

# Liquid Argon and Energy Reconstruction a theorist's take

Alex Friedland

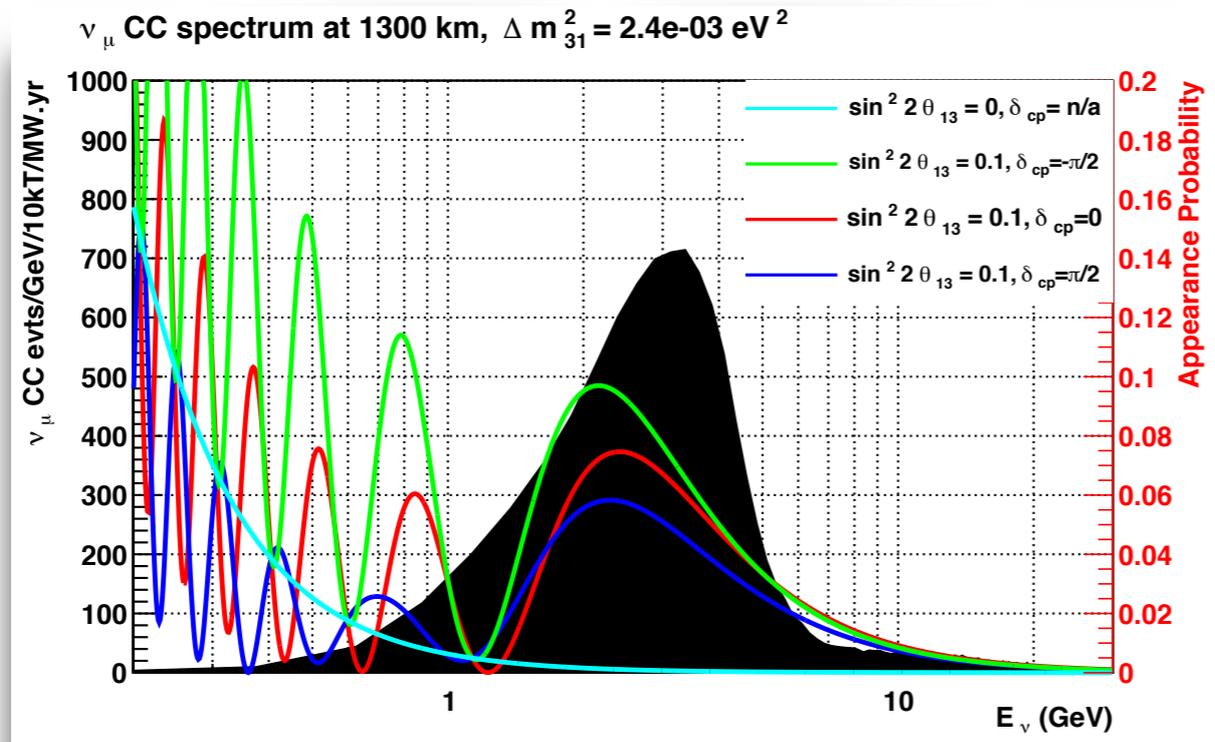
**SLAC** NATIONAL  
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# Invitation

- ✦ A home-grown simulation campaign to model the performance of LAr detectors (e.g. DUNE)
- ✦ work by A.F. and Shirley Li, a SLAC postdoc
  - ✦ [arXiv:1811.06159](https://arxiv.org/abs/1811.06159)
- ✦ This is actually a strange and outrageous proposition:
  - ✦ Why should a couple of theorists want to simulate something as basic as energy resolution of DUNE?
  - ✦ And why should anyone else care?



# Long-baseline neutrinos: 3-flavor oscillations



$$P(\nu_\mu \rightarrow \nu_e) \simeq \left| G_1 \sin \theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos \theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2,$$

$$G_1 \simeq \frac{\Delta m_{\text{atm}}^2}{4E_\nu} \sin 2\theta_{13} e^{i\delta}, \quad \Delta_1 \simeq \frac{\Delta m_{\text{atm}}^2}{2E_\nu} - \sqrt{2}G_F N_e$$

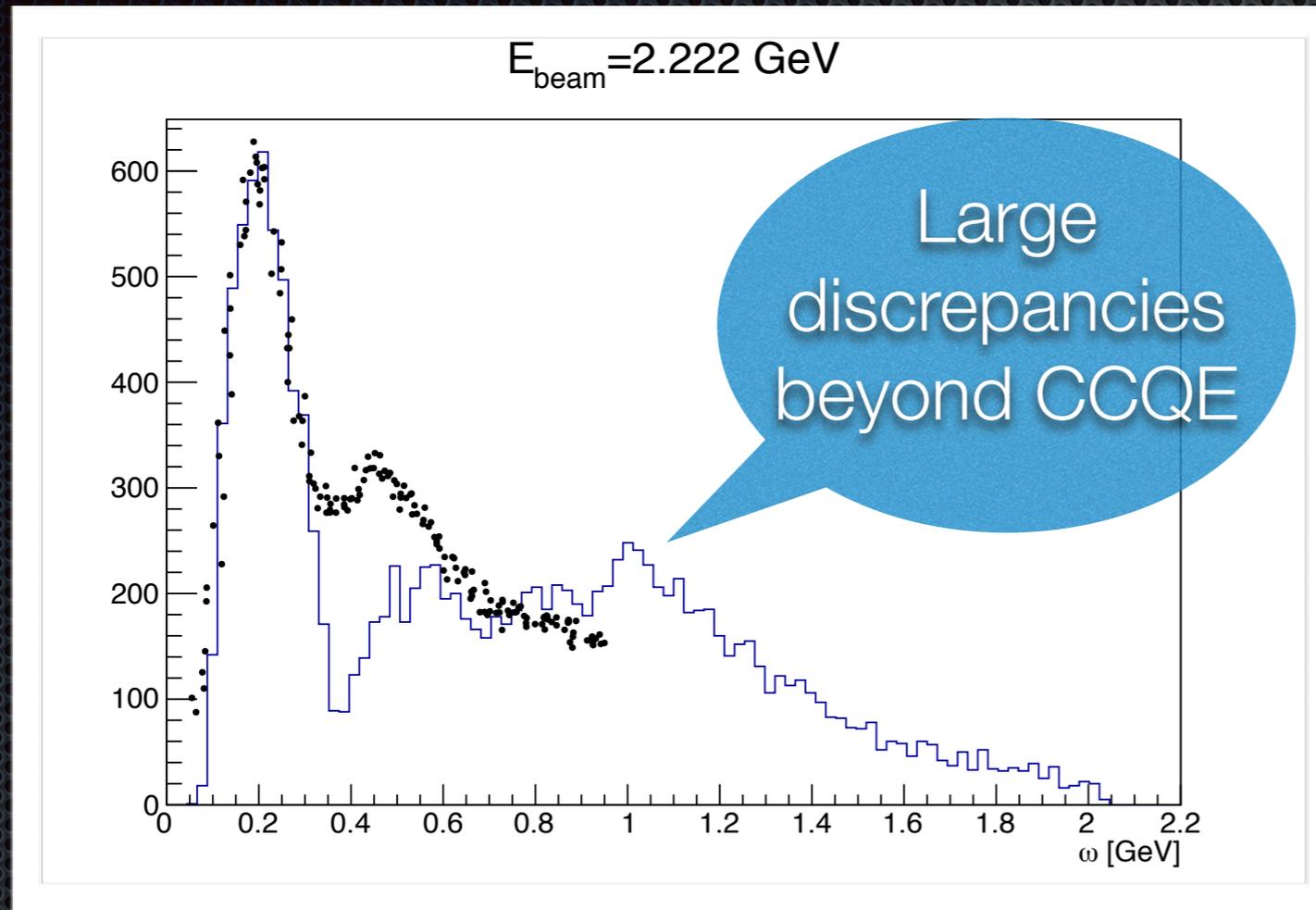
$$G_2 \simeq -\frac{\Delta m_{\odot}^2}{4E_\nu} \sin 2\theta_{12}, \quad \Delta_2 \simeq -\sqrt{2}G_F N_e$$

- Two channels, solar and atmospheric, interfere. E.g.:

# Neutrino scattering at several GeV

- A number of physical processes: quasi-elastic, deep inelastic, resonance, multi-nucleon. Generator codes, e.g. GENIE, try to model this physics.
  - See Monday's talk by Ulrich Mosel
- We need to test/validate all this physics
  - how each component is constrained by the world's best data
  - how the errors in each propagate through the oscillation analysis

# Electron scattering comparison



Artur Ankowski

- GENIE fails to reproduce electron scattering data collected at JLab last year
- And many other datasets. Paper to appear soon

How's DUNE affected by  
cross section uncertainties?

# DUNE measures energy using calorimetric method

- ✦ If it could faithfully capture all neutrino energy, in the near and far detectors, there would be no need to worry about cross sections at all
- ✦ The sensitivity arises when some of the energy is missing: one has to fill in the missing part using interaction models
- ✦ Although DUNE is a calorimetric detector, **it is not perfectly hermetic**
- ✦ **What are the missing energy channels?**
- ✦ **How are they related to energy resolution?**

# Literature survey brings confusion

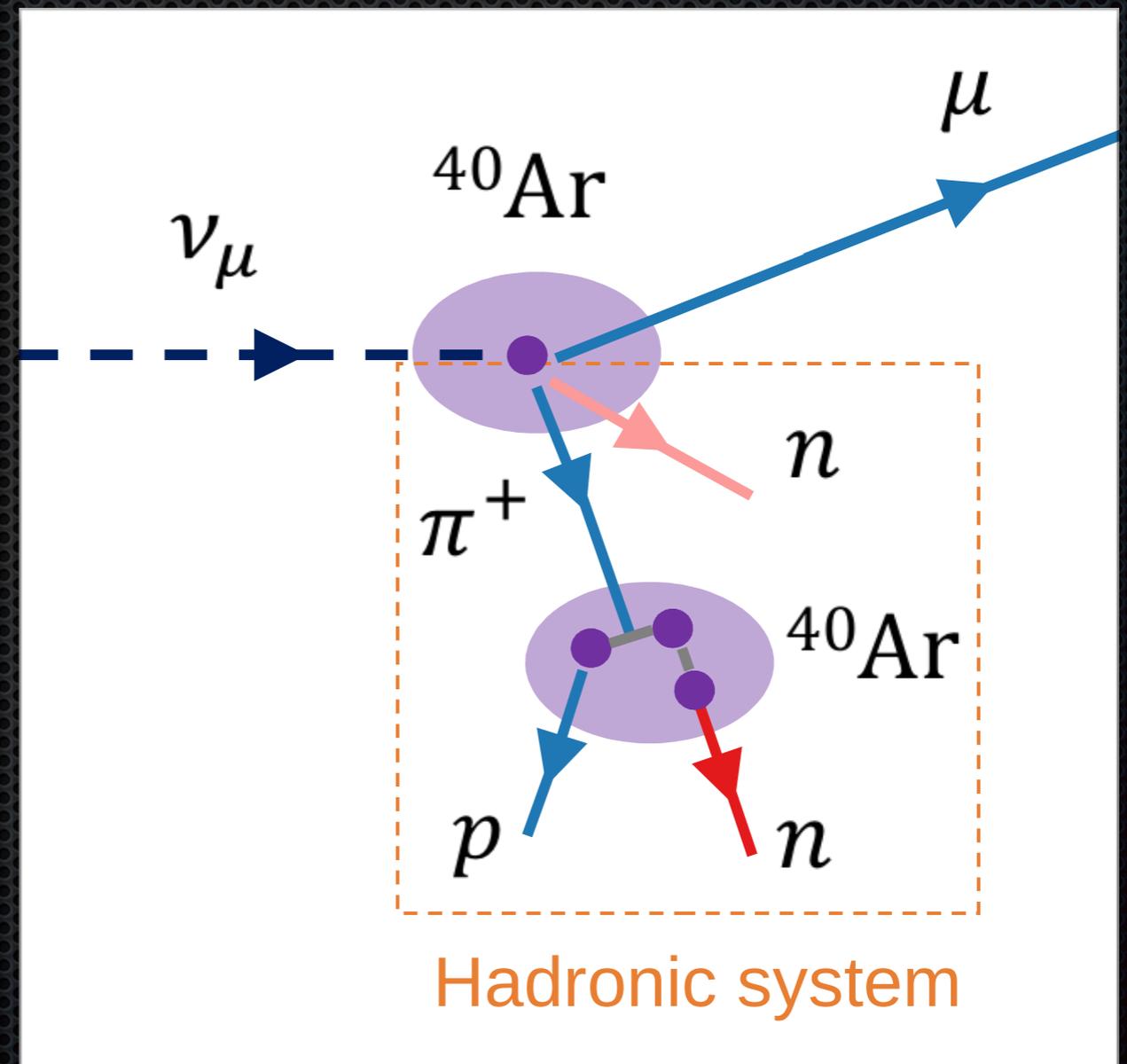
- **Missing energy** is discussed in [arXiv:1507.08561](#) [Ankowski, Coloma, Huber, Mariani and Vagnoni] and in [arXiv:1507.08560](#) [Ankowski, Benhar, Coloma, Huber, Jen, Mariani, Meloni and Vagnoni]. However, they miss a lot of missing energy (see later).
- Official DUNE **energy resolution** is provided in the CDR document, [arXiv:1512.06148](#), as documented in [arXiv:1606.09550](#). However,
  - **we could not reproduce their results**, even by following their procedures as closely as possible
  - **there is a dissenting opinion** by some of the collaboration members in [arXiv:1607.00293](#) [De Romeri, Fernandez-Martinez and Sorel], which argues that by adopting a different procedure (total ionization charge by the had. system), one gets a much better resolution
- Ongoing studies based on reconstruction (Nick Grant) find still different answers

