Enhanced NeUtrino BEams from kaon Tagging

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On behalf of the ENUBET Collaboration

Virtual Seminar Series

Outline

- The project
- The beamline and accelerator studies
  - The static transferline
  - The horn-based beamline
- The detector prototype
- The physics performance
- Future possibilities
  - A “tagged” neutrino beam
  - A site-dependent approach: synergies at CERN
- Conclusions

The Project

- ENUBET is a **ERC Consolidator Grant**. Jun 2016 - May 2022.
  Since April 2019, it's also a **CERN Neutrino Platform experiment: NP06/ENUBET**

  Go visit our website! **http://enubet.pd.infn.it/**

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

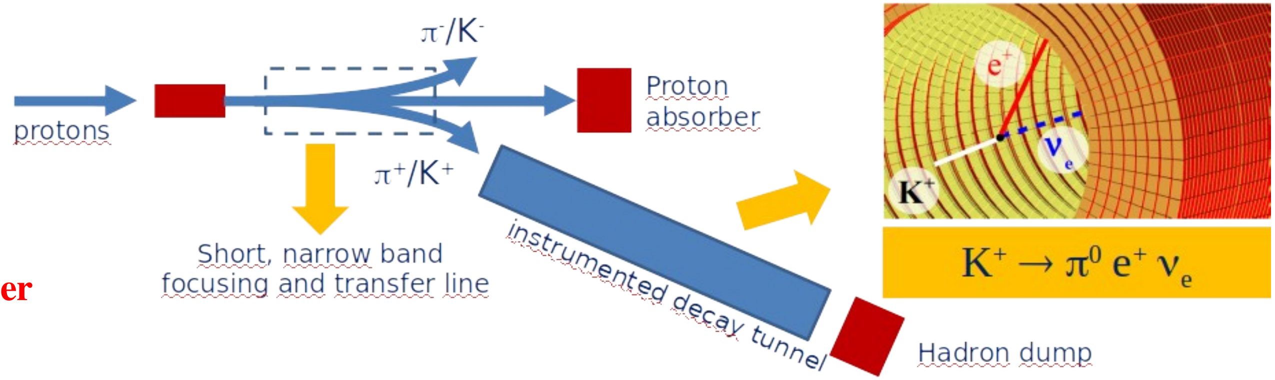
- **The goal**: Demonstrate the technical feasibility and physics performance of a **neutrino beam** where **lepton production at large angle is monitored at single particle level**

→ MONITORED Neutrino Beams

The Project

- **Why?**
  - The **uncertainty on the neutrino flux** is the main source of systematic error for cross section measurements
  - 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



K_{e3} decays: $K^+ \rightarrow e^+ \nu_e \pi^0$

to tagger

to neutrino detector

Fully instrumented decay region → ν_e flux prediction = e^+ counting

→ **"By-pass" uncertainties from hadro-production, beamline efficiency, POT**

Reduce the uncertainty on the flux of ν_e and, possibly, ν_μ below 1%

The Project

- **Why?**
  - The other source of systematic uncertainty for cross section measurements is the **reconstruction of the neutrino energy**, biased by the inaccurate reconstruction of the final state particles.
- **How?**

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 & Accelerators 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** → works with a proton "**slow extraction**" method

    = quadrupoles are placed directly downstream the ENUBET target

  - a **horn-based** beamline → needs a proton "**fast extraction**" method

    = a focusing magnetic horn between the target and the transferline

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

The Beamline & Accelerators Studies
Static transferline VS Horn-based beamline

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 →

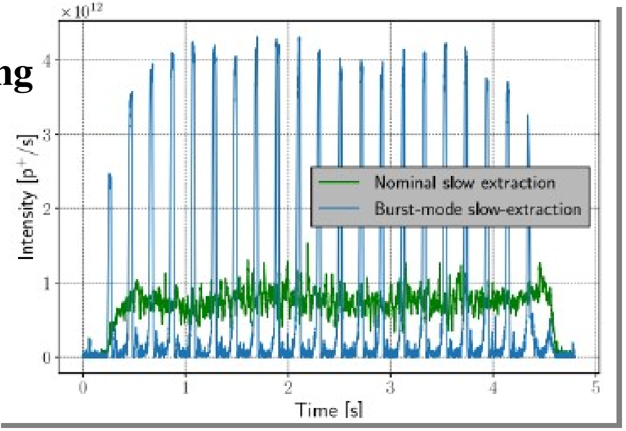
ENUBET

- ✔ 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

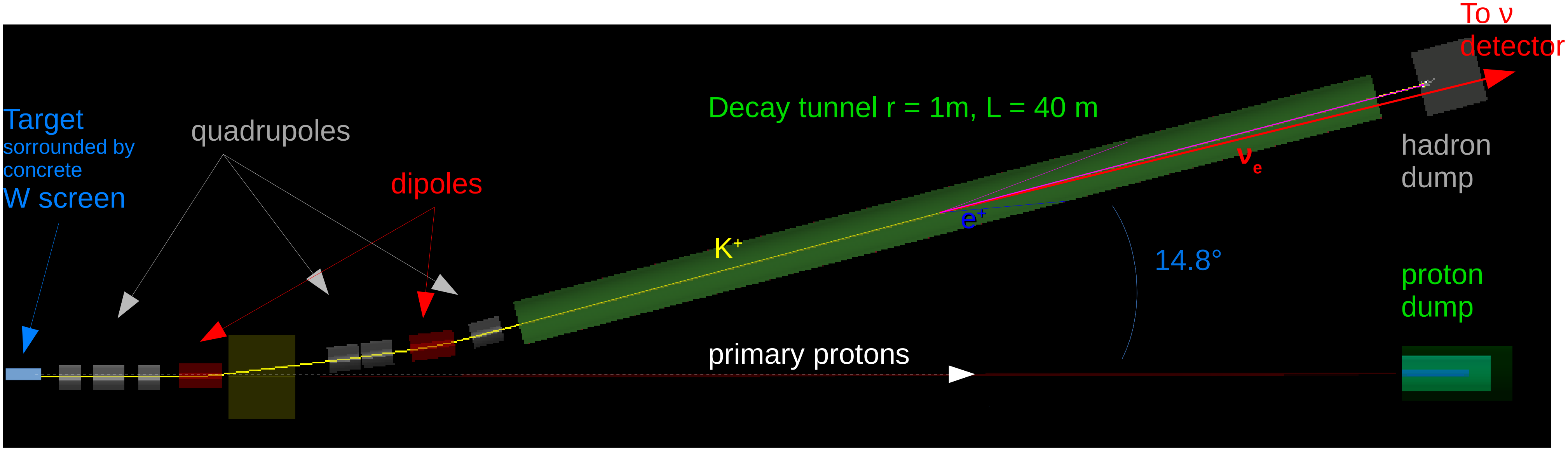
- ✔ More π & K in the wanted P range focused
→ Higher yields @ decay tunnel
→ More ν_e /POT
- ✗ Pile-up problems in the decay tunnel

➡ **Novel pulsed-slow extraction method** developed in collaboration with CERN
(BE-OP-SPS & TE-ABT-BTP)
“BURST-MODE SLOW EXTRACTION”

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



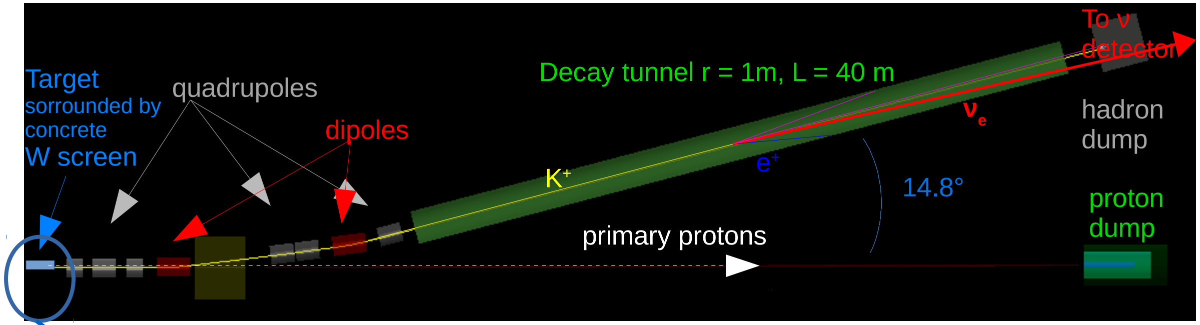
The Beamline & Accelerators Studies
The Static Transferline

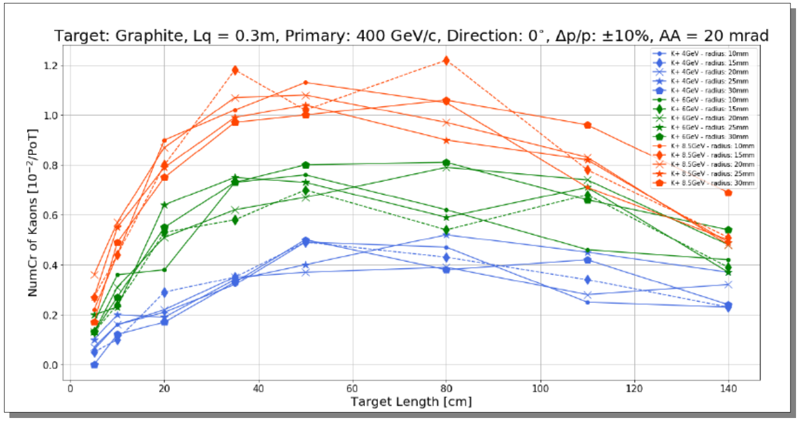


- **Proton drivers**: CERN SPS (**400 GeV**), Fermilab Main Ring (**120 GeV**), JPARC (**30 GeV**)
- Transfer line optimization guidelines:
  - Optics: optimized with **TRANSPORT** to a **10% momentum bite** centered at **8.5 GeV**
  - As short as possible (minimize early K-decays)
  - Small beam size: non-decaying particles must exit the decay tunnel without hitting the tunnel walls
- Particle transport and interaction: full simulation with **G4Beamline**
- Focusing system: **normal-conducting magnets** (numerical aperture<40 cm): quadrupoles & two bending dipoles (1.8 T field, 7.4° each). **Total bending** of the beam w.r.t the primary proton line of **14.8°**

The Beamline & Accelerators Studies

The Static Transferline – The Target





Target: Graphite, 70 cm long and with a radius of 3 cm

→ Selected after a dedicated optimization study:

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

Optimization is a trade-off between mechanical robustness against heating and the effective interaction length

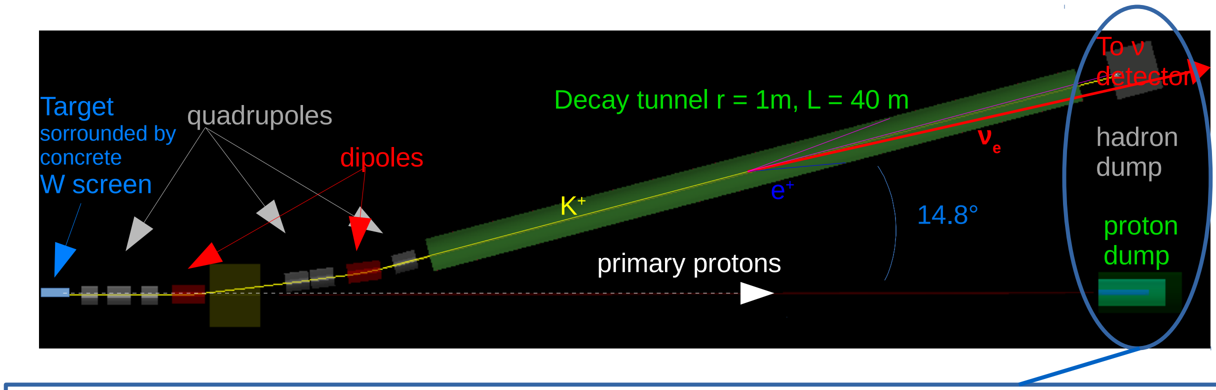
- ✓ Target tested: graphite, beryllium, inconel + various high-Z materials (gold and tungsten). Each target prototype is a cylinder with variable radii between 10 and 30 mm and lengths extending from 5 to 140 cm
- ✓ Momenta tested: **FLUKA simulation** for POT @ 400, 150, 70, and 50 GeV/c → The nominal SPS energy (400 GeV/c) is a good choice for ENUBET, especially for cross section studies in the region of interest for DUNE

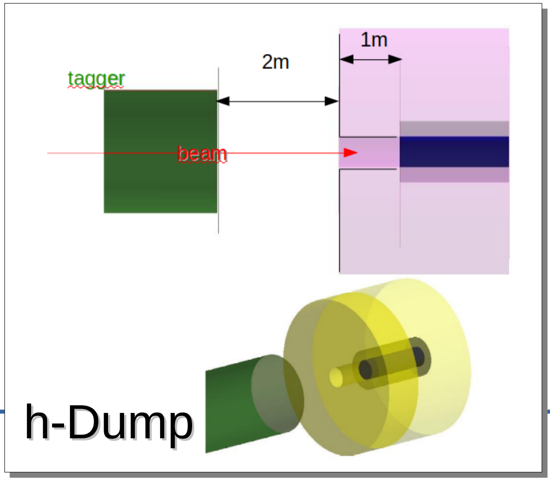
Positron screen: 10 mm Tungsten foil downstream the target

→ Get rid of the beam e^+ background in the tagger.

