Developing the Reconstruction of a Magnetised Gaseous Argon TPC for the DUNE Near Detector

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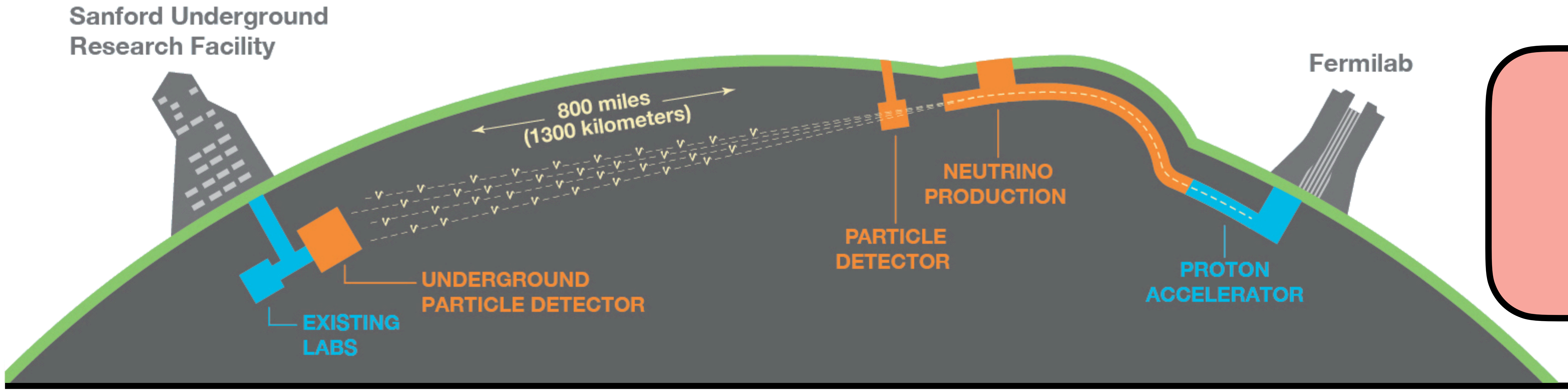
Deep Underground Neutrino Experiment

- Wide-band high-intensity (anti)neutrino beam produced at Fermilab.
- Near detector (ND) complex to control systematic uncertainties.
- **70-kt liquid argon far detector** (FD) 1.5km underground in South Dakota.



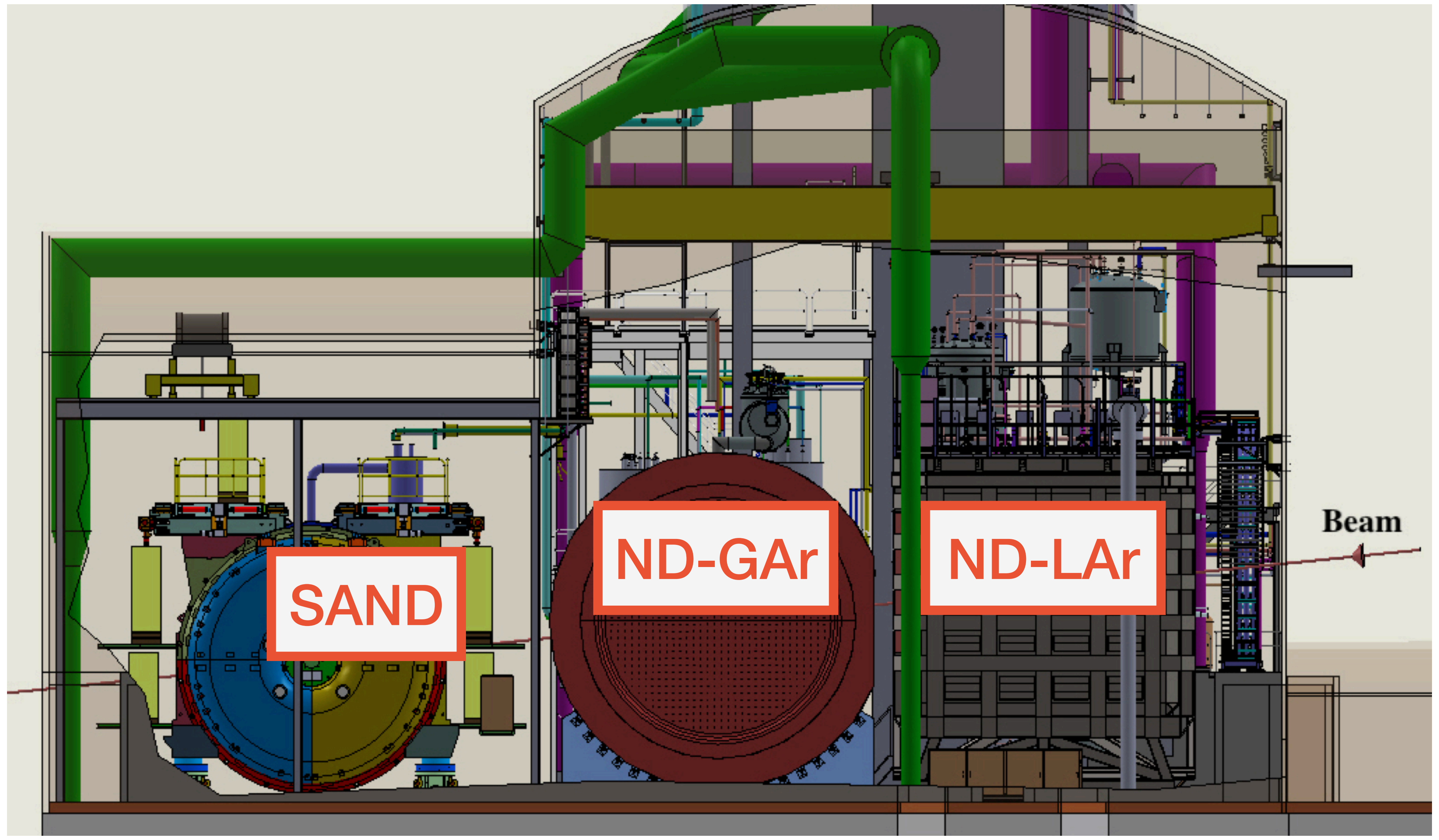
Oscillations
- Neutrino mass hierarchy
- Leptonic CP violation

Low energy
- Supernova neutrinos
- Solar neutrinos

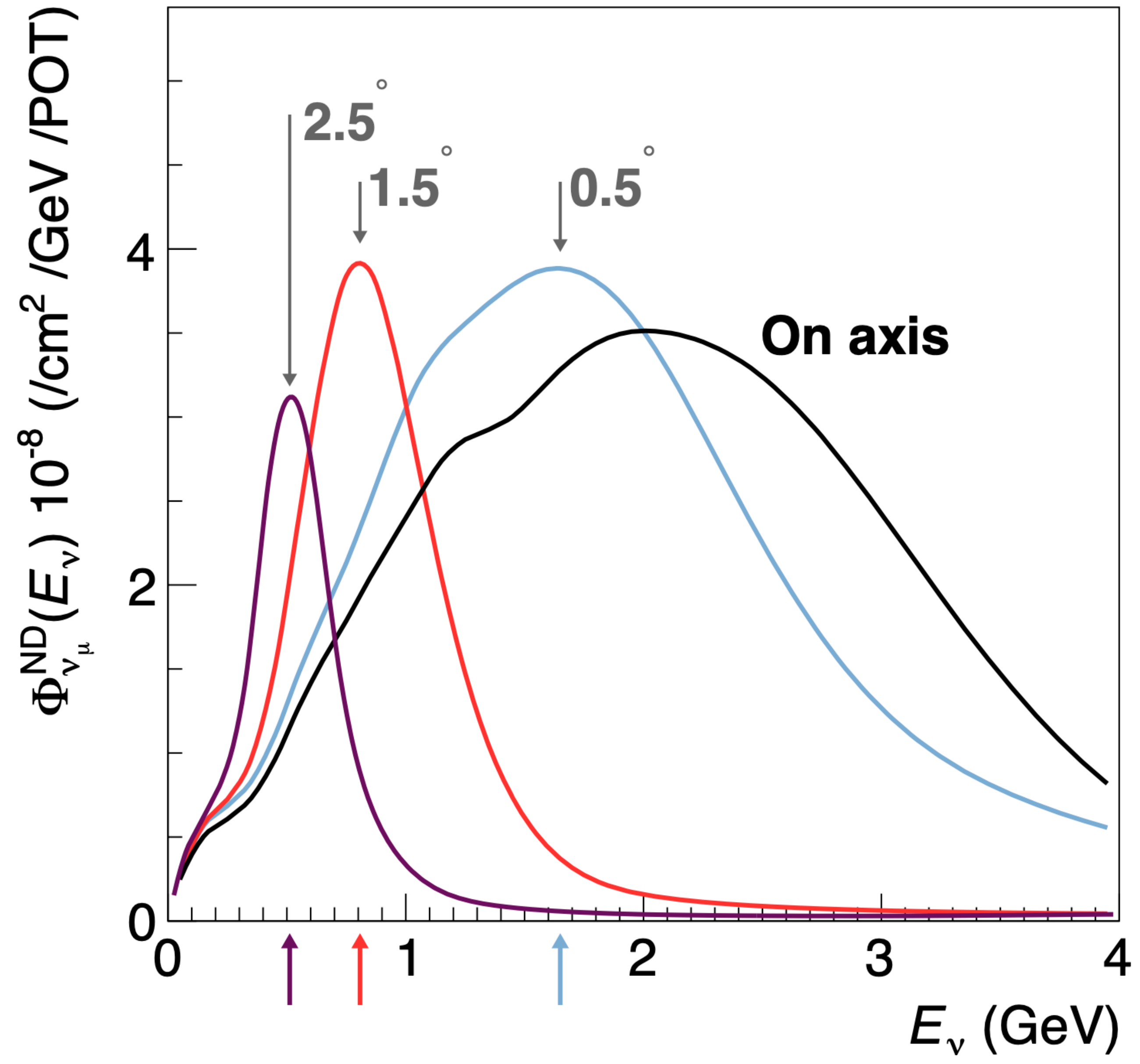
BSM
- Proton decay
- Inelastic Dark Matter

