Imperial College London

Science & Technology Facilities Council ISIS

nuSTORM accelerator facility

J. Pasternak,

on behalf of nuSTORM study team

Imperial College London

Science & Technology Facilities Council ISIS

Outline

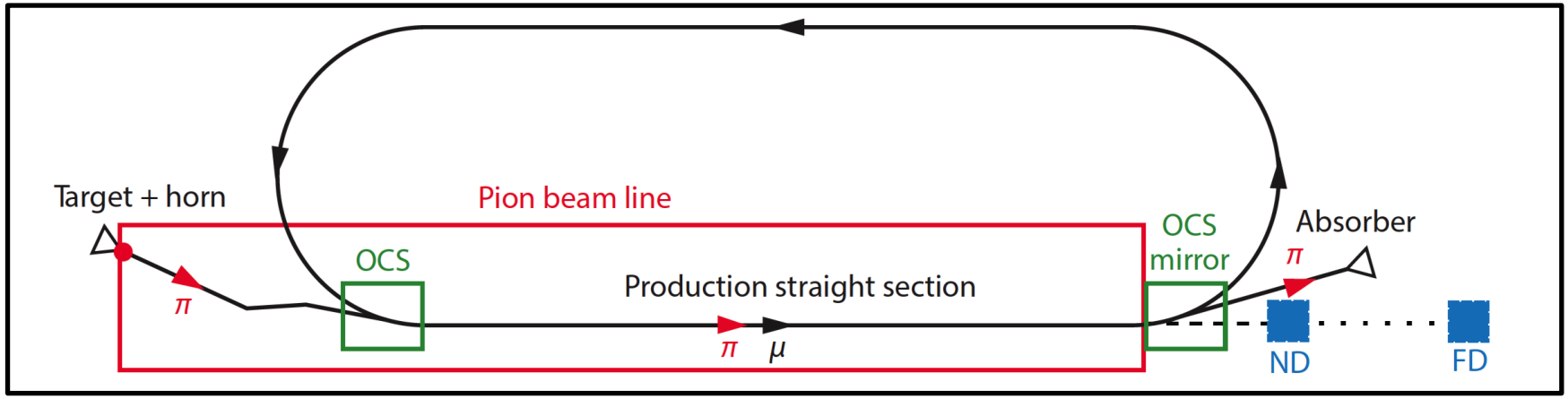
- Origin
- Motivation
- nuSTORM at FNAL
- nuSTORM at CERN
- Studies of hybrid FFA solution
- ESSnuSB opportunity
- Summary and future plans

Imperial College London

Science & Technology Facilities Council ISIS

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



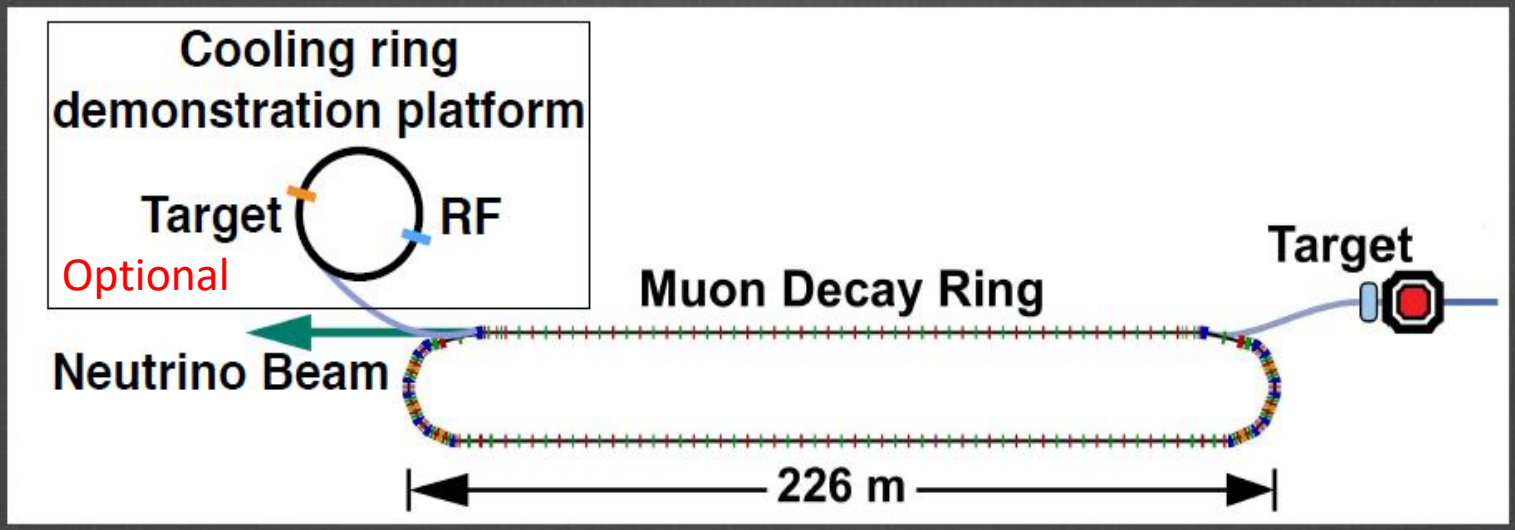
Imperial College London

Science & Technology Facilities Council ISIS

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

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

- 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

Imperial College London

Science & Technology Facilities Council ISIS

nuSTORM/ENUBET common line design

System of alternating Quadrupole-Dipole

```
mi: marker;
o11: Drift, L=1;
Q1: Quadrupole, L=1.2, K1:=k11;
o12: Drift, L=0.2;
ds1: Sbend, L=1.3, angle=0.0936;
o21: Drift, L=0.2;
Q2: Quadrupole, L=1.2, K1:=k21;
o22: Drift, L=0.2;
ds2: Sbend, L=1.3, angle=0.0936;
o31: Drift, L=0.2;
Q3: Quadrupole, L=1.2, K1:=k31;
o32: Drift, L=0.2;
ds3: Sbend, L=1.3, angle=0.0936;
o41: Drift, L=0.2;
Q4: Quadrupole, L=1.2, K1:=k41;
o42: Drift, L=0.2;
ds4: Sbend, L=1.3, angle=0.0936;
o51: Drift, L=0.2;
Q5: Quadrupole, L=1.2, K1:=k51;
o52: Drift, L=0.2;
mf: marker;
pion_transport:line=(mi, o11, Q1, o12, ds1, o21, Q2, o22, ds2,
o31, Q3, o32, ds3, o41, Q4, o42, ds4, o51, Q5, o52, mf);
```

+ Here we insert a dipole after each quadrupole with B=1.5 T to generate a dispersion in the x-axis.

+ From a rough calculation, seperating pion and kaon beam requires Dx>1.77 m.

