

WP6 Summary

F. Pupilli – INFN Padova



ESSnuSB+ 4th Annual meeting
Wik's Castle - 6/10/2026

Work Package 6 of ESSnuSB+



Co-funded by
the European Union



ESS neutrino Super Beam plus

Participants: Unimib (Milano, Italy), INFN (Padova, Italy), RBI (Zagreb, Croatia), NCSR D (Athens, Greece), AUTH (Thessaloniki, Greece)

The main difficulty we had to address was recruitment: we opened a PhD position at Milano-Bicocca, but the selected candidate eventually declined. A new PhD student started working full-time on WP6 only in November 2024 (A. Scanu). Similarly, the post-doc position from INFN was awarded in September 2024 (D. D'Ago).

We were able to significantly advance the WP6 tasks thanks to the support of the ENUBET collaboration and by reusing most of the simulation tools developed in the past.

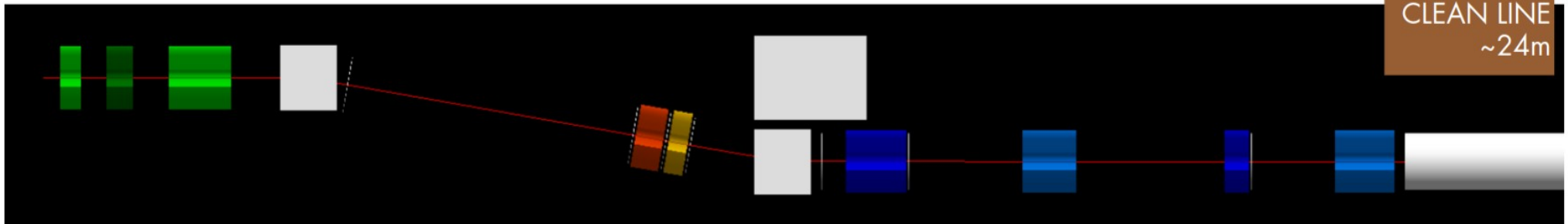
Work is now in full swing, and we are close to completing all tasks

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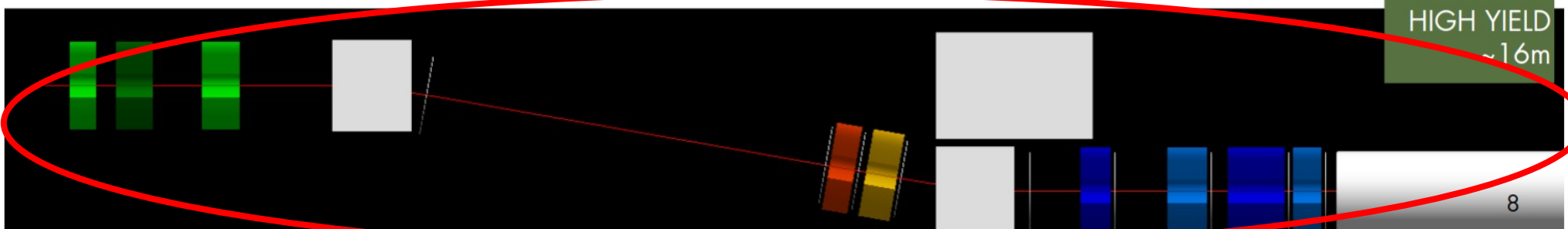
Indeed significant progress since the last Annual Meeting shown yesterday

OPTIMIZED BEAMLINE STUDIES

Working with the nominal ESS
LINAC parameters:
E=2 GeV
Spill: 8.3×10^{14} /2.86 pot/ms
No accumulator ring



- The optimal solutions provided by the genetic algorithm were tested with 1 GPOT statistics
- The killing conditions is removed.
- Detectors are placed at the exit of each quadrupole to study the beam evolution.
- The tunnel is a cylindrical virtual detector of thickness 1 cm.
- naïve observation: longer bl has lower yield but higher purity

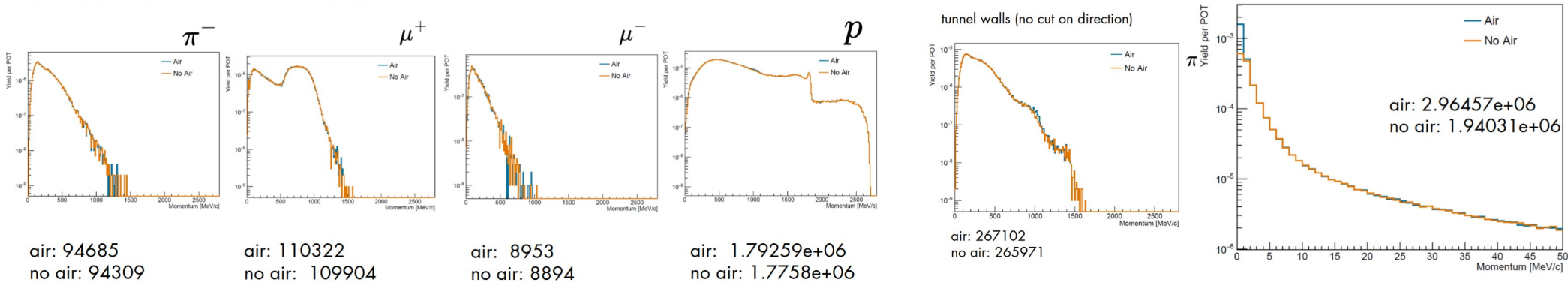


The optimization of the beamline optics with a genetic algo was completed at the time of Milos Meeting

Moving forward selecting the high yield one, allowing for a pion yield within specs ($\geq 10^{-4}$ /pot)
And introducing proper shielding to the “naked” one coming from the optimization to reduce bkg

AIR EFFECT ON TUNNEL WALLS

Effect on tunnel walls is negligible for most of particle species, increase of <1%
Quoted numbers refer to a tot of 1GPOT statistics



Investigating the effect of a residual air in the tunnel, slightly evacuated (100 mbar residual air)

Indeed no significant effect on all particle species, except for an increase of very soft electrons, coming from air ionization → no impact on the tunnel instrumentation and on the muon reconstruction for monitoring

