nuSTORM

J. Pasternak,

on behalf of nuSTORM study team

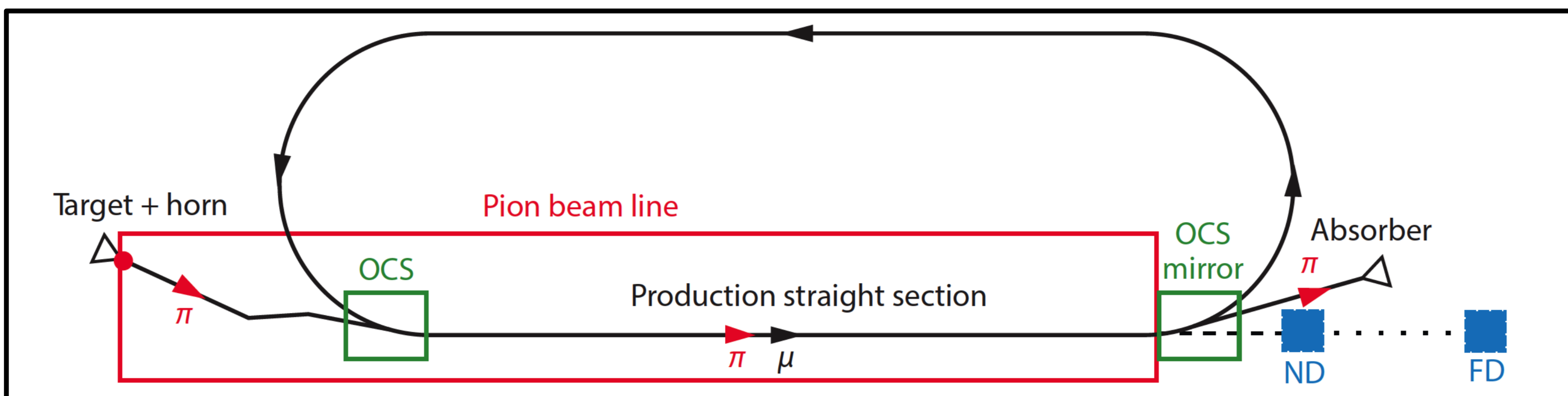
09/10/2020, ESSnuSB Workshop

Outline

- Origin
- Motivation
- nuSTORM at FNAL
- nuSTORM at CERN
- Studies of hybrid FFA solution
- ESSnuSP opportunity
- Summary and future plans

Origin - Idea

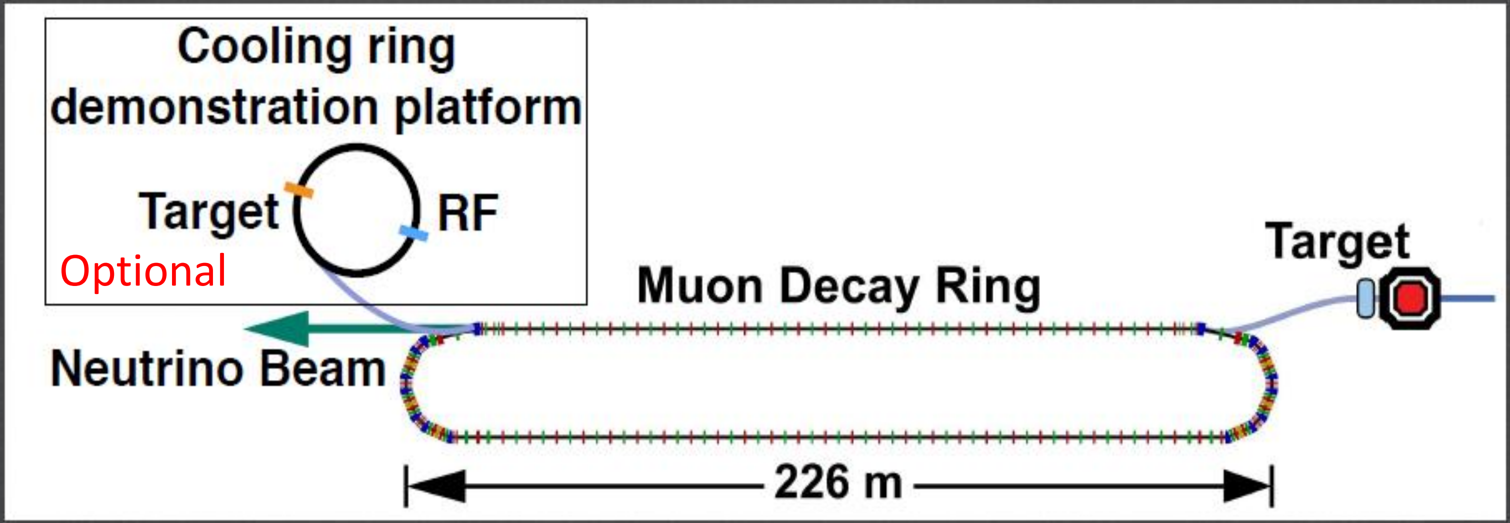
- nuSTORM (`NeUtrinos from STORed Muons') is a facility based on a low-energy muon decay ring.
- Can use existing proton driver (like SPS at CERN)
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring
  - Direct injection of pions into the decay ring to form circulating muon beam subsequently used as a source of neutrinos w/o a kicker



nuSTORM - Motivation

- Neutrino interaction physics – nuSTORM can measure neutrino cross sections precisely
  - ❑ Significantly reduce the main source of systematic errors for long base-line oscillation experiments
- Short baseline neutrino oscillation physics – search for sterile neutrinos
- Accelerator and Detector Technology Test Bed
  - Proof of principle for the Neutrino Factory concept
  - Muon Collider R&D platform

nuSTORM Overview



1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
3. Accelerator & Detector technology test bed
   - Potential for intense low energy muon beam
   - Enables μ decay ring R&D (instrumentation) & technology demonstration platform
   - Provides a neutrino Detector Test Facility
   - Test bed for a new type of conventional neutrino beam

