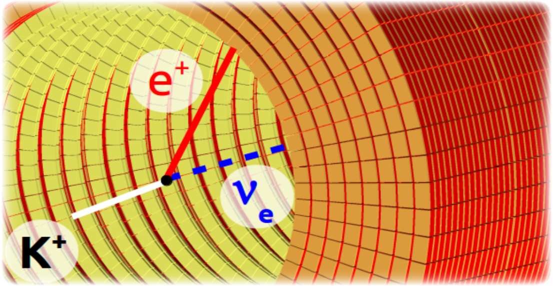


High precision neutrino cross section measurements with the ENUBET monitored neutrino beam

Valerio Mascagna

Università degli Studi di Brescia & INFN - PV

Κολυμβάρι, Aug. 30 – Sep. 11 – ICNFP2022

European Research Council
Established by the European Commission

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)

OUTLINE

- The ENUBET project overview
- Beamline studies
- The instrumented tunnel and the tagger
- Simulation and systematics
- Conclusions and outlooks

ENUBET

Enhanced NeUtrino BEams from kaon Tagging

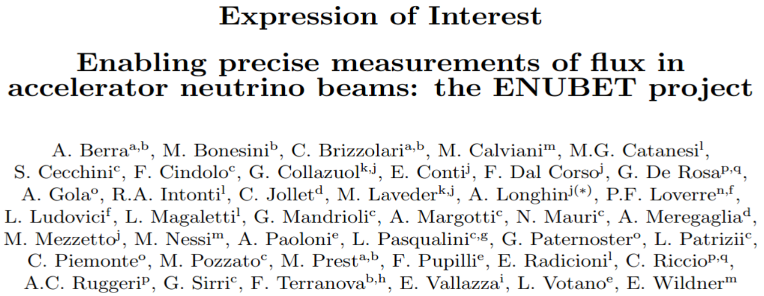
http://enubet.pd.infn.it

Project approved by the European Research Council (ERC)
5 years (ends in 2022)
overall budget: 2 MEUR

ERC-Consolidator Grant-2015, no 681647 (PE2)
P.I.: **A. Longhin**
Host Institution: **INFN**

Expression of Interest (CERN-SPSC, Oct. 2016)
CERN-SPSC-2016-036; SPSC-EOI-014

April 2019: CERN Neutrino Platform Experiment – **NP06/ENUBET**
Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna



Expression of Interest

Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project

A. Berra[a,b], M. Bonesini[b], C. Brizzolari[a,b], M. Calviani[m], M.G. Catanesi[l],
S. Cecchini[c], F. Cindolo[c], G. Collazuol[k,j], E. Conti[j], F. Dal Corso[j], G. De Rosa[p,q],
A. Gola[o], R.A. Intonti[l], C. Jollet[d], M. Laveder[k,j], A. Longhin[j(*)], P.F. Loverre[n,f],
L. Ludovici[f], L. Magaletti[l], G. Mandrioli[c], A. Margotti[c], N. Mauri[c], A. Meregaglia[d],
M. Mezzetto[j], M. Nessi[m], A. Paoloni[e], L. Pasqualini[c,g], G. Paternoster[o], L. Patrizii[c],
C. Piemonte[o], M. Pozzato[c], M. Prest[a,b], F. Pupilli[e], E. Radicioni[l], C. Riccio[p,q],
A.C. Ruggeri[p], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i], L. Votano[e], E. Wildner[m]

60 physicists & **13 institutions**

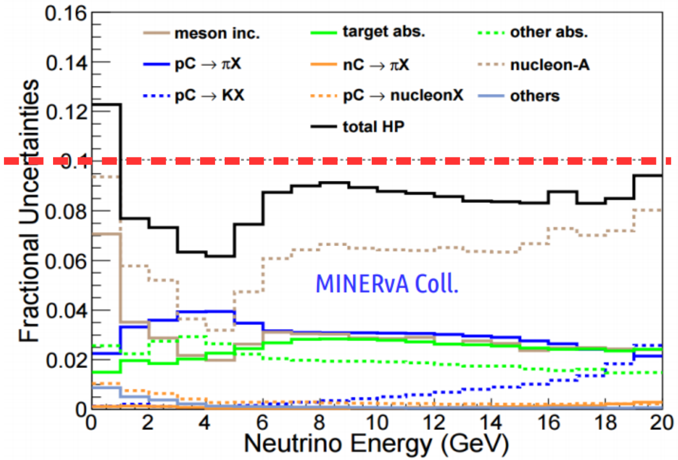
Flux uncertainty and $\nu_{e,}\nu_{\mu}$ cross sections

Last 10 years: knowledge of **$\sigma(\nu_\mu)$** improved enormously

MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA …

Nevertheless, the flux systematics **“wall”** is still there being typically the **dominant uncertainty** for cross section measurements

No absolute measurements below ~7-10%



In addition, for **$\sigma(\nu_e)$** we use the beam contamination (no intense/pure sources of GeV ν_e): data still sparse Gargamelle, T2K, NOvA, MINERvA

Poor knowledge of **$\sigma(\nu_e)$** can spoil :

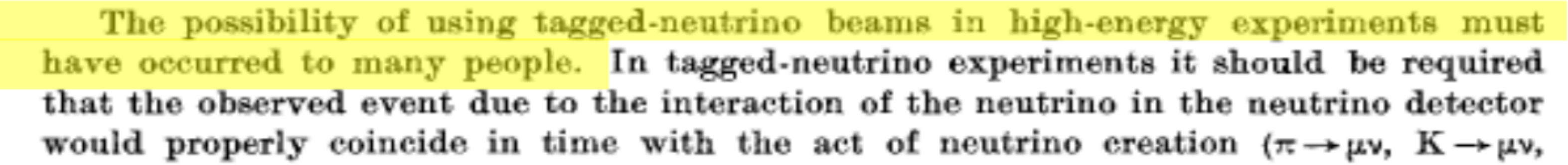
- the **CPV discovery potential**
- the insight on the underlying physics (standard vs exotic)

→ Monitored beams

Monitored neutrino beams

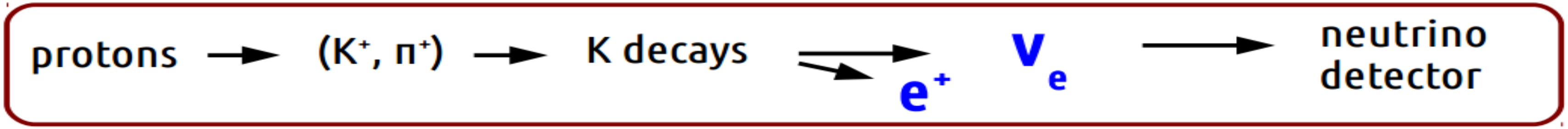
The "holy grail" of neutrino physicists:

B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257



The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$,

Based on **conventional technologies**, aiming for a 1% precision on the **ν_e flux**



protons → (K^+, π^+) → K decays → e^+ ν_e → neutrino detector

Monitor (~ inclusively) the decays in which ν are produced

→ "by-pass" of the hadro-production, beam-line efficiency uncertainties, ...

