Introduction on neutrino experiment workflow with emphasis on challenges

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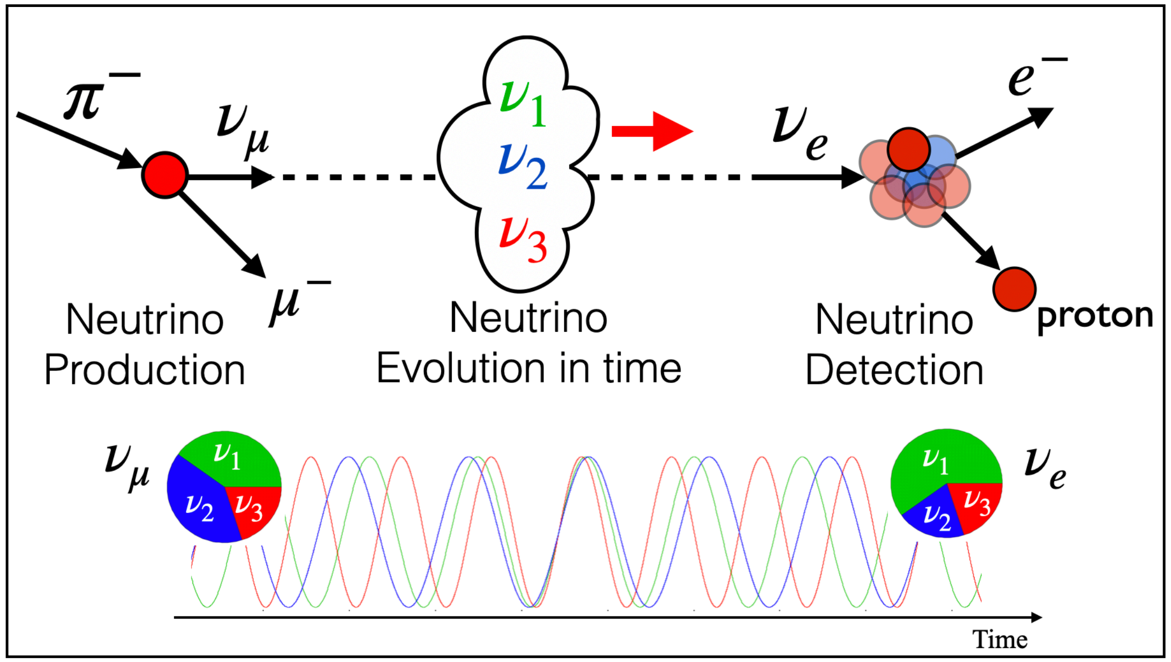
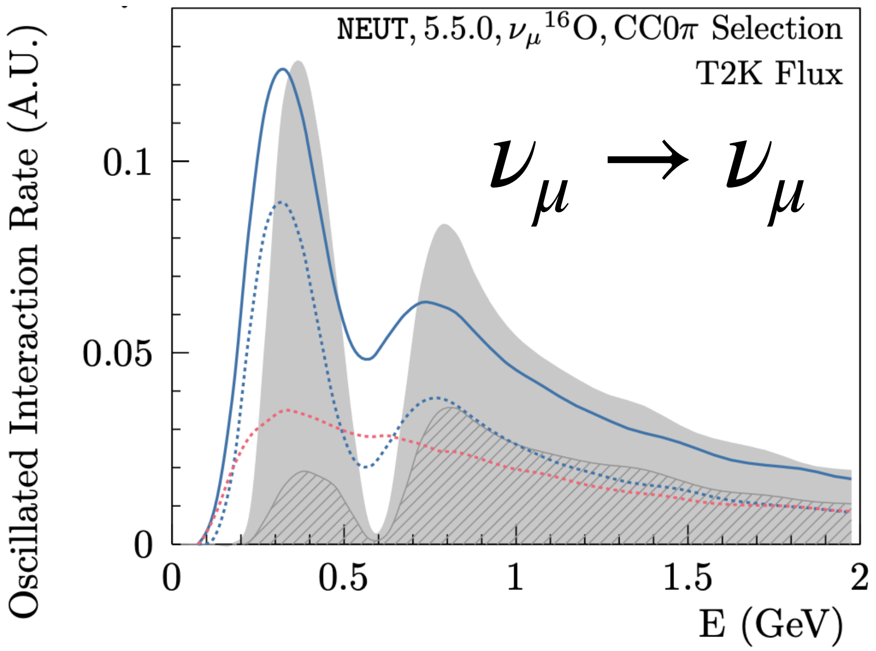
IPA Machine Learning Workshop

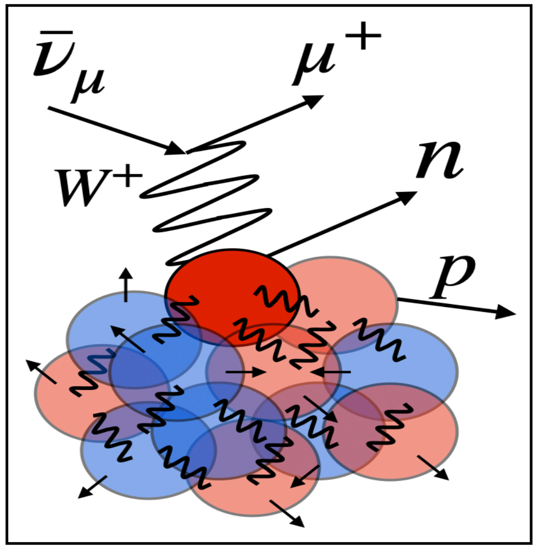
21st of March 2023

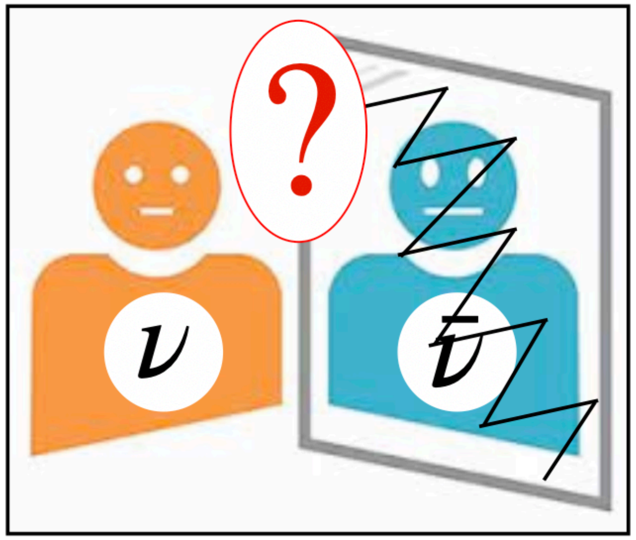
Physics with Accelerator Neutrinos (in a nutshell)

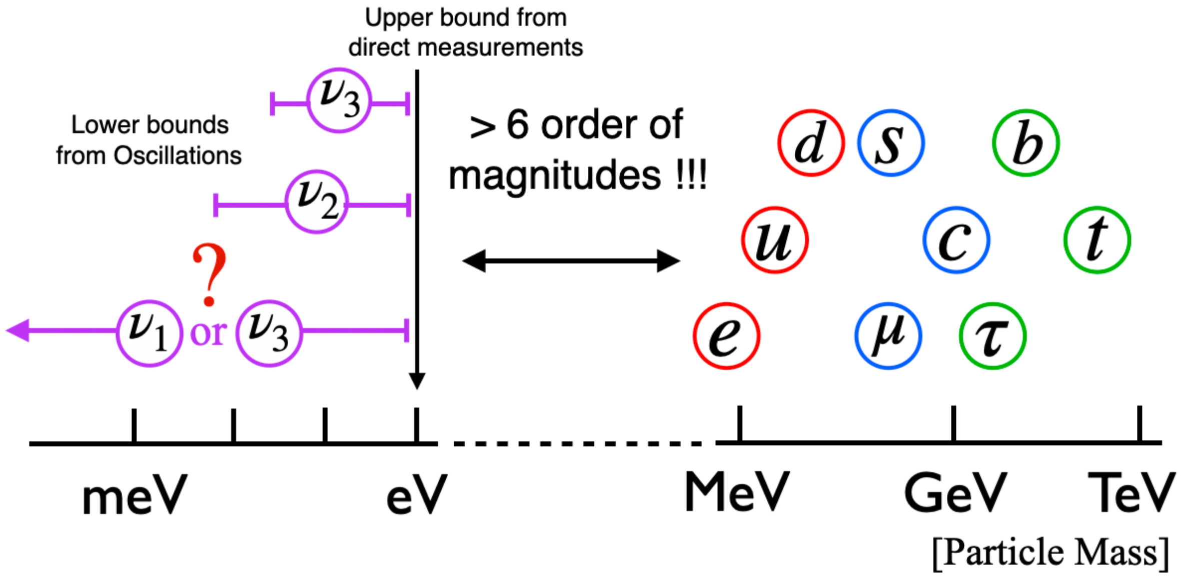
- Neutrinos (ν's) are produced by collisions of accelerated protons (10's GeV) on solid targets (e.g. graphite) and detected by massive particle detectors
- Search for violation of CP symmetry in ν oscillations, new sterile ν states, etc.

