The neutrinos from STORed Muons (nuSTORM) facility

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on behalf of the nuSTORM Collaboration

Introduction

- Neutrinos from Stored Muons (nuSTORM) is an experiment that aims to create a neutrino flux with %-level precision from muon decay in a racetrack shaped storage ring.
- The ring can be tuned to accept muons with momenta in the 1-6 GeV/c range which consequently decay into electrons, muon and electron neutrinos.
- nuSTORM's high brightness muon beam and %-level neutrino flux precision, with equal ν_μ and ν_e production rates, enables diverse physics applications for both particle and accelerator physics communities, such as precise cross section measurements, BSM searches, and muon collider development.

Scientific Programme

Cross Section Measurements

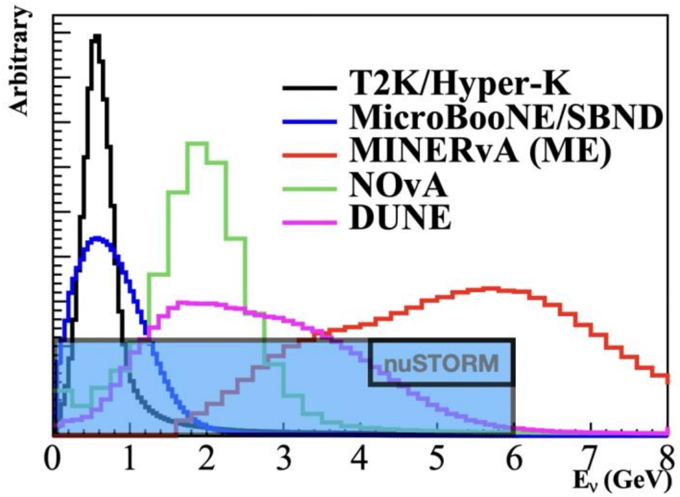
- The tuneable muon storage ring enables customization of the neutrino energy spectrum to match current and future long-baseline experiments, providing critical constraints on cross-section models.

Beyond Standard Model Physics

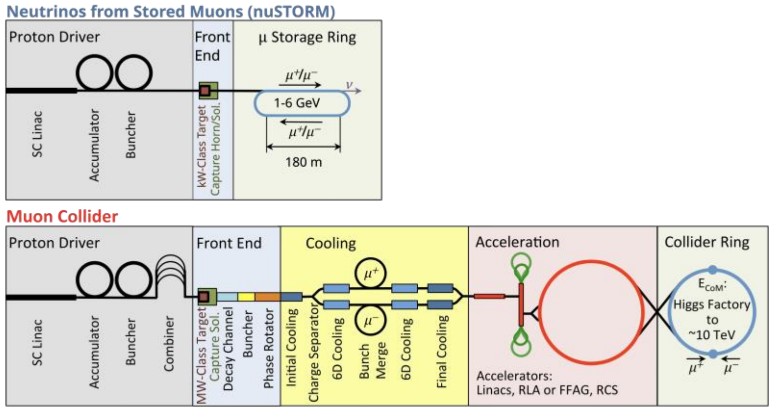
- The combination of a precisely known flux with high-statistics measurements allows nuSTORM to be sensitive to exotic and rare scattering processes.

Muon Collider Demonstrator

- nuSTORM's muon storage technology shares key design elements with muon collider development, serving as a valuable testbed for target systems, magnetic components, and beam instrumentation.
- A Muon Collider Demonstrator complex is proposed at CERN, featuring shared infrastructure between nuSTORM and the 6D cooling test facility, maximizing synergies in targetry and capture systems.



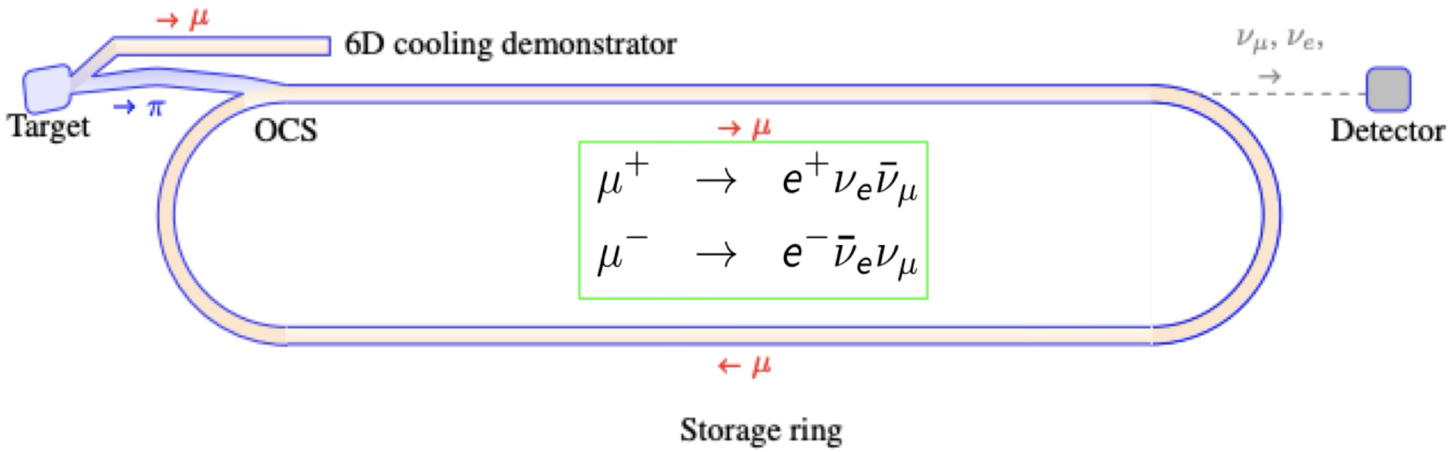
Original plot: Katori T. YETI2019, Jan. 7, 2019



Adapted from M. A. Palmer
IPAC'14, DOI: 10.18429/JACoW-IPAC2014-TUPME012

Layout

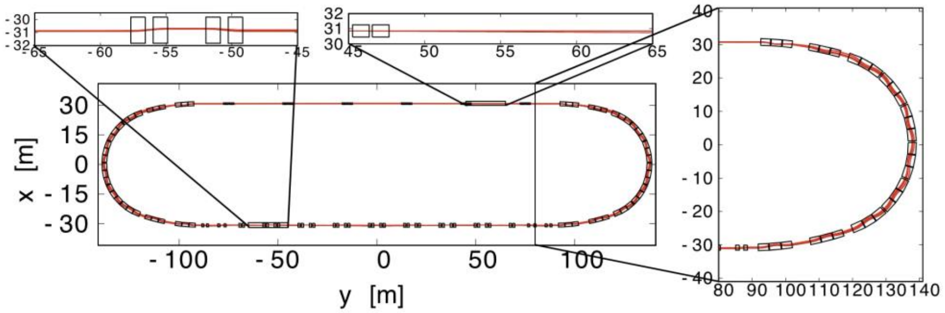
- Pions are created using a proton driver scheme, captured by a magnetic horn and injected into the ring along the production straight.
- The pions decay into muons along the production straight, creating a “flash” of muon neutrinos at a detector downstream. The muons which are accepted into the ring circulate and subsequently decay to produce muon and electron neutrino signals.
- 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 $p_\mu \pm 16\%$. The two momenta are related as $p_\pi = 0.76 p_\mu$.
- This separation ensures that undecayed pions do not circulate in the ring, whilst ensuring the physical aperture of the magnet is constrained to be as small as possible.
- Low momentum pions from the target can be used by the 6D Cooling demonstrator experiment.