# As a desperate measure, we decided to simulate events by ourselves

- Rules of our game: we do not use any internal proprietary DUNE tools
- Our simulation framework is based on combining GENIE (version 2.12.8) for primary interactions and FLUKA (version 2011.2x.2) for event propagation in LAr
  - GENIE is the generator used by all Fermilab experiments
  - FLUKA has a strong reputation, especially for propagating neutrons and gammas (as recently confirmed by ArgoNeuT)
- We want something that is fast, flexible, and can transparently separate different contributions. Complementary to full detector simulations.
- One year later, here are the results

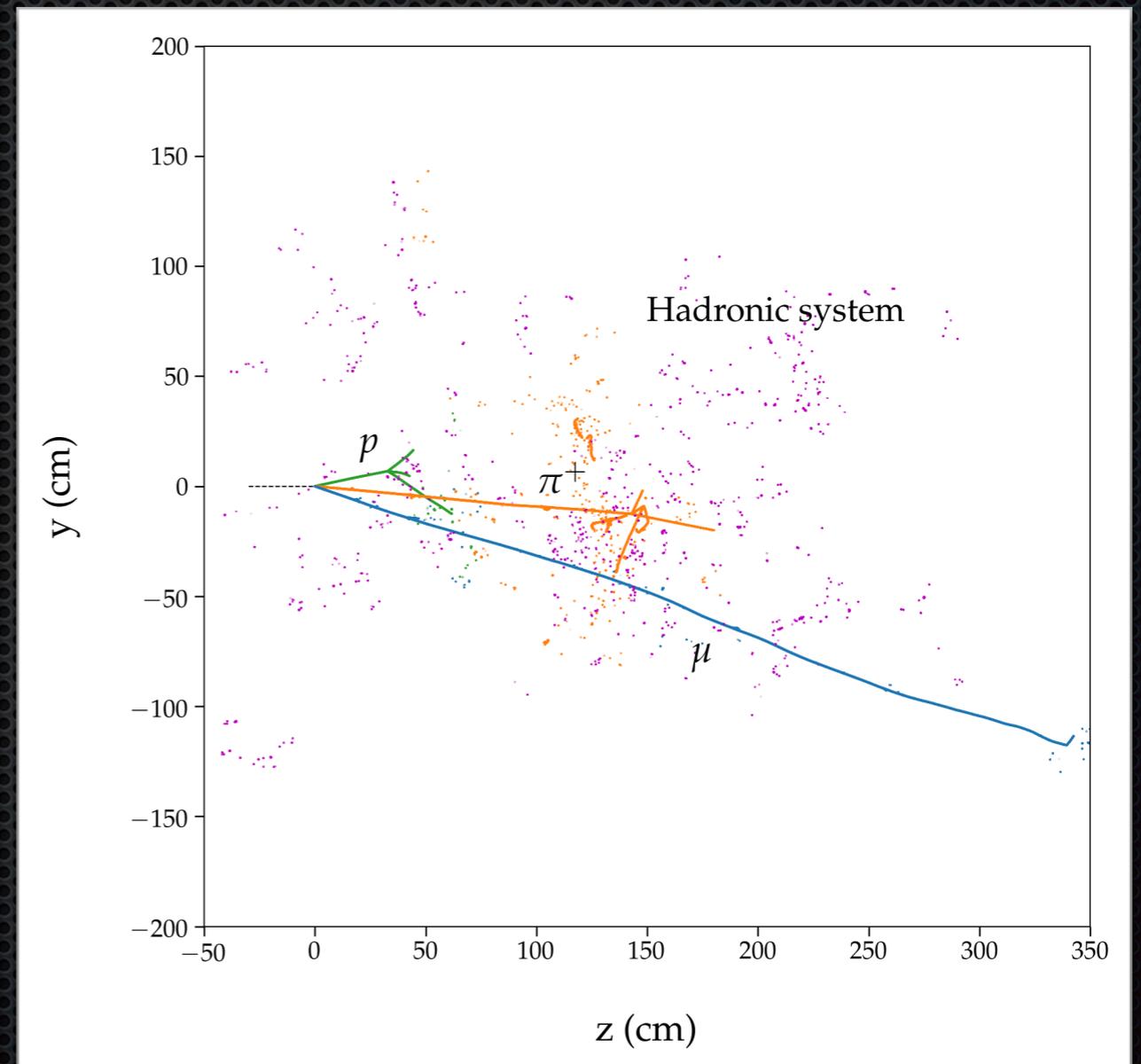
# Neutrino events in DUNE, a cartoon

- Incoming neutrino interacts with Ar nucleus, creating a lepton (muon track or electron EM shower) and a number of hadrons (protons, pions, neutrons)
- These particles propagate through LAr
  - Charged particles leave ionization tracks
  - All can have secondary interactions, knocking out more particles. Shower development



# Neutrino event at DUNE, from our simulations

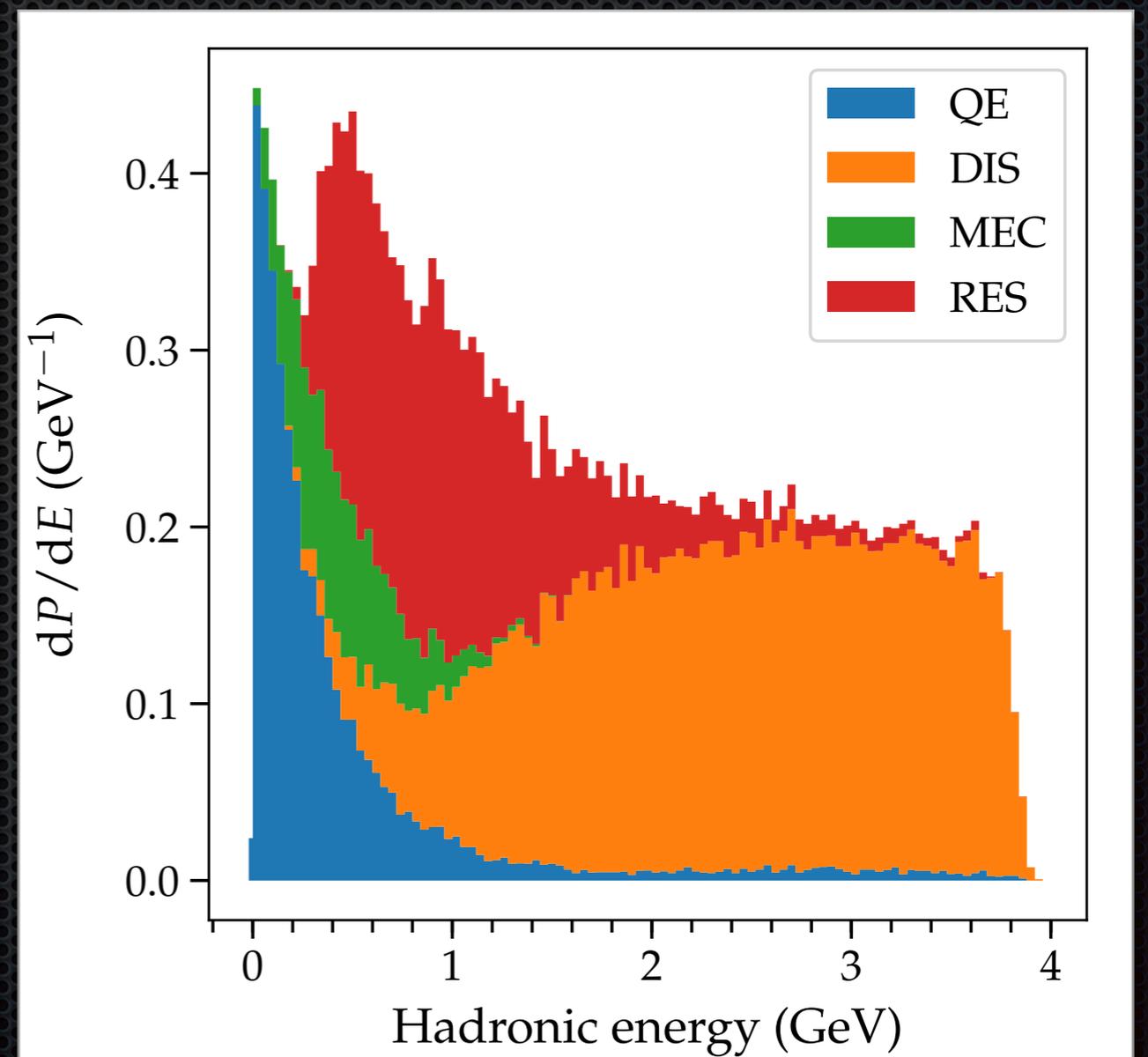
- Muon is the longest track. Decays in the end (Michele electron seen)
- Charged pion is intermediate. Secondary interaction
- Proton track is short. Also secondary interaction
- Spray of small charge deposits. Mostly due to neutrons.



# Hadronic energy distribution

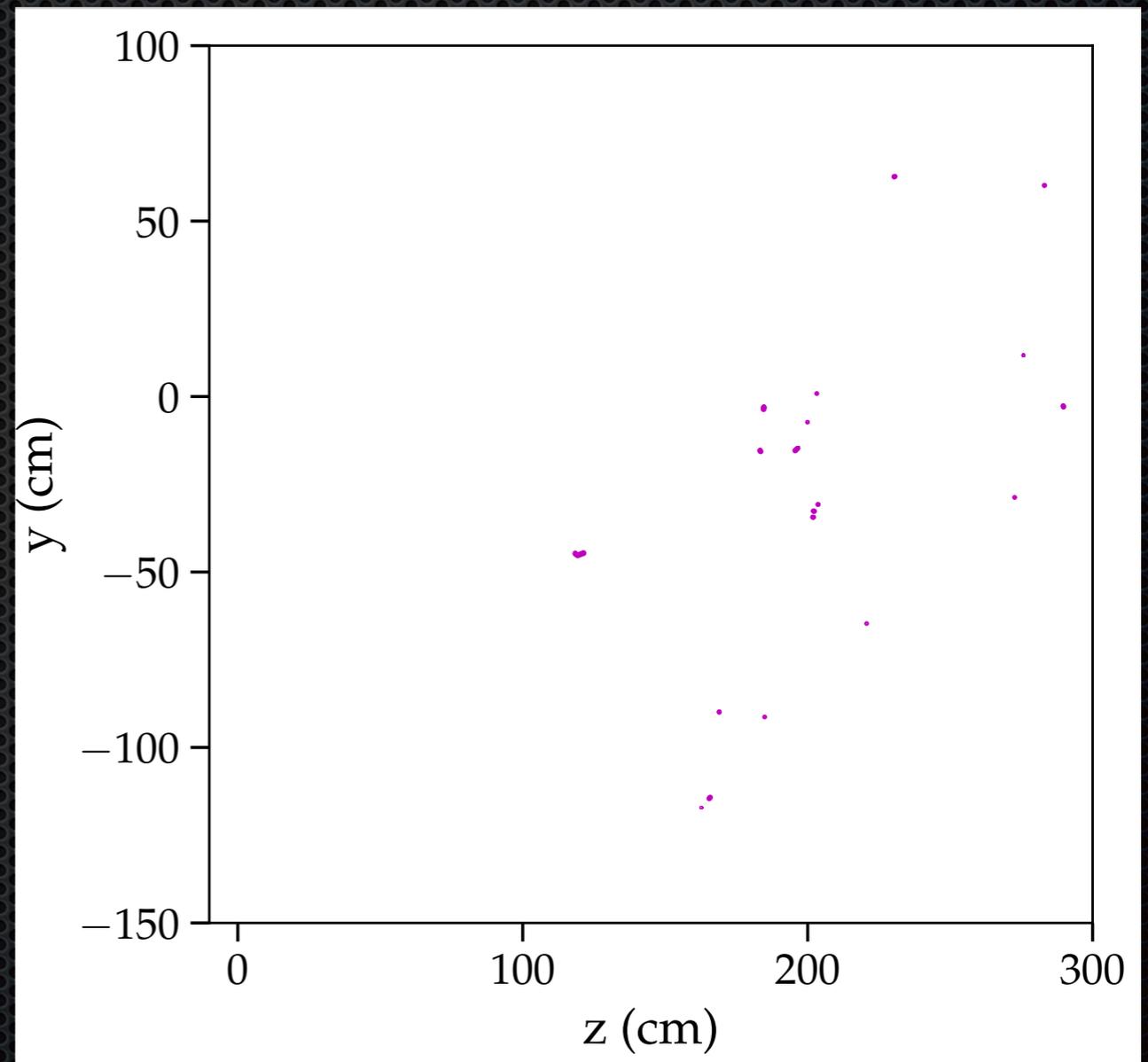
$$E_\nu = 4 \text{ GeV}$$

- ✦ Composition of the events indeed shows DIS and resonant component prominent (multiple hadrons)
- ✦ Events have rich structure. The distribution is broad.



