Liquid Argon and Energy Reconstruction

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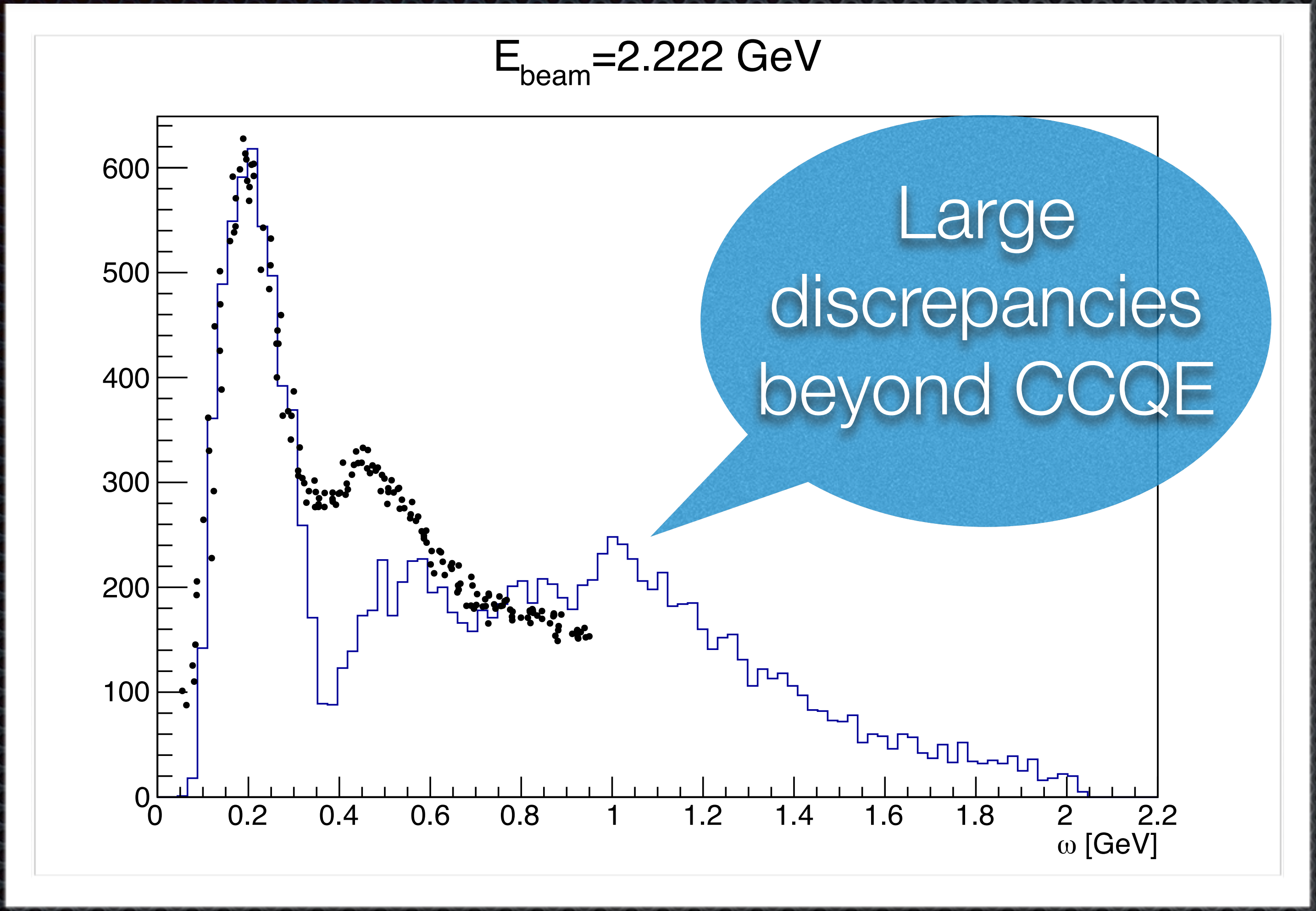
see arXiv:1811.06159,

10.1103/PhysRevD.99.036009

Invitation: Electron scattering comparison



Large discrepancies beyond CCQE

- GENIE fails to reproduce electron scattering data collected at JLab last year …
- … and many other datasets. A series of papers in preparation

How’s DUNE affected by cross section mismodeling?

Calorimetric method

- If we 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?

Situation in the literature unclear

- 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,
  - 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

see arXiv:1811.06159,

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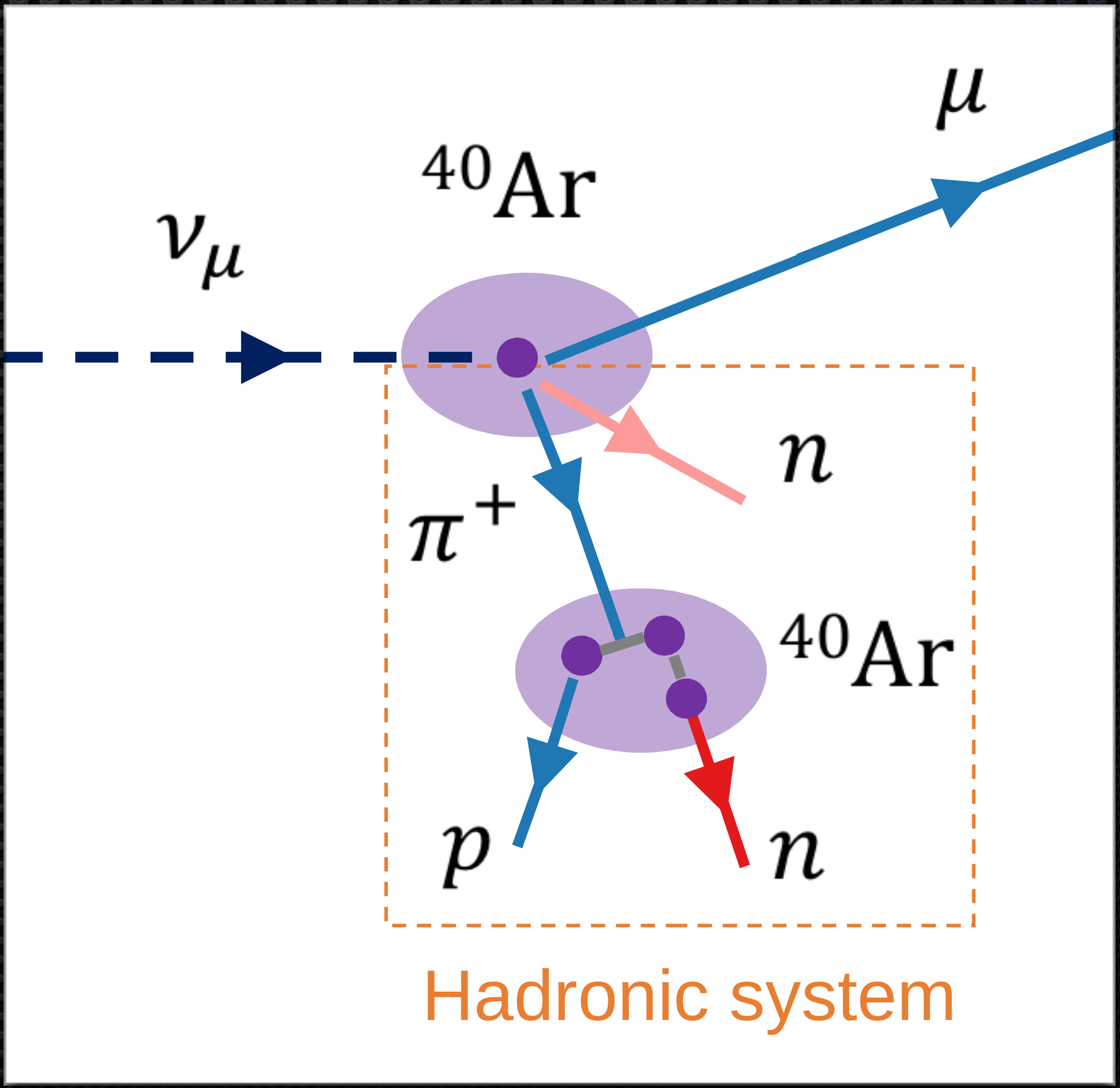
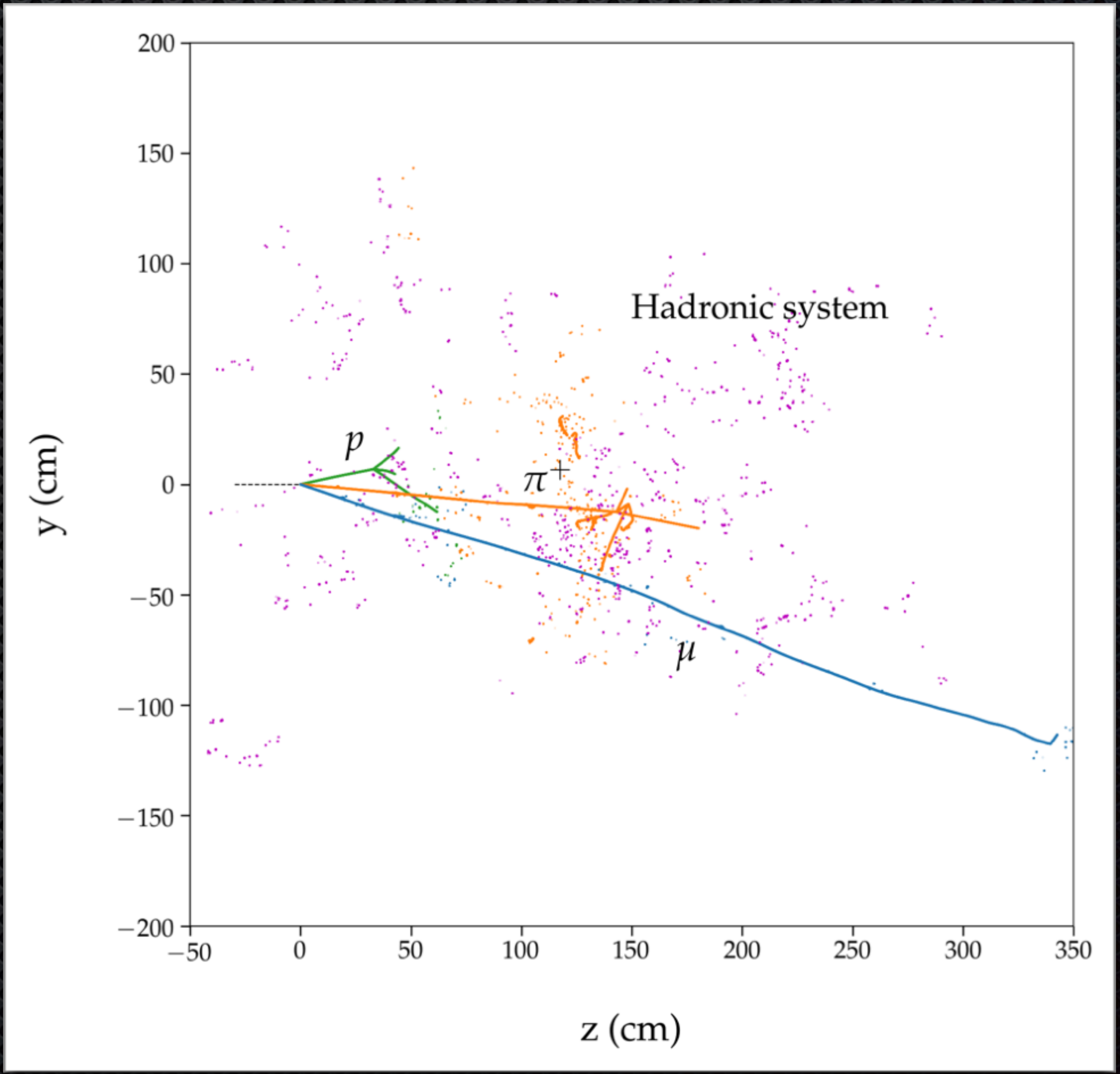
Neutrino events in DUNE, a cartoon

