Neutrino energy reconstruction in the DUNE far detector

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for the DUNE collaboration

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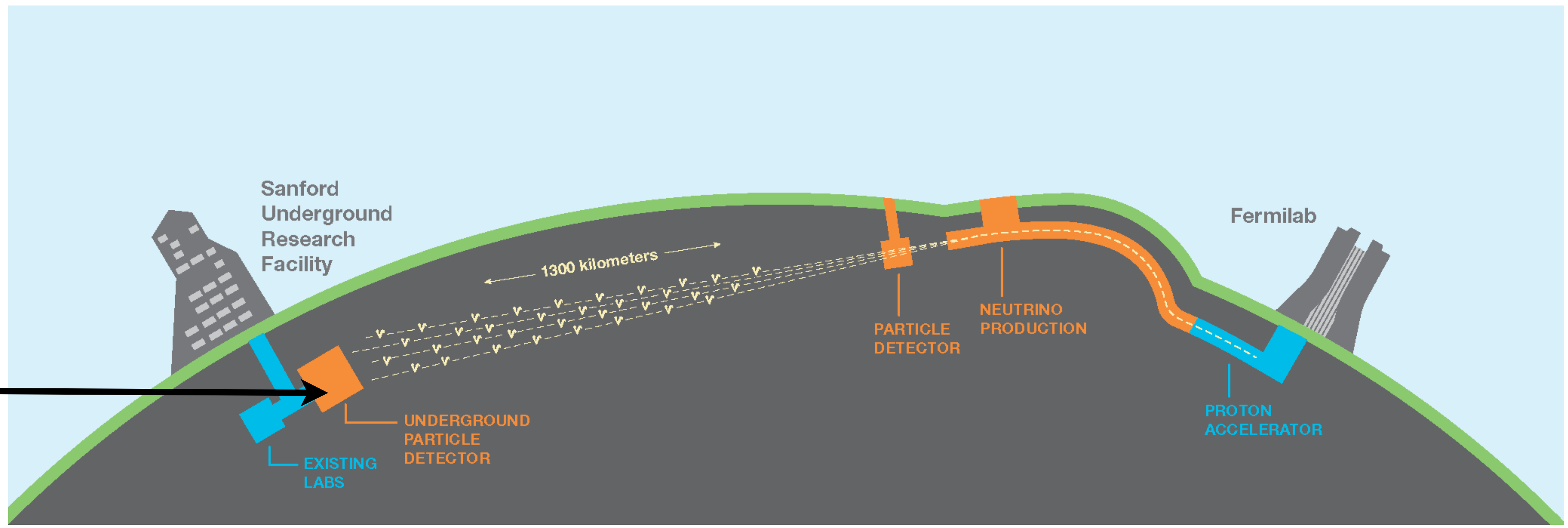
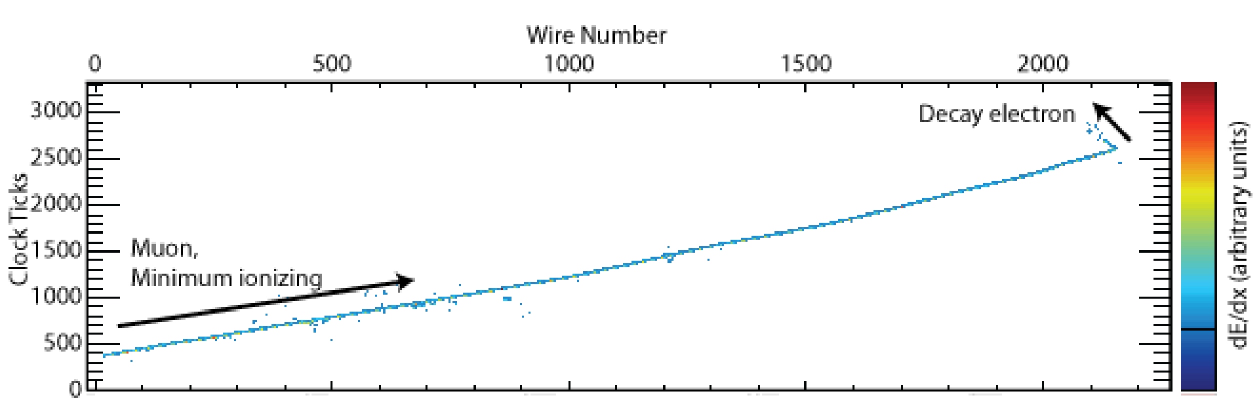
Introduction

DUNE far
detector

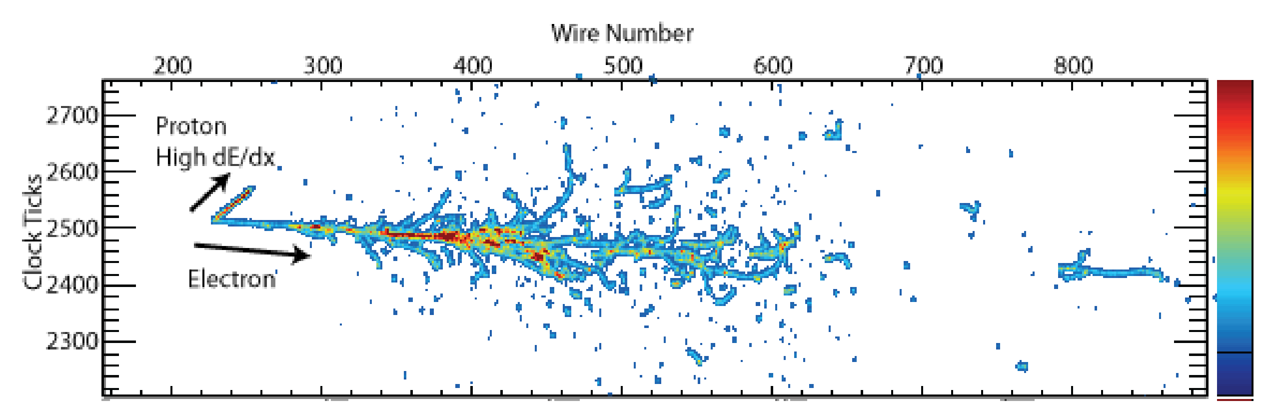


We are working on reconstructing neutrino energy in events selected as ν_μ CC and ν_e CC in the DUNE far detector, which is a liquid argon time projection chamber (LArTPC).

ν_μ CC event in LArTPC



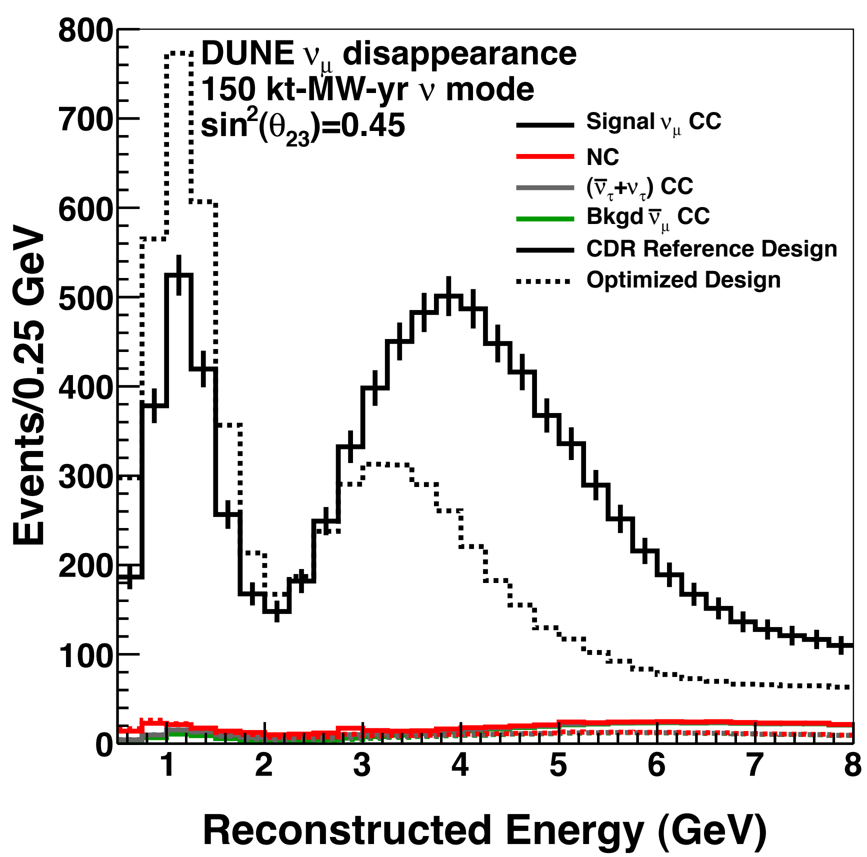
ν_e CC event in LArTPC

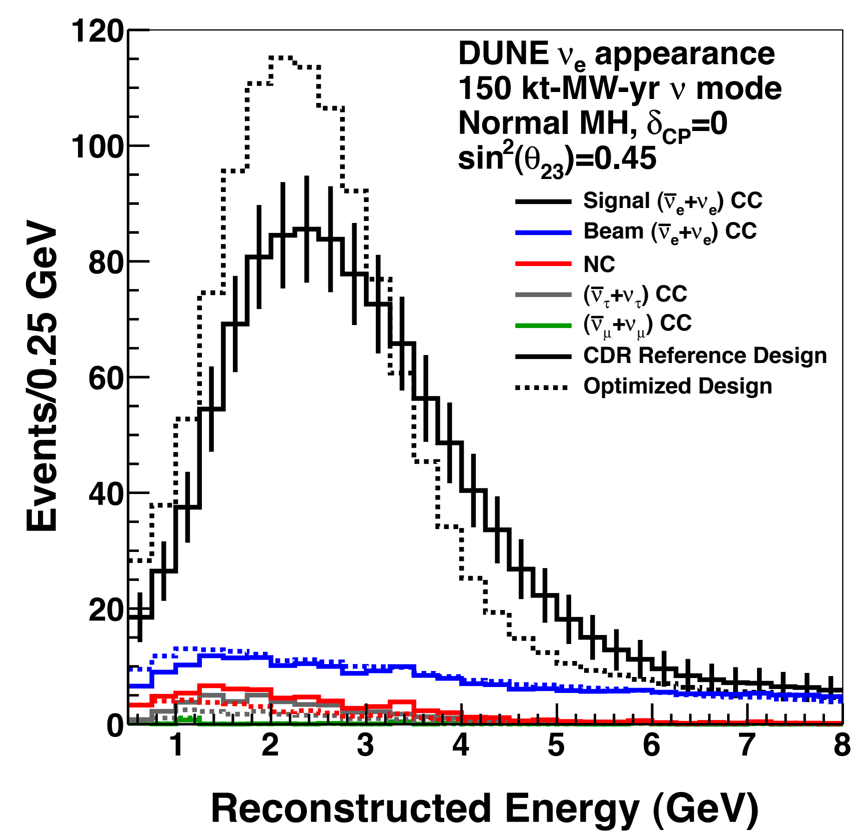


Ref: http://docs.dunescience.org/cgi-bin/ShowDocument?docid=183&asof=2016-1-30

Introduction

Neutrino energy reconstruction is extremely important for DUNE since it will make measurements of neutrino oscillation parameters including the possible CP-violating phase δ_{CP}. Neutrino oscillation depends on true energy, but the energies of the neutrinos interacting in the far detector are unknown, and must be reconstructed as accurately as possible.





Ref: https://arxiv.org/abs/1512.06148

Introduction

We use realistic simulations of the far detector and real reconstruction.

For events selected as ν_μ CC, divide event into longest reconstructed track and hadronic energy.

For events selected as ν_e CC, divide event into reconstructed shower with highest charge and hadronic energy.

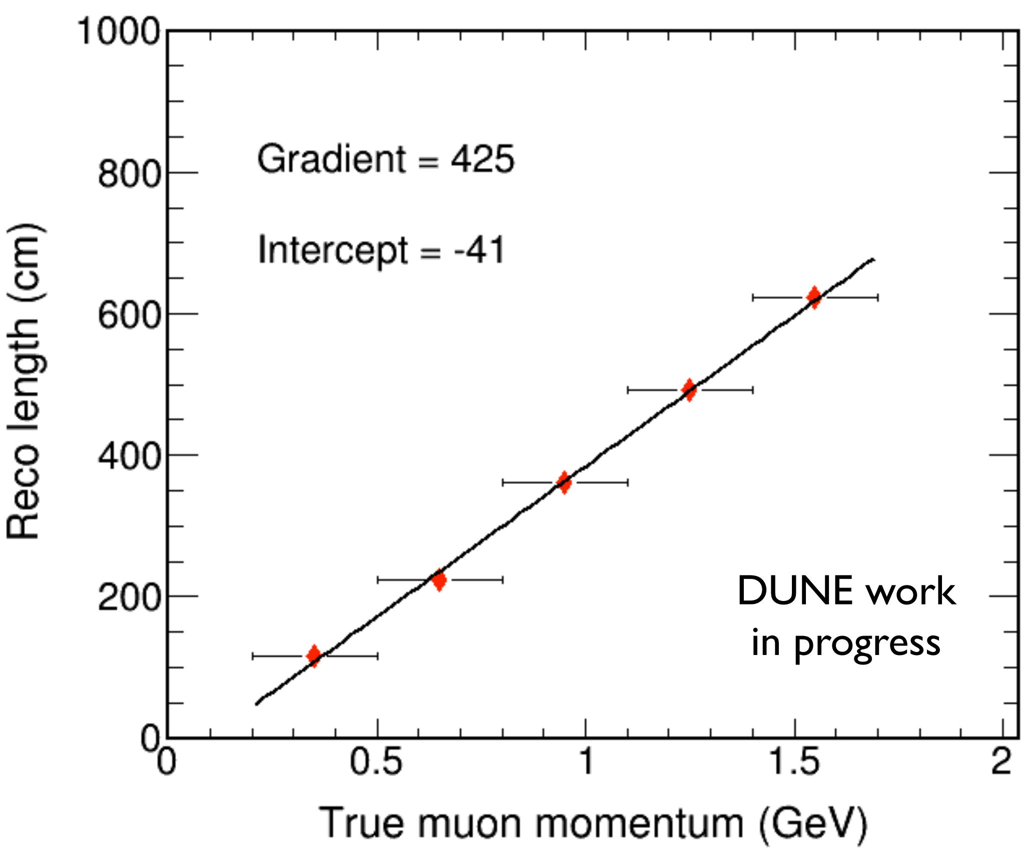
Estimate the hadronic energy using calorimetric information from hits not in track or shower, converting ADC counts to energy after making corrections for electron lifetime and recombination.