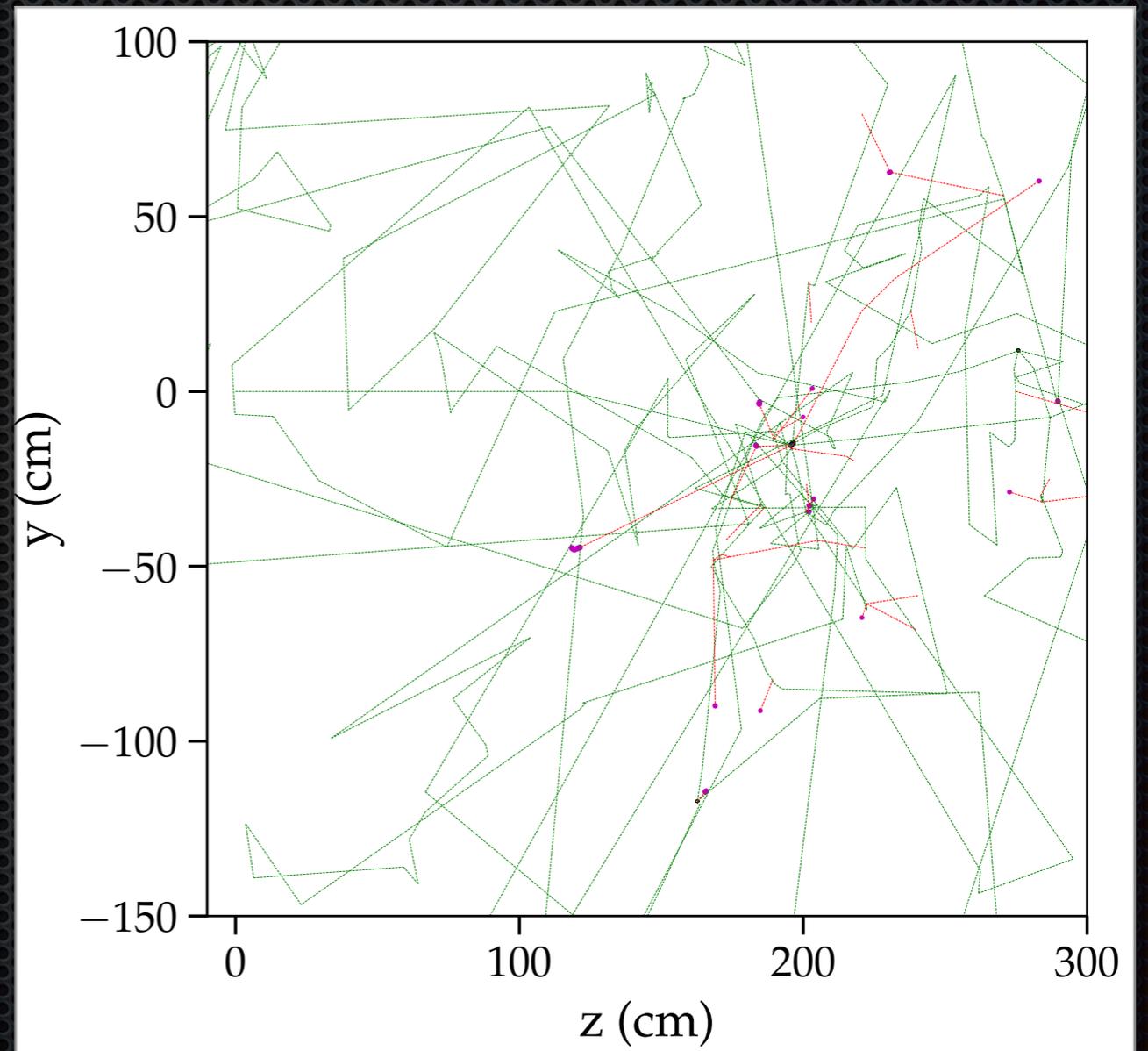
# Neutrons

- Neutrons deserve a special focus, since they by themselves do not leave ionization tracks
- They do lose energy, through nuclear breakup.
- Some of this energy is truly lost.
- Some does appear as ionization, when nuclei de-excite, emitting gammas. These gammas Compton scatter, with m.f.p.  $\sim 14$  cm. This gives rise to the “spray”



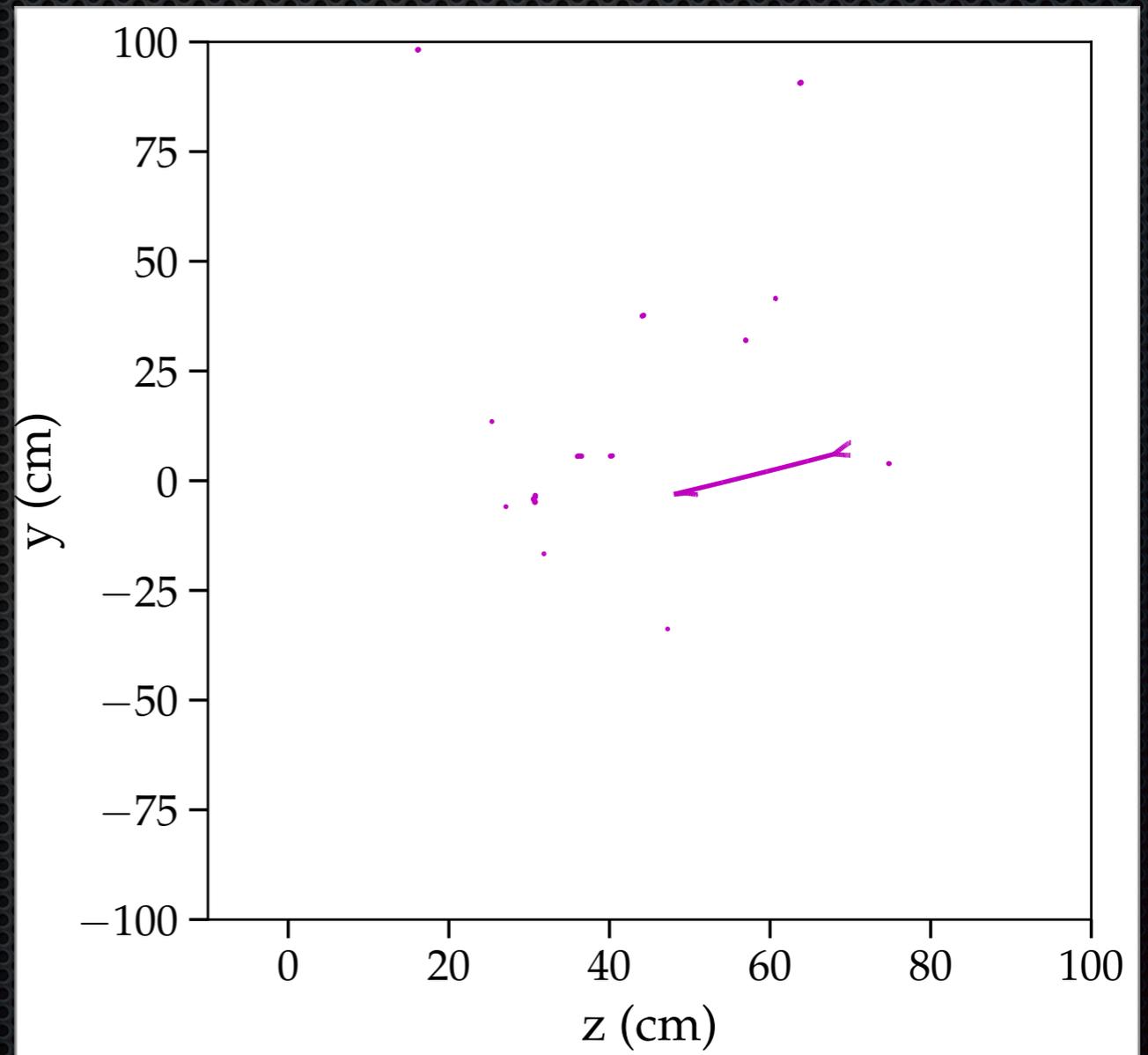
# Neutrons

- Same as previous slide, with particle trajectories shown



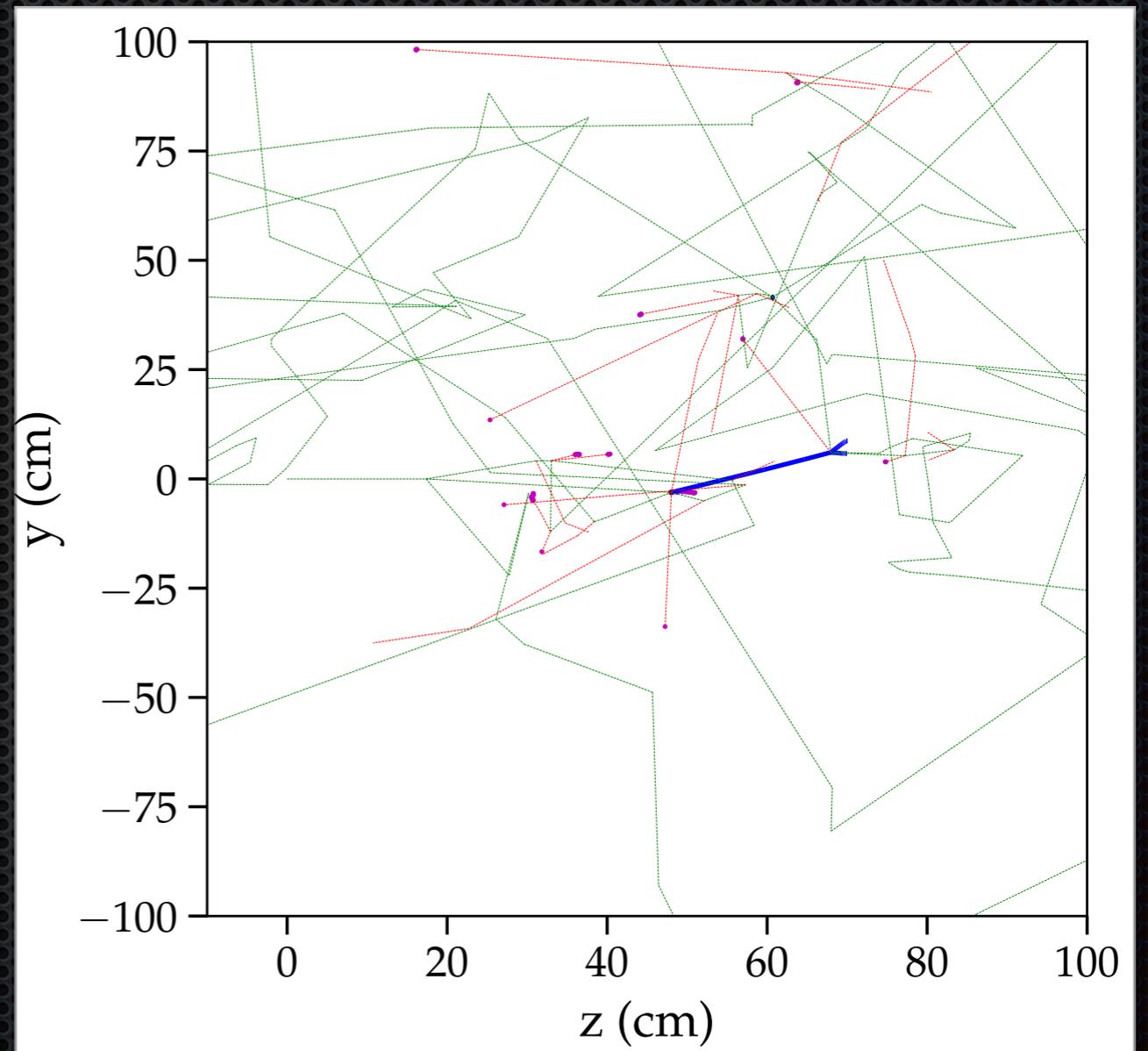
# Neutrons

- Sometimes energetic secondary nucleons are knocked out. That could include protons, which do live ionization tracks.
- These protons are special: they don't connect to the main event and don't necessary point at the primary vertex. Special attention needed!



# Neutrons

- Same as previous slide, with particle trajectories shown



# Other observations

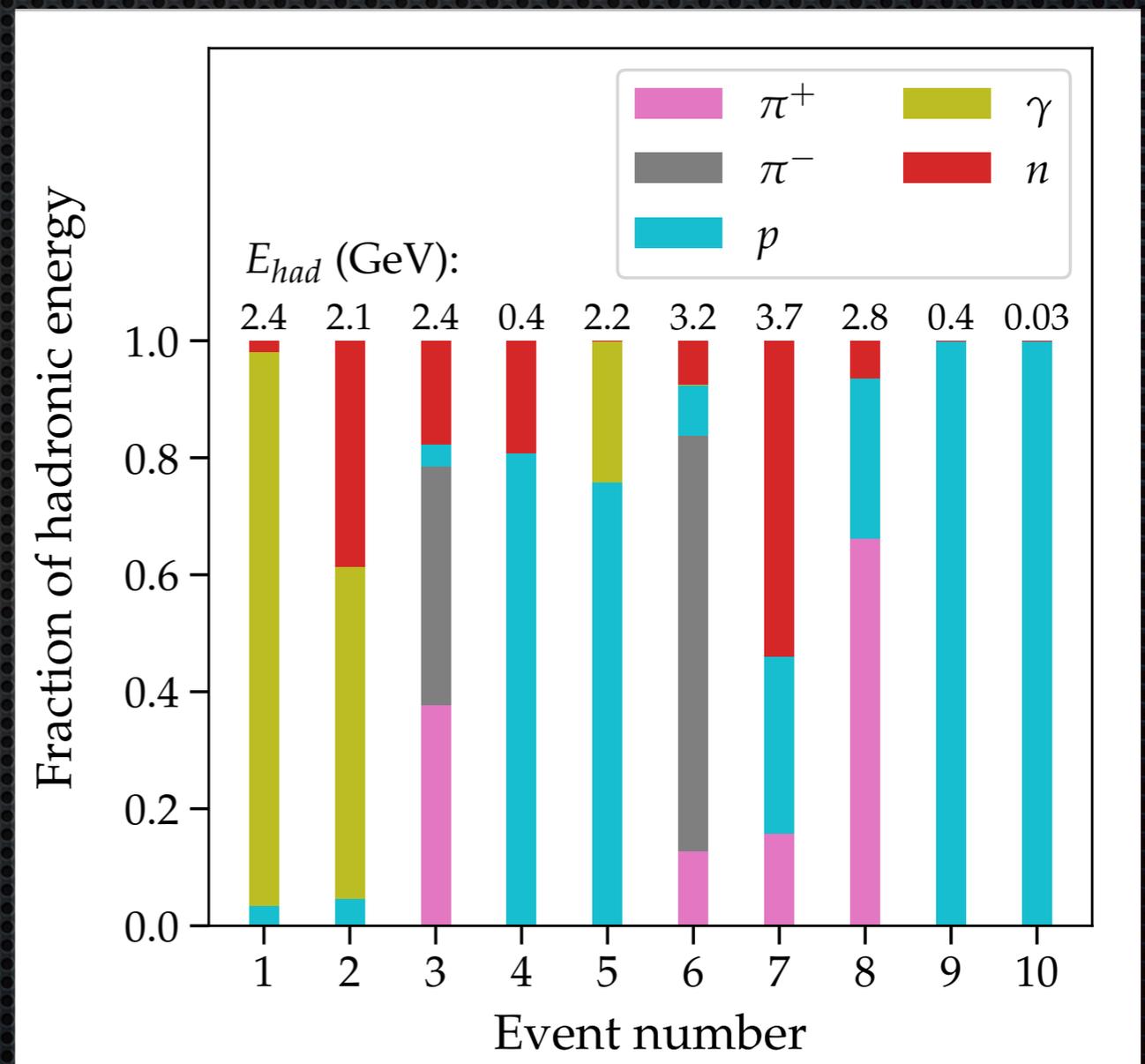
- Muons are relativistic and lose energies as minimally ionizing particles,  $\sim 2$  MeV/cm. A 4 GeV muon travels 20 m
- Protons are typically non-relativistic, lose more energy per unit length (12 MeV/cm for 50 MeV p).
  - Depends on  $\beta^{-2}$ , as can be easily understood in the impulse approximation
  - This explains why proton tracks are shorter
  - This also introduced important subtlety: since proton ionization is denser, it is more prone to recombination (quenching)
    - If a proton could be identified, its true  $dE/dx$  could be inferred from the observed charge by applying the quenching corrections