Traditional

- **Passive** decay region
- ν_e flux relies on **ab-initio simulations** of the full chain
- **large uncertainties**

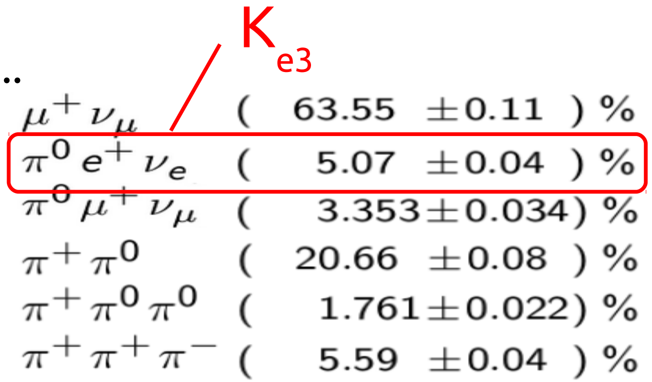
↔

Monitored

- **Fully instrumented**

$K^+ \to e^+ \nu_e \pi^0$ → large angle e^+

- **ν_e flux prediction = e^+ counting**



K_{e3}

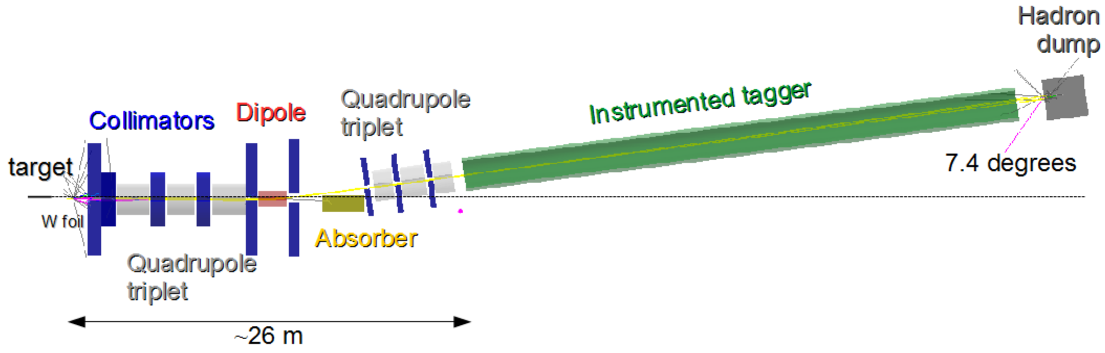
$\mu^+\nu_\mu$	(63.55 ±0.11) %
$\pi^0 e^+ \nu_e$	(5.07 ±0.04) %
$\pi^0 \mu^+ \nu_\mu$	(3.353±0.034) %
$\pi^+\pi^0$	(20.66 ±0.08) %
$\pi^+\pi^0\pi^0$	(1.761±0.022) %
$\pi^+\pi^+\pi^-$	(5.59 ±0.04) %

A **neutrino beam** for precision physics

The next generation of short baseline experiments for cross-section measurements and for precision ν-physics (e.g. CP violation program, sterile neutrinos, NSI at production/detection/propagation) should rely on:

- a direct measurement of the fluxes
- a narrow band beam: energy known a priori from beam width
- a beam covering the region of interest from sub- to multi-GeV

The ENUBET facility fulfills simultaneously all these requirements

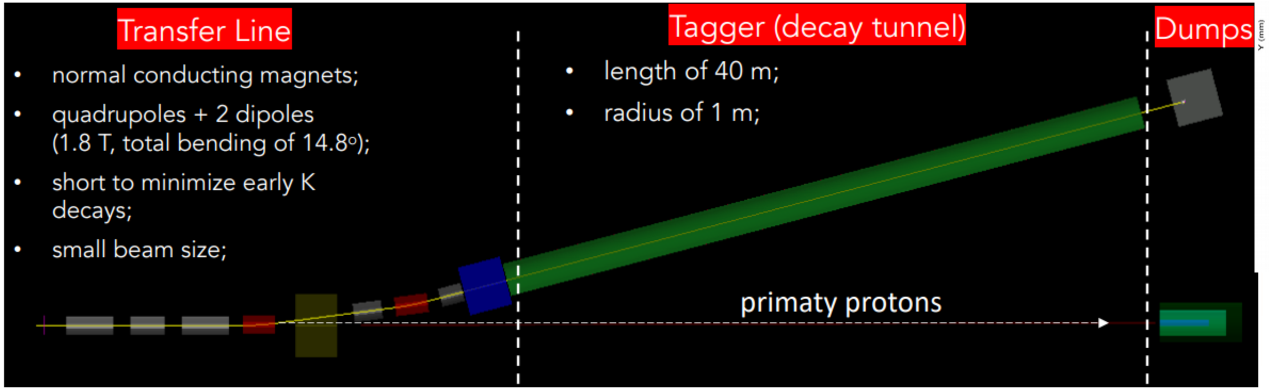


~ 500 t neutrino detector @ 100 m from the target

e.g.:

- ICARUS (FNAL)
- ProtoDUNE (CERN)
- Water Cherenkov (JPARC)

The ENUBET beamline: final design



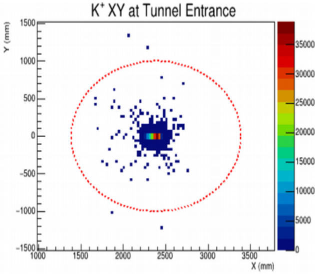
Transfer Line

- 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



Beam spot…

… and rates @ Tunnel entrance for 400 GeV POT

π^+ [10^{-3}]/POT	K^+ [10^{-3}]/POT
4.13	0.34

~1.5 X w.r.t. previous results!

Large bending angle of 14.8°

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

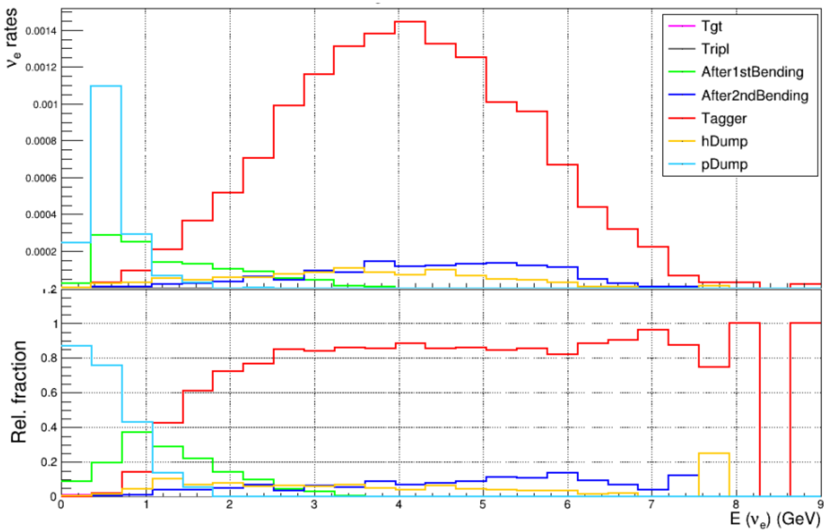
Transfer Line

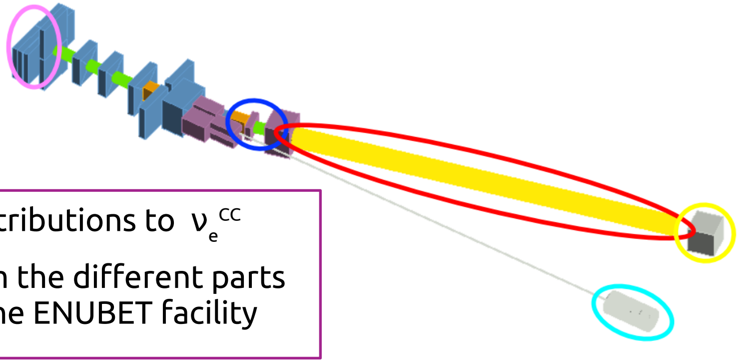
- optics optimization w/ **TRANSPORT** (5% momentum bite centered @ 8.5 GeV) **G4Beamline** for particle transport and interactions
- **FLUKA** for irradiation studies, absorbers and rock volumes included in simulation (not shown above)
- optimized graphite target 70 cm long & 3 cm radius (dedicated 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