DUNE Near Detector

After Phase II upgrade



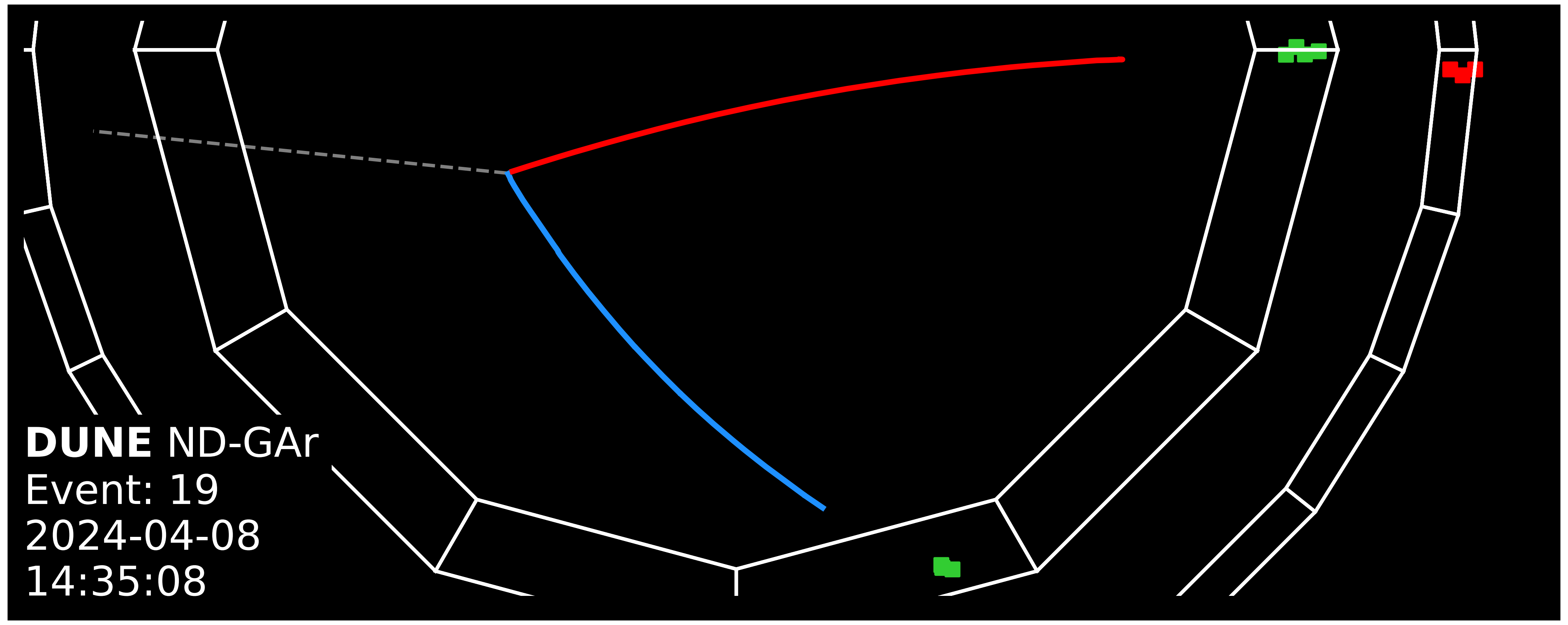
See next talk by A. Wilkinson

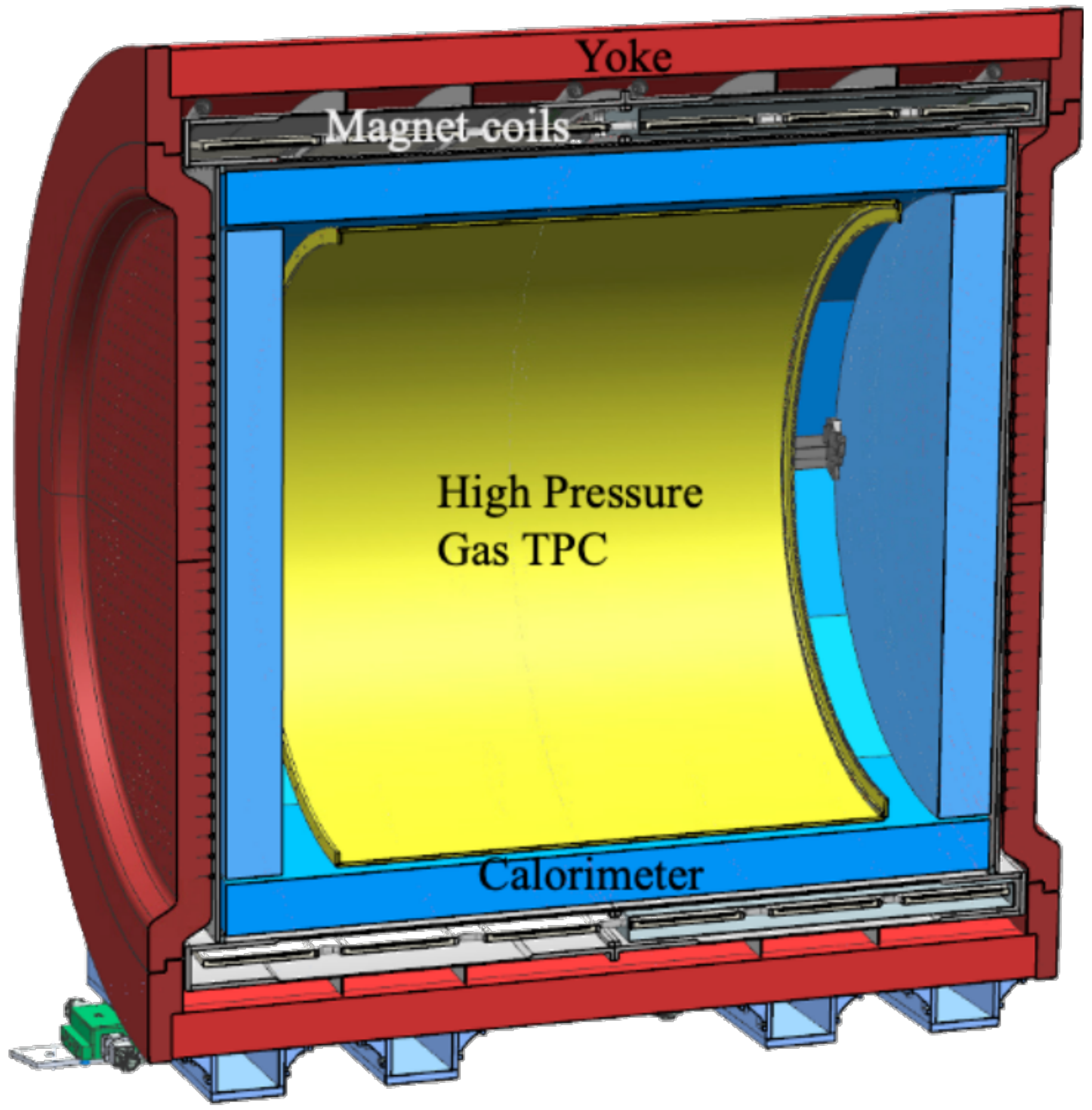


- Its main role is to measure the unoscillated neutrino spectra.
- Constrain **systematic uncertainties** (flux, cross section and detector response) for the oscillation physics.
- It also allows for precision measurements of **neutrino interactions** and opportunities to look for **BSM physics**.

ND-GAr concept

- ND-GAr is a magnetised high-pressure gaseous argon TPC, surrounded by an ECal and a muon tagger, for DUNE ND Phase II.
  - **Lower tracking thresholds** and larger angular acceptance.
  - Allow for **particle identification** and **momentum and sign reconstruction**.

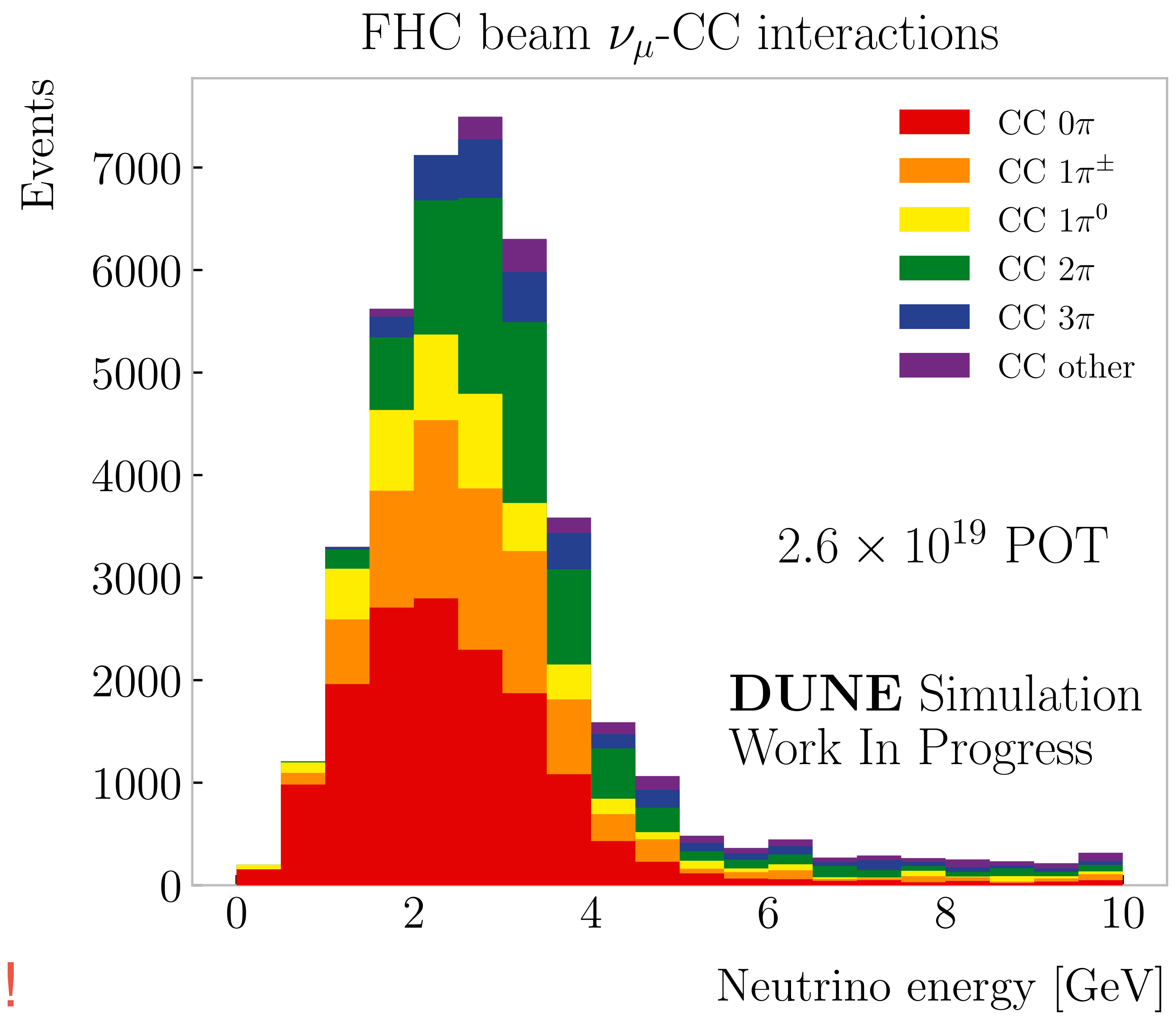




- Considering the use of GEMs for HPgTPC charge readout.
- ECal combines high-granularity tiles and cross scintillator strips.
- The superconducting magnet provides a 0.5 T field with a 1% uniformity.

Motivation

- One of the goals of ND-GAr is to **characterise the charged and neutral pion energy spectrum** in ν_μ and $\bar{\nu}_\mu$ CC interactions.
  - Measure low energy pions in order to distinguish between different FSI models.
  - Select topologies with 0π, 1π and $\geq 2\pi$ so as to inform the pion mass correction in the FD prediction.

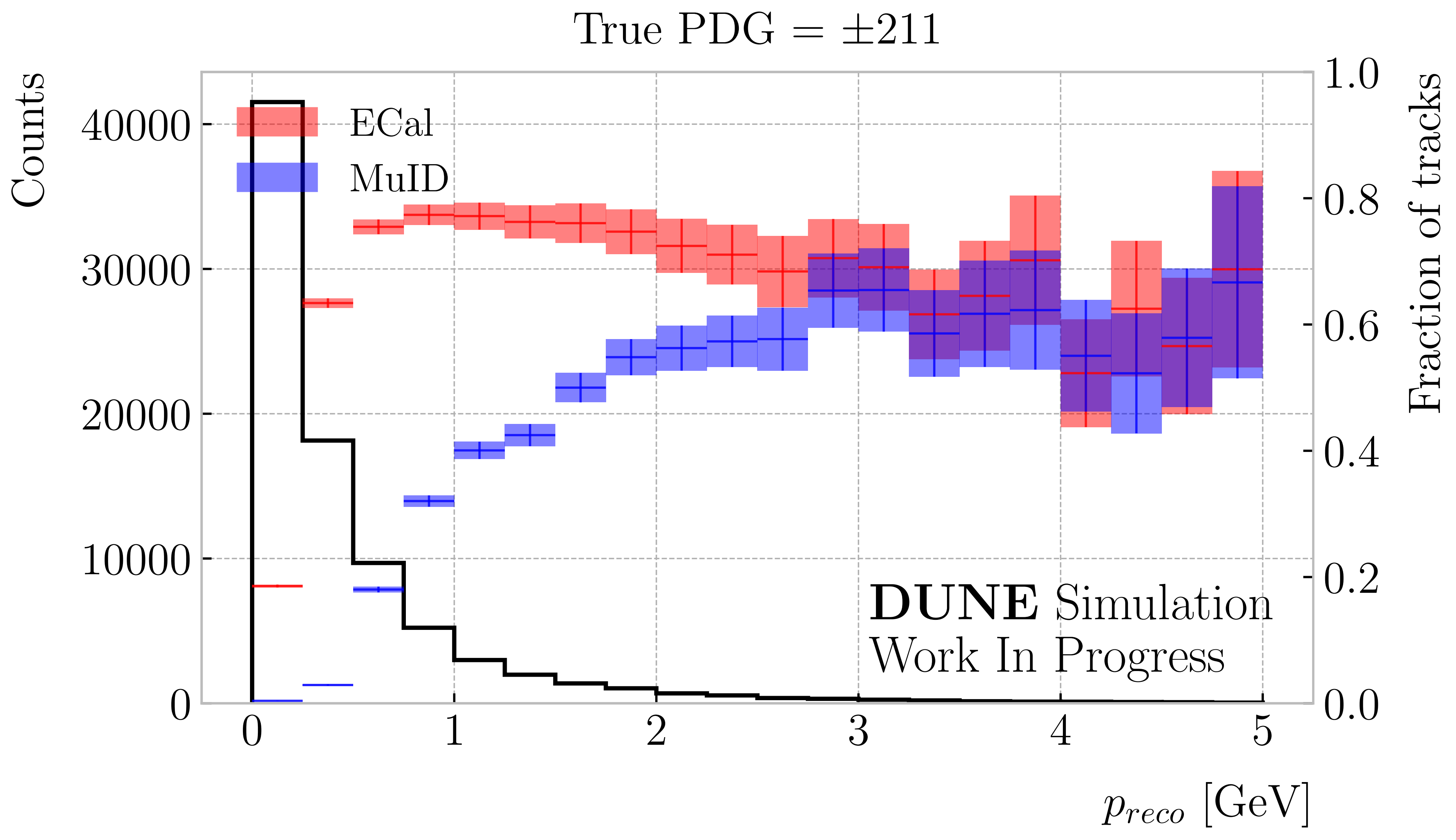


- To that end, we **need a reliable PID** able to identify pions with a high purity and across a broad energy range.
- **Current** reconstruction provides **low-level reconstruction** objects (tracks, clusters, …), now we need to **develop the high-level reconstruction** (PID, energy reconstruction, flavour estimation, …).