ν_μ CC track momentum by range

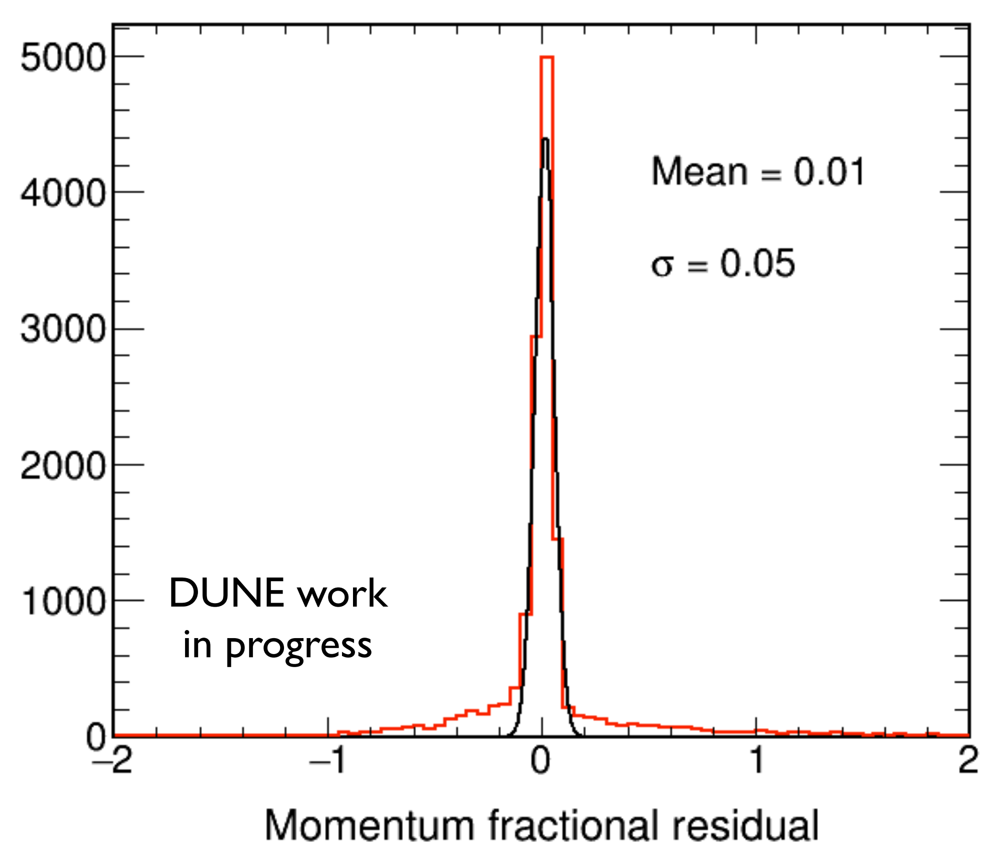
If the longest track is contained within the detector, estimate its momentum from its range. Calibrate track momentum by range using Monte Carlo.

Estimate reco track momentum as (range - intercept) / gradient.

Range momentum calibration



Range momentum fractional residual

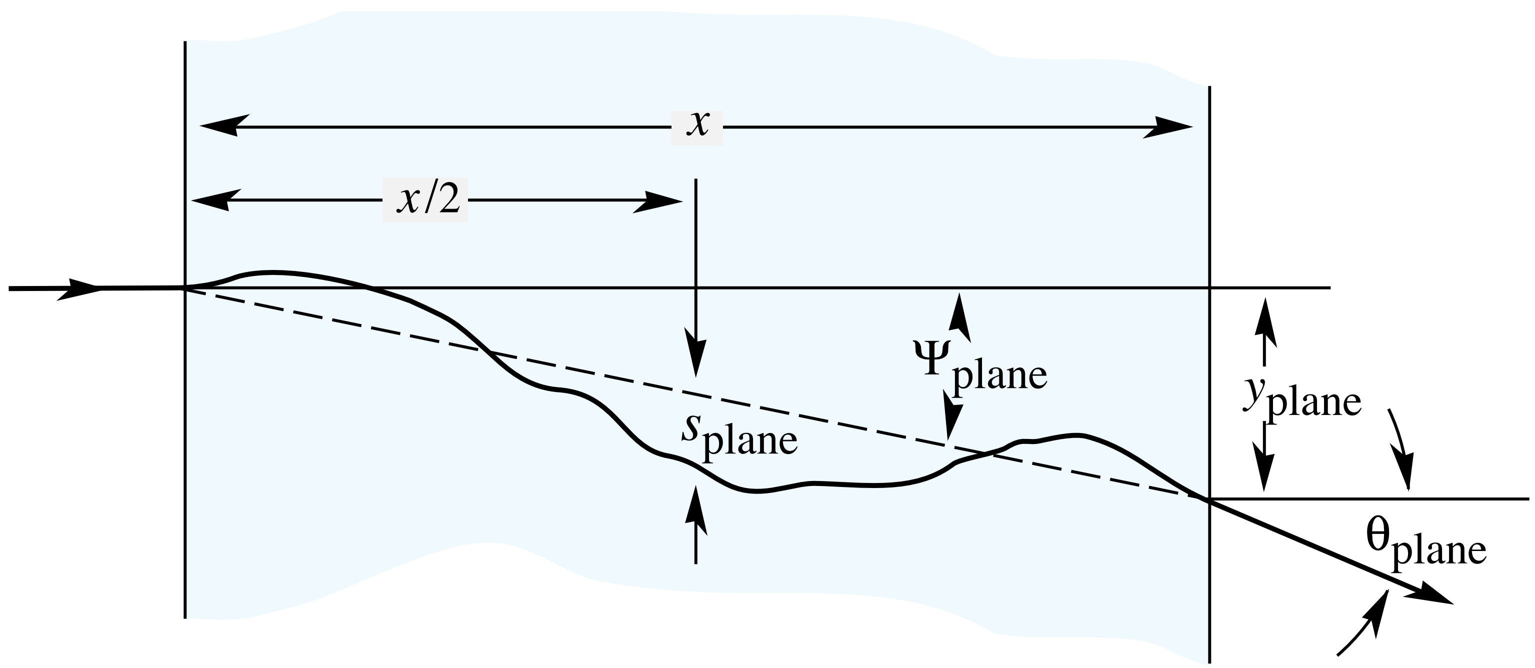


True ν_μ CC events with contained track

MCS track momentum

If the longest reco track exits the detector, estimate its momentum from multi-Coulomb scattering (MCS).

Divide the track into segments of equal length. Fit a straight line to each segment. Scattering angle is angle between successive segments.



Ref: http://pdg.lbl.gov/2014/reviews/rpp2014-rev-passage-particles-matter.pdf

At high momentum, the scattering angle is small, while it is larger at low momentum.

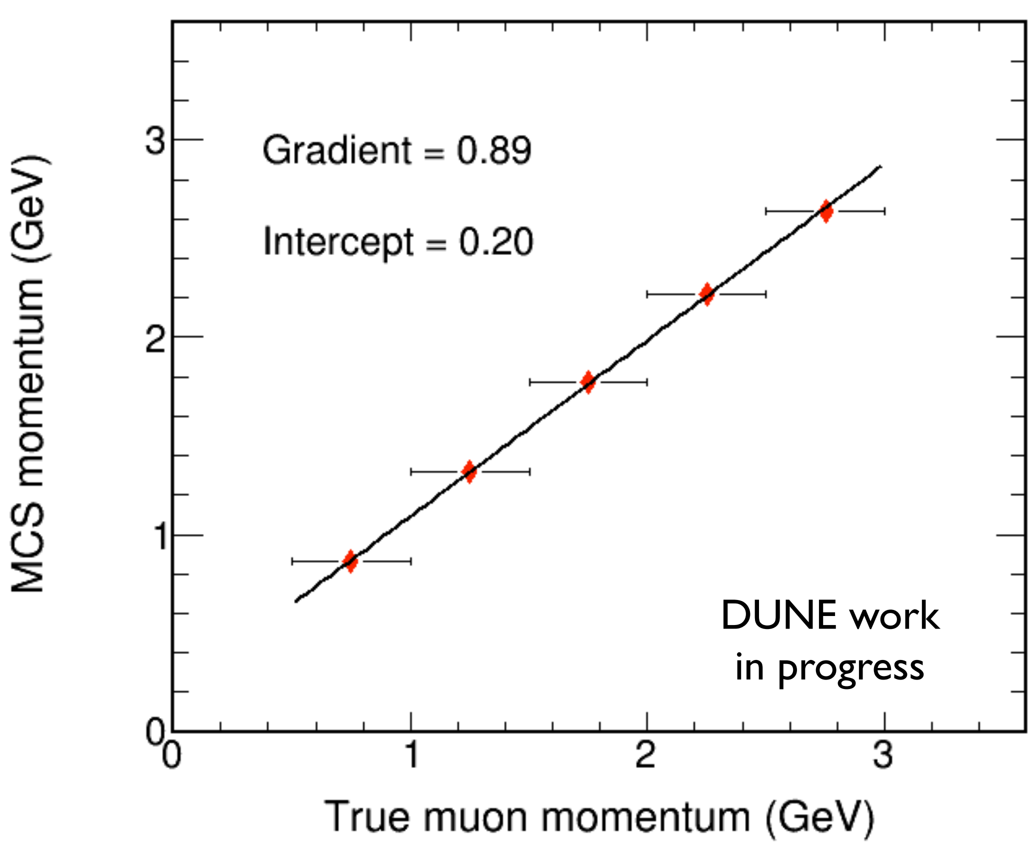
Refs: https://arxiv.org/abs/1703.06187, https://arxiv.org/pdf/hep-ex/0606006v1.pdf

ν_μ CC MCS track momentum

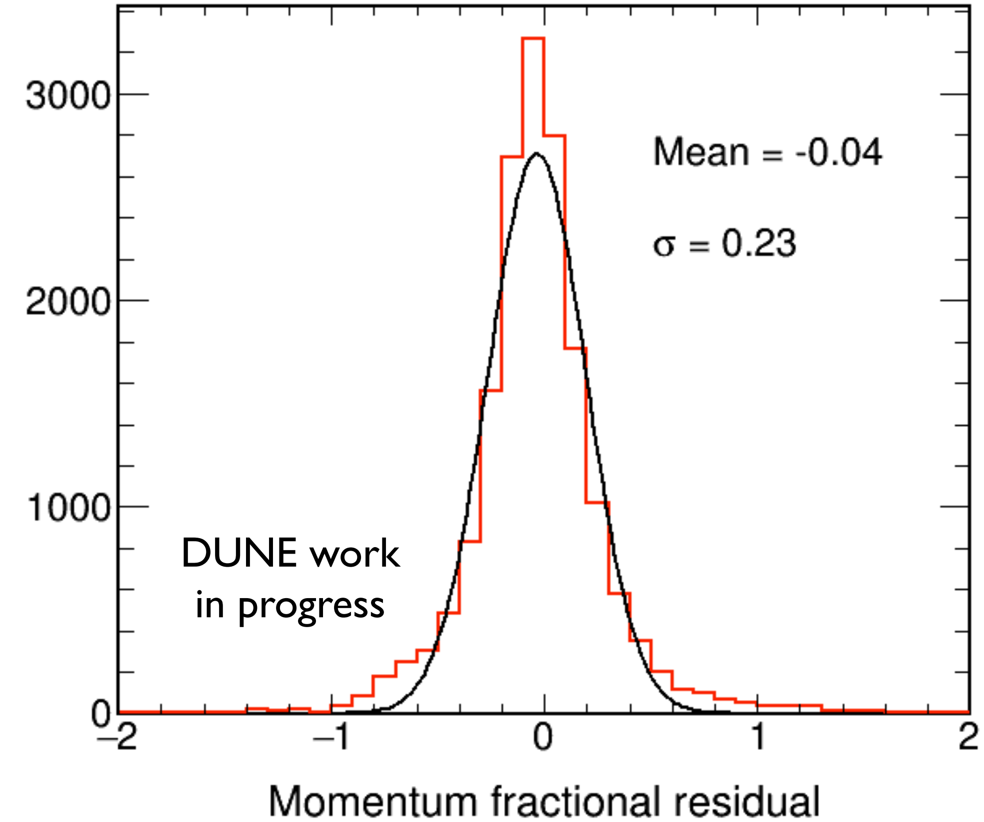
Calibrate MCS momentum using Monte Carlo.

Estimate reco track momentum as (MCS - intercept) / gradient

MCS momentum calibration



MCS momentum fractional residual



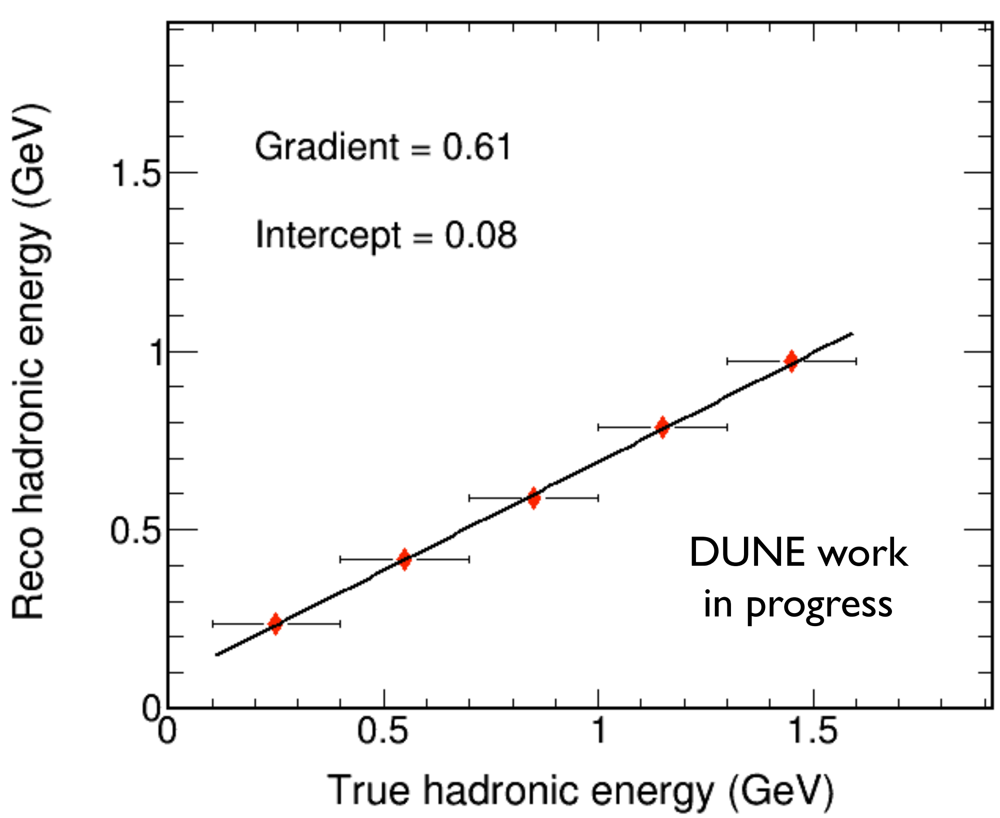
True ν_μ CC events with exiting track

ν_μ CC hadronic energy

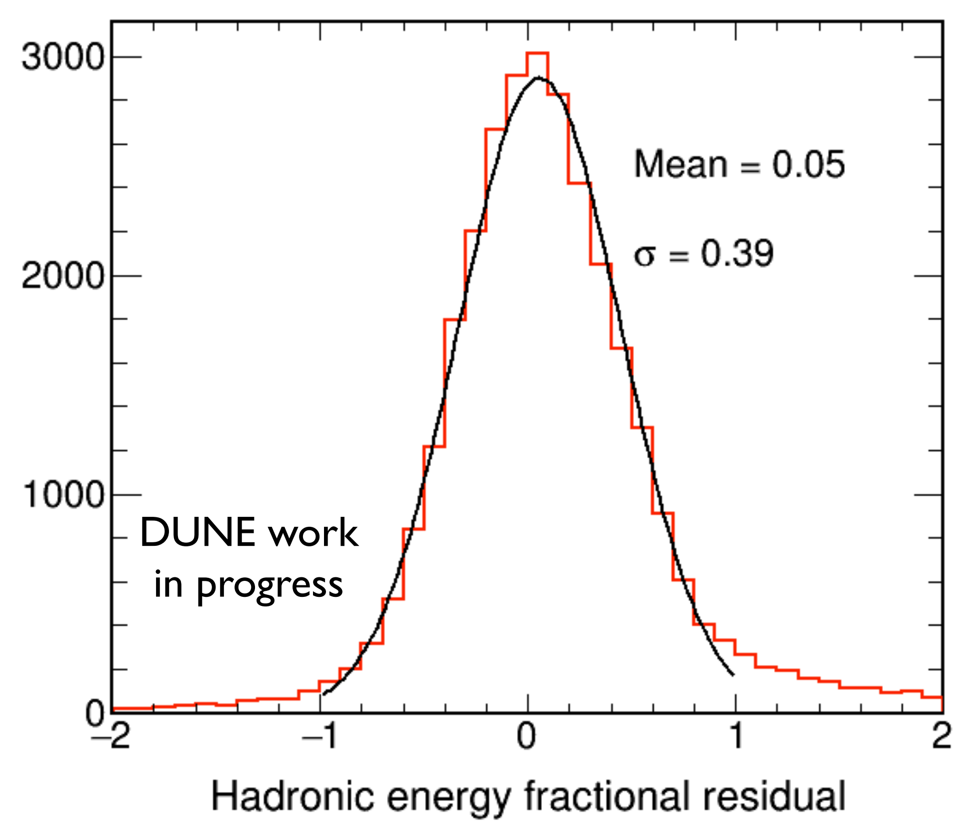
Estimate the hadronic energy from reconstructed hits that are not in the longest track. Make calibration using Monte Carlo.