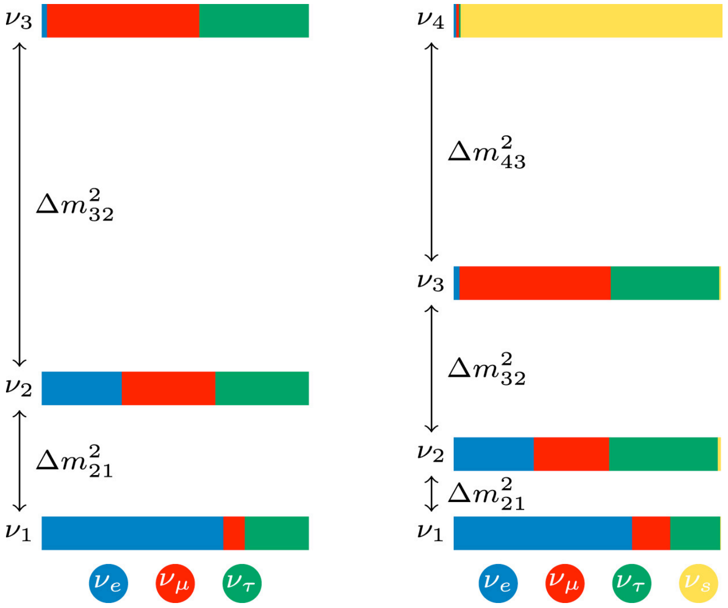








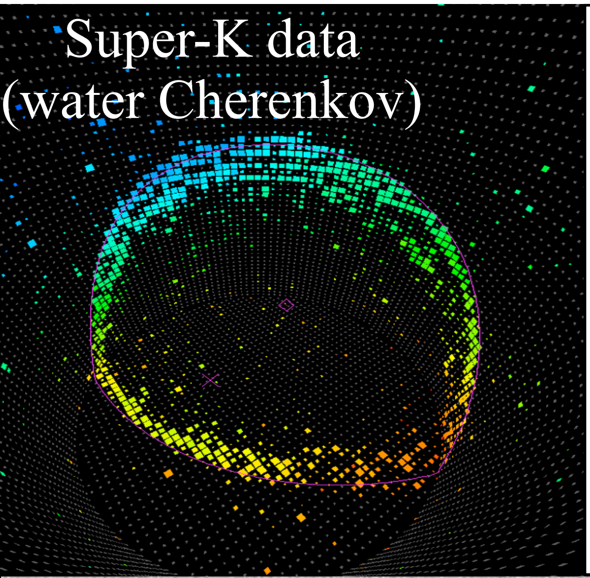


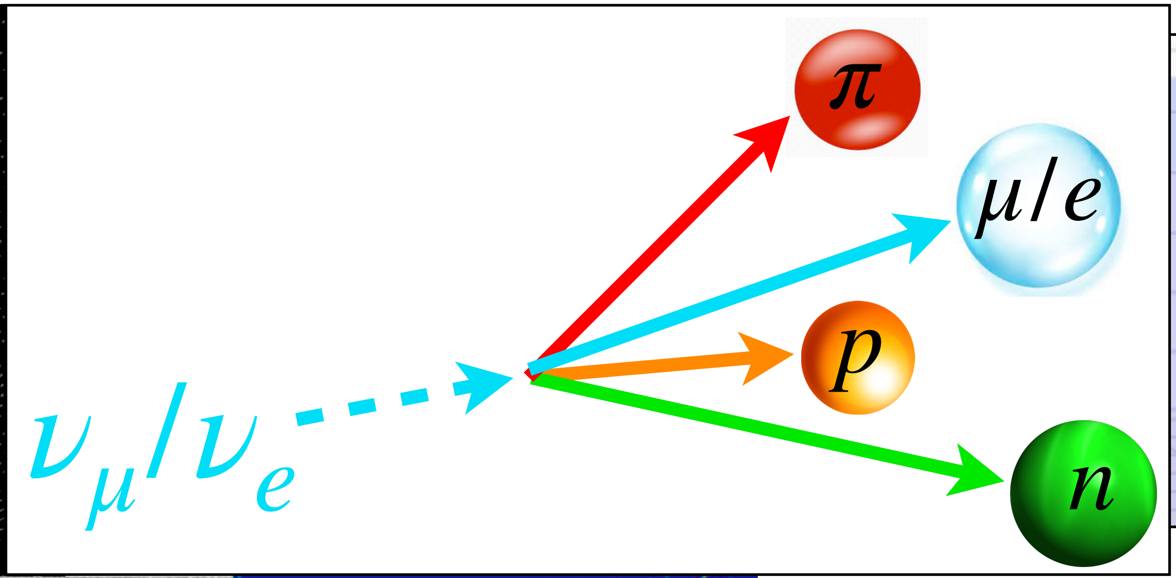


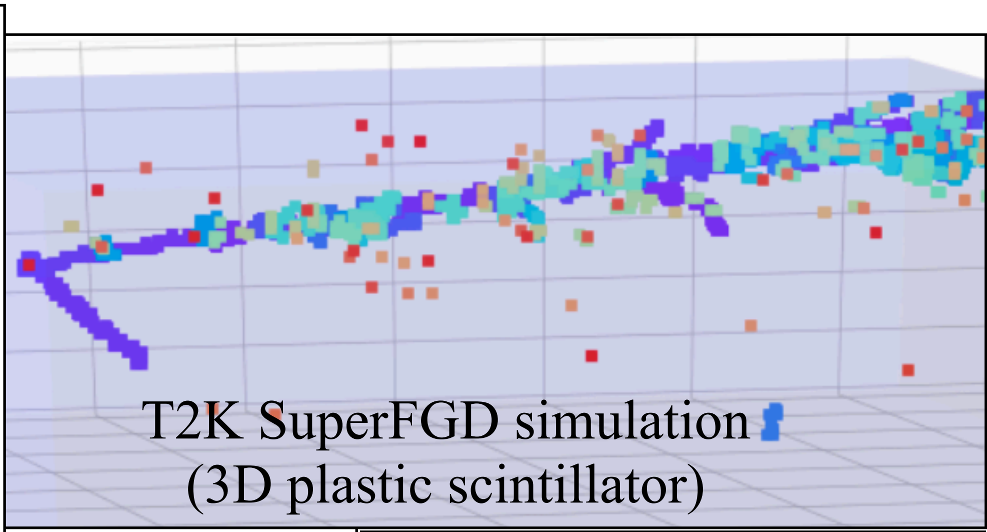
Detection of Accelerator Neutrinos

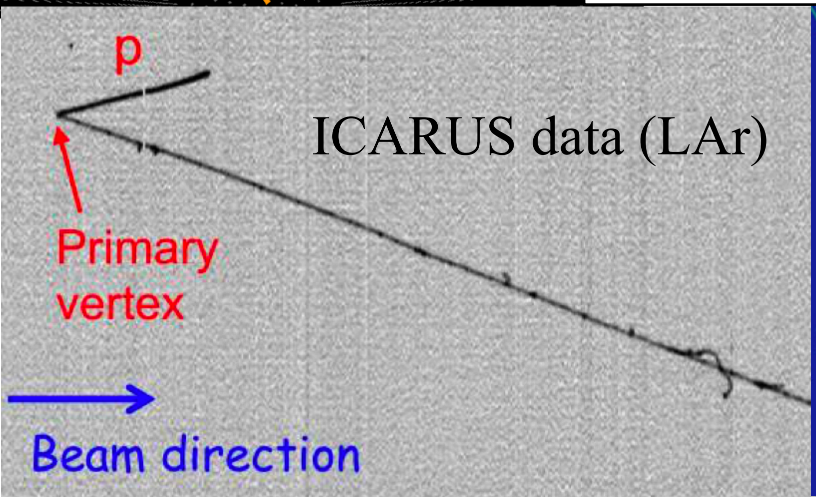
- Neutrinos are neutral ⇒ detect charged particles produced by ν interactions
- Several detector technologies: Cherenkov light, liquid argon time projection chamber (LArTPC), segmented plastic scintillator, and multi-detector systems

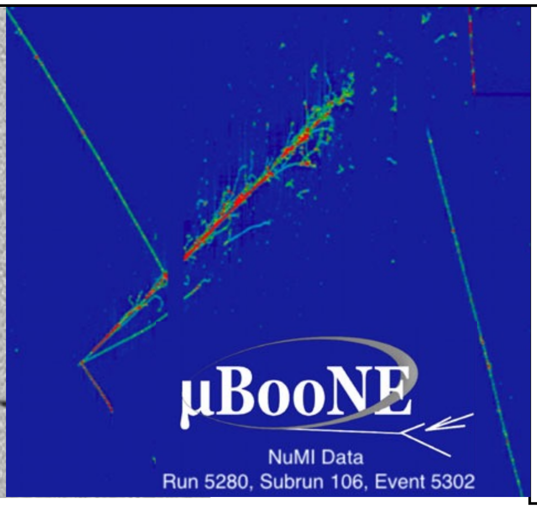
⇒ Our focus today is on *"imaging" neutrino detectors*

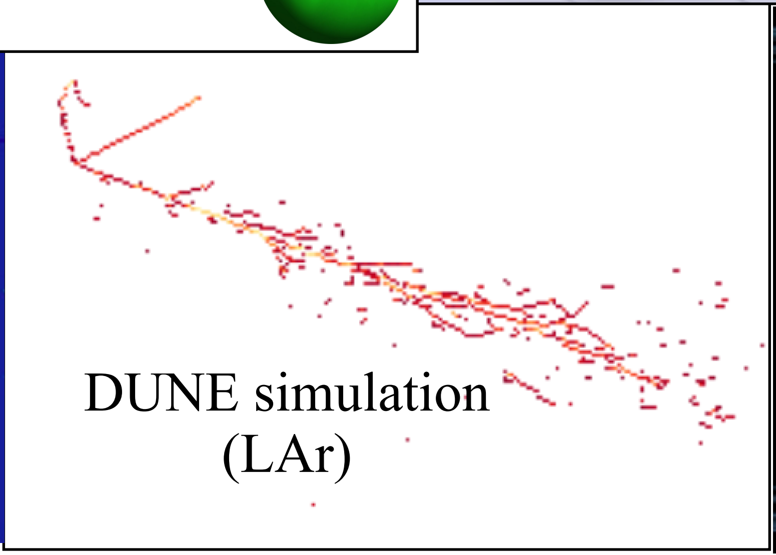

Super-K data (water Cherenkov)

