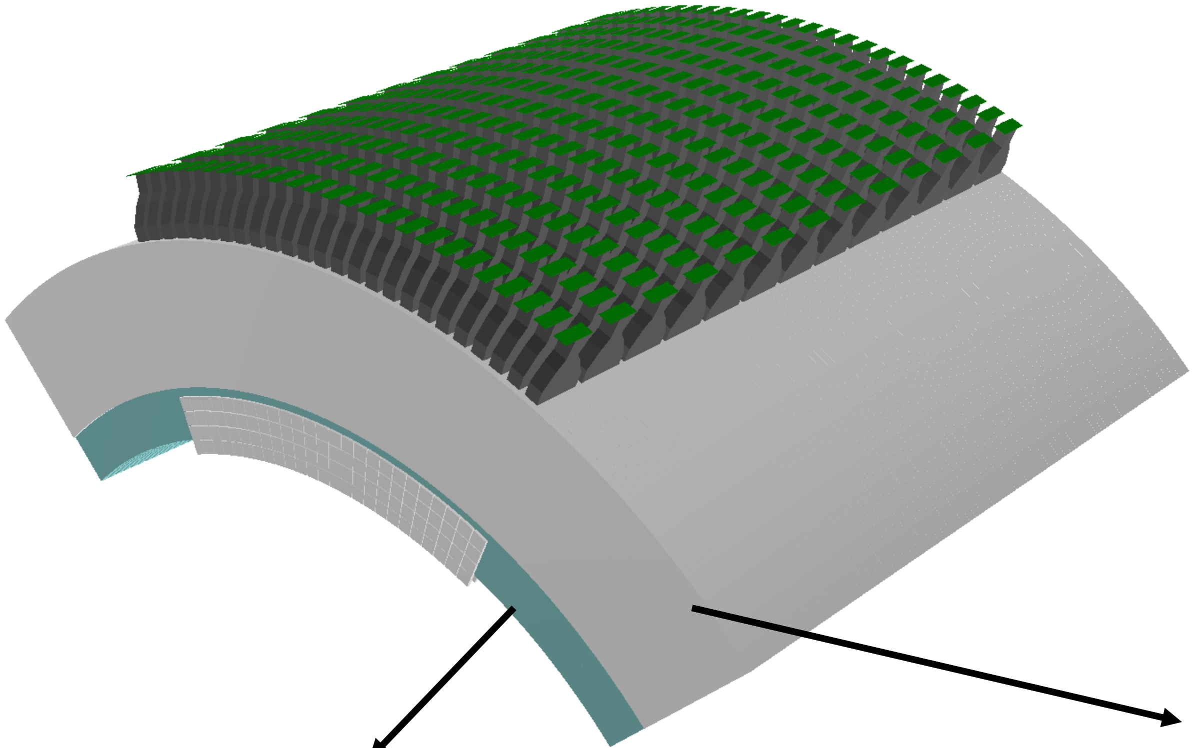
Neutrons/cm^2 for 10^{20} POT



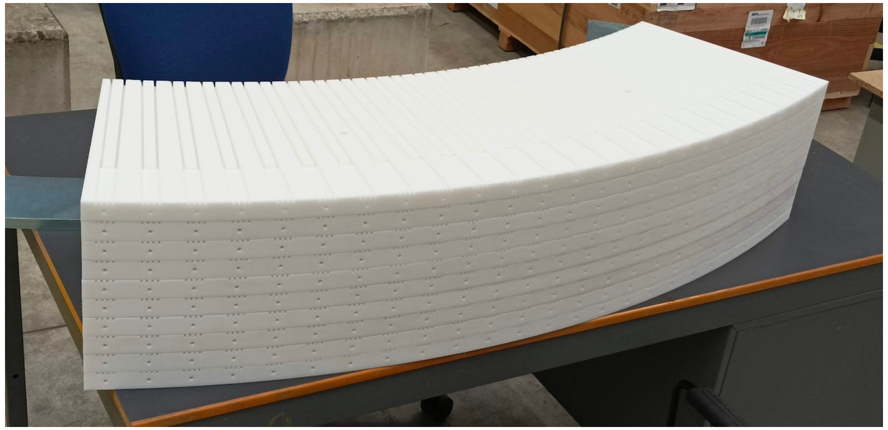
Demonstrator

Weight ~7 t



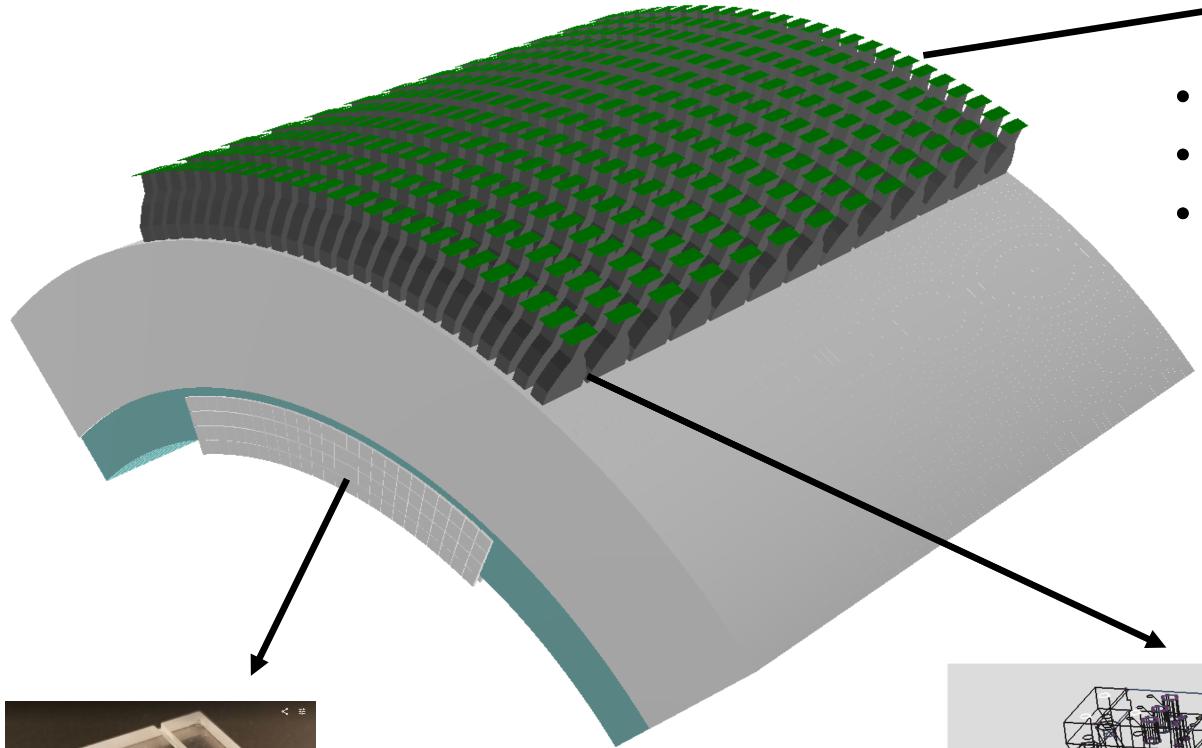


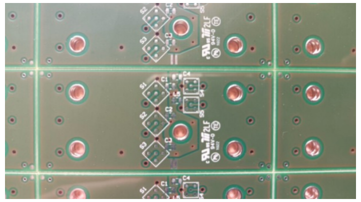
Machined iron for calorimeter absorber layers



