NP06/ENUBET and synergies with nuSTORM

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

F. Terranova (Univ. of Milano-Bicocca and INFN) on behalf of
the ENUBET and nuSTORM Collaboration

ENUBET: ERC Consolidator Grant. Jun 2016 - May 2022. PI: A. Longhin.
Since April 2019, ENUBET is also **a CERN Neutrino Platform experiment: NP06/ENUBET**

The ENUBET Collaboration:
60 physicists, 12 institutions
Spokespersons: A. Longhin, F. Terranova
Technical Coordinator: V. Mascagna

Aim of this presentation

- Present the ENUBET concept to PBC since it is new to this audience
- Show that a significant part of the work **for a site-dependent implementation** of ENUBET and nuSTORM (CERN) can be done within PBC
- Even in a site-independent approach (EU and SPSC), working with PBC is essential for:
  - Gaining a **more realistic estimate** of costs and technical challenges in the implementation
  - Envision a graded strategy from **K/π precision beam to muon beam** to muon colliders
- Exchange ideas among experts of fixed target experiments and neutrino physics on the physics opportunities offered by these novel machines (in collaboration with CERN-PE-ND) and the **best neutrino detectors**
- Discuss a possible role for existing detector at CERN, with emphasis on ProtoDUNE-SP, ProtoDUNE-DP and the Neutrino Platform extension of EHN1 (**a big investment made by CERN in 2015-2018!**)

High-precision beams in the DUNE/HK era

- We have been living with «beams for oscillations» hoping to get precision physics «for free»
- It worked at 10% level! But all good things come to an end.
- There is too large a leap between our knowledge of standard neutrino properties (firstly cross sections) and the needs of the next generation experiments.
- We need appropriate tools to perform precision physics:
  - High power beams and large mass detectors (osc. DUNE, HK + long term proposals)
  - **High precision beams for cross section, neutrino interactions and BSM physics measurements (ENUBET and NuSTORM)**

Flux at per-cent level measured in a direct manner

Good knowledge of the neutrino energy without using final-state particle reconstruction

Superior control of flavor and contamination at source

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

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

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

ENUBET, in particular is aimed at

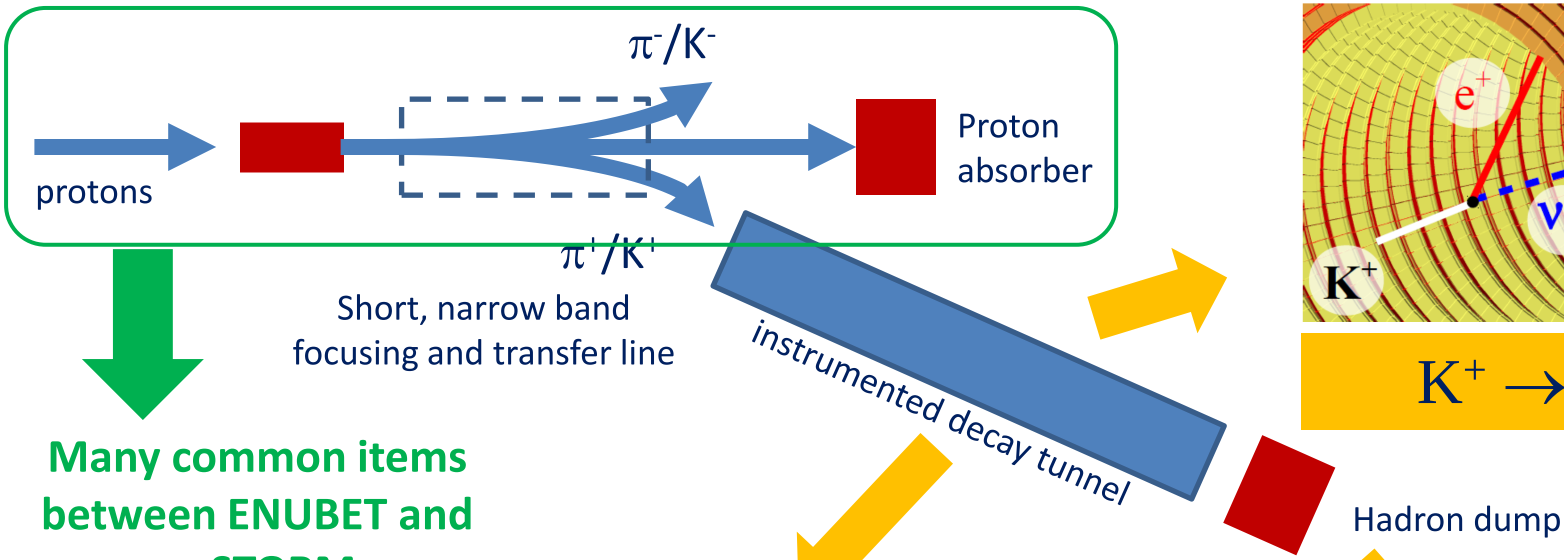
- Designing a narrow band neutrino beam at the GeV scale and measure at 1% the **flux, flavor** and (at 10%) the **energy of the neutrinos** produced at source

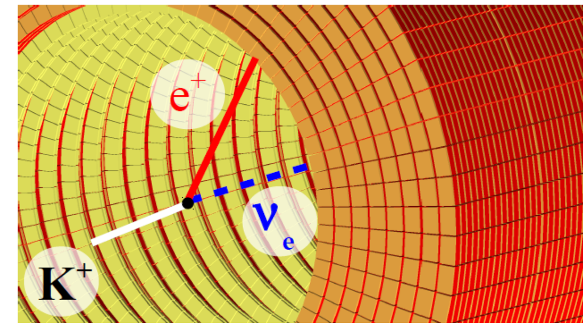
NuSTORM: offers an **unprecedented statistics of ν_e** and a major leap toward Neutrino Factories and **the muon collider**

It is the core technology for

- A new generation of short-baseline experiments to achieve a 1% precision on the **ν_e and ν_μ cross sections** and **remove all the biases** due the ν energy reconstruction
- It is essential to lower <3% the systematic budget of **DUNE and HyperK** and enhance remarkably their discovery reach
- Is the most natural follow-up of the previous generation of x-sect experiments (including the possibility to upgrade **the ProtoDUNE** or **the SBN physics programme**)