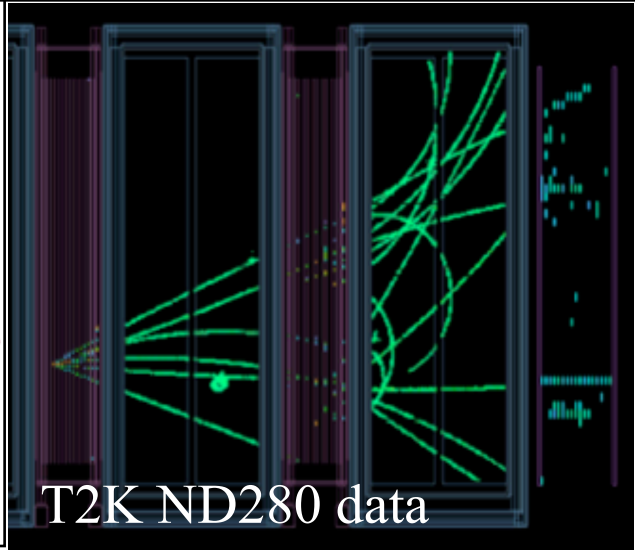



T2K SuperFGD simulation (3D plastic scintillator)


ICARUS data (LAr)

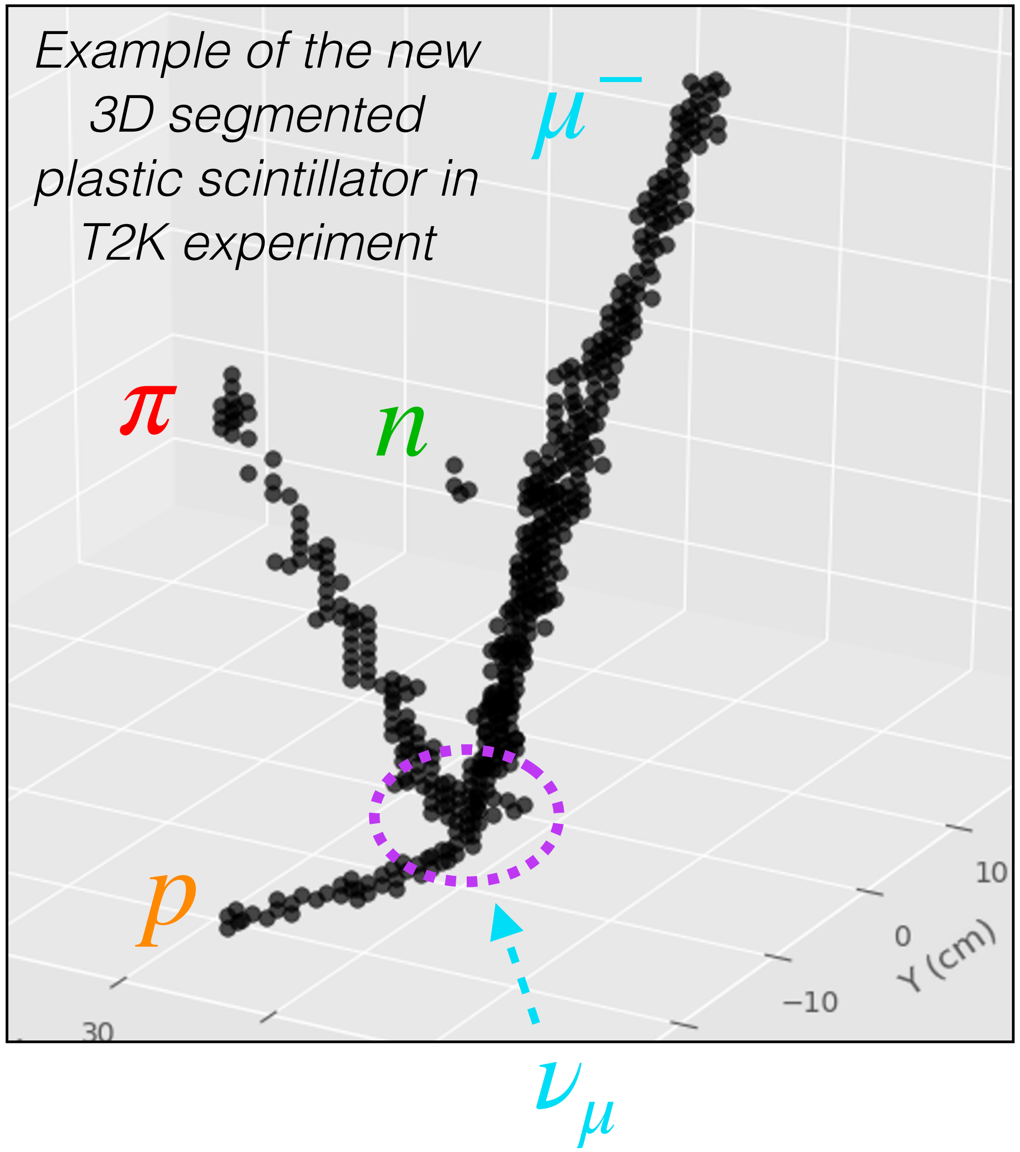



DUNE simulation (LAr)


T2K ND280 data

Detection of Accelerator Neutrinos

- Neutrinos interact weakly hence experiments require massive detectors (from a few tonnes to several kilotons) to collect enough data
  - ✦ A compromise between the detector mass and the tracking resolution (i.e. # of readout channels) is necessary


Example of the new 3D segmented plastic scintillator in T2K experiment

A. Precisely identify and reconstruct the kinematics of outgoing lepton (muon or electron), pions, protons, neutrons

- characteristic patterns for different particles

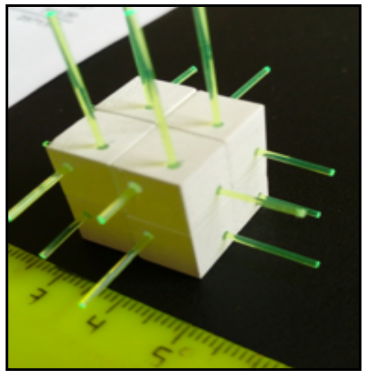
B. “Invisible” particles deposit a cluster of energy around the ν interaction vertex (in jargon “vertex activity”)

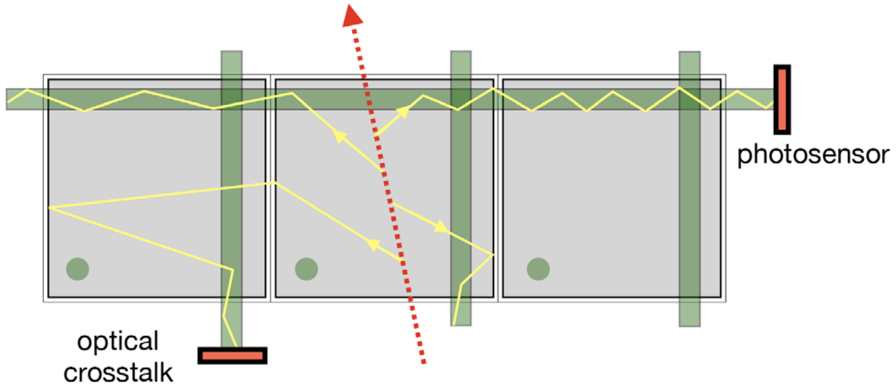
The goals is to identify the type of neutrino, identify the final state topology and reconstruct the kinematics of the interaction

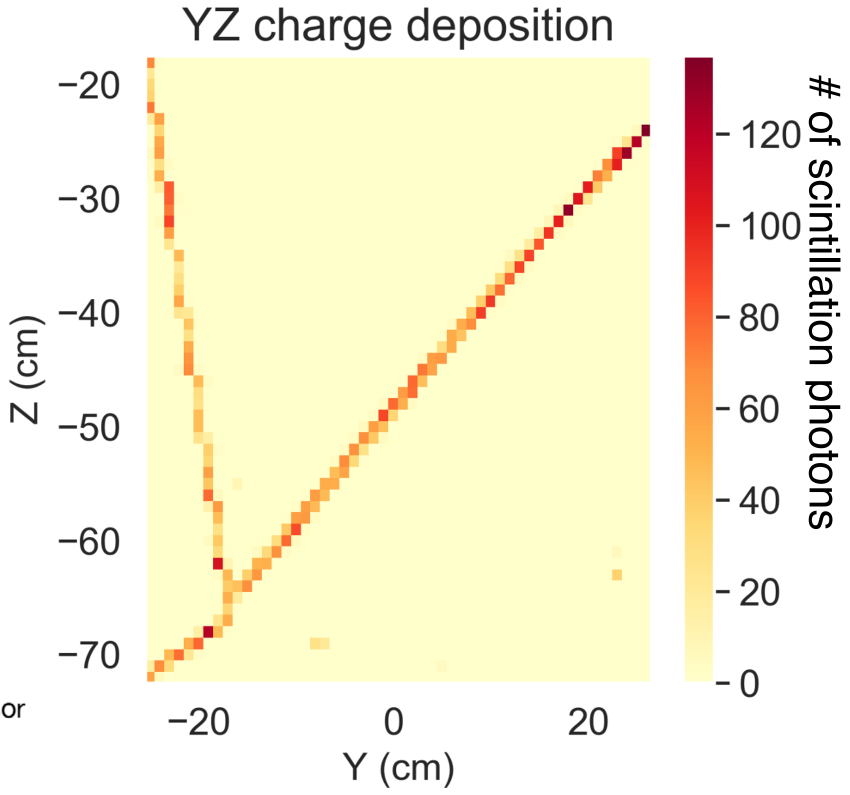
→ high dimensional problems !

