Enhanced NeUtrino BEams from kaon Tagging

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NuFact 20|21

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On behalf of the
ENUBET Collaboration

The ENUBET project: a monitored neutrino beam

- ENUBET is a **ERC Consolidator Grant.** Since April 2019, it's also a **CERN Neutrino Platform experiment: NP06/ENUBET** and part of Physics Beyond Colliders. Go visit our website! https://www.pd.infn.it/enubet

- **The ENUBET Collaboration:** 60 physicists, 13 institutions

- **The goal**: Demonstrate the technical feasibility and physics performance of a **neutrino beam** where **lepton production at large angle is monitored at single particle level** → **MONITORED Neutrino Beams**

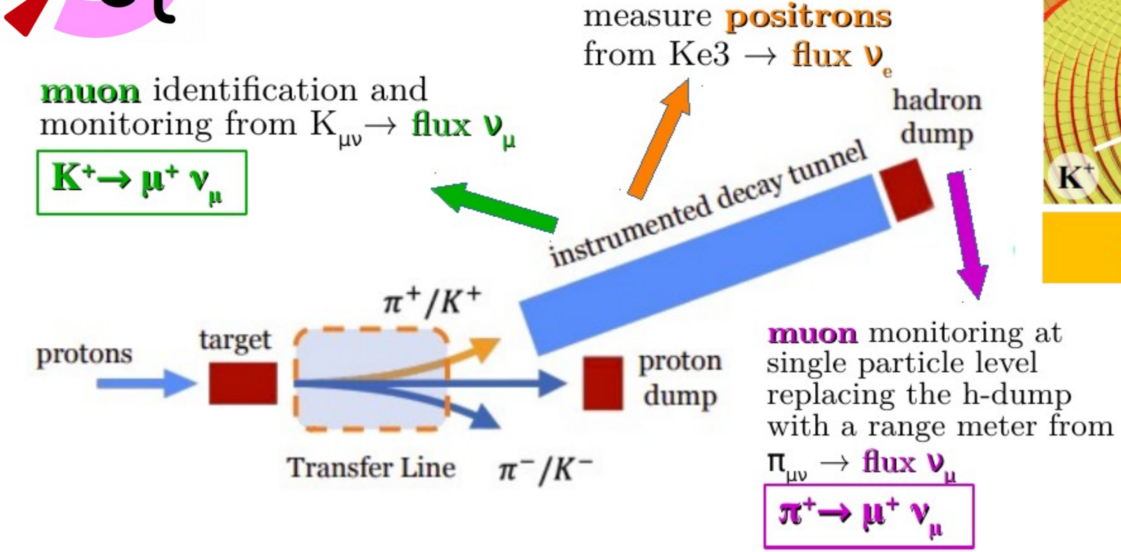
The Project

- **Why?**
  - Systematics for cross section measurements:

    The uncertainty on the neutrino flux is currently the main source
    + Reconstruction of the neutrino energy, biased by the inaccurate reconstruction of the final state particles.
  - Need high-precision determination of ν_e and ν_μ x-sec at the energy of interest for DUNE and HyperK to reduce substantially the systematics of long-baseline experiments
    → Increase the sensitivity to oscillation parameters, in particular, the CP violating phase δ

- **How?** Conventional facility where we monitor the decays in which neutrinos are produced event-by-event
  → “By-pass” the uncertainties from hadro-production, beamline effciency, POT counting
  → Reduce the uncertainty on the flux of ν_e, and, possibly of ν_μ, below 1%

The Project



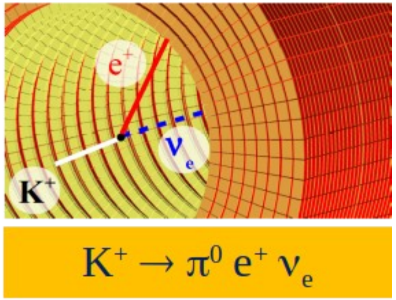
muon identification and monitoring from $K_{\mu\nu} \rightarrow$ flux ν_μ

$K^+ \rightarrow \mu^+ \nu_\mu$

measure **positrons** from Ke3 → flux ν_e

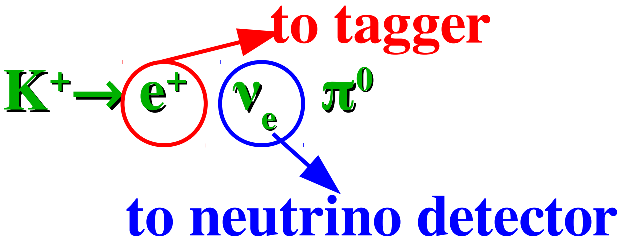
muon monitoring at single particle level replacing the h-dump with a range meter from $\pi_{\mu\nu} \rightarrow$ flux ν_μ

$\pi^+ \rightarrow \mu^+ \nu_\mu$



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

K_{e3} decays:



Fully instrumented decay region →

ν_e flux prediction = e^+ counting

ENUBET is a very narrow band beam (5-10% momentum bite)

→ Strong correlation between the energy of each ν and its interaction vertex due to kinematics.

“Narrow band off axis technique” method → Reconstruction of the energy in the neutrino detector without relying on final state particles →

Neutrino energy known at 10-20% level

Ideal tool to study neutrino interactions in nuclei

The Beamline & Accelerator Studies

- Conventional beamline where the pions and kaons are produced by protons on a fixed target. Mean energy of the hadrons selected = 8.5 GeV

  Selected particles are transported to the decay tunnel that is located off the axis of the proton beam

- 40 m long decay tunnel instrumented with calorimeters along its wall to monitor the leptons → Ke3 decays become the only source of ν_e : ~ 97% of the overall ν_e flux. Ke3 positrons emitted at large angles → hit the walls of the instrumented tunnel

- 2 possible focusing:

  - a purely static system = quadrupoles are placed directly downstream the ENUBET target → with a proton **“slow extraction”** scheme
  - a horn-based beamline = a focusing magnetic horn between the target and the transferline → needs a proton **“fast extraction”** method

Pro&cons for the 2 designs → **ENUBET is pursuing both options**

The Beamline & Accelerator Studies

Static extraction of protons
“Slow Extraction”
full intensity extracted continuously in few seconds

horn pulsed at 2-10ms in the flat top
“Fast Extraction”
all protons extracted in O(1-10μs) by kicker magnet

Need sustainable level for particle rate →

ENUBET

- ✔ No need for fast-cycling horn
- ✔ **Strong rate reduction** in the instrumented decay tunnel (no pile-up effects)
- ✔ Possibility to monitor the muon rate after the dump at % level (flux of ν_μ from pion decay)
- ✔ Pave the way to a "tagged neutrino beam"
- ✗ Needs more POT to reach wanted ν_e statistics

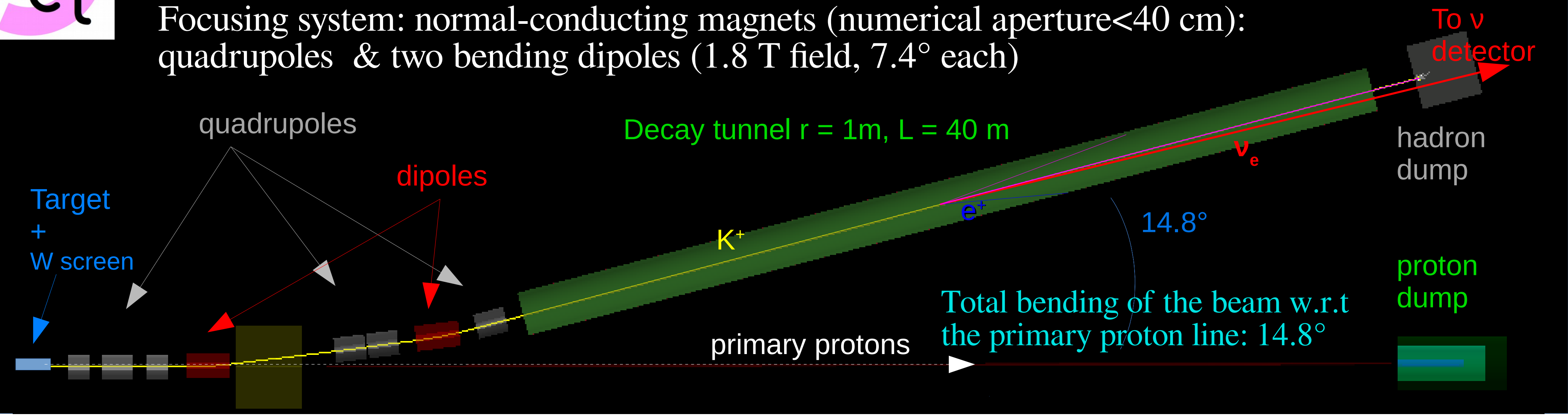
- ✔ More π & K in the wanted P range focused
  → Higher yields @ decay tunnel
  → More ν_e /POT
- ✗ Pile-up problems in the decay tunnel

