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).

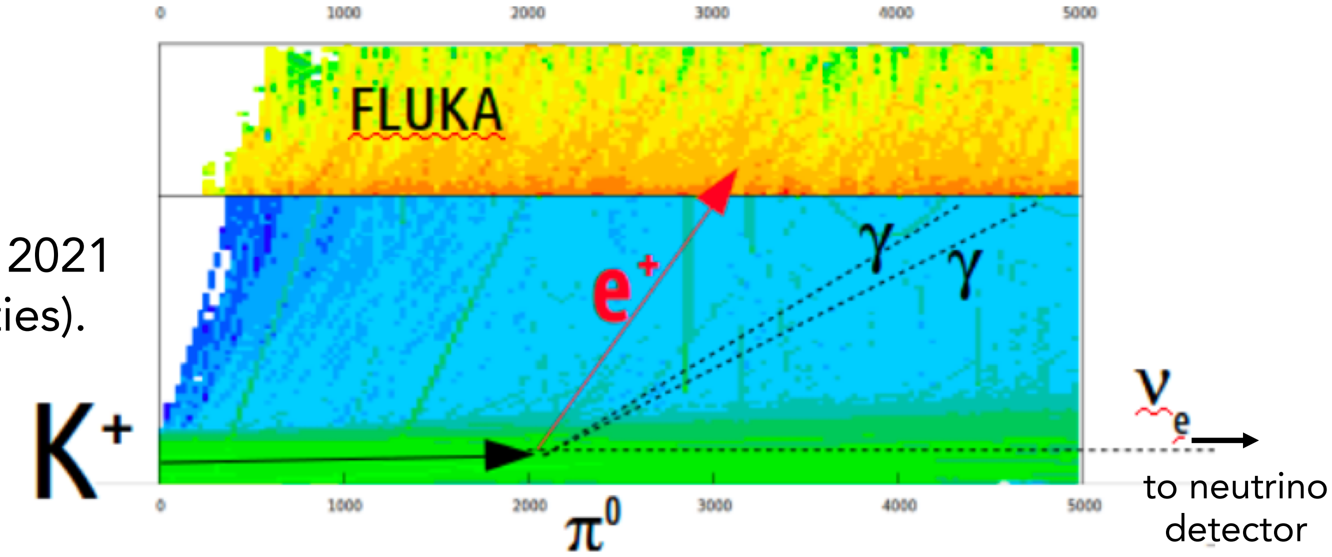
NP06/ENUBET Status

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

GDR Neutrino Meeting, November 23-24, 2020

Outline

- ENUBET is the project for the realization of the first monitored neutrino beam. In the next slides:
  - how to reach the purpose of the project;
  - physics performance and status;
  - next steps for 2021-2022;



- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (now extended to 2022 to overcome COVID difficulties). PI: A. Longhin;

- Since April 2019: ENUBET also a CERN Neutrino Platform Experiment – NP06/ENUBET;

- ENUBET Collaboration: 60 physicists & 12 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

Systematics matter!

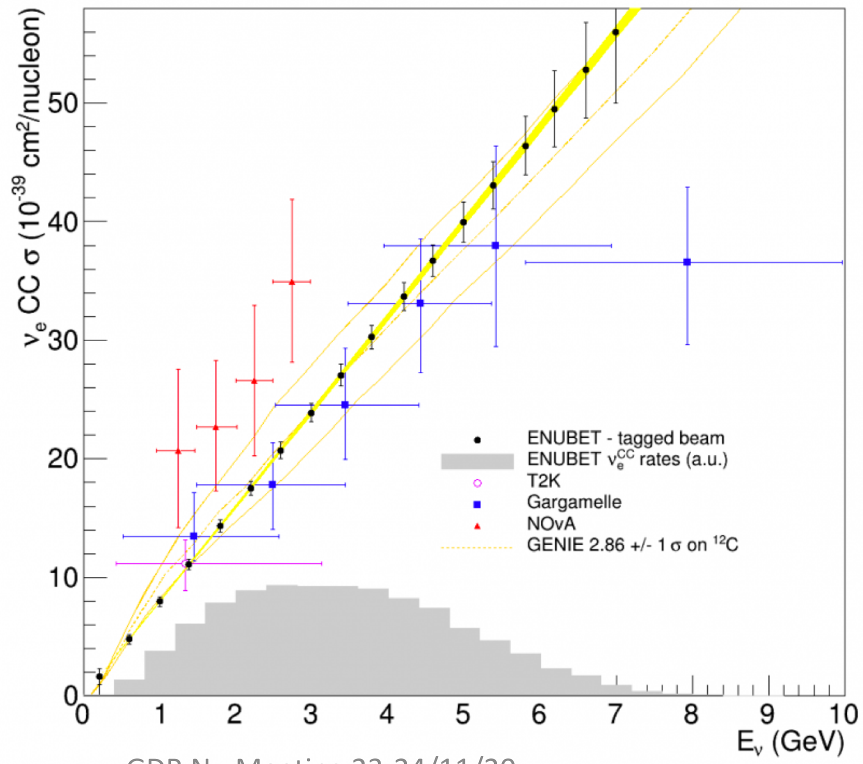
Future experiments (DUNE & HyperK) are conceived for precision oscillation neutrino measurements:

- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP violation 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!

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;
- energy of the neutrino at 10% precision level;

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

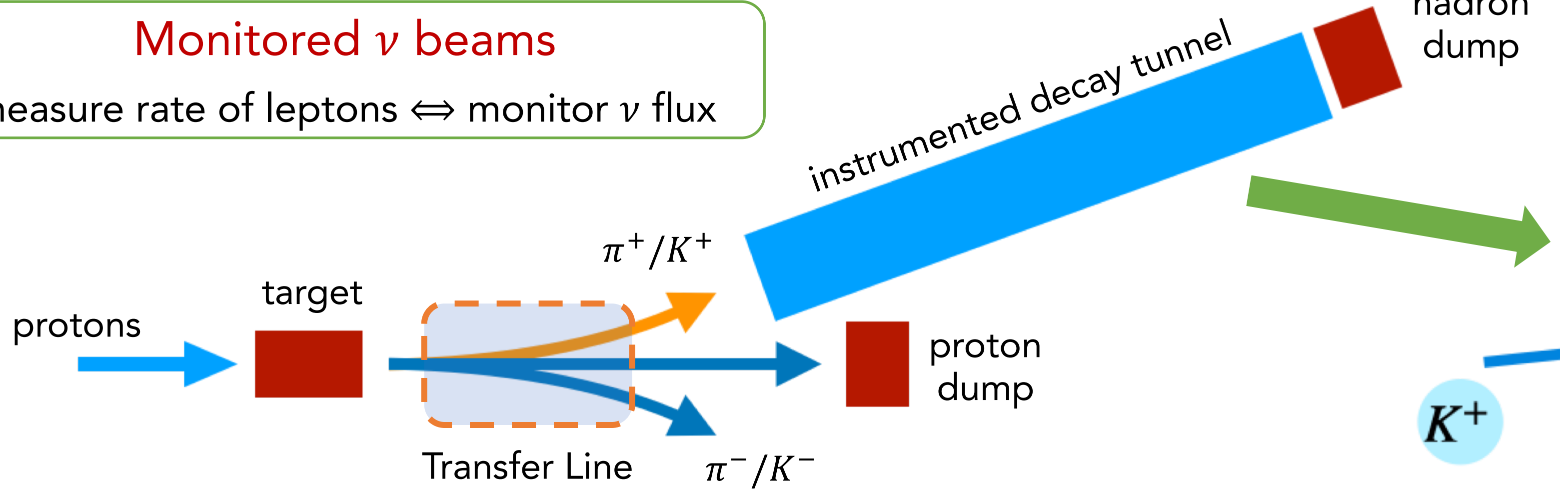
To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure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

