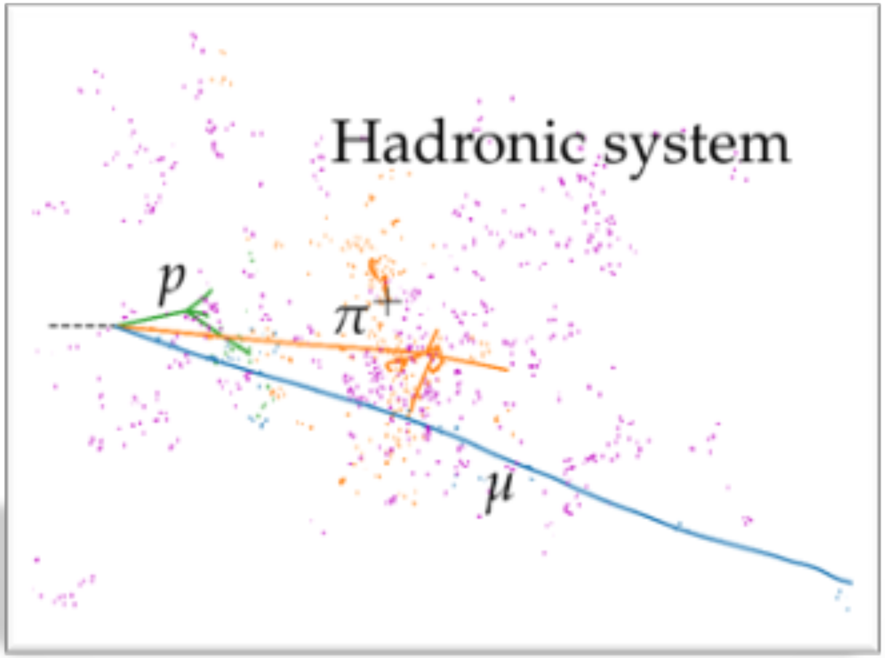
# Understanding the Energy Resolution of Liquid Argon Detectors

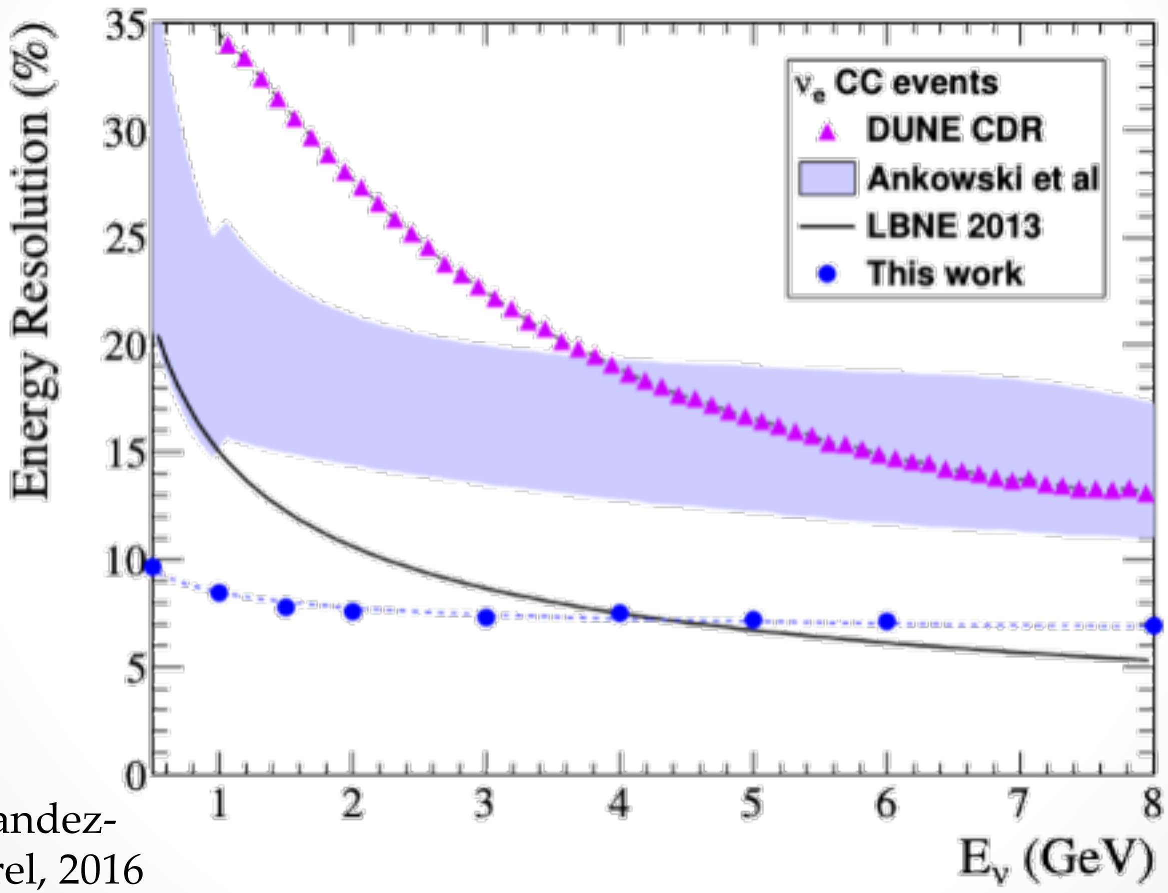



Shirley Li (Fermilab)

Brookhaven Particle Physics Seminar, Sep 2021

# What is $\sigma(E_\nu)$?

Energy resolution from previous works

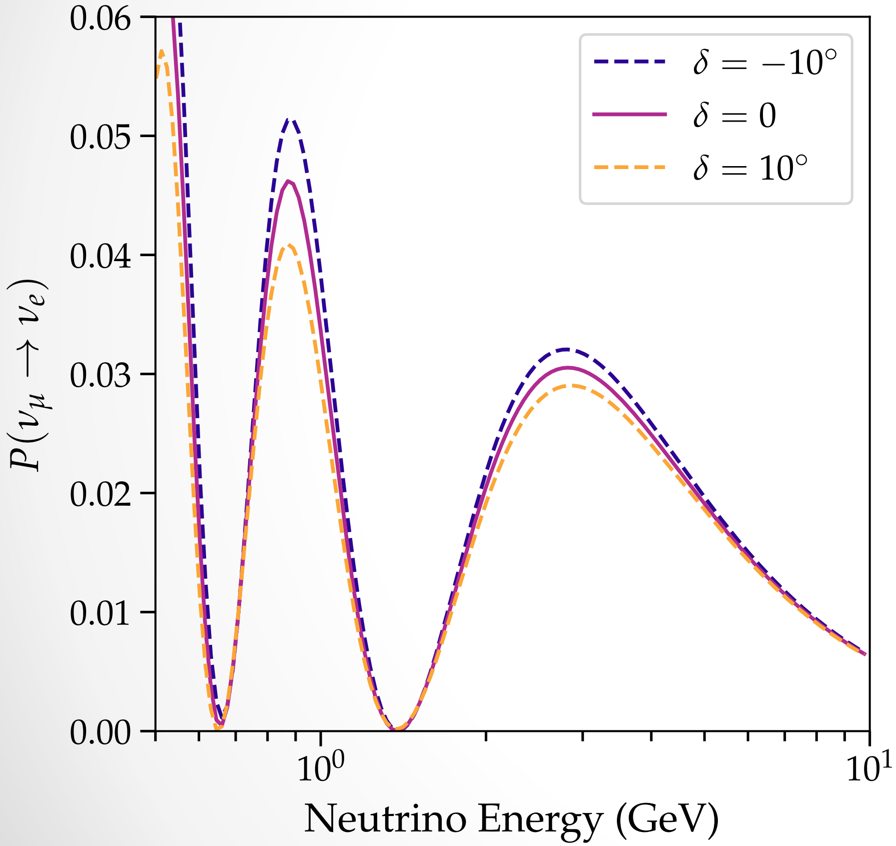



Romeri, Fernandez-Martinez & Sorel, 2016

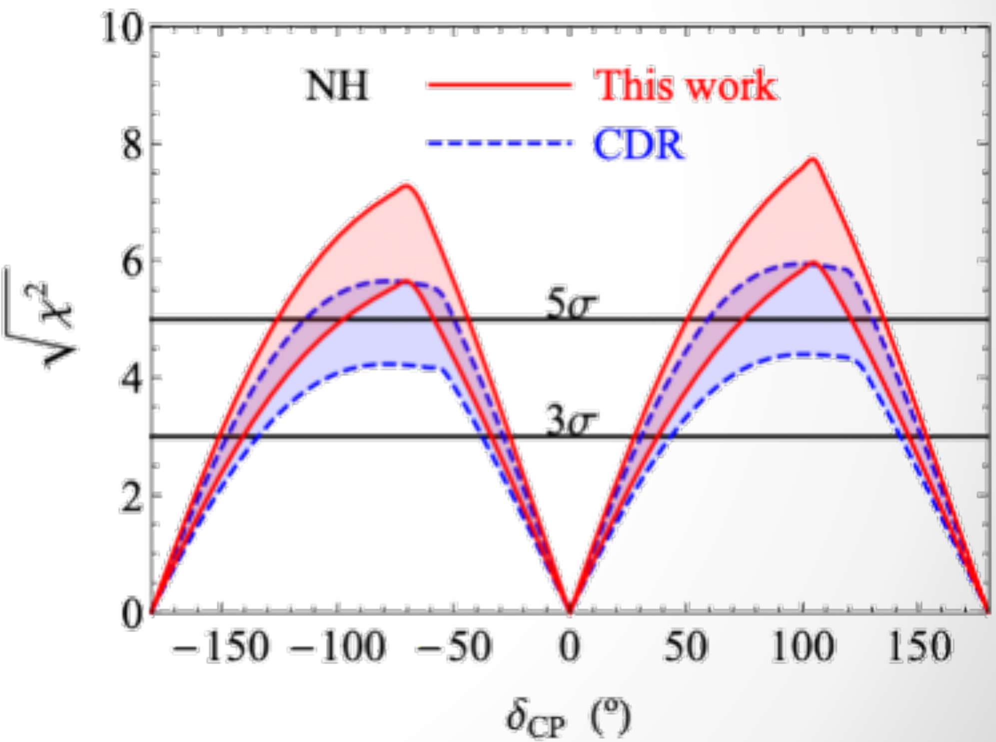
No consensus

# Why do we care?

Energy resolution impacts oscillation measurements



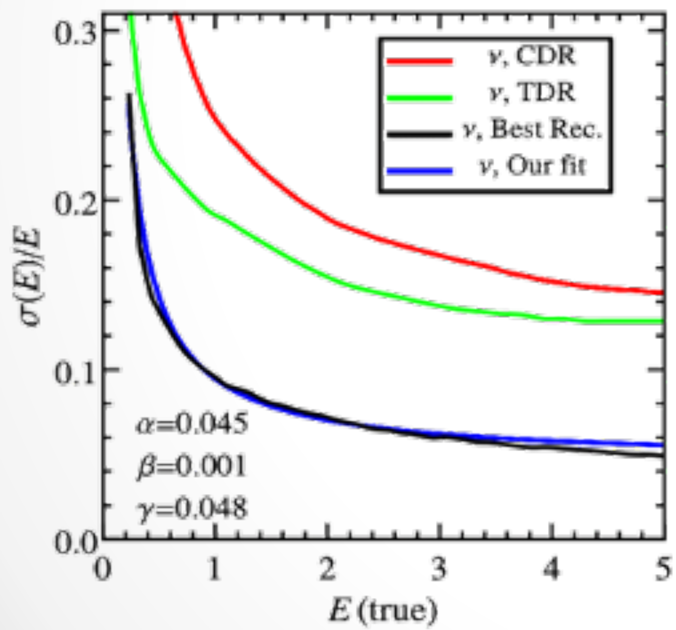

Romeri, Fernandez-Martinez & Sorel, 2016



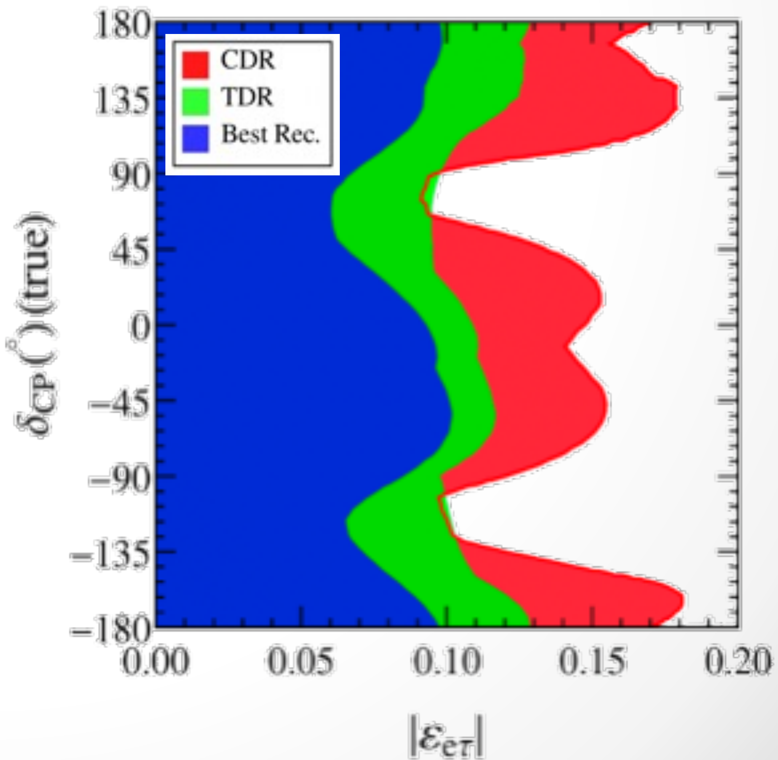
# Why do we care?