Monitored neutrino beams (*)





$$K^+ \to \pi^0 e^+ \nu_e$$

Many common items between ENUBET and nuSTORM

NEW! (2019-20) muon identification and monitoring for

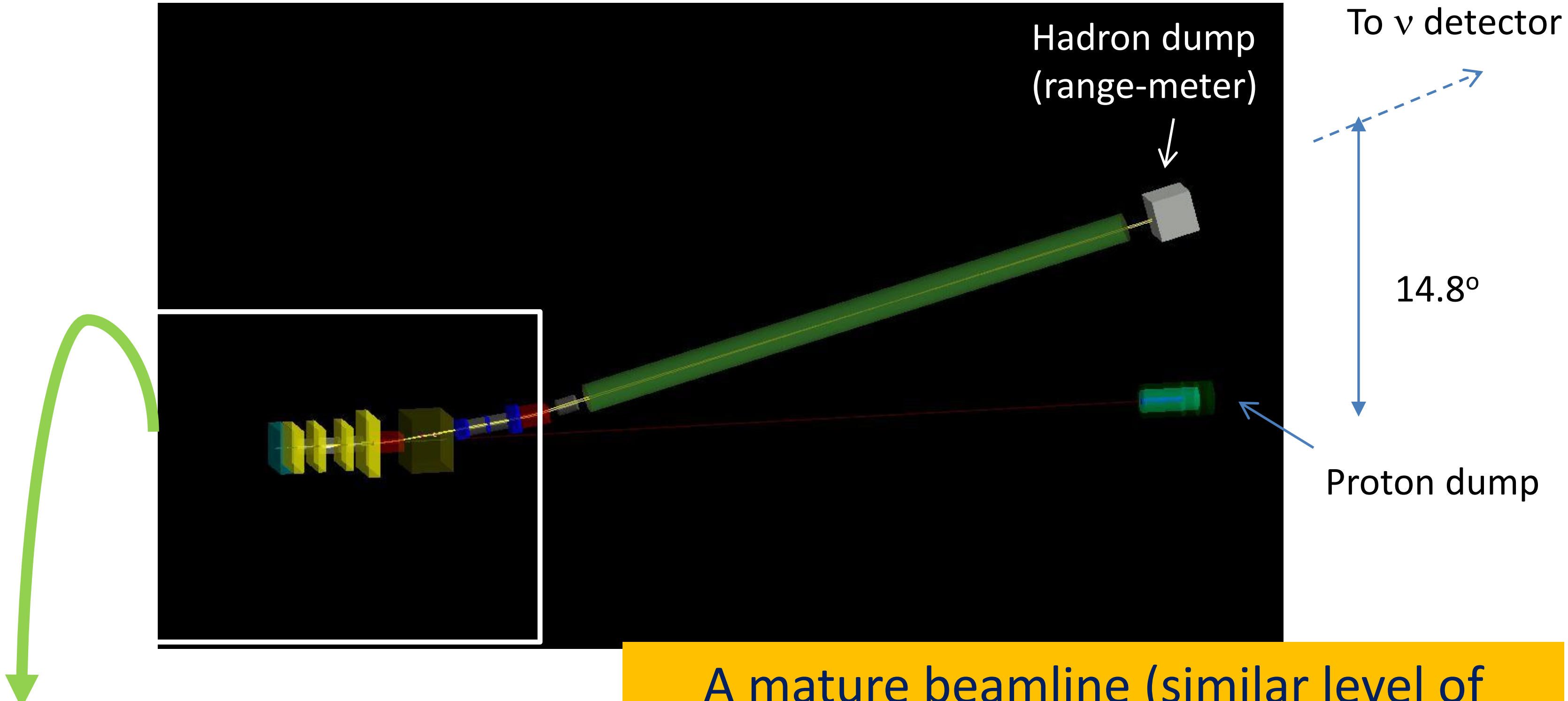
$$K^+ \to \mu^+ \nu_\mu$$

NEW! (2019-20) muon monitoring at single particle level replacing the hadron dump with a real range-meter

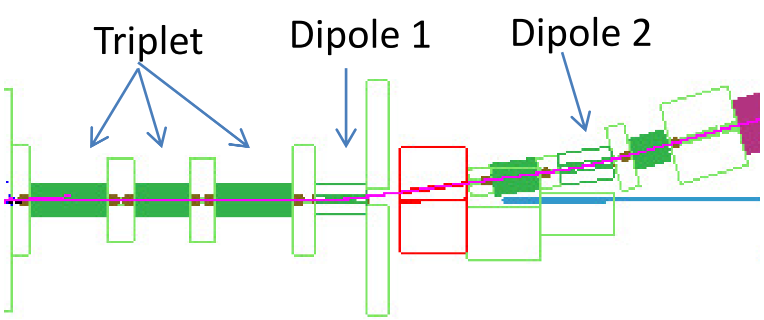
$$\pi^+ \to \mu^+ \nu_\mu$$

ENUBET will be the first "**monitored neutrino beam**" where nearly all systematics are bypassed monitoring the leptons in the decay tunnel at single particle level

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



A mature beamline (similar level of details of NuSTORM) that make the interaction with PBC more productive



Proton dump: **OK** but **engineering studies needed**

Hadron dump: **OK** (with neutron shieldings NEW!)

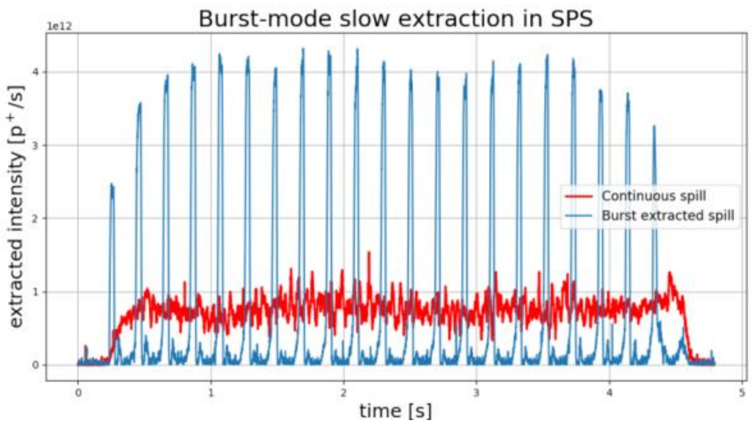
Target simulation: **OK**

Transfer line:

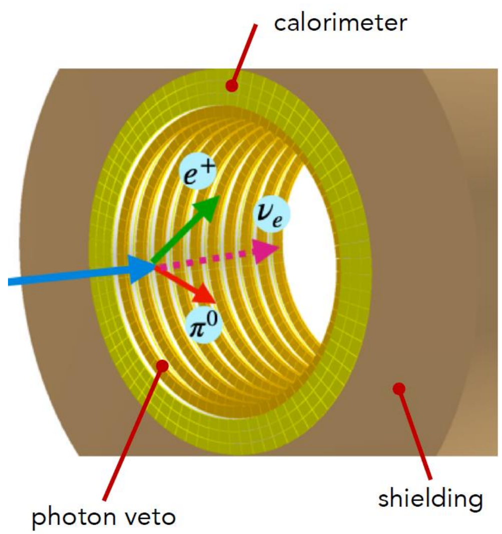
- TRANSPORT/G4Beamline (optics and background shielding **OK**)
- FLUKA (doses and neutron shieldings **~OK**)
- GEANT4 (systematics, **in progress**)

Beam design

We are performing this R&D using the CERN-SPS as a benchmark, in collaboration with CERN A&T Division (p=400 GeV/c, 4.5 10^{19} pot/spill)



M. Pari, M. A Fraser et al, IPAC2019



Focusing:

We need a "slow" extraction to mitigate the rate of leptons in the decay tunnel

Horn: 2-5 ms extractions in the flat top

Purely static focusing: 2 s extraction

Bring-home message: since 2020, the horn is not strictly needed in ENUBET!!

Tunnel instrumentation:

We need cost-effective detectors to identify muons and positrons

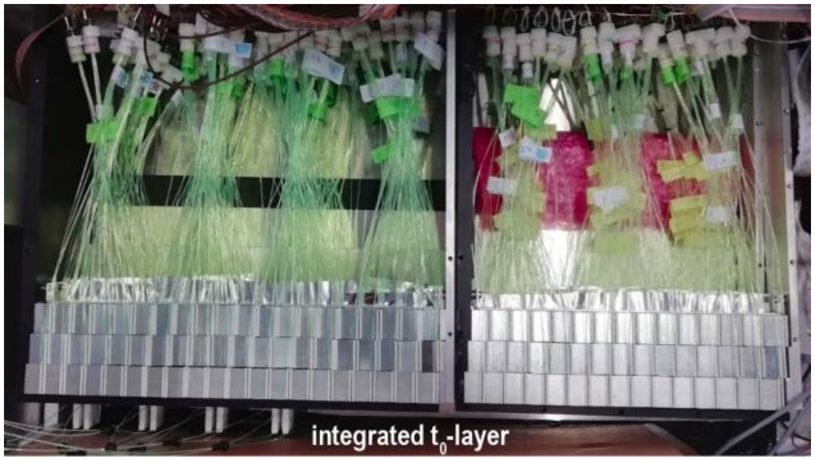
Modular sampling calorimeters (4.3 X0) with a photon veto

Typical rate per channel: 500 kHz/ch

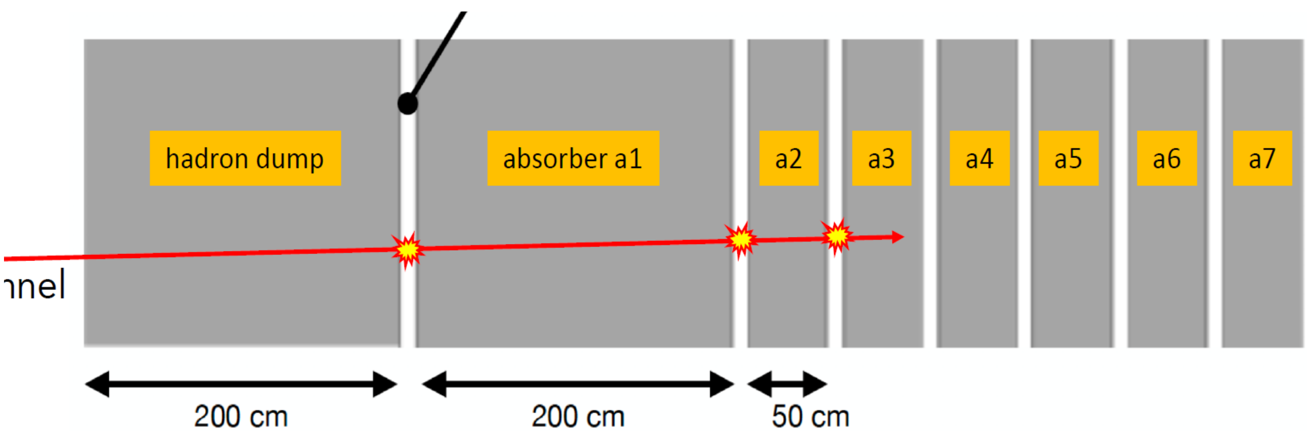
Doses: <10^{10} n/cm^2 at the SiPMs, 0.1 Gy at the scintillator

Instrumentation in the decay tunnel

All instrumentation to monitor positrons and muons have been prototyped, tested in beams of charged particles and **used to validate the MC**



- Longitudinally segmented calorimeter (**OK**)
- SiPMs on top of the calo above a PE borated shield to reduce (x18) radiation damage **OK**
- Test of the photon veto (t0-layer) **OK**
- Custom digitizer: **in progress**



Muon range-meter in the hadron dump: **in progress**

Max rate 1 MHz/cm^2

F. Acerbi et al., JINST 15 (2020) 08, P08001

F. Acerbi et al. JINST 14 (2019) 02, P02029

F. Acerbi et al., Nucl. Instrum. Meth.A 956 (2020) 163379

Particle identification

The PID is performed by the energy pattern in the modules and the photon veto. The event selection is based on 12 variables employed by a Neural Network.