# Other observations, cont

- Charged hadrons also lose some of their energy to nuclear breakup. Some of it then reappears in the “spray” from de-excitation gammas.
- EM showers can be created not only by the final-state electron, but also by  $\pi_0$ 's. As the end of these are a lot of low-energy gammas, hence also some “spray”

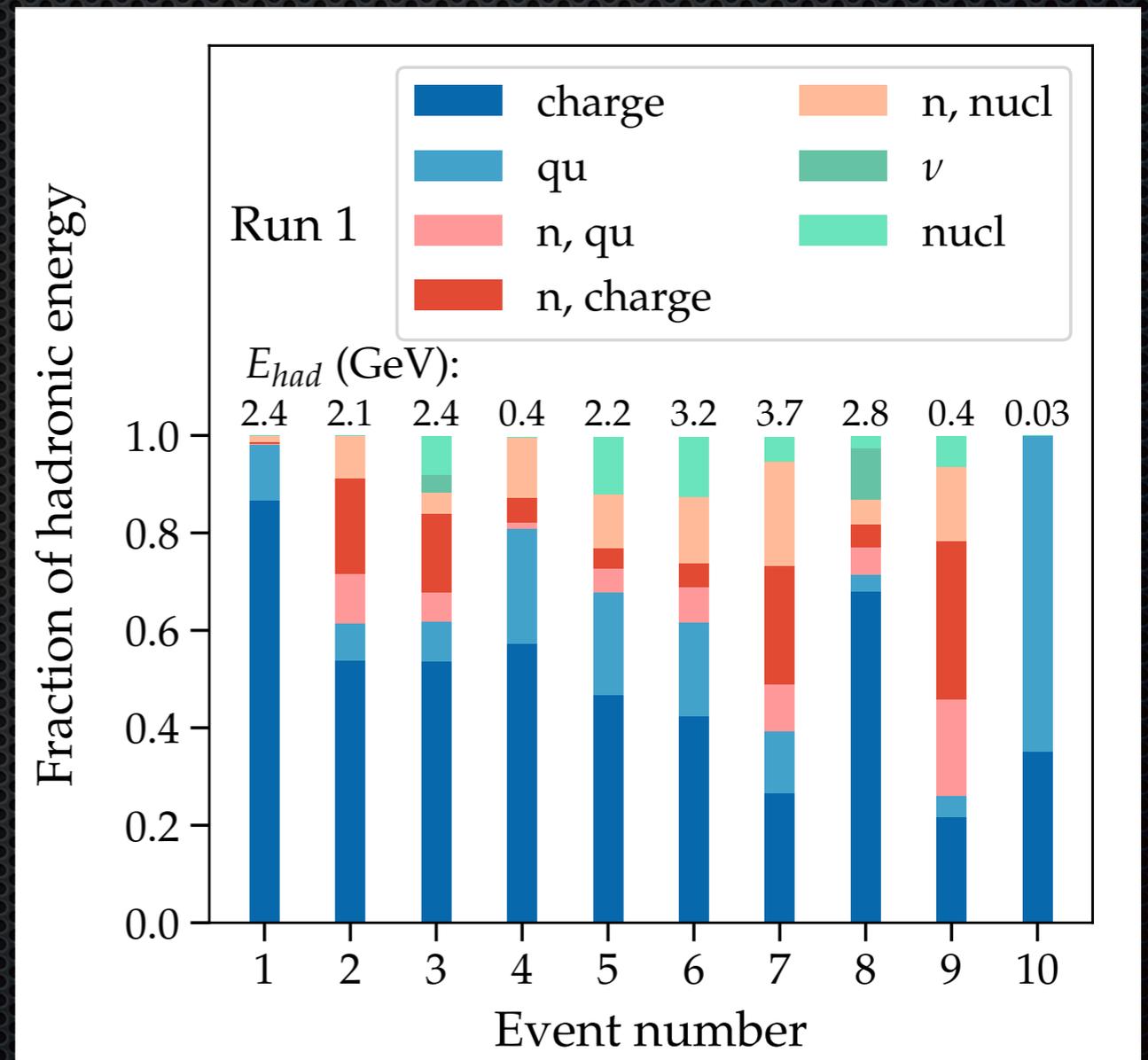
# Event composition: prompt particles

- For illustration, before showing the full results, let's look at the first 10 events of the simulation



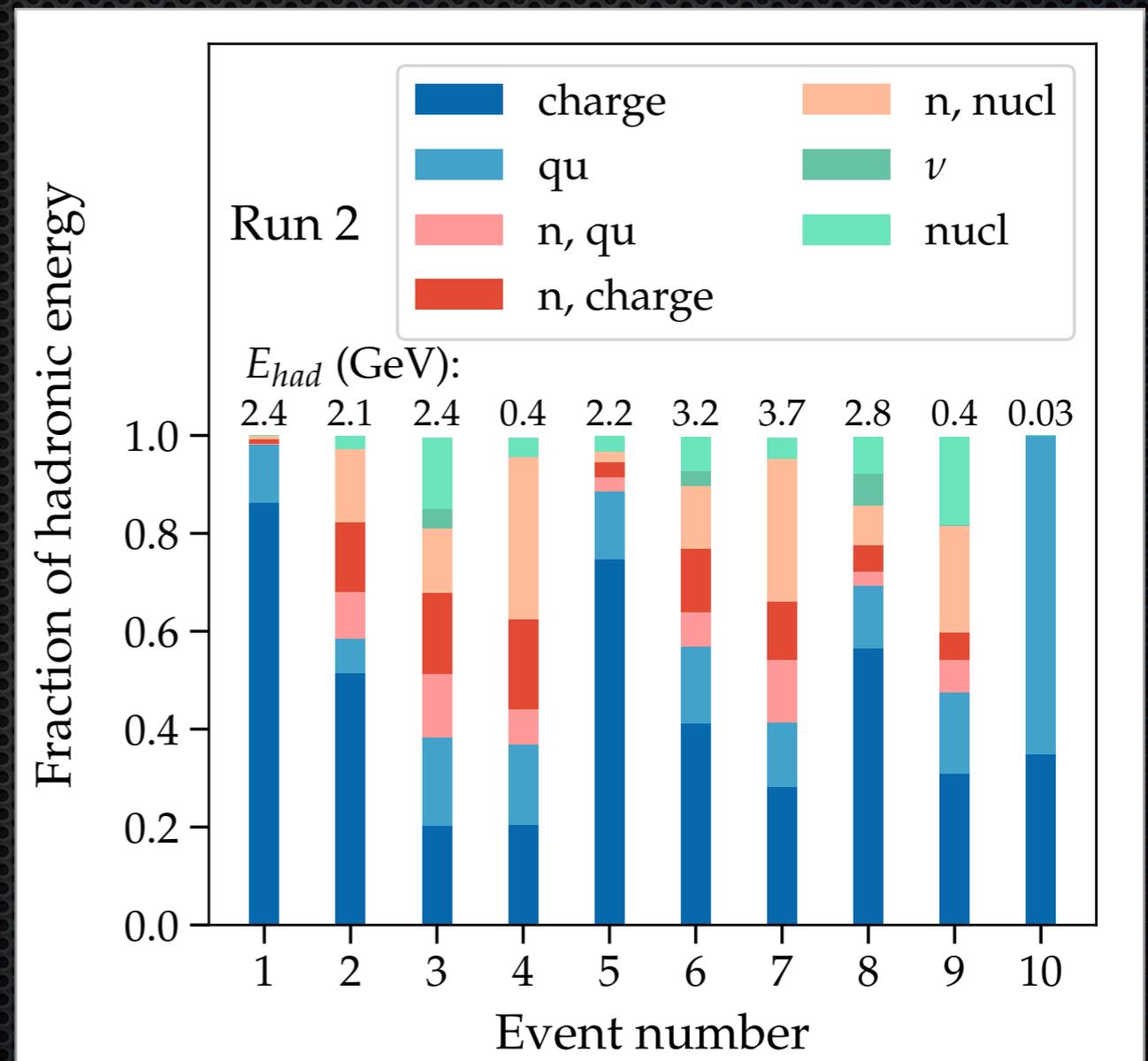
# Simulating energy flow

- ✦ Running all ten events through FLUKA
- ✦ Notice very different breakdowns
- ✦ Even at the same hadronic energy: cf. events 1 and 3



# Simulating energy flow, again!

- ✦ Since shower development is an inherently stochastic process, the same events can be realized differently! Need large simulation statistics!



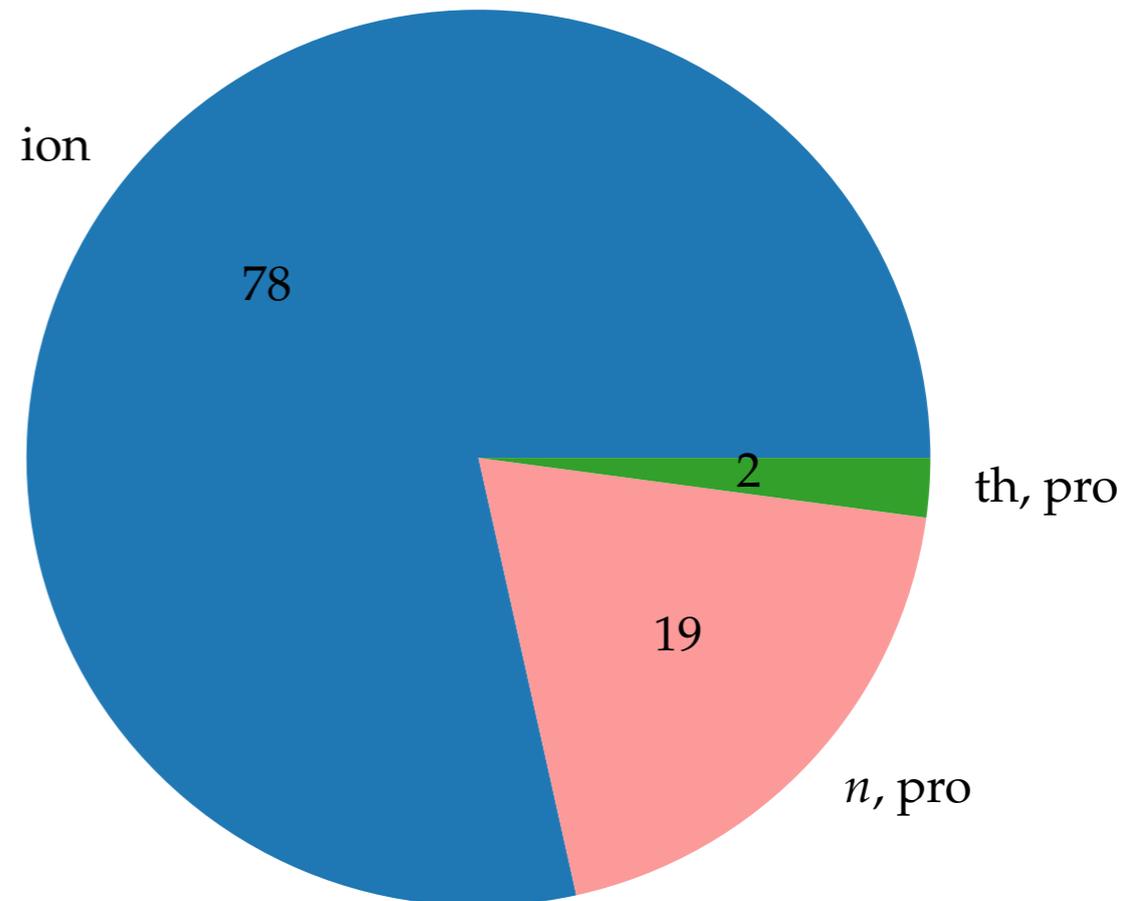
# Missing energy budget: prompt particles

$$E_\nu = 4 \text{ GeV}$$

- Simulating 10,000 GENIE scattering events
- Only prompt interactions for now, no shower propagation
- CDR thresholds seen to have small effect

