The ENUBET project

A. Longhin (Padova University and INFN)
on behalf of the **ENUBET Collaboration**

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (G.A. n. 681647).

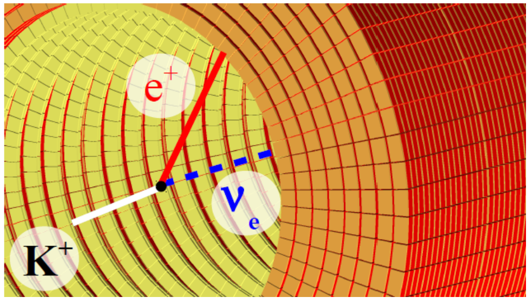
CNNP2020
Conference on Neutrino and Nuclear Physics
Arabella Hotel, Kleinmond
South Africa 24-28/02/2020

Overview and outline

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**

Two pillars:

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



Enhanced NeUtrino BEams from kaon Tagging

ERC-CoG-2015, G.A. 681647 (2016-21)
PI A. Longhin, **Padova University, INFN**

Achievements

- **Beamline simulation + accelerator studies**
- Experimental validation of detector **prototypes**

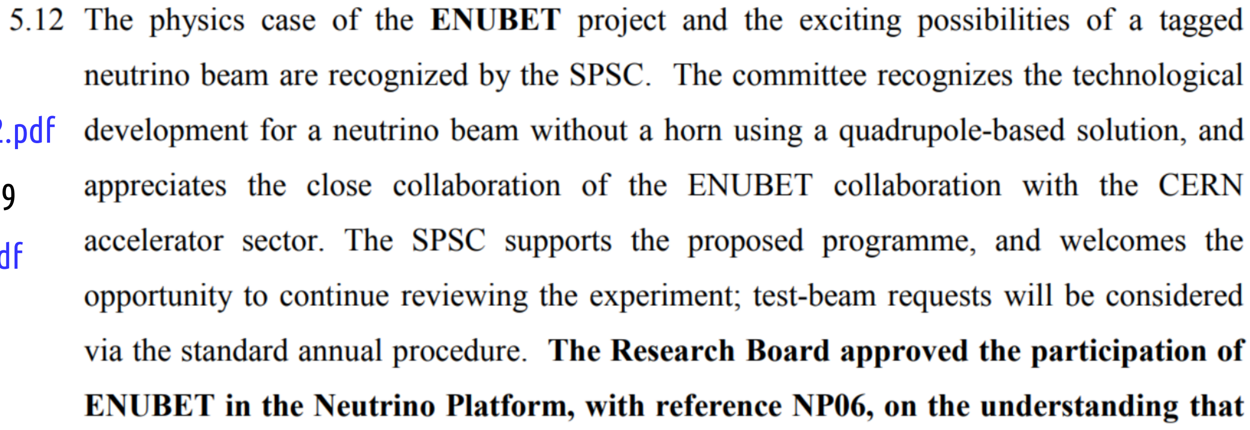
ENUBET: 60 physicists, 12 institutions

ENUBET in the CERN 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

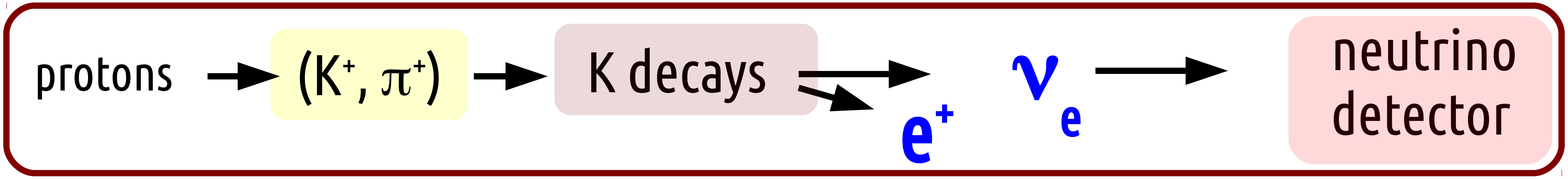


5.12 The physics case of the **ENUBET** project and the exciting possibilities of a tagged neutrino beam are recognized by the SPSC. The committee recognizes the technological development for a neutrino beam without a horn using a quadrupole-based solution, and appreciates the close collaboration of 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**

MoU finalized

Monitored beams

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 **event-by-event**
- "By-pass" **hadro-production, PoT, beam-line efficiency** uncertainties

- **Fully instrumented decay region**

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

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

Removes the **leading source of uncertainty in ν cross section measurements**

To get the correct spectra and avoid swamping the instrumentation → needs a **collimated momentum selected hadron beam** → **only decay products in the tagger**

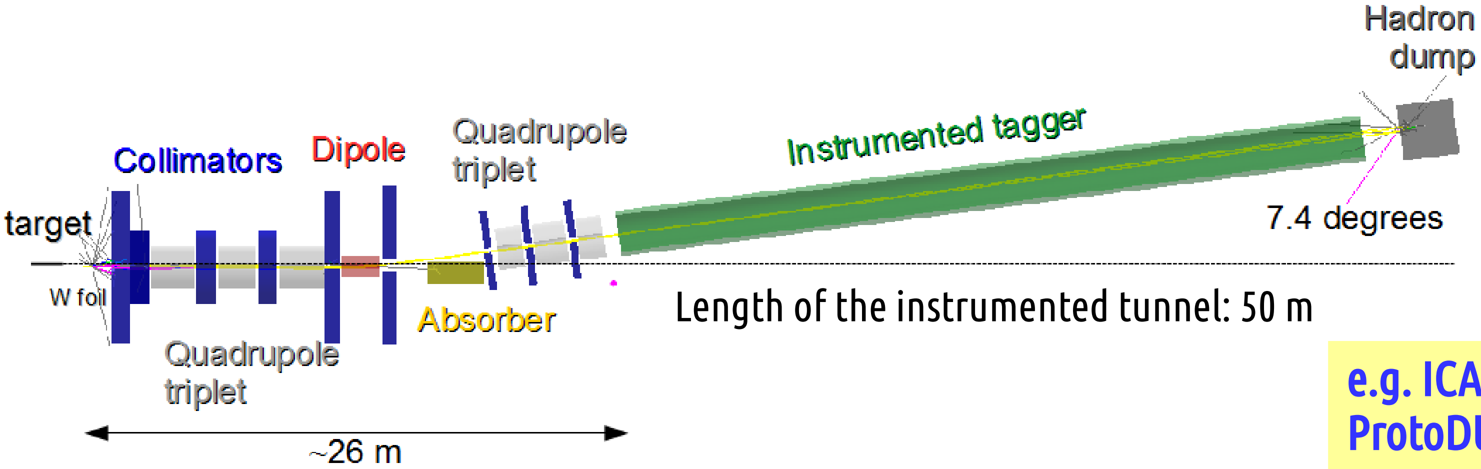
→ Correlations with interaction radius allows an **a priori knowledge of the ν_μ spectra**

A neutrino beam for precision physics

The next generation of **short baseline** experiments for **cross-section** measurements and for **precision ν-physics** (e.g. $\nu_\mu \rightarrow \nu_e$ **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

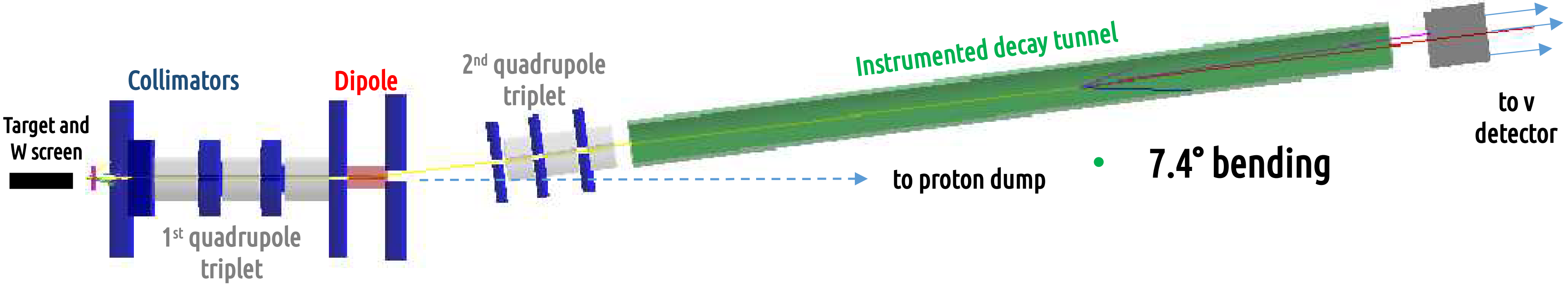


Length of the instrumented tunnel: 50 m

~ 500 t neutrino detector @ 100 m from the target

e.g. ICARUS@FNAL or ProtoDUNE-SP/DP@CERN or a Water Cher. @ J-PARC

The ENUBET single dipole beamline



- 7.4° bending

- **Proton driver**: **CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **Target**: Be, graphite. 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 the 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 and GEANT4
  - Normal-conducting magnets 2 quad triplets (15 cm wide, L < 2 m, B = 4 to 7 T/m)
    1 bending dipole (15 cm wide, L = 2 m, B =1.8 T)
- **Decay tunnel:** r = 1 m. L=40 m, low power hadron dump at the end

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 (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**” →

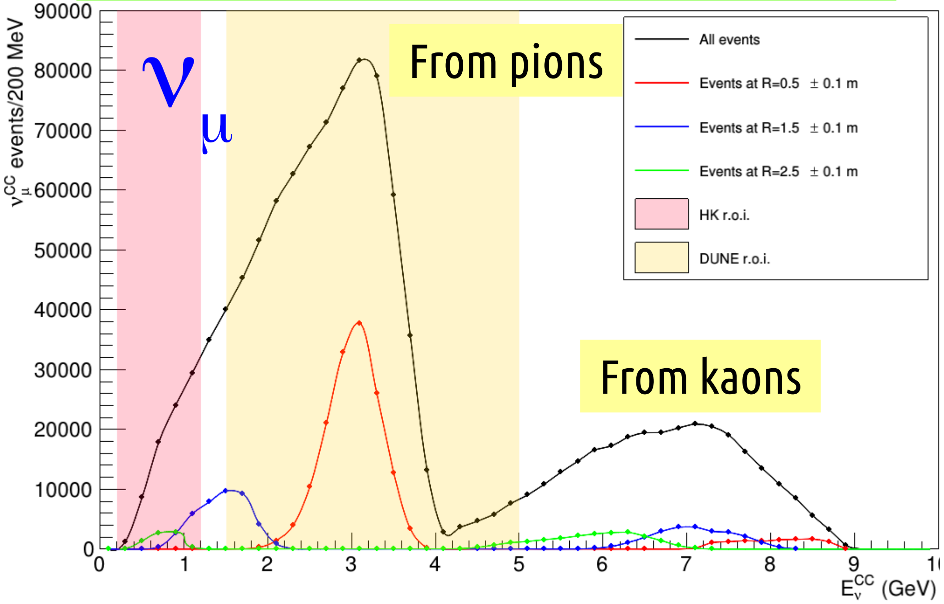
  ν interaction at the detector **associated in time** with the observation of the **lepton from the parent hadron** in the decay tunnel (more later)
- Monitor the μ after the dump at % level (**flux of ν_μ from π**)

Neutrino events per year at the detector

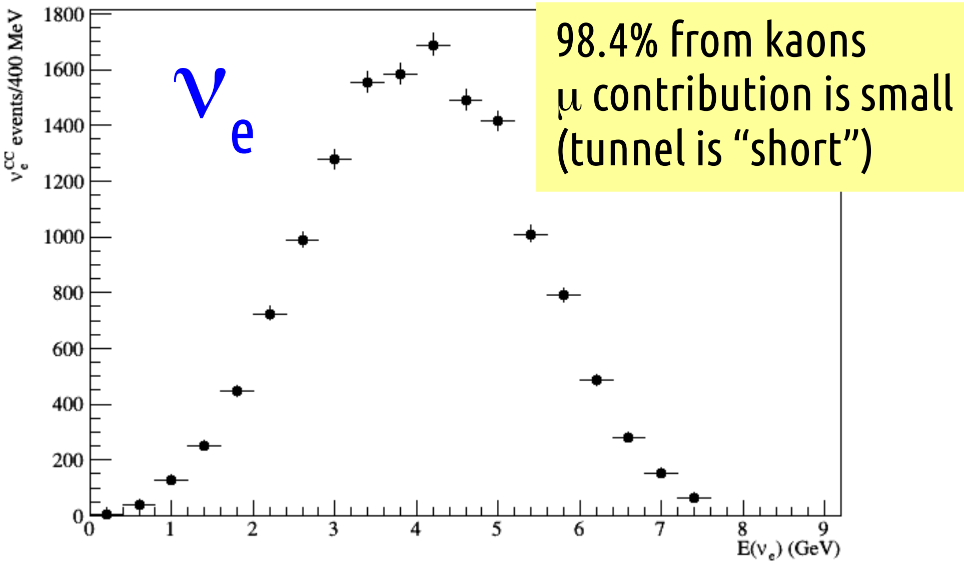
- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab, WC at J-PARC)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5×10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5×10^{20} pot at FNAL

- 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 $K_{\mu2}$)
- ν_μ from π: could be constrained by μ detectors downstream of hadron - dump

1.2 million ν_μ Charged Current per year



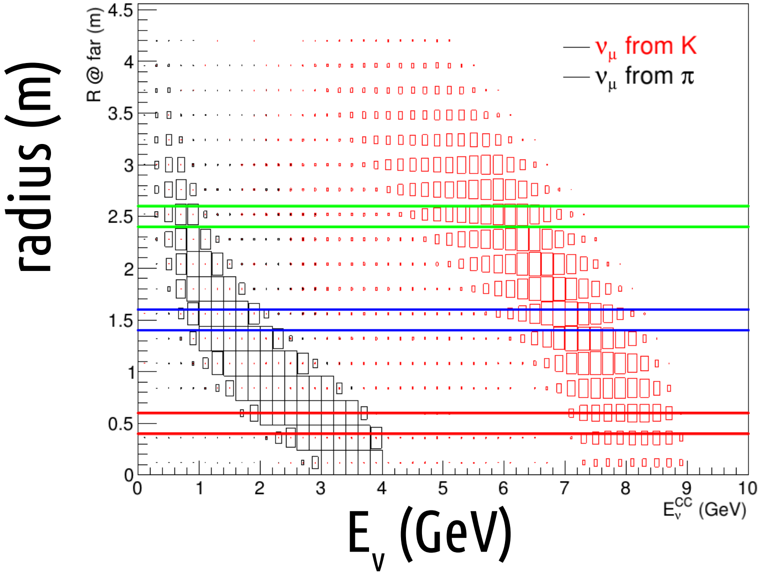
14000 ν_e Charged Current per year



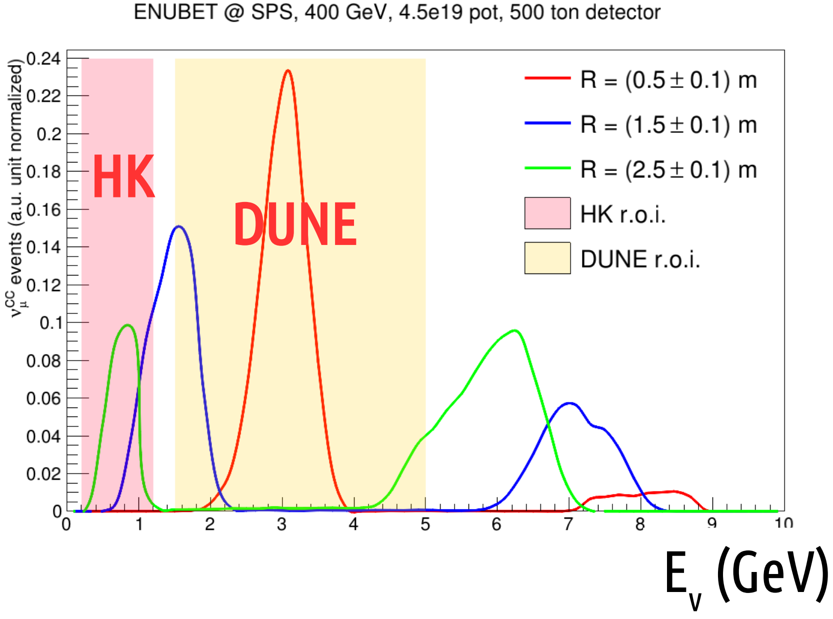
98.4% from kaons
μ contribution is small
(tunnel is "short")

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.



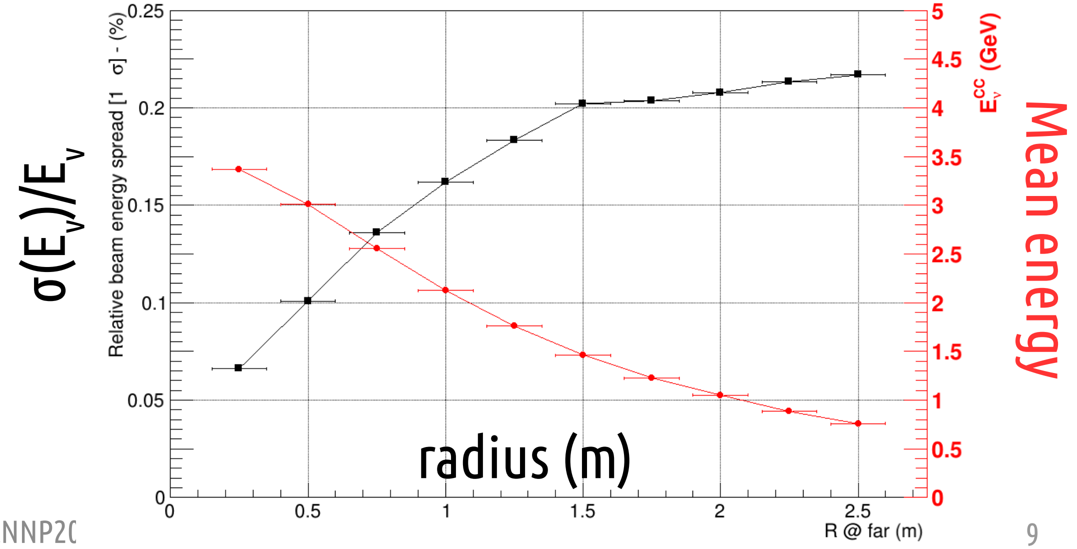
ν_μ ^{CC} in radial bins (1 norm.)



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

- 8 % for r ~ 50 cm, <E_ν>~ 3 GeV
- 22% for r ~ 250 cm, <E_ν> ~ 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



Systematics on the ν_e flux

Golden sample $\varepsilon \sim O(10^{-2})$

$$\phi(\nu_e) = \alpha\, N(K_{e3}) + \varepsilon\;\; N(\mu) \longrightarrow$$

Uncertainties from K yields, efficiency and stability of the transfer line are by-passed by the **e^+ tagging**

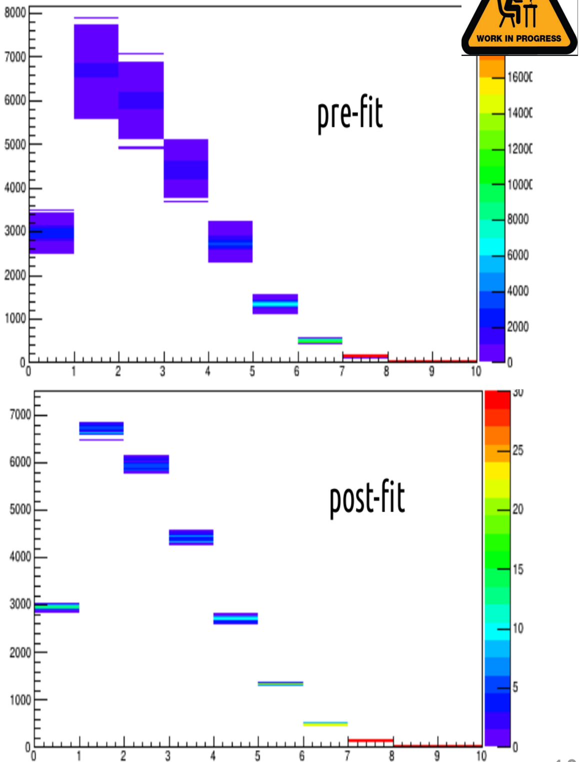
α encodes the residual geometrical (decay lengths, beam spread) and kinematic factors from K decays → **“easy” corrections**.

The **background** in the positron sample has to be controlled → simple robust detector validated at test beams (**$e/\pi^{\pm 0}/\mu$ separation**)

Silver sample $\phi'(\nu_e) = \alpha\, N(K) \times BR(K_{e3})$

Measuring the **inclusive rate of K decays** also very powerful. Additional uncertainty from Branching ratios < 0.1%.

- Quantitative assessment in progress. Finally possible thanks to the development of a complete simulation framework + good S/N.
- Degree of **cancellation allowed by the large correlations between e^+ rate and ν_e flux** being tested with toy simulations + likelihood fit on the flux normalization factors (bin-by-bin)→

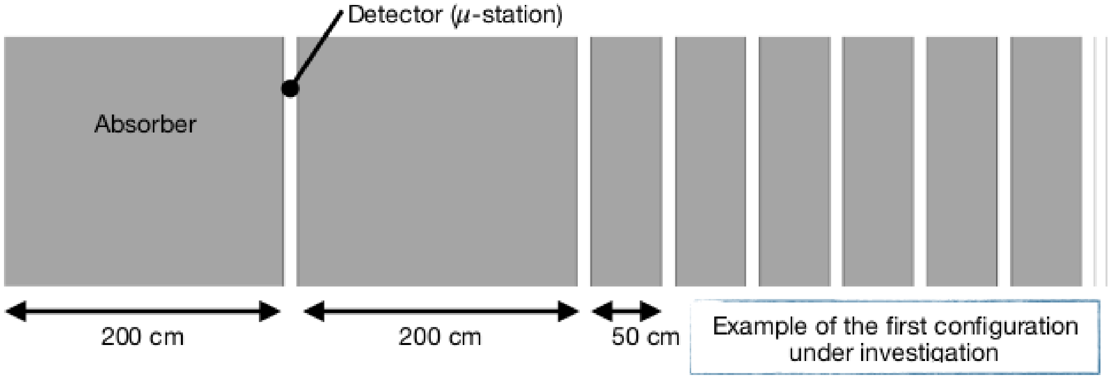


Extending the scope: muon neutrino component

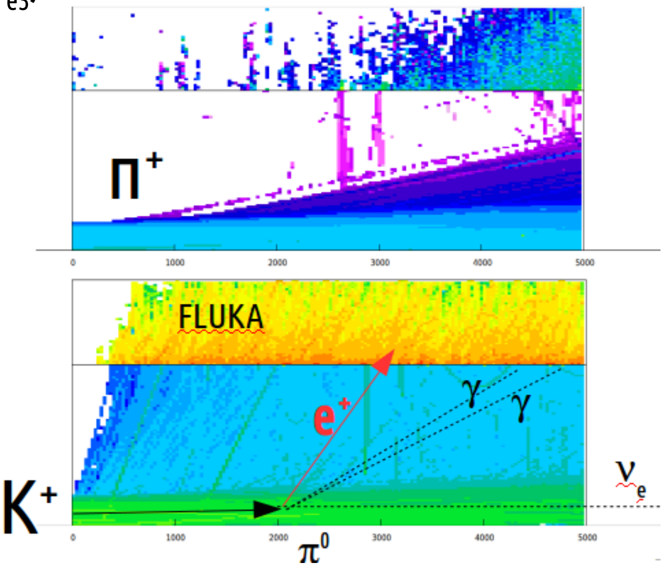
1) High-Energy ($K^+ \rightarrow \mu^+ \nu_\mu$): tagger → in progress (main focus so far K_{e3})

2) Low-Energy ($\pi^+ \rightarrow \mu^+ \nu_\mu$): use μ^+ as a proxy for measuring ν_μ.

