CERN Summer Student Program 2022

Study of the Magnetic Horn for Neutrinos from Stored Muons (nuSTORM)

Chu Hon Kin

Department of Physics, The Chinese University of Hong Kong

Supervised by Prof. Kenneth Long, Tiago Alves and Marvin Pfaff

Content

1. Introduction to nuSTORM
2. Background of magnetic horn
3. Simulation of pion production
4. Data analysis of the pion distribution

nuSTORM

- Produces high intensity neutrino beam
  - $\bar{\nu}_e$ (ν_e) & ν_μ ($\bar{\nu}_\mu$) from the decay of stored muons
  - Known flavor composition and energy spectrum
- Serves a definitive neutrino-nucleus scattering programme
  - Neutrino interaction cross-section measurement

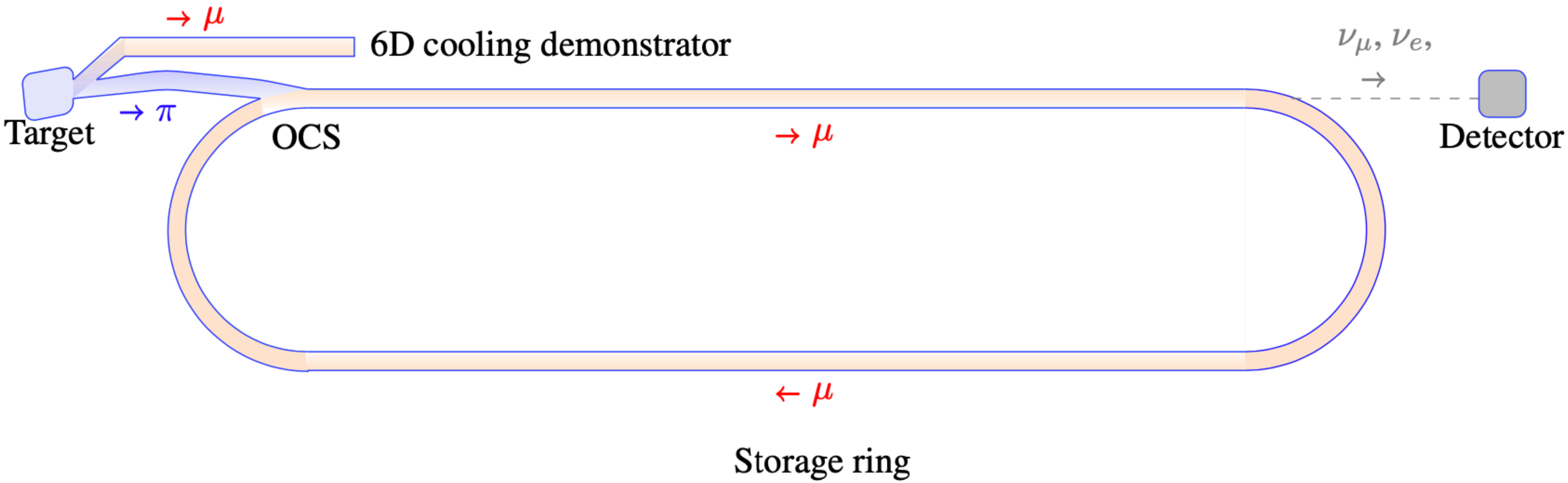
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

nuSTORM

Accelerator facility

1. Target and magnetic horn
   - Target: smashed by a proton beam
   - Horn: focuses charged particles to form a beam
2. Pion transfer line
   - Delivers pions within a ±10% spread of momentum p_π
3. Muon storage ring
   - Pion decay in the production straight
   - Stores muons with p_μ from 1-6 GeV/c and an acceptance of ±16% p_μ
4. Detector
   - Set beyond the production straight

nuSTORM



Schematic of the nuSTORM muon and neutrino beam facility (proposed implementation at the CERN SPS)

L. A. Ruso et al. (nuSTORM collaboration) (2022)

Magnetic Horn

Objectives:

- Simulate the proton beam collision process
- Track the kinematics of the produced pions and muons
- Select pions with p_π suited for the transfer line
- Obtain the beam properties for accelerator design

Magnetic Horn

Background

- Proposed by Simon van der Meer at CERN in 1961
- Uses a magnetic field
  - Captures and focuses charged particles right after their production
  - Creates a sharp beam before the particles decay

Magnetic Horn

Components

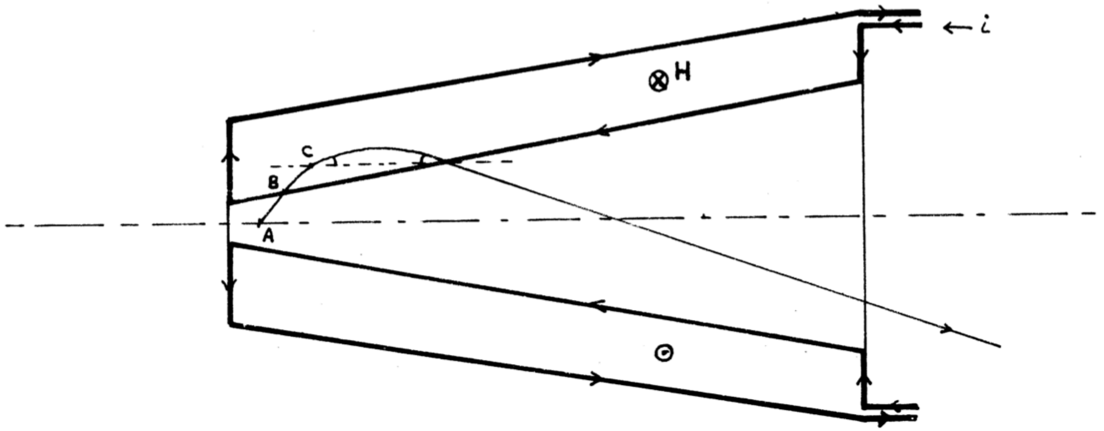
- Target
  - Placed inside the empty tunnel of the horn (field free)
  - Collided by proton beam
- 2 coaxial conducting cylinders/cones
  - Current flows through in opposite directions
  - B field $\propto 1/r$ between the conductors
- Argon gas between the conductors
  - Reduces corrosion