	$p$	$\pi^\pm$	$\gamma$	$\mu$	$e$	others
Thresholds (MeV)	50	100	30	30	30	50

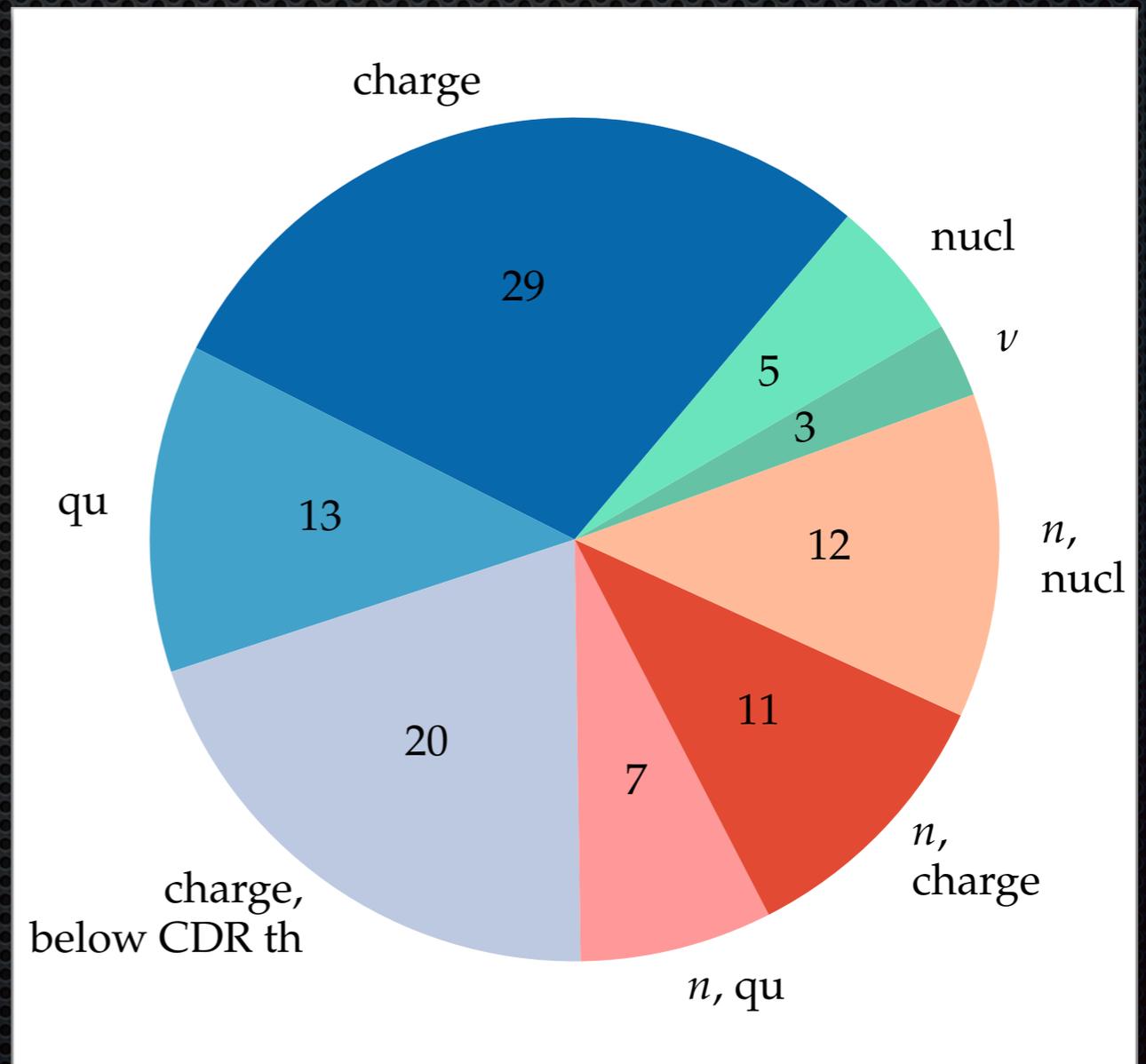
- Prompt neutrons are more important, consistent with 1507.08561



# Missing energy budget full event

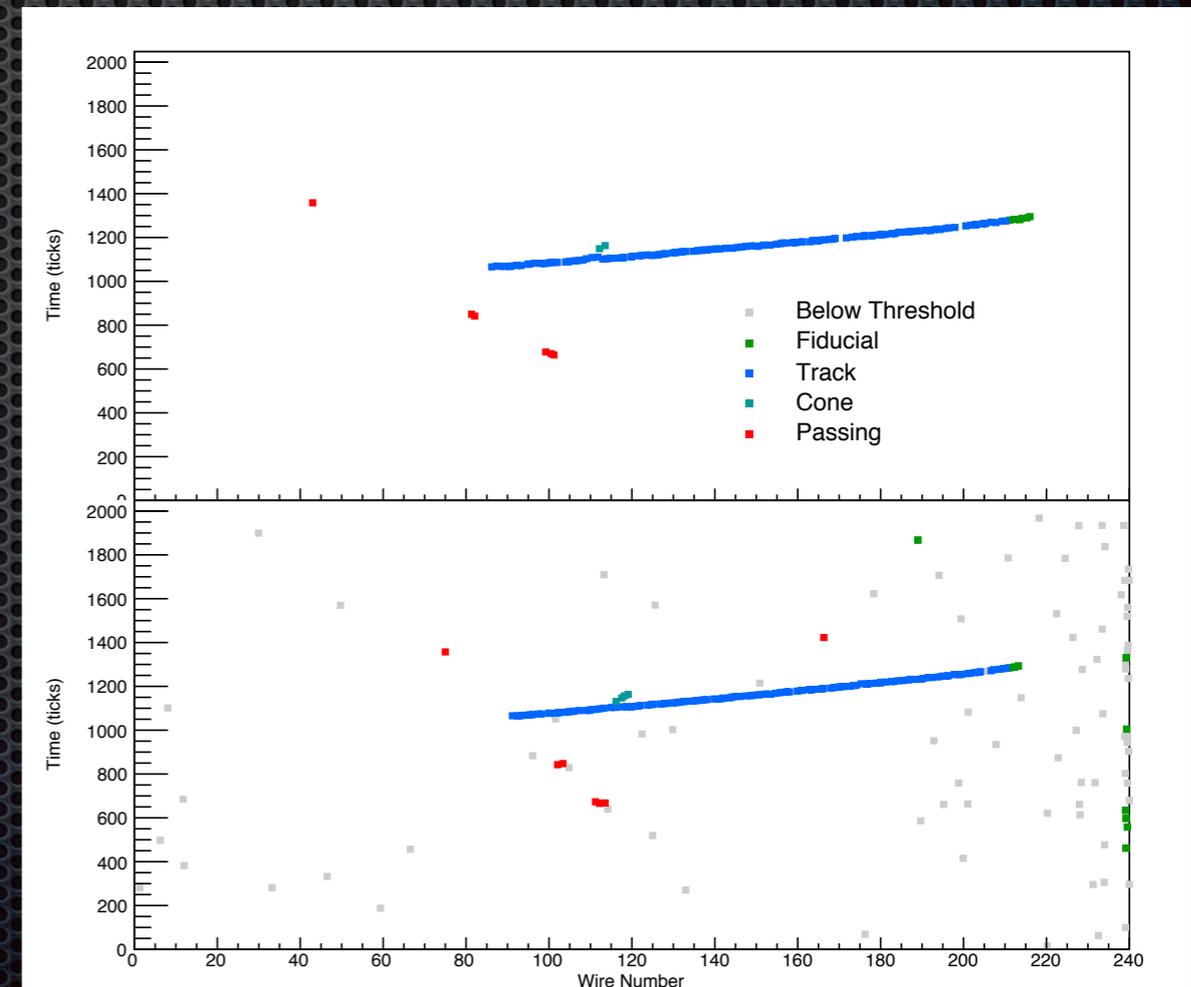
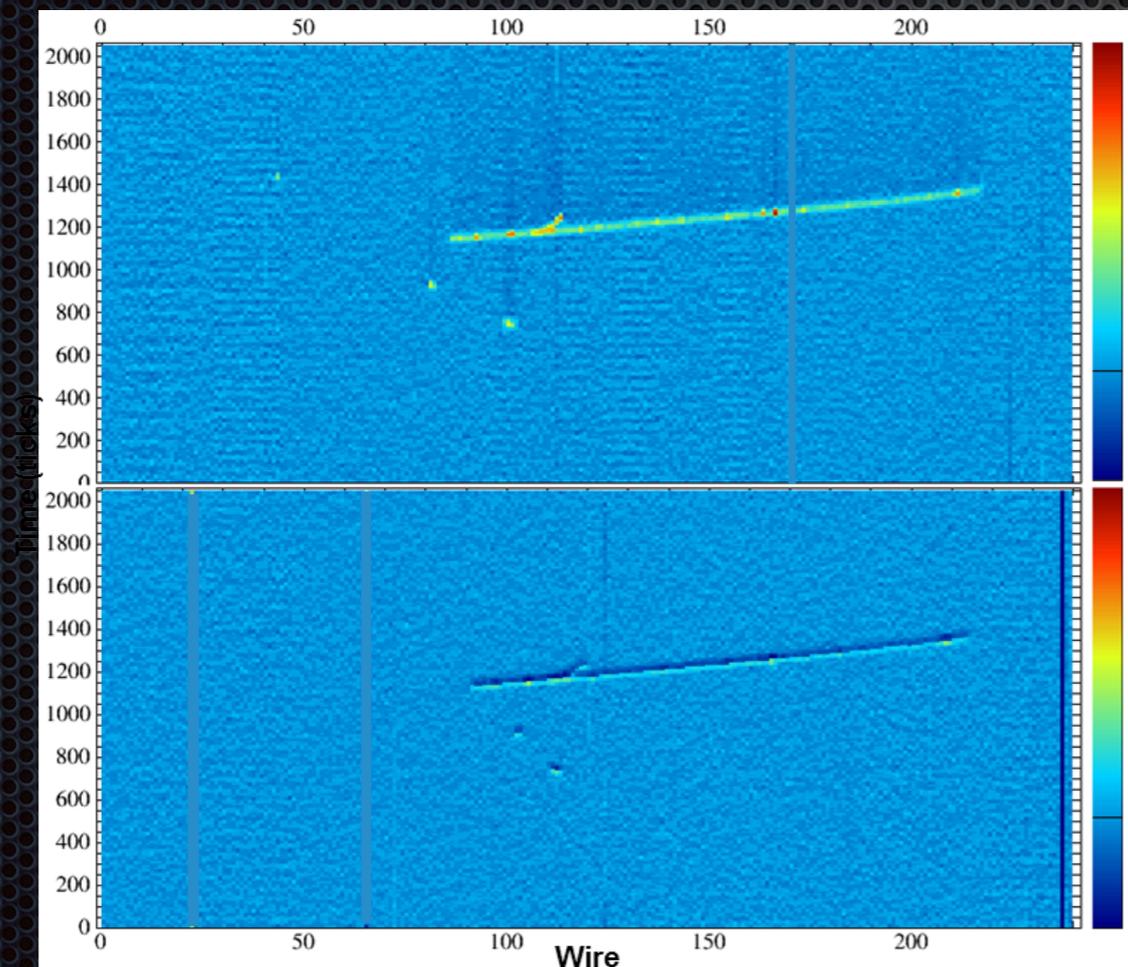
$$E_\nu = 4 \text{ GeV}$$

- However, this has little to do with the real missing energy budget!
- Fully propagating events and imposing the CDR thresholds, we find this for the hadronic system
  - Neutrons are separated in their own subcategories



# Are CDR thresholds too conservative?

- ArgoNeuT sees “spray” from de-excitation gammas, including Compton electrons below 1 MeV [arXiv:1810.06502]



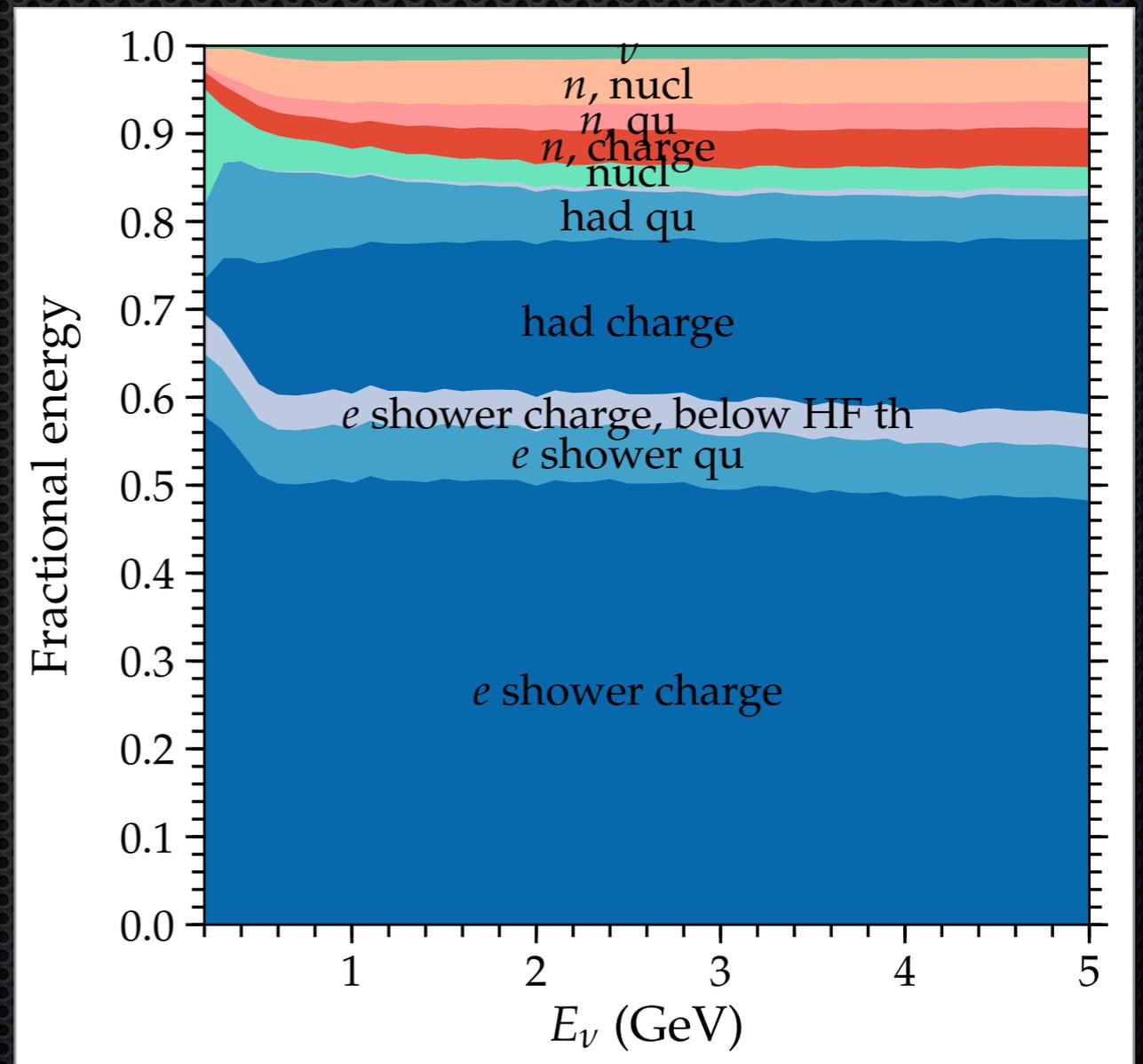
# Did the CDR intend to include subthreshold energy?