Reco hadronic energy tends to be too low since neutral particles are not reconstructed in the DUNE far detector. On average 40% of the energy is missing, but there are fluctuations in this from event to event, and this limits energy resolution.

Hadronic energy calibration



Hadronic energy fractional residual



True ν_μ CC events.

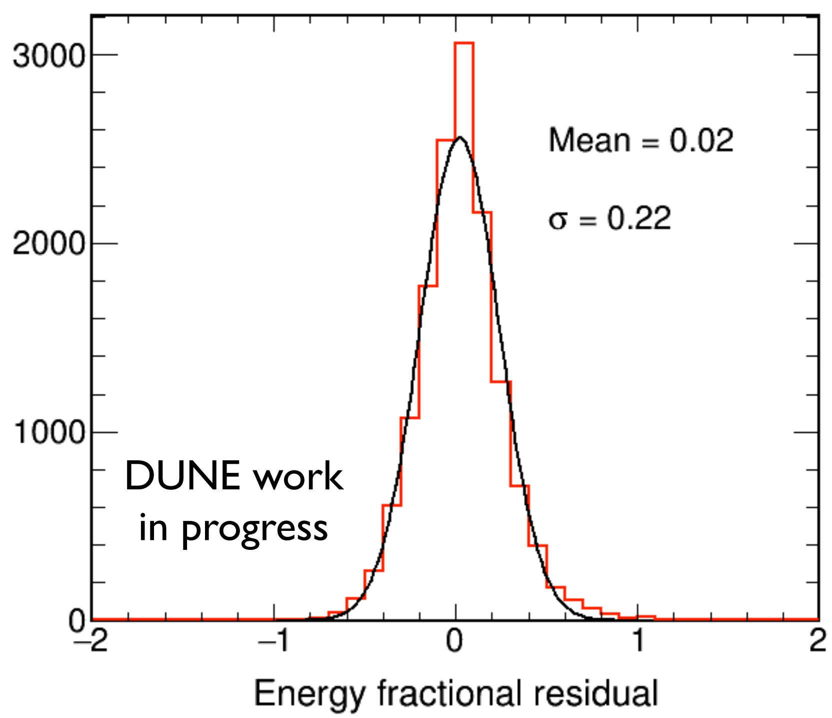
Tail < -1 in resolution plot is due to subtraction of intercept (which is > 0) when making correction.

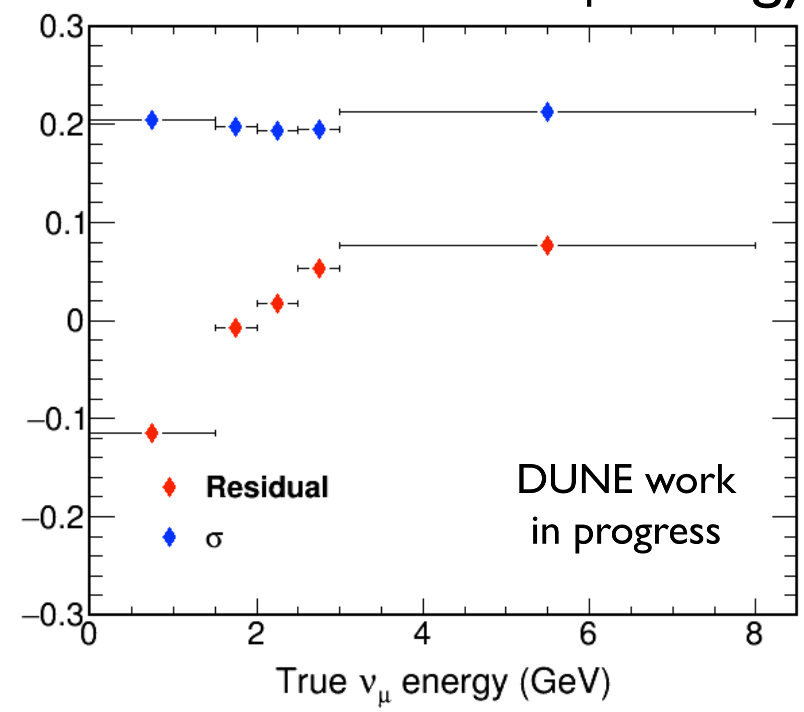
ν_μ CC energy resolution

Overall

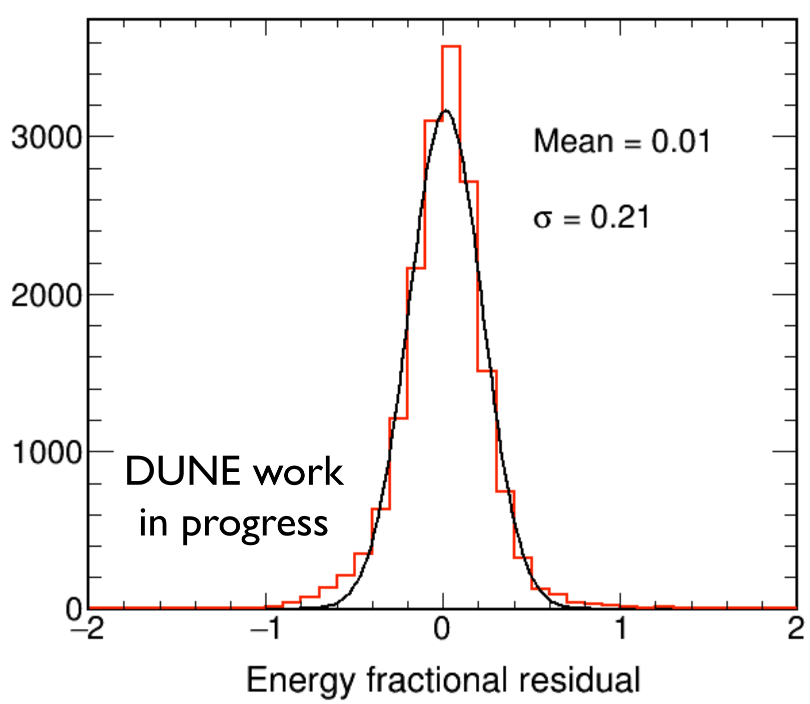
As function of true ν_μ energy

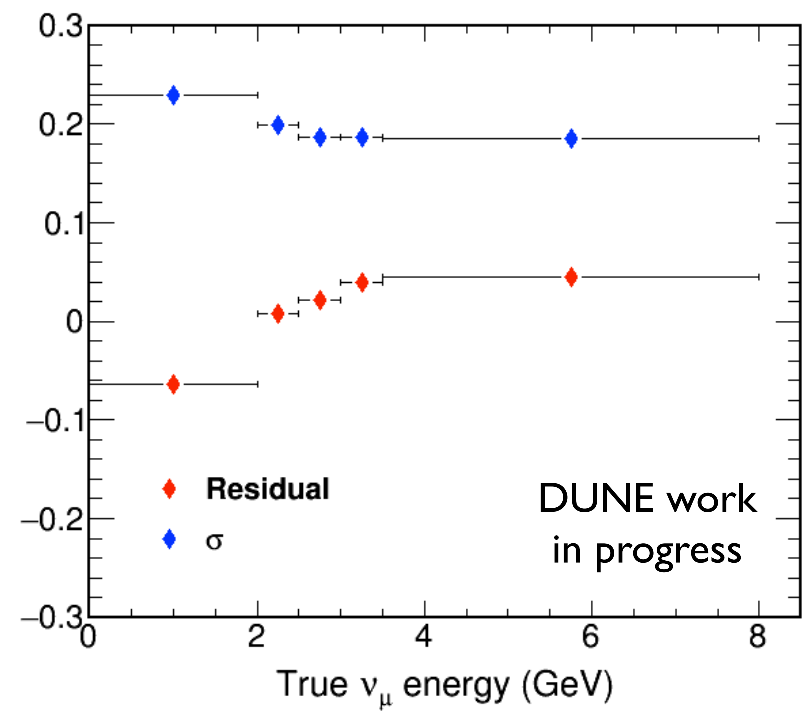
True ν_μ CC events with contained track





True ν_μ CC events with exiting track



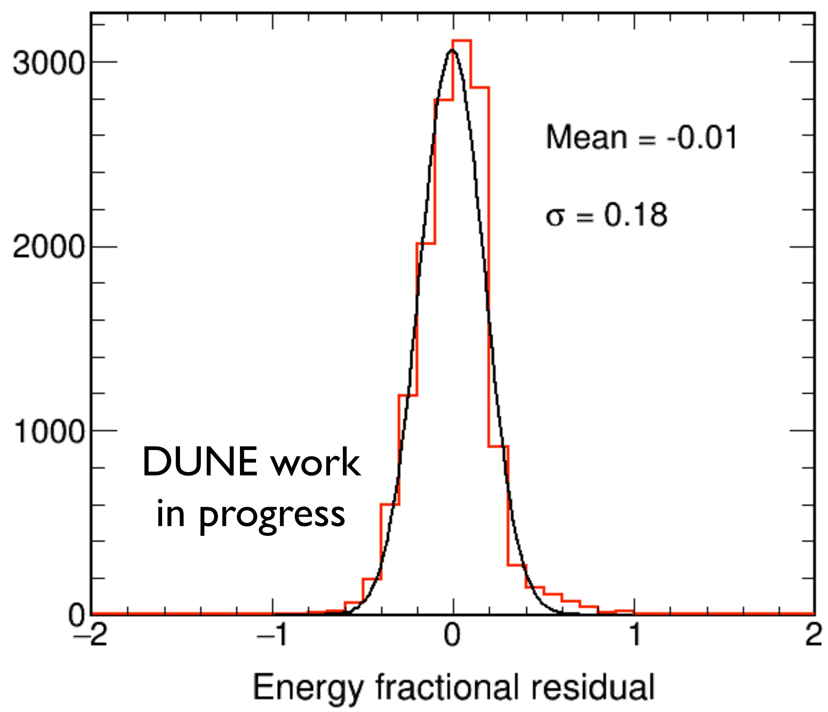


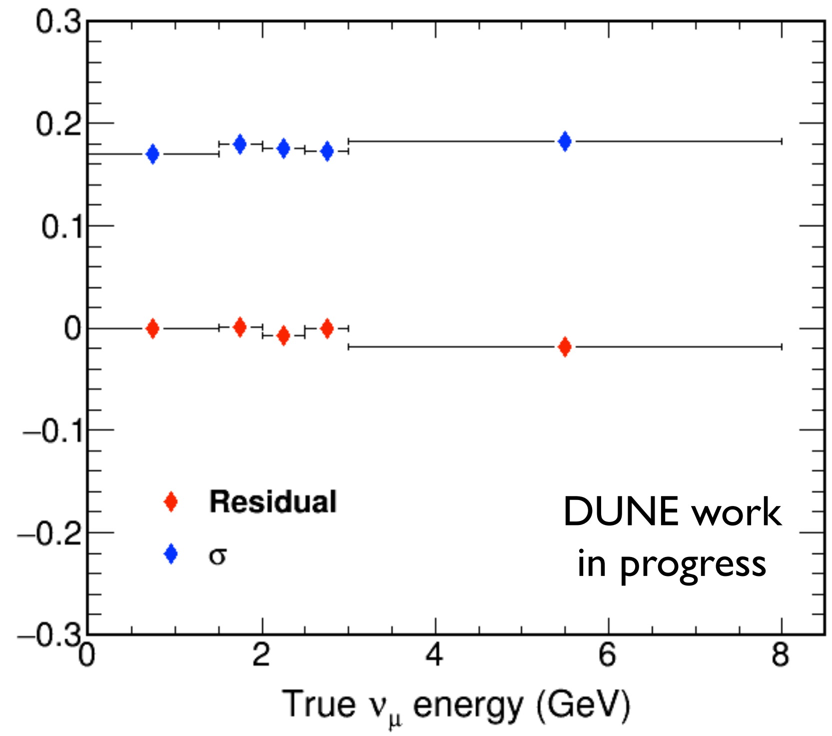
There is a clear bias as a function of true ν_μ energy.

ν_μ CC energy resolution

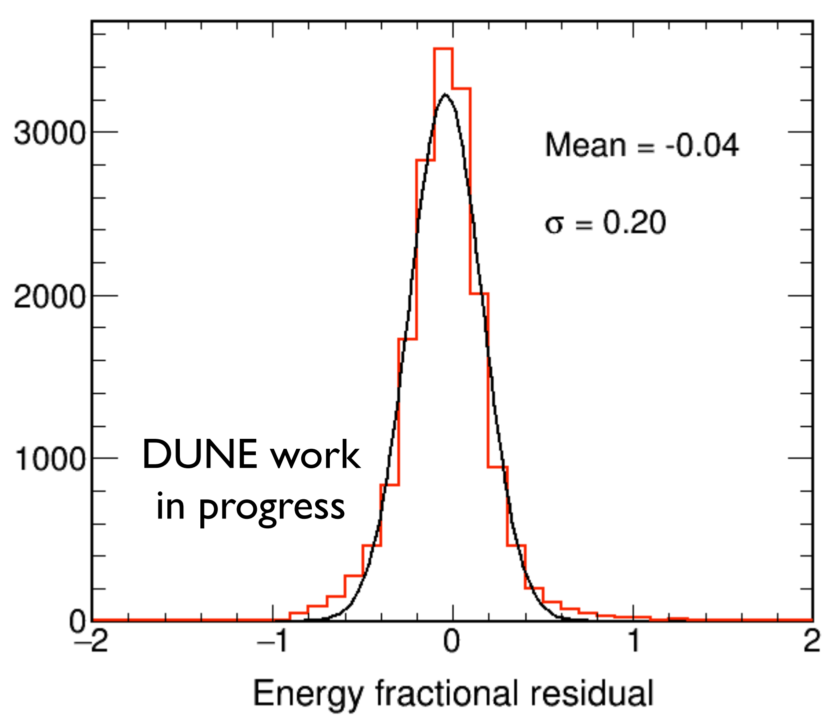
Overall | **As function of true ν_μ energy**