- ✓ Thickness chosen after a series of simulations with FOM=beam e^+ hitting the tagger/K^+ flux

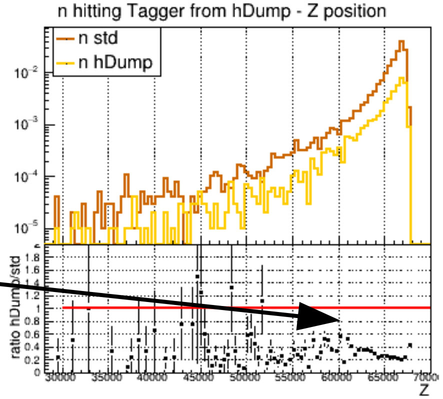
The Beamline & Accelerators Studies
The Static Transferline – The proton & hadron dumps





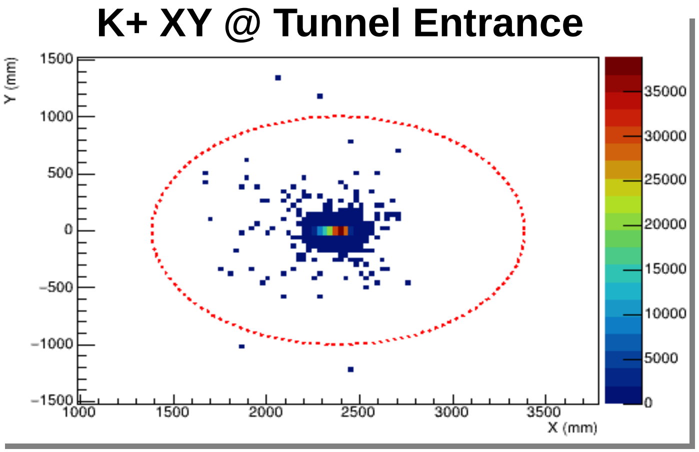
Similar structure, 3 cylindrical layers:

- **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



- **Proton Dump**: 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 Beamline & Accelerators Studies
The Static Transferline – The Fluxes

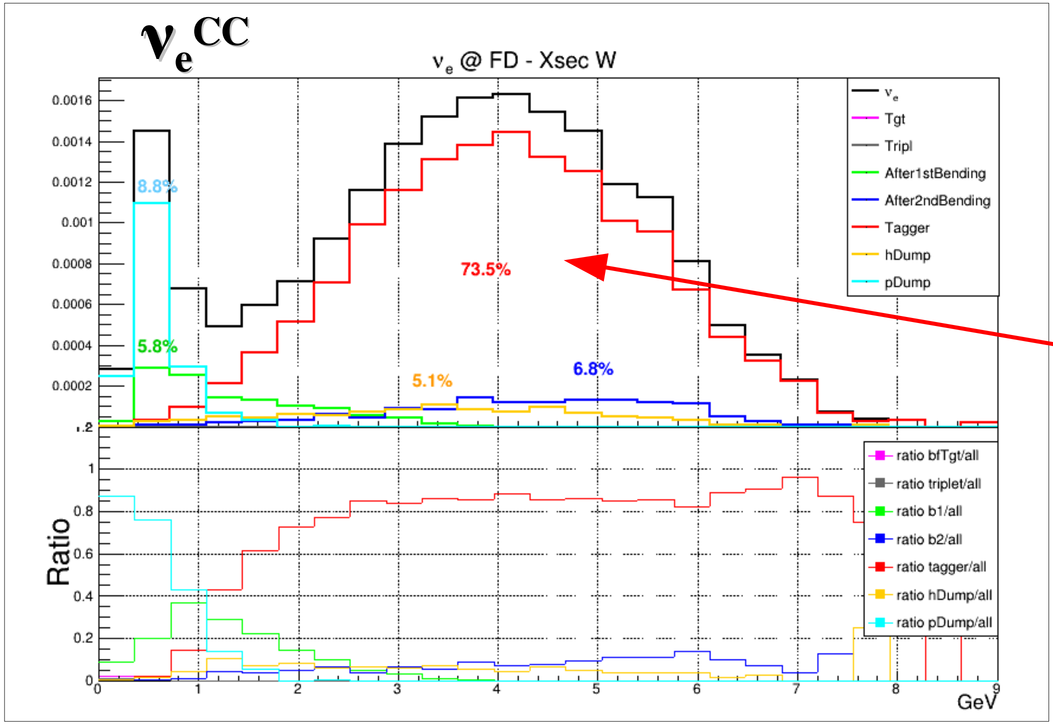


Rates at Tunnel Entrance	π^+ 8.5 GeV ± 5% [10^{-3}]/POT	K^+ 8.5 GeV ± 5% [10^{-3}]/POT
400 GeV POT	4.2	0.4

Flux at the tagger better than project proposal

ENUBET proposal*
8.5 GeV/c±20%

E_p (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})
30	0.24	0.027
50	0.58	0.069
60	0.73	0.091
70	0.80	0.095
120	1.25	0.16
450	3.65	0.43



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

73.5% of the total ve flux generated inside 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

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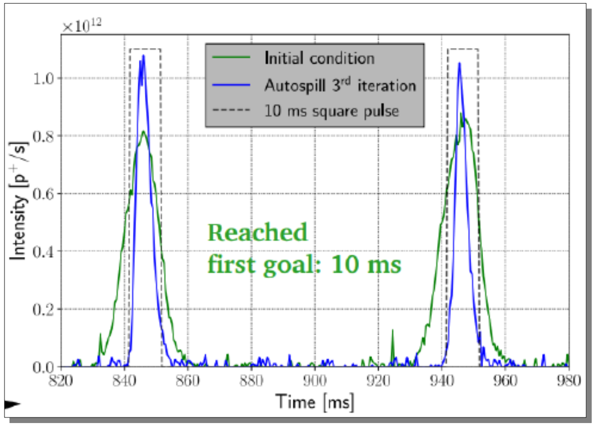
* A. Longhin, L. Ludovici, F. Terranova, **EPJ C75 (2015) 155**

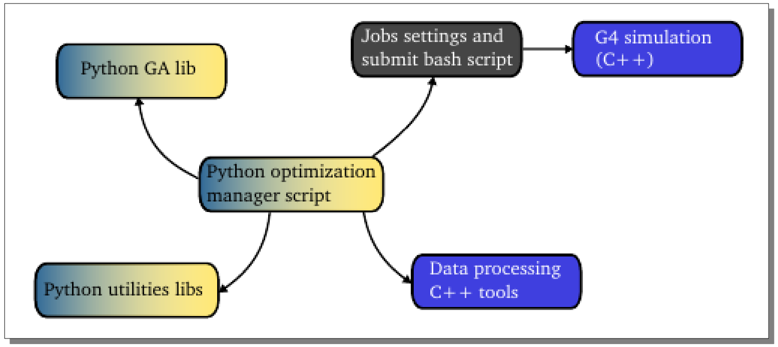
The Beamline & Accelerators Studies
The Horn-based beamline



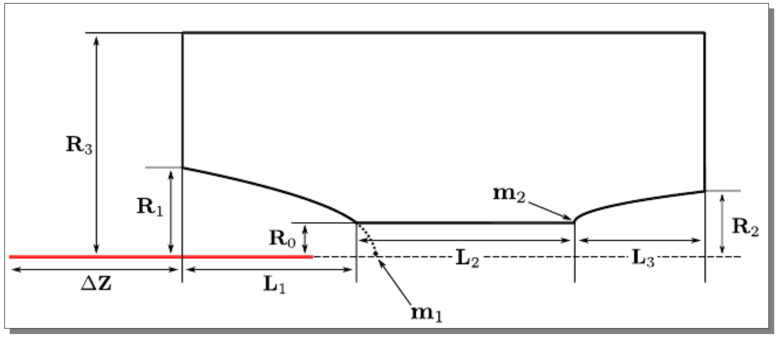
Burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa

10ms pulses repeated at 10 Hz at the SPS

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 fully take advantage of the flux increase

The Detector

- **e^+ tagging** in **[1-3] GeV** range
- e^+/π^+ separation

→ **Longitudinal segmented calorimeter** with energy resolution $< 25\%/\sqrt{E(\text{GeV})}$

- **Sampling calorimeter**: sandwich of plastic scintillators and iron absorbers

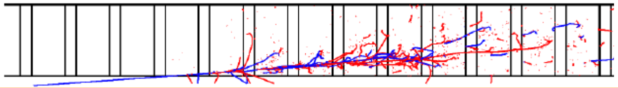
  Basic unit → LCM = Later Compact Module

- WLS-fibers/SiPMs for light collection/readout

Calorimeter

Longitudinal Segmentation, Plastic scintillator + absorbers

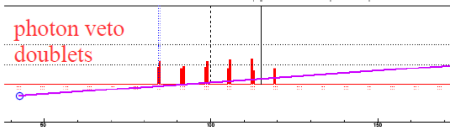
→ $e^+/\pi^+/\mu$ separation

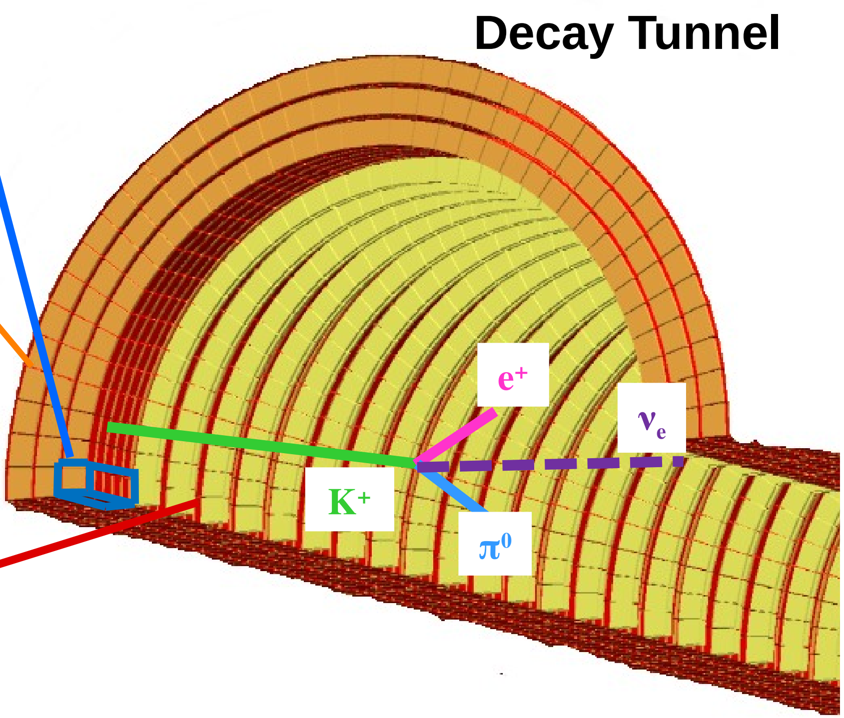


Integrated photon veto

Plastic scintillators, Rings of 3x3 cm^2 pads

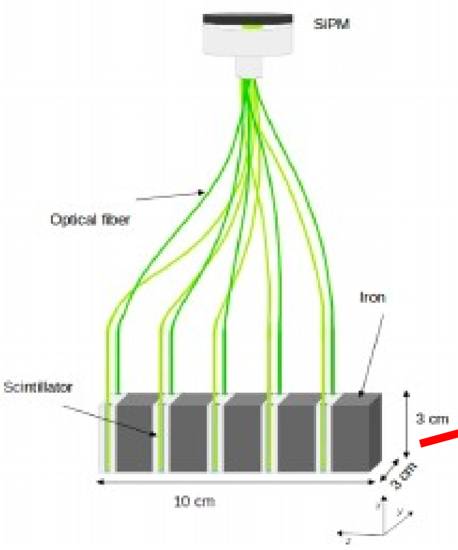
→ π^0 rejection



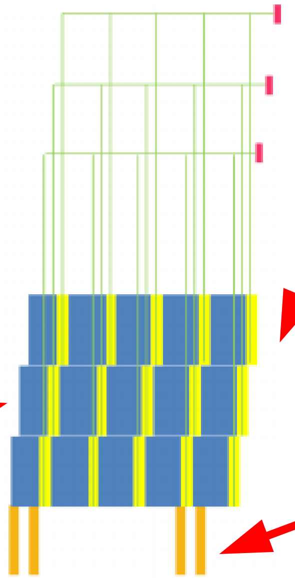


The Detector

A Lateral readout Compact Module LCM



Calorimeter layout



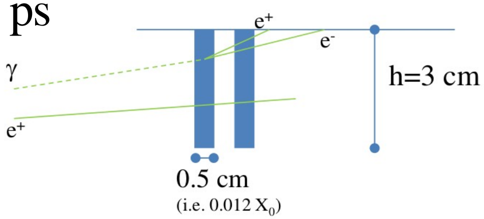
beam

Calorimeter with e/π/μ separation capabilities:

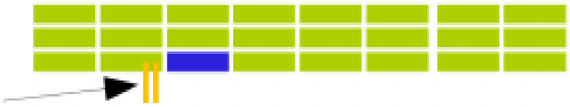
- LCM: sandwich of **5 steel tiles (3x3x1.5 cm^2)** interleaved with **5 plastic scintillator tiles (3x3x0.5 cm^2)**
  - longitudinal segmentation
  - SiPM active area: 4x4mm^2 , Cell size: 40 μm
- three radial layers of LCM
- Each LCM has **10 WLS (1mm) fibers coupled with SiPM**

Photon-Veto allows π^0 rejection and timing:

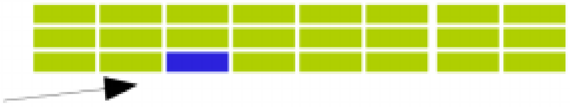
- plastic scintillator tiles arranged in doublets forming inner rings (3x3x0.5 cm^2 mounted below the LCM)
- time resolution of ~400 ps



