A high precision narrow-band neutrino beam:
the ENUBET project

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on behalf of the ENUBET Collaboration

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Enhanced NeUtrino BEams from kaon Tagging

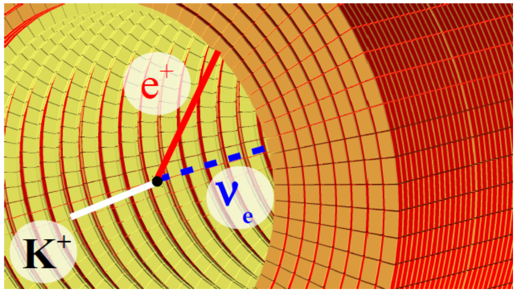
The goal of ENUBET is to demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level:**

(K_{e3} decays)

$K^+ \rightarrow \boxed{e^+}\ \boxed{\nu_e}\ \pi^0$

to tagger

to neutrino detector



Two pillars:

- Build/test a **demonstrator** of the instrumented decay tunnel
- Design/simulate the layout of the **hadronic beamline**

Outline

- **Beamline simulation**
- Experimental validation of detector **prototypes**
- Updated **physics performance**

Since 2019, ENUBET is a CERN Neutrino Platform Experiment: NP06/ENUBET

ENUBET Collaboration: 60 physicists, 12 institutions

A narrow-band beam for the precision era of ν physics

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

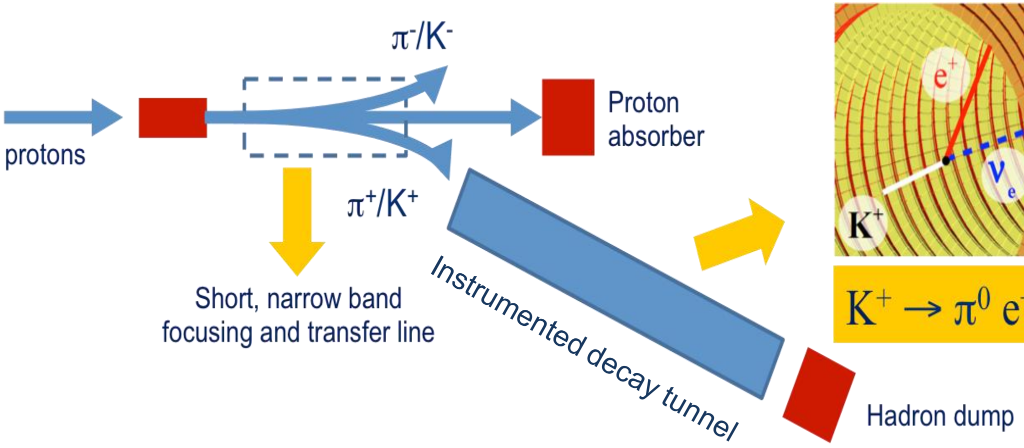
↓

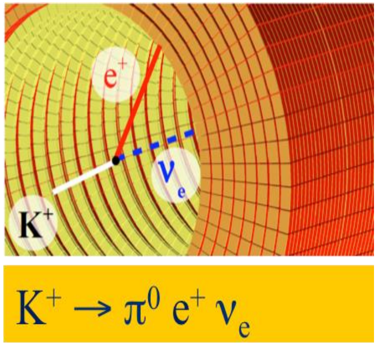
The ideal tool to study neutrino interactions in nuclei

Flavor composition known at the 1% level

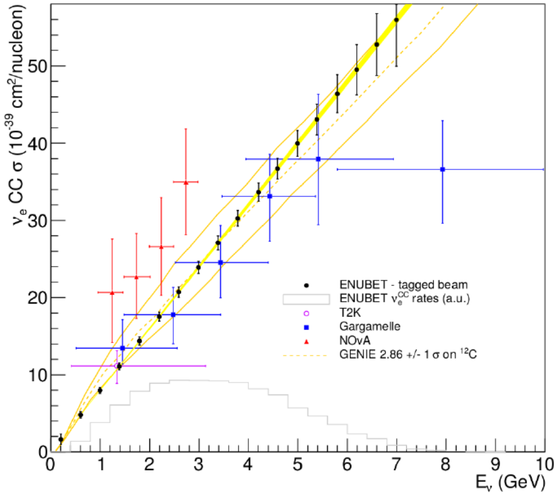
↓

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



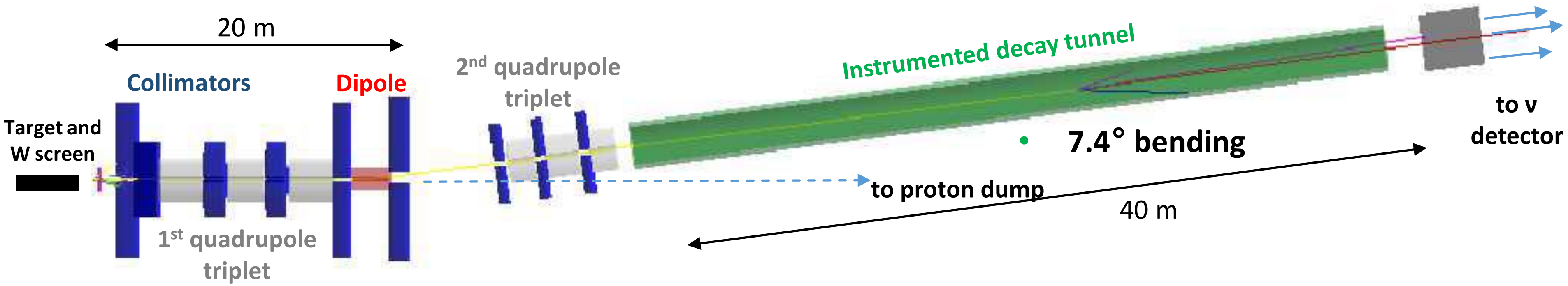


$K^+ \rightarrow \pi^0 e^+ \nu_e$



- Monitor the decays in which ν are produced event-by-event
- “By-pass” uncertainties from POT, hadro-production, beamline efficiency
- **Fully instrumented decay region → ν_e flux prediction = e^+ counting**

The ENUBET beamline (baseline option)



- **Proton driver**: **CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **Target**: Be, graphite target. FLUKA
- **Focusing:**
  - **Horn**: 2 ms pulse, 180 kA, 10 Hz during the flat top *[not shown in fig.]*
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **Transfer line**
  - Kept **short** to minimize early K-decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino flux component)
  - Optics: optimized with TRANSPORT to a **10% momentum bite centered at 8.5 GeV/c**
  - Particle transport and interaction: full simulation with G4Beamline
  - Normal-conducting magnets (numerical aperture<40 cm): Two quadrupole triplets, one (or two) bending dipole
- **Decay tunnel:** r = 1 m, L=40 m, low power hadron dump at the end
- **Proton dump**: position and size under optimization

The ENUBET beam line – particle yields

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

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

The horn-based option still allows ~ × 5 more statistics but the static option gained momentum since initial estimates were ~ × 4 too conservative with respect to present simulations!

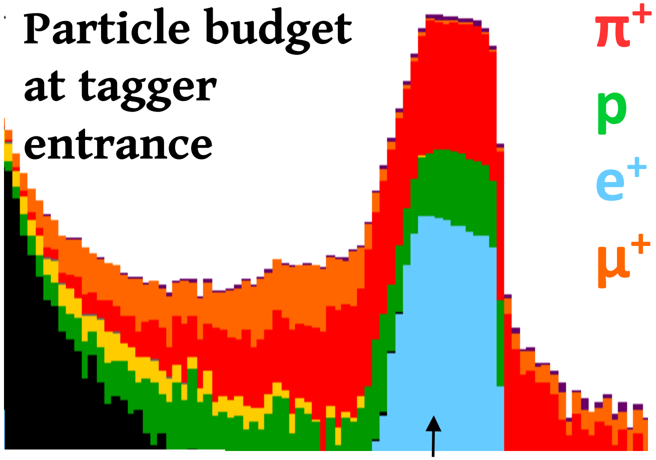
Advantages of the static extraction:

- No need for fast-cycling horn
- Strong **reduction of the rate** (pile-up) in the instrumented decay tunnel
- Pave the way to a **“tagged neutrino beam”** → ν interaction at the detector **associated in time** with the observation of the **lepton from the parent hadron** in the decay tunnel (more later)
- Monitor the μ after the dump at % level (**flux of ν_μ from π**) [*under evaluation*]

The static beamline

G4Beamline simulation for particles at the entrance and exit of the dacay tunnel

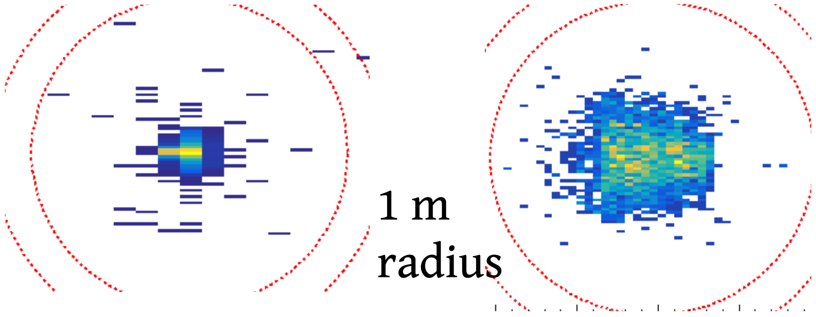
Particle budget at tagger entrance



p (MeV/c)

Momentum bite (8.5 ± 10%) GeV/c

Divergence of the kaon beam

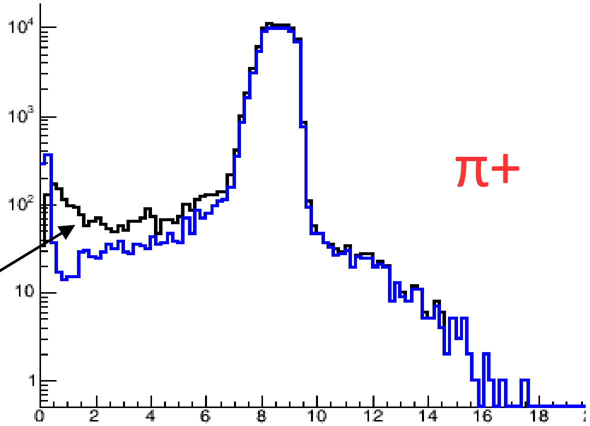


Spectra at:

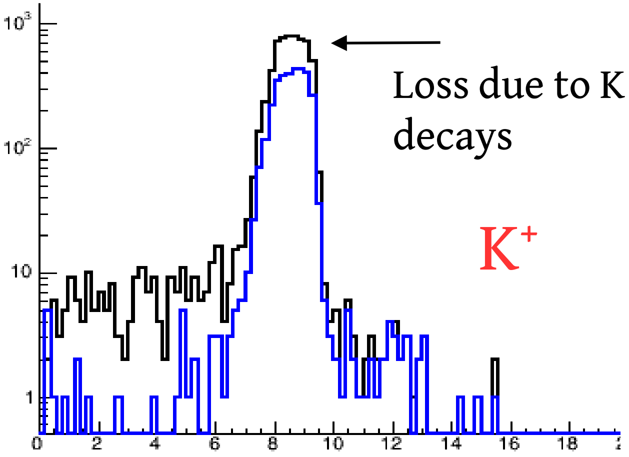
tagger entrance

tagger exit

Low energy high angle π



p (GeV/c)



Loss due to K decays

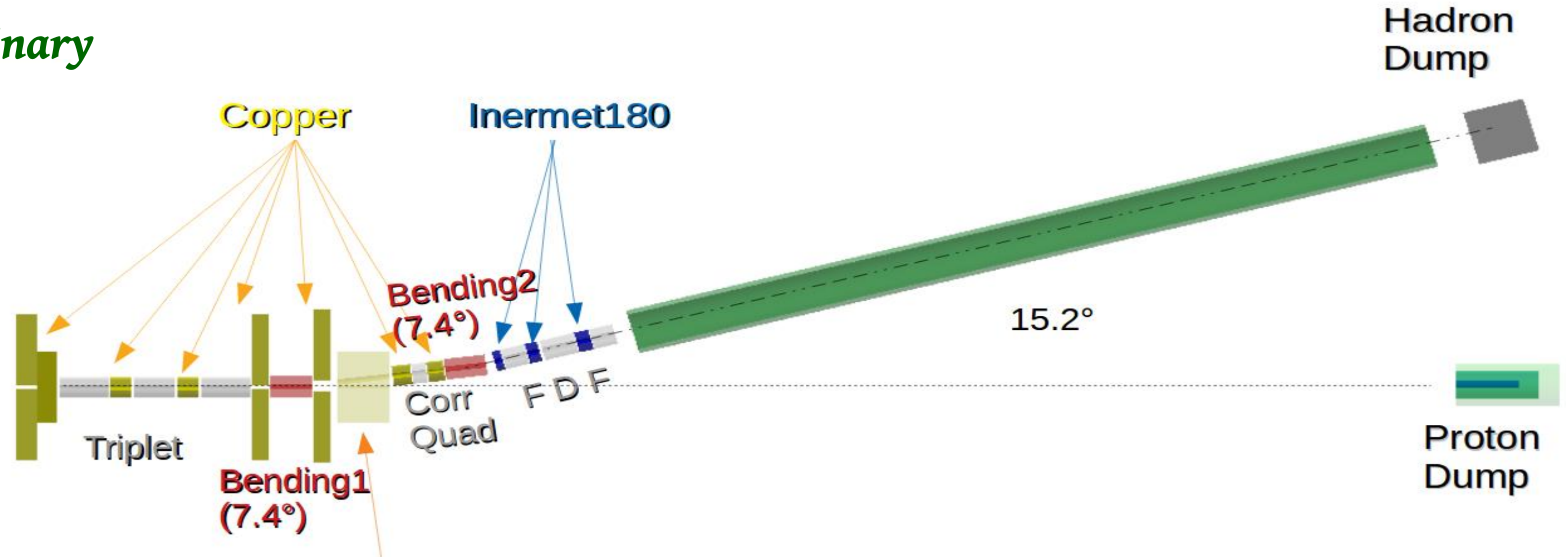
p (GeV/c)

Beamline studies

Additional static focusing options

Put all inputs/schemes together
→ pindown the best design in terms of physics and technical feasibility

Preliminary



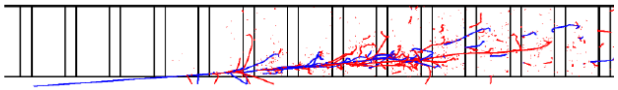
Example: 2 dipoles scheme with an intermediate quadrupole

- improve the quality of the beam in the tagger scheme
- larger bending angle (15.1°) reducing background from muons, less probable for neutrinos produced on the 0° line to reach the detector

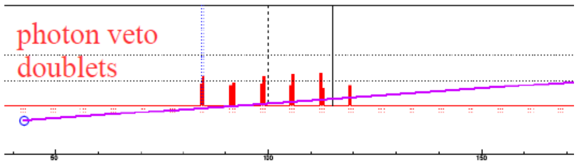
The ENUBET tagger

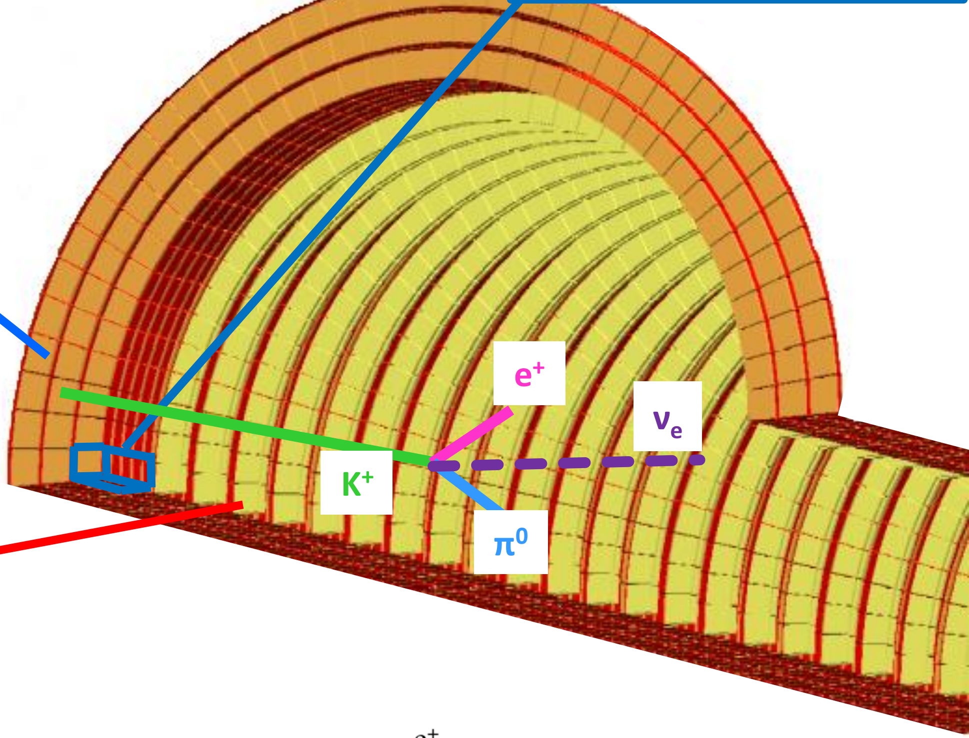
Ultra Compact Module
3×3×10 cm³ – 4.3 X_0

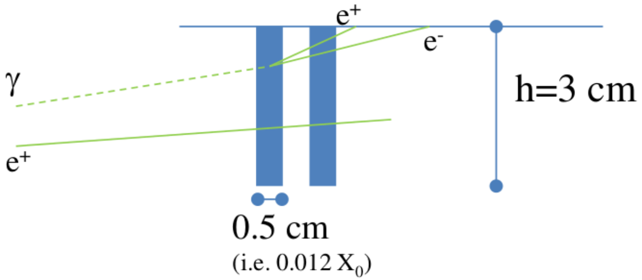
Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation



Integrated photon veto
Plastic scintillators
Rings of 3×3 cm² pads
→ π^0 rejection