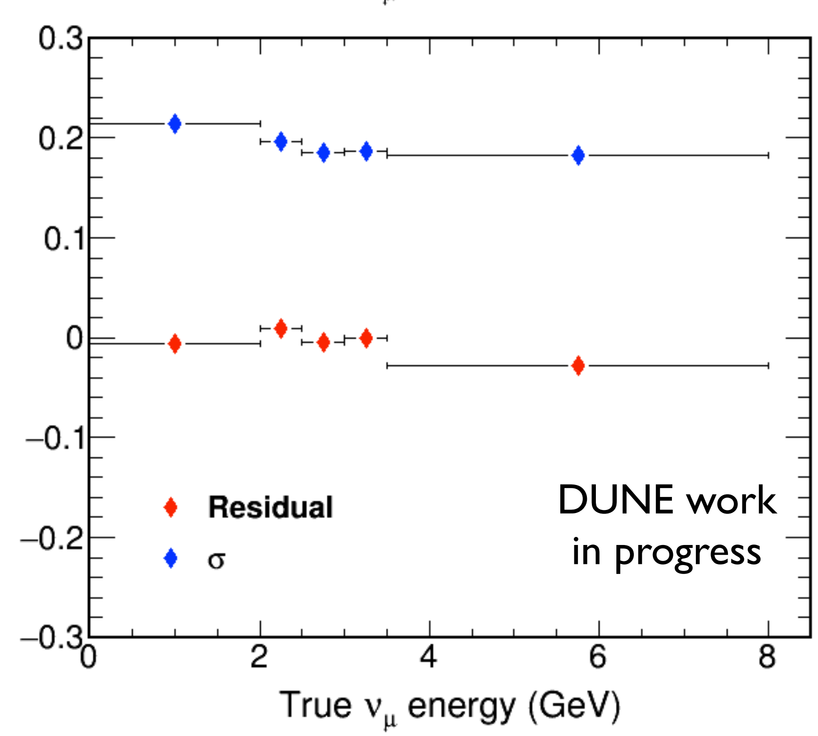
True ν_μ CC events with contained track





True ν_μ CC events with exiting track





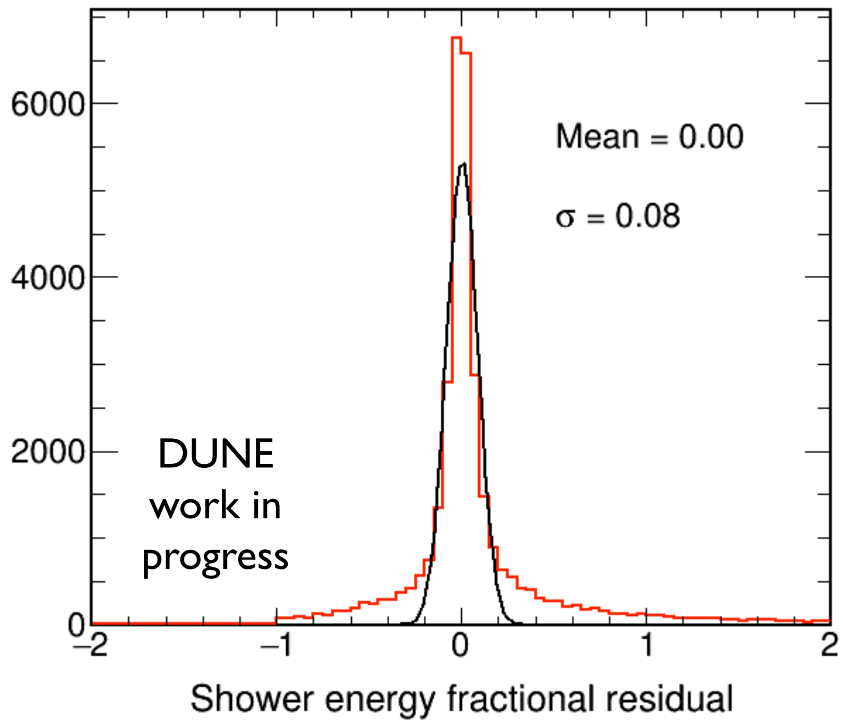
Make ad hoc tweaks of gradient and intercept of correction of hadronic energy.

This reduces bias as a function of ν_μ energy.

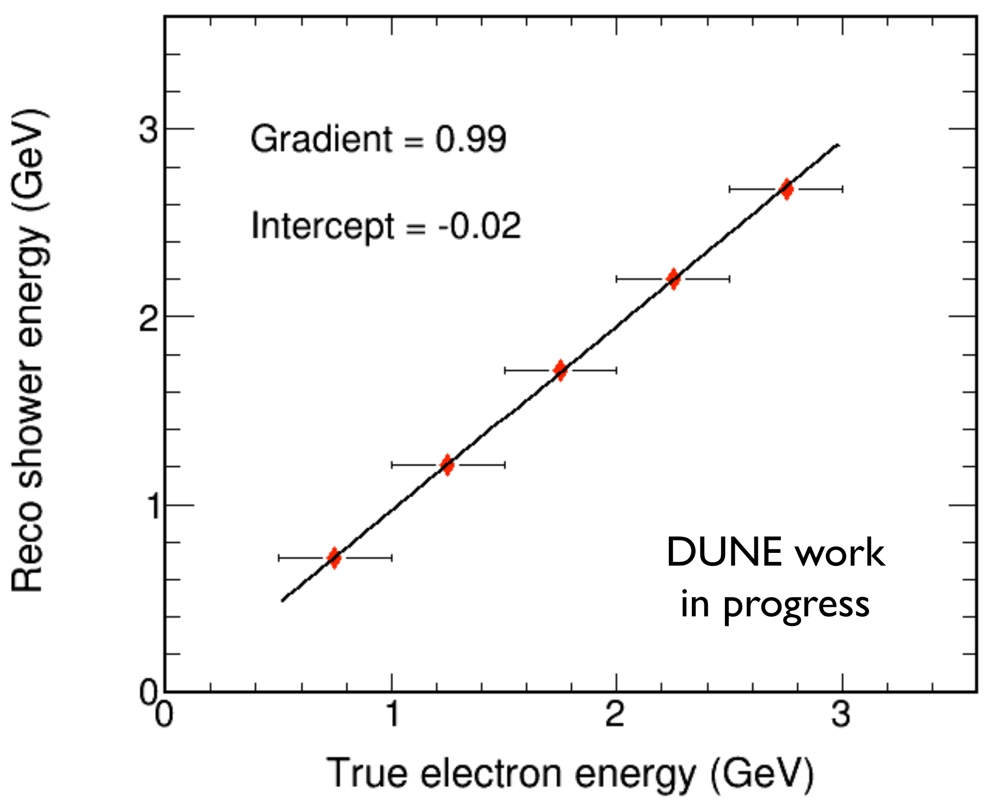
ν_e CC shower energy

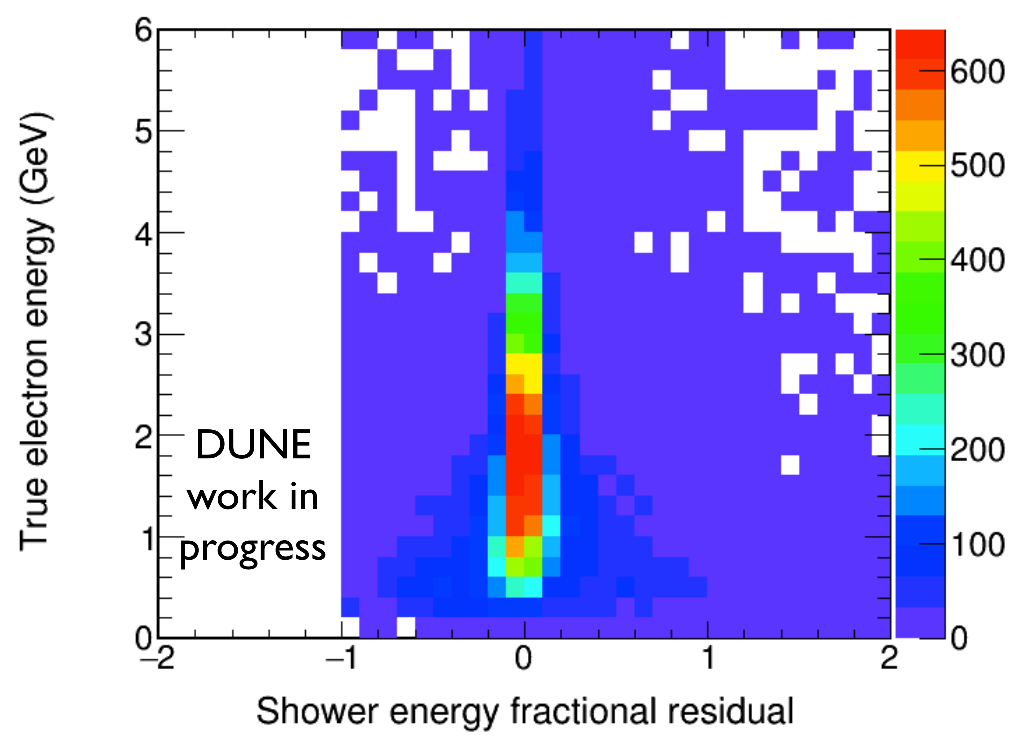
Make calibration of energy of reconstructed shower with highest charge using Monte Carlo.

Shower energy fractional residual



Shower energy calibration

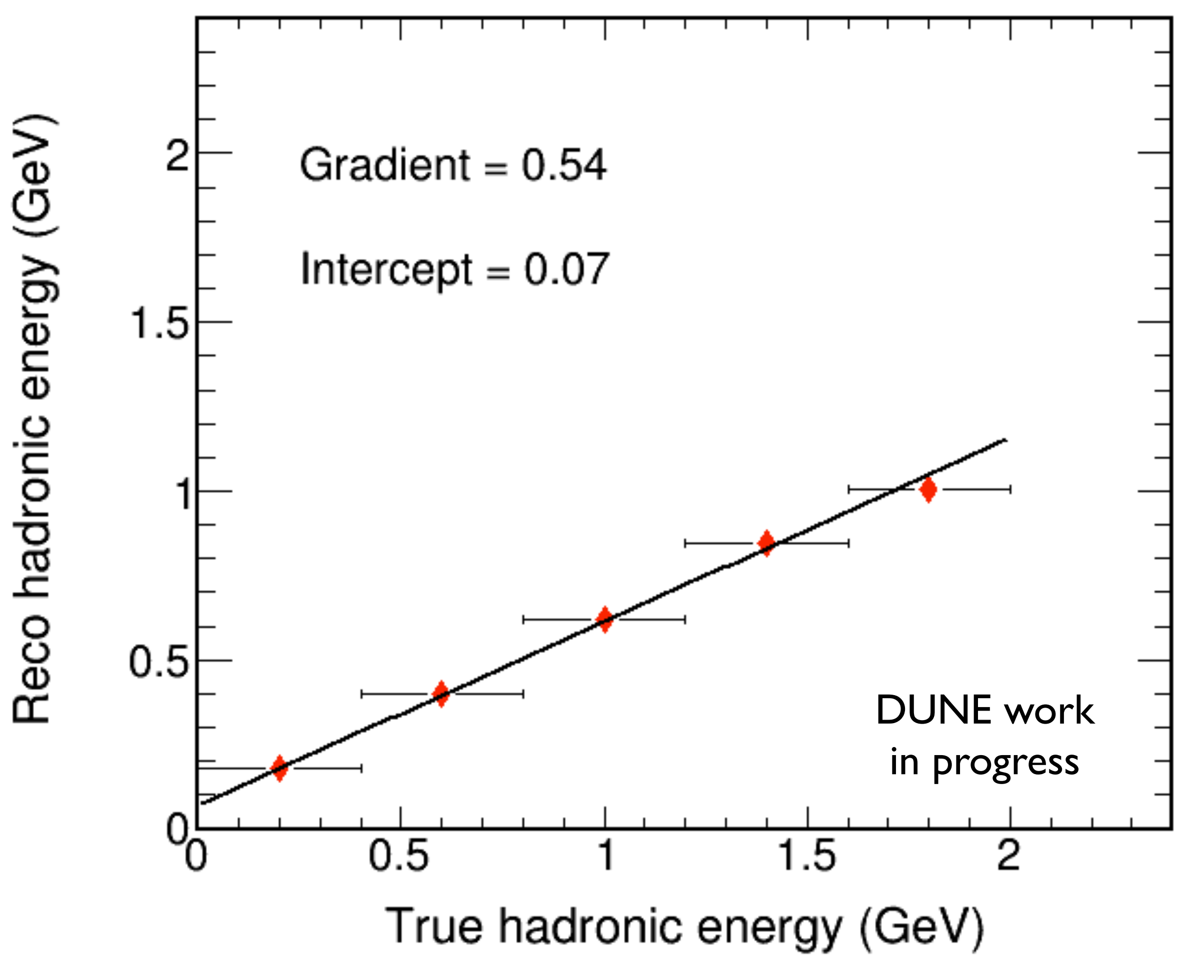




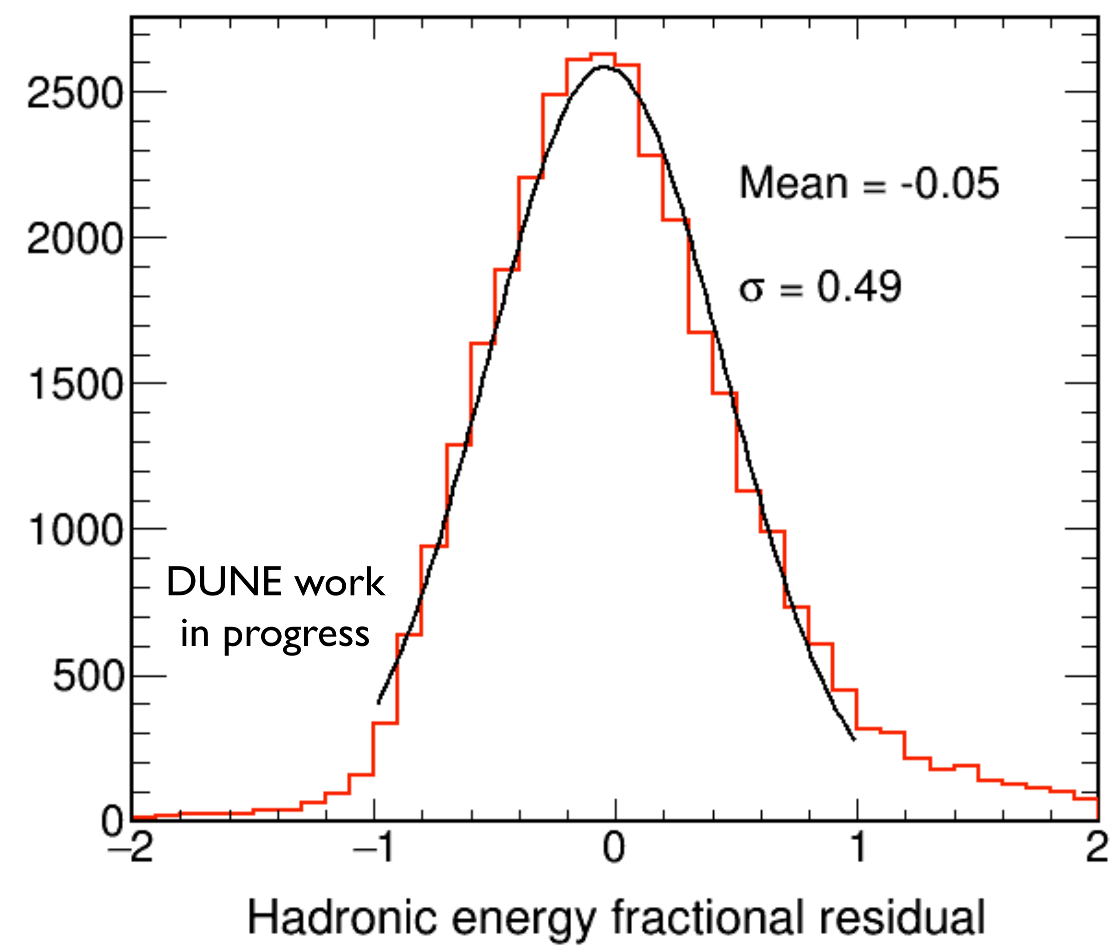
ν_e CC hadronic energy

Also make a calibration of ν_e CC reco hadronic energy using Monte Carlo. Again the missing energy from neutral particles fluctuates from event to event, which limits the overall energy resolution.

