The ENUBET ERC project:
a new concept neutrino beam for precision physics

A. Longhin

Beihang-Padova, 22/10/2019

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).

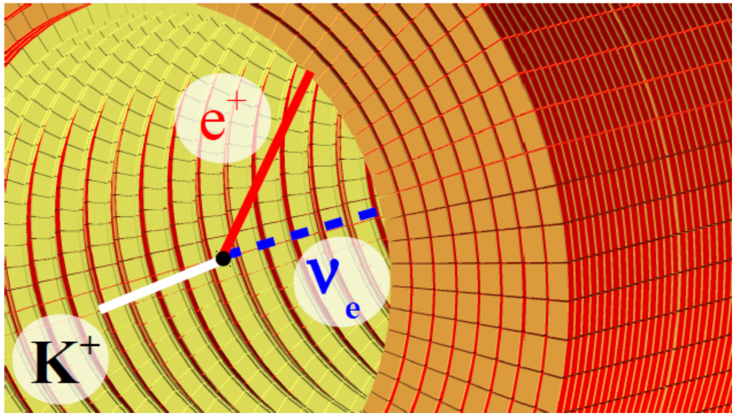
Enhanced Neutrino BEams from kaon Tagging

ERC-Consolidator Grant
2016-21, 2M€ budget
P.I.: A. Longhin, Host Institution: **UNIPD**
Beneficiary **INFN**

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**

60 physicists, 12 institutions



Univ.: Padova, Bologna, Milano Bicocca, Insubria, Napoli, Bordeaux.
Research inst.: INFN, CERN, FBK (Trento, IT), INR (Russia), IN2P3 (Bordeaux, FR), Ruđer Bošković Institut (Zagreb, Croatia).

A word on the European Research Council calls

Are you a researcher with an **excellent scientific profile** and with **visionary research projects** in mind that you want to **realise in Europe**? The European Research Council (ERC) has a funding scheme that will meet your needs.

The "spot" :
(from webpage)

Consolidator 2015: 585 M€, 302 grantees

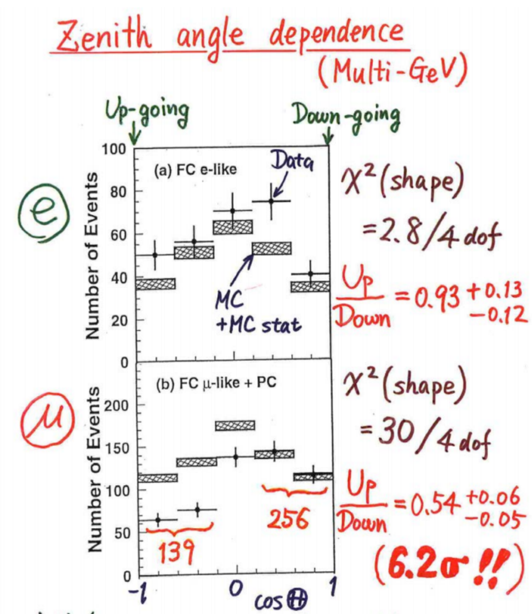
- **1 researcher; 1 host institution; 1 project**;
- 1 selection criterion: **scientific excellence**
- No consortia, no networks, no co-financing
- **any field** of research, including social sciences and humanities
- **Independent researchers** from **anywhere in the world**
- Research: in the 28 **EU** member states or **associated countries**
- **Any career stage** (Consolidator = "*for already independent excellent researchers 7-12 years after PhD) -up to 2 million euro for a period of 5 years*")
- Host institutions **must provide conditions for the researcher** to direct the research and manage its funding
- Grant is '**portable**' to another host institution, if the grantholder wishes so

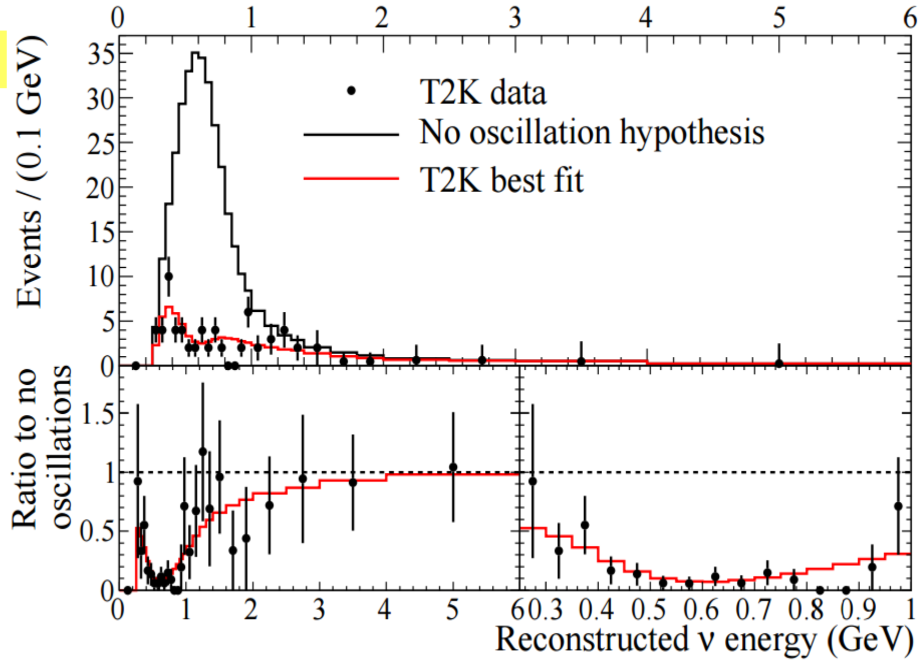
The context: neutrino oscillations

"The discovery that neutrinos can convert from one flavour to another and therefore have nonzero masses is a major milestone for elementary particle physics. It represents compelling experimental evidence for the incompleteness of the Standard Model as a description of nature... Neutrino oscillations and the connected issues of the nature of the neutrino, neutrino masses and possible CP violation among leptons are today major research topics in particle physics."

2015 Nobel prize to Kajita and Mc Donald

Discovery: atmospheric neutrinos. SuperK (1999)





Oscillations studied with an artificial beams (T2K)

A lot of exciting and challenging physics is still ahead. The current focus is the measuerement of Prob($\nu_\mu \rightarrow \nu_e$) to assess leptonic CP violation.

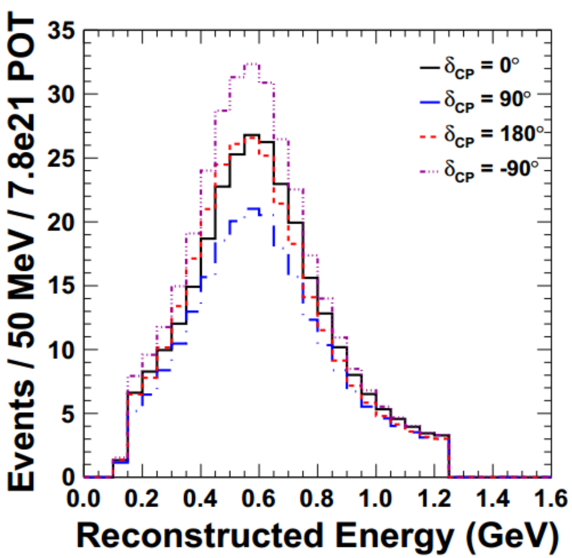
A world level effort (DUNE-HyperKamiokande starting construction).

Pivotal importance of the ν_e cross section

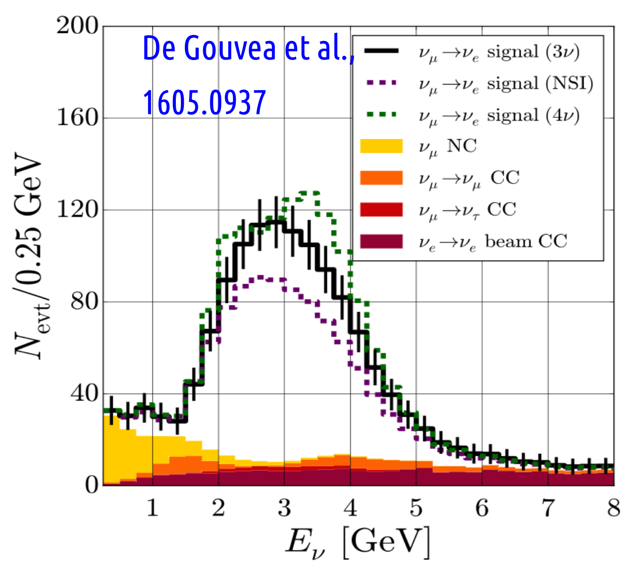
Leptonic CP violation : $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$

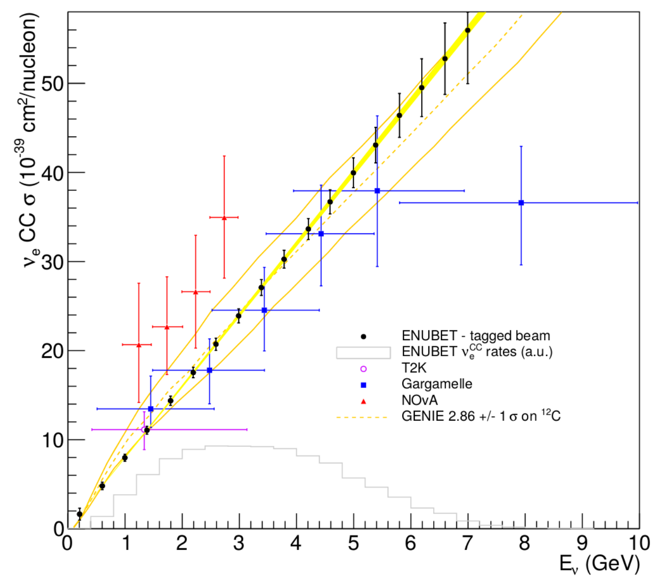
- the δ_{CP} phase induces **mainly a change in normalization in interaction rates** of electron neutrinos (in opposite directions for nu and anti-nu)
- knowing well the ν_e cross section **crucial to boost the potential of future experiments** (HyperK, DUNE) by decreasing their **systematics budget**.
- **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



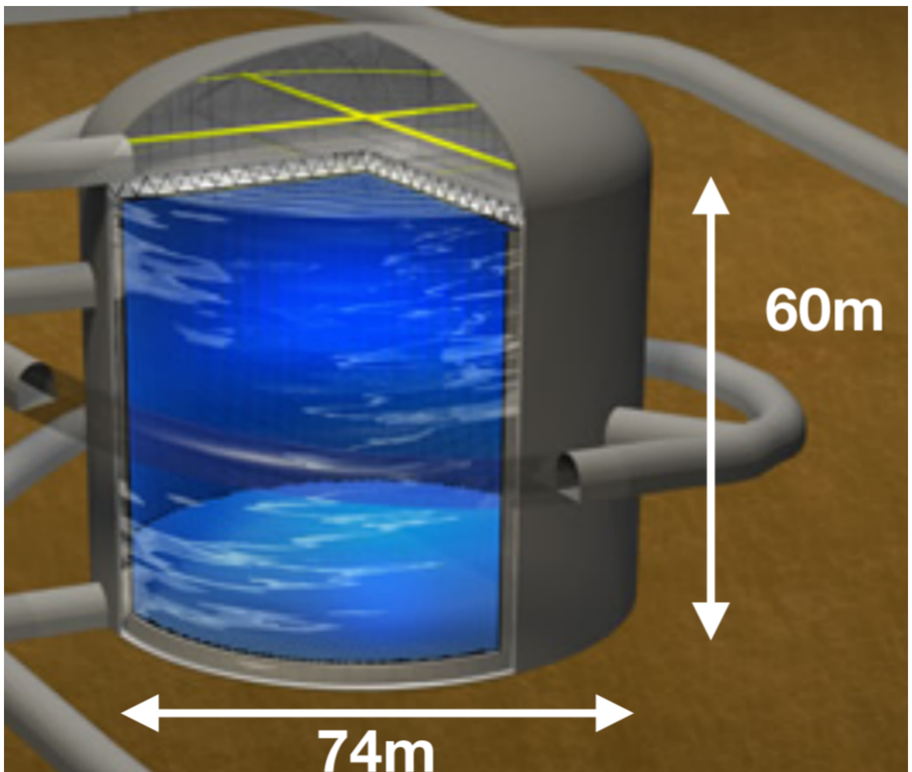
DUNE

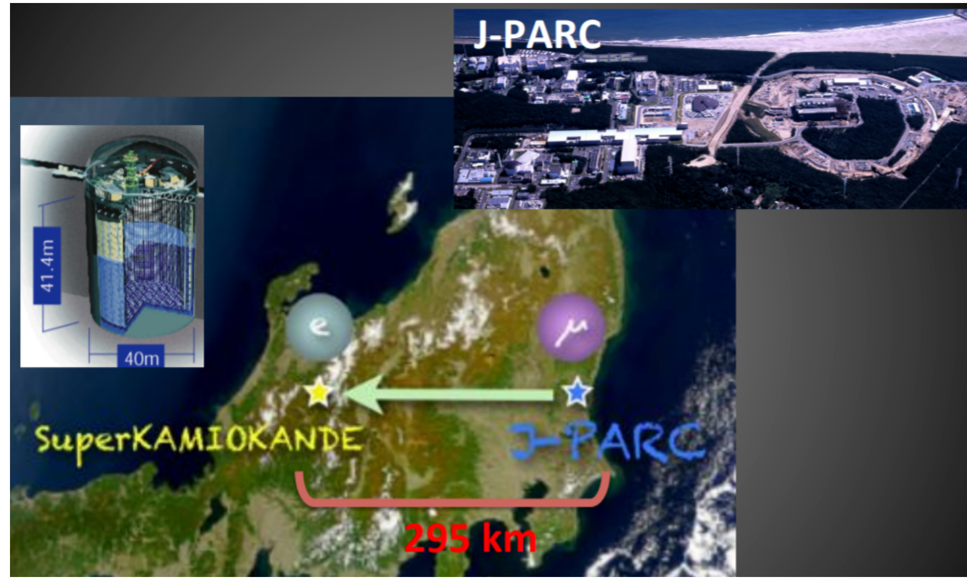




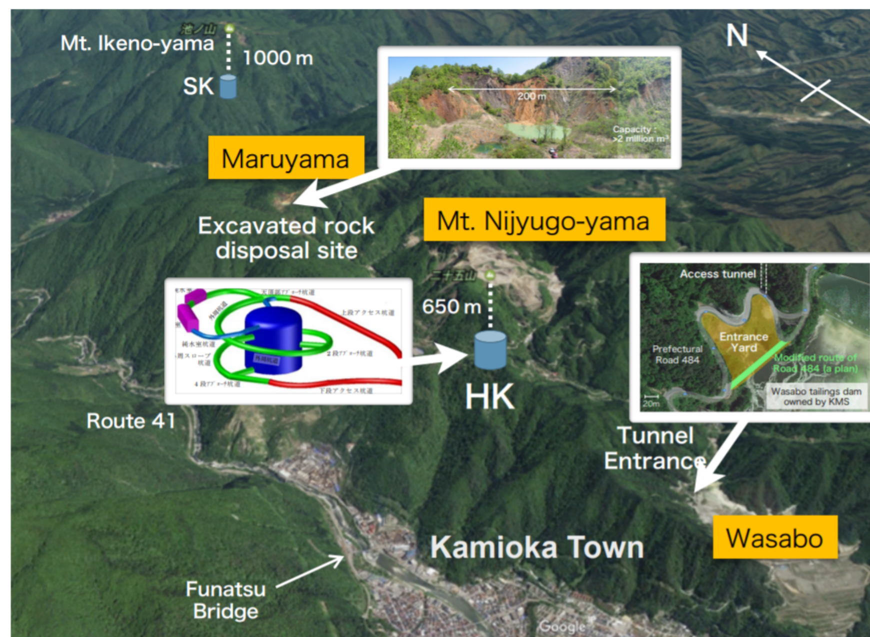
Hyper-Kamiokande

190 kton mass (~8 x SuperKamiokande)
1.3 MW neutrino beam from the pacific coast
295 km baseline



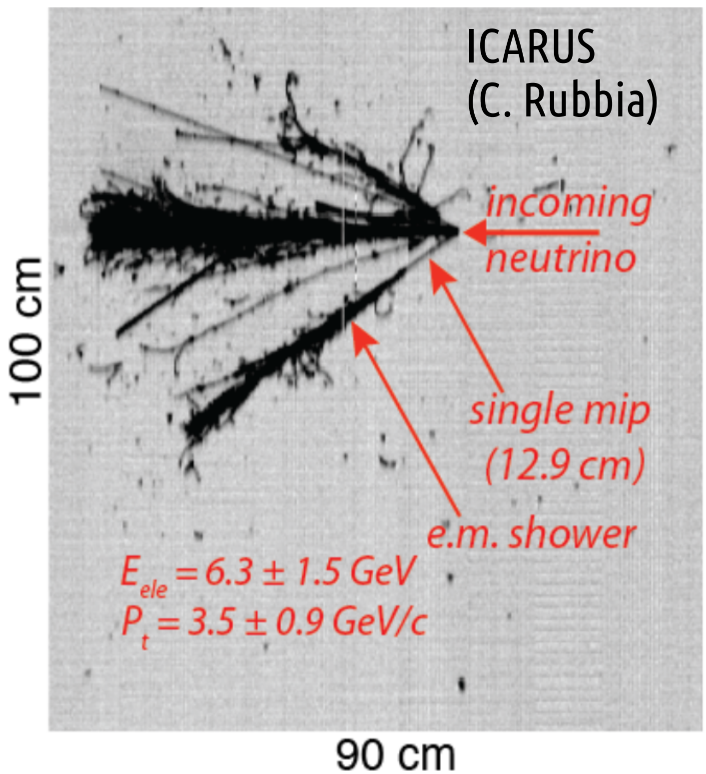


8 km south of Super-K
650 m rock overburden



DUNE

Based on the **Liquid Argon Time Projection Chamber** detector technique. Can get large mass and **terrific views of neutrino interactions**! This is a prototype built at CERN (**protoDUNE SP cryostat**)



The ENUBET physics motivation

THE FUNDAMENTAL QUESTION

The role of neutrinos in the dominance of **matter over anti-matter** in our universe ?

