Neutrino cross sections and energy reconstruction

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Precision neutrino experiments require accurate cross sections

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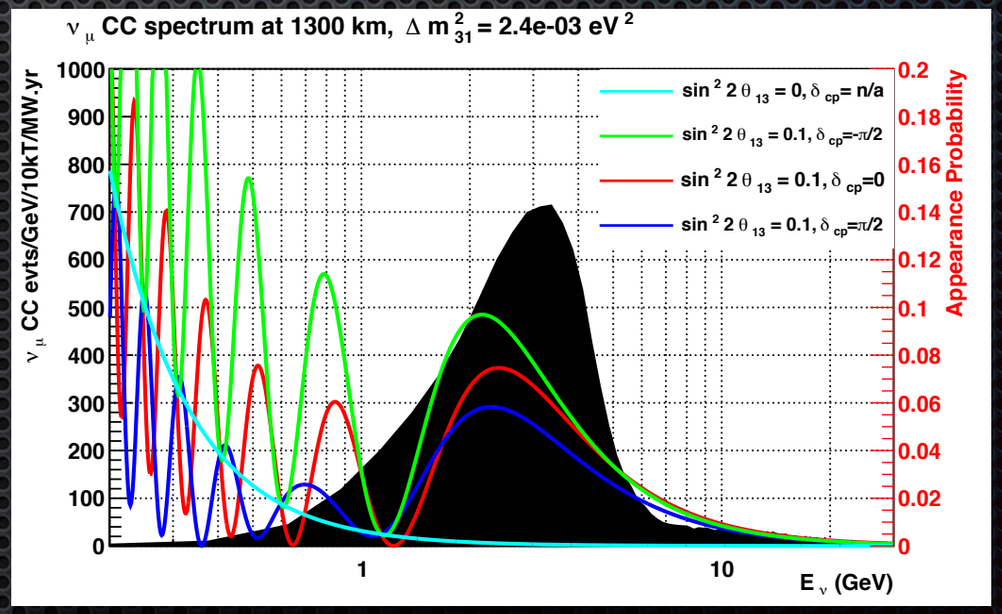
Still, is this really true? And why?

Basic observations

- We are trying to measure conversion/survival probabilities for neutrinos $P(\nu_i \to \nu_j)$ and antineutrinos $P(\bar{\nu}_i \to \bar{\nu}_j)$ w/ high precision
- OK: measure the event rates in near and far detectors and take a ratio.
- Use the same target.
- Simple, no cross sections?

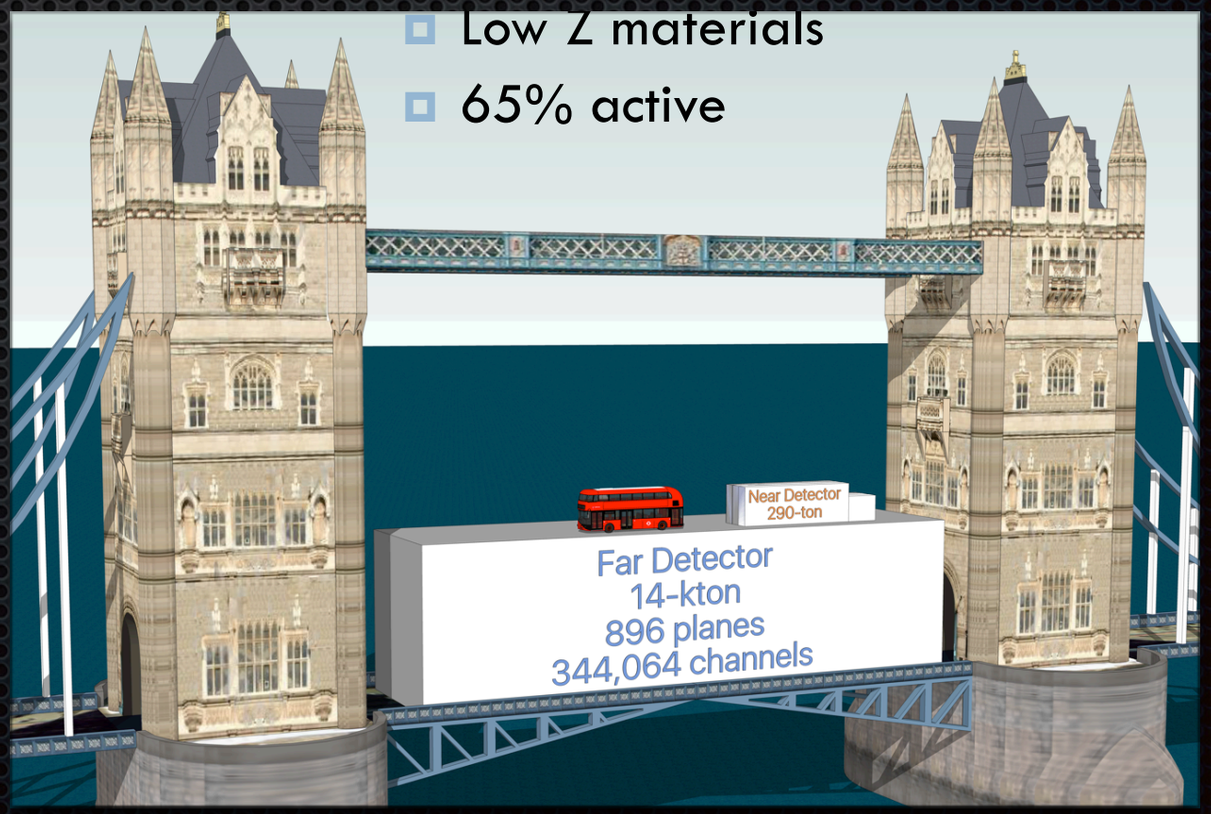
Oscillation probabilities are functions of neutrino energy

- For example, the location of the oscillation features (dips) tell us about the values of Δm^2.
- The depth of the dips tells us about the mixing angles.
- Unlike electron beams, neutrino beams are not monochromatic (in fact pretty broad)

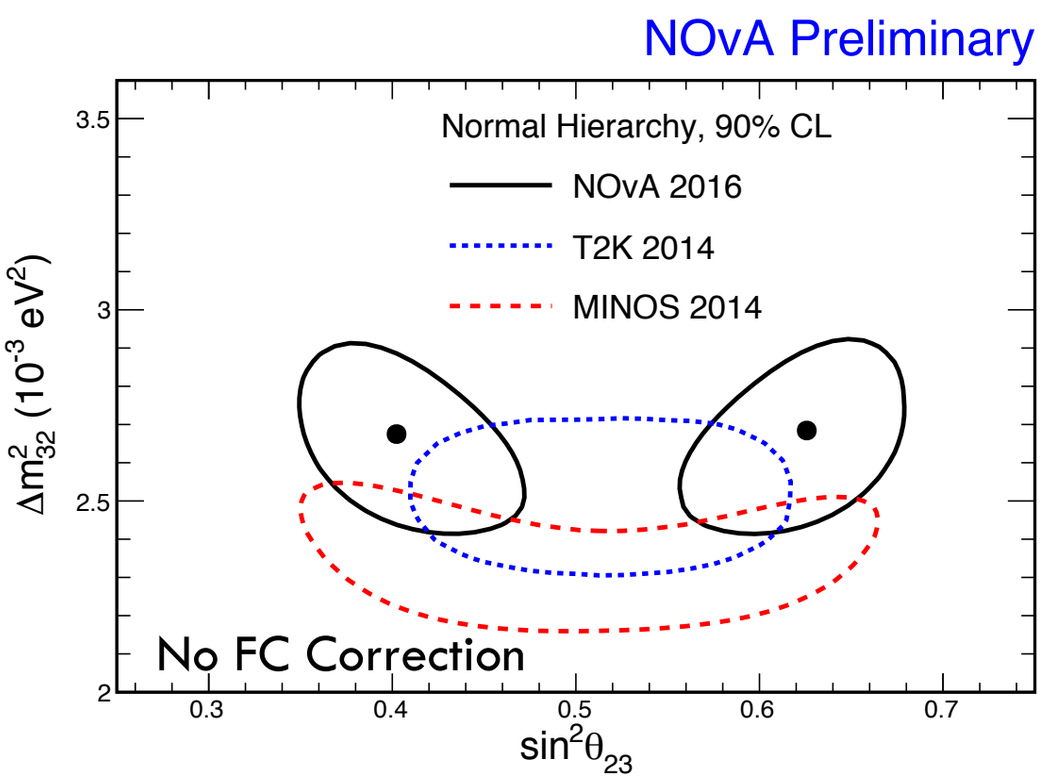


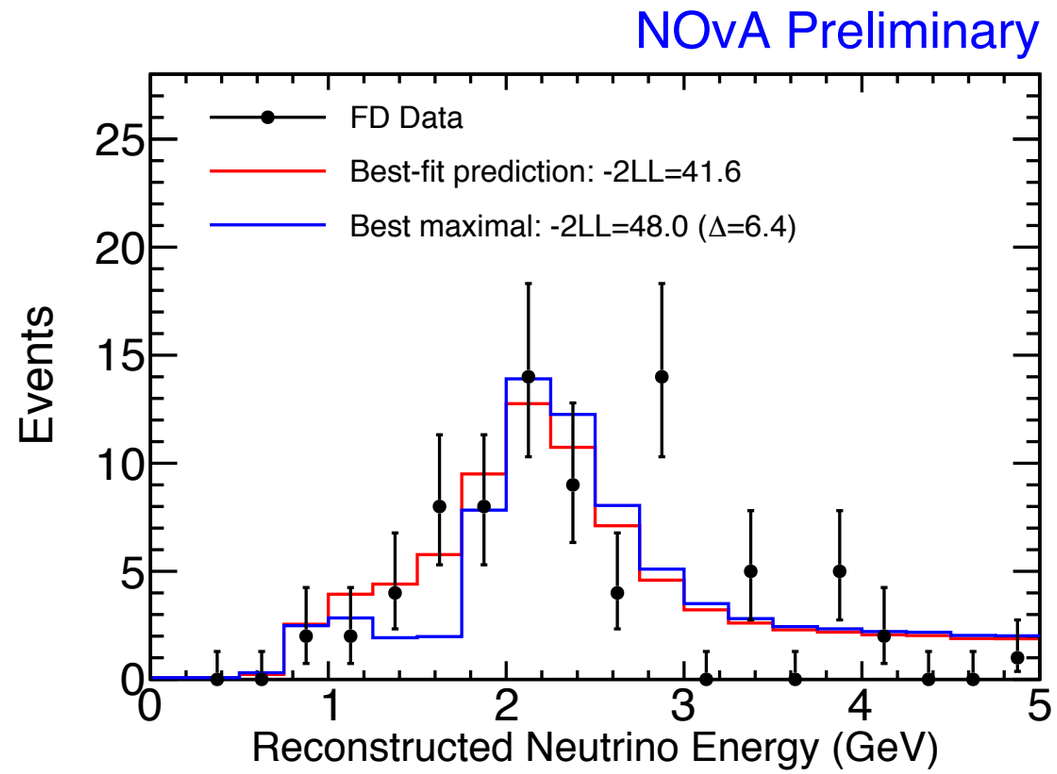
This is so even for the so-called “narrow” beams

- Consider NOvA (FNAL to Northern Minnesota, 810 km baseline)
- Good sensitivity to the “atmospheric” parameters (θ_{23} and Δm^2_{23})



NOvA at Neutrino 2016





Best Fit (in NH):

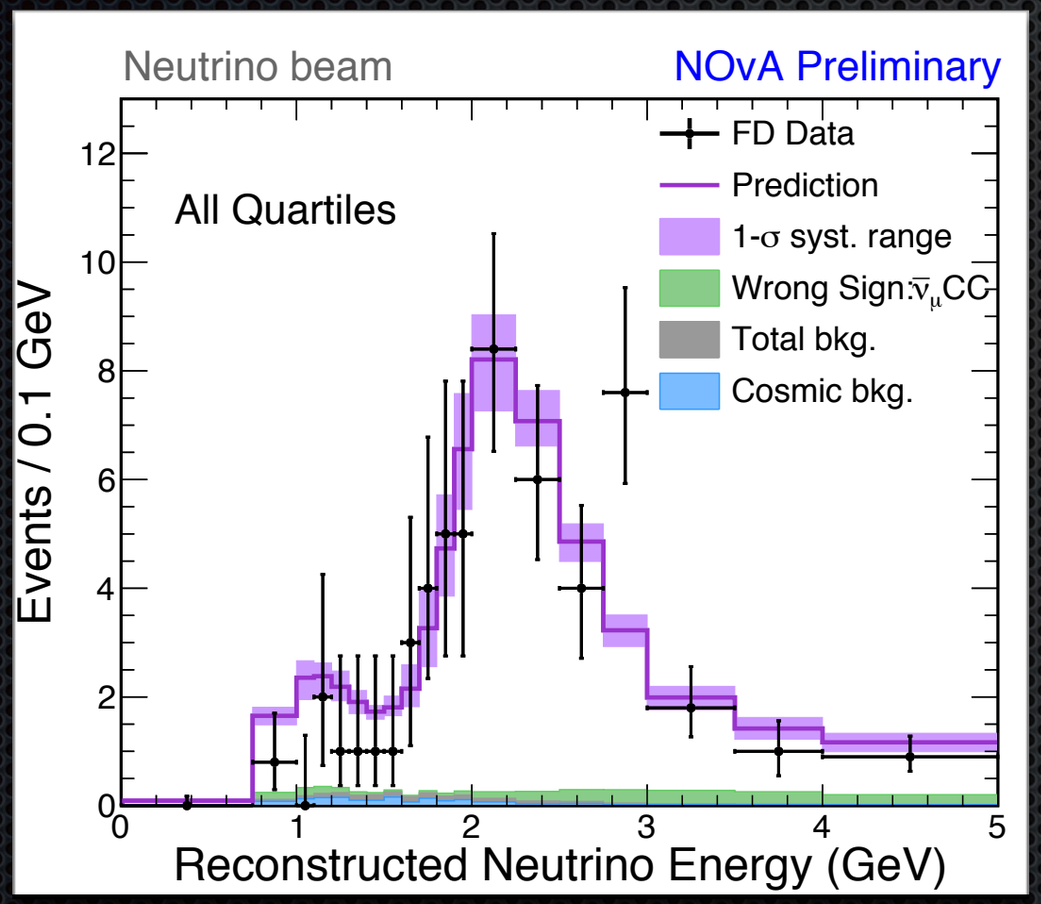
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