Not large acceptance in the calorimeter (forward) →
muon stations following the hadron dump

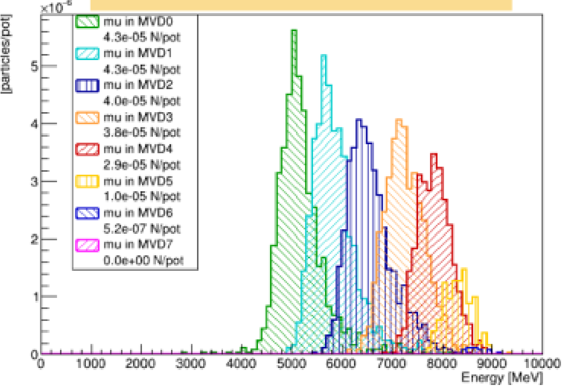


Example of the first configuration under investigation

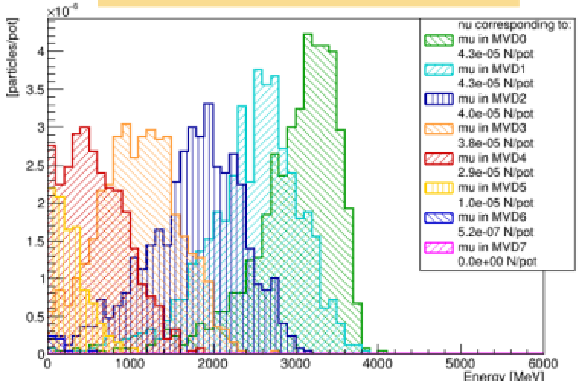


Estimation of muon and neutron rates in progress → choice of detector technology
Systematics: impact of punch through, absorber non uniformity, detection efficiency, halo muons

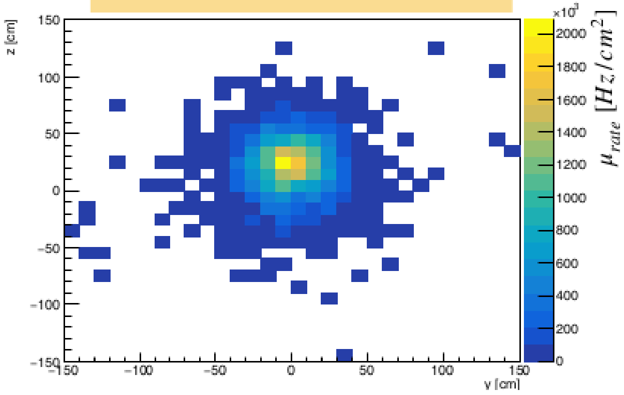
Muon energy @ different μ-stations



Neutrino energy @ different μ-stations



Muon rate @ first μ-station



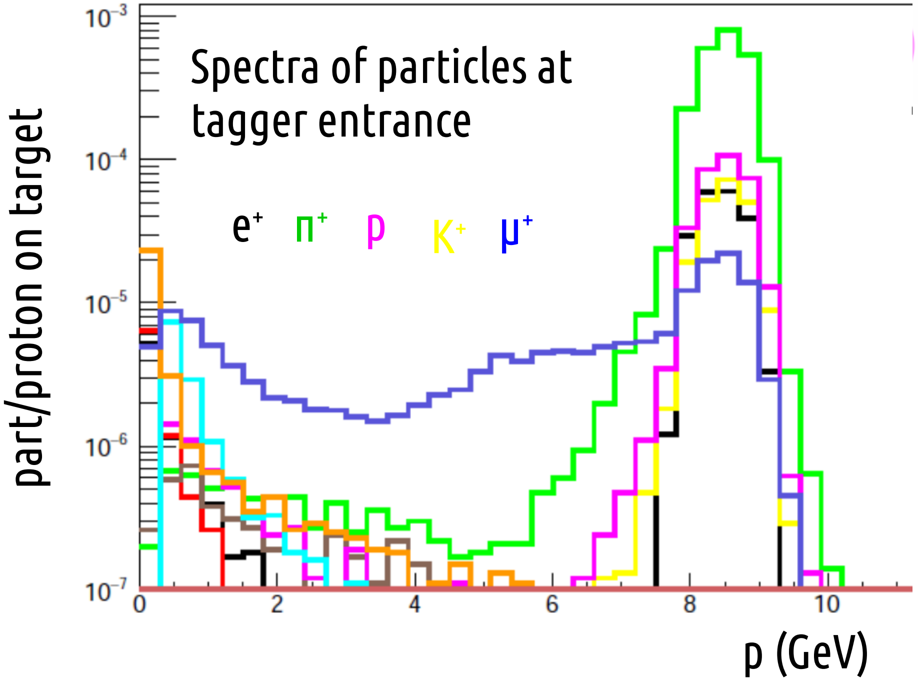
Beamline option B (2 dipoles)

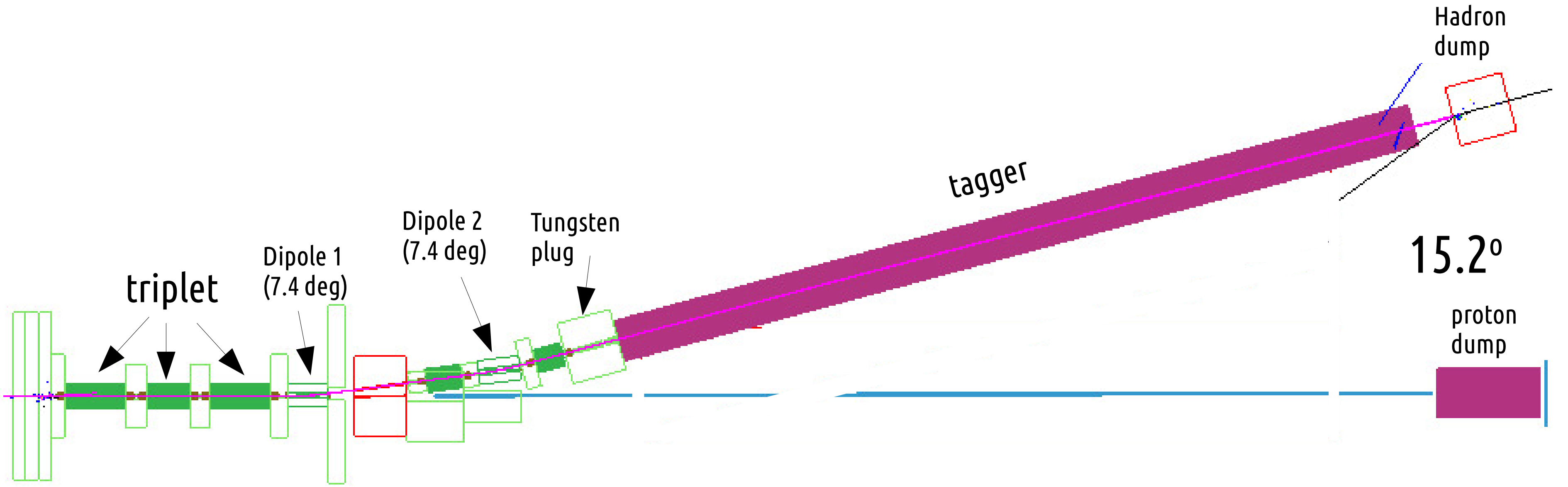
A relatively new design:

2-dipoles → large bending angle (15.2°)

Increased length and reduced rates but →

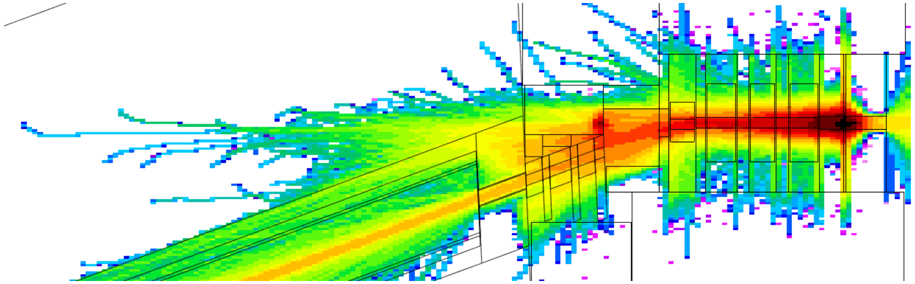
A better collimated (contained) beam with reduced backgrounds (i.e. from “forward going” high energy muons.





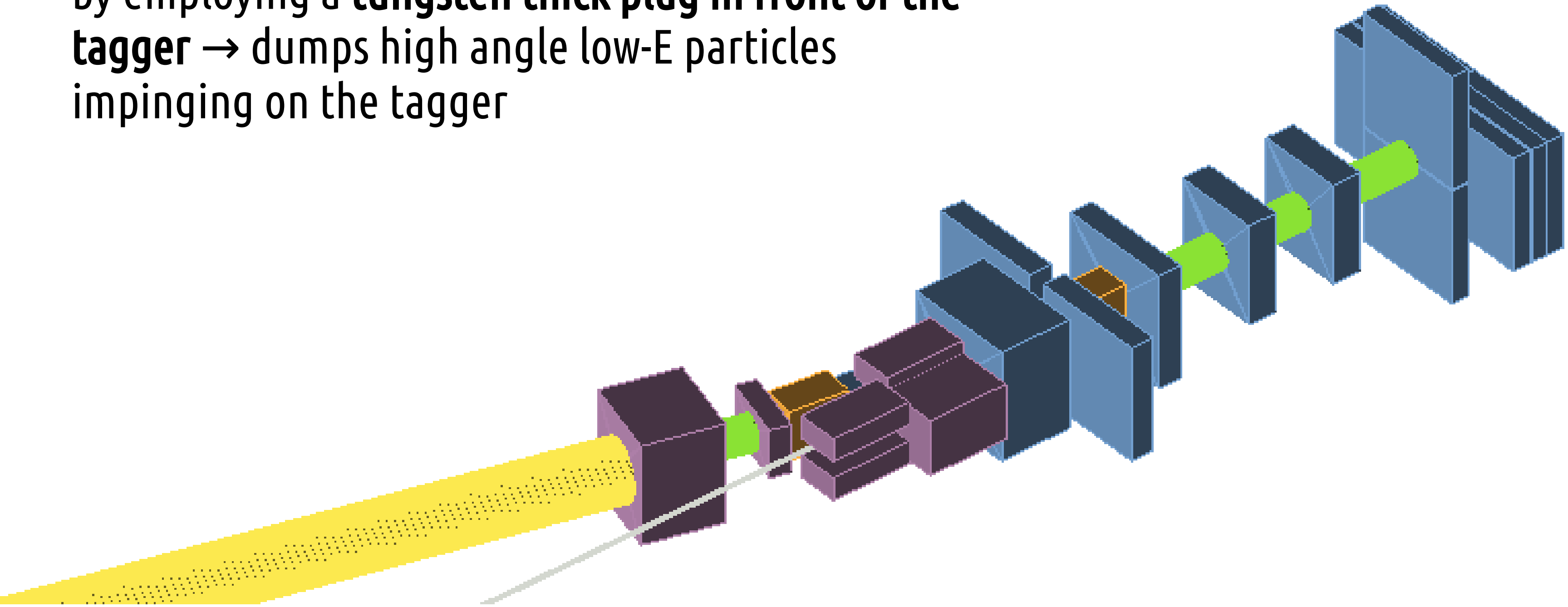
Beamline option B (2 dipoles)

2-dipoles → large bending angle (15.2°)



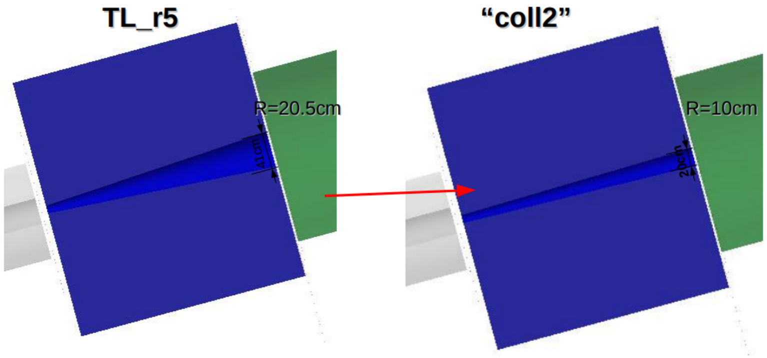
The **shielding** has also been significantly improved by employing a **tungsten thick plug in front of the tagger** → dumps high angle low-E particles impinging on the tagger

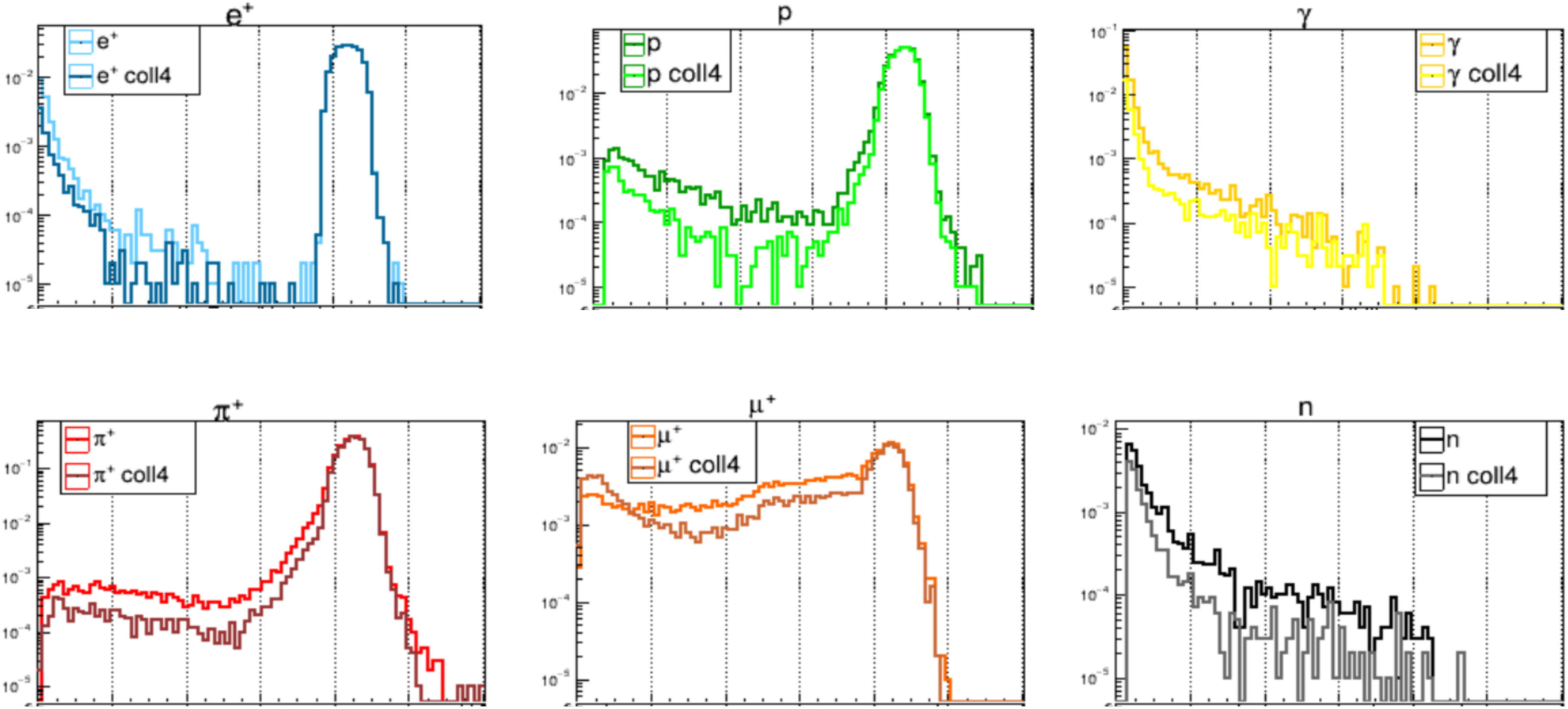
p (GeV)



Improvements in the shielding design

- Reshaping of the tungsten filter placed in front of the tagger
- Pions and kaons in the momentum bite reduced by 2%, all backgrounds reduced by large factors





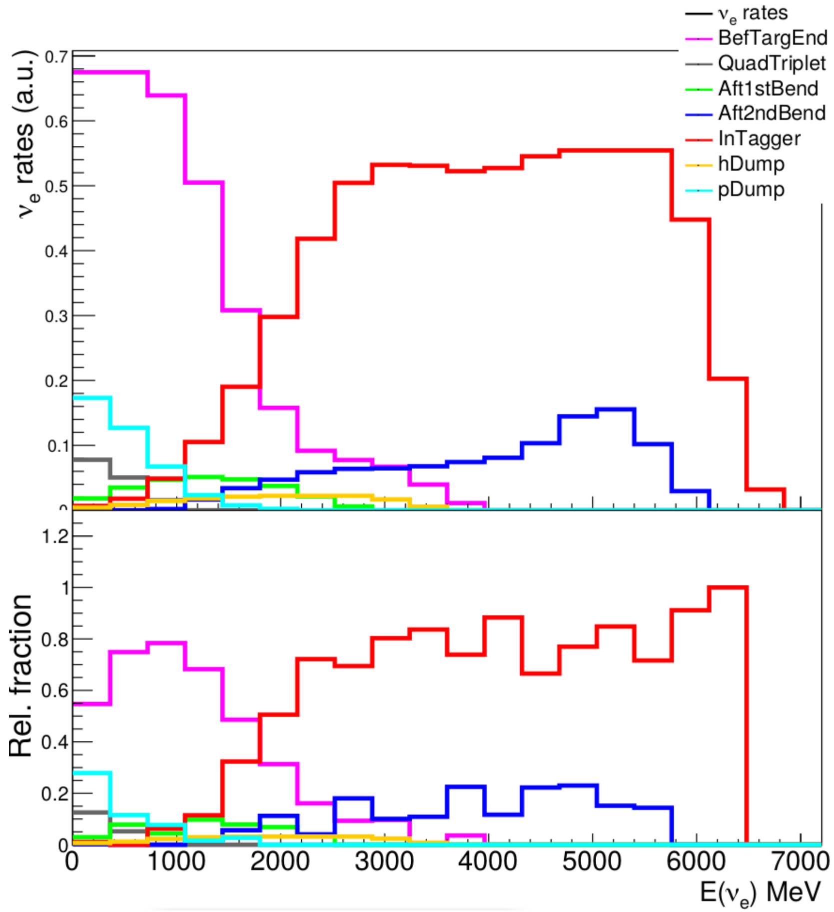
Beamline option B (2 dipoles)

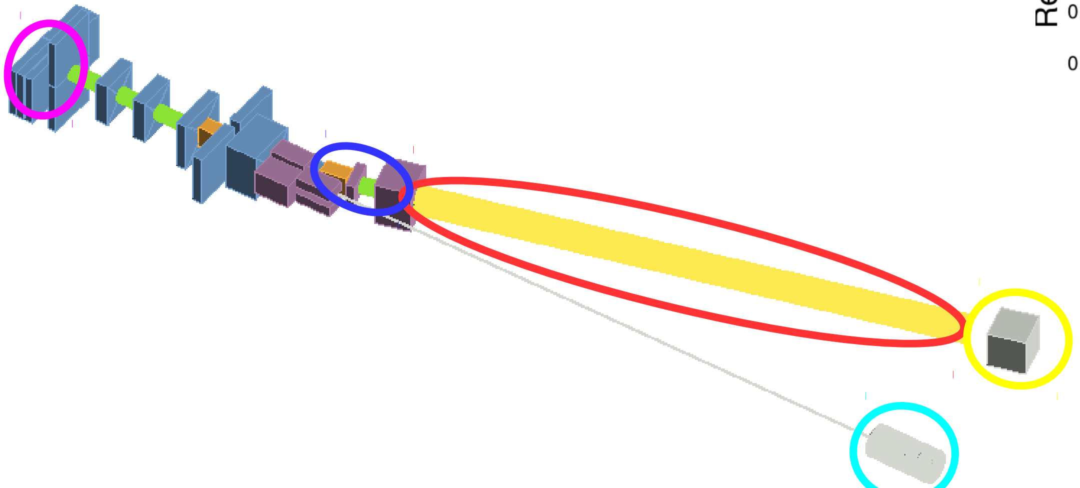
2-dipoles scheme → large bending angle (15.2°)

The length of the beamline collinear with the tagger also kept at minimum

ν_e from early decays of charged or neutral kaons (not taggable) have a lower probability to reach the ν detector. *Removable with energy cut.*

10-15% contamination from the straight section in front of the tagger (pointing to the detector) can be *accounted for with simulation* (geometry).





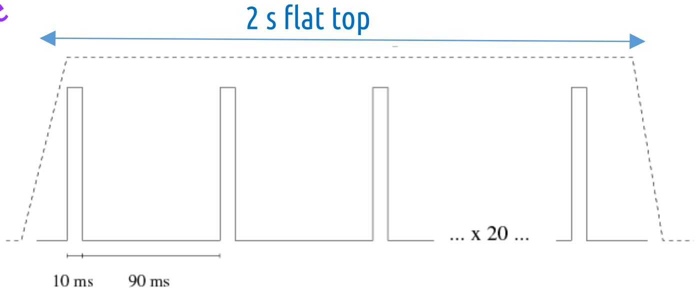
A very significant advantage of this new beamline design!

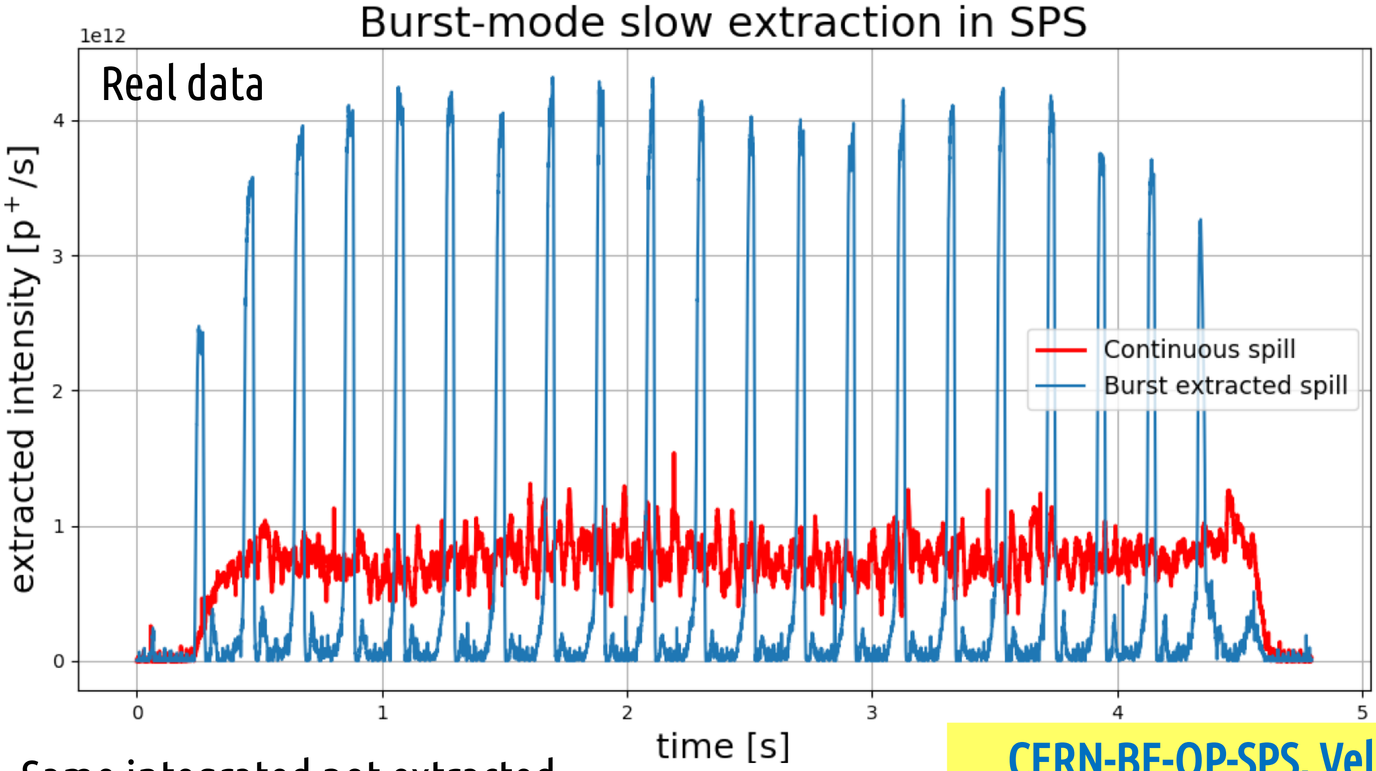
Machine studies for the horn-based option

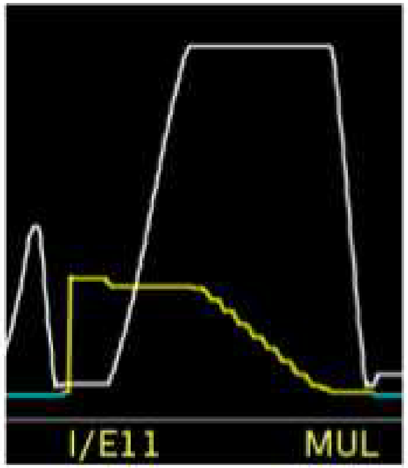
"burst " slow extraction: trigger the third integer betatron resonance with a periodic pattern

From an idea "on slide" to
a working implementation !

