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

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Outline

I. Neutrinos and DUNE

II. ND-GAr and reconstruction

III. (New) connections between Experiment and Theory

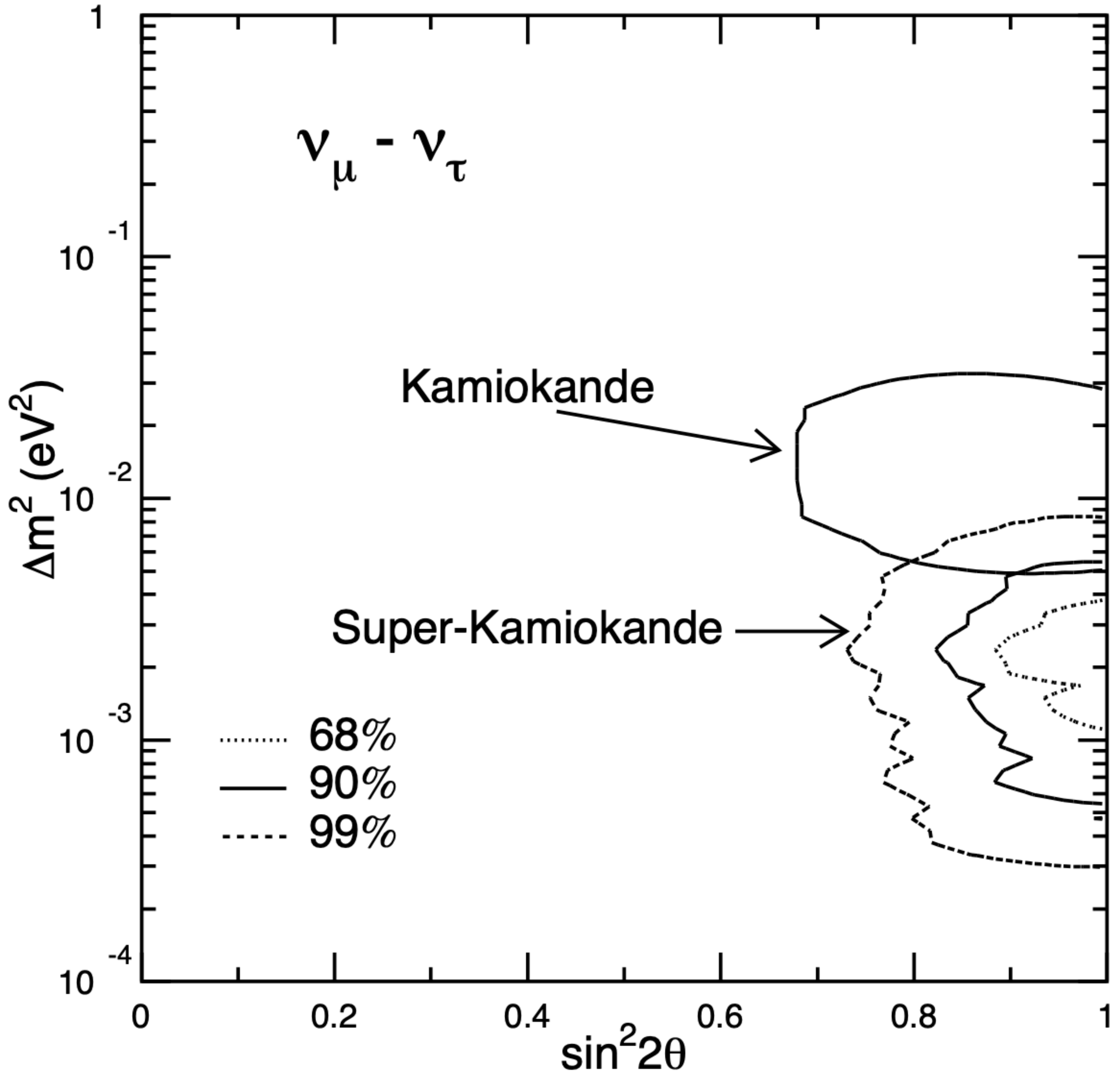
Neutrinos and DUNE

Standard model and neutrinos

- Neutrinos are massless in the vanilla SM.
- If neutrinos do oscillate then neutrinos MUST be massive.

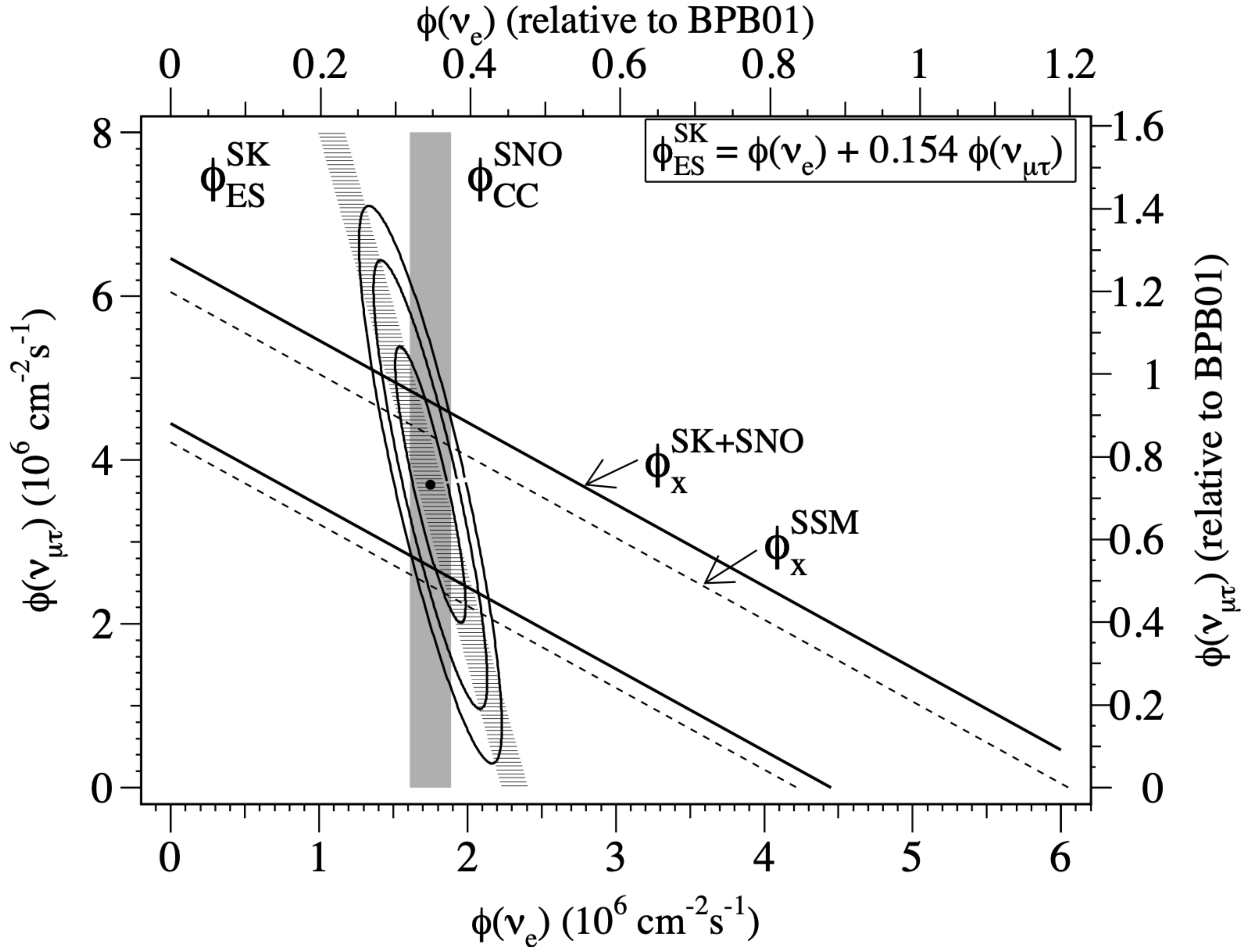
First evidence of atmospheric oscillations

arXiv:hep-ex/9807003



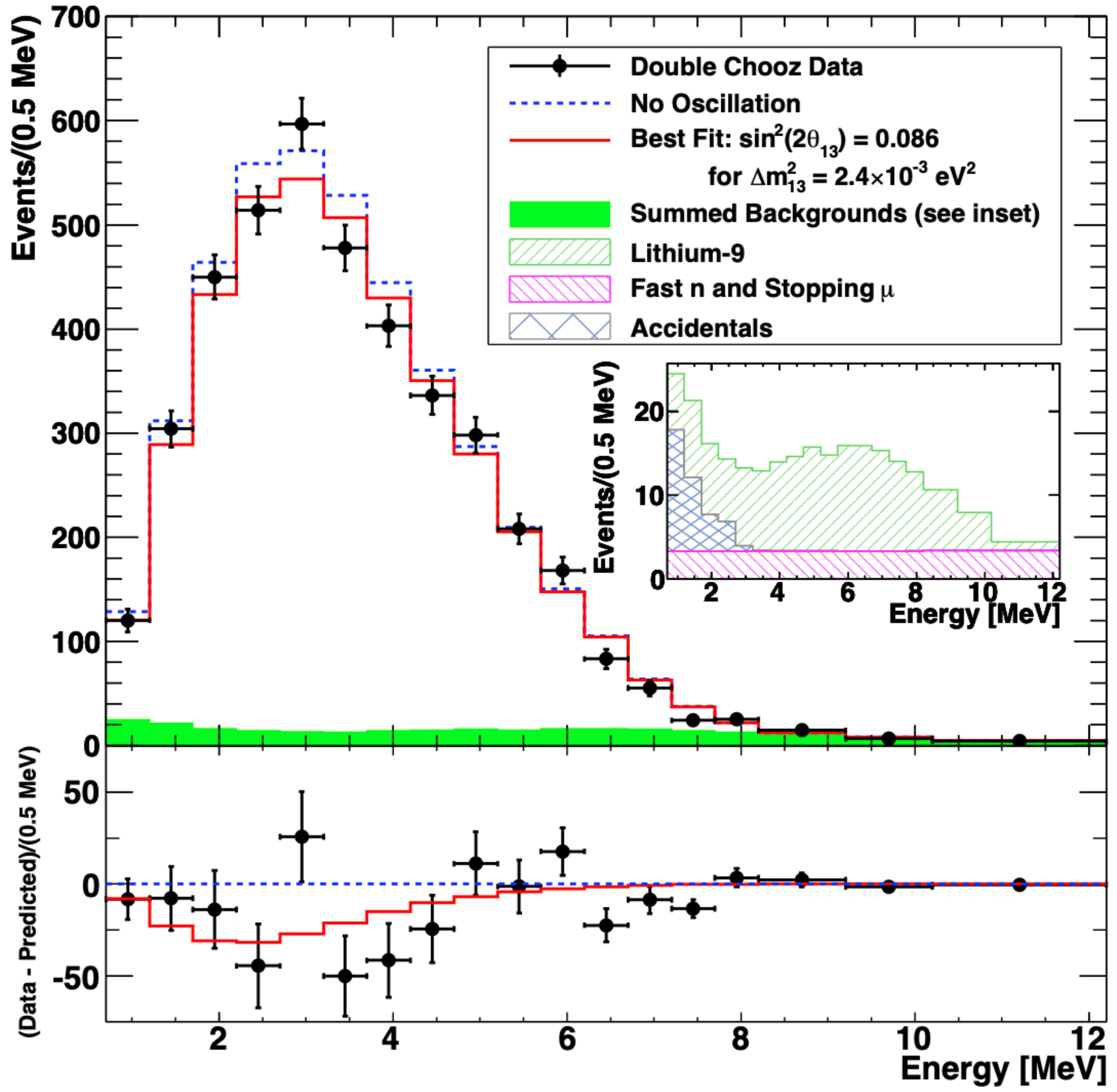
First evidence of solar oscillations

arXiv:nucl-ex/0106015



First evidence of reactor oscillations

arXiv:1112.6353



Neutrino oscillations

$$c_{ij} = \cos\,\theta_{ij}$$
$$s_{ij} = \sin\,\theta_{ij}$$
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Flavour eigenstates $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$ Mass eigenstates

Reactor/accelerator sector

Majorana phases

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \mathrm{e}^{i\alpha_1/2} & 0 & 0 \\ 0 & \mathrm{e}^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

Solar sector

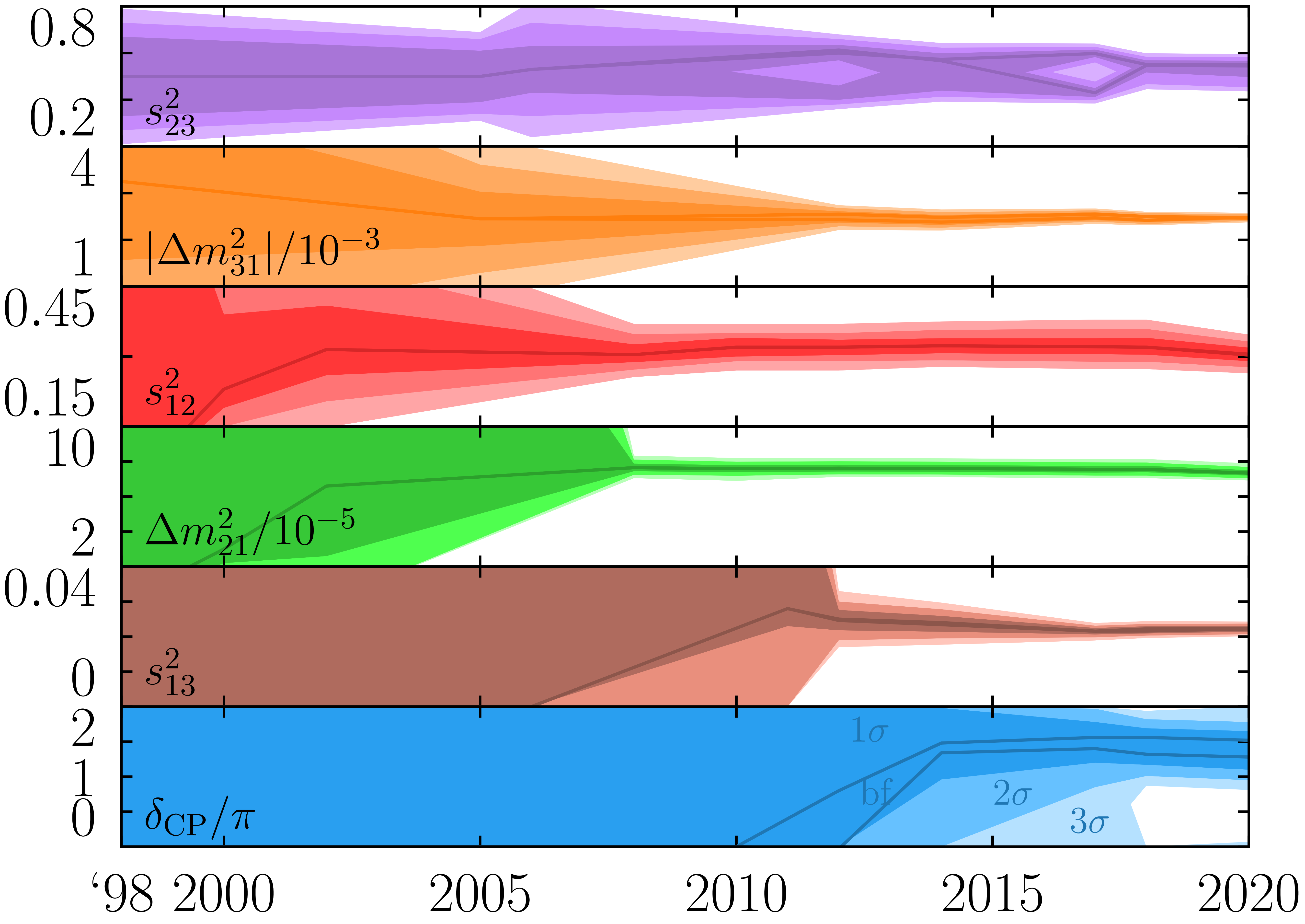
- 3 mixing angles: θ_{12}, θ_{23} and θ_{13}.
- 3 CP phases: 1 Dirac + 2 Majorana
- 2 mass splittings: Δm^2_{21} and Δm^2_{31}.

In the two flavour approximation…

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Where are we now?

arXiv:2212.00809

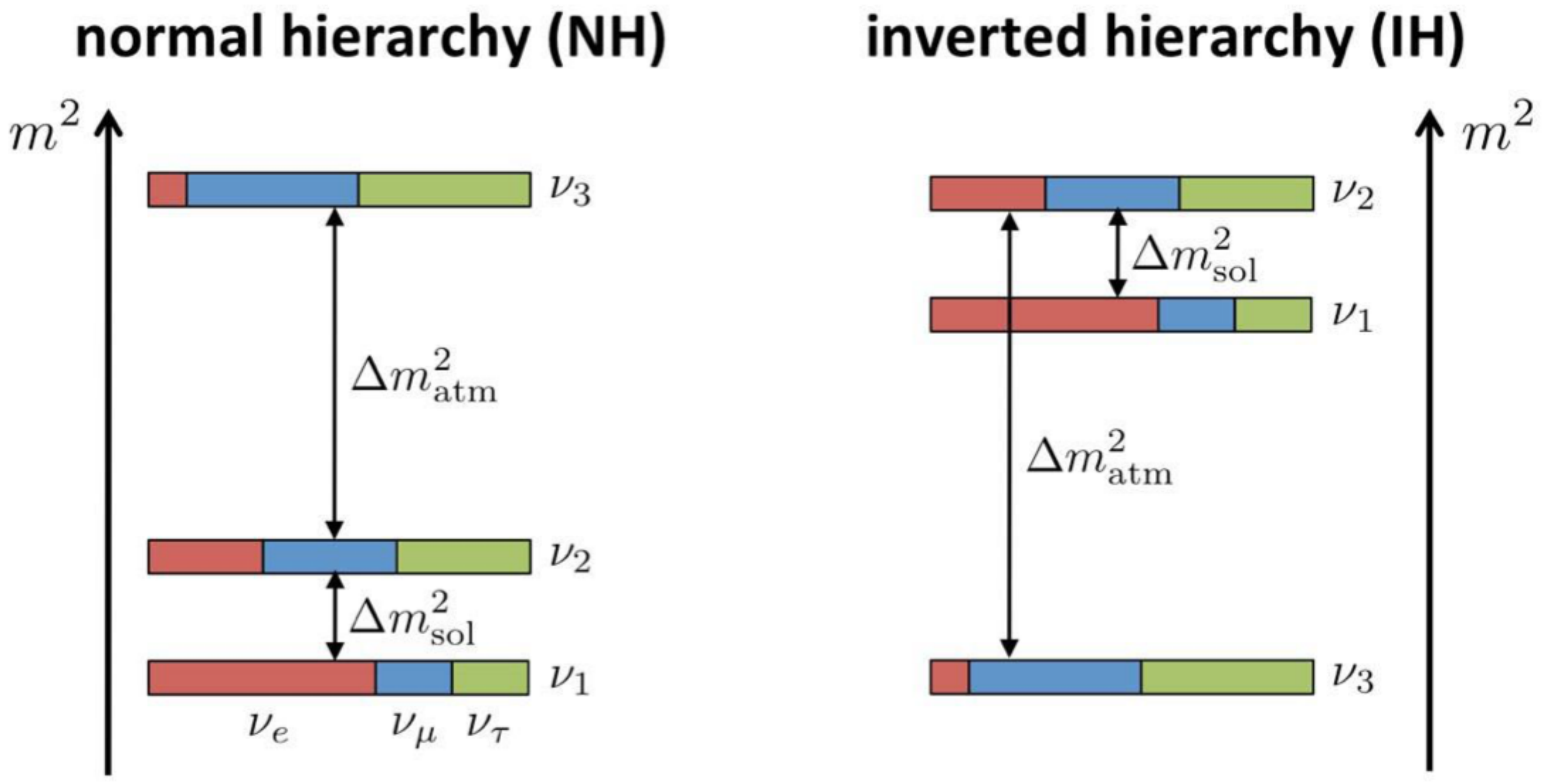


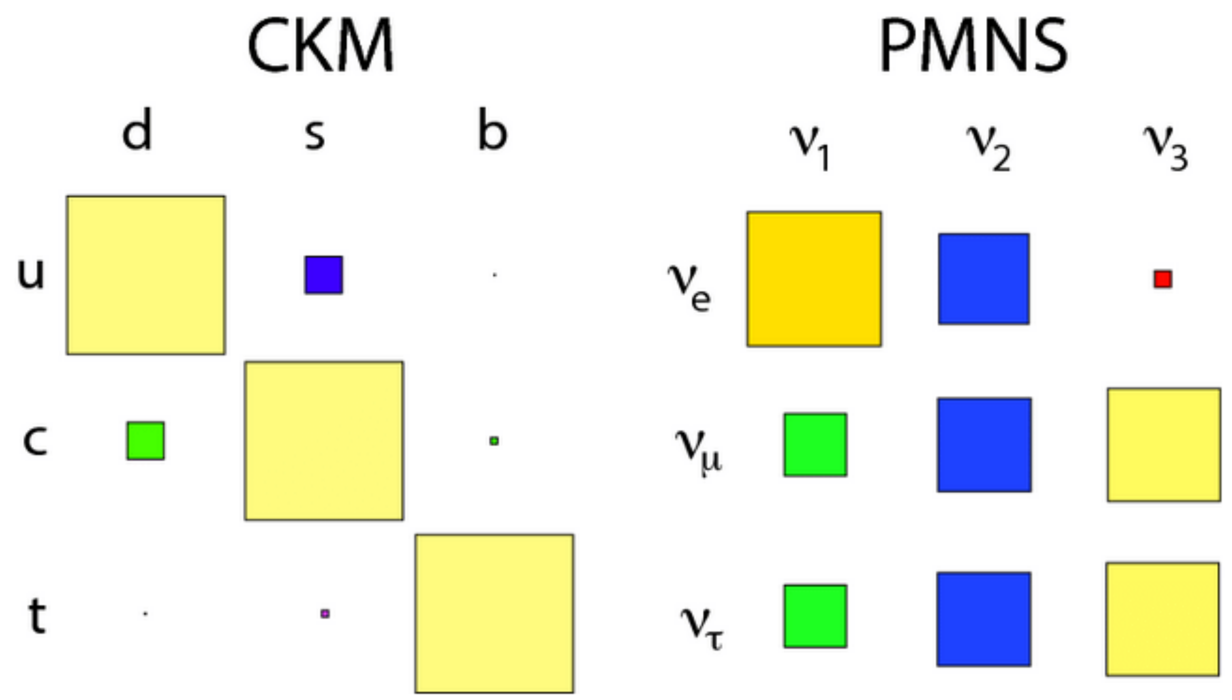
Parameter	Best fit $\pm$ 1σ	3σ range
Δm^2_{21} [eV^2 $\times$ 10^{-5}]	$7.55^{+0.22}_{-0.20}$	$6.98 - 8.19$
$\lvert\Delta m^2_{31}\rvert$ [eV^2 $\times$ 10^{-3}] (NO)	$2.51^{+0.02}_{-0.03}$	$2.43 - 2.58$
$\lvert\Delta m^2_{31}\rvert$ [eV^2 $\times$ 10^{-3}] (IO)	$2.41^{+0.03}_{-0.02}$	$2.34 - 2.49$
$\sin^2\theta_{12}/10^{-1}$	3.04 ± 0.16	$2.57 - 3.55$
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	$4.23 - 6.04$
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	$4.27 - 6.03$
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	$2.03 - 2.38$
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	$2.04 - 2.38$
δ_{CP}/π (NO)	$1.12^{+0.16}_{-0.12}$	$0.76 - 2.00$
δ_{CP}/π (IO)	$1.50^{+0.13}_{-0.14}$	$1.11 - 1.87$

Valencia global fit
globalfit.astroparticles.es
(Updated version shown at Neutrino 2024)

Open questions

- What is the origin of the neutrino masses?
- Are neutrinos Majorana particles?
- Do neutrinos violate CP-symmetry?
- Is the mass ordering normal or inverted?
- Is θ_{23} maximal?
- Why is the mixing in the quark sector so different?
- Are there more neutrinos?





