Electron Shower Reconstruction and Selection in LArTPCs

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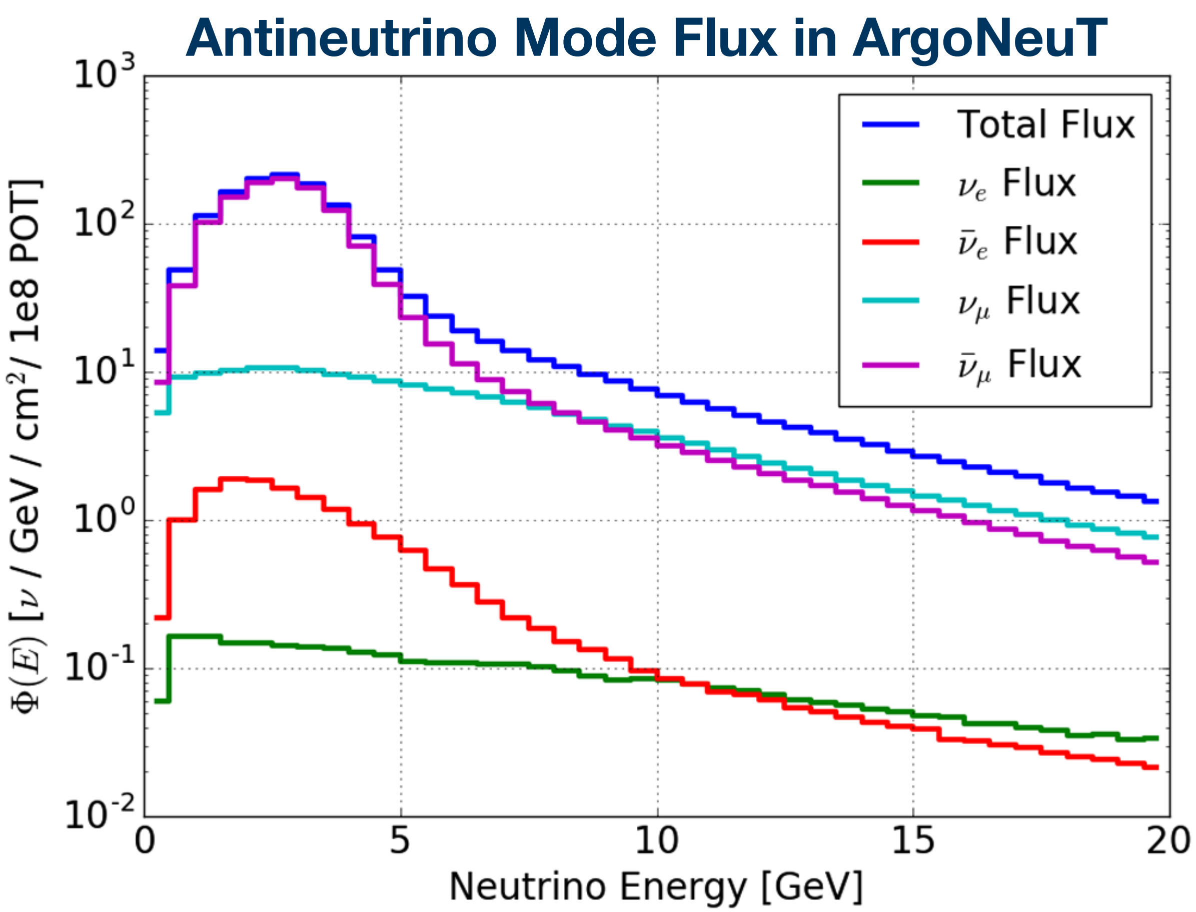
Workshop on Calibration and Reconstruction for LArTPC Detectors
December 11, 2018

Where are we going in this talk?

- Exploring techniques for effectively discriminating electron neutrino signals from photon backgrounds in LArTPCs.
- I'll briefly describe my shower reconstruction strategy and its advantages for electron reconstruction.
- But we'll focus on methods that could be applied to any reconstructed shower data product.
- ArgoNeuT will be used as a case study.
- All this work is very much "in progress."

Why ArgoNeuT?



The first LArTPC to be deployed at FNAL for studying neutrinos.

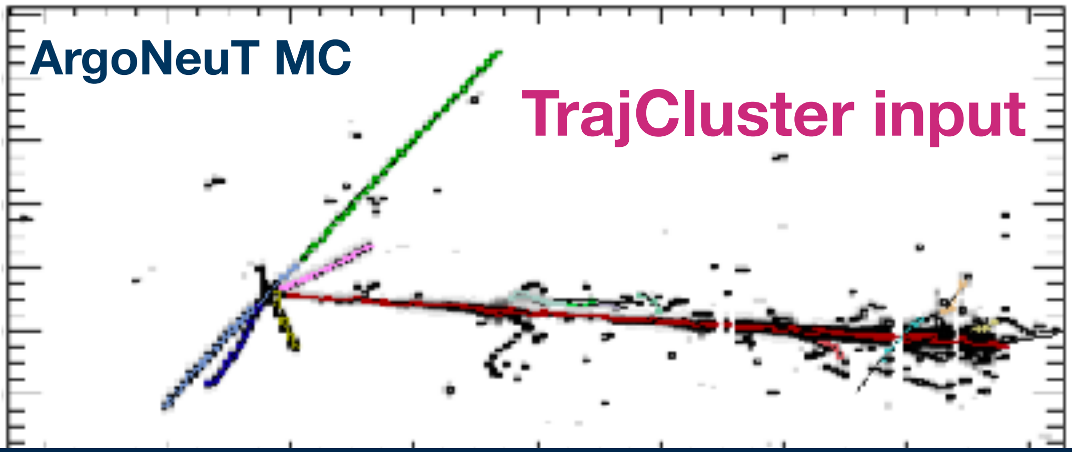
Sat in front of the MINOS ND, 100 m underground, in the NuMI beam line.

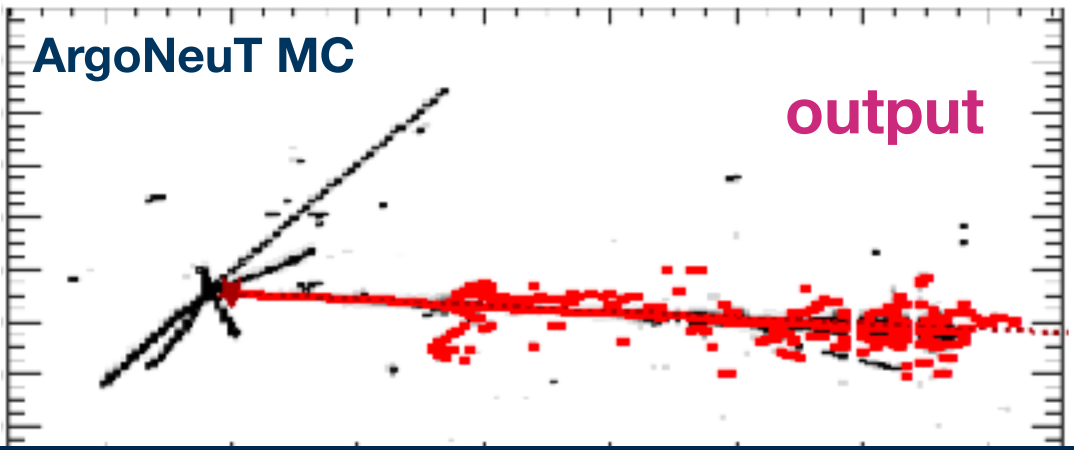
Electron neutrino energies peak in the same range where DUNE's ν_e spectrum peaks.

Acciari *et al.* Phys. Rev. D **95**, 072005 (2017)

Shower Reconstruction for Electrons

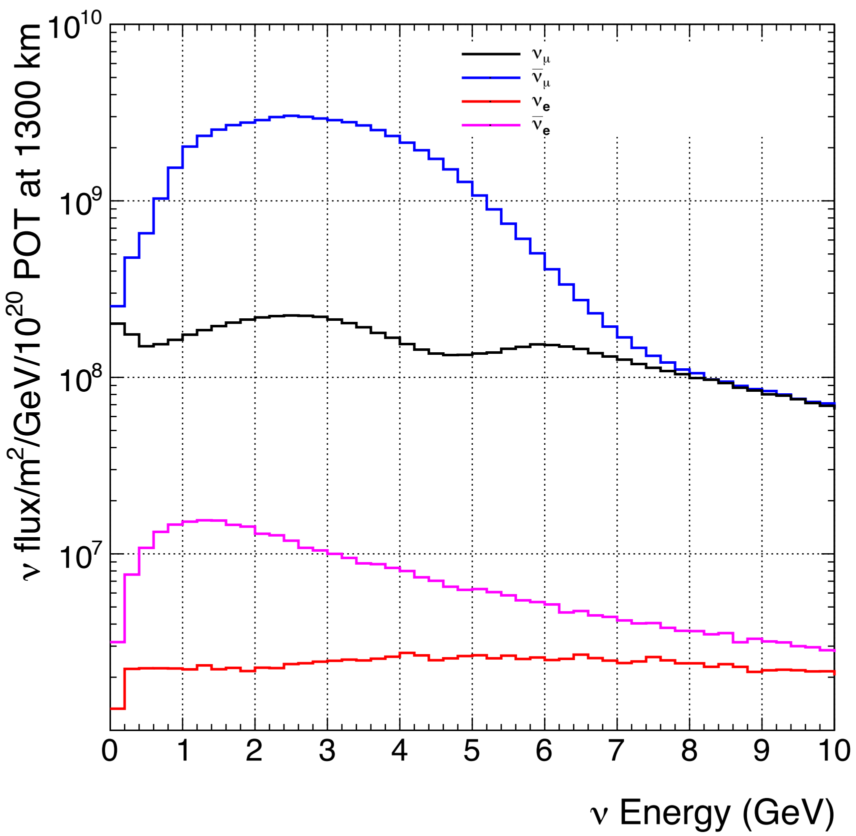
- **Goal:** Efficiently reconstruct *electron* showers
- **Strategy:** Start with reconstructed 3D tracks, then build showers in 2D on each plane from clusters of hits identified as "shower-like" based on MCS momentum and topology. Only look for leading shower in an event (or slice, for larger detectors).
- Accurately identifying a parent electron track means we can use reliable track information to define the shower vertex, direction, and dE/dx.
- By design, this preferentially reconstructs electrons.