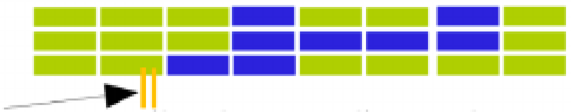
Exploit event topology for PID



e^+ (signal) topology



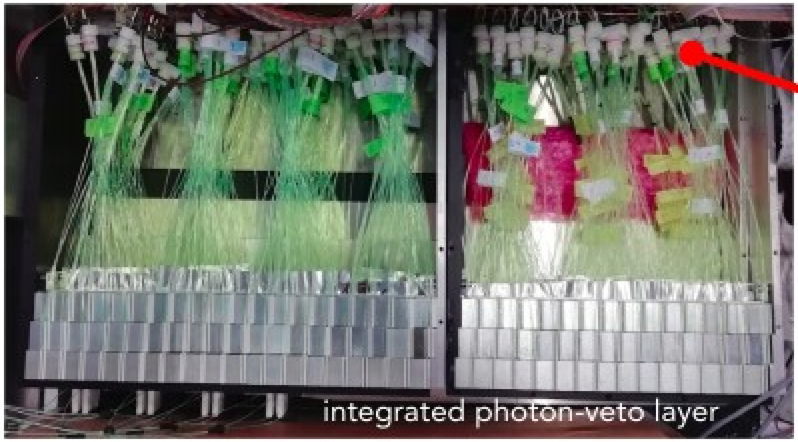
π^0 (background) topology



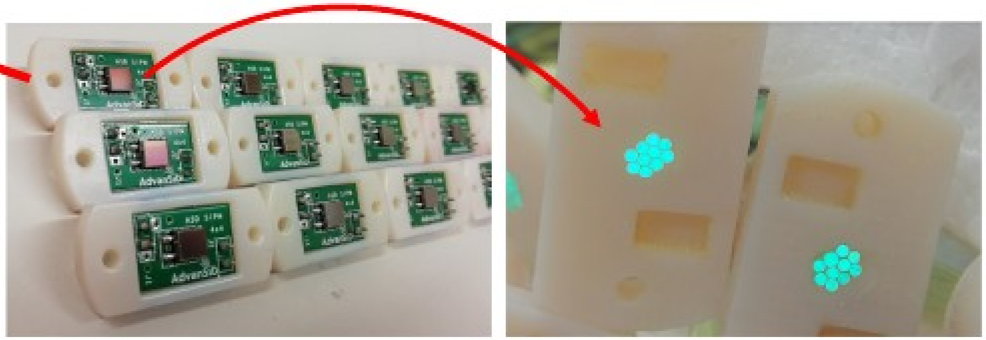
π^+ (background) topology

The Detector
Prototype Test Results

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

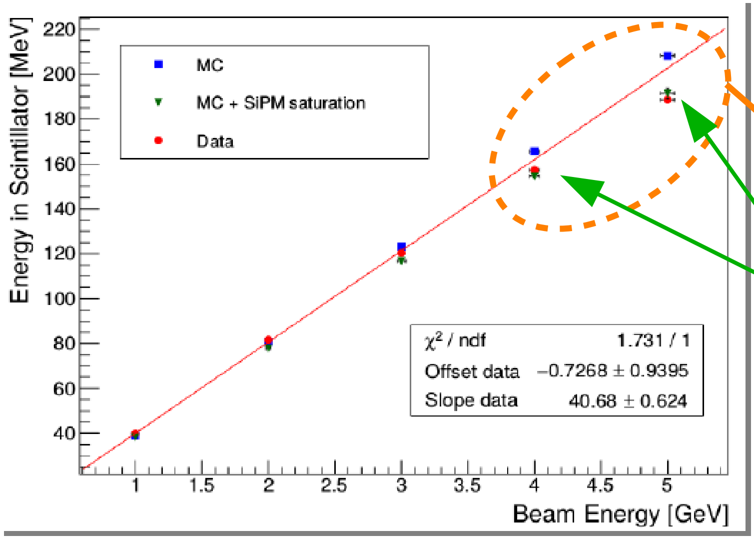


Large SiPM area (4x4 cm^2) for 10 WLS readout (1 LCM)



SiPMs installed outside of calorimeter, above shielding:

- 7 planes on a 3x4 matrix → 30 X_0 , 3.15 $\lambda_{0,}$ Transverse dim. 12X9cm^2
  → Containmnent of em showers up to 5 GeV
- Beams tested: e^-, μ^-, π^- with momentum [1-5] GeV
- Angles tested w.r.t beam direction (mimic K_{e3} positron): 0, 50, 100, 200 mrad

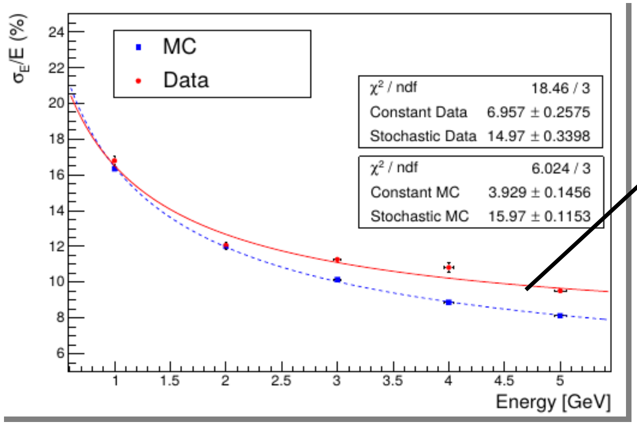


Reconstructed Energy: Data/MC comparison at 100mrad

SiPM saturation effect ($P_{x\text{-talk}}$~44%)
→ dedicated meas. campaign @ INFN lab →
MC corrected for the effect, accounts for non-linearities

The Detector
Prototype Test Results

Energy Resolution at 0mrad



- Fit $\sigma_E/E = S/\sqrt{E(\mathrm{GeV})} \oplus C$
- **17% en res. at 1 GeV**
- Impact point of the particle affects contribution to saturation at higher en: particles near the edge of the tile are shared between adjacent LCM → lower contribution to saturation than those in the center

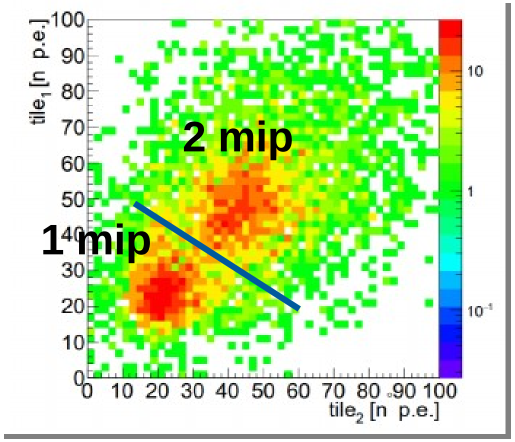
→ Mean Energy deposited by π^- in each plane of the calorimeter from data evaluated and compared to simulation: discrepancy below 10% and comparable to uncertainty due to low-energy hadronic shower simulation

Photon veto detector = **t_0-layer** needs
- **γ ID capability**
- **Precise timinig**

Doublets of plastic scintillator tiles

→ Positrons of K decays in ENUBET cross 5 tiles on average

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



→ **Results published in 2020**, F. Acerbi et al., JINST 15 P08001

Next:
- ✔ Optical simulation is being included in the detector simulation to replicate the SiPM saturation effect due to the particle impact point
- ✔ Collaboration with FBK* to test different sensors → Identification of the most suitable

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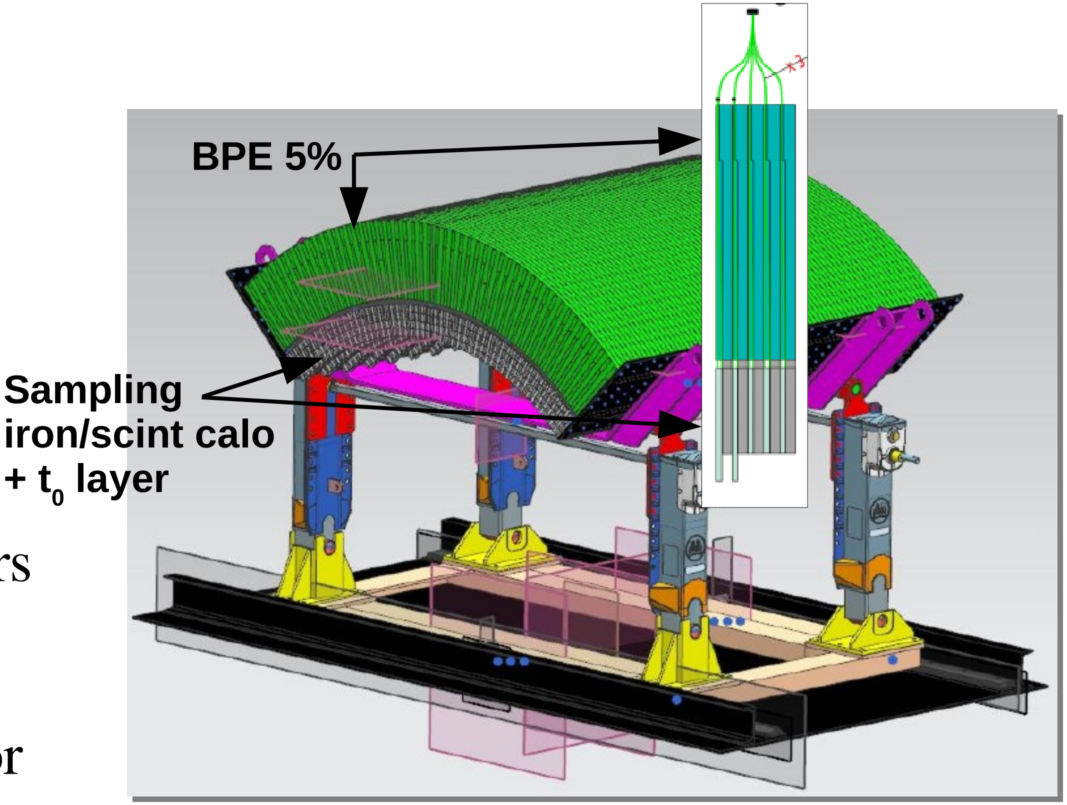
* Fondazione Bruno Kessler

The Detector
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

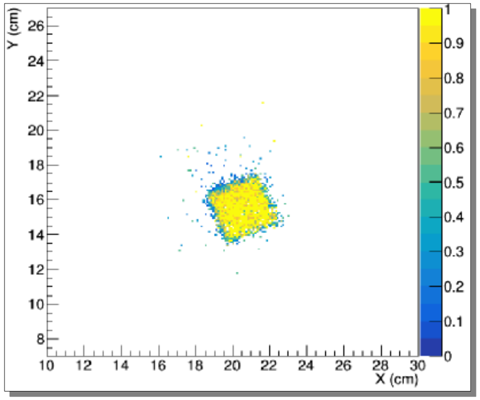
- Will **instrument central 45°,** rest kept for mechanical considerations
- **Modular design → can be extended to a full 2π** object by joining 4 of these modules

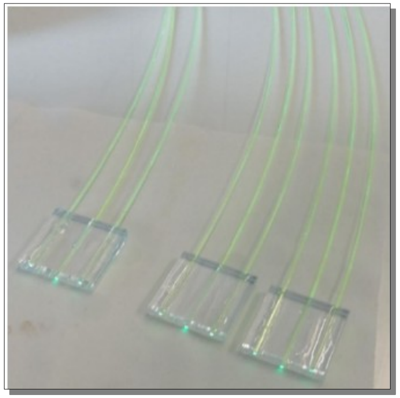


The Detector
The Demonstrator

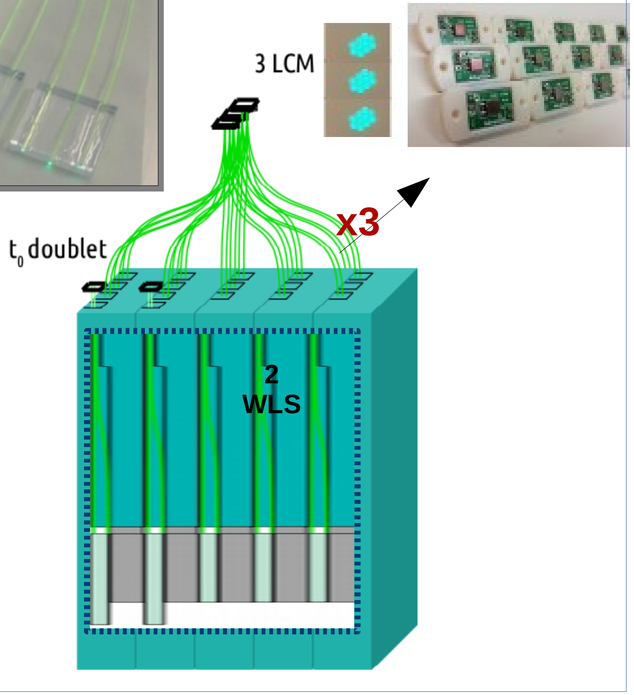
Several activities currently on-going towards the test of the demonstrator

- 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 Tagger Simulation

- Response simulated at **hit level** (no scint. process no light propagation) assuming **2 s slow extraction with 4.5 10^{13} POT/spill**
- **GEANT4** Standalone package (**G4TAG**) reproducing the detectors in the decay tunnel:
photon veto + calorimeters → monitoring of positrons from $K_{e3} \rightarrow \nu_e$
& of muons from $K_{\mu 2}$ and $K_{\mu 3} \rightarrow \nu_\mu$
stations after the h-dump → monitoring of muons from π decay → low-E ν_μ monitoring

K_{e3} POSITRON MONITORING

- **Event Building**: - Hits in the instrumentation belonging to the same decay are correlated in space and time
  - "Seed" of the event = visible energy deposit in LCMs of innermost layer > 28 MeV
  - LCM & t_0 signals of the seed are clustered by position and time
- **Signal/Background Discrimination** by longitudinal, transverse and radial segmentation of the calorimeter + γ background suppression with t_0-layer

  EM Showers: more localized w.r.t. hadronic showers
  Muons + non-interacting hadrons: discarded by their single-track topology in the event seed selection
- **TMVA**: **Neural Network** with set of **19 variables**
  - t0-related variables → suppression of photon-like events
  - calorimeter energy related variables → suppression of hadronic K decays & non-collimated pions

→ S/N ~2 & 22% efficiency

The Physics Performance
The Tagger Simulation

$K_{\mu 2}$ & $K_{\mu 3}$ MUON MONITORING

- **Event Building**: - Space and time clustering of energy deposits compatible with a **track from a muon**
  - "Seed" of the event = visible energy deposit in LCMs of innermost layer compatible with a mip: $5 < E < 15$ MeV
  - Track Length ≥ 3 LCMs in 1st layer + 2LCMs in 2nd and 3rd layer
  → Total of 7 LCMs all in different positions along the longitudinal direction