Open questions

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DUNE will be able to answer these

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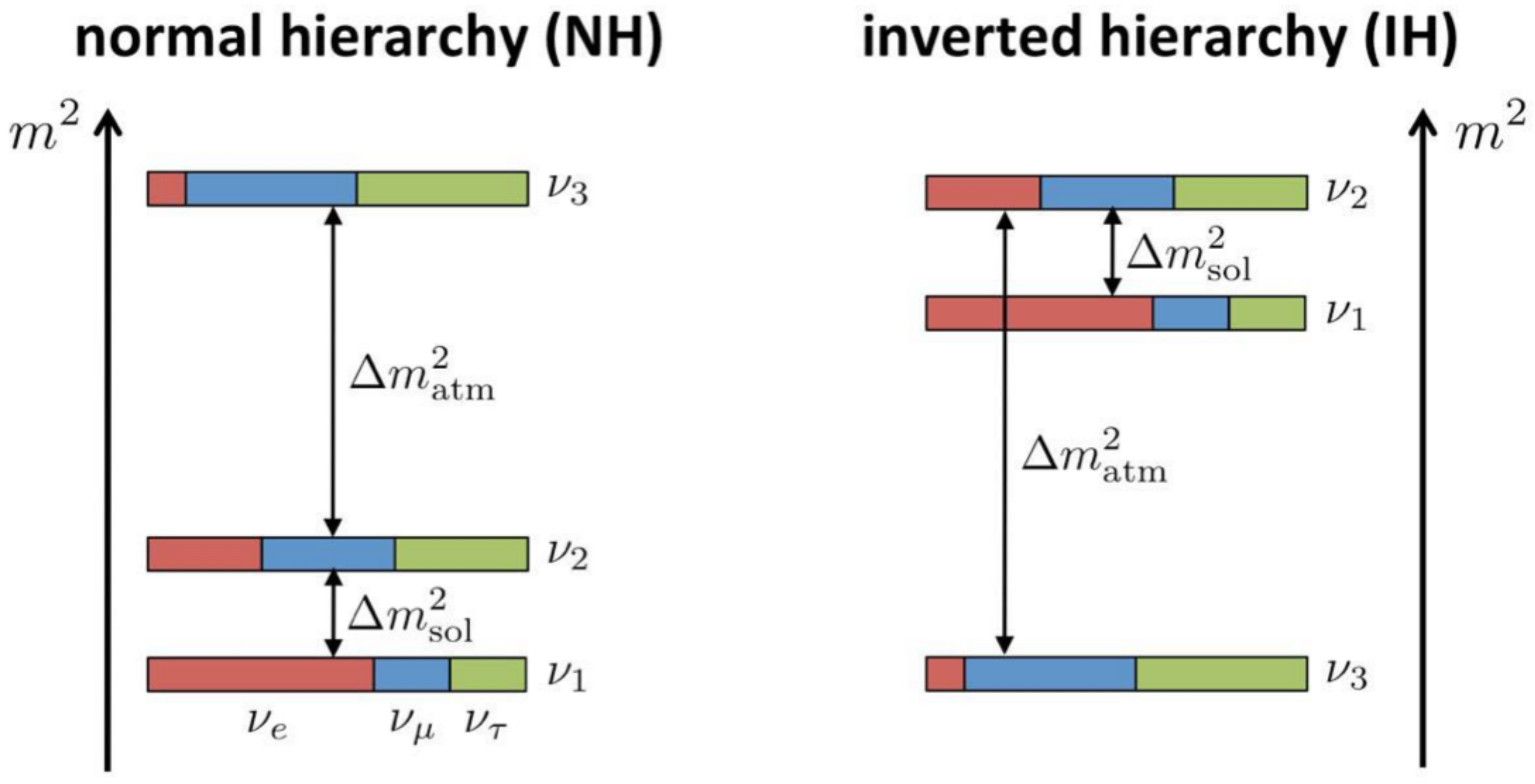
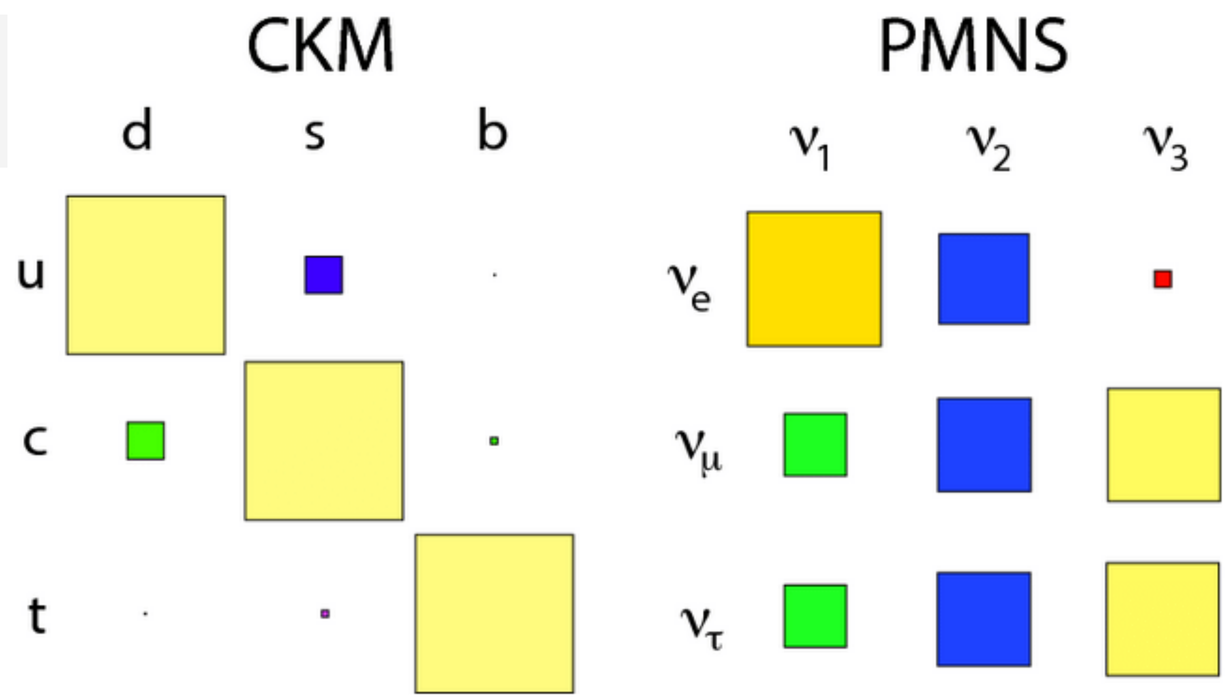
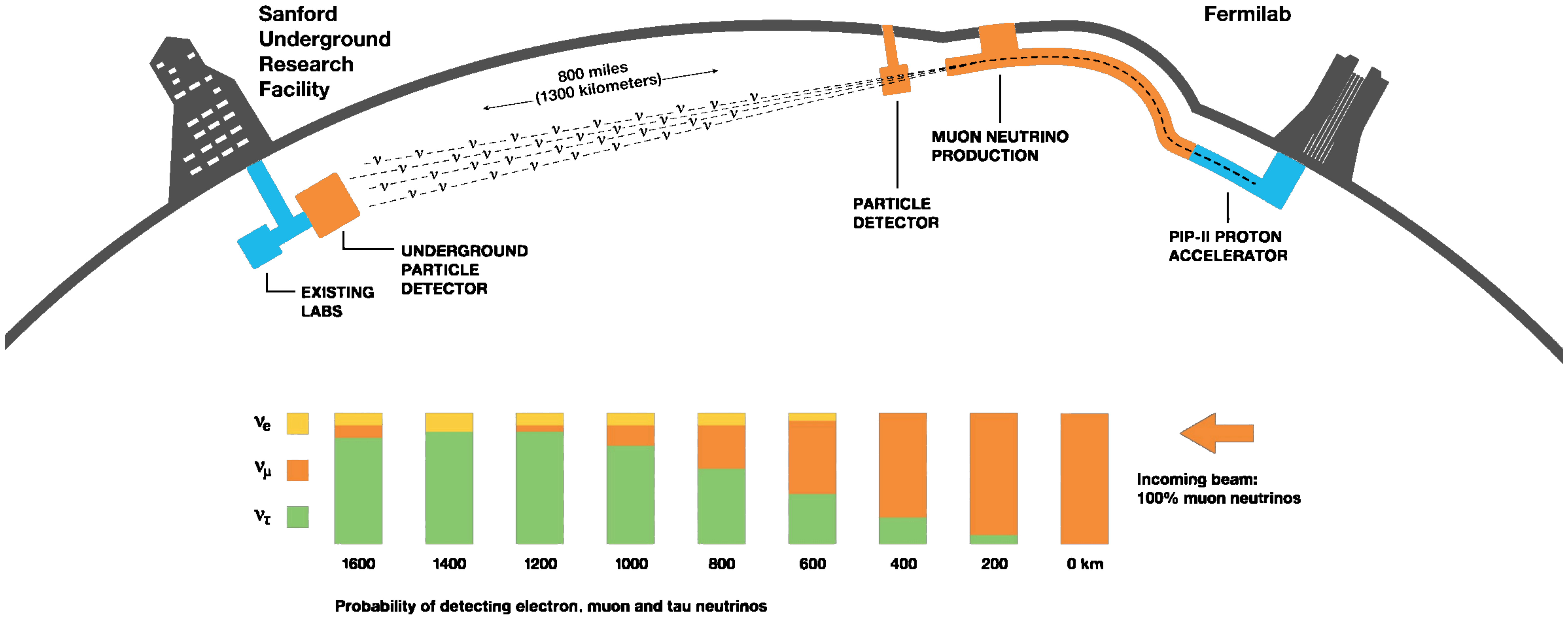




Deep Underground Neutrino Experiment

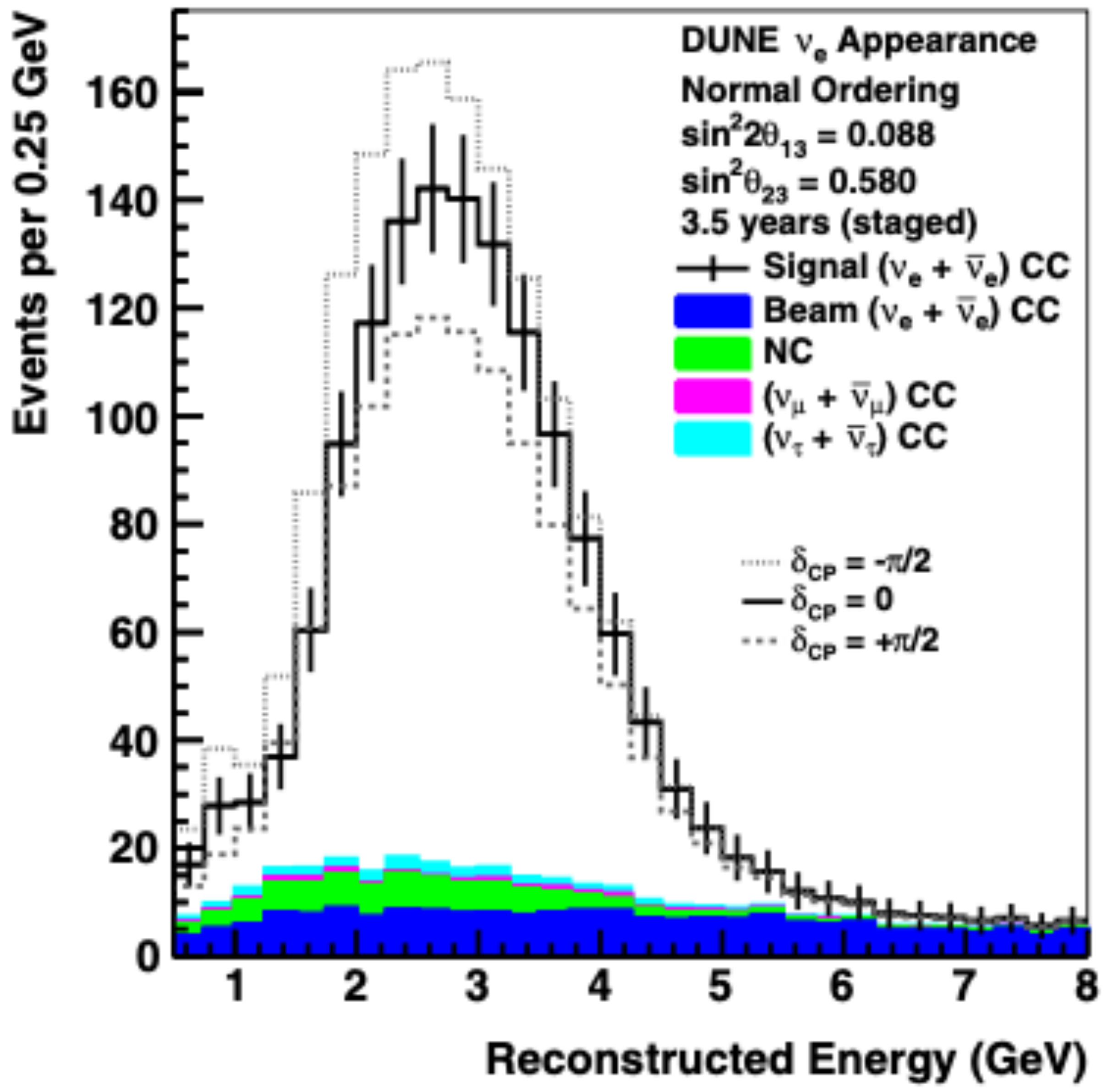


- Wide band high intensity (anti)neutrino beam produced at Fermilab.
- 70-kt liquid argon far detector 1.5km underground in South Dakota.
- Near detector complex to control systematic uncertainties.

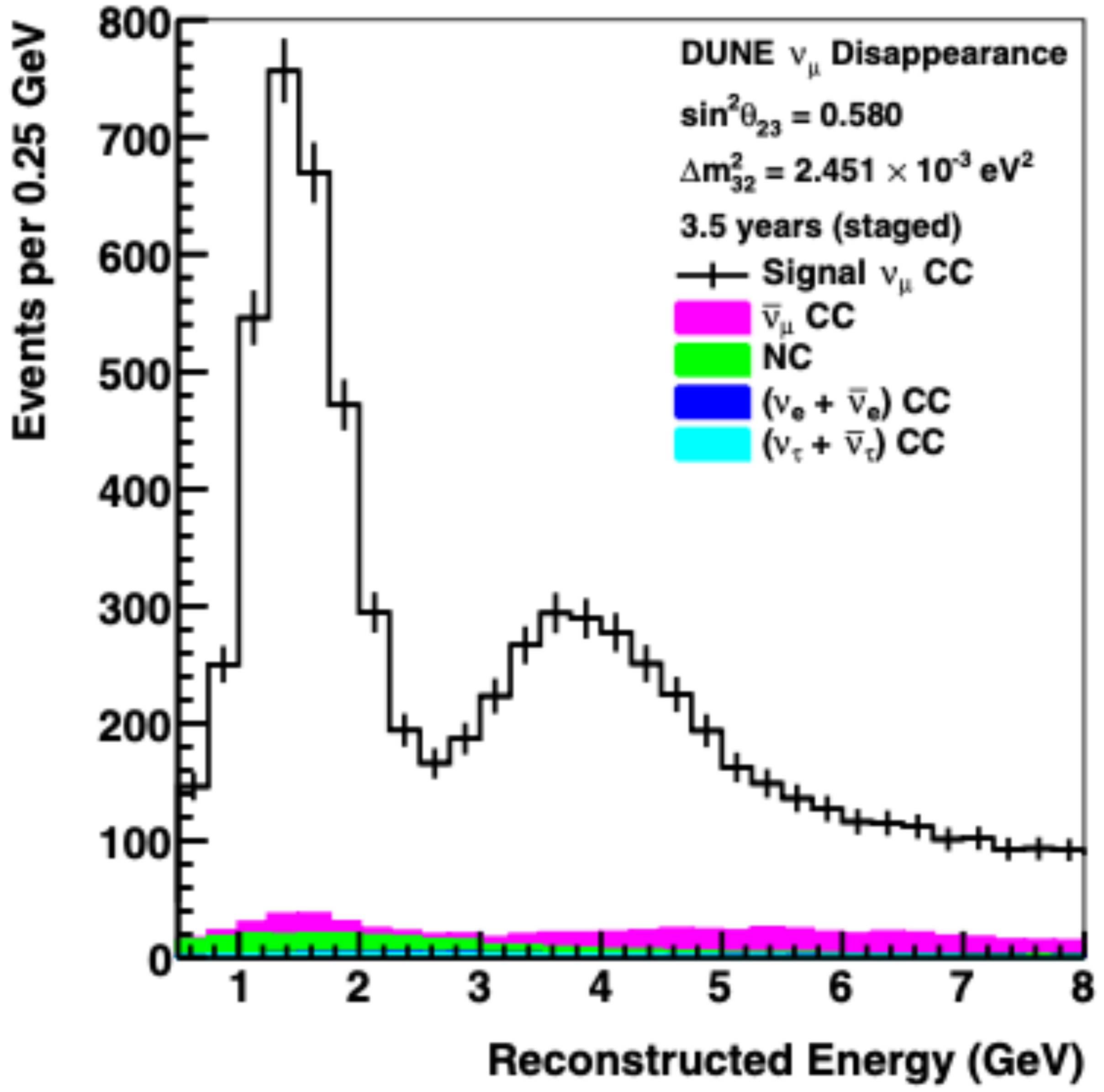
What will DUNE measure?

- In the FD we will observe both the appearance of ν_e and the disappearance of ν_μ.
- From the disappearance spectrum we get $2\theta_{23}$ and Δm^2_{32}.
- The appearance spectrum allows for θ_{23} and θ_{13} sensitivity.
- Comparing neutrino and antineutrino modes and the appearance shape we obtain δ_{CP}.

arXiv:2006.16043



$\nu_\mu \to \nu_e$



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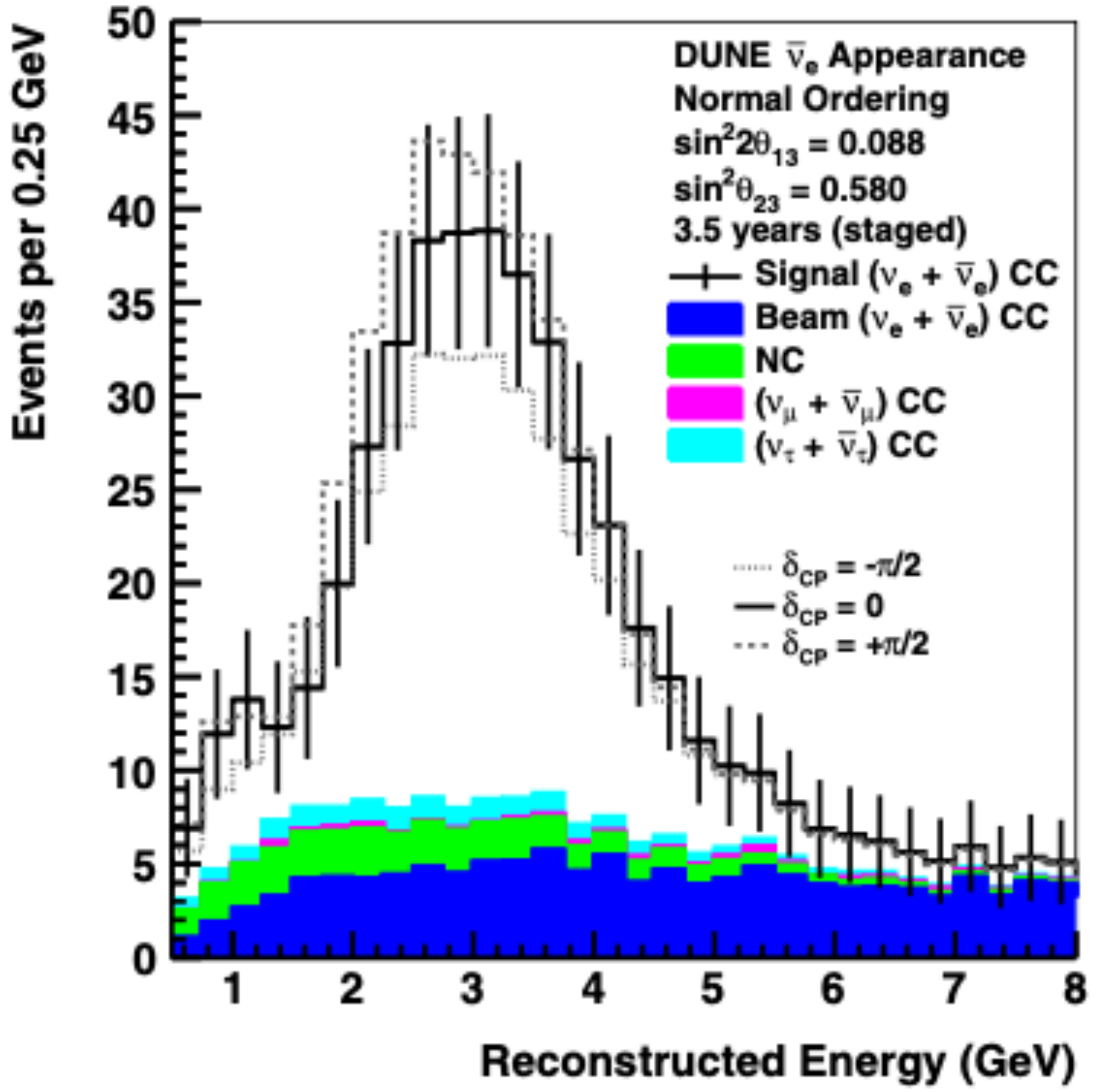
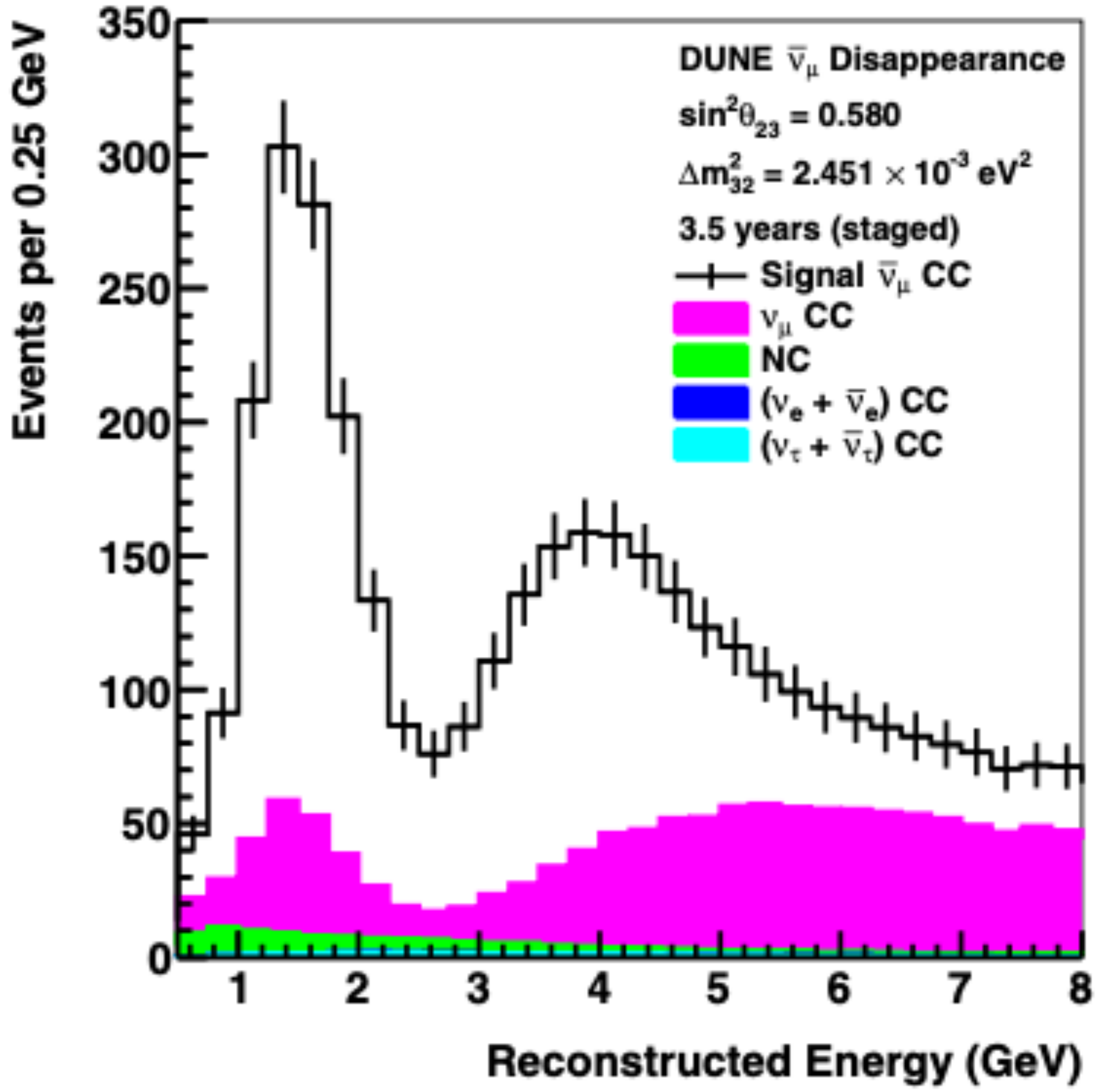


