The ENUBET monitored neutrino beam for high precision cross section measurements

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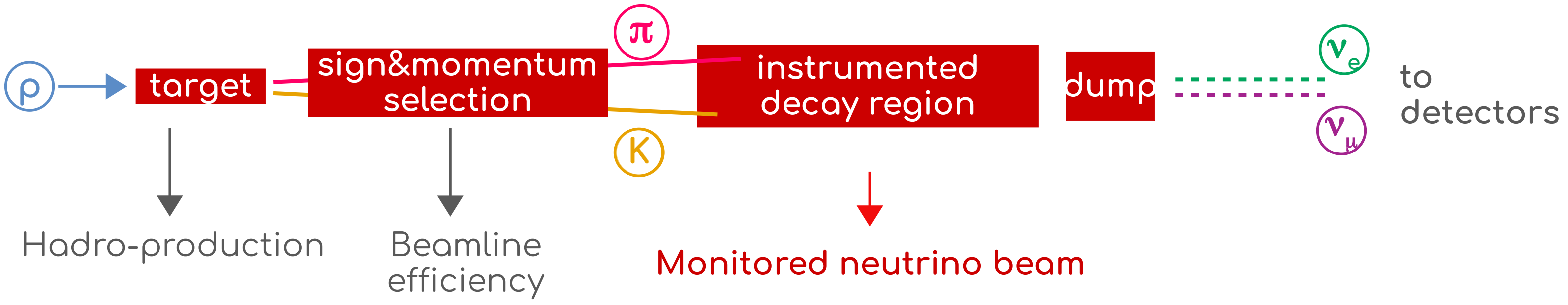
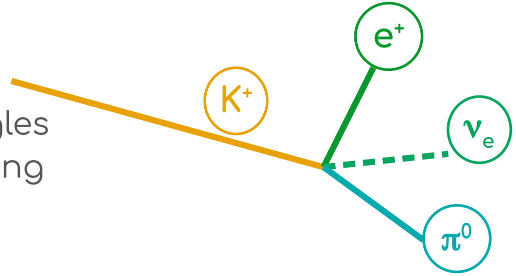
on behalf of the ENUBET Collaboration

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement N. 681647)

NP06/ENUBET: Enhanced NeUtrino BEams from kaon Tagging



→ O(10%) flux uncertainty



Novel ν_e source from $K^+ \rightarrow e^+ \pi^0 \nu_e$ decays, lepton production at large angles is monitored at single particle level by calorimetric techniques, i.e. tagging the e^+ in an instrumented decay pipe

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

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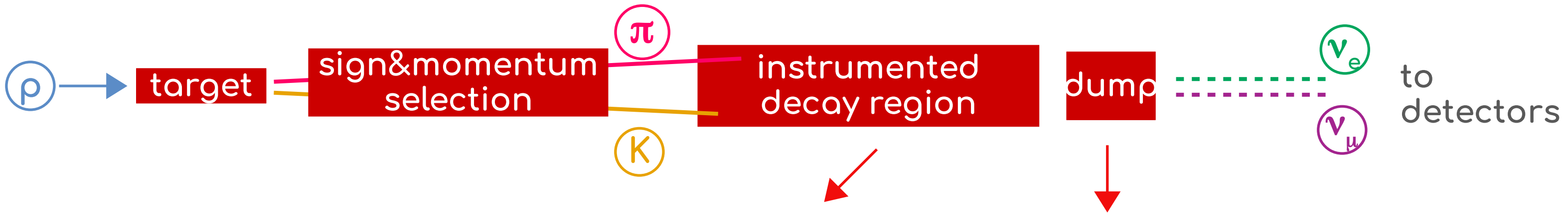
NP06/ENUBET: Enhanced NeUtrino BEams from kaon Tagging



Positrons from: $K^+ \rightarrow \pi^0 e^+ \nu_e$
Muons from: $K^+ \rightarrow \mu^+ \nu_\mu$, $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

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

PIMENT project

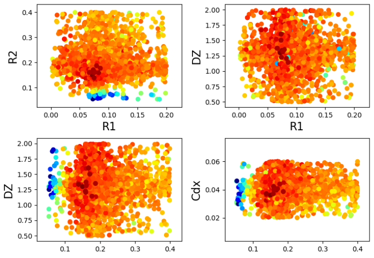
Design optimized to reach a **O(1%)** precision on the ν_e flux → ν_e flux prediction = e^+ counting

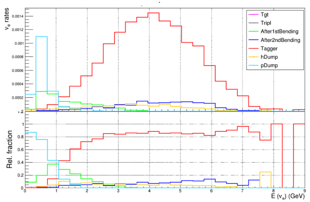
Two main steps:

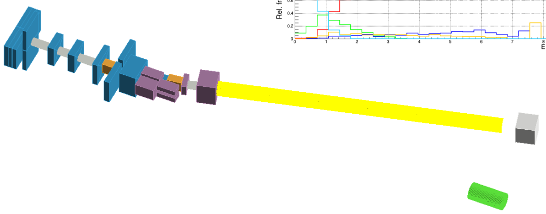
- layout of the π/K focusing and transport system with suitable proton extraction schemes
- special instrumented beamline capable of performing lepton monitoring from decays of K in a ν beam decay tunnel at single particle level

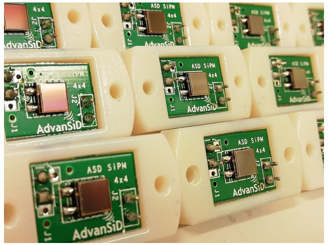
The ENUBET project

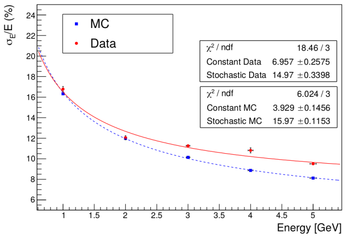
Beamline design and simulation → **Detector development and characterization** → **Assessment of systematics and performance**

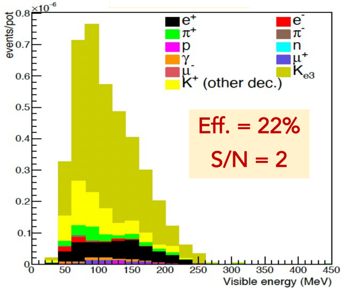


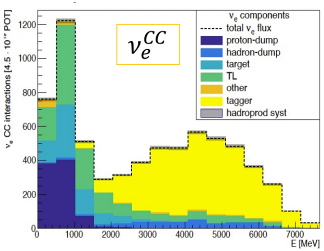




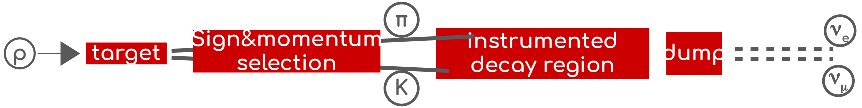








Beamline design and simulation



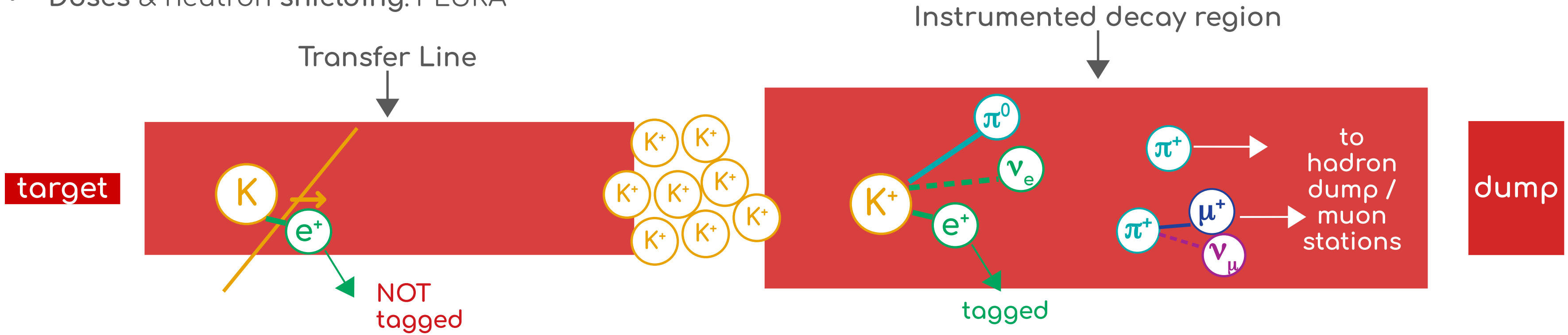
Beamline design

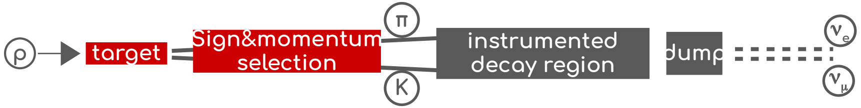
Requirements:

- Use of **conventional** normal-conducting **magnets**
- Keep under control level of **background** transported to the tunnel: fine tuning of **shielding and collimators**
- **Careful optics design**: non decaying particles should exit the decay pipe without hitting the walls
- **Maximize** number of K^+ **at tunnel entrance**
- Minimize total length of the transferline (~20 m) to **reduce kaon decay** in the **not instrumented region**

Design process:

- Tune beamline **optics** with TRANSPORT
- **Implementation** and validation with G4beamline/GEANT4
- **Doses** & neutron **shielding**: FLUKA





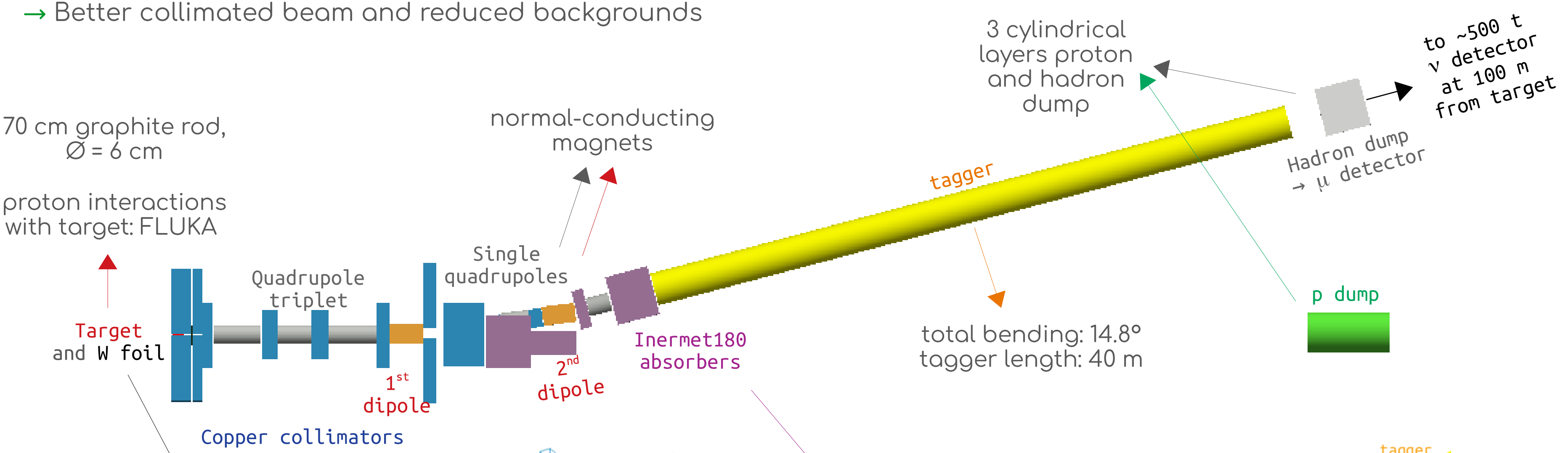
The ENUBET transferline

Reference beamline: 8.5 GeV, 10% momentum bite.
Focusing system: a quadrupole triplet before the bending magnets (14.8° bending)

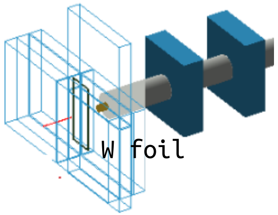
→ Larger bending angle (w.r.t. original proposal) and increased length

→ Better collimated beam and reduced backgrounds

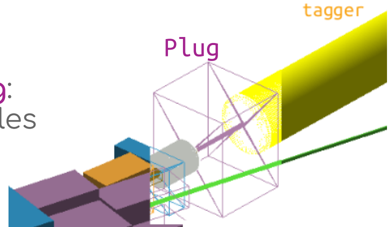
GEANT4/G4beamline

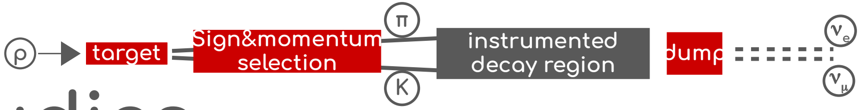


Improved **shielding** - **W foil** (50 mm): dumps low energy e^+ entering tunnel

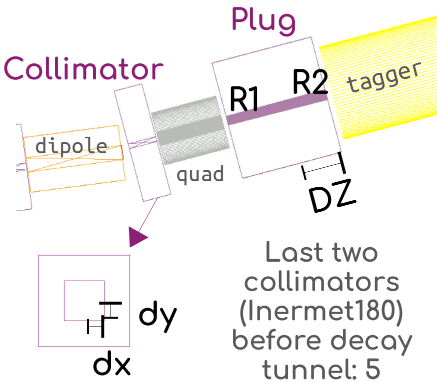


Improved **shielding** - Plug: dumps low energy particles hitting the tagger, backgrounds reduced





Beamline optimization studies



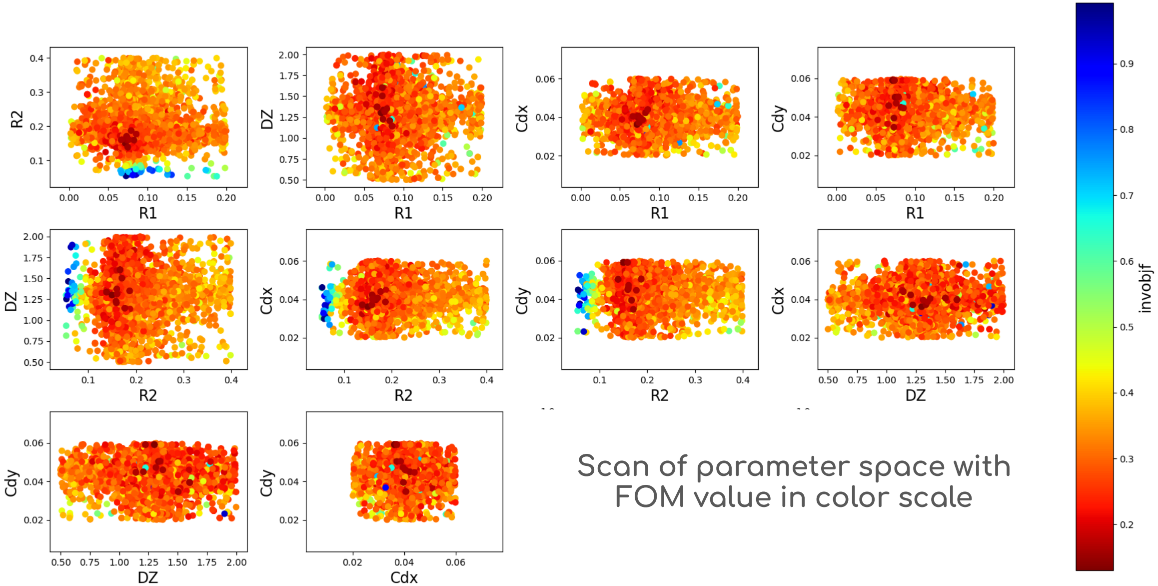
Goal: improvement of S/N ratio
→ enhancing π/K flux at tunnel entrance while keeping background level low

Strategy: scan parameters space of beamline to maximize the **Figure Of Merit**

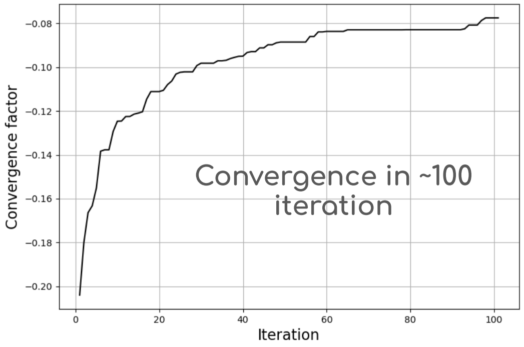
Full facility implemented in GEANT4 allows to control all parameters with external cards .
Optimization with developed framework based on a **genetic algorithm**

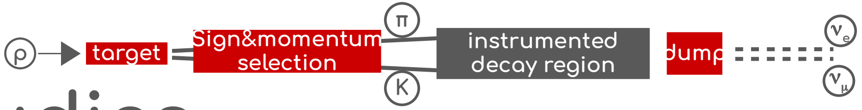
FOM: **K^+ at tunnel entrance** (signal) scaled by **background particles hitting tunnel walls** (positrons & pions from beamline and not from tunnel K_{e3} events)

Last two collimators (Inermet180) before decay tunnel: 5 parameters



Scan of parameter space with FOM value in color scale





Beamline optimization studies

FOM: signal/background

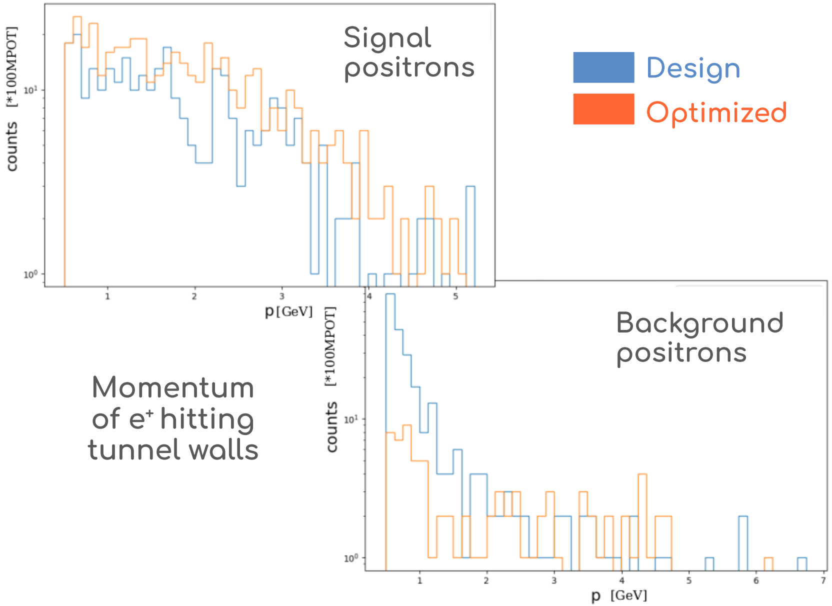
Signal = K^+ at tunnel entrance
Background = positrons and pions hitting tunnel walls from beamline and not from tunnel events

