The Implementation of a Monitored and Tagged Neutrino Beamline at CERN for the nuSCOPE Experiment

by **Marc Andre Jebramcik, Nikolaos Charitonidis (CERN), Fabio Pupilli (INFN)**

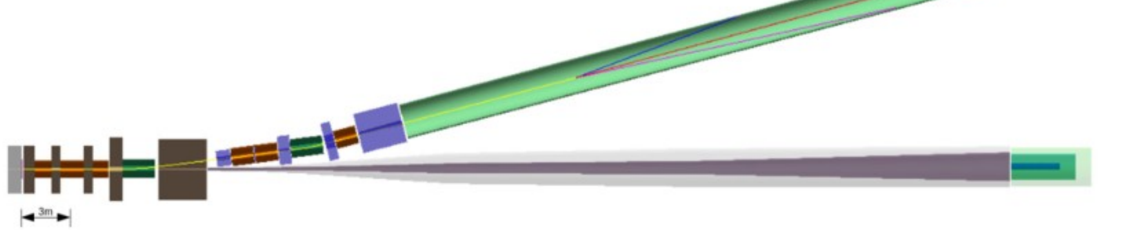
on behalf of the nuSCOPE collaboration and everyone involved

04.09.2025

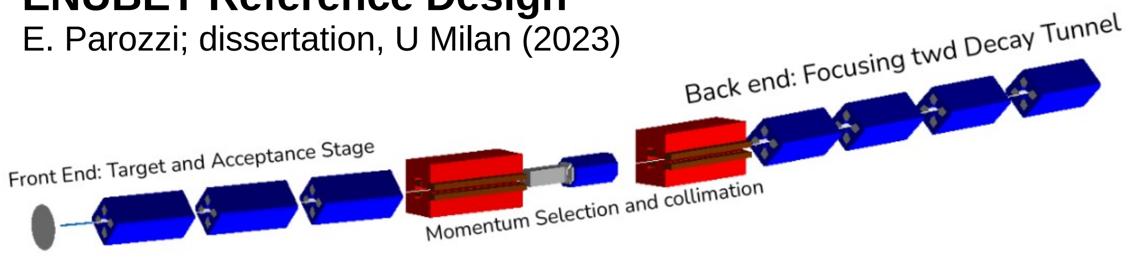
The ENUBET beamline as the starting point of the nuSCOPE beamline at CERN

- **nuSCOPE physics case: see L. Munteanu's talk at 11:45 pm (WG2)**
- **ENUBET** is a proposed experiment that features a short-baseline secondary beamline
- the ENUBET physics case focuses mostly on measuring the flux of ν_e and ν_μ from kaons and pions using an instrumented decay tunnel to measure the corresponding neutrino cross sections
- The high-energy proton beam impinges a graphite target that produces K^+ and π^+. The beamline momentum is selected to be at p=8.5 GeV/c or lower if desired
- **NuTag**: Full reconstruction of neutrino kinematics from measuring the kinematics of parent meson and daughter lepton via pixel monitors (two-body decay) → paradigm change
- **nuSCOPE:** the ENUBET-NuTAG merger that combines the two projects under the PBC framework to exploit their synergies
  - We expect 1E6 ν_μ events and 1E4 ν_e events with <1% flux syst.
  - Enables neutrino energy measurement event by event with <1% resolution
  - Submitted to the ESPPU (see arXiv:2503.21589)

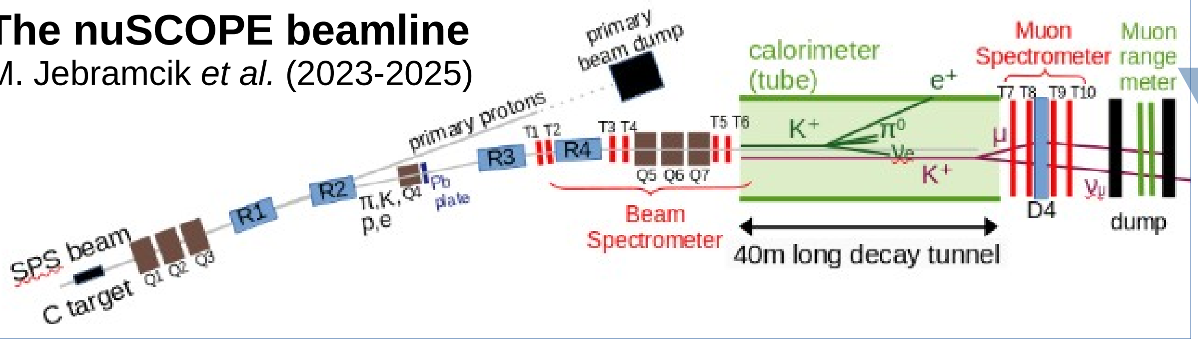
ENUBET Baseline Design
F. Acerbi *et al*.; EPJ C (2023) 83:964



ENUBET Reference Design
E. Parozzi; dissertation, U Milan (2023)

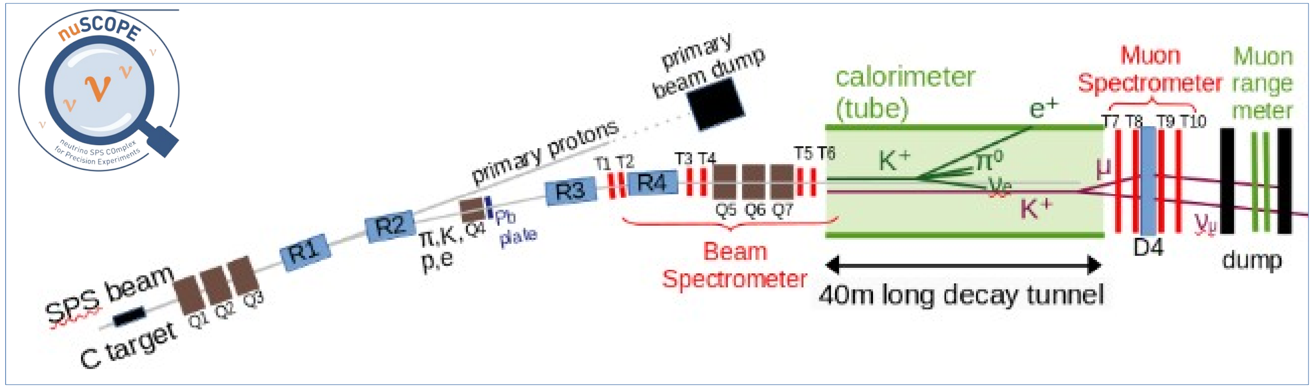


The nuSCOPE beamline
M. Jebramcik *et al.* (2023-2025)



Evolution to a combined beamline

The beamline characteristics at SPS Energy



- The current beamline design is the product of an extensive optimization process at 400 GeV/c proton momentum
- The beamline design merges the beamline requirements for both the ENUBET and the NuTAG proposals → pixel detectors in addition to calorimeter in decay tube
- The beamline's meson production is maximized and the event rate is adjusted to meet the pile-up constraints of the NuTAG pixel detectors.

Parameter	**Value**
Primary proton energy	400 GeV/c
Beamline momentum (mesons)	up to 8.5 GeV/c
Extraction type	slow: 4.8s or 9.6s from the SPS
Spill intensity	1.0E13 protons/spill
Event rate	1 – 2 THz
Instantaneous power	170 – 340 W
K^+ / π^+ per proton	1.3E-3 / 1.9E-2
K^+ / π^+ rate	up to 2.7 GHz / 40 GHz
Annualized proton requirement	2E18 – 3E18 protons/year
Total proton requirement (1% stat. error on ν_e x-section)	1.4E19 protons (assumes 500t LAr detector)
Beamline length to decay tube	23 m
Bending magnet strength	1.8 T

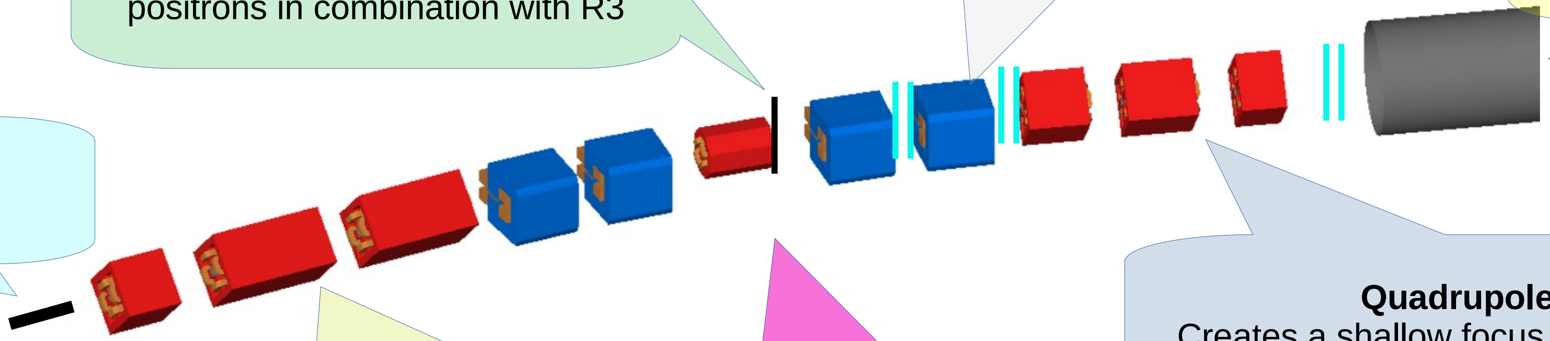
Some beamline features

Momentum measurement:
4 pixel detectors at R4 determine the particle momentum

Pb plate:
Energy modulates and removes positrons in combination with R3

Start of decay tunnel followed by μ spectrometer

Graphite target:
6mm radius; 1.3m long
(comparable to CNGS)



Quadrupole triplet
Creates a shallow focus in the decay tunnel

Quadrupole triplet
matches phase advance between the target and the R1 (bending magnet)

Split-up double-bend achromat (18 deg.)
Momentum selection with a focus in the middle