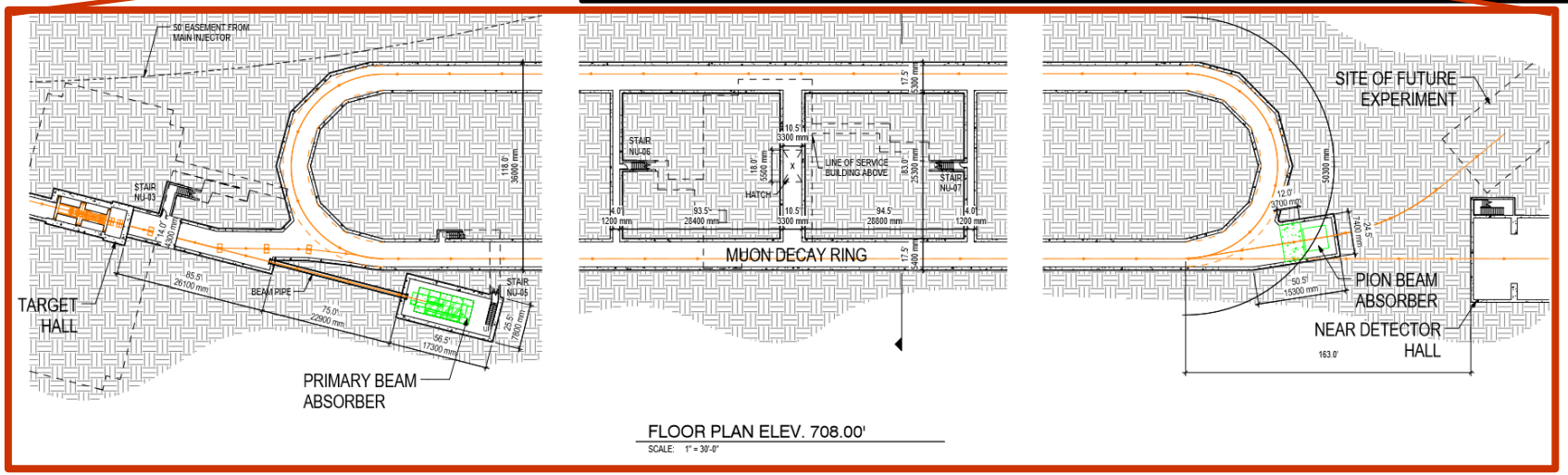
+ We slightly relax the constraints for matching at end point, as well as the initial conditions of alfx, alfy.

Imperial College London

Science & Technology Facilities Council ISIS

nuSTORM @ FNAL

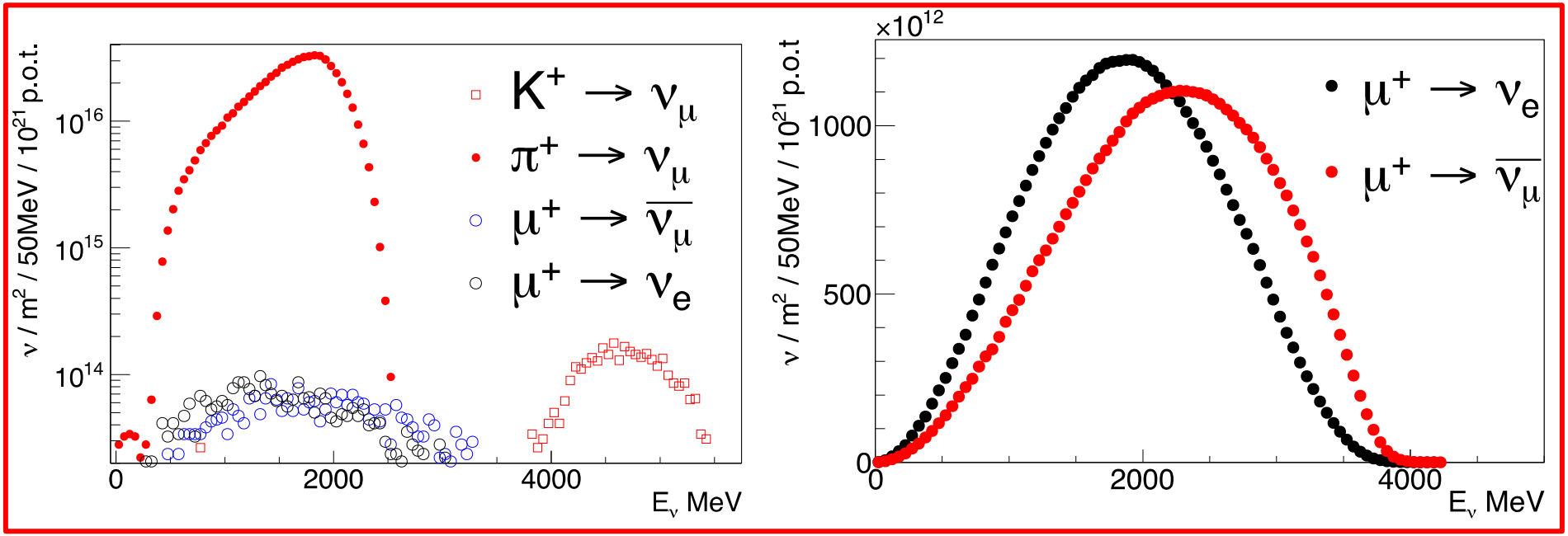
- Serious proposal developed for FNAL
- FNAL taken to project definition report stage



Imperial College London

Science & Technology Facilities Council ISIS

Neutrino Flux

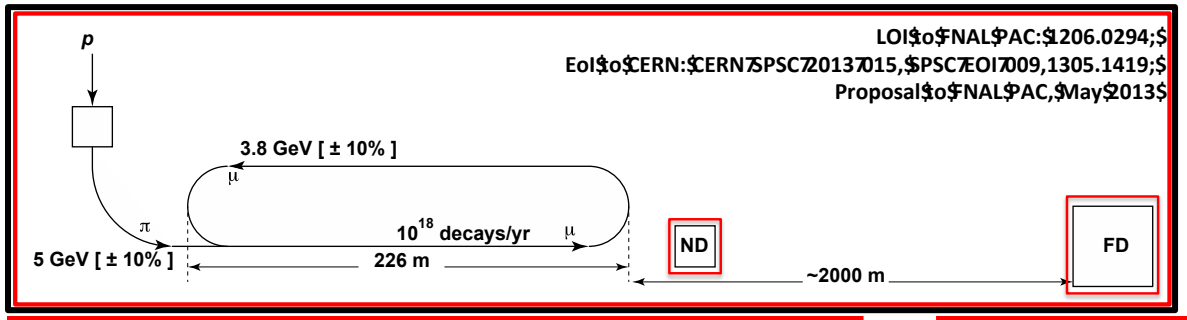


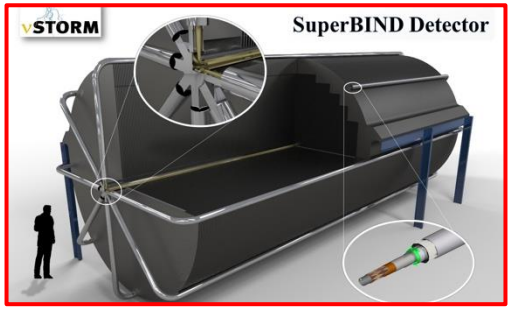
- Multiple channels available
- Good time separation
- Good source of electron neutrinos!
- Polarity of muon beam would be switched