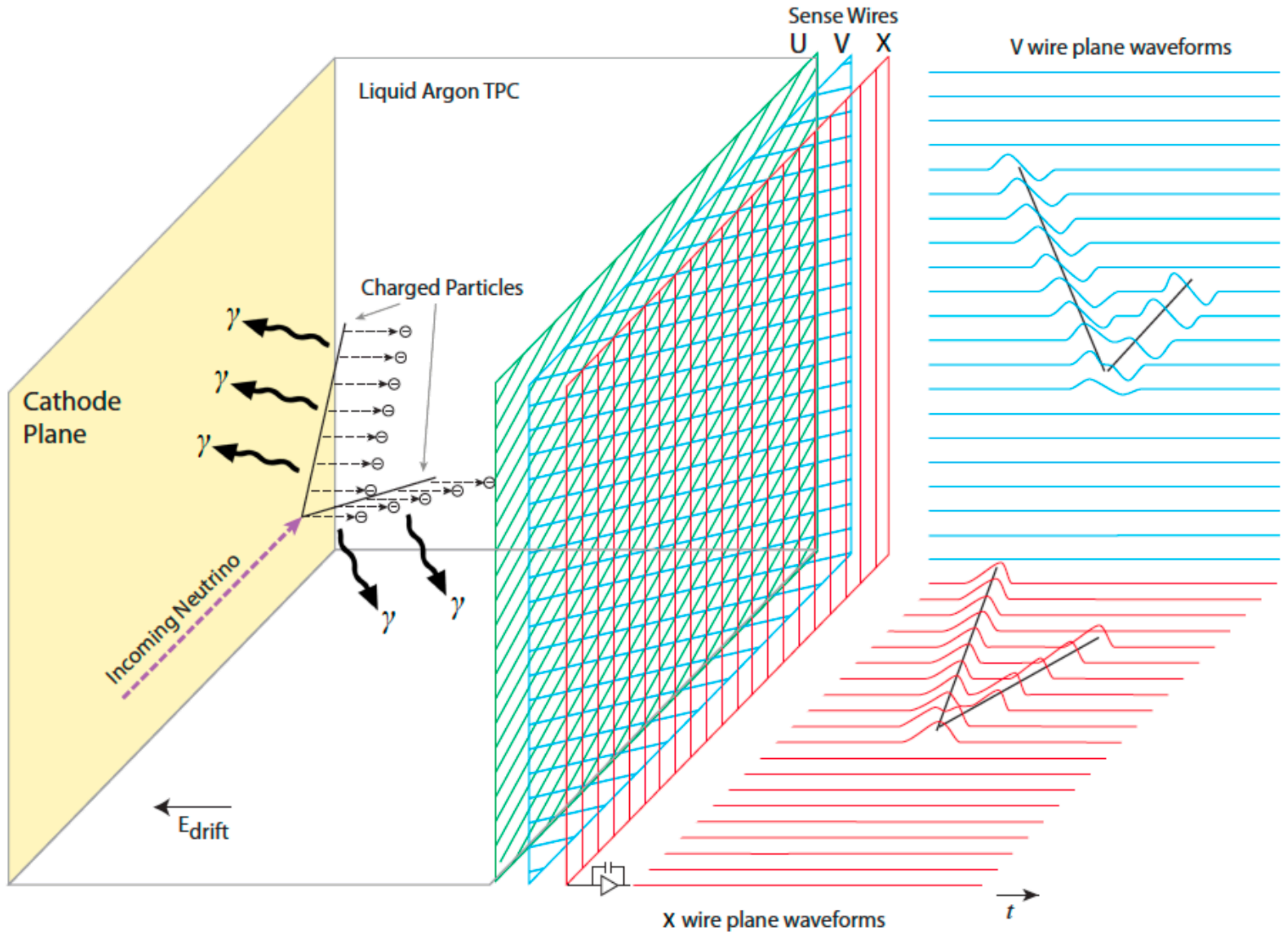
$\bar\nu_\mu \to \bar\nu_e$



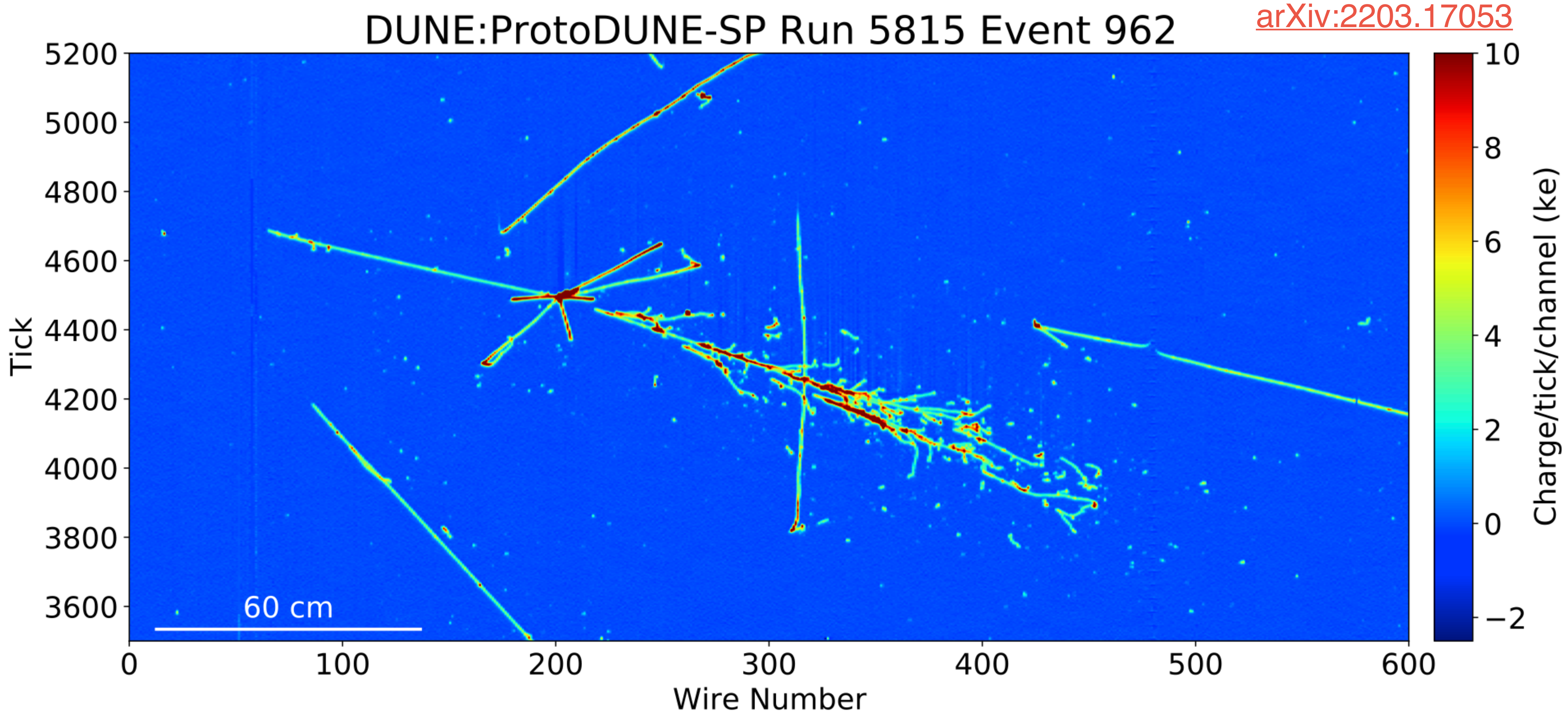
$\bar\nu_\mu \to \bar\nu_\mu$

DUNE Far Detector

- 4 underground LArTPCs, allowing for high-resolution and low background measurements of the beam neutrino spectra.
- Other exciting physics opportunities: supernova, solar and atmospheric neutrinos, proton decay and other BSM physics.



Horizontal drift geometry

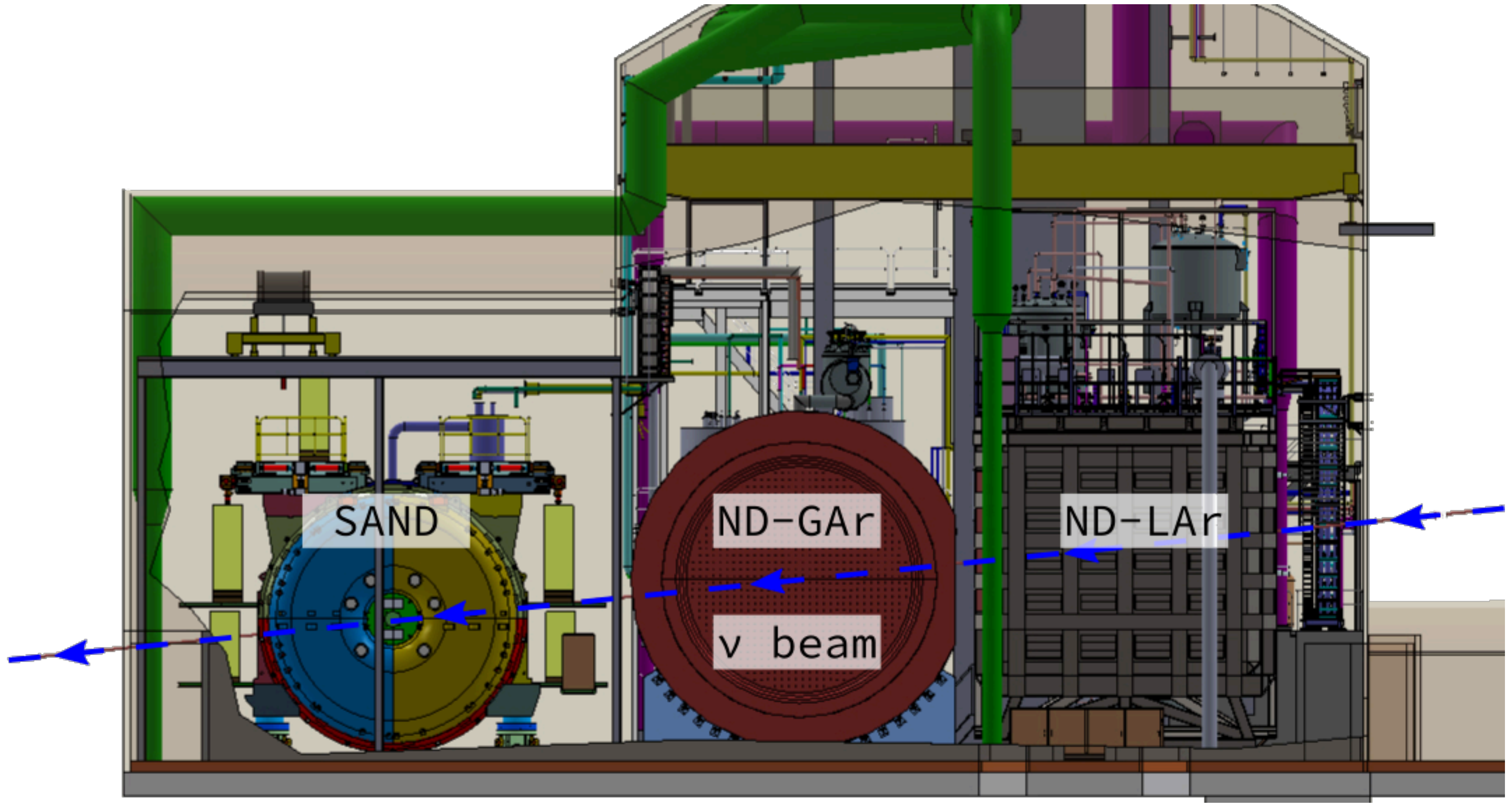


arXiv:2203.17053

A 7 GeV/c beam π^+ interaction in ProtoDUNE-SP

DUNE Near Detector

- Its role is to measure the unoscillated neutrino spectra.
  - Can be used to predict the FD event rates.
- Constrains the systematic uncertainties (flux, cross section and detector response) for the oscillation physics.
- It also allows for precision measurements of neutrino interactions and plenty of BSM opportunities.



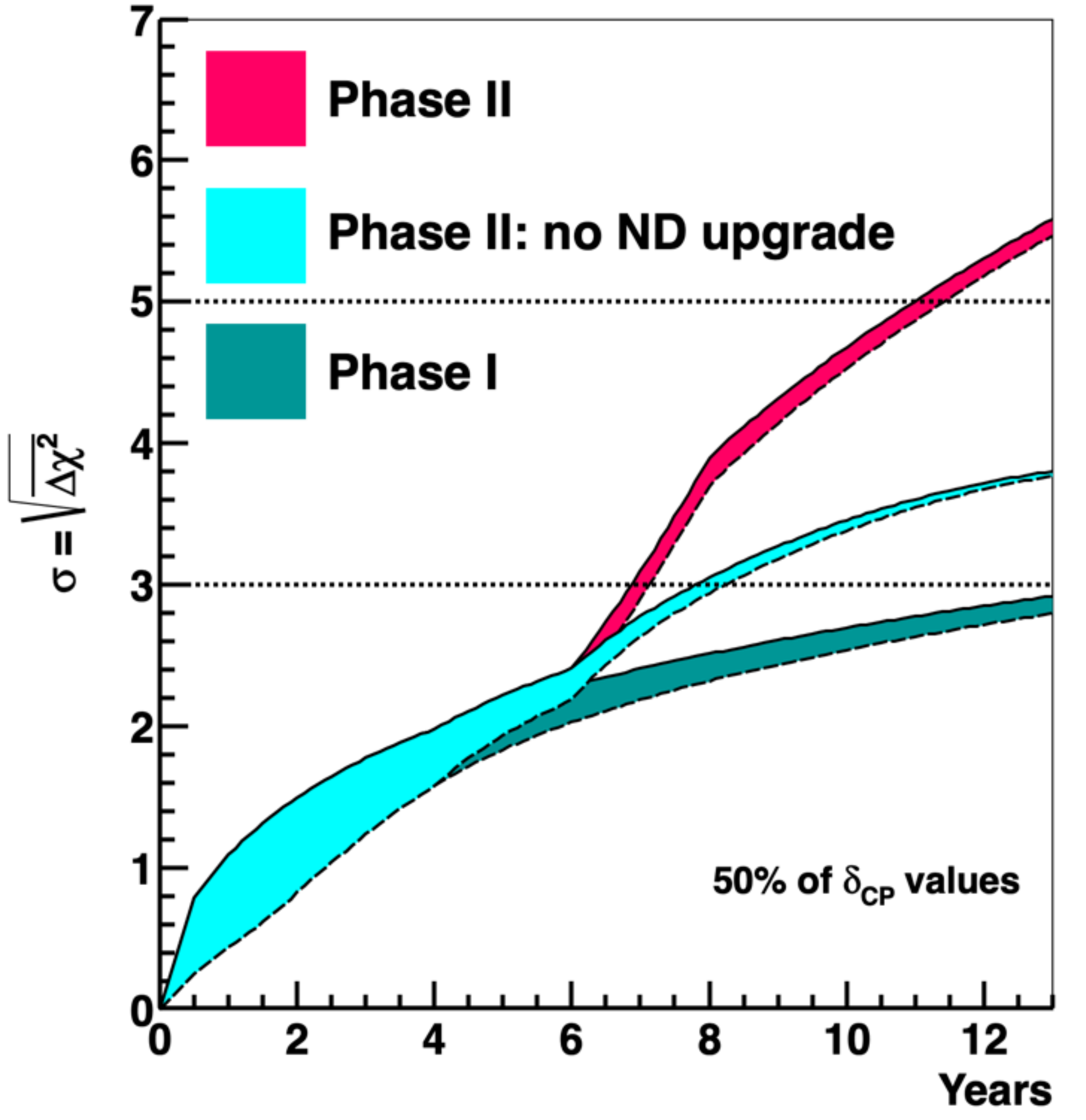
- ND-LAr
- TMS/ND-GAr
- SAND

PRISM

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

arXiv:2203.06100

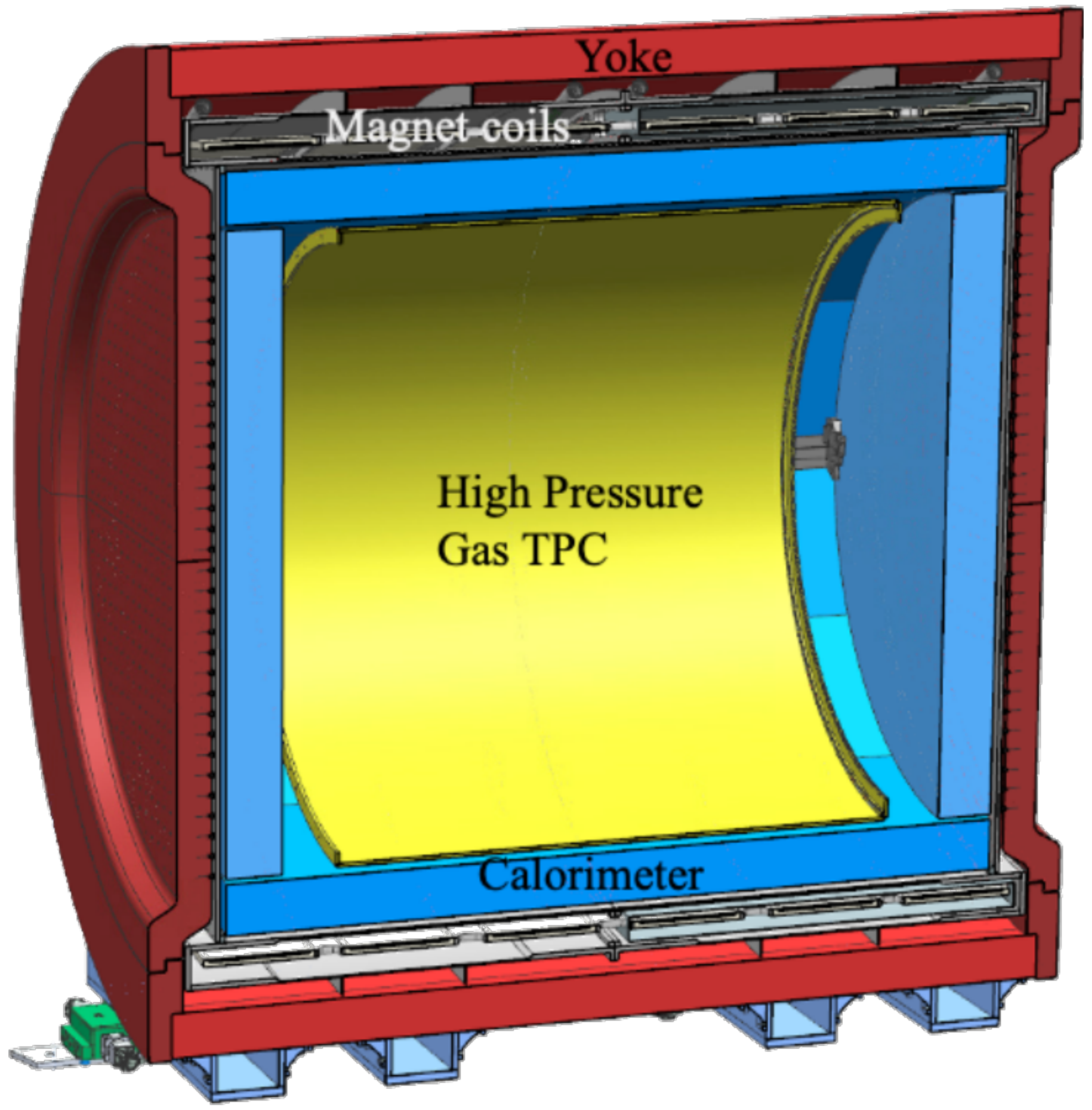


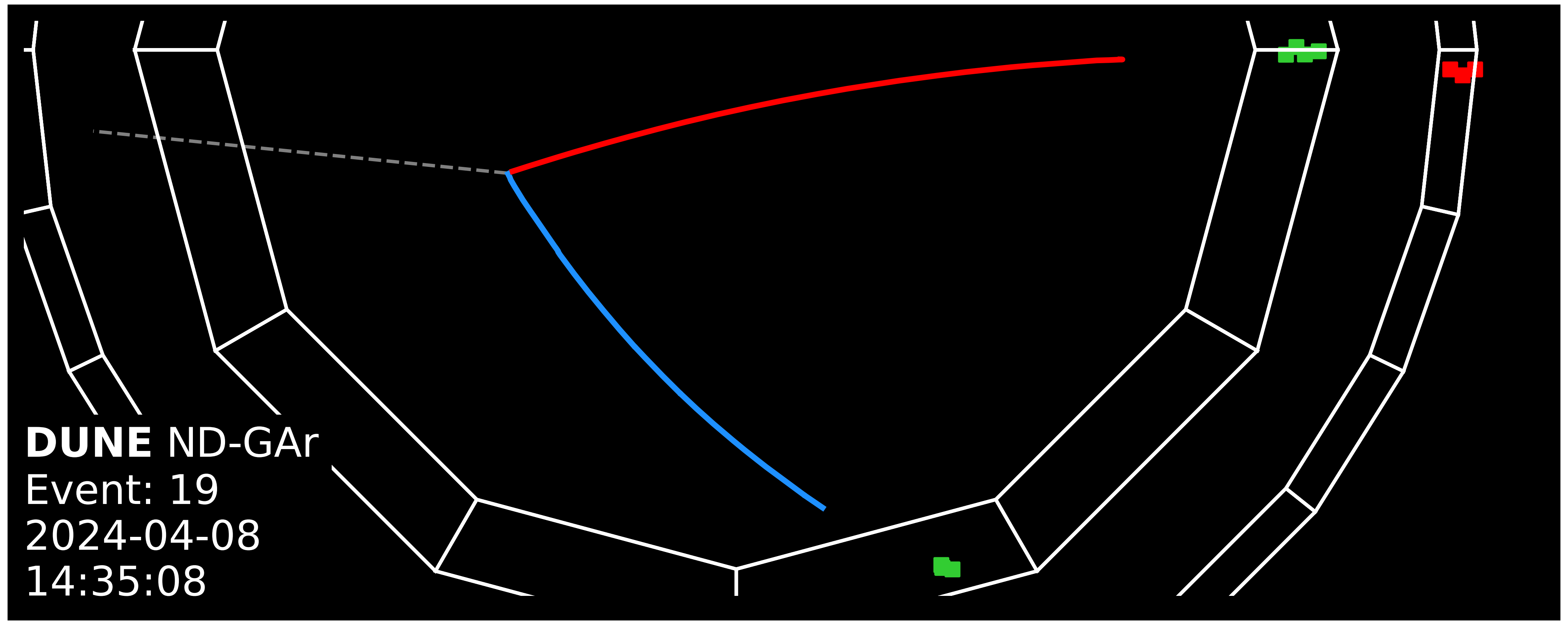
- DUNE will be built using a **staged approach**.
- Phase I is sufficient for early physics goals.
- **Phase II is necessary** to reach the design sensitivity for δ_{CP}.
  - A **ND upgrade** is needed in order to reach the desired sensitivity!

