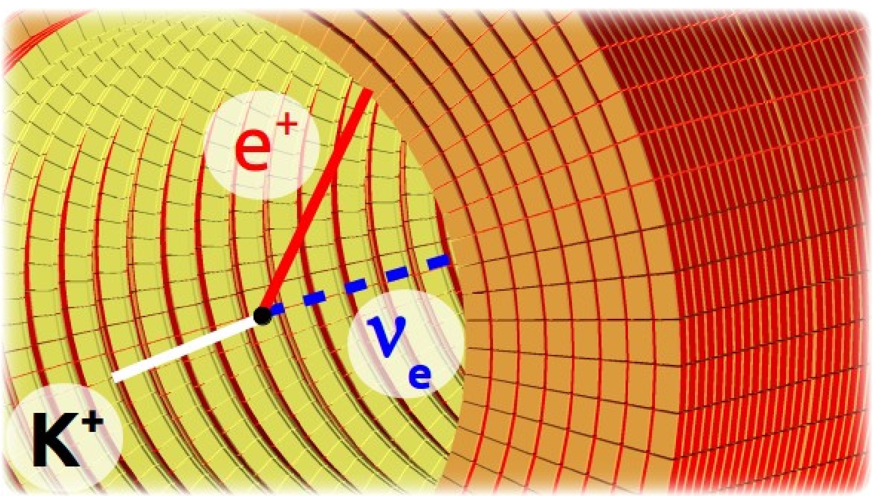
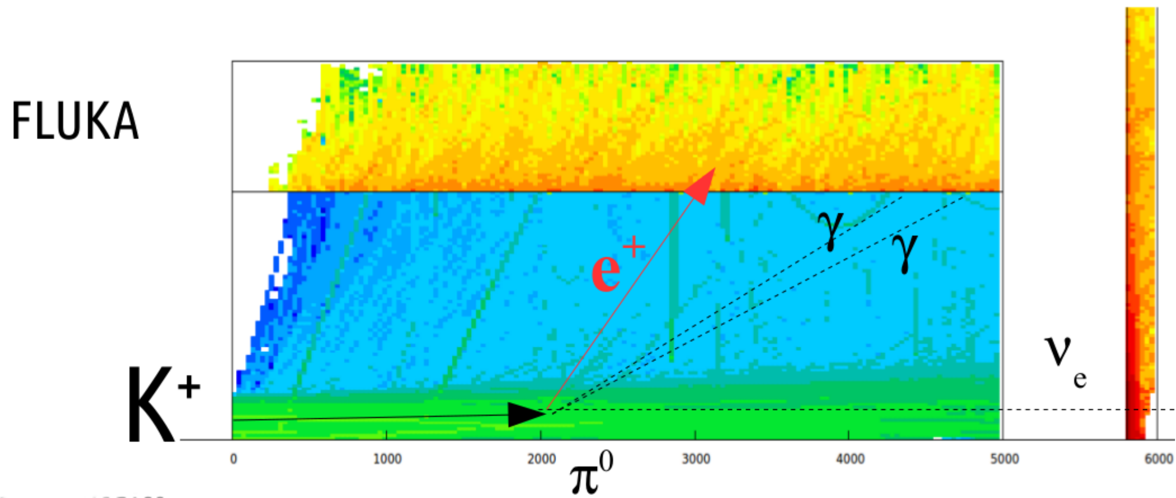
Fasci monitorati per la determinazione ad alta precisione del flusso di neutrini: il progetto ENUBET





Claudia Brizzolari on behalf of the ENUBET collaboration

IFAE 2019, 8-10 April 2019, Napoli

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Neutrino cross sections and flux uncertainties

- **Precise knowledge of σ(ν)** → important for future neutrino oscillation experiments (DUNE, HyperK)
- **$\sigma(\nu_\mu)$**: remarkable improvement in the last 10 years (MiniBooNE, SCIBooNE, T2K, MINERνA, NOνA...), but still **no absolute measurements below 7-10%**
- **$\sigma(\nu_e)$**: $\sigma(\nu_\mu) \leftrightarrow \sigma(\nu_e)$ delicate at low energies, **no intense/pure source of GeV ν_e available**

↓

Poor knowledge of $\sigma(\nu_e)$ can spoil the CPV discovery potential and the insight on the underlying physics (standard vs exotic, matter vs antimatter)

Main limiting factor: **systematic uncertainties in the initial flux determination**

Monitored neutrino beams

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

Proposed solution

- Monitor the neutrino flux inside the decay tunnel with conventional technologies
- Aim for a ν_e source pure and precise (1%) from a kaon-based beam

Protons → Target (K^+,π^+) → K_{e3} decays → ν_e @ neutrino detector

e+

Measure positrons (emission angle ≈ 88 mrad) in a **FULLY INSTRUMENTED decay region**

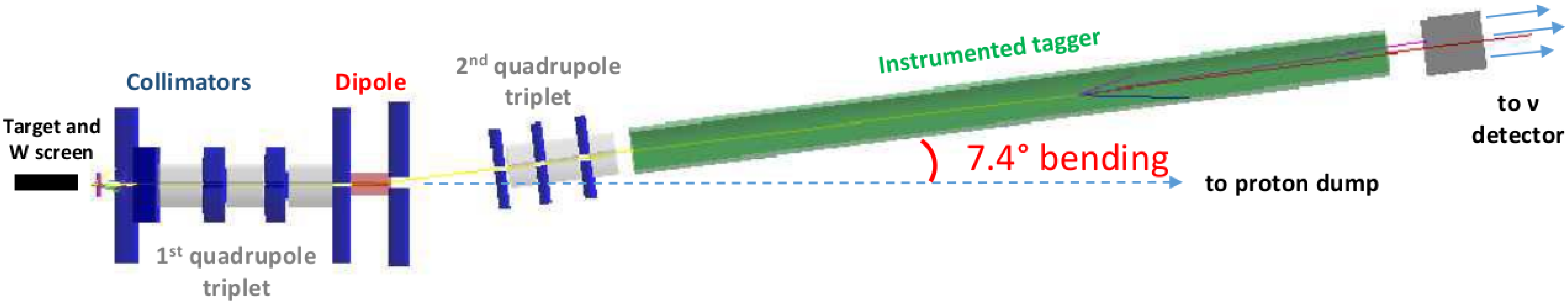
- "By-pass" uncertainties from POT,hadro-production, beamline efficiency
- **ν_e flux prediction = e^+ counting**