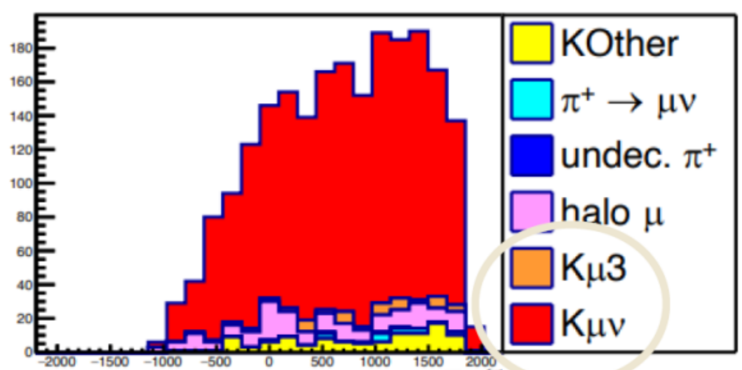
Full simulation: particle transported in the beamline (including beam halo and tertiary interaction), detector response, pile-up, event building, PID algorithms

Doses at the detector and transfer line

Data-driven simulation of detector response

Codes: FLUKA (target and doses), **G4Beamline** (beamline), **GEANT4** (neutrinos and systematics)

Muons from $K_{\mu 2}$ ($\sim\nu_\mu$)



Position along the tunnel

S/N = 6.1

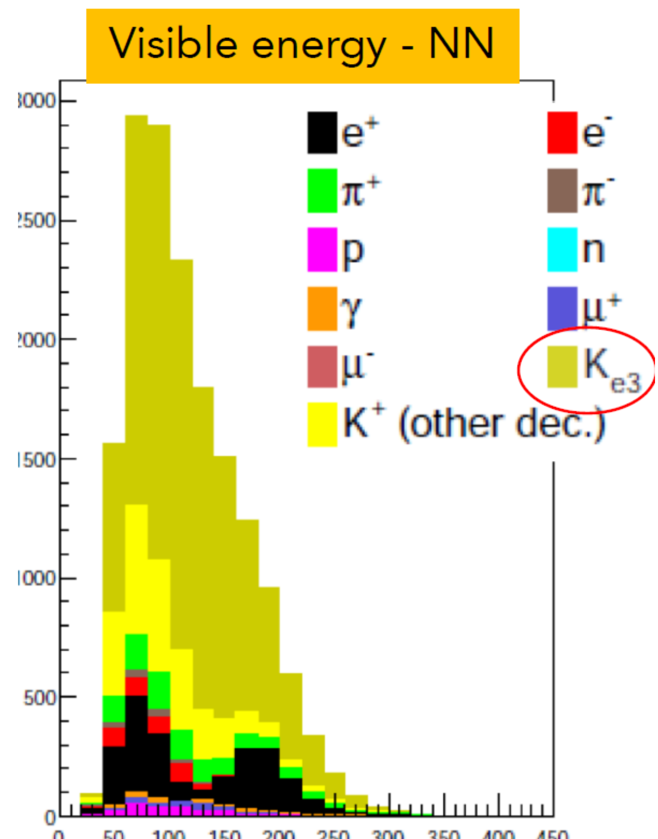
Efficiency: 34%

(dominated by geometrical eff.)

Positrons from K ($\sim\nu_e$)

S/N = 2.1 Efficiency: 24%

(dominated by geometrical eff.)



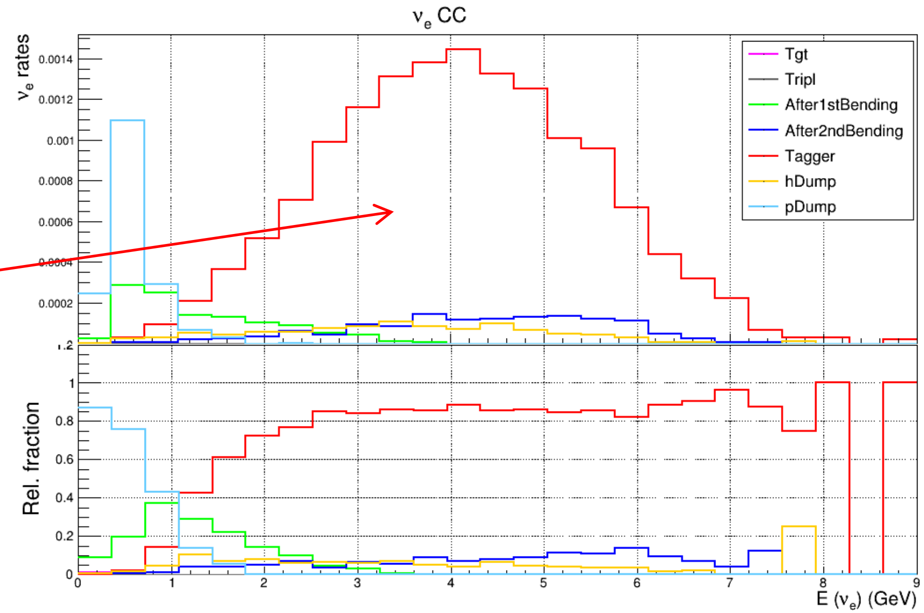
Physics performance: ν_e

10^4 fully reconstructed ν_e CC in about 2 y of data taking <u>without horn!!</u>

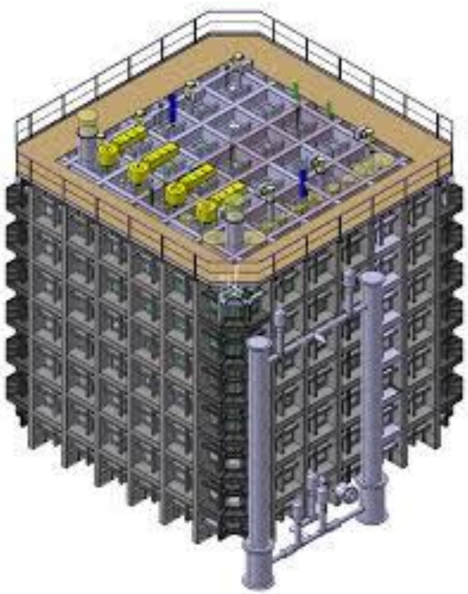
80% of the detected events (apart the low energy tail) produce a positron impinging in the decay tunnel

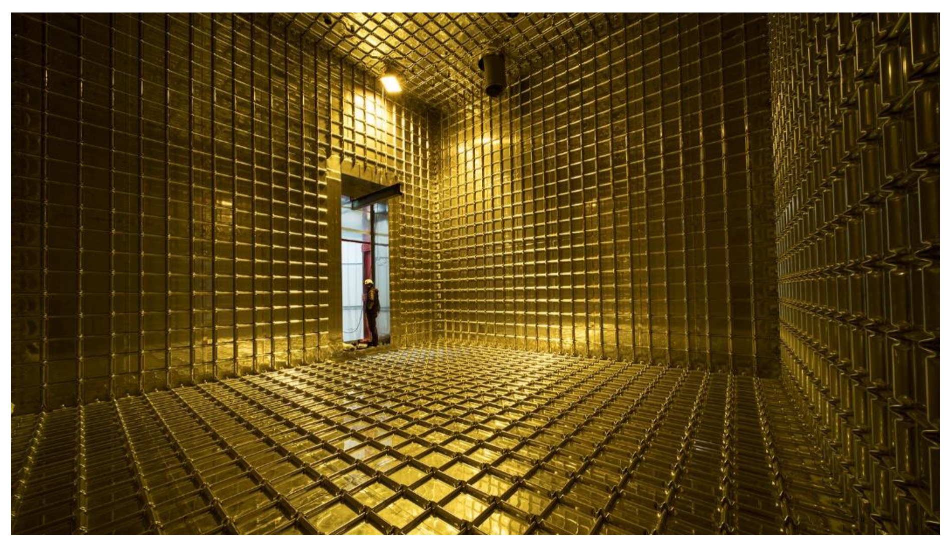
The following results are given under the assumption of a **500 ton neutrino detector** located 50 m from the hadron dump