ν_e CC energy distribution @ detector





Contributions to ν_e^{CC}

from the different parts of the ENUBET facility

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

- @ SPS with 4.5E19 POT/year
- 500 tons detector @ 50 m from tunnel end

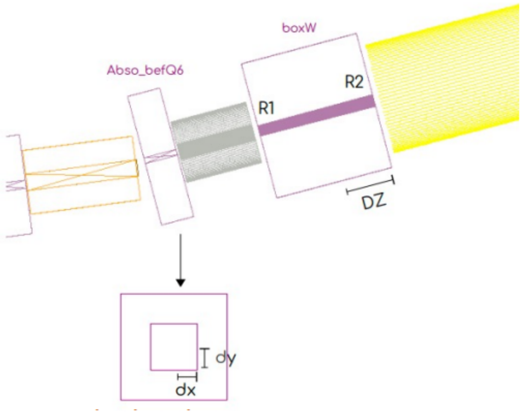
Taggable component (> 1 GeV)

About 80% of total ν_e is produced by decays in the tunnel

Non taggable components

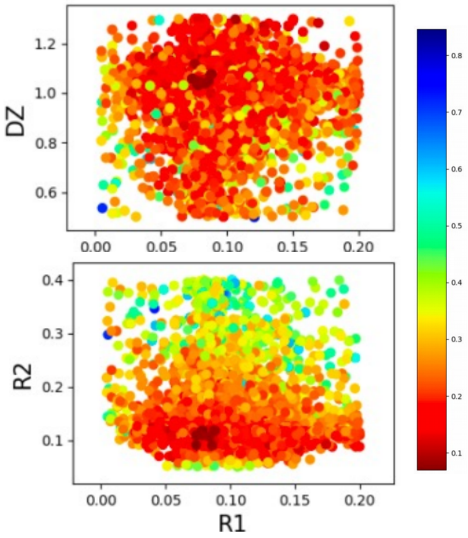
- Below 1 GeV: main component produced in p-dump
  - clear separation from taggable ones (energy cut)
  - further improvements in separation optimizing p-dump position
- Above 1 GeV: contributions from straight section before tagger and hadron-dump
  - rely on simulation for this component

Beamline optimization studies



Optimization campaign is progress:

- **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;



FOM dependence on optimization parameters

FOM = signal/background

Signal: π/*K* @ tagger entrance

Background: e+ and π hitting the 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^+	π^+ [10^{-3}]/K^+
Design	7	59
Optimized	2	35

preliminary

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)

The **ENUBET** tagger

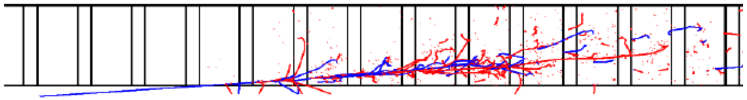
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

