Light Calorimetry Feasibility Studies

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BNL WireCell Meeting
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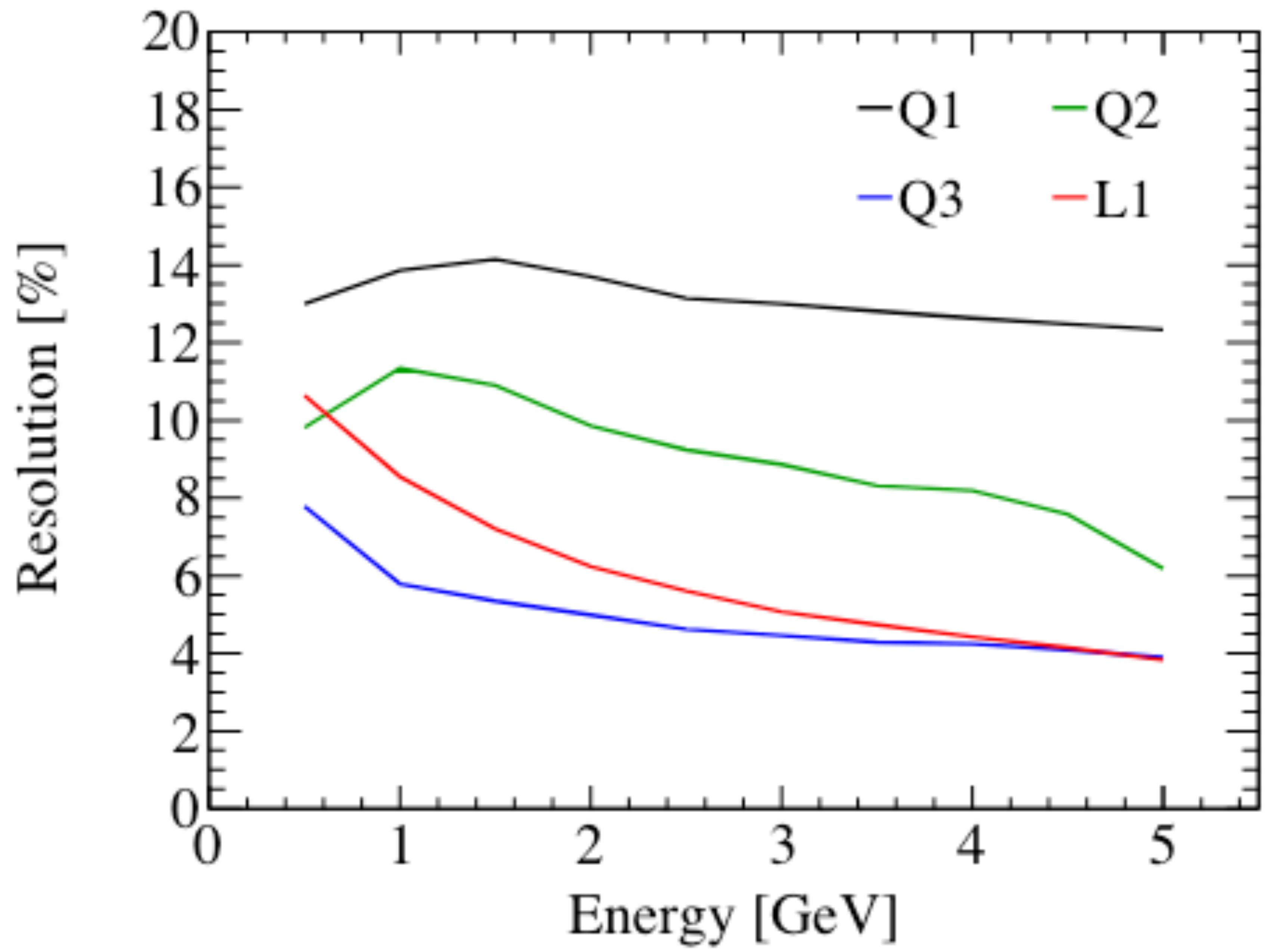
Introduction

- investigating methods to reconstruct the **true neutrino energy**, particularly using light information, with a focus on electron-neutrino (inclusive) interactions

- largely follows work presented in: *Self-compensating light calorimetry with liquid argon time projection chamber for GeV neutrino physics* (https://doi.org/10.1103/PhysRevD.111.032007)

- does the $L1$ (light-only) based calorimetry improve neutrino energy reconstruction in SBND? how about charge based methods?
    - lower energy beam (BNB) compared to paper (focuses on 3 GeV)
    - what happens when we include realistic detector effects (using SBND detsim)?



Fermilab THE UNIVERSITY OF CHICAGO SHORT-BASELINE NEAR DETECTOR SBND

LAr as a Calorimeter

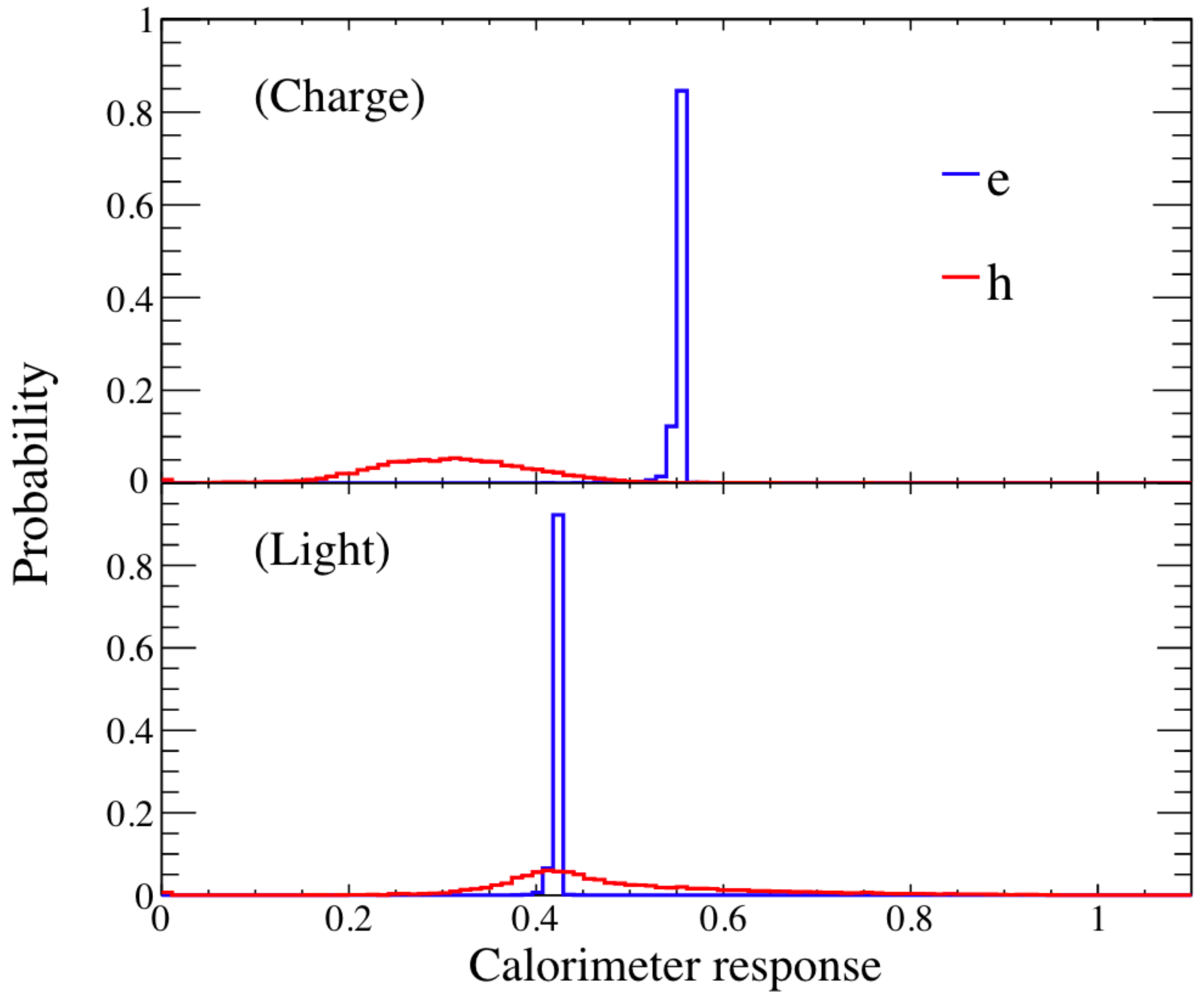


FIG. 4. The calorimeter responses (R_{cal}, the ratio of the visible energy to the available energy) in LArTPC for the EM component (e, blue) and the hadronic component (h, red). The top panel shows the charge calorimetry and the bottom panel shows the light calorimetry. 10^5 ν_e CC events are simulated with neutrino energy of 0.5–5 GeV. The area of each distribution is normalized to 1.

- light information may be particularly useful since the light calorimetric response for EM and hadronic components are similar
- some pros:
    - does not require PID
    - largely independent on TPC reconstruction paradigm
- some cons:
    - need to have very well calibrated, very uniform photo-detectors

SBND as a testbench…

- SBND has a very large number of photodetectors (302 total), with just over 100 PMTs currently operational (X-ARAPUCAs still being commissioned)

- I have studied light calorimetry in SBND (from a $Q + L$ perspective) for EM shower energy reconstruction (Neutrino2024 poster here)

- we have all the ingredients to study whether neutrino energy light calorimetry is feasible with the SBND detector!

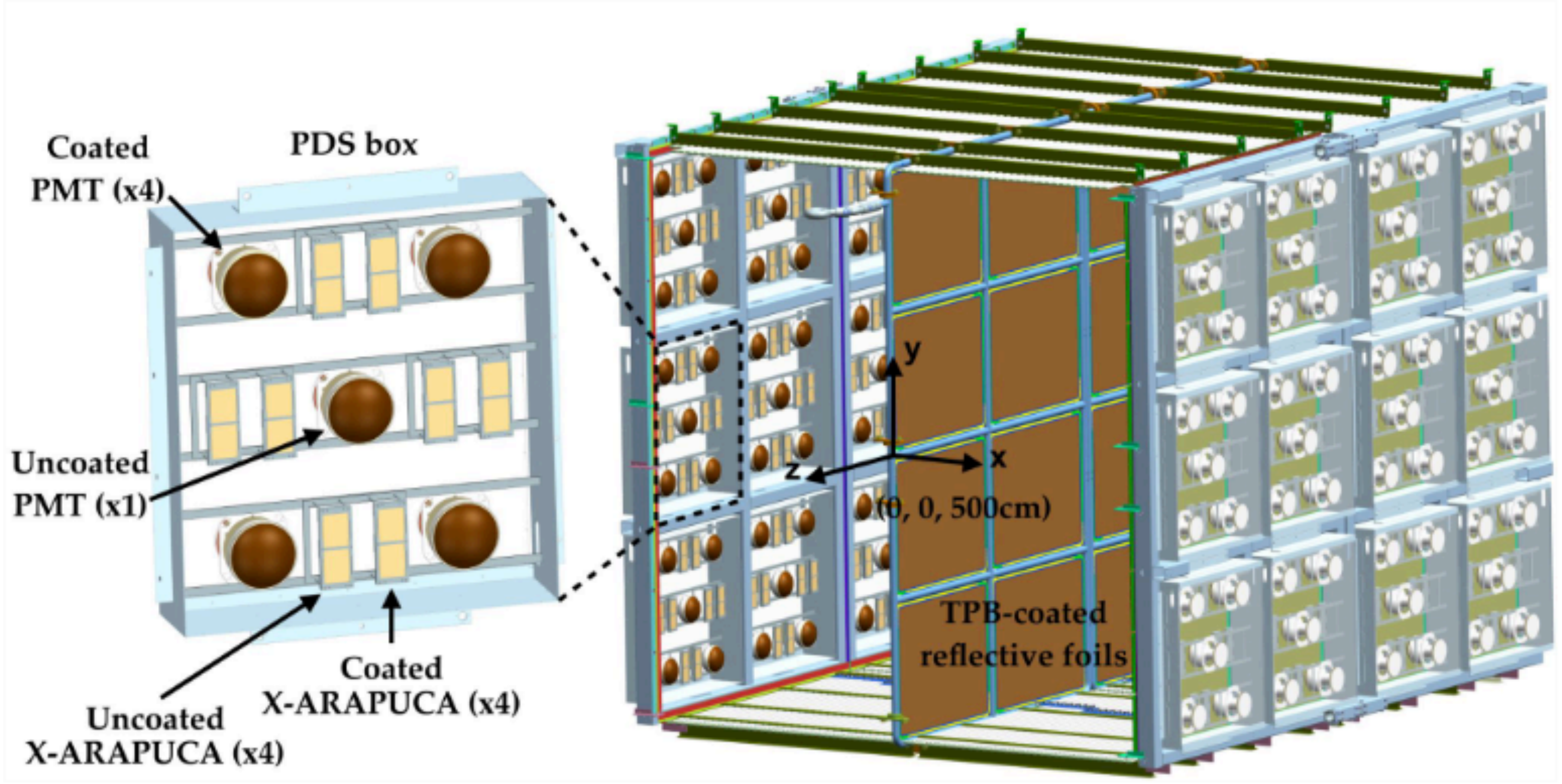
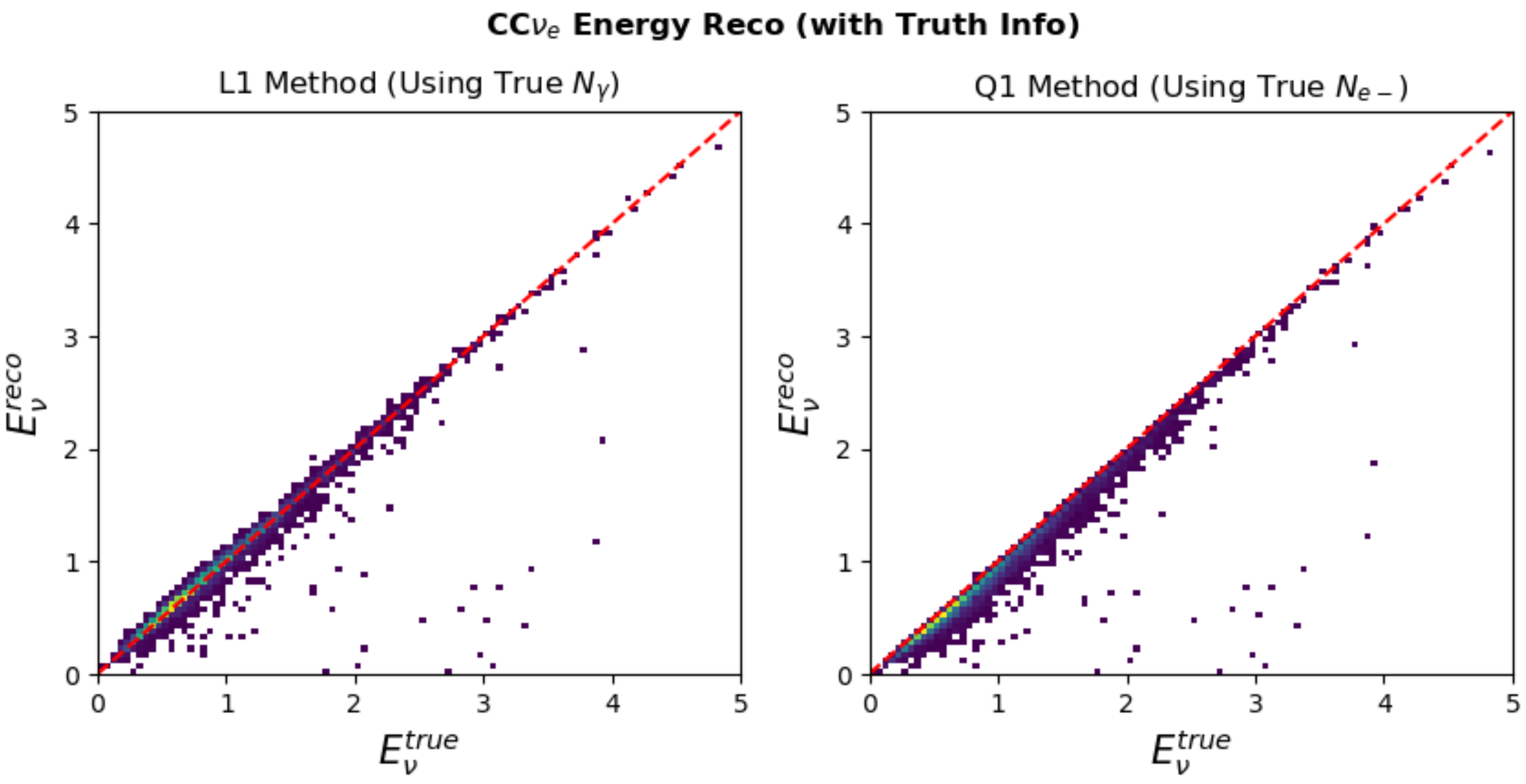