ν_e CC



Beamline optimized for DUNE





Physics performance: ν_μ

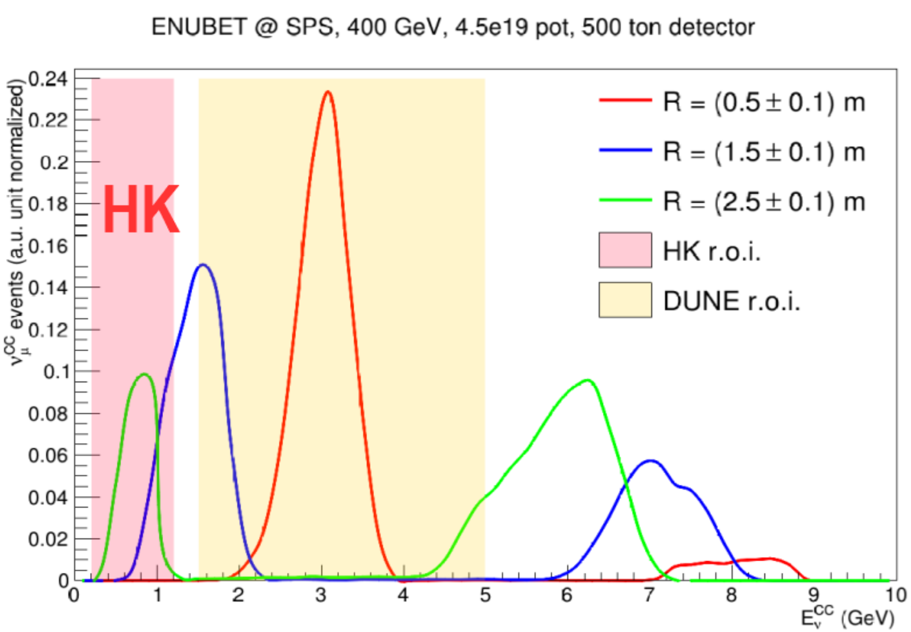
Flux:

- Muons from π monitored by the range-meter
- High energy muons monitored by $K_{2\mu}$

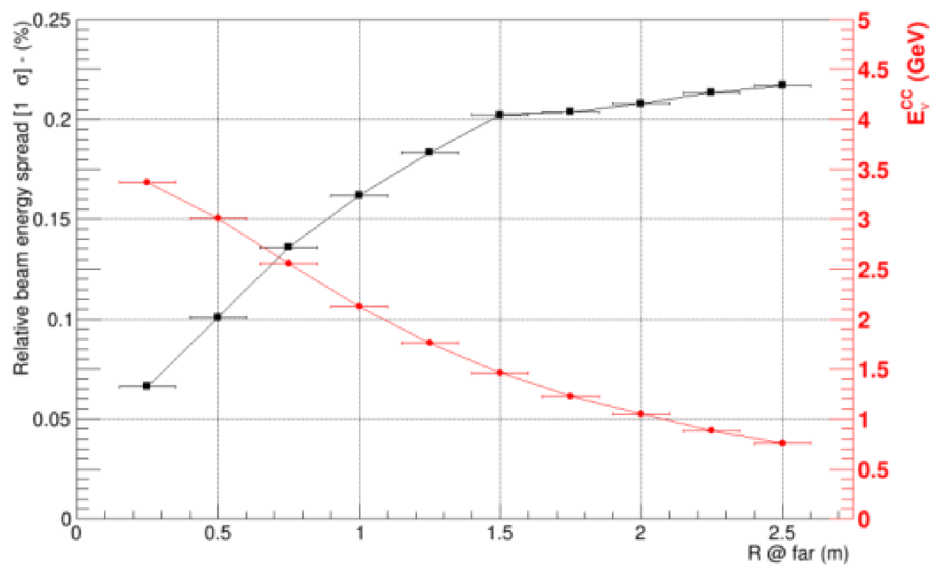
Energy:

- Since the momentum bite is <10% and the detector distance is small, strong correlation between the position of the neutrino vertex and its energy.
- We dubbed this technique "narrow-band off-axis technique" (*)
- **We provide the ν energy on a event-by-event basis without relying on final state particles in ν_μ CC**

About **O(10^6)** fully reconstructed ν_μ CC per year (preliminary)

