Monitored neutrino beams:
NP06/ENUBET

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on behalf of the ***ENUBET Collaboration***

Istituto Nazionale di Fisica Nucleare

ERC Consolidator grant
(P.I. A. Longhin - *2016-2022*)

CERN Neutrino Platform
Experiment (**NP06** - *2019-2024*)

Part of the **Physics Beyond Colliders (PBC)** initiative

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

60 physicists
13 institutions

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).

The role of cross sections in the precision era

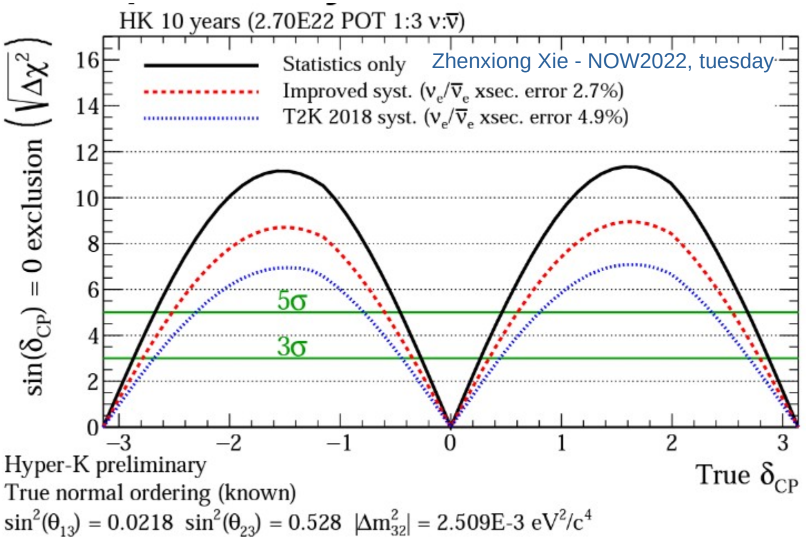
Full exploitation of data from future oscillation programs (DUNE, Hyper-K) strongly dependent on the control of **systematics**

→ statistics not an issue (large θ_{13}, superbeams, huge mass)

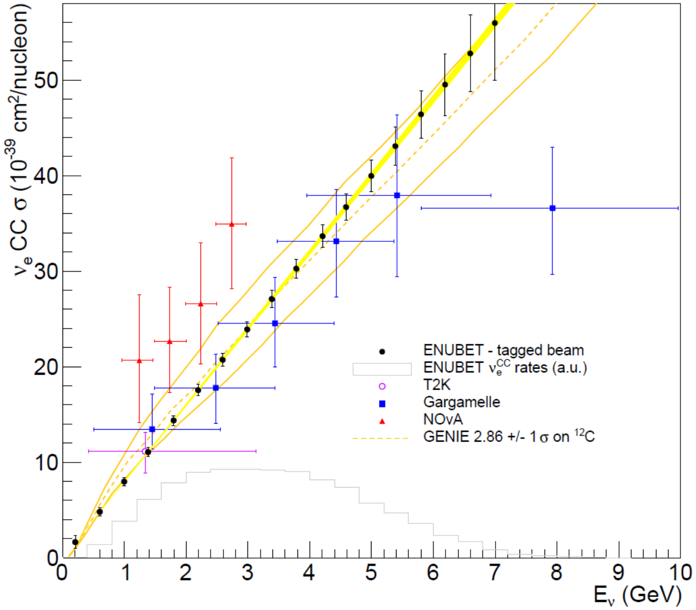
→ the well known **near-to-far ratio** technique **challenged** by the required precision:

- difference in angular acceptance
- large pile-up effects at ND
- different detector technology for the two sites

Fundamental a better knowledge of $\sigma_{\nu\mu}$ and $\sigma_{\nu e}$



ENUBET impact on ν_e



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

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

From the European Strategy for Particle Physics Deliberation document:

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

ENUBET: the first monitored neutrino beam

Monitored ν beams

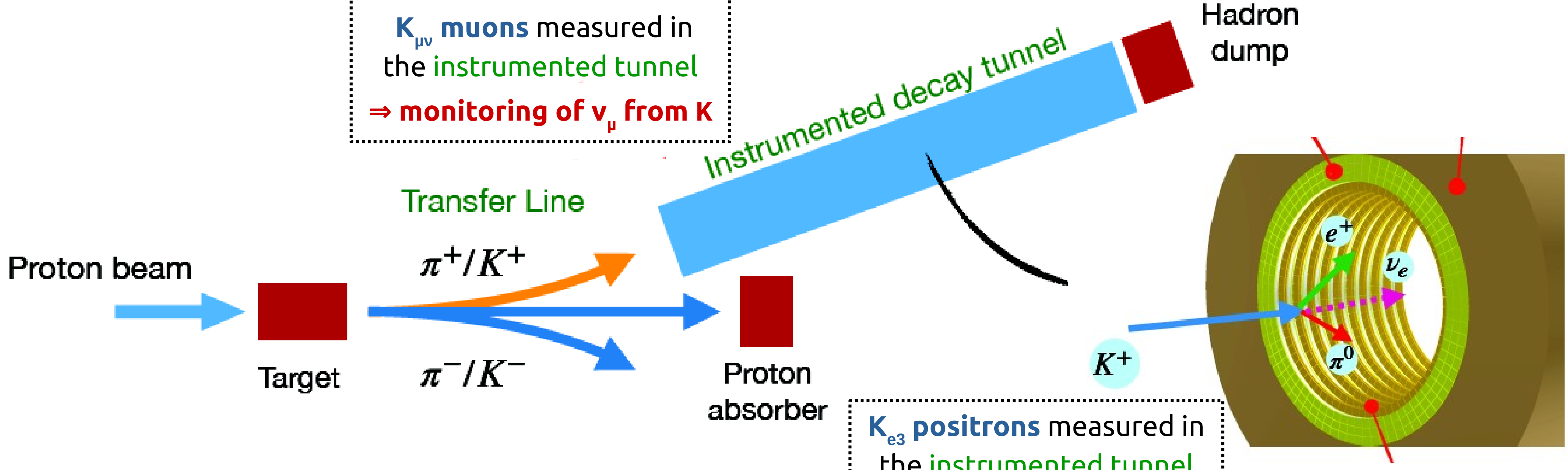
Measure rate of leptons ⇔ monitor ν flux

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

Conventional beamline with instrumented decay tunnel

muons measured by a range meter in the hadron dump

⇒ monitoring of ν_μ from π



$K_{\mu\nu}$ muons measured in the instrumented tunnel

⇒ monitoring of ν_μ from K

K_{e3} positrons measured in the instrumented tunnel

⇒ monitoring of ν_e

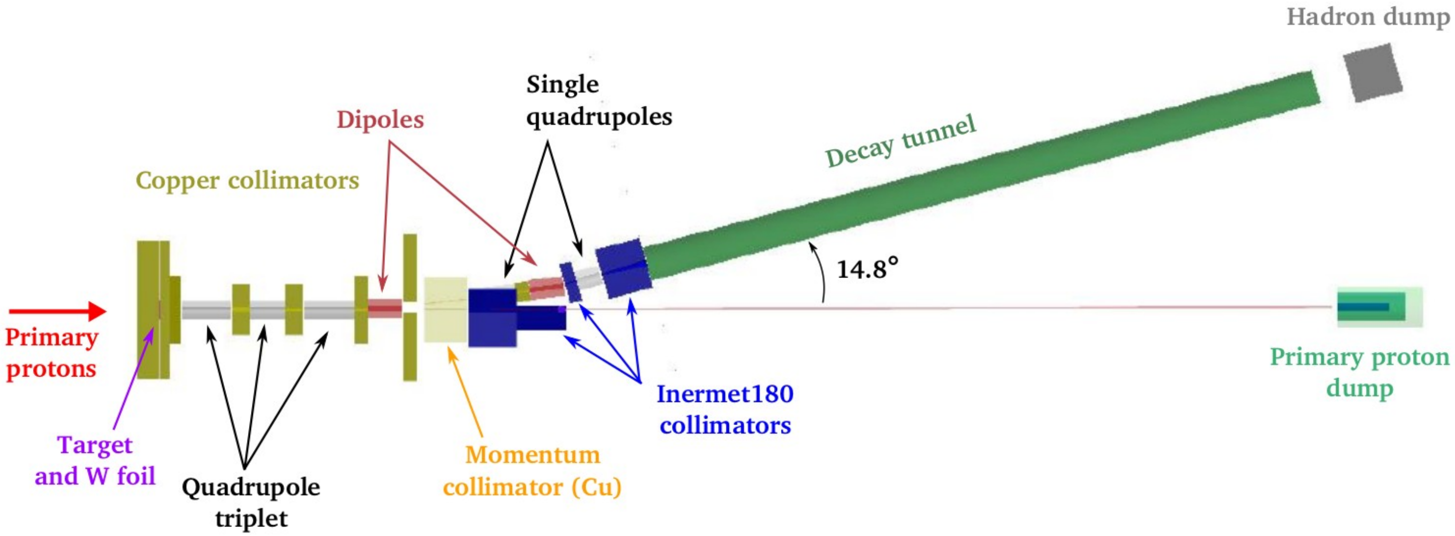
Main systematics contribution bypassed:

Hadron production, beamline geometry and focusing, POT

- **ERC project** focused on the determination of the ν_e flux by measuring K_{e3} positrons
- **NP06 CERN project** is extending the measurement to muons from K and π to fully monitor the ν_μ flux

The ENUBET beamline

Fully static focusing (by quadrupole triplet) ⇔ coupled to slow proton extraction (assuming 4.5×10^{13} – 400 GeV pot in 2 s)



Transfer line

- Normal conducting magnets
- quadrupole + 2 dipoles
  (1.8 T, total bending angle of 14.8°)
- kept short to minimize early K decays
- Small beam spot at tunnel entrance

Decay tunnel

- Length of 40 m
- Radius of 1 m

Large bending angle of 14.8°:

- Better collimated beam + reduced muon background + reduced ν_e from early decays

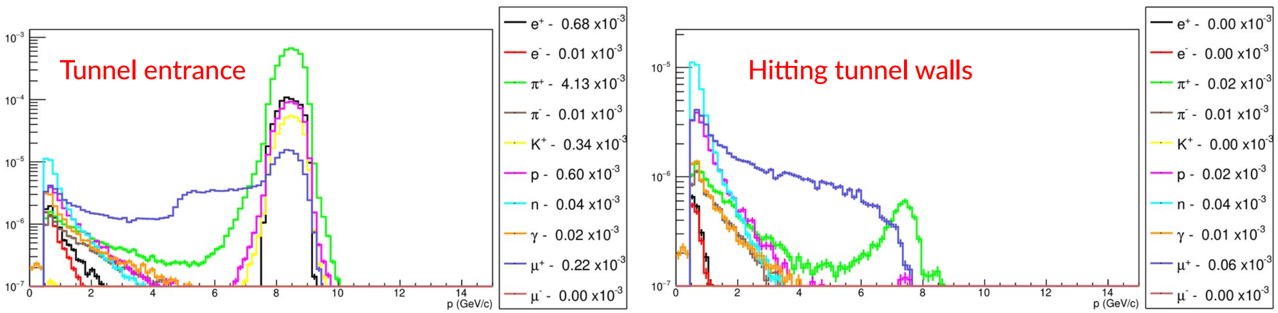
Transfer line design:

