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).

Monitored neutrino beams and the next generation of high precision cross section experiments

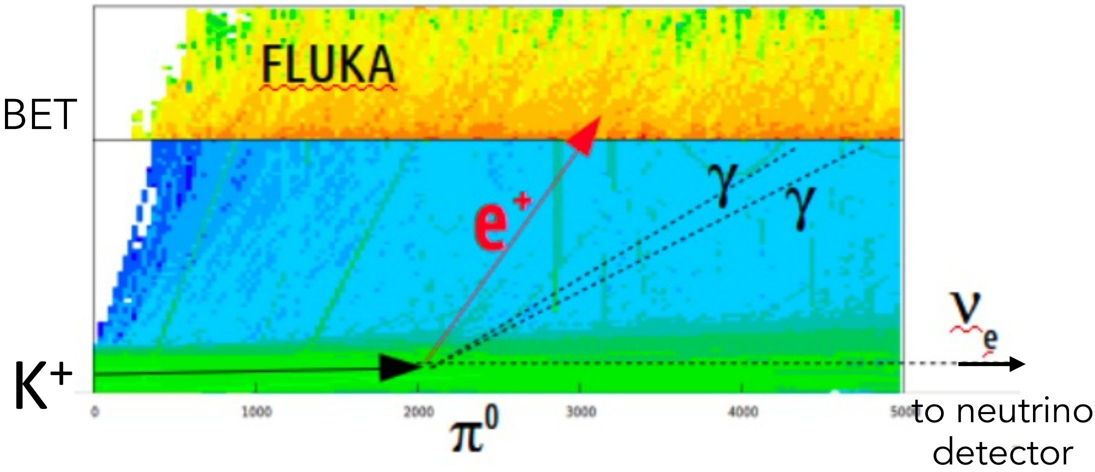
A. Branca (on behalf of the ENUBET Collaboration) - University of Milano-Bicocca & INFN

iNPC2022
Cape Town, South Africa

The 28th International Nuclear Physics Conference
September 11-16, 2022 – Cape Town, South Africa

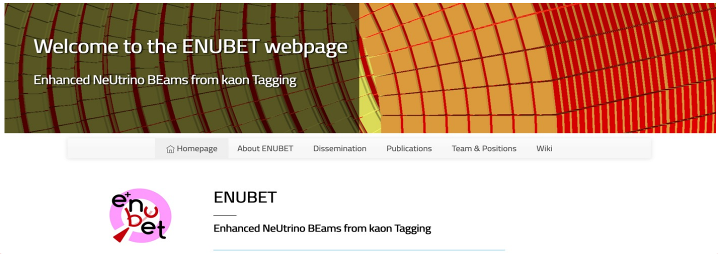
Outline

- ENUBET is the project for the realization of the first monitored neutrino beam.
  In the next slides:
  - 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;



- A next generation of neutrino detectors:
  - What detector technology do we need?

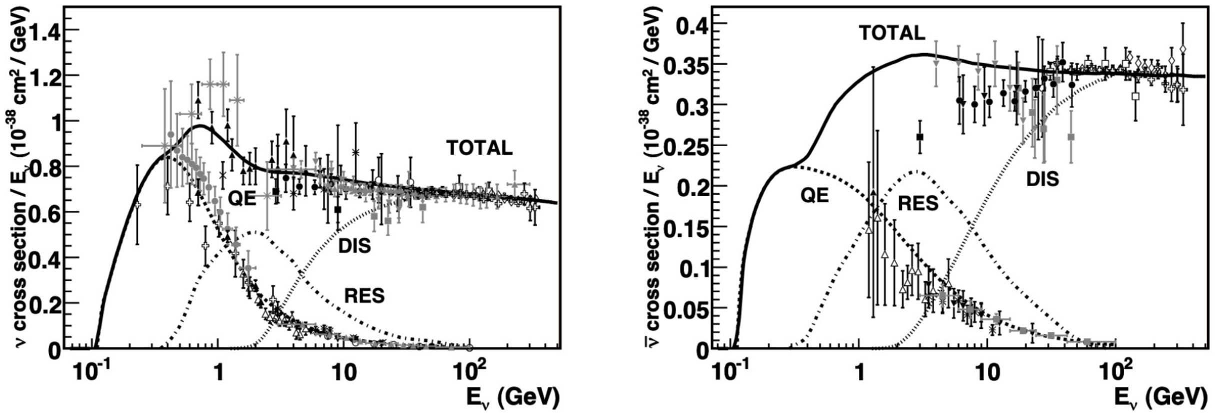
Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/


Welcome to the ENUBET webpage
Enhanced NeUtrino BEams from kaon Tagging

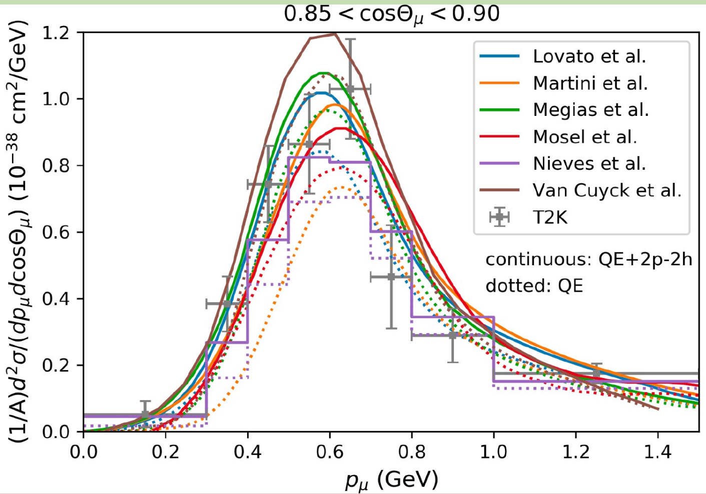
ENUBET
Enhanced NeUtrino BEams from kaon Tagging

A precision era for neutrino-nucleus interactions

Total $\nu_\mu/\bar{\nu}_\mu$ cross section per nucleon



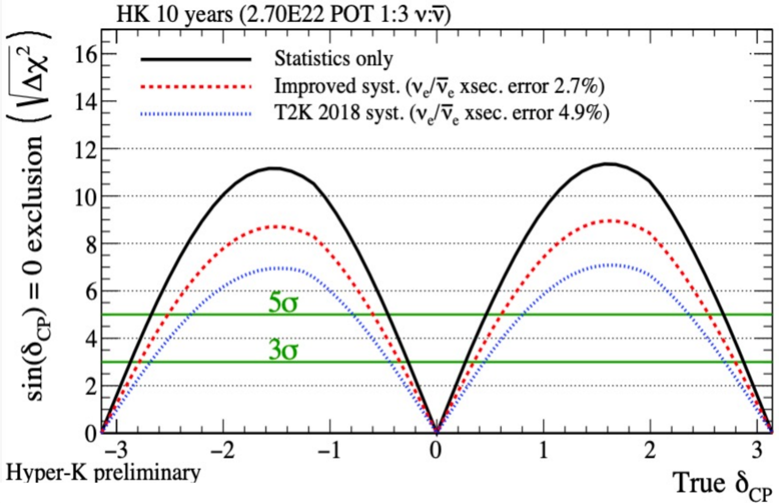
Double-diff. ν_μ cross section: data (T2K) VS models

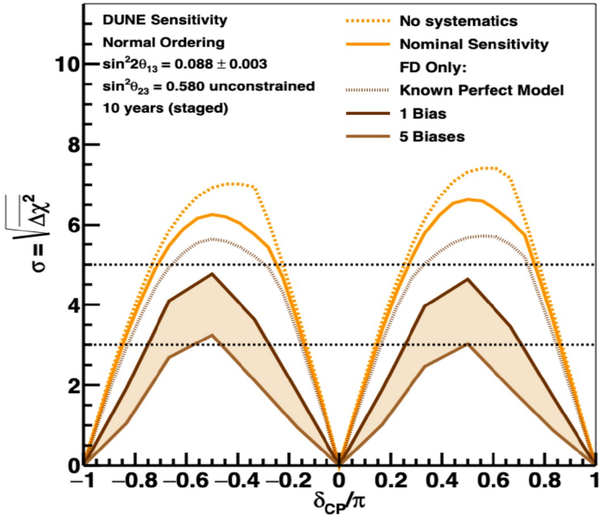


Fight large errors

Disentangle different models

HK (left) and DUNE (right) sensitivity to CP phase





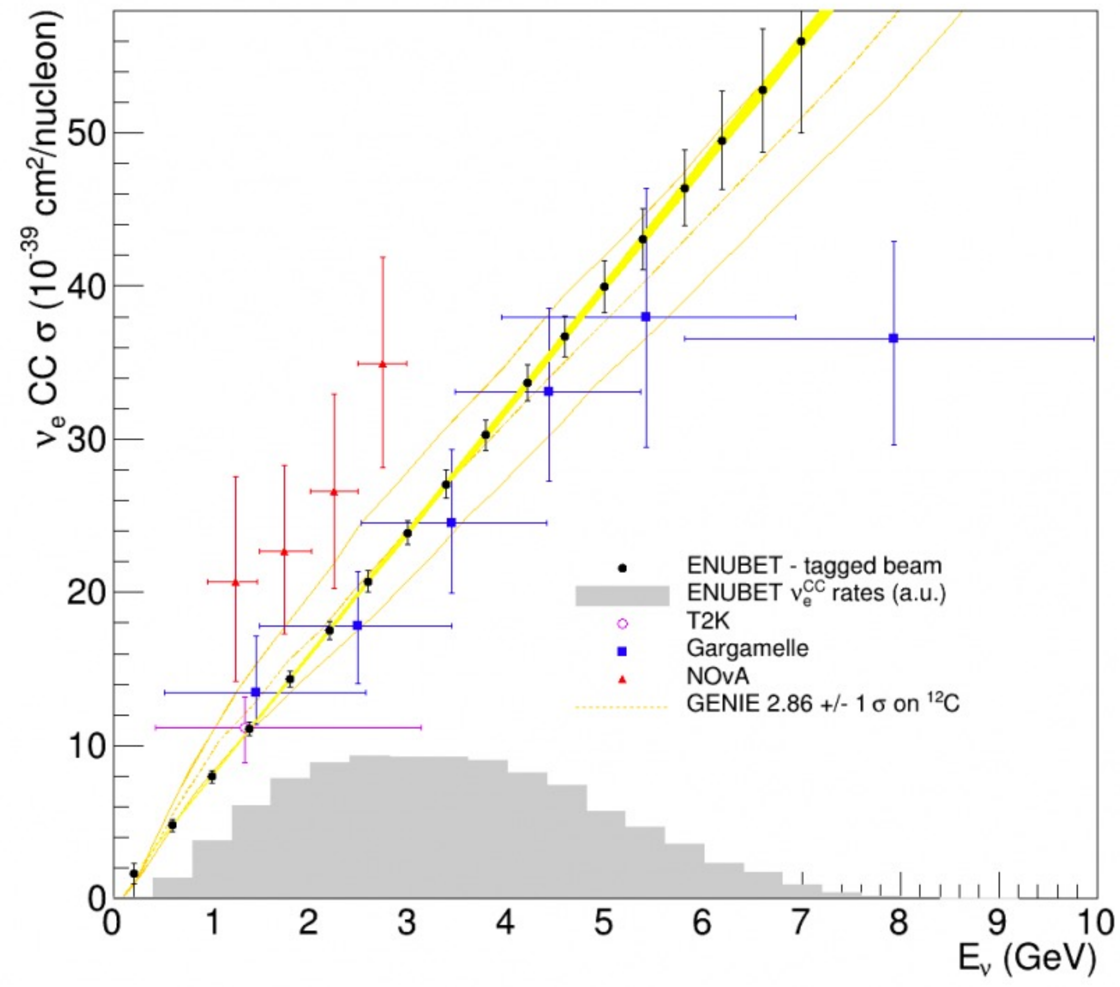
Boost sensitivity

Precision measurements of the neutrino cross sections are beneficial for:

- Improving theoretical knowledge: allow to disentangle different neutrino interaction models;
- Next generation long-baseline experiments: boost in the sensitivity to the neutrino oscillation parameters;

The aim of the ENUBET project

ENUBET impact on ν_e cross section



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

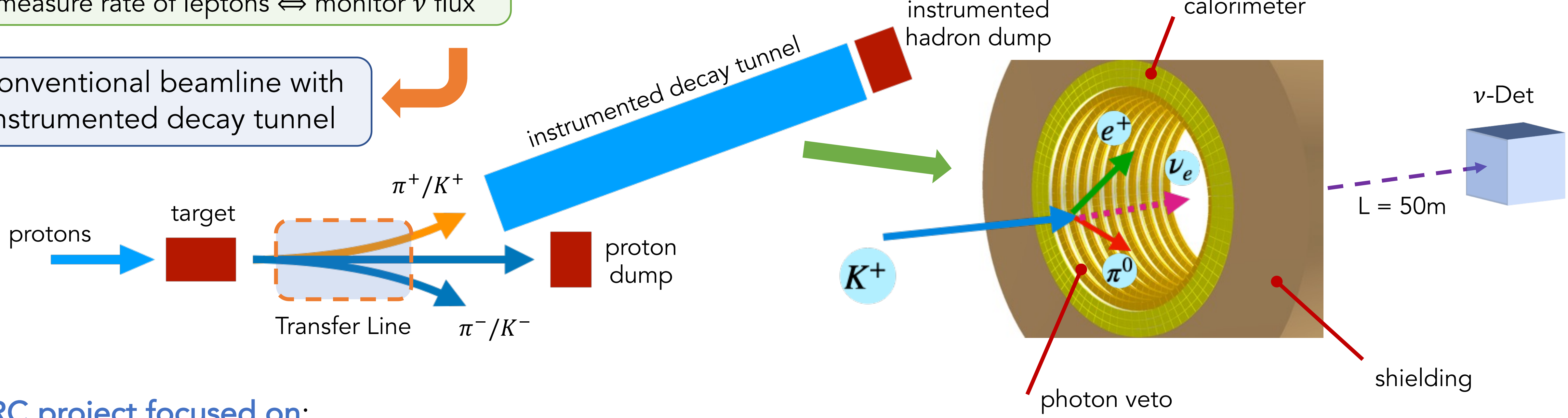
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam

measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

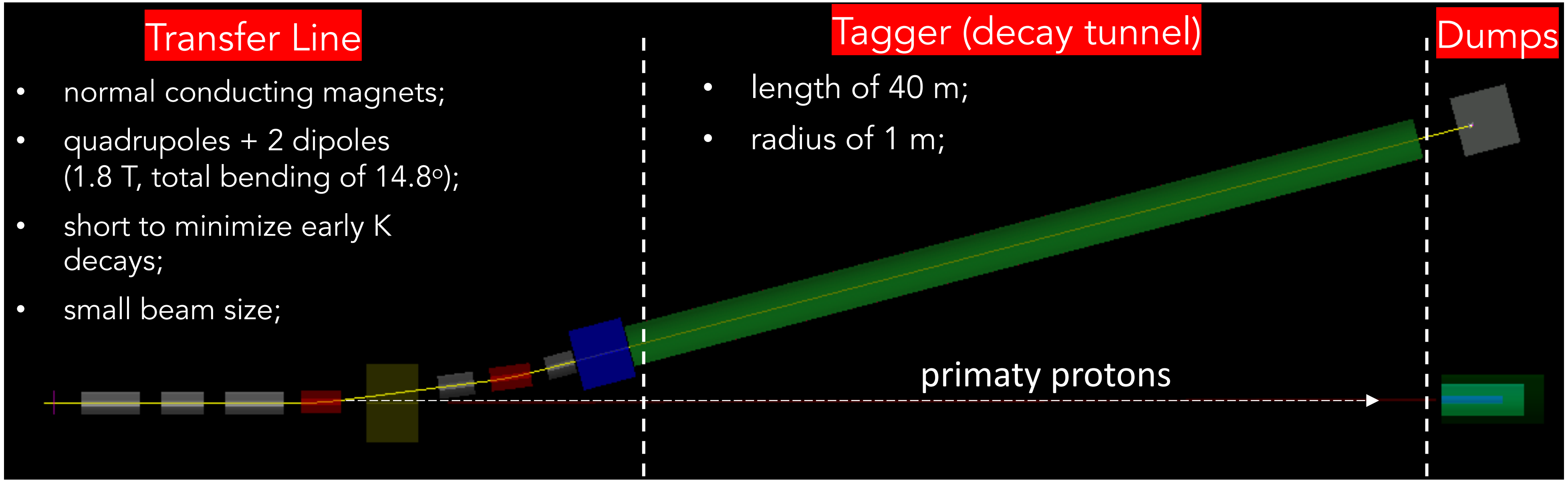
A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155