This is what I'm going to talk about today!

Different PID approaches

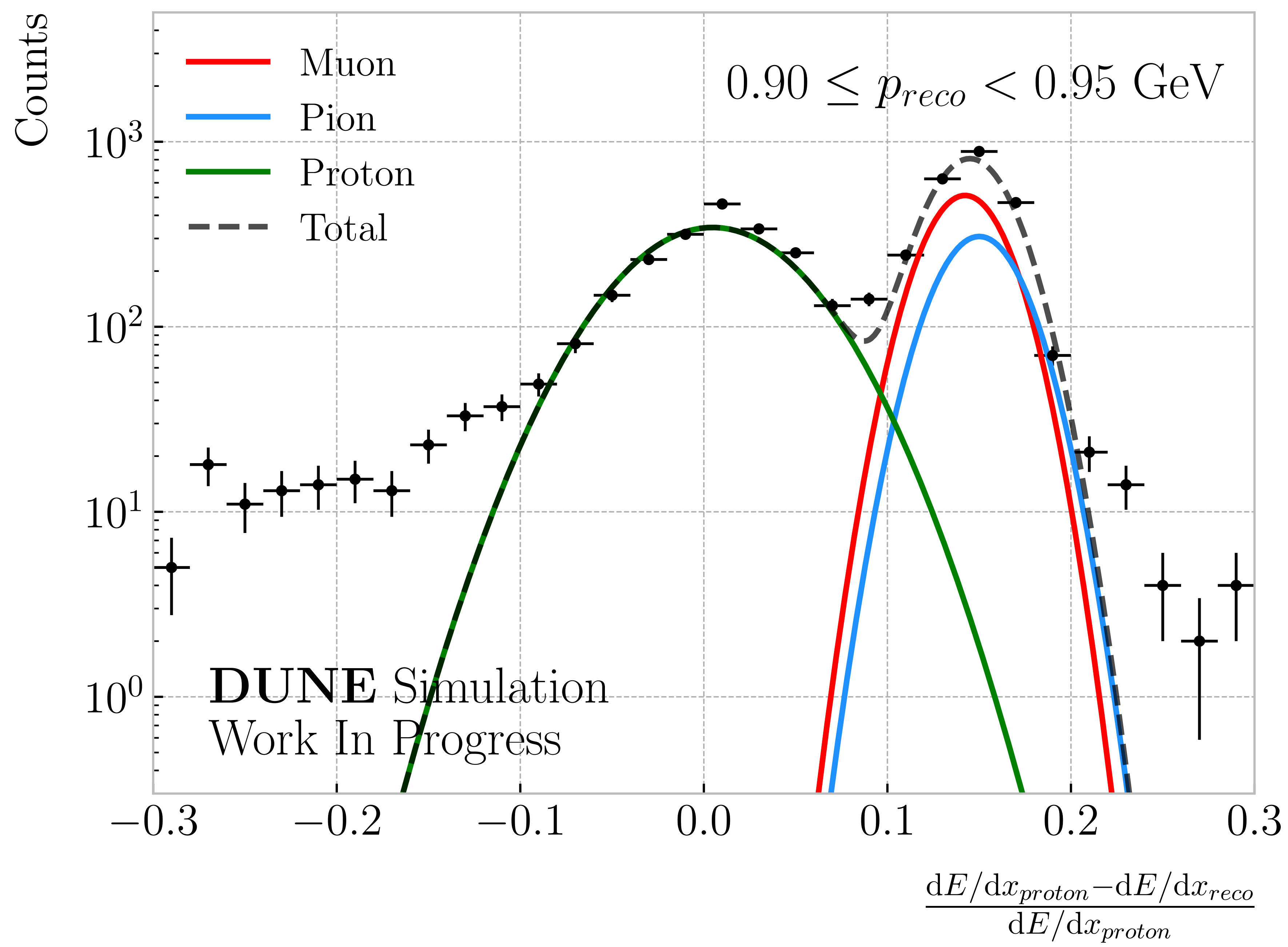
- In order to correctly identify electrons, muons, pions, kaons and protons ND-GAr can use a combination of:
  - Calorimetry in the TPC.
  - ECal and muon tagger information.

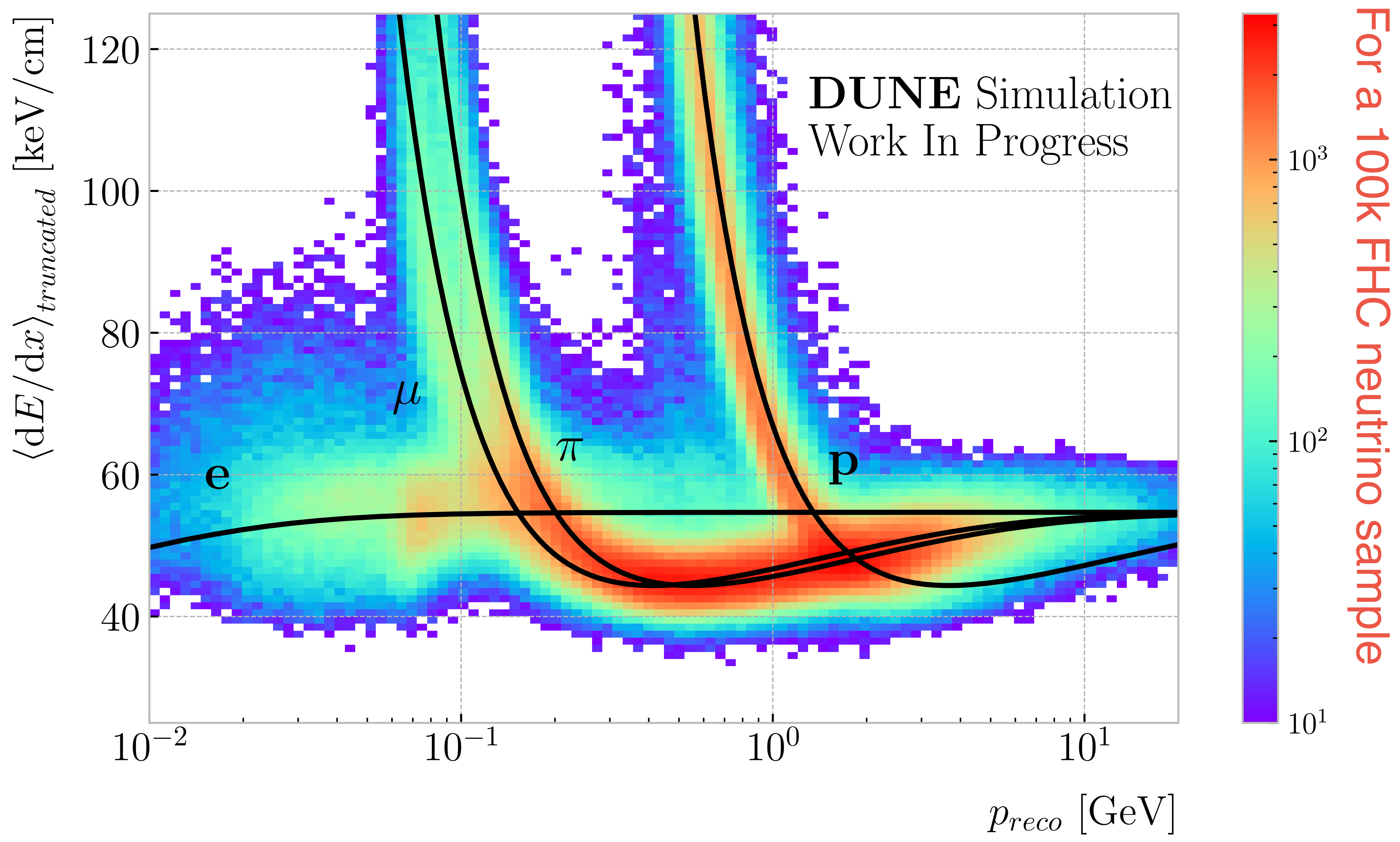


- For charged particles, we can use the HPgTPC dE/dx as a starting point for the PID.
- Then, using the associations between the tracks and the ECal/MuID activity we can build new observables to help with PID.
- In the case of neutral particles information from the ECal exists; we can try to reconstruct them using information from the charged part of the event.

dE/dx in the HPgTPC

- Calorimetry in the TPC can be used for PID, e.g. low momentum proton selection.
- Use a MC sample of stopping protons to model the non-linear relation between readout charge and deposited energy.





- Compute mean of truncated distribution to avoid fluctuations due to high-E tail.
- We achieve a 2% resolution in energy loss for MIPs and 5% for protons.
- Good separation of pions below 200 MeV and protons up to 1 GeV.

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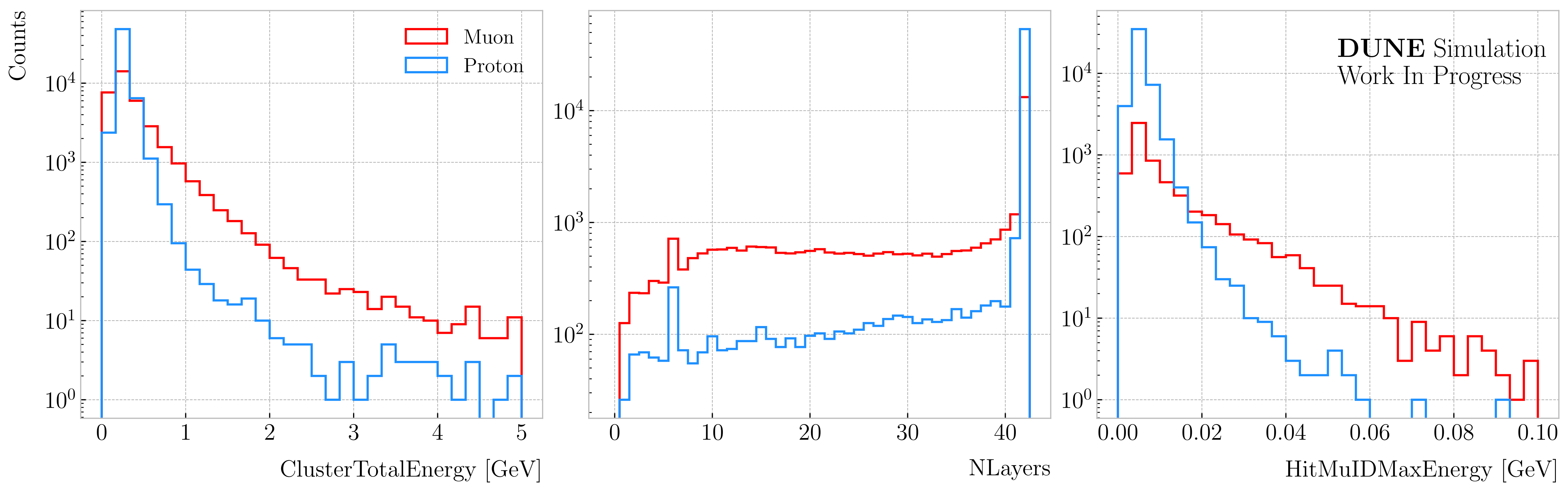
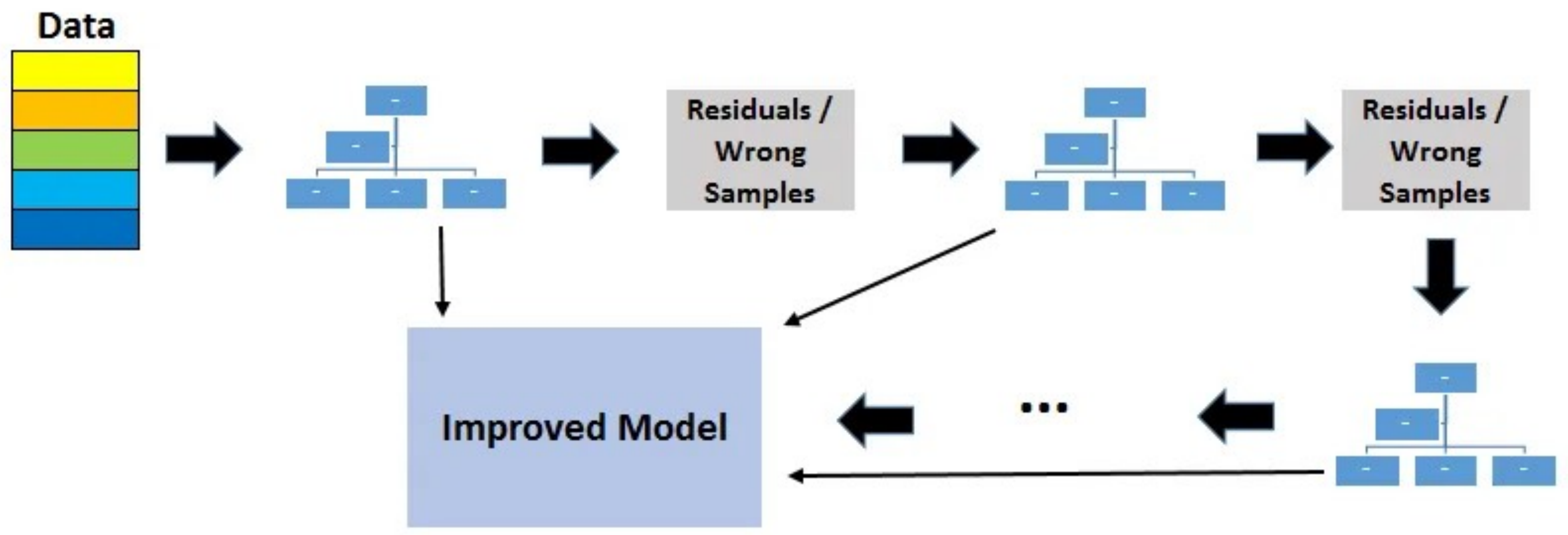
PID with ECAL and μID