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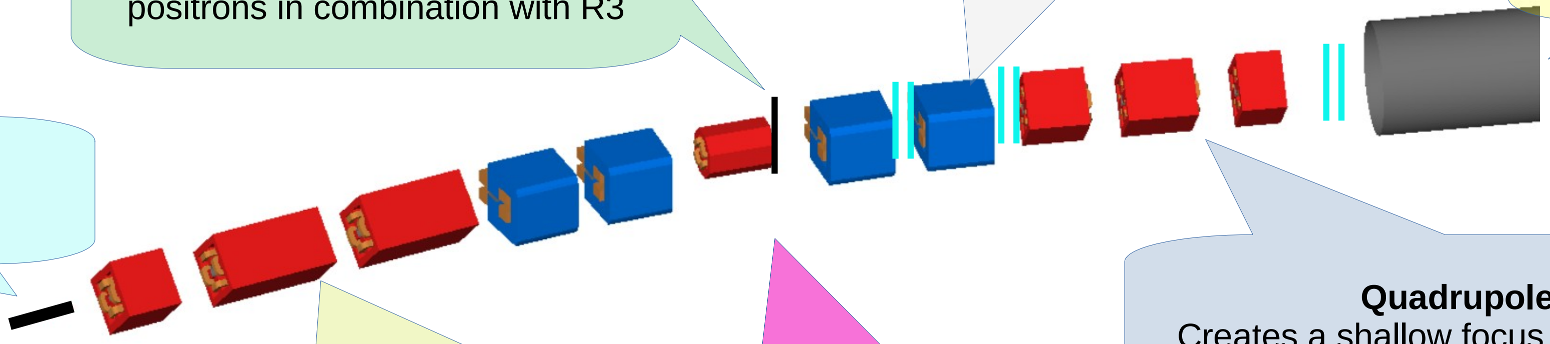

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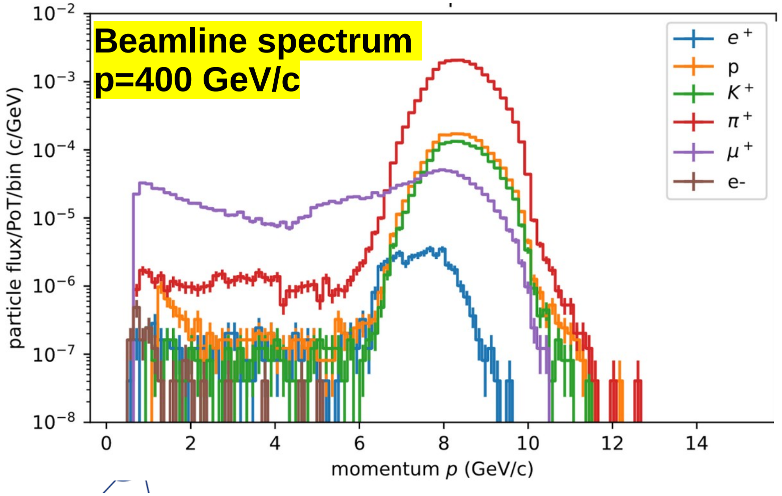
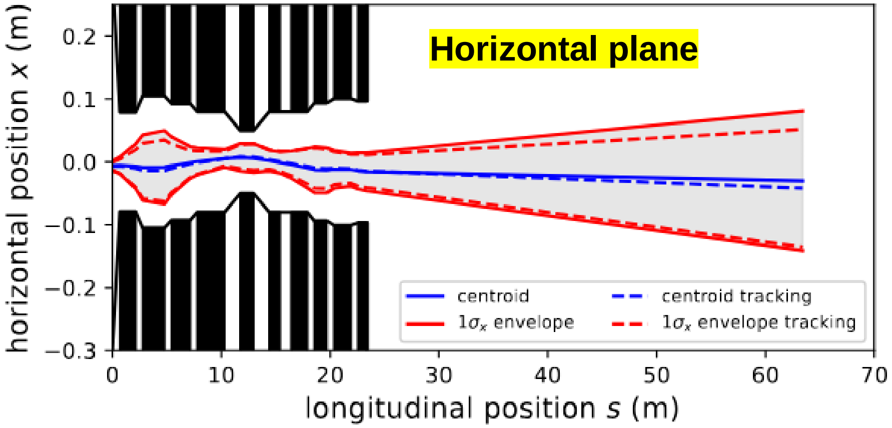
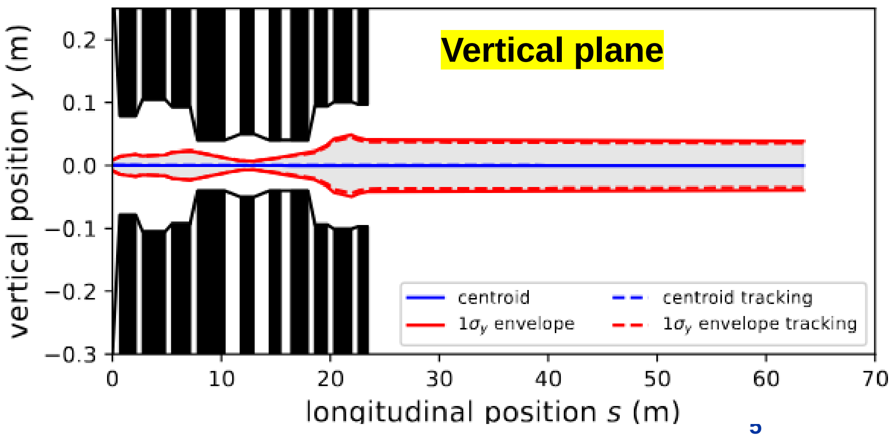
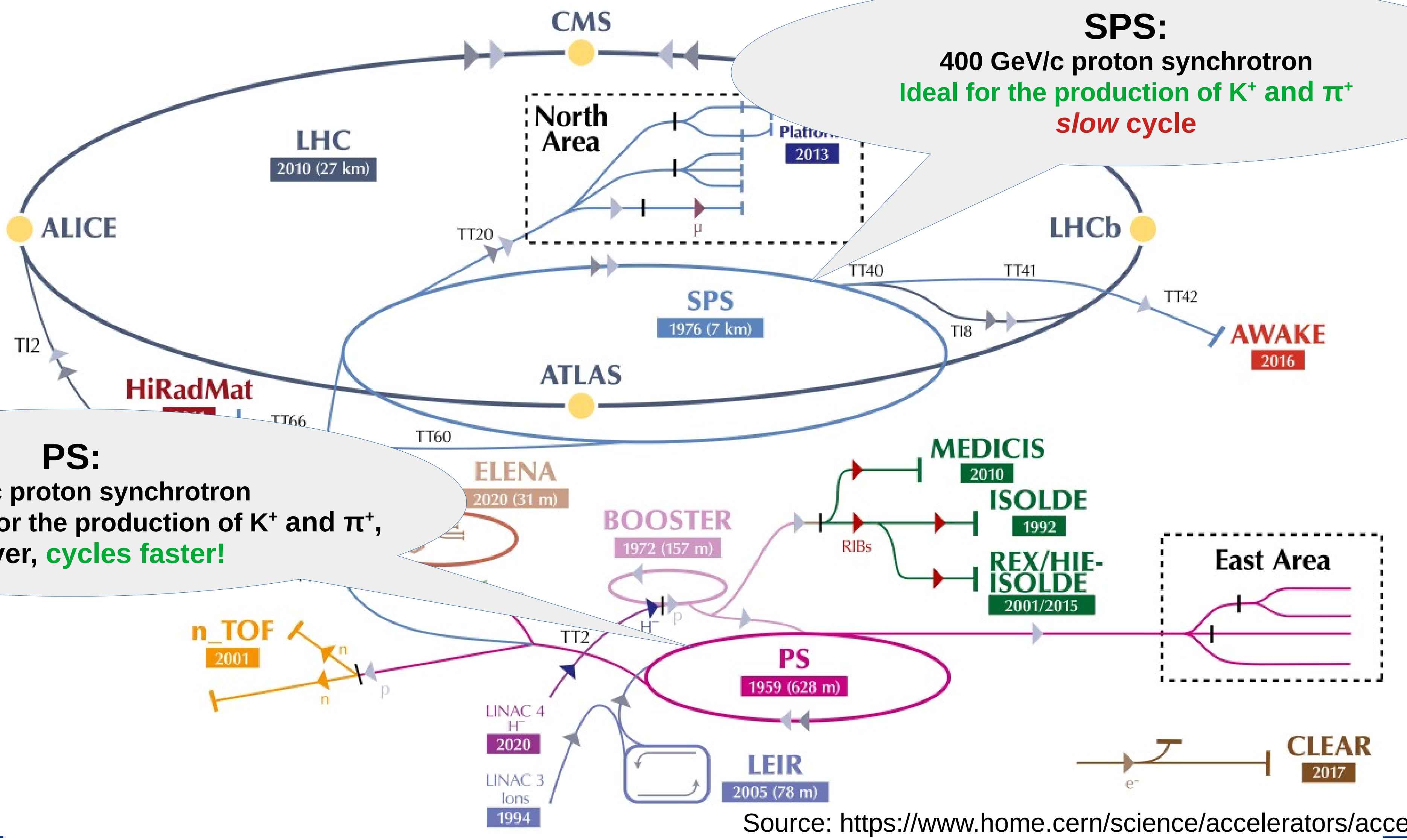






The CERN Accelerator Complex



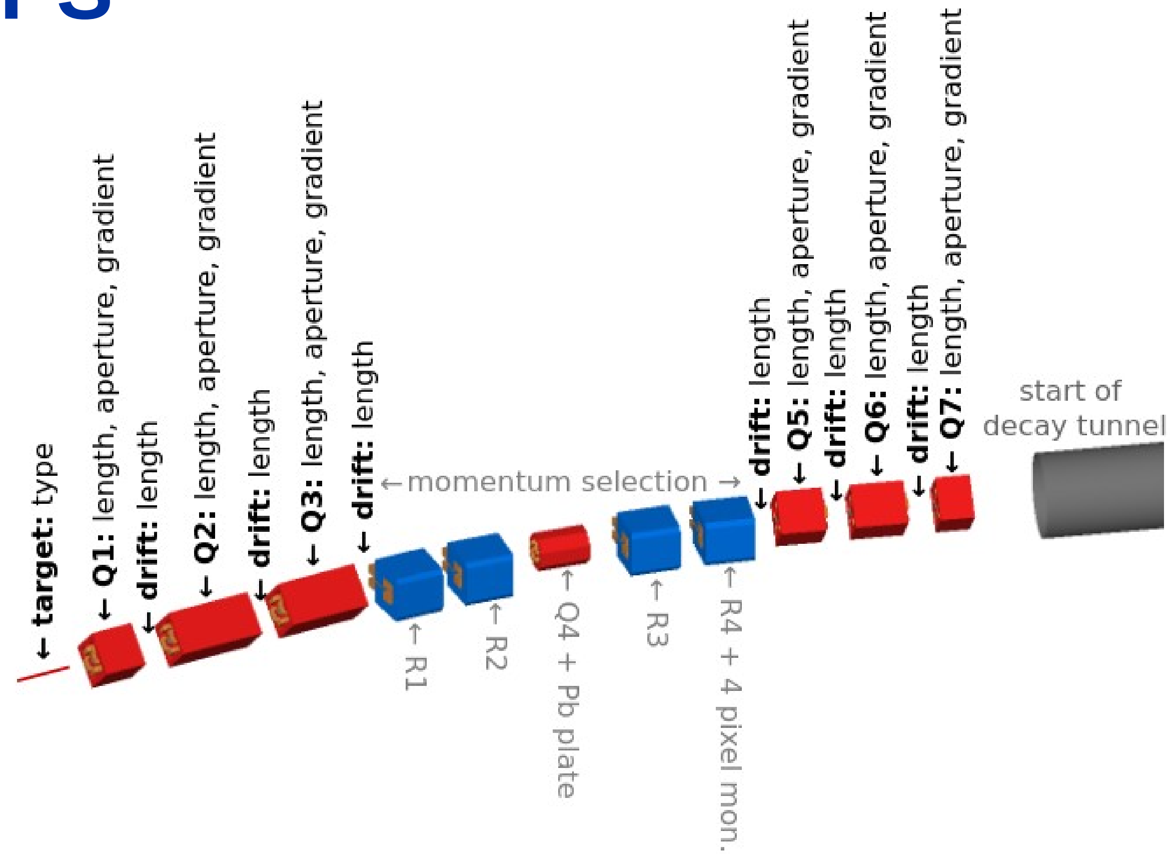
SPS:
400 GeV/c proton synchrotron
Ideal for the production of K^+ and π^+
***slow* cycle**