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

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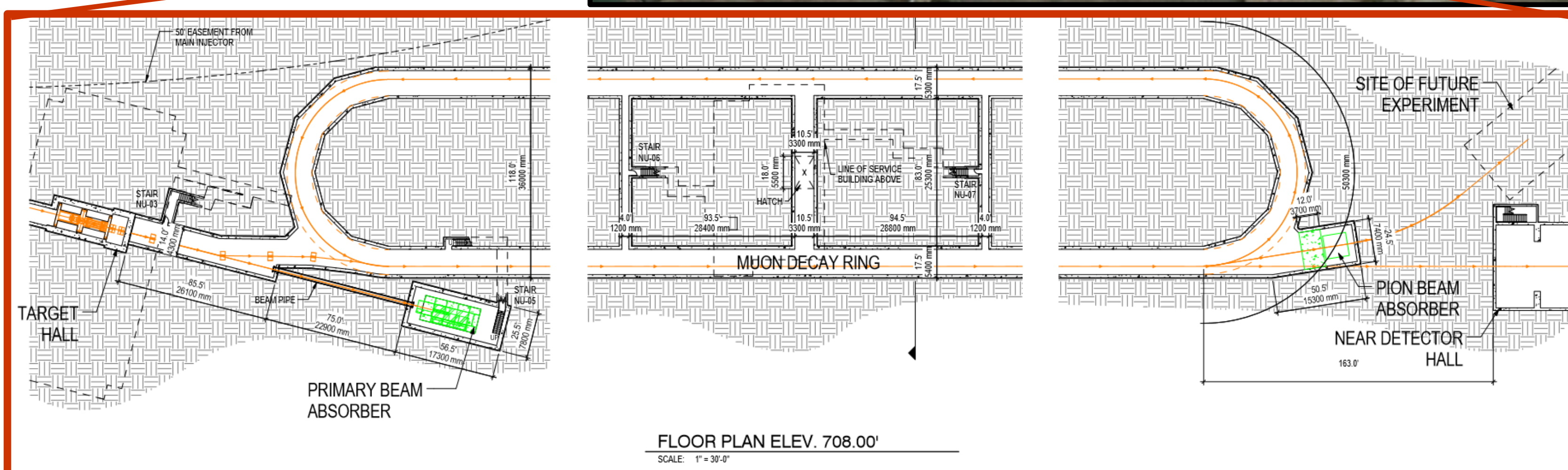
nuSTORM @ FNAL

- Serious proposal developed for FNAL
- FNAL taken to project definition report stage



