Simulation and Design of the neutrinos from Stored Muons (nuSTORM) Experiment

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on behalf of the nuSTORM Collaboration

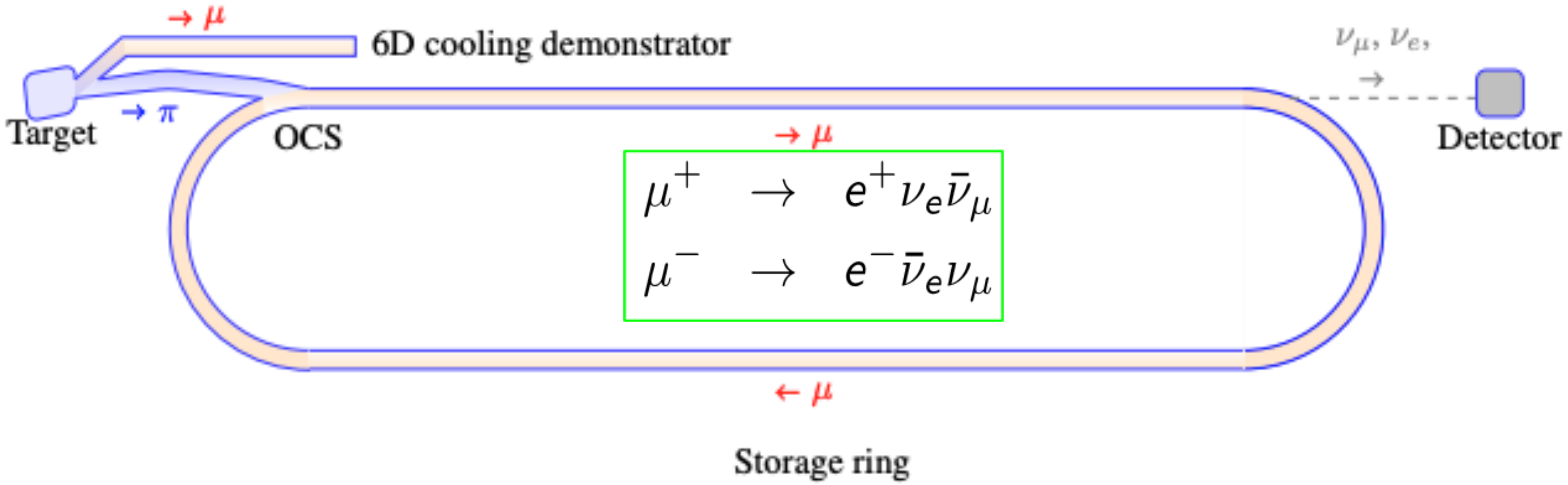
IMPERIAL

John Adams Institute for Accelerator Science

UKRI Science and Technology Facilities Council

Introduction

- nuSTORM is an experiment that aims to create a neutrino flux with %-level precision from muon decay in a racetrack shaped storage ring.
- Pions are created from a traditional proton driver and horn scheme, and injected into the ring along the production straight. The pions decay along the production straight, creating a "flash" of muon neutrinos at a detector downstream. The muons from the decay circulate in the ring, and the undecayed pions are dumped.
- The ring can be tuned to accept muons with momenta in the 1-6GeV/c range which consequently decay into electrons, muon and electron neutrinos. The upper bound on stored muon momentum comes from the strength of the bending magnets in the arcs.
- Each configuration of the ring is parameterised by the pion momentum (p_π) and muon momentum (p_μ). In the current baseline design, the lattice has been designed to accept pions of momenta $p_\pi \pm 10\,\%$ and muon of momenta $p_\mu \pm 16\,\%$. Also, the two momenta are related as $p_\mu = 0.76 p_\pi$, with this constraint coming from the design on the Orbit Combination Section (OCS) magnet.



Scientific Program

Cross Section Measurements

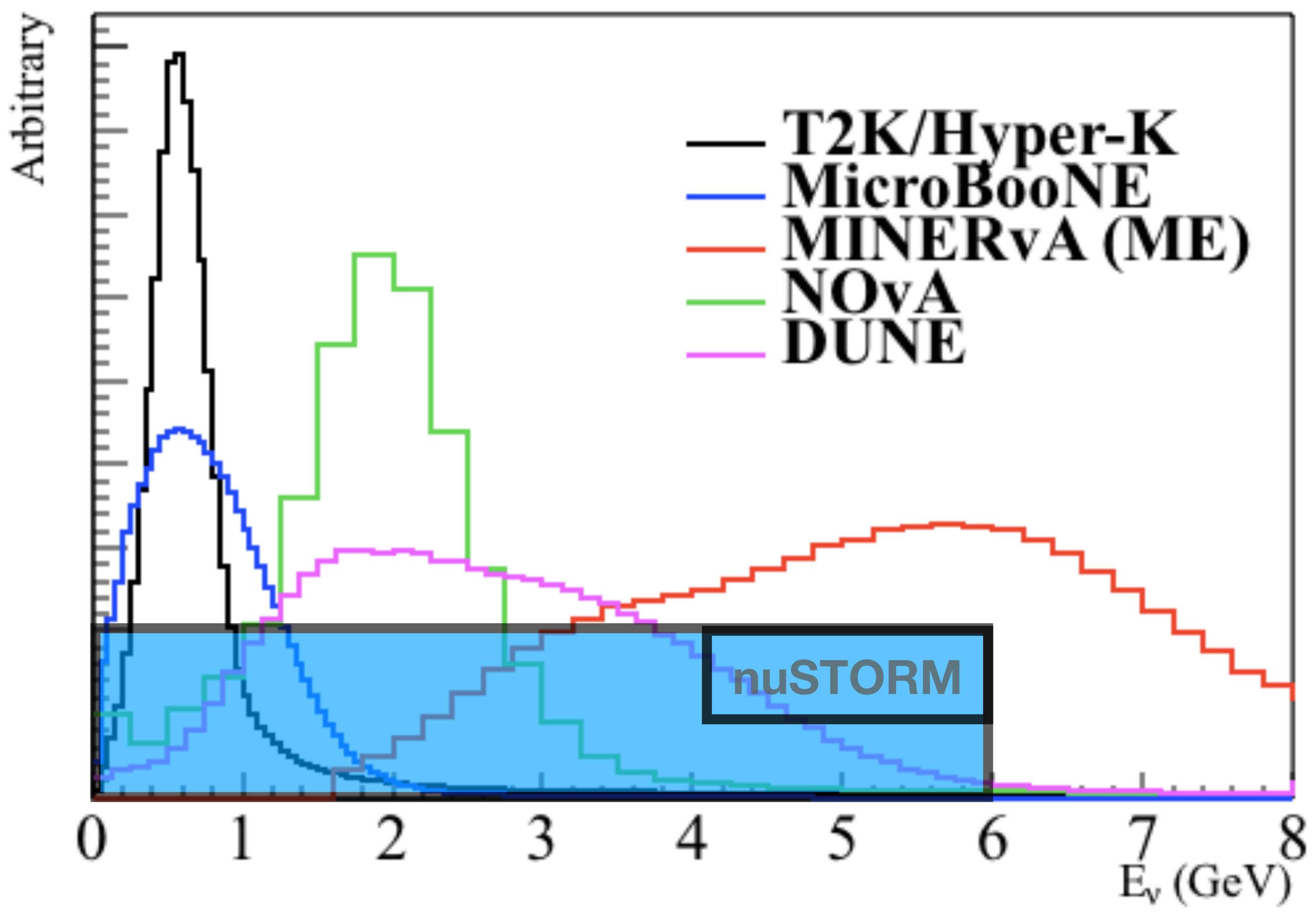
- One of the sources of error in LBL neutrino experiments is the constraint on flux and x-sec models.
- With a %-level precision on the neutrino flux, nuSTORM can constrain these cross section models
- With a tuneable muon storage ring, the neutrino flux can also be tuned to the energy spectrum of current (and future) long baseline neutrino experiments.

Beyond Standard Model Physics

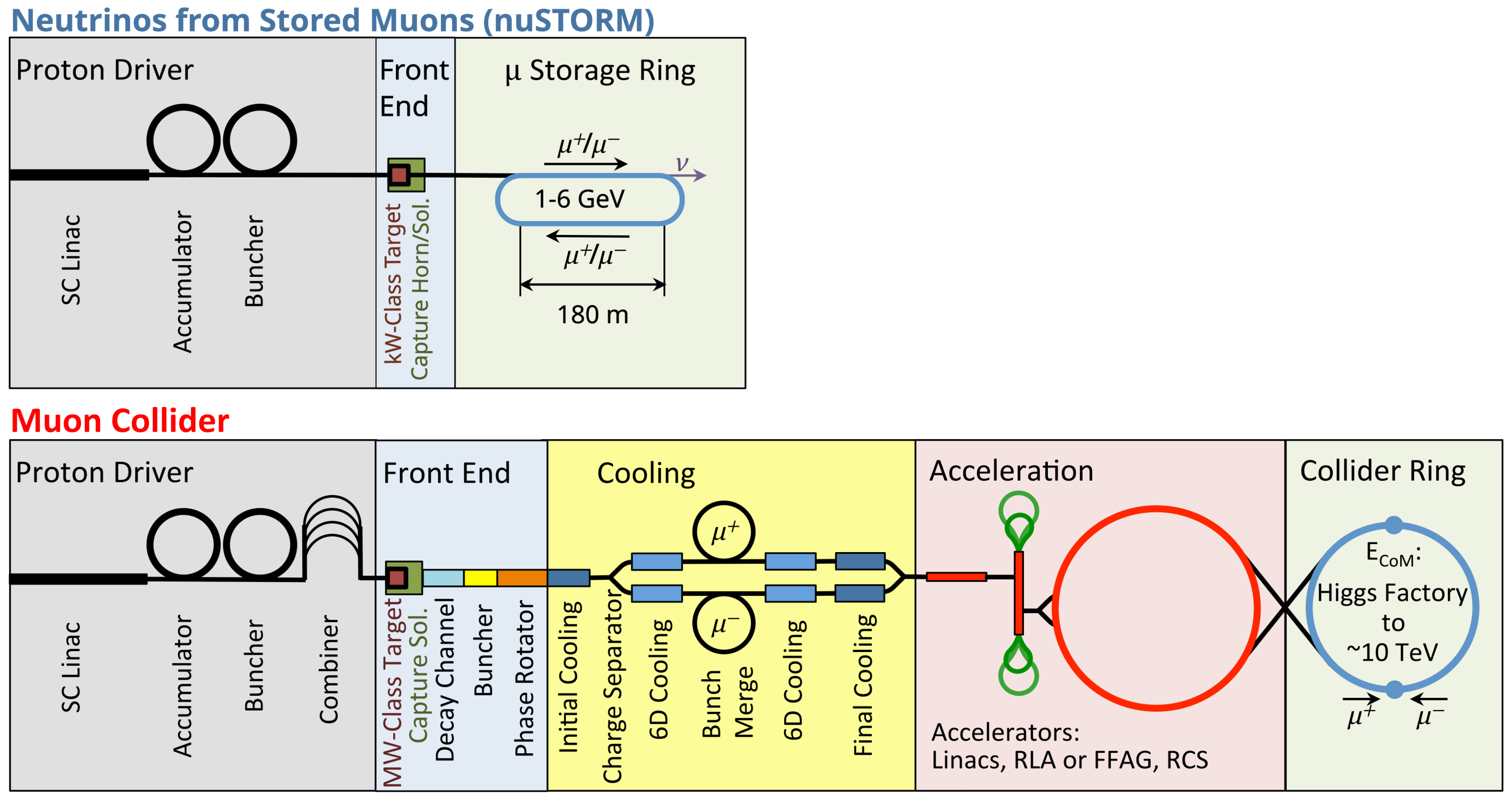
- Combining the well constrained flux with high statistics, many exotic and rare scatterings can be studied.
- nuSTORM can also probe short baseline oscillations and sterile neutrinos, with a 2014 study showing a 10σ sensitivity to the LSND and MiniBOONE anomalies.