Improvement of one order of magnitude cross-section measurement @GeV scale

↓

Determine absolute ν_e flux at neutrino detector with O(1%) precision

The ENUBET beamline



- **Proton driver**: CERN SPS (400 GeV), Fermilab Main Ring (120 GeV), JPARC (30 GeV)
- **Target**: 1 m Be, graphite target (FLUKA)
- **Focusing**:
  → Horn: 2 ms pulse, 180 kA, 10 Hz during the flat top (not shown in figure)
  → Static focusing system: a quadrupole triplet before the bending magnet
- **Transfer line**:
  → Kept short (~**20 m**) → minimize early K decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino component)
  → Optics: reference momentum **8.5 GeV/c ± 10%** (TRANSPORT)
- **Decay tunnel**: L = **40 m**, low power hadron dump at the end
- **Proton dump**: position and size under optimization

The ENUBET narrow-band beam

Absolute flux of ν_e and ν_μ at the 1% level

↓

Remove the leading source of uncertainty in neutrino cross section measurement

Energy of the neutrino known at the 10% level

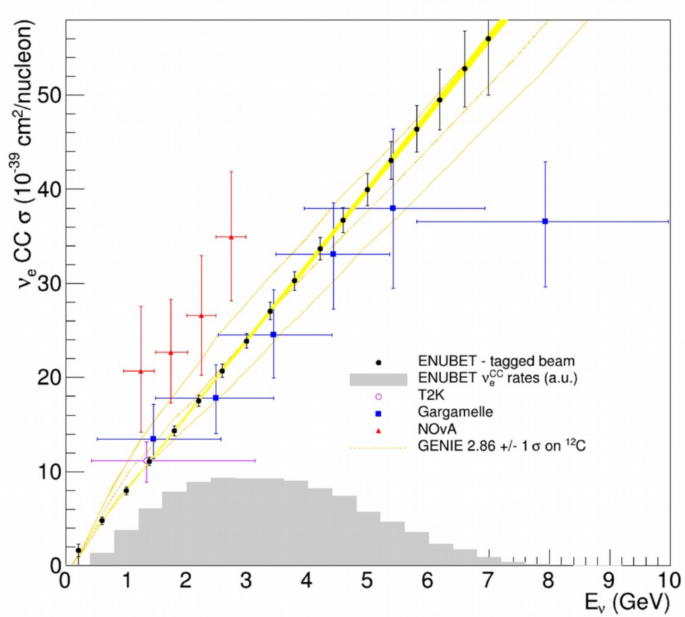
↓

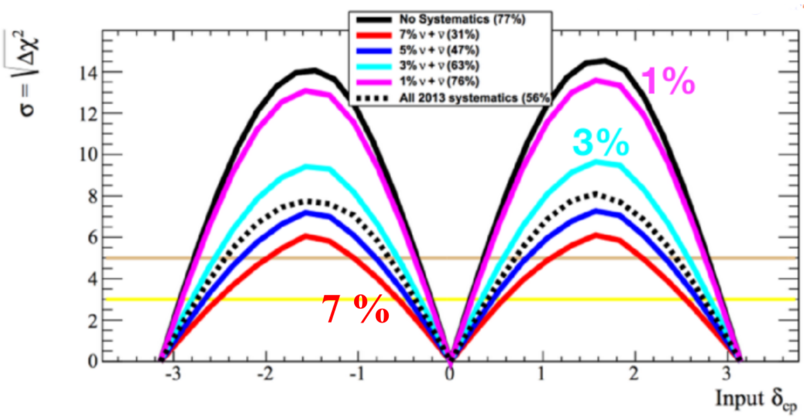
The ideal tool to study neutrino interactions in nuclei

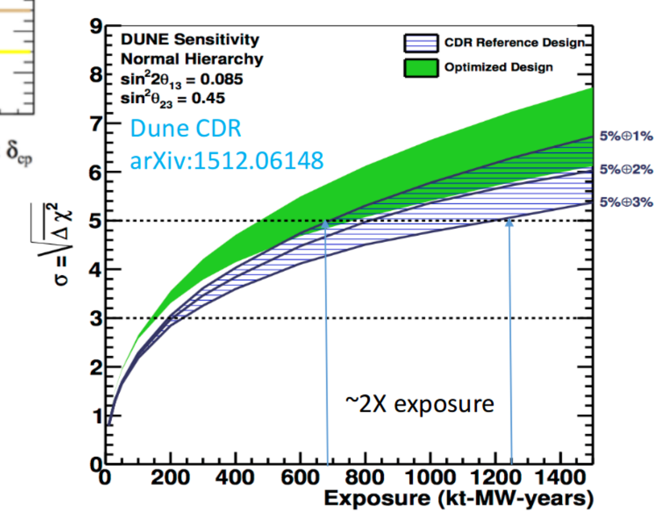
Flavor composition known at the 1% level

↓

The ideal tool to study NSI and sterile neutrinos at the GeV scale







The ENUBET beamline: yields

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction length	π/cycle (10^{10})	K/cycle (10^{10})	Proposal[b]
Horn	77	7.9	2 ms[a]	347	36	x2
Static	19	1.4	2 s	86	6.3	x4

