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Progress of studies on the Neutrinos from Stored Muons -nuSTORM facility

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on behalf of nuSTORM study team

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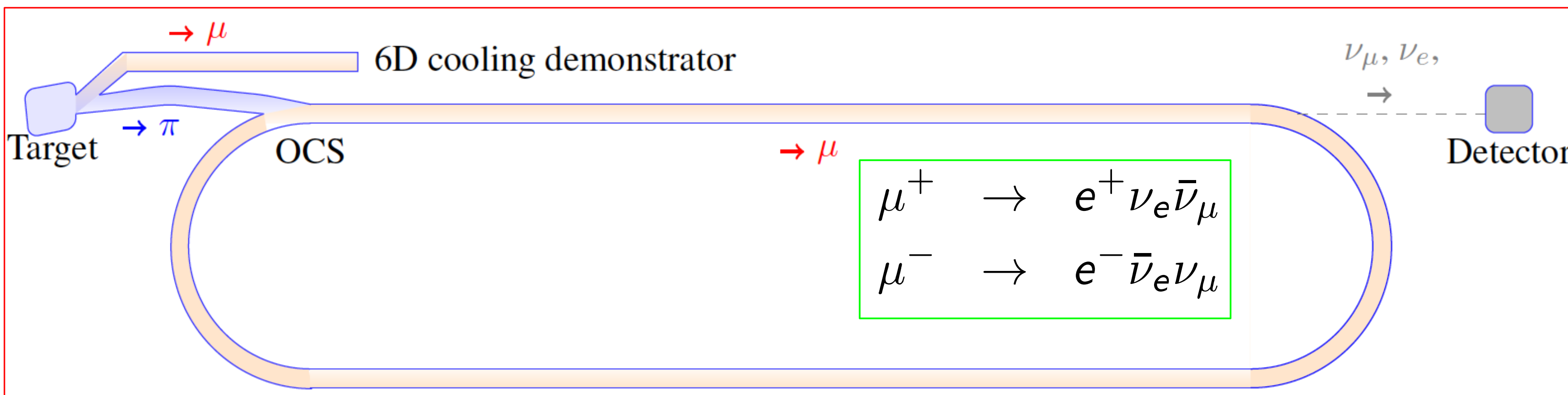
Outline

- Origin
- Motivation
- nuSTORM at CERN
- Studies of hybrid FFA solution
- Recent studies of beam capture, transport and injection
- Flux estimation
- 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
- Initially proposed at FNAL, now working towards the conceptual design for CERN



nuSTORM, arXiv:2203.07545

Motivation

nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of neutrino and anti-neutrino scattering cross-sections with percent-level precision (for both electron and muon flavours);
- 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 and a Neutrino Factory.

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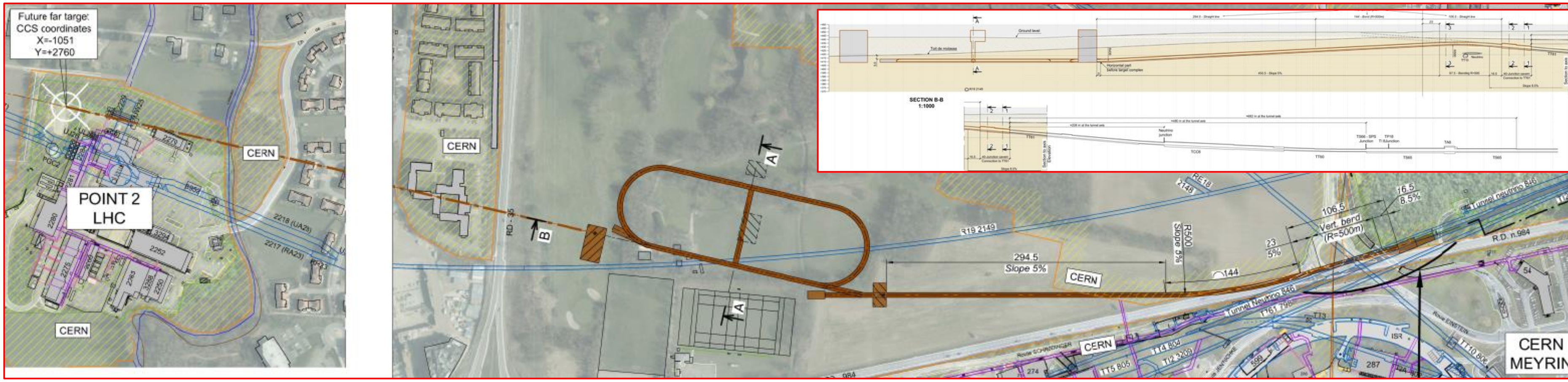
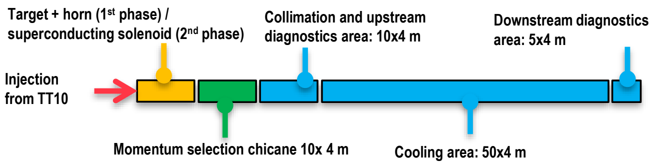
nuSTORM at CERN