Energy resolution impacts BSM searches

Non-standard interaction: $$H = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_{21} & 0 \\ 0 & 0 & k_{31} \end{bmatrix} U^{\dagger} + V_{CC} \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{bmatrix}$$




Chatterjee, Bhupal Dev & Machado, 2021

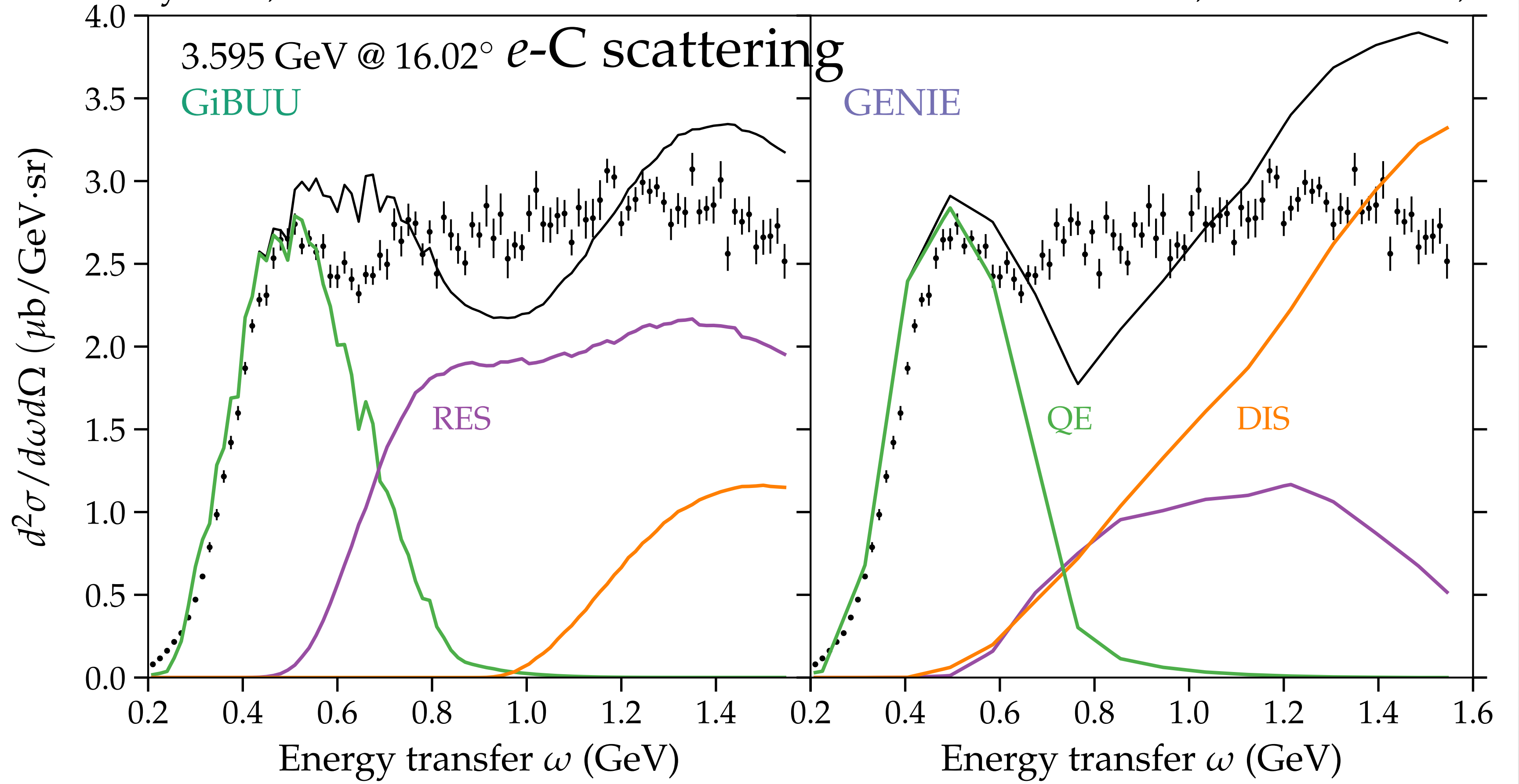


# $\sigma(E_\nu)$ & $\nu$-A cross sections

## Large $\nu$-A cross section uncertainties

Data from Day et al., 1993

Ankowski, Friedland & Li, in prep



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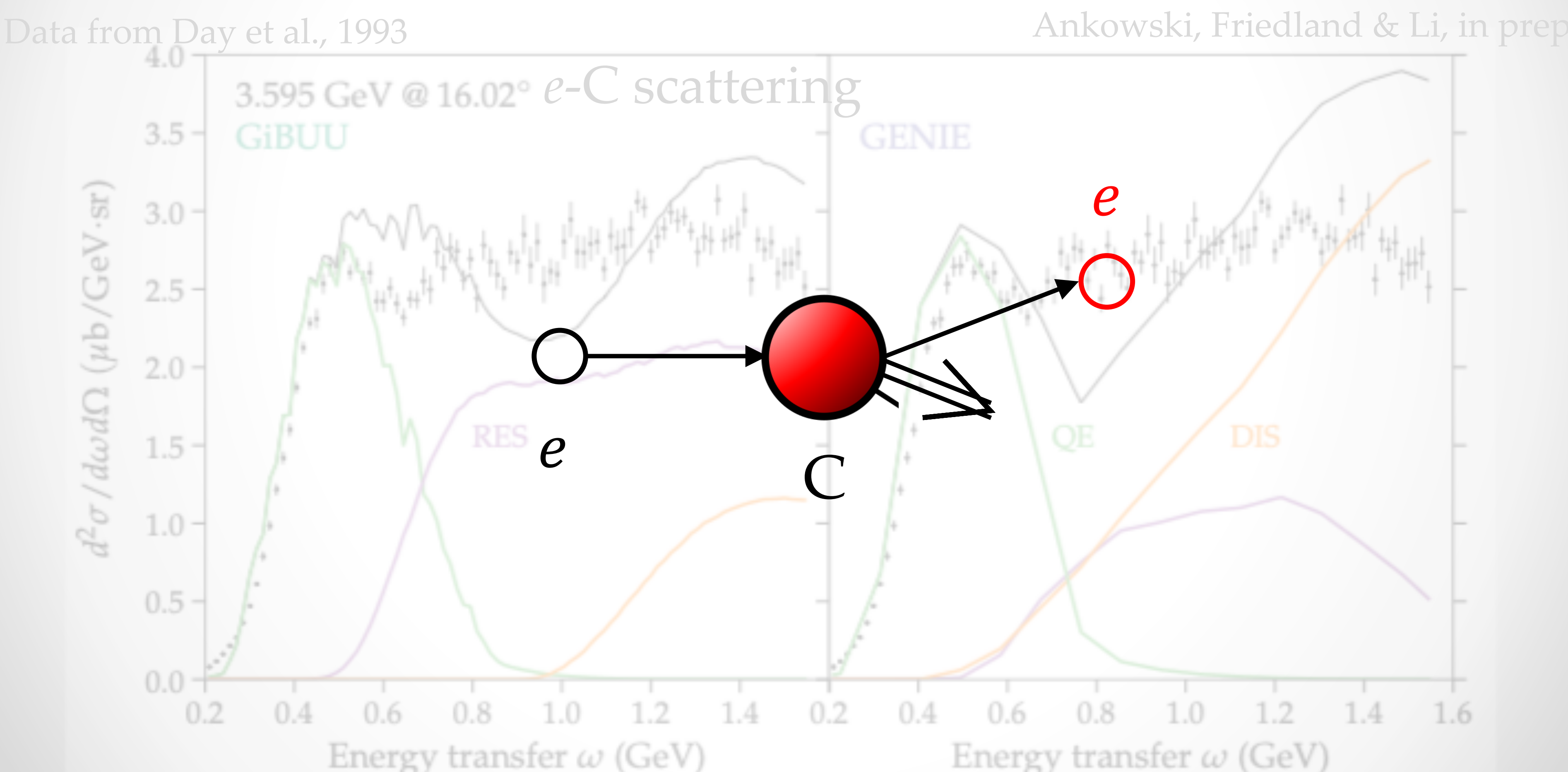

# $\sigma(E_\nu)$ & $\nu$-A cross sections

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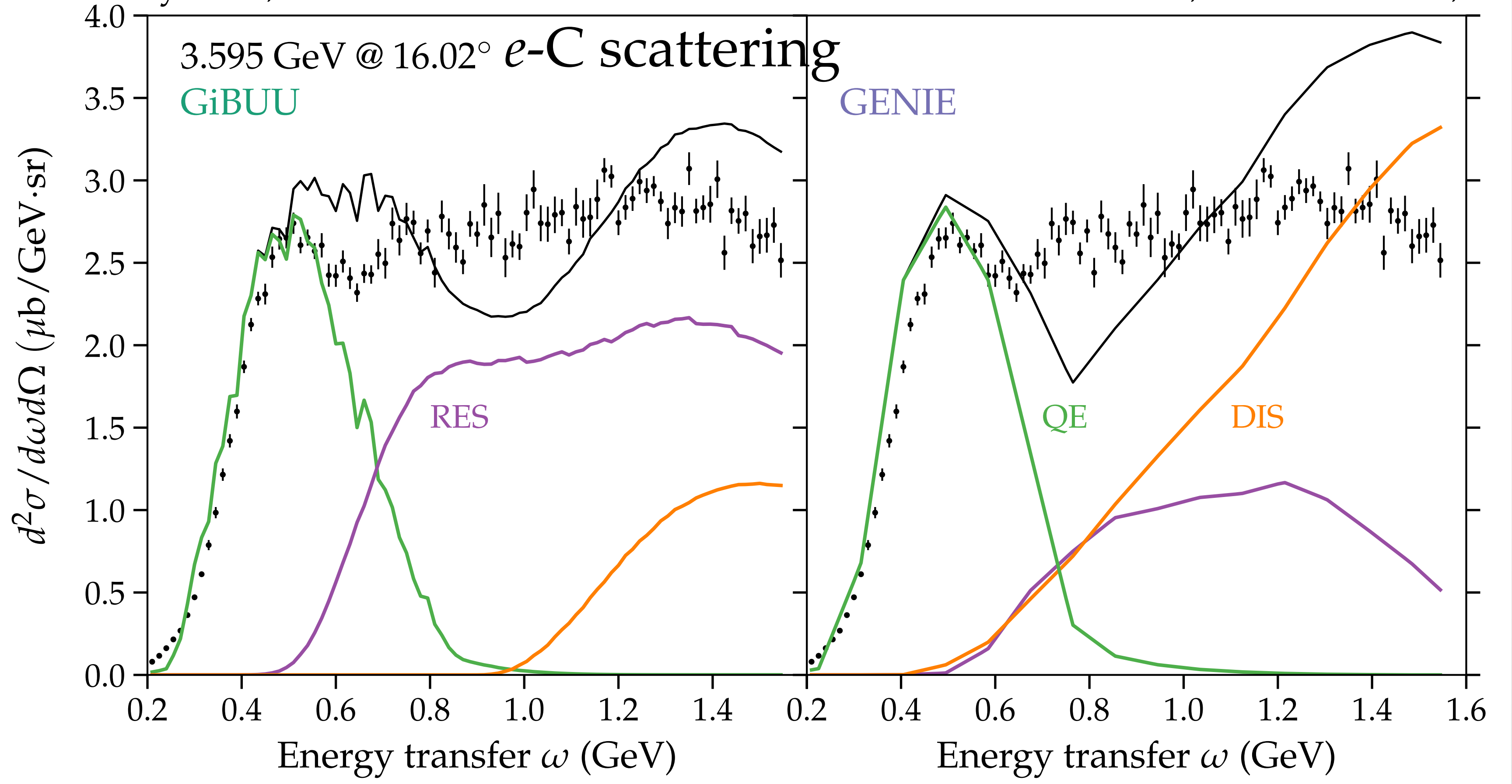
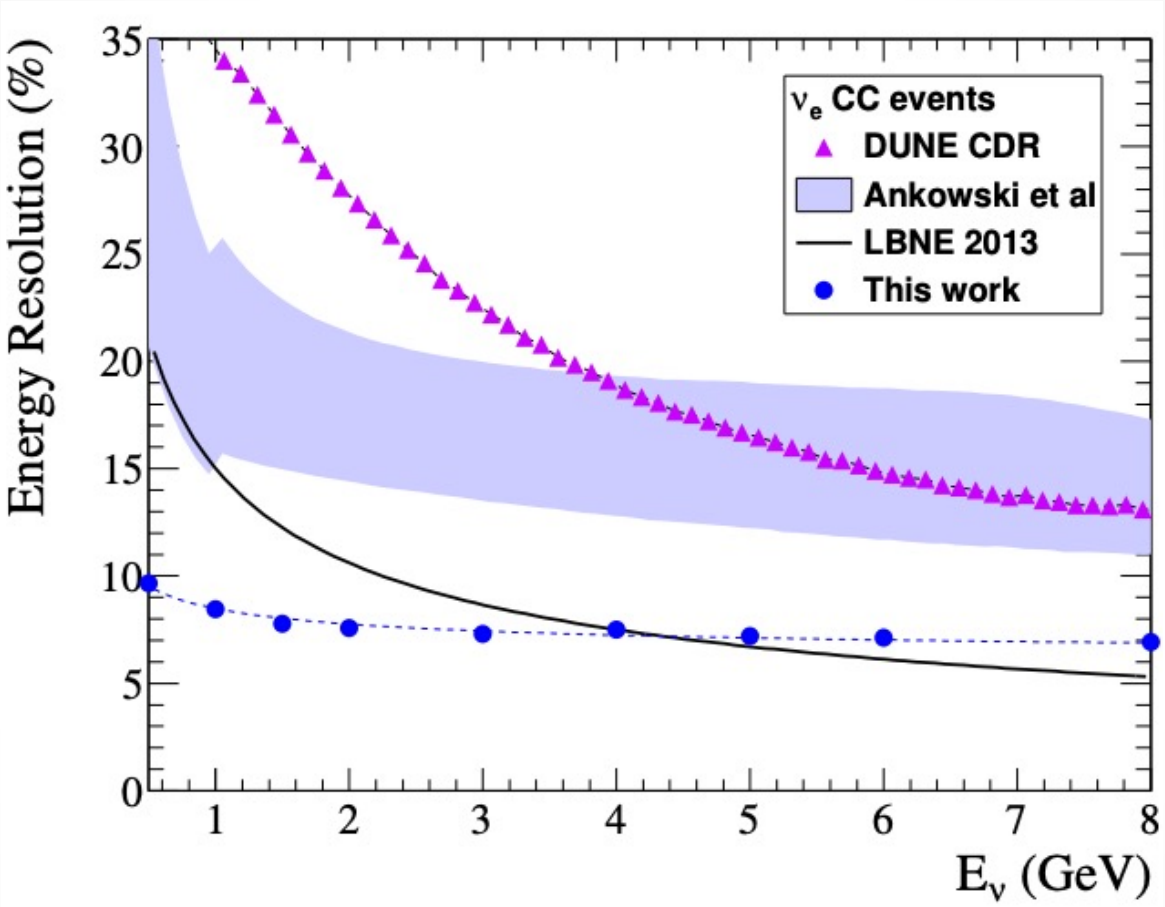