Hadronic energy calibration

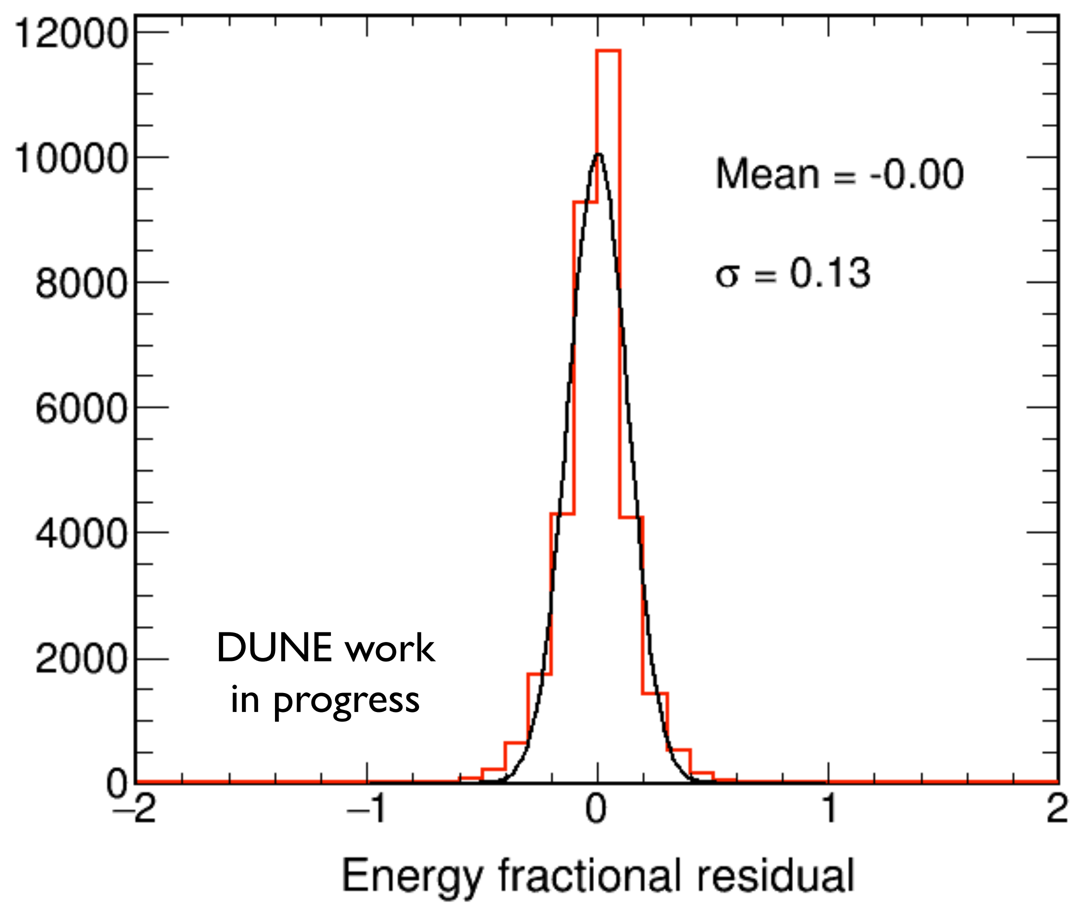


Hadronic energy fractional residual

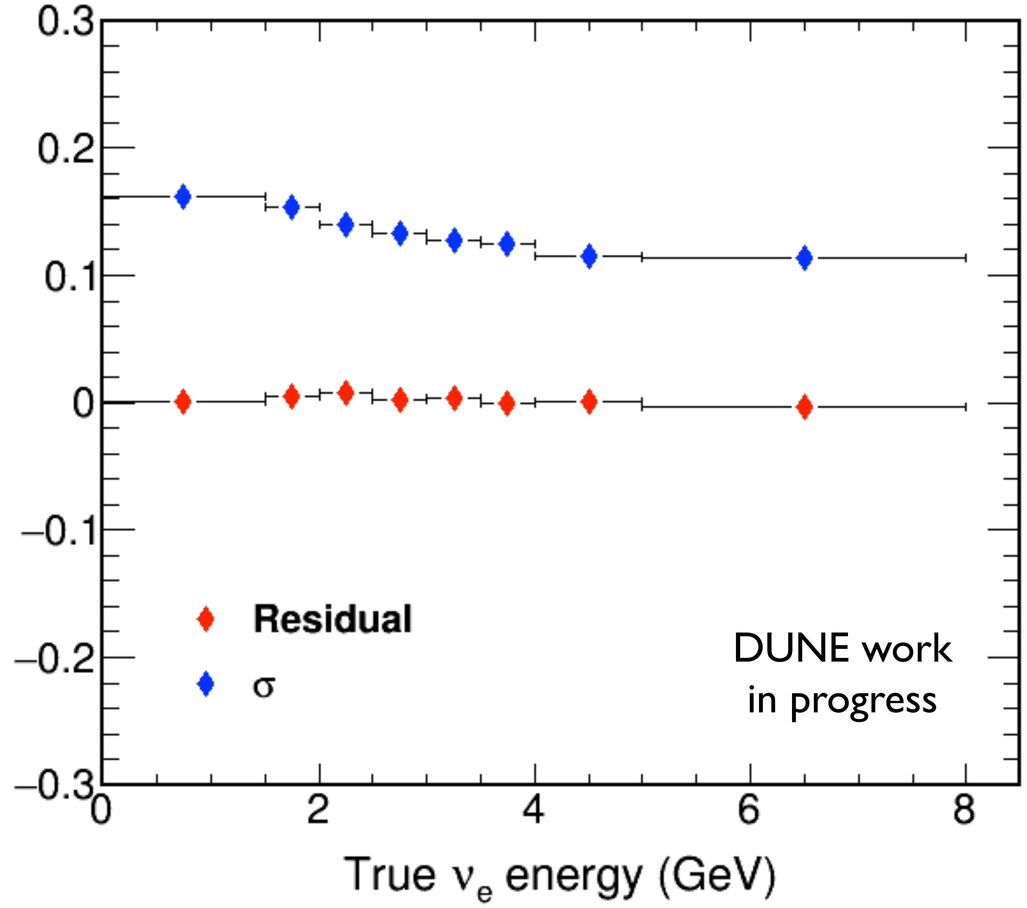


ν_e CC energy resolution

Overall ν_e energy resolution



ν_e energy resolution as function of true energy



Conclusion

We have implemented a complete first version of neutrino energy reconstruction in the DUNE far detector. This reconstruction is done by making separate estimates of the lepton and hadronic energies in CC events. We achieve overall energy resolutions of 20% for ν_μ CC and 13% for ν_e CC events.

The resolutions of each component of the neutrino energy reconstruction in % are summarised below:

	ν_μ CC	ν_e CC
Longest reco track (contained)	5	-
Longest reco track (exiting)	20	-
Reco shower with highest charge	-	8
Hadronic energy	39	49

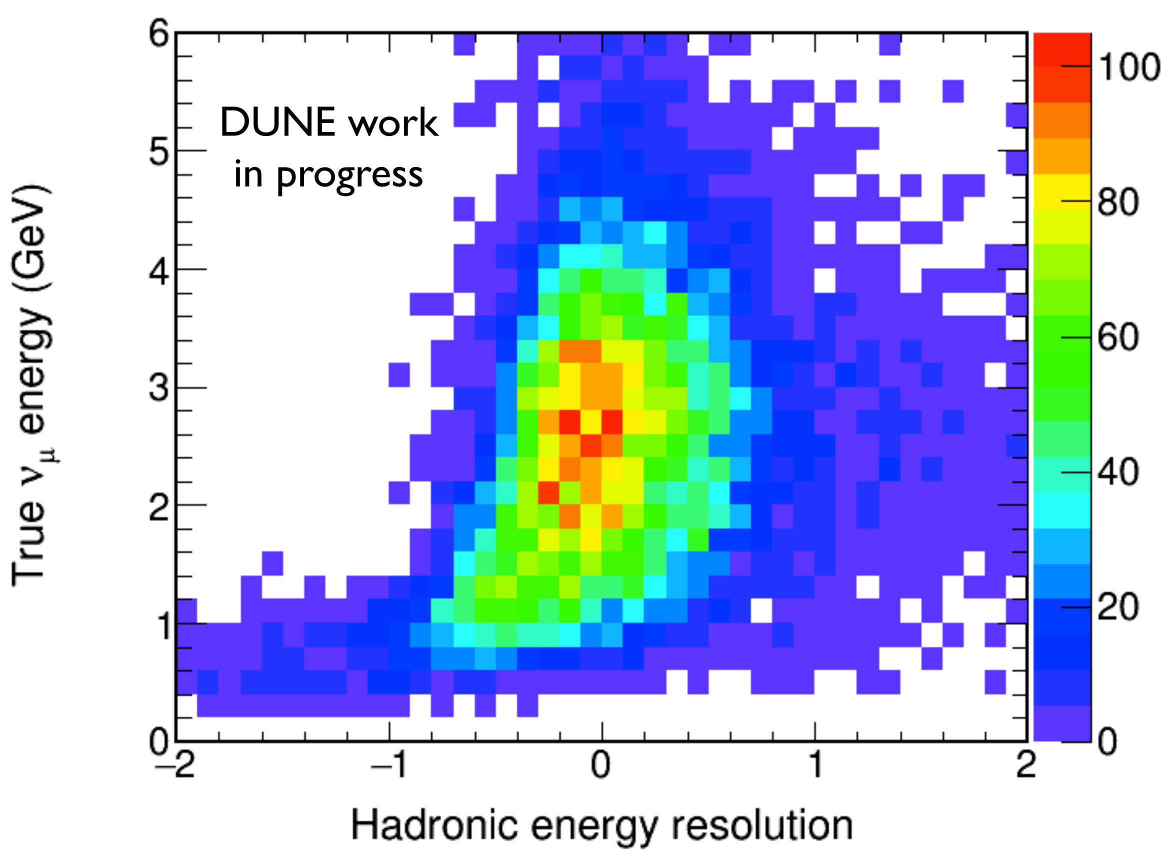
BACKUP SLIDES

ν_μ CC energy resolution

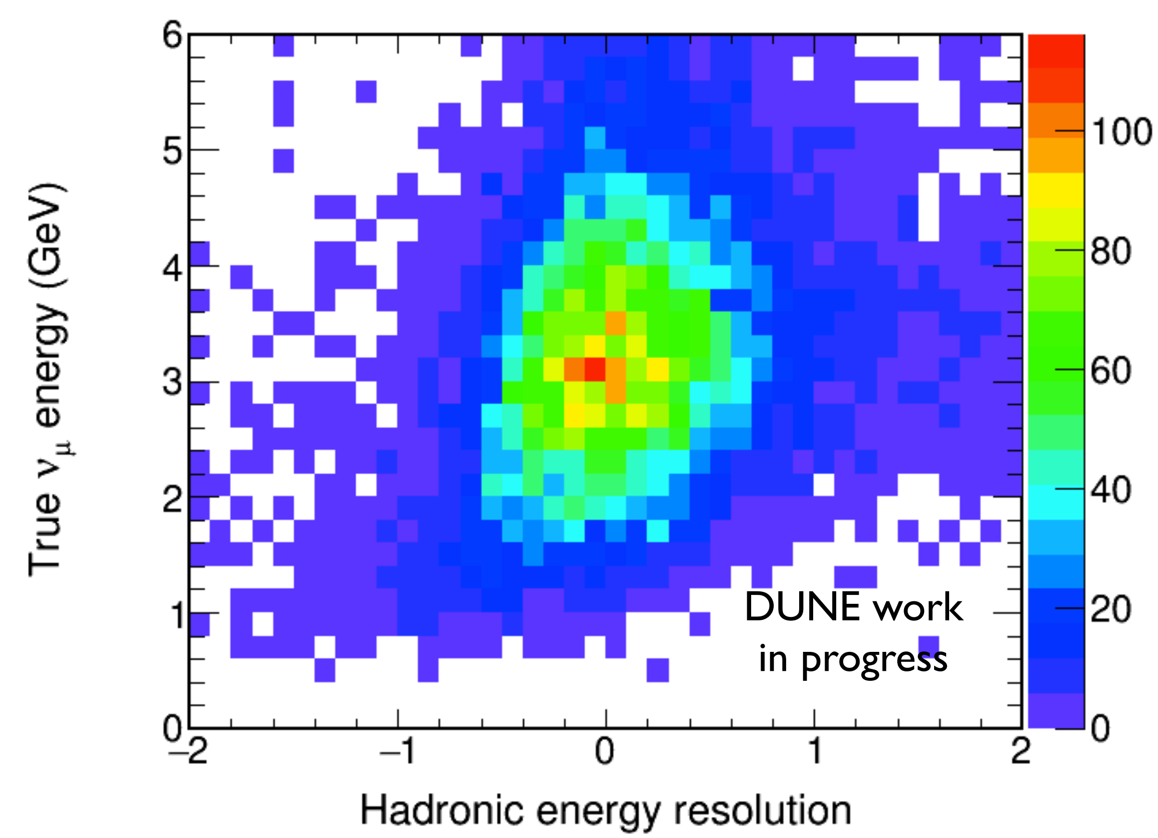
What is reason for bias as a function of true ν_μ energy ?

There is no bias in reco momentum by range or MCS momentum as a function of either true muon momentum or true ν_μ energy. Nor is there a bias in reco hadronic energy as a function of true hadronic energy (please see backup). The culprit is hadronic energy fractional residual as a function of true ν_μ energy:

True ν_μ CC events
with contained track



True ν_μ CC events
with exiting track

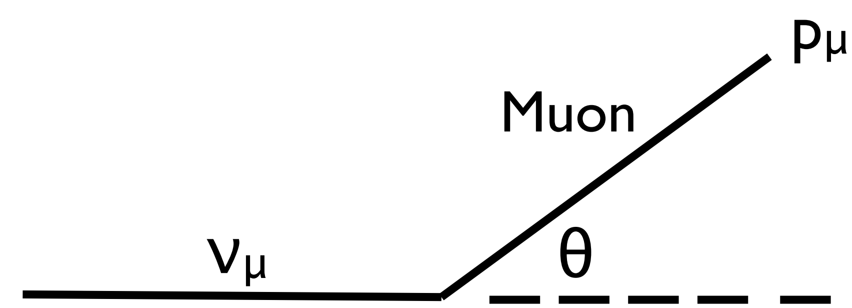


Kinematic energy reconstruction

Bias as a function of true energy is worse for events with contained tracks and worse at low true energy. It is also worse for ν_μ CCQE events than for CC res or CC DIS events.

Try kinematic reconstruction of ν_μ energy to see whether it can help for some or all ν_μ CCQE events:

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$



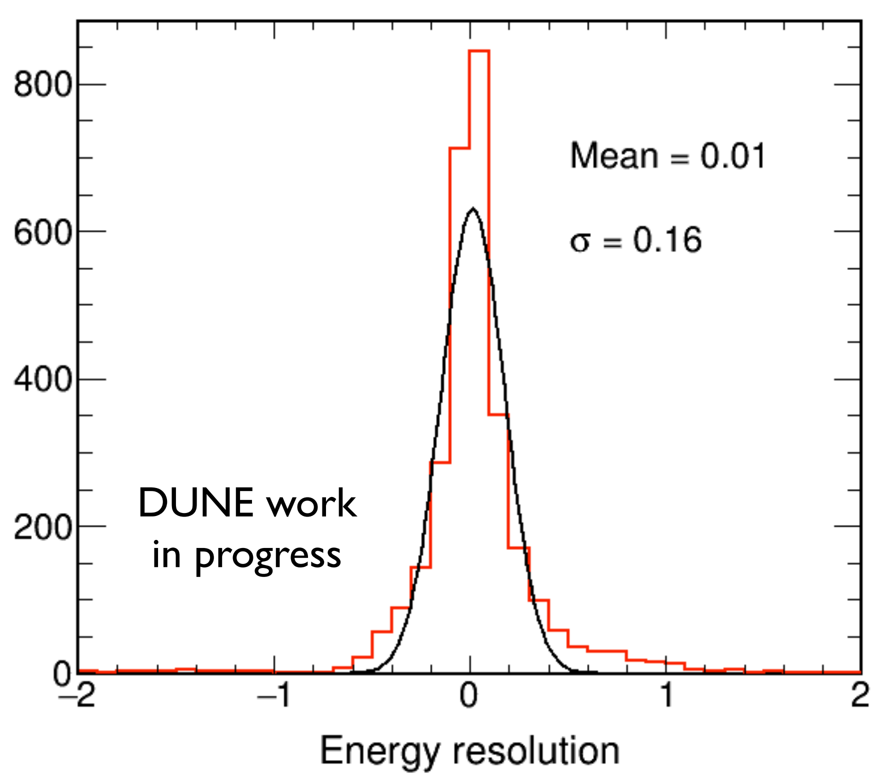
E_b = binding energy. This formula is only valid for CCQE events. It neglects the Fermi momentum of the struck nucleon and any possible final-state interactions.