- optics optimized with TRANSPORT for mesons with **p=8.5 GeV ± 10%** (narrow-band beam)
- particle tracking and interactions simulated with G4Beamline
- doses and irradiation studies with FLUKA, absorbers and rock volumes included
- optimized graphite target 70 cm long, 6 cm diameter (dedicated studies on geometry and materials)
- tungsten foil after proton target to suppress positron background
- tungsten alloy (Inermet 180) @ tagger entrance to suppress backgorund

Full facility implemented in GEANT4:

- Control over all parameters
- Access to particle histories

Assessment of the ν flux systematics



Trade-off between a large meson yield (larger ν flux) and a sustainable bkg on tunnel walls

Rates @ tunnel entrance	
π^+ [10^{-3}]/pot	K^+ [10^{-3}]/pot
4.13	0.34

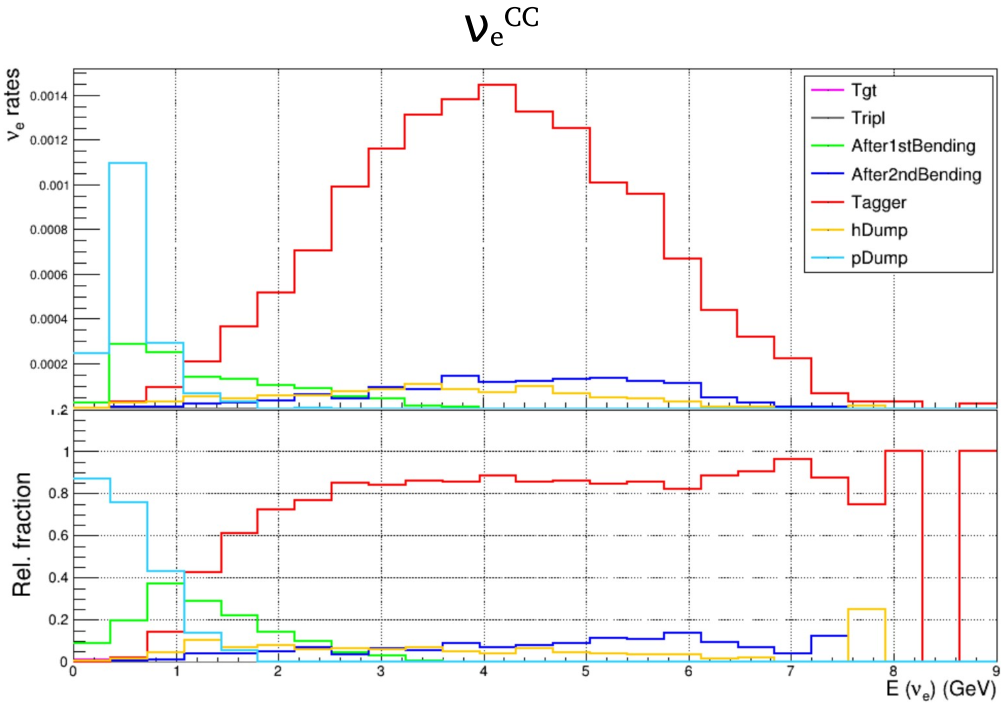
~1.5x w.r.t. previous results

ν_e^{CC} spectrum @ detector

Assumptions:

- @ SPS (400 GeV) with 4.5×10^{19} pot/year
- 500 tons LAr ν-det (6×6 m^2) @ 50 m from h-dump

→ 10^4 ν_e^{CC} interactions in ~3y of data taking



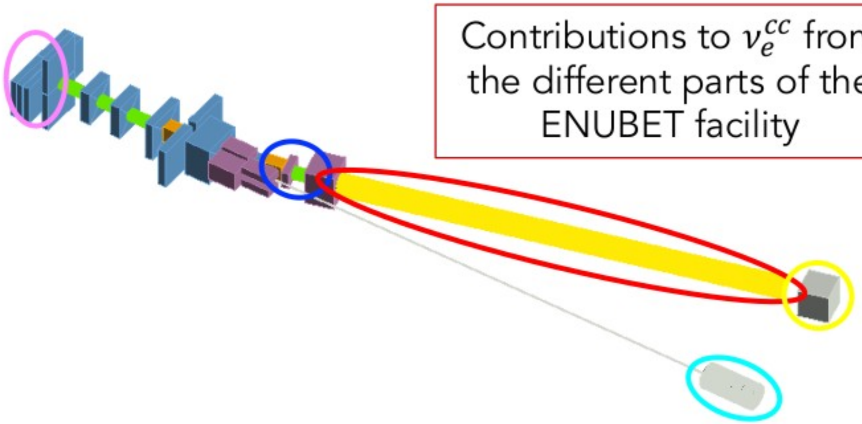
Taggable component:

About 80% of total ν_e^{CC} 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 optimizing p-dump position

- Above 1 GeV: contributions from straight section before instrumented decay tunnel and h-dump
  - ✓ rely on simulation for this component



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

ν_μ^{CC} spectrum @ detector

Narrow-band off-axis technique

Narrow momentum beam O(5-10%)

↓

(E_ν,R) strongly correlated

- E_ν = neutrino energy
- R = radial distance of interaction vertex from beam axis

→

8×10^5 ν_μ^{CC} interactions in ~3y

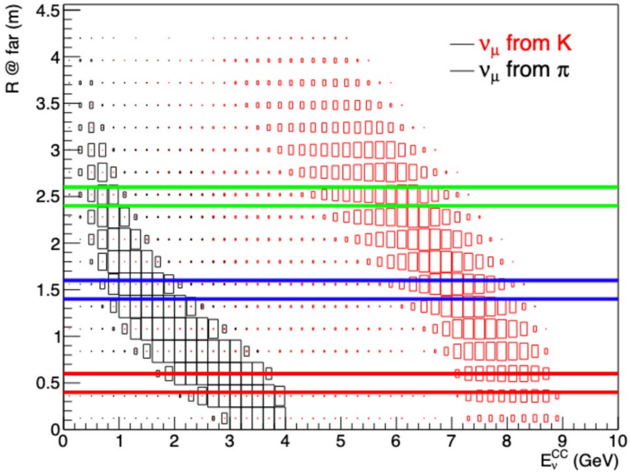
A-priori precise determination of E_ν

no need to rely on the reconstruction of the ν_μ^{CC}-int final state

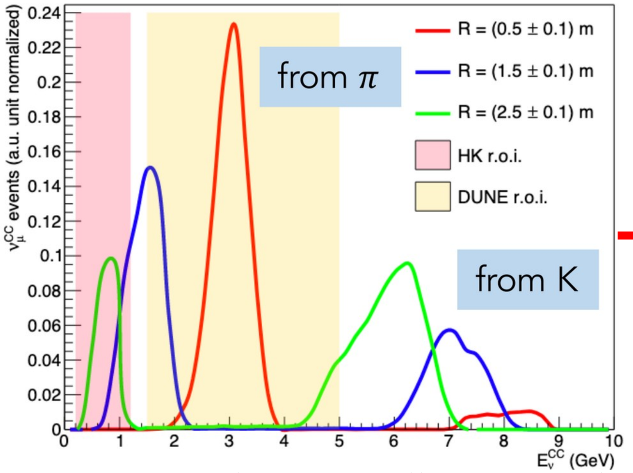
↓

- 8-25% E_ν resolution in the DUNE energy range
- 30% E_ν resolution in Hyper-K energy range
  (DUNE optimized TL → 8.5 GeV meson beam)
  - ✓ Ongoing R&D: Multi-Momentum TL (4.5,6,8.5 GeV)
    → cover Hyper-K and DUNE r.o.i. by changing magnetic fields only

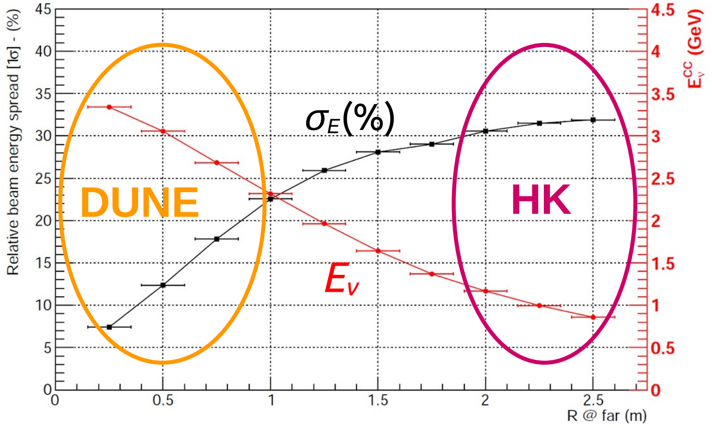
Further details in:
F. Acerbi et al., CERN-SPSC-2018-034



select interactions with slices in R

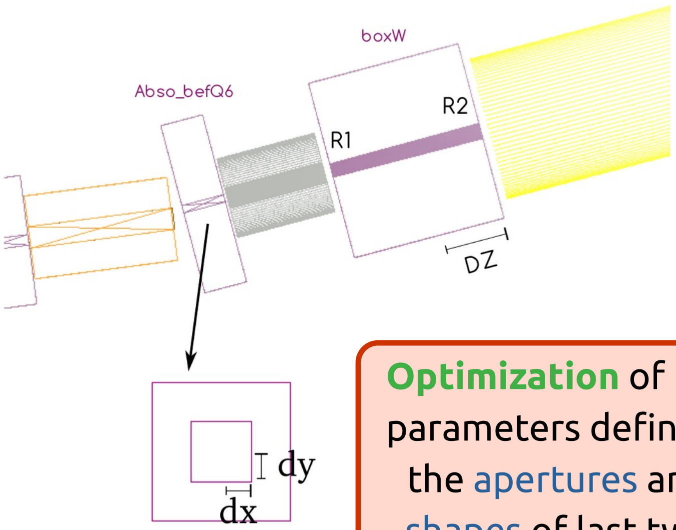


π/K populations well separated



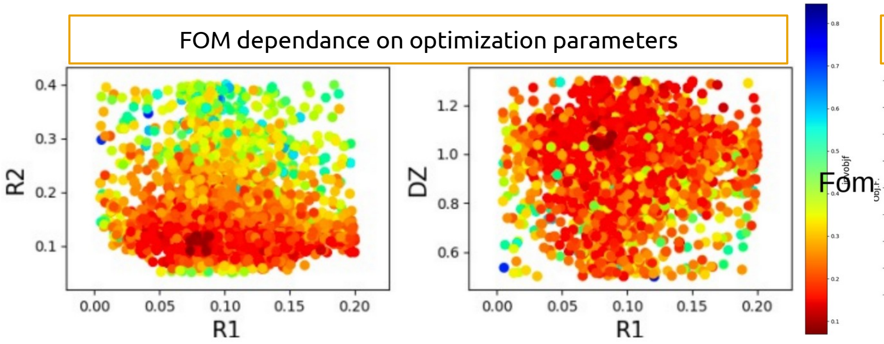
Width of π peaks ≈ E resolution [σ_E(%)]

Beamline optimization studies



Optimization of the parameters defining the apertures and shapes of last two collimators

FOM dependance on optimization parameters



Evolution of best parameters (black: FOM)

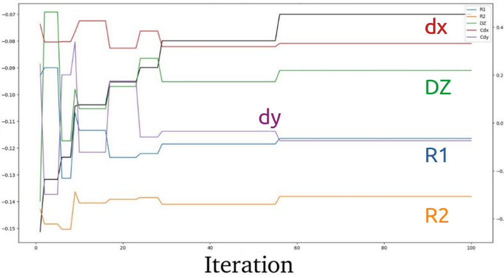


Figure of merit (FOM) = Signal/Background

- Signal: K @ tagger entrance
- Bkg: e^+ & π hitting tunnel walls (excluding the ones from K decays in tunnel)