Muon Collider Demonstrator

- As a muon storage ring, nuSTORM exhibits synergies with muon collider research, serving as a test bed for technologies for magnets and beam instrumentation.
- Hence, a Muon Collider Demonstrator complex has been envisioned at CERN, allowing for shared targetry and capture between nuSTORM, the 6D cooling test facility.



Original plot: Katori T. YETI2019, IPPP, Durham, UK, Jan. 7, 2019

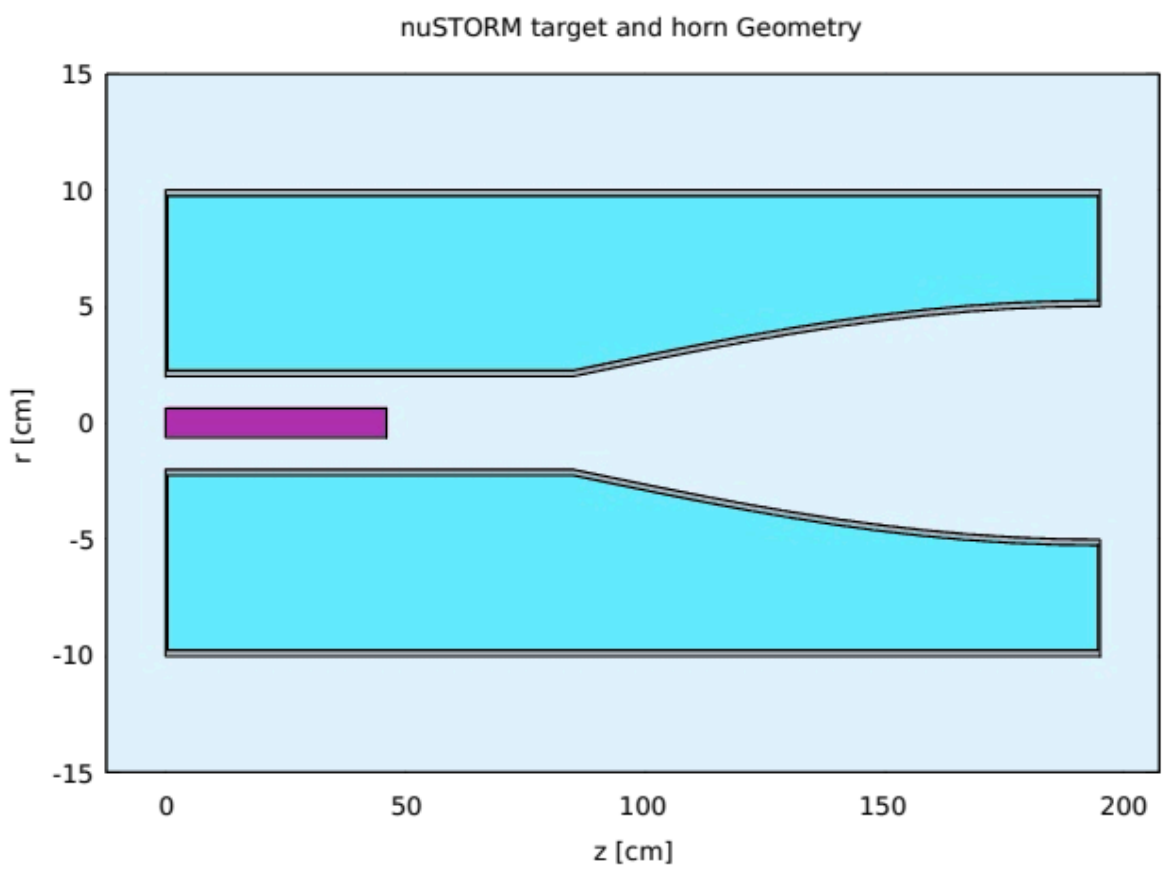


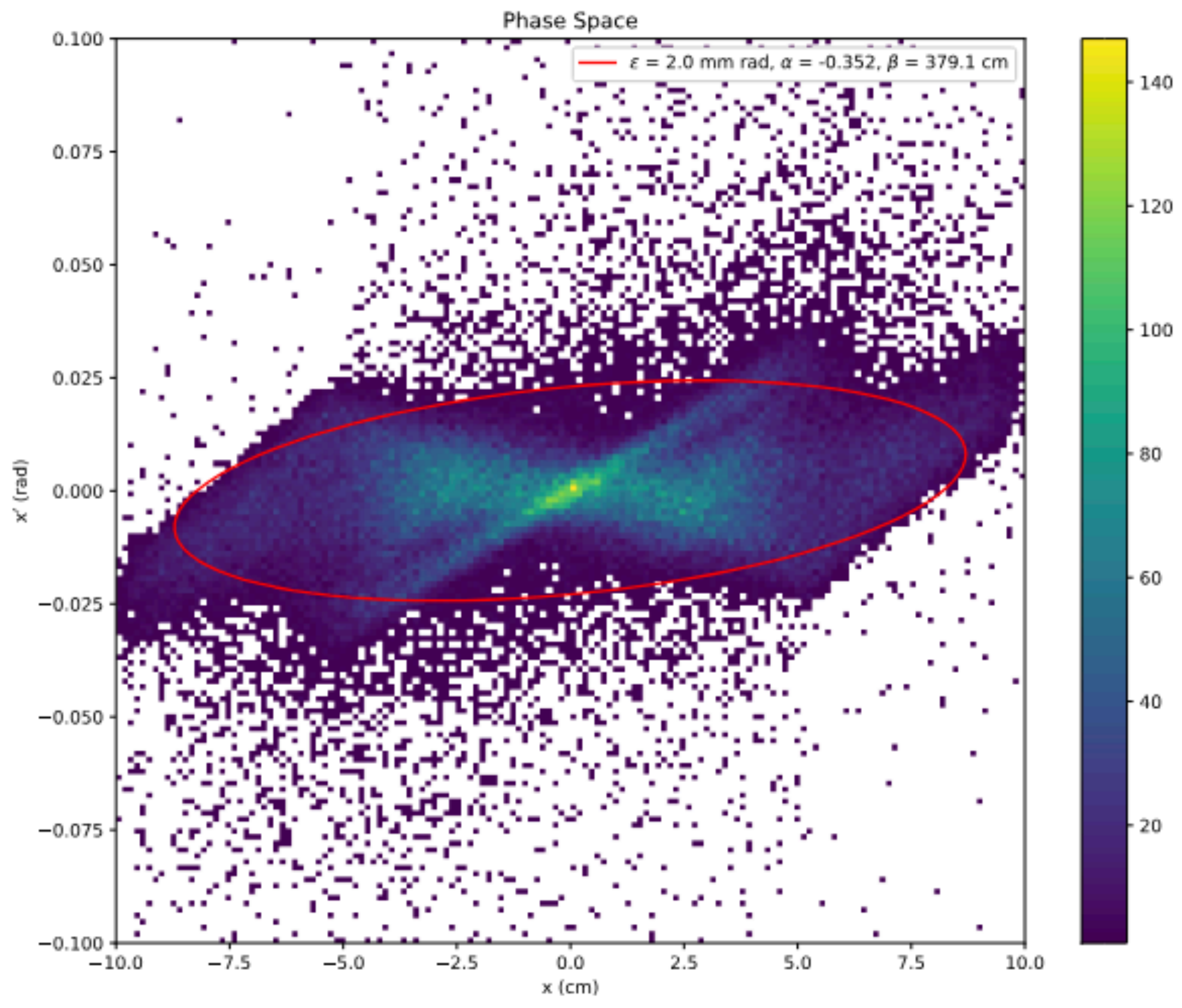
Adapted from M. A. Palmer, "The US Muon Accelerator Program", in Proc. IPAC'14, DOI: 10.18429/JACoW-IPAC2014-TUPME012

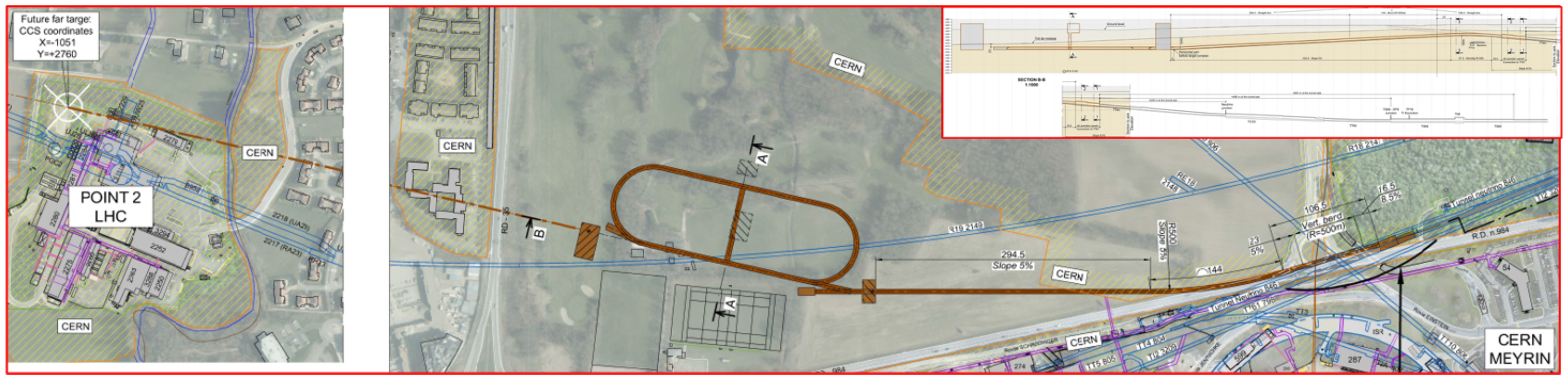
Rohan Kamath / 17 September 2024
NuFact '24

Siting and Targetry

- nuSTORM has been designed to work with existing proton driver schemes such as Main Injector, SPS etc.
- However, current horn studies and optimisation are tailored to a CERN siting, using SPS or PS based on a possible siting of the muon collider demonstrator in the TT10 area. (CERN-PBC-REPORT-2019-003)
- The studies are conducted using FLUKA with the target material as Inconel, with dimensions L = 46 cm and r = 6.3 mm.
- The horn current is tuneable with 219 kA optimal for 5 GeV/c pions.
- Studies to optimise the horn for low energy pions (including using a second horn) are currently ongoing.