- **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



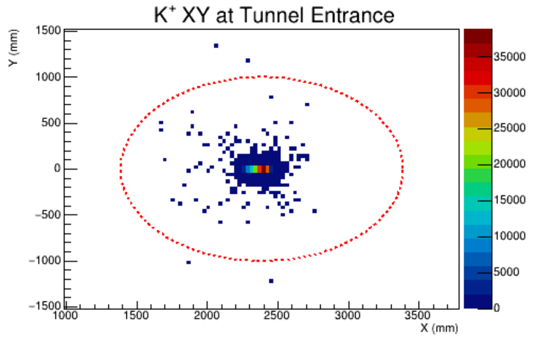
Transfer Line

- normal conducting magnets;
- quadrupoles + 2 dipoles (1.8 T, total bending of 14.8°);
- short to minimize early K decays;
- small beam size;

Tagger (decay tunnel)

- length of 40 m;
- radius of 1 m;

Dumps



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;

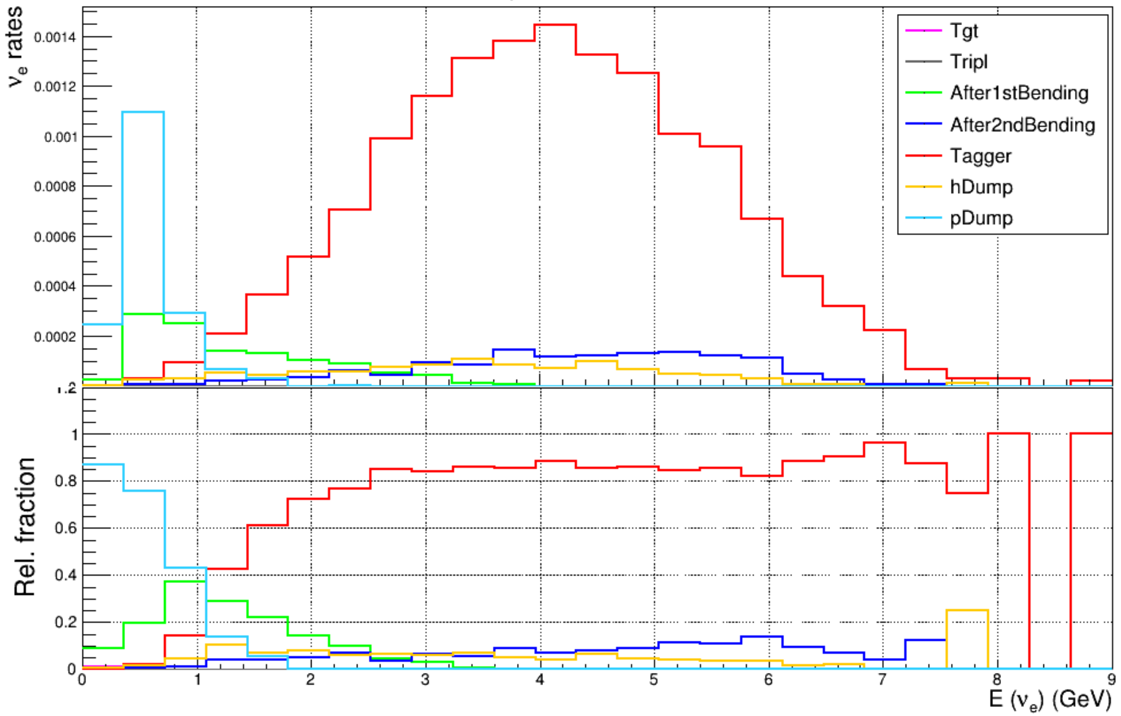
Taggable component

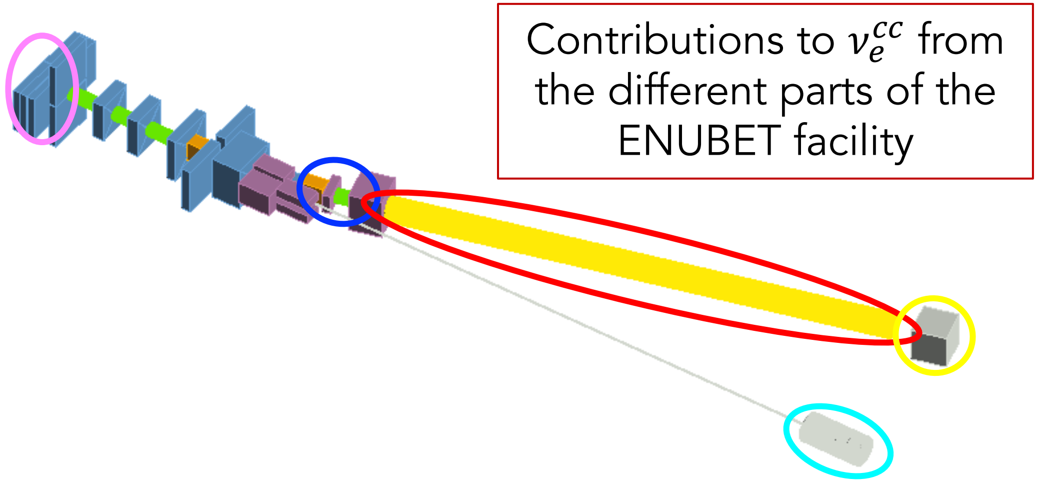
About 80% of total ν_e flux is produced by decays in the tunnel (above 1 GeV)

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;

ν_e CC spectra





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;

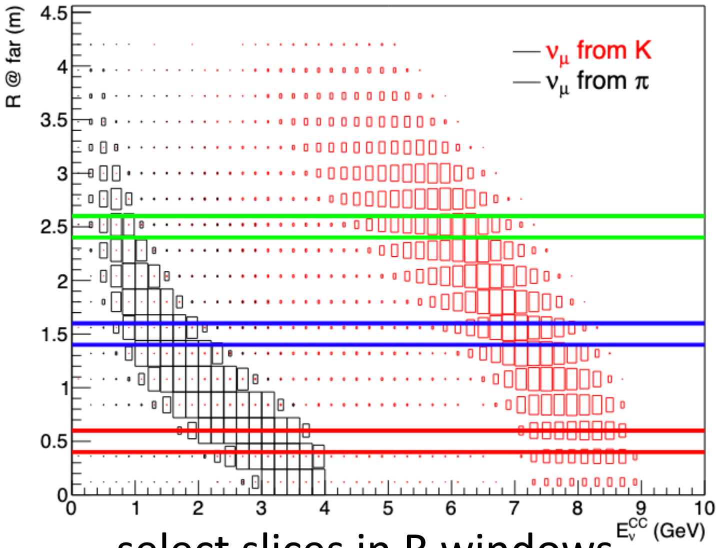
R = radial distance of interaction vertex from beam axis;

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

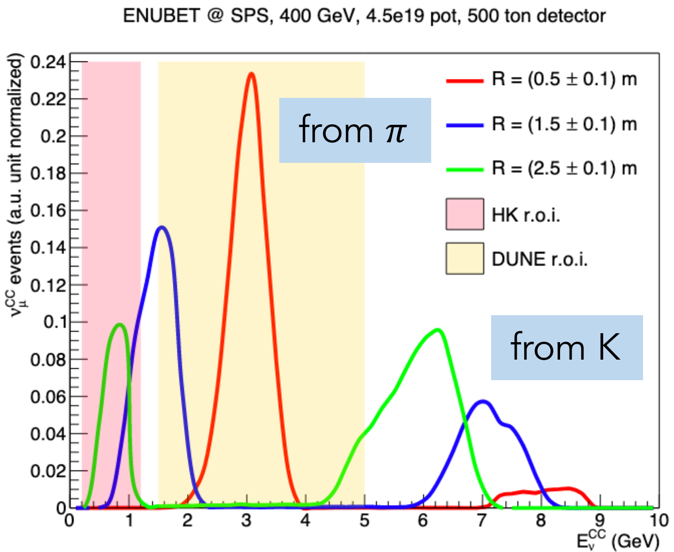
Precise determination of E_ν:

no need to rely on final state particles from ν_μ^{CC} interaction

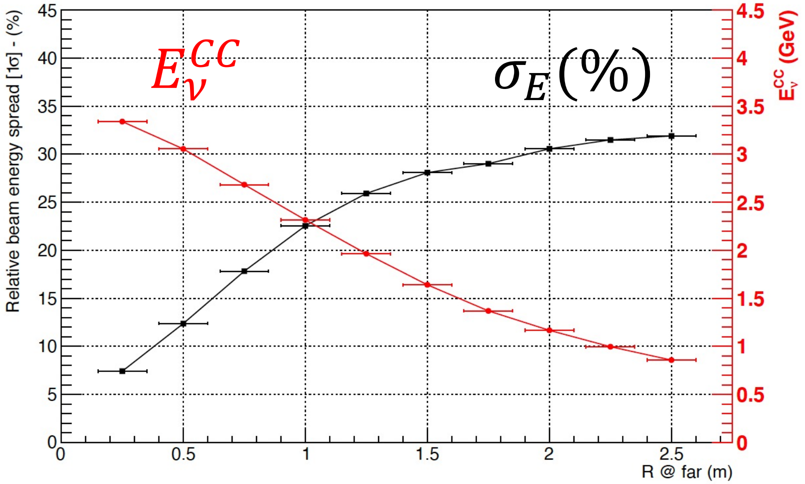
- 8-25% E_ν resolution from π in DUNE energy range;
- 30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):
  - ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



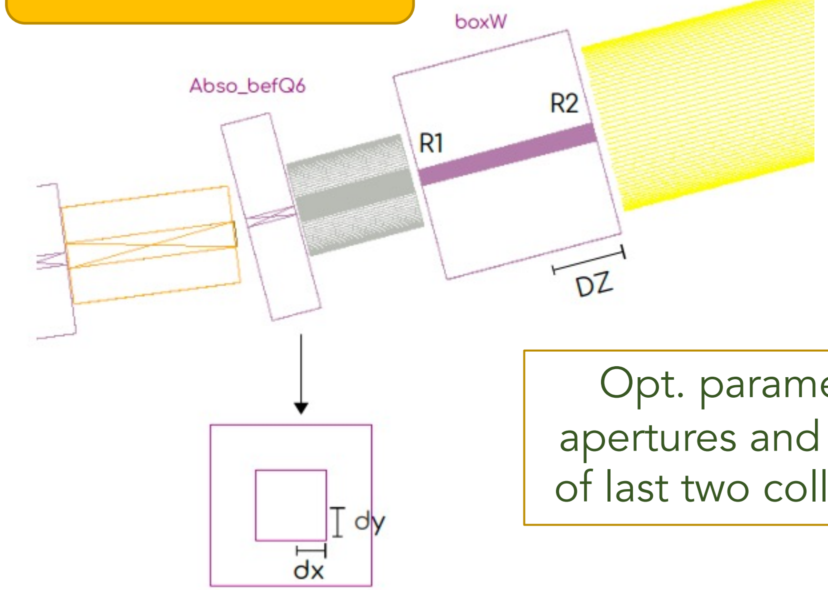
π/K populations well separated



from pion peaks at different R

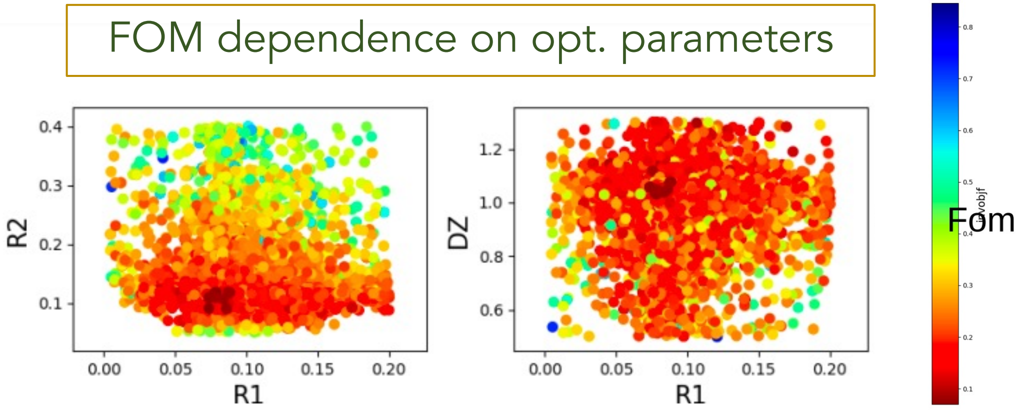
The ENUBET beamline:optimization studies

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

Preliminary

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

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;

Preliminary

- 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);

Decay tunnel instrumentation

Shielding

- 30 cm of borated polyethylene;
- SiPMs installed on top -> factor 18 reduction in neutron fluence;

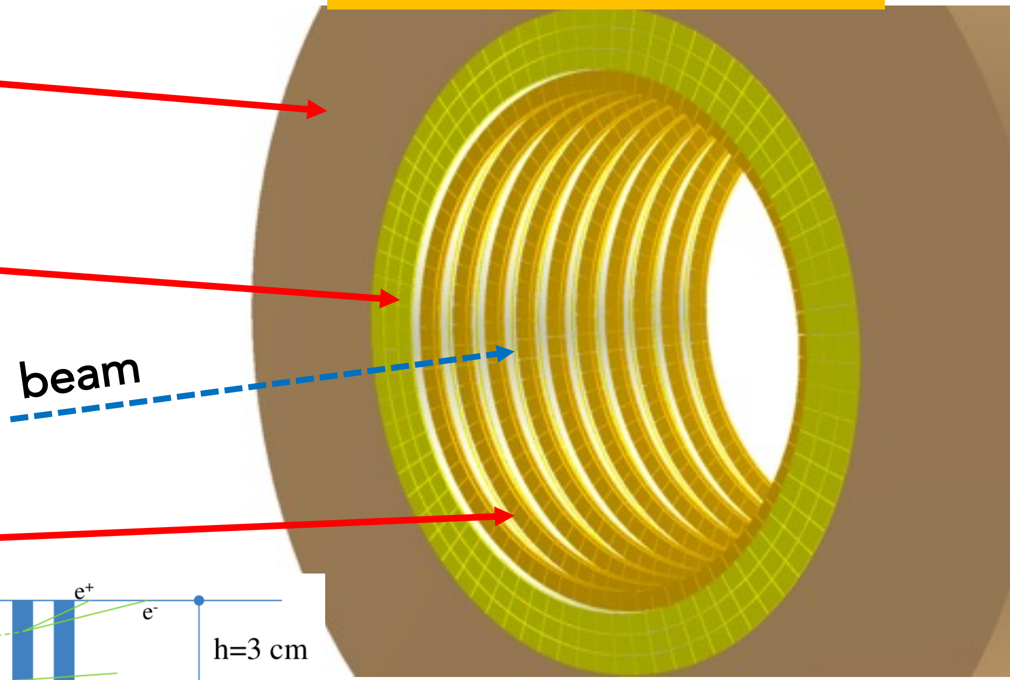
Calorimeter with $e/\pi/\mu$ separation capabilities:

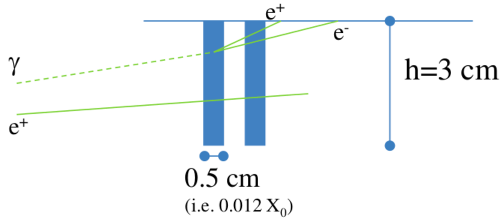
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

Photon-Veto allows π^0 rejection and timing:

- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of ~ 400 ps;

Calorimeter layout





Exploit event topology for PID

e^+ (signal) topology

π^0 (background) topology

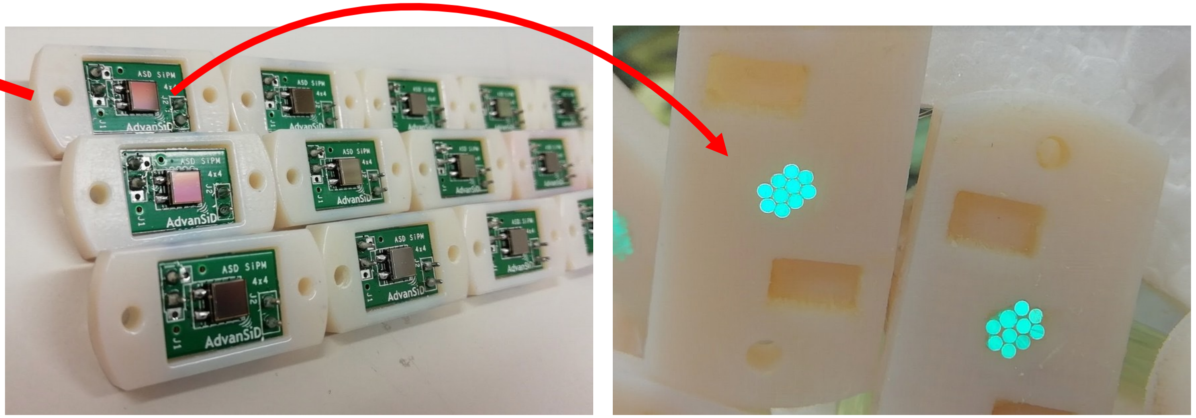
π^+ (background) topology

μ^+(signal/bkg) topology

Decay tunnel instrumentation prototype & tests

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

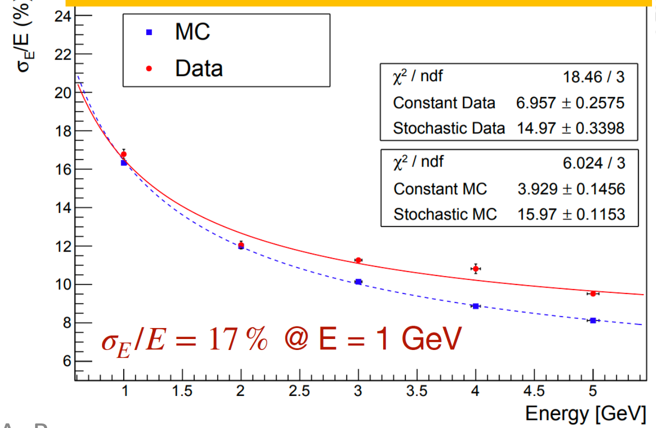
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



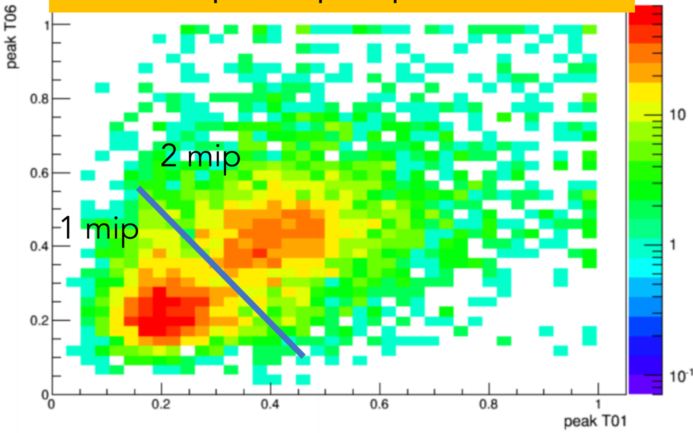
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

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

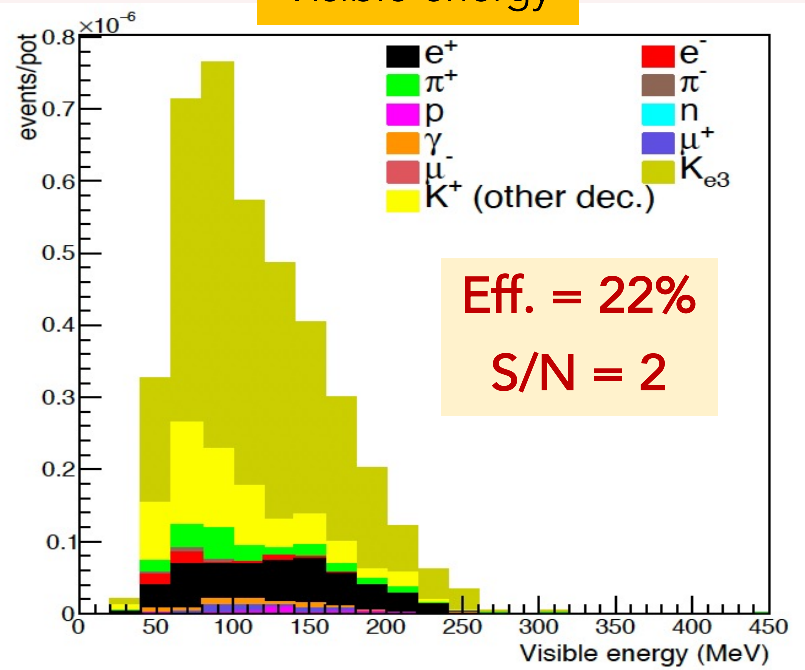
Lepton reconstruction and identification performance

✓ **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

Visible energy



Eff. = 22%

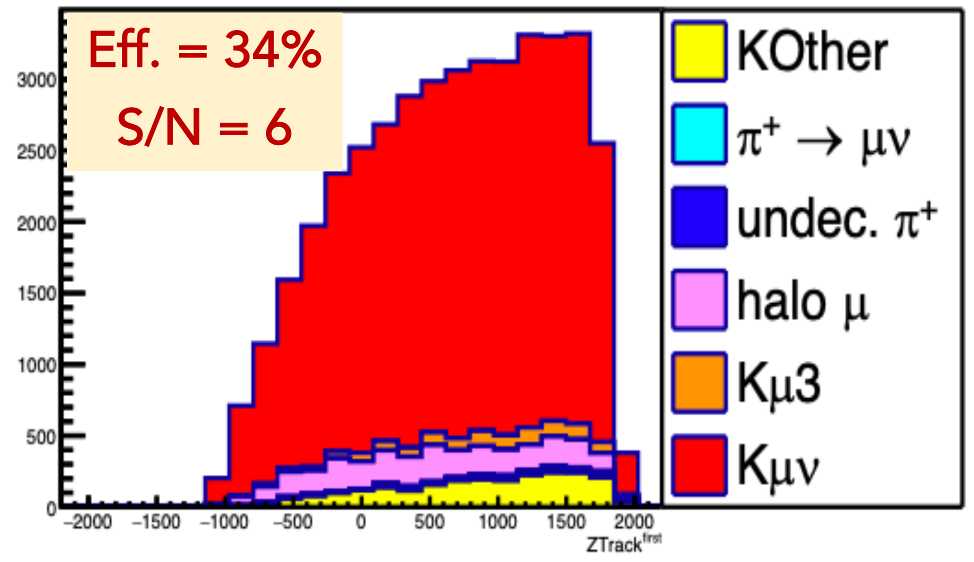
S/N = 2

Efficiency ~half geometrical

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

$K_{\mu 2}$ muons -> constrain ν_μ

Tagger impact point



Eff. = 34%

S/N = 6

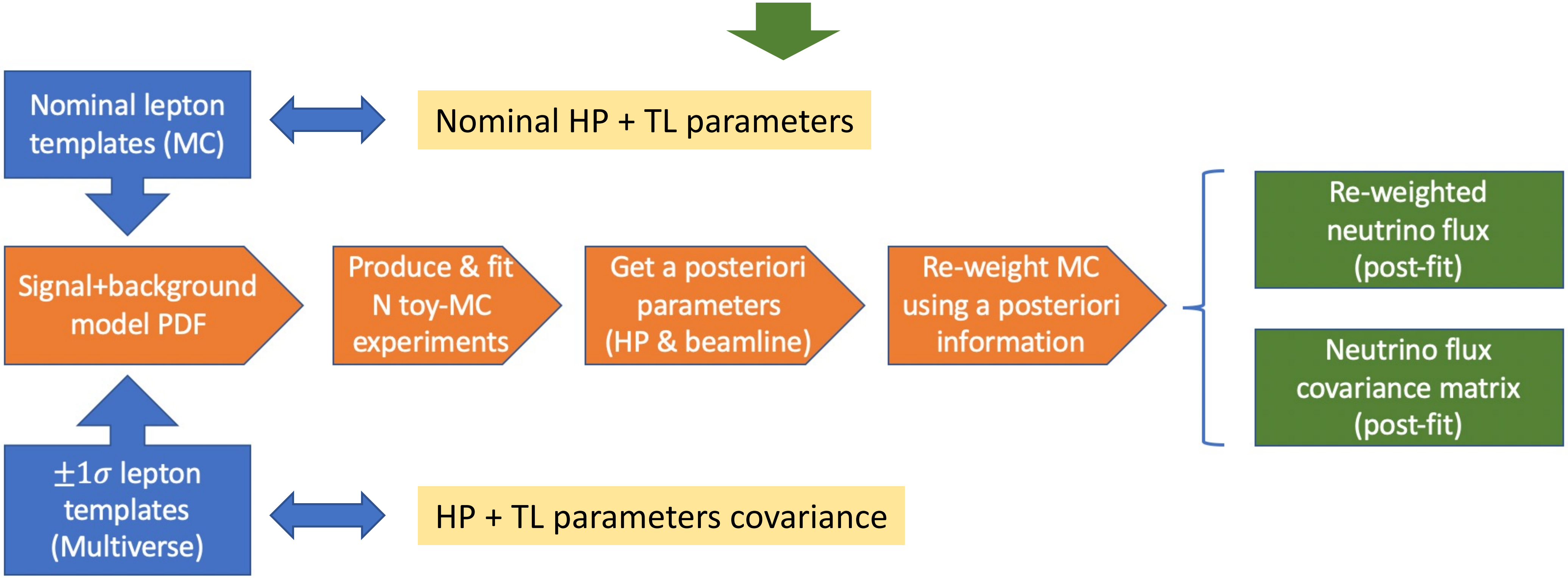
Efficiency ~half geometrical

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

ν-Flux: assessment of systematics

Monitored ν flux from narrow-band beam: measure rate of leptons ⟺ monitor ν flux

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



Nominal lepton templates (MC)

Nominal HP + TL parameters

Signal+background model PDF

Produce & fit N toy-MC experiments

Get a posteriori parameters (HP & beamline)

Re-weight MC using a posteriori information

Re-weighted neutrino flux (post-fit)

Neutrino flux covariance matrix (post-fit)

$\pm 1\sigma$ lepton templates (Multiverse)

HP + TL parameters covariance

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

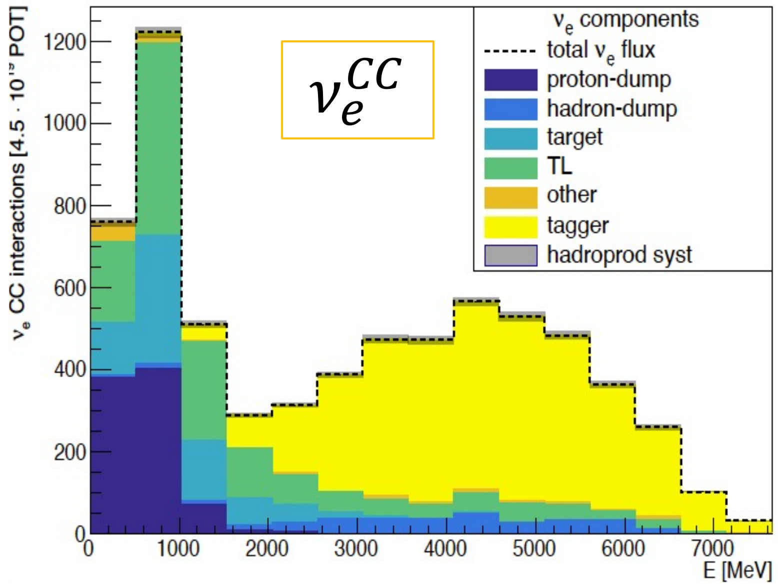
- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

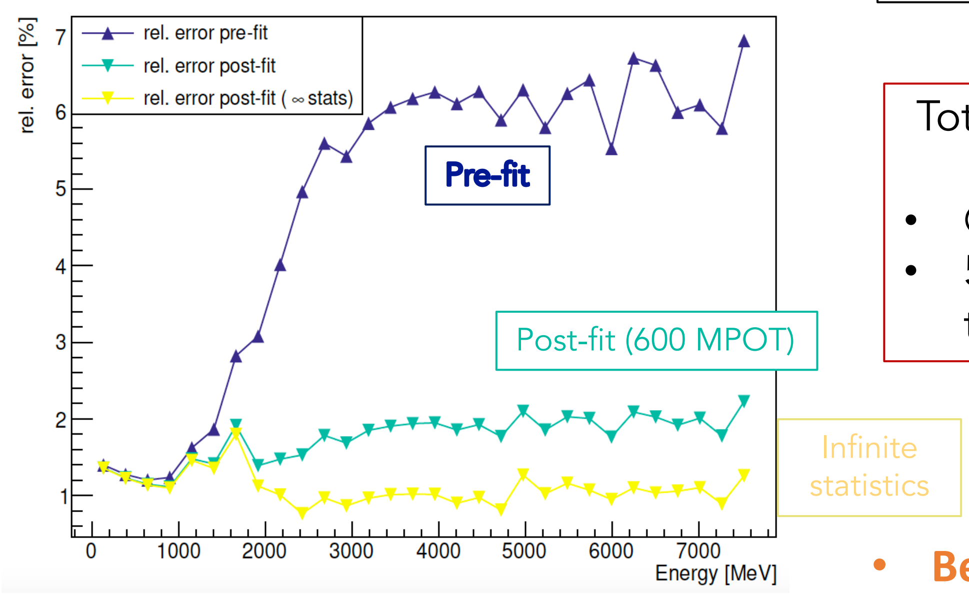
ν-Flux: impact of hadro-production systematics