- **Signal/Background Discrimination**: Backgrounds:
  - Larger contribution = halo muons
  - Second order = μ from π decays at large angles + beam π or π from K decays
  - **TMVA**: **Neural Network** with set of **13 variables**
    - muon impact point along the tagger → suppression of halo muons
    - calorimeter energy related variables → suppression of pions (not mip-like)

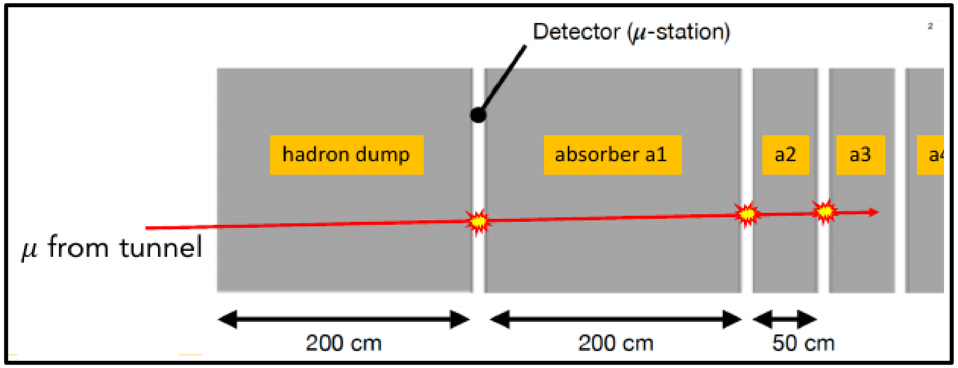
→ S/N ~6 & 34% efficiency

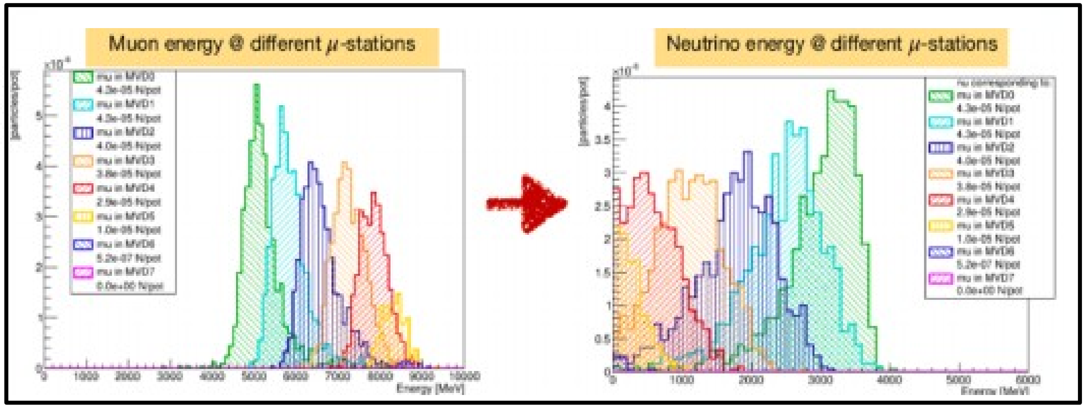
The Physics Performance
The Muon Chambers

Low-E ν_μ from π decays can be constrained by monitoring associated μ → **emitted at low angle**

→ **go through** the tunnel and **the h-dump**

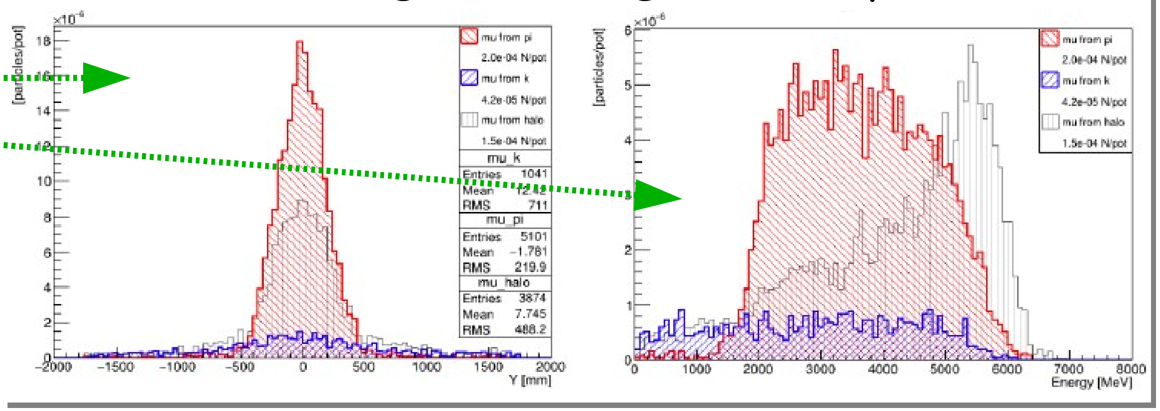
→ Instrumented h-Dump: **detector layers interleaved by absorber**





—, — signals, — background (halo-μ)

→ Can measure **μ spatial distribution & energy**



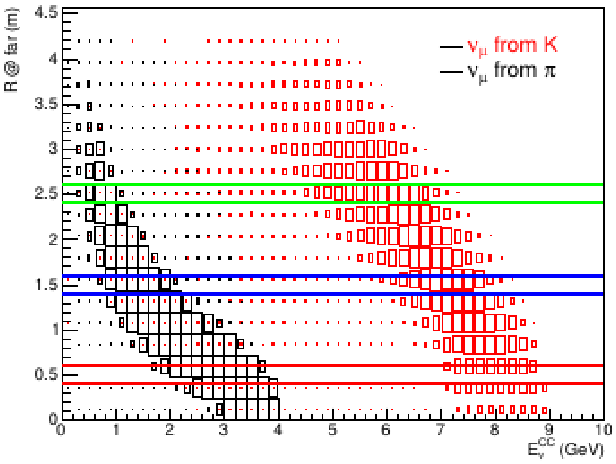
- Detector needs to cope with muon rate 2 MHz/cm^2 & neutron fluence 10^{12} 1MeV-eq/cm^2

→ Selecting best technology in collab with Univ. Of Thessaloniki

The Physics Performance
Narrow-band Off-axis Technique

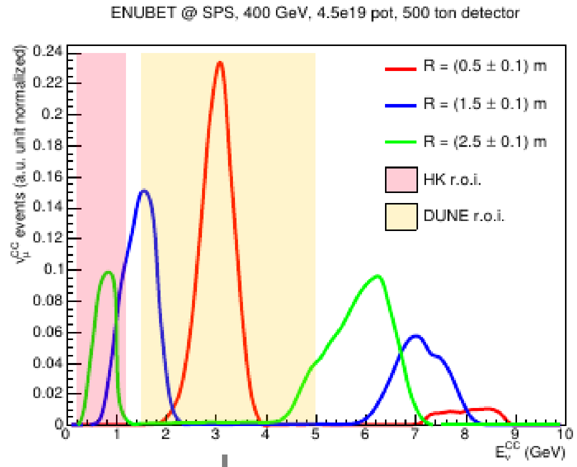
Narrow momentum width of the beam (O(5-10%))
+ finite transverse dimension of the neutrino detector

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

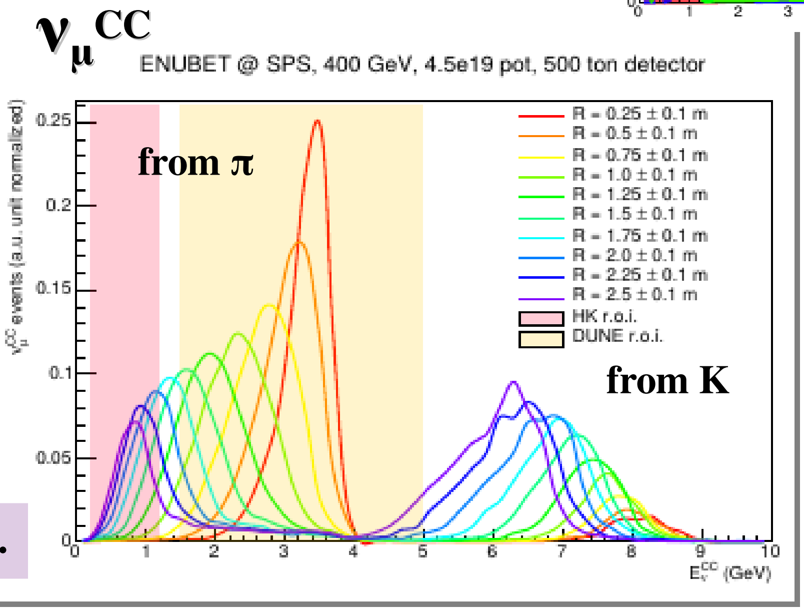


By selecting interactions in radial windows of ±10 cm

we collect respective samples of ν_μ CC events



With realistic beam
provided by latest simulations including beam halo and off-momentum mesons



500 ton LAr
cross-sectional area 6x6 m^2
50m from tagger exit

Unit norm.

The Physics Performance
Narrow-band Off-axis Technique

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

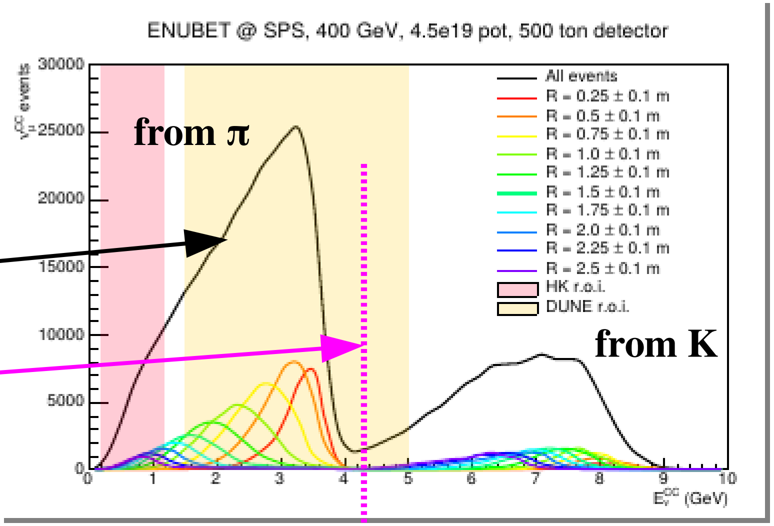
Strong correlation between **E_ν** in the detector and the **radial distance (R) of the interaction vertex from the beam axis**

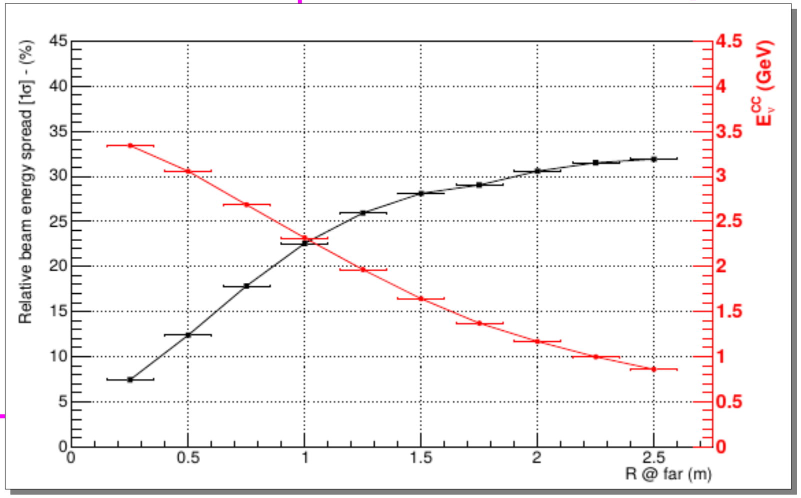
- **500 ton LAr detector**
- **Interaction rates from convolution of flux and CC x-sec,** full detector response not yet included
- **Total 4 10^5 ν_μCC**, assuming 4.5 10^{19} POT

- Loose energy cut enough to separate π/K component
- **Width of pion peak at different R** → estimator of the **precision on E_ν**

→ **8% to 25%** @ DUNE energies

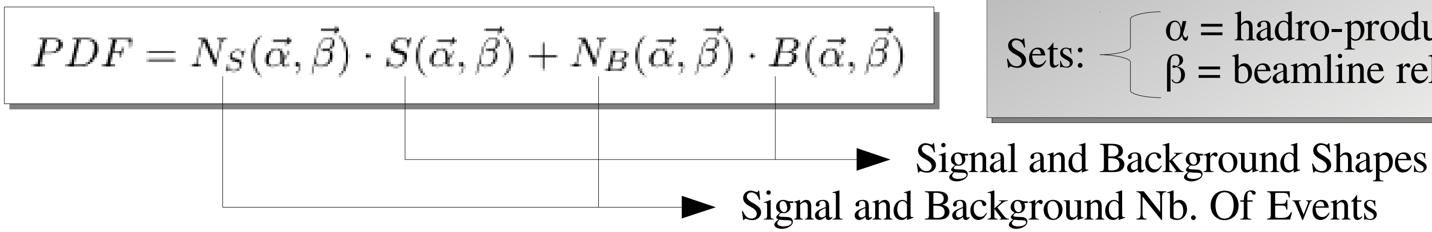
In HK r.o.i 30% → possible improvement with multi-momentum beamline





The Physics Performance
Assessment Of 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:



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

Signal and Background Shapes

Signal and Background Nb. Of Events

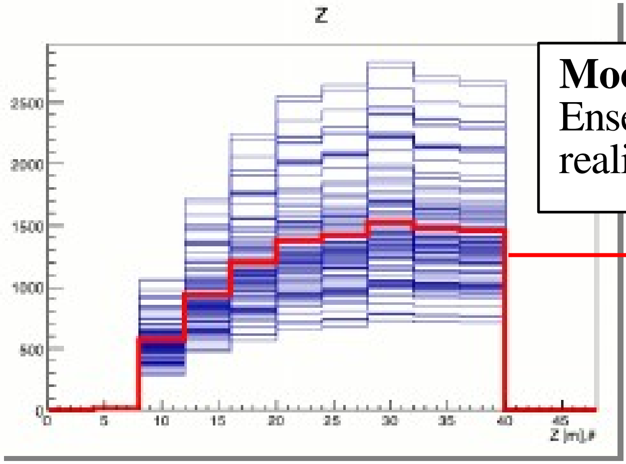
Sets:
α = hadro-production nuisances
β = beamline related nuisances

