The non-hermeticity of calorimetric neutrino detectors

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Collaborator: Alex Friedland

Fermilab, June 2018

Outline

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Why
neutrino energy?

Outline

Calorimetric energy reconstruction

Why neutrino energy?

Outline

Calorimetric energy reconstruction

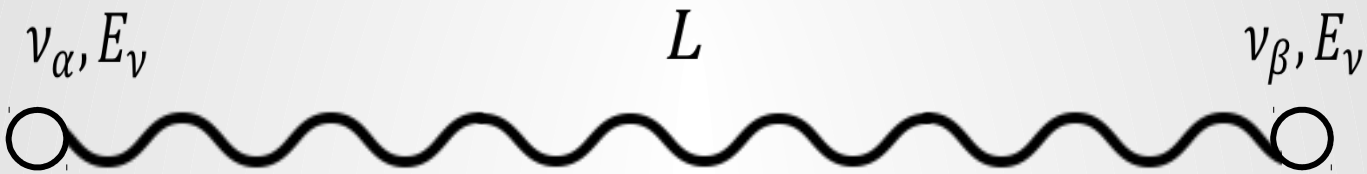
Why neutrino energy?

Our work

Outline

Why
neutrino energy?

Neutrino oscillation



$$P\left(\nu_\alpha \to \nu_\beta \middle| E_\nu, L, \text{Mixing parameters}\right)$$

Mixing parameters:

Mixing parameters:

$\theta_{12}, \quad \theta_{13}, \quad \theta_{23},$

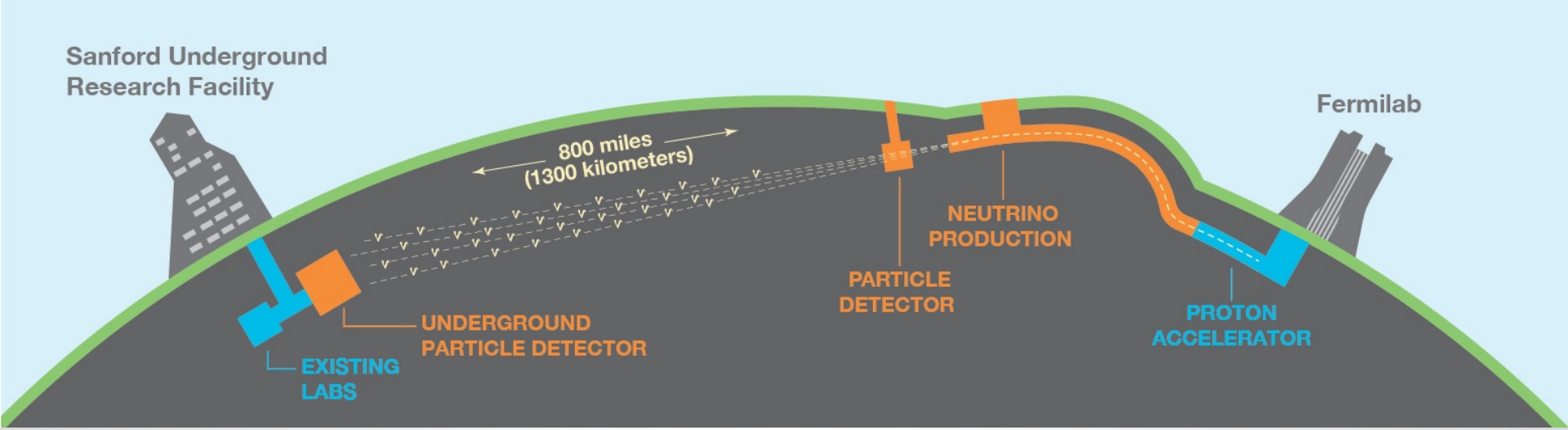
$\Delta m^2_{21}, \quad |\Delta m^2_{32}|,$