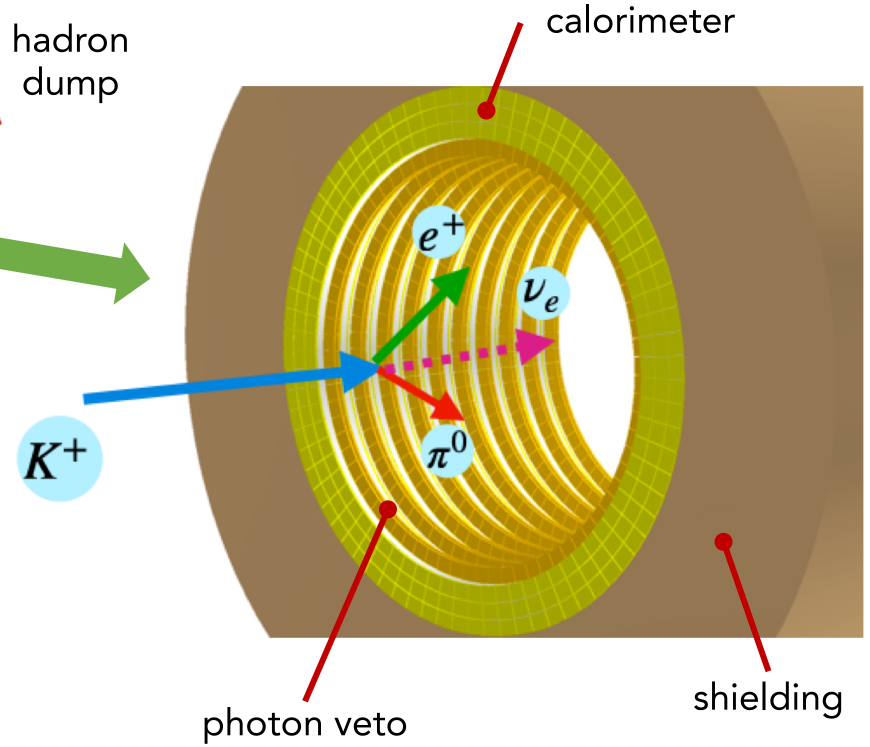
ENUBET: the first monitored neutrino beam

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

Monitored ν beams

measure rate of leptons $\Leftrightarrow$ monitor ν flux





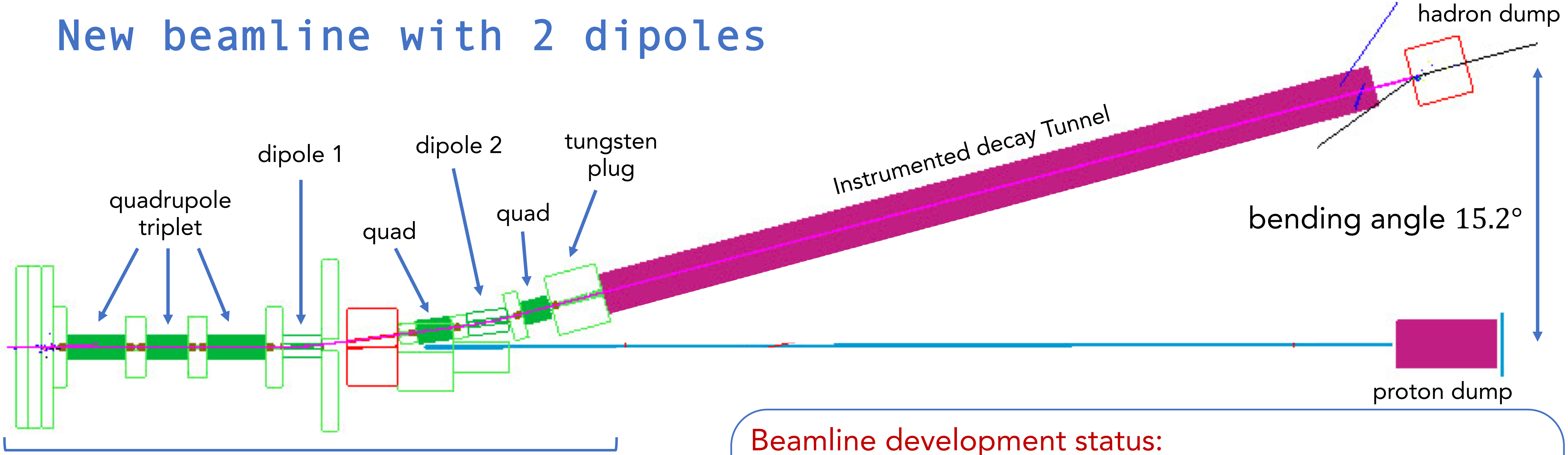
A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

- **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;

New beamline with 2 dipoles



2 dipoles allow a large bending angle (15.2°):

- cons: increased length and reduced rates BUT…
- pros:
  - ❖ better beam containment (collimated);
  - ❖ reduced backgrounds (positrons & forward going muons): better PID (next slides);
  - ❖ reduced not-tagged neutrino contamination (next slides);

Beamline development status:

- ❖ target simulation: done;
- ❖ proton dump: done but engineering studies needed;
- ❖ hadron dump: done including neutron shielding (NEW);
- ❖ transfer line:
  - ❖ TRANSPORT/G4Beamline for the optics and background shielding: done;
  - ❖ FLUKA for doses and neutron shielding: done but other studies needed;
  - ❖ GEANT4 for systematics assessment: in progress;

Particle rates and pile-up

Double dipole beamline with slow-extraction scheme (2 s):

- maximum total rate of about 500-600 kHz/ch;

