Status of WP6: a monitored neutrino beam at the ESS

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Summary

WP6 aims to design a Monitored Neutrino Beam to operate before the long-baseline experiment, i.e. during the construction phase of the ESSnuSB accumulator, enabling high-precision cross-section measurements below 1 GeV.

Objectives
• Define the neutrino physics programme to be delivered at the ESS during the construction of the accumulator. • Design the extraction line of the protons from the linac to the target station, and the secondary focusing system for the monitored neutrino beam. • Design of the instrumented decay tunnel. • Compute the final neutrino yield and the expected systematic uncertainties on the flux.

D6.3	Physics performance of the monitored neutrino beam

Work completed and summarized in docdb n.2272 (see below).

D6.4	Update of LEMNB physics performance including the full systematic budget

Due soon and work in progress (see below).

Work Package 6 of ESSnuSB+

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Participants: Unimib (Milano, Italy), INFN (Padova, Italy), RBI (Zagreb, Croatia), NCSRD (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

WG organization

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- Coordinator: **Francesco Terranova** (University of Milano-Bicocca, Italy)
- Co-Coordinator: **Andrea Longhin** (INFN-Padova, Italy)
- Co-Convenor: **Daniele D'Ago** (Istituto Nazionale di Fisica Nucleare, INFN, Padova, Italy)

new!

Filippo Bramati (Università degli Studi di Milano-Bicocca, Italy)

Antonio Branca (Istituto Nazionale di Fisica Nucleare, INFN, Milano-Bicocca, Italy)

Giulia Brunetti (Università degli Studi di Milano-Bicocca, Italy)

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Mauro Mezzetto (Istituto Nazionale di Fisica Nucleare, INFN, Padova, Italy)

Andreas Psallidas (NCSR 'Demokritos', Agia Paraskevi, Greece)

Fabio Pupilli (Istituto Nazionale di Fisica Nucleare, INFN, Padova, Italy)

Anna Scanu (Università degli Studi di Milano-Bicocca, Italy)

George Stavropoulos (NCSR 'Demokritos', Agia Paraskevi, Greece)

Francesco Terranova (Università degli Studi di Milano-Bicocca, Italy)

Spyros Tzamarias (Aristotelio Panepistimio Thessalonikis, AUTH, Greece)

Olga Zormpa (NCSR 'Demokritos', Agia Paraskevi, Greece)

18 members, 2 hired by the project (D. D'Ago, A. Scanu)