- 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

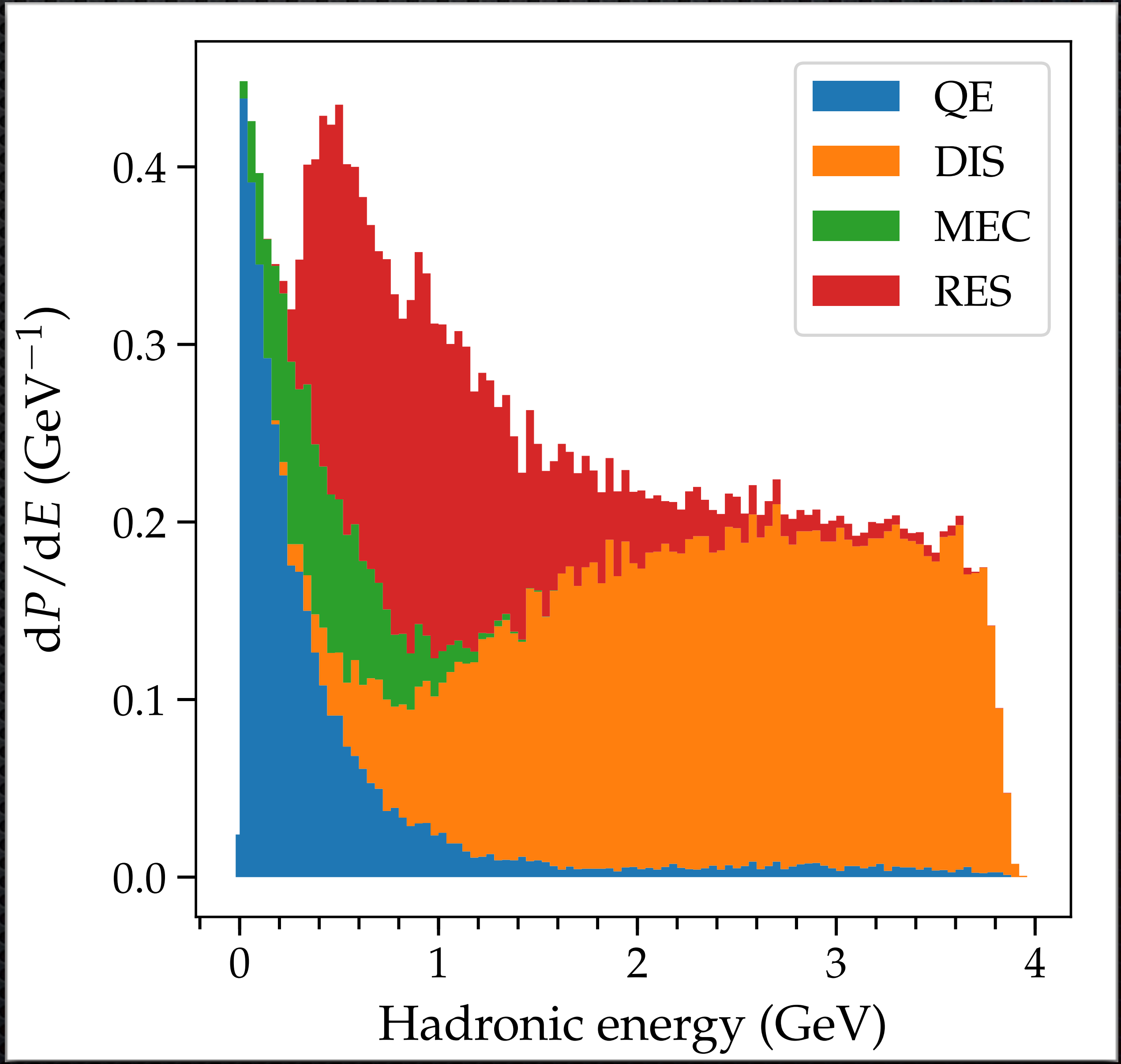
- Muon is the longest track. Decays in the end (Michel electron seen)
- Charged pion is intermediate. Secondary interaction
- Proton track is short. Also secondary interaction
- Spray of small charge deposits. Mostly due to neutrons.



Hadronic energy distribution

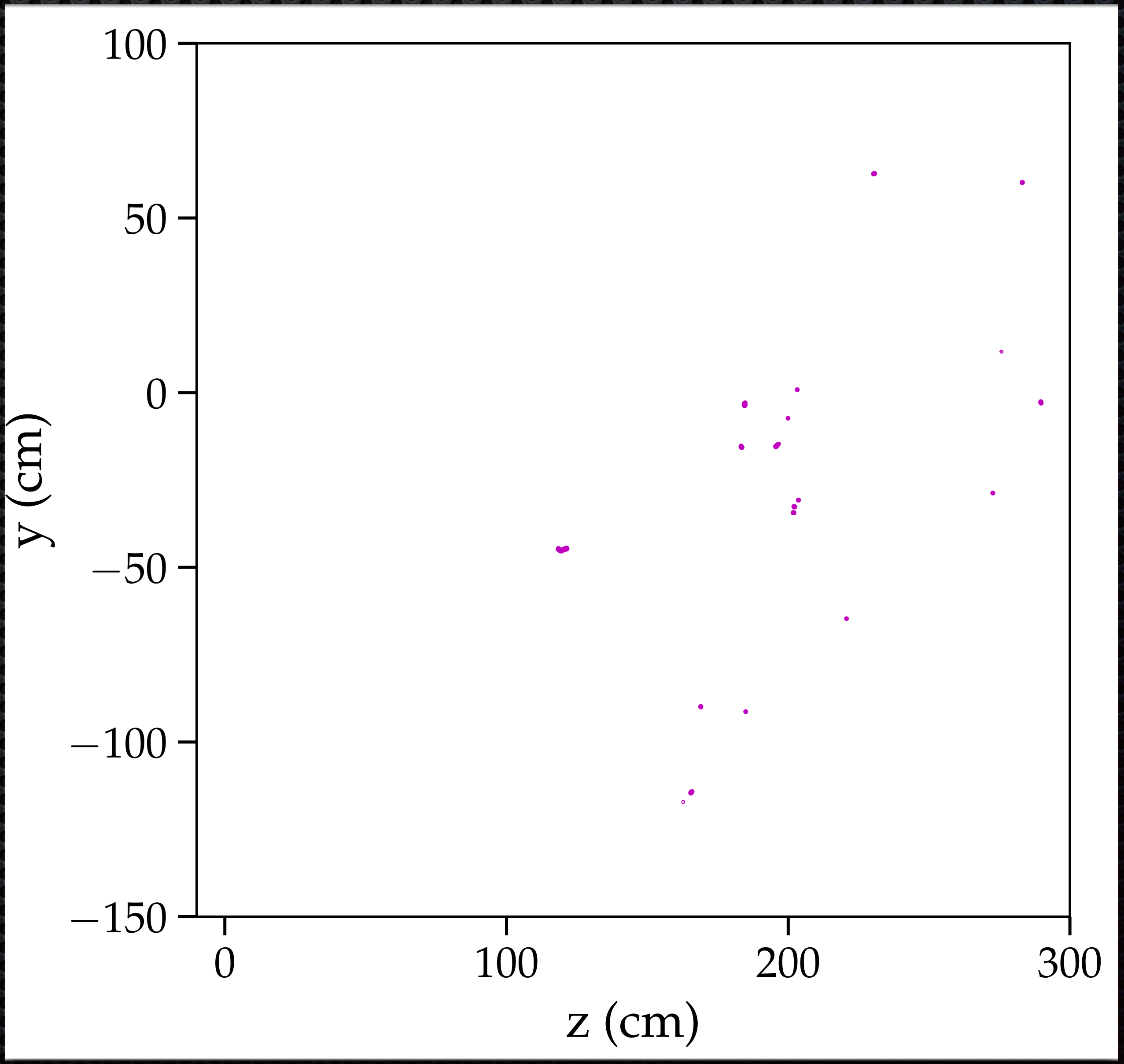
$E_\nu = 4\,GeV$

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



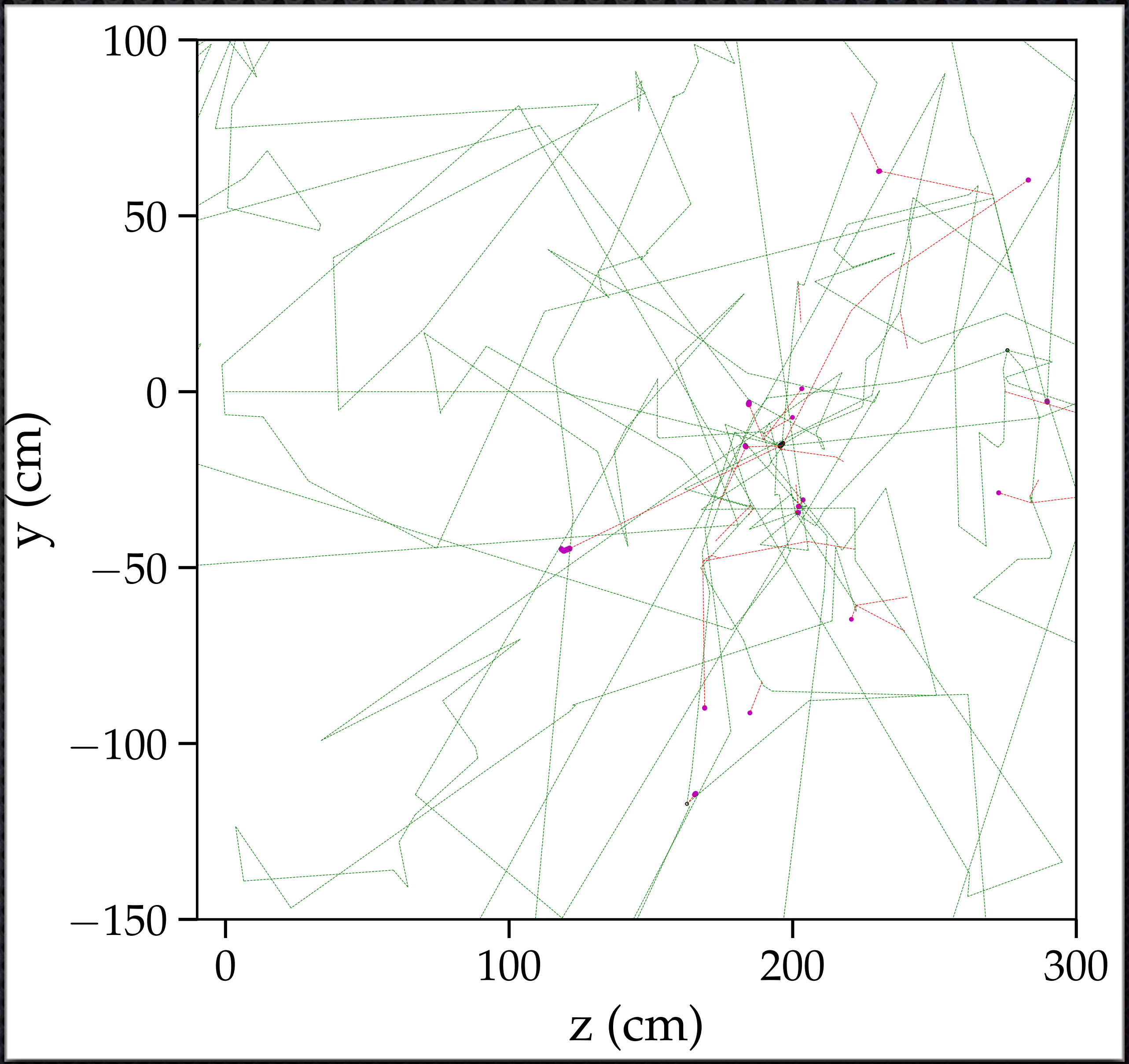
Neutrons

- 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. ~ 14 cm. This gives rise to the “spray”