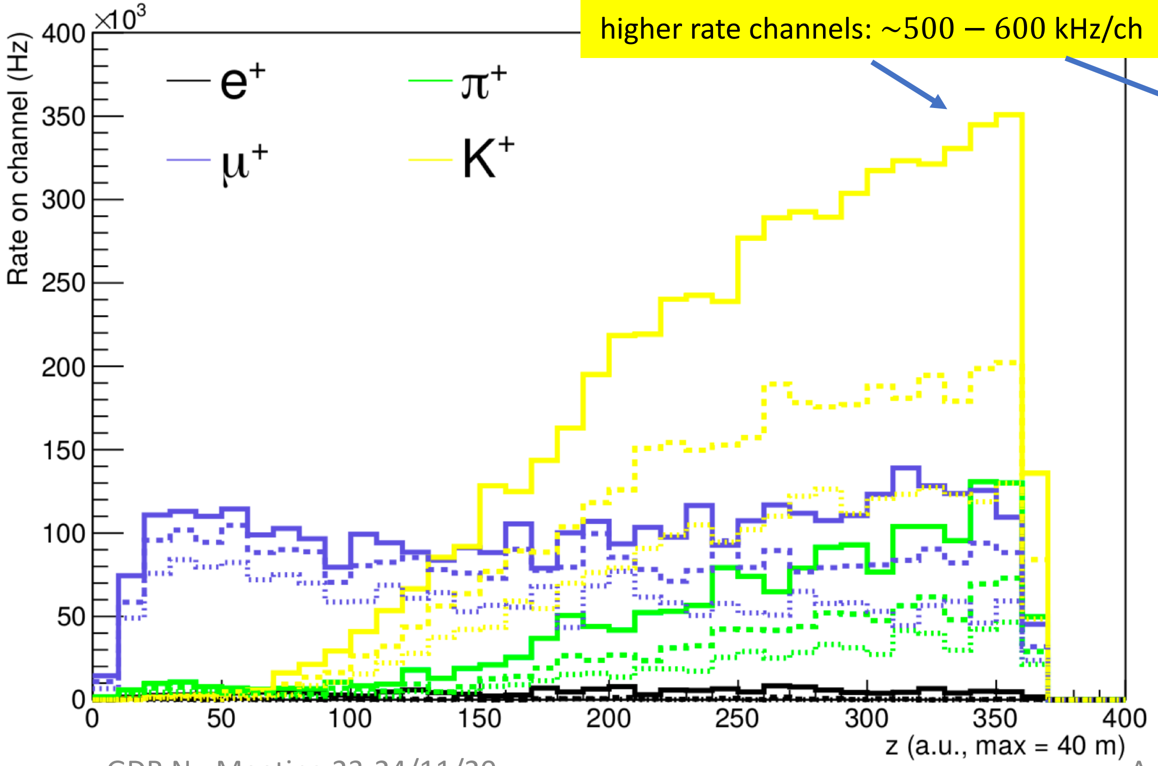
Rates breakdown contribution along the decay tunnel:

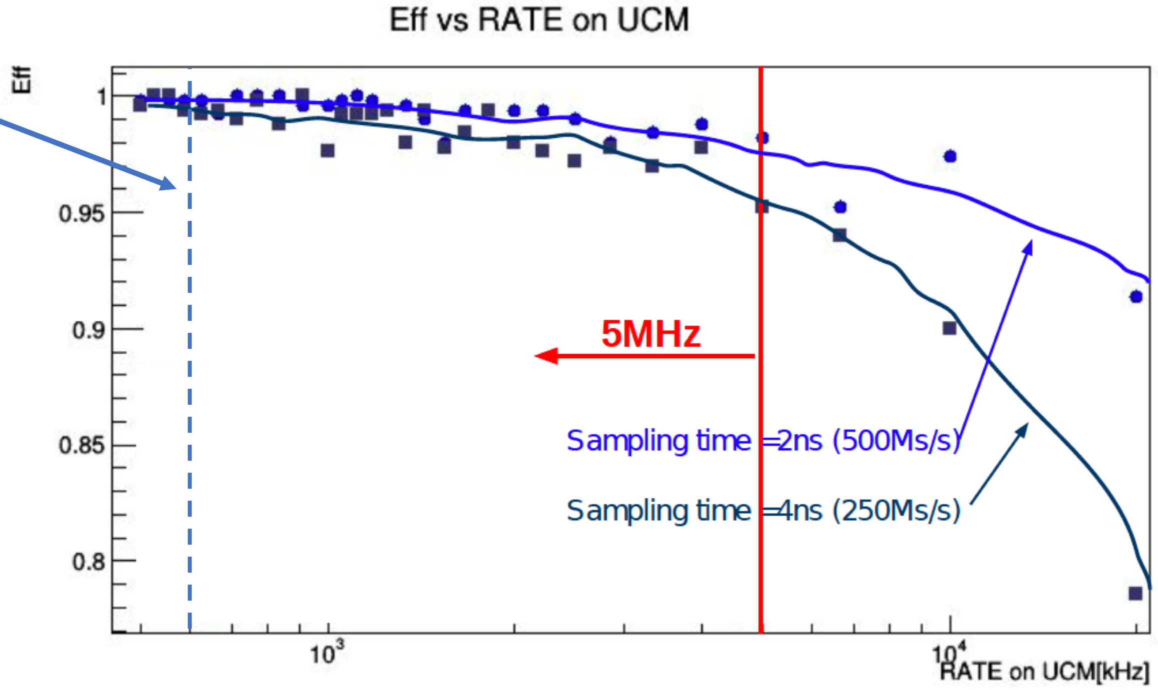
- Kaons: dominate at high Z;
- muons: almost uniform contribution;
- pions: contribution grows toward the end of tunnel;

Waveform analysis has been developed (NEW):

- pile-up detection efficiency loss < 1% up to ∼1 MHz/ch;
- high detection efficiency (> 97%) preserved up to 5 MHz/ch: can cope also with higher rates obtained with horn focusing;
- 250 Ms/s is still a suitable sampling time;

