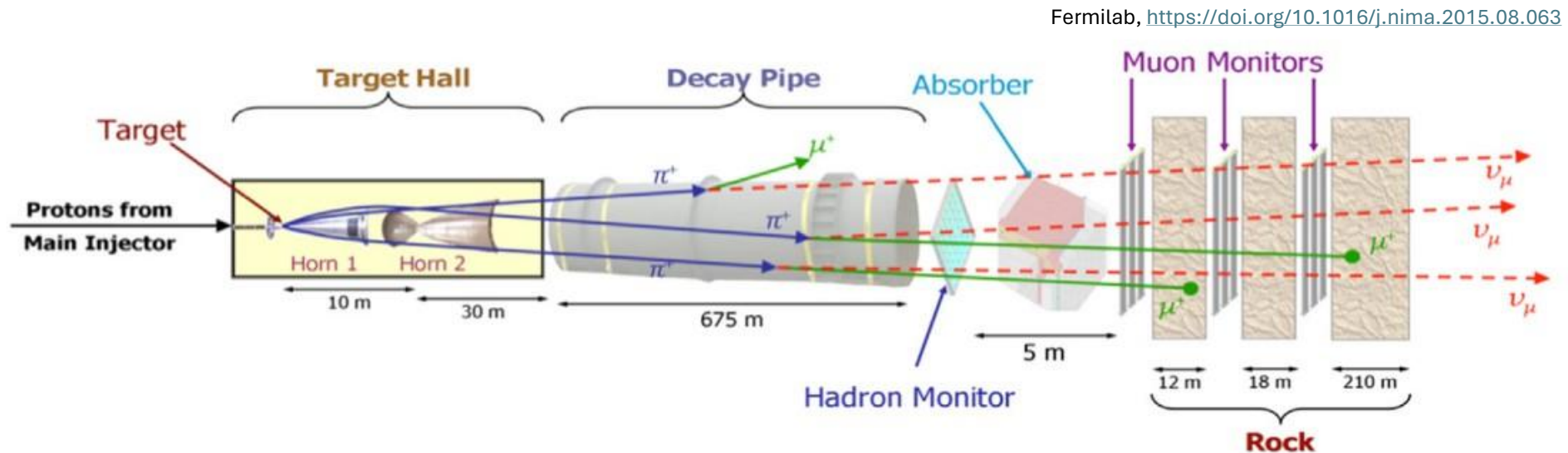


Simulation studies for the nuSTORM facility

Wonjong Chang

About nuSTORM – Why nuSTORM?

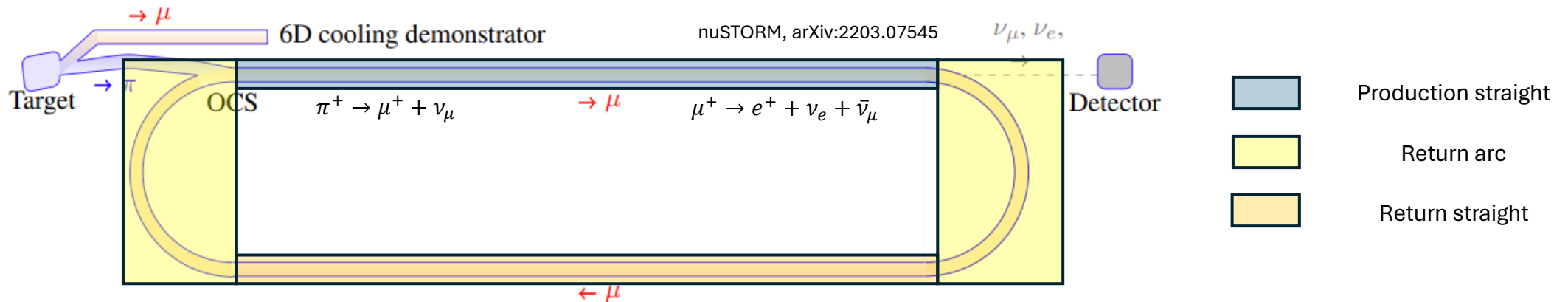
- Accelerator neutrino experiments obtain neutrinos from pion decay $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$ or $\bar{\nu}_\mu$
- Complicated hadron interactions produce other neutrino parents such as kaons and this ratio is a source of uncertainty
- Neutrino beam is mostly composed of ν_μ and therefore very low ν_e flux



NuMI neutrino beam at Fermilab neutrino production

About nuSTORM – What is nuSTORM?

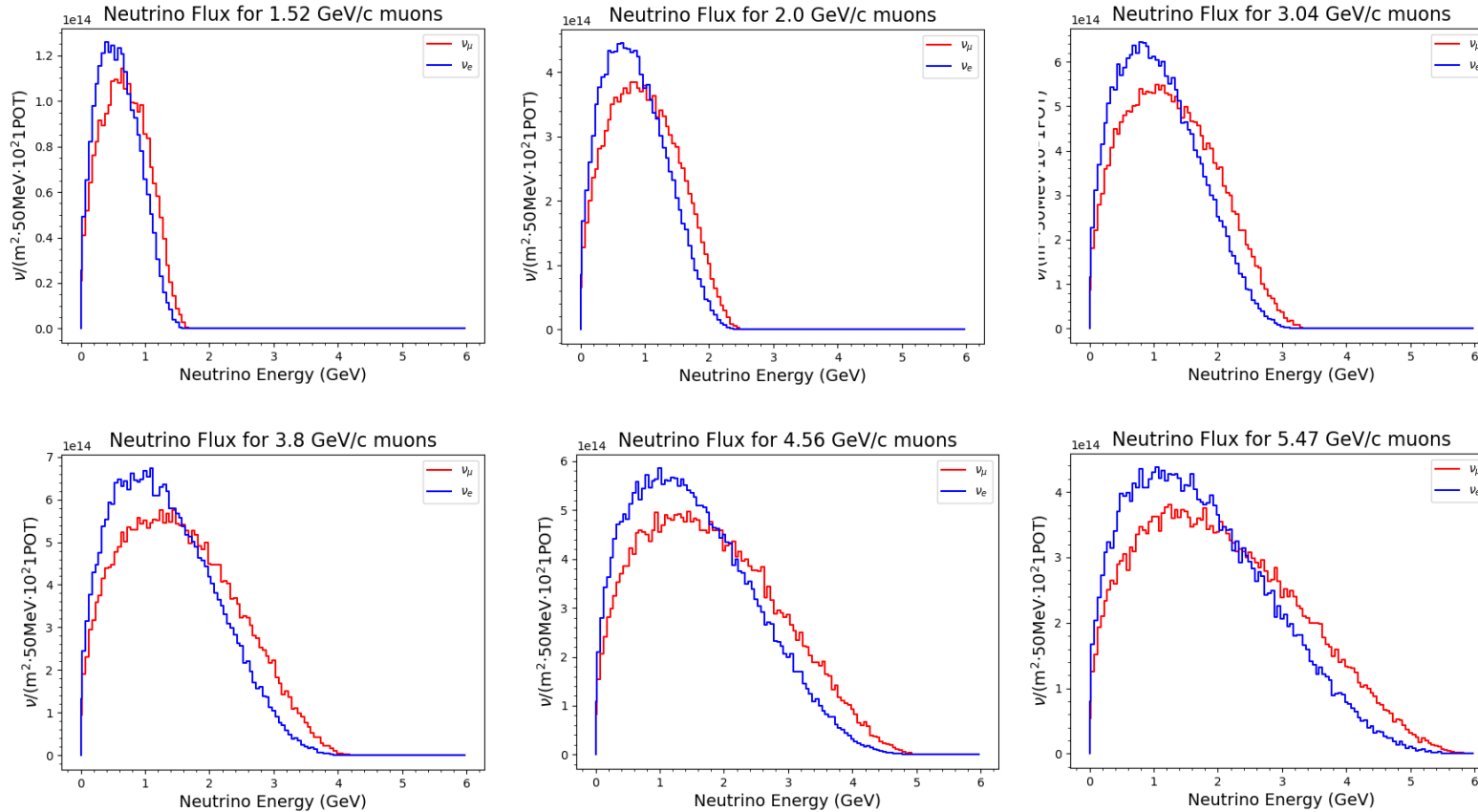
- nuSTORM(neutrinos from STORed Muons) is a future generation accelerator neutrino experiment.
- nuSTORM facility
 - Target station - produces pions by colliding protons onto a target
 - Production straight - decays the pions into muons that decay into neutrinos
 - ν_μ signal from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\nu_e + \bar{\nu}_\mu$ signal from $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
 - Return arcs and return straight
 - p_μ tuneable in range of 1 – 6 GeV/c with spread of $\pm 16\%$
- Physics goal
 - % level uncertainty cross section for both ν_e, ν_μ
 - BSM searches
 - muon collider demonstrator