> Preliminary results:
> ~28% gain in flux
> ~2.4 years to 10^4 ν_e^{cc}

Preliminary

Rates at tunnel entrance	π^+ [10^{-3}]/POT	K^+ [10^{-3}]/POT
Design	4.13	0.34
Optimized	5.27	0.44

Background hitting tunnel walls	e^+ [10^{-3}]/K	π^+ [10^{-3}]/K
Design	7	59
Optimized	2	35



ν_e^{CC} at detector

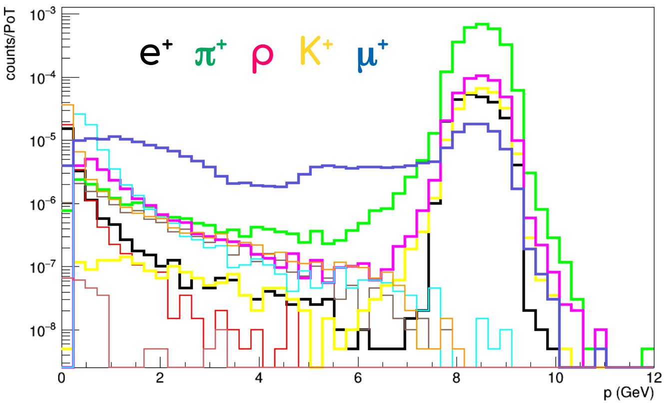
Assumption: 500 t neutrino detector located 50 m from the hadron dump

→ 10^4 fully reconstructed ν_e^{CC} in about 3 y of data taking

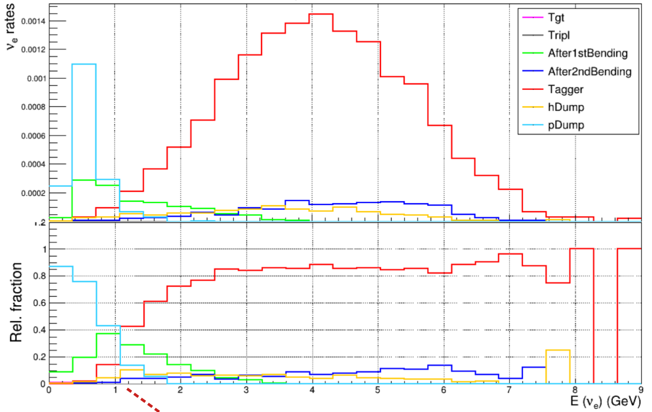
Rates at tagger entrance for 400 GeV POT	
π^+ [10^{-3}]/POT	K^+ [10^{-3}]/POT
4.13	0.34

~1.5 increase wrt previous results

Spectra of particles at tagger entrance

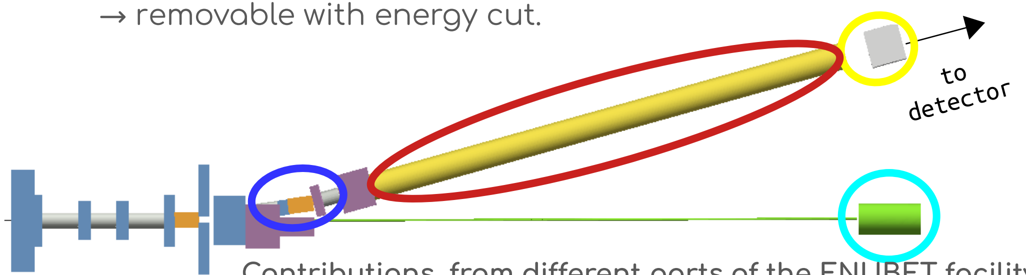


ν_e^{CC} spectra



Events:

- **80%** directly monitored (positrons in the decay tunnel)
- **10%** from decay in the transfer line (straight section in front of the tagger, pointing to the detector)
  → removable with simulation
- **10%** low energy events from early decays of kaons
  → removable with energy cut.



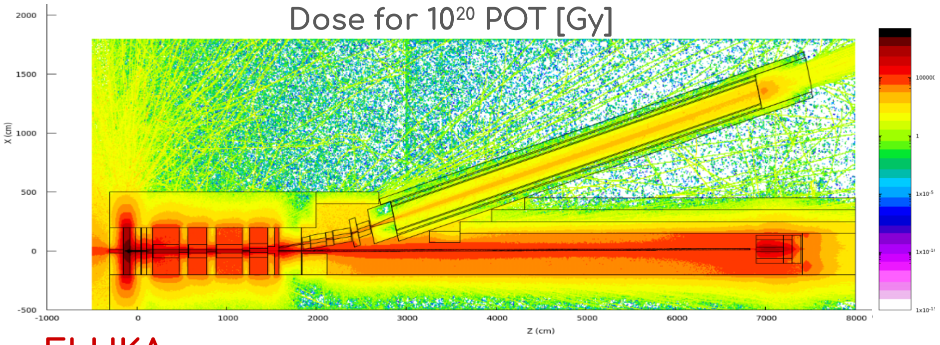
Contributions from different parts of the ENUBET facility

- main component produced in p dump
- clear separation from K_{e3} neutrinos

- straight section before tagger
- hadron dump

More on the ENUBET beamline

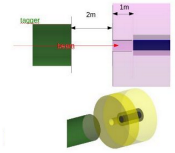
- A detailed FLUKA simulation of the setup has been implemented (includes proper **shielding** around the magnetic elements)
  - **Hottest** point: first collimator and quadrupole closest to target
  - After first bending: reduction of dose to beamline elements
  - Layer of **borated polyethylene** shielding for SiPMs and electronics

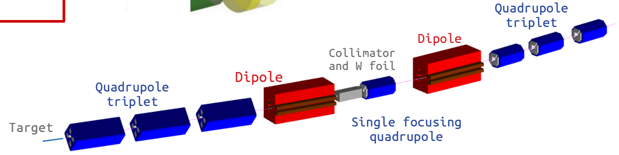


FLUKA

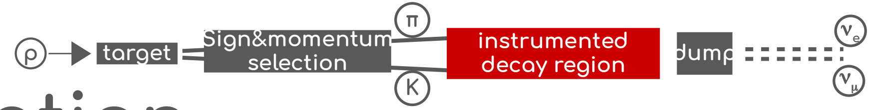
- Proton extraction schemes
- Target studies
- Beamline optimization
  - Proton and Hadron dump design
- New beamline design that covers a larger momentum range: Multi Momentum Beamline

→ talk by E.Parozzi
"The design of the ENUBET beamline"
WG3: Accelerator Physics
on Friday (Aug 5th)

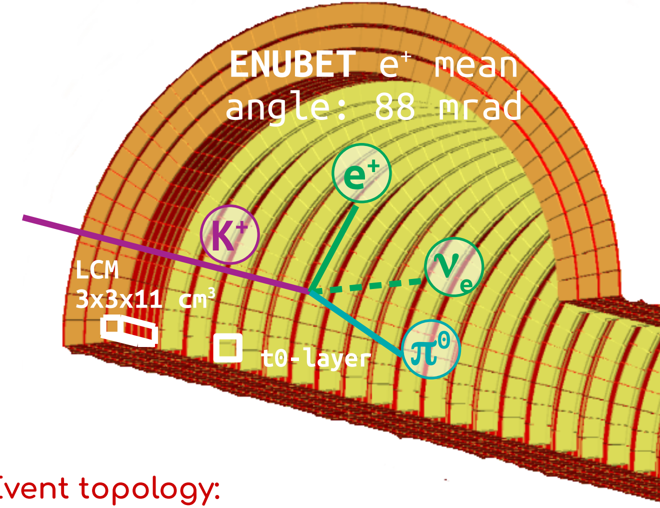




Detector development and characterization



Decay tunnel instrumentation



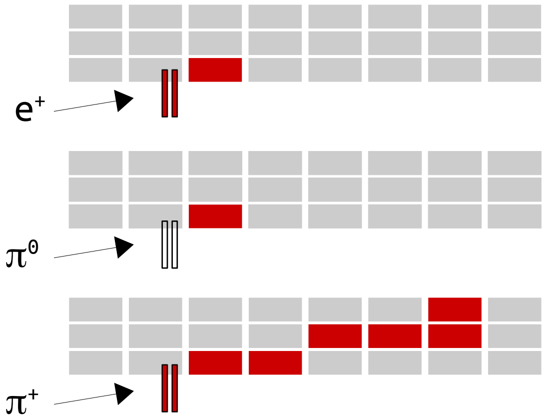
Calorimeter Longitudinal segmentation: three radial layers (**LCM** = Lateral Compact Modules) , plastic scintillator + iron absorber → $e^+/\pi^+/\mu$ separation

Light readout system SiPMs on top of the calorimeter, above a **borated polyethylene** shield

Lateral light readout system: **WLS fibers** running along the edges of the tiles → reduced (x18) neutron damage the SiPMs

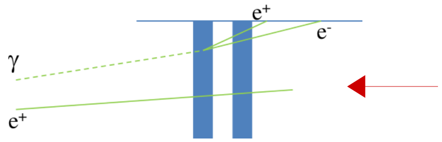
Photon veto Plastic scintillator tiles arranged in doublets forming inner rings → π^0 rejection

Event topology:



September 2018 @ CERN-PS: response to MIP, e and π tested for a calorimeter prototype and an integrated photno veto "t_0-layer".