Magnetic Horn

Magnetic field

- Acts as a focusing lens for the charged particles
- Deviated particles are bent back to the hollow centre

Van der Meer's sketch of a magnetic horn



S. van der Meer (1961)

Magnetic Horn

Current polarity

- Direction of the horn current
- Determines what pion charge is favoured
  - Positive for π^+
  - Negative for π^-

Simulations

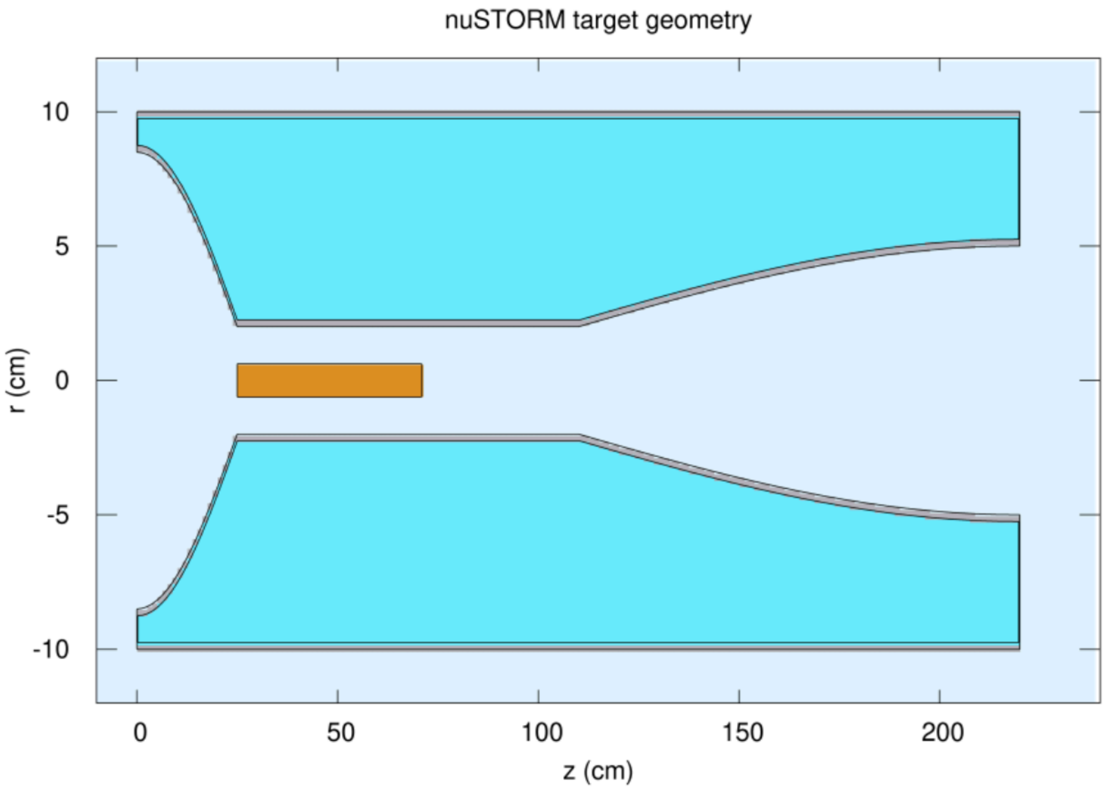
1. pyg4ometry
    - Builds the target and horn geometry
    - Sets the beam parameters
    - Sets the horn current and polarity
2. FLUKA
    - Defines the magnetic field
    - Simulates proton beam collision on fixed target
    - Tracks produced pions and muons

pyg4ometry

Target and horn geometry

- Aluminium conductor (in grey)
  - 2.2 m long
  - 2.5 mm thick
  - 25 cm upstream
  - 1.1 m downstream
- Inconel target (in orange)
- Argon gas (in blue)

Cut-off view of the magnetic horn



pyg4ometry

Beam parameters

- Gaussian beam
- Energy: 100 GeV (SPS)
- σ: 2.67mm

Horn current

- 115.6, 219 or 315.4 kA
- Polarity: ±1

Optimization for Pion Momentum

Fermilab optimization study

- 219 kA for 5 GeV/c pions

Linear estimation

- $I = \frac{219}{5} p_\pi$

Optimized current for different pion momenta

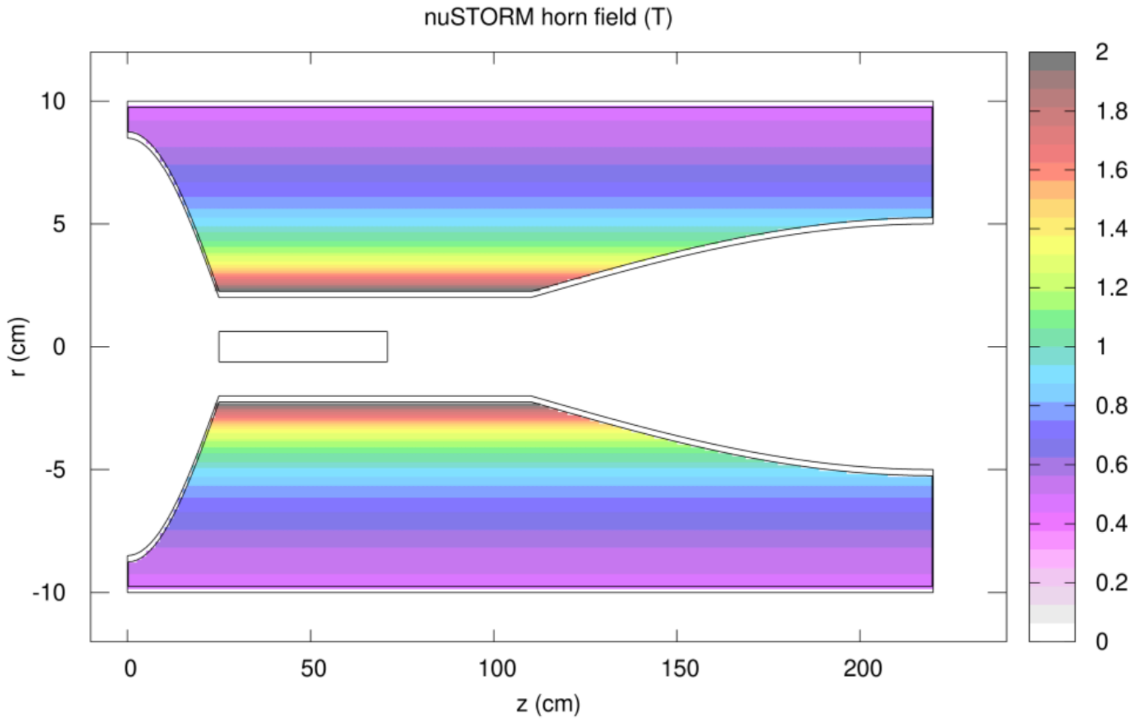
I (kA)	115.6	219	315.4
p_π (GeV/c)	2.64	5	7.2