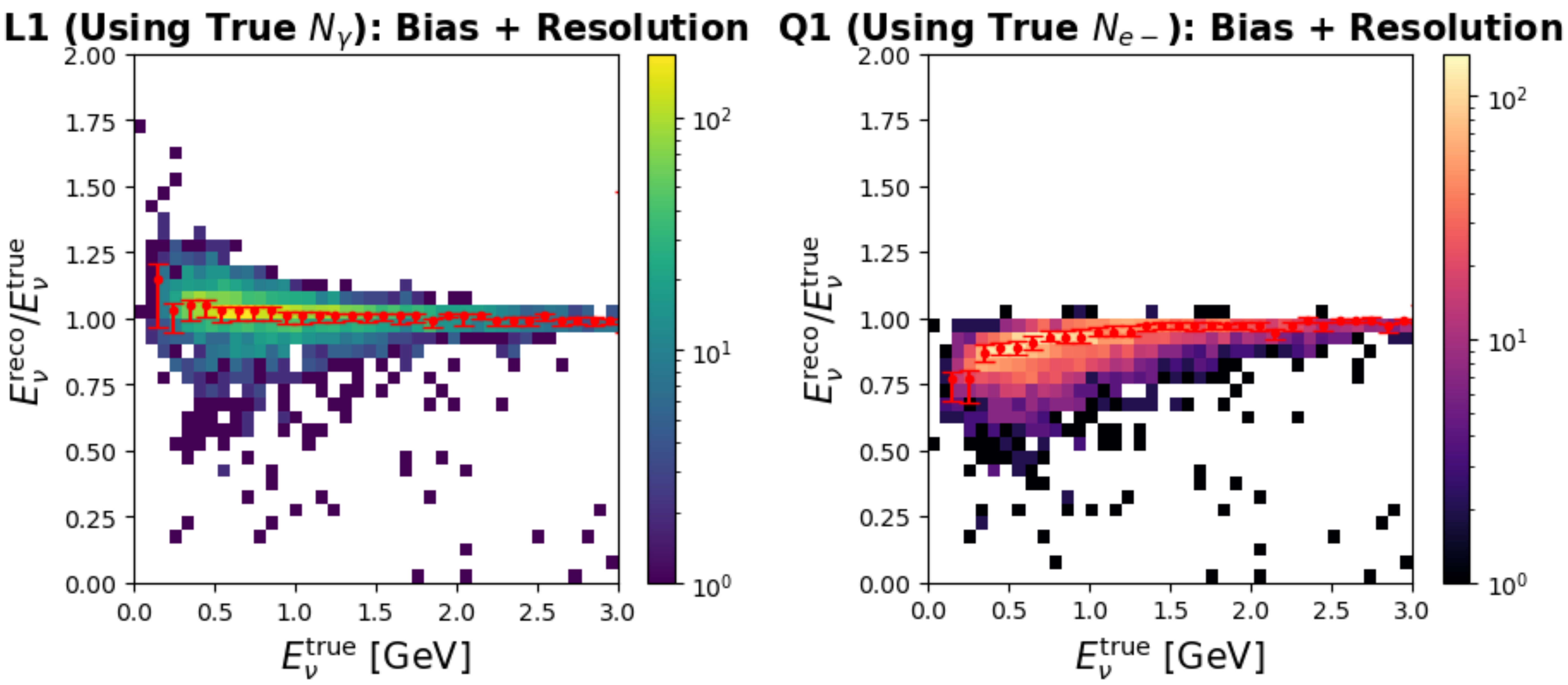
Figure 7. PMT and X-ARAPUCA arrangement in a PDS-box (left), together with a view of SBND's photon detection system (right) [2].

Calorimetry Methods

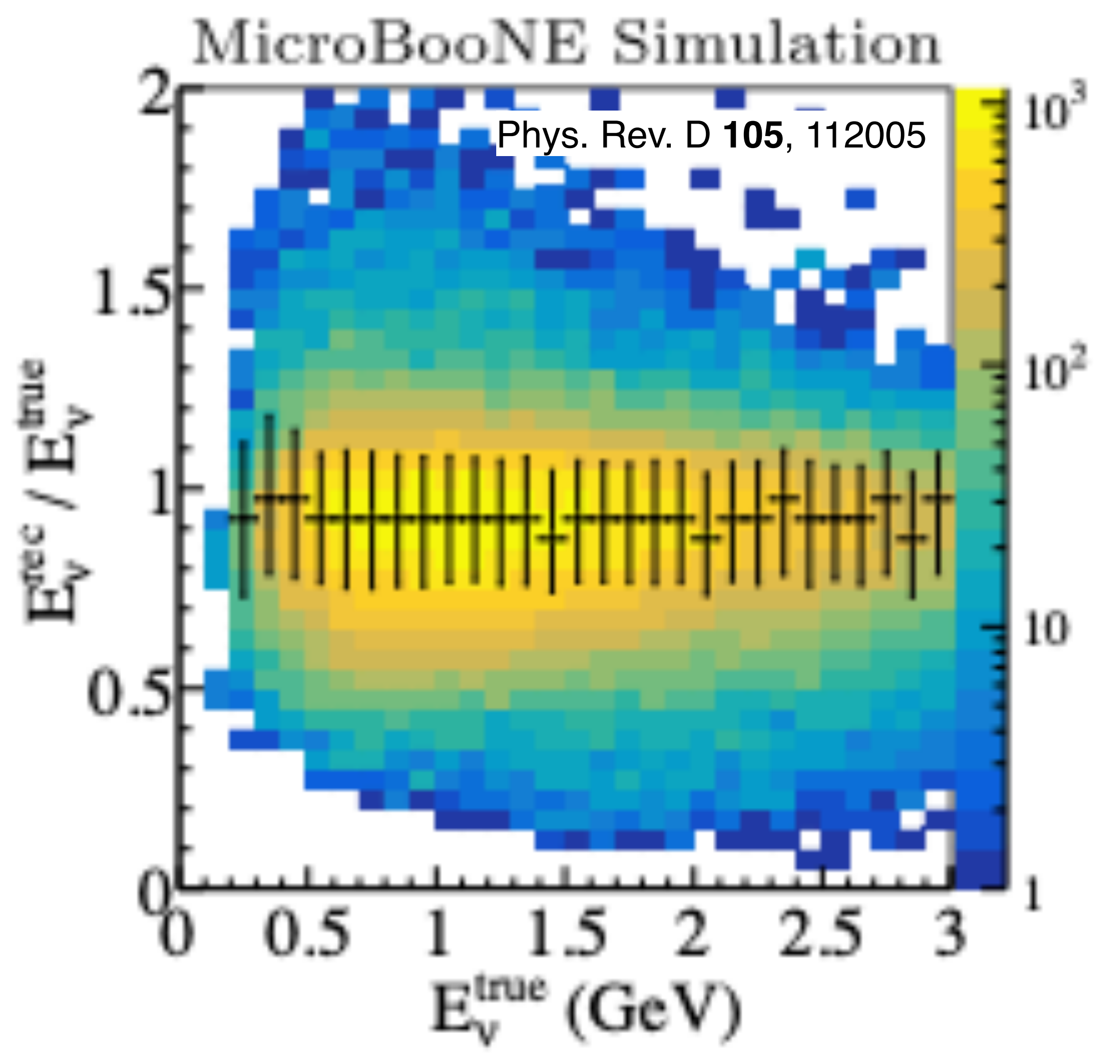
- L1 method (simple light scaling): $L1 = \frac{L}{0.5} W_{ph}$
- Q1 method (simple charge scaling): $Q_1 = \frac{Q}{0.5} W_{ph}$
- Q2 method (like Q1 but separate EM/hadronic): $Q_2 = \left(\frac{Q_e}{0.5} + \frac{Q_h}{0.5} \right) W_{ph}$
- Calorimetry: $E_\nu^{rec} = \sum_i (K_i^{rec} + m_i + B_i)$
  - for QE-like, such as $1e1p$, simplifies to: $E_{\nu,cal} = E_{e-} + K_{p,range}$

Truth Energy Resolution





- using **truth** information from simulated energy depositions from CCν_e contained interactions
- the *intrinsic* resolution of this method



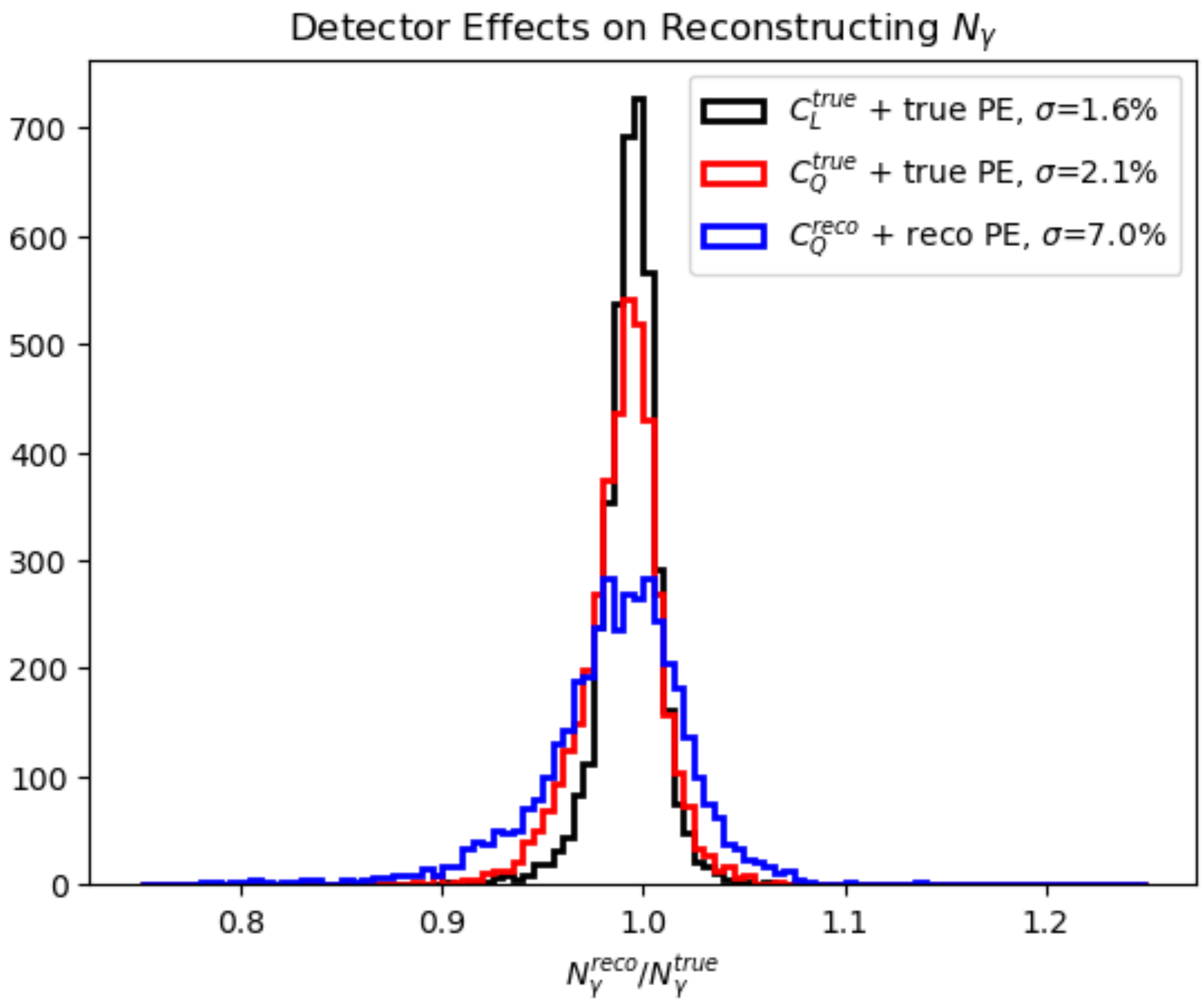
(g) ν_e CC candidates, FC

Reconstructing L (Detector effects)

1. photon propagation (Poisson statistics)
   - the # of photons that reach the photodetectors are subject to Poisson fluctuations and is is spatially dependent (geometric visibility)

2. realistic spatial corrections
   - to construct the spatial correction map, realistically we need to use charge information

3. reconstruction
   - using full detector simulation + reconstruction



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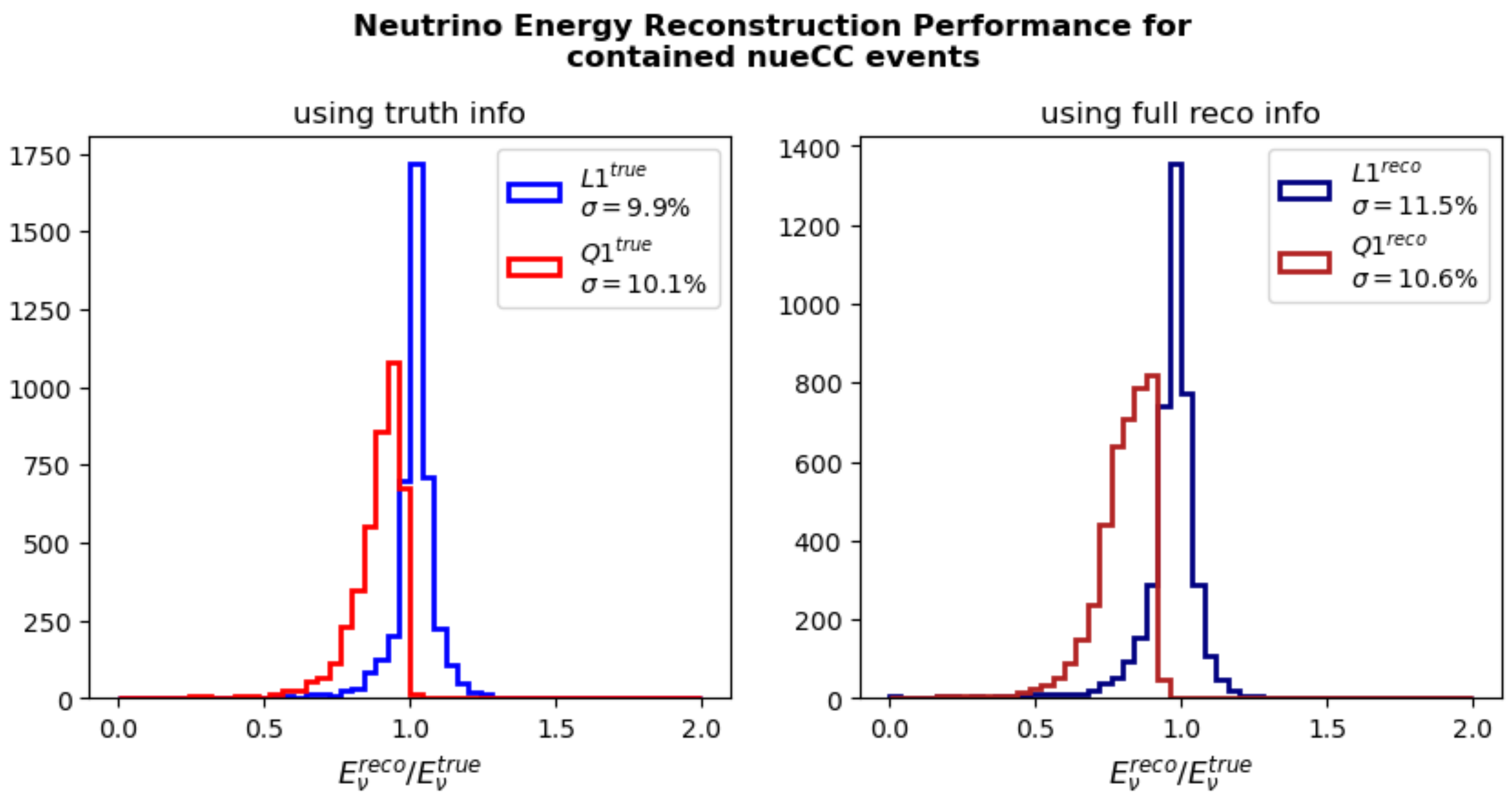
Full Detector Simulation



