Picture Credit: Getty Images

Challenges in modern neutrino oscillation experiments

Shirley Li

Collaborators: A. Ankowski, A. Friedland

BAPTS, Mar 2019

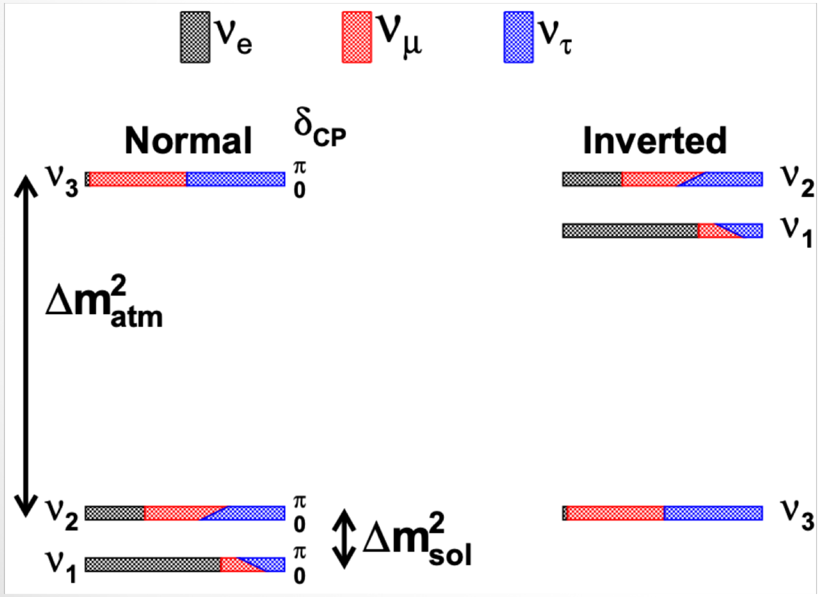
Neutrino oscillation

Mapping out PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{ij} = cos\theta_{ij}, s_{ij} = sin\theta_{ij}$

Qian & Vogel, 2015



Current measurements:

<u>2—5% error:</u>
$\theta_{12}, \theta_{13}, \delta m^2_{12}, \delta m^2_{23}$

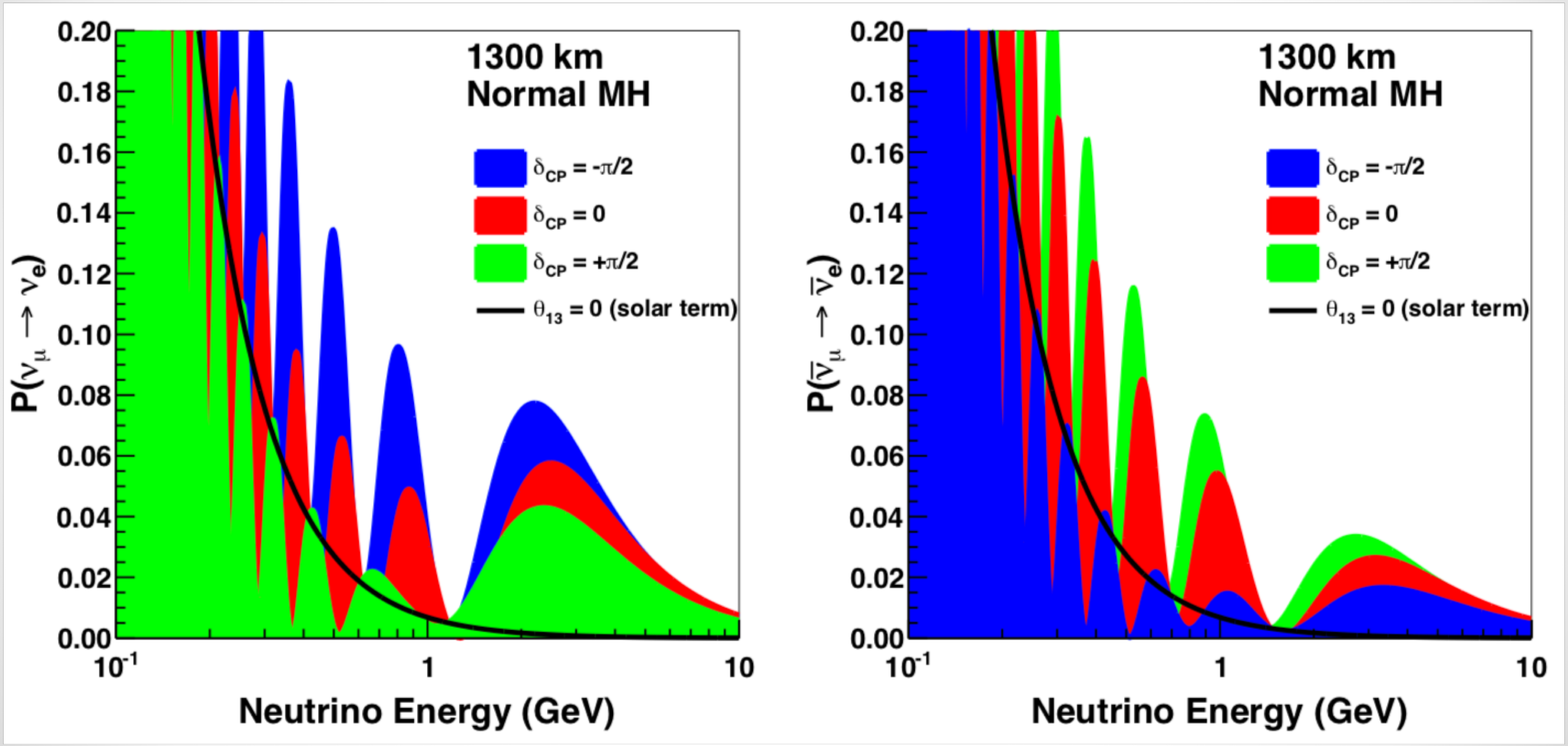
<u>10% error:</u>
θ_{23}

<u>No measurements:</u>
δ_{CP}, mass hierarchy (MH)