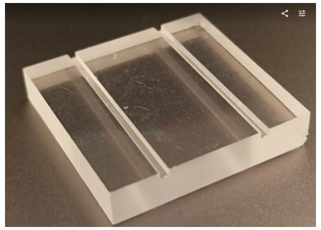
5% Borated Polyethylen arcs

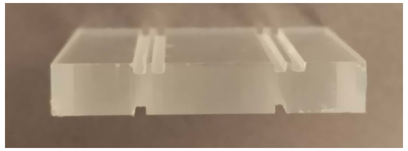
Demonstrator



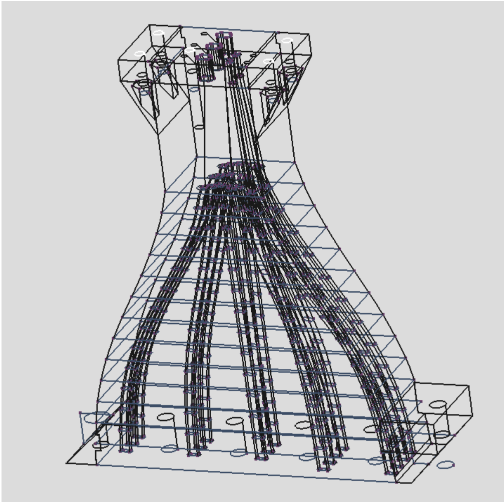


- ~1800 channels;
- SiPM Hamamatsu;
- Hybrid readout (custom+commercial digitizers)