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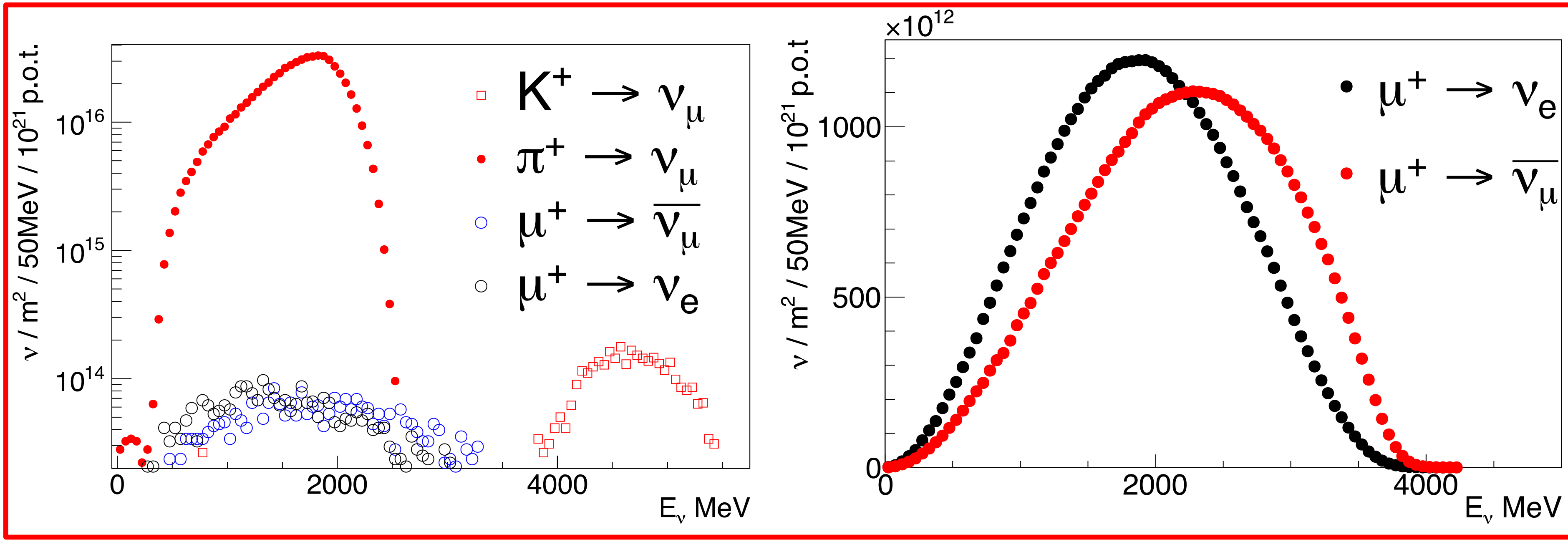
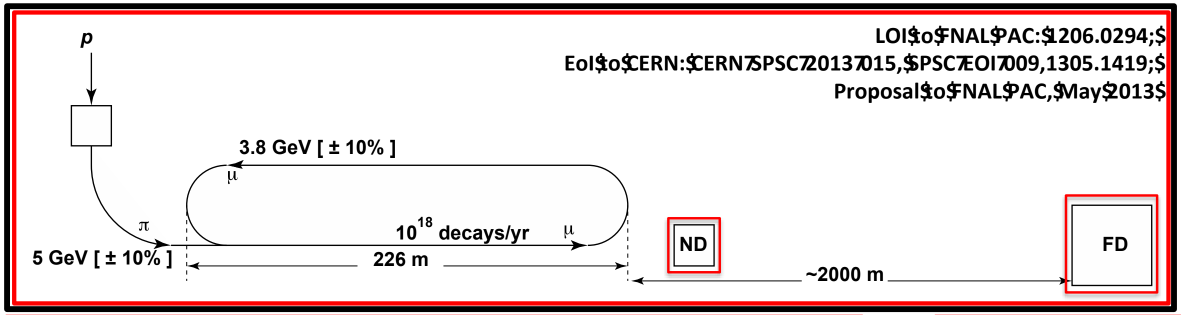
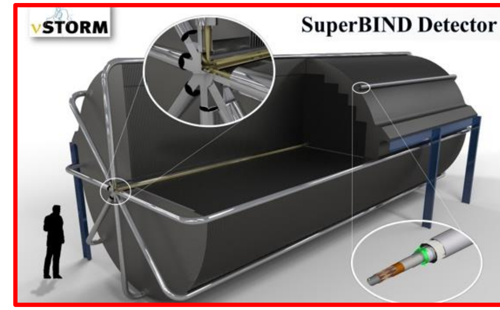
Neutrino Flux

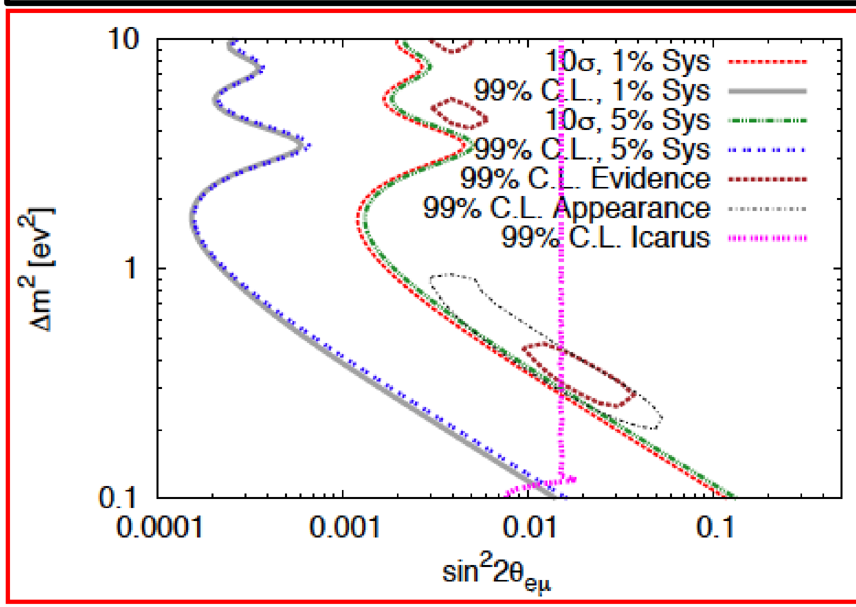


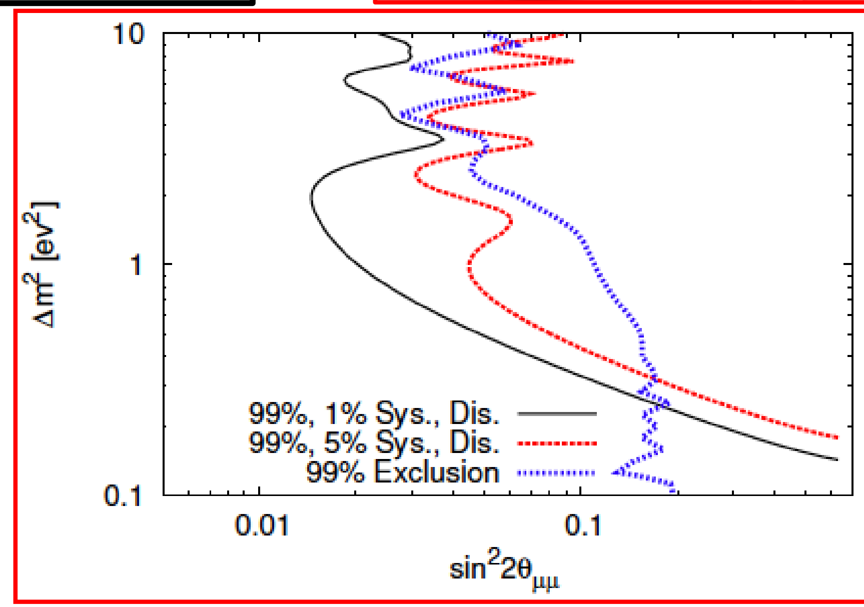
- Multiple channels available
- Good time separation
- Good source of electron neutrinos!
- Polarity of muon beam would be switched