Measuring δ_{CP} and MH

$$0.5\text{—}5\ \text{GeV}\ \nu_\mu \xrightarrow{\sim 1000\ \text{km}} \nu_e$$

DUNE 2015

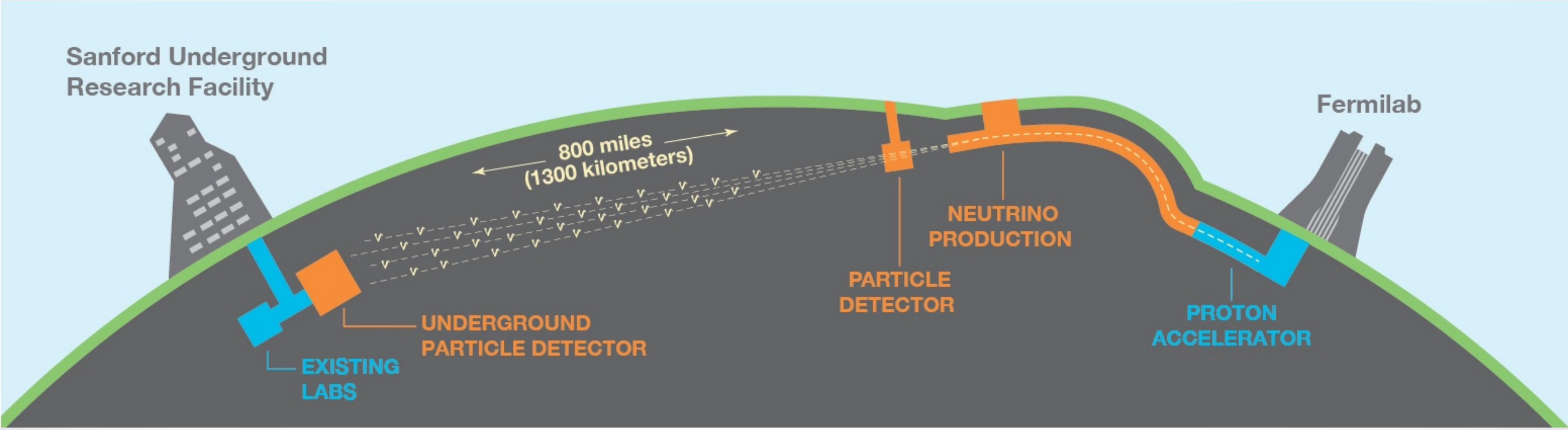


Need to measure $N(E_{\nu_e})$

Long baseline experiment

DUNE

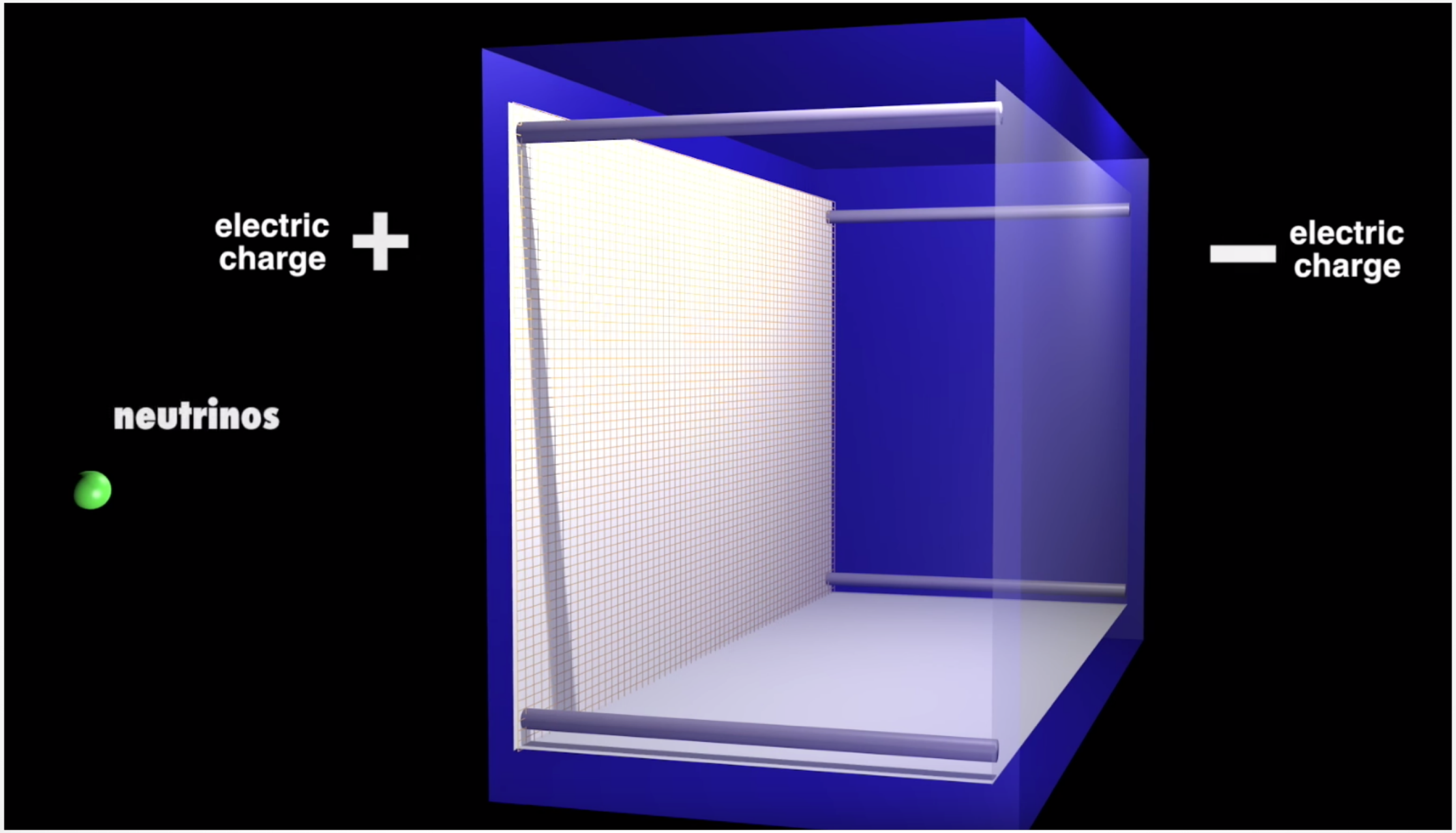
Figure: dunescience.org



DUNE detector

Animation by Fermilab Creative Services, 2016

40 kton liquid argon TPC

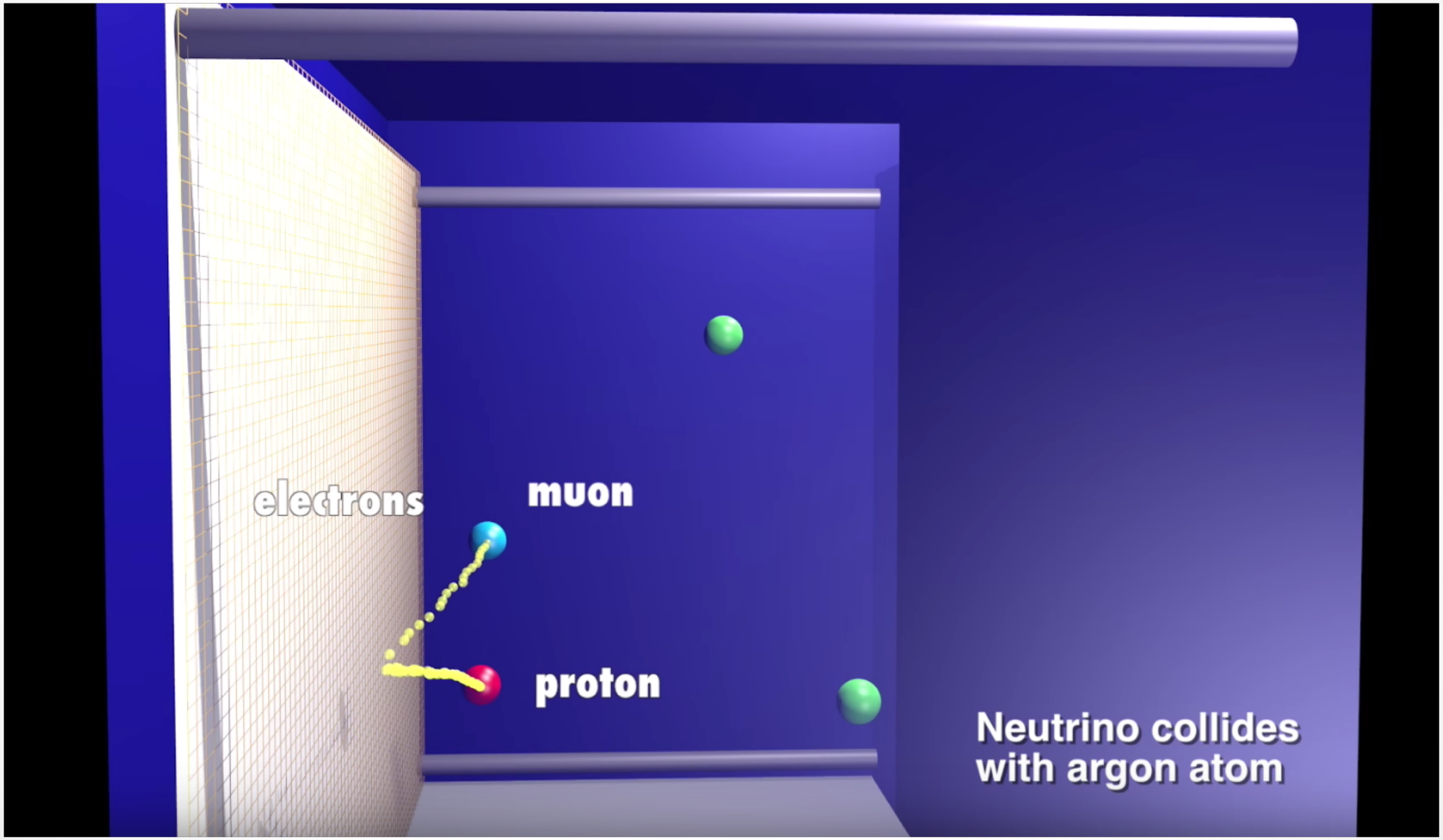


Detects charged particles above thresholds

DUNE detector

Animation by Fermilab Creative Services, 2016

40 kton liquid argon TPC

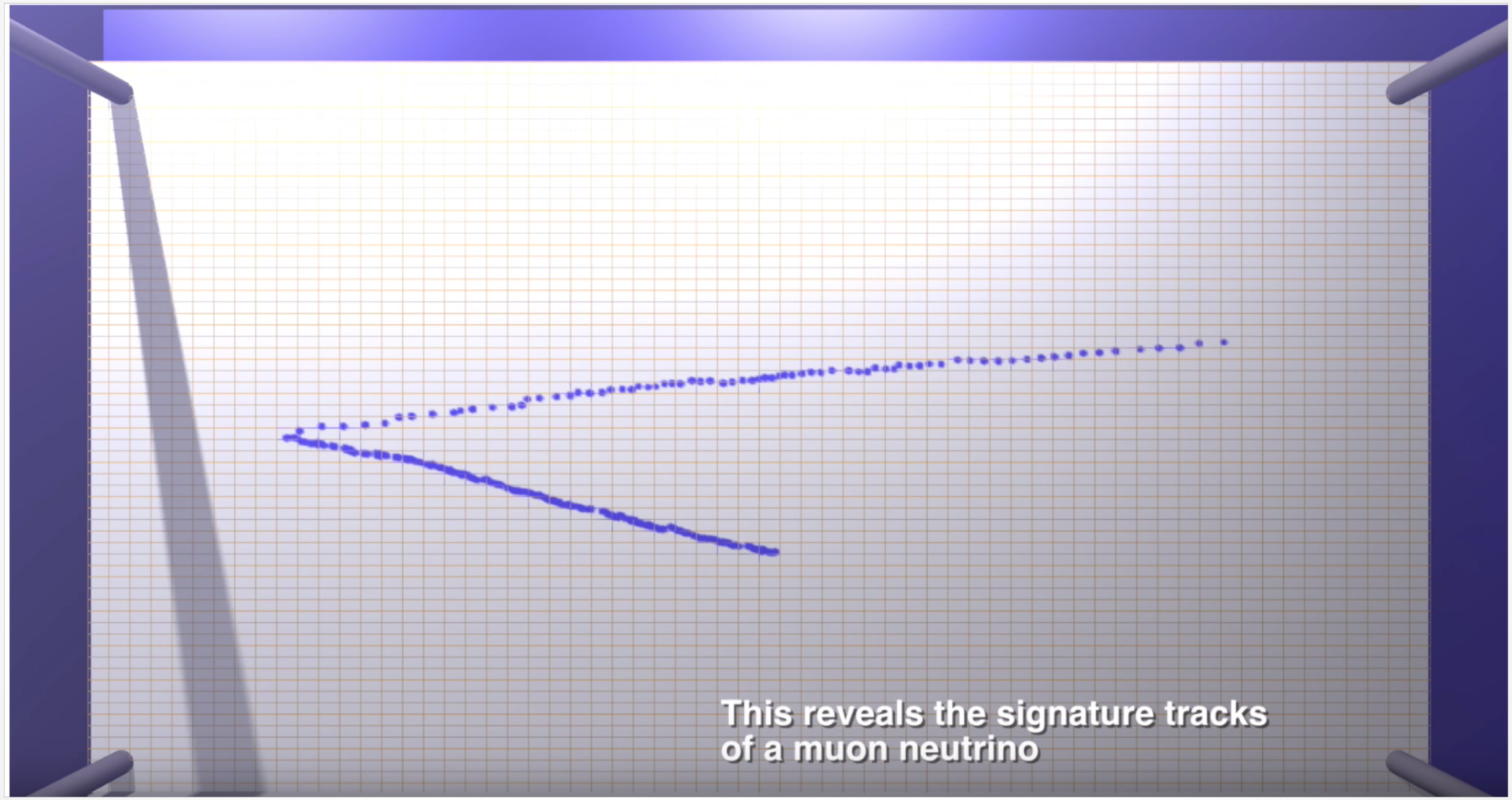


Detects charged particles above thresholds

DUNE detector

Animation by Fermilab
Creative Services, 2016

40 kton liquid argon TPC

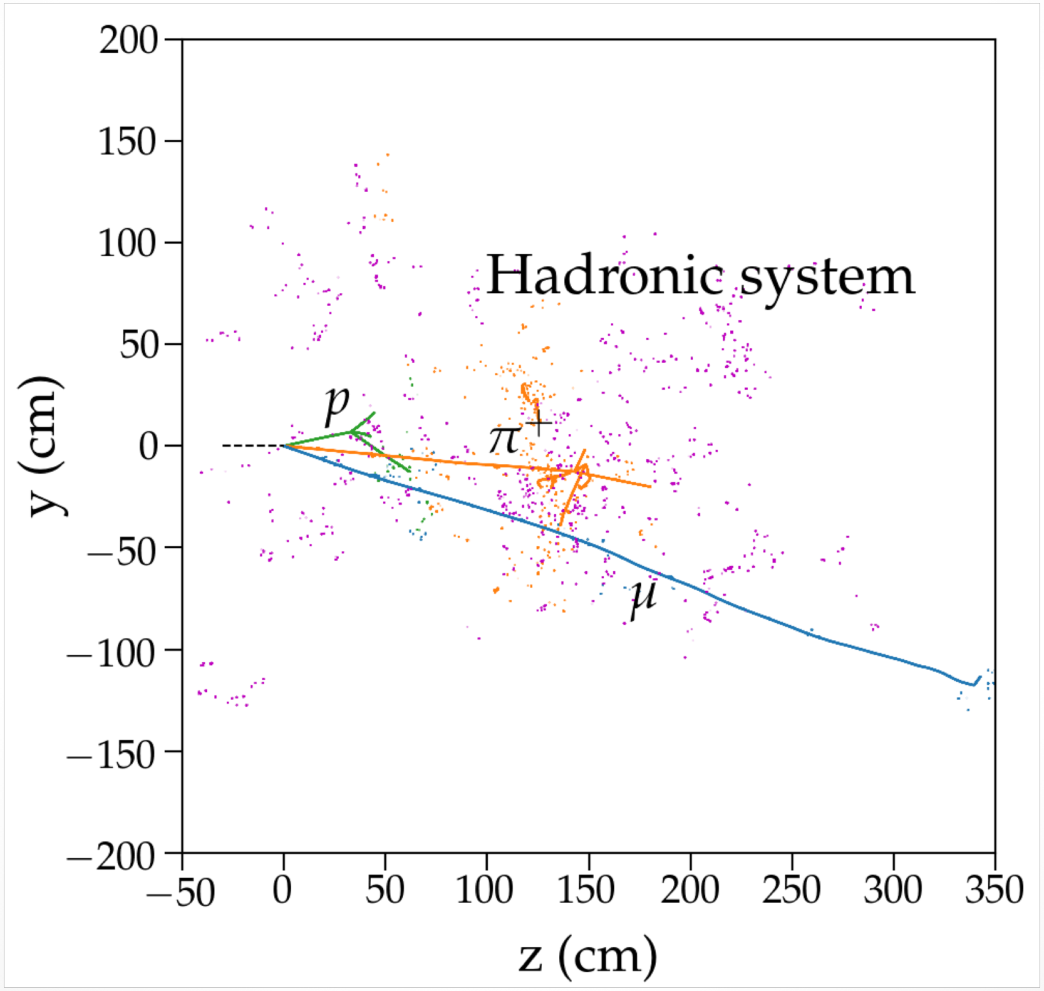


Detects charged particles above thresholds

The overarching question

How well can we measure neutrino energy?

Simulated with GENIE+FLUKA

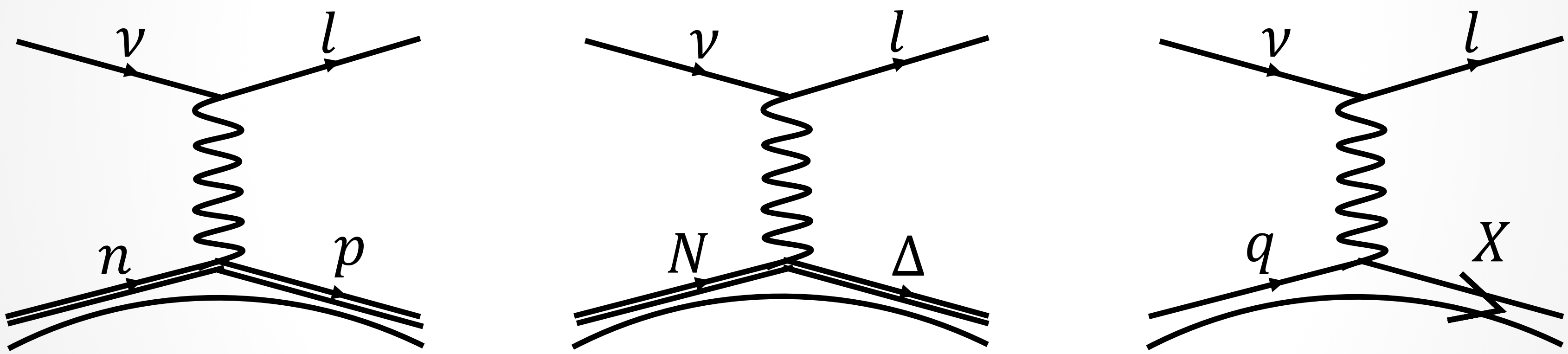


Friedland & Li, 2018

Neutrino-nucleus cross sections

0.5 GeV – 5 GeV

quasi-elastic scattering	resonance production	deep inelastic scattering



a nucleon	a nucleon + a meson	multiple particles

Complete theoretical description is difficult

What needs to be understood?

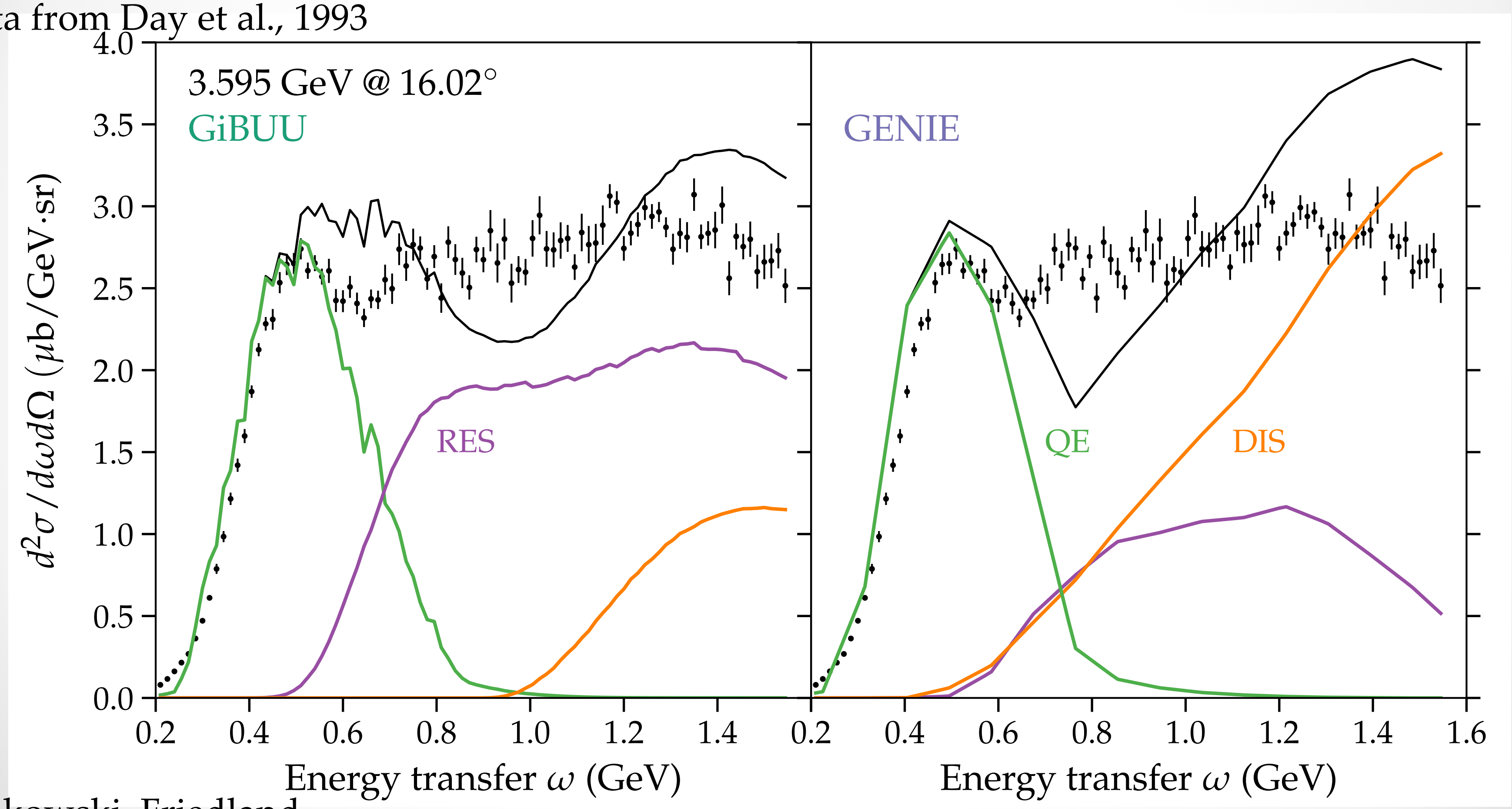
My wish list:

- *What are current cross section uncertainties?*
- *How much will they affect CP, MH measurements?*
- What level of accuracy is needed?
- How can we reduce uncertainties?

Status of cross section prediction

Electron scattering: generator vs. data

Data from Day et al., 1993



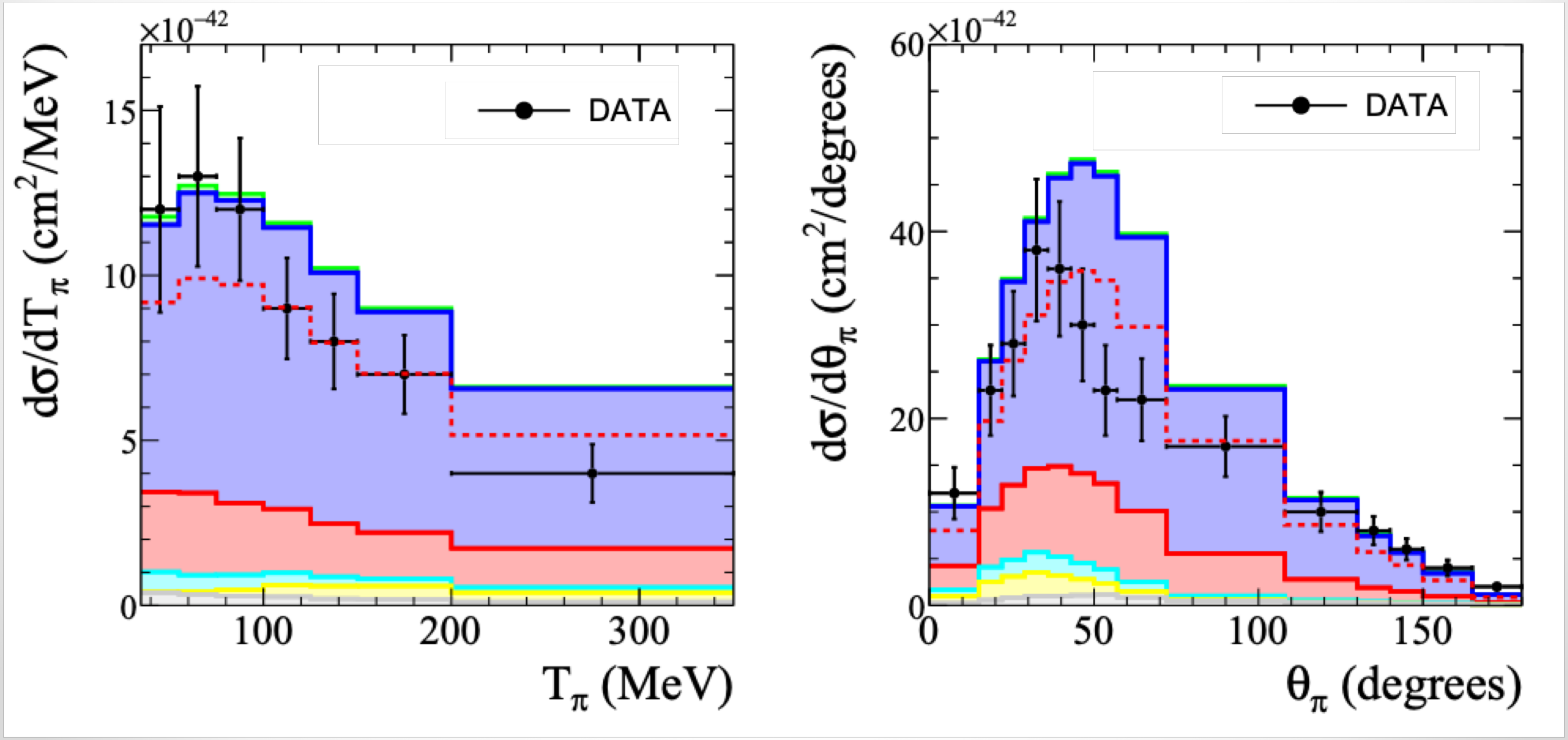
Ankowski, Friedland & Li, in prep

Status of cross section prediction

Exclusive channels

MINERνA data vs. GENIE prediction

MINERνA 2019



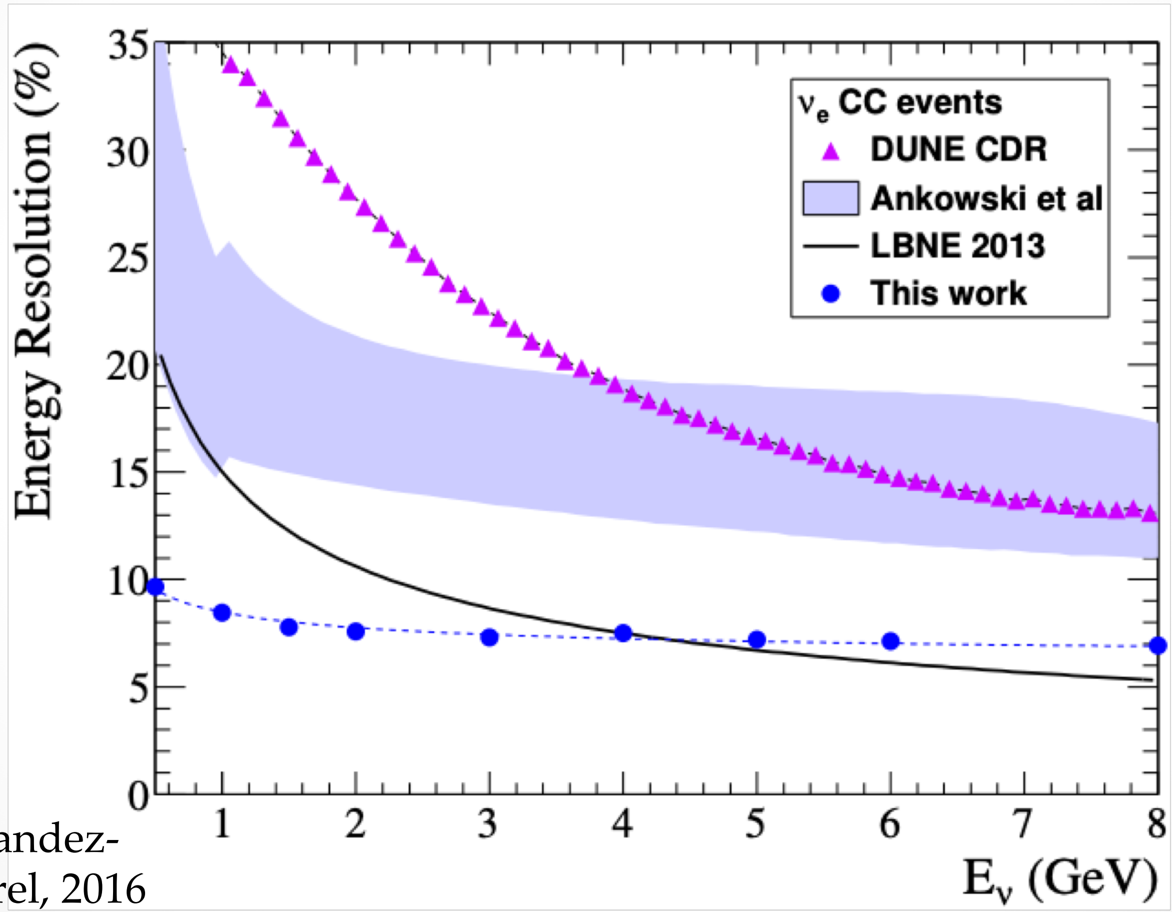
The impact of cross section

different cross sections --> different E_ν measurements

one cross section --> ??

No consensus in the field

Energy resolution from prior work



Romeri, Fernandez-Martinez & Sorel, 2016

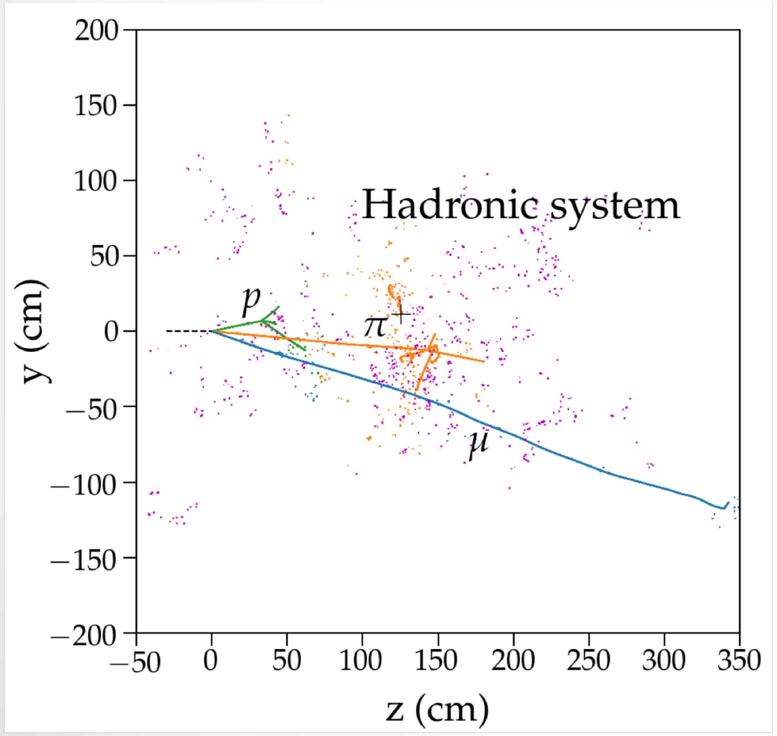
Disagreement in procedure > physics difference

Calorimetric energy reconstruction

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

Simulated with GENIE+FLUKA

Friedland & Li, 2018



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 $E_\nu = f(E_l, E_h)$

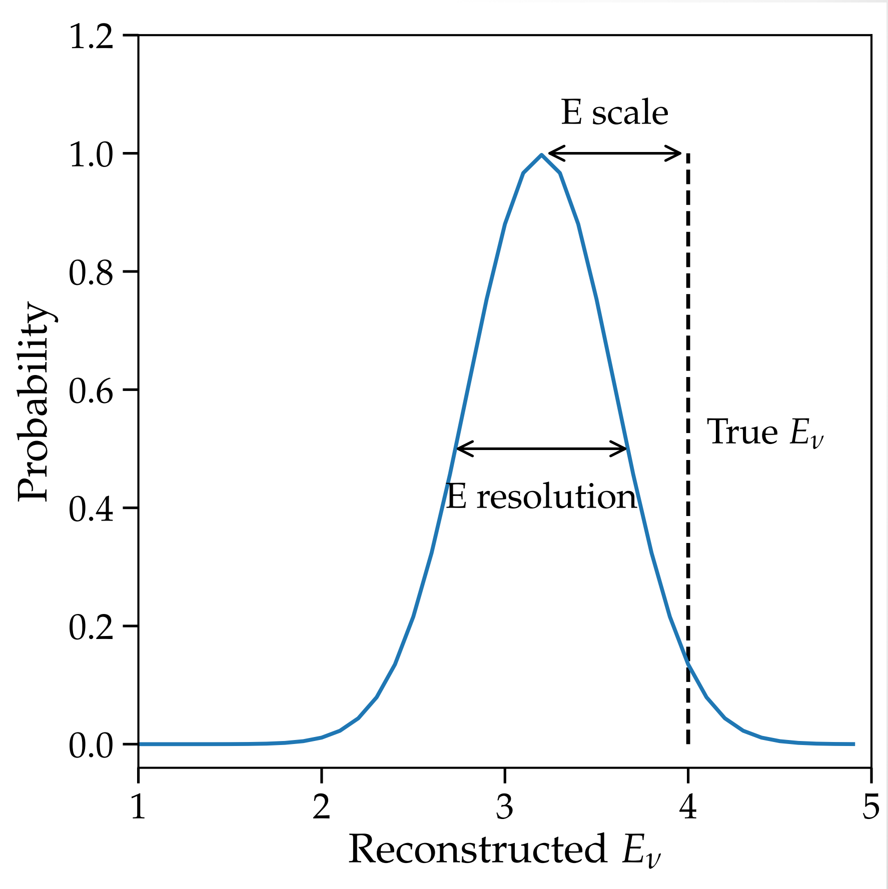
How to characterize its performance?

Calorimetric energy reconstruction

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

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

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



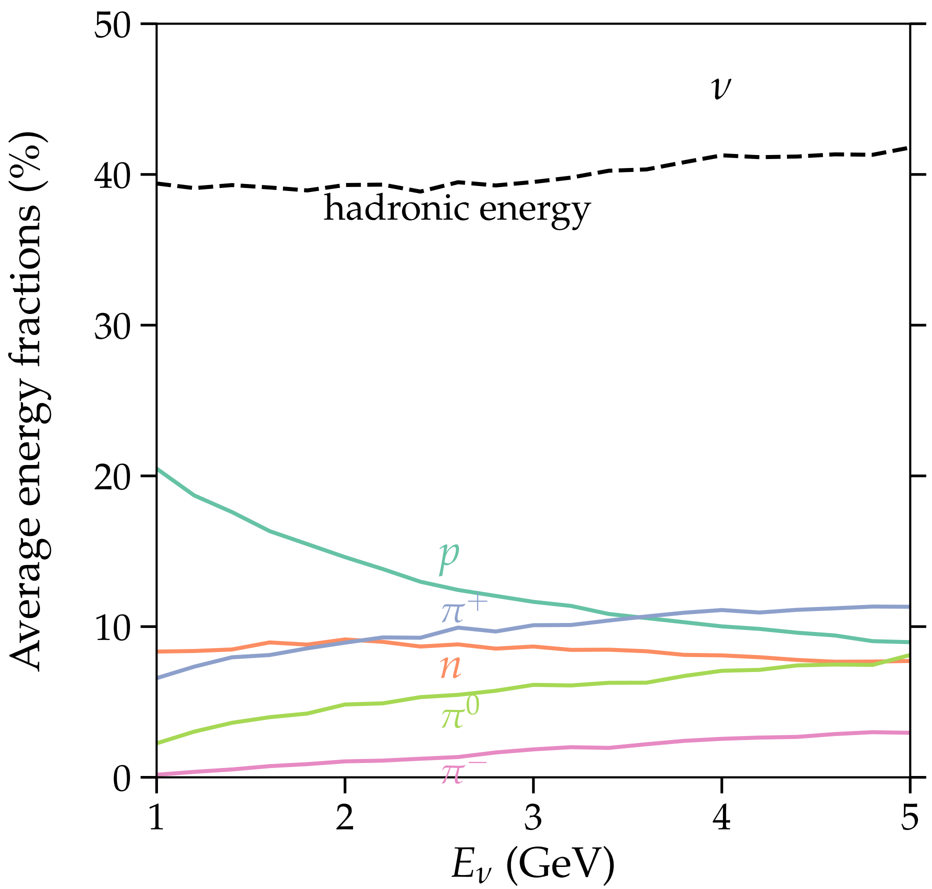
Understanding missing energy is the key

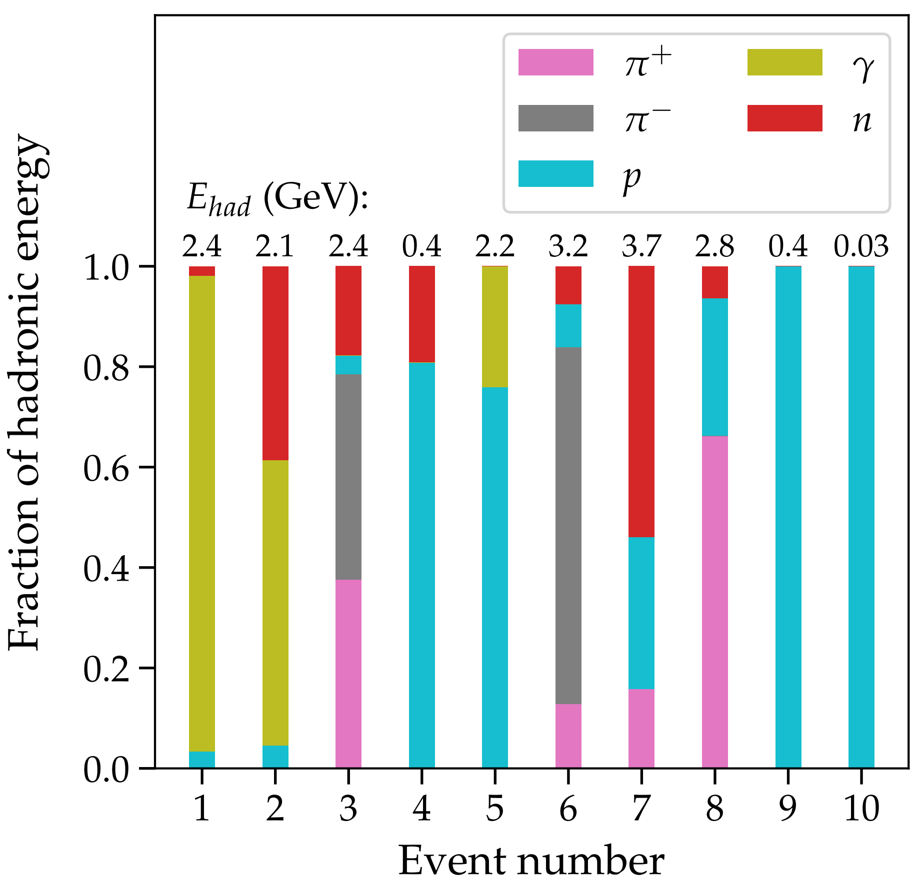
Hadronic system

Friedland & Li, 2018

Varied composition

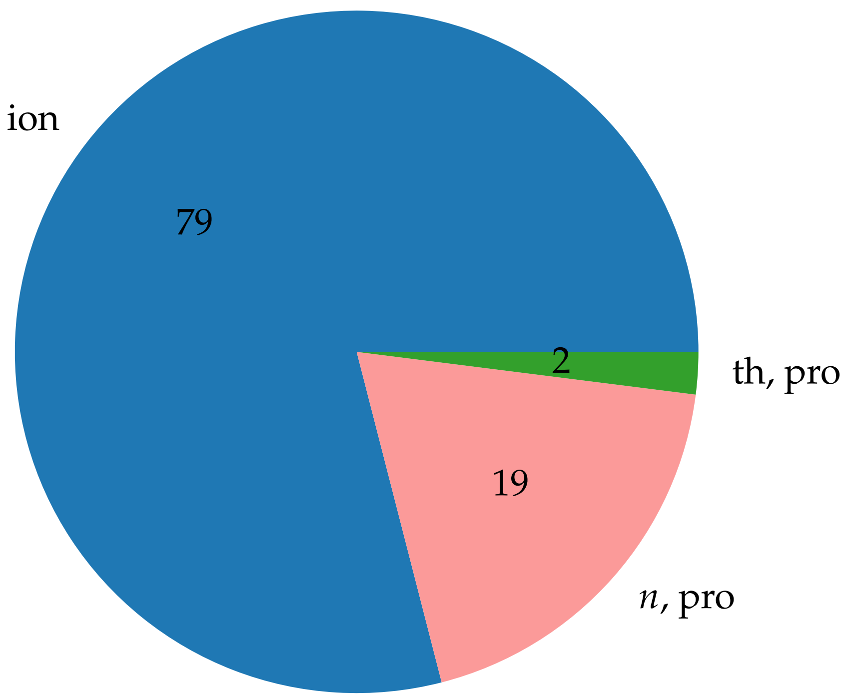
GENIE simulation





Missing energy in E_h

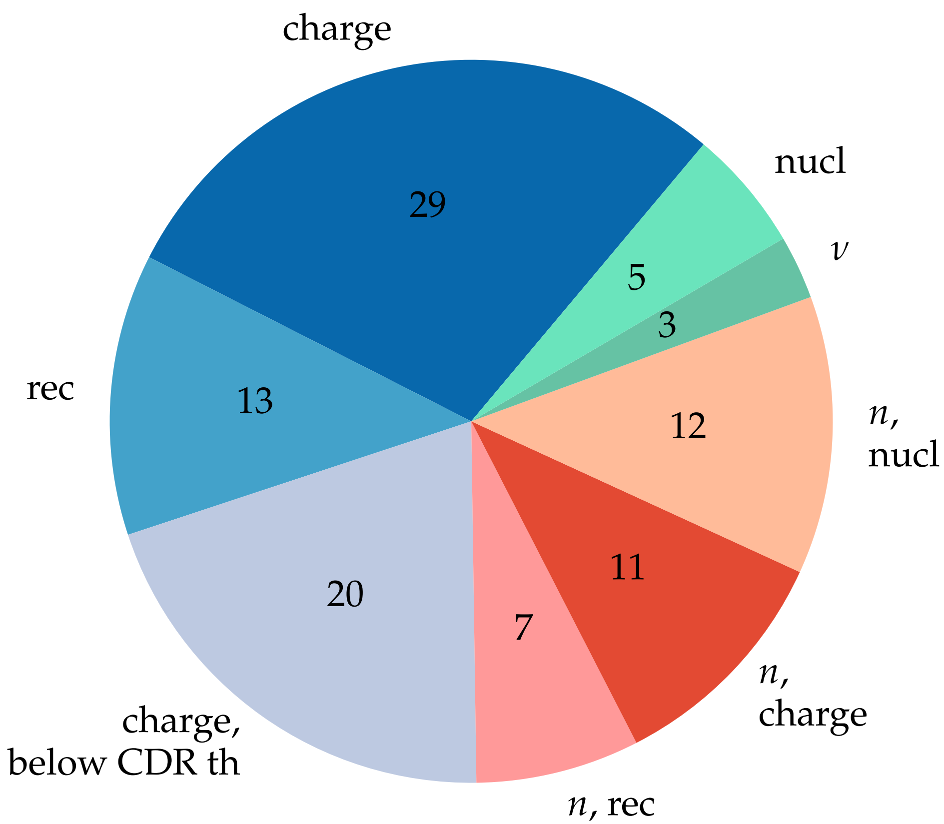
After primary vertex



Friedland & Li, 2018

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

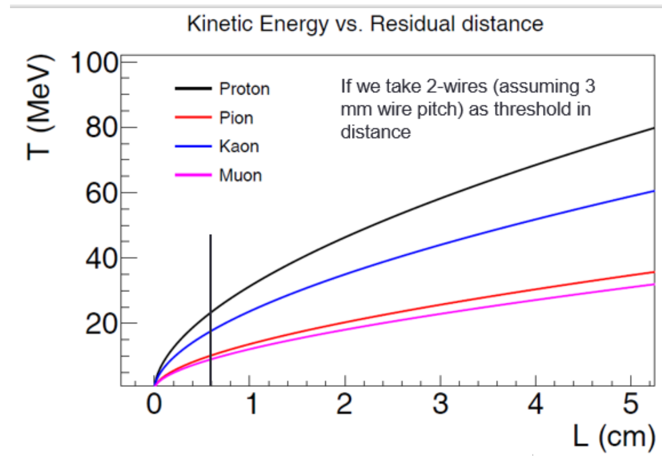
Detection thresholds

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



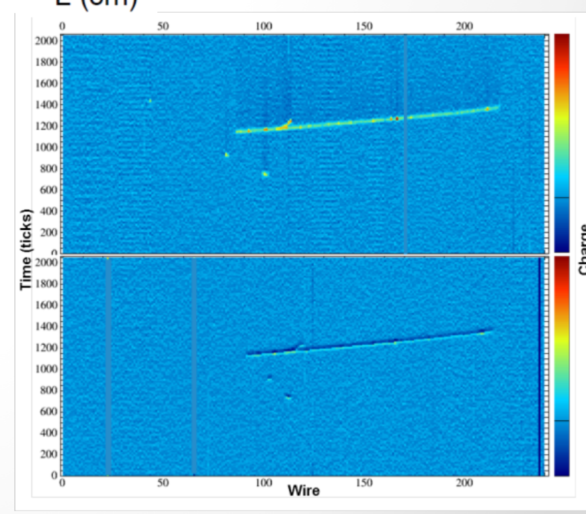
Reasonable estimates

Figure from X. Qian

Promising optimistic case

E < 1 MeV

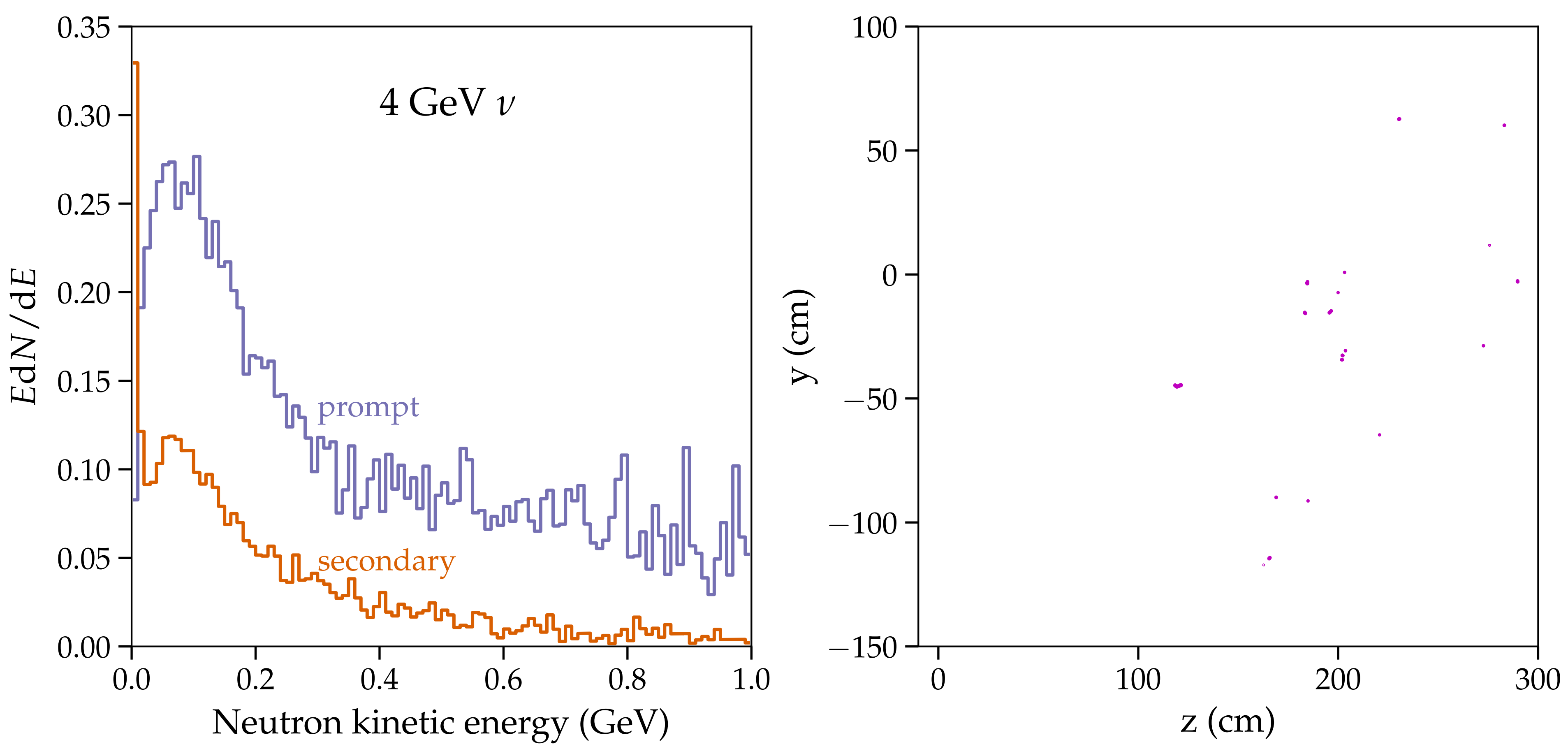
ArgoNeuT 2018



Neutrons

Friedland & Li, 2018

Simulated with GENIE+FLUKA

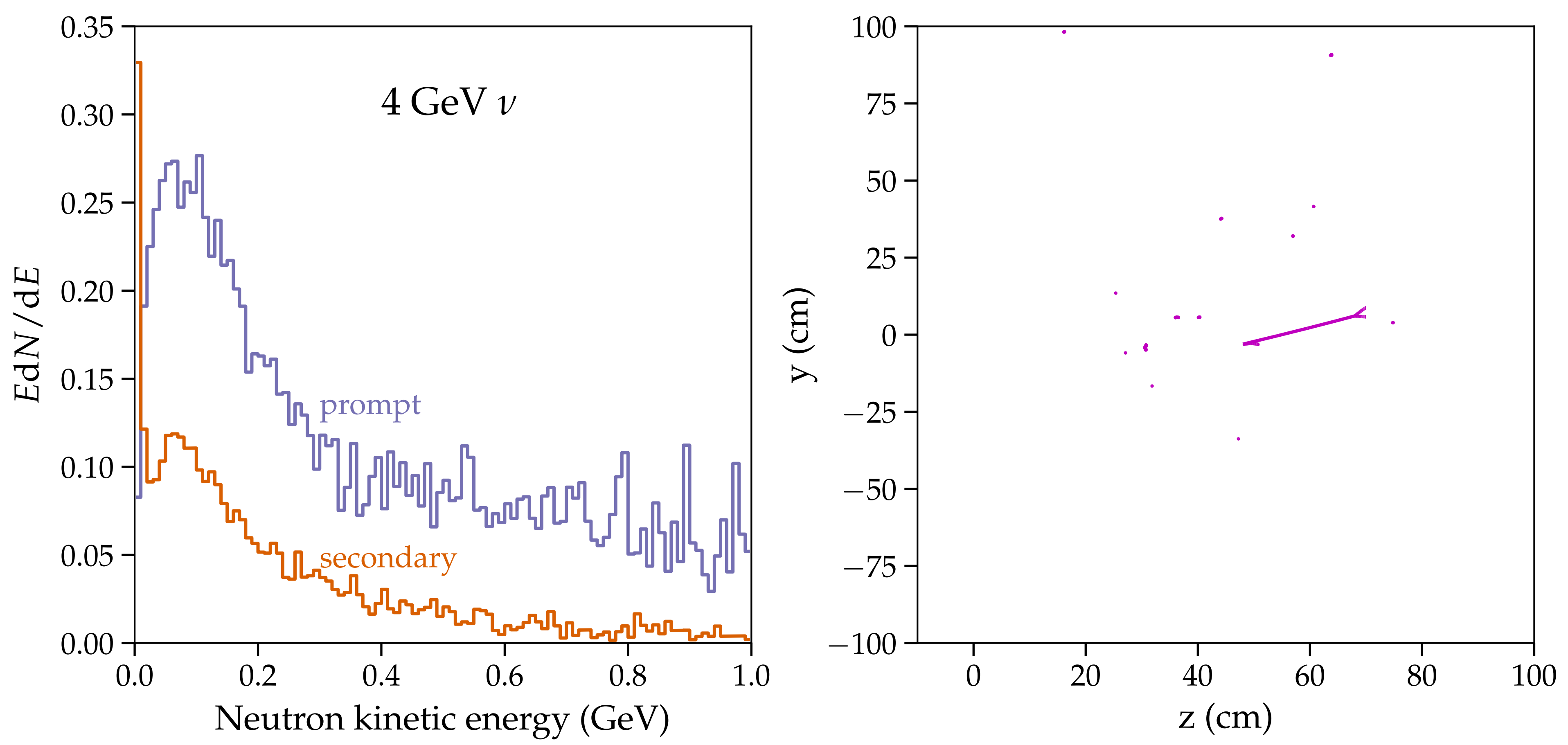


Extremely challenging to reconstruct neutrons

Neutrons

Friedland & Li, 2018

Simulated with
GENIE+FLUKA

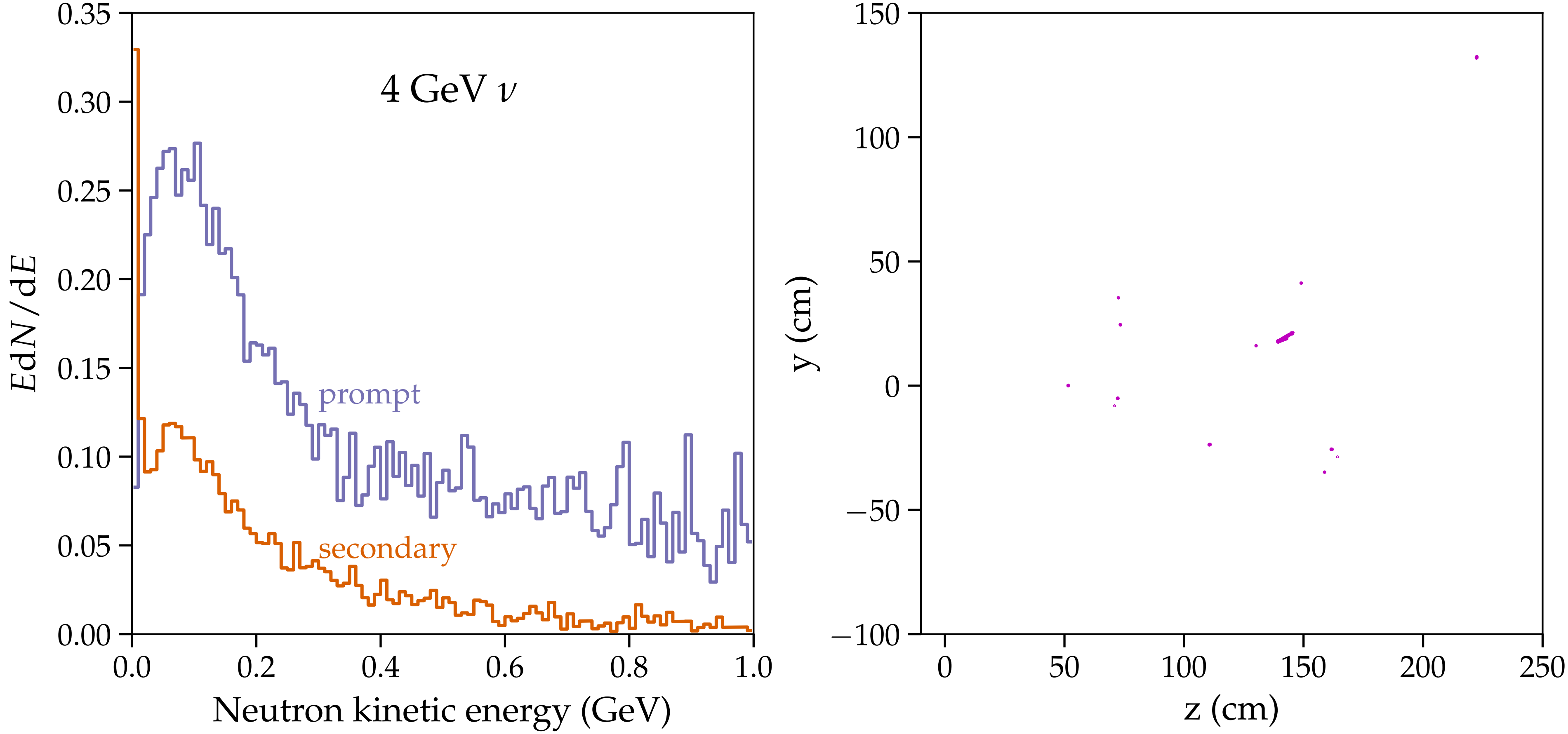


Extremely challenging to reconstruct neutrons

Neutrons

Friedland & Li, 2018

Simulated with GENIE+FLUKA

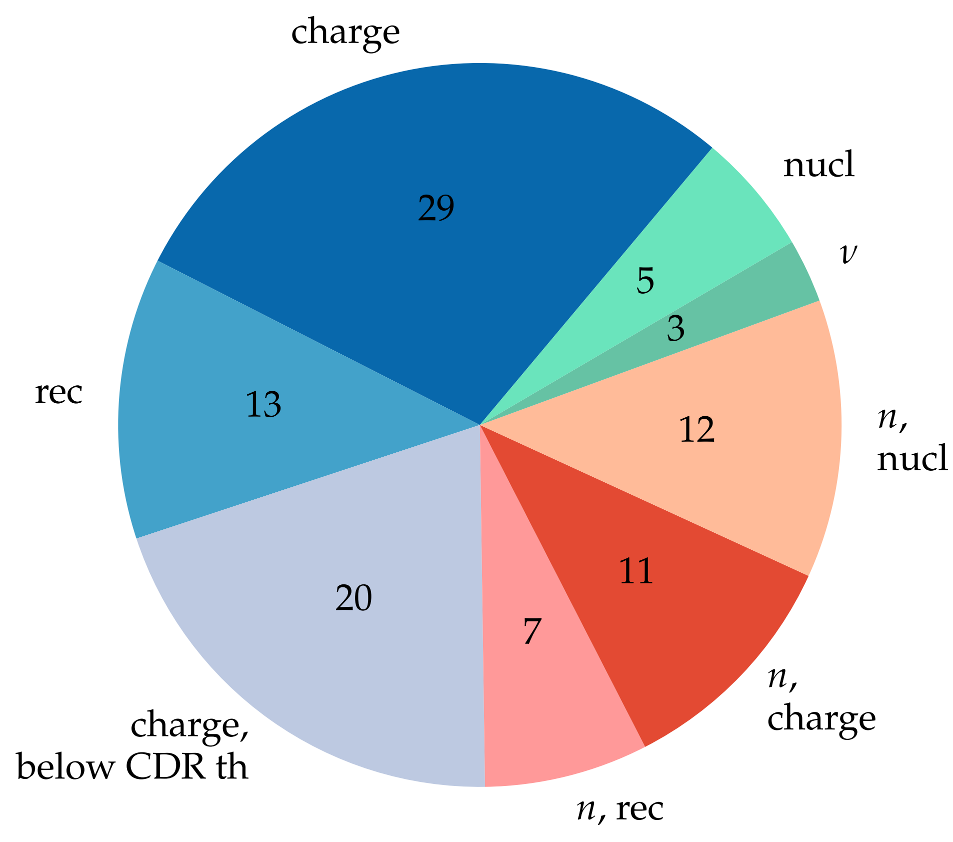


Extremely challenging to reconstruct neutrons

Missing energy in E_h

Friedland & Li, 2018

Reducible vs. irreducible

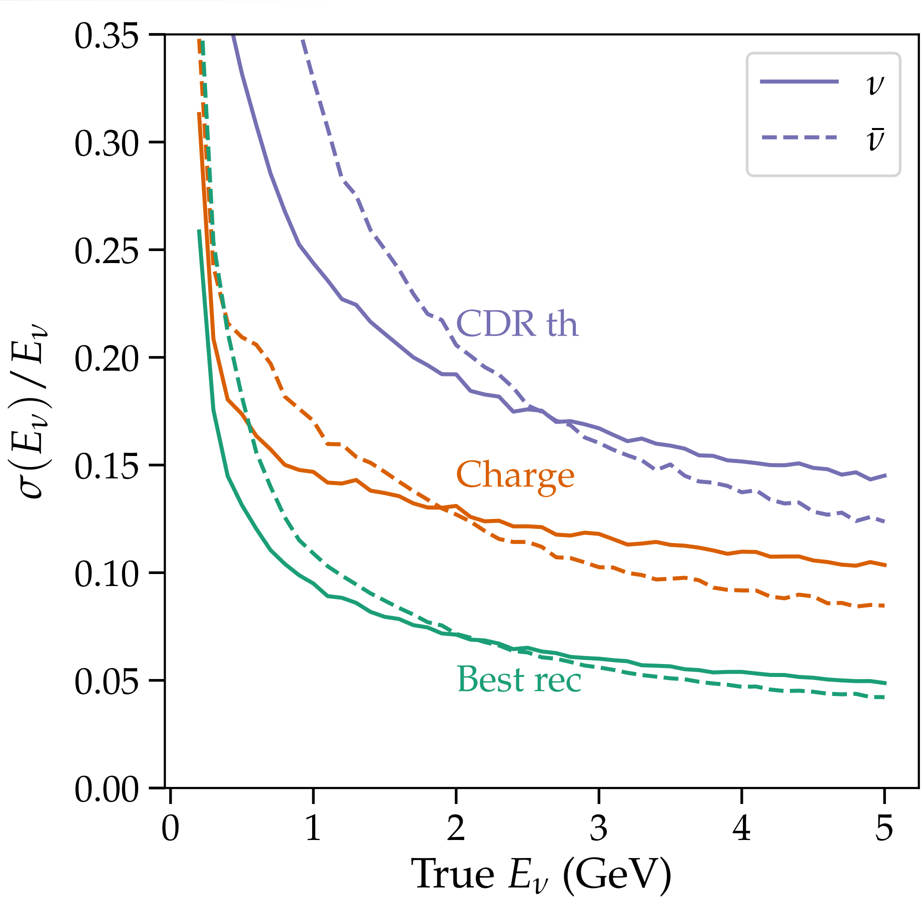


1. Reducible: threshold, rec
2. Irreducible: nucl, ν, neutron

Irreducible missing energy has to be simulated correctly

Energy reconstruction results

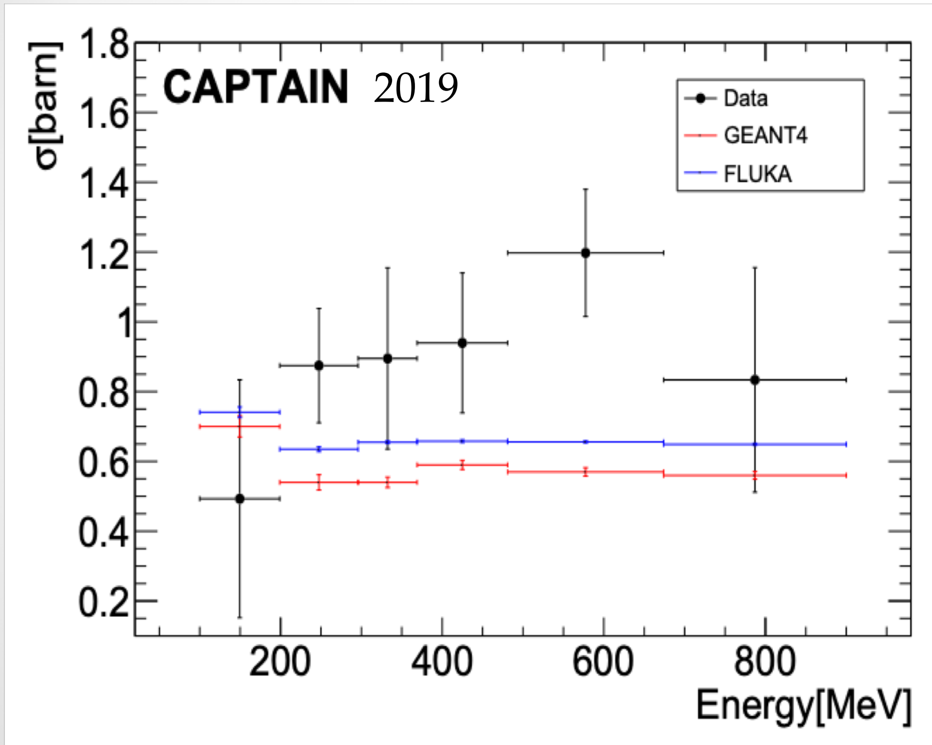
Friedland & Li, 2018



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

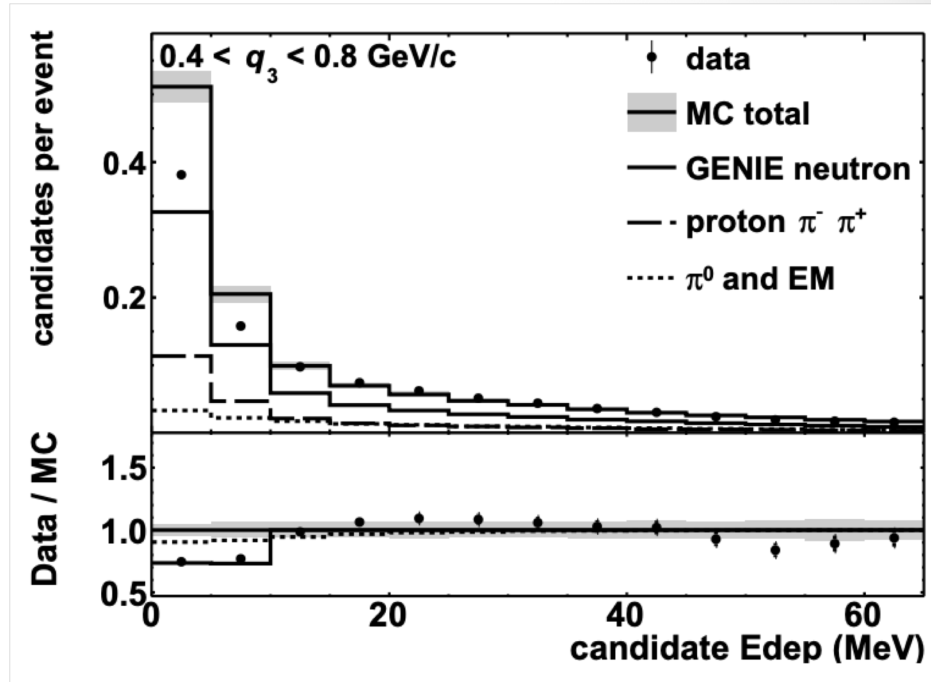
Recent experimental work

Neutron in argon measurements



Neutron in CH_2 measurements

MINERvA 2019



Conclusions

1. Basic performance of liquid argon were not understood

2. We understand missing energy of neutrino events: neutrons, nuclear breakup, recombination

3. Improve reconstruction strategy

4. Details in arXiv:1811.06159, PRD 2019

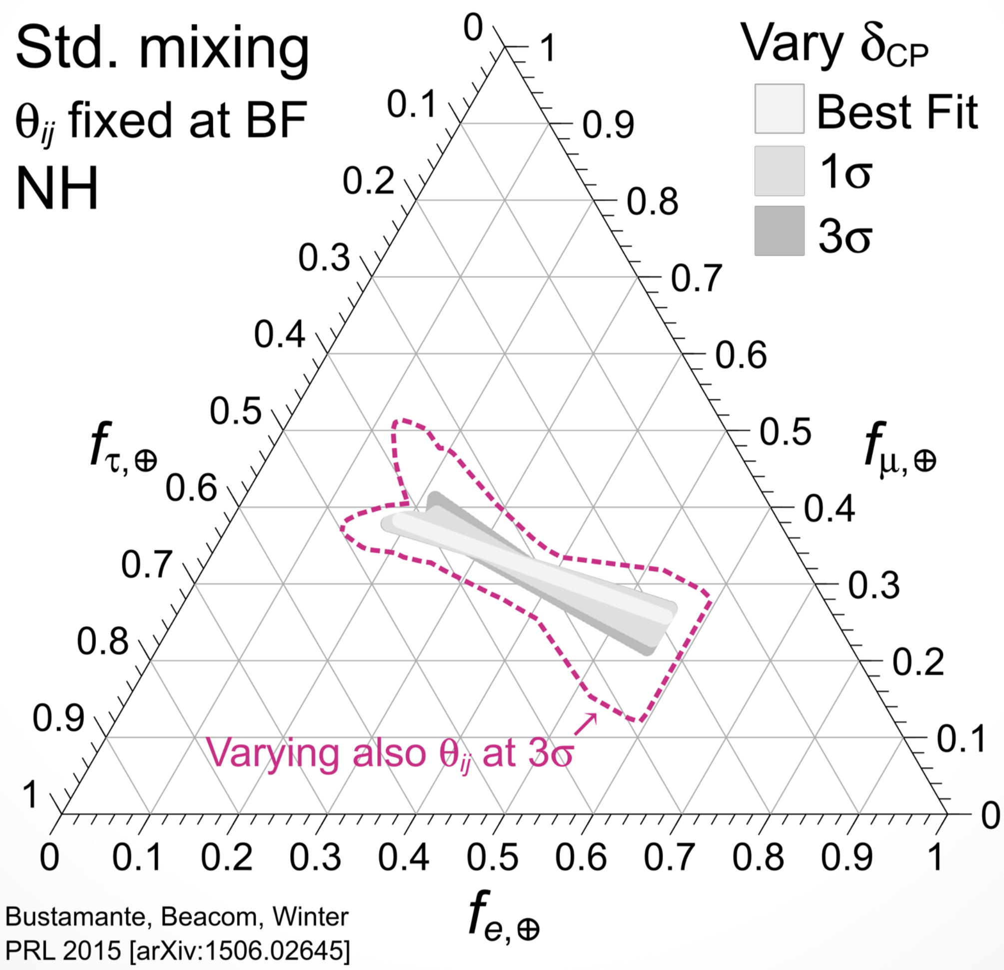
Outlook

1. Many questions unanswered
2. Neutrino-nucleus cross sections at ~ 50% level
3. Framework to explore cross section uncertainties