- **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

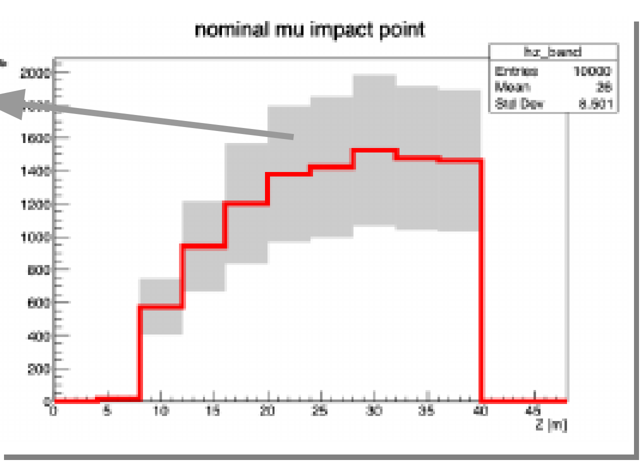
Ex: **Z position** = impact point along the tagger, **for μ from K decays**



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

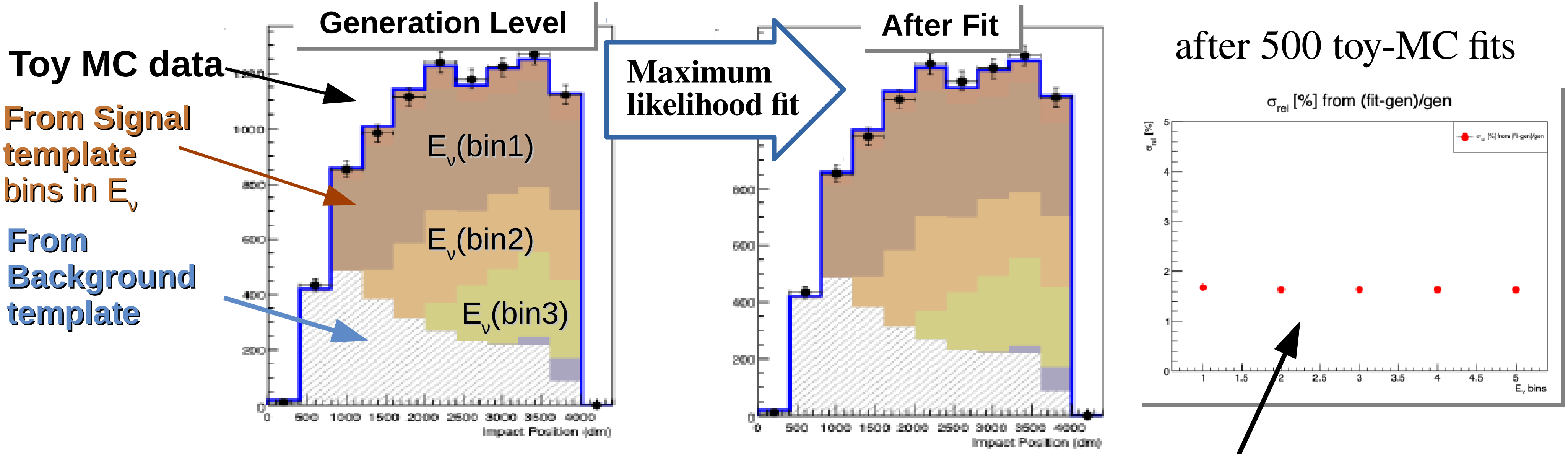
1σ band evaluated from varied histograms



The Physics Performance
Assessment Of 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



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

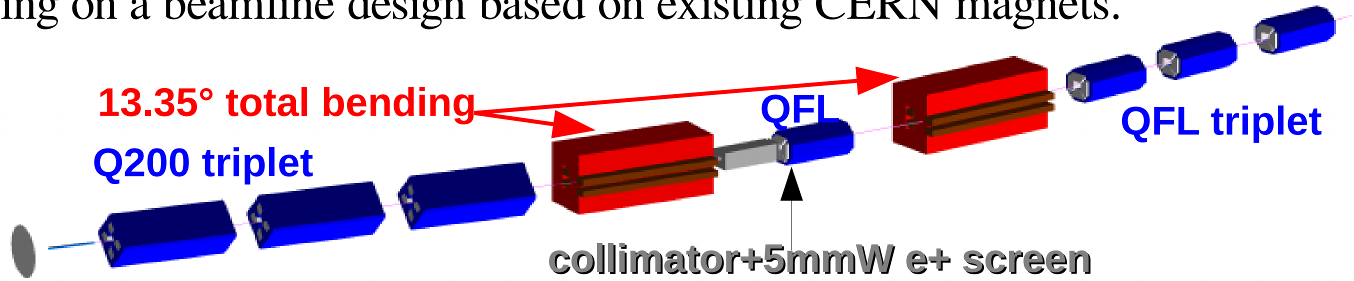
- **Next Step:** From a toy to the real ENUBET case using full simulation
  - Use real hadroproduction data (400 GeV POT, NA56/SPY) and related syst. uncertainties to correct MC
  - Use facility parameters to assess impact

Future Developments & Possibilities

Honourable Mentions:

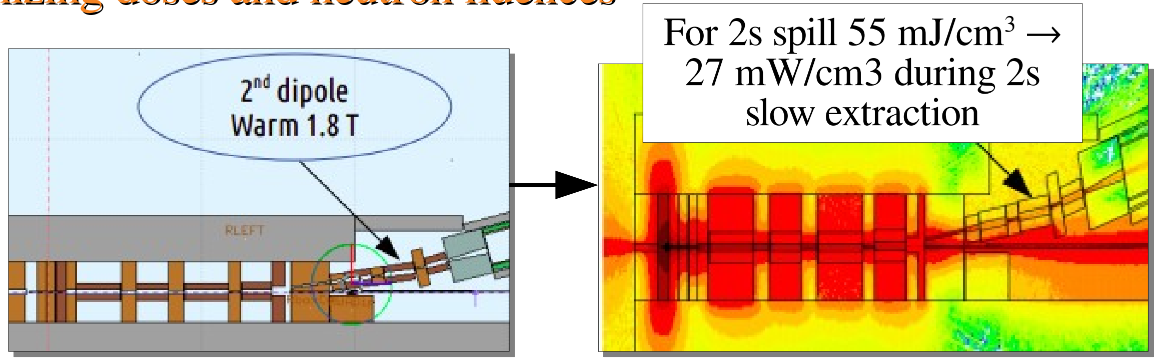
- **Multi momentum beamline:** to achieve a design flexible enough to explore also Hyper-K ROI at lower momenta → currently working on a beamline design based on existing CERN magnets.

overall max angular acceptance ±20mrad both planes



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

- **Super conducting dipole:** the static transferline is also fully implemented in FLUKA to estimate ionizing doses and neutron fluences



For 2s spill 55 mJ/cm^3 → 27 mW/cm3 during 2s slow extraction

Estimated doses would allow the use of a super conducting second dipole without quenching risk

→ Increase total bending angle

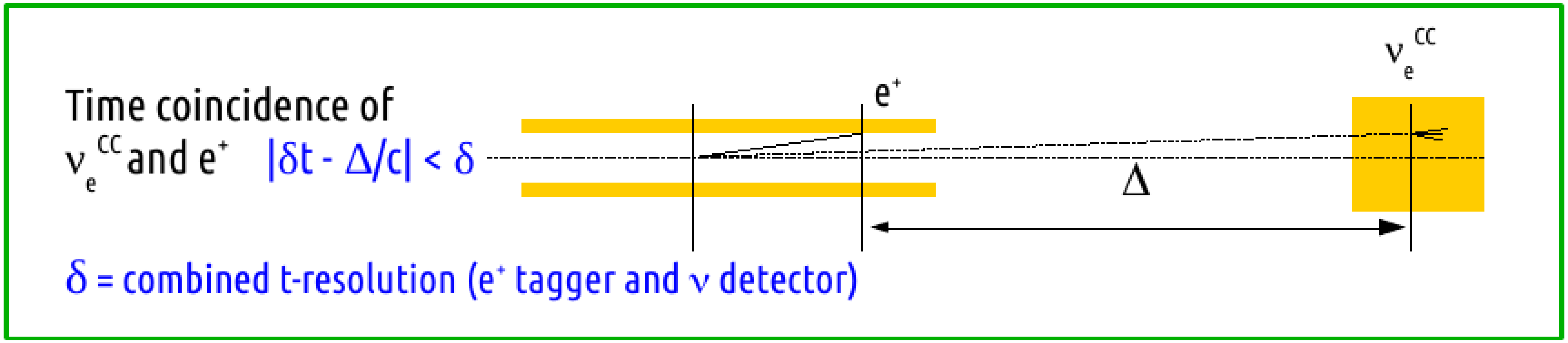
→ Better separation of ν_e component from tagger at the far detector

+ better momentum separation w.r.t higher and lower meson momenta → cleaner spectrum at tagger entrance

→ Currently working on optic optimization (TRANSPORT) & G4Beamline implementation

Future Developments & Possibilities
Tagged Neutrino Beams

In a **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:


Time coincidence of ν_e^{CC} and e^+ $|\delta t - \Delta/c| < \delta$

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

- **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

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

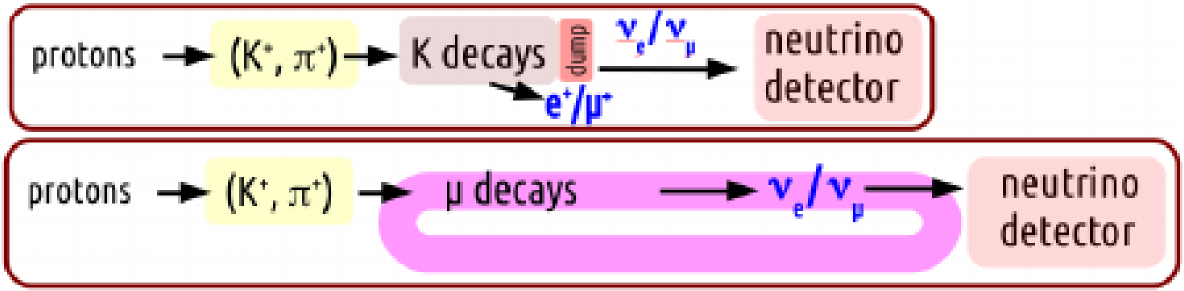
- Main Synergy with ENUBET:
- Target Facility
- 1st stage of meson focusing
- proton dump

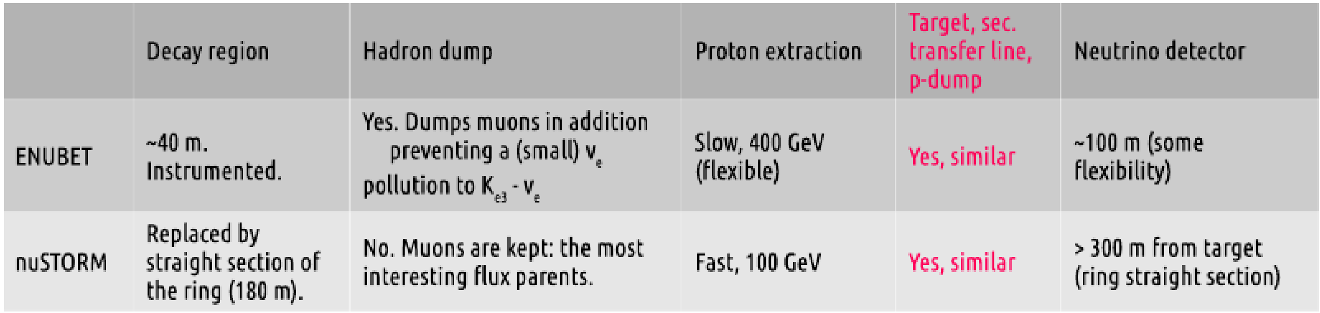
→ ENUBET specific: opportunity for a tagged neutrino beam

- Emphasis on the implementation at CERN and possible use of existing facilities/detector

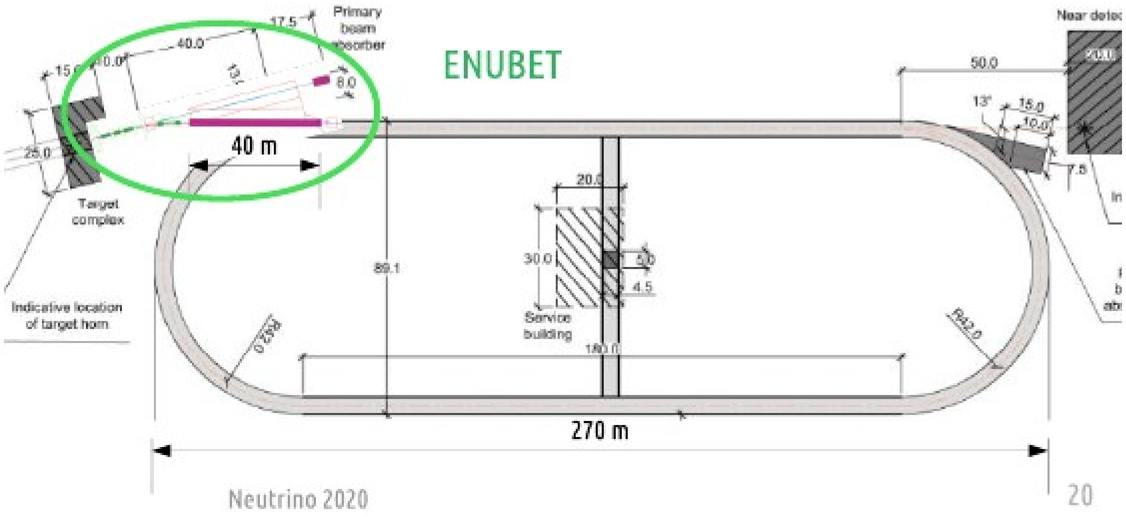
- The 2 collaborations are currently evaluating the synergy at facility-level