FLUKA

Magnetic field

- Located in the argon gas region
- $B = \frac{\mu_o I}{2\pi r}$
- $\vec{B} = \langle r = 0, \phi = pol * B, z = 0 \rangle$

Magnetic field gradient



FLUKA

Output (only pions and muons)

- PDGID
- Total energy (GeV)
- Position (cm)
- Momentum (GeV/c)
- Likelihood weighting

Output sample files

Current	Proton on target (POT)	Tracking plane
±315.4 kA	10 million	plane right after horn downstream
±219 kA		
± 115.6 kA		
0 kA	1 million	target surface

ROOT Data Analysis

Sanity check for the simulations

- Particle position
- Particle composition
- Pion energy distribution

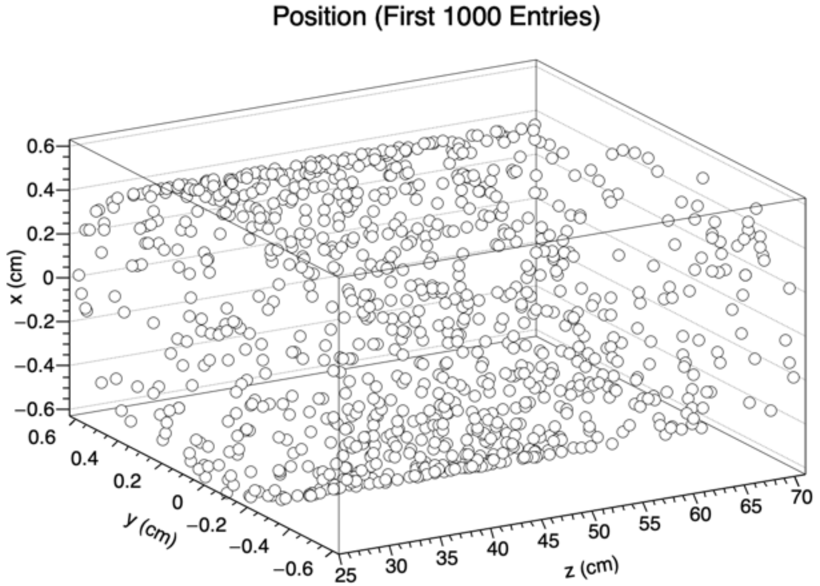
Optimize the pion acceptance

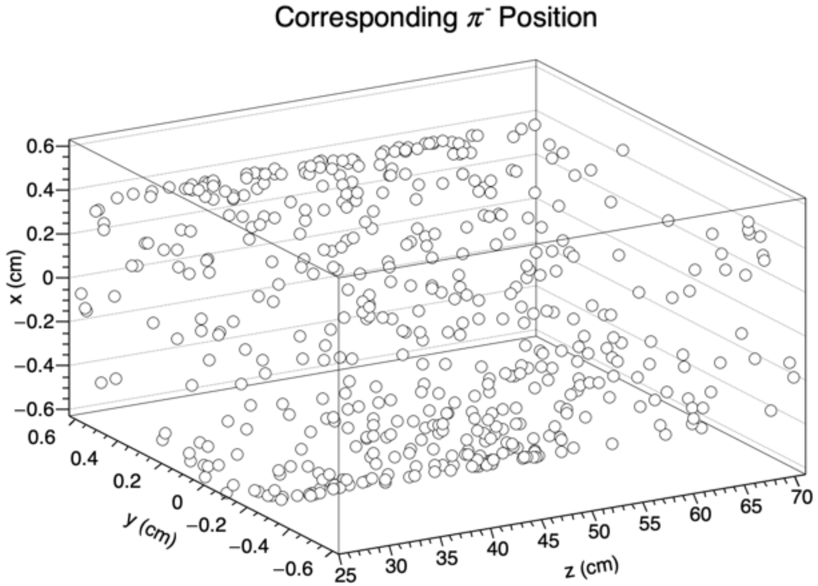
- Pion transverse position
- Pion phase space