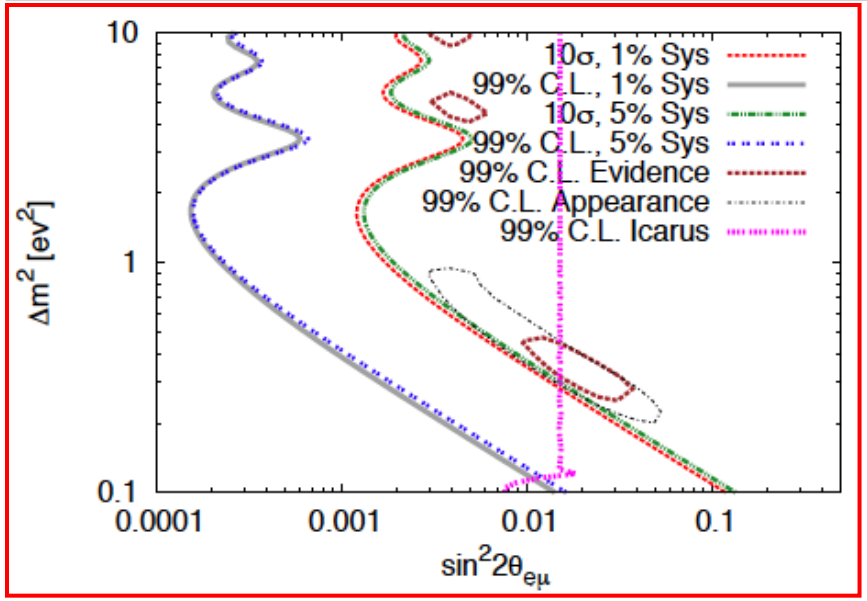
Imperial College London

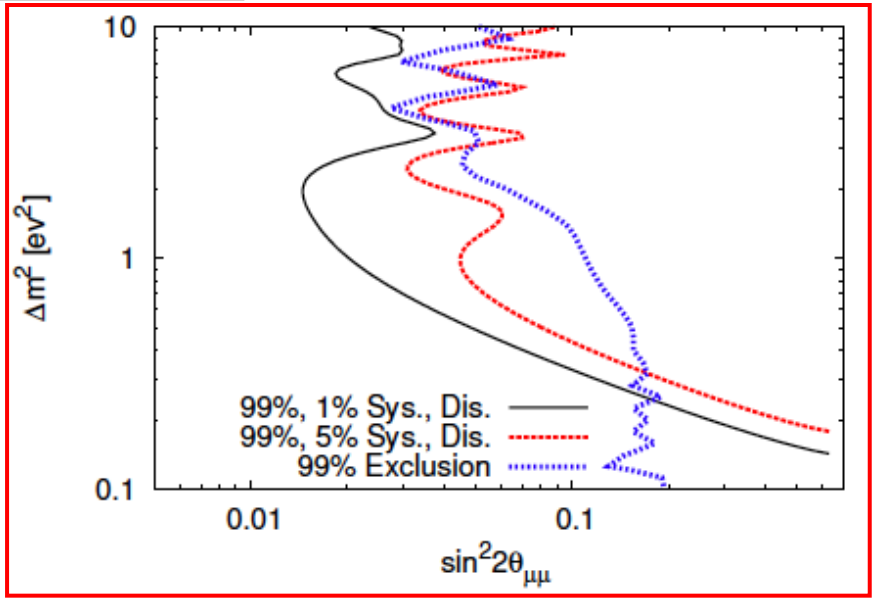
Science & Technology Facilities Council ISIS

Sterile neutrino search @ FNAL



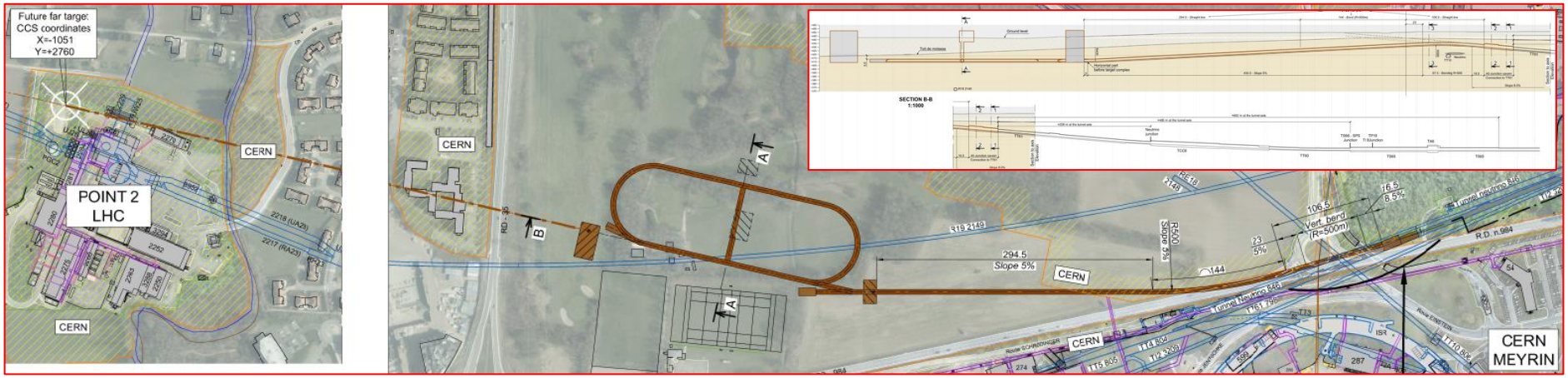






Adey et al., PRD 89 (2014) 071301

nuSTORM siting at CERN



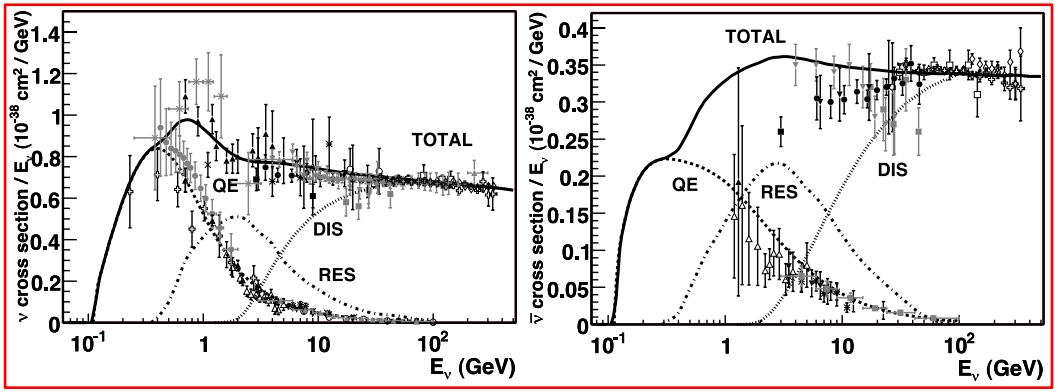
- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made ‘on or off axis’
  - Preserves sterile-neutrino search option