- show additional smearing for simple scaling methods based on reconstruction ($Q1$ uses Pandora reco, sums all hits in a recob::Slice)

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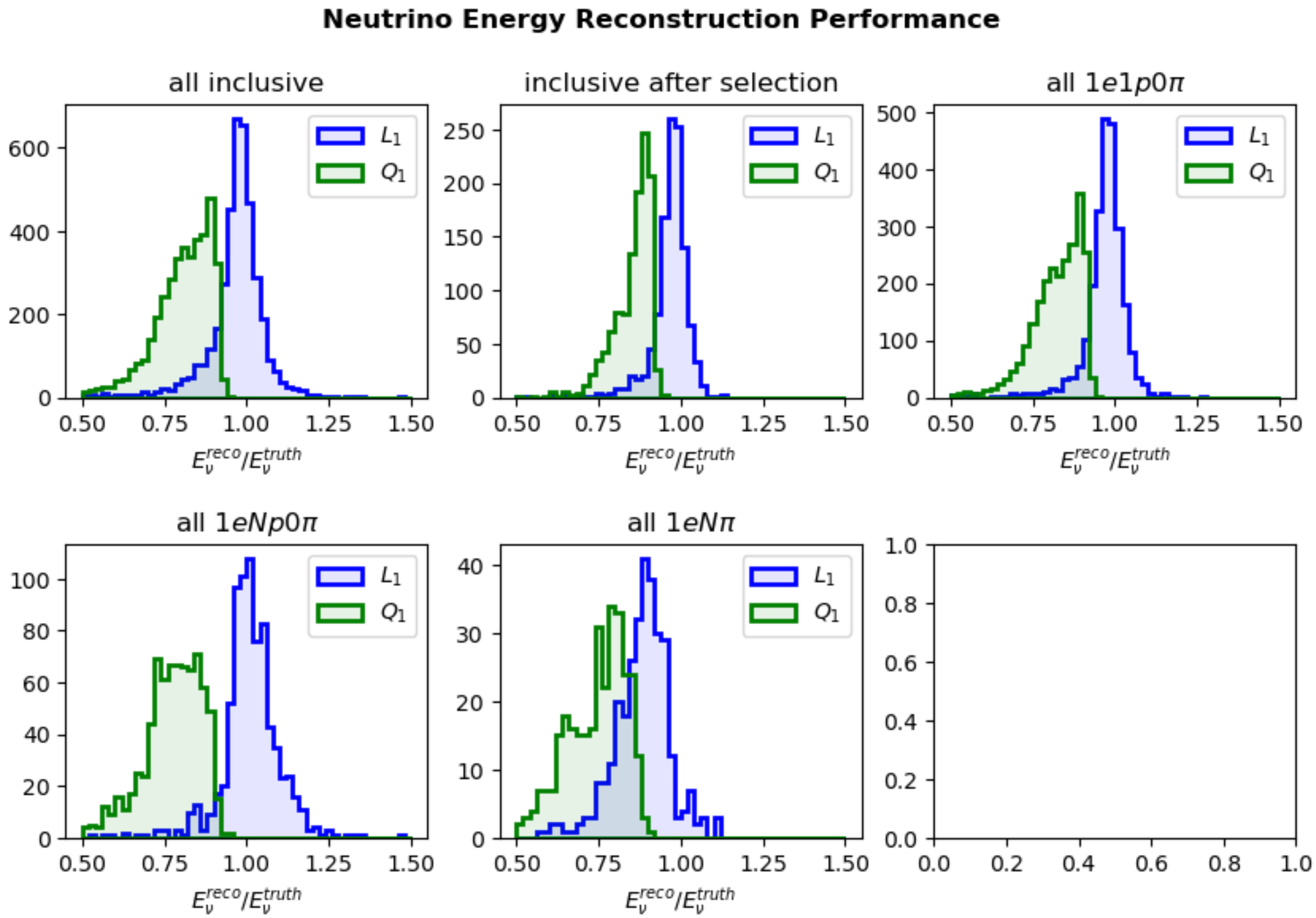
performance w.r.t. interaction channels

- can compare performance for inclusive, *selected* inclusive (using current Pandora-based selection), and exclusive channels
- should expect to see slightly different results based on final state particles
- note: Pandora does not have neutrino energy estimation for any inclusive (ν_μ or ν_e)
- particle gun studies (protons, electrons, pions) also performed as sanity checks

performance w.r.t. interaction channels



- showing only contained events, using **reconstructed quantities**
- with more hadronic activity (Np or $N\pi$), distributions have more features
- for inclusive (with and without selection), $L1$ method remains relatively symmetric
- more details in backup

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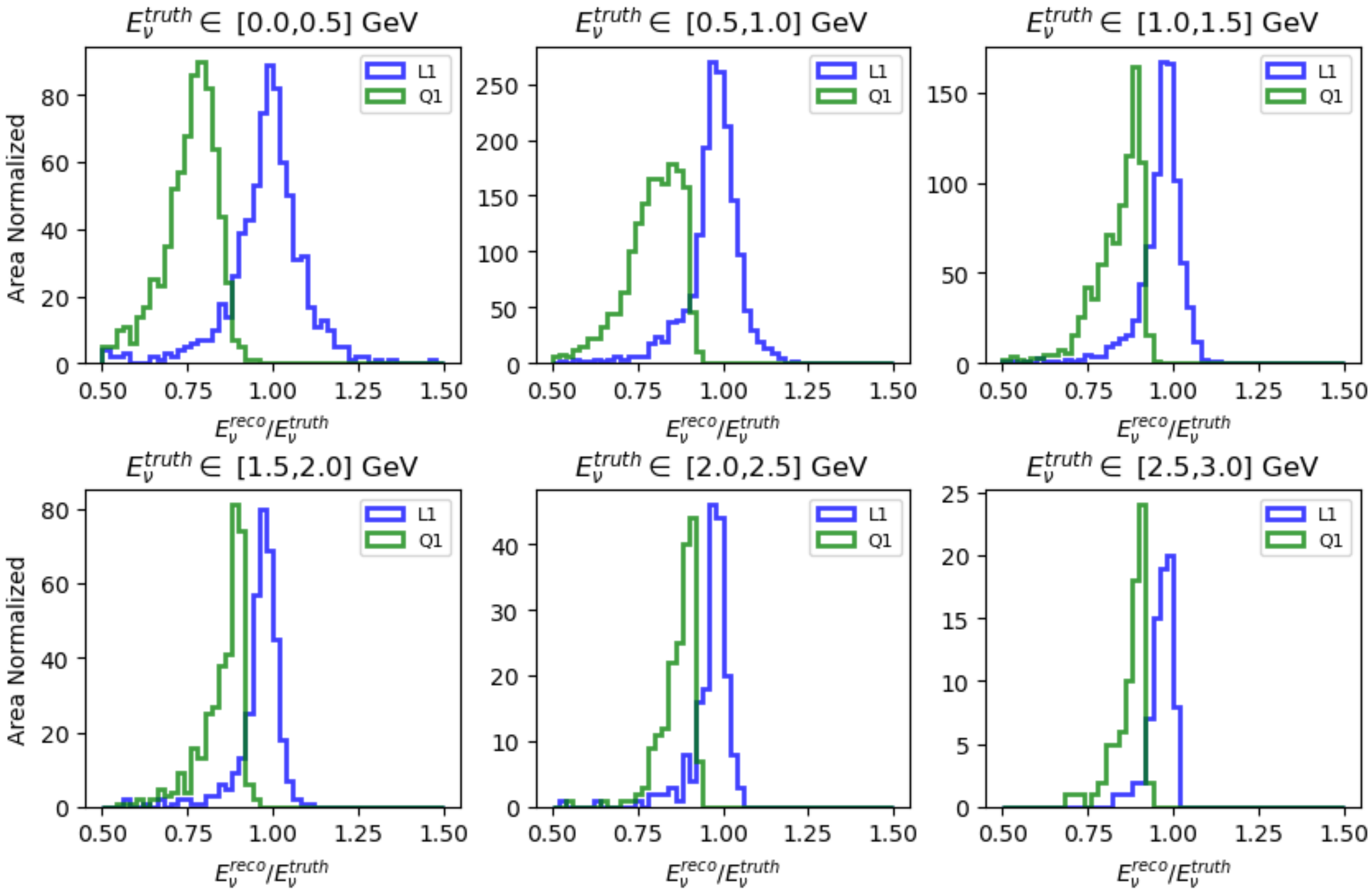
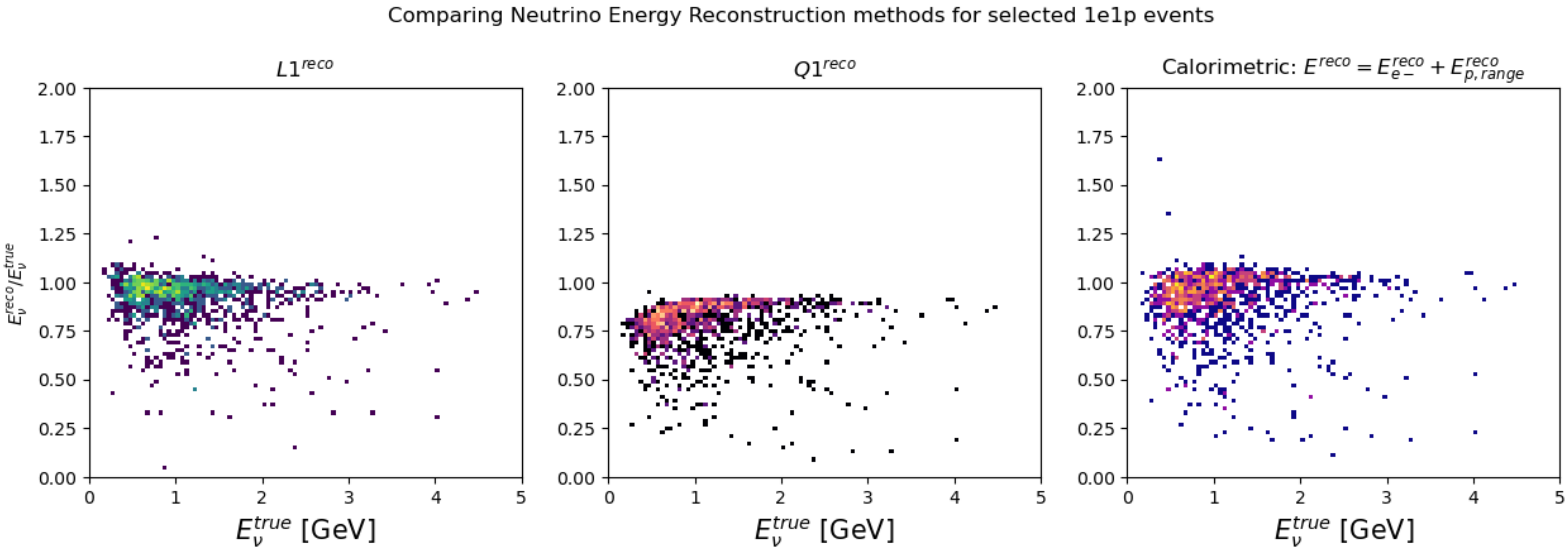
performance w.r.t. energy bins



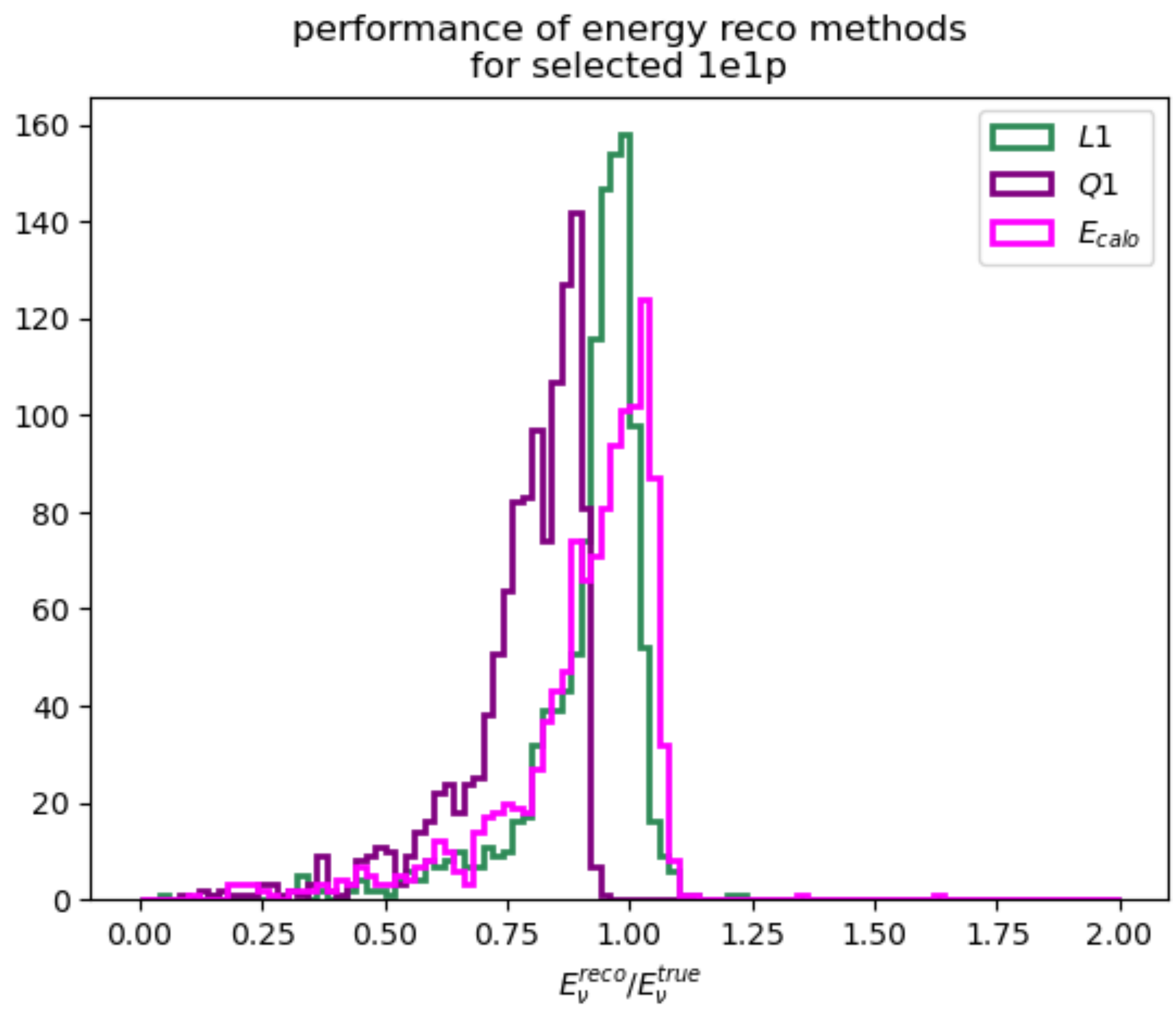
- showing only contained events, using **reconstructed quantities**

$1e1p$ case



- how do these simple scaling methods compare to PID based reco methods?
- have also tired $Q2$, but $Q2$ has similar or worse performance to $Q1$