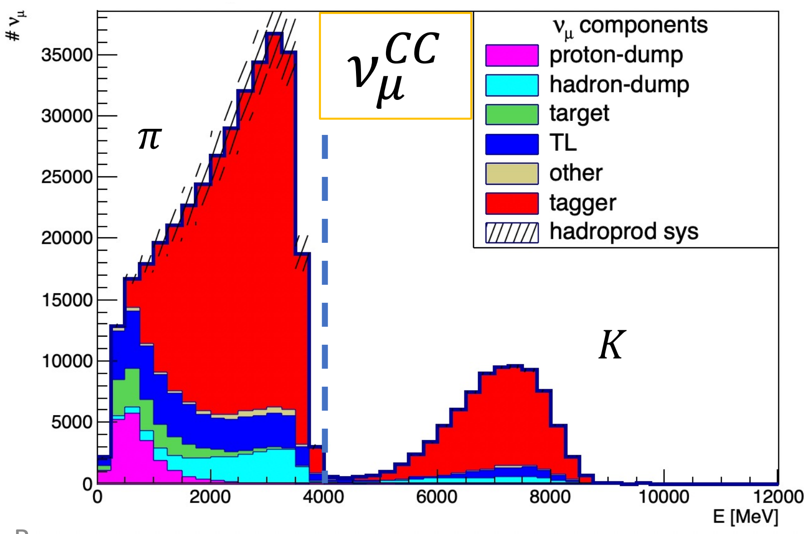
A. Branca et al., PoS NuFact2021 (2022) 030

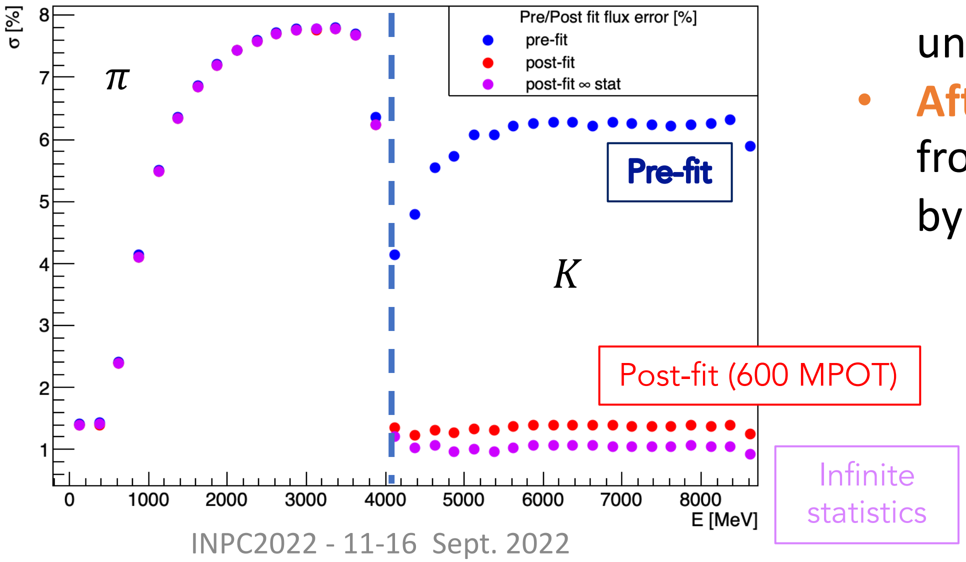
Neutrino interaction rates @ detector

Pre & Post fit relative errors on rates









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;

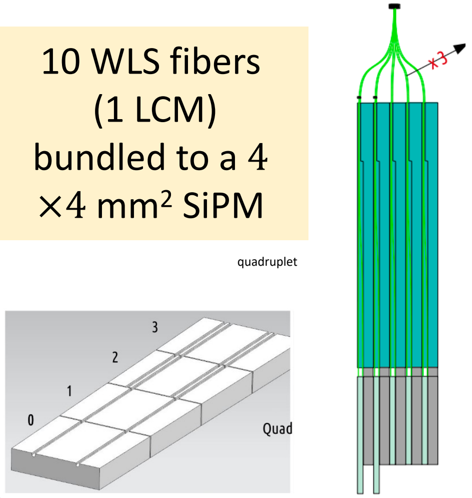
- **Before constraint**: 6% systematics due to hadro-production uncertainties;
- **After constraint**: 1% systematics from fit to lepton rates measured by tagger;

Achieved ENUBET goal of 1% systematics from monitoring lepton rates

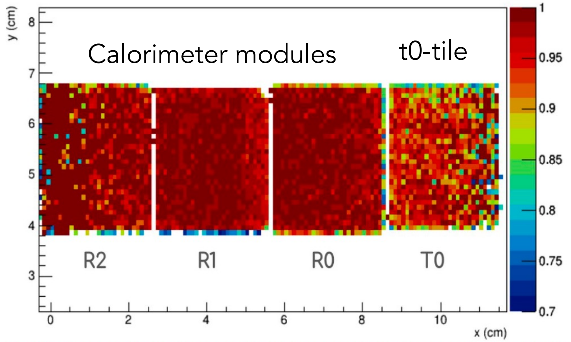
The demonstrator

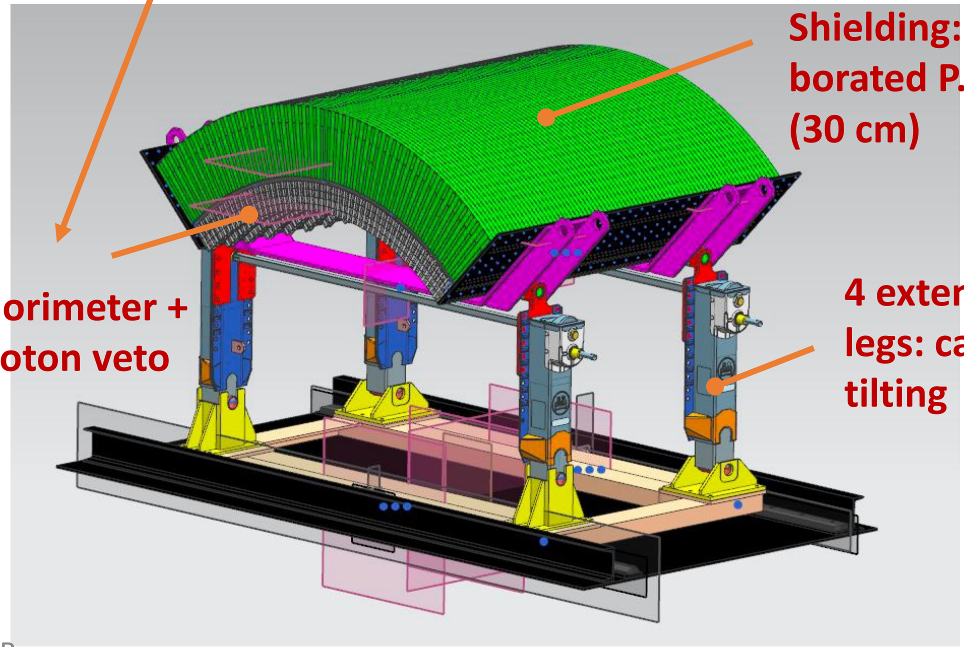
New frontal readout scheme & fibers bundling

10 WLS fibers (1 LCM) bundled to a 4×4 mm^2 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

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

Construction @ LNL-INFN Labs


Iron arcs and borated polyethylen shielding


Lifting test of demonstrator

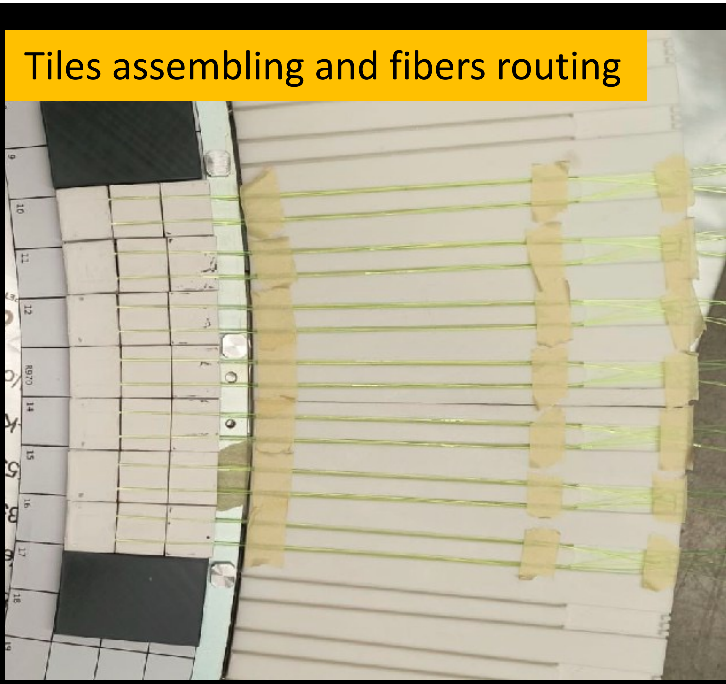

Fiber concentrator (boundling/routing to SiPMs)

The demonstrator

Construction @ LNL-INFN Labs

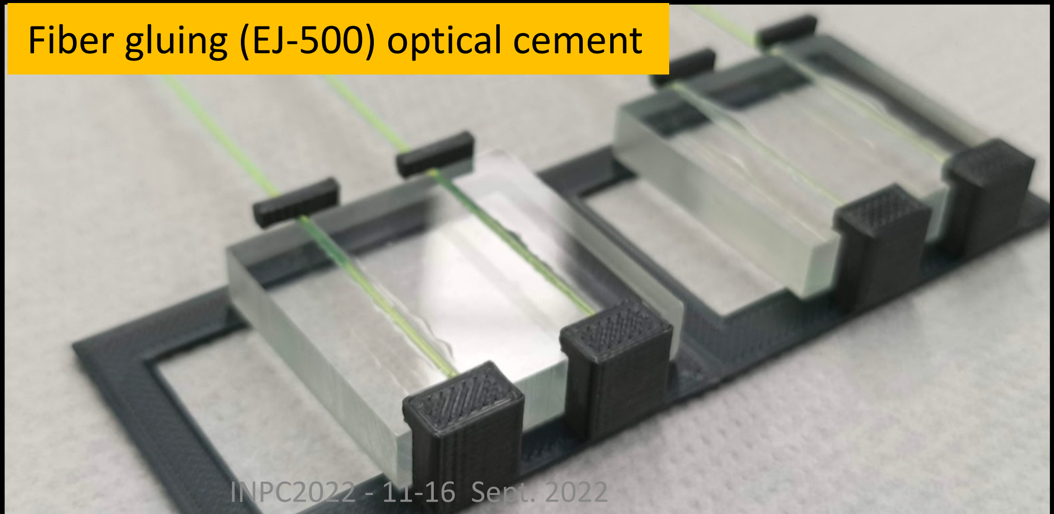
- The scintillator tiles

EJ-204 scintillator tiles – grooves for WLS fibers



Tiles assembling and fibers routing

Tile painting (EJ-510 / TiO_2 painting)



Fiber gluing (EJ-500) optical cement

A next generation high precision ν-N cross section program

The ENUBET monitored neutrino beam allows:

High Precision Neutrino Flux ϕ:

- Absolute normalization and flavor content known at 1% level;
- High flux of electron neutrino, the appearing flavor at long-baseline exp for which less information are available;

A priori knowledge of Neutrino Energy E:

- At 8-25% level on an event by event basis;
- No need to rely on the reconstruction of the final state interactions;

Expected neutrino interaction rate at the detector:

A. Branca, G. Brunetti, A. Longhin, M. Martini,
F. Pupilli, F. Terranova, Symmetry 2021, 13, 1625

$$N \sim \int \phi(E) \times \sigma(E) \times \mathcal{E}(E)\, dE$$

What detector technology do we need?

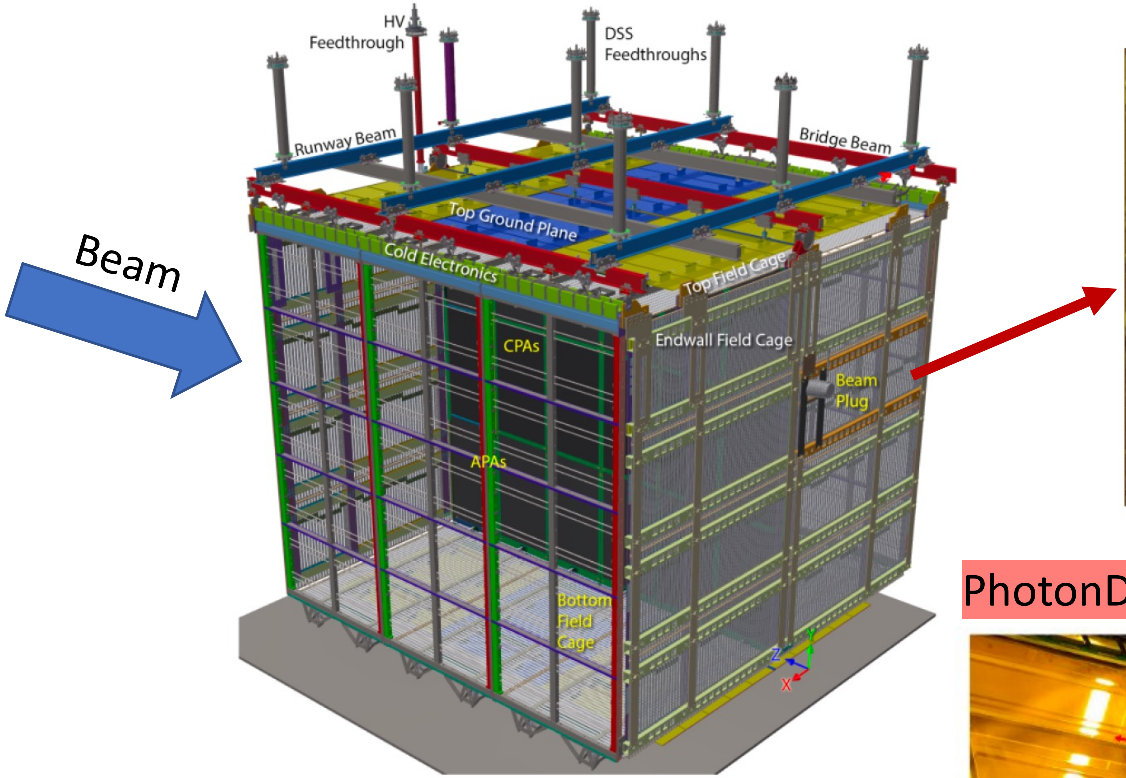
Auspicable a facility based on different detection techniques!