What information is stored in a neutrino image

Similar chain can be applied to LArTPC







Charged particles deposit energy (E_{loss}) produce scintillation light in each readout channel (“hit”) and collected on the readout view

→ # of scintillation photons

→ photon time of arrival

Only “traditional” analysis methods in this talk

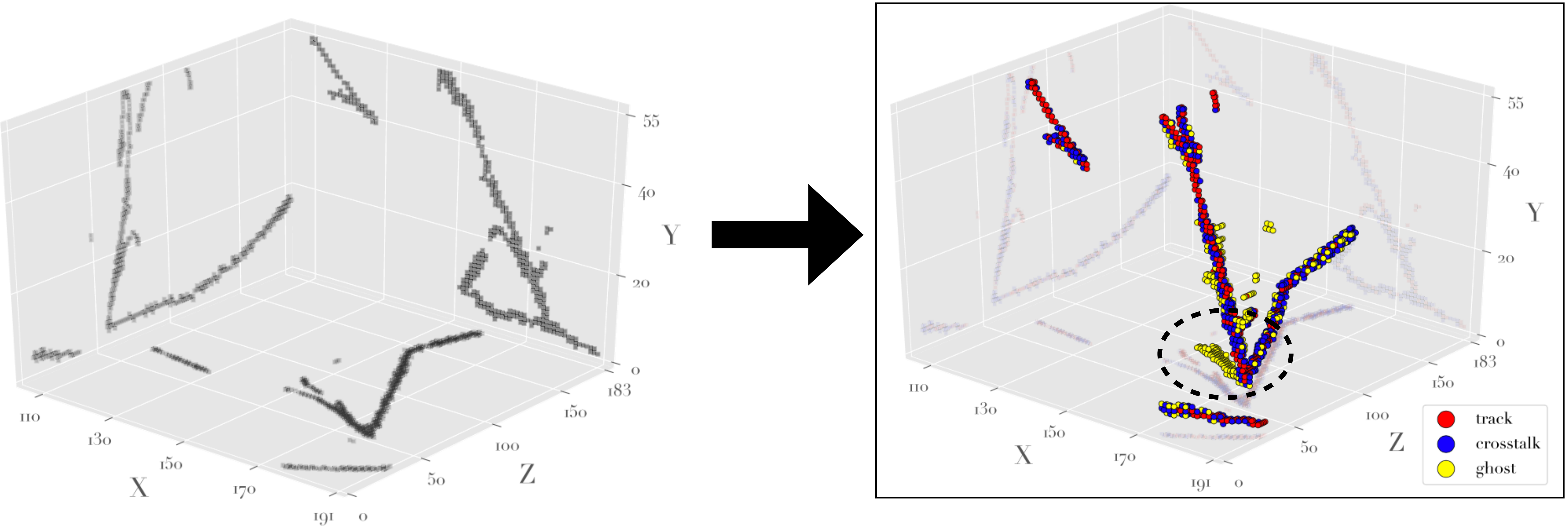
Generating a MC sample of neutrino interactions require the simulation of:

- *Neutrino interaction process* (what has to be measured)
- Propagation of each single particle in the detector
  → *not always very accurate (e.g. neutrons, pion/proton inelastic interactions)*
- Detector response (geometry, scintillation, photosensor, readout electronics,…)

Time consuming. To be tuned with data (beam tests and/or small experiments)

Reconstructing the image of a neutrino interaction

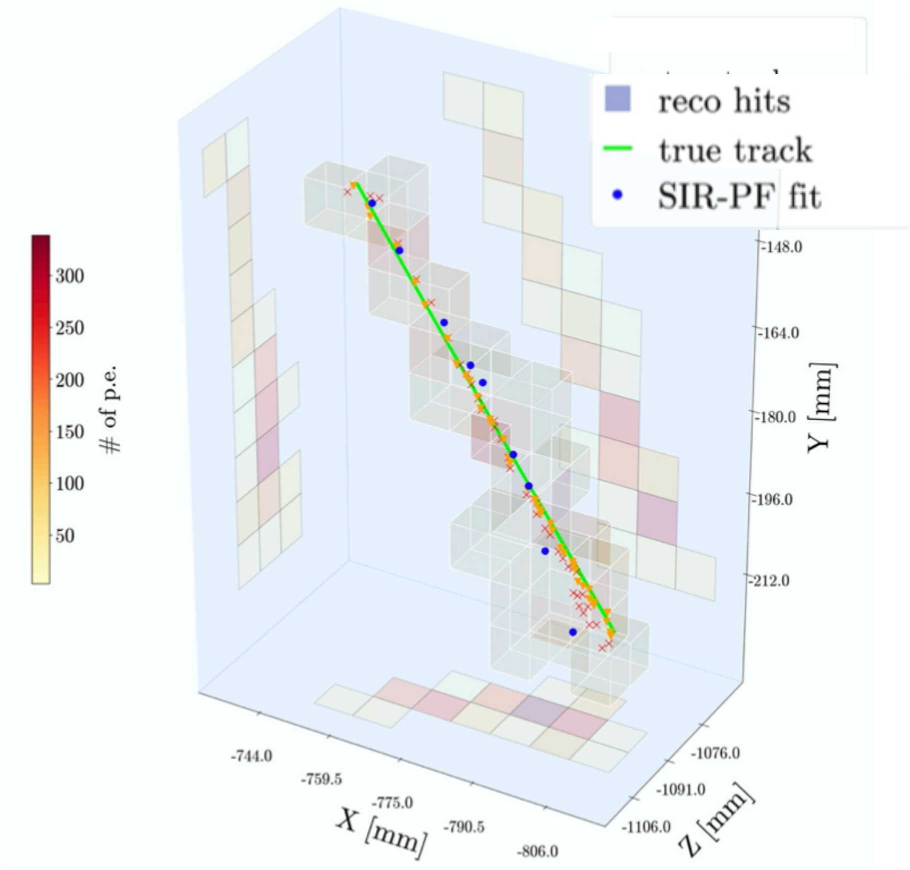
Combine the different 2D views and reconstruct the 3D image

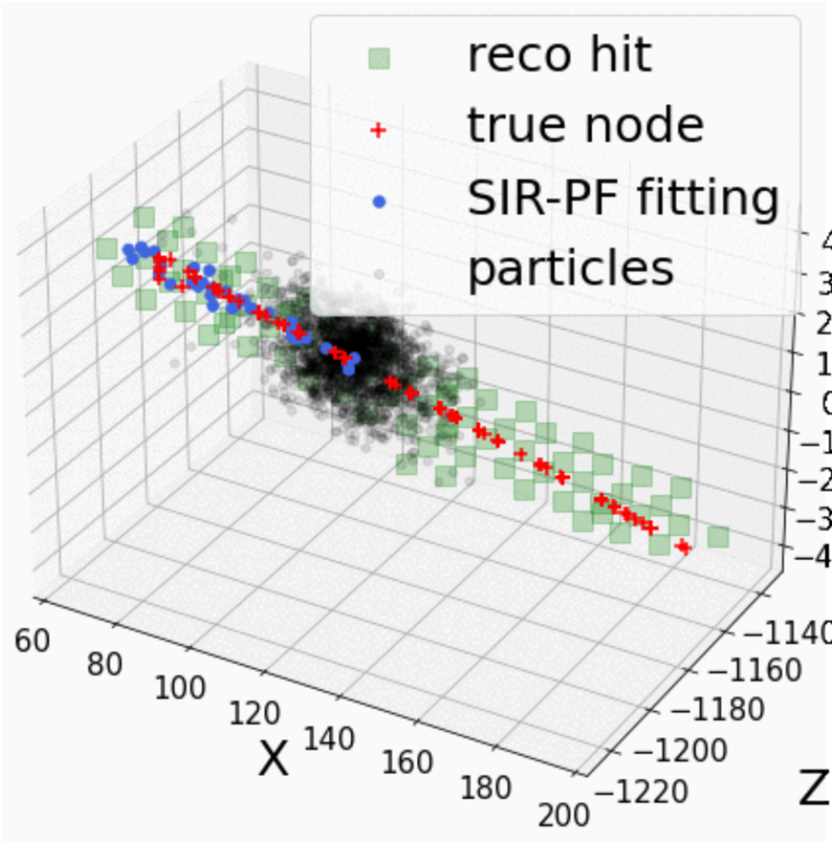


- *Remove ambiguities* by fitting E_{loss} in each channel
- *Pattern recognition:* clustering (e.g. DBSCAN, Minimum Spanning Tree, hit ordering), cluster growth and track construction ⇒ list of clusters and tracks

Reconstructing the kinematics of a neutrino interaction

Track Fitting, i.e. reconstruct the position of the particle along the track signature left in the detector (e.g. Bayesian Particle Filters, Kalman Filters)



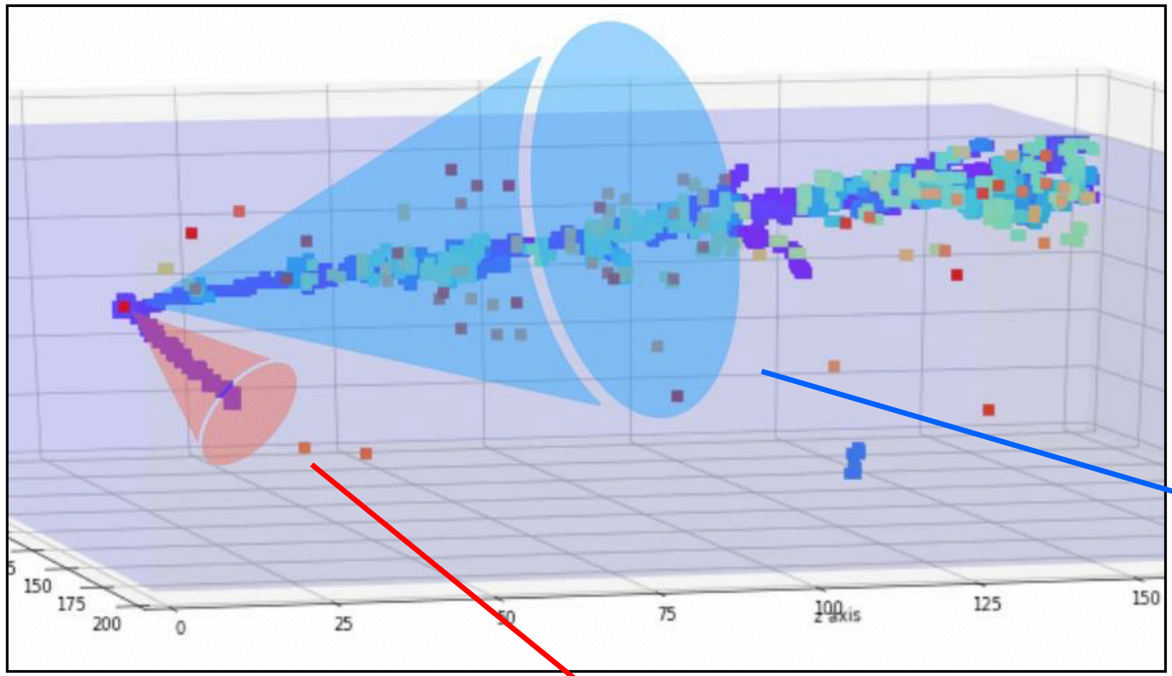


Prior information belongs to the modelling of the physics processes that affect the propagation of particles in matter and of the detector response (hyper-dimensional space)

Reconstruct the particle range, direction, curvature in magnetic field and its E_{loss} in each point of the track (in different detectors)
⇒ obtain its full kinematics !