An optimization campaign is ongoing:

- Goal: further improvement of the π/K yield at tunnel entrance while keeping background at low level
- Strategy: scan parameter space of beamline to maximize FOM
- Tools:
  - ✓ full facility implemented in GEANT4 → control with external cards all parameters
  - ✓ systematic optimization within framework based on genethic algorithm

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

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

Preliminary

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

The instrumented decay tunnel (I)

Requirements:

- Allow **$e^+/\pi^{\pm,0}$ separation** in the GeV energy region
- **Suppress** background from **beam halo** (μ, γ, non collimated hadrons)
- Sustain O(MHz) rate and **suppress pile-up effects** (recovery time ≤ 20 ns)
- **Doses**: $<10^{10}$ n/cm^2 at SiPMs, 0.1Gy at scintillator

Calorimeter

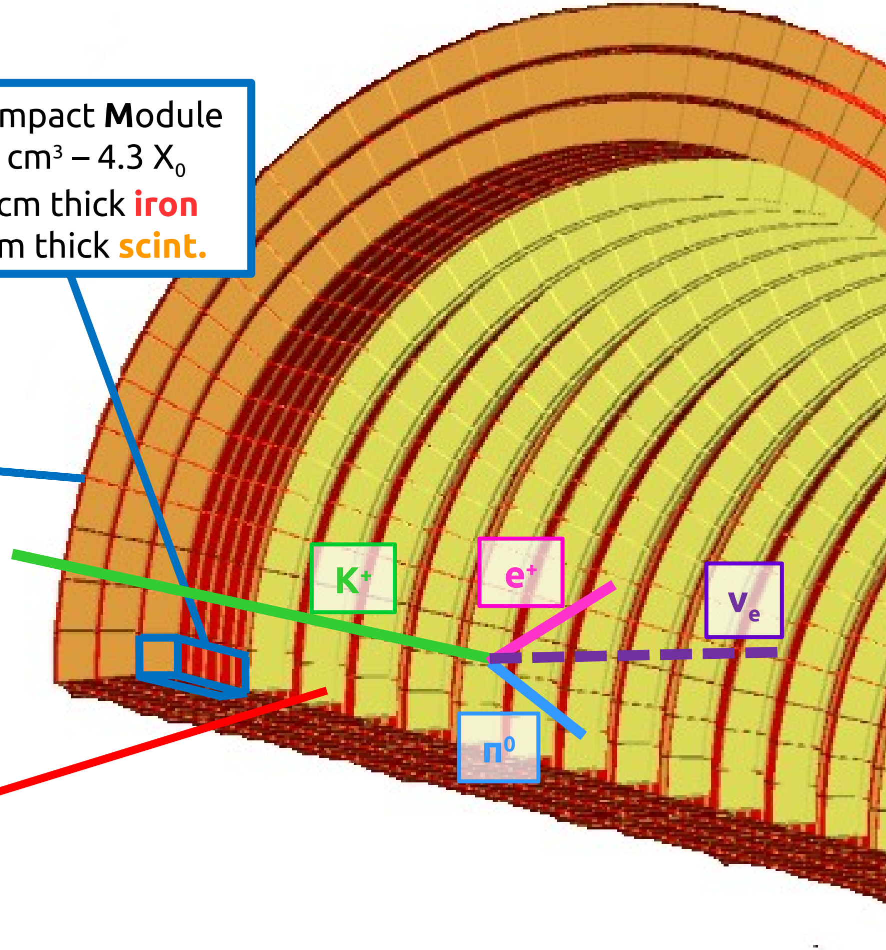
- Longitudinal segmentation
- Plastic scintillator + Iron absorbers
- Lateral light readout with WLS+SiPM

→ $e^+/\pi^\pm/\mu$ separation

Integrated photon veto (t0-layer)

- Plastic scintillators
- Rings of 3×3 cm^2 pads readout by SiPM

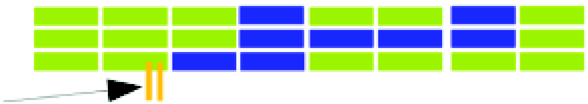
→ π^0/γ rejection



Lateral **C**ompact **M**odule
3×3×10 cm^3 – 4.3 X_0
Five 1.5 cm thick **iron**
Five 0.7 cm thick **scint.**

e^+ (signal) topology

π^0 (background) topology

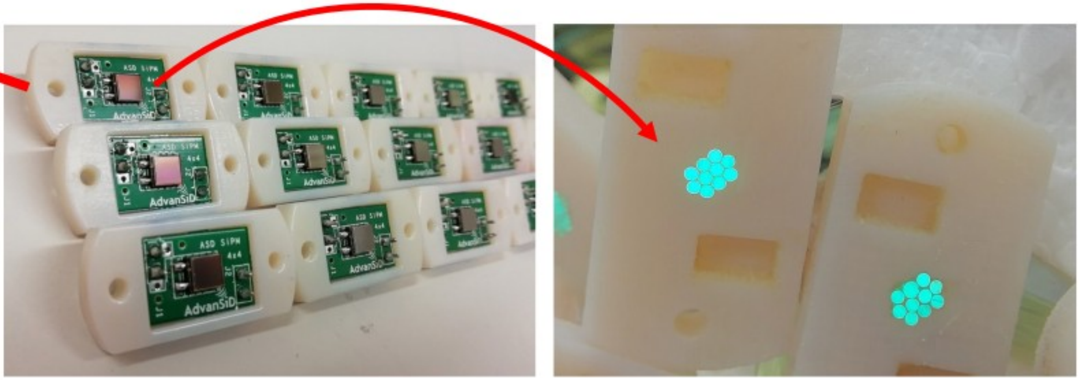


π^+ (background) topology

The instrumented decay tunnel (II)

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

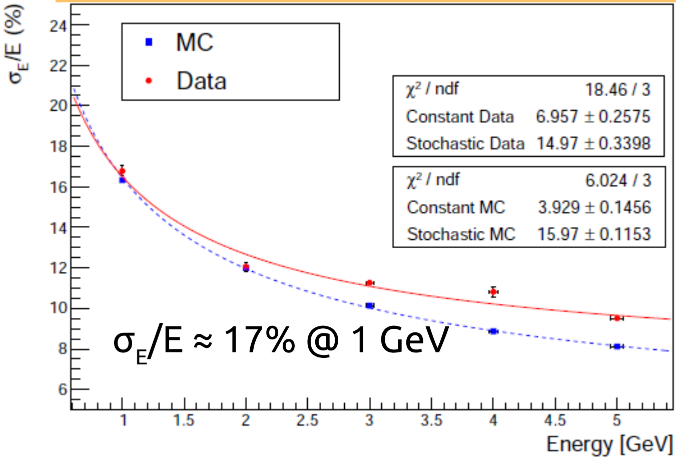
Large area (4x4 mm^2) SiPM for 10 WLS (one LCM)



SiPM installed outside calorimeter, above shielding: reduce (factor 18) neutron radiation damage and aging

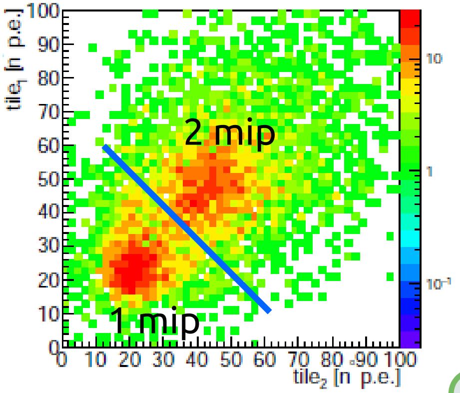
Tested during 2018 test-beam runs @ CERN PS-T9

Electron energy resolution



$\sigma_E/E \approx 17\%$ @ 1 GeV

Photon veto



Status of prototyping:

- ✓ Lateral readout calorimeter prototype successfully tested
- ✓ Photon veto tested
- ➢ Custom digitizer: in progress

Choice of technology finalized and cost-effetive!

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

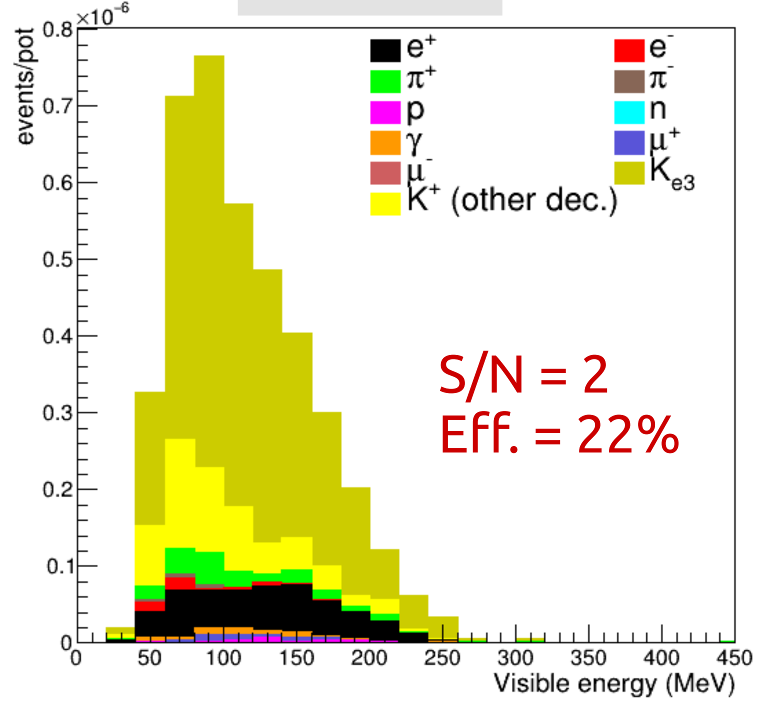
Lepton identification (I)

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

- Large angle muons and positrons from kaon decays identified exploiting the energy pattern in the tagger
- Event selection based on 19 discriminating variables for positrons (13 for muons) employed by a Neural Network

Positrons from K_{e3} ($\sim\nu_e$)

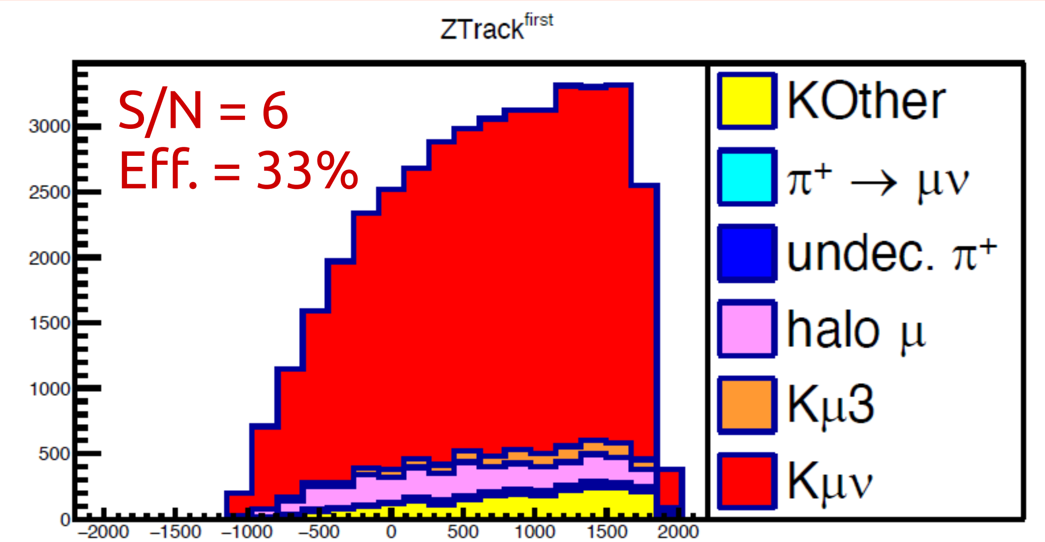
Visible energy



(Efficiency ~ half geom.)