Sterile neutrino search @ FNAL



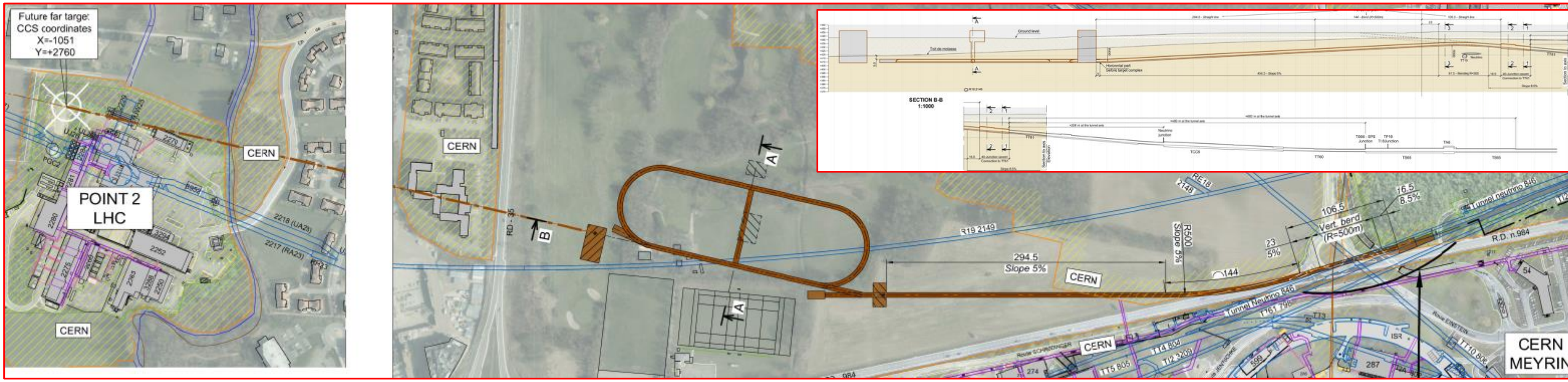






Adey et al., PRD 89 (2014) 071301

nuSTORM siting at CERN



- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made ‘on or off axis’
  - Preserves sterile-neutrino search option

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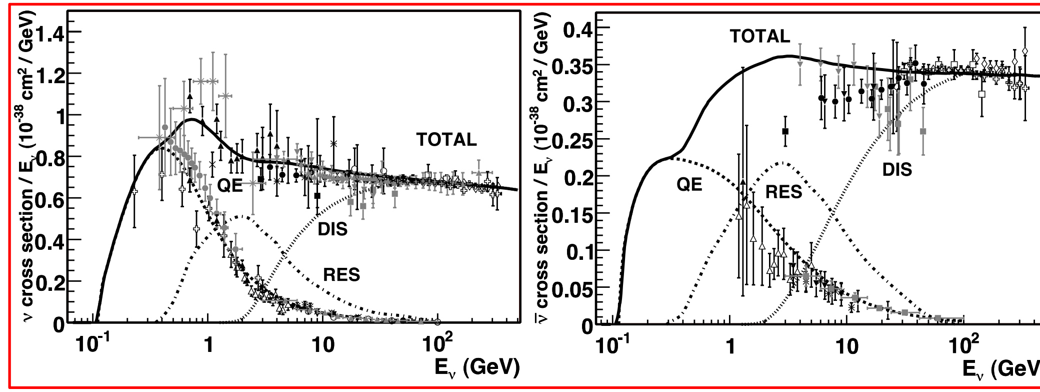
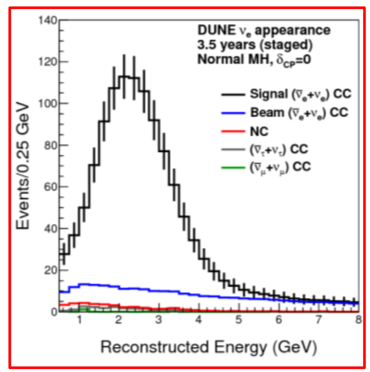
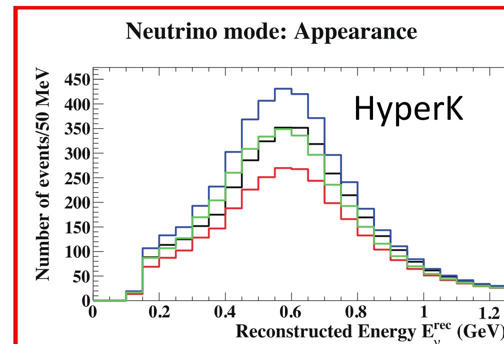
Cross section programme: novel energy range