About nuSTORM - flux

- nuSTORM currently has 6 flux settings for 6 pions energy spectrum going into the storage ring

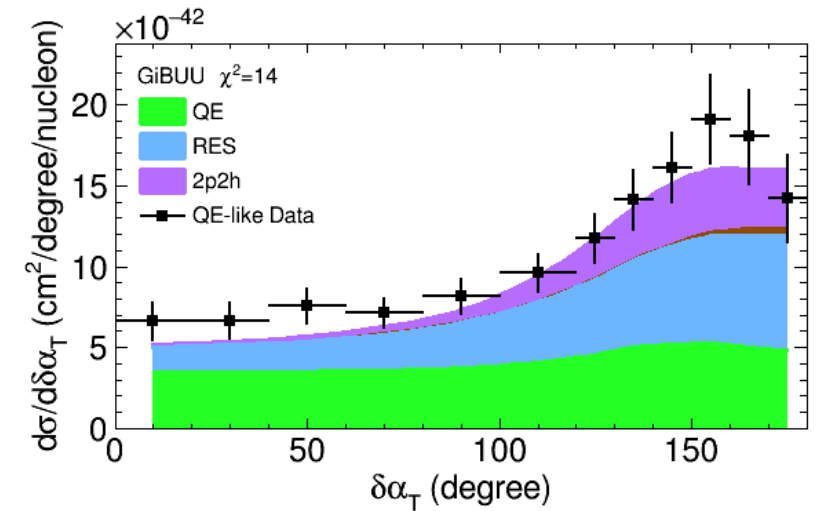
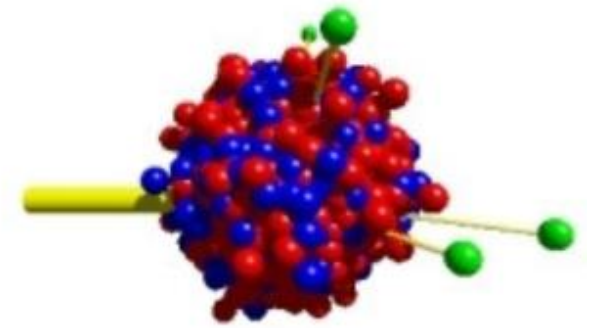
P. Jury, R. Kamath, P. Kyberd, K. Long, M. Pfaff



Normalized ν_e and ν_μ nuSTORM flux at current stage

Cross section - GiBUU

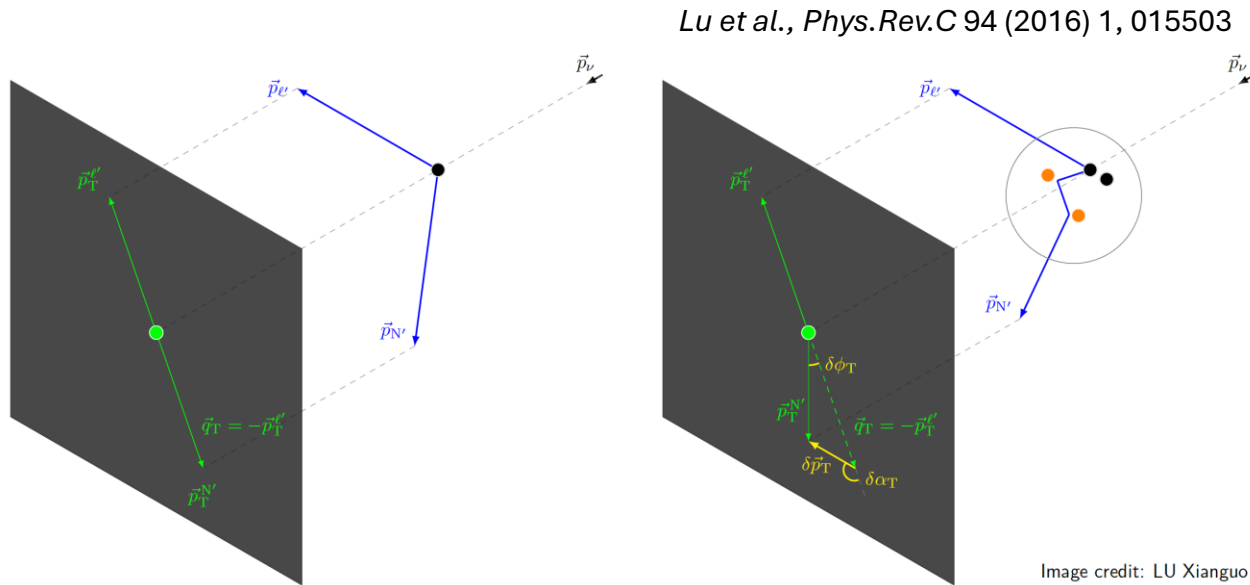
- GiBUU(Giessen Boltzmann-Uehling-Uhlenbeck) is used for cross section evaluation
- Developed by theorists in Germany
- Originally started out as a heavy ion collision simulation and is good at evaluating nuclear effect
- Concise structure and does not need artificial degree of freedom like some other neutrino event generators