ND-GAr and reconstruction

ND-GAr concept

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

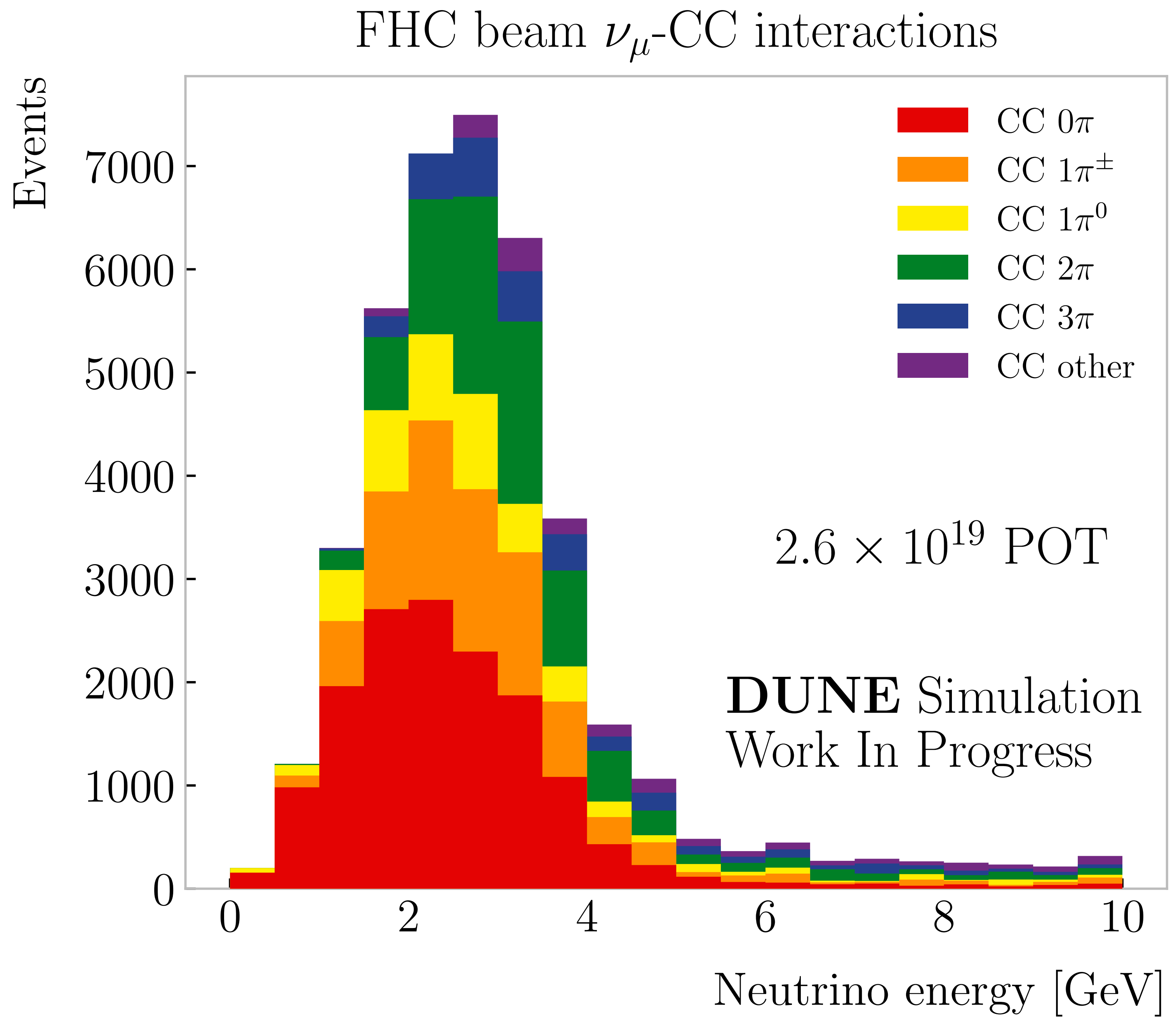


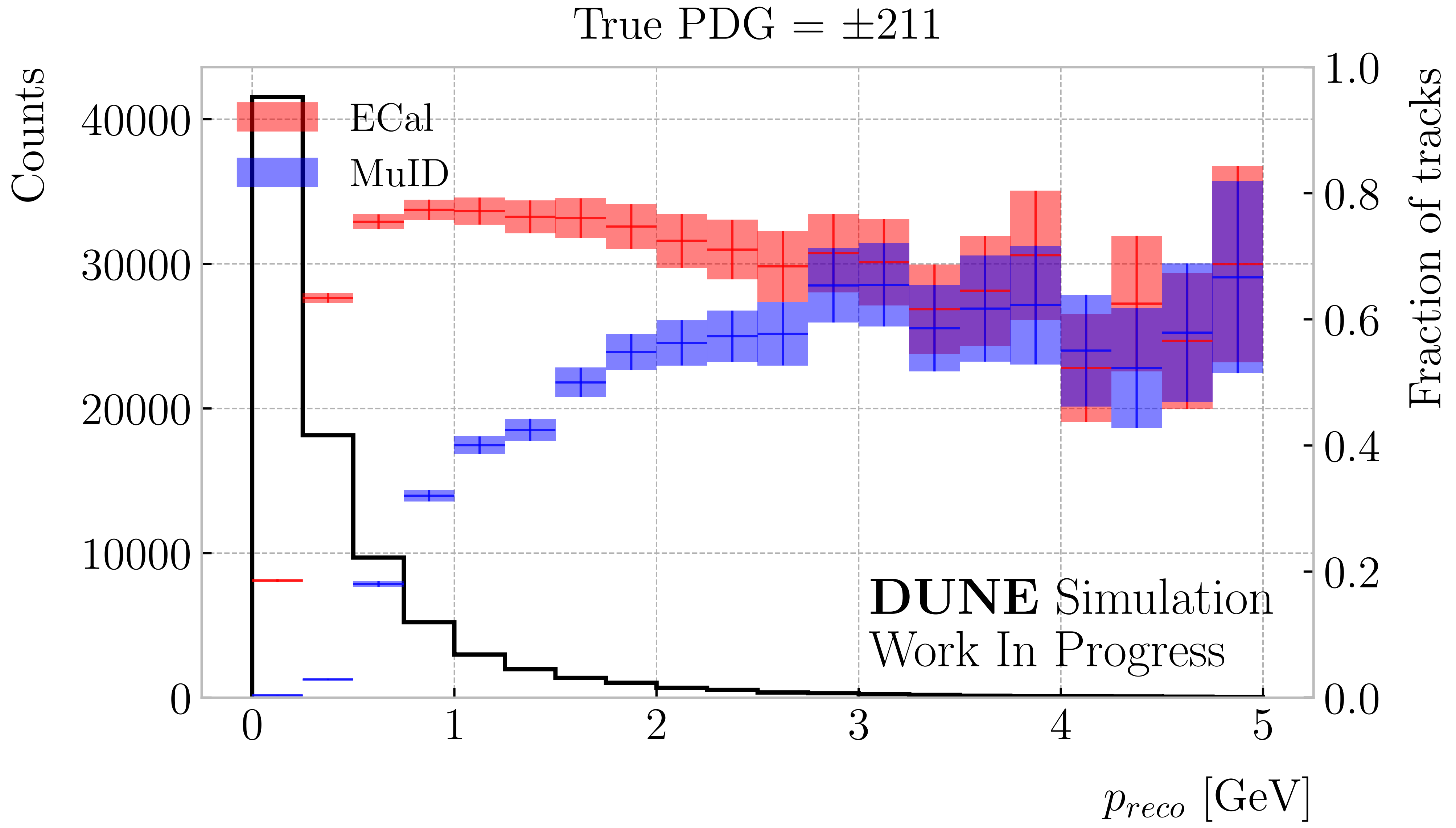


- Considering the use of GEMs for HPgTPC charge readout.
- ECal combines high-granularity tiles and cross scintillator strips.
- The superconducting magnet provides a 0.5 T field with a 1% uniformity.

ND-GAr and PID

- 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.
- We **need a reliable PID** able to identify pions with a high purity and across a broad energy range.

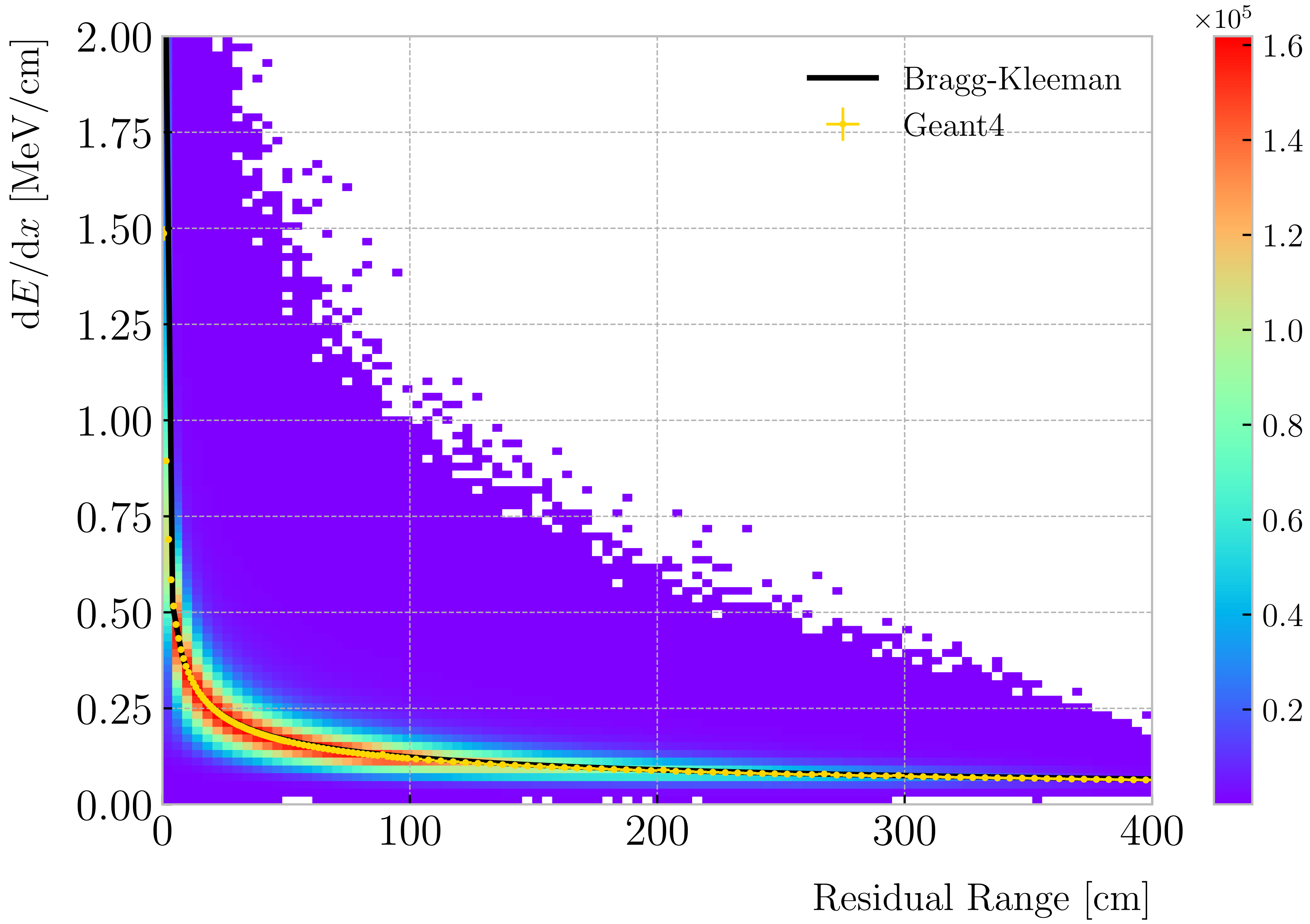




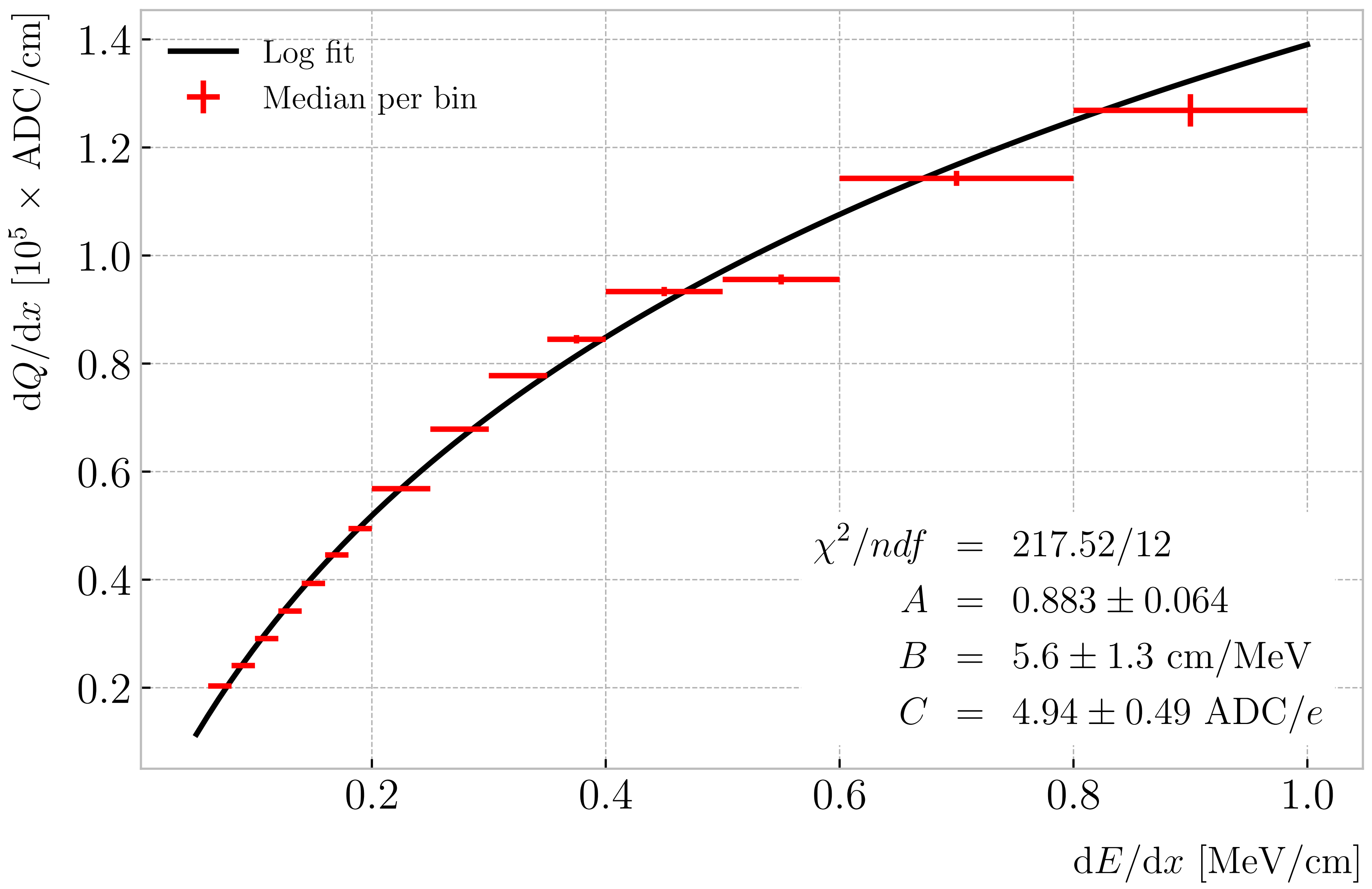
- In order to correctly identify particles, ND-GAr can use a combination of:
  - Calorimetry in the TPC.
  - ECal and muon tagger information.

dE/dx calibration

- Use stopping proton MC sample to calibrate charge deposits.
- Compare truth-level energy deposits to charge using range.
- Bin in dE/dx and fit a log function to account for saturation.

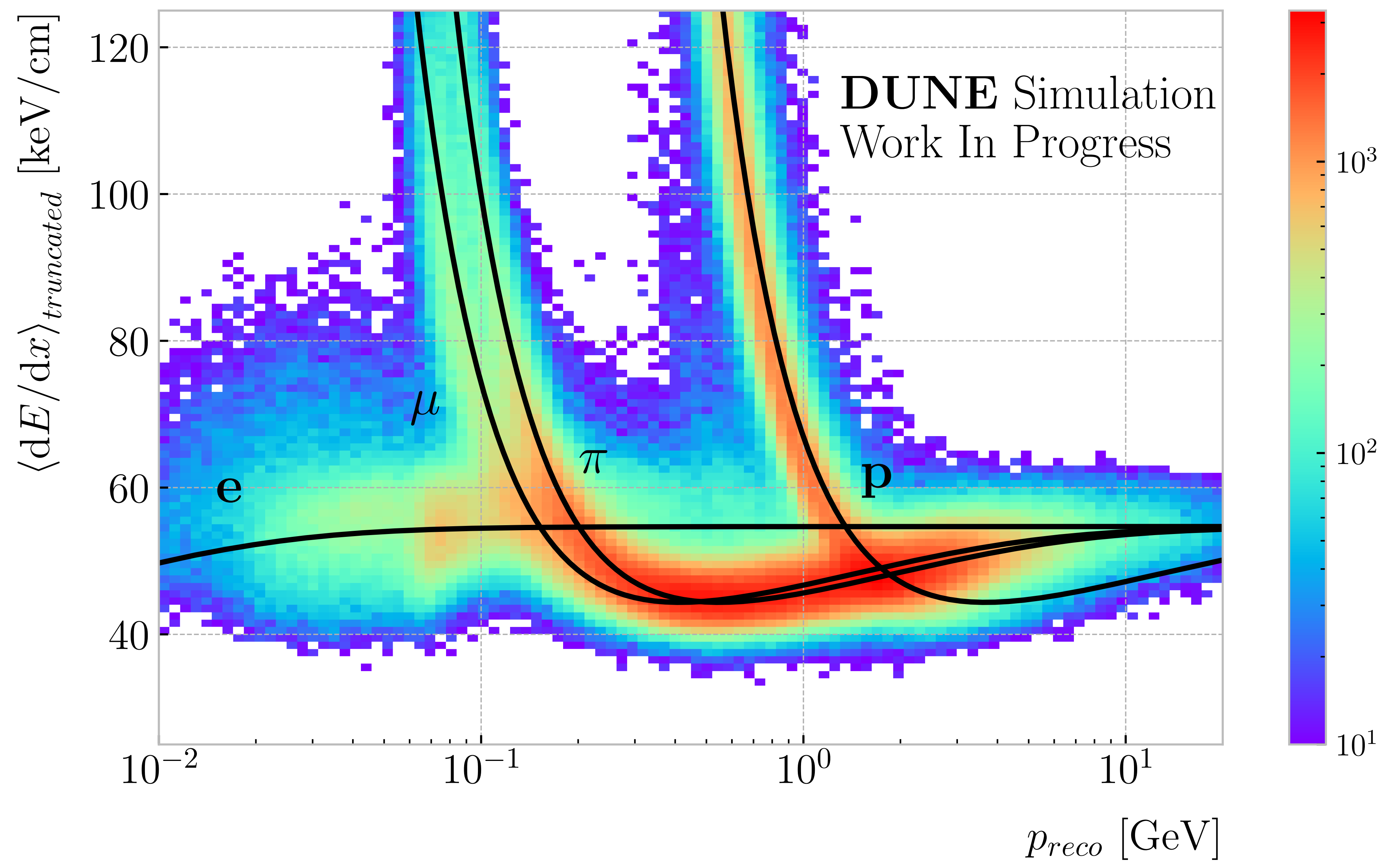


$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{e^{\frac{\mathrm{d}Q}{\mathrm{d}x} B \frac{W_{ion}}{G_{cluster} C}} - A}{B}$$