- Guidance from:
  - Models:
    - Region of overlap 0.5—8 GeV
  - DUNE/Hyper-K far detector spectra:
    - 0.3—6 GeV







- Cross sections depend on:
  - Q^2 and W:
    - Assume (or specify) a detector capable of:
      - Measuring exclusive final states
      - Reconstructing Q^2 and W
    - → E_μ < 6 GeV

- So, stored muon energy range: **$1 < E_\mu < 6$ GeV**

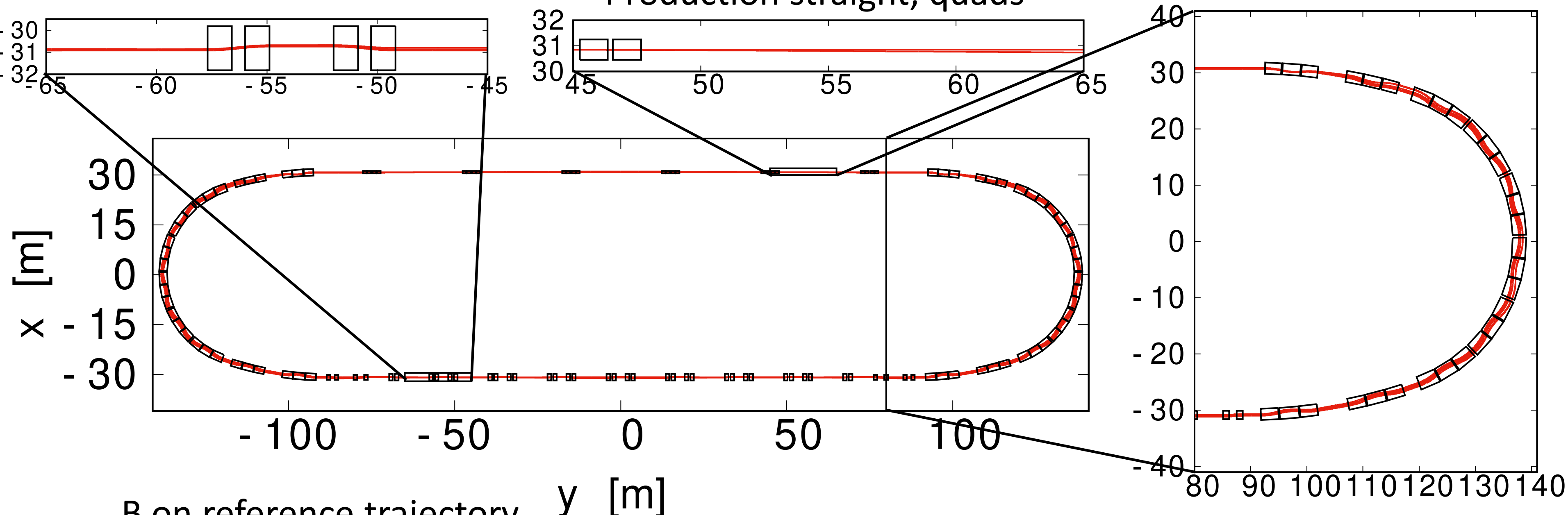
Storage ring designs

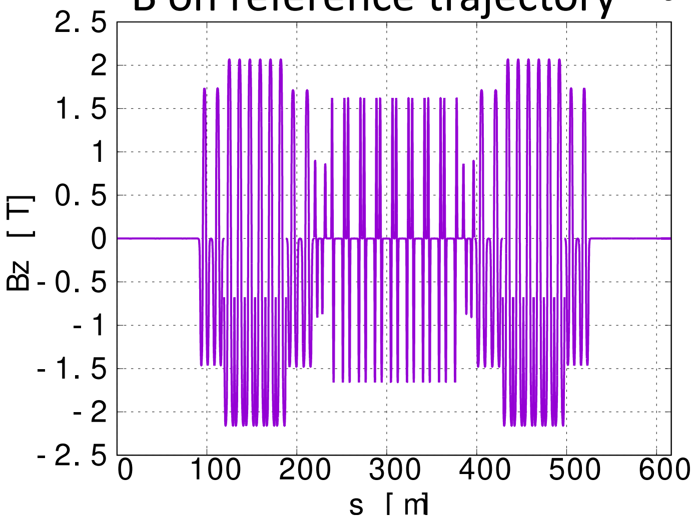
- FODO design (example: A. Liu's design)
  - Separate-function magnets
  - Relative momentum acceptance ~±9%
  - Large, natural chromaticity, some losses induced by resonances
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production
- Full FFA (Fixed Field Alternating gradient) design
  - Combined function magnets
  - Relative momentum acceptance ~±16% or more
  - Zero chromaticity, no resonance crossing
  - Small dispersion and scalope angle in the the injection/production straight
    - Reduced efficiency of muon storage and some effects on the neutrino spectrum
- Hybrid design
  - Combined function magnets in the arcs and in the return straight, quads in the injection/production straight
  - Relative momentum acceptance ~±16%
  - Relatively small chromaticity originating from the injection/production straight
    - Tune spread between integer and half integer lines
    - Some extra correction possible
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production

Hybrid design assumptions

- Long straight sections kept at 180m (as in FNAL designs)
- Arc modified to accommodate higher momentum (up to 6.5 GeV/c orbit)
- Dispersion in the arcs is kept smaller to reduce the magnet aperture
- FFA parts (both arcs and straight FFA) were made with a fully transparent optics (both phase advances modulo π).
- For the quad production the solution made of regular cells is selected
- Extra matching sections added in the straight FFA part