(a) 2 ms at 10 Hz during flat top (2 s) to empty the accelerator after a super-cycle
(b) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

Horn option → more efficient in terms of meson yields,
however
Static option → **yields x4 larger wrt preliminary estimates** from optic optimization

PROS:

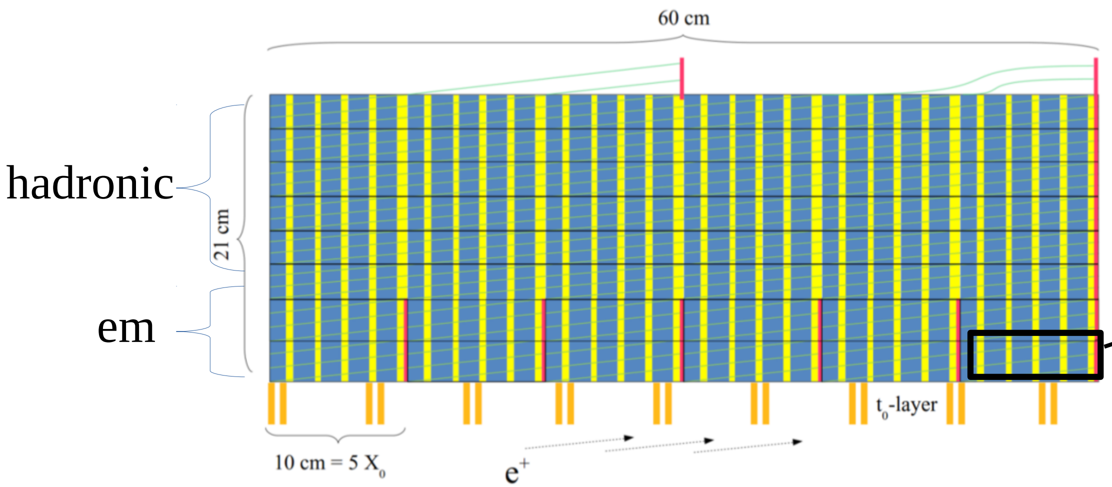
- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Monitor muons after the dump at 1% level (→ flux of ν_μ from π) [under evaluation]
- **Possibility to associate in time the ν interaction at the detector with the observation of the lepton from the parent hadron in the decay tunnel**

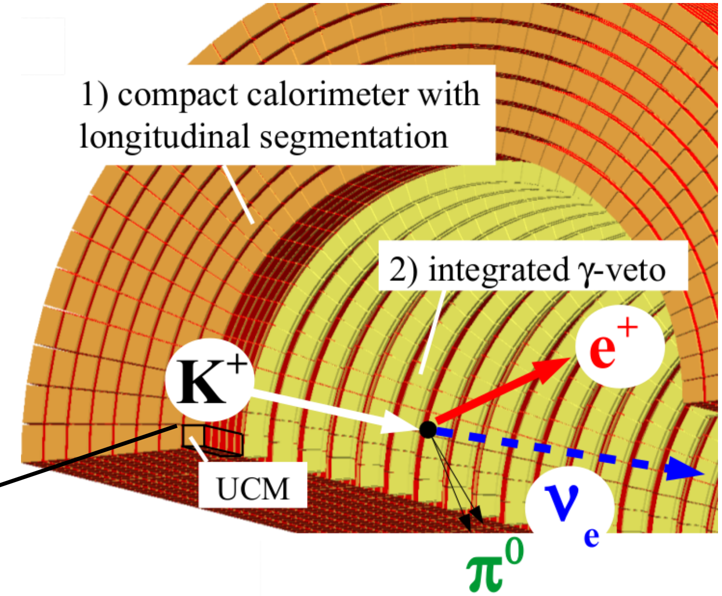
Neutrino tagged beams

The Tagger

$e^+/\pi^+/\mu^+$ separation

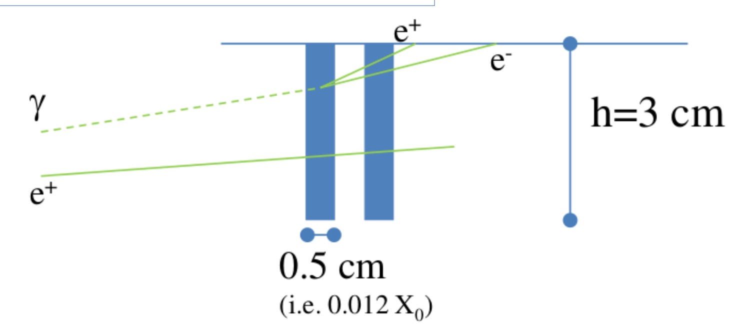
Longitudinally segmented sampling calorimeter