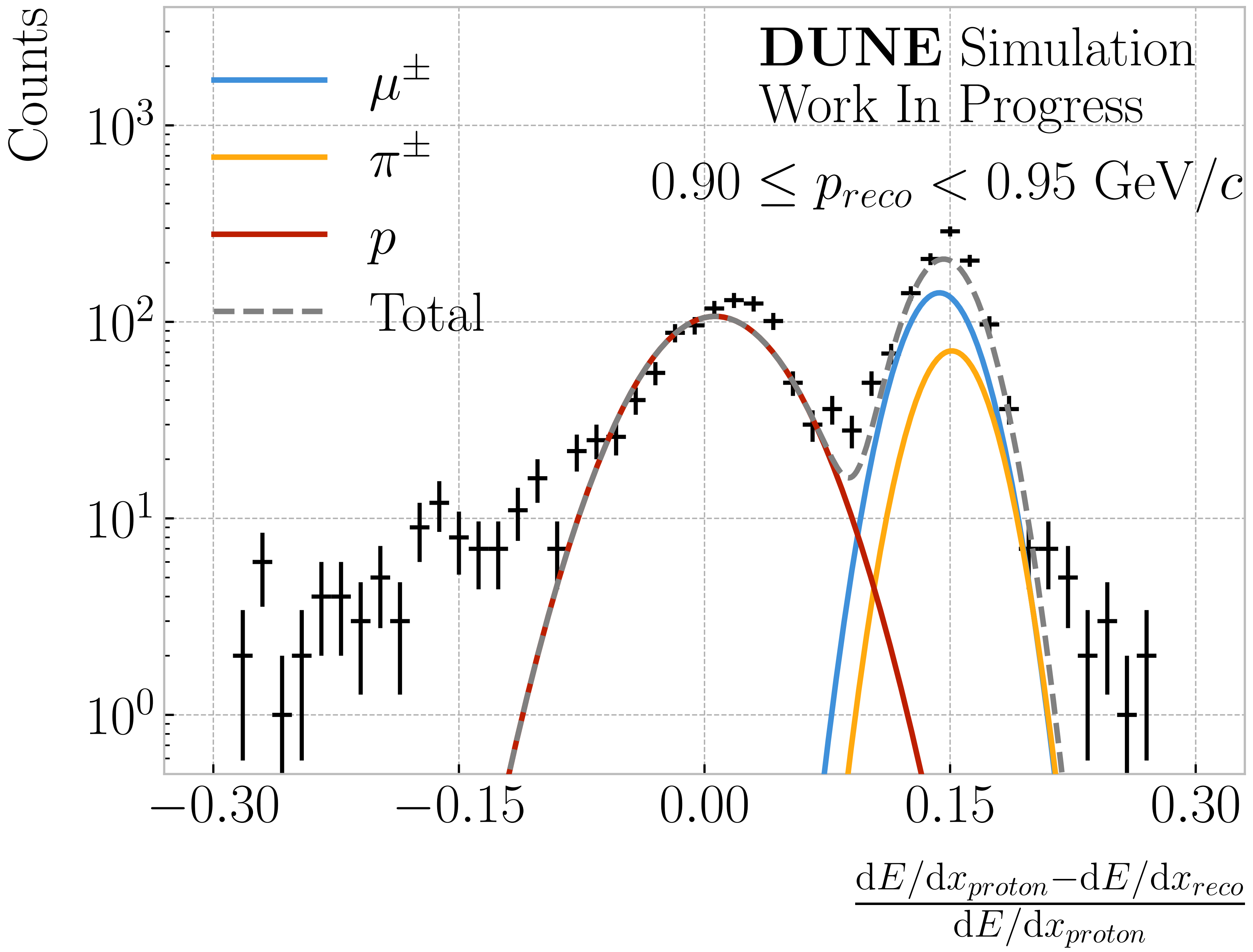


dE/dx and PID

- 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 $200\ \mathrm{MeV}/c$ and protons up to $1.0\ \mathrm{GeV}/c$.

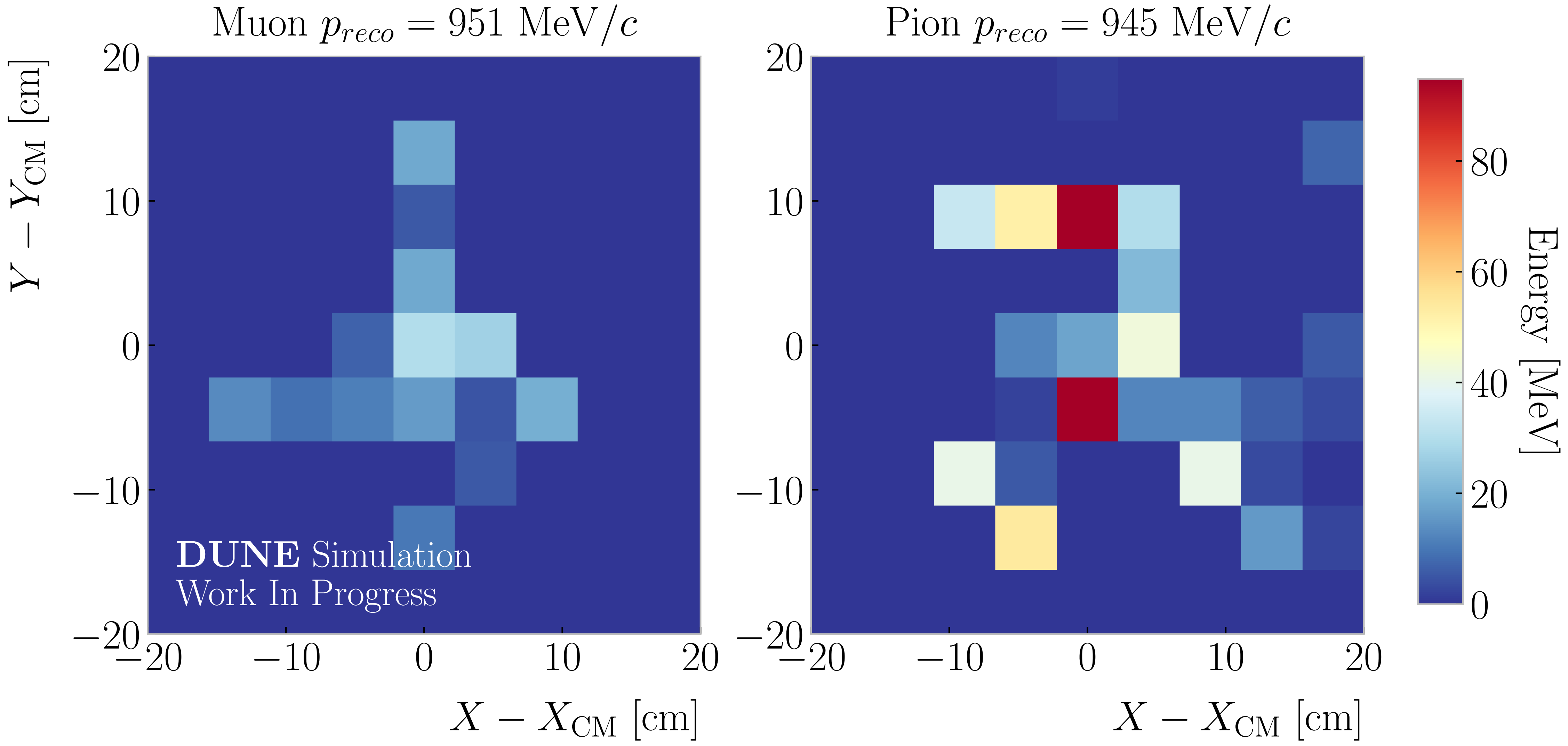


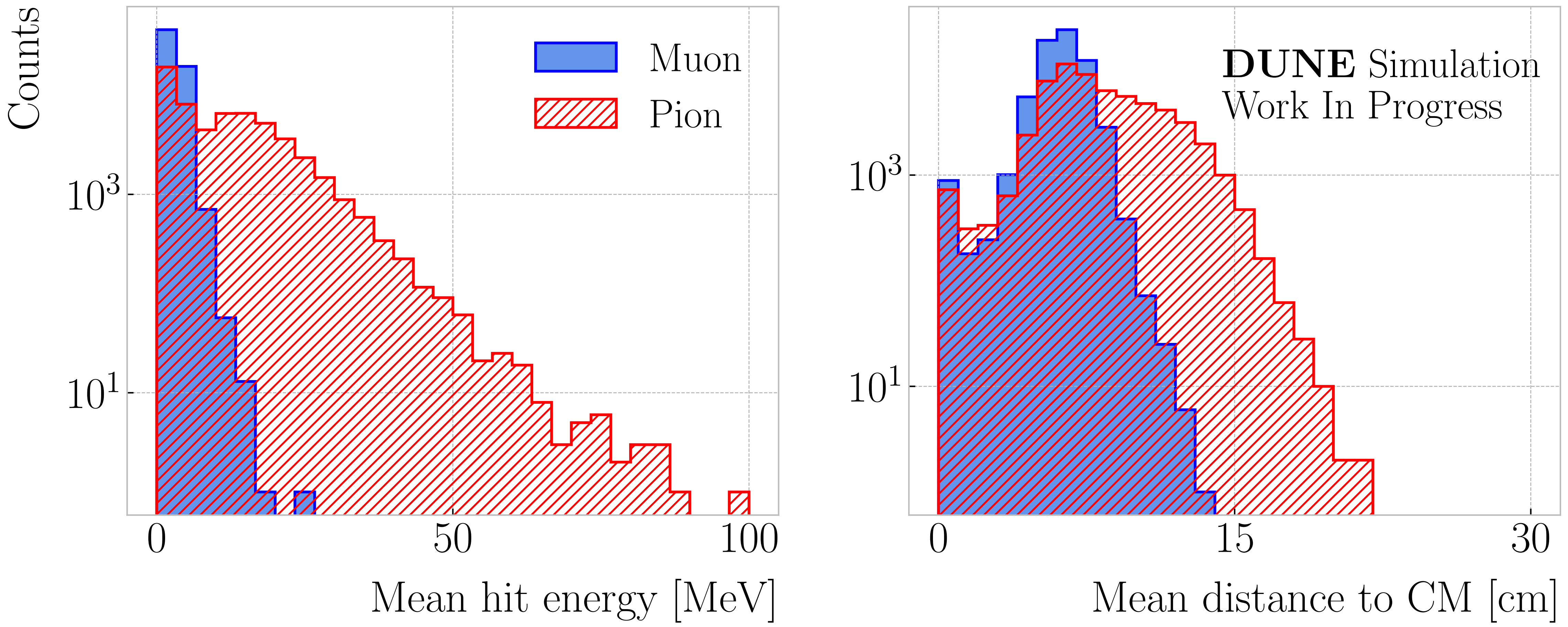
For a 100k FHC neutrino sample



PID with ECAL and μID

- It's not possible to separate muons and pions in the HPgTPC for momenta $\geq 200\ \mathrm{MeV}/c$.
- Hadronic interactions in the ECal look significantly different from those of muons.

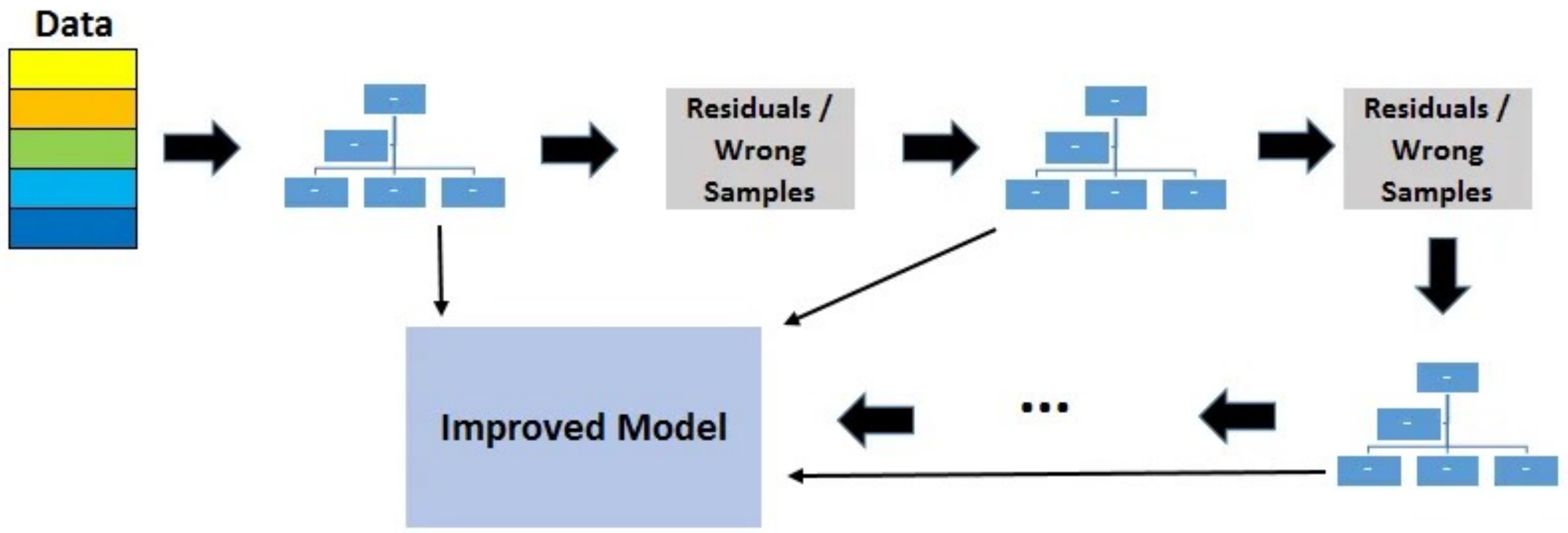


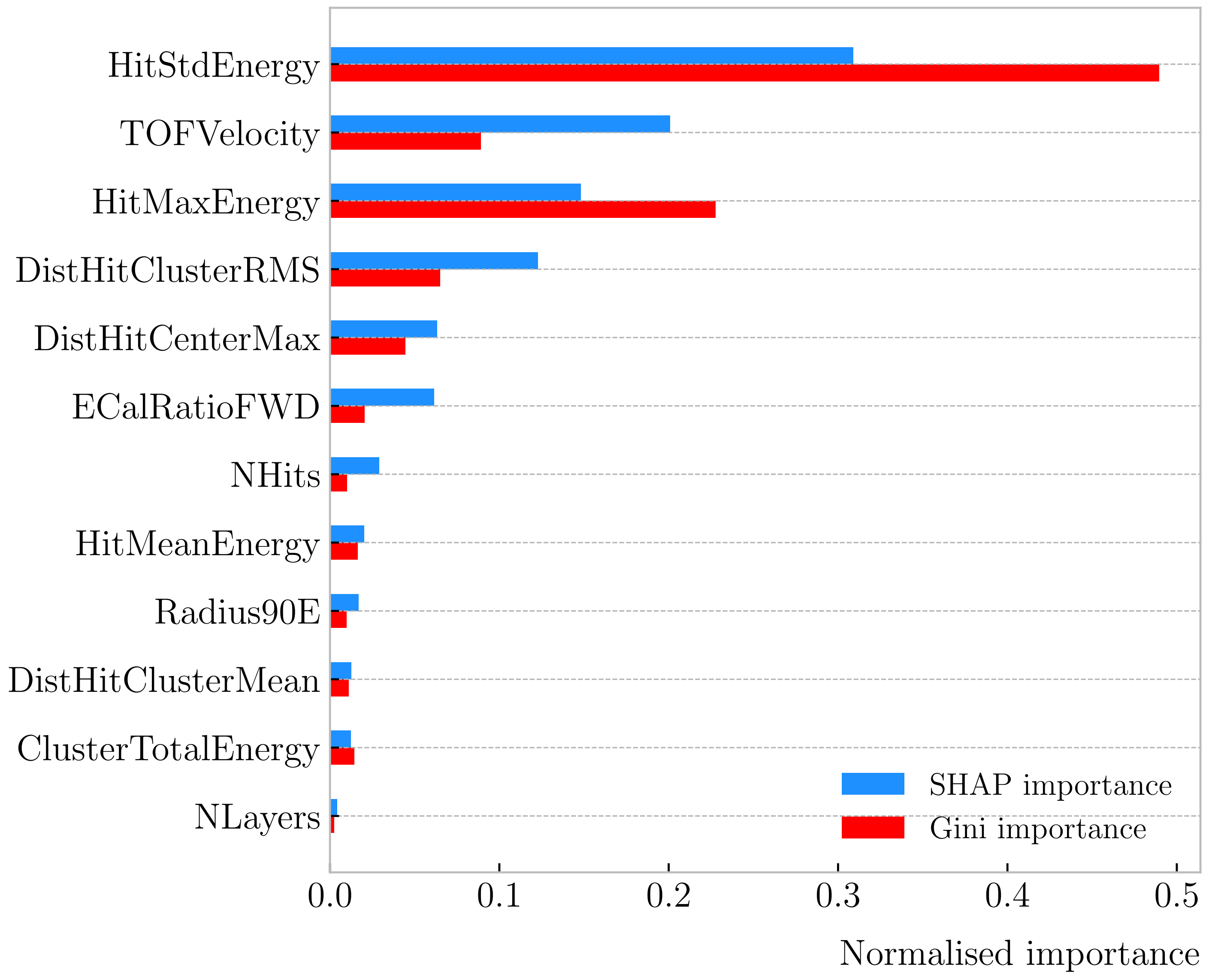


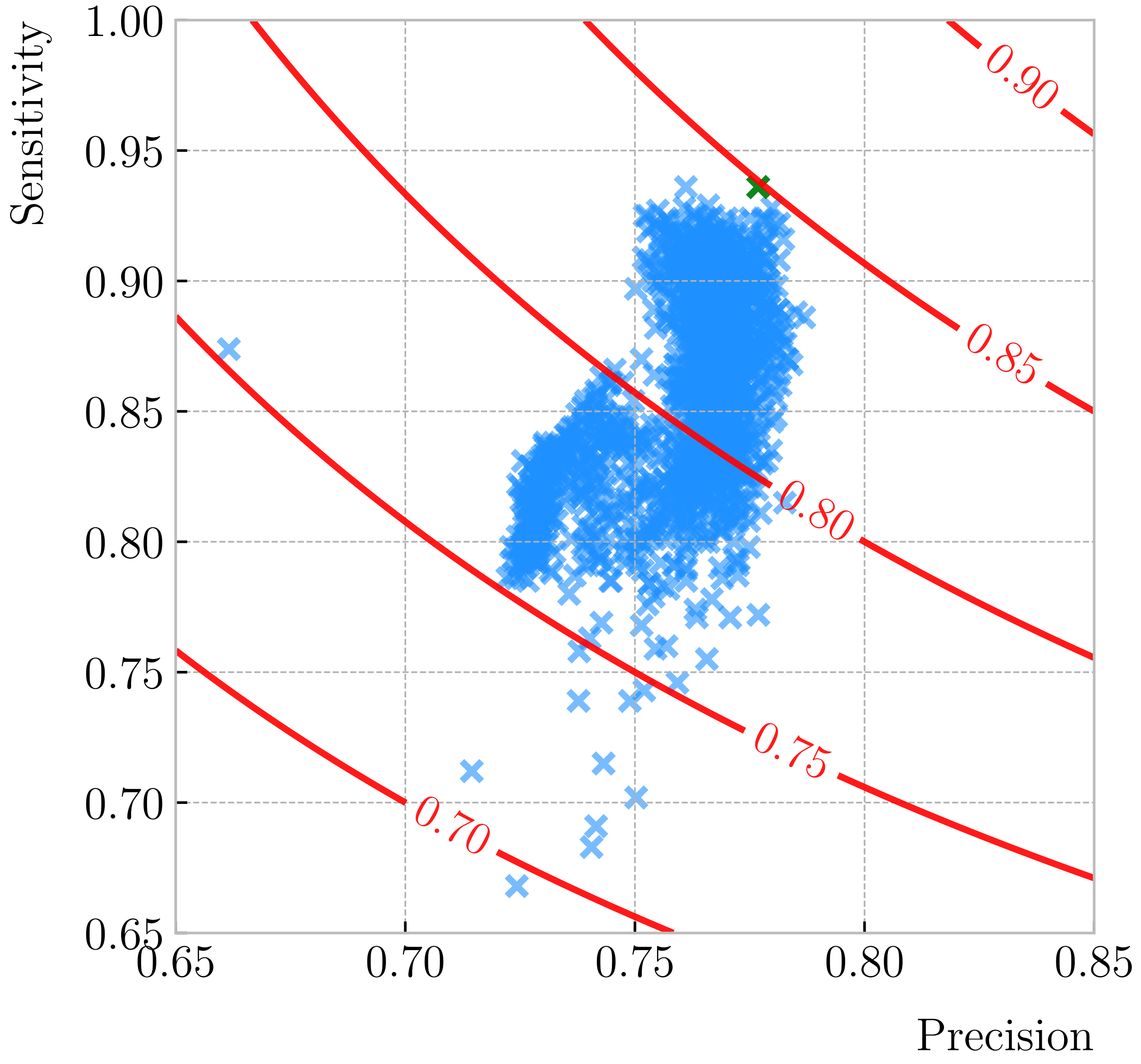
- ECal and MuID can provide additional information, as pion interactions will be more hadron-like.
- We can extract a number of variables that encapsulate this information.

BDT approach

- 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.