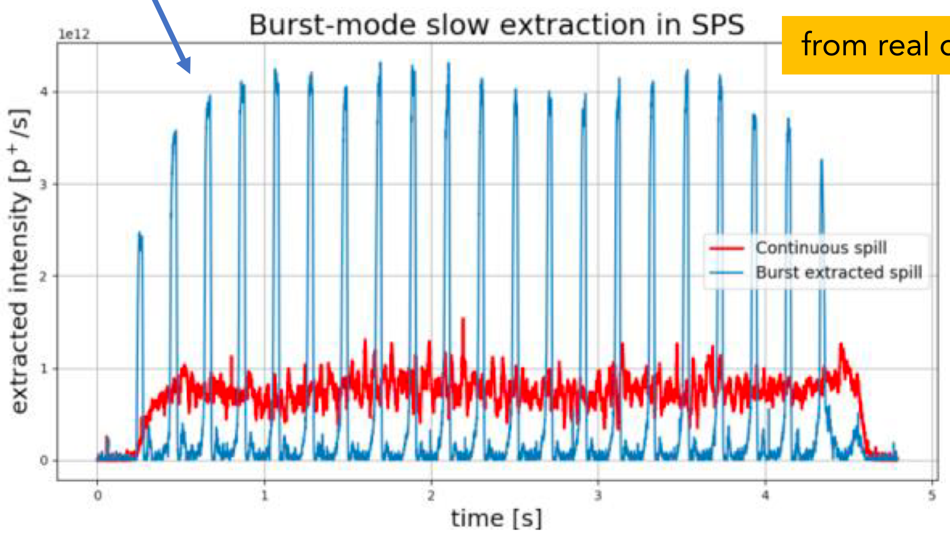
higher rate channels: ∼500 – 600 kHz/ch





Horn based focusing

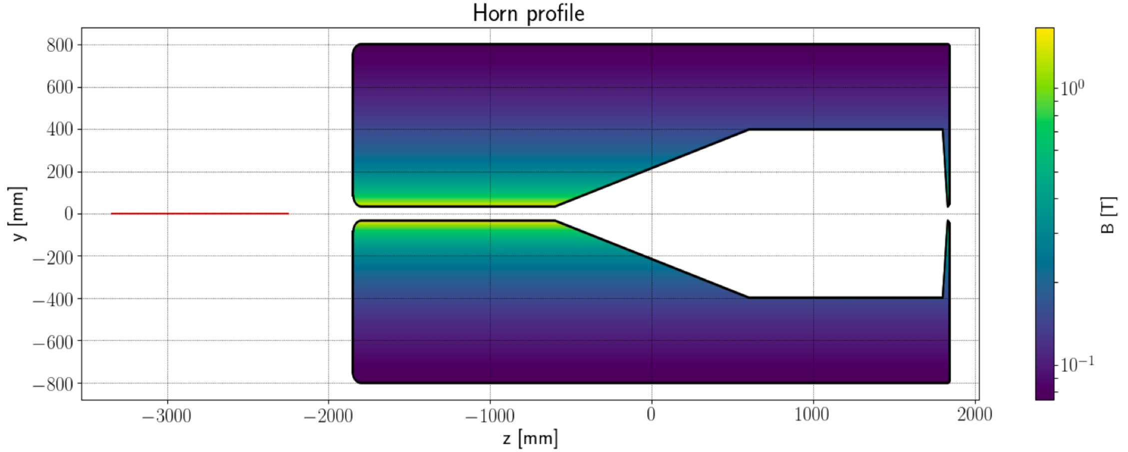
Burst mode slow extraction: protons are "squeezed" in time intervals with active horn



M. Pari, M. A Fraser et al, IPAC2019

- tested at SPS during 2018;
- same integrated POT as for continuous spill;
- no increase in measured losses;
- MAD-X simulation finalized in 2019 to reach 2-10 ms burst length;
- final tests at SPS in 2022 (after LS2);

Update with the new beamline ongoing



Ongoing re-optimization of the horn for the new beamline:

- current and shape of conductors are being optimized to maximize the flux exploring a large parameter space (genetic algorithm employed, in progress);

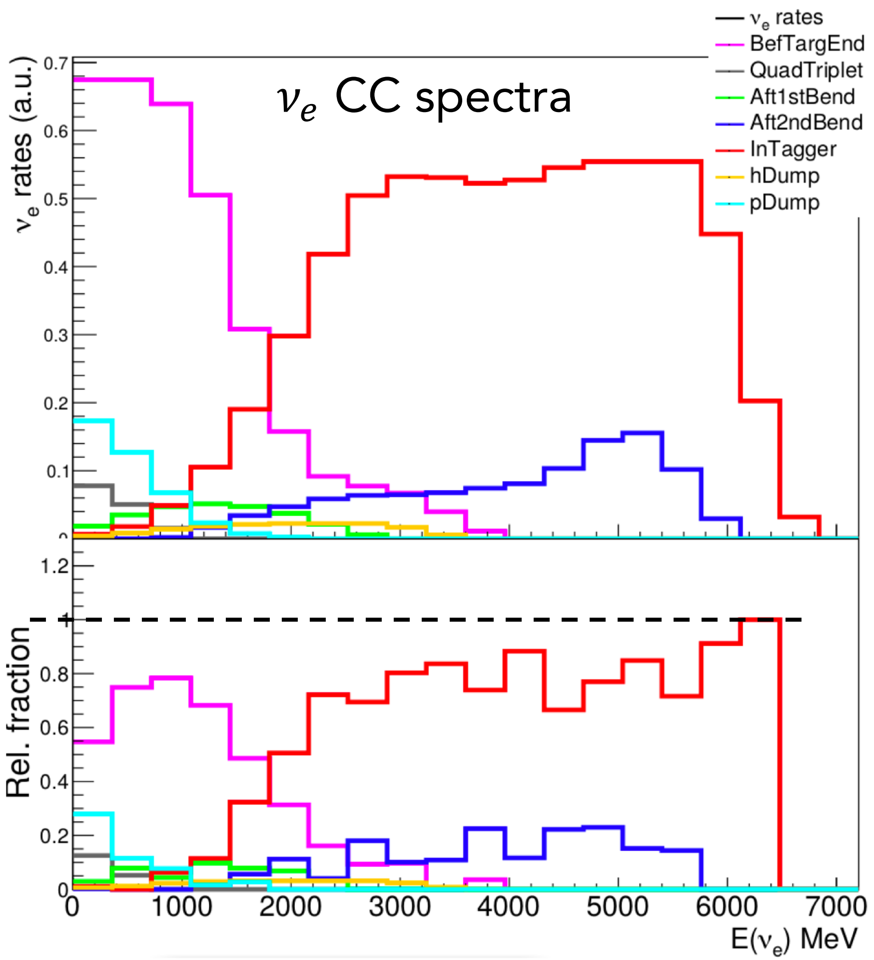
Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction length	π/cycle (10^{10})	K/cycle (10^{10})	Proposal [c]
Horn	97	7.9	2 ms [a]	438	36	x 2
"static"	19	1.4	2 s	85	6.2	x 4

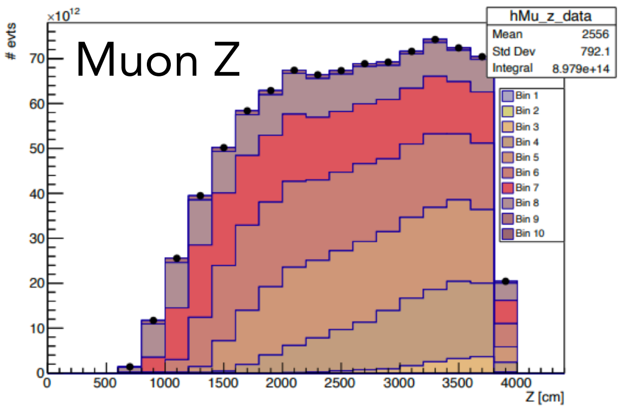
Preliminary result: a factor 5 in flux increase with horn focusing option

Electron neutrino flux components

- Contribution dominated by Kaon decays (98.4%): muon contribution small since tunnel short;
- Taggable component: 80% monitored by measuring positron in decay tunnel;
- Not taggable component 1: 10% low energy neutrinos from $K^{0+/-}$ decays in the target region
  - reduced contribution thanks to large bending angle;
  - can be removed with energy cut;
- Not taggable component 2: 10% neutrinos from K^{+} decays in the straight section in front of the tagger
  - length of beamline collinear with detector reduced at minimum (1 quad)