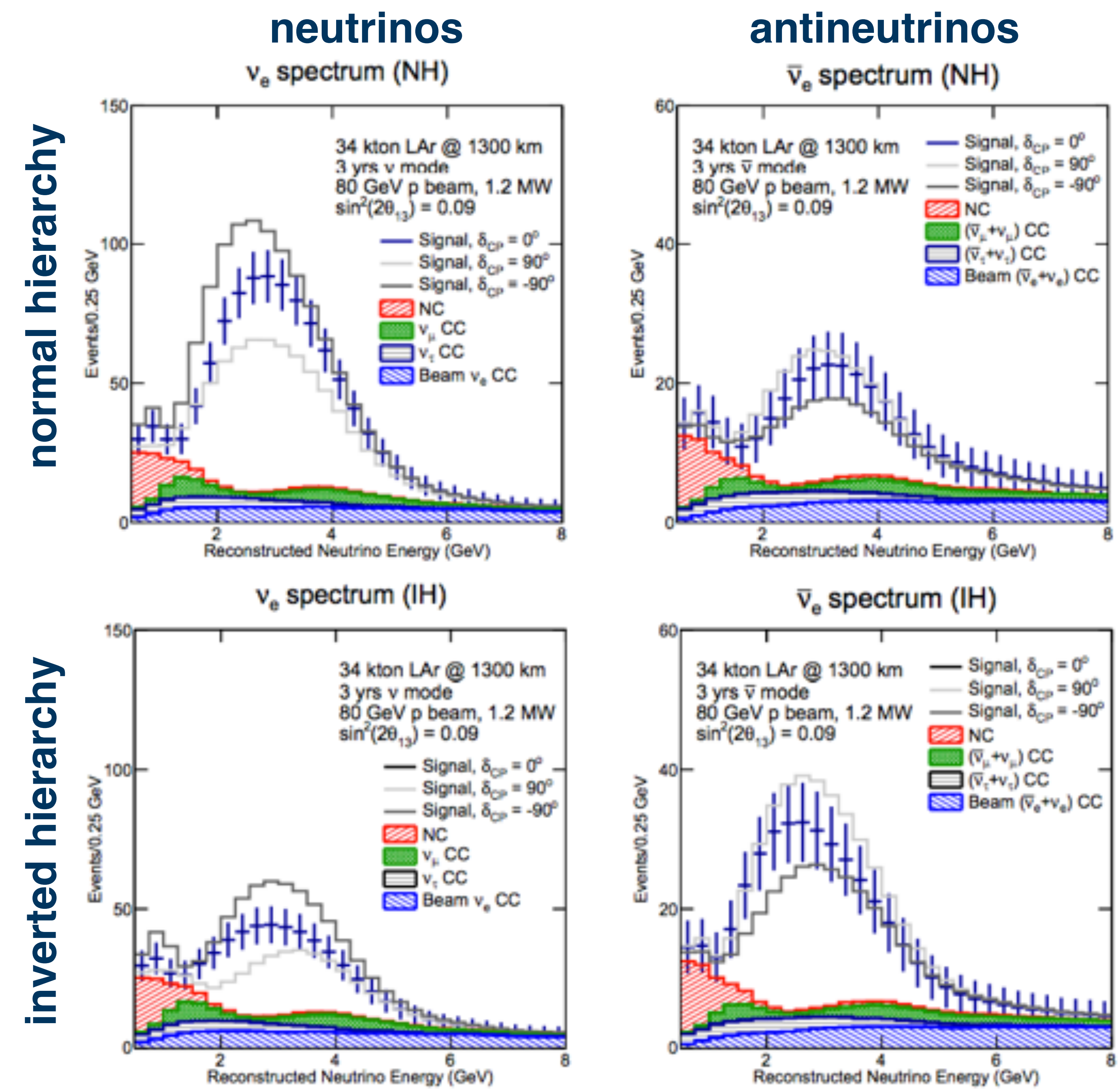




Electron Neutrinos in DUNE

Antineutrino Mode Flux in DUNE

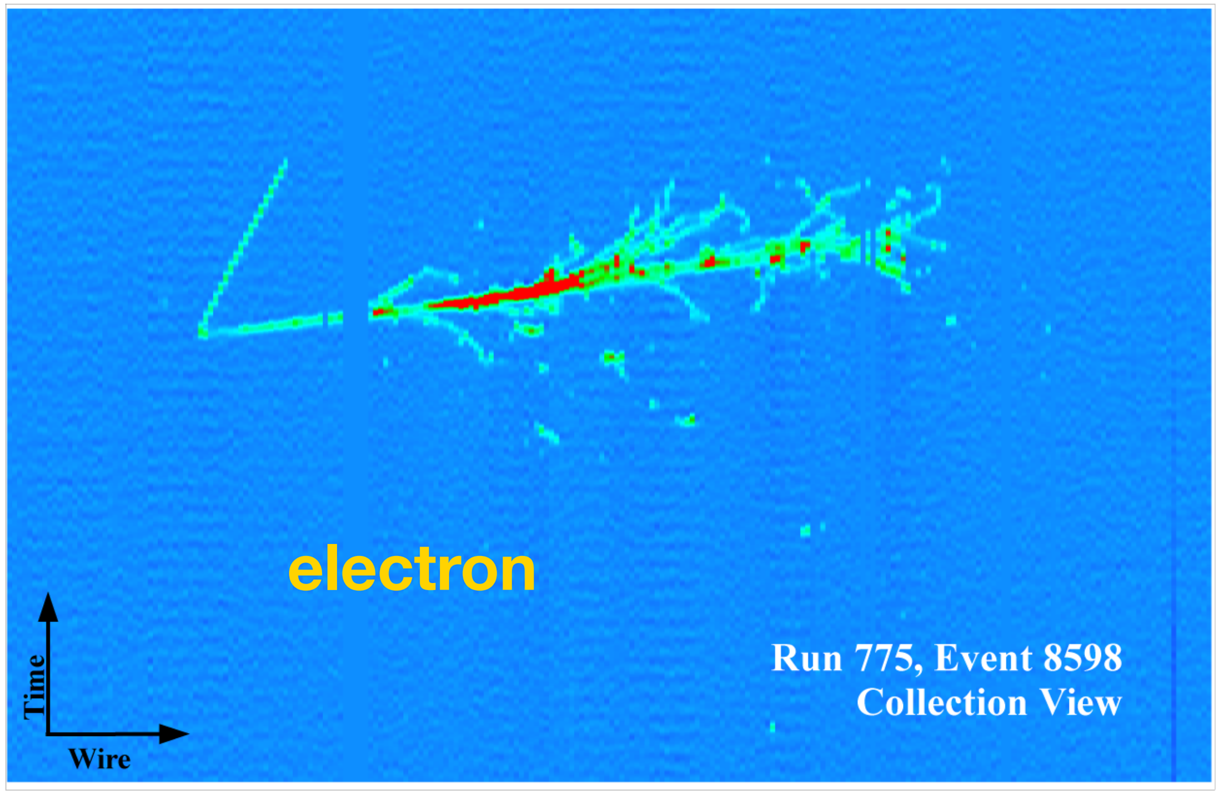


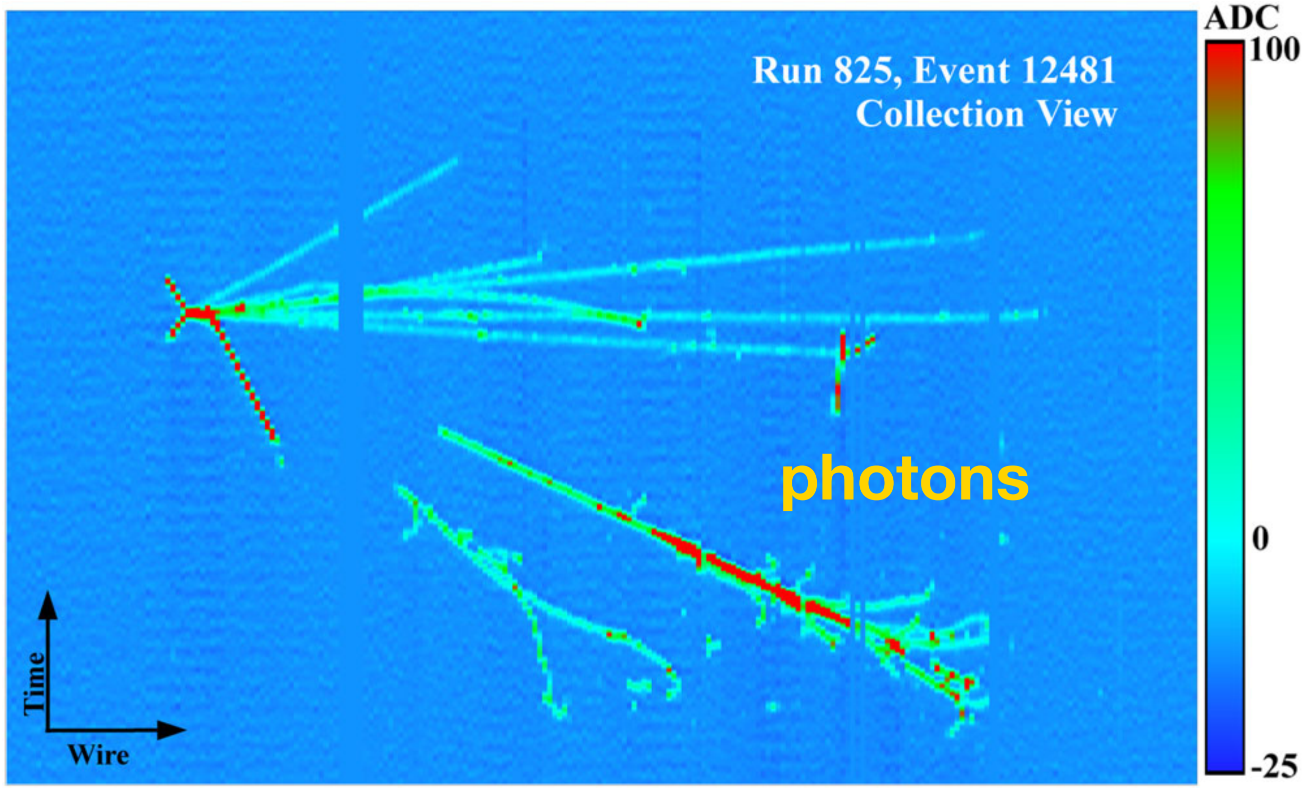


DUNE will precisely measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation parameters, including δ_{CP}. The requires efficient and pure electron shower selection.

R. Acciarri *et al.* FERMILAB-DESIGN-2016-04 (2016).

Separating Electrons and Photons





Photons from neutral pion decay represent a significant background to electron neutrino searches.

LArTPCs allow us to use both topology and calorimetry to differentiate electrons from photons.

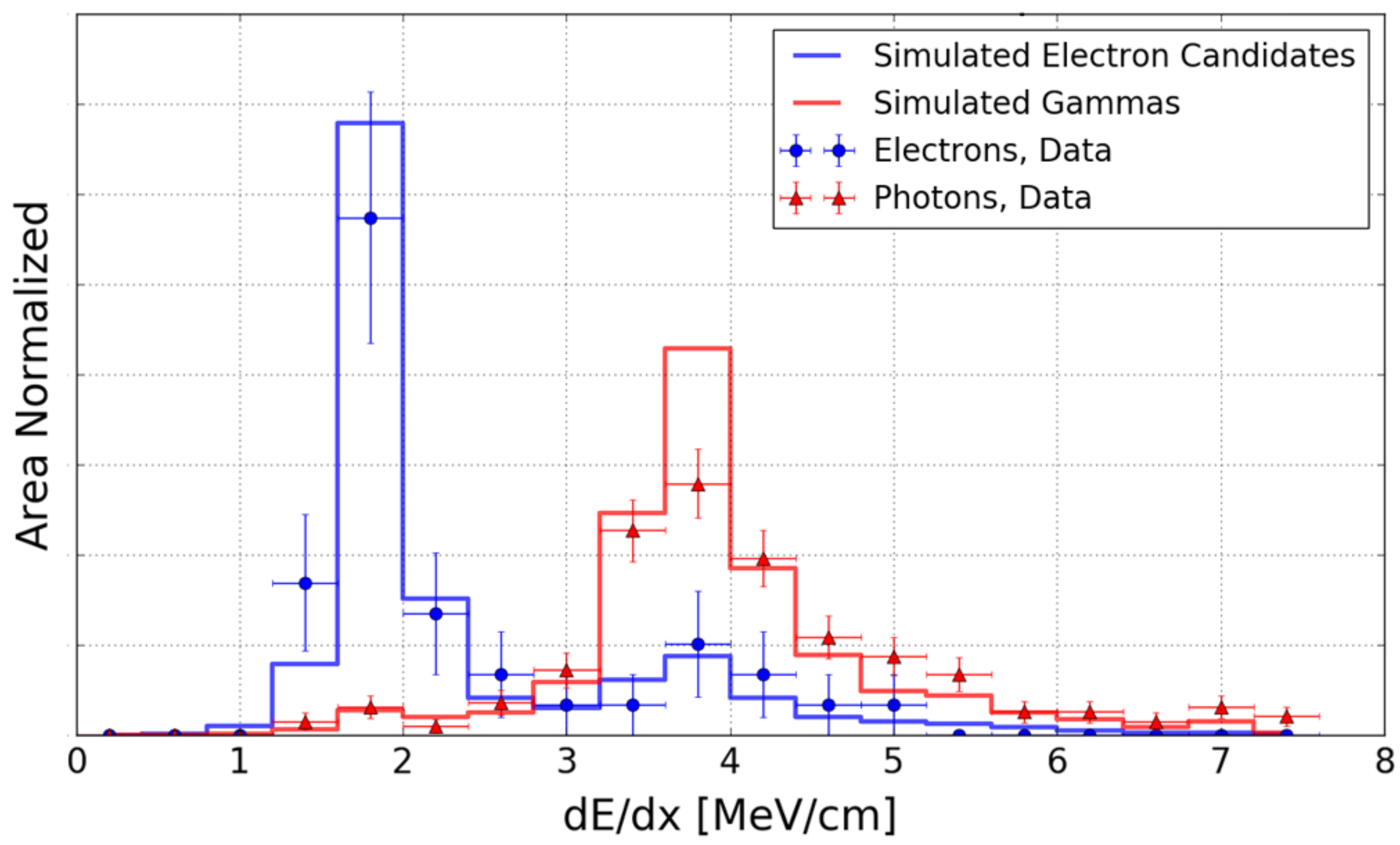
Acciari *et al.* Phys. Rev. D **95**, 072005 (2017)

dE/dx

ArgoNeuT demonstrated that measuring dE/dx at the start of an electromagnetic shower can successfully separate electrons (1 MIP) from photons (2 MIPs).

In many ways, this result represents the best case scenario. The ArgoNeuT analysis relied on hand scanning events to select the electron and photon samples based on topology.

The electron candidate sample (37 events) was found to have ~20% gamma contamination.



Acciari *et al.* Phys. Rev. D **95**, 072005 (2017)

Vertex Separation

Topological discrimination of electrons and photons relies on the characteristic gap between the neutrino interaction vertex and the start of the photon shower. However, a significant fraction of photons mimic electron topologies by converting very close to the neutrino vertex.

Topological identification is further complicated by hadronic overlap in non QE-like events, which are prominent at DUNE energies.