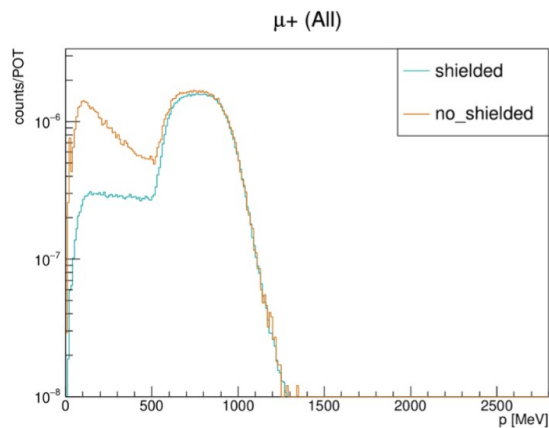
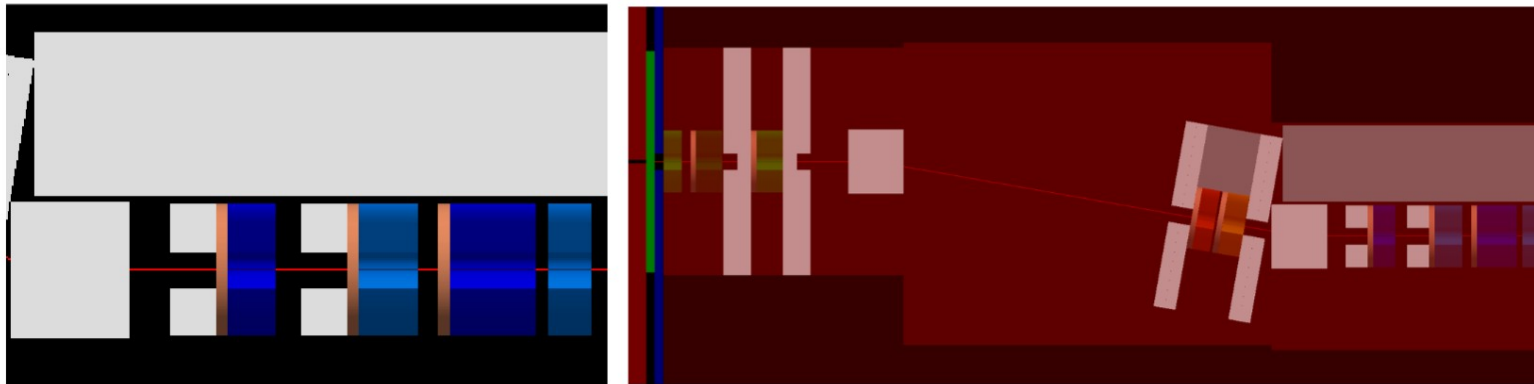
As correctly pointed, check the effect of air at normal pressure, cause it will ease the construction of the decay tunnel → TO BE DONE

SHIELDING DESIGN

Downstream of the bending:

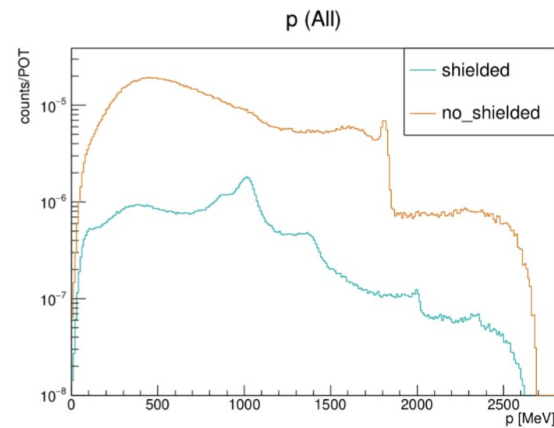
- Concrete shield added before each quad (except quad9)
- Vertical slits (400 mm thick) before quad6 and quad7
- Slit side reduced to allocate proton dump
- p dump at ~10 cm from the quad side

Final design of the beamline
with shieldings in place



$$shielded : (7.581 \pm 0.009) \times \frac{10^{-5}}{POT}$$

$$nonshielded : (11.03 \pm 0.03) \times \frac{10^{-5}}{POT}$$



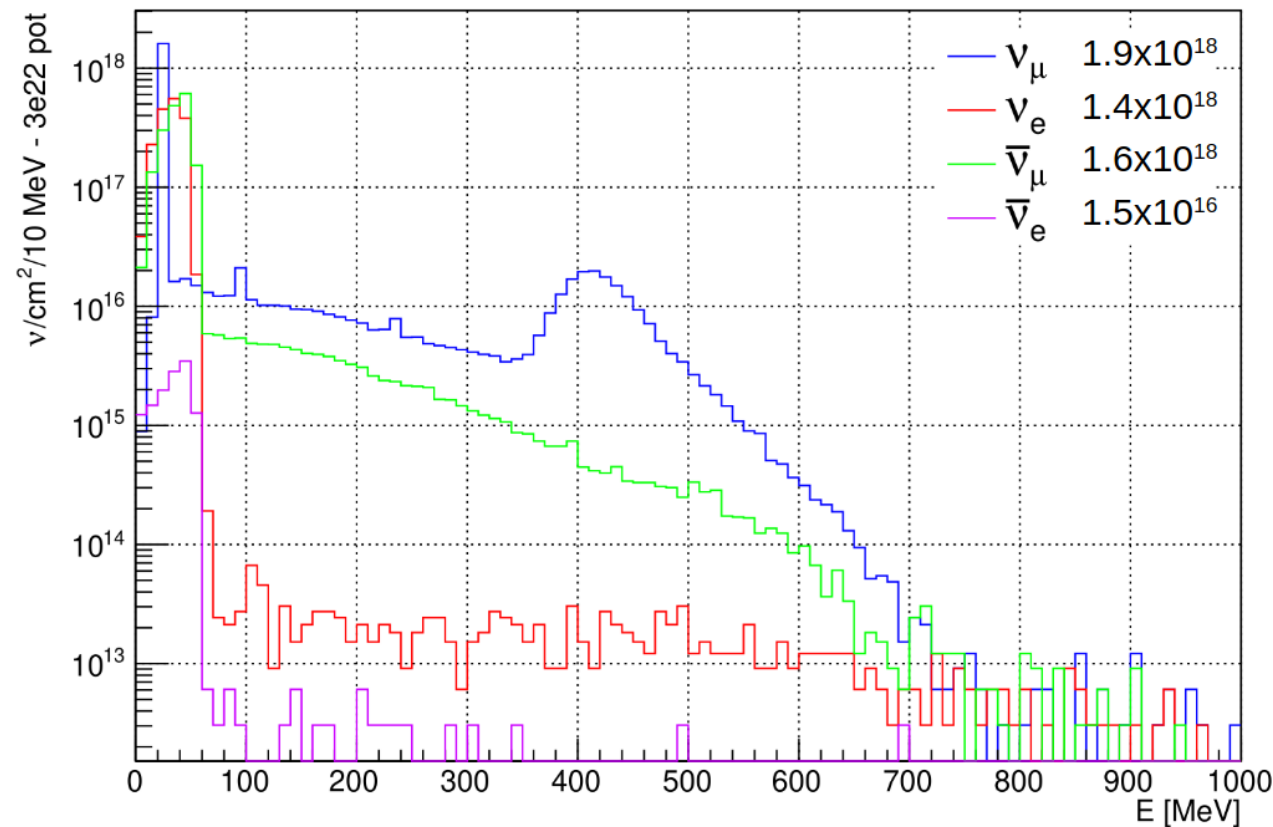
$$shielded : (1.235 \pm 0.001) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (17.93 \pm 0.01) \times \frac{10^{-4}}{POT}$$

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After the implementation of the shieldings there's a significant reduction of the background on the instrumented tunnel walls