Muons from $K_{\mu2}$ ($\sim\nu_\mu$)

Longitudinal position along tunnel



(Efficiency ~ half geom.)

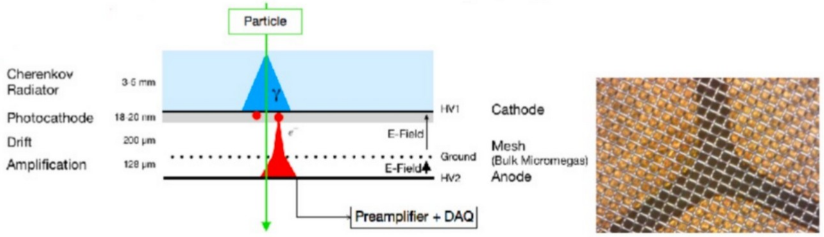
K_{e3} BR ~5% and K make ~5-10% of beam composition

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

Lepton identification (II)

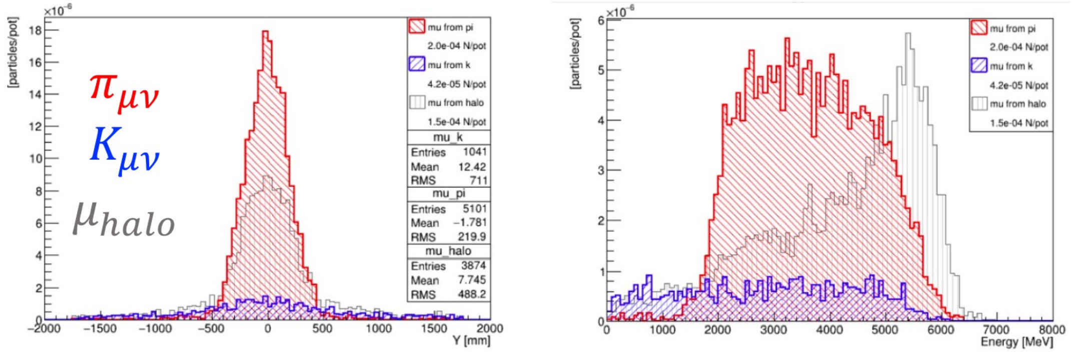
$\pi_{\mu 2}$ muon reconstruction to constrain low energy ν_μ

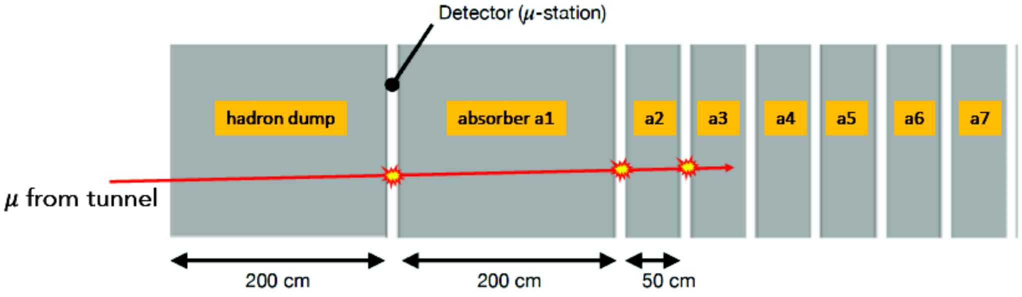
✔ **Low angle muons:** out of tagger acceptance
→ need muon stations after the hadron dump



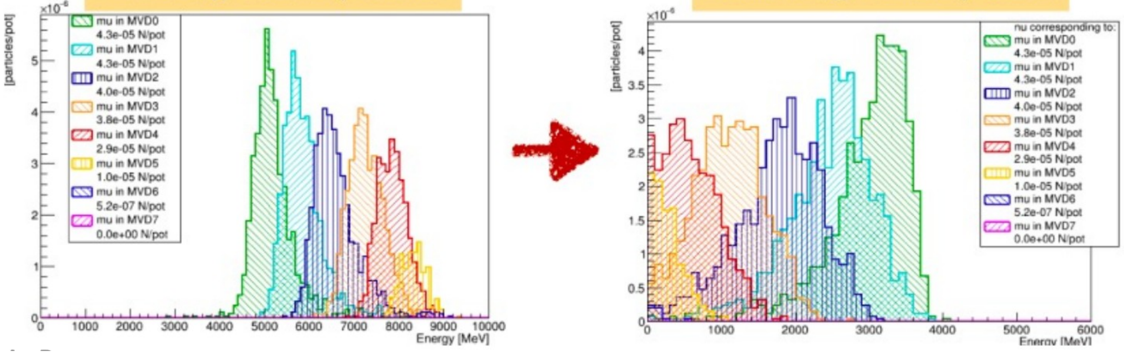
Possible candidate: fast Micromega detector with Cherenkov radiator (PIMENT project)

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



Muon energy @ different μ-stations

Neutrino energy @ different μ-stations

Exploit:

- Correlation btw number of transversed stations (μ energy from range-out) and ν 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

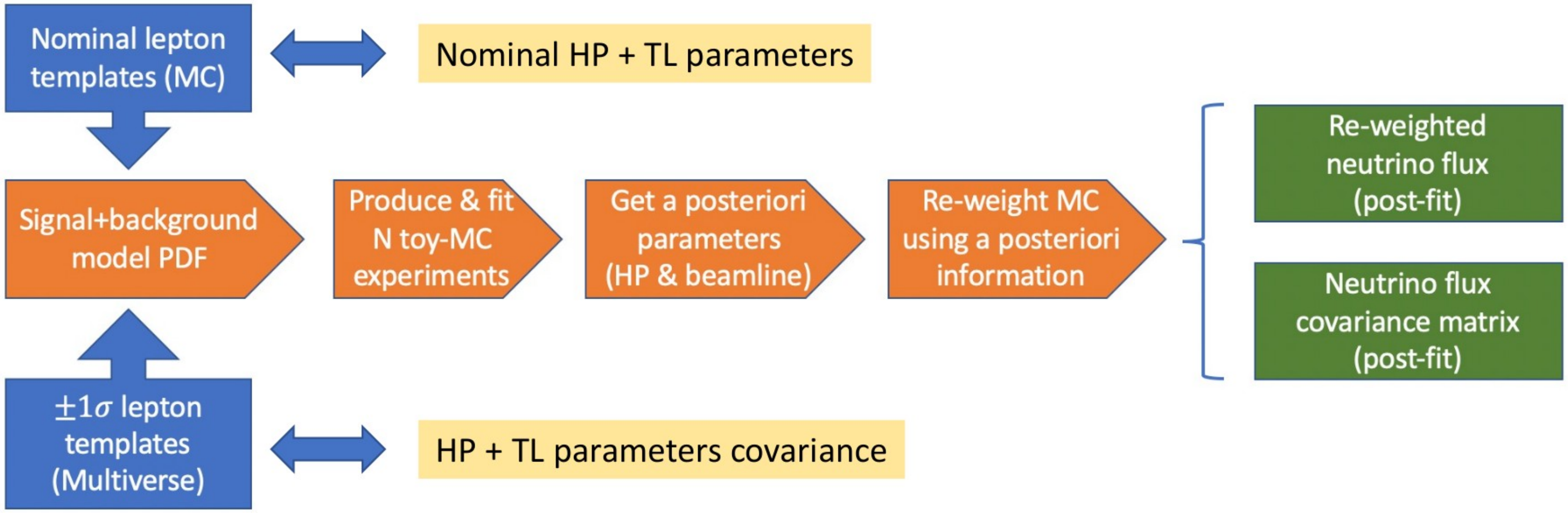
Work in progress

ν-flux: assessment of systematics

Monitored neutrino 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

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



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

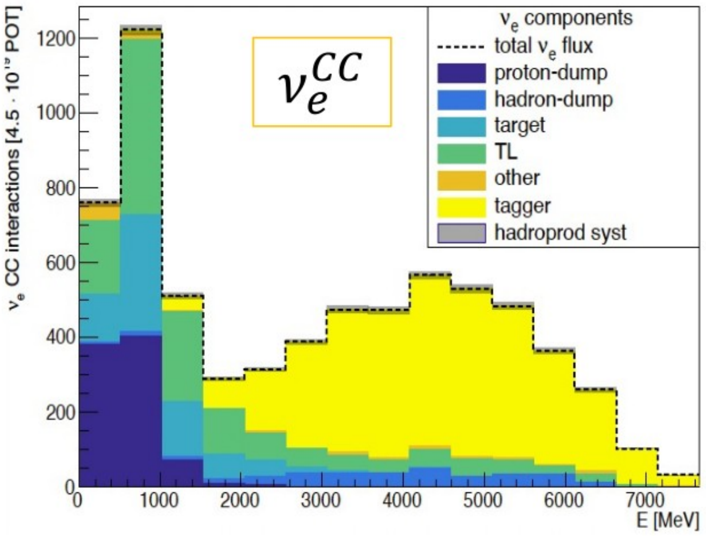
Used hadro-production data from NA56/SPY experiment to:

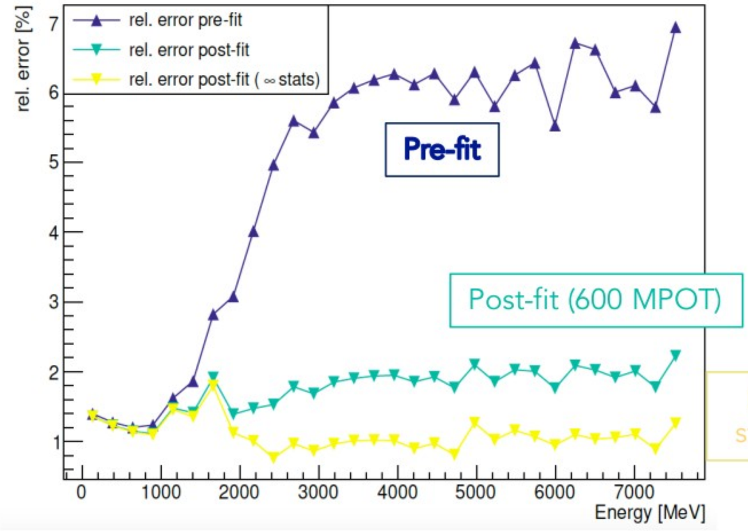
- reweight MC lepton templates and get their nominal distributions
- compute lepton templates variations using multi-universe method