- Measure the $\sigma \times \mathcal{E}$ with same detector technologies used in long-baseline program;
- Disentangle interaction from detector effects using complementary techniques (high/low density and fine grained detectors);

Long-baseline program: ProtoDUNE (LAr TPC)

Measuring σ×Ɛ for DUNE: exploit the ProtoDUNE-SP detector @ CERN

- Already installed and under test-beams @ CERN (goal: demonstrate DUNE FD detector technology);
- The large size allows almost full containement of neutrino interactions;

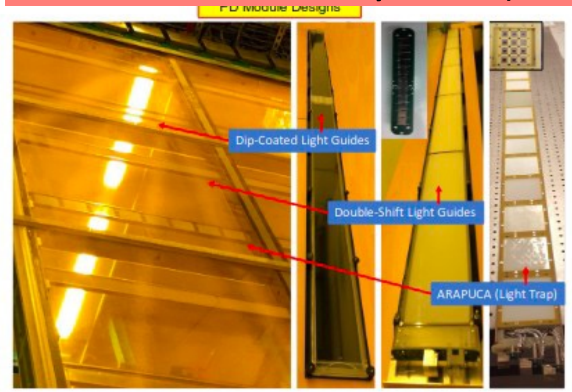


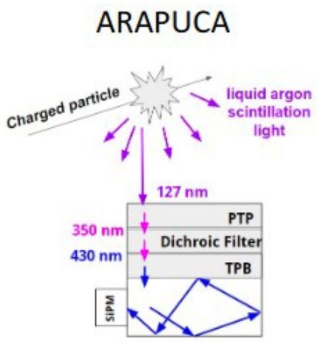
One of the two drift volumes

Dimensions:

- 7 m along beam direction;
- 7.2 m along drift direction;
- 6.1 m n height;
- Total mass about 400 tonnes;

PhotonDetection System (embeded in anode plane)



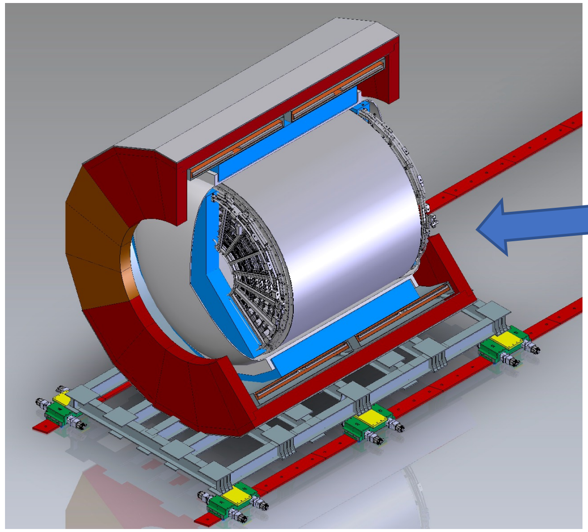


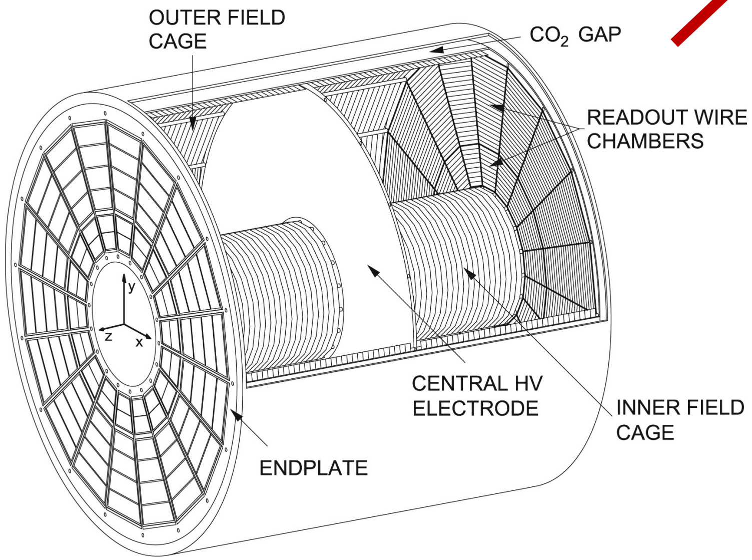
Decoupling interaction from detector ε: LAr and GAr

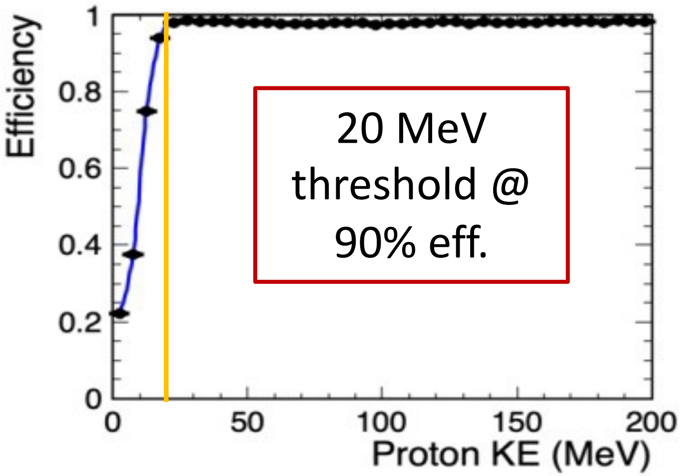
Ideal solution: exploit simulatneously liquid and gas TPC

- Gas phase TPC will be emploied in the ND-GAr at the DUNE ND complex;
- TPC based on the design of ALICE; but operated @ x10 bigger pressure -> enhance neutrino event rate;
- Advantages of high pressure gas w.r.t. Lar TPC:
  - High momentum resolution (use of magnetic field);
  - Improved particle ID (in particular p-pion separation);
  - Low energy treshold (allows full reconstruction of hadronic system in neutrino interaction);

- Active volume divided in two parts by central cathode;
- Radius of 2.6 m;
- Length of 5 m;
- Total mass of 1 tonne;







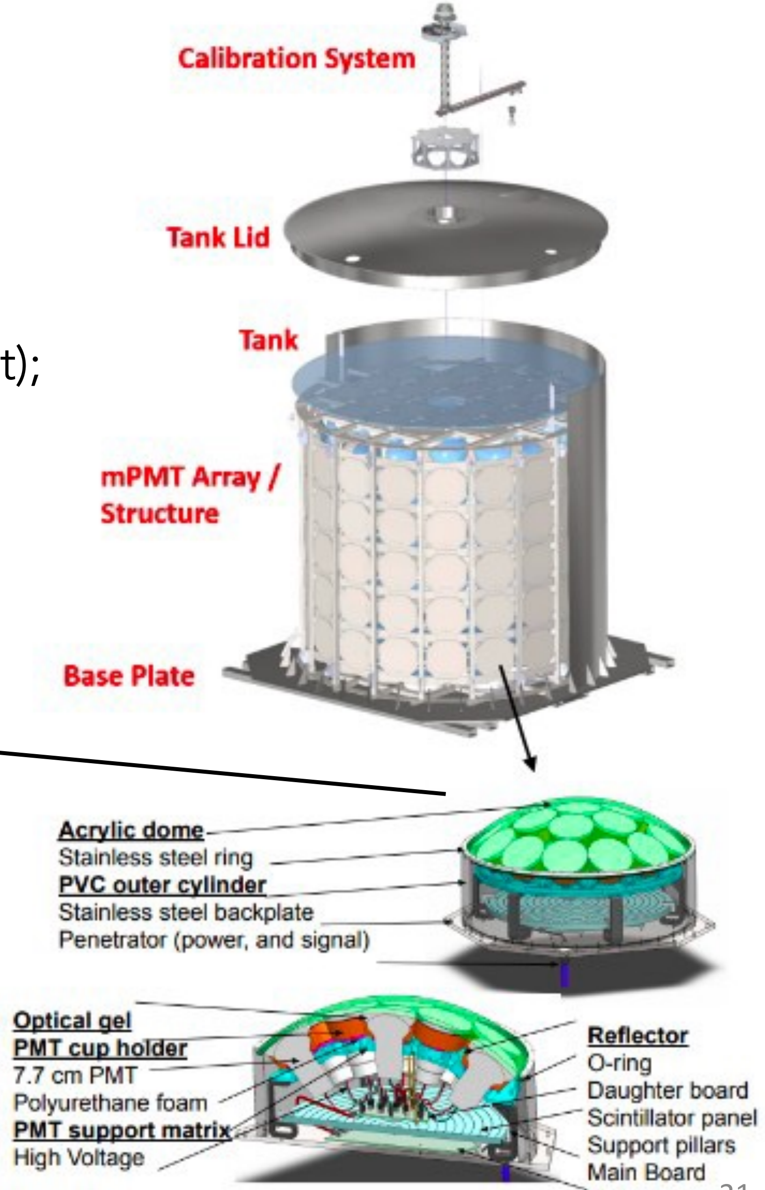
20 MeV threshold @ 90% eff.

Long-baseline program: WCTE (water)

Measuring $\sigma \times \varepsilon$ for Hyper-K: the proposed WCTE could represent an interesting opportunity

- Start of detector assembly by November 2023 and start of operations in April 2024;
- Detector technology and event reconstruction smilar to that of Hyper-K FD -> reduction of systematics in cross sections and oscilation analyses;
- Fiducial mass is contained:
  - Can perform ν_μ^{CC} cross section measurements (ν_e^{CC} sample not significant);
  - Muon containement limited -> envisage a downstream spectrometer;

- Diameter of 3.8 m;
- Height of 3.5 m;
- Total mass about 40 tonnes;
- multi-PMT photon detectors, 19 PMT each, for Cherenkov light detection;

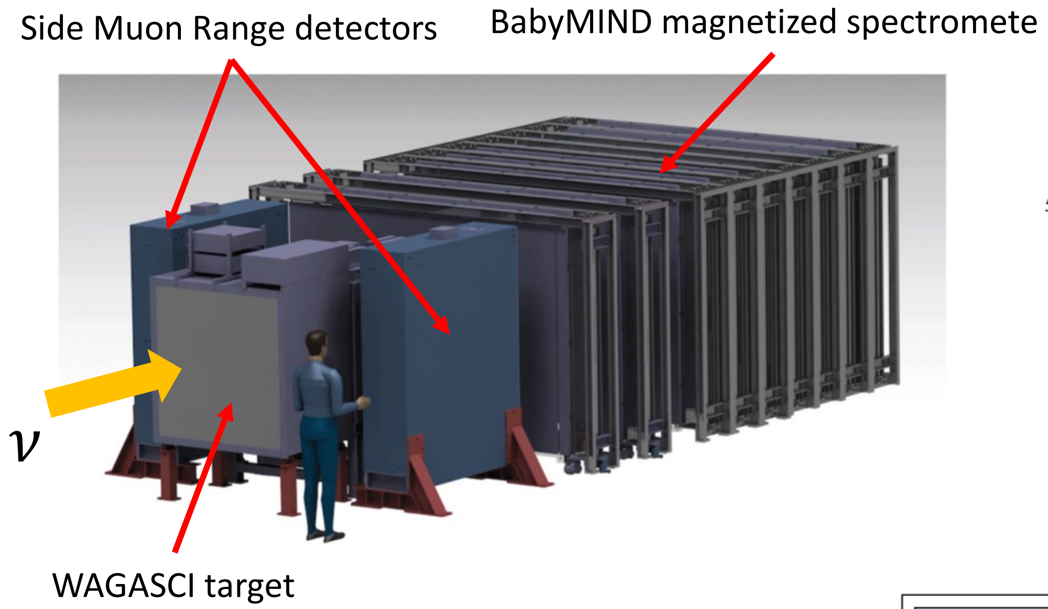


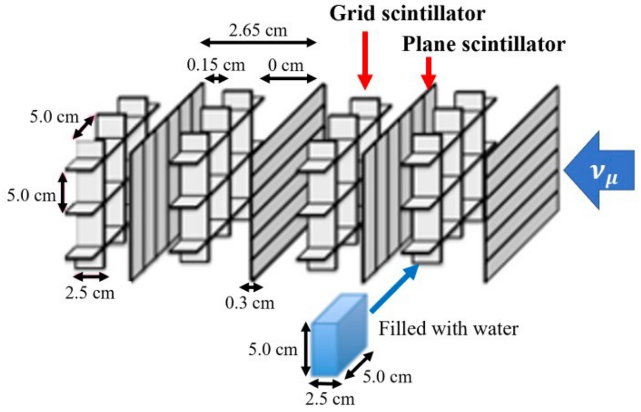
Decoupling interaction from detector ℰ: water Cherenkov

Ideal solution: use of fine-grained detectors with water target

WAGASCI:

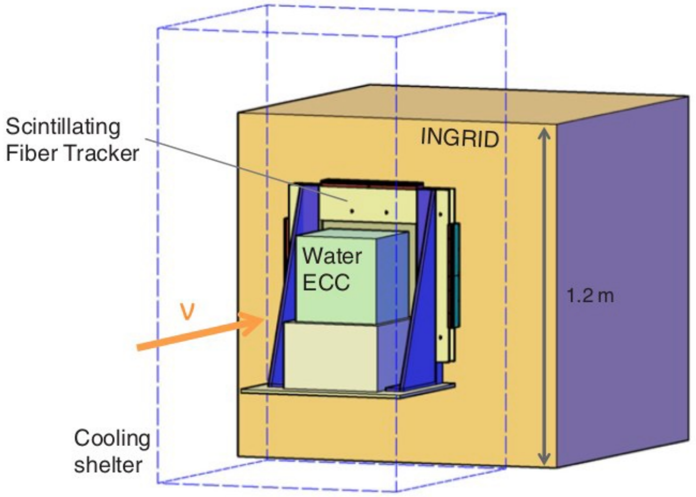
- 0.6 tonne water target;
- 3D grid-like structure of plastic scintillator enclosing cells of O(cm) linear size;
- Two mu side modules (steel plates and scintillator slabs);
- Downstream mu spectrometer (BayMIND);

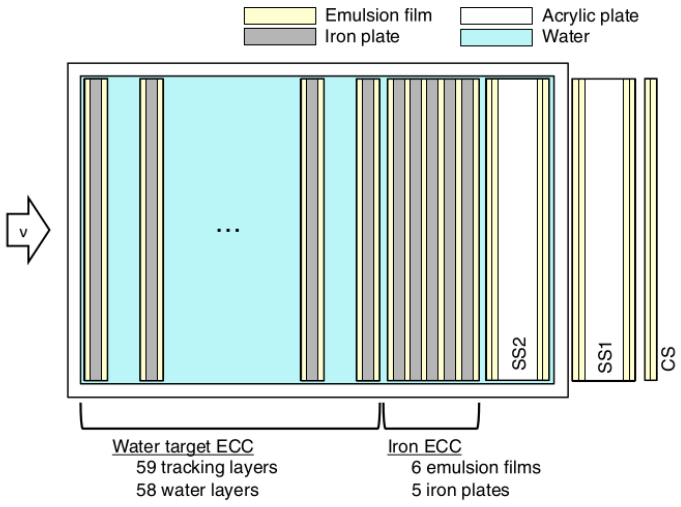




NINJA:

- Sandwich structure: nuclear emulsion films and iron plates (500 μm thick) intervealed with water layers (2 mm thick);
- Downstream: tracker (scintillating fiber) -> match/timestamp of tracks in emulseion;
- One INGRID module -> muon range;