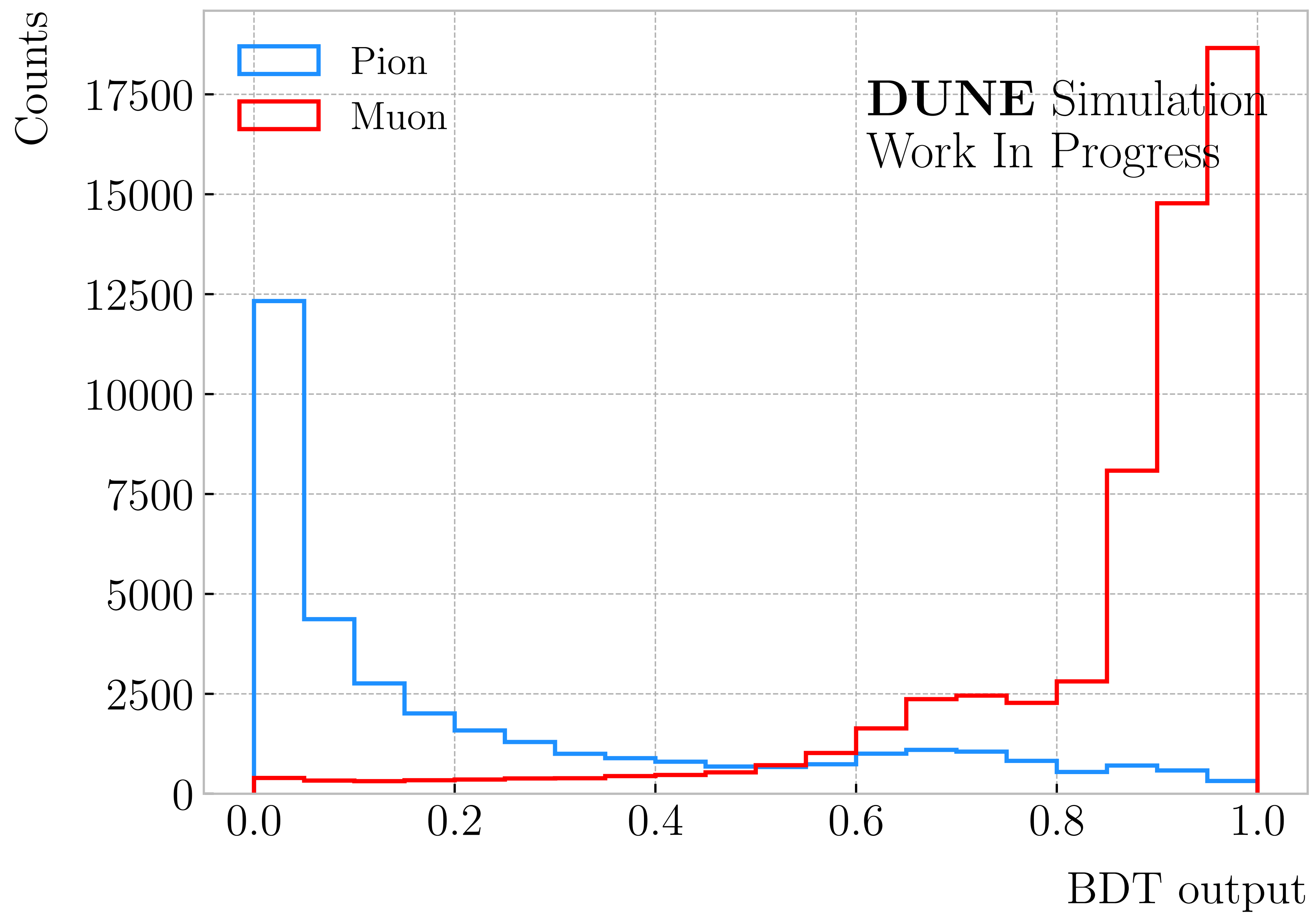
- It's not possible to separate muons and pions in the HPgTPC using dE/dx for momenta $\geq$ 200 MeV.
- ECal and MuID can provide additional information, as pion interactions will be more hadron-like.

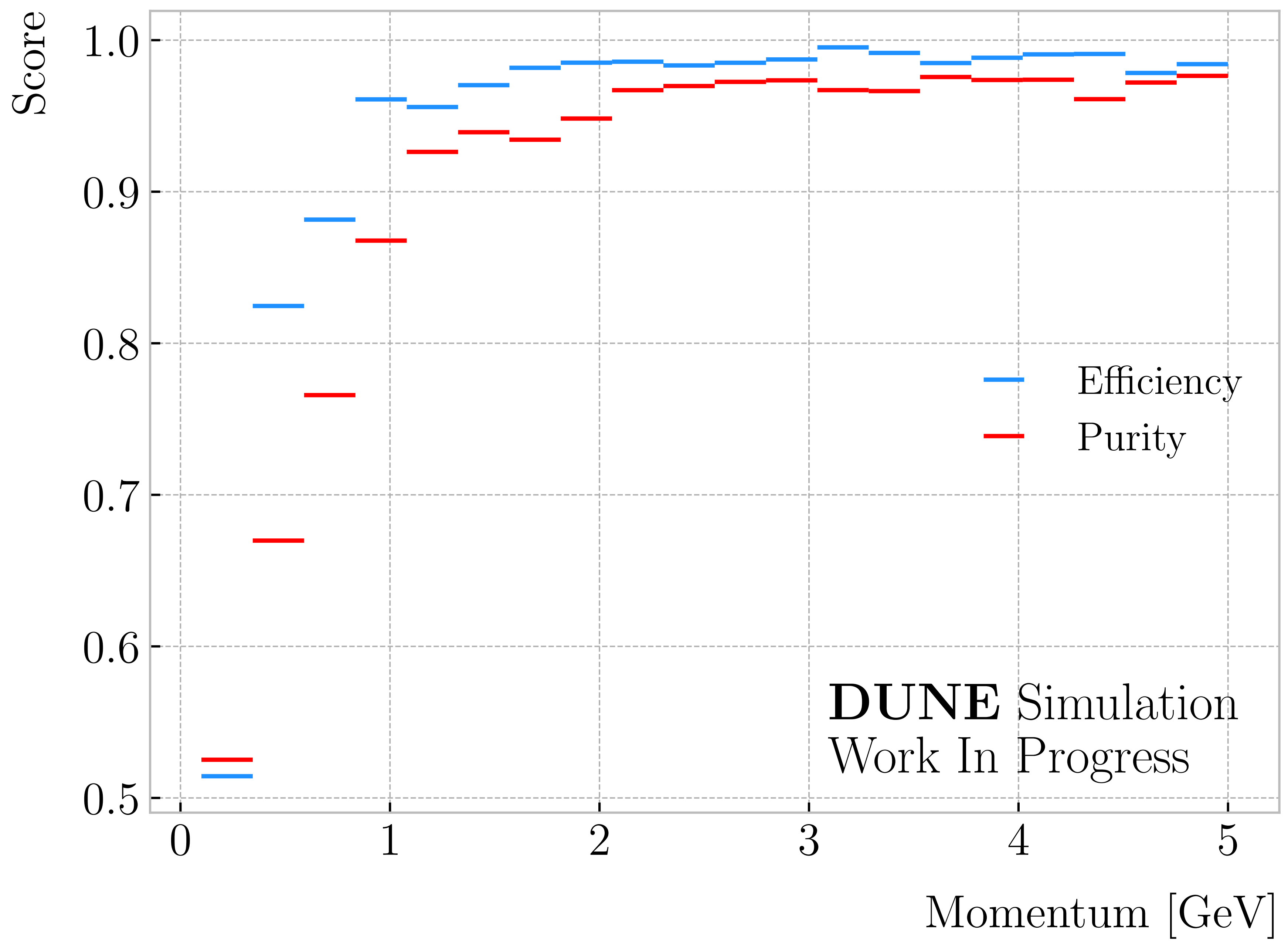




- Boosted Decision Trees (BDTs) trained on a collection of ECal features allow for a track-by-track classification.
- A BDT is a good option for this classification problem, as they are easy to interpret and can handle data without any pre-processing.

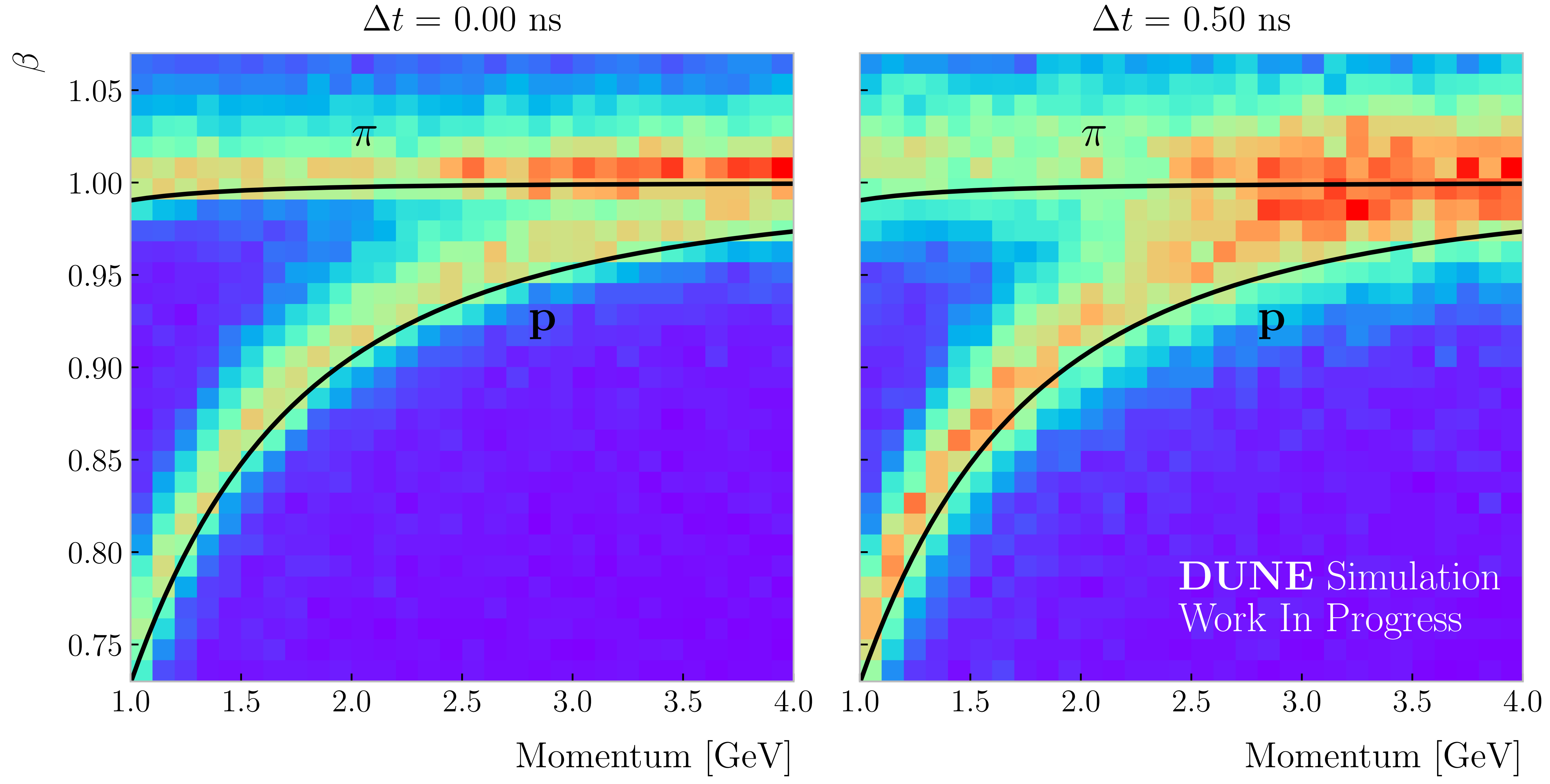
PID with ECAL and μID



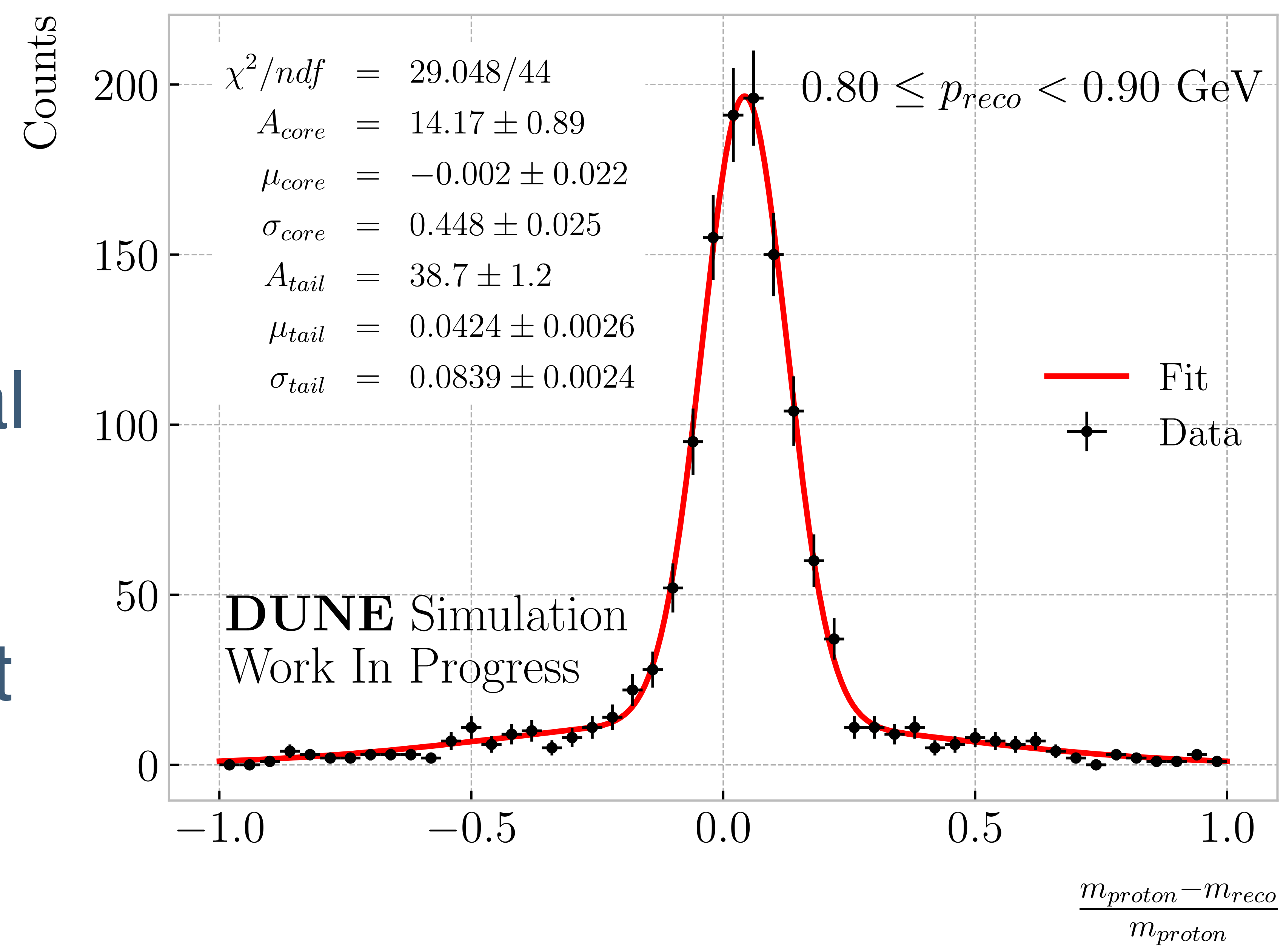


- 5 BDTs were trained in different momentum ranges, optimising in each case the input features and hyperparameters.
- The training data comes from single particle events, while the performance was assessed using FHC neutrino events.

ECal Time-of-Flight



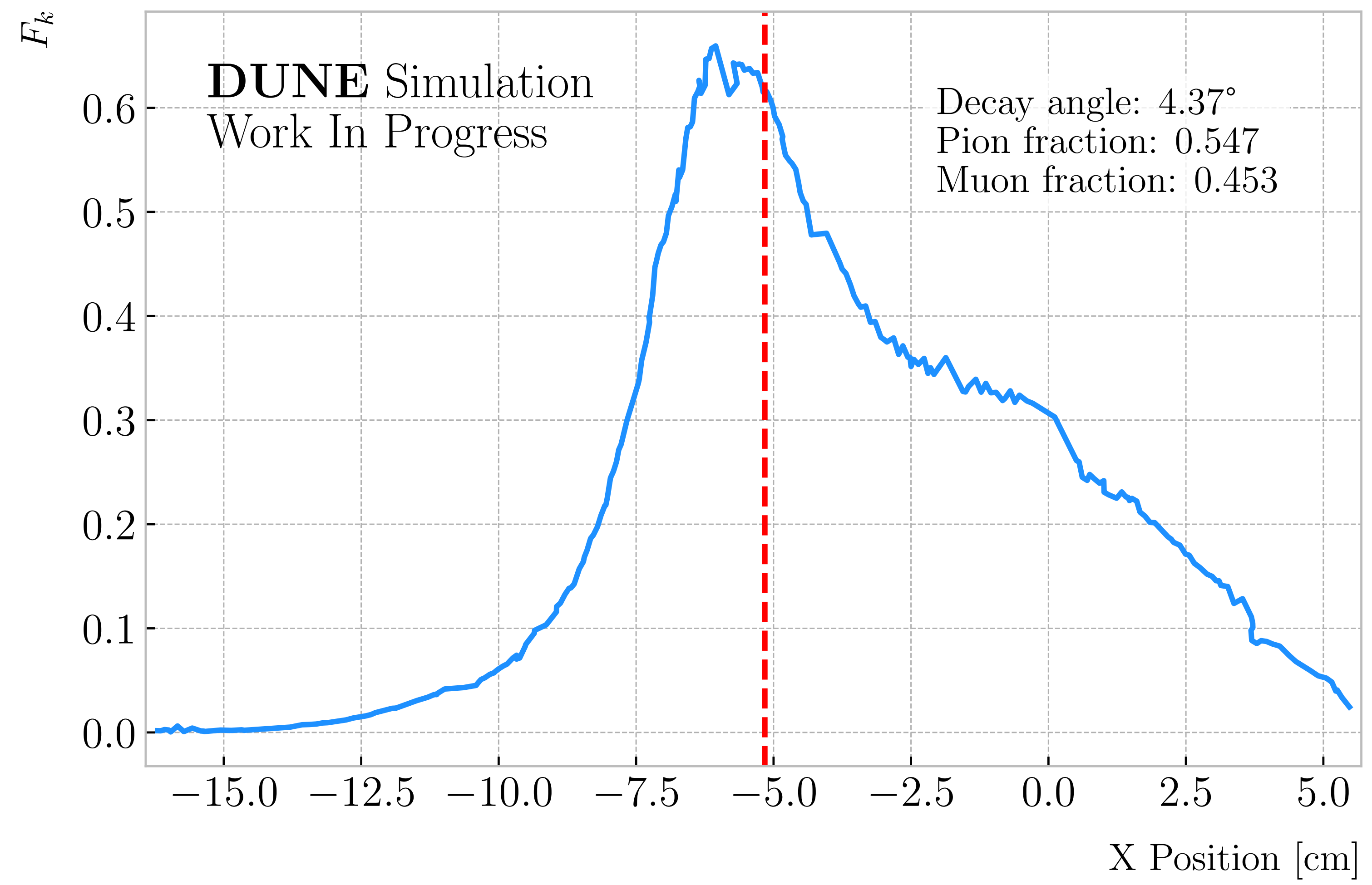
- For momentum values $\geq$ 0.8-1.0 GeV it's not really possible to separate pions and protons using the TPC dE/dx.
- We can perform a ToF measurement using the arrival time to the ECal inner layers.

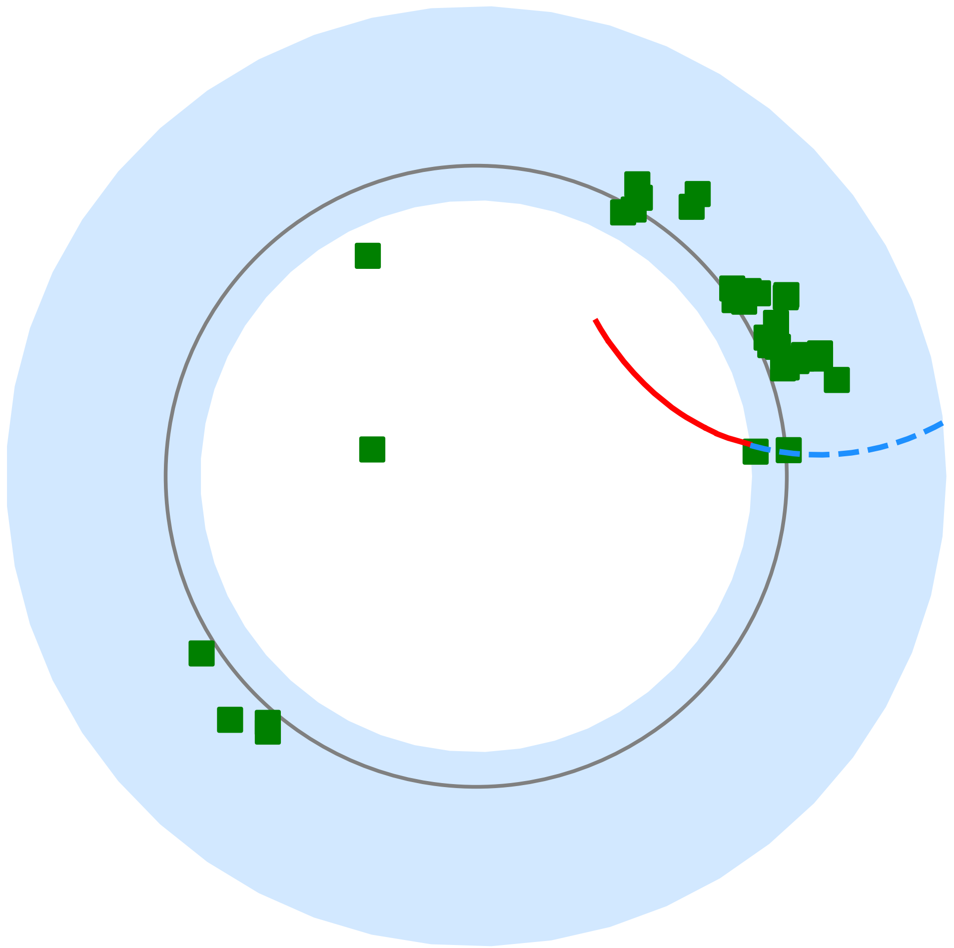


- Tried different ECal time resolution values and arrival time estimators.
- Although resolution degrades fast with momentum, it allows for efficient separation up to 3.0 GeV.