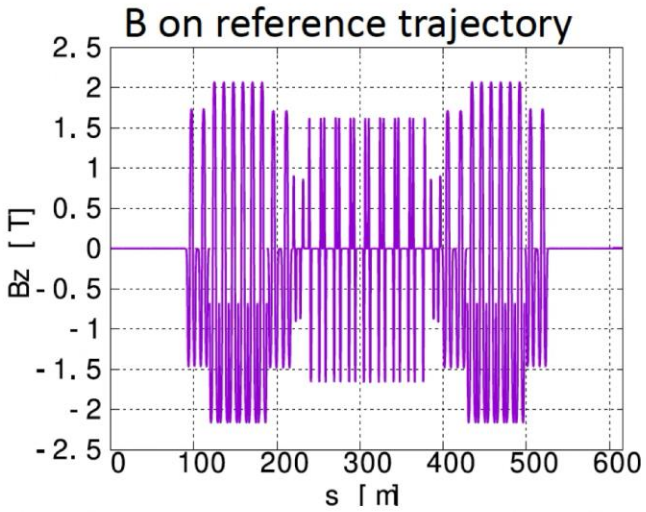


J.B. Lagrange, J. Pasternak

Physics & Design Motivations

- nuSTORM requires a large dynamic acceptance, a large momentum acceptance and a good muon capture efficiency.
- This can be achieved with a Fixed Field Alternating Gradient (FFA) lattice.
- We need dispersion across the entire lattice in a pure FFA design, however, the best capture efficiency occurs when the injected pions and recirculating muons have the same orbit (zero dispersion).
- We use a conventional normal conducting FODO lattice for the production straight to minimise dispersion and hence maximise muon capture efficiency.
- The arcs consist of tightly packed super conducting FFAs for optimum neutrino production.
- The return straight consists of normal conducting 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.

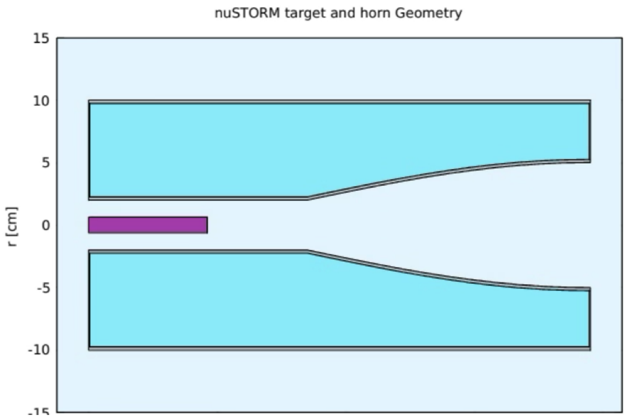


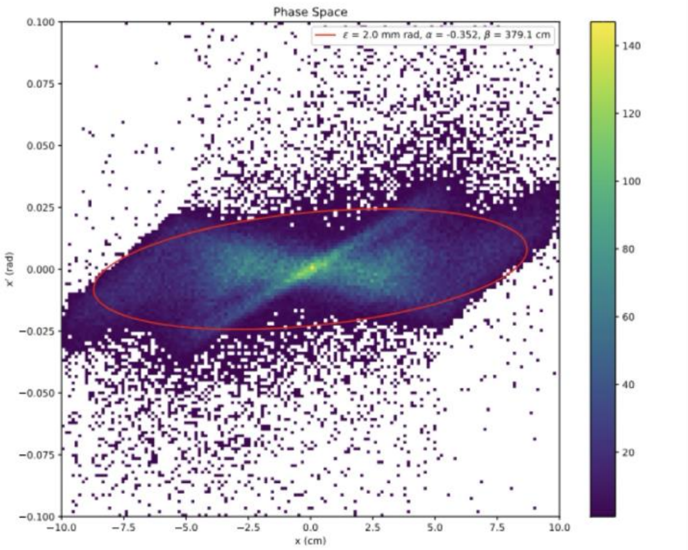


P. Jurj, J. Back

Siting, Targetry and Capture

- Current horn studies and optimization are specifically configured for a CERN installation, utilizing SPS or PS systems based on the proposed muon collider demonstrator siting in the TT10 area (CERN-PBC-REPORT-2019-003)
- Target simulations are performed using FLUKA with an Inconel target of dimensions L = 46 cm and r = 6.3 mm
- The magnetic horn operates with variable current, with 219 kA identified as optimal for 5 GeV/c pion production
- Ongoing studies focus on horn optimization for low-energy pions.





T. Alves, P. Jurj

Beam Tracking Studies

BDSIM, a Geant4-based lattice simulation tool, was employed to track pions and muons from the horn through to the end of the production straight section

- Muon capture efficiency analysis examined the fraction of muons accepted into the ring's phase space as a function of muon momentum

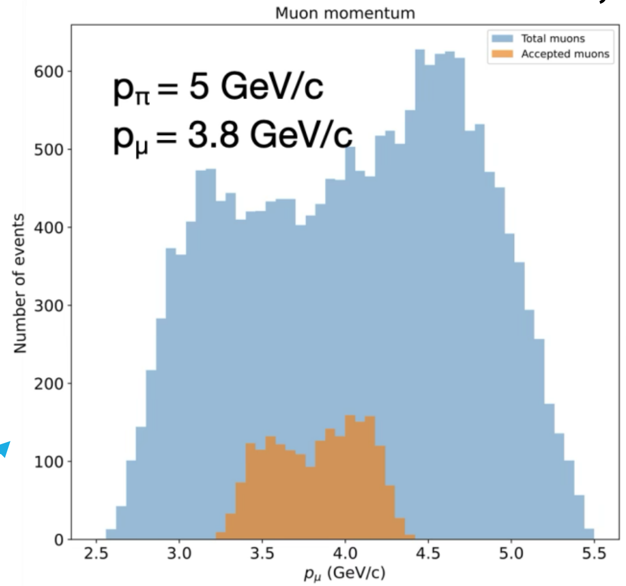
High momentum regime:

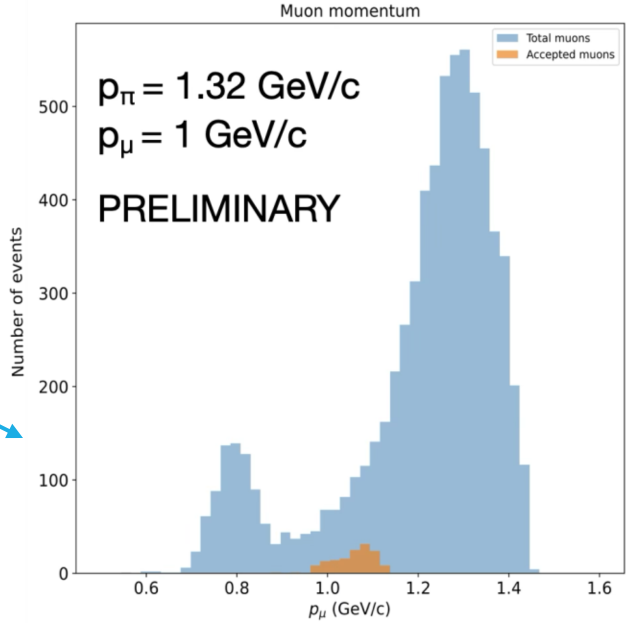
- Muons at the production straight exit exhibit a characteristic trapezoidal momentum distribution
- Achieves good muon capture efficiency into the storage ring

Low momentum regime:

- Momentum distribution shows distinctive double-peak structure with a valley at the target muon momentum
- Results in reduced muon capture efficiency

Physical mechanism: Lower momentum muons experience reduced Lorentz boost, causing decay products with significant transverse momentum to have larger angular divergence, leading to losses at the accelerator aperture





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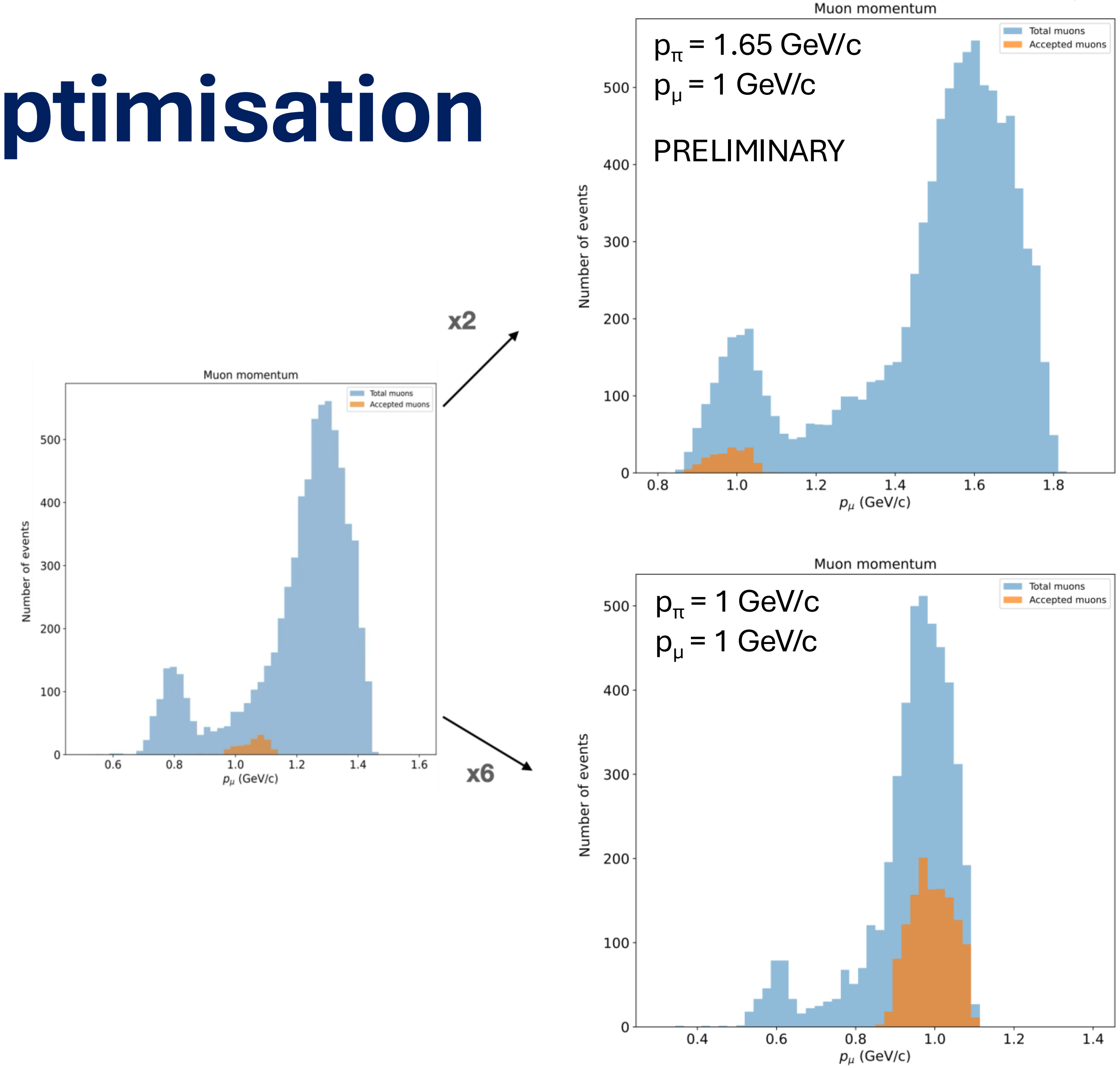
Muon Production Optimisation

Mitigation Strategy

- Alternative capture scheme investigated whereby muons are selectively accepted from either the forward or backward momentum peaks of the double-peak distribution

