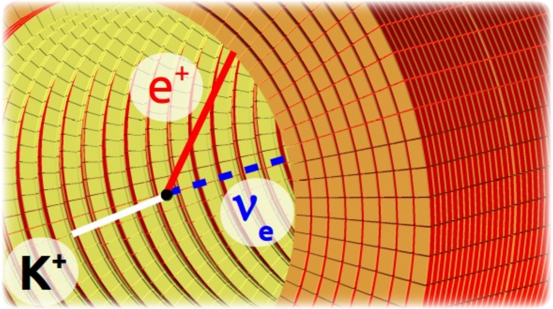


Decay tunnel instrumentation for the ENUBET neutrino beam

Valerio Mascagna

Università degli Studi dell'Insubria & INFN - MiB

Siena, Oct. 14-17 – IPRD19

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
- The instrumented tunnel and the tagger
- Prototyping and testbeam results
- Conclusions and outlooks

Enhanced NeUtrino BEams from kaon Tagging

http://enubet.pd.infn.it

Project approved by the European Research Council (ERC)
5 years (06/2016 – 06/2021)
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

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, 12 institutions:

60 physicists, 12 institutions

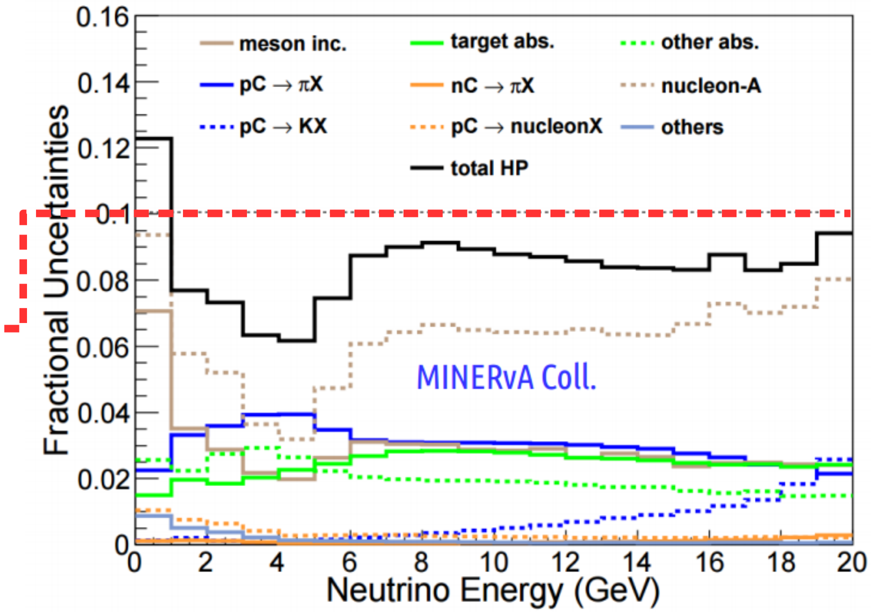
Flux uncertainty and $\nu_{e,}\nu_{\mu}$ cross sections

Last 10 years: knowledge of **σ(ν_μ)** 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 **σ(ν_e)** we use the beam contamination (no intense/pure sources of GeV ν_e): data still sparse

Gargamelle, T2K, NOvA, MINERvA

Poor knowledge of **σ(ν_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:

> 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 ($\pi \to \mu\nu$, $K \to \mu\nu$,

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

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}

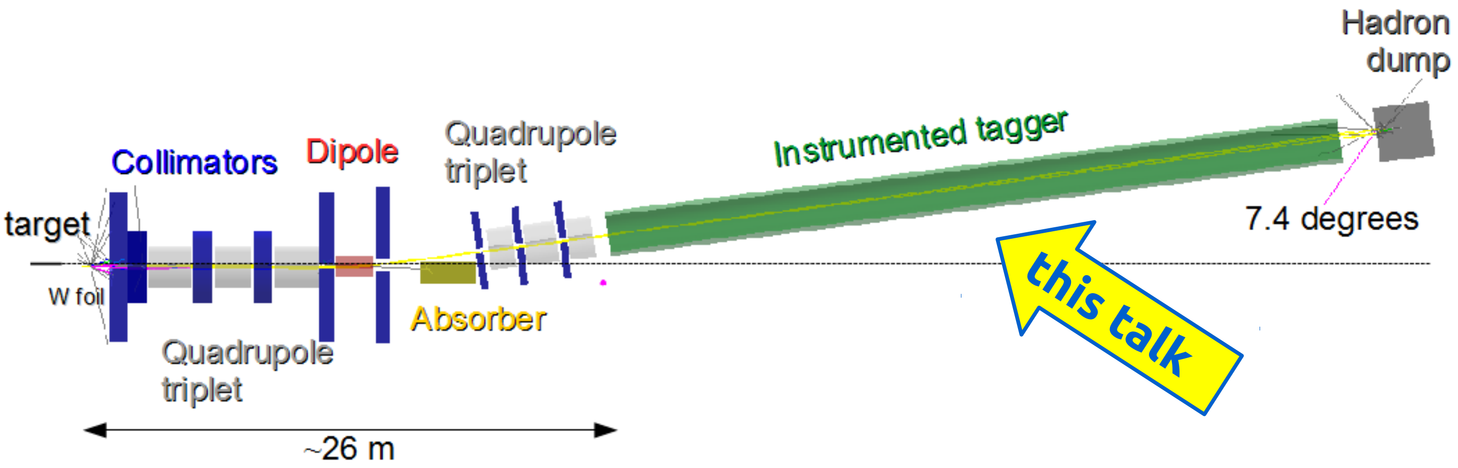
$\mu^+ \nu_\mu$	(63.55 ±0.11) %
$\pi^0 e^+ \nu_e$	(5.07 ±0.04) %
$\pi^0 \mu^+ \nu_\mu$	(3.353±0.034) %
$\pi^+ \pi^0$	(20.66 ±0.08) %
$\pi^+ \pi^0 \pi^0$	(1.761±0.022) %
$\pi^+ \pi^+ \pi^-$	(5.59 ±0.04) %