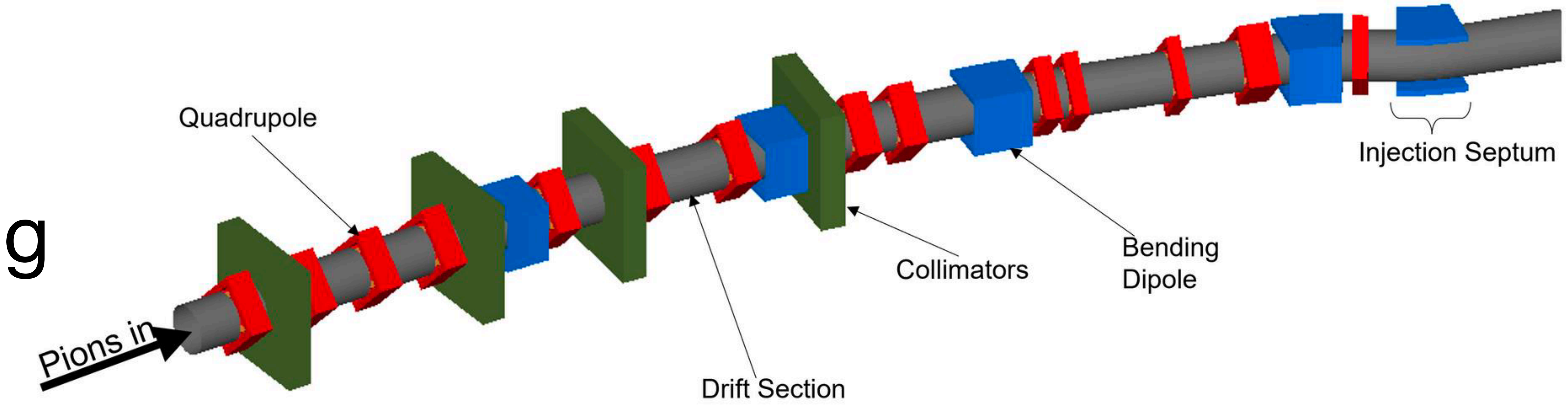


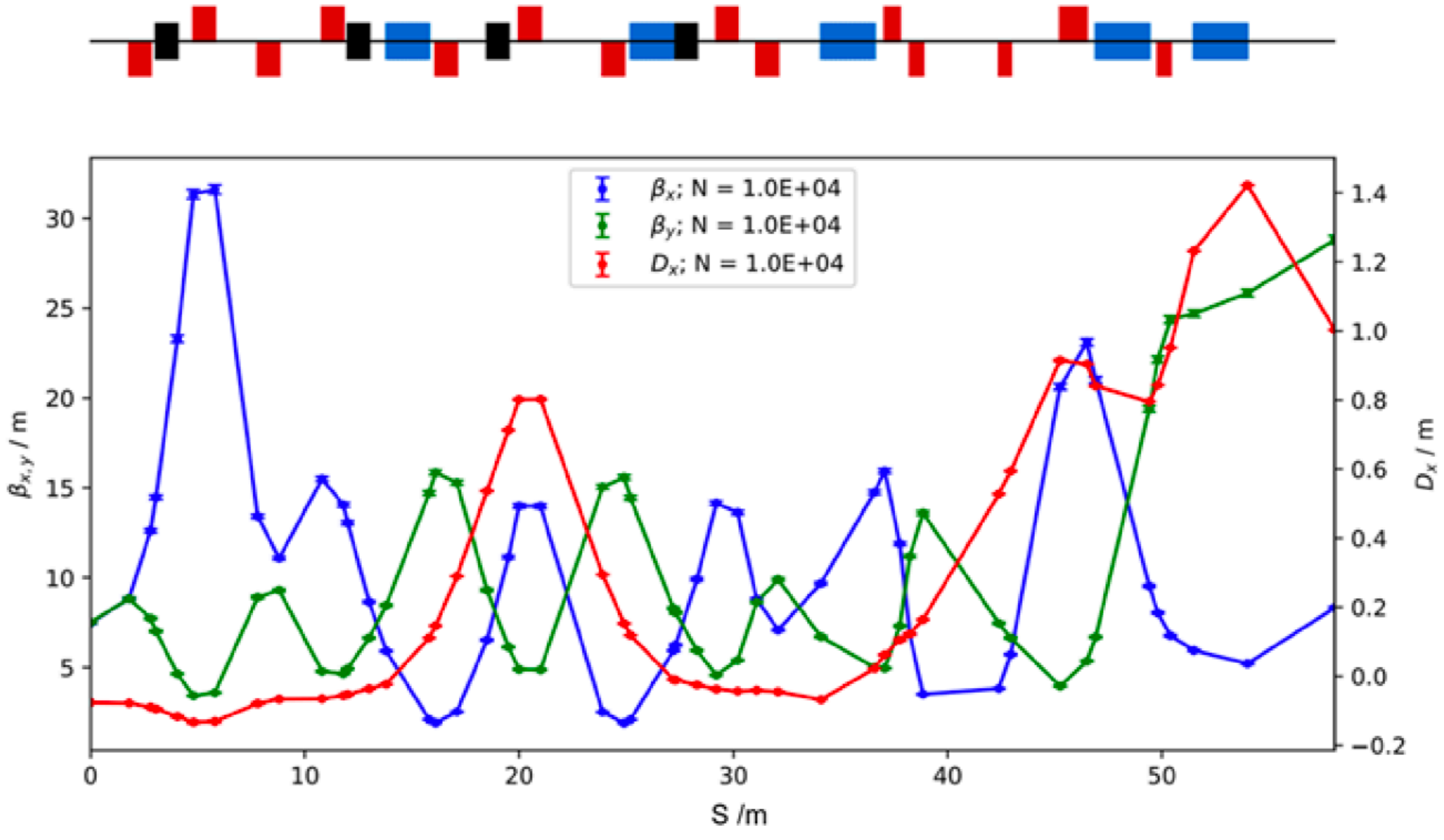
Pion Transport Line

- A transport line from the horn to the storage ring has been designed using MAD-X.

- A tracking study has also been completed, using the output from the the aforementioned horn FLUKA studies.

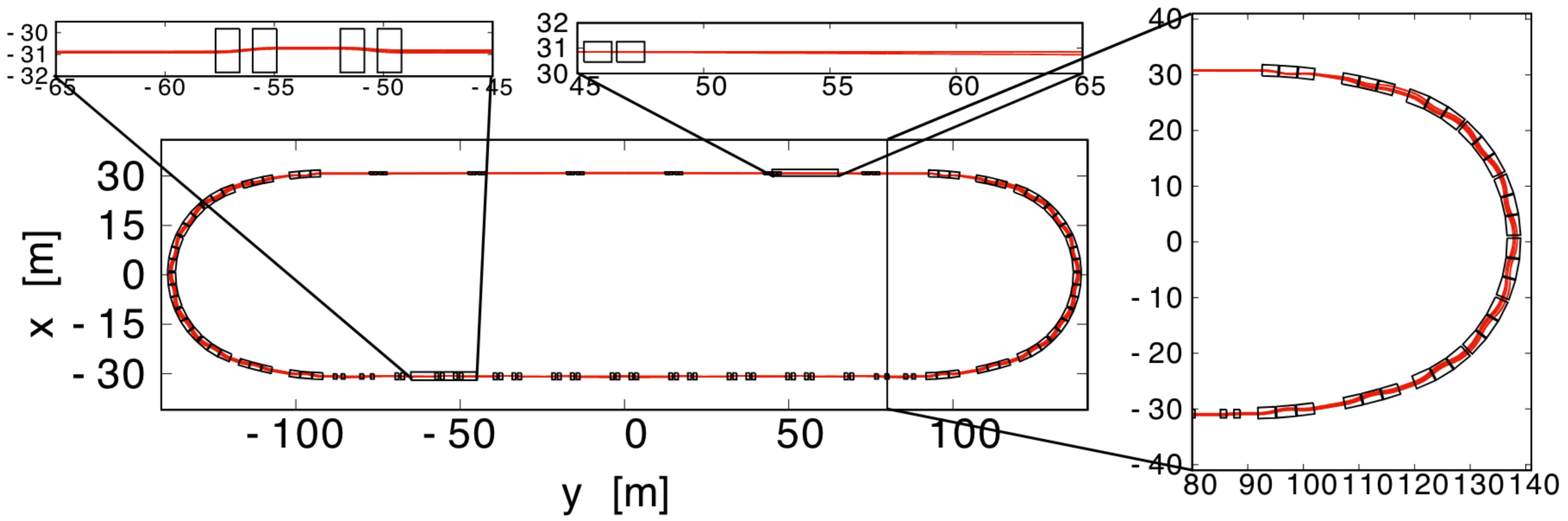
- Ongoing studies focus on beam matching for the optimised horn settings at low pion energies.