PS:
25 GeV/c proton synchrotron
Clearly less ideal for the production of K^+ and π^+, however, cycles faster!

Source: https://www.home.cern/science/accelerators/accelerator-complex

K⁺ and π⁺ flux at the PS and SPS

- To make sure we maximize the number of mesons at any momentum (SPS or PS), we have carried out a full self-consistent beamline optimization of the beamline at both energies
- Optimization achieved via multi-objective genetic algorithms (MOGA) using 26 free parameters:
  - Production target (material, length, radius)
  - Quadrupole parameters (aperture, length, gradient)
  - Drift spaces (lengths)



Yield comparison: SPS vs. PS

@p=400 GeV/c | @p=25 GeV/c

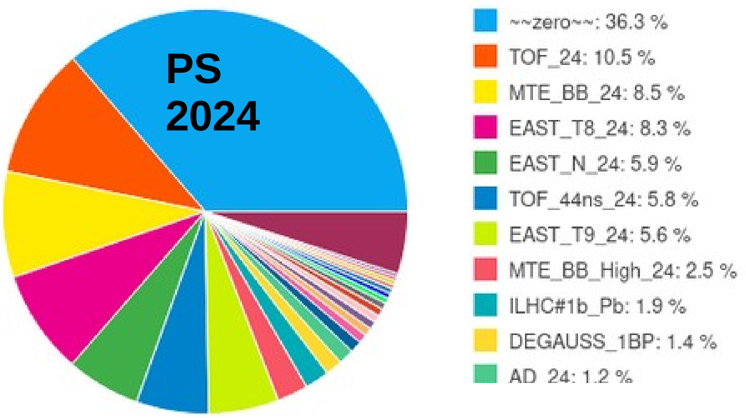
Particle yield	SPS: ENUBET design	SPS: Optimized beamline	PS: Optimized design
K^+/PoT (10^{-4})	3.6	12.6	0.31
π^+/PoT (10^{-2})	0.4	1.9	0.047

Factor 3.5

The proton sharing at the PS after LS3

The Present

- The PS has produced 4.6E19 protons on average over the last four years (2021-2024)
- The SPS received on average 1.6E19 protons/year during that time span from the PS
- The SHiP experiment requests 4.0E19 protons-on-target (PoT) per year from the SPS for after LS3.



The Future:

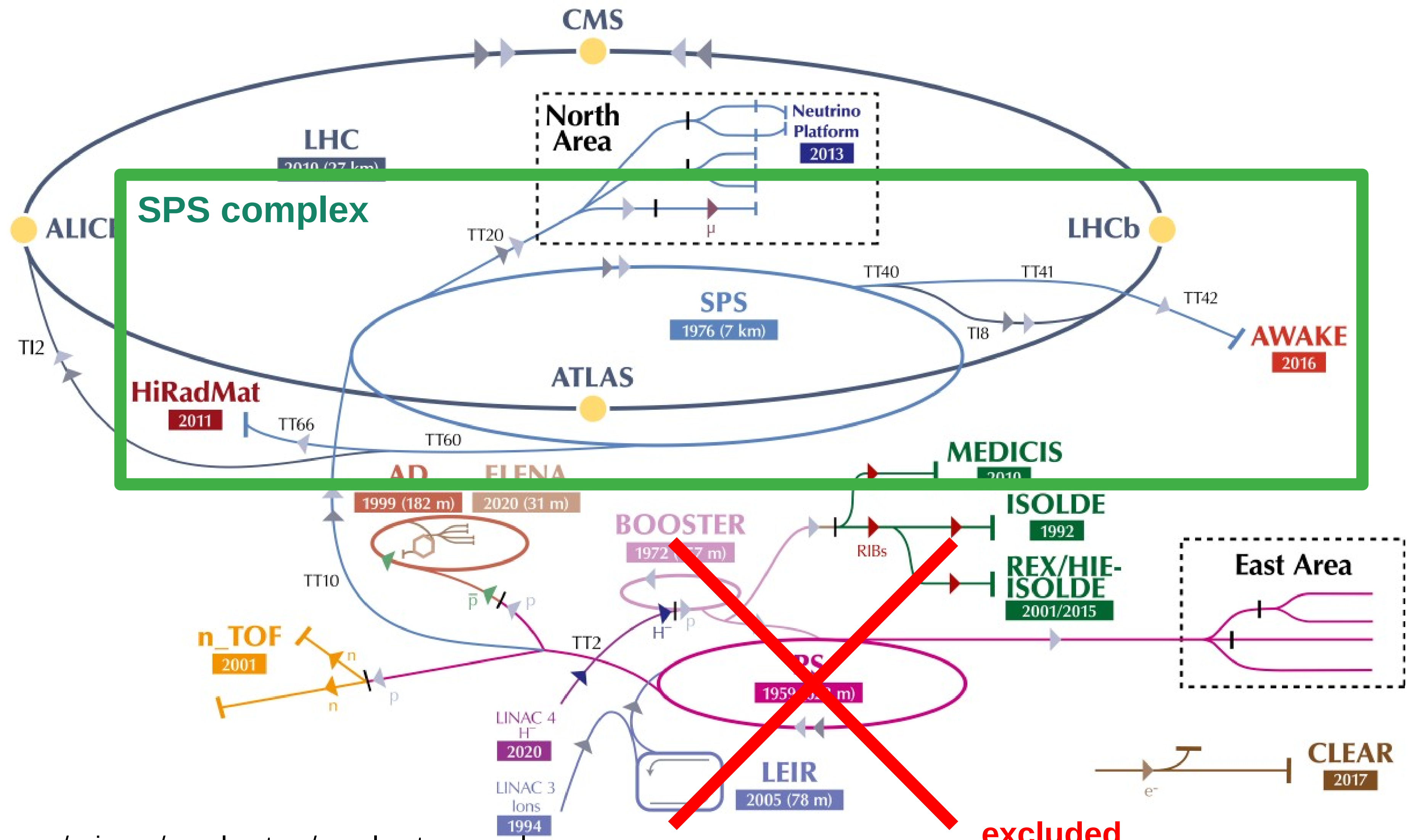
- The SHiP cycle of the SPS is fast and the annually intensity extracted from the SPS will be in the range of ~5E19 protons
- The amount of protons that are required from the PS are challenging but the ZERO cycles had been between 35% and 65% over the last 4 years

Source: https://cds.cern.ch/record/2847433?ln=en

The Prospects:

- PoT requirement for 1% stat. uncertainty on the inclusive ν_e cross-section (1E4 ν_e):
  - **PS: ~6E20 PoT vs SPS: 1.4E19 PoT**
- **At the PS: Even if** the beamline receives >1.0E19 PoT/year (highly optimistic) from the PS, it will take multiple decades to reach its PoT requirement

PS excluded. SPS energies are required!