Position

0 kA simulation

- contains all particles coming out from the cylindrical target

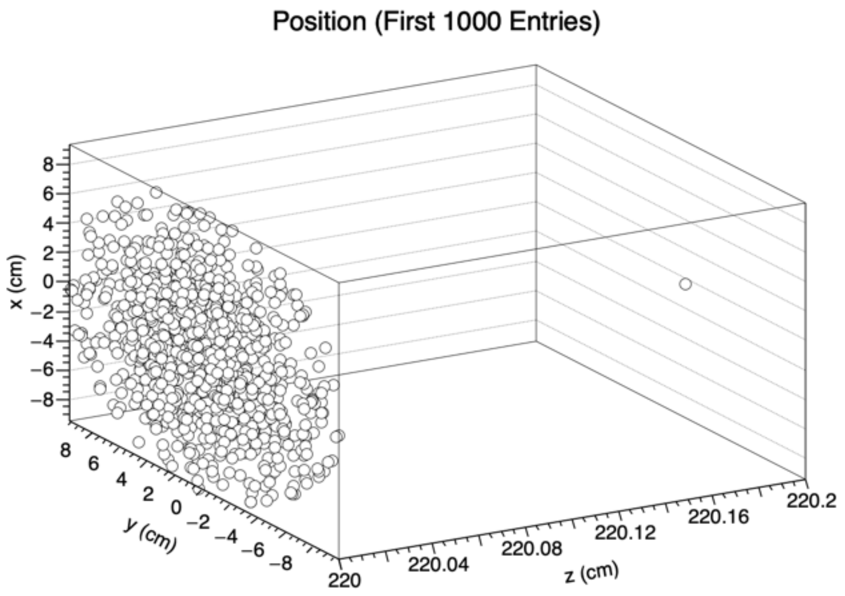


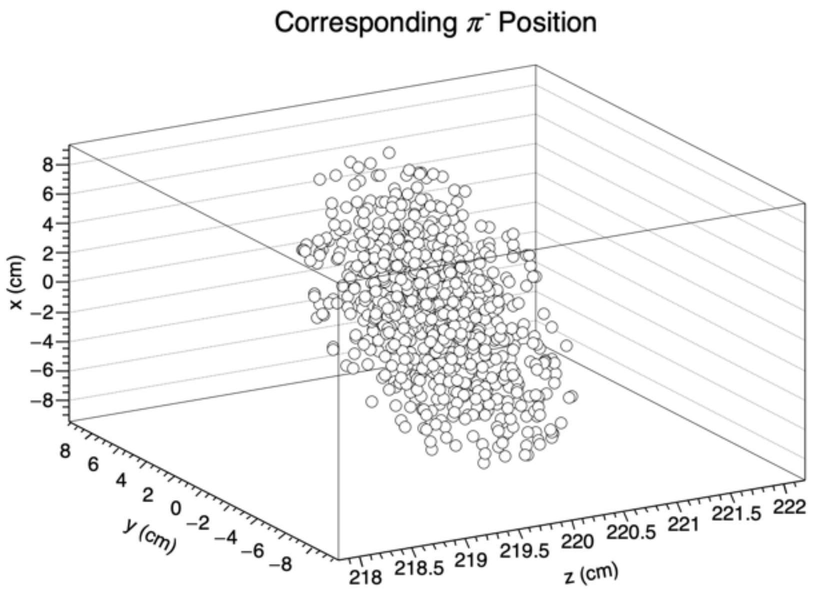


Position

-219 kA simulation

- contains particles hitting the plane at z = 2.2 m





Particle Composition

From 0 kA simulation

- Ratio of produced π^- to π^+ is close to unity

Negative current favours π^- and μ^-

Current (kA)	Entries	π^-	π^+	μ^-	μ^+
-315.4	29419298	86.10%	10.46%	3.36%	0.08%
-219	23651640	82.86%	13.98%	3.06%	0.11%
-115.6	16465278	74.43%	23.00%	2.39%	0.19%
0	17137843	49.71%	50.10%	0.06%	0.13%

Particle Composition

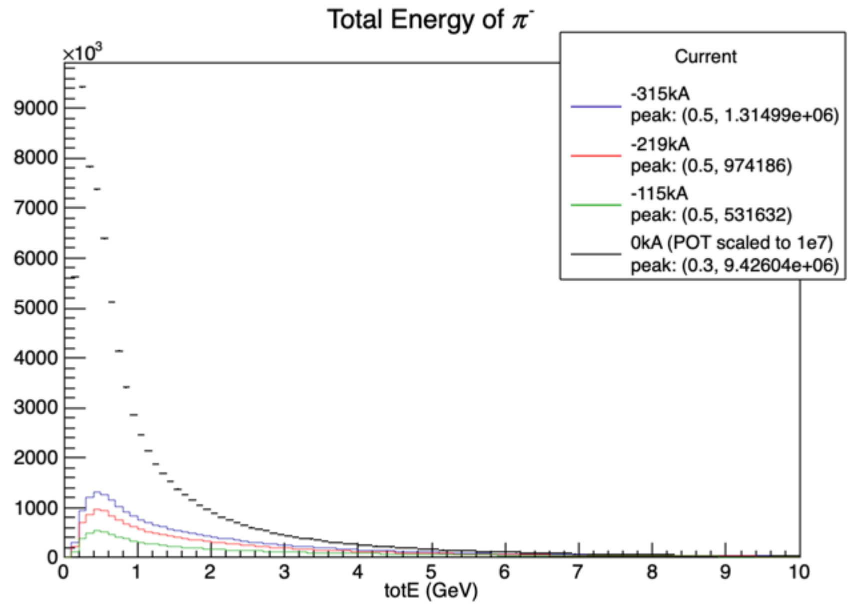
Current (kA)	Entries	π^-	π^+	μ^-	μ^+
+315.4	29880856	9.14%	87.48%	0.07%	3.31%
+219	24031887	12.16%	84.75%	0.09%	3.00%
+115.6	16707648	19.81%	77.68%	0.15%	2.36%
0	17132589	49.69%	50.11%	0.06%	0.13%