Imperial College London

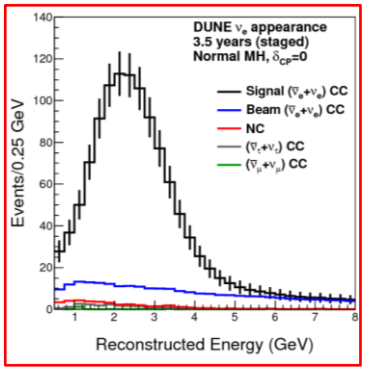
Science & Technology Facilities Council ISIS

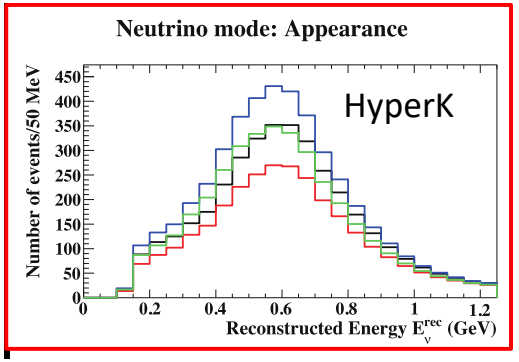
Cross section programme: novel energy range

- 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

Imperial College London

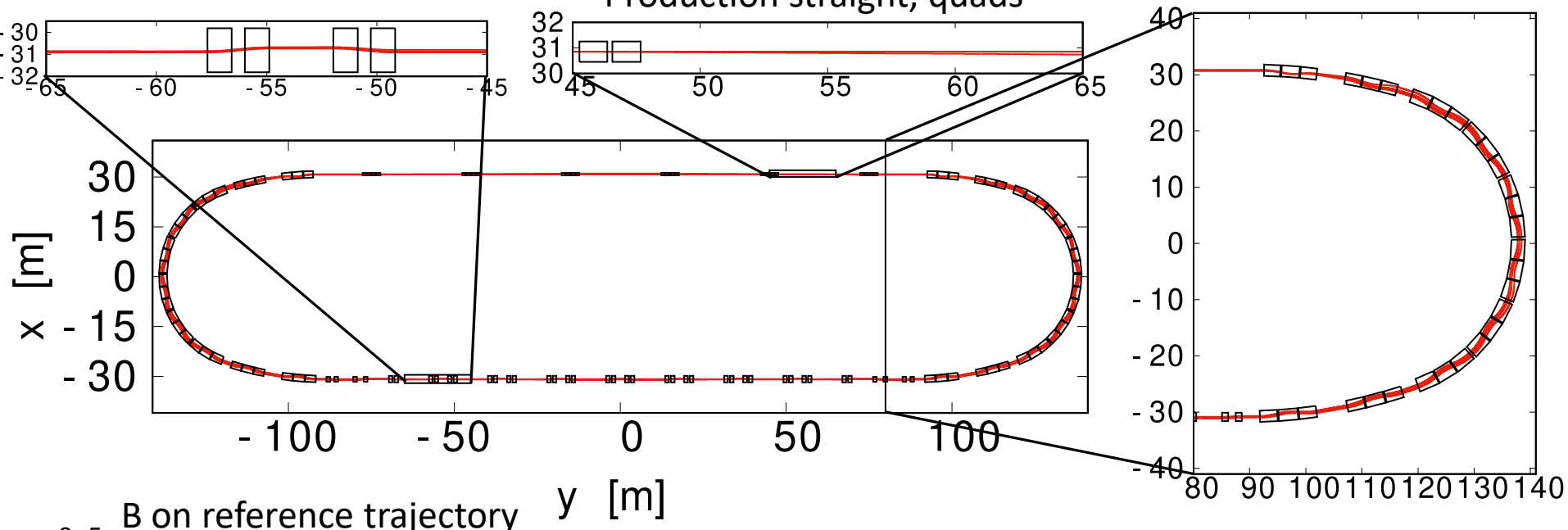
Science & Technology Facilities Council ISIS

Hybrid design

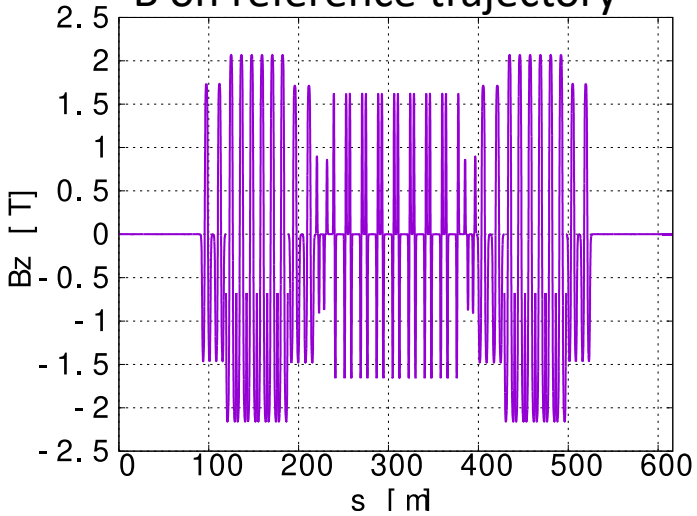
Arc with two matching sections, FFA magnets