Performance Enhancement Results

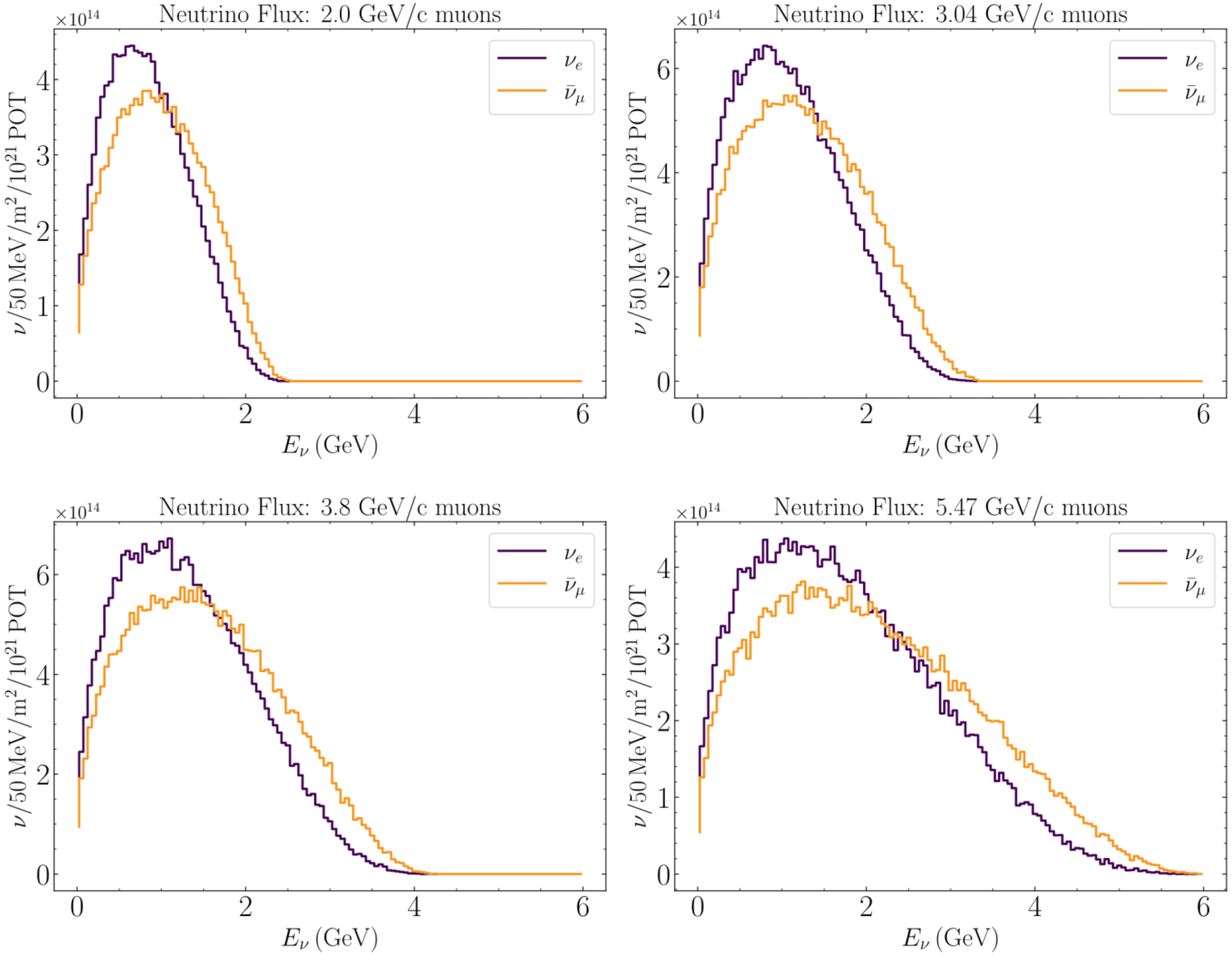
- Significant improvements observed in capture efficiency for 1 GeV/c muons (normalized to protons on target):
- Backward peak selection: ×2
- Forward peak selection: ×6



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

Neutrino Flux Simulations

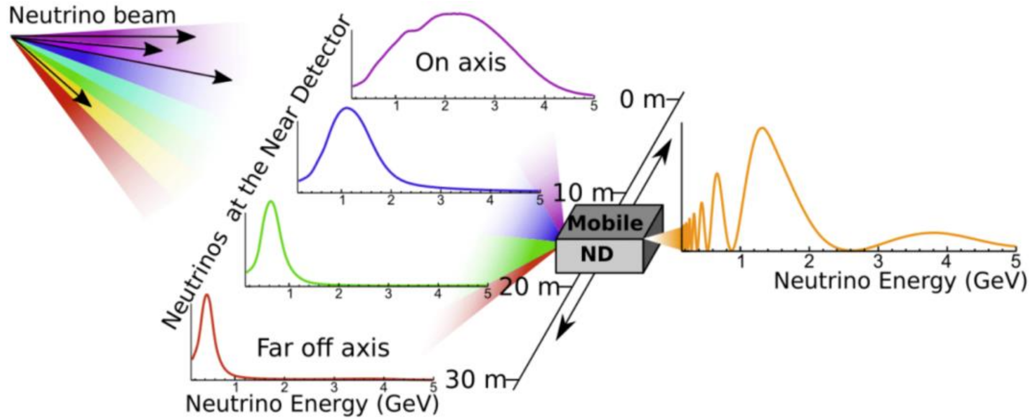
- NuSIM (NuSTORM SIMulator) - Bespoke Python framework for fast simulation of the nuSTORM neutrino spectrum.
- The code can take a FLUKA pion distribution as input and simulate the neutrino spectrum at the detector.
- Six configurations of stored muon momenta have been simulated. These numbers have been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