Neutrino fluxes at LEMMOND



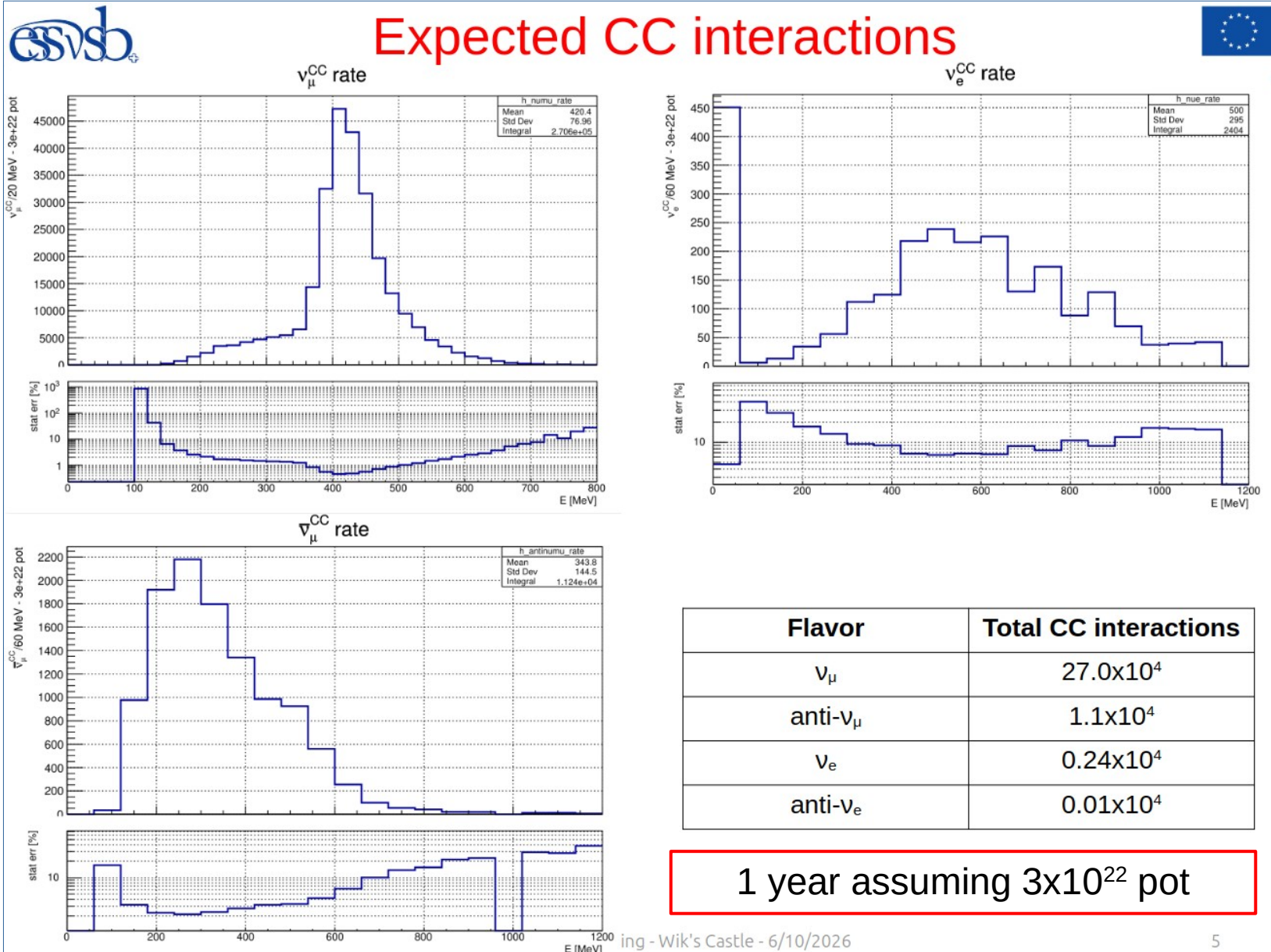
- Peak around 400 MeV in the ν_μ flux originated from decays of momentum selected π^+
- Sharp peak at low energy due to the monochromatic line at ~ 29.8 MeV from the DAR of π^+ (and at ~ 236 MeV from DAR of K^+)
- Large contribution at low energy to anti- ν_μ and ν_e fluxes from DAR of μ^+ with $E_{\max} \sim 52.8$ MeV
- At higher energies ν_e exhibit the shape expected from 3-body decays of μ^+ (shadowed in the case of anti- ν_μ by the large contribution from DIF of π^-)

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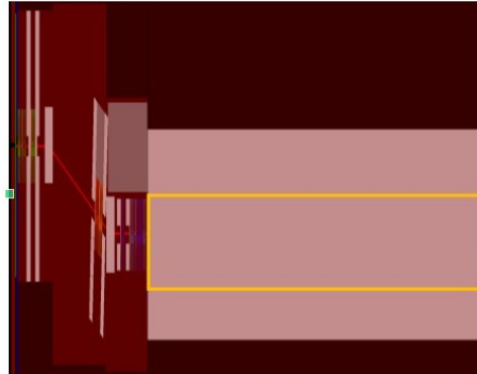
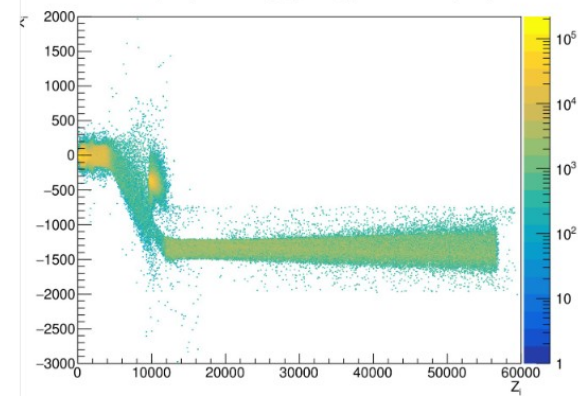
The final version of the beamline allowed to move from mock-up neutrino fluxes to realistic fluxes at LEMMOND ...