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 particle yields

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**

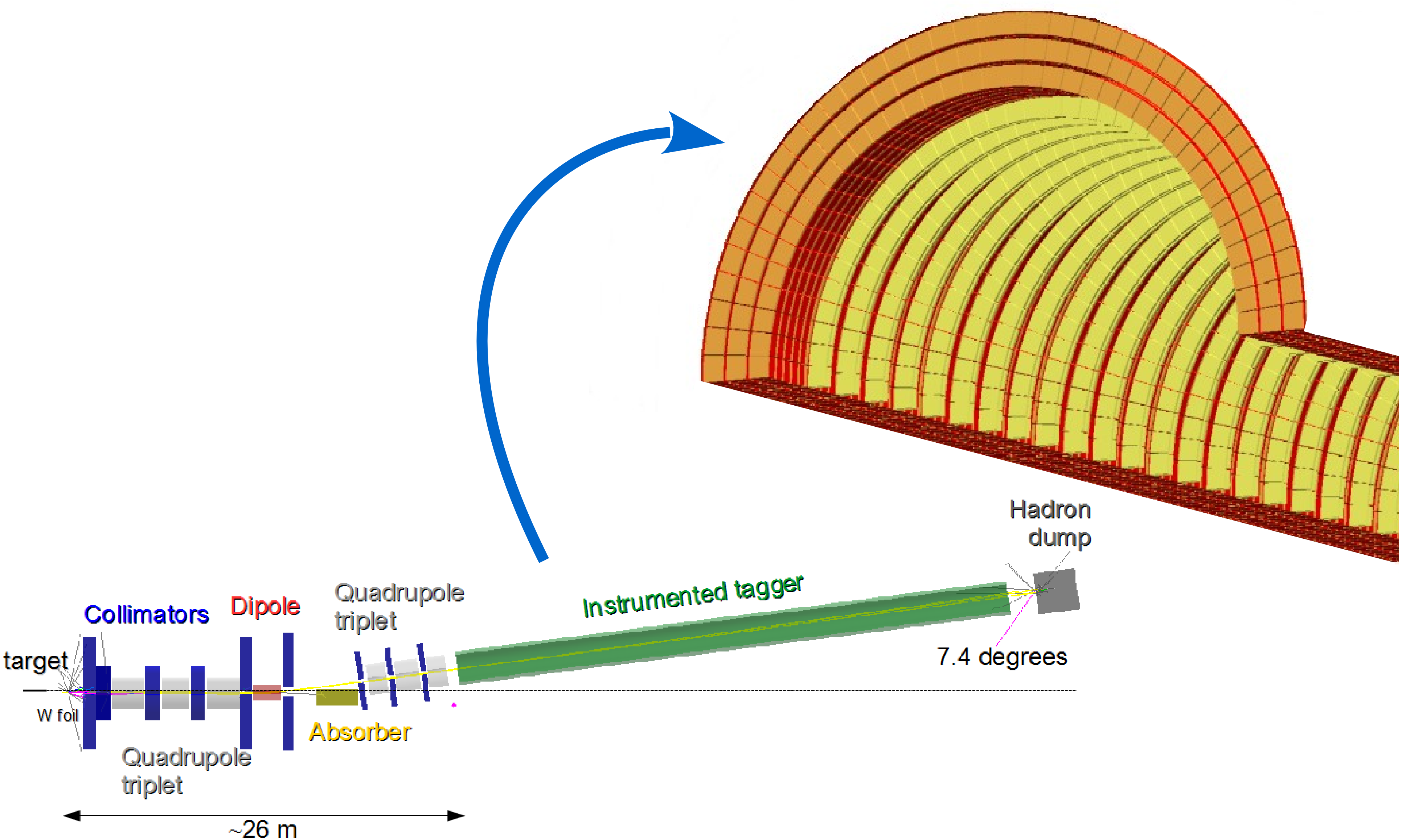
(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

The horn-based option still allows ~x 5 faster statistics but the static option gained momentum since initial estimates were ~ x 4 too conservative wrt present simulations!

Furthermore … advantages of the static extraction:

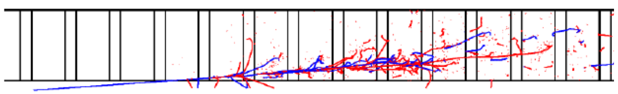
- No need for fast-cycling horn
- Strong **reduction of the rate** (pile-up) in the instrumented decay tunnel
- Pave the way to a "**tagged neutrino beam**" →
  - ν interaction at the detector **associated in time** with the observation of the **lepton from the parent hadron** in the decay tunnel [**under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

The ENUBET tagger

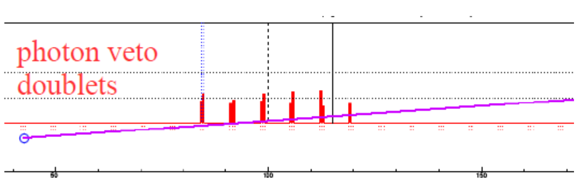


The ENUBET tagger

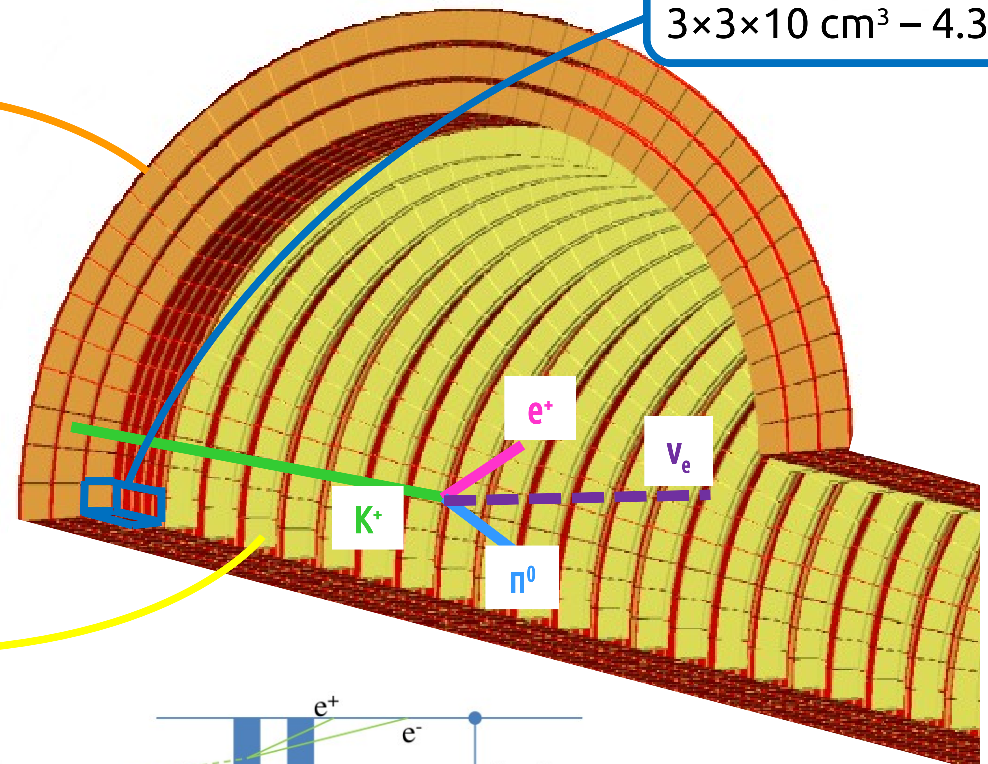
Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ **$e^+/\pi^\pm/\mu$ separation**

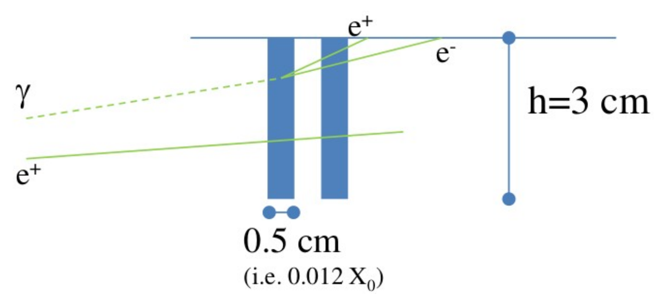


Integrated photon veto
Plastic scintillators
Rings of 3×3 cm² pads
→ **π^0 rejection**



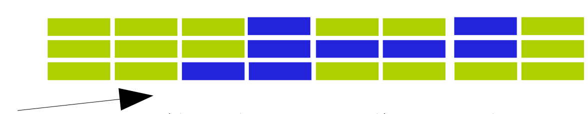
Ultra **C**ompact **M**odule
3×3×10 cm³ – 4.3 X_0