ENUBET #2YearsChallenge







Proton current

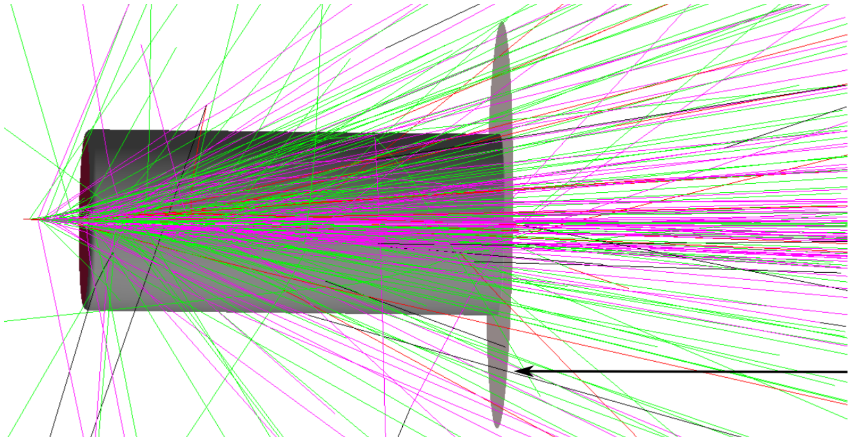
Same integrated pot extracted.
Protons squeezed into intervals with active horn

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

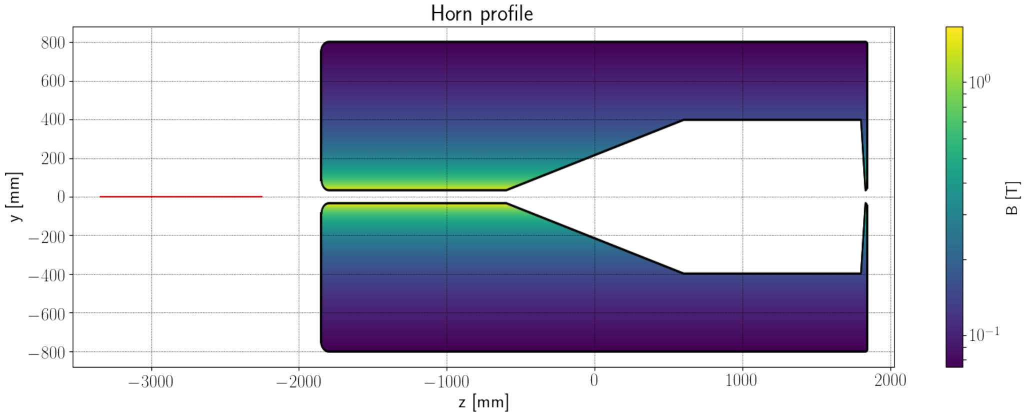
https://indico.cern.ch/event/777458/
https://ipac2019.vrws.de/papers/wepmp035.pdf

Horn focusing reloaded

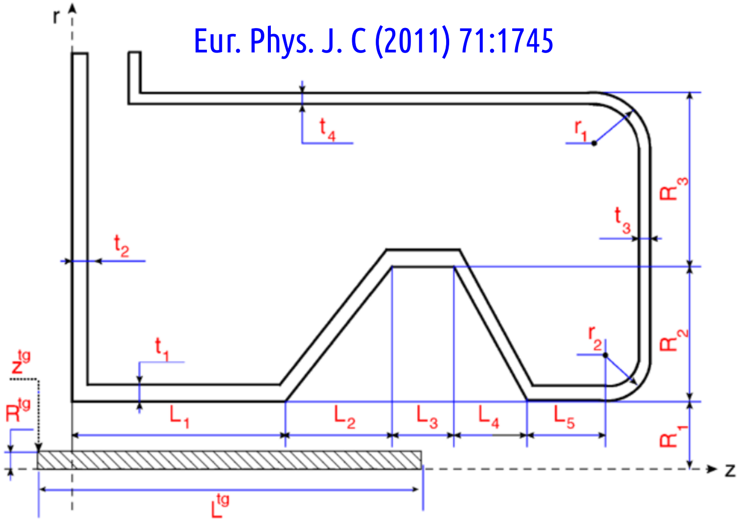
A larger collection efficiency (~neutrino flux) and a somewhat shorter beamline can be achieved using a magnetic horn in place of a quadrupole triplet.



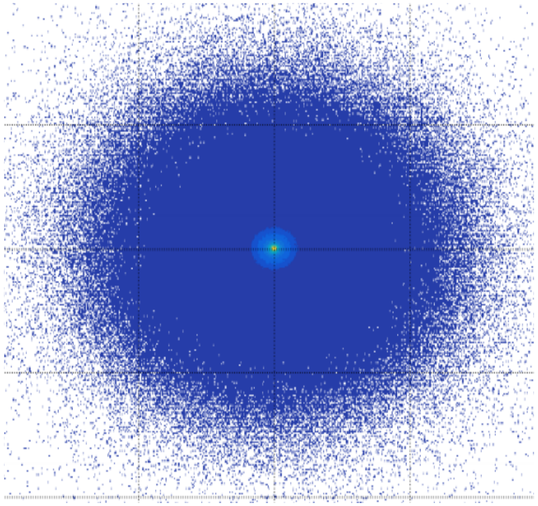
We are **resuming a systematic optimization of the horn shape** after initial analysis that indicated a gain of about a factor 5.



Search the parameter space maximizing a figure of merit



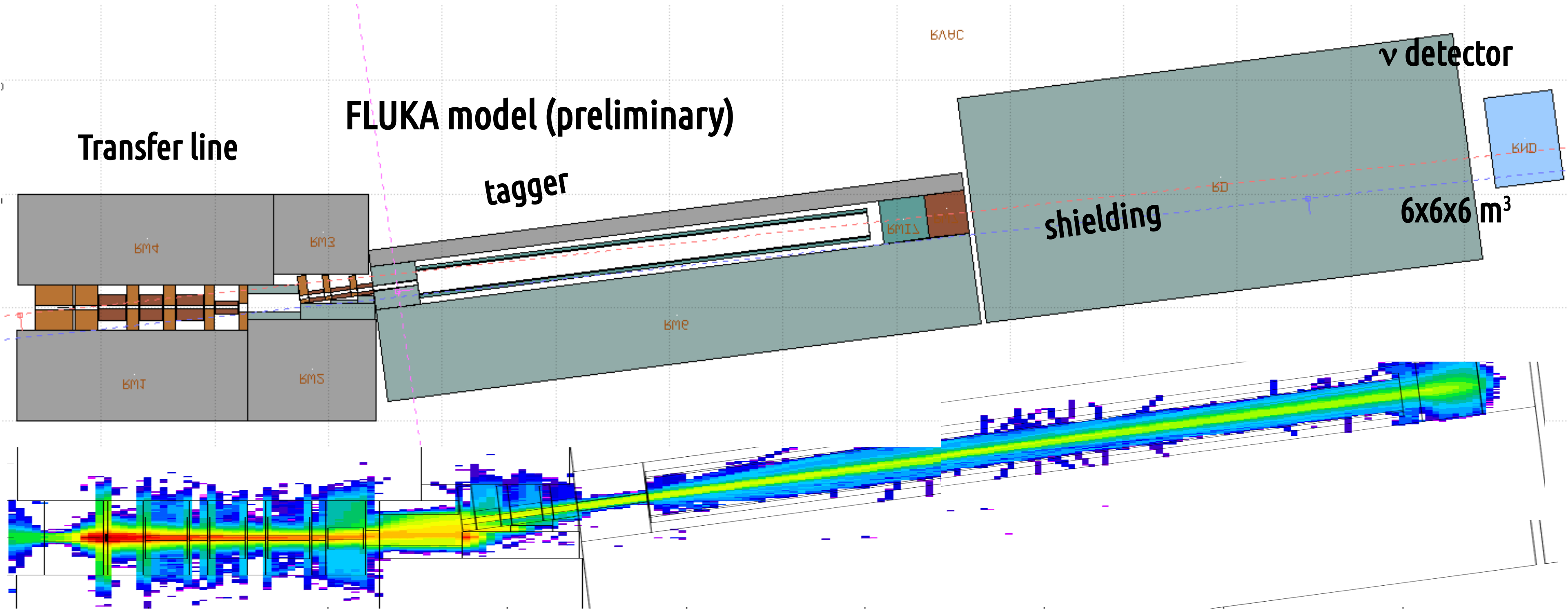
Eur. Phys. J. C (2011) 71:1745



Phase space at horn exit

The hadronic beamline: FLUKA simulation

1) Optimize shielding to **reduce backgrounds** in the tagger (μ, n, high angle e^+ and π^+)



FLUKA model (preliminary)

Transfer line

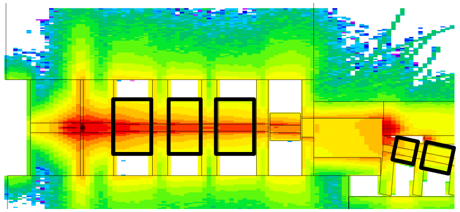
tagger

shielding

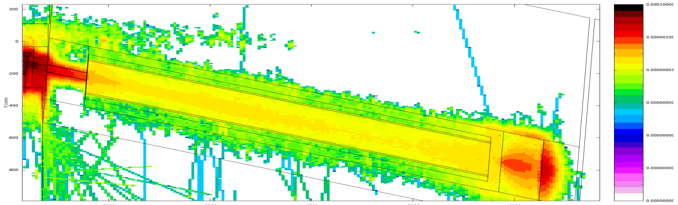
ν detector

6x6x6 m^3

2) Specs of **rad-hard upstream focusing quads**

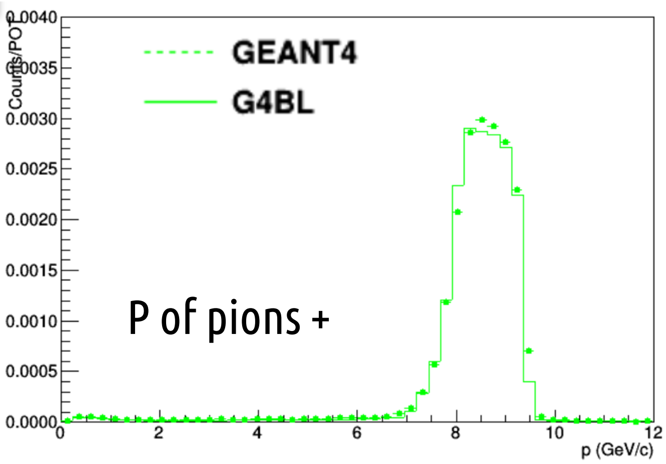


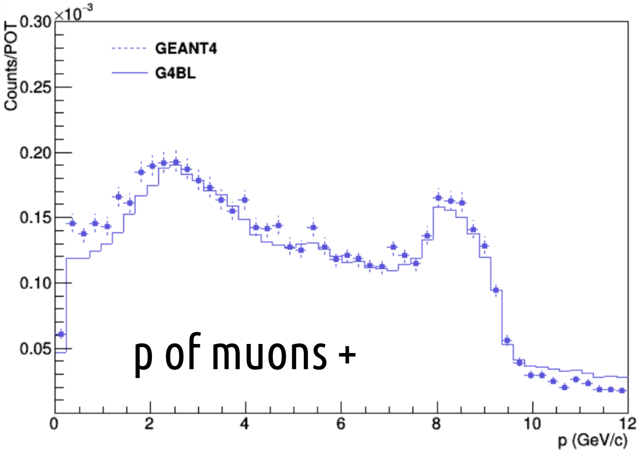
3) **neutron** irradiation

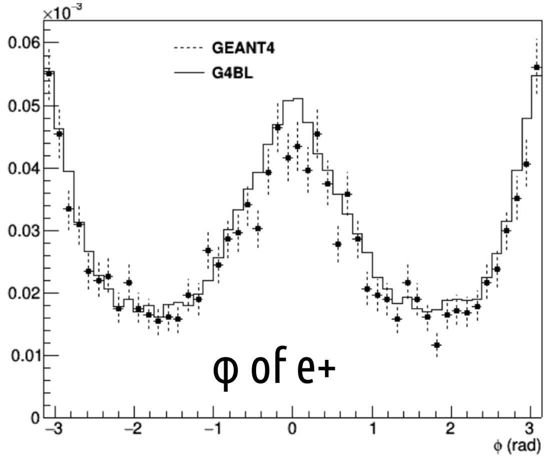


GEANT4 simulation of the beamline

G4Beamline used for designing the beamline (quick tracking)
Developed a **new GEANT4 simulation code**. Good agreement found for the single dipole beamline →



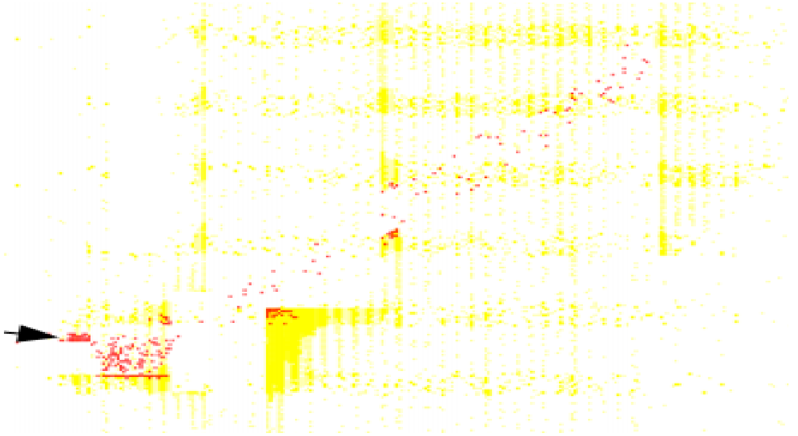




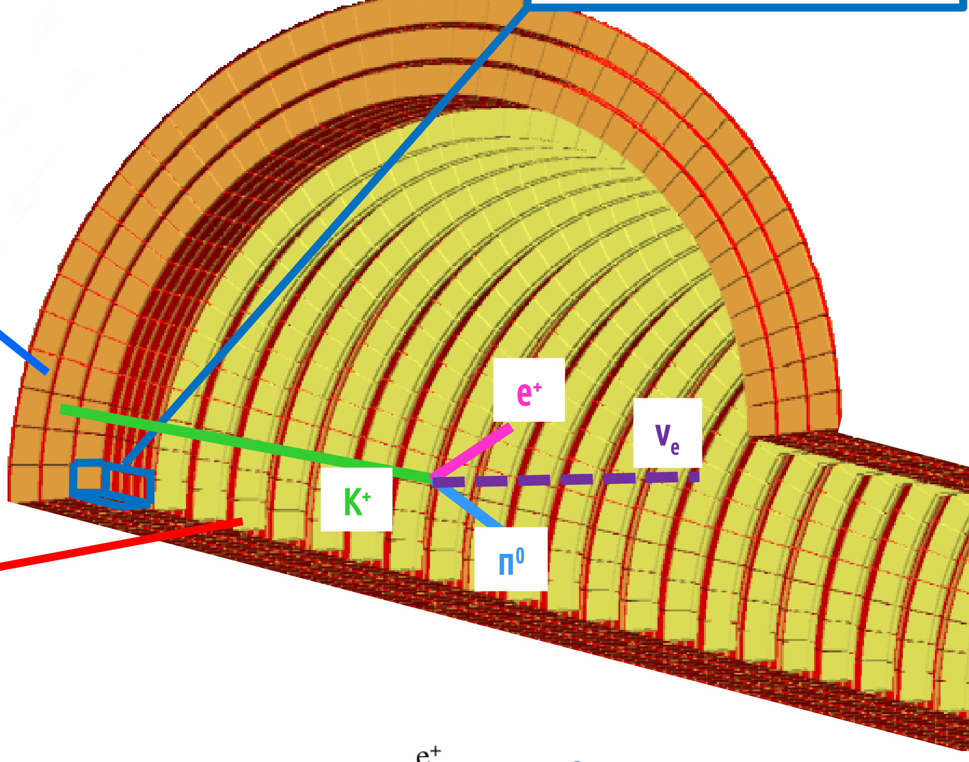
GEANT4 holds memory of all particle history →

- Identify the **origin of background**
- **Break down neutrino components**
- **Optimize reduction of target files** (FLUKA) by connecting particles at the tagger entrance with the corresponding ones at target exit.
- Automatically produces FLUKA geometry input file
- Settings configurable with control card (mac file) and stored into a ROOT file → beamline **systematics**
- Merging with **GEANT4 tagger simulation** ongoing
  - - from beam elements to detectors

Origin of backgrounds can be “mapped” → tweaking of geometry/materials



The ENUBET tagger



Ultra Compact Module
3×3×10 cm^3 – 4.3 X_0

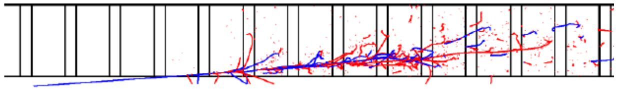
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ **$e^+/\pi^\pm/\mu$ separation**

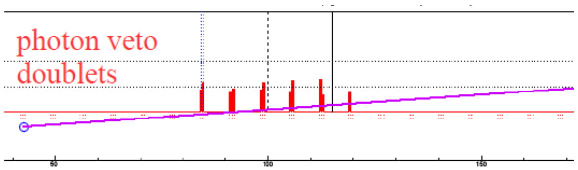


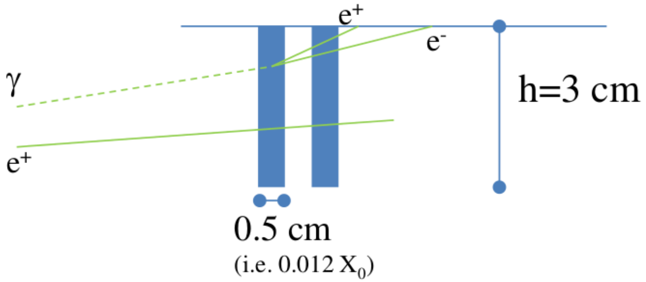
Integrated photon veto

Plastic scintillators

Rings of 3×3 cm^2 pads

→ **π^0 rejection**





e^+ (signal) topology

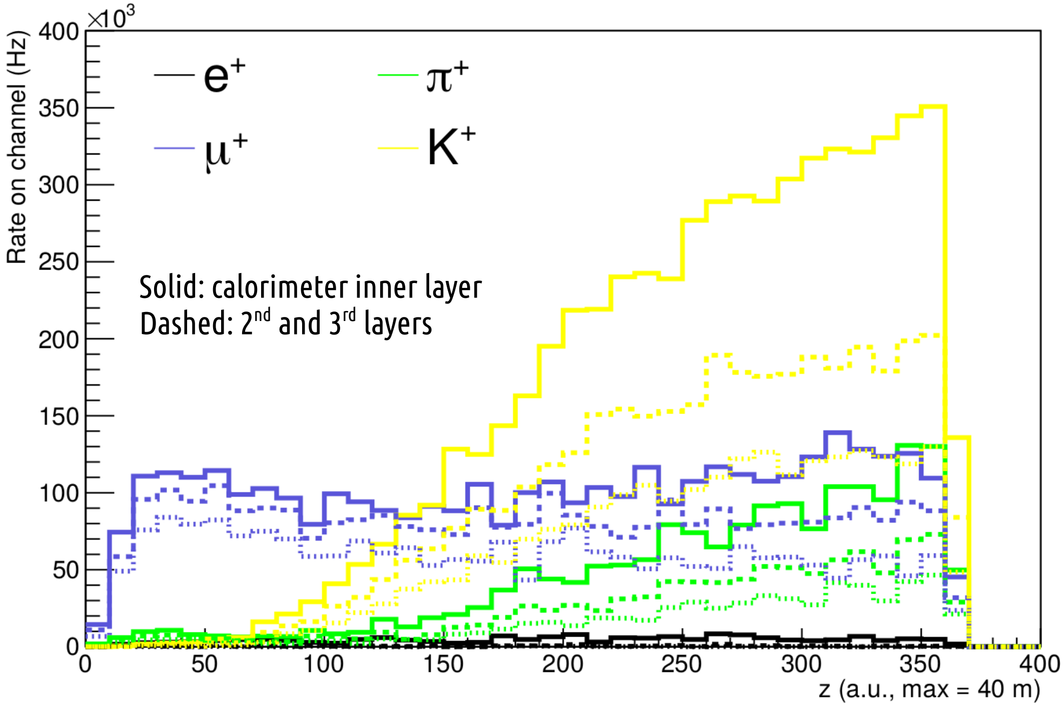
π^0 (background) topology

π^+ (background) topology

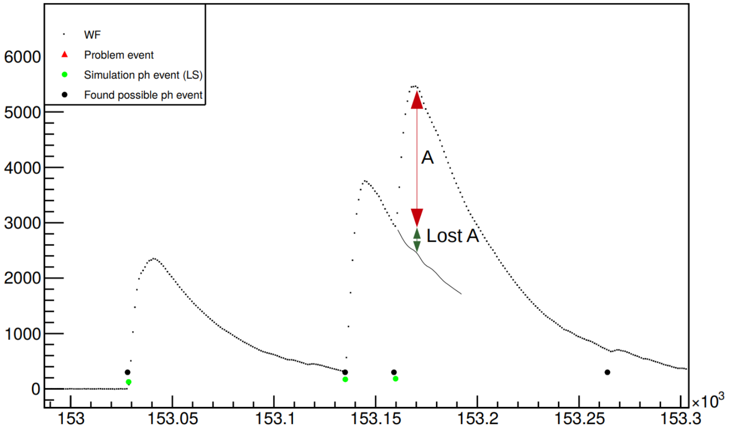
Input rates and readout

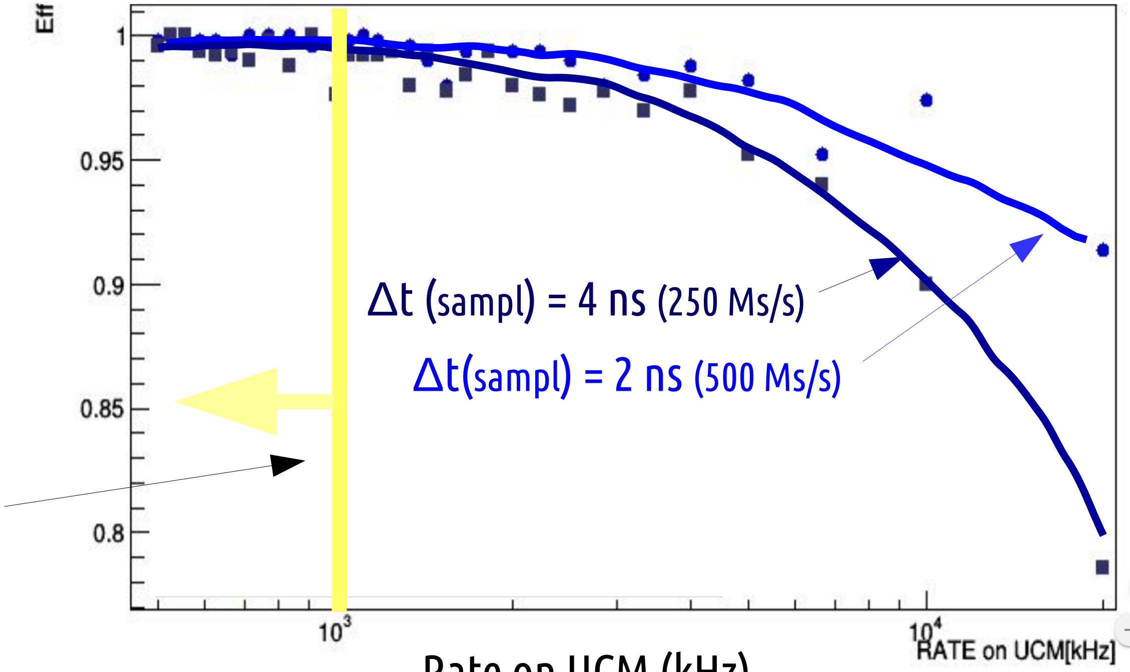
Double dipole beamline with slow extraction → Max. tot rate ~**500 kHz/ch**.