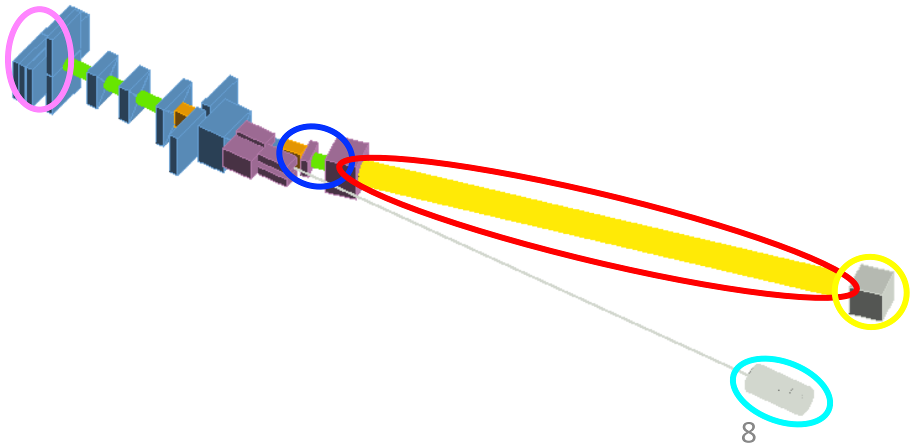
assumption: 500 t detector located 50 m from hadron dump





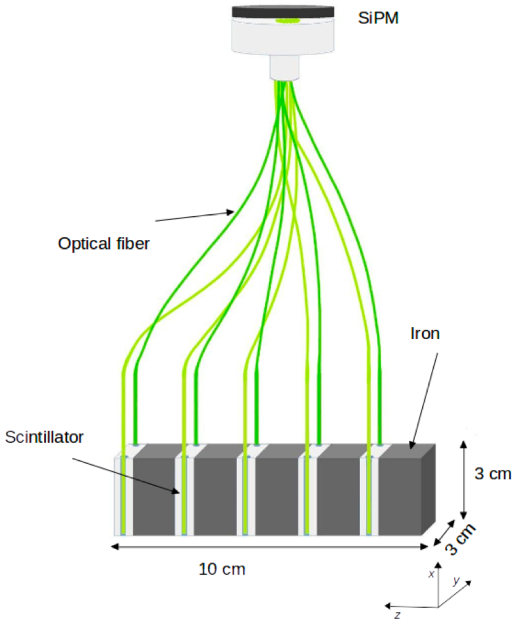
Reduce uncertainty in the tagged neutrino component (in progress):

- exploit correlation between shape of observed lepton distributions and neutrino energy to build observable templates;
- build model from templates and fit to observed data;

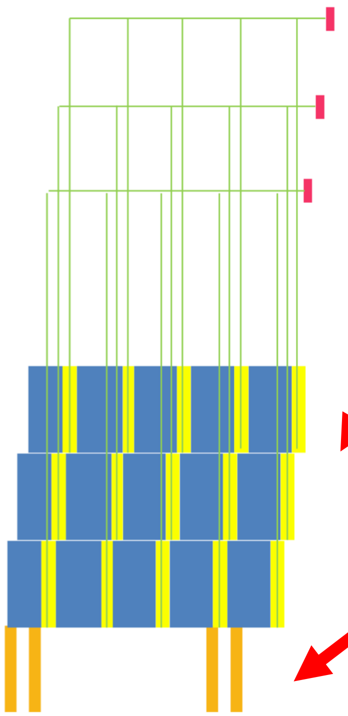


Decay tunnel instrumentation schematics

A Lateral readout Compact Module LCM



Calorimeter layout



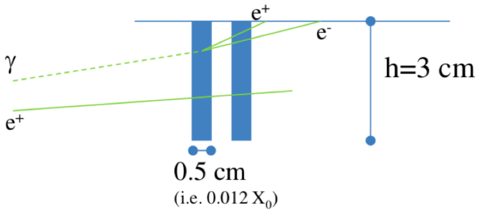
beam

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 $\sim$400 ps;



Exploit event topology for PID

e^+ (signal) topology

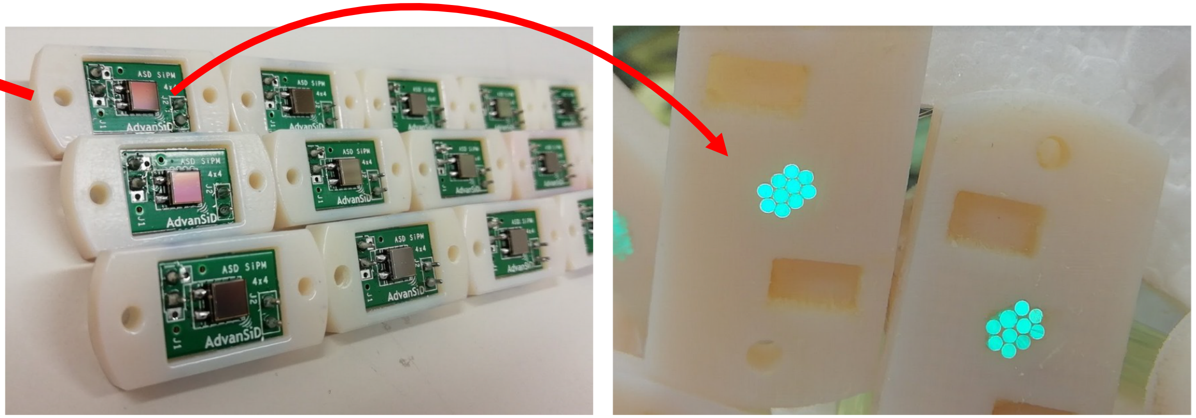
π^0 (background) topology

π^+ (background) topology

Decay tunnel instrumentation prototype & tests

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

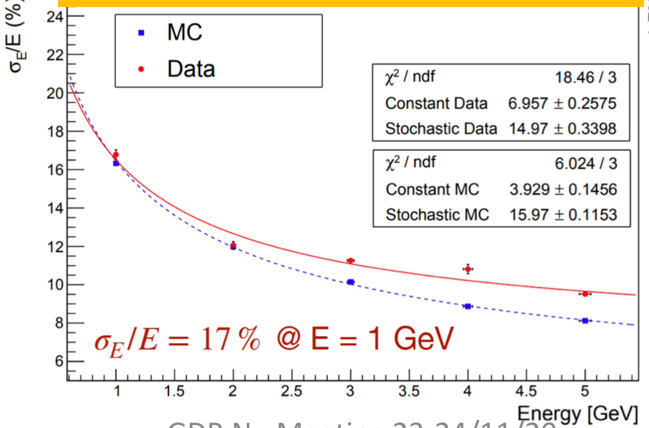
Large SiPM area (4x4 cm^2) for 10 WLS readout (1 LCM)



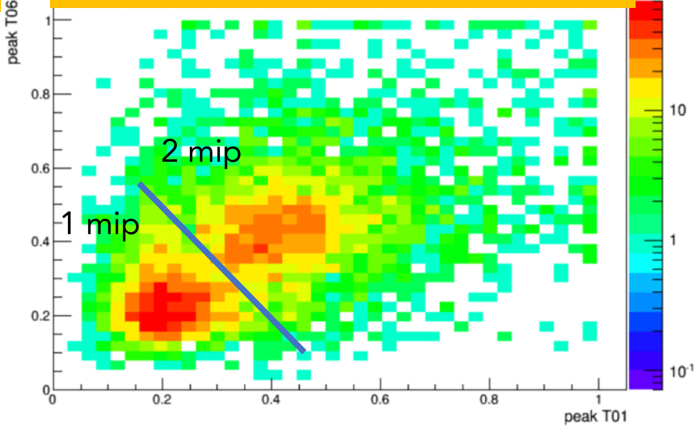
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