Source: https://www.home.cern/science/accelerators/accelerator-complex

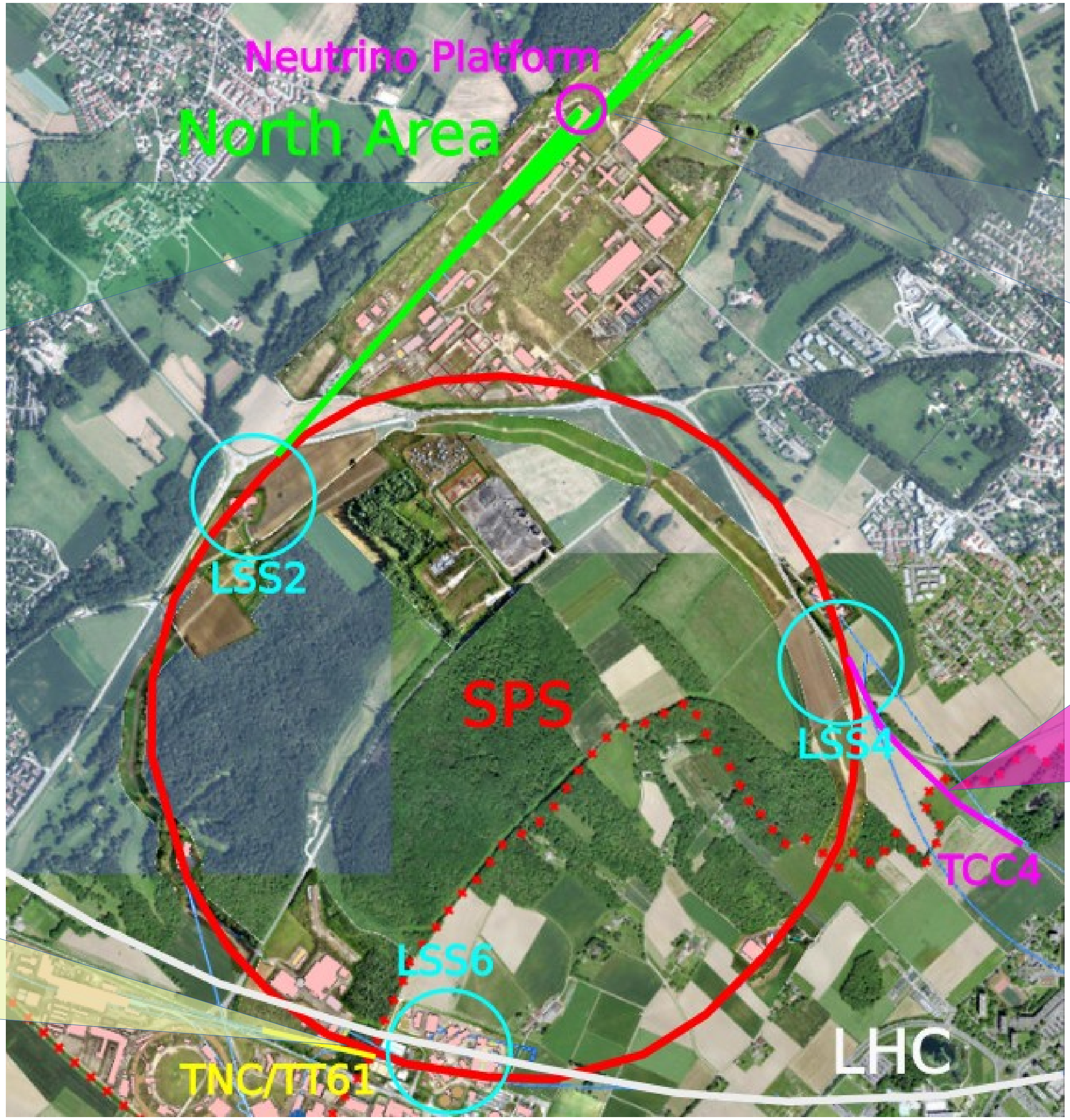
The SPS landscape

North Area (LSS2)

- The prime location for fixed target experiments with a 4.8s slow extraction (p=400 GeV/c)
- Two surface buildings **EHN1 and EHN2** and one underground cavern **ECN3** with experiments:
  - EHN1: H2, H4, H6, H8
  - EHN2: AMBER experiment (M2)
  - ECN3: NA62 replaced by SHiP (P42)

HiRadMat (LSS6)

- Fast extraction (μs) at p=440 GeV/c to the TNC tunnel that houses HiRadMat
- Fast extraction for LHC Beam 1



Neutrino Platform (EHN1)

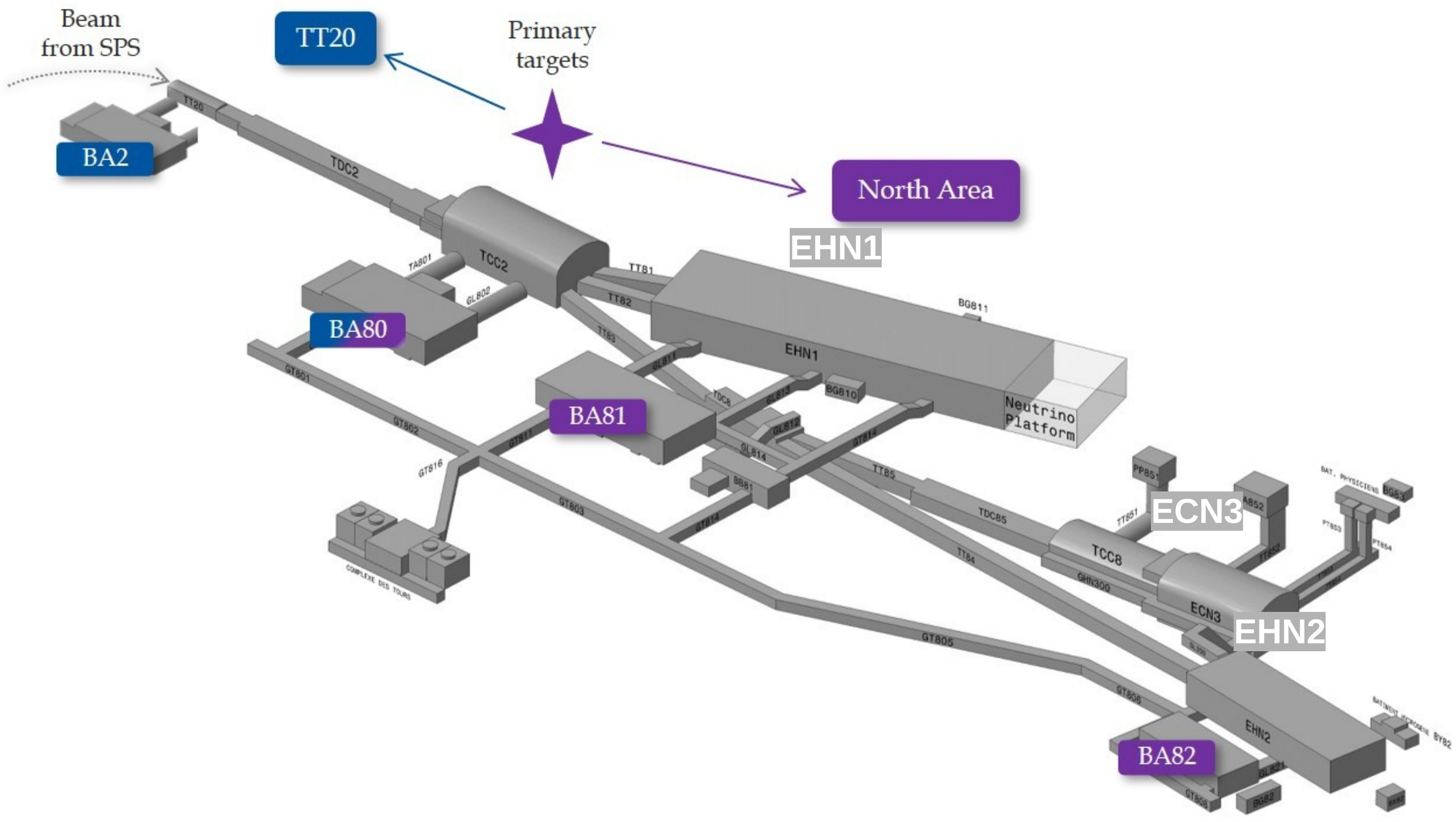
- In the EHN1 extension (Neutrino Platform) are the two ProtoDUNEs
- H2-VLE and H4-VLE provide beam to the two (6m x 6m x 6m), ~400t LAr detectors

AWAKE (LSS4)

- Fast extraction (μs) at p=400 GeV/c to TCC4 that houses the plasma-wakefield experiment AWAKE
- Fast extraction for LHC Beam 2

The North Area

- It can be considered to integrate the nuSCOPE beamline into the three experimental areas in the North Area: the two surface halls EHN1 and EHN2 & the underground cavern ECN3
- **The underground cavern ECN3** will be occupied by the SHiP experiment and will start running in Run 4.
- **The surface buildings EHN1 and EHN2** have strong radiation protection constraints extremely constraining (<1.0E9 particles/spill in the future) → Neither the primary nor secondary beam comply (>1E11 π^+/spill)
- **Geometric issues**: The beamline features a 18-degree bending angle (the beamline penetrates the building walls)
- <u>**An implementation of the nuSCOPE beamline in the North Area requires a new infrastructure**</u>



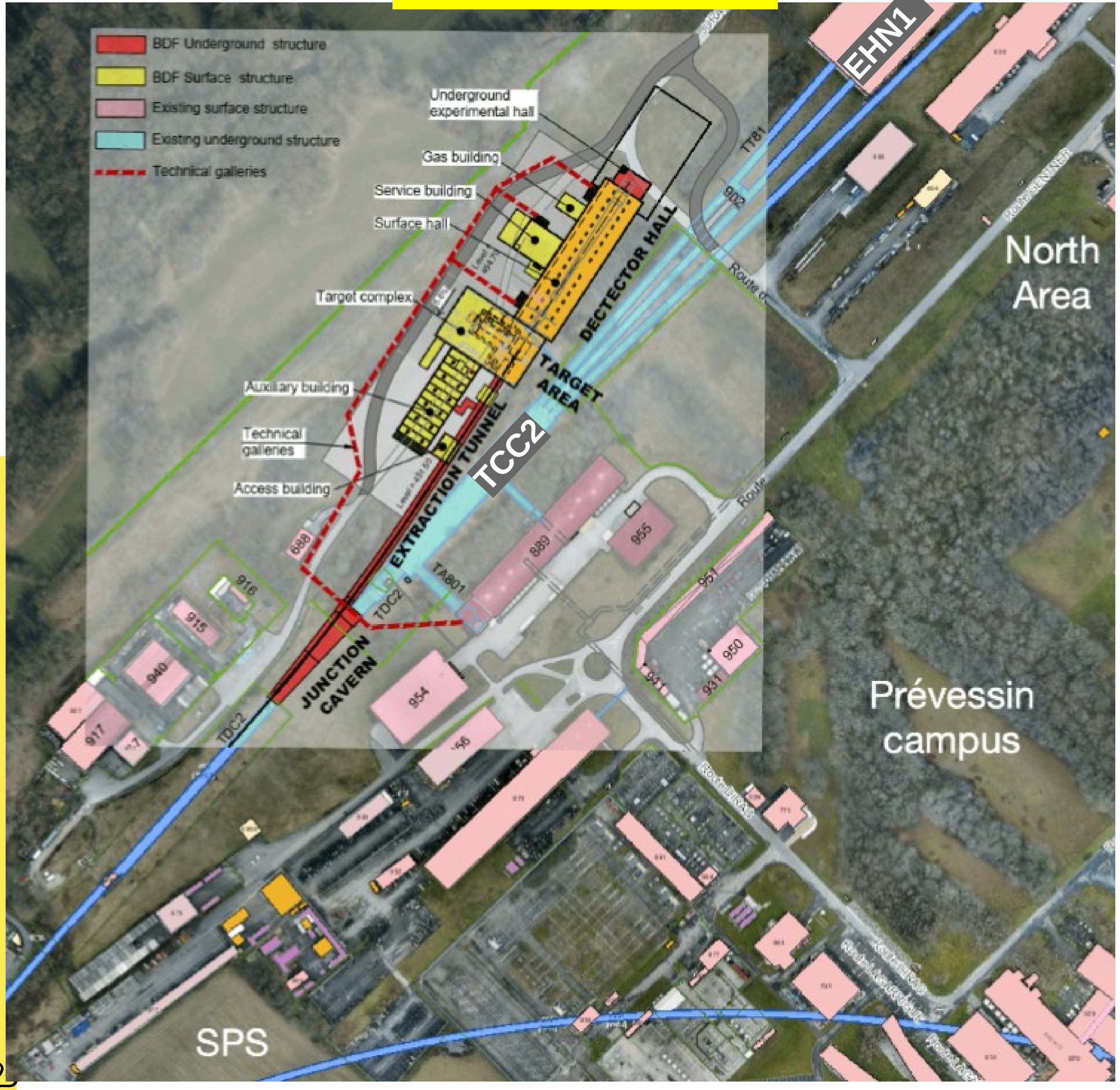
Source: https://section-mpc.web.cern.ch/sites/default/files/inline-images/TT20%20and%20NA%20facillities_5.jpg

ECN4 – a new North Area facility?

