NP06-ENUBET report

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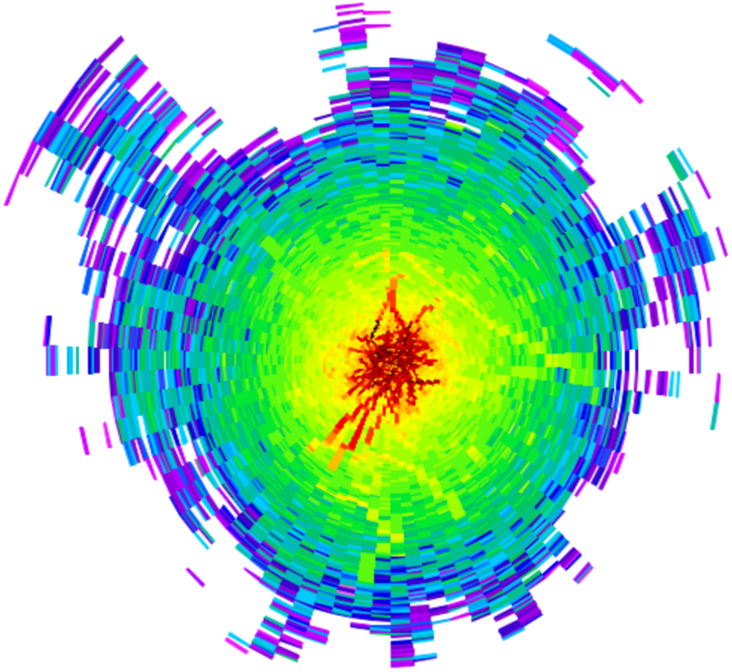
Padova Univ. and INFN
On behalf of the ENUBET Coll.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (G.A. n. 681647).

SPSC meeting, 13 April 2021

Highlights

Updates in the beamline study and proton extraction
Improvements in the simulation
Leptons reconstruction in the tagger
Prototyping and steps to the Demonstrator



Annual report, coll. growth, extension

[x]Aristotle University of Thessaloniki. Thessaloniki 541 24, Greece.

Annual report

https://cds.cern.ch/record/2759849/files/SPSC-SR-290.pdf

NP06/ENUBET Annual Report for the SPSC

The ENUBET Collaboration

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New forces from **Thessaloniki Univ**.

Already active on:
- waveform processing algorithms

Next:
- members of the PICOSEC collaboration (fast MicroMegas with reduced gap)

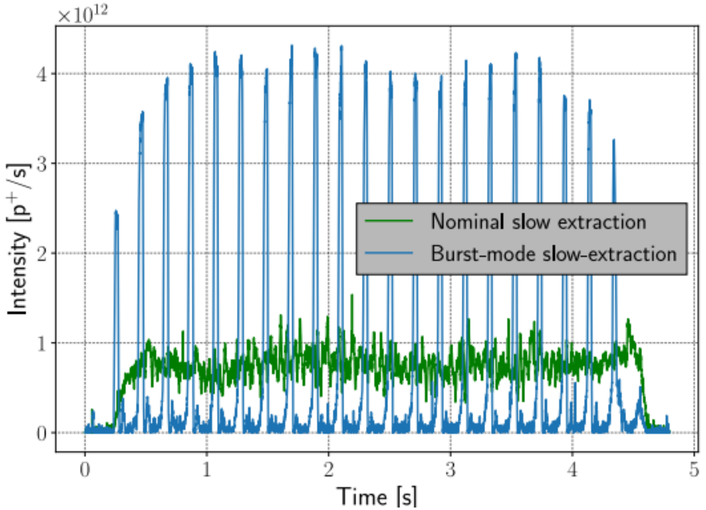
- instrumentation of the forward region: physics and detector studies (also at next test beams)

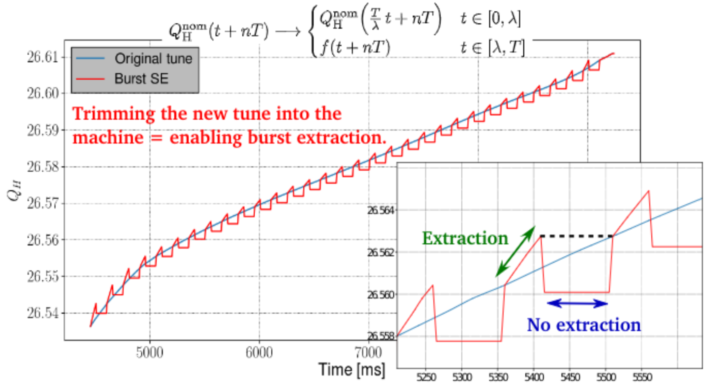
The ERC project has been extended by 12 months up to June 2022.

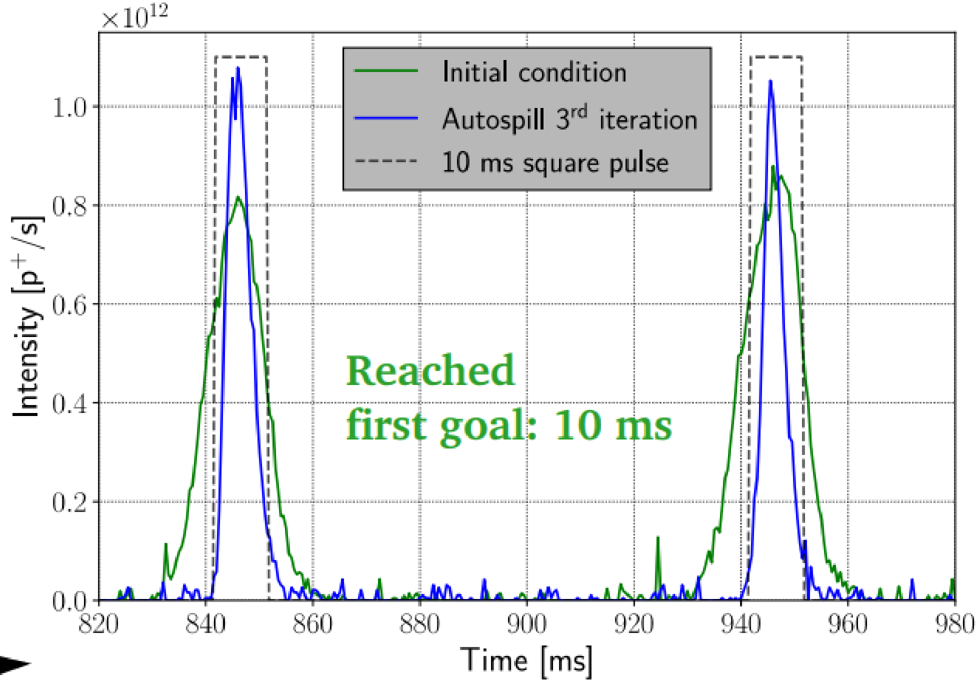
Proton extraction R&D for horn focusing

CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

before LS2: burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa







PhD thesis of M. Pari (UniPD + CERN doctoral). Defended 23/2/21.

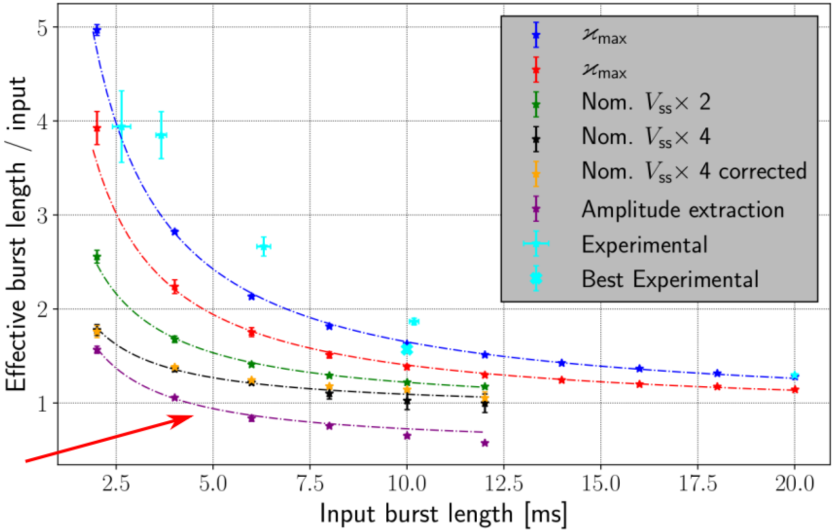
Proton extraction R&D

during LS2: burst mode slow extraction

a **full simulation** to validate the experimental results and **explore possible improvements**, which could not be tested in the machine before the shutdown.

Two different methods (increase of extraction **sextupole strength** and **amplitude extraction**)

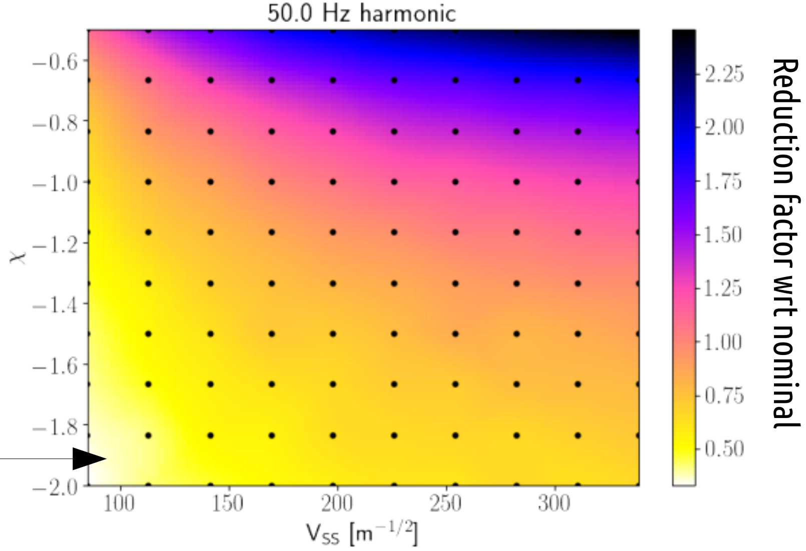
pulses between **3 and 10 ms** seems at reach without hardware interventions → tests after LS2



PhD thesis of M. Pari

Reduction of ripples in the usual slow extraction

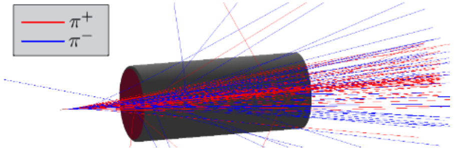
Tuning different set of sextupoles: the quad-correcting ones used to act on the chromaticity (X) and the ones used for the extraction (V_{ss})

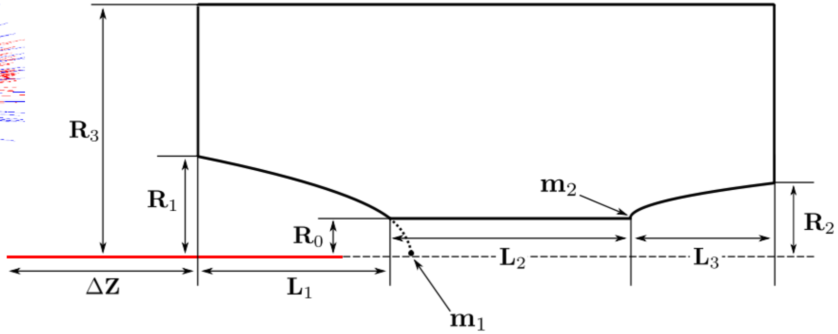


x 2 reduction of the 50 Hz ripples amplitude expected here wrt to nominal

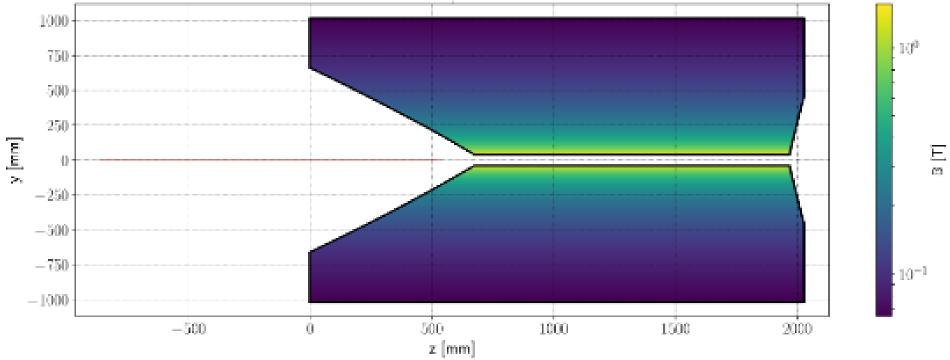
CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