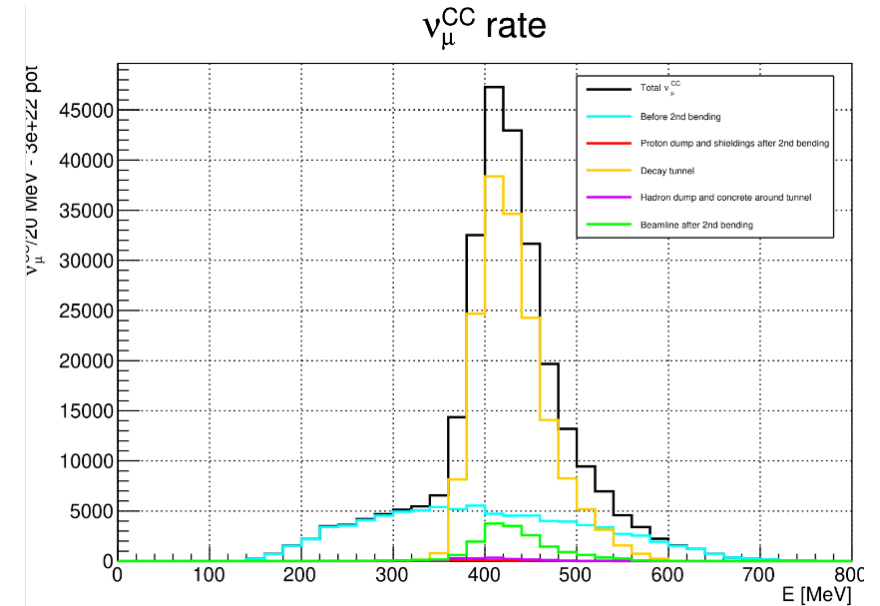
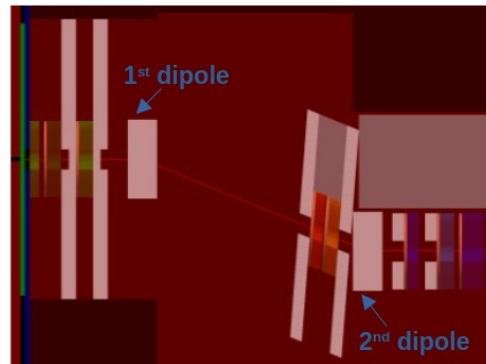
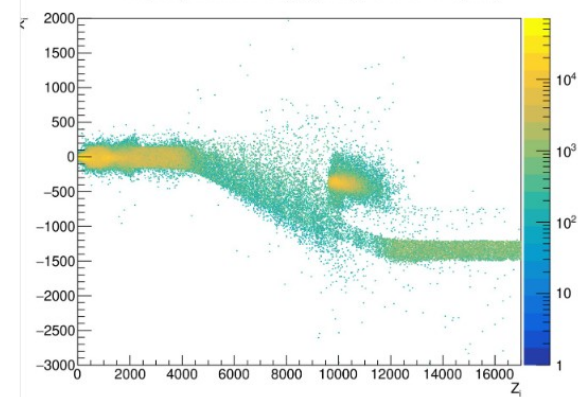
... And to estimate the expected statistics in terms of CC interactions at LEMMOND

Muon neutrinos (E-weighted, mu threshold)

14: X_1 vs Z_1 - Full Z Range [0, 75 m] (Momentum Weighted)



14: X_1 vs Z_1 - Zoomed Z Range [0, 17 m] (Momentum Weighted)

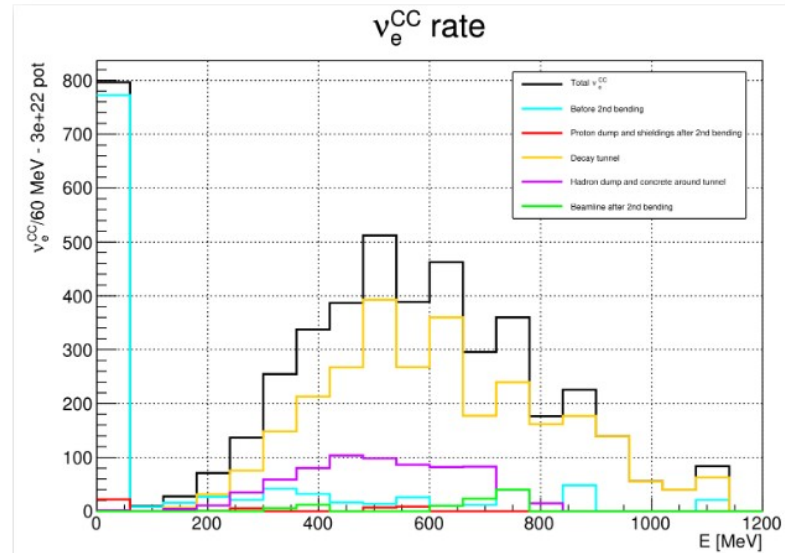
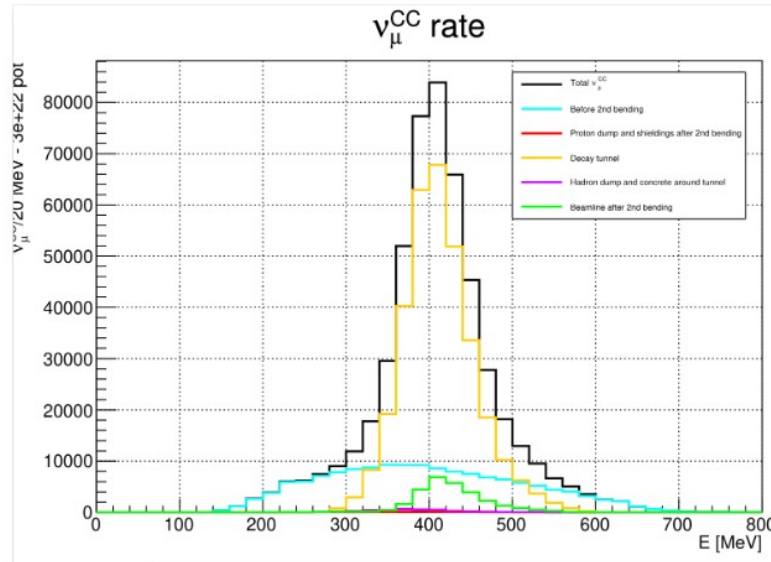


The study of the neutrino production point showed that a large fraction ($\sim 70\%$) of the interacting ones comes from the monitoring region of the facility, for which a 1% systematic uncertainty is expected

Moving the facility closer to LEMMOND?

Given the quite large beam divergence, reducing the distance of the neutrino detector has a relevant impact on the collected statistics

Considering a distance of 25 m:



Flavor	Total CC interactions
ν_μ	51.2×10^4
anti- ν_μ	1.9×10^4
ν_e	0.47×10^4
anti- ν_e	0.02×10^4



Almost x2 increase in statistics

Fraction of ν_μ CC interactions in the monitored region: 70% [80% in the 350÷550 MeV range]