- ✦ The CDR numbers make sense as particle ID thresholds
- ✦ Perhaps the intention was to add sub threshold particles to the vertex (Richard Gran, private comm)
- ✦ However, it's not clear what FastMC actually did

```
2318  
2319 //cout<<"brTrkf_reco = "<<brTrkf_reco<<endl;  
2320  
2321 // Regardless of the above, add this calorimetrically to the energy reconstruction.  
2322 // There is a note here that I require it be "above threshold" but not clear I really require that.  
2323 // Decide whether to add the below threshold energy fuzz to the total, which I think I do.
```

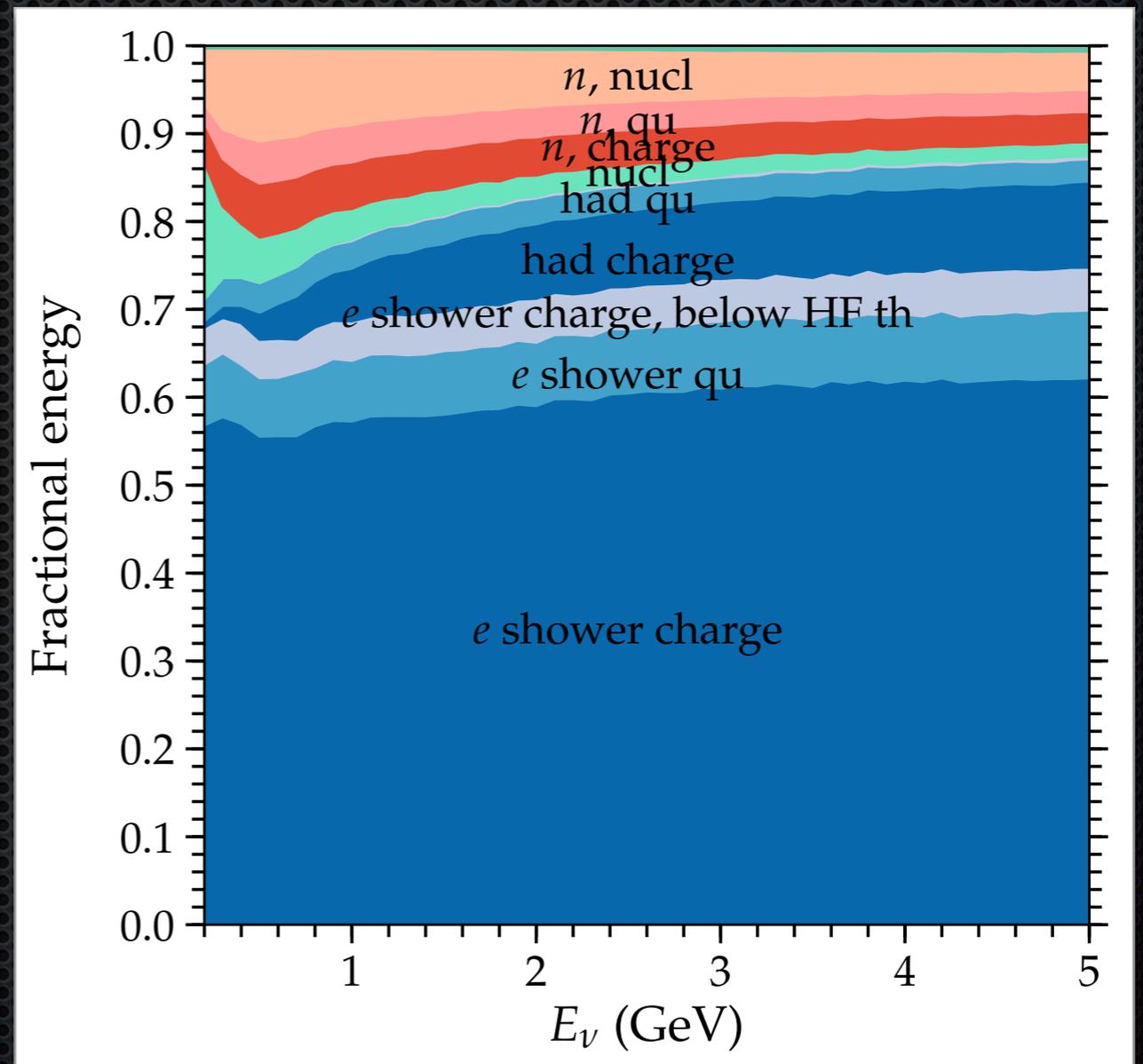
# Missing energy budget full simulation

- Repeat the same simulation on a dense grid of neutrino energies
- Thresholds have been lowered to those motivated by ArgoNeuT
- Electron showers are now included



# Missing energy budget full simulation

- ✦ The same, but for antineutrinos
- ✦ Notice the neutron parts are different now, as expected



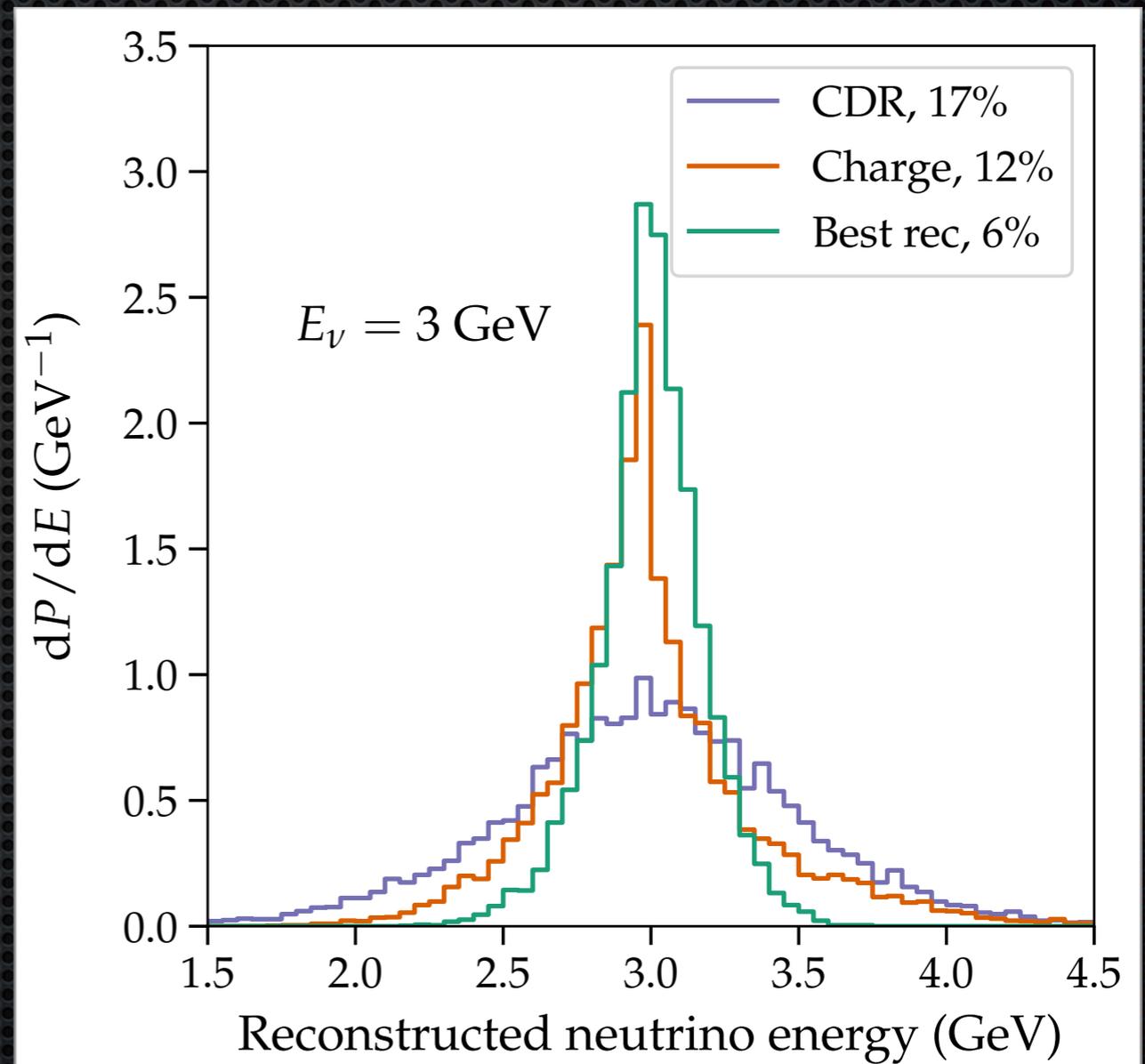
# From missing energy to resolution

- With all channels well characterized, one can work backwards and reconstruct the true energy.
  - Divide observed charges by the expected visible fraction
- Of course, this requires accurate models of both primary and secondary processes
- Even with perfect physics, however, one cannot reconstruct the exact true energy on an event-by-event basis
  - The procedure works only on average, but events are inherently stochastic. Hence the inferred true value will fluctuate.

# Energy reconstruction

## 3 GeV neutrino

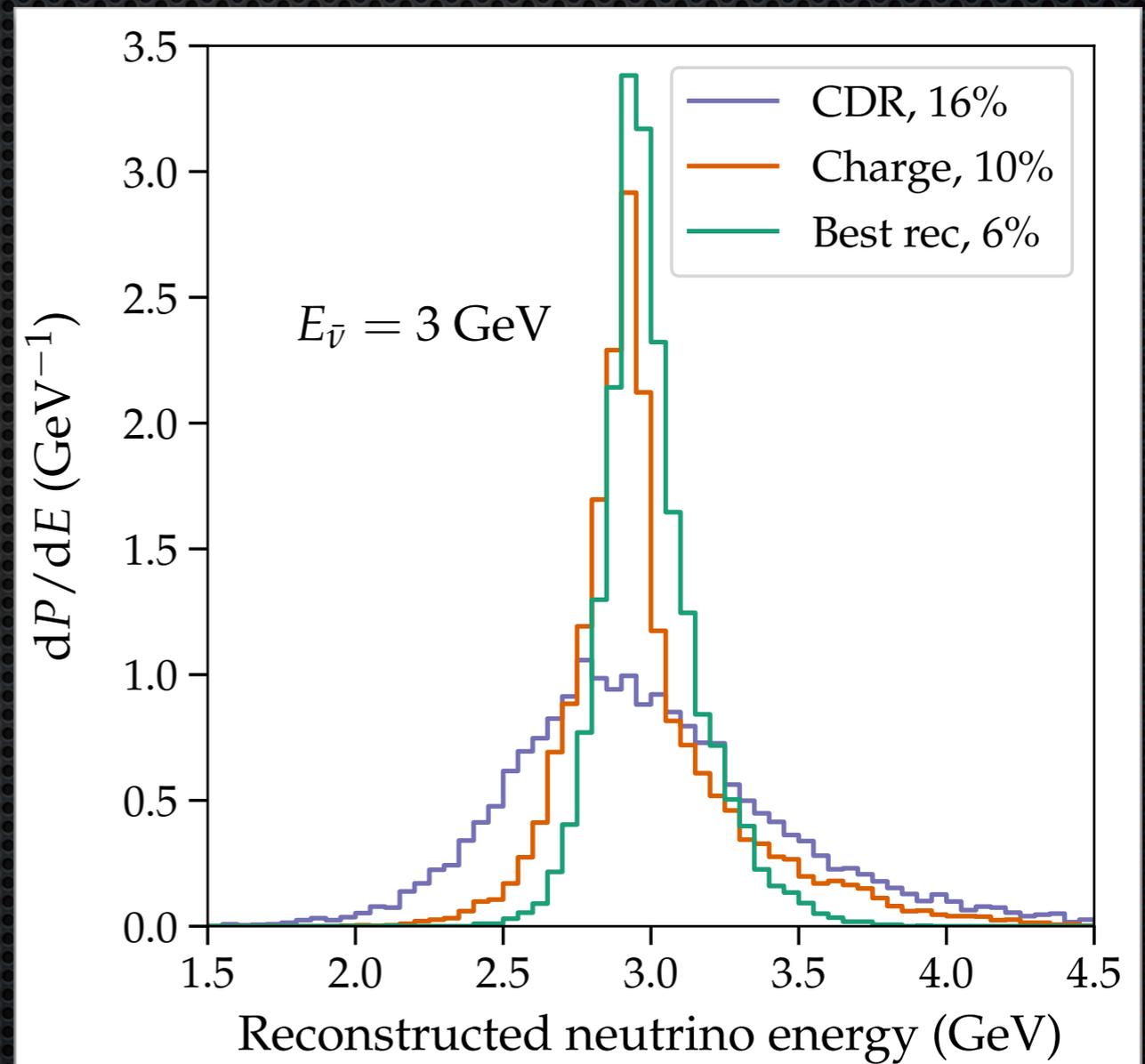
- Applied the reconstruction procedure in three scenarios:
  1. CDR thresholds
  2. total charge calorimetry
  3. detailed event reconstruction (quenching corrections, low thresholds)