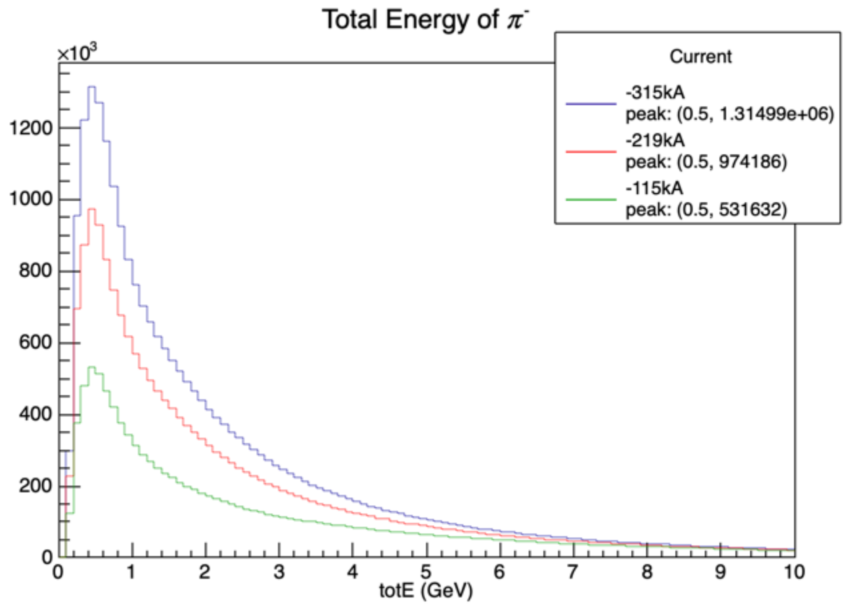
Energy Distribution

0 kA files only contain 10^6 POT

-> Each entry is weighted by 10

For negative horn currents

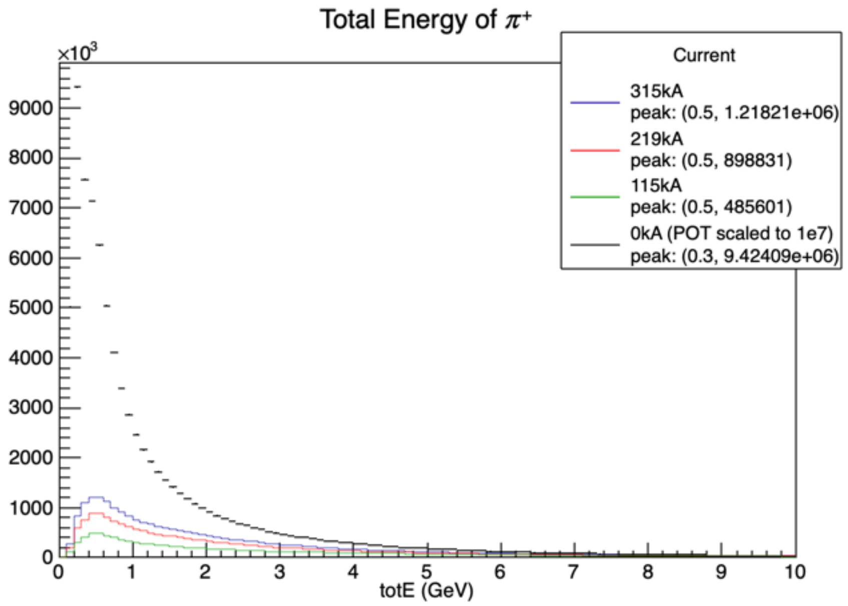


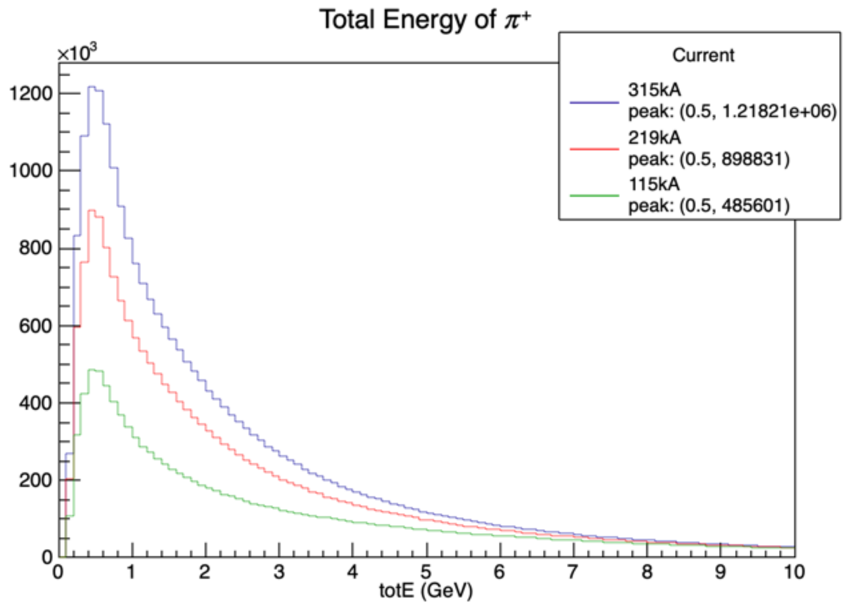


Energy Distribution

More pions are collected with a stronger B field

For positive horn currents



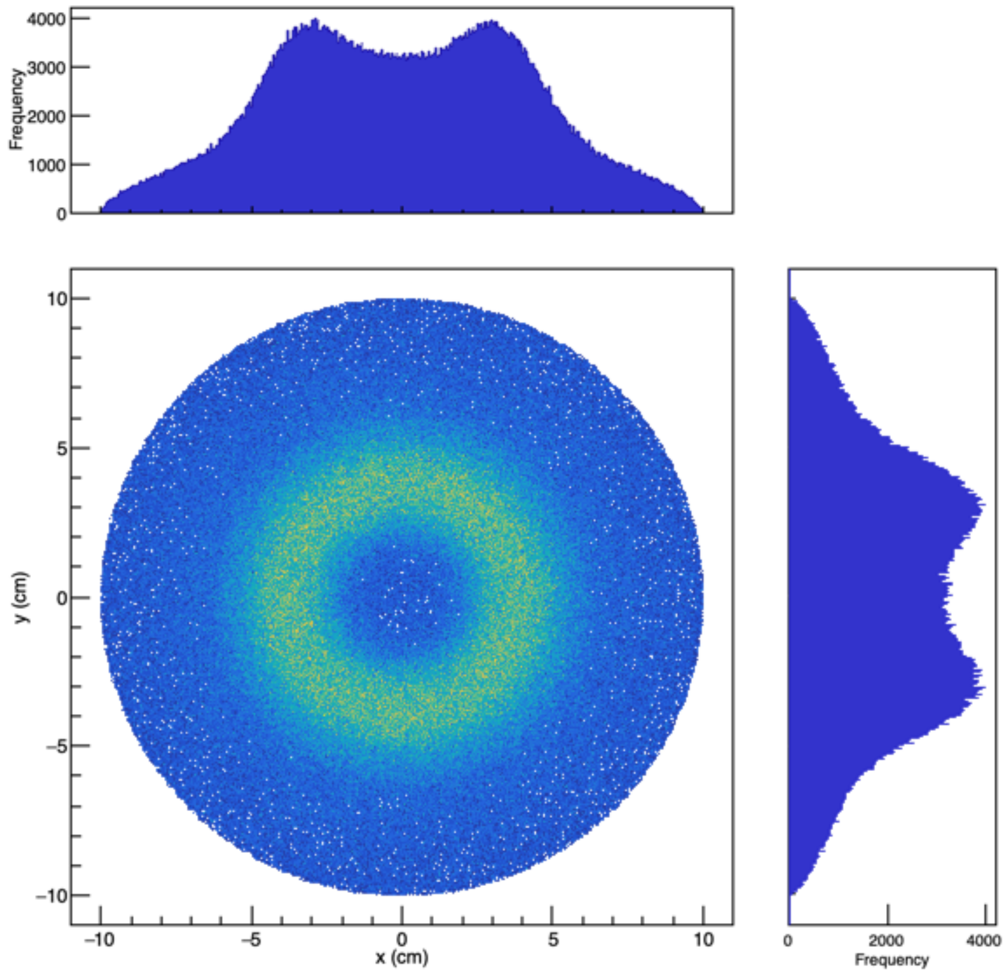


Pion Transverse Position

-219 kA simulation

- Selects 5 GeV/c π^-
- Donut shaped