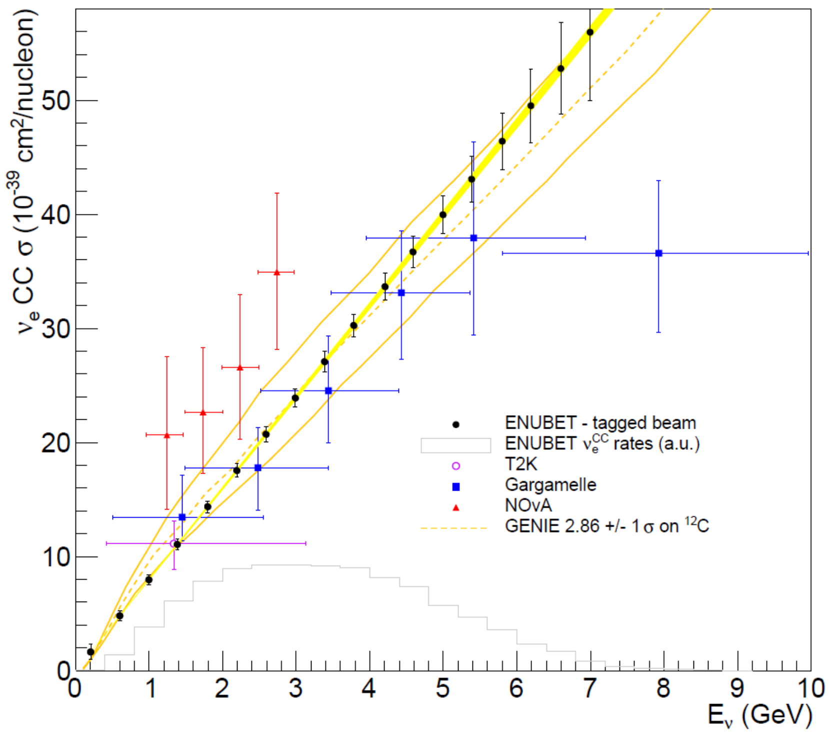


(*) F. Acerbi et al., CERN-SPSC-2018-034

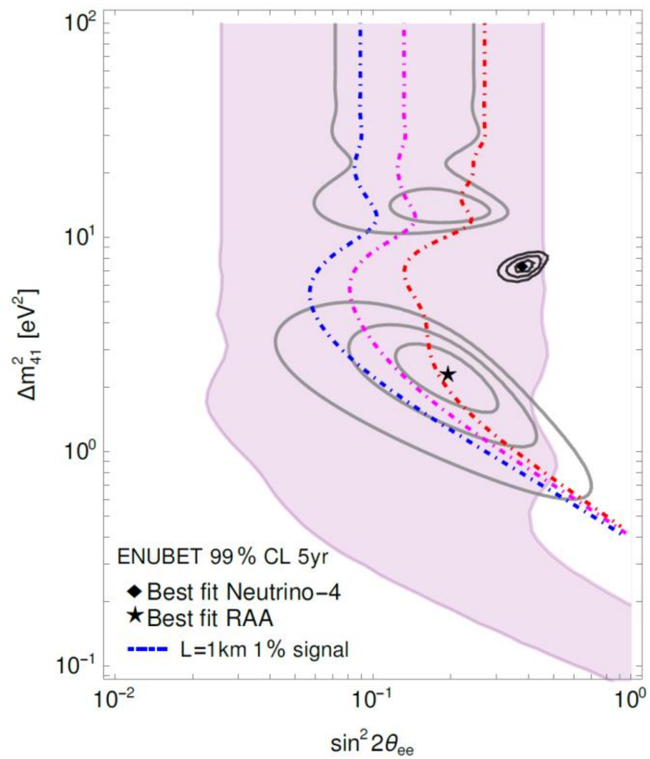


WORK IN PROGRESS

Impact



Electron neutrino cross section



Sterile neutrinos

L. Delgadillo, P. Huber, arXiv:2010.10268

Others to be investigated in detail, yet

- Differential distributions in the 1-4 GeV range for ν_μ and ν_e with reduced bias from the knowledge of Eν
- DAR at the proton dump (beam dump physics at 400 GeV)
- **Tagged neutrino beams**

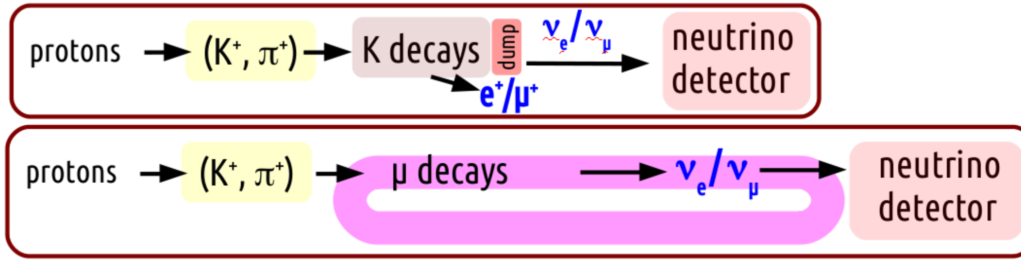
Comparison of needs

Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c	100-400 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}	4 x 10^{13} (@400 GeV)
Cycle length	3.6 s	2-5 s
Nominal proton beam power	156 kW	164 kW
Maximum proton beam power	240 kW	
Protons on target (PoT)/year	4 ◊ 10^{19}	4 10^{19} pot/y
Total PoT in ~~5 year~~'s data taking	2 ◊ 10^{20}	~9 10^{19} pot
Nominal / short cycle time	6/3.6 s	2 s (slow) (*)
Max. normalised horizontal emittance (1 ‡)	8 mm.mrad	600 mm mrad
Max. normalised vertical emittance (1 ‡)	5 mm.mrad	
Number of extractions per cycle	2	**1 (slow)** 10 (horn)
Interval between extractions	50 ms	**- (slow)** 100 ms (h)
Duration per extraction	10.5 μs	**2-4s (slow)** 2-5 ms (h)
Number of bunches per extraction	2100	
Bunch length (4 ‡)	2 ns	
Bunch spacing	5 ns	
Momentum spread (dp/p)	2 ◊ 10^{-4}	

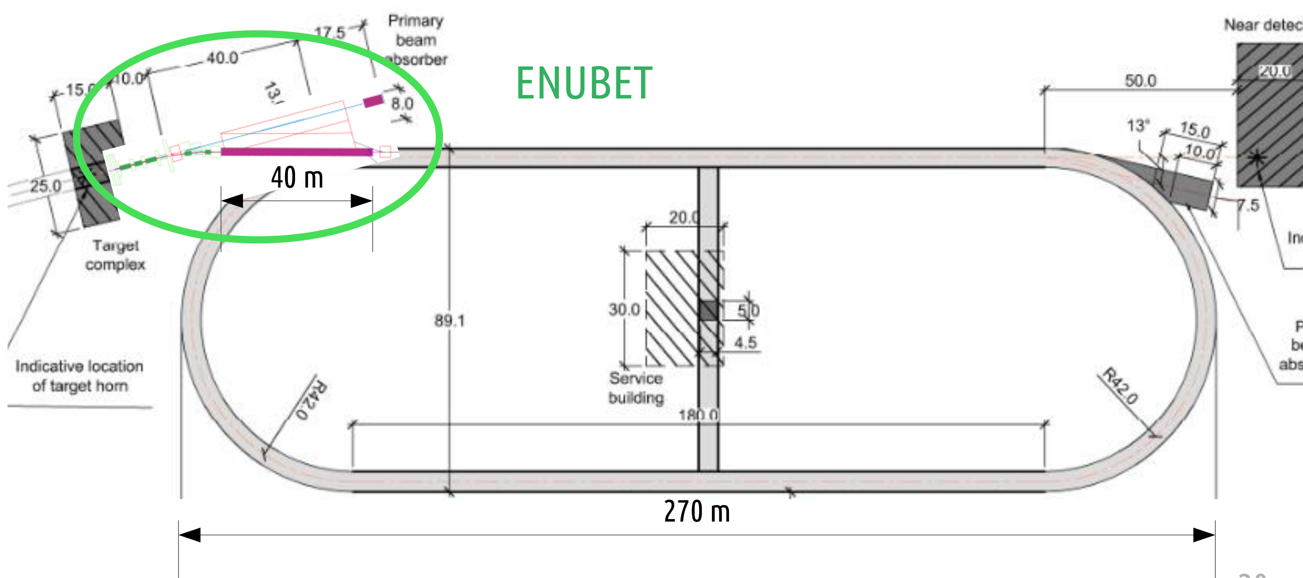
(*) For horn option 2-10 ms in 2s flat top at 10 Hz + many s (20s ?) of inactivity