Almost even illumination from muons. At increasing z rates are dominated by kaon decay products (NB K+ initial fraction~ 5-10%!). Tail from uncollimated pions at the end of the tunnel.



Waveform analysis developed.





Δt (sampl) = 4 ns (250 Ms/s)

Δt(sampl) = 2 ns (500 Ms/s)

Rate on UCM (kHz)

Pileup eff. loss ~ negligible up to ~ 1 MHz

250 MS/s digitization sampling OK.

Could cope also with the higher rates implied in the horn focusing scheme.

K_{e3} positrons reconstruction

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

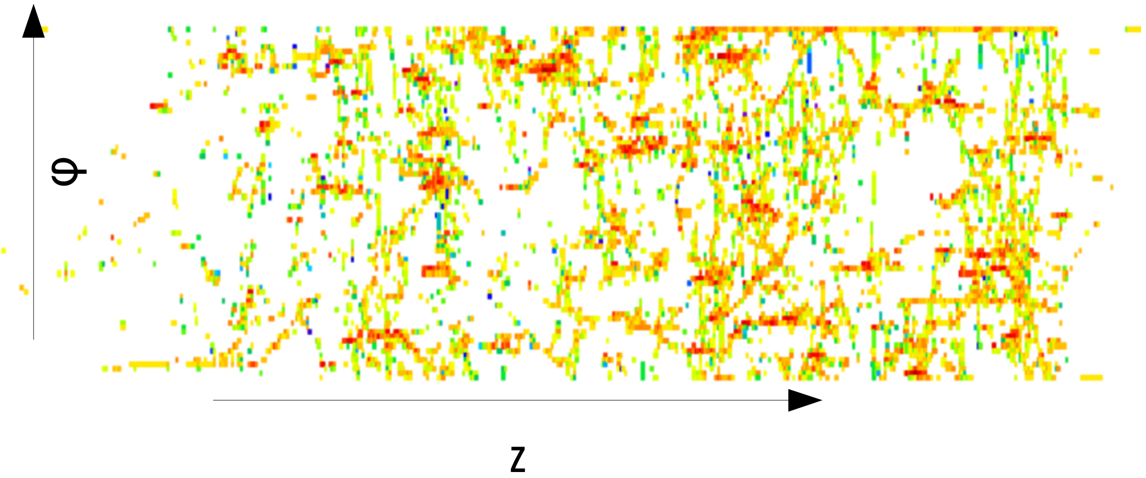
Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018.
Includes particle **propagation** and **decay**, from the transfer line to the detector, hit-level detector response, **pile-up** effects.

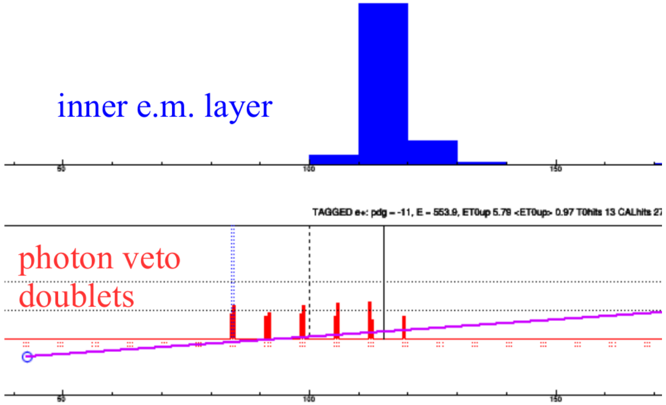
The Ke3 branching ratio is ~5 % and Kaons are about 5-10% of the incoming hadron beam

Analysis chain

1) Event Builder → Identify the **seed** of the event (UCM with largest energy deposit in inner layer and > 28 MeV). **Cluster neighboring cells** close in time. **Iterate** on not-yet-clustered cells.

Hit map for genuine positrons





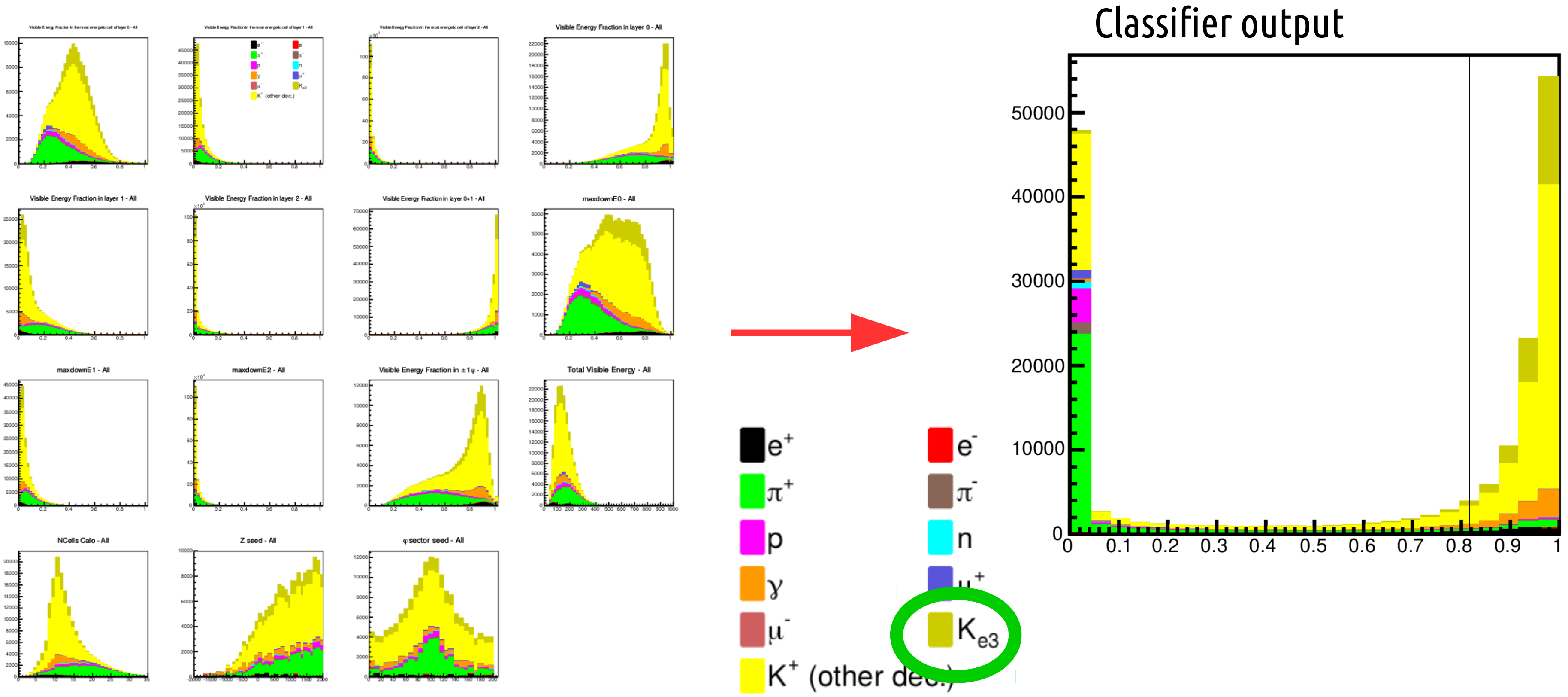
K_{e3} positrons reconstruction

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

Analysis chain

1) 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

2) e/π/μ separation → **Multivariate** analysis based on **15 variables** (13 on pattern of the energy deposition in the calorimeter + z, φ) with TMVA (MLP NN)



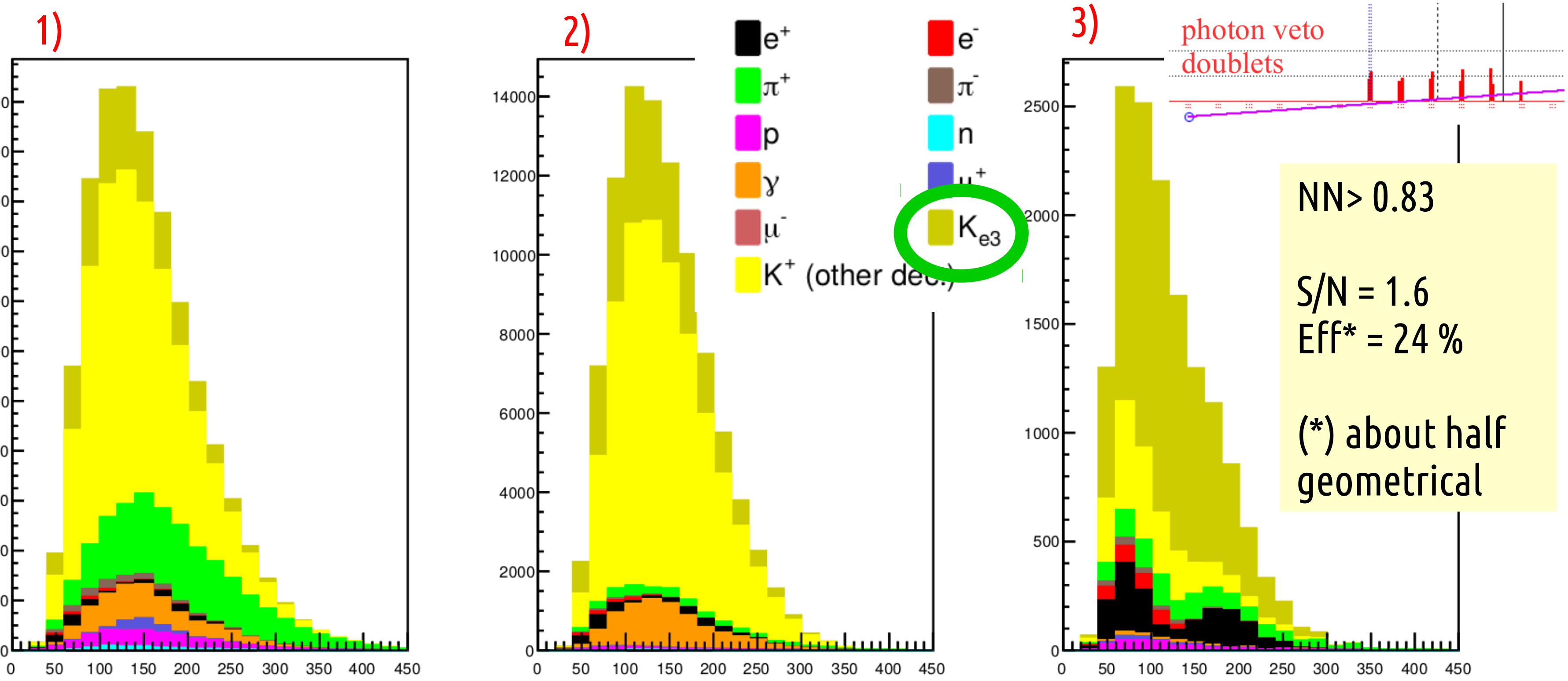
K_{e3} positrons reconstruction

Analysis chain

1) 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

2) e/π/μ separation → **Multivariate** analysis based on **15 variables** (13 on pattern of the energy deposition in the calorimeter + z, φ) with TMVA (MLP NN)

3) e/γ separation → Signal on the tiles of the **photon veto (0-1-2 mip)**



NN> 0.83

S/N = 1.6
Eff* = 24 %

(*) about half geometrical

K_{e3} positrons reconstruction

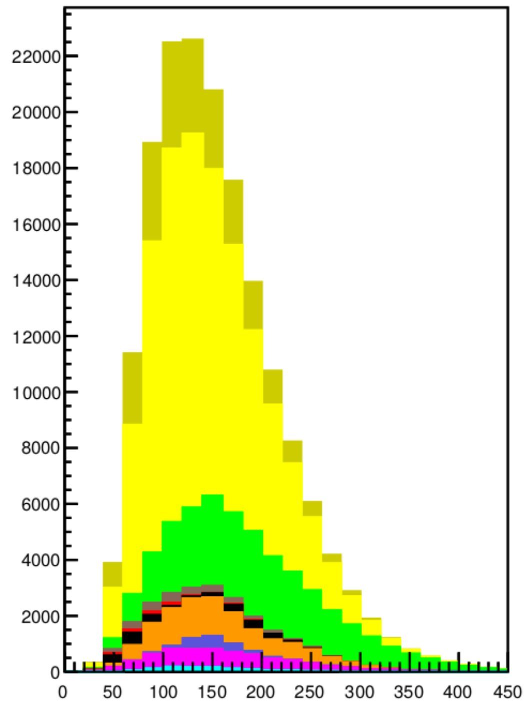
Analysis chain

1) 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

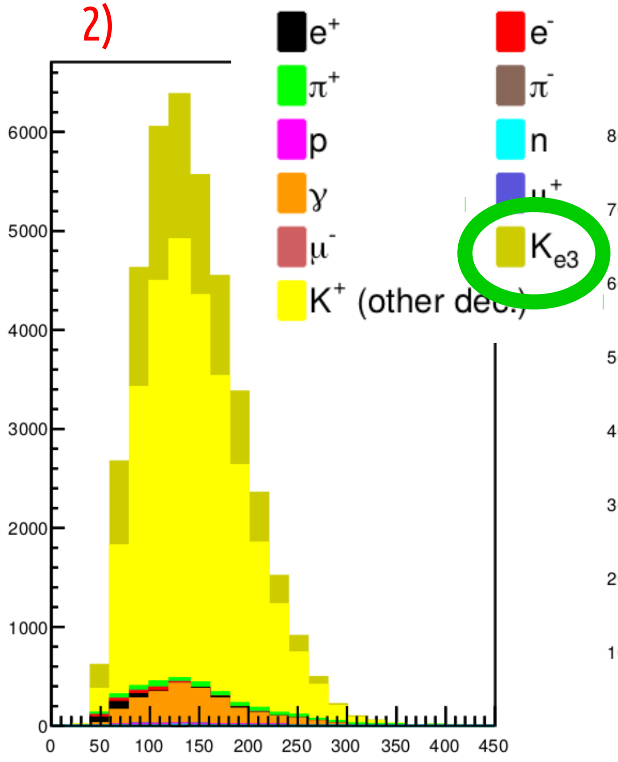
2) e/π/μ separation → **Multivariate** analysis based on **15 variables** (13 on pattern of the energy deposition in the calorimeter + z, φ) with TMVA (MLP NN)

3) e/γ separation → Signal on the tiles of the **photon veto (0-1-2 mip)**

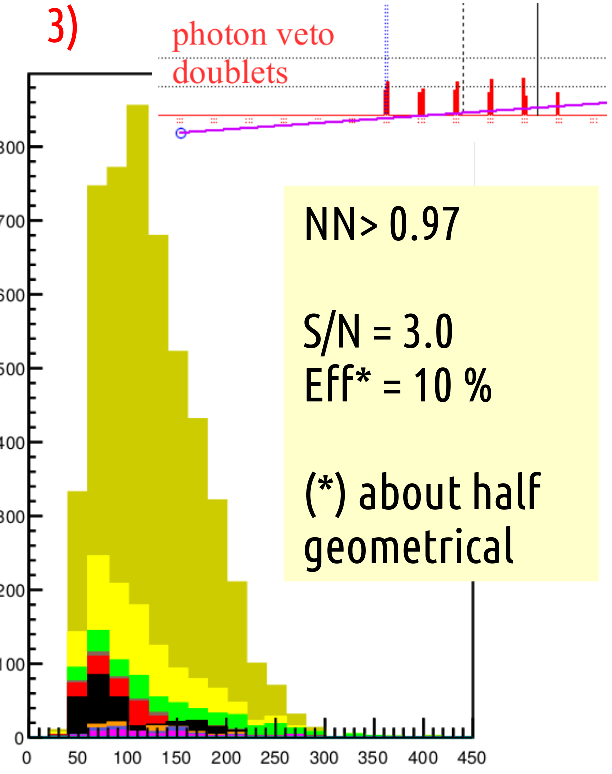
1)



2)



3)

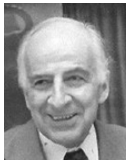


NN> 0.97

S/N = 3.0
Eff* = 10 %

(*) about half geometrical

Time tagging

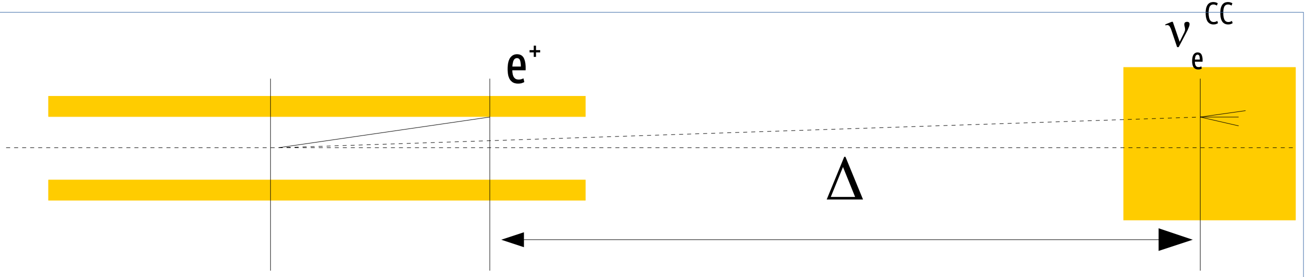

Pontecorvo

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



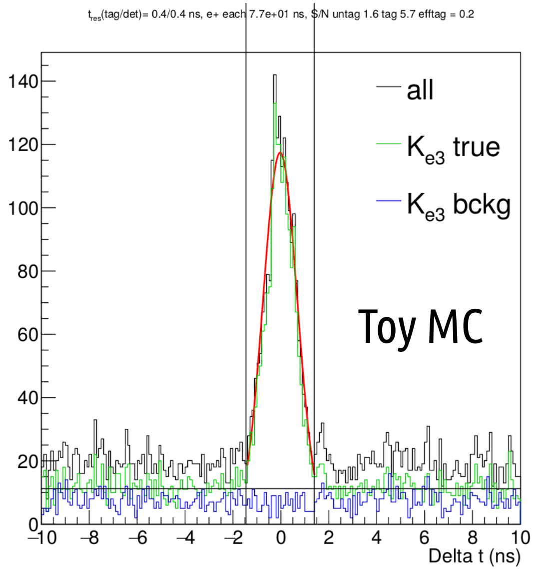
δ = combined t-resolution (e^+ tagger and ν detector)

I.e. with 2.5×10^{13} pot / 2s slow extraction and double dipole beamline (with 20% eff. S/N 1.6):

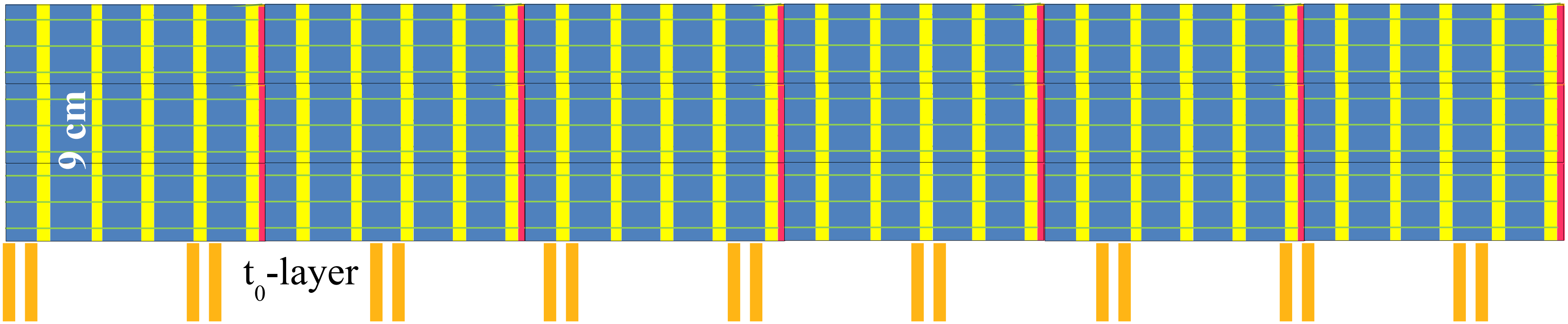
genuine K_{e3} cand. : → **1 every ~ 77 ns**

background K_{e3} cand. ~ 0.6 x → 1 cand / ~ 130 ns

Already with $\delta=0.4\oplus0.4$ ns resolutions results in a correct association with an interesting purity →

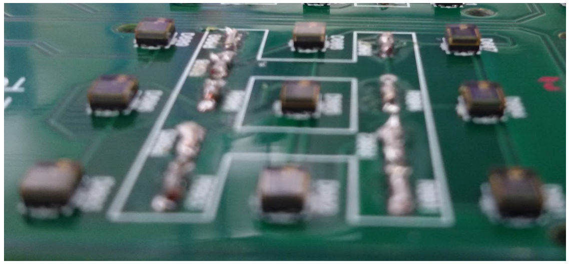


The tagger: shashlik with integrated readout

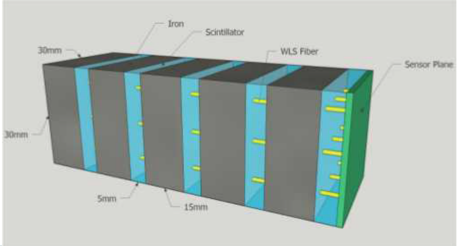


10 cm = 5 X_0

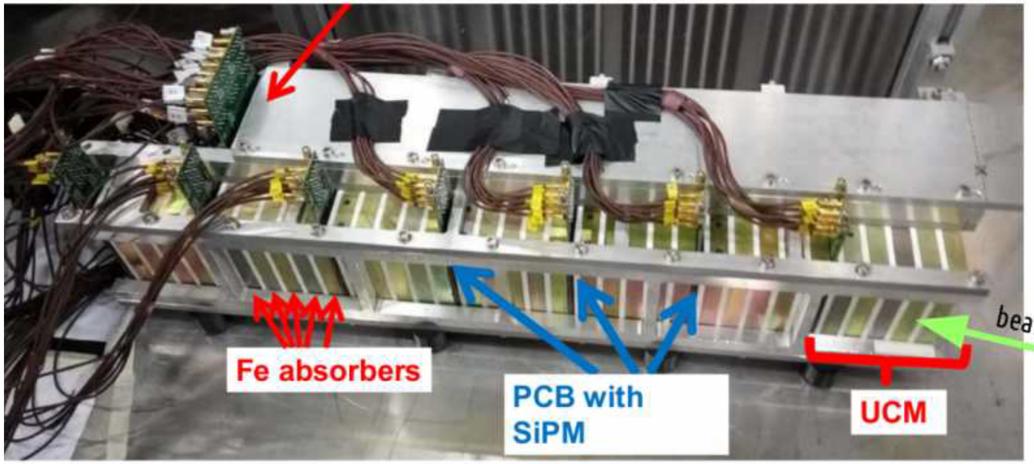
e^+



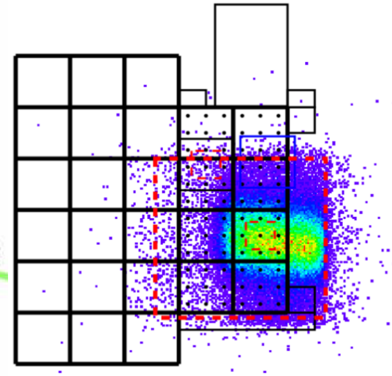
UCM: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter



CERN PS test beam Nov 2016



Beam spot

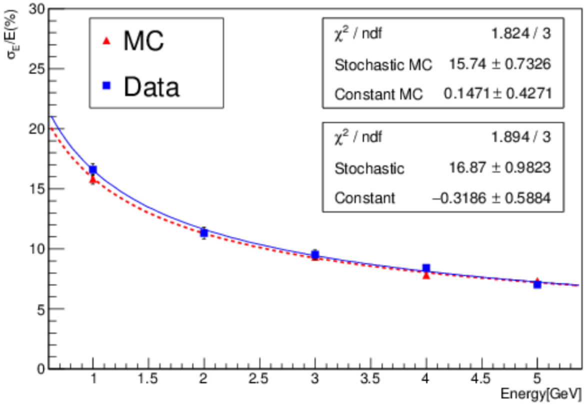


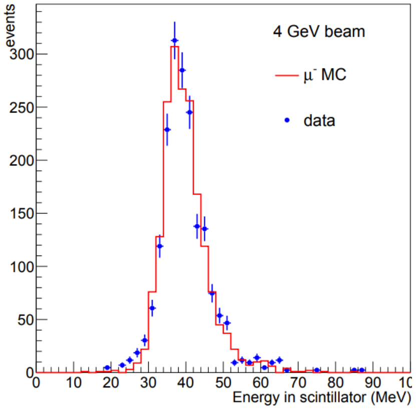
Test beam results with shashlik readout

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

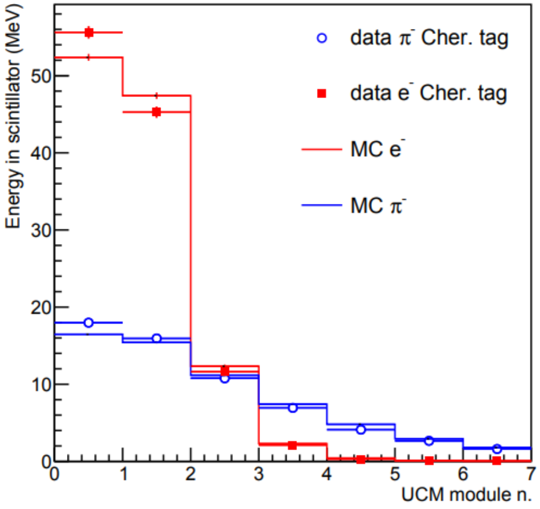
Tested response to MIP, e and π^-

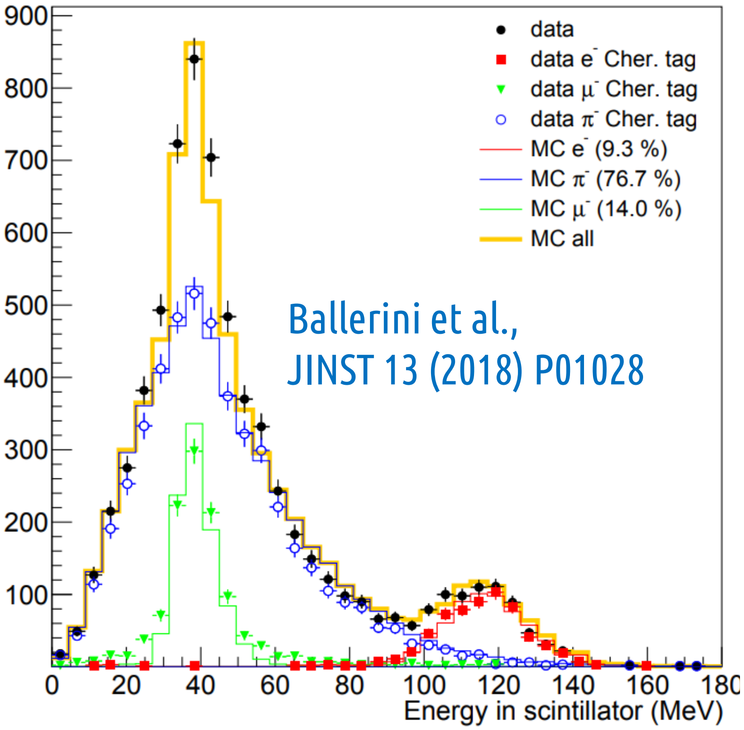
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement





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



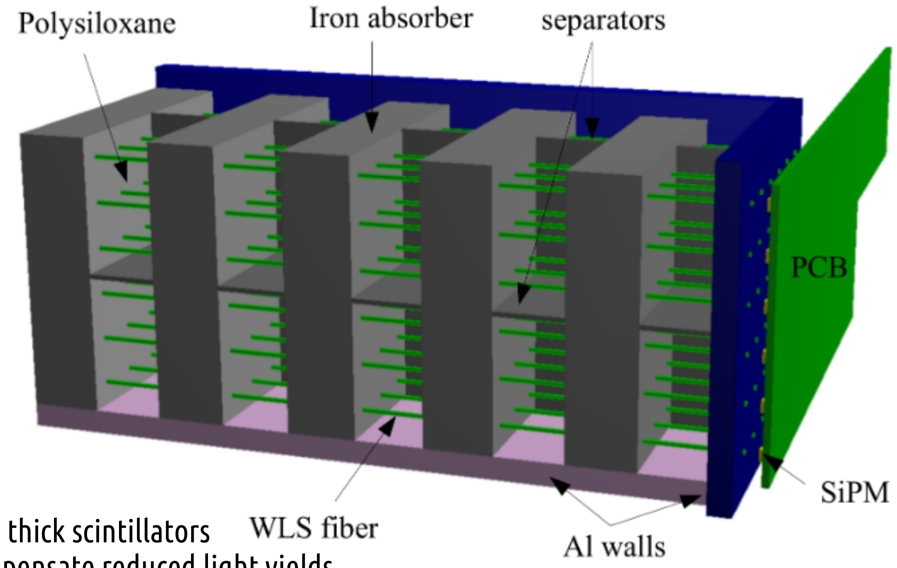


Ballerini et al., JINST 13 (2018) P01028

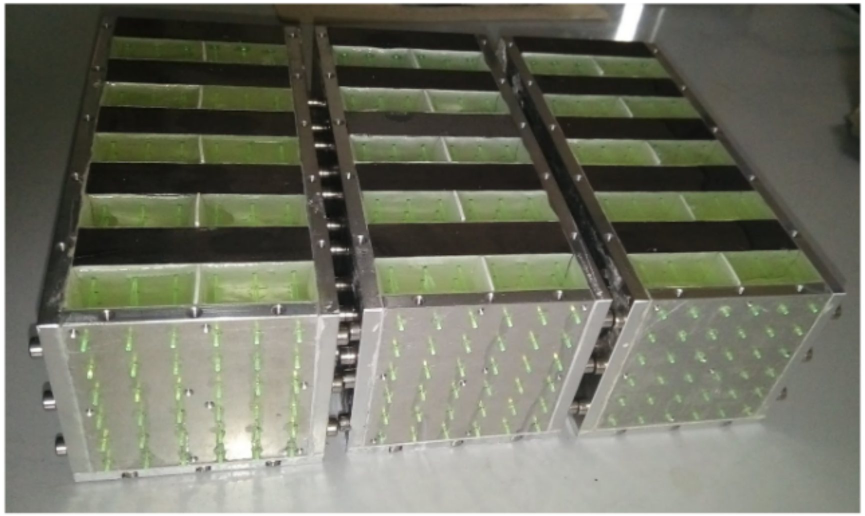
Polysiloxane shashlik prototypes

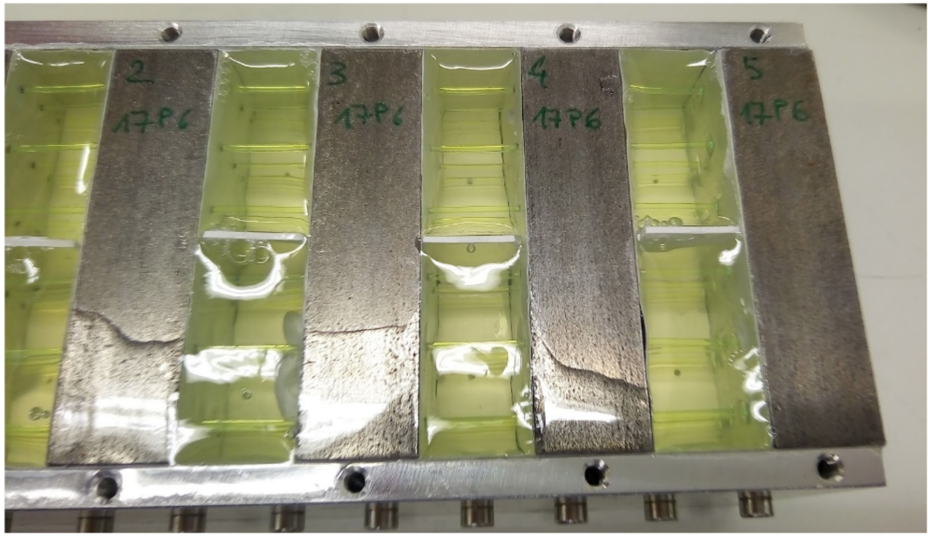
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)

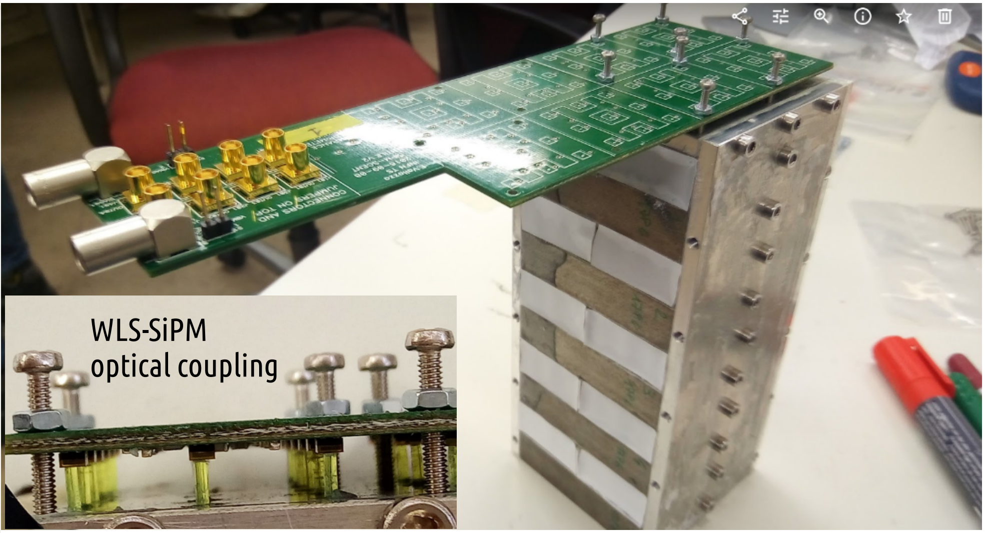
A **13X_0 shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)



15 mm thick scintillators
to compensate reduced light yields







Polysiloxane shashlik prototypes

Light yield (normalized to thickness) is ~ 1/3 of plastic scint.
→ tests light transmission on WLS fibers in absence of air gap
Energy resolution, particle-ID and uniformity ~ plast. scint.


ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 956, 11 March 2020, 163379

Polysiloxane-based scintillators for shashlik calorimeters

F. Acerbi [a], A. Branca [b, c], C. Brizzolari [d, k], G. Brunetti [b], S. Carturan [c, f], M.G. Catanesi [g], S. Cecchini [h], F. Cindolo [h], G. Collazuol [b, c], F. Dal Corso [b], G. De Rosa [i, j], C. Delogu [b, c], A. Falcone [d, k], A. Gola [a], C. Jollet [l], B. Kliček [m], Y. Kudenko [n], M. Laveder [b, c] … M. Vesco [b, c]

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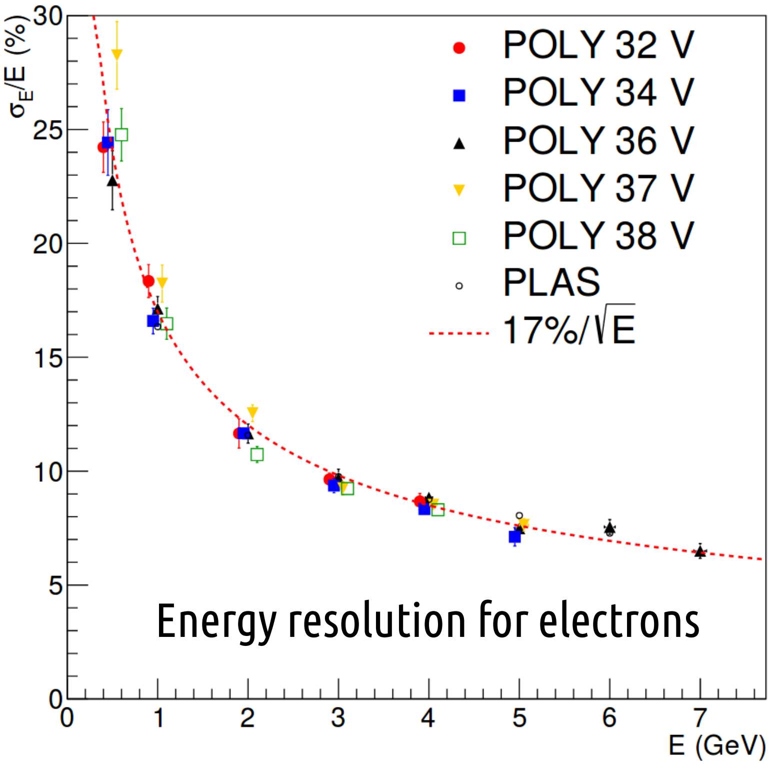
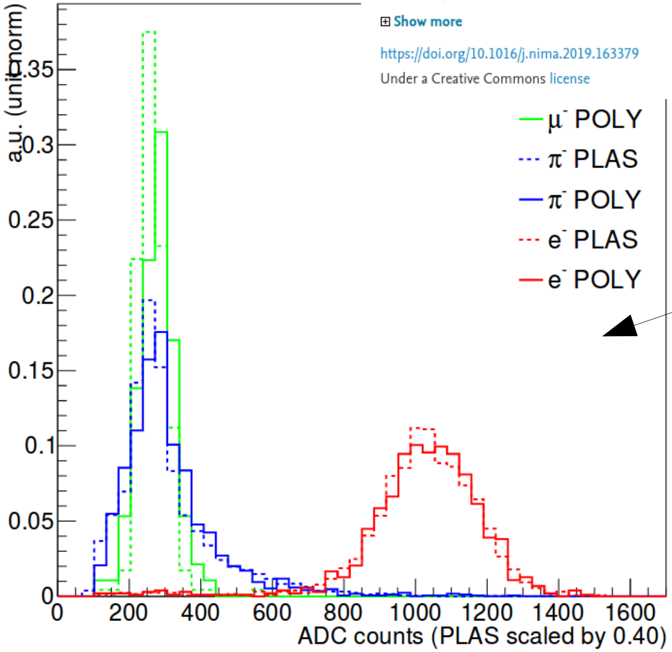
NIM A 956 (2020) 163379
(arXiv:2001.03130)

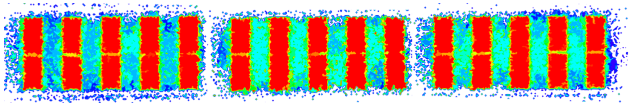


Energy resolution for electrons

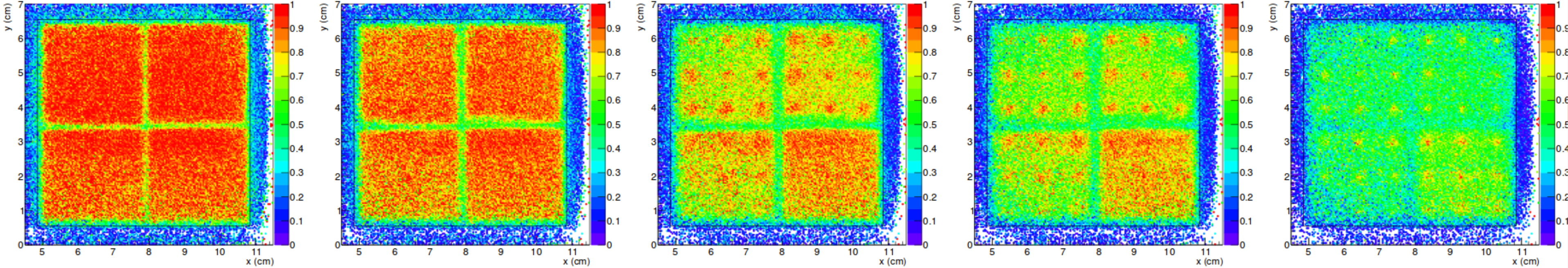


Particle ID

Polysiloxane (solid)
Plastic (dashed)

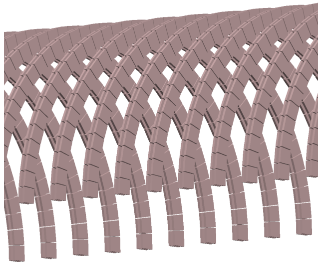


Efficiency maps at increasing thresholds →



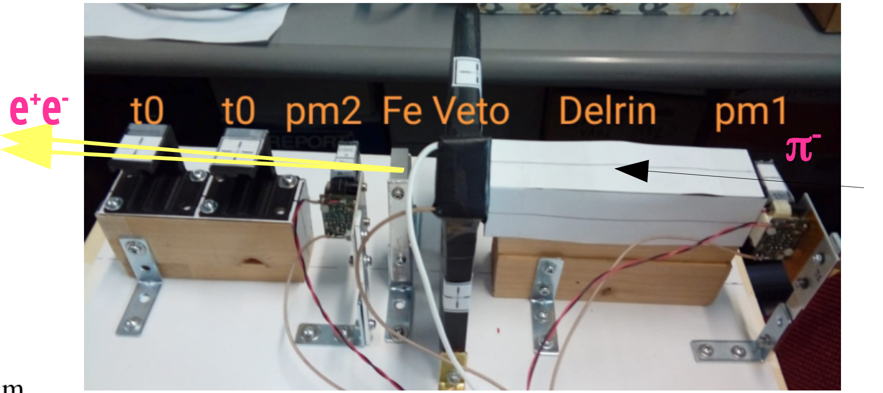
The photon veto

@ CERN-PS T9 line 2016-2018



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

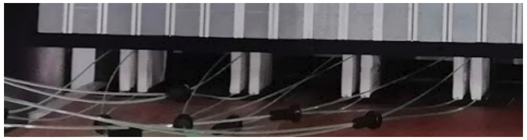
Trigger: PM1 + VETO +PM2

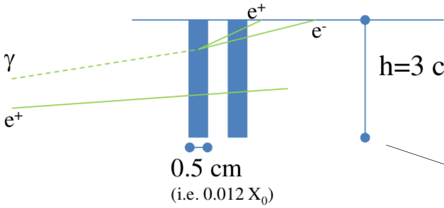


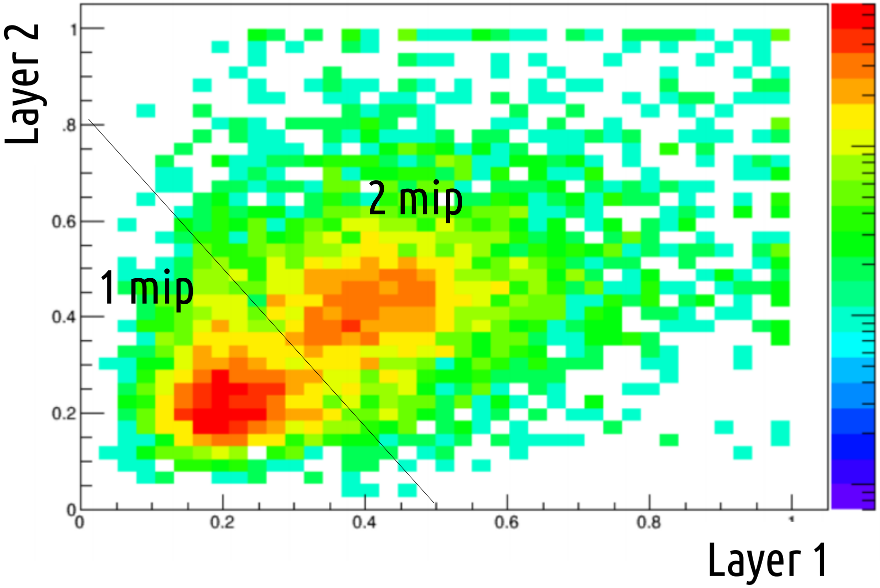
- **γ / e^+ discrimination + timing**

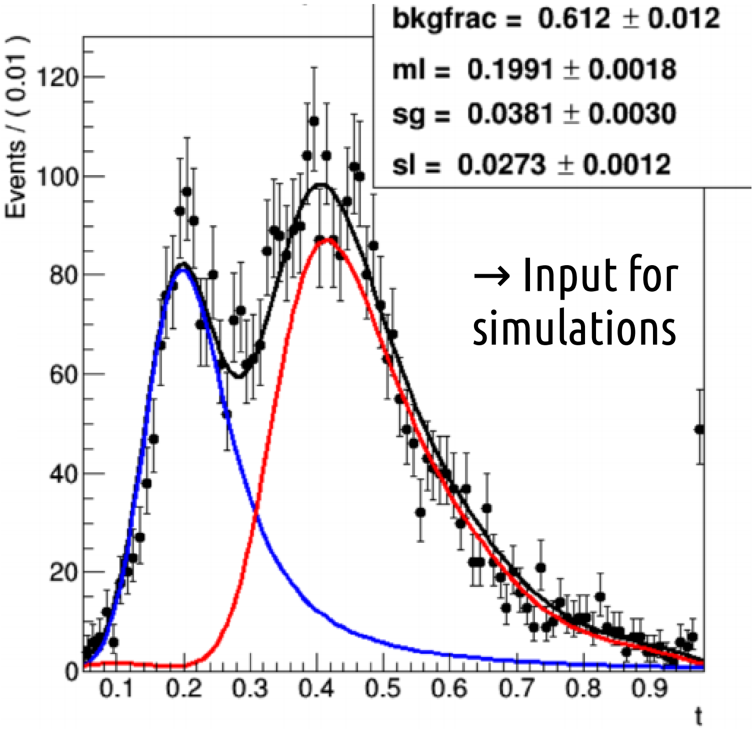
scintillator (3×3×0.5 cm³) + WLS Fiber (40 cm) + SiPM

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







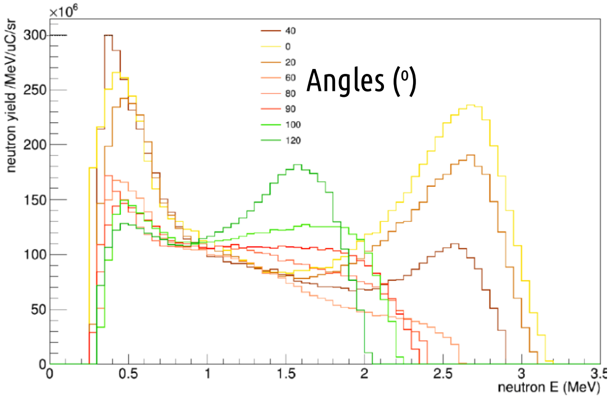


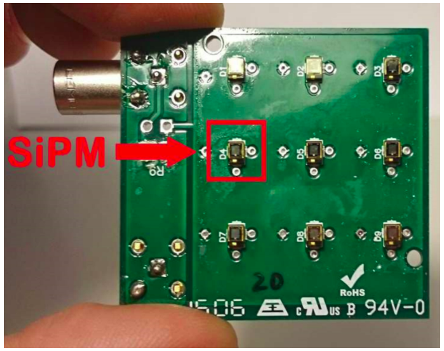
→ Input for simulations

SiPM irradiation @ INFN-LNL (Legnaro)