GiBUU comparison with MINERvA data.
 $CC0\pi$ on hydrocarbon target

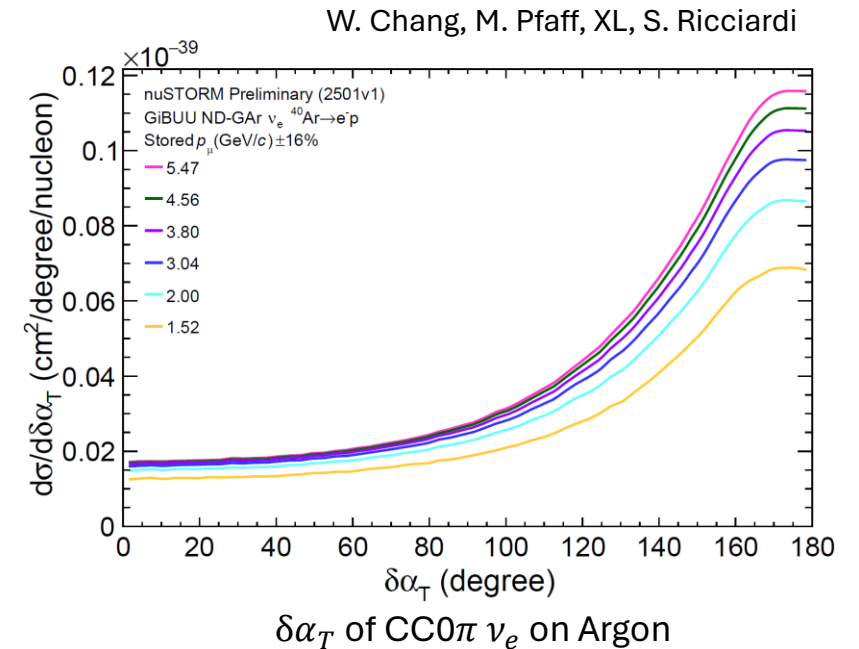
Cross section - TKI

- What is TKI and why measure it?
 - TKI stands for Transverse Kinematic Imbalance
 - When measuring cross section need to reconstruct neutrino energy
 - Nuclear effects must be considered for reconstruction, but they could not be directly measured
 - Try to evaluate nuclear effects by considering kinematics of outgoing particles in the transverse plane of neutrino direction to minimise effect from neutrino energy
- Been measured and still being measured by many experiments such as T2K, MINERvA, SBND, MicroBooNE and more



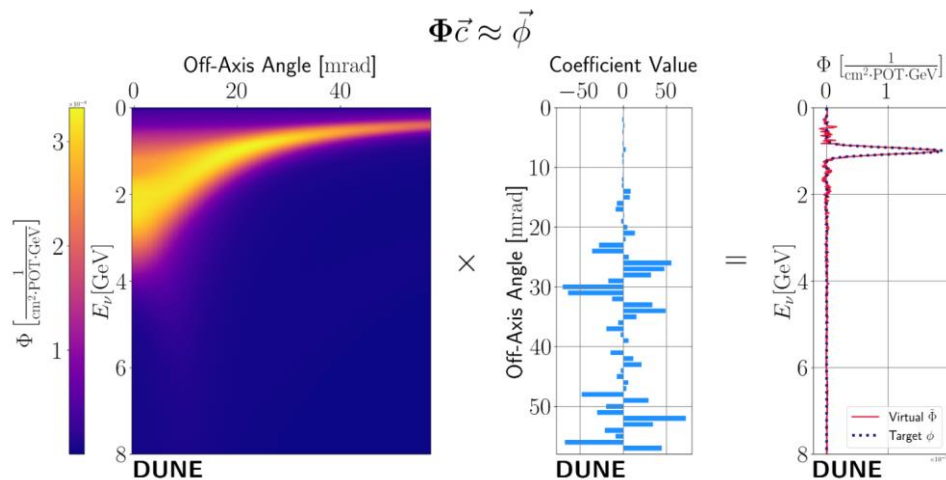
TKI variable definition

Image credit: LU Xianguo

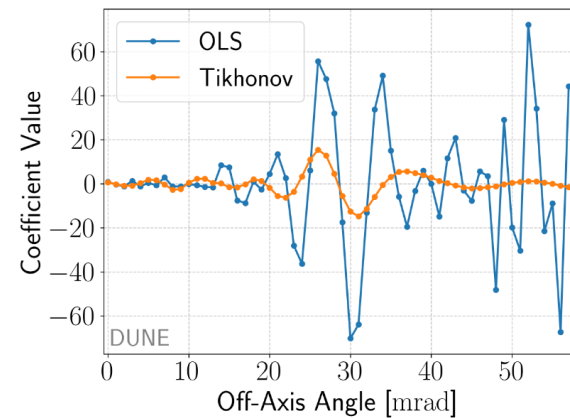


Cross section - Synthetic beam

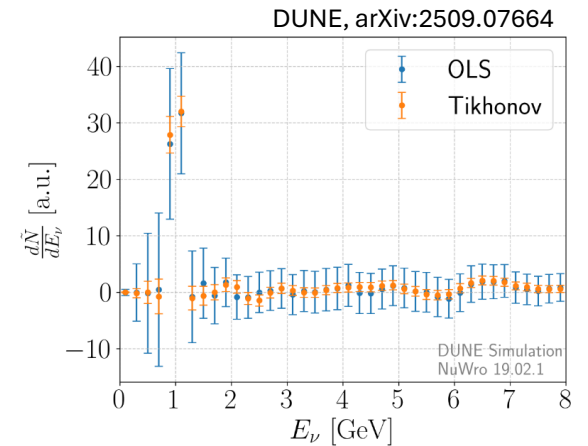
- Since nuSTORM has 6 fluxes they could be linearly combined to imitate other experiment's flux and provide low uncertainty cross section data for other experiments
- DUNE is studying PRISM(Precision Reaction Independent Spectrum Measurement) to make a virtual flux
 - DUNE PRISM uses their own near detector flux to synthesize desired flux
 - 58 off-axis fluxes at different of-axis angles are used for synthesis
- nuSTORM has advantages for synthetic beam
 - nuSTORM can synthesize fluxes with lower uncertainty due to lower flux uncertainty, and no correlation between fluxes
 - nuSTORM can provide ν_e synthetic beams with good statistics and low uncertainty



DUNE PRISM with 58 off-axis angle near detector fluxes used to create a narrow gaussian at 1GeV



(a)

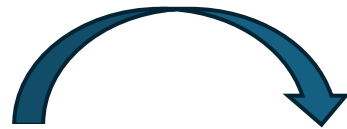


(b)

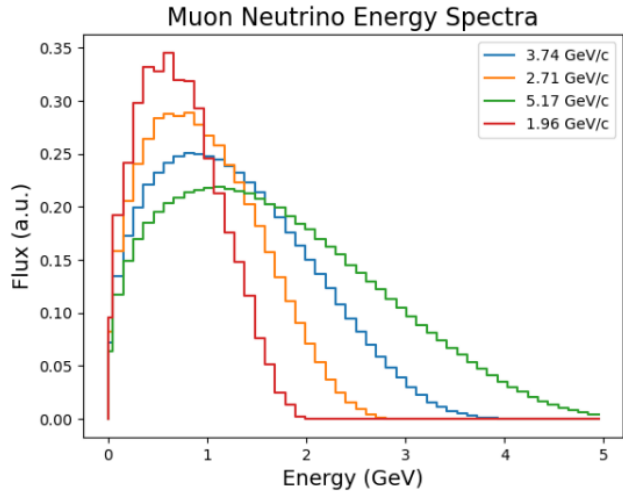
Fit coefficients and flux with and without regularization