- There has been a comprehensive design study of a new ECN4 facility for the BDF/SHiP facility leading up to 2020
- A facility in parallel to the target area TCC2 of the North Area
- Key components of the ECN4 proposal for BDF/SHIP can be taken over; however, there are stark differences in terms of integrated and instantaneous intensity
- **BDF/SHiP**: 4E19 PoT/year and 4.0E13 PoT/1.2s spill duration = 2.1 MW
- **nuSCOPE:** ~2E18 PoT/year (factor 1/20) and 1.0E13 PoT/9.6s spill duration = 67 kW (factor 1/32)
- The intensity difference would possibly lead to a simpler target complex

https://doi.org/10.23731/CYRM-2020-002

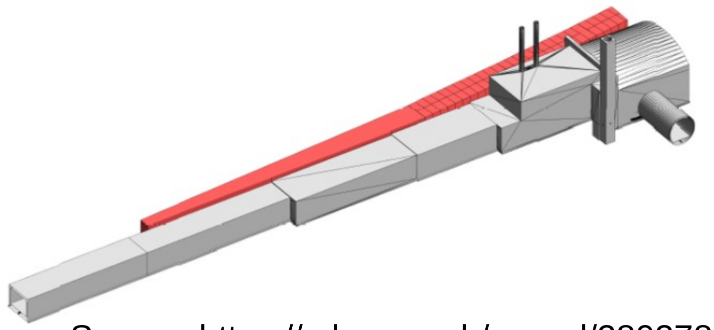
BDF/SHiP in ECN4



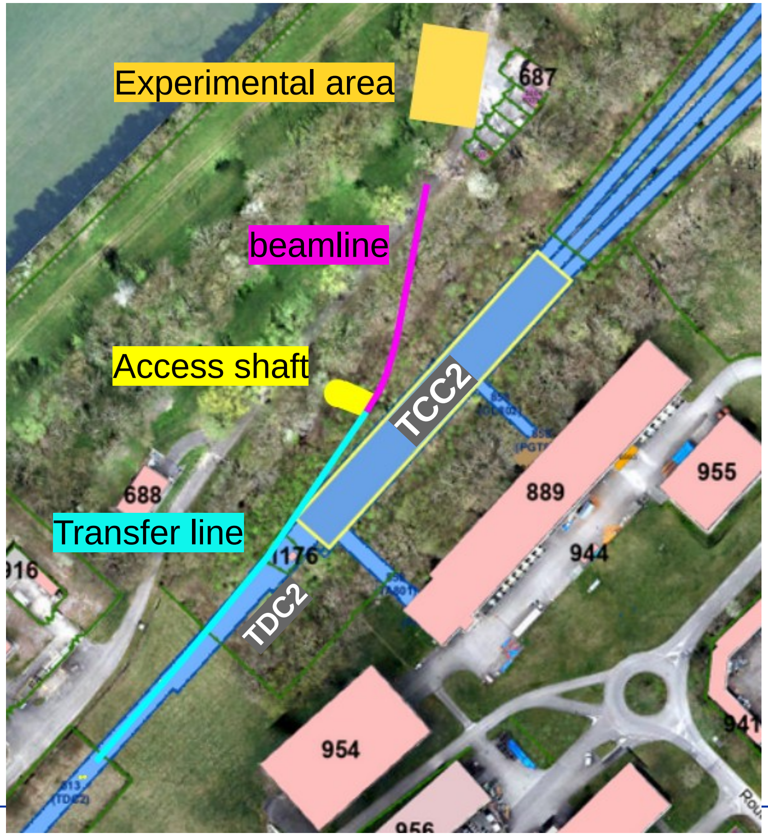
ECN4 – a new North Area facility

- A junction cavern is required followed by a transfer line paralle to TCC2
- Once sufficient separation is created, the beamline's target station starts
- The experimental area could be a surface building if the decay tunnel points roughly 10 degrees upwards
- Beam delivery to the nuSCOPE in ECN4:
  - The BDF/SHiP proposal was envisaging a dedicated high-intensity cycle (Splitter 1 is replaced by laminated bipolar splitter – performance questionable)
  - Ideally, an additional splitter upstream of Splitter 1 would serve the beamline with beam (highly questionable)
  - A dedicated cycle via the proposed SHiP solution might be forced **(not preferred!)**; however, there could be the possibility of creating a P42 mirror image at the T2 target
- **ECN4 is a feasible solution that builds on the substantial work that has been done by the BDF/SHiP study group**

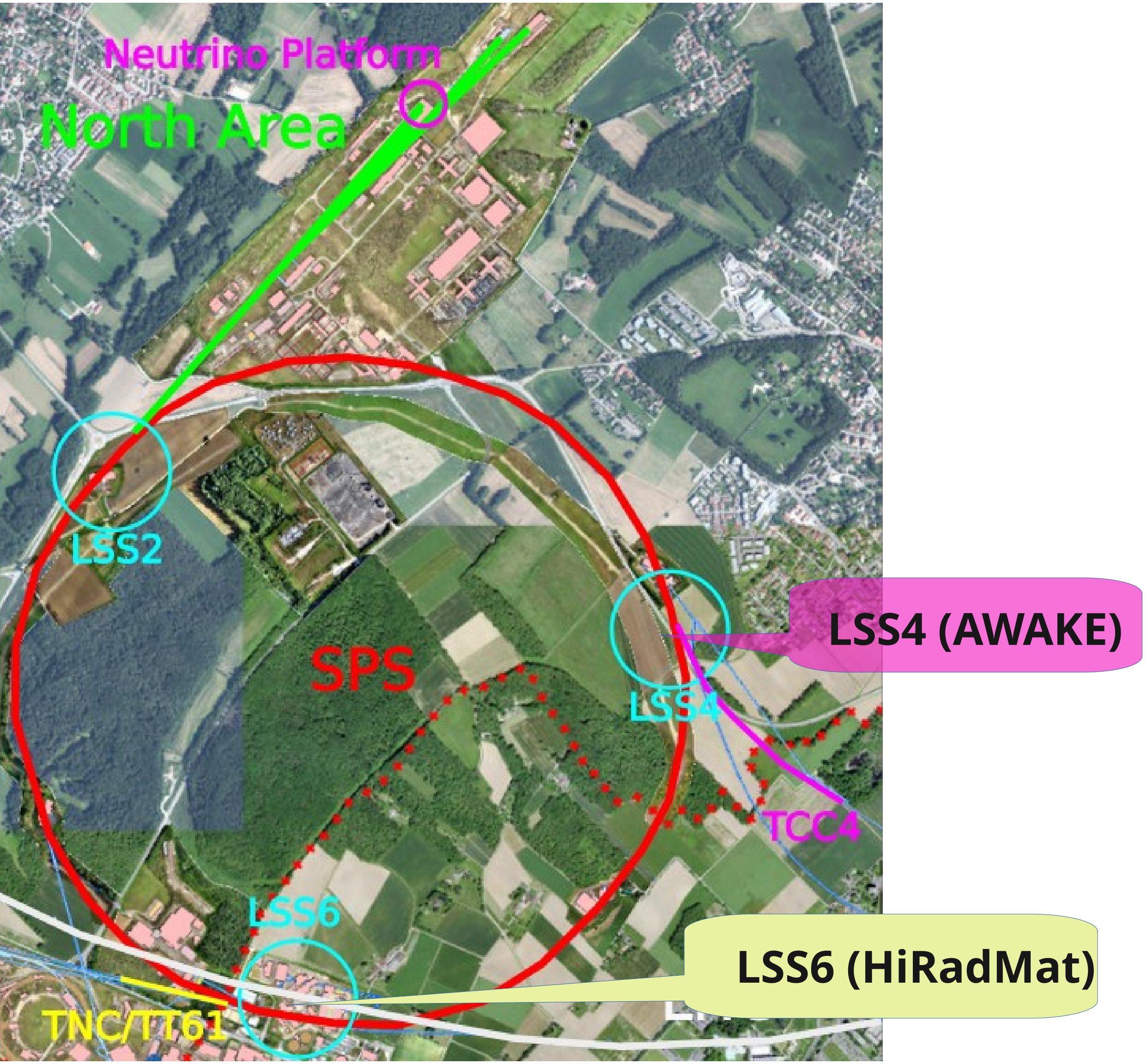
Alternative to a junction cavern to reduce impact on TCC2



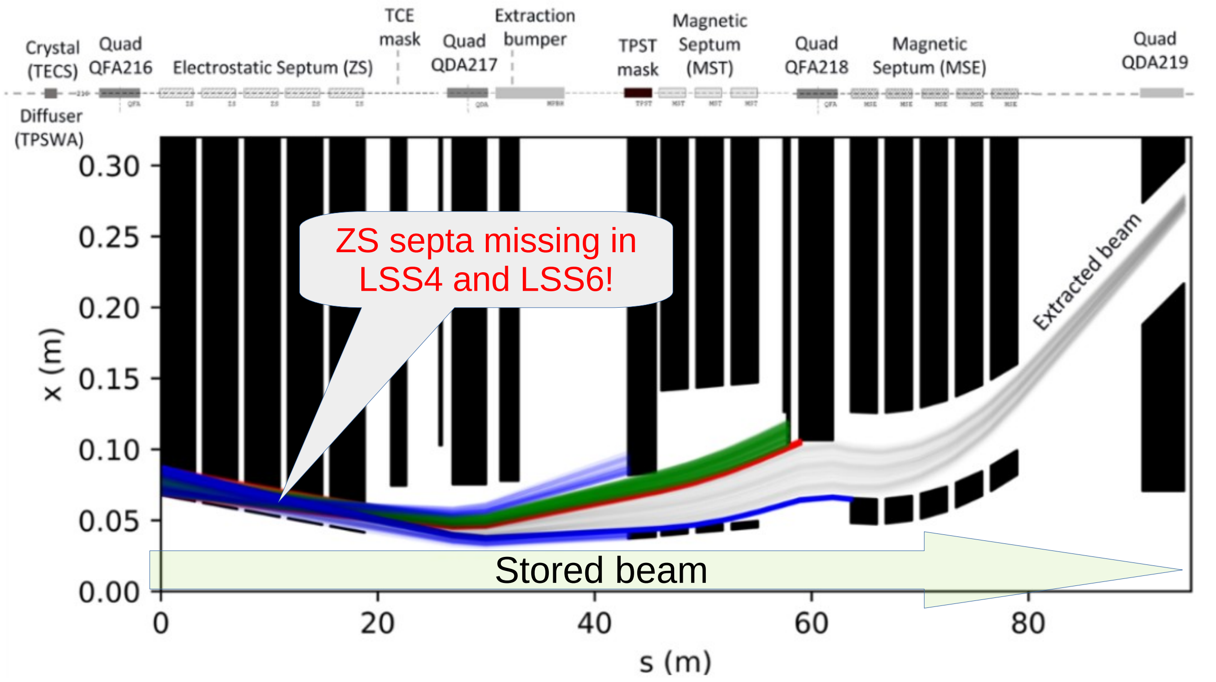
Source: https://cds.cern.ch/record/2802785



Other options? Yes!