Horn optimization





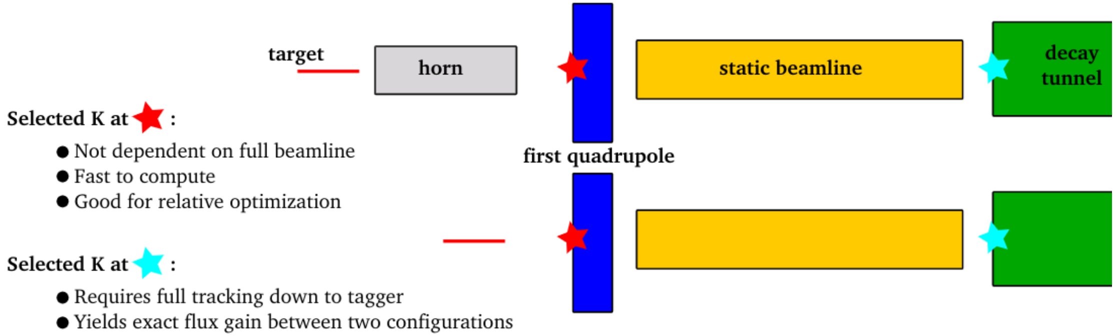
- New **double-parabolic** geometry (formerly MiniBooNE-like)
- New **genetic algorithm** implemented successfully to sample the large space of parameters.
- FoM is ~ number of collimated K^+ with p ~8.5 GeV/c
- Convergence in O(100) iterations
- First candidate designs worked out



We were able to reach values of the **standalone FoM (★)** **of x 3 higher than the static case**. These results confirm an improvement w.r.t. early studies.

When plugged to the existing beamlines the gain factor reduces to only **x 1.5 → next step:** dedicated beamline optimization (★) to profit of the horn-option initial gain → larger apertures for initial quads.

Can extend the same systematic optimization tool.



Target optimization

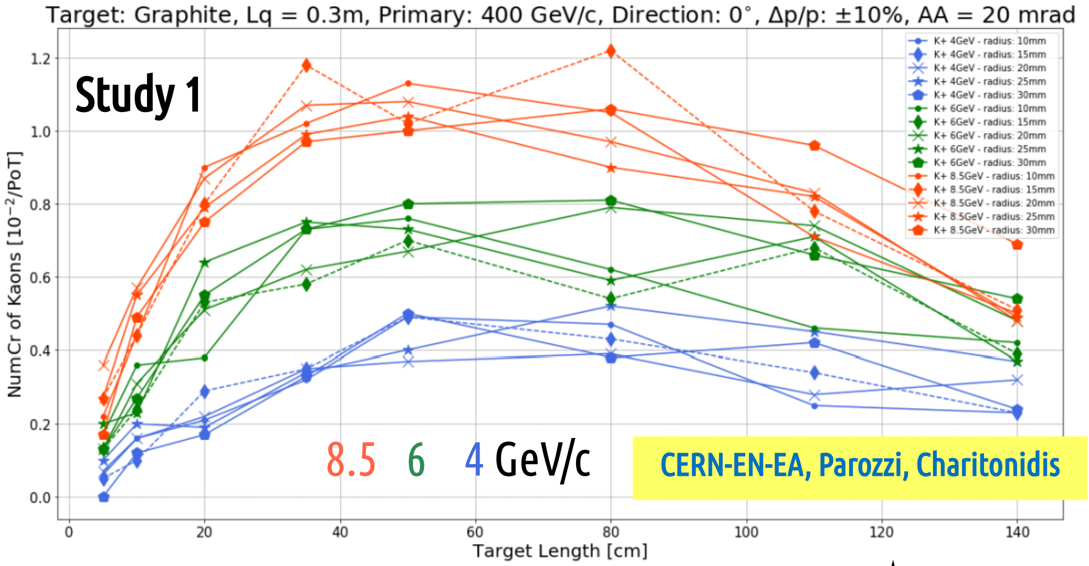
Explored the parameter space of the geometry (also tronco-conical) and some materials (graphite, Inconel) to maximise the yields of mesons in our region of interest with FLUKA.

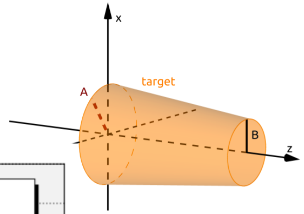
The current targets are both more efficient and robust under the point of view of implementation and lifetime.

New baseline targets:

- **Graphite: L/ø = 700/60 mm**
- **Inconel: L/ø = 500/60 mm**

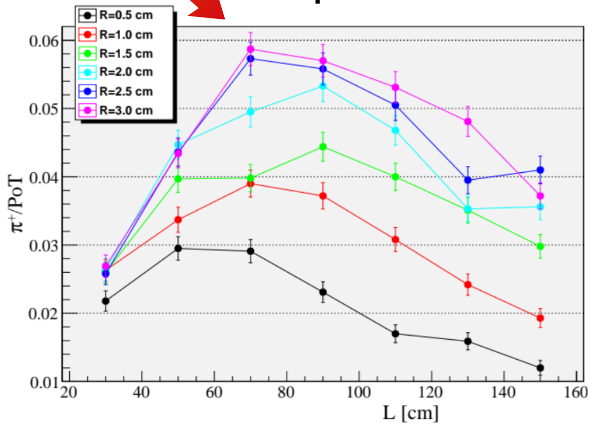
(*) The two studies used different choices for the FOMs



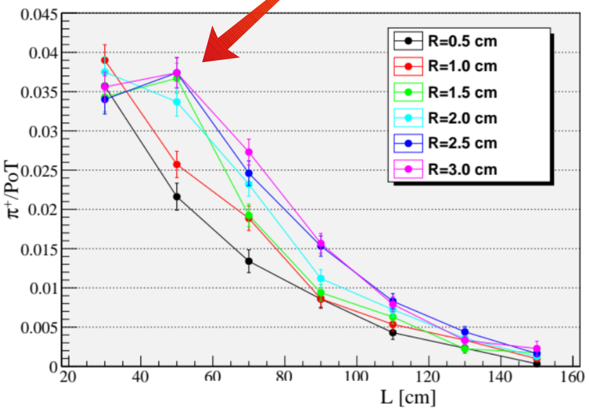


Study 2

Graphite



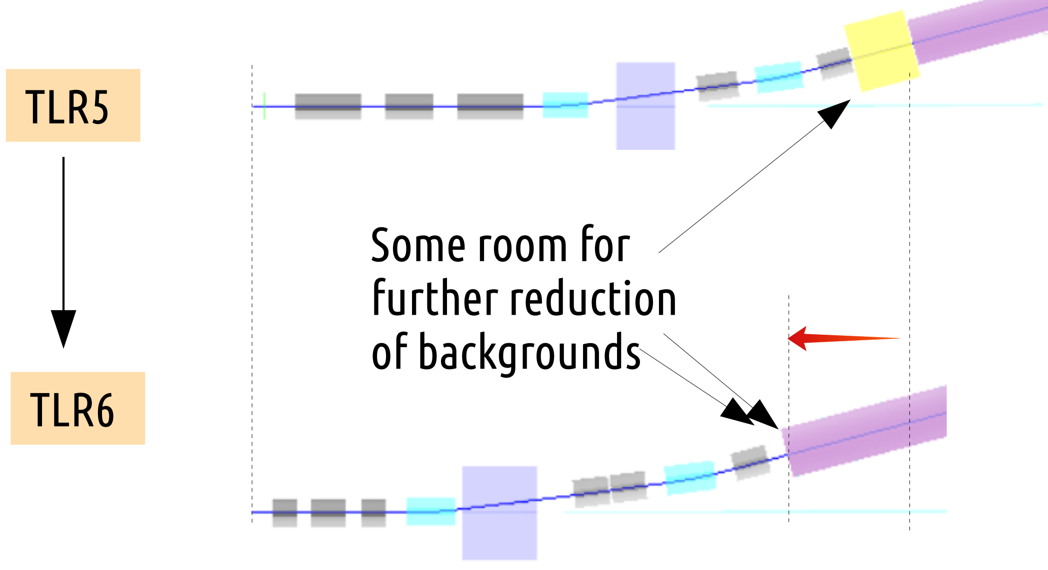
Inconel



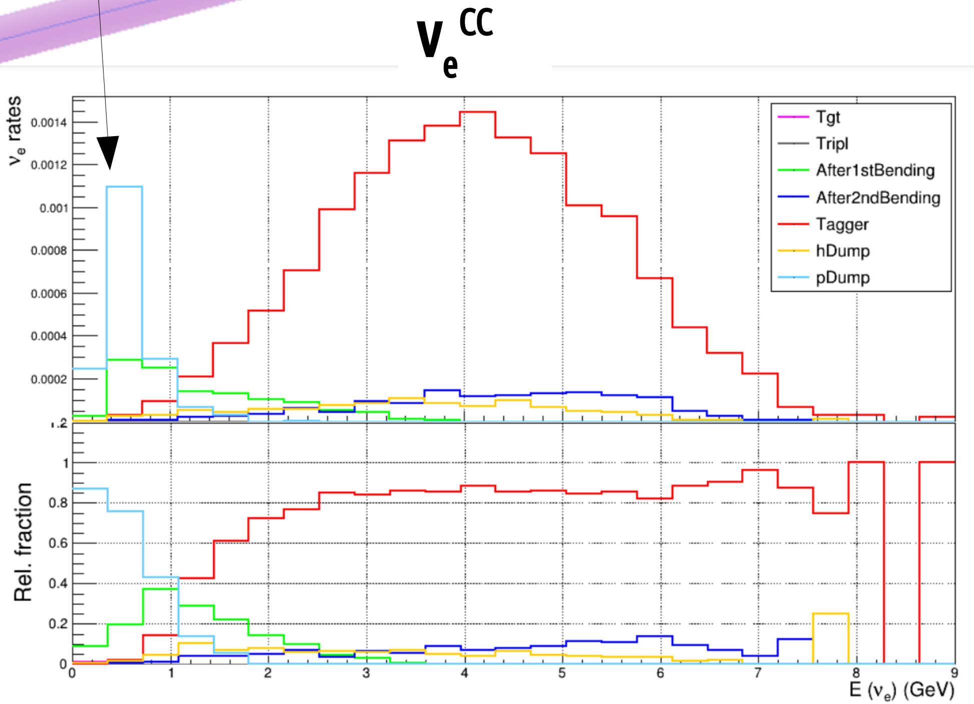
New transferline

- A new design ("TLR6") worked out;
- Optimizes length, optics and collimation
- Implements the optimized target.
- Significant suppression of ν_e from the target region at low-E.
- With 4.5×10^{19} POT/y → 10^4 ν_e^{CC} on 500 t @ 100m from target
- in ~ 2 y (3.5 y with TLR% with optimized target)

Transfer line	π^+ $[10^{-3}/\mathrm{POT}]$ $[8.5 \pm 5\%]$ GeV/c	K^+ $[10^{-3}/\mathrm{POT}]$ $[8.5 \pm 5\%]$ GeV/c	Ratio w.r.t previous results
previous TL	2.05	0.185	
TLR5	3.4	0.28	1.5
TLR6	4.2	0.4	2