Straight FFA

Production straight, quads



B on reference trajectory

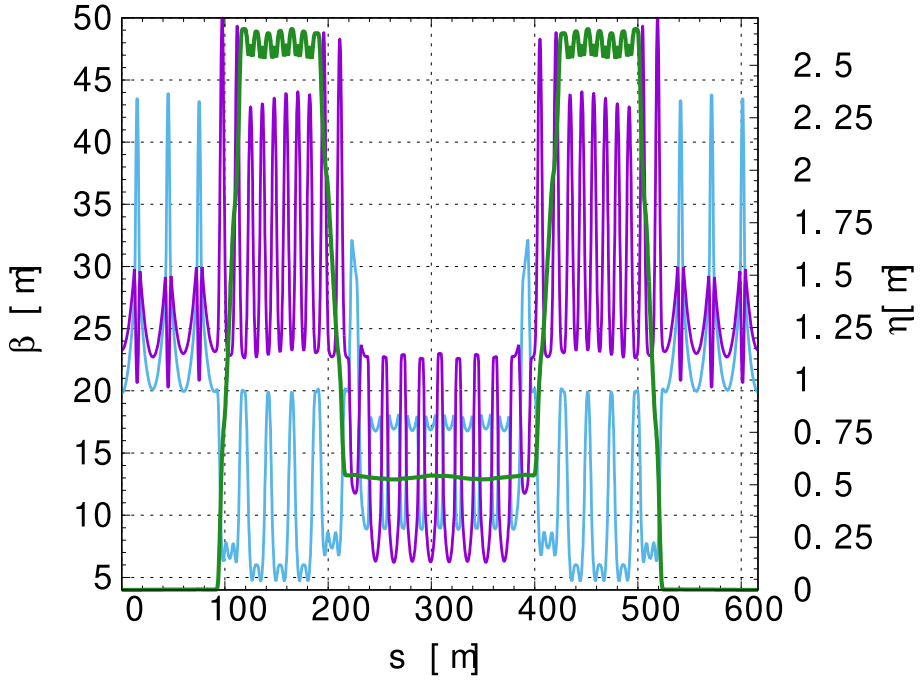


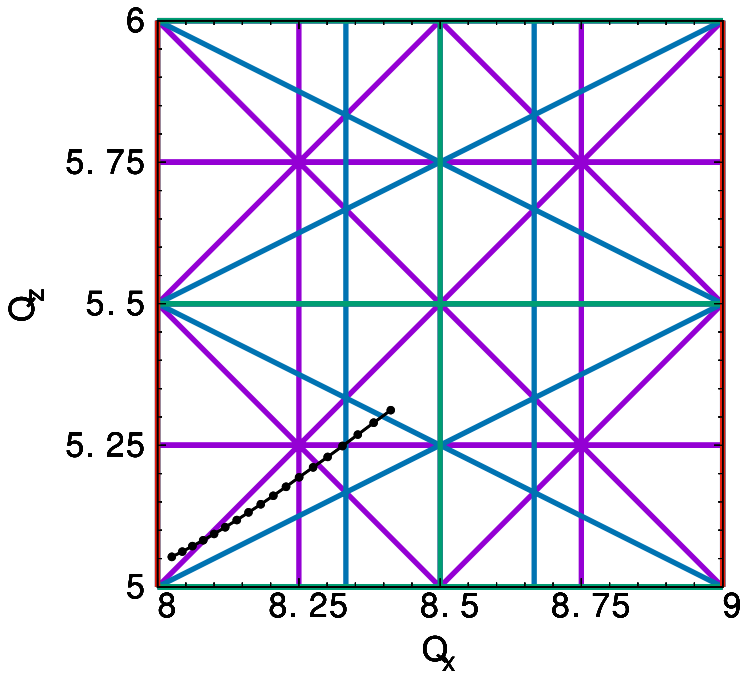
- SC magnets in the arcs
- NC magnets in the straights
- Several types of the lattice cells combined
- Injection in the dedicated straight at the end of the arc

Imperial College London

Science & Technology Facilities Council ISIS

Hybrid optics

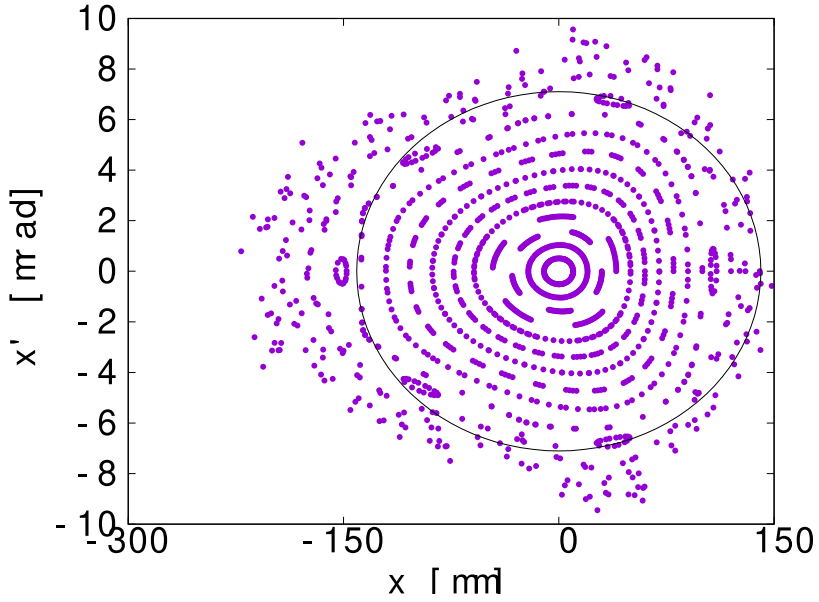


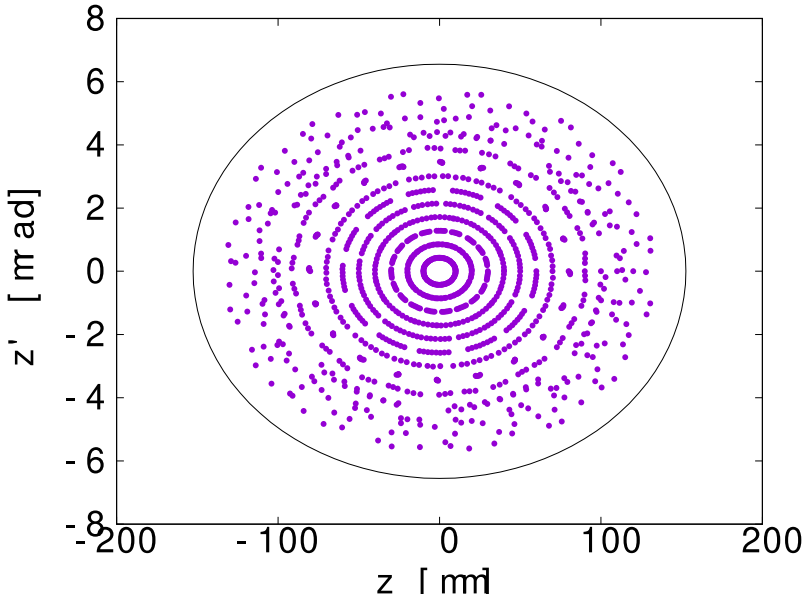


- Good dispersion matching to zero in the production straight
- Relatively large beta functions in the production straight for good neutrino production efficiency

Tune shift for ±16% relative momentum spread

Hybrid ring, tracking





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

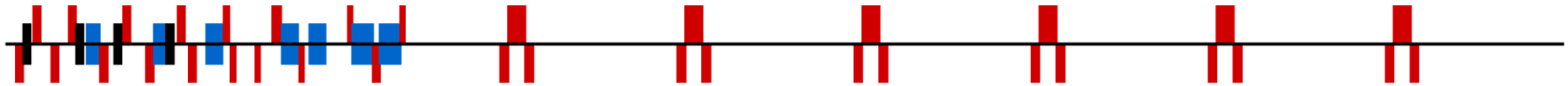
Current focus and near future plans for Hybrid design