# Energy reconstruction

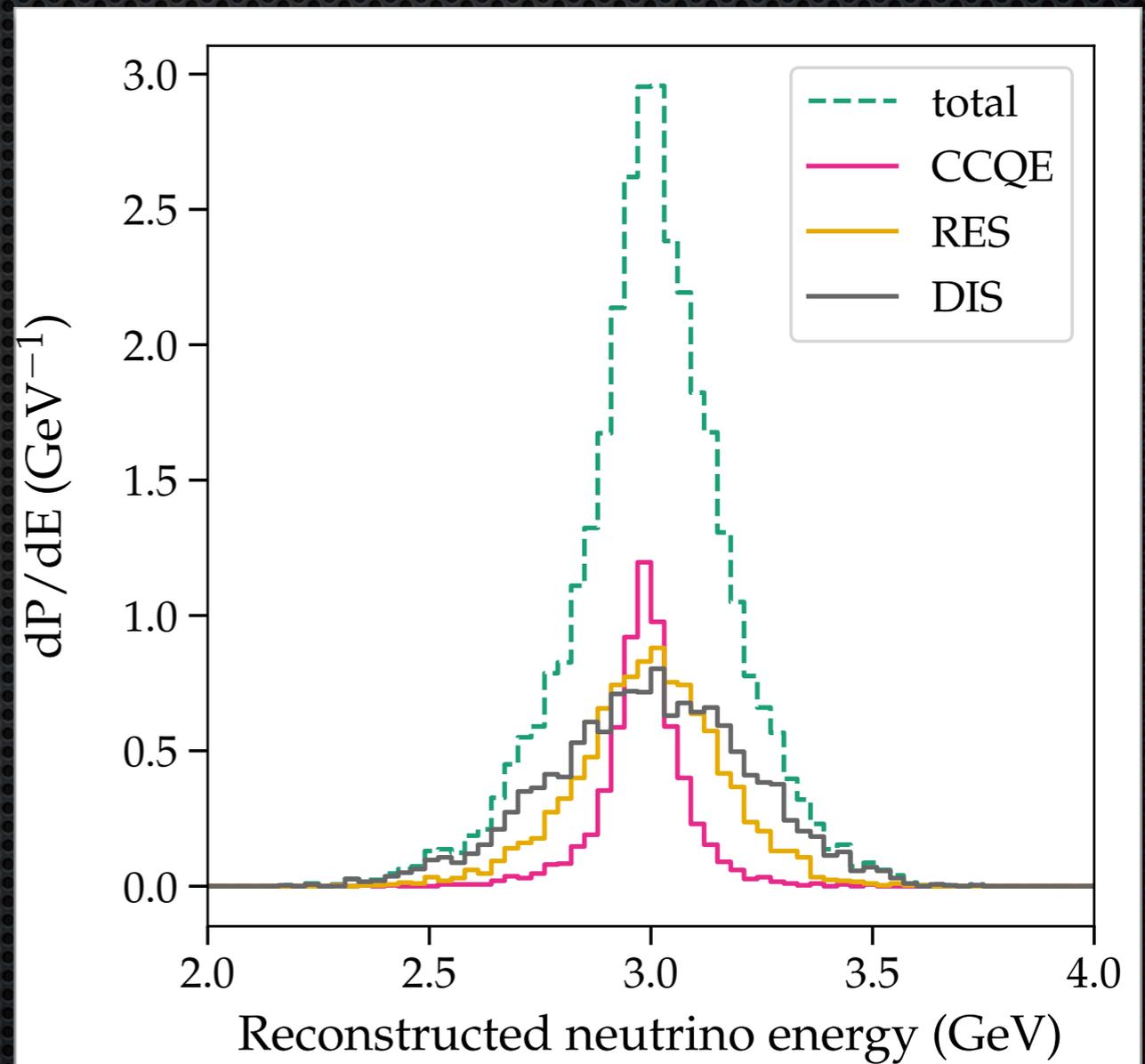
## 3 GeV antineutrino

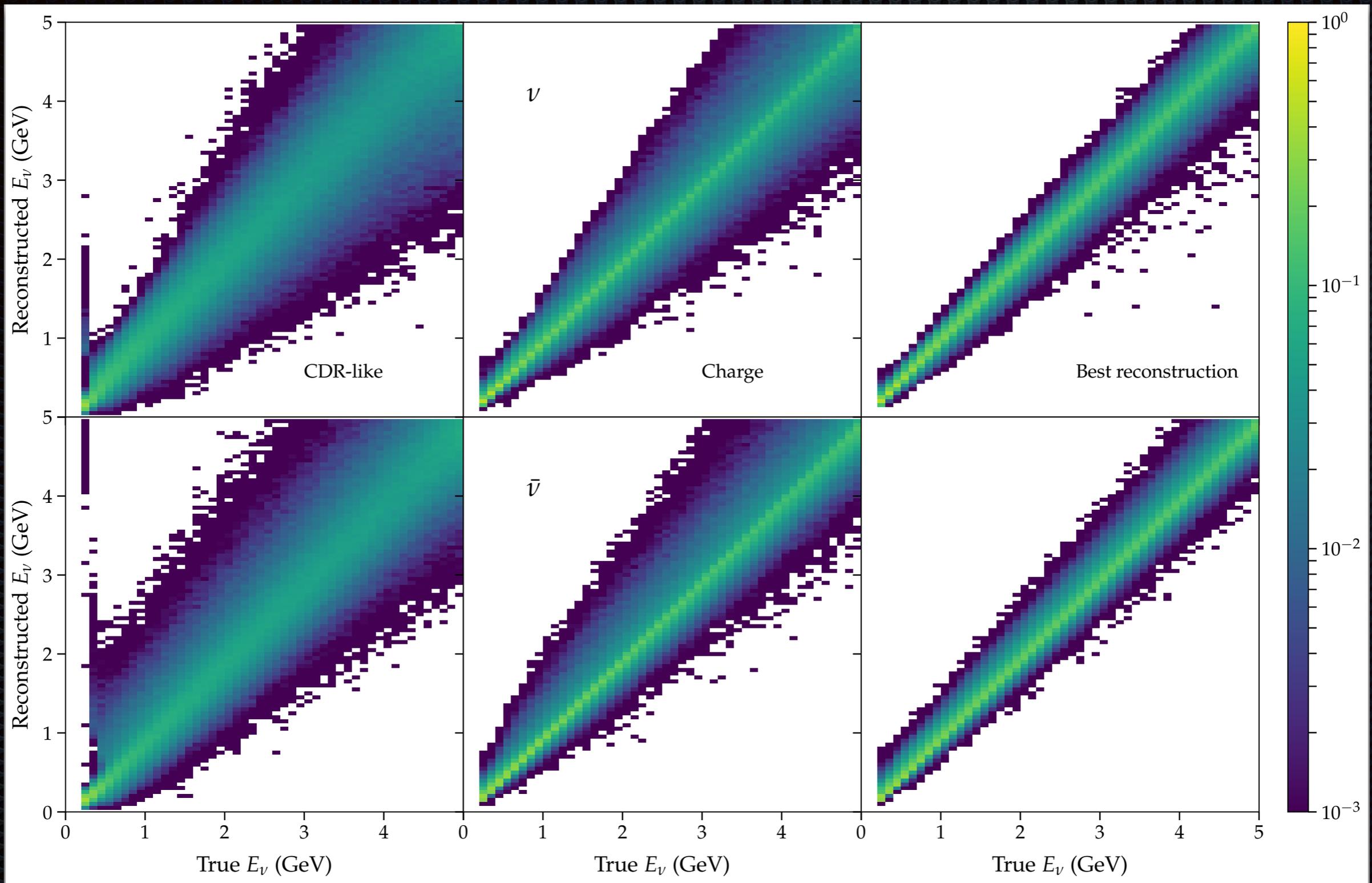
- ✦ The same for antineutrinos
- ✦ Notice the reconstructed energy for scenario 3 is very asymmetric



# Shape of $E_{\text{rec}}$

- Even in the case of neutrinos, the histogram of reconstructed energy is not actually Gaussian
- This has a physical origin: a subclass of events, QE scattering, has a narrower distribution
- This subset could be used for even better energy resolution, 2-3%
- Best approach: report data separately by energy deposition/event topology (cf NOvA quartiles)

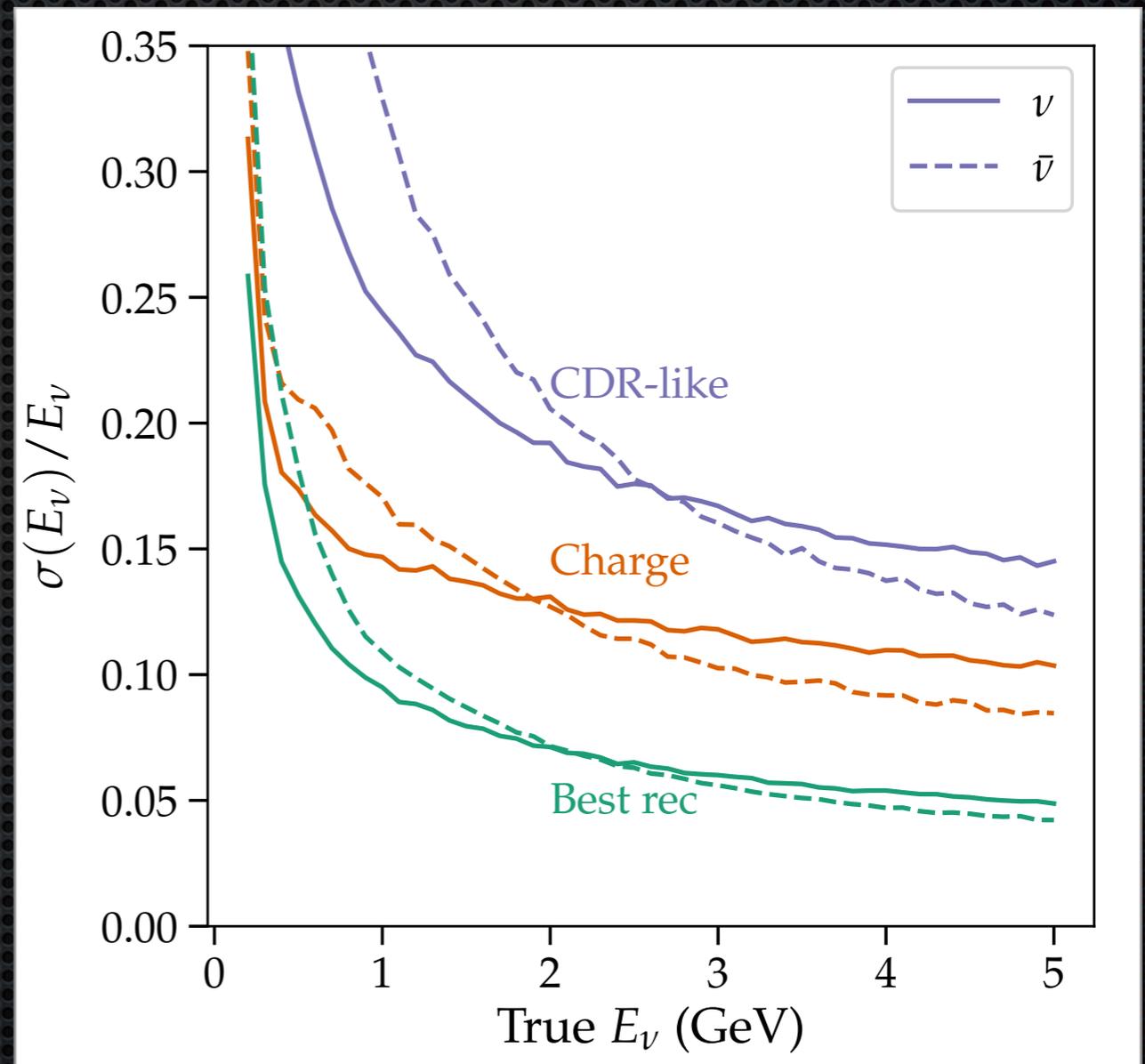




Migration matrices  $E_{\text{true}} \leftrightarrow E_{\text{rec}}$

# Resolution as a function of true neutrino energy

- Although the migration matrices are non-Gaussian, one can still characterize energy resolution by their standard deviation
- Dramatic hierarchy of resolutions between scenarios 1, 2, and 3 persists across the DUNE energy range
- Anti-neutrinos are better measured above  $\sim 2$  GeV, neutrinos below



# Discussion

- Depending on experimental performance and analysis strategy the resolution can differ by as much as a factor of 3
- Generally, the more information we extract about an event, the better the resolution
- “Which improvements are most important?”
  - For example, the price of the CDR thresholds is 6% -> 16%
  - The price for lumping all hadronic charges together without particle ID is 6% -> 12%

# Discussion, cont.

- Not all missing energy channels are created equal. Their impact on the resolution is not directly related to the size of the corresponding pie slice.
- For example, EM showers make up a large part of the electron neutrino energy budget. Even at 0.1 MeV thresholds, one misses about 300 MeV out of 2 GeV. But they are very stable, the resolution is  $\sim 1.5\%$
- By comparison, neutron categories fluctuate a lot. Energy going to nuclear breakup is not visible. In scenario 3 becomes limiting factor.  $\sim 10\% / \sqrt{E_\nu}$