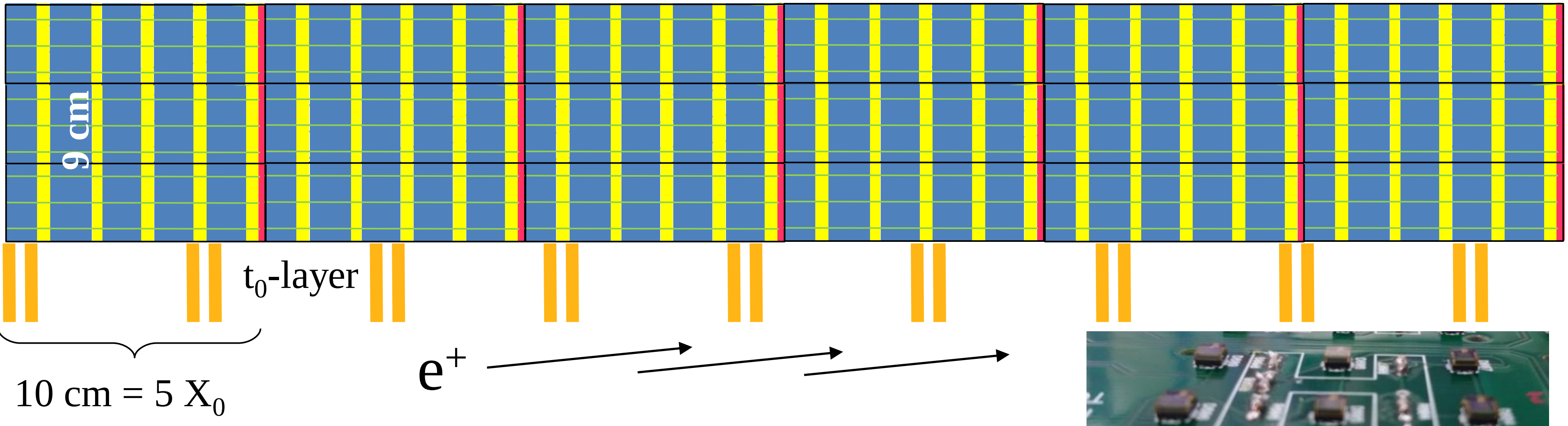


e^+ (signal) topology

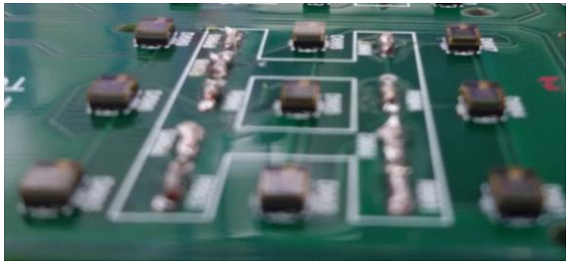
π^0 (background) topology

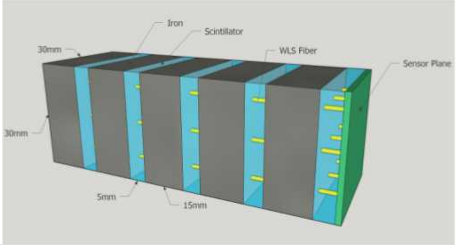
π^+ (background) topology

The tagger: shashlik with integrated readout

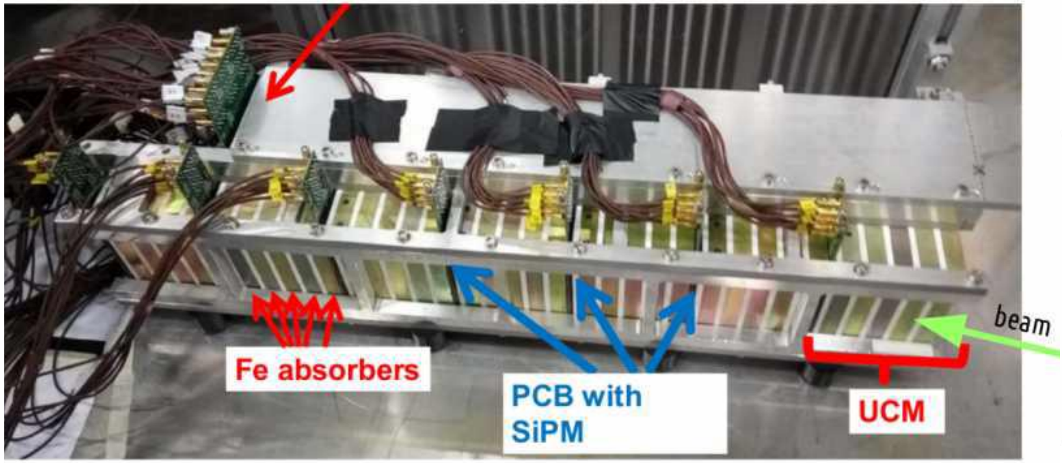


UCM: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter

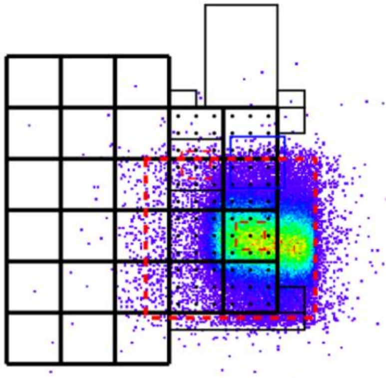




CERN PS test beam Nov 2016



Beam spot

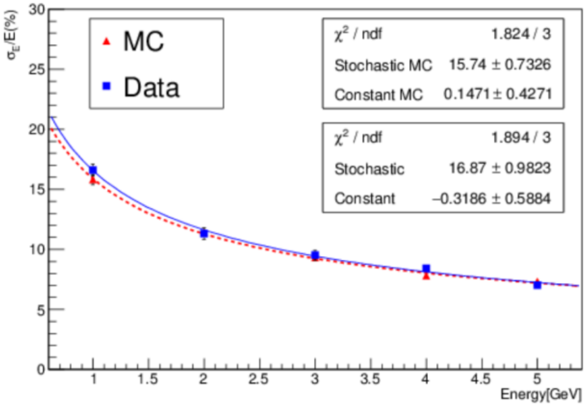


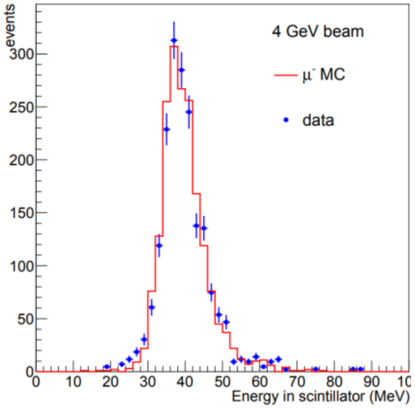
Test beam results with shashlik readout

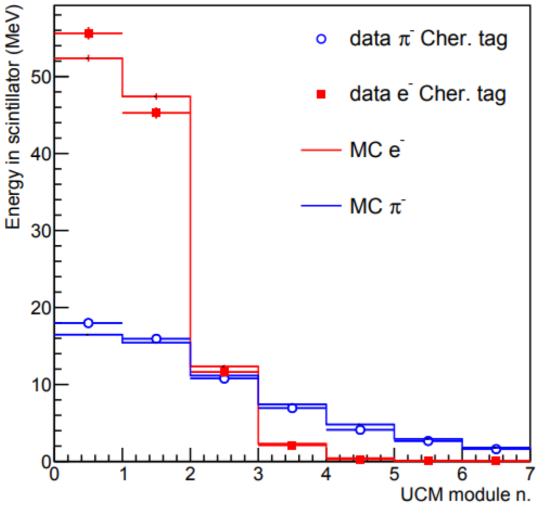
Calorimeter prototype performance with test-beam data at CERN-PS T9 line 2016-2017

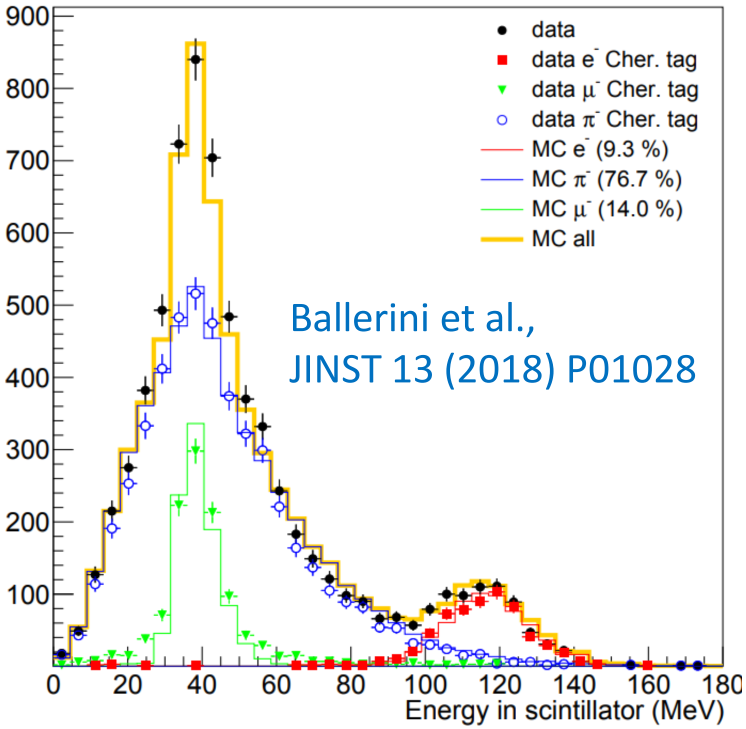
Tested response to mip, e and π^-

- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement
- Longitudinal profiles of partially contained π reproduced by MC at 10% precision