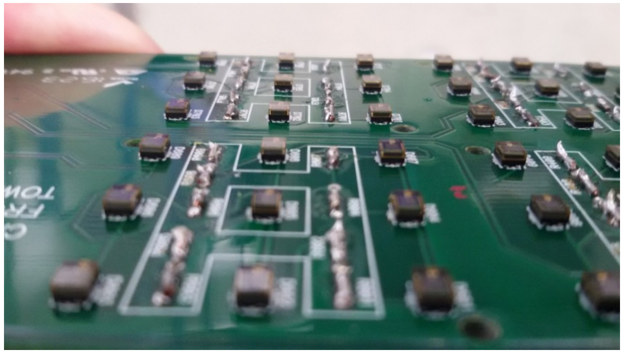


e^+/γ separation

Plastic scintillator exploiting 1 mip – 2 mip separation



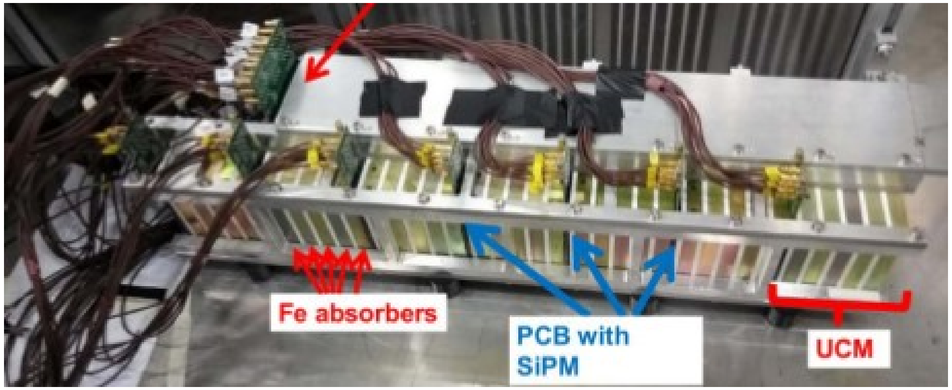
Tagger prototypes performances



Two readout schemes, tested at CERN:

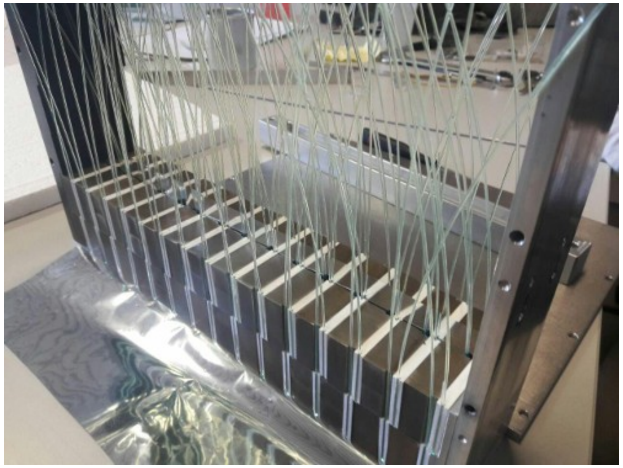
Compact "shashlik":

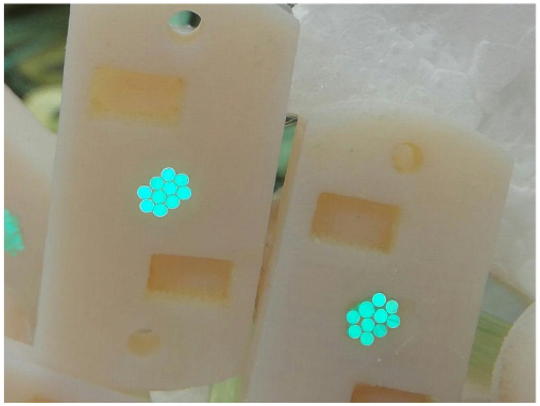
- Compact readout based on SiPMs embedded in calorimeter bulk
- PROS: scalable technology
- CONS: SiPMs exposed to large neutron flux (10^{11} 1MeV-eq n/cm^2)



"Lateral":

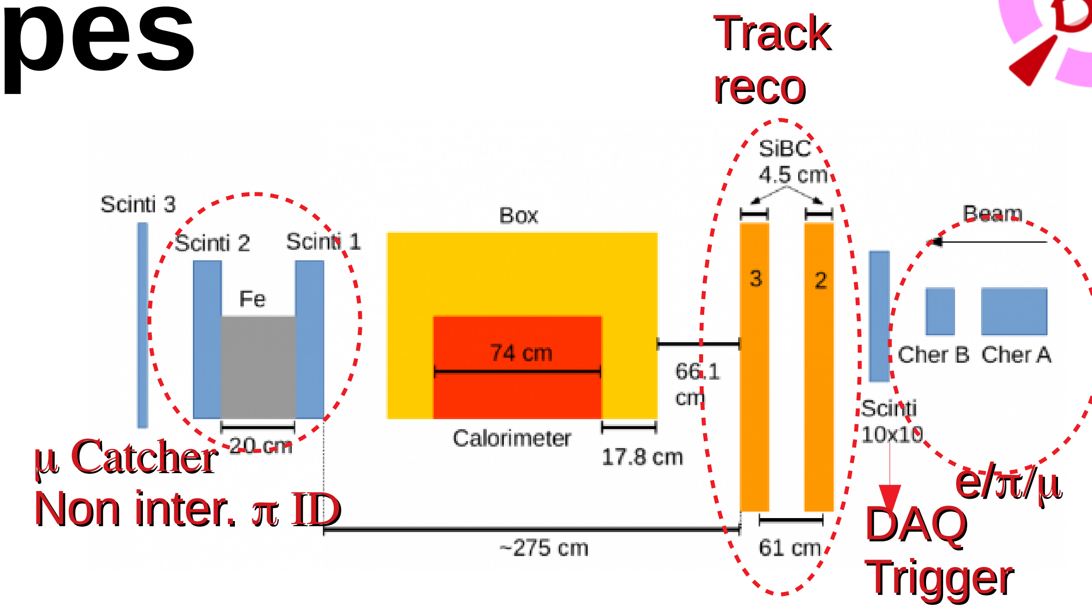
- Fibers bundled and coupled to SiPMs 40 cm from the bulk of the calorimeter
- PROS: SiPMs less exposed to radiation, more cost-effective
- CONS: less compact