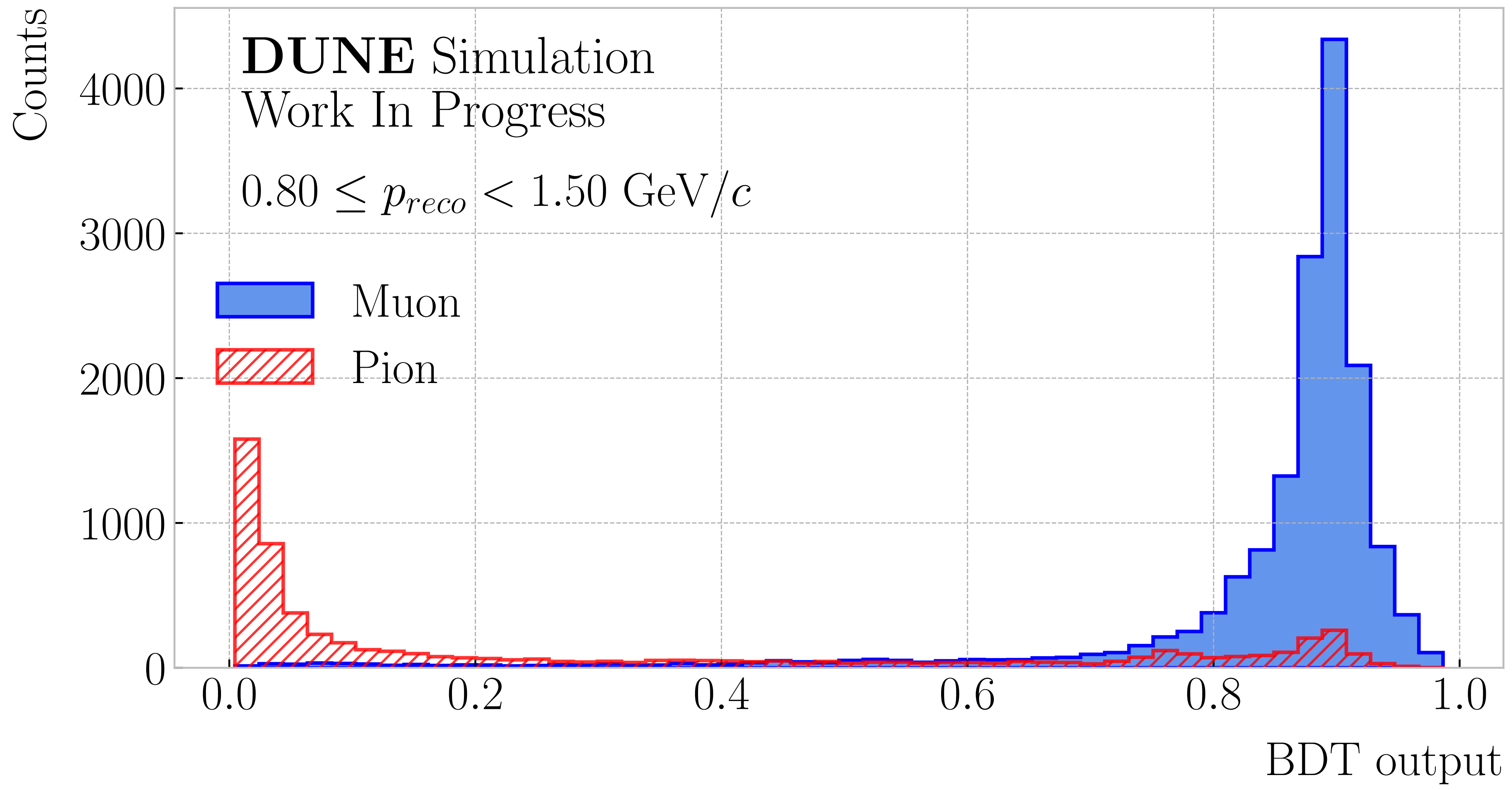


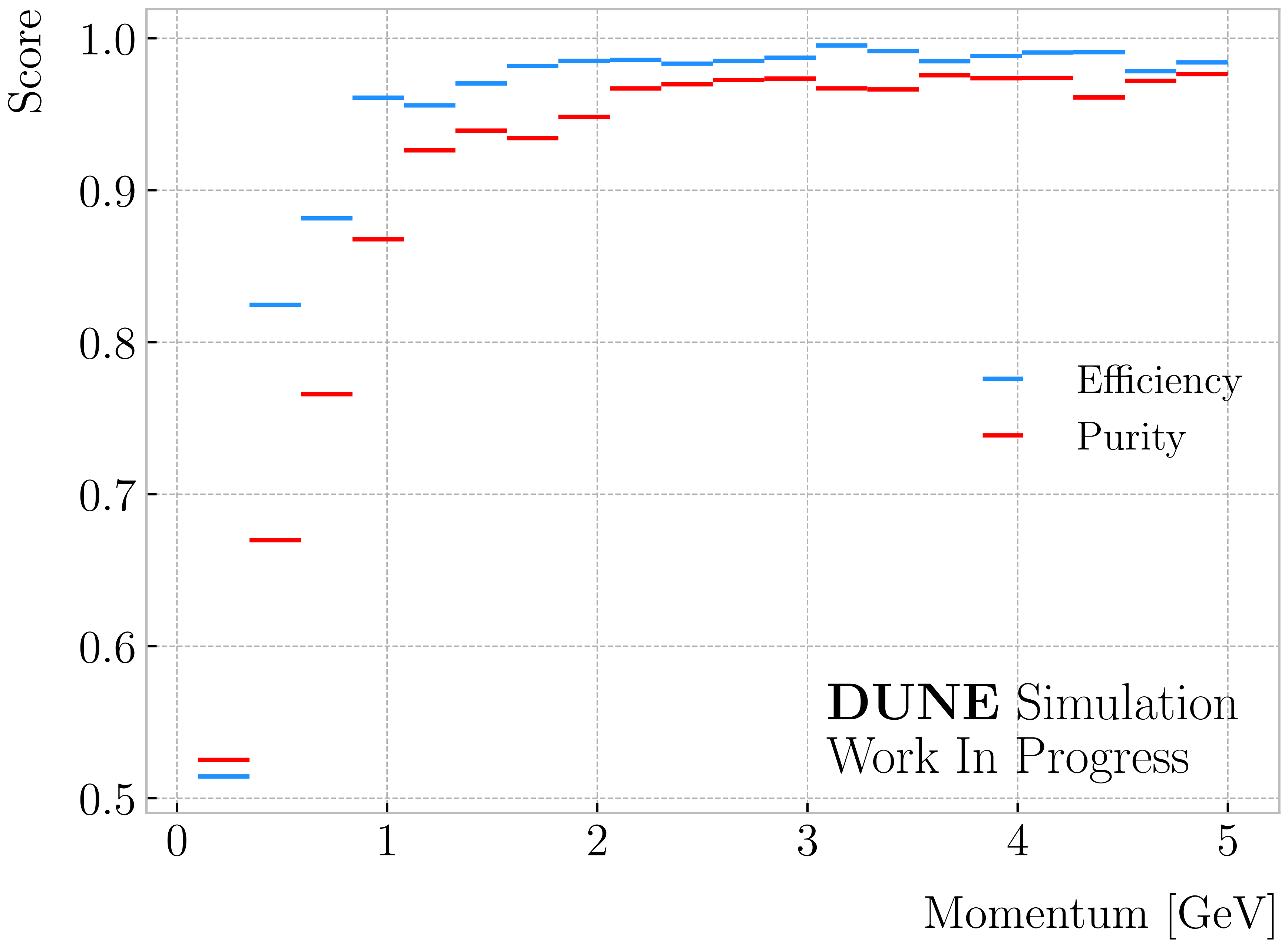


- Interactions change with energy, train different BDTs in a set of momentum bins.
- We studied the feature importance and optimised the hyperparameters for each BDT.

Muon selection performance

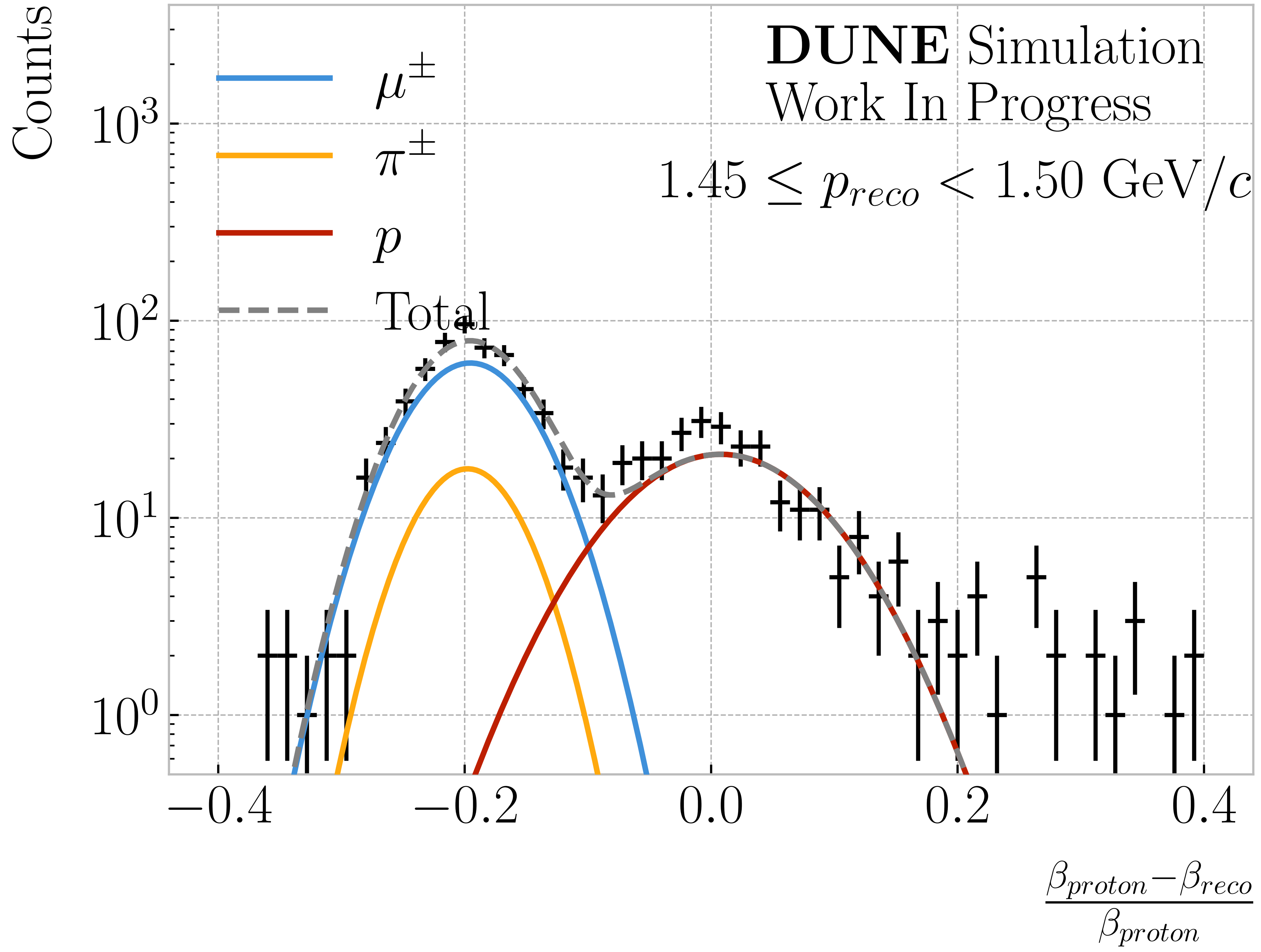
- The training data comes from single particle events, while the performance was assessed using FHC neutrino events.
- We achieve 95% purity in the track-by-track muon selection above $1\ \mathrm{GeV}/c$, can be complemented with dE/dx at low momentum.

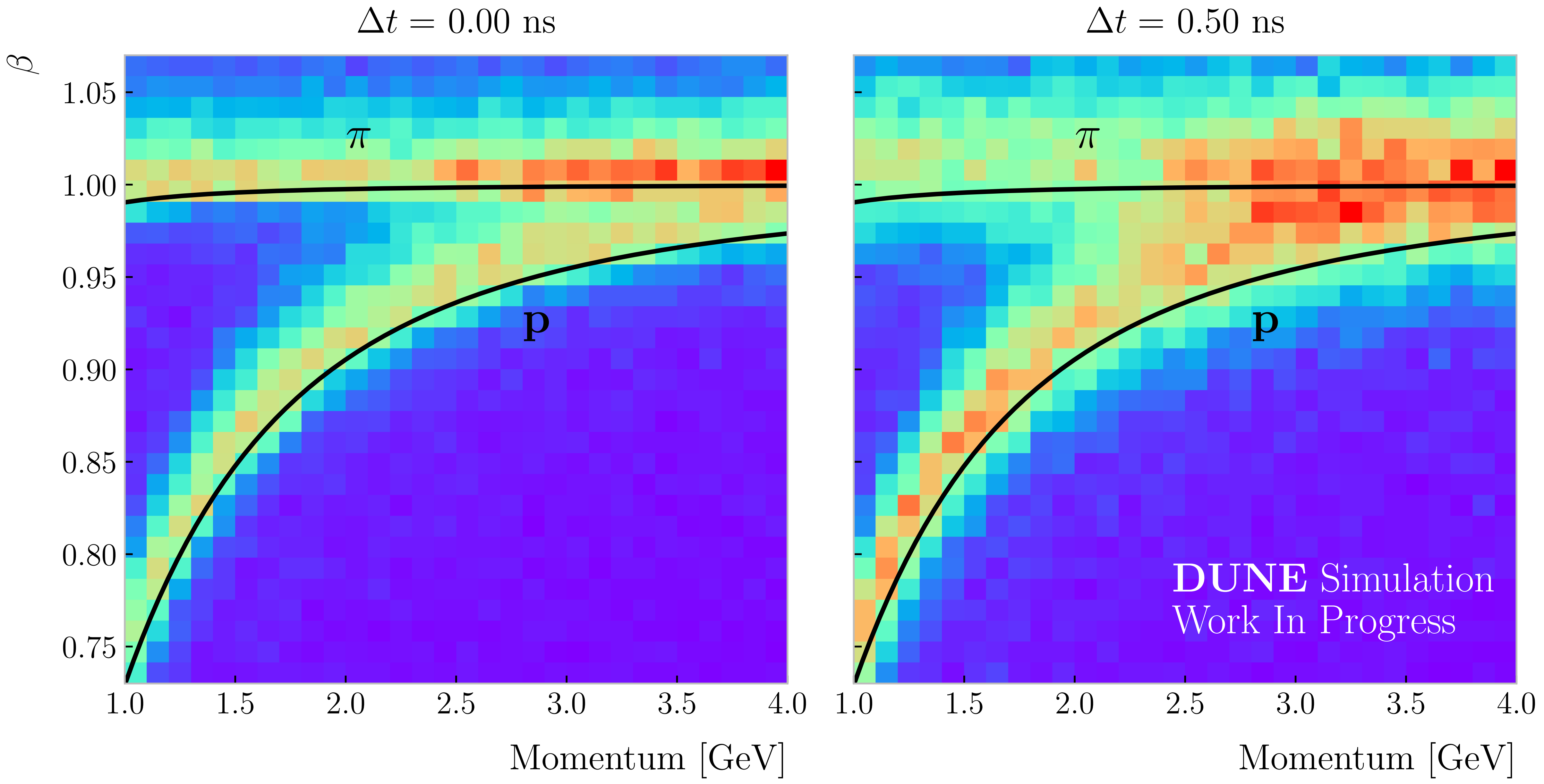




ECal Time-of-Flight

- A time-of-flight measurement with the inner layers of the ECal can be used for PID at higher momenta.

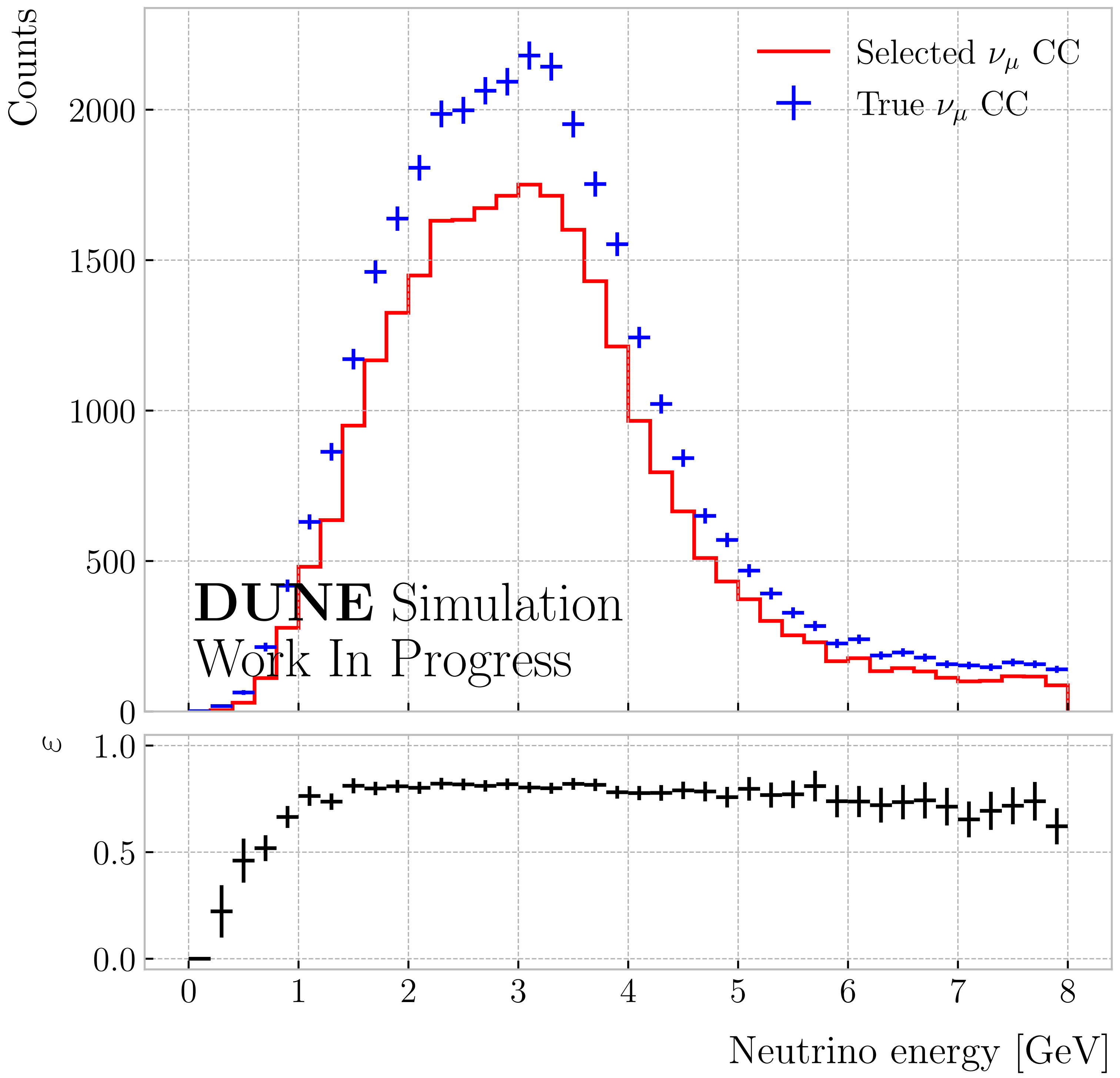


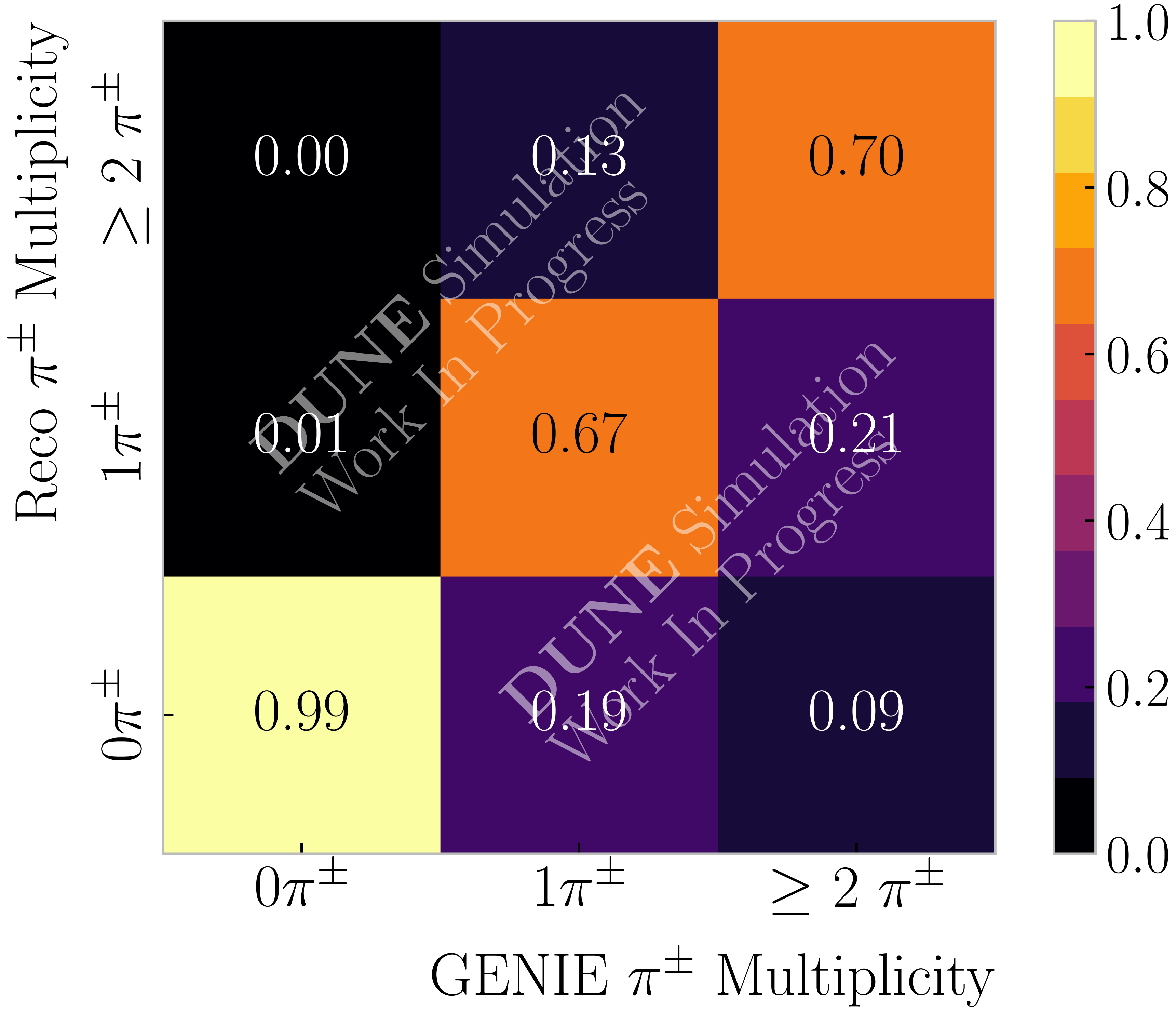


- Although resolution degrades fast with momentum, it allows for efficient proton selection up to 3.0 GeV$/c$.

Event selection

- The different PID approaches can be combined in order to cover different cases and energies.
- First analyses on their way to understand selection capabilities for the oscillation program.