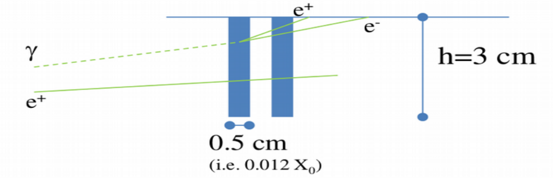
→ **$e^+/\pi^\pm/\mu$ separation**

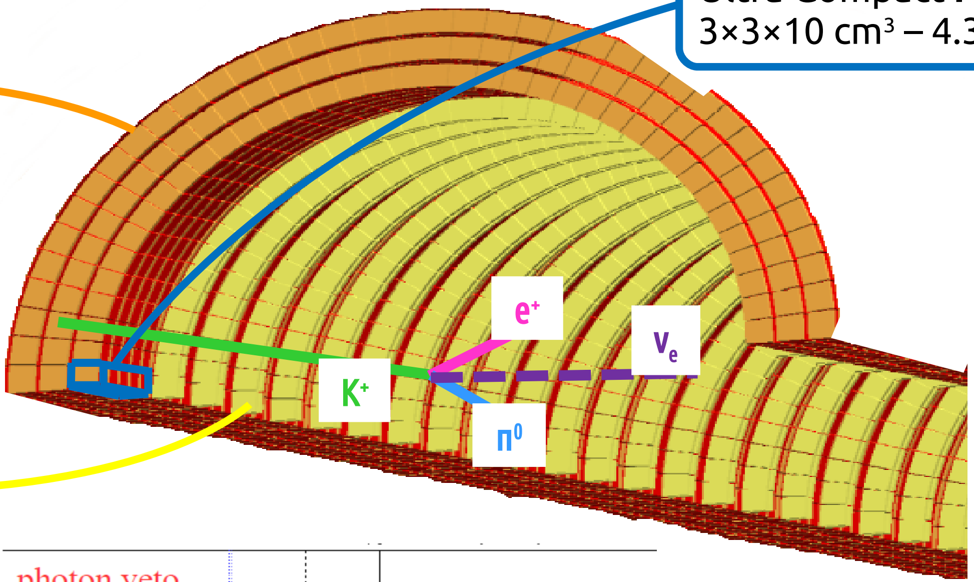


Integrated photon veto

Plastic scintillators, rings of 3×3 cm^2 pads

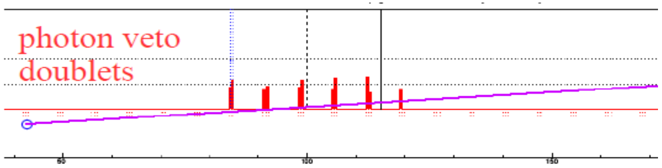
→ **π^0 rejection**





Ultra **C**ompact **M**odule

$3\times3\times10$ cm^3 – 4.3 X_0



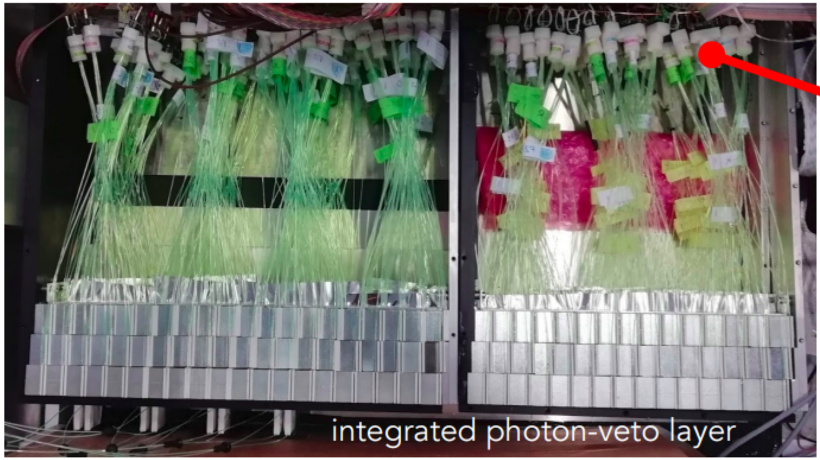
e^+ (signal) topology

π^0 (background) topology

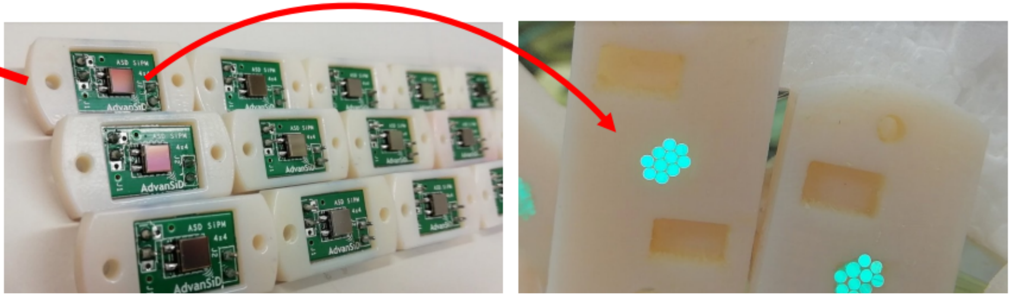
π^+ (background) topology

The **ENUBET** tagger prototype(s)

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

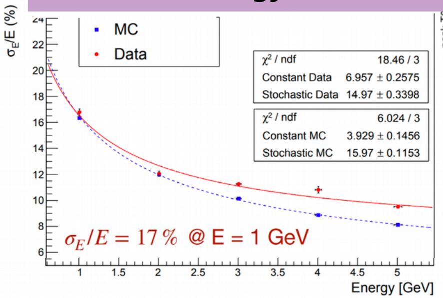


Large SiPM area (4x4 mm2) for 10 WLS readout (1 LCM)



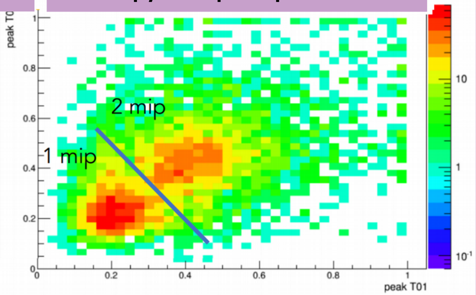
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Electron energy resolution



$\sigma_E/E = 17\,\%$ @ E = 1 GeV

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!

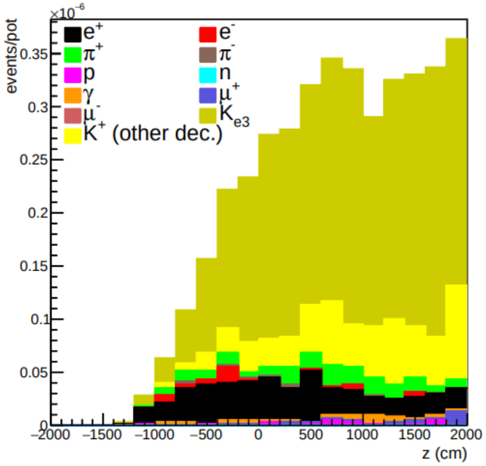
→ *F. Acerbi et al, JINST (2020), 15(8), P08001*

Lepton reconstruction

Full **GEANT4 simulation** of the detector:

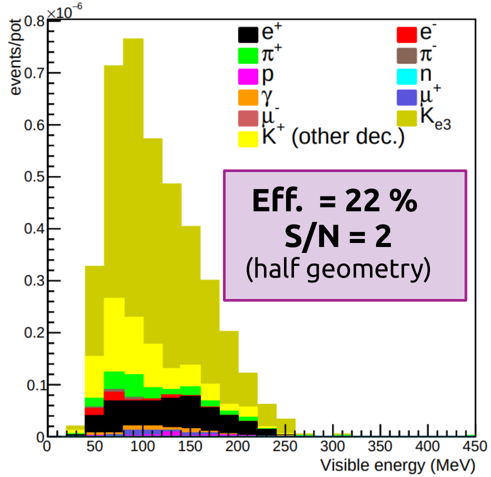
- **validated** by prototype tests at CERN in 2016-2018;
- hit-level detector response;
- pile-up effects included (waveform treatment in progress);
- event building and PID algorithms (2016-2020)

Recontructed events



→ Large angle e+ and mu 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



Eff. = 22 %
S/N = 2
(half geometry)

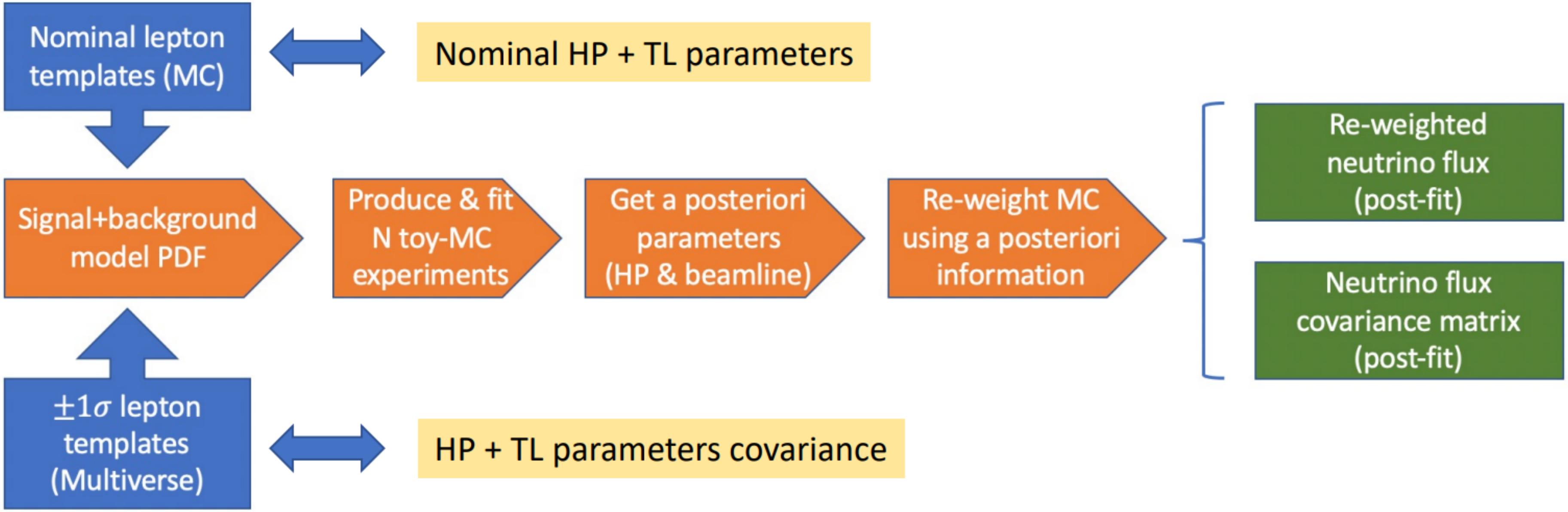
K_{e3} (BR ~5%) and K make ~5 – 10% of the beam composition