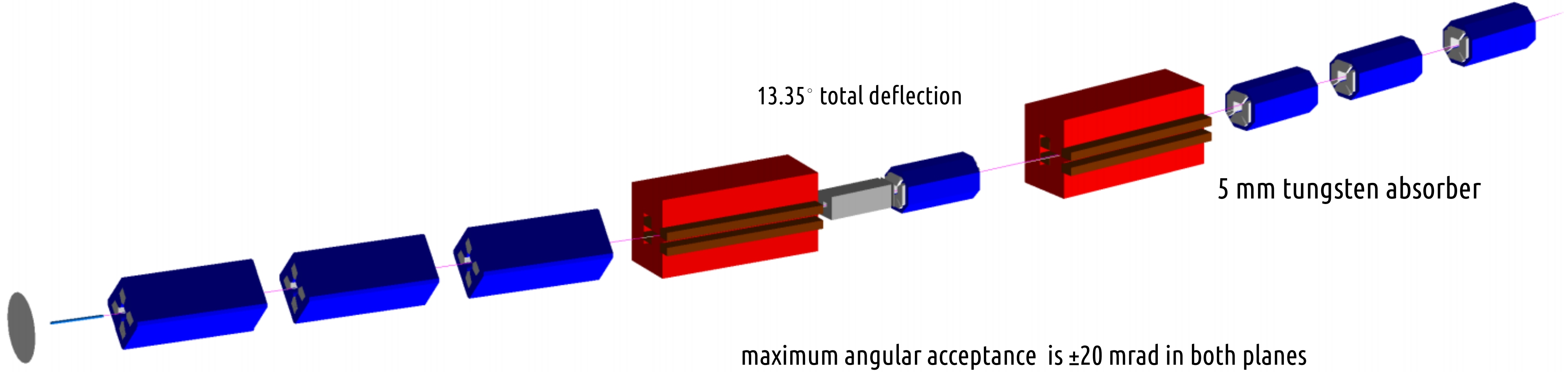


Shielding not displayed



Multi-momentum transferline

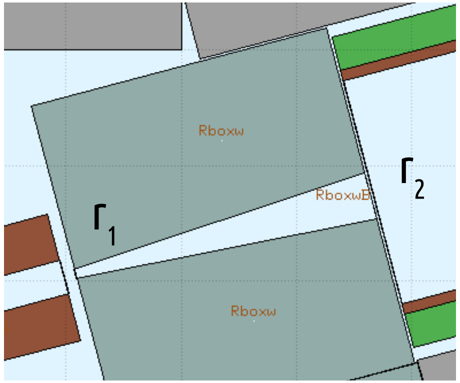
- A parallel study to **add flexibility** and allow a set of **different neutrino spectra** spanning from the **"Hyper-K" to DUNE** regions of interest. Focus **8.5**, **6** or **4** GeV/c secondaries.
- Tools: Optics optimization - TRANSPORT + G4Beamline. Validation + higher order effects with MADX/PTC-TRACK. Background reduction studies: FLUKA
- Detailed description of existing magnetic elements
- Under consideration: whole beamline tilted w.r.t. target → suppresses e^+ more than K^+



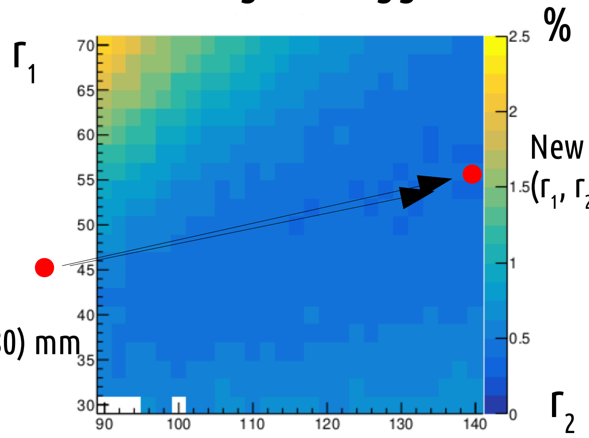
CERN-EN-EA, Parozzi, Charitonidis

Optimization of the final collimator

Standalone fast G4 sim.
Tweaking of radii



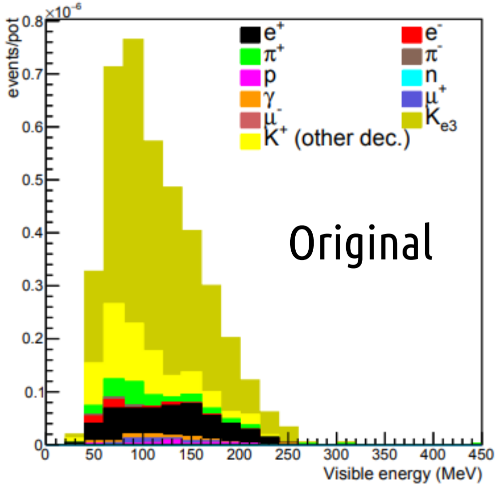
Fraction of transmitted
π^+ hitting the tagger



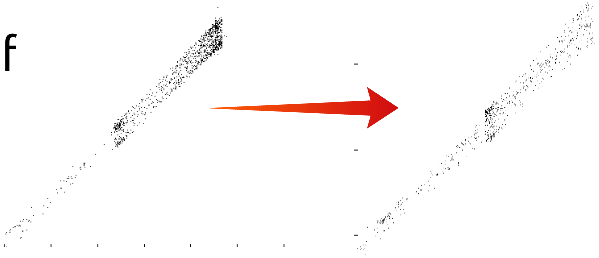
Original
(r_1, r_2)= (45, 80) mm

New best
(r_1, r_2)= (56, 140) mm

Background e+ and π^+
reduced by ~ 22 %



XZ distribution of
the vertex of
background π^+



New collimator will be soon implemented into a new version

In the pipeline:

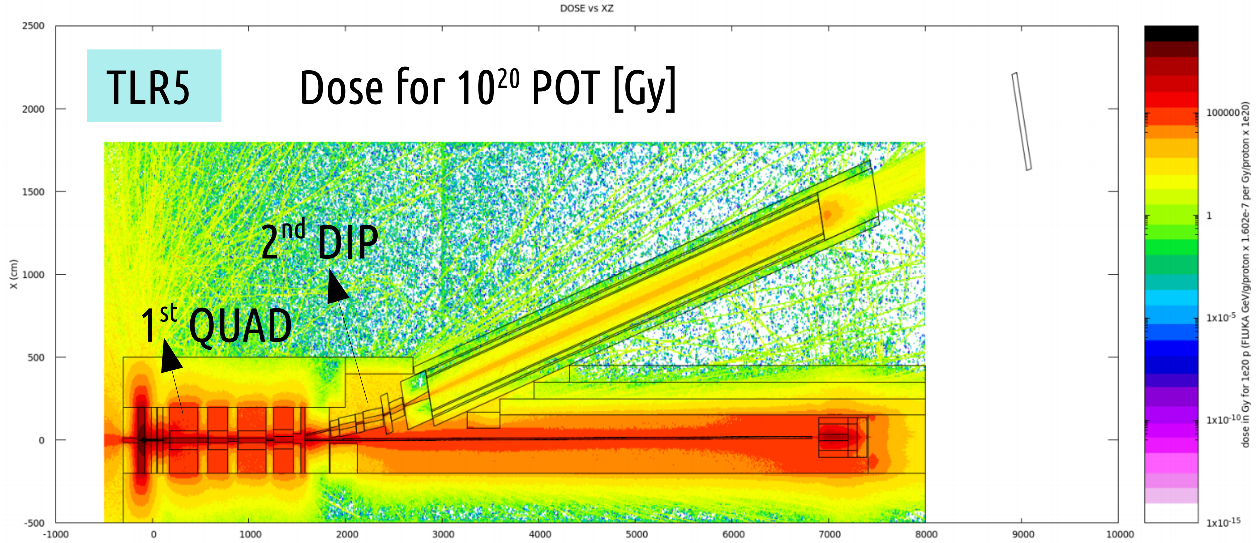
- Testing other shapes (i.e. bi-conical)
- Extend genetic algorithm used for the horn

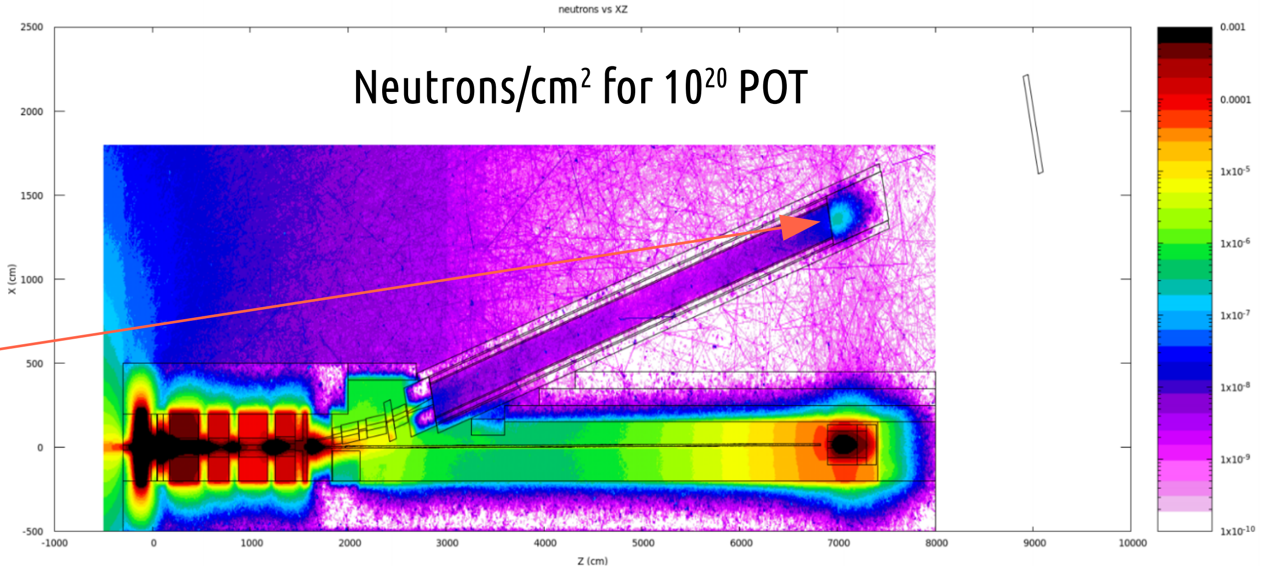
Irradiation studies

The dose at the hottest point of the quadrupole closest to the target is of about 100-300 kGy.

The dose at the second dipole leaves room for thinking about a SC option (could easily double/triple the bending angle)

Optimization of the hadron dump with G4beamline will be soon ported to FLUKA

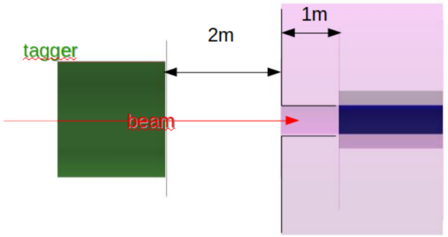


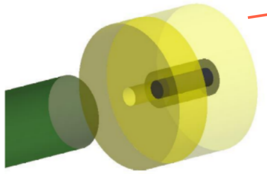


Borated concrete

Iron

Graphite





The ENUBET tagger

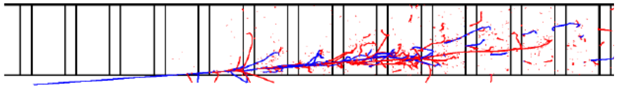
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