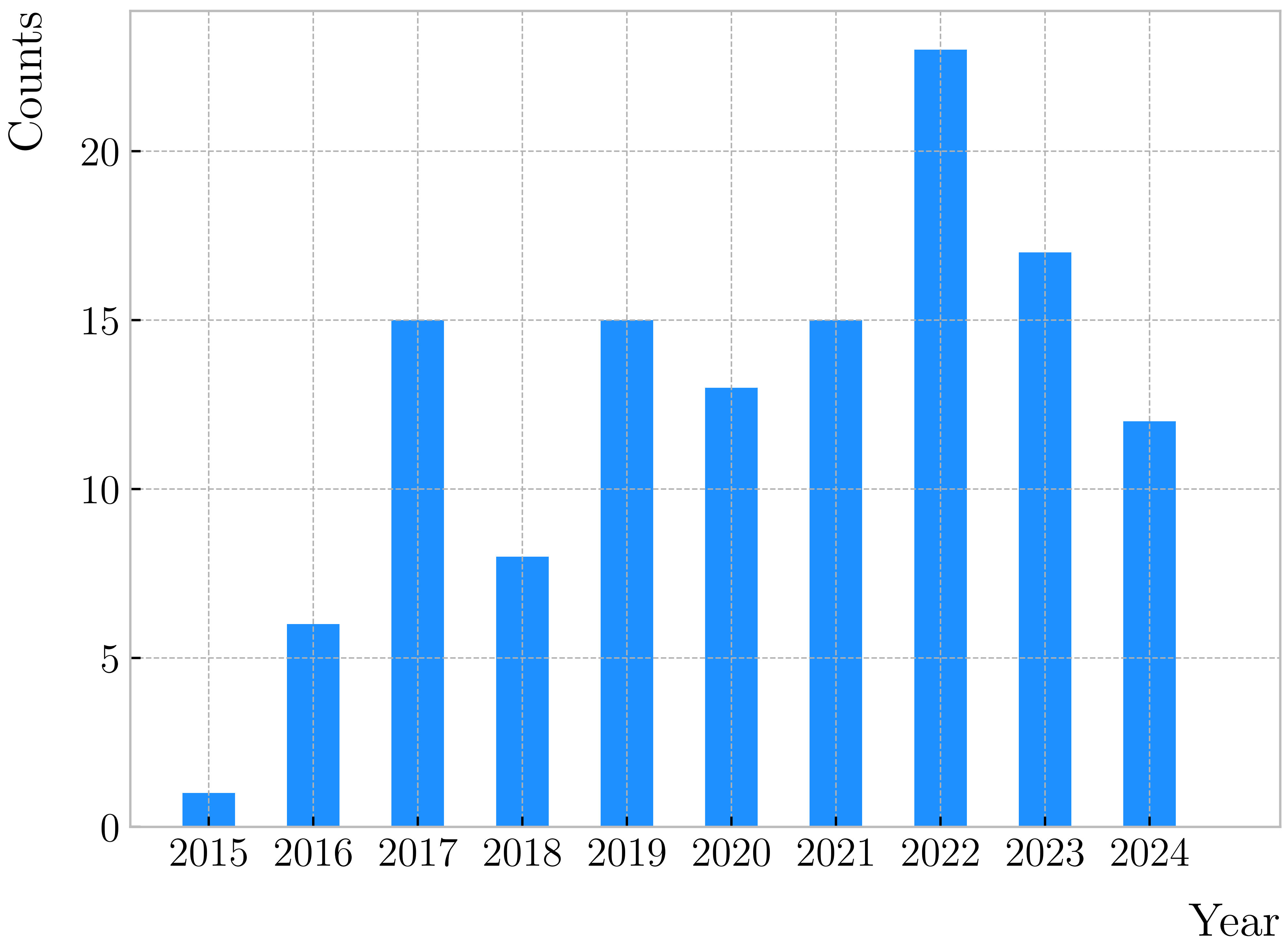




(<u>N</u>ew) connections between <u>Ex</u>periment and <u>T</u>heory

ND-GAr and BSM

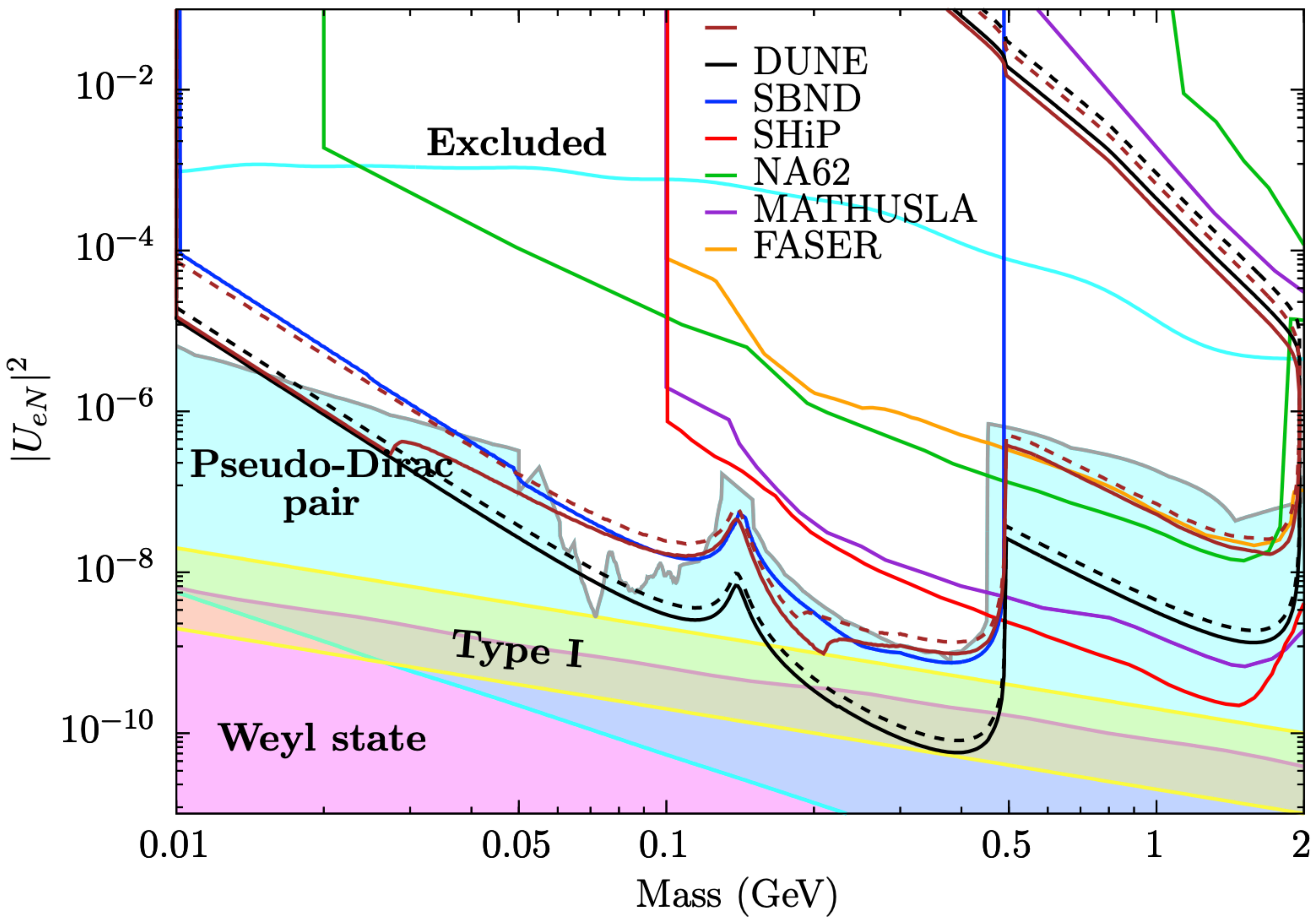
- The DUNE ND will sit next to the most powerful neutrino beam to date.
    - Privileged position to look for new physics.
- BSM searches strengthen the ND-GAr physics case.
- DUNE Phase II ND Workshop @ Imperial received lots of interest from the theory community.
- Searching on INSPIRE for “dune near detector” gives 125 papers since 2014 (published, subject phenomenology-HEP).



BSM phenomenology

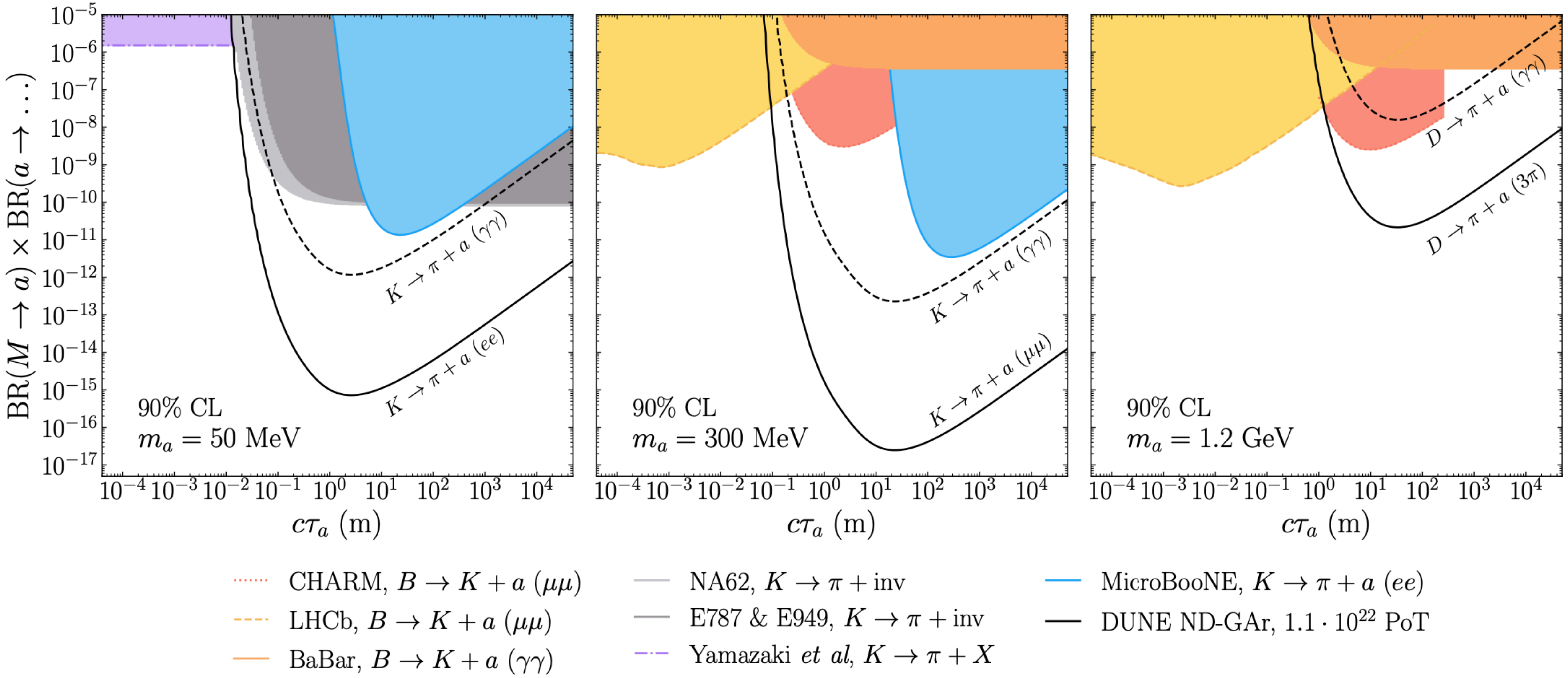
- The theory community has shown its interest in the BSM physics potential on ND-GAr.
  - Potential to reach into phase space predicted by type-I seesaw models (Pascoli et al).

arXiv:1905.00284



BSM phenomenology

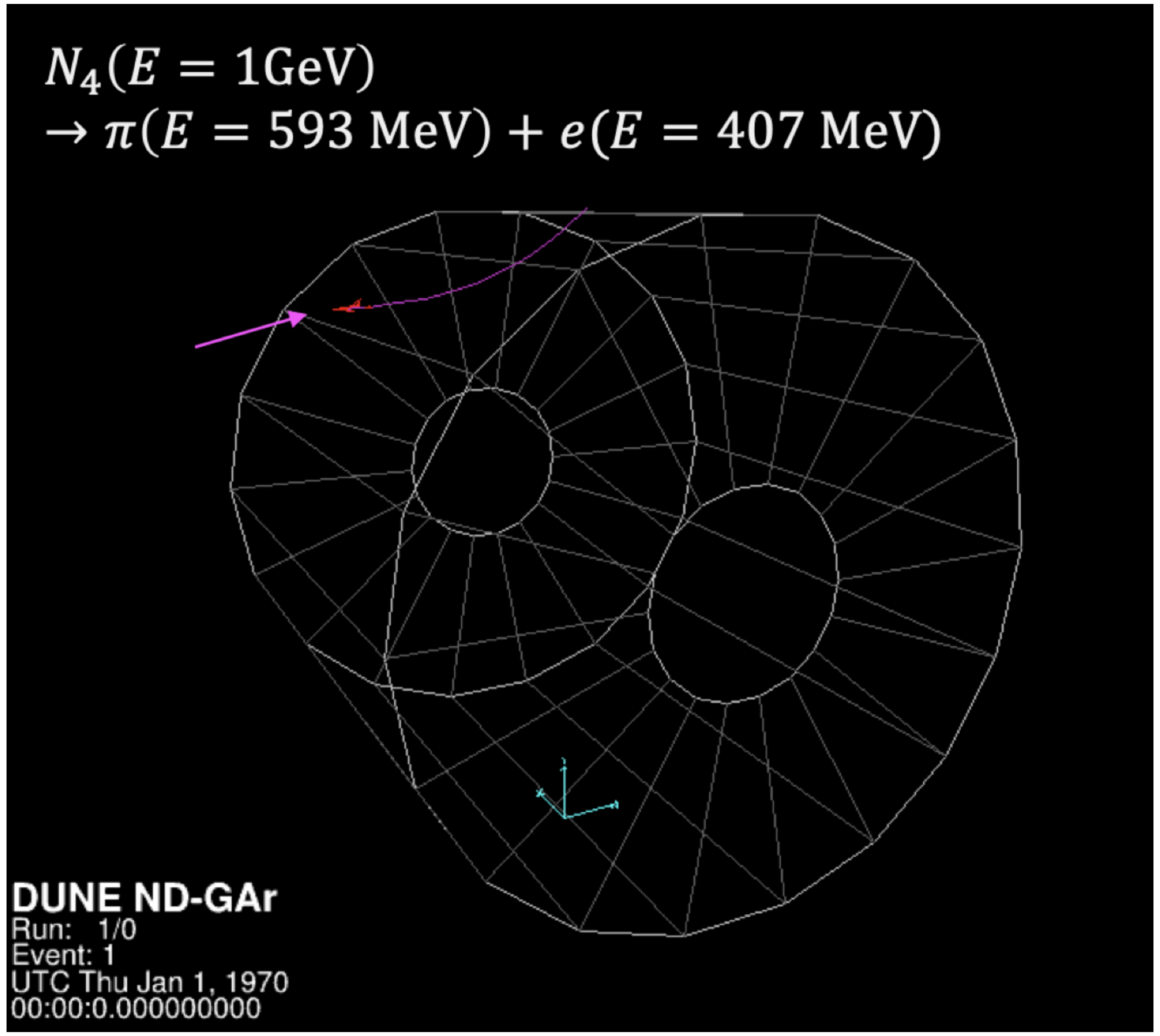
- The theory community has shown its interest in the BSM physics potential on ND-GAr.
  - Potential to reach into phase space predicted by type-I seesaw models (Pascoli et al).
  - Searches for LLPs, improve current limits up to one order of magnitude (Coloma et al).



arXiv:2309.06492

BeamHNL

- We need to re-evaluate our HNL sensitivities using end-to-end reconstruction.
- ND-GAr group is pursuing the integration of BeamHNL into its simulation and reconstruction.
  - GENIE module to generate long-lived particle events.
- Could help systematically explore the HNL phase space for multiple channels.
- First events generated, expect to use it in future analyses.

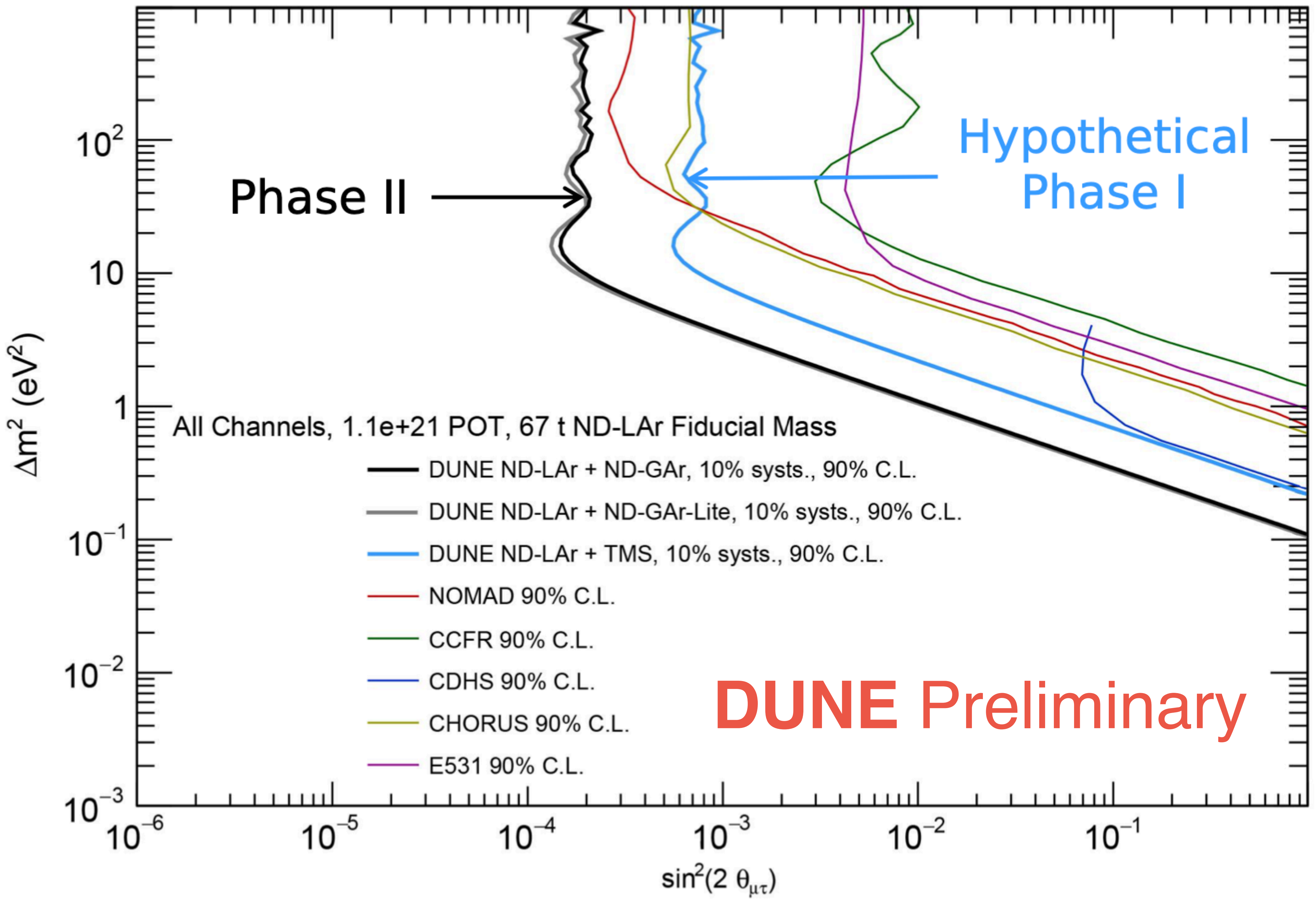

$N_4(E = 1\text{GeV})$
$\rightarrow \pi(E = 593\text{ MeV}) + e(E = 407\text{ MeV})$

Credit K.J. Plows and FML

Anomalous tau neutrino appearance

- Other promising analyses, like ν_τ appearance from short-baseline oscillations driven by sterile neutrino mixing.

- The excellent reconstruction in ND-GAr for tau decay into muons at high energies ($E_\mu \geq 6\ \mathrm{GeV}$) enhances the reach of DUNE for Phase II.



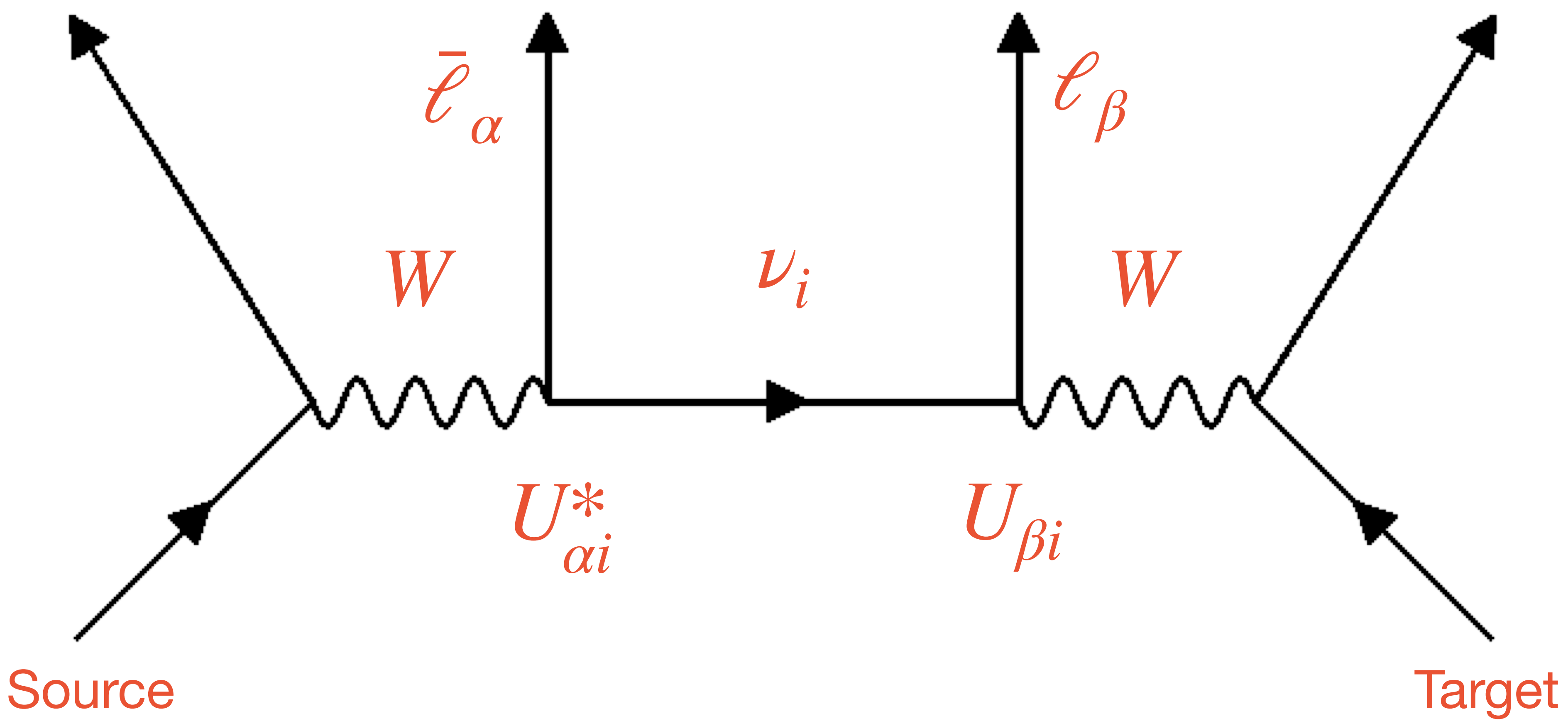
Credit H. Razafinime

Conclusions

- DUNE will give a definitive answer to the neutrino mass hierarchy, θ_{23} and δ_{CP} questions, and take neutrino oscillation physics to a precision era.
- ND-GAr is a key component of DUNE, it's needed to reach its ultimate physics goals.
- The ND-GAr simulation and reconstruction software is in a mature state, ready to use in production soon.
  - Current goal is to check impact on oscillation physics with full reconstruction.
- The DUNE ND, and ND-GAr in particular, offers plenty of BSM opportunities.
  - Perfect ground for connections between theorists and experimentalists.