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

ν-flux: assessment of systematics

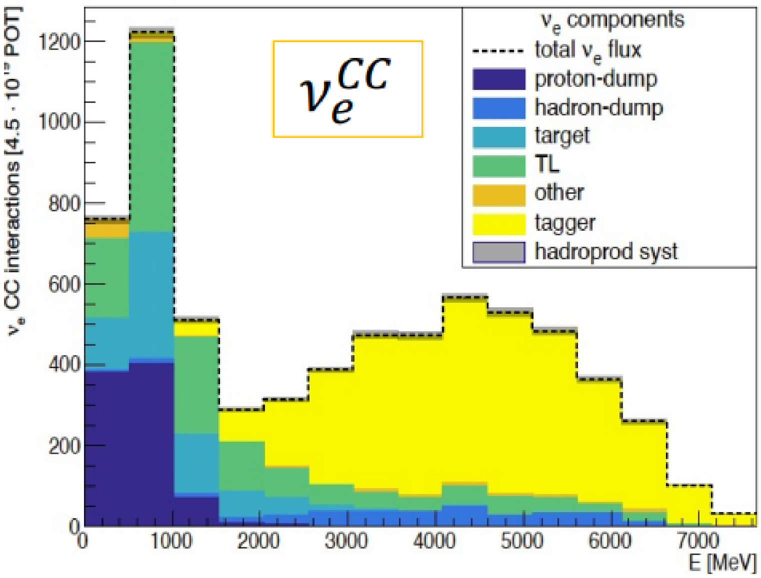
Monitored ν-flux from narrow-band beam: measure rate of leptons ⟺ monitor ν-flux

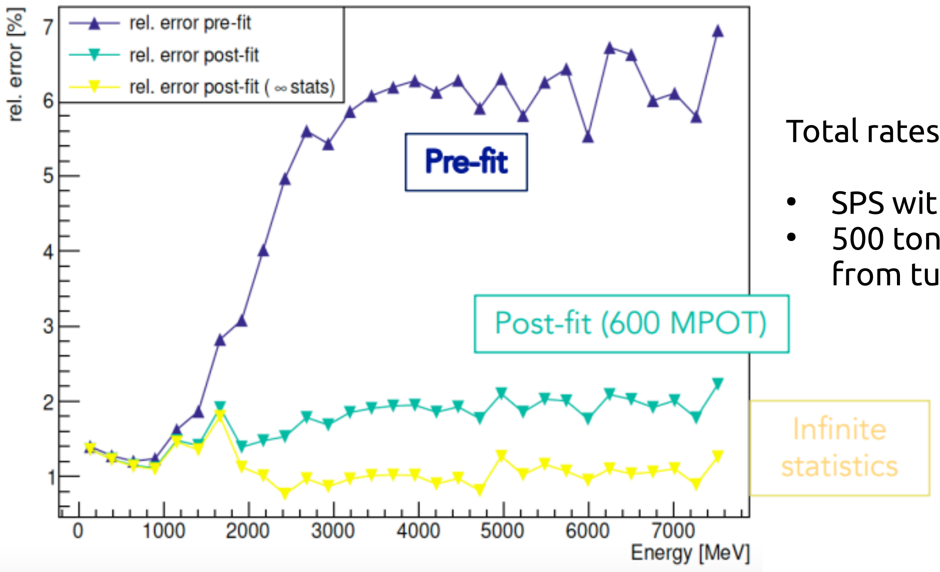
- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;



hadro-production data from NA56/SPY experiment to Reweight MC lepton templates, get their nominal distribution, compute lepton templates variations using multi-universe method

ν-flux: impact on hadro-production systematics





Total rates in 1 year:

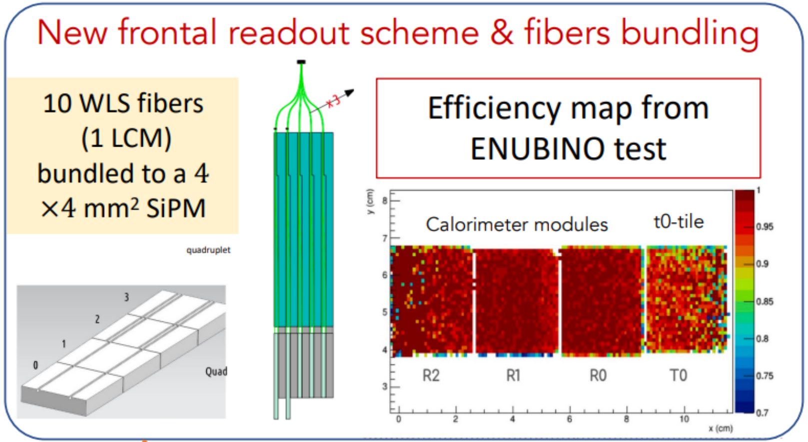
- SPS with 4.5E19 POTS/year
- 500 ton detector @50m from tunnel end

Before constraint
6% systematics due to hadro-production uncertainties

After constraint
1% from fit to lepto rates masured by tagger

Achieved ENUBET goal
of 1% systematics from monitoring lepton rates

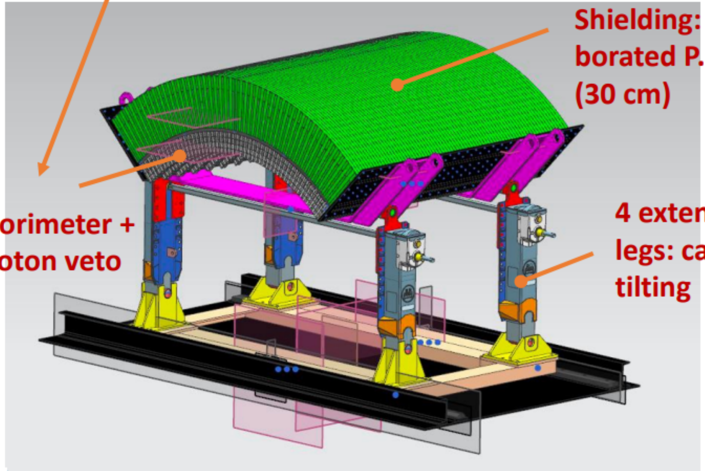
The demonstrator



New frontal readout scheme & fibers bundling

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

Efficiency map from ENUBINO test



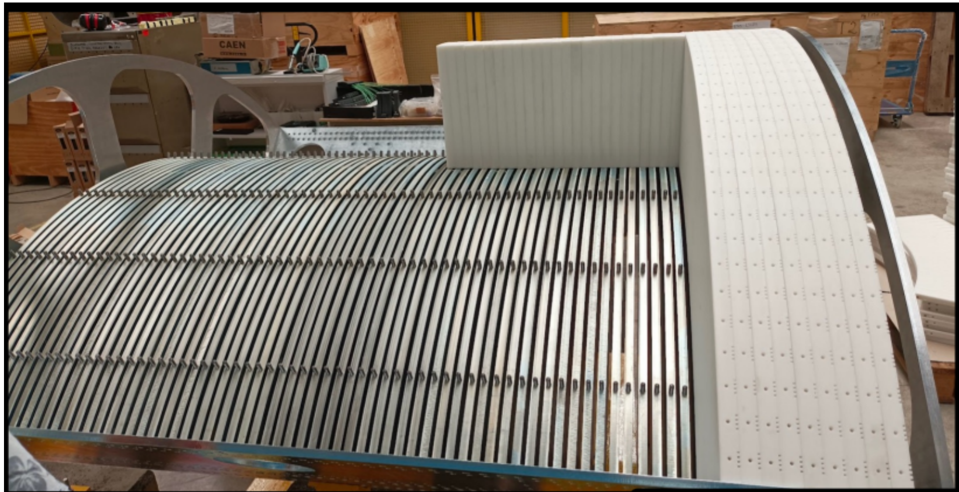
Shielding: borated P.E. (30 cm)