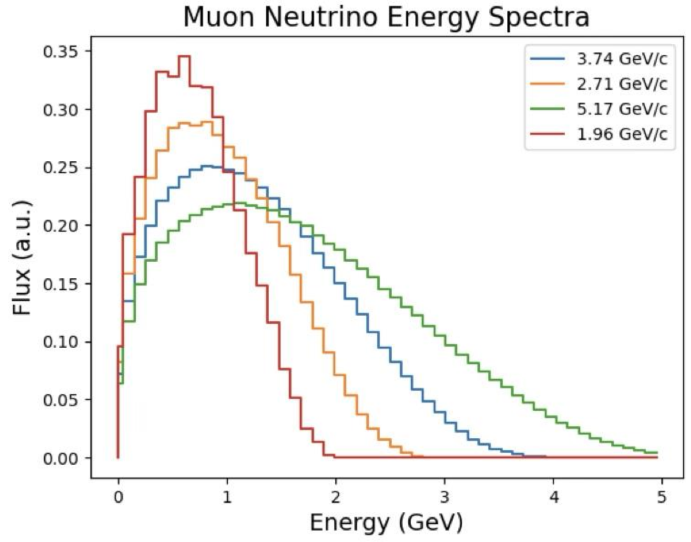


R. Kamath

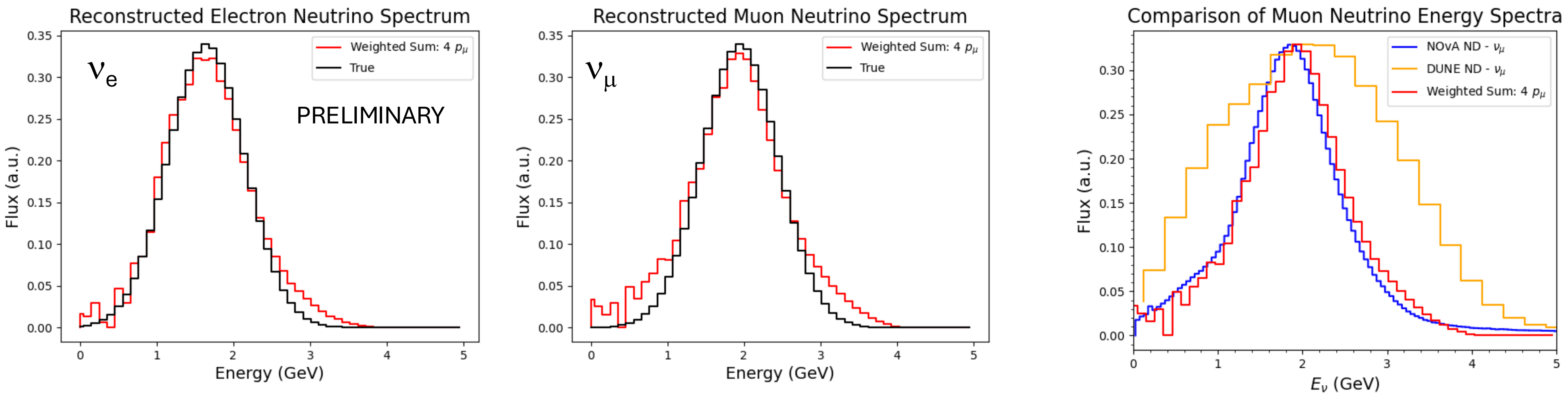
Synthetic Neutrino Beams @ nuSTORM

- The PRISM technique, to be implemented at Hyper-K and DUNE, leverages the systematic variation of neutrino energy spectra as a function of off-axis beam angles
- nuSTORM operates with the detector positioned on-axis but achieves spectral flexibility through linear combination of neutrino fluxes from different stored muon momentum configurations
- These can be used to generate quasi-monoenergetic (Gaussian) neutrino beams to constrain cross section models.
- Uniquely, synthetic **electron-neutrino** beams can be synthetised at nuSTORM.





Synthetic Neutrino Beams @ nuSTORM



- Synthetised ν_e and ν_μ beams using fluxes from 4 muon momenta.
- Dual binning schemes utilizing both stored muon momentum and off-axis angle (determined by interaction vertex position) to achieve superior spectral control and precision are currently under investigation.

Updates...

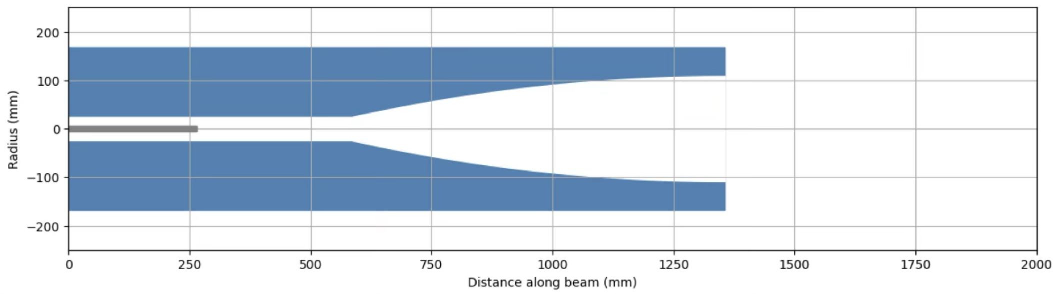
- Systematic tracking studies reveal that muon capture efficiency exhibits significant momentum dependence, with reduced performance in the low-energy regime directly impacting achievable neutrino flux levels
- Current research efforts are pursuing a two-pronged approach:
  - First, quantifying baseline sensitivity projections within the existing lattice configuration to establish performance benchmarks
  - Second, investigating potential lattice modifications to mitigate low-energy capture losses
- Parallel optimization studies focus on enhancing upstream pion production through systematic horn geometry refinements, providing an alternative pathway to flux improvements that partially offsets muon capture efficiency limitations.

R. Kamath, P. Jurj

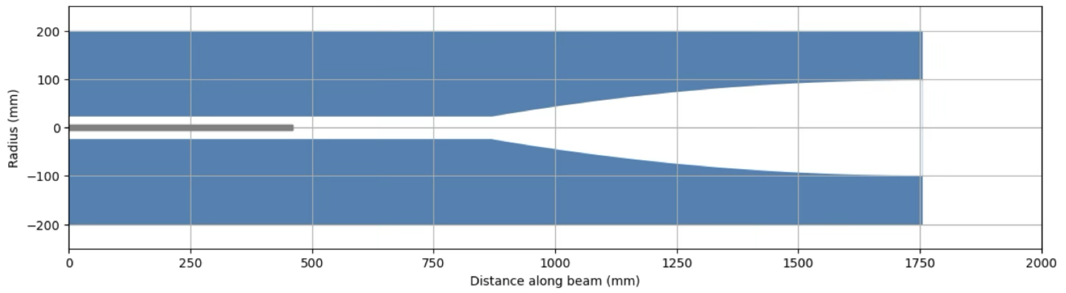
Bayesian Optimisation

- The baseline nuSTORM magnetic horn is optimized for 5 GeV/c muons to support sterile neutrino searches, but this design produces suboptimal pion yields at lower energies.
- To address this limitation, Bayesian optimization was performed at two different pion energies to determine optimal horn configurations for each energy regime.
- Separate optimizations were conducted for 2 GeV/c and 5 GeV/c pions (±10% acceptance) using 100 GeV protons on an Inconel target.
- Method and preliminary results have been presented at IPAC 25.
- Significant yield improvements vs. baseline: **+104.3%** (2 GeV/c pions) and **+38.3%** (5 GeV/c)
- Outstanding work:
  - confirm the phase space of the pions collected with the optimized design can be efficiently transported to the ring,
  - Recalculate sensitivities using increased yield.

2GeV/c Optimised Horn



5GeV/c Optimised Horn



Assumption for Physics Studies

- Improvements from Bayesian Optimisation not taken into account yet
- Simulated neutrino flux used in studies assumes:
  - regular flux from decays, i.e. no synthetic beams used
  - 10^{21} POT
  - 5m x 5m detector front face, 50m down stream of the end of the production straight

Neutrino Interaction Study:

- ND-GAr type detector

(Beyond) Standard Model Studies:

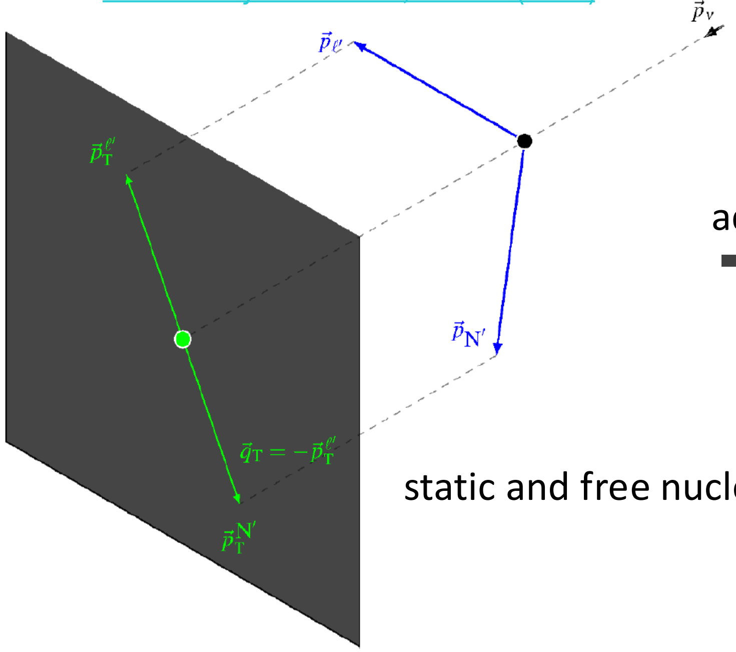
- ProtoDUNE-type (LArTPC) detector with 100t fiducial volume

W. Chang, M. Pfaff, X. Lu

Neutrino Nucleus Interaction Studies

- First cross-section studies conducted using Transverse Kinematic Imbalance (TKI) variable $\delta\alpha_T$.
- TKI introduces a set of energy-independent variables quantifying the momentum imbalance in the transverse plane.
  - This allows the study of nuclear effects in both, the initial and final state independent of nucleon model uncertainties.

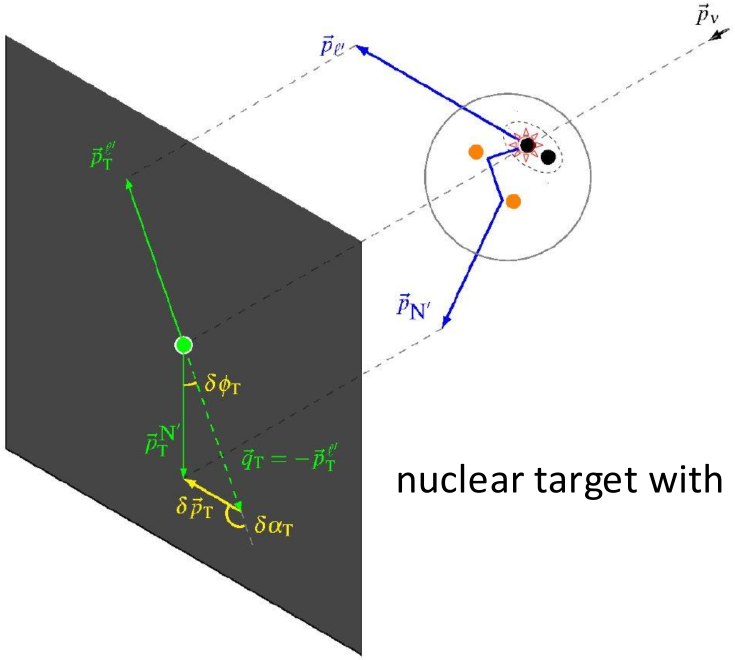
Lu *et al*. Phys. Rev. C **94**, 015503 (2016)



static and free nucleon target

additional nucleons

Lu *et al*. Phys. Rev. C **94**, 015503 (2016)



nuclear target with A > 1

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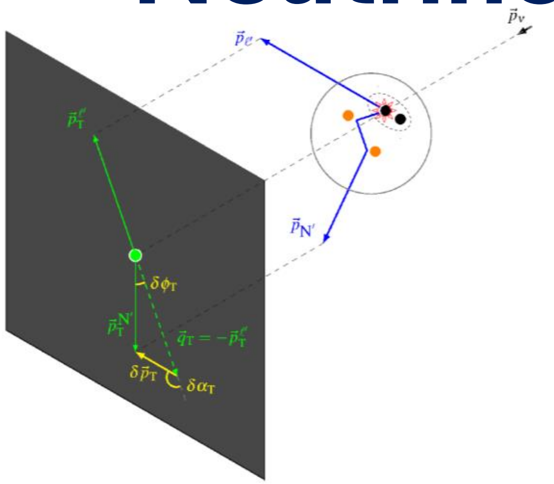
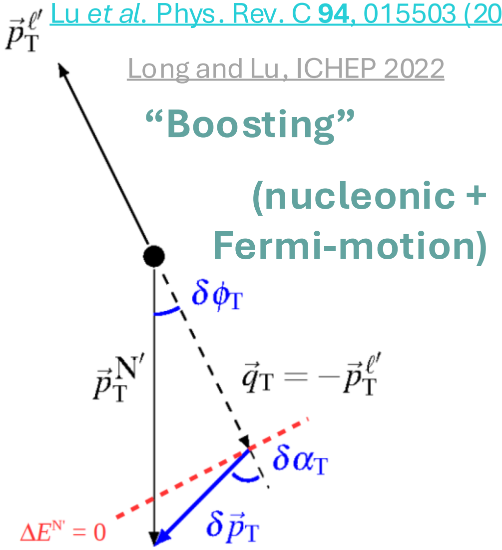
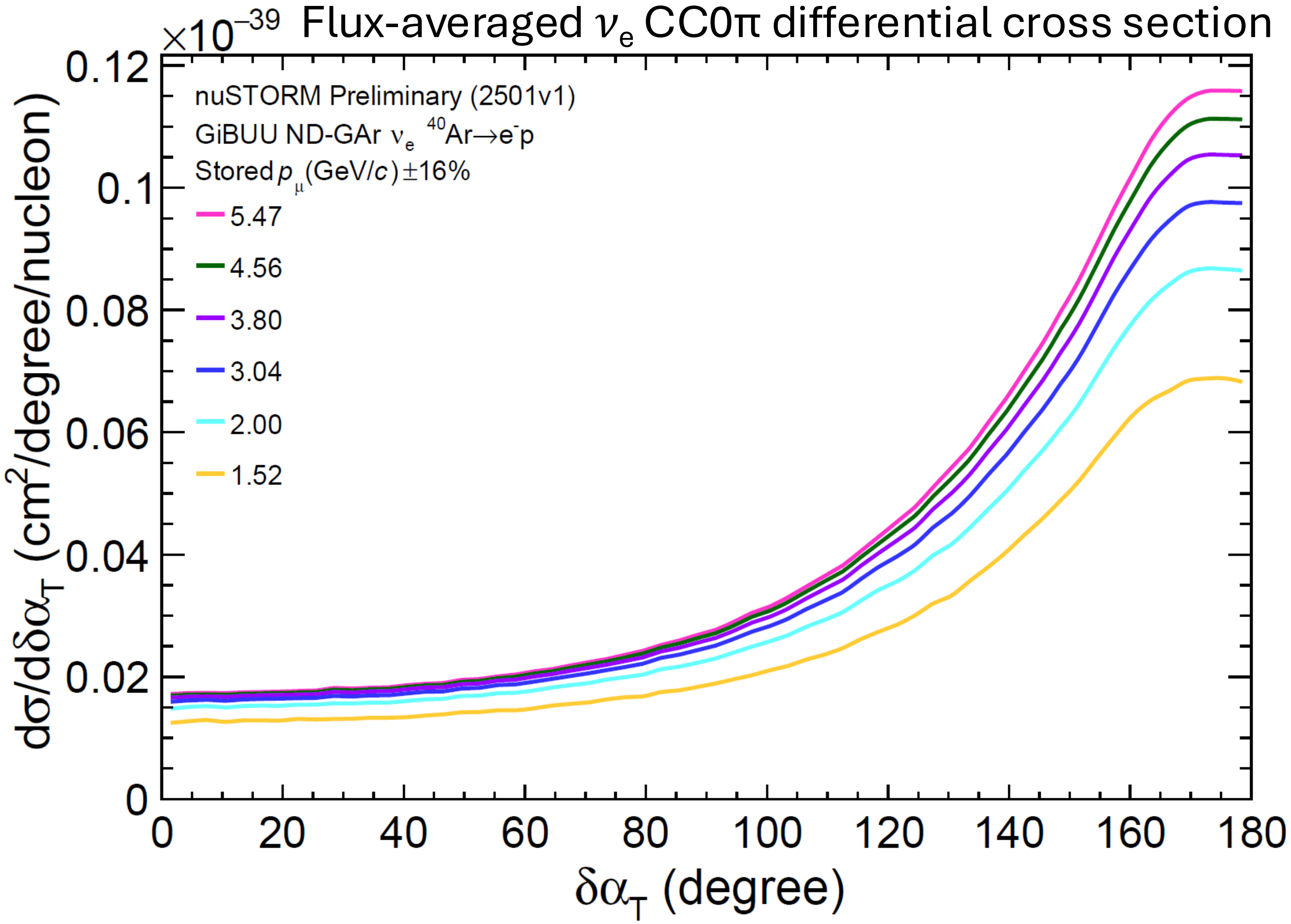
Neutrino Nucleus Interaction Studies