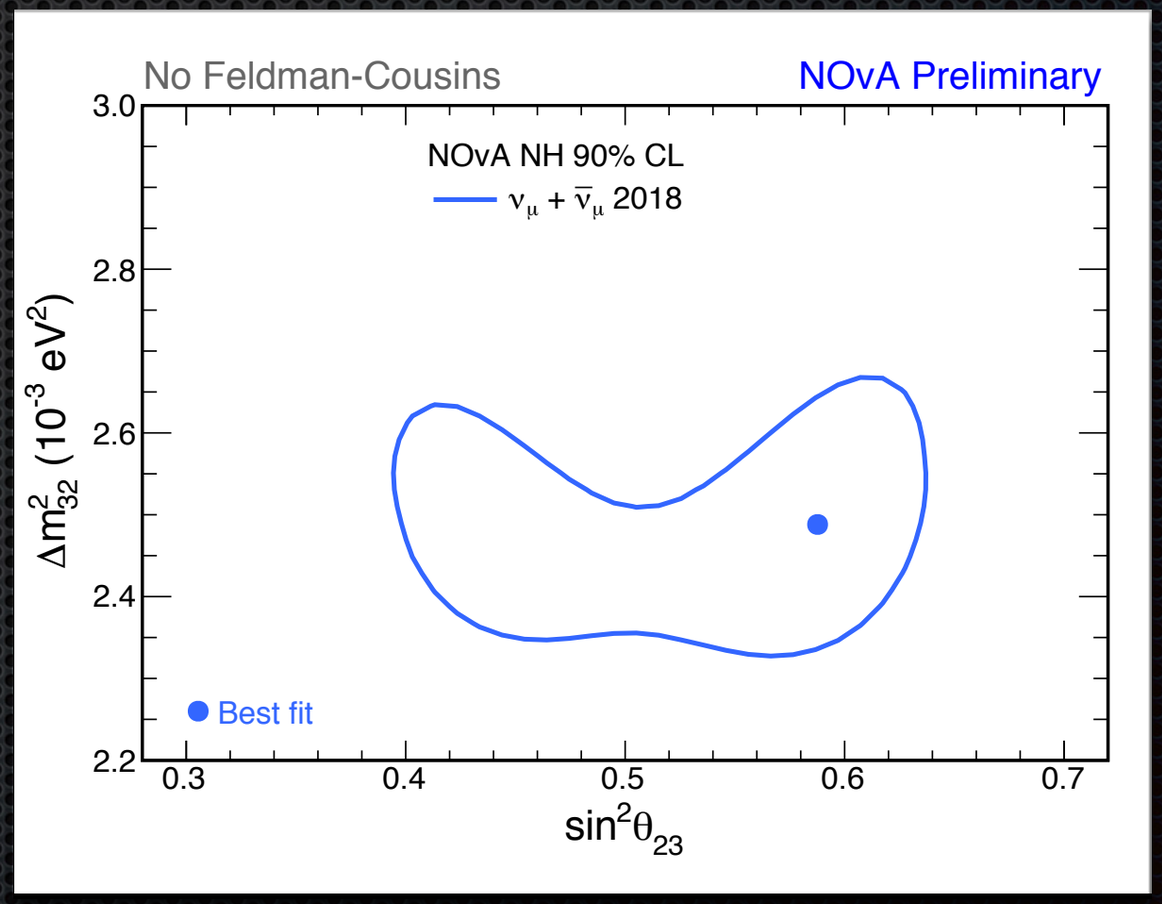
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

NOvA at Neutrino 2018

Refined energy reconstruction

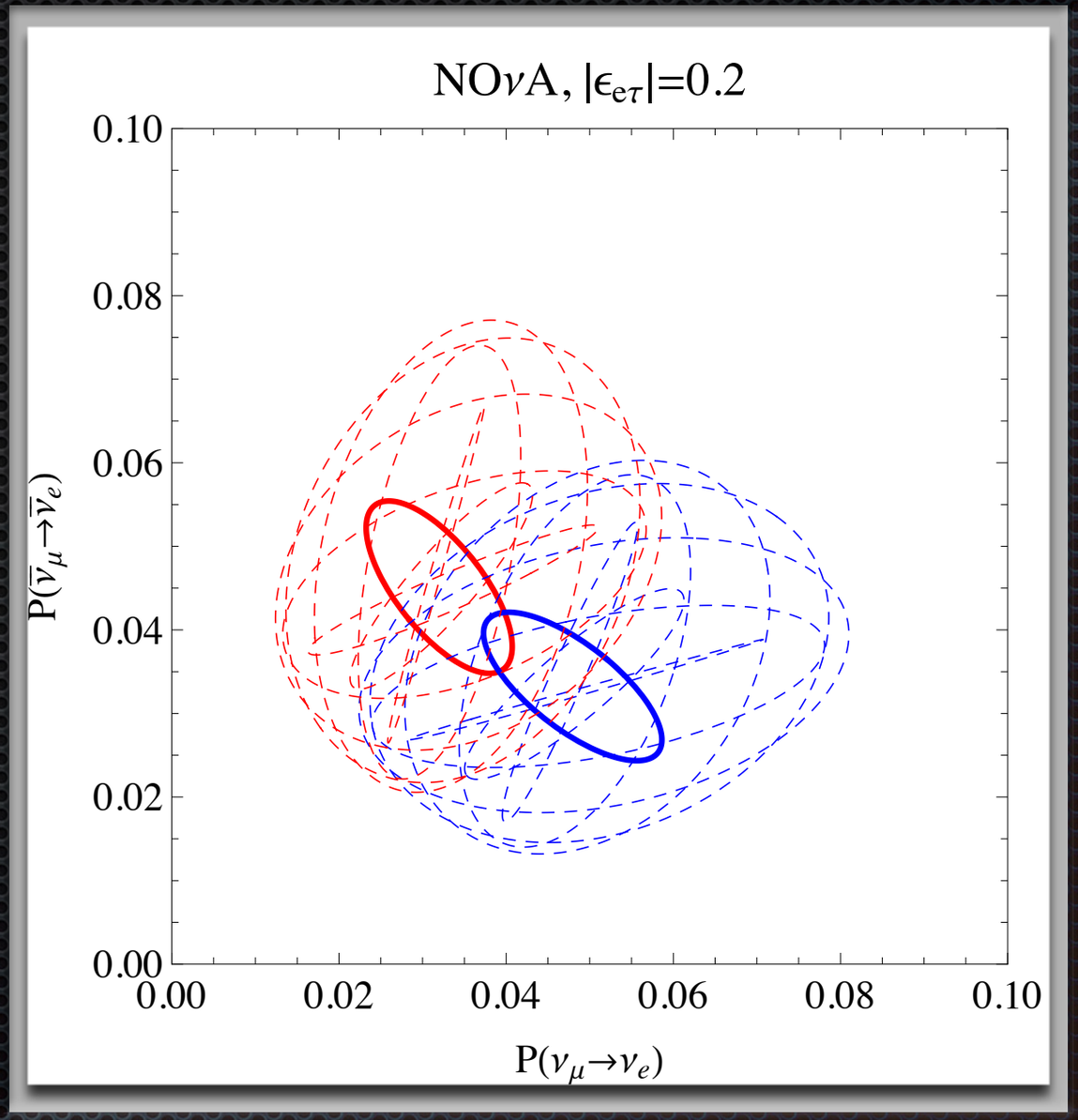




- Maximal mixing is no longer strongly disfavored

Even more critical when going beyond the minimal paradigm

- New physics can confuse parameter extraction, introduce degeneracies
- The solution is to map out oscillation probability as a function of energy.
- To search for this, we must have good energy resolution



A.F., I. Shoemaker, arXiv:1207.6642

Thus the crucial link is the measurement of energy

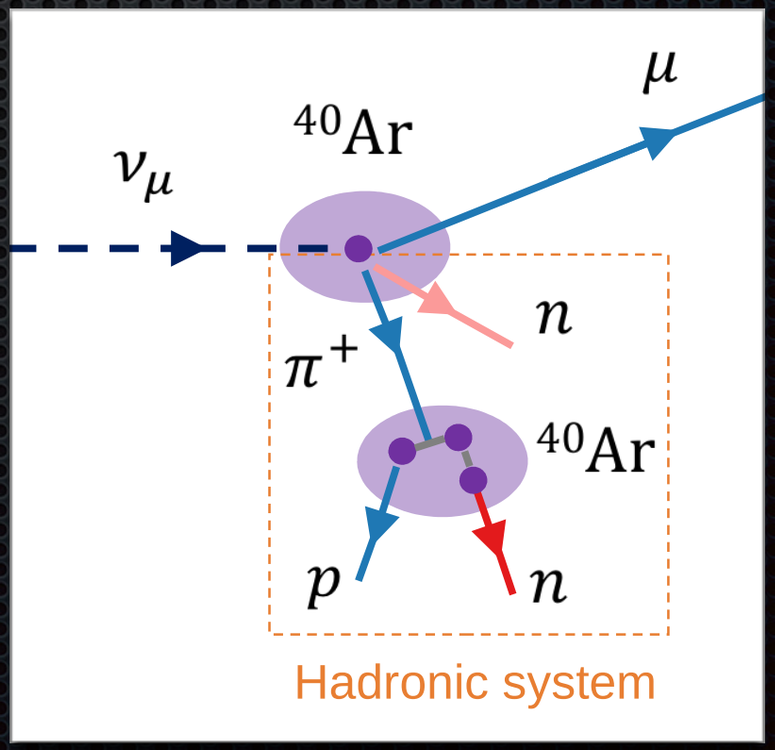
- Assume we have excellent near and far detectors, which can both measure neutrino energies well. Then we (mostly) don't need cross section physics.
- Oscillation papers as the main product
- Neutrino cross section information as a by-product.
- One-way information flow: from experiment to cross section models.
- For the oscillation studies, one could crudely assign the difference between observed and modeled cross sections to some process. Say, call it "tuning 2p2h". This may have little to do with the actual, physical 2p2h rate.

So why again do we need cross section models?

- The question is actually more interesting than it sounds
  - We need them to measure neutrino energy
- Experiments do not have a direct way to measure energy precisely
- The cross section model is then needed to improve this measurement
  - by filling in the missing information

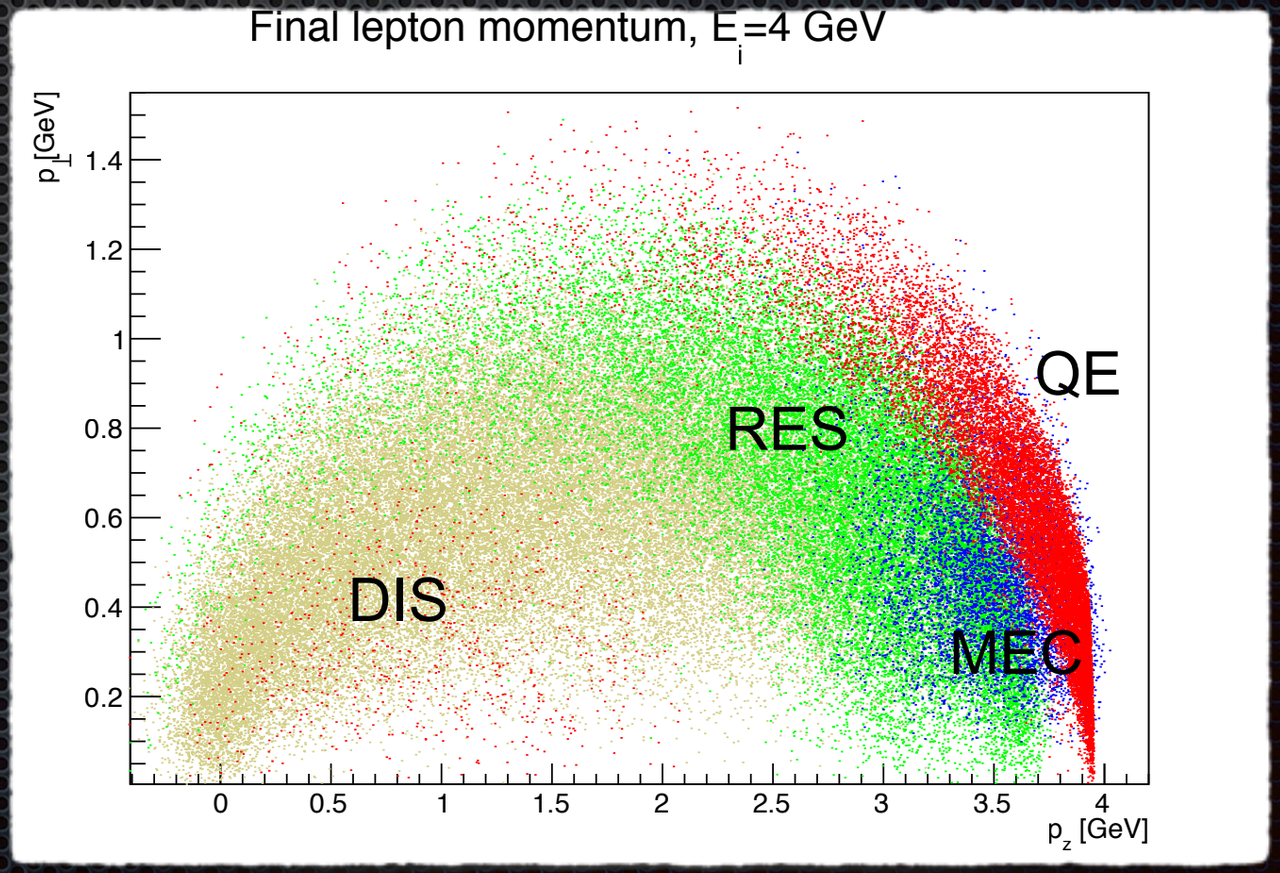
Measuring neutrino energy

- CC interactions create a charged lepton + some hadrons in the final state.
- The most direct way is to measure the energies of all these particles and add them up. Calorimetry.
- This is how NOvA and DUNE work and this will be our focus here.
- NOvA and DUNE are not perfect calorimeters. Have missing energy channels.



Digression: Can't we use only the charged lepton?

- "kinematic method": use energy and angle of the final-state lepton + energy-momentum conservation
- Neglects Fermi motion of the struck nucleon
- Works only when the invariant mass of the hadronic system is known (e.g., QE)
- DUNE operates at energies of several GeV, where one has a variety of possible hadronic final states



Prerequisite: missing energy and resolution

- This turns out to be a very interesting physics problem in its own right. Broad implications for the performance of the experiment beyond cross section uncertainties.
- At first, we wanted to make use of published results on this. However, the literature turns out to be incomplete, confusing, and even contradictory, both on the missing energy and on energy resolution. Hence, we ended up simulating the problem from scratch.