$\delta_{\mathrm{CP}}, \quad \mathrm{sign}(\Delta m^2_{32})$

Long baseline experiments

DUNE and NOvA

Figure: dunescience.org

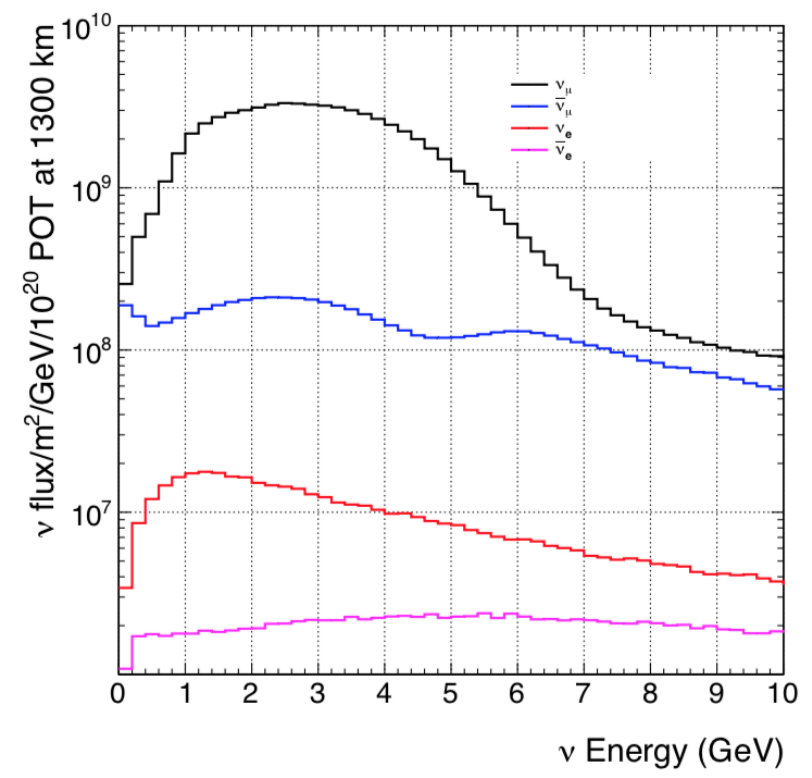


Both are calorimetric detectors

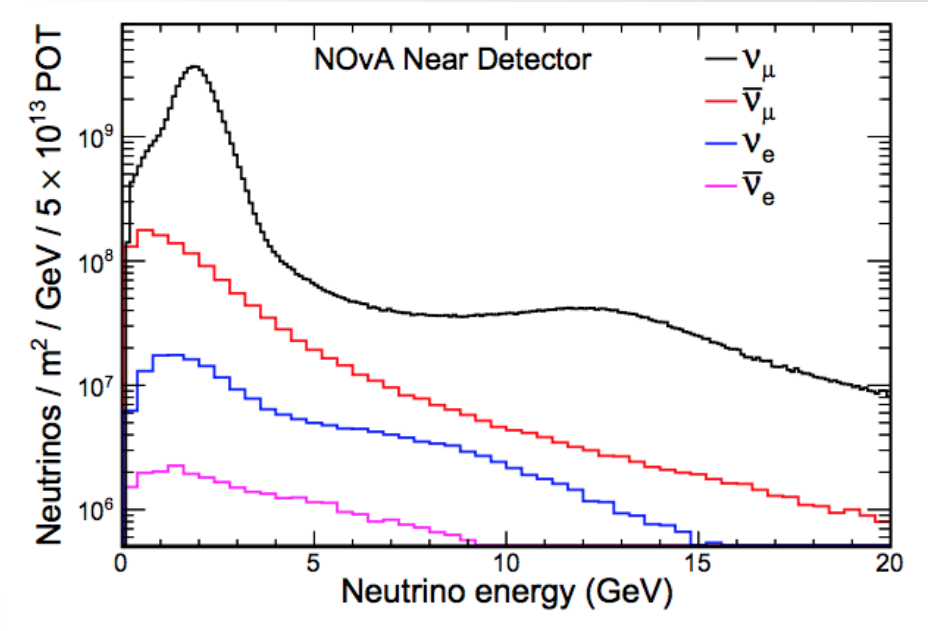
Long baseline experiments

GeV ν_μ & $\bar{\nu}_\mu$ beam

DUNE 2015



NOvA 2018



Beam energy is fixed by oscillation parameters

Mixing parameters

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\sin^2 2\theta_{13} \sin^2 \theta_{23} + \cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Nunokawa, Parke, Funchal, 2005

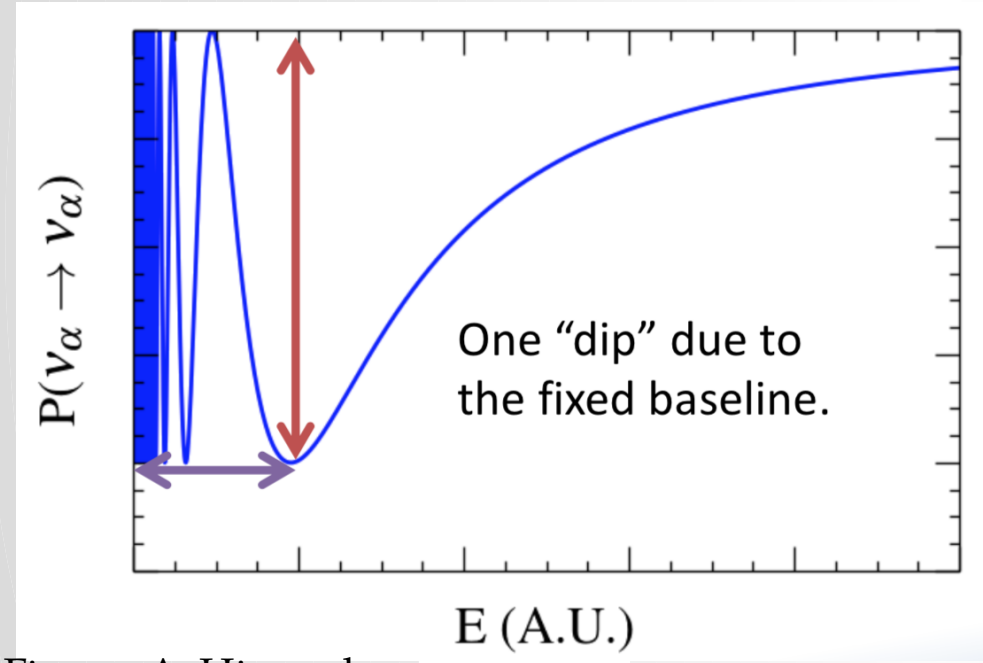
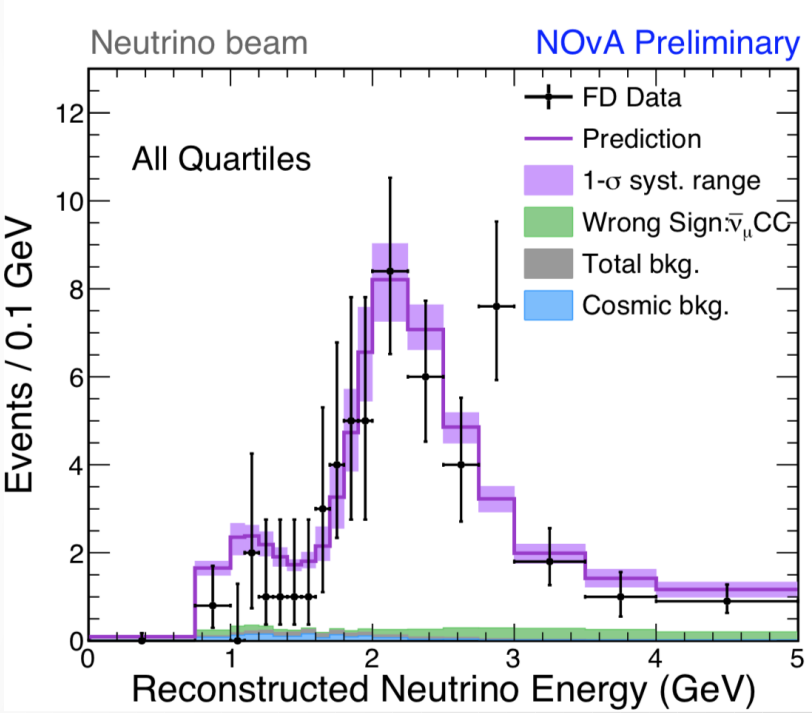