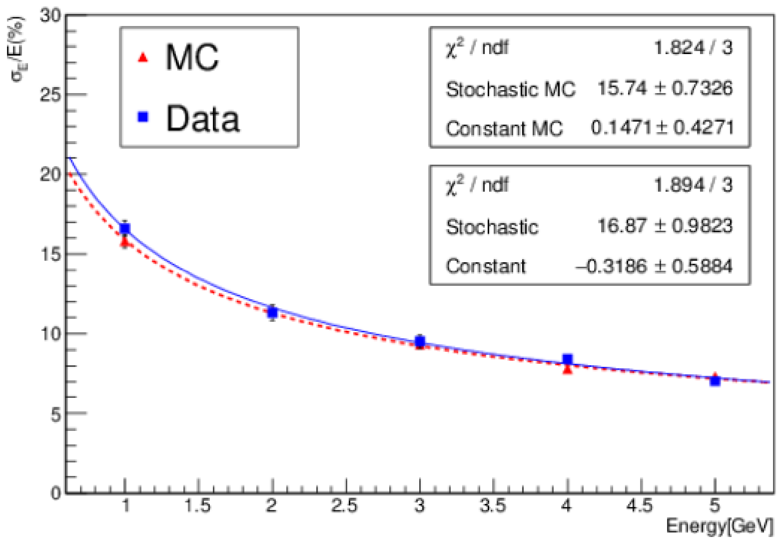




Tagger prototypes performances

Experimental setup @ CERN →





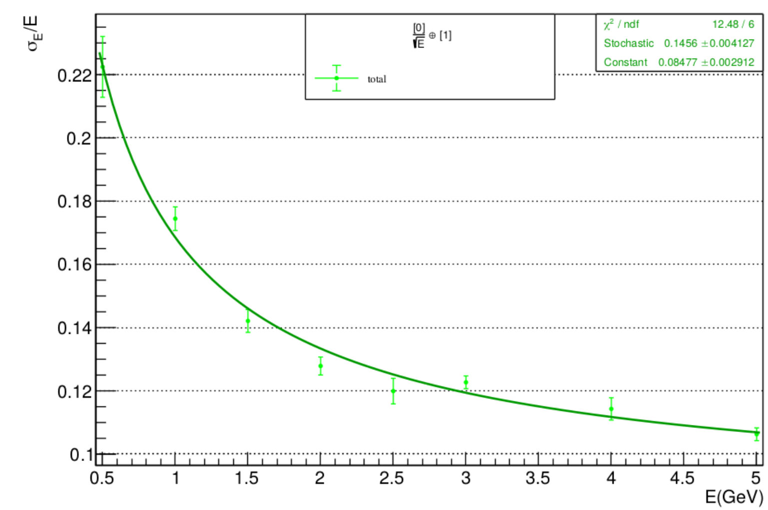
Ballerini et al., JINST 13 (2018) P01028

← **Results for the shashlik prototypes:**

- ~17%/√E energy resolution
- Good agreement data/MC

Results for the lateral readout prototypes: →

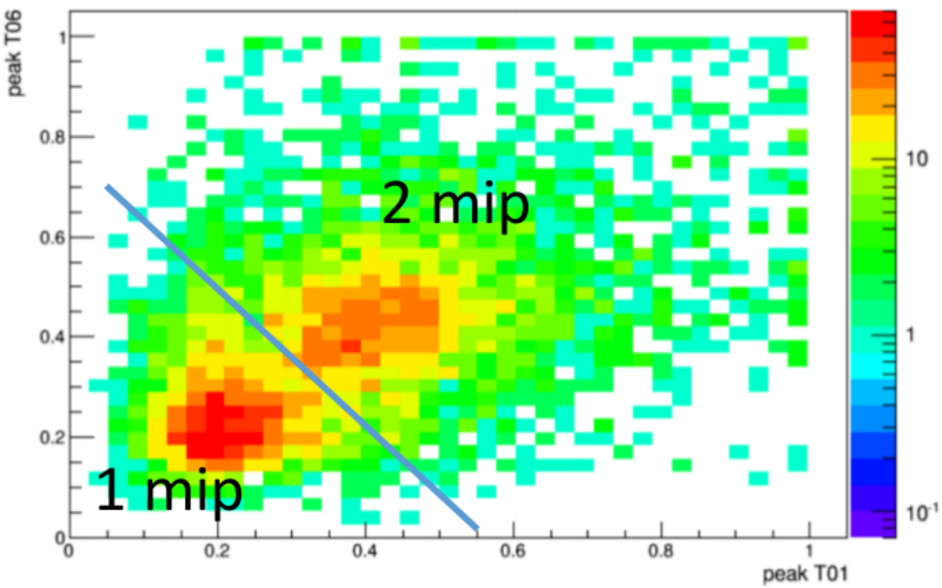
- ~17%/√E energy resolution
- Bigger constant term, probably due to non-uniformity in light collection

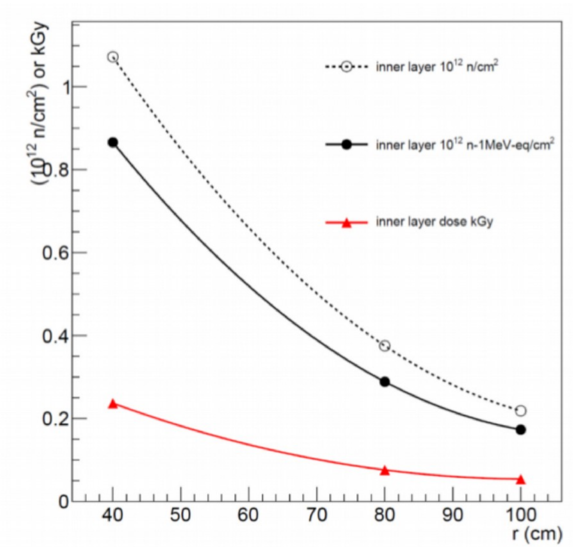


t_0 layer and irradiation studies

γ/e⁺ discrimination (photon-veto)