Other related work

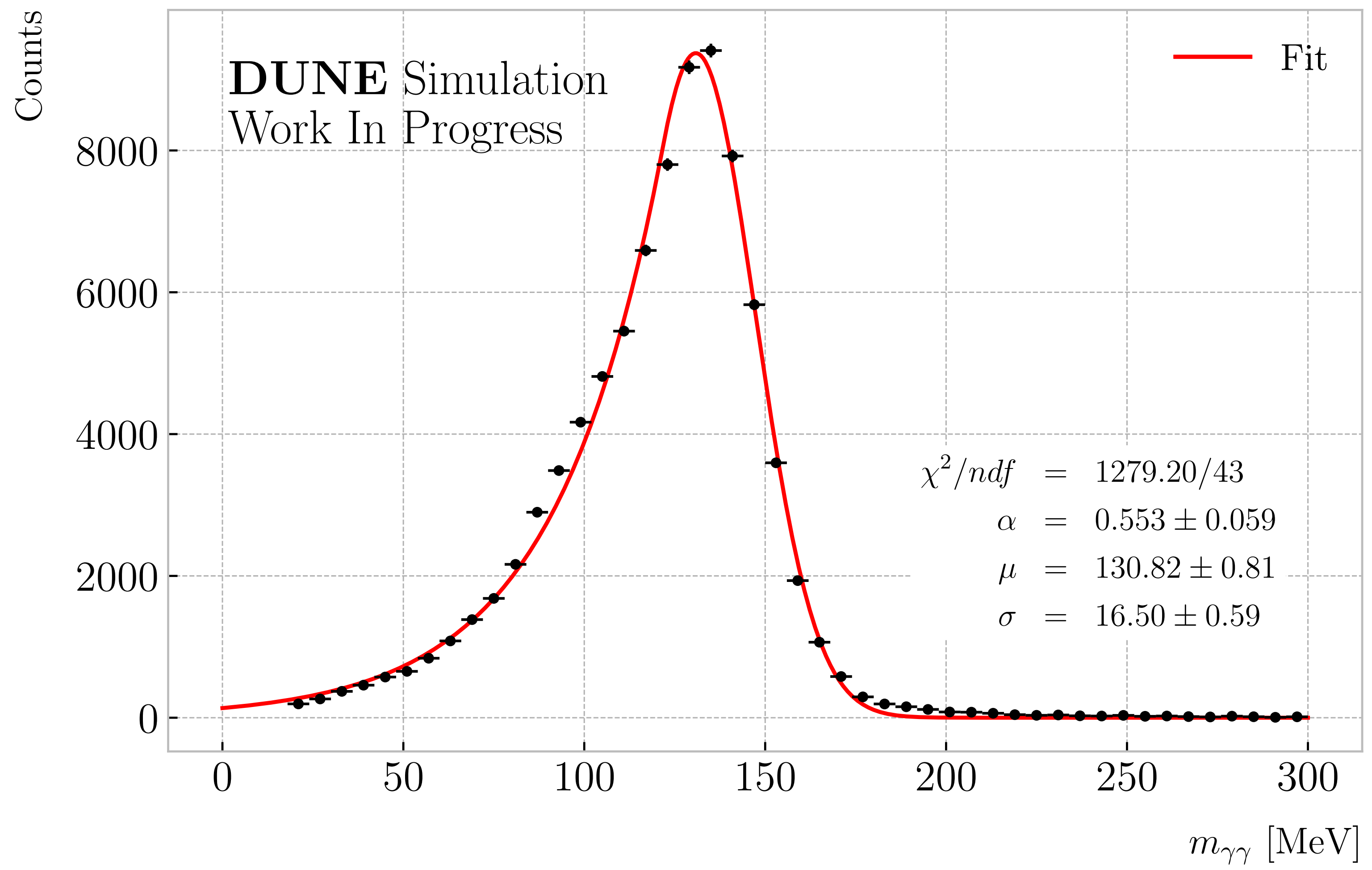
- Identify discontinuities in track fit parameters in order to detect pion decays in the TPC reconstructed as single tracks.





- Improve the associations between HPgTPC tracks and ECal clusters, increasing the efficiency while maintaining a high purity.

- Improved ECal clustering algorithm to allow a more efficient neutral pion reconstruction.



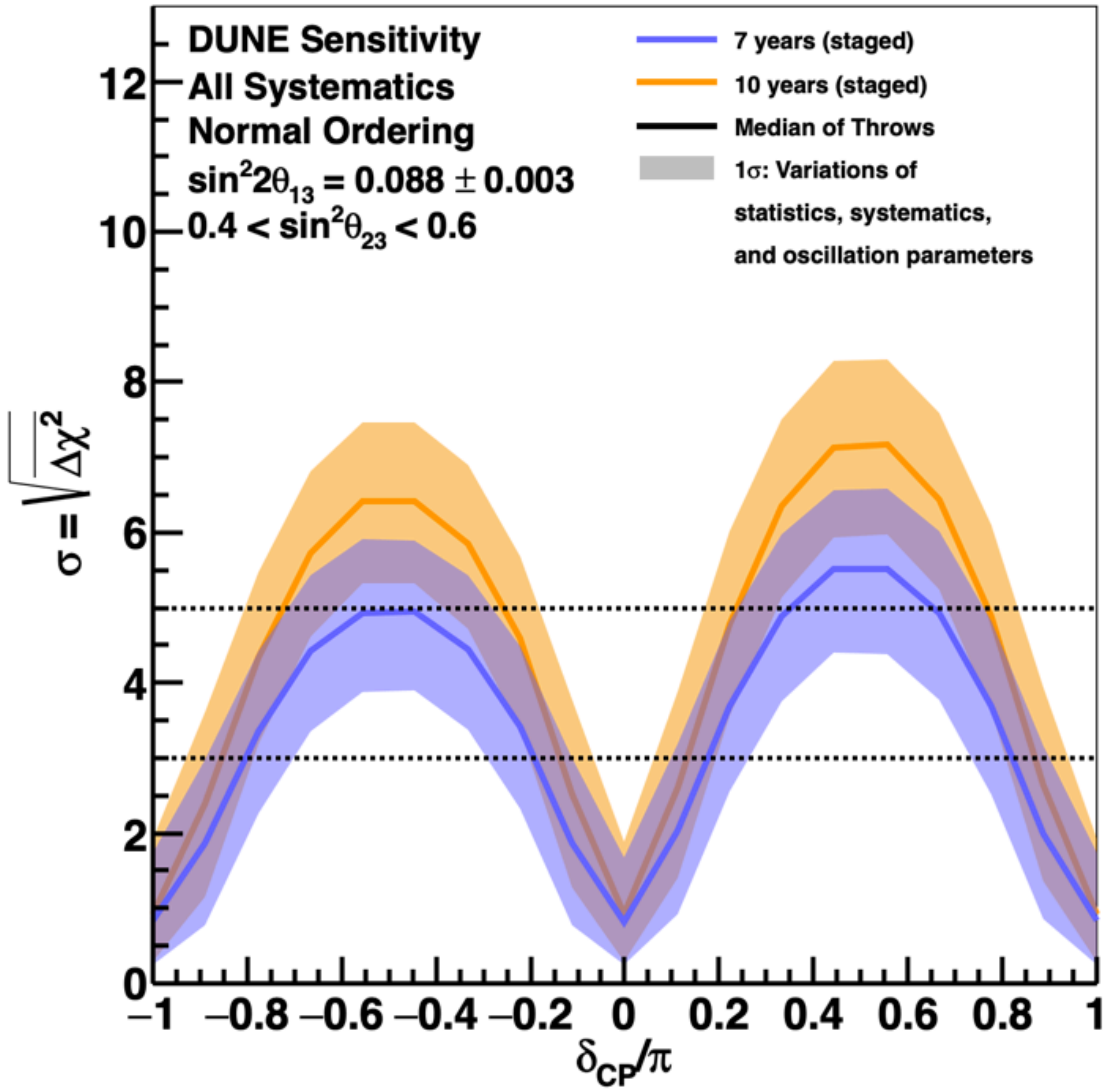
What's next?

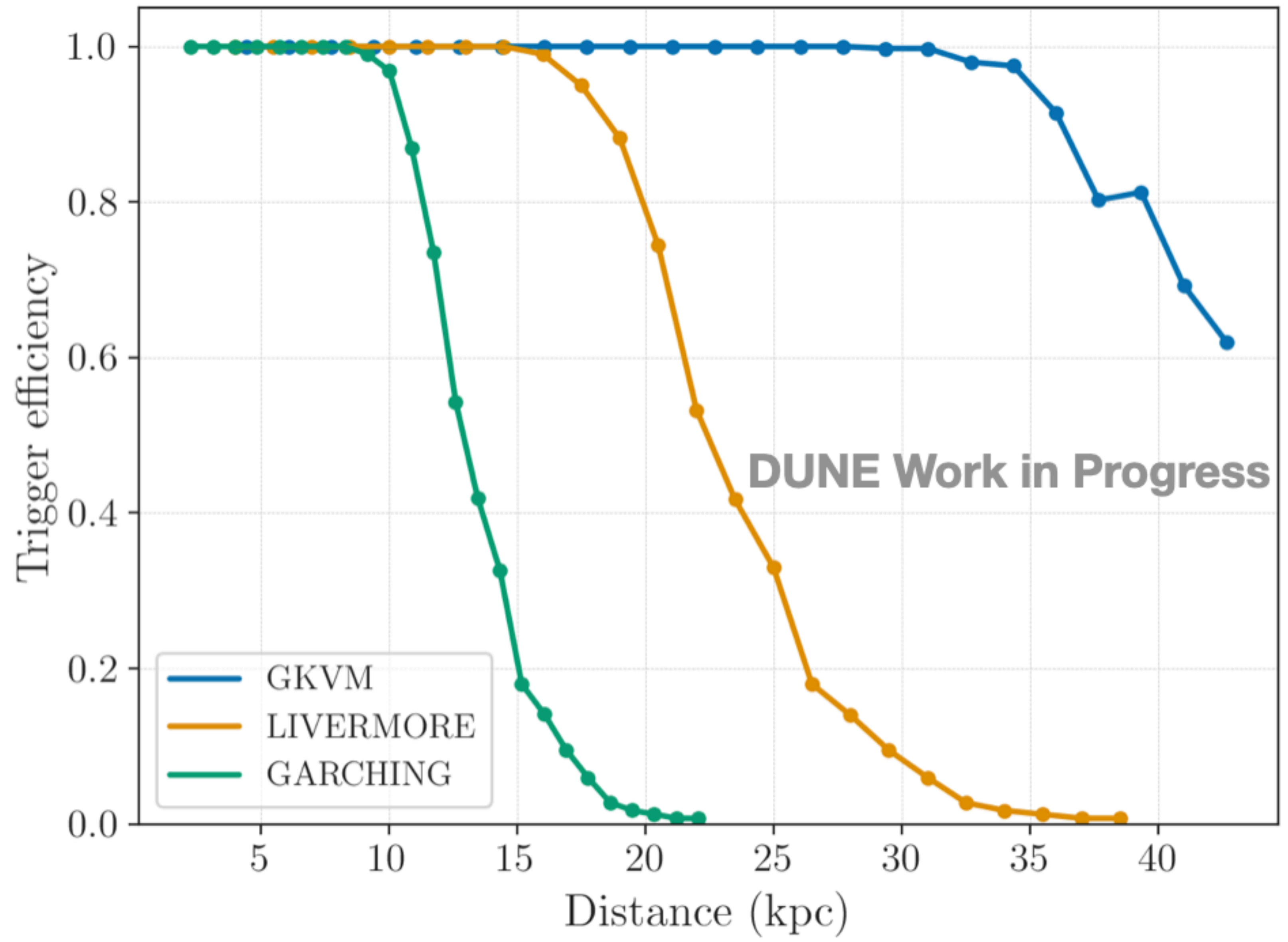
- Currently testing the implementation of the code in the ND-GAr software stack, will be ready to use soon in a mini production.
- In parallel, working on propagating the new reco objects to the DUNE analysis files.
- Combine different sources of PID and check how they impact the event selection.
  - Select primary muons in ν_μ CC interactions.
  - Compare reconstructed charged pion multiplicity to MC truth.
- Write my thesis.

Backup slides

What's DUNE going to measure?

- Determine the **neutrino mass hierarchy**.
- Measure the value of the **leptonic CP violation**.
- Perform **precision measurements** of the three-flavour model.