Backup slides

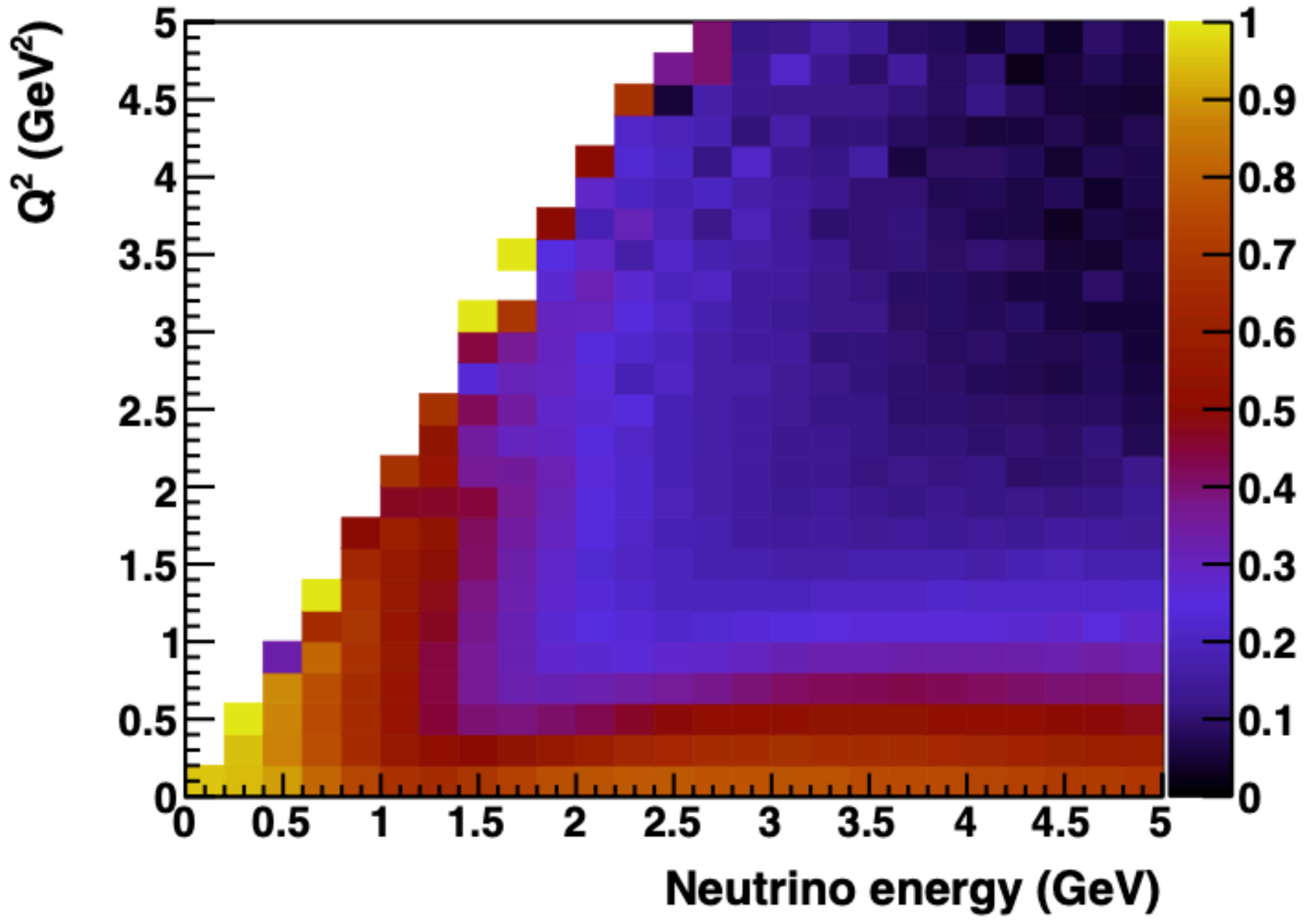
Neutrino oscillations



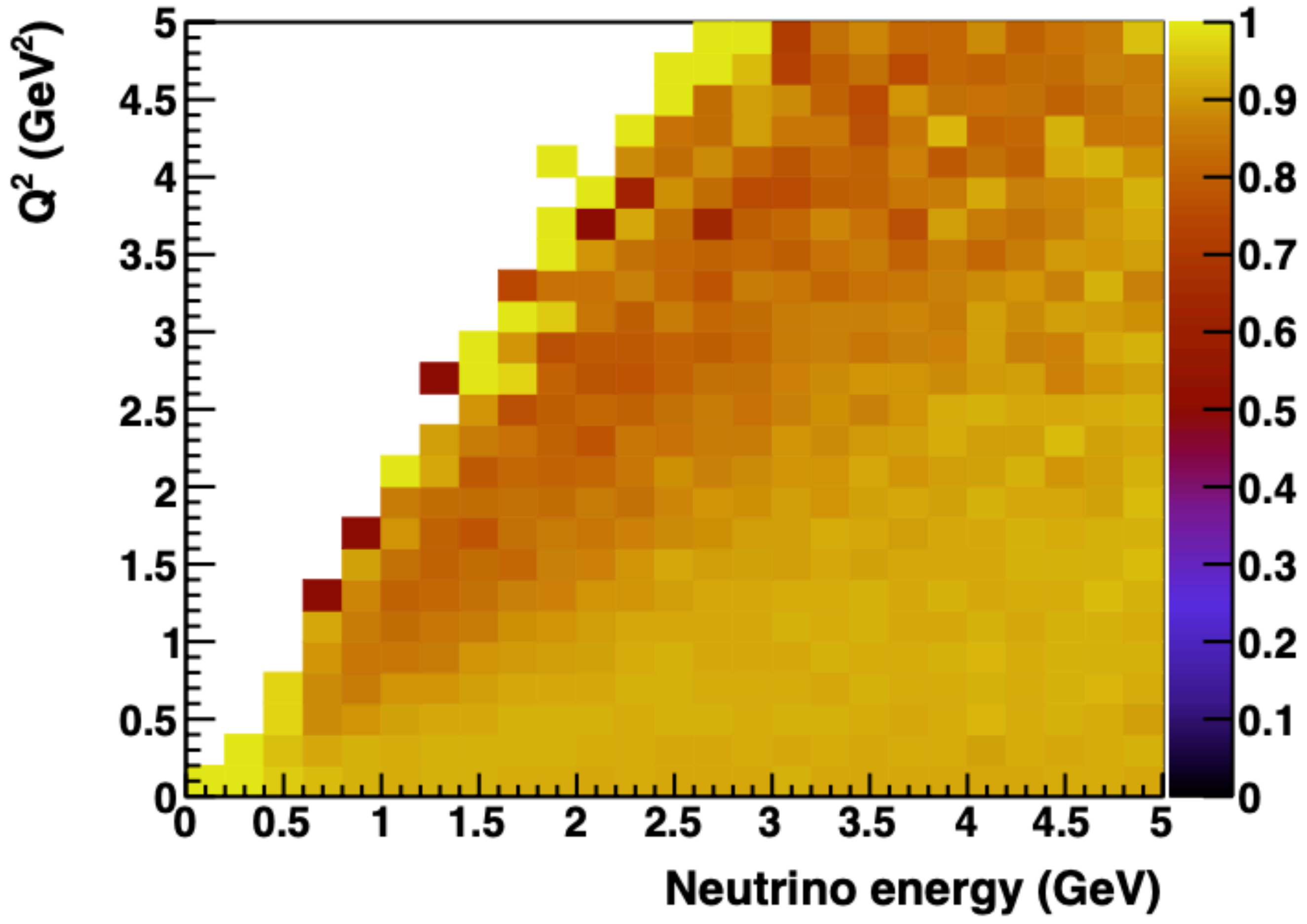
ND-GAr requirements

- 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.

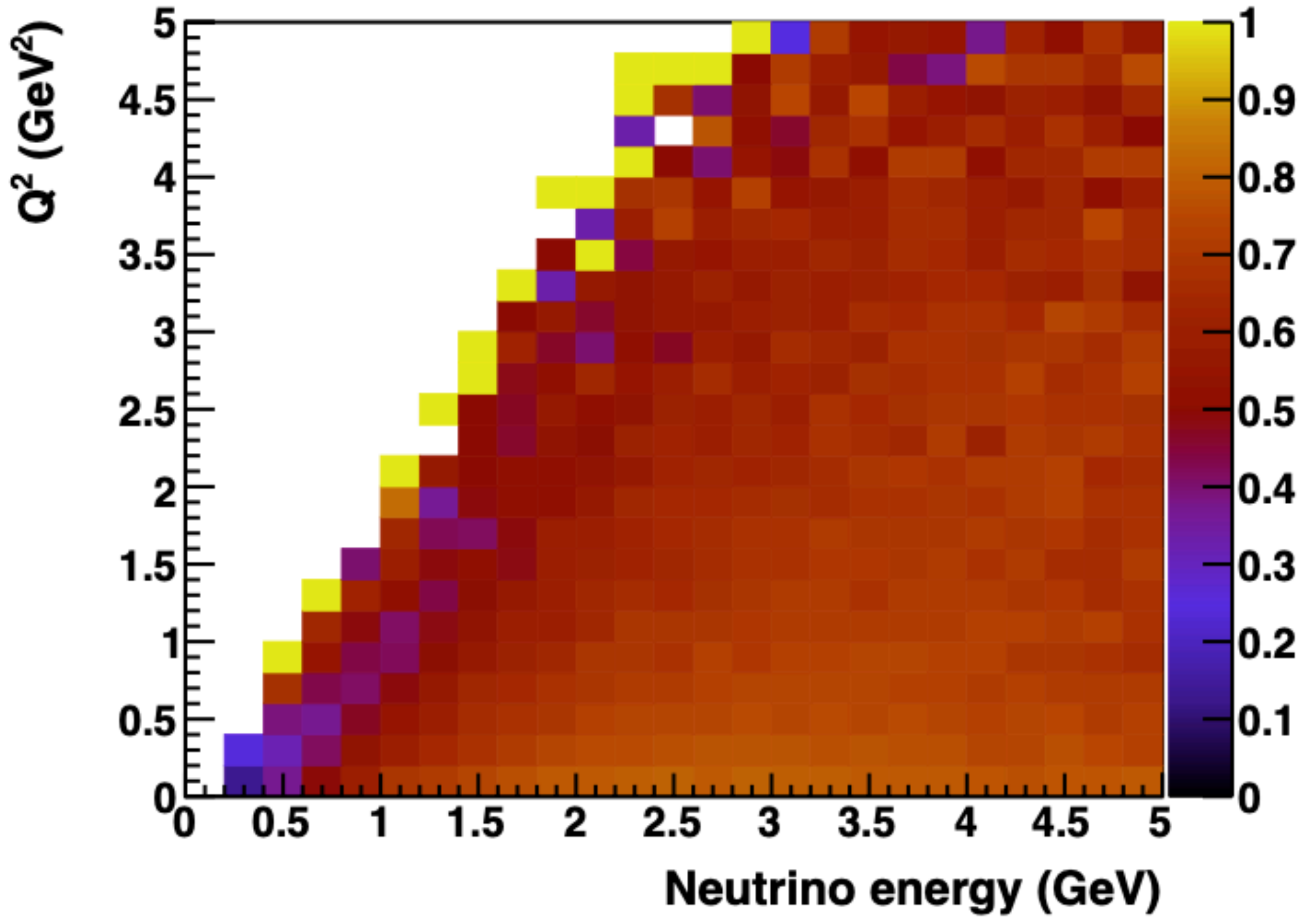
ND-LAr



ND-GAr

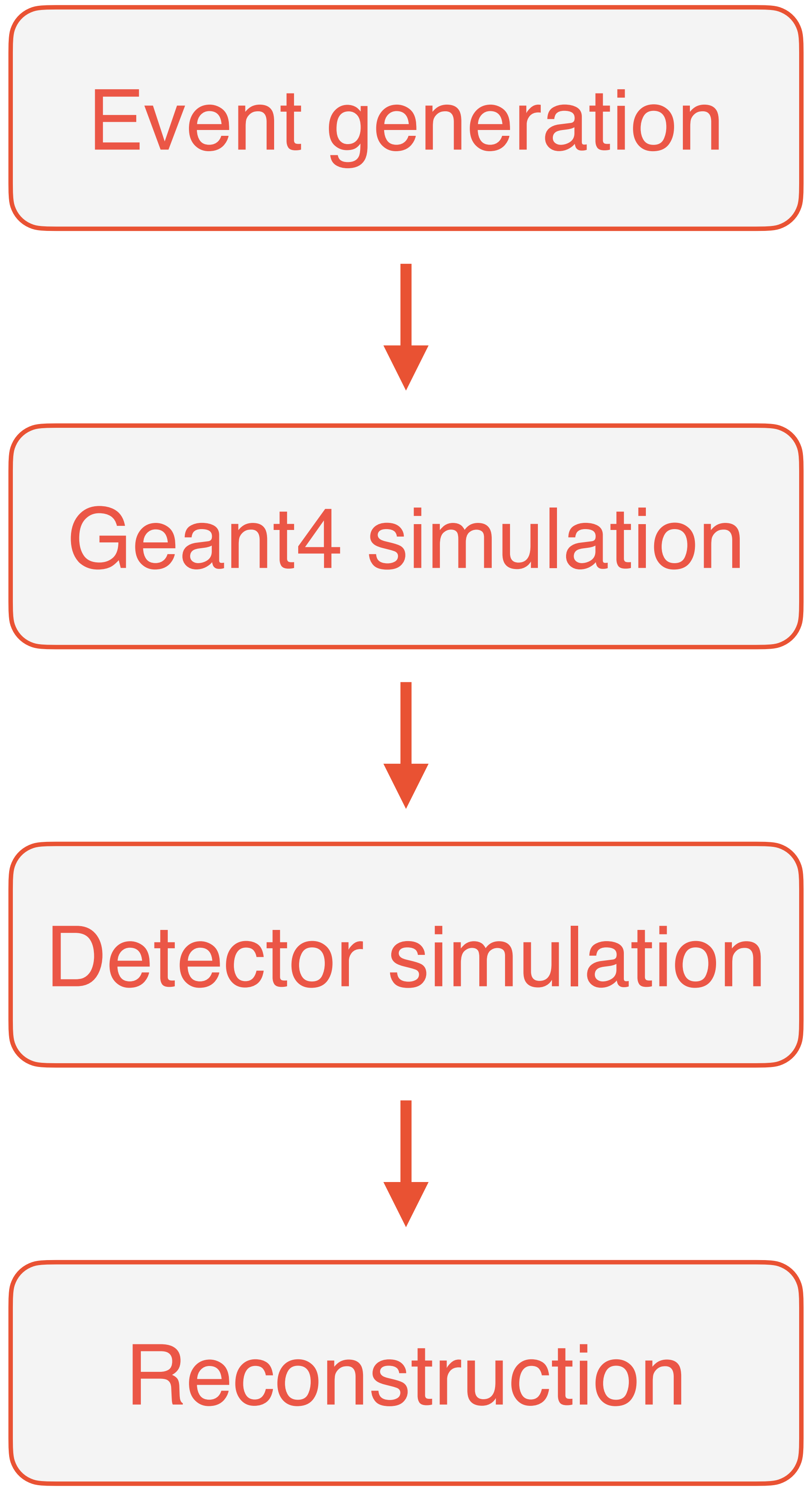


FD-HD



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.



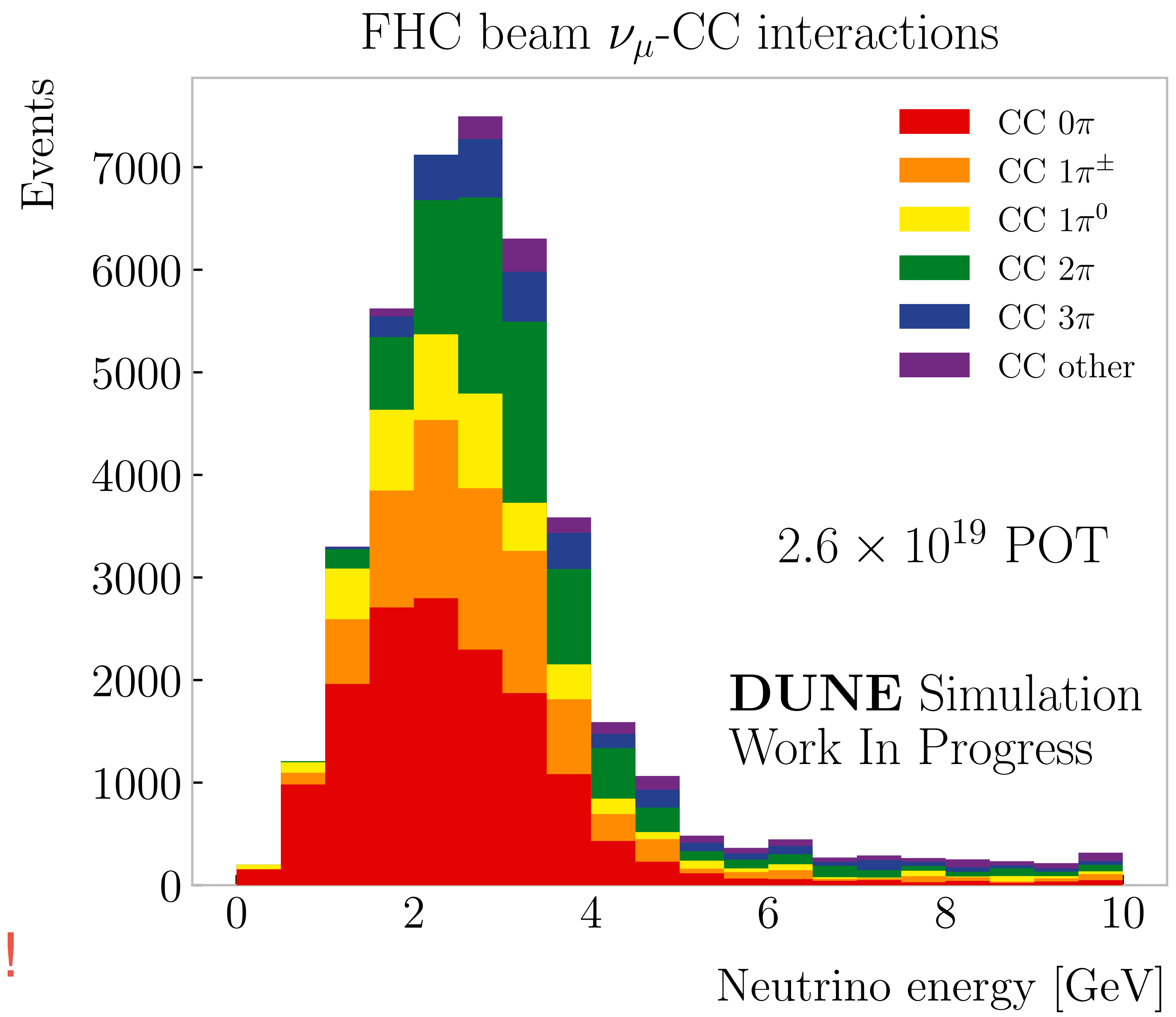
General generation-simulation-reconstruction workflow

ND-GAr and pions

- 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.

- We **need a reliable PID** able to identify pions with a high purity and across a broad energy range.

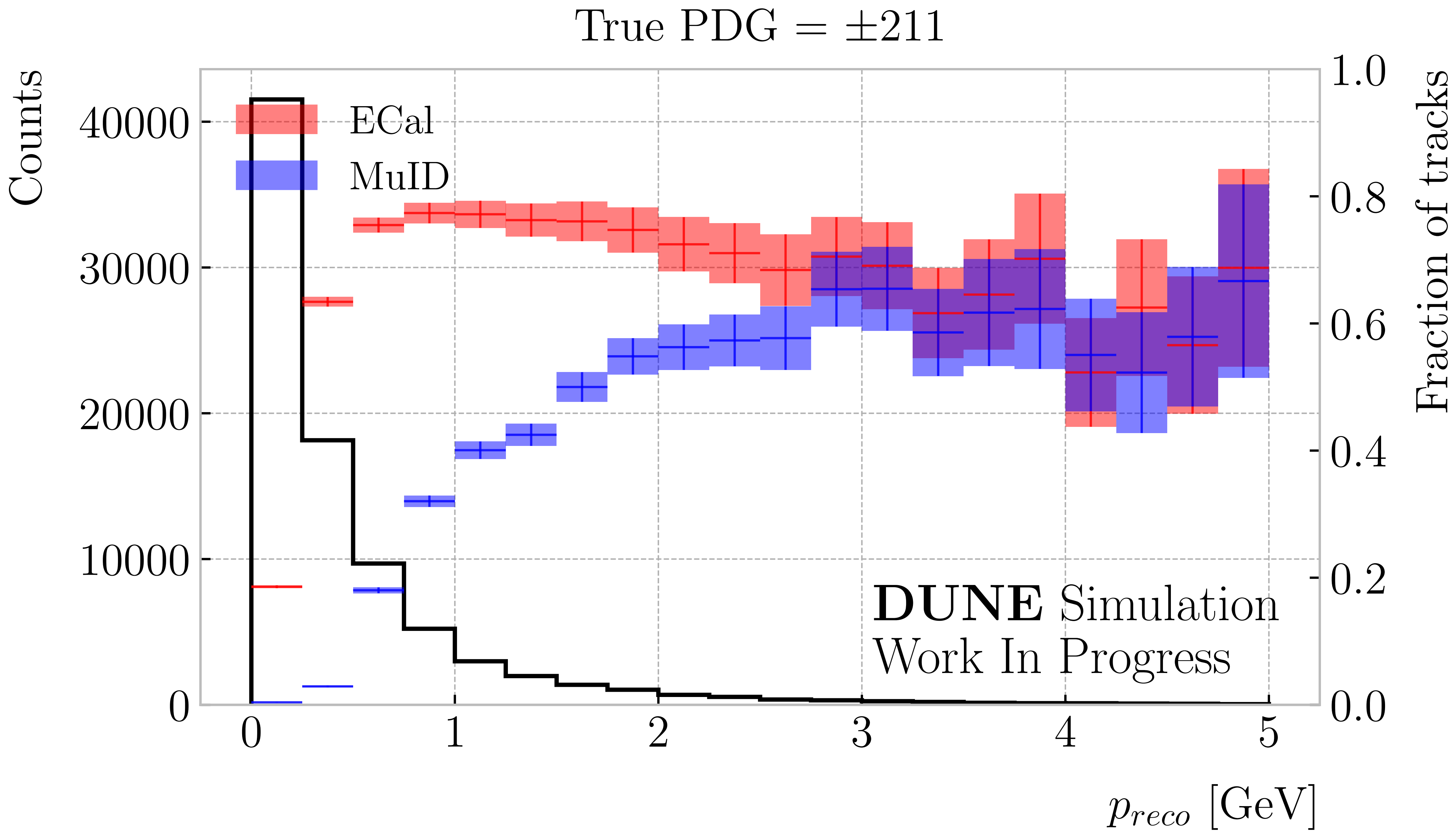
- **Current** reconstruction provides **low-level reconstruction** objects (tracks, clusters, …), now we need to **develop the high-level reconstruction** (PID, energy reconstruction, flavour estimation, …).



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.