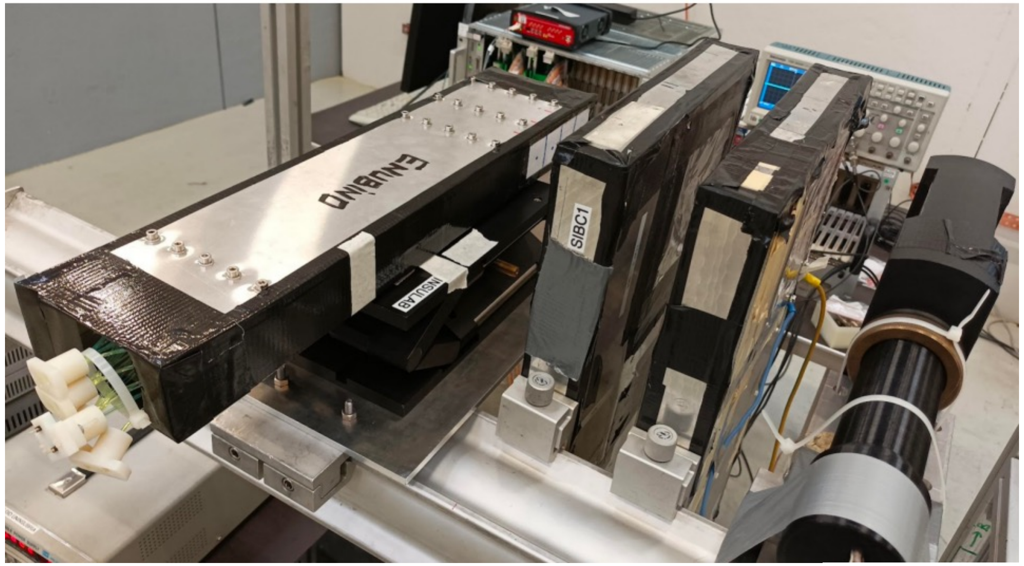


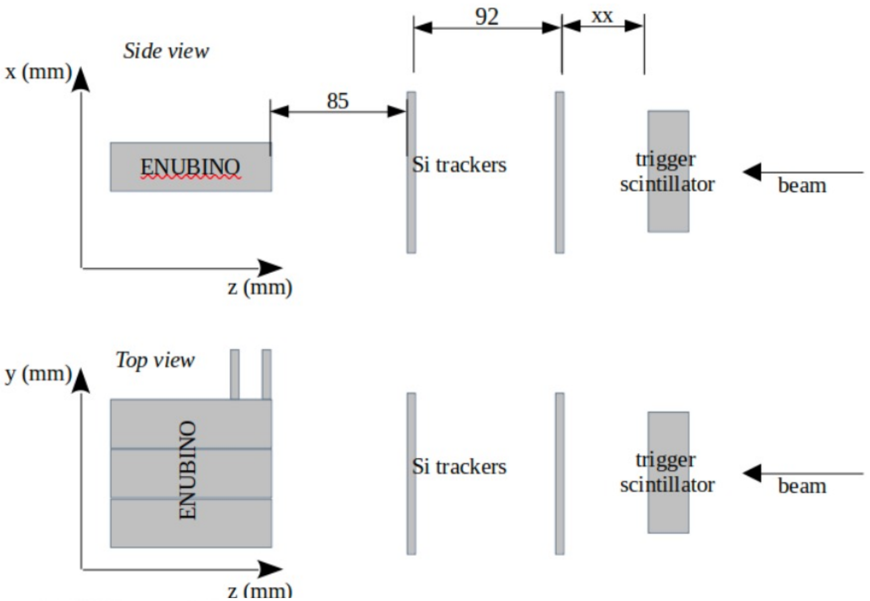
- 6375 scintillator tiles in different shapes;



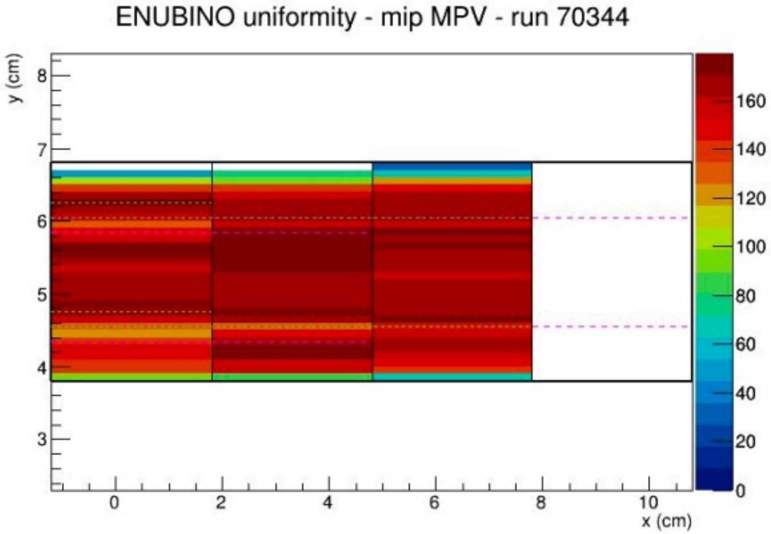
- 3D printed fiber routers;