November 2021 @ CERN-PS: small prototype ("Enubino") used to test new fiber redout scheme



Photon veto working principle

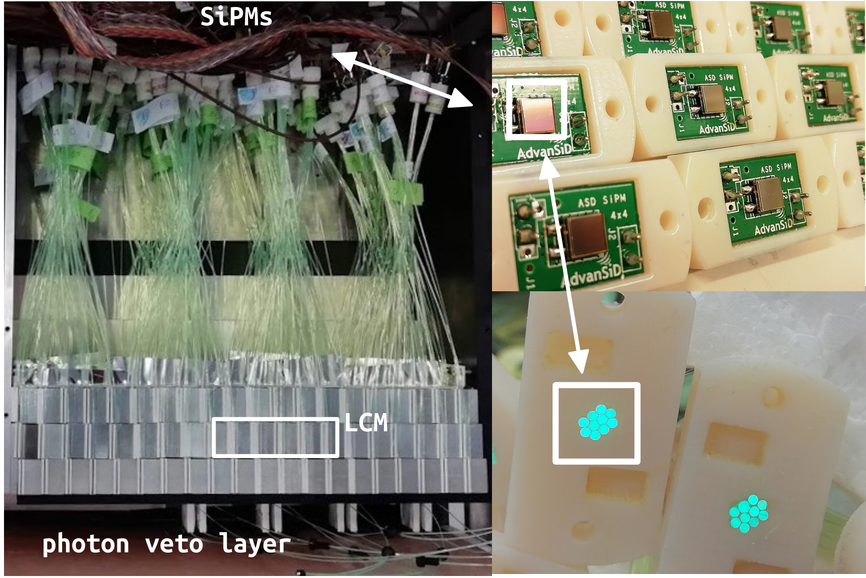
Prototypes & tests

Tested during 2018 test beams runs @ CERN-PS

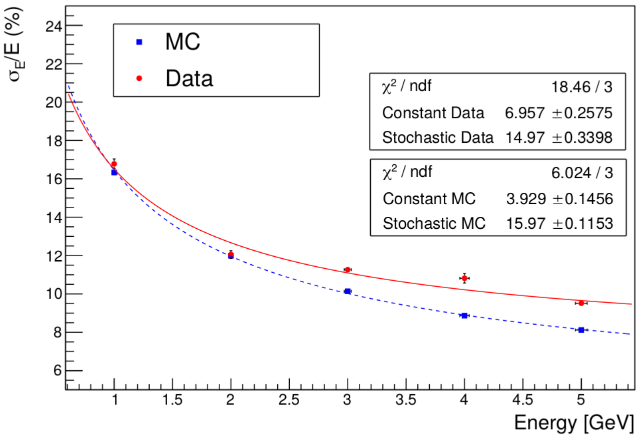
- 1 LCM = 4.3 radiation lengths
  - compact sampling calorimeter
  - large SiPM area (4x4 mm^2) for 10 WLS fibers
- Internal photon veto layer (scintillator doublet)
- Space for shielding (factor 18 dose reduction)

Prototype successfully tested!

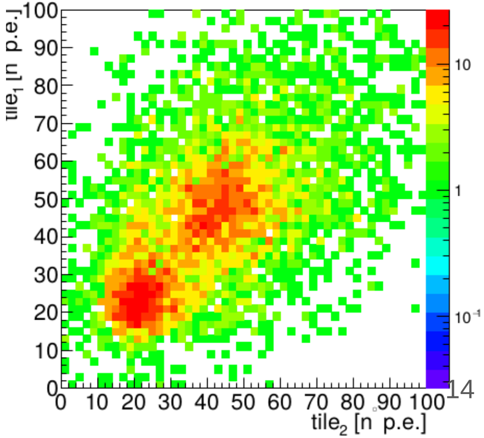
- new prototype: “Enubino” (pre-demonstrator)
  → new fiber redout scheme + BPE
- larger prototype: “Demonstrator”
  → final experimental validation (performance / scalability / cost effectiveness)



Electron energy resolution



1mip/2mip separation

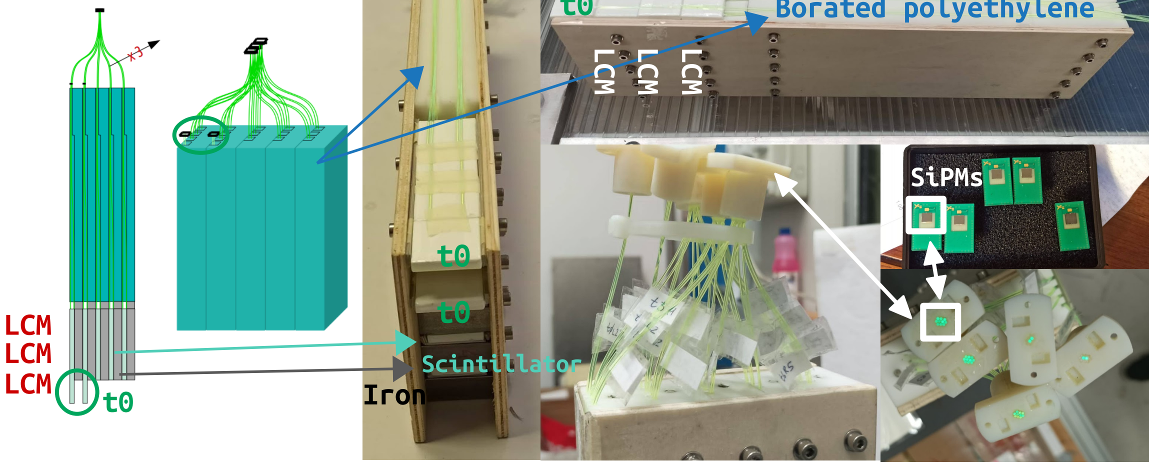


F. Acerbi et al, JINST 15 (2020) P08001

ENUBINO

2021 test beam @ CERN-PS: Enubino

- Sampling calorimeter: plastic scintillator + iron absorber **+ BPE**
- Fibers collect the scintillation light **frontally**
  - uniform light collection
  - fiber routing through BPE to SIPMs

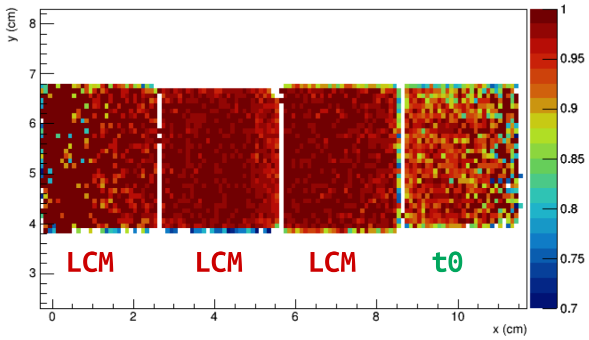


New frontal readout scheme & fibers bundling:

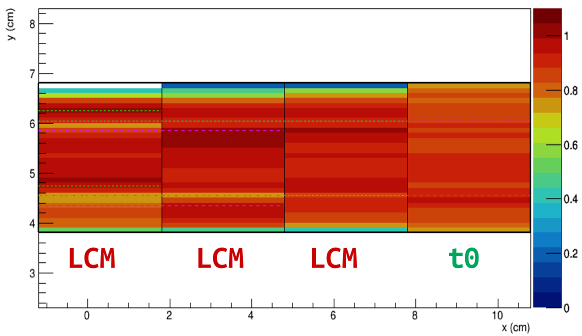
- 10 WLS fibers (1 LCM) bundled to a 4×4 mm^2 SiPM
- 2 WLS fibers for each t0 tile bundled to a 4×4 mm^2 SiPM