Rules of the game

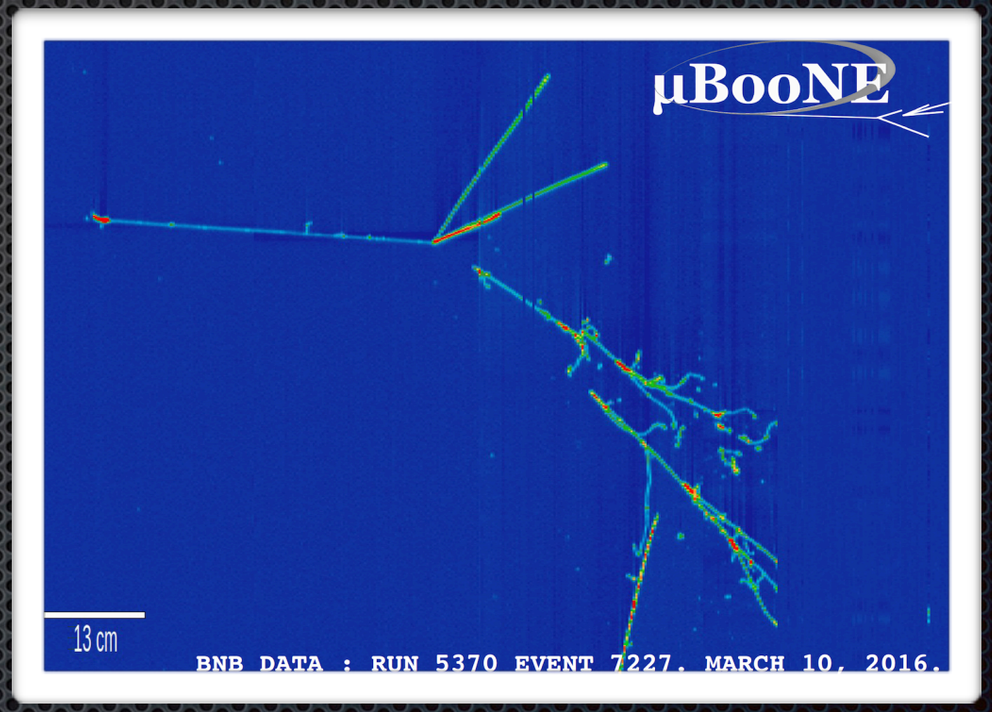
- We do not use any internal proprietary DUNE tools
- Our simulation framework is based on combining GENIE (version 2.12.8) for primary interactions and FLUKA (version 2011.2x.2) for event propagation in LAr
  - GENIE is the event generator used by all Fermilab experiments
  - FLUKA has a solid reputation, 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 (arXiv:1811.06159, PRD 2019)

Basic findings

- Energy reconstruction strongly depends on the detector performance and analysis strategy. Depending on assumptions, the energy resolution of DUNE can vary by as much as a factor of 3.
- The first key step is to identify the missing energy channels:
  - subthreshold particles,
  - charge recombination,
  - neutrinos created in pion/muon decays,
  - energy lost to nuclear breakup.

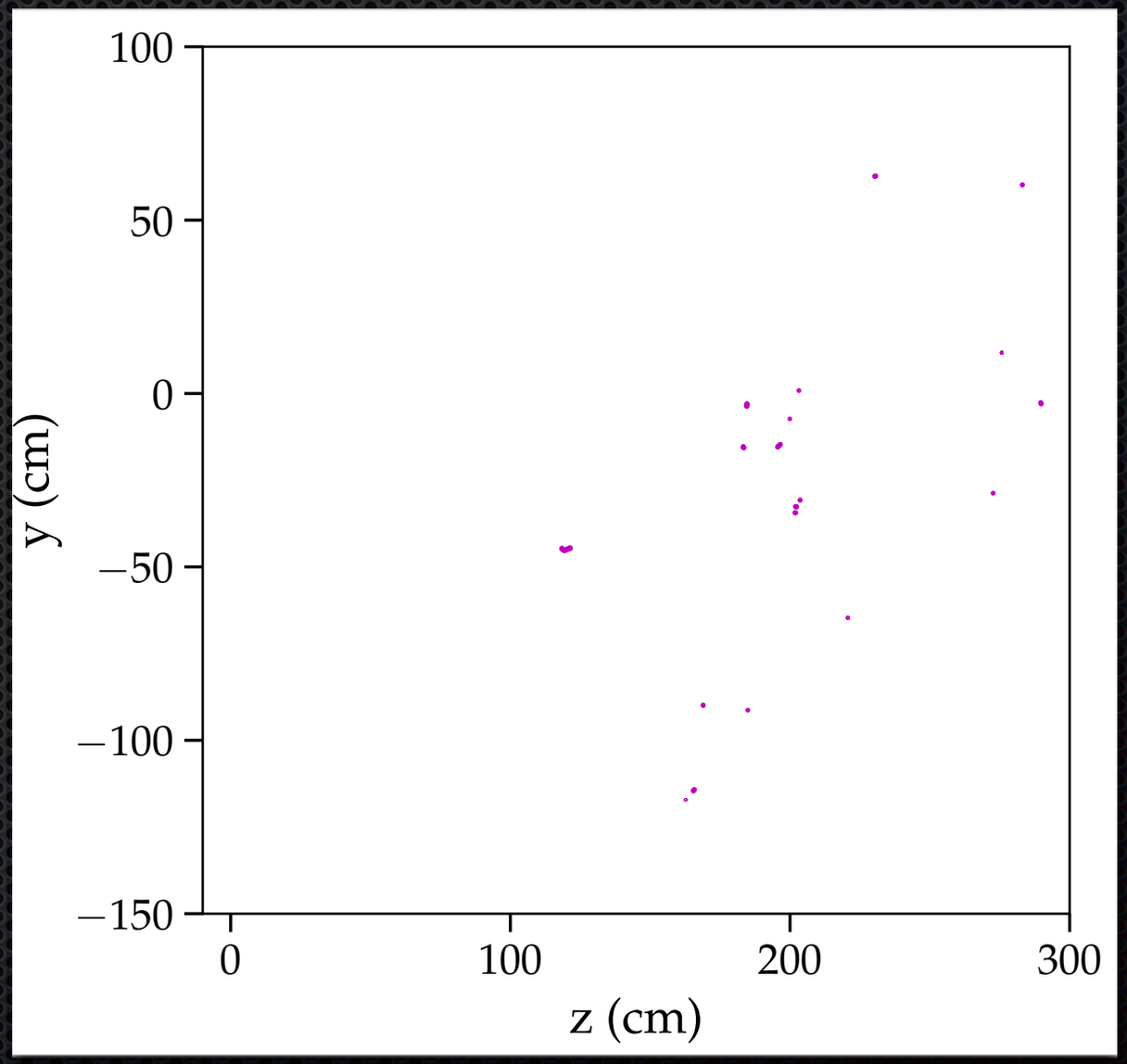
Missing energy crucially depends on the composition of the final-state hadronic system

- Electromagnetic showers have many tracks and charge blips. The latter are from gammas Compton scattering. Different charge/energy conversion compared to a charged pion track.
- Protons vs charged pions have different charge density along their tracks. This means different charge recombination. The efficiency of calorimetry is tied to the efficiency of particle-ID



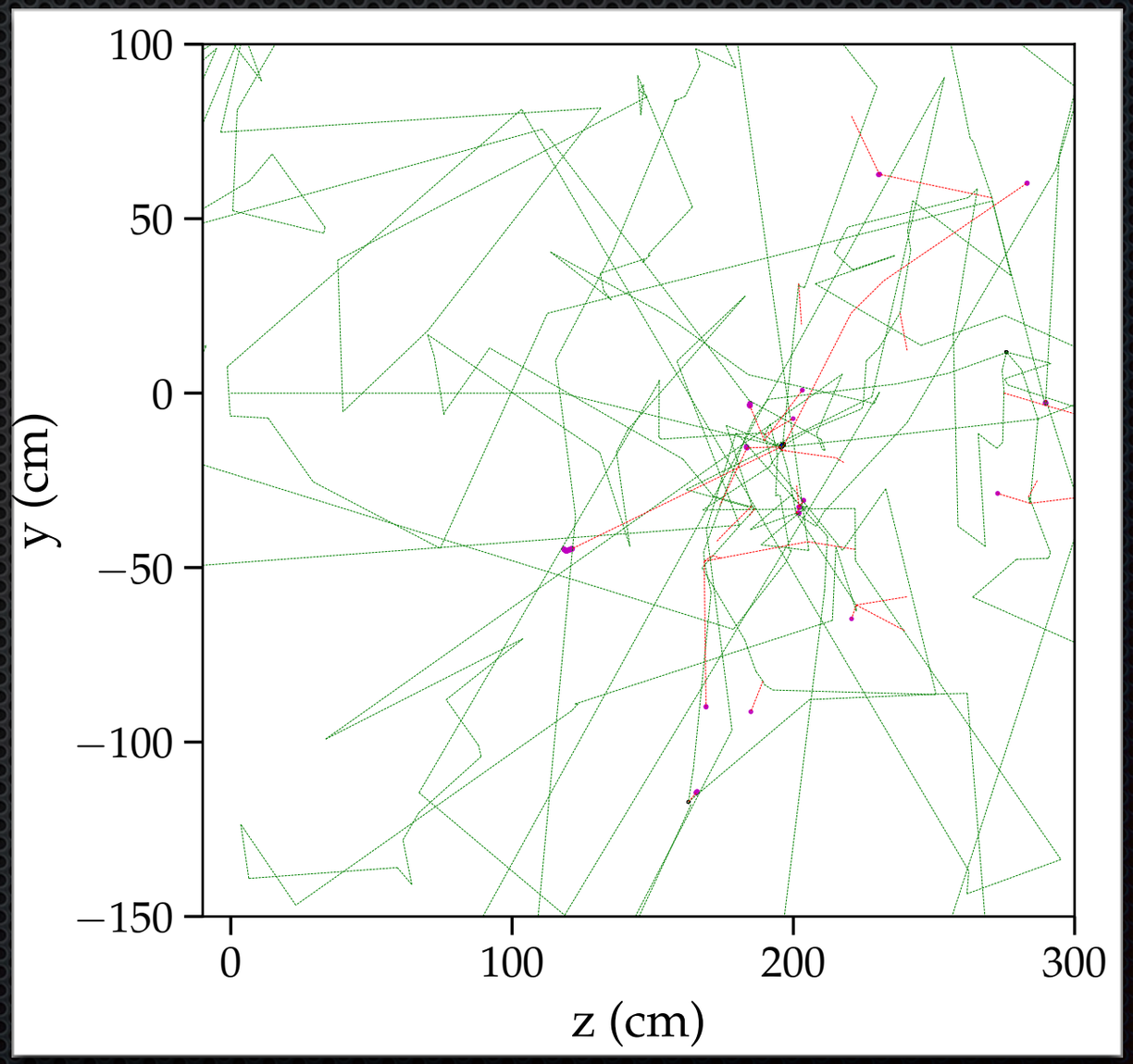
Neutrons

- 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”



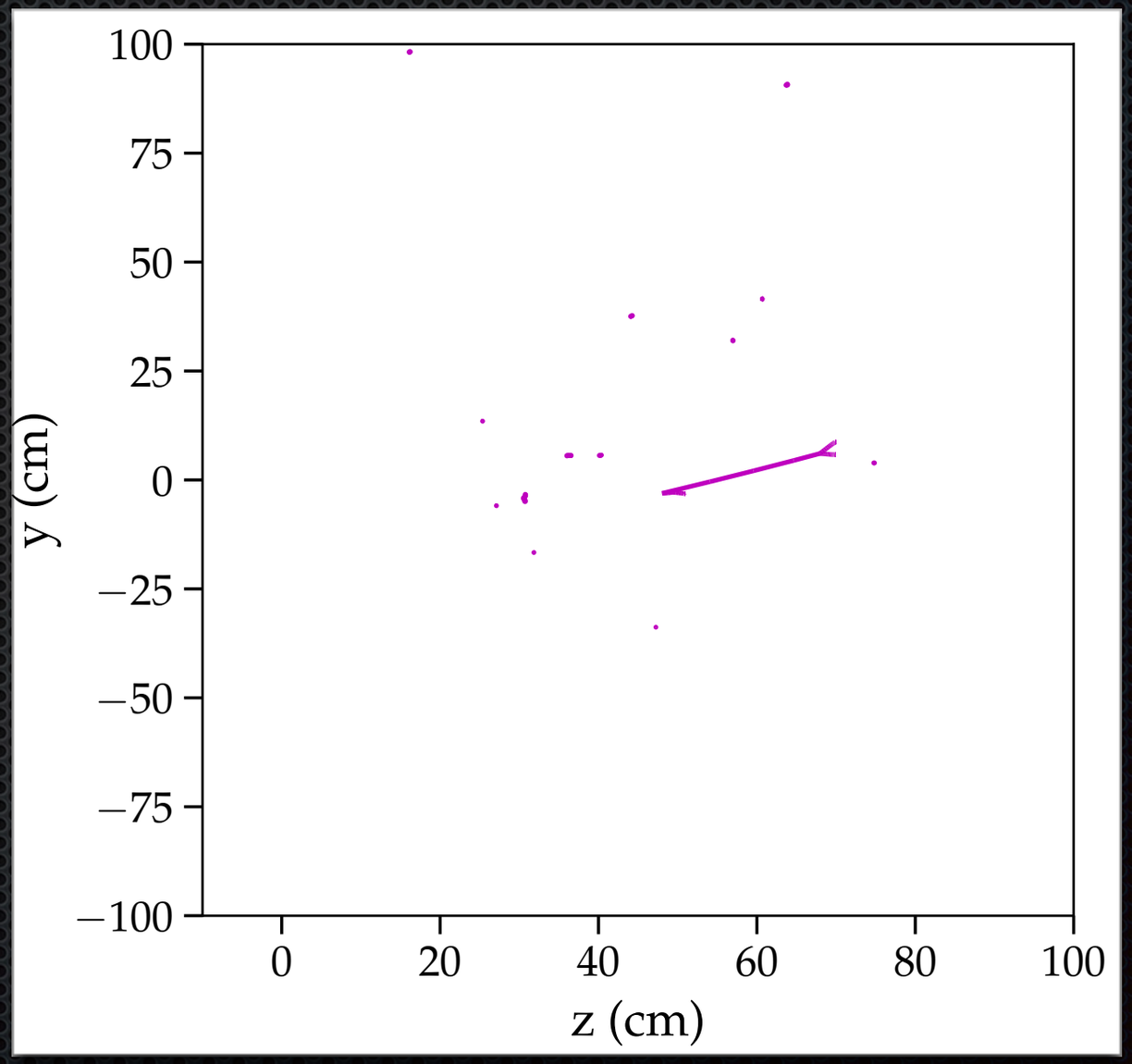
Neutrons

- 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!