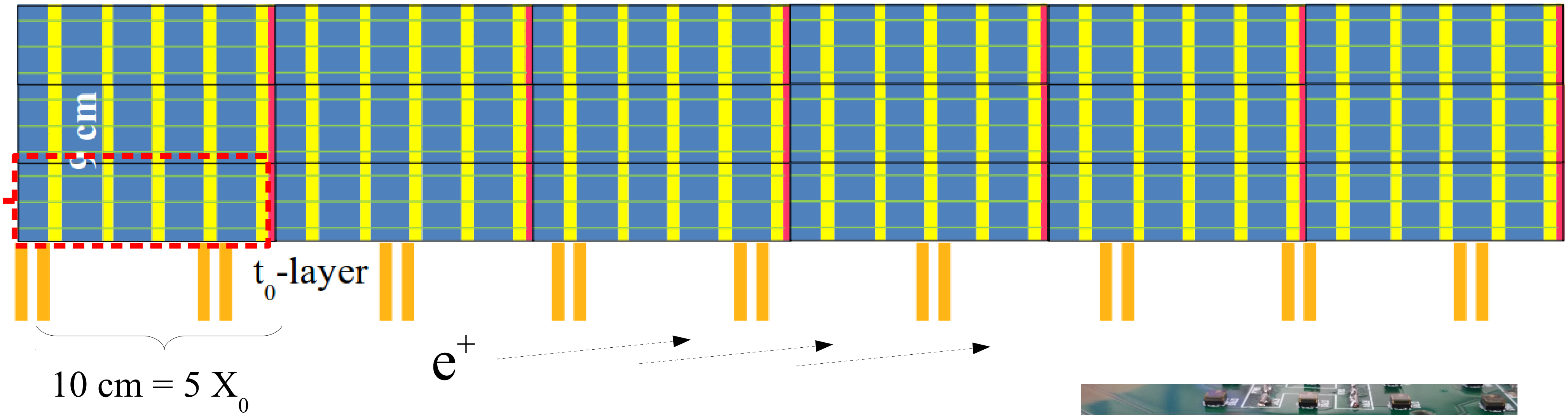
e^+ (signal) topology

π^0 (background) topology

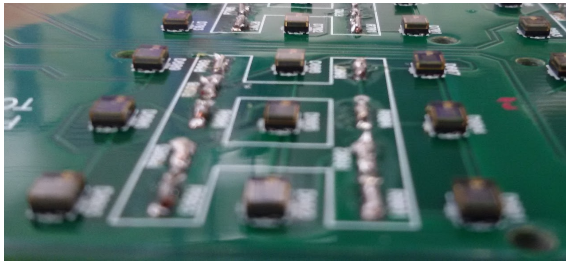


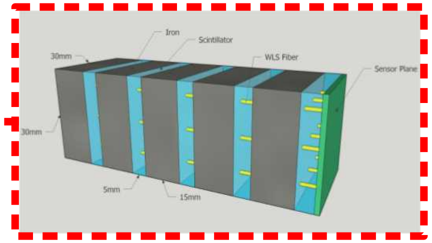
π^+ (background) topology

The tagger: shashlik calorimeter

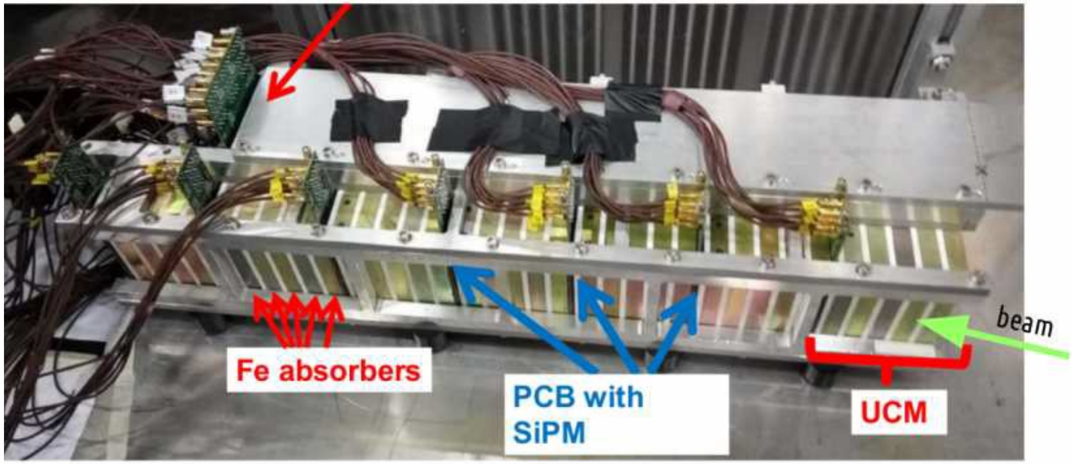


UCM: ultra compact module.
SiPM and electronics **embedded** in the shashlik calorimeter

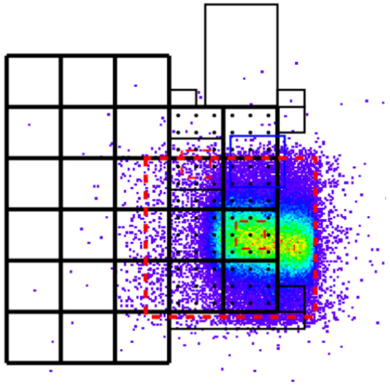




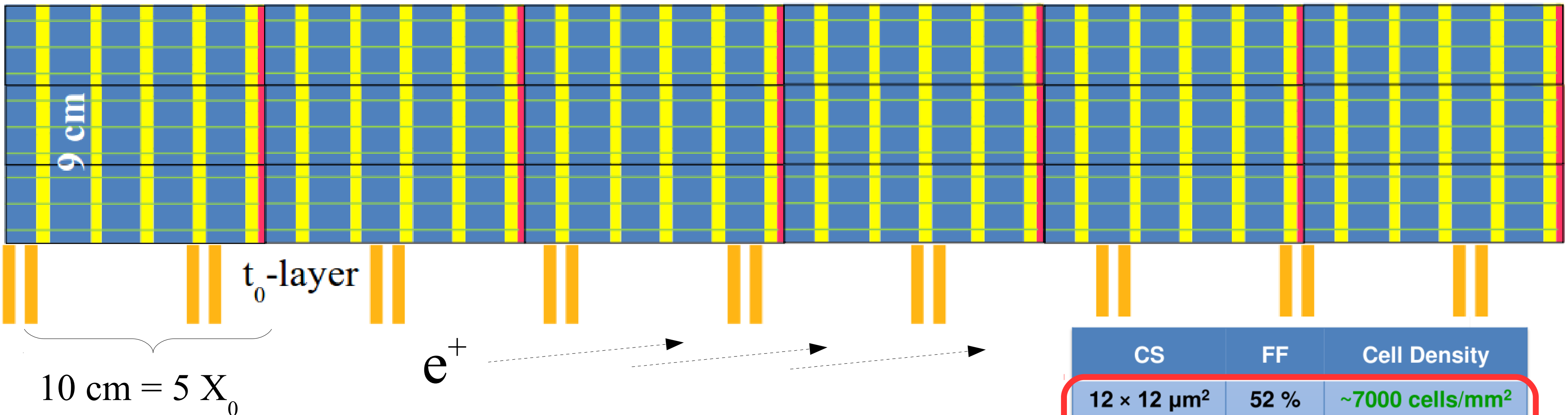
CERN PS test beam Nov 2016



Beam spot



The tagger: shashlik calorimeter SiPMs



UCM: ultra compact module.