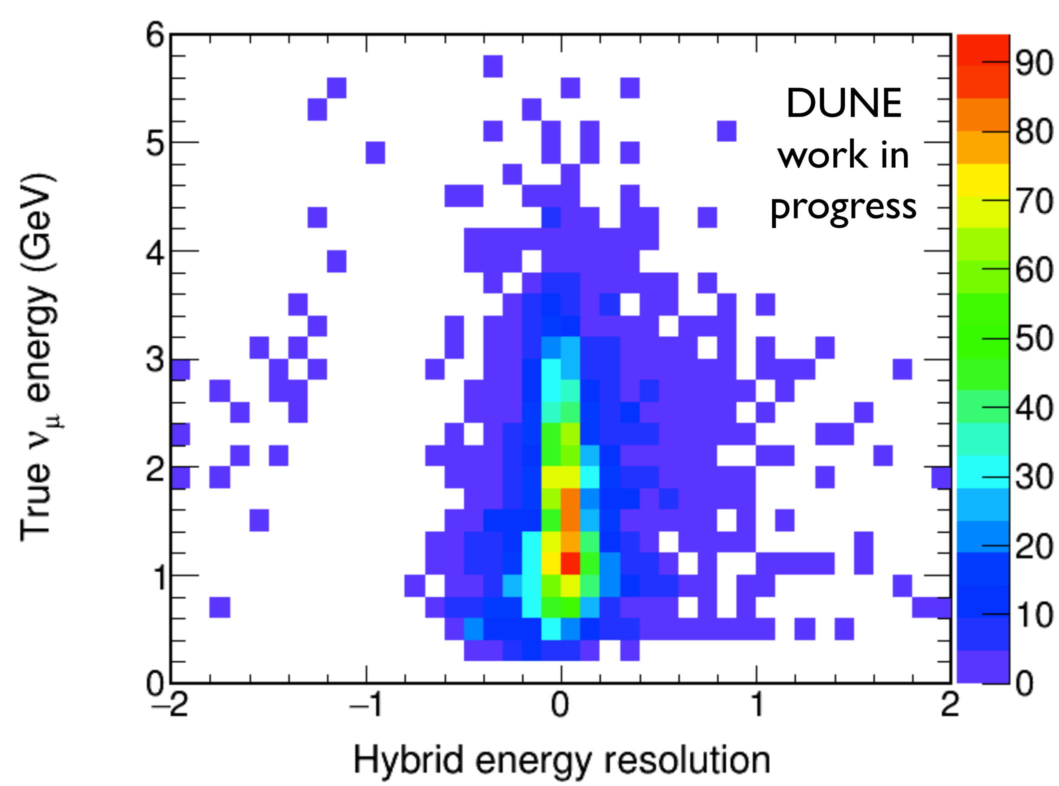
Equation ref: Phys. Rev. D 85 031103

Hybrid energy reconstruction

Use hybrid reconstruction for ν_μ CCQE events: if ratio of track + hadronic reco energy / kinematic reco energy > 1.5, use track + hadronic, otherwise use kinematic reconstruction.

True ν_μ CCQE events with contained track

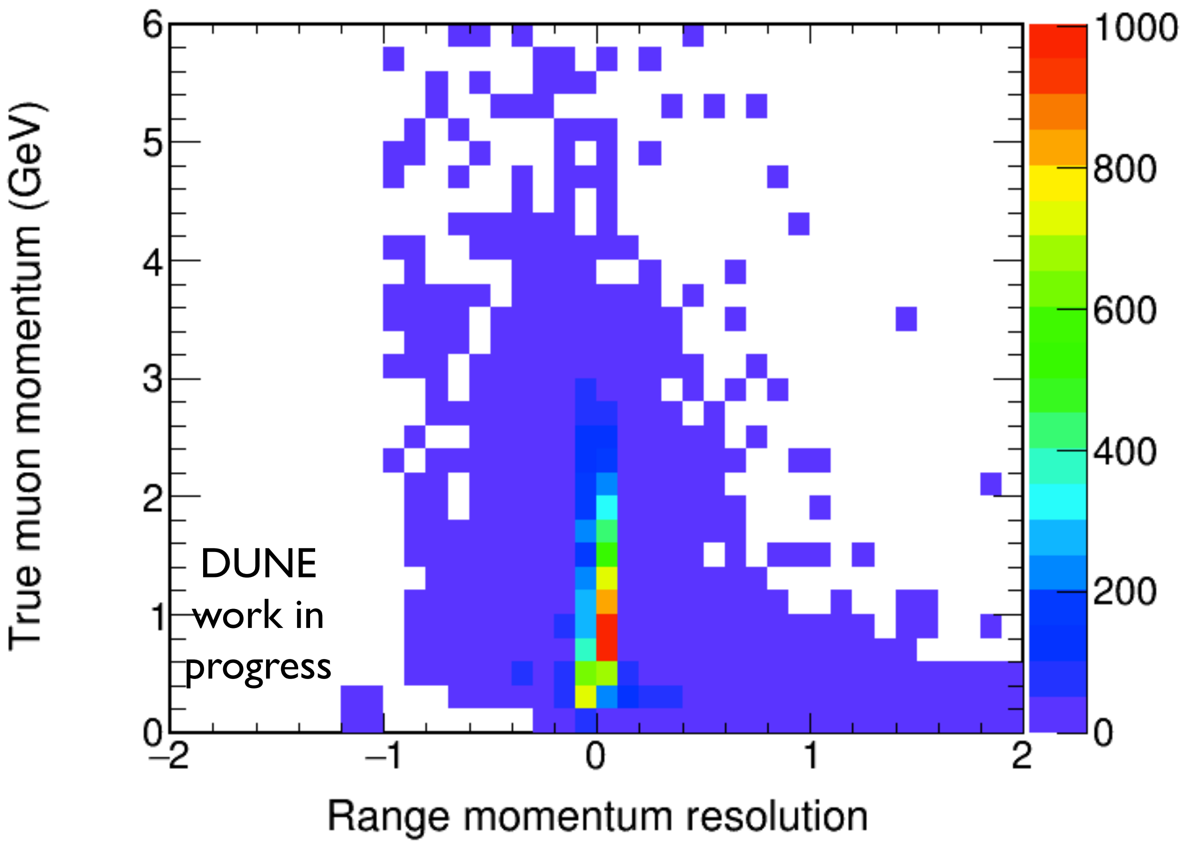


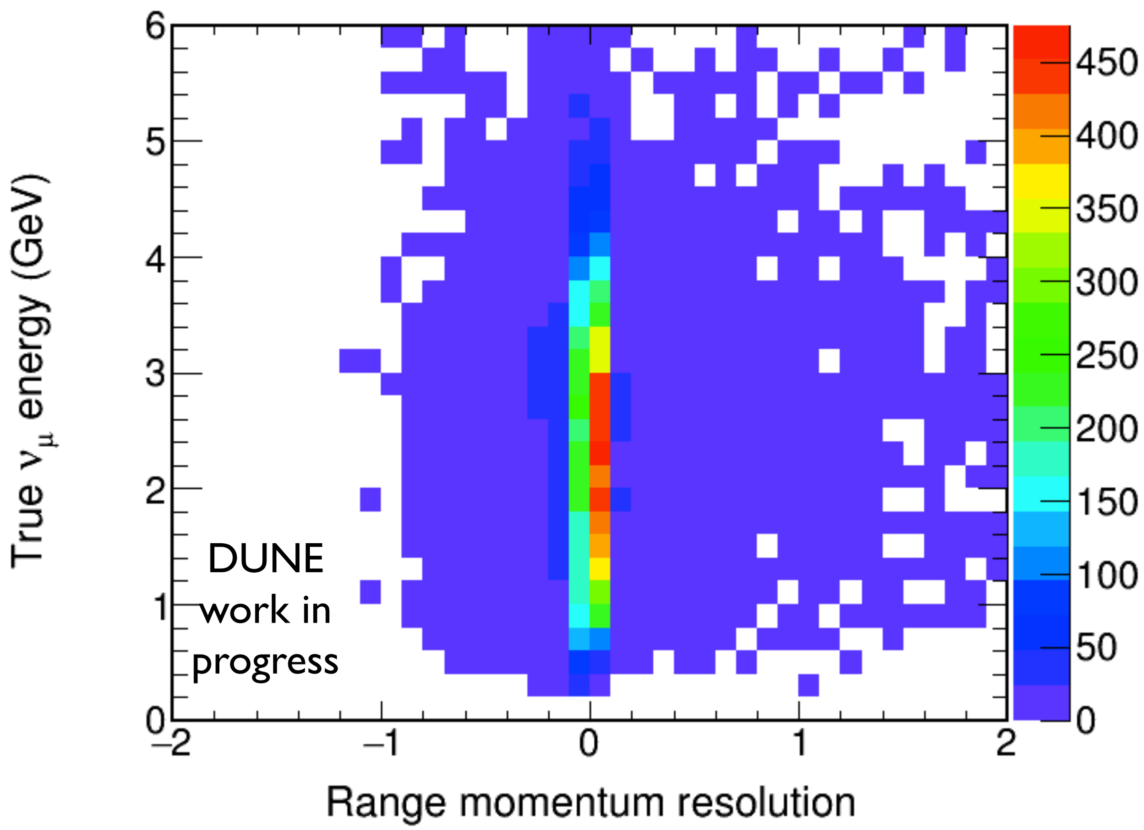


Very small dependence on true energy.