$1e1p$ case



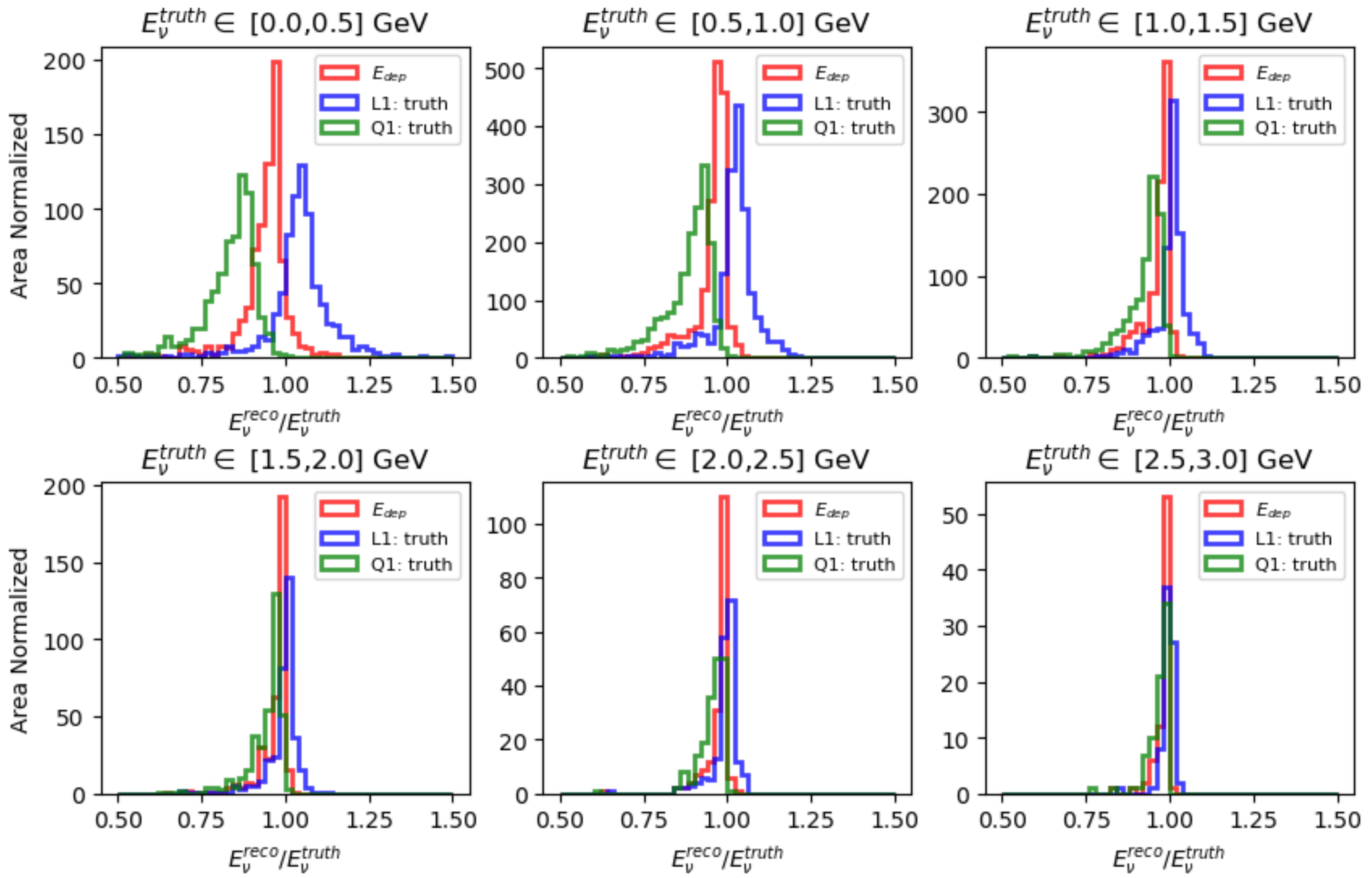
- compare in 1D
- after scaling such that the peak value lines up with 1, standard deviations of each method:
- $\sigma_{L1} \approx 13\,\%$
- $\sigma_{Q1} \approx 15.5\,\%$
- $\sigma_{calo} \approx 17\,\%$

summary

- have performed some detailed studies on the feasibility of using light calorimetry for neutrino energy reconstruction in SBND
    - quantified the intrinsic energy resolution of the light calorimetry method, and can also quantify various detector effects
- in SBND, there is no general neutrino energy estimator (e.g. for inclusive selections), so a light or charge based method may be very useful
- thank you to Chao, Haiwang, and Hanyu for their feedback and guidance!

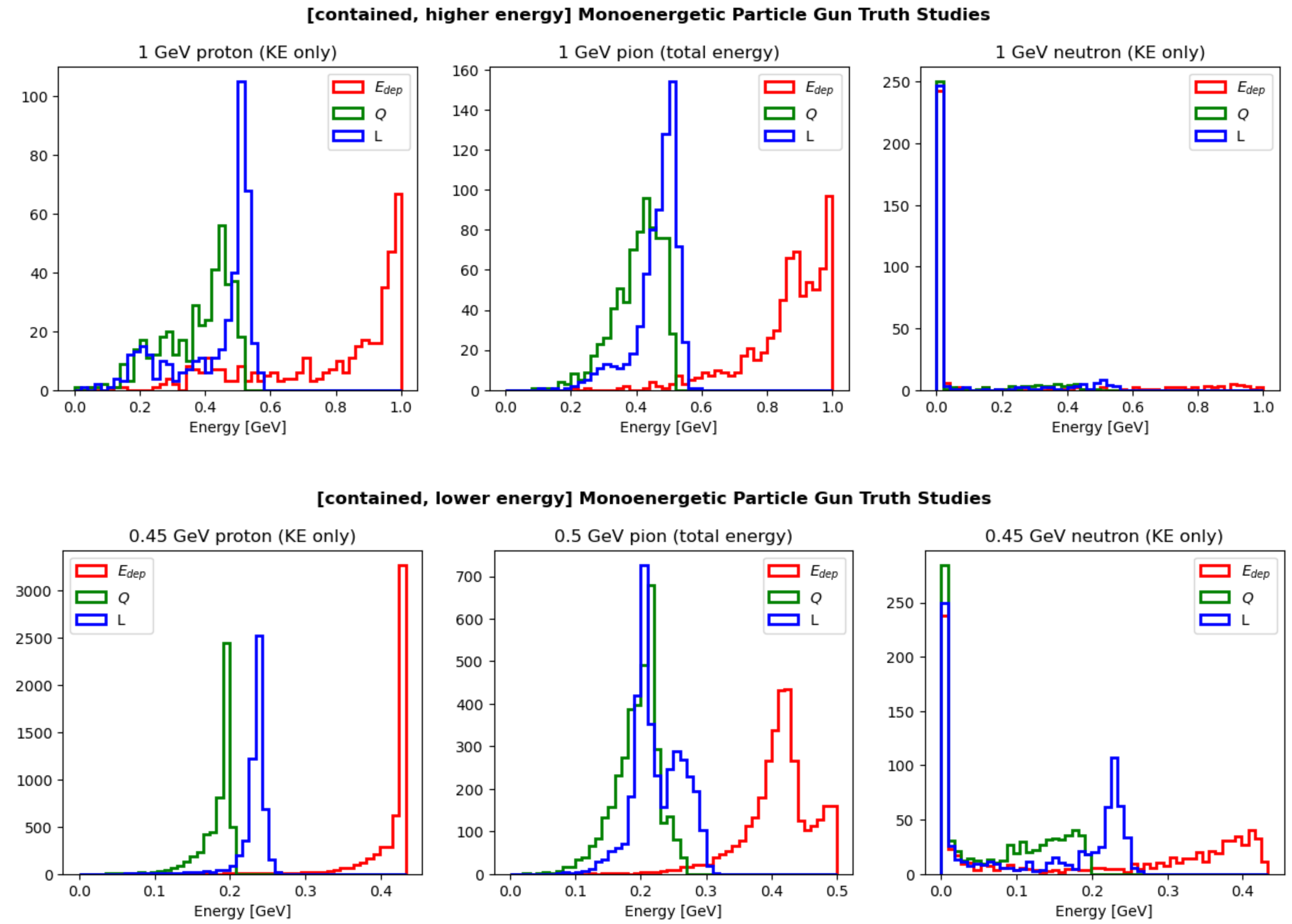
backup

energy dependence



- below 500 MeV, Q_1 and L_1 are similar
- between 0.5 and 2.0 GeV, L_1 seems to be better
- but Q_1 may improve higher than 2.5 GeV to become comparable? low stats

particle gun

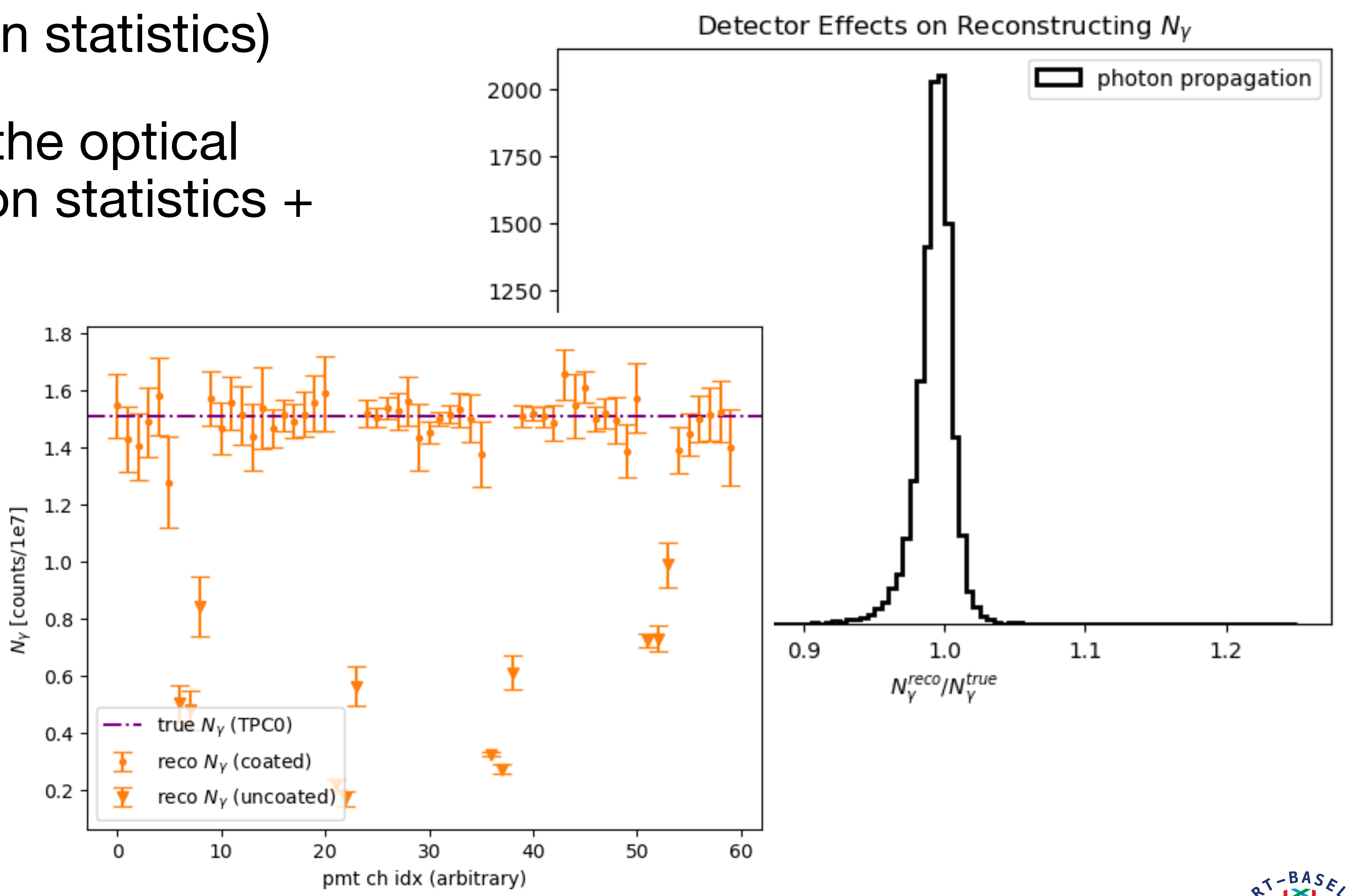


- two monoenergetic samples, higher energy (1 GeV) and lower energy (~0.5 GeV, more similar to expected energies from BNB final state particles)
- require containment for these plots, but neutron case doesn't work well (still escapes)

detector effects, N_γ^{reco} vs. N_γ^{true}

1. photon propagation (Poisson statistics)

- # of photons that make it to the optical detector is affected by Poisson statistics + geometric “inefficiencies”
- can use a weighted average to calculate the N_γ, where the errors are Poisson-ion
- uncoated PMTs have some strange behavior, ignoring them for now



detector effects, N_γ^{reco} vs. N_γ^{true}

2. spatial corrections

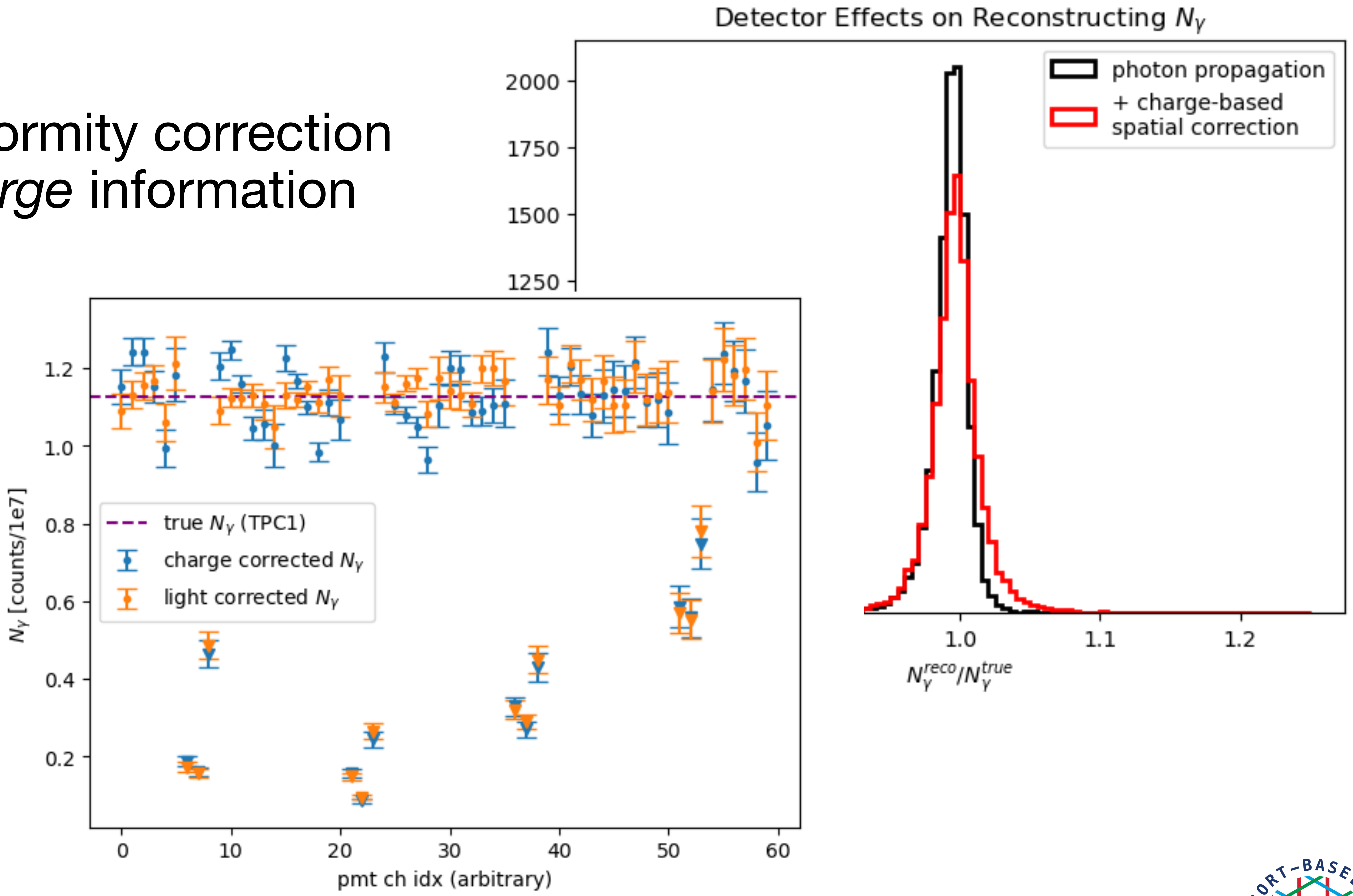
- a realistic "spatial" non-uniformity correction map must be made with *charge* information