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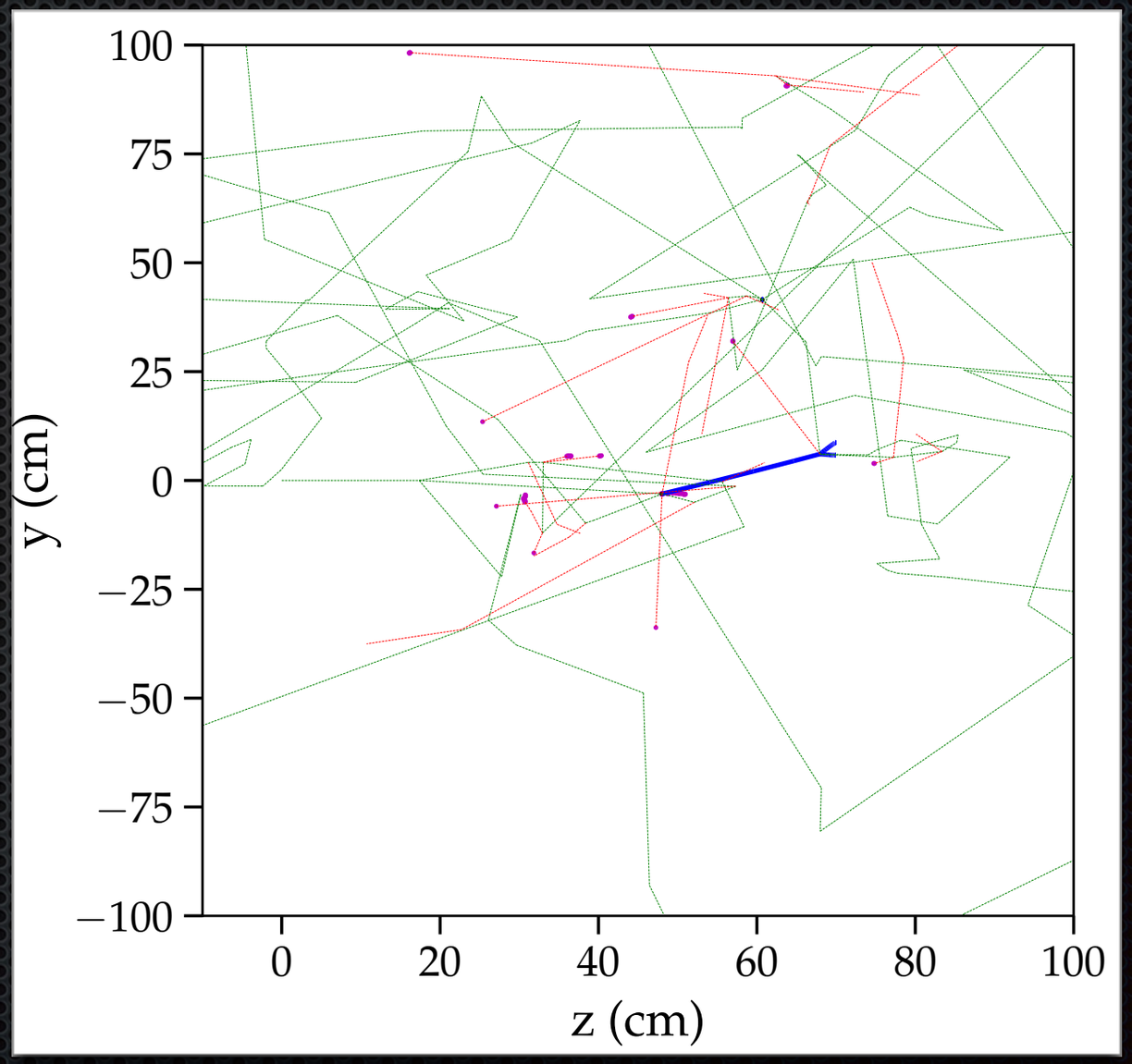
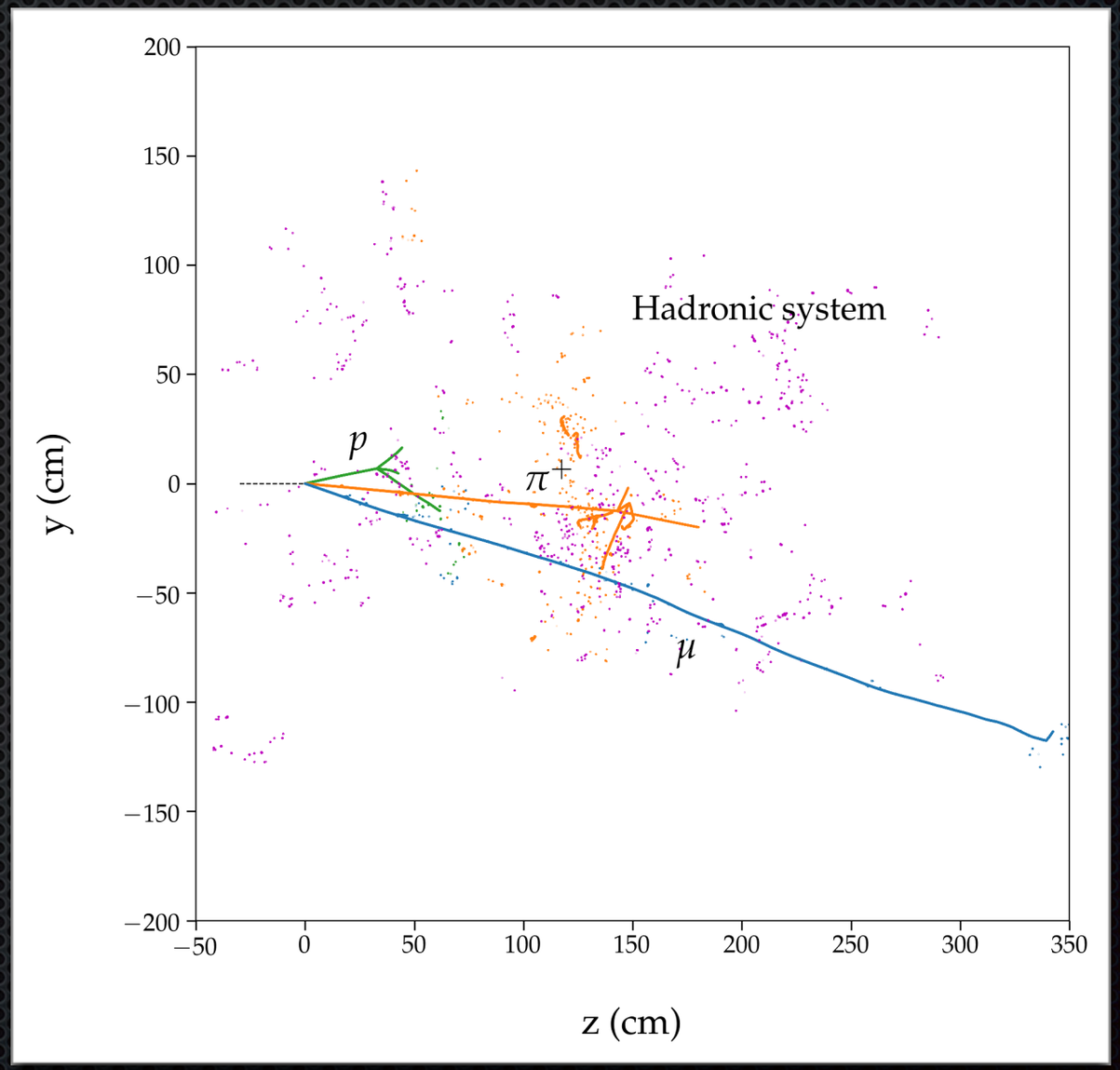


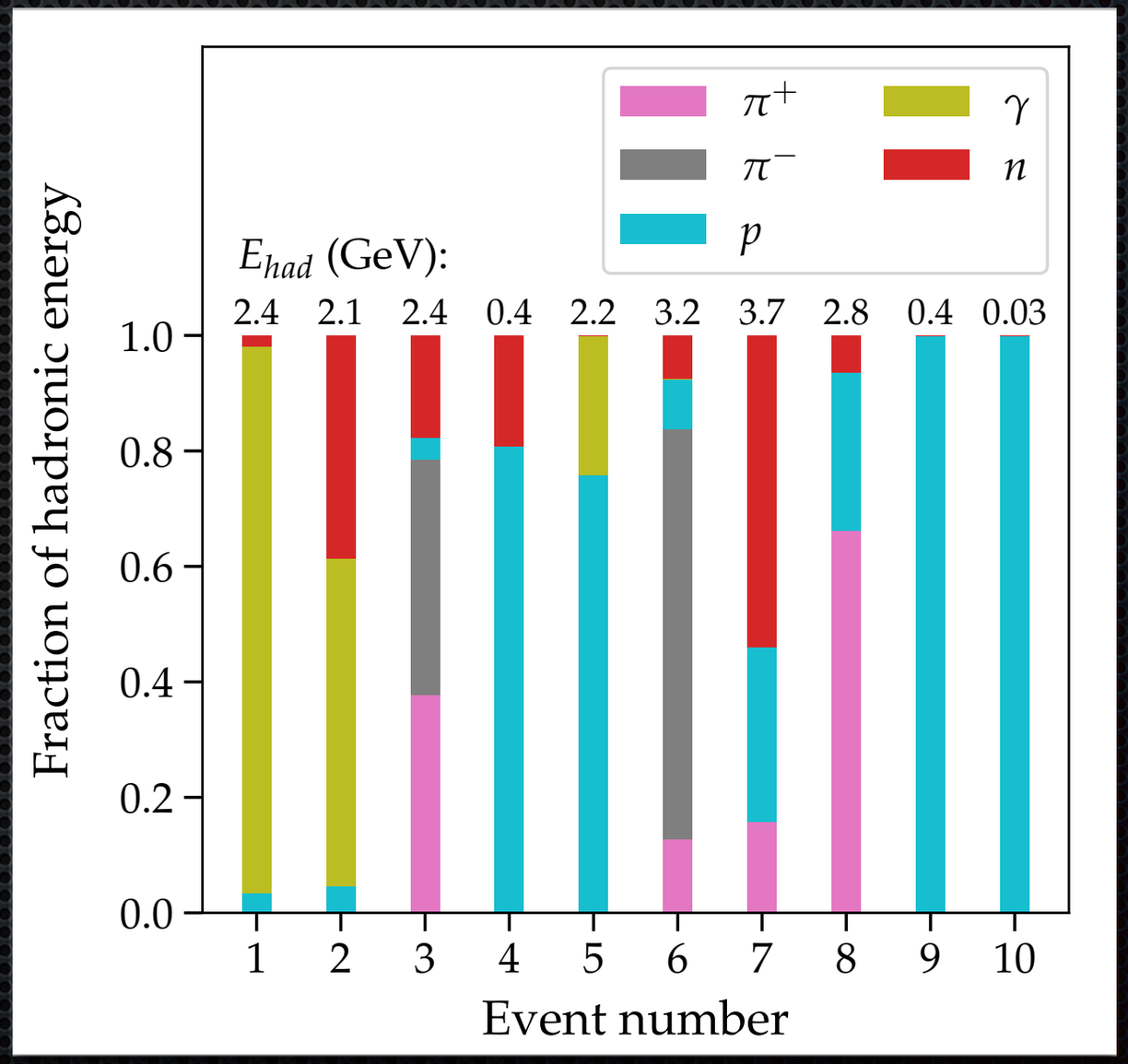
Example event at DUNE, from our simulations

- 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.



