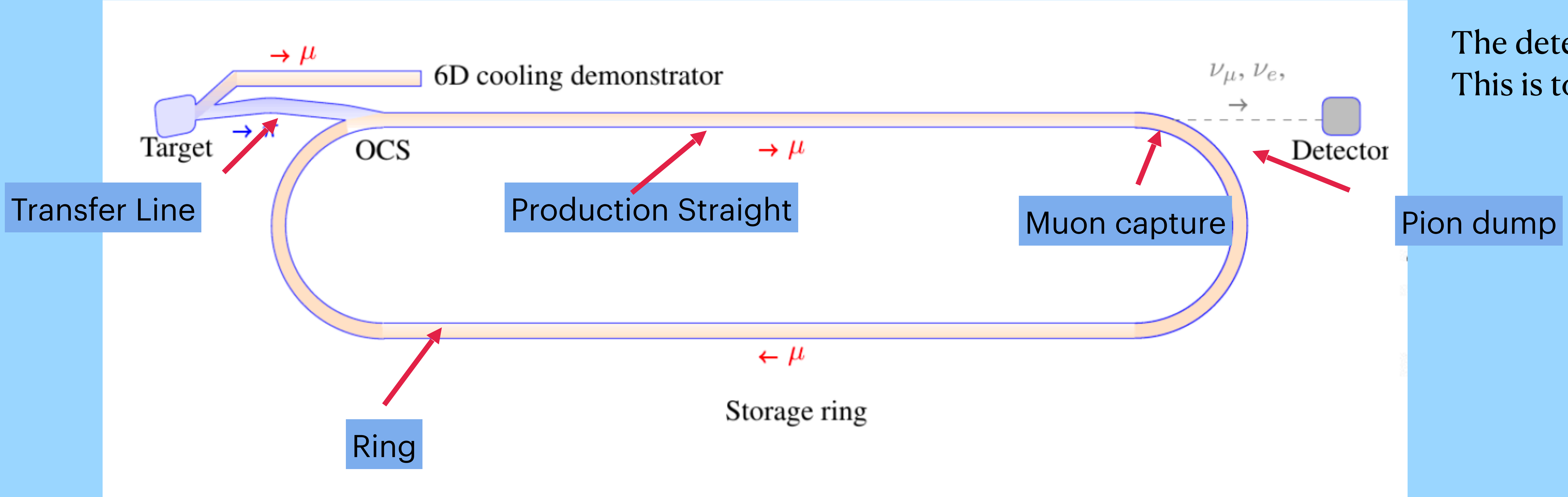
nuSIM the nuSTORM simulation

- Description of the programme
- Description of the data sets - format and access
- Brief discussion of uncertainties
- Studies by Marvin Pfaff, Tiago Alves and Xianguo Lu
- Preliminary results: Possibility of using the PRISM technique in nuStorm: Paul Kyberd

nuSTORM simulation

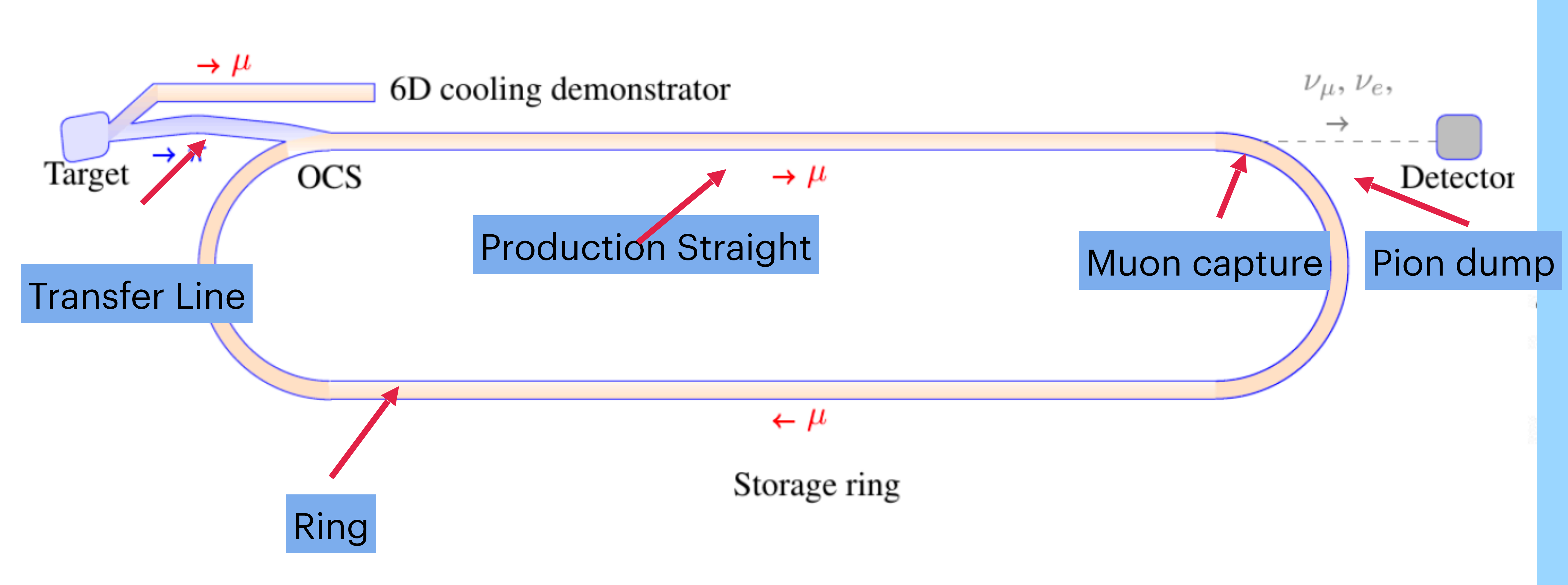


The detector is 50m downstream from the end of the ring
This is to give room for the pion dump

To explore the physics potential of the ring generate Data Sets at different pion momenta - at present 2, 3, 4, 5, 6, 7 GeV

Any central pion momenta can be chosen and any beam profile in position and momentum space.

nuSTORM simulation



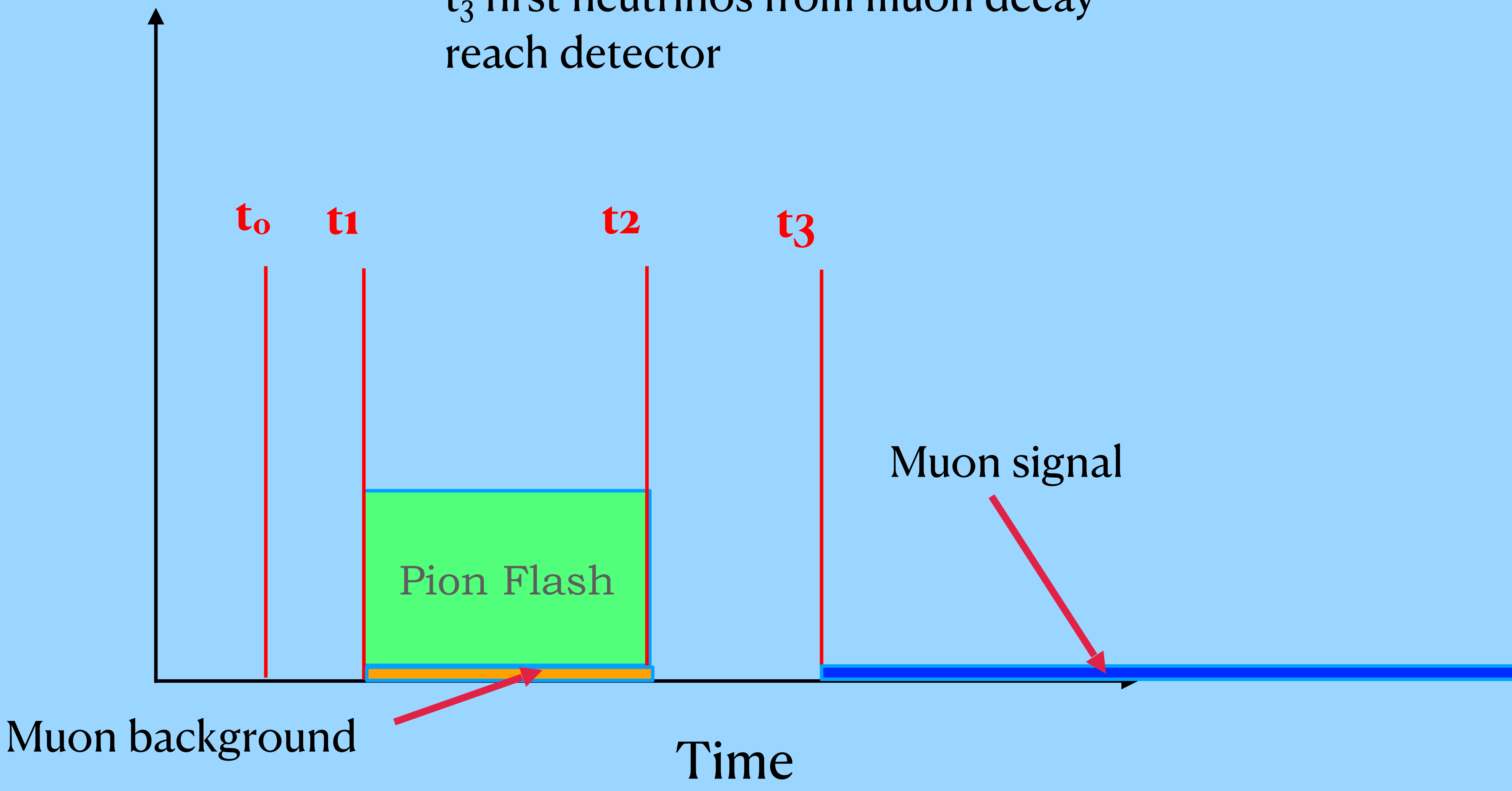
Only particles which decay in the production straight give a significant signal in the detector.

t_0, first pions leave the target.

t_1 first neutrinos from pion decay reach detector

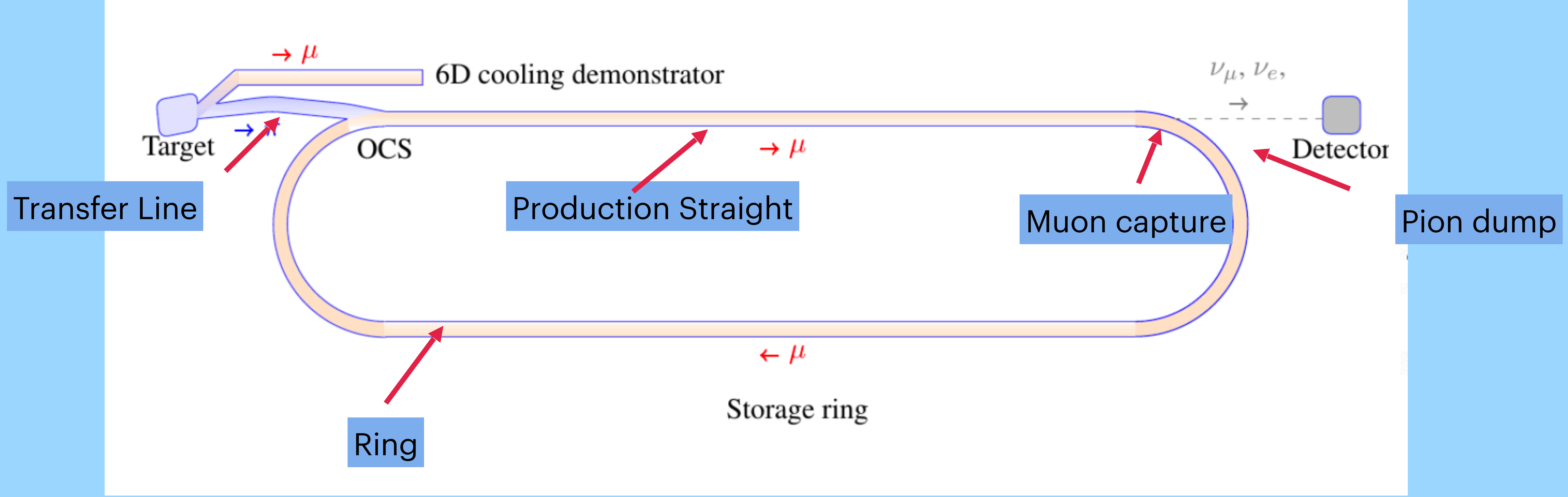
t_2 last neutrinos from pion decay reach detector

t_3 first neutrinos from muon decay reach detector



- Pion Flash … ν_μ produced by the pions in the production straight
- Muon background … ν_μ and ν_e produced by muons which decay before they are captured. Background to flash signal
- Muon Signal … ν_μ and ν_e produced by muons captured in the ring.

Simulation by nuSIM



M. Pfaff MSc thesis

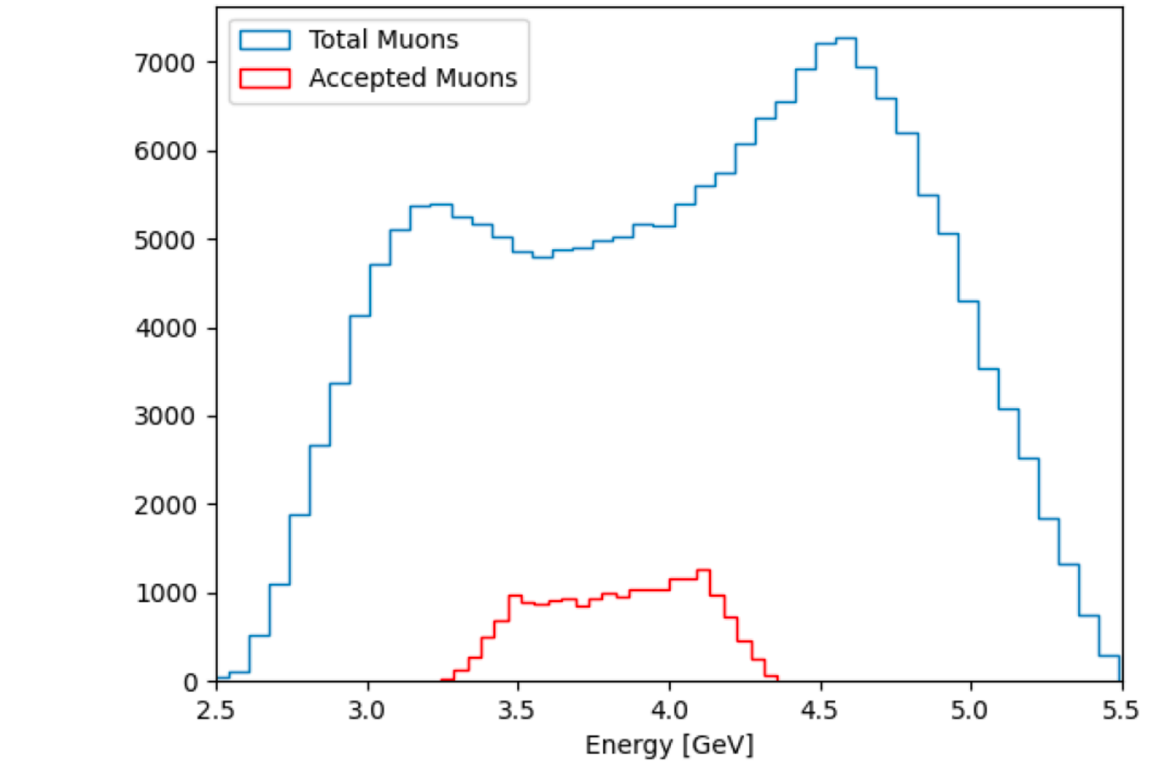


Fig 9 – The Energy Spectrum for the Total Muons and the Accepted Muons for a 5GeV/c Reference Pion Momenta

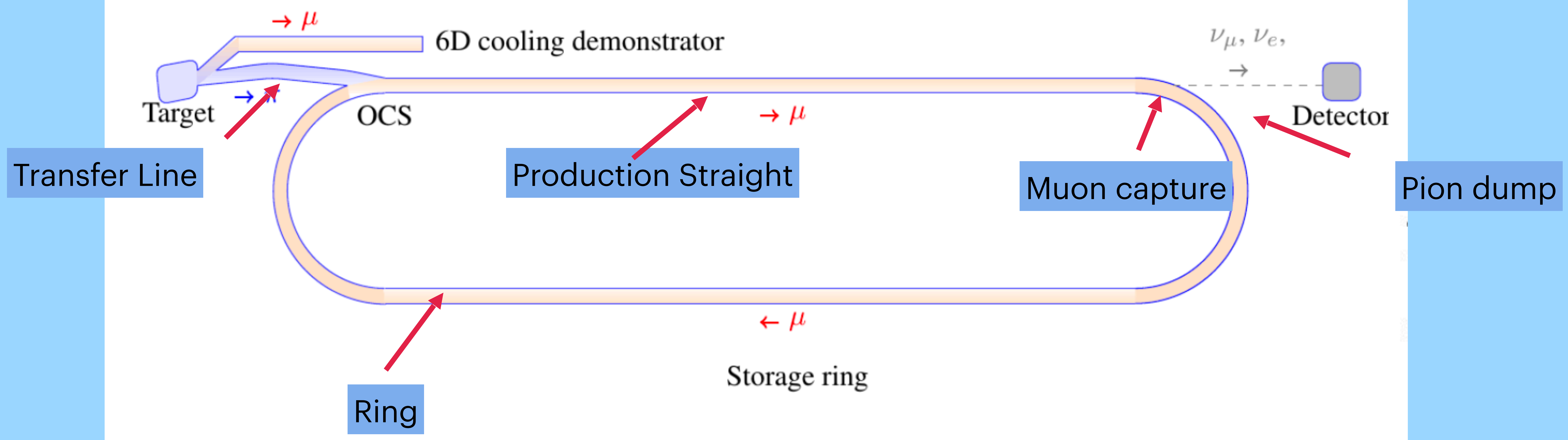
We use Fluka to design and optimise the horn to get the best pion flux.

The result is an ensemble of particles with a particular position and momentum distribution from which those that match the acceptance of the transfer line are accepted.

nuSim then performs a "parallel transport" of the beam maintaining the position and momentum, relative to the beam axis.
Effect of the magnet ignored, except to turn the beam axis to run parallel to the machine axis

At the end of the production straight only muons inside the ring acceptance are tracked further

Simulation by nuSIM



M. Pfaff MSc thesis

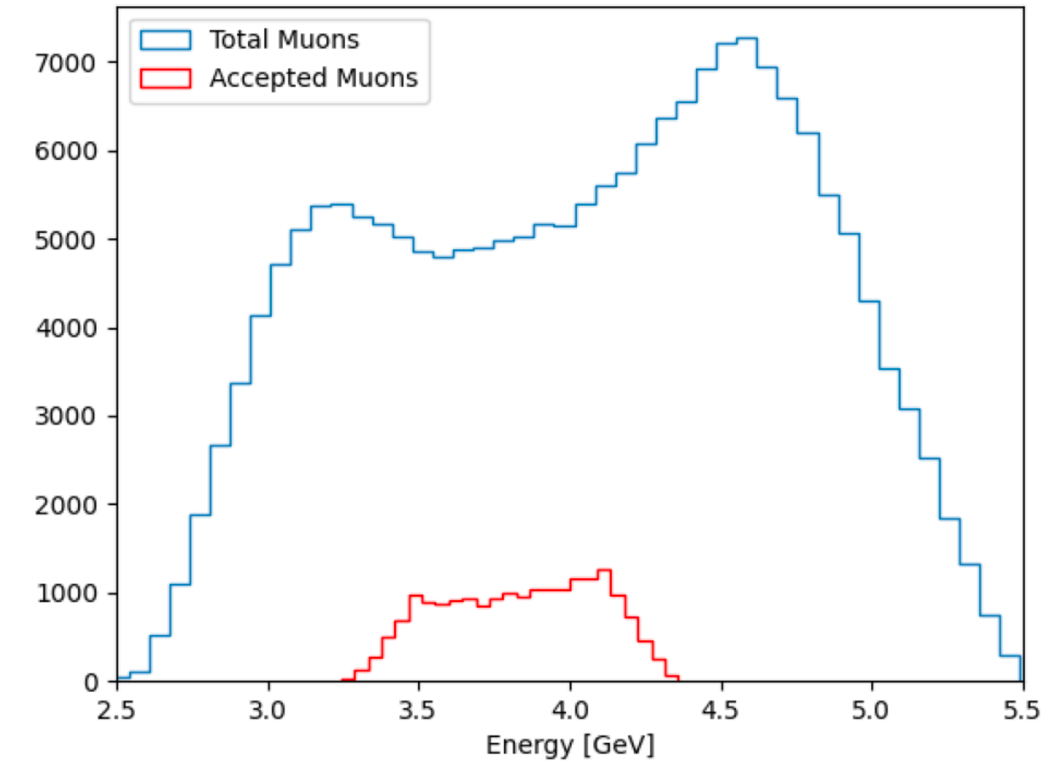


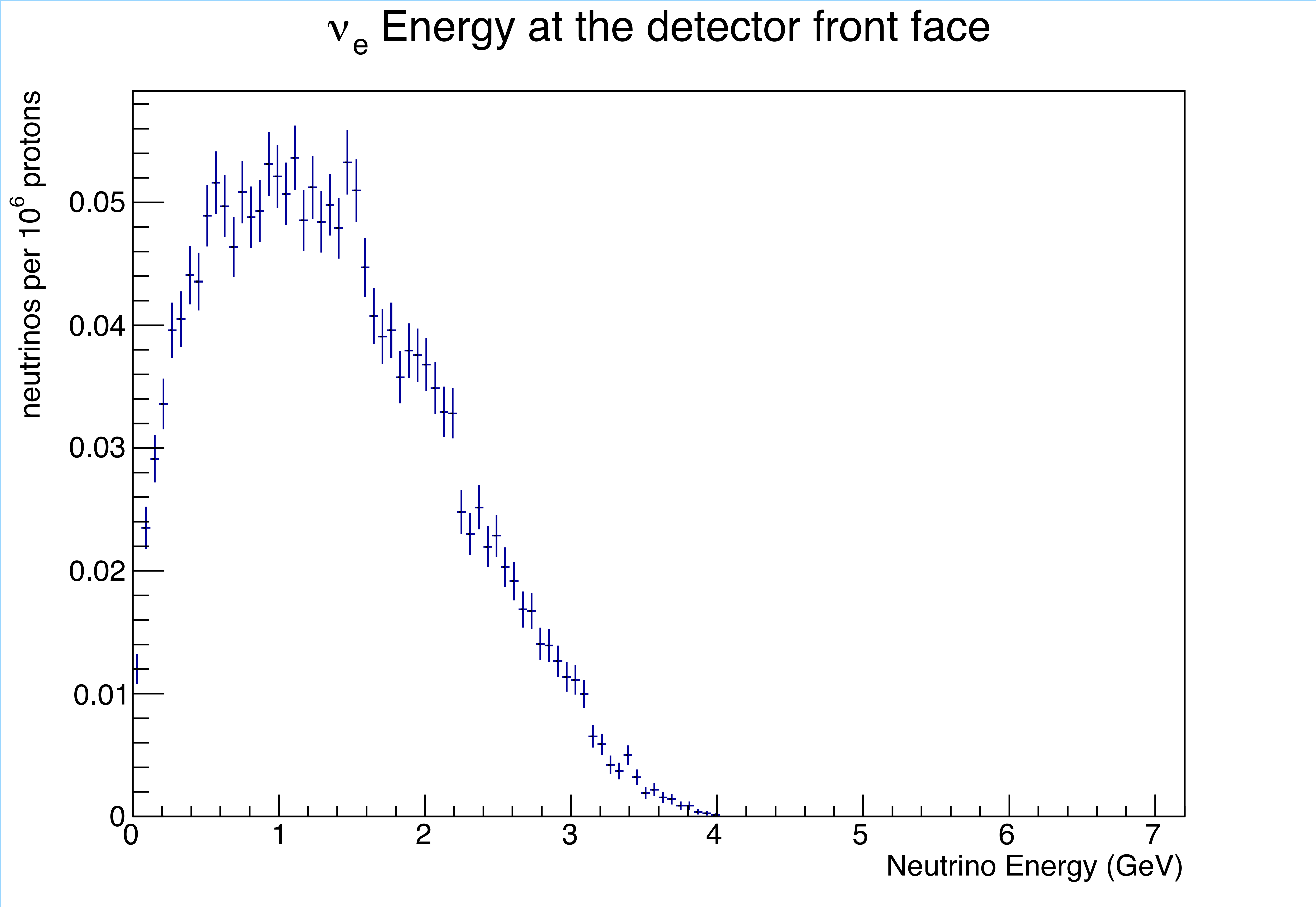
Fig 9 – The Energy Spectrum for the Total Muons and the Accepted Muons for a 5GeV/c Reference Pion Momenta

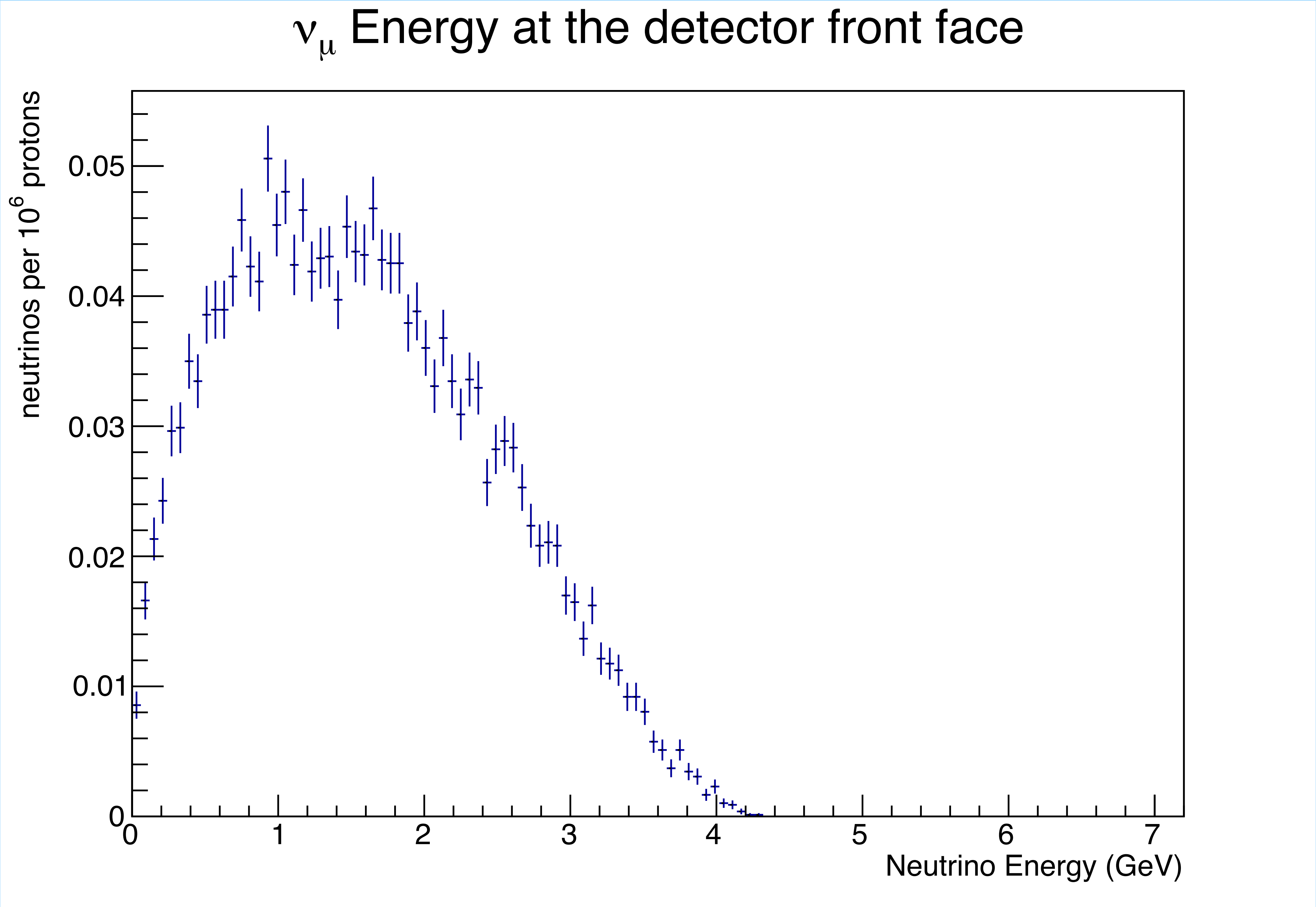
The neutrinos from the decay of pions and muons are tracked
Those that cross the plane of the detector front face have their energy and position recorded

A *history* of each event is kept:
the position and momentum of each particle is kept at three fixed positions: at the target; the start of the production straight; and the end of the straight (muon capture).
Similar data at the point of the pion decay, the point of the muon decay; the point at which the neutrinos cross the plane at the front face of the detector.
Partial events are also stored: pions which have not decayed by the end of the production straight; muons which are not captured by the ring

nuSIM Results

Finally a plot of the neutrino energy spectrum for those neutrinos which pass through the detector is stored in a separate file.





Normalised to protons on target.
Errors are statistical from the simulation.
Working to produce higher statistics runs

νSTORM

Current Uncertainties

The spectrum shape is defined by

- A 180 metre source a few centimetres wide, sitting 50m upstream of the detector
- The decay kinematics of pion and muon decay

These are both well defined … uncertainties statistical on simulation

The a full understanding of the relative normalisation of the muon signal awaits the completion of the bdSIM model of the whole ring

This is an uncertainty on the relative run times needed to complete a particular measurement

Absolute normalisation
The fluka simulation of the pion production has not been optimised for different pion energies

More work to do on Fluka

Availability of Data Sets

The data sets are freely available at
data.nuStorm.org

Index of /

Name	Last modified	Size	Description
E2NormSpectraMuBack513.root	2023-03-09 21:36	5.2K	
E2NormSpectraPiFlsh512.root	2023-03-09 21:36	4.9K	
E2historyMuBack513.root	2022-11-24 14:01	27M	
E2historyPiFlsh512.root	2022-11-24 13:59	7.4M	
E2spectraMuBack513.root	2022-11-24 14:02	4.4K	
E2spectraPiFlsh512.root	2022-11-24 13:59	4.3K	
E3NormSpectraMuBack515.root	2023-03-09 21:45	5.2K	
E3NormSpectraMuSig516.root	2023-03-09 21:45	4.8K	
E3NormSpectraMuSig530.root	2023-03-14 10:52	5.1K	
E3NormSpectraMuSig539.root	2023-03-29 16:13	5.2K	
E3NormSpectraMuSig540.root	2023-03-29 17:10	5.2K	
E3NormSpectraMuSig541.root	2023-03-29 20:54	5.3K	
E3NormSpectraPiFlsh514.root	2023-03-09 21:45	5.0K	
E3historyMuBack515.root	2022-11-24 17:20	27M	
E3historyMuSig516.root	2022-11-24 17:22	26M	

There is a conditions.txt file with details of the data sets

Run	Pion central Energy	Pions	Conditions
506	5	200k	muon signal
507	5	50k	pion Flash
508	5	200k	muon background
509	7	50k	pion Flash
510	7	200k	muon background
511	7	200k	muon signal
512	2	50k	pion Flash
513	2	200k	muon background

And some accompanying details

```
These data sets correspond to runs of nuSIM, where the initial pion momenta and
emittances are those produced by a simulation of a possible horn configuration.
Full optimisation is only performed at one momentum setting and other settings
are obtained bby scaling from this value.

These datasets are for pi plus production. Since the neutrino production is completely
symmetric in the nuSTORM facility, there is no need to create a separate set of spectra
for pi minus production, althought the absolute normalisation is a factor of 3 lower
for the pi minus beam
```

Naming conventions

E3NormSpectraMuBack515.root	2023-03-09 21:45	5.2K
E3NormSpectraMuSig516.root	2023-03-09 21:45	4.8K
E3NormSpectraMuSig530.root	2023-03-14 10:52	5.1K
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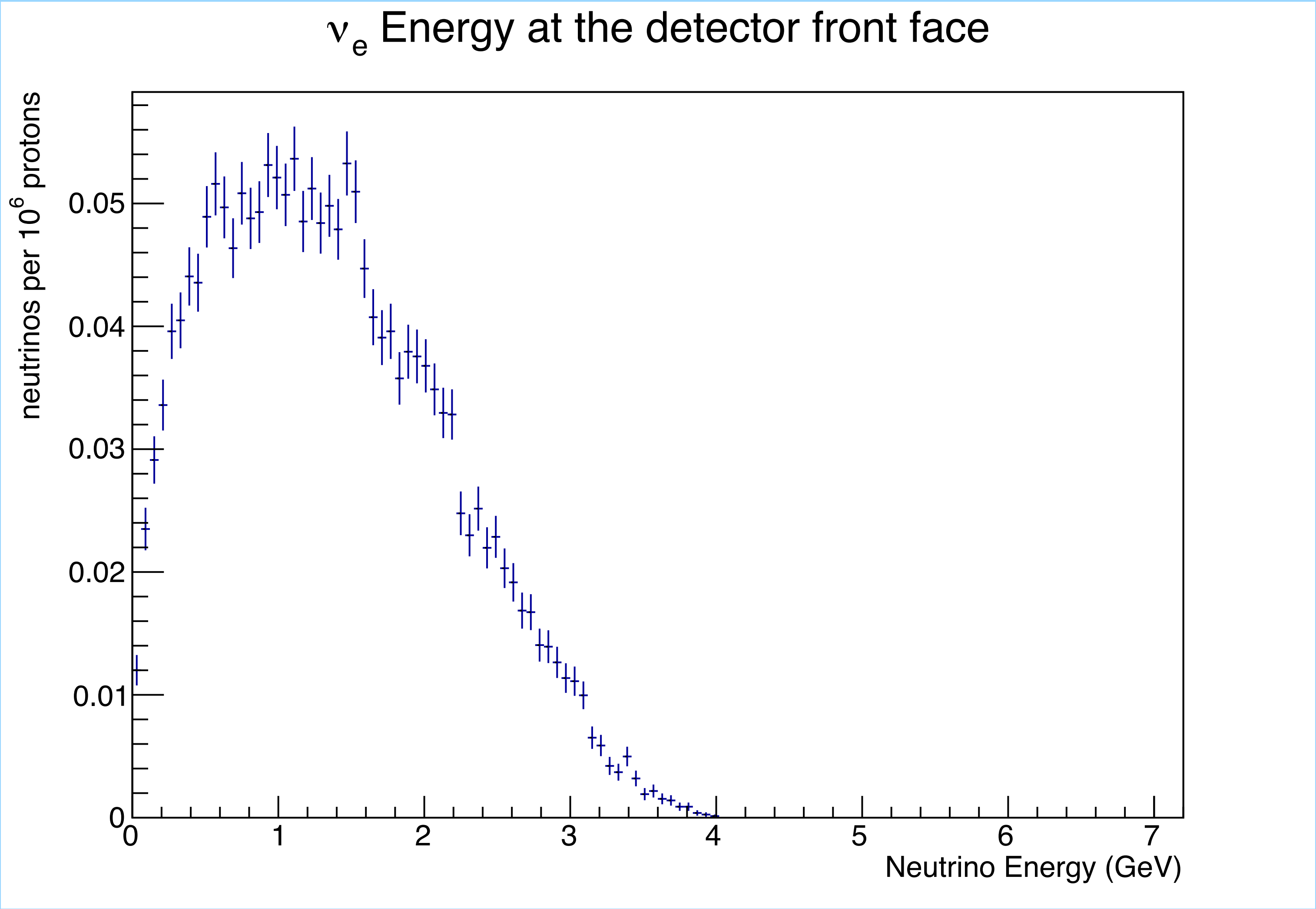
E3NormSpectraMuSig541.root	2023-03-29 20:54	5.3K
E3NormSpectraPiFlsh514.root	2023-03-09 21:45	5.0K

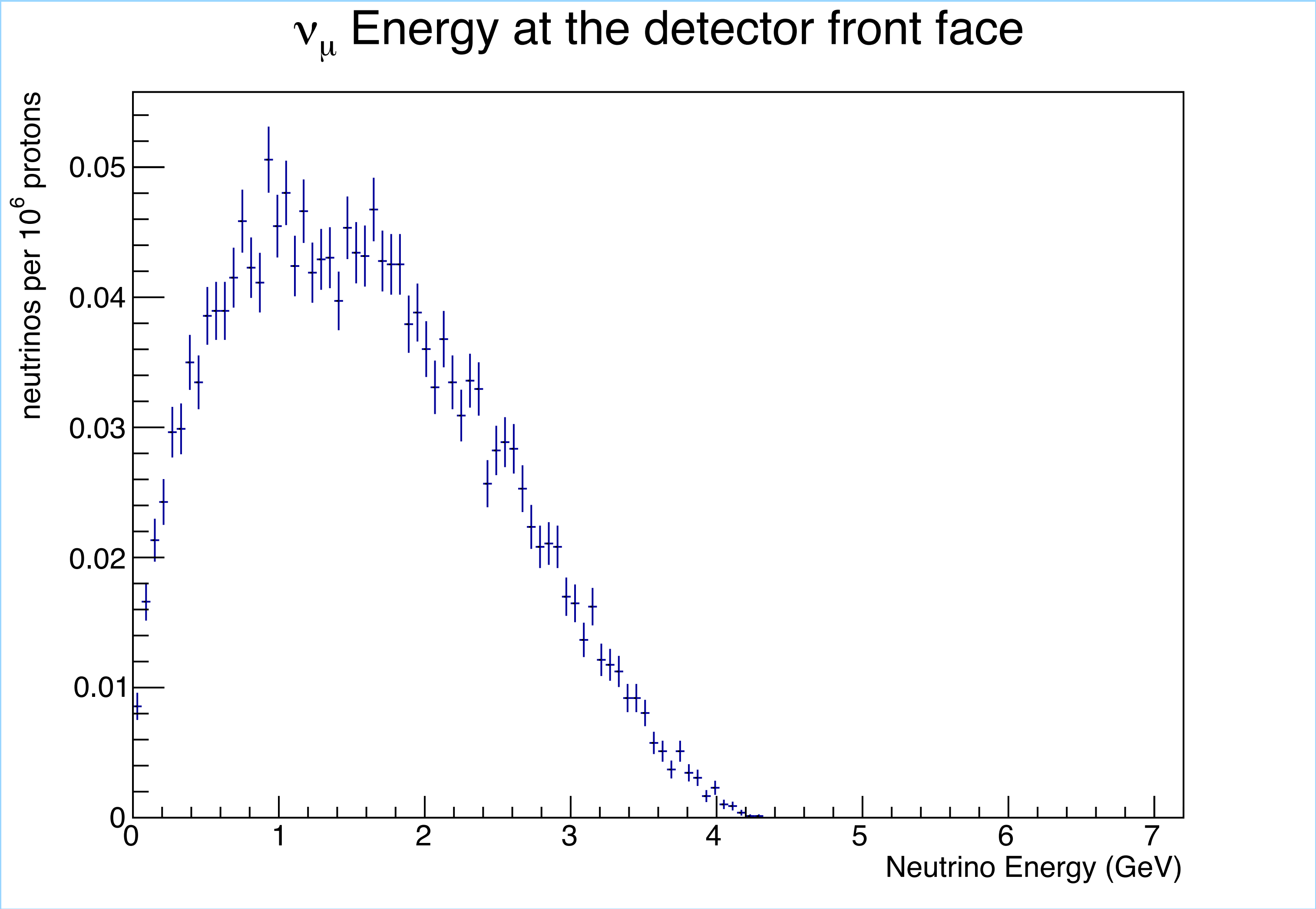
The files of immediate interest will be the normalised Spectra

E3 is parent pion energy

MuSig, MuBack, PiFlsh is the type of spectra

xxx is the run number for my book keeping





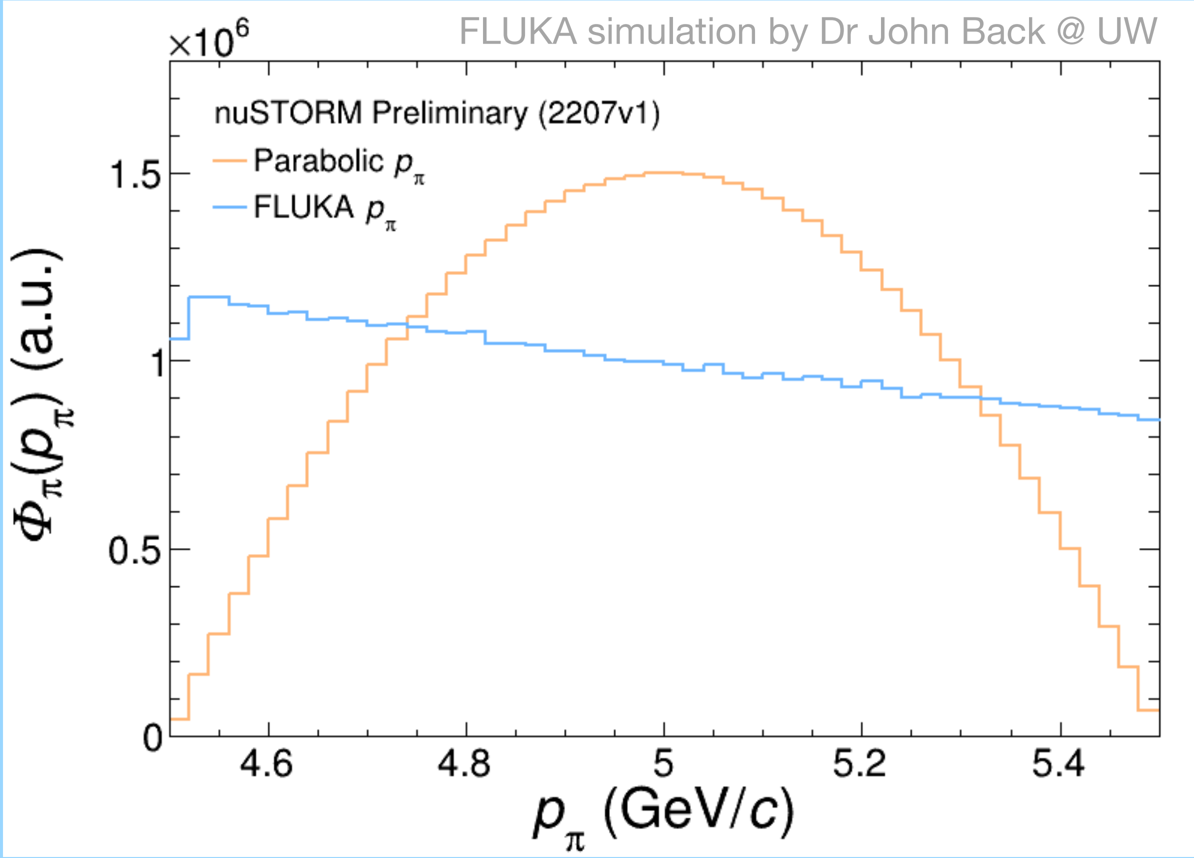
Standard root histograms for the two different neutrino flavours

Questions/comments/requests for different data
paul.Kyberd@brunel.ac.uk

A brief word on existing studies

Demonstration of Energy Spectrum insensitivity to beam parameters	Marvin Pfaff
Transverse Kinematic imbalance	Tiago Alves, Marvin Pfaff, Xianguo Lu
“Prism like” - preliminary results	Paul Kyberd

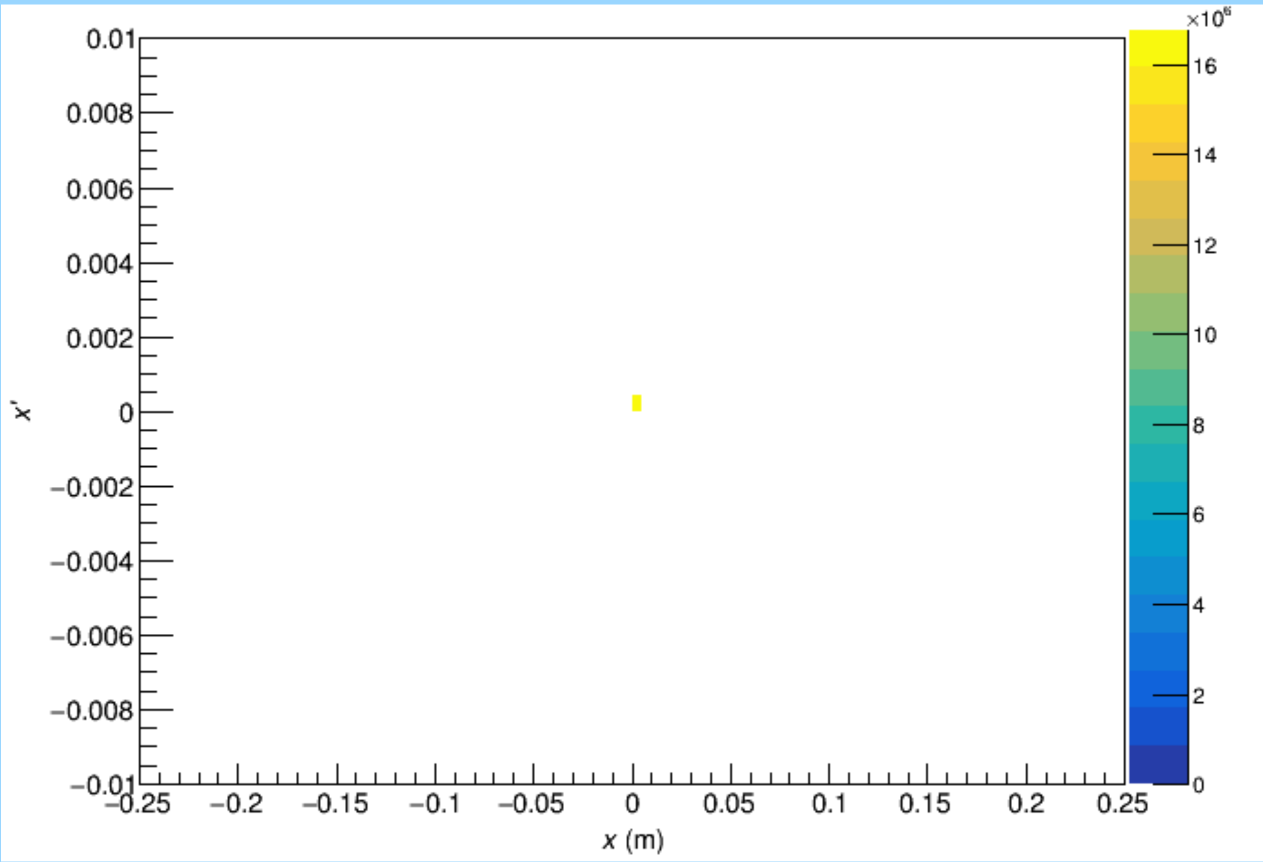
nuSIM beam studies



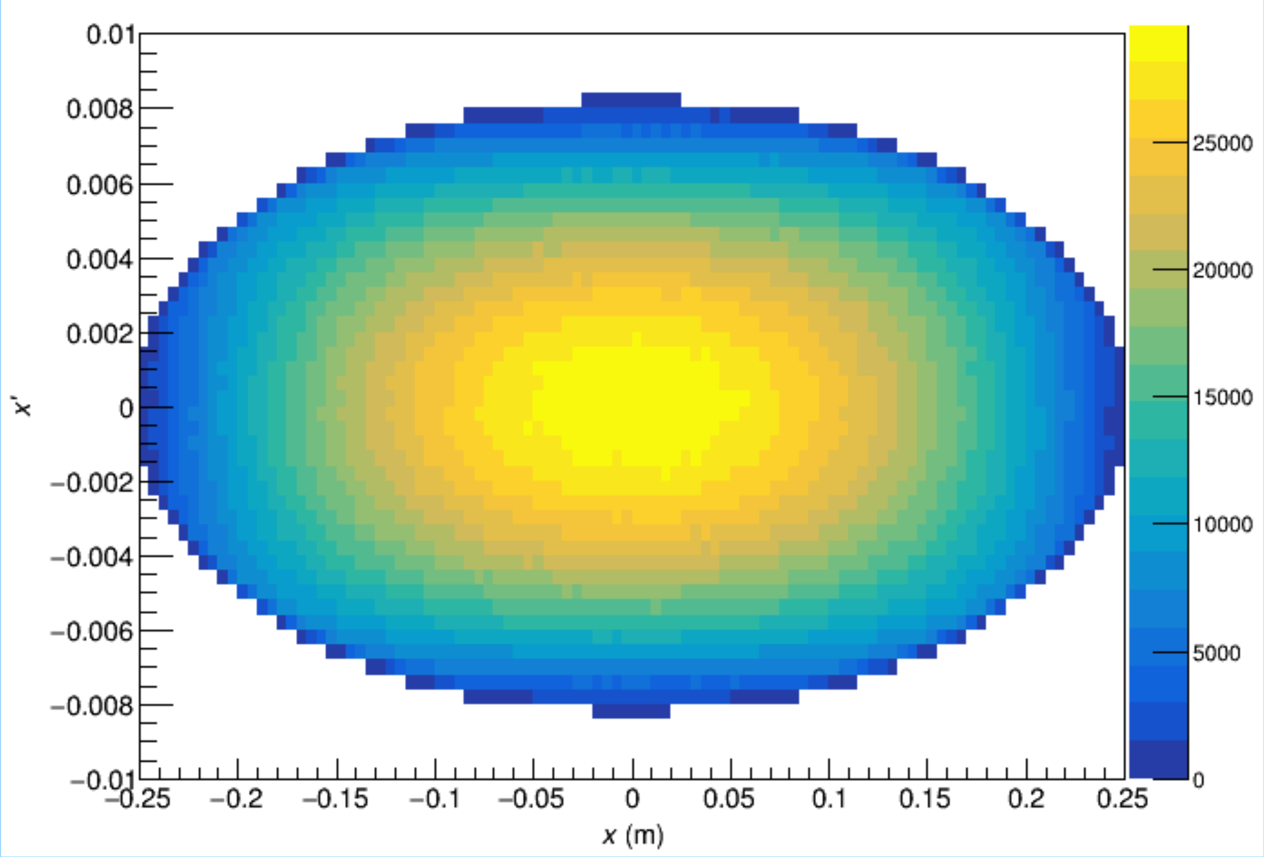
Pion Momentum @ Target

- Dedicated beam studies tried to identify influence of different nuSIM „beam settings“ on neutrino spectra
- Different pion momentum and phase space distributions studied according to naive, ideal and simulated (FLUKA) case

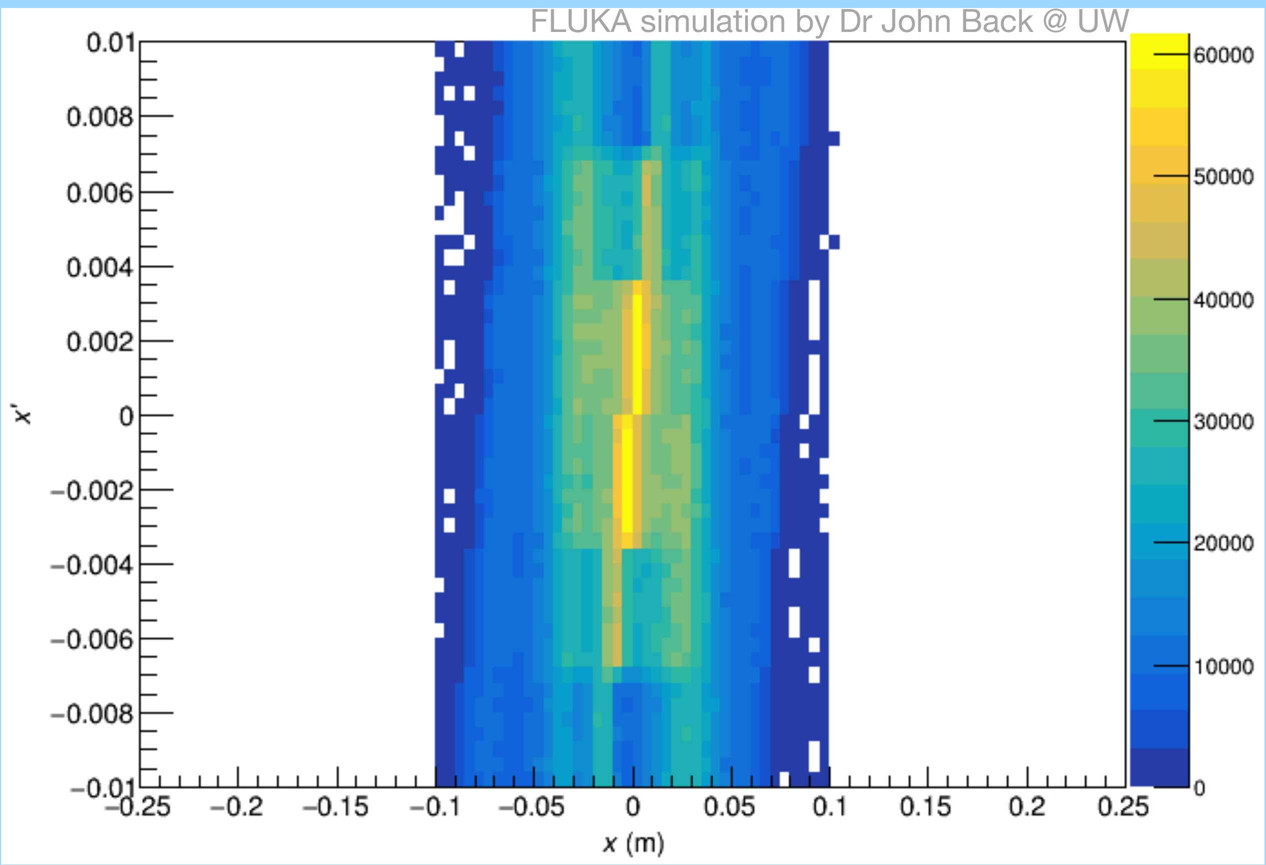
Pion Phase Space @ Target



“Pencil beam” → no spread



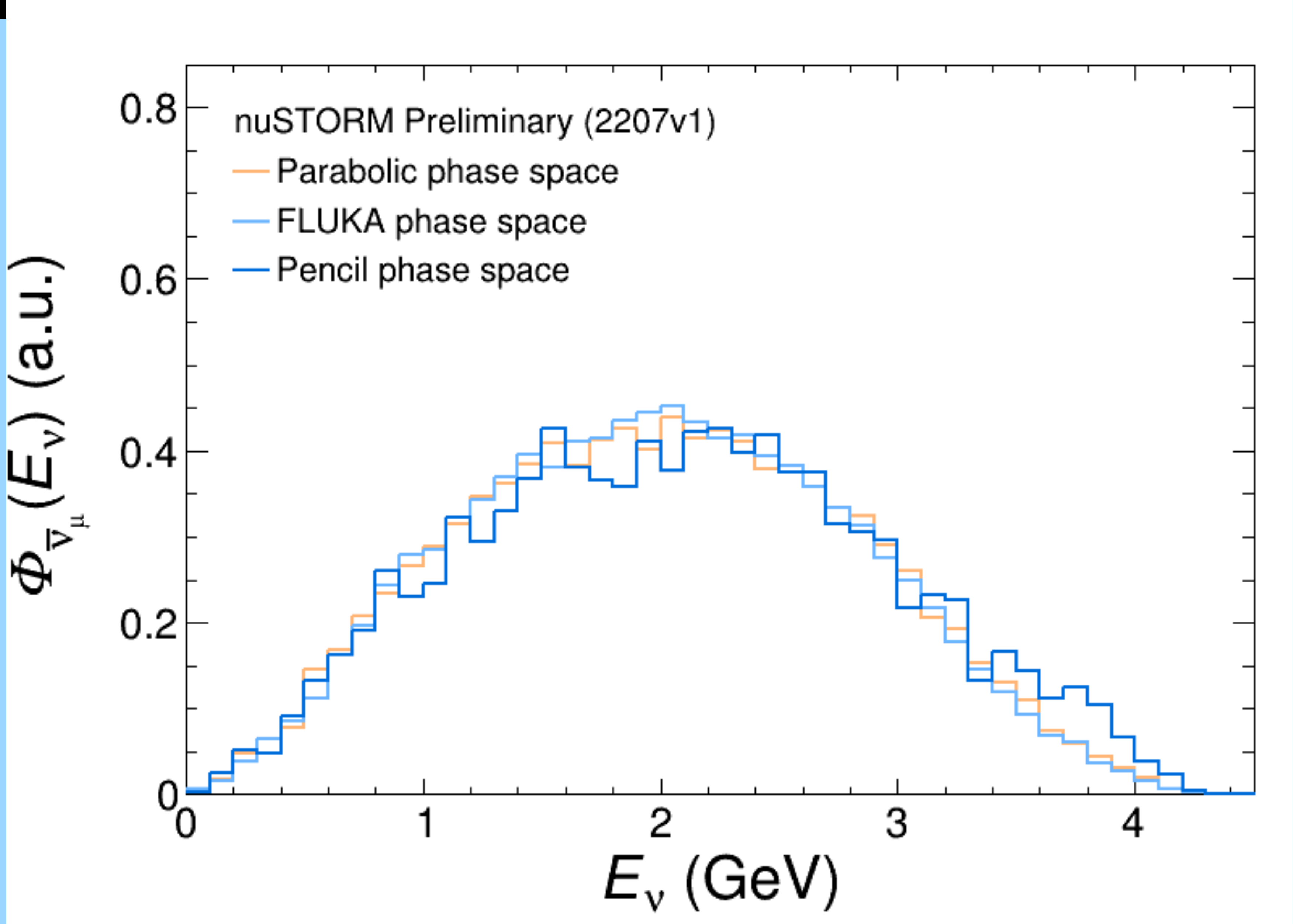
Parabolic in x, x’, y & y’



FLUKA distribution

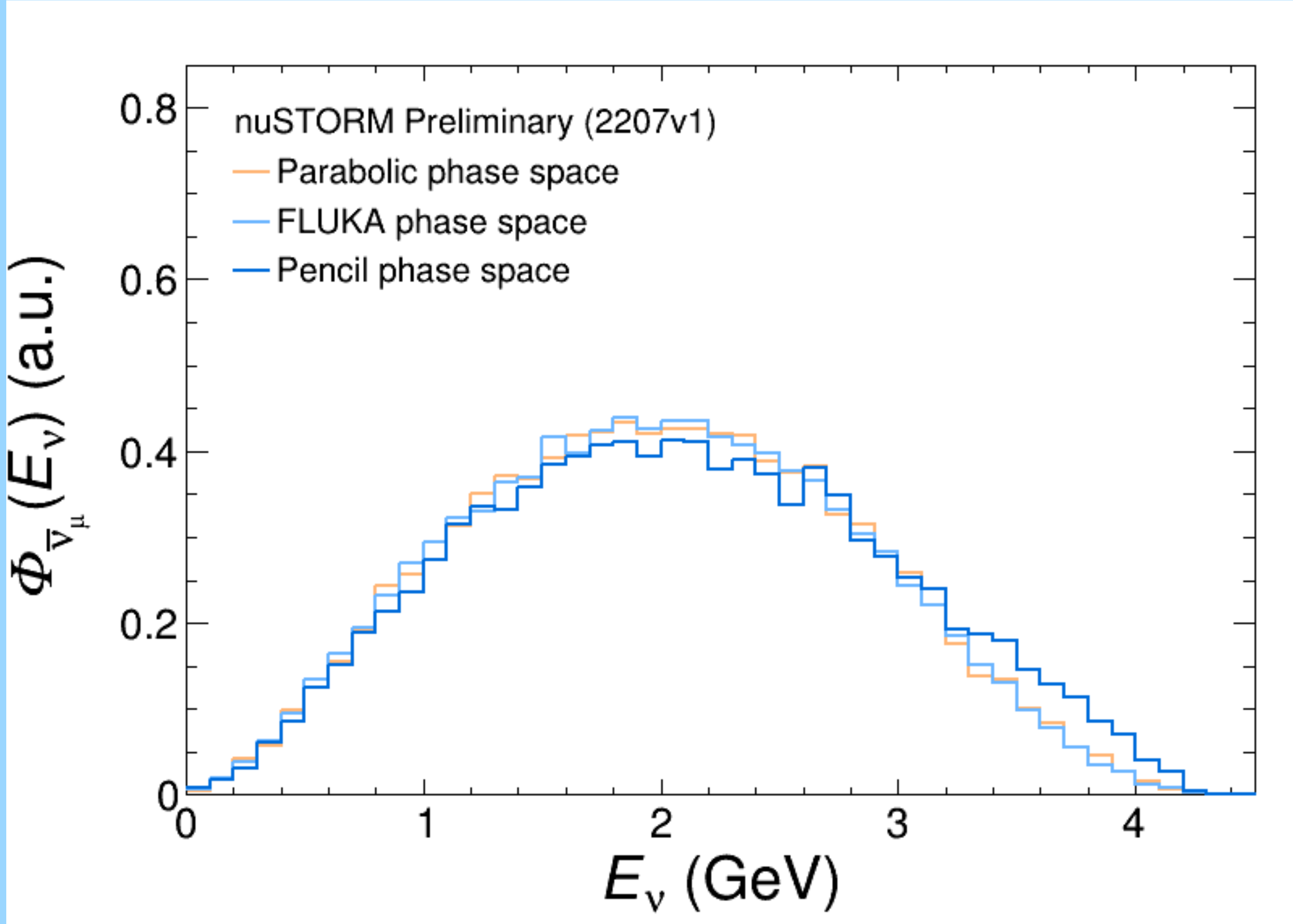
nuSIM beam studies

Area Normalised Flux



Parabolic Momentum

Area Normalised Flux



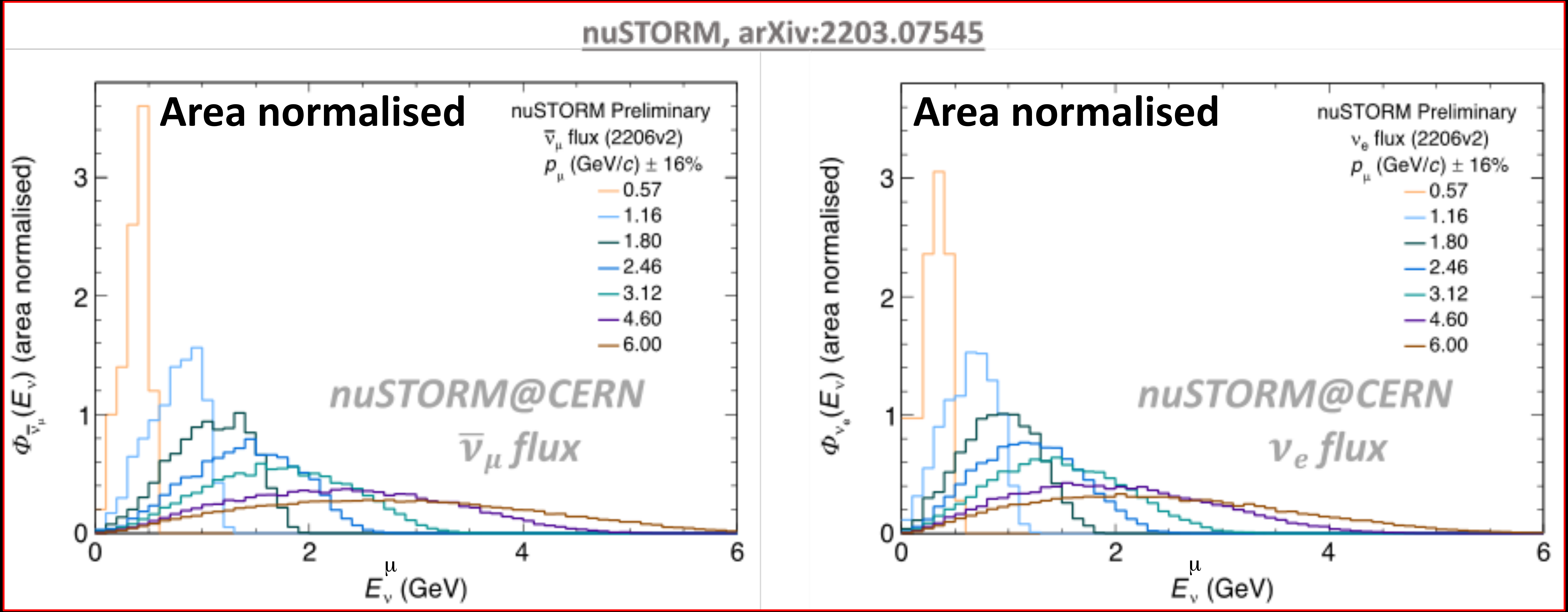
FLUKA Momentum

- Neutrino fluxes at detector front face 50 m past the end of the production straight
- Parabolic and FLUKA phase space cases identical in shape but spectrum for pencil beam slightly skewed towards higher energies
- No difference in shape between the different momentum settings with the same phase space setting

→ nuSIM „beam settings“ have marginal influence on shape of neutrino spectra and no differences could be found between ideal and simulated cases

T. Alves, M. Pfaff

nuSTORM@CERN: flux estimation

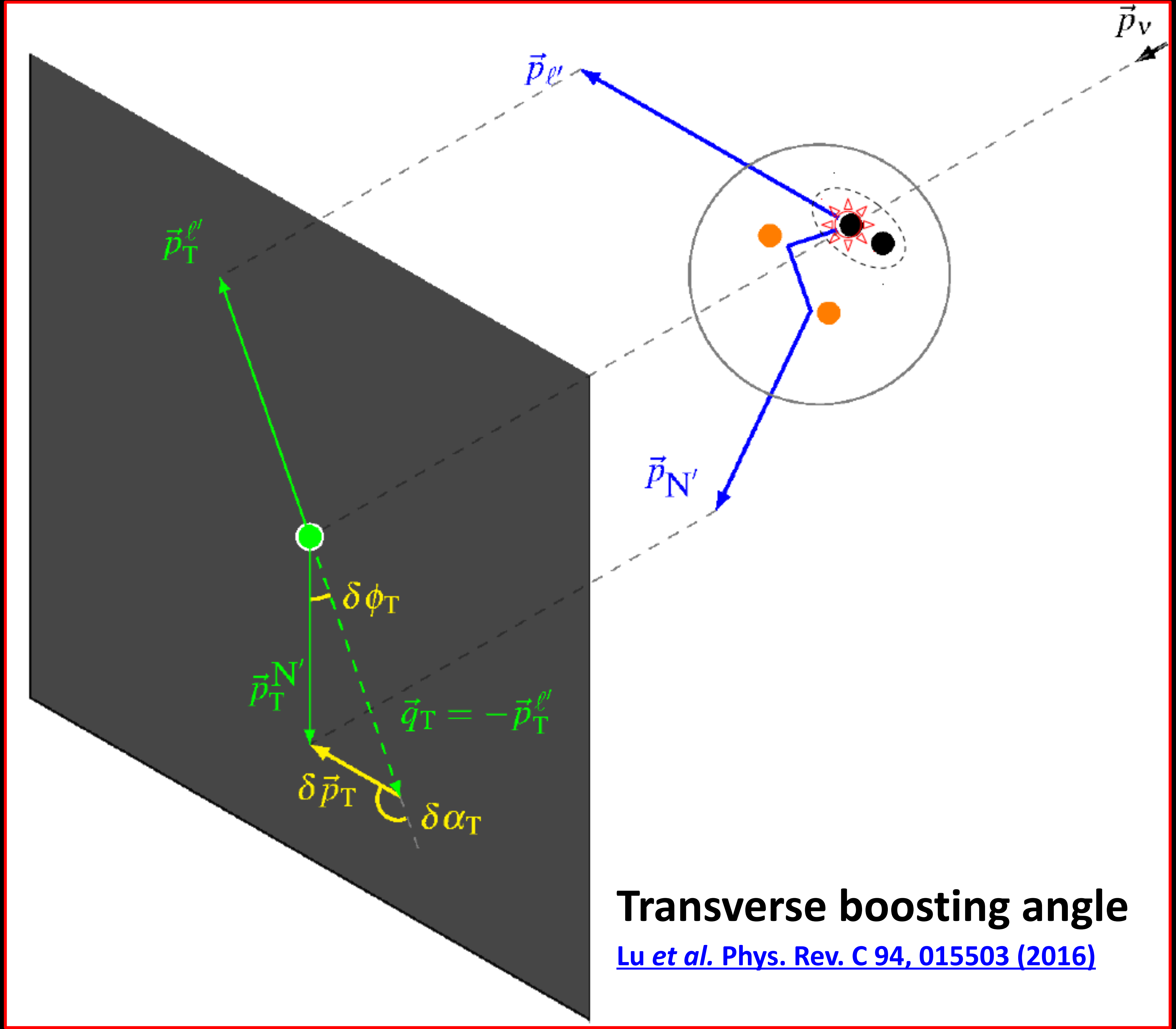


- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE.   : 2.4 GeV
- Set by stored-muon momentum

- Unique opportunity:
  - E_ν-scan measurements
- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance

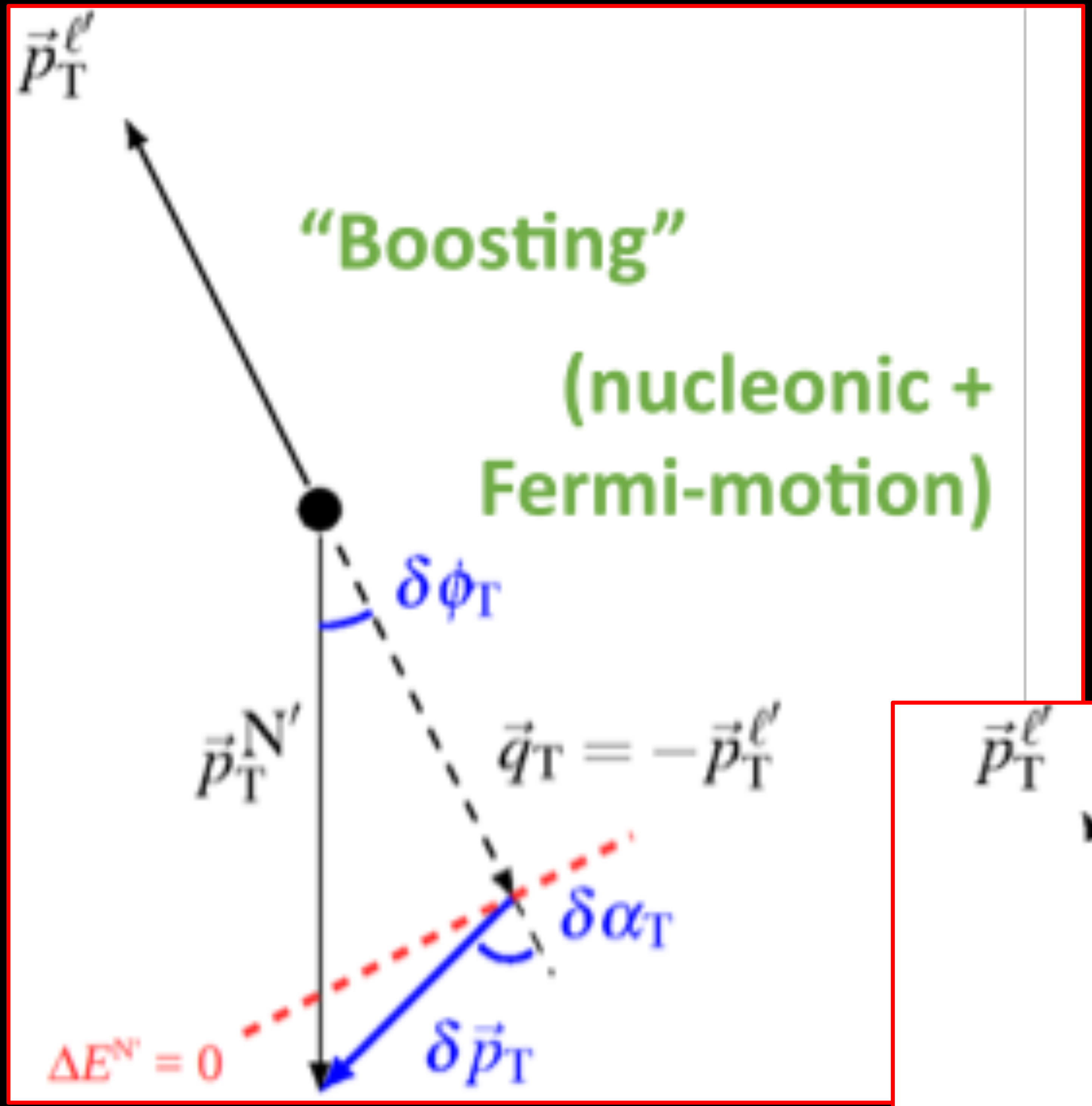
nuSTORM@CERN: E_ν-scan measurements

X. Lu

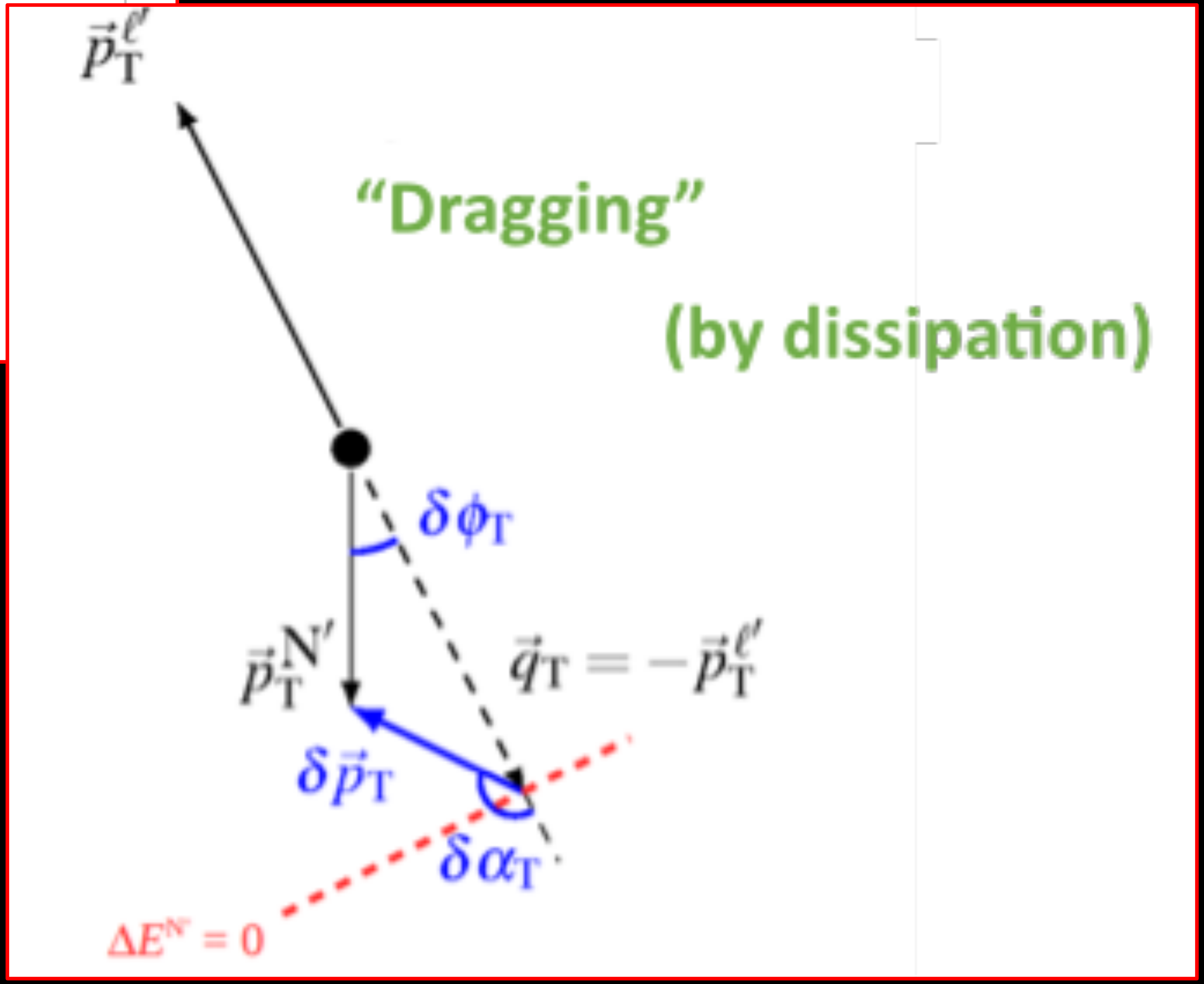


Transverse boosting angle

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



Quasi-elastic cross section function of $\delta\alpha_{\mathrm{T}}$

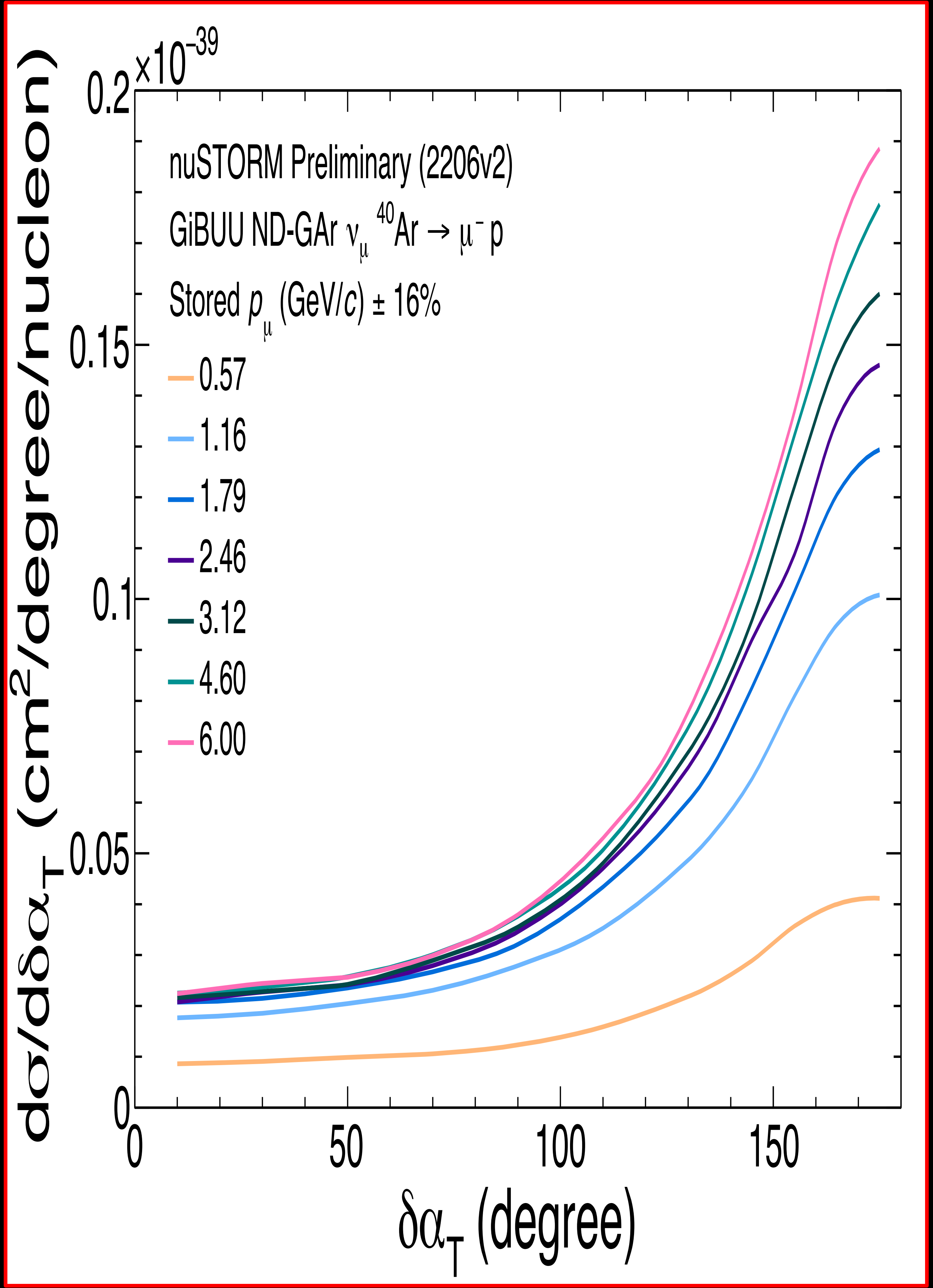


- Low $\delta\alpha_{\mathrm{T}}$: impact of nuclear effects low:
  - "Nuclear model calibration"
- High $\delta\alpha_{\mathrm{T}}$: energy-dependent nuclear effects:
  - Constrain nuclear models of, e.g. 2p2h, pion absorption, …

nuSTORM@CERN: E_ν-scan measurements

T. Alves
M. Pfaff
X. Lu

Quasi-elastic Differential cross section vs $\delta\alpha_T$



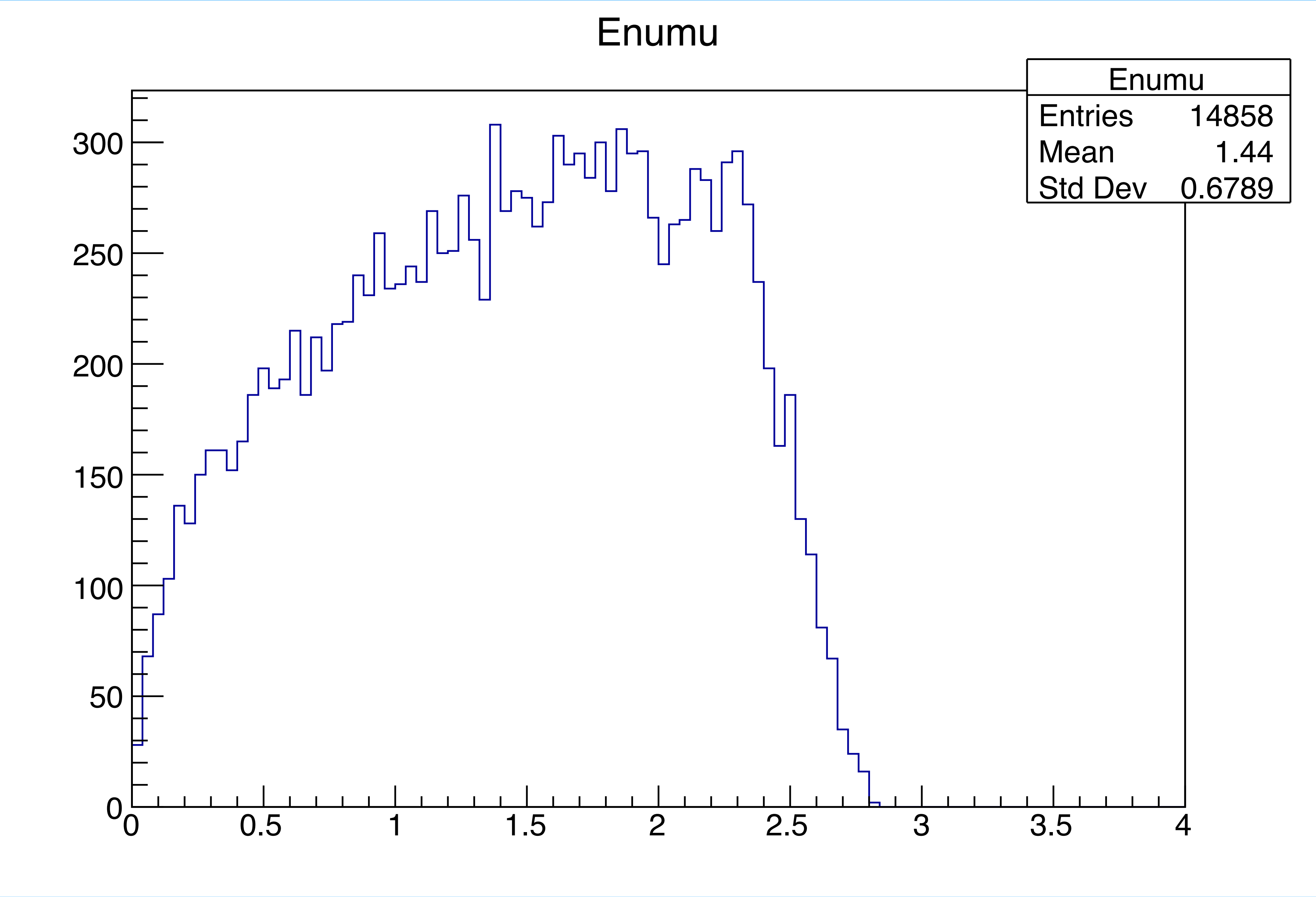
- Cross-section estimation using (preliminary) nuSTORM flux
- Energy evolution "tunable" to optimise sensitivity of measurement
- Start of study of energy dependence of various exclusive measurements:
  - To provide precise constraints on nuclear effects and their evolution

Studies with the nuSIM simulations

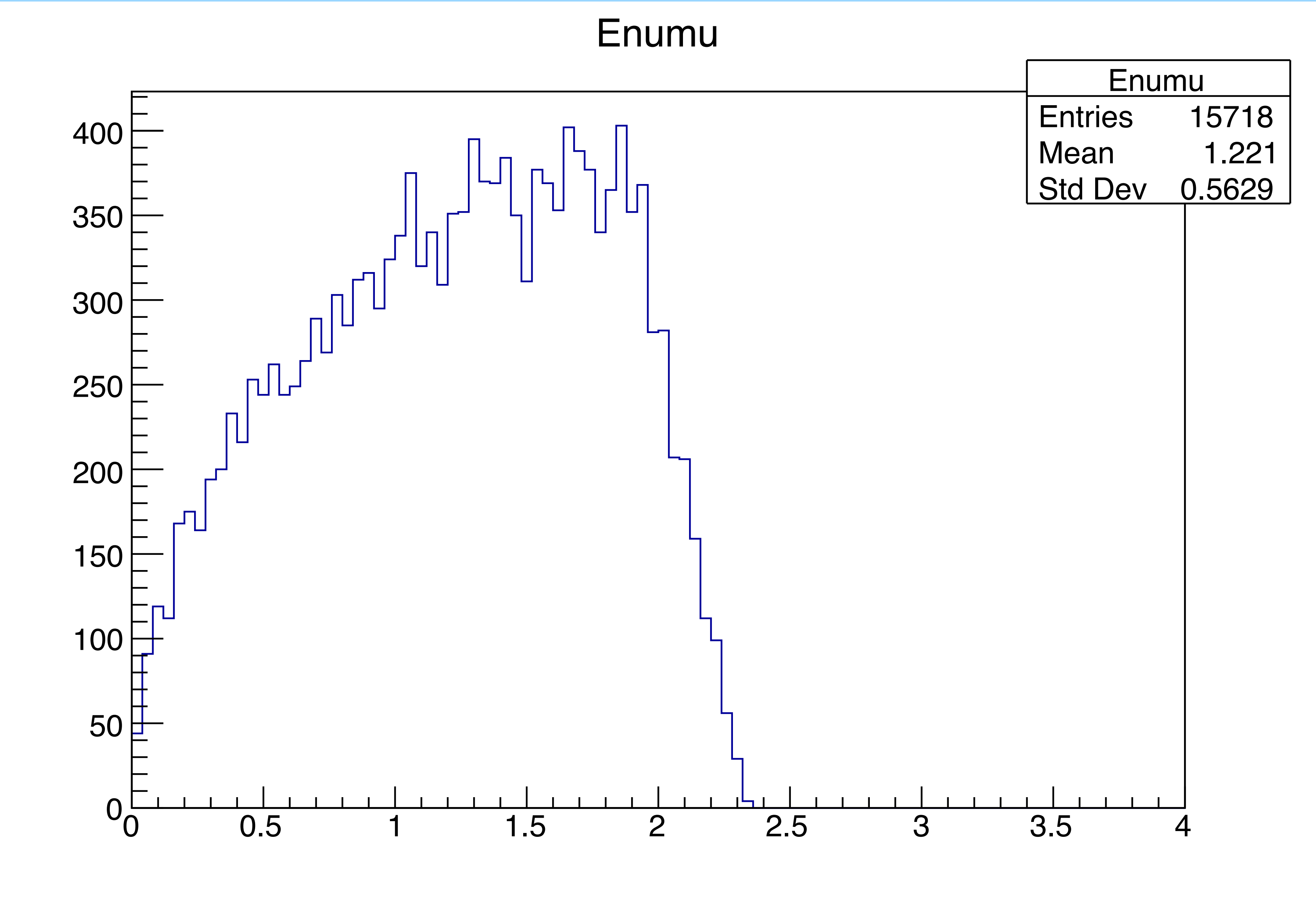
Is the PRISM technique (DUNE) applicable to nuSTORM.?

In particular can we create a synthetic beam with a narrower effective energy range.

The DUNE-PRISM Near Detector. Cai et. al. *"Specifically, the relationship between the energy of the decay parent particle and the final state neutrino energy changes as a function of observation angle away from the parent boost direction; this can be seen in Figure 1a. The NOvA and T2K long-baseline oscillation experiments already use this feature—often called 'the off axis effect'—to achieve a more narrowly peaked neutrino energy spectrum than can be achieved by a purely on-axis experiment."*



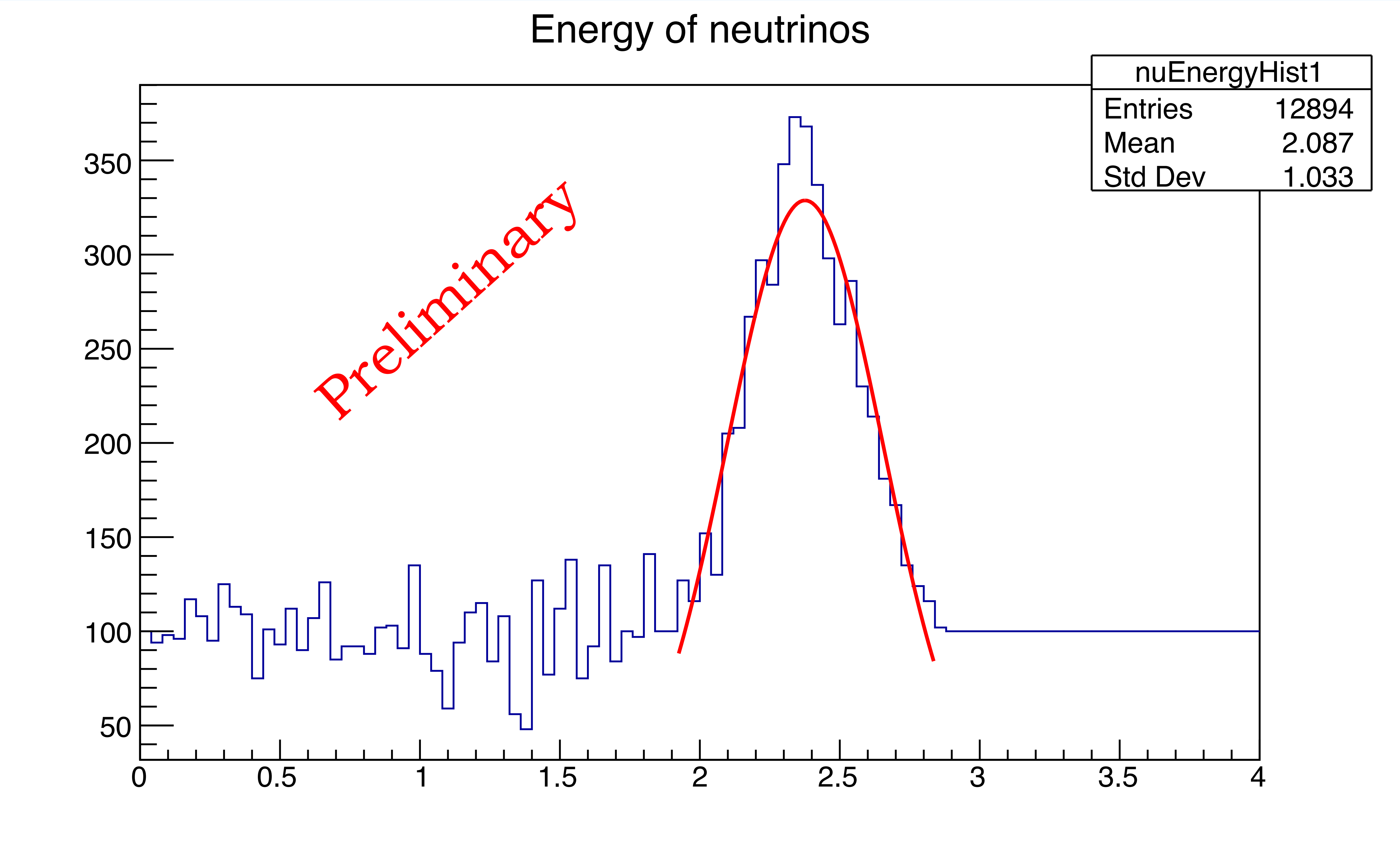
6 GeV pions



5 GeV pions

Pion Flash Spectra

Synthetic Beam



Pion flash neutrinos - bin by bin subtraction with the 5 GeV spectra normalised by the ratio of the number of entries - and by the ratio of the spectrum end points. Offset of 100 so negative values visible

A Gaussian fit to estimate the peak and width
2.38 +/- 0.28

Only two datasets are required

Conclusion

Current Status
• Data sets at data.nustorm.org
• Accurate normalised υ_μ and υ_e energy spectra available
• A number of studies completed

Plans
• Improve statistical accuracy
• Work on bdSIM and Fluka to improve the absolute normalisation
• A complete studies
• Start design of a baseline detector