Figure: A. Himmel
Fermilab seminar,
2018



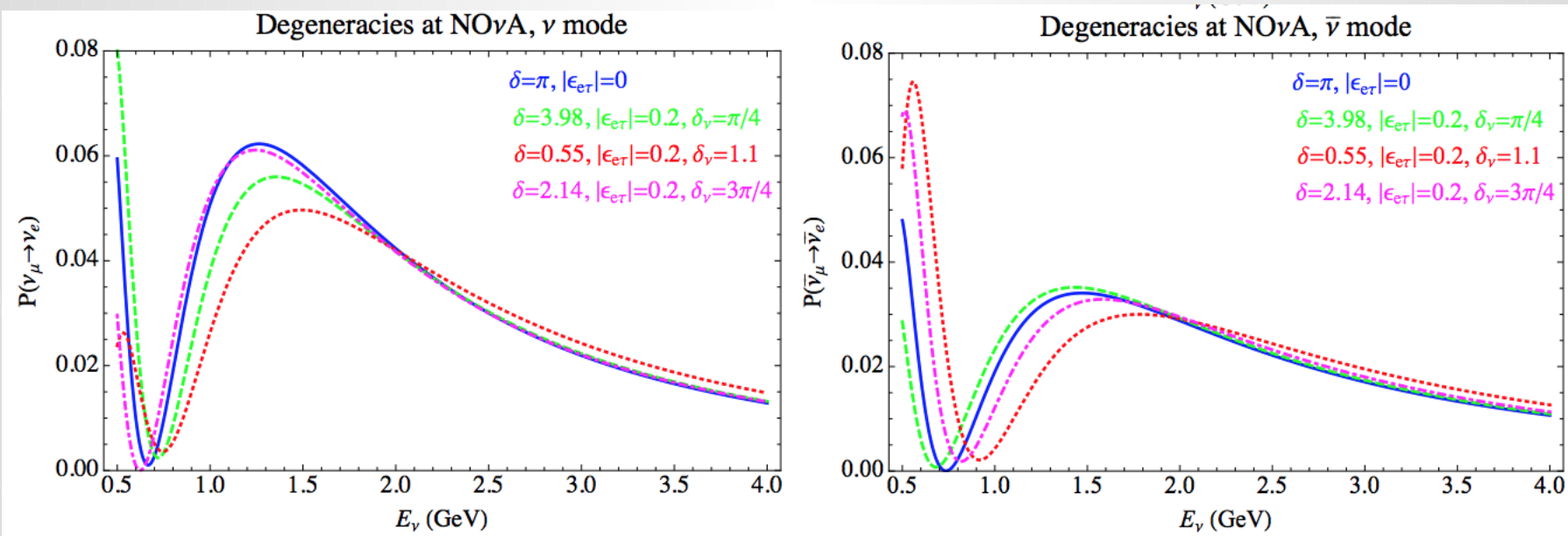
NOvA Neutrino 2018

Mixing effects generally depend on neutrino energy

Beyond 3-ν mixing

Non-standard interaction

$$H_{mat}^{flav} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 & |\varepsilon_{e\tau}|\, e^{-i\delta_\nu} \\ 0 & 0 & 0 \\ |\varepsilon_{e\tau}|\, e^{i\delta_\nu} & 0 & 0 \end{pmatrix}$$



Friedland, Shoemaker 2012

Potential new signatures in neutrino spectra

Outline

Calorimetric energy reconstruction

Why neutrino energy?