Neutrons

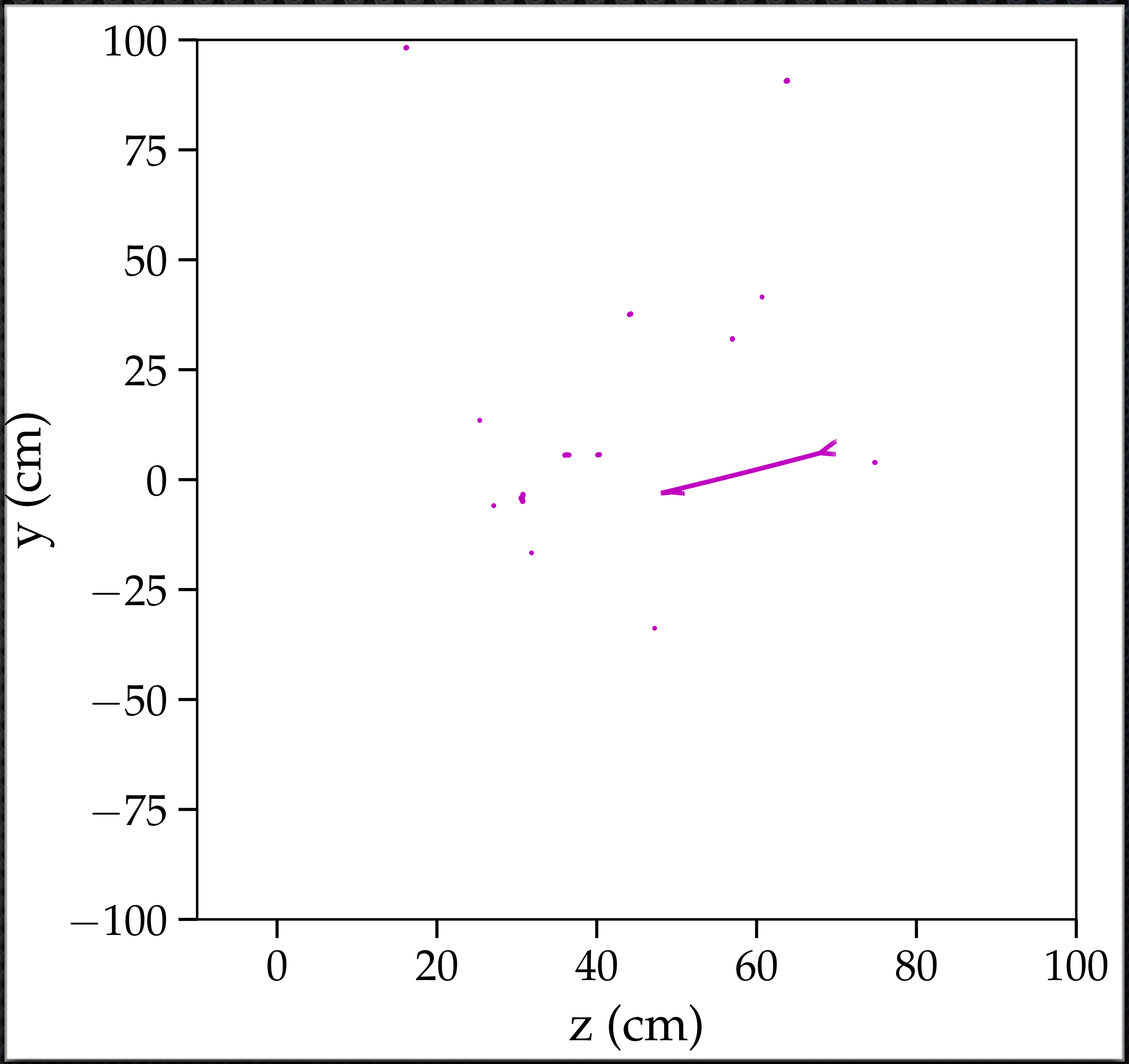
- Same as previous slide, with particle trajectories shown



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

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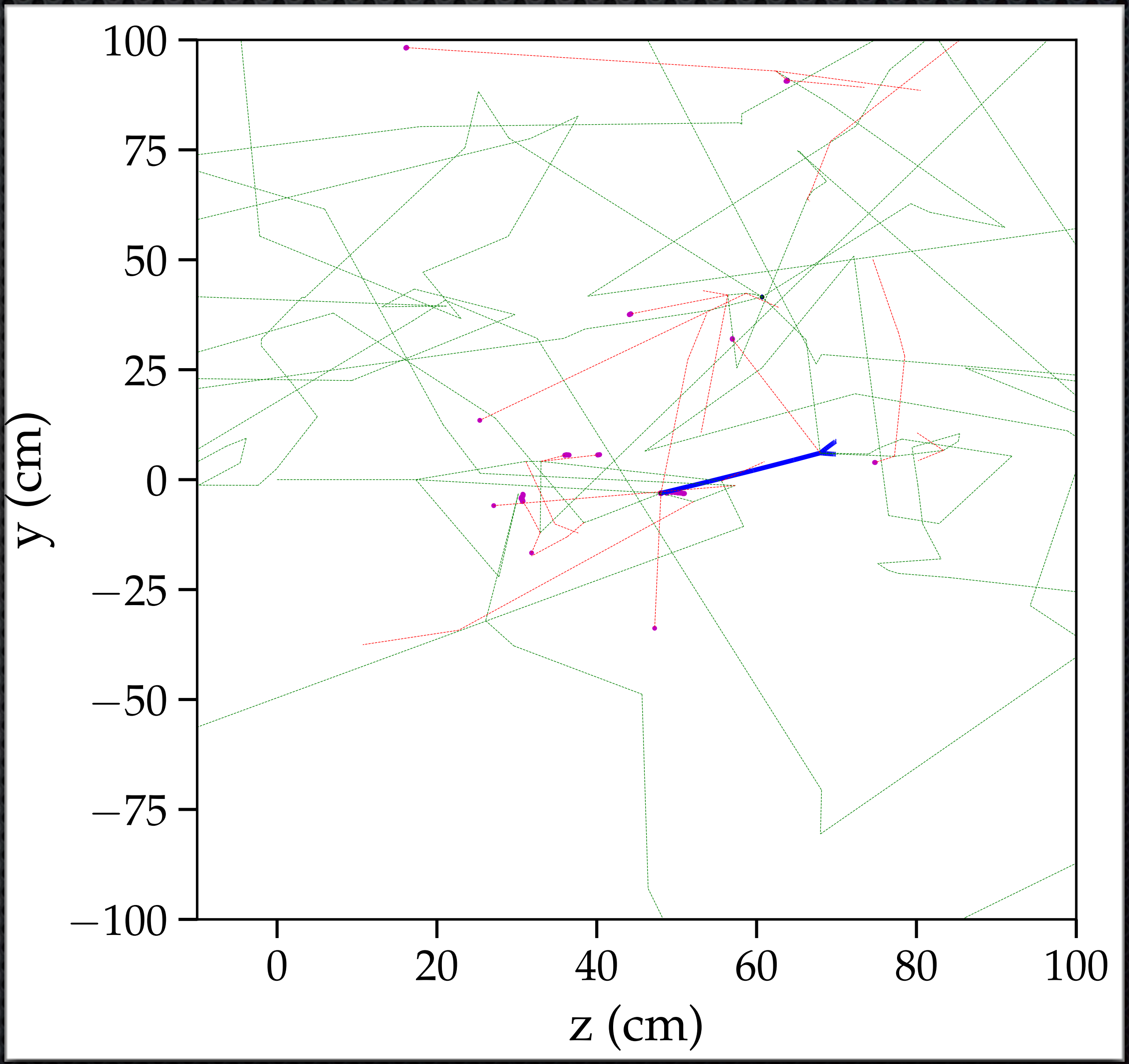


Charge recombination: role of particle ID

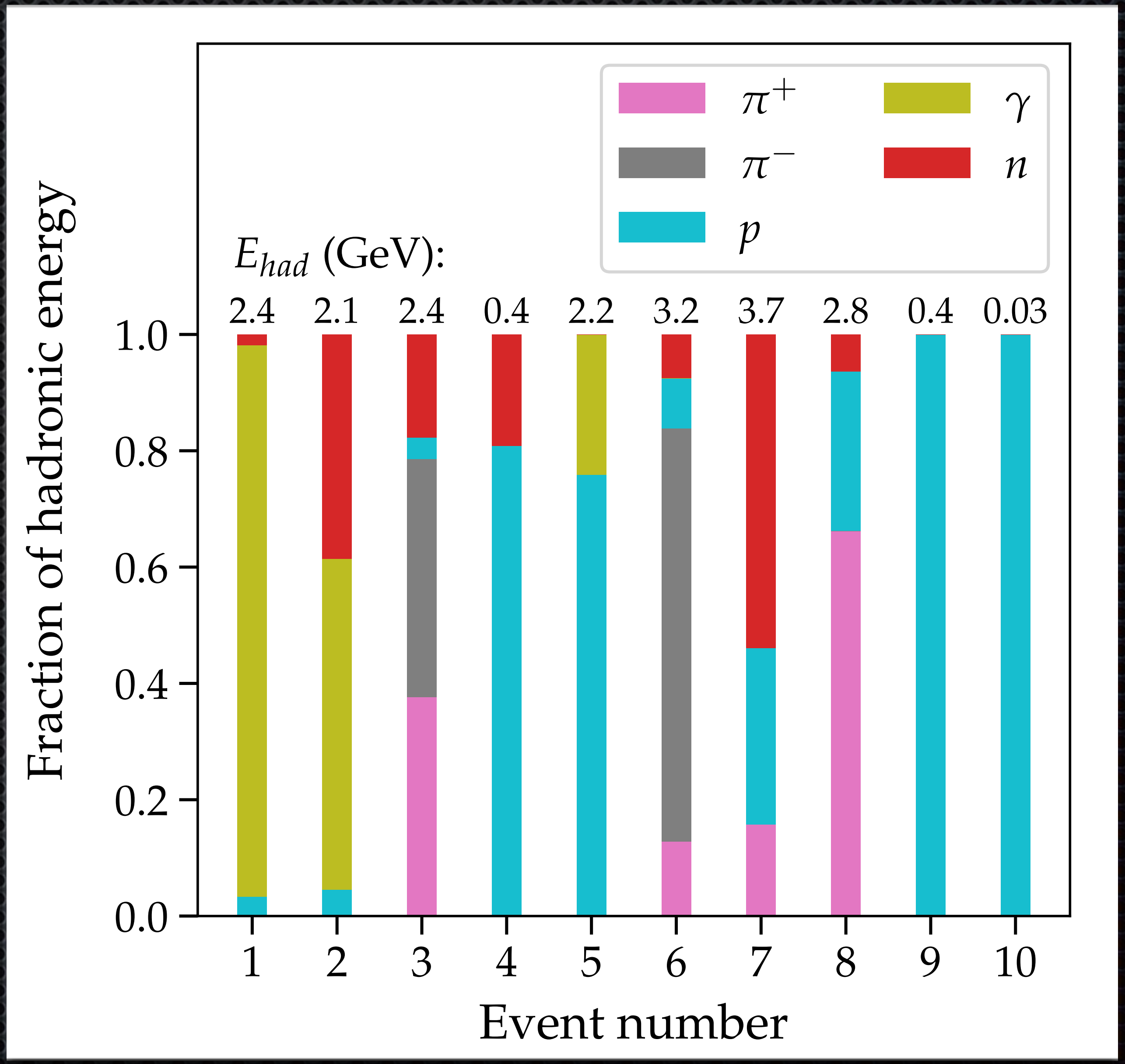
- Muons are relativistic and lose energies as minimally ionizing particles, ~2 MeV/cm. A 4 GeV muon travels 20 m
- Protons are typically non-relativistic, lose more energy per unit length (12 MeV/cm for 50 MeV p).
  - Depends on β^{-2}, as can be easily understood in the impulse approximation
  - This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