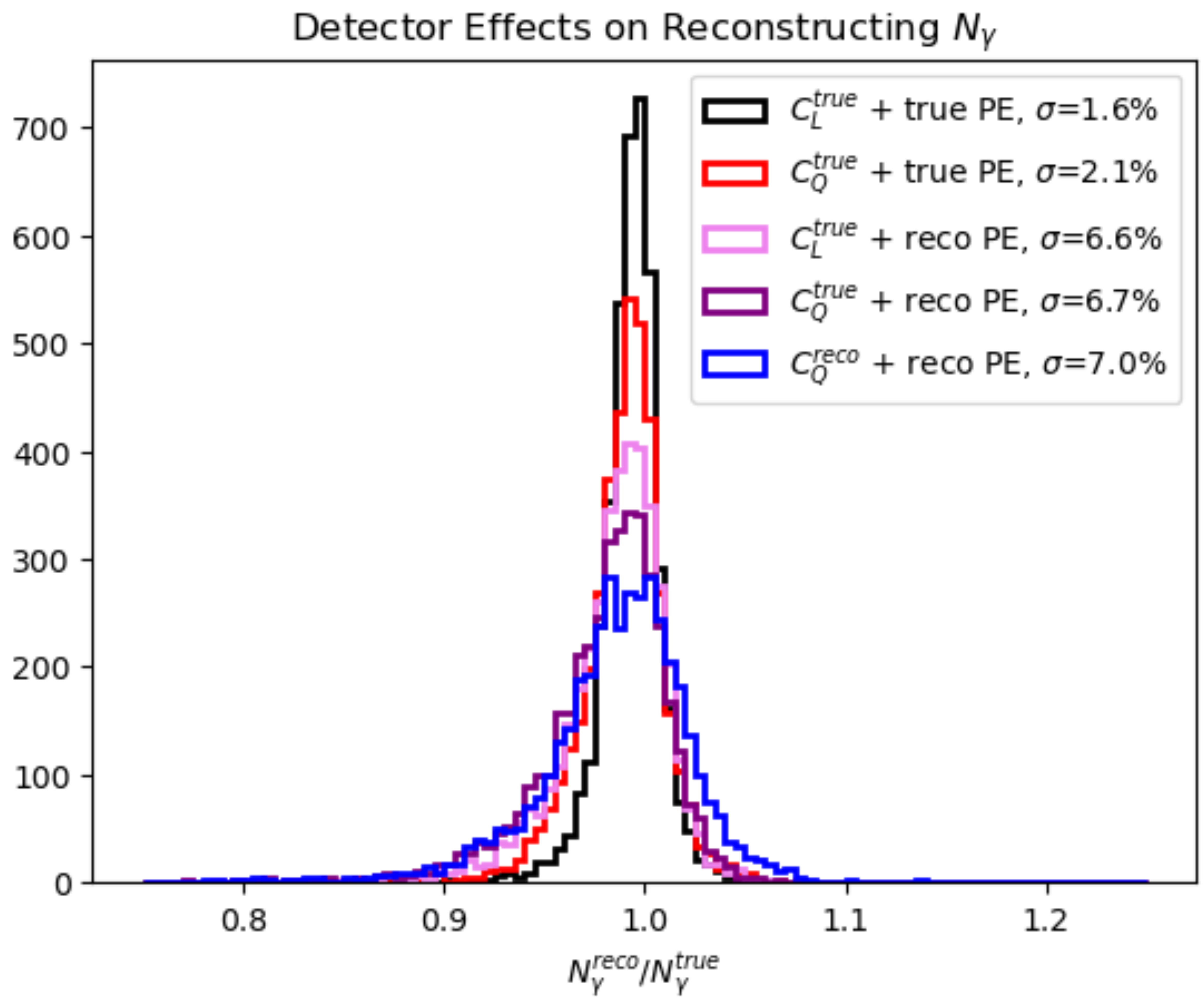
- this assumes that $dQ \approx dL$ in the construction of the correction map

$$f_{j,avg} = \frac{\sum_i (dL)_i \cdot f_j(\bar{x}_i)}{L}$$

$$\Downarrow$$

$$f_{j,avg} = \frac{\sum_i (dQ)_i \cdot f_j(\bar{x}_i)}{Q}$$

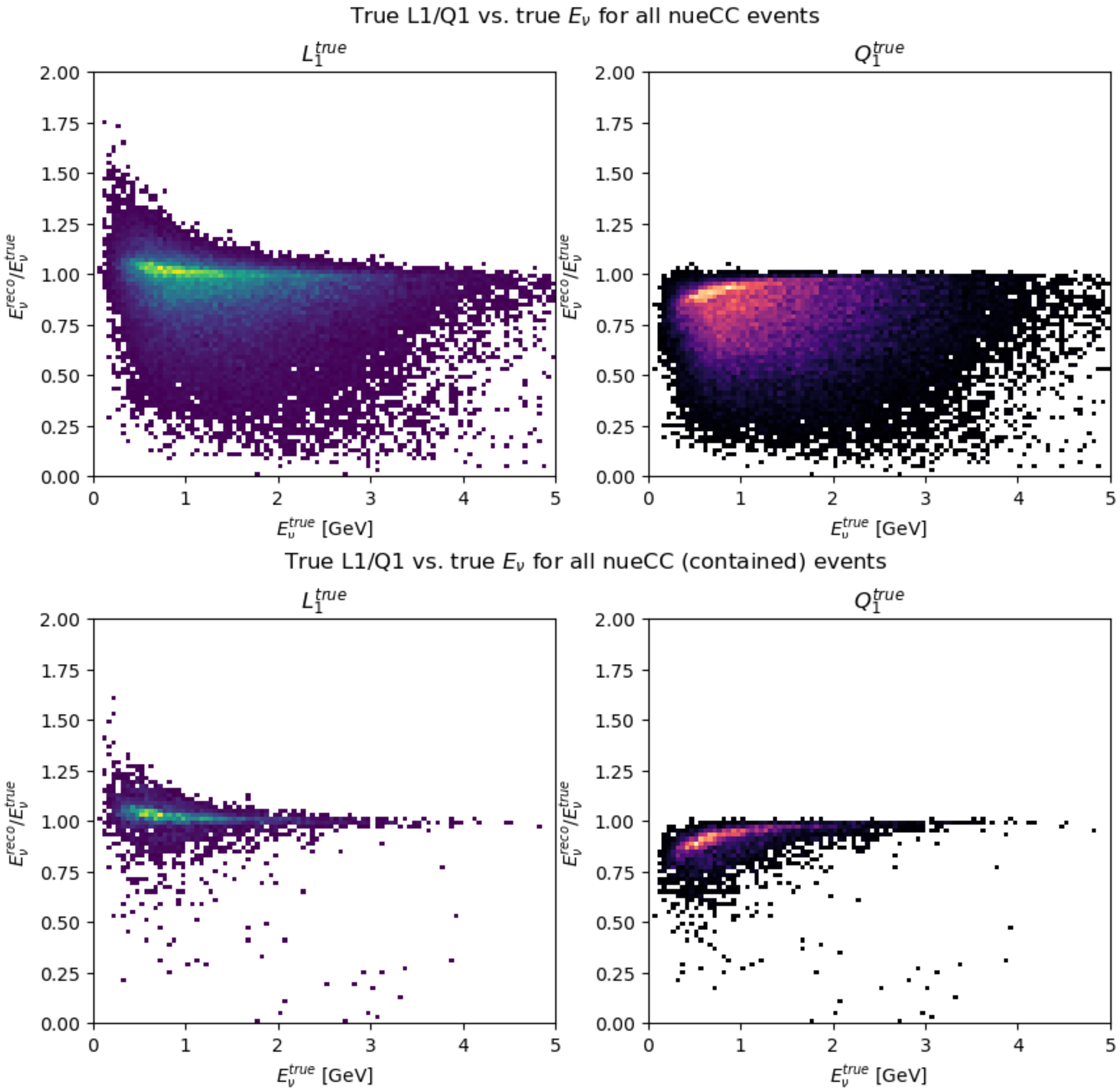




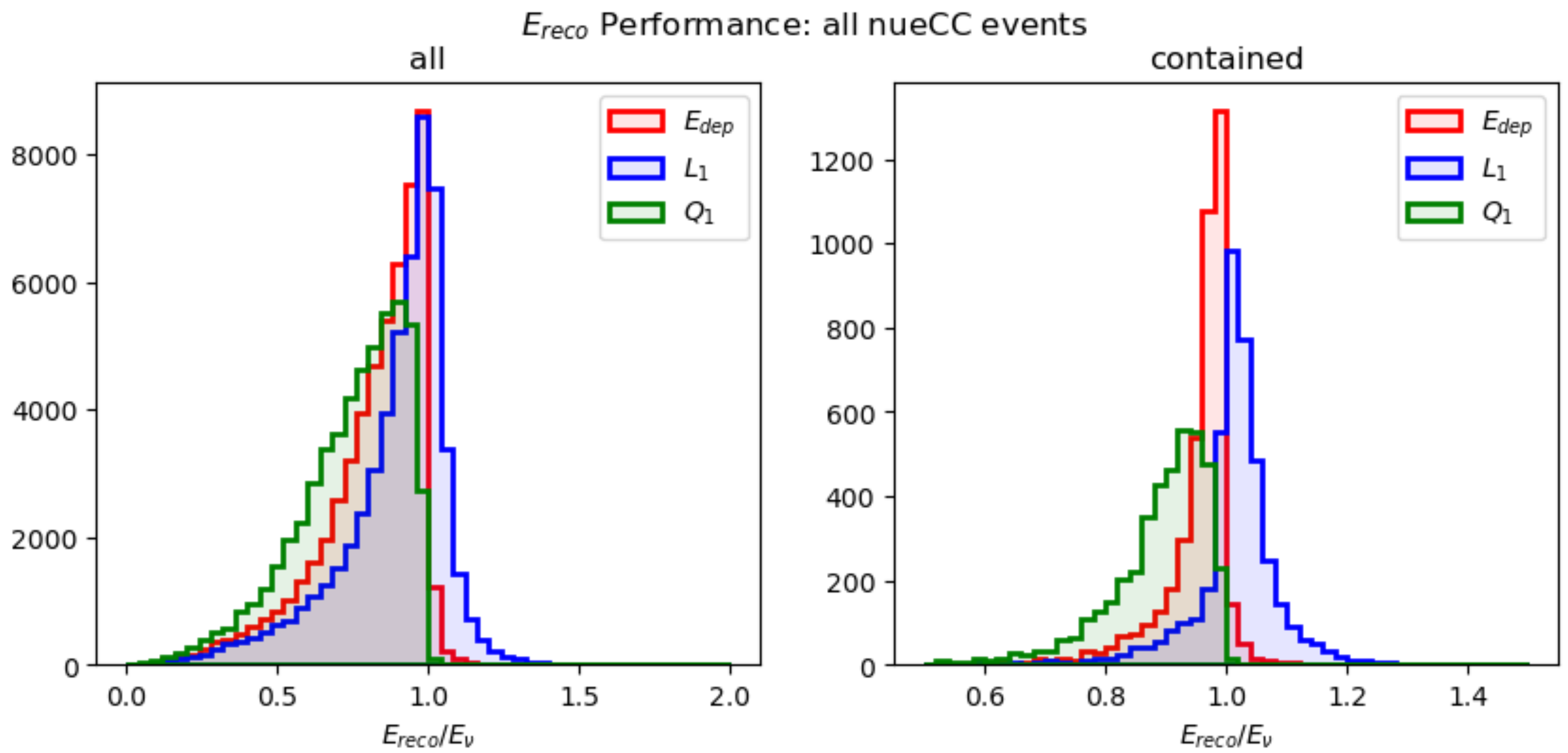
- detector simulation + light reconstruction contributes most of the additional smearing (black vs. pink), about 5%
- using reconstruction based charge-correction contributes maybe another ~0.5% of smearing
- σ here is standard deviation

$$C_L \propto \frac{\sum_i dL_i \cdot \epsilon_i}{L} \qquad C_Q \propto \frac{\sum_i dQ_i \cdot \epsilon_i}{Q}$$

