The ENUBET Neutrino Cross Section Experiment

11th Symposium on Large TPCs for low-energy rare event detection
11–13 Dec 2023

Giulia Brunetti – Milano-Bicocca University
on behalf of the ENUBET Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN Istituto Nazionale di Fisica Nucleare

ENUBET

Enhanced NeUtrino BEams from Kaon tagging

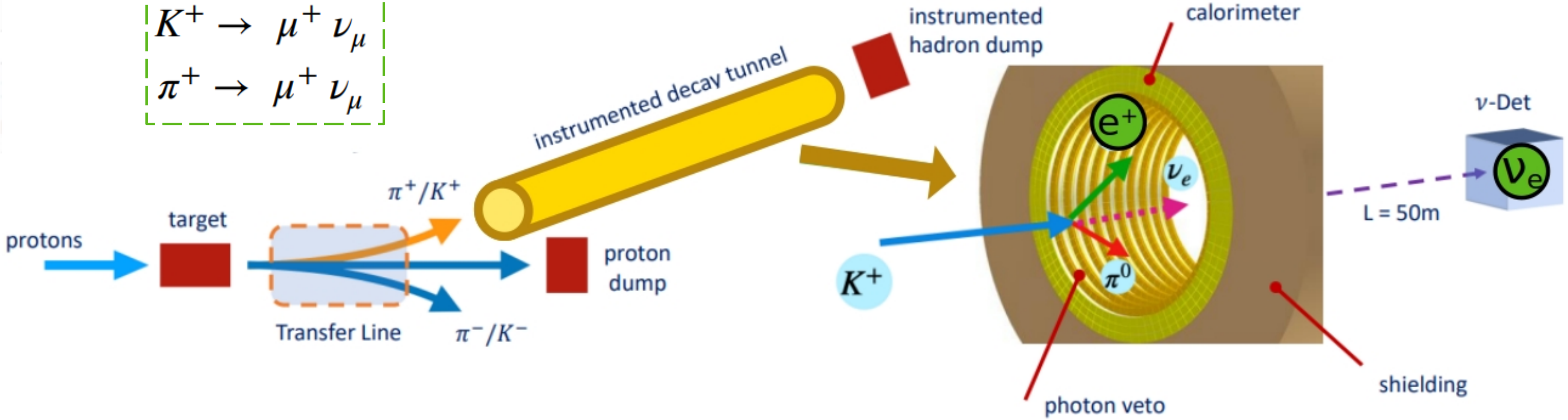
- **What?** ENUBET is a project for the first MONITORED Neutrino Beam = facility that offers control of the ν_e and ν_μ neutrino flux and flavor at 1% level
- **Why?** Long-baseline neutrino oscillation experiments have entered the precision-era → need high-precision cross sections: knowledge on the flux is the main systematics
- **How?** A neutrino beam where the production of neutrino-associated leptons is monitored at single particle level in an instrumented decay region
  - Conventional narrow-band beam with an instrumented decay tunnel to measure neutrino flux directly, by passing other flux related systematics:
    - Hadron production
    - Beamline geometry and focussing
    - Protons on target (PoT)

- Initial Proposal: A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015)
- ERC Project (2016-2022)
  - Aim: Measure positrons from K_{e3} decay (in tunnel) to determine the ν_e flux

$$K^+ \rightarrow \pi^0 \, e^+ \, \nu_e$$

- CERN Neutrino Platform: NP06/ENUBET (2022-present), part of the Physics Beyond Colliders initiative
  - Aim: Extend measurement to anti-muons from $K_{\mu 2}$ (in tunnel) and $\pi_{\mu\nu}$ (in dump) decays to determine the ν_μ flux

$$K^+ \rightarrow \mu^+ \, \nu_\mu$$
$$\pi^+ \rightarrow \mu^+ \, \nu_\mu$$

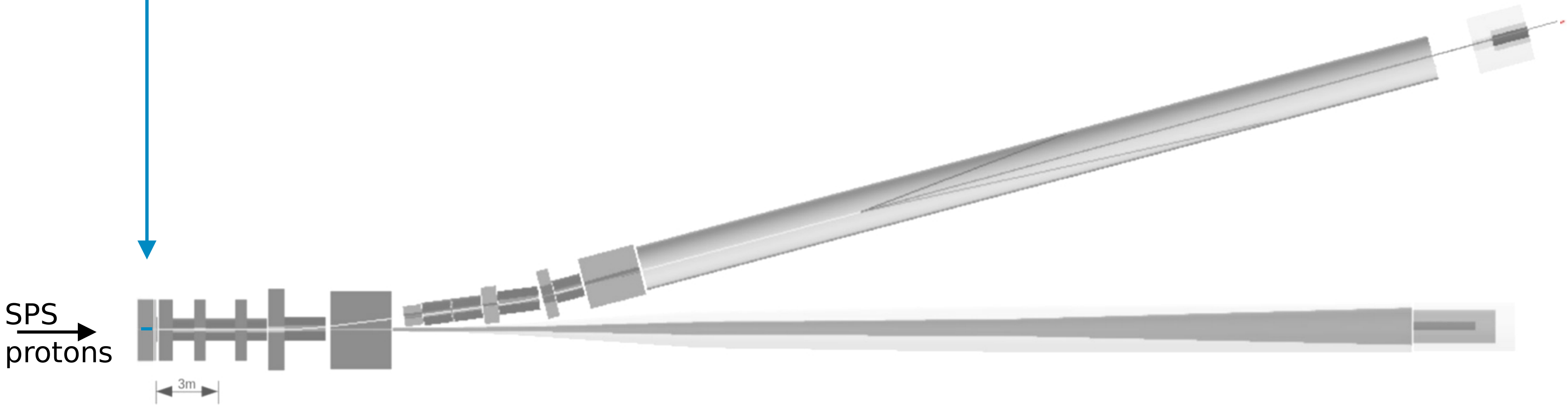


The Beamline

Eur. Phys. J. C (2023) 83:964

Target

- 70 cm long, 3 cm radius graphite
- Tungsten foil downstream to suppress positrons



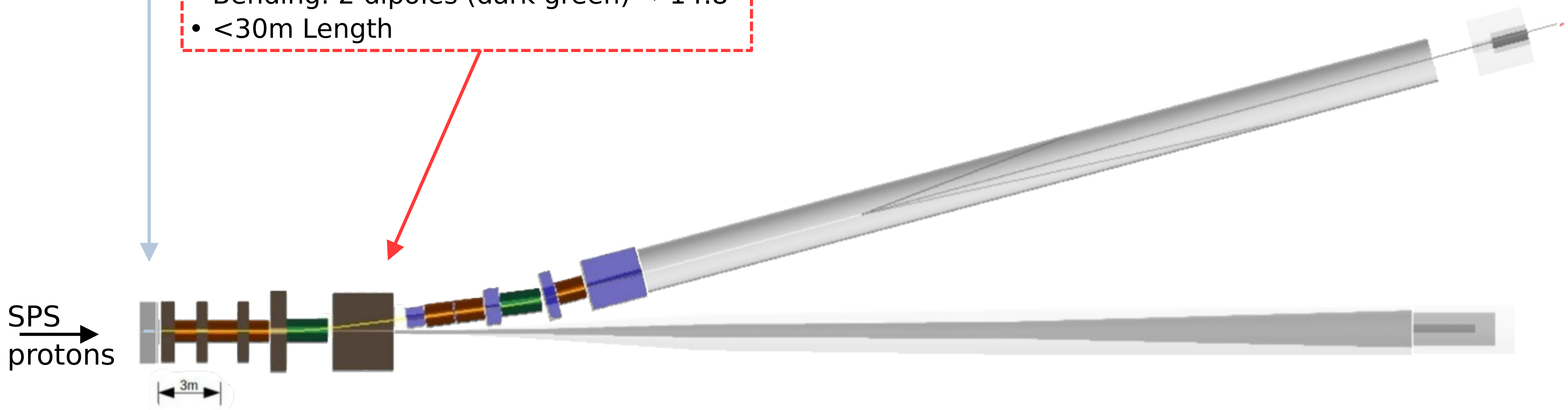
Transfer Line

- Optimized for the DUNE energy range: 5% momentum bite centered at 8.5 GeV/c, optimized with TRANSPORT
- G4Beamline used for particle transport and interactions
- FLUKA used for irradiation studies
- Length optimised to reduce early hadron decays

Target

- 70 cm long, 3 cm radius graphite
- Tungsten foil downstream to suppress positrons

- Focussing: quadrupoles (orange)
- Bending: 2 dipoles (dark green) → 14.8°
- <30m Length



Transfer Line

- Optimized for the DUNE energy range: 5% momentum bite centered at 8.5 GeV/c, optimized with TRANSPORT
- G4Beamline used for particle transport and interactions
- FLUKA used for irradiation studies
- Length optimised to reduce early hadron decays

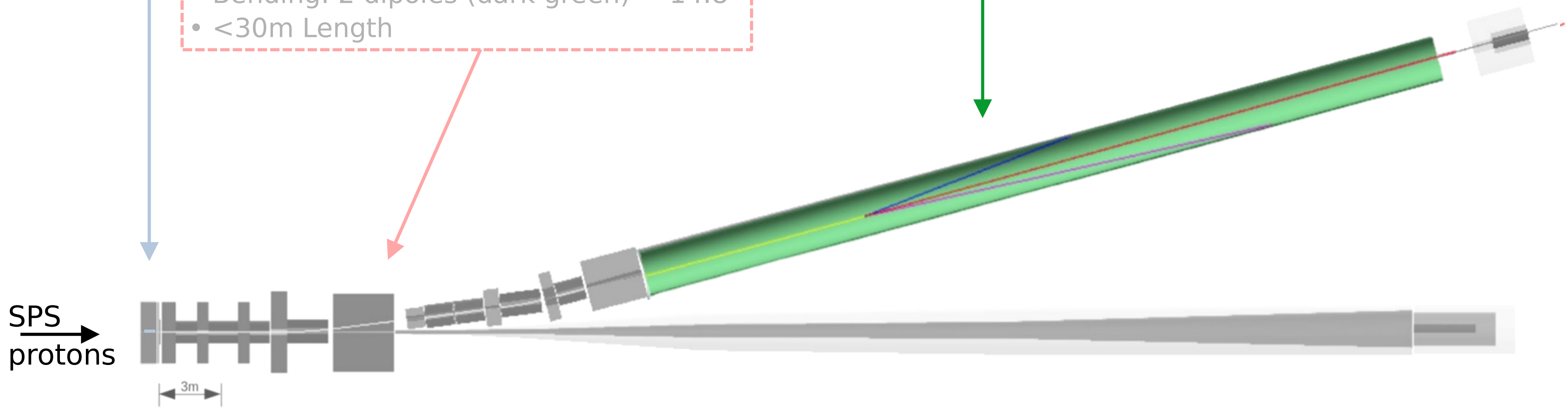
Decay Tunnel/ Tagger

- Length tuned to maximise K_{e3} decays
- 40m long, 1m radius

Target

- 70 cm long, 3 cm radius graphite
- Tungsten foil downstream to suppress positrons

- Focussing: quadrupoles (orange)
- Bending: 2 dipoles (dark green) → 14.8°
- <30m Length



Transfer Line

- Optimized for the DUNE energy range: 5% momentum bite centered at 8.5 GeV/c, optimized with TRANSPORT
- G4Beamline used for particle transport and interactions
- FLUKA used for irradiation studies
- Length optimised to reduce early hadron decays

Decay Tunnel/ Tagger

- Length tuned to maximise K_{e3} decays
- 40m long, 1m radius

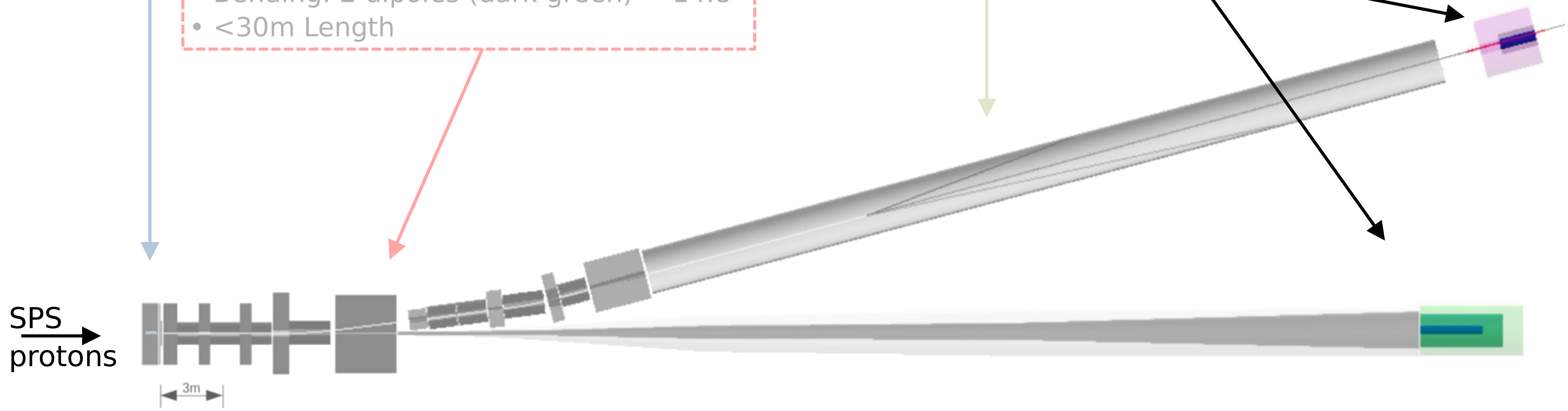
Target

- 70 cm long, 3 cm radius graphite
- Tungsten foil downstream to suppress positrons

Dumps

- 2 dumps: proton and hadron
- 3 cylindircal layers, optimised to avoid backscattering flux in tunnel

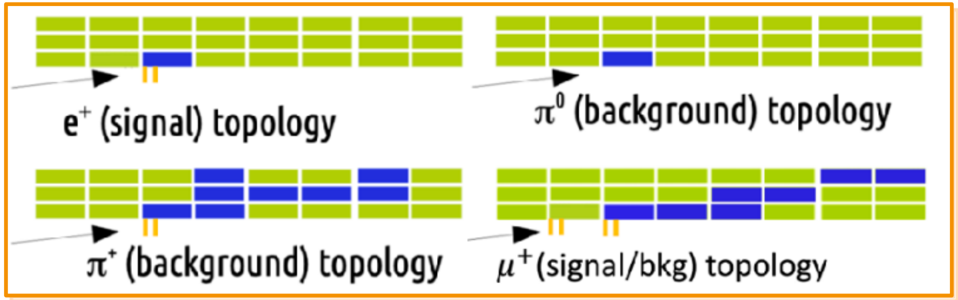
- Focussing: quadrupoles (orange)
- Bending: 2 dipoles (dark green) → 14.8°
- <30m Length

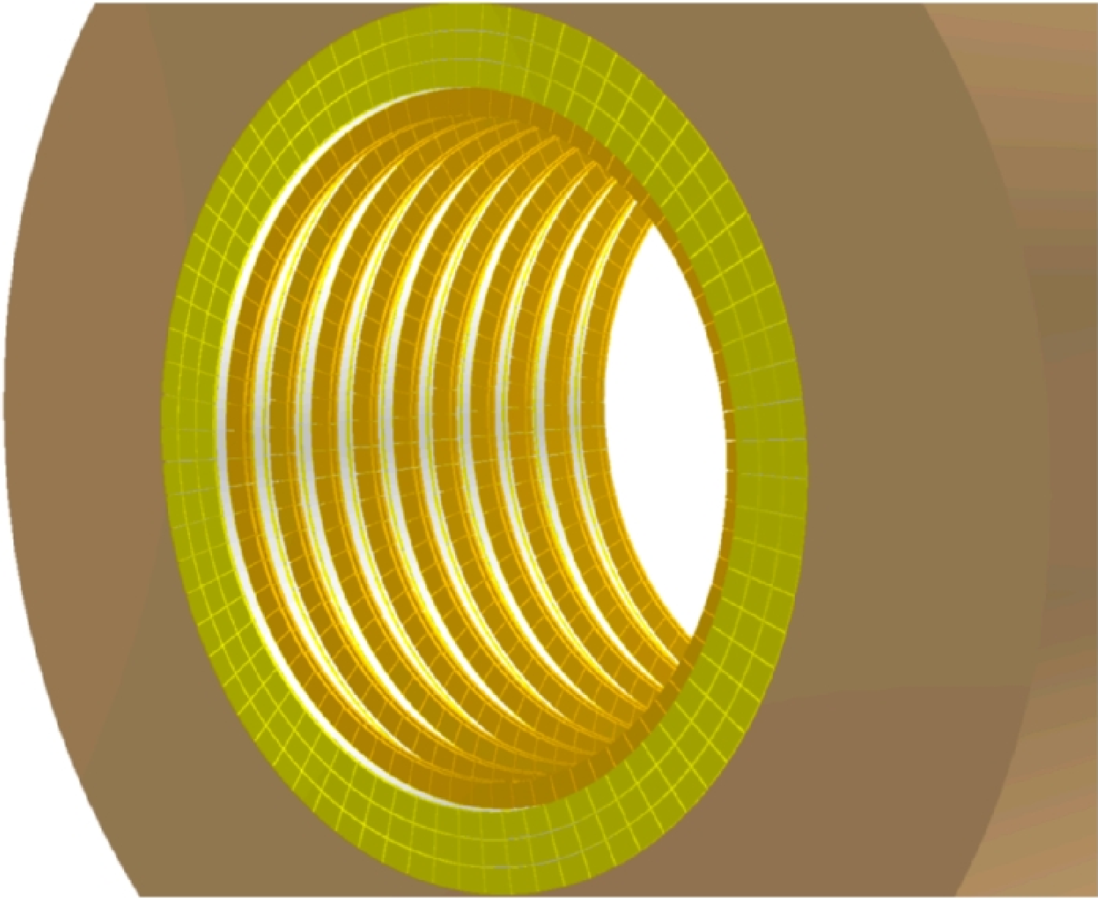


The Tagger

A decay tunnel instrumented with a calorimeter to **identify the leptons in the tunnel at single particle level**

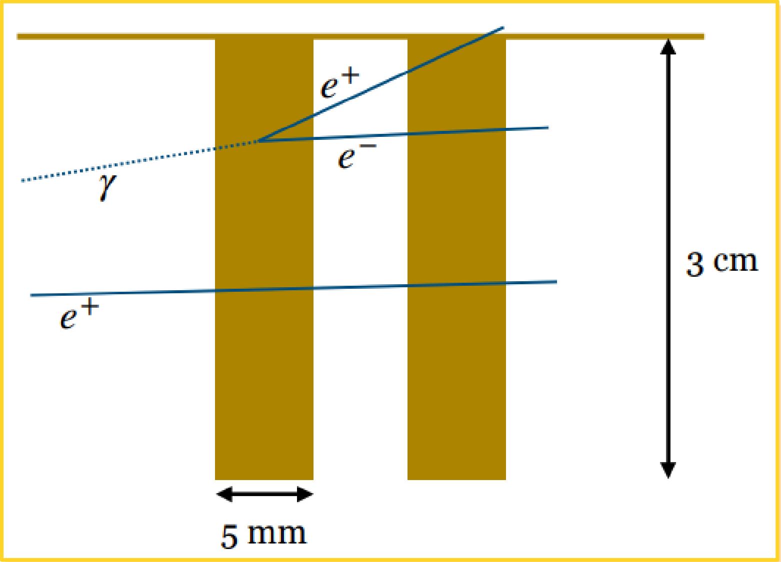
PID based on the pattern of energy deposit in the calorimeter modules:

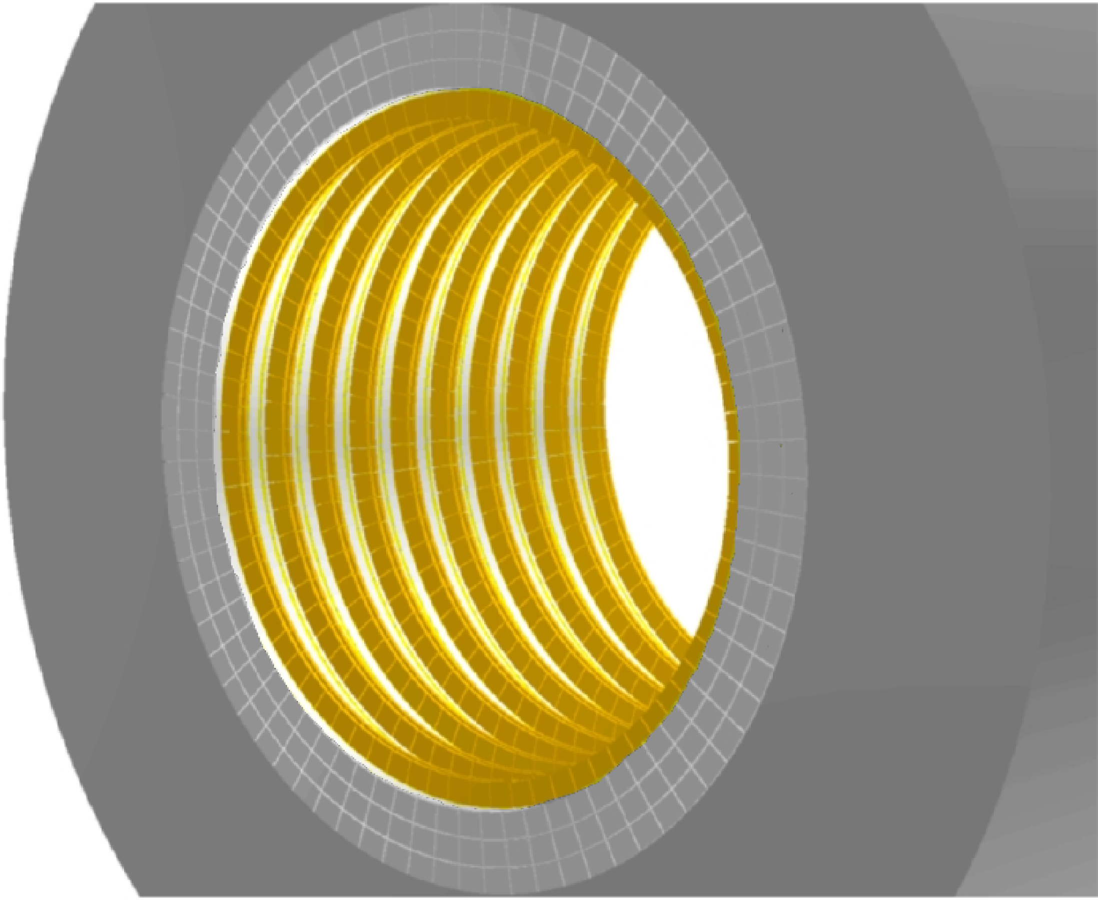




The Photon-Veto

- π^0 rejection and timing, time resolution of ~400 ps
- plastic scintillator tiles arranged in doublets forming inner rings



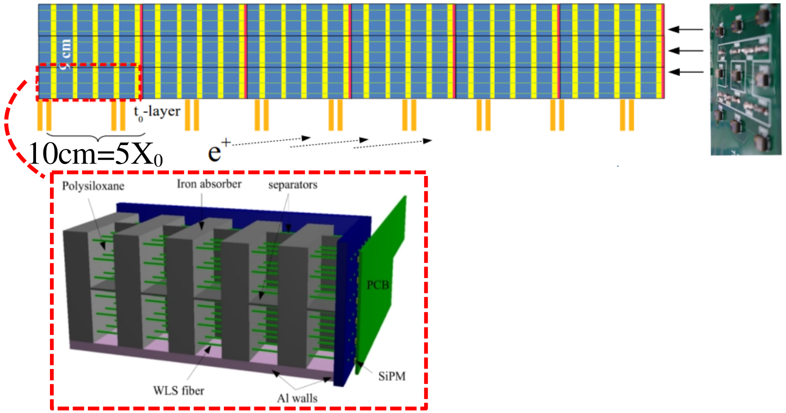


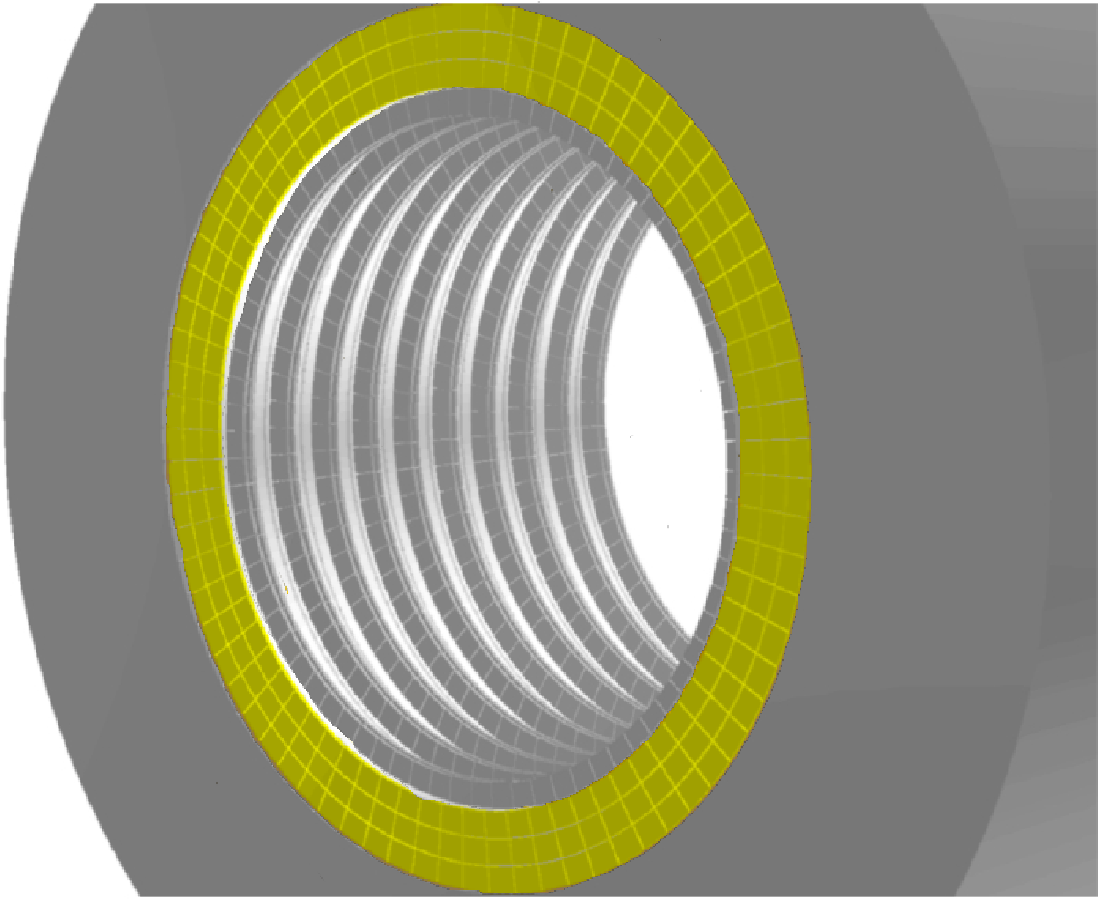
The Photon-Veto

- π^0 rejection and timing, time resolution of ~400 ps
- plastic scintillator tiles arranged in doublets forming inner rings

The Calorimeter

- e/π/μ separation
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers
- 3 radial layers of lateral readout calorimetric modules (LCMs) longitudinal segmentation
- WLS-fibers/SiPMs for light collection/readout





The Photon-Veto

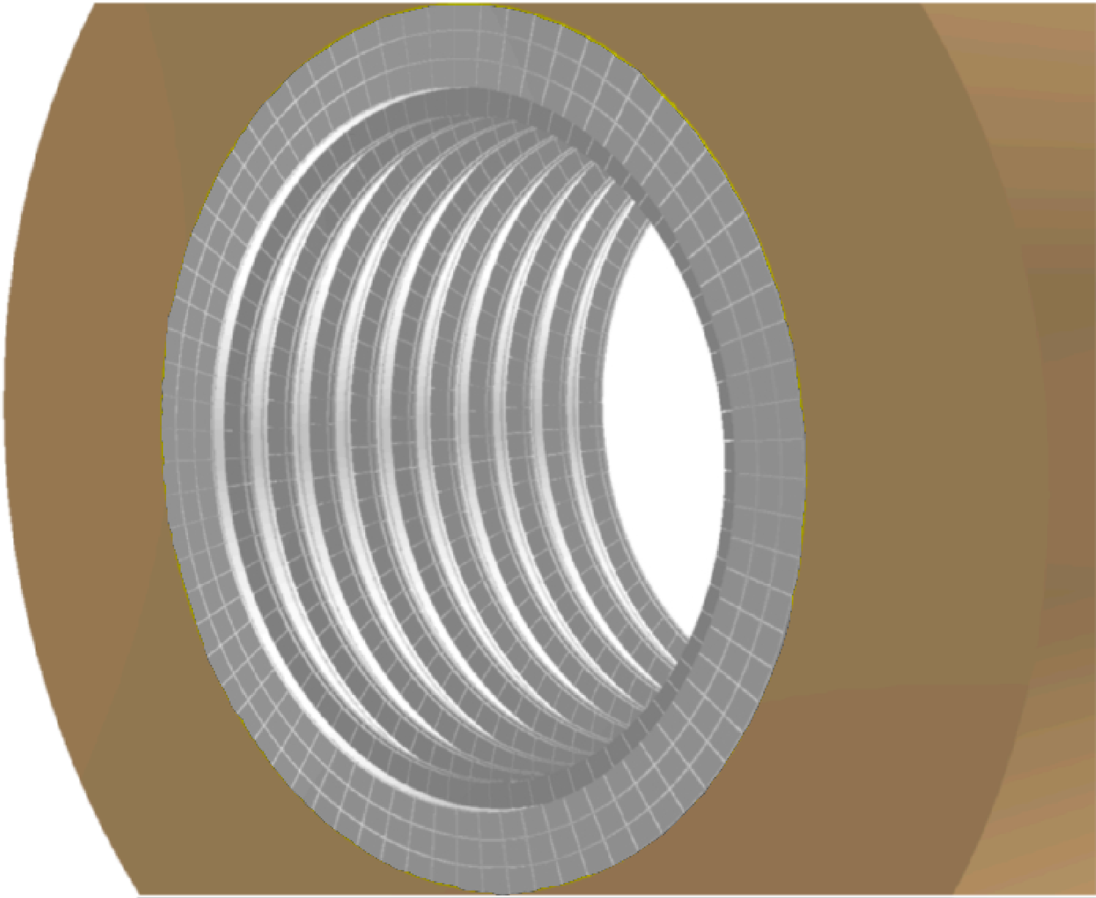
- π^0 rejection and timing, time resolution of ~400 ps
- plastic scintillator tiles arranged in doublets forming inner rings

The Calorimeter

- e/π/μ separation
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers
- 3 radial layers of lateral readout calorimetric modules (LCMs) longitudinal segmentation
- WLS-fibers/SiPMs for light collection/readout

The Shielding

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



The Demonstrator

Years of successful R&D! Time Line:

2016-2018 @ CERN:

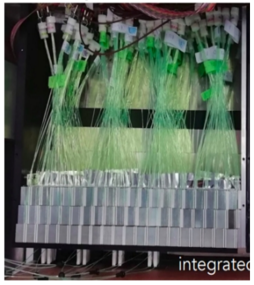
Test of the shashlik prototype: Tested response to MIP, e and π

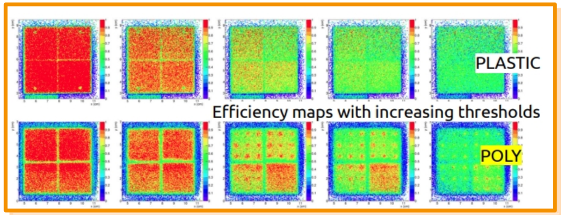
Ballerini et al., JINST 13 (2018) P01028

Test of the lateral readout prototype: Electron energy resolution, linearity, 1mip/2mip

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

Lateral WLS-fibers for light collection





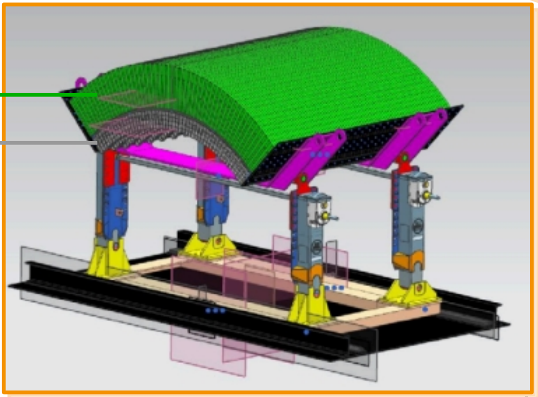
Test with polysiloxane scintillator

F. Acerbi et al., Nucl. Instrum. Methods Phys. Res. A, 956 (2020)

2021 ENUBINO: pre-demonstrator w/ 3 LCM tested @ CERN for uniformity and efficiency

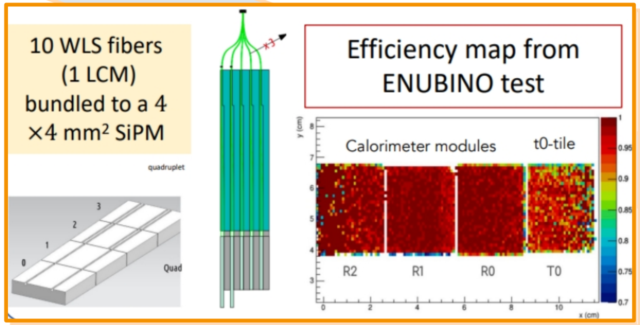
Shielding

Calorimeter
+
Photon veto



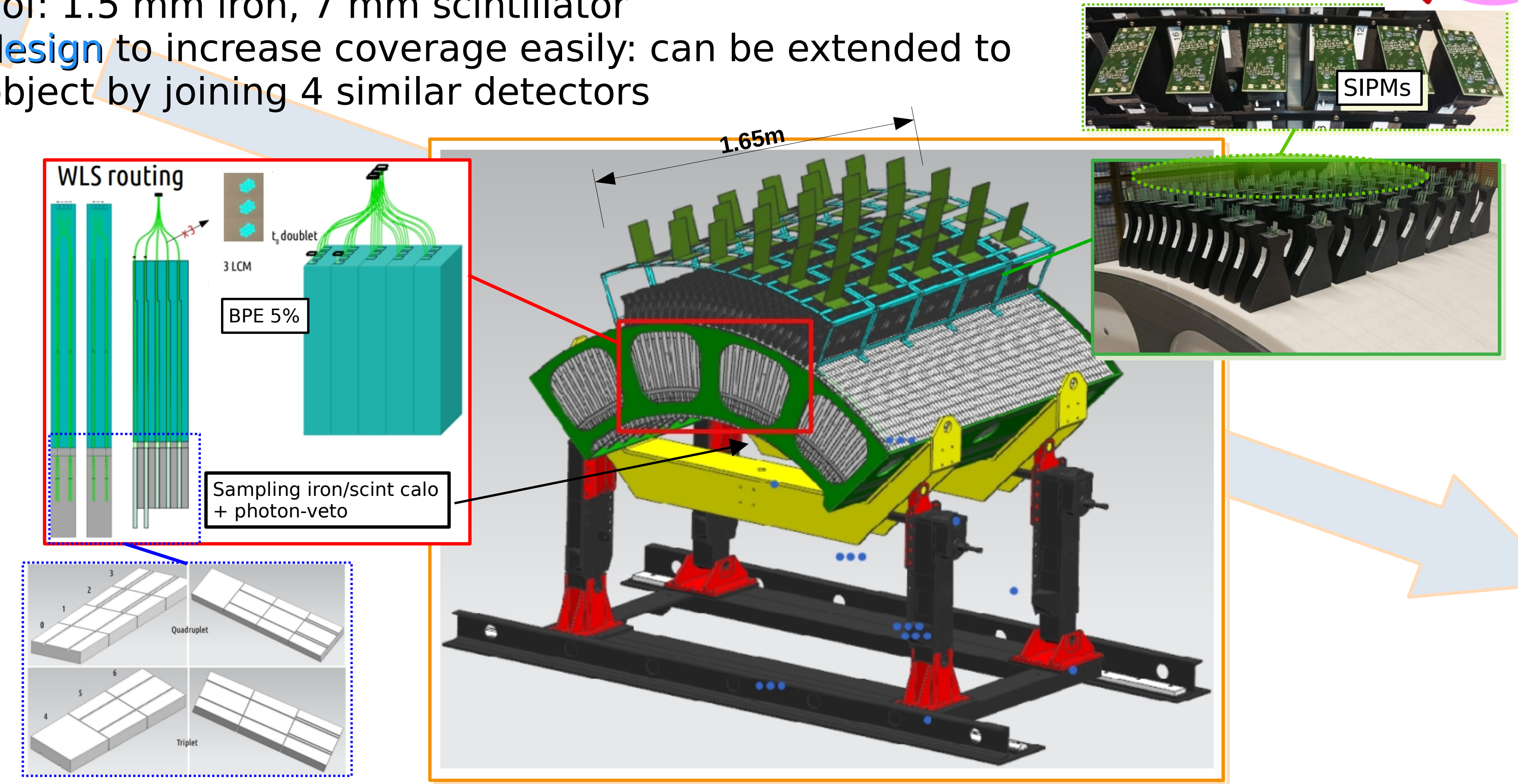
10 WLS fibers (1 LCM) bundled to a 4 ×4 mm² SiPM

Efficiency map from ENUBINO test



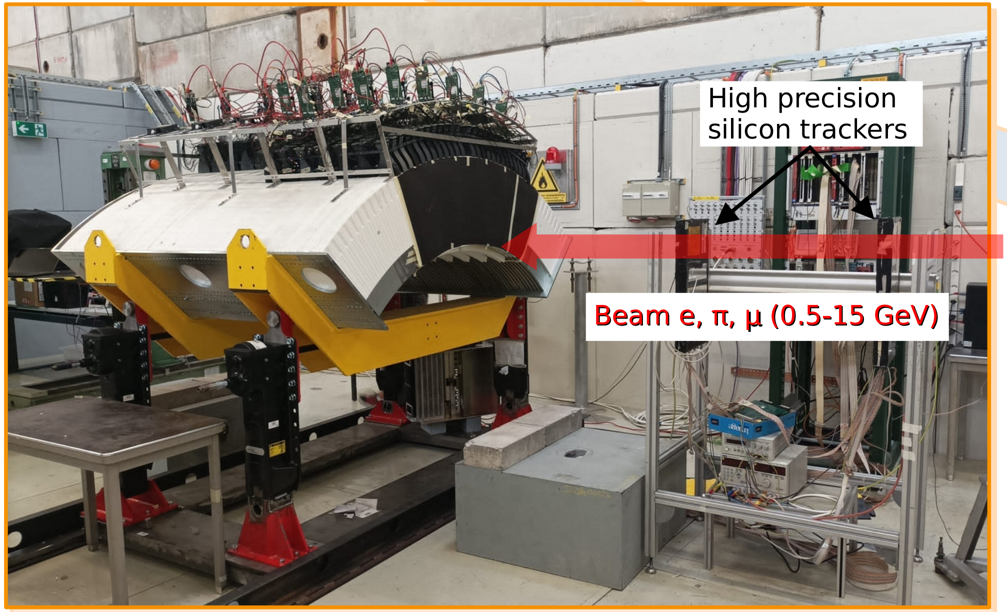
October 2022: Part of the decay tunnel was built and tested @ CERN

- 1.65 m long, 3.5 ton, 90˚ coverage
- 75 layers of: 1.5 mm iron, 7 mm scintillator
- Modular design to increase coverage easily: can be extended to a full 2π object by joining 4 similar detectors

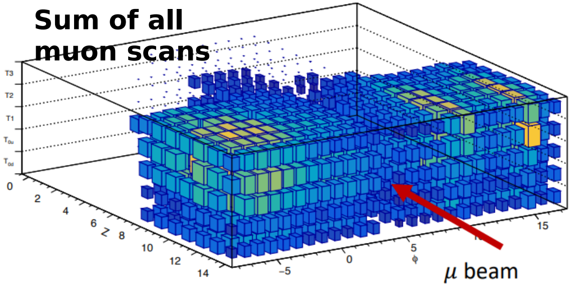


August 2023: Extended configuration (>x3 !) tested @ CERN

- (R,φ,Z)=3x25x7 LCMs
- 1275 channels in total

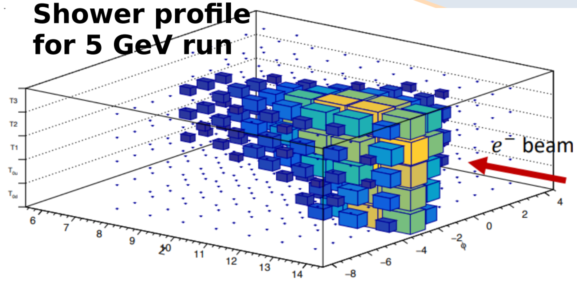


Calibration runs with 10 GeV muons



- All channels covered with lots of statistics
- Allow good equalisation of channels

Energy scans with electron beams

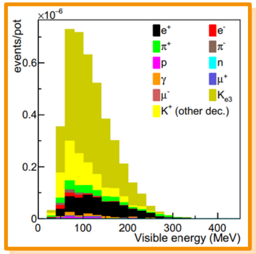


- Scans with different energies
- Performed for linearity and resolution studies

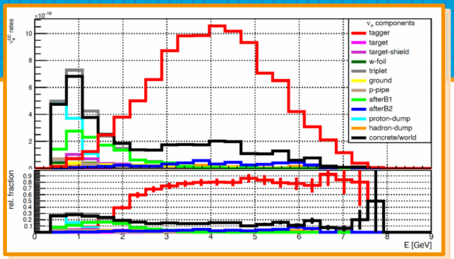
2022 & 2023 data to be published → Stay Tuned!

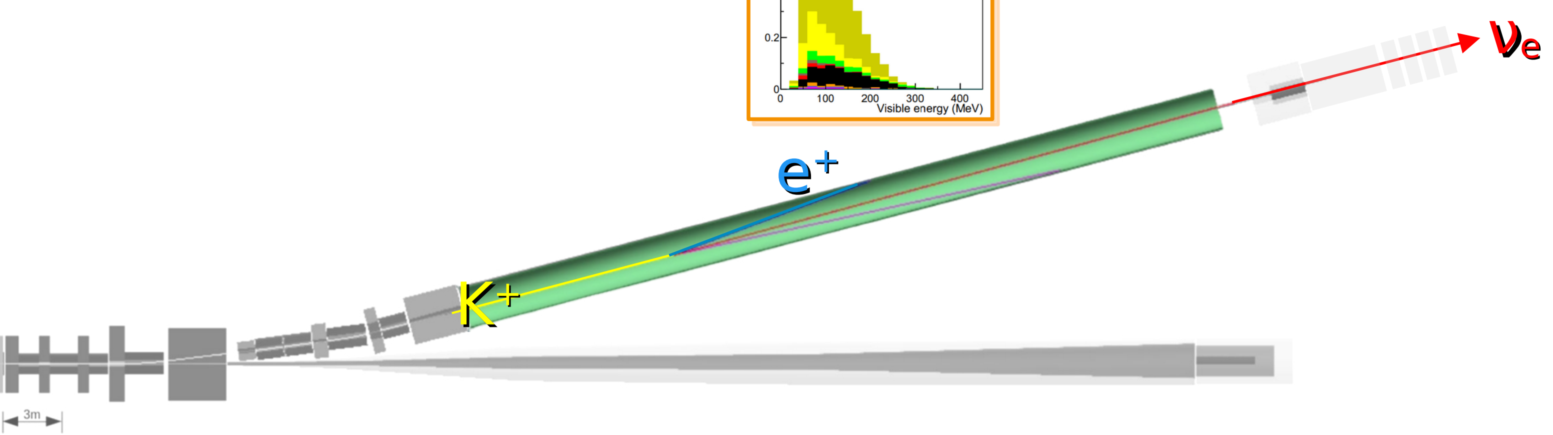
Lepton Monitoring

- Tagger: leptons from K
  - e^+ from K_{e3}

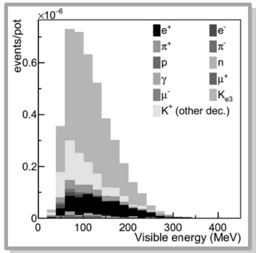


Constrain ν_e

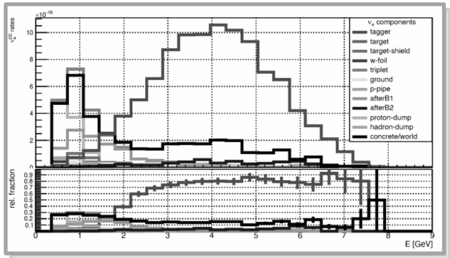


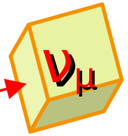


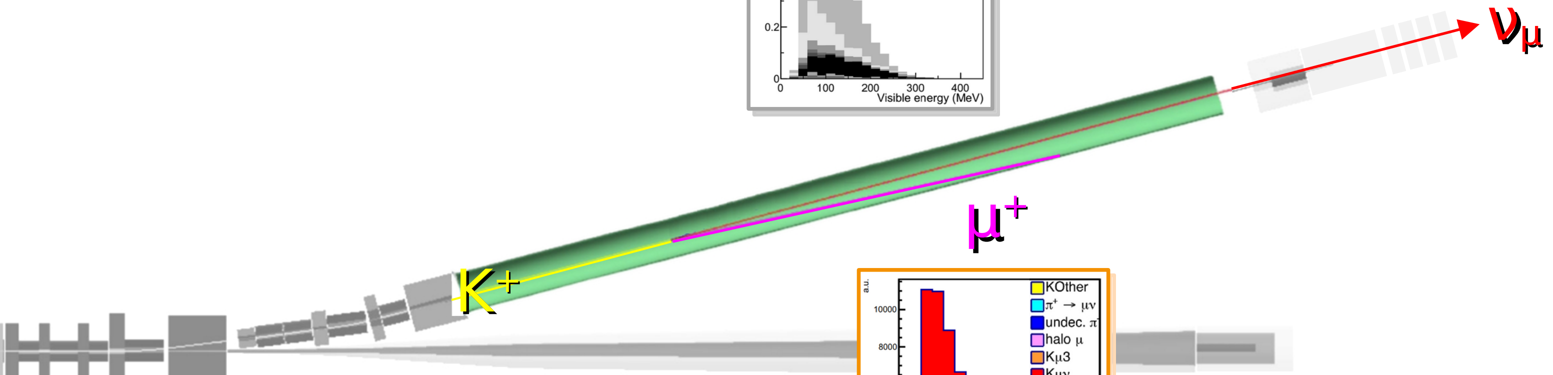
- Tagger: leptons from K
  - e^+ from K_{e3}
  - μ^+ from $K_{\mu 2}$

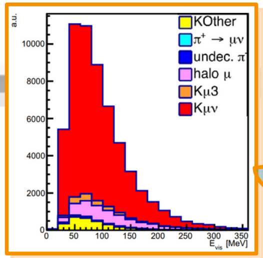


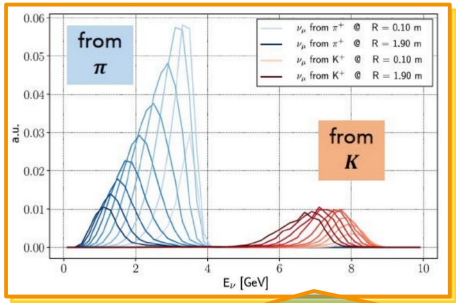
Constrain ν_e





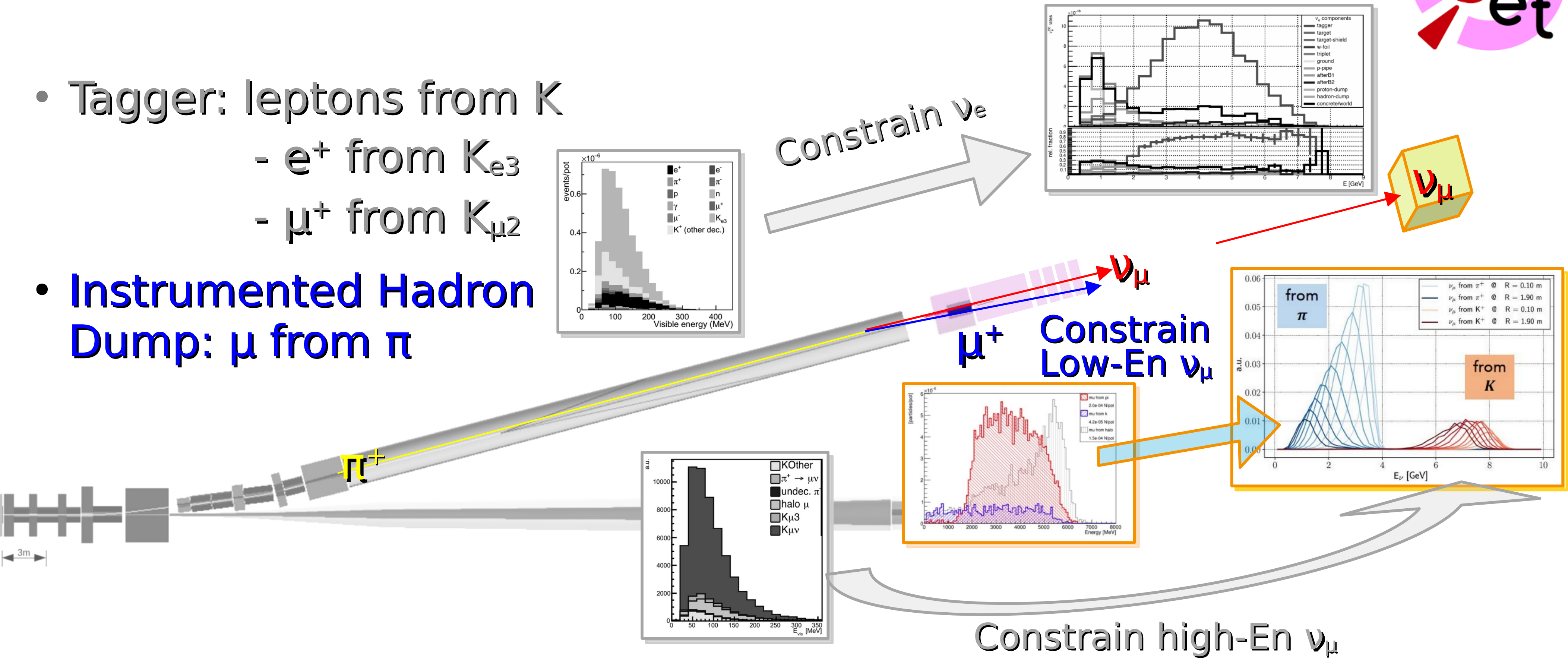






Constrain high-En ν_μ

- Tagger: leptons from K
  - e^+ from K_{e3}
  - μ^+ from $K_{\mu 2}$
- Instrumented Hadron Dump: μ from π

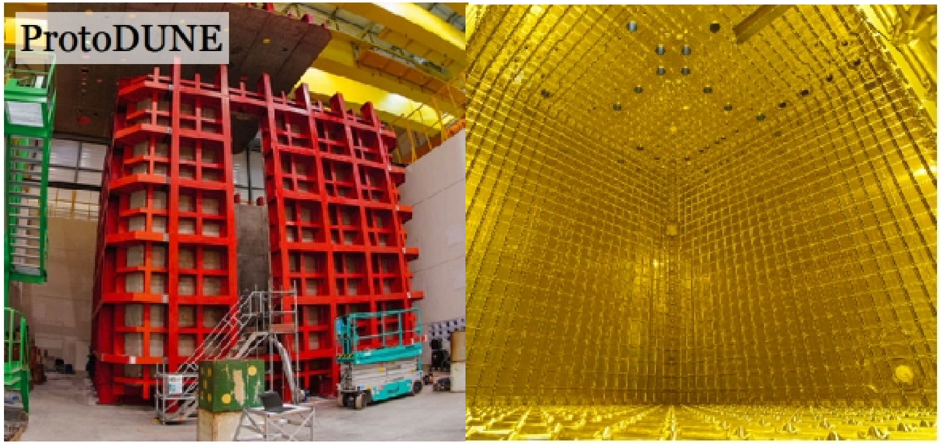


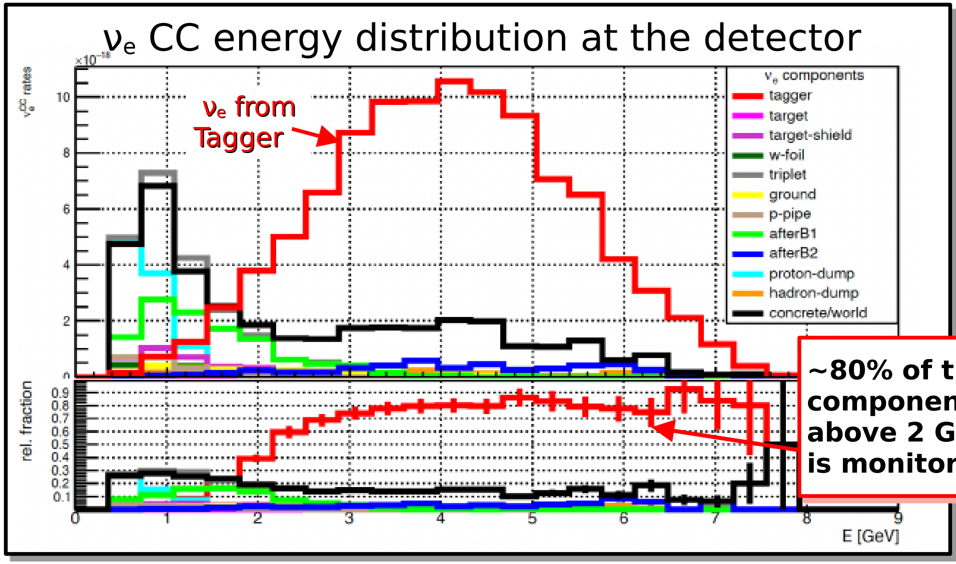
The ν_e in the Neutrino Detector

10^4 ν_e events in ~2.3 years

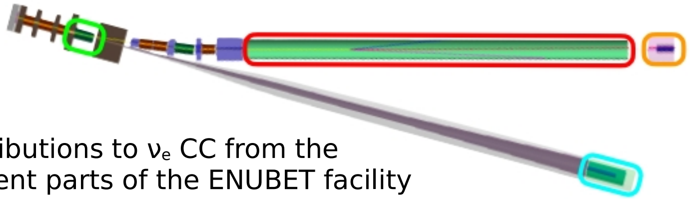
Assuming:

- CERN SPS with 4.5 10^{19} POT/year
- 500 tonne detector @ 50 m from tunnel end → i.e. ProtoDUNE





~80% of the component above 2 GeV is monitored



Contributions to ν_e CC from the different parts of the ENUBET facility

The ν_μ in the Neutrino Detector

For ν_μ CC events we can measure the neutrino energy “a priori“

Narrow-band Off-axis Technique

Narrow momentum beam O(5-10%) →

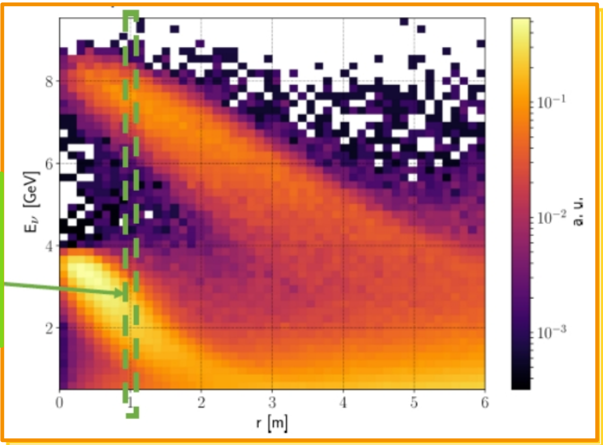
E_ν = neutrino energy

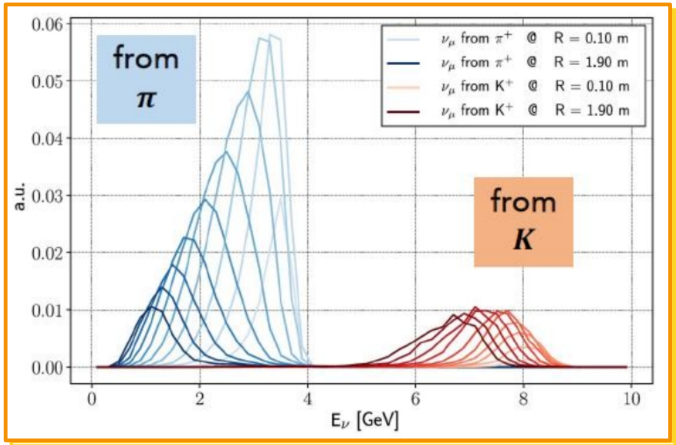
R = radial distance of interaction vertex from beam axis

Strongly Correlated

→ Precise determination of E_ν, no need to rely on final state particles

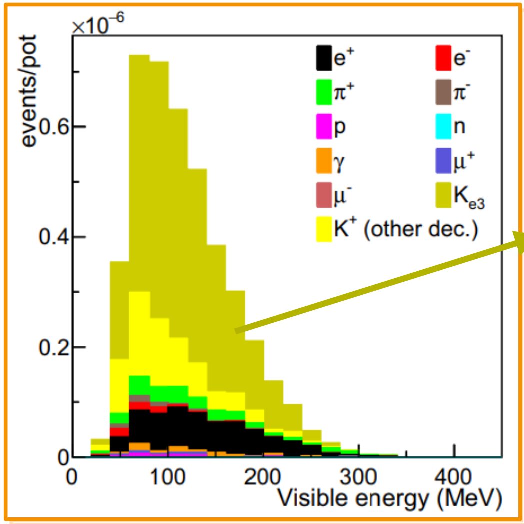
Select ν_μ with given energy with a cut on R





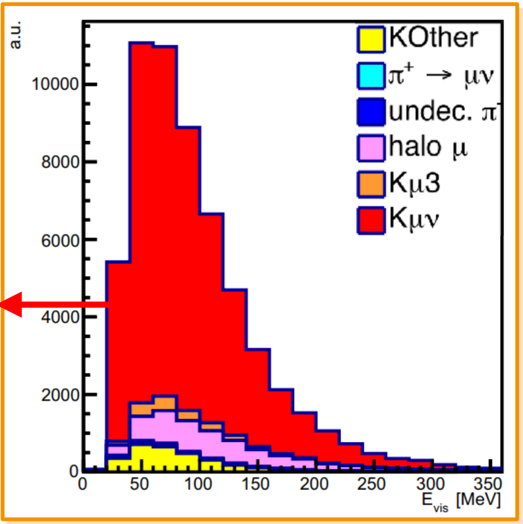
- π/K populations well separated
- 10-25% E_ν resolution from π in the DUNE energy range
- On-going studies for a multi-momentum beamline to cover Hyper-K ROI

Lepton Reconstruction



e^+ from K_{e3} → Constrain ν_e

- K^+ ~5-10% of beam
- K_{e3} BR ~5%
- S/N = 2
- Eff = 22% (half geometrical)

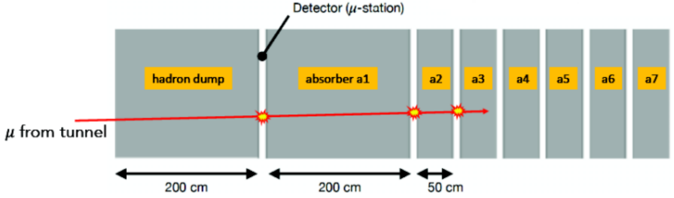


μ from $K_{\mu 2}$ → Constrain ν_μ

- S/N = 6
- Eff = 34% (half geometrical)

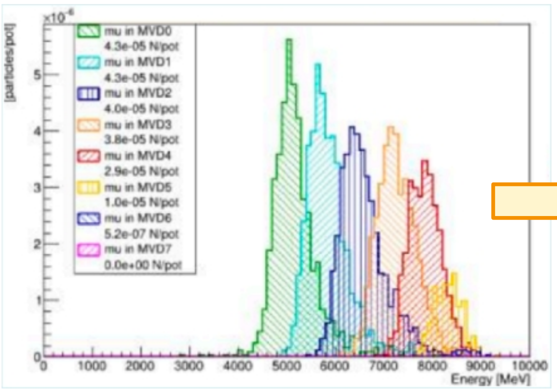
- **GEANT4 detector simulation validated** with prototype tests @ CERN 2016-2018
  - Pile-up effects are included (waveform treatment in progress)
- **Event building and PID algorithms available,** developed 2016 → 2020:
  - **e^+ and μ from K^+** selected by searching for energy clusters
  - PID completed with a NN trained on discriminating variables: En. deposition, topology, photon veto etc.

- **Forward Leptons:** Measuring muons from pion decays to constrain low-energy ν_μ
  - Low angle muons out of tagger acceptance → **Muon stations** post hadron-dump

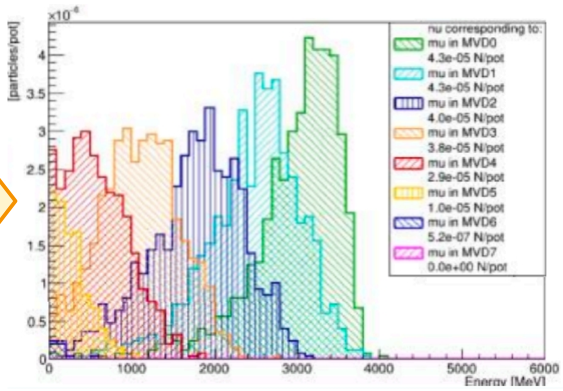


  - Upstream station constraints the detectors:
    - Muon rate (~2 MHz/cm^2)
    - Radiation hardness (~10^{12} $MeV\text{-}n_{eq}/cm^2$)
- Exploit the Correlation between traversed stations and neutrino energy:

Muon energy @ different μ-station



Neutrino energy @ different μ-station

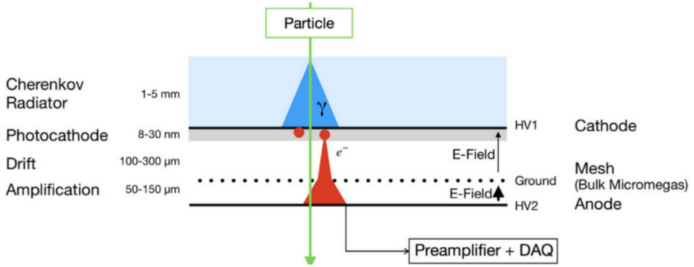


Need to cope with high flux + need fast timing →

PIMENT

PICOSEC **M**icromegas Detector for **EN**UBE**T**

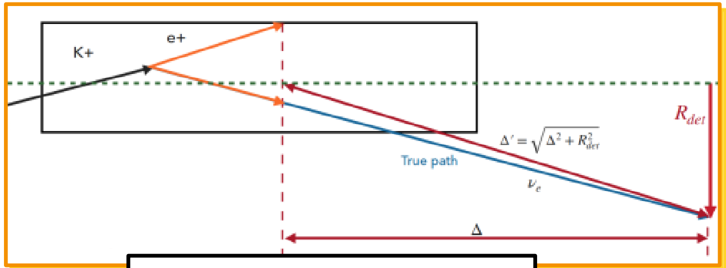
Fast Micromegas detectors employing Cherenkov radiators + thin drift gap with sub-25 ps precision



cea irfu université PARIS-SACLAY PICOSEC Micromegas

Bonus, beyond the monitored beam: Time-tagged beams

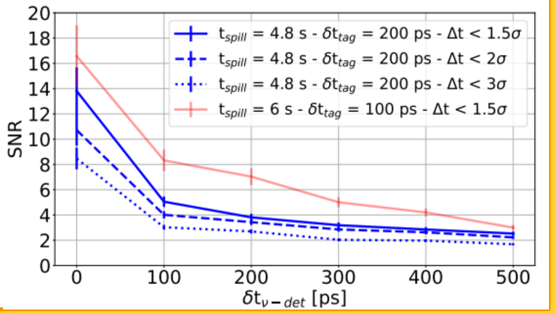
Time coincidence between e^+ and ν_e → Sub-ns sampling would allow:

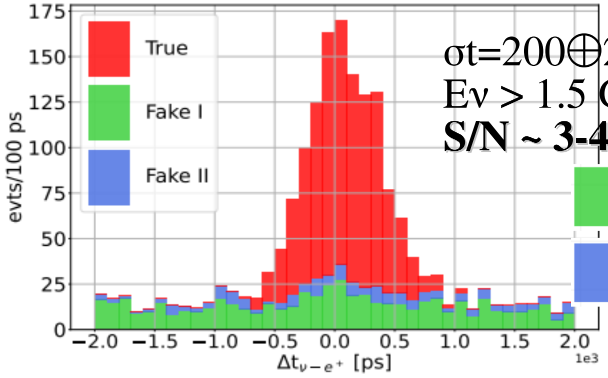


$\Delta t = t(\nu_e) - [t(e^+) + \Delta'/c]$

- Correlation event-by-event
- Determine the neutrino flavor

Signal to noise ratio of tagged ν_e-e^+ pairs **as a function of the neutrino detector time resolution**





$\sigma t = 200 \oplus 200$ ps
$E\nu > 1.5$ GeV
S/N ~ 3-4

Fake matches of e^+ candidates withe ν_e produced inside tagger

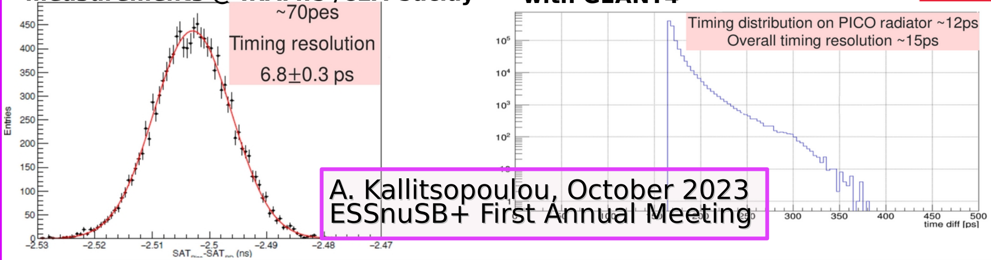
Fake matches of e^+ candidates withe ν_e produced outside tagger

- Path difference between the e^+ and ν_e → "irreducible" time spread: $\sigma_{\Delta t}$ = 74 ps
- Assuming a **time resolution δt = 200 ps** for both the ν detector and the tunnel instrumentation:

→ ENUBET t_0-layer with PICOSEC Micromegas

First Indications from laser test measurements @ IRAMIS /CEA-Saclay

First simulation studies with GEANT4

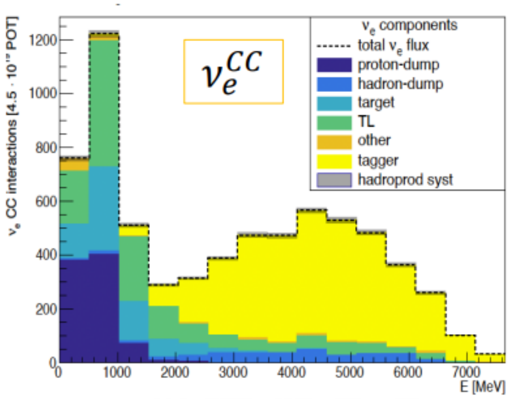


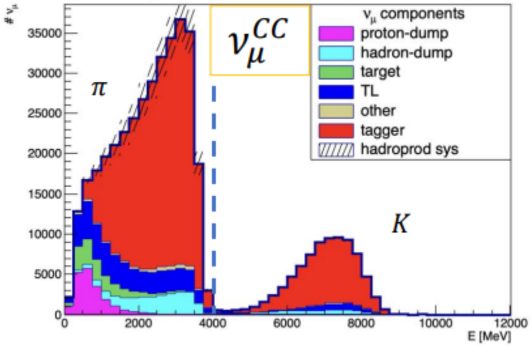
A. Kallitsopoulou, October 2023
ESSnuSB+ First Annual Meeting

The PICOSEC Micromegas Detector on ENUBET — Alexandra Kallitsopoulou
L'amphithéâtre Vulpian, Université Paris Cité — 09:30 - 09:50
Tomorrow

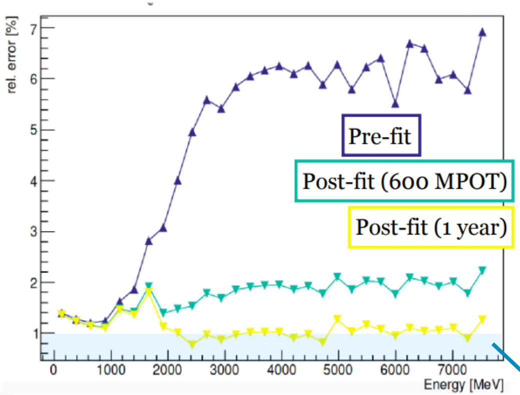
Systematics

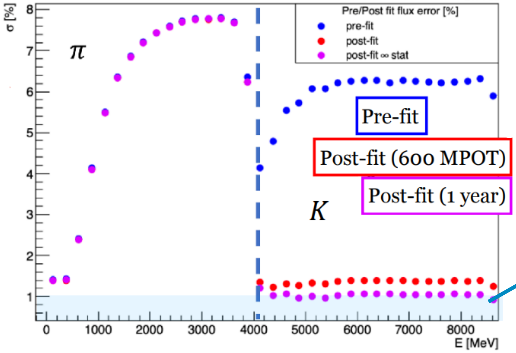
Neutrino interaction rates @ detector





Pre & Post fit relative errors on rates



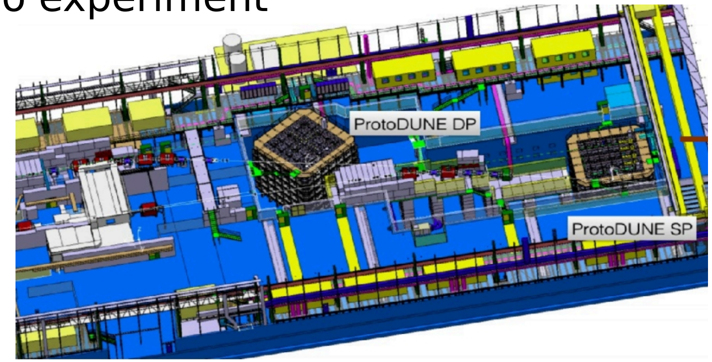


- Rates in 1 year of data taking
- Before Constraint: 6% systematics due to hadro-production uncertainties
- After Constraint: 1% systematics from fit to lepton rates measured by tagger

Achieved ENUBET goal of 1% systematics from monitoring lepton rates

Towards a real experiment

- Can we build this facility at CERN at a moderate cost without interfering with the rest of the CERN programme?
  - → Studies & discussions on-going in the framework of Physics Beyond colliders
  - → Hope to be ready for a proposal in 2025
  - → It could be done in the North Area: a short baseline neutrino experiment exploiting the existing detectors (protoDUNE)



Cheapest Option

Dedicated beamline extracted from North area to ProtoDUNE

Pros	Cons
• Maximum use of existing facilities • Slow extraction already implemented	• Potential radiation issues • Interference with other experiments

Cleanest Option

Dedicated extraction line near the North area toward ProtoDUNE

Pros	Cons
• Minor radiation issues • No interference with other experiments	• Higher Cost • Potential issue with slow extraction

Thank You!

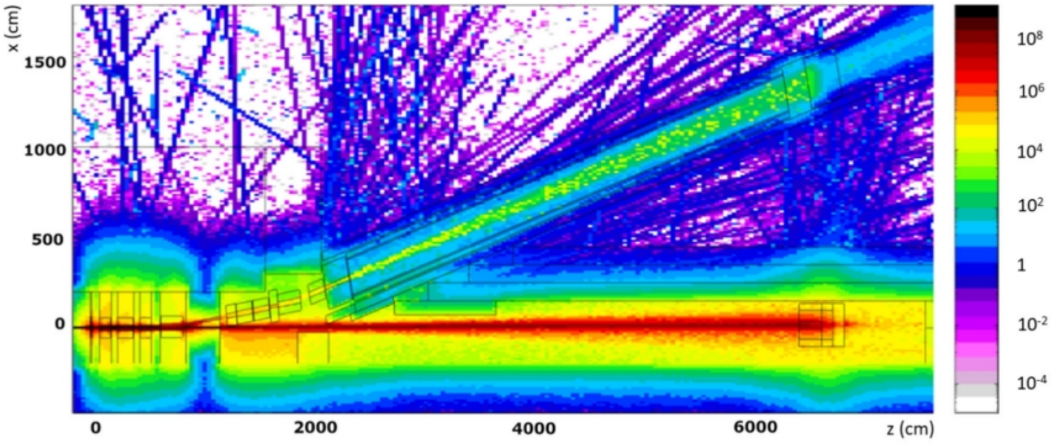
6 Countries

17 Institutions

72 Physicists

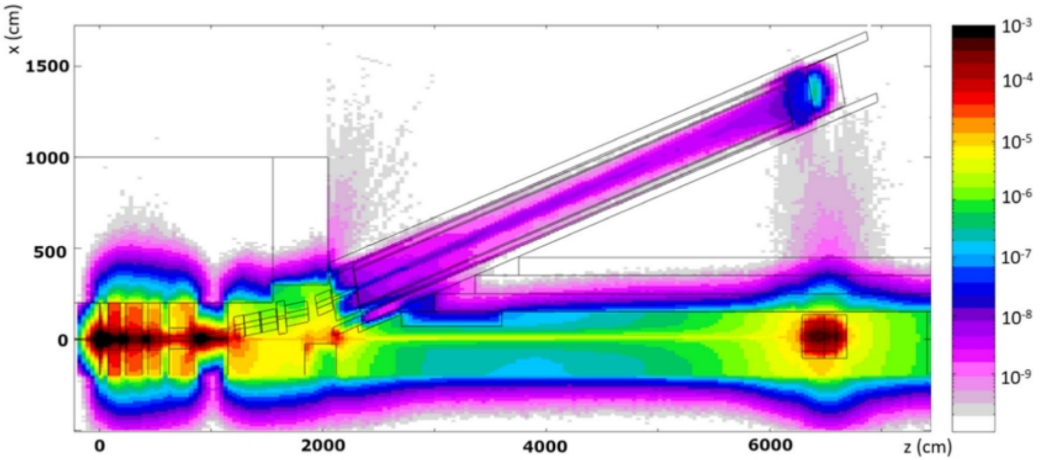
Back-Ups

Dose map in Gy for 10^{20} pot.



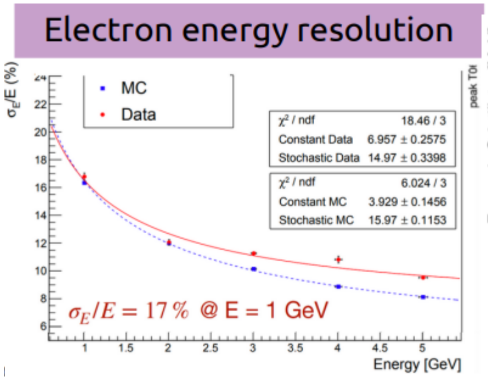
The first quadrupole in the map is located between z=200 and 500 cm

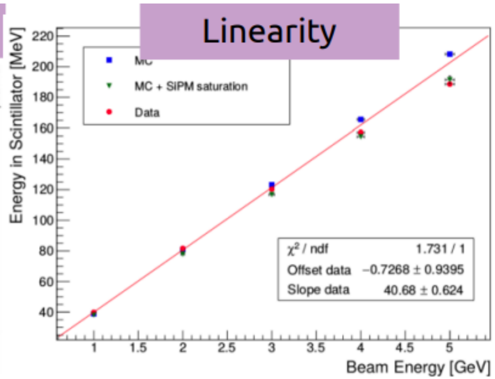
1-MeV-eq neutron fluences

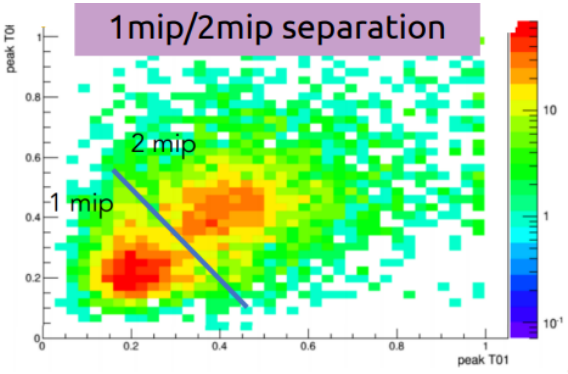


Back-Ups

Test beam(s) 2017-2018 @ CERN PS T9 beamline

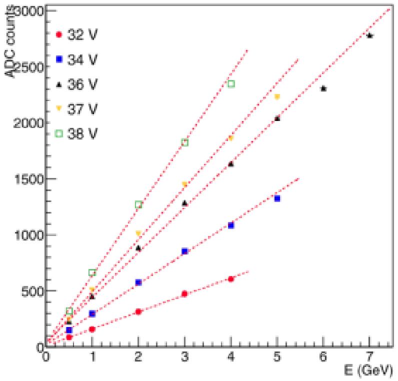


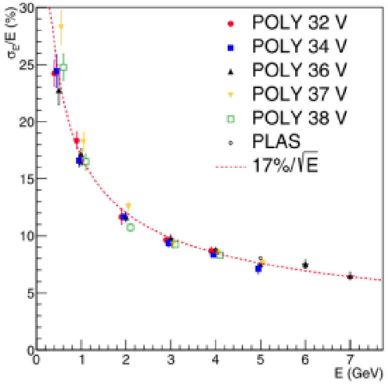




Test with polysiloxane scintillator

- 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)



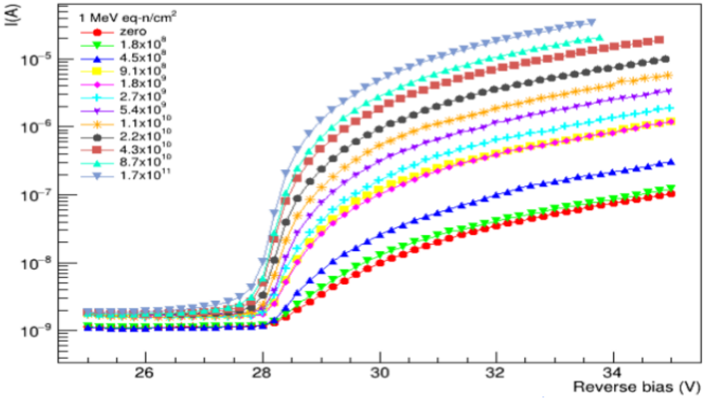


Back-Ups

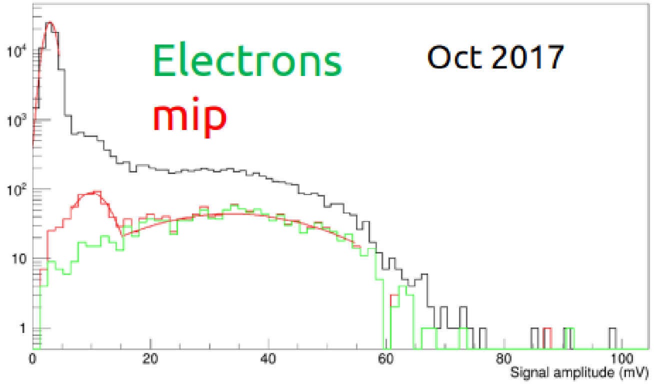
SiPM irradiation @ LNL

Dark current vs bias at increasing n fluences

FBK HD-RGB 1x1mm² 12μm cell size



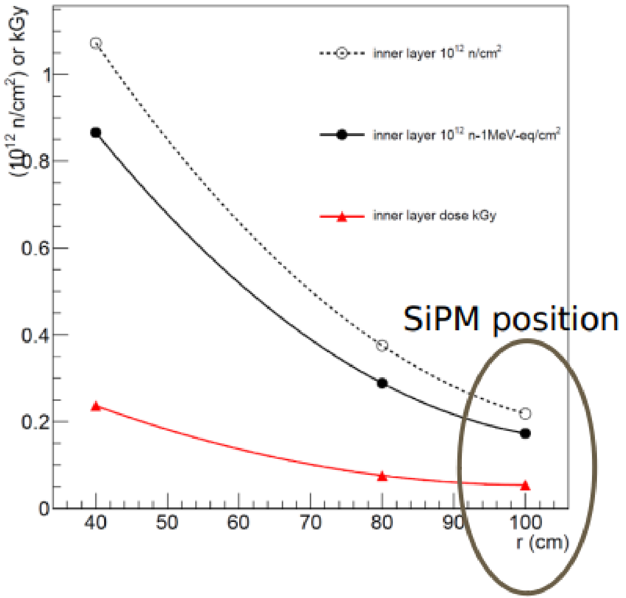
A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS



(FBK-HD-RB Advansid)

1.2 x 10^{11} n-1MeV-eq/cm²

Expected 5-years neutron doses from K decays (**FLUKA**)



Back-Ups

LCM=Lateral Compact Module:

$3\times3\times11\ cm^3$ – 4.3 X_0

Five 1.5 cm thick iron

Five 0.7 cm thick scint.

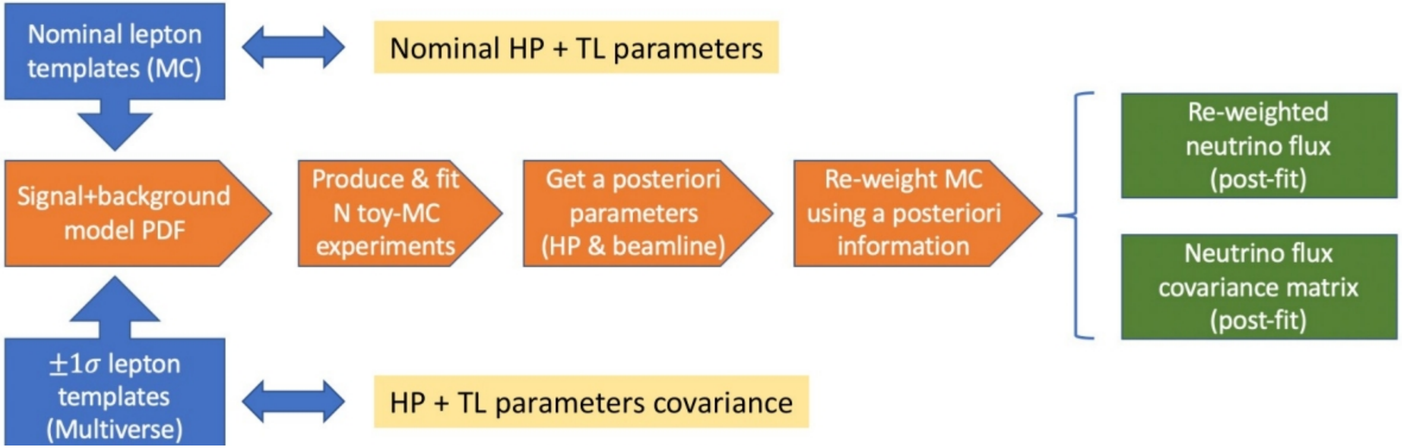
Requirements:

- 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

Back-Ups

Assessment of systematics

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



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

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