Achievements at the time of RP2 (30/06/2025) and last Collaboration Meeting

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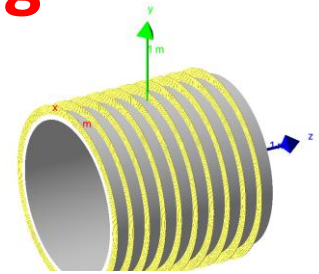
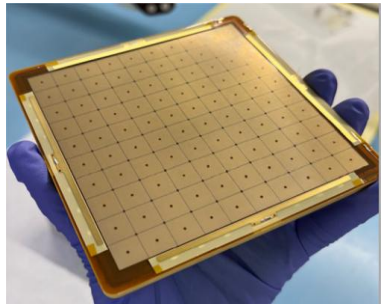
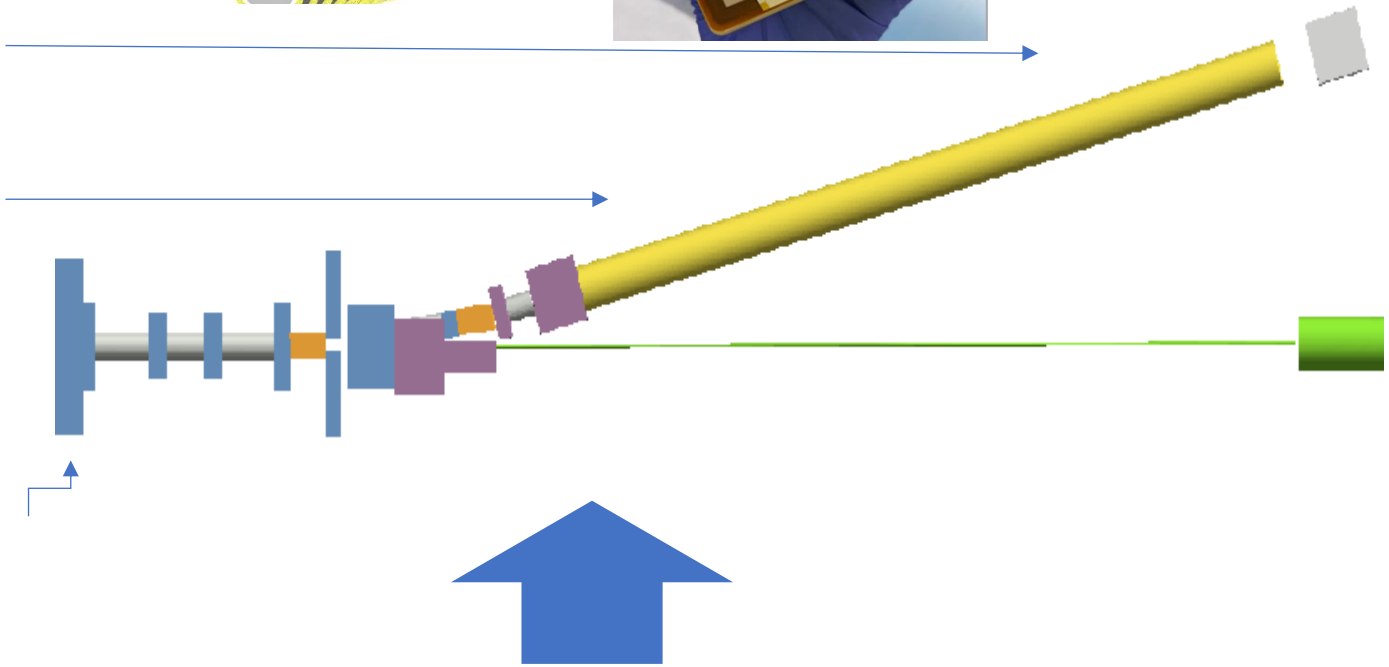


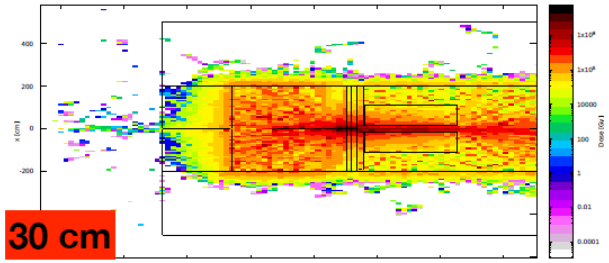


- Identification of the most suitable tunnel instrumentation – PICOSEC detectors

- Completion of particle identification in the tunnel and evaluation of muon efficiencies



- Full FLUKA simulation of the target area for dose assessment



- Identification of the baseline beamline layout and its implementation in G4beamline

Achievements after RP2 (7/2025 – 6/2026)

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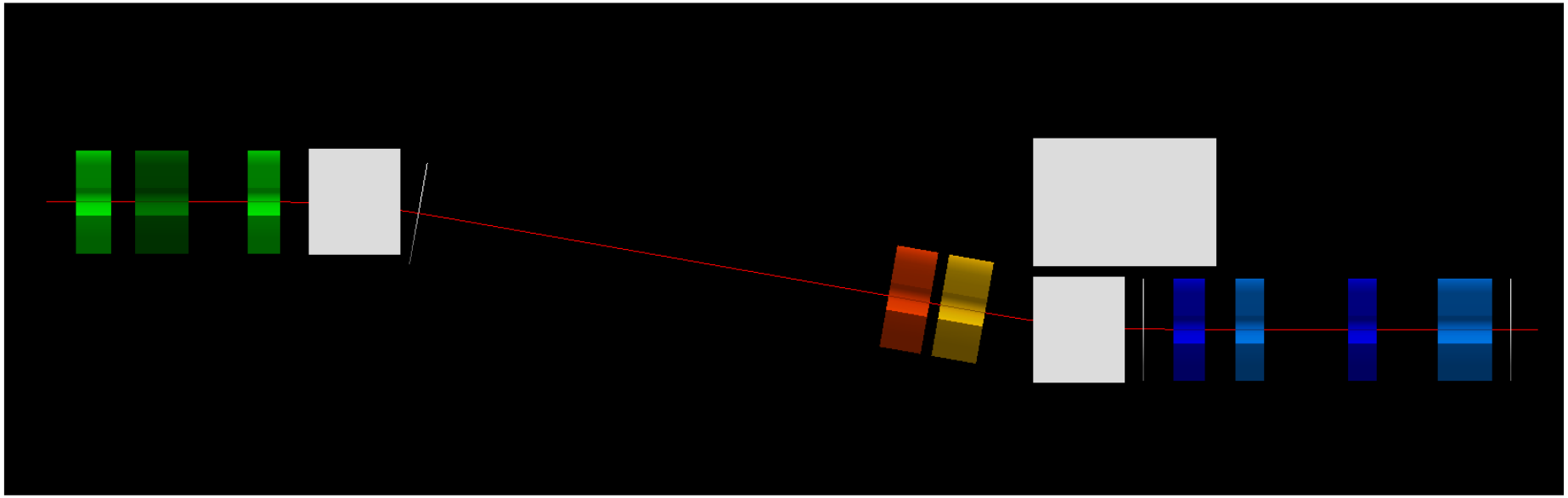
We were able to move from an initial beamline layout to a fully optimized one. The optimization was carried out using a genetic algorithm