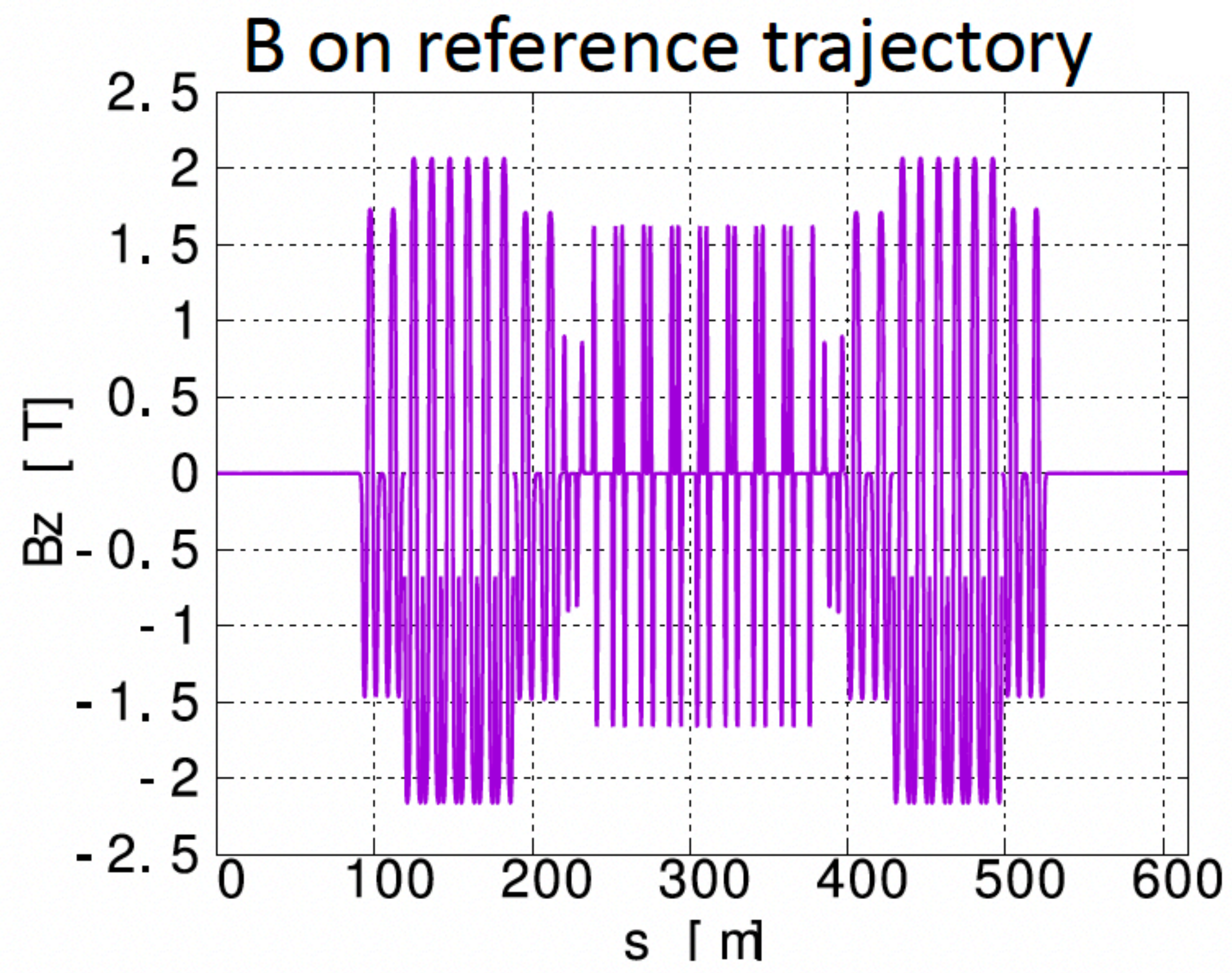




Lattice

- nuSTORM requires a large dynamic acceptance, a large momentum acceptance and a good muon capture efficiency.
- However, we need dispersion across the entire lattice in a pure FFA design, but the best capture efficiency occurs when the injected pions and recirculating muons have the same orbit (zero dispersion).
- We use a conventional FODO lattice for the production straight to minimise dispersion and hence maximise muon capture efficiency.
- The arcs consist of tightly packed FFAs for optimum neutrino production.
- The return straight consists of straight FFAs, to maximise momentum acceptance, minimising chromaticity.
- The ring design has been optimised for 3.8 GeV/c muons from 5 GeV/c pions for the aforementioned sterile neutrino study in 2014.