➡ **Novel pulsed-slow extraction method**
developed in collaboration with CERN
(BE-OP-SPS & TE-ABT-BTP)

“BURST-MODE SLOW EXTRACTION”

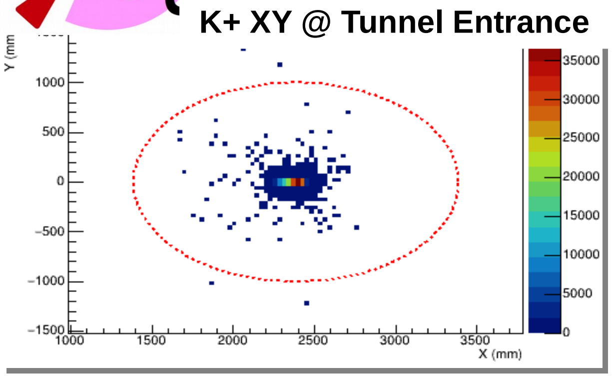
The Beamline & Accelerator Studies – The Static Transferline

Focusing system: normal-conducting magnets (numerical aperture<40 cm): quadrupoles & two bending dipoles (1.8 T field, 7.4° each)



- **Proton drivers**: CERN SPS (**400 GeV**), Fermilab Main Ring (**120 GeV**), JPARC (**30 GeV**)
- **Transfer line optimization**:
  - Optics optimized with **TRANSPORT** to a **10% momentum bite** centered at **8.5 GeV**
  - As short as possible to minimize early K-decays
  - Small beam size: non-decaying particles must exit the decay tunnel without hitting the tunnel walls
- **Particle transport and interaction**: full simulation with **G4Beamline**

The Static Transferline – ν_e

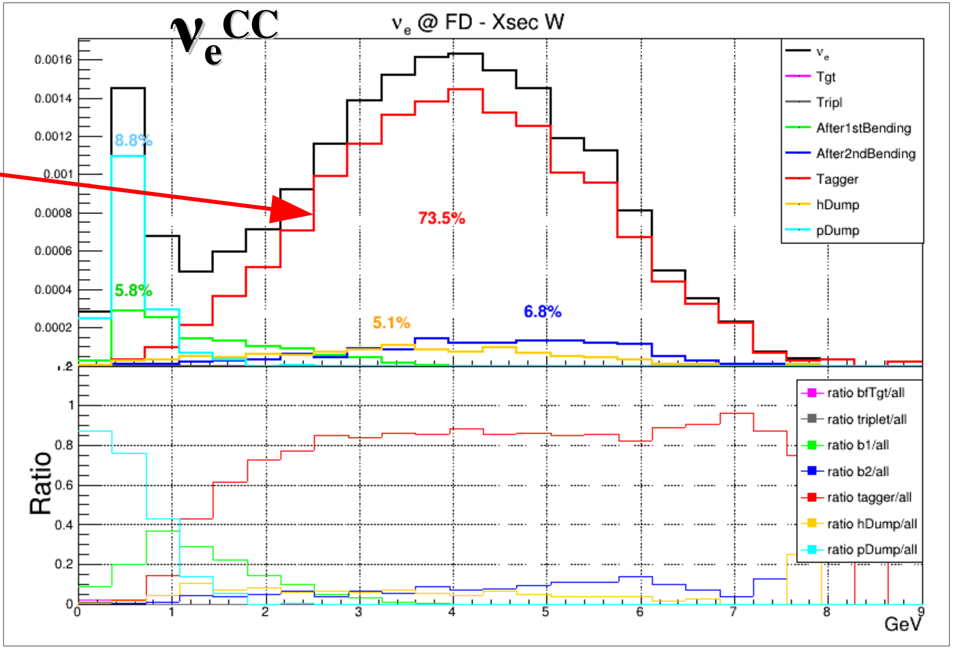

K+ XY @ Tunnel Entrance

Rates at Tunnel Entrance	$\pi^+[10^{-3}]$/POT 8.5 GeV ± 5%	$K^+\ [10^{-3}]$/POT 8.5 GeV ± 5%
400 GeV POT	4.2	0.4

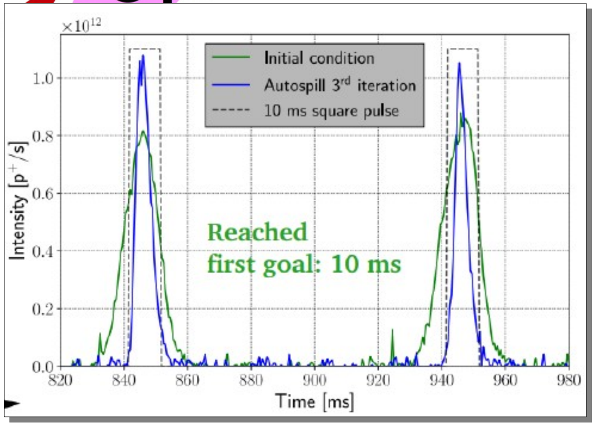
At nominal **SPS 4.5 10^{19} POT/year** **$10^4\ \nu_e^{CC}$** **@500ton ν-detector located 50m from the tunnel** in about **2 years**

73.5% of the total νe flux generated in the tunnel
→ more than 80% above 1 GeV

- Below 1 GeV main component is produced in the proton-dump region → further improve the separation against it by optimizing the proton dump position.
- 12% given by the straight section in front of the tagger → corrected for by relying on the simulation



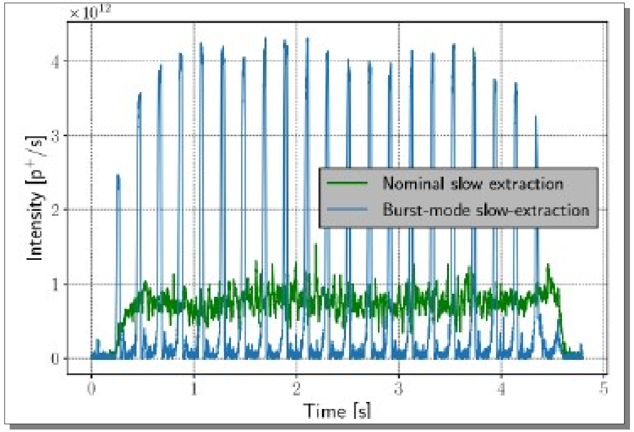
The Beamline & Accelerator Studies – The Horn-based beamline



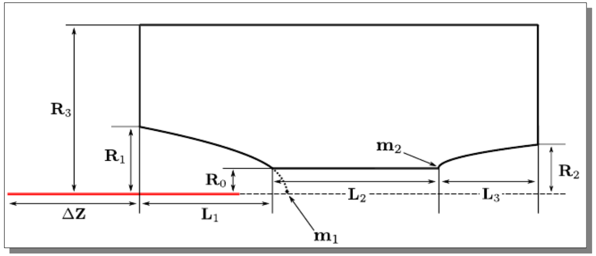
10ms pulses repeated at 10 Hz at the SPS

Multiple ms-long pulses slow-extracted during the flat-top at a fixed repetition rate

Burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa



Horn optimization

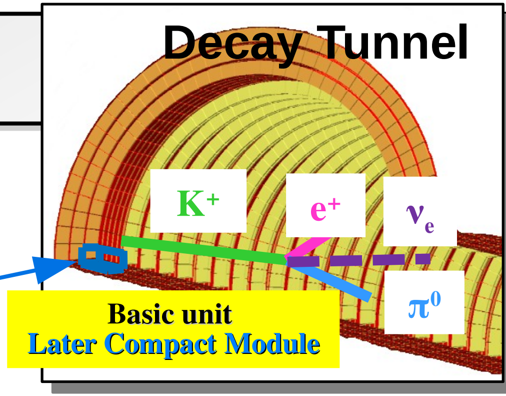


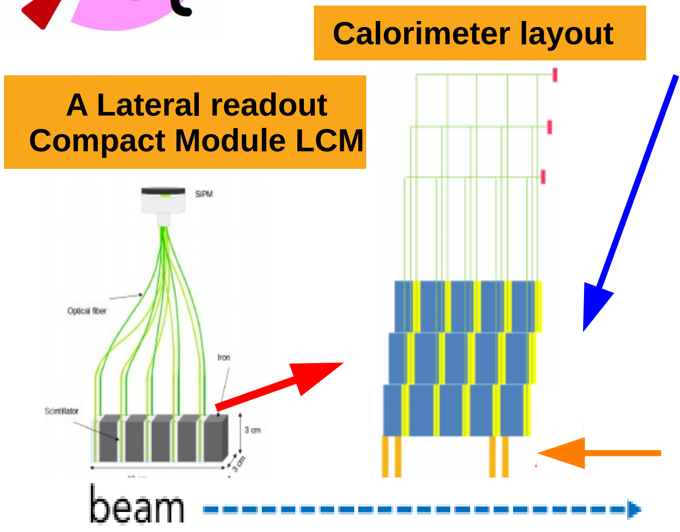
- ENUBET has its own framework to optimize the horn design using a Genetic Algorithm
- External constraints to fulfill hardware requirements
- **FOM** = Number of K^+ in ENUBET mom. bite focused at first quadrupole after the horn (distance+acceptance), beam-line independent

✔For different geometries&constraints reached FOM factor 3 higher than static case

✔Next: further studies on a dedicated beamline specific to the horn to take advantage of the flux increase

The Detector



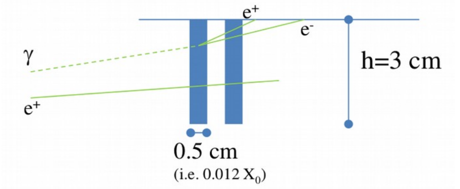


Calorimeter with e/π/μ separation capabilities:

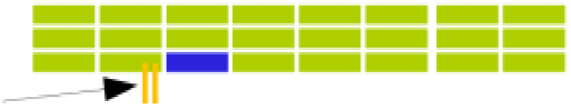
- Sandwich of **5 steel tiles (3x3x1.5 cm^2)** interleaved with **5 plastic scintillator tiles (3x3x0.5 cm^2): LCM**
  - longitudinal segmentation
  - SiPM active area: 4x4mm^2 , Cell size: 40 μm
- three radial layers of LCM
- Each LCM has **10 WLS (1mm) fibers coupled with SiPM**

Photon-Veto allows π^0 rejection and timing:

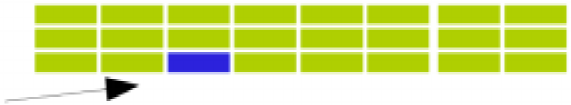
- plastic scintillator tiles arranged in doublets forming inner rings (3x3x0.5 cm^2 mounted below the LCM)
- time resolution of ~400 ps



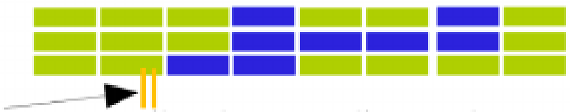
Exploit event topology for PID



e^+ (signal) topology



π^0 (background) topology



π^+ (background) topology

The Physics Performance – The Detector Simulation & Lepton ID

- **Full GEANT4 simulation** reproducing the detectors in the decay tunnel
- The **PID** is performed by the energy pattern in the modules and by the photon veto.

Signal in → **photon veto + calorimeters** → monitoring of **positrons** from $K_{e3} \rightarrow \nu_e$; **muons** from $K_{\mu 2}$ and $K_{\mu 3} \rightarrow \nu_\mu$

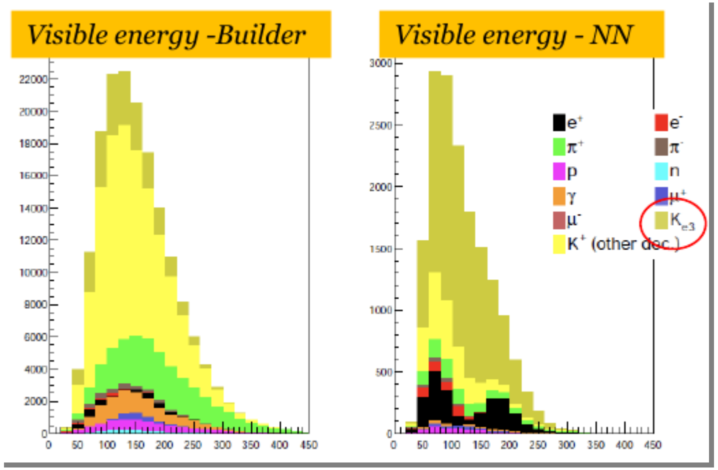
Signal in → **stations after the h-dump** → monitoring of **muons** from π decay → **low-E** ν_μ

Analysis Chain – Ke3 positron monitoring

1) **Event builder:** start from event seed and cluster energy deposits compatible in space and time with same decay
2) **e/μ/π/γ separation**: Event selection based on 19 variables employed by a **TMVA Neural Network**

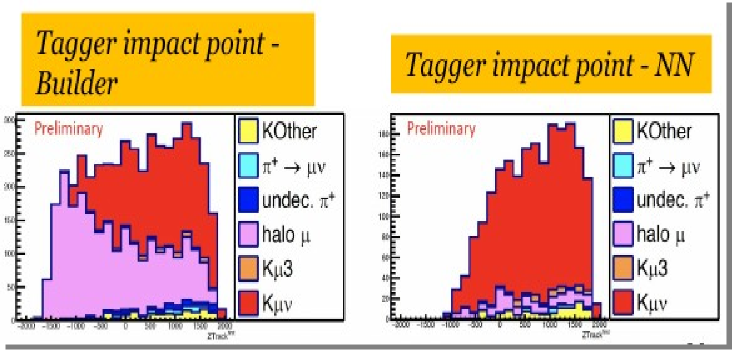
Analysis Performance - Ke3

S/N = 2.1
Efficiency = 22%
(~half of eff. loss is geometrical)


Visible energy -Builder

Visible energy - NN

Analysis Performance – K→μ monitoring


Tagger impact point - Builder

Tagger impact point - NN

S/N = 6
Efficiency = 34%
(~half of eff. loss is geometrical)

The Static Transferline – ν_μ

Narrow-band Off-axis Technique

F. Acerbi et al., CERN-SPSC-2018-034

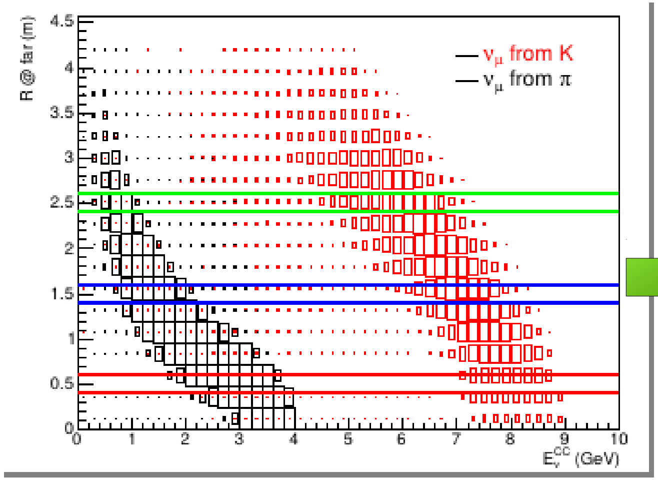
Narrow momentum width of the beam (O(5-10%))
+ finite transverse dimension of the neutrino detector