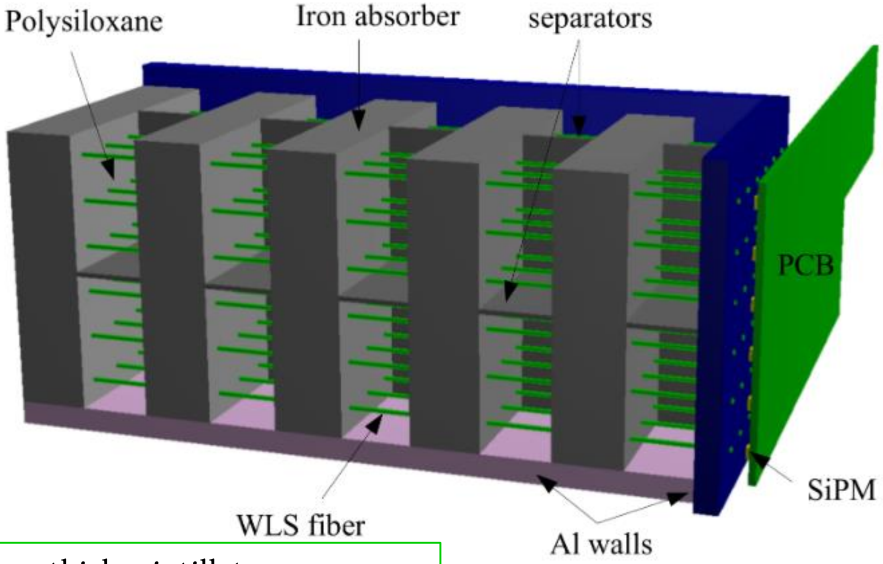


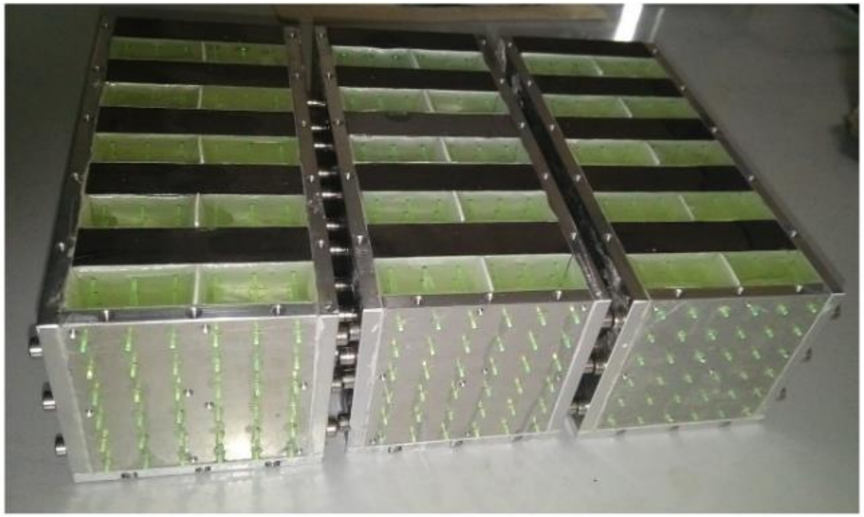


Ballerini et al.,
JINST 13 (2018) P01028

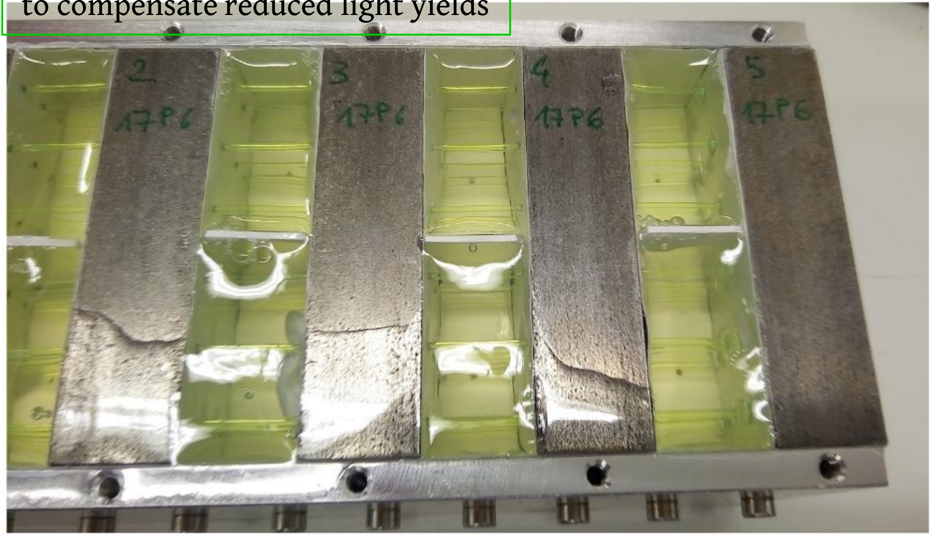
Polysiloxane shashlik prototypes

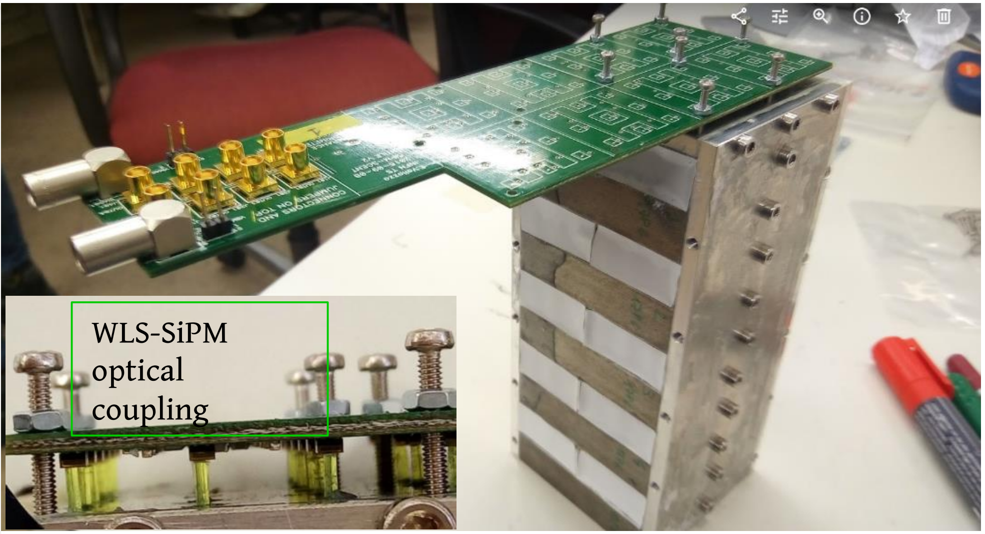
Increased resistance to irradiation (no yellowing), **simpler** (just pouring + reticulation)
A **13X$_0$ shashlik prototype** tested in October 2017 (**first application** in HEP) and May 2018.





15 mm thick scintillators
to compensate reduced light yields



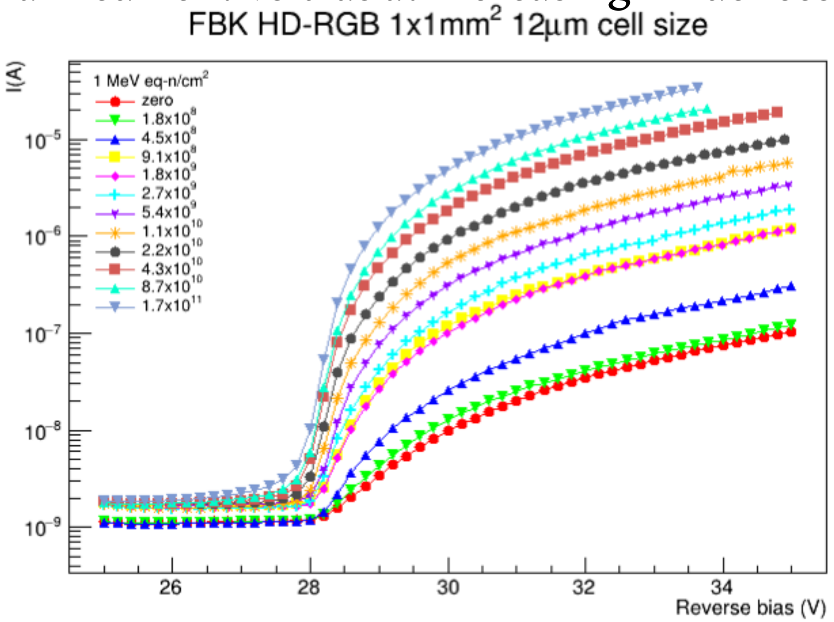


WLS-SiPM optical coupling

SiPM irradiation measurements at INFN-LNL and CERN

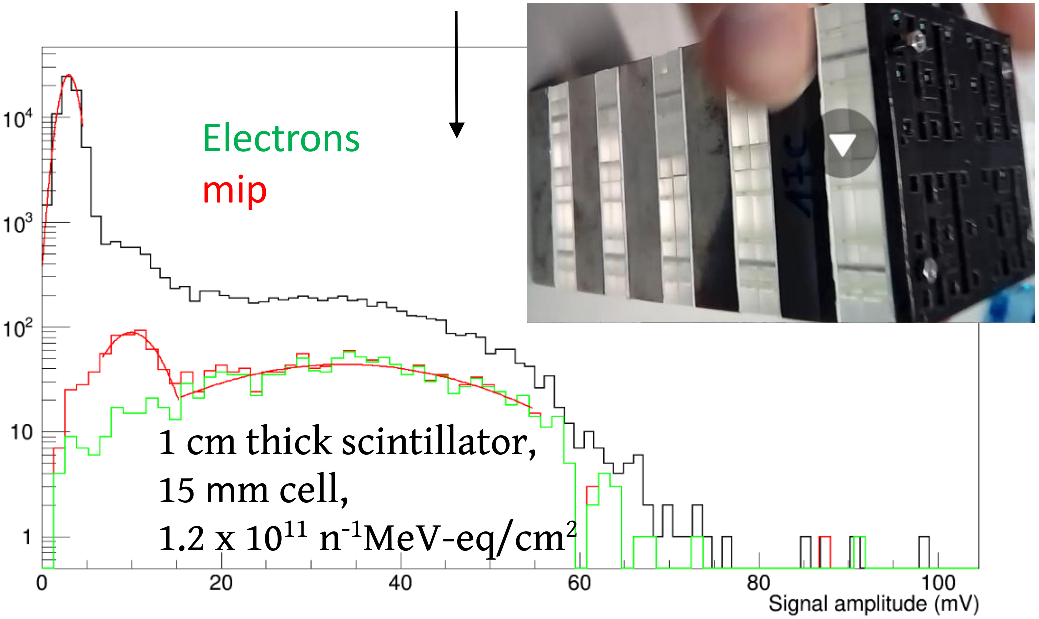
- At the CN Van de Graaf on July 2017⟶ 1-3 MeV n with fluences up to $10^{12}/cm^2$ in a few hours

Dark current vs bias at increasing n fluences



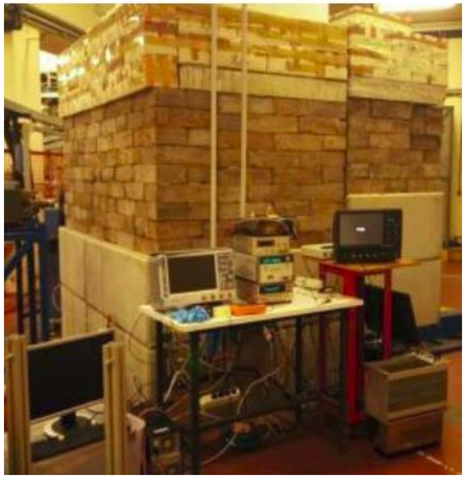
F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

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



1 cm thick scintillator,
15 mm cell,
1.2×10^{11} n^{-1}MeV-eq/cm²

(FBK-HD-RB Advansid)



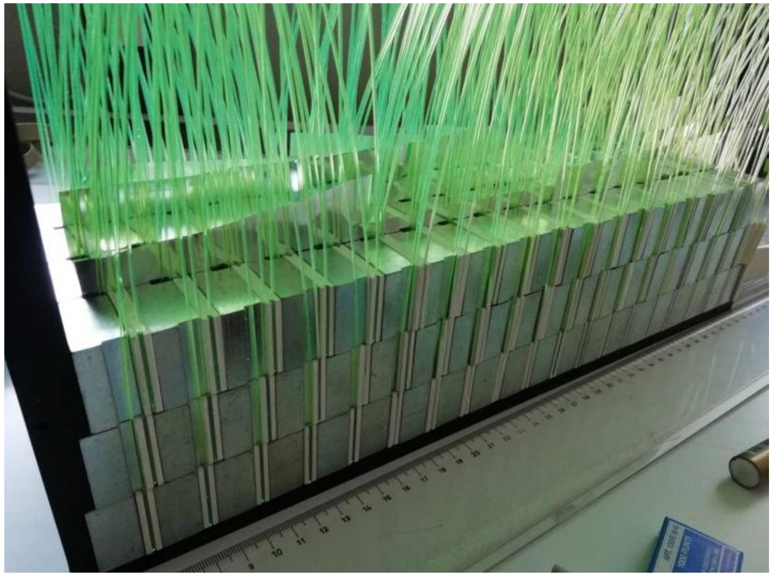
- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used from **channel-to-channel intercalibration** even after maximum irradiation.