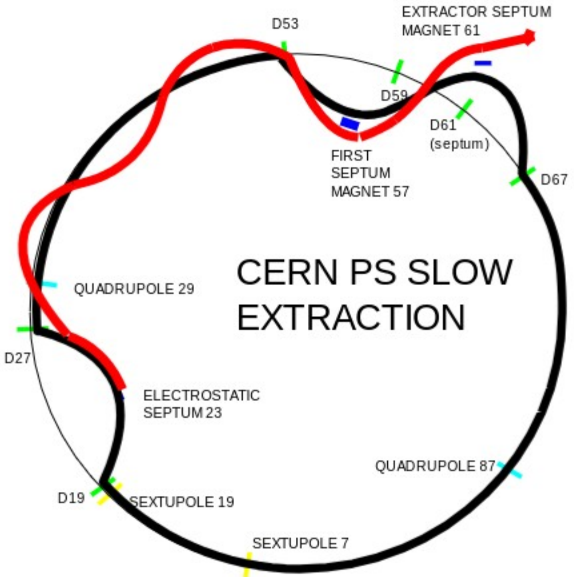
- There are two other extraction possibilities at the SPS:
  - **LSS4 (AWAKE)** and **LSS6 (HiRadMat)**
- The main issue is the lack of a slow-extraction setup that is strictly required for the nuSCOPE beamline!
- LSS4 and LSS6 feature magnetic septa for the fast extraction; however, electrostatic wire septa (ZS) septa are missing. LSS6 featured wire septa until the LHC extraction was established in the early 2000s.
- LSS6 (HiRadMat) preferred over LSS4 (AWAKE)



Source: https://doi.org/10.1103/PhysRevAccelBeams.22.123501

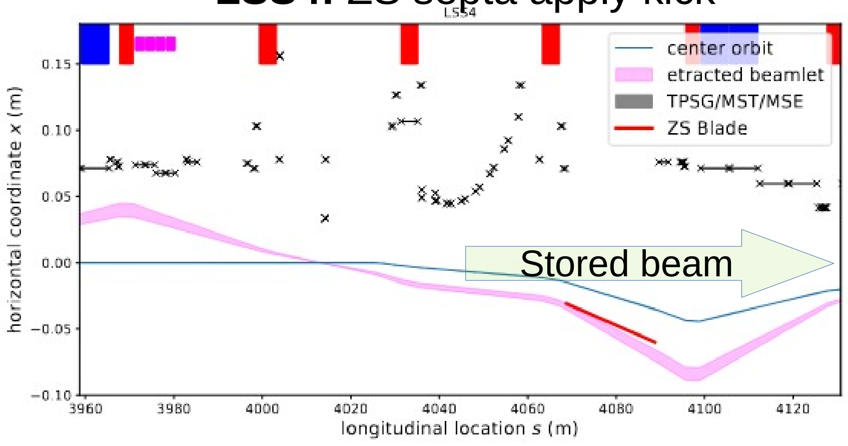
A new non-local slow-extraction setup

- A **local extraction setup** like in LSS2 (North Area) cannot be established in LSS4 and LSS6 because the fast extraction kickers for the LHC extraction occupy the ideal location for the ZS septa
- A **non-local solution** like in the PS appears much more promising: ZS septa are put into an upstream LSS!

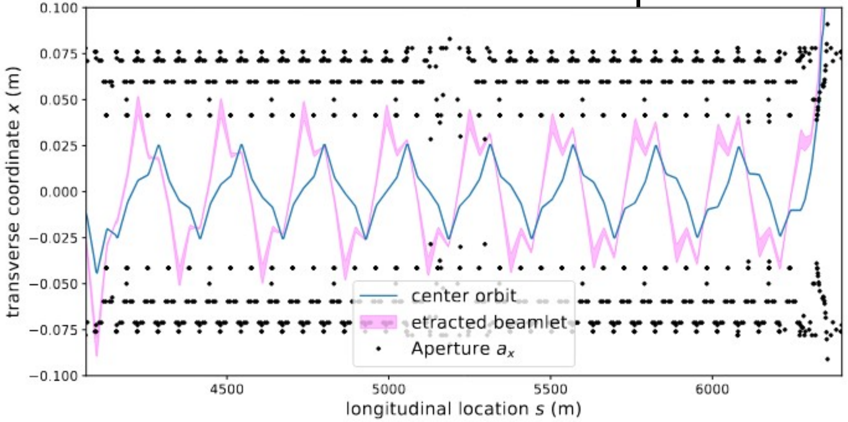


- **Example: Extraction to LSS6 (HiRadMat)**

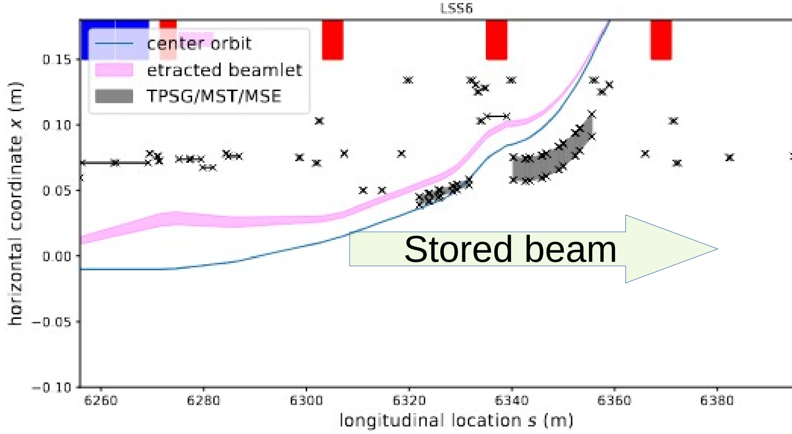
LSS4: ZS septa apply kick



LSS4 to LSS6: Transport



LSS6: Extraction



Source: https://indico.cern.ch/event/385590/contributions/912478

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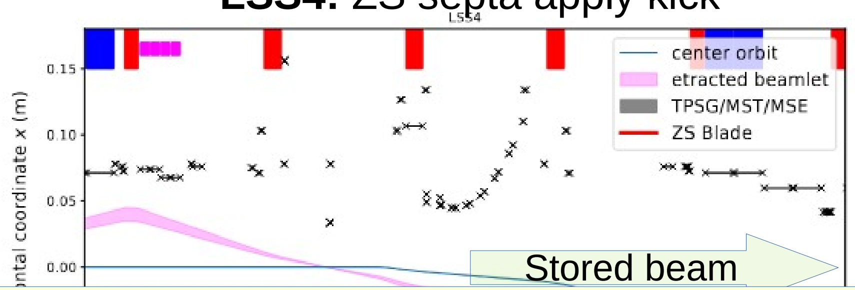
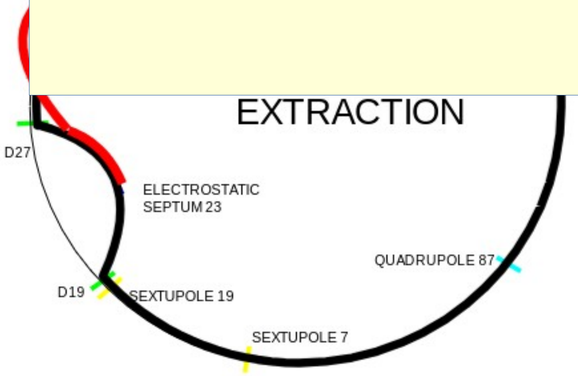


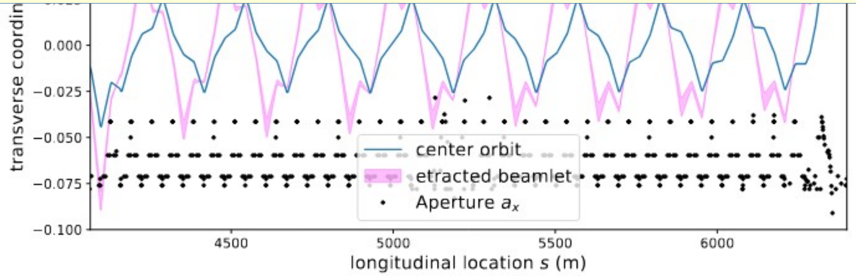
Establishing a slow extraction at LSS6 (HiRadMat) appears possible on the conceptual level !

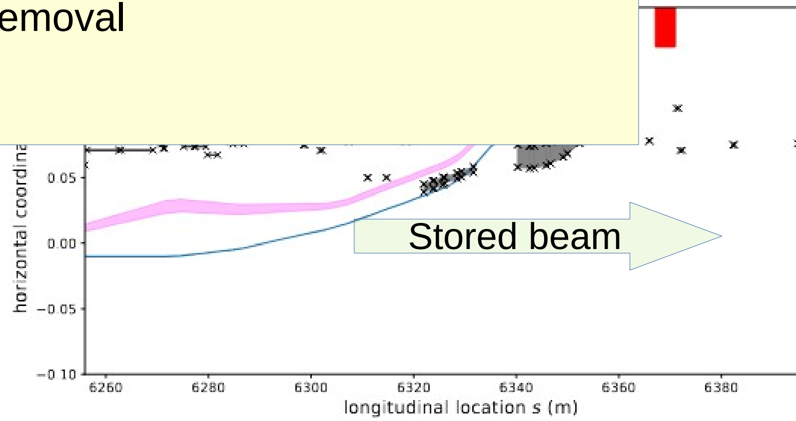
A) The LHC fast extraction does not have to be modified!