# Example: how low should thresholds be?

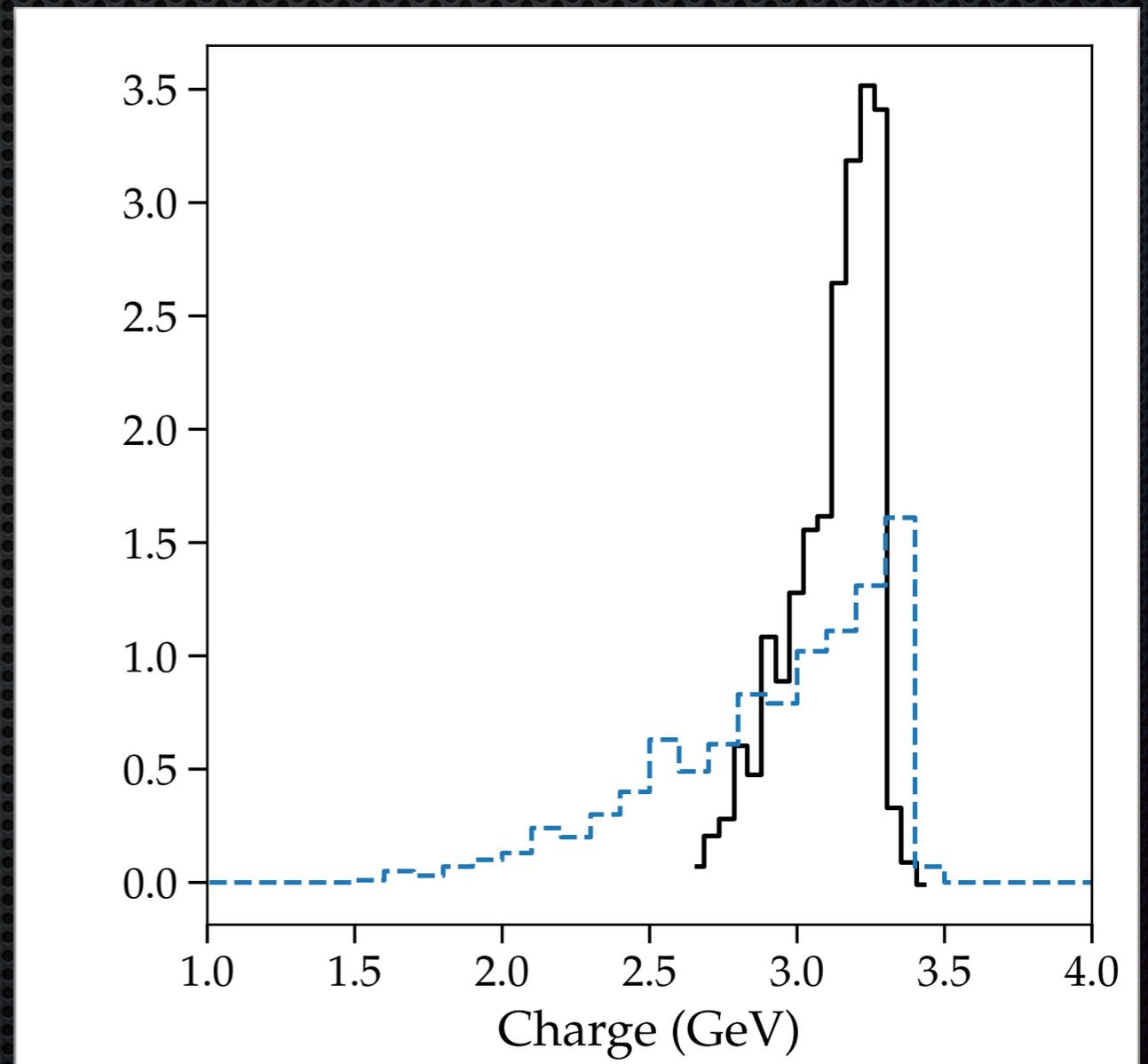
- If we cut at 0.5 MeV, the resolution becomes 6%  $\rightarrow$  6.5%
  - (demonstrated 50% efficiency at ArgoNeuT)
- If we cut at 3 MeV (demonstrated 50% efficiency at ArgoNeuT), the resolution becomes 6%  $\rightarrow$  8%
  - This is the point which cuts out the spray from the rest.
  - Lowering thresholds from 50 MeV to 3 MeV captures low-energy protons, 16%  $\rightarrow$  8% (factor of 2)
  - Including the spray further improves the resolution by 25%

# Comparison to other results out there

- CDR results use FastMC: apply Gaussian smearing prescriptions to GENIE outputs. Not a real simulation, no direct comparison possible.
  - Thresholds too conservative, artificial obstacle
- Ongoing DUNE simulation uses a reduced detector geometry. A lot of escaping muons, which are then averaged over.
- Advantage of our study is that we can separate conceptual limitations from things which can be easily improved.

# Literature comparison: total charge calorimetry

- ✦ Our scenario 2 is chosen to reproduce Di Romeri et al. We do not find any agreement?
- ✦ Something about LArSoft/GEANT4? Further validation studies warranted.



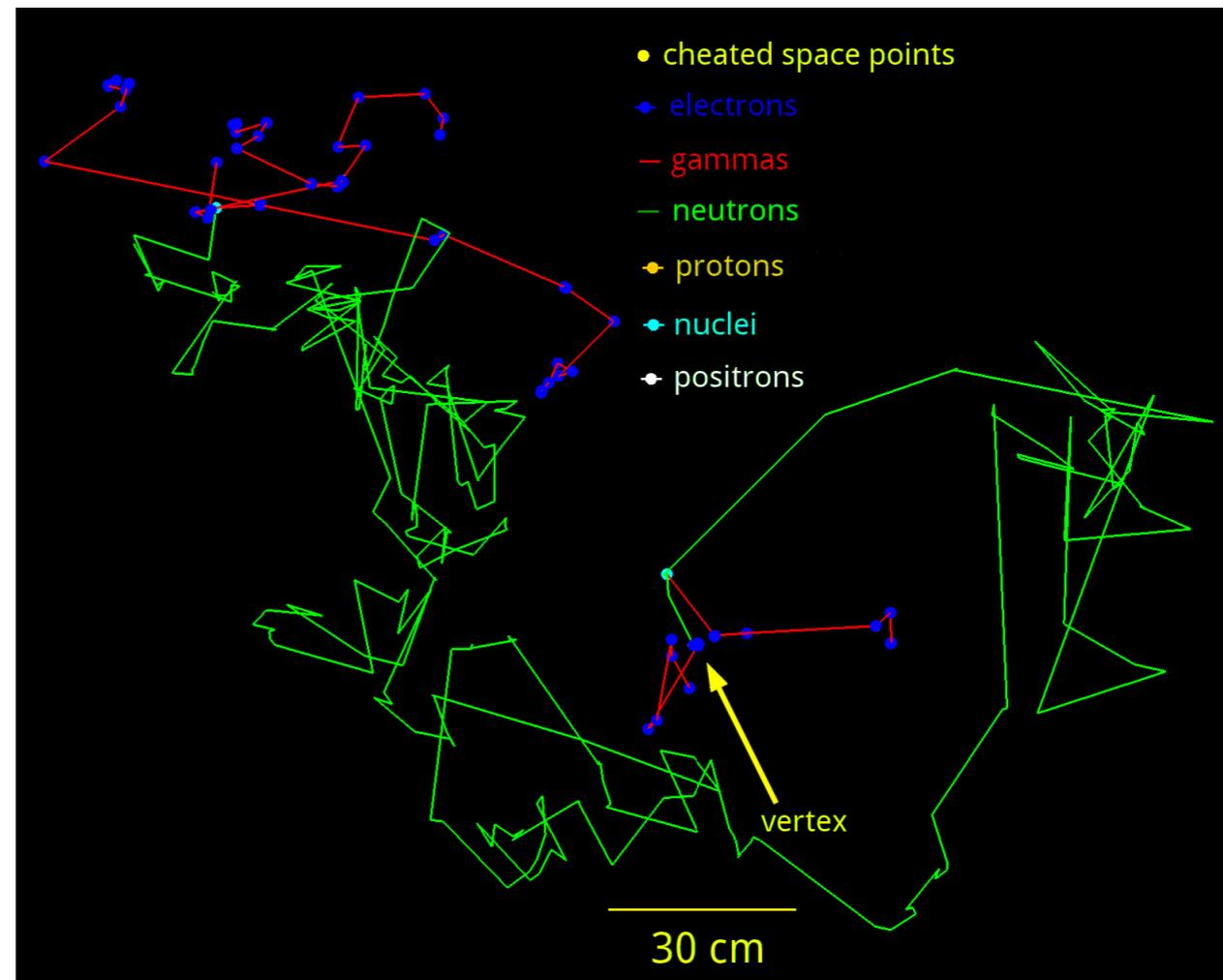
# Outlook

- DUNE is a calorimeter with several leakage channels
  - We quantified its non-hermeticity
- Full event reconstruction and low thresholds bring large benefits
- Calibration studies are key:
  - Test beam data at ProtoDUNE very important
  - Neutron studies are highly motivated
- Framework to simulate the effects of generator physics (GENIE tunes, GENIE vs GiBUU vs NuWro, etc)
- Not a substitute for actual detector and reconstruction simulations. We hope to encourage this work.

Backup

# MARLEY Simulation by UC Davis group (Credit: S. Gardener et al)

- $E_\nu = 16.3$  MeV
- $e^-$  deposited 4.5 MeV
- No primary  $\gamma$ s from vertex
- $^{39}\text{K}$  deposited 68 keV
- n deposited 7.6 MeV (mostly from capture  $\gamma$ s)
- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
- Neutrons bounce around for a long time!

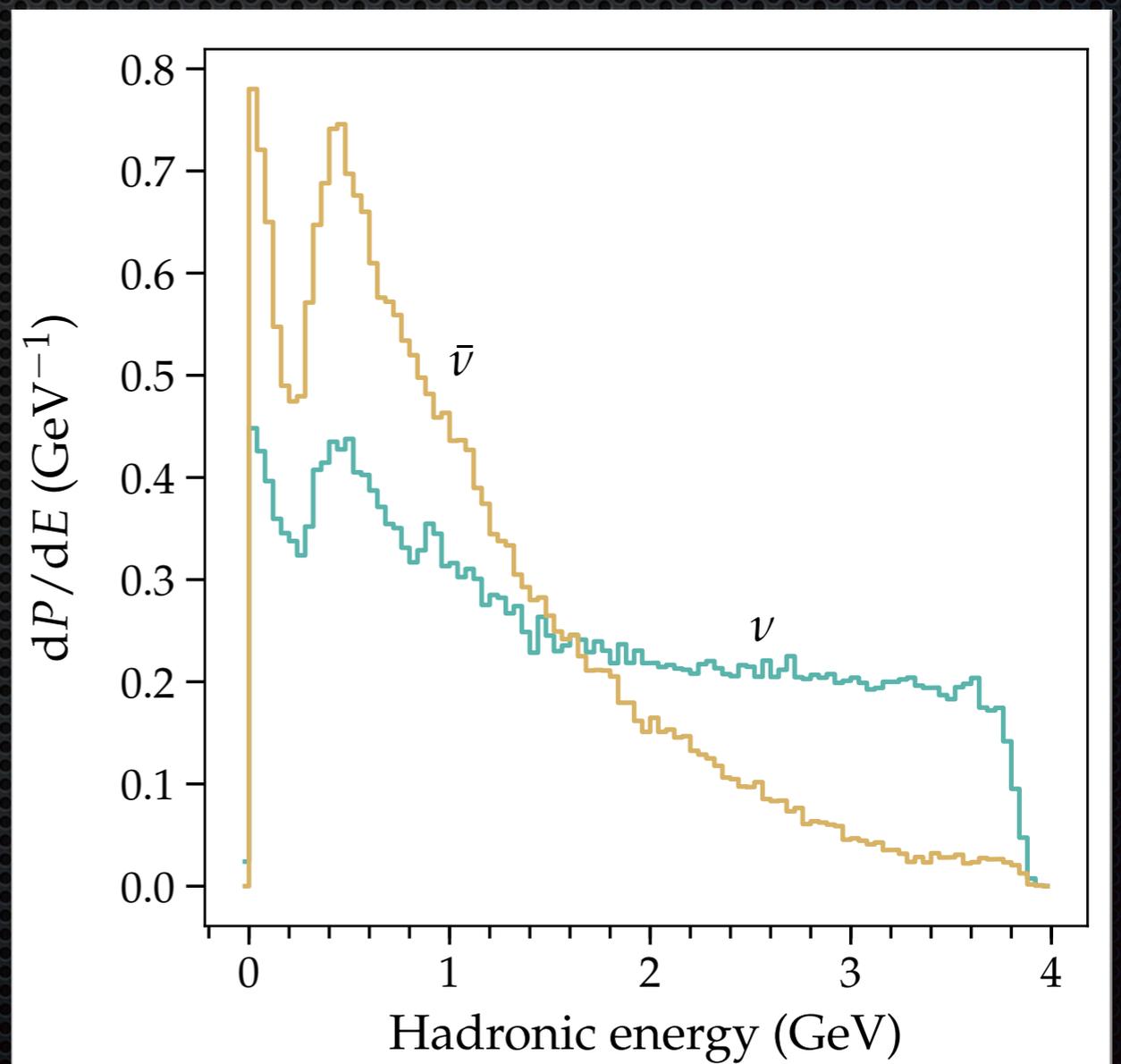


The same physics is relevant for SN neutrino measurements

# Hadronic energy distribution

$$E_\nu = 4 \text{ GeV}$$

- On average, in neutrino events ~40% of energy goes in the hadronic system.
  - But the distribution is very broad!
- Approximating scattering as DIS on valence quarks, the distribution would be flat (helicity). This breaks down at lower energy (resonances)
- For antineutrinos, the average hadronic energy is less. The helicity argument gives  $(1-y)^2$ .
  - But the final state contains more neutrons



# Digression: why several GeV?

- This is clearly a very challenging energy range to model interactions. Why would anyone choose it?
- Dictated by physics of the problem
  - Earth matter effect is used to distinguish mass hierarchies
  - But the matter term  $\sqrt{2}G_F n_e$  has dimension of inverse length! To have significant matter effects in Earth, one needs baselines  $\sim 10^3$  km. But then to have an oscillation maximum with atmospheric splitting,  $\Delta m^2/2E_\nu$  requires energies of several GeV

# Neutrons

- Distribution of neutron energies from 4 GeV neutrinos