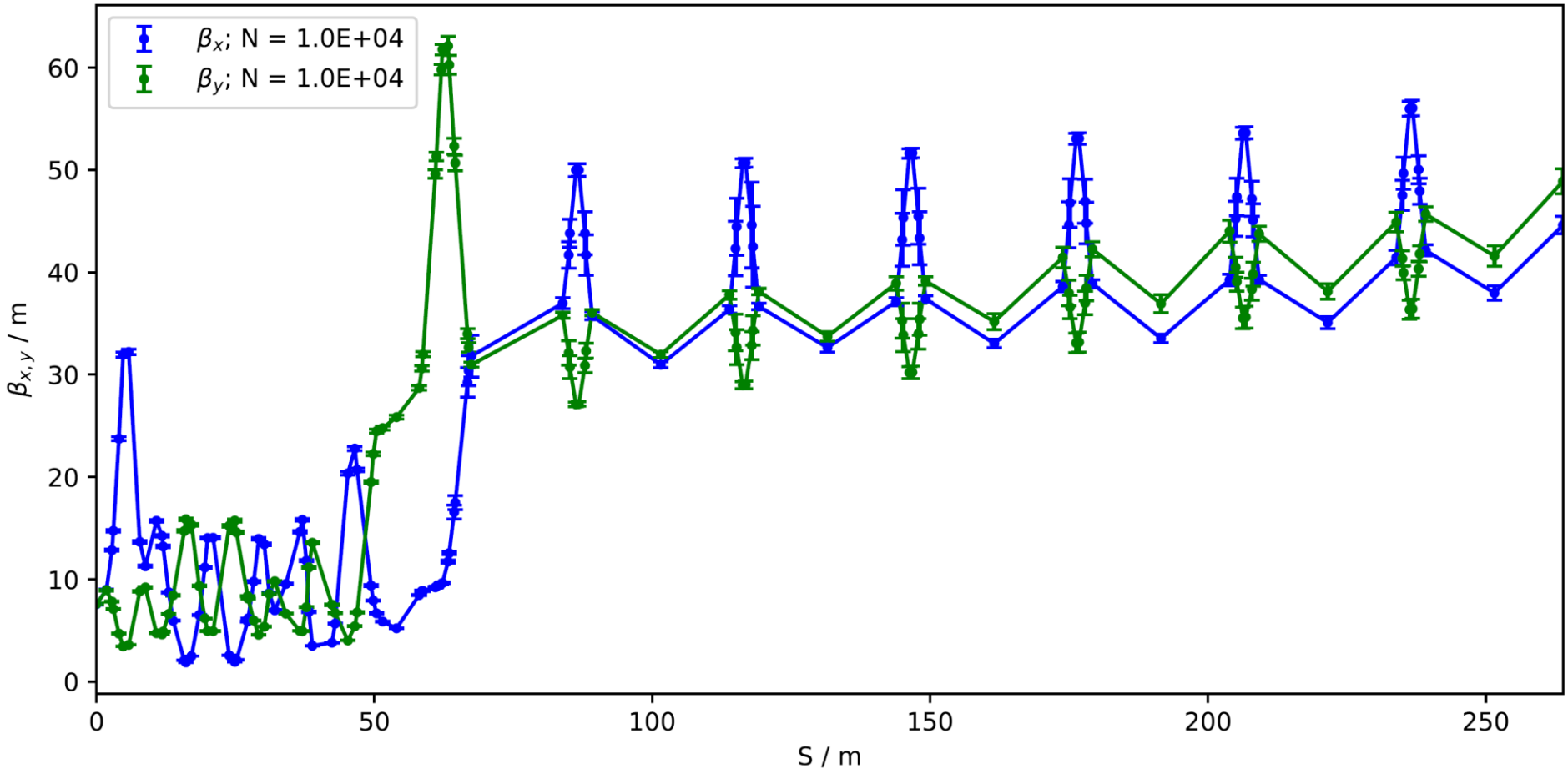
- Work on the Hybrid FFA design:
  - Cross check between codes
  - Possibly a modest chromaticity correction to reduce the tune spread to ~0.2
  - Further design work on injection
- Evaluation of the performance: momentum spread, DAs, transmission and the neutrino fluxes, and comparison with other lattices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