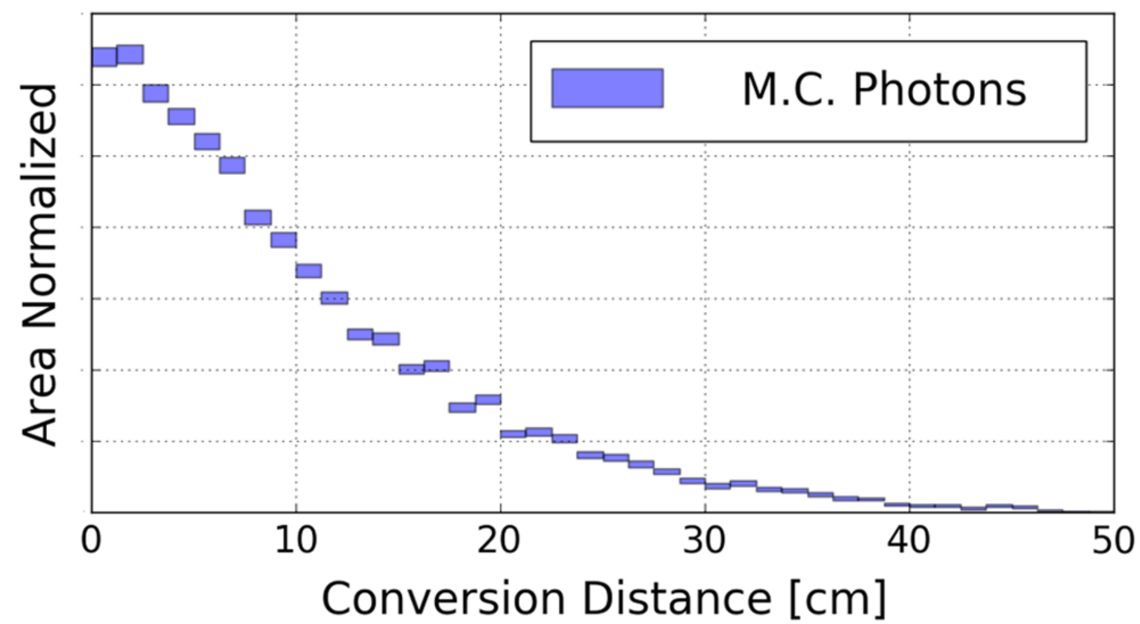
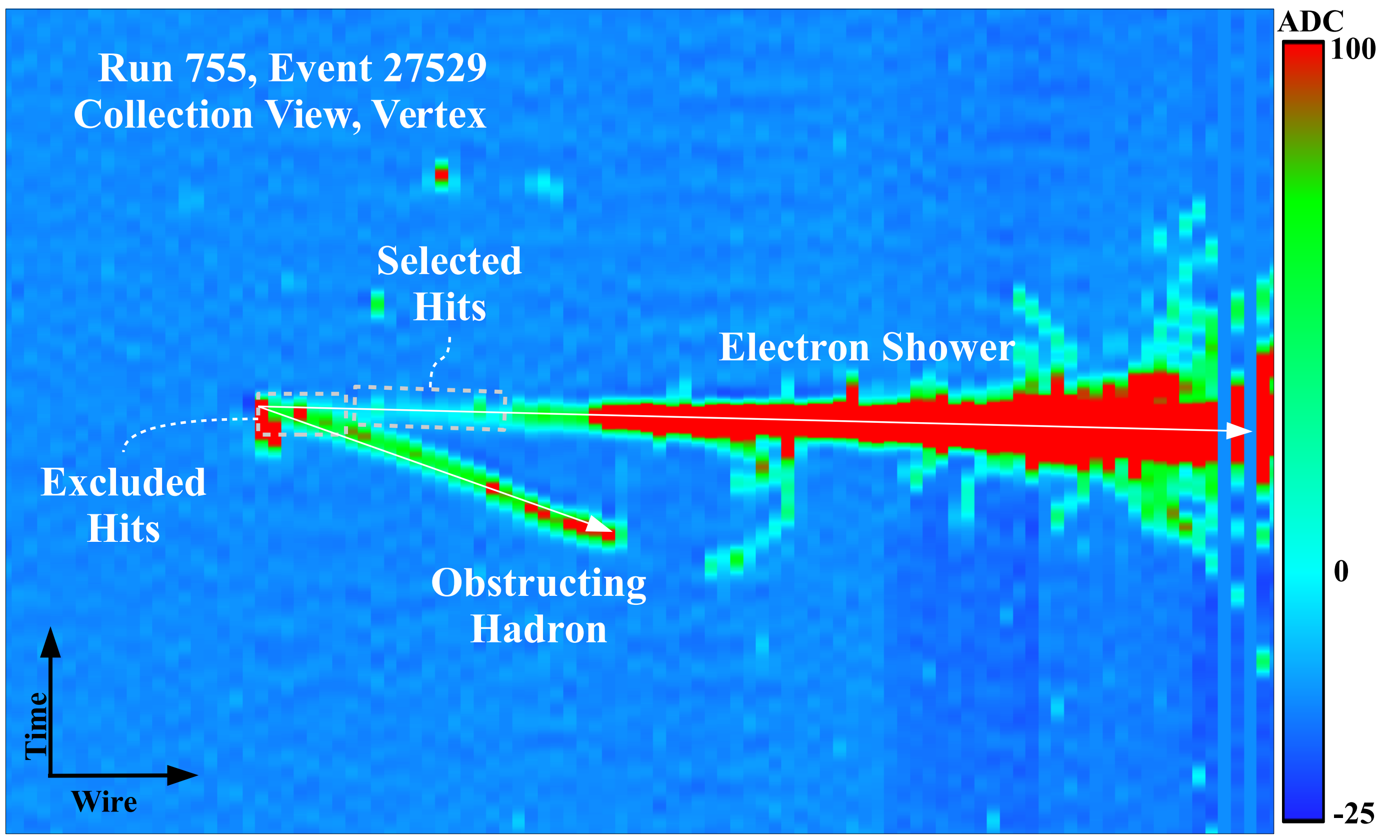
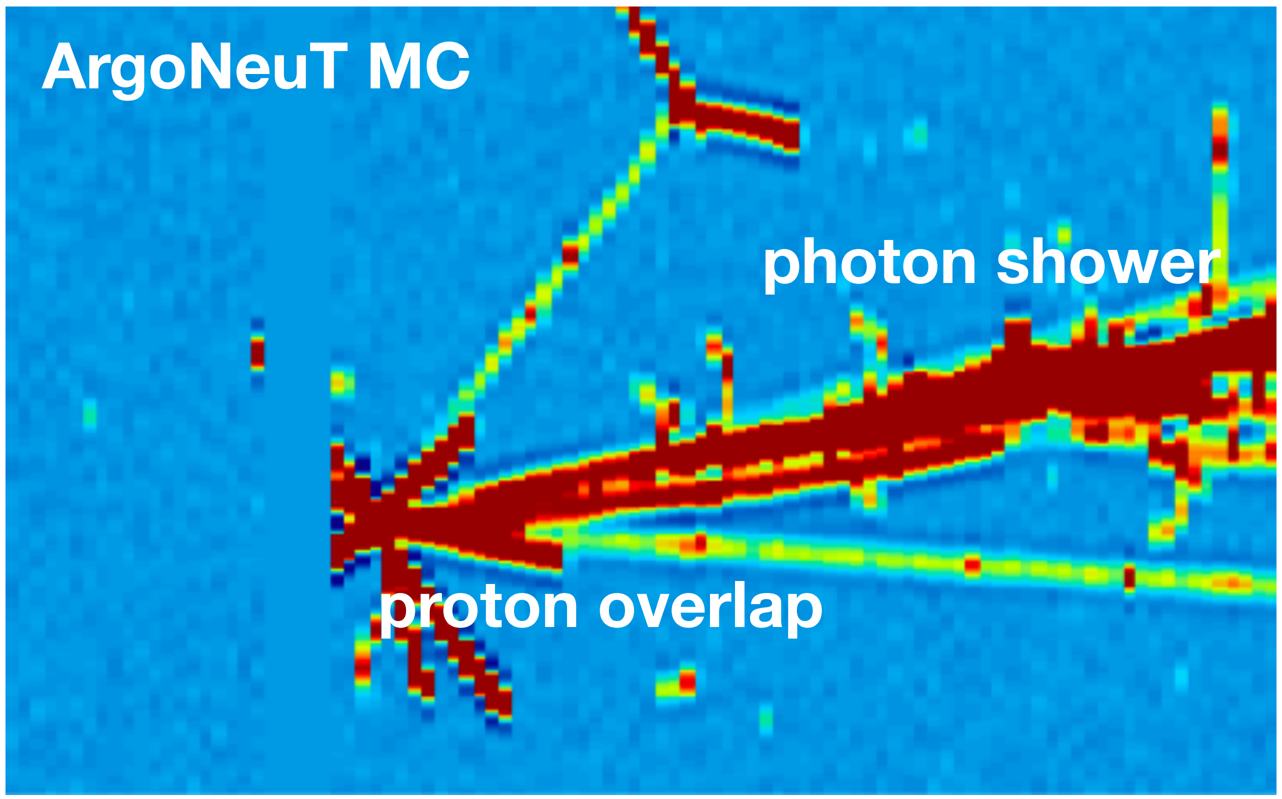


FIG. 4. The conversion distance of each gamma in the Monte Carlo sample used for this analysis, which is about 7000 gammas in the energy range of several hundred MeV, as modeled by GEANT4 [37].

Acciari *et al.* Phys. Rev. D **95**, 072005 (2017)

Hadron Overlap





In this analysis, hits with hadron overlap were excluded by hand.

Small vertex gap + proton overlap makes this photon look like an electron topologically.

Acciari *et al.* Phys. Rev. D **95**, 072005 (2017)

Looking Forward

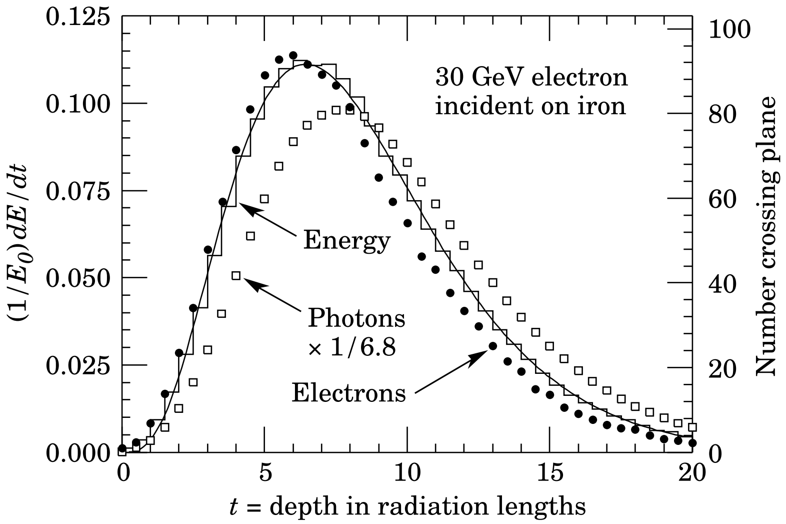
- dE/dx + vertex separation can be extremely powerful for distinguishing electrons from photons.
- But high levels of hadronic activity around the neutrino vertex make it more difficult to reconstruct showers and use these variables effectively.
    - Photons that overlap hadrons produced at the vertex can mimic electrons.
    - Conversely, track overlap can make electrons look like photons.
    - *Often these issues can be resolved by eye* — reconstruction improvements, in addition to the calorimetry work presented here, are necessary.
- **How can we use the entire shower topology to improve our selection and reject misidentifications caused by hadronic overlap?**
- Here, I'm thinking holistically about separating CC ν_e events from NC π^0 events, rather than single photon showers from single electron showers, to overcome current reconstruction limitations in busy events.

Electromagnetic Cascades

When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$t = x/X_0 \, , \qquad y = E/E_c \, , \tag{33.35}$$

so that distance is measured in units of radiation length and energy in units of critical energy.



The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [60]:

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \tag{33.36}$$

The maximum $t_{\rm max}$ occurs at $(a-1)/b$. We have made fits to shower profiles in elements ranging from carbon to uranium, at energies from 1 GeV to 100 GeV. The energy deposition profiles are well described by Eq. (33.36) with

$$t_{\rm max} = (a-1)/b = 1.0 \times (\ln y + C_j) \, , \qquad j = e, \gamma \, , \tag{33.37}$$

longitudinal development

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by [62,63]

$$R_M = X_0\, E_s/E_c \, , \tag{33.38}$$

where $E_s \approx 21$ MeV (Table 33.1), and the Rossi definition of E_c is used.

In a material containing a weight fraction w_j of the element with critical energy E_{cj} and radiation length X_j, the Molière radius is given by

$$\frac{1}{R_M} = \frac{1}{E_s} \sum \frac{w_j\, E_{cj}}{X_j} \, . \tag{33.39}$$

Measurements of the lateral distribution in electromagnetic cascades are shown in Refs. 62 and 63. On the average, only 10% of the energy lies outside the cylinder with radius R_M. About 99% is contained inside of $3.5R_M$, but at this radius and beyond composition effects become important and the scaling with R_M fails. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and Grindhammer [61] describes them with the function

$$f(r) = \frac{2r\, R^2}{(r^2 + R^2)^2} \, , \tag{33.40}$$

where R is a phenomenological function of x/X_0 and $\ln E$.

At high enough energies, the LPM effect (Sec. 33.4.6) reduces the cross sections for bremsstrahlung and pair production, and hence can cause significant elongation of electromagnetic cascades [46].

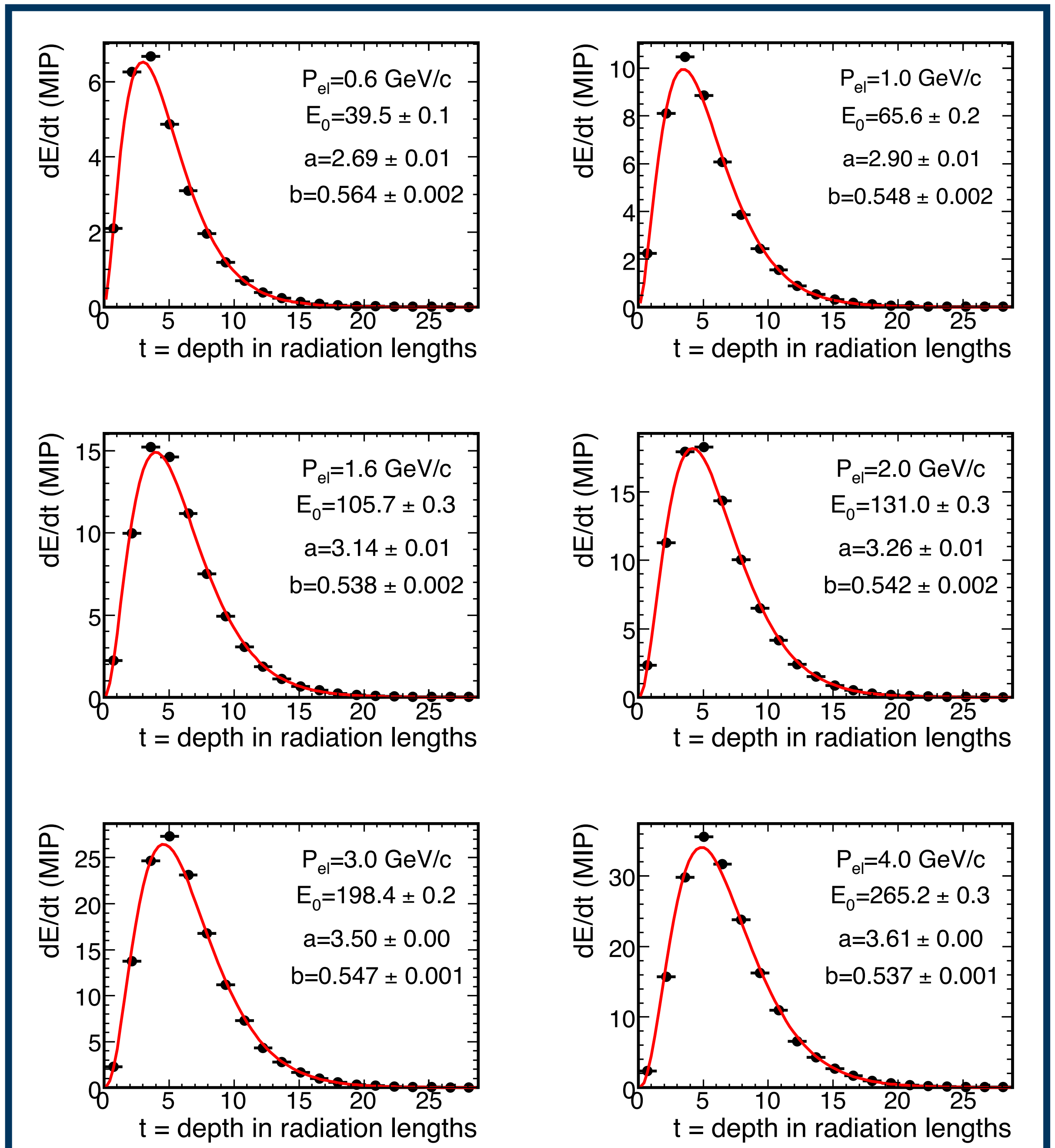
transverse development

the point: **we know what an EM shower should look like.**

What Have Other Experiments Done?

