The ENUBET project

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

SPSC open session
CERN, 23 Jan 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).

ENUBET: 54 physicists, 12 institutions

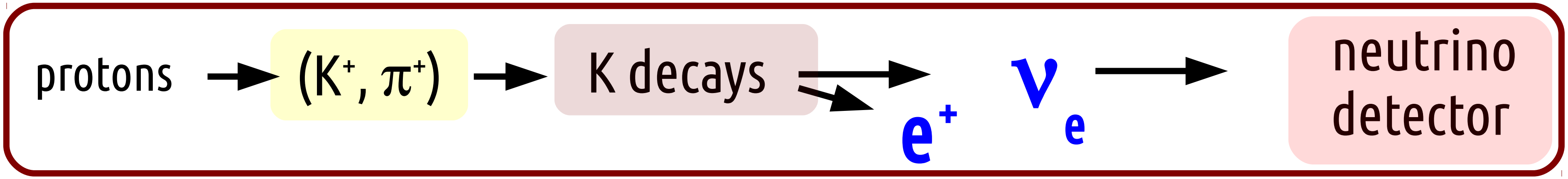
Outline

- The **physics of monitored ν beams** and goals of ENUBET
- The **hadronic beamline**:
  → Proton extraction: the CERN-SPS machine studies
- The **positron tagger**:
  → detector prototyping at CERN-PS (2016-2018)
- → **ENUBET and CERN** in the second half of the project

ENUBET: 54 physicists, 12 institutions

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**

ENUBET goals and highlights

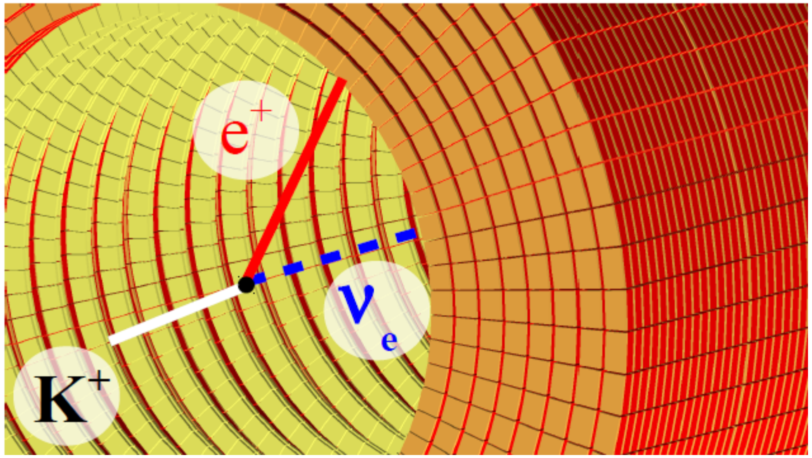
Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level.**

Two pillars:

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

Recent achievements

- **End-to-end simulation** of the hadronic **beamline**
- Updated **physics performance**
- Experimental results on the beamline **instrumentation prototypes**



Neutrino beams for precision physics: the ERC ENUBET project

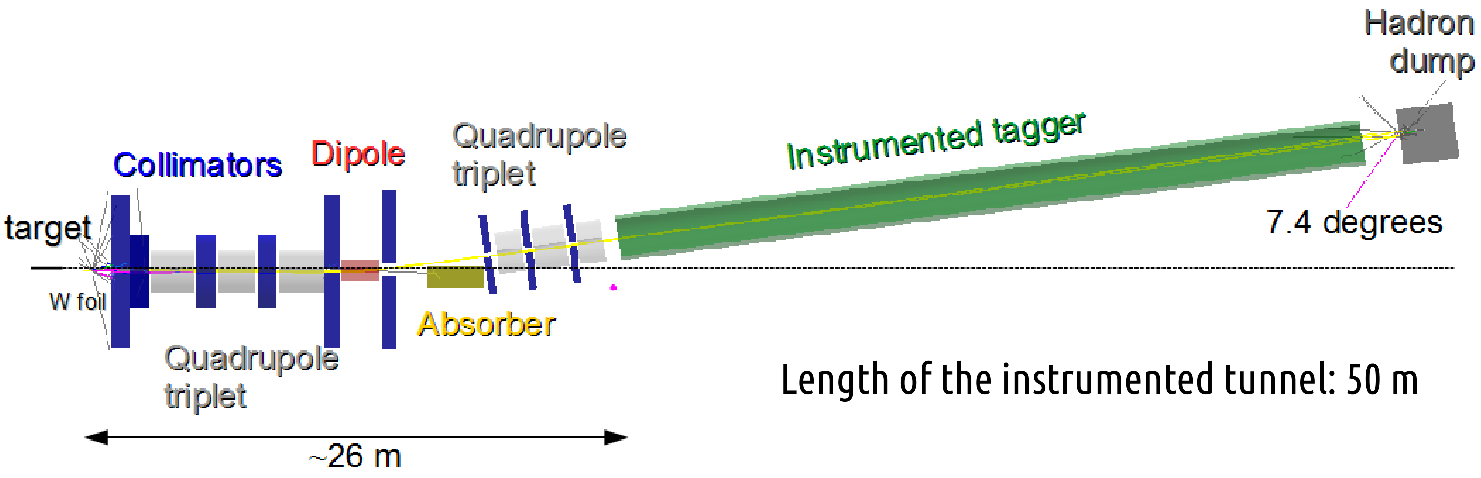
Enhanced **N**e**U**trino **BE**ams from kaon **T**agging

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

The next generation of **short baseline** experiments for **cross-section** measurements and for **precision ν physics** (e.g. **CP violation program**, sterile ν NSI) 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

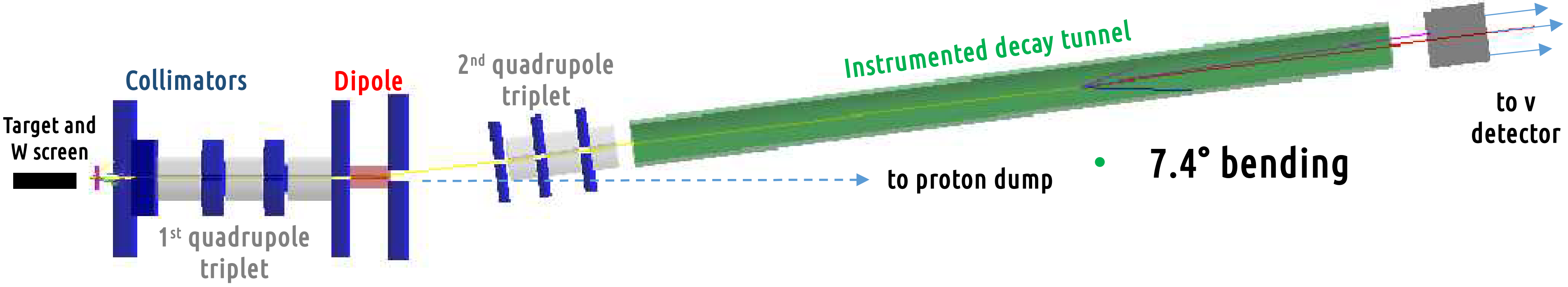


Length of the instrumented tunnel: 50 m

~ 500 t neutrino detector @ 100 m from the target

e.g.ICARUS@FNAL or ProtoDUNE-SP/DP@CERN

The ENUBET beamline (baseline option)



- 7.4° bending

- **Proton driver**: **CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **Target**: 1 m Be, graphite target. FLUKA.
- **Focusing**
  - **Horn**: 2 ms pulse, 180 kA, 10 Hz during the flat top *[not shown in 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

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 5**

(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.

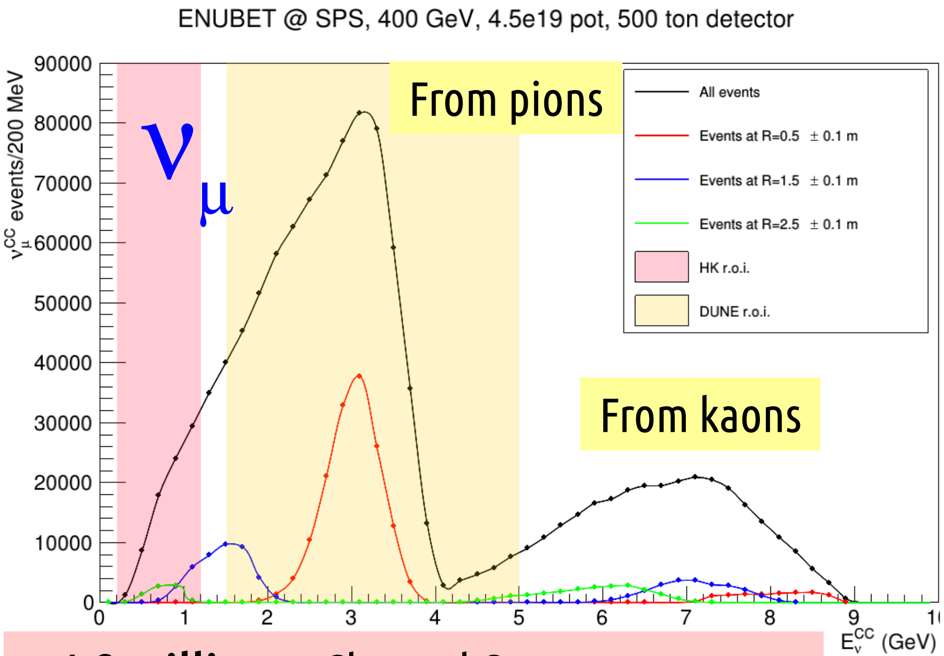
The horn-based option still allows ~x5 faster statistics but the static option gained momentum since initial estimates were ~ x 5 too conservative wrt to present simulations!

Furthermore … advantages of the static extraction:

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

Neutrino events per year at the detector

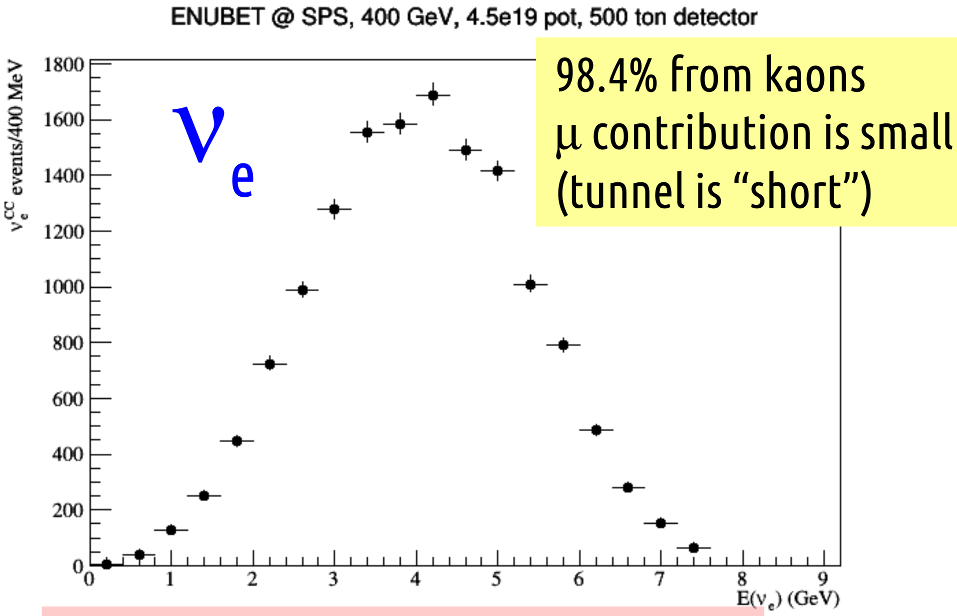
- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5 x 10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5 x 10^{20} pot at FNAL



From pions

From kaons

1.2 million ν_μ Charged Current per year



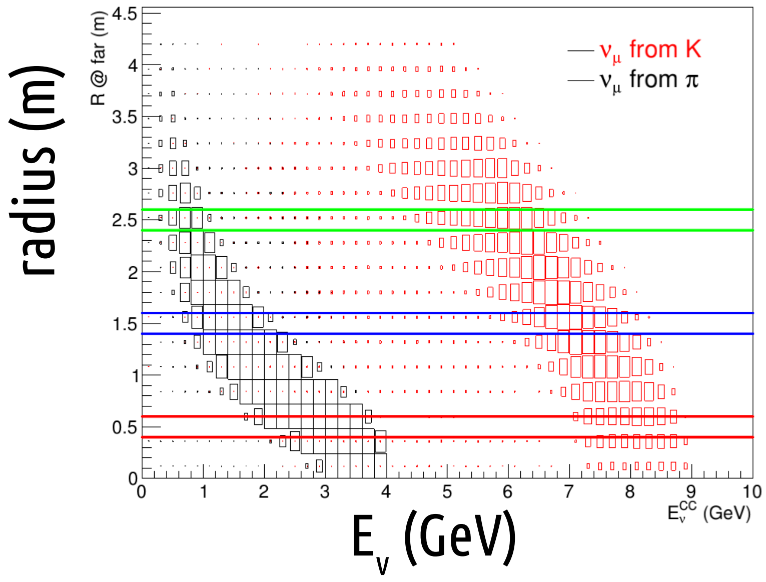
98.4% from kaons
μ contribution is small
(tunnel is “short”)

14000 ν_e Charged Current per year

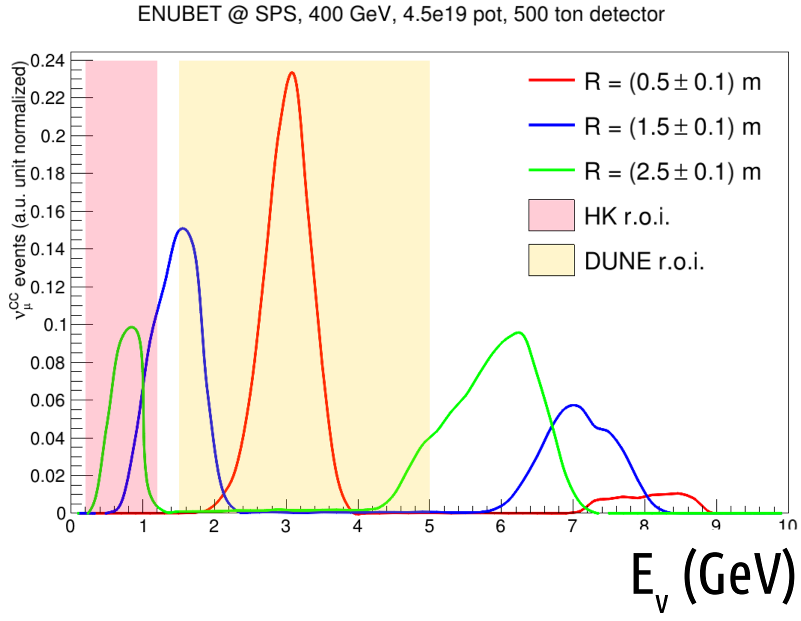
- ν_μ from K and π are **well separated** in energy (narrow band)
- ν_e and ν_μ from K are constrained by the tagger measurement (K_{e3}, mainly $K_{\mu 2}$).
- ν_μ from π: μ detectors downstream of the hadron dump (under study)

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.

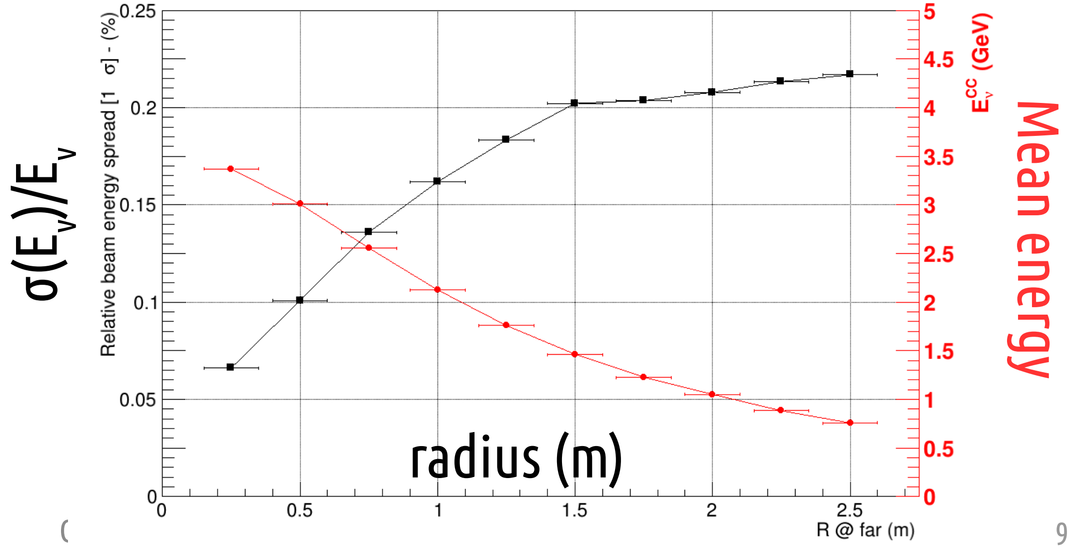


ν_μ ^{CC} in radial bins (1 norm.)



The beam width at fixed R
(≡ neutrino energy resolution) for the pion component is

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



ν_μ CC events at the ENUBET narrow band beam

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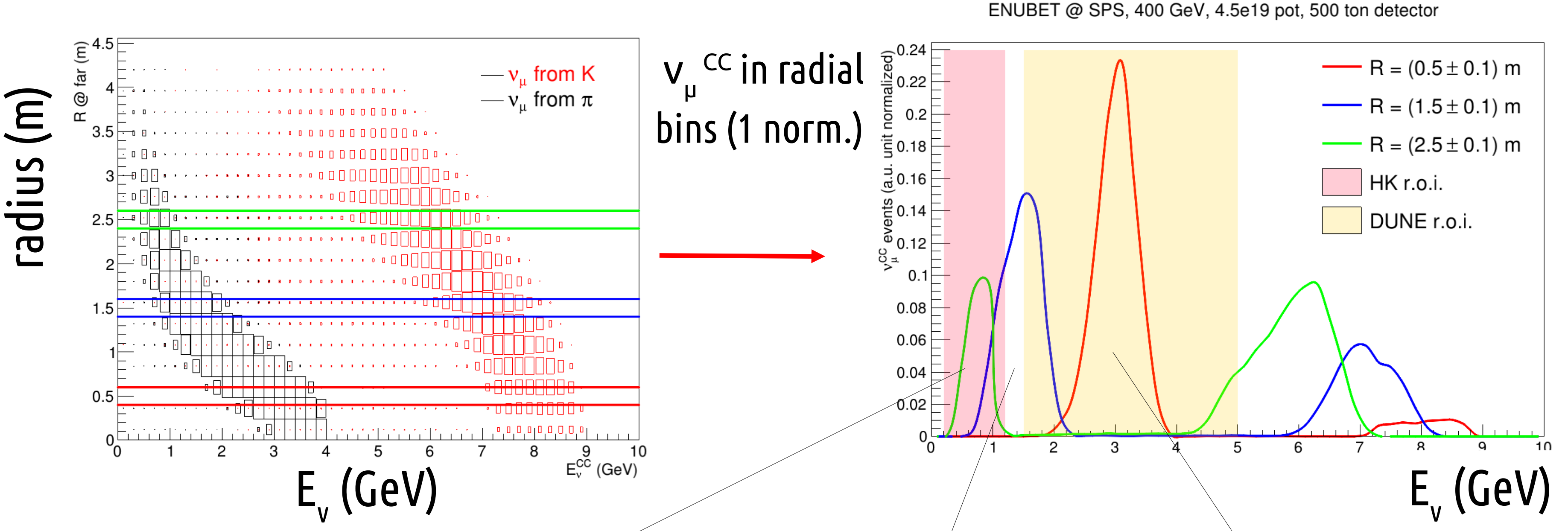
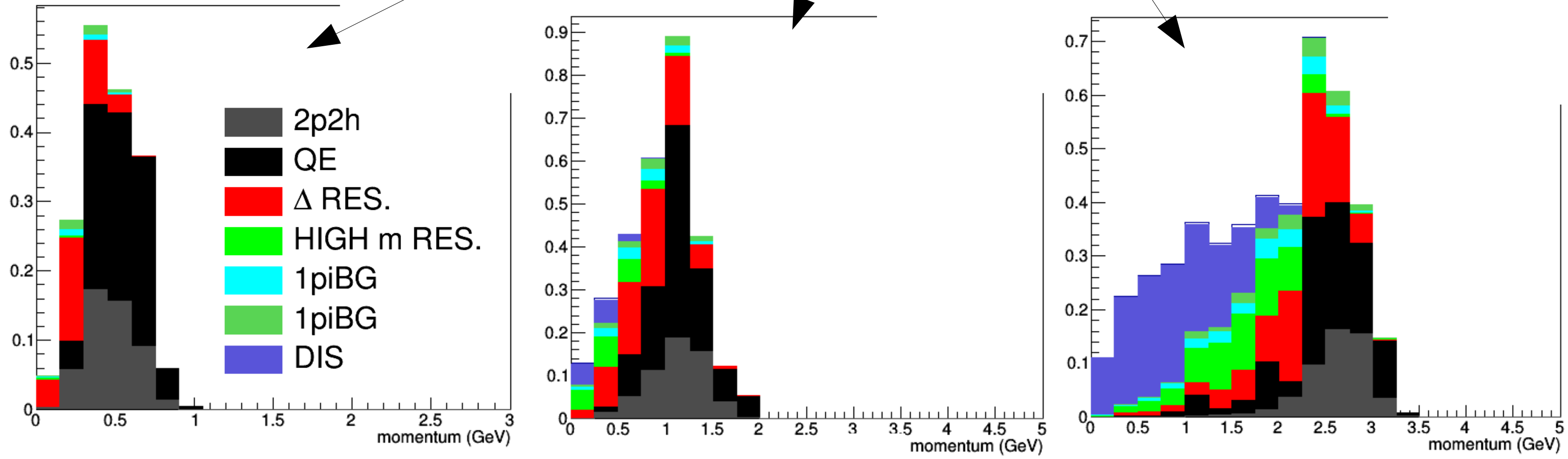


Momentum of ν_μ CC μ^- on Ar.

GiBUU generator (Gauss flux approx.)



Systematics on the neutrino flux

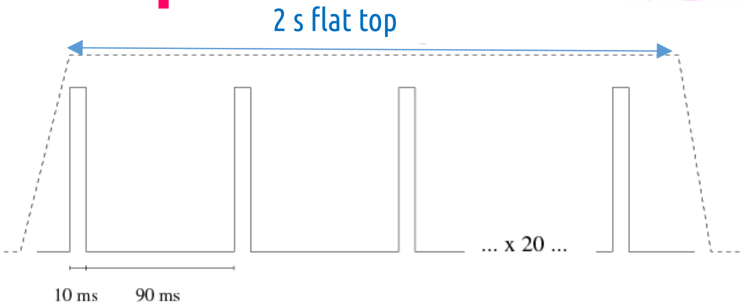
Positron tagging eliminates the leading sources of systematics but **can we get to 1%**? Detailed analysis being performed in the second phase. Statistical analysis based on toy Monte Carlo with the full simulation. Address the effect of each uncertainty and the degree of cancellations allowed by the large correlations between e^+ rate and ν_e flux.

Sources	Size
K production yield	~Irrelevant (e^+ tag)
Secondary transport efficiency, geometry, currents, stability.	~Irrelevant (e^+ tag)
Integrated PoT	~Irrelevant (e^+ tag)
Geometrical efficiency and fiducial mass	< 0.5%. *PRL 108 (2012) 171803 [Daya Bay]*
3-body kinematics and mass	< 0.1%. *Chin. Phys. C38 (2014) 090001 [PDG]*
Branching ratios	< 0.1%. Irrelevant (e^+ tag) except for estimation of "background" from non-K_{e3} decay modes
e/π separation	test beams
Detector backg. From NC π^0 events	< 1%. *EPJ C73 (2013) 2345 [ICARUS]*
Detector corrections	< 1%. factorization if the target is the same as for the long baseline CPV experiment

Machine studies for the horn-based option

- Performed Jul/Aug/Nov 2018 at the SPS

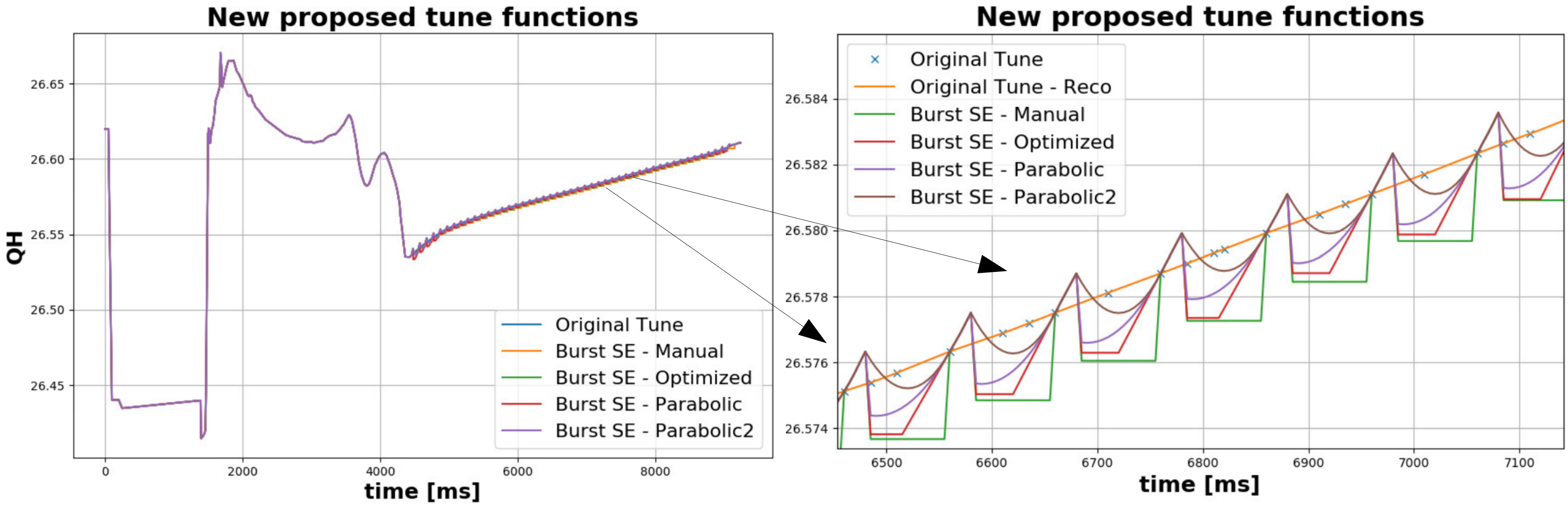
CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard



- 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

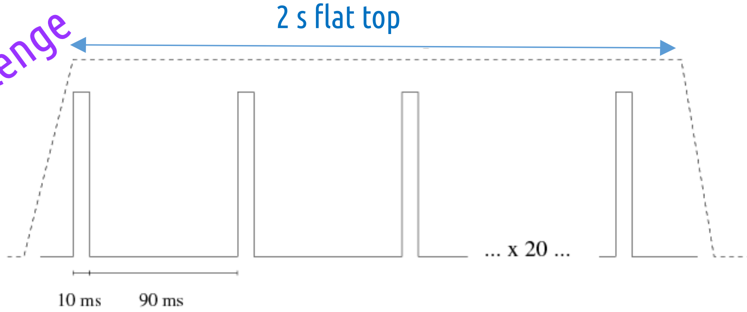
M. Pari (CERN doctoral student, Univ. of Padova) @ SLAWG meeting of 5/12/2019
https://indico.cern.ch/event/777458/

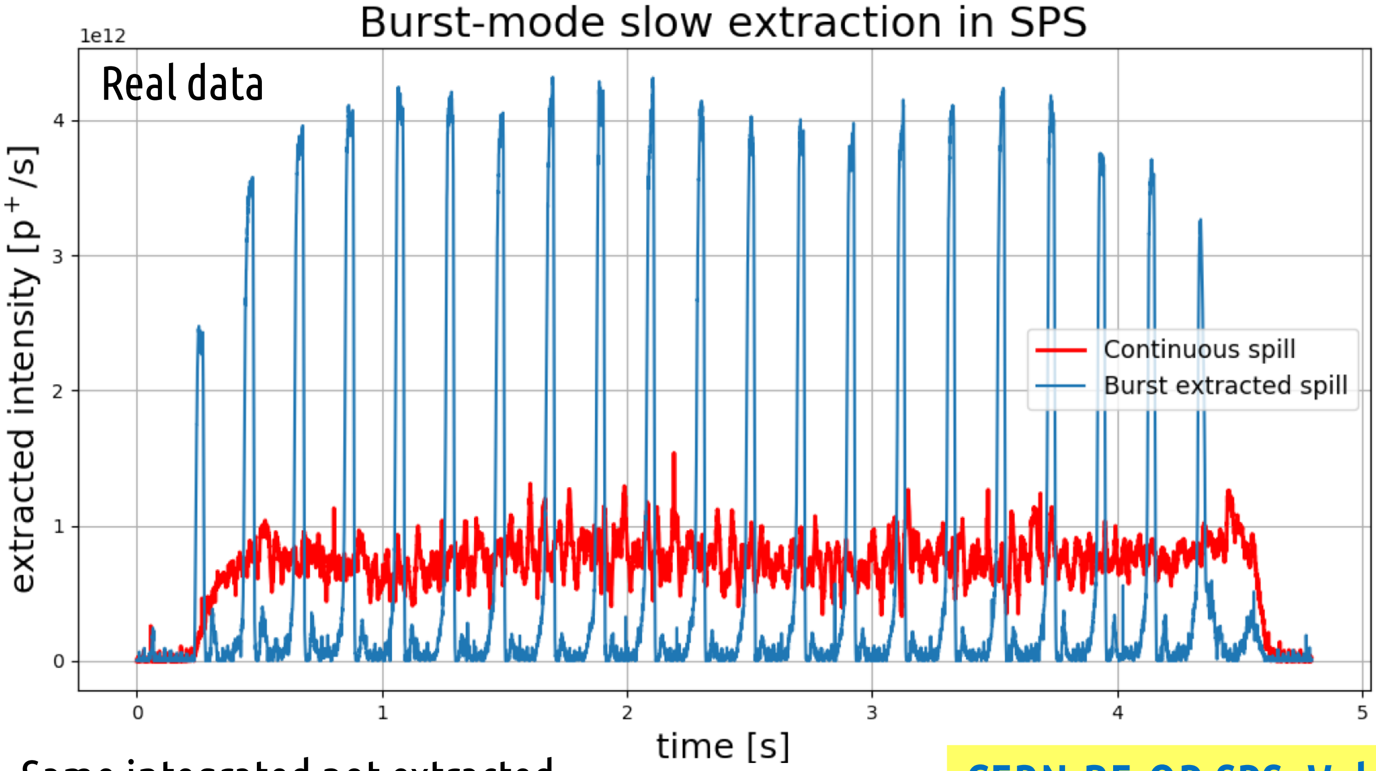


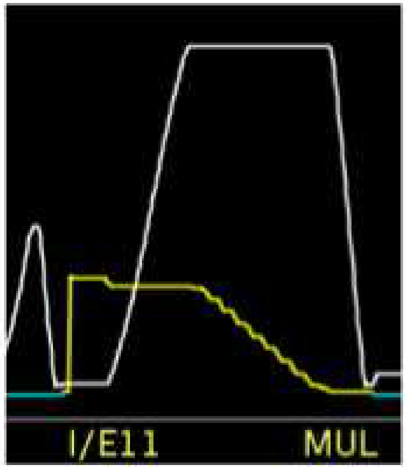
Machine studies for the horn-based option

From an idea “on slide” to
a working implementation !

ENUBET #2YearsChallenge




Burst-mode slow extraction in SPS



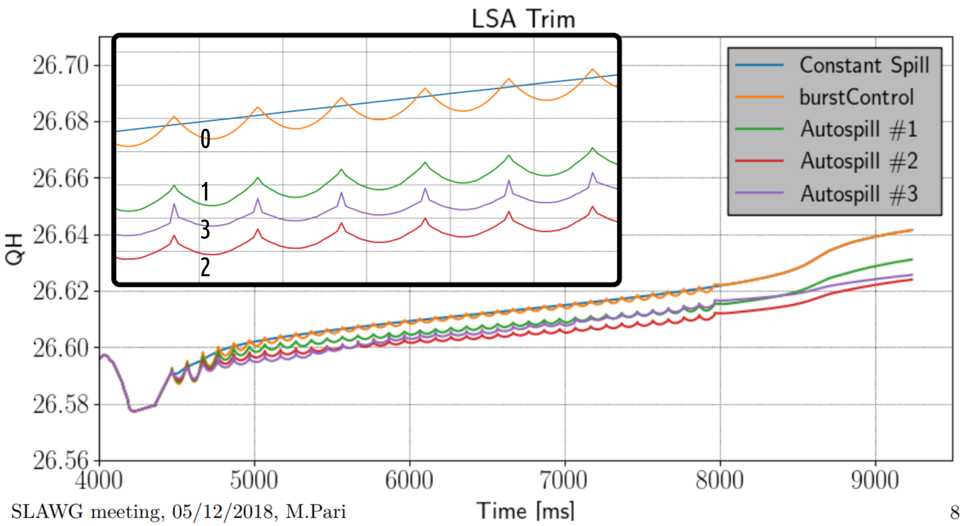
Proton current

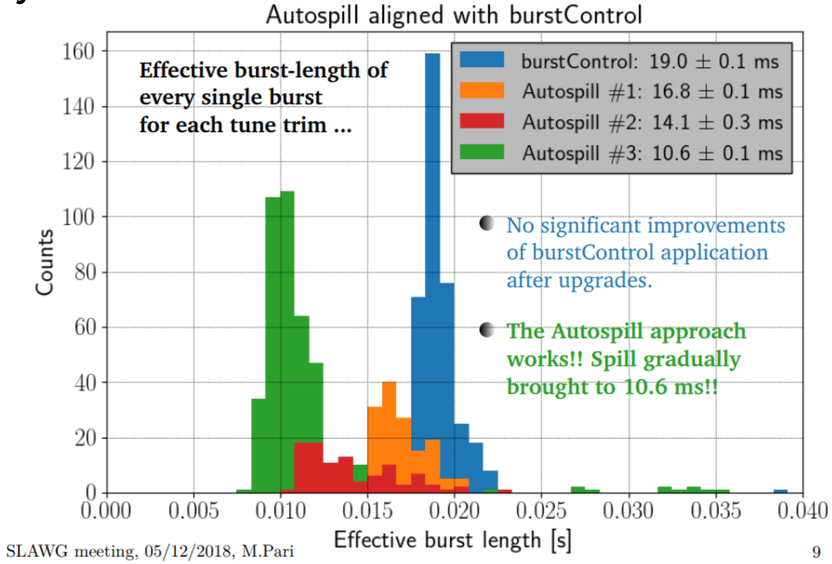
Same integrated pot extracted.
Protons squeezed into intervals with active horn

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

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.

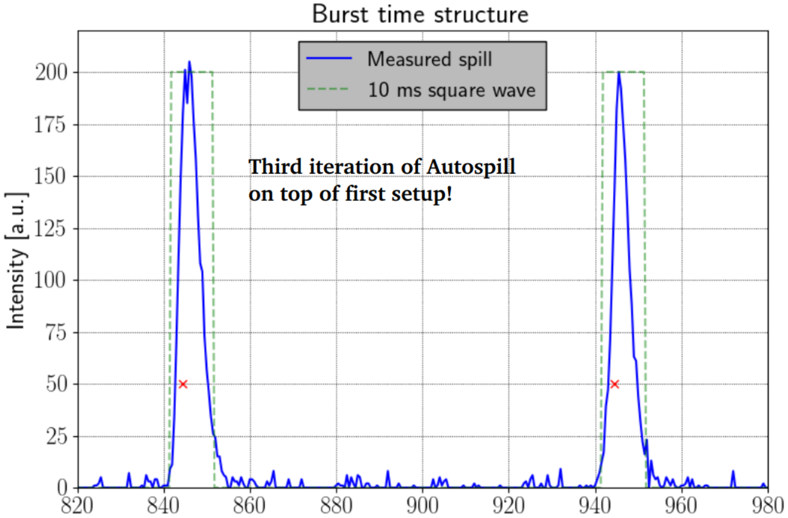




Effective burst-length of every single burst for each tune trim ...

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

- 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**!



Third iteration of Autospill on top of first setup!

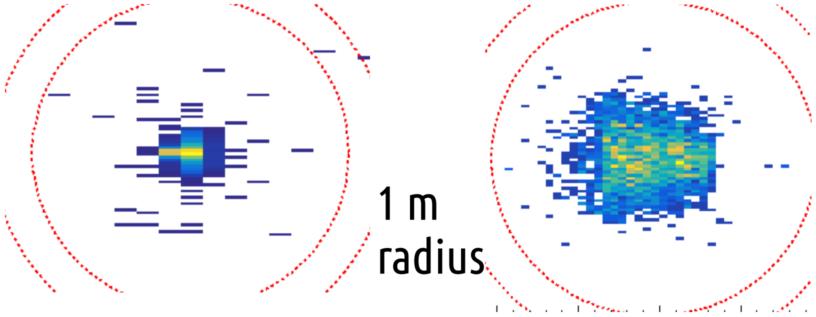
CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

The static beamline: emittance, particle content

Divergence of the kaon beam

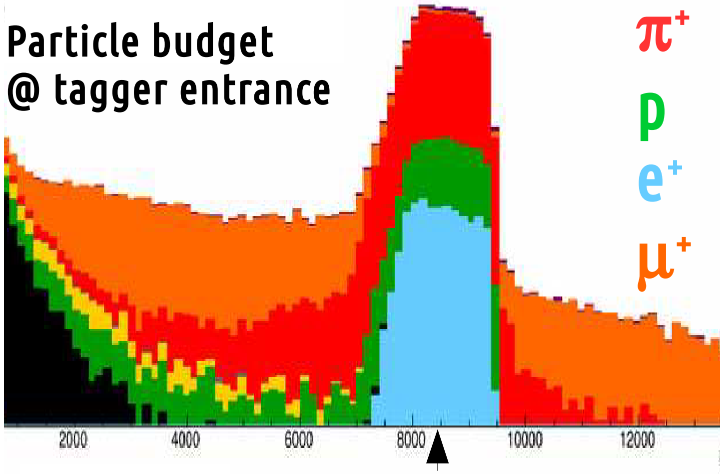
K^+ @ tagger entrance

exit



1 m radius

Particle budget @ tagger entrance



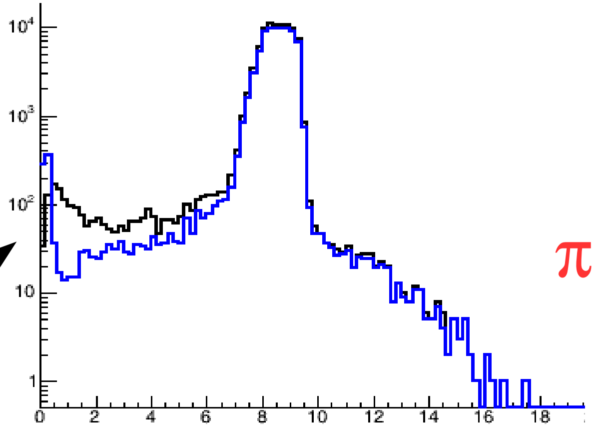
p (MeV/c)

Momentum bite
(8.5 ± 10%) GeV/c

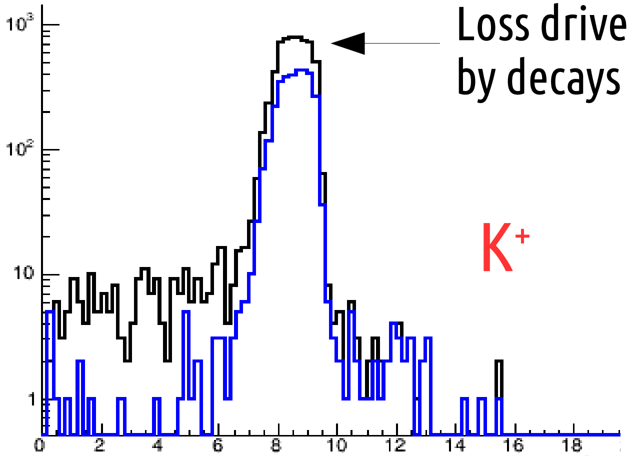
Spectra @

tagger entrance
tagger exit

Low energy
high angle π



p (GeV/c)

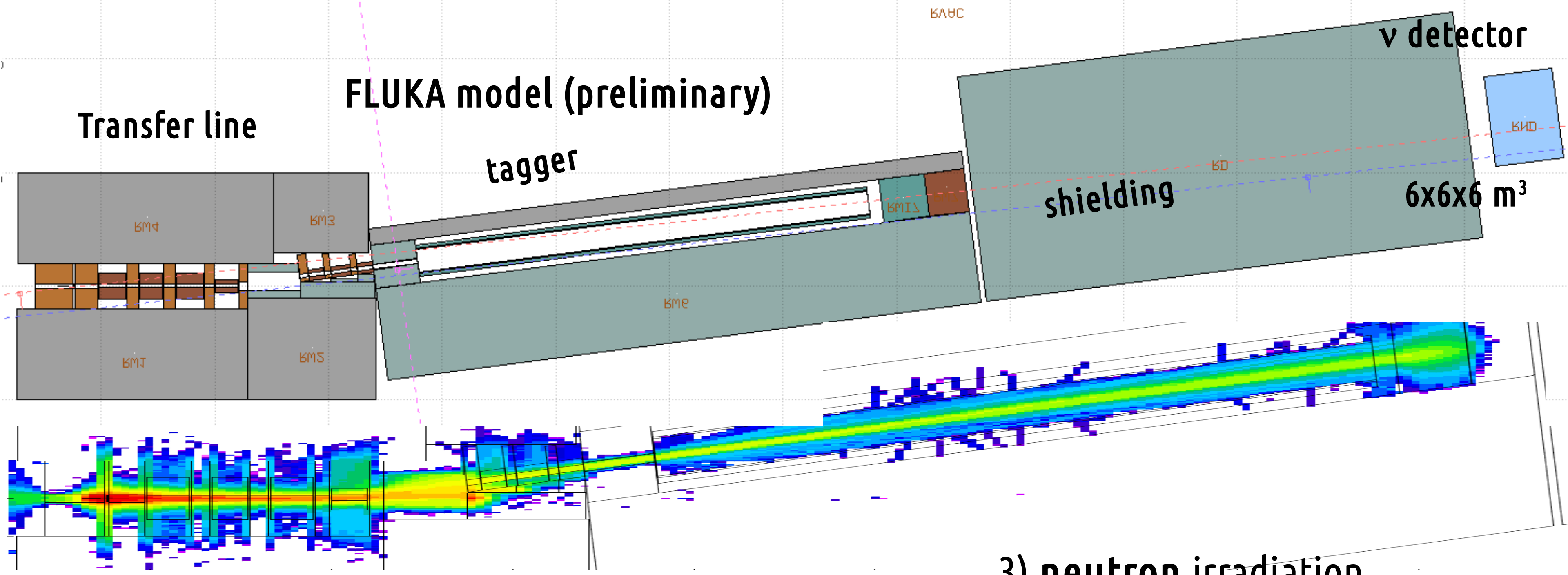


Loss driven
by decays

p (GeV/c)

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

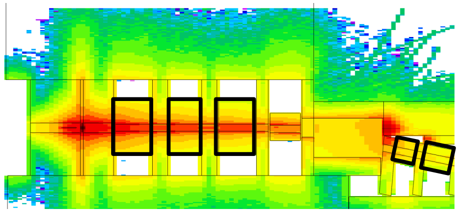
tagger

shielding

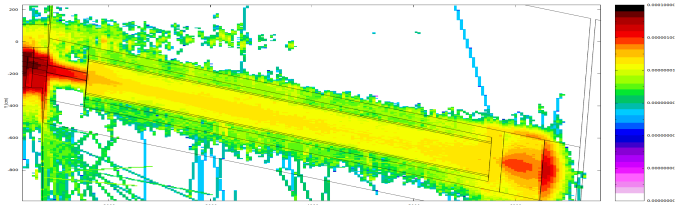
ν detector

6x6x6 m^3

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



3) **neutron** irradiation

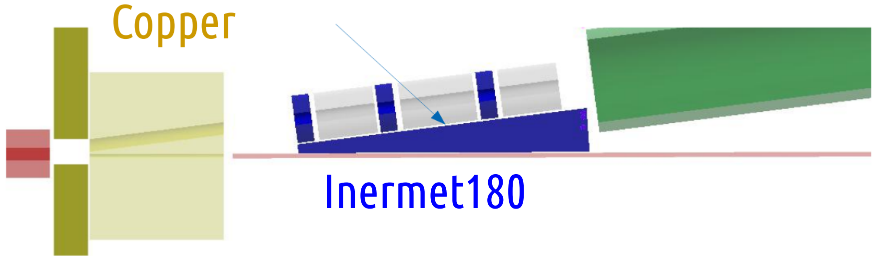


This is an item where the expertise of CERN A&T has been (and will be) extremely useful

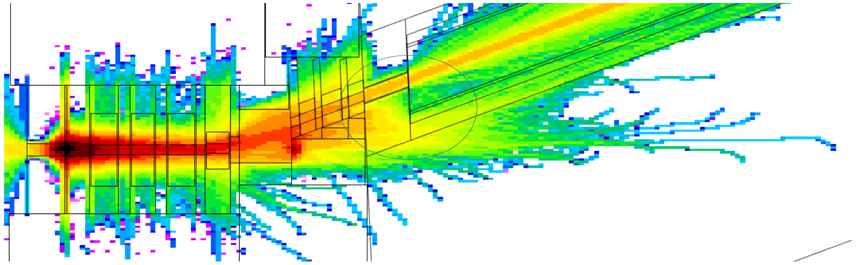
Beamline shielding tuning studies

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

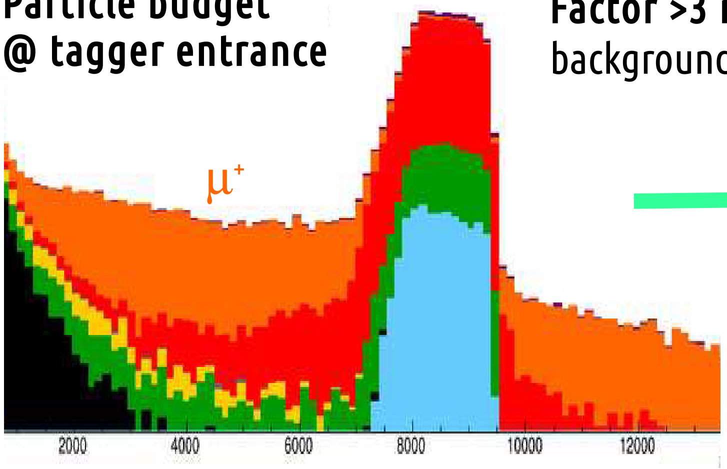
G4Beamline



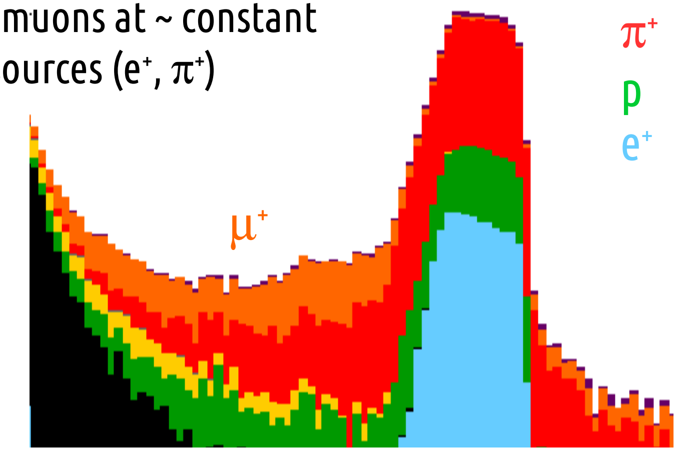
FLUKA (muon energy deposition map)



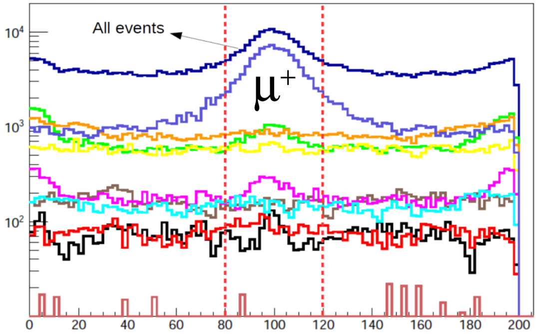
Particle budget @ tagger entrance



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



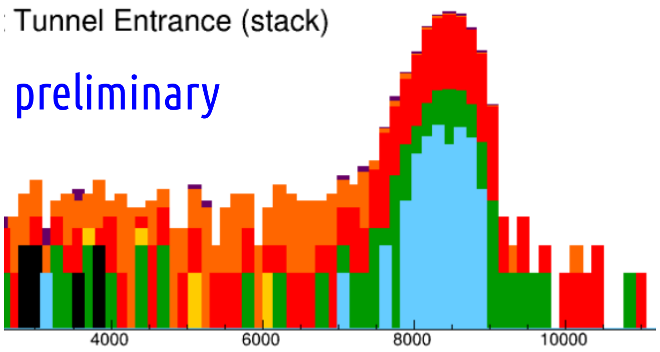
Azimuthal angle



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

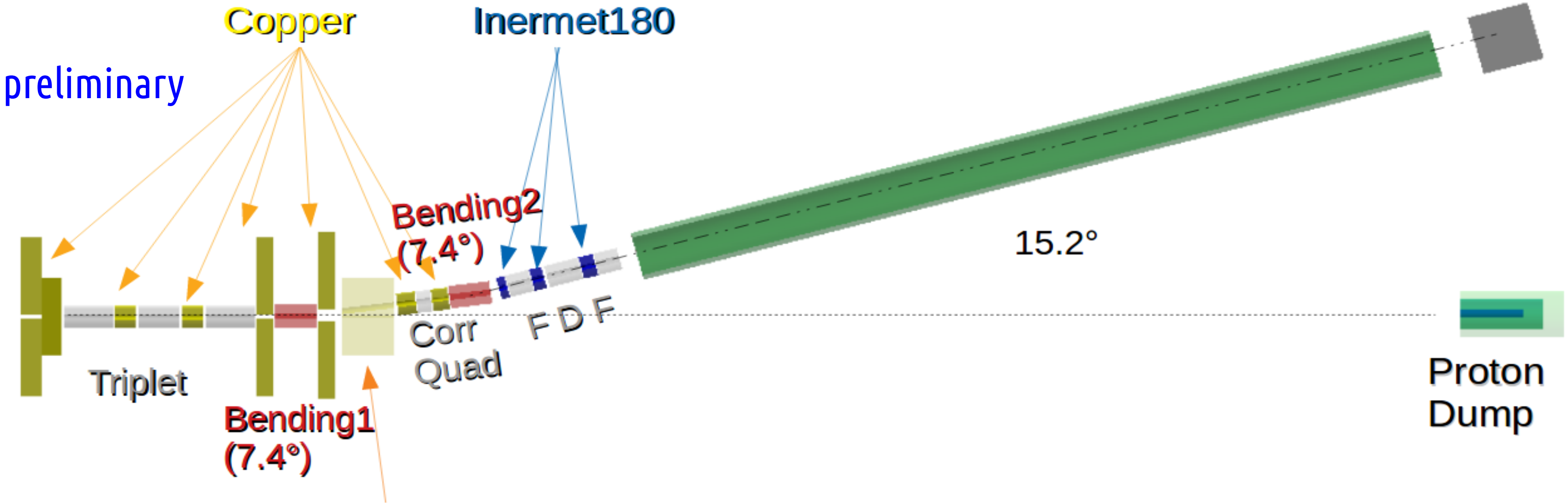
Additional beamline options



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



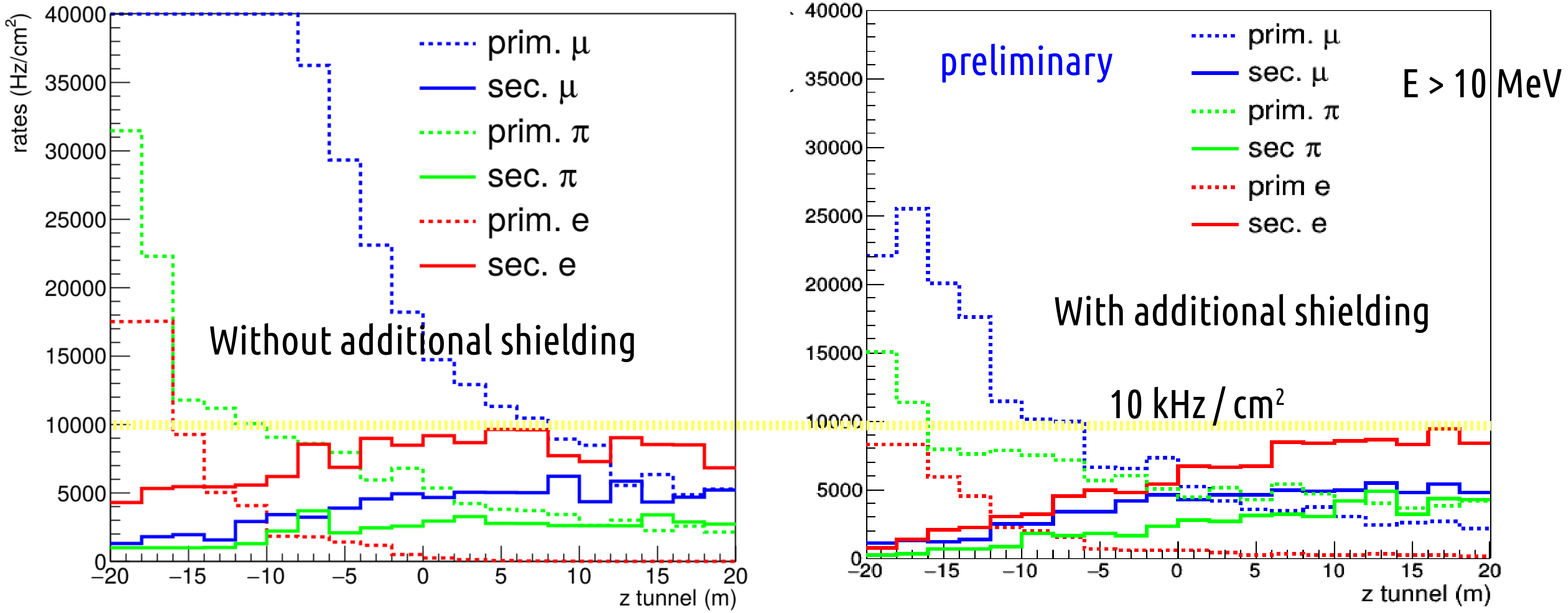
- We are putting all these inputs together
- → pindown the best scheme in terms of physics and technical feasibility

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)



Without additional shielding

preliminary

E > 10 MeV

With additional shielding

10 kHz / cm^2

- 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

K_{e3} positrons reconstruction

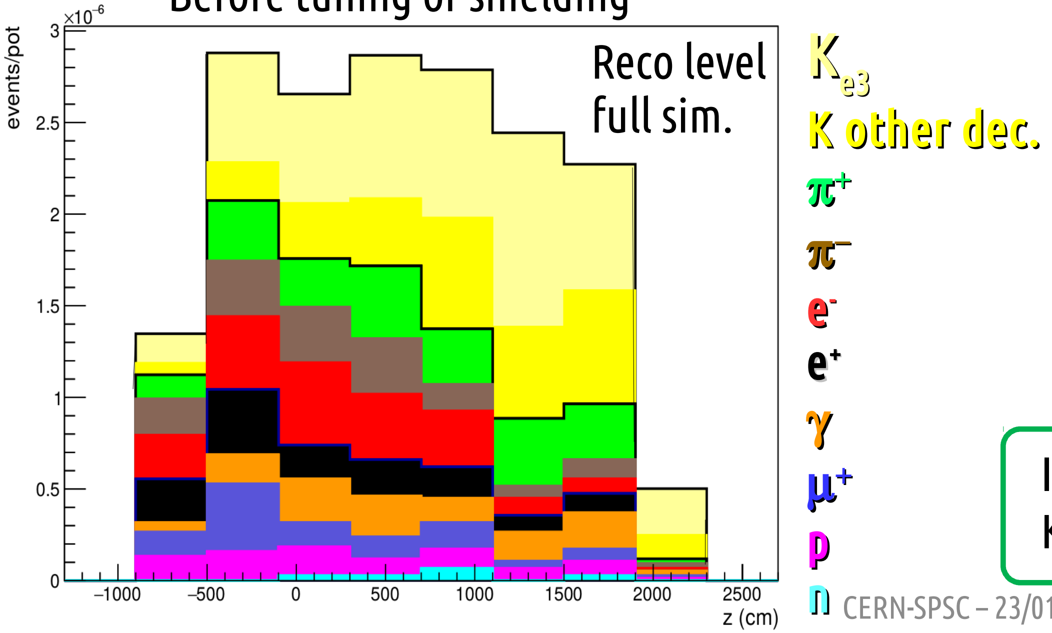
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

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 UCMs 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

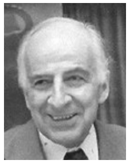


ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

φ cut → 0.46

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

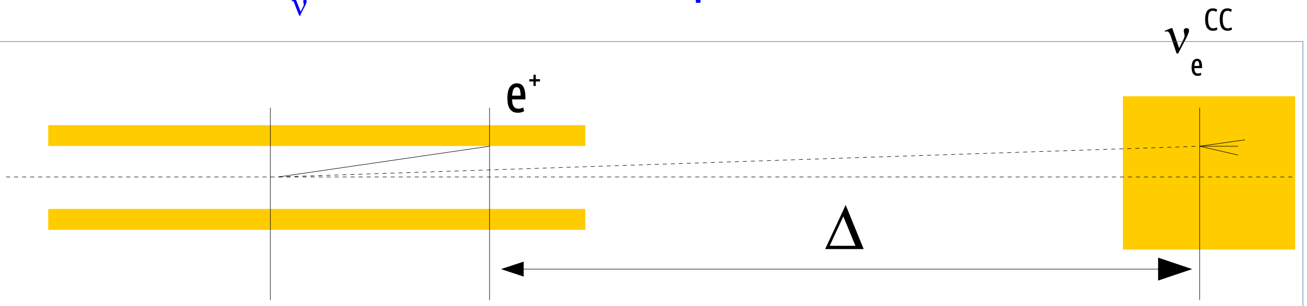
Time tagged neutrino beams ?



- 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)

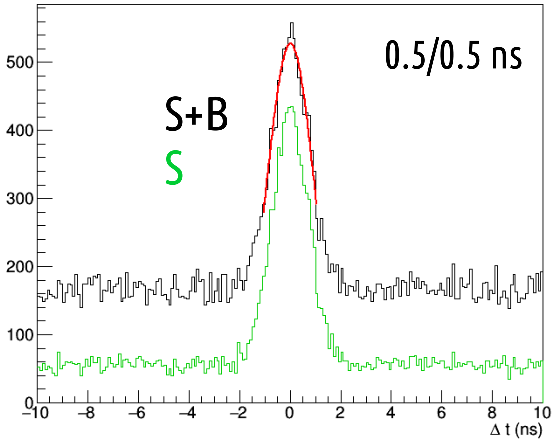
Presently with 2.5e13 pot / 2s slow extraction:

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

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 × 10 → Foresee overburden/cosmic ray tagger
- small K^+ momentum bite small (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 based tracker) we are considering alternative technologies to improve the timing both at the tagger (direct readout of **cherenkov light**, **LYSO** crystals with embedded SiPM) and neutrino detector side (SiPM based readout of **Ar scintillation light**).

The ENUBET tagger

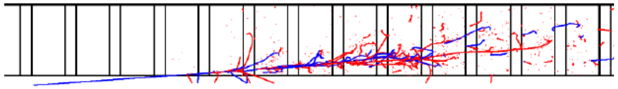
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

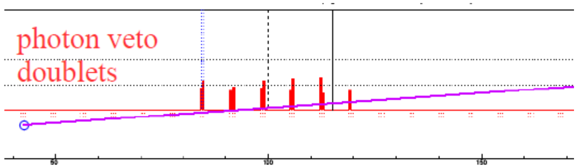


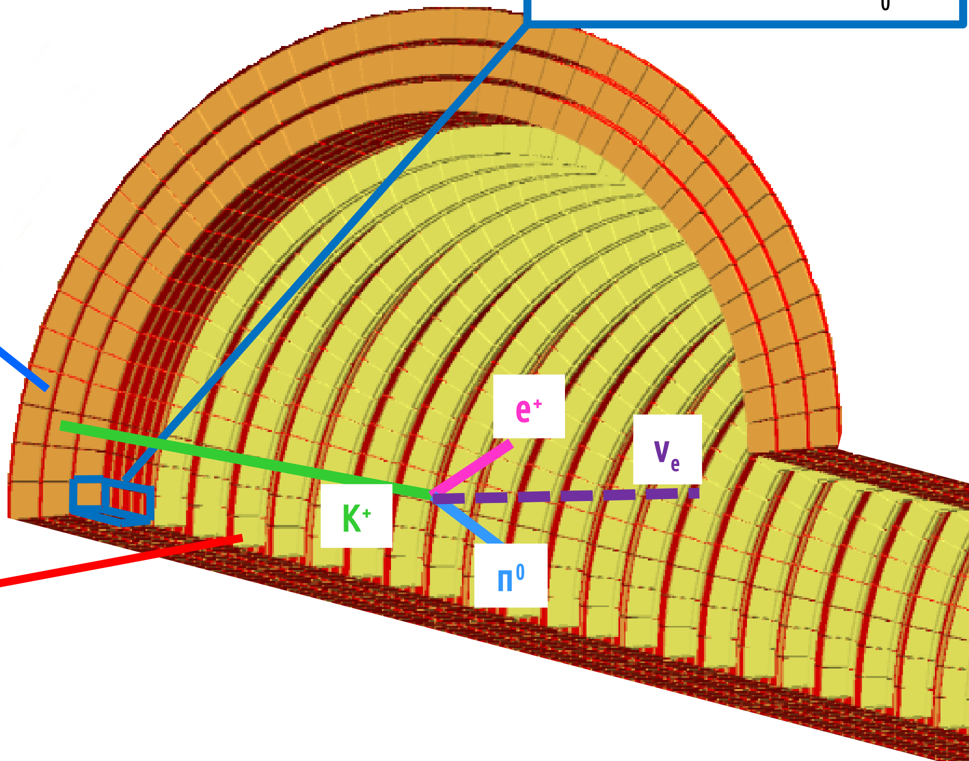
Integrated photon veto

Plastic scintillators

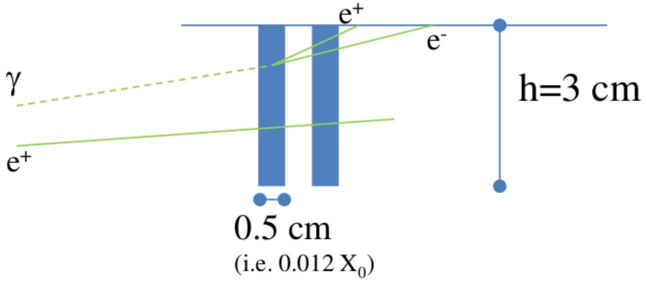
Rings of 3×3 cm² pads

→ π^0 rejection





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

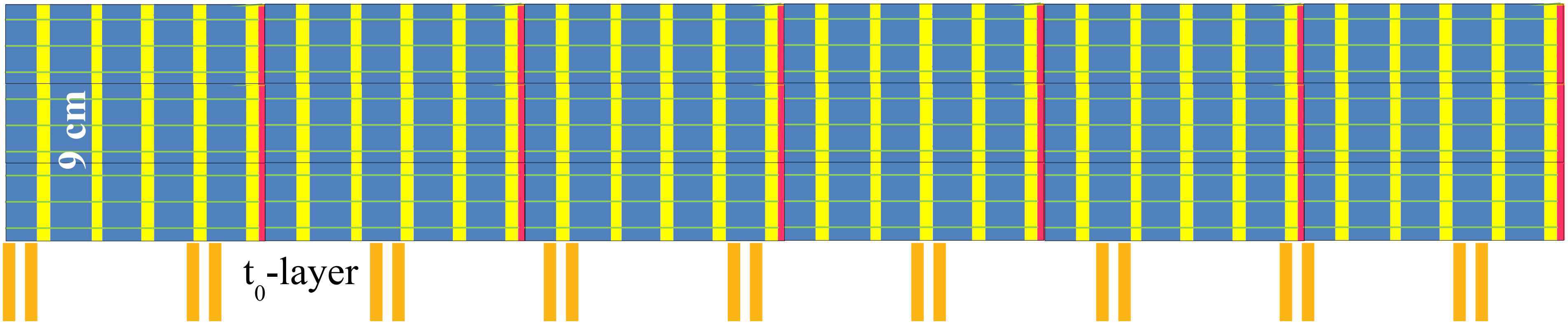


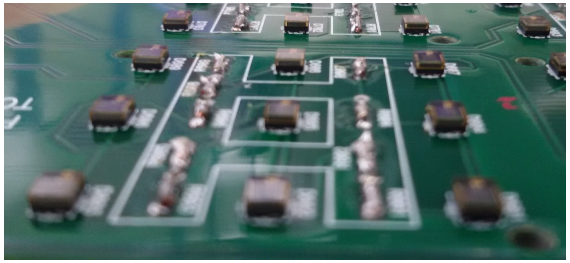
e^+ (signal) topology

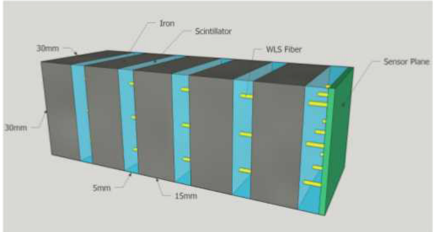
π^0 (background) topology

π^+ (background) topology

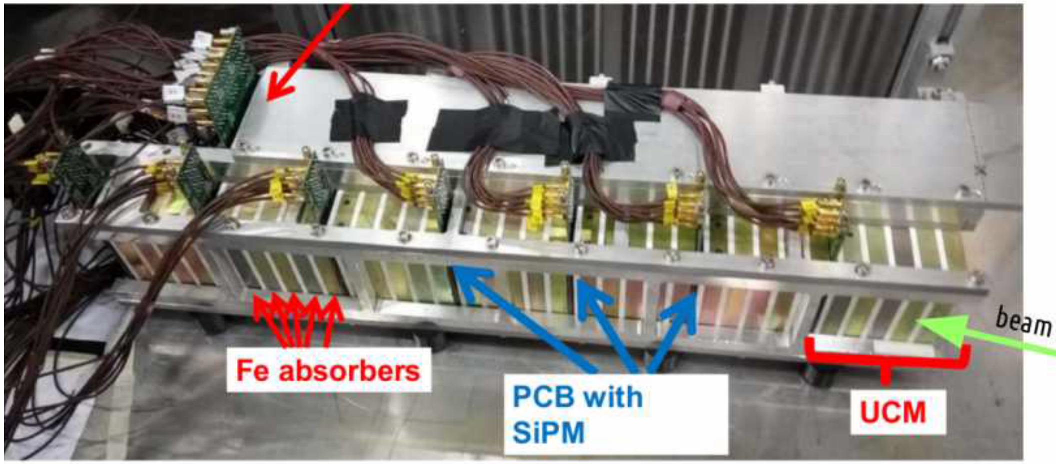
The tagger: shashlik with integrated readout

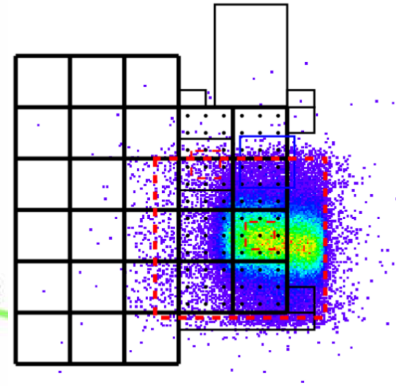






CERN PS test beam Nov 2016



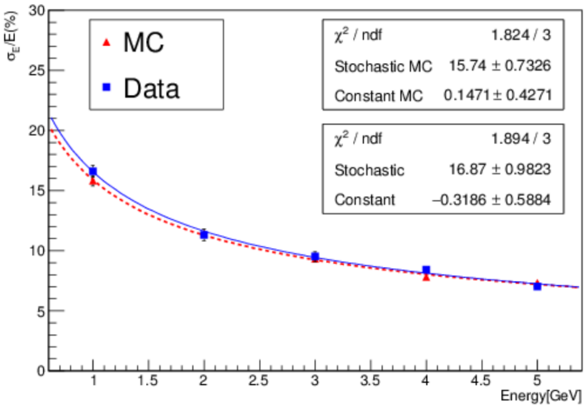


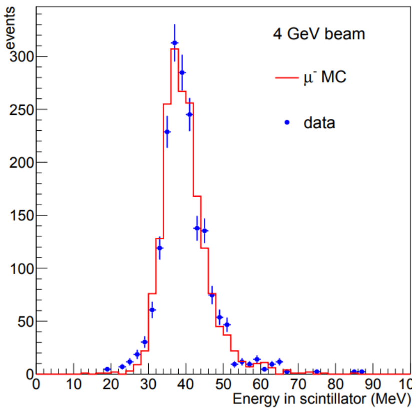
Test beam results with shashlik readout

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

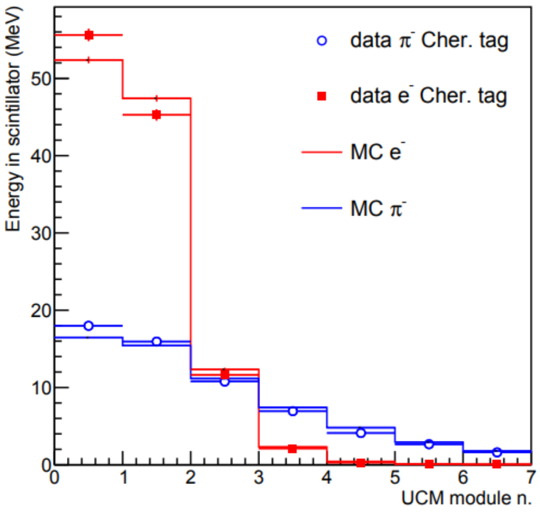
Tested response to MIP, e and π^-

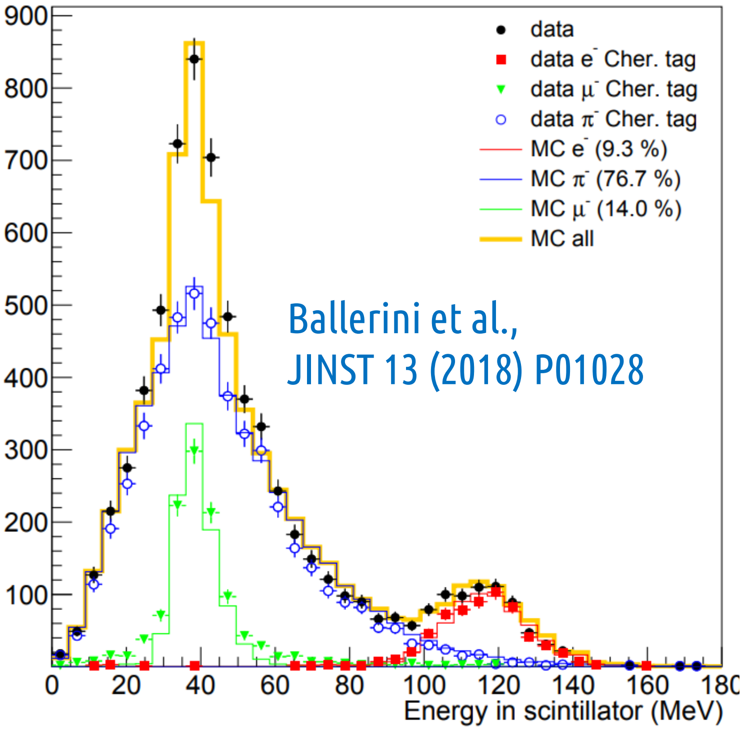
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement





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



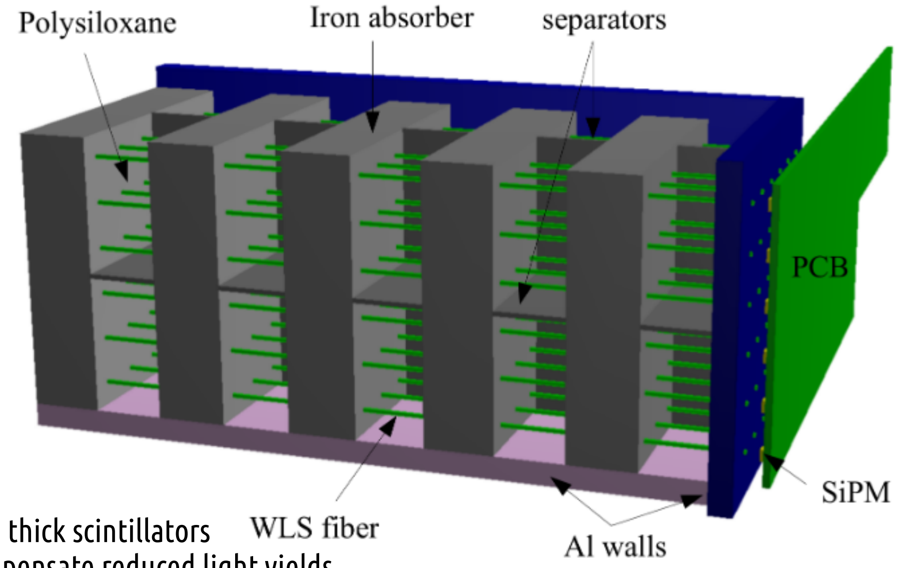


Ballerini et al.,
JINST 13 (2018) P01028

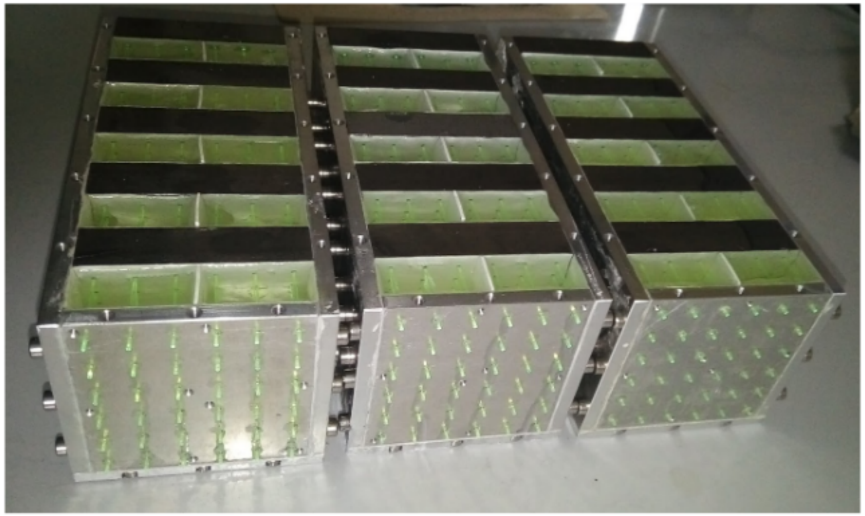
Polysiloxane shashlik prototypes

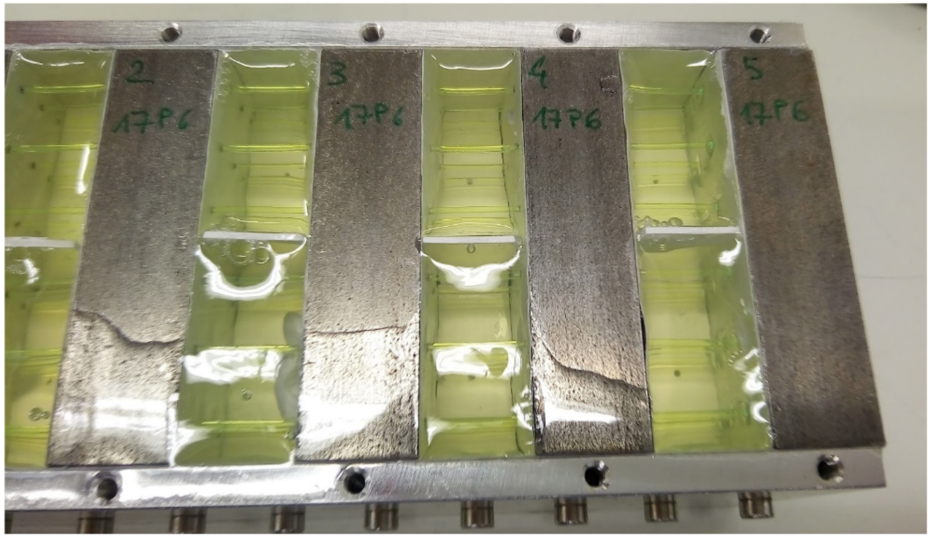
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)

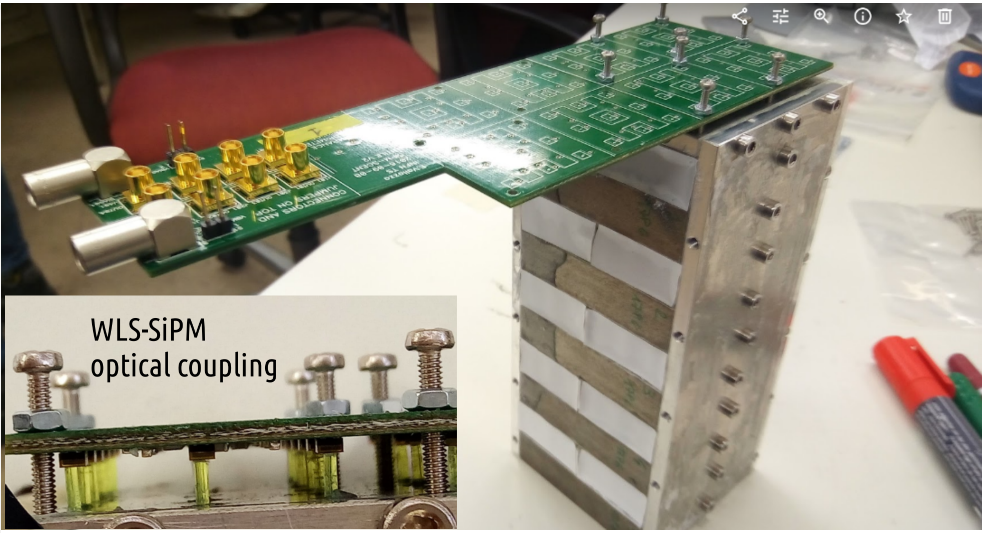
A **13X$_0$ shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)



15 mm thick scintillators
to compensate reduced light yields





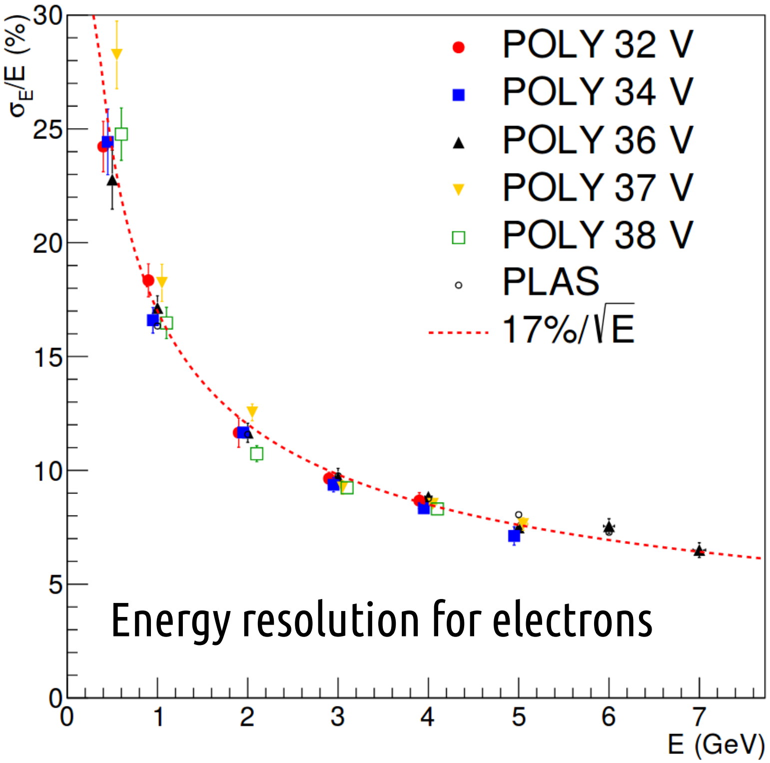


Polysiloxane shashlik prototypes

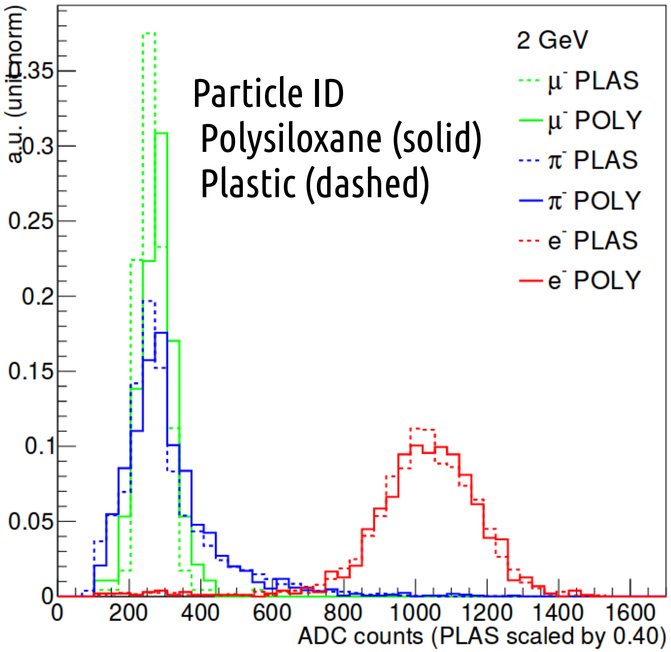
Light yield (normalized to thickness) is ~ 1/3 of plastic scintillator

→ 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



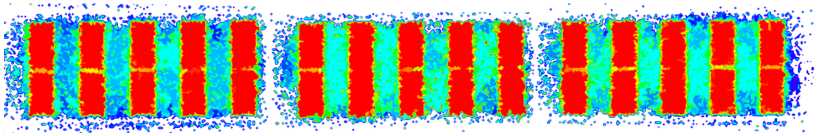
Energy resolution for electrons



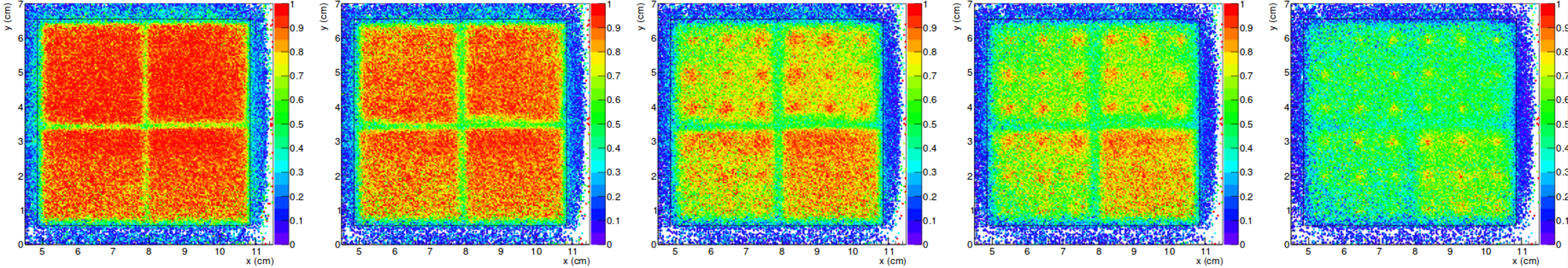
Particle ID

Polysiloxane (solid)

Plastic (dashed)



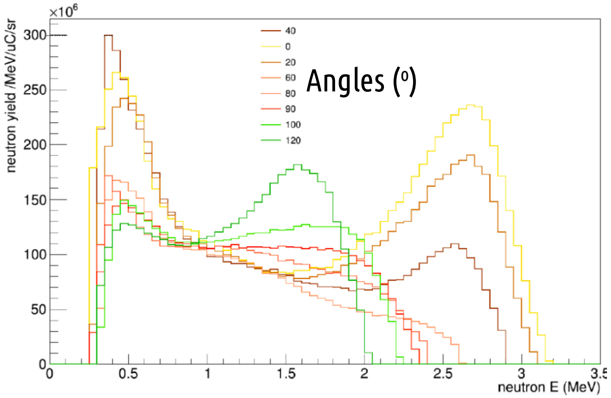
Efficiency maps at increasing thresholds →

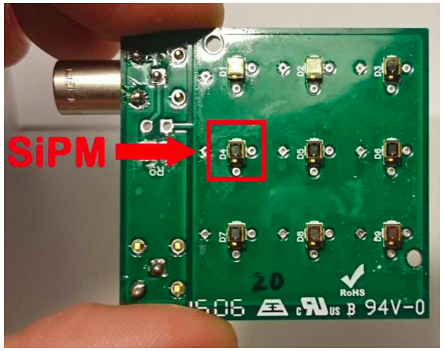


SiPM irradiation measurements at INFN-LNL

- 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)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

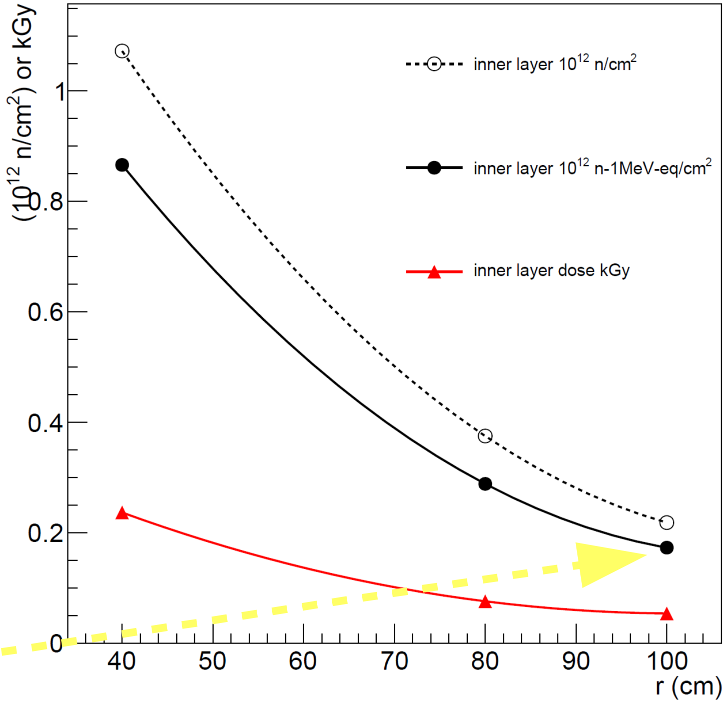
n spectra (from previous works at the same facility)

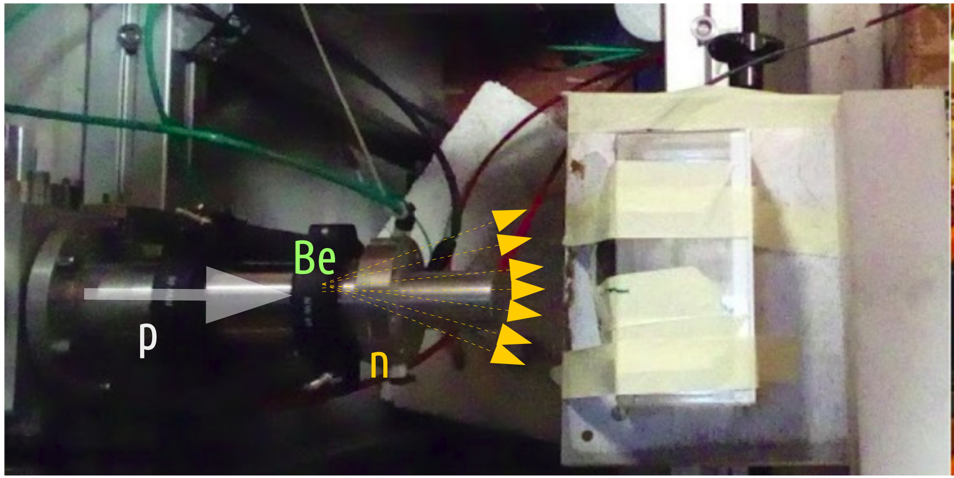


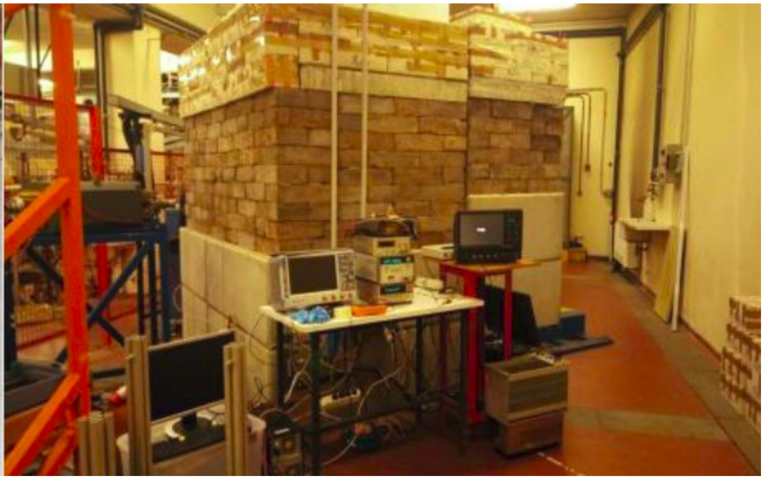


→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm^{2}** 1 MeV-eq (max non ionizing dose for 10^{4} ν_e^{CC} at a 500 t ν detector at r = 1 m)

Expected n doses from K decays (FLUKA)



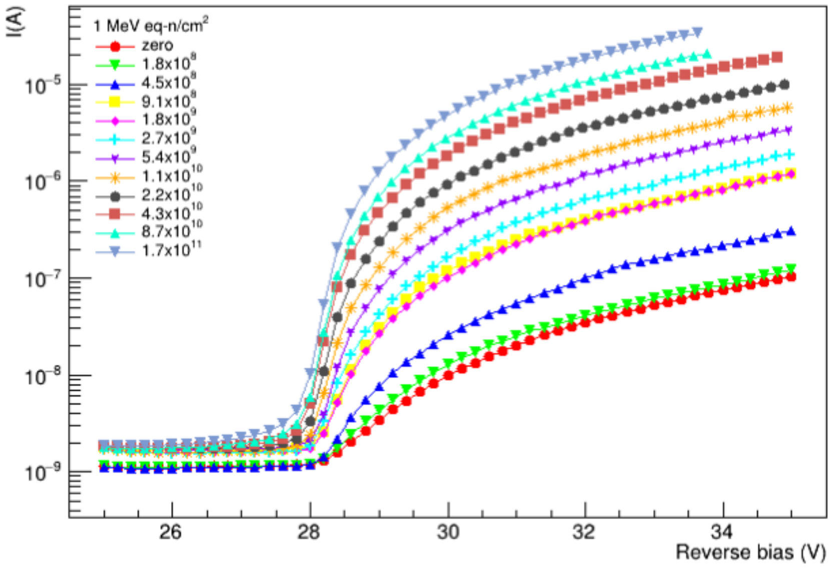




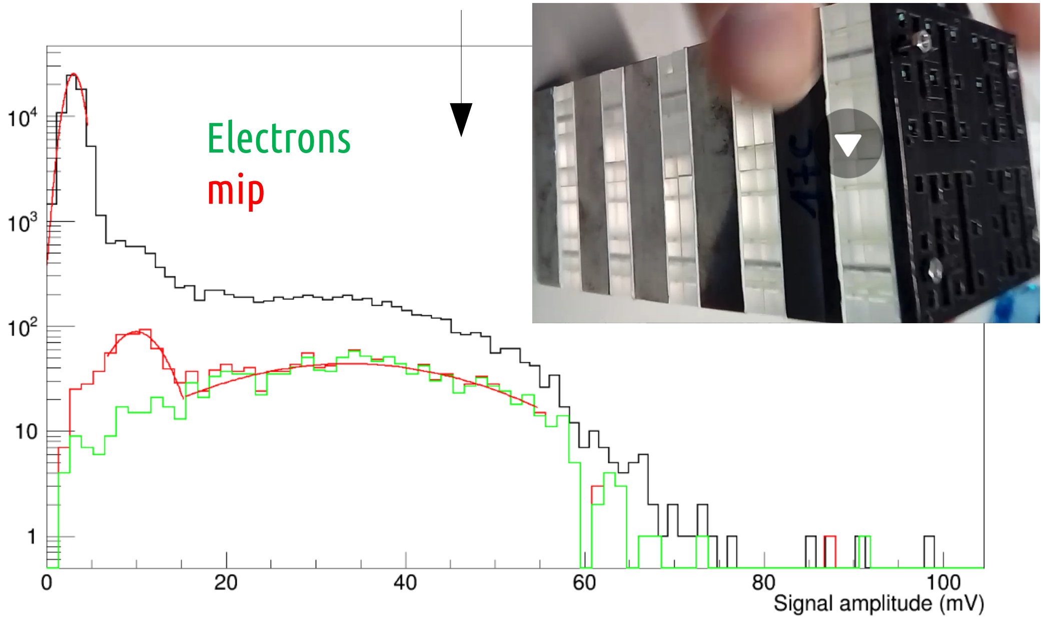
SiPM irradiation measurements at CERN

Dark current vs bias at increasing n fluences

FBK HD-RGB 1x1mm^2 12μm cell size



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



Submitted to Journal

Irradiation and performance of RGB-HD Silicon Photomultipliers for calorimetric applications

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

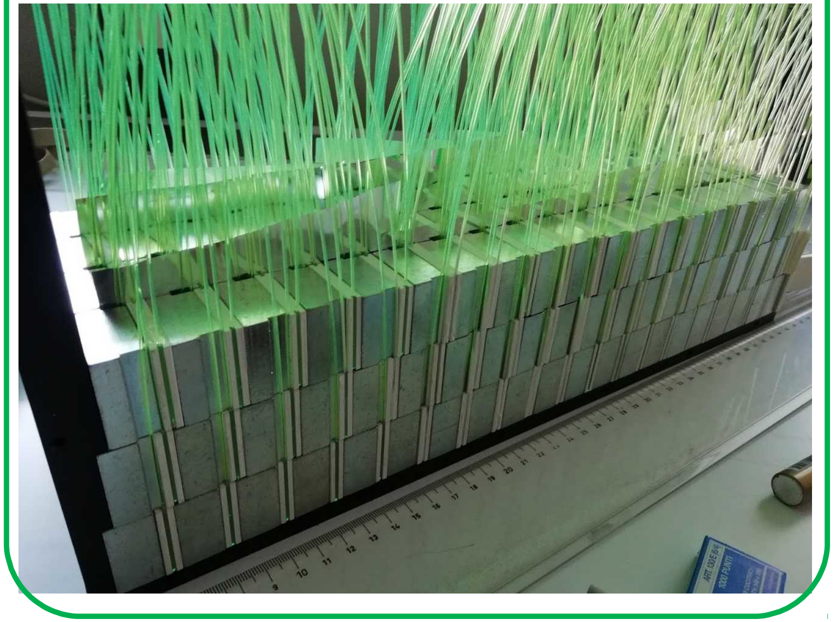
(FBK-HD-RB Advansid)

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

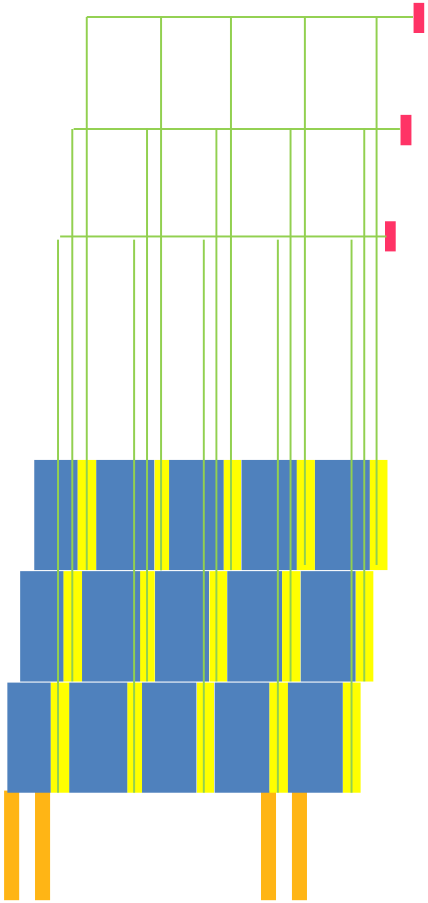
The tagger: lateral readout option

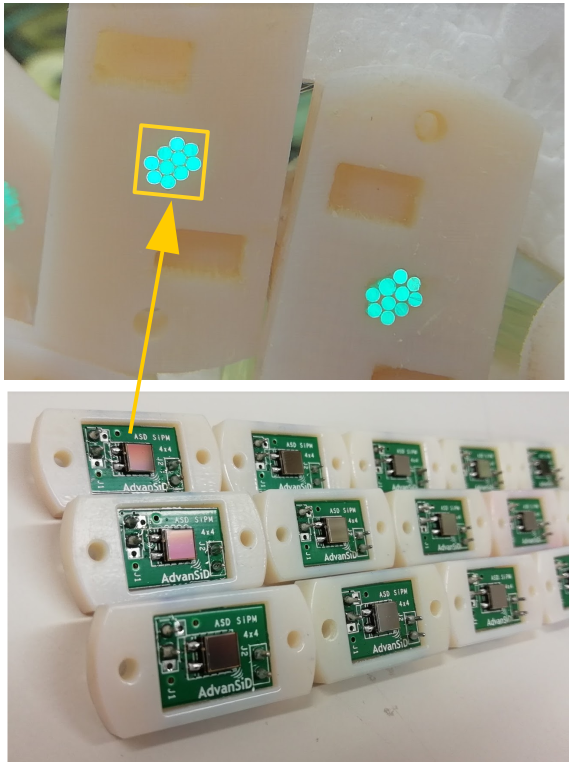
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM).
SiPM are not immersed anymore in the hadronic shower → less compact but ..
much **reduced neutron damage** (larger safety margins), better **accessibility**, possibility of replacement. Better reproducibility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

Sampling calorimeter with
lateral WLS light collection



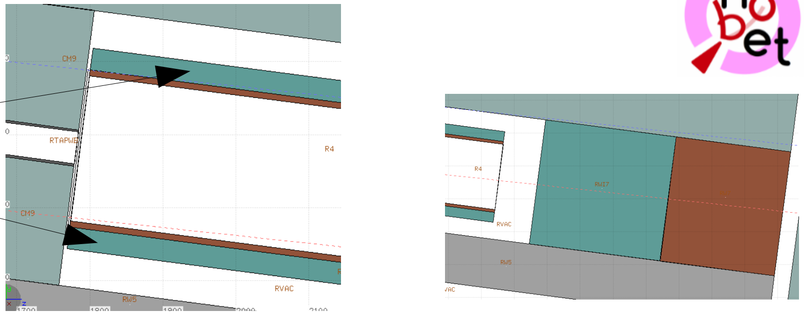
May 2018, CERN-PS test beam



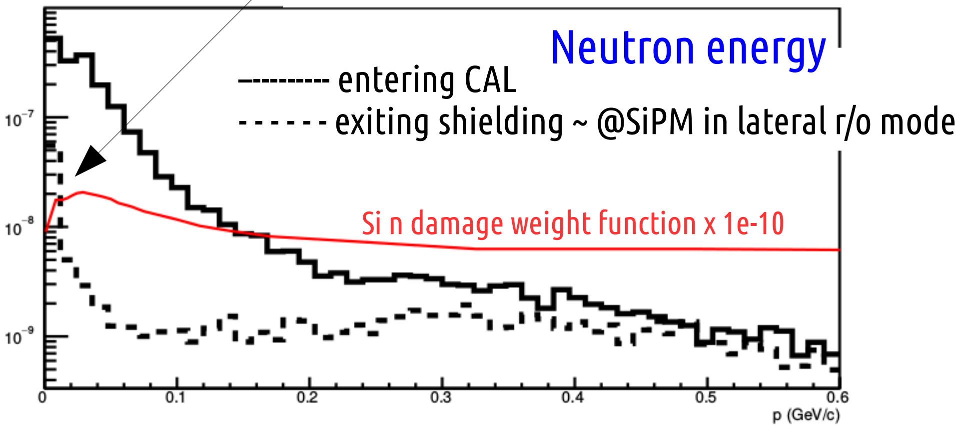


Large SiPM for 10 WLS
4x4 mm^2

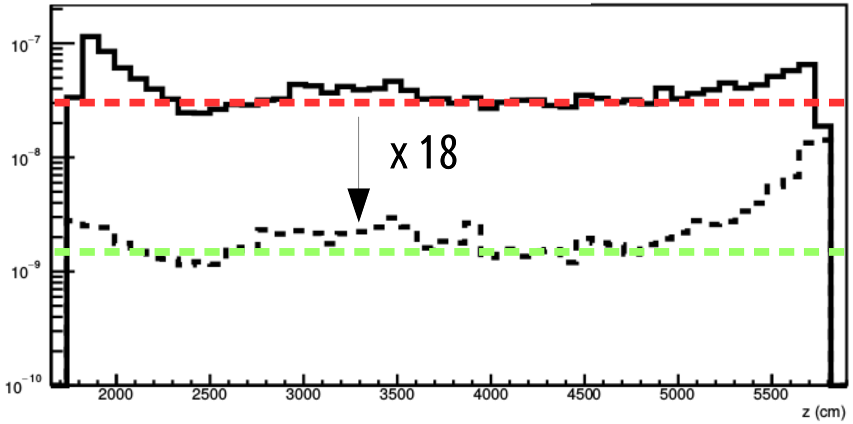
Achievable n reduction in the lateral readout scheme



- 30 cm of polyethylene between CAL and SiPM
- FLUKA full simulation. **400 GeV p**.
- Beam backgrounds included → tuning of materials in progress
- Very good suppression especially below 100 MeV.
- **Factor ~18** reduction averaging over spectrum.
- Further Improvement at low-E with **borated-polyethylene** (in progress)

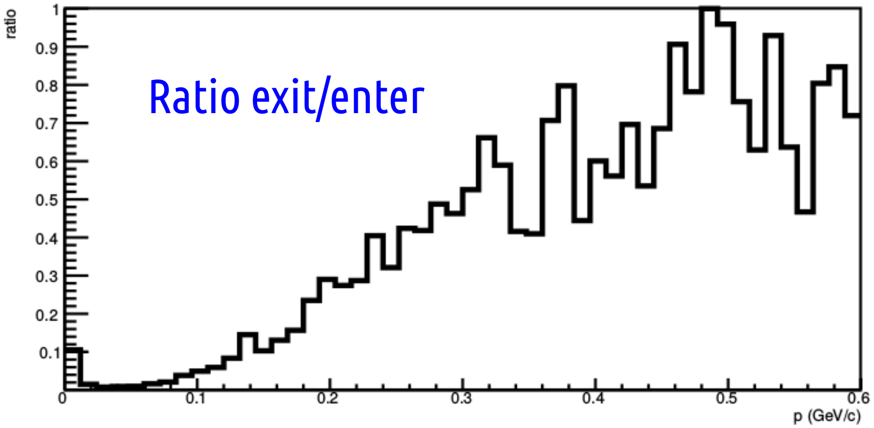


n longitudinal position along the tunnel

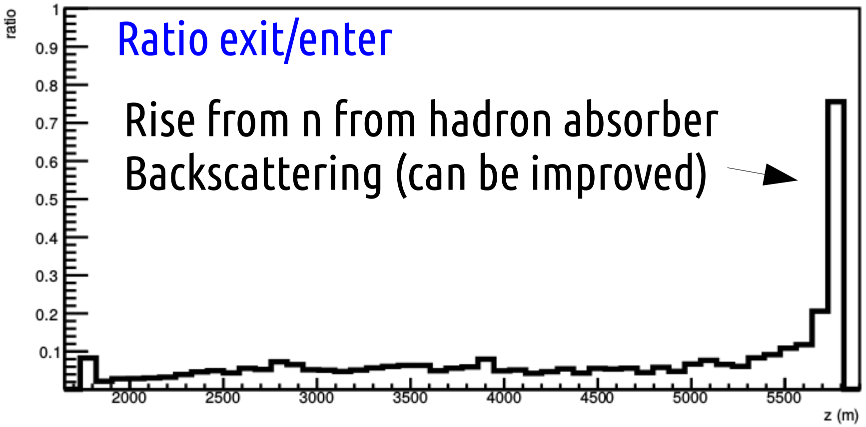


preliminary

TAGGER EXIT/ENTR. pot 1.98e+06

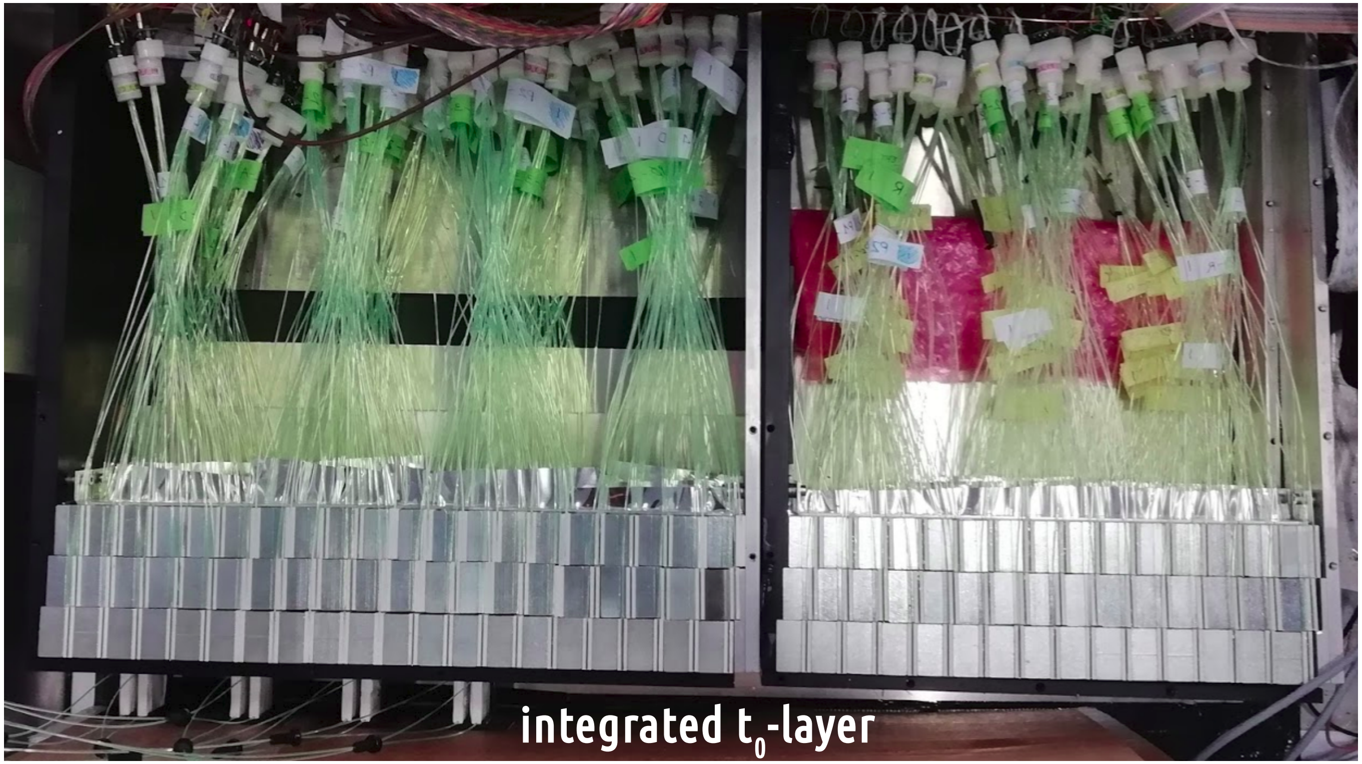


TAGGER EXIT/ENTR. pot 1.98e+06

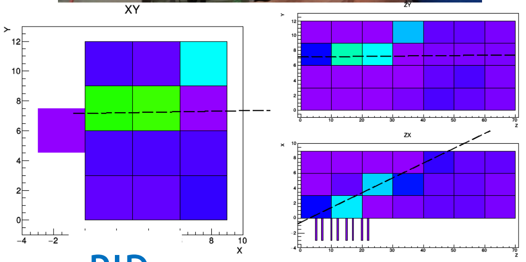


The Tagger – Detector R&D

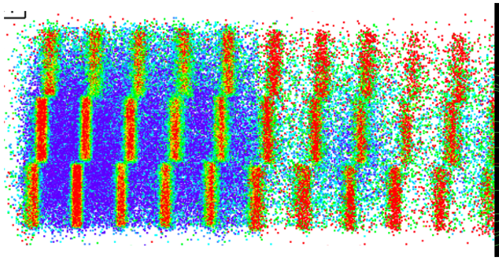
September 2018 CERN-PS: a module with hadronic cal. for pion containment and **integrated t_0-layer**



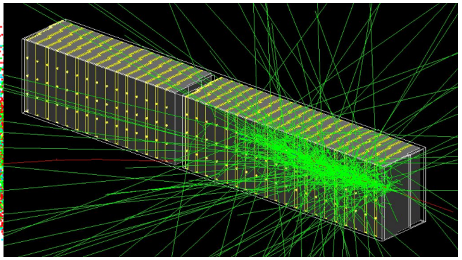
- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match. In progress.