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 SCIONIX and milled by local Company
- ENUBINO: pre-demonstrator w/ 3 LCM tested @ CERN in November 2021 to study uniformity and efficiency

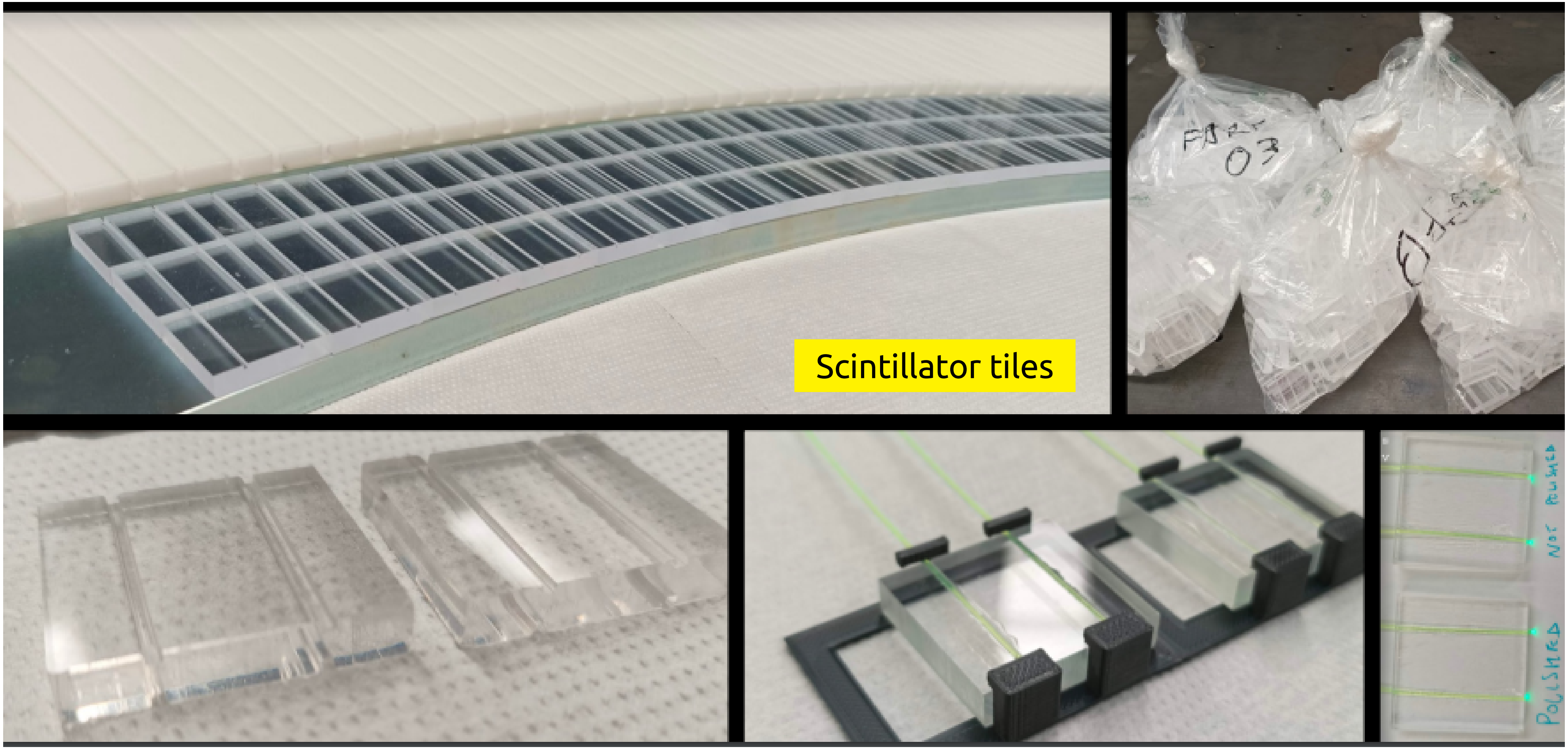
The demonstrator (@ INFN-LNL)



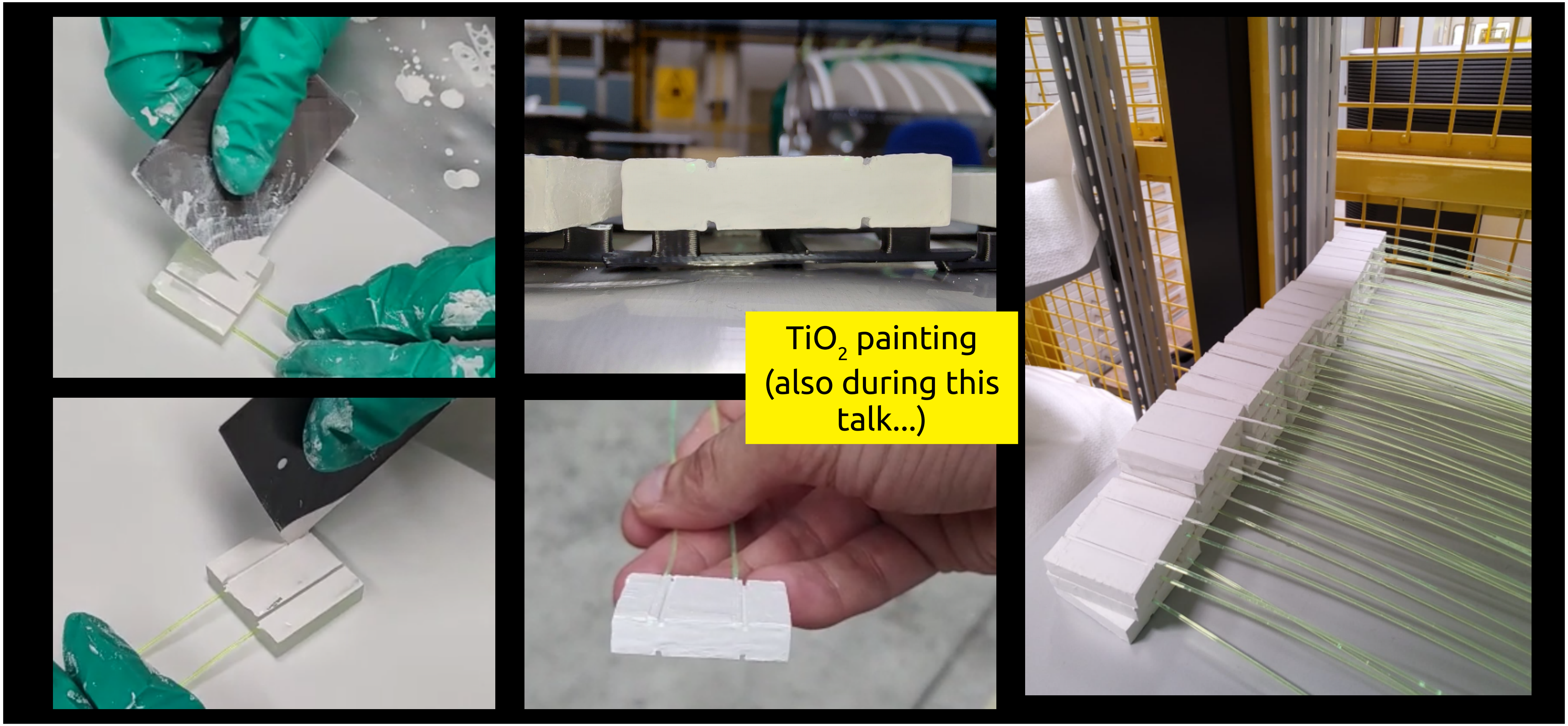
Darkening

15 mins lift test
1.5 x total weigth

The demonstrator (@ INFN-LNL)