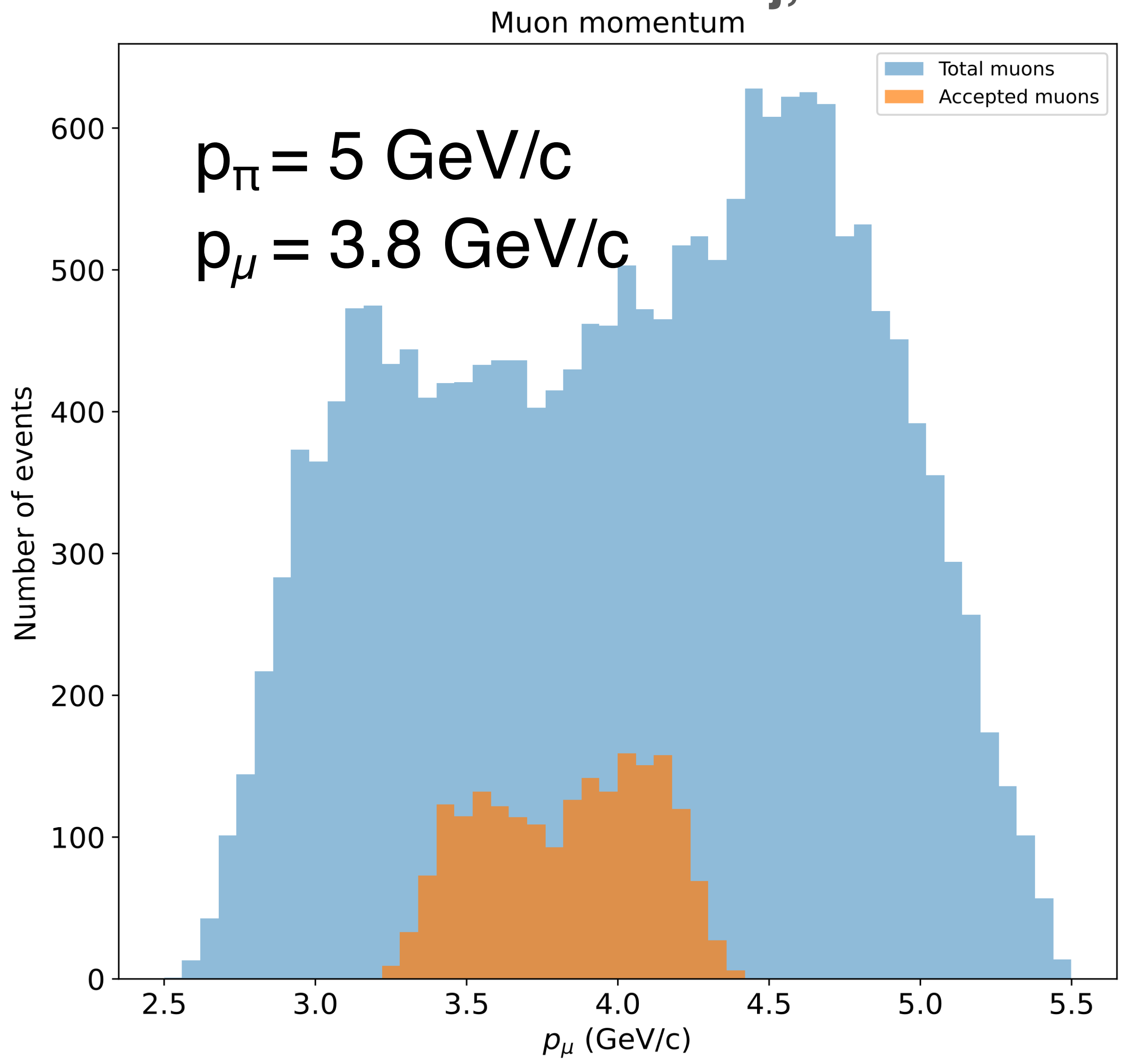


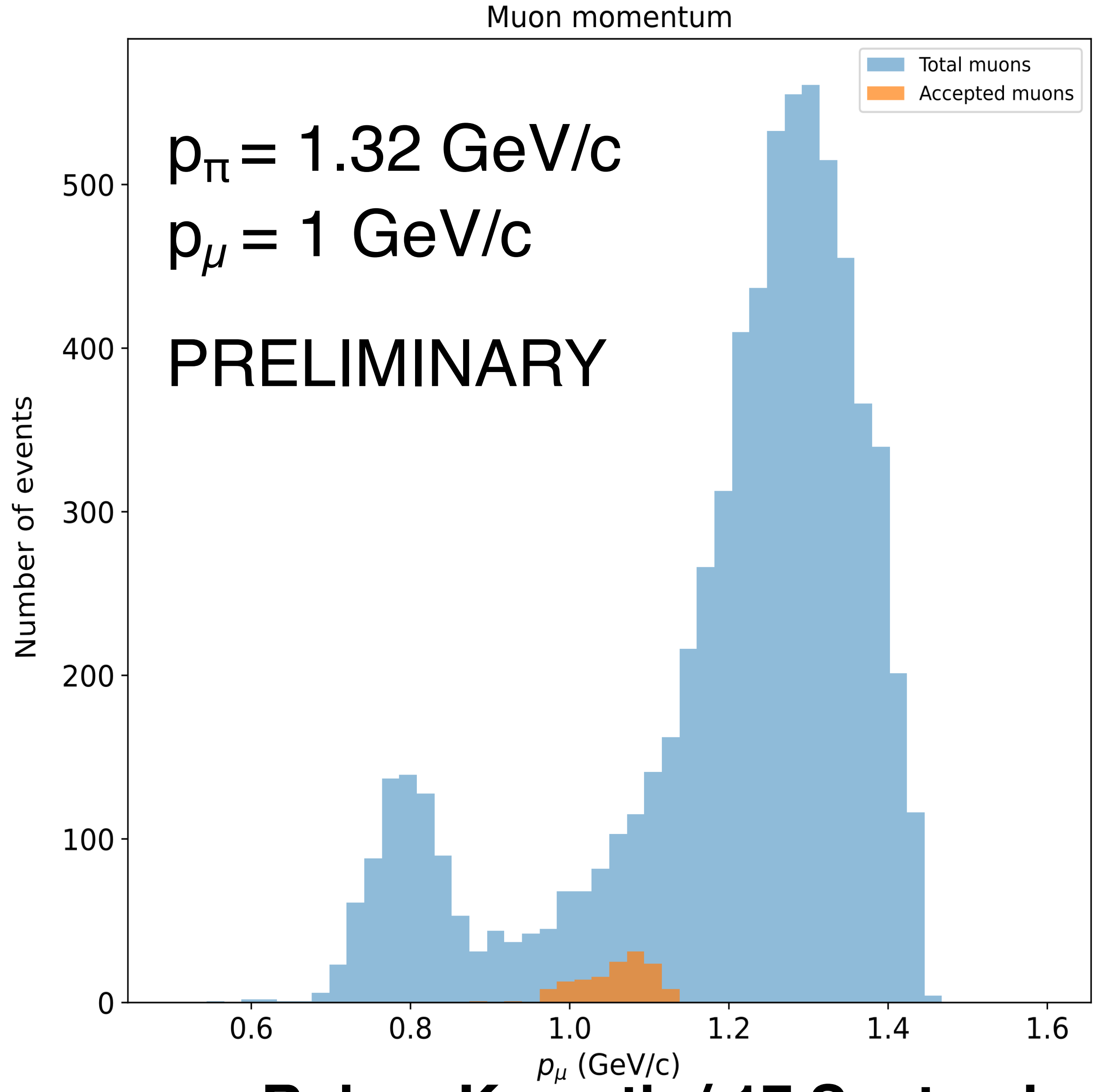


Muon production (BDSIM)

P. Jurj, T. Alves

- BDSIM is a Geant-4 based lattice simulator, and has been used to conduct a tracking study of pions and muons from horn to the end of the production straight.
- There was an investigation of the muon capture efficiency i.e. the muons accepted into the phase space of the ring as a function of muon momentum parameter of the setting.
- Baseline design: $p_\mu = 0.76 p_\pi$
- Higher momenta:
  - The muons at the end of the production straight have a characteristic trapezoidal shape,
  - Good muon capture efficiency.
- 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 aperture

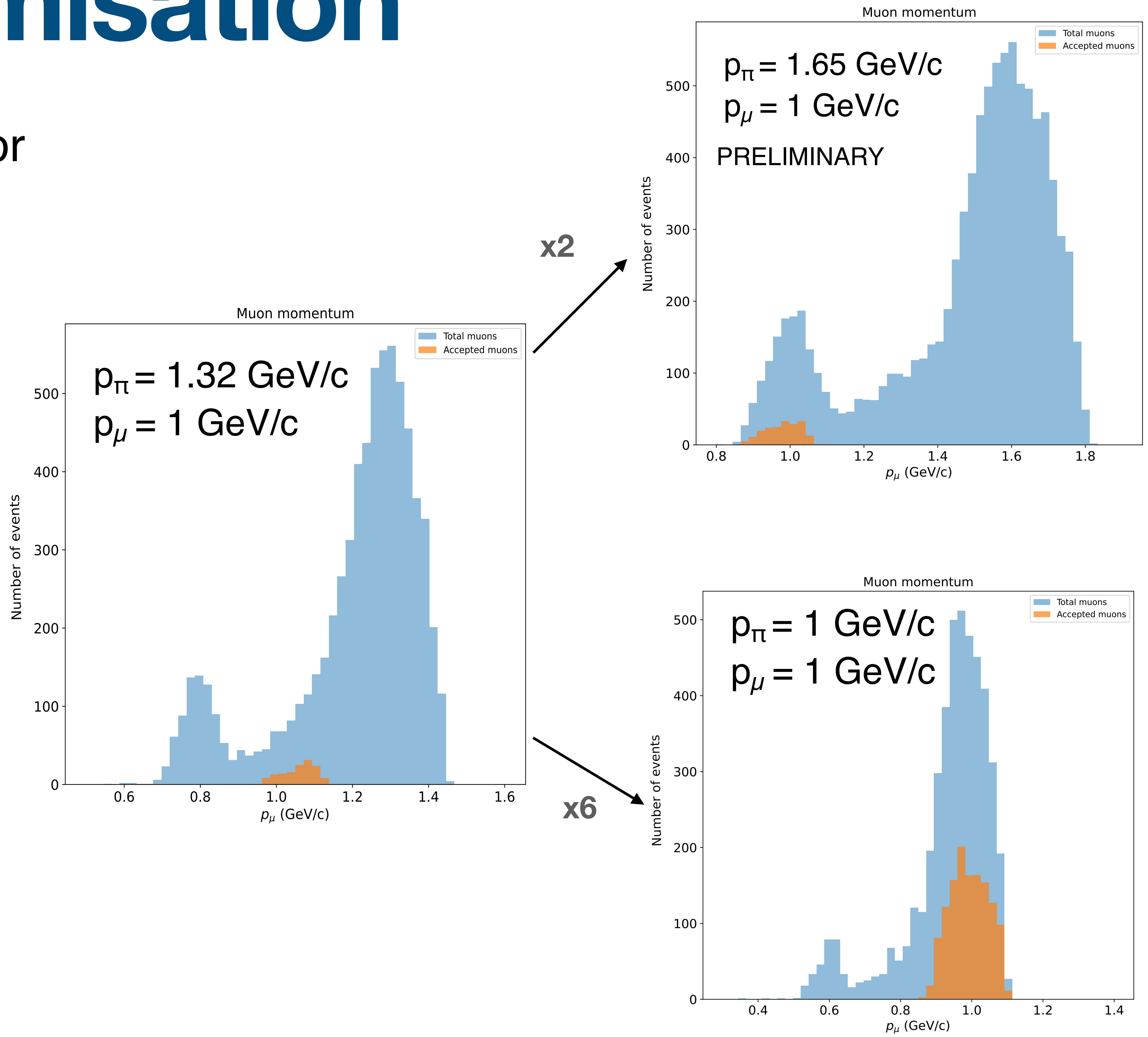




P. Jurj, P. Kyberd

Muon production optimisation

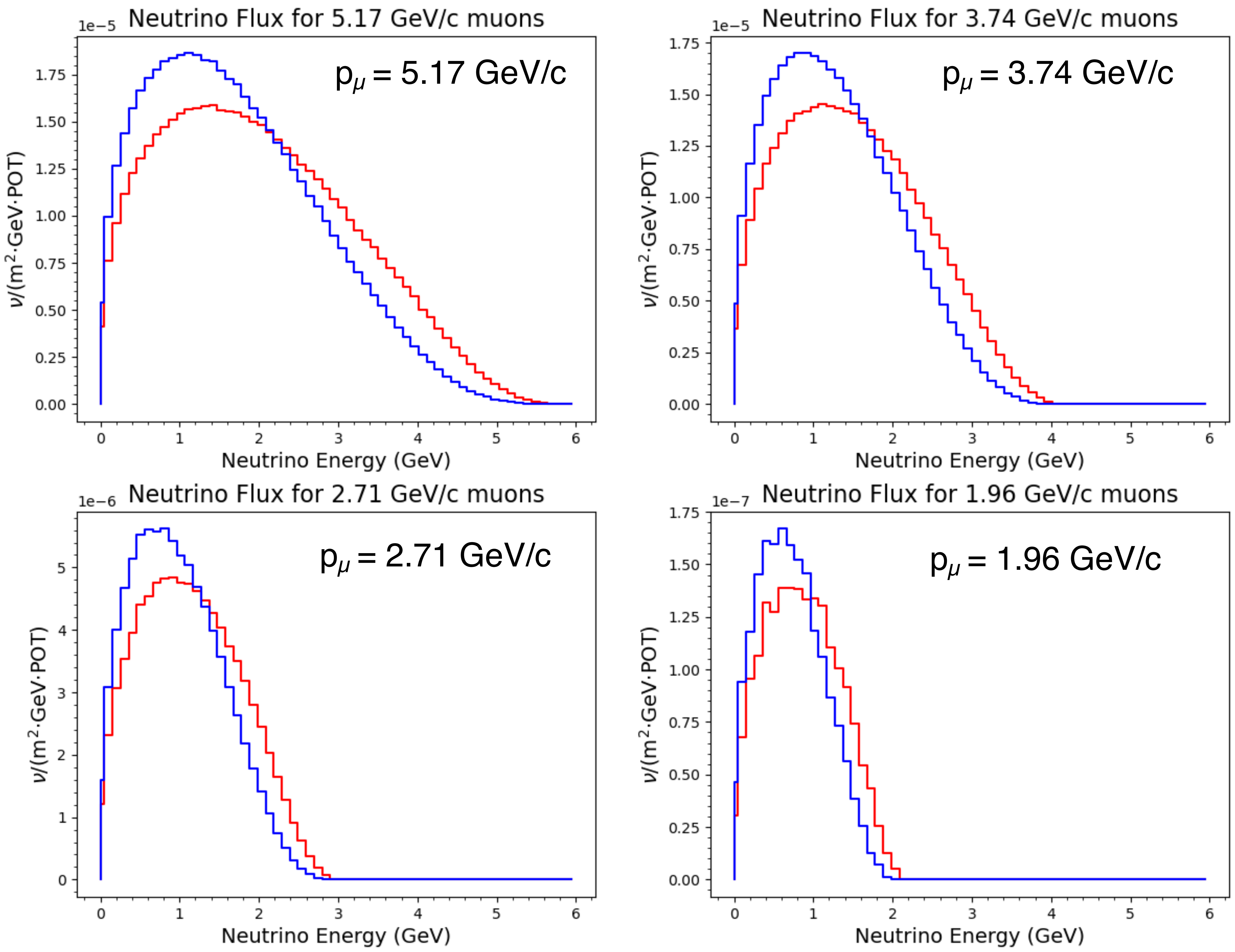
- Consider accepting muons from either the forward or backward peaks
- Observed improvements in the capture efficiency of 1 GeV/c muons (after normalising to number of protons on target)
    - Backward peak: ×2
    - Forward peak: ×6
- Study currently expanded at all stored muon momenta of interest.
- The potential implications of both acceptance settings on the lattice design and on the physics program are currently being investigated.