Other notes

- 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 π_0’s. As the end of these are a lot of low-energy gammas, hence also some “spray”

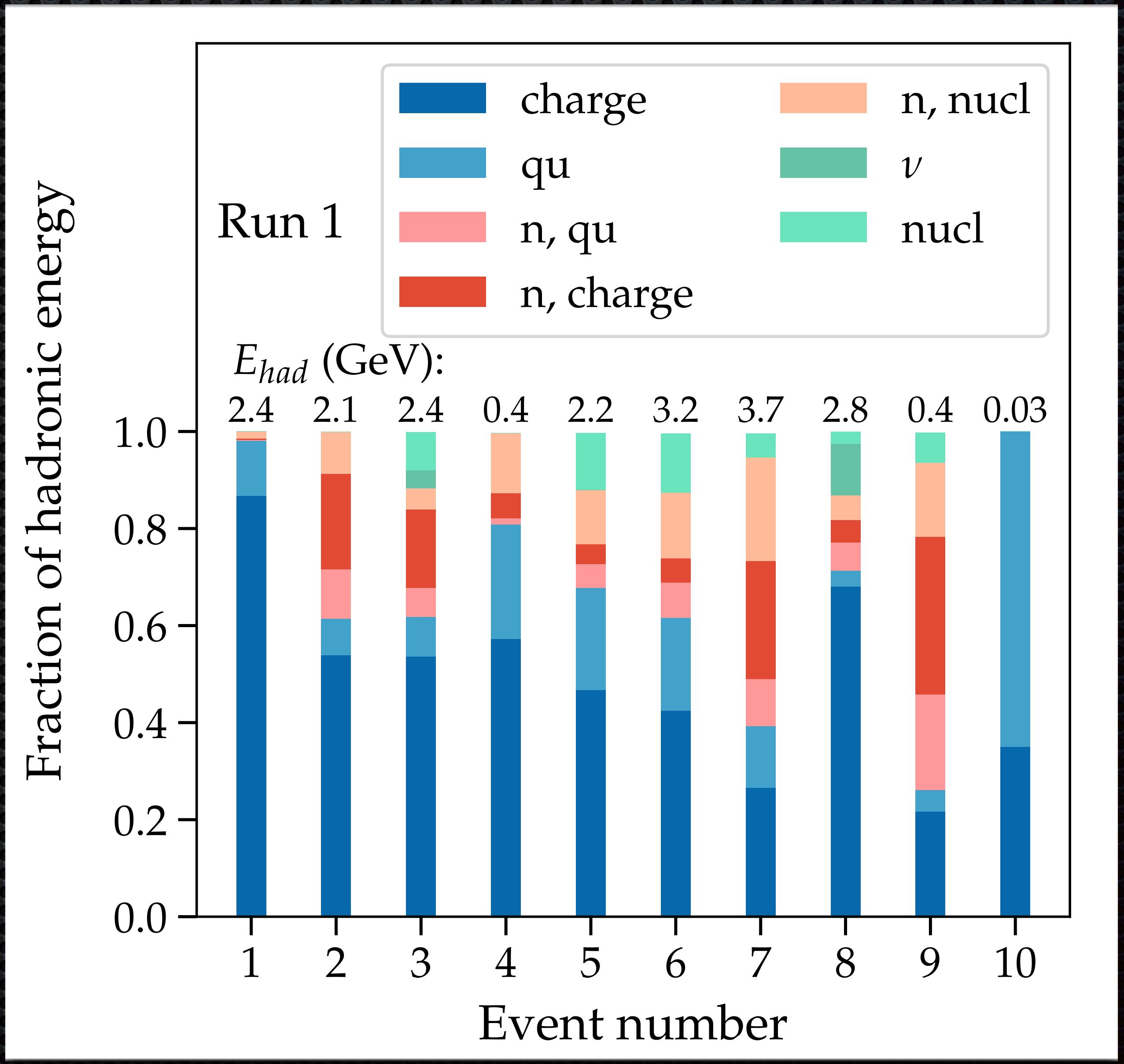
Event composition: prompt particles

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



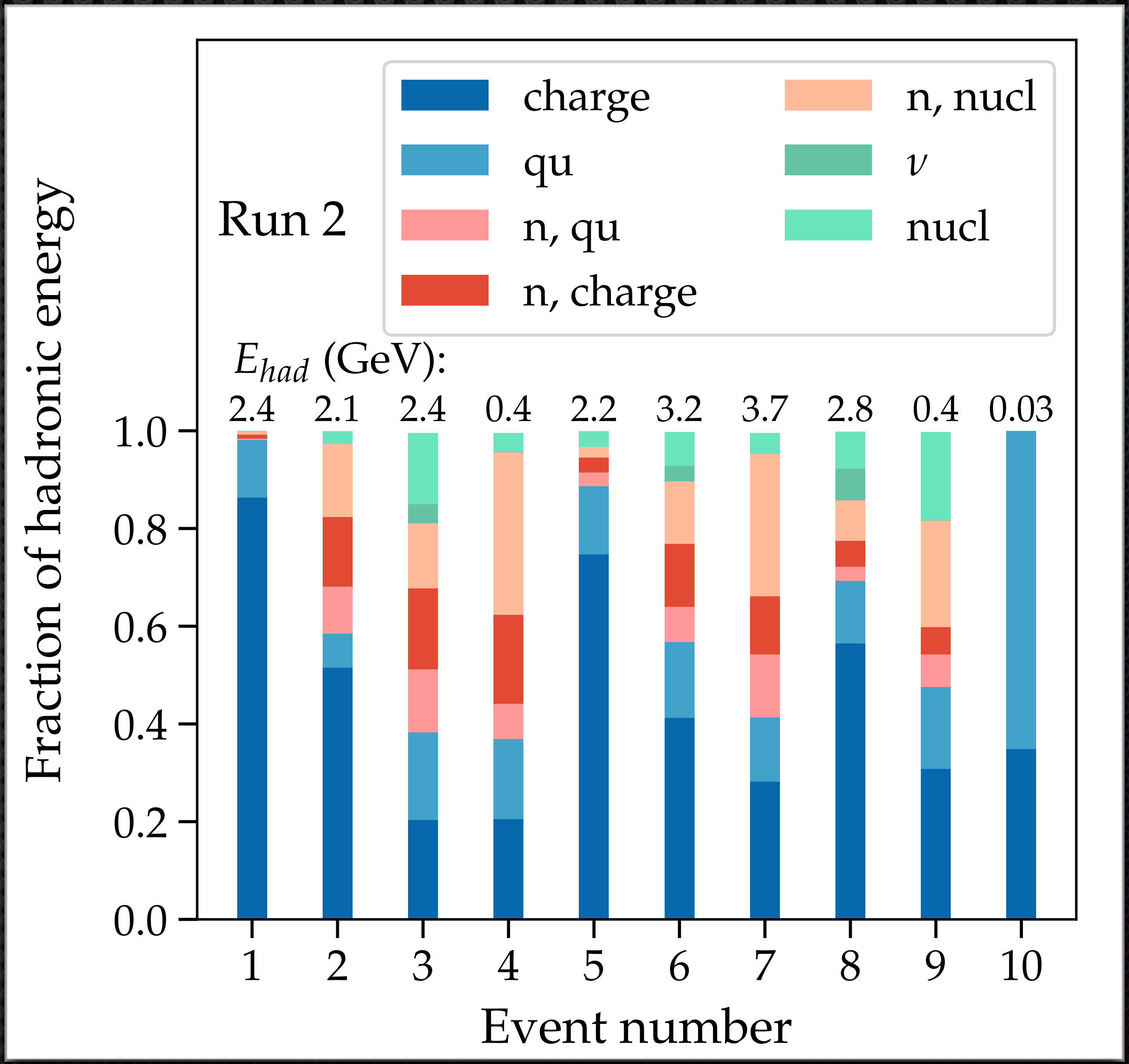
Simulating energy flow

- 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!