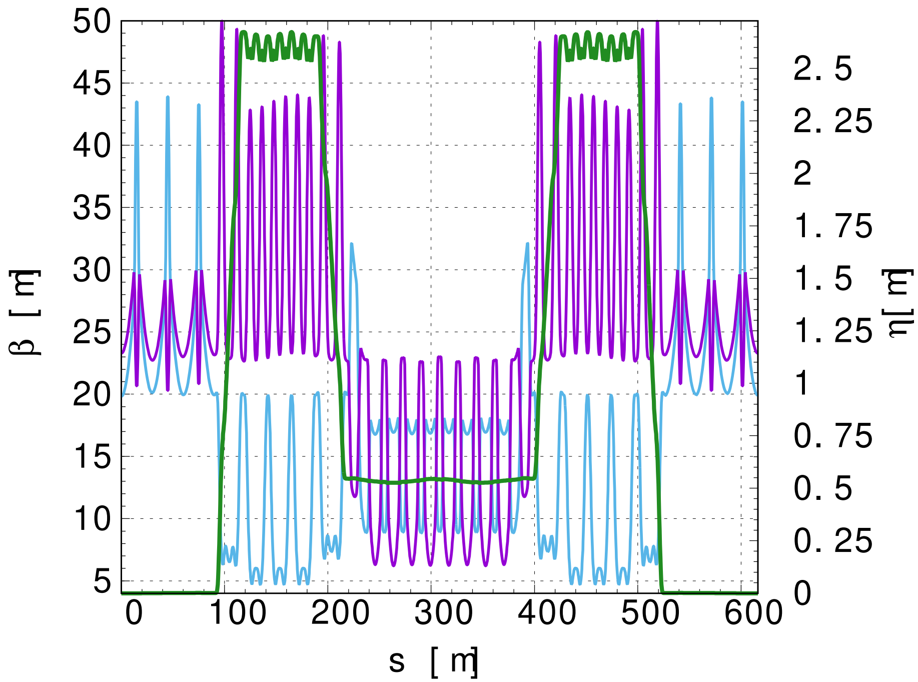
Hybrid design

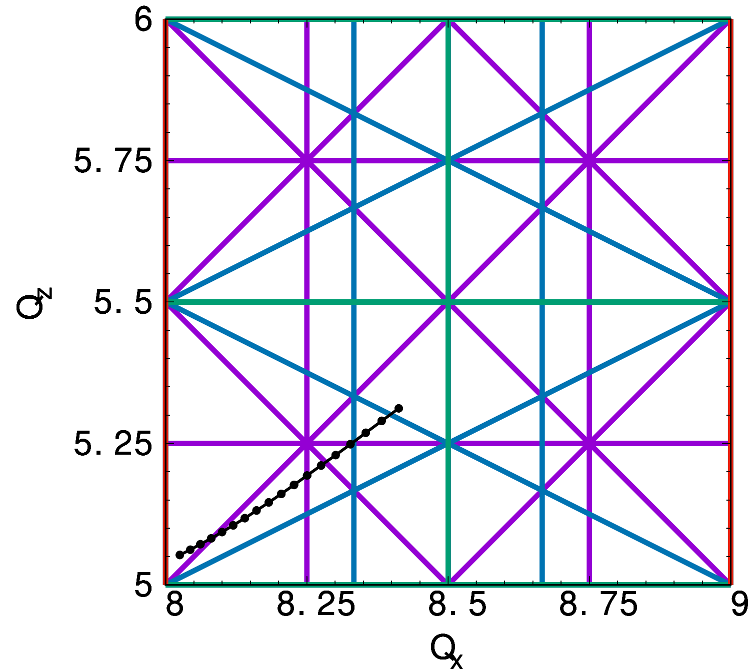




- SC magnets in the arcs
- NC magnets in the straights
- Several types of the lattice cells combined
- Injection in the dedicated straight at the end of the arc

Hybrid optics





- Good dispersion matching to zero in the production straight
- Relatively large beta functions in the production straight for good neutrino production efficiency