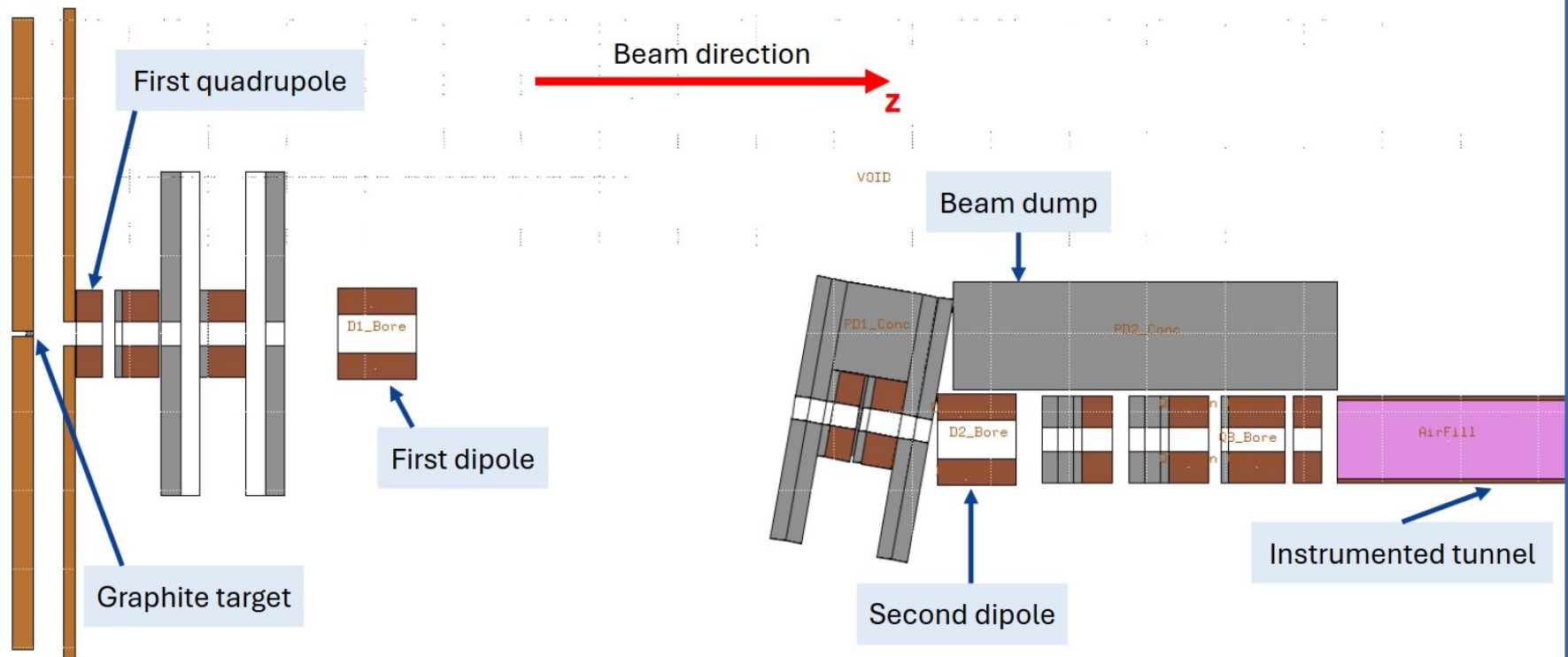
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We propose to move to this configuration to enhance the collected statistics

Detailed view of the beamline components



Wednesday, October 7th, 2026

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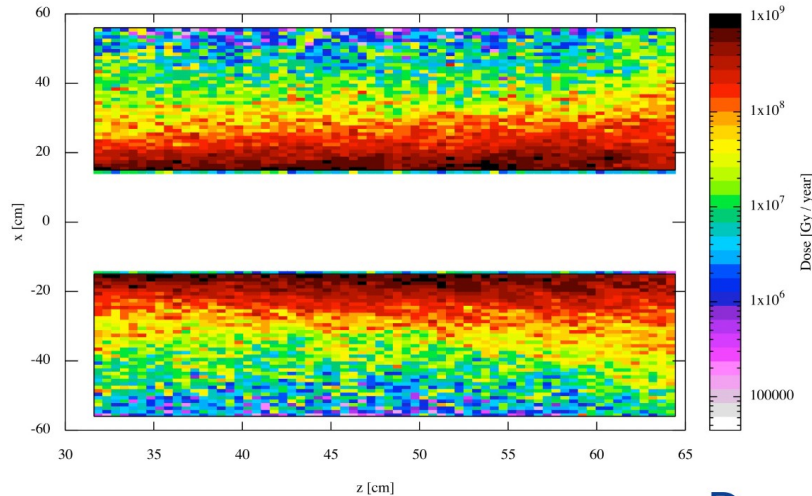
Full detailed FLUKA model of the facility in place

Ready for dose assessment at the beamline elements and at the tunnel instrumentation

Absorbed dose at Q1



Q1 Absorbed dose - 3e22 POT per year



First quadrupole

Wednesday, October 7th, 2026

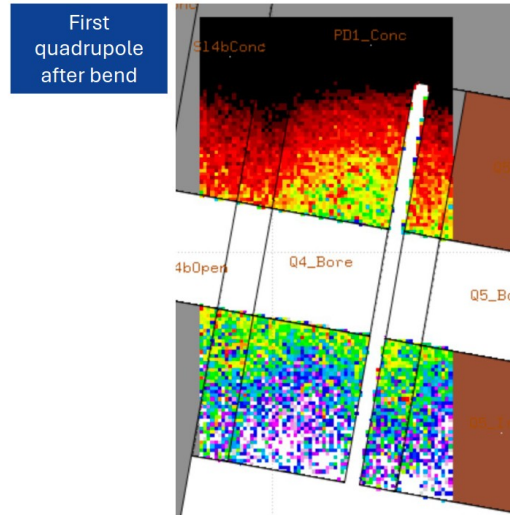
Two main hotspots:

- first quadrupole (close to the target)
- Quadrupoles before the second bending dipole (close to the uninteracting primary p beam)

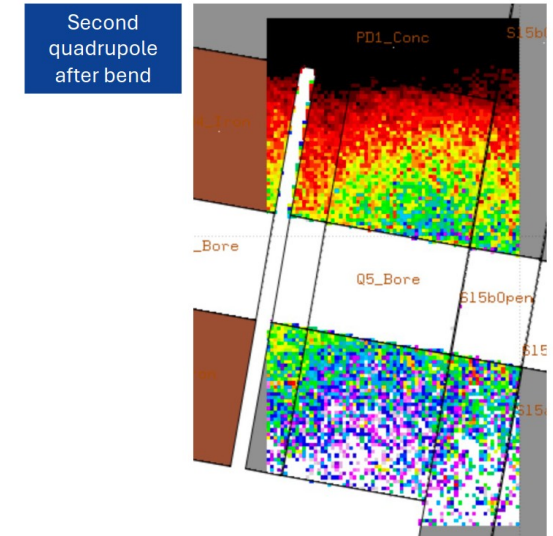
As pointed out, introduce in the magnets material some resin volume to estimate dose on that, cause insulation resin is the main reason for magnets failure due to radiation

Also, try to implement realistic quadrupoles (at the moment iron cylinders)

Dose distribution around Q4 and Q5



Wednesday, October 7th, 2026



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Also, try to conduct thermal studies

April: hadron dump prototype

- 3 PICOSEC: 2 96-pad detector and 1 7-pad detector
- **SAMPIC** used as digitation chain
- **Objective:**
 - Get time resolution of the 3 detectors
 - Test detectors under realistic conditions

Tried to recover the 3rd 96-pad detector, but unfortunately no signal observed when mounted in the setup