How do cross section uncertainties impact oscillation analysis?

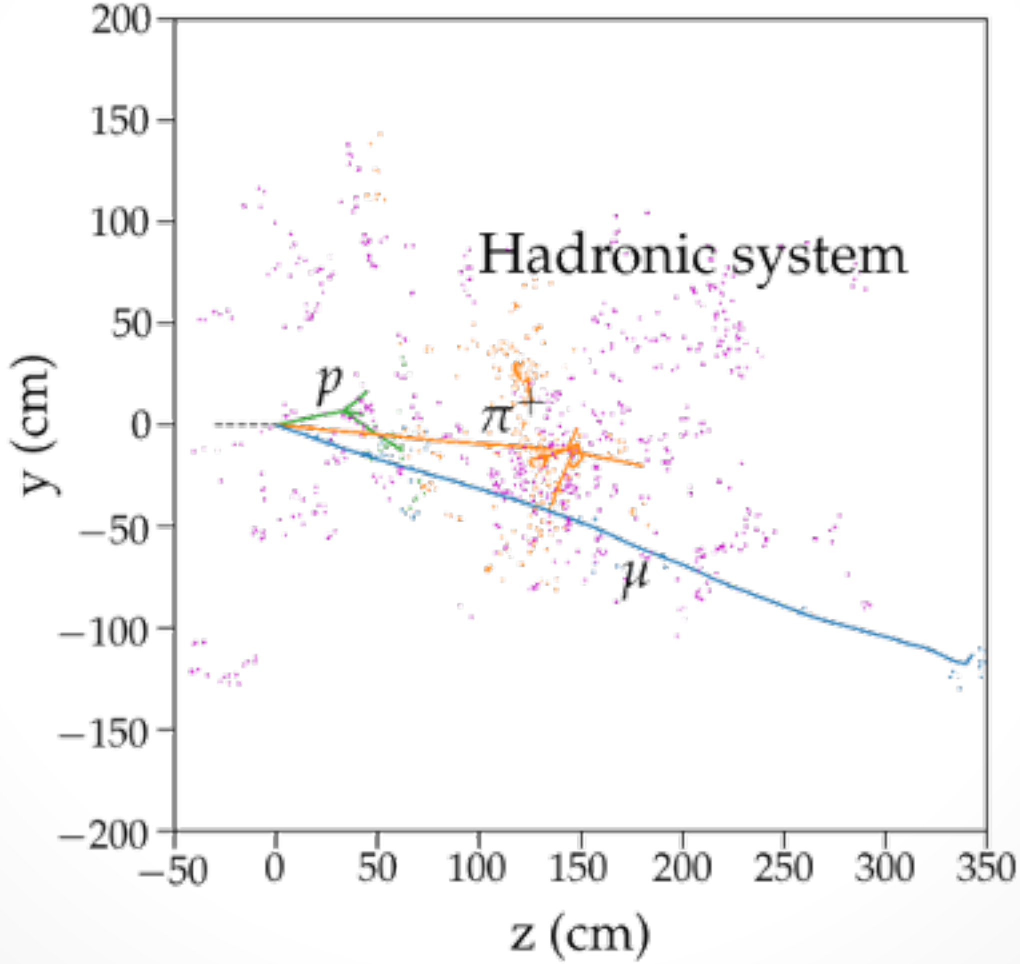



All done with the (~) same cross section models!

# The overarching question

How well can we measure neutrino energy?

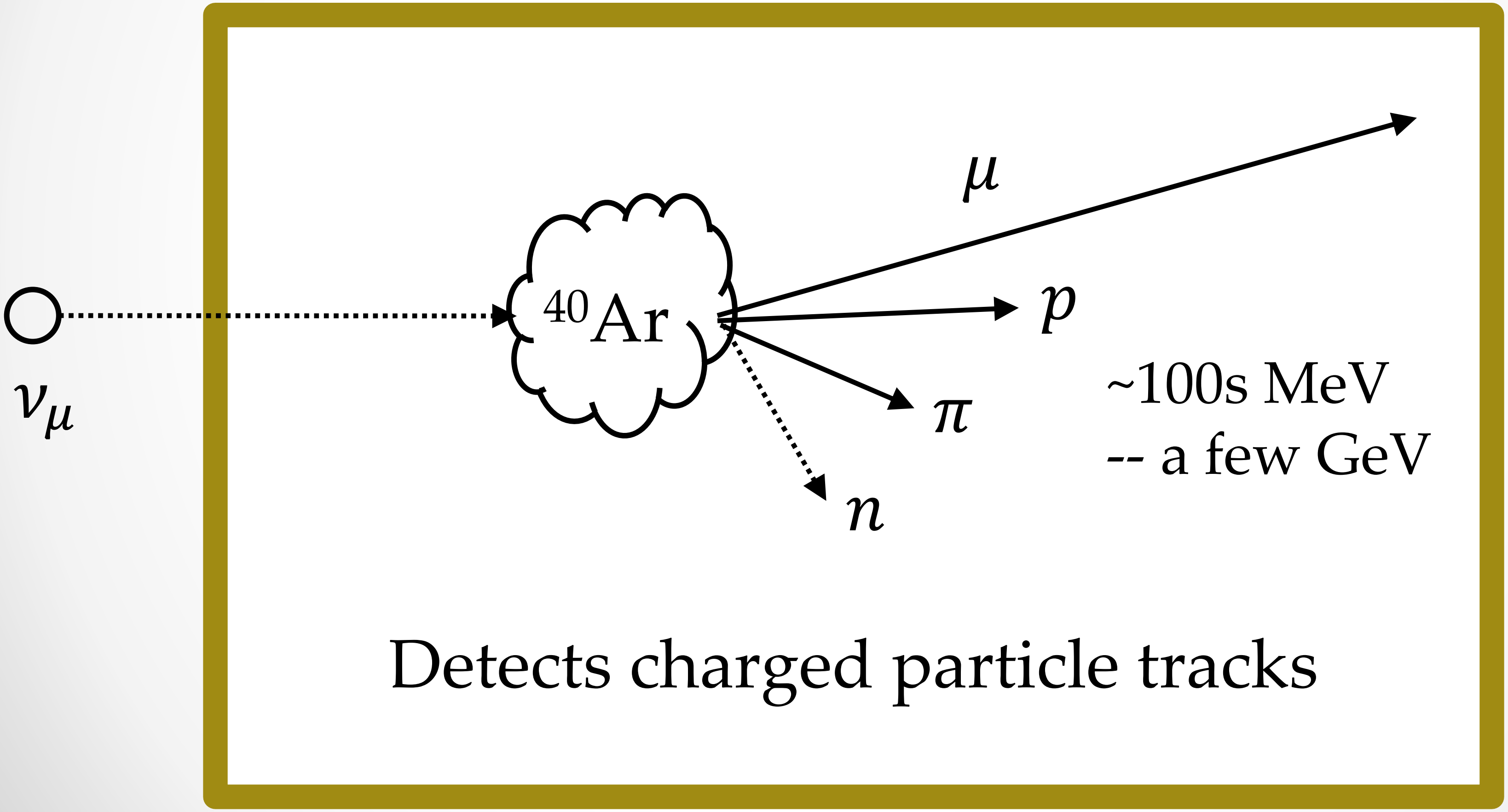
Simulated with GENIE+FLUKA




Friedland & Li, 2018

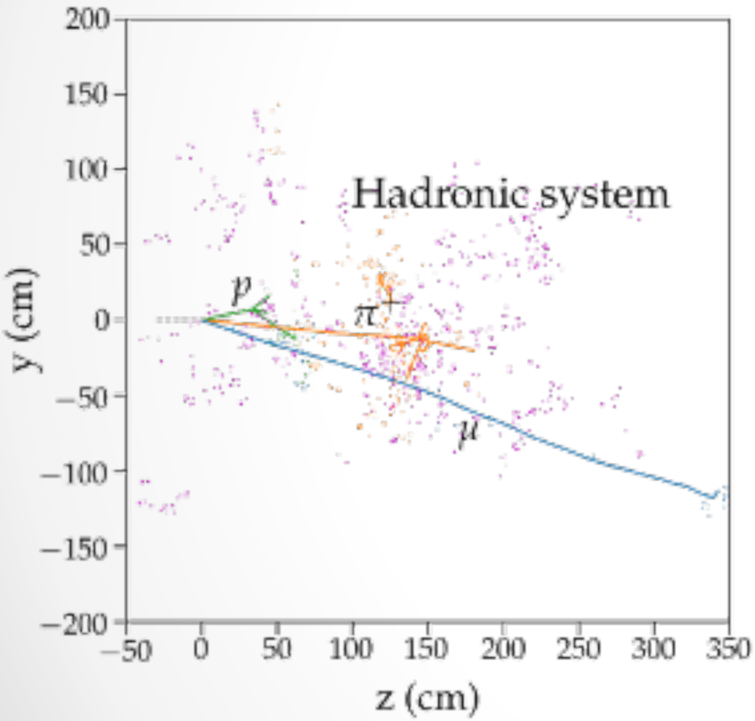
# The scope of the work

A theorist's view of liquid argon detectors
(GENIE+FLUKA)



# Calorimetric energy reconstruction

Signal: $\nu_l + A \rightarrow l + X$




1. Separate $l$ and hadronic system
2. $E_l$ : total collected charge -> energy
3. $E_h$: total collected charge -> energy
4. $E_\nu = E_l + E_h$ or $E_\nu = f(E_l, E_h)$

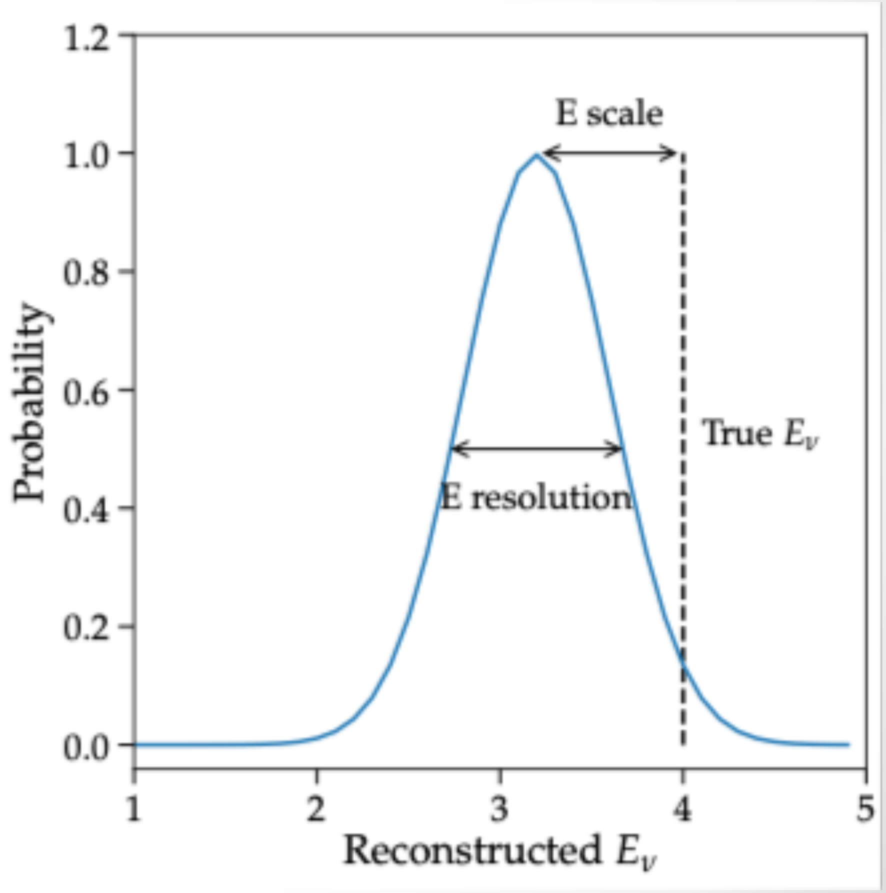
How to characterize its performance?