- ENUBET/nuSTORM programme presented at last Physics Beyond Colliders Annual Workshop

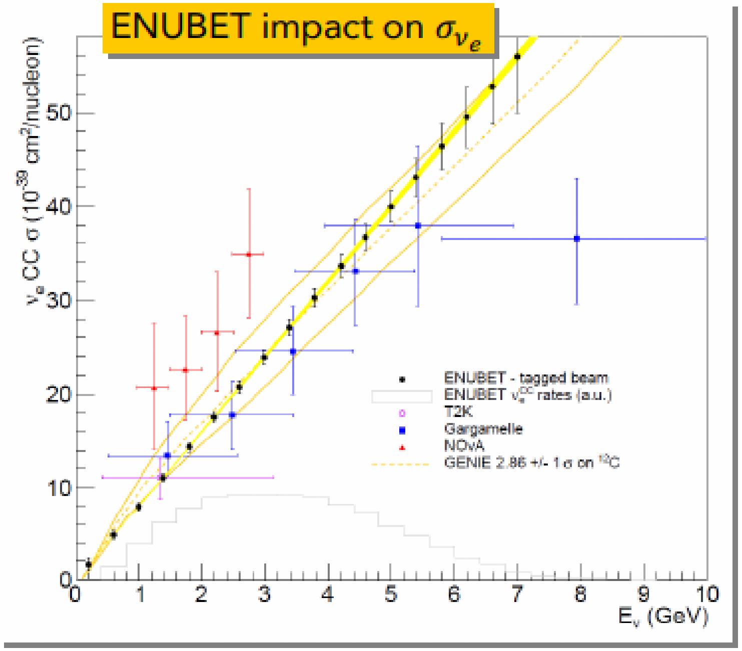




	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section 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)



Conclusions



- The ENUBET project is an ERC Consolidator Grant, extended to 2022, and part of the Neutrino Platform experiments at CERN (NP06) that 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**

  Will do so employing:

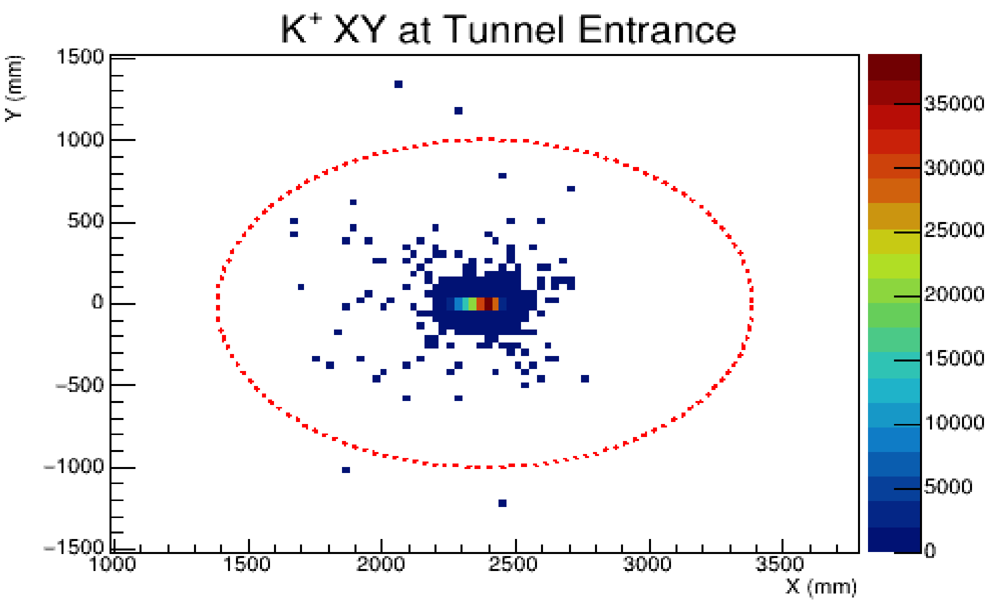
- **A Conventional narrow-band neutrino beam**
  - Static transferline: → good S/B & efficiency
    → good neutrino yields
    → ROOT tools + complete GEANT4 simulation in place for single particle e^+/μ^+ monitoring, physics performance and systematics assessment
  - Very appealing Horn-based option → experimental proton “burst” slow-extraction tested
    → Horn+dedicated beamline optimization on-going
- **An Instrumented decay tunnel → Longitudinal segmented calorimeter**
  - Test beam campaigns at CERN on calorimeter modules completed
  - New Frontal readout option + Construction of the demonstrator and electronics in progress → next step: test at PS East Hall summer 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**

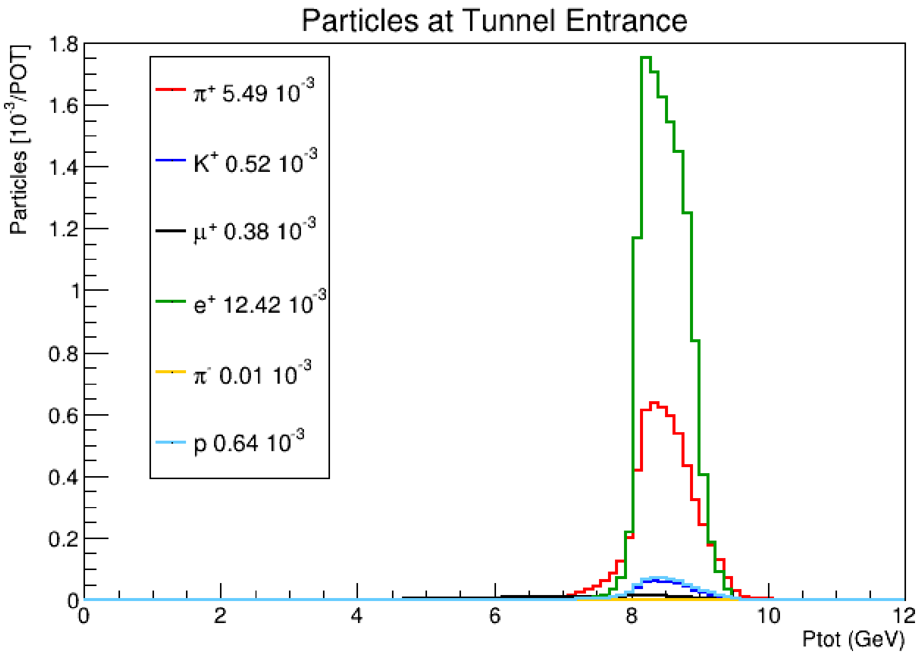
Thank You!

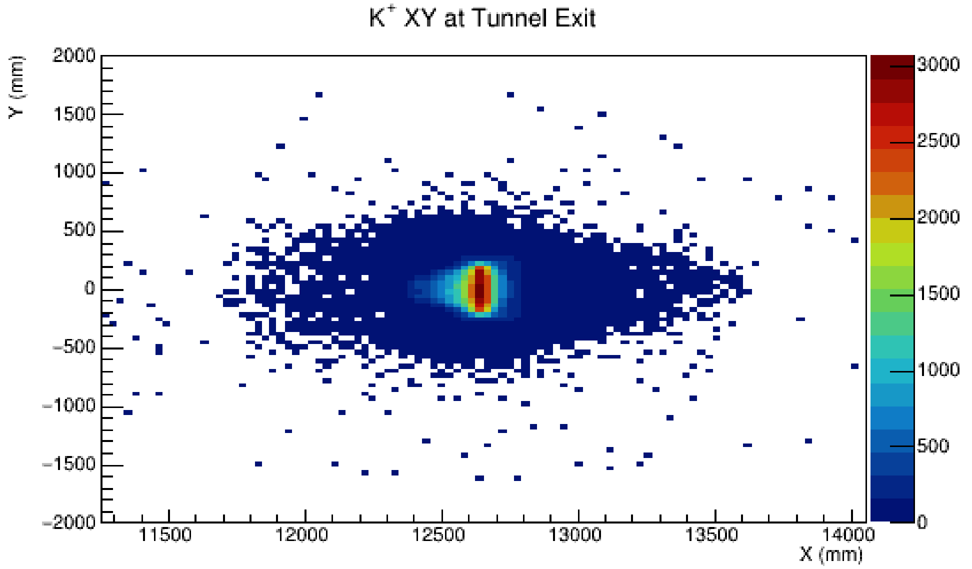
https://enubet.pd.infn.it/

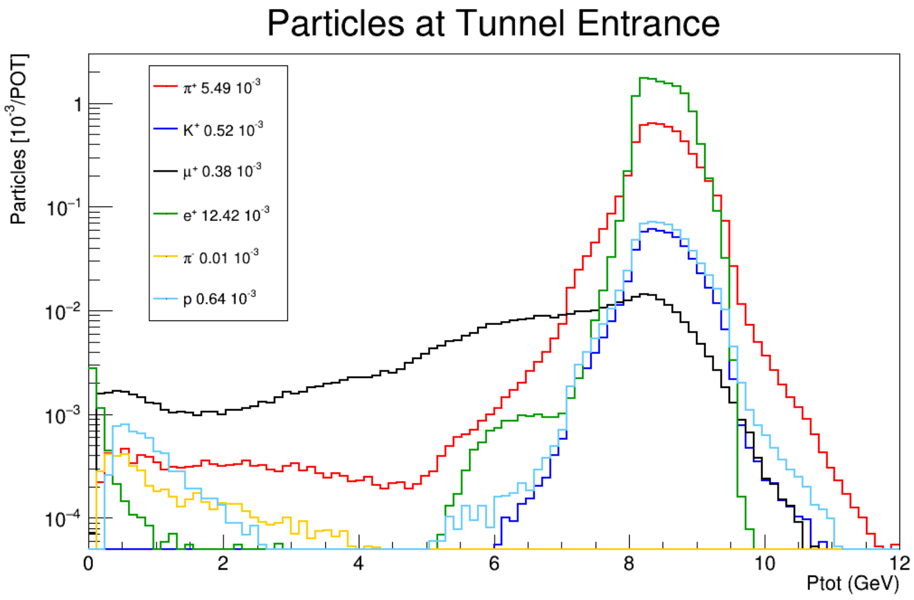
Back-Ups

Static TL spectra @ Tunnel entrance

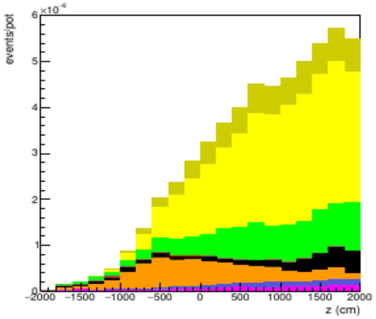




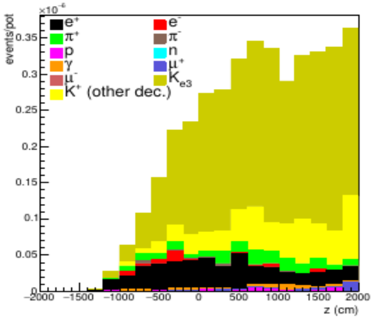




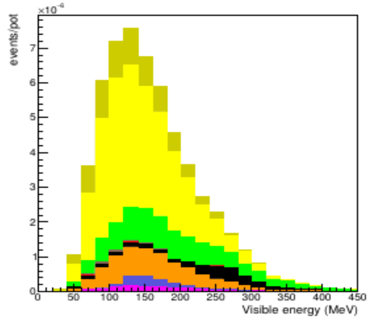
Positron & Muon Monitoring



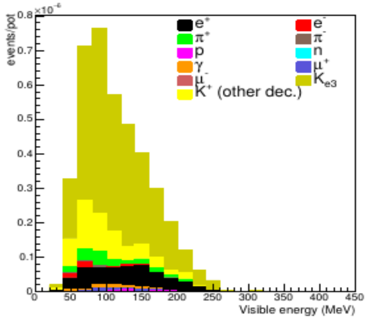
Longitudinal position after event building

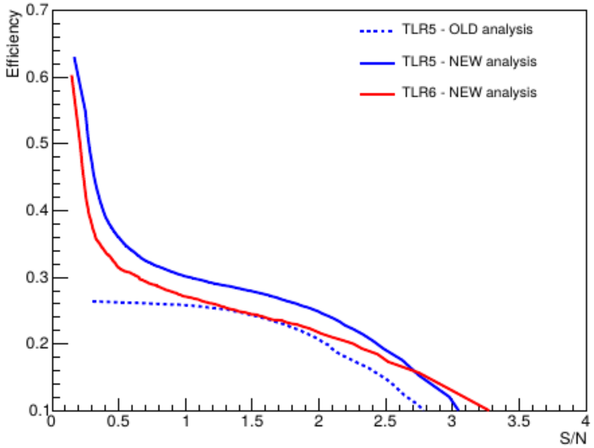


after the NN discrimination.