- SiPM were irradiated at the CN Van de Graaf on July 2017
- 7MV and 5 mA proton currents on a Be target
- ^{9}Be(p,n)^{9}B, ^{9}Be(p,np)2α, ^{9}Be(p,np)^{8}Be and ^{9}Be(p,nα)^{5}Li
- → 1-3 MeV n with fluences up to 10^{12}/cm^2 in a few hours

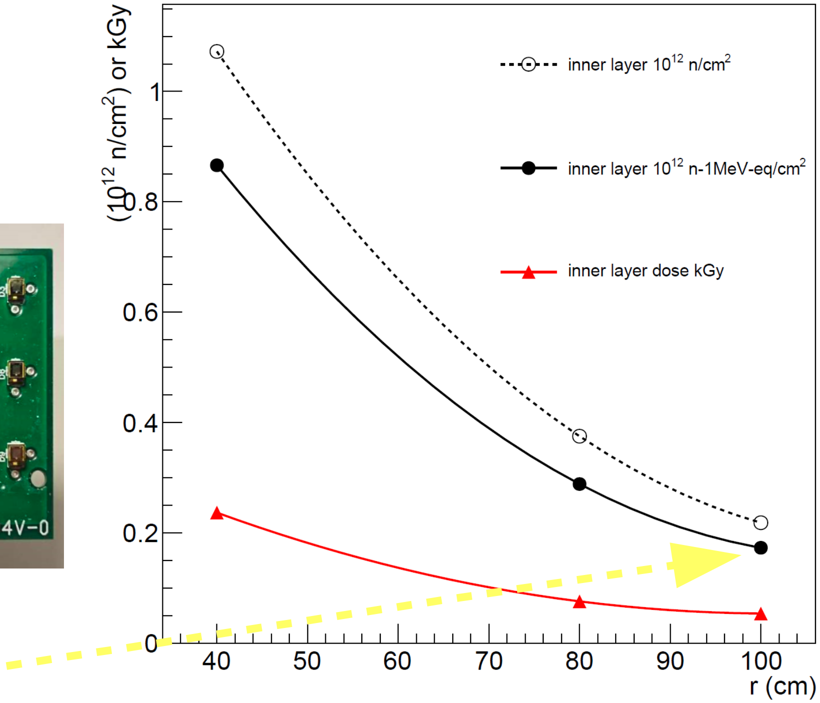
n spectra (from previous works at the same facility)

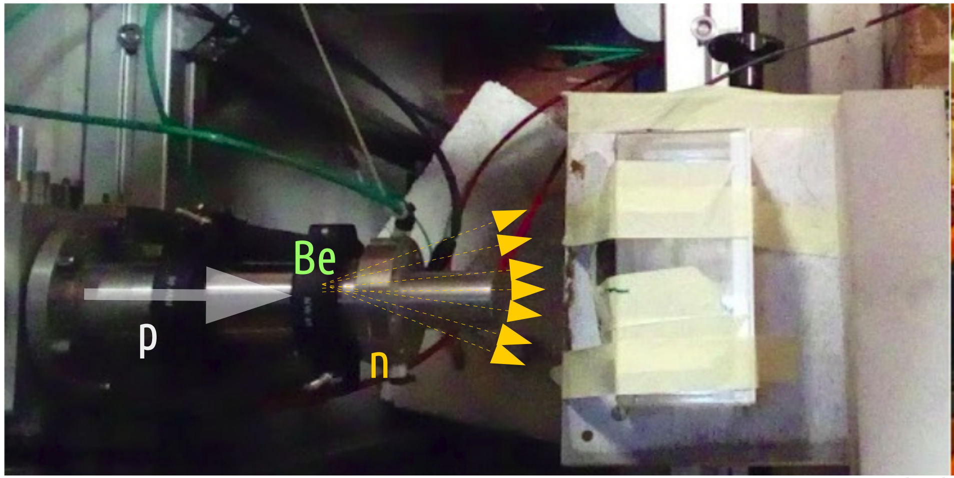


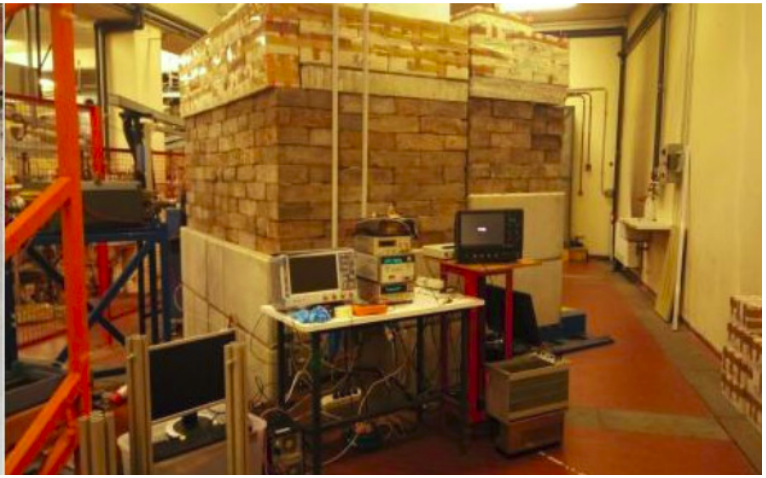


→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm^2** 1 MeV-eq (max non ionizing dose for 10^4 ν_e^{CC} at a 500 t ν detector at r = 1 m)

Expected n doses from K decays (FLUKA)

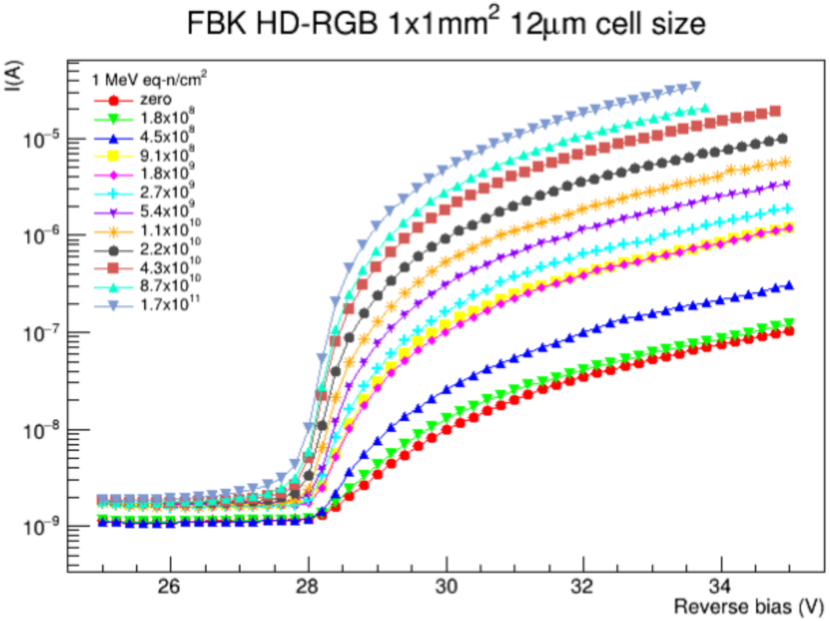






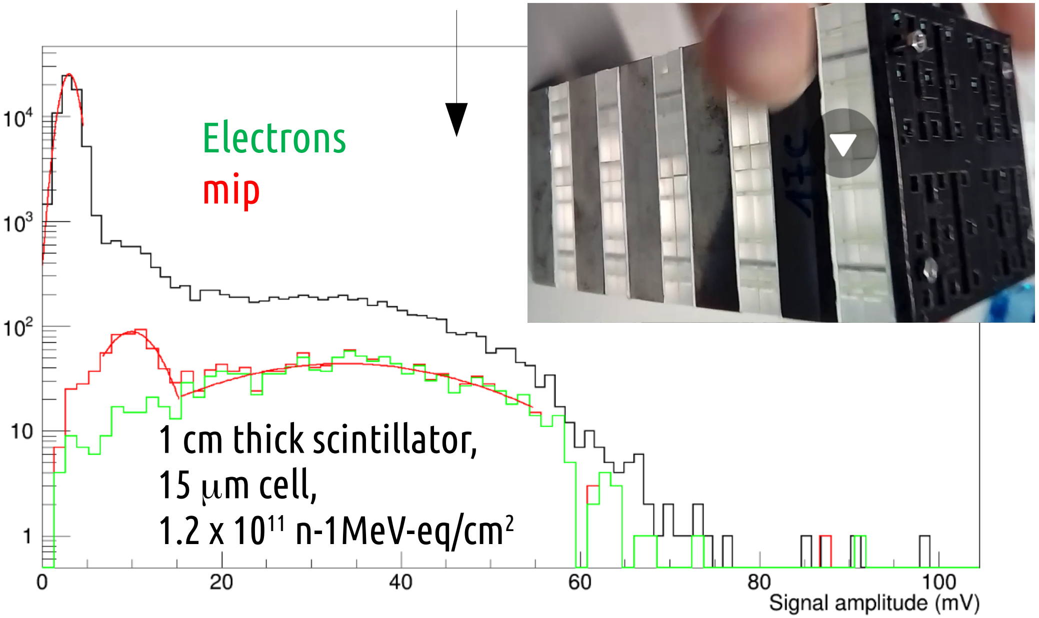
SiPM irradiation measurements at INFN-LNL and CERN

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



1 cm thick scintillator,
15 μm cell,
1.2×10^{11} n-1MeV-eq/cm^2

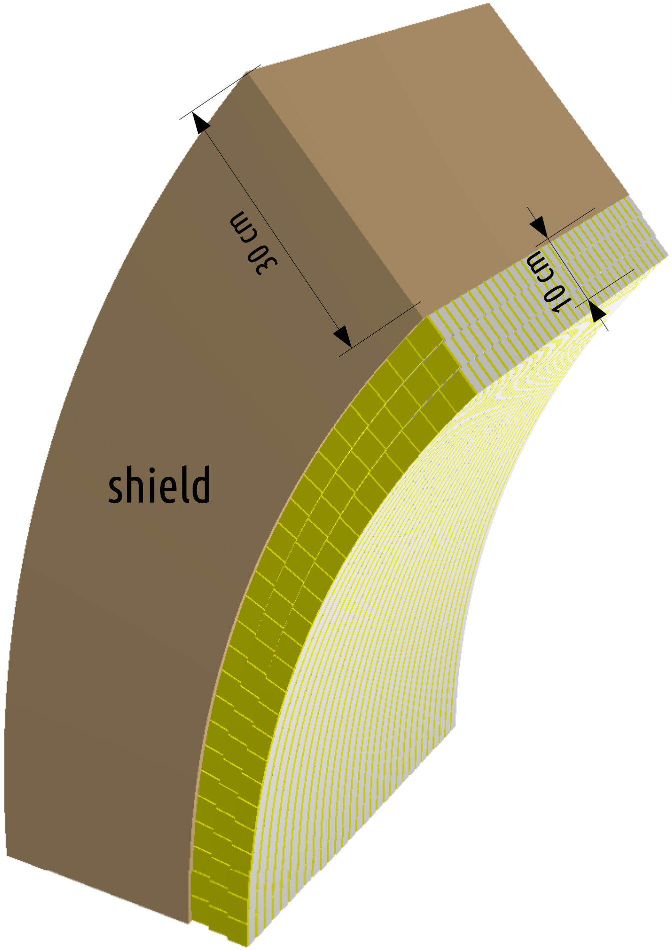
(FBK-HD-RB Advansid)

- 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 for **channel-to-channel intercalibration** even after maximum irradiation.

Achievable neutron reduction with lateral readout

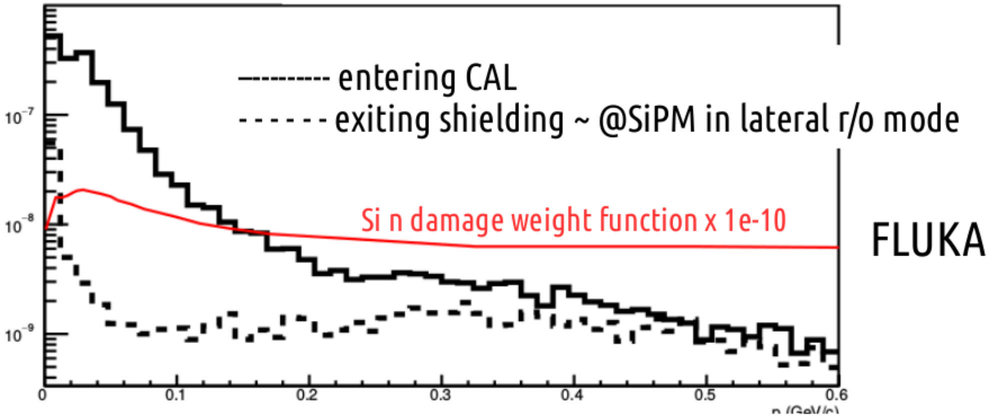
- 30 cm of borated polyethylene in front of SiPM
- FLUKA full simulation. **400 GeV protons**.

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

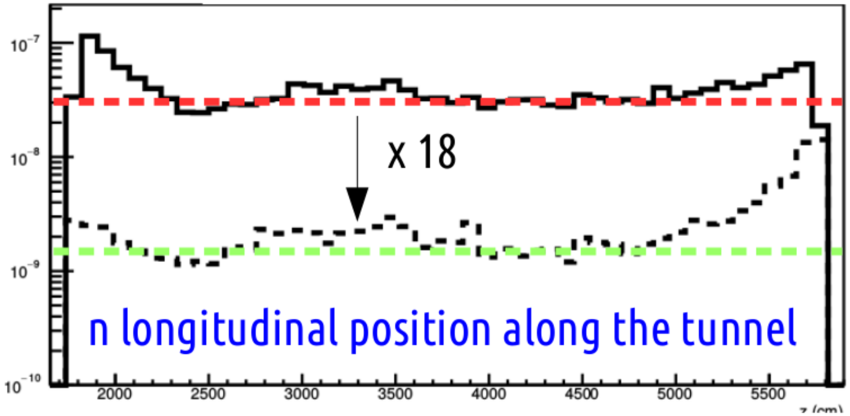


preliminary

Neutron energy



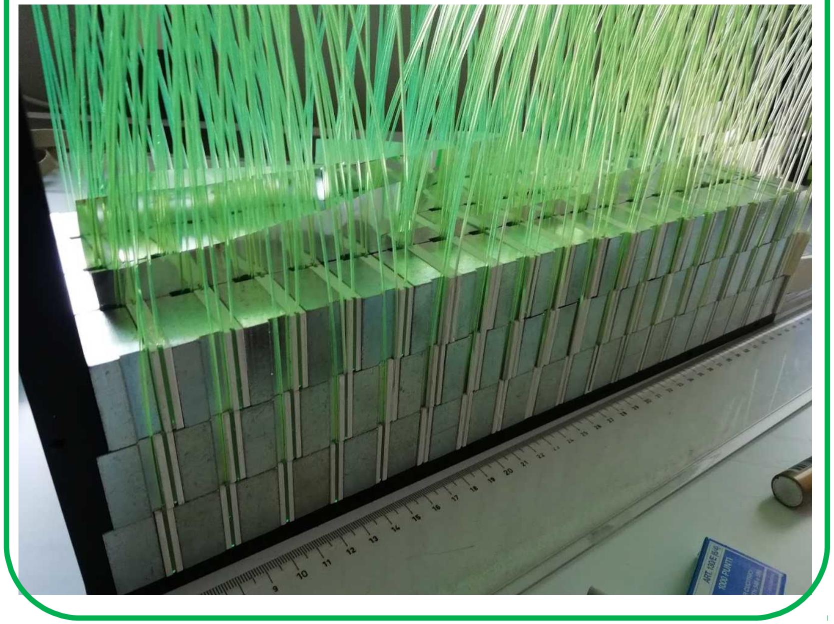
FLUKA



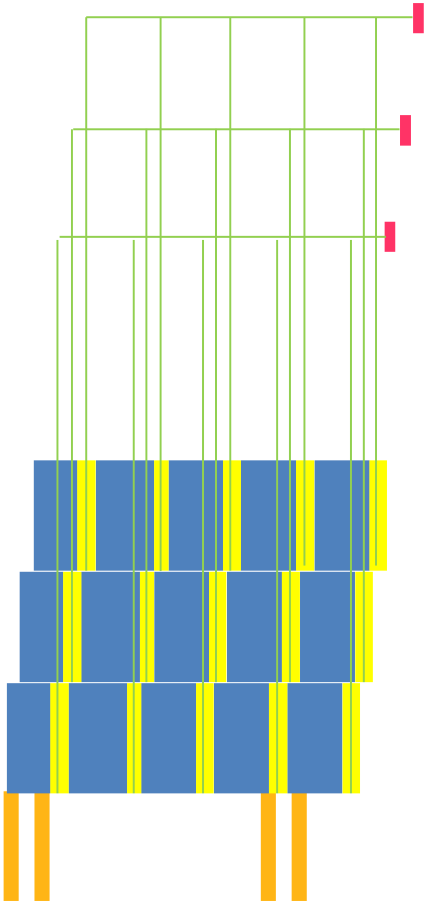
The tagger: lateral readout option

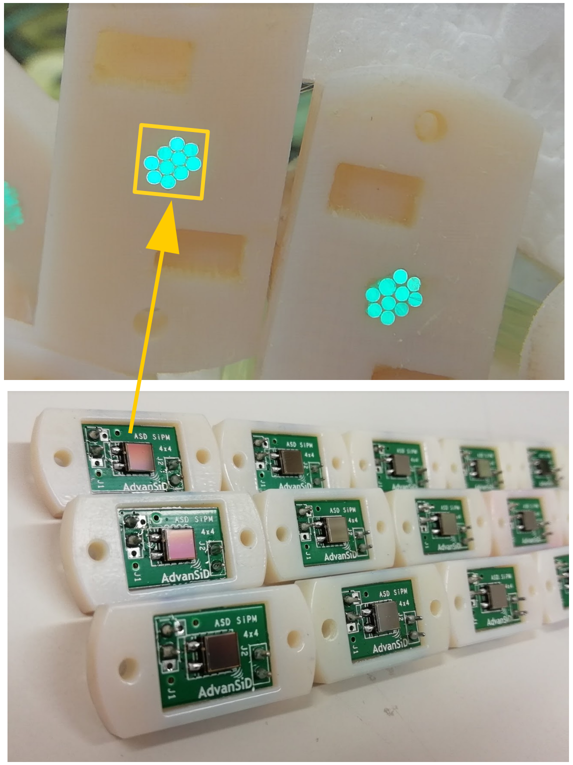
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM).
SiPM are not immersed anymore in the hadronic shower → less compact but ..
much **reduced neutron damage** (larger safety margins), better **accessibility**, possibility of replacement. Better reproducibility of the **WLS-SiPM optical coupling**.

Sampling calorimeter with lateral WLS light collection



May 2018, CERN-PS test beam

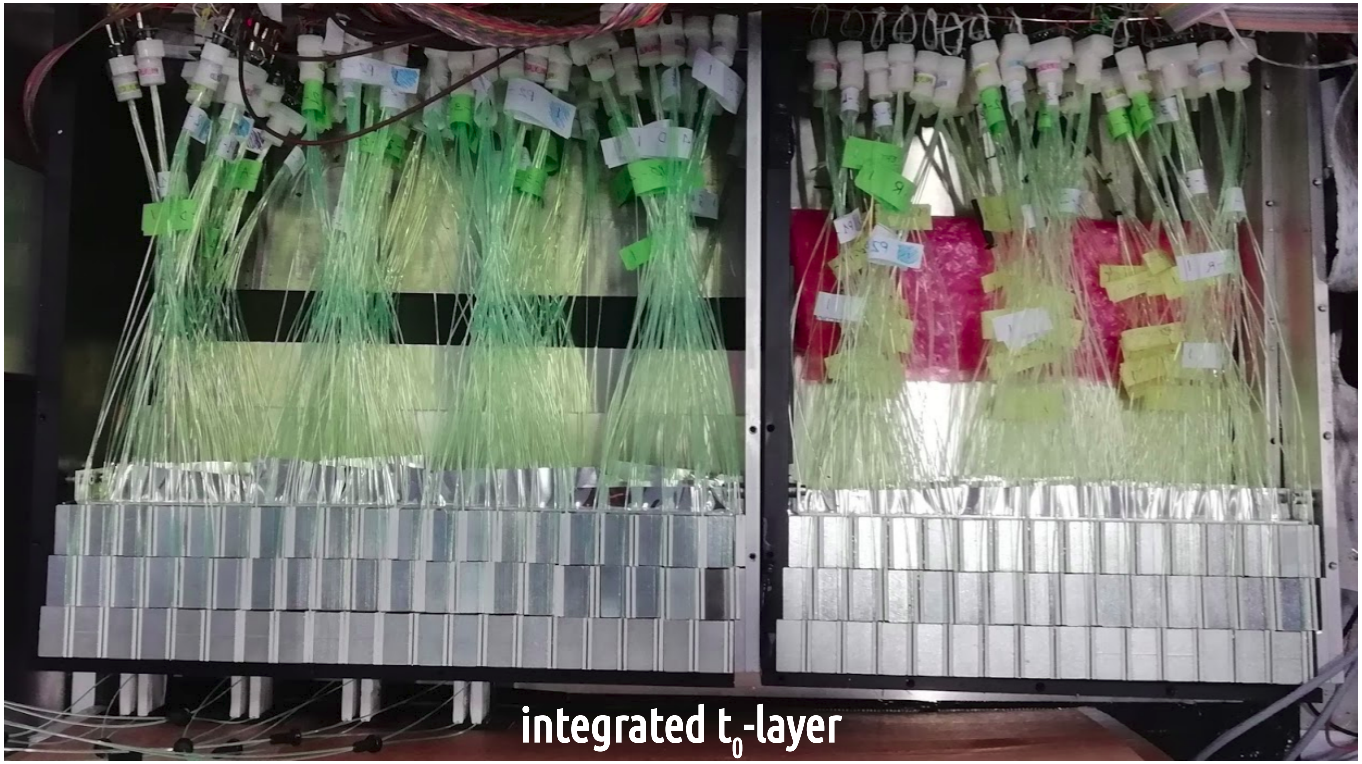




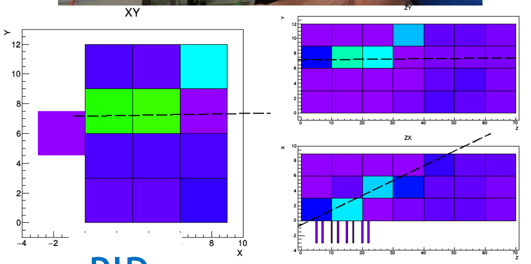
Large SiPM for 10 WLS
4x4 mm^2

The Tagger – Detector R&D

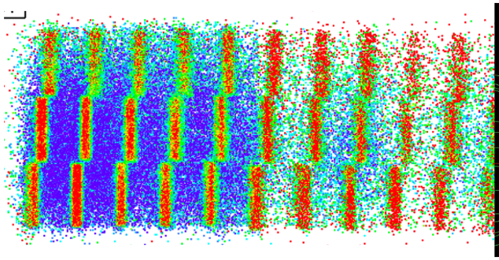
September 2018 CERN-PS: a module with hadronic cal. for pion containment and **integrated t_0-layer**


integrated t_0-layer

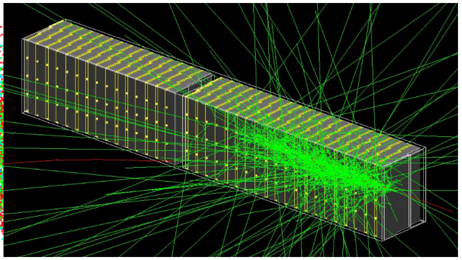
- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match. In progress.