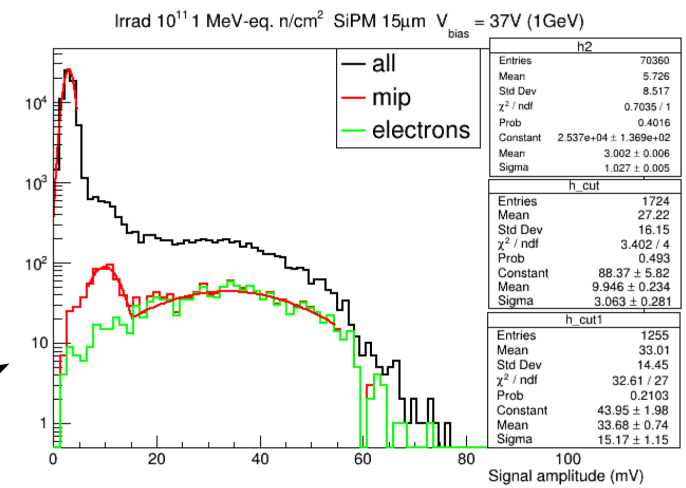
- light collection efficiency → >95%
- Time resolution → ~400 ps
- First 1mip/2mip separation using photon conversion from π^0 gammas





Irradiation studies

- SiPM irradiated @ LNL-INFN
- Characterization of 12, 15 and 20 µm SiPM cells up to 1.2 10^{11} n/cm^2 1 MeV-eq



Even after max irradiation electrons & mip remain well separated

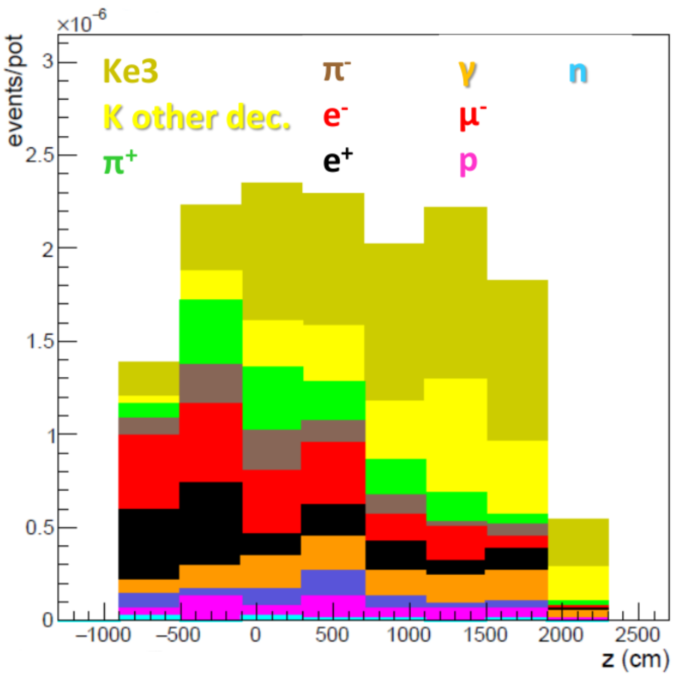
F. Acerbi et al., JINST 14 (2019) P02029

K_{e3} positron reconstruction

Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. The simulation includes particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain *[F. Pupilli et al., POS NEUTEL 2017 (2018) 078]*

- Event builder: identify the seed of the event and cluster neighboring modules
- e/π/μ separation: TMVA multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter)
- e/γ: signal on the tiles of the photon veto



ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36
S/N Φ cut	**0.46**

Instrumenting half of the decay tunnel:
K_{e3} e^+ at single particle level with a S/N = 0.46

Conclusions

ENUBET is a narrow-band beam with high precision monitoring of the flux at source (O(1%)) and control of the E_ν spectrum (20% at 1 GeV → 8% at 3 GeV)

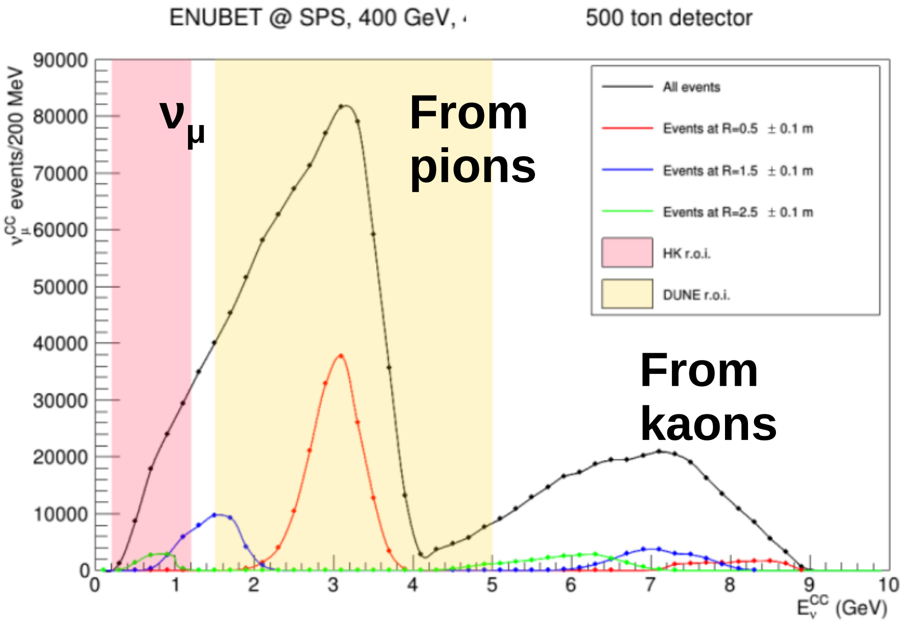
- **In 2018, the collaboration has:**
  → provided the first end-to-end simulation of the beamline
  → proved the feasibility of a purely static focusing system
- **full simulation of the e^+ reconstruction:** single particle level monitoring S/N ~0.5
- **Completed the beam tests campaign before LS2**
  → identified best options for instrumentation (shashlik and lateral readout)
- **Strengthened the physics case**
  → slow extraction + "narrow band"