inclusive

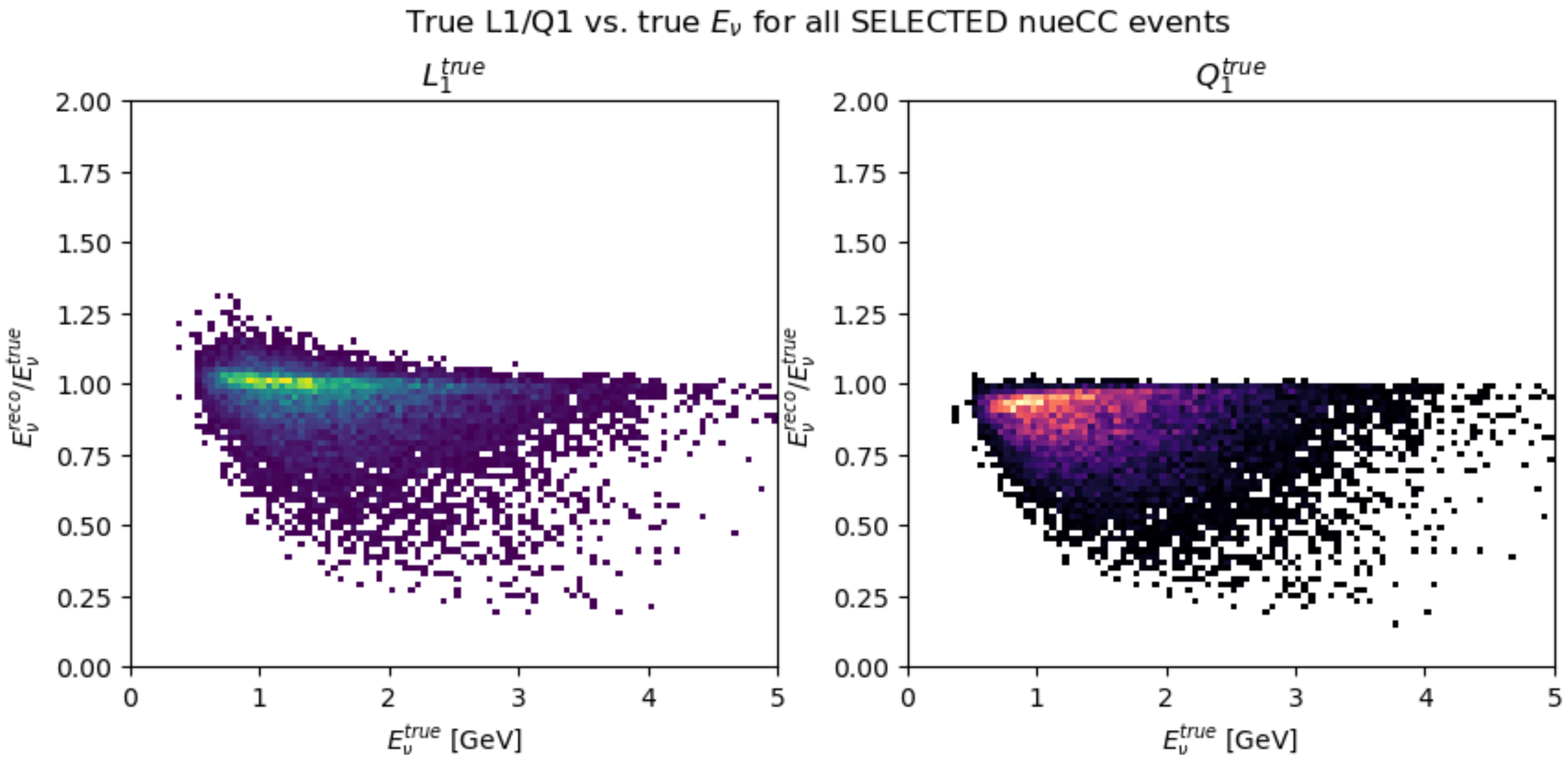


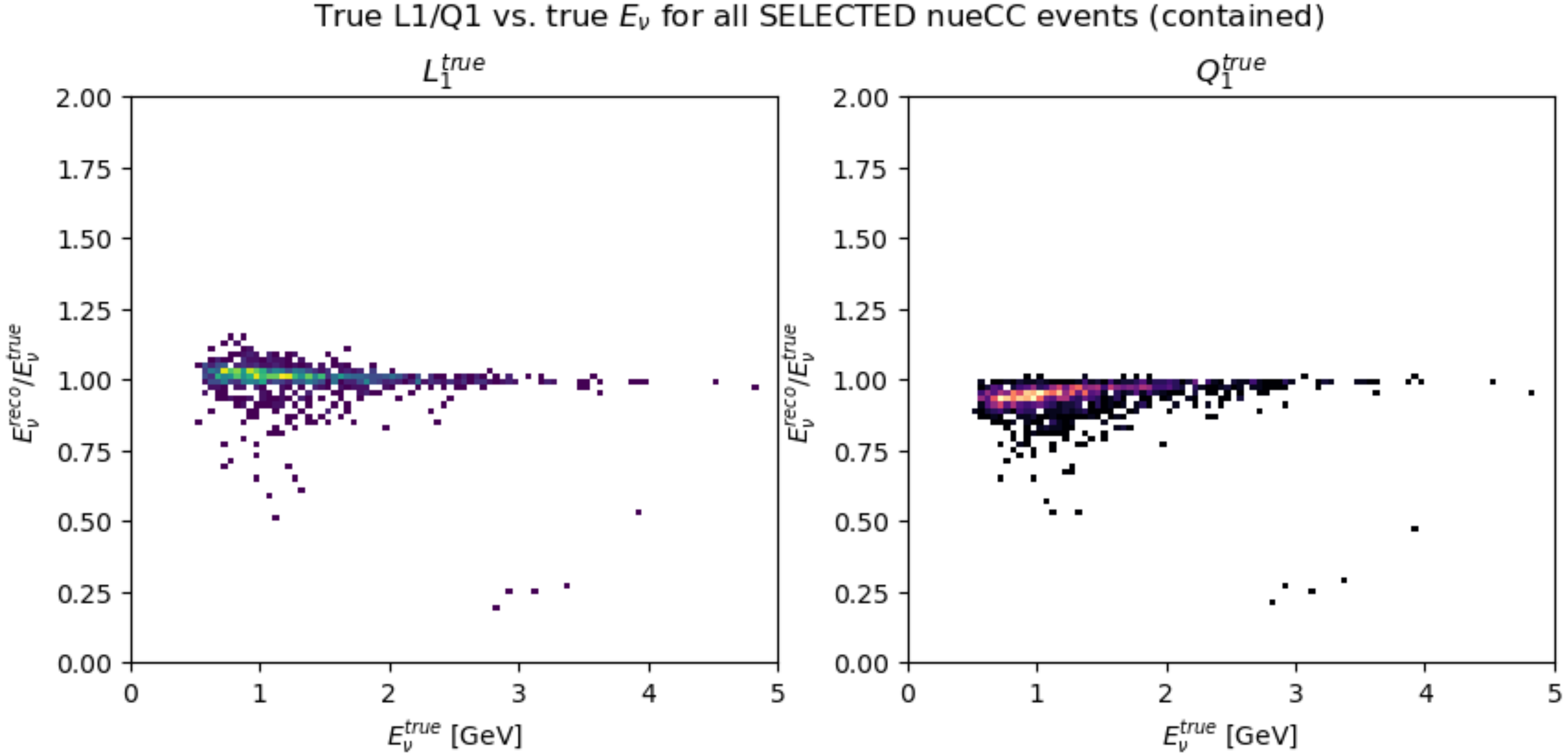
True L1/Q1 vs. true E_ν for all nueCC events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]
True L1/Q1 vs. true E_ν for all nueCC (contained) events

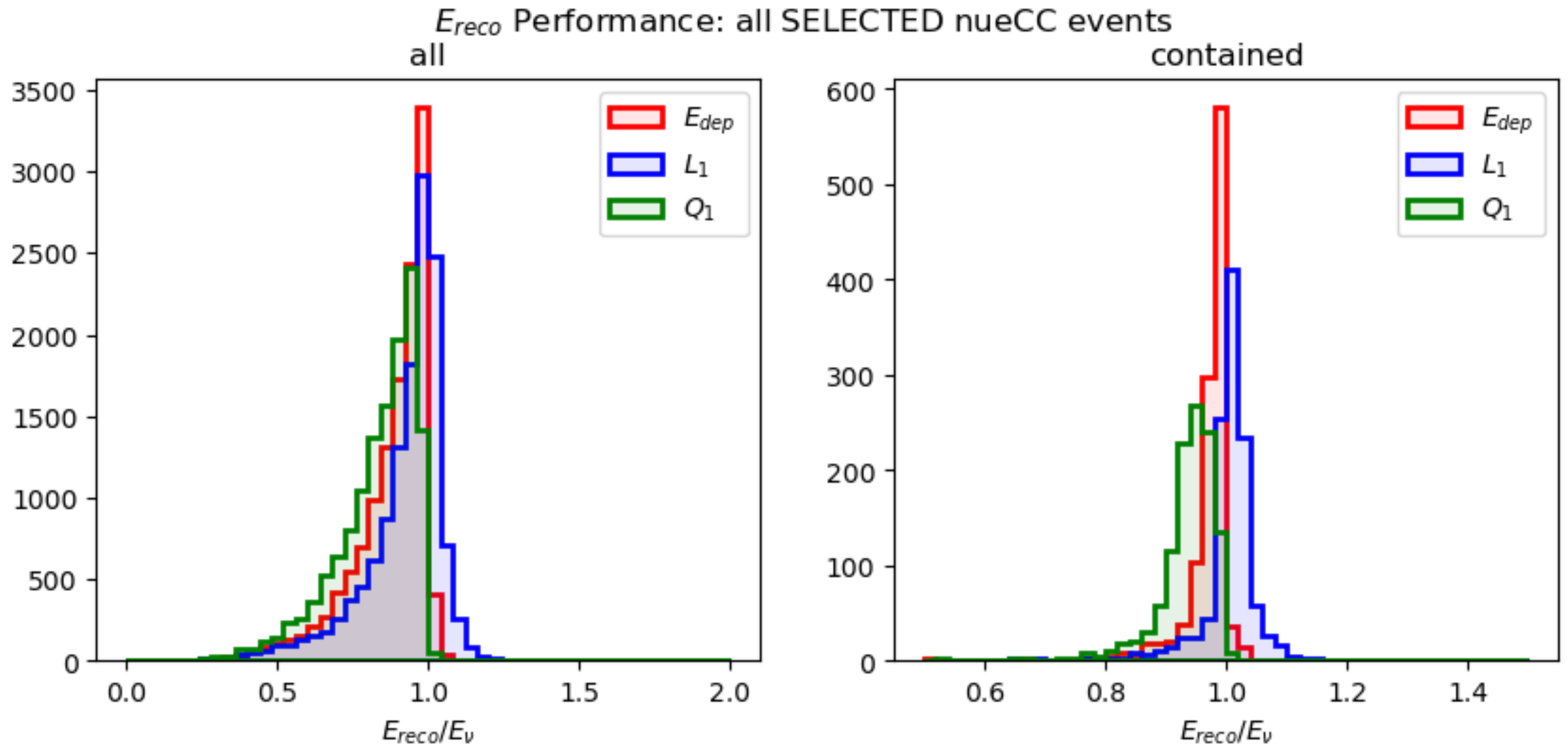


E_{reco} Performance: all nueCC events
all
contained
E_{dep}
L_1
Q_1
E_{reco}/E_ν

inclusive, selected







- ran my selection for nueCC events
  - selection does not require containment
  - selection does require electron's reco energy > 500 MeV

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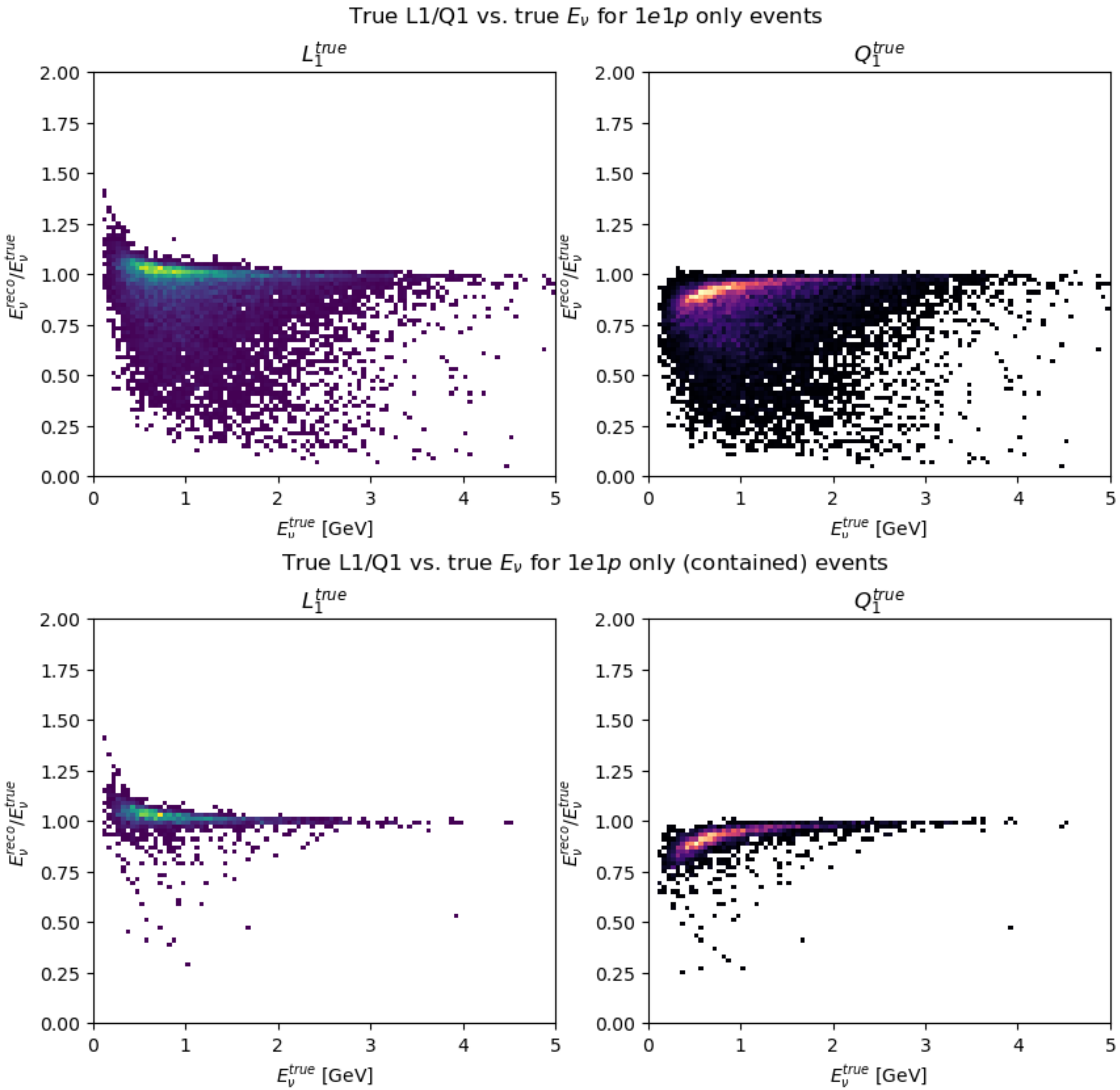
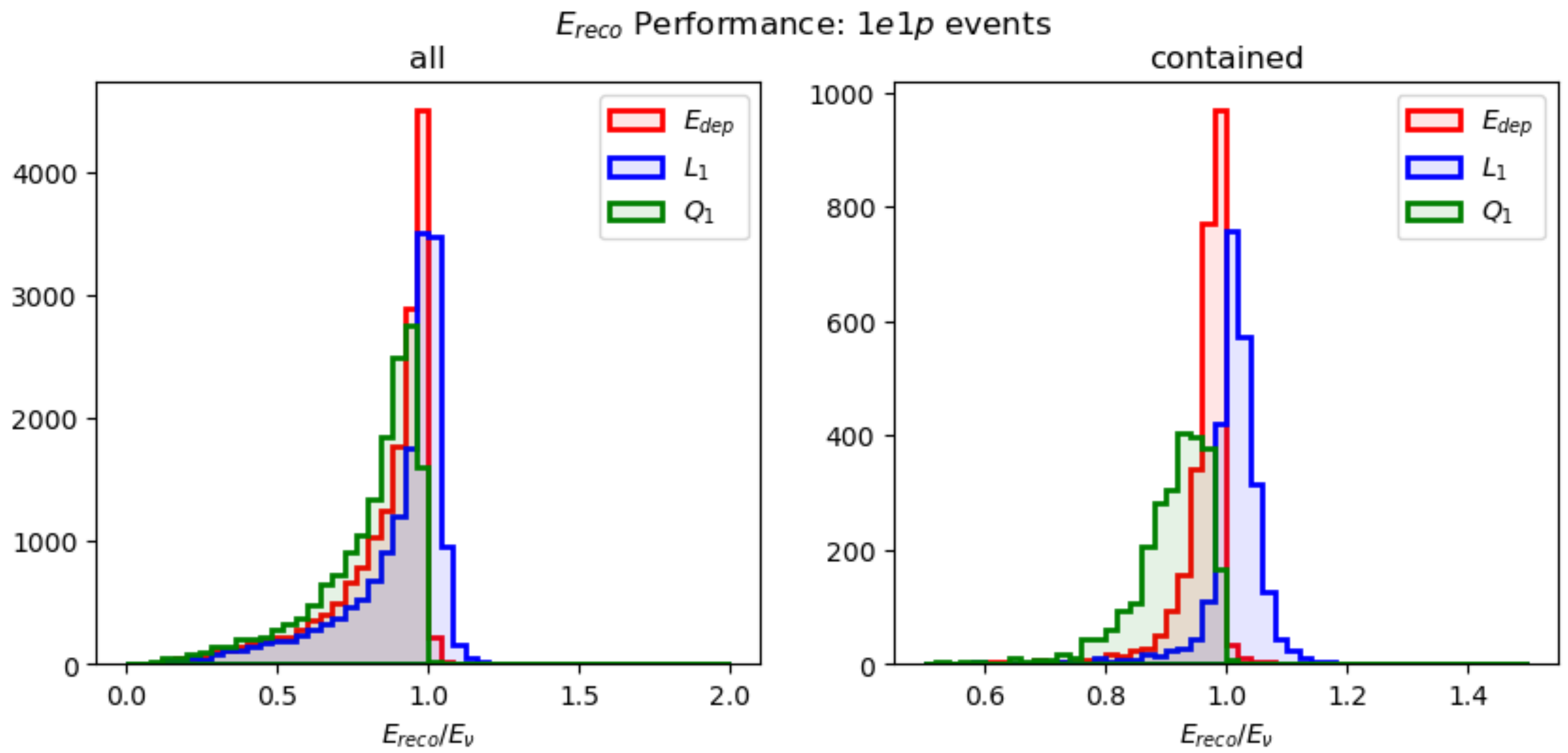
1e1p0pi