Fixed parameters:

- Number of magnets
- Sequence of magnets
- Dipole bending angle = 10°
- Dipole lengths = 1 m
- Dipole apertures = 0.5 x 0.5 m2
- Quadrupole apertures ø = 30 cm
- Sep 4* = 5.4 m

The genes that are considered are 29:

- 11 distances between objects
- 9 quadrupole lengths
- 9 quadrupole gradients

After the optimization of the main beamline components, we addressed the positioning of the shielding and we reoptimized seeking the optimal signal-to-noise ratio. **The final results have been presented in the D6.3 document and they confirmed the estimates reported in M19.**

Previous deliverables

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Deliverable title: **Design of the LEMNB transfer line (WP6)**

Due delivery date: **2025-9-30**

Actual delivery date: **2025-9-29**

Docdb link

Content: transfer line between the LINAC and the LEMNB target

Deliverable title: **Completion of the LEMNB end-to-end simulation of the beamline (WP6)**

Due delivery date: **2025-12-31**

Actual delivery date: **2025-12-31**

Docdb link

Content: First end-to-end simulation of the beamline. Preliminary shielding

D 6.3

Deliverable title: **Physics performance of the monitored neutrino beamline (WP6)**

Due delivery date: **2026-06-30**

Actual delivery date: **2026-06-30**

Docdb link

Content: Flux estimate with realistic shieldings

Key results: flux and statistics

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LEMMOND: 5 m diameter, 50 m from the tunnel end. Flux and interactions per year for $3x10^{22}$ pot/y

Flavour	Total flux
ν_μ	$1.9x10^{18}$
anti-ν_μ	$1.6x10^{18}$
ν_e	$1.4x10^{18}$
anti-ν_e	$1.5x10^{16}$

Flavour	Total CC interactions
ν_μ	$29.9x10^4$
anti-ν_μ	$1.2x10^4$
ν_e	$0.25x10^4$
anti-ν_e	$0.01x10^4$

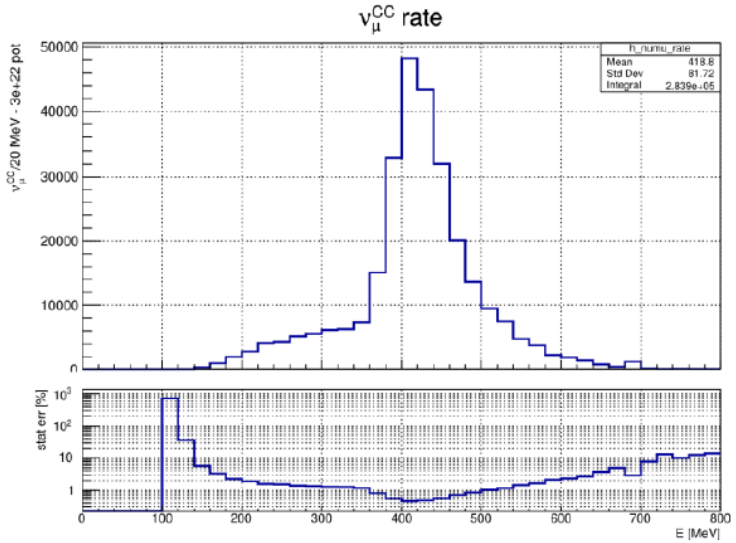


Figure 6. Muon neutrino CC interactions.