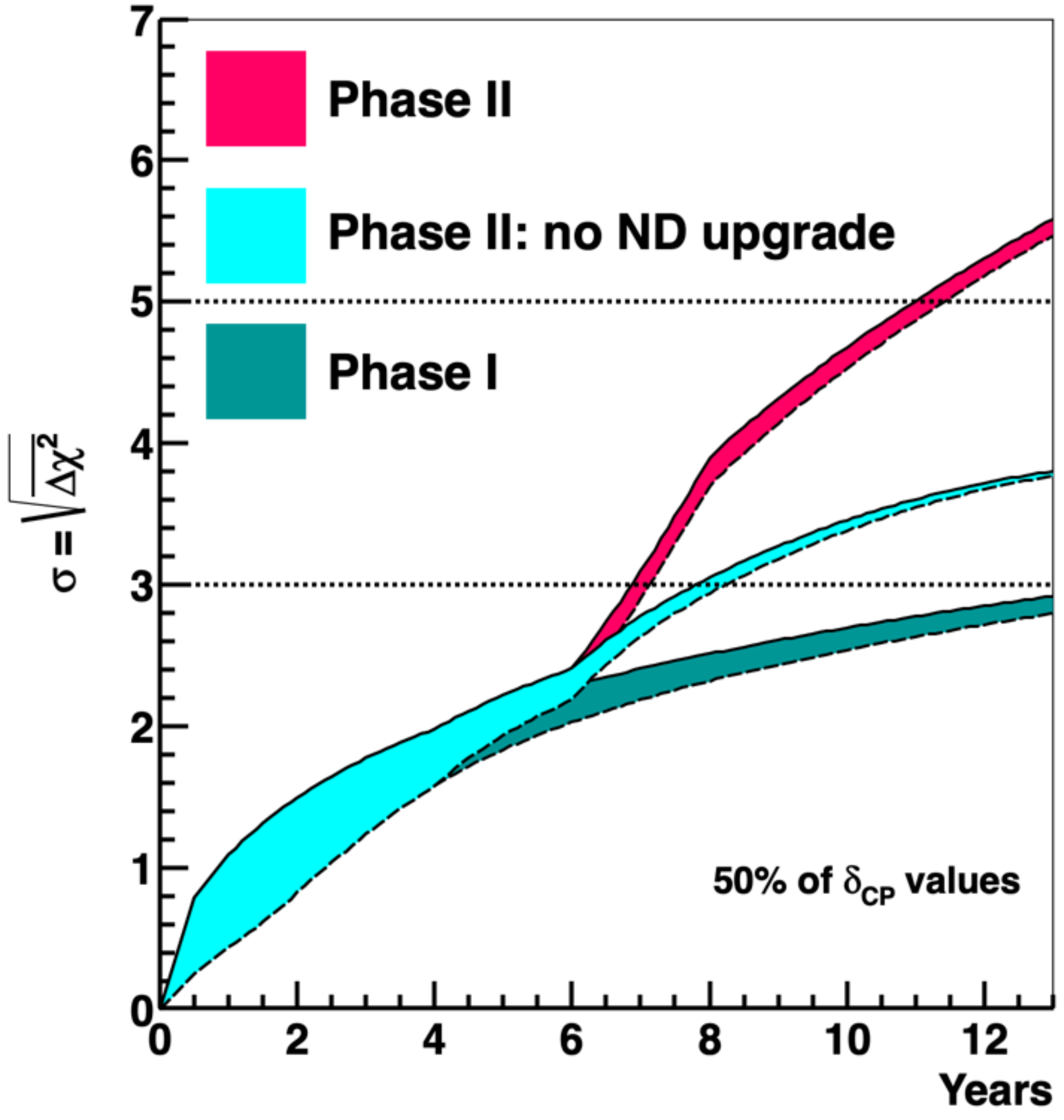




- FD will be able to detect supernova, solar and atmospheric neutrinos.
- Other BSM phenomena, like proton decay, inelastic DM, …

Phases of DUNE

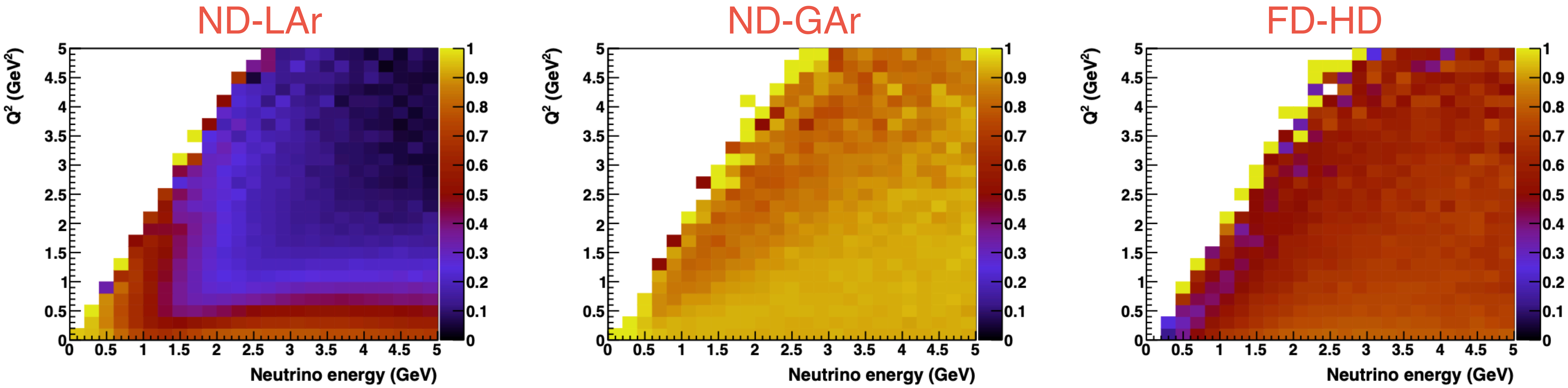
Parameter	Phase I	Phase II
FD mass	20 kt fiducial	40 kt fiducial
Beam power	up to 1.2 MW	2.4 MW
ND config.	ND-LAr, TMS, SAND	ND-LAr, ND-GAr, SAND



- DUNE will be built using a **staged approach**.
- Phase I is sufficient for early physics goals.
- **Phase II is necessary** to reach the design sensitivity for δ_{CP}.
  - A **ND upgrade** is needed in order to reach the desired sensitivity!

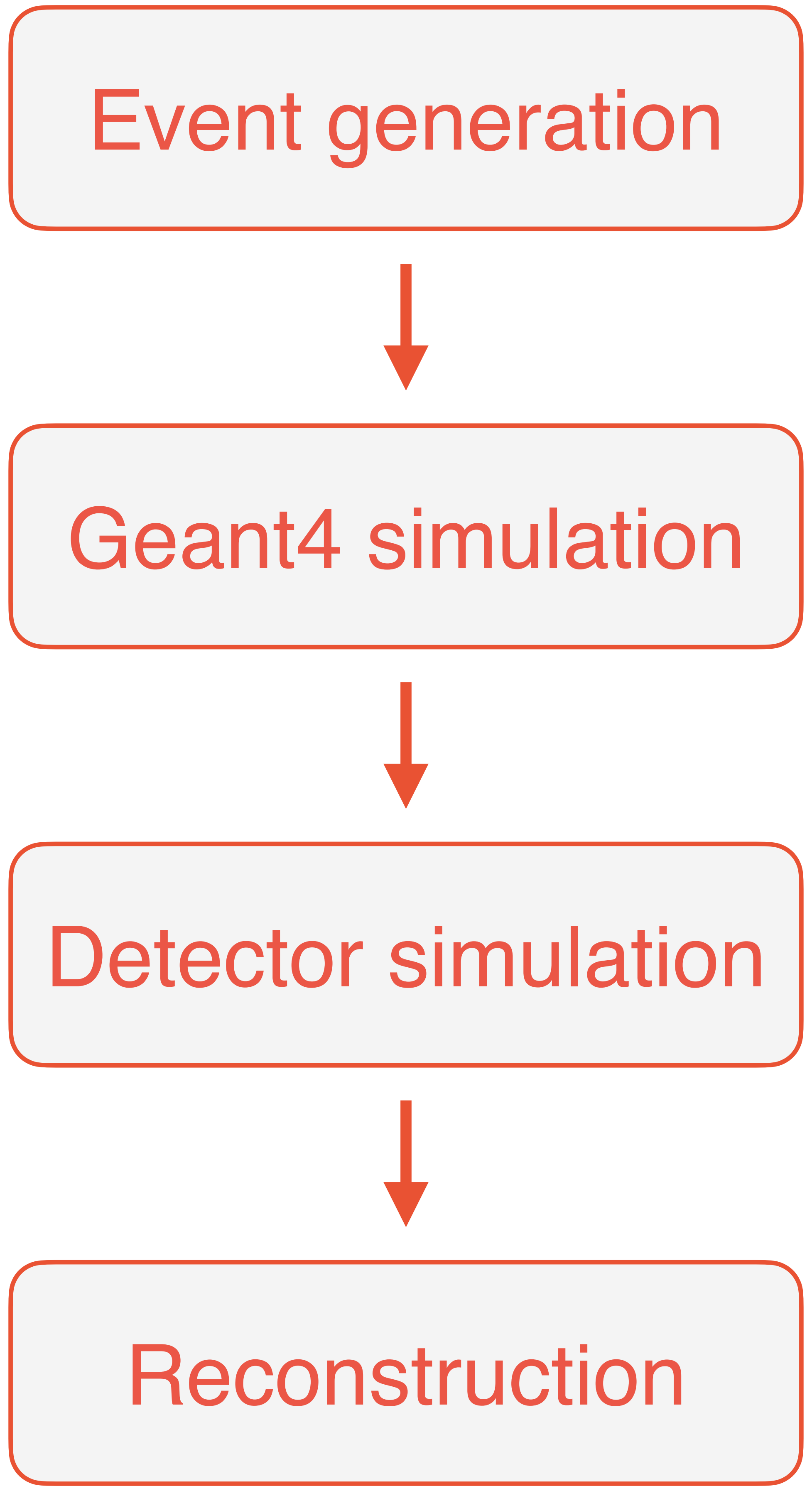
Why ND-GAr?

- It must **track the muons exiting ND-LAr**, in order to measure the ν_μ and $\bar{\nu}_\mu$ spectra.
- It must measure neutrino interaction off argon with a **kinematic acceptance similar to that of the FD**, to constrain systematics not accessible to ND-LAr.
- It must be able to **characterise the charged and neutral pion energy spectrum** in ν_μ and $\bar{\nu}_\mu$ CC interactions from a few GeV down to the low energy region where FSI are expected to have their largest effect.



GArSoft

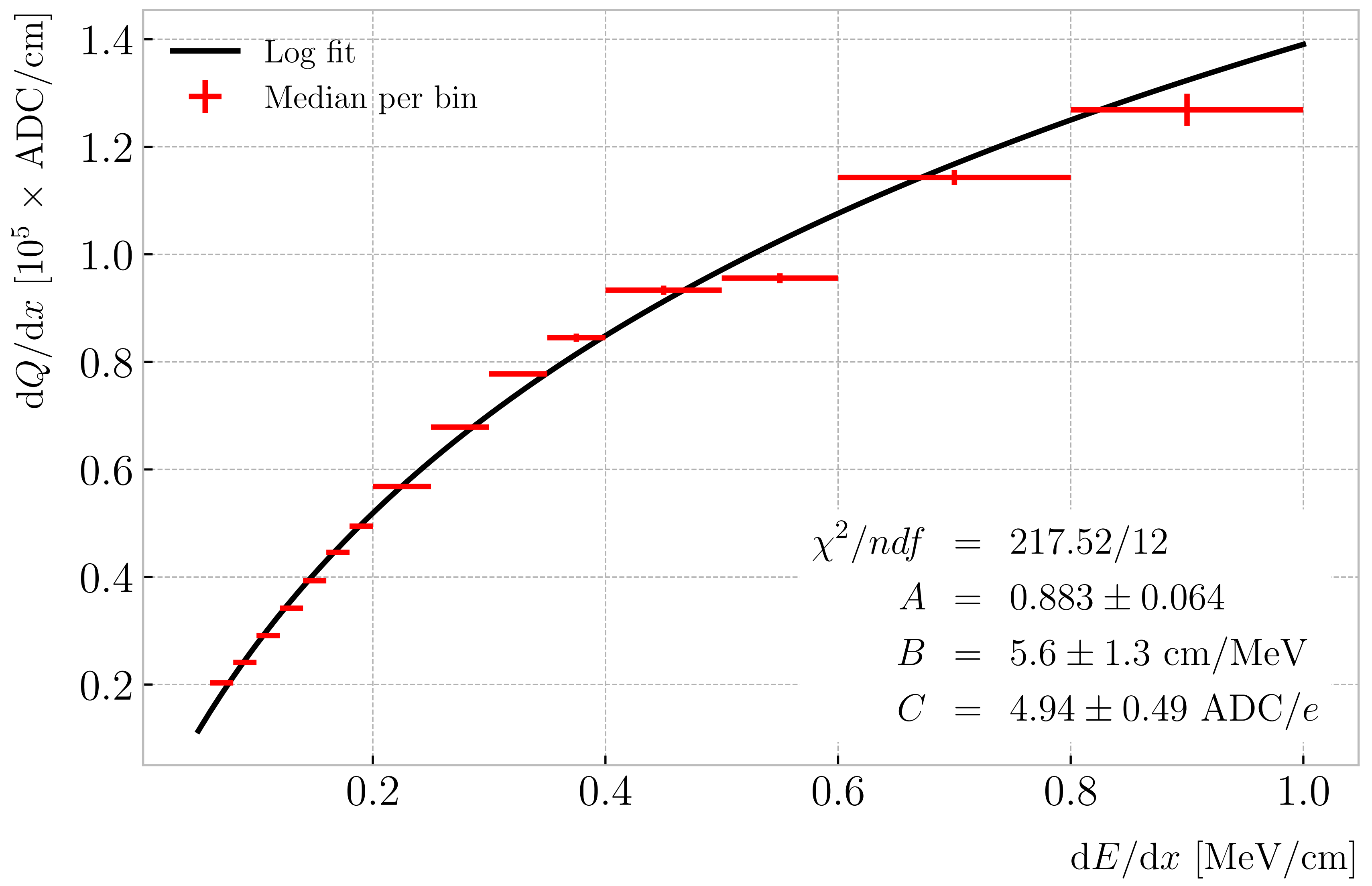
- GArSoft is ND-GAr's **simulation and reconstruction toolkit**.
- Five event generators are provided (SingleGen, GENIE, CRY, RadioGen and TextGen), producing truth data products.
- The `GArG4` module runs a Geant4 simulation using the detector geometry.
- It simulates the electron drift, the electronics response and the digitisation of the raw data.
- Low (hits and clusters) and high level (fitted tracks, vertices and associations) reconstruction products are also produced.