Cross section - Synthetic beam

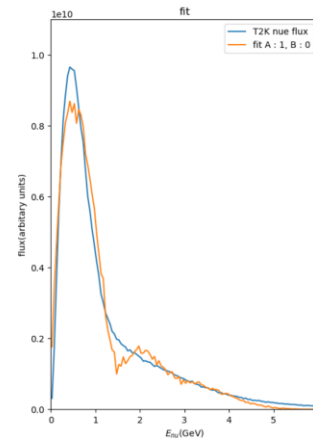
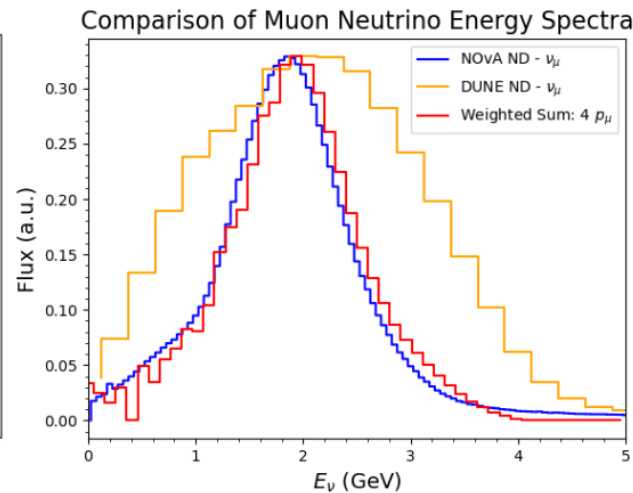
- nuSTORM in-house method is being developed
- Try to minimise FOM (figure of merit) $FOM = \sum_{E_\nu} \frac{(f(E_\nu) - \Phi_{LC}(E_\nu))^2}{A + B f(E_\nu)^2}$ where $\Phi_{LC}(E_\nu)$ is the linear combination of nuSTORM fluxes
- A and B could be tuned so that the fit could be more focused in the peak or the tail depending on the application



R. Kamath

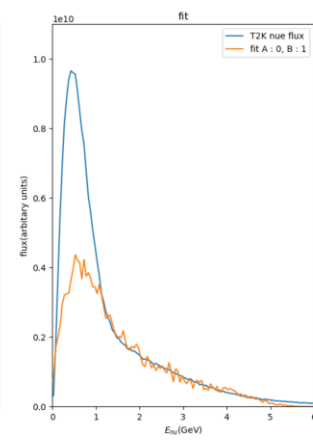
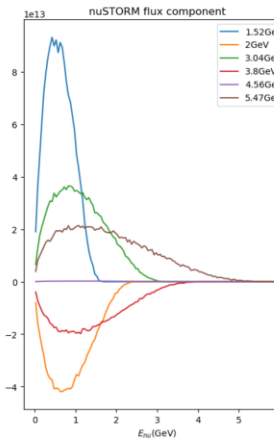


nuSTORM fluxes used to synthesized NOvA ND flux

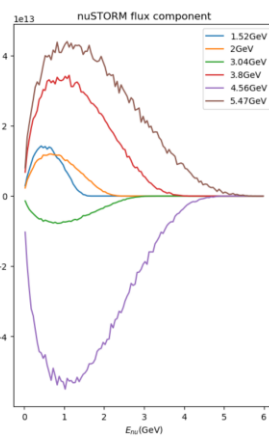


nuSTORM fluxes used to synthesized T2K ND FHC ν_e flux with different parameter settings (left - A = 1, B = 0, right - A=0, B=1)

T2K nue

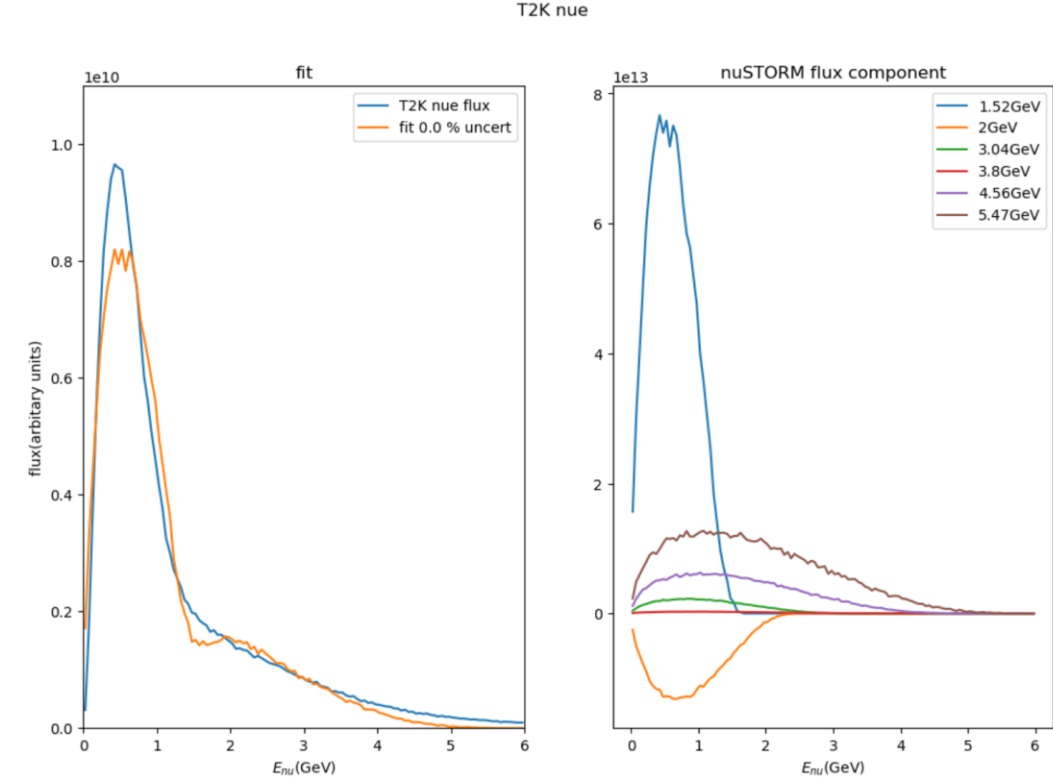


T2K nue



Cross section - Synthetic beam

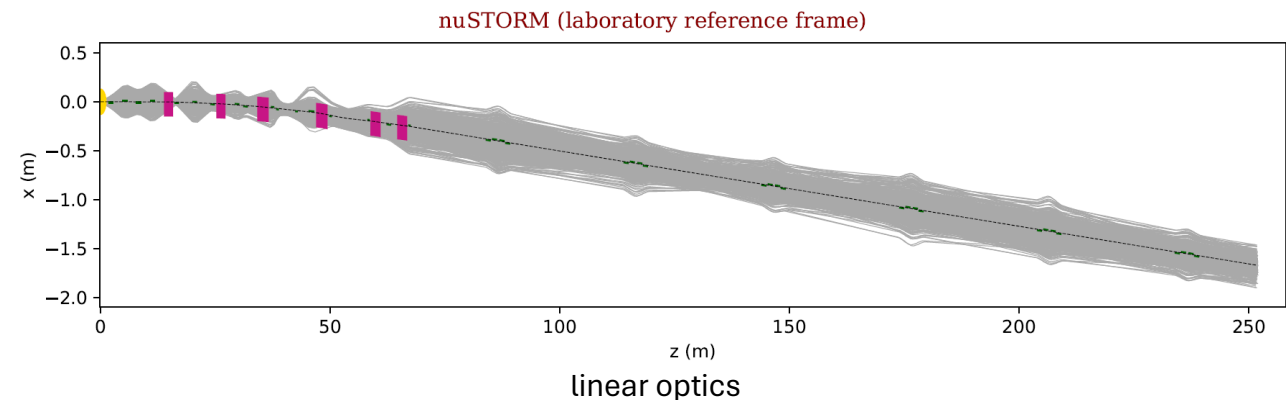
- New fitting method being developed influenced by DUNE PRISM
- Puts penalty on fluctuation of both coefficient and synthesized flux
- Able to fit peak well and reduce the “wobble” in the flux at the same time
- Penalty parameter could be optimized depending on the focus of the fit



nuSTORM fluxes used to synthesized T2K ND FHC ν_e flux with new fitting method

Linear optics

- Currently nuSTORM simulation is not simulating the beam completely. The phase space is teleported passed the arc(frozen phase space).
- bdsim is used to simulate pions and muons but it is slow which makes work like beamline optimization computationally heavy
- LhARA linear optics code has the possibility do the full simulation while being much faster than bdsim(~10 times)
- Pions in the production straight has been simulated
- Ideally LhARA linear optics and bdsim should show very close results



Linear optics

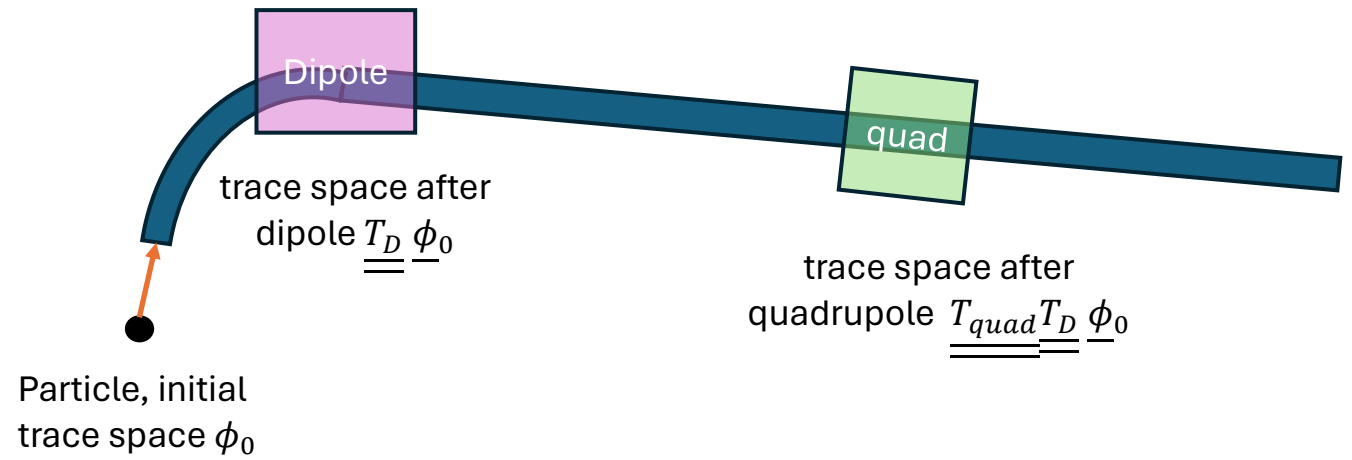
- bdsim(Beam Delivery Simulation) is a Geant4 based toolkit for simulating particles in a 3D modelled accelerator
- LhARA linear optics package was written for LhARA(Laser-hybrid Accelerator for Radiobiological Applications) to allow rapid simulation
- Both use linear optics. bdsim uses linear optics as default option and LhARA linear optics code is completely based on linear optics
- Treat beam line as a combination of beamline elements such as drift tube, dipoles, quadrupoles...
- Express trajectory of particles in the phase space and propagate them with a transfer matrix

$$\begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ p_x \\ p_y \\ p_z \end{bmatrix}$$

Phase space in vector form

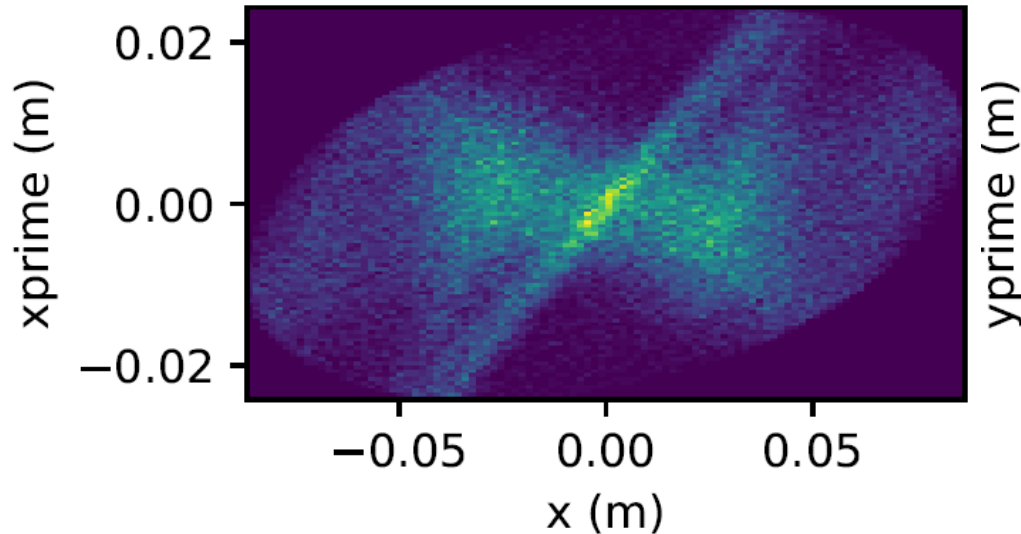
$$\underline{\phi} = \begin{pmatrix} x_{\text{RPLC}} \\ x'_{\text{RPLC}} \\ y_{\text{RPLC}} \\ y'_{\text{RPLC}} \\ z_{\text{RPLC}} \\ \delta_{\text{RPLC}} \end{pmatrix}$$

Trace space used for calculation

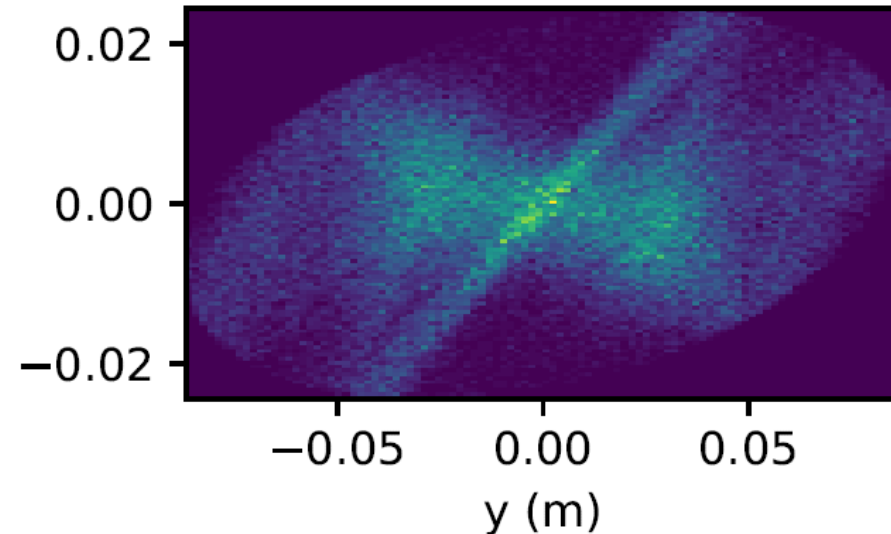


Linear optics – pions at source

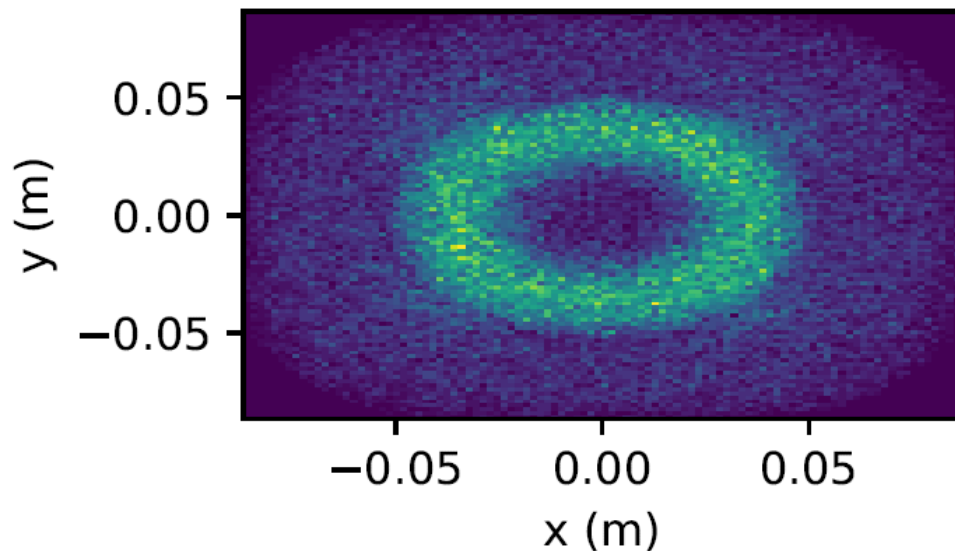
x phase space



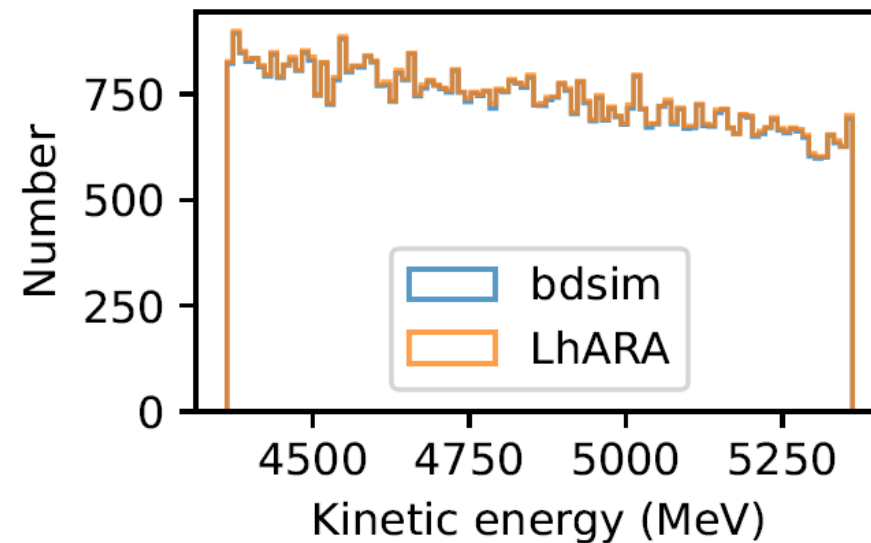
y phase space



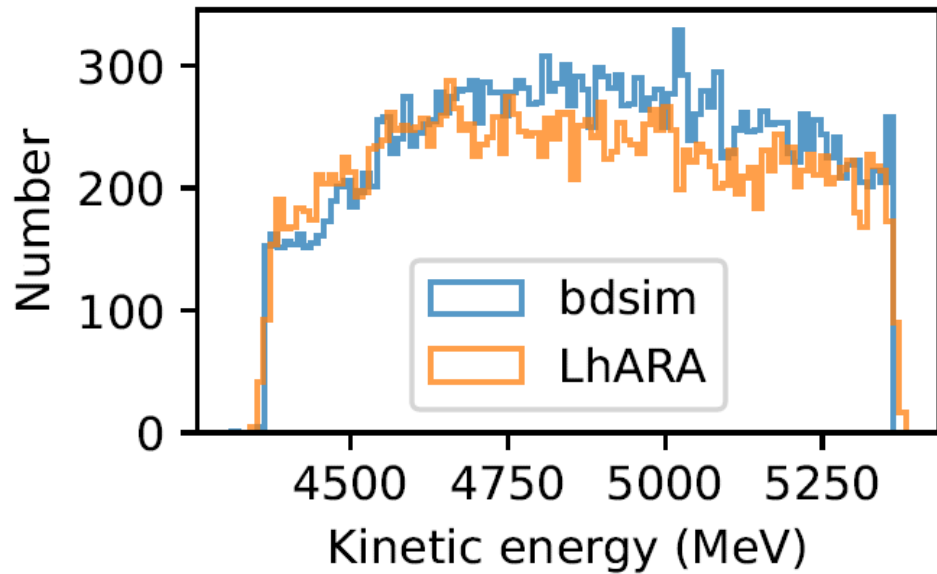
Spatial distribution



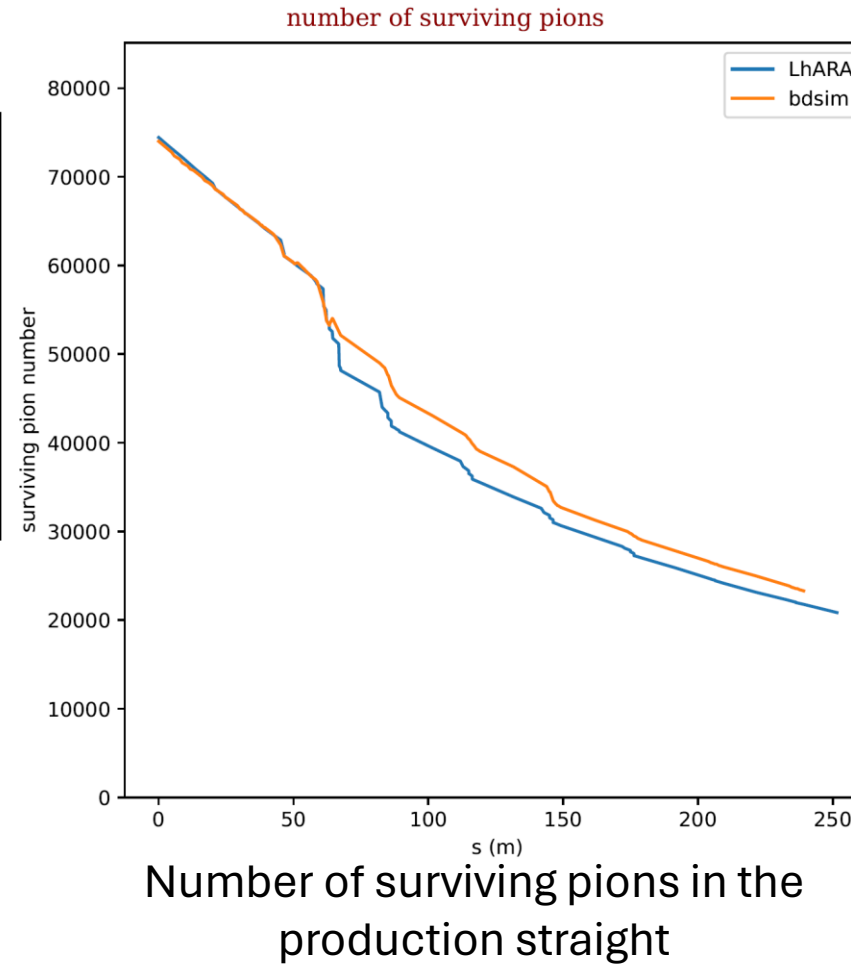
Energy spectrum



Linear optics – bdsim and LhARA comparison



Energy spectrum of pions at the end of the production straight



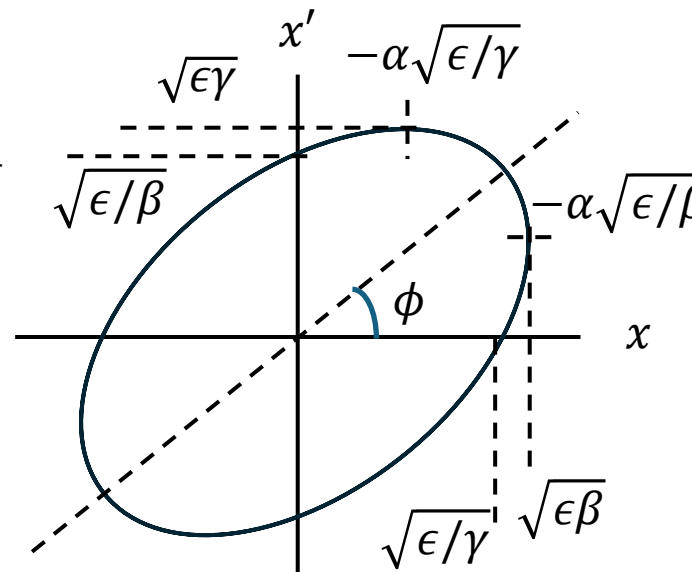
Number of surviving pions in the production straight

- Survival rate after progressing through the production straight for linear optics and bdsim are reasonably close
- Bdsim-31%, LhARA-29%
- Energy spectrum also shows similar trends
- But shows discrepancy which comes from the different dipole field description and is currently being fixed and tested

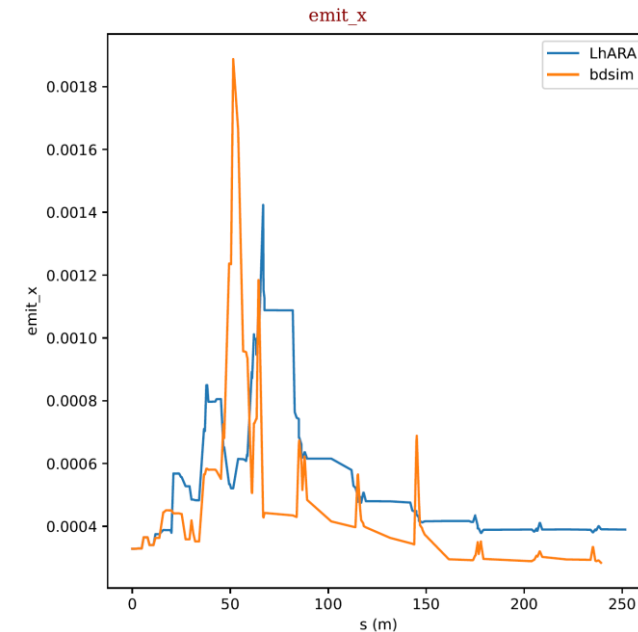
Linear optics – bdsim and LhARA comparison

- For more detailed comparison Courant–Snyder parameters (Twiss parameters) that compares the geometry of the phase space are being compared

- Twiss parameters - when phase space envelope is represented with equation $\gamma x^2 + 2\alpha x x' + \beta x'^2 = \epsilon$
- x is just the x coordinate and x' is derivative of x along the beam axis
- Same parameters could be defined for y as well



Twiss parameter definition

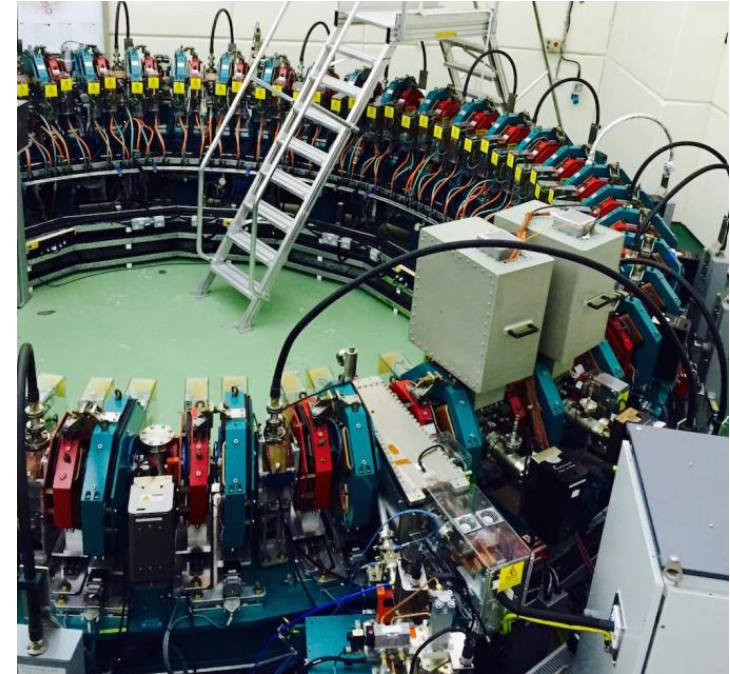


RMS x emittance ϵ_x of LhARA and bdsim with 5GeV pions through production straight

Linear optics – FFA magnets

- FFA stands for Fixed Field Alternating gradient
 - Has field of $B = B_0 \left(\frac{r}{r_0}\right)^k$ form and is able to bend and focus beam at the same time
 - Synchrotrons need to ramp up the magnetic field as particle energy increases
 - FFA's don't need this since they have fixed field
 - No synchronization issues and does not require a power supply that varies voltage over time
 - High repetition rate which allows higher fluxes
 - Has potential usage in medical accelerators and future muon colliders
- FFA magnets are included in the nuSTORM beamline in the return arc and straight
 - Allows to increase nuSTORM's dynamic acceptance
 - Methods to simulate FFA magnets in the LhARA linear optics code is being studied

arXiv:1604.05221



The EMMA non-scaling FFAG at the STFC Daresbury Laboratory, UK

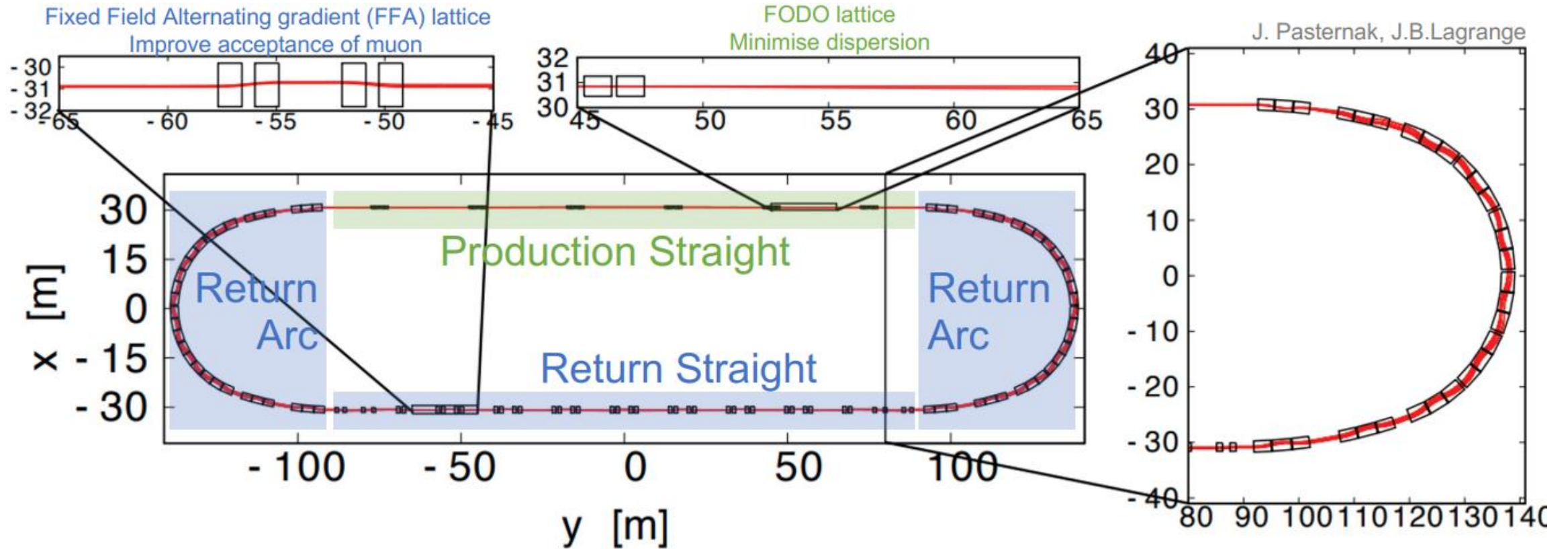
Summary and future plans

- nuSTORM is an accelerator neutrino experiment ready for the future
 - % level uncertainty cross section
 - Synthetic flux to synthesize cross section from flux of interest
 - Unique low uncertainty ν_e measurements
- New technology and simulation methods are being developed
 - Testbed for future muon collider
 - Fast linear optics accelerator simulation



Backup

nuSTORM beamline



LhARA transfer matrix

$$\underline{\phi} = \begin{pmatrix} x_{\text{RPLC}} \\ x'_{\text{RPLC}} \\ y_{\text{RPLC}} \\ y'_{\text{RPLC}} \\ z_{\text{RPLC}} \\ \delta_{\text{RPLC}} \end{pmatrix} \quad \begin{aligned} x'_{\text{RPLC}} &= \frac{\partial x}{\partial s} = \frac{cp_{x \text{ RPLC}}}{cp_0}; \\ y'_{\text{RPLC}} &= \frac{\partial y}{\partial s} = \frac{cp_{y \text{ RPLC}}}{cp_0}; \\ z_{\text{RPLC}} &= \frac{s}{\beta_0} - ct = \frac{\Delta s}{\beta_0}; \text{ and} \\ \delta_{\text{RPLC}} &= \frac{E}{cp_0} - \frac{1}{\beta_0} = \frac{\Delta E}{cp_0}. \end{aligned}$$

$$\underline{T}_D = \begin{pmatrix} \cos(\phi) & \rho \sin(\phi) & 0 & 0 & 0 & \frac{\rho}{\beta_0} (1 - \cos(\phi)) \\ -\frac{\sin(\phi)}{\rho} & \cos(\phi) & 0 & 0 & 0 & \frac{\sin(\phi)}{\beta_0} \\ 0 & 0 & 1 & l & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\frac{\sin(\phi)}{\beta_0} & -\frac{\rho}{\beta_0} (1 - \cos(\phi)) & 0 & 0 & 1 & \frac{l}{\beta_0^2 \gamma_0^2} - \frac{l - \rho \sin(\phi)}{\beta_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\underline{T}_{\text{drift}} = \begin{pmatrix} 1 & l & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & l & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{l}{\beta_0^2 \gamma_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

dipole transfer matrix

Drift tube transfer matrix

Trace space and variable definition

$$\underline{T}_{\text{Fquad}} = \begin{pmatrix} \cos(\sqrt{k_q} l_q) & \frac{\sin(\sqrt{k_q} l_q)}{\sqrt{k_q}} & 0 & 0 & 0 & 0 \\ -\sqrt{k_q} \sin(\sqrt{k_q} l_q) & \cos(\sqrt{k_q} l_q) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh(\sqrt{k_q} l_q) & \frac{\sinh(\sqrt{k_q} l_q)}{\sqrt{k_q}} & 0 & 0 \\ 0 & 0 & \sqrt{k_q} \sinh(\sqrt{k_q} l_q) & \cosh(\sqrt{k_q} l_q) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{l_q}{\beta_0^2 \gamma_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\underline{T}_{\text{Dquad}} = \begin{pmatrix} \cosh(\sqrt{k_q} l_q) & \frac{\sinh(\sqrt{k_q} l_q)}{\sqrt{k_q}} & 0 & 0 & 0 & 0 \\ \sqrt{k_q} \sinh(\sqrt{k_q} l_q) & \cosh(\sqrt{k_q} l_q) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos(\sqrt{k_q} l_q) & \frac{\sin(\sqrt{k_q} l_q)}{\sqrt{k_q}} & 0 & 0 \\ 0 & 0 & -\sqrt{k_q} \sin(\sqrt{k_q} l_q) & \cos(\sqrt{k_q} l_q) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{l_q}{\beta_0^2 \gamma_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Focusing and defocusing quadrupole transfer matrix

More information available on <https://github.com/ImperialCollegeLondon/LhARALinearOptics/tree/main>

nuSTORM PiFlash flux

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