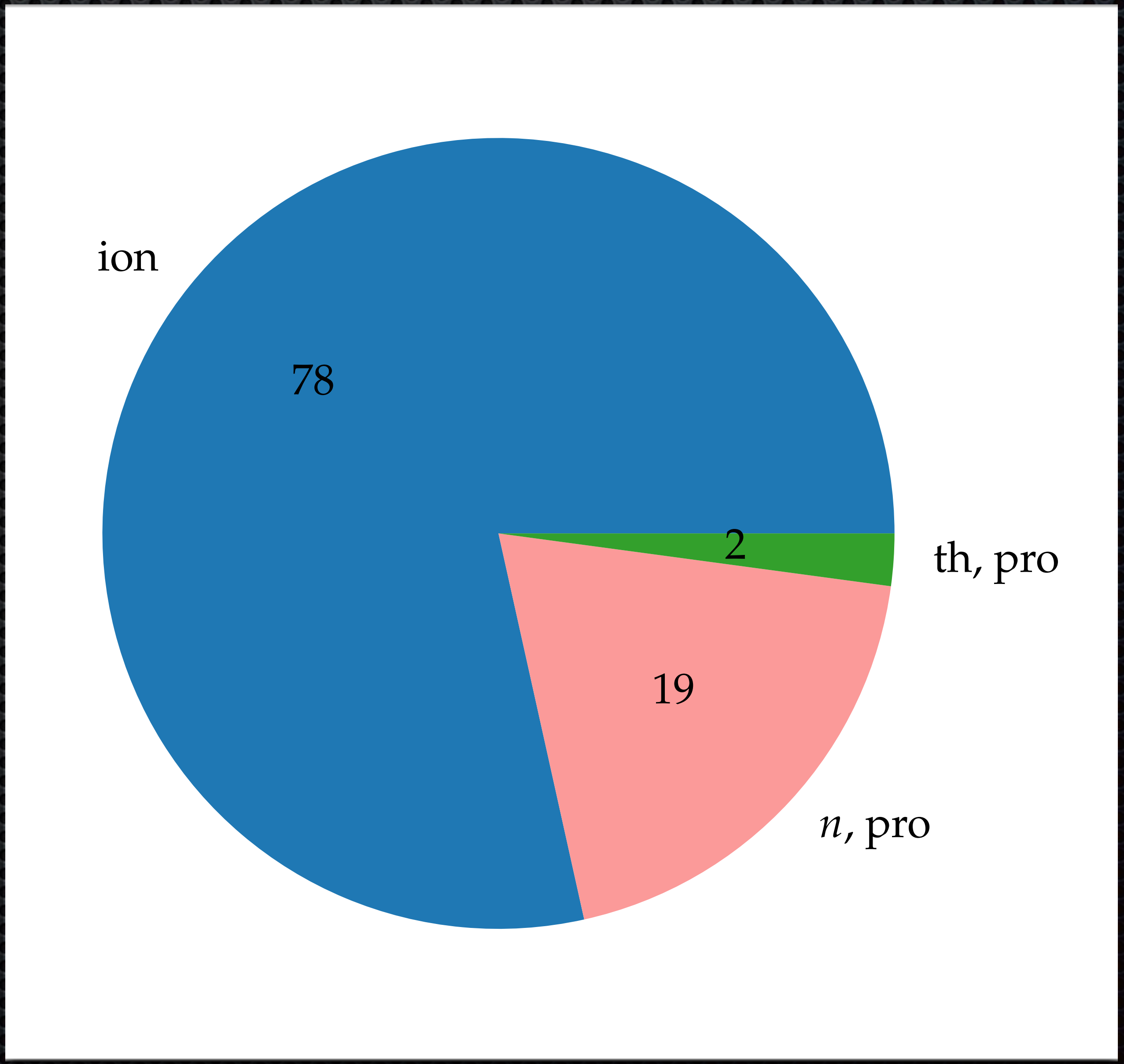
Missing energy budget: prompt particles

$E_\nu = 4\,GeV$

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

	p	$\pi^\pm$	γ	μ	e	others
Thresholds (MeV)	50	100	30	30	30	50

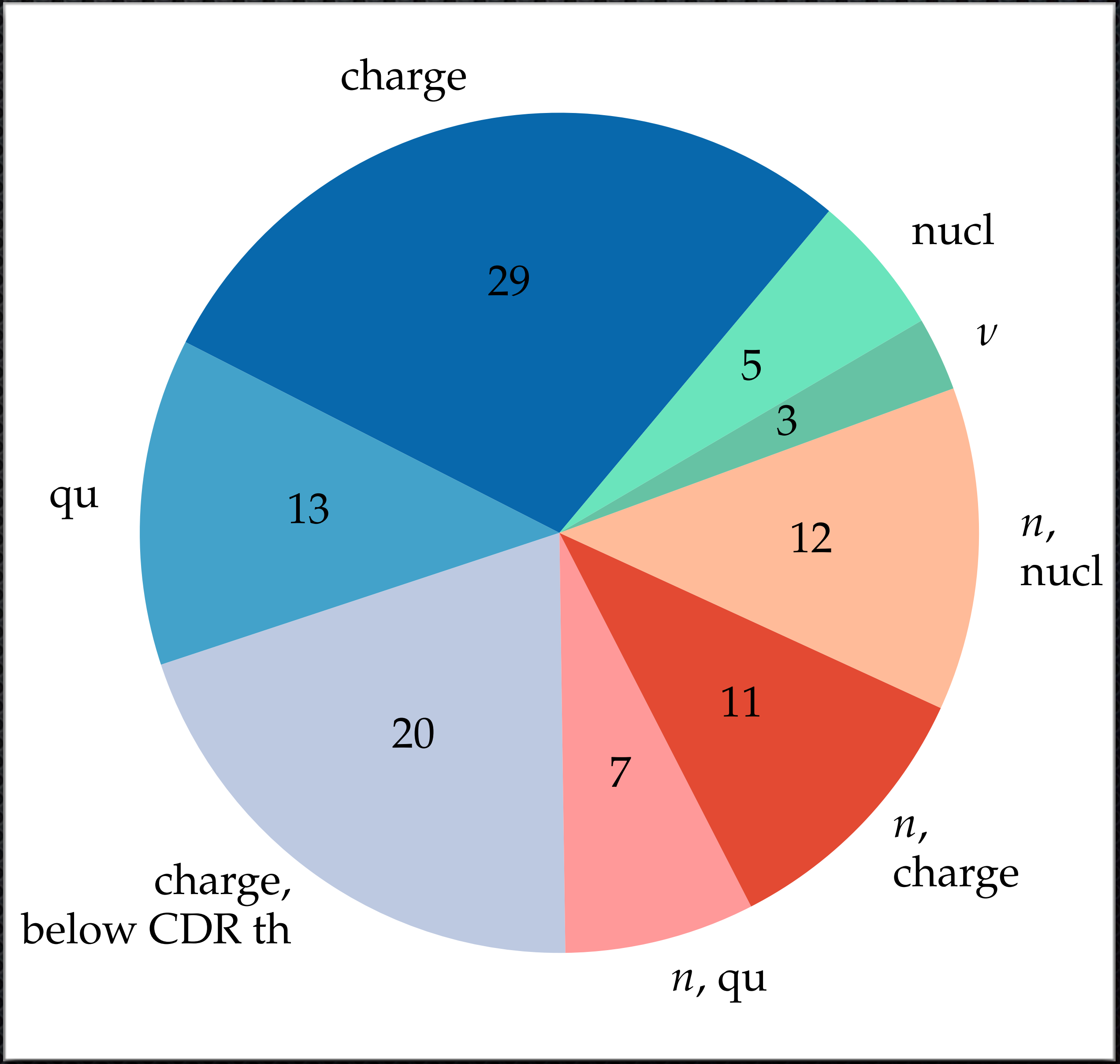
- Prompt neutrons are more important, consistent with 1507.08561



Missing energy budget full event

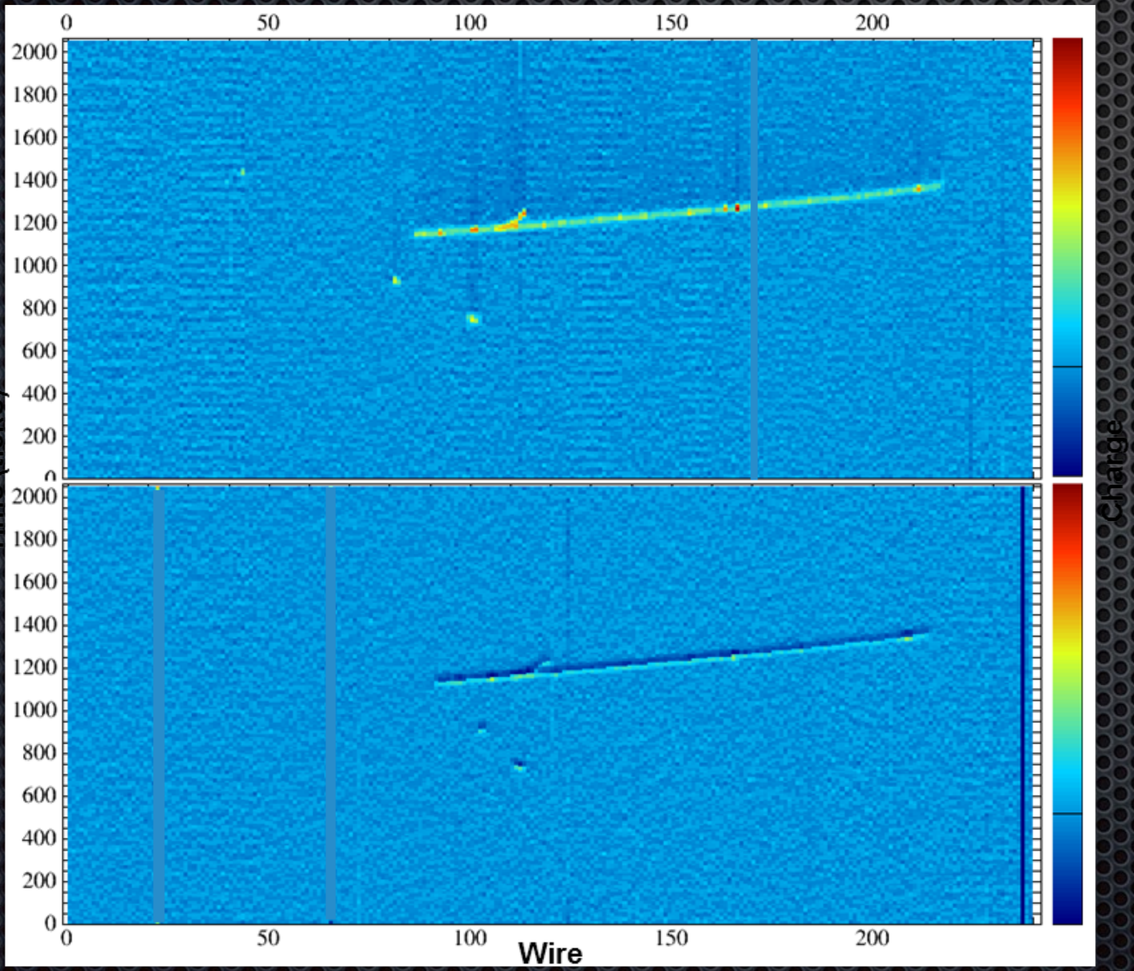
$E_\nu = 4\,GeV$

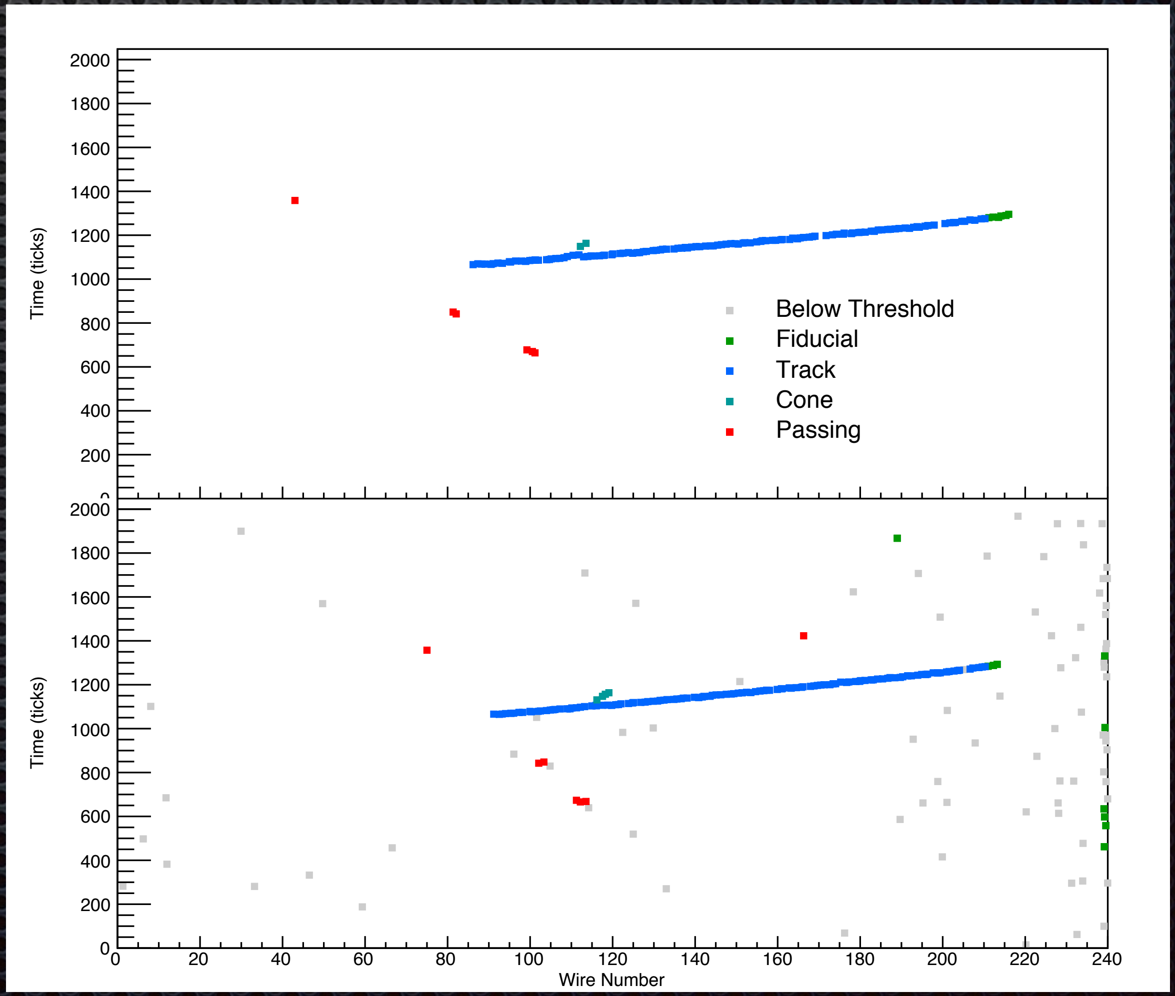
- However, this has little to do with the real missing energy budget!
- Fully propagating events and imposing the CDR thresholds, we find this for the hadronic system
  - Neutrons are separated in their own subcategories



Are CDR thresholds too conservative?