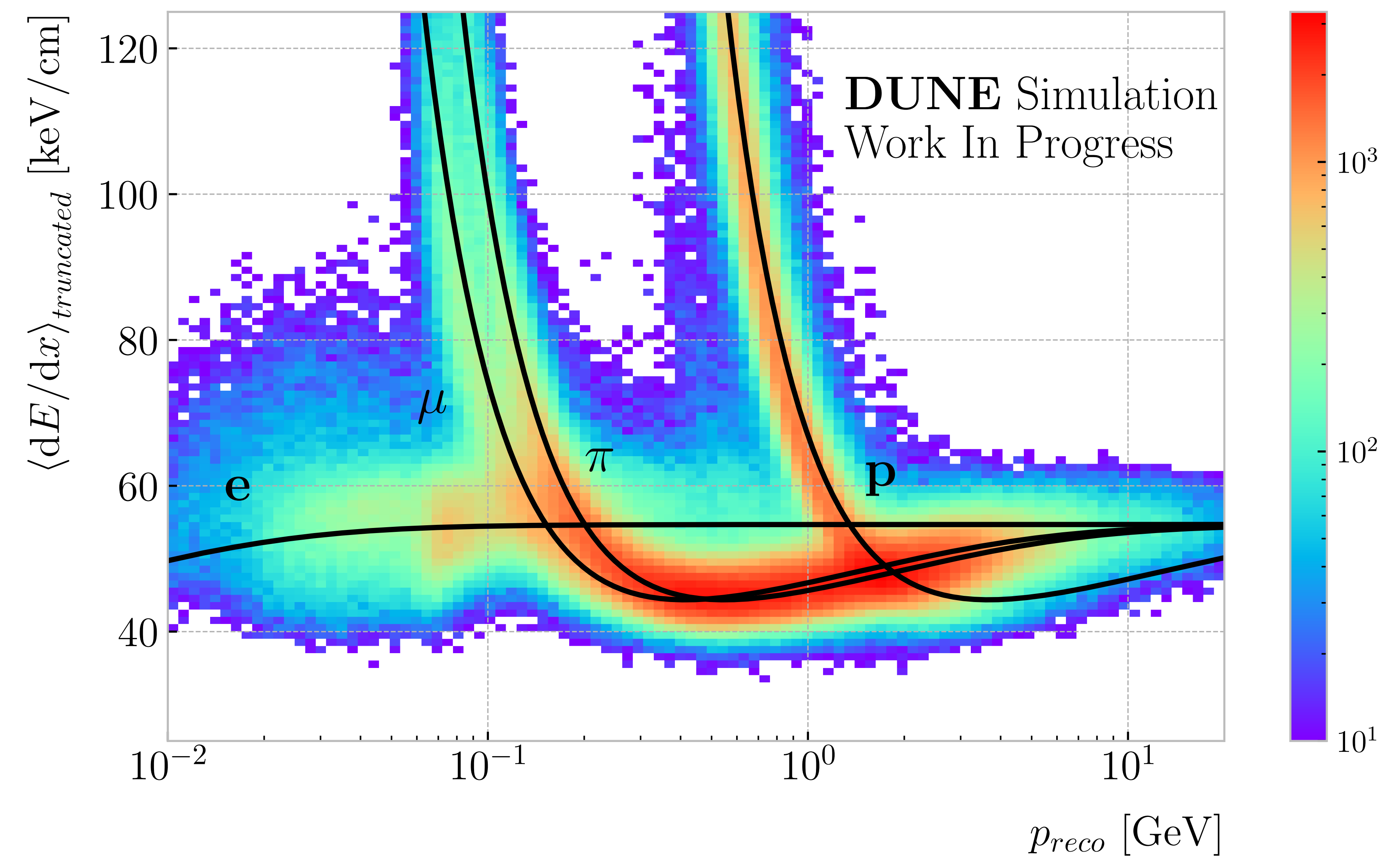


General generation-simulation-reconstruction workflow

dE/dx in the HPgTPC

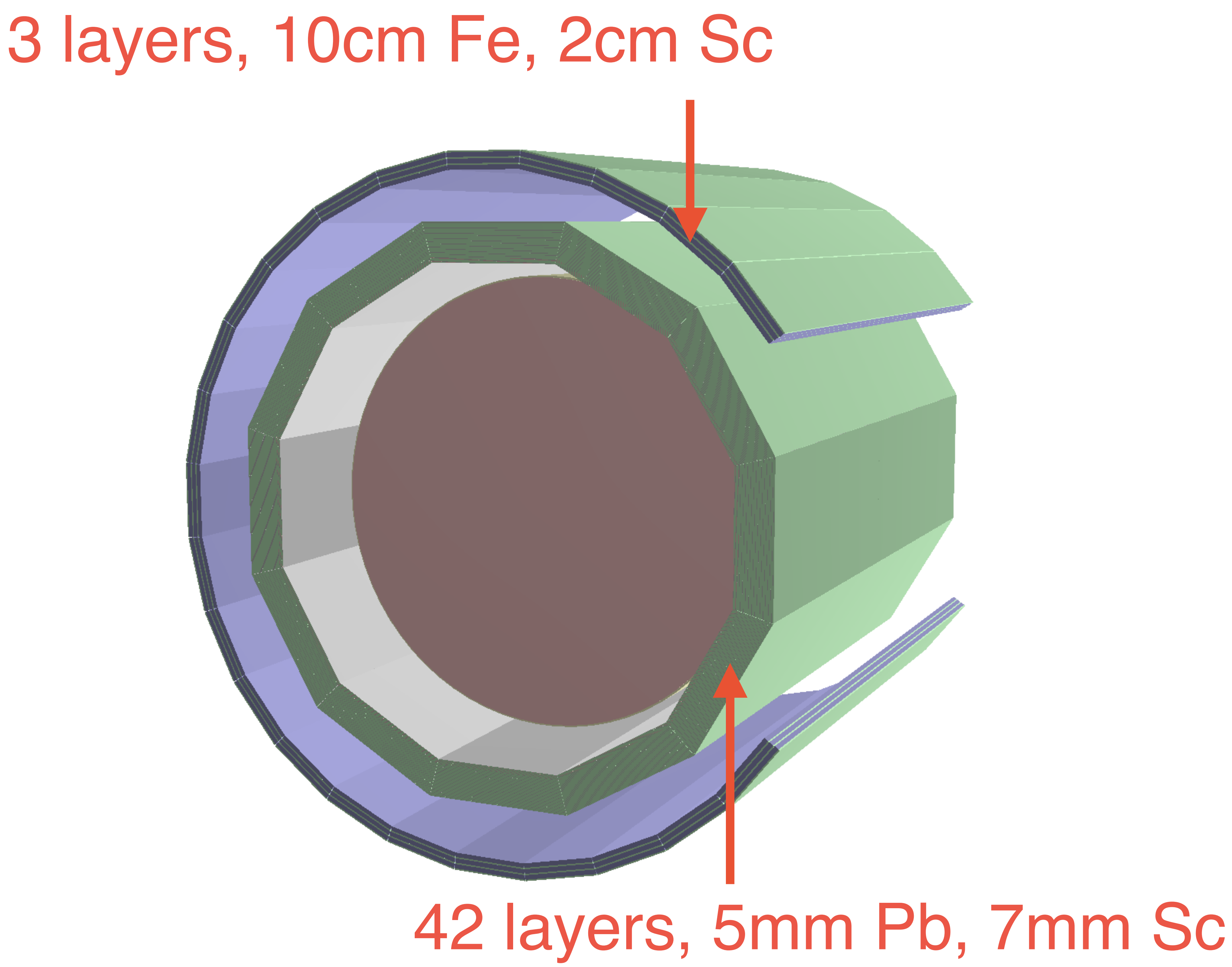
- Use mean $\mathrm{d}E/\mathrm{d}x$ in the TPC to get PID in the momentum regions where separation is good without looking at the truth value.
- We need to account for the non-linearity between introduced by the diffusion and lifetime effects and electronic response.
  - A sample of stopping protons was used to model the saturation
- Define our $\mathrm{d}E/\mathrm{d}x$ as the truncated mean of the 60% lowest energy clusters in the track, to avoid fluctuations from the Landau tail.

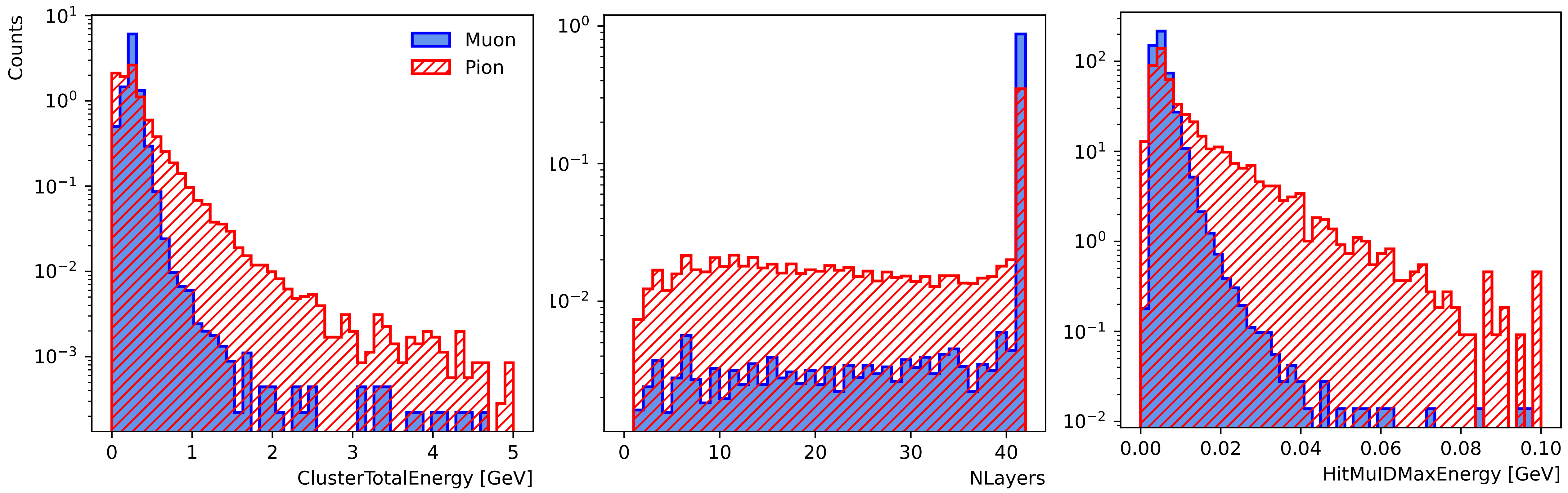




PID with ECAL and μID

- It's not possible to separate muons and pions in the HPgTPC using calorimetry for momenta ≥ 300 MeV.
- ECal can provide additional information, as pion interactions will be more hadron-like.
- We can also use the muon tagger, as pions are less likely to reach that layer.





- BDTs trained on a collection of features allow for a track-by-track classification.
- The features we used for the ECAL and μID are related to the energy of the hits and their spatial distribution.

ECal Time-of-Flight

- For momentum values $\geq$ 0.8-1.0 GeV it's not really possible to separate pions and protons using the TPC dE/dx.
- A possible solution is using a ToF measurement using the inner ECal layers.
- We can use the ECal hits to obtain an estimate of the arrival time of the particle, and then infer its mass based on the track length.

$$\beta = \frac{\ell}{c\tau} \longrightarrow m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

- The time can be estimated using one or multiple hits.
- In both cases we need to correct the length of the tracks and the time of the hits based on the entry point of the track into the ECal.