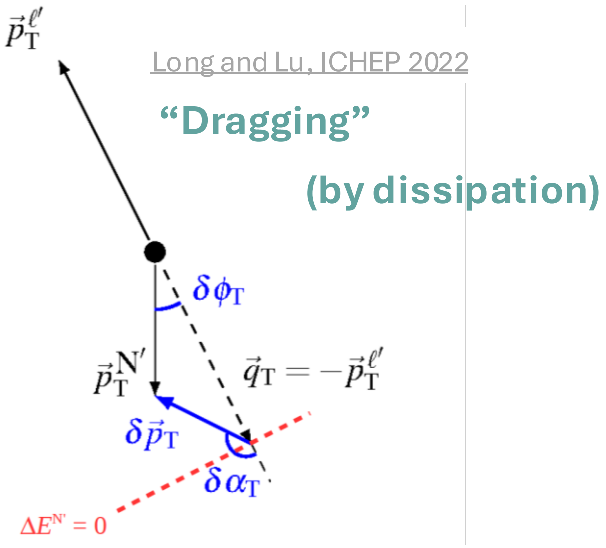


Transverse boosting angle

Lu *et al.* Phys. Rev. C **94**, 015503 (2016)



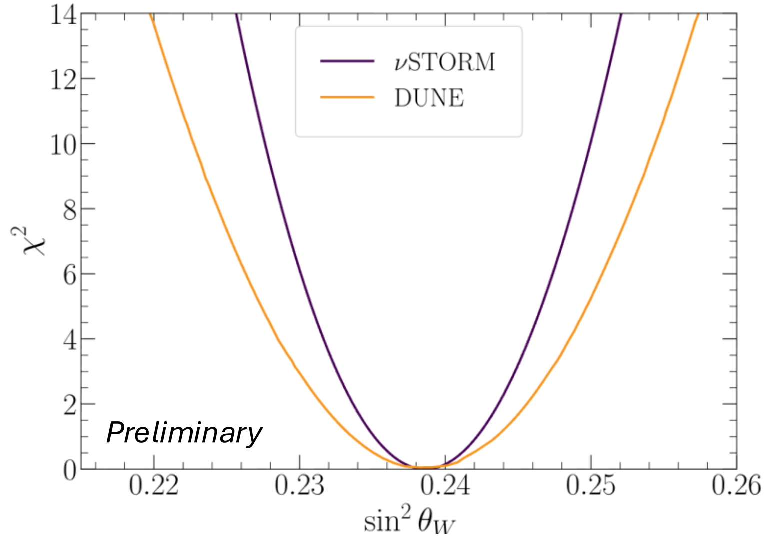




D. Pesari, Y. Perez-Gonzales
J. Turner, A. Vogiatzi

Standard Model (SM) Precision Measurements

- nuSTORM can make several Standard Model precision measurements.
- The most precise measurement result of the weak mixing angle from neutrino scattering (NuTEV) is in tension with LEP result
- The nuSTORM sensitivity is competitive with DUNE ND through precision neutrino-electron scattering measurements.
- nuSTORM is in the unique position to measure these with high statistics ν_μ and ν_e samples and can therefore break degeneracies with the flux normalisation.



paper on arXiv soon!

D. Pesari, Y. Perez-Gonzales
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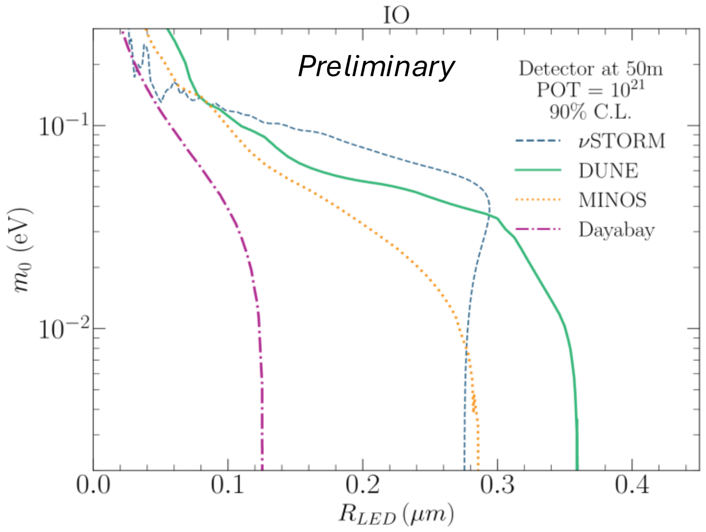
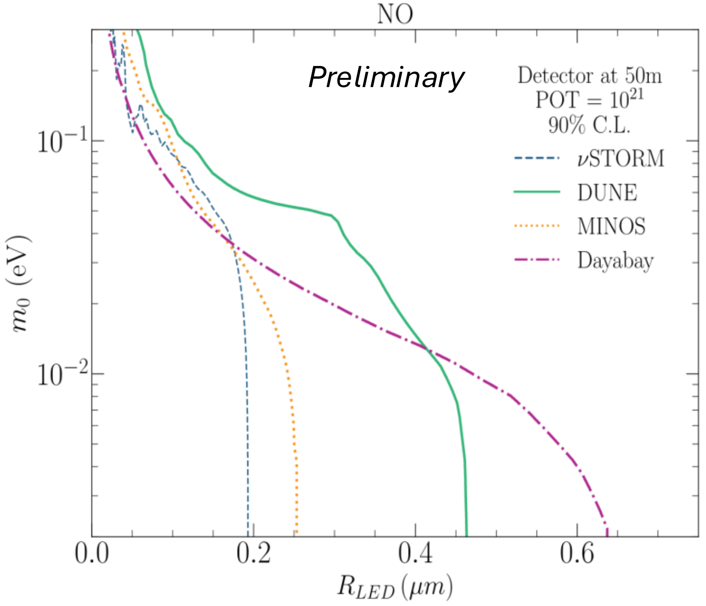
Beyond Standard Model (BSM) Measurements