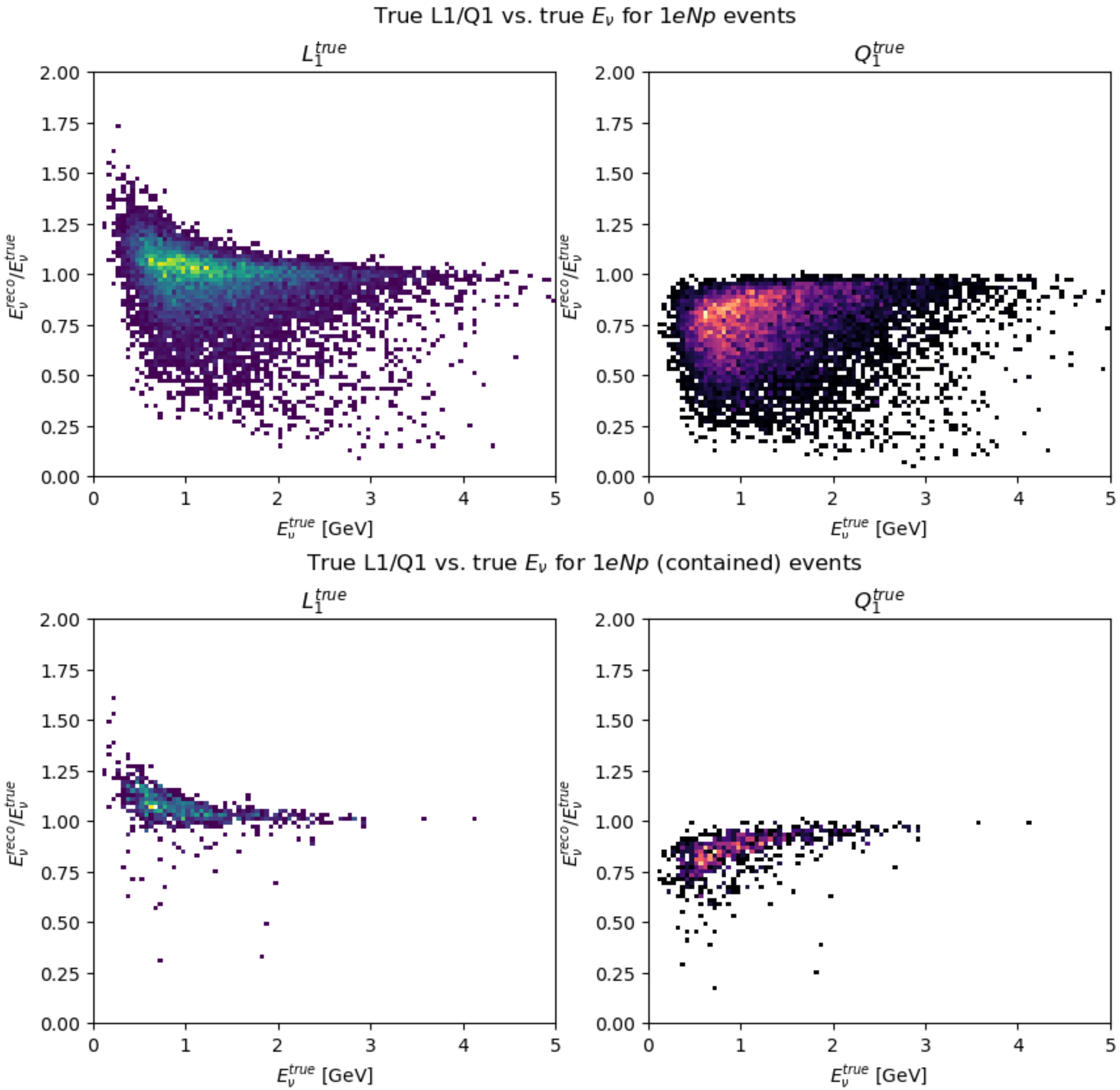


True L1/Q1 vs. true E_ν for 1e1p only events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]
True L1/Q1 vs. true E_ν for 1e1p only (contained) events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]

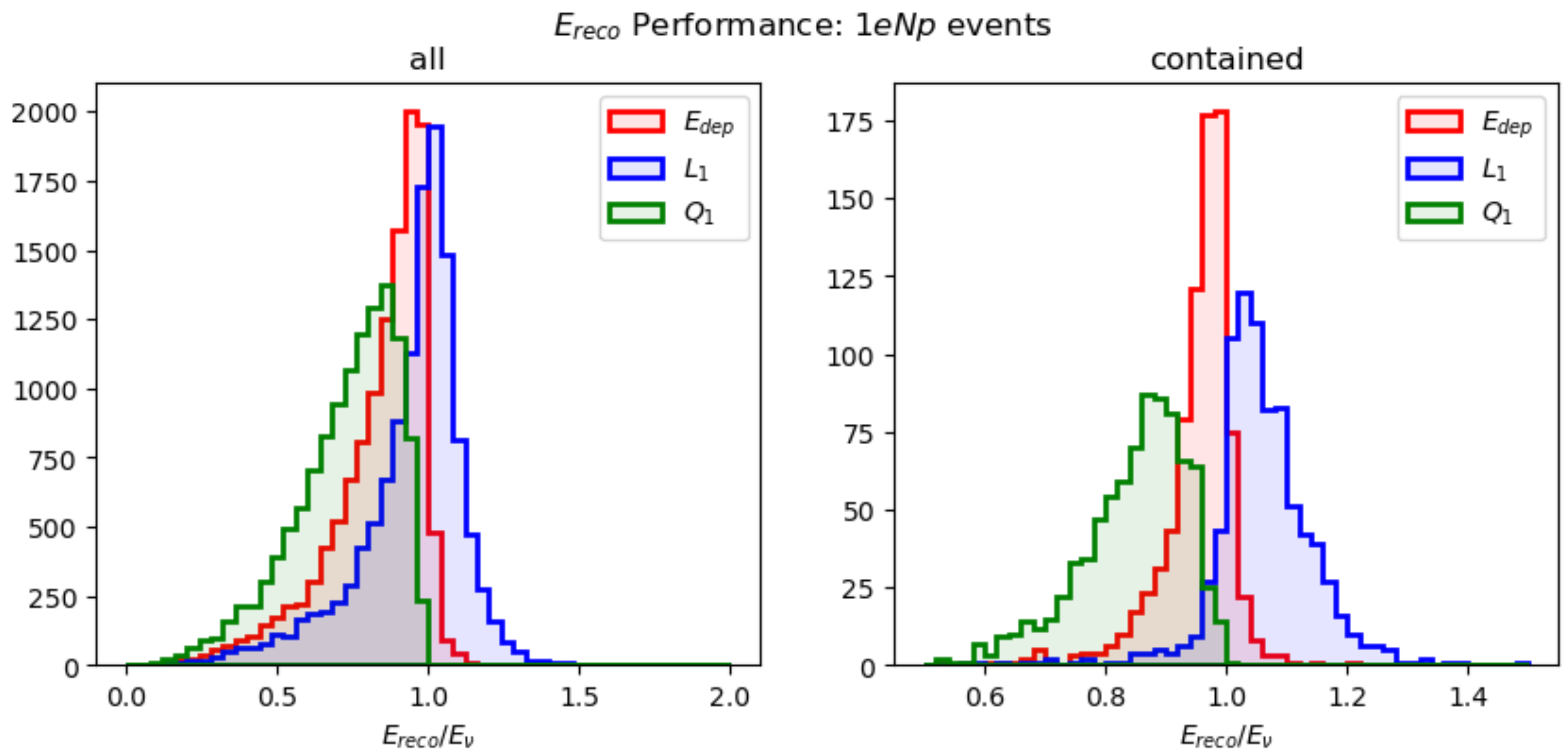


E_{reco} Performance: 1e1p events
all
contained
E_{dep}
L_1
Q_1
E_{reco}/E_ν

1eNp0pi

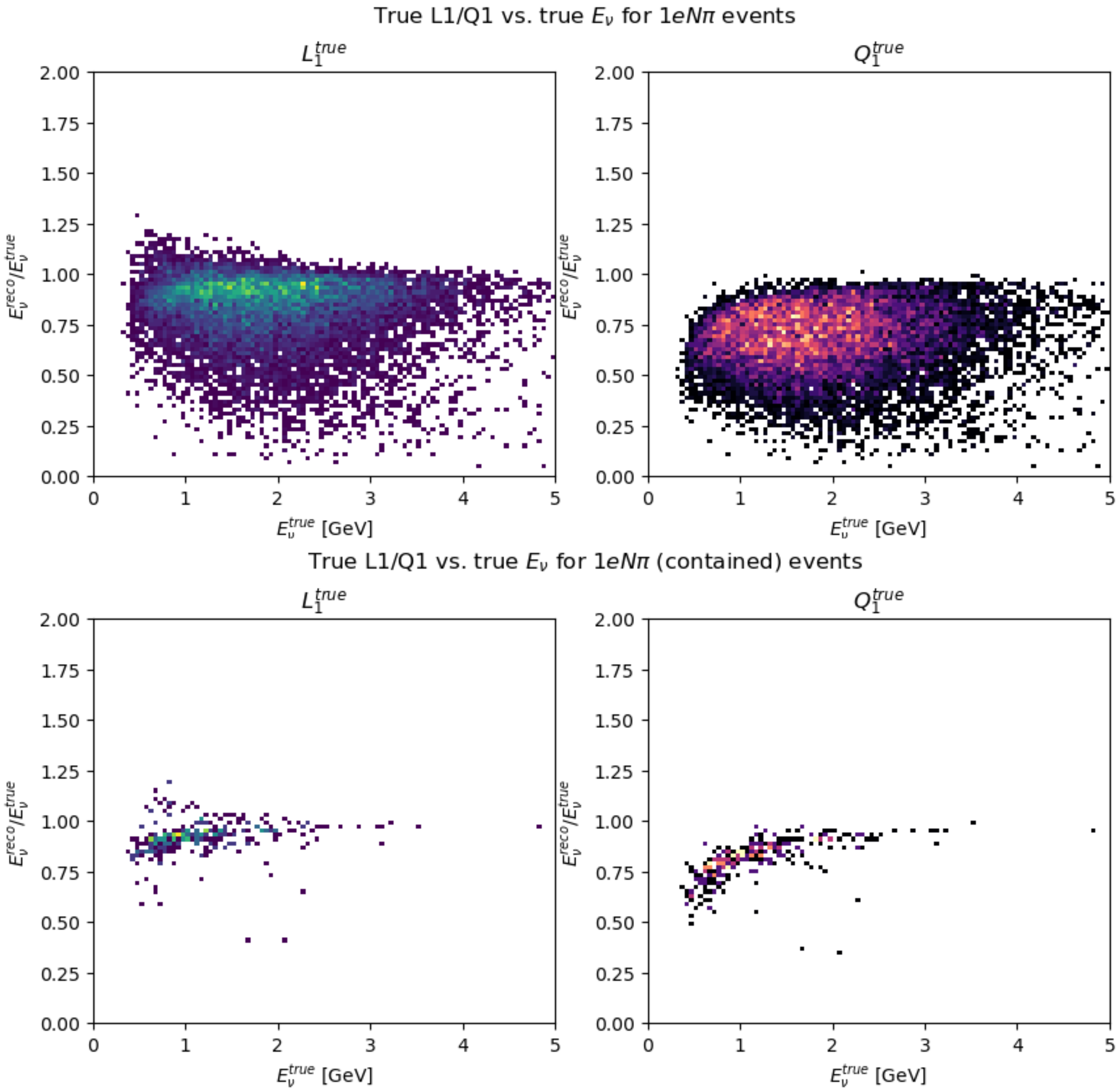


True L1/Q1 vs. true E_ν for 1eNp events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]
True L1/Q1 vs. true E_ν for 1eNp (contained) events