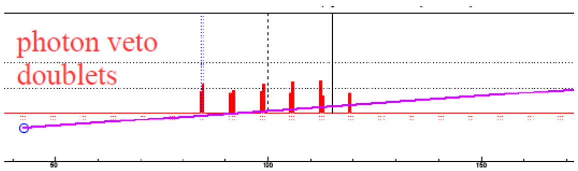


Integrated photon veto

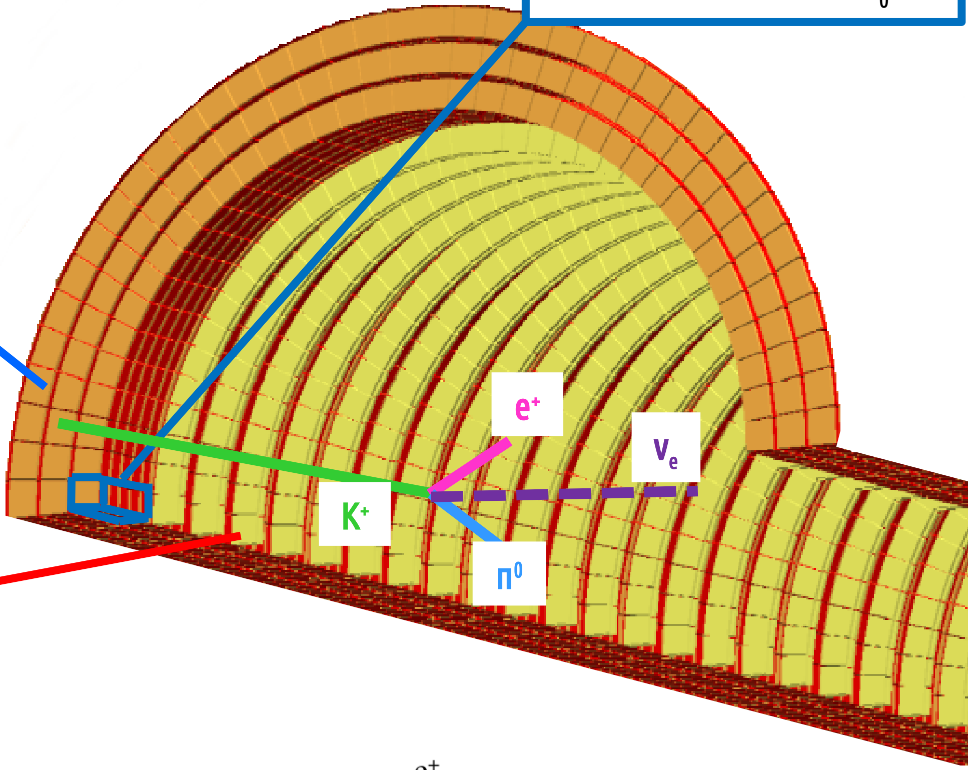
Plastic scintillators

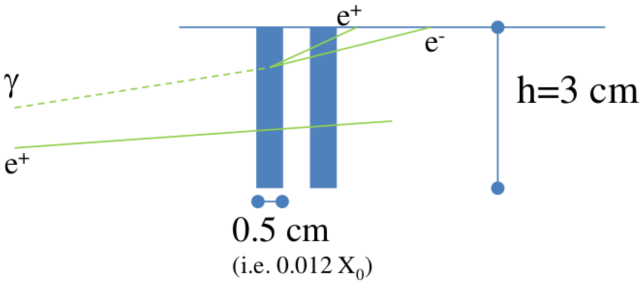
Rings of 3×3 cm² pads

→ π^0 rejection

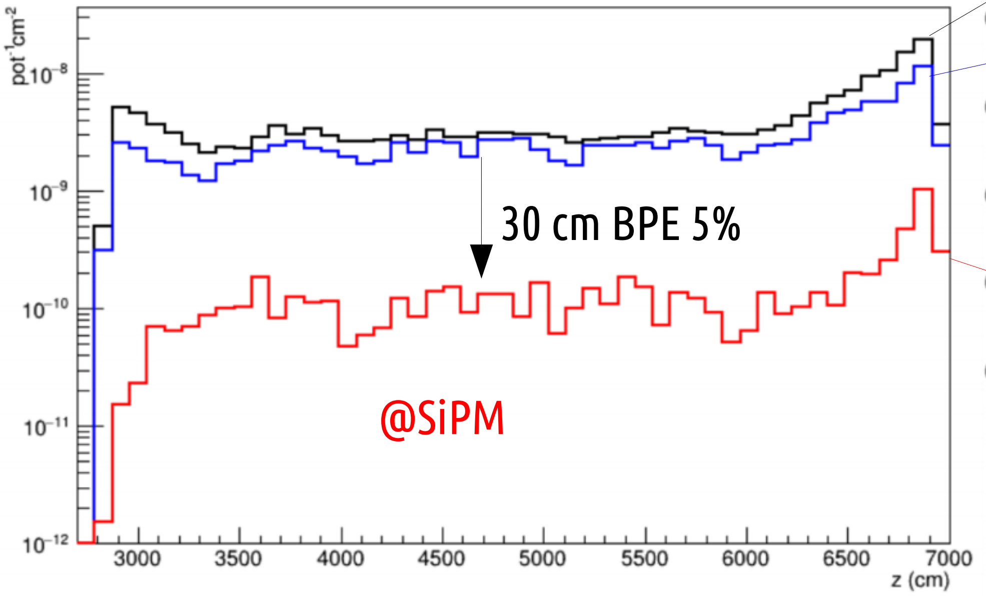


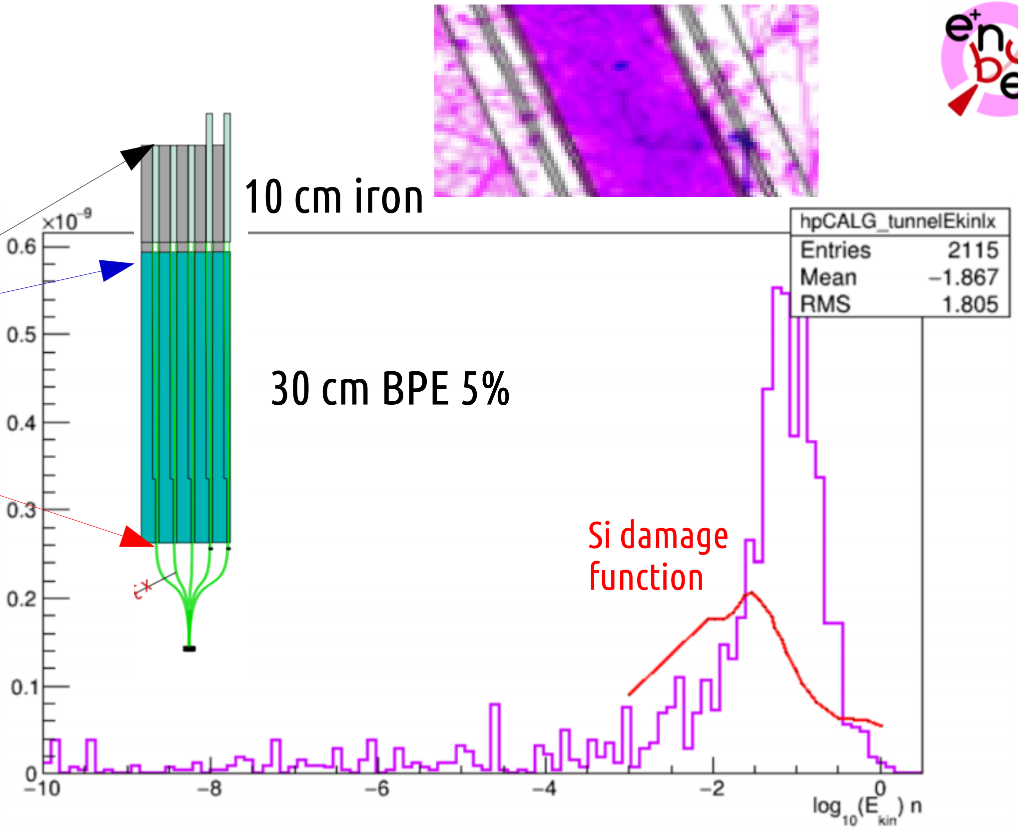
Lateral Compact Module
3×3×10 cm³ – 4.3 X_0





Neutrons in the tagger





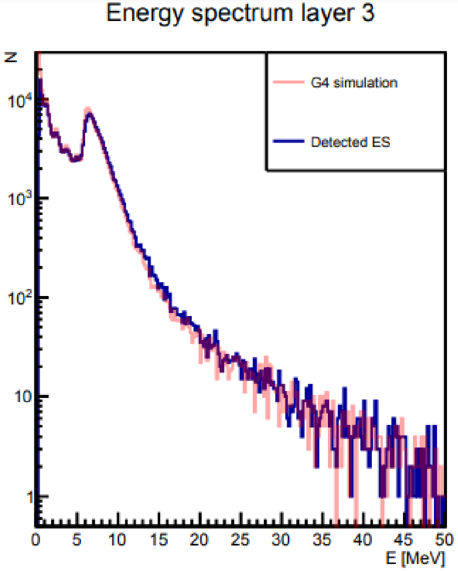
BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7×10^{-11} n/POT/cm^2 **~ 10 x reduction**
(7×10^{9} n/cm^2 for 10^{20} POT)

E_{kin} of surviving neutrons is O(10-100) MeV

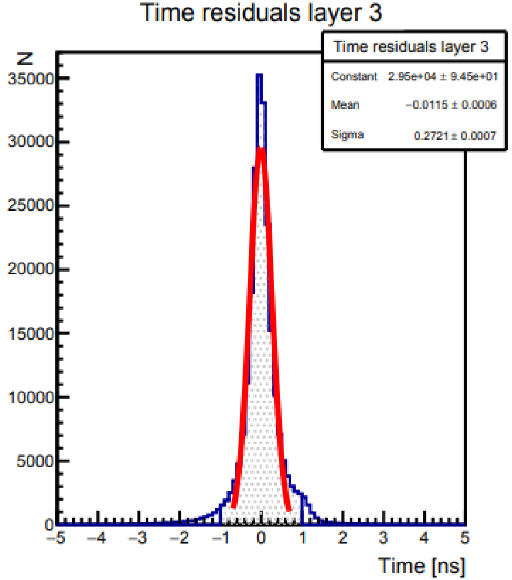
Waveform analysis

The energy is now reconstructed as it will happen for real data i.e. considering the **amplitudes digitally-sampled signals at 500 MS/s**. **Pile-up** effects treated rigorously.

Matching between true level energy deposits from GEANT4 and fully reconstrucred waveforms



Matching between true and reconstructed time (500 MS/s). 270 ps.



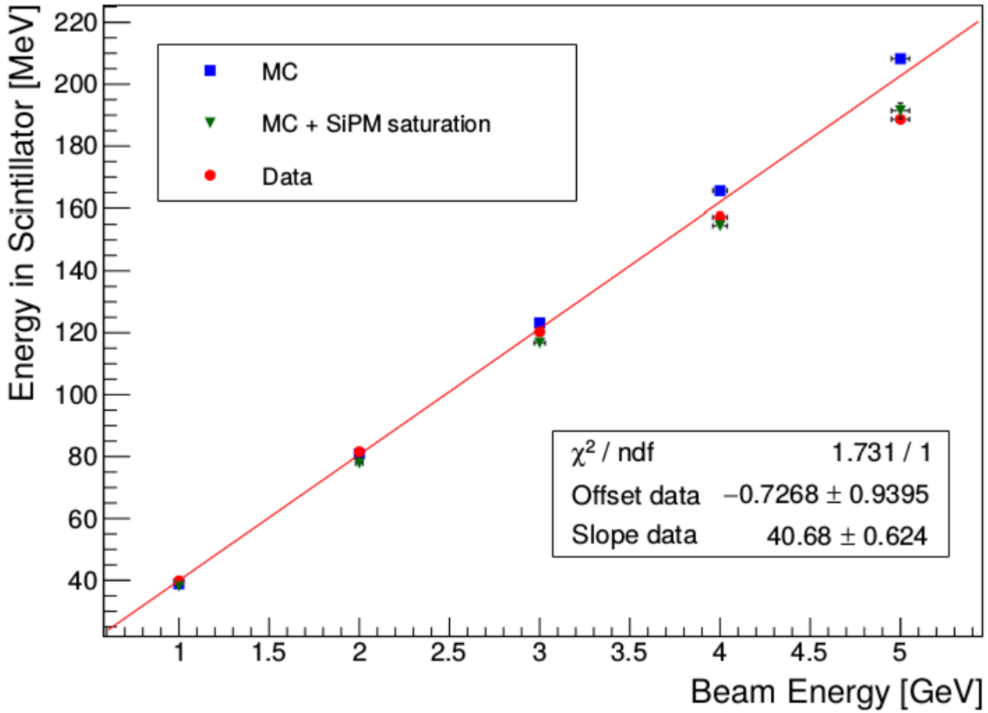
Peak finding efficiencies:
Slow ~ 4.5 x 10^{13} POT in 2s
Fast ~ horn ~ 10 x slow

Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%

Instrumentation

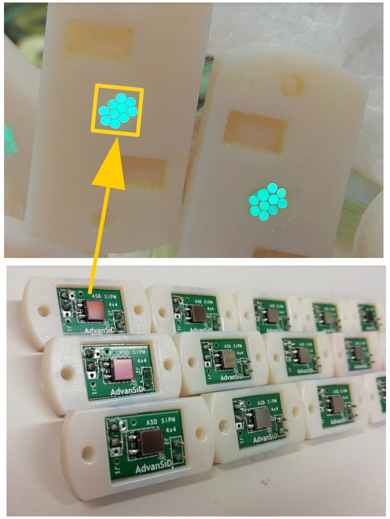
JINST paper published

$$N_{\rm fired} \simeq N_{\rm max}\left(1 - e^{-N_{\rm seed}/N_{\rm max}}\right)$$



$$N_{\rm seed} \equiv (1 + P_{x-talk}) \cdot N_{pe}$$

$$N_{\rm max} \simeq 5000 < 9340$$

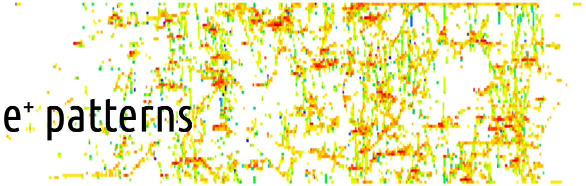


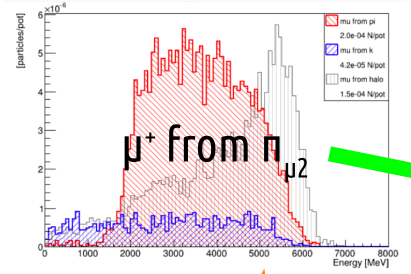
New SiPMs under test (NUV, RGB high density and low cross talk from FBK)

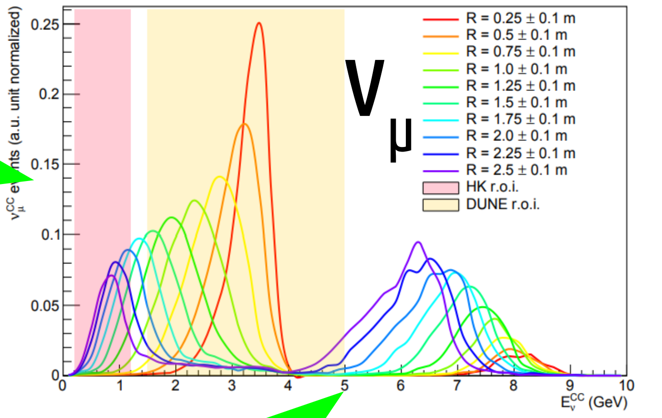
Lepton monitoring

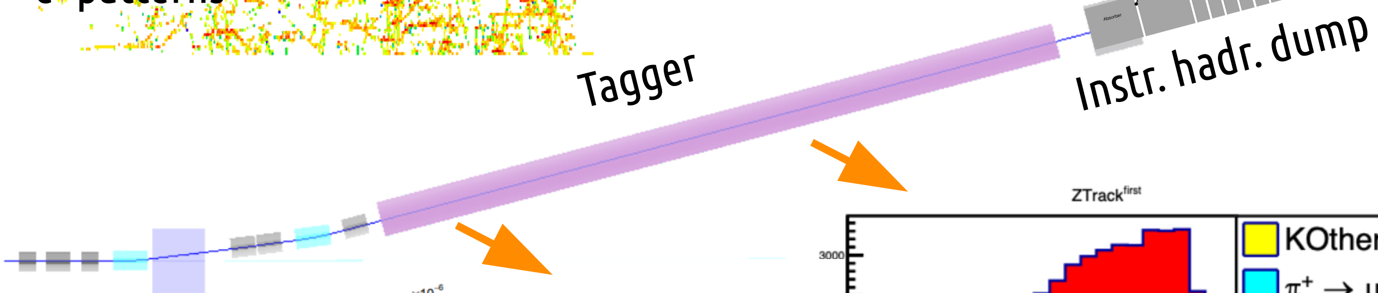
Tagger: leptons from K (ν_e and high-E ν_μ)

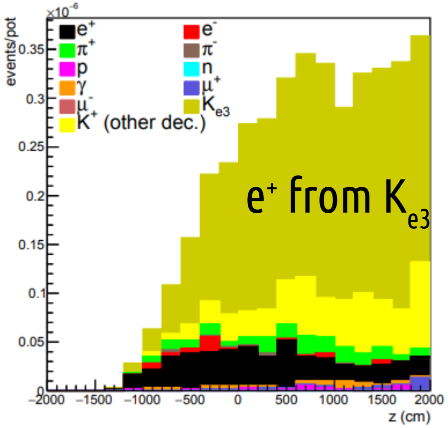
Hadron dump instr: μ from π (low-E ν_μ)

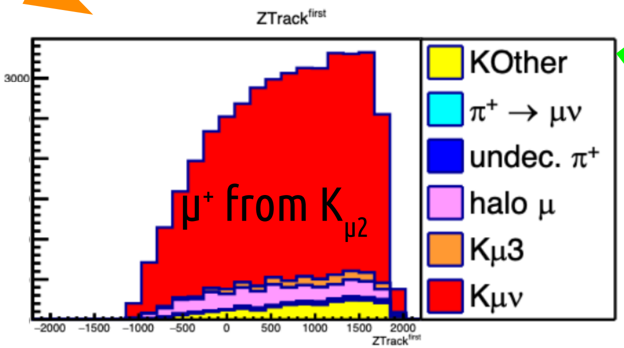


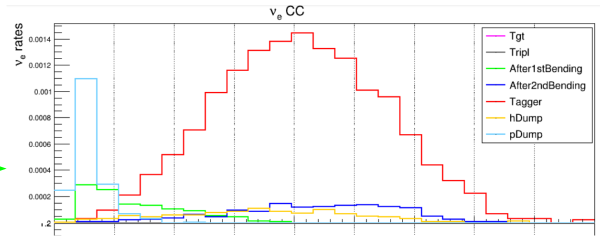












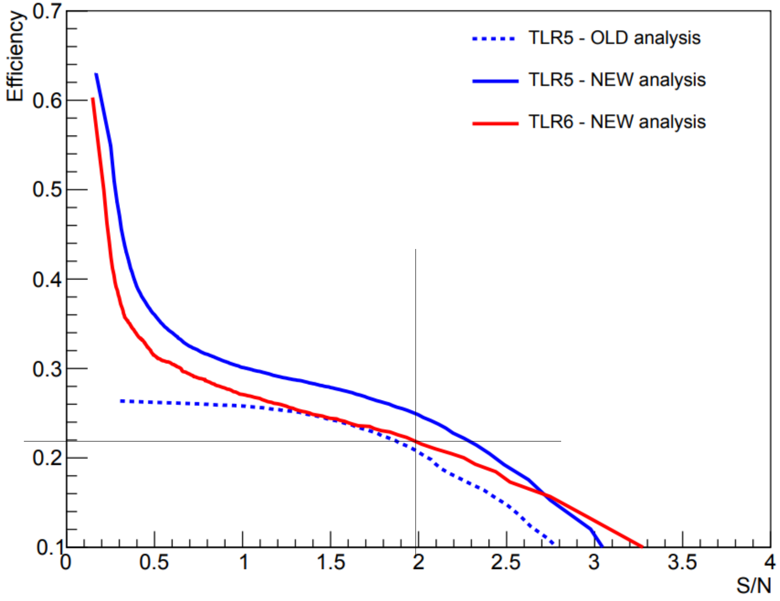
Positron reconstruction

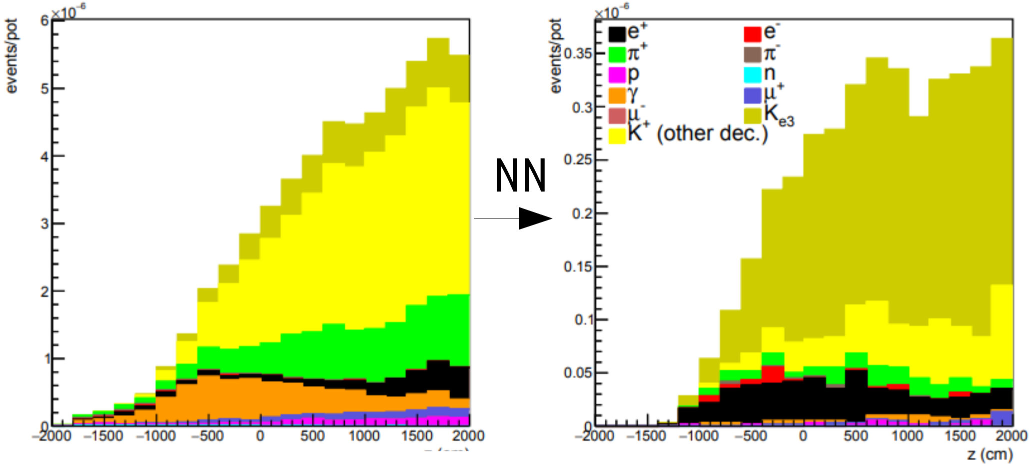
TLR6

In the positron reconstruction algorithms the t_0-layer variables have been embedded in our multi-variate analysis in a transparent way.

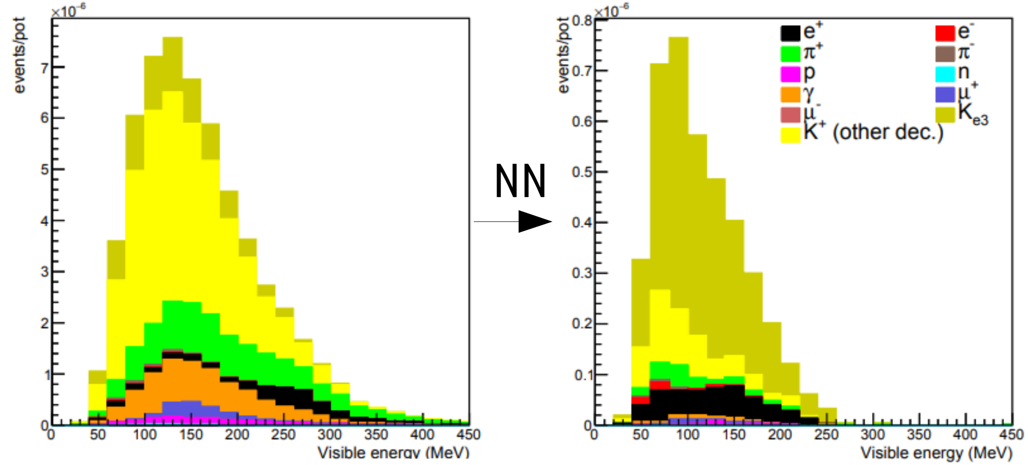
K_{e3} positron selection:

efficiency ~22%   **S/N of ~2**





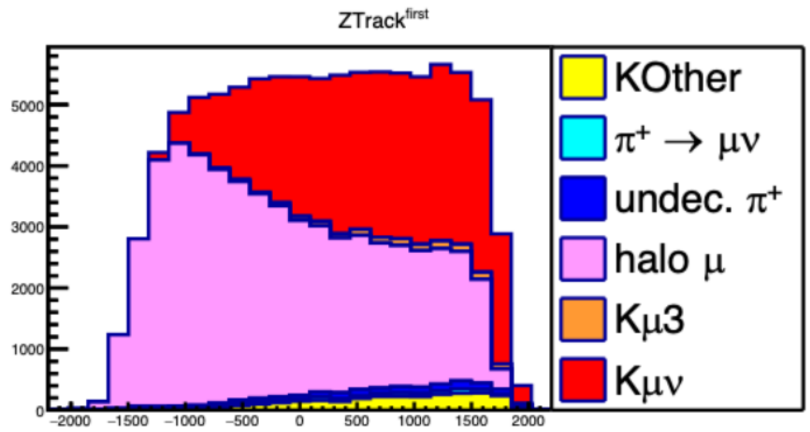
Z, coord. along the tagger (cm)



Visible energy (MeV)