  - With 5 cm outer radius

5 GeV/c π^- transverse position



Position-Momentum Phase Space

$$x' = \frac{p_x}{p_z} \text{ (dimensionless)}$$

x’ against x, y’ against y

Diagonal line

- Unaffected by B field

Dispersed region

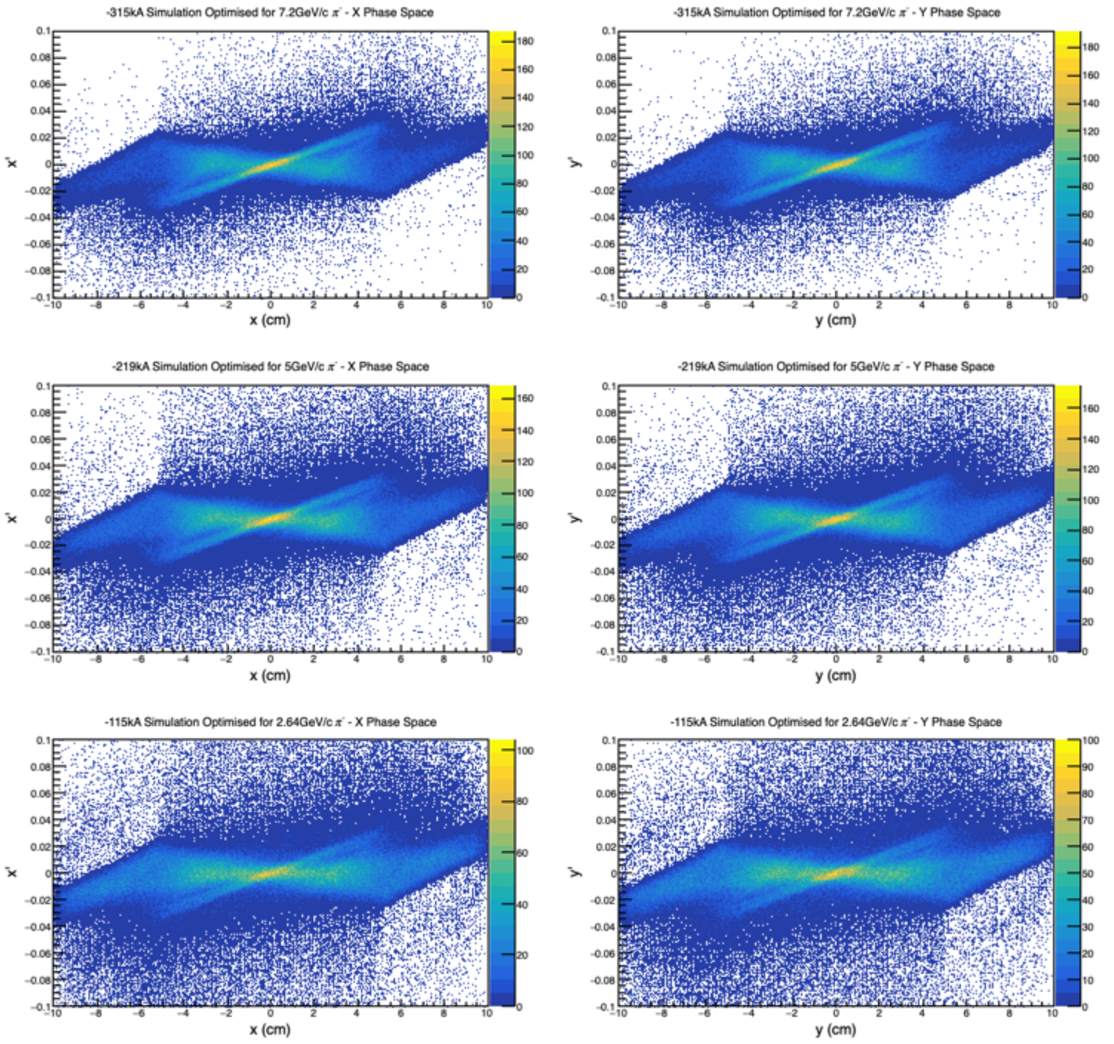
- Confined by B field

Momentum versus position

7.2 GeV/c

5 GeV/c

2.64 GeV/c



x

y

Acceptance

Emittance ε and Twiss parameters α, β, γ

- $\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2$ (ellipse)