5 x (ABSORBER + SCINTI) → **~4 X_0**

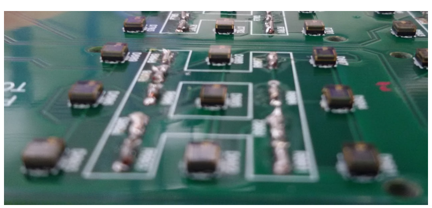
Fe-15mm + EJ200

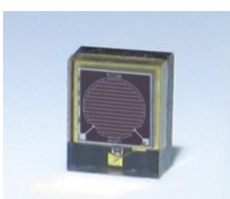
TiO2 painting

WLS: Kuraray Y11 double clad, 1mm diameter

9 SiPMs summed (AC coupled, 47 pF)

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

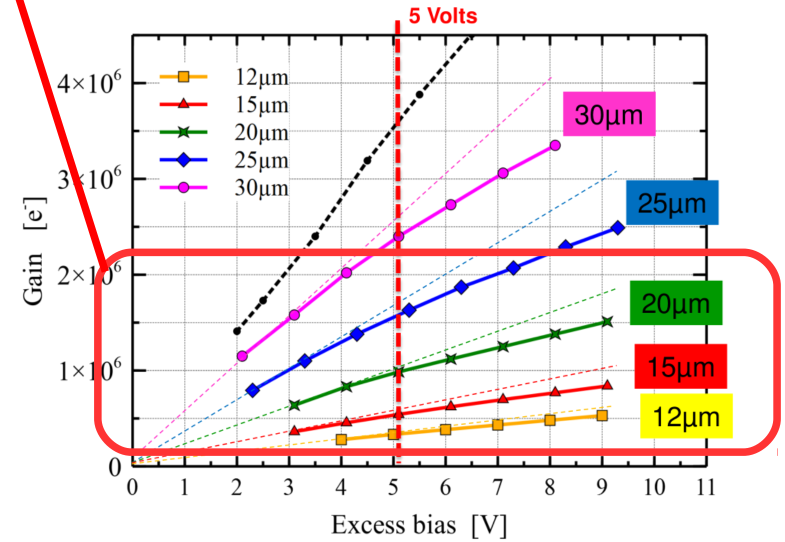




Required:
Fast ~10ns ← avoid pileup
Rad.hard (10^{12} n/cm^2)

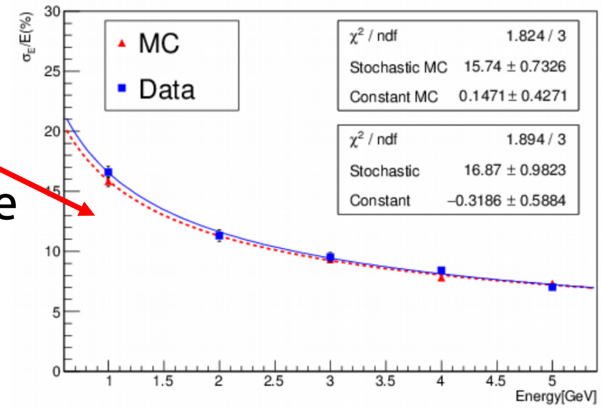
Tested

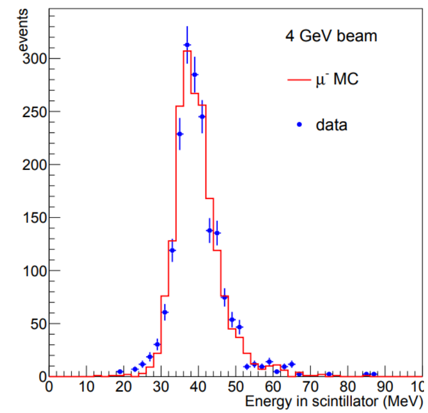
CS	FF	Cell Density
12 × 12 μm²	52 %	~7000 cells/mm²
15 × 15 μm²	62 %	~4444 cells/mm²
20 × 20 μm²	66 %	2500 cells/mm²
25 × 25 μm²	72 %	1600 cells/mm²
30 × 30 μm²	77 %	~1111 cells/mm²



Tested response to MIP, e and π⁻

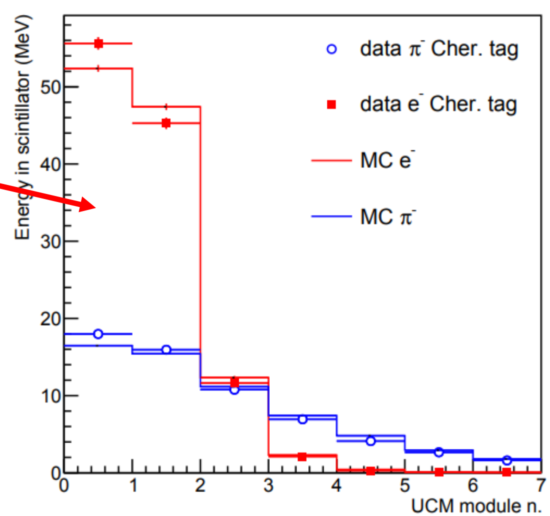
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips

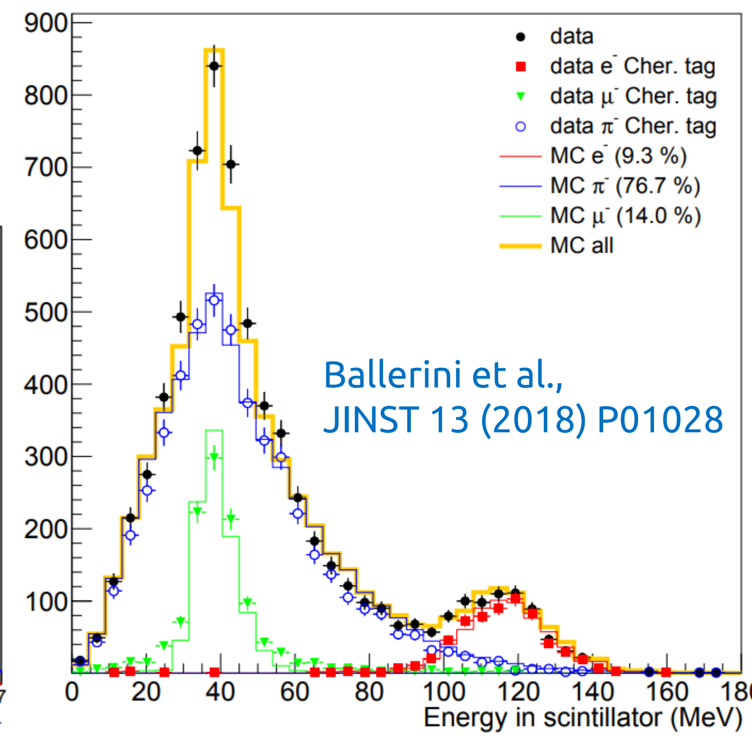




MC/data already in good agreement

Longitudinal profiles of partially contained π reproduced by MC @ 10% precision



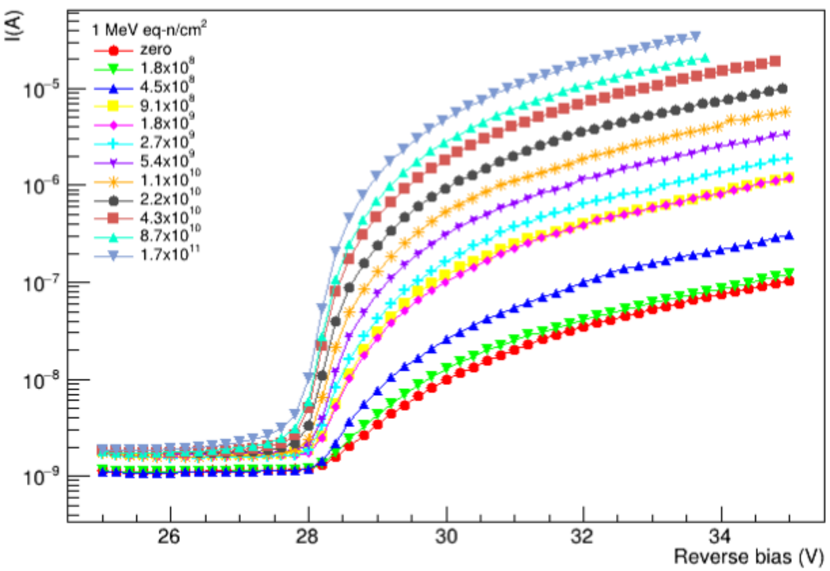


Ballerini et al., JINST 13 (2018) P01028

SiPM irradiation @ LNL

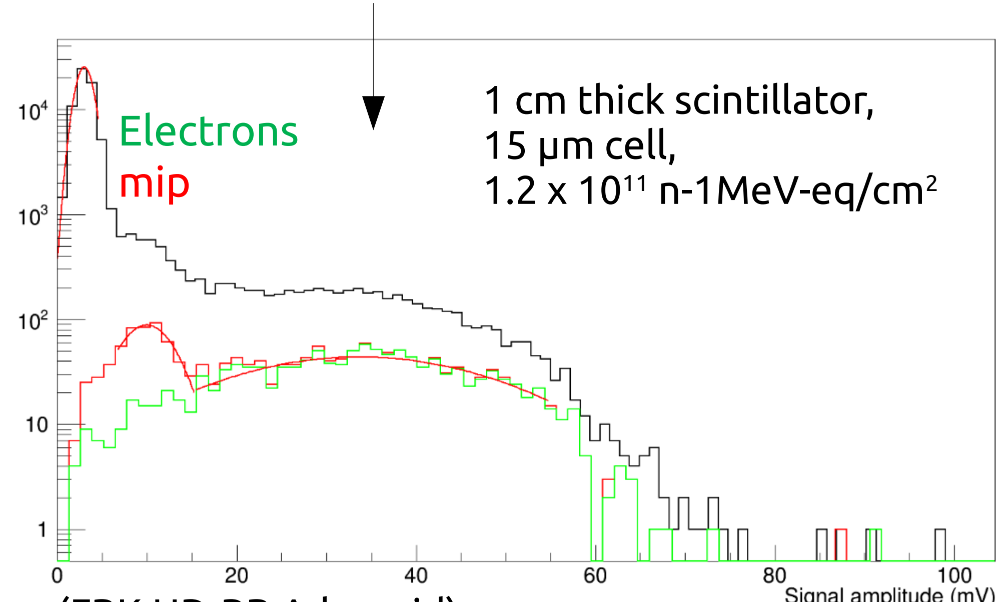
Dark current vs bias at increasing n fluences

FBK HD-RGB 1x1mm^2 12µm cell size

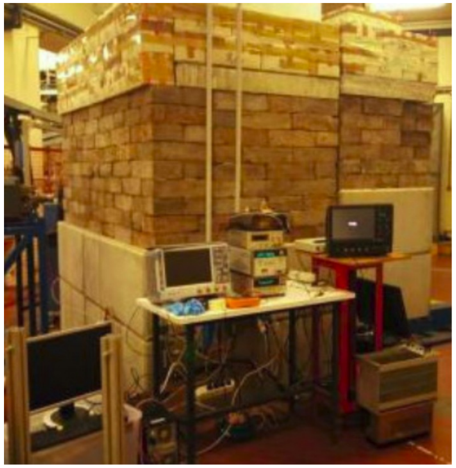


F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

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



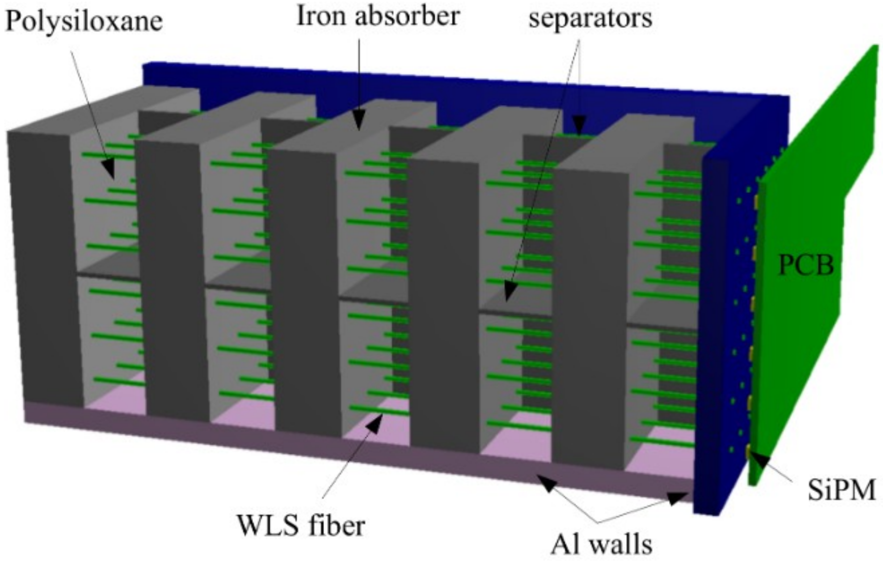
(FBK-HD-RB Advansid)

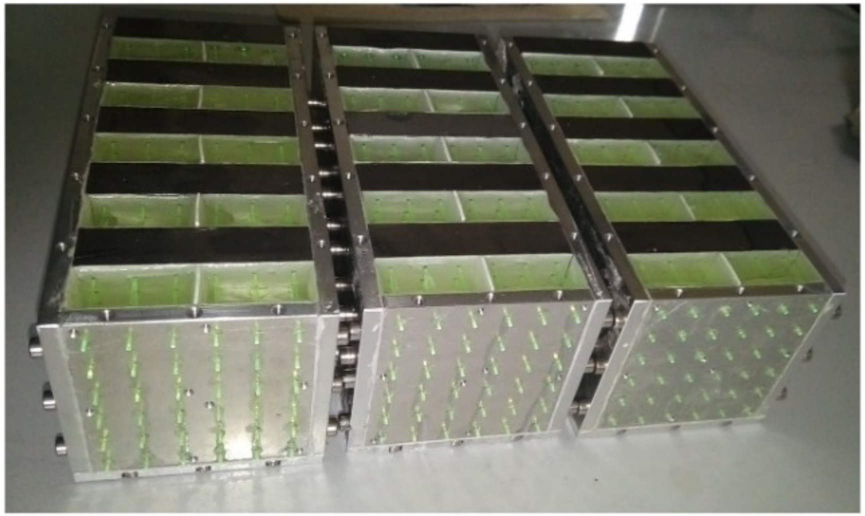


- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used from **channel-to-channel intercalibration** even after maximum irradiation.

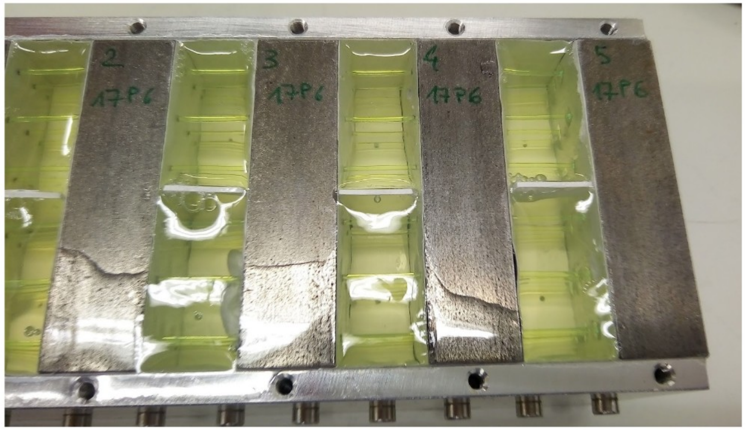
The tagger: polysiloxane prototypes

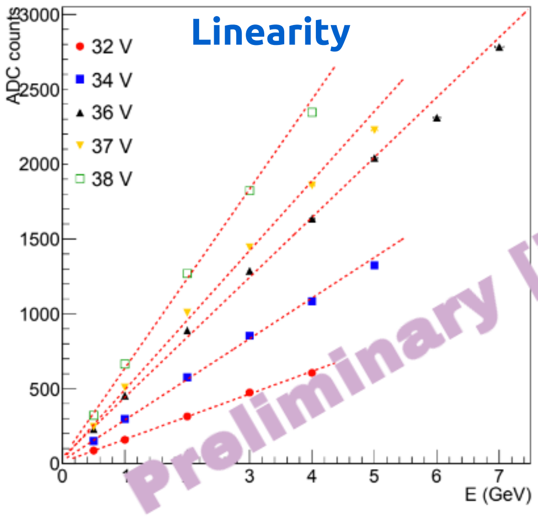
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)
A **$13X_0$ shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)