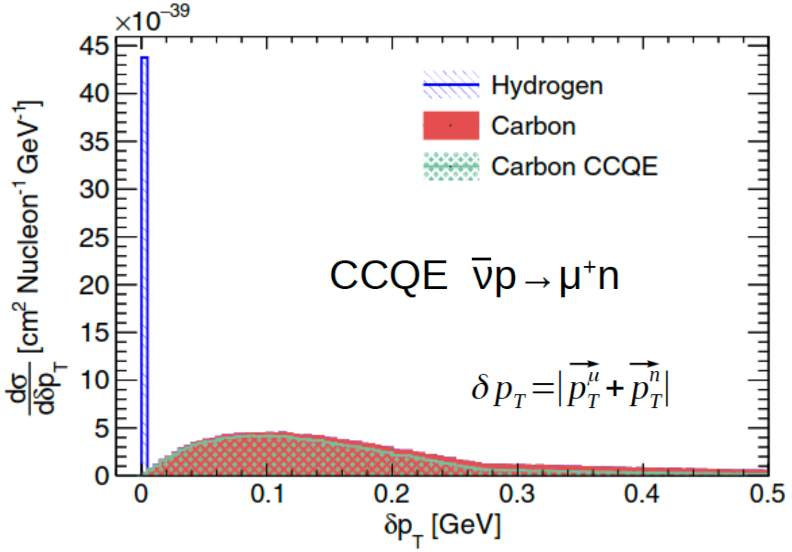
Thresholds: 200 MeV hadrons / 50 MeV protons & pions

Neutrino interactions with Hydrogen

Precision measurement of neutrino scattering off hydrogen and deuterium:

- Clean and solid base to build reliable models not affected by nuclear effects;
- Can be extrapolated to higher Z materials;
- Detailed studies on the nucleon structure exploiting a bare weak probe;

Indirect approach: exploit the transverse momentum imbalance due to nuclear effects have been proposed to disentangle hydrogen interactions from those to other nuclei in composite materiale (graphite targets);



Direct approach: using a liquid-hydrogen target, providing a fully unbiassed measurement

- ➢ Challenging due to safety requirements constraints for underground facilities;
- ➢ Proposal to use the magnetized bubble chamber technique with modern digital camera techniques;


FERMILAB 15’ bubble chamber

Conclusions and next steps

- **ENUBET will be the first monitored neutrino beam for neutrino cross-section measurements @ O(1%):**
  - Final design of beam transfer line allows to get $10^4\ \nu_e^{CC}$ events in ~3 years (@ SPS), ongoing fine-tunning of parameters;
  - Design of decay tunnel instrumentation finalized: demonstrator under test-beam @ CERN in October 2022;
  - Detector simulation and PID studies done: achieved good identification of both positron and muon;
  - Achieved 1% level in flux precision evaluating impact of hadroproduction systematic;
  - Next: assess subleading impact on neutrino flux due to detector effects;

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

- **A next generation of neutrino detector is needed:**
  - Facility based on different neutrino detector technology;
  - Boost sensitivity of DUNE and HyperK studying neutrino interaction on Argon and Water;
  - Improve theoretical knowledge: decouple cross section from detector effects, envisage detectors based on low-Z targets;

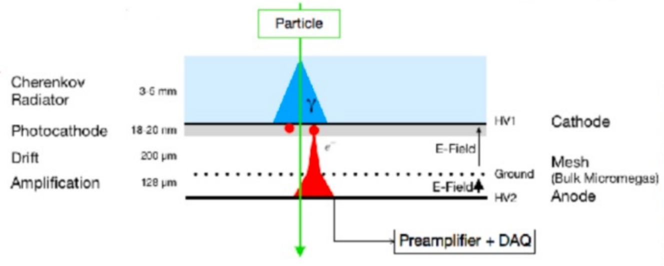
Thank you for your attention!

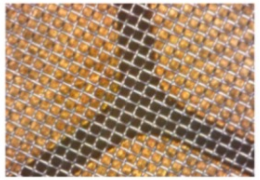
Additional Material

Lepton reconstruction and identification:

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

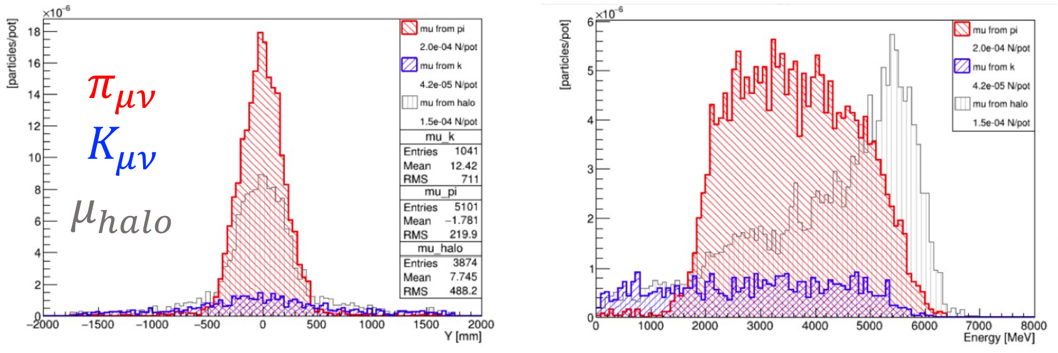
✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump

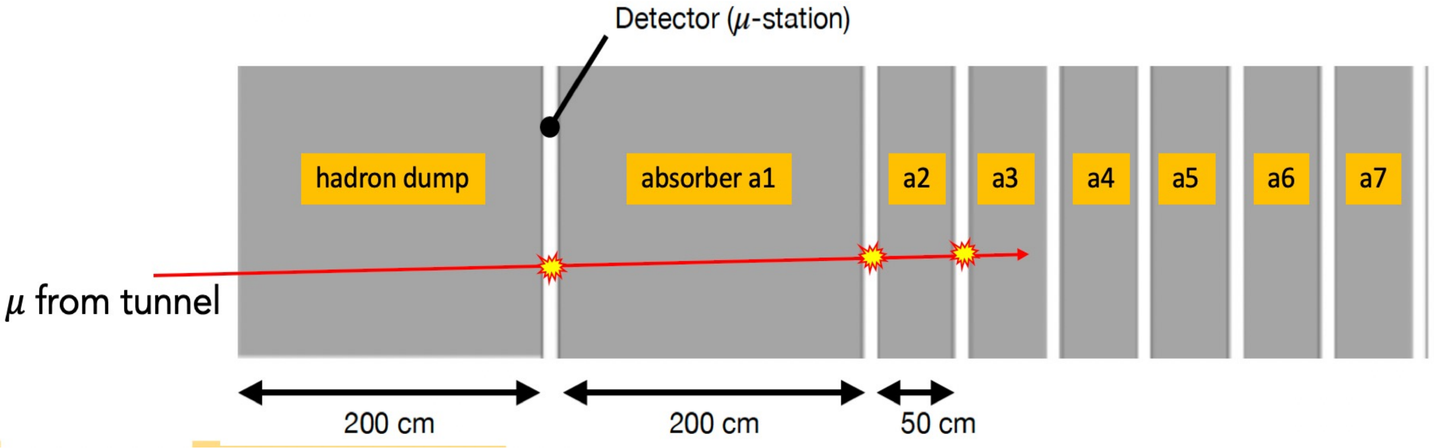




Possible candidates: fast Micromega detectors with Cherenkov radiators (PIMENT project)

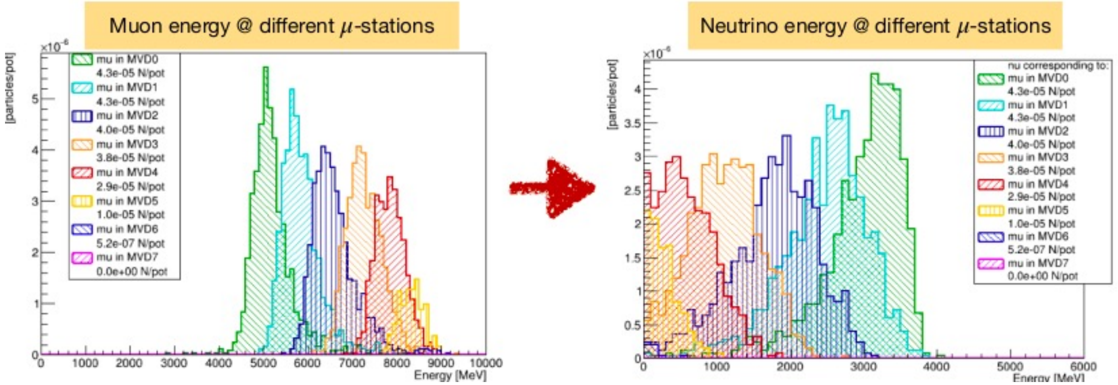
Exploit differences in distributions to disentangle components





Muon energy @ different μ-stations

Neutrino energy @ different μ-stations



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

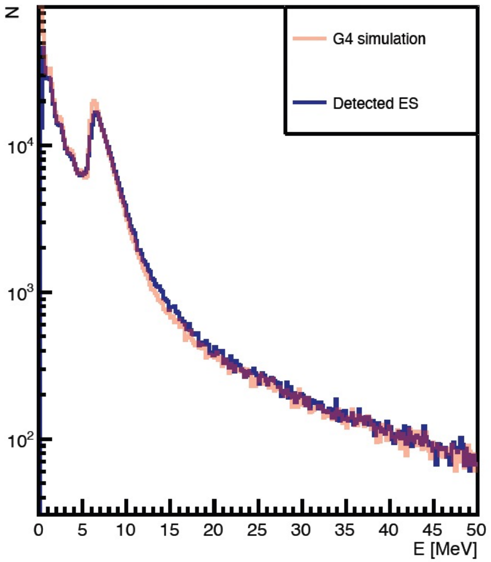
Implementation of waveform generation in the full simulation: as in real data (digitally sampled signals @ 500 MS/s) -> real pile-up treatment

- 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;

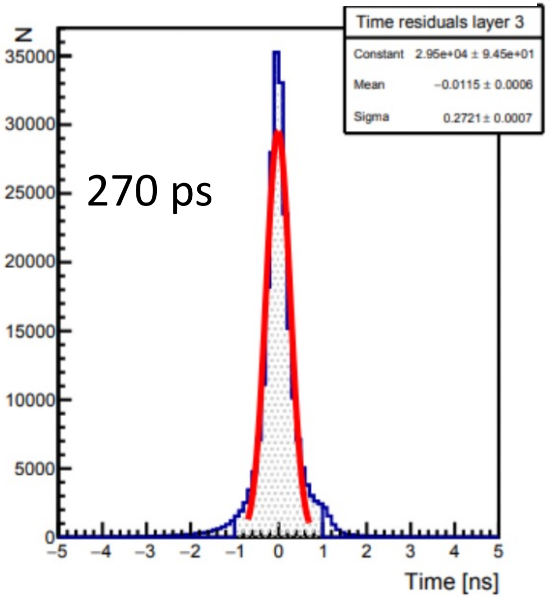
Complete assessment of pile-up effects on detector performance

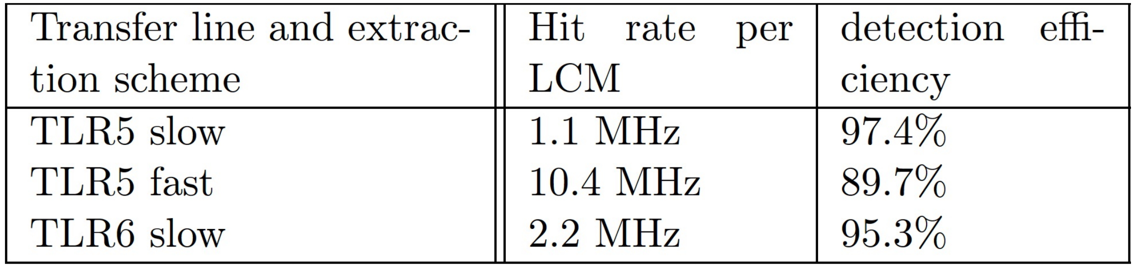
pulse-detection algorithm optimized for faithful energy evaluation, high efficiency, and accurate time resolution

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%

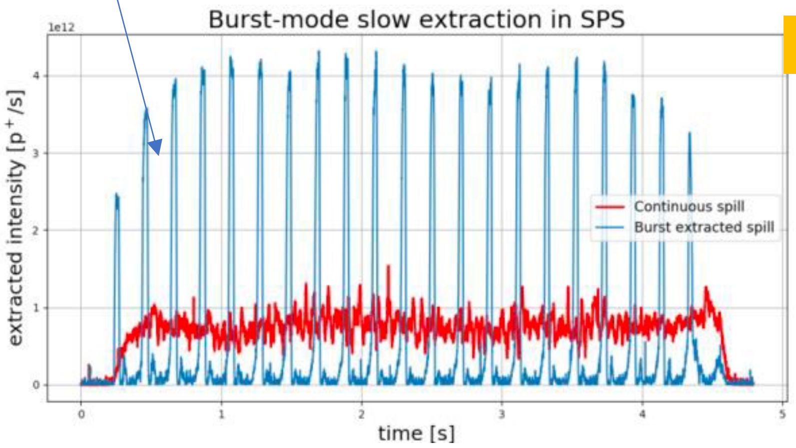
Slow extraction = 4.5×10^{13} POT in 2 s;
Fast extraction (horn) = 10× slow extraction;

Horn based focusing

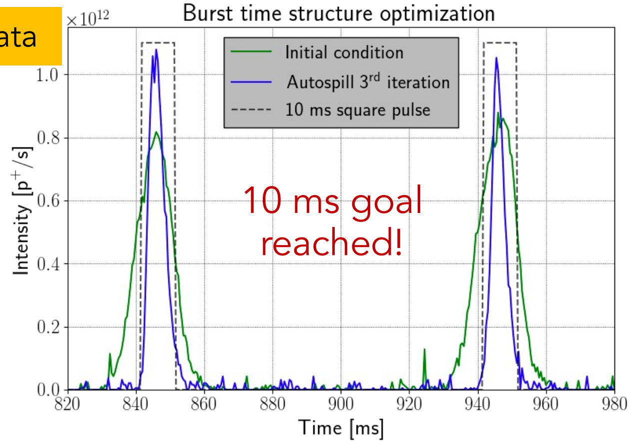
M.Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

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

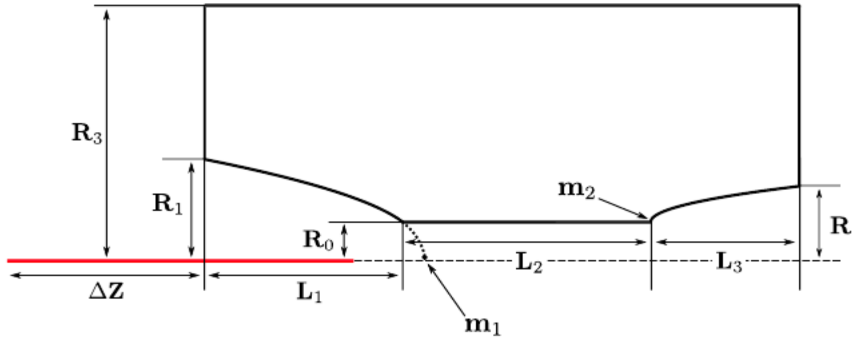


from real data



10 ms goal reached!