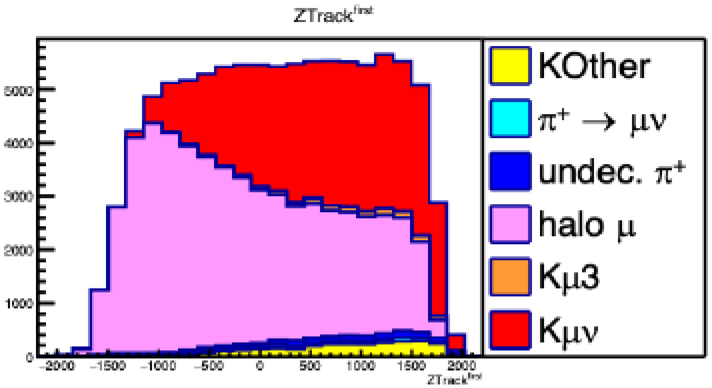


Total Energy after event building

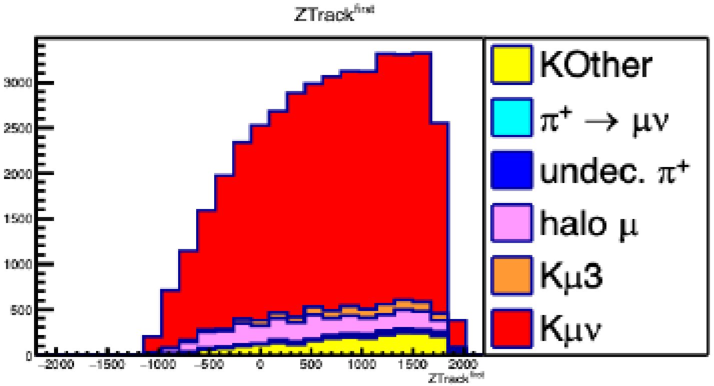




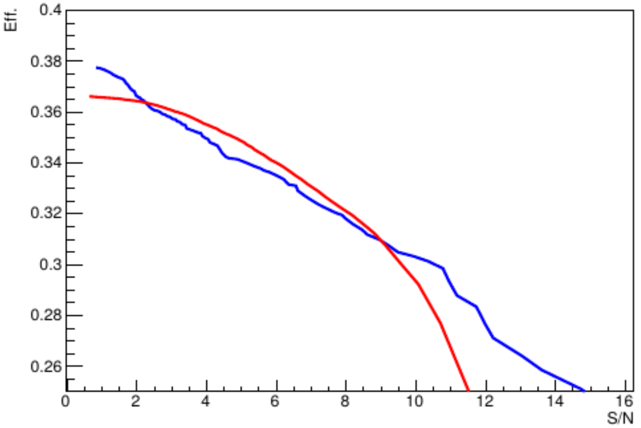
Efficiency as a function of the signal-to-noise ratio in the selection of Ke3 events. Red: Latest Results. Blue: previous results



Distribution of the impact point along the calorimeter for muons from kaon decays. Red and Orange: Signal Kμ2, Kμ3 Purple: main background: halo muons Other colors: Subdominant background contributions



Same after NN cut



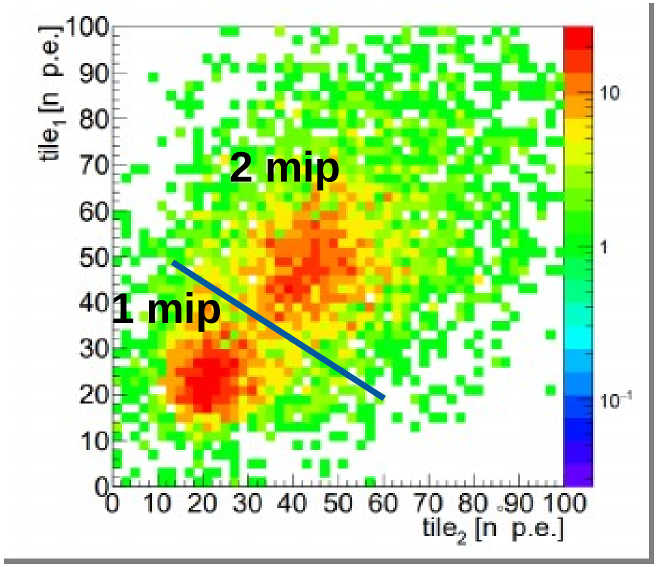
Signal efficiency versus signal-to-noise ratio for Kμ2 and Kμ3 events selection. Red: latest results, Blue: previous results

The Detector
Prototype Test Results - Photon Veto

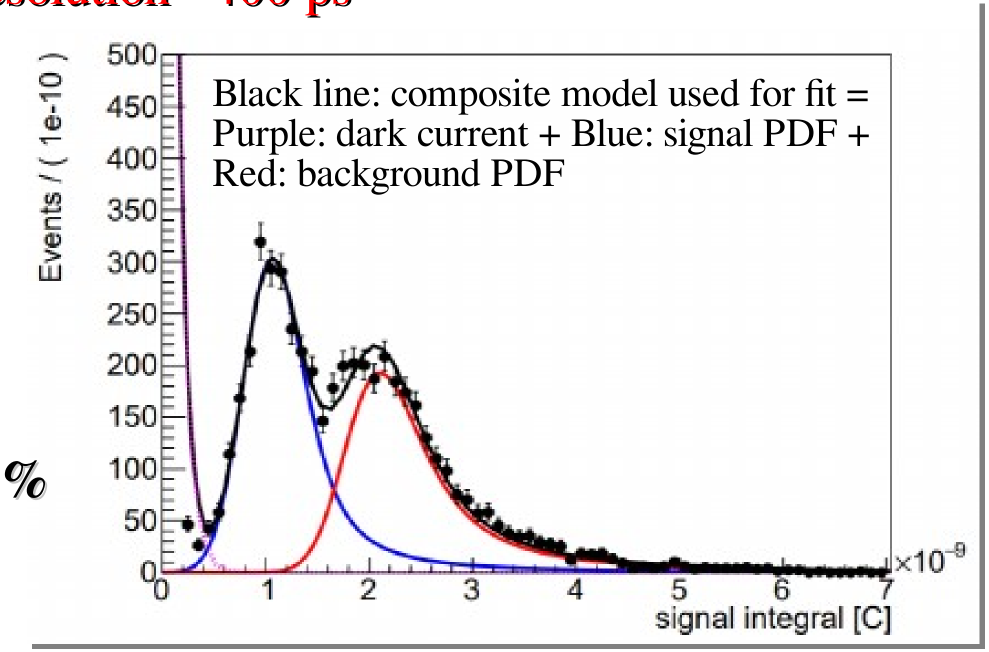
- Photon veto detector = **t_0-layer** need
  - **γ ID capability**
  - **Precise timinig**

  with:
  - γ ID efficiency at 99%
  - Time resolution ~ 1 ns
- **Doublets of plastic scintillator tiles** 3x3x0.5 cm^2 mounted below the LCM every 7 cm
  → Positrons of K decays in ENUBET cross 5 tiles on average

Test beam results*



✔ Light yield for a single mip crossing a t_0 tile → collection of 25 p.e. with time resolution ~400 ps



Black line: composite model used for fit =
Purple: dark current + Blue: signal PDF +
Red: background PDF

✔ 1-mip/2-mip separation:
- Single t_0-tile selects **1-mip signal with ε=87%**
- **Background rejection ε=89%** (2-mip like)
- **95% Purity**

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* F.Acerbi et al., 2020, JINST 15 P08001

The Physics Performance
The Waveform Simulation

- Pile-Up Study with waveform simulation: ENUBET is currently implementing in the simulation a framework to simulate the calorimeter response including the effects of the pile-up

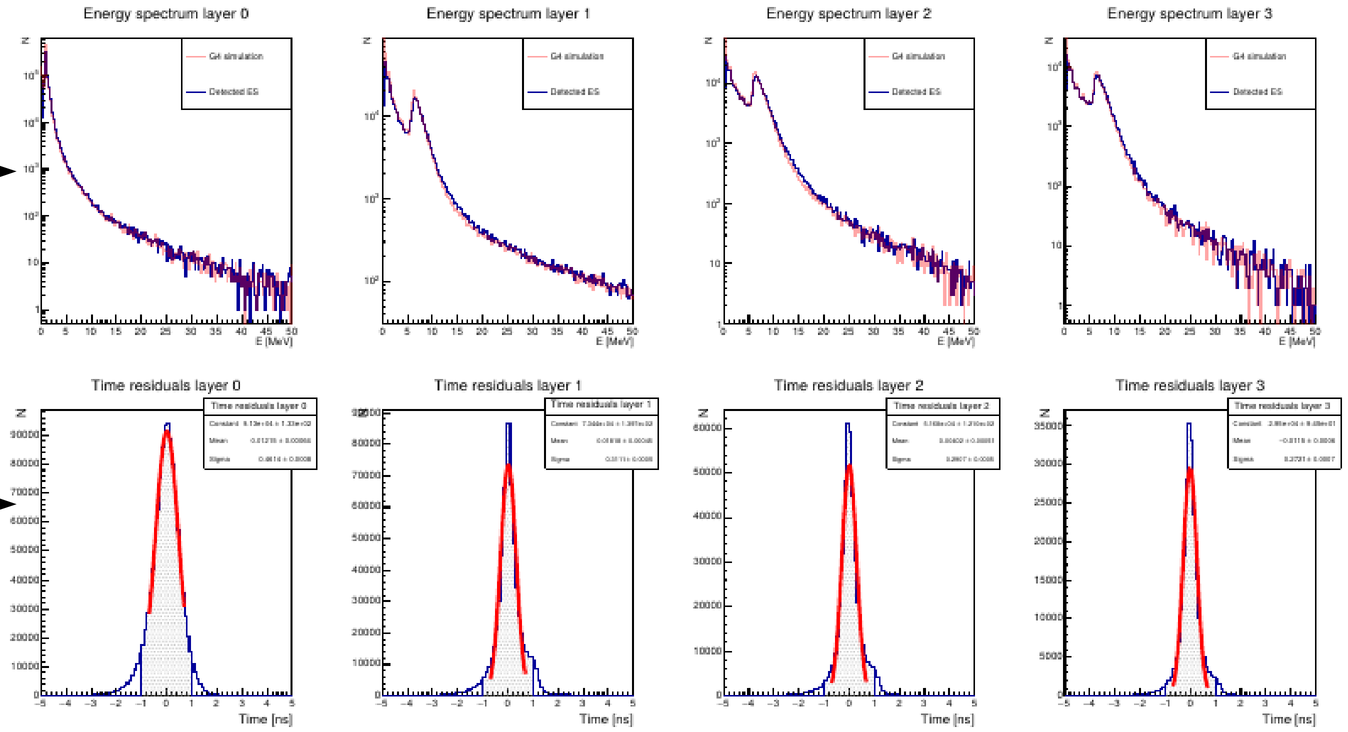
→ **Waveform simulation will be included in the lepton reconstruction chain** once fully debugged

1. Convert each visible energy deposit coming from G4TAG into photons hitting the SiPMS
   Conversion factor ~15 photo-e/MeV from test beams
2. SiPM response simulated with GosSiP (Generic framework for the Simulation of Silicon Photomultipliers)
   → Generation of a waveform for each channel
   → Waveform processed by Pulse detection algorithm
   → Convert back the result to time series of energy deposits
   → Back to Event Builder

Calorimeter layers

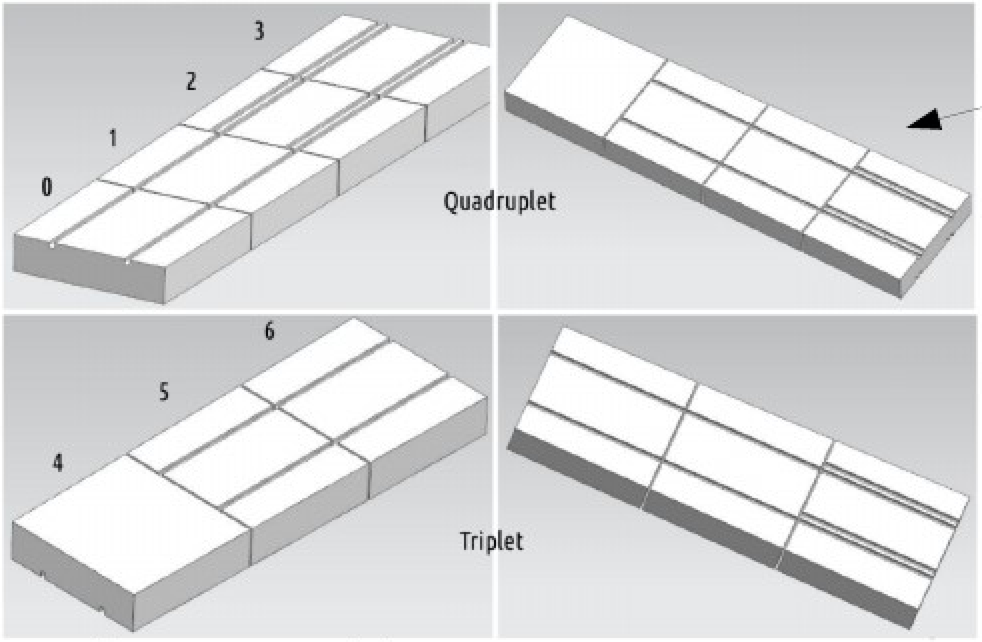
__ deposited en from GEANT4
__ deposited en measured after waveform sim.

Residuals between original hit times and pulse time detected

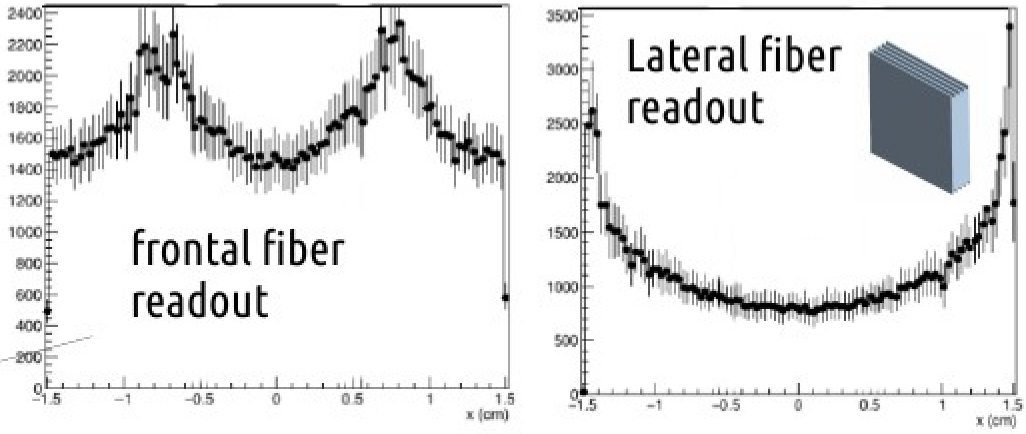


Frontal Light Readout

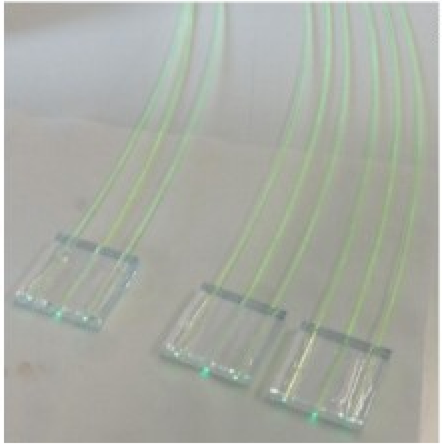
- From lateral to frontal light collection
- Safer for injection molding. More uniform, efficient.
- Each tile has readout grooves and “transit” grooves.
- Readout grooves on alternate sides.
- Staggering for the two tiles at larger r.