B) ZS wire septa and other modifications of the SPS are required, e.g., two-orbit bump configuration, crab-cavity test stand removal

Further analysis required in the future







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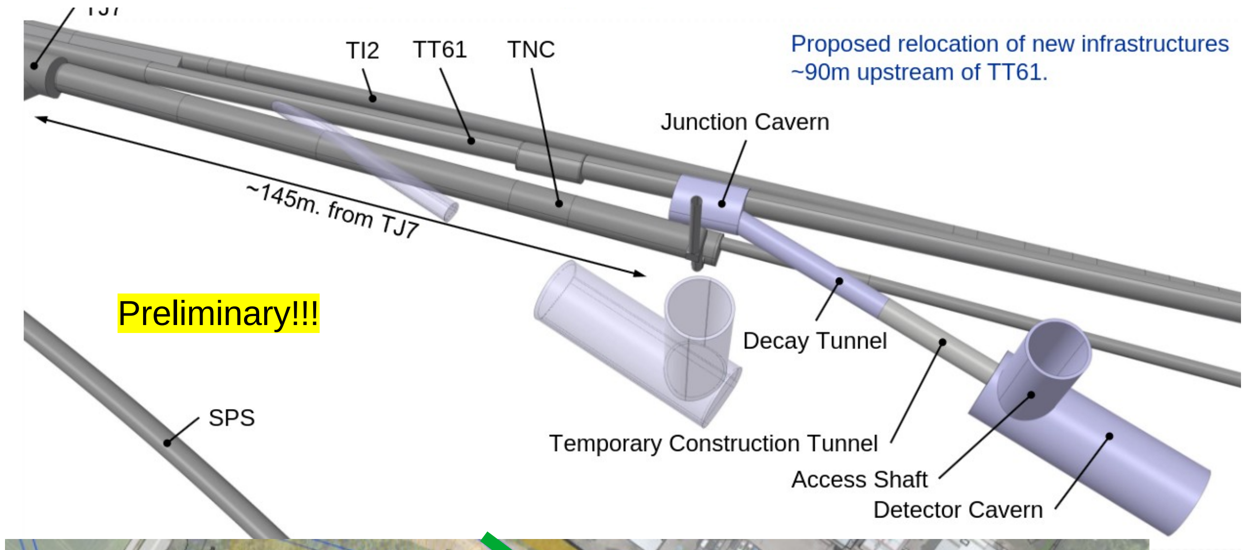
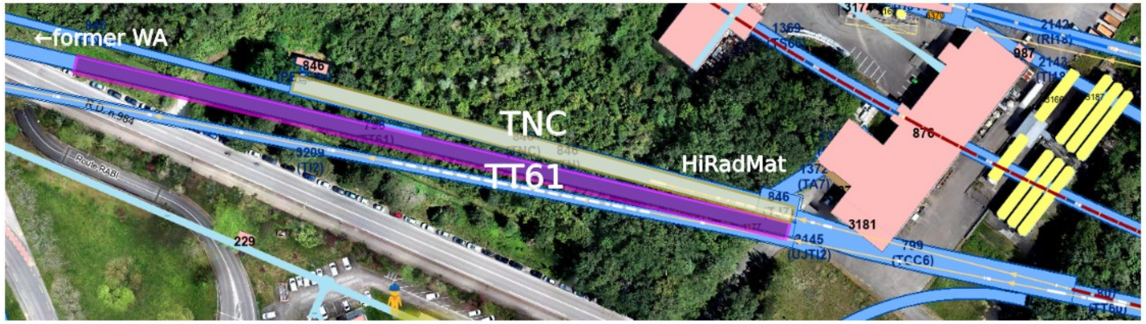
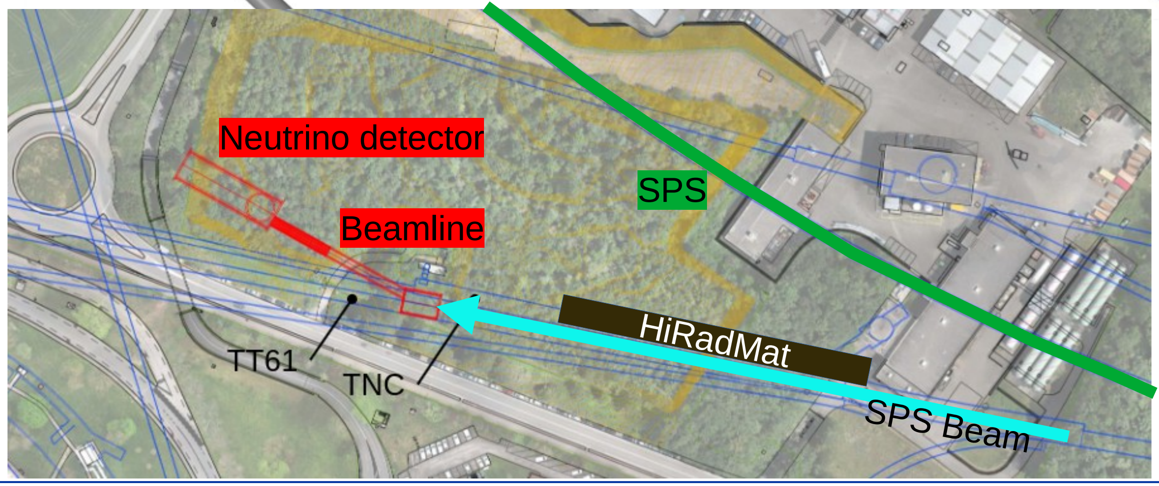
Possible implementation in TNC/TT61/TCC6

- The HiRadMat facility occupies the first third of the TNC tunnel that is downstream of the underground cavern TCC6 (was housing the production targets for the former West Area)
- The TT61 tunnel is mostly vacant – Initial part contains shielded HiRadMat read-out.
- The implementation of the nuSCOPE beamline there has the advantage of being shielded by the soil and some infrastructure already exists. Also, a momentum of p=430+ GeV/c could be envisaged
- We aim for a parallel operation of the beamline and HiRadMat

- We are currently in touch with the Civil Engineering Department to figure out feasible ways to realize the arrangement in the most efficient way

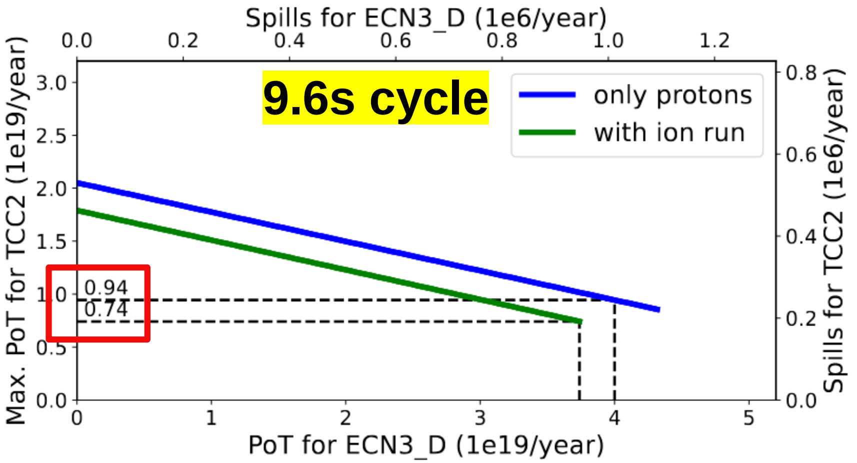


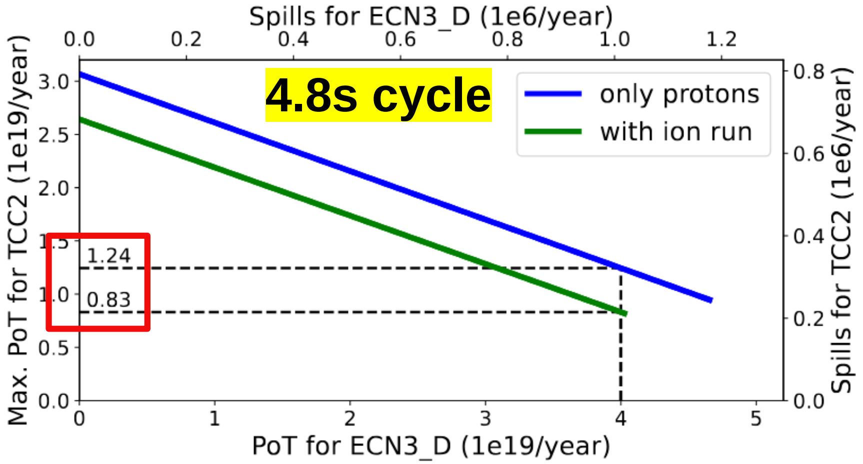




A second look at the proton sharing at the SPS

- At this point in time, a 9.6s SPS cycle for the North Area is strongly considered for Run 4.





- **Receiving a fraction of the North Area intensity**
  - The beamline is located in a new ECN4 facility or some other facility at LSS4/6, it is possible to access the North Area cycle (shared) or take its intensity entirely (dedicated) → **limits on the instantaneous rate of the experiments have to be respected**
  - Assuming the beamline would receive 25% of the TCC2 intensity, the beamline then receives between 1.9E18 and 3.1E18 PoT per year.
  - In 5 years, the statistical uncertainty on the inclusive ν_e cross section would end up between 1.2% and 0.95% depending on the SPS cycle length and number of heavy-ion runs
- **Enhanced cycle flexibility (2nd slow-extraction setup)**
  - In case the beamline is served via a 2nd slow-extraction setup, a variety of ways of serving the beamline with beam opens up; e.g., **A) simultaneous extractions** or **B) back-to-back extraction within the same cycle**
  - There might be ways to make the beamline at least partially transparent (nuSCOPE protons not deducted from other experiments' protons)