ν-flux: impact of hadro-production systematics

Neutrino interaction rates @ detector

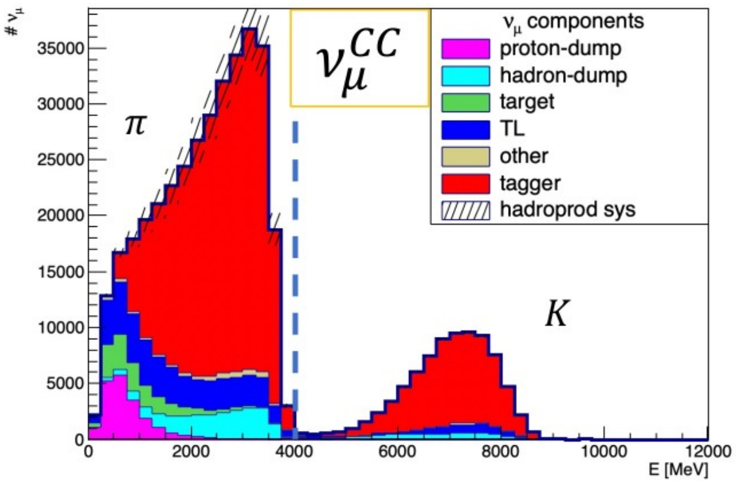
Pre- & Post-fit relative errors on rates

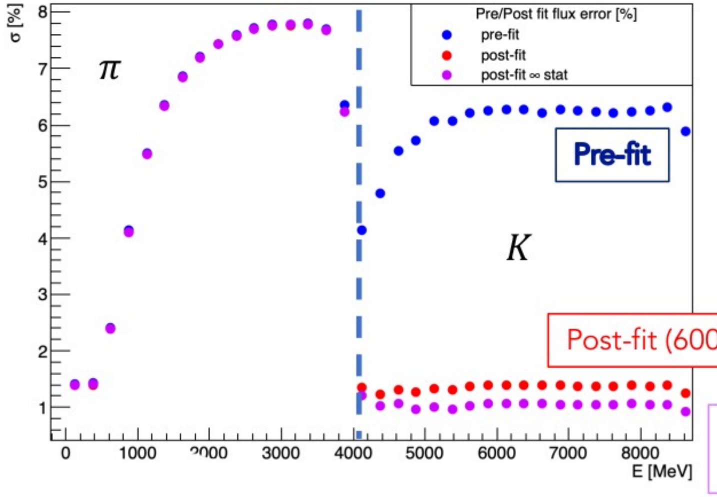




Total rates in 1 y of data taking

- @ SPS with 4.5x10^{19} pot/y
- 500 ton det @ 50 m from h-dump





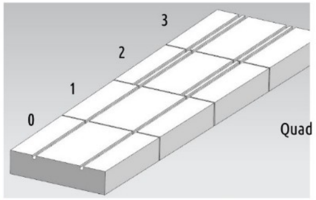
- Before constraint: **6% syst.** due to hadro-production uncertainties
- After constraint: **1% syst.** from fit to lepton rates measured by tagger

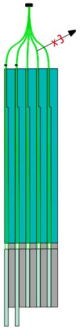
Achieved ENUBET goal of 1% systematics from lepton rates monitoring

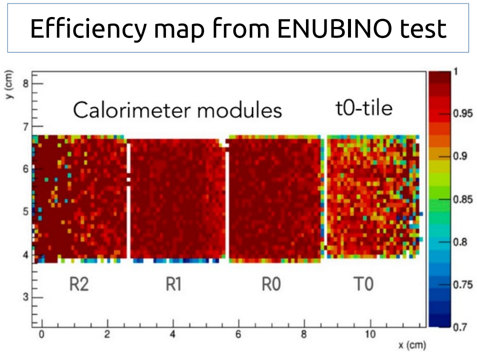
The tagger demonstrator

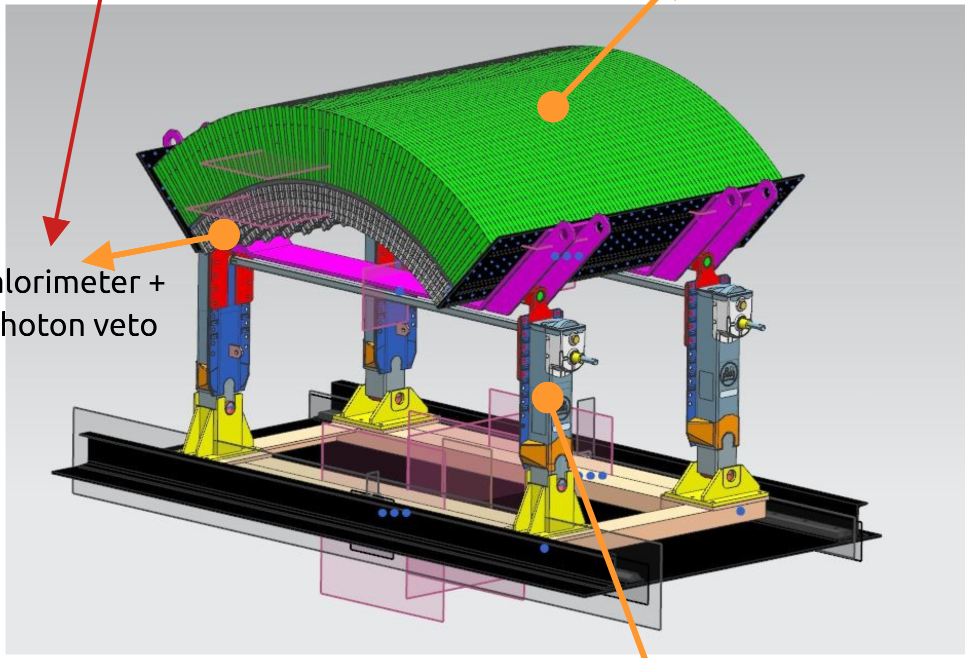
New frontal readout scheme & fibers bundling

10 WLS fibers (1 LCM) bundled to a 4x4 mm2 SiPM






Efficiency map from ENUBINO test


Borated P.E. shielding (30 cm)

calorimeter + photon veto

4 extensible legs: calorimeter tilting

- Detector prototype under contruction to demonstrate:
  - ➔ Performance / scalability / cost effectiveness

Test beam @ CERN-PS in october 2022

  - 1.65 m longitudinal & 90° in azimuth (central 45° instrumented)
  - 75 layer of: iron (1.5 cm thick) + scintillator (0.7 cm thick) → 15x3x25 LCMs

- Modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions)

- New lateral readout scheme with frontal grooves instead of lateral ones:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection
  - validated by GEANT4 optical simulation

- Scintillators: produced by SCIONIX (EJ-204) and milled by local comany

- ENUBINO: pre-demonstrator prototype with 3 LCM tested @ CERN to study uniformity and efficiency

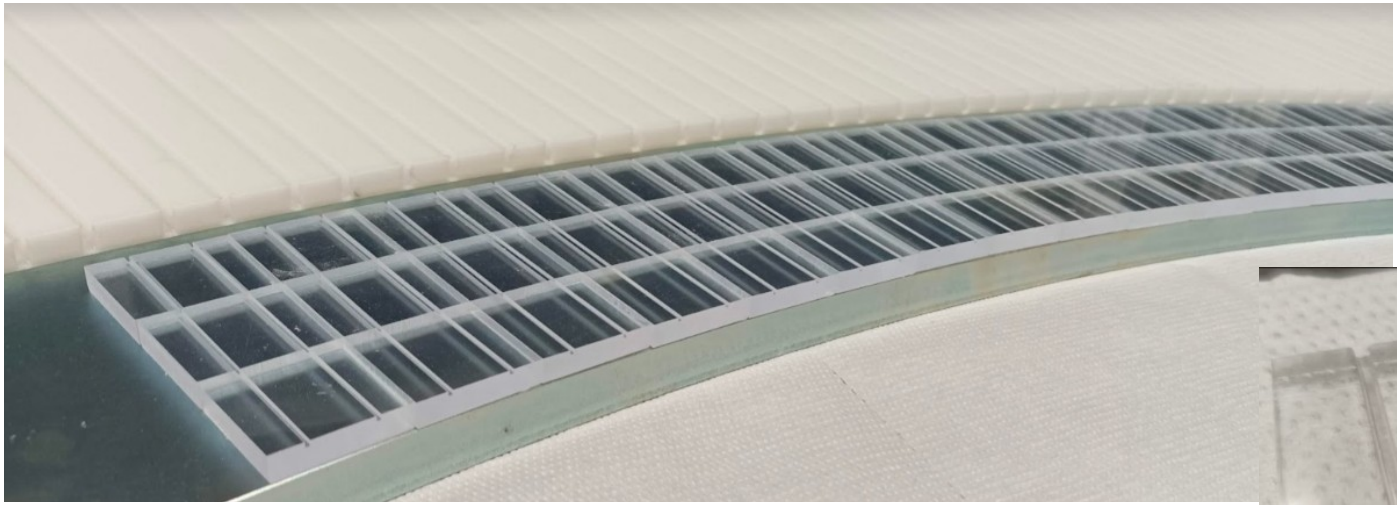
The tagger demonstrator: mechanical structure

Construction @ INFN - Legnaro National Laboratory

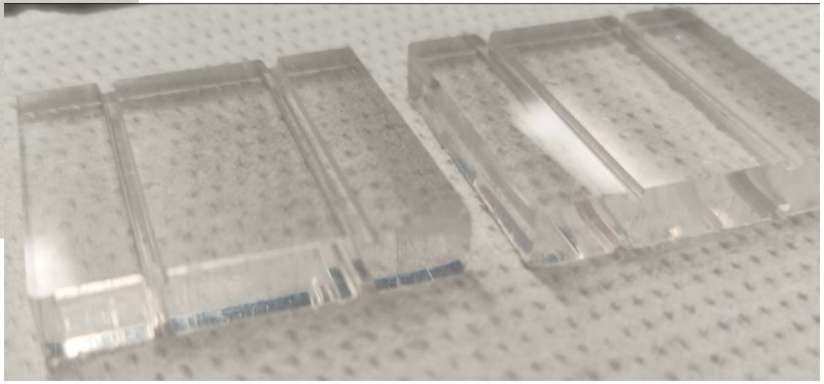
Light-tight cover

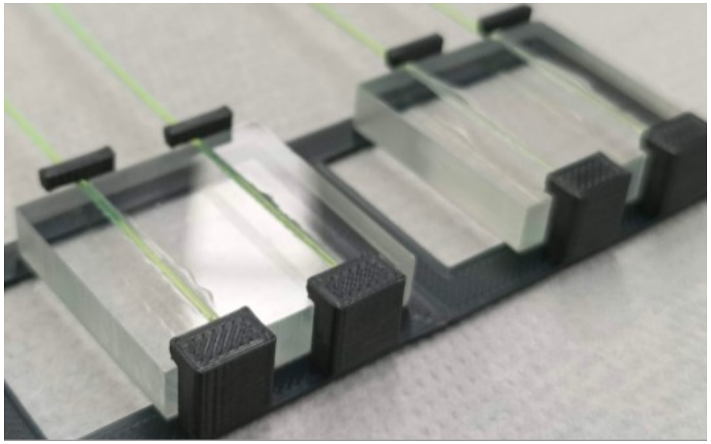
Lifting test with additional 2 tons (prototype weight ~3.2 tons)