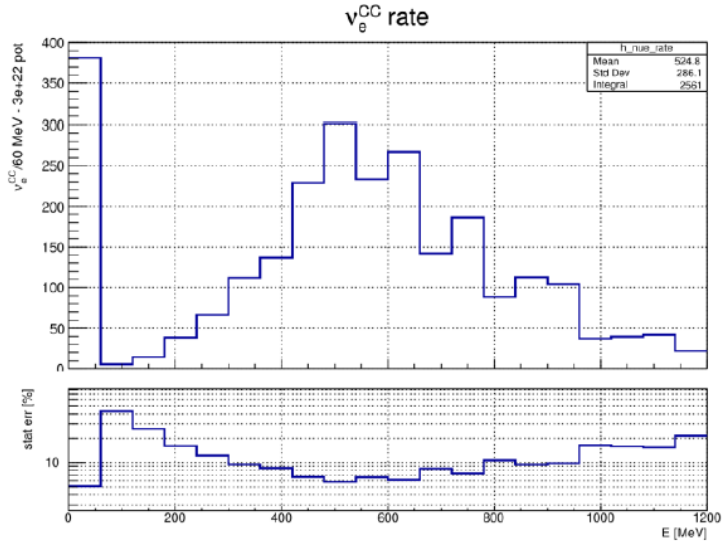
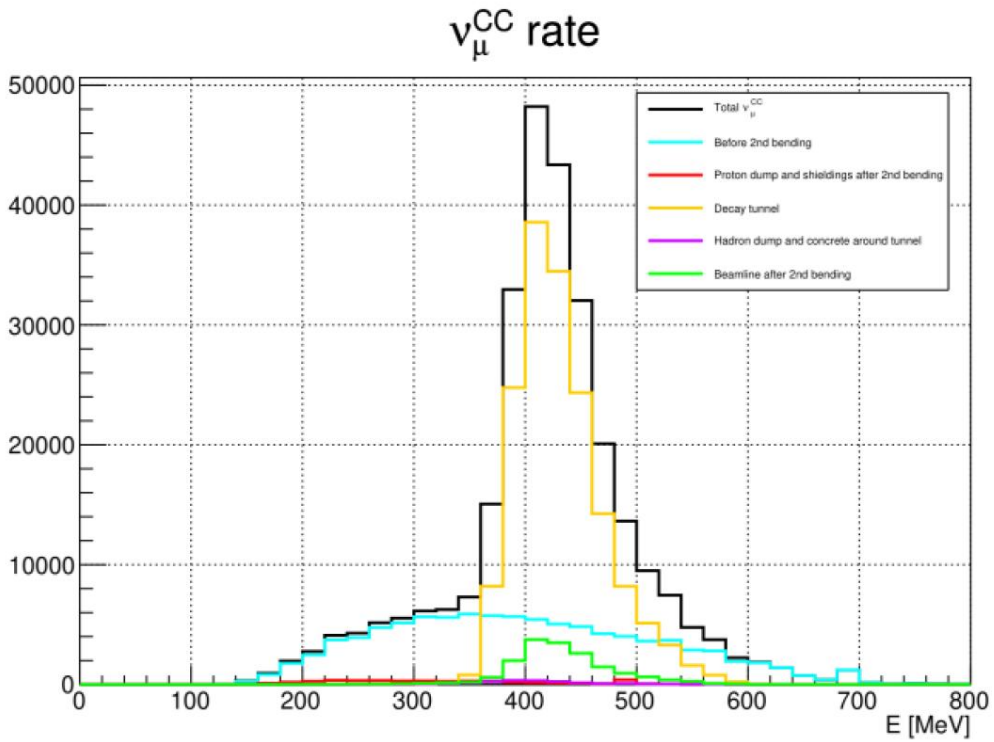
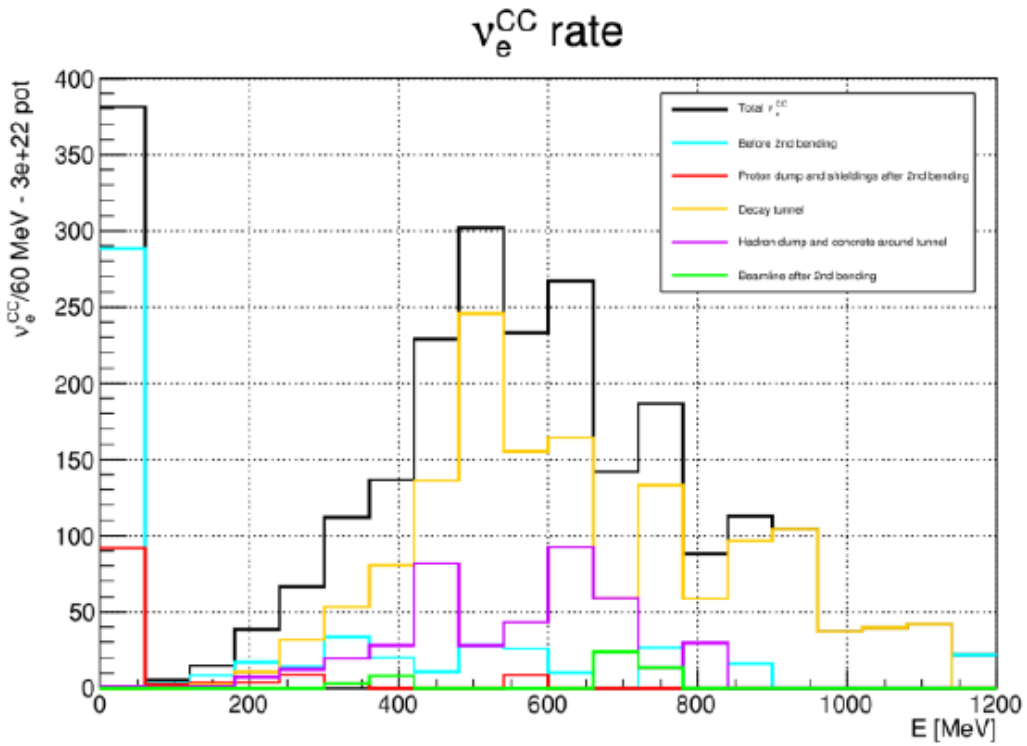