R. Kamath, P. Kyberd, K. Long, M. Pfaff

Simulated neutrino fluxes (nuSIM)

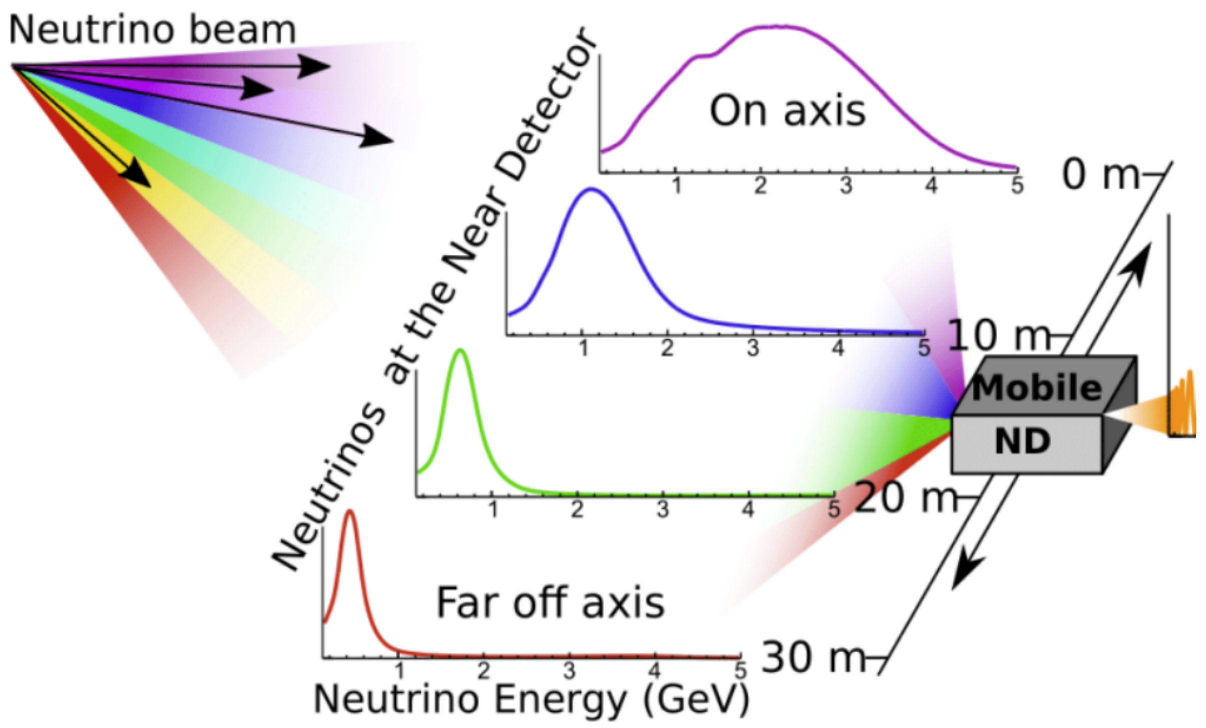
- NuSIM (NuSTORM SIMulator) - Bespoke python framework for fast simulation of the nuSTORM neutrino spectrum.
- The code can take a FLUKA pion distribution as input and simulate the neutrino spectrum at the detector.
- Six configurations of p_μ = [5.17, 3.74, 2.71, 1.96, 1.42, 1.02] GeV/c have been simulated. These numbers have been picked as they are the fewest number of settings that allow us to effectively store all muon momenta from 1-6GeV/c.
- Produced using the baseline ring configuration ($p_\mu = 0.76 p_\pi$)



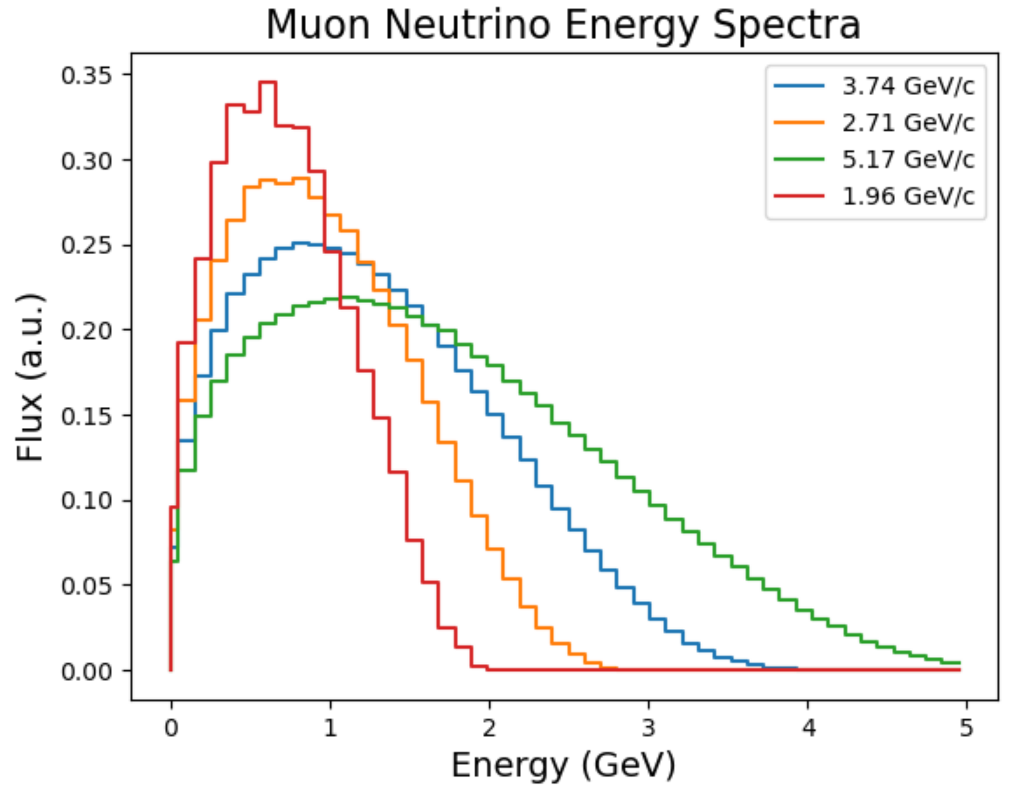
Synthetic Beams at nuSTORM

- The PRISM technique which is to be employed at Hyper K and DUNE exploits the fact that the shape of the neutrino spectrum changes with off axis angles.
- Using linear combination of these off axis spectra, synthetic neutrino beams can be made, either to model the oscillated spectrum, or to model a (quasi) mono energetic neutrino beam.
- nuSTORM: detector always on-axis, but can linearly combine fluxes from different stored-muon momenta.
- Earlier studies using 8 toy settings showed a 63% reduction of FHWM from comparison inherent muon decay spectrum.

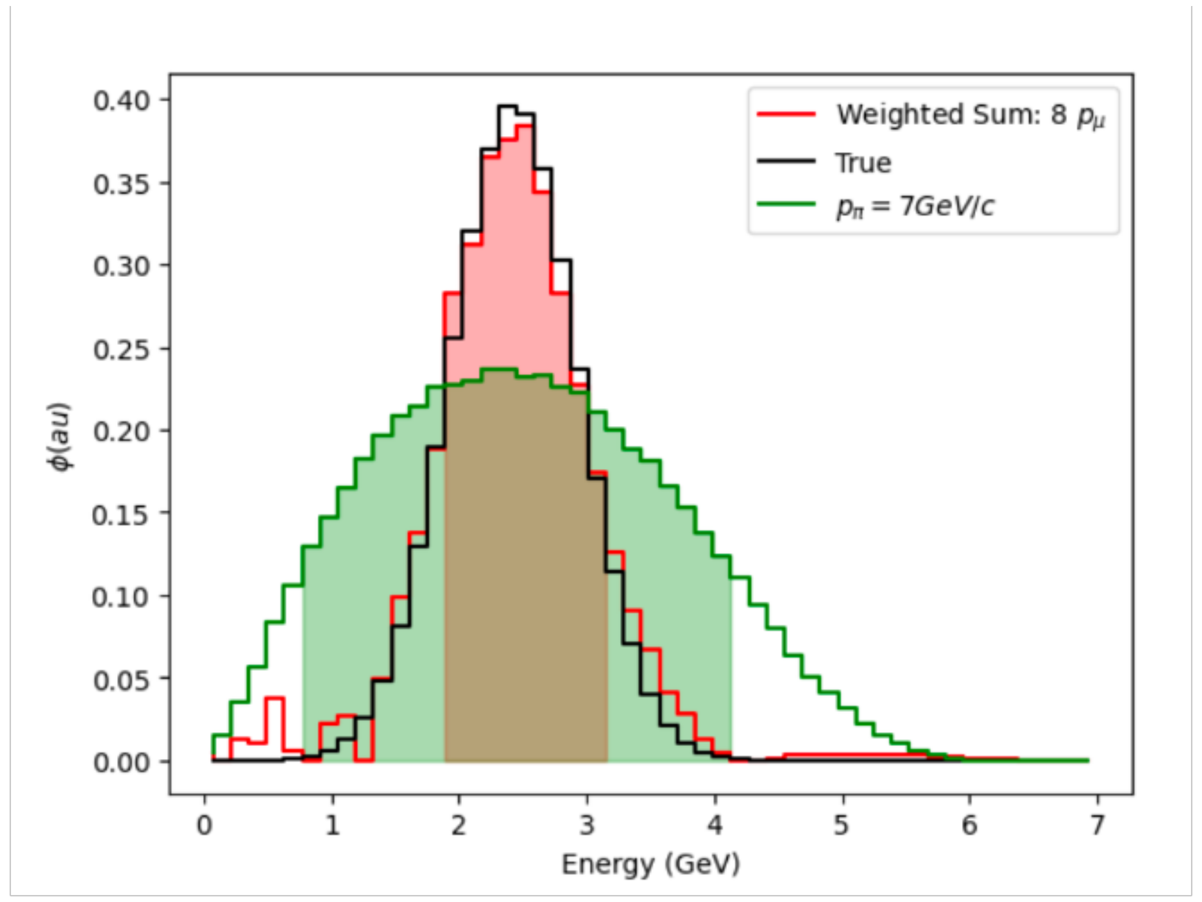
N. Ilic, IPP 50th Anniversary Symposium (28-29 May 2022)