Emittance ε

- Average spread of the coordinates on the phase space
- $A = \pi\varepsilon$
- Set $\varepsilon = 0.2\ cm$ to limit the aperture of the magnet

Acceptance

Beta function β

- Stretches the ellipse

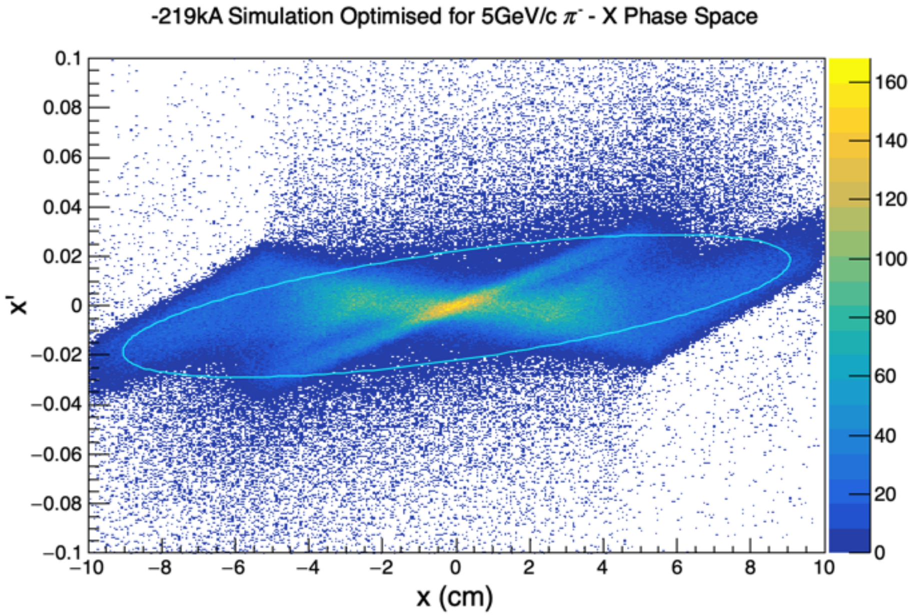
$$\alpha = -\frac{1}{2}\beta'$$

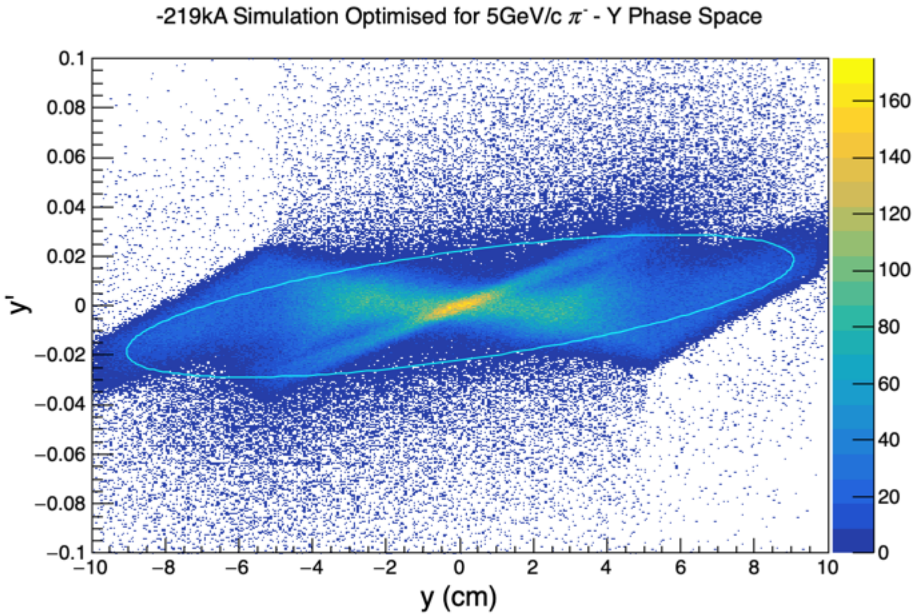
- Rotates the ellipse about the origin

$$\gamma = \frac{1 + \alpha^2}{\beta}$$

Phase Space

$$0.2 = 0.00287x^2 - 0.84xx' + 410x'^2$$





Pion Acceptance

Acceptance

	$2.64 \pm 10\%\ GeV/c$	$5 \pm 10\%\ GeV/c$	$7.2 \pm 10\%\ GeV/c$
π^-	66.0%	75.6%	80.4%
π^+	66.3%	75.9%	80.5%

Acknowledgement

I would like to thank …

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- CERN for holding the Summer Student Programme
- Physics Department at CUHK for providing me this opportunity

Reference

1. L. A. Ruso, T. Alves, S. Boyd, A. Bross, P. R. Hobson, P. Kyberd, J. B. Lagrange, K. Long, X.-G. Lu, J. Pasternak, M. Pfaff, & C. Rogers (for the nuSTORM collaboration), Neutrinos from Stored Muons (nuSTORM), arXiv:2203.07545.