Tune shift for ±16% relative momentum spread

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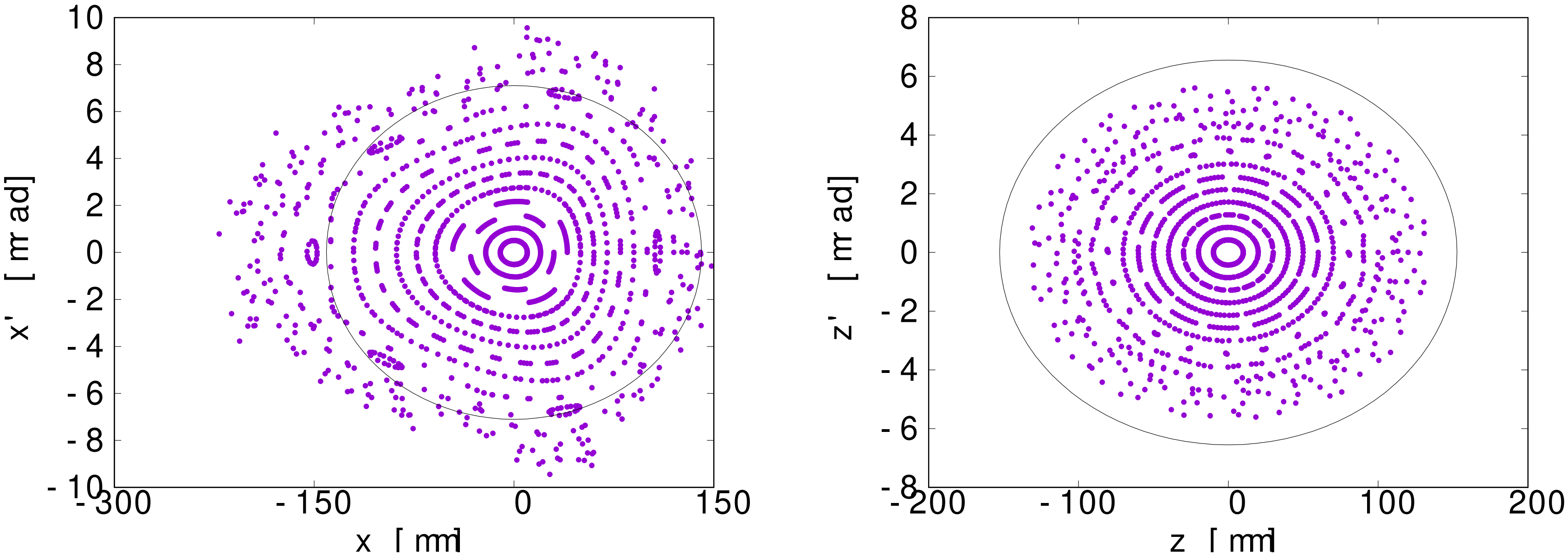
Hybrid ring, tracking



- Good DA in both planes
- Cross check with PyZgoubi (work in progress)
- Tracking with the full beam distribution (next step)

Current focus and near future plans for Hybrid design

- Work on the Hybrid FFA design:
  - Cross check between codes
  - Possibly a modest chromaticity correction to reduce the tune spread to ~0.2
  - Further design work on injection
- Evaluation of the performance: momentum spread, DAs, transmission and the neutrino fluxes, and comparison with other lattices (FODO, full FFA).

Input to the European Particle Physics Strategy Update 2018-2020

European Strategy Update

Americas:	29
Asia:	7
Europe:	81
Total:	***117***

nuSTORM at CERN: Executive Summary

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Abstract

The Neutrinos from Stored Muons, nuSTORM, facility has been designed to deliver a definitive neutrino-nucleus scattering programme using beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of muons confined within a storage ring. The facility is unique, it will be capable of storing $\mu^{\pm}$ beams with a central momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of 16%. This specification will allow neutrino-scattering measurements to be made over the kinematic range of interest to the DUNE and Hyper-K collaborations. At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known. The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better. By exploiting sophisticated neutrino-detector techniques such as those being developed for the near detectors of DUNE and Hyper-K, the nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\overset{(-)}{\nu}_e A$ and $\overset{(-)}{\nu}_\mu A$ scattering cross-sections with percent-level precision;
- Provide a probe that is 100% polarised and sensitive to isospin to allow incisive studies of nuclear dynamics and collective effects in nuclei;
- Deliver the capability to extend the search for light sterile neutrinos beyond the sensitivities that will be provided by the FNAL Short Baseline Neutrino (SBN) programme; and
- Create an essential test facility for the development of muon accelerators to serve as the basis of a multi-TeV lepton-antilepton collider.

To maximise its impact, nuSTORM should be implemented such that data-taking begins by $\approx 2027/28$ when the DUNE and Hyper-K collaborations will each be accumulating data sets capable of determining oscillation probabilities with percent-level precision.

With its existing proton-beam infrastructure, CERN is uniquely well-placed to implement nuSTORM. The feasibility of implementing nuSTORM at CERN has been studied by a CERN Physics Beyond Colliders study group. The muon storage ring has been optimised for the neutrino-scattering programme to store muon beams with momenta in the range 1 GeV to 6 GeV. The implementation of nuSTORM exploits the existing fast-extraction from the SPS that delivers beam to the LHC and to HiRadMat. A summary of the proposed implementation of nuSTORM at CERN is presented below. An indicative cost estimate and a preliminary discussion of a possible time-line for the implementation of nuSTORM are presented the addendum.

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Addendum to the Executive Summary of nuSTORM at CERN

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1 Full author list

The full author list is presented to indicate the community that is interested in the implementation and exploitation of nuSTORM.