- Detectors like MINOS and NOvA are similar to LArTPCS in that they provide a 3D picture of charged particles produced by neutrino interactions.
- LArTPCs can achieve even better spatial resolution.
- So let's take some inspiration from what others have done, given similar event information, and build upon/adapt those techniques for LArTPC analysis.

Electrons in MINOS CalDet



T. Yang thesis (2009)

Longitudinal shower development can be reasonably described by a gamma distribution.

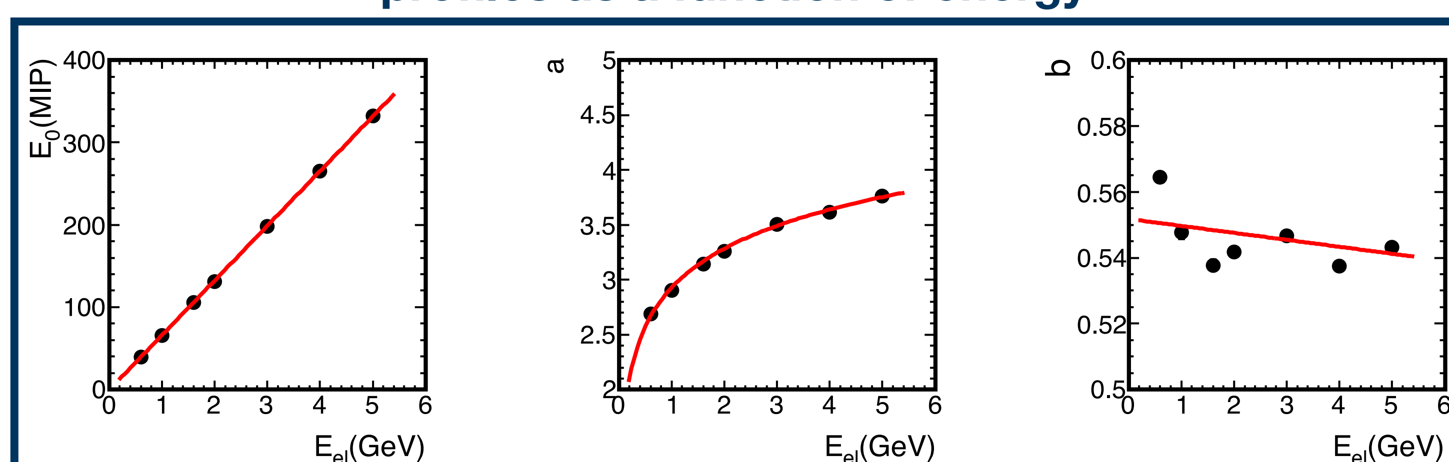
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

The maximum shower develop occurs at

$$t_{\max} = (a-1)/b$$

Similar studies can be done using transverse shower profiles.

The best fit parameters for longitudinal shower profiles as a function of energy



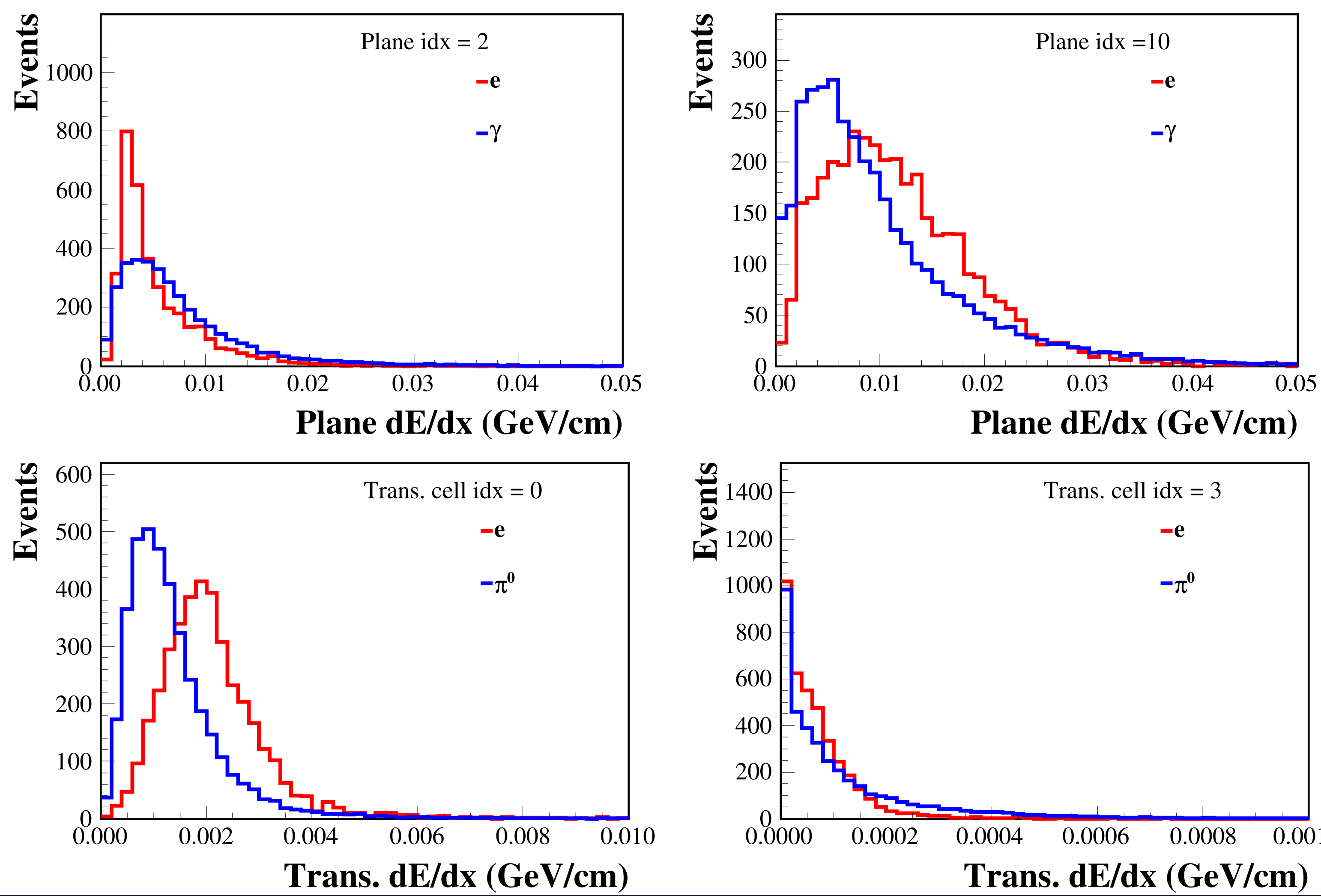
NOvA Electron Identification

NOvA created shower "templates" for each longitudinal plane and transverse cell within a shower. Candidate electrons were assigned a likelihood based on the template charge distributions.

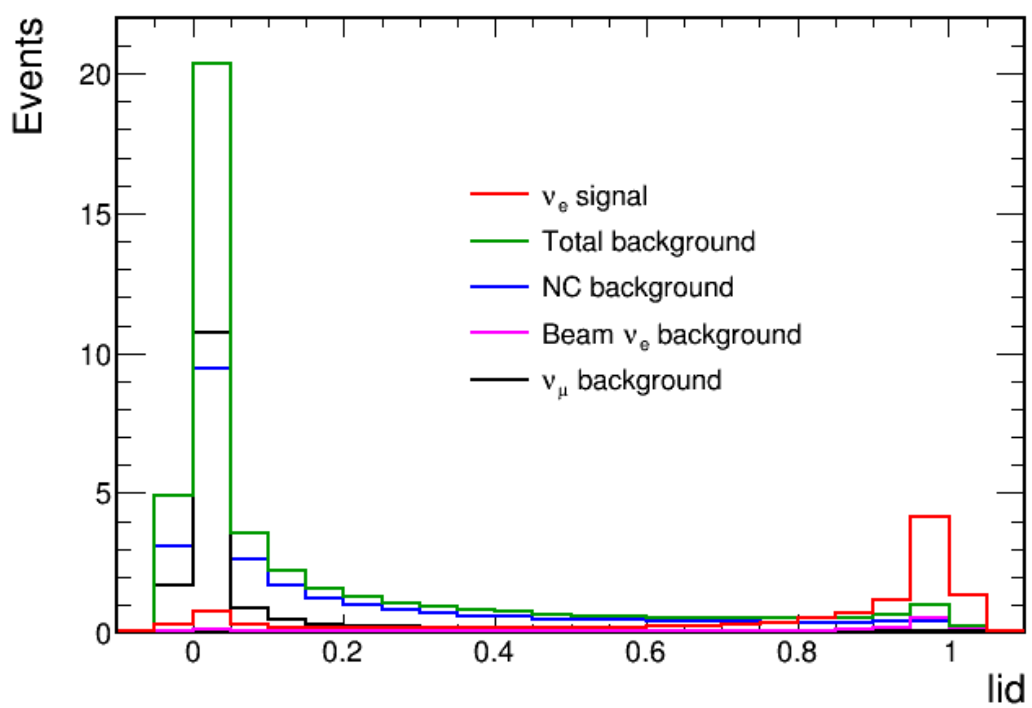
Templates were created for unique regions within the detector to account for systematic detection differences due to interaction location.

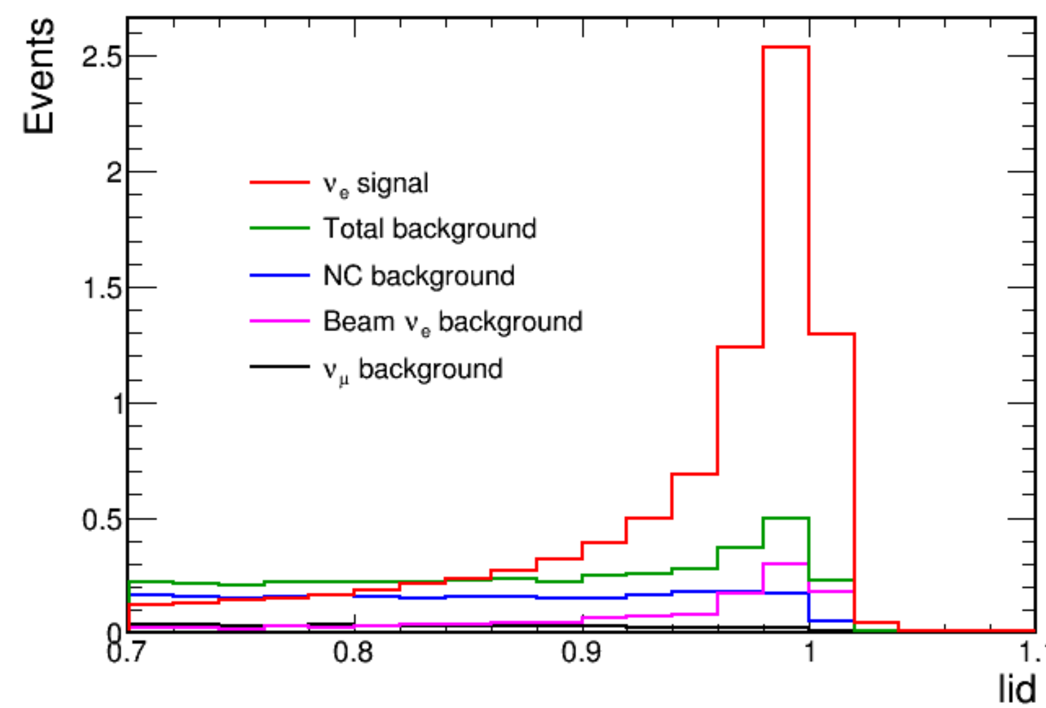
Similar strategies have been implemented for DUNE. ArgoNeuT is in a position to validate these reconstruction techniques.

E. Niner thesis (2015)



NOvA Electron Identification II





The likelihood ratios between electron score and other particle scores were used in combination with traditional variables like vertex energy, gap, pi0 mass, and angle as input to an artificial neural net.