The **demonstrator** (@ INFN-LNL)



TiO$_2$ painting (also during this talk…)

Conclusions and outlooks

- **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 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 (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 + ν_μ monitoring!*

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

Experimental proposal expected in 2024

* not included in the talk

Conclusions and outlooks

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

Backup slides

ν_μ^{CC} energy distribution @ detector

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

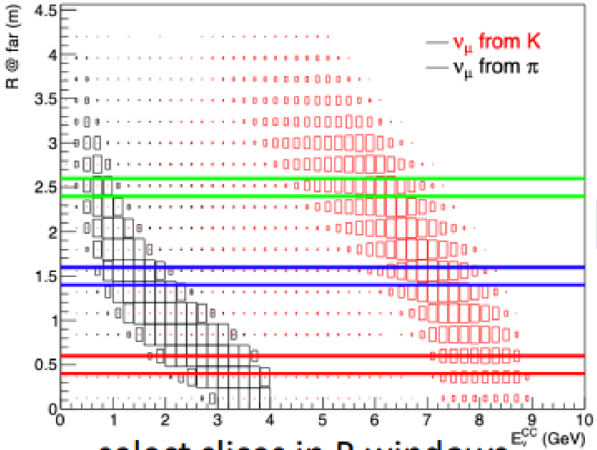
E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

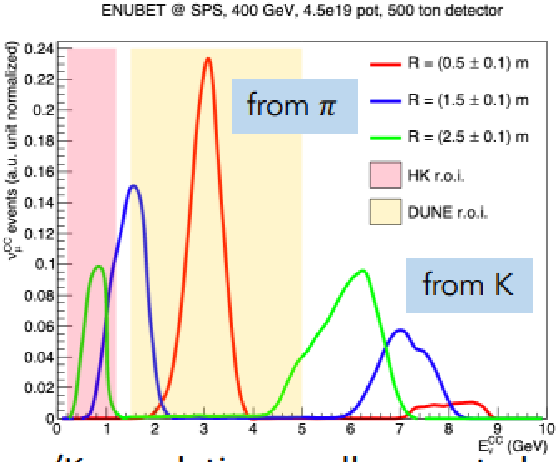
F. Acerbi et al., CERN-SPSC-2018-034

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

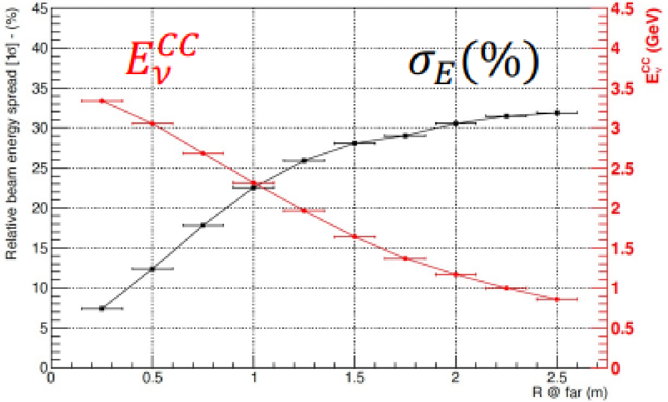
- 8-25% E_ν resolution from π in DUNE energy range;
- 30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):
  - ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