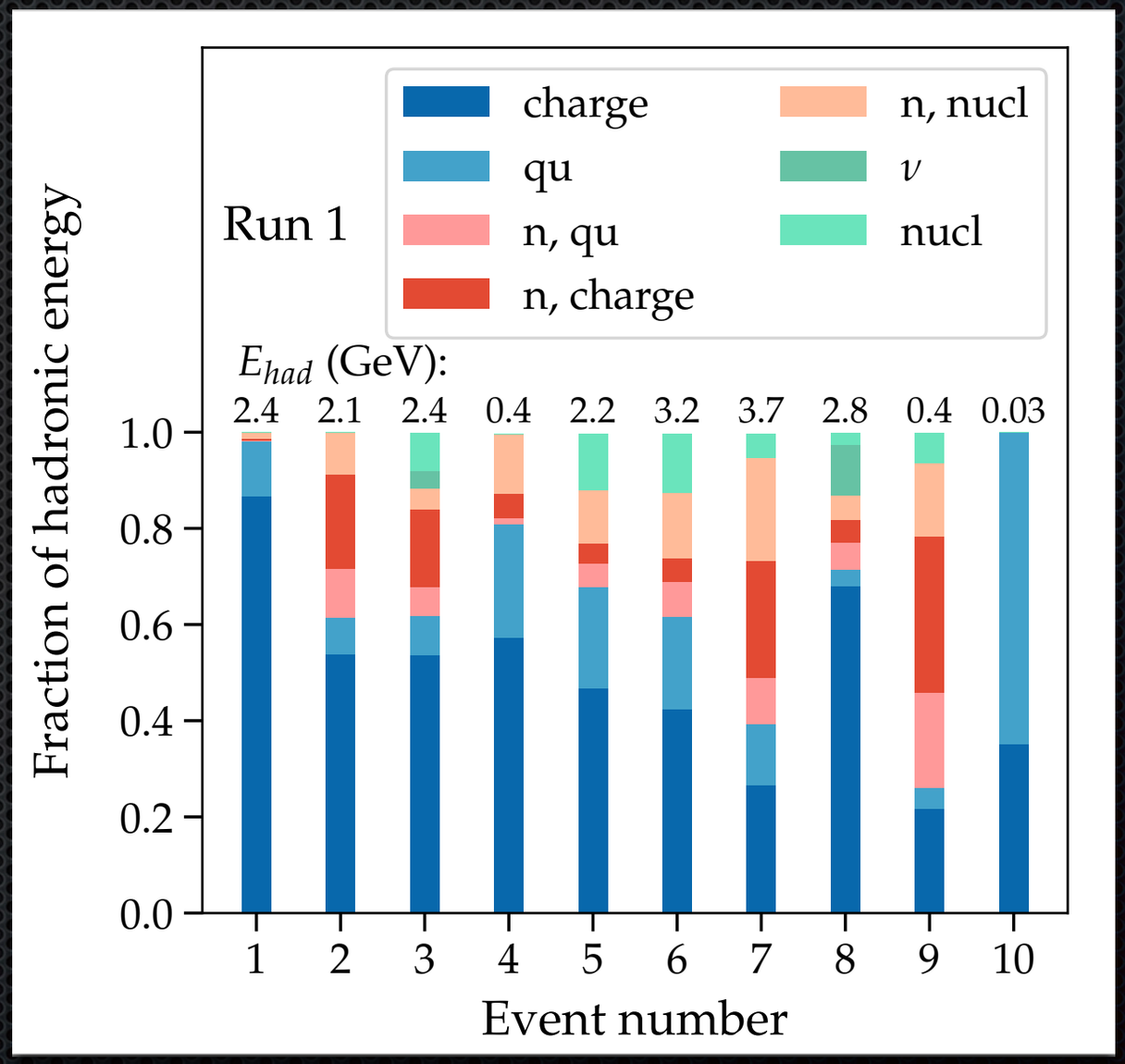
Event composition: prompt particles

- For illustration, let's look at the first 10 events of the simulation



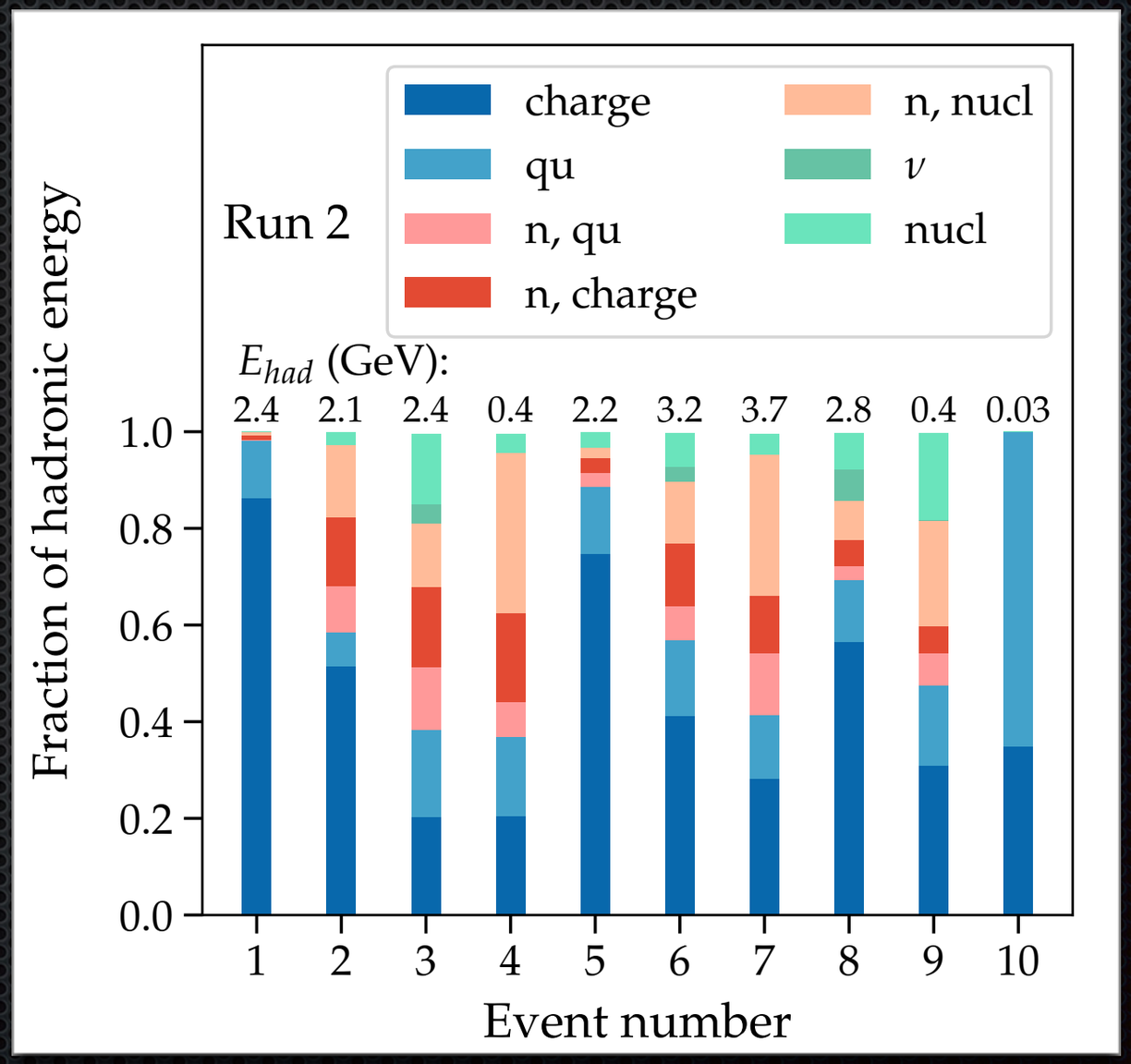
Simulating energy flow

- Now let's run these 10 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!



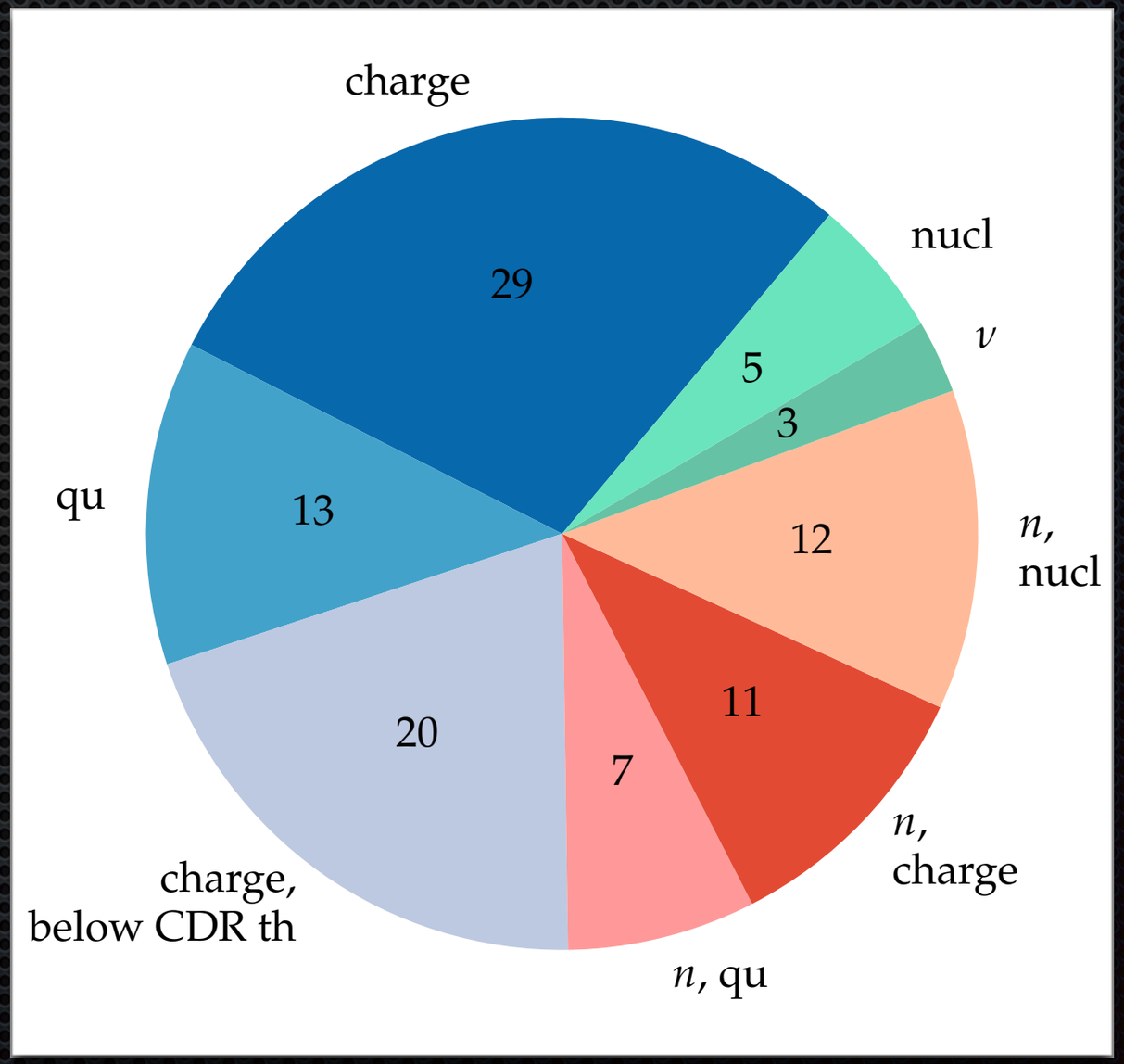
Missing energy budget full event

$E_\nu = 4\,GeV$

- 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

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

- Neutrons are separated in their own subcategories



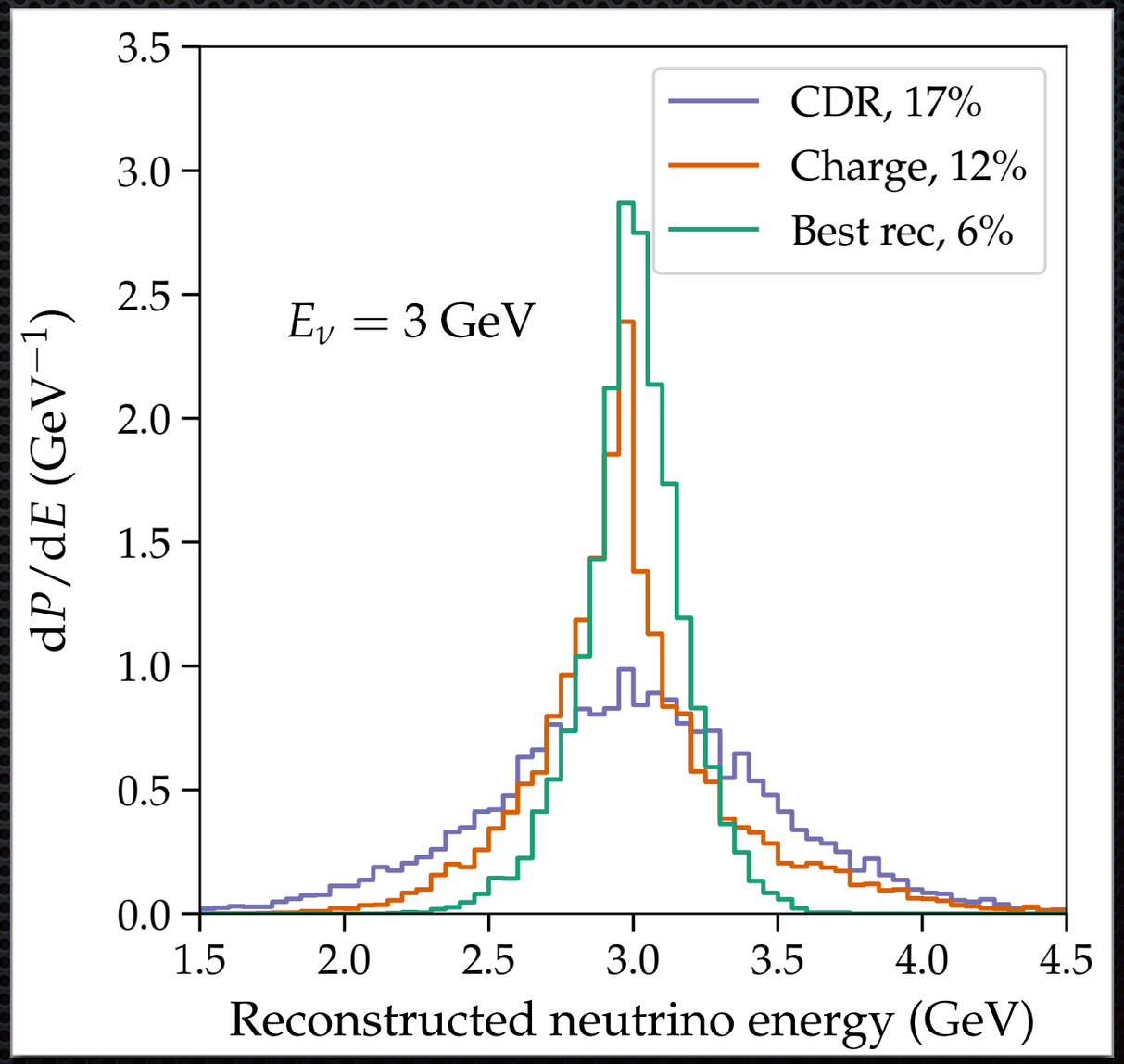
From missing energy to resolution

- With all channels well characterized, one can work backwards and reconstruct the true energy.
  - Divide observed charges by the expected visible fraction
  - The procedure works only on average, but events are inherently stochastic. Hence the inferred true value will fluctuate.