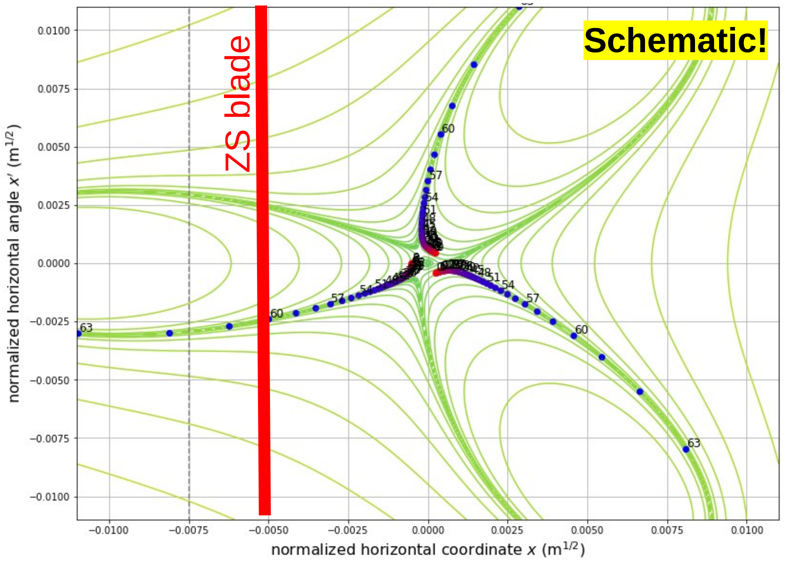
Conclusion and outlook

- Wide range of neutrino cross-section measurements (ν_μ and ν_e) with unprecedented flux control opened up by monitored and tagged beamline
- The beamline optimization was finished rapidly and the PoT requirement has shrunk significantly: 1.0E13 protons/spill with an annualized intensity of **2.0E18 – 3.0E18 PoT/year ← 25% of the TCC2 annual intensity**
- We have determined two comparable ways of implementing the beamline either in some new facility ECN4 in the North Area of the CERN campus or in the TT61/TNC region downstream of the SPS LSS6 straight section (requires a second slow-extraction setup in the SPS).
- A second slow-extraction setup could add additional flexibility to the extraction process. There might be sophisticated ways to make the nuSCOPE beamline at least partially *transparent* in terms of required protons
- More studies needed in the future to address the feasibility of such a project in more detail
- **nuSCOPE physics case: see L. Munteanu's talk at 11:45 pm (WG2)**
- **nuSCOPE workshop at CERN from October 13th to 15th (https://indico.cern.ch/event/1548855/)**

Thanks for your attention!
Questions?

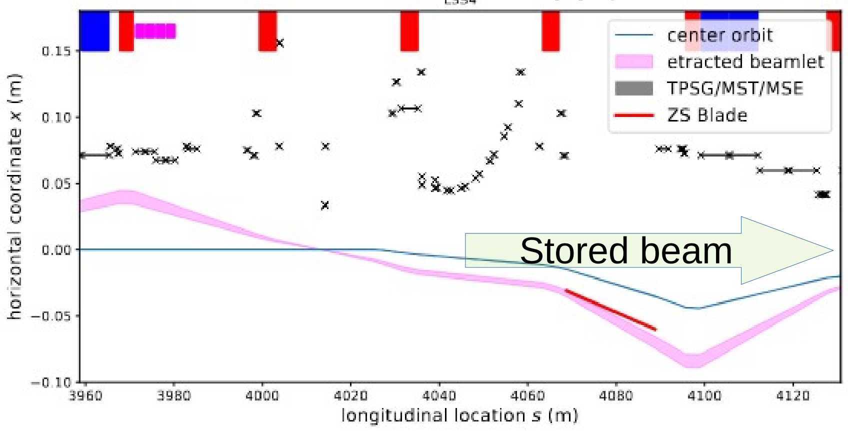
Slow extraction to LSS6?

- The SPS is operated on a Q=2/3 sextupole resonance to generate three unstable “arms” in the horizontal phase space

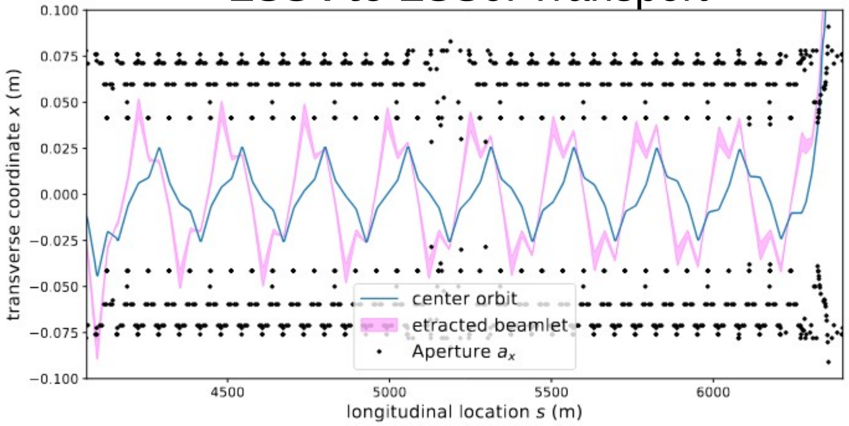


After a number of turns, the particle amplitude reaches to the averted side of the ZS wires = Extraction!

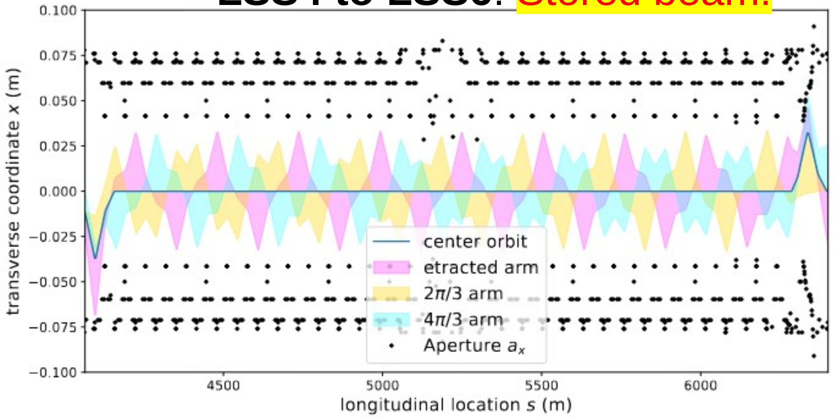
LSS4: ZS septa apply kick



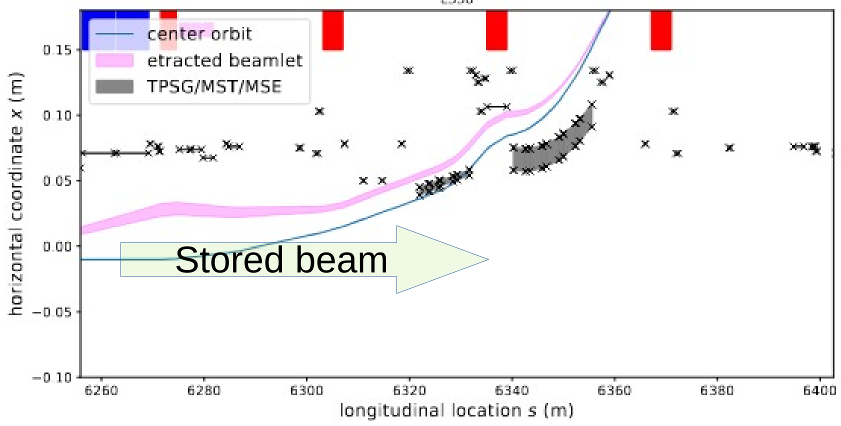
LSS4 to LSS6: Transport



LSS4 to LSS6: Stored beam!

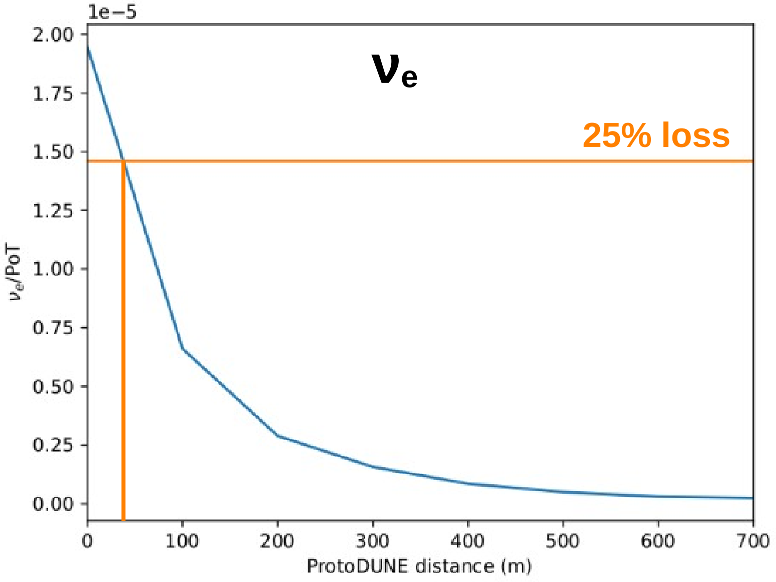


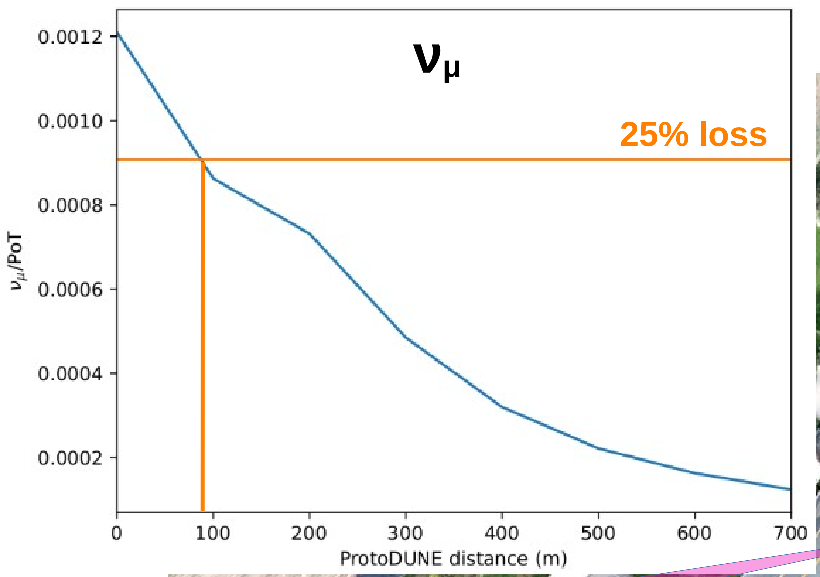
LSS6: Extraction



Using the existing ProtoDUNEs?

- Using the existing ProtoDUNE would be a sustainable, convenient and cost effective measure
- Quick loss of effective aperture for the ν_e with increasing distance between ProtoDUNE and the end of the decay tunnel. The transverse neutrino angle dominates any beam divergence in the decay tunnel





The ProtoDUNEs cannot be approached (100m radius) without interfering with EHN1!
– 400 GeV/c SPS is highly rigid –