The tagger demonstrator: scintillator tiles

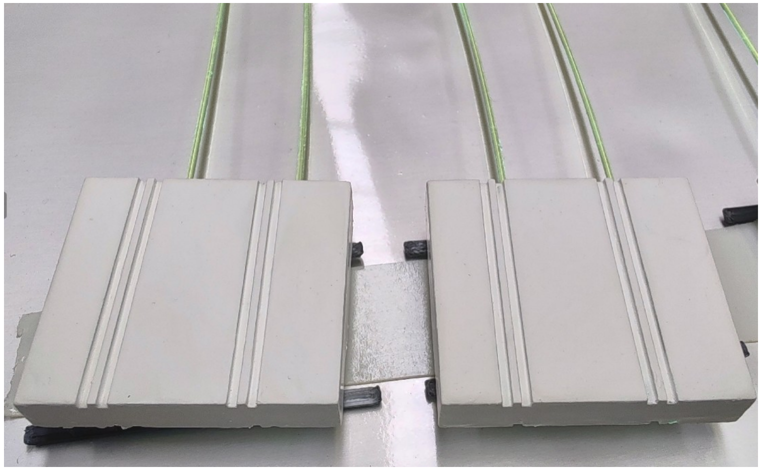


EJ-204 scintillator tiles (3x3 cm^2)
with grooves for WLS fibers

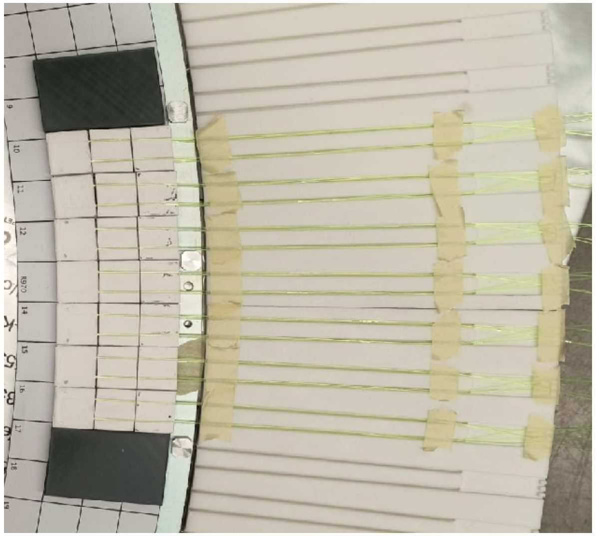




Fiber gluing
(EJ-500 optical cement)



Tile painting
(EJ-510 TiO_2 reflecting painting)



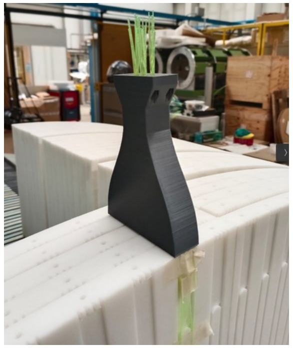
Tile assembling on arcs
and fiber routing

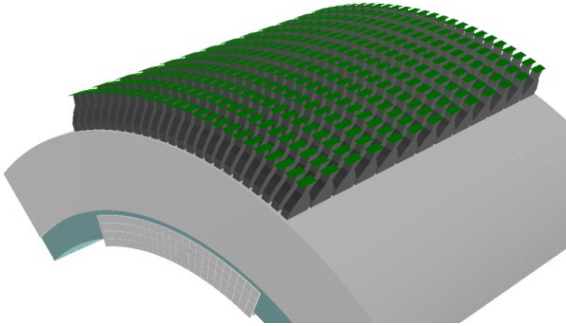
The tagger demonstrator: fiber routing and electronics

Fiber concentrators for bundling and routing to SiPMs

Custom design

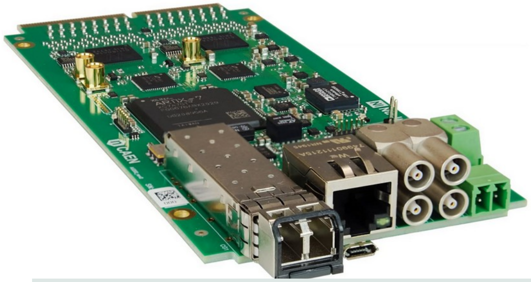
Produced with 5 consumer level 3D printers





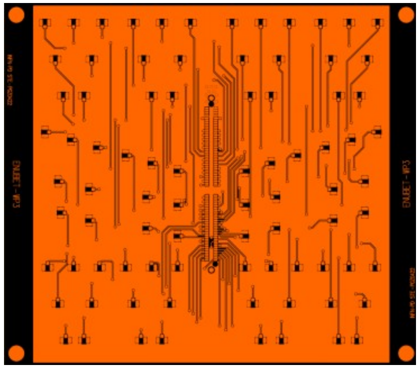
Custom + Commercial electronics

Front-End Board (SiPMs + Low V)

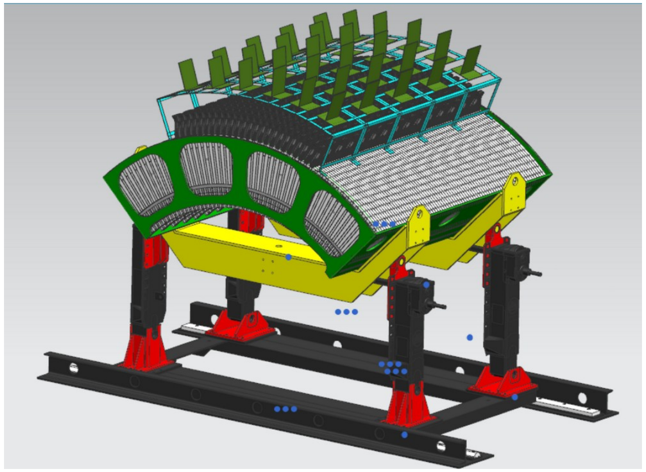


Commercial read-out board (CAEN A5202)

Custom digitizer



Custom interface board to connect 5 FEB (60 ch) to 1 A5202 (64 ch)



Summary and next steps

➢ Final design of beam transfer line in place, fine-tuning in progress:

- static transfer line: 10^4 ν_e^{CC} events in ~3 years (@ SPS)
- ongoing optimization of transfer line parameters with genetic algorithm
- multi-momentum beamline ongoing R&D: DUNE & Hyper-K optimized

➢ Design of the decay tunnel instrumentation finalized:

- prototype test-beams @ CERN: technology validation
- building final demonstrator to be tested @ CERN-PS in october 2022

➢ Detector simulation and PID studies:

- developed full GEANT4 simulation of calorimeter
- finalizing waveform simulation to fully assess the pile-up effects
- very good PID performance on both positron and muon reconstruction

➢ Systematics: hadro-production and beyond

- achieved 1% systematic goal due to hadro-production with lepton monitoring
- assess sub-leading systematics due to detector effects and beamline parameters

Looking ahead

ERC project (2016-2022) is on schedule and in the last stage

CERN site-dependent implementation (SPS+ProtoDUNE) within NP06/ENUBET (2019-2024) in PBC framework

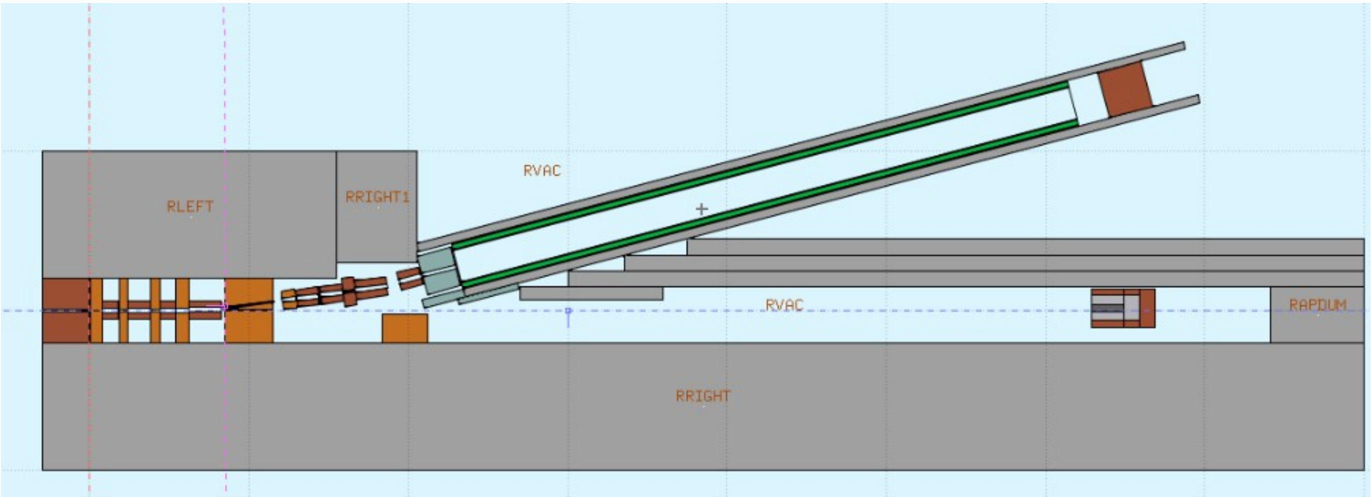
2023-2024: delivery of Conceptual Design Report with physics and cost definition

Experimental proposal expected in 2024

Additional material

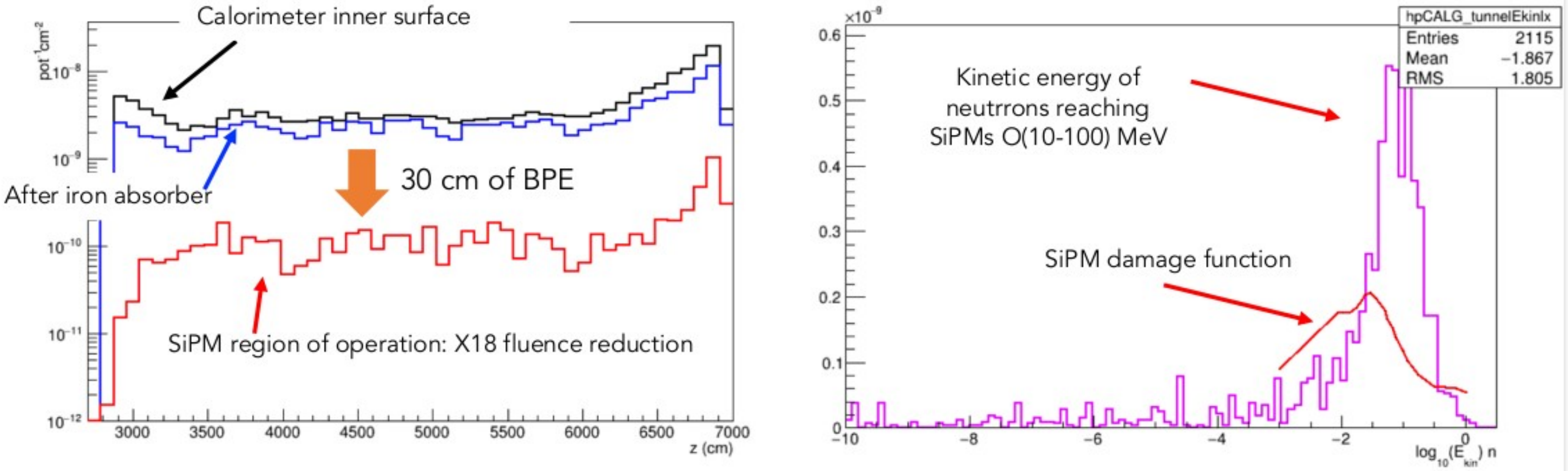
Irradiation studies

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

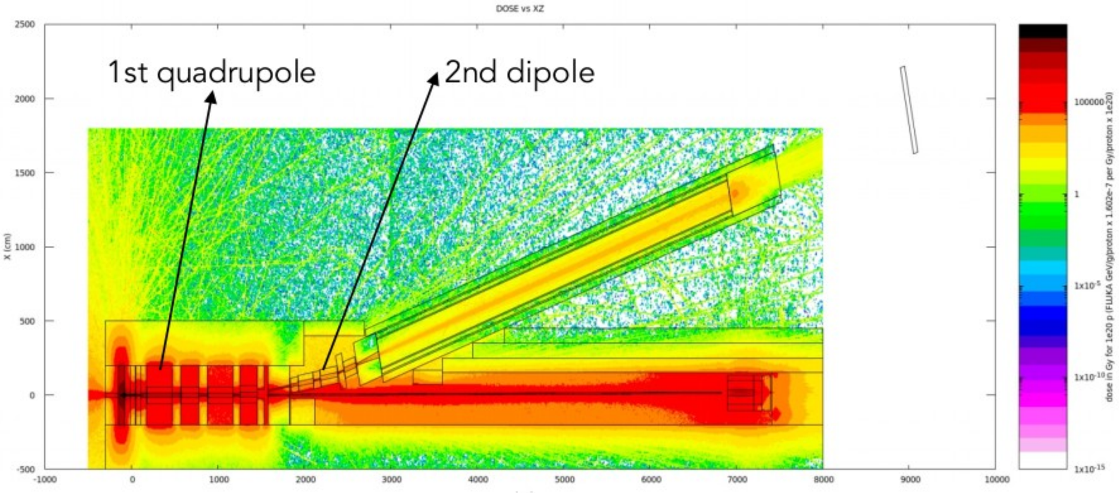


Neutron fluence provided by FLUKA guided the design of the detector tecnology for tagger:

→ SiPM outside the calorimeter abobe a 30 cm BPE shielding



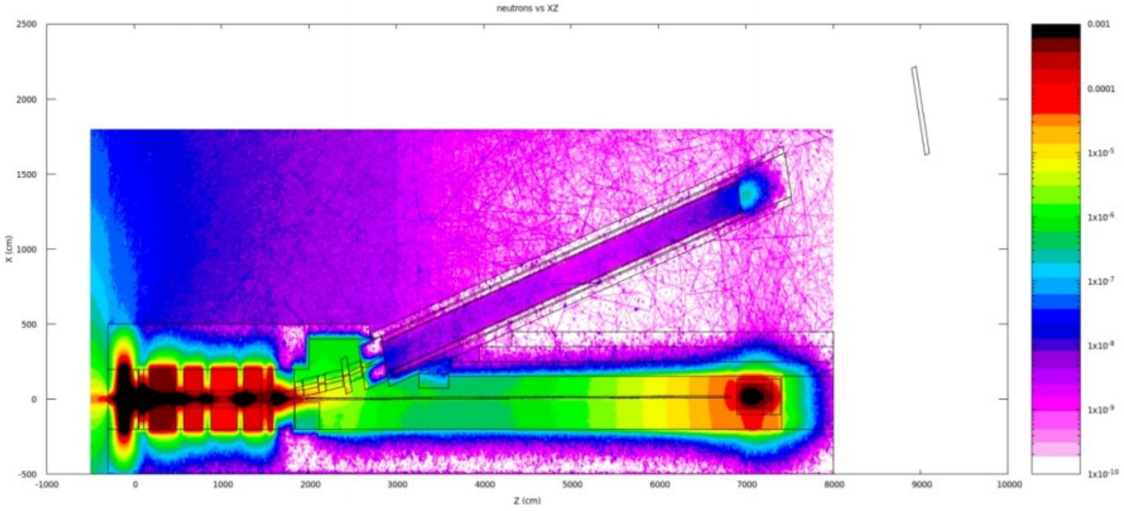
Irradiation studies



Dose for 10^{20} POT [Gy]

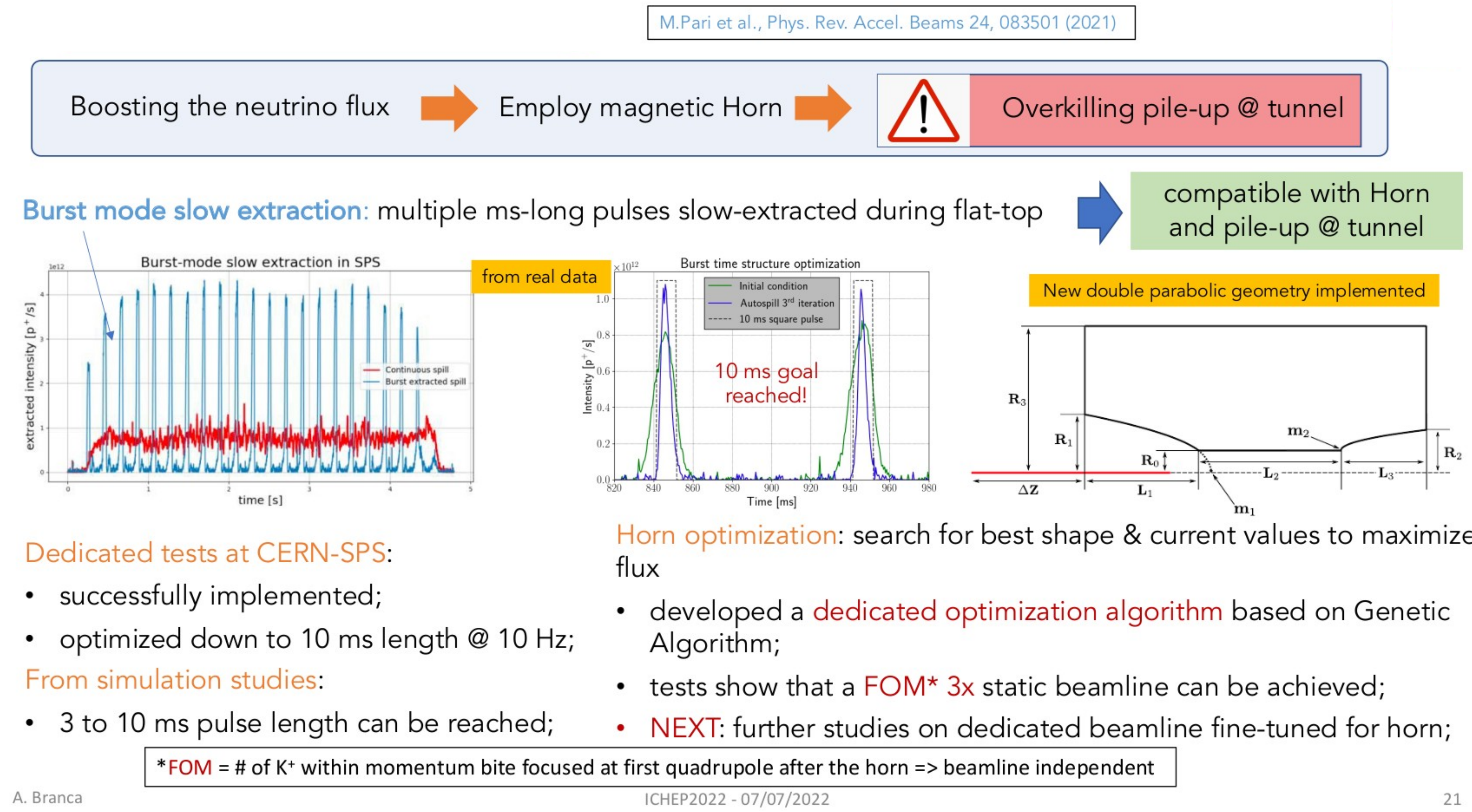
Hottest point -> quadrupole closest to target O(100-300 kGy): acceptable value for operations

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



Horn based focusing

A. Branca slide @ ICHEP2022



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

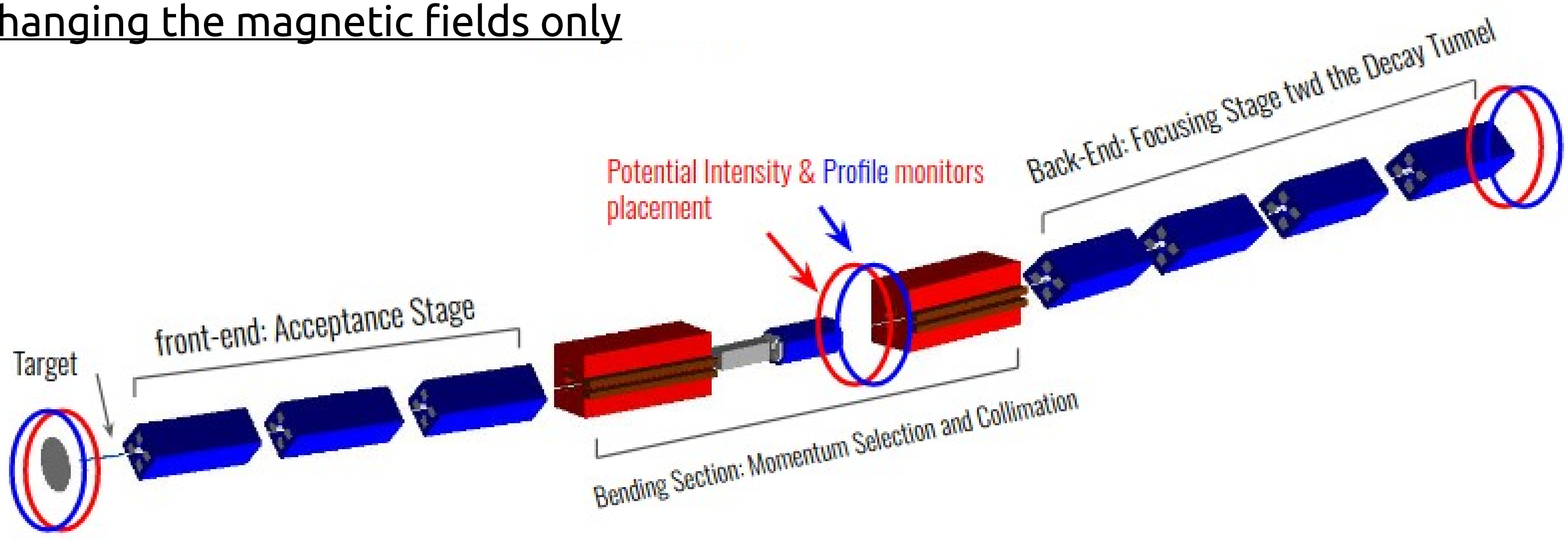
A. Branca

ICHEP2022 - 07/07/2022

21

Multi-Momentum Beamline

A parallel study ongoing for the hadron beamline to focus **8.5, 6** or **4 GeV/c** secondaries by changing the magnetic fields only