DUNE

40 kton liquid argon TPC

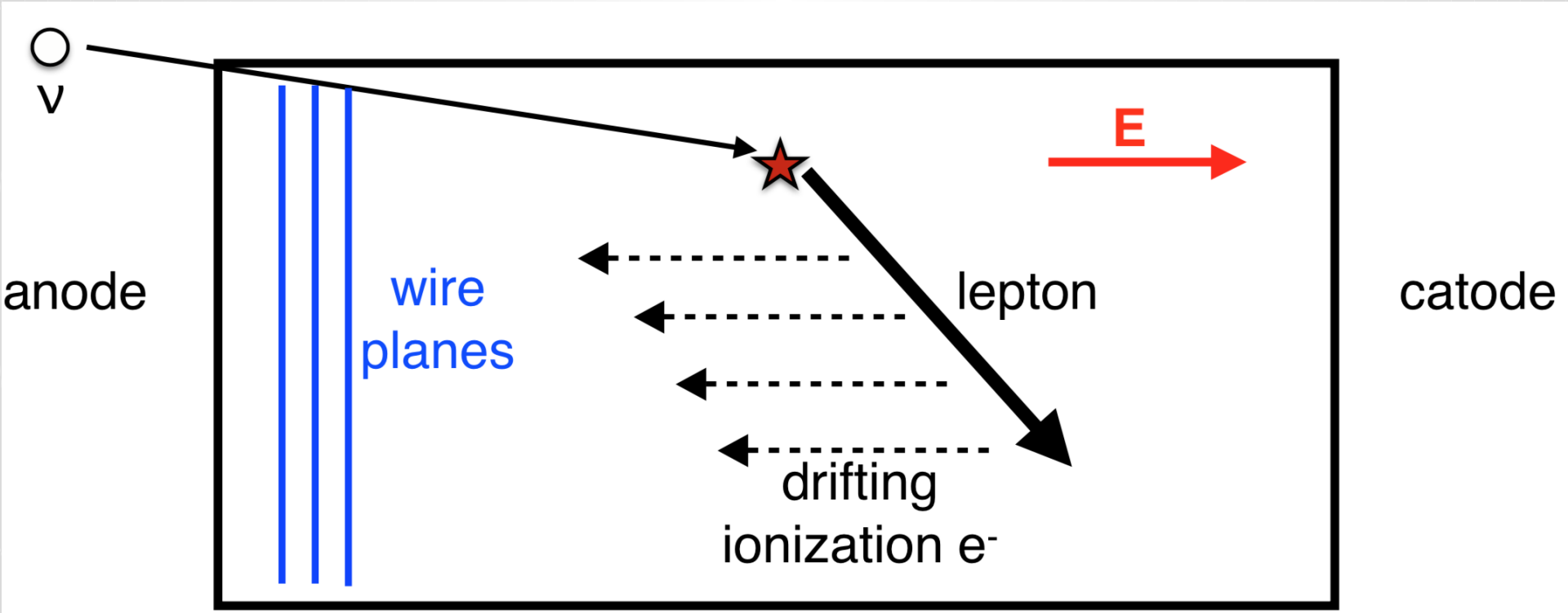
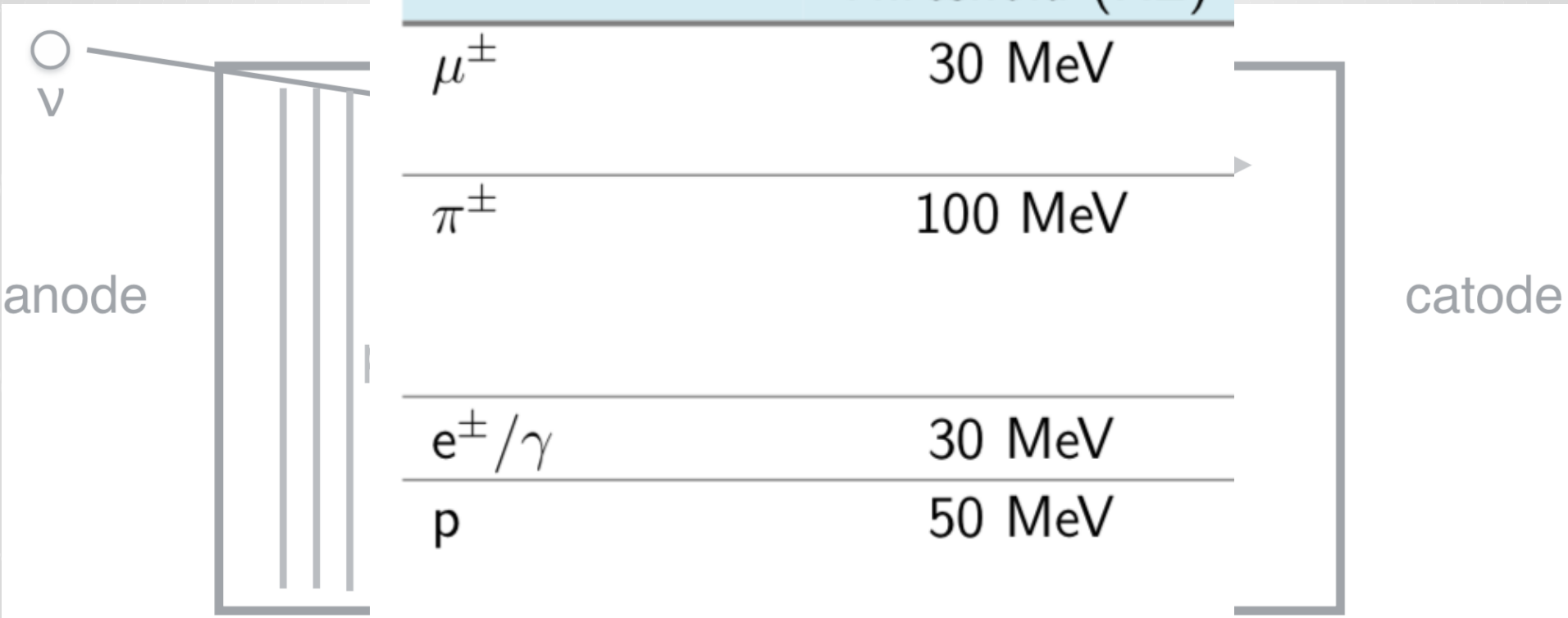


Figure: F. Capozzi
Max Planck seminar,
2017

Detects charged particles above thresholds

DUNE

DUNE 2015

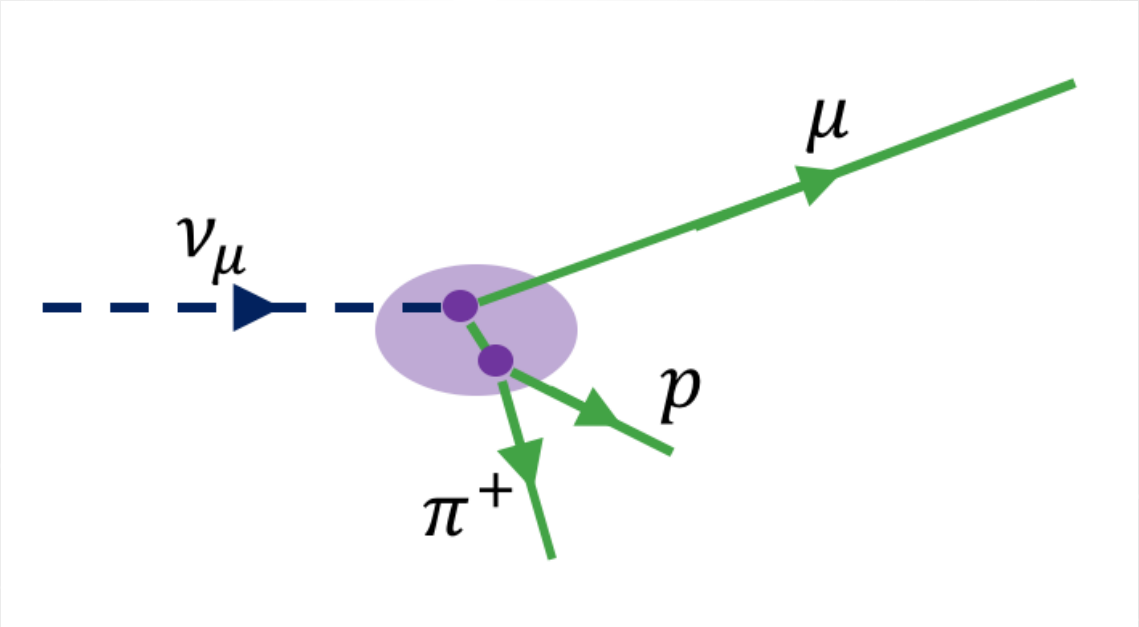


Particle type	Detection Threshold (KE)
$\mu^{\pm}$	30 MeV
$\pi^{\pm}$	100 MeV
$e^{\pm}/\gamma$	30 MeV
p	50 MeV
n	50 MeV
other	50 MeV

Figure: F. Capozzi
Max Planck seminar, 2017

A neutrino event

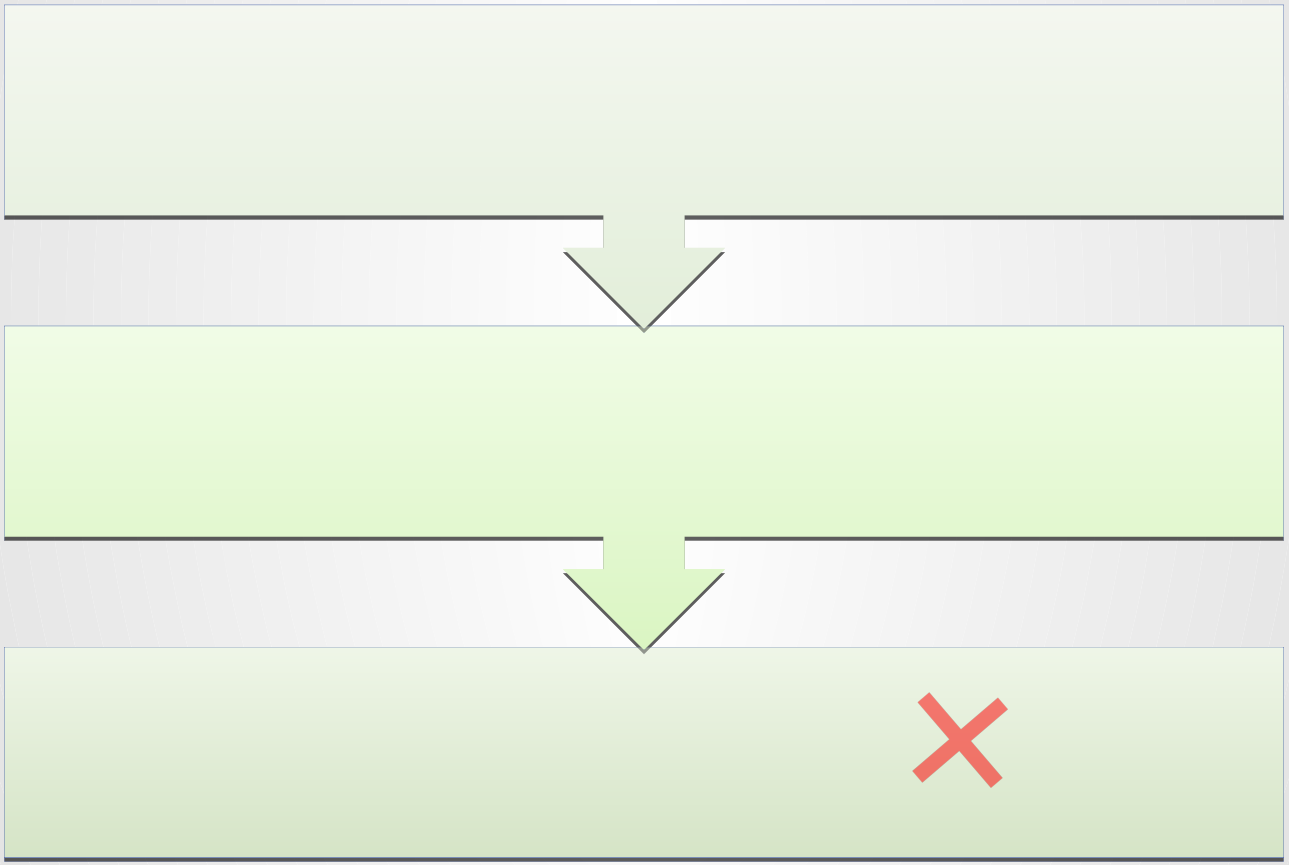
Signal: $\nu_\mu \to l + X$



Calorimetric reconstruction is needed

Neutrino energy

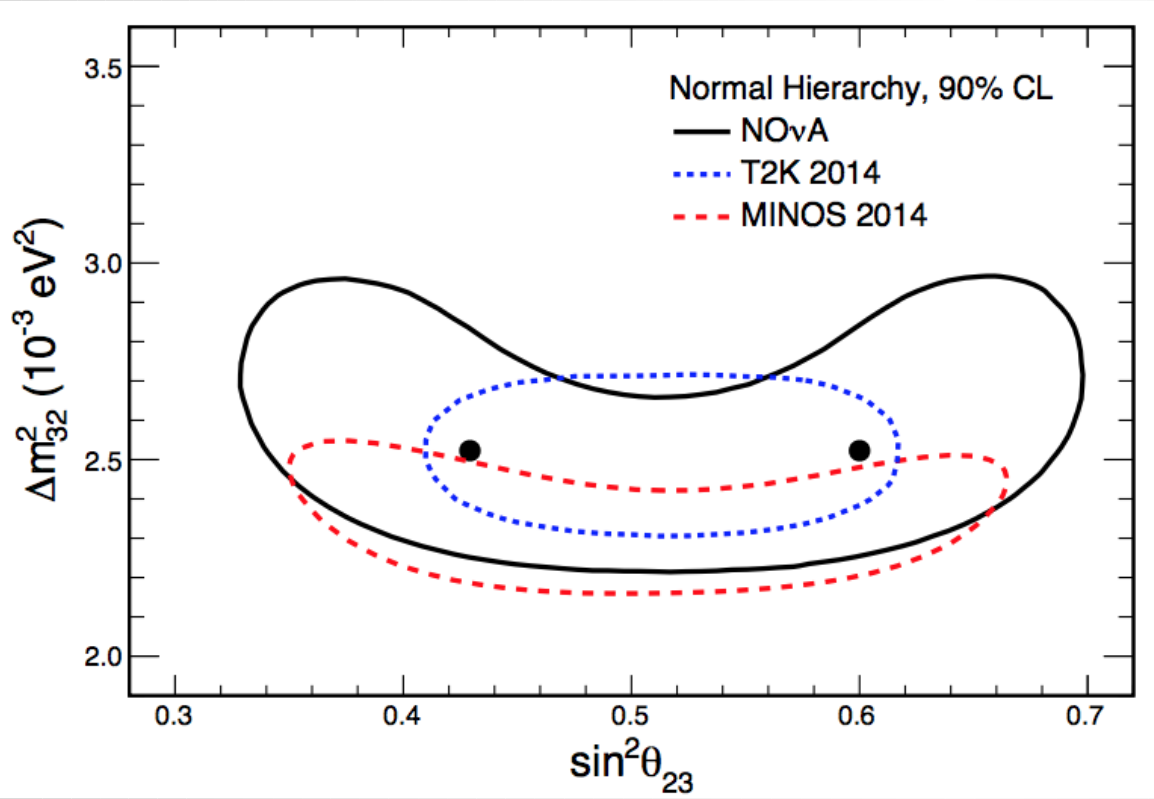
Energy conservation



How well does it work?

The evolution of NOvA

NOvA 2016

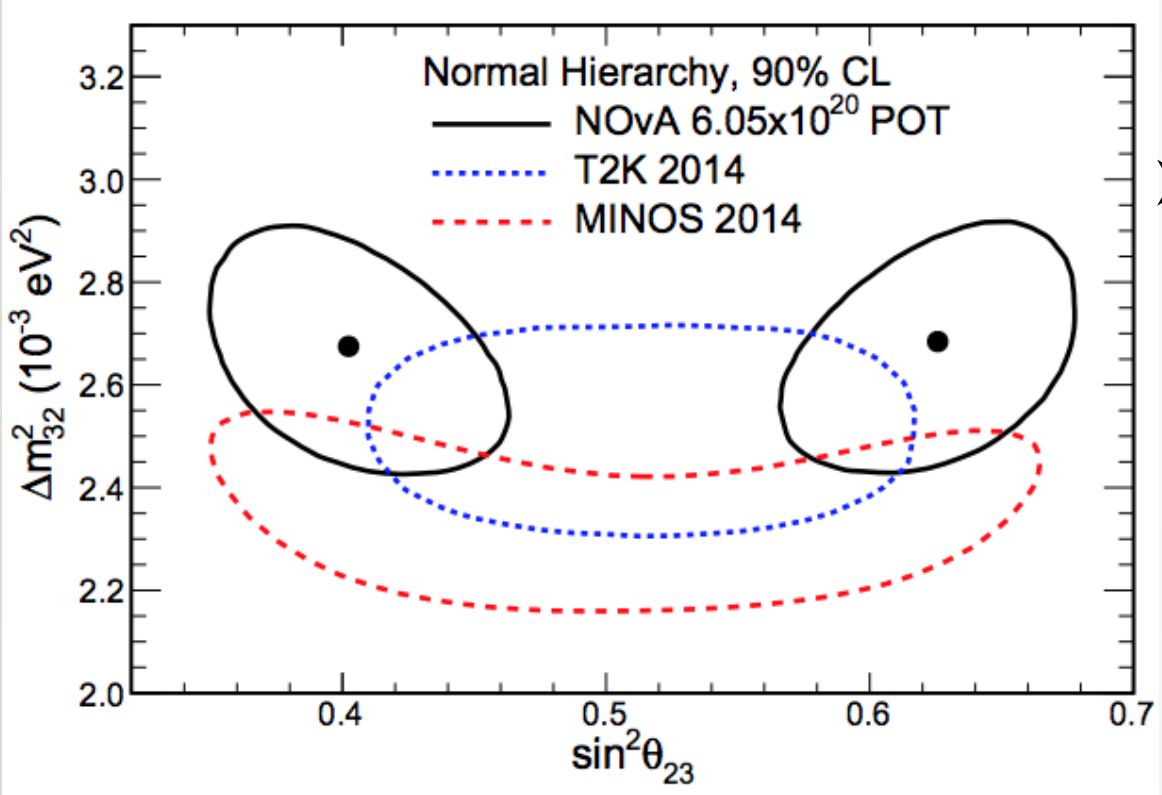


- Dominant systematic on: $\sin^2\theta_{23}$:
  - Calorimetric energy calibration: 4.1% ⊕ 3.4%

How well does it work?

The evolution of NOvA

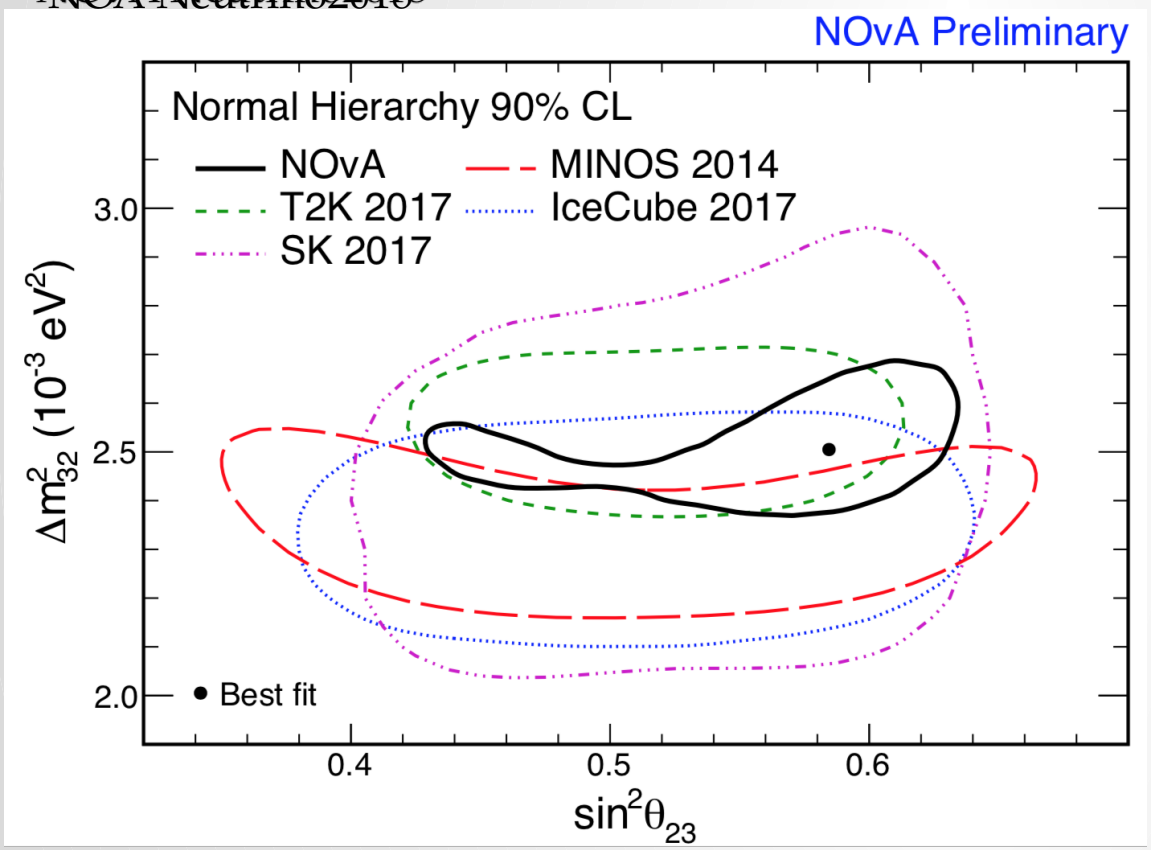
NOvA 2017



- Dominant systematic on: $\sin^2\theta_{23}$:
  - Hadronic energy scale: $0.8\% \oplus 1.6\%$

How well does it work?

The evolution of NOvA



- Dominant systematic on: $\sin^2\theta_{23}$:
  - Neutron & Calibration: ~1% ⊕ ~1%

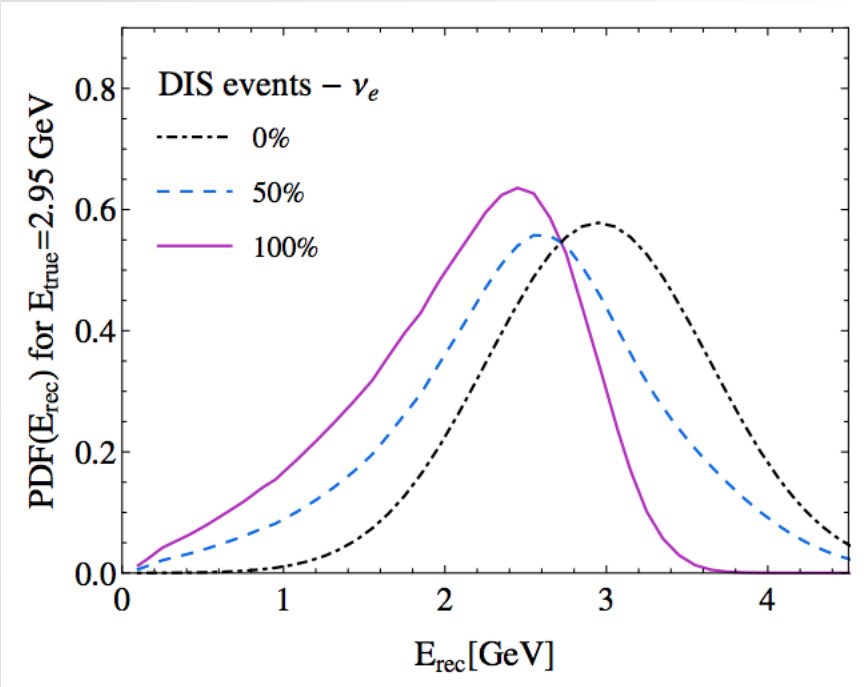
Statistical dominated; systematics improving

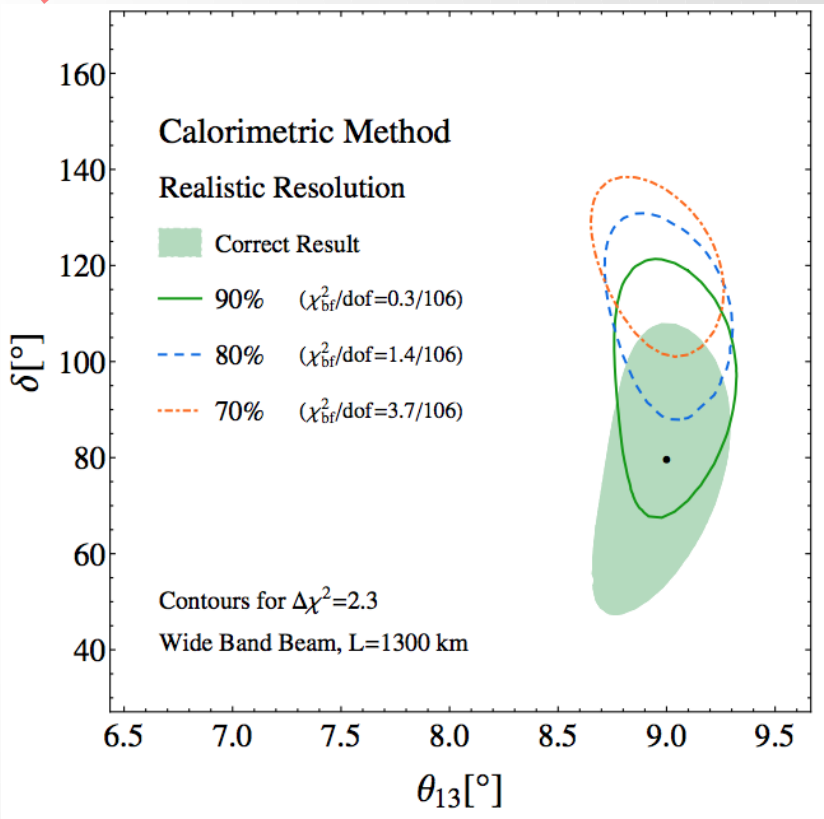
Prior work

Approach one: prompt study only

$$\nu_l + A \rightarrow l + p + \cancel{n} + \pi^{\pm} + \gamma + X$$

Ankowski et al 2015





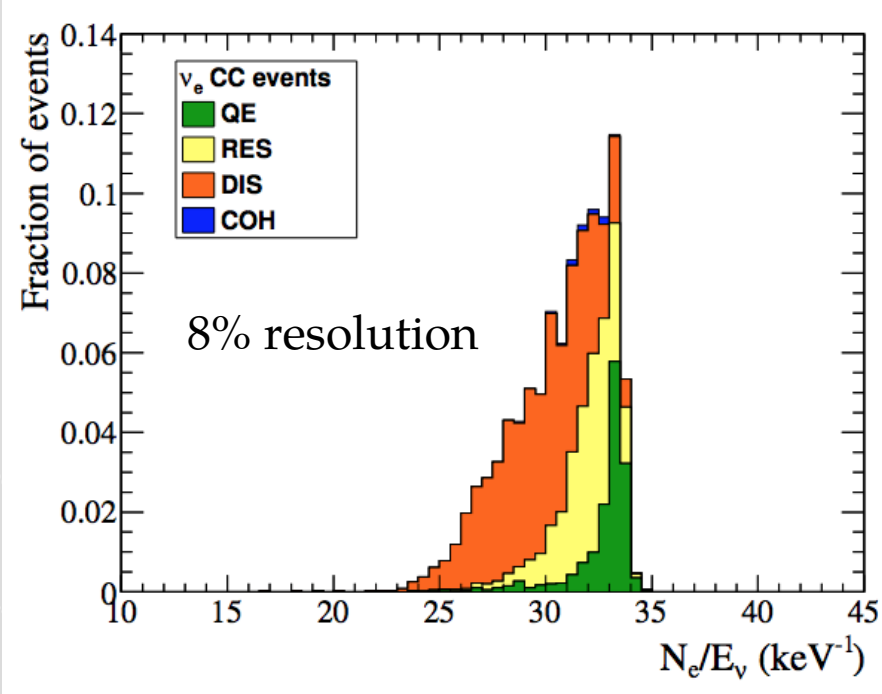
See physical connection; not quantitative