THE MEASUREMENT

Find experimental evidence of **CP violation** in the leptonic sector

CP violating effects are **small**:
we need a **O(1%) knowledge** of the **interactions of ν_e with matter**

THE OBSTACLE

conventional ν_e beams are flawed by **O(5-10%) uncertainties**

"The instrinsic limit": initial neutrino flux is not known well

→ ENUBET: 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**

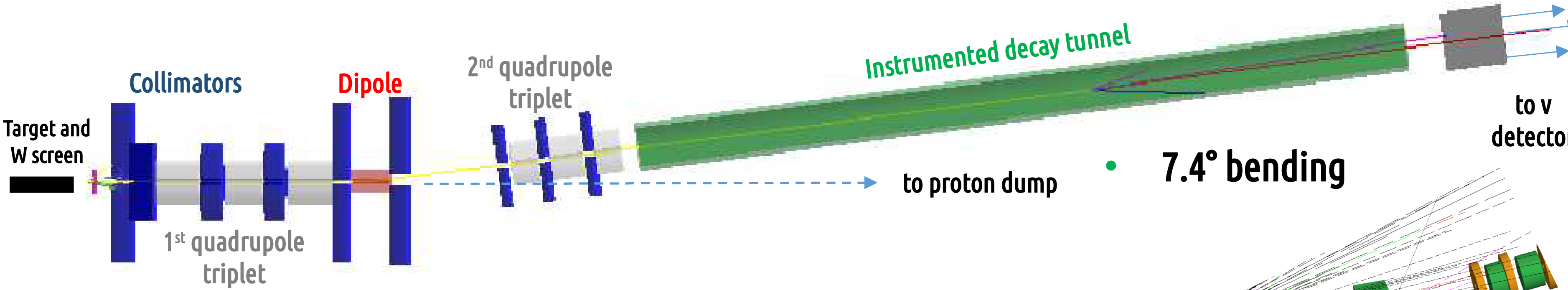
  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle e^+

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

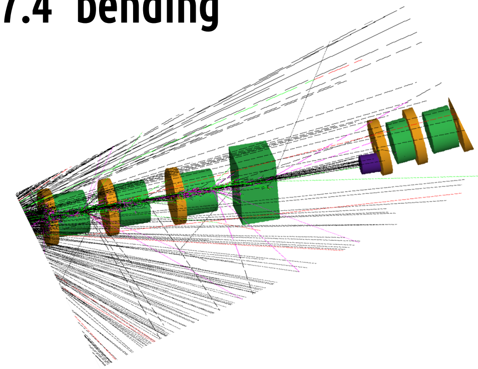
Removes the **leading source of uncertainty in ν cross section measurements**

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 spectra**

The ENUBET beamline (baseline option)



- 7.4° bending



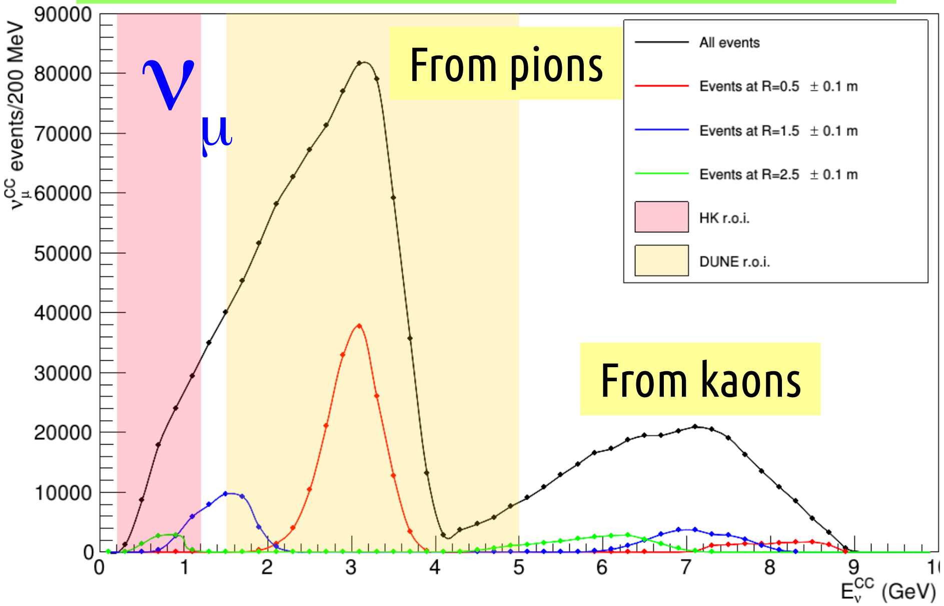
- **Proton driver**: **CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **Target**: Be, graphite. FLUKA.
- **Focusing**
  - **Horn**: 2 ms pulse, 180 kA, 10 Hz during the flat top *[not shown in fig.]*
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **Transfer 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
  - 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
- **Proton dump**: position and size under optimization

Neutrino events per year at the detector

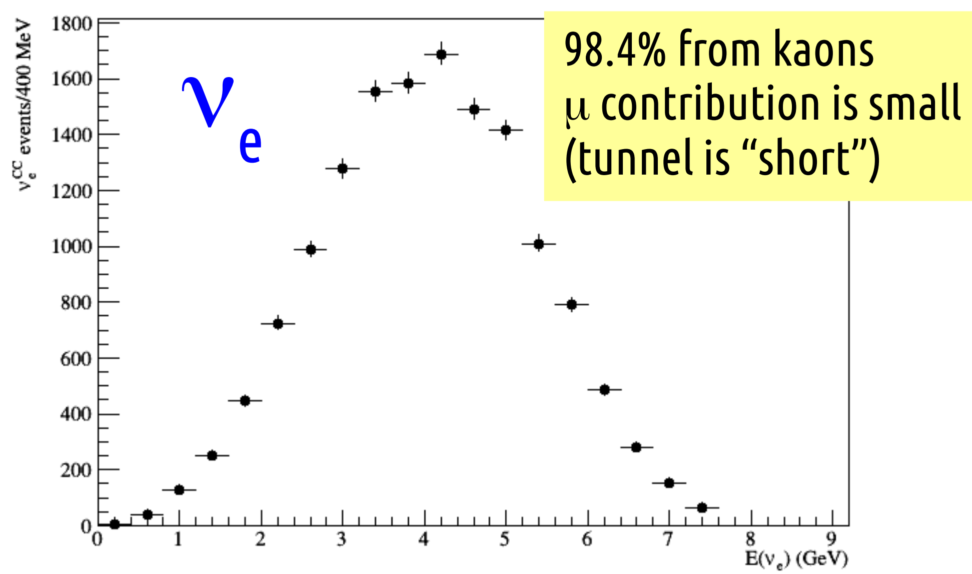
- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab, WC at J-PARC ?)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5×10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5×10^{20} pot at FNAL

- 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 $K_{\mu 2}$).
- ν_μ from π: could be constrained by μ detectors downstream of had- dump ? (under study)

1.2 million ν_μ Charged Current per year

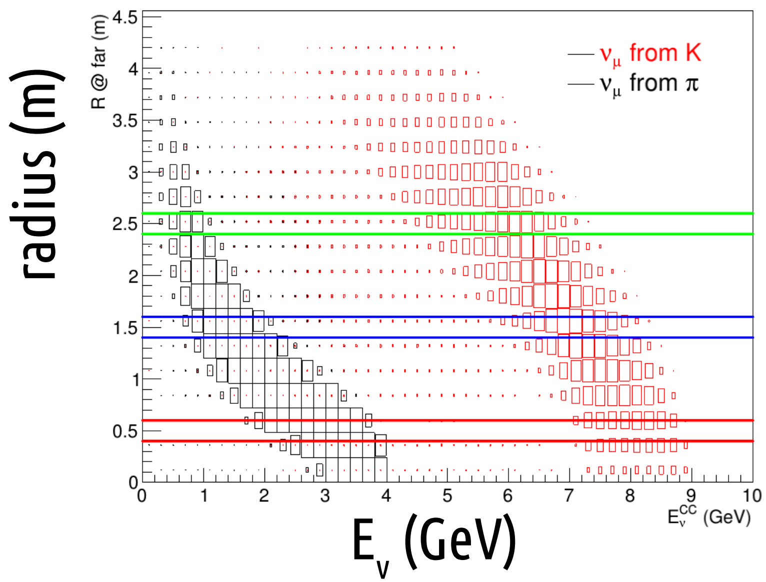


14000 ν_e Charged Current per year

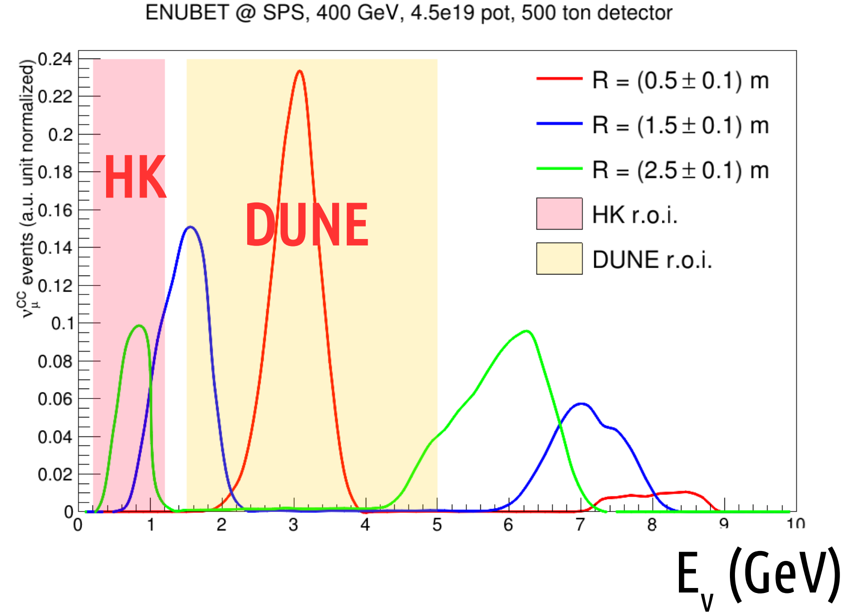


ν_μ CC events at the ENUBET narrow band beam

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



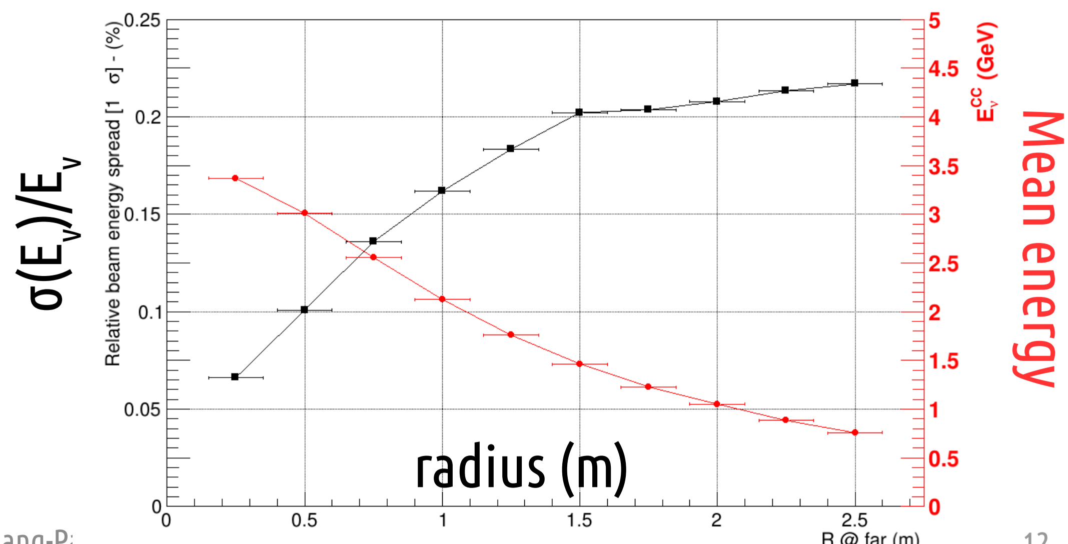
ν_μ CC in radial bins (1 norm.)



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

- 8 % for r ~ 50 cm, $\langle E_\nu \rangle$ ~ 3 GeV
- 22% for r ~ 250 cm, $\langle E_\nu \rangle$ ~ 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

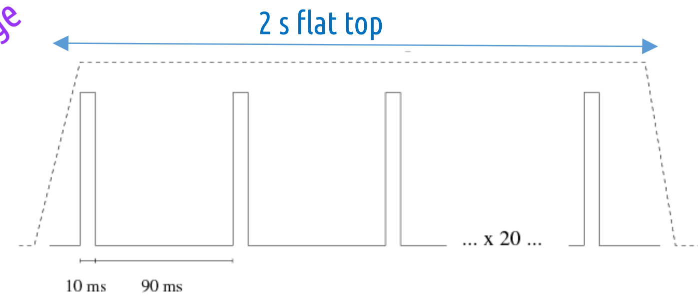


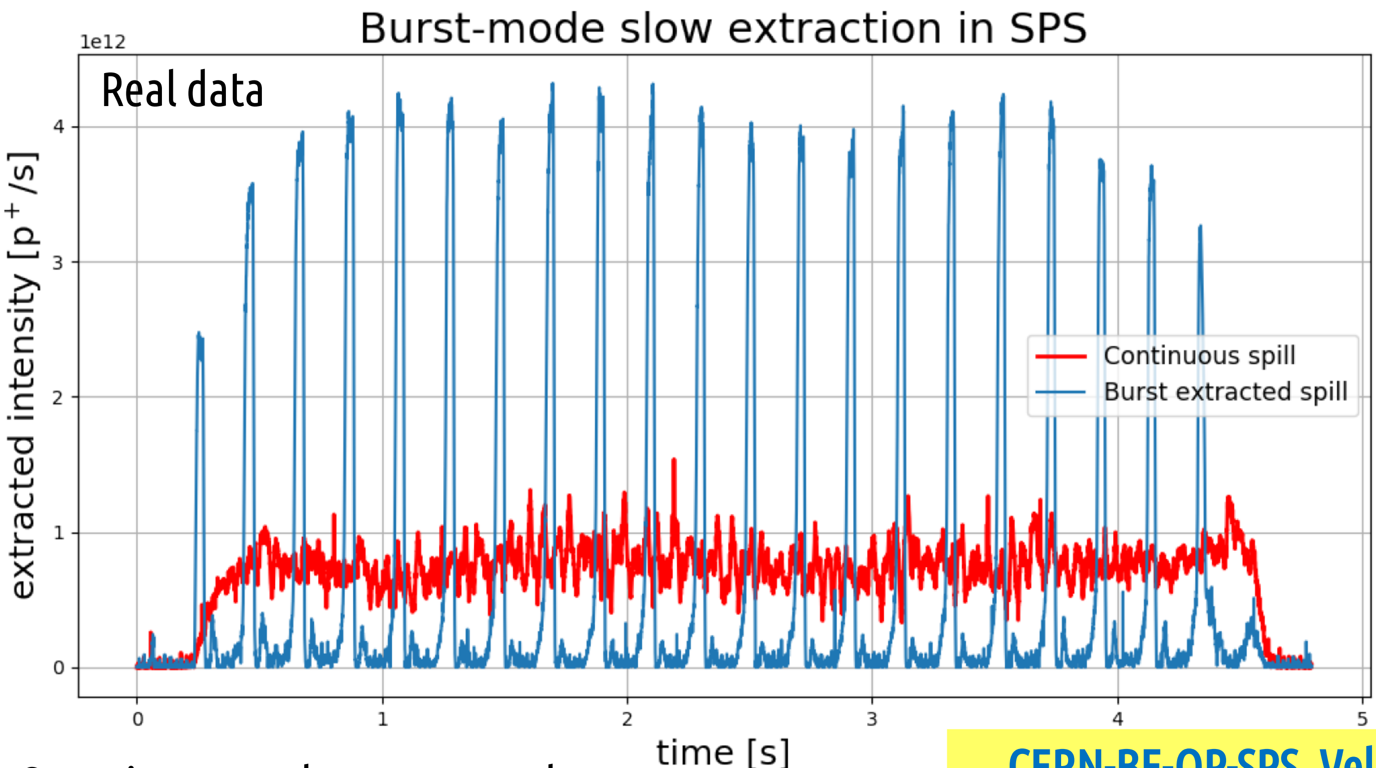
Machine studies for the horn-based option

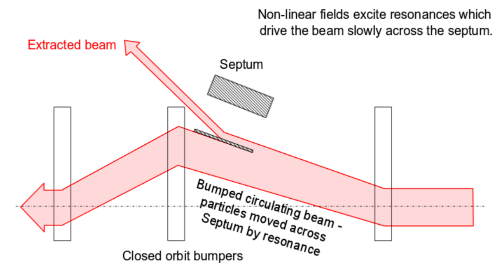
"burst " slow extraction: trigger the third integer betatron resonance with a periodic pattern

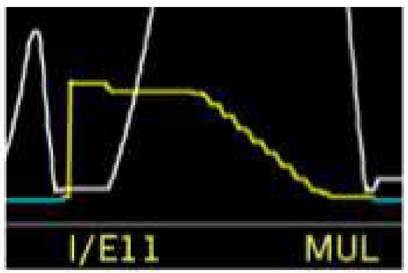
From an idea "on slide" to
a working implementation !

ENUBET #2YearsChallenge









Proton current

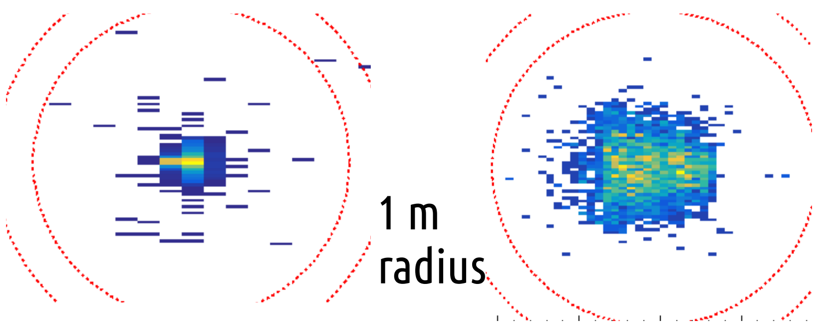
Same integrated pot extracted.
Protons squeezed into intervals with active horn

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

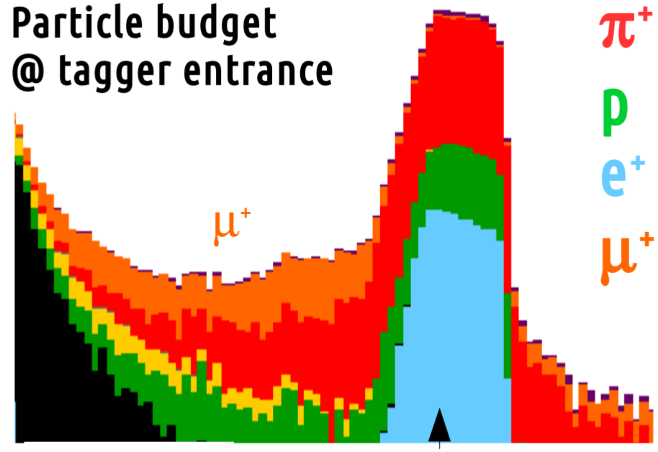
https://indico.cern.ch/event/777458/
https://ipac2019.vrws.de/papers/wepmp035.pdf

The static beamline: emittance, particle content

Divergence of the kaon beam



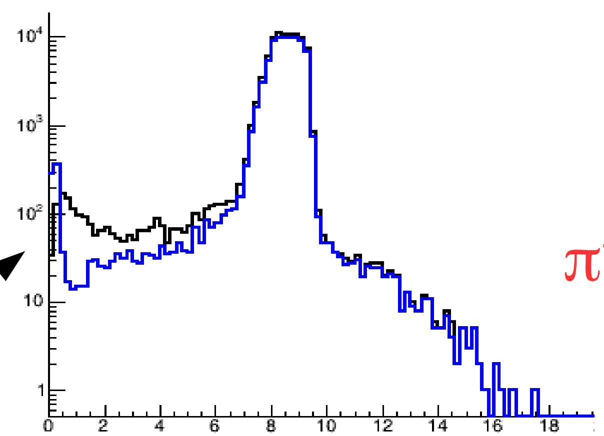
Particle budget @ tagger entrance

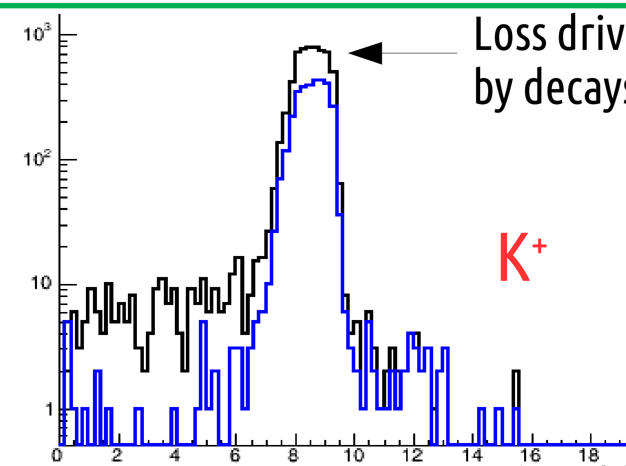


Spectra @

tagger entrance
tagger exit

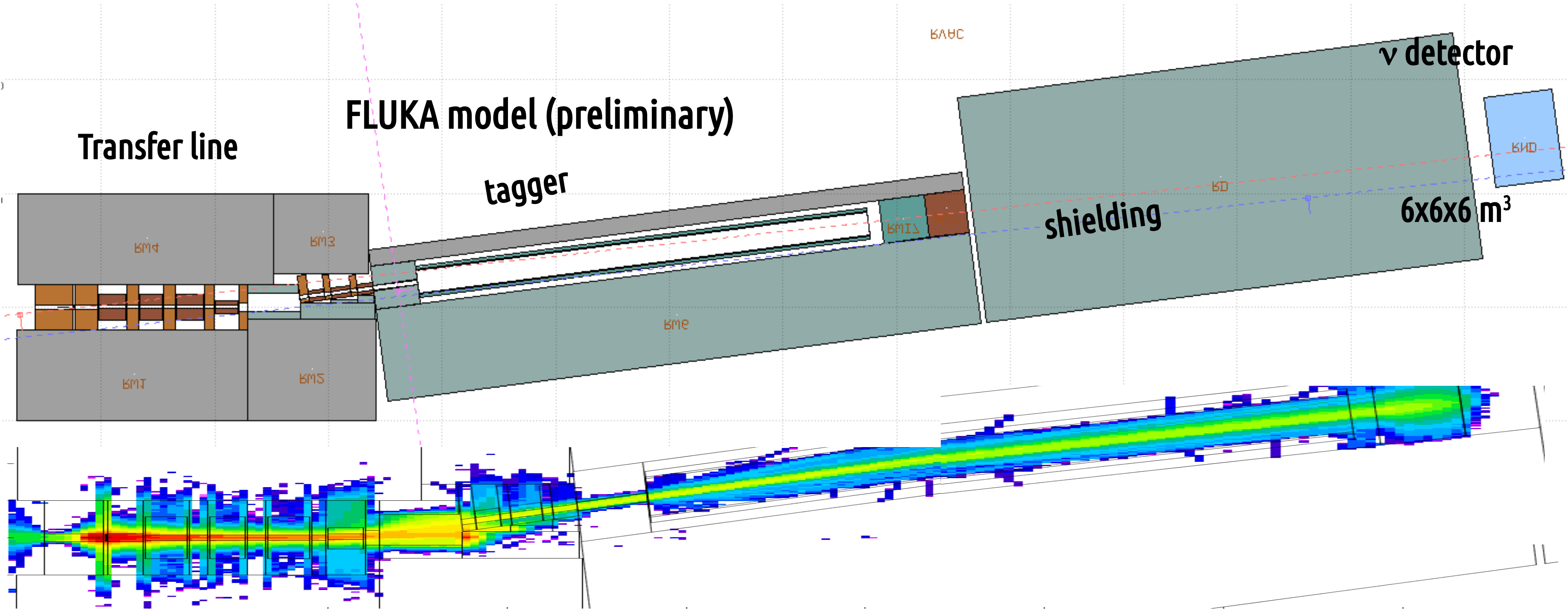
Low energy high angle π



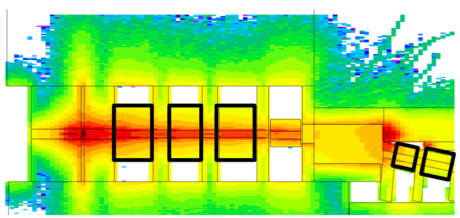


The hadronic beamline: FLUKA simulation

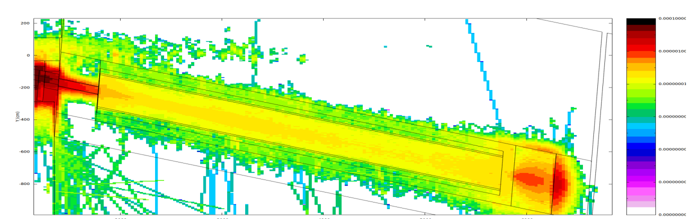
1) Optimize shielding to **reduce backgrounds** in the tagger (μ, n, high angle e^+ and π^+)