The tagger: lateral readout option

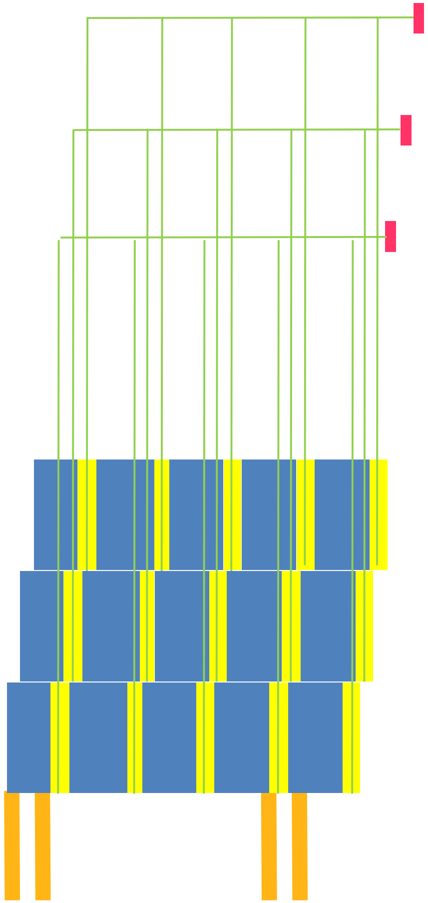
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM).

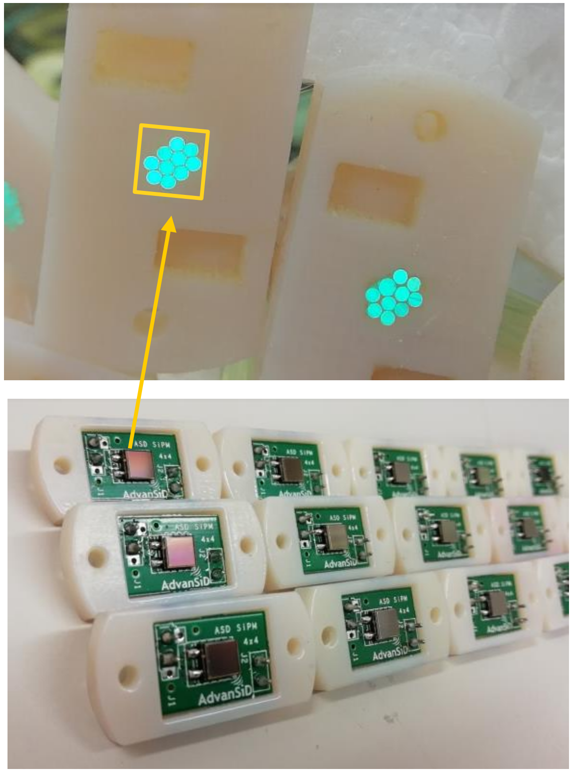
SiPM are not immersed anymore in the hadronic shower → less compact but much **reduced neutron damage** (larger safety margins), better **accessibility**, possibility of replacement. Better reproducibility of the **WLS-SiPM optical coupling.**

Sampling calorimeter with lateral WLS light collection



May 2018, CERN-PS test beam



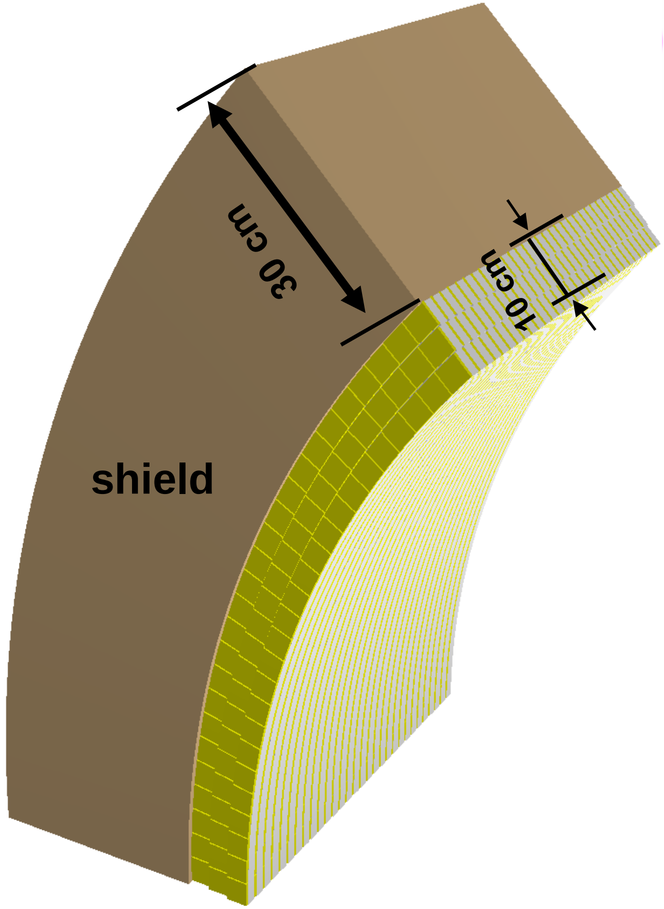


Large SiPM for 10 WLS $4x4\ mm^2$

Achievable neutron reduction with lateral readout

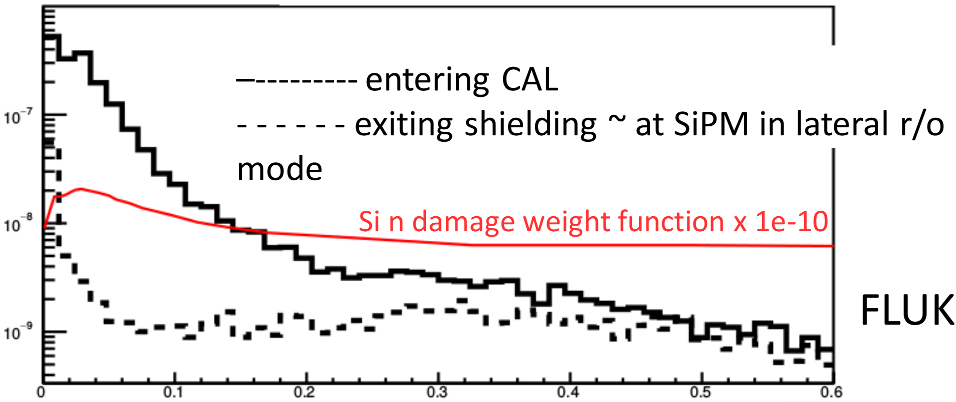
- 30 cm of borated **polyethylene** in front of SiPM
- FLUKA full simulation. **400 GeV protons.**

- Very good suppression especially below 100 MeV.
- **Factor ~18** reduction averaging over spectrum.