DUNE Off-Axis



nuSTORM momentum tuning



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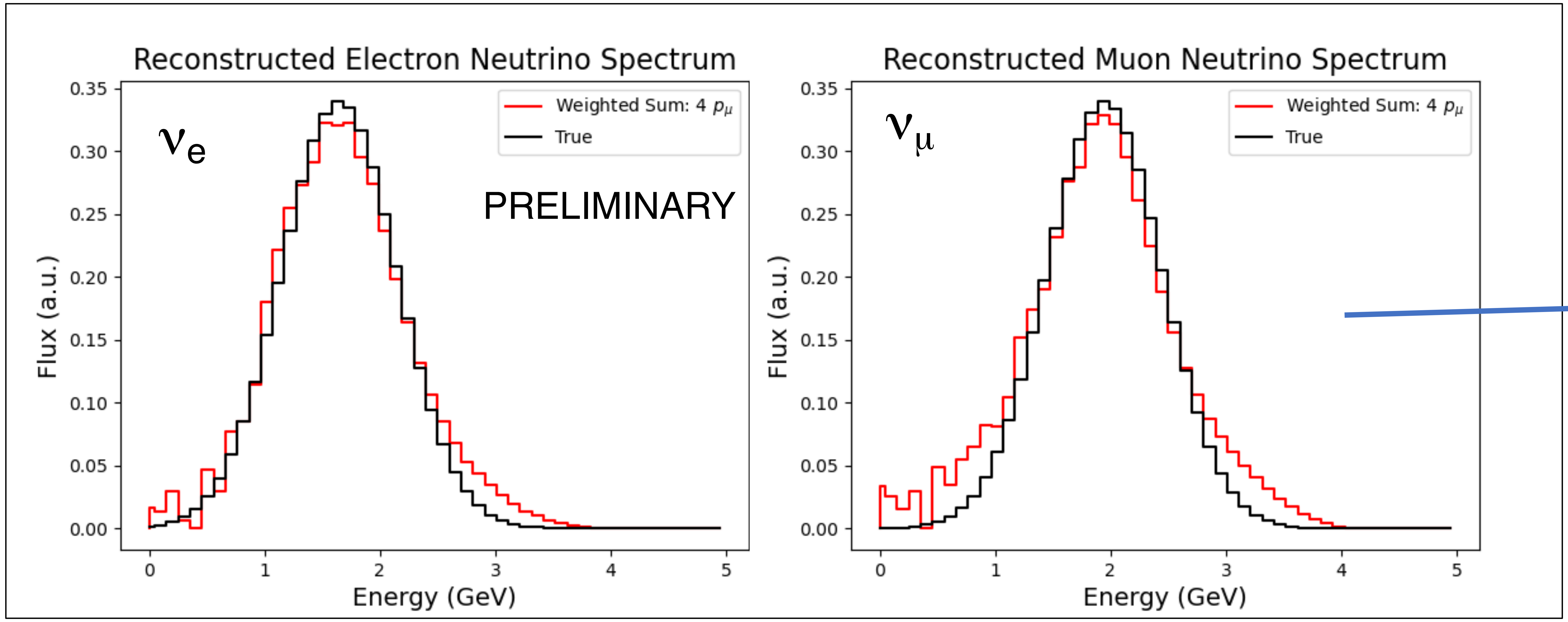
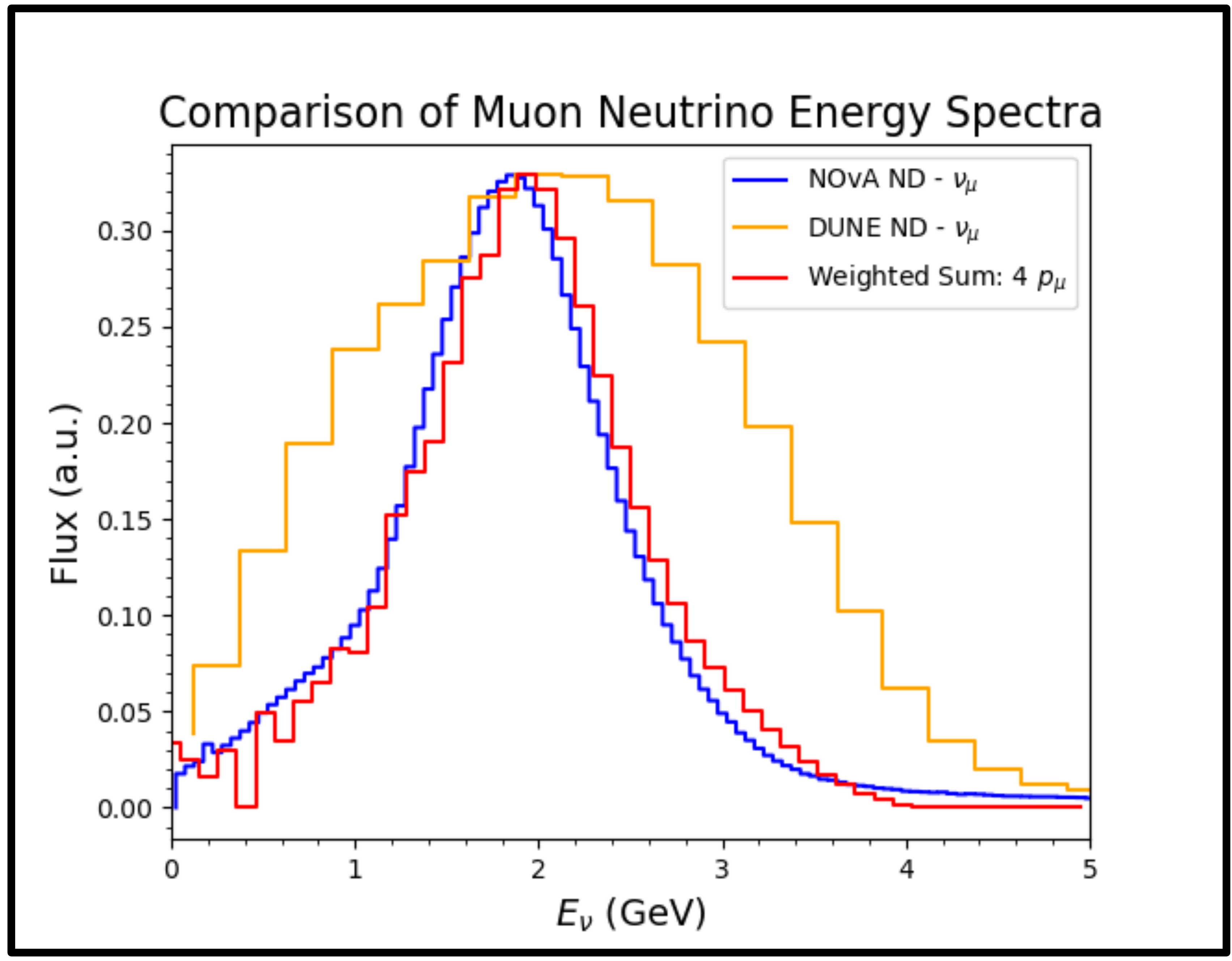




- Synthesised ν_e and ν_μ beams using fluxes from 4 muon momenta.
- Narrower beam may be achieved with more flux components
- Uniquely, synthetic electron-neutrino beams can be synthesised @ nuSTORM

Conclusion

- The neutrinos from STORed Muons (nuSTORM) experiment aims to create neutrinos from muon decay, allowing for %-level precision in the flux of neutrinos.
- This serves many ends, such as cross section analysis and beyond standard model physics searches.
- nuSTORM, which would form a part of the muon collider test facility would be synergistic with the efforts toward a muon collider, serving as a test bed for technologies for like beam monitoring.
- A hybrid FFA design for the storage ring has been presented, with high dynamical acceptance, high momentum acceptance and good muon capture efficiency.
- A study on the muon capture efficiencies has also been presented.
- The neutrino spectra from a range of stored muon momenta have been shown, along with the exploration of the feasibility of making quasi mono-energetic synthetic beams using techniques similar to nuPRISM.

Thank you!