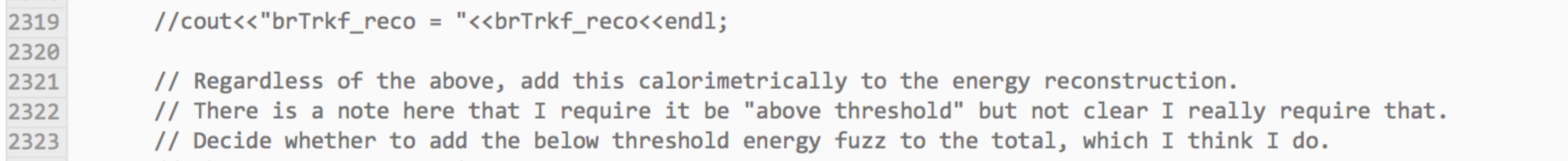
- ArgoNeuT sees “spray” from de-excitation gammas, including Compton electrons below 1 MeV [arXiv:1810.06502]





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

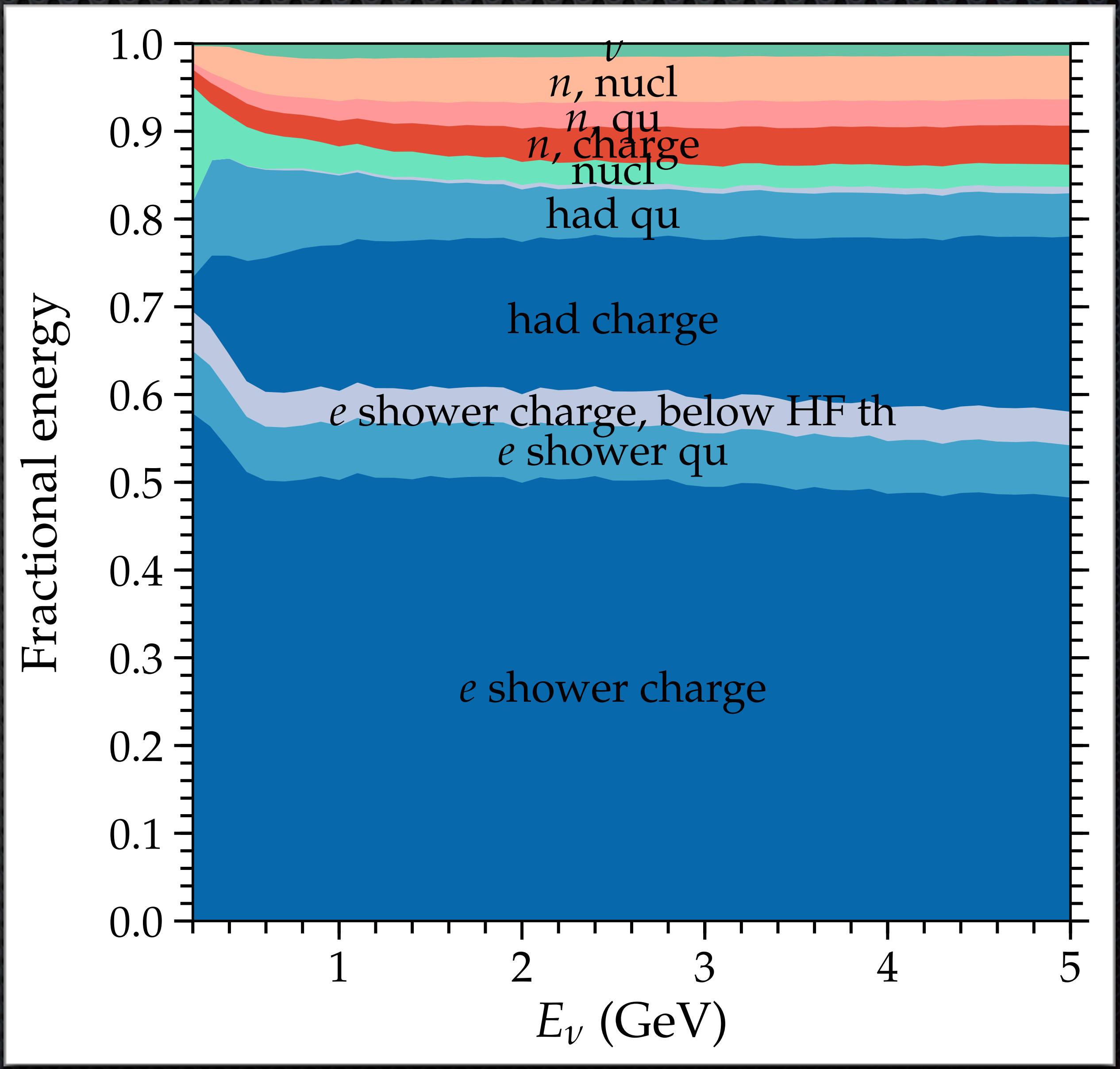


```
//cout<<"brTrkf_reco = "<<brTrkf_reco<<endl;

// Regardless of the above, add this calorimetrically to the energy reconstruction.
// There is a note here that I require it be "above threshold" but not clear I really require that.
// Decide whether to add the below threshold energy fuzz to the total, which I think I do.
```