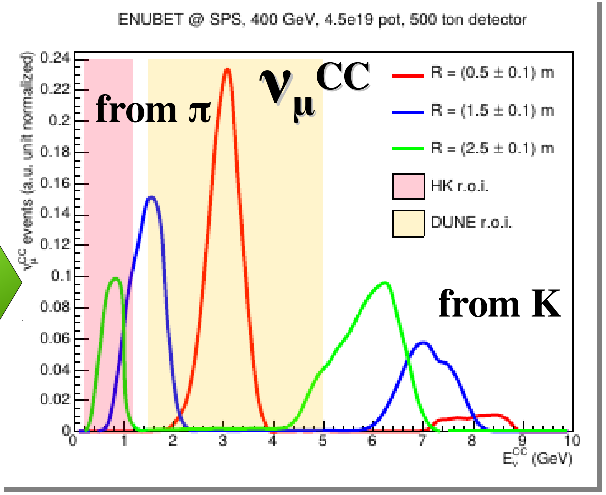
→

Strong correlation between E_ν in the detector and the radial distance (R) of the interaction vertex from the beam axis

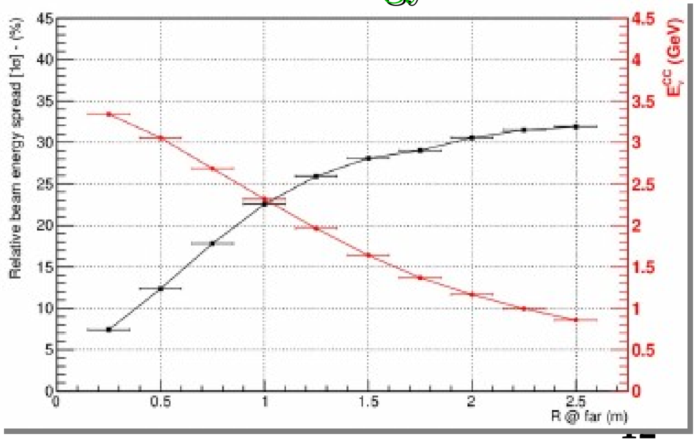
E_ν is provided on event-by-event basis without relying on final state particles in ν_μ CC

By selecting interactions in radial windows of ±10 cm we collect respective samples of ν_μ CC events





- Loose energy cut enough to separate π/K component
- Width of pion peak at different R → estimator of the precision on Eν: 8% to 25% at DUNE energy



The Detector – Prototype Test Results & The Demonstrator

Prototype of 84 LCM tested

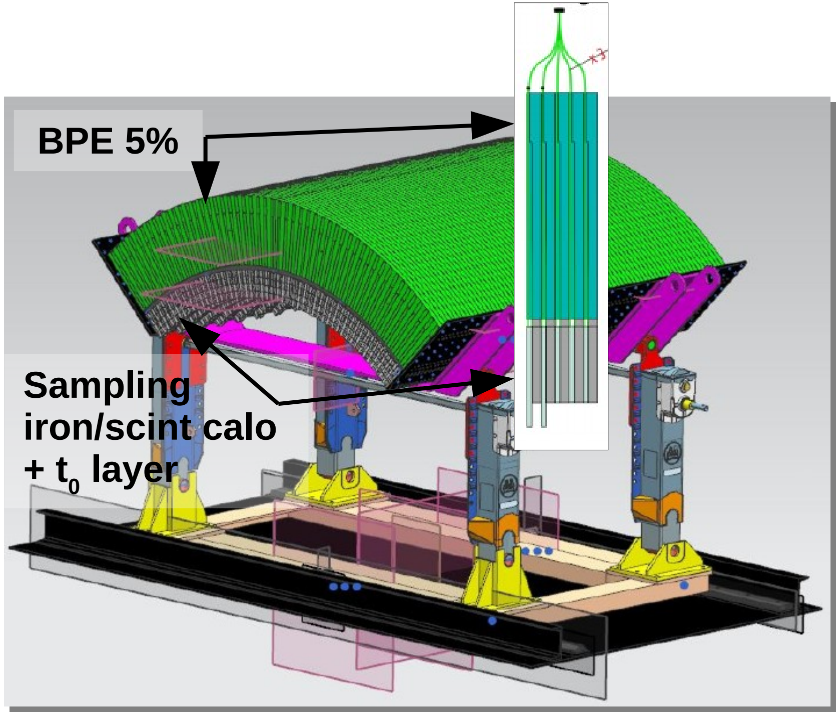
in 2018 @ CERN PS-T9

F. Acerbi et al., JINST 15 P08001 (2020)

- Containmnent of em showers up to 5 GeV
- **Energy Resolution** σ_E/E = **17% @ 1 GeV**
- **Photon-veto** (t_0-layer) 1-mip/2-mip separation:
  1-mip signal with ε=87%
  Background rej. ε=89% (2-mip like), 95% Purity

The Demonstrator

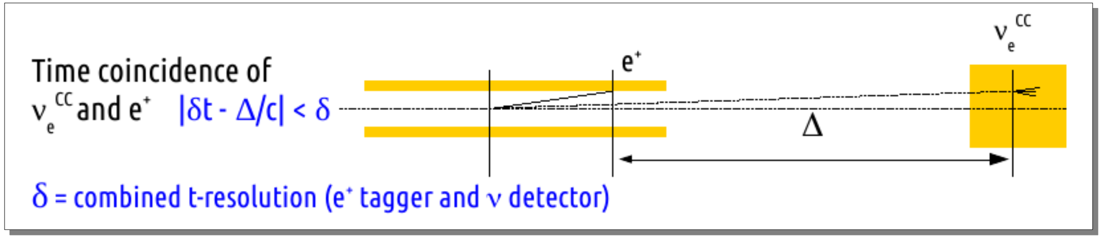
- ENUBET is building a detector prototype to demonstrate performance, scalability and cost-effectiveness
- New ligth readout scheme: from lateral to frontal light collection. Safer for injection molding. More uniform and efficient
- To be exposed at CERN in 2022
- **1.65m long, covers 90° in azimuth**
- 75 layers of iron + 75 layers of scintillators = 12 x 3 LCM
- Will **instrument central 45°,** rest kept for mechanical considerations
- Modular design → can be extended to a full 2π object by joining 4 of these modules



Future Developments & Possibilities

Tagged Neutrino Beam

the neutrino seen at the neutrino detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel:



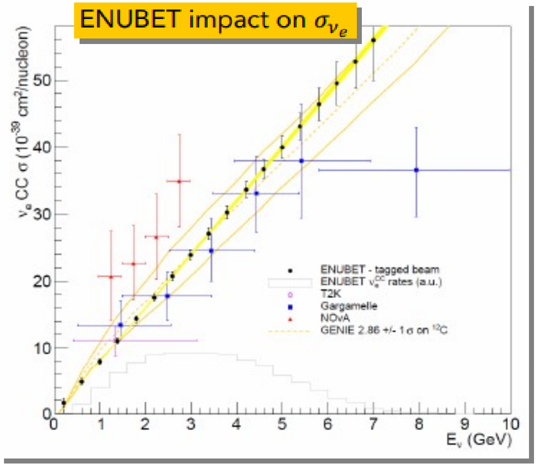
- **Detector system with time resolution at O(~100 ps) level** that would improve the performance of the standard photon veto system of ENUBET → R&D activities are ongoing to identify the proper technology (NUTECH project)
- **Slow proton exctraction scheme + Static Transferline**

Associating a single neutrino interaction to a tagged e^+ through time coincidences would be a major breakthrough

→ Purity of selected sample of neutrino interactions at unprecedented level

Conclusions

- **ENUBET** is aiming at the realization of the first monitored neutrino beam → measurement of neutrino cross-section and flavor composition at 1% precision level + energy of the neutrino at 10% precision level


ENUBET impact on σ_{ν_e}

- A Conventional narrow-band neutrino beam
  - Static transferline:
  - Very appealing Horn-based option
- An Instrumented decay tunnel → Longitudinal segmented calorimeter
  - Construction of the demonstrator and electronics in progress → test at PS East Hall in 2022
- ENUBET is on schedule and in the last phase of the project → Conceptual Design Report at the end of the project (2022): physics and costing
- Also studying: Multi momentum beamline to achieve a design fexible enough to explore also Hyper-K ROI at lower momenta & Superconducting 2nd dipole to increase total bending angle
- *ENUBET/nuSTORM Workshop on Thursday!* → Synergy with NuSTORM in the framework of PBC

Thank You!