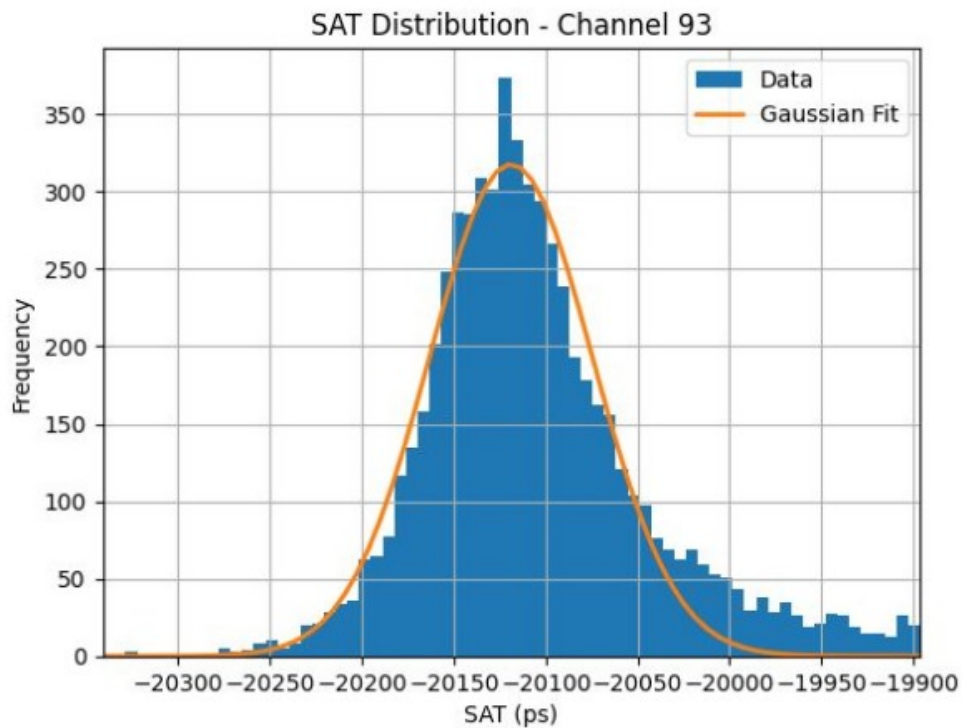


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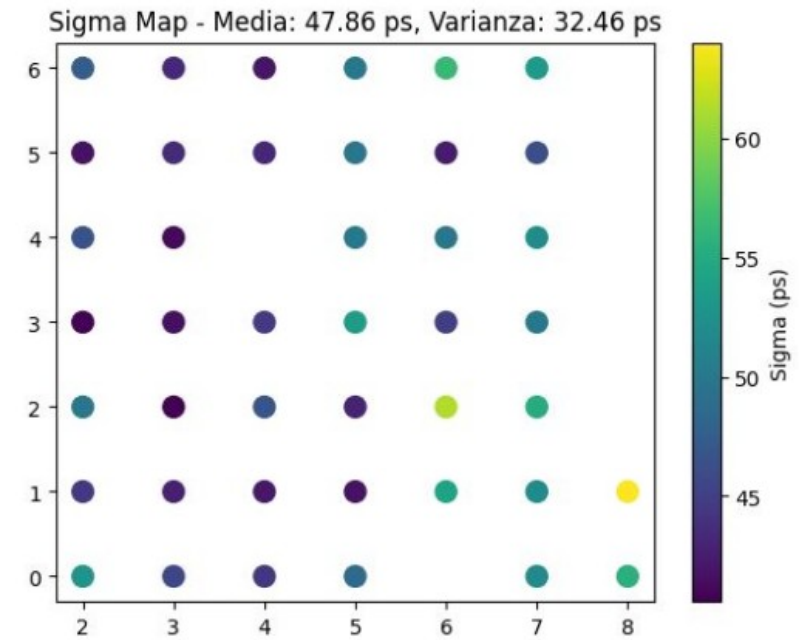
Testebeam at CERN with 3 PICOSEC detectors in various configurations

96, 1 cm², pads on each detector

PICOSEC candidate technology for the decay tunnel instrumentation



$\mu = -20118.95 \text{ ps}$, $\sigma = 44.42 \text{ ps}$

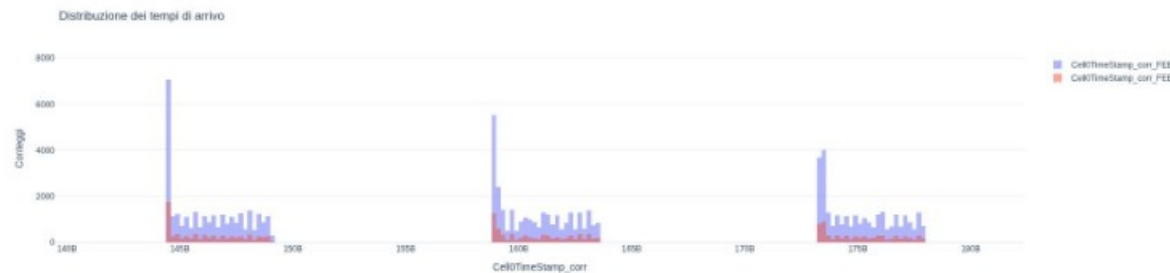
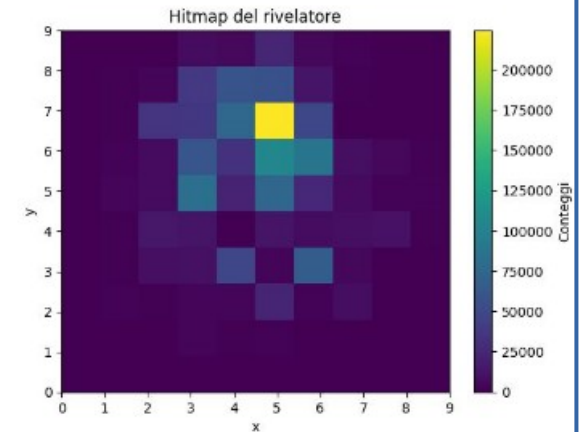


Excellent time resolution and good uniformity among the pads of the detector achieved



July: high intensity pion run

- 1MHz/cm² pion beam
- DAQ set on counting mode without MCP and trackers
- no trigger in the SAMPIC
- Set the SAMPIC to the maximum power of sampling
- Still the same problem of April tb: not able to collect all the events coming from a single spill



High intensity runs (1 Mhz/cm²)

Synergic with nuSCOPE

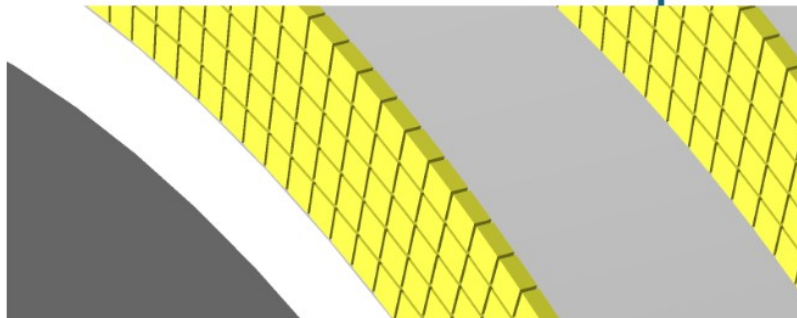
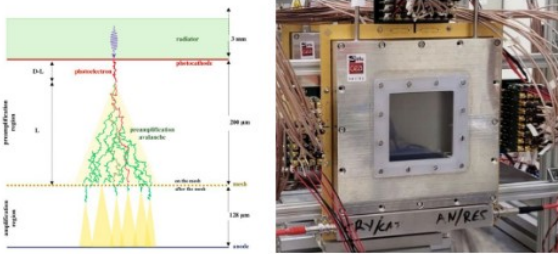
Final validation to assess the compatibility with expected rates in the LEMNB decay tunnel (see next slides) at 2 MHz/cm²