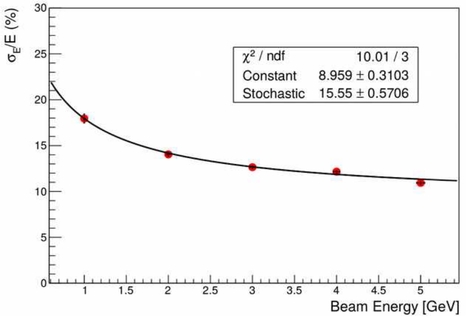
Efficiency maps



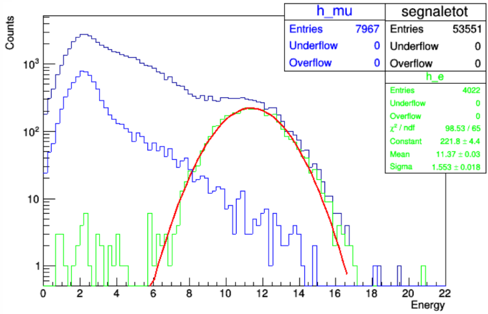
Simulation



Resolution

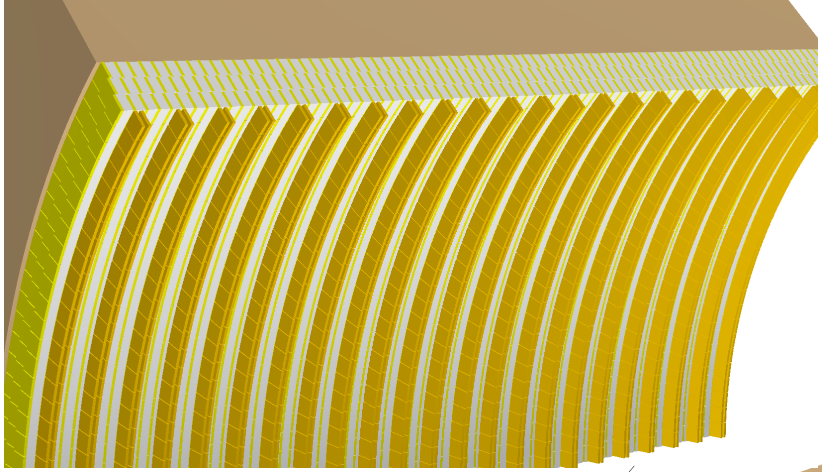


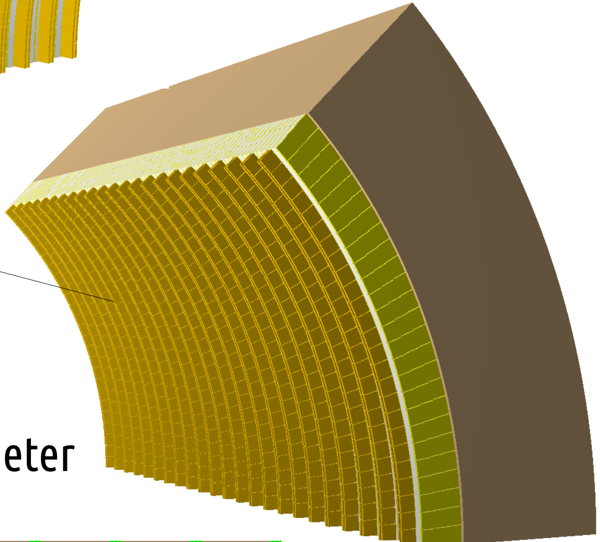
PID



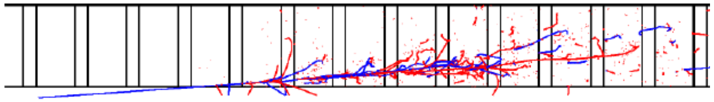
The tagger demonstrator

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

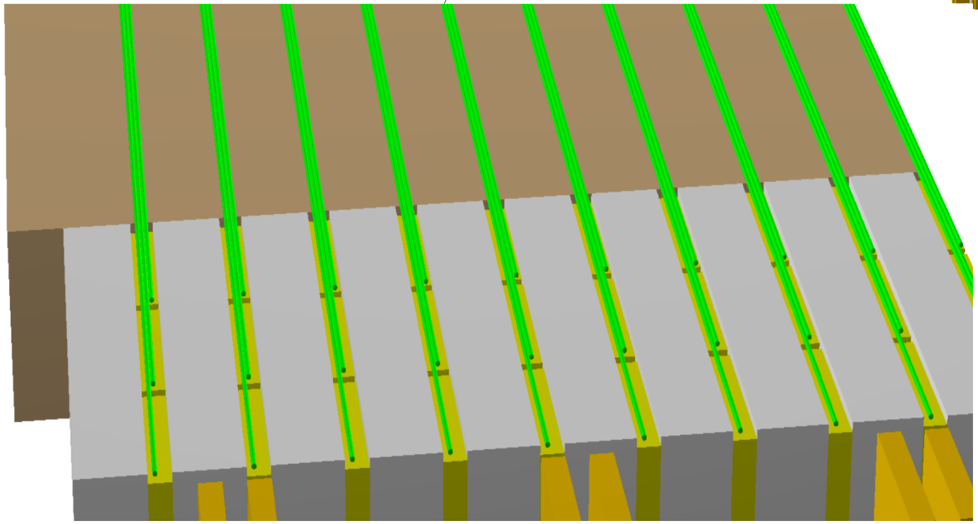




t_0-layers

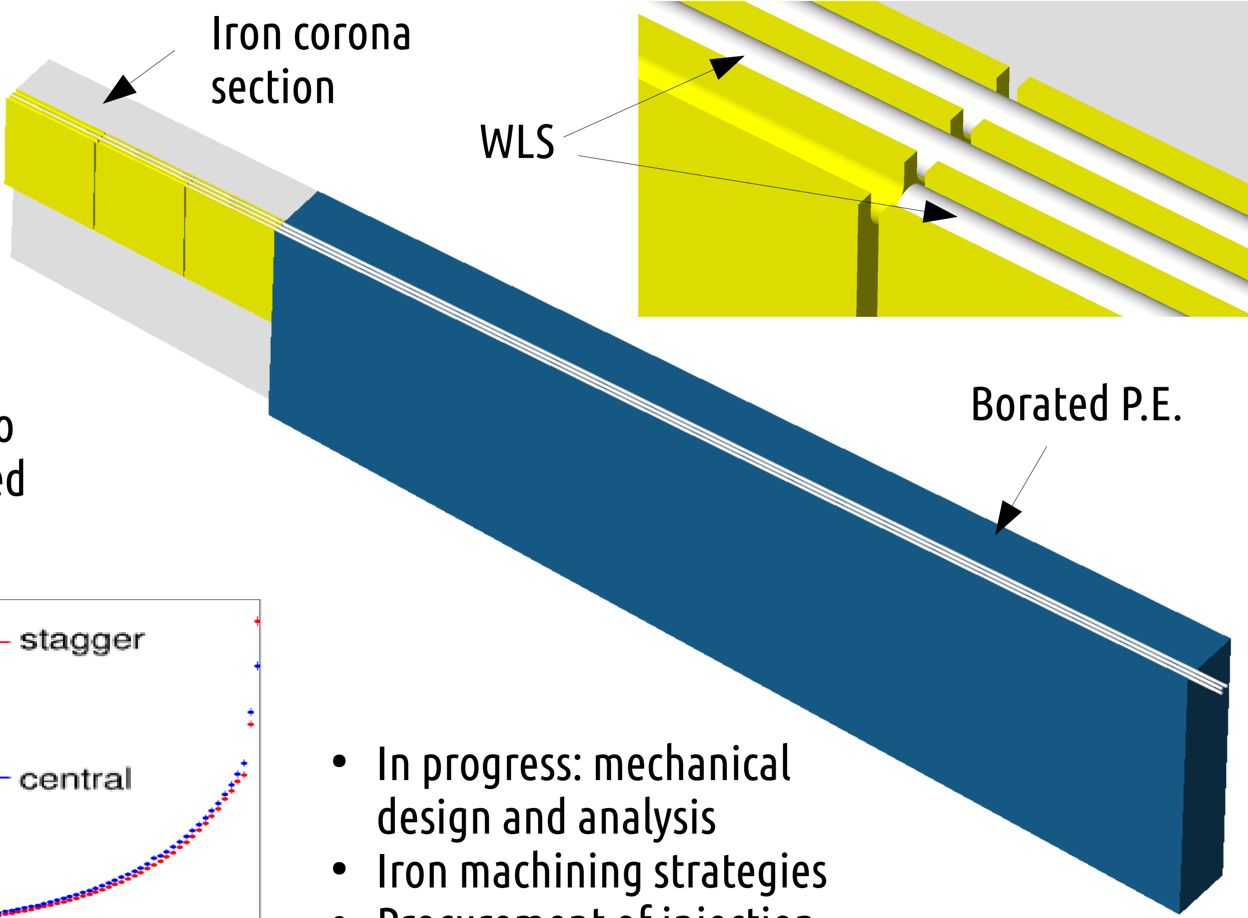


3 layers calorimeter

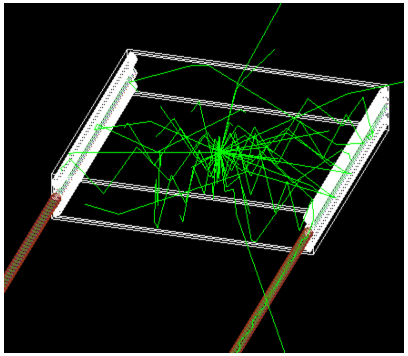


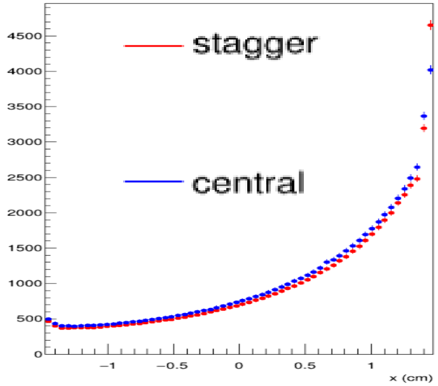
- Will be tested at the CERN renovated East Area after Long-Shutdown 2
- Demonstrate physics, scalability and cost effectiveness

Demonstrator



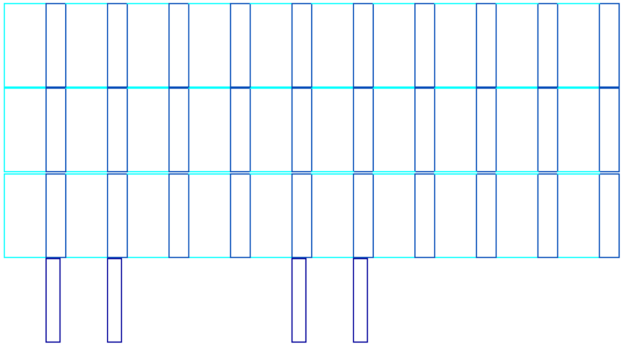
- A **new design**: staggering of WLS fibers within tiles in place of staggering the absorbers
- Optical simulations with GEANT4 to verify the effect of using a displaced groove → almost no difference

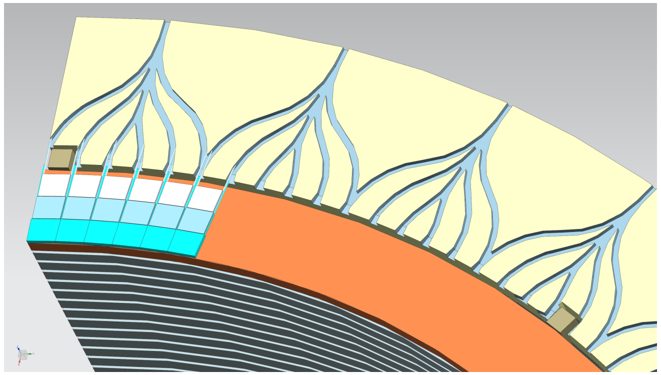




- In progress: mechanical design and analysis
- Iron machining strategies
- Procurement of injection molded tiles, SiPMs

- Spacing of t_0-layers made compatible with WLS routing (1 doublet/UCM)
- Tiles: 5-7 mm to accommodate grooves



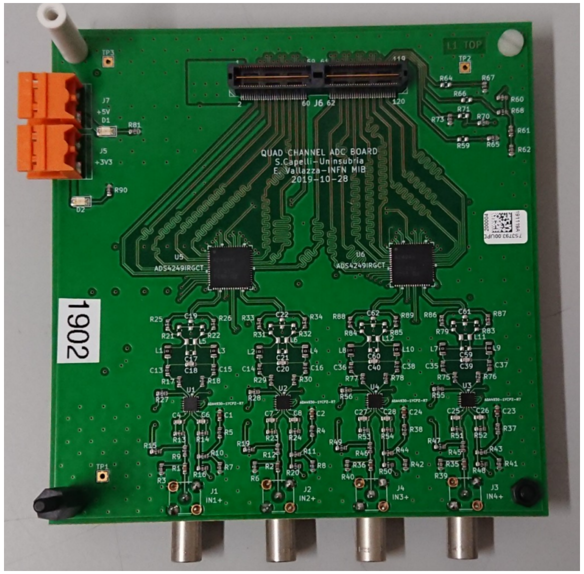


Progress with the electronics (WP3)

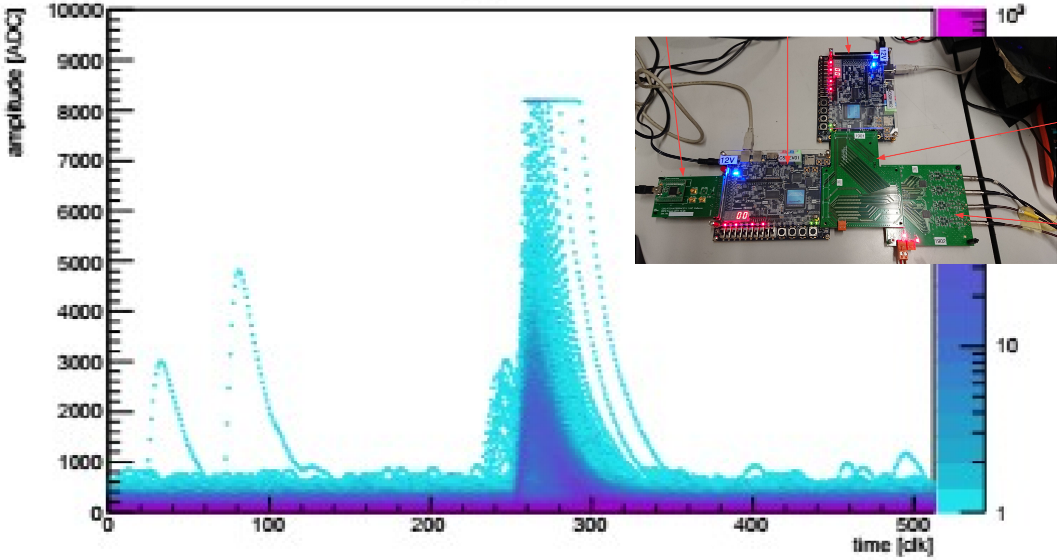
Development of custom digitizers
8 ch, 14-bit ADC, 250 MS/s
~10 ms spill (horn)
~40 MB/spill/UCM

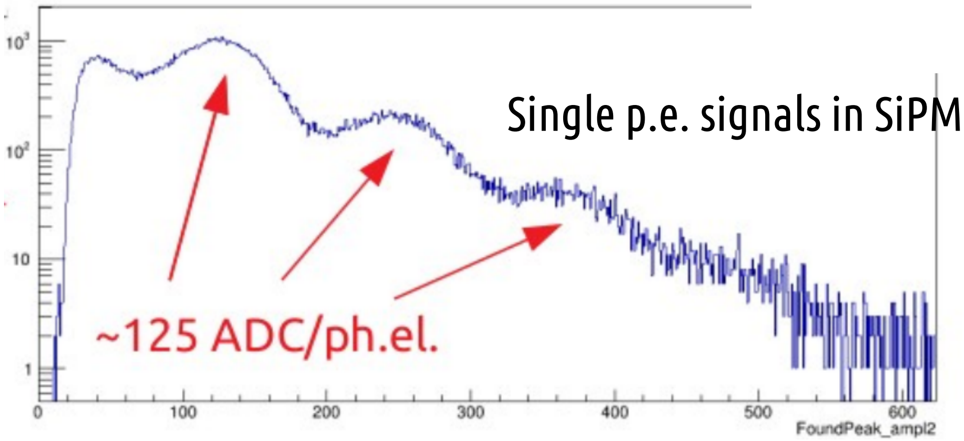
4 ch ADC board ready and validated

- 4 amplifiers with gain = 4 (ADA4930 opamps)
- 2 x ADS4249 ADCs
- Power: Weidmuller (3.3/5V) or SAMTEC conn.



Cosmic ray waveforms with the custom system



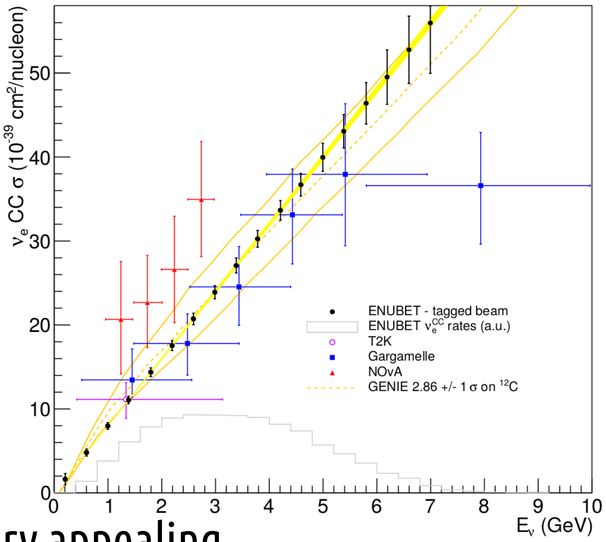


Single p.e. signals in SiPM

~125 ADC/ph.el.

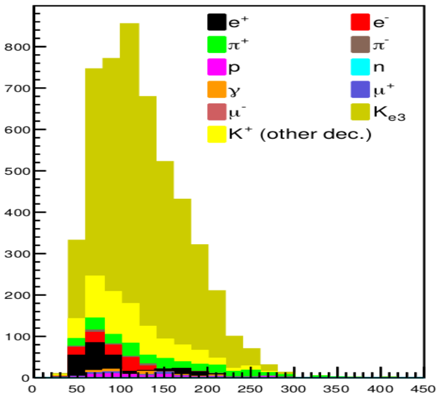
→ **final** 8 ch board with **fast synchronous FIFO USB** data transfer protocol in a few months

Summary of progress



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

Feasibility of **purely static focusing system** (10^6 ν_μ^{CC}, 10^4 ν_e^{CC} /y/500 t)
Tested **"burst" slow extraction** at CERN-SPS → **horn option** remains very appealing
Completed the **test beams** campaign before CERN Long Shutdown 2



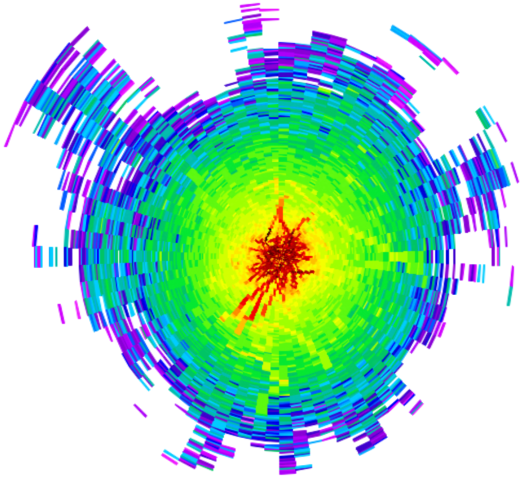
Especially, in the last year

- ○ CERN Neutrino platform – **ENUBET-NP06**
- ○ **Polysiloxane** shashlik calorimeter paper published
- ○ **End-to-end simulation** based on GEANT4
  - The framework for the treatment of **systematics**
- ○ **Double dipole beamline** with improved shielding →
  - **Single particle e+ monitoring** with a greatly improved **Signal-to-Noise**
  - Reduction of **untagged-neutrino component**
- ○ **Lateral readout** option → ensures a **long lifetime and accessibility of photosensors**
- ○ **Read-out**: developed **waveform treatment** algorithms and **custom digiziters**
- ○ **Engineering of the final prototype**

ENUBET next steps

- Full assessment of **systematics** on the neutrino fluxes
- Build the **demonstrator prototype** of the tagger (2021)
- **Conceptual Design Report** at the end of the project (2021): **physics** and **costing**
- >2021: (likely) propose a full scale experiment implementation supported by a larger international collaboration.

Thank you



Core team @ Bordeaux 3/19

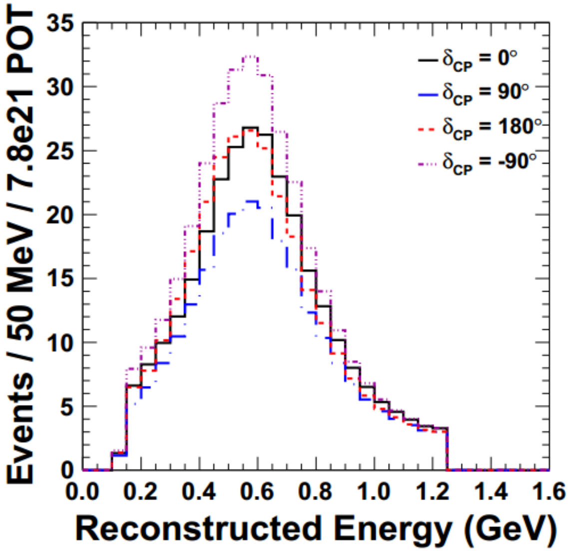
Backup

Pivotal importance of the ν_e cross section

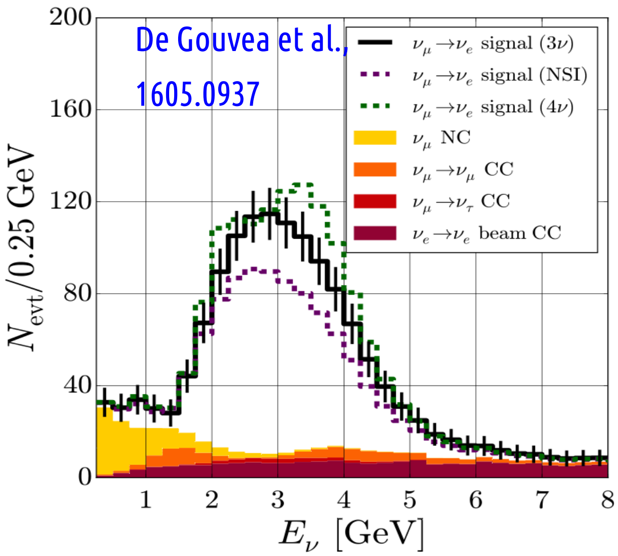
Leptonic CP violation : P($\nu_\mu \rightarrow \nu_e$) vs P(anti-$\nu_\mu \rightarrow$ anti-ν_e)

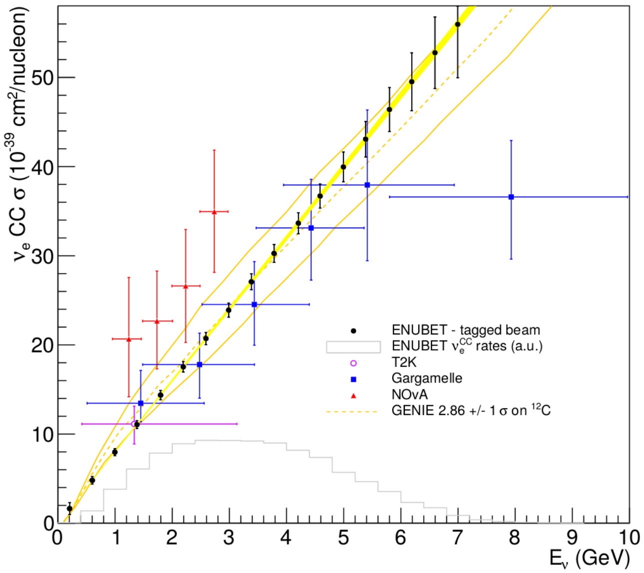
- the δ_{CP} phase induces **mainly a change in normalization in interaction rates** of electron neutrinos (in opposite directions for nu and anti-nu)
- knowing well the ν_e cross section **crucial to boost the potential of future experiments** (HyperK, DUNE) by decreasing their **systematics budget**.
- **Moreover** $\sigma(\nu_e)$ vs :E → **unravel 3-flavour CP violation** from **exotic scenarios** (sterile neutrinos, non-standard interactions) with a similar phenomenology