Back-ups

The Beamline & Accelerator Studies – The Static Transferline

The Target

Selected after a dedicated optimization study with different materials:

Graphite, 70 cm long with a radius of 3 cm

- ✓ Momenta tested: FLUKA simulation for POT @ 400, 150, 70, and 50 GeV/c → The nominal SPS energy (400 GeV/c) is a good choice for ENUBET, especially for cross section studies in the region of interest for DUNE

The Hadron Dump & The Proton Dump

Similar structure, 3 cylindrical layers

→ H-Dump design optimized to reduce the backscattering

In particular, last meters of the tunnel where the neutron fluence is more significant

→ P-Dump final position of will be optimized to reduce the number of neutrinos in the Neutrino Detector

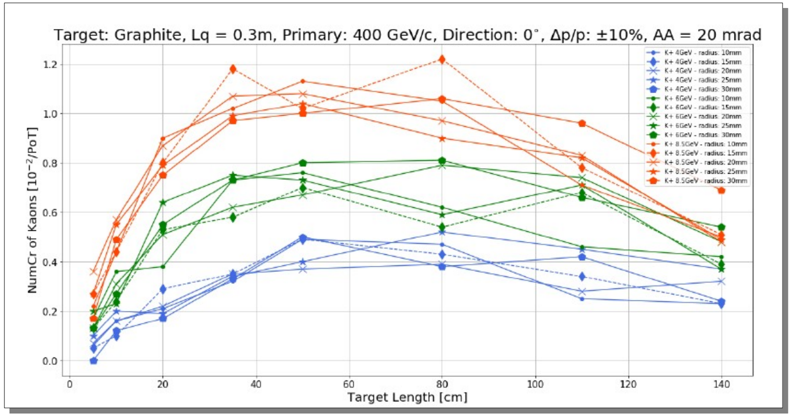
The Beamline & Accelerator Studies – The Static Transferline

The Target

→ Selected after a dedicated optimization study:

Graphite, 70 cm long with a radius of 3 cm

- **Geometry** determines the reinteraction probability and absorption of the secondary particles
- **Mechanical constraints** and cooling requirements

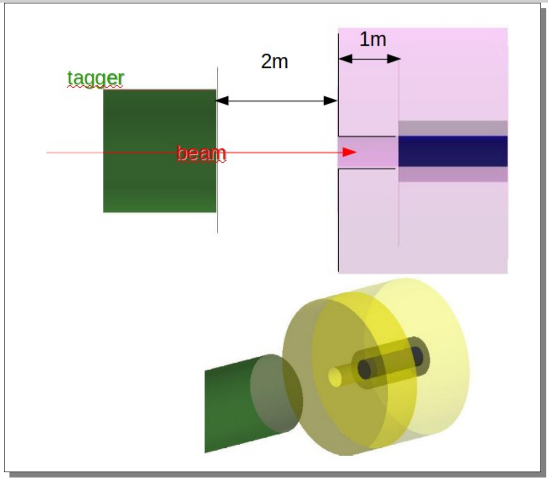


- ✓ Target tested: graphite, beryllium, inconel + various high-Z materials (gold and tungsten). Each target prototype is a cylinder with variable radii between 10 and 30 mm and lengths extending from 5 to 140 cm
- ✓ Momenta tested: FLUKA simulation for POT @ 400, 150, 70, and 50 GeV/c →

The nominal SPS energy (400 GeV/c) is a good choice for ENUBET, especially for cross section studies in the region of interest for DUNE

The Beamline & Accelerator Studies – The Static Transferline

The Hadron Dump

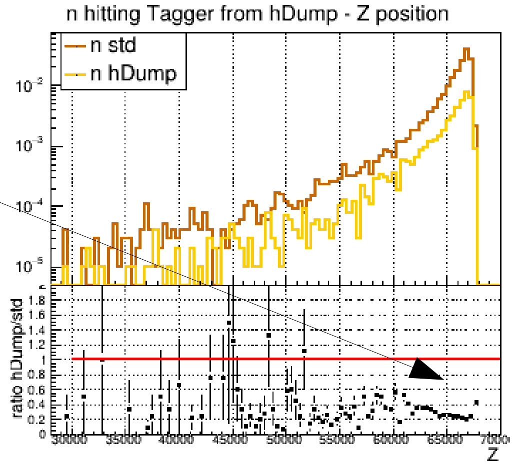


graphite core (50 cm diameter), inside a layer of Iron (1 m diameter), covered by borated concrete (4 m diameter) + 1 m of borated concrete is placed in front of the hadron dump leaving the opening for the beam

→ design optimized to reduce the backscattering

Reduction by a significant amount of the flux all along the tagger

In particular, last meters of the tunnel where the neutron fluence is more significant → Ratio w.r.t "standard" dump ~ 0.2



The Proton Dump

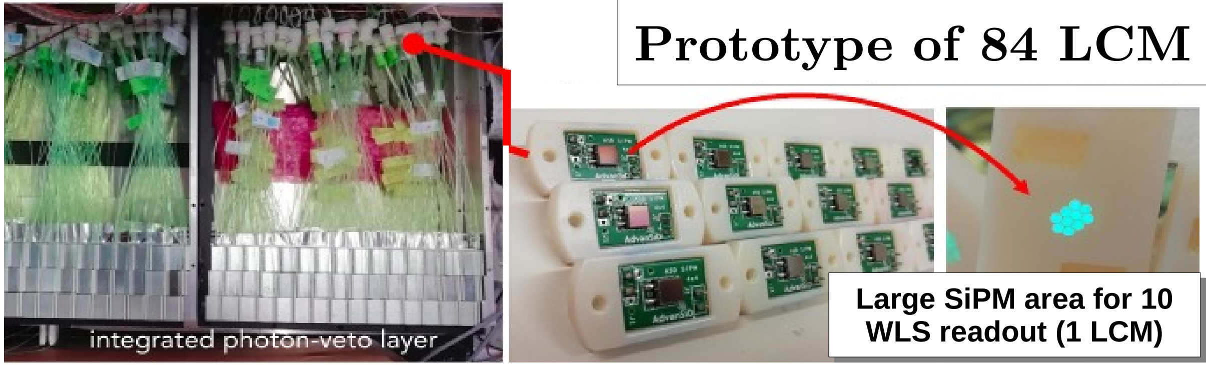
Similar structure, 3 cylindrical layers:

3 m long graphite core, surrounded by aluminum, covered by iron

→ final position of the proton dump will be optimized to reduce the number of neutrinos in the Far Detector

The Detector – Prototype Test Results

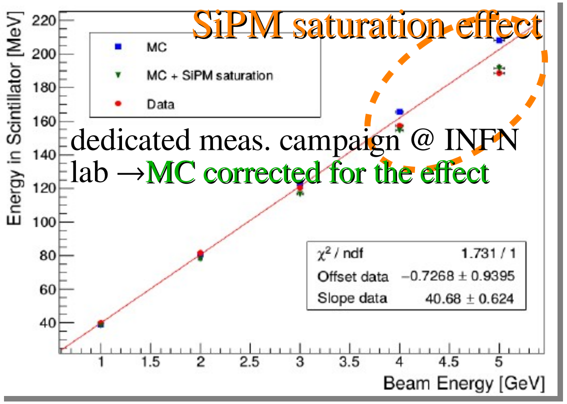
Prototype of 84 LCM tested in 2018 @ CERN PS-T9