→ efficiency & uniformity studies using mips

Efficiency map



Uniformity

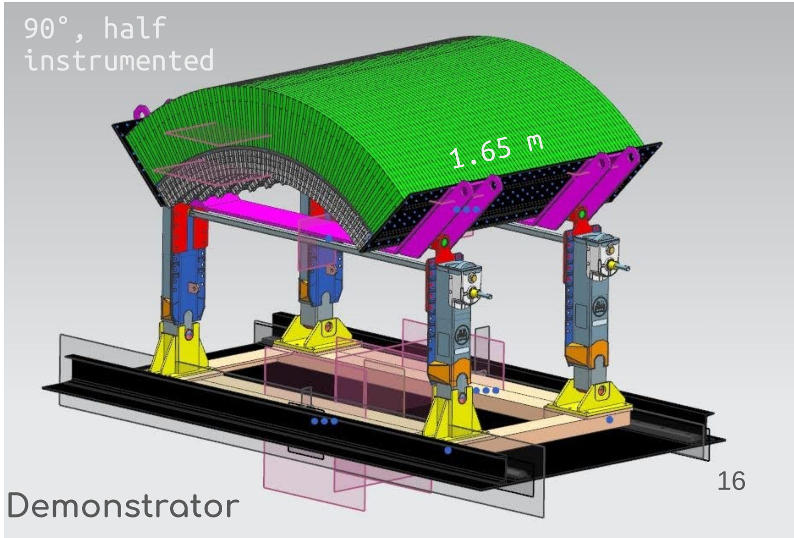


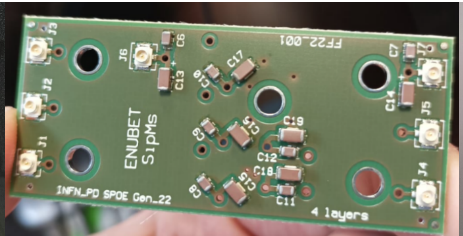
Demonstrator

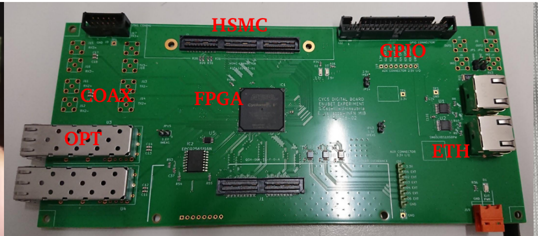
The prototype of the tagger is **under construction** for a final experimental validation at CERN-PS in **October** 2022

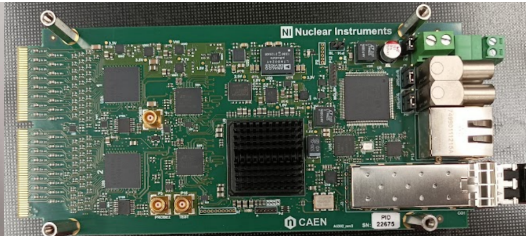
- **Calorimeter + photon veto + shielding** (30 cm BPE)
- 1.65 m long, 90° in azimuth
  - Central 45° part instrumented: rest is kept for mechanical considerations
  - 75 layers of iron (1.5 mm thick) + scintillator (7 mm thick) → 15x3x25 LCMs
- **Modular design**: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions)
- New **light readout scheme** with frontal grooves (from Enubino)

- Routers for the optical fibers produced 3D printers
- In progress: custom digitizers and SiPM powering boards



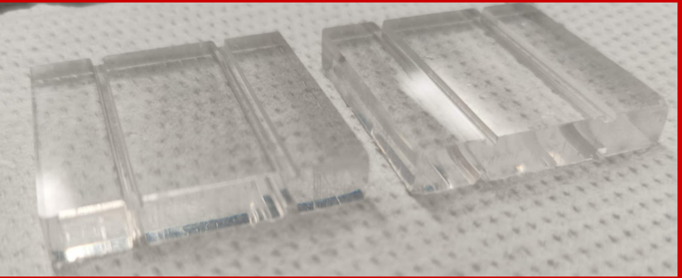


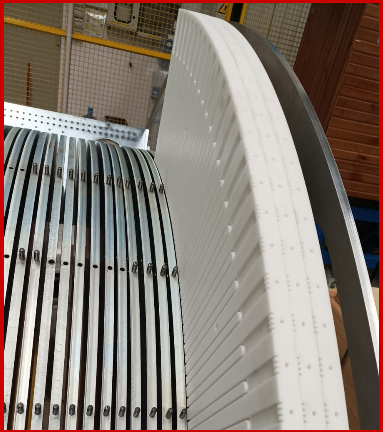


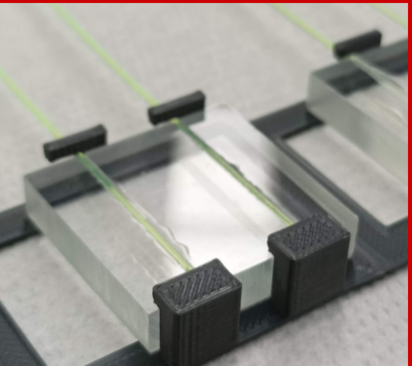


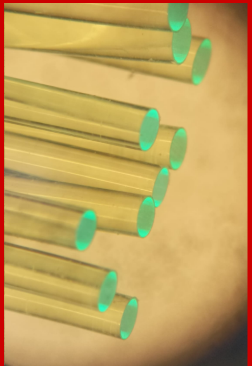

Borated polyethylene
6375 scintillator tiles
1875 channels

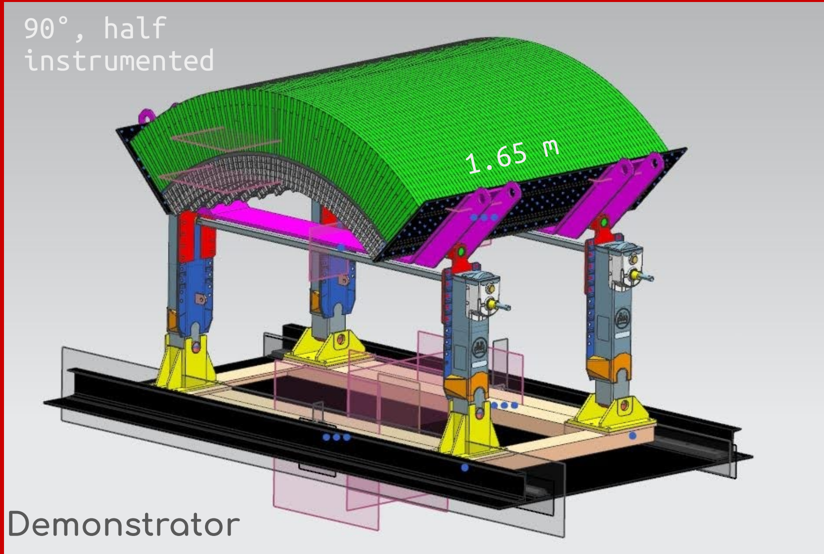

@ INFN-LNL laboratories
Demonstrator weight: ~3.2 t







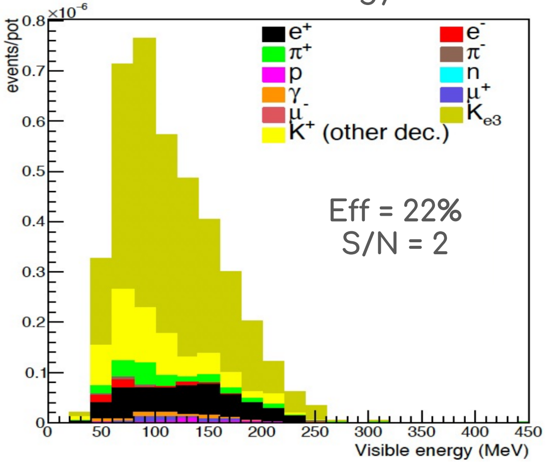



90°, half instrumented
1.65 m
Demonstrator

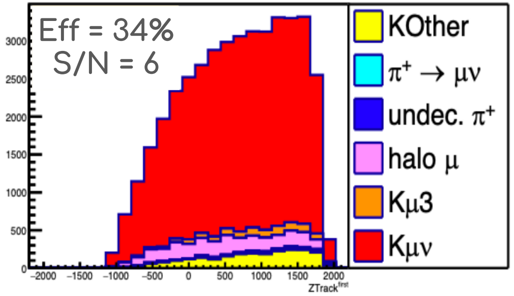
Assessment of systematics and performance

Lepton reconstruction

Visible energy



Tagger impact point



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

Full GEANT4 simulation of the detector validated by prototype tests

- particle propagation and decay from transfer line to detector
- hit level detector response
- pile-up effects included

- Large-angle **positrons** and **muons** from **K decays** → patterns in energy depositions in tagger
  → use **tagger granularity** to separate EM showers / Hadronic showers / MIP **+ photon veto**
- Signal identification done using a **Neural Network** trained on a set of discriminating variables
- Reconstruction performance in terms of **Signal to Noise ratio** (S/N) and **efficiency**

K_{e3} positrons: S/N: **2**
Efficiency: **22%** (efficiency is ~half geometrical)

$K_{\mu3}$, $K_{\mu3}$ muons: S/N: **6**
Efficiency: **34%** (efficiency is ~half geometrical)

Assessment of systematics

Monitored ν beam : measure rate of leptons @ tagger ↔ monitor ν flux

- build a **Signal + Background model** to fit lepton observables
- include hadro-production (HP) and transfer line (TL) **systematics** as nuisances

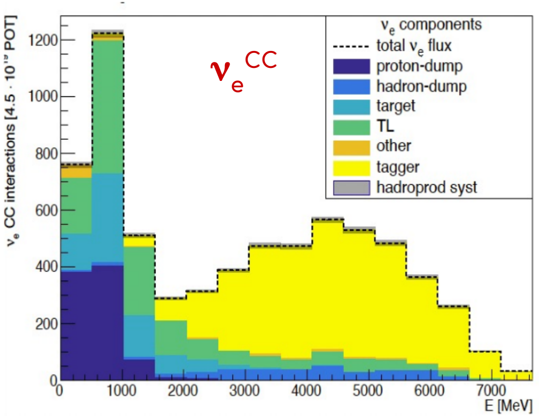
Hadro-production data from NA56/SPY experiment used to:

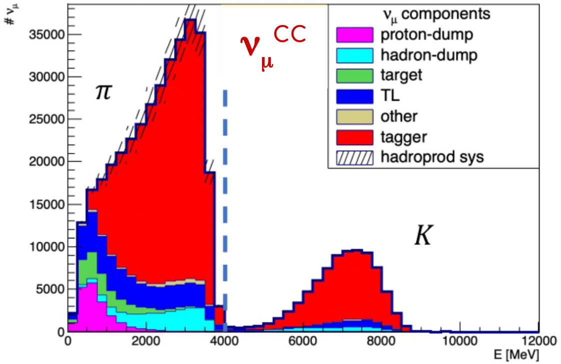
- **Reweight** MC lepton templates and get their nominal distribution
- Compute lepton templates variations using multi-universe method

A. Branca et al. PoS NuFact2021 (2022), 030

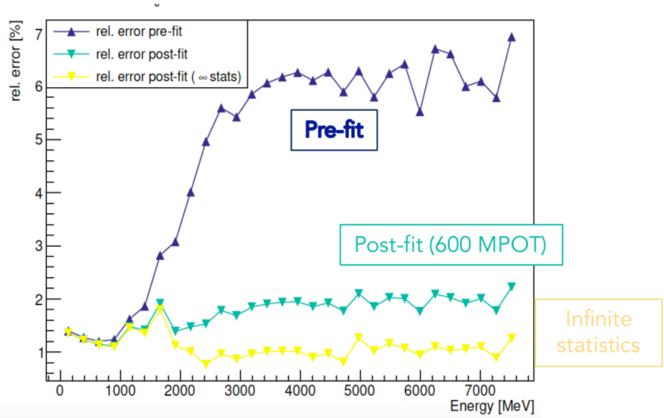
Impact of HP systematics on neutrino flux

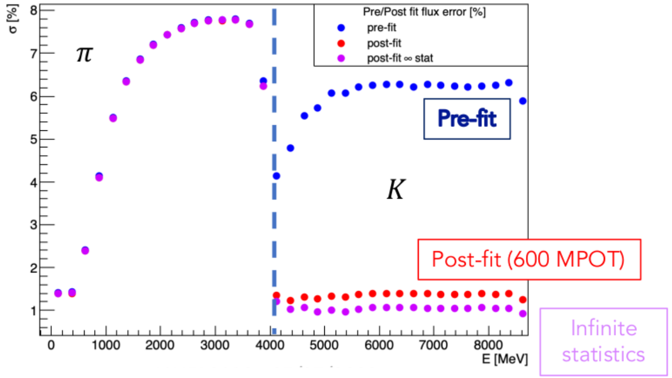
Neutrino interaction rates @ detector





Pre & Post fit relative errors on rates





Total rates assuming

- 500 ton neutrino detector at 50 m
- CERN-SPS as driver
- 4.5 10^{19} POT

Before constraint: **6%** systematics due to hadro-production uncertainties

After constraint: **1%** systematics from fit to lepton rates measured by tagger

Achieved ENUBET goal of 1% systematics from lepton monitoring!

Summary and conclusions

ENUBET goal: **first monitored neutrino beam** for neutrino cross-section measurements @ O(1%):

- ERC project started in 2016-2022;
- CERN experiment (NP06) within Neutrino Platform 2019-2024;

Final design of beamline in place, fine-tuning in progress

- static transfer line: 10^4 ν_e^{CC} events in **2/3 years (SPS)**
- **optimization** of transfer line parameters with dedicated framework in progress

Design of decay tunnel **instrumentation** finalized

- prototypes testbeams @ CERN: technology validation
- final **demonstrator** of the tagger under construction, to be tested in 2022

Tagger detector **simulation**

- **good PID** performance achieved on both positron and muon reconstruction

Systematics

- achieved **1%** systematic goal due to **hadro-production** with lepton monitoring
- assessment of systematics due to detector and beamline in progress

Thank you!

http://enubet.pd.infn.it/

Backup

Overview

Next generation long-baseline experiments (DUNE, HyperK): **precision ν oscillation measurements**

- Neutrino mass hierarchy
- CP violation in the leptonic sector
- Test of 3-neutrino paradigm

Also neutrino interaction models would benefit from improved precision on cross-sections measurements

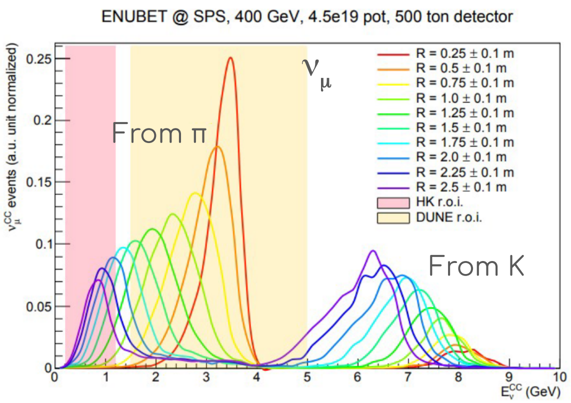
Goal of **ENUBET** : design a narrow-band neutrino beam to measure

- neutrino cross-section and flavor composition at **1%** precision level
- neutrino energy at **10%** precision level

→ Very good knowledge needed!

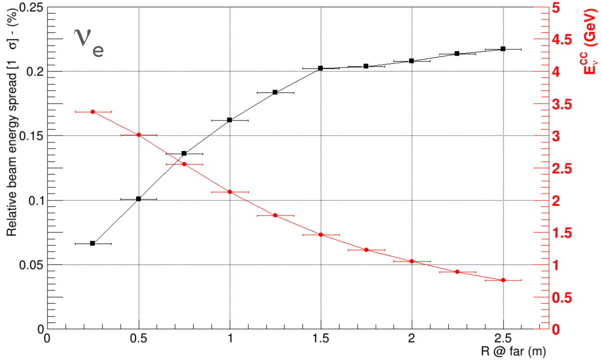
$$N_{\nu e}^{FAR} = P(\nu_\mu \to \nu_e)\, \sigma_{\nu e} \Phi_{\nu\mu}^{FAR}$$

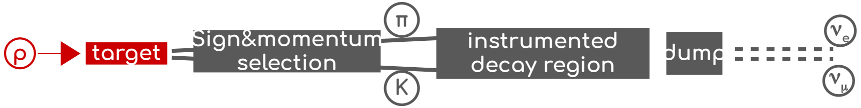
→ **Narrow band beam**: correlation between ν energy and distance of the interaction vertex from the beam axis



Estimation of neutrino energy from impact radius @detector

At ~3 (1) GeV: 10% (20%) precision on energy for the π component (DUNE/HK energy range)





Proton target design

Optimum particle production: primary proton beam = **400 GeV**, secondary kaons momentum ~**8.5 GeV**.

Goal: **maximise K** production in region of interest.

- Optimization of transverse dimensions and length
- Test of different materials (Graphite, Beryllium, Inconel)

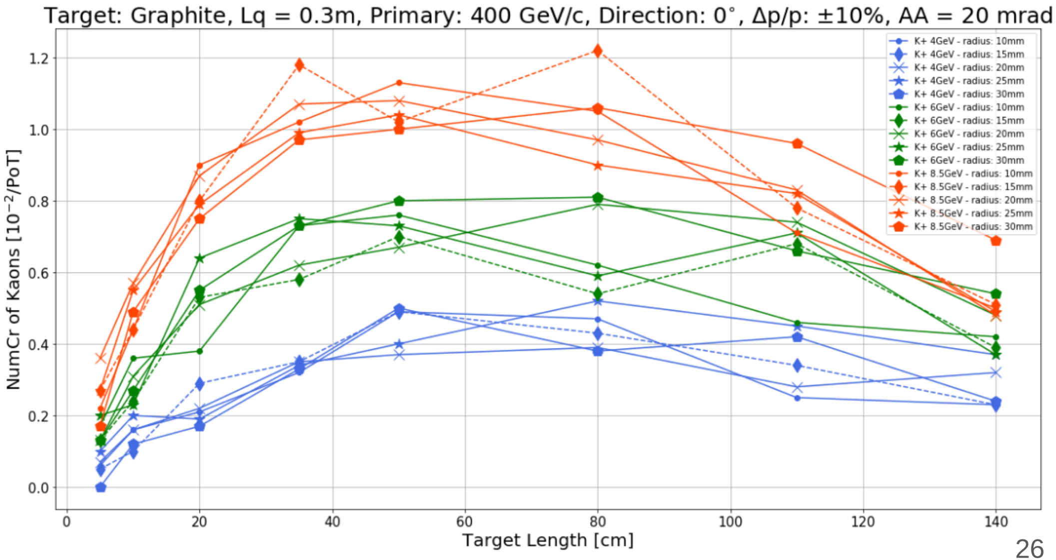
FLUKA + **G4beamline** simulations

→ maximise number of kaons of given energy (10% momentum bite) that enter a beamline with 20 mrad angular acceptance

Last version of the beamline:
Graphite target, L = 70 cm, R = 3 cm

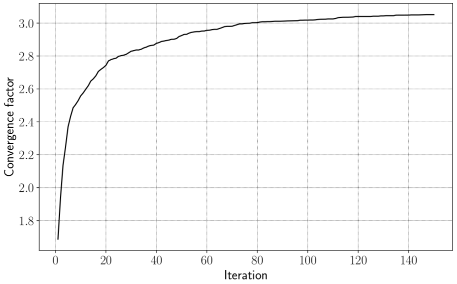
Inconel target (L = 50 cm, R = 3 cm) is also being considered