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



3) **neutron** irradiation

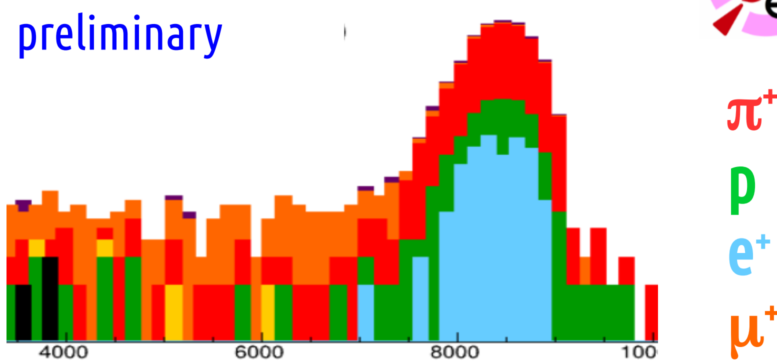


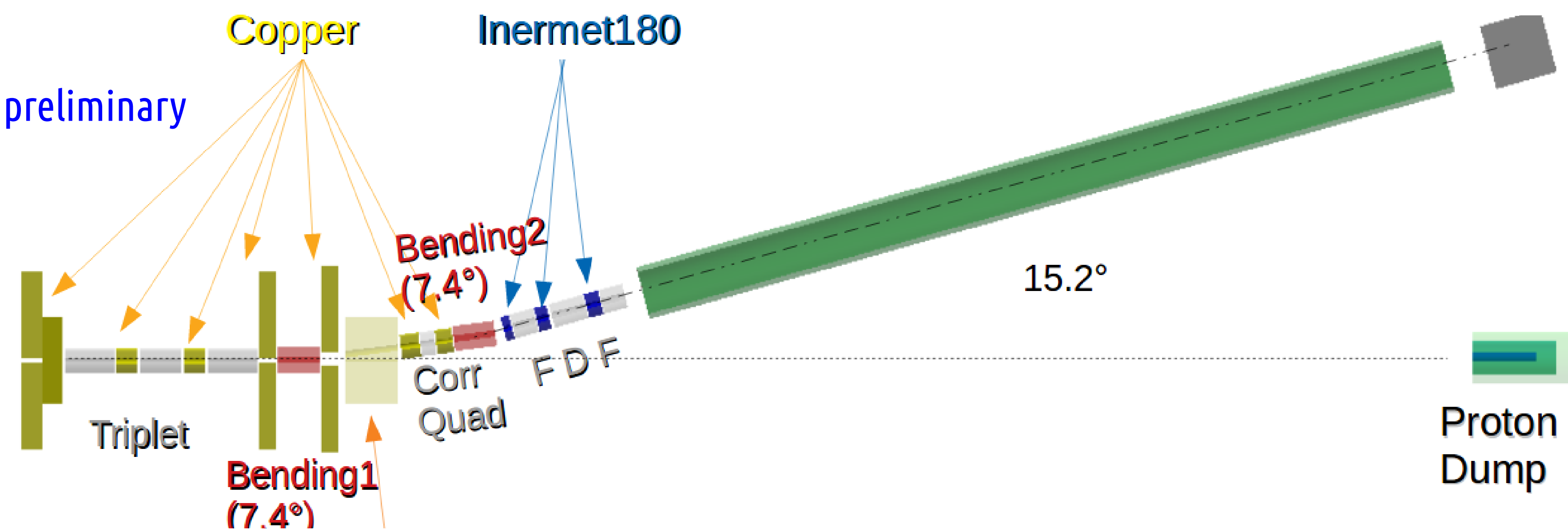
Additional beamline options

We are also simulating other beamline schemes:

2 dipoles with an intermediate quadrupole.
Increased length of beamline but … →

- Better quality of the beam in the tagger
- larger bending angle (15.2 °) reducing
  - backgrounds from muons
  - probability for neutrinos produced in the straight section to reach the ν detector

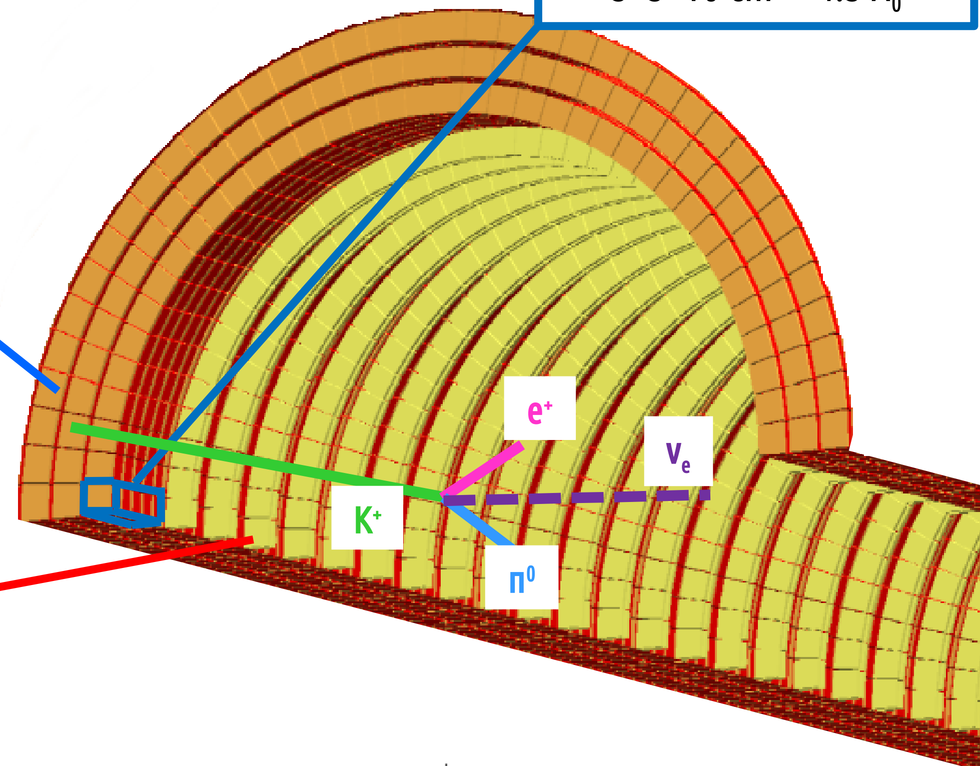




- We are putting all these inputs together
- → pindown the best scheme in terms of physics and technical feasibility

The ENUBET tagger

Ultra Compact Module
$3\times3\times10$ cm^3 – 4.3 X_0



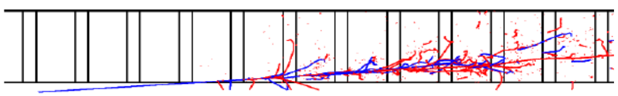
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

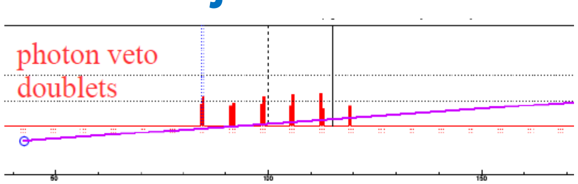


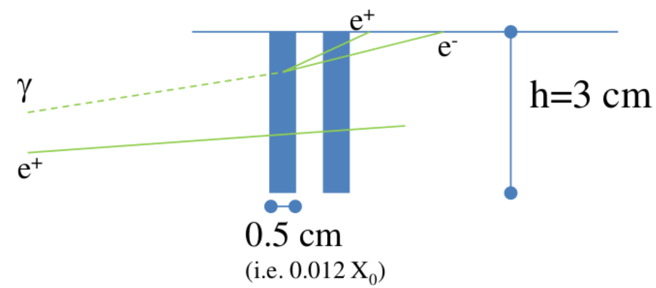
Integrated photon veto

Plastic scintillators

Rings of 3×3 cm^2 pads

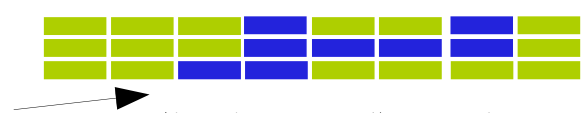
→ π^0 rejection





e^+ (signal) topology

π^0 (background) topology



π^+ (background) topology

K_{e3} positrons reconstruction

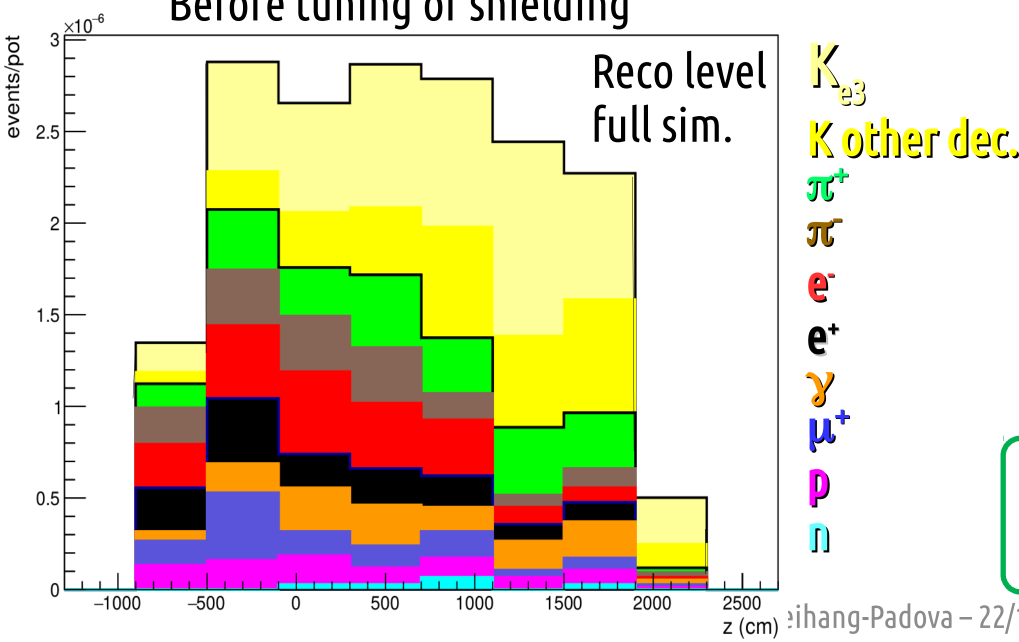
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

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.

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



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

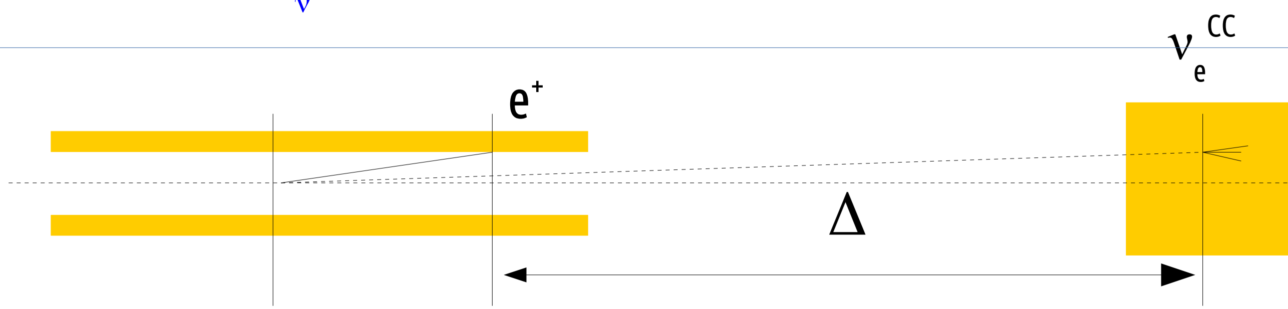
Time tagged neutrino beams ?

- 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)

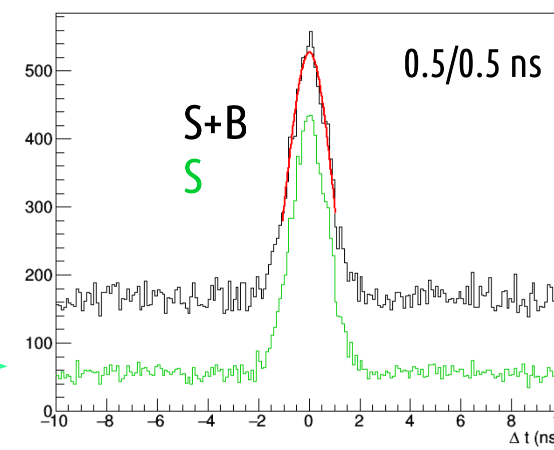
Presently with 2.5×10^{13} pot / 2s slow extraction:

genuine K_{e3} cand. : 80 MHz → **1 every ~ 12 ns**

background K_{e3} cand. ~ 2 x → 1 cand. every ~ 4 ns

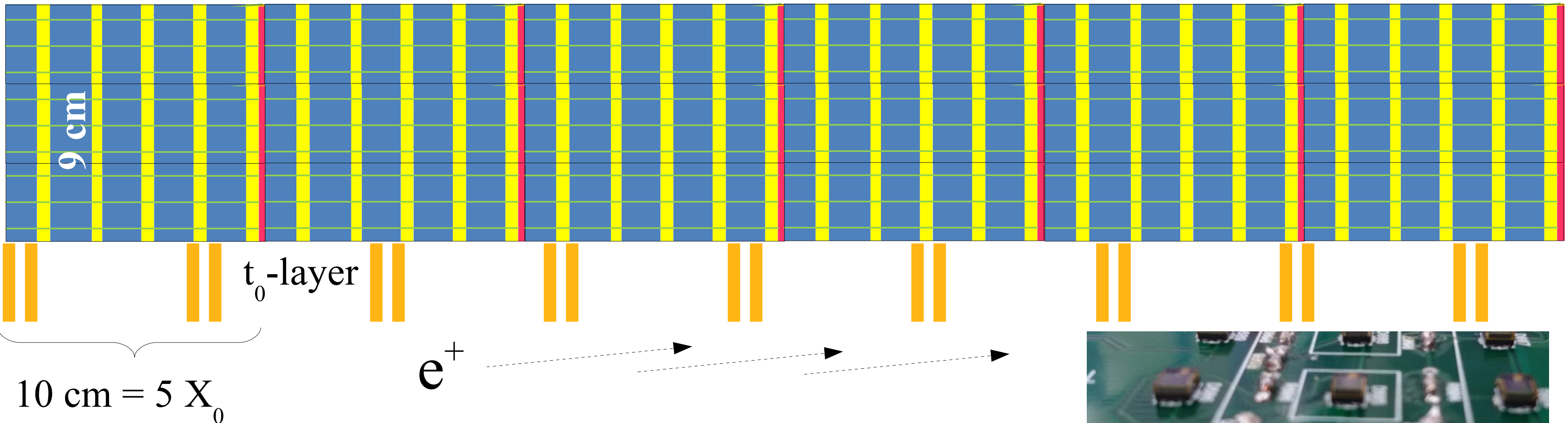
With $\delta = 0.5 \oplus 0.5$ ns resolutions: already interesting!

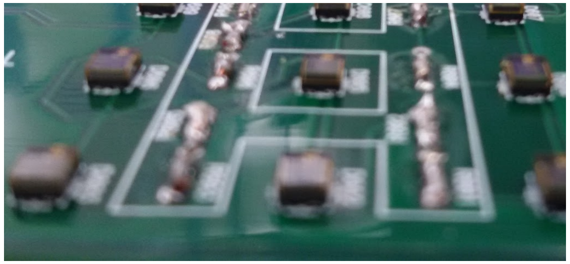
S/N ratio will likely improve with further tuning.