Figure 7. Electron neutrino CC interactions.

Key results: effectiveness of monitoring

It is fortunate that the vast majority of ν_μ CC interactions originate from neutrinos produced in the decay tunnel, which can be monitored at percent level. The main unmonitored background originates from early decays, which can be modeled by MC simulation and normalized to the monitored neutrinos. We thus aspect a systematic budget of about 1% if we can achieve the proper S/N ratio (>2) in muon identification (see A. Branca's presentation on Wednesday)





Toward project's conclusion

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- Now that we have a fully optimized beamline, we can publish the final flux and neutrino statistics for LEMMOND. **See D. D'Ago and F. Pupilli's presentations on Wednesday**
- We must also update the FLUKA dose estimates for each beamline component, including the instrumentation, taking into account the final shielding configuration. **See A. Scanu's presentation on Wednesday**
- The final task is the evaluation of the beam flux systematics. The layout and software framework have been inherited from ENUBET, and we have already established that the phase space of reconstructed muons is representative of the neutrino phase space and, hence, suitable for monitoring. **See A. Branca's presentation on Wednesday**

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)

Toward project's costing

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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 10^{22} pot/y with 2 GeV proton kinetic energy is <300 kW.

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

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

Conceptual Design Report

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[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

This paves the way to detector developments, which can enter our INFRA-TECH application in 2027:

- Fast PICOSEC detectors with implicit veto of non-relativistic particles (see talks on Wednesday)
- Exploitation (at ESS) of the Si and SiGe technologies for the LHCb upgrade currently under evaluation for ENUBET/nuSCOPE at CERN

Conclusions

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The idea of a monitored neutrino beam at ESS during the construction phase of ESSnuSB and employing the current ESS Linac is no longer a hypothesis but is grounded on a realistic implementation. WP6 has achieved nearly all of its objectives, and the remaining ones are within reach by the end 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

Main physics takeaway: we can safely claim that **a monitored neutrino beam at ESS is feasible without any LINAC upgrade under either of the following conditions**:

- Operating the LINAC with a dedicated spill at an intensity of about 10^{14} pot/spill i.e. a factor of 10 below nominal intensity

OR

- Operating the LINAC under nominal conditions, while replacing the PICOSEC detectors with silicon trackers instrumenting a smaller fraction of the decay tunnel that remains representative of the neutrino phase space.