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

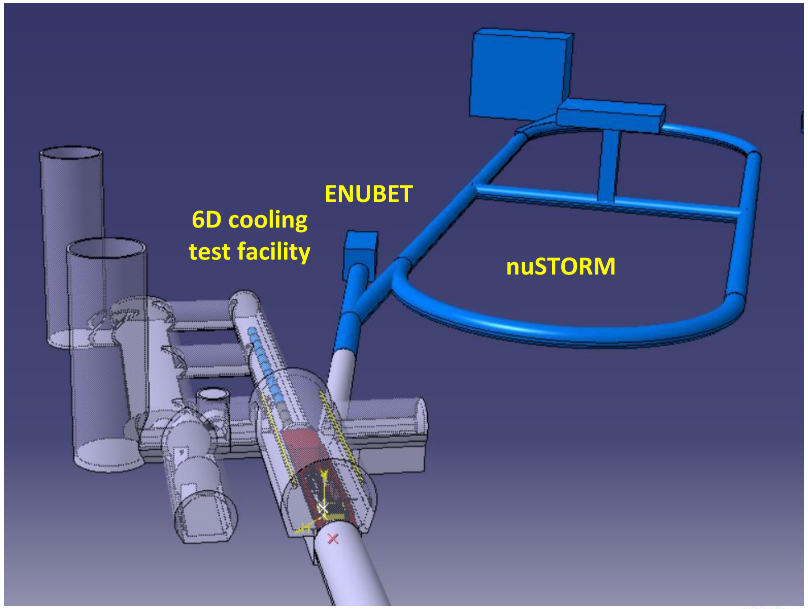
Conceptual layout

Under discussion!



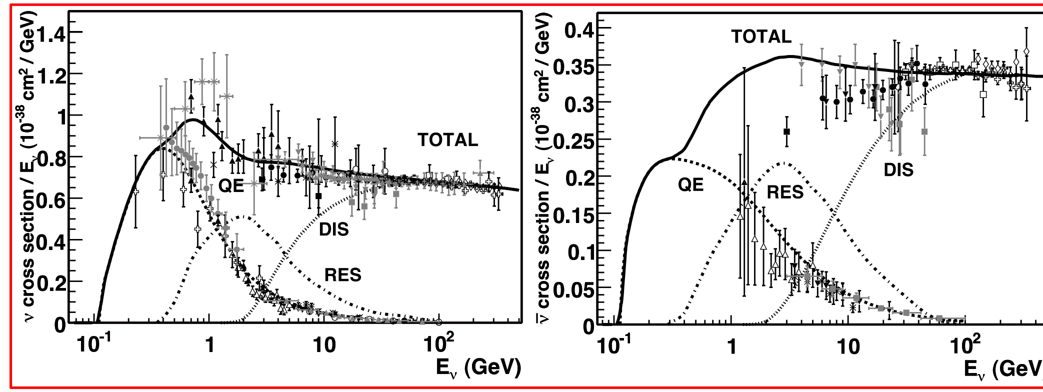
MUC Demonstrator

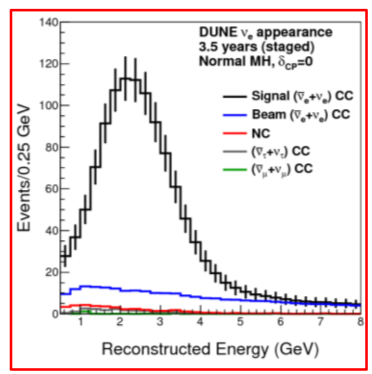
- The Facility is flexible enough to accommodate other experiments.
- nuSTORM and potentially ENUBET could be branched from the MUC Demonstrator Facility.
- The same target complex would be used profiting from its shielding and general target systems infrastructure, utilities, and accesses.
- The double deflection of the beamline could reduce radiation streaming towards the nuSTORM ring.
- Synergies between experiments would reduce costs on both sides.
- Is the 26 GeV/c beam from the PS appropriate for these two experiments?

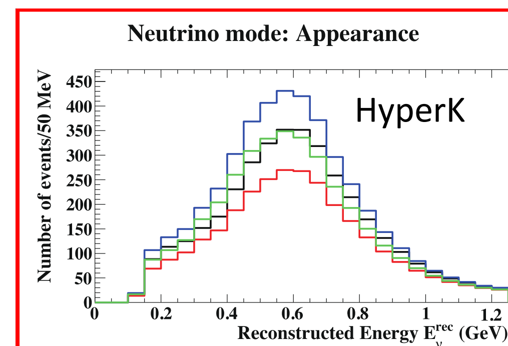


Cross section programme: variable energy range

- 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
    - $\rightarrow E_\mu < 6$ GeV

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

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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

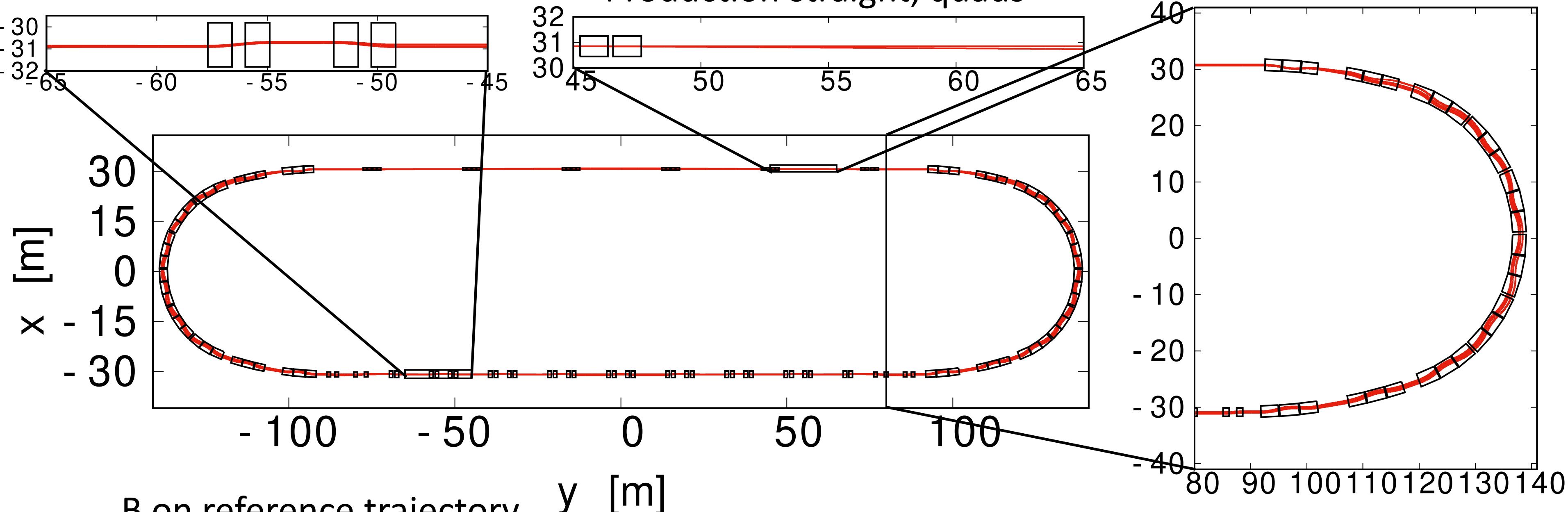
- Long straight sections kept at 180m (as in FNAL designs)
- Arc modified to accommodate higher momentum (up to 6.5 GeV/c orbit)
- Dispersion in the arcs is kept smaller to reduce the magnet aperture
- FFA parts (both arcs and straight FFA) were made with a fully transparent optics (both phase advances 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

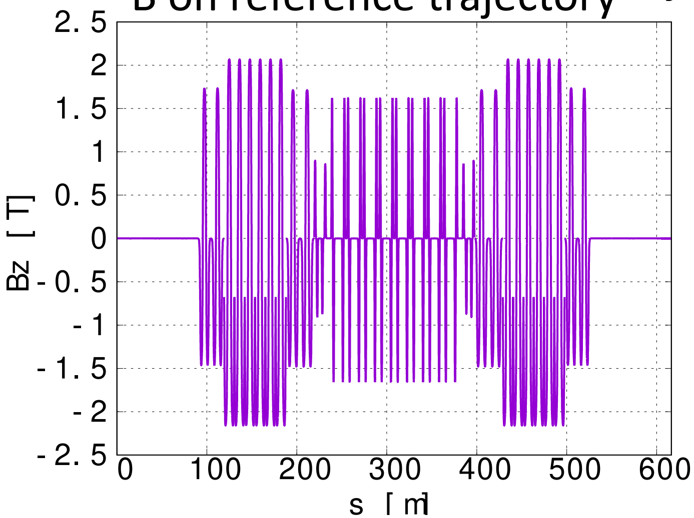
Straight FFA

Production straight, quads

Arc with two matching sections, FFA magnets



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

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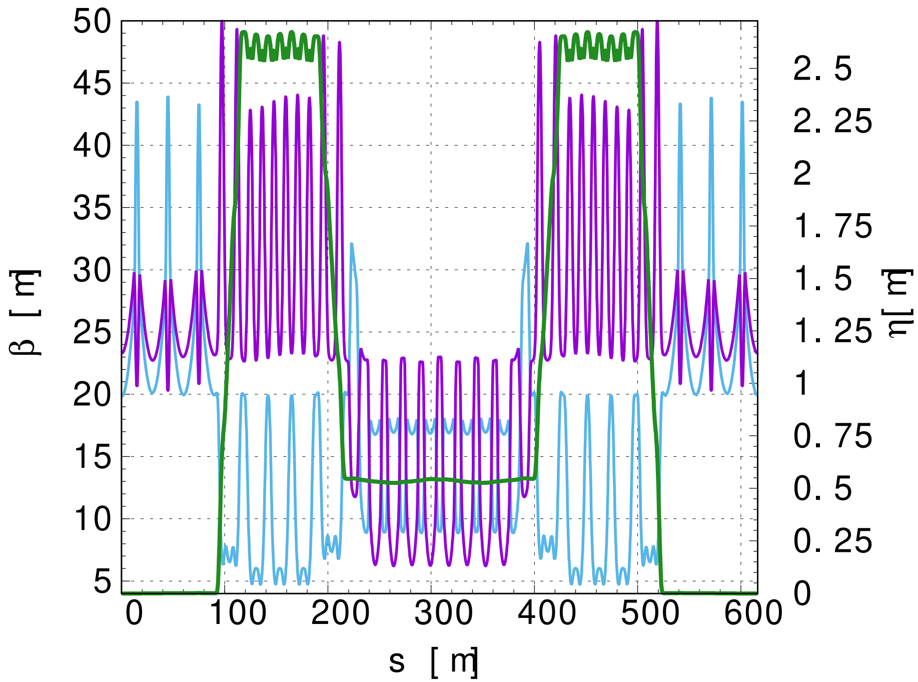
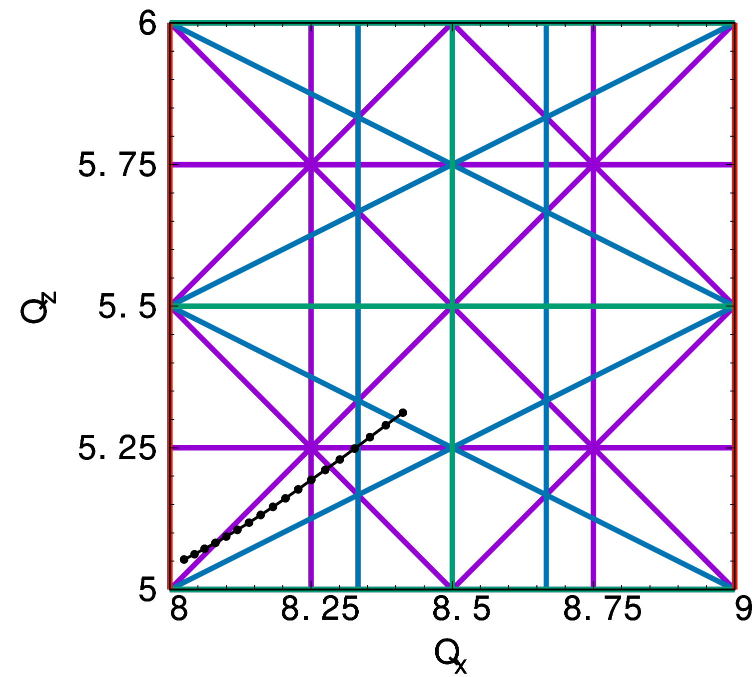
Hybrid optics





- 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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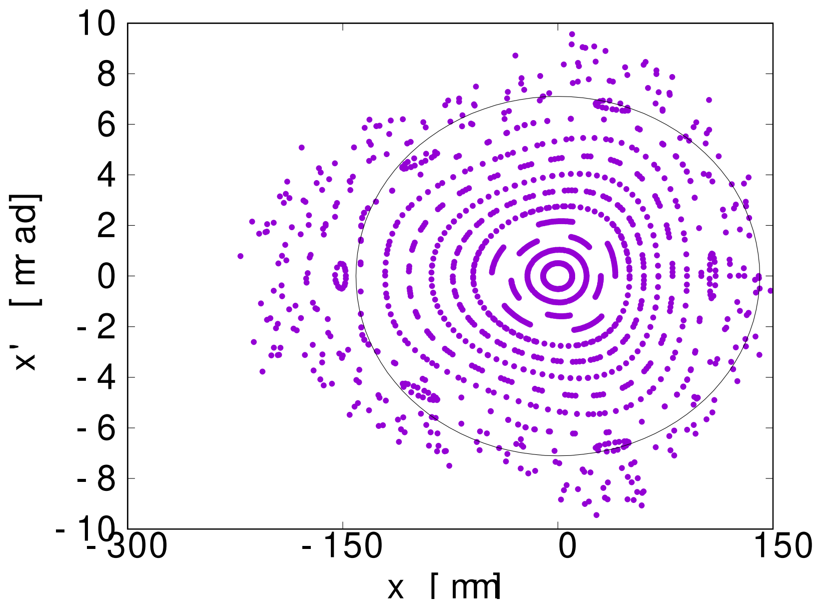
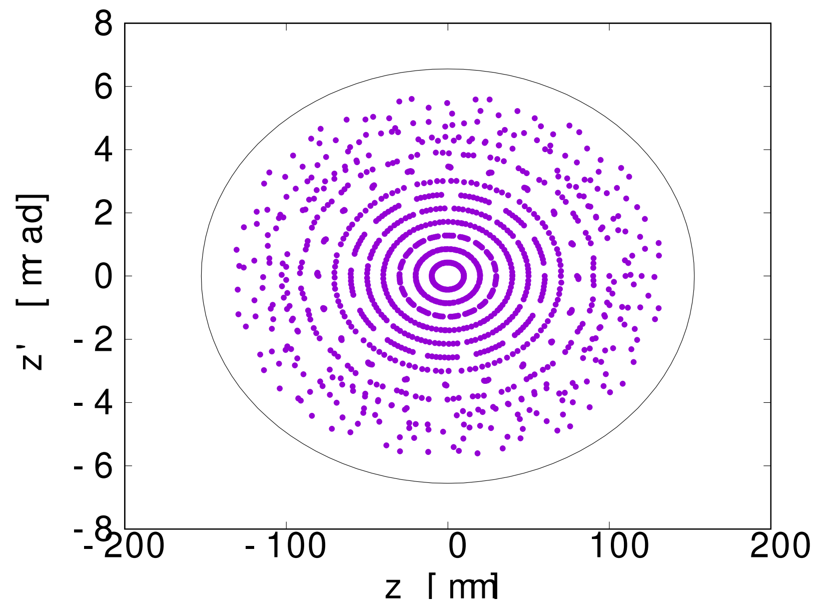
Hybrid ring, tracking



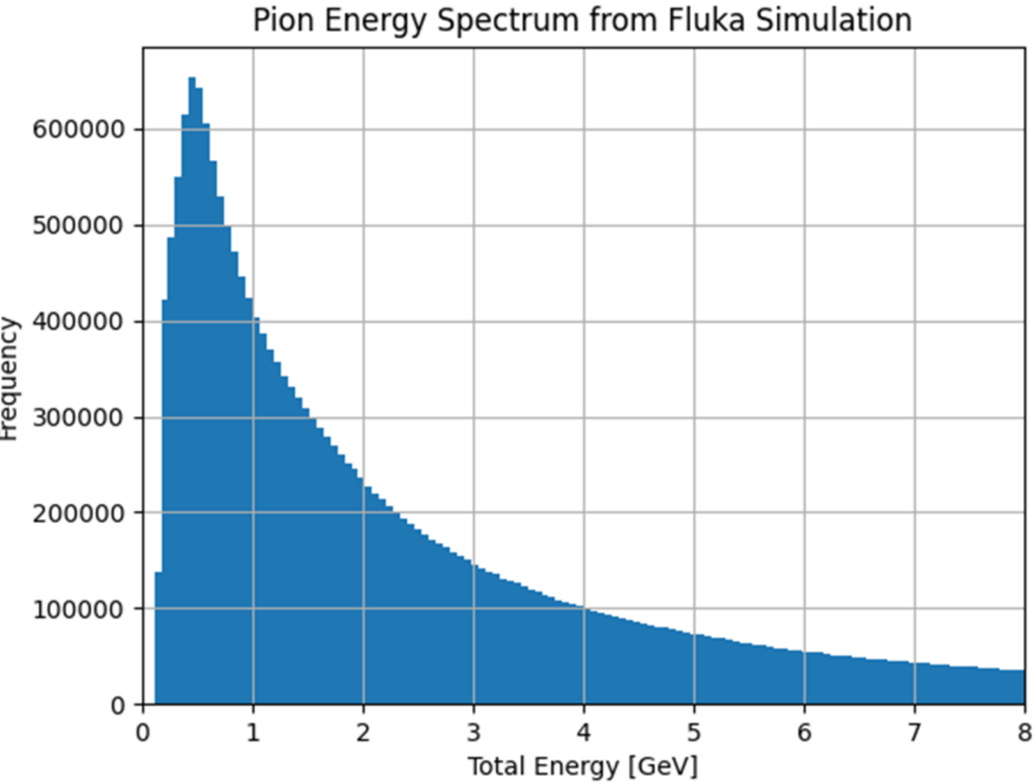


- Good DA in both planes
- Cross check with PyZgoubi (work in progress)
- Tracking with the full beam distribution (next step)

Current focus and near future plans for Hybrid design

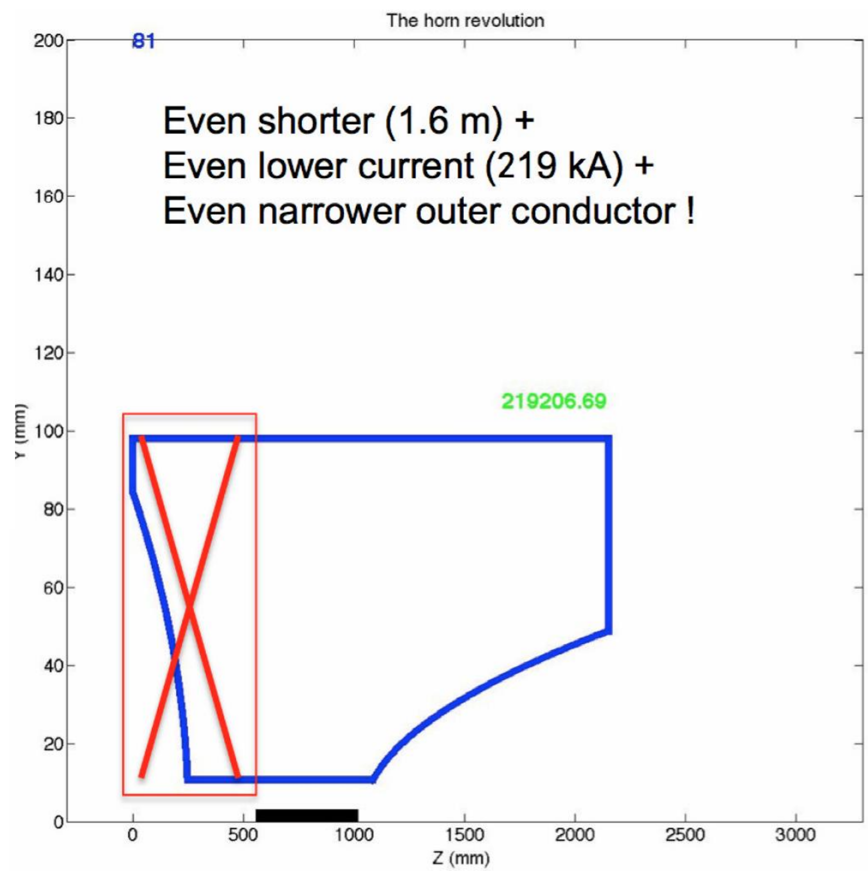
- Work on the Hybrid FFA design:
  - Cross check between codes
  - Possibly a modest chromaticity correction to reduce the tune spread to ~0.2
  - Further design work on injection
- Evaluation of the performance: momentum spread, DAs, transmission and the neutrino fluxes, and comparison with other lattices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

Target and horn simulations



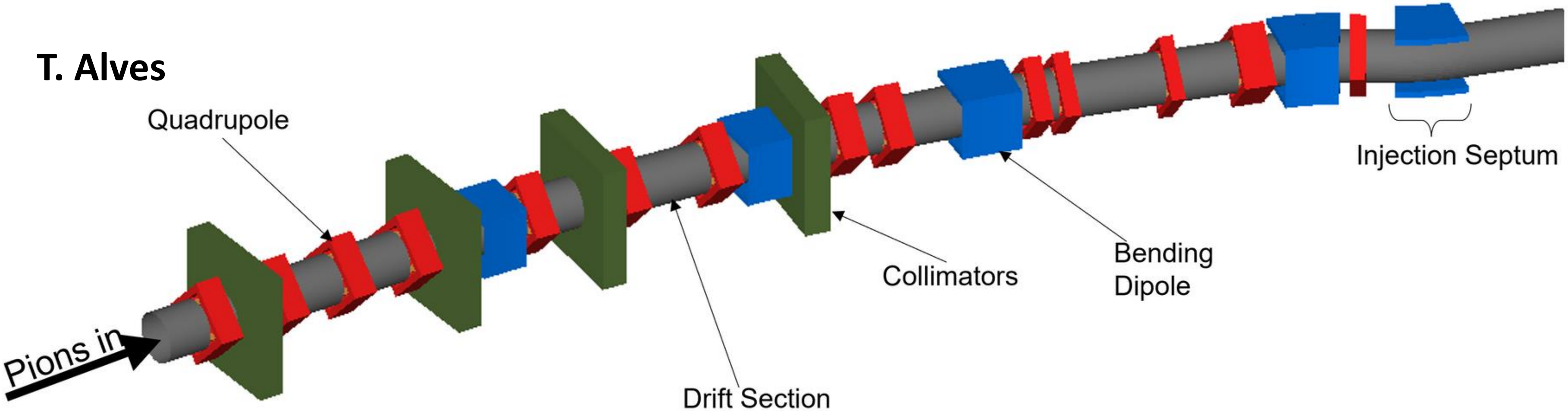
- Target simulated in FLUKA (J. Back)
- Parameters of the target adopted from the FNAL study
  - Inconel target, 46cm in length
- Horn geometry and current adopted from the FNAL study (A. Liu)

Horn geometry (Tupri005, IPAC'14)

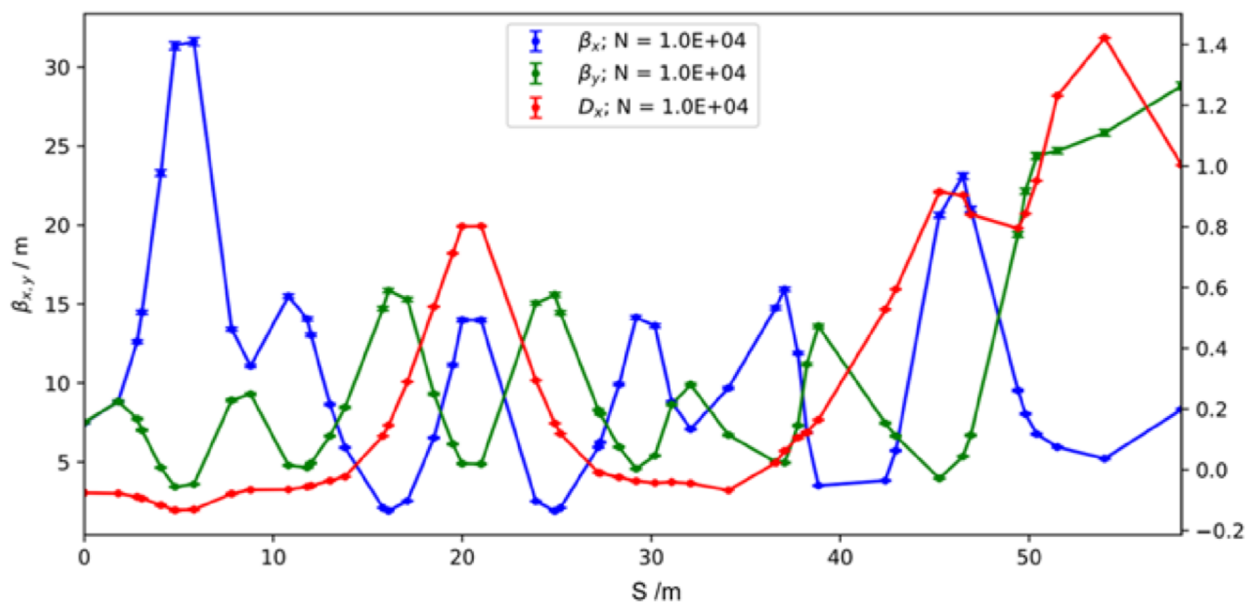


Pion beam line simulation in BDSIM

T. Alves



Layout of pion injection line



Betatron functions and dispersion for pion beam from the horn until the injection point in the nuSTORM ring calculated by tracking in BDSIM

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BDSIM study extended till the end of the production straight

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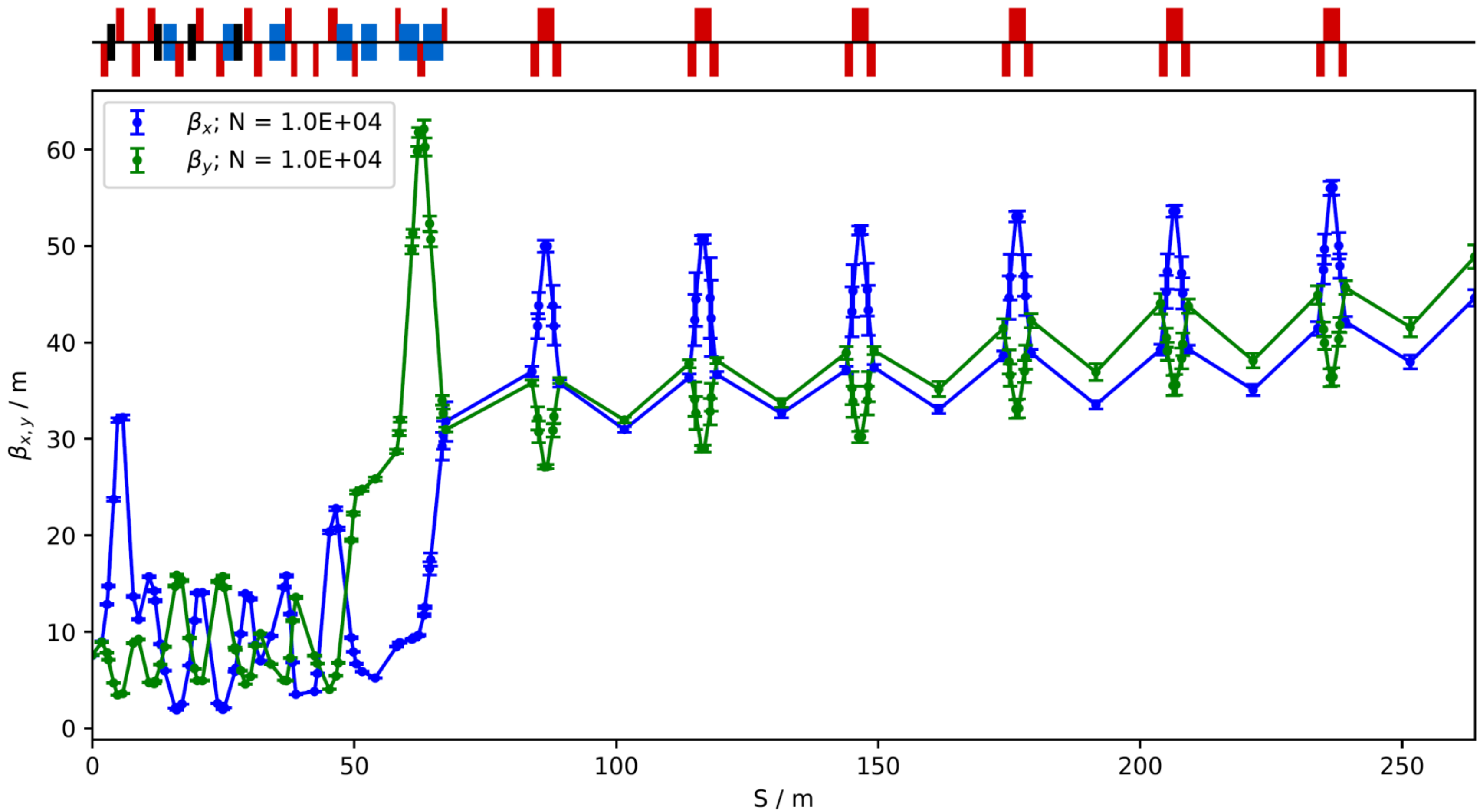
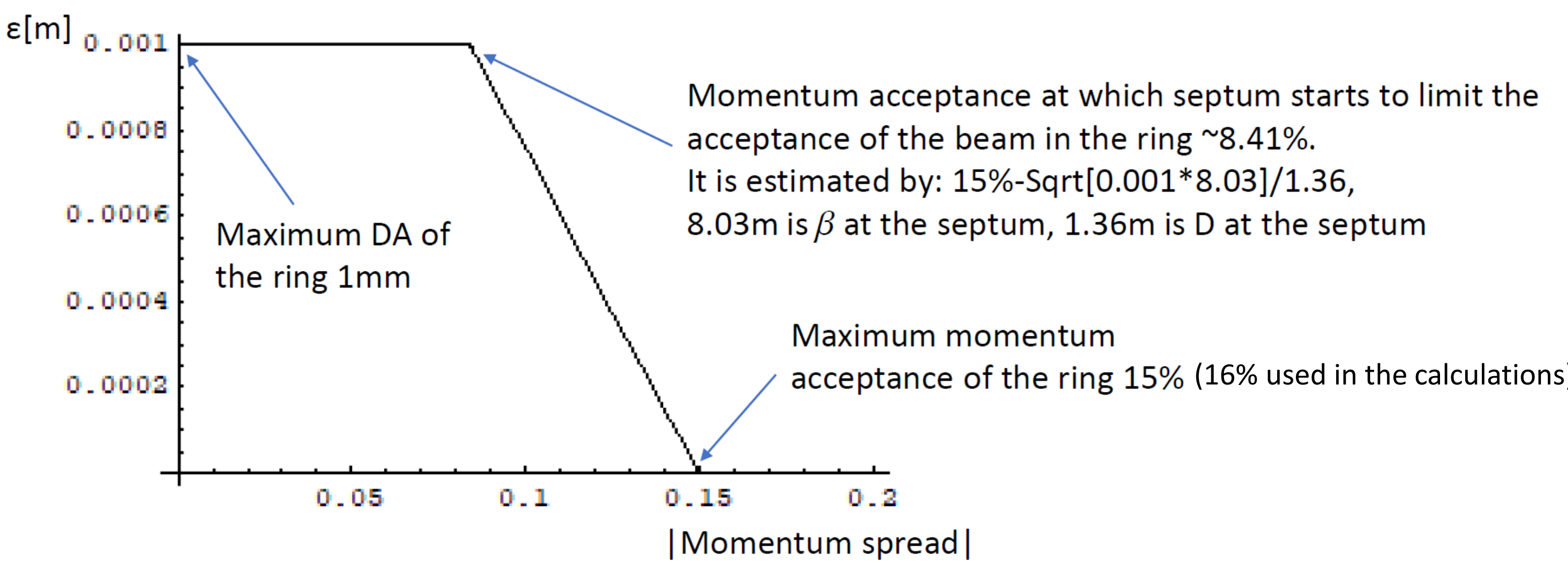


Betatron functions of pions from the horn until the end of the production straight in the nuSTORM ring calculated by tracking in BDSIM

Acceptance cut at the end of the quad straight

- $\frac{x^2}{\beta_x^q} + \beta_x^q (\frac{p_x}{p_z})^2 \leq \varepsilon(|\frac{\Delta p}{p_0}|)$

$\frac{\Delta p}{p_0} = \frac{p - p_0}{p_0}$
p_0=3.8 GeV/c (muon central momentum for 5 GeV/c pions injection)
β_x^q=19.98m (periodic beta of the quad straight)



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PS/SPS feeding comparison

T. Alves

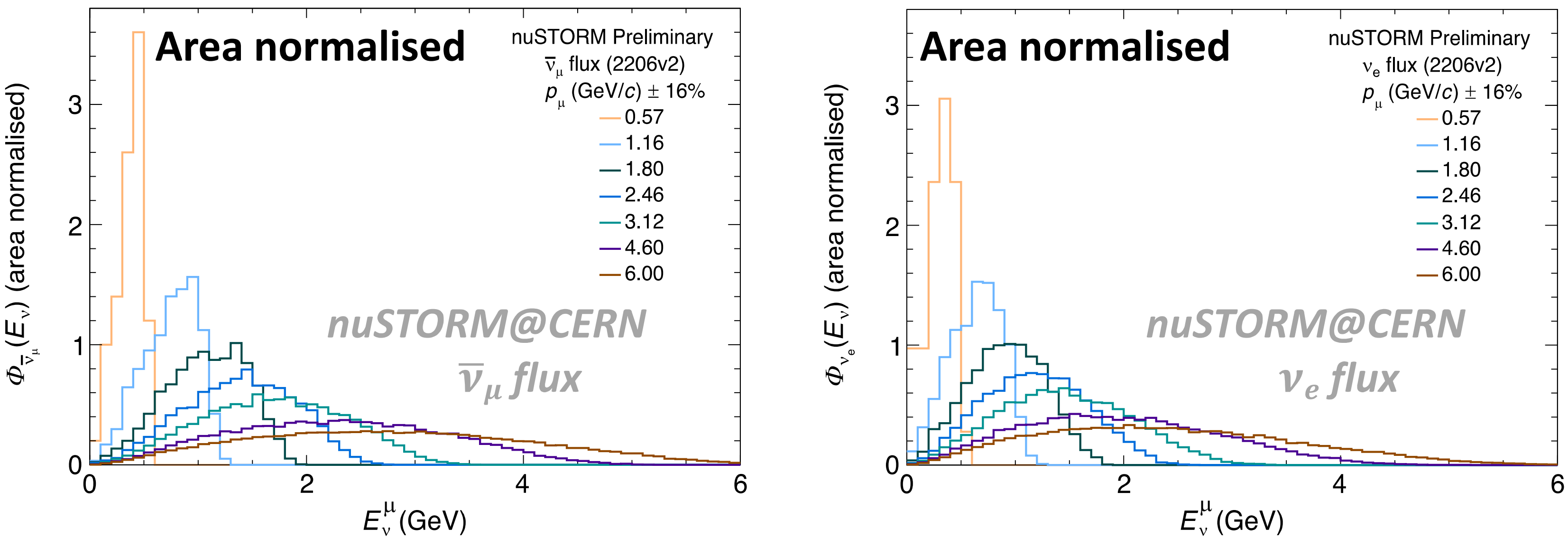
Proton Energy on target	π^+ Central Momentum	μ^+ Central Momentum	Starting π^+	Undecayed π^+ at end of decay straight	Total μ^+ produced	Accepted μ^+
$100GeV$	$5GeV/c$	$3.8GeV/c$	$986,303$	$221,718$	$192,932$	$19,074$
$100GeV$	$7.2GeV/c$	$5.42GeV/c$	$834,311$	$255,522$	$156,019$	$24,694$
$100GeV$	$2.64GeV/c$	$2.0064GeV/c$	$746,499$	$65,540$	$90,593$	$2,187$
$26GeV$	$5GeV/c$	$3.8GeV/c$	$230,775$	$53,484$	$47,438$	$4,650$

- Simulation performed using FLUKA and BDSIM assuming 10^7 POT
- Horn current scaled with momentum
- PS would give 4.14 times less accepted muons for the same POT
- Low pion momentum setting (2.64 GeV/c) requires further investigation due to high losses in the pion beam line (work in progress)
- Results will be used for the neutrino flux normalisation

nuSTORM@CERN: flux estimation

T. Alves, M. Pfaff

nuSTORM, arXiv:2203.07545



- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE.   : 2.4 GeV
- Set by stored-muon momentum

- Unique opportunity:
  - E_ν-scan measurements
- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance

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

❑ Promising recent progress on pion capture, transport and injection