Large SiPM area for 10 WLS readout (1 LCM)

- 7 planes on a 3x4 matrix → 30 X_0, 3.15 λ_0, → **Containmnent of em showers up to 5 GeV**
- Beams tested: e^-, μ^-, π^-, P in [1-5] GeV
- Angles tested w.r.t beam direction (mimic K_{e3} e^+): 0, 50, 100, 200 mrad

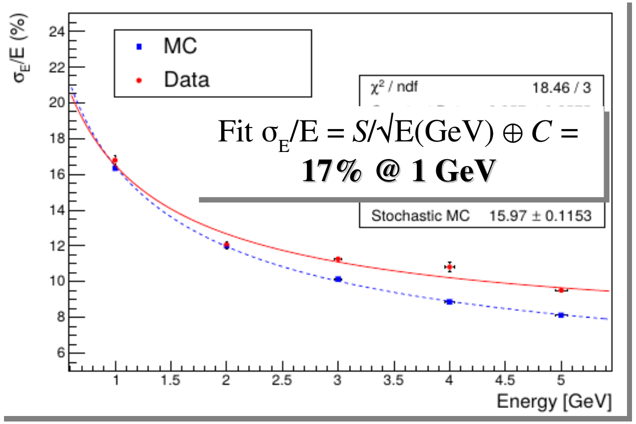
Reconstructed Energy: Data/ MC comparison at 100mrad



SiPM saturation effect

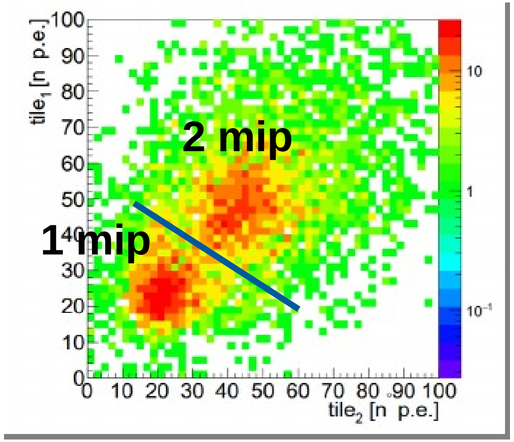
dedicated meas. campaign @ INFN lab →MC corrected for the effect

Energy Resolution at 0 mrad



Fit $\sigma_E/E = S/\sqrt{E(\text{GeV})} \oplus C$ = **17% @ 1 GeV**

Photon Veto (t_0 layer)



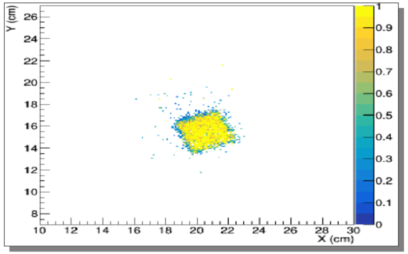
- 1-mip/2-mip separation: **1-mip signal with ε=87%** Background rej. ε=89% (2-mip like), 95% Purity
- Time resolution **~400 ps**

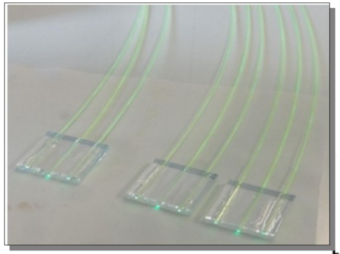
Results published: F. Acerbi et al., JINST 15 P08001 (2020)

The Detector – The Demonstrator

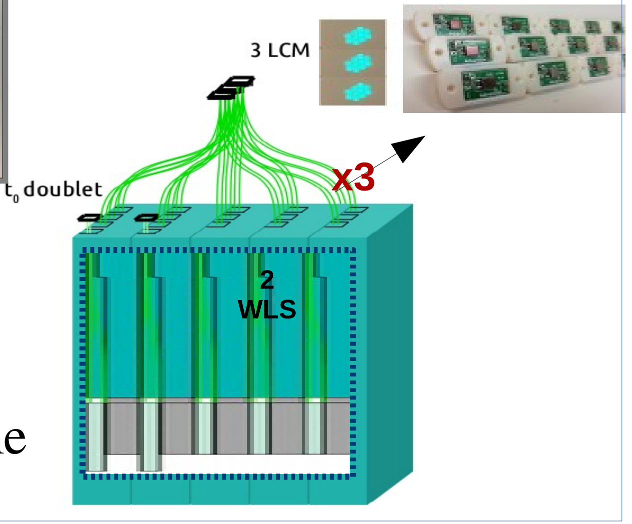
Several activities currently on-going towards the test of the demonstrator

- Large scale production of the scintillators (UNIPLAST Moscow & INR). Total nb of scintillator tiles for the demonstrator will be ~10000
- Improved light readout scheme completely validated by GEANT4 optical simulation → distance between fibers optimized to achieve best possible light collection & uniformity
- Efficiency map measurement of tiles with similar final shape at INFN-Bologna with a cosmic ray tracer





- **ENUBINO**: pre-demonstrator small prototype = 3 LCMs is being assembled and will be soon characterized with cosmics at INFN-LNL



WLS routing and
SiPM matching scheme

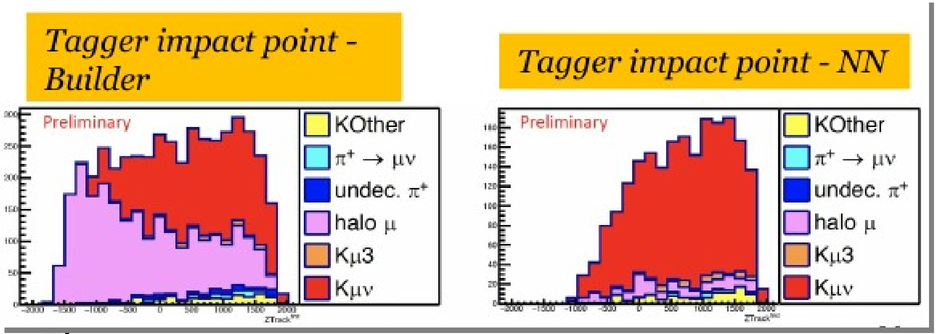
The Physics Performance – The Detector Simulation & Lepton ID

Analysis Chain – Kμ2 & Kμ3 muon monitoring

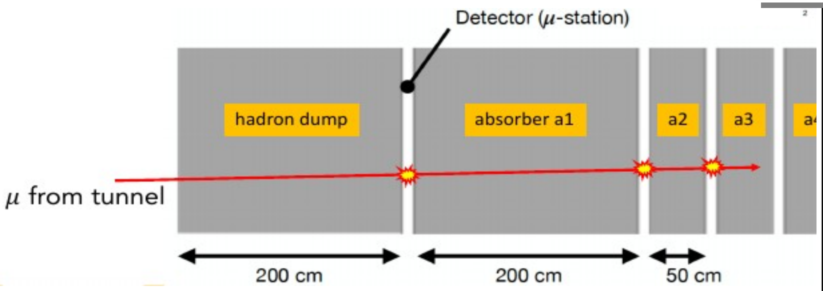
1) **Event builder:** Space and time clustering of energy deposits compatible with a track of a muon
2) **S(μ-like)/B separation**: Event selection based on a **TMVA Neural Network** with 13 vars
   Main background from halo muons is identified and can be used as control sample

Analysis Performance

S/N = 6
Efficiency = 34%
(~half of eff. loss is geometrical)



Instrumented hadron dump with detector layers interleaved by absorber



Detector technology constrained by muon and neutron rates.

πμ2 monitoring to constrain low-energy ν_μ

✔ **Monitor associated μ** emitted at low angle that go through the tunnel and the hadron dump.
✔ Correlation between number of traversed stations (muon energy from range-out) and neutrino energy; difference in distribution to disentangle signal from halo- muons.