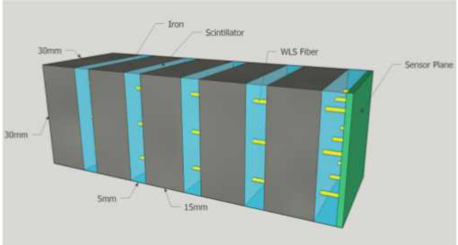
Toy MC

The tagger: shashlik with integrated readout

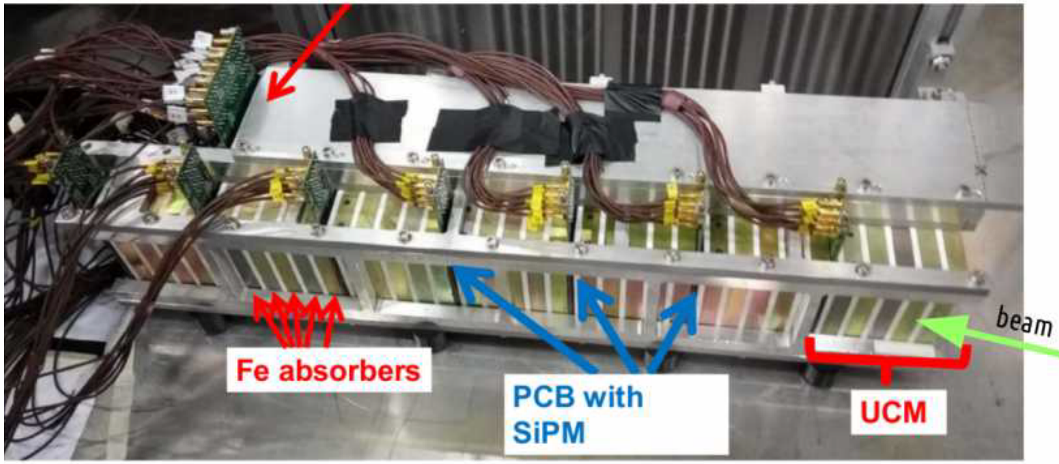




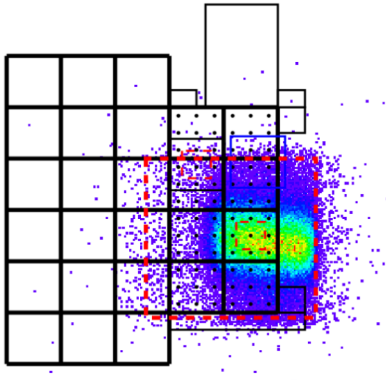
UCM: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter



CERN PS test beam Nov 2016



Beam spot

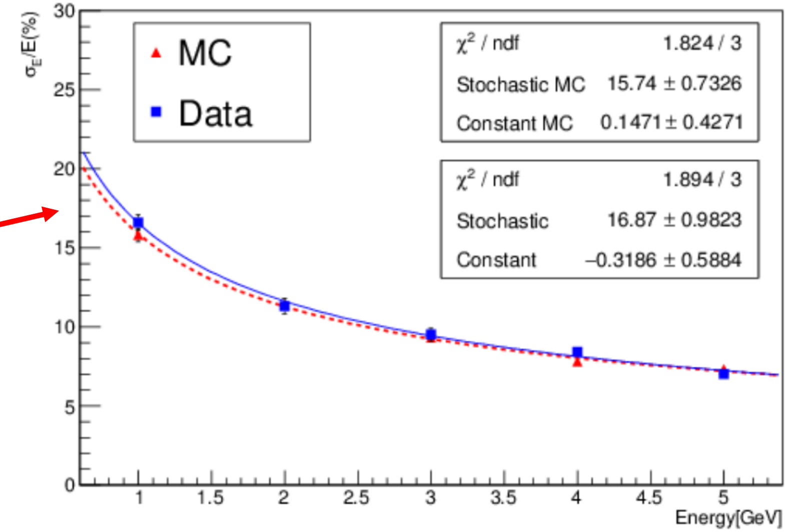


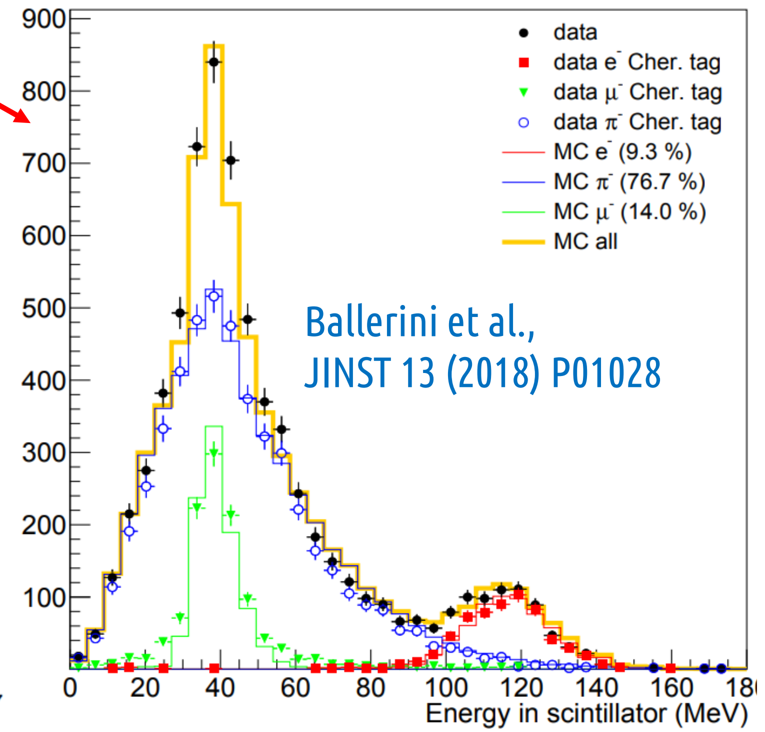
Test beam results with shashlik readout

@ CERN-PS T9 line 2016-2017

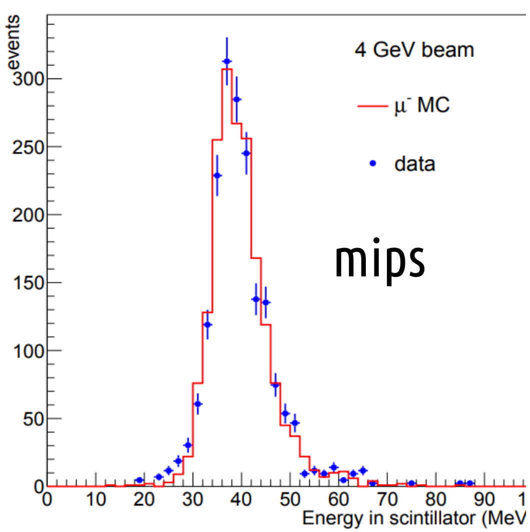
Tested response to muons electrons and pions

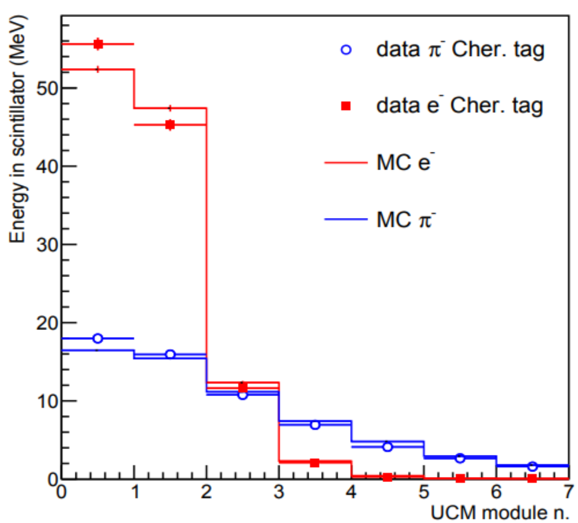
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in the 1-5 GeV range
- 0 to 200 mrad → no significant differences
- Equalize channel-to-channel response with minimum ionizing particles (mips)
- MC/data in good agreement
- longitudinal profiles of partially contained π reproduced by MC @ 10% precision





Ballerini et al., JINST 13 (2018) P01028

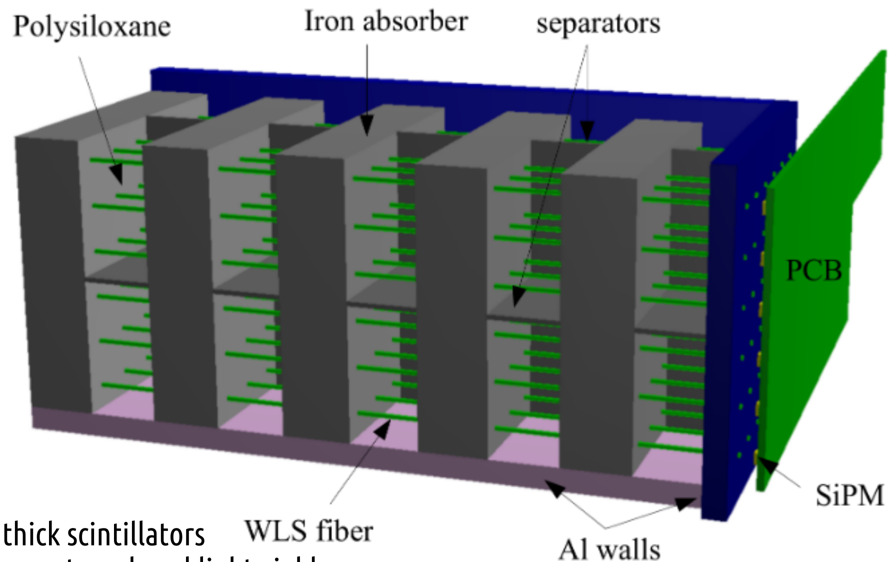




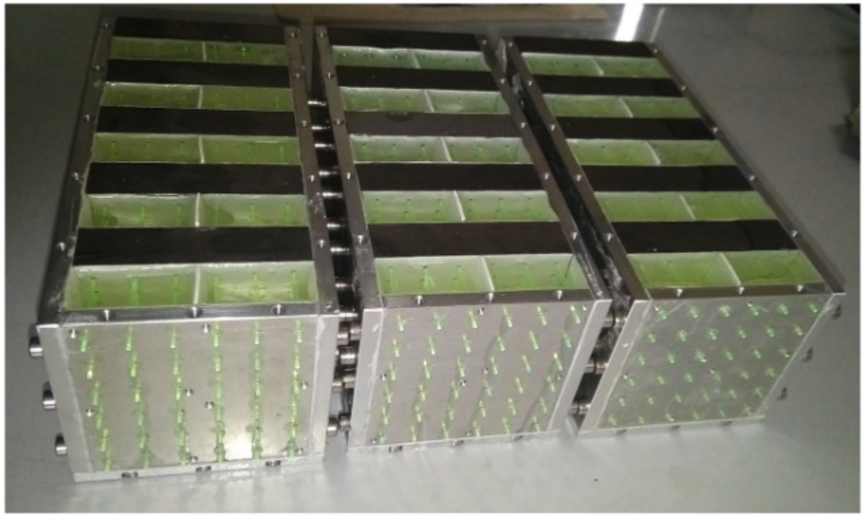
Polysiloxane shashlik prototypes

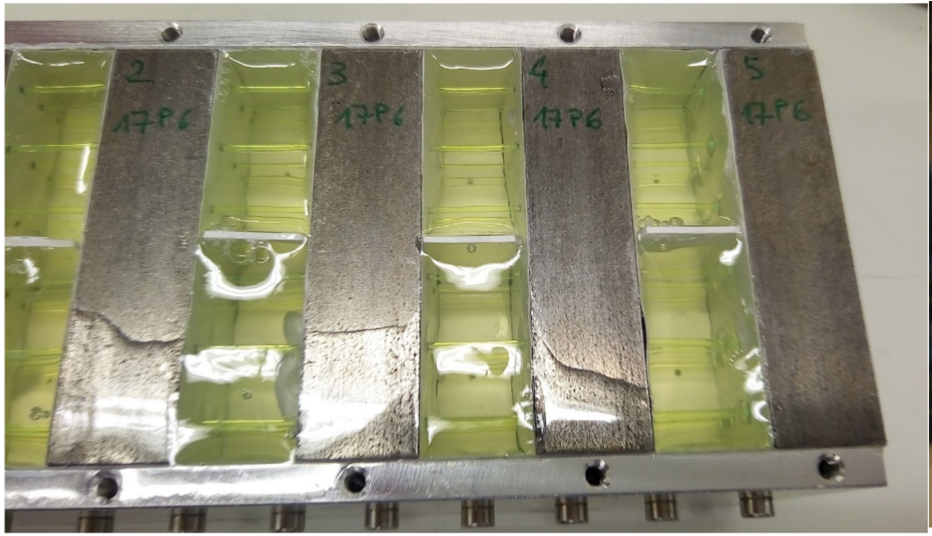
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)

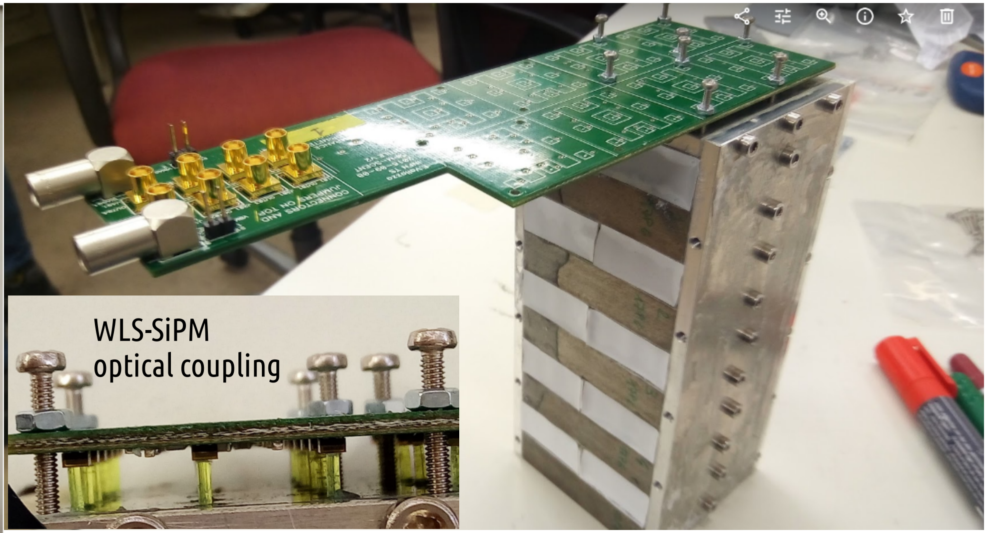
A **13X_0 shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)



15 mm thick scintillators
to compensate reduced light yields



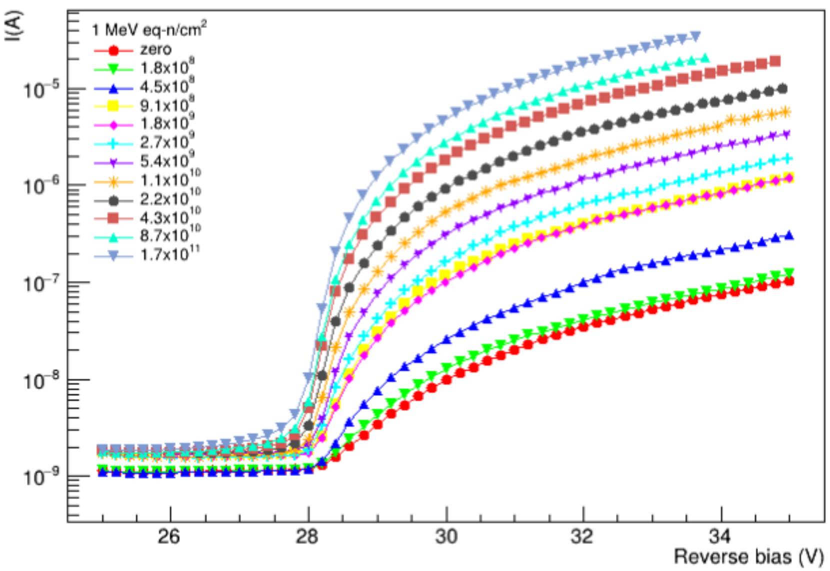




SiPM irradiation measurements at INFN-LNL and CERN

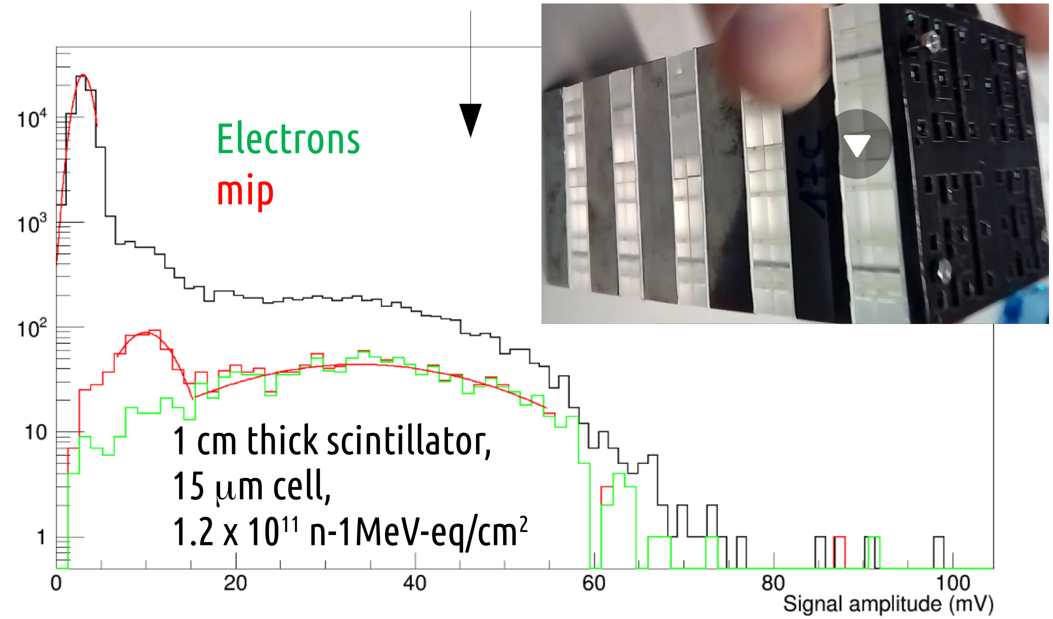
- @ the CN Van de Graaf on July 2017→ 1-3 MeV n with fluences up to $10^{12}/cm^2$ in a few hours

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



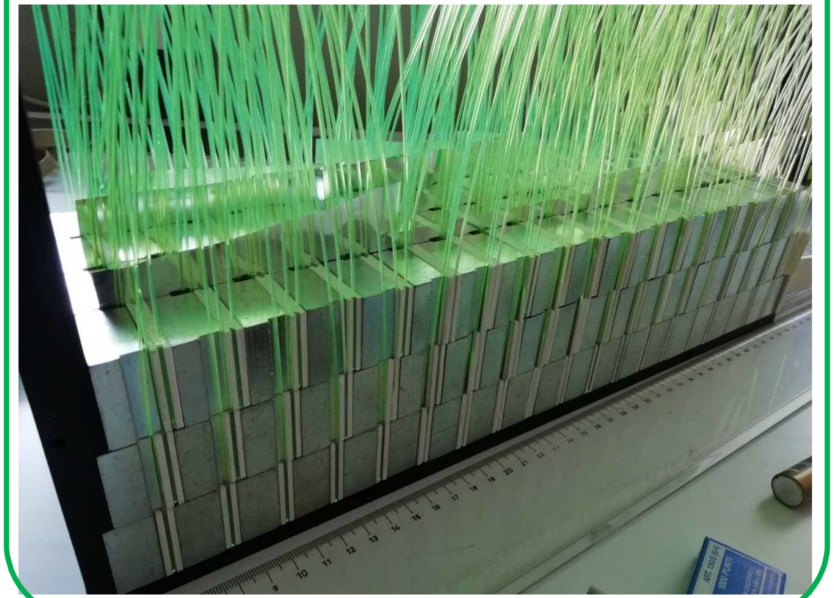
(FBK-HD-RB Advansid)

- 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.

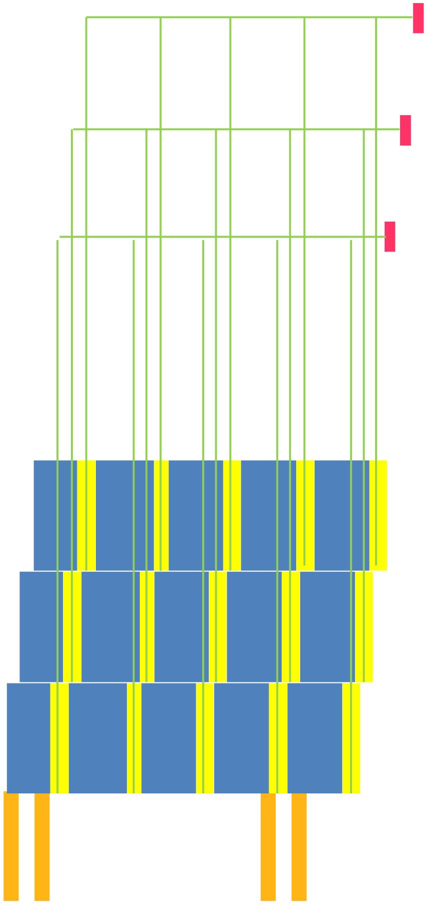
The tagger: lateral readout option

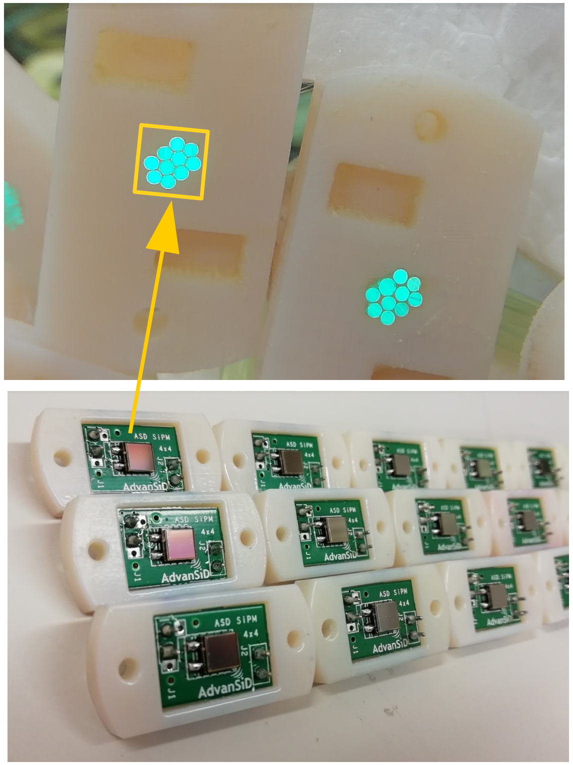
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM).
SiPM are not immersed anymore in the hadronic shower → less compact but ..
much **reduced neutron damage** (larger safety margins), better **accessibility**, possibility of replacement. Better reproducibility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

Sampling calorimeter with lateral WLS light collection



May 2018, CERN-PS test beam



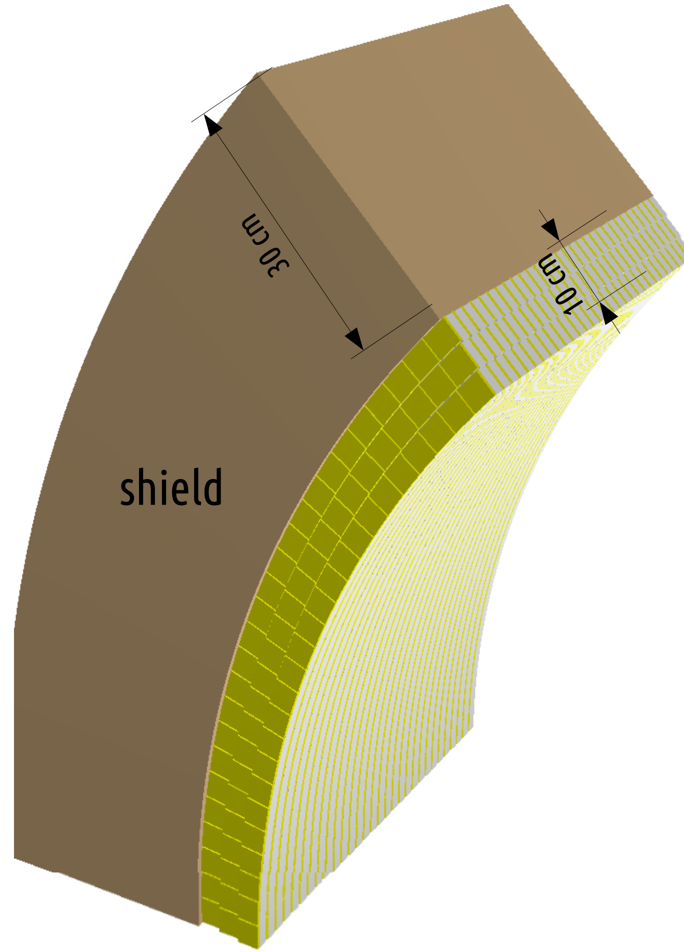


Large SiPM for 10 WLS
4x4 mm^2

Achievable neutron reduction with lateral readout

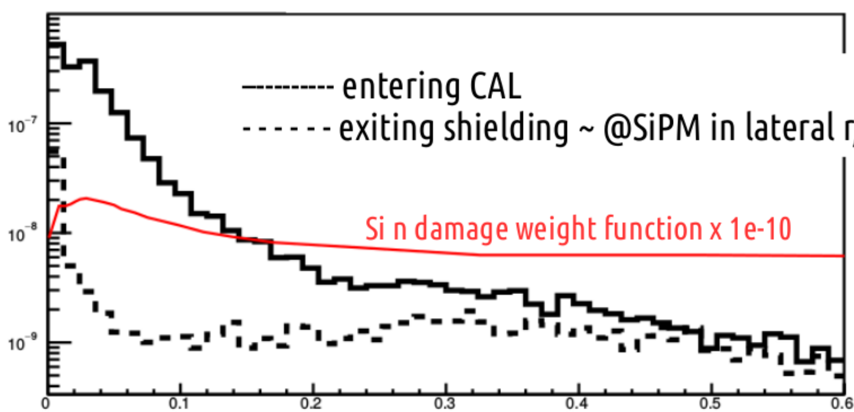
- 30 cm of borated **polyethylene** in front of SiPM
- FLUKA full simulation. **400 GeV protons**.

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

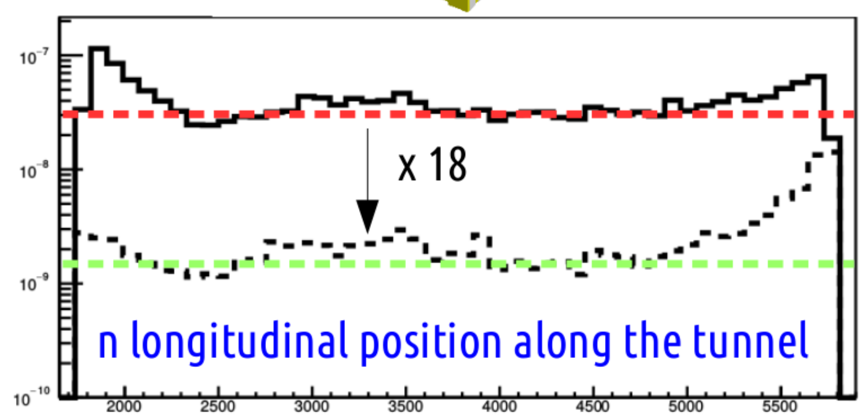


Neutron energy

preliminary

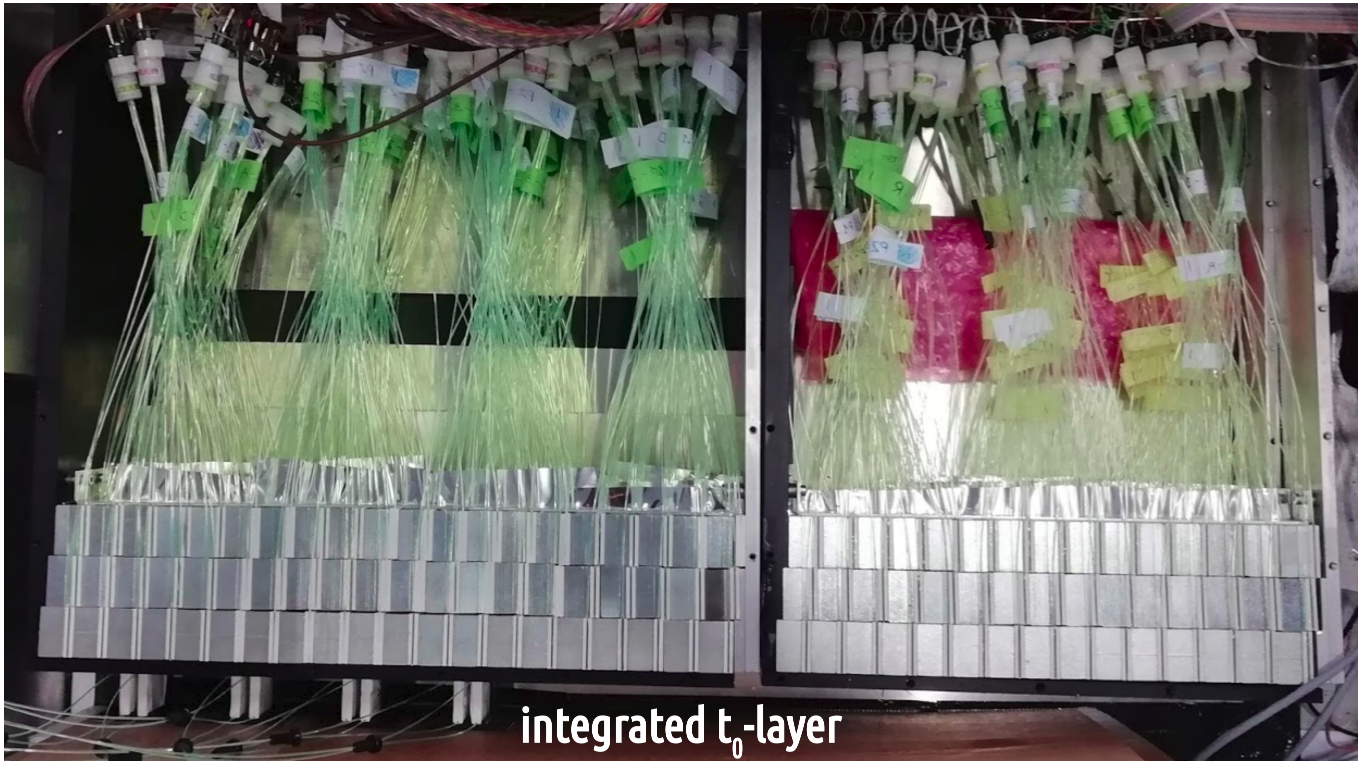


FLUKA

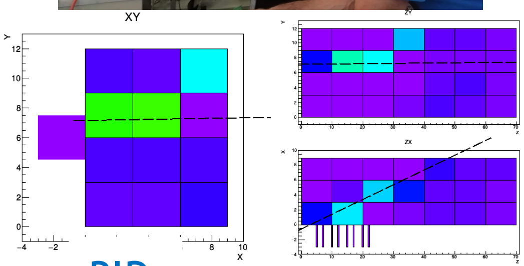


The Tagger – Detector R&D

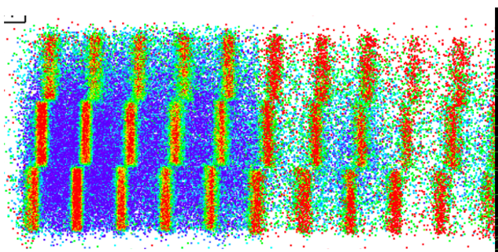
September 2018 CERN-PS: a module with hadronic cal. for pion containment and **integrated t_0-layer**



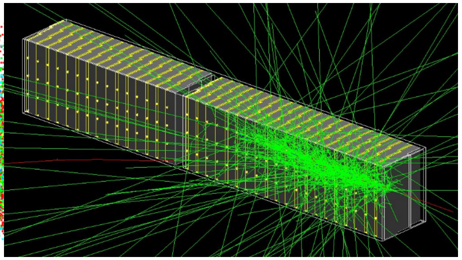
- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match. In progress.



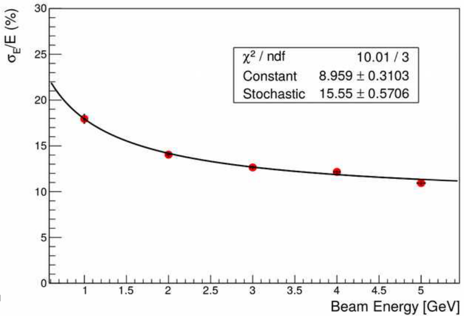
Efficiency maps



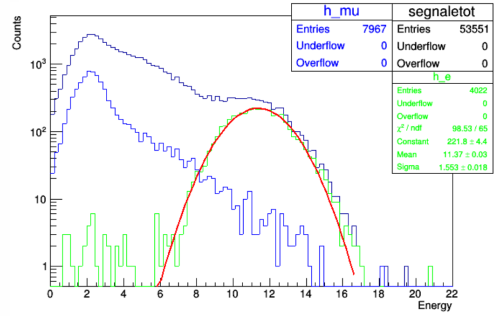
Simulation



Resolution



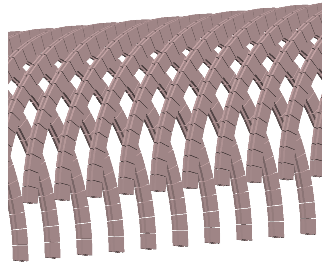
PID



Beihang-Padova

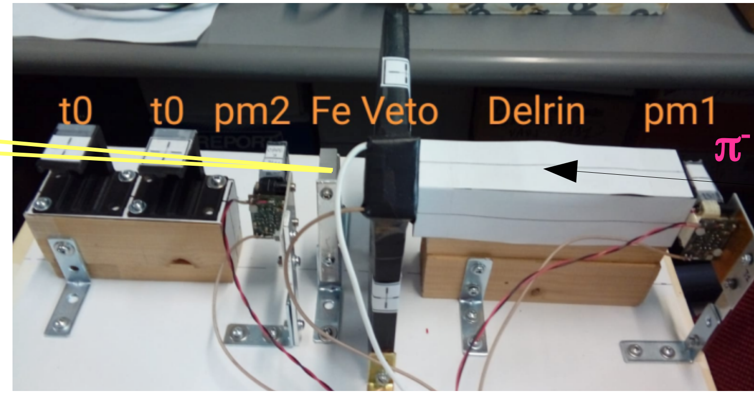
The photon veto

@ CERN-PS T9 line 2016-2018



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

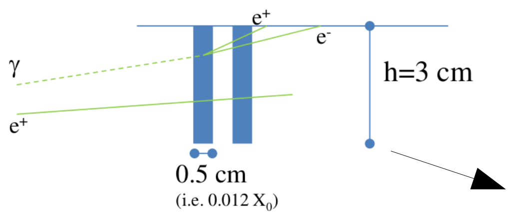
Trigger: PM1 + VETO +PM2

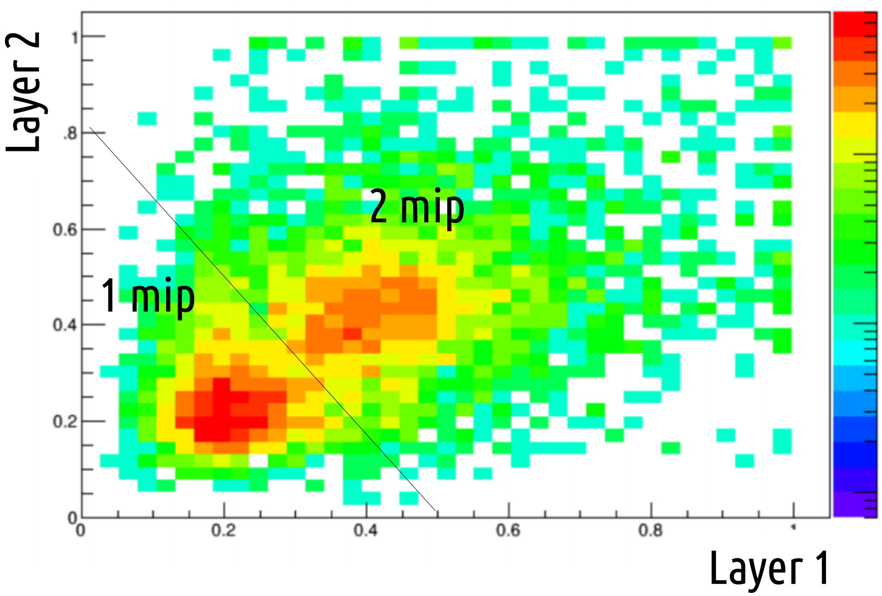


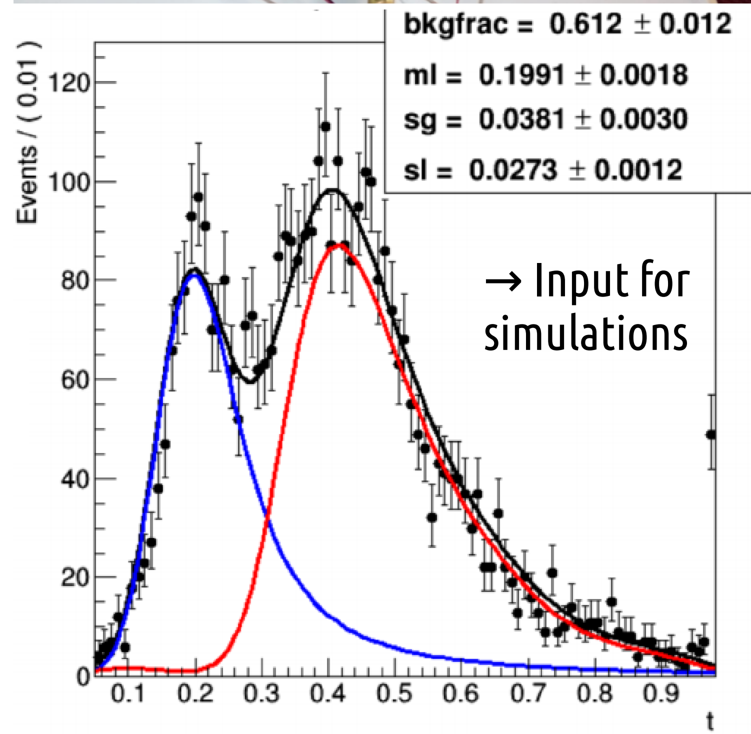
• γ / e^+ discrimination + timing

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

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





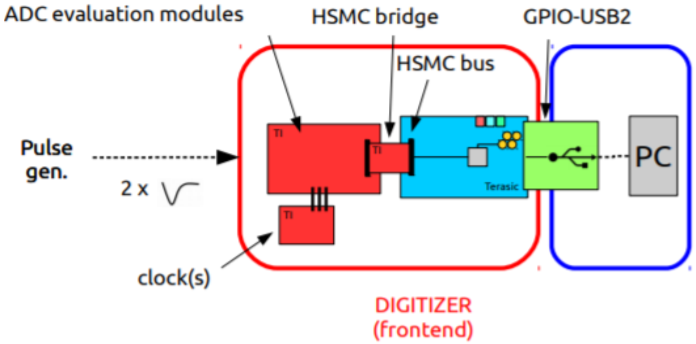


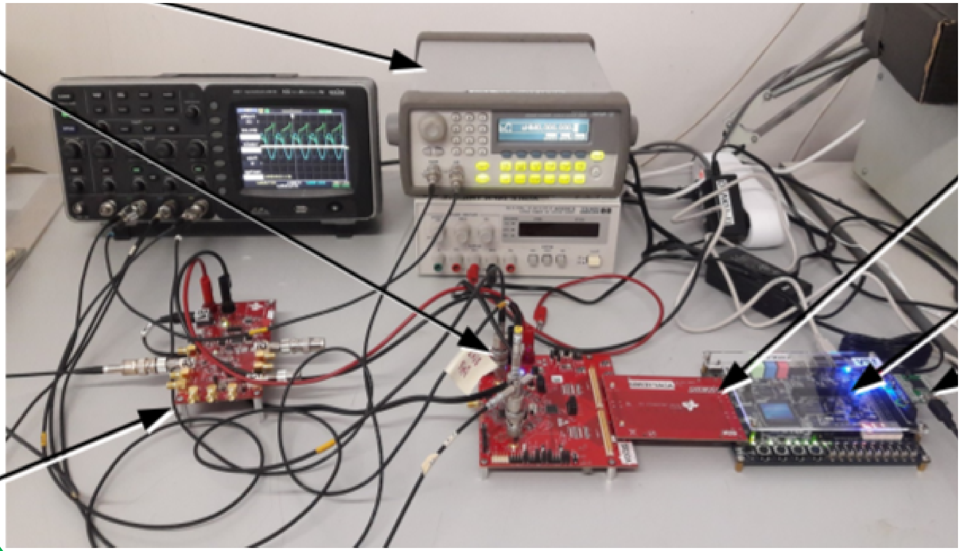
→ Input for simulations

Custom electronics and algorithms

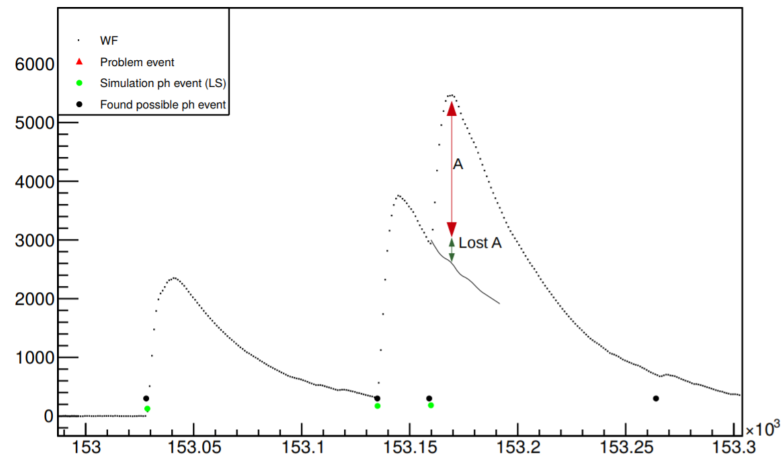
We are developing in parallel:

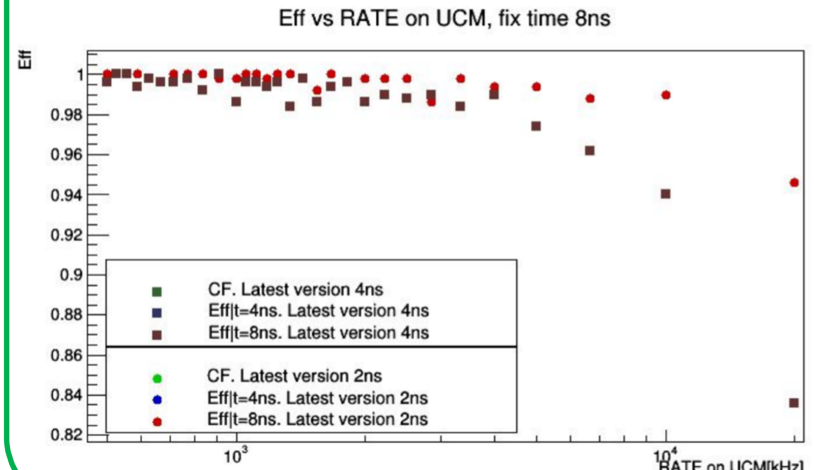
1) custom ("cost-effective") electronics to readout the tagger in "triggerless-mode" by digitizing waveforms @ 250-500 MS/s.





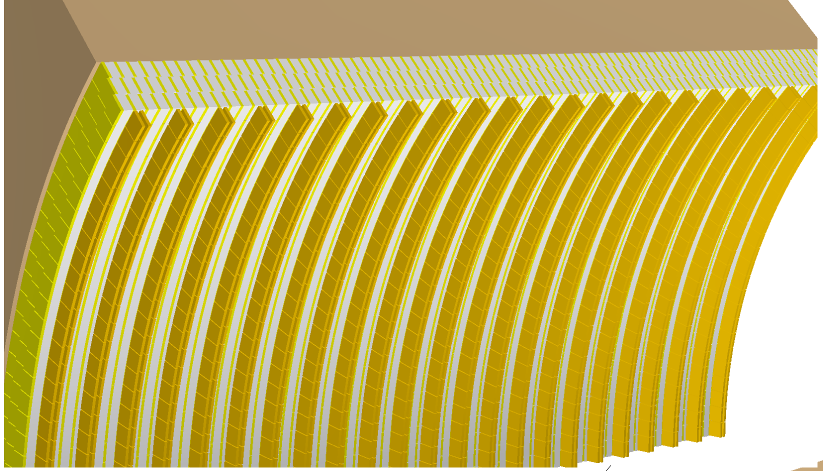
2) "smart" algorithms for data reduction and treatment of pile-up

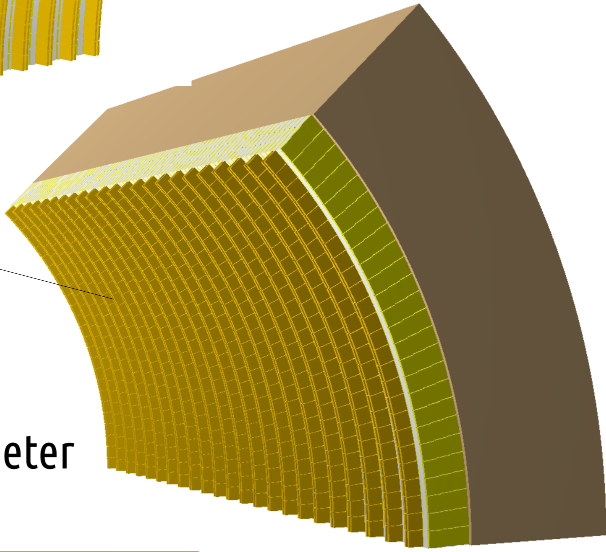




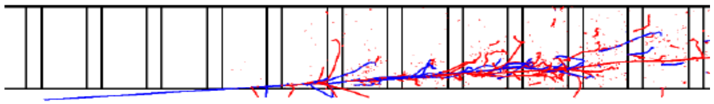
The tagger demonstrator

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



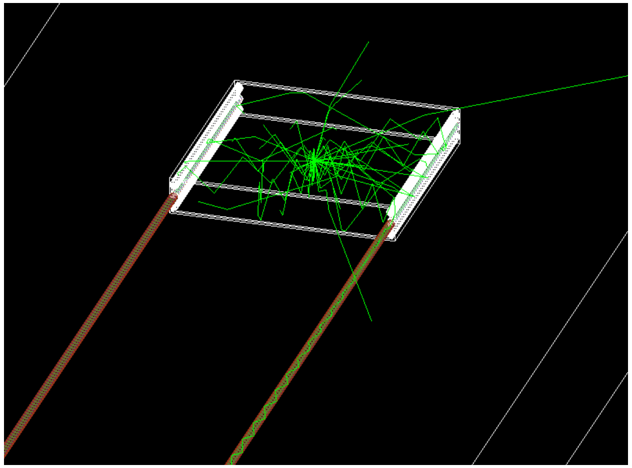


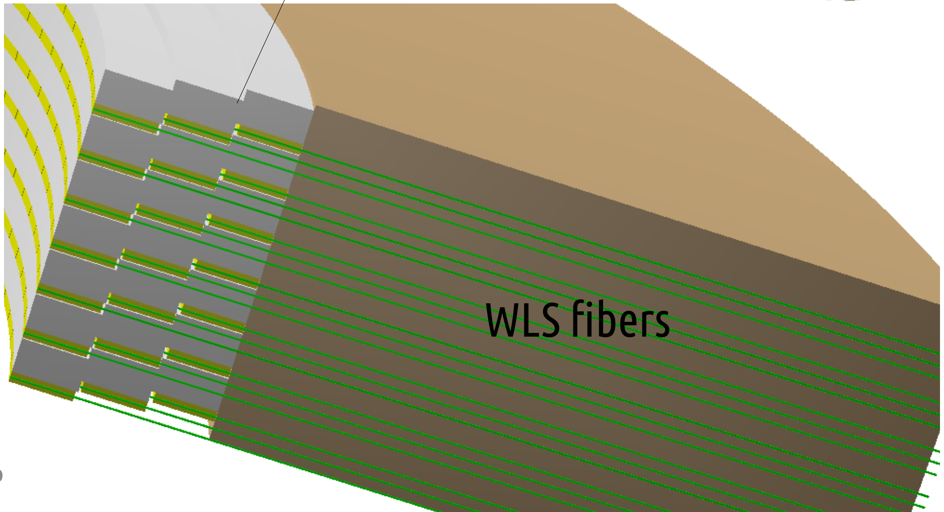
t_0-layers



3 layers calorimeter

Geant4 simulations





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

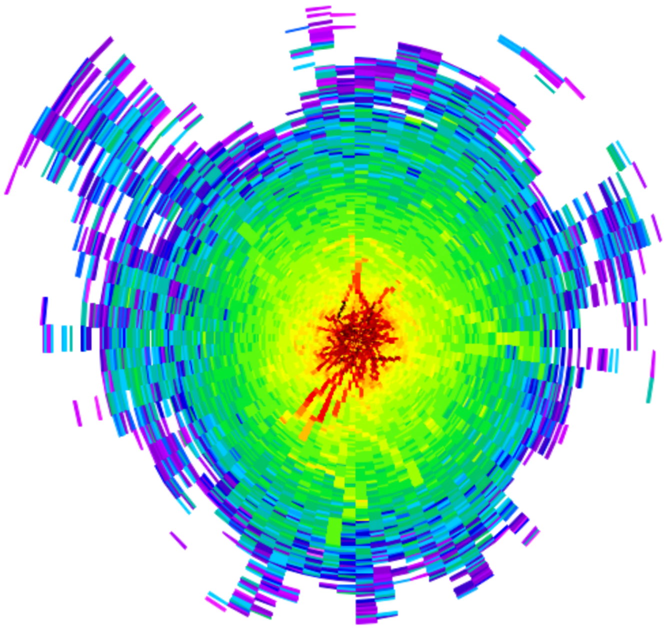
228th meeting of the Research Board, 5/3/2019
https://cds.cern.ch/record/2668519/files/M-228.pdf

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 signed 02/10
UNIPD-INFN-CERN

ENUBET so far

A very diversified program involving:



- Accelerator physics
- Electronics (design and tests)
- Mechanics
- Reconstruction/simulation
- Advanced high-level analysis
- Test beams at CERN, Frascati.
- Visibility in the neutrino community (conferences, workshops).
- Attracted already several students (master, PhD).

http://enubet.pd.infn.it

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

ENUBET next steps

- **2019**: freeze **light readout technology**, finalize **tuning of the beamline design** (improve current S/N for e^+), full assessment of **systematics** on the fluxes
- **By 2021: Conceptual Design Report**: **physics** and **costing**
- Build the **demonstrator prototype** of the tagger
- **>2021**: (likely) propose a full scale experiment implementation supported by a larger international collaboration.

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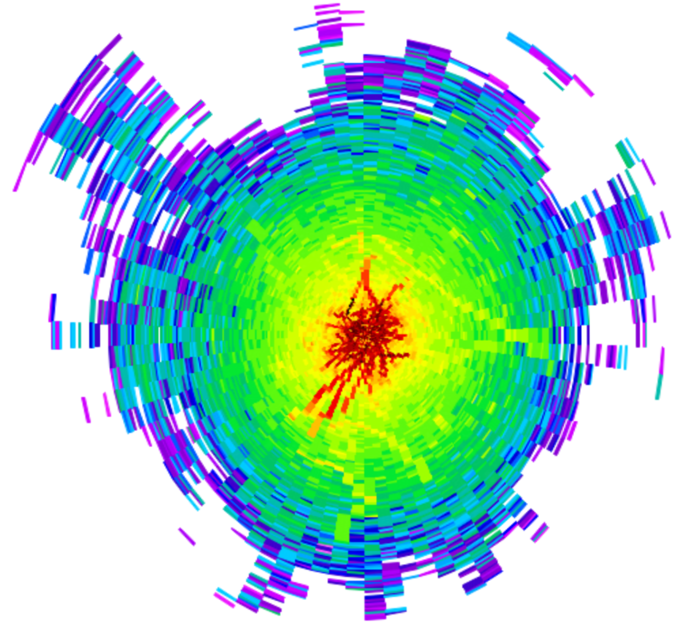
谢谢你
的倾听


Core team @ Bordeaux 3/19

Backup

Conclusions



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% @ 1 GeV → 8% @ 3 GeV)

In the first two and a half 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 **test beams** campaign before LS2
- Strenghtened the **physics case**: → slow extraction + "**narrow band off-axis technique**"

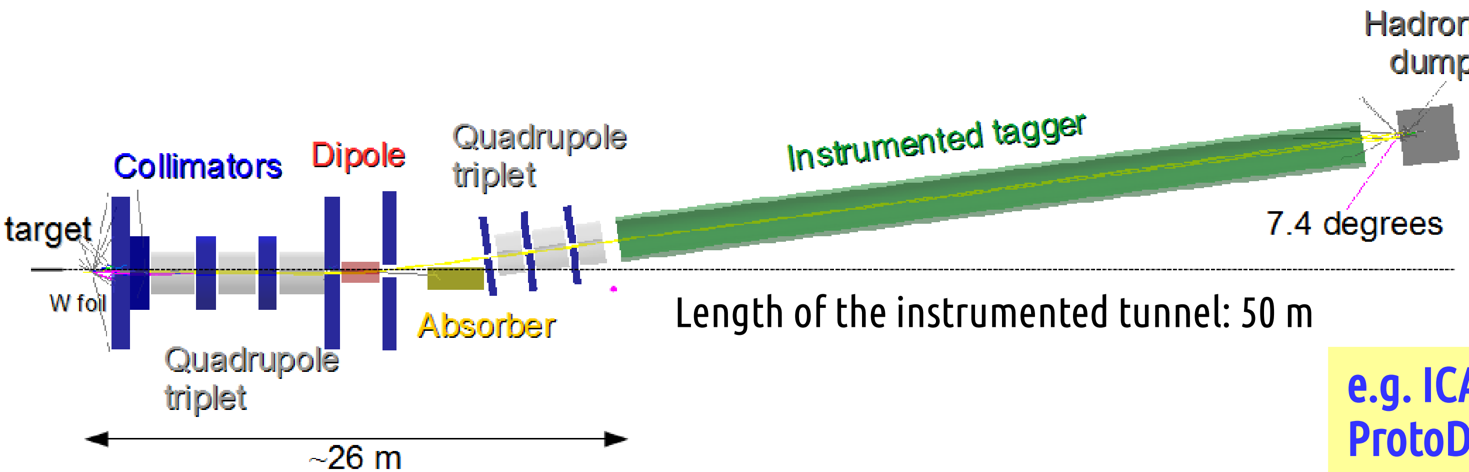
The ENUBET technique is **very promising** and the results we got so far **exceeded our expectations**

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



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 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**) [under evaluation]

Systematics on the ν_e flux

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

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

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

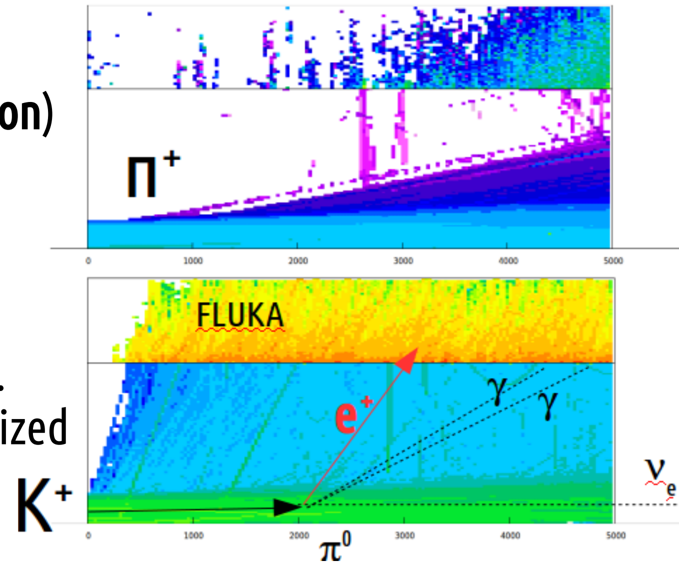
α encodes the residual geometrical (decay lengths, beam spread) and kinematic factors from K decays → "**easy" corrections**.

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** is also very powerful.
Branching ratios known to < 0.1% (additional uncertainty is small).
Residual background is **stray pions from beam tails** (well characterized in terms of azimuth and longitudinal position)



- **can we get to 1% ?** assessment in progress: **toy Monte Carlos** + **full simulation**
- Address the effect of each uncertainty and the degree of **cancellations allowed by the large correlations between e^+ rate and ν_e flux**.

Time tagged neutrino beams: challenges

- Proton **extraction** ~ 2s → Static focusing with slow extraction is mandatory
- σ_t of the tagger < 1 ns → OK
- σ_t of the ν detector < 1 ns → **Feasible but at the limit of present technology**
- Cosmic background $\times$ 10 → Foresee overburden/cosmic ray tagger
- small K^+ momentum bite (not to spoil the ν_e energy reco.) → **Feasible but implies flux reduction**
- Tagger-detector time sync. << 1 ns → OK (direct optical links)

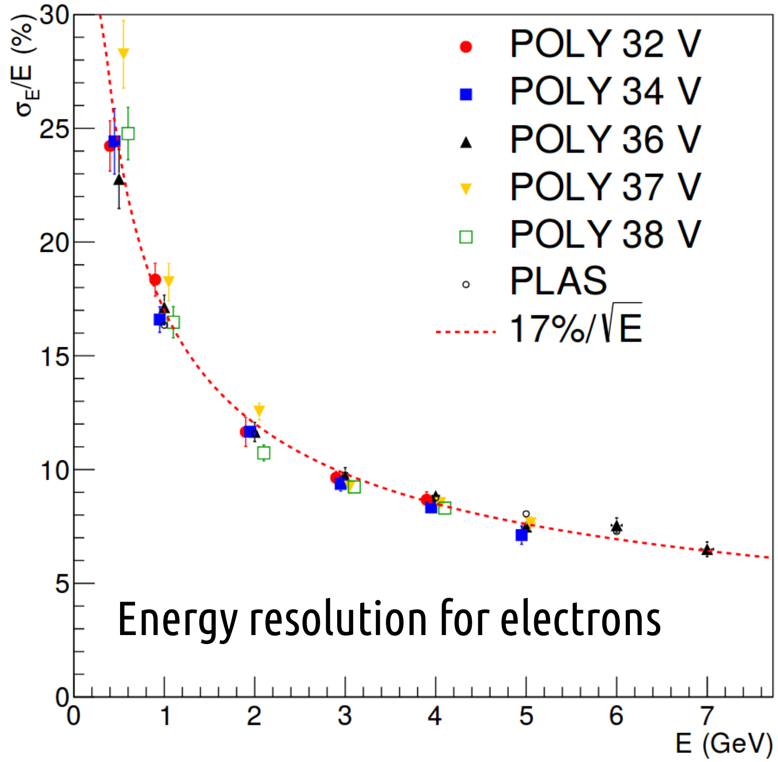
In parallel to the **t_0-layer baseline option** (light plastic scintillator tracker) we are considering alternative technologies (NUTECH project MIUR).

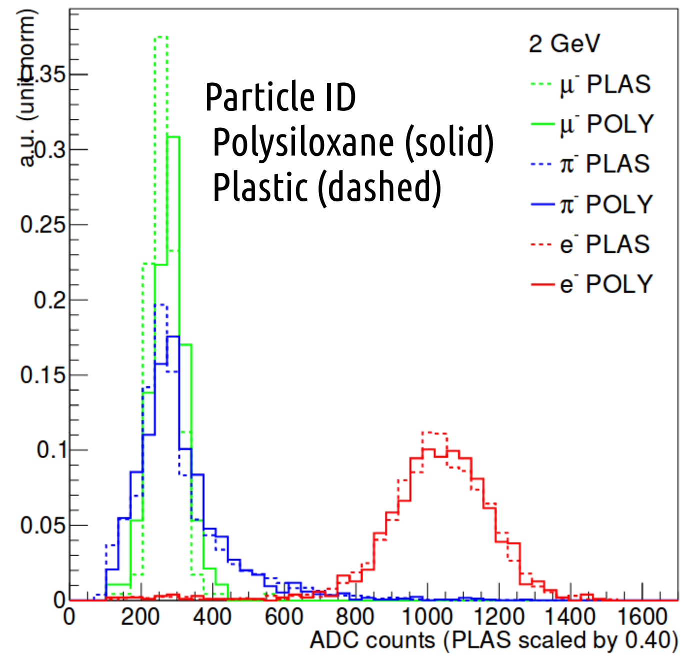
Improve the timing both:

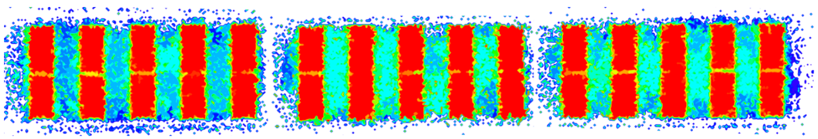
- at the tagger
  - direct readout of **cherenkov light**, **LYSO** crystals with embedded SiPM, MicroMegas
- and at the neutrino detector side
  - SiPM based readout of **Ar scintillation light**

Polysiloxane shashlik prototypes

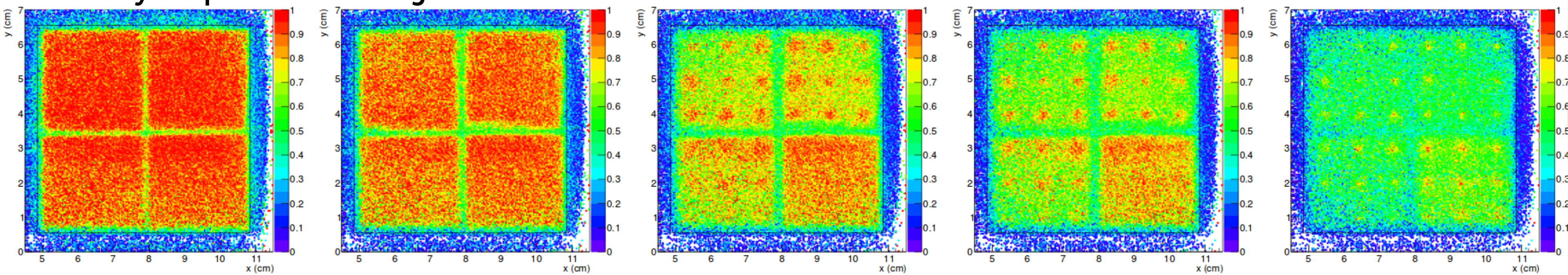
Light yield (normalized to thickness) is ~ 1/3 of plastic scintillator
→ tests light transmission on WLS fibers in absence of air gap
Energy resolution, particle-ID and uniformity in line with the one achieved with plastic scintillator