Energy reconstruction 3 GeV neutrino

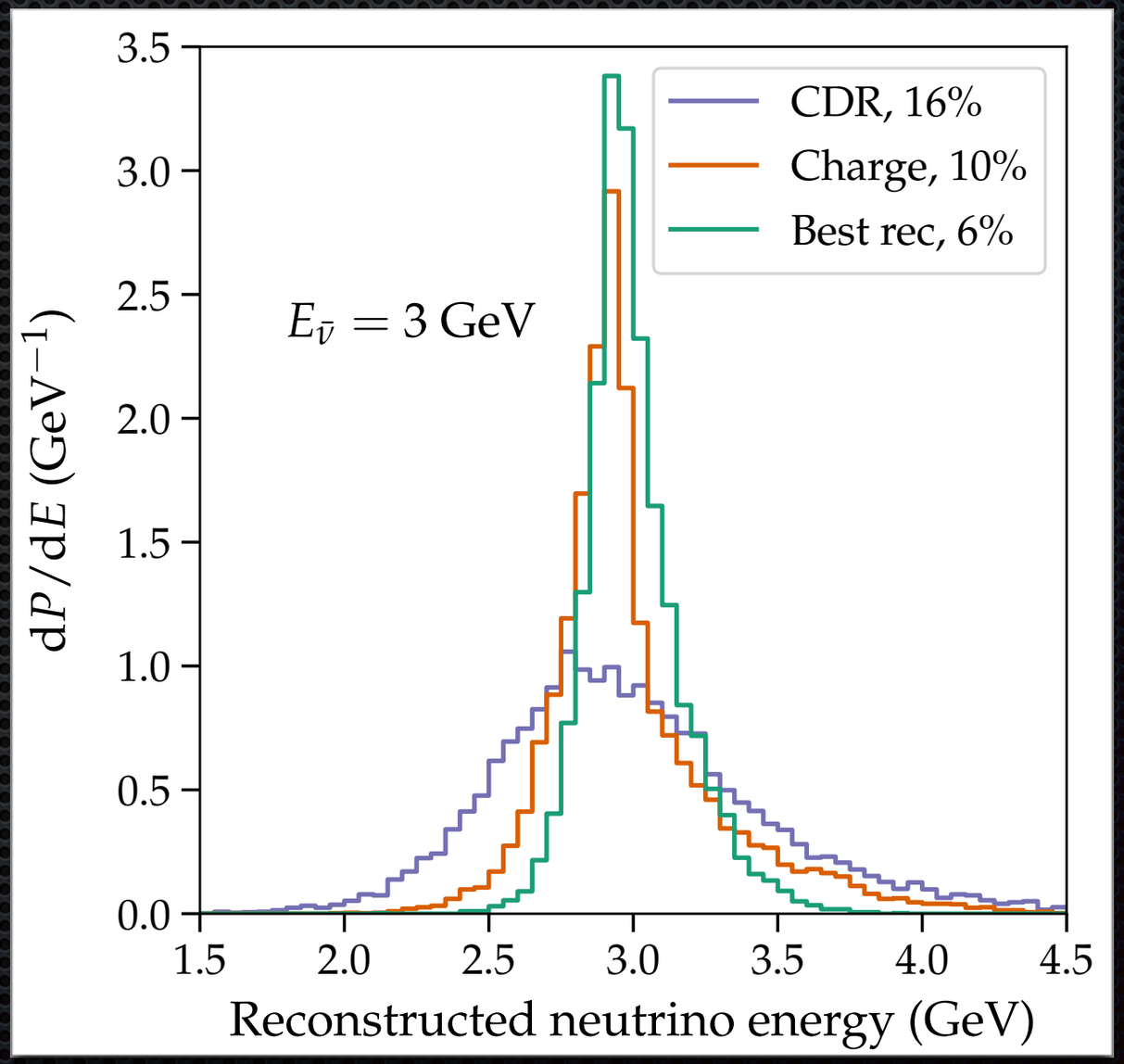
- Applied the reconstruction procedure in three scenarios:

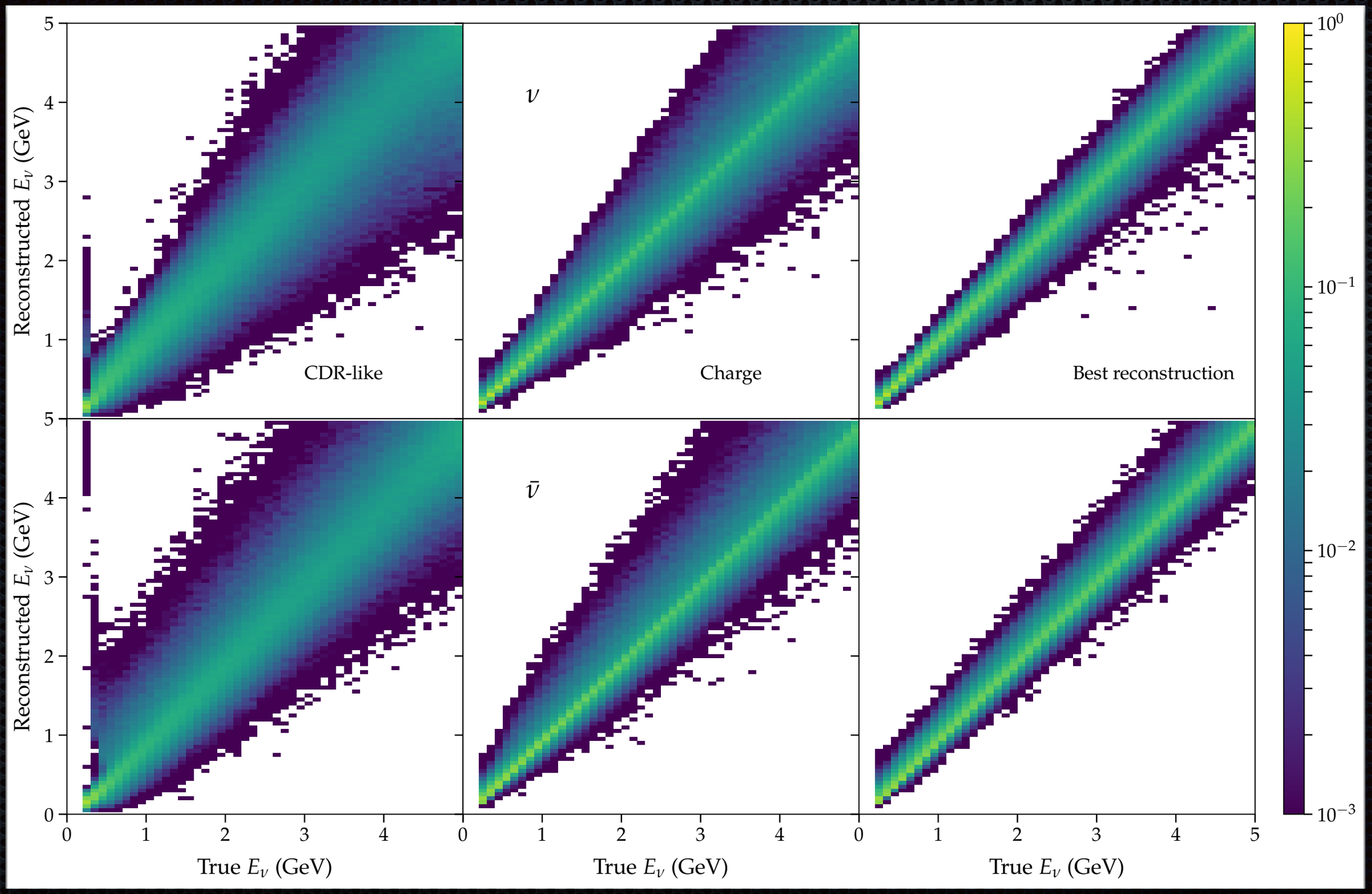
1. CDR thresholds
2. total charge calorimetry
3. detailed event reconstruction (particle ID corrections, low thresholds)



Energy reconstruction 3 GeV antineutrino

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

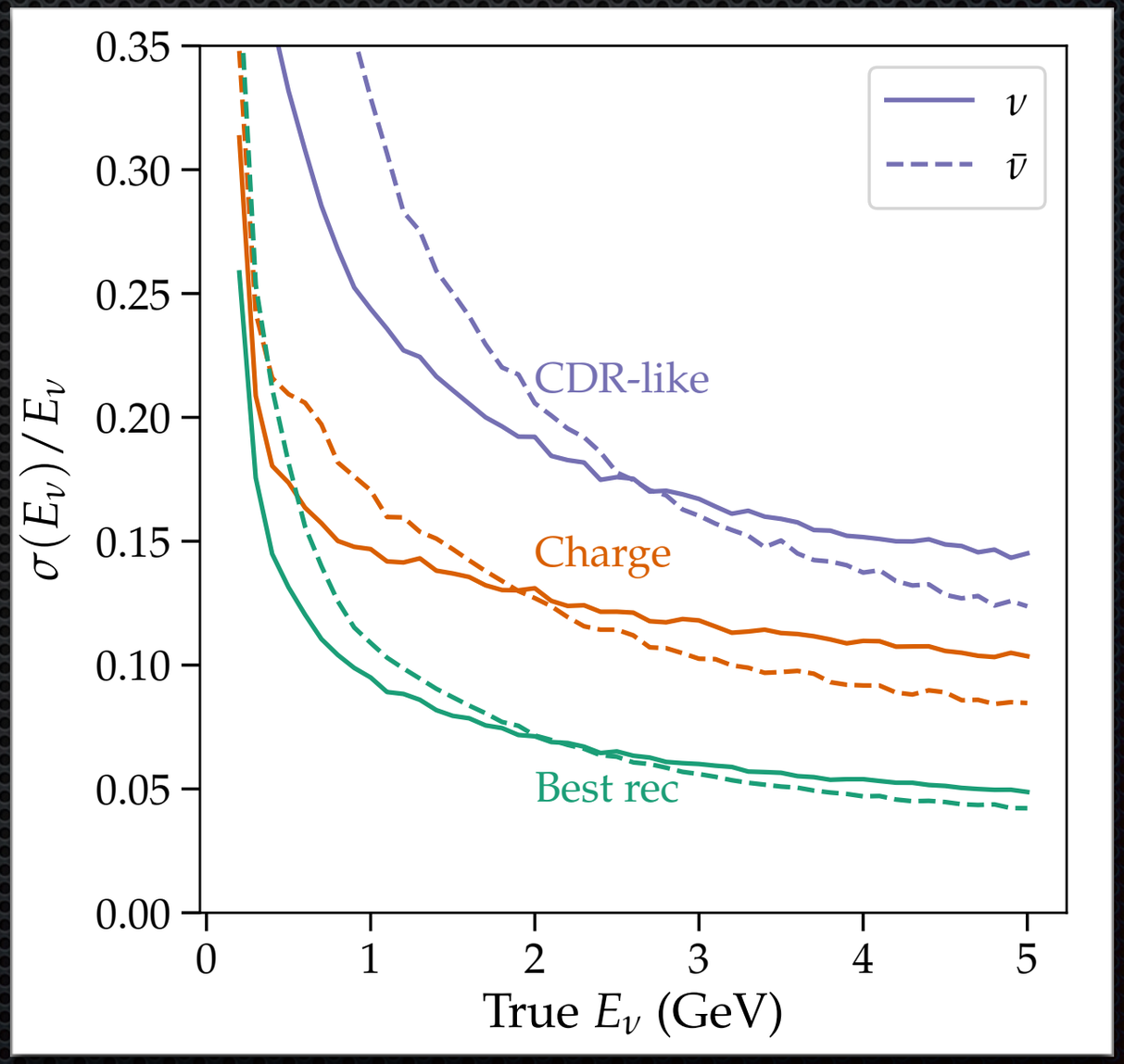




Migration matrices E_{true}<->E_{rec}

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 ~ 2 GeV, neutrinos below



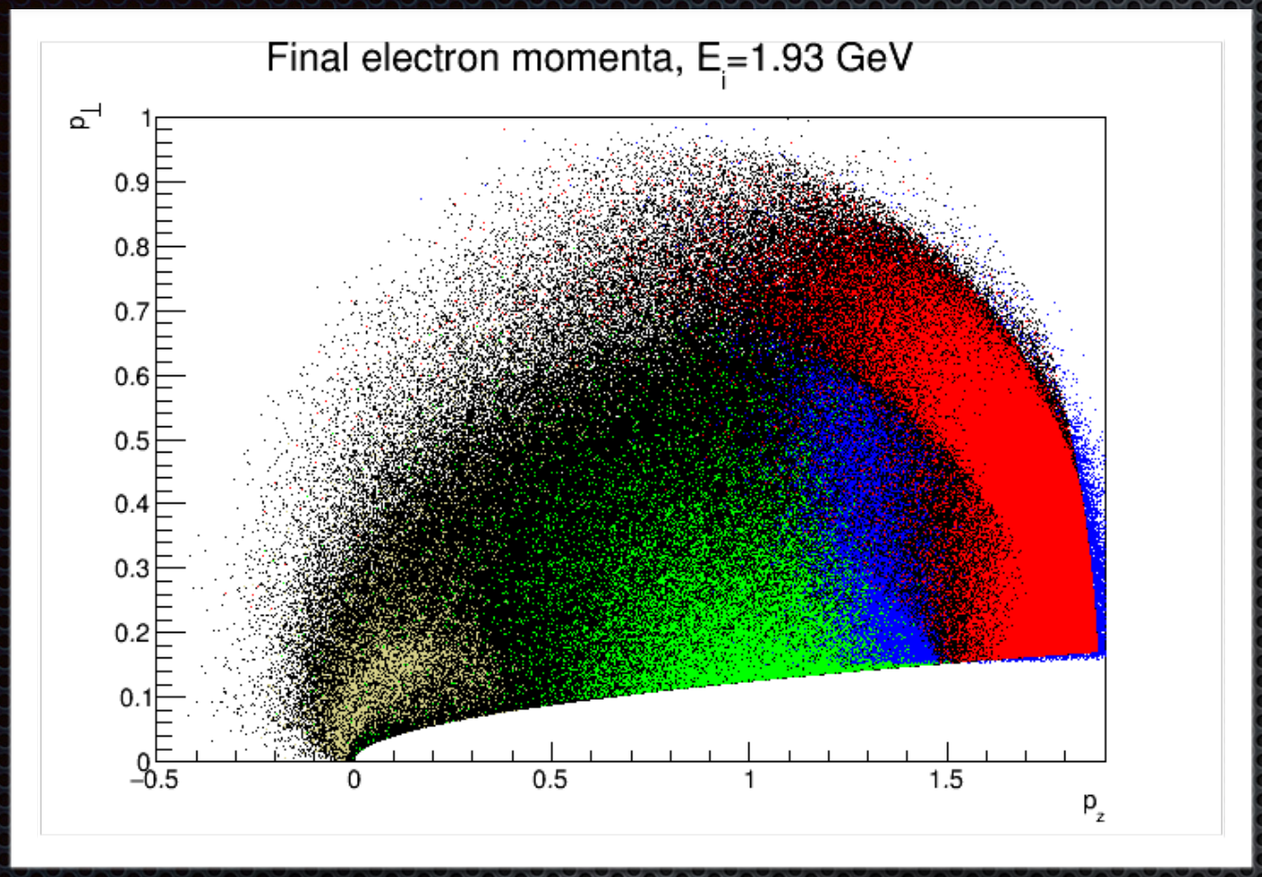
The entire process relies on the details of the cross section model