The Physics Performance – The Systematics

- Model to describe the measured observables built from distributions predicted by the simulation. **The systematic effects are introduced as nuisance parameters in the model**

The model PDF: $PDF = N_S(\vec{\alpha},\vec{\beta}) \cdot S(\vec{\alpha},\vec{\beta}) + N_B(\vec{\alpha},\vec{\beta}) \cdot B(\vec{\alpha},\vec{\beta})$

Sets:
α = hadro-production nuisances
β = beamline related nuisances

► Signal and Background Shapes

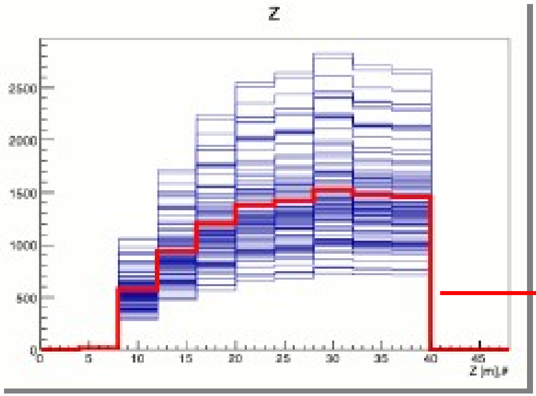
► Signal and Background Nb. Of Events

- Toy Monte Carlo to study level of Improvement in the systematics ↔ Gain in neutrino flux precision

Multi-verse Method

How does the obsevable change with hadroproduction variations? → uncertainty envelope created

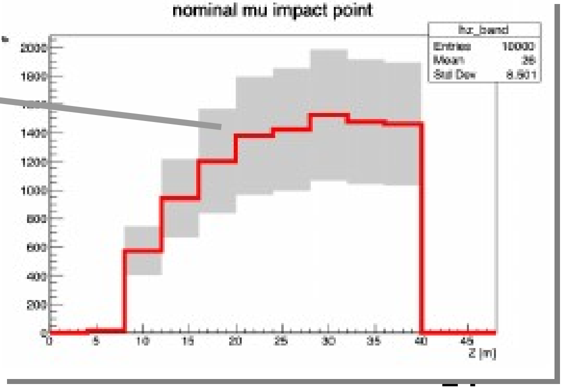
Ex: **Z position** = impact point along the tagger, **for μ from K decays**



Mock observable distribution
Ensemble of N possible realization of the distributions

Nominal distribution
=mean value of varied histos computed by sampling the hadroproduction parameters from their PDFs

1σ band evaluated from varied histograms

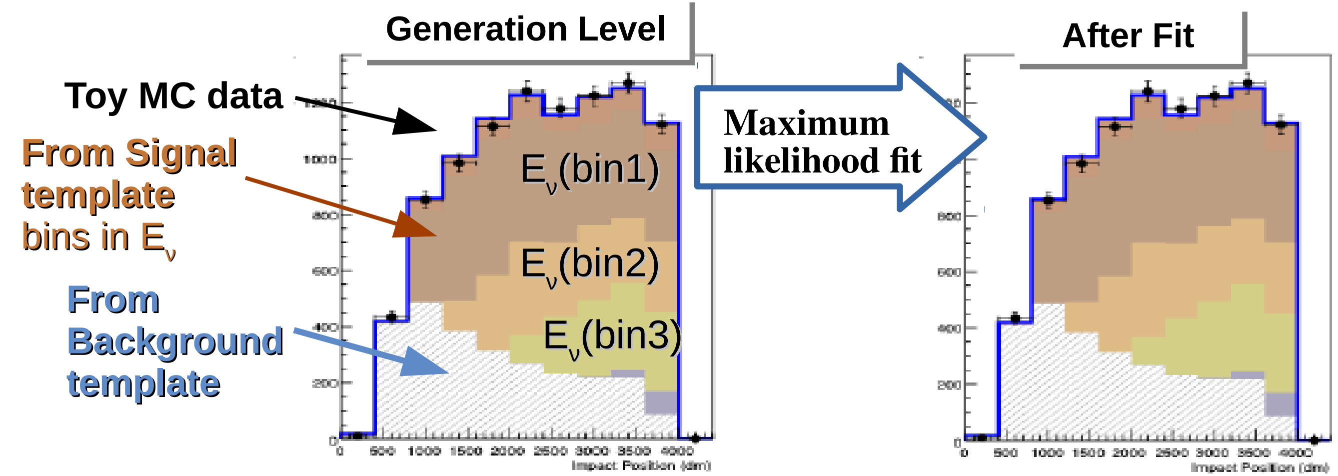


G.Brunetti - ENUBET

The Physics Performance – The Systematics

- A software framework written within ROOFIT to **constrain the neutrino flux from the reconstructed leptons** → Maximization of an extended likelihood of the observed data

✔ **Machinery validated** using the impact point along the tagger of muons from kaon decays



Generation Level

Toy MC data

From Signal template bins in E_ν

From Background template

E_ν(bin1)

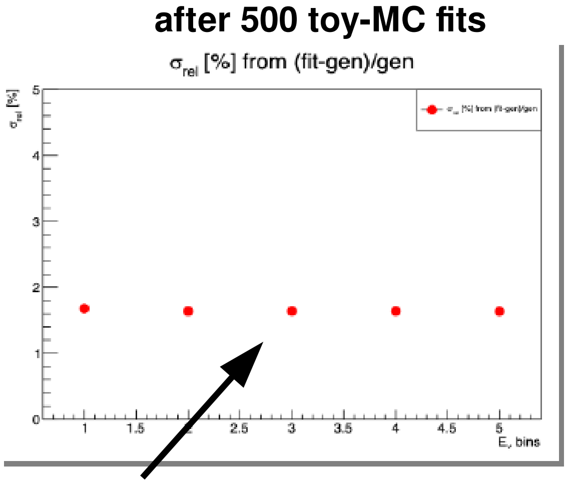
E_ν(bin2)

E_ν(bin3)

Maximum likelihood fit

After Fit

after 500 toy-MC fits



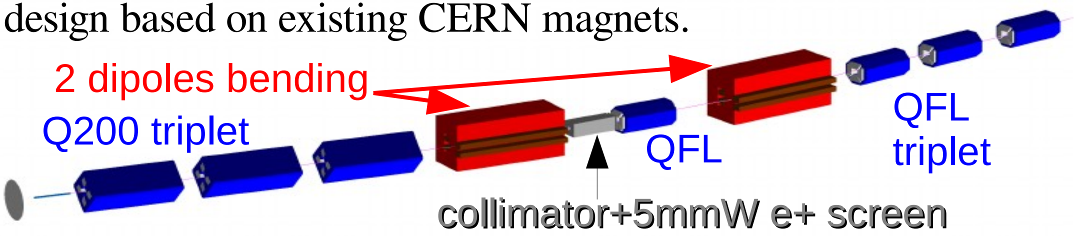
➡ Constraint on the Neutrino Flux: Relative error for the neutrino spectrum ~1.8%, with initial systematic uncertainty of ~15%

- **Next Step:** From a toy to the real ENUBET case using full simulation
  - Use real hadroproduction data (400 GeV POT, NA56/SPY) and related syst. uncertainties to correct MC
  - Use facility parameters to assess impact

Future Developments & Possibilities

- **Multi momentum beamline:** to achieve a design flexible enough to explore also Hyper-K ROI at lower momenta → currently working on a beamline design based on existing CERN magnets.

overall max angular acceptance
±20mrad in both planes

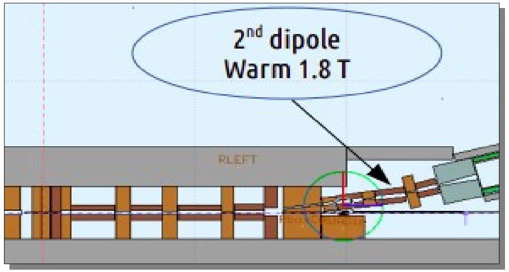


→ Will be finalized with MADX/PTC-TRACK higher order effects validation and FLUKA background reduction studies