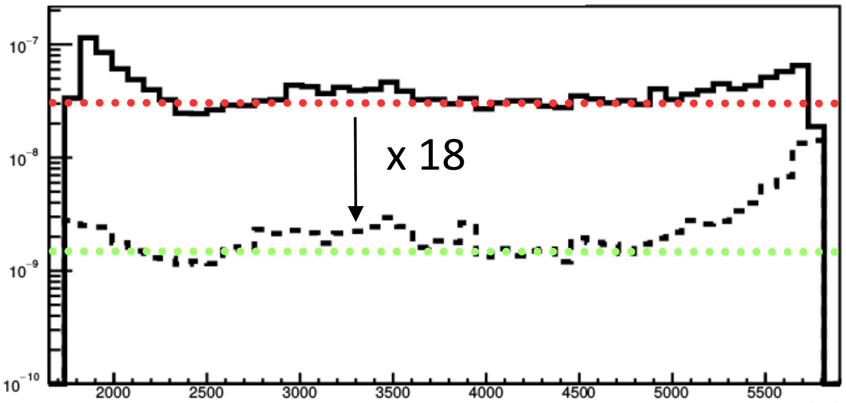


preliminary

Neutron energy



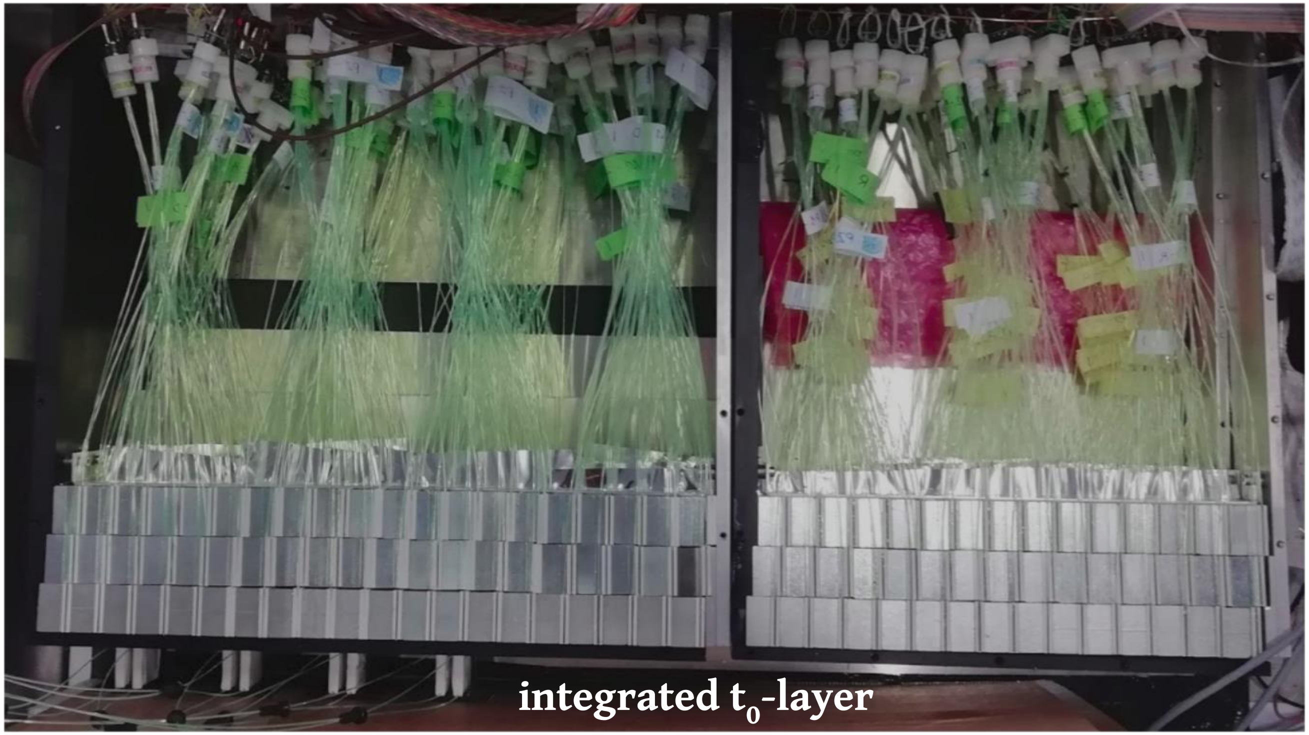
FLUKA



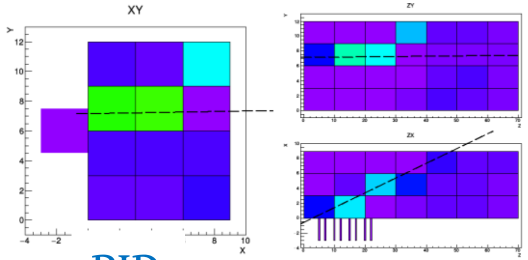
Neutron longitudinal position along the tunnel

Test beam results with lateral readout option

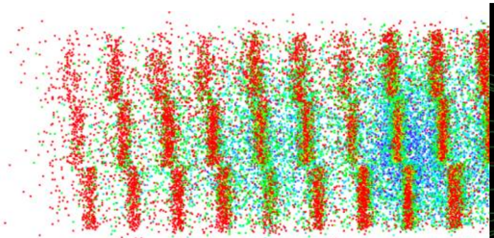
September 2018 CERN-PS: a module with hadronic calorimeter for pion containment and **integrated t_0-layer**



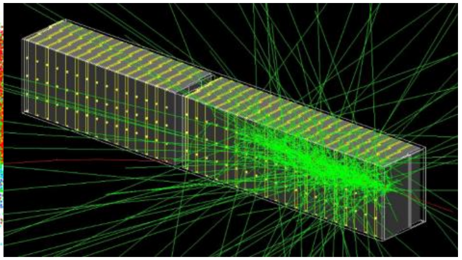
- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match (*In progress*).



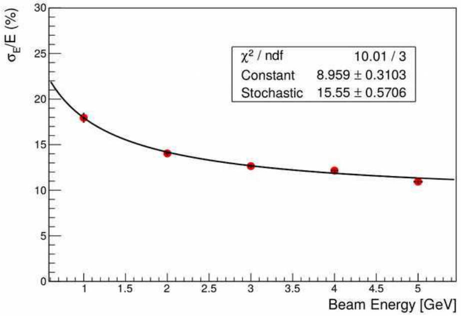
Efficiency maps



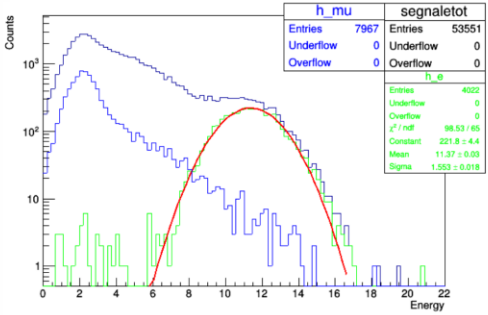
Simulation



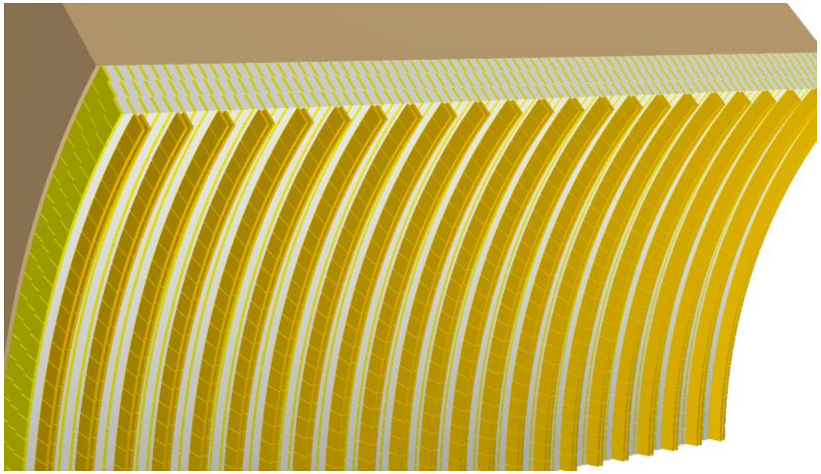
Resolution



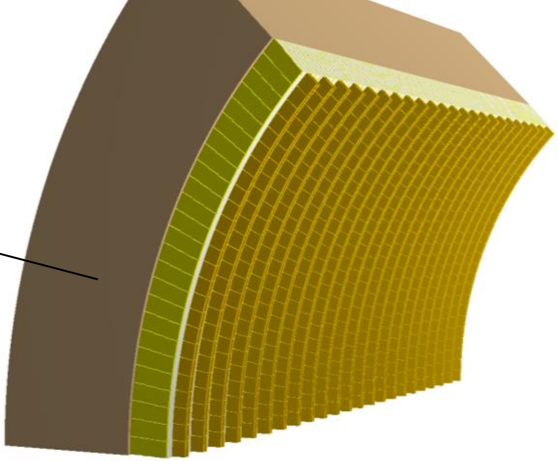
PID

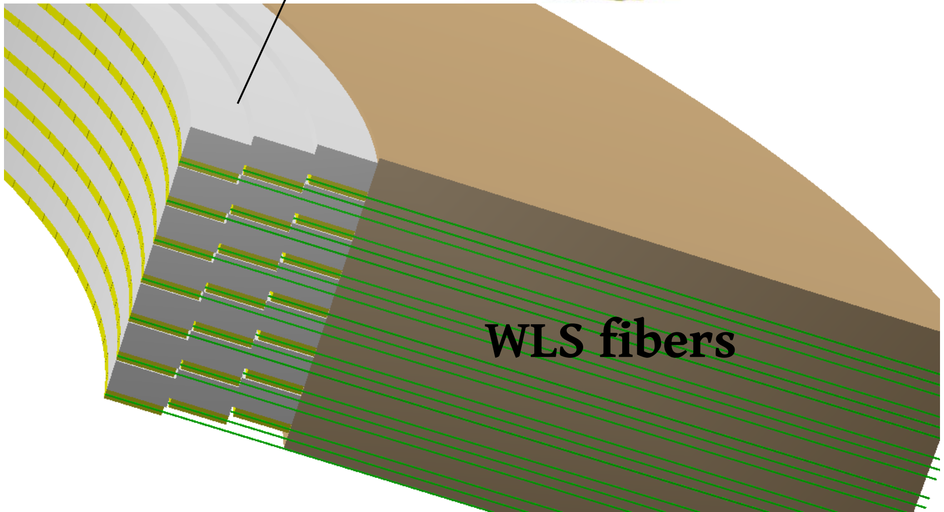


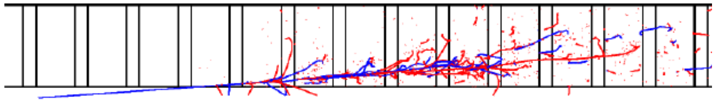
The tagger demonstrator



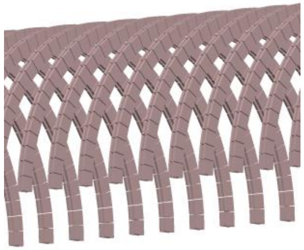
- Length ~ **3 m**
  - allows the containment of shallow angle particles in realistic conditions
- Fraction of ϕ
- Due by 2021







The photon veto



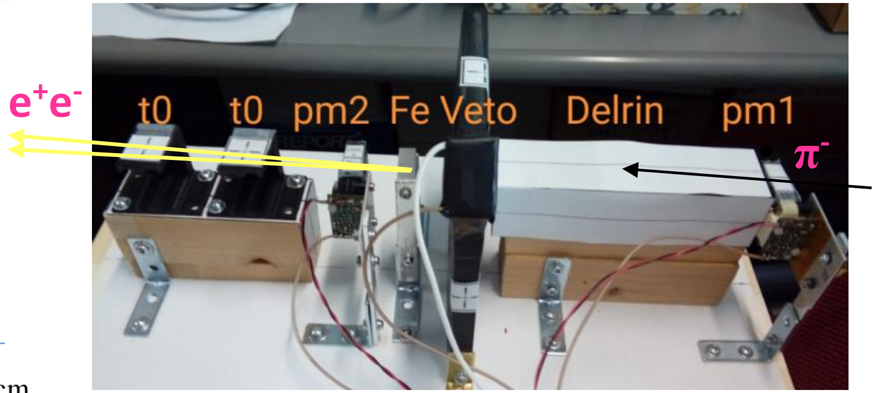
At CERN-PS T9 line 2016-2018

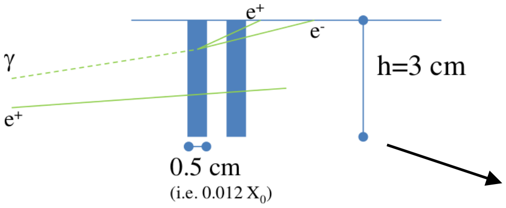
- **γ / e^+ discrimination + timing**
- scintillator ($3\times3\times0.5$ cm^3) + WLS Fiber (40 cm) + SiPM