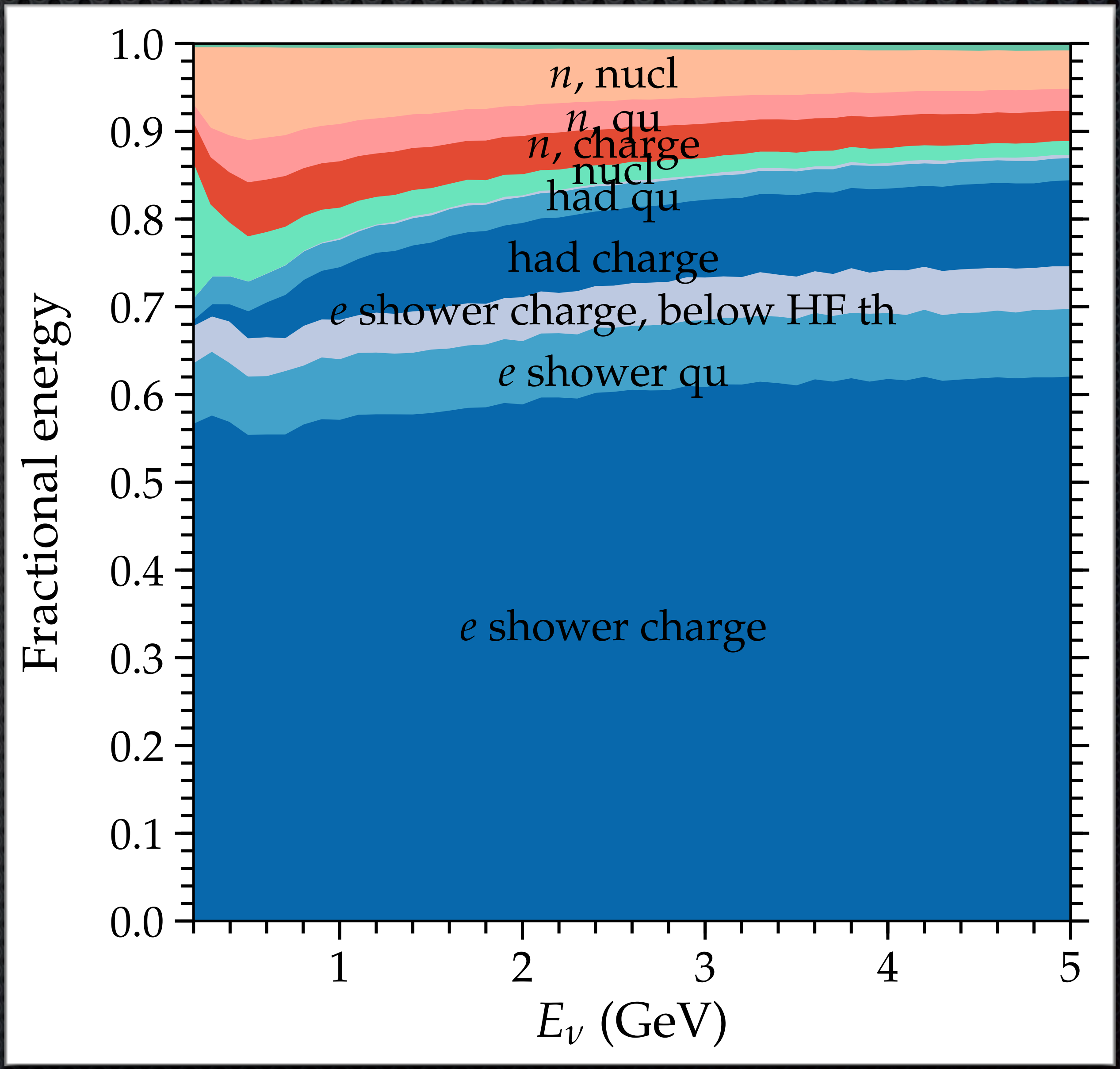
Missing energy budget full simulation

- 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



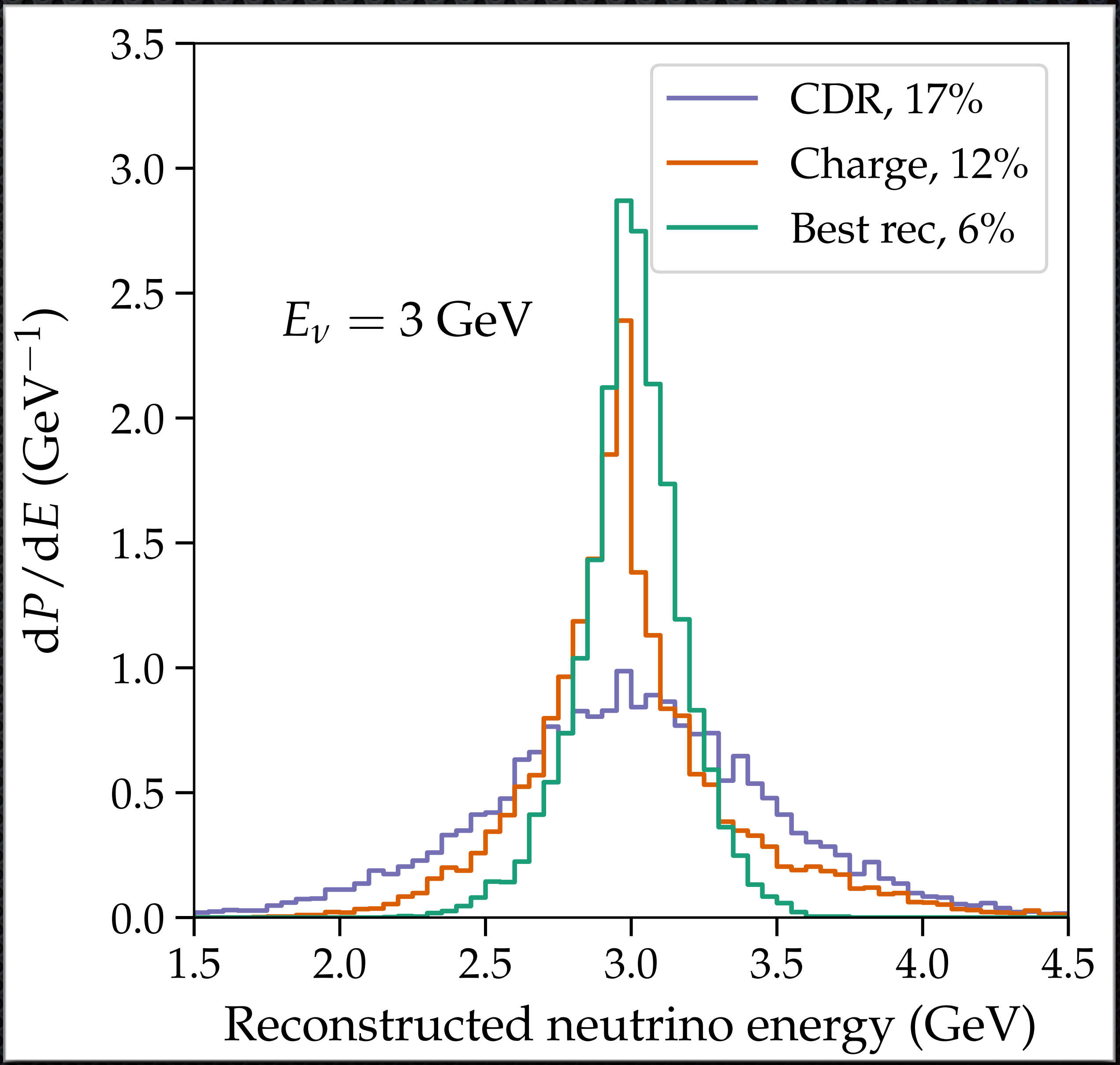
From missing energy to resolution

- 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

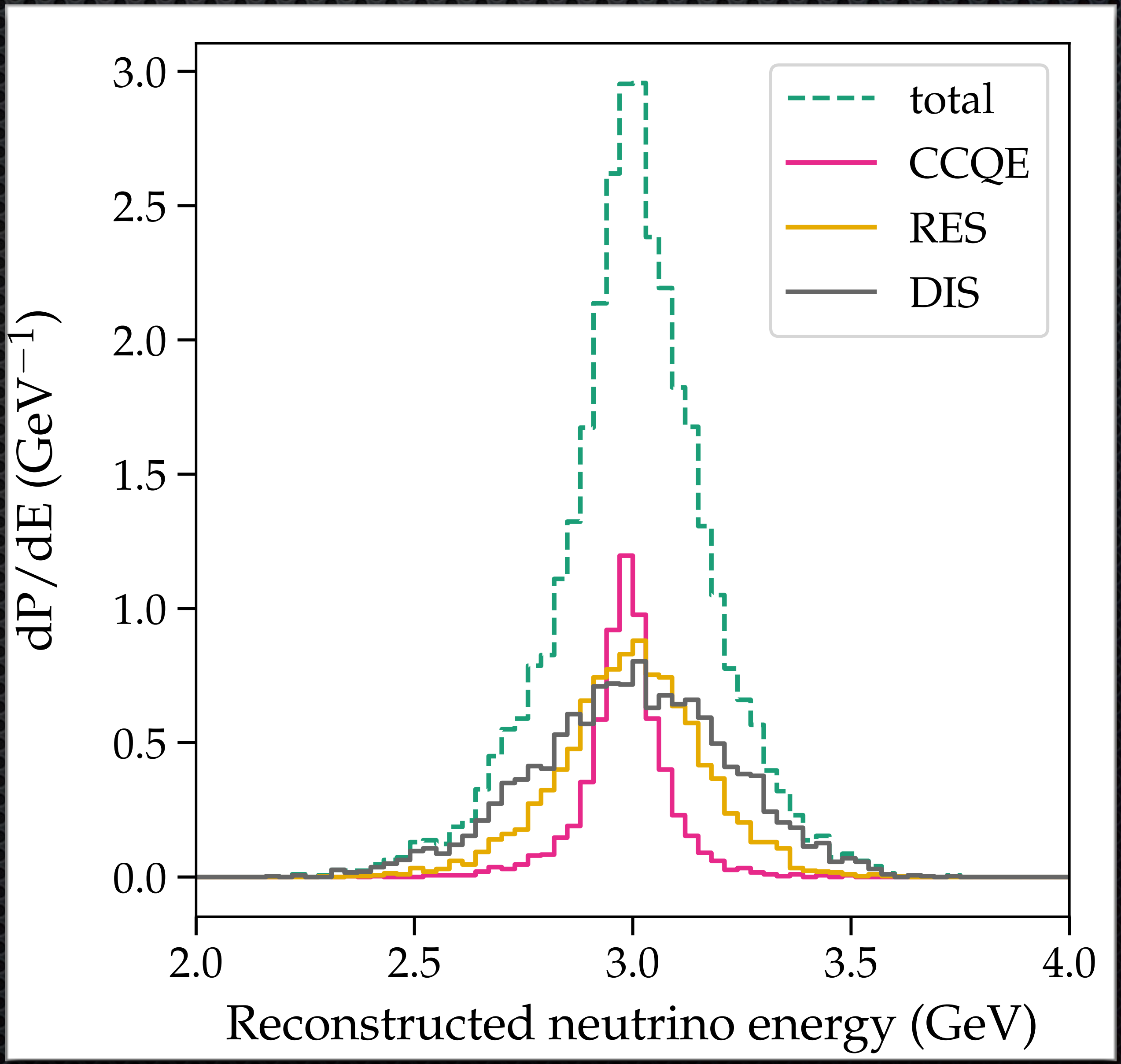
- Applied the reconstruction procedure in three scenarios:

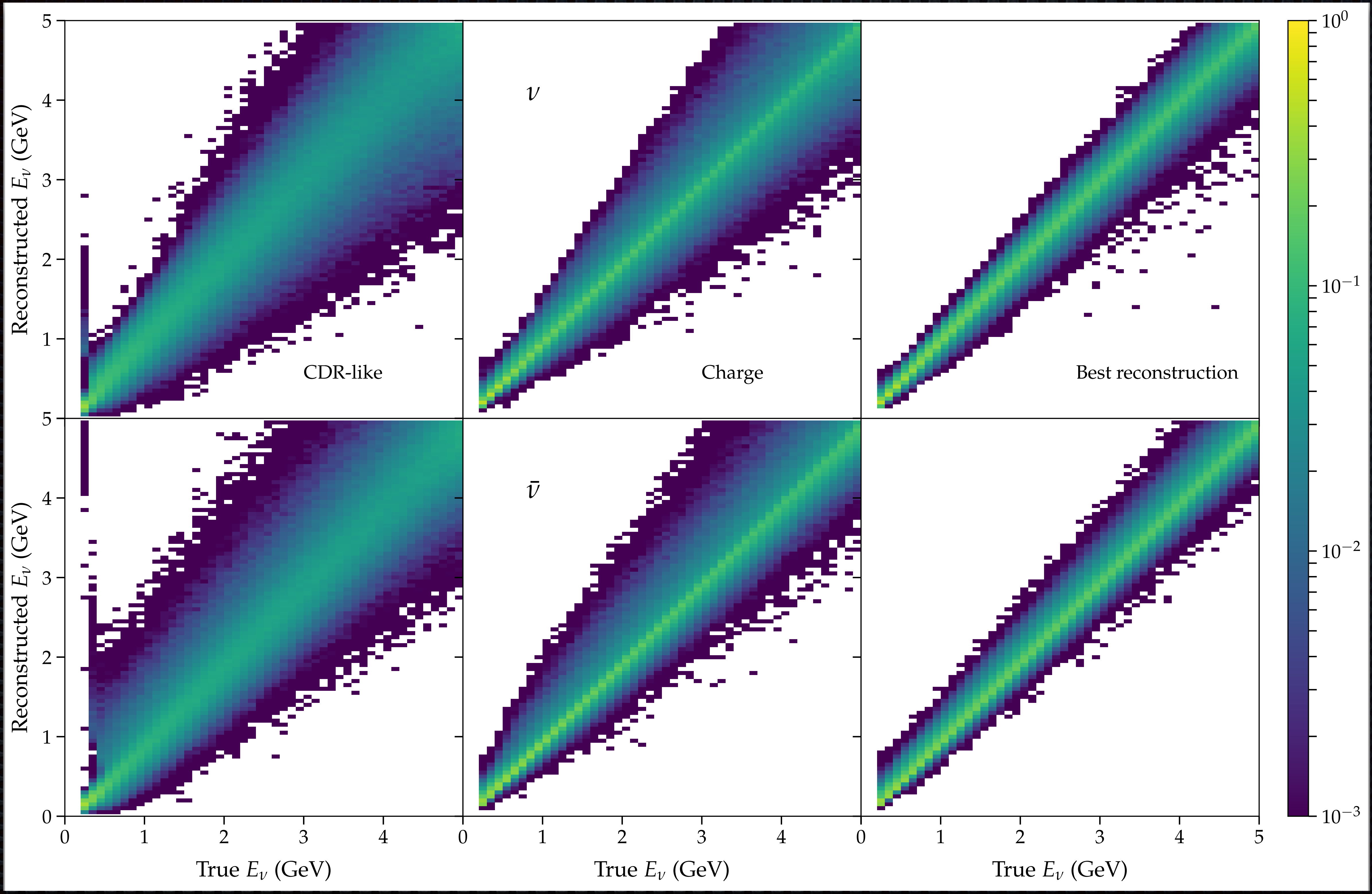
  1. CDR thresholds
  2. total charge calorimetry
  3. detailed event reconstruction (quenching corrections, low thresholds)



Shape of E_{rec}

- The histogram of reconstructed energy is not actually Gaussian
- This has a physical origin: a sub-class 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)