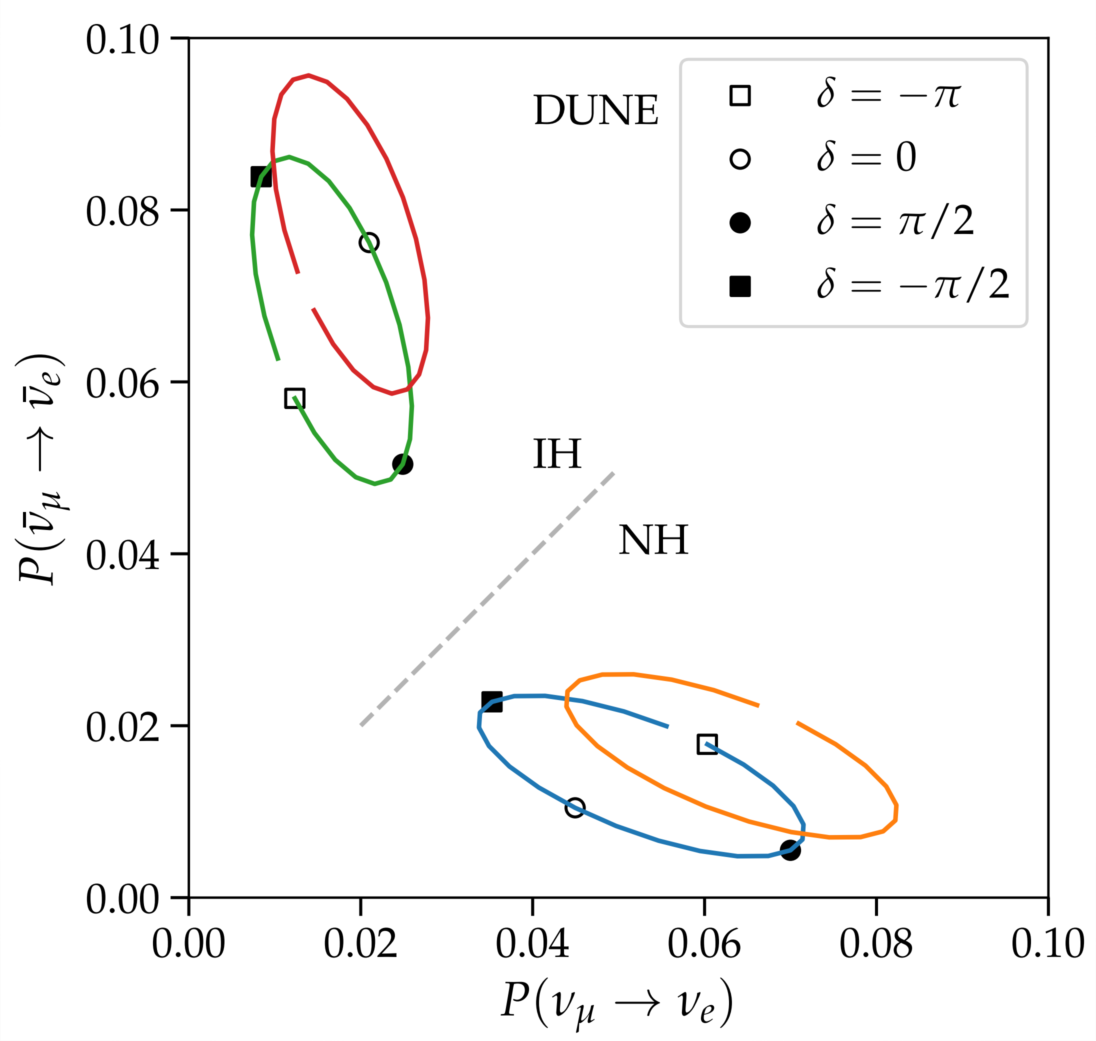
Backup

δ_{CP}

Figure by Bustamante

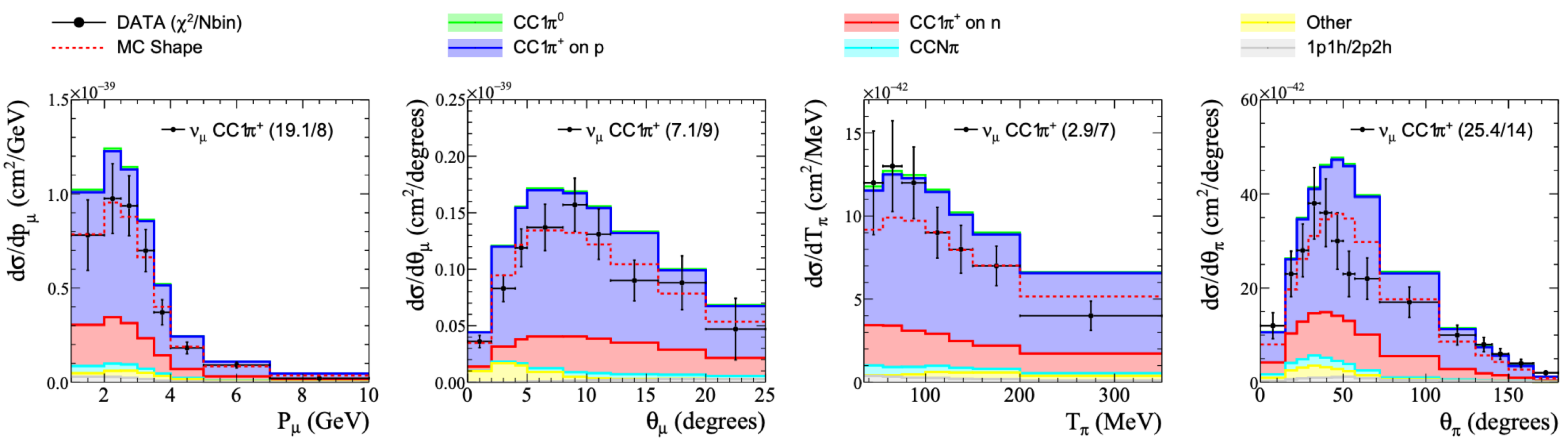


Bi-probability plot



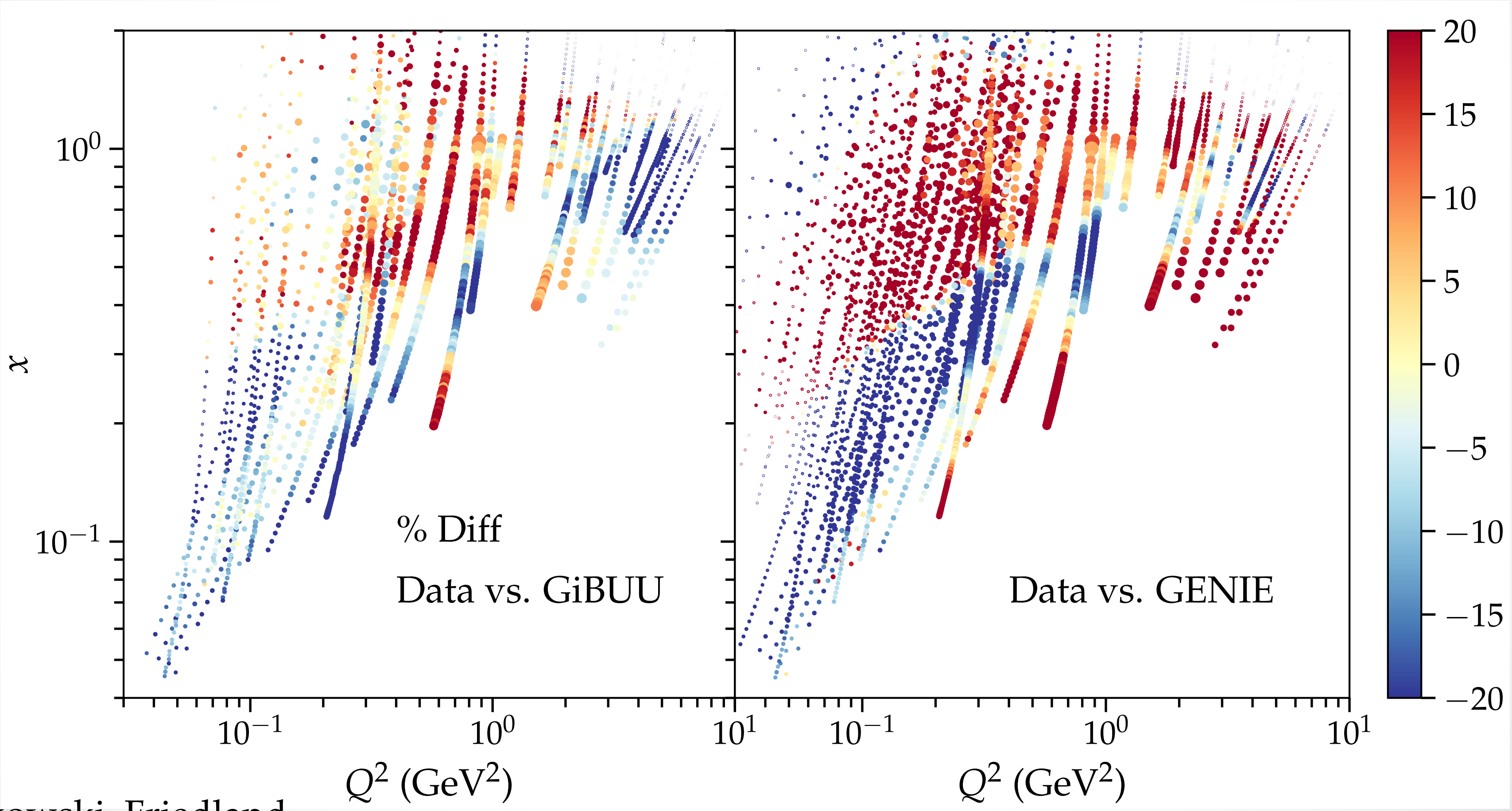
MINERνA data

MINERνA 2019



Status of cross section prediction

Electron scattering: generator vs. data

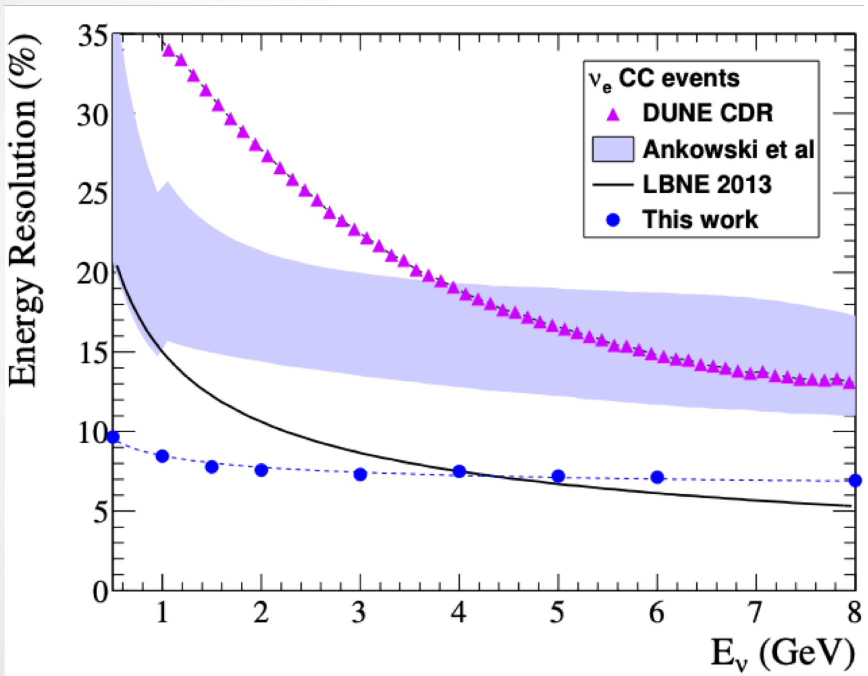


Ankowski, Friedland & Li, in prep

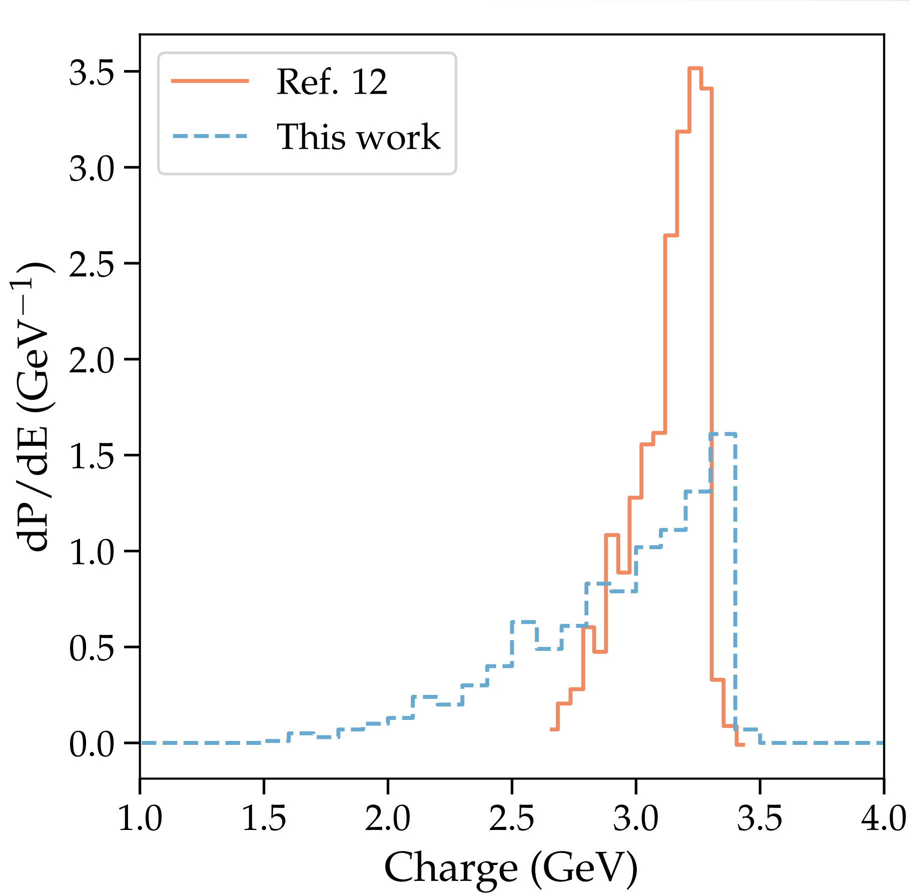
Shirley Li (SLAC)

Comparisons to other work

Romeri, Fernandez-Martinez & Sorel, 2016

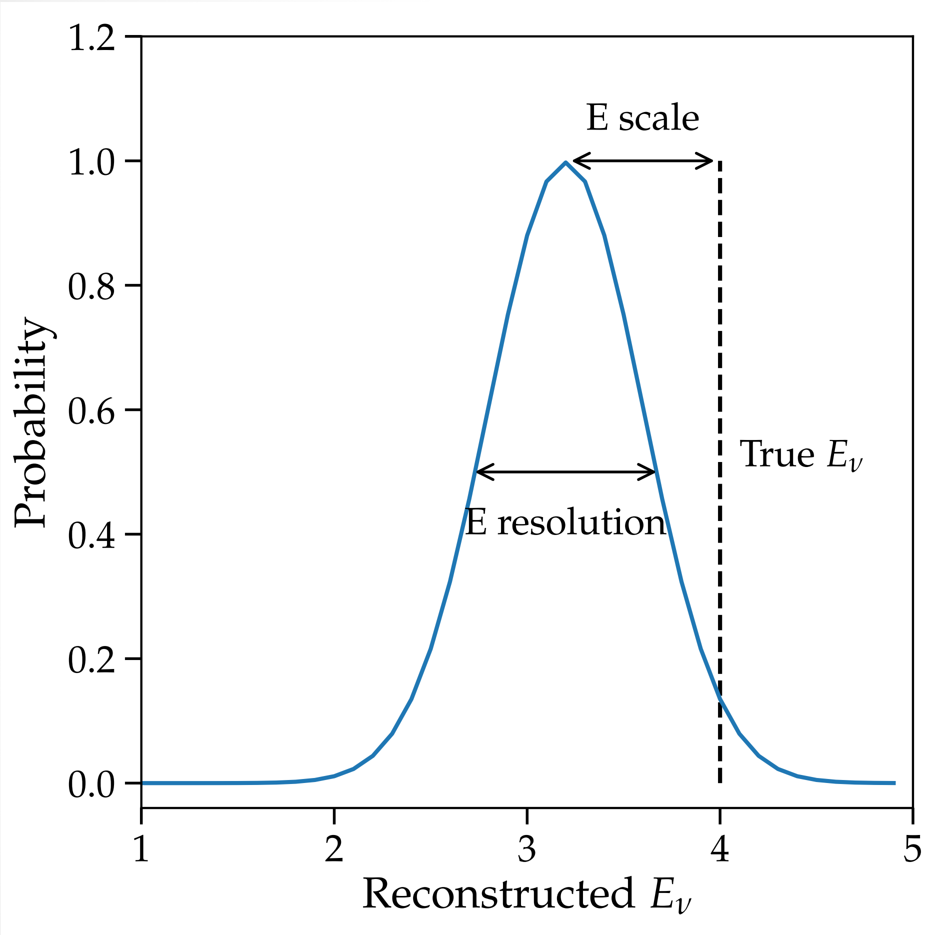


Friedland & Li, 2018



Further studies warranted

Connection to cross section



Different generators predict different E scale and E resolution

1. n

2. p vs. pi