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:

K_{e3} positron reconstruction to constrain ν_e

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

✓ **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);

Analysis chain:

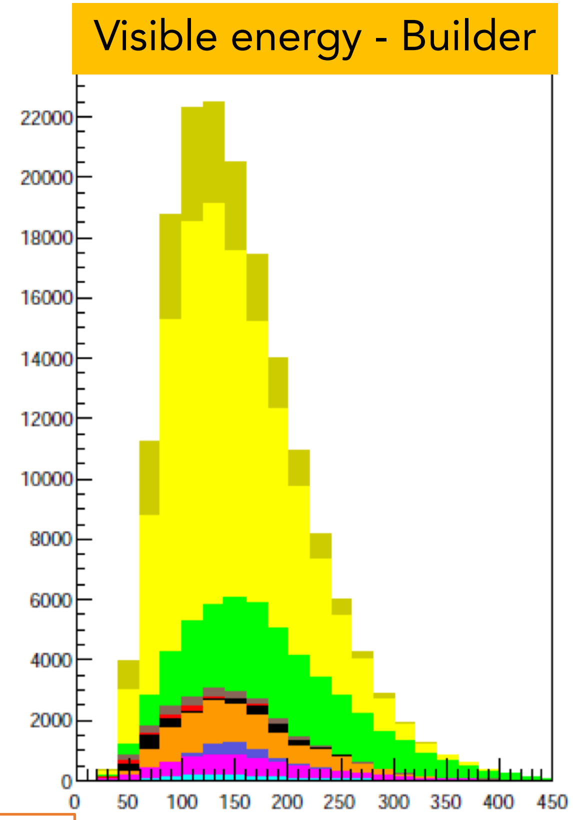
1. Event builder: start from event seed and cluster energy deposits compatible in space and time;
2. e / π / μ / γ separation: multivariate analysis (MLP-NN from TMVA) exploiting 19 variables (energy pattern in calorimeter, event topology, photon-veto);

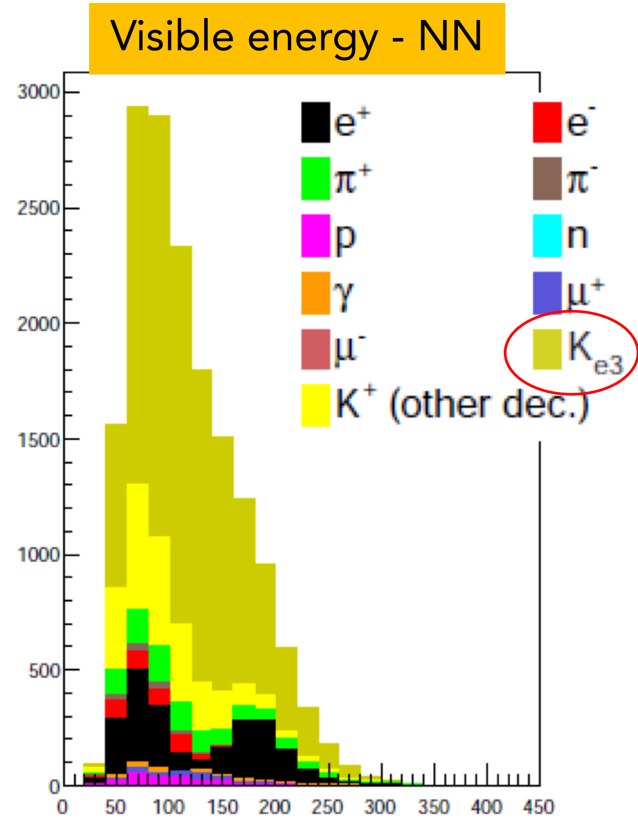
Analysis performance

S/N = 2.1

Efficiency = 24% (~half geometrical)

Better performances for positron PID in the new beamline!



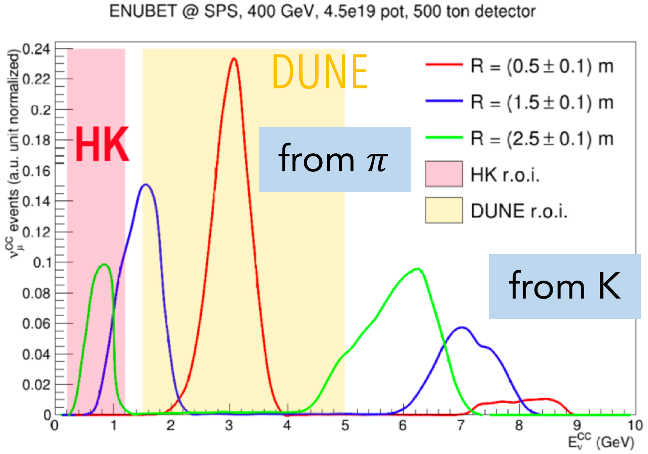


K_{e3} BR ~5% and K make ~5 – 10% of beam composition

Lepton reconstruction and identification:

$K_{\mu 2,3}$ muon reconstruction to constrain high-energy ν_μ

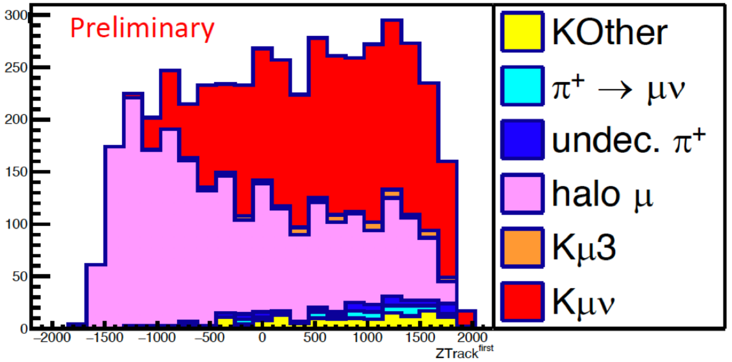
✓ **High angle muons**: reconstruction of track in tagger with dedicated event builder and multi variate analysis. Main background from halo muons is identified and can be used as control sample



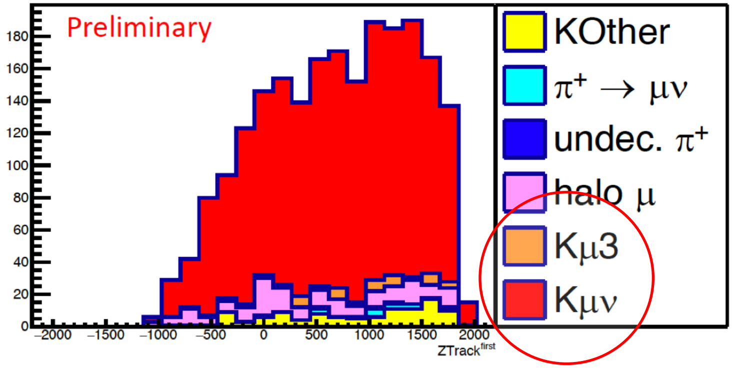
Analysis chain:

1. Event builder: start from event seed and cluster energy deposits compatible in space and time;
2. μ-like background separation: multivariate analysis (MLP-NN from TMVA) exploiting 13 variables (energy pattern, track isolation and topology);

Tagger impact point - Builder



Tagger impact point - NN



Analysis performance

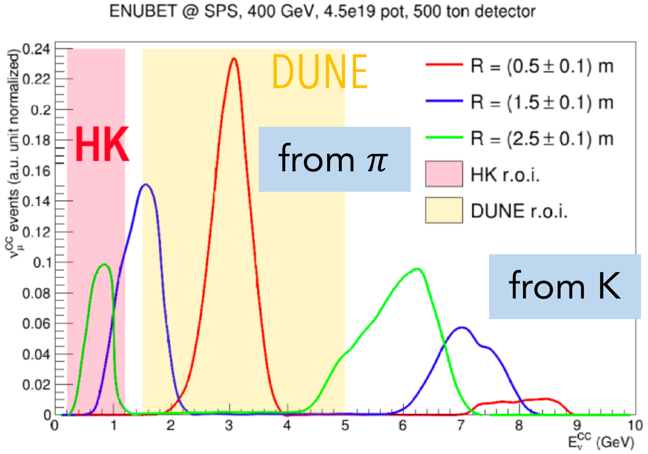
S/N = 6.1

Efficiency = 34% ($K_{\mu 2}$) & 21% ($K_{\mu 3}$) (~half geometrical)

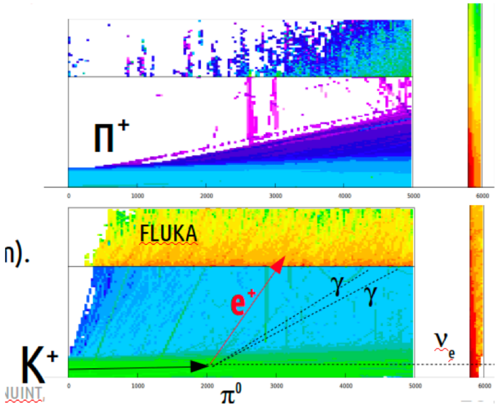
NEW: we demonstrate the capability of muon monitoring

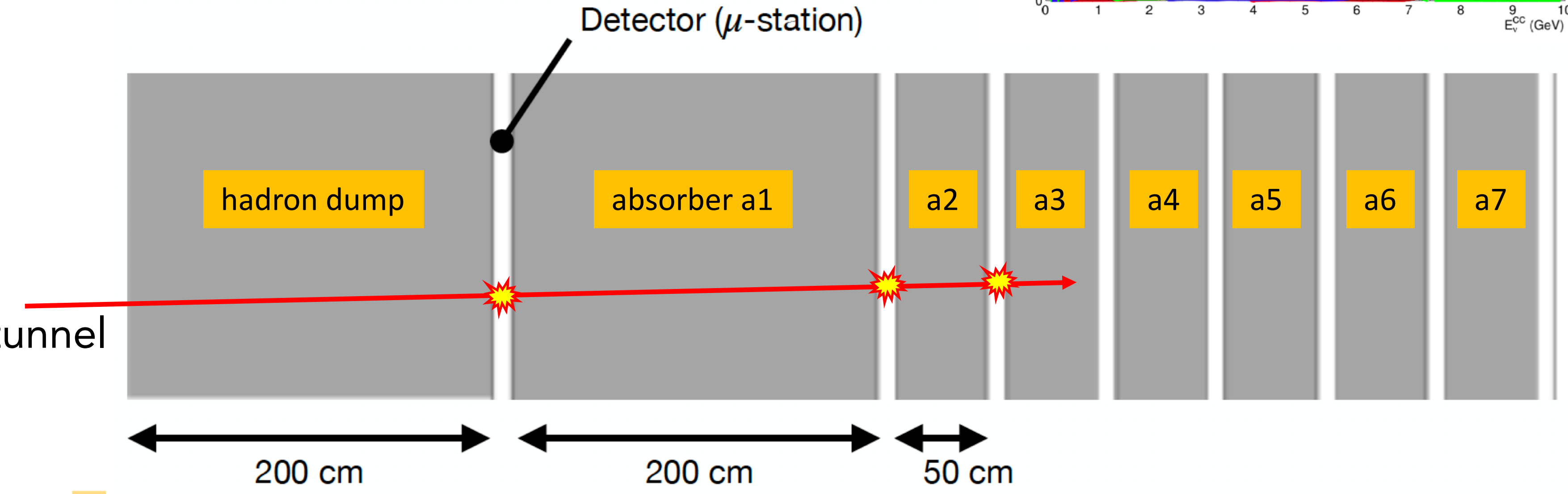
Lepton reconstruction and identification:

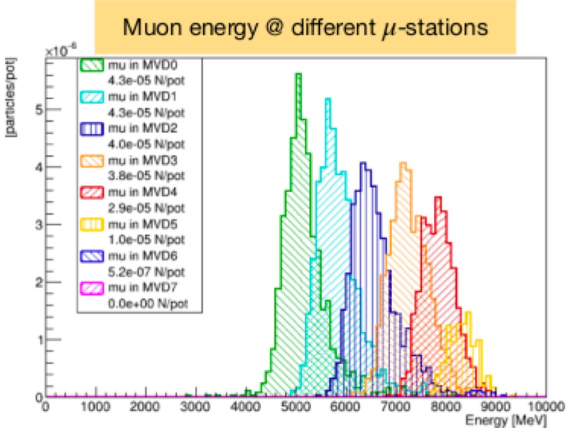
$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

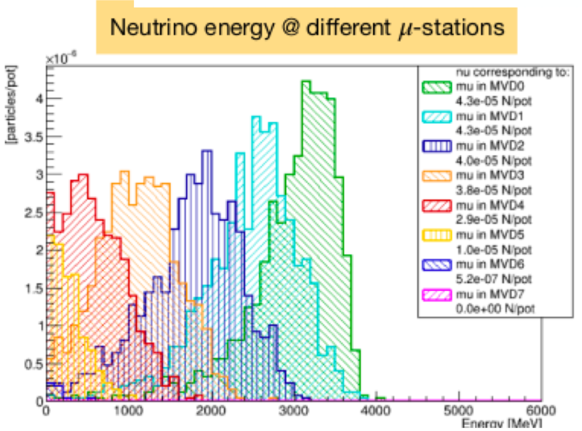


✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump









Exploit:

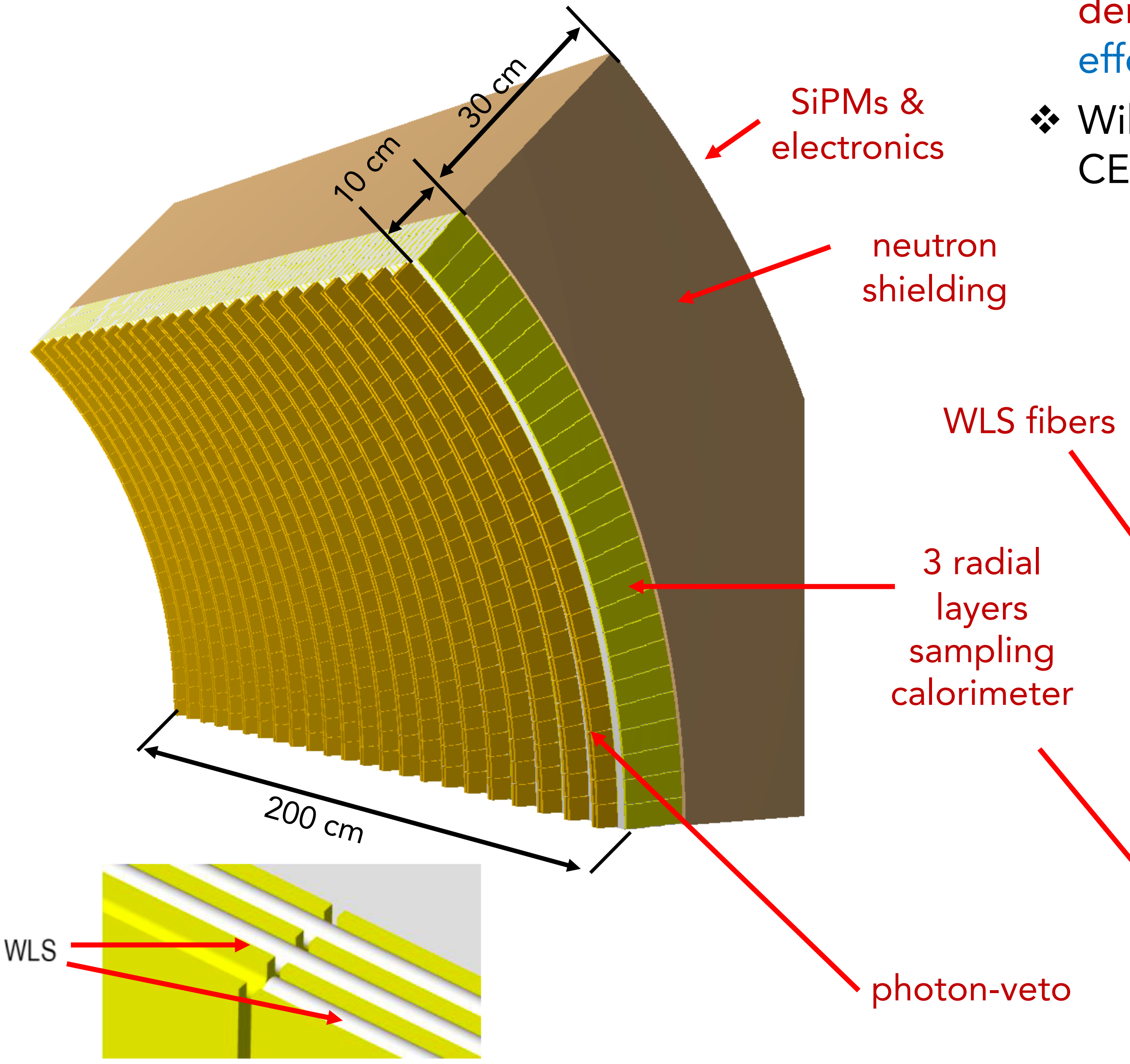
- ❖ correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- ❖ difference in distribution to disentangle signal from halo-muons;

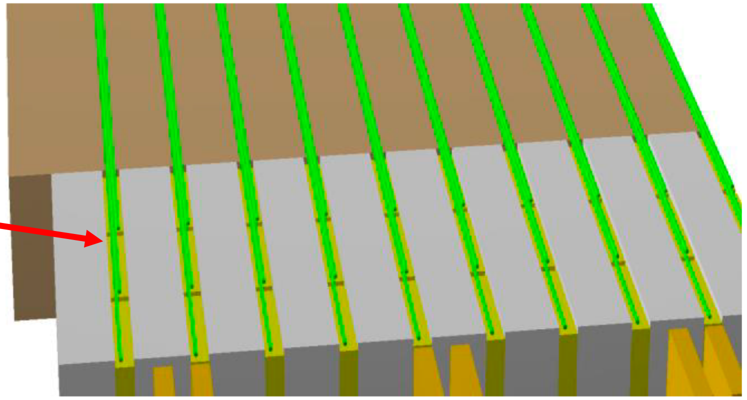
Detector technology: constrained by muon and neutron rates;

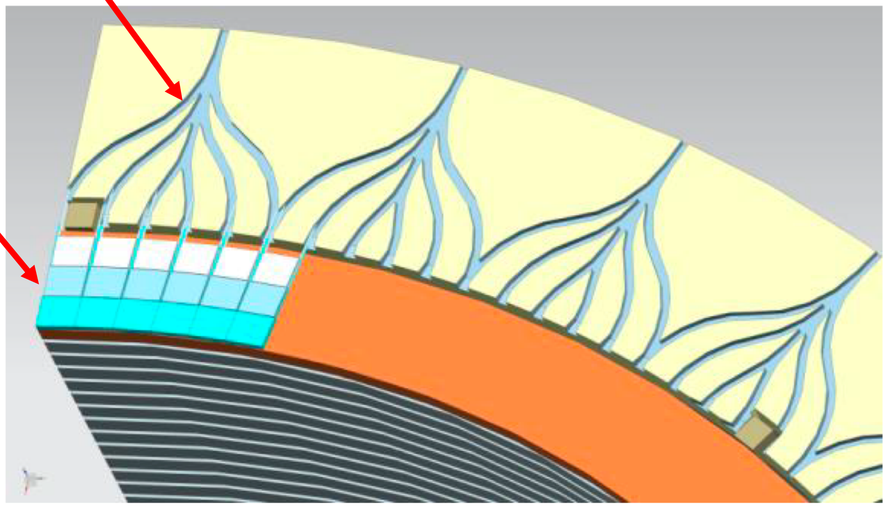
Systematics: punch through, non uniformity, efficiency, halo-μ;

ENUBET demonstrator

- Build prototype (1.7 m long / 45° coverage) to demonstrate performance, scalability and cost-effectiveness;
- Will be tested in the renovated East-Area at the CERN-PS: after LS2 (2021-2022);







Conclusions

ENUBET: a project for the first monitored neutrino beam

Status of the project in very good shape:

- New double-dipole beamline with improved shielding developed;
- Burst mode slow extraction: further optimization developed, final tests after LS2;
- Horn optimization ongoing: preliminary x5 gain in flux;
- Finalized technology for calorimeter: lateral readout calorimeter;
- Positron reconstruction: very good performance with new beamline;
- Constrain also muon neutrino: demonstrated muon monitoring capability;
- Full assessment of systematics on neutrino flux: in progress and will be released by 2021;
- Construction and testing of demonstrator: during 2021-2022;
- Conceptual Design Report by 2022;