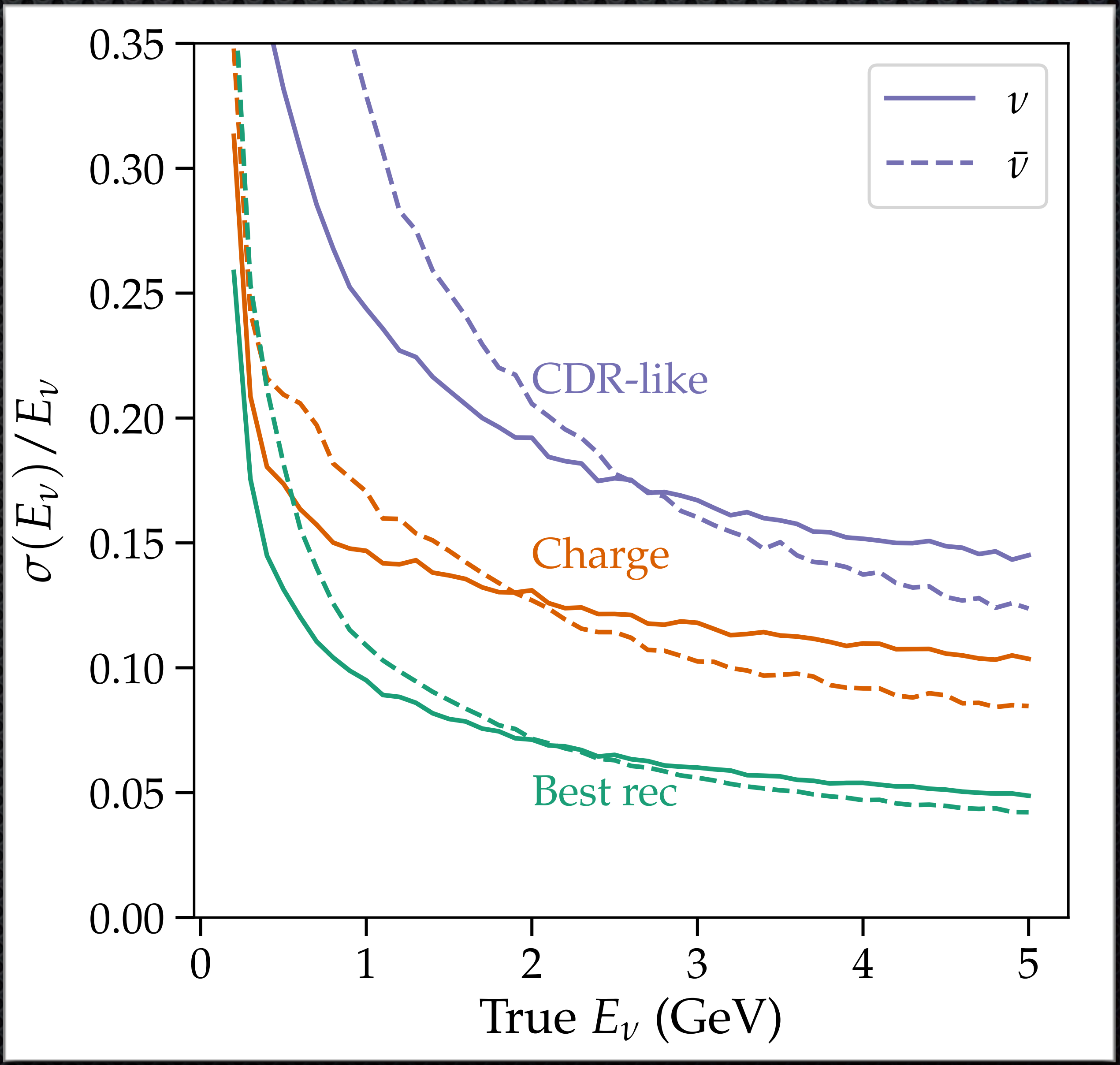




Migration matrices E_{true}<->E_{rec}

Resolution as a function of 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 ~ 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.

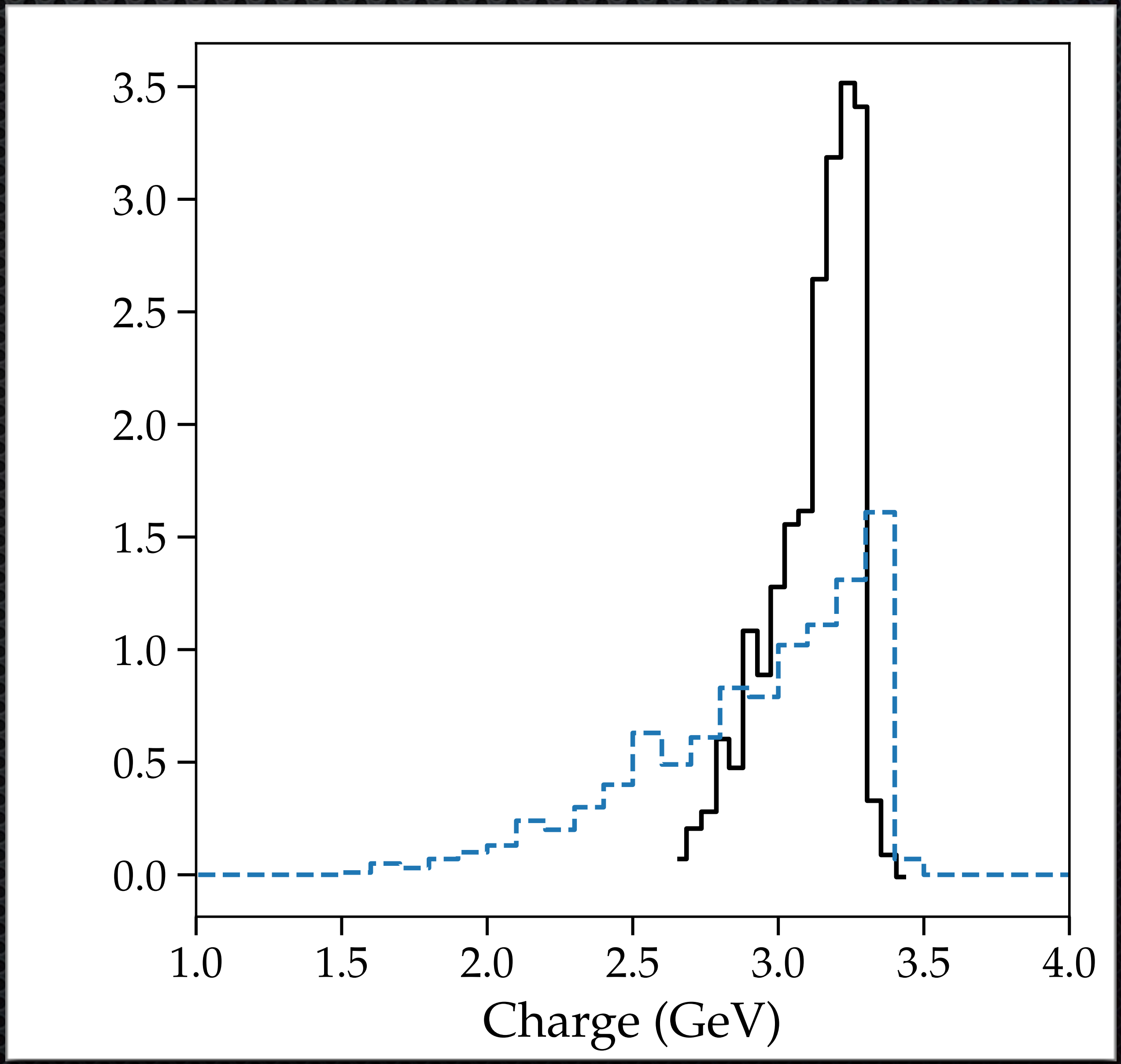
- Not all missing energy channels are created equal. Their impact on the resolution is not directly related to the size of the corresponding pie slice.
  - For example, EM showers make up a large part of the electron neutrino energy budget. Even at 0.1 MeV thresholds, one misses about 300 MeV out of 2 GeV. But they are very stable, the resolution is ~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%->6.5%
  - (demonstrated 50% efficiency at ArgoNeuT)
- If we cut at 3 MeV (demonstrated 50% efficiency at ArgoNeuT), the resolution becomes 6%->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% -> 8% (factor of 2)
  - Including the spray further improves the resolution by 25%

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.

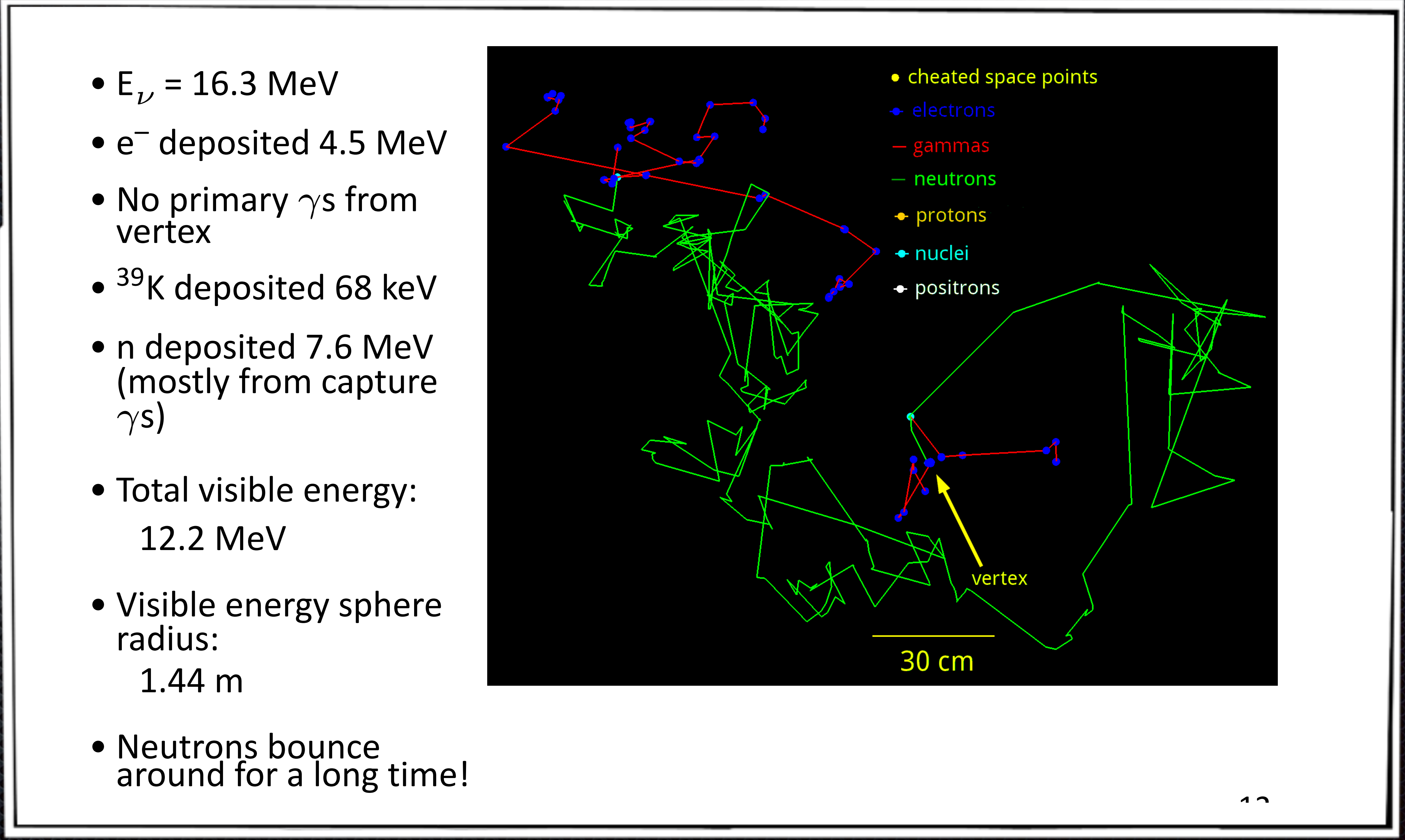


Outlook

- 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) -> Energy scale calibration uncertainties
- 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_ν = 16.3 MeV
- e^- deposited 4.5 MeV
- No primary γs from vertex
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- 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

Neutrons

- Distribution of neutron energies from 4 GeV neutrinos