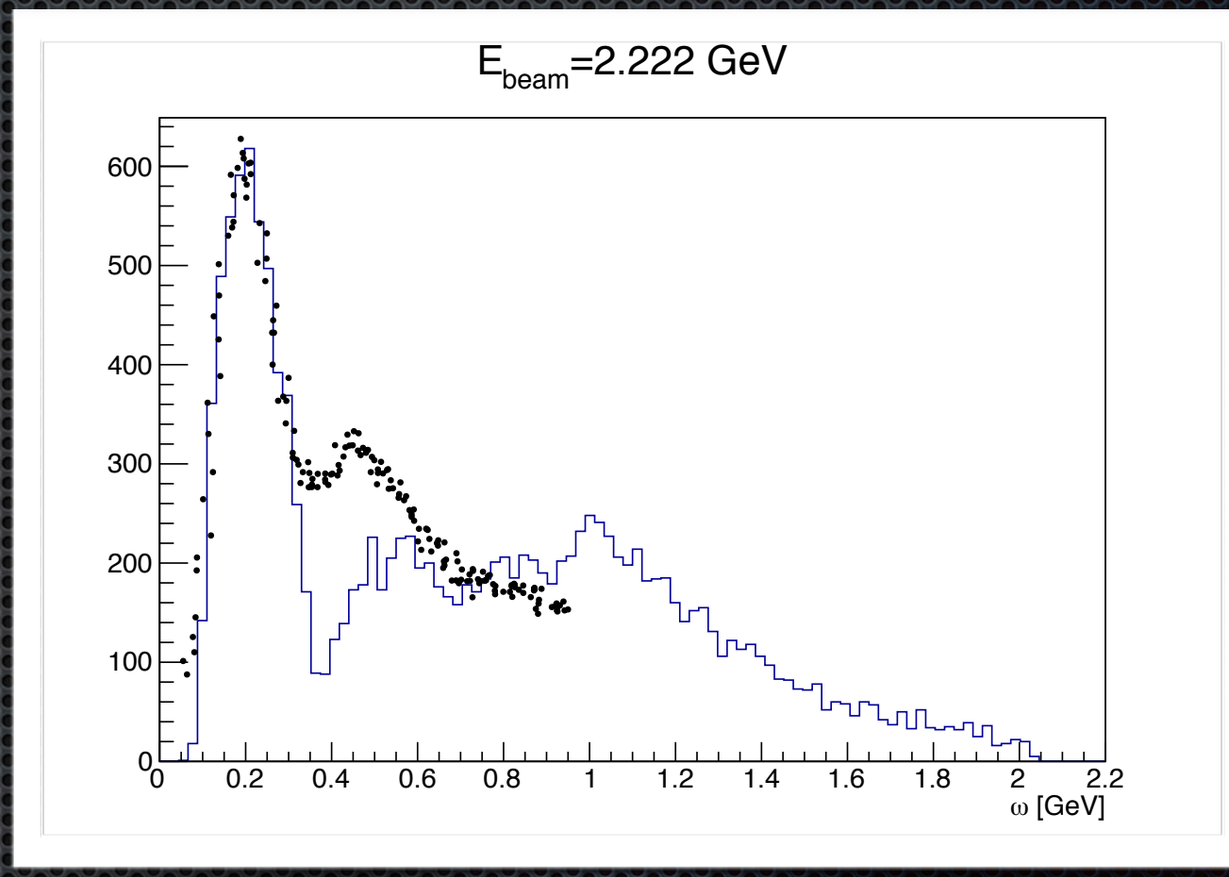
- We predict the full hadronic system w/ GENIE and then infer how much should be visible for given reconstruction assumptions
- Which properties are important depends on the detector performance!
  - For example, in our best-case scenario, neutron production is key (multiplicities and energies)
  - On the other hand, without particle-ID information, we also need to know how many charged pions vs protons we have in the final state

How do we validate our generator?

- Compare to other generators
- Test against well-measured processes

use electron scattering

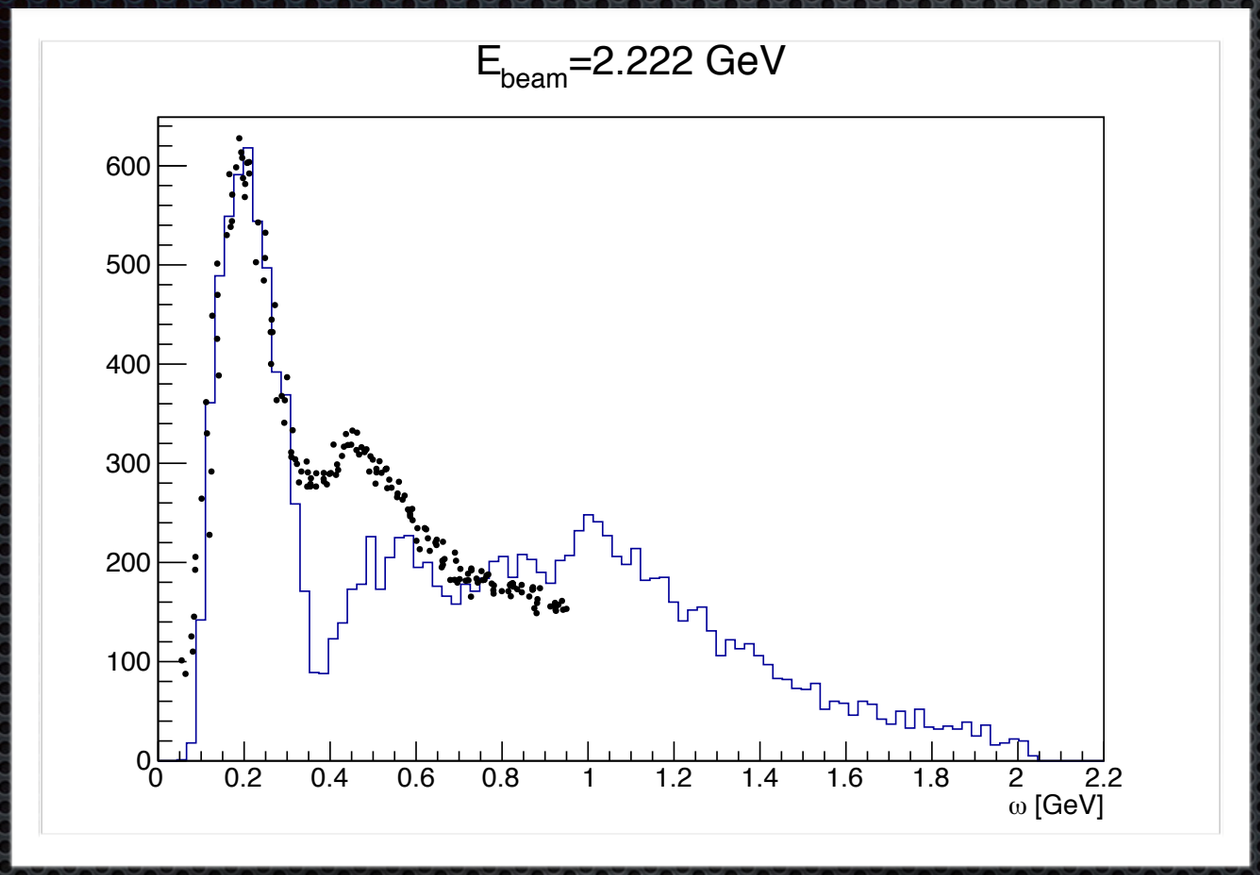




- Common physics includes
  - Initial nucleon momentum distribution (spectral function)
  - Final state interactions
  - Hadronization at several GeV, meson exchange currents, etc

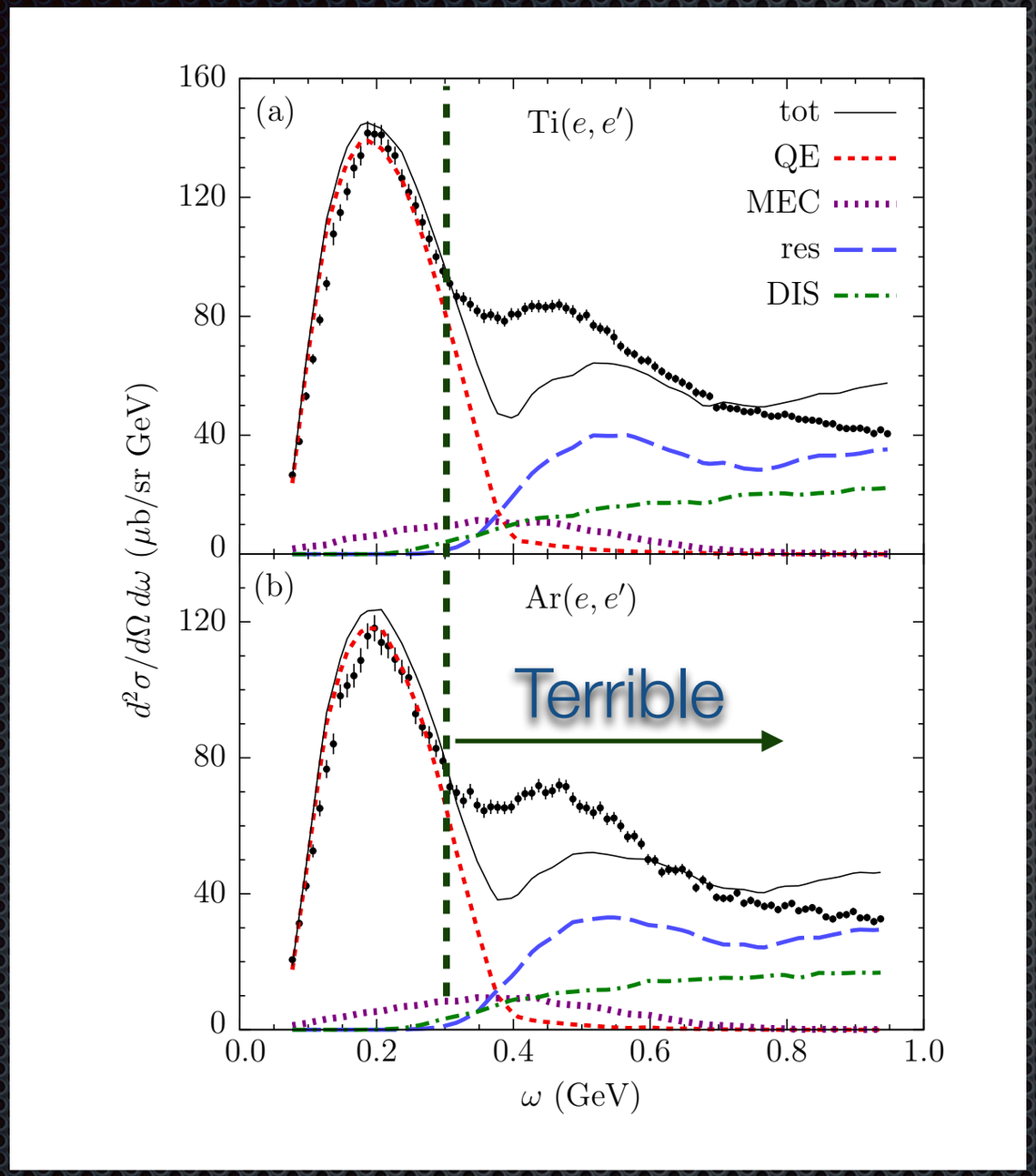
- (Axial response is needed separately)

use electron scattering



- GENIE generator predictions show dramatic discrepancies with a variety of inclusive electron scattering data
  - Artur Ankowski, A.F., Shirley Li, the last 2 years