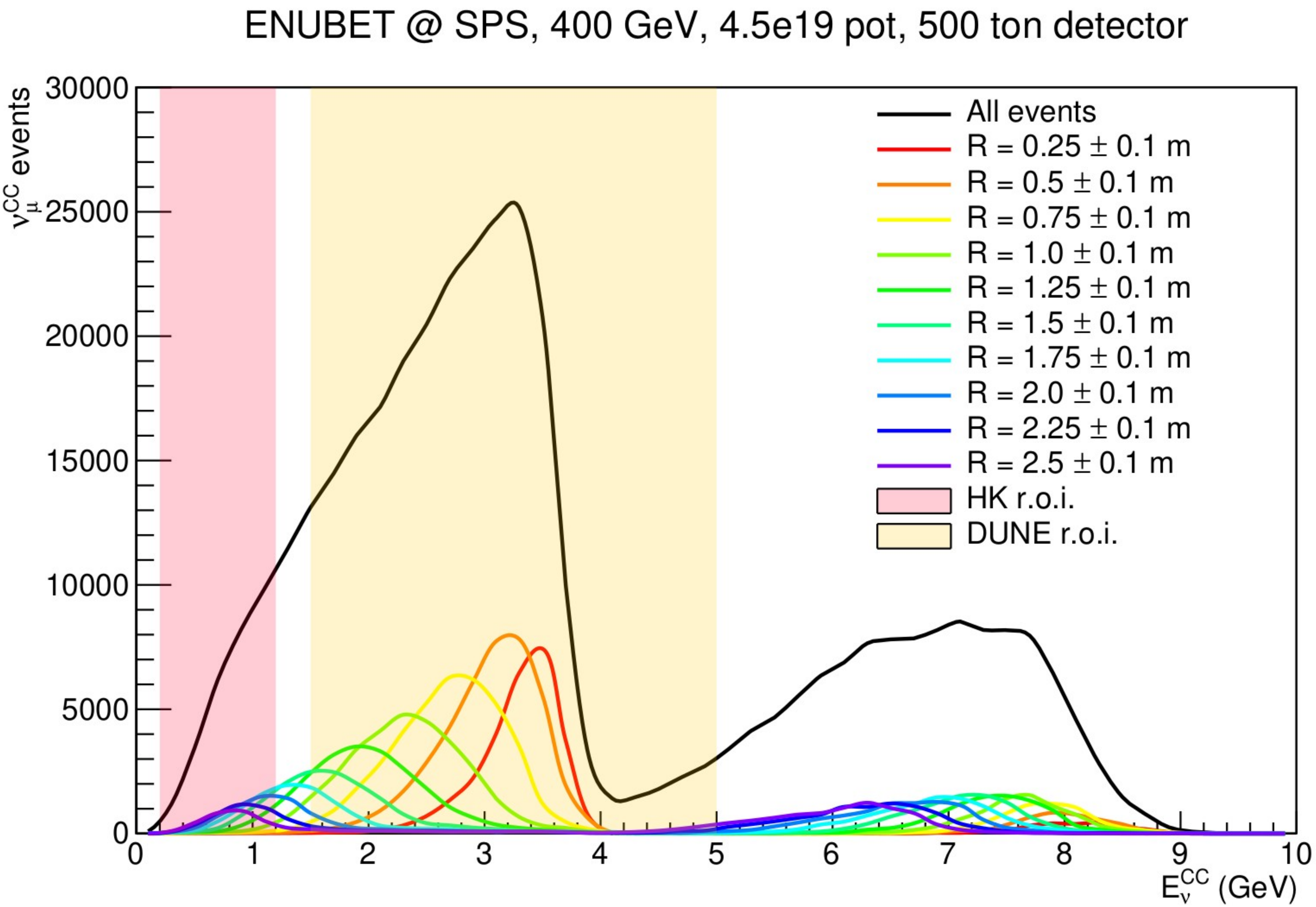


Layout summary:

- First quadrupole distance from the target: 30 cm
- Target tilted by 1° w.r.t. beamline to reduce background and primary re-interaction
- 5 mm W absorber after collimation → to reduce the positrons bgk
- Primary Protons Momentum: 400 GeV
- Secondary Momenta: 8.5 GeV - 6 GeV - 4 GeV

Add flexibility and allow a set of different neutrino spectra from Hyper-K to Dune regions of interest

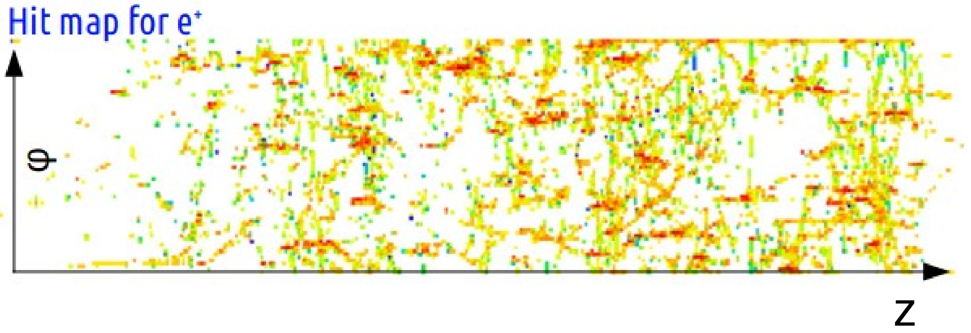
ν_μ^{CC} spectrum @ detector



K_{e3} positron identification

Full GEANT4 simulation of the detector

- hit-level detector response
- validated by prototype tests @ CERN



Analysis chain:

1) Event builder:

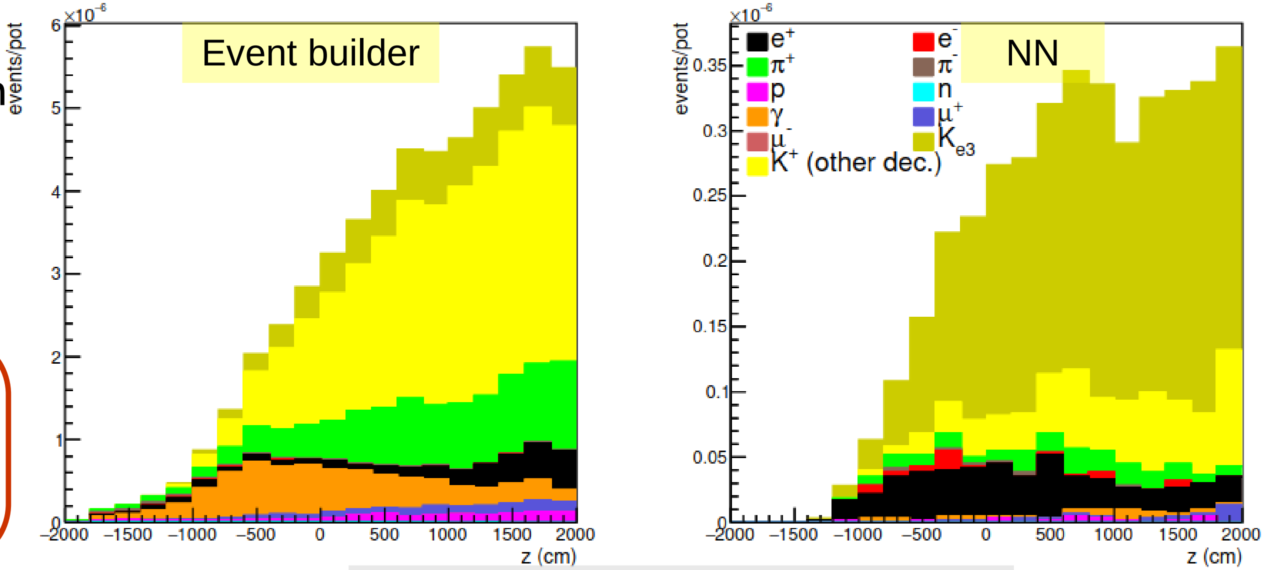
- start from event “seed” (LCM with E>28 MeV in first layer) to <u>preselect e.m. showers</u>
- cluster energy deposits compatible in space ($-5<\varphi_{seed}<5$; $-3<z_{seed}<10$) and time ($-1<\Delta t<1$ ns)
- associate T0 hits on the 8 upstream tiles wrt to seed in the same φ sector (Δt within 1 ns)

2) e / π / γ / μ separation:

- Multivariate analysis (MLPNN from TMVA) exploiting 19 variables (<u>energy pattern in calorimeter, event topology, photon-veto</u>)

Performance

S/N = 2
Efficiency: 22% (~ half geom.)



Longitudinal position along tunnel

Variable used in the fitting procedure to constrain the ν_e flux → Today A. Branca talk

K_{e3} BR ~5% and K make ~5–10% of beam composition

Waveform simulation and reconstruction

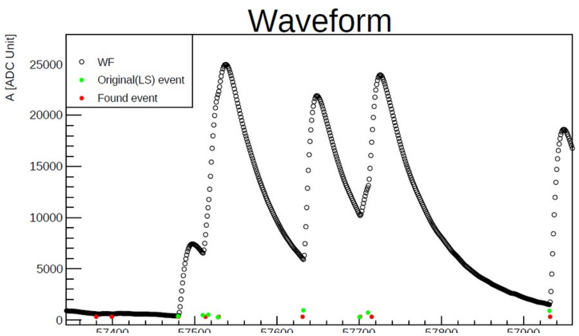
Software framework implemented to simulate tagger response at single channel level
→ fully realistic treatment of pile-up effects

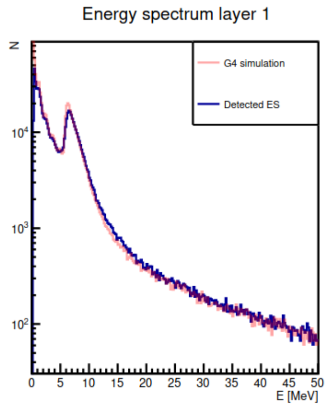
Conversion of energy deposits in p.e. Conversion factor (15p.e./MeV) from test beam data

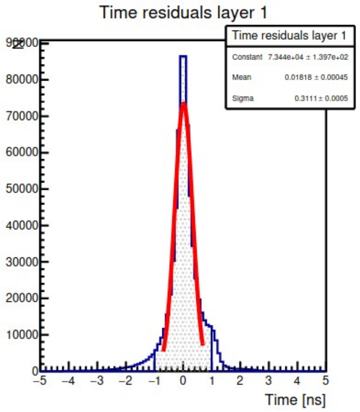
→ SiPM response simulated using the GosSiP software Waveform digitization

→ Pulse detection algorithm → Peak amplitude and time determination

→ Standard analysis chain

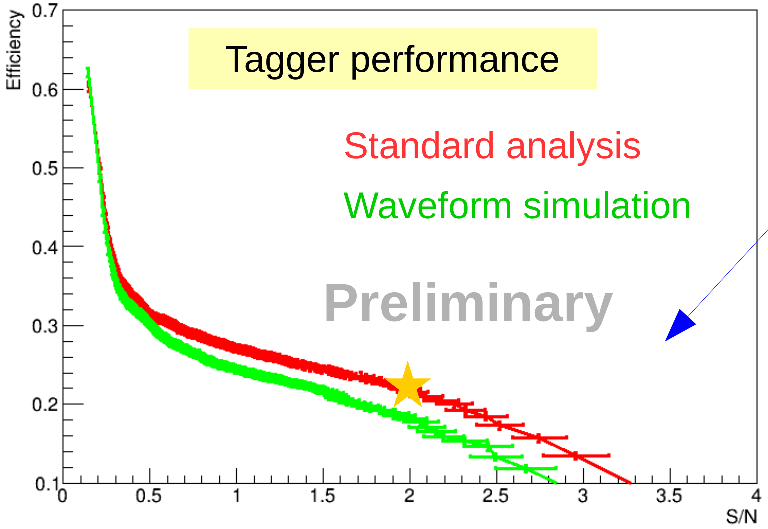






Eff.: 95÷98%

σ_t: 0.3÷0.4 ns



Efficiency vs S/N for different cuts on the NN classifier

- Improvement to close the gap expected when processing the NN training sample with the same chain
- Full control on the pile-up effects and on the reconstruction chain up to the signal processing level