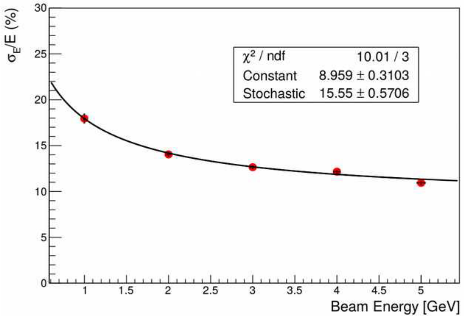
Efficiency maps



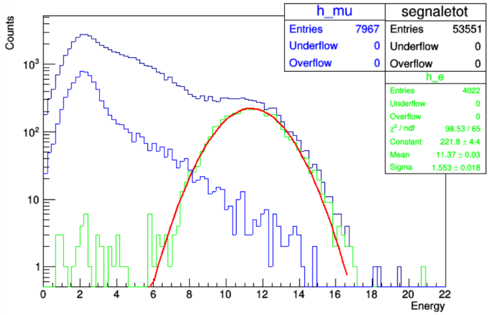
Simulation



Resolution



PID



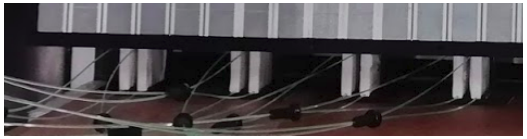
The photon veto – test beam

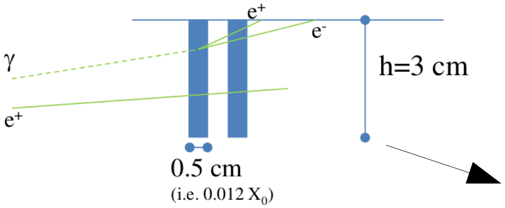
@ CERN-PS T9 line 2016-2018

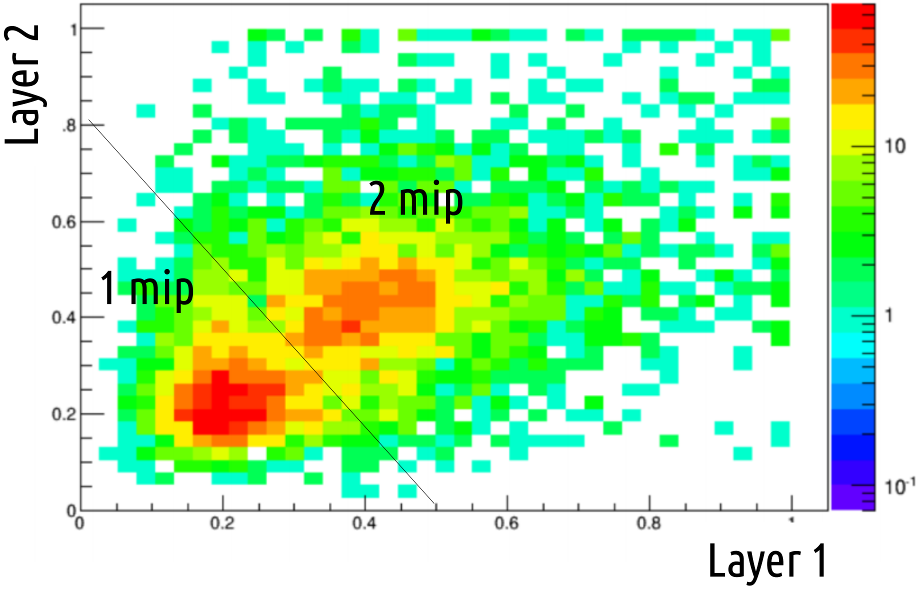
- **γ / e^+ discrimination + timing**

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

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

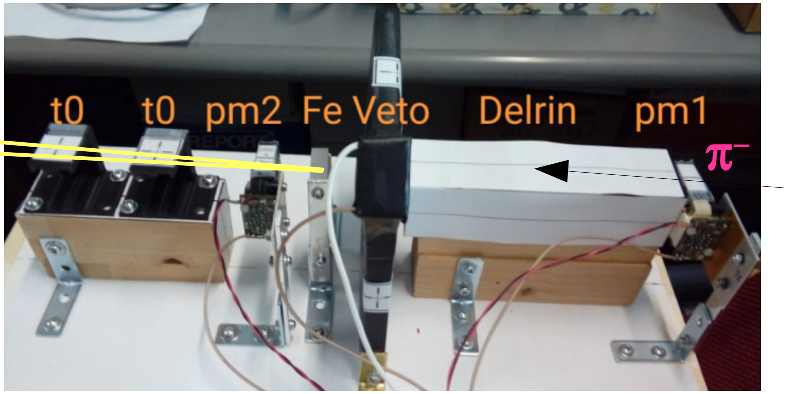


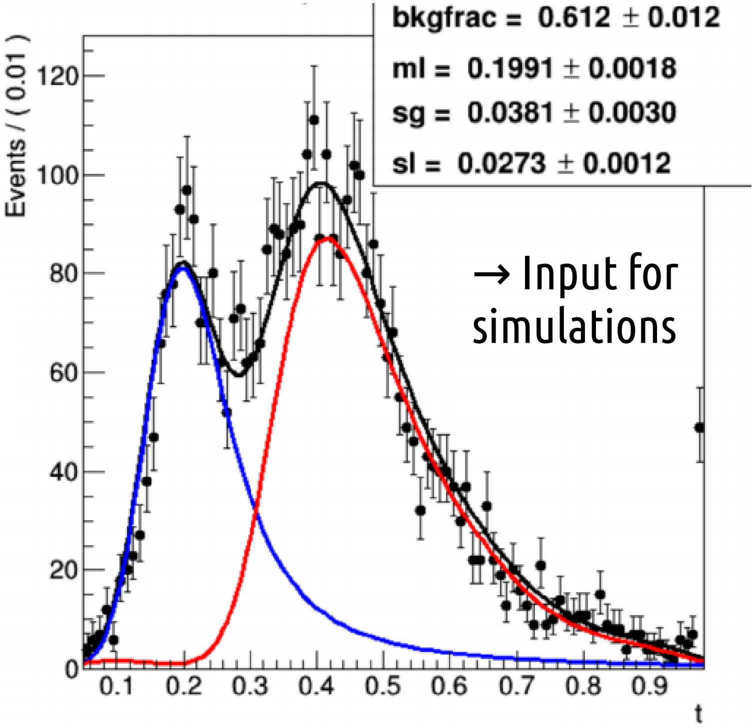




charge exchange: $\pi^- p \rightarrow n\, \pi^0\, (\rightarrow \gamma\gamma)$

Trigger: PM1 + VETO +PM2





→ Input for simulations

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% at 1 GeV ➞ 8% at 3 GeV)

2018 has been a special year, we have

- provided the first **end-to-end simulation of the beamline** (Jul)
- Proved the feasibility of a **purely static focusing system** ($10^6\ \nu_\mu^{CC}$, $10^4\ \nu_e^{CC}$ /y/500 t)
- **full simulation of e^+ reconstruction**: **single particle level** monitoring. S/N ~ 0.5
- Tested with data the **"burst" slow extraction** scheme at the CERN-SPS (Aug-Nov)
- **completed the test beams** campaing (Sep) before LS2
  - → identified best options for instrumentation (**shashlik** and **lateral** readout)
- Strengthened the **physics case**:
  - → slow extraction + "**narrow band off-axis technique**"

The ENUBET technique is **very promising** and the results we got in the **last twelve months exceeded our expectations**

Next steps

- In **2019** we need to:
  - **decide on the light readout technology** for the final demonstrator (shashlik versus "lateral readout")
  - **improve the design of the beamline** to reduce beam halo contamination (current e^+ S/N can be significantly improved)
  - re-optimise the **tunnel radius** to increase geometrical acceptance

- **Systematic assessment on predicted neutrino fluxes**
- Develop new ideas to **enhance precision also on ν_μ**
  - from $K_{\mu 2}$ with μ id in the tagger
  - from π : counting μ from π in hadron-dump (could be feasible with a 2s extraction).
- **CDR** at the end of the project (2021): **physics** and **costing**
- Build a **demonstrator prototype** of the tagger (2021)

A very special thank to CERN

- First 2 years of the project: collaboration with the CERN groups for
  - **machine studies performed at the SPS**
  - **East Area beamline** for the characterization of the prototypes

  → **prominent contribution for the success of ENUBET.**
- **Requests for 2019-2021**
  - support and consulting from CERN accelerator experts in the design of the beamline in collaboration with personnel employed 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.
    - For 2021, we request (2 weeks + 3 weeks)

Padova June 2016

CERN Nov 2016

CERN Aug 2017

CERN Oct 2017

INFN-LNL Jun 2017

THANKS!

CERN May 2018

CERN Sep 2018

Milan Oct 2017

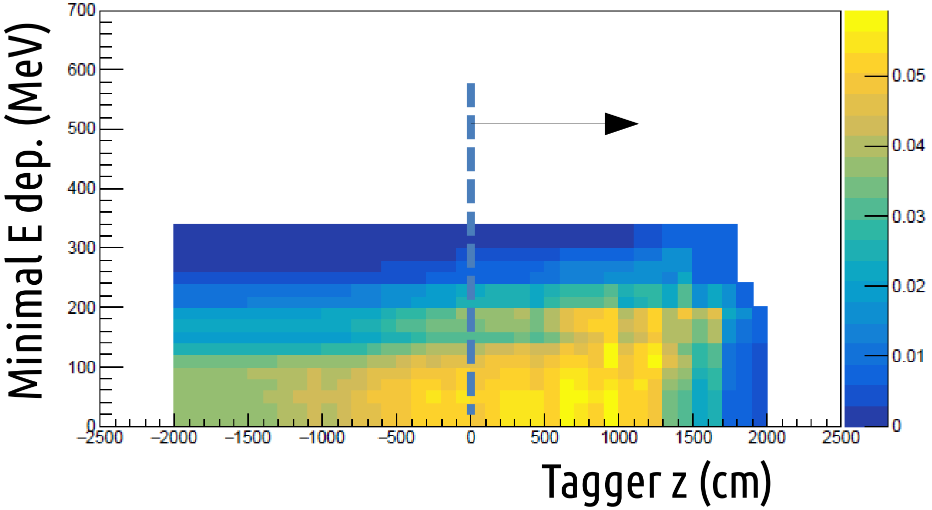
Positron ID from K decay

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/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


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**

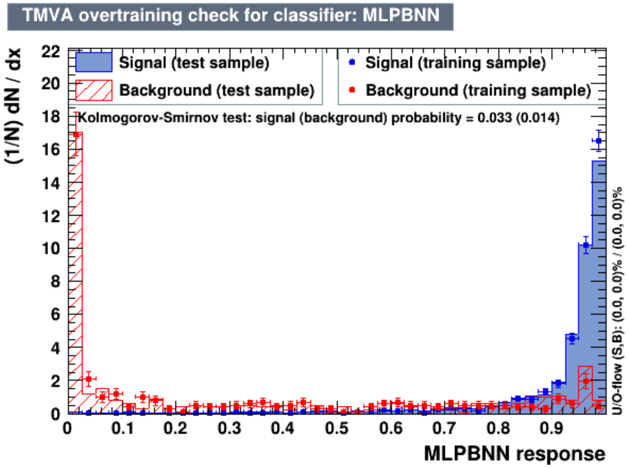
Instrumenting half of the decay tunnel:
K_{e3} e^+ at single particle level with a S/N = 0.46

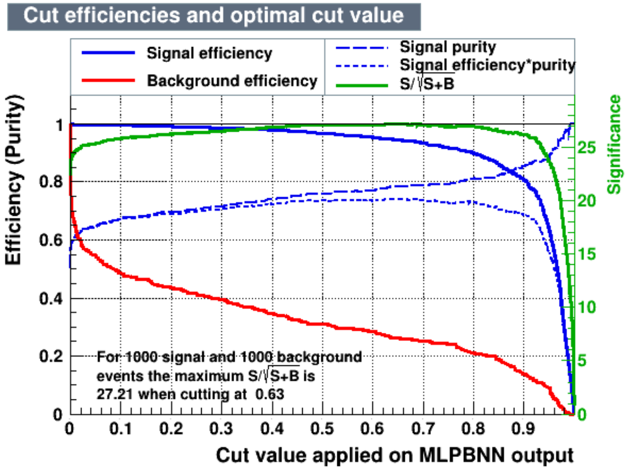
The Tagger – positron ID from K decay

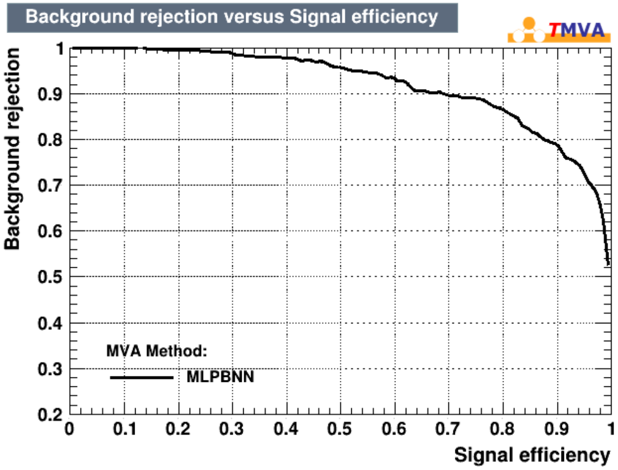
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV ▭ link neighboring modules with time (1ns) and position requirements

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

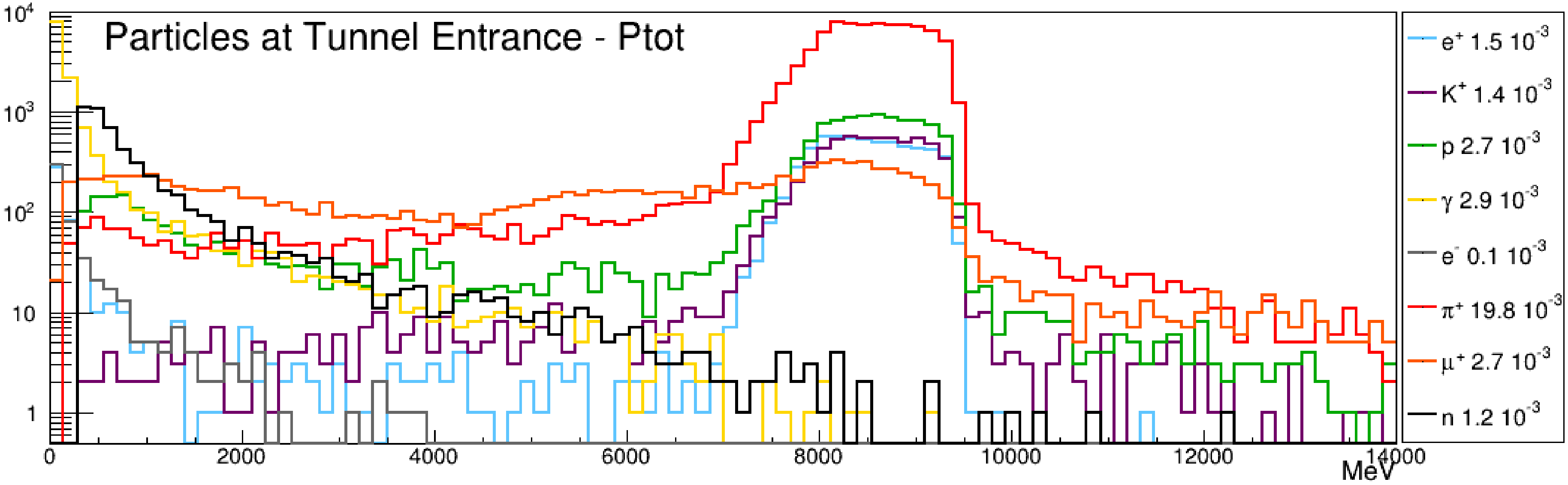
Response to signal and background

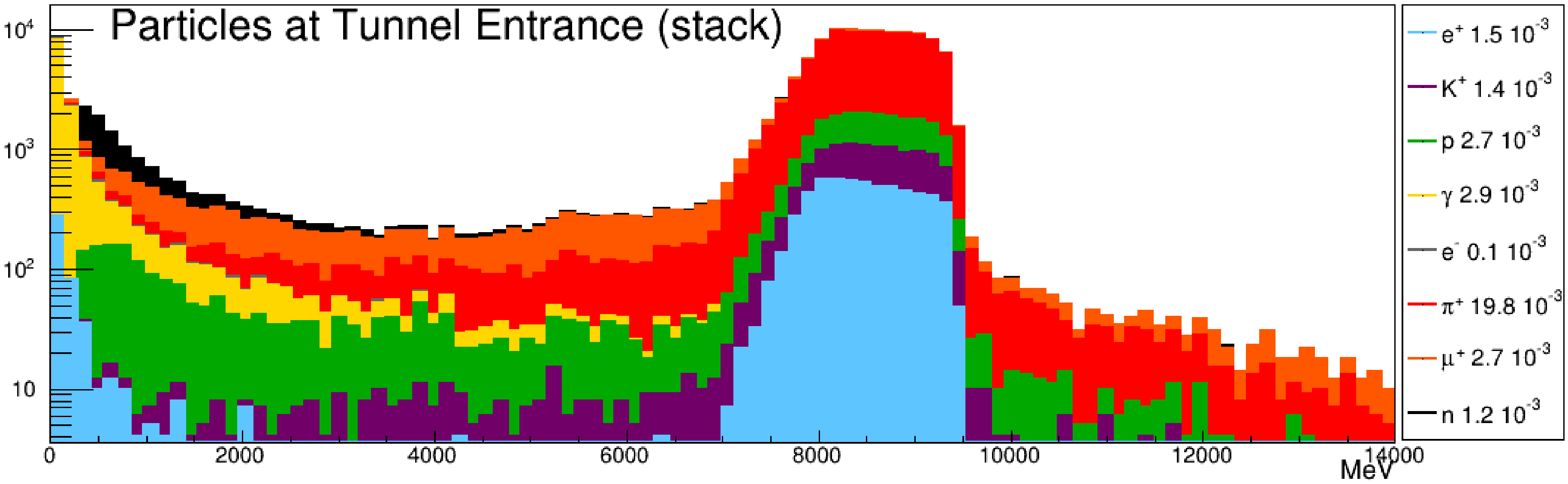

TMVA overtraining check for classifier: MLPBNN


Cut efficiencies and optimal cut value


Background rejection versus Signal efficiency

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
10^4
10^3
10^2
10
1
0
2000
4000
6000
8000
10000
12000
14000
MeV
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}


Particles at Tunnel Entrance (stack)
10^4
10^3
10^2
10
0
2000
4000
6000
8000
10000
12000
14000
MeV
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}