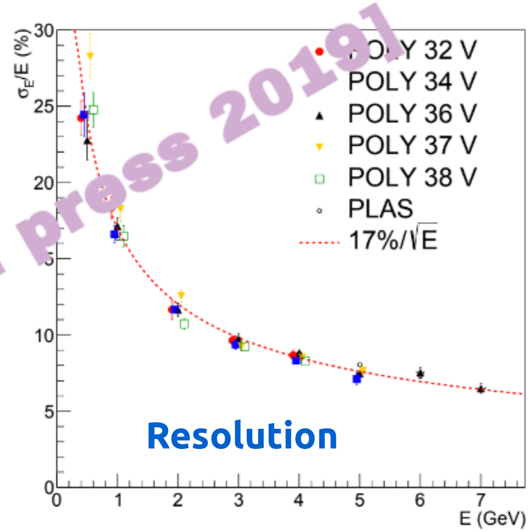




15 mm thick scintillators
to compensate reduced light yields





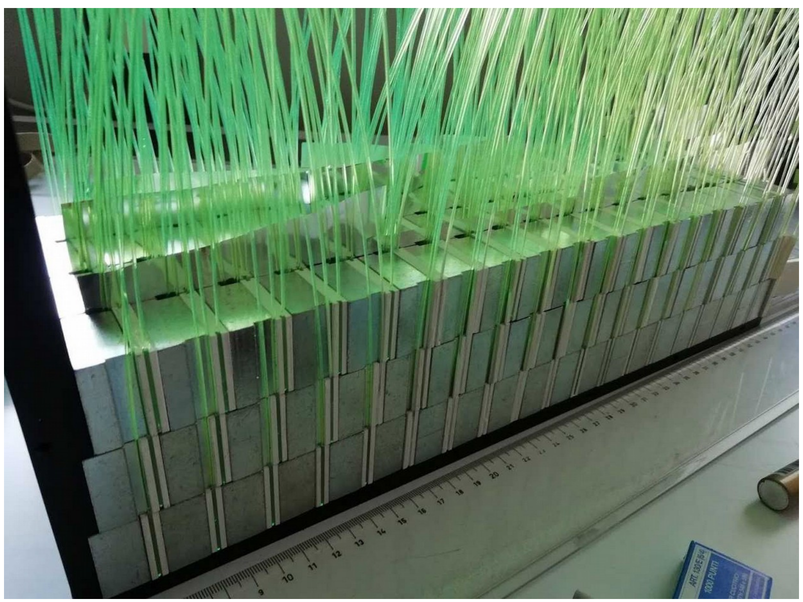


The tagger: lateral readout option

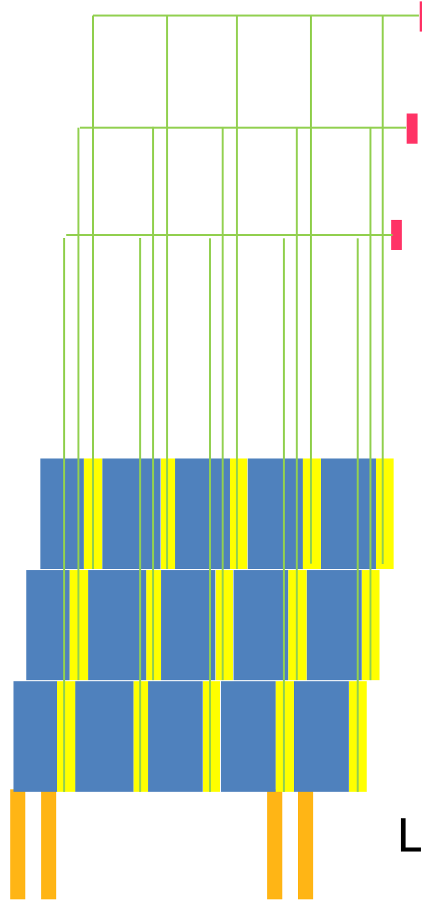
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM)
SiPM are not immersed anymore in the hadronic shower → less compact but…

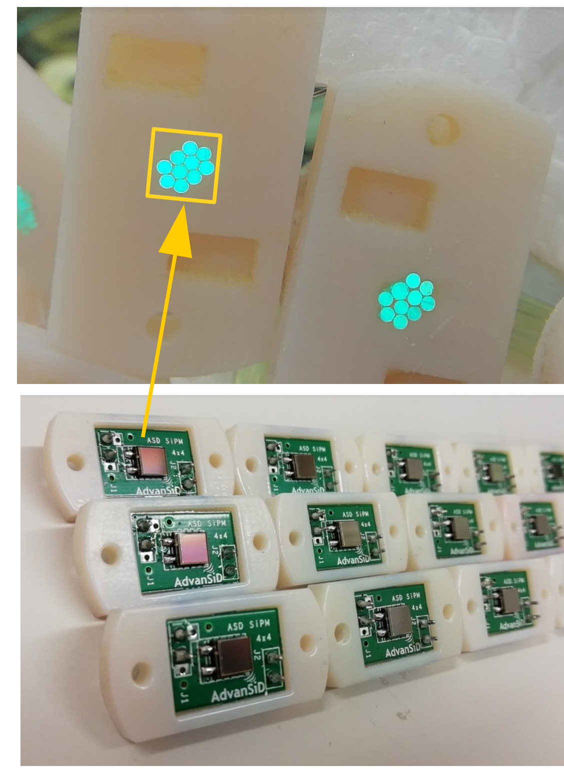
much **reduced neutron damage** (larger safety margins), better **accessibility**, possibility of replacement. Better reproducibility of the **WLS-SiPM optical coupling**.