# Calorimetric energy reconstruction

Signal: $\nu_l + A \rightarrow l + X$

1. Should work perfectly if $E_l \rightarrow$ ionization $\left(\frac{dE}{dx}\right) \rightarrow$ charge

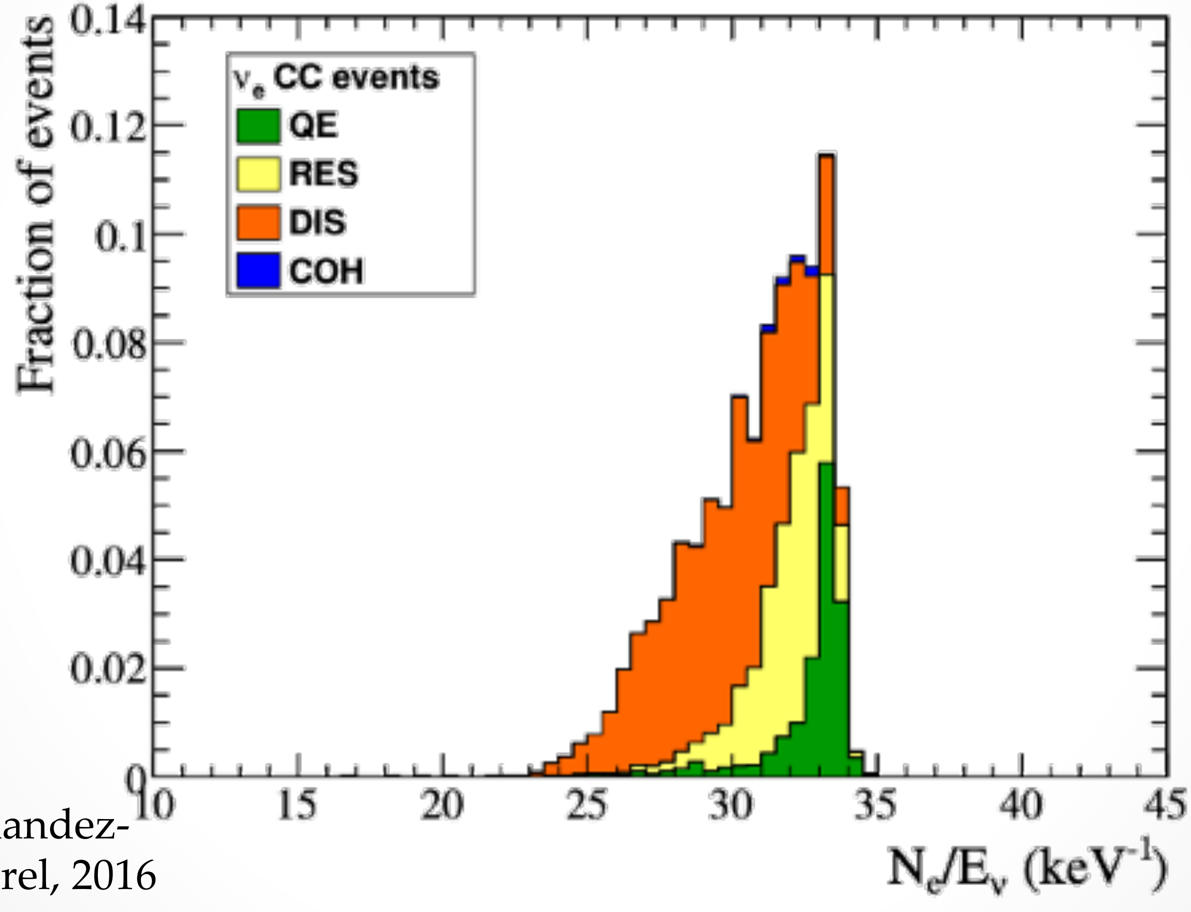
2. Problem arises if $E_h \rightarrow \begin{cases} \text{ionization} \\ \text{missing energy} \end{cases}$