Backup

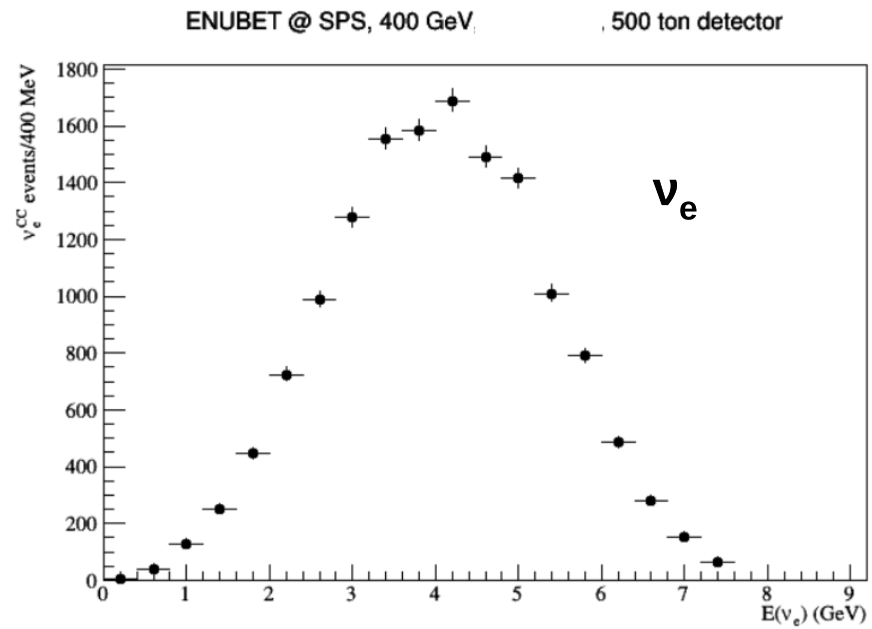
The ENUBET narrow-band beam

Neutrino events per year at the detector

- Detector mass: 500 t (e.g. Protodune-SP or DP at CERN, ICARUS at Fermilab)
- Baseline (i.e. distance between the detector and the beam dump): 50 m
- 4.5 x 10^{19} pot at SPS (0.5/1 y in dedicated/shared mode) or 1.5 x 10^{20} pot at FNAL



1.2 million ν_μ Charged Current per year



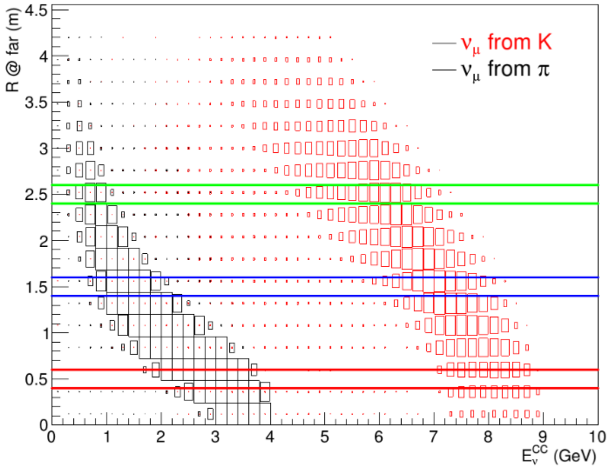
14000 ν_e Charged Current per year

- ν_μ from K and π are well separated in energy (narrow band)
- ν_e and ν_μ from K are constrained by the tagger measurement (K_{e3}, mainly $K_{\mu2}$)
- ν_μ from π: μ detectors downstream of the hadron dump (under study)

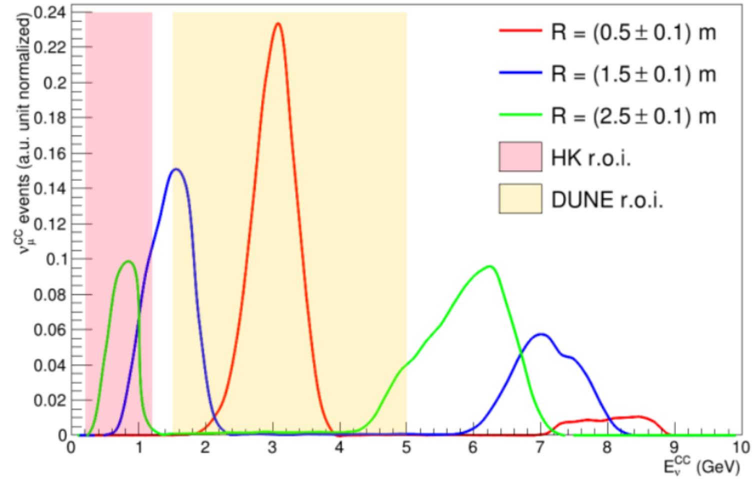
The ENUBET narrow-band beam

ν_μ CC events at the ENUBET narrow band beam

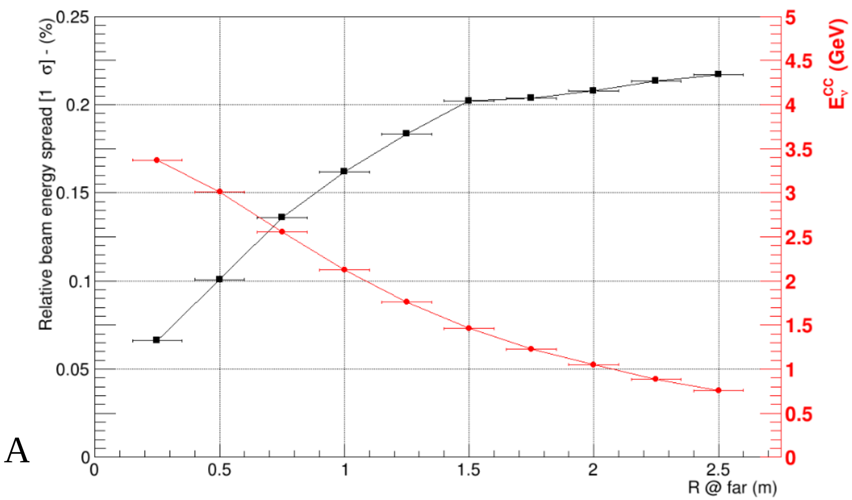
The neutrino energy is a function of the distance of the neutrino vertex from the axis beam