Graphite target radius scan



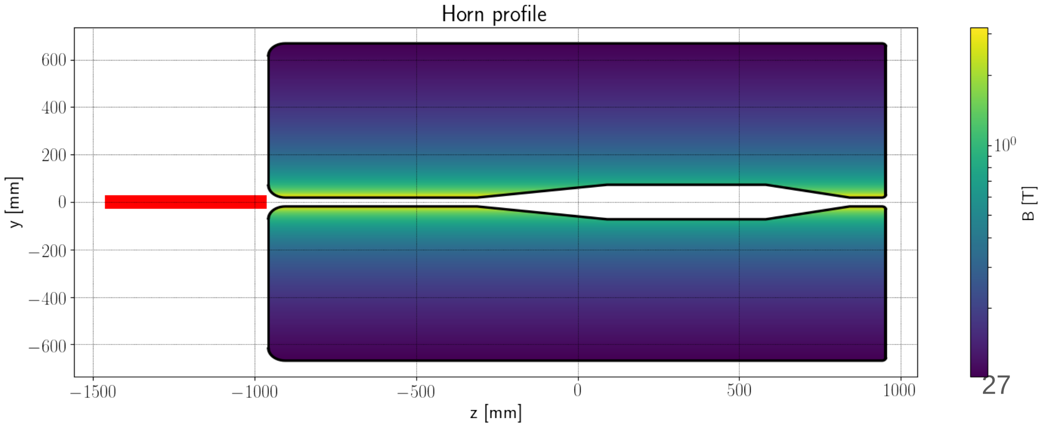
Horn studies

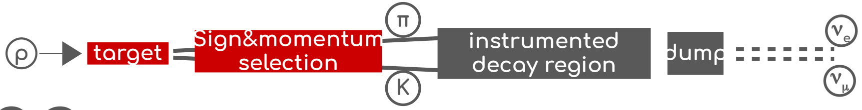
- More π and K in the wanted momentum range: higher yields at the decay tunnel = more ν_e/POT
- Pile-up problems in the decay tunnel
- Needs dedicated pulsed-slow extraction method developed in collaboration with CERN
  - "burst mode slow extraction" achieved at the SPS



- Genetic Algorithm used to design a satisfactory horn geometry
  - FoM is number of collimated K+ with momentum ~8.5 GeV/c
  - Factor x3 higher than the static case reached at first quadrupole

- First candidate designs reached:
  - MiniBooNE-type geometry with INCONEL target: HW constraints fullfilled
- The good standalone FoM of x3 does not match full baseline beamline:
  - development of dedicated horn-version of ENUBET beamline in progress

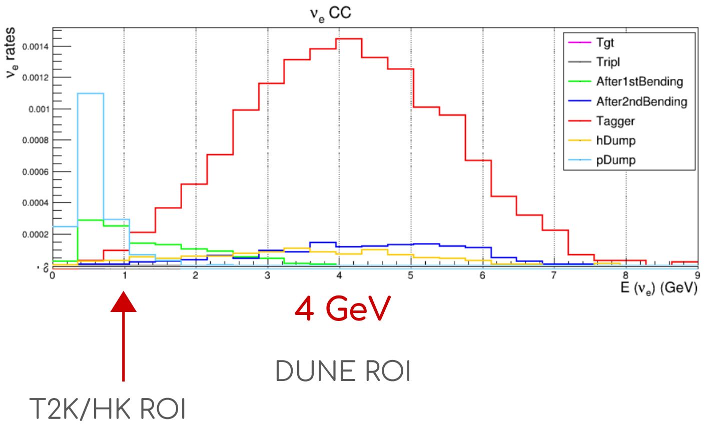




Multi Momentum beamline

Neutrinos from reference beamline are peaked ~4 GeV (DUNE R.o.I, Region of Interest).

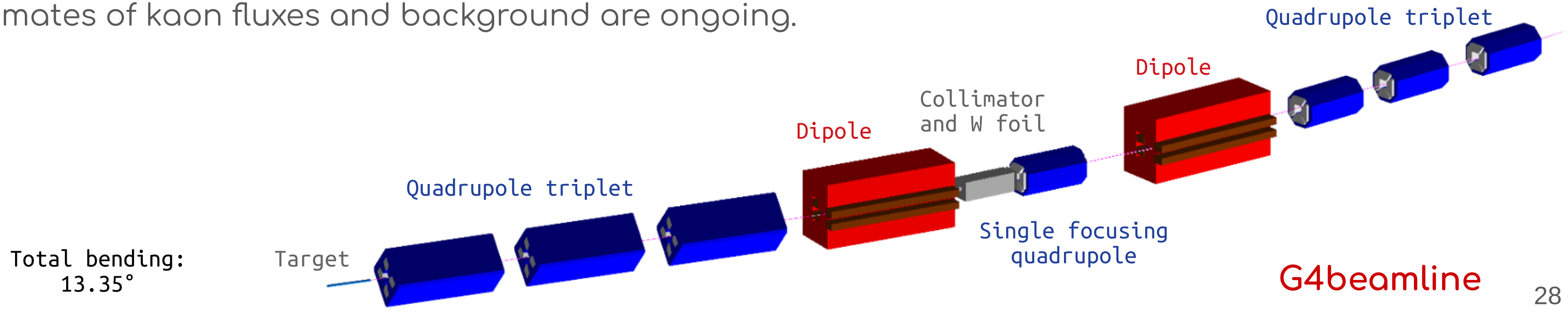
New beamline design: secondary multi momentum (4, 6, 8.5 GeV) → cover full range of interest (including the low-energy region, T2K/HyperK R.o.I.)



Optics optimization: **TRANSPORT, G4beamline**.

Contains detailed description of existing magnetic elements

First estimates of kaon fluxes and background are ongoing.



Positron reconstruction

Full GEANT4 simulation of the detector, validated by prototype tests at CERN during 2016-2018.

- particle propagation and decay from transfer line to detector
- hit level detector response
- pile-up effects included

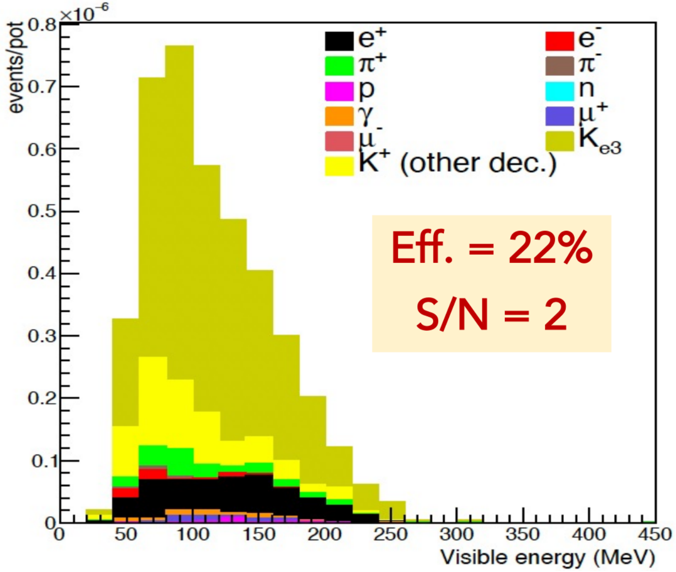
Analysis chain:

- **Event builder →** identify the seed of the event (LCM with largest energy deposit in inner layer and of E>28 MeV). Cluster neighbour LCM deposits compatible with propagation of shower
- **e/π/μ separation →** multivariate analysis exploiting 19 variables (energy pattern deposition in calorimeter, event topology, and photon-veto energy deposition)
- **e/γ separation →** signal on the tiles of the photon veto (0-1-2 mip)

S/N = 2

Efficiency: 22% (dominated by geometrical efficiency)

Visible energy



Muon neutrinos

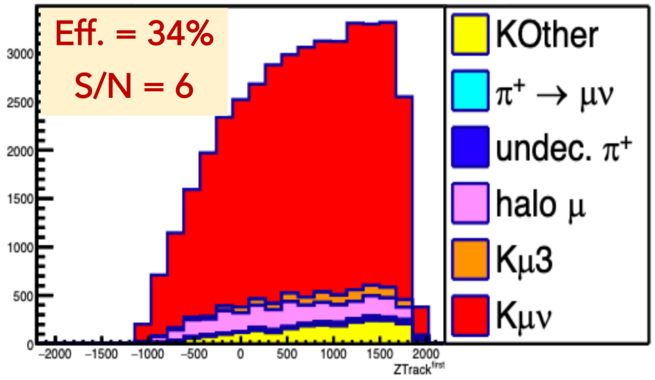
High-Energy: $K^+ \to \mu^+ \nu_\mu$, $K^+ \to \pi^0 \mu^+ \nu_\mu$ → constrained by the tagger

Low-Energy: $\pi^+ \to \mu^+ \nu_\mu$ → constrained by detctors following the hadron dump

$K^+ \to \mu^+ \nu_\mu$ Efficiency = 35% S/N = 6.1

$K^+ \to \pi^0 \mu^+ \nu_\mu$ Efficiency = 21% S/N = 6.1

Tagger impact point

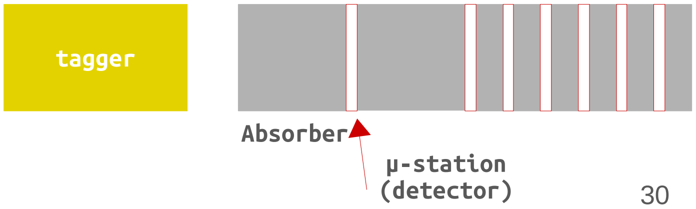


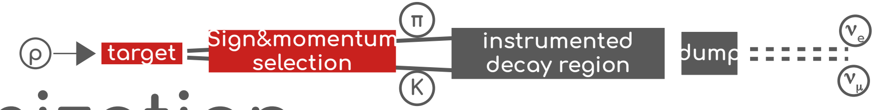
- **Event builder →** identify seed of the event (inner layer LCM withm E = 5-15 MeV). Cluster all LCM deposits compatible with muon-track topology and propagation
- **μ-like background separation →** multivariate analysis exploiting 13 variables (energy deposition, track isolation and topology)

$\pi^+ \to \mu^+ \nu_\mu$

Muon stations after hadron dump: pions have a large forward boost, muons from decays exit the tunnel.

