nuSTORM: neutrino physics on the path to the Muon Collider

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on behalf of the nuSTORM Collaboration

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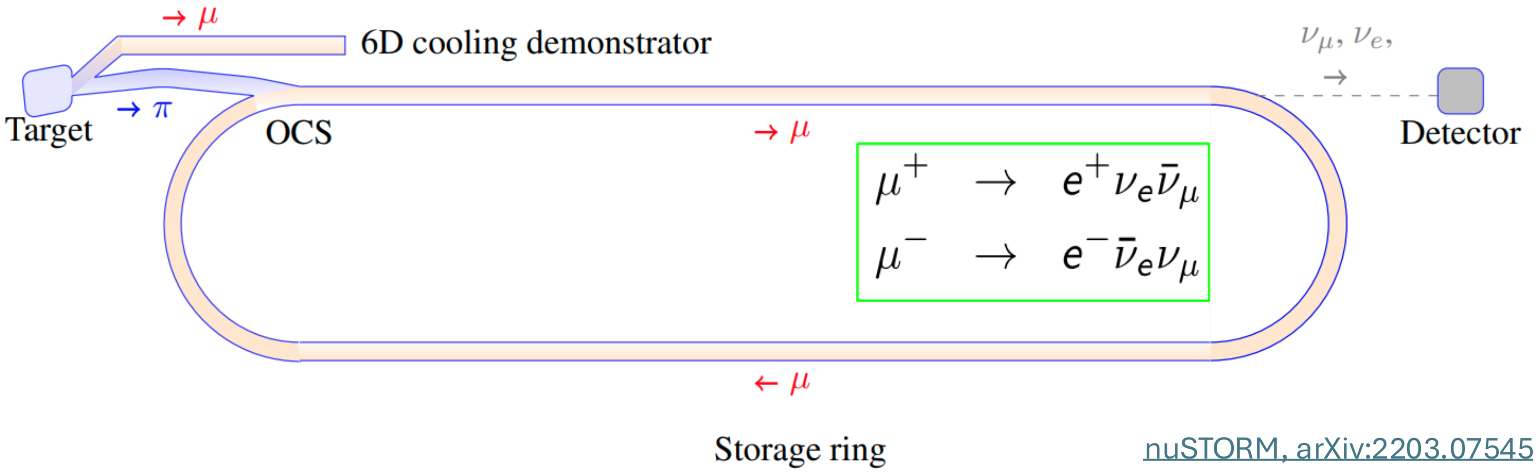
νSTORM

IMPERIAL

Neutrinos from Stored Muons (nuSTORM)

- nuSTORM facility
  - Designed to produce a neutrino flux with %-level precision
  - Muon decays in a racetrack-shaped storage ring
- Based on a muon storage ring
  - Can be tuned to accept muons with momenta in the 1-6 GeV/c ± 16% range
  - Stored muons decay into electrons, muon and electron neutrinos



nuSTORM, arXiv:2203.07545

Scientific programme

Cross section measurements

- %-level precision on the neutrino flux
  - Superior neutrino-nucleus interaction cross-section measurements
- Tunable muon storage ring
  - Neutrino flux can be tuned to the energy spectra of long-baseline neutrino experiments

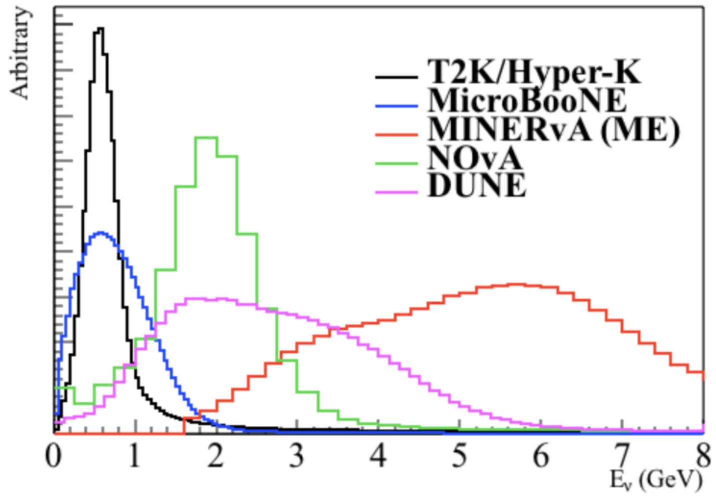
Beyond Standard Model searches

- Rare processes
  - By combining the precisely known flux with high statistics
- Probe short-baseline neutrino oscillations
  - High-sensitivity sterile neutrino searches