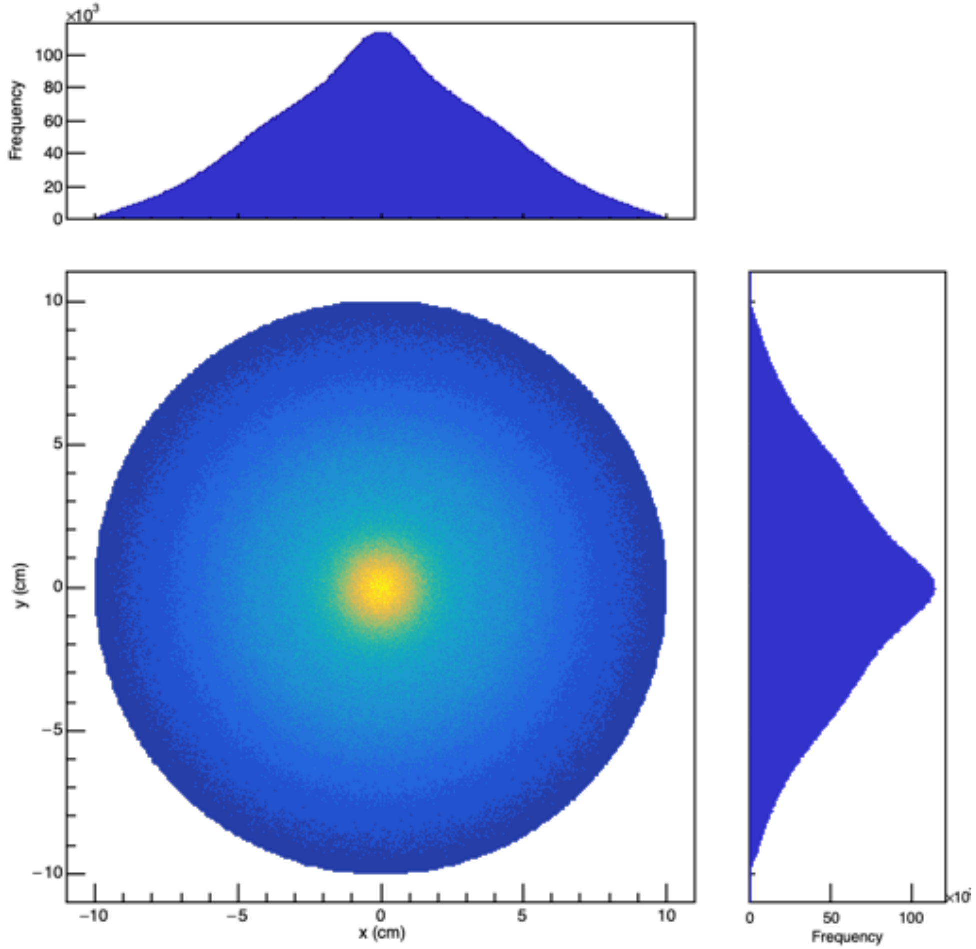
2. S. van der Meer, A directive device for charged particles and its use in an enhanced neutrino beam, CERN Document Server, CERN-61-07.

3. A. Liu, A. Bross, & D. Neuffer, Optimization of the magnetic horn for the nuSTORM non-conventional neutrino beam using the genetic algorithm, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 794, 11 Sep 2015, p.200-205.

Thank you!

Appendix

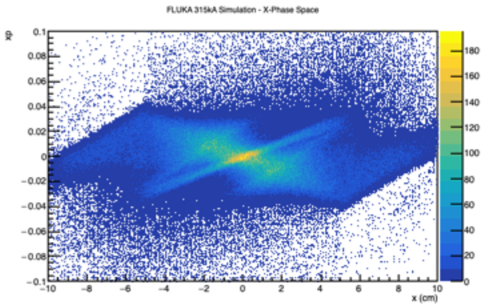
Transverse position of 2.64 GeV/c π^- in -219 kA simulation

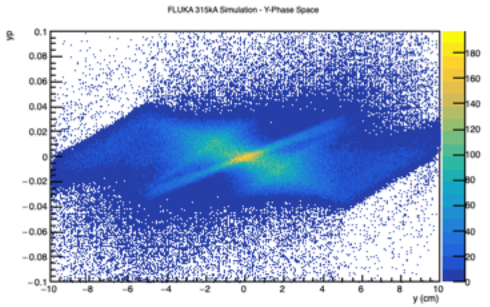


Appendix

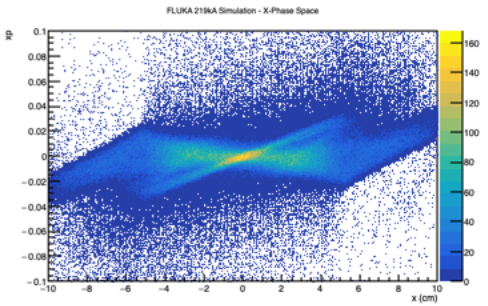
5 GeV/c π^- phase spaces under different field strength

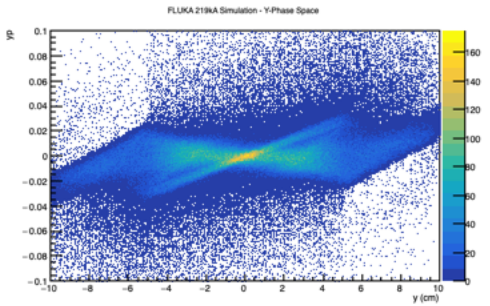
-315kA



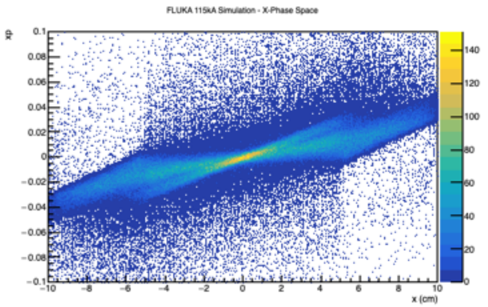


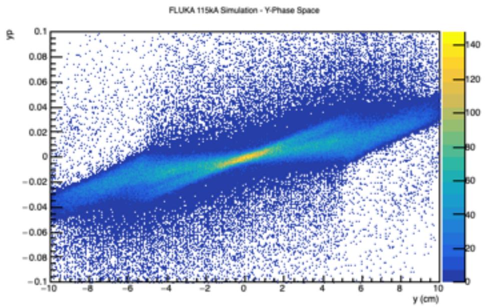
-219kA





-115kA





x

y