nuSTORM & ENUBET



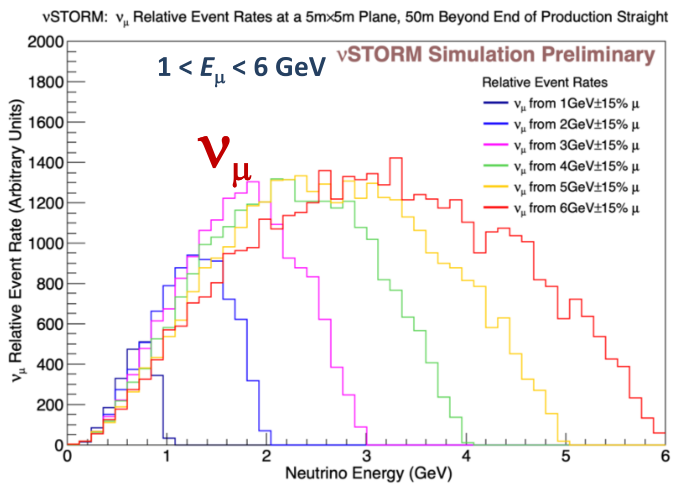
	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section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

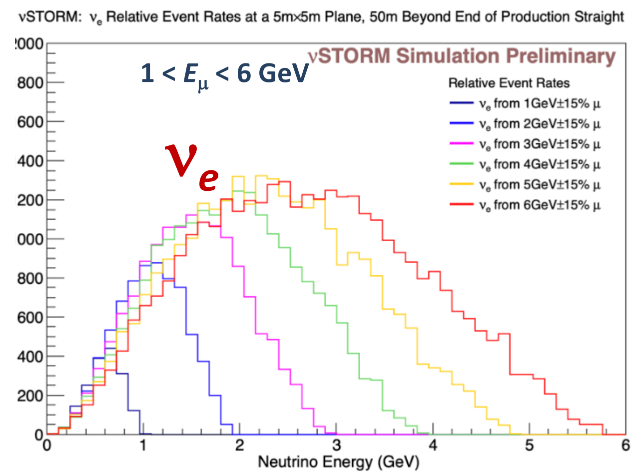
- Different concepts, budget, geometry.
- Main synergy: target facility, 1st stage of meson focusing, proton dump.



Specification: energy range: $1 < E_\mu < 6$ GeV

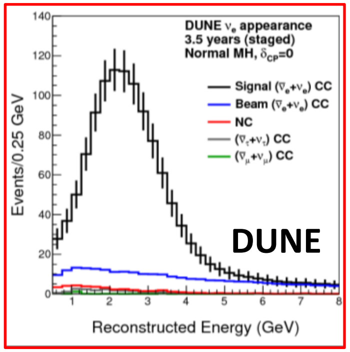
Relative rates:

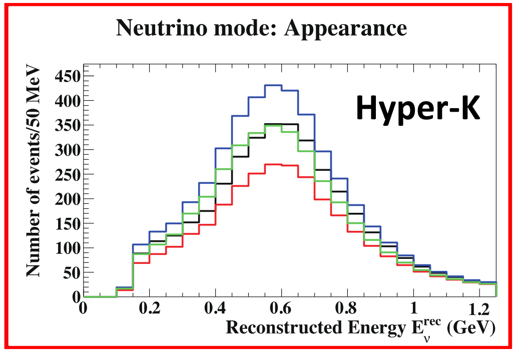


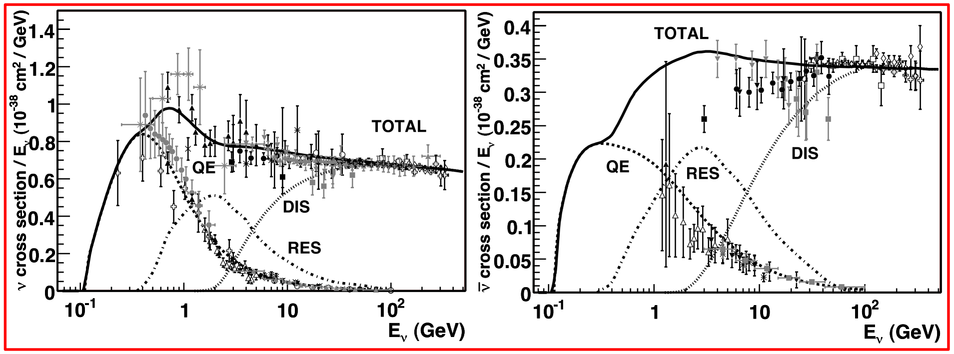


Unique capabilities:

- Exploit energy and off-angle technique to obtain narrow energy spectra
- Cover energy range:
  - With most significant model uncertainty
  - Spanned by Hyper-K and DUNE