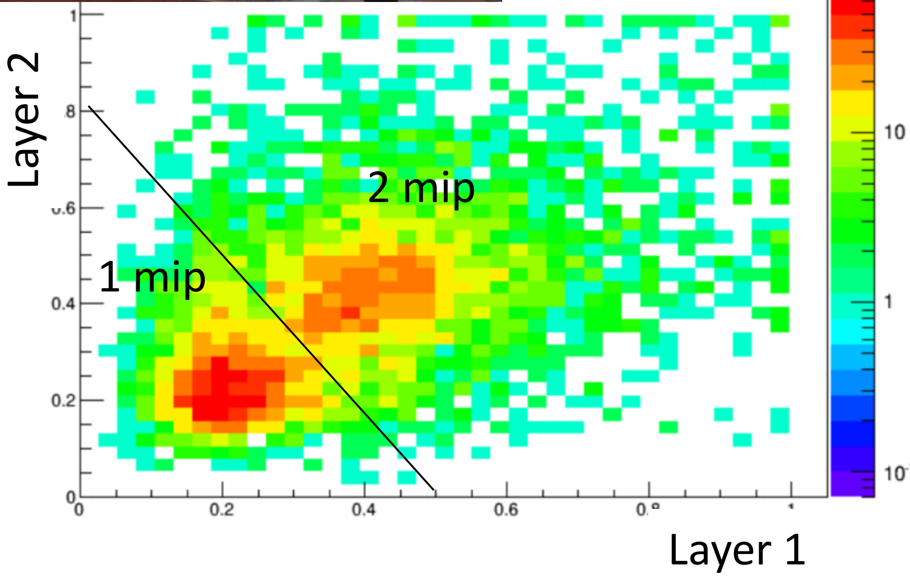
- light collection efficiency → >95%
- time resolution → **$\sigma_t \sim 400$ ps**
- 1mip/2mip separation

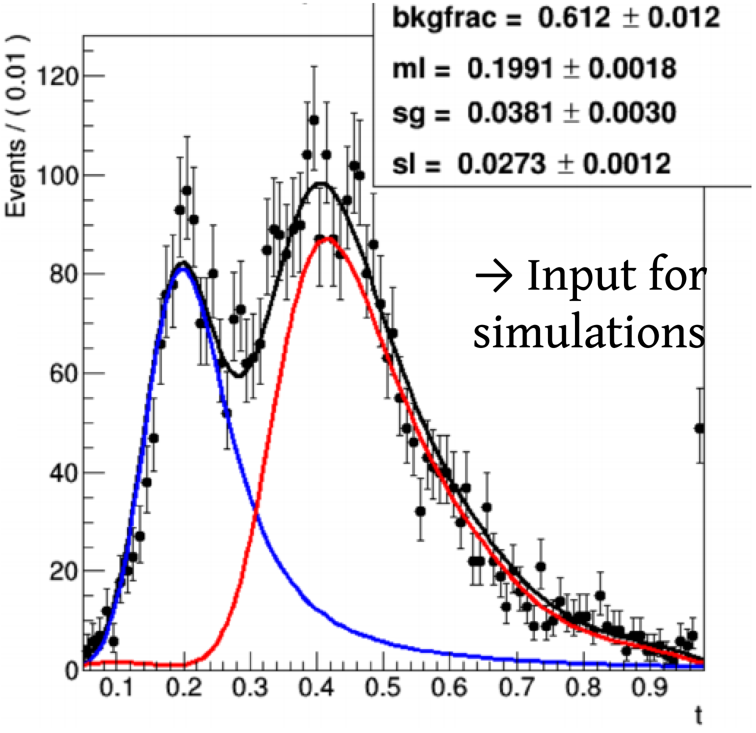
charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 + $\overline{\text{VETO}}$ +PM2









→ Input for simulations

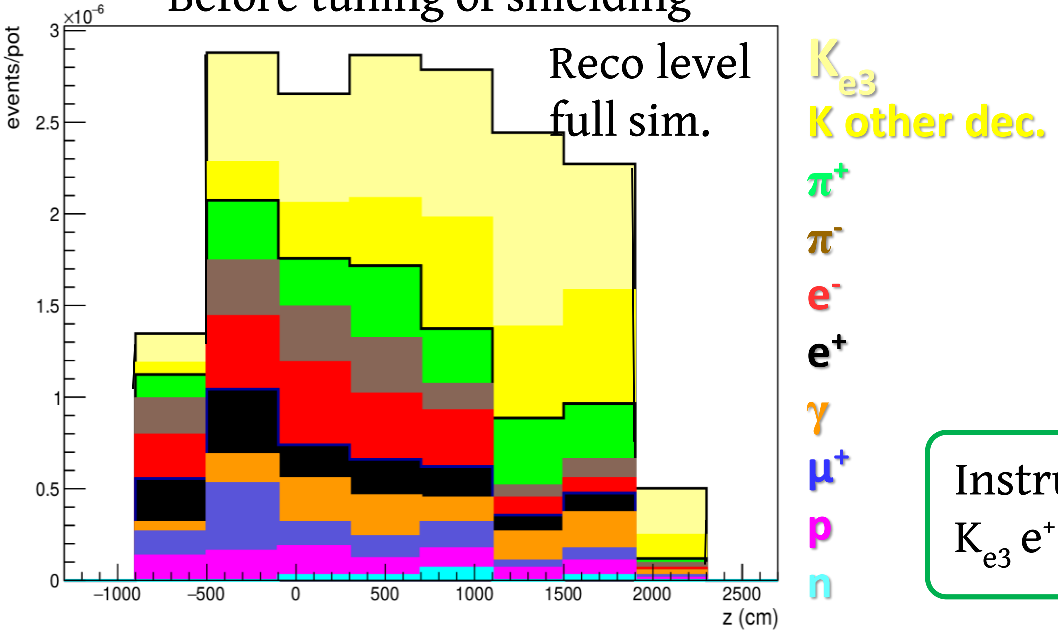
K_{e3} positrons reconstruction

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

Analysis chain

Event Builder →	Identify the **seed** of the event (UCM with largest energy deposit in inner layer and > 20 MeV). **Cluster neighboring cells** close in time. **Iterate** on not-yet-clustered cells.
e/π/μ separation →	**Multivariate** analysis based on **6 variables** (pattern of the energy deposition in the calorimeter) with TMVA
e/γ separation →	Signal on the tiles of the **photon veto (0-1-2 mip)**

Before tuning of shielding



Reco level full sim.

ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

ϕ cut → **0.46**

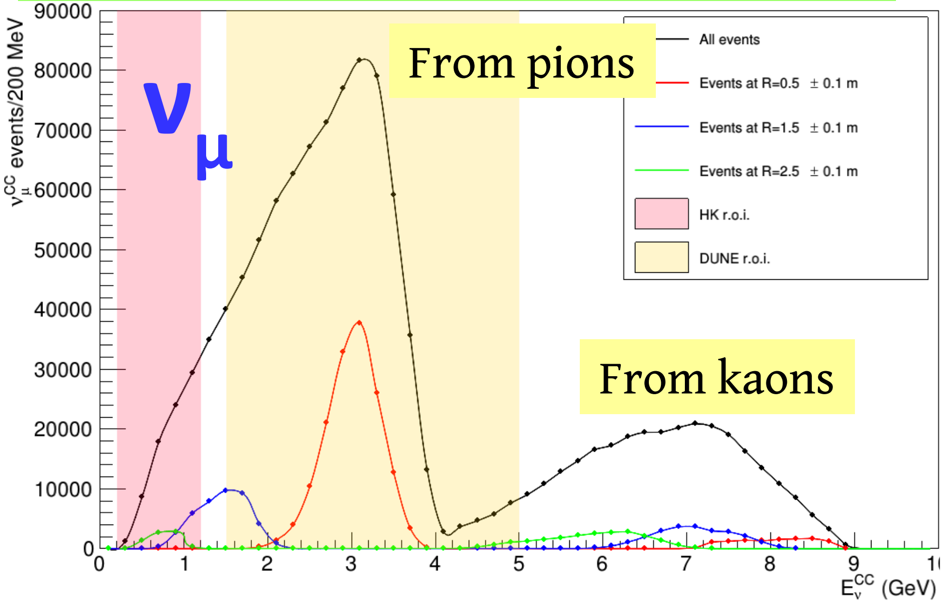
Instrumenting half of the decay tunnel:
K_{e3} e^+ at single particle level with a S/N = 0.46

Neutrino events per year at the detector

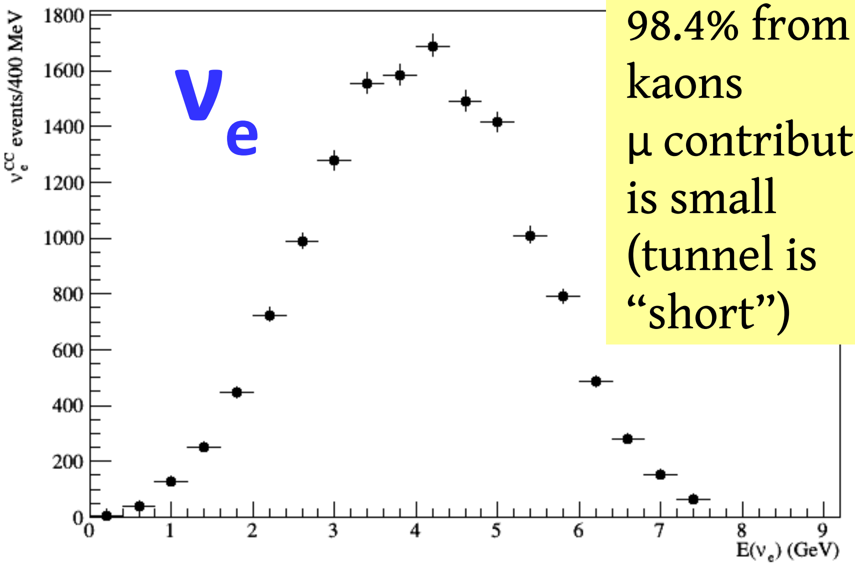
- **Detector mass:** 500 t (e.g. Protodune-SP or DP at CERN, ICARUS at Fermilab, WC at J-PARC)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5 x 10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5 x 10^{20} pot at FNAL