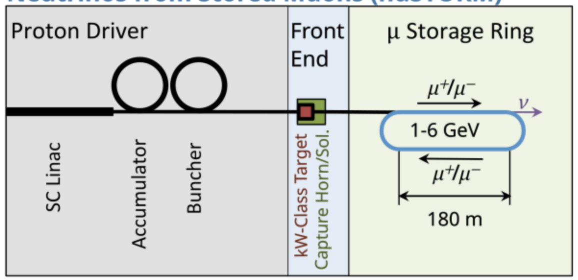
Muon Collider testbed

- Muon storage ring
  - Great potential to serve as a testbed for technologies essential for the Muon Collider

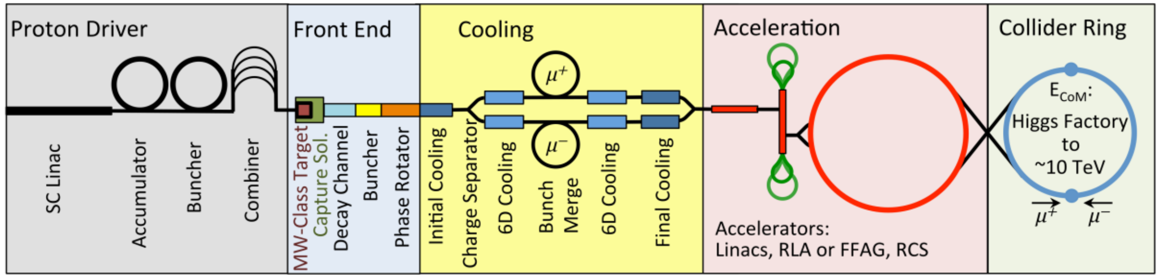
Katori T. YETI2019, IPPP, Durham, UK, Jan. 7, 2019



Neutrinos from Stored Muons (nuSTORM)



Muon Collider

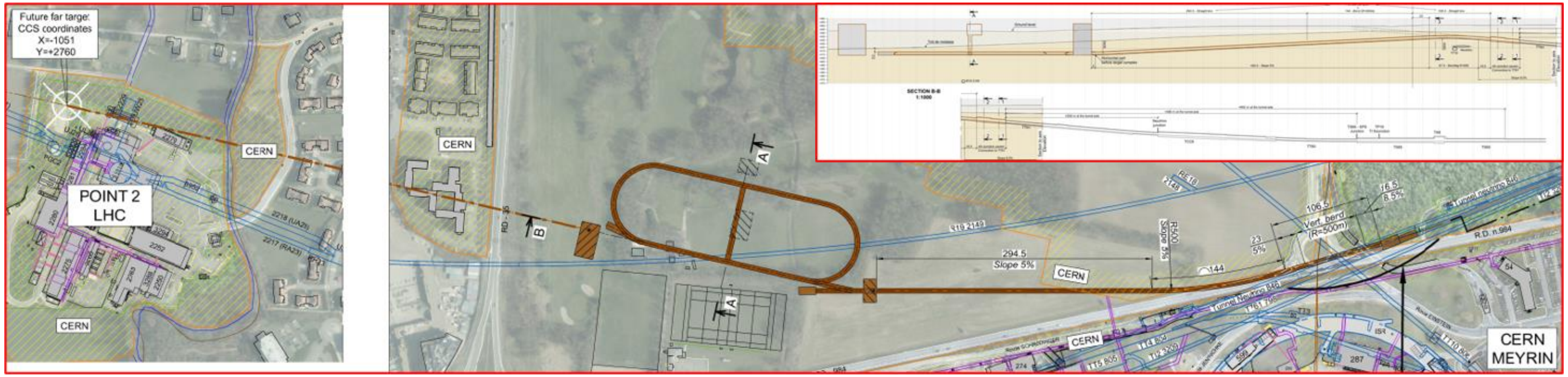


Adapted from M. A. Palmer, "The US Muon Accelerator Program", in Proc. IPAC'14, DOI: 10.18429/JACoW-IPAC2014-TUPME012

Progress overview

- A CERN siting has been investigated (nuSTORM, CERN-PBC-REPORT-2019-003)
- Simulation-driven optimisation studies in progress at multiple subsystems of the facility
- Identified opportunities for synergies with a Muon Collider R&D programme

CERN-PBC-REPORT-2019-003; DOI:10.17181/CERN.FQTB.O8QN



Potential siting of nuSTORM at CERN

Pion production and transport

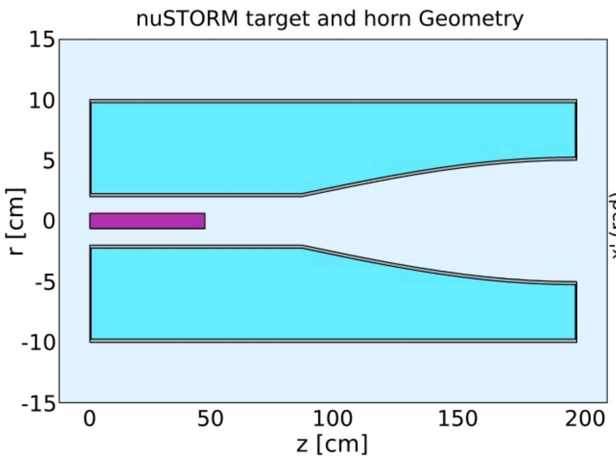
Target & horn

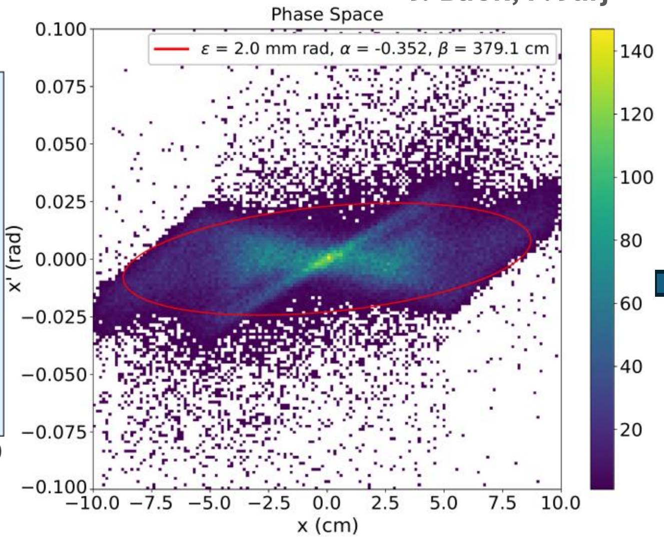
- Current iteration tailored for using protons from the CERN SPS or PS
- Optimised for 5 GeV/c pions
- Ongoing FLUKA studies to optimise the capture of low-energy pions (e.g. using a second horn)

Pion transport line

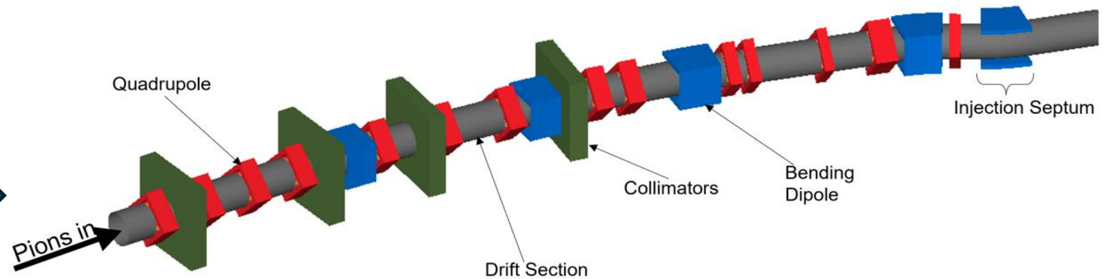
- Transfers the pions from the target to the storage ring
- Design validated in a tracking study using Beam Delivery Simulation (BDSIM) software
  - BDSIM implementation extended to include the production straight section of the ring, to study muon production

J. Back, P. Jurj

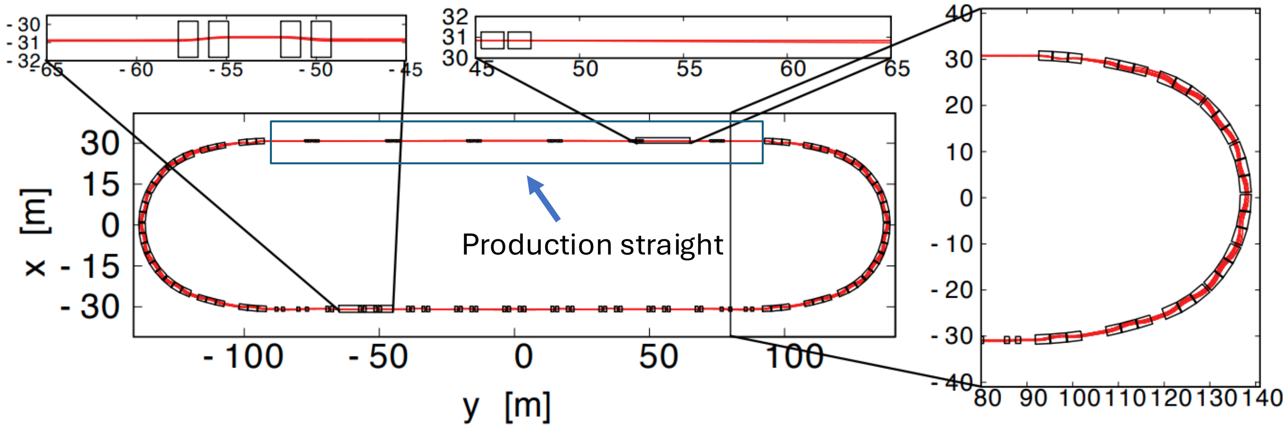




T. Alves, J. Pasternak



Storage ring



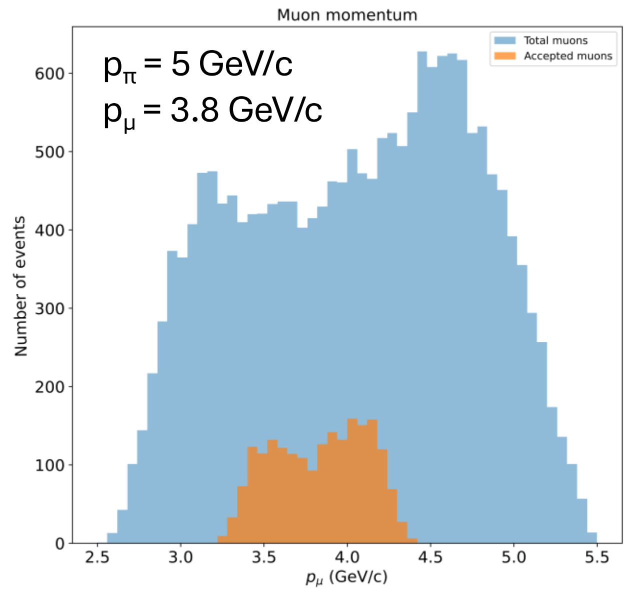
- Ring designed to have large dynamic and momentum acceptances
  - 1 mm rad and ± 16%
  - Arcs and the return straight — Fixed Field Alternating Gradient (FFA) lattice
  - Production straight — conventional FODO lattice, to maximise muon capture efficiency
- ν energy spectrum — determined from the ring optics
- Ring instrumentation — precise beam intensity measurements
- Full BDSIM implementation of the ring currently in progress

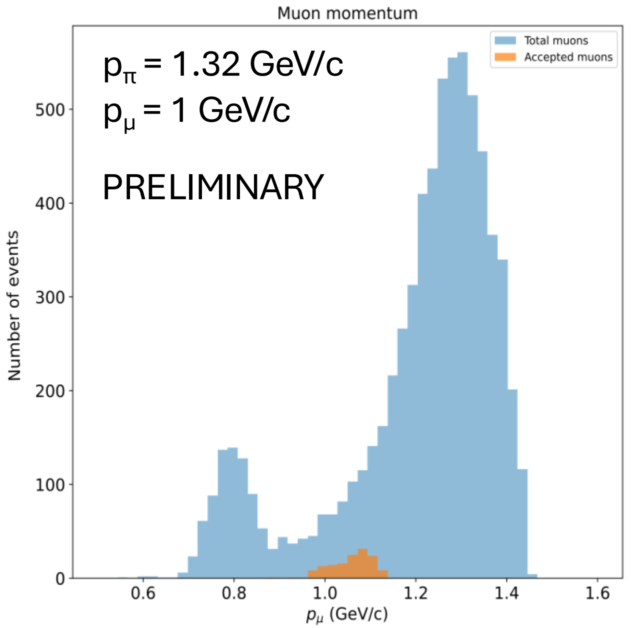
Muon production (BDSIM)

- Pions tracked in BDSIM from horn to the end of the production straight
  - Study muons that reach the end of the production straight
- **Baseline** design - ring accepts muons with a mean momentum:

  $$p_\mu = 0.76\, p_\pi$$

  - Optimised for 3.8 GeV/c muons / 5 GeV/c pions
  - Chosen to avoid overlap between the target muon momenta and the momenta of the undecayed pions
- At lower momenta - double peak feature, with the valley near the target muon momentum
  - Decreased muon capture efficiency
  - Cause: due to a lower Lorentz boost, decayed muons with significant transverse momentum have a larger divergence and are lost in the accelerator apertures

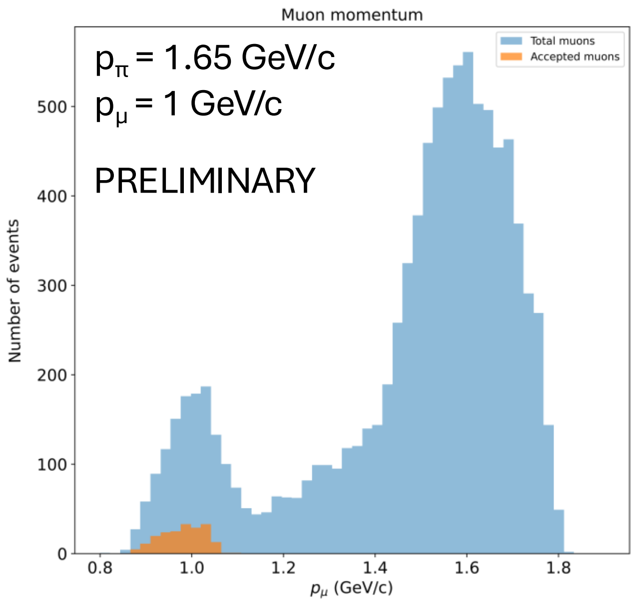


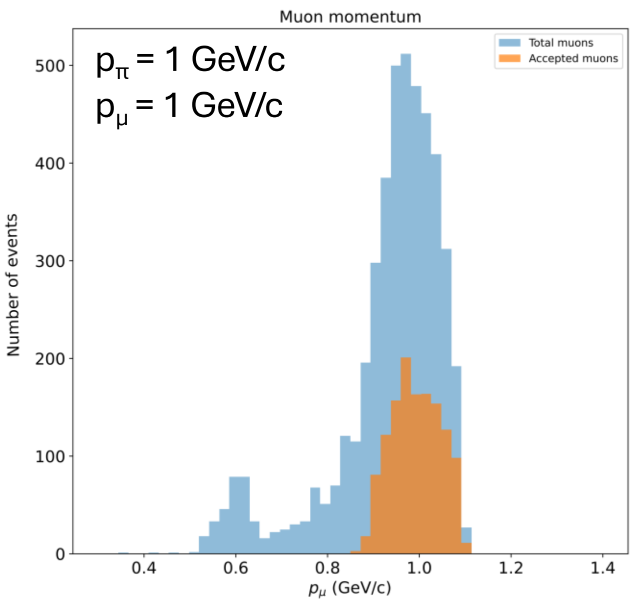


Muon production optimisation (BDSIM)

P. Jurj, P. Kyberd

- Mitigation
  - Consider accepting muons from either the forward or backward peaks
- Observed improvements in the capture efficiency of 1 GeV/c muons (after normalising to number of protons on target)
  - Backward peak: ×2
  - Forward peak: ×6
- Study currently expanded at all stored muon momenta of interest

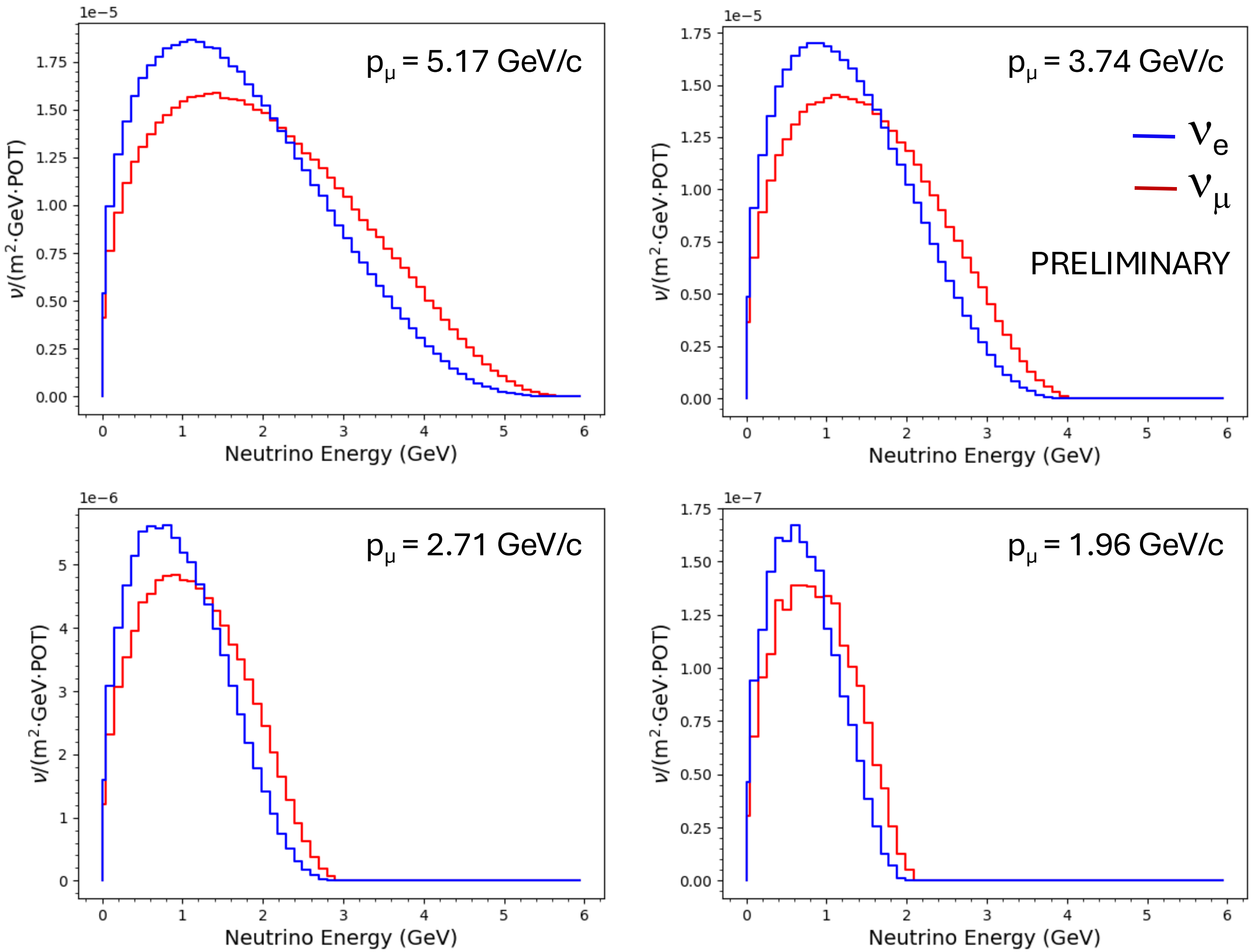




Simulated neutrino fluxes (nuSIM)

R. Kamath, P. Kyberd, K. Long

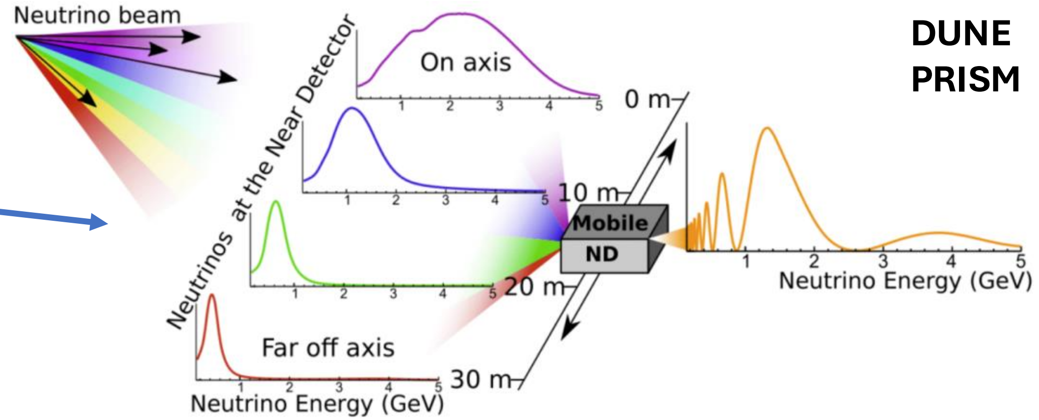
- **NuSIM** - Python framework for fast simulation of the nuSTORM neutrino spectrum
- The code can take a FLUKA pion distribution as input and simulate the neutrino spectrum at the detector
- **Figure**: muon and electron neutrino spectra for four stored muon central momenta
  - Produced using the baseline ring configuration ($p_\mu = 0.76\ p_\pi$)



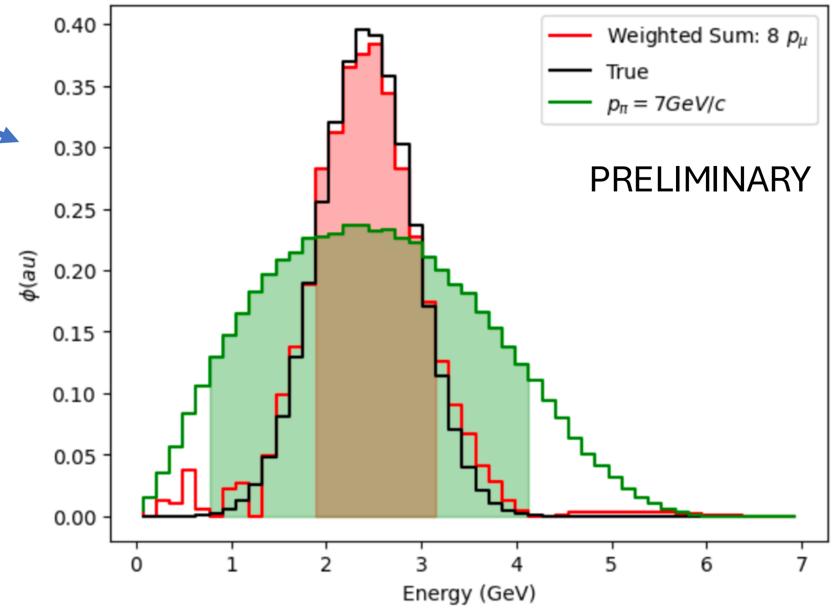
Synthetic beams at nuSTORM

- Similar concept to the PRISM technique of DUNE and HyperK, which exploit the movement of near-detectors **off-axis**
- nuSTORM: detector **always on-axis**, but can linearly combine fluxes from **different stored-muon momenta**
- Toy study using fluxes from 8 muon momenta: synthetic beam narrower and more Gaussian
  - Neutrino peak energy of 2.5 GeV, with 0.5 GeV SD can be obtained
  - Large reduction in FWHM compared to neutrinos from muons at 7 GeV/c pion setting