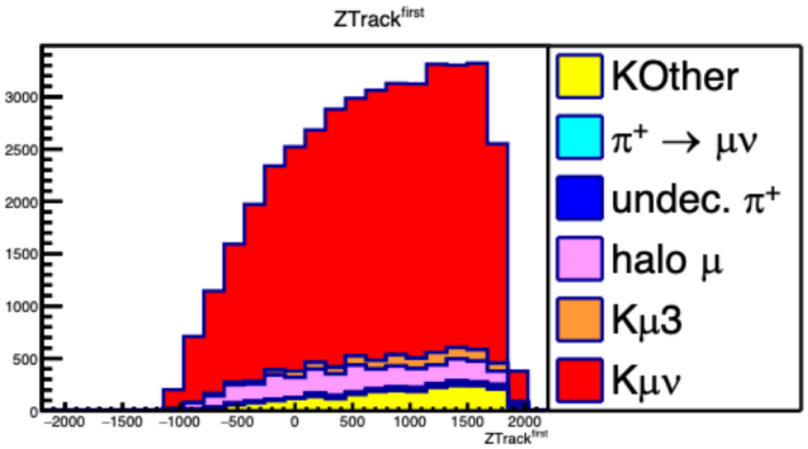
Muon reconstruction

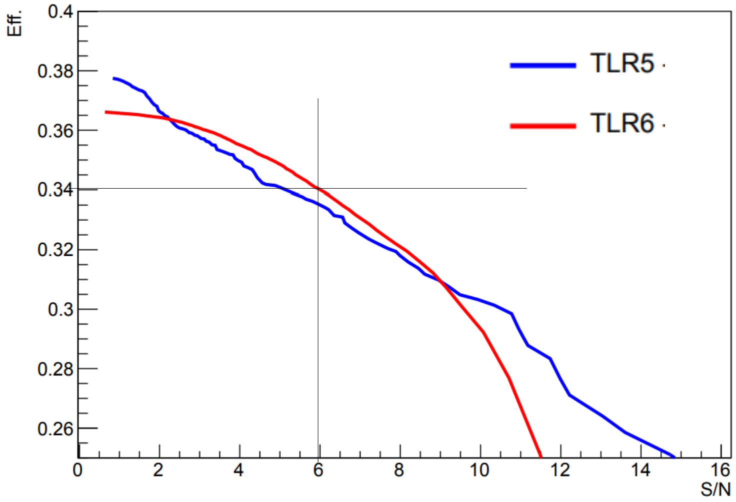
TLR6



Z coord. along the tagger (cm)

NN



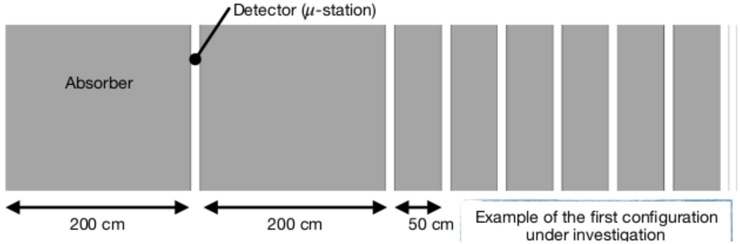


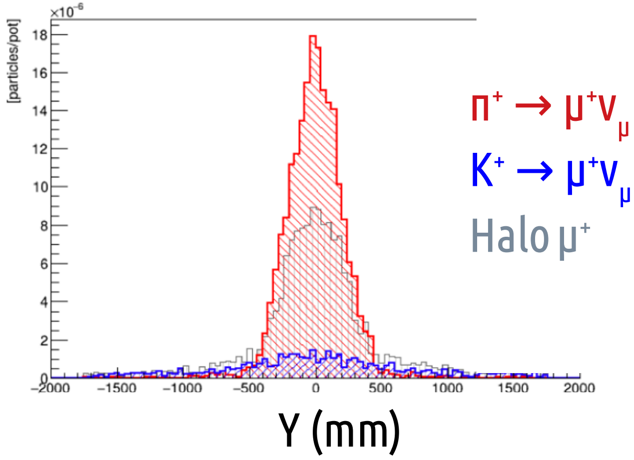
μ^+ from $K_{\mu\nu}$ selection:

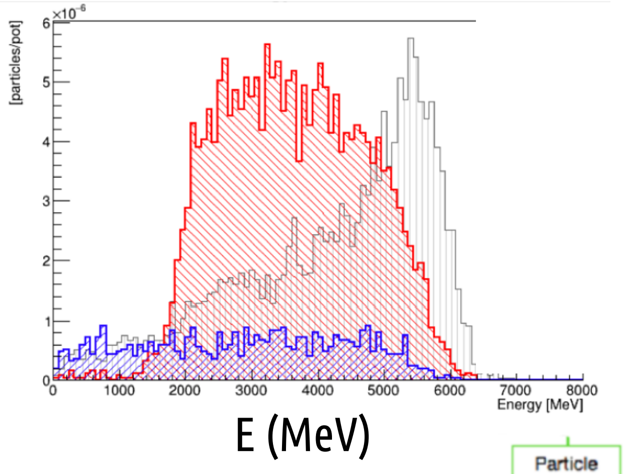
efficiency ~34% **S/N of ~6**

Foeward region muons reconstruction

Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.

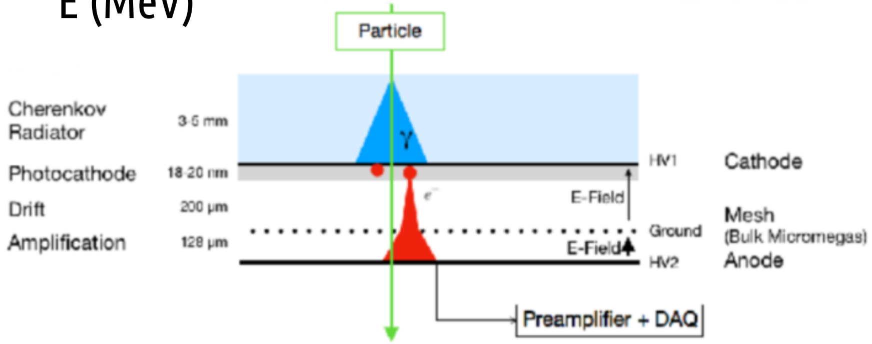


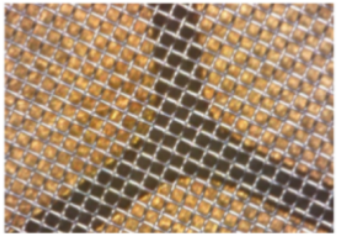




The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 $MeV\text{-}n_{eq}/cm^2$.

Design being defined. Possible candidate: fast Micromegas detectors employing Cherenkov radiators + thin drift gap (PICOSEC coll.). Bonus: excellent timing.

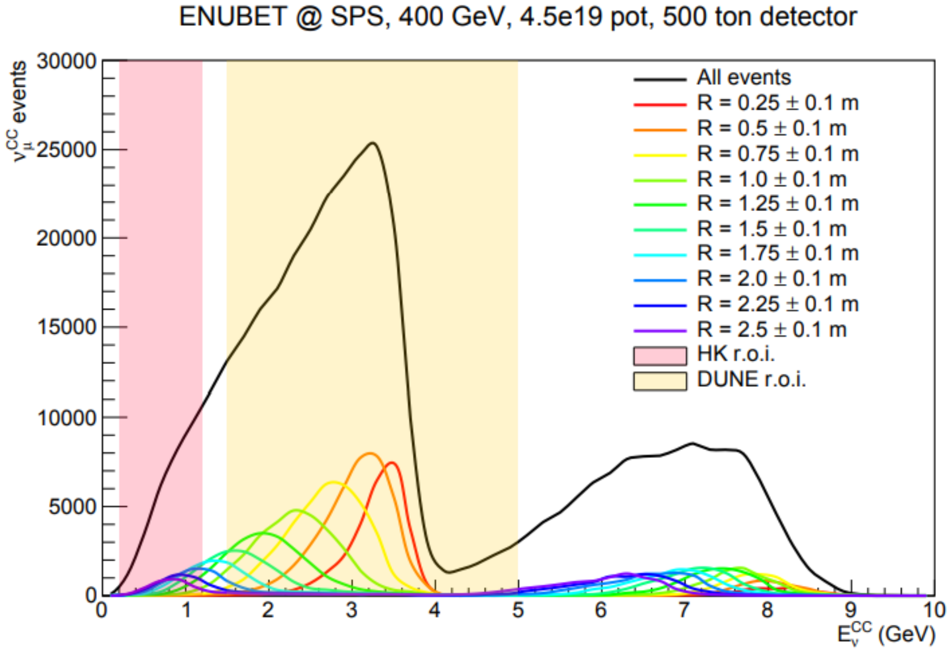


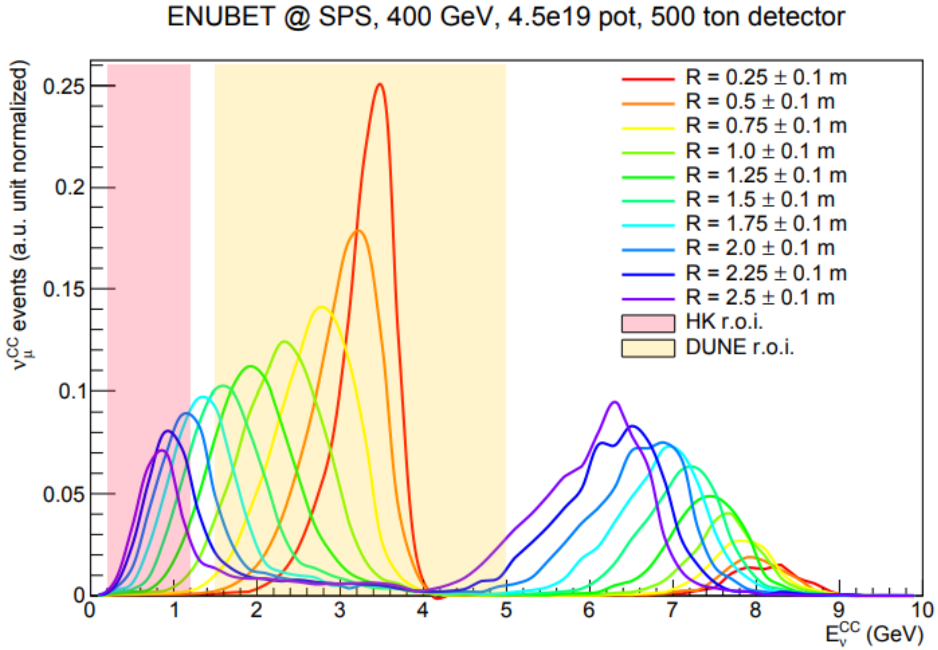


Narrow-band, off-axis technique

Neutrino interactions in bins of the **radial distance from the center of the beam** allow to **single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. A kind of "off-axis" but without having to move the detector (thanks to the low distance of the detector) !

TLR6



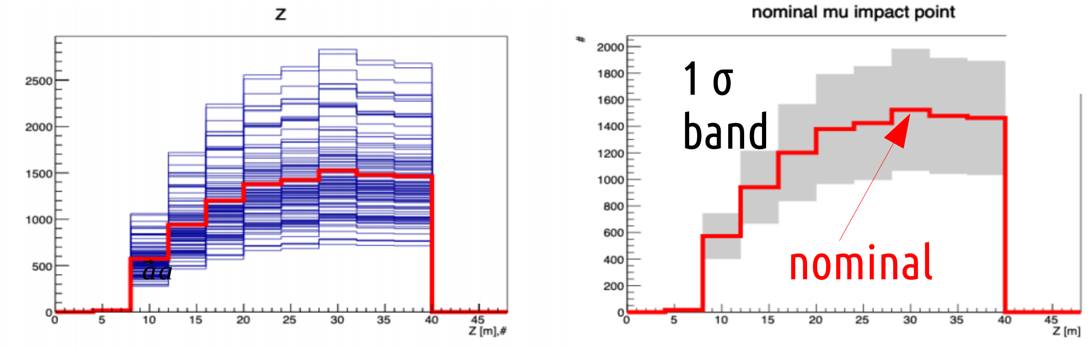


Framework for systematics

A software framework written within **ROOFIT** to **constrain the neutrino flux from the reconstructed leptons**.