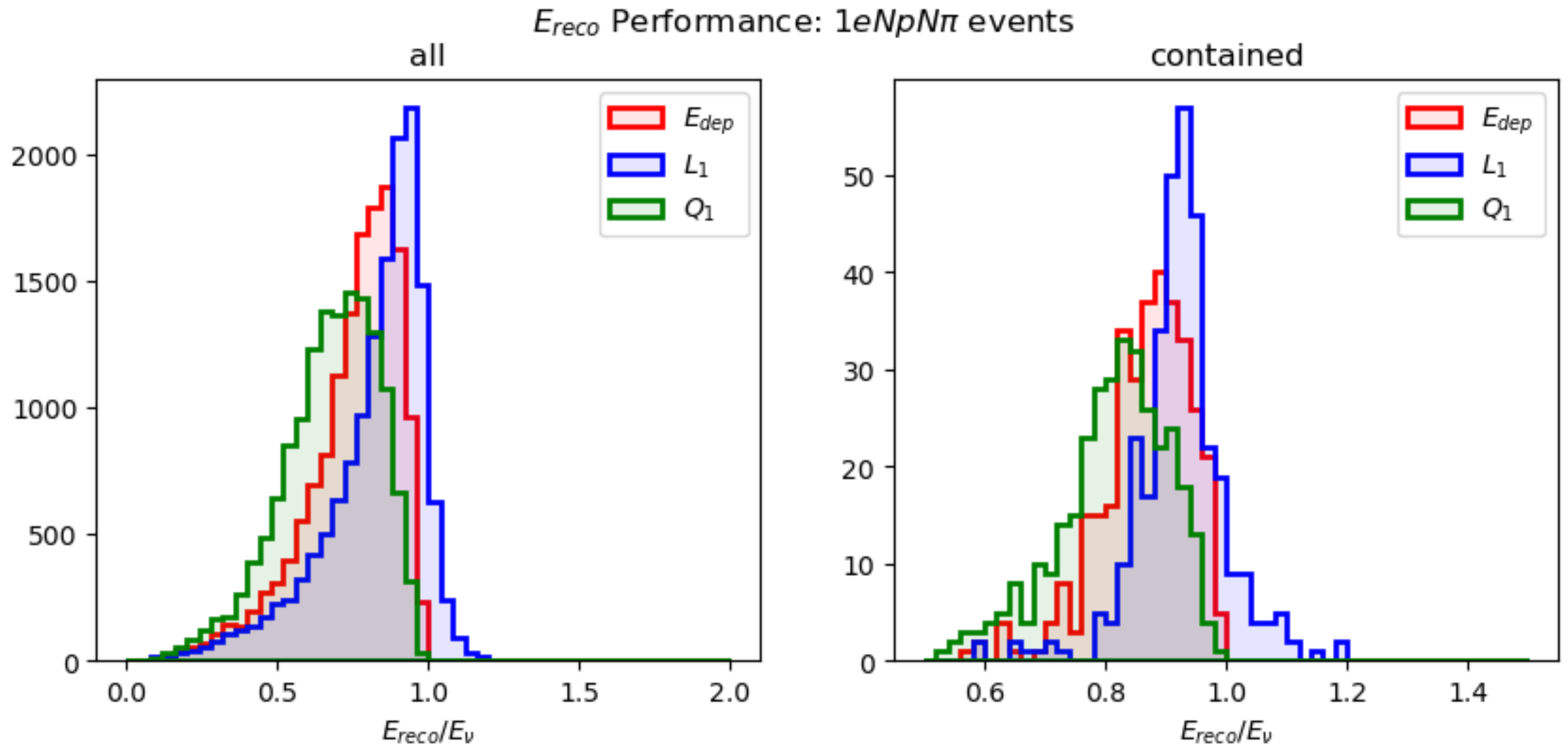


E_{reco} Performance: 1eNp events
all
contained
E_{dep}
L_1
Q_1
E_{reco}/E_ν

1eNpNpi

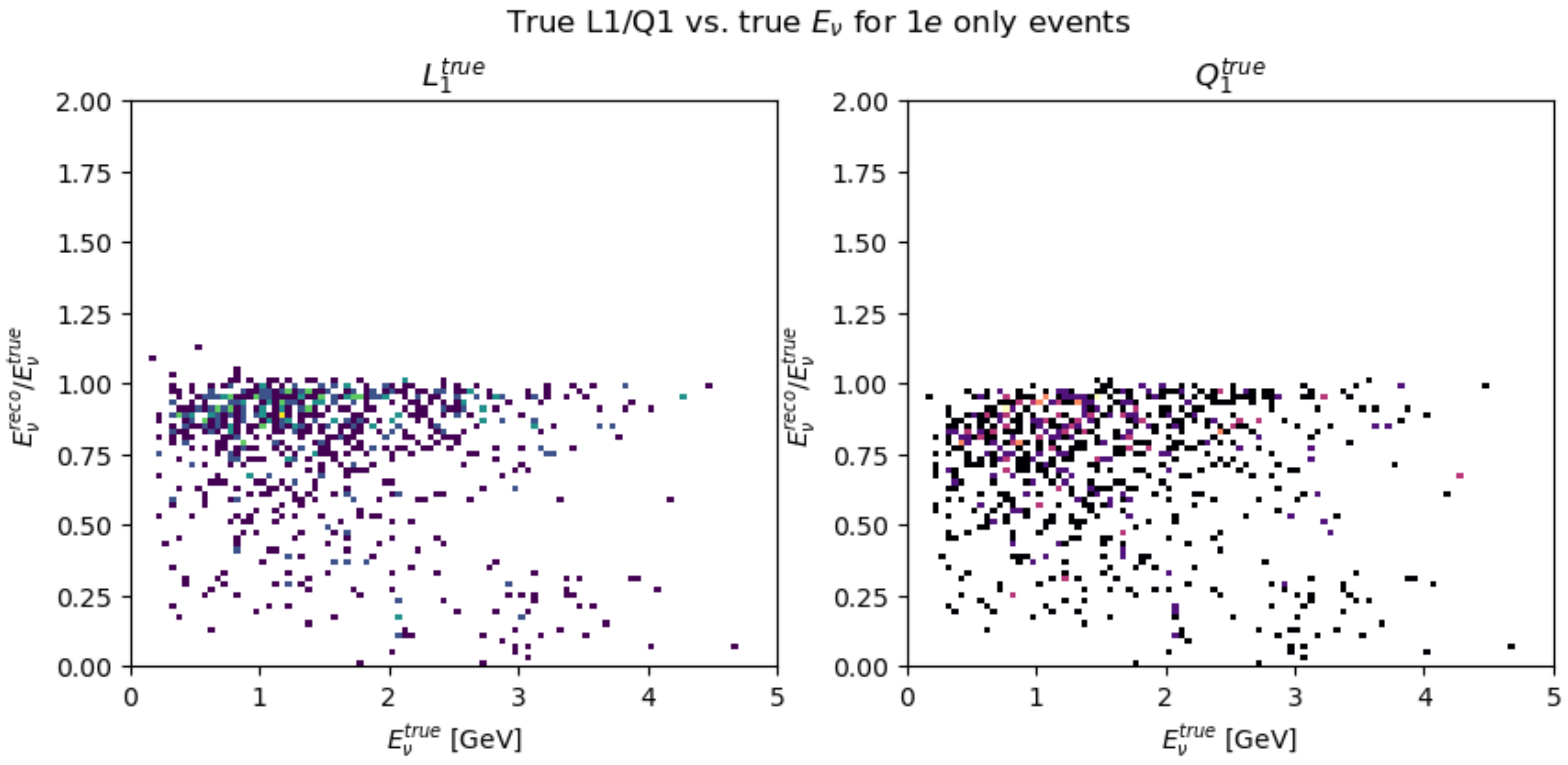


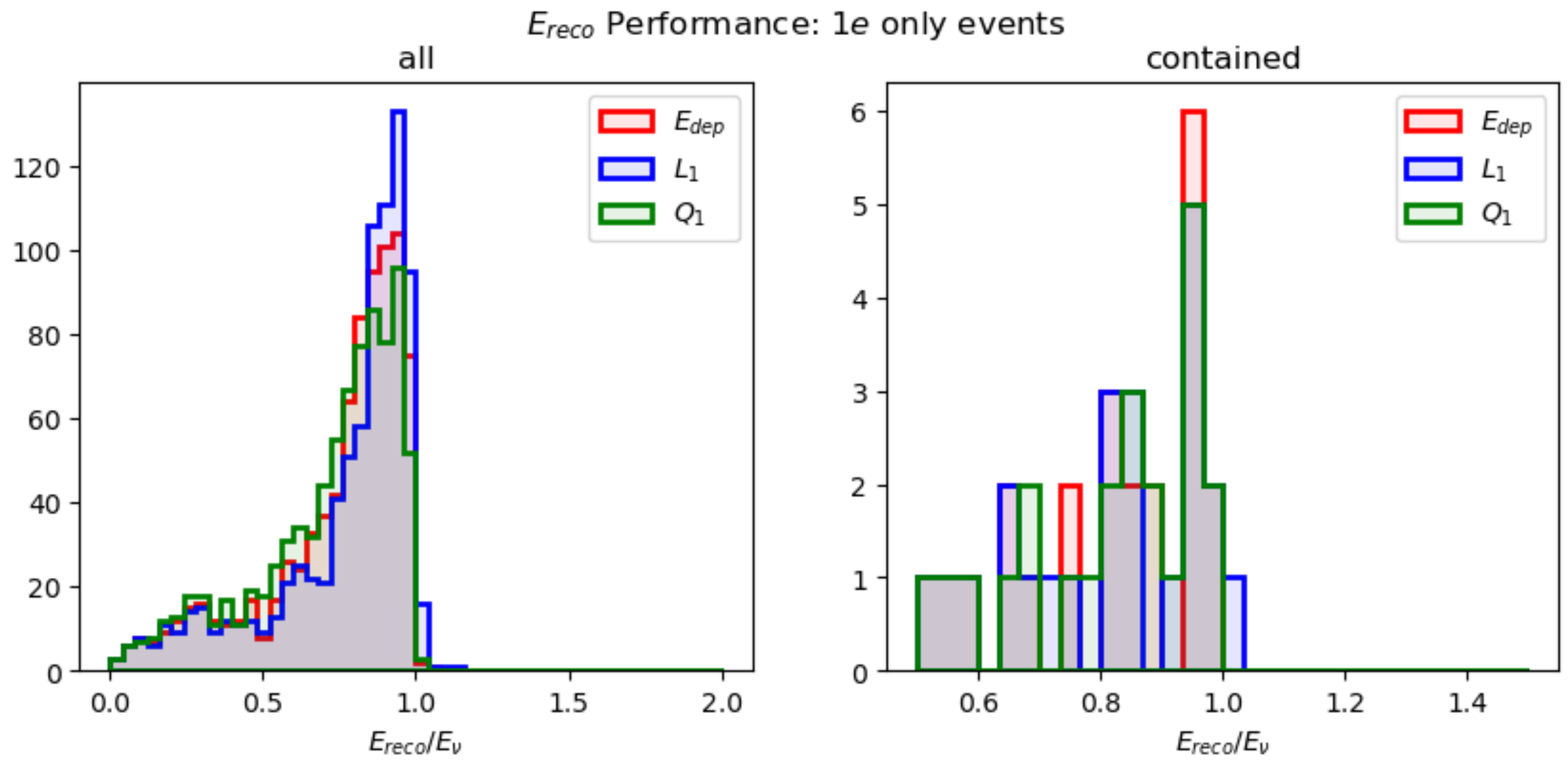
True L1/Q1 vs. true E_ν for 1$eN\pi$ events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]
True L1/Q1 vs. true E_ν for 1$eN\pi$ (contained) events
L_1^{true}
Q_1^{true}
$E_\nu^{reco}/E_\nu^{true}$
E_ν^{true} [GeV]



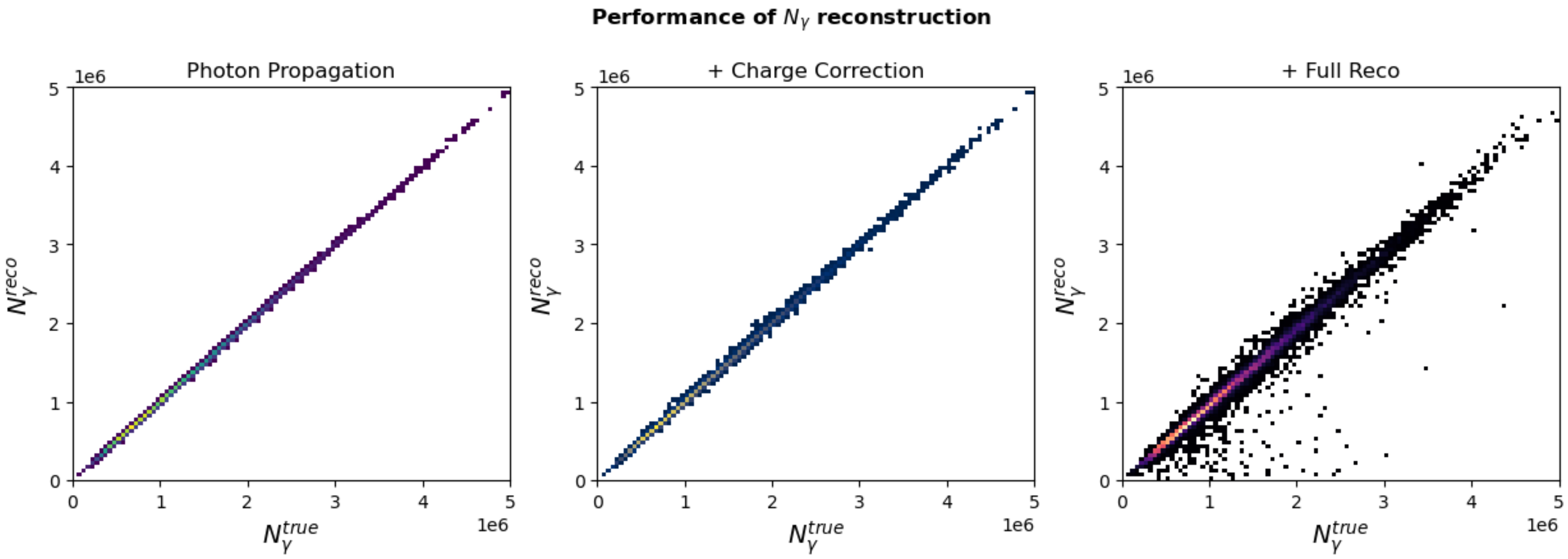
E_{reco} Performance: 1$eNpN\pi$ events
all
contained
E_{dep}
L_1
Q_1
E_{reco}/E_ν

1e only

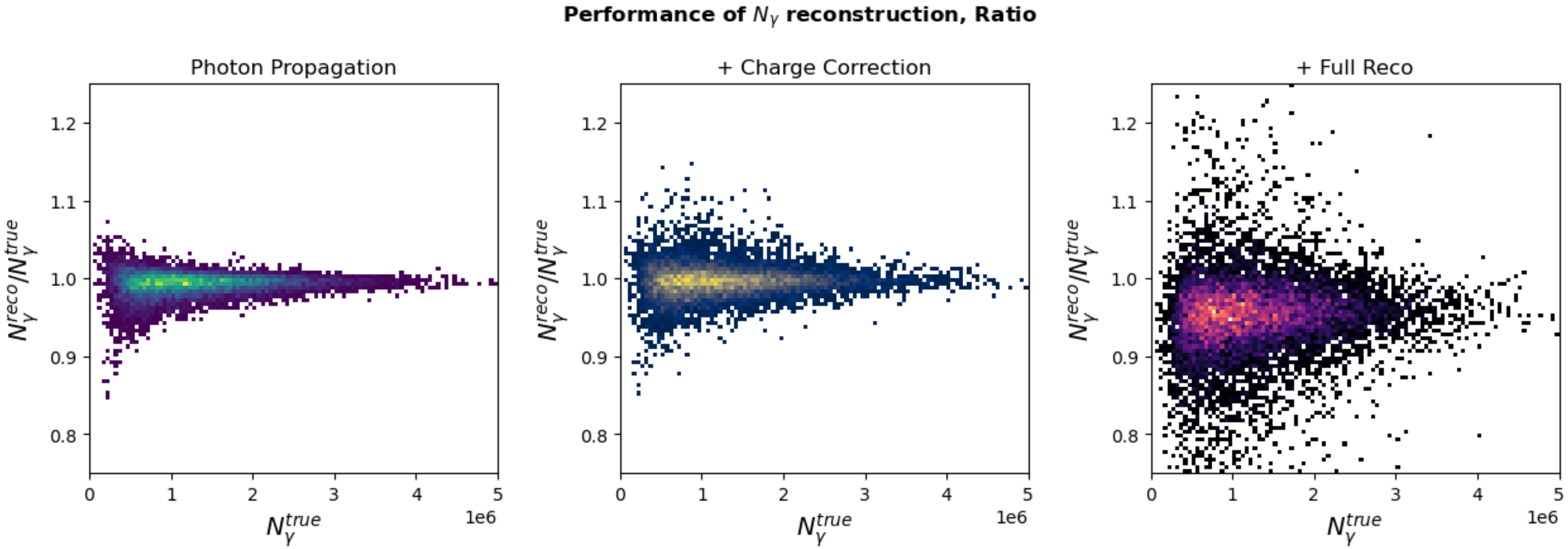




- stats too low to apply containment cut



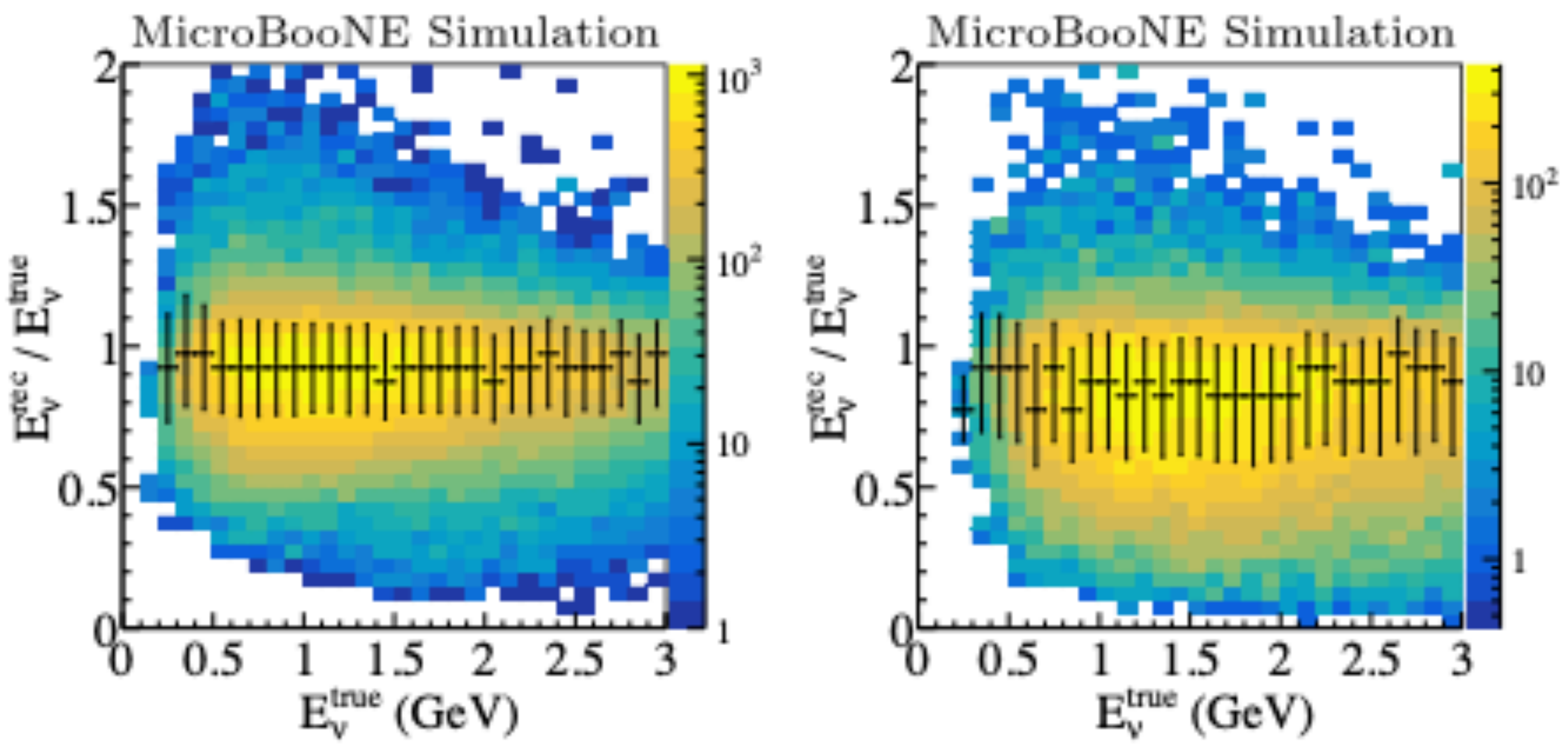
Performance of N_γ reconstruction
Photon Propagation
+ Charge Correction
+ Full Reco
N_γ^{reco}
N_γ^{true}
1e6



Performance of N_γ reconstruction, Ratio
Photon Propagation
+ Charge Correction
+ Full Reco
$N_\gamma^{reco}/N_\gamma^{true}$
N_γ^{true}
1e6

how to define "resolution"?

- for an **inclusive** channel, difficult to get some benchmarks of neutrino energy reconstruction performance
    - for light calorimetry paper, injected neutrinos of single energy in infinitely large TPC, used $\sigma_{RMS}/\bar{E}$
    - for uboone Pandora results, E_ν^{reco} → 15%, only $1eNp$ channel, method not described
    - for uboone WireCell results, E_ν^{reco} → 10-15%, inclusive, using the 68% *quartile from the peak value*
    - for uboone DL results, E_ν^{reco} → ~20% resolution, only $1e1p$ channel, method not described



(g) ν_e CC candidates, FC (h) ν_e CC candidates, PC

WireCell ν_eCC Inclusive:
The black points in the energy resolution plots represent the peak positions for each bin indicating the typical bias, and the error bars represent 68.3% quantiles from each bin's peak position.

smearing matrices $e-$ and p reco