N. Ilic, IPP 50th Anniversary Symposium (28-29 May 2022)

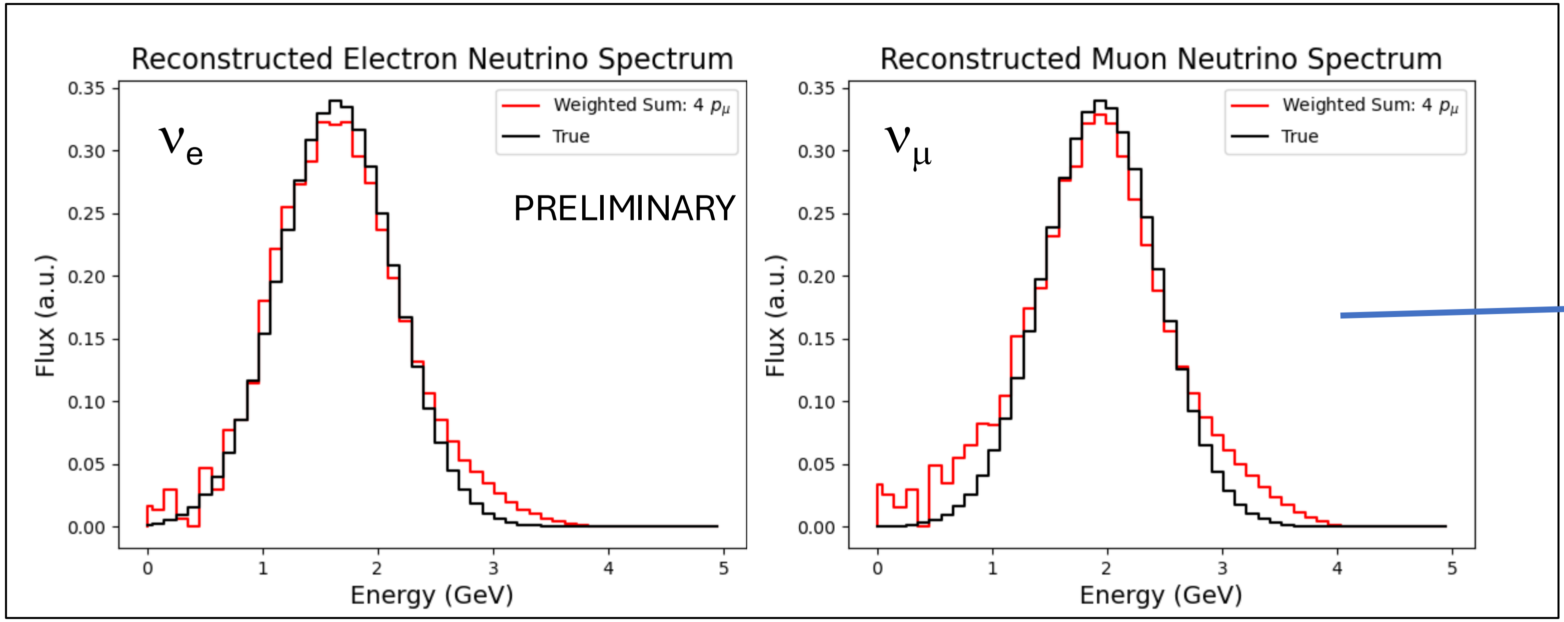


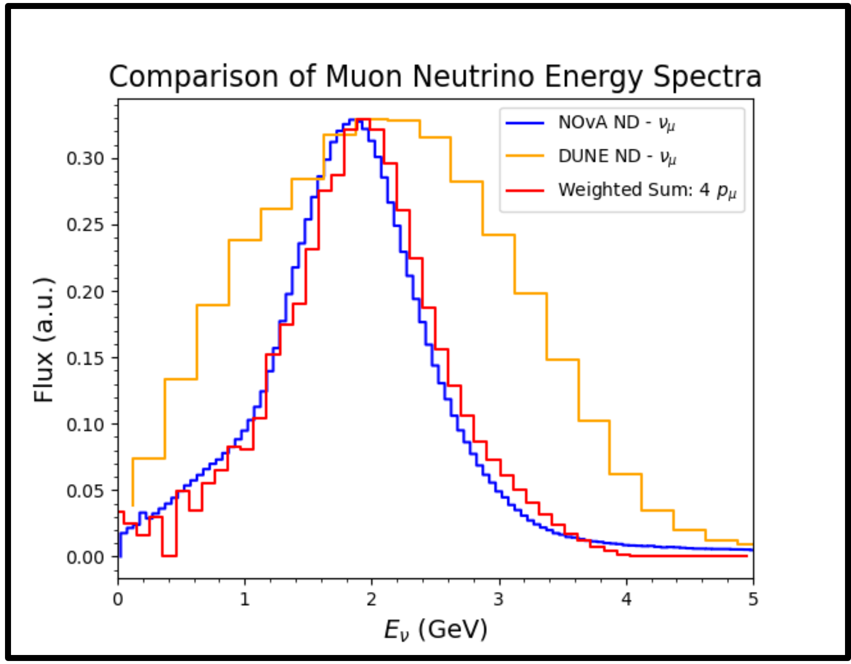
R. Kamath



Synthetic beams at nuSTORM

R. Kamath

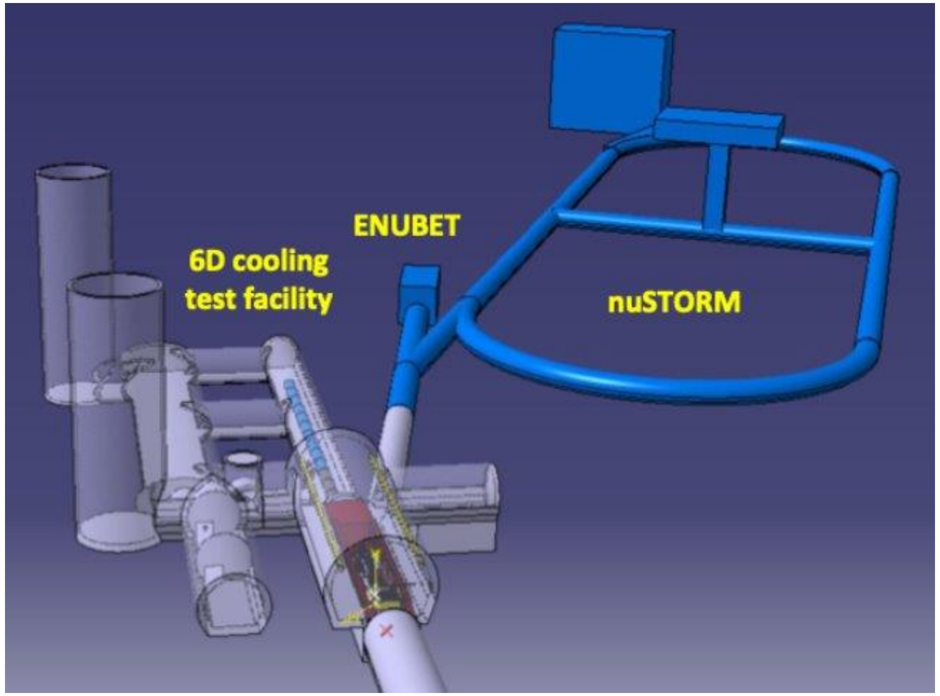




- Synthetised ν_e and ν_μ beams using fluxes from 4 muon momenta
- Narrower beam may be achieved with more flux components
- Uniquely, “quasi mono-energetic” **electron-neutrino** beams can be synthetised @ nuSTORM

Muon accelerator testbed

- nuSTORM will provide the world's highest power stored muon beam
- Opportunity to develop and test technologies critical to the progress towards a Muon Collider
  - **FFA** technology has applications for muon fast acceleration and is an attractive option for muon collider
  - **Instrumentation** for muon-beam monitoring
- Same muon production mechanism as the Muon Cooling Demonstrator
  - Opportunity to share the **target complex**



F. J. Saura Esteban et al., "Muon Collider Graphite Target Studies and Demonstrator Layout Possibilities at CERN", in Proc. IPAC'22, DOI: 10.18429/JACoW-IPAC2022-THPOTK052

Summary

NuSTORM

Novel neutrino beam:

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

Precisely known neutrino flux:

1. Intensity
   - %-level from ring instrumentation
2. Energy spectrum
   - From accelerator tune
3. Flavour composition
   - Unique, well defined: 50% ν_e, 50% $\overline{\nu_\mu}$

Rich scientific programme:

1. %-level (νN) cross-section measurements
2. BSM physics searches
3. **Testbed for Muon Collider**

- Multiple optimisation studies **in progress**
  - Focus on improving the neutrino production efficiency at low energies
- **Synthetic beams** are being investigated
  - Preliminary results show narrower neutrino fluxes can be produced

Thank you!

Back up

Creating a synthetic beam

R. Kamath

- For each muon momentum setting p_μ, a neutrino flux is obtained $\phi_i(E_\nu)$
- One can weight each spectrum with a coefficient c_i and can create a linear combination of multiple fluxes as follows:

$$\Phi_{LC}(E_\nu) = \sum_i^{N_\mu} c_i \phi_i(E_\nu)$$

- Coefficient optimisation carried out using the following Figure of Merit (FOM):

$$FOM = \sum_{E_\nu} \frac{(f(E_\nu) - \Phi_{LC}(E_\nu))^2}{A + Bf(E_\nu)^2}$$

- Parameters A and B can be tuned to change the weighting of the chi-sq fit by the flux in each bin
- A constraint that $\Phi_{LC} > 0$ for all E_ν may be added