Details of detector configuration

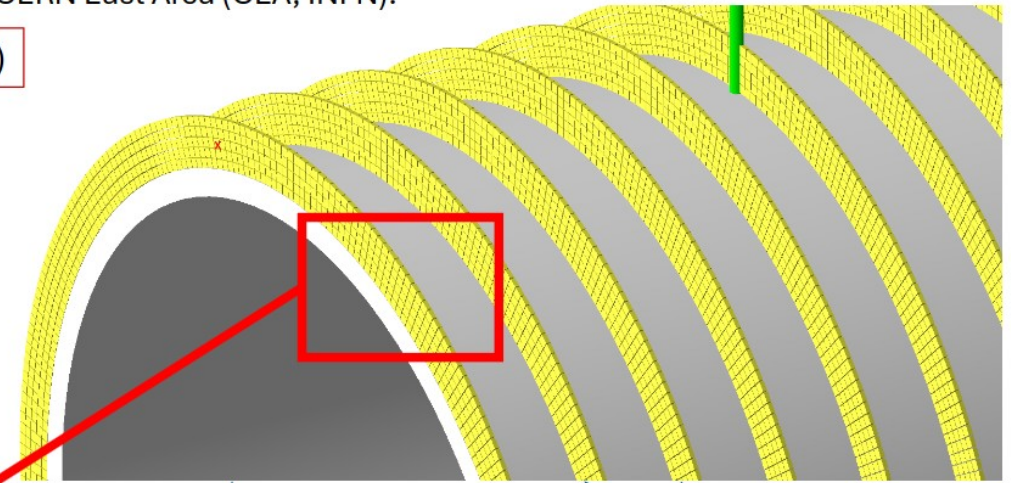
Two **96-channel PICOSEC prototypes** were built and tested at CERN East Area (CEA, INFN):

- granularity 1 cm^2 per channel
- 3 mm MgF_2 crystal
- $\text{Ne}:\text{C}_2\text{H}_6:\text{CF}_4$ (80:10:10) gas mixture

(see R. Speziali talk)



- 5 radial layers
- $\sim 1 \text{ cm}^2$ pads
- 5 mm pad thickness



Detector radius is
50 cm up to the
border of the
1st detector layer

10 cm spacing
between detector
layers

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Full G4 simulation of the proposed instrumented decay tunnel equipped with PICOSEC detectors
Already run in the past with a pion mock-up beam, now using the full beamline simulation as input

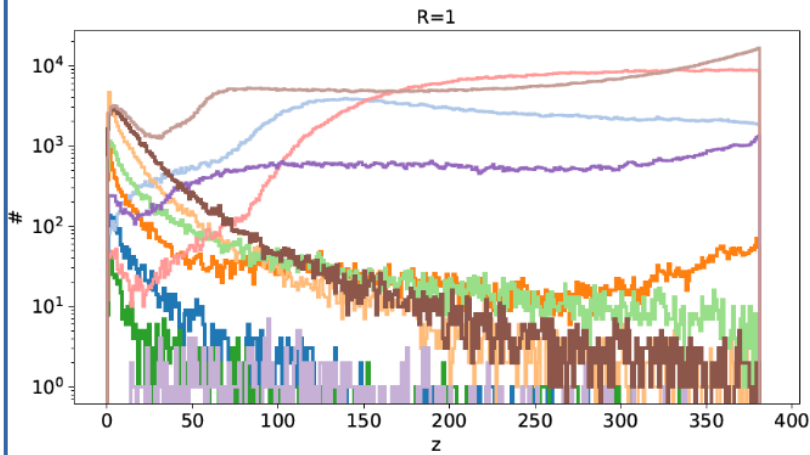
Effect of iron shielding: hits contributions

Iron shield in front of the first detector layer to reduce the particle rate:

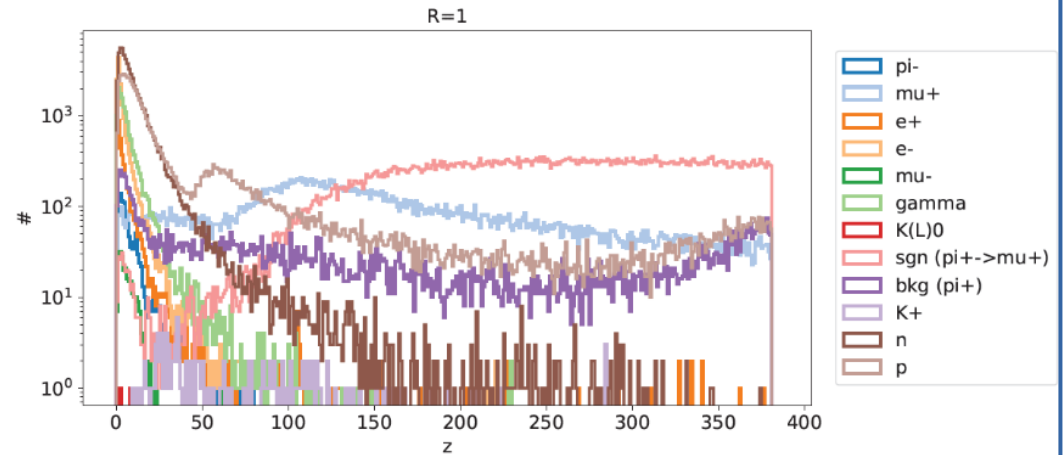
- from the optimization using the mockup pion beam the optimal thickness was found to be 5 cm to obtain rates within the detector specs

Effect of the 5 cm iron shielding on the signal and background from the beamline

Hits by particle @ 1st layer: no iron shielding



Hits by particle @ 1st layer: 5 cm iron shielding



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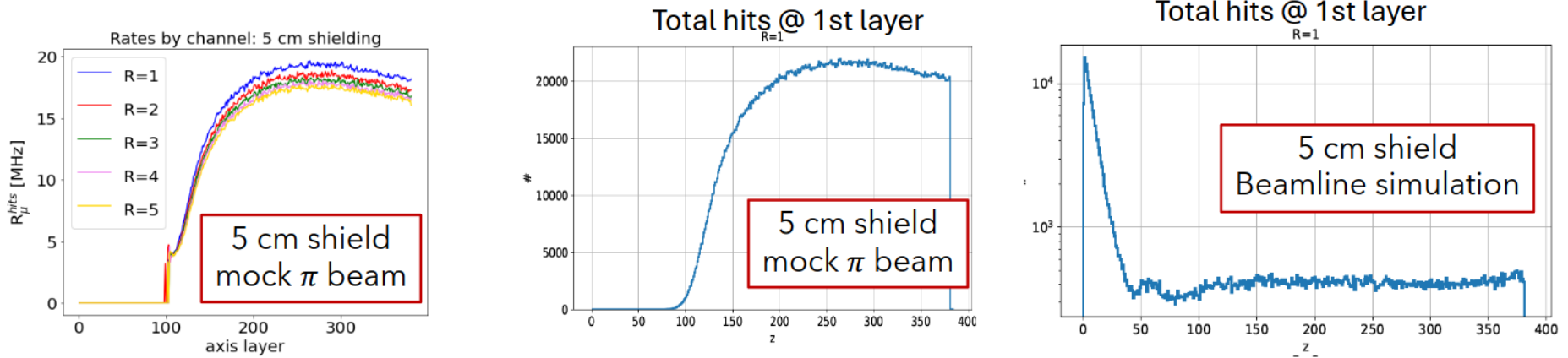
Iron shield before the first layer of detectors to filter out background particles and reduce the particle rates on the detector pads

(Further reduction should come from the large Cherenkov threshold for protons in the MgF_2 crystal used as radiator in the PICOSEC detectors)

Effect of iron shielding: rate estimation

The available beamline simulation statistics correspond to 10 GPOT, which is unfortunately insufficient to estimate the rate at the detector channels.