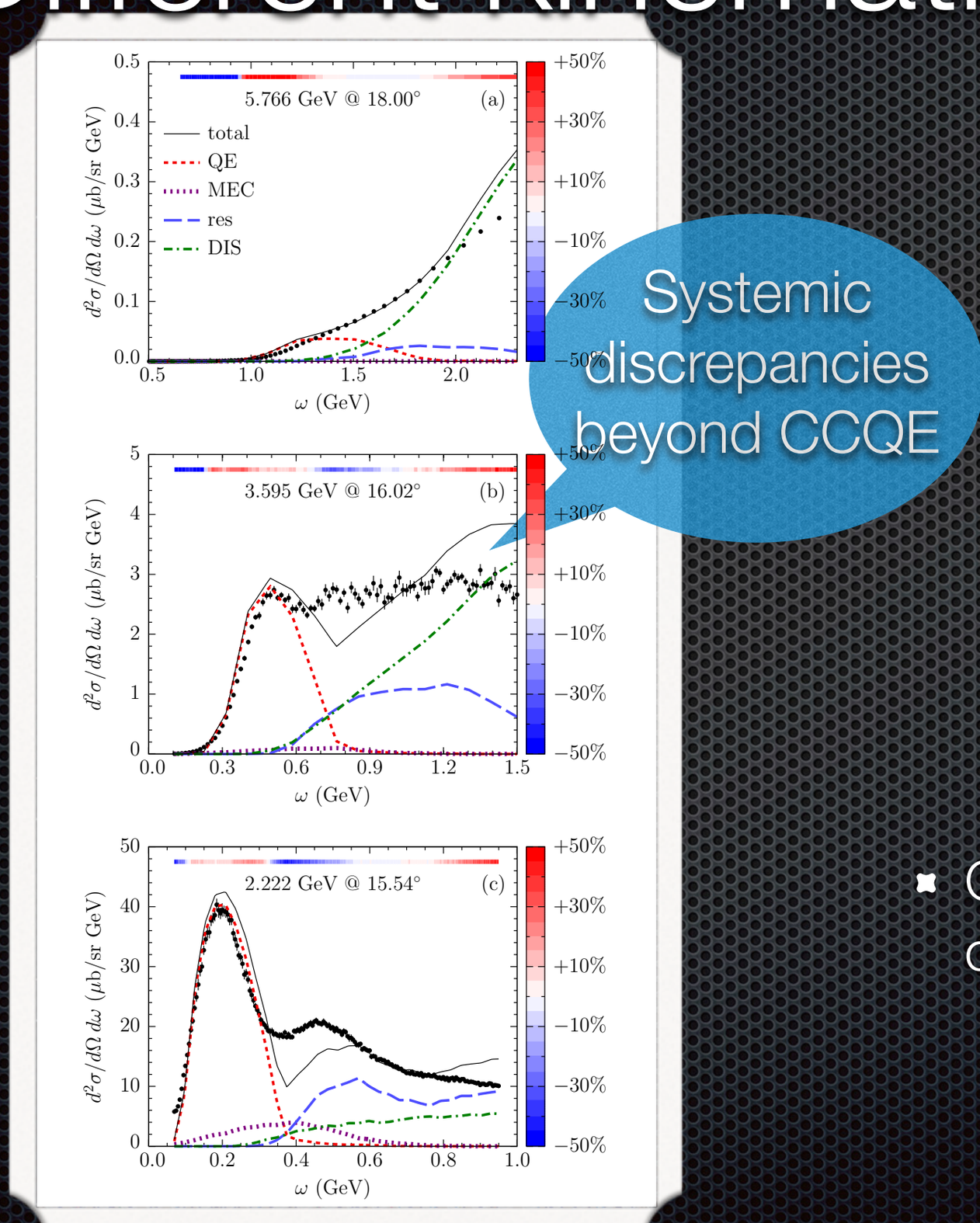
Electron scattering comparison



See the talk by Artur

- Data collected at JLab in 2017

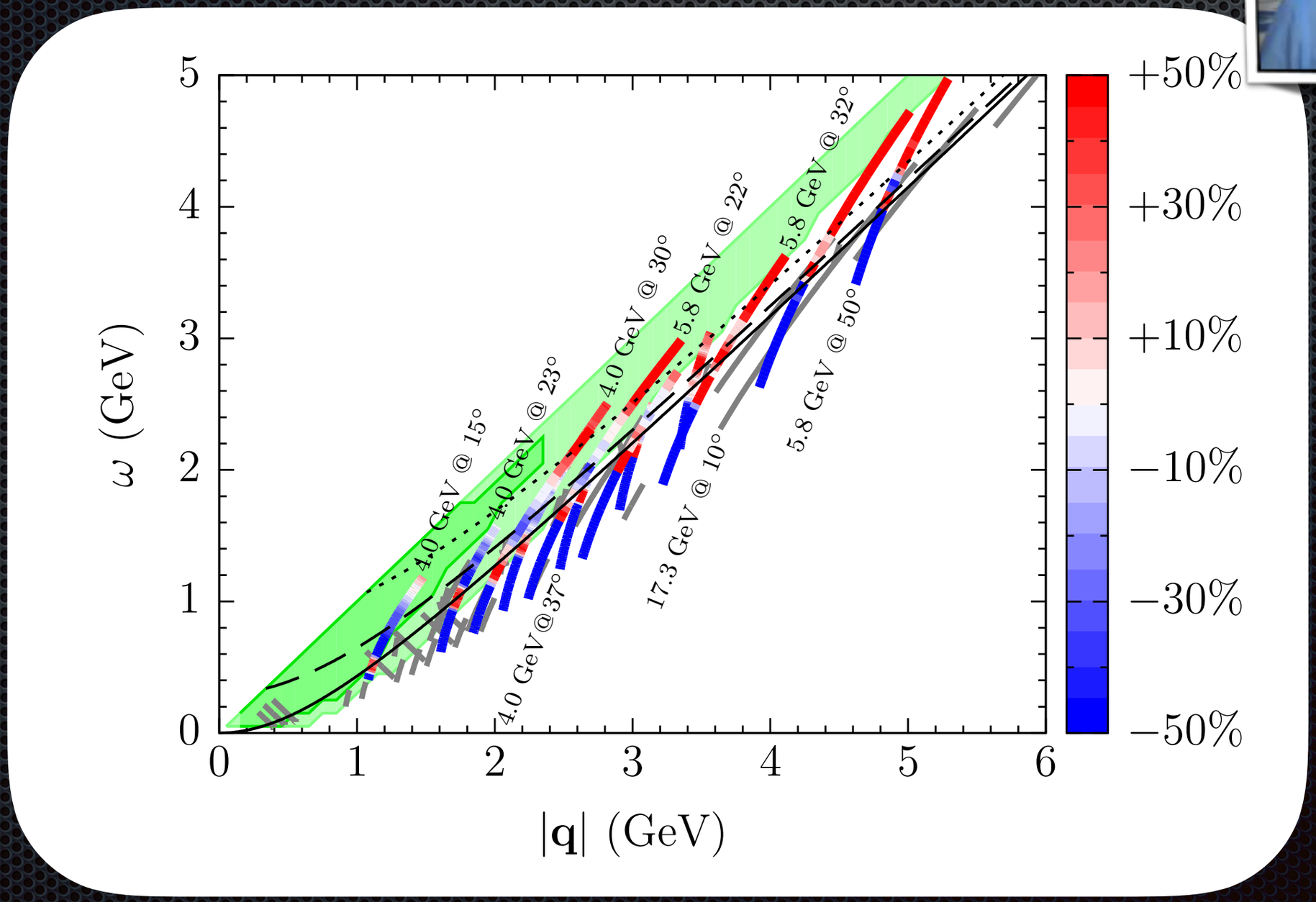
Different kinematic regimes



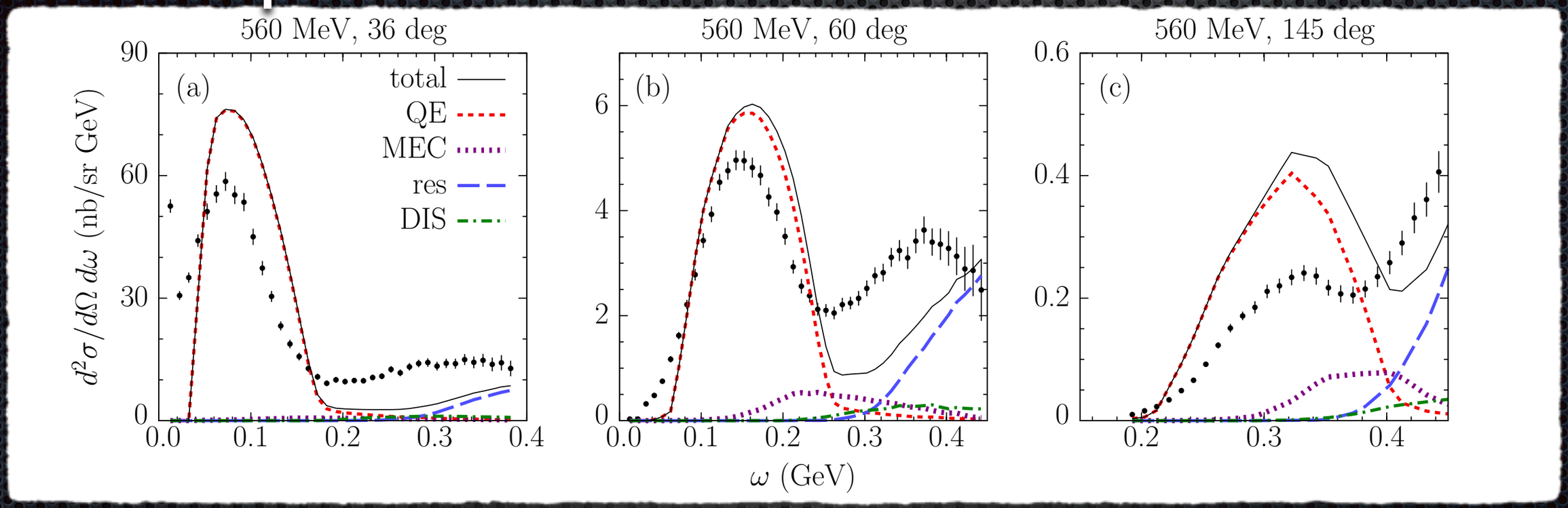
Systemic discrepancies beyond CCQE

- Chronic problems with many other datasets.

Mapping out the pattern of discrepancies



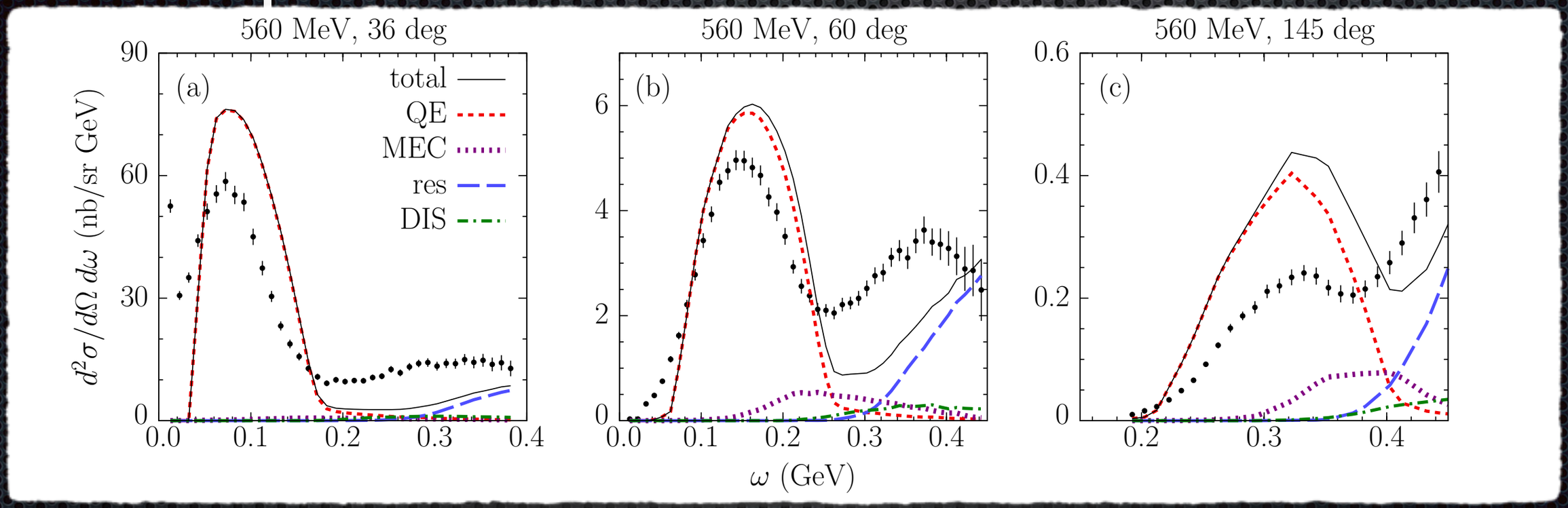
Comparing to earlier comparisons



- T. Katori (NuInt 2012) noted in a couple of comparisons of GENIE that the agreement was poor
- Different energy regime, 0.5 GeV datasets.

https://indico.fnal.gov/event/5361/session/21/contribution/58/material/slides/0.pdf

Comparing to earlier comparisons



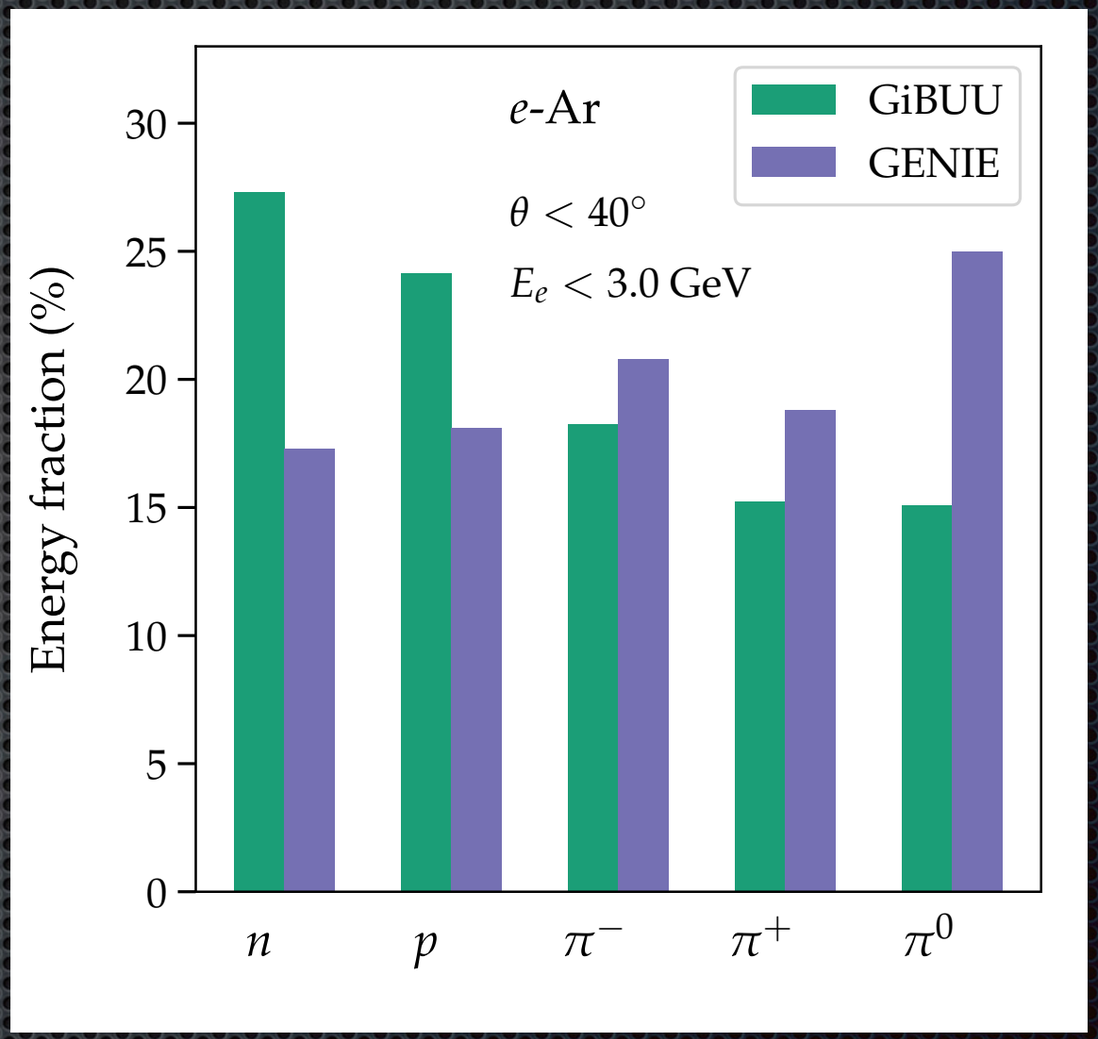
- Different energy regime, 0.5 GeV datasets. Recommended cure: Dytman 2p2h. Not pursued further.
- Too bad! By extending the comparisons to the several-GeV regime relevant to DUNE, we see that while the QE peak shows better agreement (RFG), the regime of inelasticities exhibits stark discrepancies

Summary of inclusive electron scattering comparisons

- Pattern of dramatic discrepancies beyond the QE peak
- 50% or larger discrepancies, both near the Delta peak and beyond, in transition to DIS
- The same pattern is present in Carbon and deuterium
- Without better hadronic physics, this problem cannot be cured

Impact on hadronic final states

- Inaccurate model of pion production leads to incorrect prediction for the properties of the hadronic system
- The problem can be further compounded by nuclear physics, namely the development of the intra-nuclear cascade: primary hadrons undergo FSI, knock out nucleons, lose energy, get absorbed, etc



Summary

- Cross section physics enters neutrino oscillation studies via its impact on energy measurement
  - The model is used to fill in the missing pieces
- The key predictions for DUNE are exclusive hadronic final states
  - Things like neutrons, proton-pion composition
  - Which one is most important depends on the performance of the detector
- Inclusive electron comparisons indicate hadronic inelasticities (resonances/SIS/DIS) are mis-modeled in GENIE. This is troubling for the composition prediction.
- Nuclear physics — transport of particles — further compounds the issue

What data would help?

- Exclusive data from electron scattering
- Data on the hadronic final states from NOvA and MINERvA
- More experiments such as ANNIE (“The Accelerator Neutrino Neutron Interaction Experiment”) and CAPTAIN to understand neutron production and interactions in LAr

Thank you!

Postscript: Why do DUNE at 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 ~ 10^3 km. But then to have an oscillation maximum with atmospheric splitting, $\Delta m^2/2E_\nu$ requires energies of several GeV