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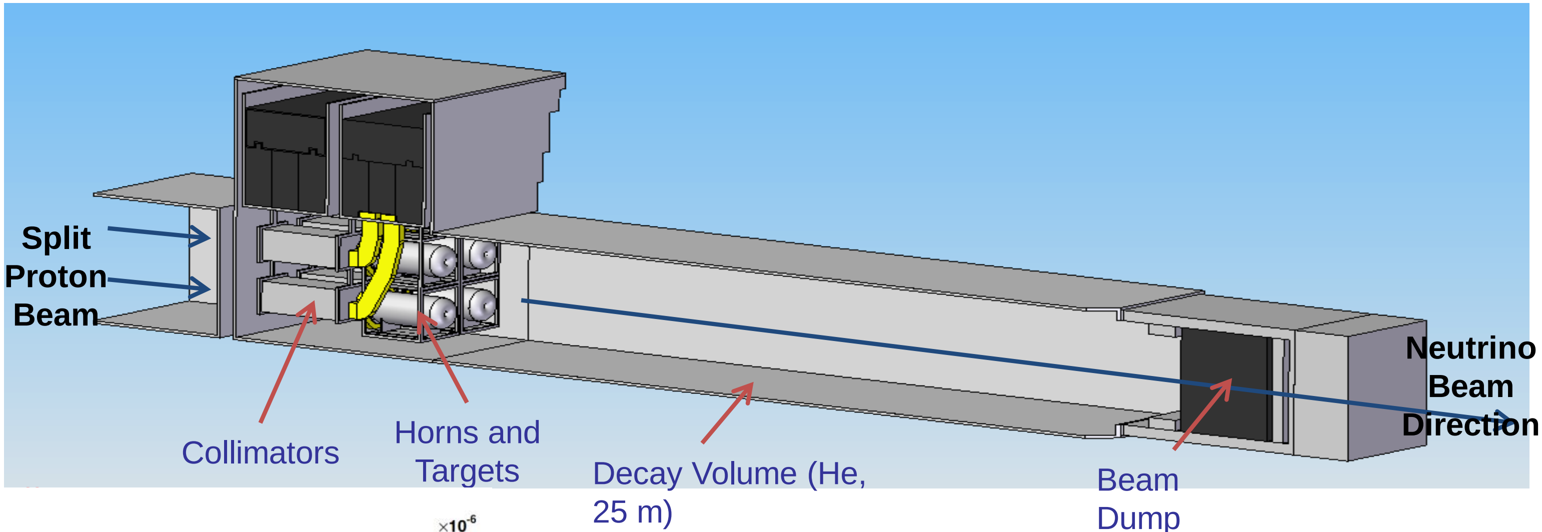
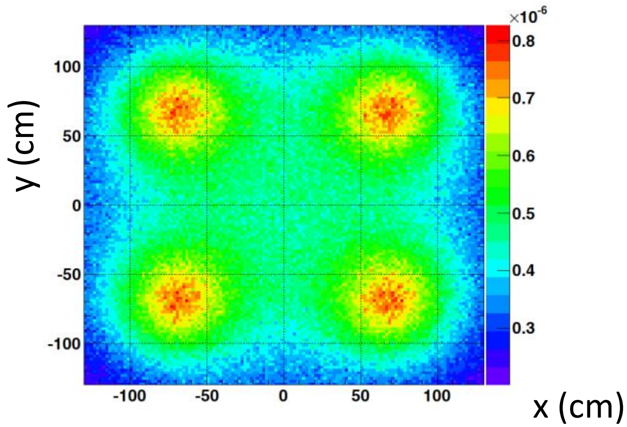
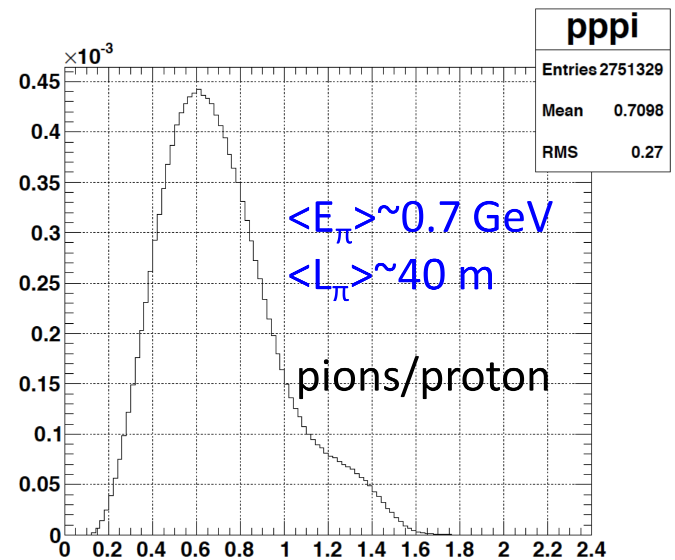
\+ Snowmass LOI already submitted

Towards nuSTORM-like muon accumulator using ESSnuSB





pions at the level of the beam dump (per proton, 56%)



From M. Dracos

nuSTORM-like muon accumulator can use pions at the level of the beam dump:

- It can address questions in low energy neutrino interactions, muon physics, etc.
- We hope the design can be performed soon

Summary

- nuSTORM can measure neutrino interaction precisely, which can reduce systematic errors of neutrino oscillation experiments seeking CP violation signal and can contribute to the sterile neutrino search.
  - Can also serve as the R&D test bed for muon accelerators (like the Muon Collider or the Neutrino Factory) and neutrino detectors
    - Technologies for muon storage, 6Dcooling, parametric cooling or rapid muon acceleration (vertical FFA) can be tested experimentaly.
- Solid designs exist and could be implemented straightaway (FODO or FFA)
- FFA design allows to substantially increase the ring's momentum acceptance (and so the neutrino flux), while maintaining a very large transverse acceptance
- ❑ Novel Hybrid ring shows very promising results and we are working to demonstrate its performance.
  - Next meeting: October 23rd, 13:30 (London time)
    - Contact: Ken Long (k.long@imperial.ac.uk)
- ❑ ESSnuSB opens a possibility to use low energy nuSTORM-like muon accumulator ring