Sampling calorimeter with
lateral WLS light collection



May 2018, CERN-PS test beam



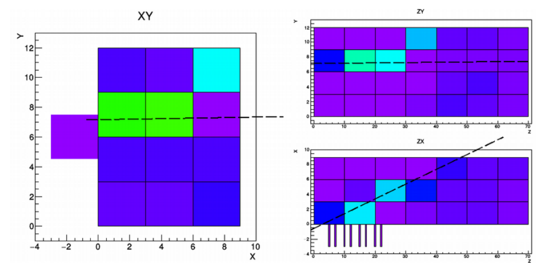


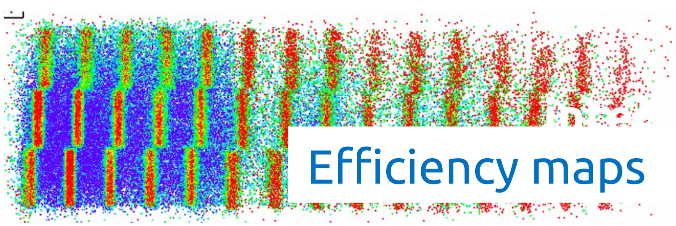
Large SiPM (4x4 mm²) for 10 WLS

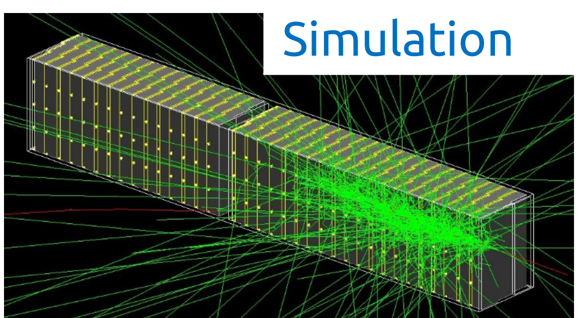
The tagger: lateral readout option

September 2018 CERN-PS: a module with hadronic cal. for pion containment + **integrated t_0-layer!**

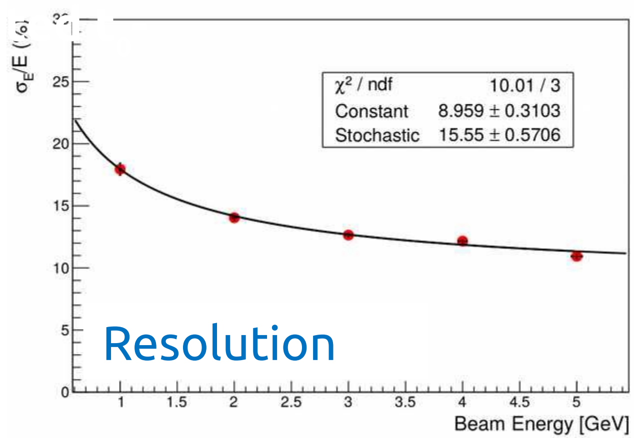
- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match. In progress.

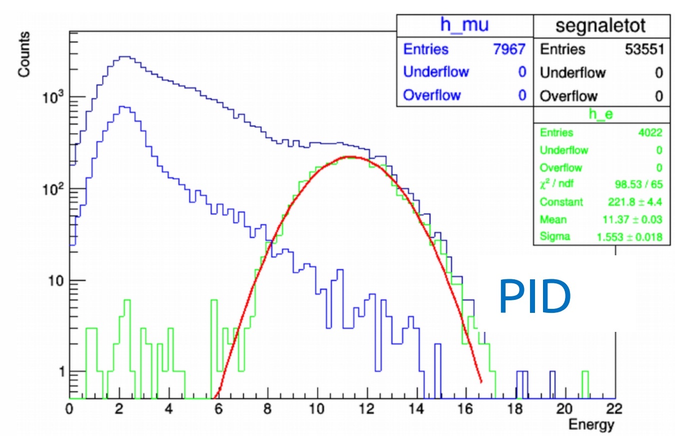






Preliminary results





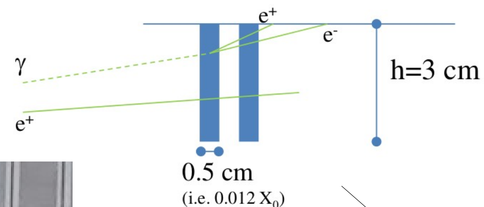
The tagger: photon-veto

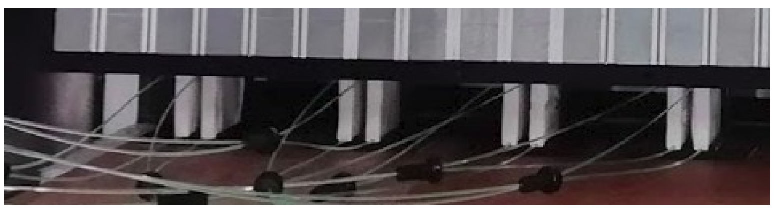
@ CERN-PS T9 line 2016-2018

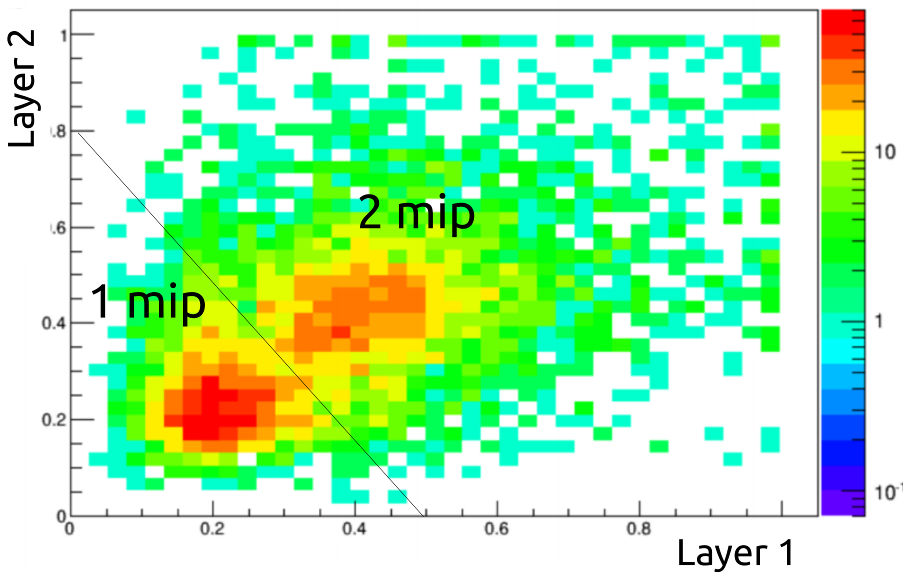
- **γ / e^+ discrimination + timing**

scintillator ($3\times3\times0.5$ cm^3) + WLS Fiber (40 cm) + SiPM

- light collection efficiency → >95%
- time resolution → **σ_t ~ 400 ps**
- 1mip/2mip separation