E. Niner thesis (2015)

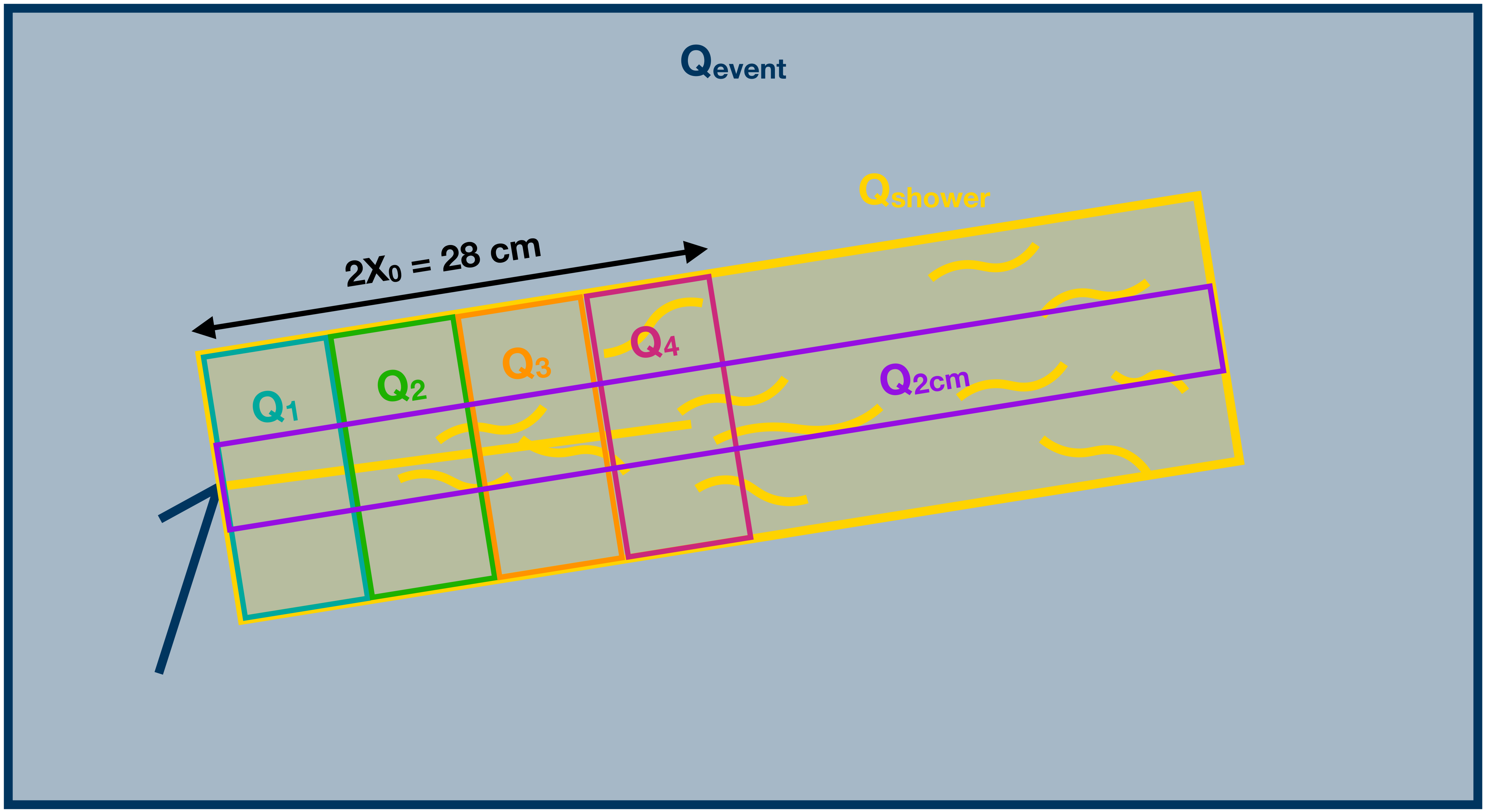
ArgoNeuT Considerations

- **Statistics:** ArgoNeuT only ran for 5 months. There's a limit to what can be done with the dataset and MC. We lack the statistics to produce likelihood templates like NOvA.
- **Containment:** ArgoNeuT's detector was 47(w) x 40(h) x 90(l) cm^3. The radiation length in argon is 14 cm.
  - Energy reconstruction must correct for lack of containment.
  - A large fiducial cut is placed on the downstream end of the detector to better ensure that electrons begin to shower within the detector volume.
- **MINOS:** We can make use of the MINOS ND to reject charged current muon neutrino events because muons produced in ArgoNeuT can be easily tagged with MINOS data.

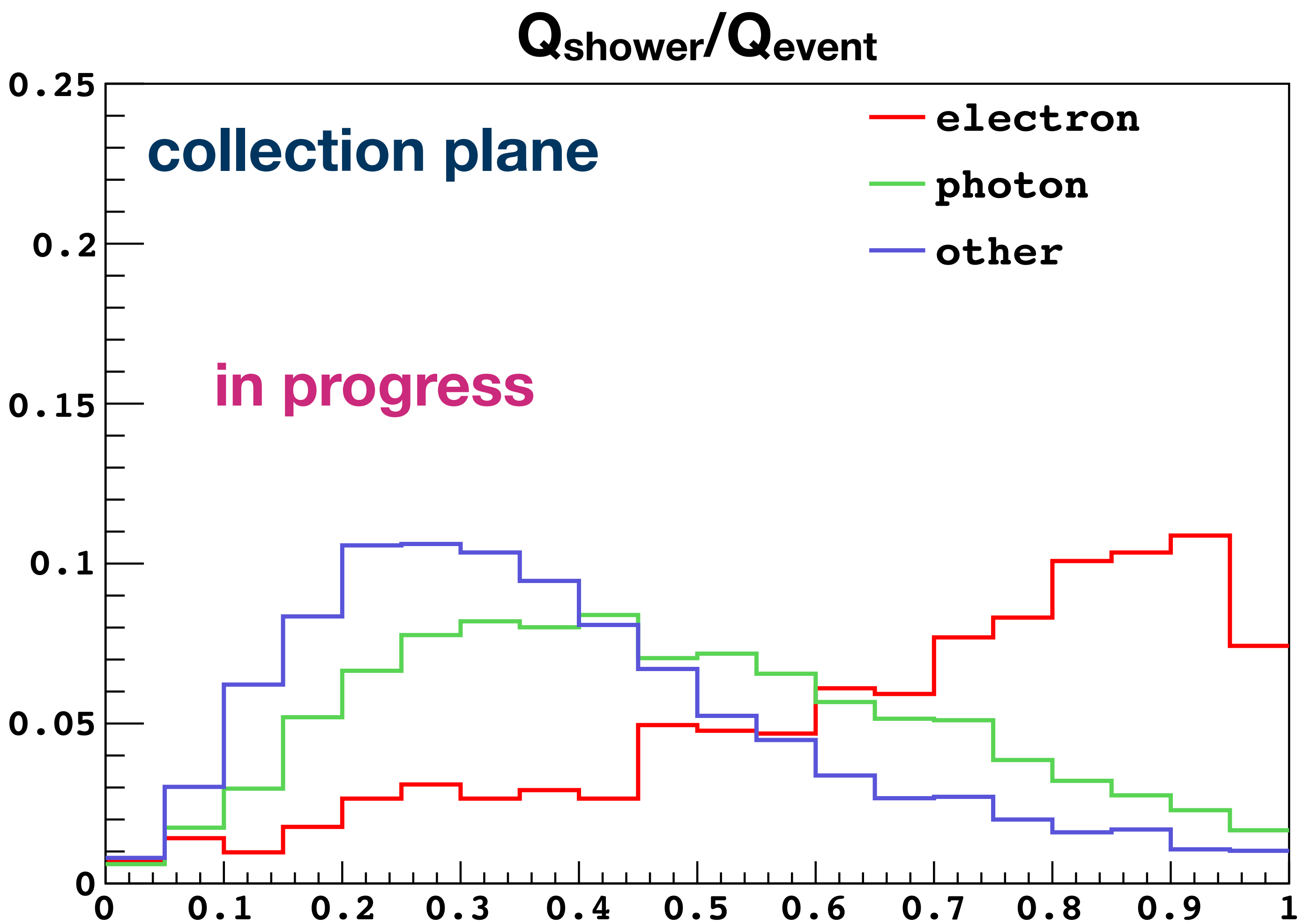
Nevertheless, we can adapt these ideas to study electron neutrinos in ArgoNeuT and inform reconstruction at the GeV scale for future LArTPCs.

let's define some charge regions

not to scale

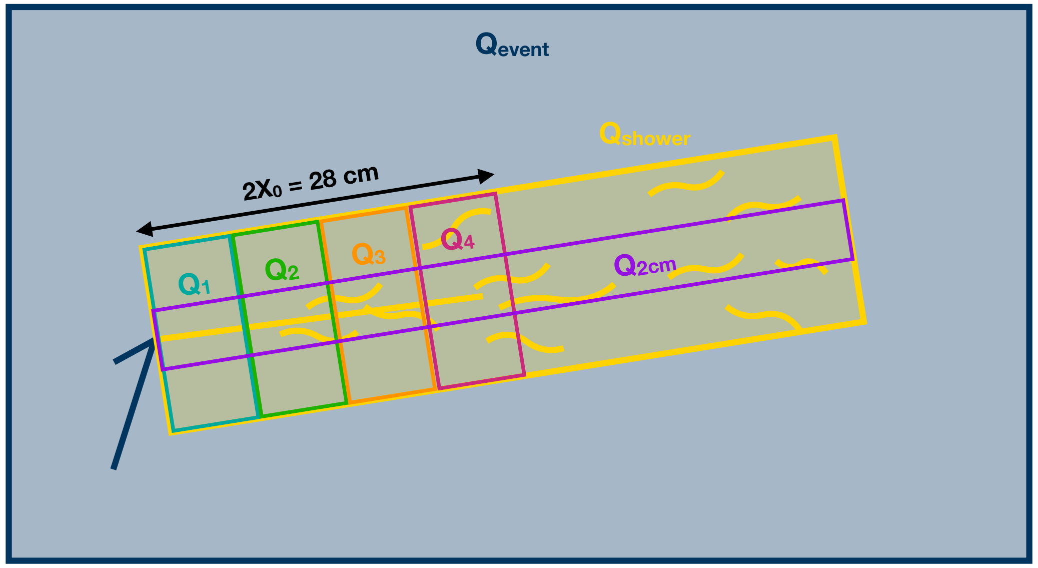


Charge Ratio I



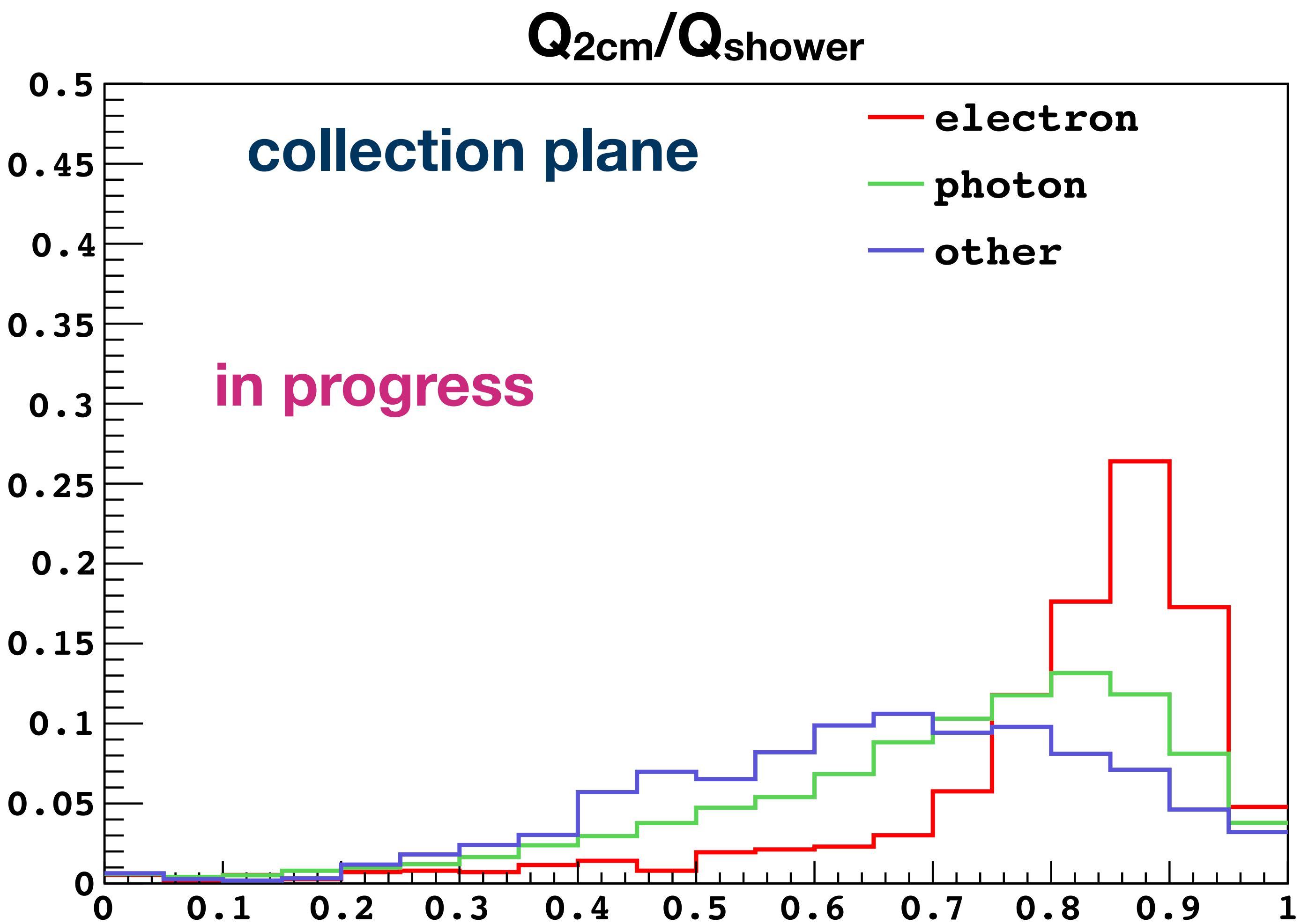
In a larger TPC, you could imagine replacing Q_{event} with Q_{slice}, where each "slice" is a spatially clustered group of energy depositions. In theory (and hopefully in practice) each neutrino interaction, cosmic, etc. is contained in its own slice.

not to scale



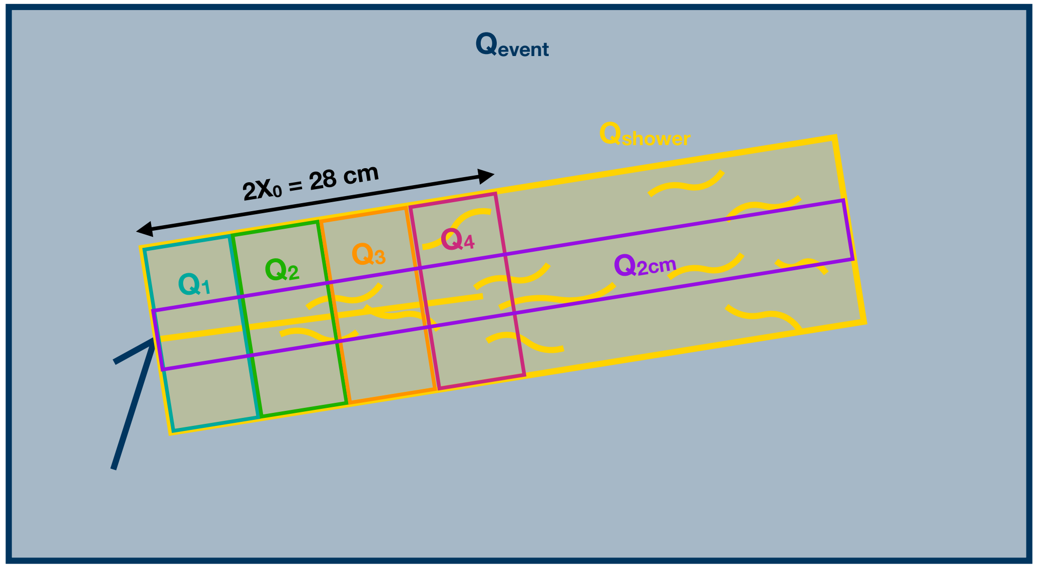
Need further study to determine how much of this difference is related to the different energy spectrums between electrons and photons in ArgoNeuT.