- nuSTORM additionally has sensitivity to several new physics measurements.
- Large Extra Dimensions (LED) could explain the lightness of neutrino masses and the weakness of gravity.
- Using a protoDUNE like detector with 50 m baseline, nuSTORM has sensitivity to μm LED length scales.
- nuSTORM can set stringent limits on the LED length scale especially in the NH regime, due to an intense ν_μ beam from pion and muon decay.





paper on arXiv soon!

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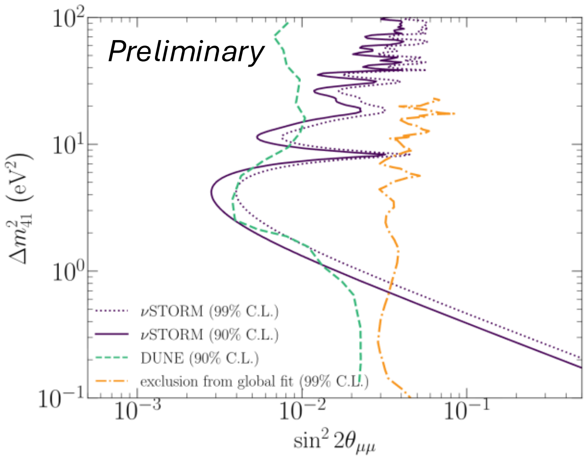
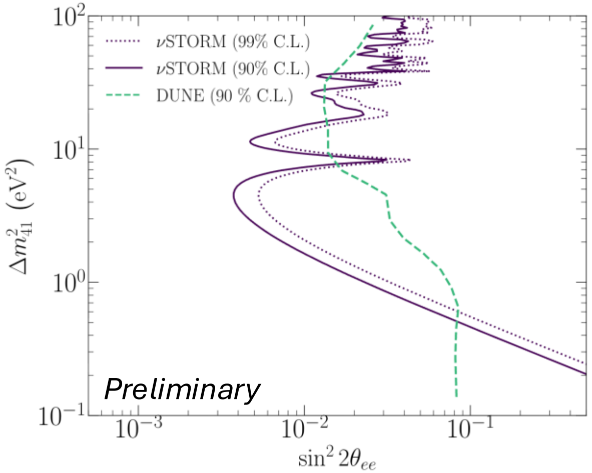
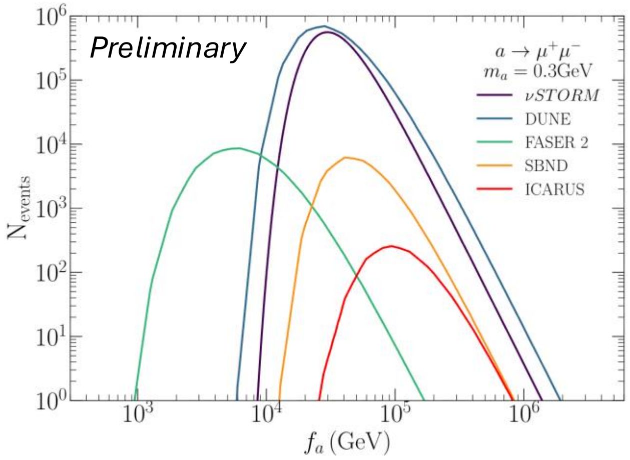
Other Recent (B)SM Sensitivity Studies

- nuSTORM can constrain the presence of an additional light sterile & is complementary to other short-baseline programmes.
- With its high flux and low uncertainty, nuSTORM is sensitive to rare events in the Standard Model and beyond such as neutrino tridents, lepton flavour violation (LFV) and axion decay.
- It outperforms previous and current generation detectors and is competitive to future detectors.







Neutrino Trident (No. of events) *Preliminary*

Channel	SBND	μBooNe	ICARUS	DUNE	ν STORM
$e^\pm\mu^\mp$	10	0.7	1	2993 (2307)	173
	2	0.1	0.2	692 (530)	29
e^+e^-	6	0.4	0.7	1007 (800)	107
	0.7	0	0.1	143 (111)	5
$\mu^+\mu^-$	0.4	0	0.0	286 (210)	14
	0.4	0	0.0	196 (147)	9

LFV (95 % C.L.) *Preliminary*

Experiment (Uncertainty)	BR ($\pi^+ \to \mu^+\nu_e$)
BEBC	8×10^{-3}
SBND (10%)	1.5×10^{-3}
SBND-PRISM (10%, 5%)	1.2×10^{-3}
SBND-PRISM (10%, 2%)	8.9×10^{-4}
nuSTORM(1%)	7.1×10^{-4}
Statistics only	4.7×10^{-5}

paper on arXiv soon!

Summary

- nuSTORM will deliver high-precision neutrino beams of ν_{μ} and ν_e flavours from stored muon decay with %-level flux accuracy, enabling high-precision cross-section measurements and BSM searches.
- A hybrid lattice design successfully balances competing requirements through optimized FODO/FFA configuration, achieving excellent high-momentum muon capture while maintaining large momentum acceptance and minimizing chromaticity.
- Low-energy capture efficiency challenges, identified through BDSIM simulations, reveal momentum-dependent losses due to increased angular divergence, requiring targeted lattice modifications and upstream pion production optimization.
- The construction of synthetic neutrino beams akin to the PRISM concept has also been demonstrated, including the novel construction of a pure synthetic electron neutrino beam.
- First cross-section studies have been conducted and additional studies of the achievable precision on the ν_e/ν_μ cross-section ratio are planned.
- Current phenomenogical work shows very good sensitivity to both precision measurements of the Standard Model and BSM phenomena like light sterile neutrinos and Large Extra Dimensions.

Thank you

Back up