Understanding missing energy is the key

# A concrete example

Charge distributions of neutrino events



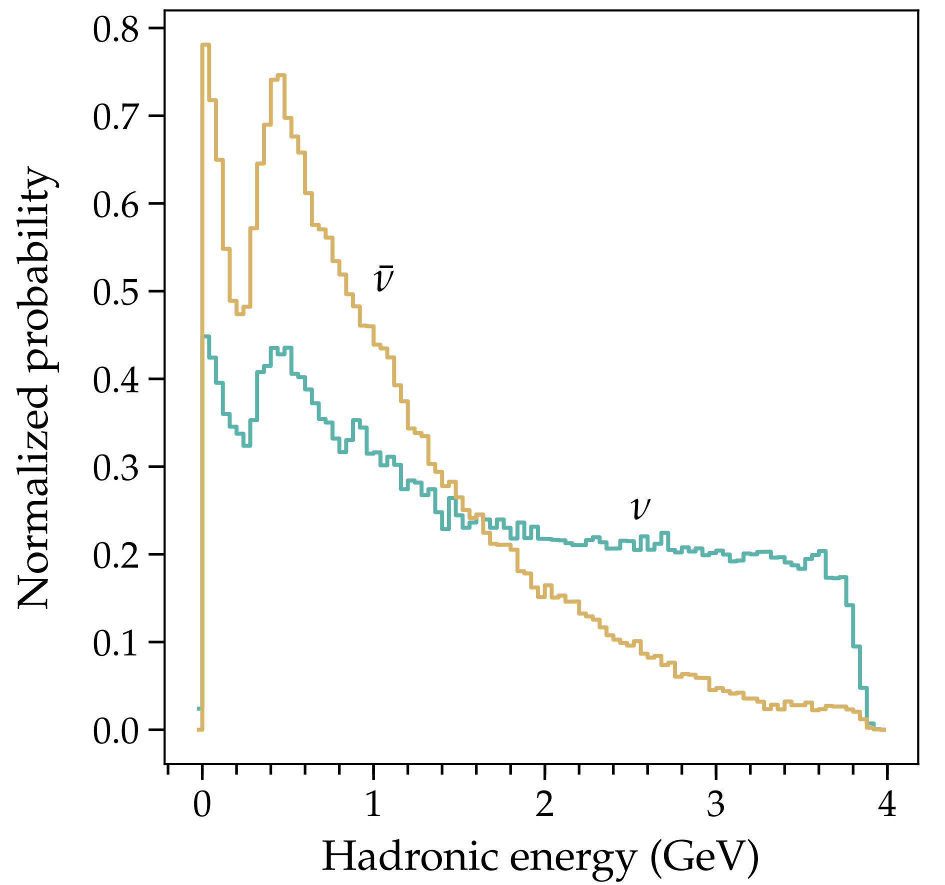

Romeri, Fernandez-Martinez & Sorel, 2016

# Hadronic energy

Prompt $\nu$ vertex: $\nu_l + A \rightarrow l + X$

Friedland & Li, 2018

GENIE
default model



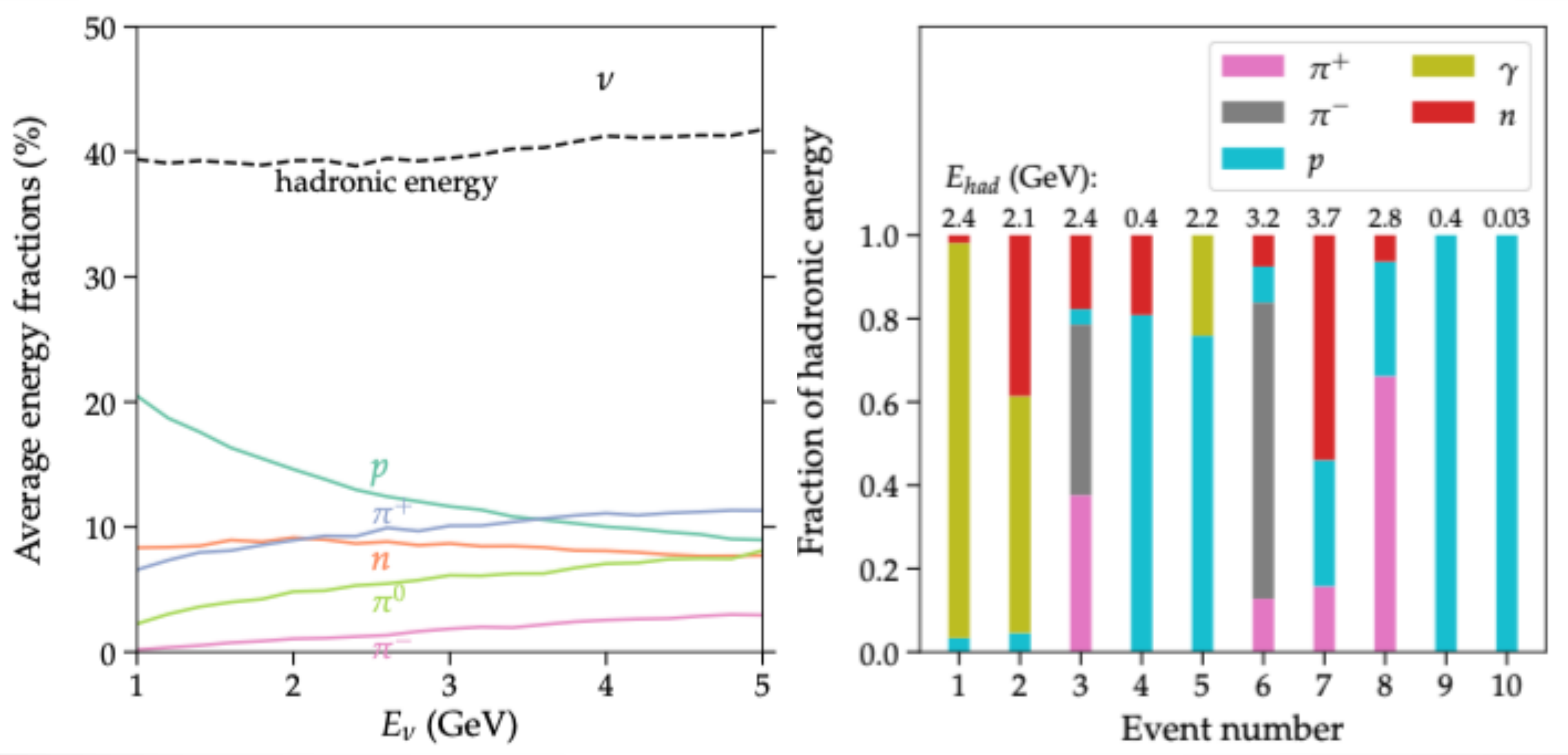

30 – 40% of neutrino energy, large fluctuations

# Hadronic system

Friedland & Li, 2018

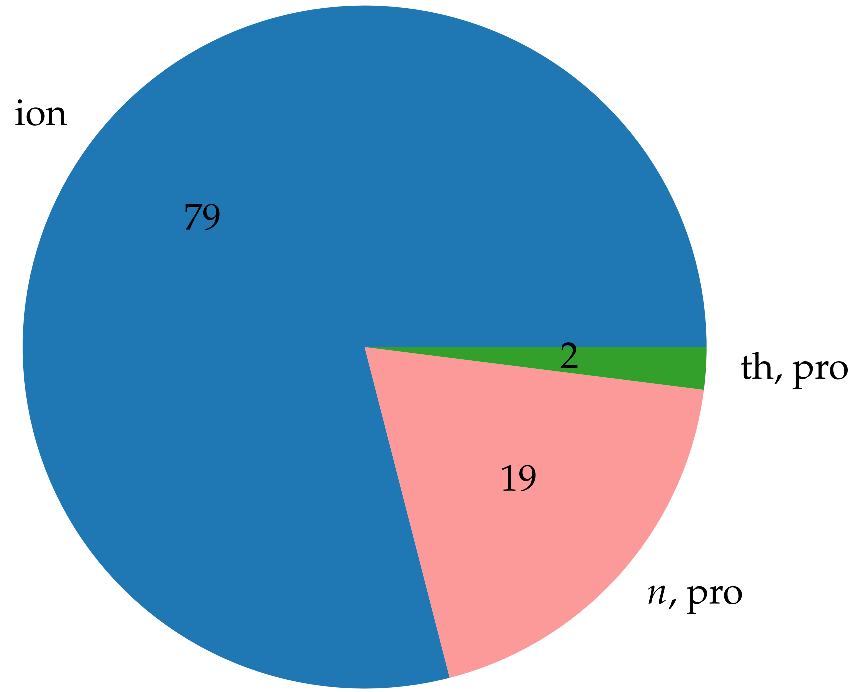
## Varied composition

GENIE simulation



# Missing energy in $E_h$

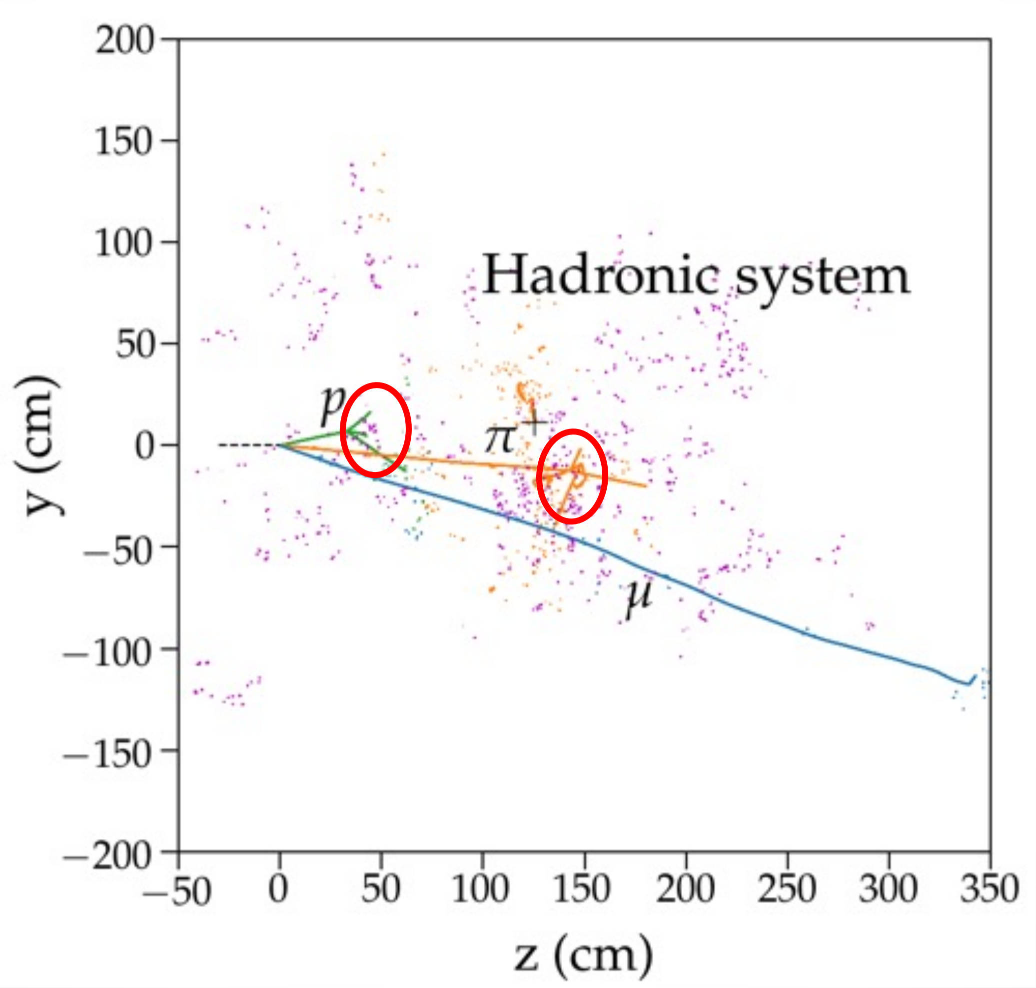
After primary vertex




Friedland & Li, 2018

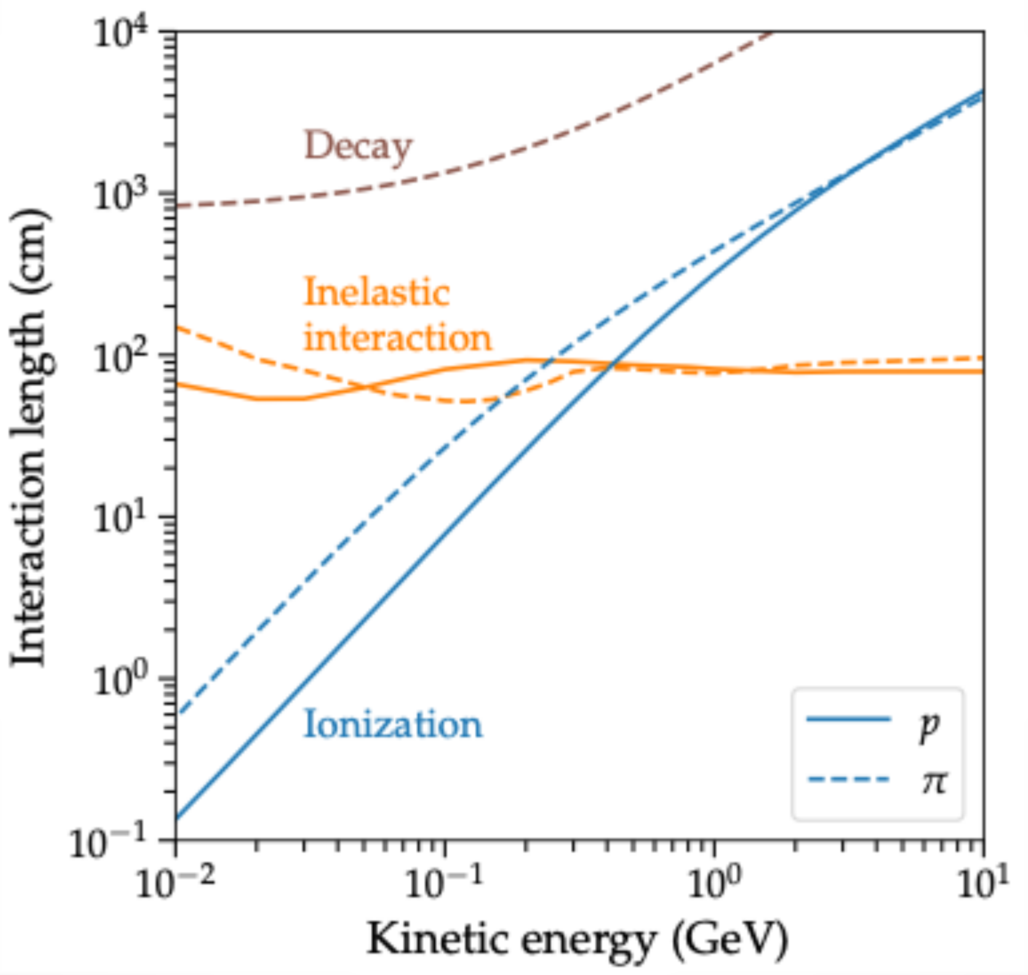
Only neutrons matter??

# Particle propagation




Friedland & Li, 2018

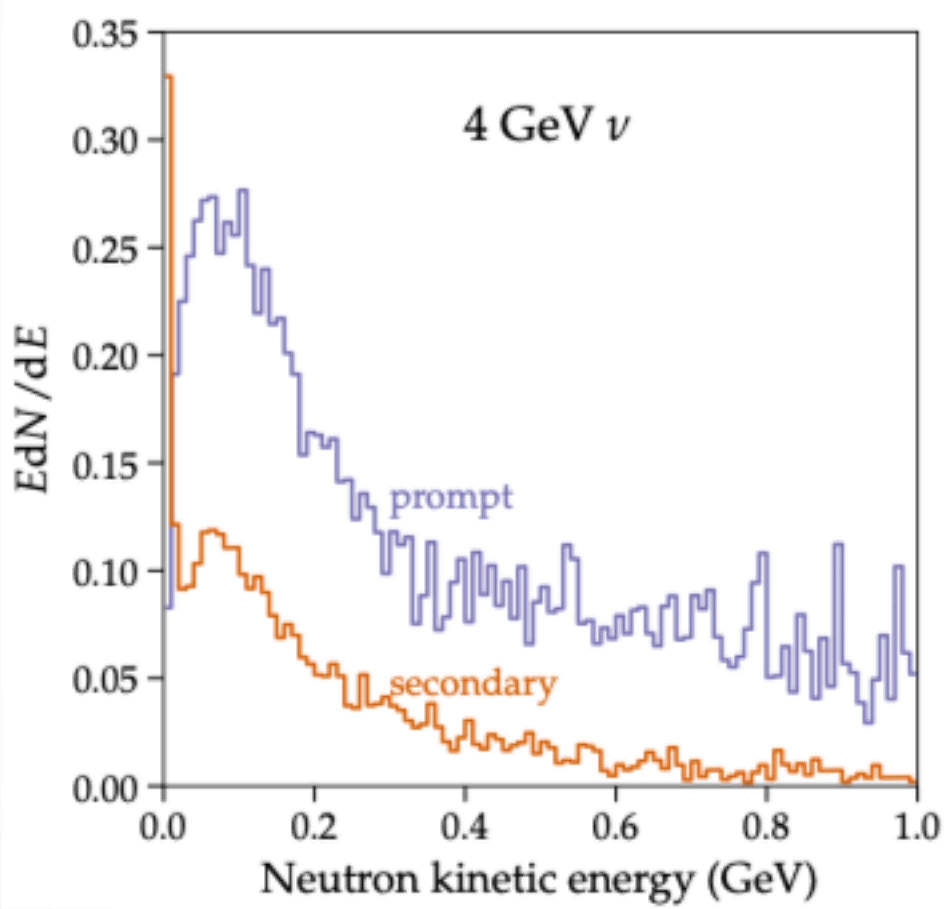
# Protons & Pions

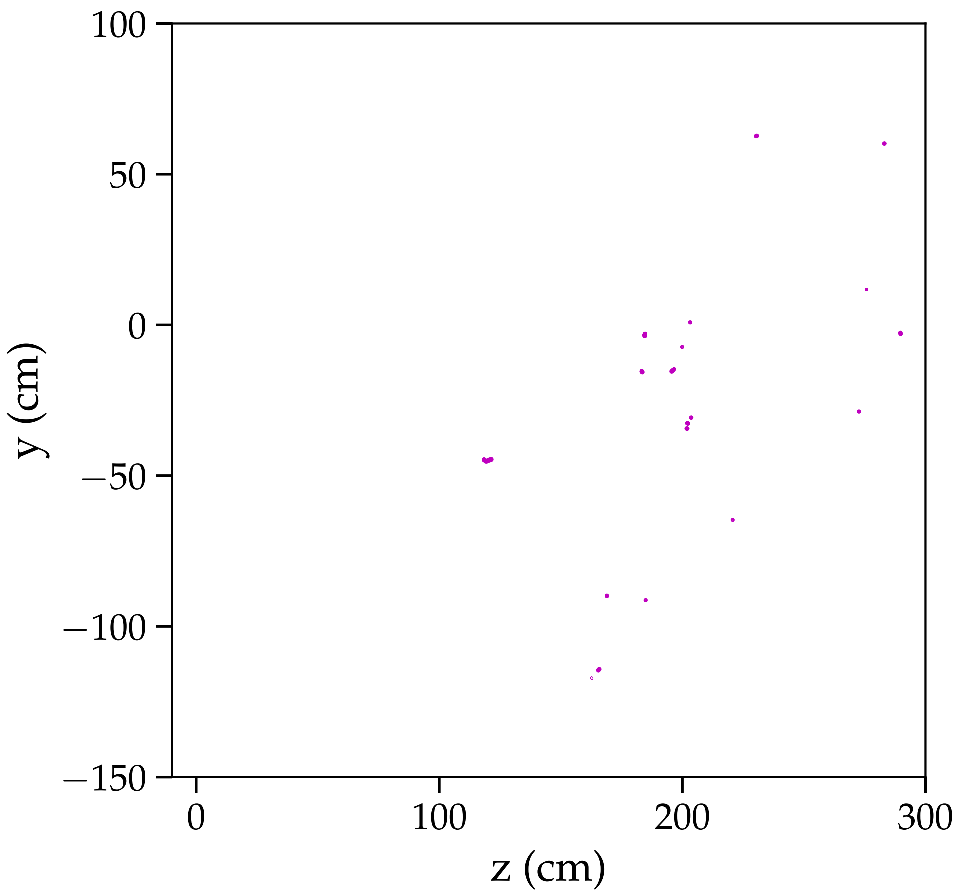


# Neutrons

Friedland & Li, 2018

Simulated with
GENIE+FLUKA



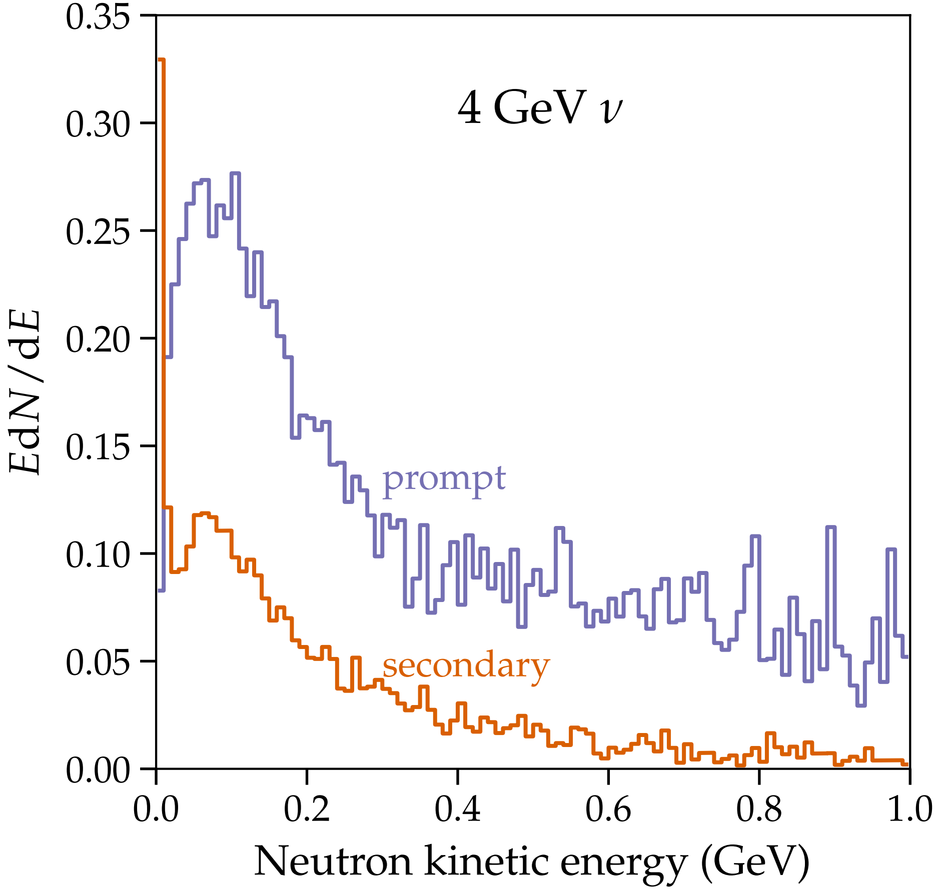



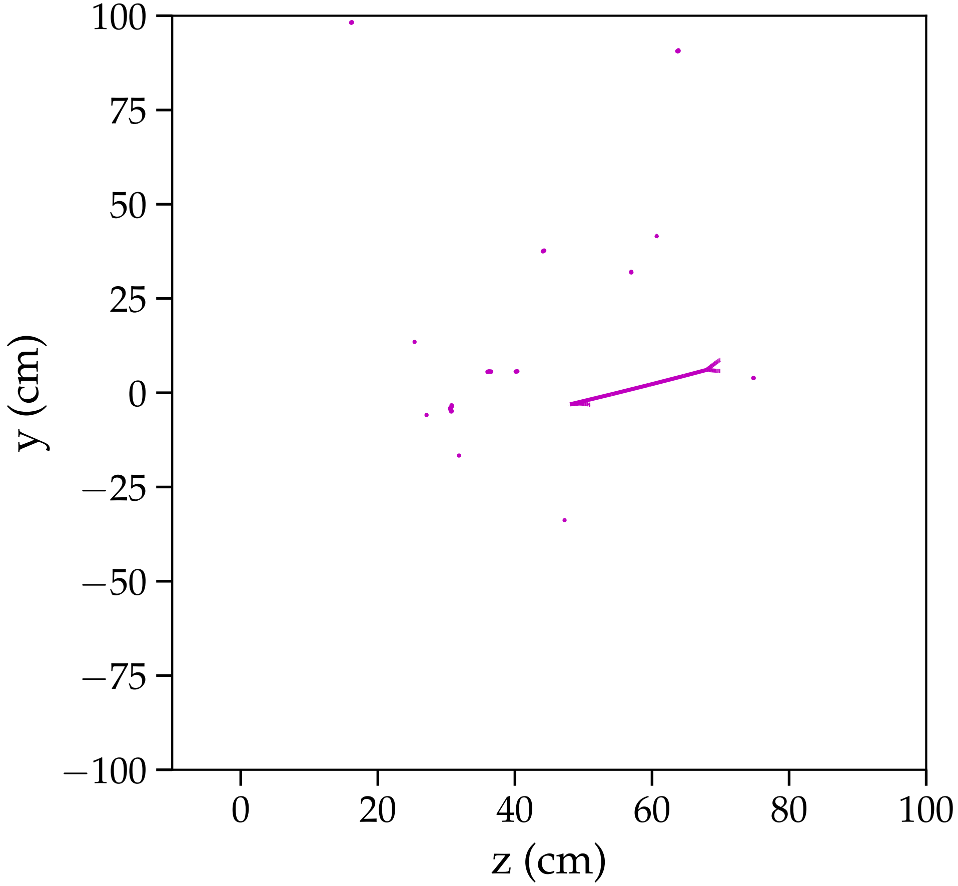

Extremely challenging to reconstruct neutrons

# Neutrons

Friedland & Li, 2018

Simulated with GENIE+FLUKA



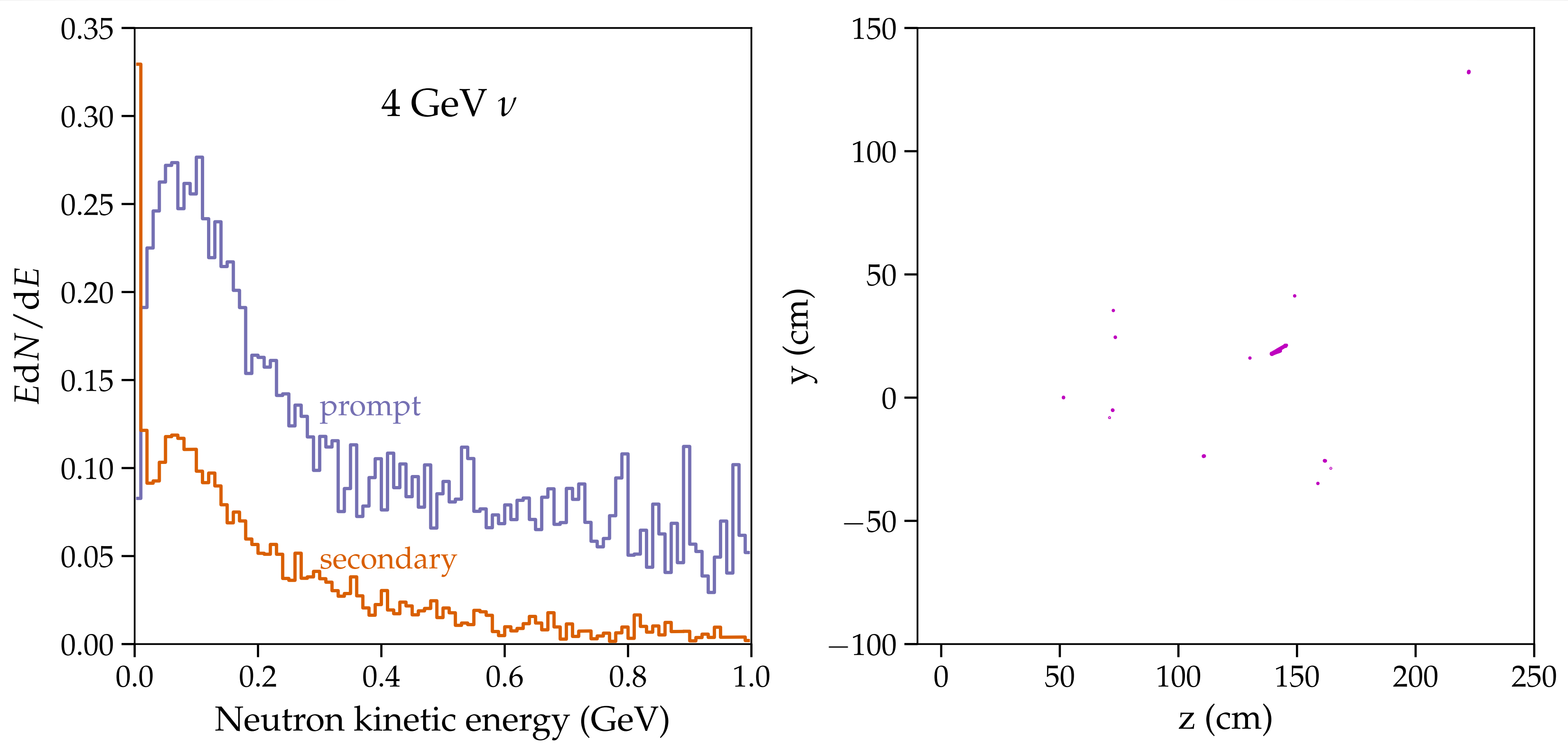




Extremely challenging to reconstruct neutrons

# Neutrons

Friedland & Li, 2018

Simulated with GENIE+FLUKA



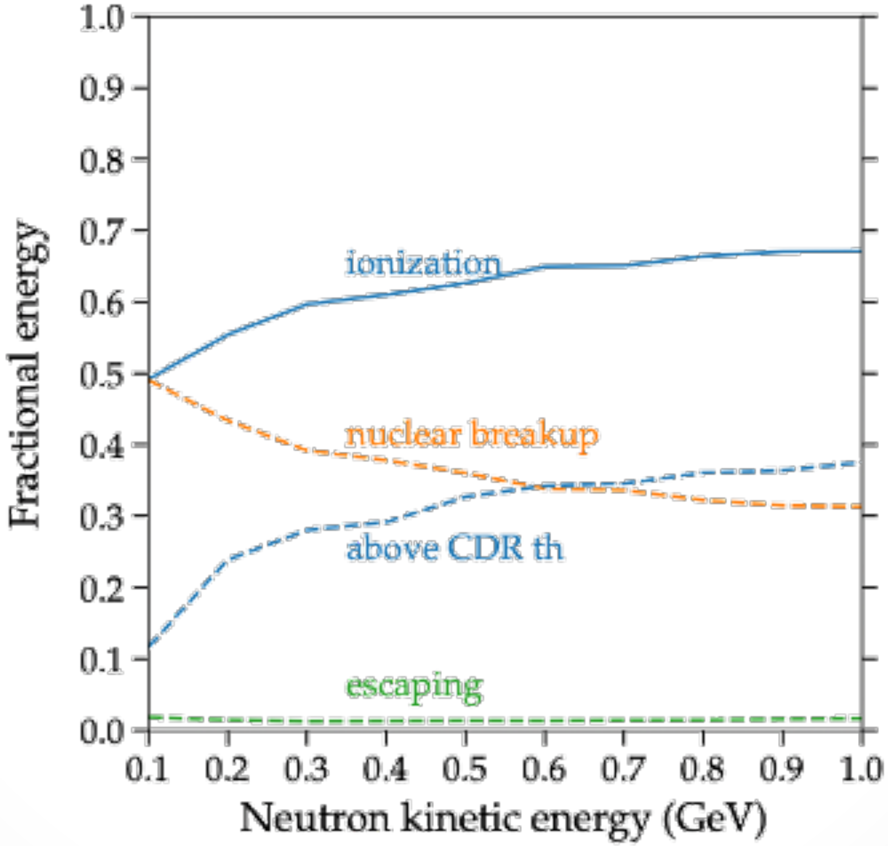

Extremely challenging to reconstruct neutrons

# Secondary particle propagation

Friedland & Li, 2018

Neutrons

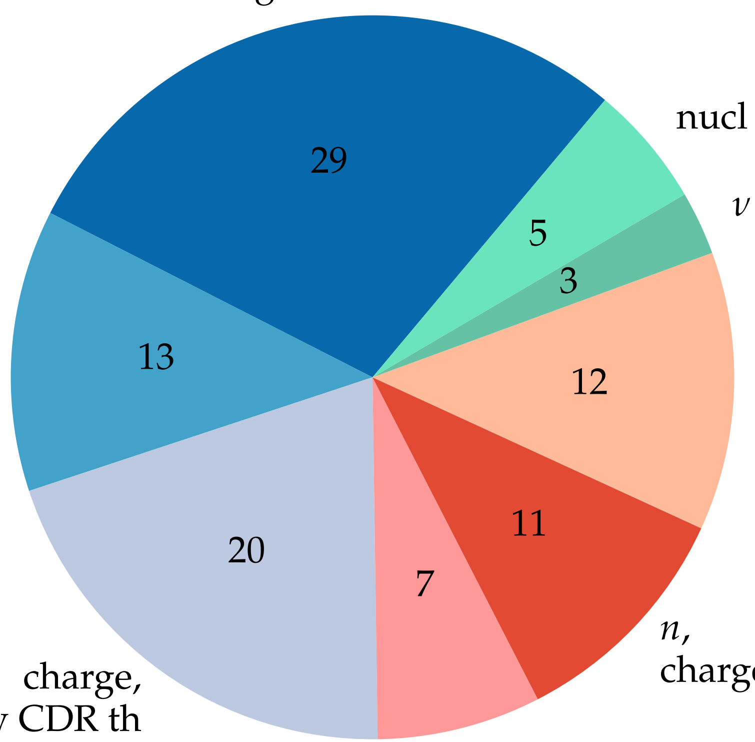
FLUKA




Neutron deposit ~ 50% of its energy in ionization

# Missing energy in $E_h$

After full propagation




Friedland & Li, 2018

1. Recombination:
   charge $\propto \frac{1}{1+0.1\frac{dE}{dx}}$

2. Nuclear breakup:
   $p + {}^{40}\text{Ar} \rightarrow 3p + X$
   Energy -> nuclear binding energy

3. Thresholds

4. Neutrons

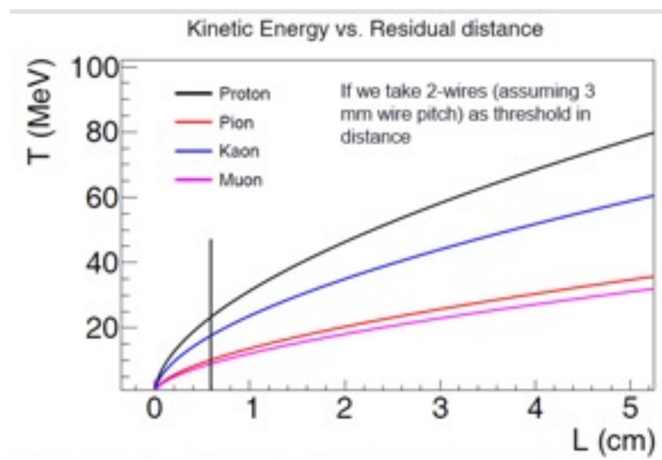
# Detection thresholds

## Uncertain; large possible range

**Extremely conservative**

| Particle type | Detection Threshold (KE) |
|---|---|
| $\mu^{\pm}$ | 30 MeV |
| $\pi^{\pm}$ | 100 MeV |
| $e^{\pm}/\gamma$ | 30 MeV |
| p | 50 MeV |
| n | 50 MeV |
| other | 50 MeV |

DUNE 2015



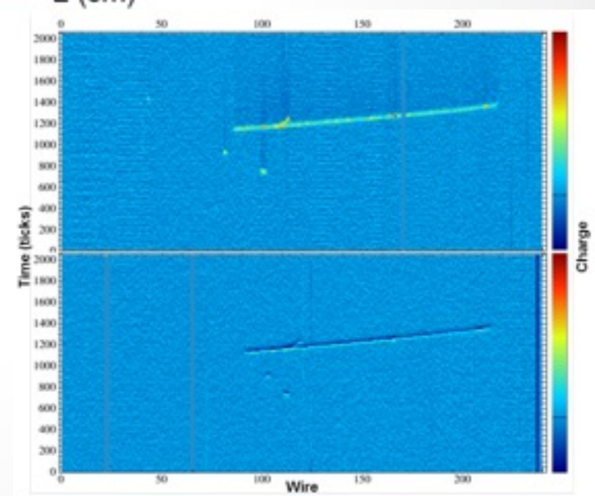

**Reasonable estimates**

Figure from X. Qian

**Promising optimistic case**

E < 1 MeV

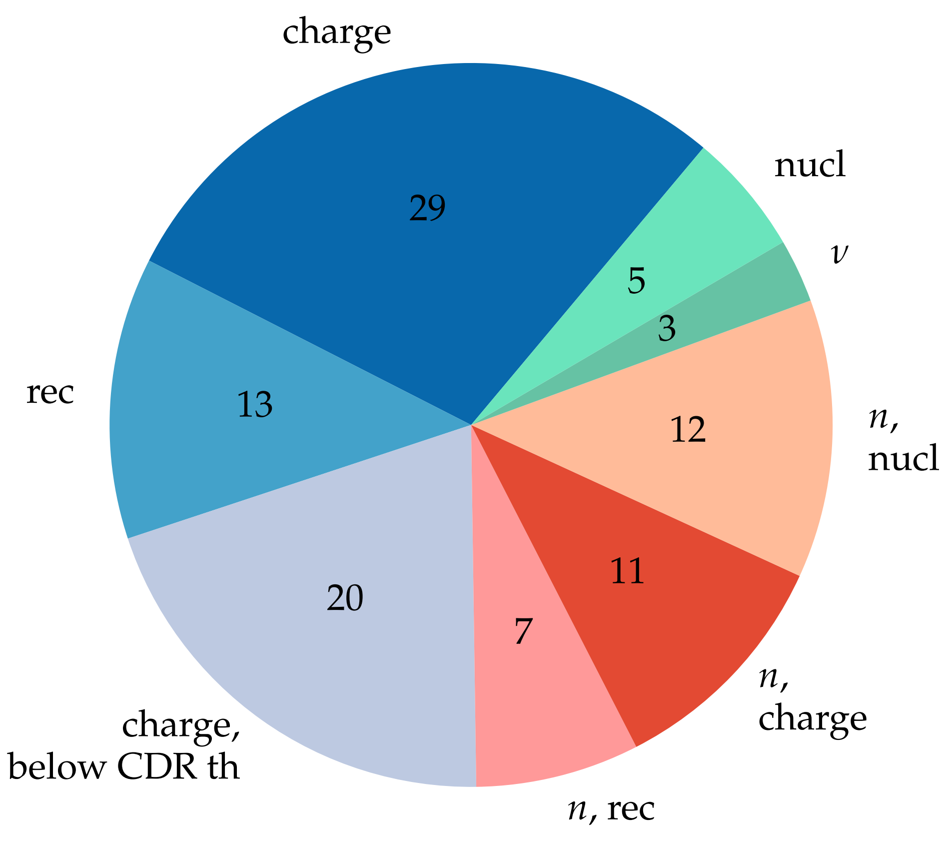
ArgoNeuT 2018



# Missing energy in $E_h$

Friedland & Li, 2018

## Reducible vs. irreducible

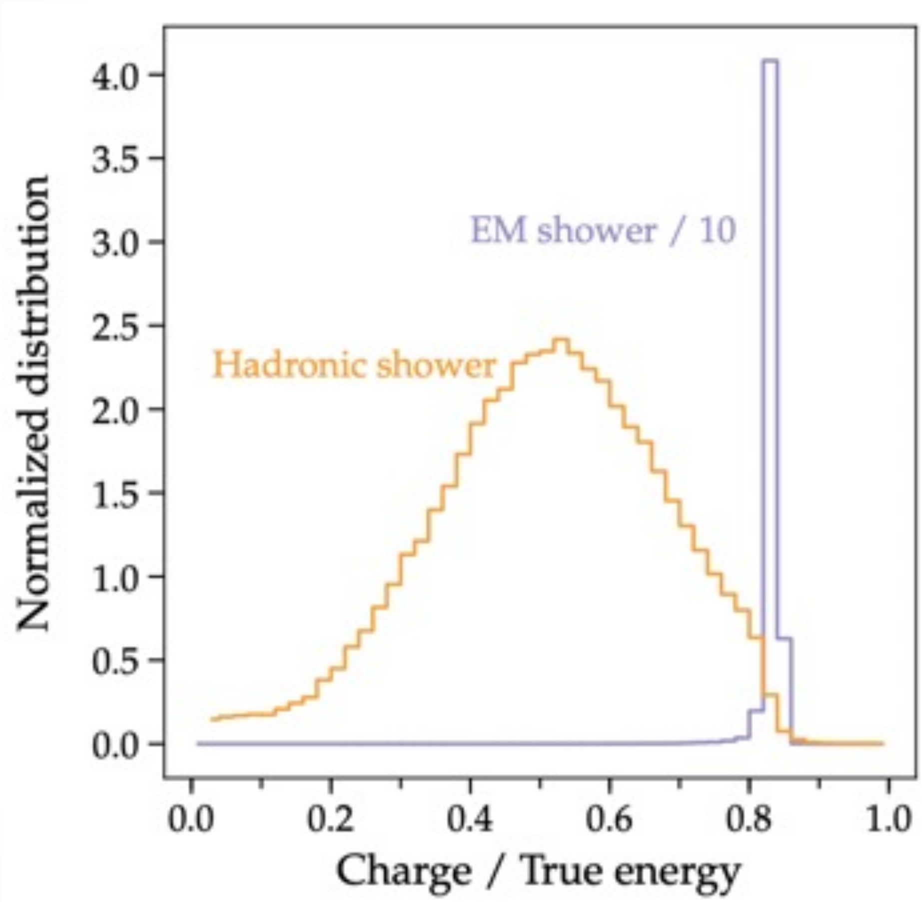



1. Reducible: threshold, rec
2. Irreducible: nucl, $\nu$, neutron

Irreducible missing energy has to be simulated correctly

# Missing energy fluctuations

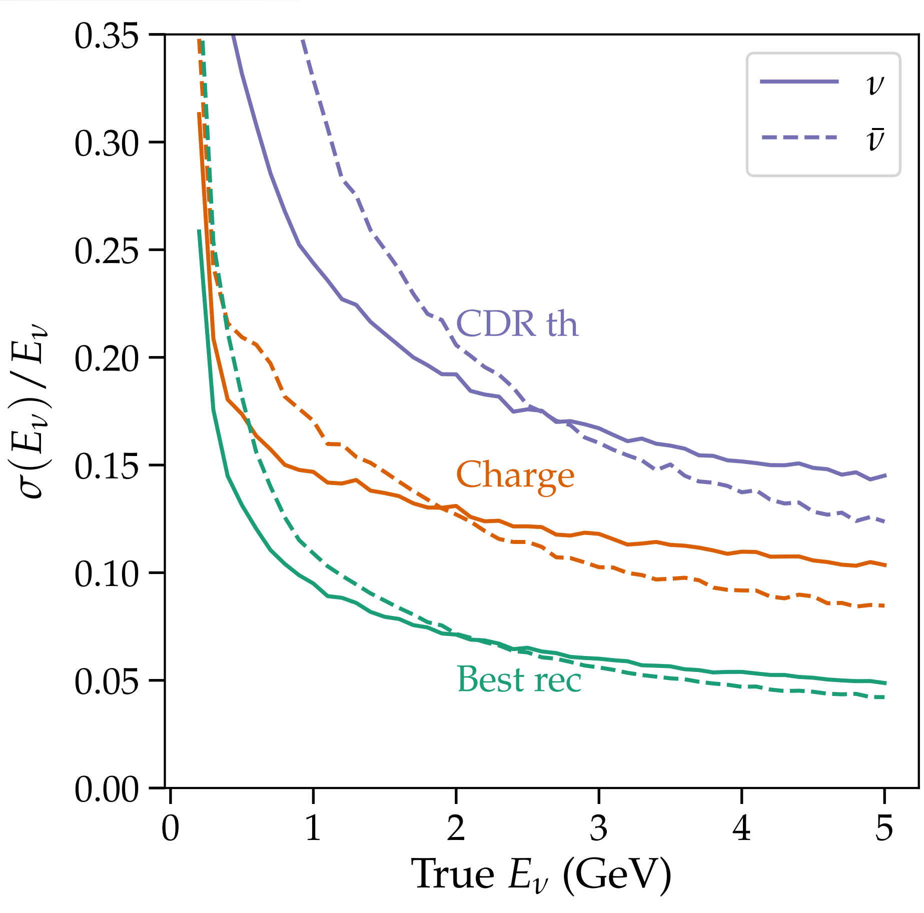
Friedland & Li, 2018




Large fluctuations in hadronic showers

# Energy reconstruction results

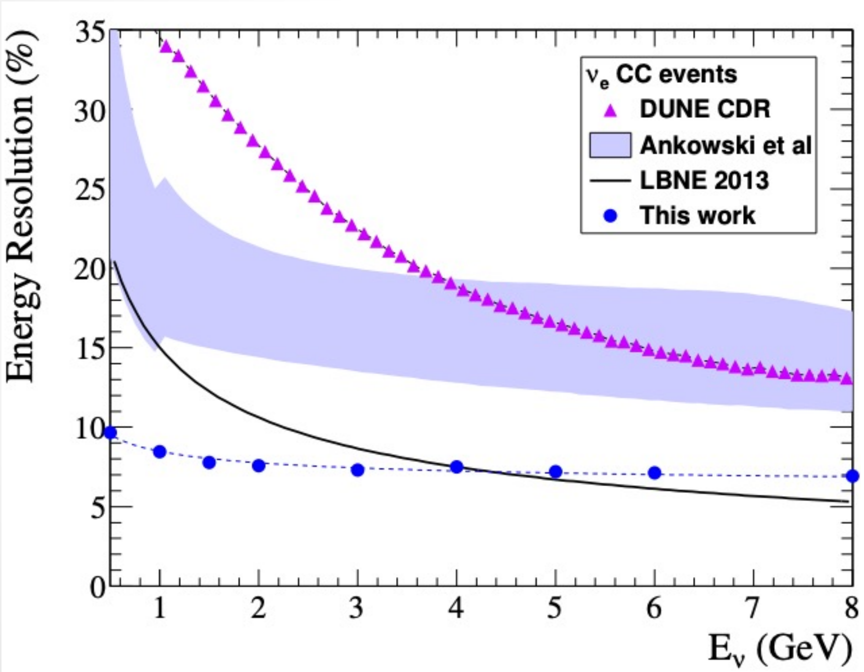
Friedland & Li, 2018



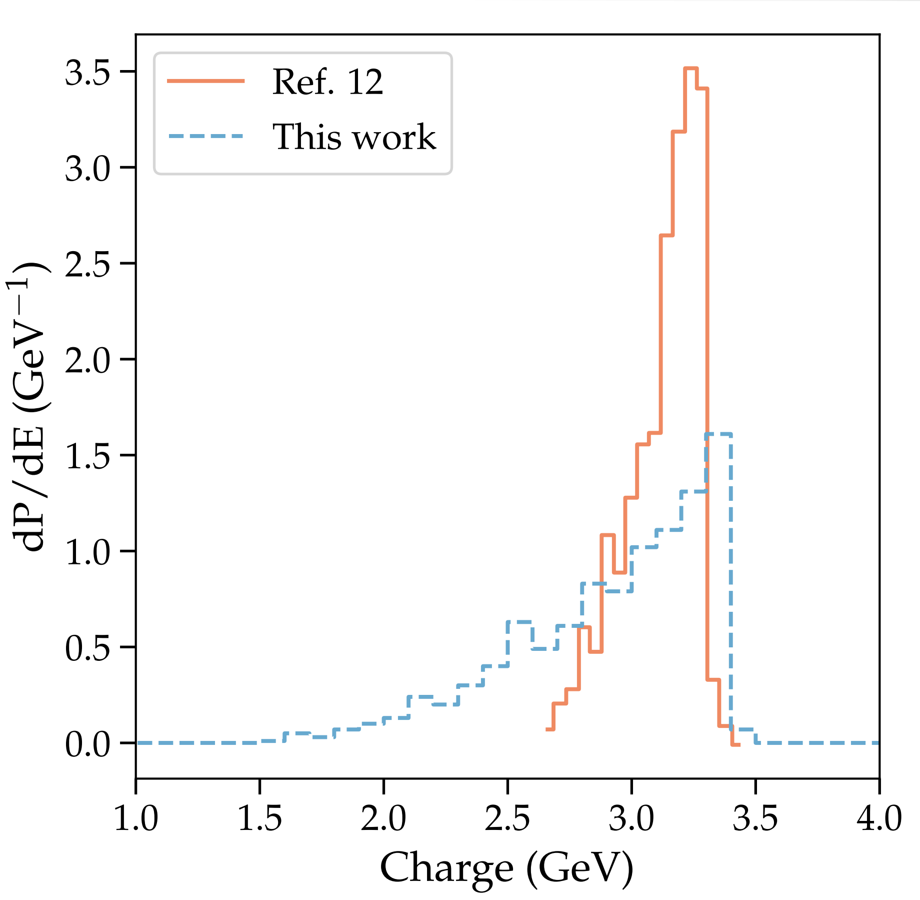

1. CDR th: method as it is
2. Charge: collect all charges with no thresh.
3. Best rec: no thresh., correct for recombination

# Comparisons to other work

Romeri, Fernandez-Martinez & Sorel, 2016