Range momentum resolution

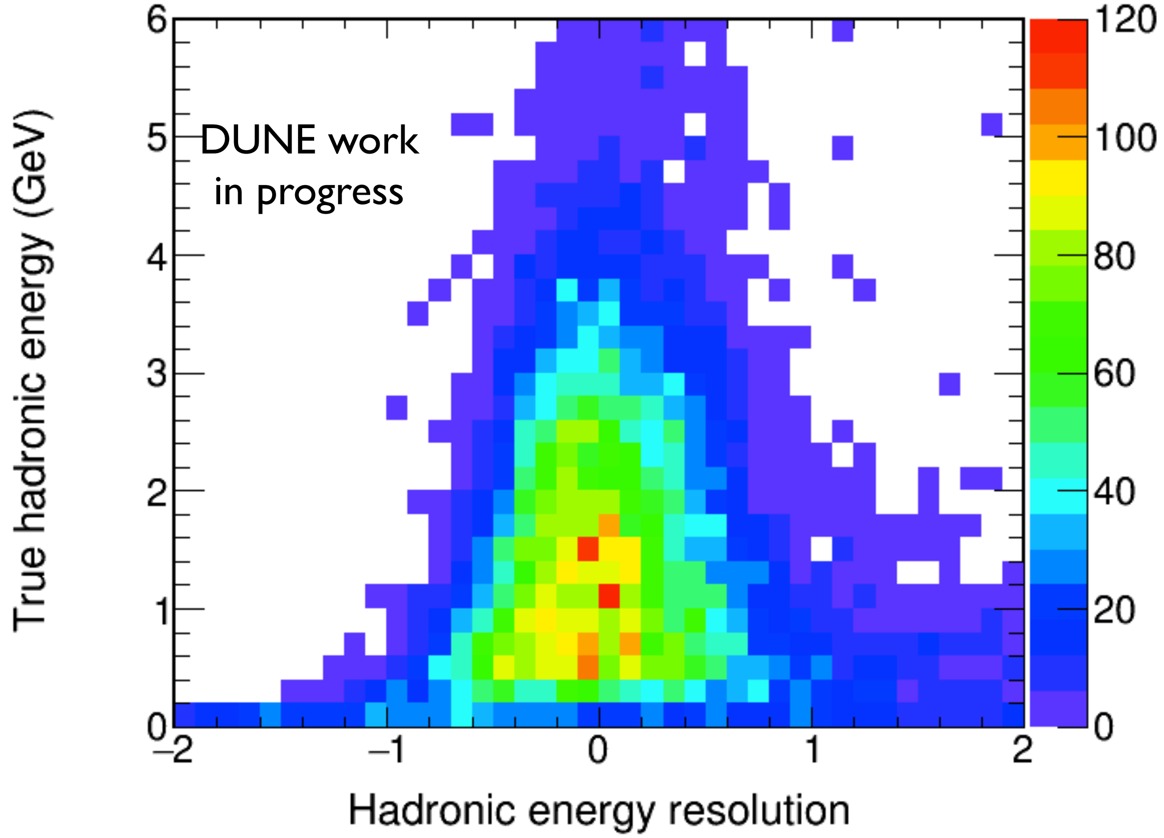
True ν_μ CC events with contained track

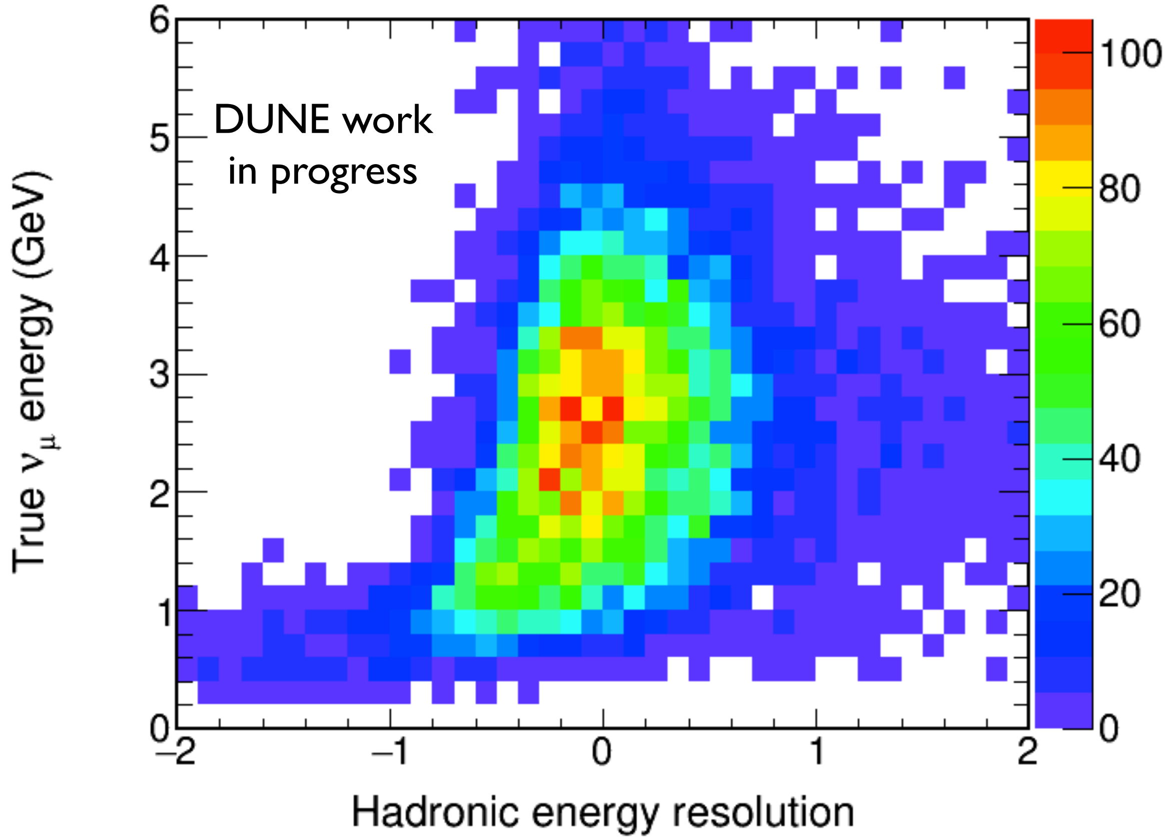




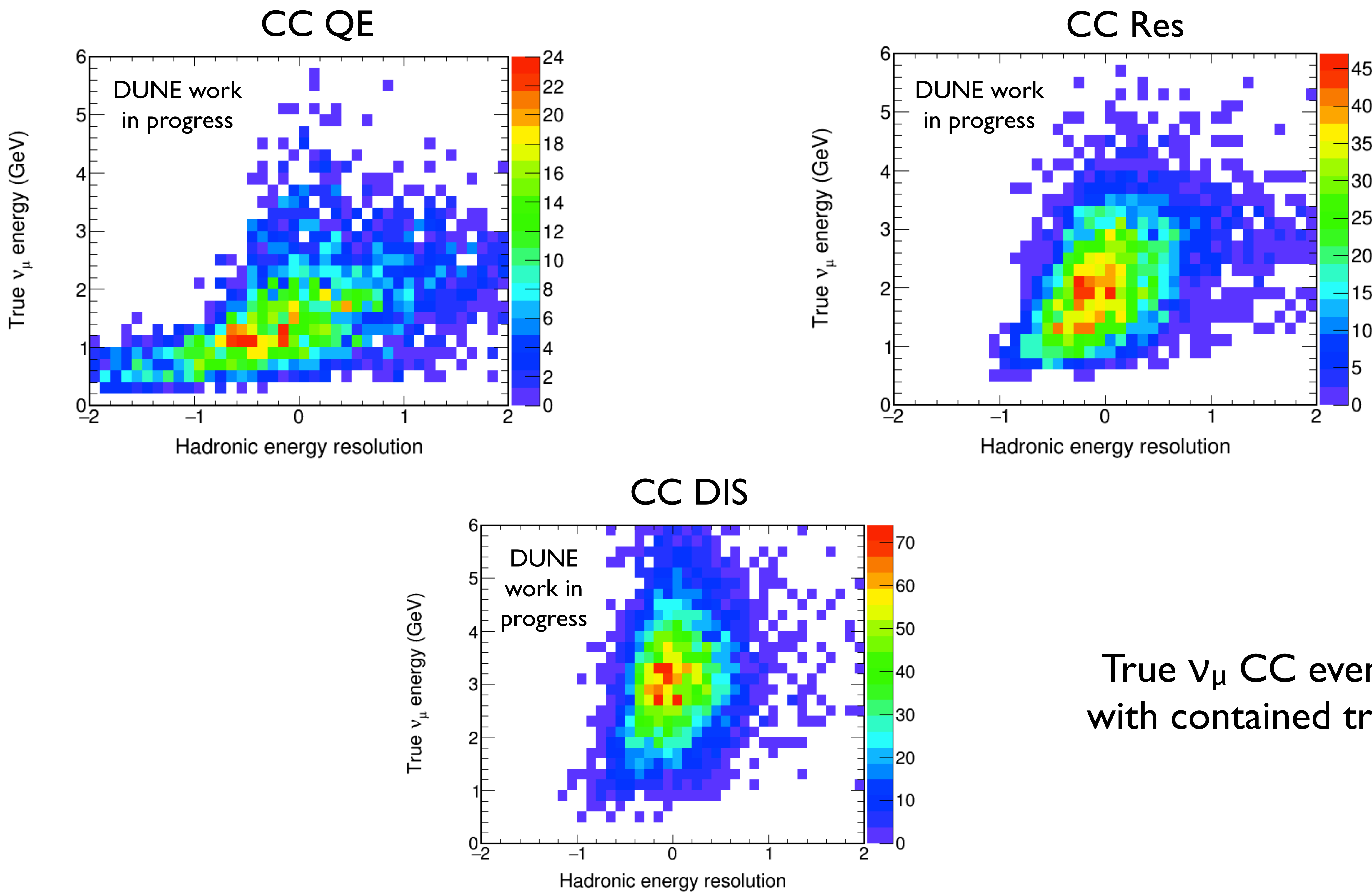
Hadronic energy resolution

True ν_μ CC events with contained track





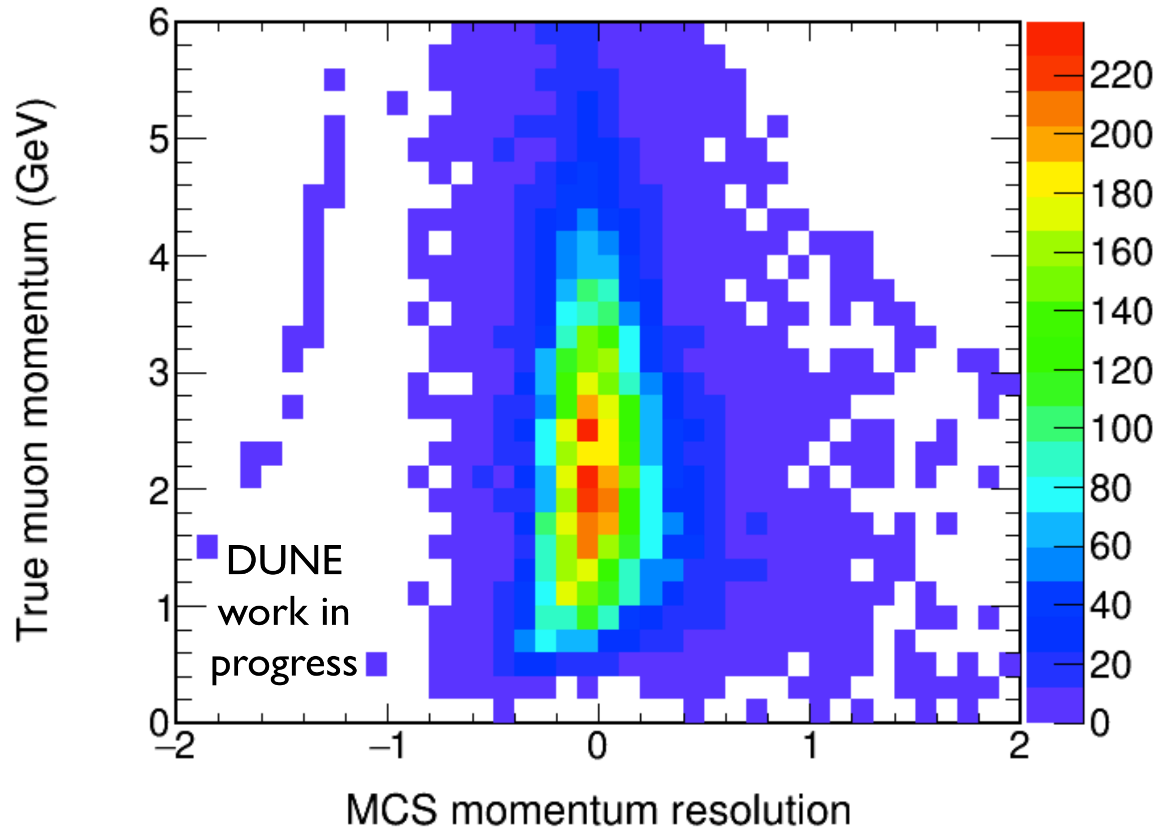
Hadronic energy resolution

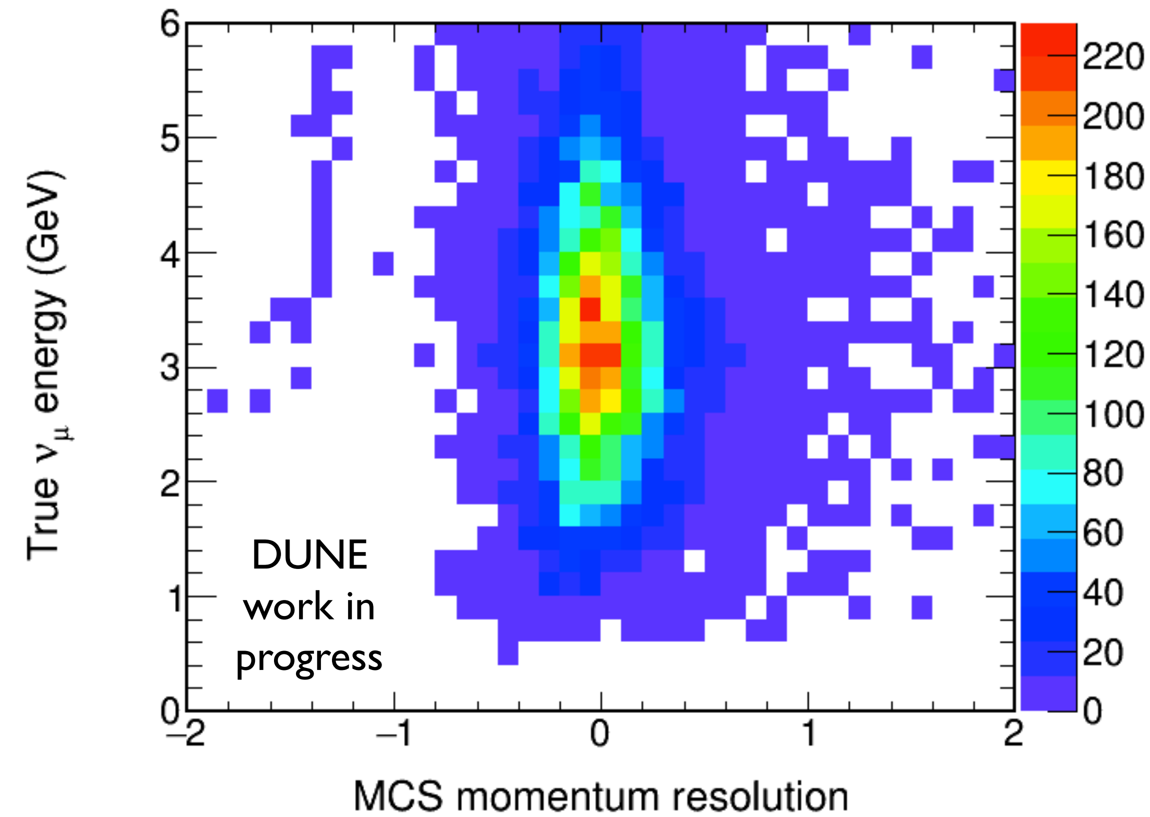


True ν_μ CC events with contained track

MCS momentum resolution

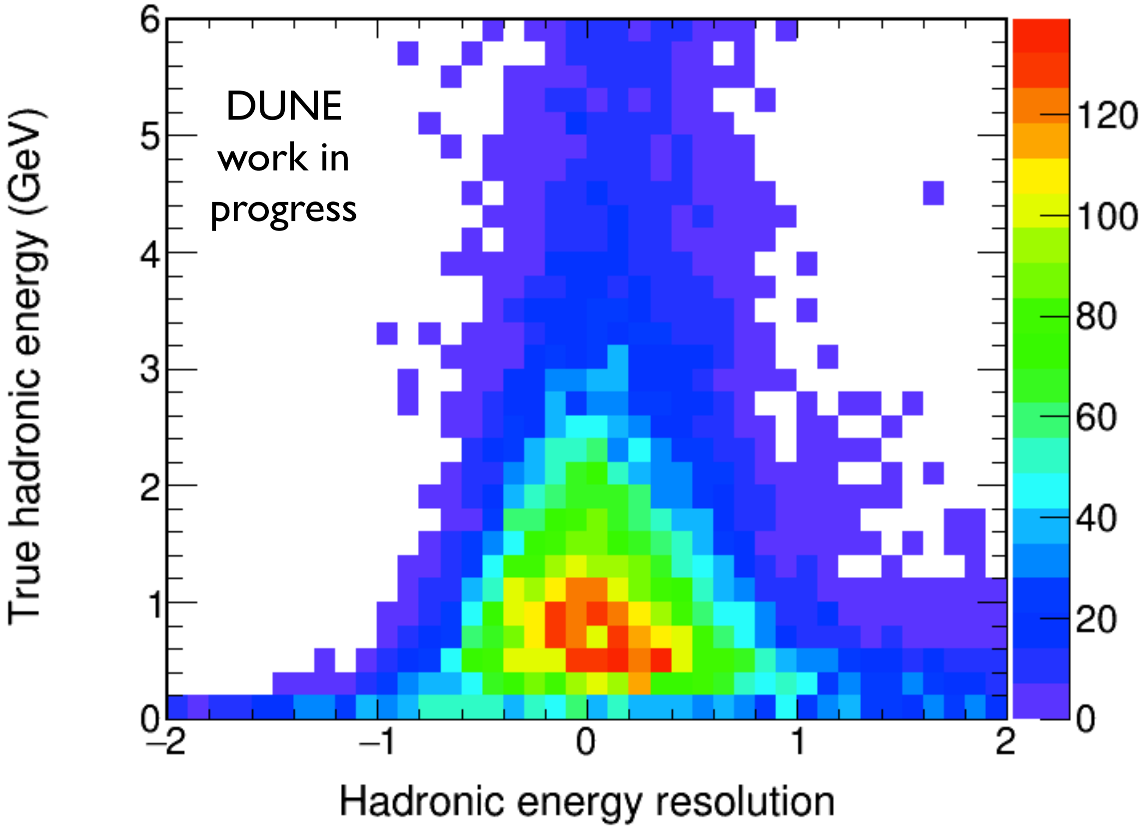
True ν_μ CC events with exiting track

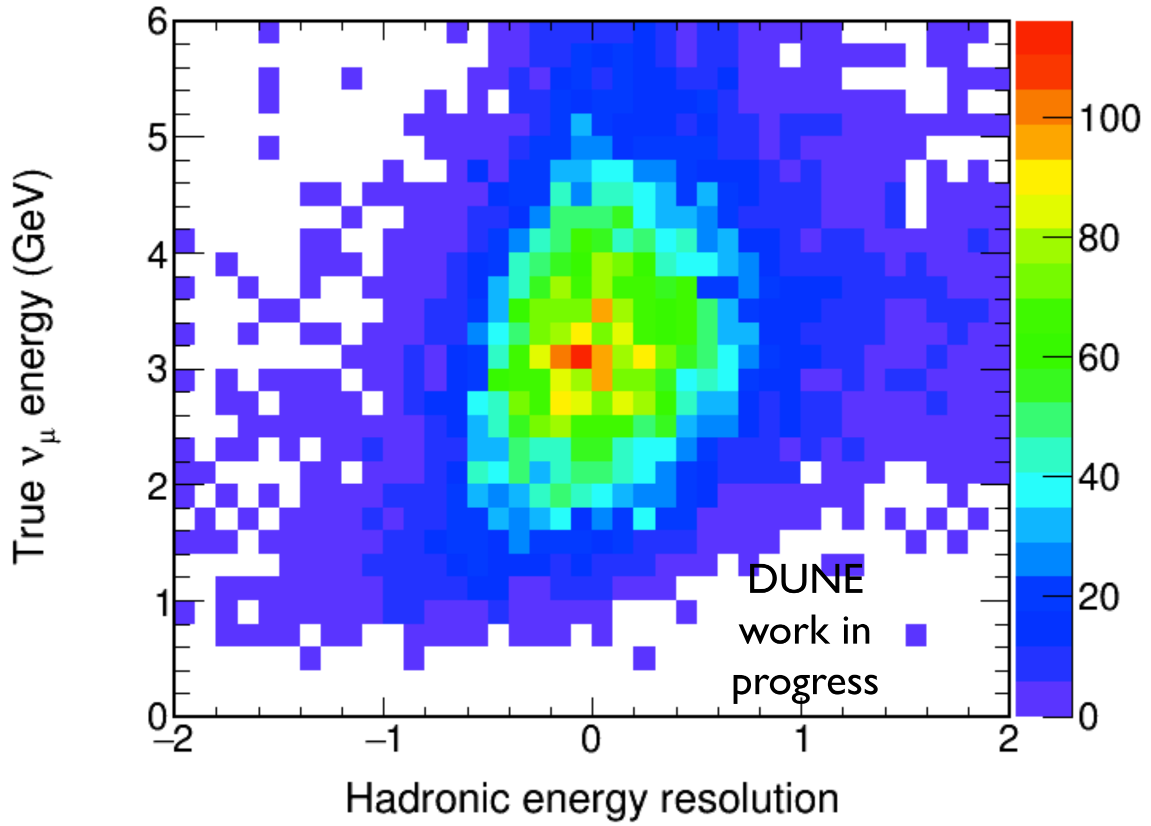




Hadronic energy resolution

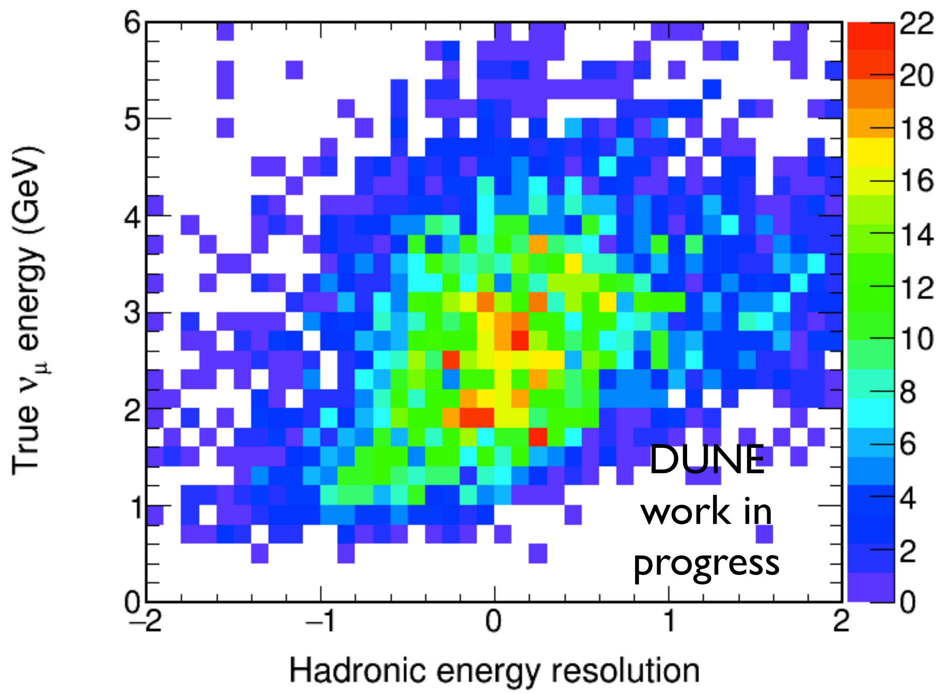
True ν_μ CC events with exiting track



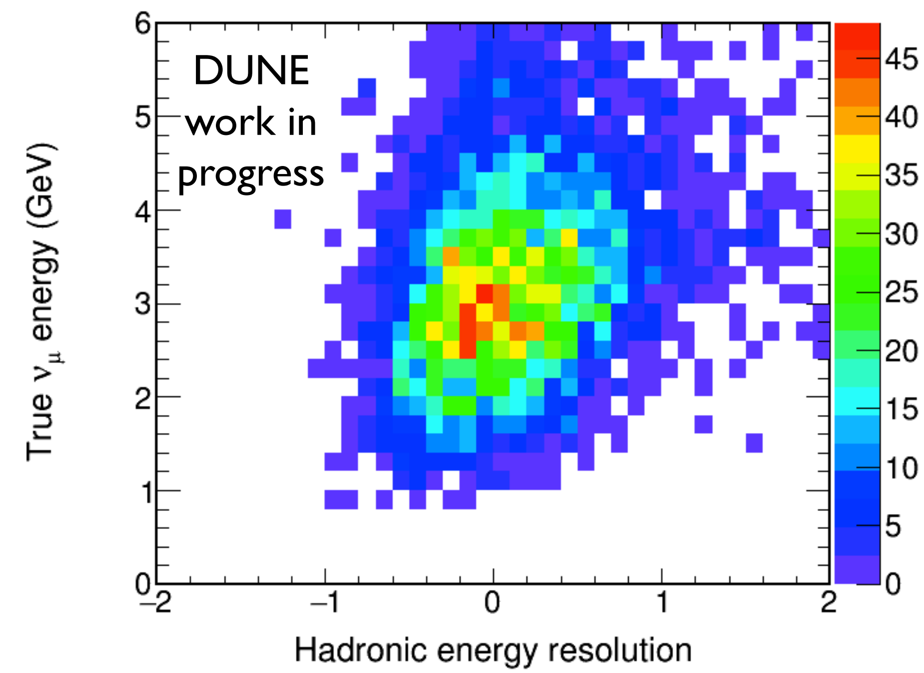


Hadronic energy resolution

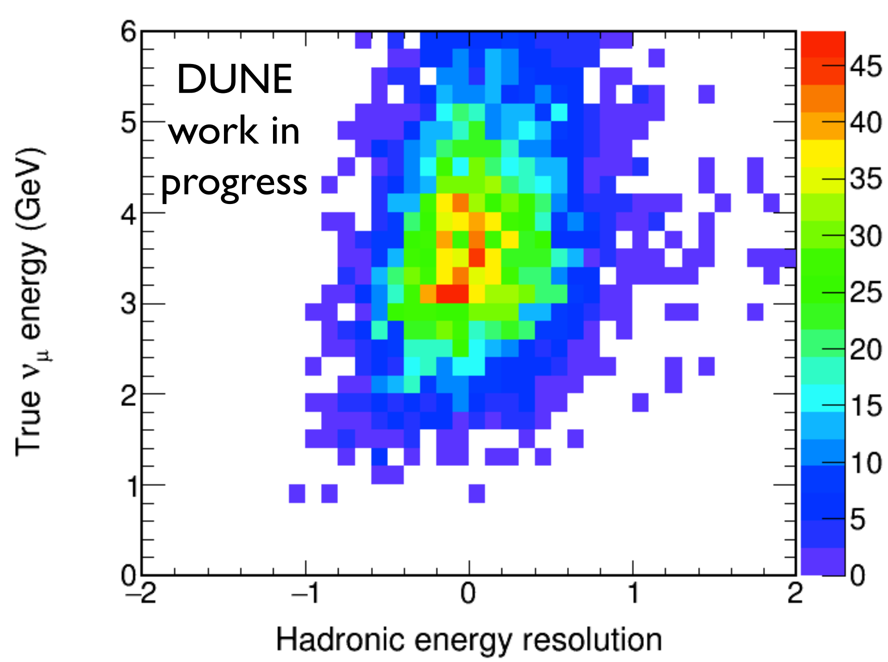
CC QE



CC Res



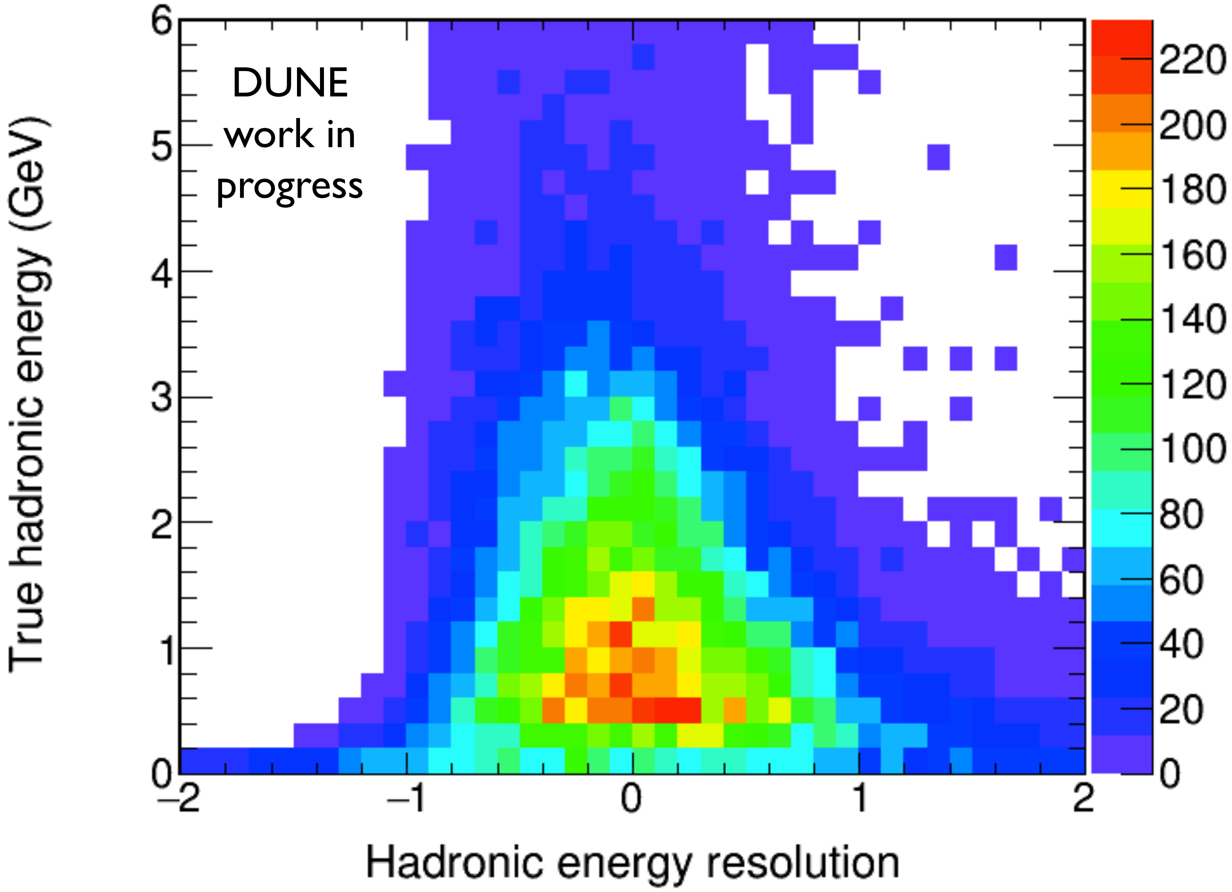
CC DIS

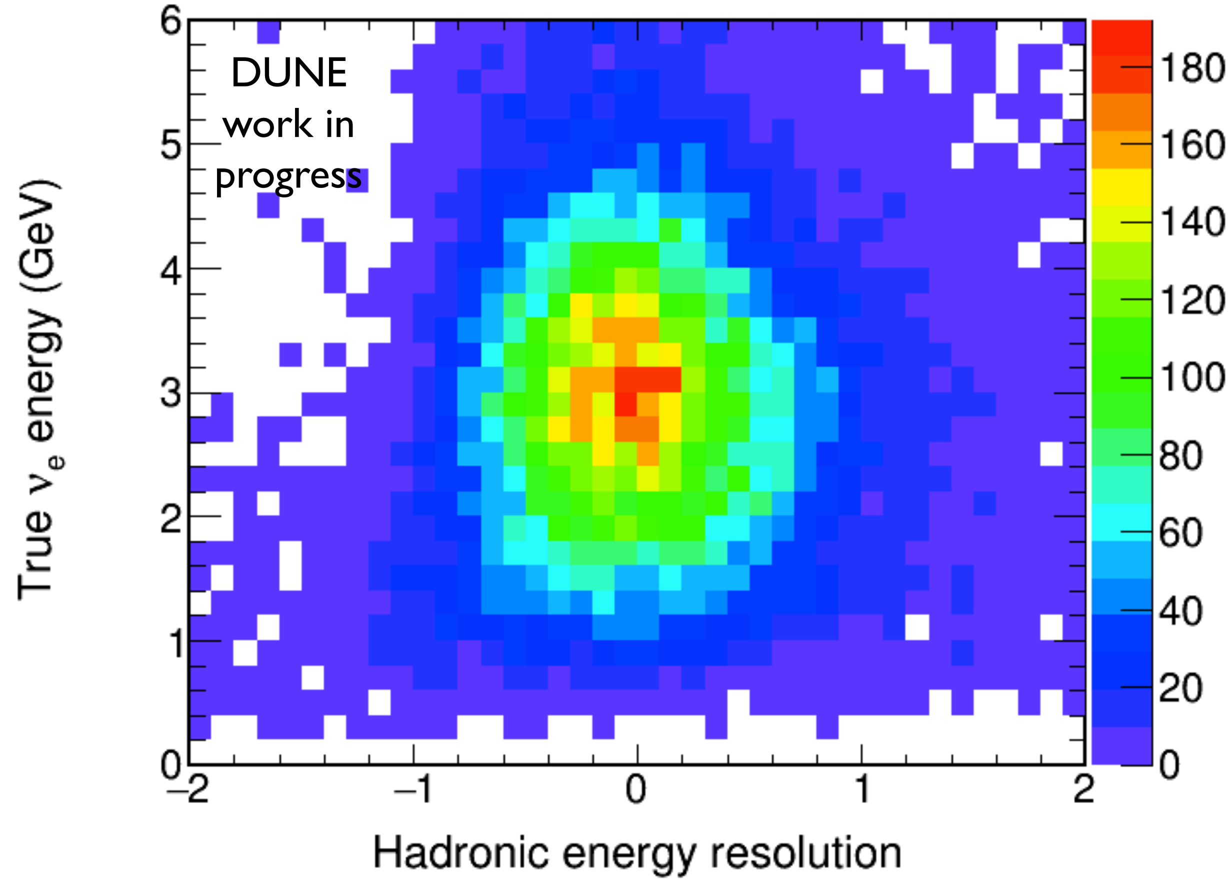


True ν_μ CC events
with exiting track

Hadronic energy resolution

True ν_e CC events





Multiple Coulomb scattering

This description is taken from an ICARUS paper at

https://arxiv.org/pdf/hep-ex/0606006v1.pdf

A charged particle traversing a medium is deflected through many small angle scatterings.

Divide the track into segments of equal length. Fit a straight line to each track segment.

For each consecutive pair of segments, the scattering angle is the difference between the segment angles.

Multiple Coulomb scattering

Compute the RMS of the scattering angle distribution

Repeat for different segment lengths, and fit for p and C in

$$\theta^{rms}_{meas} = \sqrt{\left(\frac{13.6\ MeV}{\beta c\, p} z \sqrt{\frac{l}{X_0}} \cdot \left[1 + 0.038 \cdot ln\left(\frac{l}{X_0}\right)\right]\right)^2 + \ (C \cdot l^{-3/2})^2}$$

where β is velocity, p momentum and z charge of particle
X_0 is radiation length, l is segment length, C $l^{-3/2}$ is noise

One advantage of this method is that it can be used equally well for stopping and exiting particles.

Hit charge correction

Lifetime correction to correct for recombination with ions in "bulk" of liquid argon, i.e. not in a column or box around the charged particle track being considered (but they can be from another track).

Ionisation charge = charge collected x exp(drift time / lifetime).