Back up

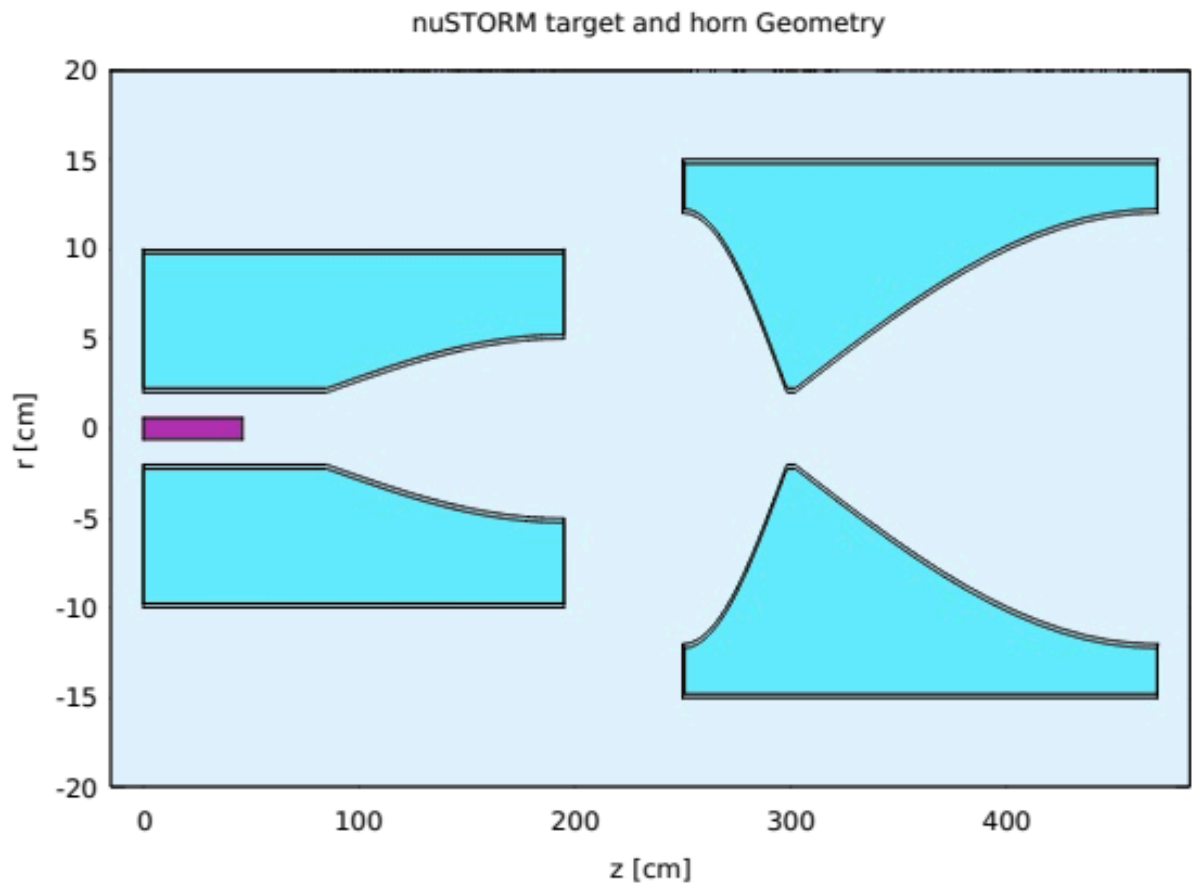
BSM Physics

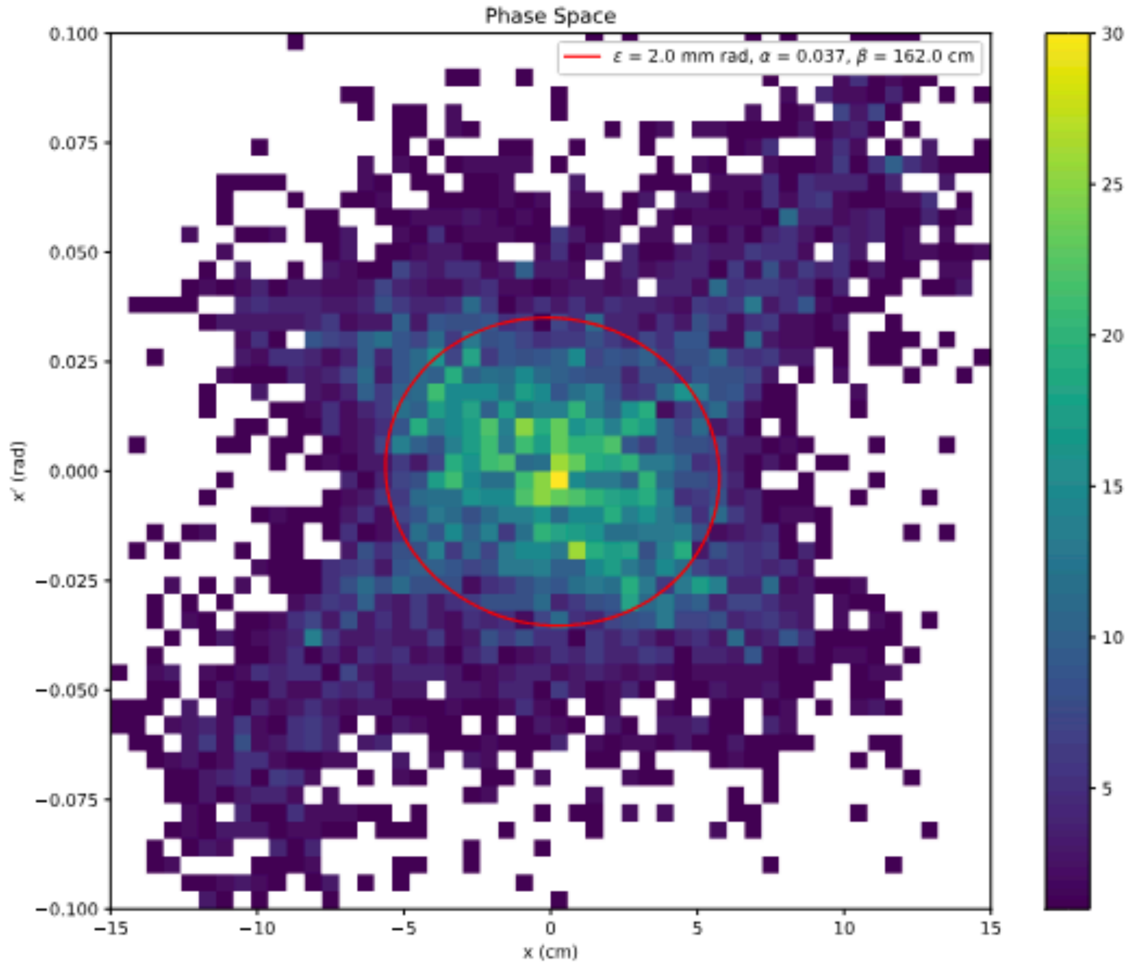
Source	3+1 Oscillations	Anomalous matter effects	Lepton flavor violation	Decays in flight	Neutrino-induced upscattering	Dark-particle-induced upscattering
Reactor	DANSS upgrade, JUNO-TAO, NEOS II, Neutrino-4 upgrade, PROSPECT-II					
Radioactive Source	BEST-2, IsoDAR, THEIA, Jinping					
Atmospheric	IceCube upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-K, THEIA				IceCube upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-K, THEIA	
Pion/Kaon decay-at-rest	JSNS[2], COHERENT, CAPTAIN-Mills, IsoDAR, KPIPE		JSNS[2], COHERENT, CAPTAIN-Mills, IsoDAR, KPIPE, PIP2-BD			COHERENT, CAPTAIN-Mills, KPIPE, PIP2-BD
Beam Short Baseline	SBN			SBN		
Beam Long Baseline	DUNE, Hyper-K, ESSnuSB			DUNE, Hyper-K, ESSnuSB, FASERν, FLArE		
Muon decay-in-flight	νSTORM				νSTORM	
Beta Decay and Electron Capture	KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE-^{39}Ar, PTOLEMY, $2\nu\beta\beta$					

Y.F. Perez-Gonzalez : Exploring the Physics Opportunities of nuSTORM (6 April 2023)

Second Horn Design

- First horn used to maximise collected pions
- Second horn used to reduce the angular divergence of the under- and overfocused pions
- Initial results for 1 GeV/c pions:
    - Yield ↗ by ~ 70% (2 mm rad)
    - Yield ↗ by ~ 105% (1 mm rad)
    - Optimisation still required





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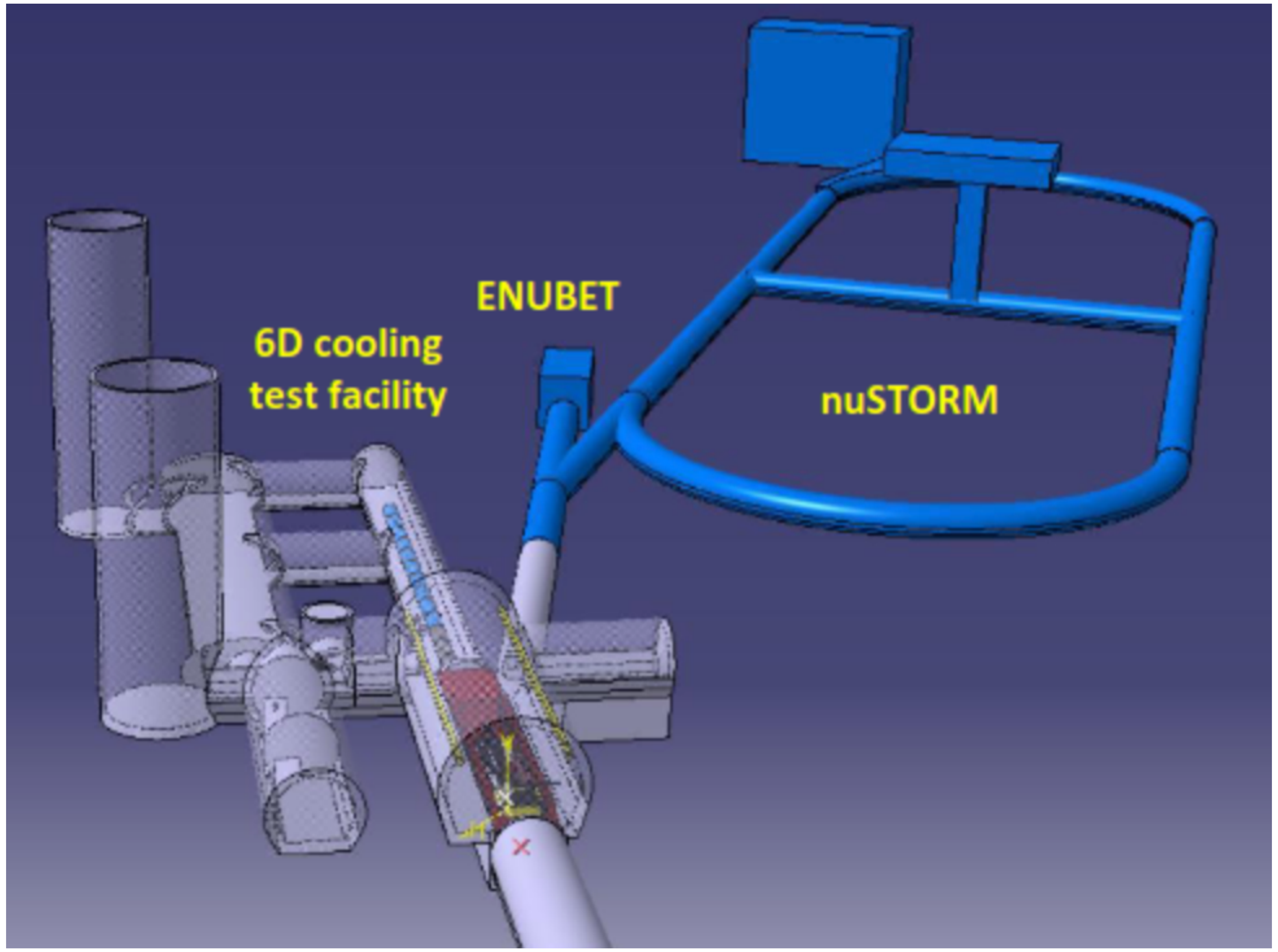

Creating the synthetic beam

- For each muon (pion) momentum setting p_μ we obtain a flux $\phi_i(E_\nu)$.
- Weighting each of these spectra with a coefficient c_i, we can create linear combination of these fluxes $\Phi_{LC}(E_\nu)$ like so:

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

Figure of Merit of the Synthetic Beam

- We optimise for the coefficients using the following Figure of Merit (FOM) equation:

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

- Here, parameters A and B can be tuned to change the weighting of the the chi-sq fit by the flux in each bin.
- We also add a constraint that $\Phi_{LC} > 0$ for all E_ν.