nuSTORM in PBC: conclusion of 1 phase

CERN-PBC-2019-003

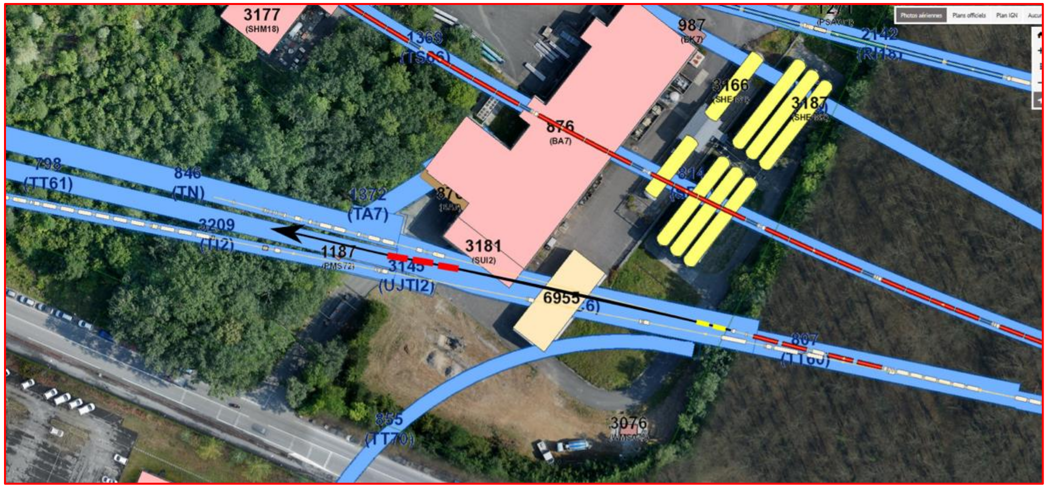
- nuSTORM will be a unique facility, physics pilars:
  %-level *electron* and muon neutrino cross-sections
  Exquisitely sensitive sterile-neutrino/BSM searches
  Serve 6D cooling experiment & muon accelerator test bed

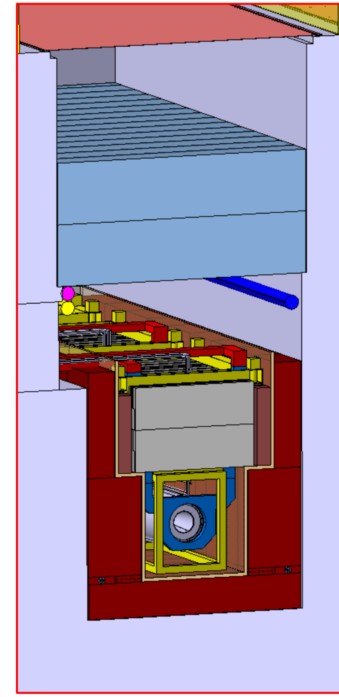
- Feasibility of executing nuSTORM at CERN:
  Established through Physics Beyond Colliders study

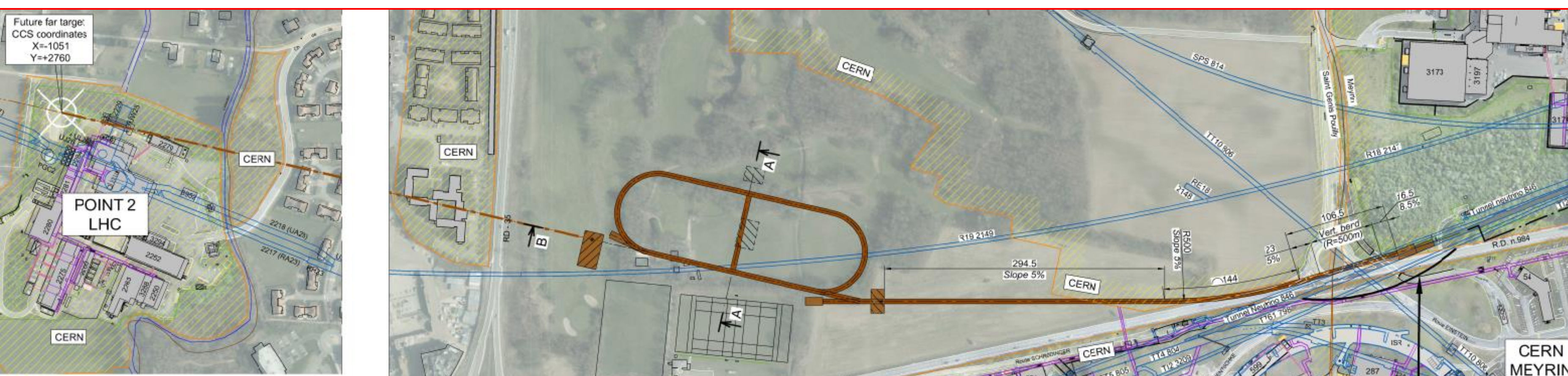
- nuSTORM: a step towards the muon collider:
  Proof-of-principle and test bed for stored muons for particle physics
  Ionization cooling:
    Experimental demonstration of 6D ionization cooling
      Required in *p*-driven neutrino factory and muon collider
    Broad range accelerator R&D programme, see Rogers et al in:
      https://conference.ippp.dur.ac.uk/event/967/overview

nuSTORM in PBC: conclusion of 1 phase

CERN-PBC-2019-003







Specific goals in PBC
(not included in NP06/ENUBET @ SPSC)

Quantify **physics reach** of ENUBET and nuSTORM beyond the original "1% flux precision":

- Implies study/specification of accelerator and detector
- Involve the CERN Neutrino Division (PE and TH) while up to now we mostly worked with A&T.

Evaluate **facility-level ENUBET/nuSTORM synergy**

Emphasis should be the implementation at CERN and possible use of existing facilities/detector + cost but we should stay open-minded

Study potential of ENUBET/nuSTORM facility as:

Accelerator-science test bed for tagged neutrino beam (**ENUBET specific -** see also next talk) and nuSTORM as muon collider technology demonstrator (**nuSTORM specific)**

Conclusions

- Both ENUBET and nuSTORM are **mature projects**, with clear baseline solutions and detailed machine studies.

- We need your help to make a step forward:
  - Reap the physics opportunities beyond the “basic ones”. We are already **clustering a community** interested in precision cross section study, BSM and dedicated detector
  - **Cost is the name of the game.** And this require a site-specific study to understand compliance with lab standards, available component, infrastructures
  - We are strong in beamline design but **weak in detailed engineering studies** for the components. This is essential to put forward a document with the strength and quality of a Conceptual Design Report

We look forward to seeing ENUBET and nuSTORM up and running in the DUNE/HyperK era!

ENUBET and nuSTORM in PBC

Building activities to address three threads (pillars):

- Physics – joint programme ENUBET/nuSTORM:
  Cross section
  BSM: Sterile, NSI, Dark Matter searches etc.

- Detectors – joint programme ENUBET/nuSTORM:
  - Cross section and BSM
    - Common requirement: exclusive final state detection
    - **ENUBET specific**: use of ProtoDUNE, cosmic rejection in slow extraction, tagged neutrino beam

- Accelerator:
  - ENUBET/nuSTORM from SPS to beam dump
  - **nuSTORM specific**: Muon collider test bed and technology demonstrator
  - **ENUBET specific**: opportunity for a tagged neutrino beam