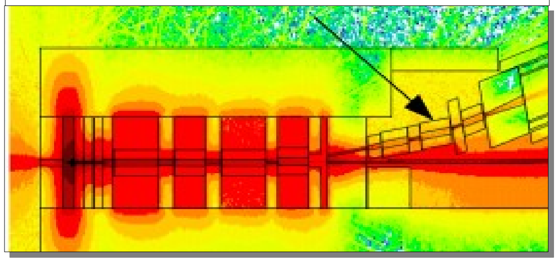
- **Super conducting dipole**: could help in better separating the ν_e component from tagger at the far detector + better momentum separation w.r.t higher and lower meson momenta → cleaner spectrum at tagger entrance

→ The static transferline is also fully implemented in FLUKA to estimate ionizing doses and neutron fluences

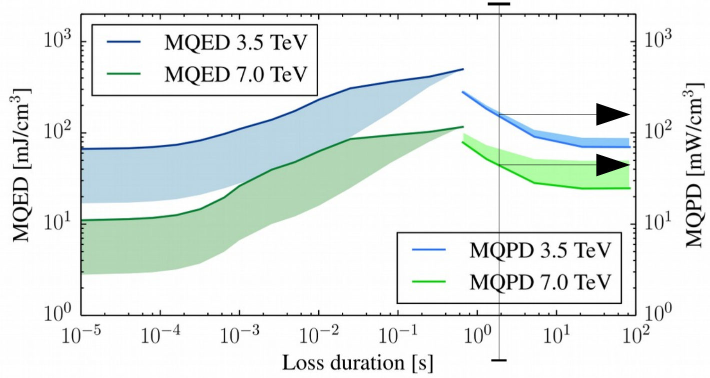
→ Investigating possibilities for 2nd dipole



For 2s spill 0.055 mJ/cm³ → 0.027 mW/cm3 during 2s slow extraction



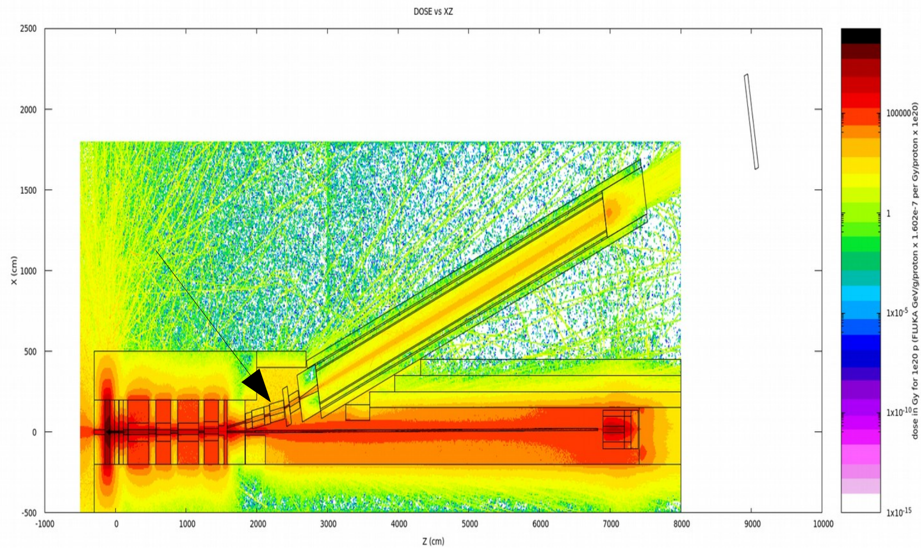
Comparison with: https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.061002



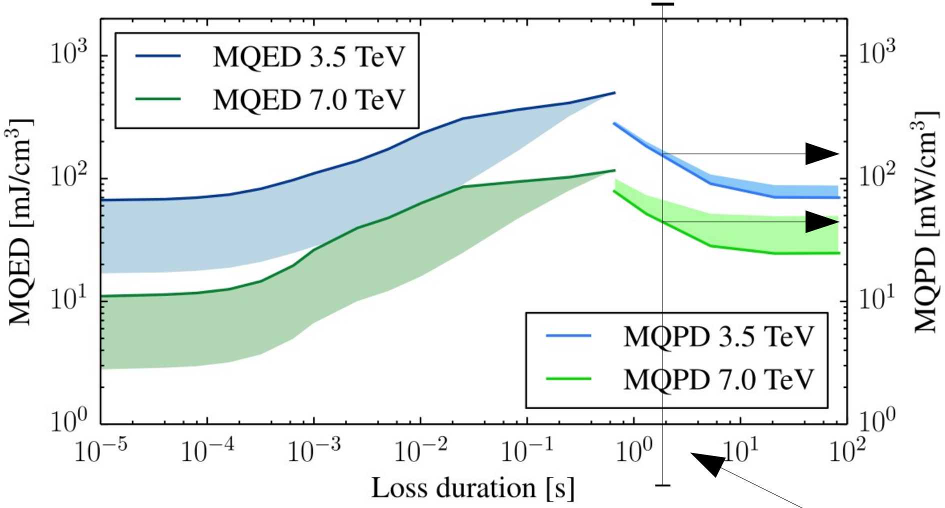
Doses

In Gy for 1e20 POT

Hot side ~ 70 kGy with 10^{20} pot
Inside Iron ~10 kGy with 10^{20} pot



https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.061002 .



Hottest region (conservative value): 70 kGy = 70 kJ/kg per 1e20 POT

Iron: 7800 kg/m³ → 1 kg = 1/7800 m³ = 128 cm³

70 kGy = 70 kJ/kg = 70 kJ/128 cm³ = 0.55 kJ/cm³

1e20 POT = 1e7 spill (each ~1e13 POT/spill)

per spill, over 2 s: 0.55 kJ/cm³/1e7 = 0.055 mJ/cm³

→ 0.027 mW/cm³ during a 2s slow extraction

It looks safe: from LHC studies for a 2s long loss the critical power is between 40 and 150 mW/cm³ (7.0 and 3.5 TeV)

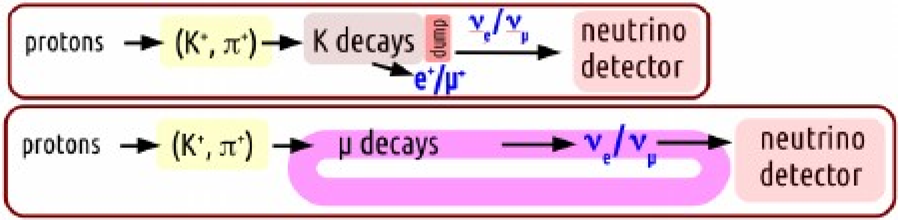
Future Developments & Possibilities

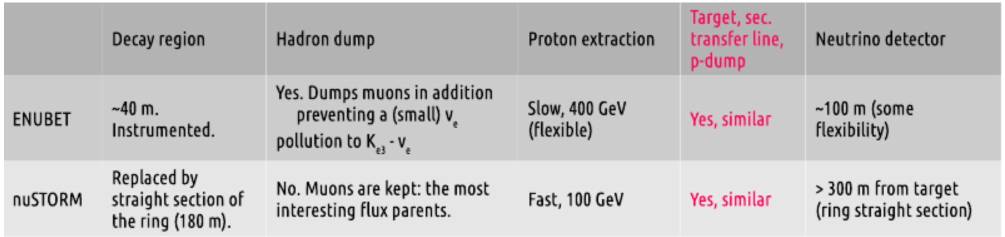
Synergy with NuSTORM

- NuSTORM: a step towards the muon collider
- Experimental demonstration of ionization cooling: Proof-of-principle for stored muons for particle physics.
- Feasibility of executing nuSTORM at CERN through Physics Beyond Colliders
- Main Synergy with ENUBET:
  - Target Facility
  - 1st stage of meson focusing
  - proton dump

→ ENUBET specific: opportunity for a tagged neutrino beam

- Emphasis on the implementation at CERN and possible use of existing facilities/detector
- The 2 collaborations are currently evaluating the synergy at facility-level
- *ENUBET/nuSTORM Workshop on Thursday!*





	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)