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;

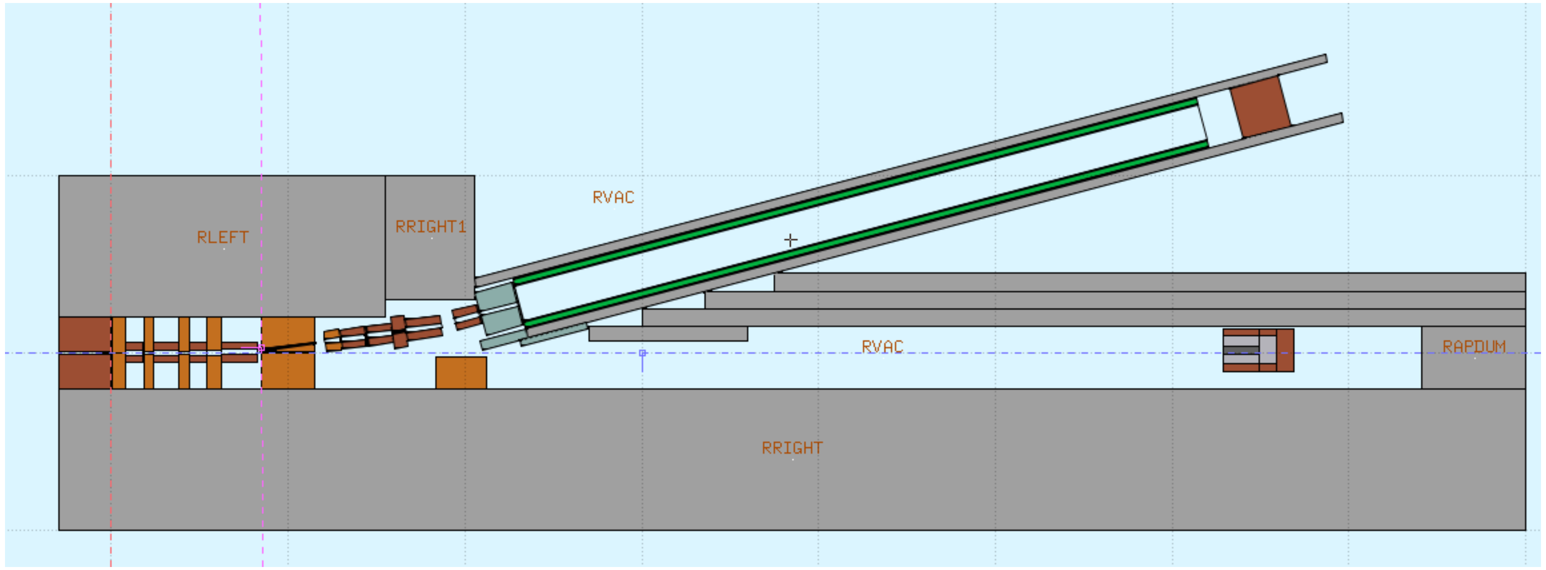
Horn optimization: search for best shape & current values to maximize flux

- 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

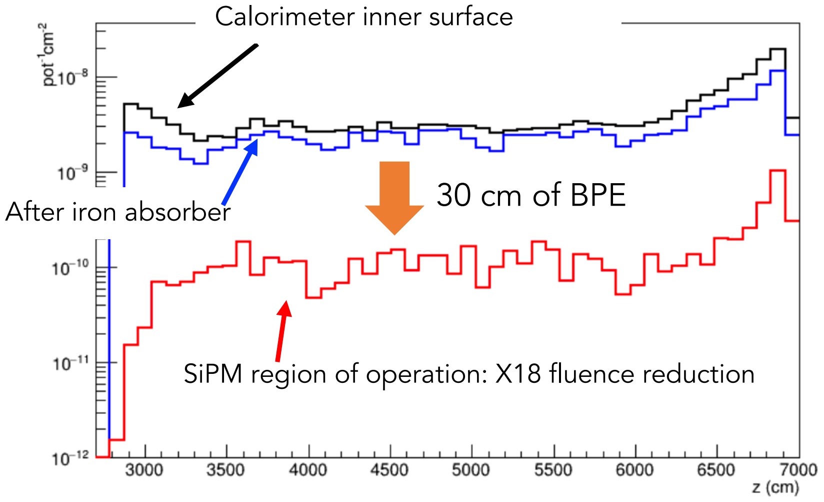
FLUKA irradiation studies

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:

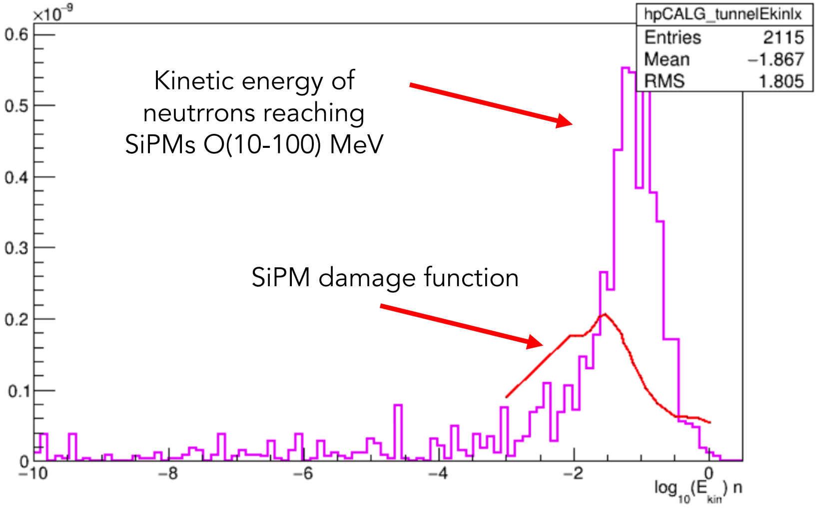
-> SiPMs outside of the calorimeter


Calorimeter inner surface

After iron absorber

30 cm of BPE

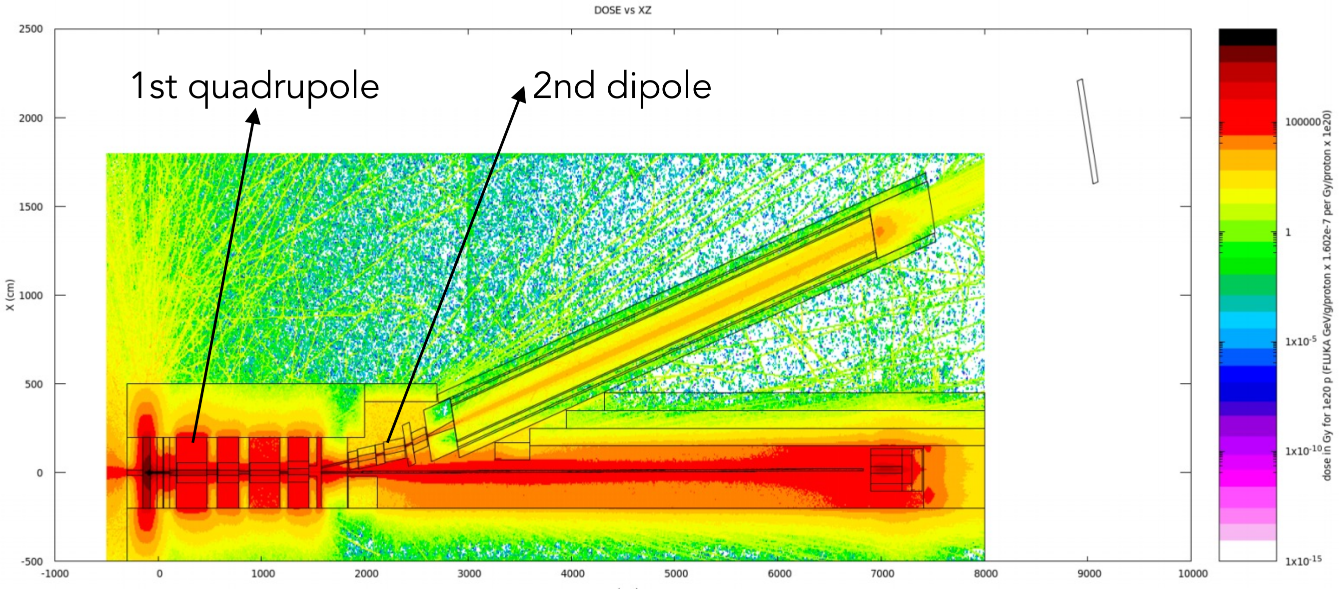
SiPM region of operation: X18 fluence reduction


Kinetic energy of neutrrons reaching SiPMs O(10-100) MeV

SiPM damage function

hpCALG_tunnelEkinlx	
Entries	2115
Mean	−1.867
RMS	1.805

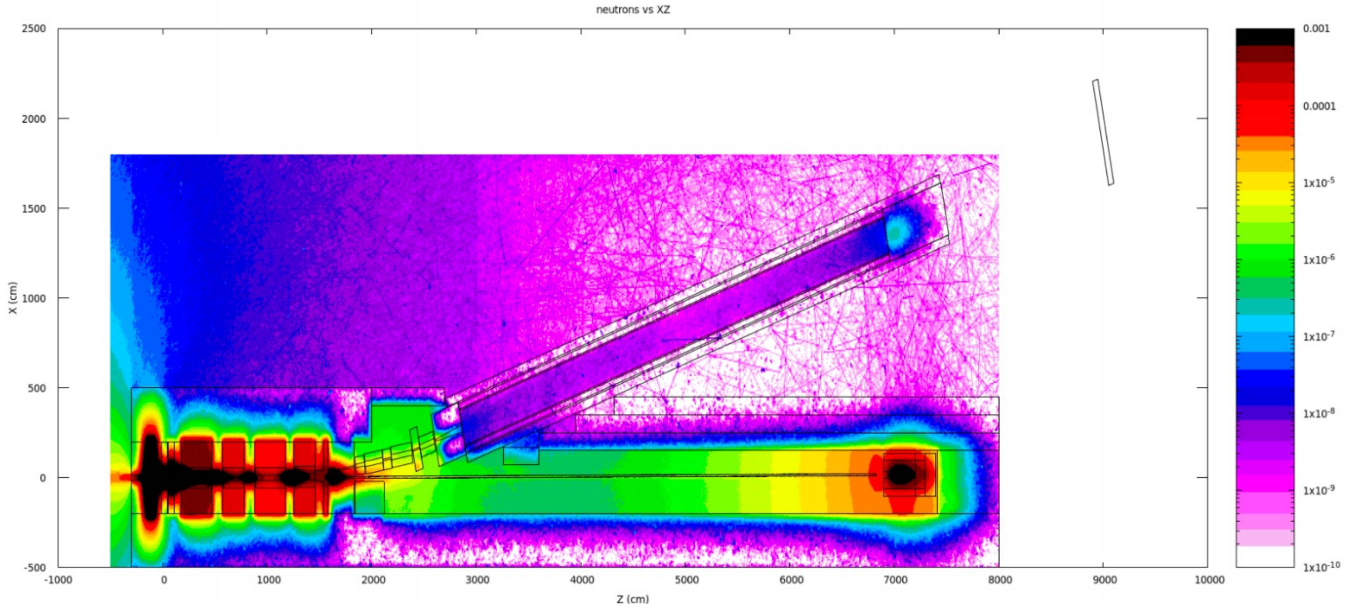
FLUKA irradiation studies



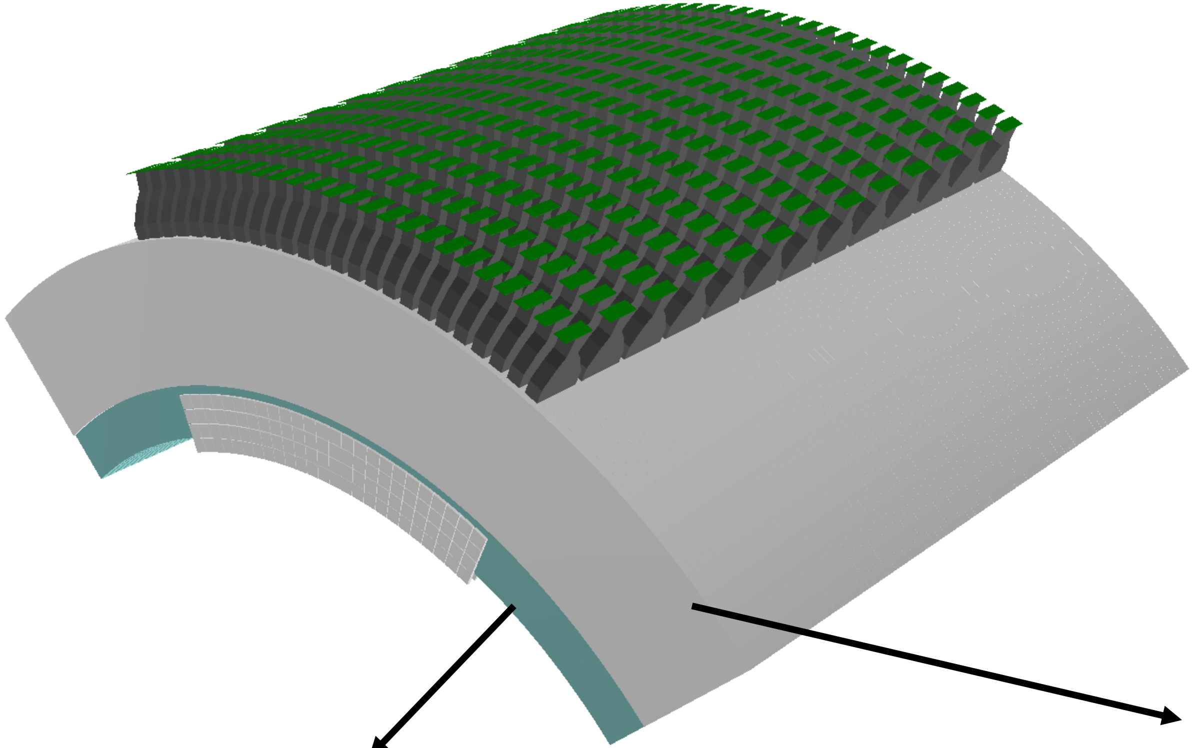
Dose for 10^{20} POT [Gy]