To validate the machinery the impact point along the tagger of muons from kaon decays is considered.

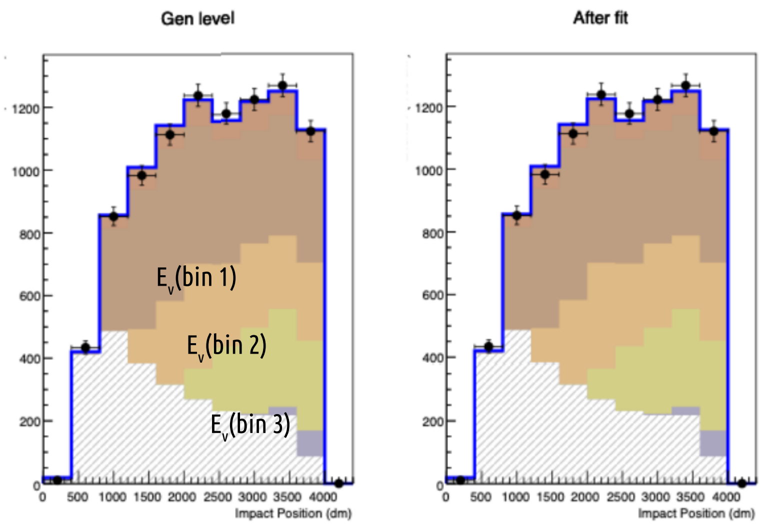
Uncertainty envelope created by sampling hadro-production parameters of **a toy model** (multiverse method).



Extended likelihood fit of lepton variables with **templates in bins of the associated neutrino energy**:

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

Nuisance parameters from uncertainties related to **hadroproduction** (α) and **beam parameters** (β).

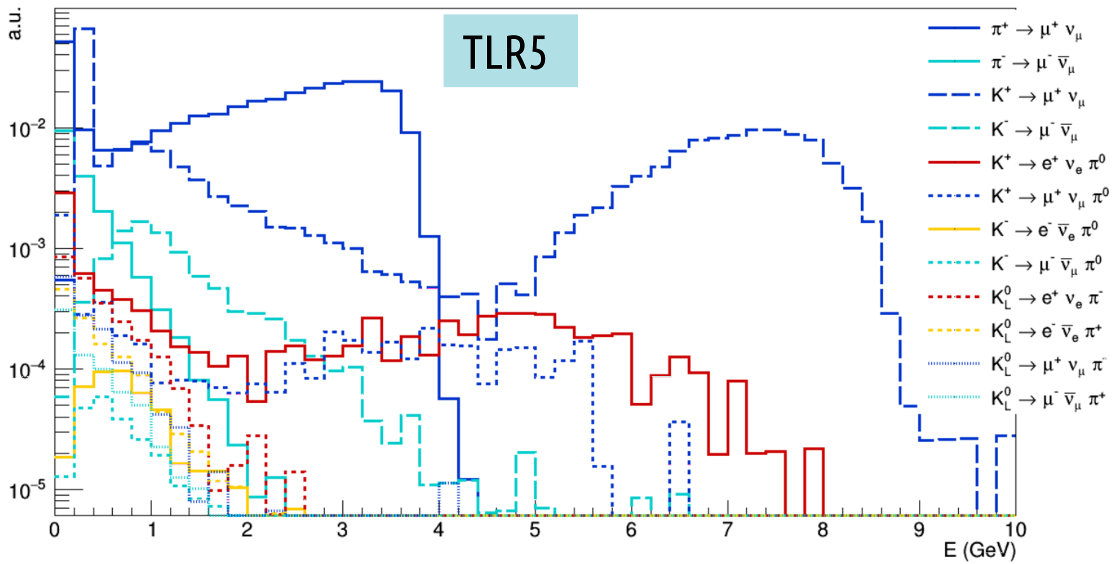


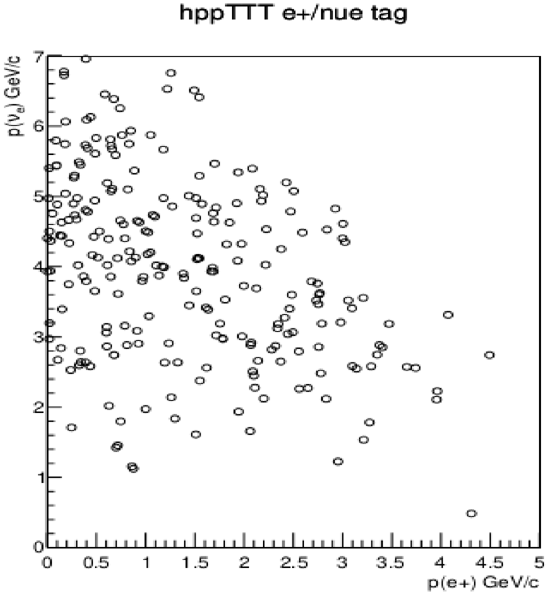
Fit the relative normalizations of the templates in E_ν → flux constraint.

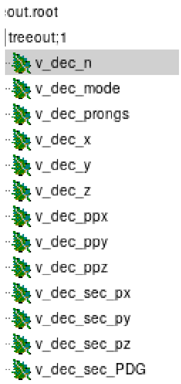
In progress: from a toy to the **real ENUBET case using full simulation**.

Framework for systematics

- → created a **common data model** to be used for systematic studies (G4TL+G4TAG).
- Unify p-target (FLUKA). Full simulation including the beamline G4 (G4TL). Tagger simulation and lepton reconstruction G4 (G4TAG).
- Information of **all decays producing neutrinos** is stored and linked to the parent particle at the level of target and at the tunnel entrance.
- Allows a full description of **ν-flux components** and **linking neutrinos to the relative reconstructed leptons**.

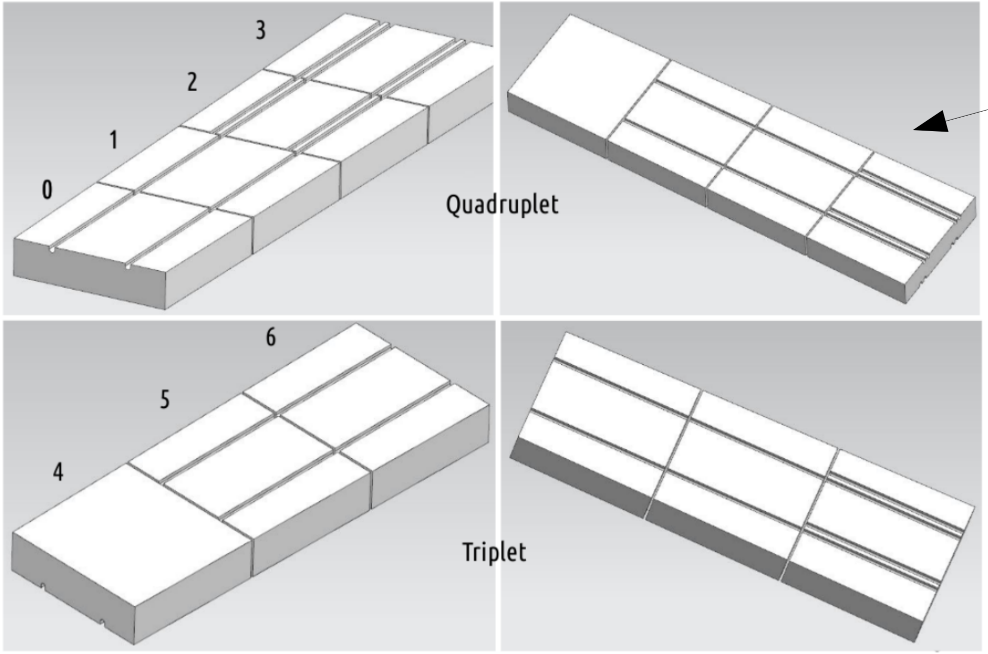




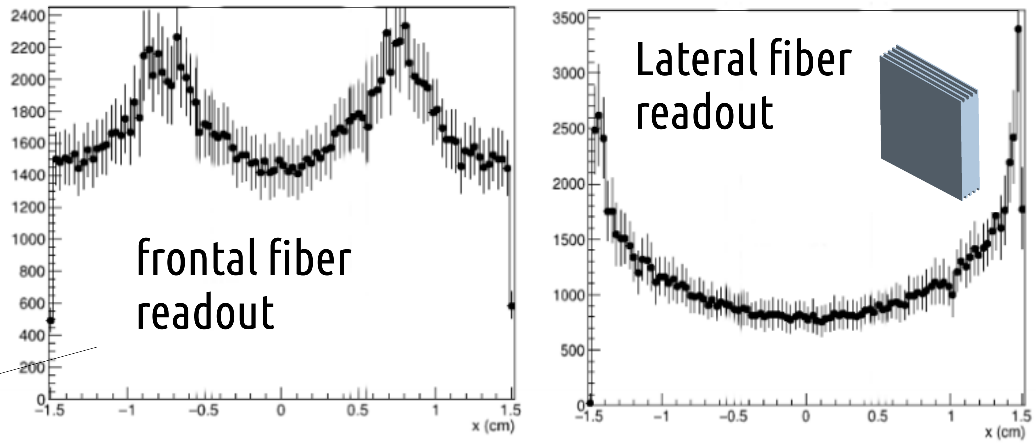


Updated light readout scheme

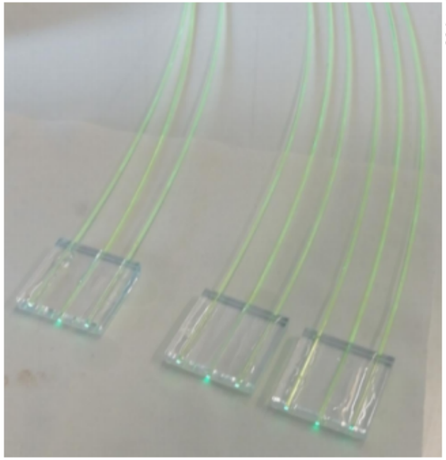
- From lateral to frontal light collection
- Safer for injection molding. More uniform, efficient.
- Each tile has readout grooves and “transit” grooves.
- Readout grooves on alternate sides.
- Staggering for the two tiles at larger r.