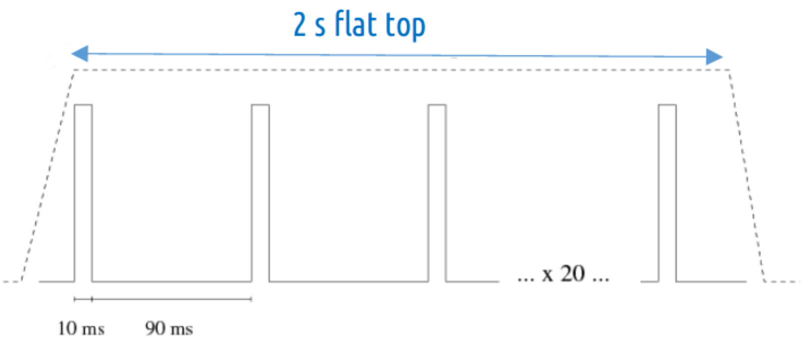
ν_μ CC in radial bins

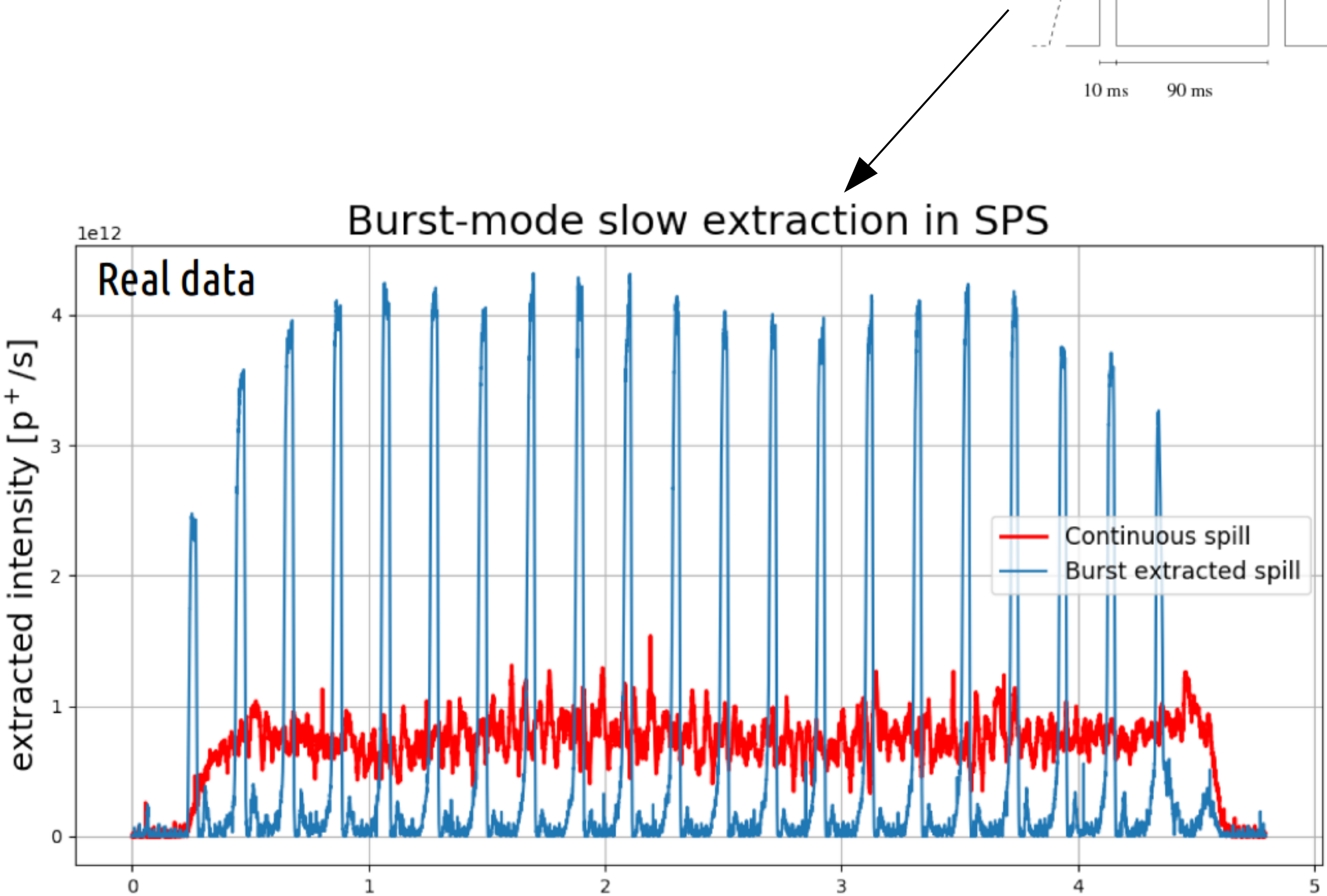


Initial neutrino energy inferred from the measurement of the neutrino interaction vertex distance with respect to the axis of the decay tunnel



Machine studies for the horn-based option





CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard