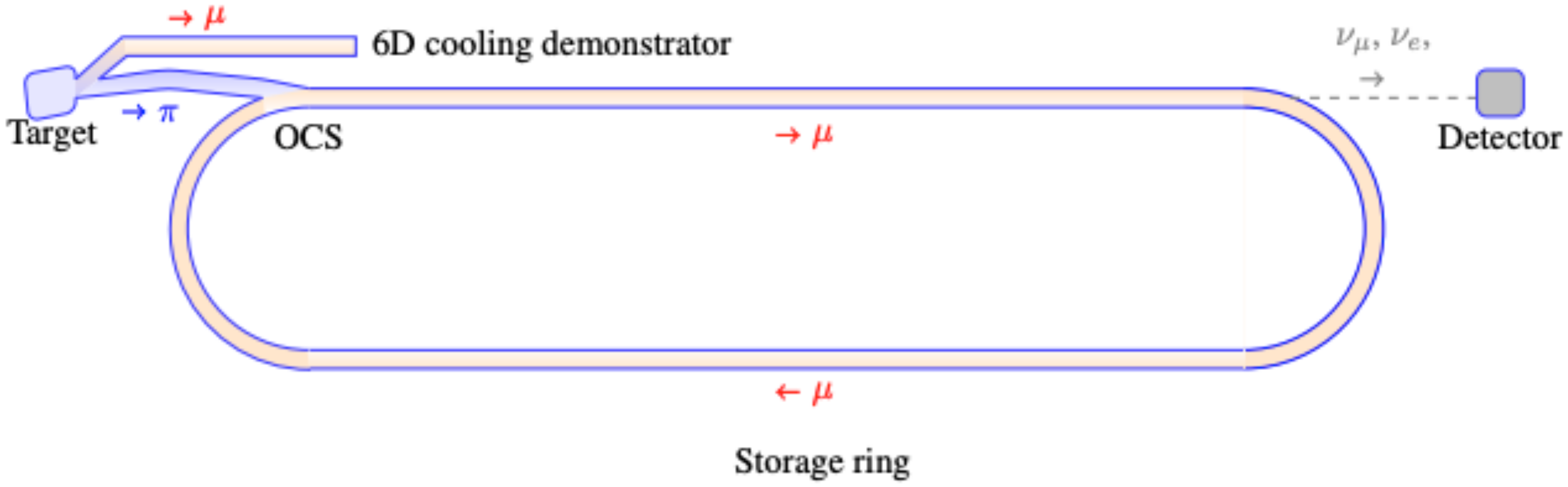
Synthetic Beams at nuSTORM

Creating quasi monochromatic fluxes from a tuneable muon storage ring

Rohan Kamath / 23 November 2023 /Joint Autumn Meeting of nuSTORM and UK Muon Beams Collaboration

Background

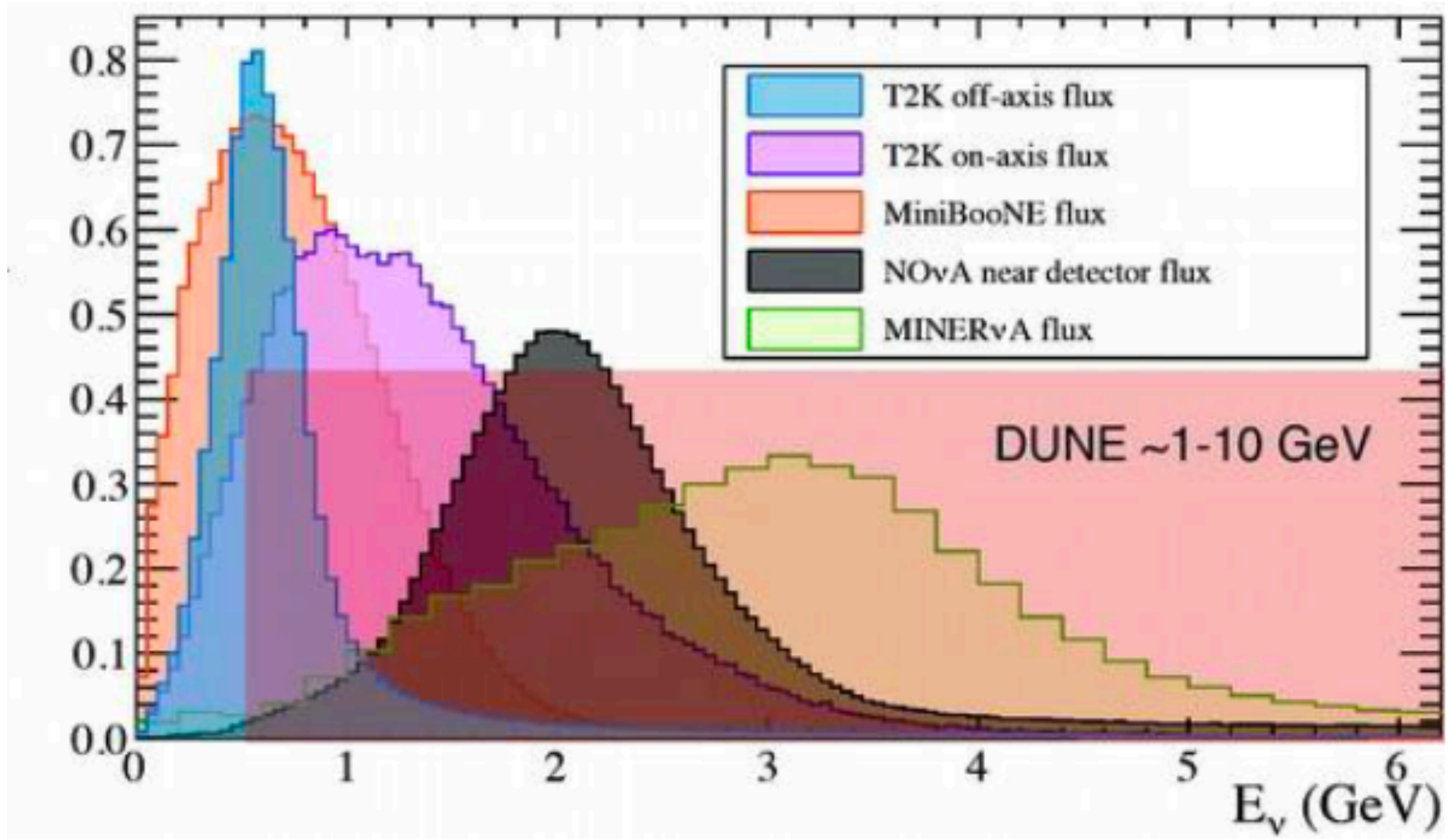
The nuSTORM layout



The current design of the nuSTORM facility

Advantages of a tuneable muon ring

- The main advantage of the tuneable muon ring is the fact that we can effectively probe the entire energy range of the main long baseline neutrino experiments, aiding cross section analysis.



Wilkinson C. 17th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (26-28 October 2017)

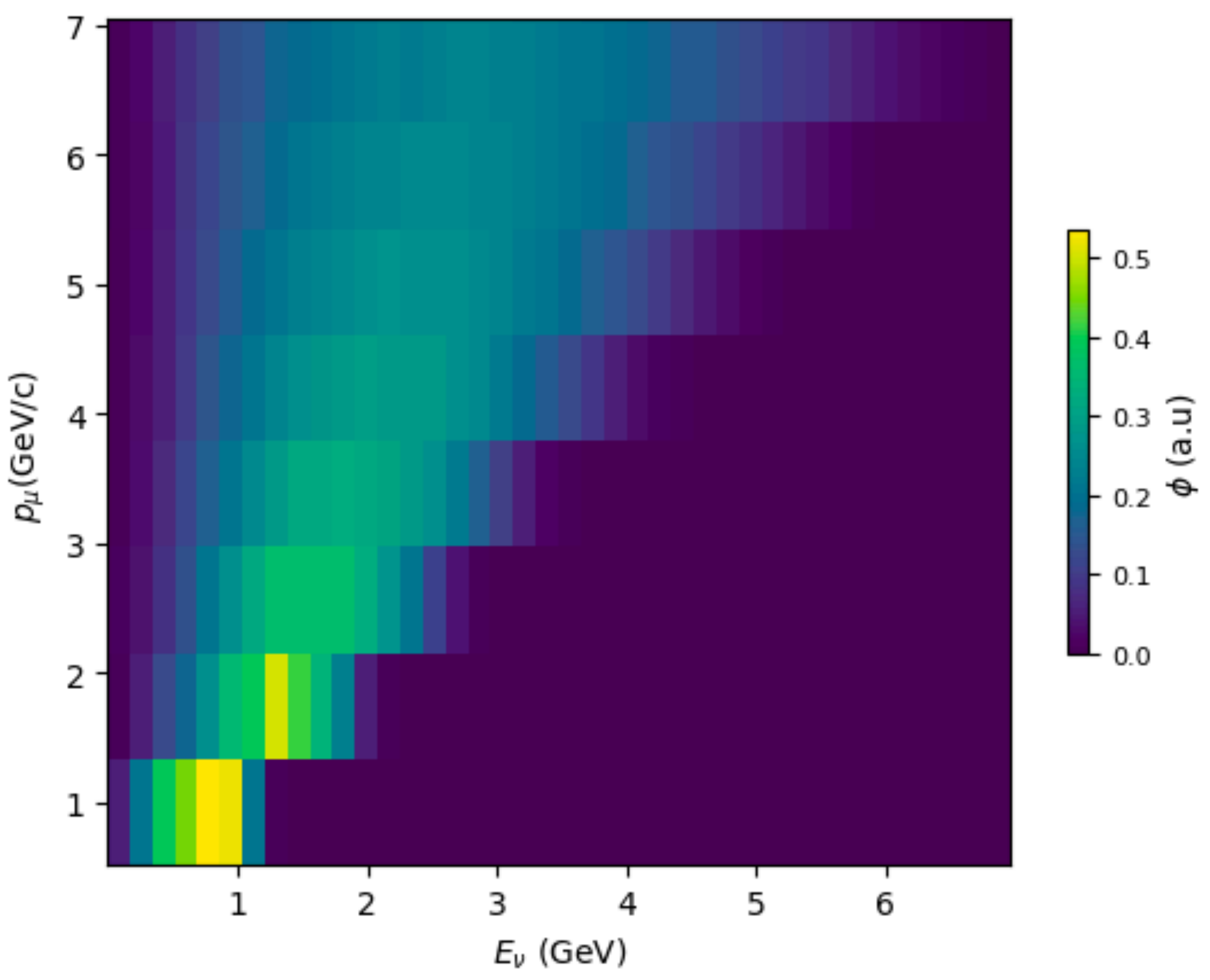
But can we do more?

- Having different muon momenta means that we have different spectra of neutrino energies.
- We can build linear combinations of these neutrino energies to create “synthetic” neutrino beams.
- This is similar to a Fourier transform, where we use independent modes with different weights to create an arbitrary wave.
- For example, having a mono energetic beam greatly helps inform cross section interaction models.

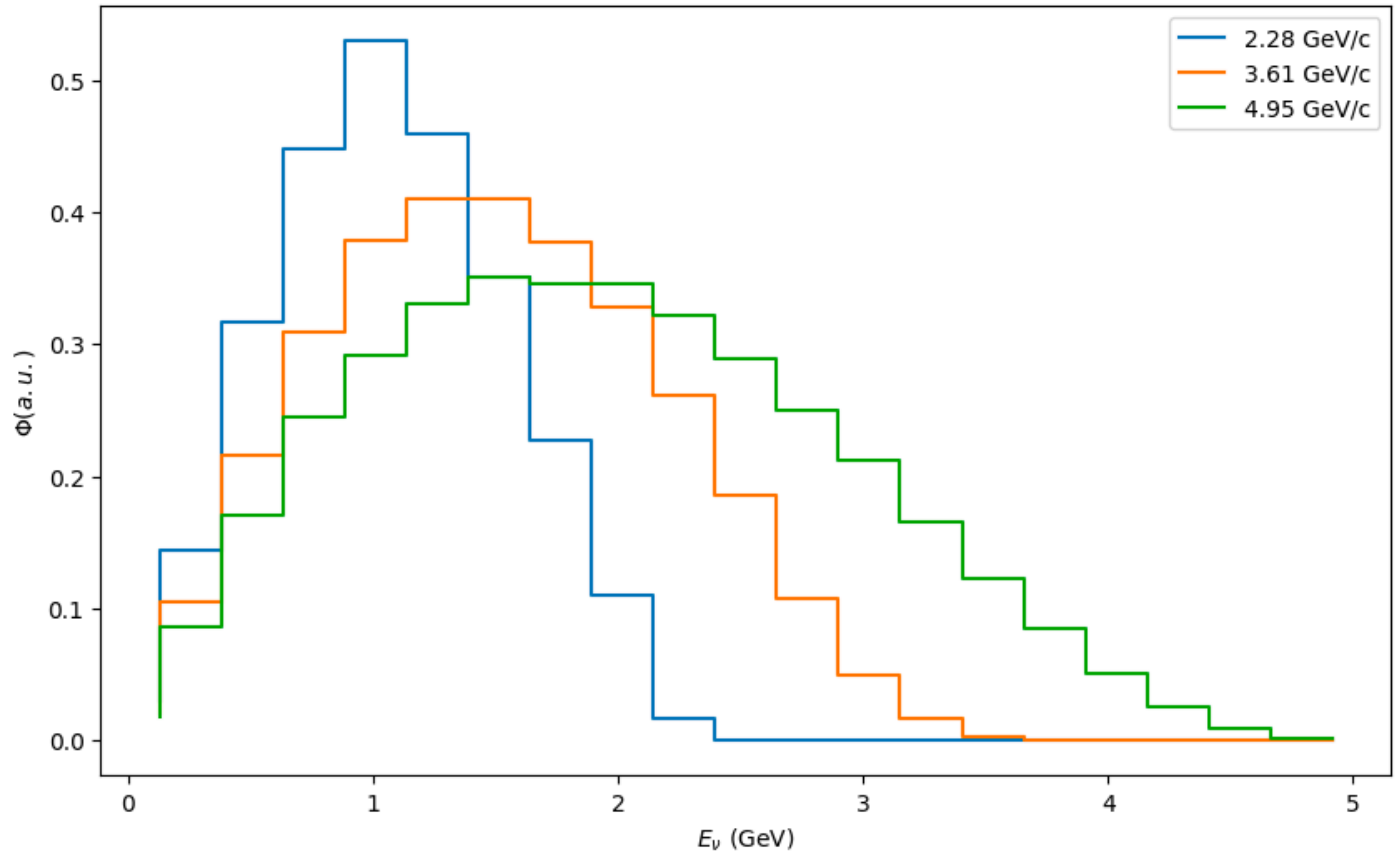
The nuSTORM spectra

- We use nuSIM to simulate the spectra for pion energies from 1 to 8GeV/c
- Kinematically, the decay products of the muons are isotropic, but the boost from the muon rest frame to the lab frame “squeezes” them.
- The higher the boost, the more the squeeze. Hence, at lower energies, the only neutrinos that reach the detector are when the decay happens forwards or backwards.

The nuSTORM Spectra



A heatmap of nuStorm events



Neutrino energy spectra at three muon momentum settings.

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:

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

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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.

Regularisation

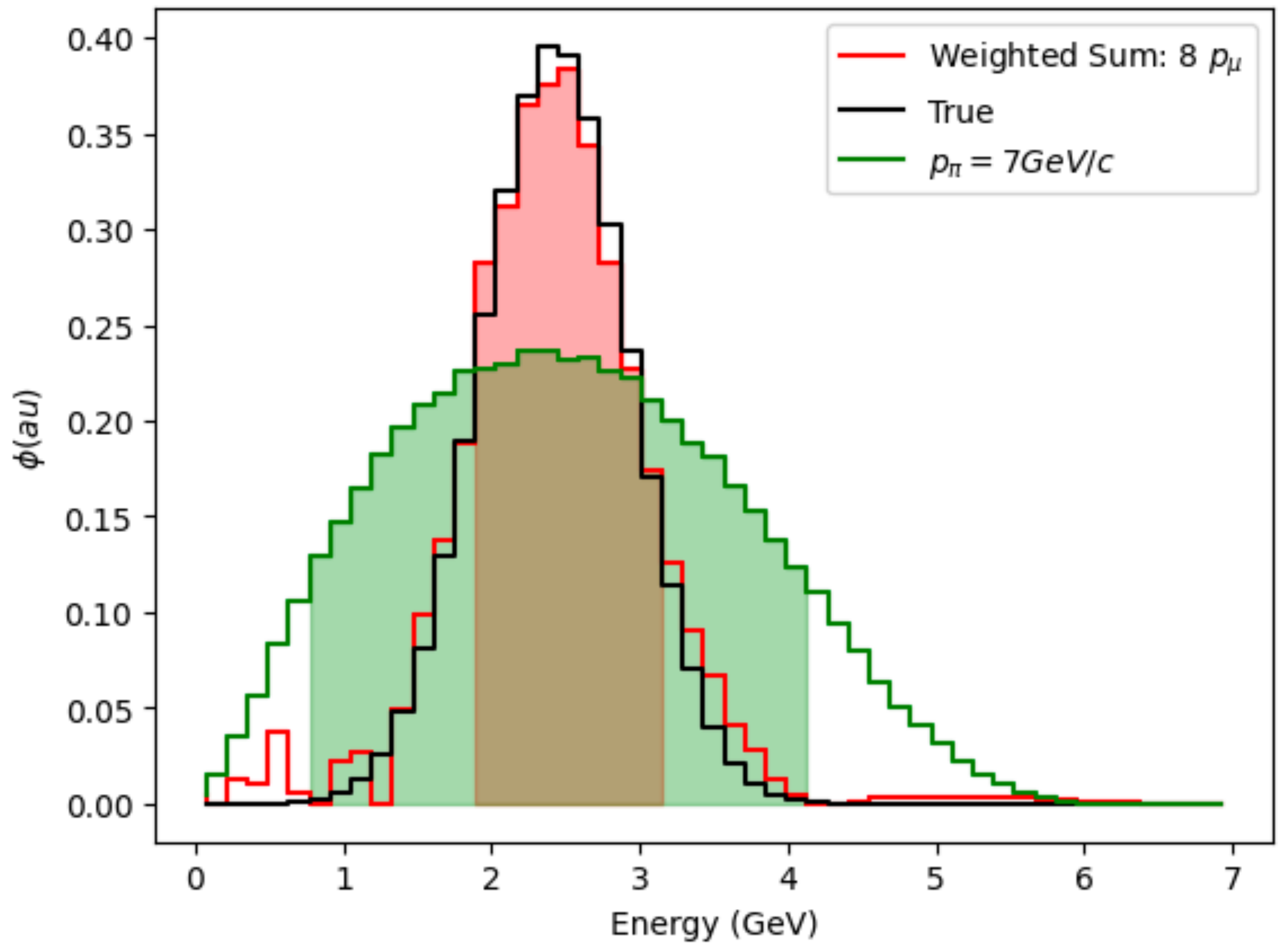
- Finally, we add a regularisation term to the FOM to ensure errors are kept at a minimum.

$$\sum_{i=2}^{N_\mu} \frac{(c_i - c_{i-1})^2}{K}$$

- Whilst fluxes can cancel each other the errors on those bins would add, hence, this represents a penalty term so that the coefficients don't explode. K stands for the strength of the regularisation.

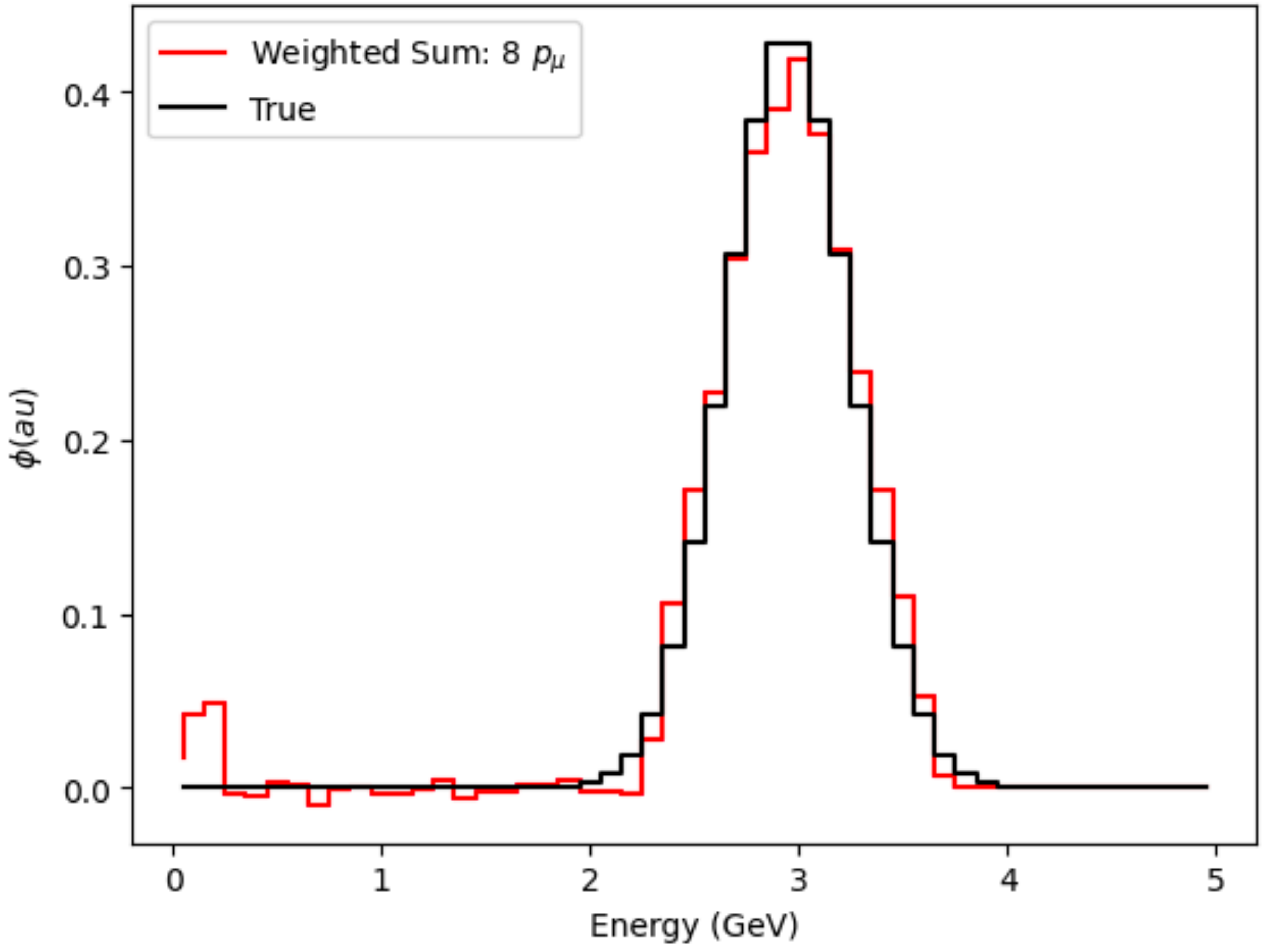
Results

- We used linear combinations of 8 muon settings to a synthetic neutrino beam.
- As shown in the figure, a 2.5GeV, 0.5GeV SD gaussian beam has been reconstructed.
- This is a 63.5% reduction in FWHM.
- The fit gets better for wider distributions.



Synthetic beams with the pion flash

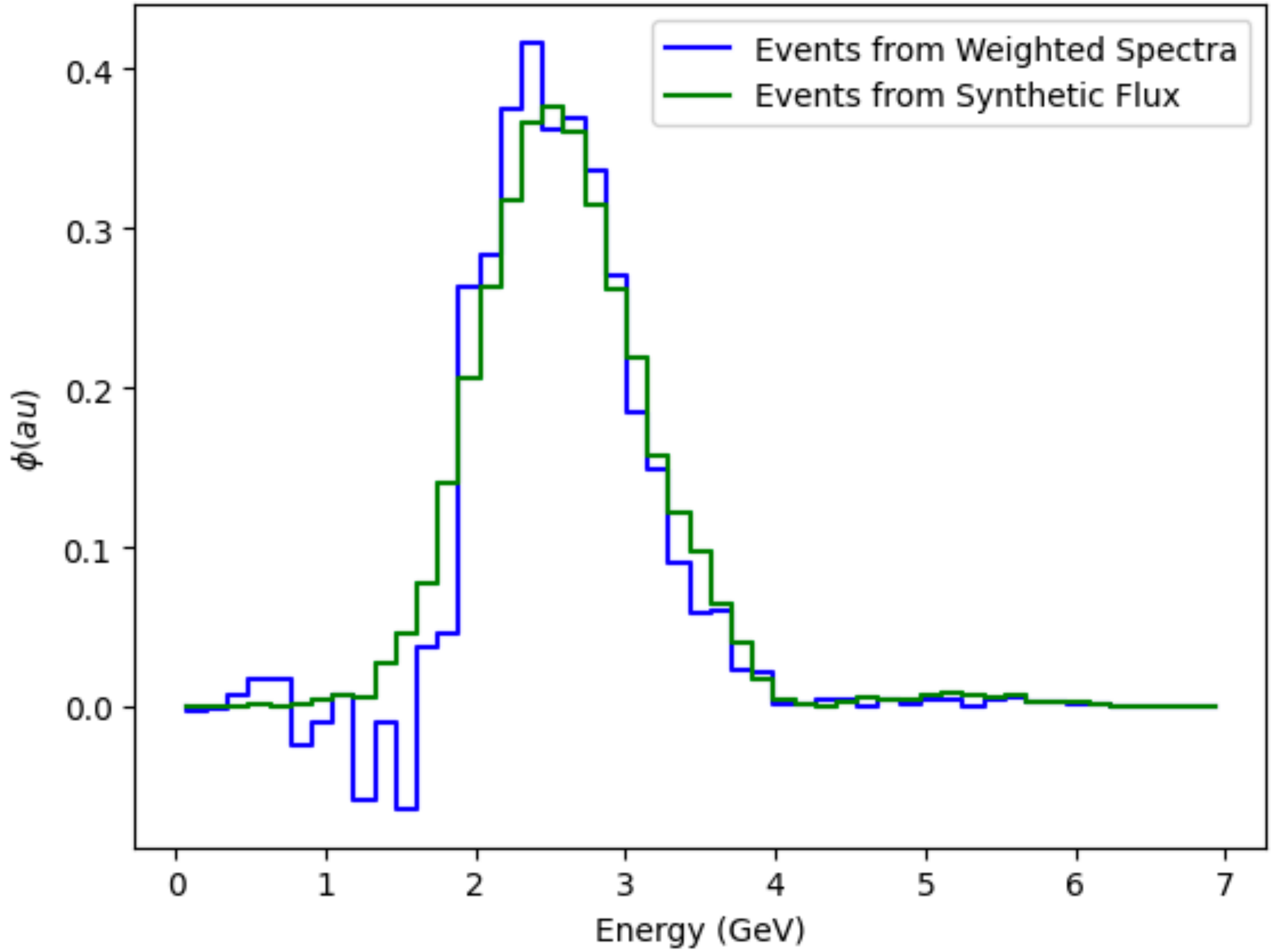
- We can also build something similar with the pion flash neutrinos.
- This is a 3GeV, 0.3 GeV SD synthetic beam from the pion flash neutrinos.



Synthetic beams to real events (WIP)

- We can pass the 8 constituent neutrino spectra through a “detector” to see the events that come out of them.
- Linear combinations of these events (using the optimised parameters from the fit) would give us the events we expect to see in the detector.
- For this, we used the GENIE generator to generate events from through interaction from the above spectra with argon nuclei.
- CC events have been considered for the analysis.

Synthetic beams to real events (WIP)



Next Steps:

- Normalisation: These fluxes/events have not been normalised to POT.
- Errors: Note that these (preliminary) plots did not have any error bars associated. The errors can be added once we have a better idea of event rates.
- Detector Geometry: No detector geometry/volume/design has been taken into account. The energy spectra for GENIE involve the true energy, with no smearing due to reconstruction or detector efficiencies.

Thank you!