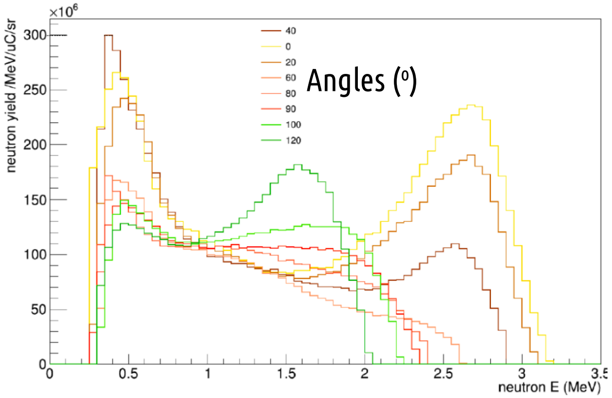
Efficiency maps at increasing thresholds →

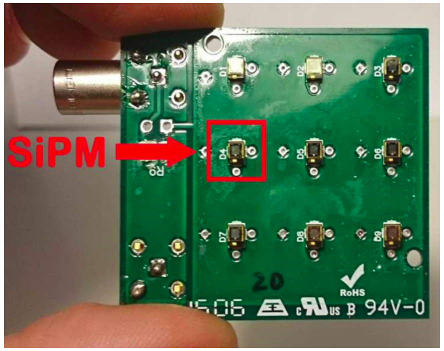


SiPM irradiation measurements at INFN-LNL

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

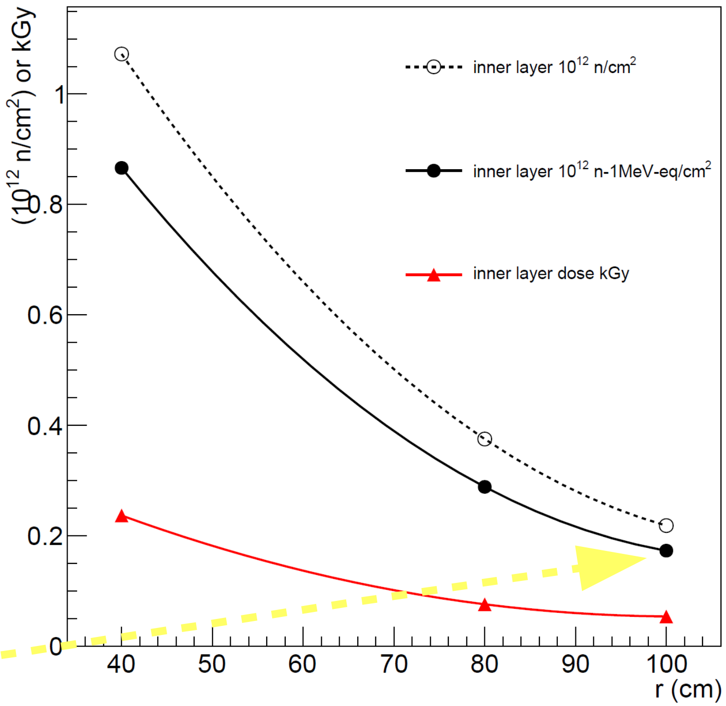
n spectra (from previous works at the same facility)

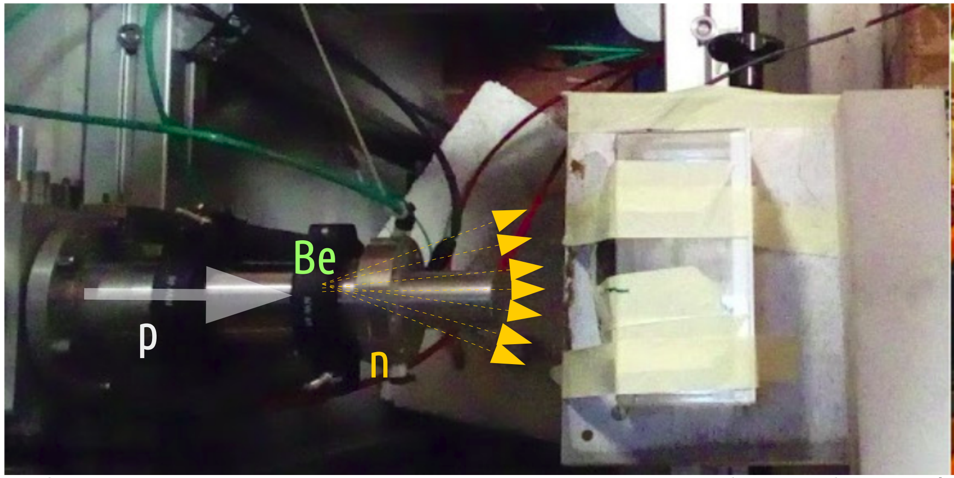


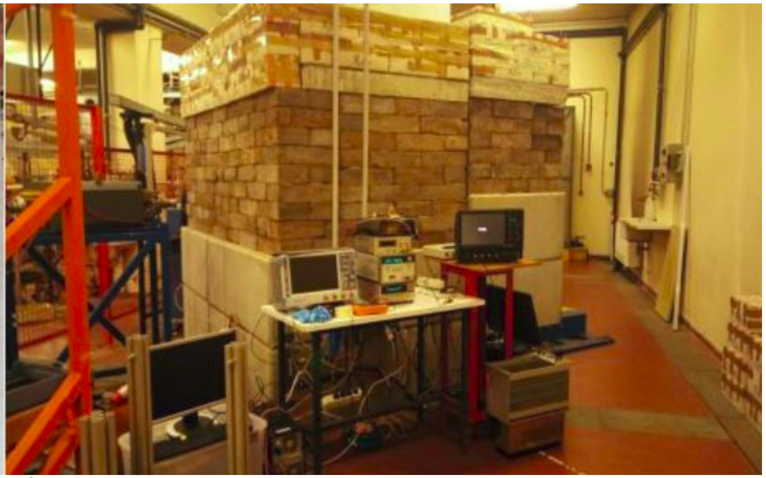


→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm²** 1 MeV-eq (max non ionizing dose for 10^4 ν_e^{CC} at a 500 t ν detector at r = 1 m)

Expected n doses from K decays (FLUKA)



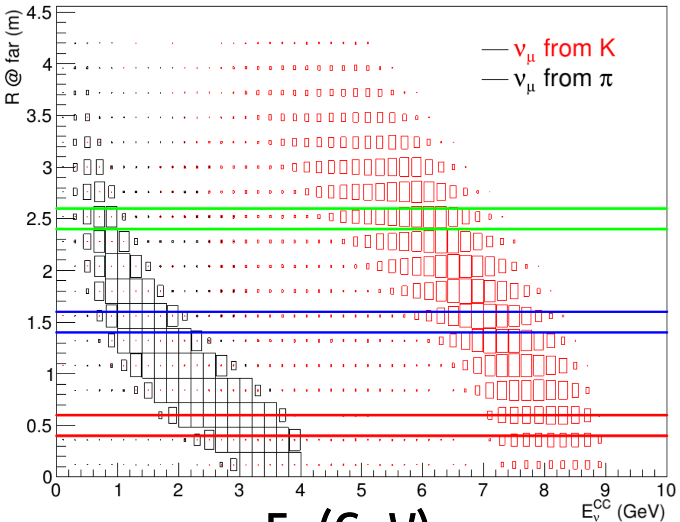




ν_μ CC events at the ENUBET narrow band beam

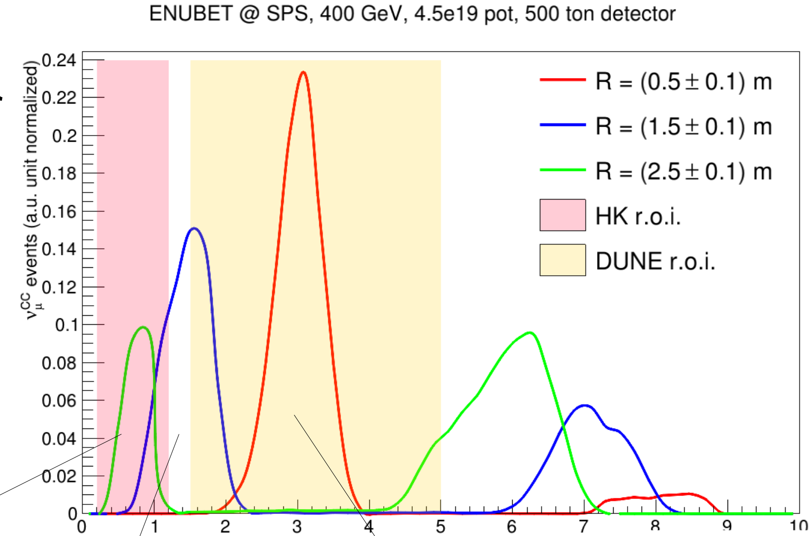
The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

radius (m)



E_ν (GeV)

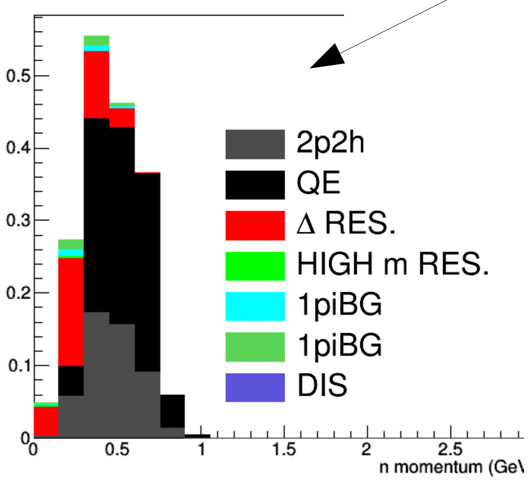
ν_μ ^{CC} in radial bins (1 norm.)

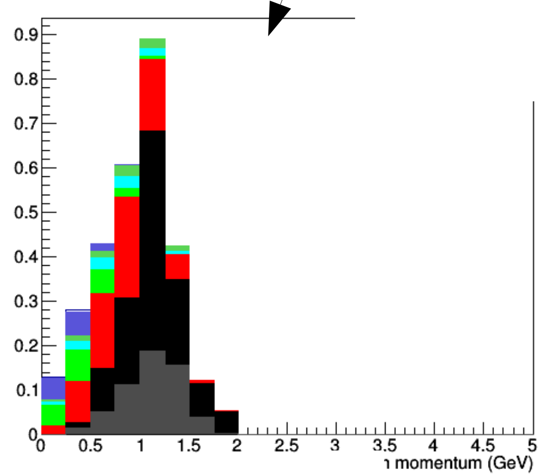


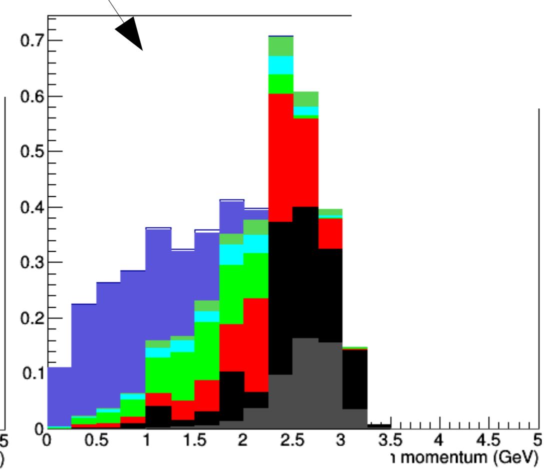
E_ν (GeV)

Momentum of ν_μ ^{CC} μ^- on Ar.

GiBUU generator (Gauss flux approx.)

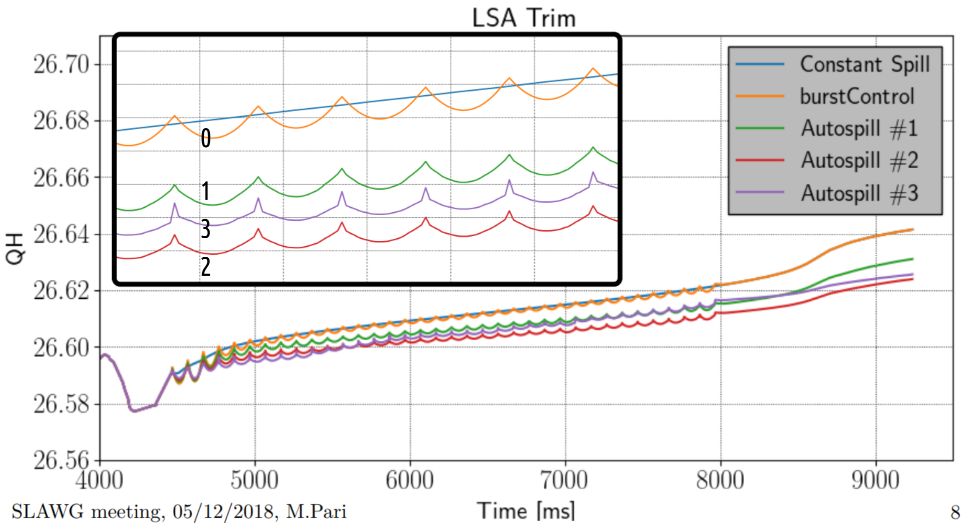


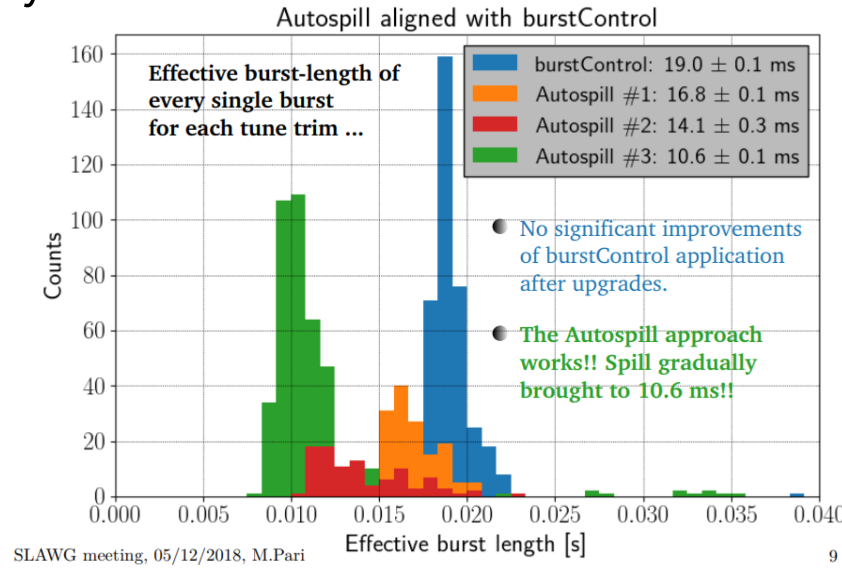


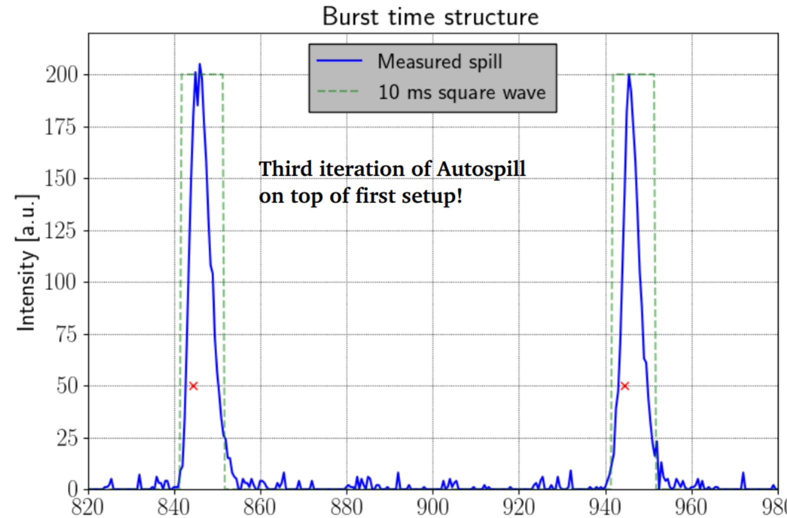


Machine studies for the horn-based option

- 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.







- 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

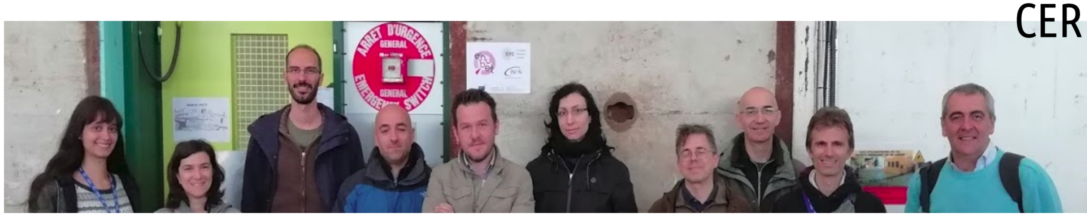
CERN Aug 2017

CERN Oct 2017

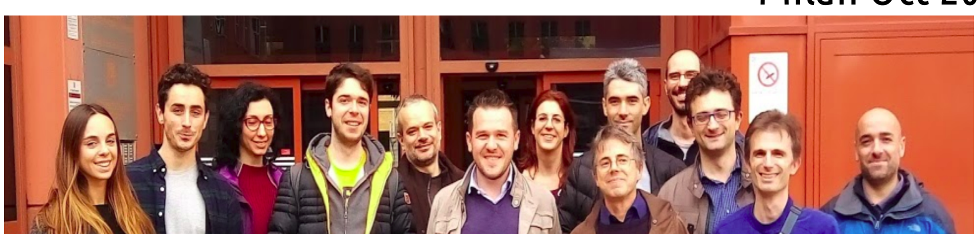
INFN-LNL Jun 2017

CERN May 2018

CERN Sep 2018



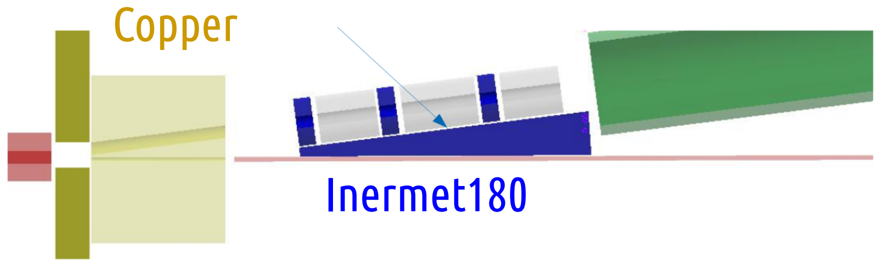
Milan Oct 2017



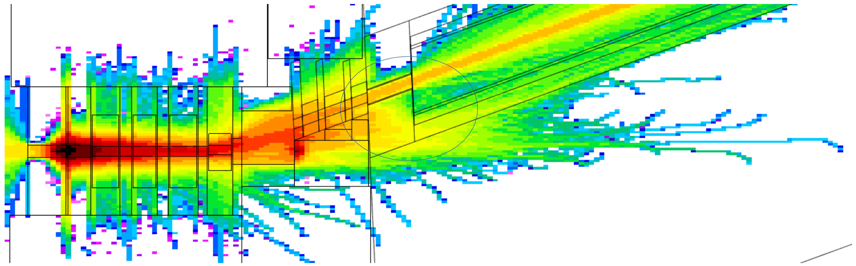
Beamline shielding tuning studies

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

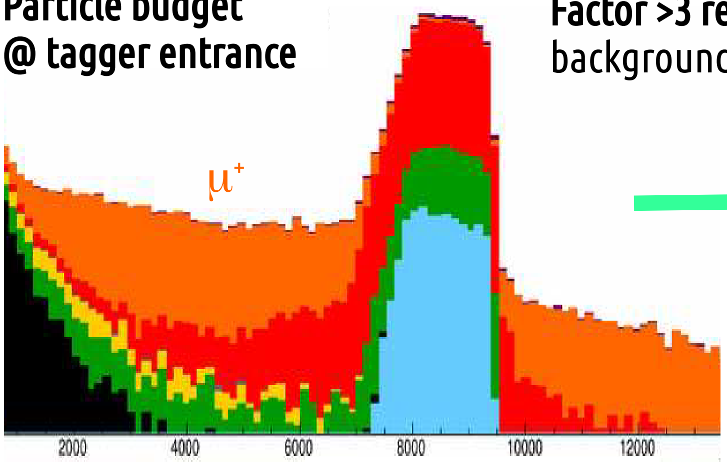
G4Beamline



FLUKA (muon energy deposition map)