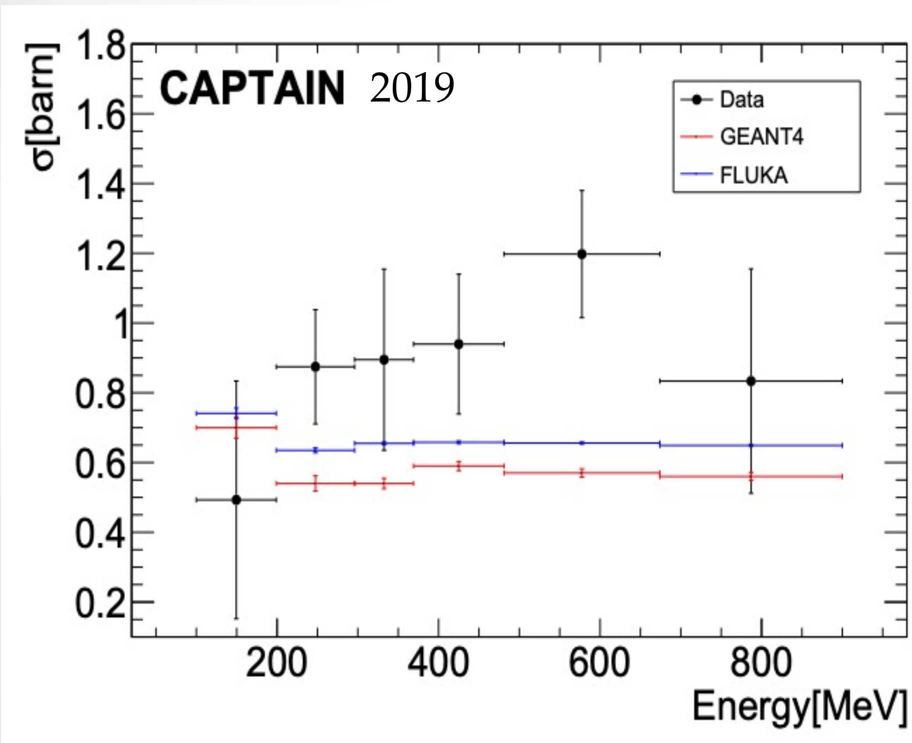

Friedland & Li, 2018




Further studies warranted

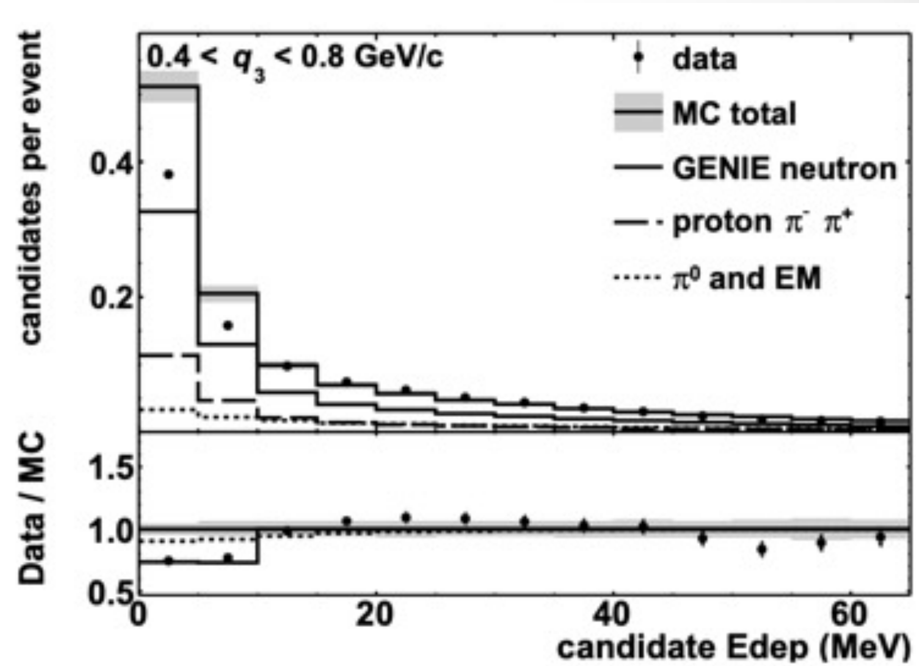
# Recent experimental work

## Neutron in argon measurements



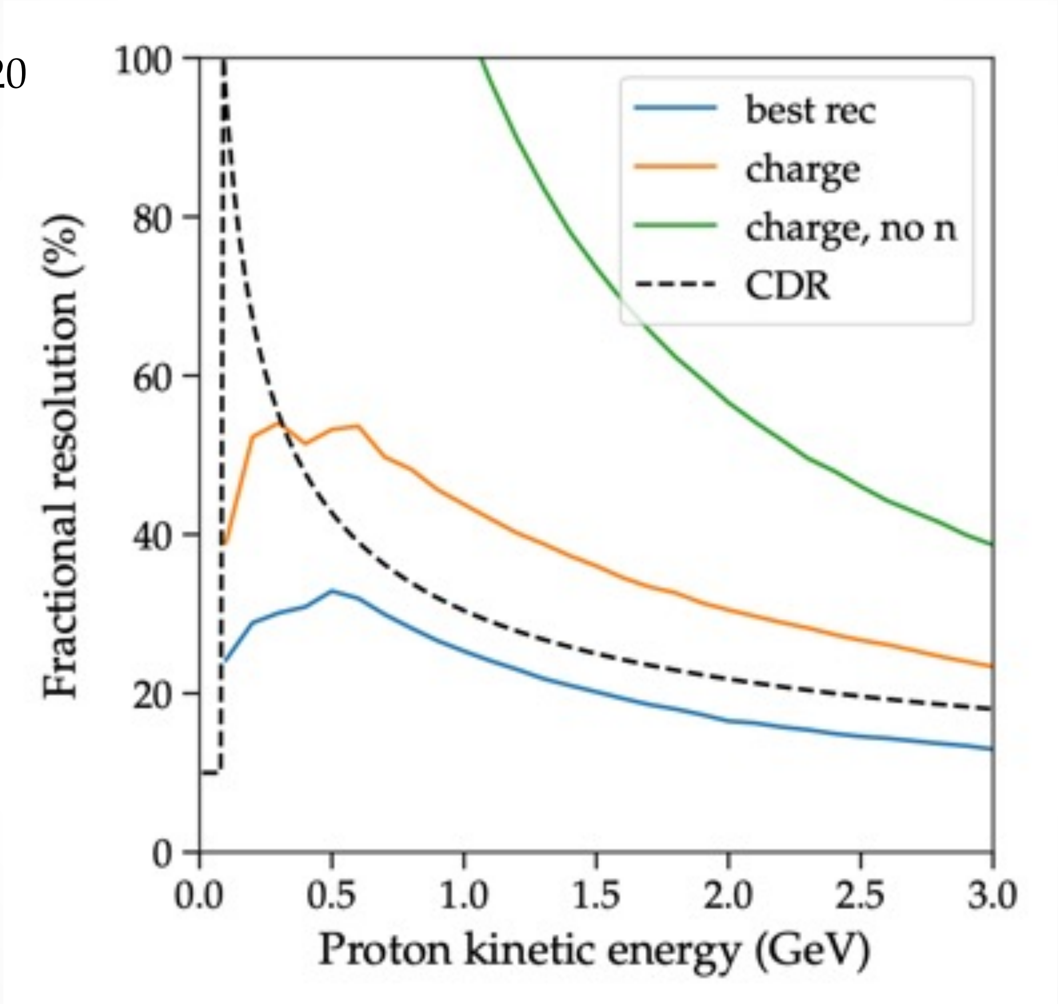

## Neutron in $CH_2$ measurements

MINERvA 2019



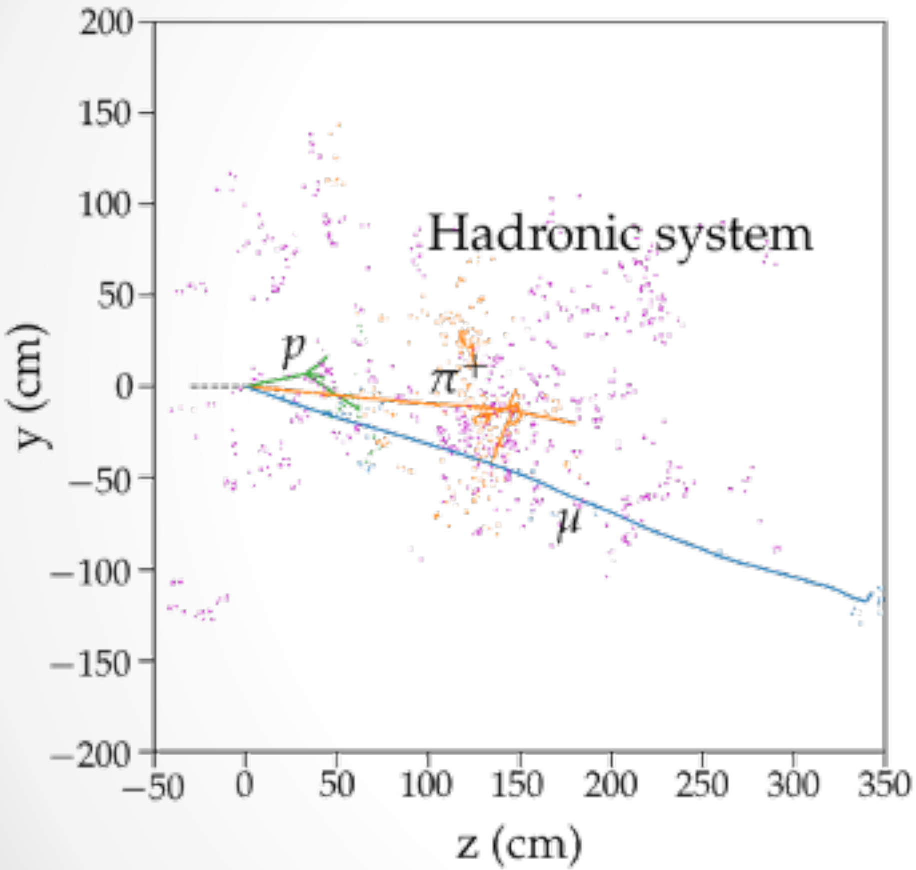
# Test beams

Friedland & Li, 2020




Same discussions for proton, pion, and neutron beams

# Connection to $\nu$-A cross sections




- Proton vs. Pion: Quenching
- Spectrum:
  Thresholds
- Number of Final-State Particles:
  Nuclear Breakup Energy

All Exclusive Final States Play A Role

# Conclusions

1. Energy resolution is a key quantity in terms of understanding the performance of LAr detectors

2. Uncertainties from $\nu$-A interactions, particle propagation, and analysis choices

3. We investigated the impacts of different analysis choices

4. Further studies needed