Estimation of muon and neutron rates in progress → choice of detector technology





GEANT4 - beamline optimization

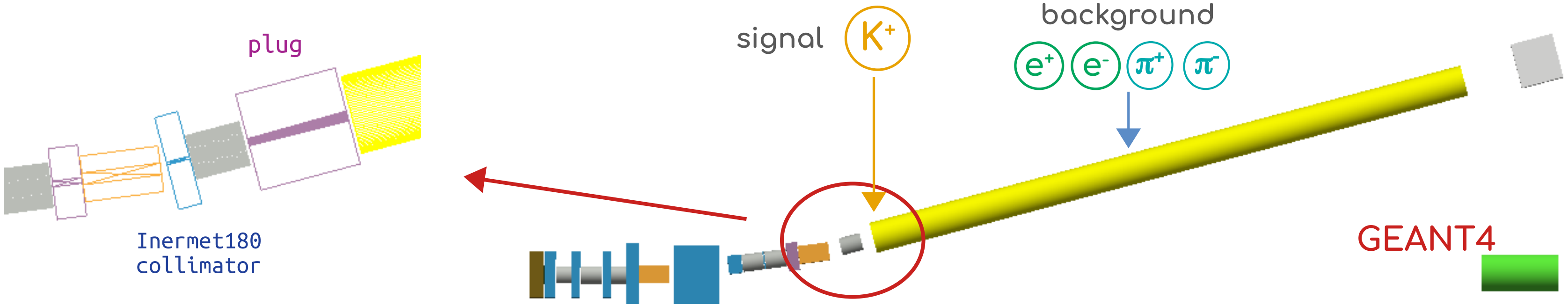
New design from **G4beamline** (feat. new proton target) → suppression of low energy ν_e from target region

Further reduction of background: optimization and final design of collimators and absobers at the end of the transfer line (position, dimension and apertures) in progress with **GEANT4**

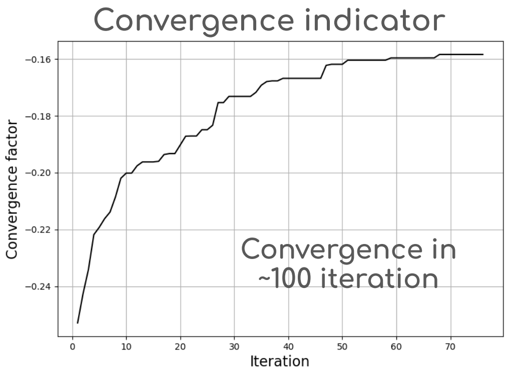
→ New genetic algorithm implemented to sample the parameter space

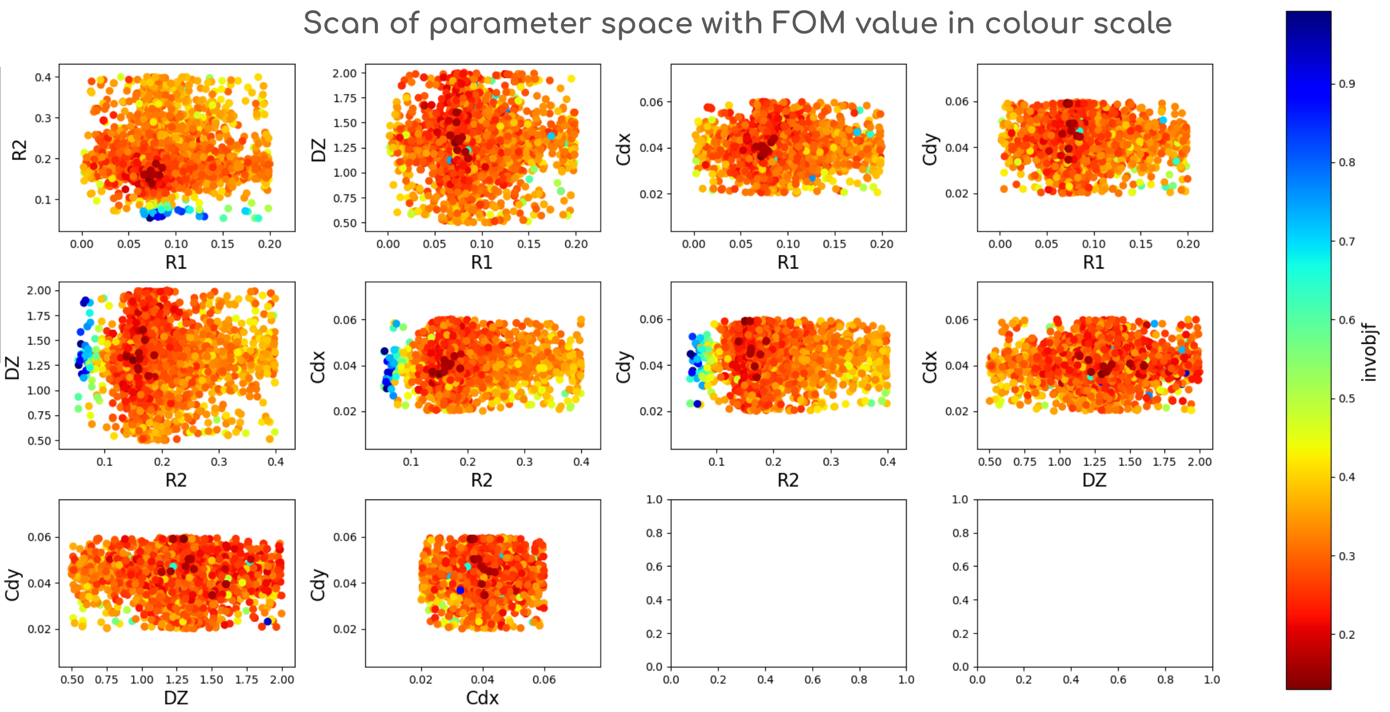
- Convergence in O(100) iterations
- Figure Of Merit = ratio $K^+_{\text{entering tagger}}$ / background$_{\text{hitting tunnel}}$ (bkg = e^{+-}, π^{+-})

  = signal/background to be maximized

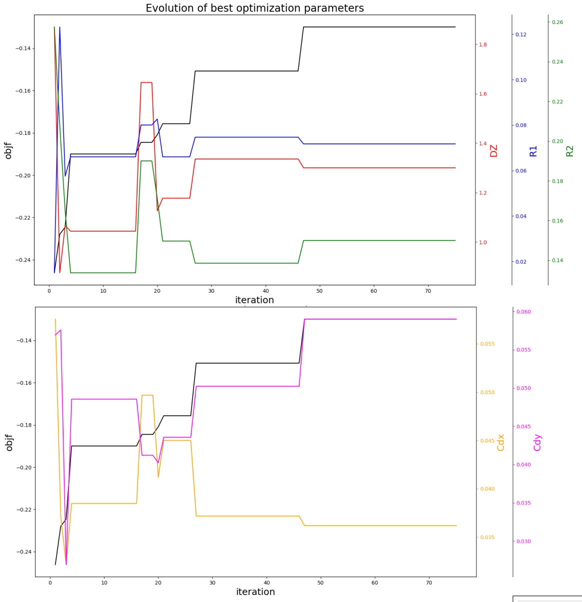


Plug + collimator optimization



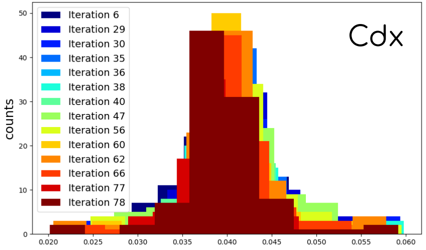


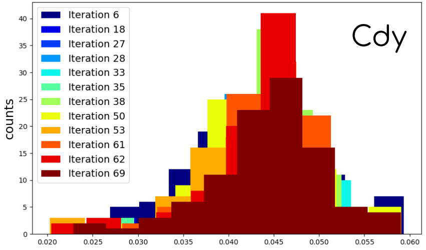
Plug + collimator optimization



Evolution of best optimization parameters

Evolution of FOM distribution: collimator before quad





Evolution of FOM distribution: tungsten plug