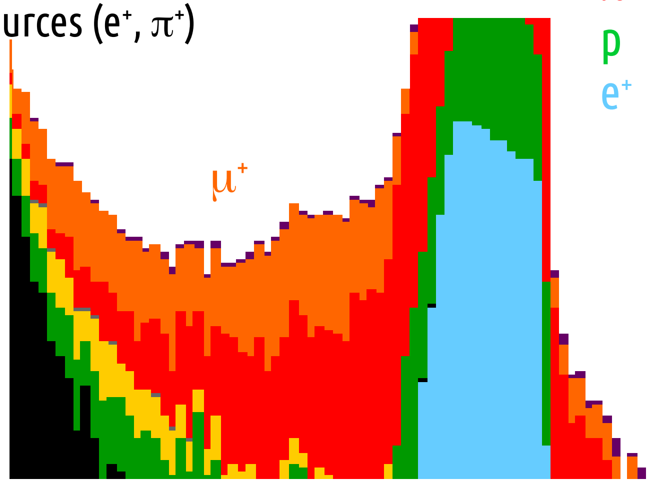


Particle budget @ tagger entrance

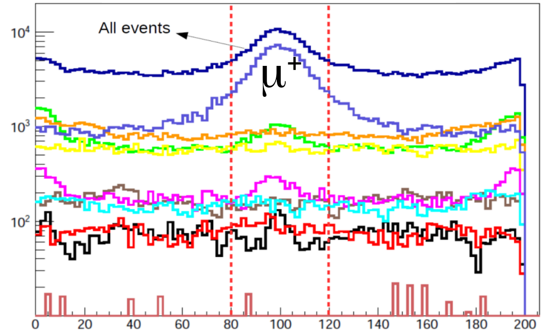


Azimuthal angle

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



The bulk of μ^+ along dipole bending plane



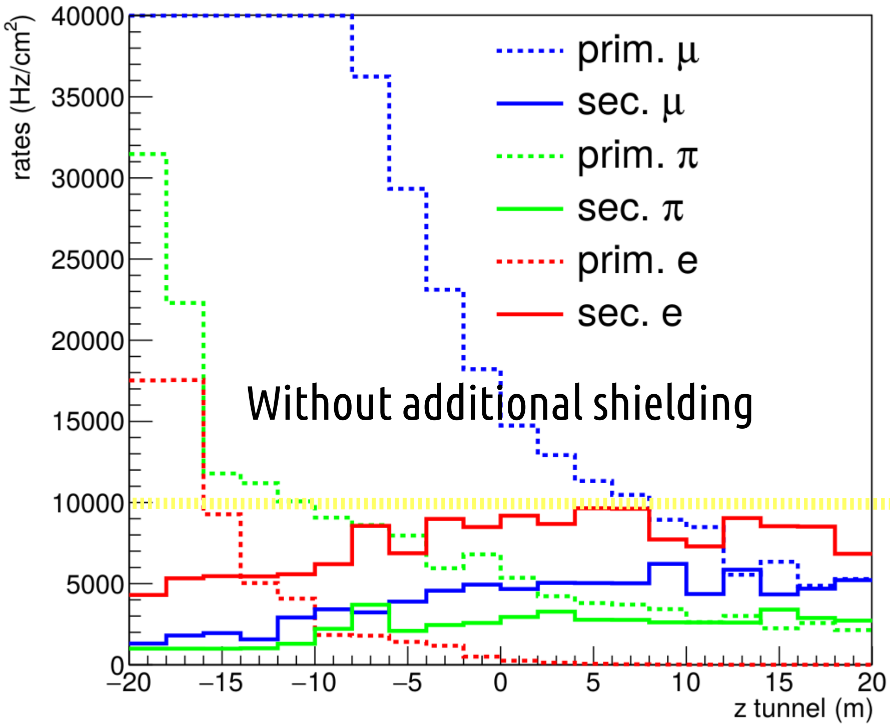
Besides shielding a further reduction of muons can be achieved by removing a section in ϕ in the upstream part of the tagger

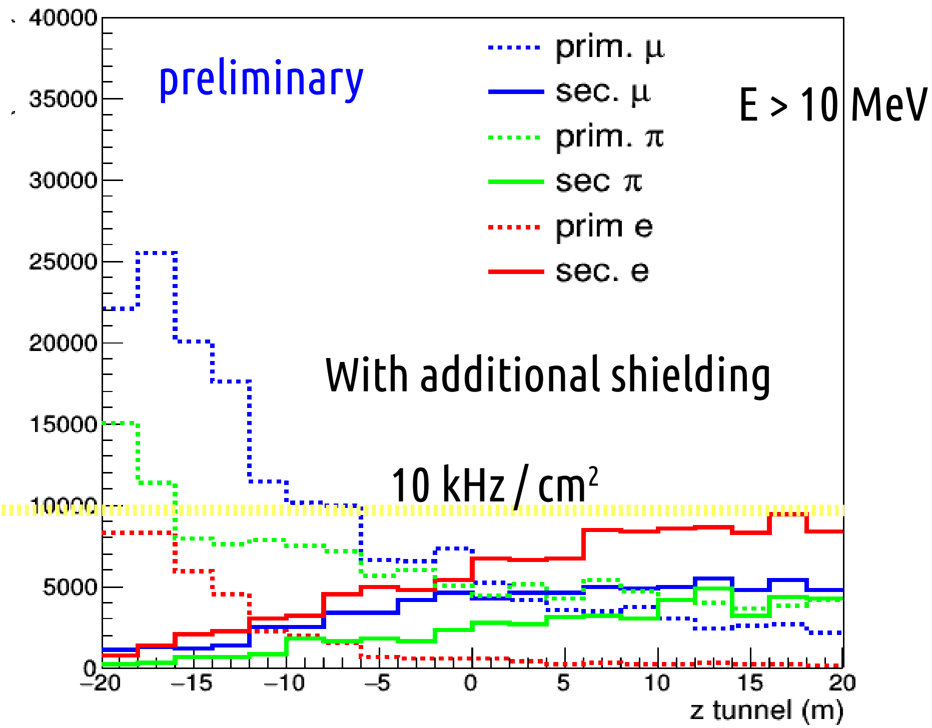
Particle rates in the tunnel

Static focusing system
4.5 x 10^{13} pot in 2 s (400 GeV)

Radius = 1 m from the axis of the tunnel

Rates vs longitudinal position in the tunnel (before any reconstruction)



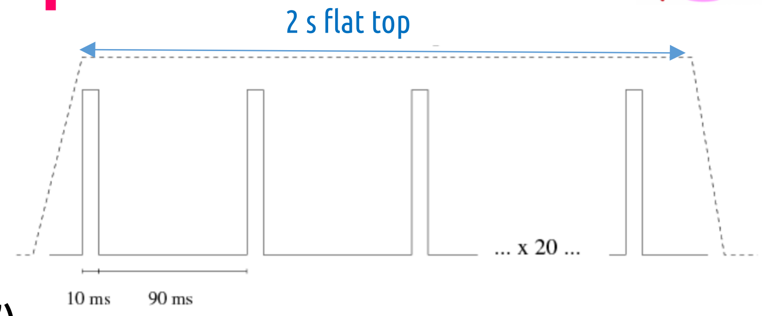


- Primary particles background largely reduced with tuning in the shielding
- The second part of the tunnel is significantly favored in terms of signal-to-background
- With static focusing scheme rates in the second half are below 10 kHz/cm^2

Machine studies for the horn-based option

- Performed Jul/Aug/Nov 2018 at the SPS

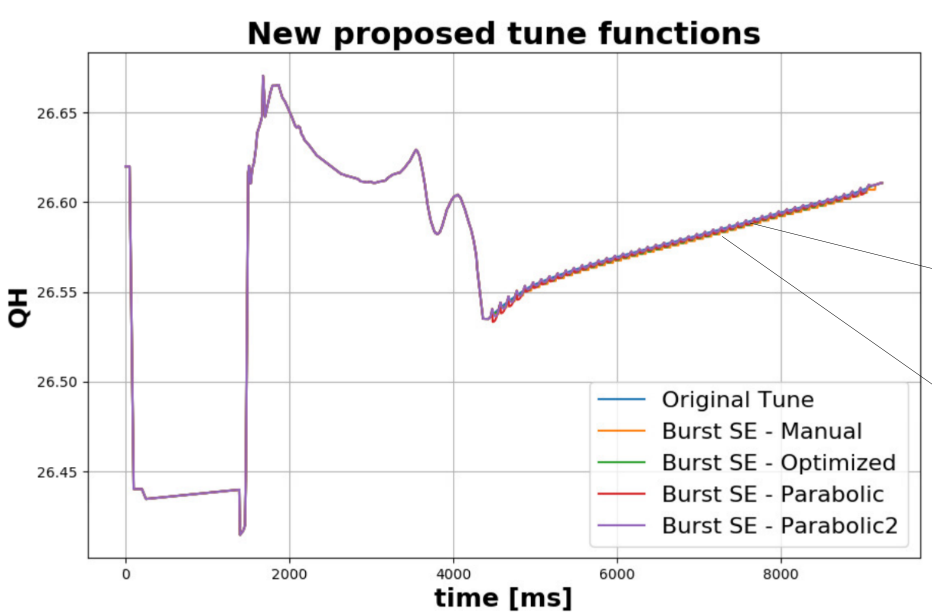
CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

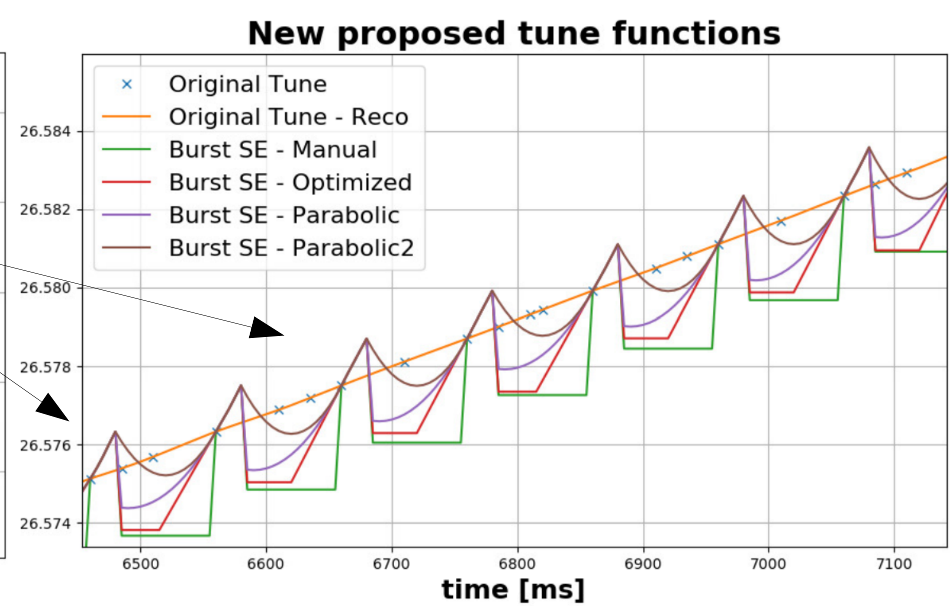


- Idea: synchronize proton beam and horn current pulses
- + keep rates compatible with tagger (10 ms pulses “slow extr.”)

“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/





Positron ID from K decay

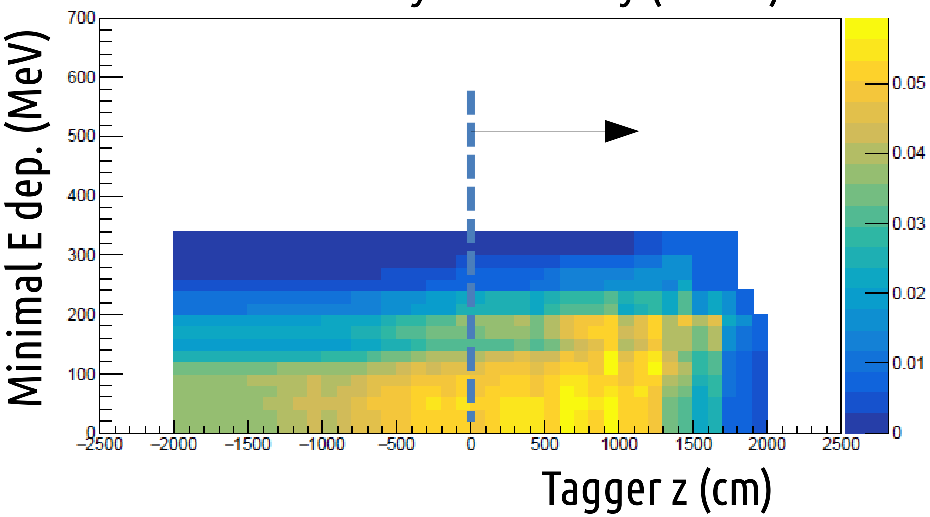
Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018.
Includes particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain

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

- Event Builder → Identify the seed of the event (UCM with large energy deposit) and cluster neighboring modules (in time and space)
- $e/\pi/\mu$ 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

Purity x Efficiency (Ke3 e^+)



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

φ cut → 0.46

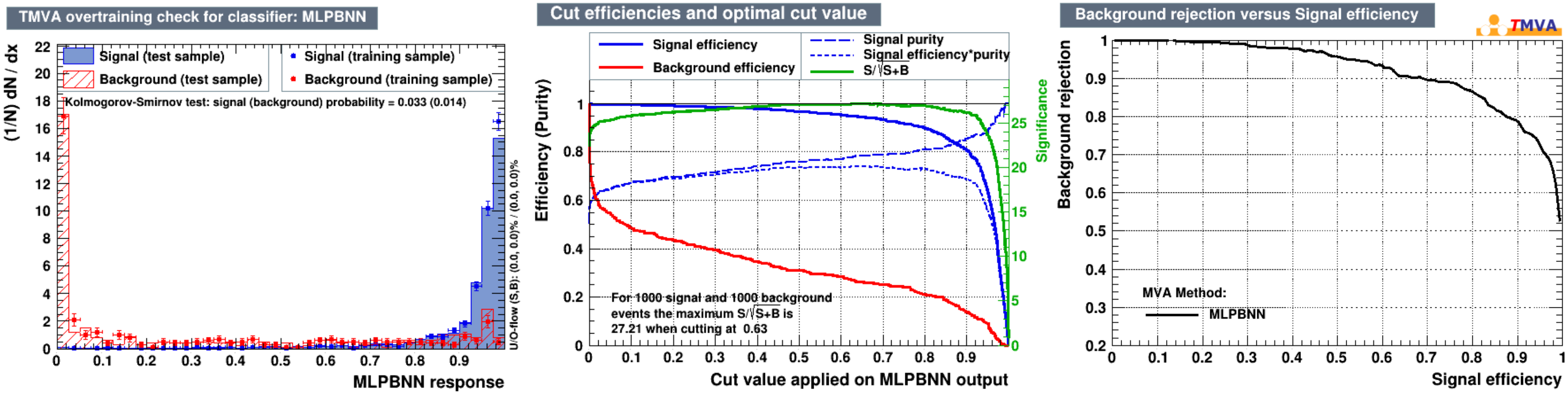
Instrumenting half of the decay tunnel:
K_{e3} e^+ at single particle level with a S/N = 0.46

The Tagger – positron ID from K decay

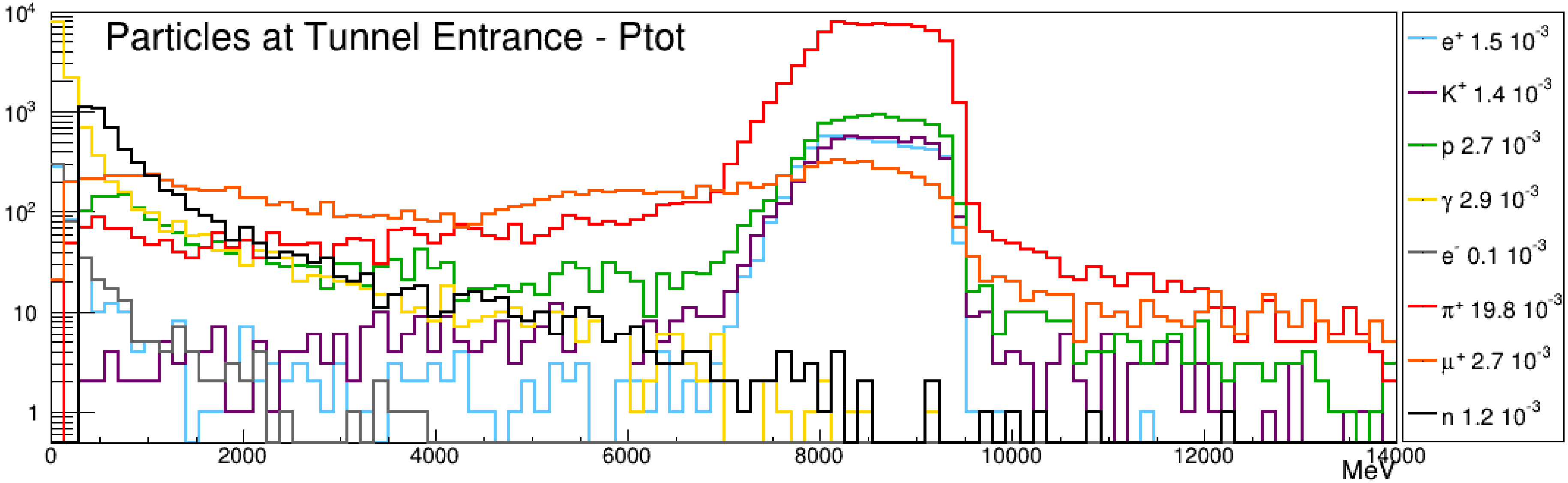
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV ▭ link neighboring modules with time (1ns) and position requirements

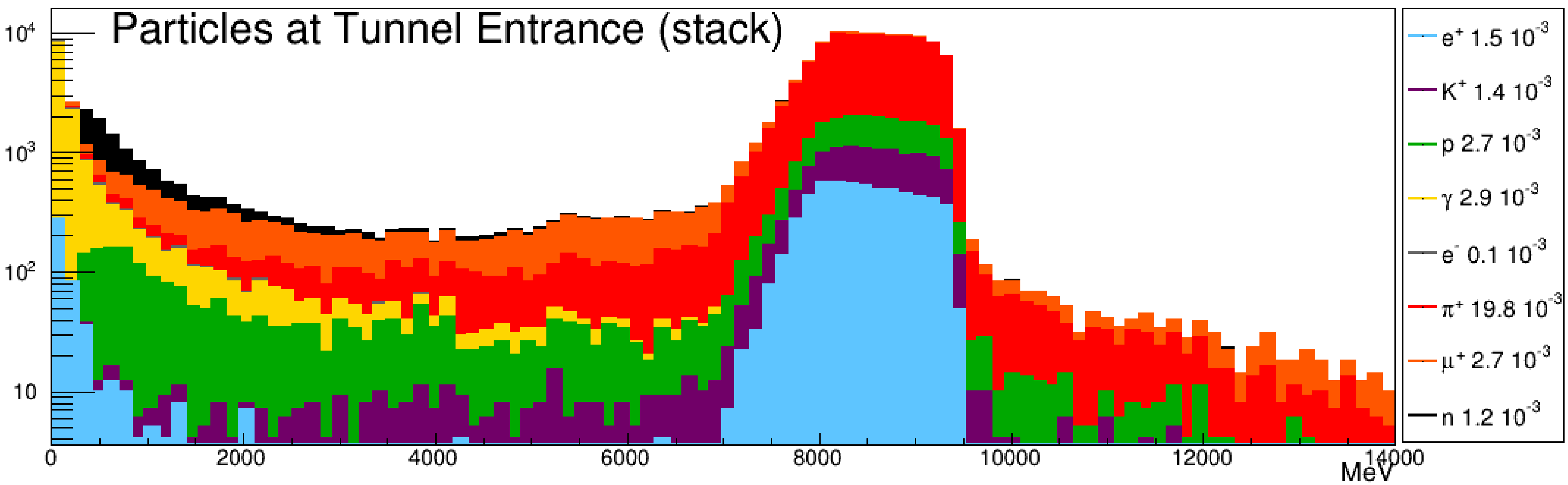
e/π separation → (Neural network) TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)

Response to signal and background



e/γ separation → π^0 rejection: we require 3 layers of t0 before first calorimeter energy deposit compatible with a mip (0.65-1.7 MeV)


Particles at Tunnel Entrance - Ptot
e+ 1.5 10-3
K+ 1.4 10-3
p 2.7 10-3
γ 2.9 10-3
e- 0.1 10-3
π+ 19.8 10-3
μ+ 2.7 10-3
n 1.2 10-3
MeV


Particles at Tunnel Entrance (stack)
e+ 1.5 10-3
K+ 1.4 10-3
p 2.7 10-3
γ 2.9 10-3
e- 0.1 10-3
π+ 19.8 10-3
μ+ 2.7 10-3
n 1.2 10-3
MeV