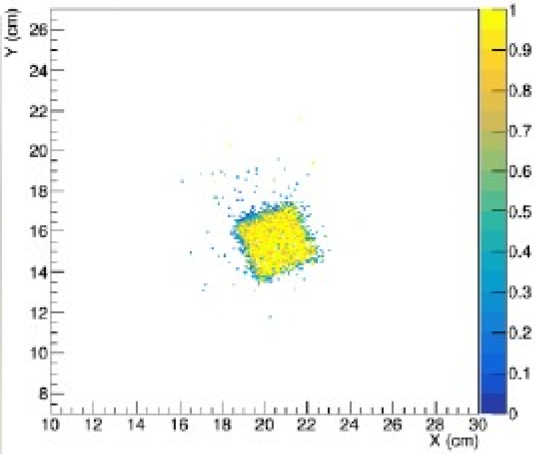


GEANT4 optical simulation



Uniformity tests with cosmic rays

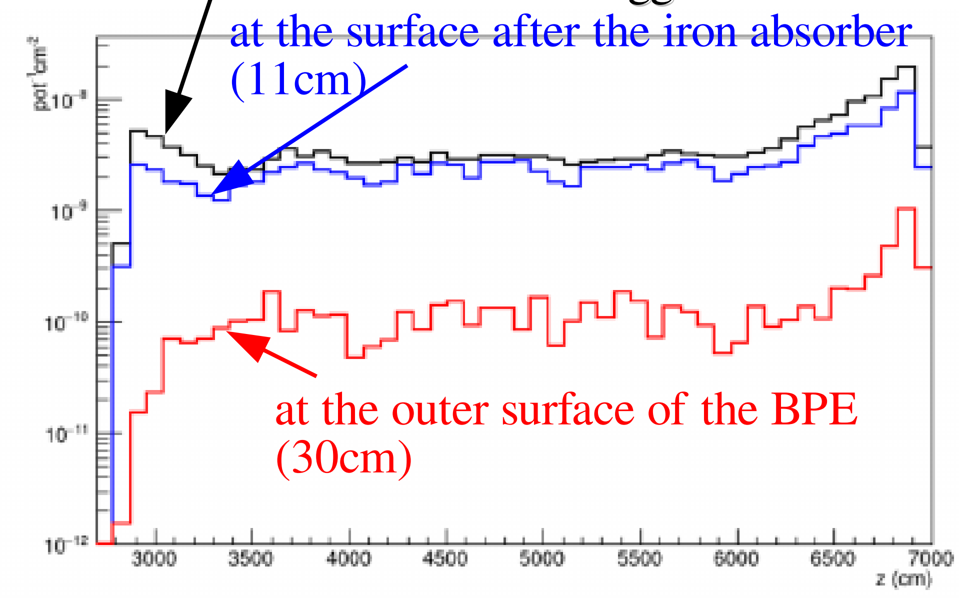




Calorimeter BPE shield

- The SiPM are protected by a shielding of Borated polyethylene (BPE, 5% Boron concentration) with a thickness of 30 cm. → Neutron reduction induced amounts to a factor of ~ 18 (average over the expected energy spectrum) and it's about 7×10^{-11} n/POT/cm2 in the middle region of the tagger (3.5×10^{9} n/cm^2 for 5×10^{19} POT)

Distribution of neutrons (neutrons/POT/cm^2) as a function of Z

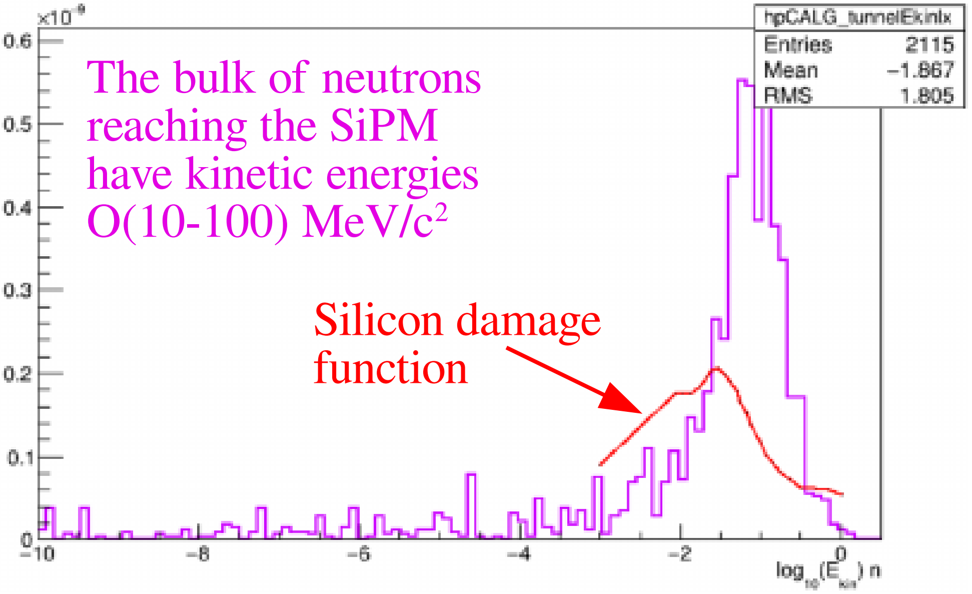


at the inner surface of the tagger

at the surface after the iron absorber (11cm)

at the outer surface of the BPE (30cm)

FLUKA estimate of kinetic energy spectrum of neutrons reaching the SiPMs in the middle section pof the tunnel

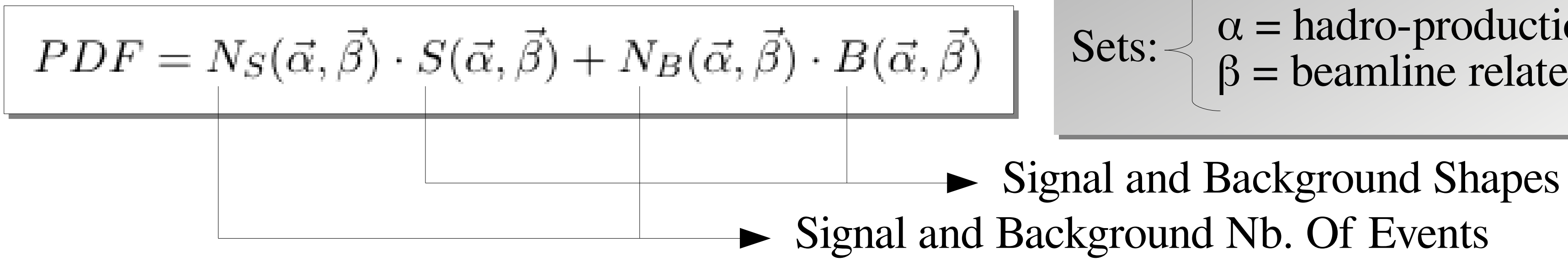


The bulk of neutrons reaching the SiPM have kinetic energies O(10-100) MeV/c^2

Silicon damage function

The Physics Performance
Assessment Of The Systematics

- ENUBET/NP06: Monitoring of the leptons produced together with the neutrinos → Better constraints on neutrino flux by-passing usual uncertainties on neutrino beams (hadro-prod. …)
  Parameters constrained from data used to reweight the simulation → higher precision on ν flux
- 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:



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

► Signal and Background Shapes

► Signal and Background Nb. Of Events

→ Systematics can affect both shape & normalization

- Maximization of an extended likelihood of the observed data where **nuisance parameters are constrained by a-priori knowledge**of the hadro-production $pdf(\vec{\alpha}|0,1)$ and the facility $pdf(\vec{\beta}|0,1)$ → Estimation of nuisance specific to ENUBET

Approach tested using **toy Monte Carlo** to study level of
Improvement in the systematics ↔ Gain in neutrino flux precision

The Physics Performance Assessment Of The Systematics

- ROOT RooFit package → Signal and Background templates:

  - built from distributions predicted by the simulation

  - allowed to change around their nominal values:

$$N(\vec{\alpha},\vec{\beta}) = N_0 \cdot (1 + \vec{r}_\alpha \cdot \vec{\alpha} + \vec{r}_\beta \cdot \vec{\beta})$$

$$T(\vec{\alpha},\vec{\beta}) = T_0 \cdot + \vec{\alpha} \cdot \Delta\vec{T}_\alpha + \vec{\beta} \cdot \Delta\vec{T}_\beta$$

Normalization

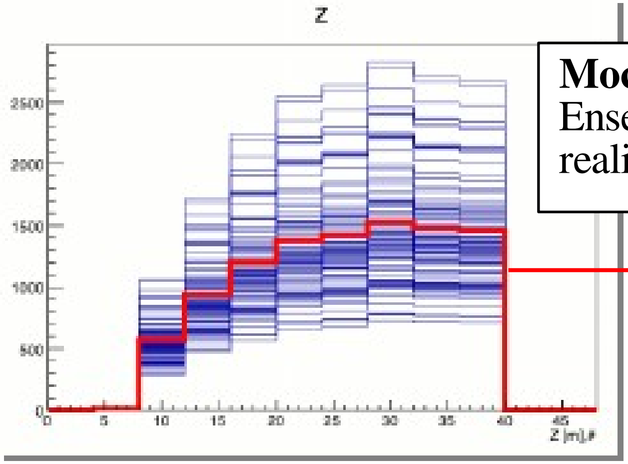
Shape

Nominal

r, ΔT = changes due to 1σ change in α and β

- Generation of set of Toy Monte Carlo experiments by setting the nuisance parameters to values extracted from their PDFs
- Fit each experiment to study the improvement on nuisance parameters due to the generated pseusdo-data

Ex: **Z position** = impact point along the tagger, **for μ from K decays → How does the obsevable change with hadroproduction variations?→** Multi-verse Method



Mock observable distribution
Ensemble of N possible realization of the distributions

Nominal distribution
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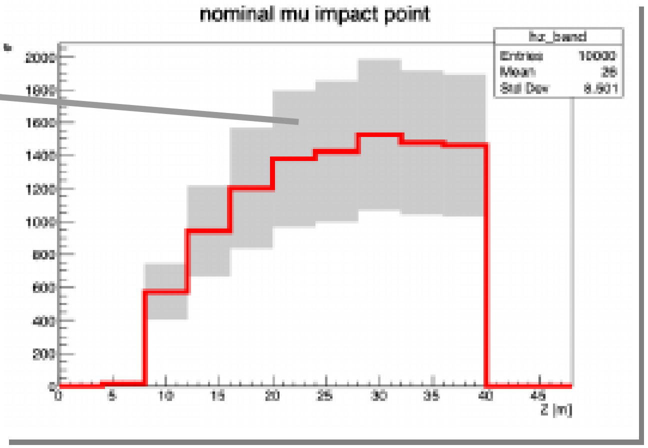
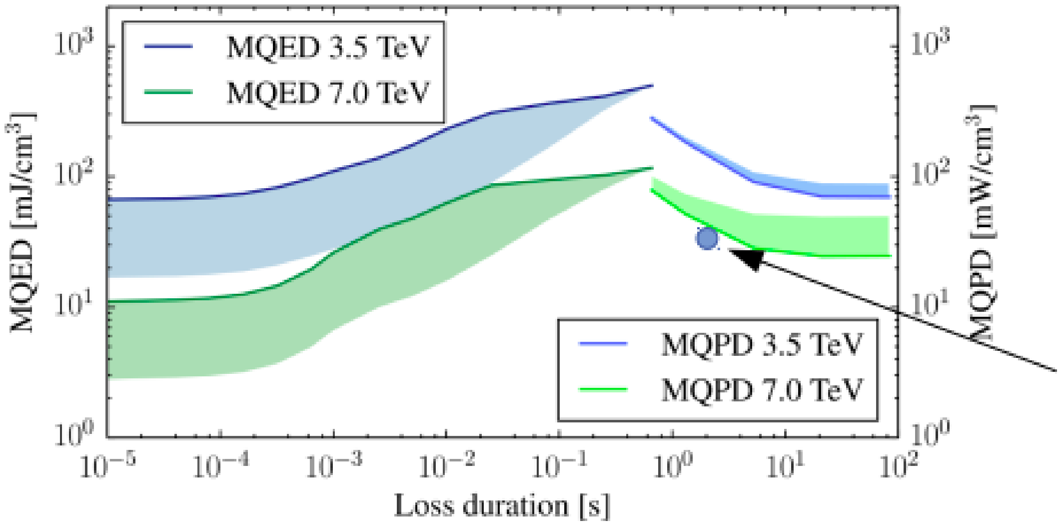
1σ band evaluated from varied histograms



SC Dipole

Comparison with:

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



Hottest region: 70 kGy = 70 kJ/kg per 1e20 POT

Iron: 7800 kg/m^3 → 1 kg = 1/7800 m^3 = 128 cm^3

70 kGy = 70 kJ/kg = 70 kJ/128 cm^3 = 547 kJ/cm^3

~1e13 POT/spill su 2 s

1e20 POT = 1e7 spill

per spill, su 2 s: 547 kJ/cm^3/1e7 = 55 mJ/cm^3

→ 27 mW/cm^3 during 2s slow extraction