- 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 $K_{\mu 2}$).
- ν_μ **from π** : μ detectors downstream of the hadron dump (under study)

1.2 million ν_μ Charged Current per year



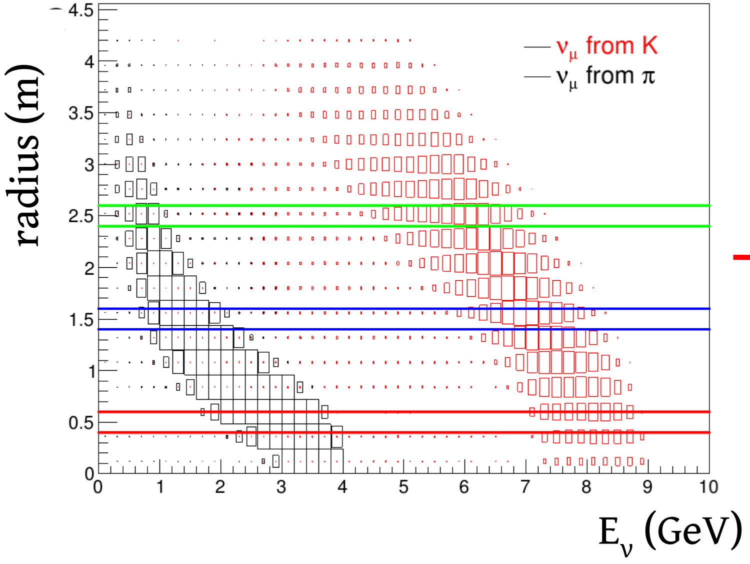
14000 ν_e Charged Current per year

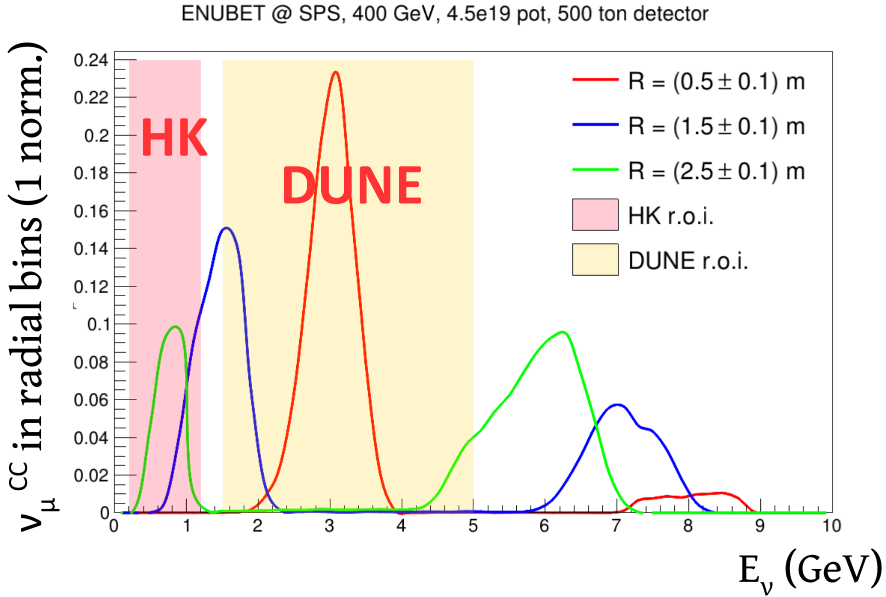


98.4% from kaons
μ contribution is small (tunnel is "short")

ν_μ CC events at the ENUBET narrow band beam

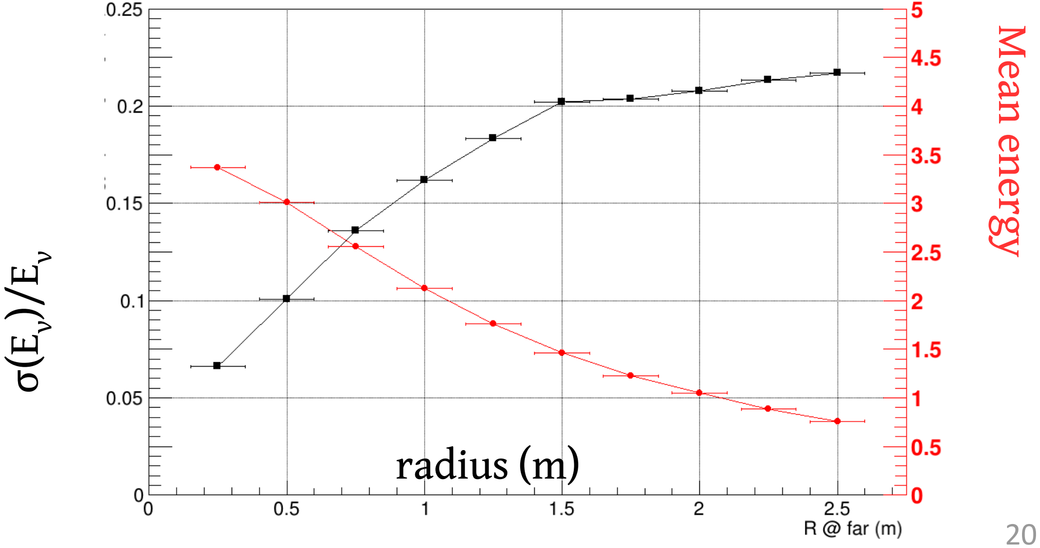
The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.





The beam width at fixed R (≡ ν energy resolution for π component) is:

- 8 % for r ~ 50 cm, $<E_\nu>$~ 3 GeV
- 22% for r ~ 250 cm, $<E_\nu>$ ~ 0.7 GeV



+ Binning in R allows to explore the energy domains of **DUNE/HK** and enrich samples in specific processes (quasi-elastic, resonances, DIS) for **cross section** measurements

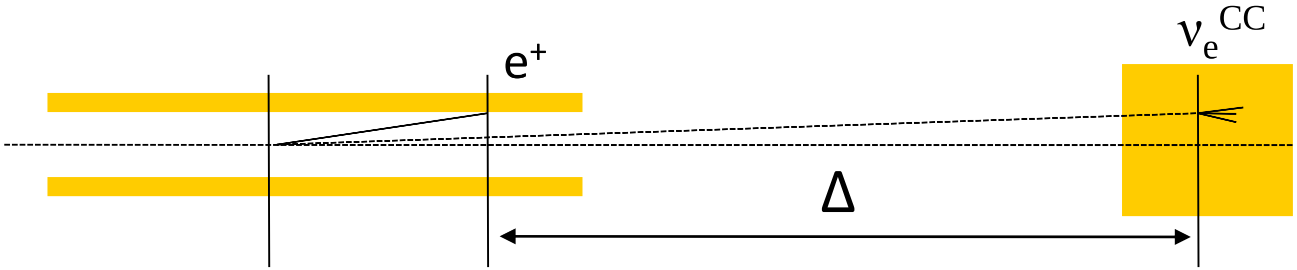
Time tagged neutrino beams

- Event time dilution → **Time-tagging**
- Associating a single neutrino interaction to a tagged e^+ with a small "accidental coincidence" probability through time coincidences

E_ν and flavor of the ν measured "a priori" event by event.
Compare "E_ν from decay kinematics " ↔"E_ν from ν interaction products "

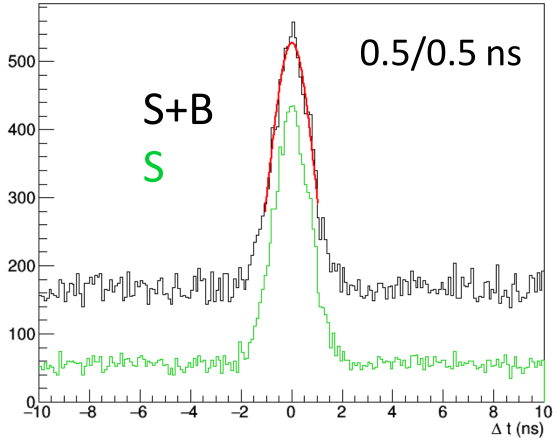
Time coincidence of ν_e^{CC} and e^+

$|\delta t - \Delta/c| < \delta$



δ = combined t-resolution (e^+ tagger and ν detector)

Presently with 2.5 × 10^{13} pot / 2s slow extraction:
genuine K_{e3} cand. : 80 MHz → **1 every ~ 12 ns**
background K_{e3} cand. ~ 2 x → 1 cand. every ~ 4 ns
With δ=0.5 ⊕ 0.5 ns resolutions: already interesting!
S/N ratio will likely improve with further tuning.



Toy MC

Conclusions and next steps

ENUBET is a **narrow band beam** with a 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 the first two and a half years

- first **end-to-end simulation of the beamline**
- feasibility of a **purely static focusing system** (10^6 ν_μ^{CC} , 10^4 ν_e^{CC} /y/500 t)
- **full simulation of e^+ reconstruction**: **single particle level** monitoring
- completed the **test beams** campaign
- strengthened the **physics case:** → slow extraction + "**narrow band off-axis technique**"

The ENUBET technique is **very promising** and the results we got so far **exceeded our expectations**

- 2019: freeze **light readout technology** (shashlik versus "lateral readout")
- 2019: Further **tuning of the beamline design** (improve current S/N for e^+)
- **CDR** at the end of the project (2021): **physics** and **costing**
- Build the **demonstrator prototype** of the tagger (2021)

THANK YOU!