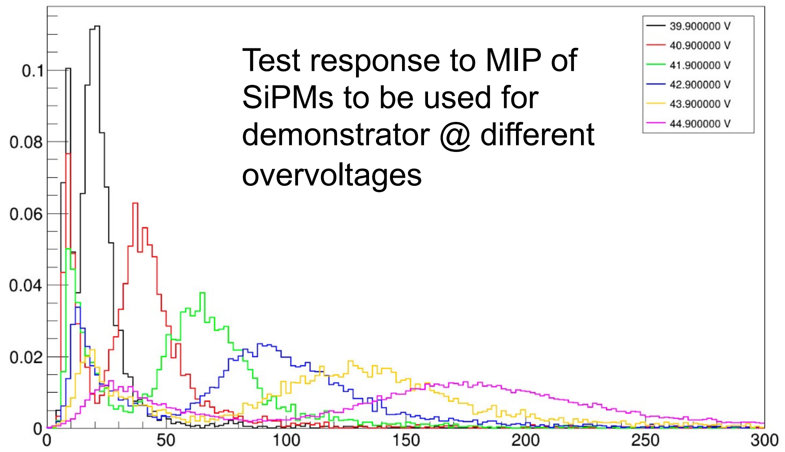
ENUBINO @ CERN-PS test-beam in Nov.2021





- Tested final configuration chosen for demonstrator;
  - 15 GeV hadronic beam;
  - Light collection uniformity;
  - Response to MIP;
  - Frontal light readout scheme test;
  - SiPM choice;

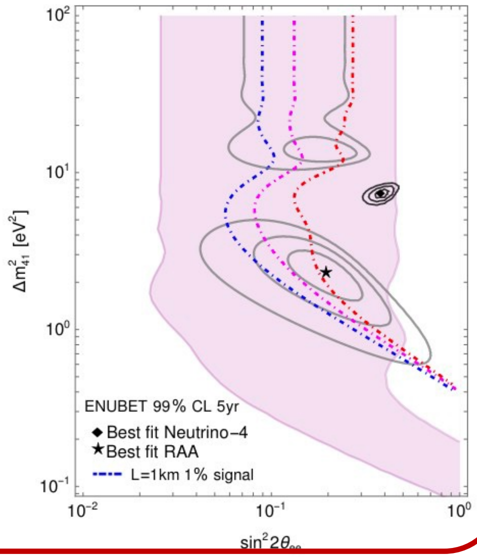




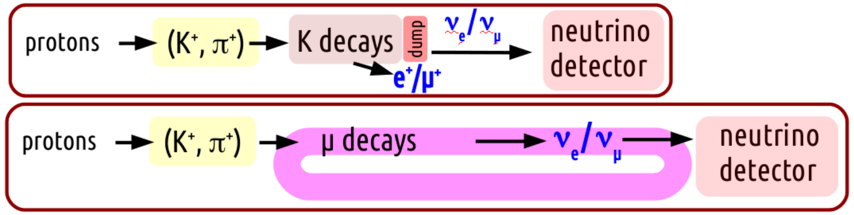
ENUBET within Physics Beyond Collider framework

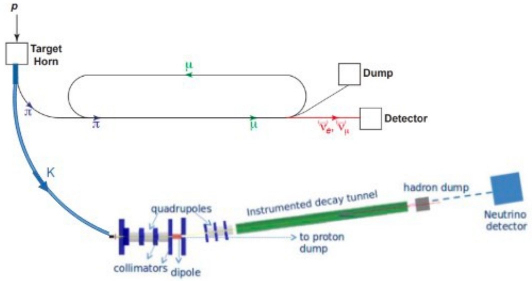
Accelerator and engeneering detailed studies, assessment of the facility costs, investigate posssibility to exploit ENUBET for cross section experiments at CERN North Area

Assess Beyond Standard Model physics opportunities



Assess synergy with nuSTORM. Common points: proton extraction line, target station, first stage of meson focusing, proton dump, neutrino detector





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

Multi-momentum beamline studies to span HyperK and DUNE region of interests