We can estimate the rate per channel by exploiting the rate computed for the mock pion beam, simulated with a total statistics corresponding to 10^8 pions:



Estimated channel rate is:

$$R_{ch}^{line} = \frac{N_{hit}^{line} \cdot N_{POT}^{mock}}{N_{peak-hit}^{mock} \cdot N_{POT}^{line}} \cong 33 \text{ MHz/ch}$$

corresponding to 3.3 MHz/ch after accounting for a one-order-of-magnitude reduction in POT/spill. Slightly above the detector specs (2 MHz/ch), but can be reduced by fine-tuning the iron shield thickness.

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Estimated rate per channel (assuming 1/10 of the nominal spill intensity, i.e. 8.3×10^{13} pot/spill):

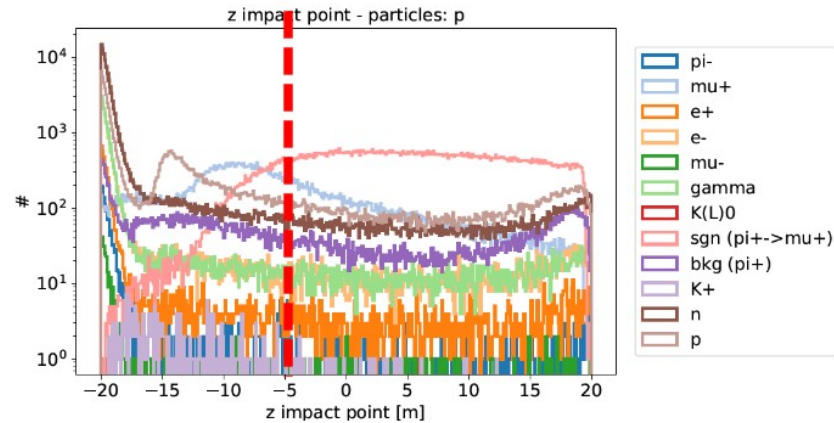
3.3 Mhz/cm²

With a fine tuning of the shielding the rate could be kept within detector specs (2 MHz/cm²)

Signal VS Background

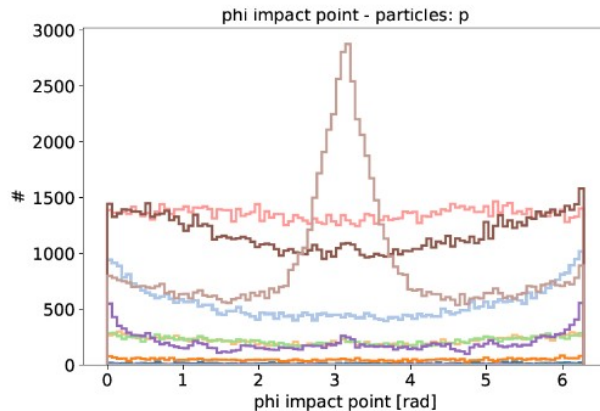
A first preliminary estimation of the signal to background ratio:

Preliminary estimation



	SNR
Sgn/Bkg (total)	1.4
Sgn/halo-mu	6.4
Sgn/Protons	3.2
Sgn/Pions	20

Impact point > -5 m && # of hits > 5



Does not include

- information on azimuthal angle
- possible discrimination of protons from Cherenkov light in Picosec
- Full reconstruction and PID

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The preliminary estimation of S/N ratio looks promising.
Expect to reach good enough PID performance ($S/N \geq 2$) when including full reco and signal discrimination (work in progress), allowing for muon neutrino flux monitoring at 1% level

Status of the WP6 part of the project

n.	Milestone	Status
4	Identification of the location and layout of the LINAC transfer line	Completed
7	Implementation of the static focusing system in MADX and G4beamline	Completed
12	MC simulation framework for the tunnel instrumentation is set up	Completed
18	Analysis framework for the evaluation of the systematics is set up	Completed
19	Preliminary estimate of the neutrino flux in the monitored neutrino beam	Completed

n.	Deliverable	
6.1	Design of the LEMNB transfer line	Completed
6.2	Completion of the LEMNB end-to-end simulation of the beamline	Completed
6.3	Physics performance of the monitored neutrino beam	Completed
6.4	Update of LEMNB physics performance including the full systematic budget	By 10/2026 (month 46)

Request of postponement by 1.5 months accepted by EU Project Officer
Allows to **complete the on-going work on the muon reconstruction** in the decay tunnel for neutrino flux monitoring

Conceptual Design Report



[Reference option – “slow” detectors (PICOSEC) with spills of reduced intensity (10^{14} pot/spill)]

- Beamline design
- Beamline component, shielding and doses
- Tunnel instrumentation technology (PICOSEC)
- PID and efficiency for monitoring
- Flux and statistics at LEMMOND

Main outcome of our studies

[Alternative option – silicon detectors in a fraction of the tunnel with nominal spill duration (10^{15} pot/spill)]

Mentioned but to be studied after the project

Additional slides

Toward project's costing

Component	Type	Aperture (cm)	Length (cm)	K (T/m)	Dipole field B (T)
Q1	Quadrupole	Ø 30	32.82	+15.87	—
Q2	Quadrupole	Ø 30	47.44	-12.64	—
Q3	Quadrupole	Ø 30	48.11	+4.45	—
D1	Dipole	50 × 50	100	—	+0.58
Q4	Quadrupole	Ø 30	32.73	+2.01	—
Q5	Quadrupole	Ø 30	40.00	-2.53	—
D2	Dipole	50 × 50	100	—	-0.58
Q6	Quadrupole	Ø 30	39.52	+0.51	—
Q7	Quadrupole	Ø 30	50.48	-1.20	—
Q8	Quadrupole	Ø 30	72.44	+1.18	—
Q9	Quadrupole	Ø 30	36.53	-1.04	—

Beamline components
finalized. To be priced.

Beamline shielding: close to completion. To be priced

Target: cylindrical graphite target, (L=20 cm, R=3 cm). Average power from $3 \cdot 10^{22}$ pot/y with 2 GeV proton kinetic energy is <300 kW.

Detector instrumentation corresponds to about 60 m^2 (PICOSEC) and $6 \cdot 10^5$ channels

Other components: proton dump, infrastructures and power supplies to be discussed with WP2.