Imperial College London

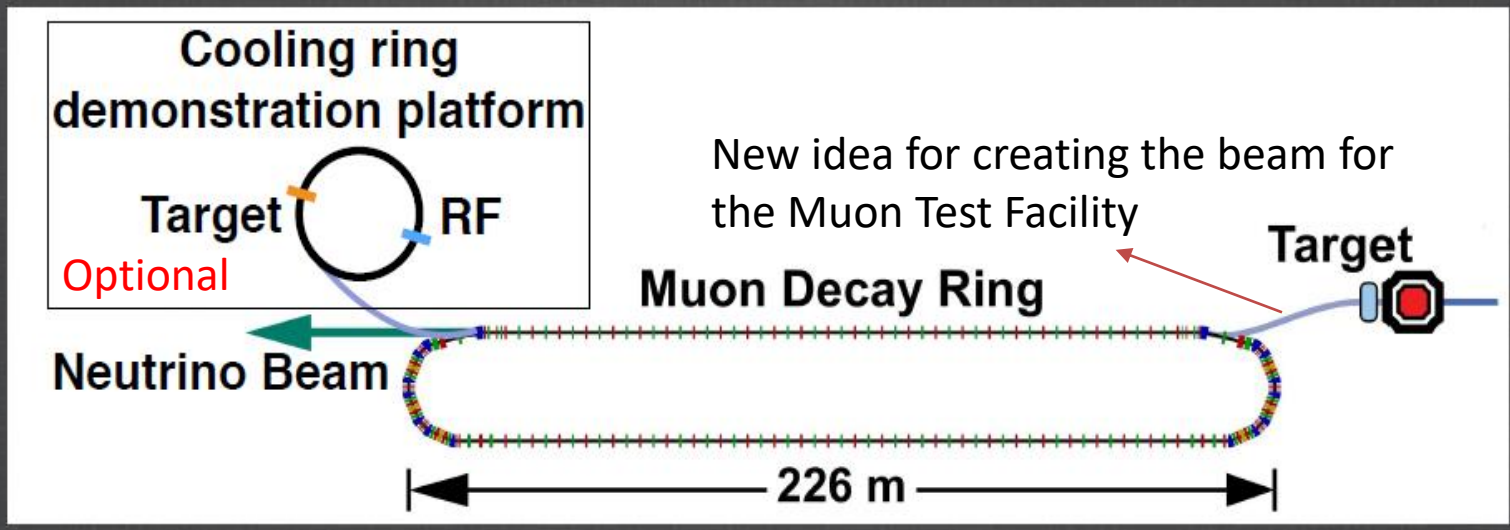
New work in BDSIM, Tiago Alves

Science & Technology Facilities Council ISIS





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

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

- 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

Imperial College London

Science & Technology Facilities Council ISIS

A novel pion transport line front-end

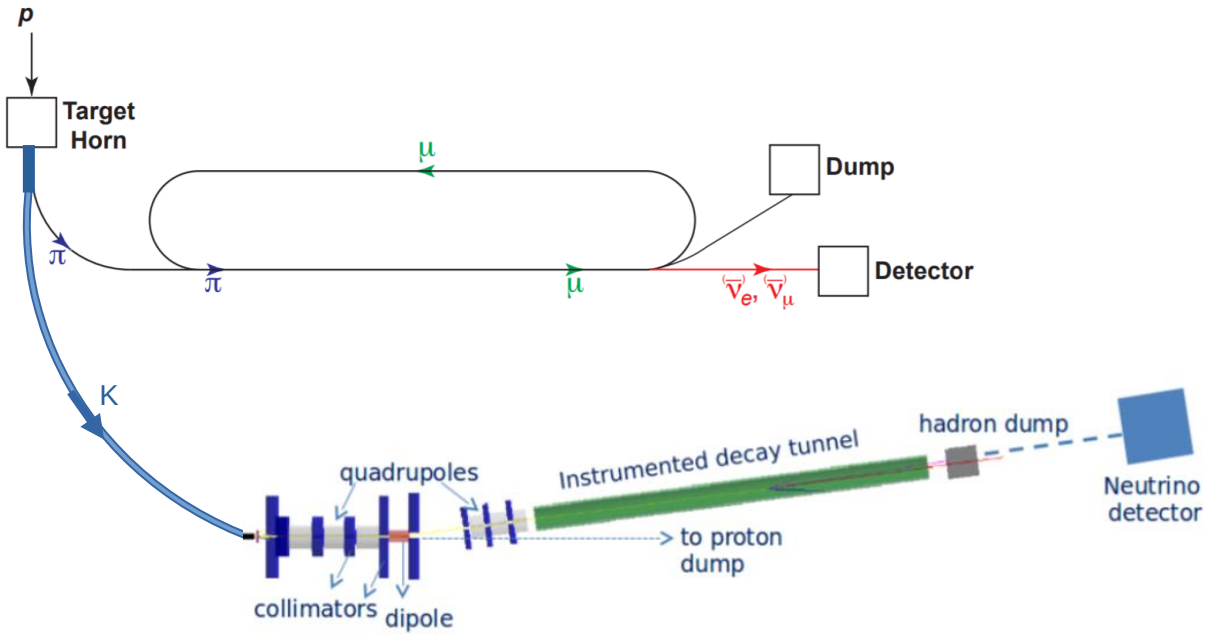


Figure: the lattice that allows parallel running of both nuSTORM and ENUBET experiment.

Tracking with large momentum spread

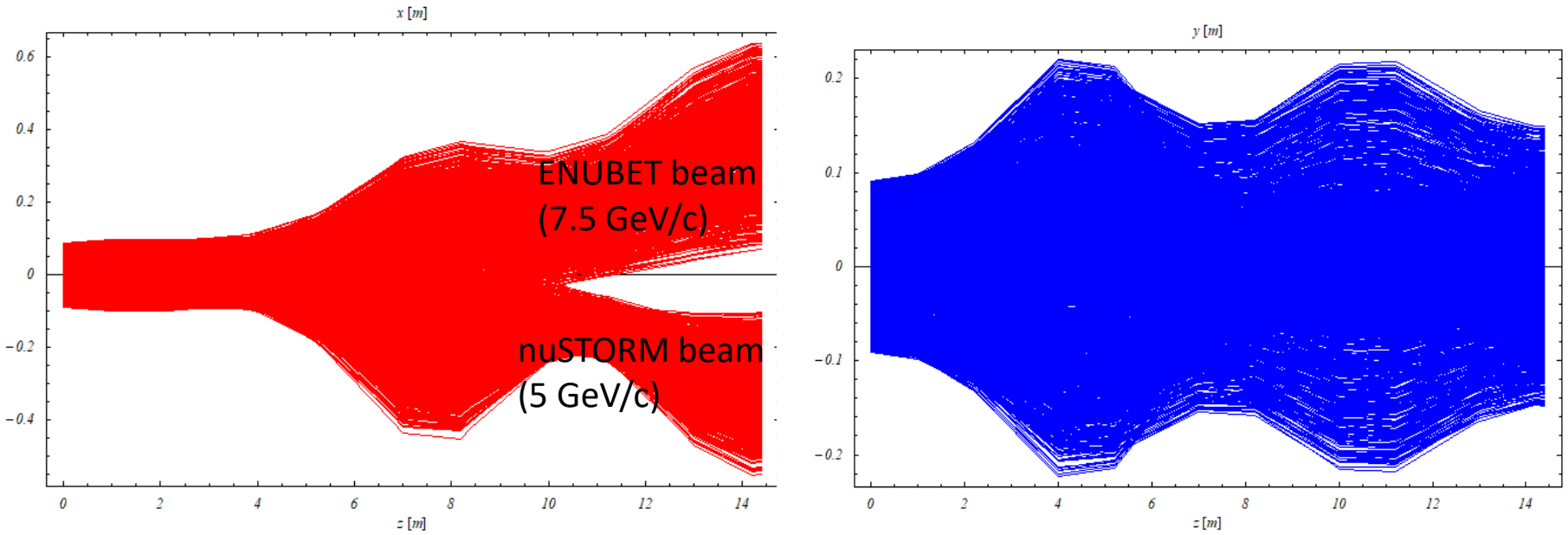


Figure: tracking ~1000 particles along the common transport line with large momentum spread (10%). The initial alpha and beta are assumed to be the same.

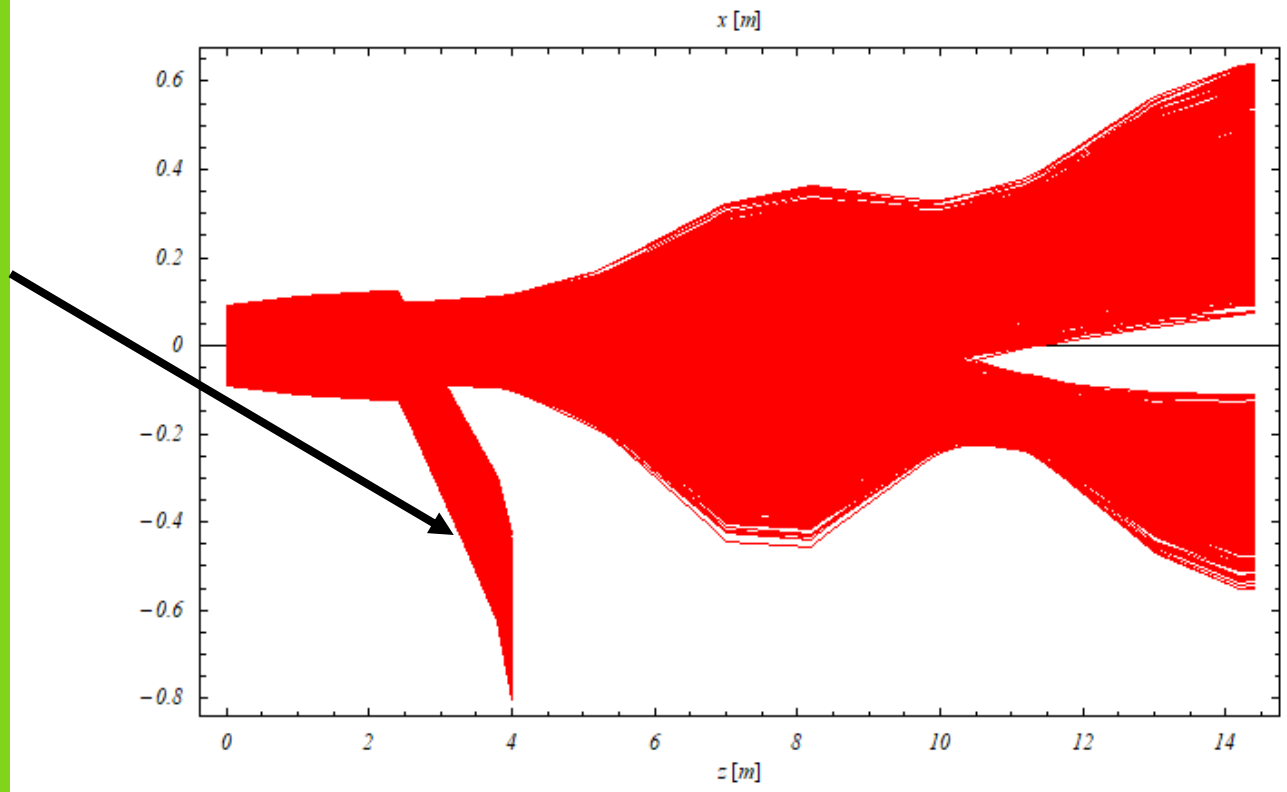
Imperial College London

Science & Technology Facilities Council ISIS

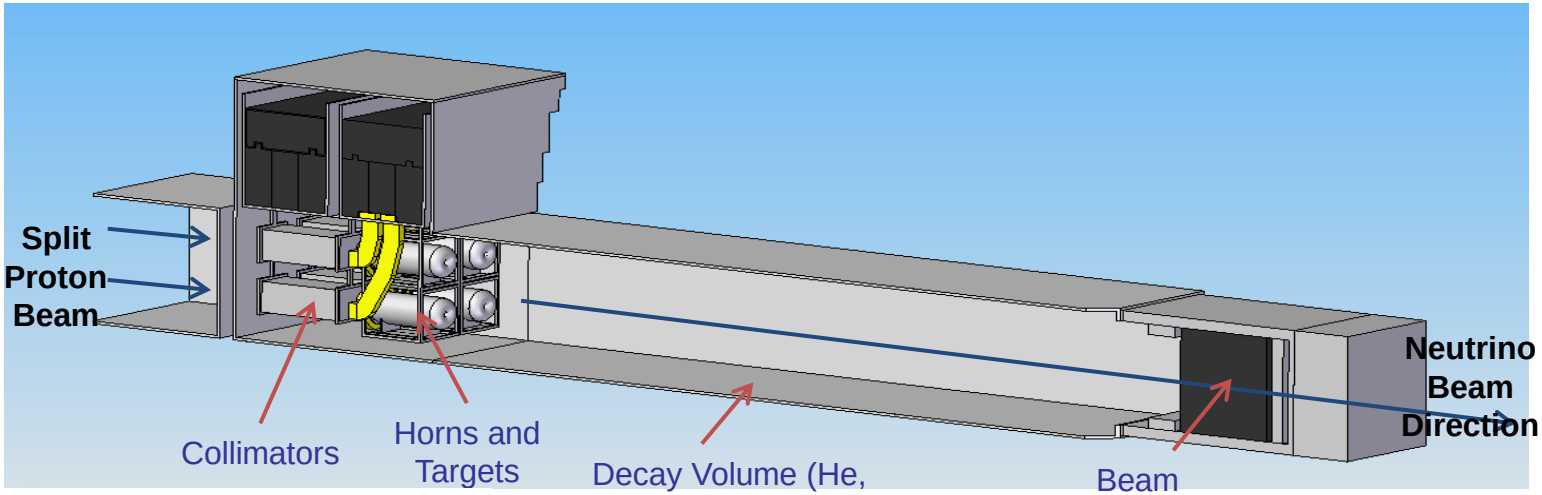
Beam for the muon test facility +-10%

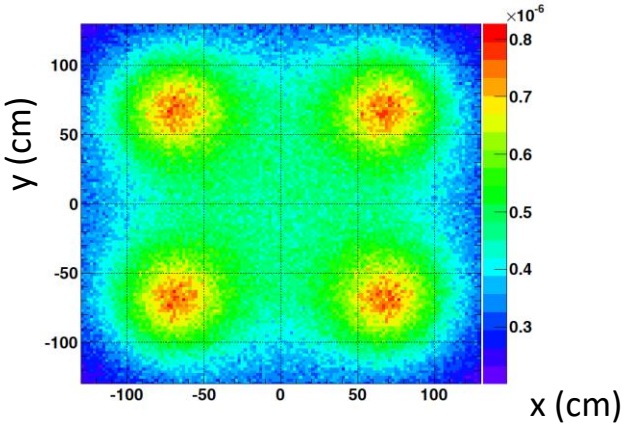
300 MeV/c beam for muon test facility:

- Horn and first quad tuned for 300 MeV/c and the first dipole reduced in field by a factor of 3 with respect to 6.25 GeV/c
- Seems to be able to clear the second quad.
- Maybe try to clear the 3rd quad?
- Current design cannot be optimized for running simultaneously the muon cooling facility and nuSTORM/ENUBET.

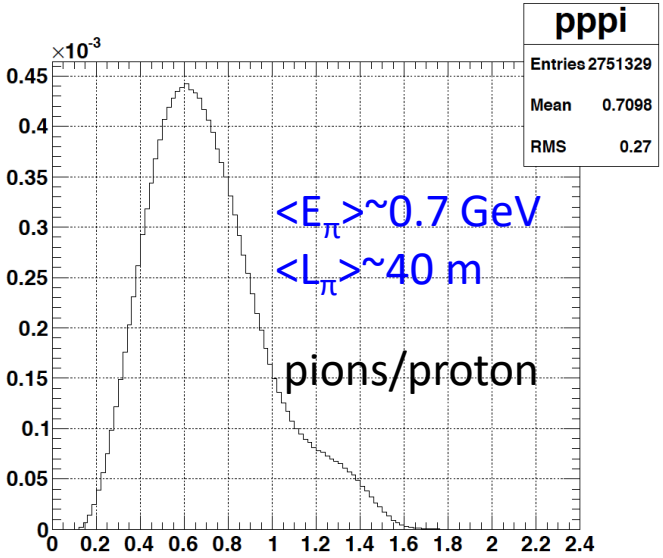


Towards nuSTORM-like muon accumulator using ESSnuSB





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



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

From M. Dracos

Imperial College London

Science & Technology Facilities Council ISIS

Summary

- nuSTORM can measure neutrino interaction precisely, which can reduce systematic errors of neutrino oscillation experiments seeking CP violation (DUNE and T2K/HK) 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 experimentally.
- 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.

❑ New ideas to combine nuSTORM, ENUBET and Muon Test Facility

❑ ESSnuSB opens a possibility to use low energy nuSTORM-like muon accumulator ring