Charge Ratio II



The Moliere radius in argon is 9 cm, which is impractical given the size of ArgoNeuT.

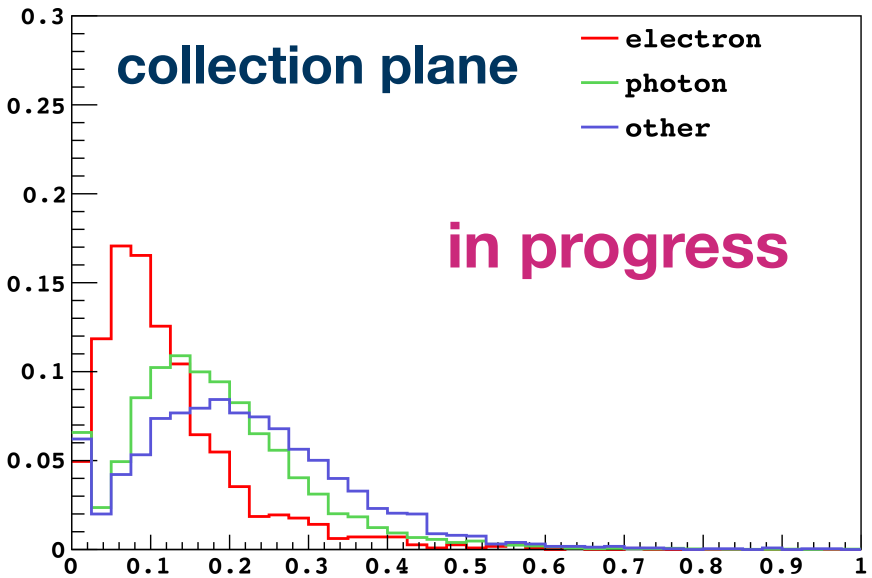
not to scale



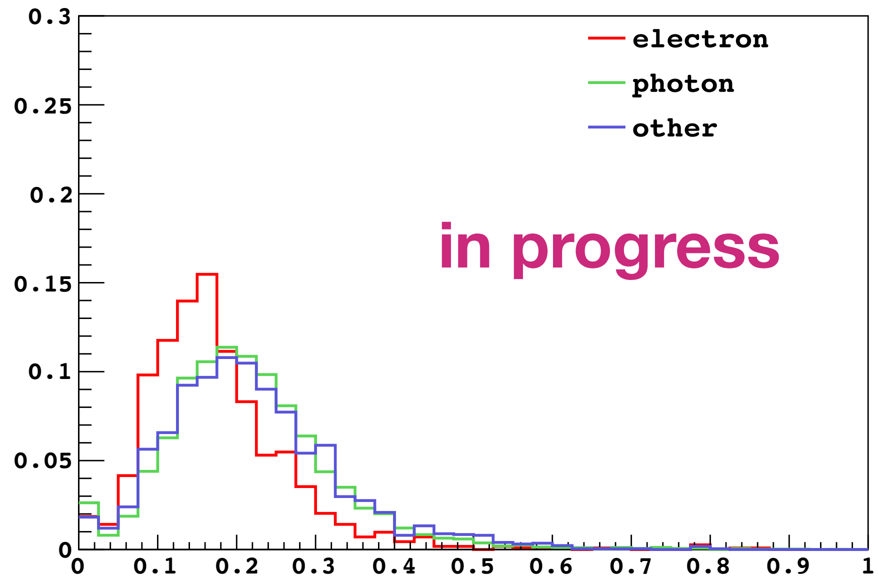
Studies of reconstructed shower purity indicate that hadron overlap affects photon reconstruction (i.e. reconstructed photons are not as pure as electrons).

Charge Ratio III

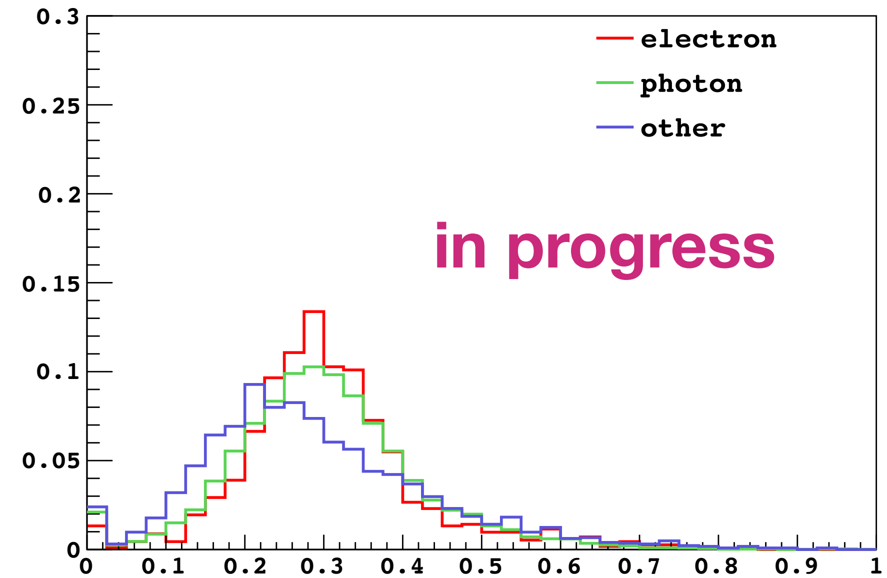
$Q_1 / \sum Q_n$



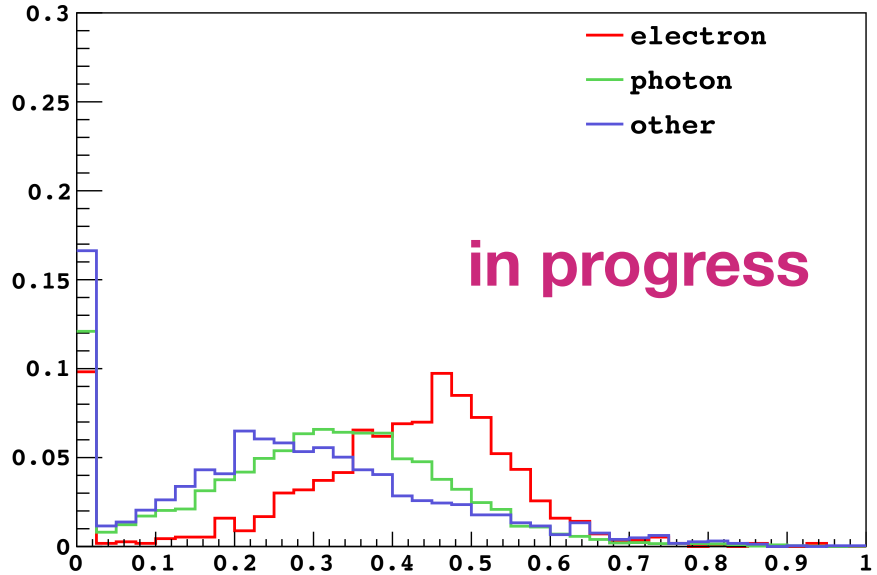
$Q_2 / \sum Q_n$



$Q_3 / \sum Q_n$



$Q_4 / \sum Q_n$



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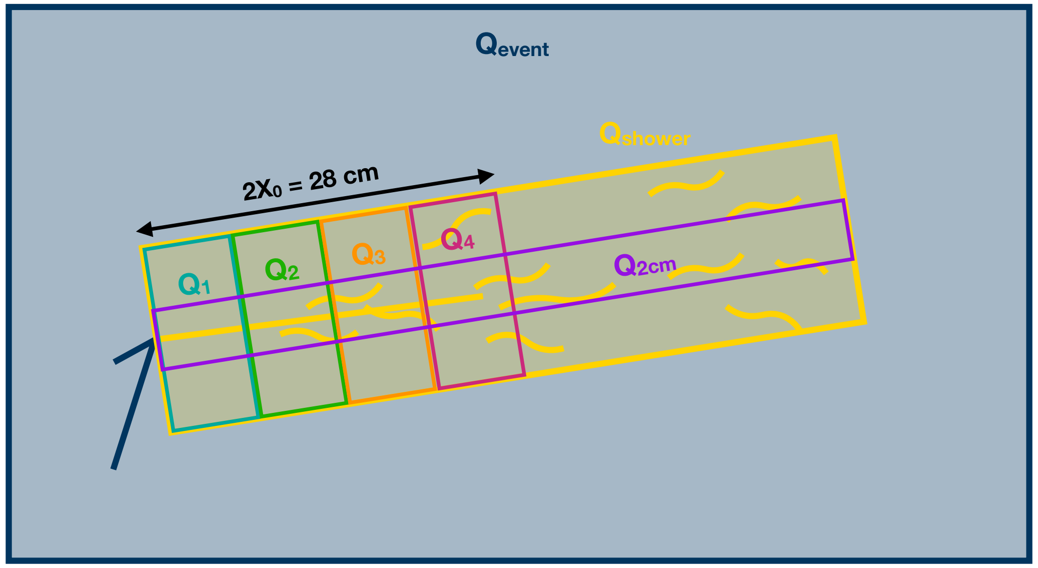


Summary

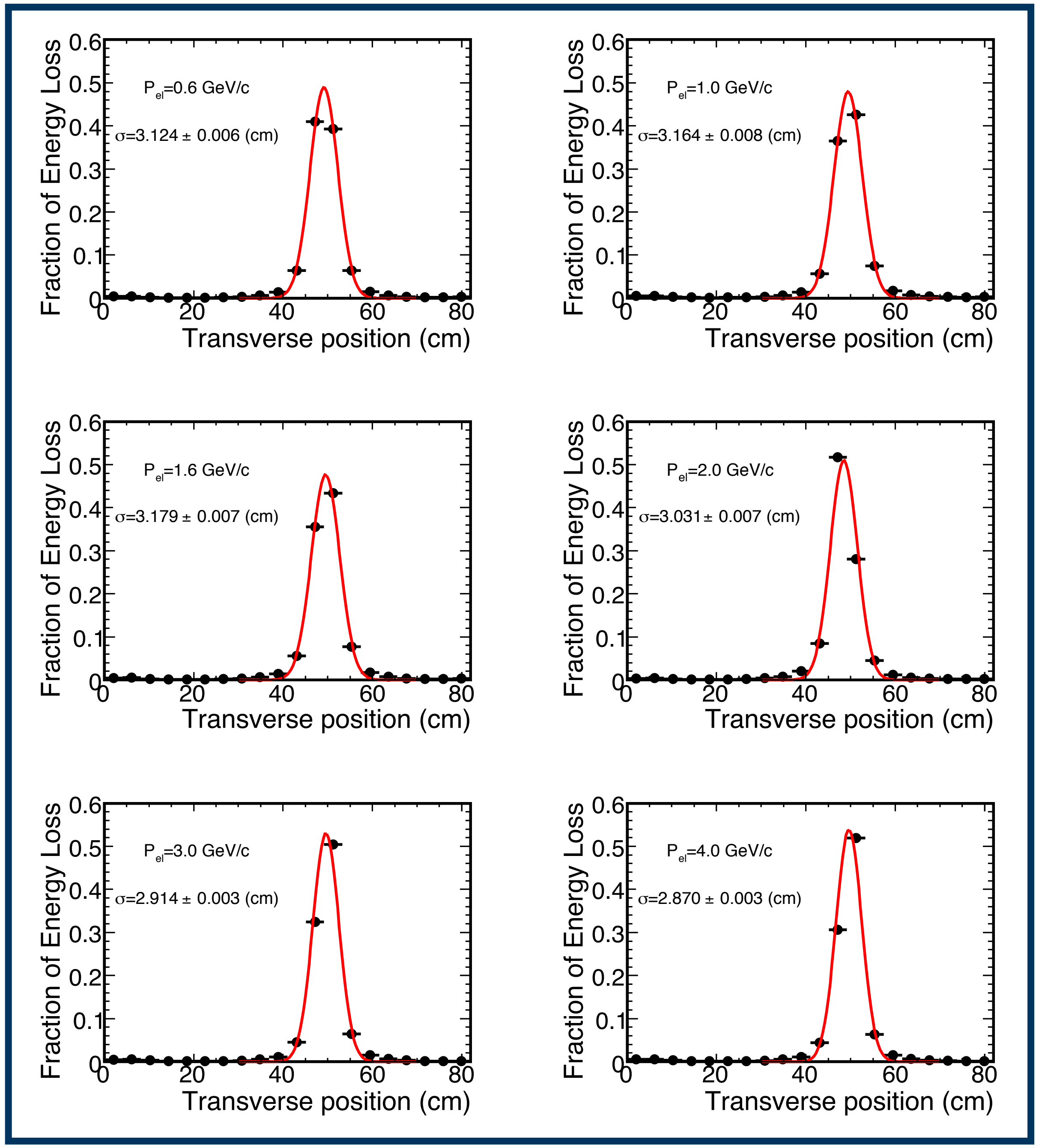
- We can use these variables, in combination with the traditional dE/dx and vertex separation to improve our background rejection.
- For electron neutrino searches at a few GeV, hadronic overlap with photons can mimic electron topology near the neutrino vertex. Hadronic overlap with electrons can mimic photons.
- These tools let us look at the entire structure of the shower to select candidate electrons when dE/dx and vertex separation are insufficient.
- ArgoNeuT is in a unique position to be able to validate reconstruction strategies being developed for DUNE.

Discussion

- LArTPCs like DUNE with GeV-scale electron signals need to develop reconstruction and selection strategies that accommodate hadron overlap near neutrino vertices.
- This requires more than just dE/dx and vertex separation for highly efficient selection.
- We need large electron and photon samples to study shower topology and calorimetry as a function of energy.
- Consider iterative reconstruction: once CC ν_e events are reasonably accurately identified, revisit reconstruction to improve observables such as energy, angle, etc.