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

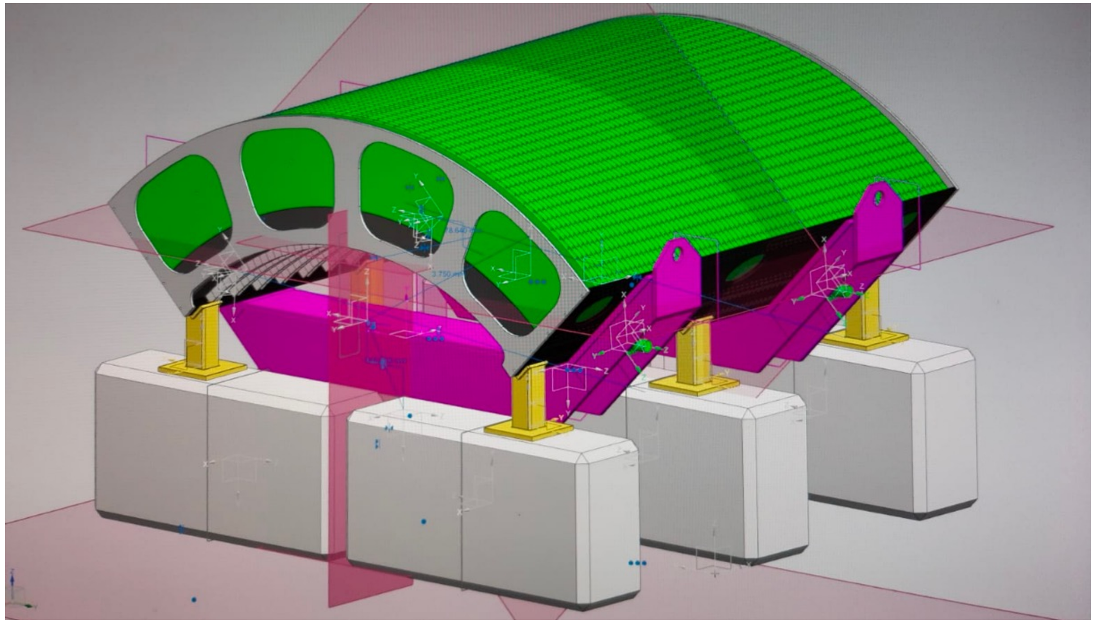
Neutrons/cm^2 for 10^{20} POT



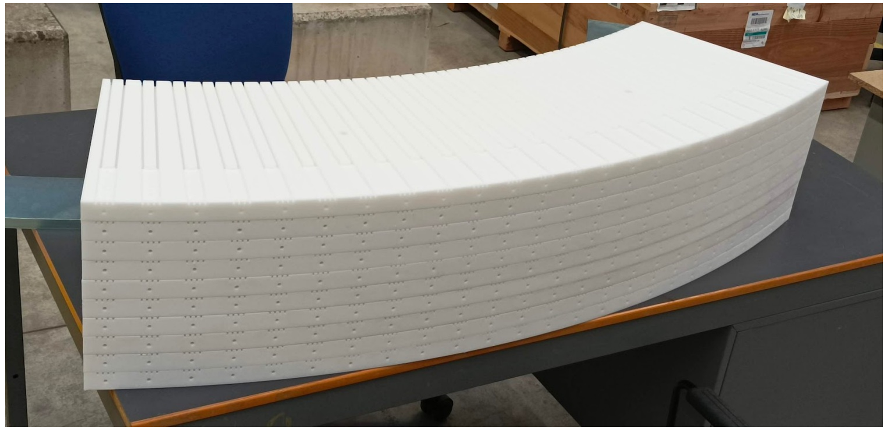
Demonstrator



Weight ~7 t

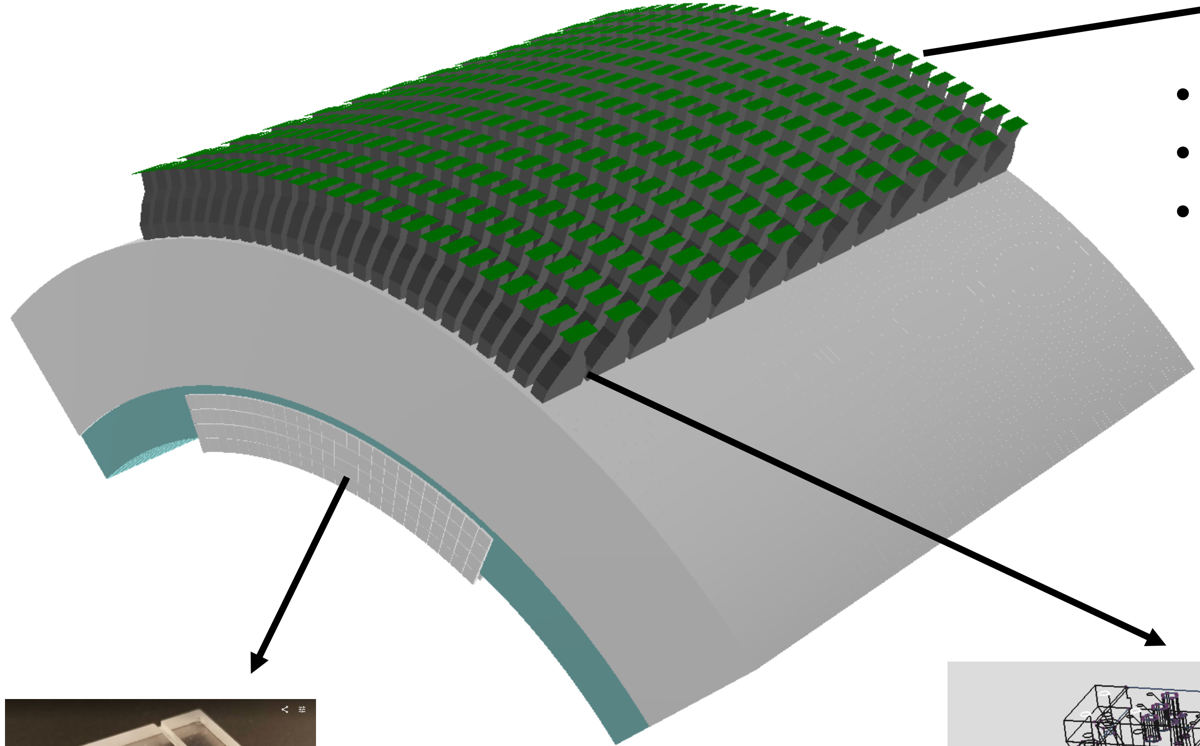


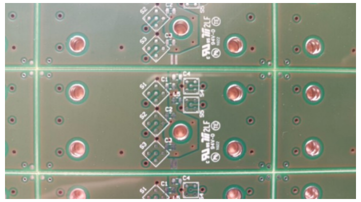
Machined iron for calorimeter absorber layers



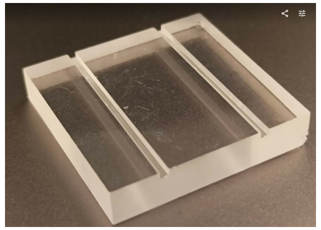
5% Borated Polyethylen arcs

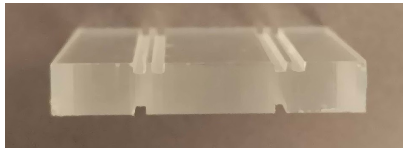
Demonstrator



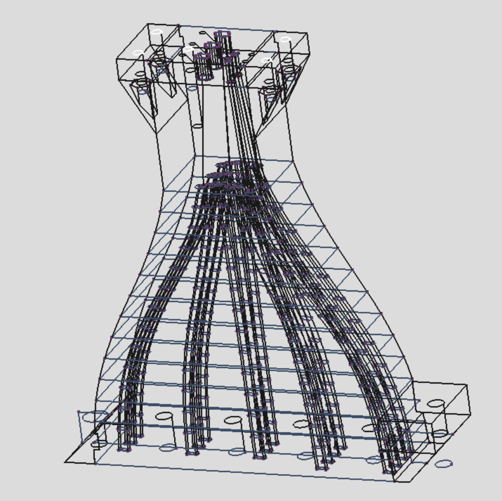


- ~1800 channels;
- SiPM Hamamatsu;
- Hybrid readout (custom+commercial digitizers)



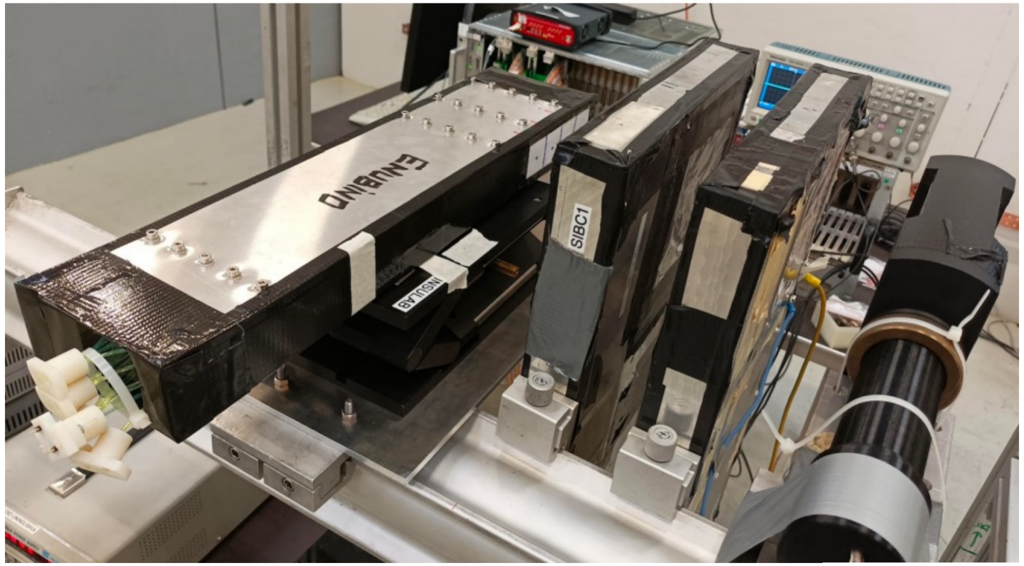


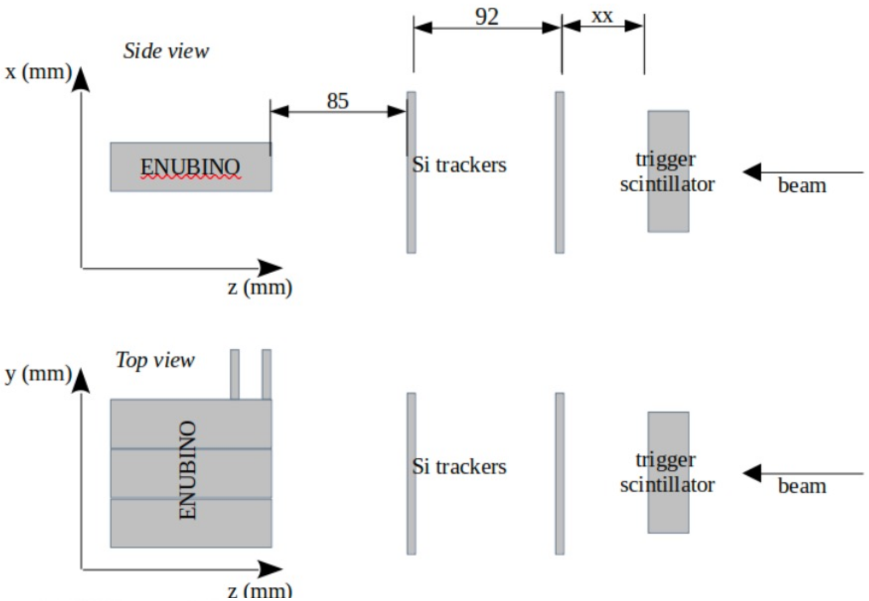
- 6375 scintillator tiles in different shapes;



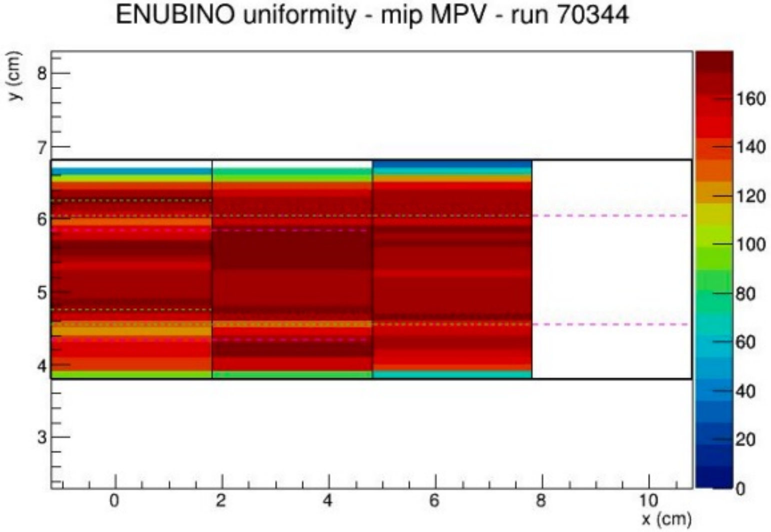
- 3D printed fiber routers;

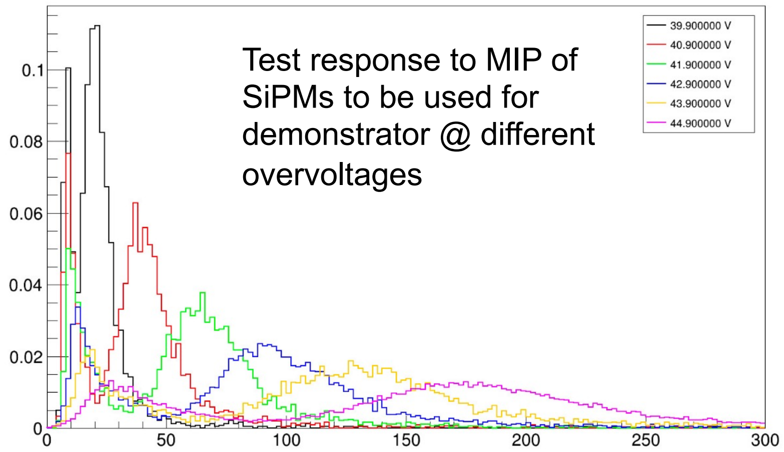
ENUBINO @ CERN-PS test-beam in Nov.2021





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

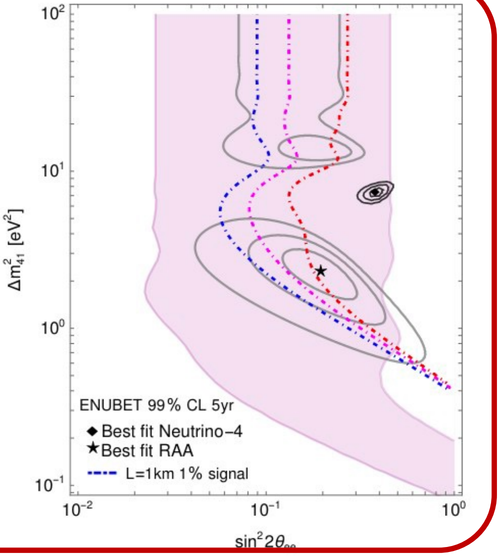

ENUBINO uniformity - mip MPV - run 70344


Test response to MIP of SiPMs to be used for demonstrator @ different overvoltages

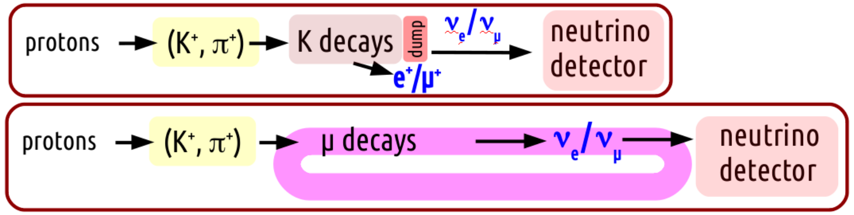
ENUBET within Physics Beyond Collider framework

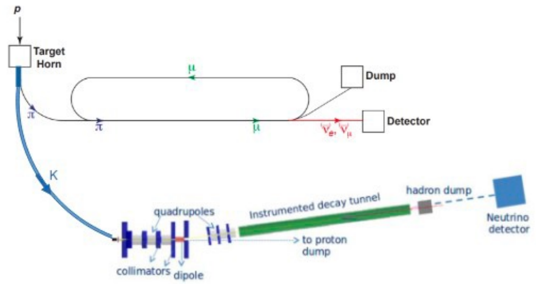
Accelerator and engeneering detailed studies, assessment of the facility costs, investigate posssibility to exploit ENUBET for cross section experiments at CERN North Area

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