π/K populations well separated

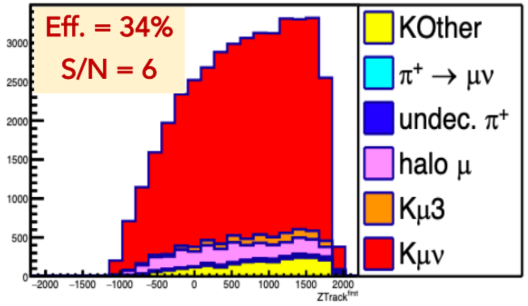


from pion peaks at different R

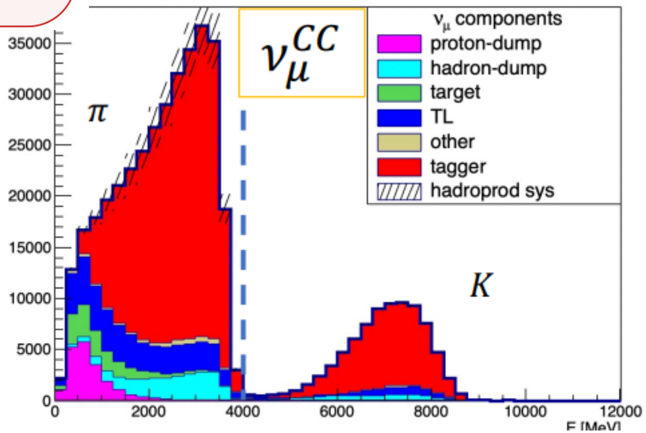
Monitoring nu mu

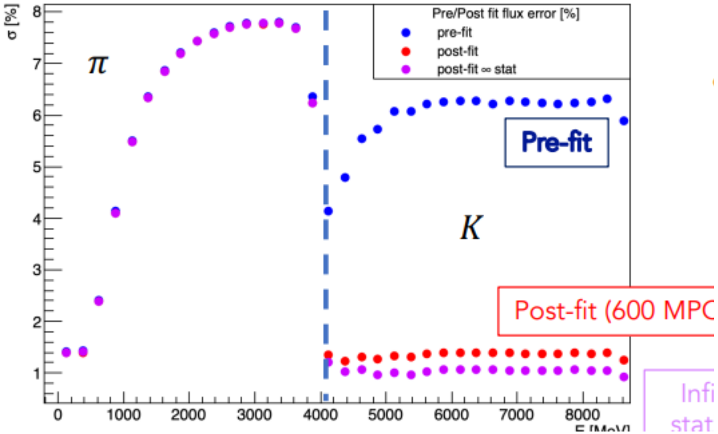
$K_{\mu 2}$ muons -> constrain ν_μ

Tagger impact point

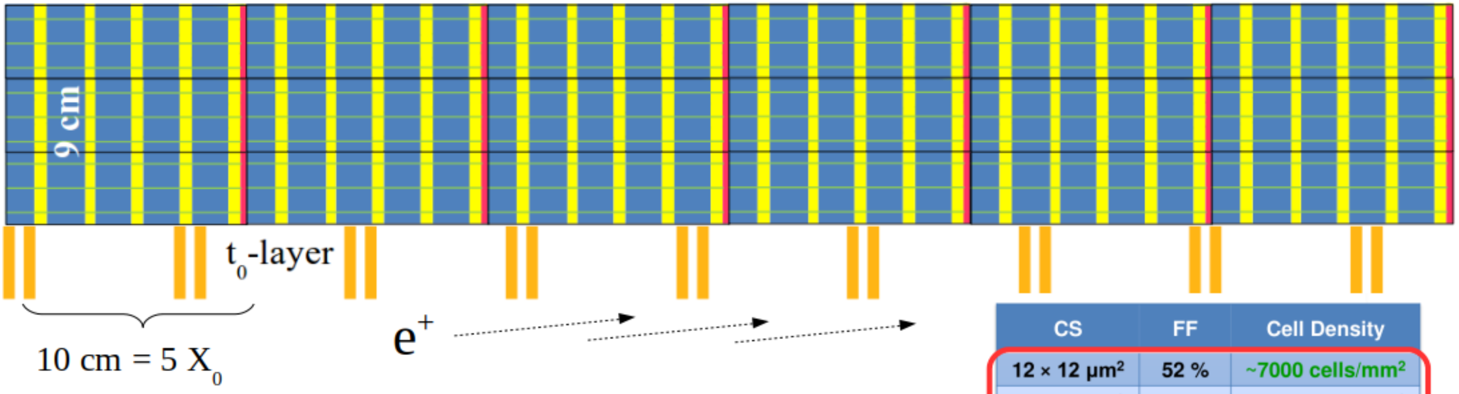


Efficiency ~half geometrical





The tagger: **shashlik** calorimeter **SiPMs**



UCM: ultra compact module.

5 x (ABSORBER + SCINTI) → **~4 X_0**

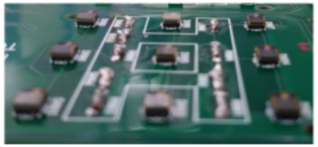
Fe-15mm + EJ200

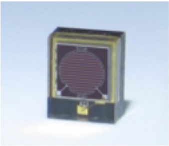
TiO2 painting

WLS: Kuraray Y11 double clad, 1mm diameter

9 SiPMs summed (AC coupled, 47 pF)

SiPMs: **FBK HD-RGB, 1mm^2**

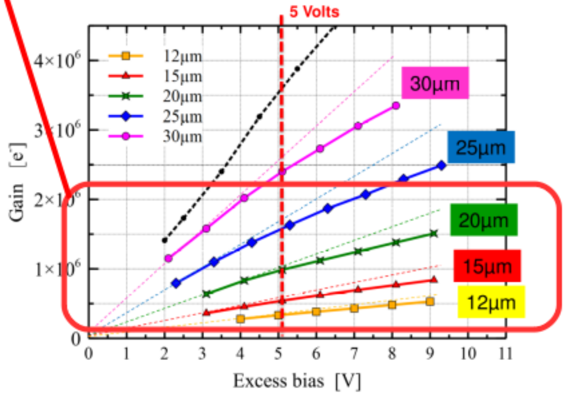




Required:
Fast ~10ns ← avoid pileup
Rad.hard (10^{12} n/cm^2)

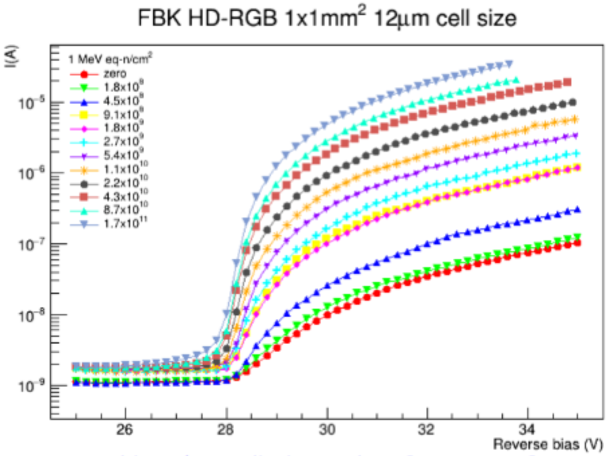
CS	FF	Cell Density
12 × 12 µm²	52 %	~7000 cells/mm²
15 × 15 µm²	62 %	~4444 cells/mm²
20 × 20 µm²	66 %	2500 cells/mm²
25 × 25 µm²	72 %	1600 cells/mm²
30 × 30 µm²	77 %	~1111 cells/mm²

Tested



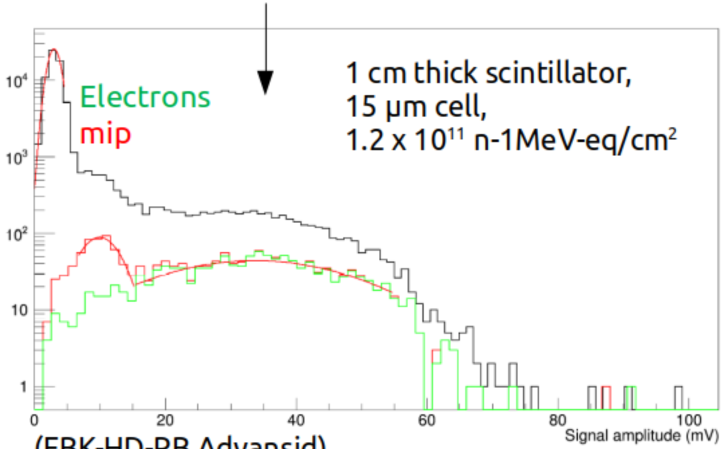
SiPM irradiation @ LNL

Dark current vs bias at increasing n fluences



F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS T9 in Oct 2017

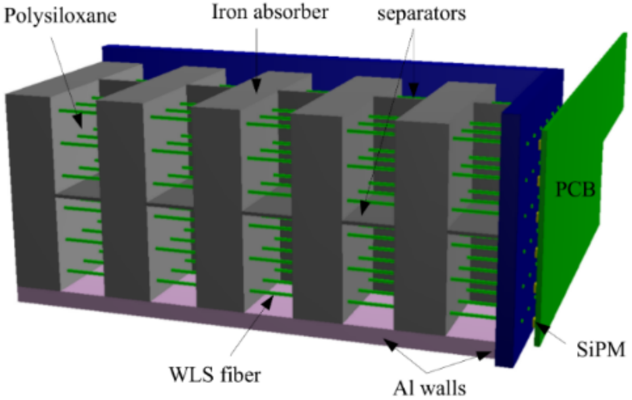


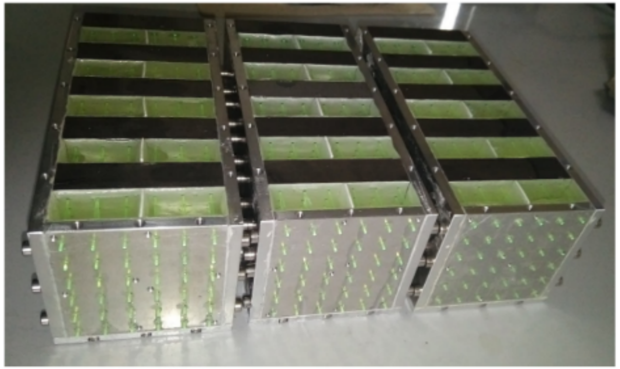
(FBK-HD-RB Advansid)

- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used from **channel-to-channel intercalibration** even after maximum irradiation.

The tagger: polysiloxane prototypes

Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)
A **13X_0 shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)





15 mm thick scintillators
to compensate reduced light yields