Backup

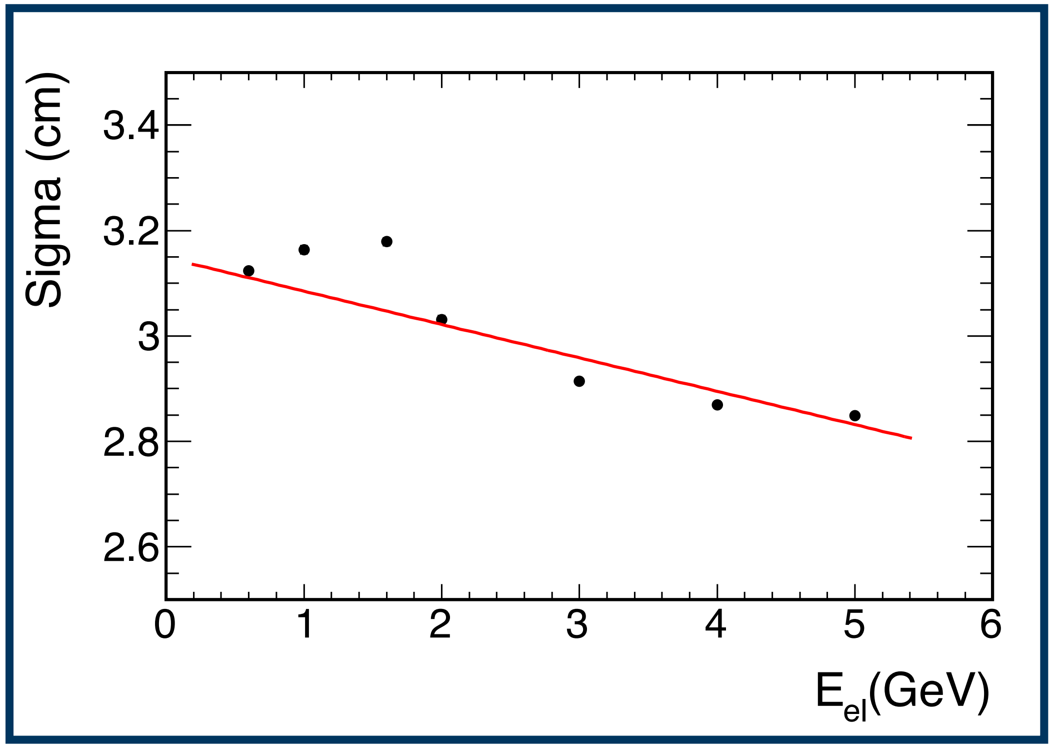
Electrons in MINOS CalDet II



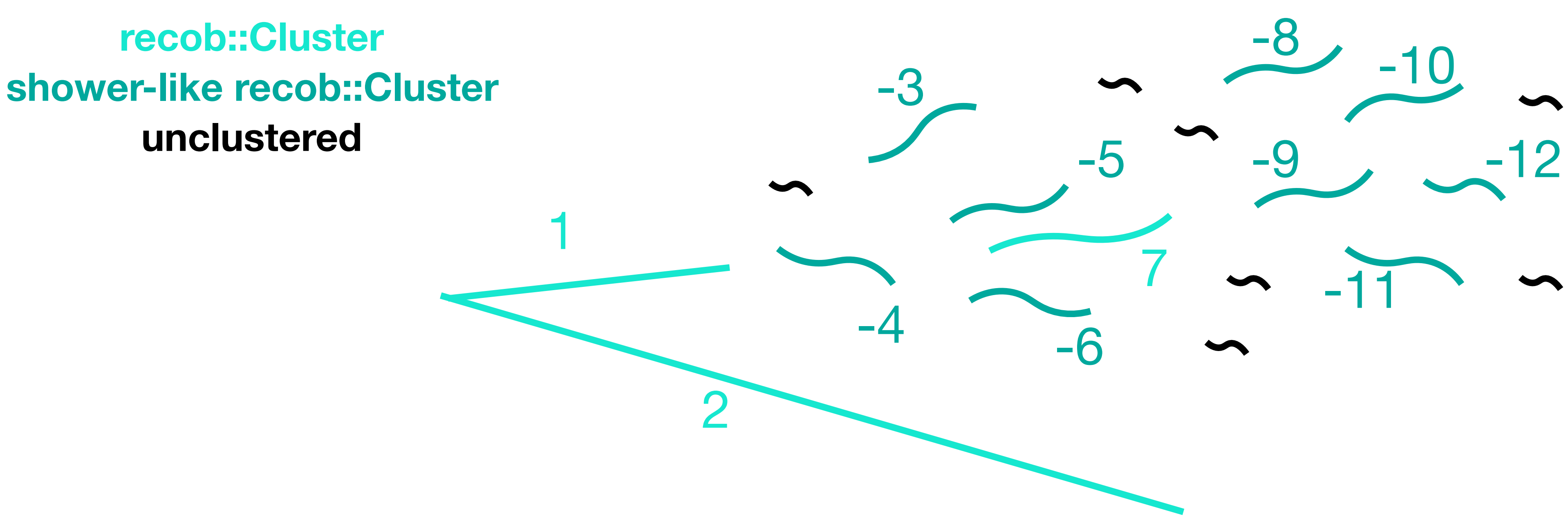
T. Yang thesis (2009)

The transverse width of a shower scales with the Molière radius of a material.

There is also a small energy dependence.



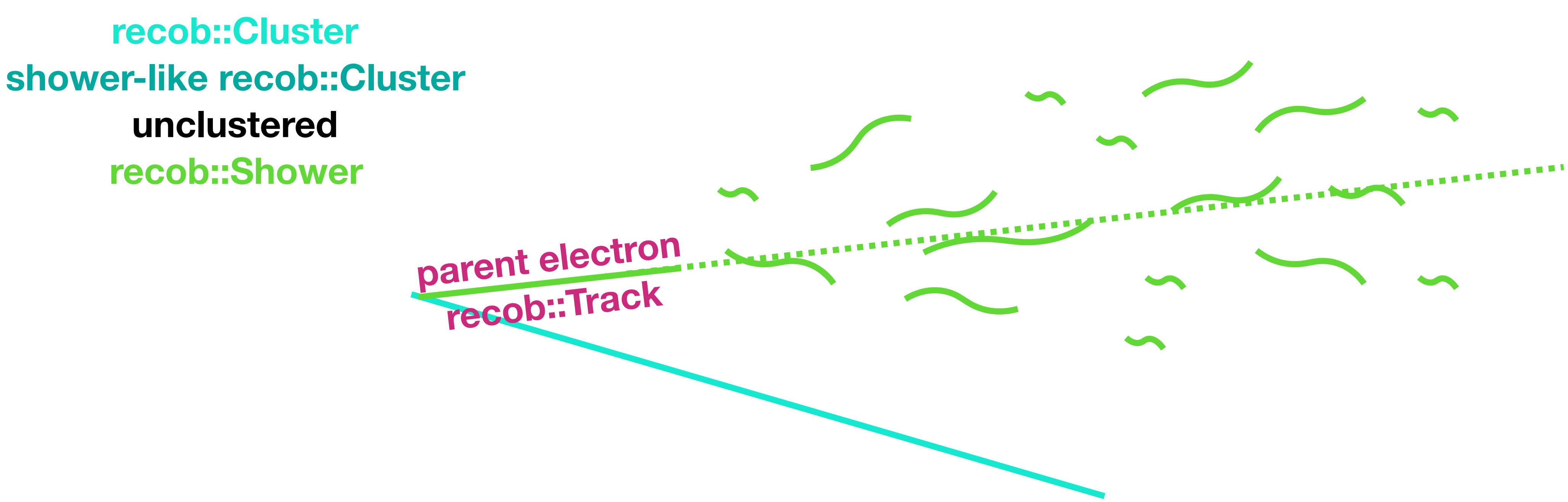
Shower Reconstruction for Electrons



TCShower is built on top of TrajCluster (see Bruce's talk), which can be configured to label "shower-like" clusters of hits.

The shower-like decision is made based on MCS momentum and proximity to other clusters with user-defined thresholds.

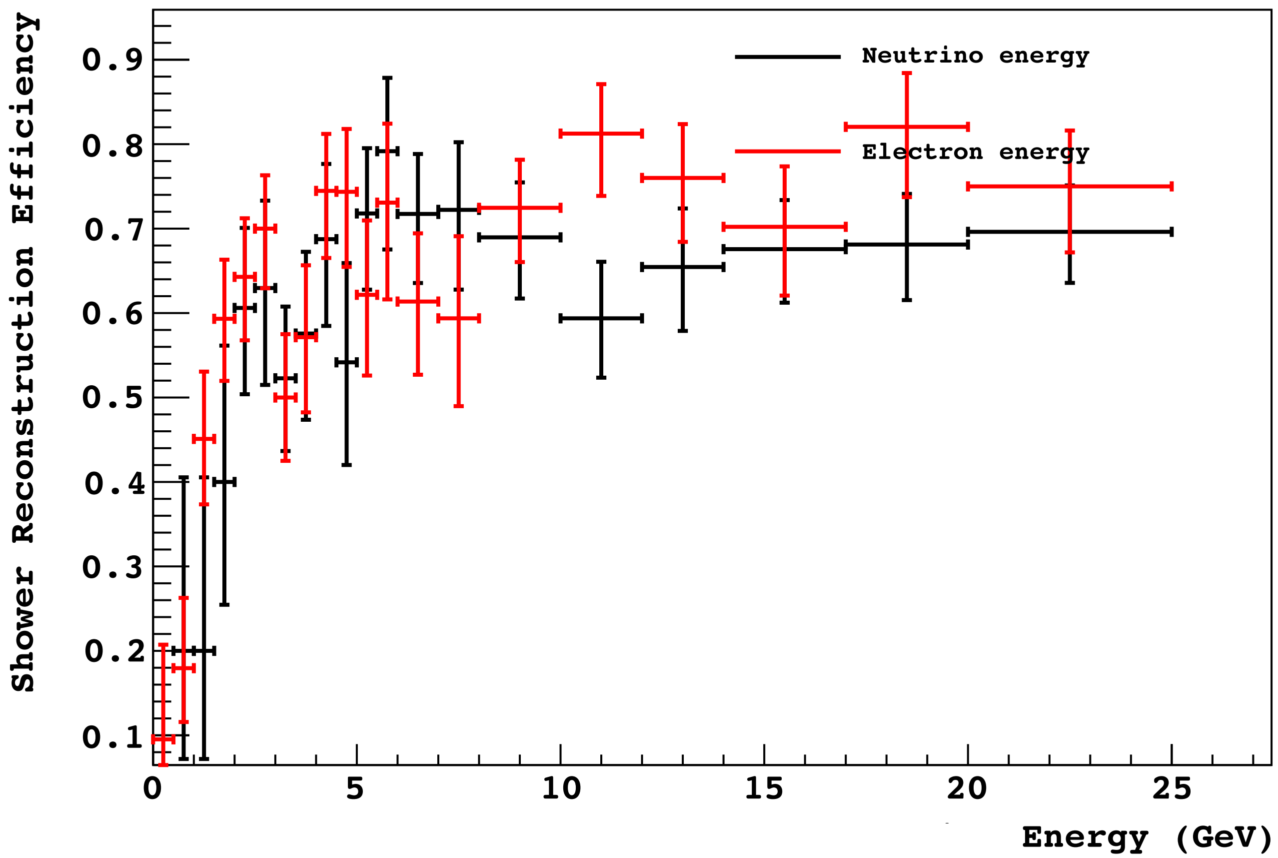
Shower Reconstruction for Electrons

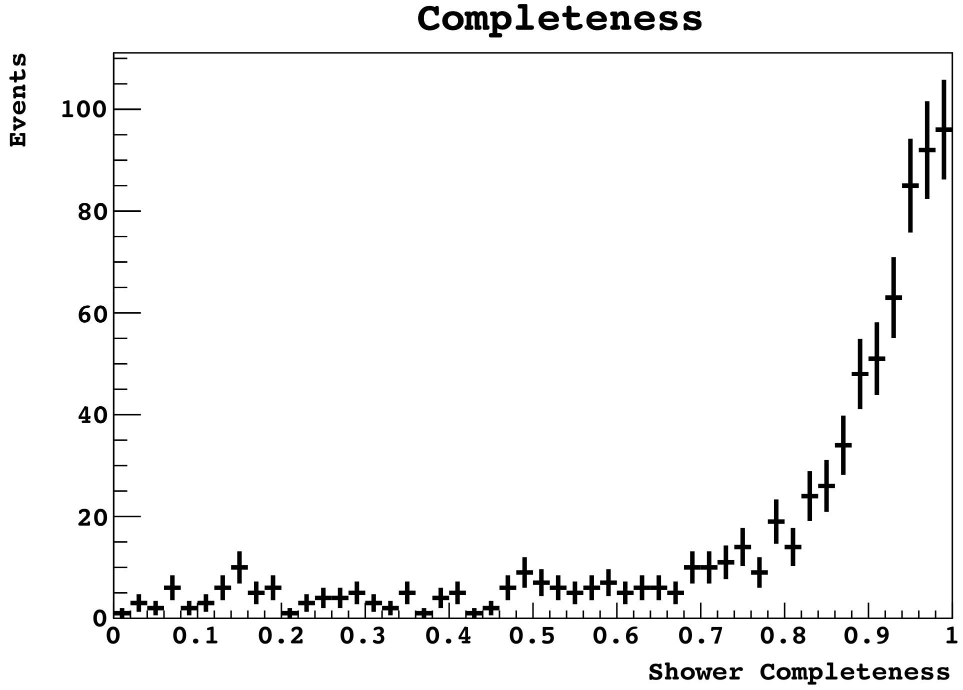


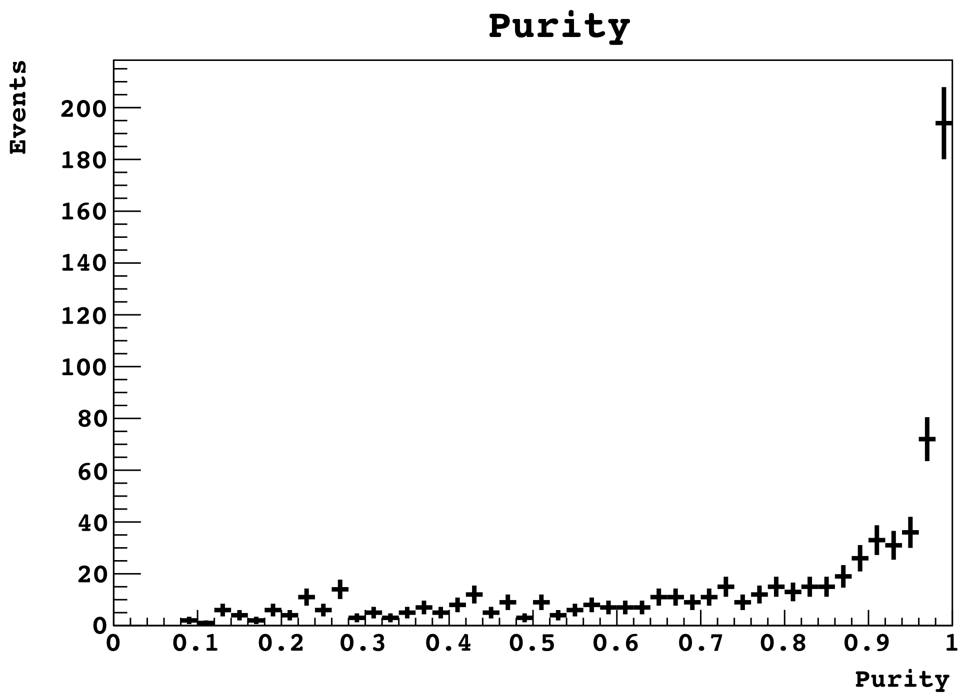
Showers are constructed on each plane around candidate electron tracks. If the candidate track passes a number of thresholds (e.g. minimum number of shower-like hits, reasonably even distribution of hits around track, etc.) it is saved as a shower. A second iteration over hits is done to improve the shower completeness.