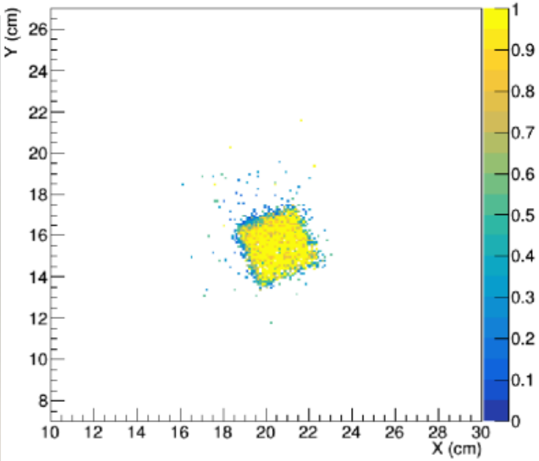


GEANT4 optical simulation



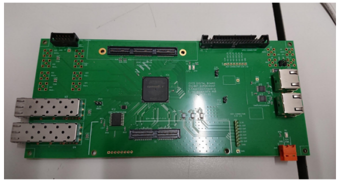
Uniformity tests with cosmic rays



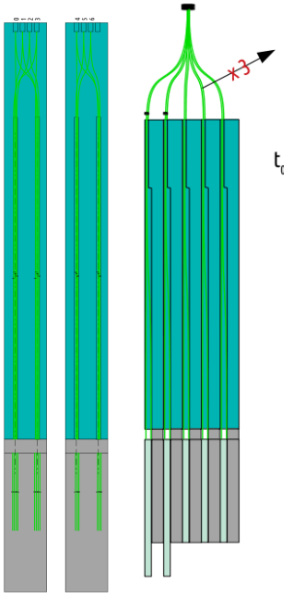


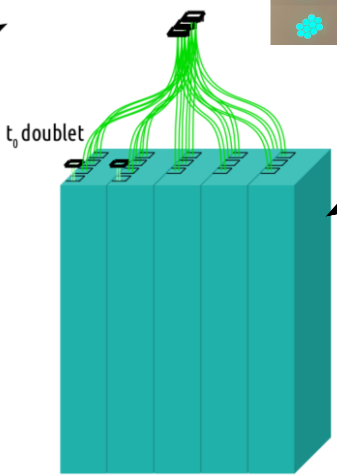
Towards the demonstrator

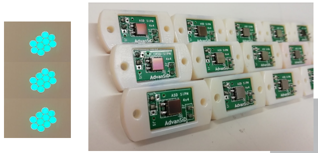
Custom digitizers
@ 500 MS/s

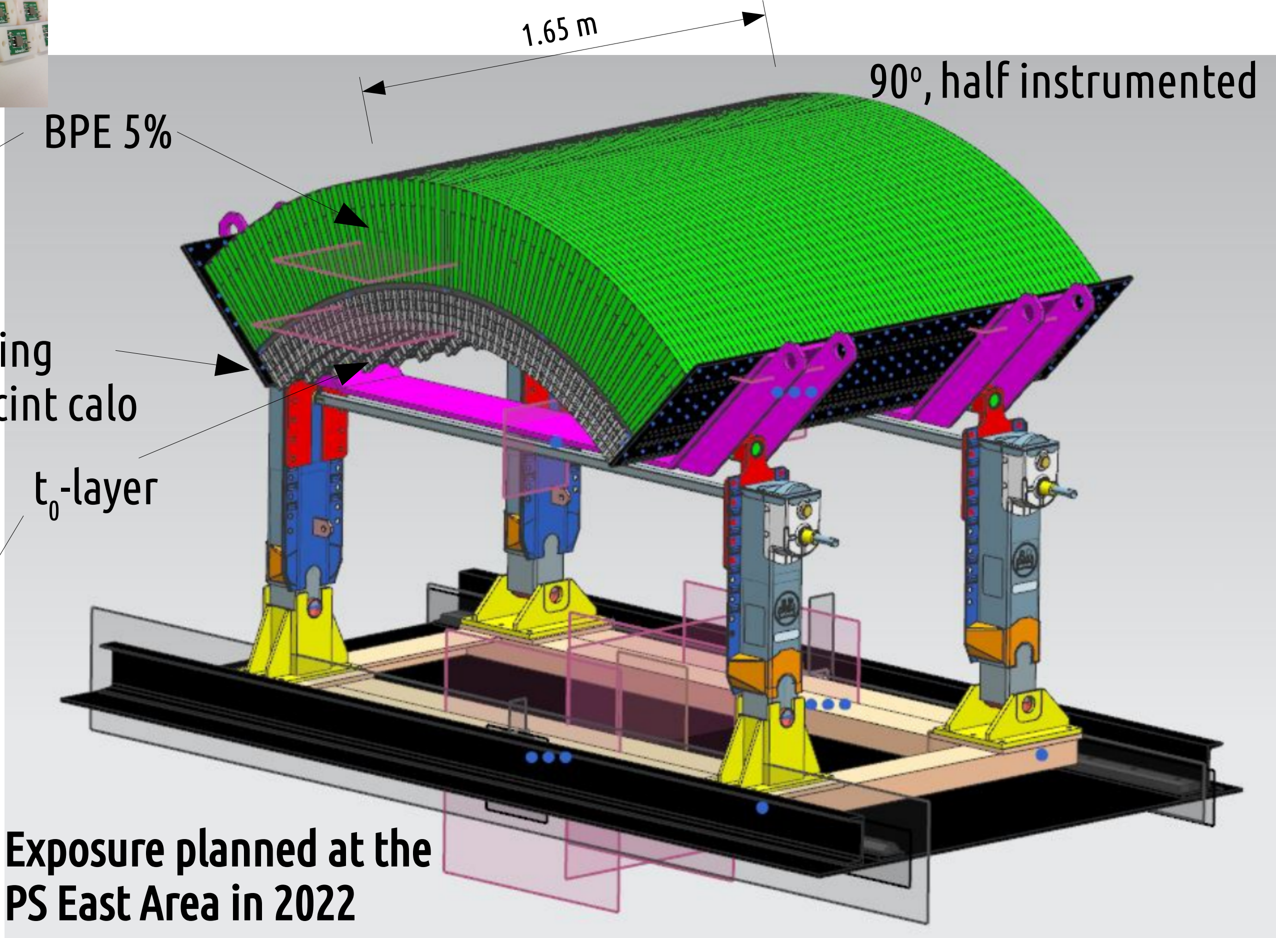


WLS routing









90°, half instrumented

BPE 5%

Sampling
iron/scint calo

t_0-layer

Exposure planned at the
PS East Area in 2022

Joint studies with nuSTORM in PCB

The positive outcome of the European Strategy for Particle Physics has triggered a shared effort with nuSTORM: investigate the presence of realistic synergies in terms of physics reach and a possible coordinated technical implementation.

Joint presentation at the Physics Beyond Colliders workshop (03/21)

The rationale of ENUBET νSTORM

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important

European Strategy for Particle Physics Deliberation document (pag. 5)

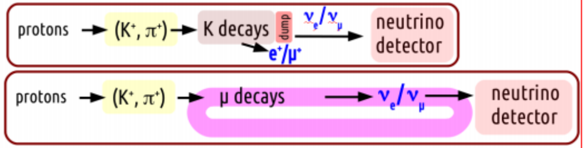
ENUBET and nuSTORM (see also the European Strategy Physics Briefbook, arXiv:1910.11775)

ENUBET, in particular is aimed at

- Designing a narrow band neutrino beam at the GeV scale and measure at 1% the **flux, flavor** and (at 10%) the **energy of the neutrinos** produced at source

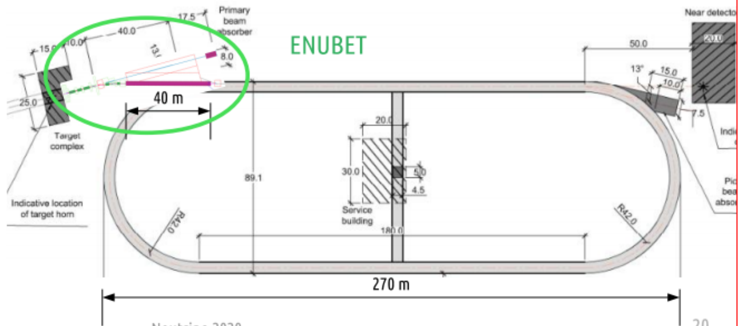
NuSTORM: offers an **unprecedented statistics of ν_e** and a major leap toward Neutrino Factories and **the muon collider**

nuSTORM & ENUBET



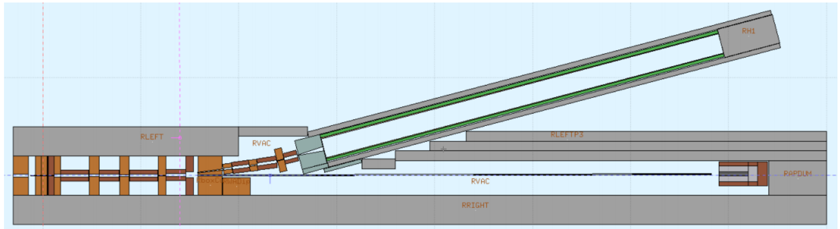
	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section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

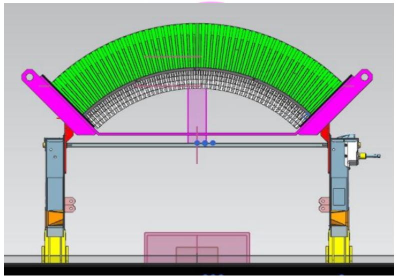
- Different concepts, budget, geometry.
- Main synergy: target facility, 1st stage of meson focusing, proton dump.



A. Longhin Neutrino 2020 20

Conclusions



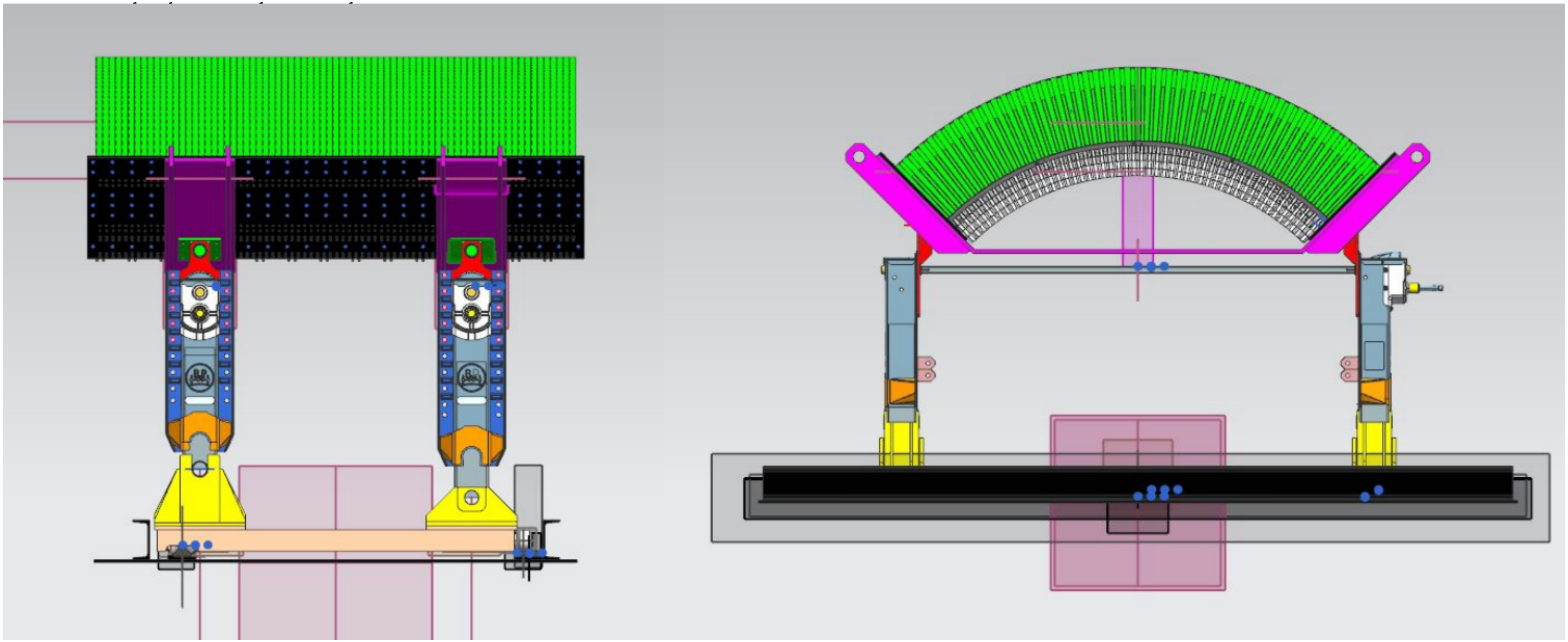


- **ENUBET is on schedule** and we are entering the last phase of the project
- **The new beamline: single particle e^+/μ^+ monitoring** with good **S/B, efficiency and neutrino yields with a** much reduced **untagged-ν_e component**
  - **Multi-momentum** option on its way
- Experimental test of **"burst" slow extraction** @ SPS → could go down to 3 ms
  - **horn option** remains very appealing: further optimization ongoing
- **Frontal readout** option → **long lifetime/accessibility of SiPM**
- Completed the **test beams** campaign before CERN LS2
- **Redundant end-to-end simulation** as a framework for the treatment of **systematics**
- **Construction of the demonstrator and electronics in progress → test at PS East Hall summer 2022**

  - **PBC:** Engineering studies, explore synergies with nuSTORM
  - **Conceptual Design Report** at the end of the project (2022): **physics** and **costing**

Bonus slides

Design of the demonstrator



FLUKA irradiation studies

The double dipole beamline has been ported to FLUKA and the neutron and ionizing doses have been updated. The double dipole allows to **decrease the neutron flux at the location of photo-sensors by about one order of magnitude with respect to the single-dipole one**