Capability of parametrising efficiently such hyper-dimensional space is crucial to maximise the reconstruction performance

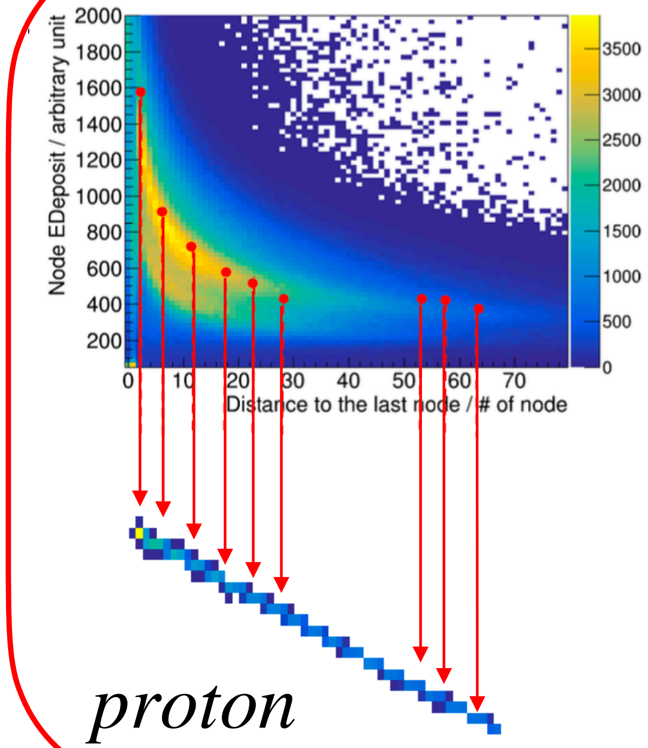
Reconstructing the kinematics of a neutrino interaction

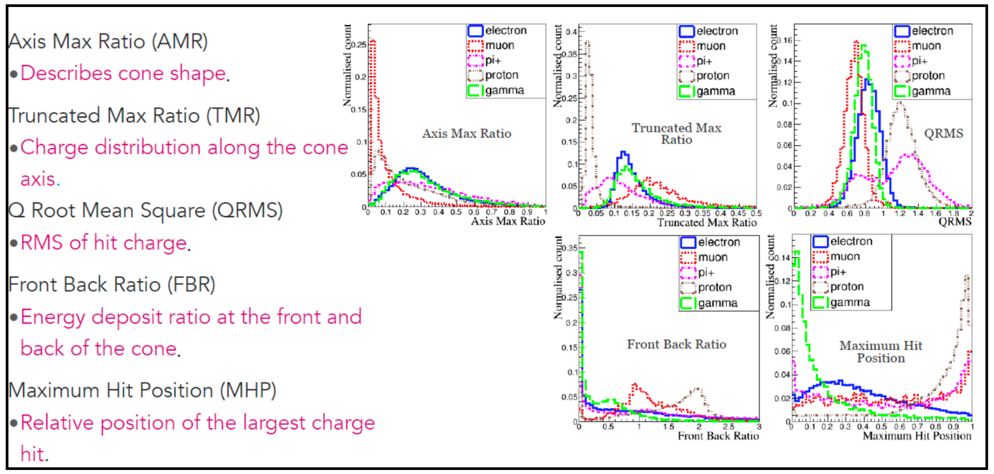


Particle Identification (PID) and Energy reconstruction

Often Boosted Decision Trees are used to parametrize the outputs of the previous analysis steps

Not trivial to parametrize the full parameter space





Axis Max Ratio (AMR)

- Describes cone shape.

Truncated Max Ratio (TMR)

- Charge distribution along the cone axis.

Q Root Mean Square (QRMS)

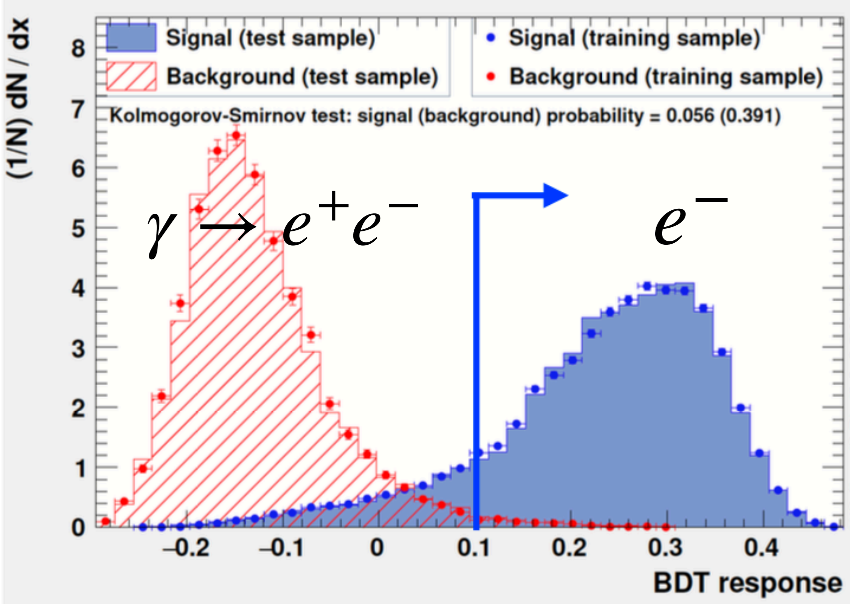
- RMS of hit charge.

Front Back Ratio (FBR)

- Energy deposit ratio at the front and back of the cone.

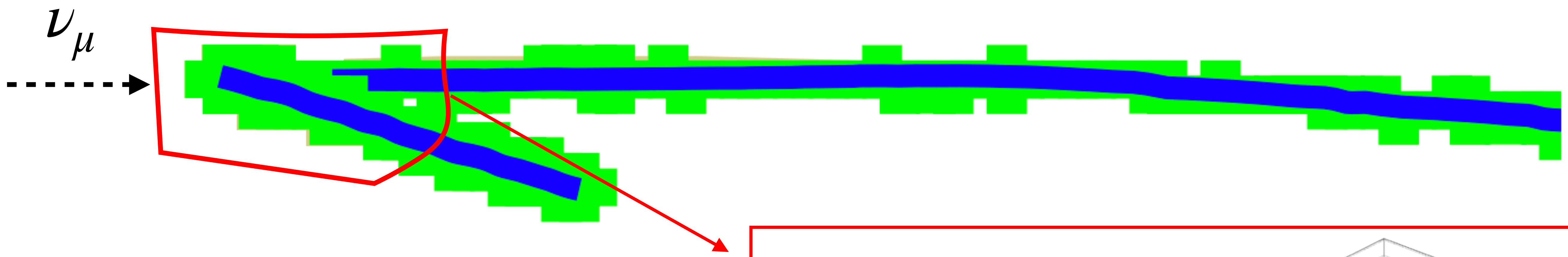
Maximum Hit Position (MHP)

- Relative position of the largest charge hit.



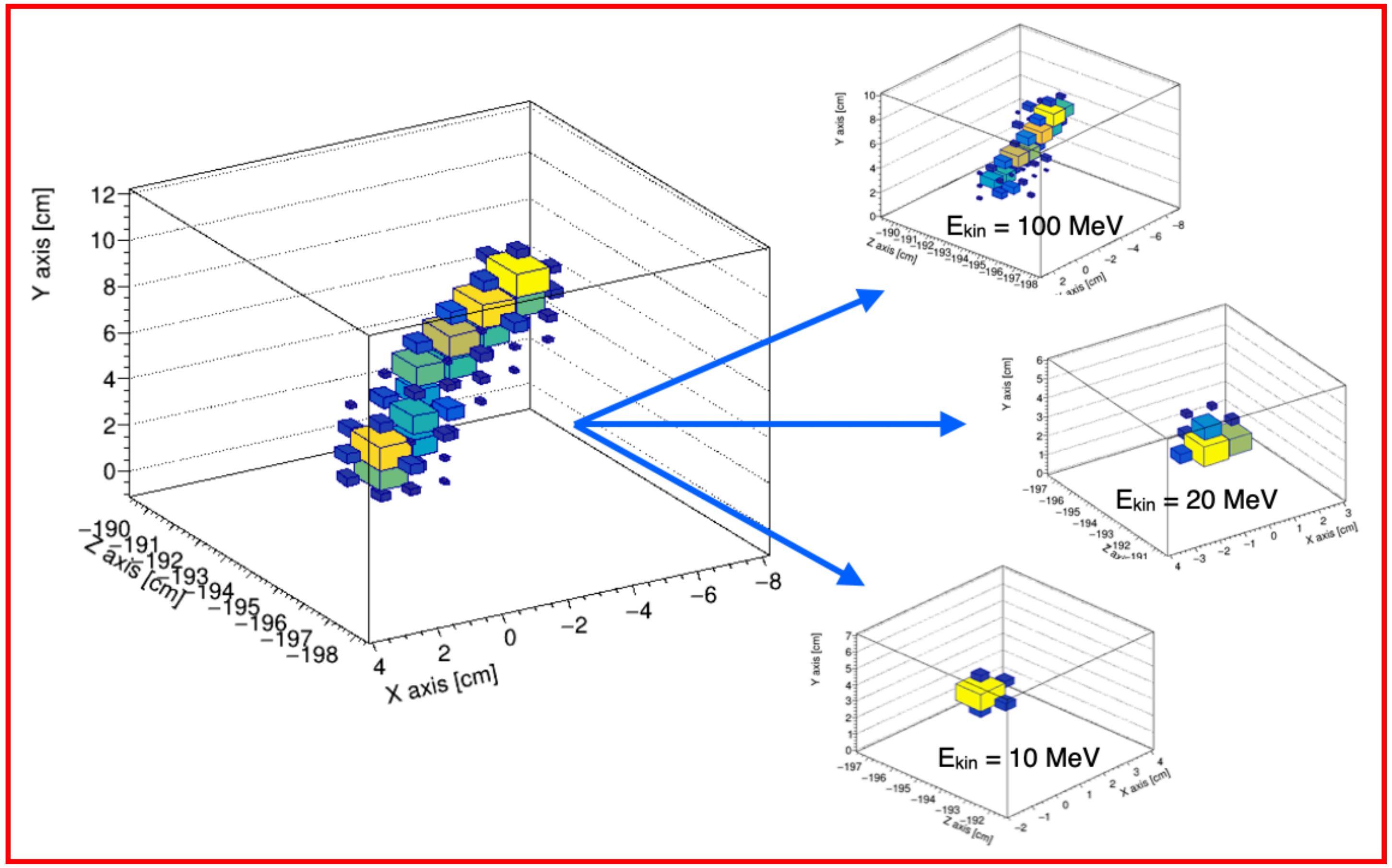
Reconstructing the kinematics of a neutrino interaction

Measure the calorimetric energy deposited by low-energy particles stopping near the neutrino interaction vertex - *"Vertex Activity"*



Overlap of different particles may bring to mis-reconstruction of the ν interaction final state

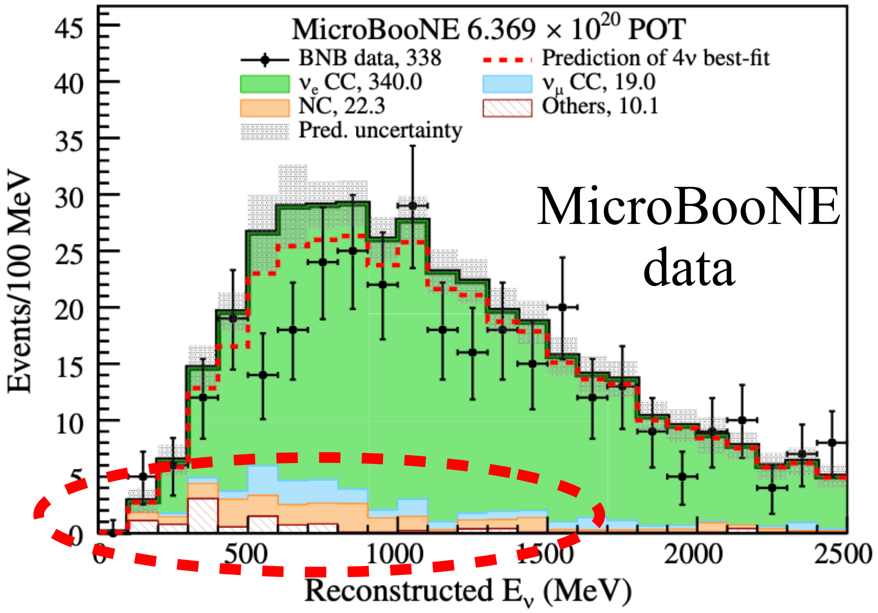
Ambiguity in the type, number and energy of the particles

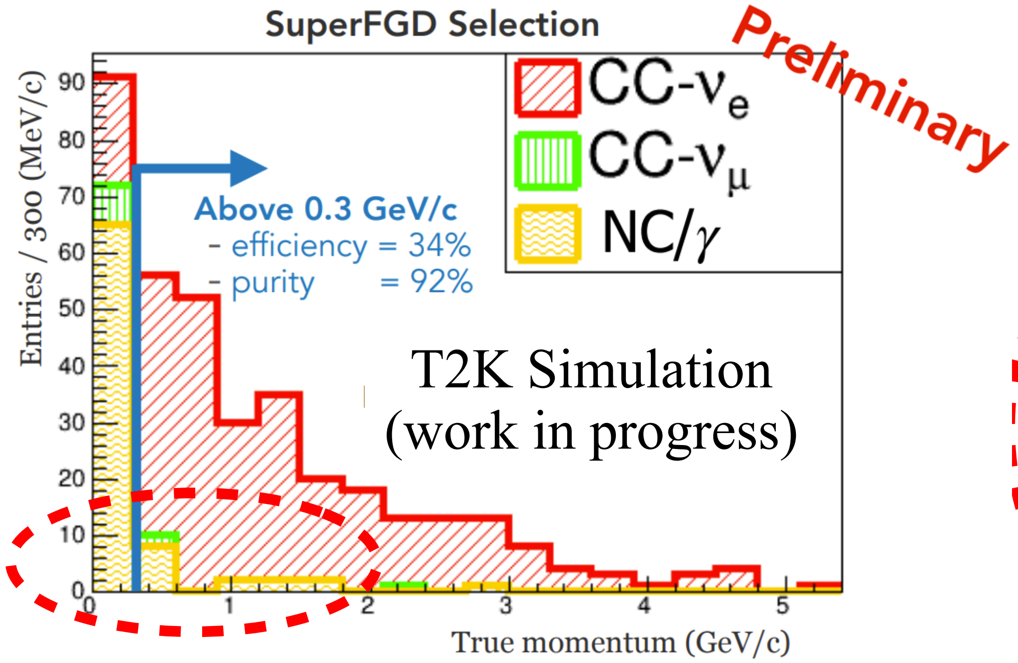


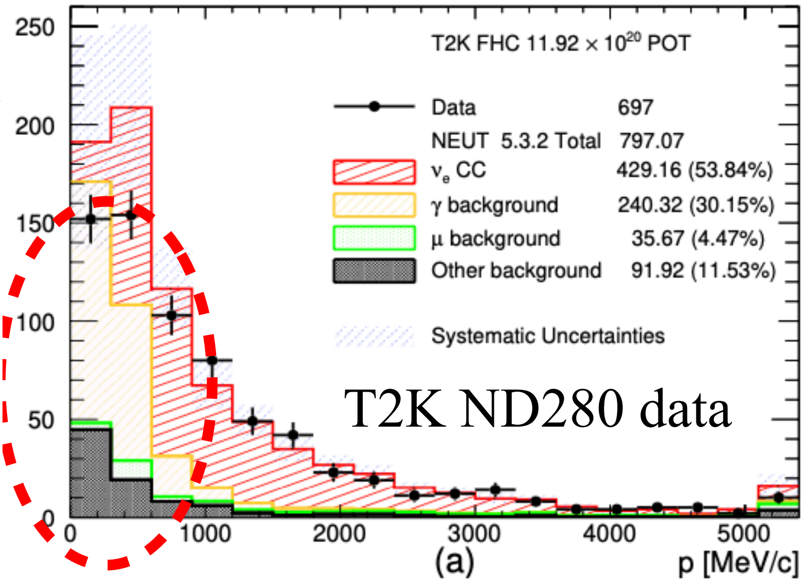
Some of the main challenges: background and PID

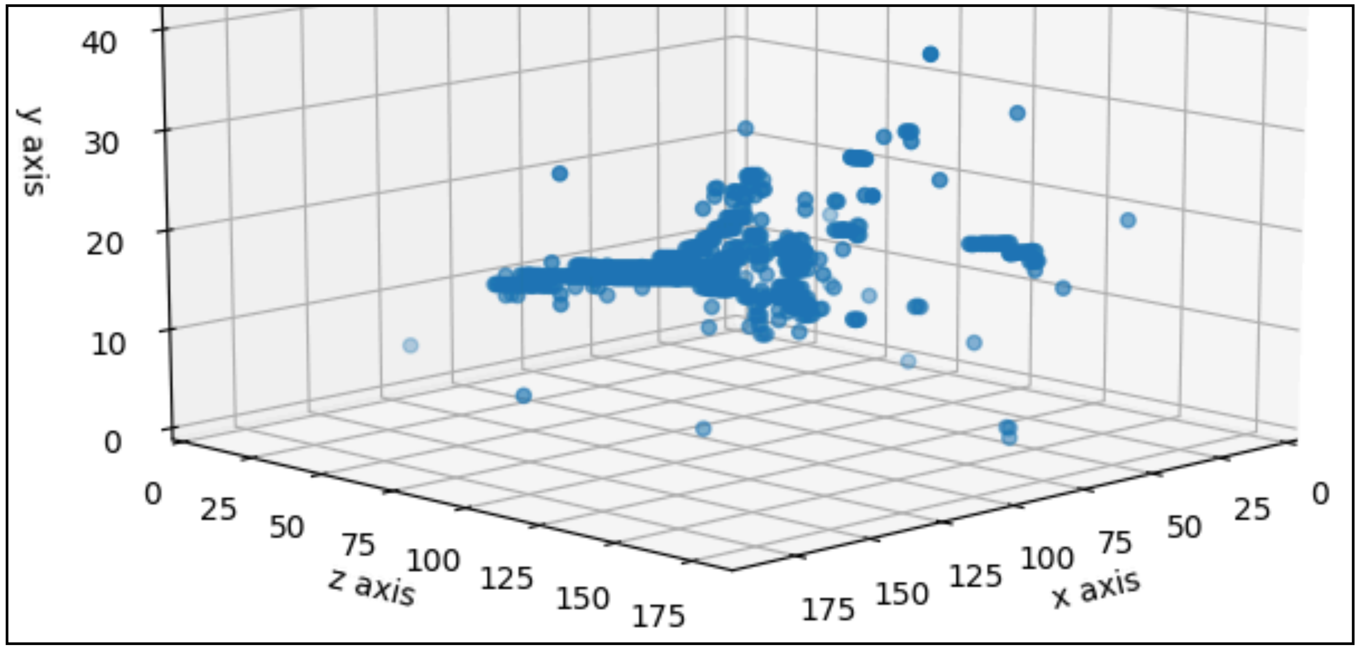
It's crucial to obtain a high purity sample of ν_e interactions

- for every ν_e we have ~100 ν_μ interactions, which can produce $\pi^0 \rightarrow \gamma\gamma$
  $\Rightarrow$ sensitive to background even with a very high rejection factor !







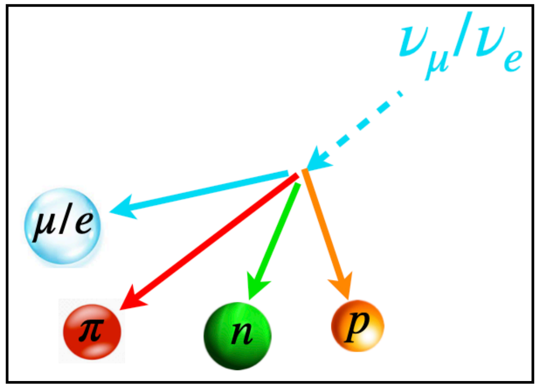


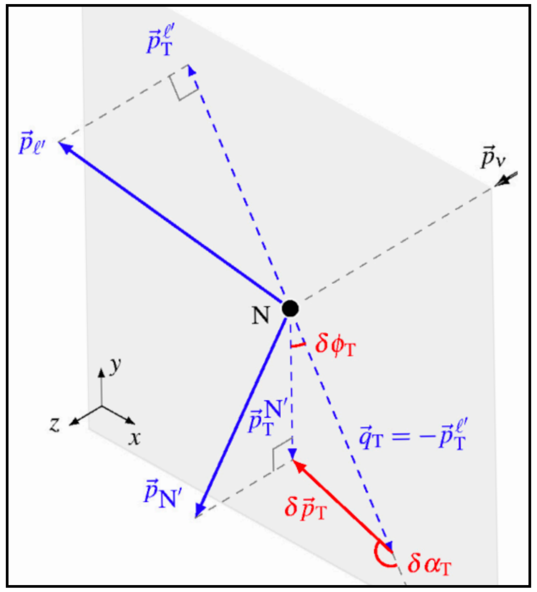
$\gamma \rightarrow e^+e^-$ background often from ν_μ interactions outside the detector but misidentified as a ν_e interaction

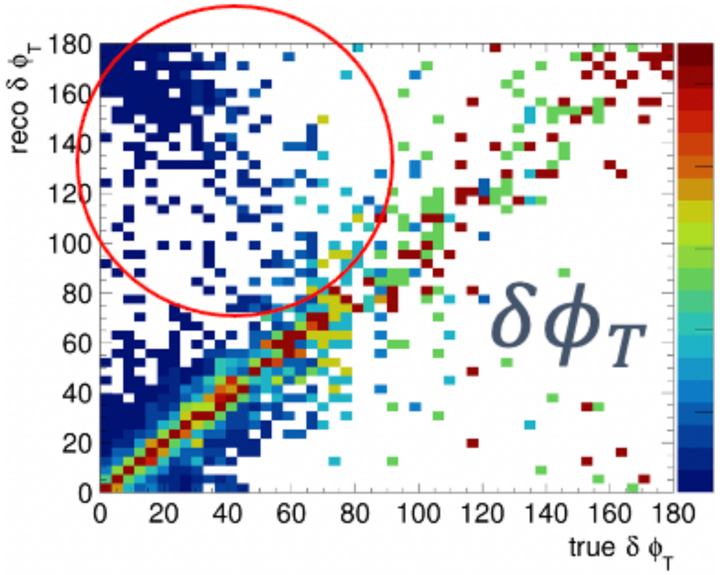
$\Rightarrow$ Distinguish them by looking at

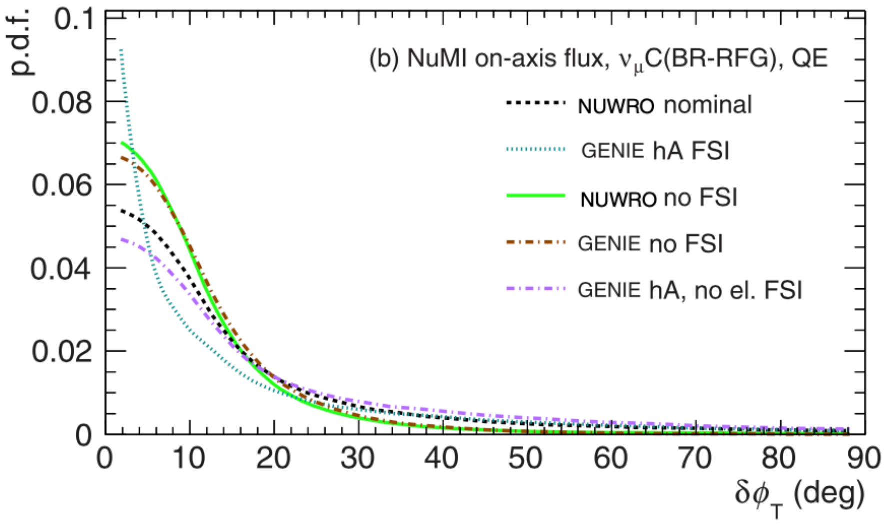
- ✦ Energy deposited along the track
- ✦ Spread of the E.M. shower
- ✦ Charge + Tracking

Some of the main challenges: ν interaction kinematics

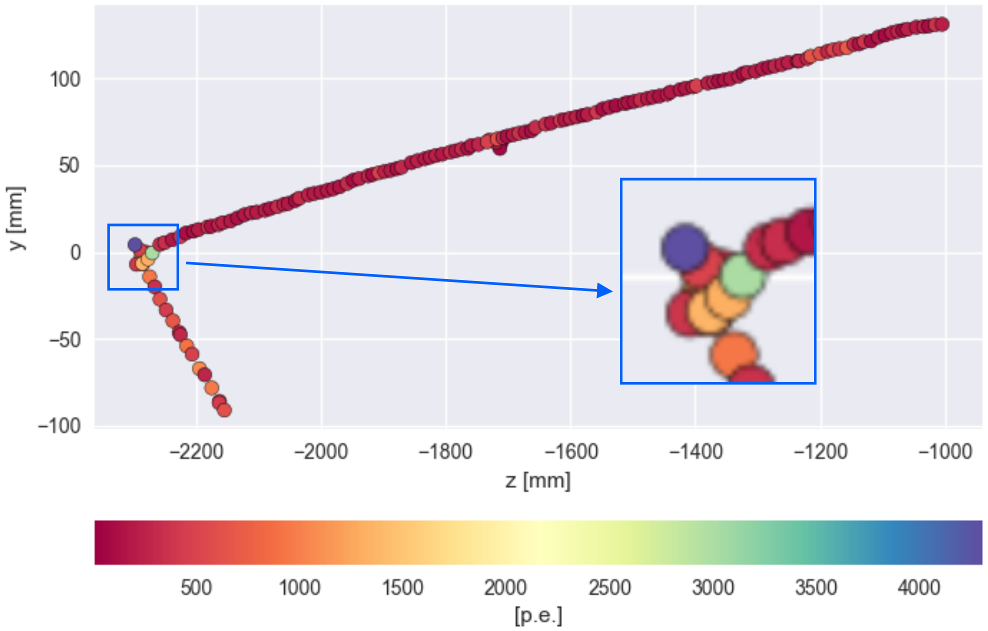


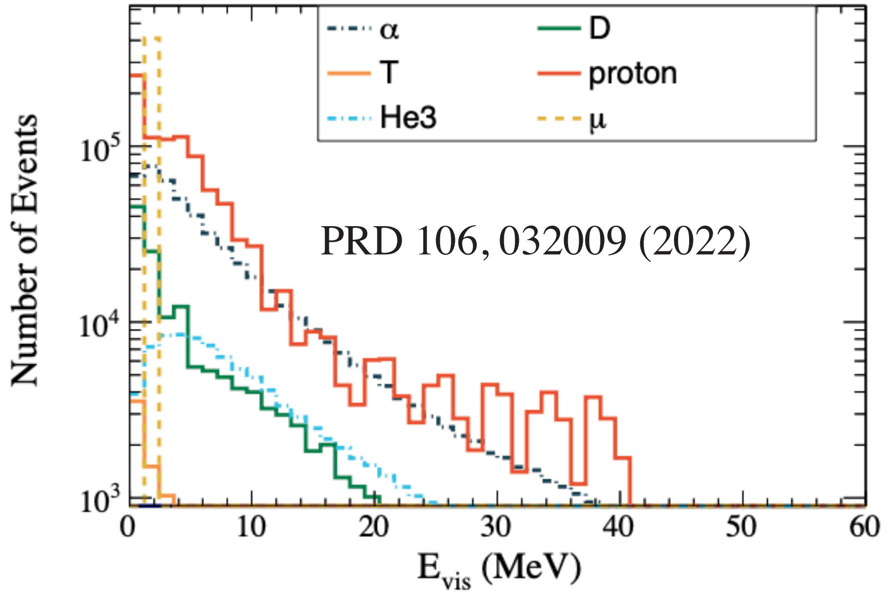






Improving the resolution to the transverse momentum of the neutrino interaction final state is key to better infer the different interaction models





PRD 106, 032009 (2022)

VA per particle type (3cm)

The overlap between particles can vary between different neutrino MC generators

Where Deep Learning can be useful ?

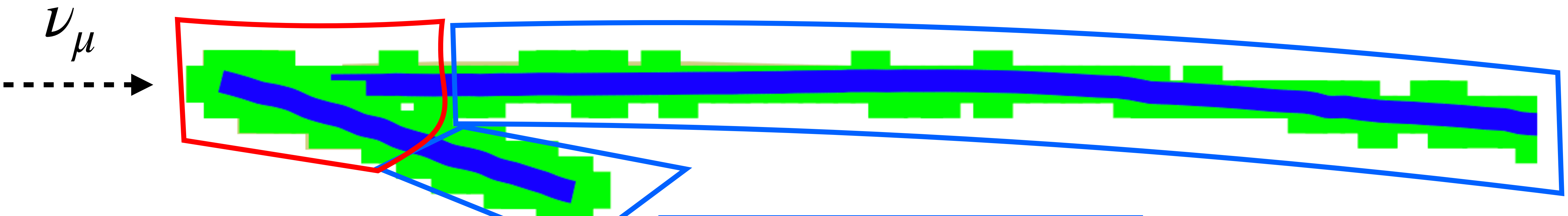
- Fast simulations and full reconstruction of the neutrino interaction final state
  - ✓Pattern recognition, track fitting, PID, energy reconstruction, etc.
  - ✓An accurate simulation for the required level of details is key to deal with systematics ⇒ data independent from the physics measurement
  - ✓Training on a simulation that does not depend on the arbitrary choice of the neutrino interaction generator is also key ⇒ avoid to bias the results
- Enhancing the experiment performance would highly impact the outcome of the current and future neutrino experiments
- Some other applications
  - ✓Tuning of neutrino generators for systematic studies
  - ✓Speed up parameter inference, e.g. to set confidence/credible intervals

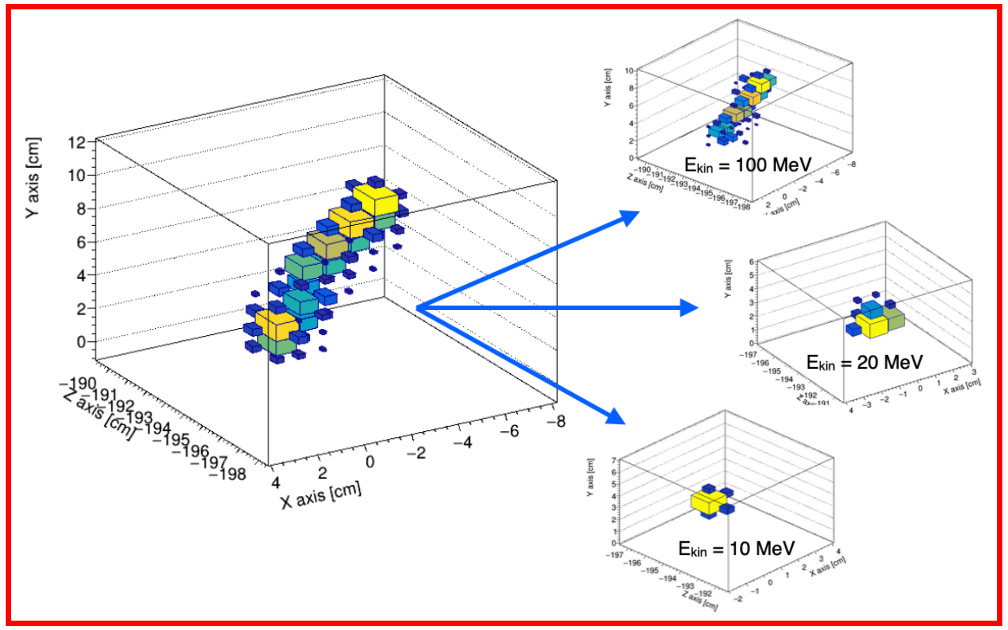
Deep learning can help to boost the sensitivity to neutrino oscillations as well as the searches for new physics Beyond the Standard Model

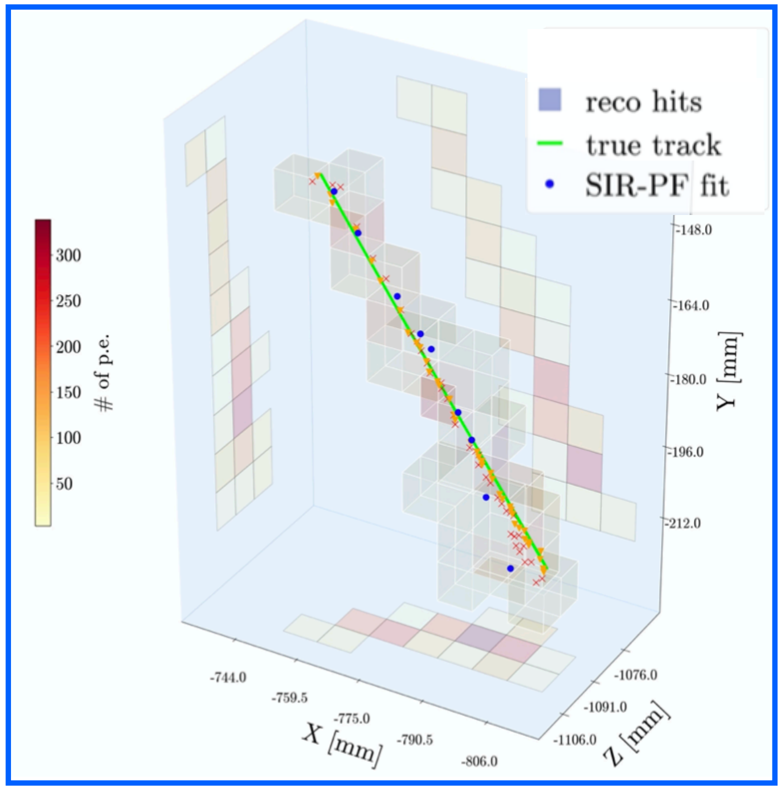
A possible approach: factorise the neutrino event

- In principle single-particle data are reproducible with precision in beam tests ⇒ training is safer when it relies on single-particle simulations as they can be unambiguously compared to beam test data

- Factorize a neutrino interaction into single-particle objects

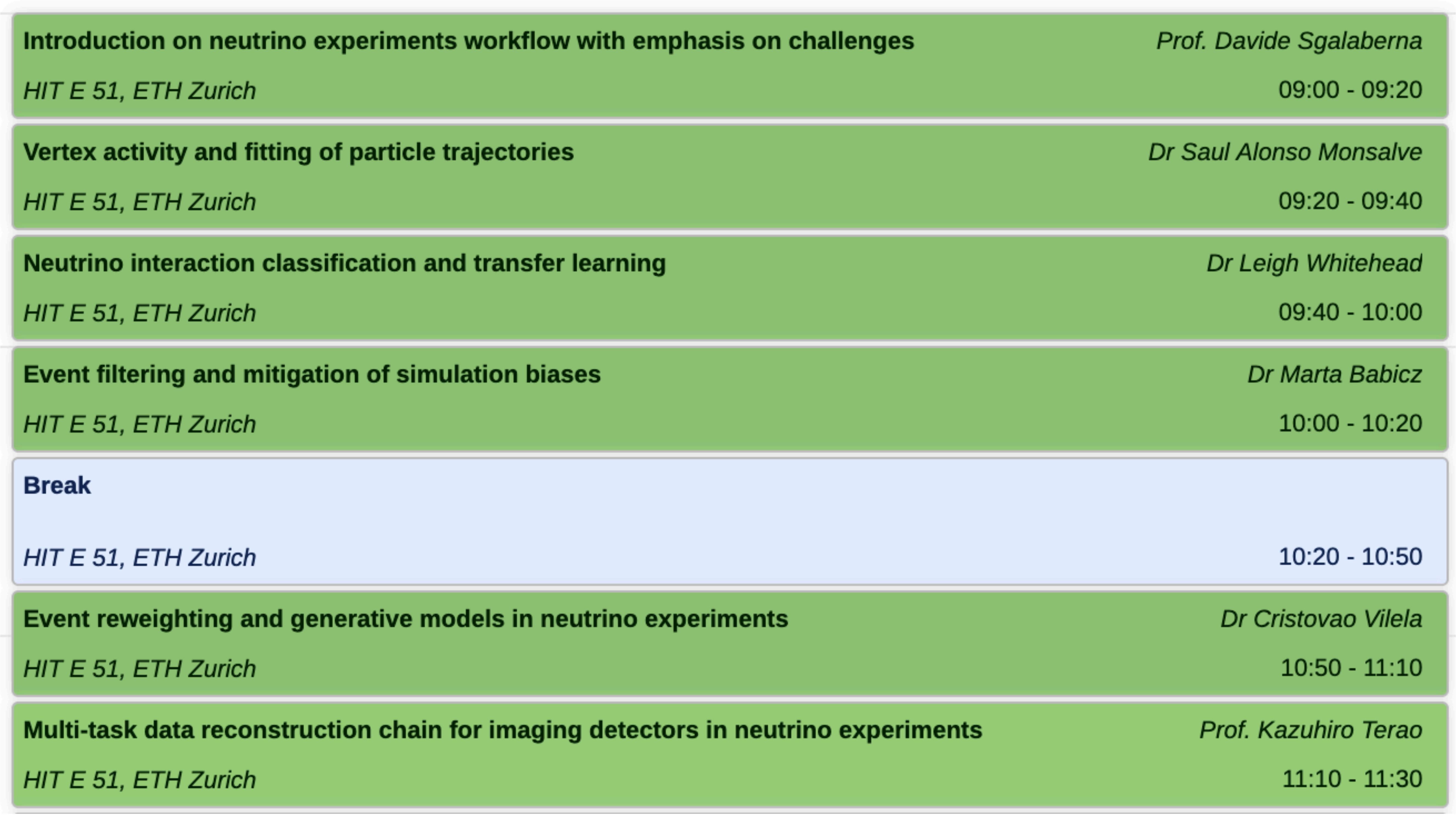






Non-trivial work shall be done on the single-particle data to understand systematics and propagate them through the chain

The Neutrino session



Introduction on neutrino experiments workflow with emphasis on challenges	*Prof. Davide Sgalaberna*	*HIT E 51, ETH Zurich*	09:00 - 09:20
Vertex activity and fitting of particle trajectories	*Dr Saul Alonso Monsalve*	*HIT E 51, ETH Zurich*	09:20 - 09:40
Neutrino interaction classification and transfer learning	*Dr Leigh Whitehead*	*HIT E 51, ETH Zurich*	09:40 - 10:00
Event filtering and mitigation of simulation biases	*Dr Marta Babicz*	*HIT E 51, ETH Zurich*	10:00 - 10:20
Break		*HIT E 51, ETH Zurich*	10:20 - 10:50
Event reweighting and generative models in neutrino experiments	*Dr Cristovao Vilela*	*HIT E 51, ETH Zurich*	10:50 - 11:10
Multi-task data reconstruction chain for imaging detectors in neutrino experiments	*Prof. Kazuhiro Terao*	*HIT E 51, ETH Zurich*	11:10 - 11:30