The reliable recob::Track information can be used to determine vertex, angle, and dE/dx.

Shower Reconstruction Performance



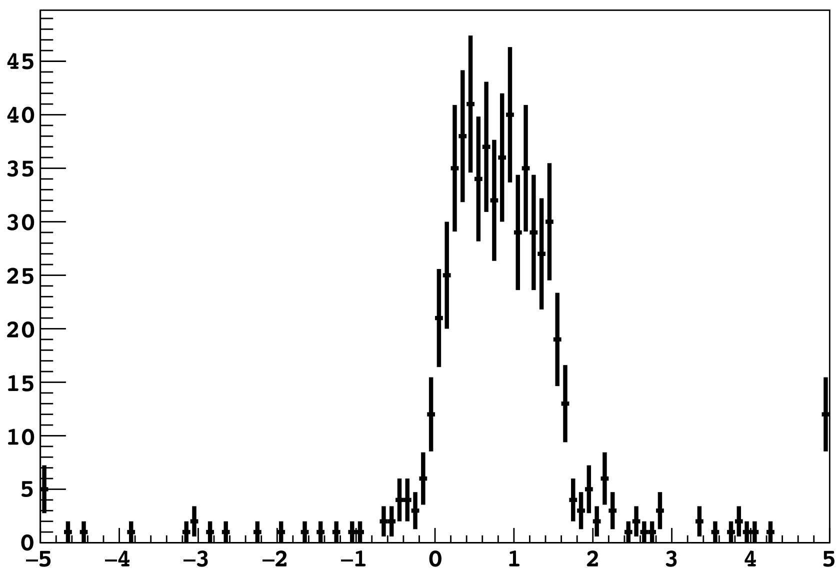




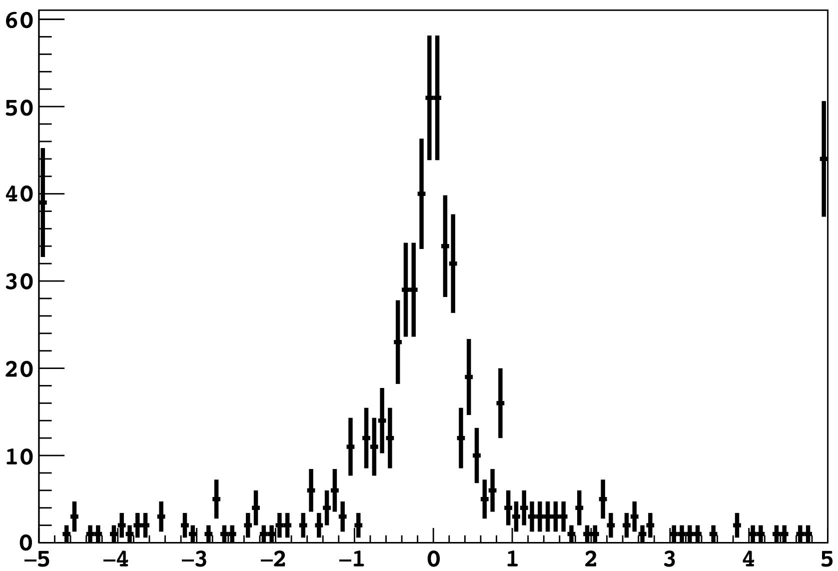
Produced from a sample of 1000 CC nue events

Shower Reconstruction Performance

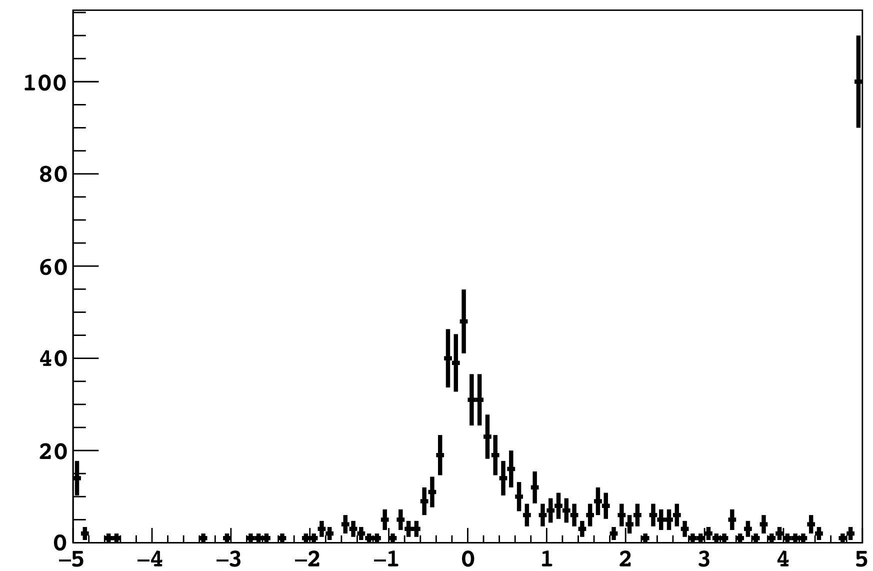
x vertex resolution (reco - truth)

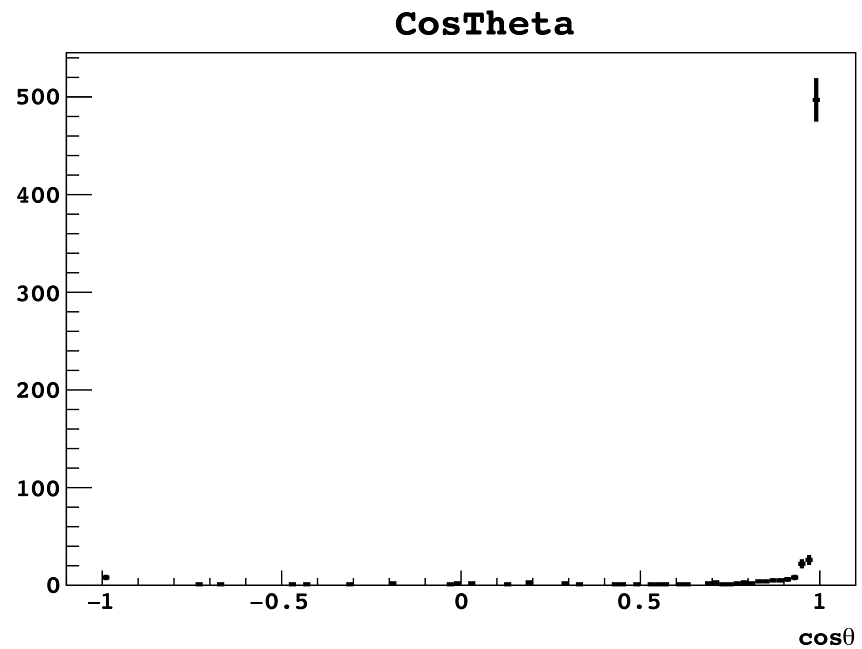


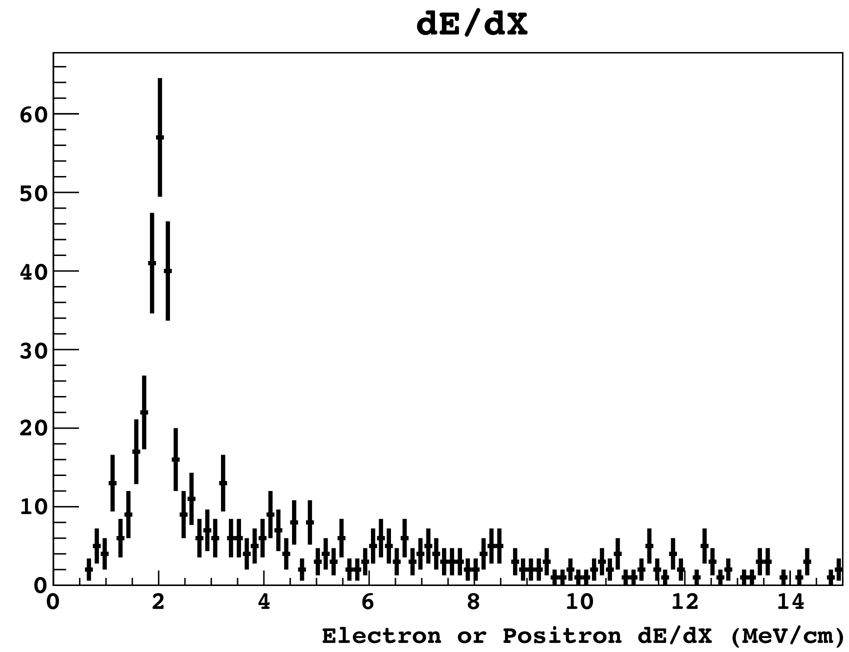
y vertex resolution (reco - truth)



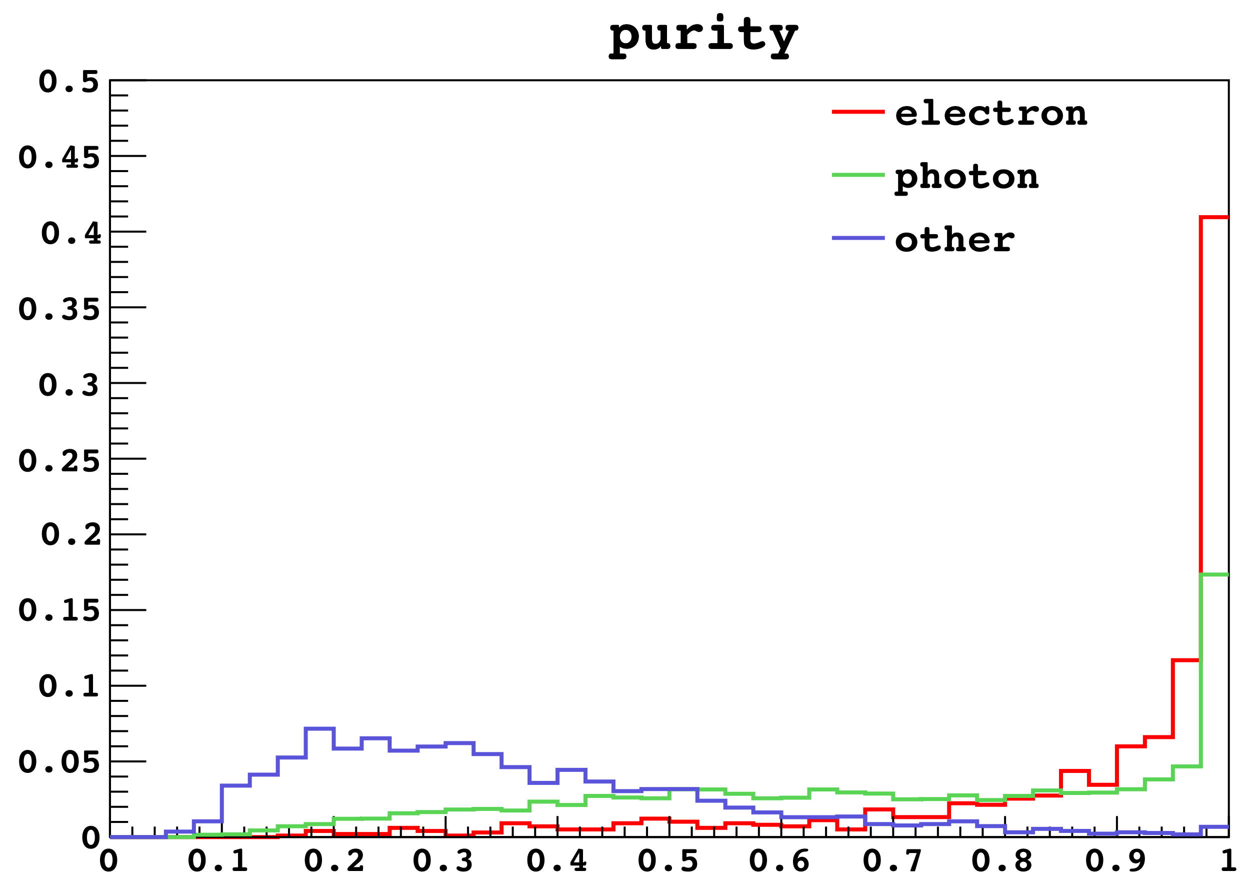
z vertex resolution (reco - truth)







Shower Reconstruction by Particle ID



Shower ID determined by the MCParticle that contributes the most hits to the reconstructed shower.

Reconstruction strategy performs best on electrons.