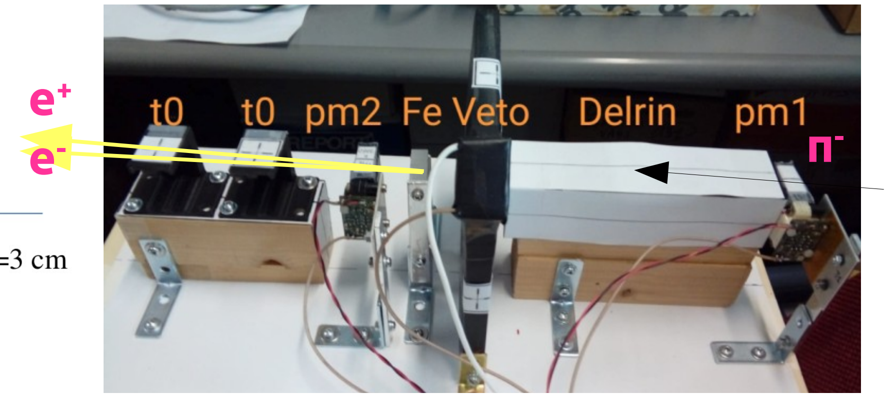


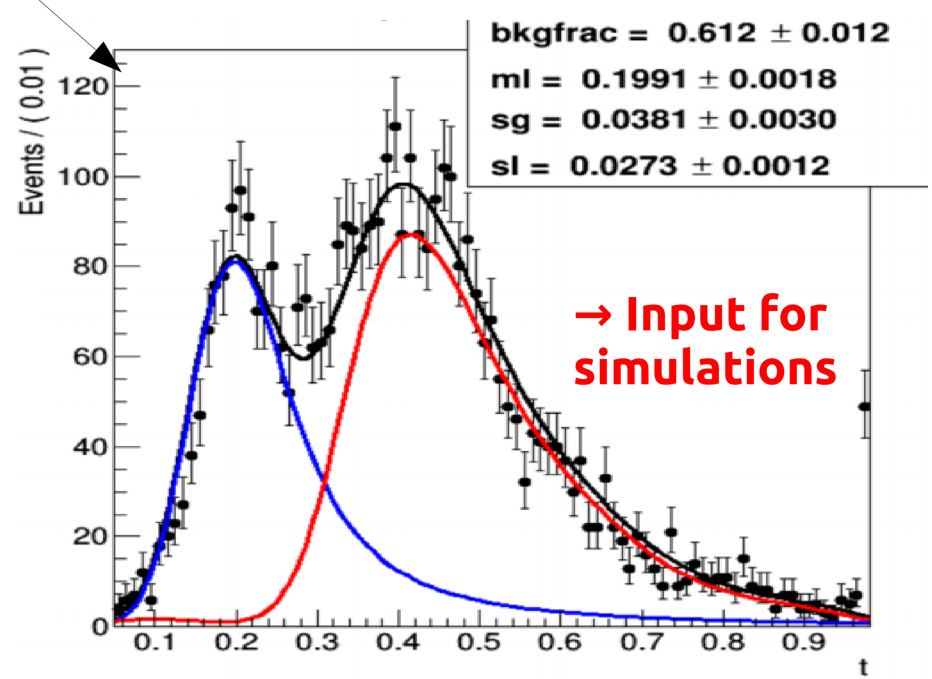




charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

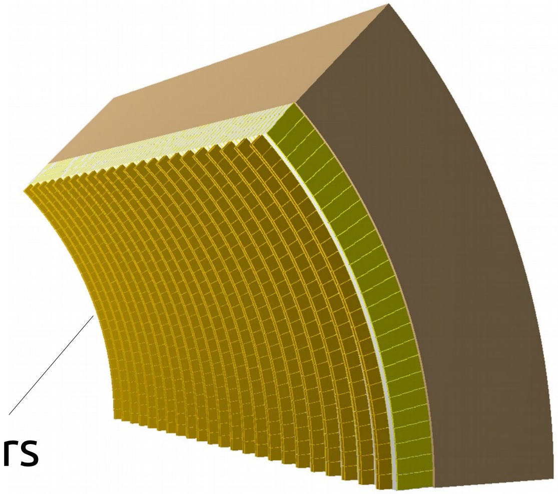
Trigger: PM1 + VETO +PM2

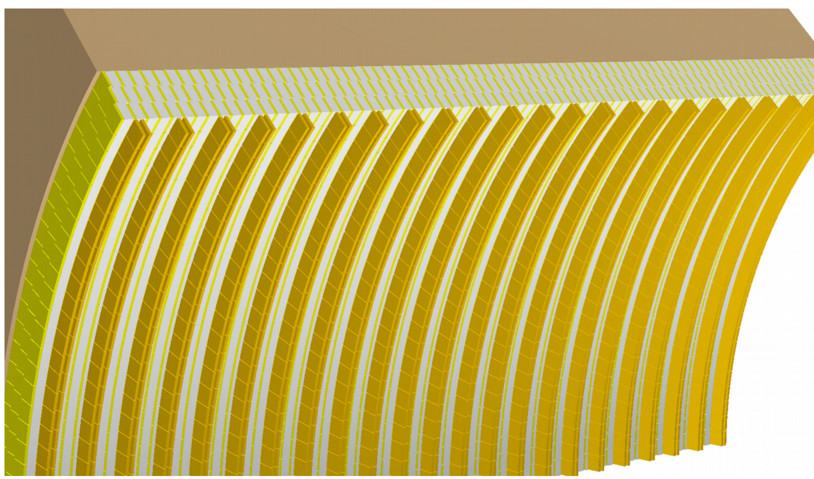


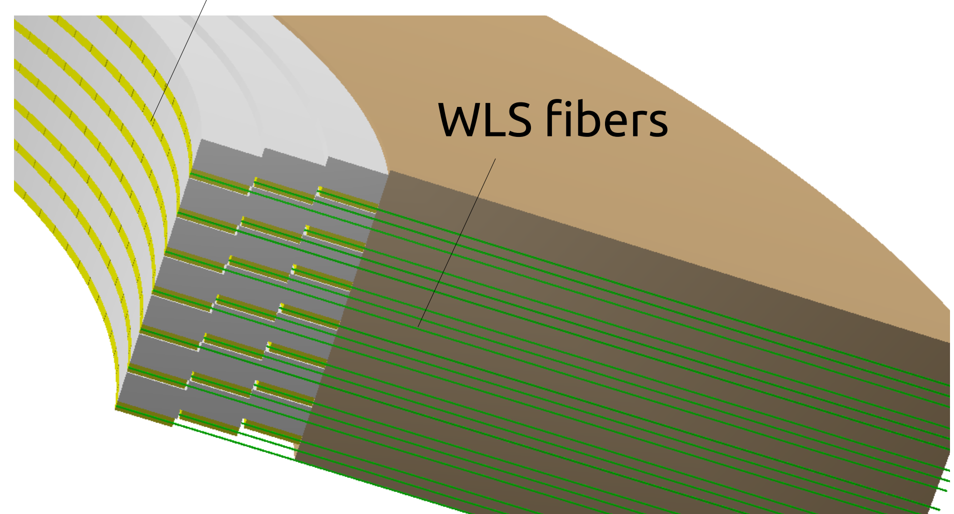


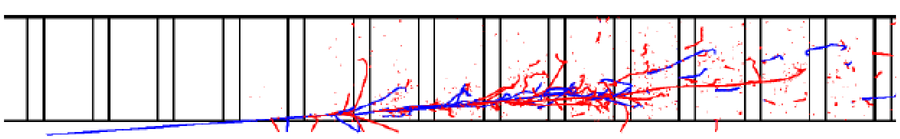
The tagger **demonstrator**

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









ENUBET in the neutrino platform

- **CERN: already gave a prominent contribution for the success of ENUBET**
  - **Machine studies performed at the SPS**
  - **East Area beamline** for the characterization of the prototypes

- For **2019-2021 → recognition in the Neutrino Platform as ENUBET/NP06**
  - Support and consulting from CERN accelerator experts in collaboration with personnel by the project
  - Test of the final proton extraction scheme in the SPS after LS2
  - Use of the renovated East Area for the final validation of the demonstrator

132th meeting of the SPSC, 22nd–23rd/01/2019
https://cds.cern.ch/record/2654613/files/SPSC-132.pdf

228th meeting of the Research Board, 5/3/2019
https://cds.cern.ch/record/2668519/files/M-228.pdf

MoU being finalized

5.12 The physics case of the **ENUBET** project and the exciting possibilities of a tagged neutrino beam are recognized by the SPSC. The committee recognizes the technological development for a neutrino beam without a horn using a quadrupole-based solution, and appreciates the close collaboration of the ENUBET collaboration with the CERN accelerator sector. The SPSC supports the proposed programme, and welcomes the opportunity to continue reviewing the experiment; test-beam requests will be considered via the standard annual procedure. **The Research Board approved the participation of ENUBET in the Neutrino Platform, with reference NP06, on the understanding that**

Conclusions

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

In the first 2.5 years

- first **end-to-end simulation of the beamline**
- Tested the **"burst" slow extraction** scheme at the CERN-SPS
- 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 **prototyping** and the **test beams** campaign before LS2
- Defined the **final readout scheme** for the tagger

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

CONCLUSIONS & OUTLOOKS

THANK YOU!

ENUBET info/wiki

http://enubet.pd.infn.it/