Hyper-K



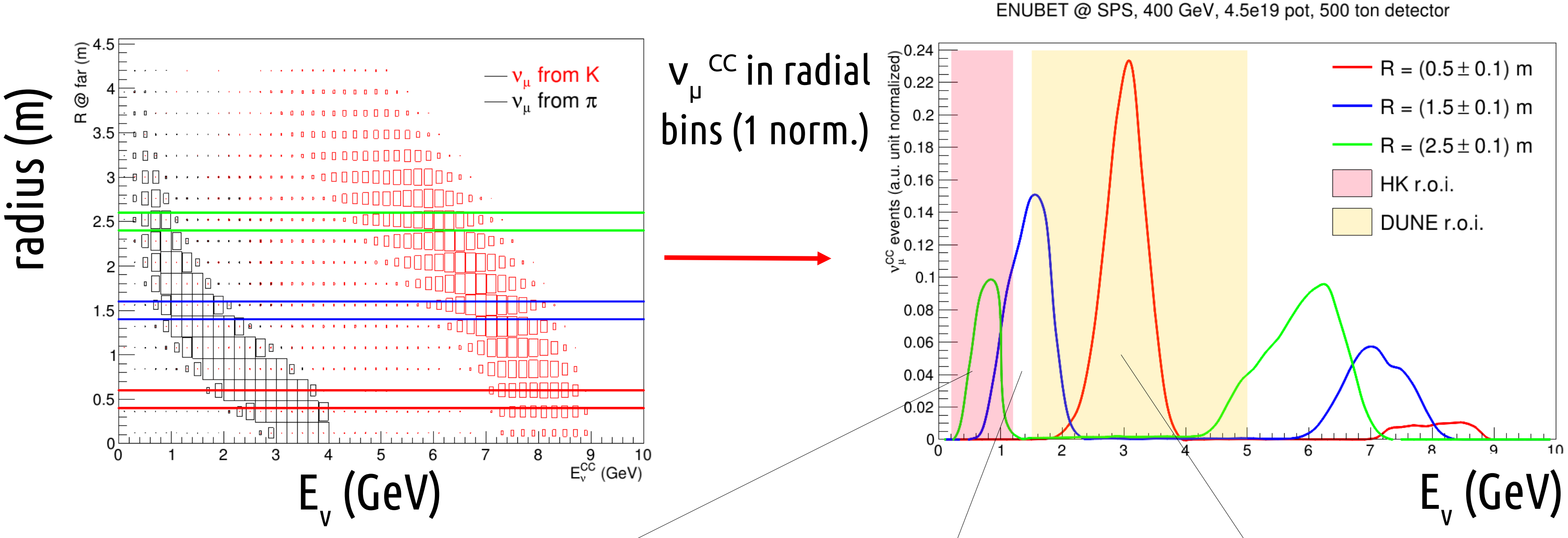
DUNE





ν_μ CC events at the ENUBET narrow band beam

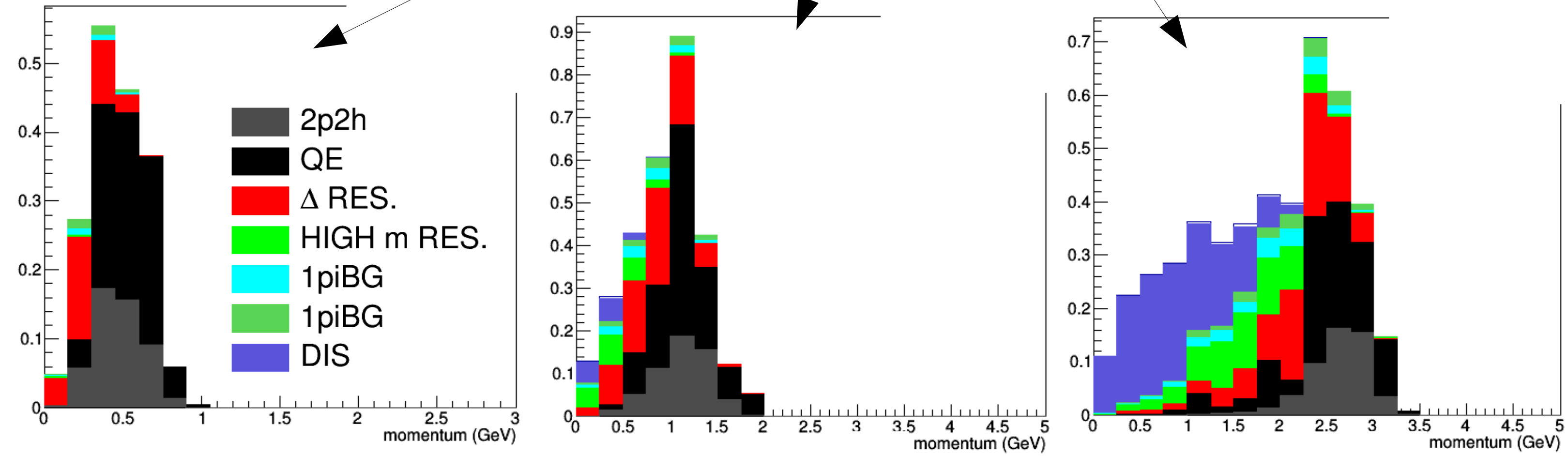
The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.



ν_μ ^{CC} in radial bins (1 norm.)

Momentum of ν_μ ^{CC} μ^- on Ar.

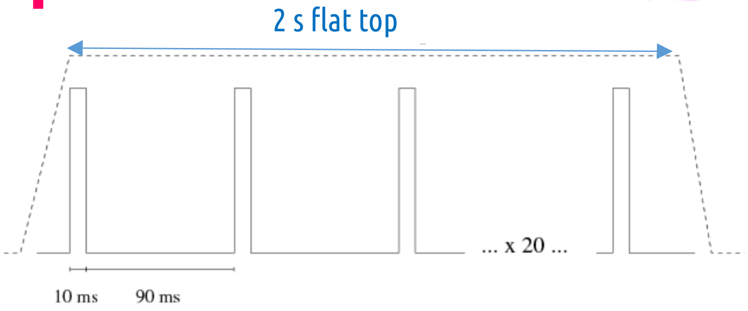
GiBUU generator (Gauss flux approx.)



Machine studies for the horn-based option

- Performed Jul/Aug/Nov 2018 at the SPS

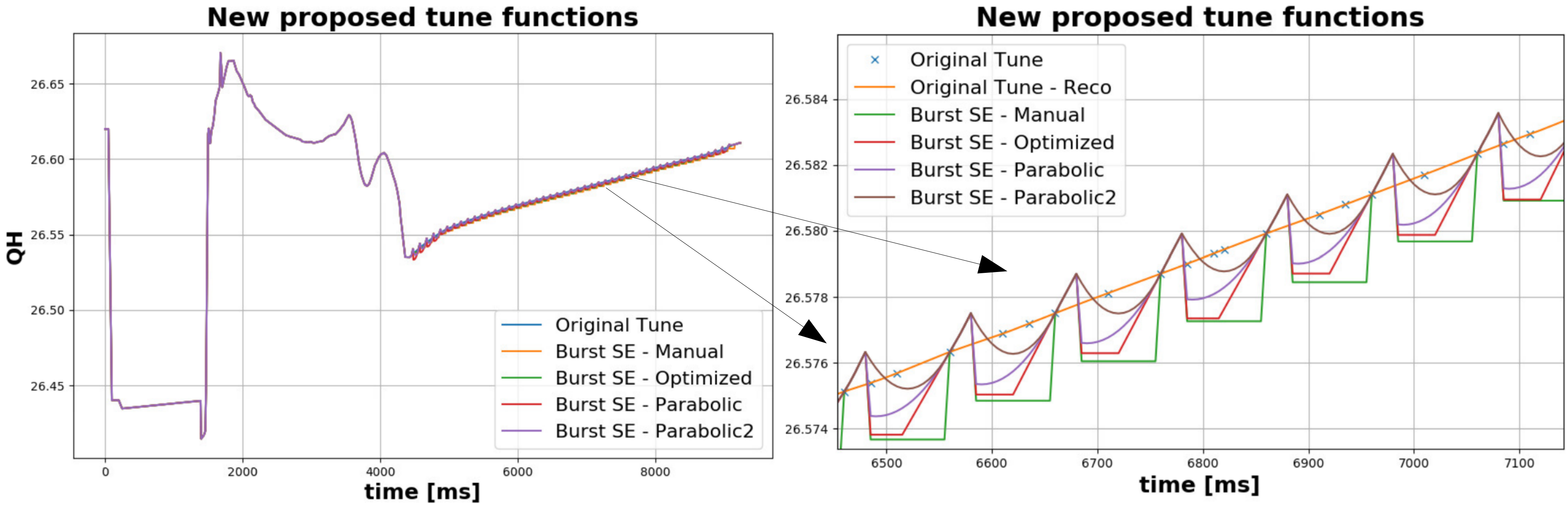
CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard



- Idea: synchronize proton beam and horn current pulses
- \+ keep rates compatible with tagger (10 ms pulses “slow extr.”)

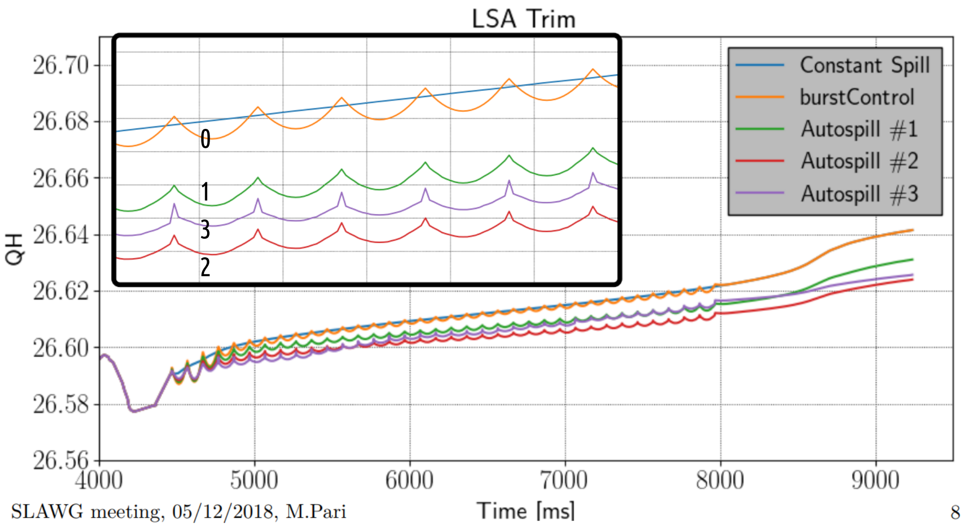
“burst ” slow extraction: trigger the third integer betatron resonance with a periodic pattern

M. Pari (CERN doctoral student, Univ. of Padova) @ SLAWG meeting of 5/12/2019
https://indico.cern.ch/event/777458/

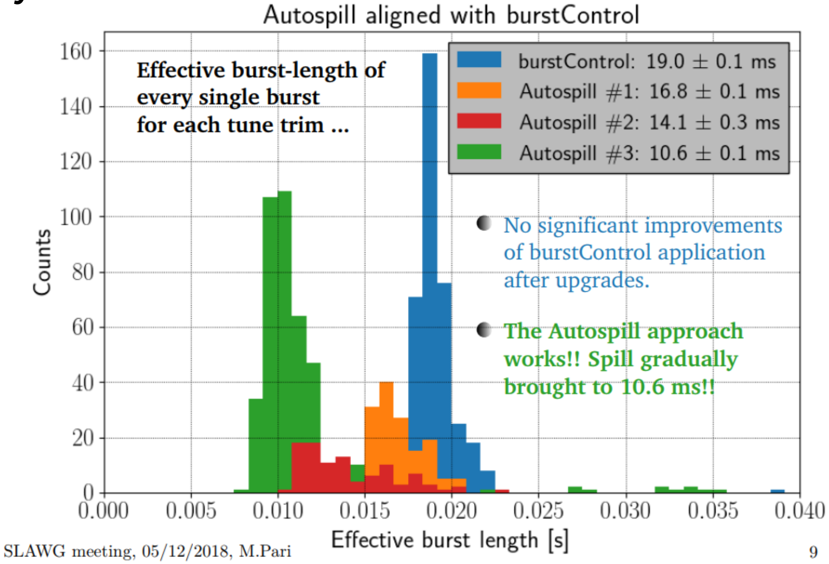


Machine studies for the horn-based option

- Difficult to get below 20 ms → implemented a feed-forward mechanism using BCT data
- Iterative procedure (AutoSpill) → can "sharpen" peaks **up to 10 ms in 3 iterations**
- at the cost of a somewhat larger variance in peak intensity.



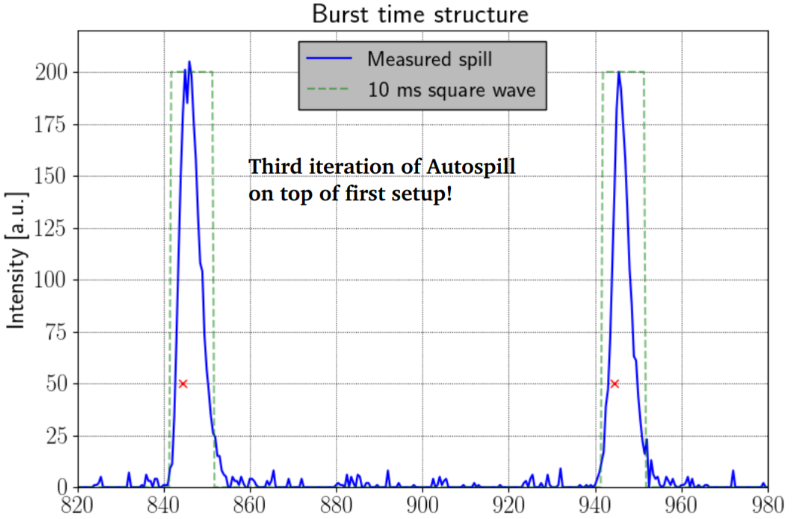
SLAWG meeting, 05/12/2018, M.Pari 8



Effective burst-length of every single burst for each tune trim ...

- No significant improvements of burstControl application after upgrades.
- The Autospill approach works!! Spill gradually brought to 10.6 ms!!

SLAWG meeting, 05/12/2018, M.Pari 9



Third iteration of Autospill on top of first setup!

- Versatile/general: **mixed continuous-burst possible**.
- General **software tool** developed for CR operations.
- Present studies suggest that this mode **does not increase significantly radiation losses at septa**
- ENUBET: would the static focusing be preferred, burst mode could be used to **constrain cosmics background**.
- Now focusing on simulation/further ideas, improvement in diagnostics used for feedback (BCT).
- Studies performed in a limited time → will **benefit greatly of more data in the future**!

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


Padova June 2016


CERN Nov 2016


CERN Aug 2017


CERN Oct 2017


INFN-LNL Jun 2017


CERN May 2018

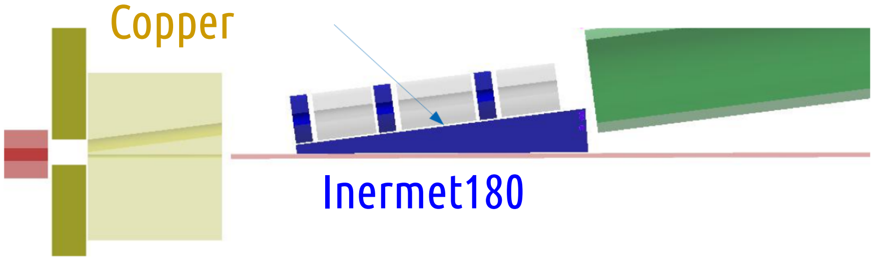

CERN Sep 2018


Milan Oct 2017

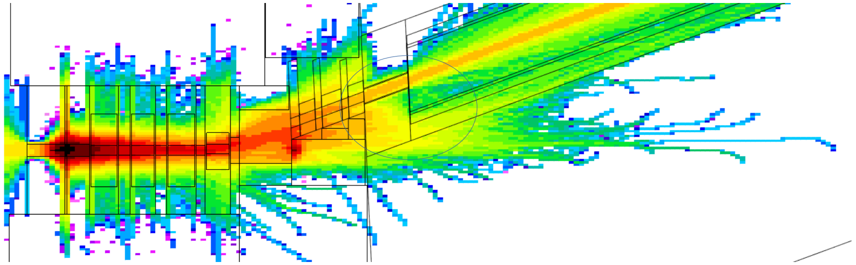
Beamline shielding tuning studies

- Studies in progress to optimize the shielding to shield muons and other backgrounds.

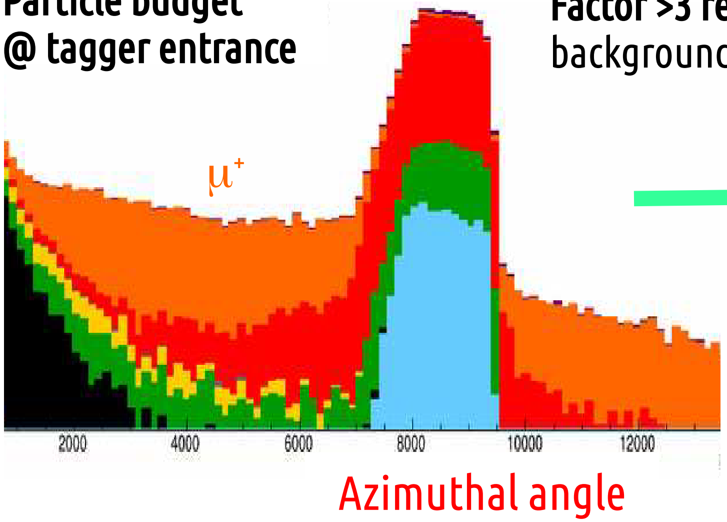
G4Beamline



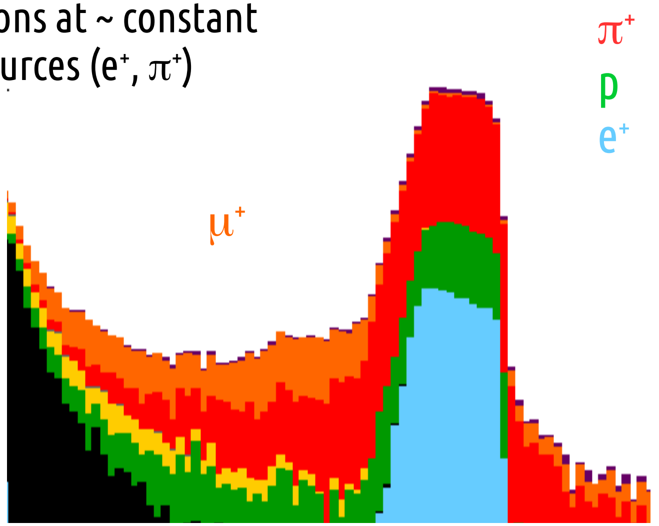
FLUKA (muon energy deposition map)



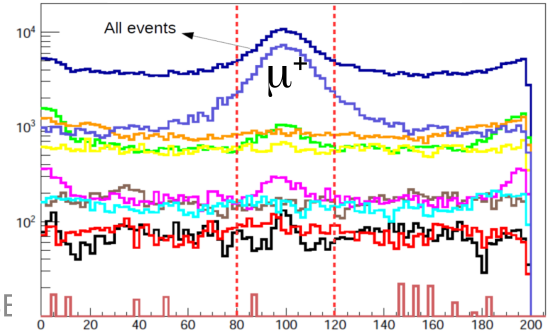
Particle budget
@ tagger entrance



Factor >3 reduction in muons at ~ constant background from other sources (e^+, π^+)



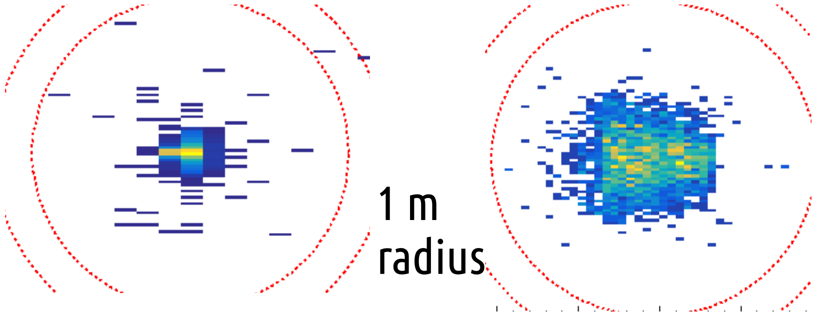
The bulk of μ^+ along dipole bending plane



Besides shielding a further reduction of muons can be achieved by removing a section in ϕ in the upstream part of the tagger

The static beamline: emittance, particle content

Divergence of the kaon beam

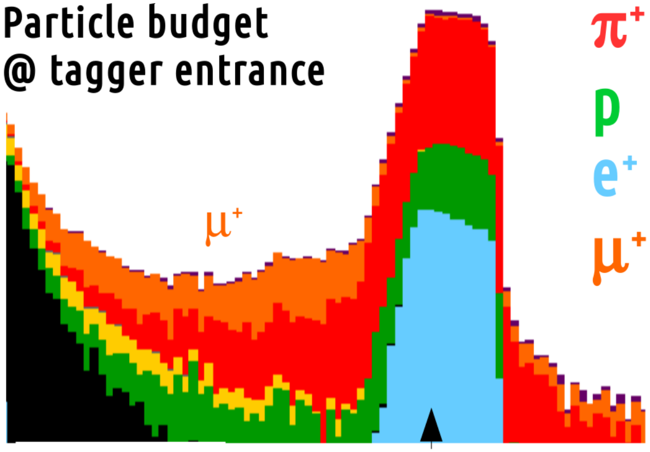


K^+ @ tagger entrance

exit

1 m radius

Particle budget @ tagger entrance



π^+

p

e^+

μ^+

p (MeV/c)

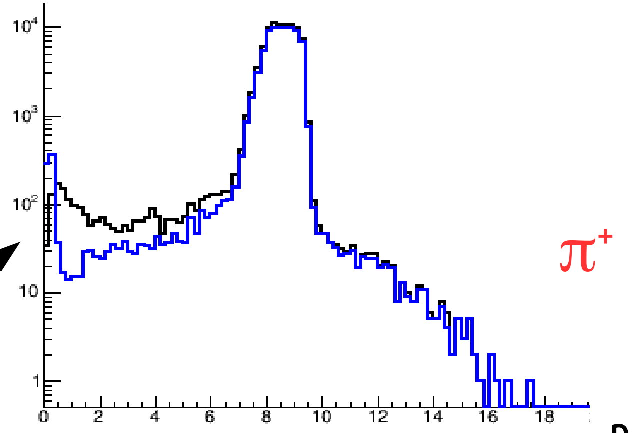
Momentum bite (8.5 ± 10%) GeV/c

Spectra @

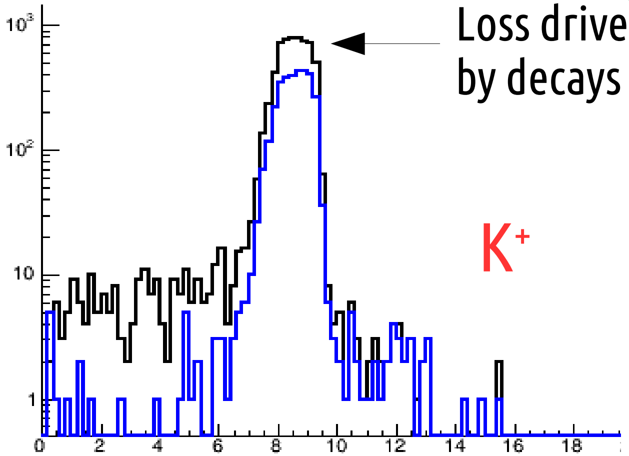
tagger entrance

tagger exit

Low energy high angle π



p (GeV/c)



Loss driven by decays

p (GeV/c)