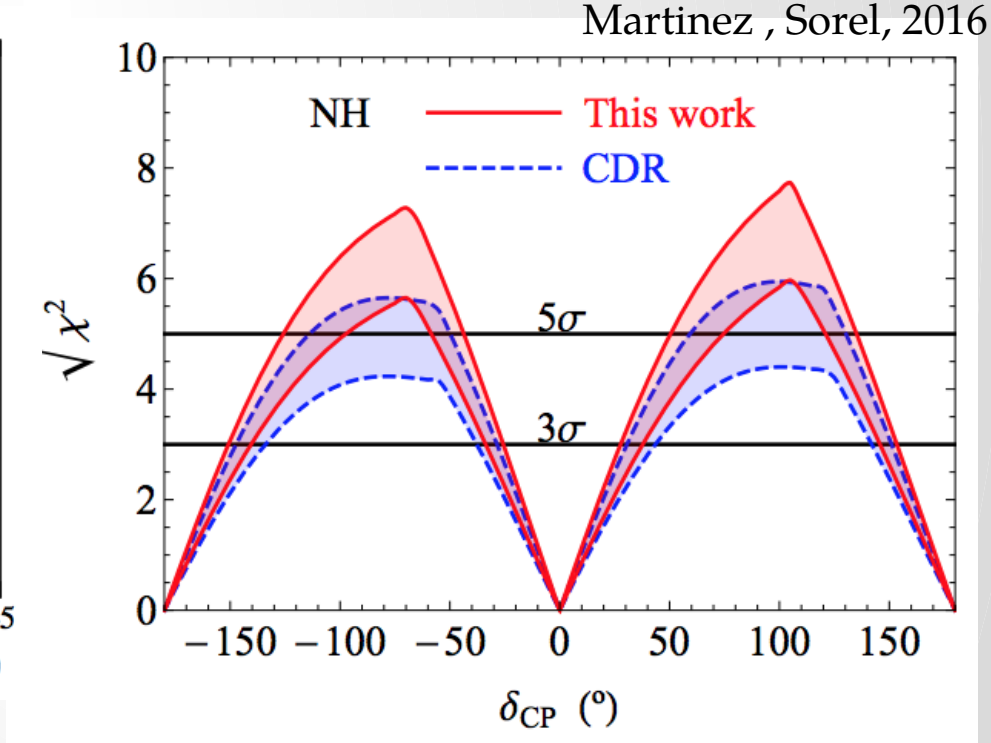
Prior work

Approach two: collect all charges from simulation chain

$$\nu_l + A \rightarrow l + p + n + \pi^{\pm} + \gamma + X$$

De Romeri, Fernandez-Martinez , Sorel, 2016





Test of best-case scenario; hide physical connection

Outline

Calorimetric energy reconstruction

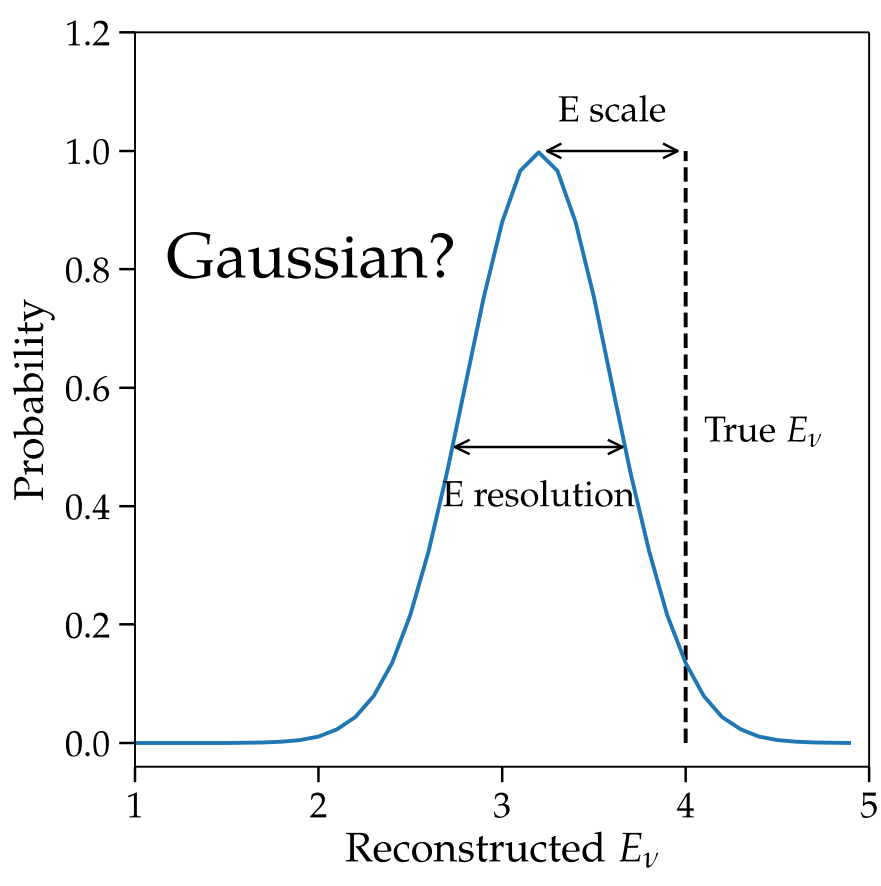
Why neutrino energy?

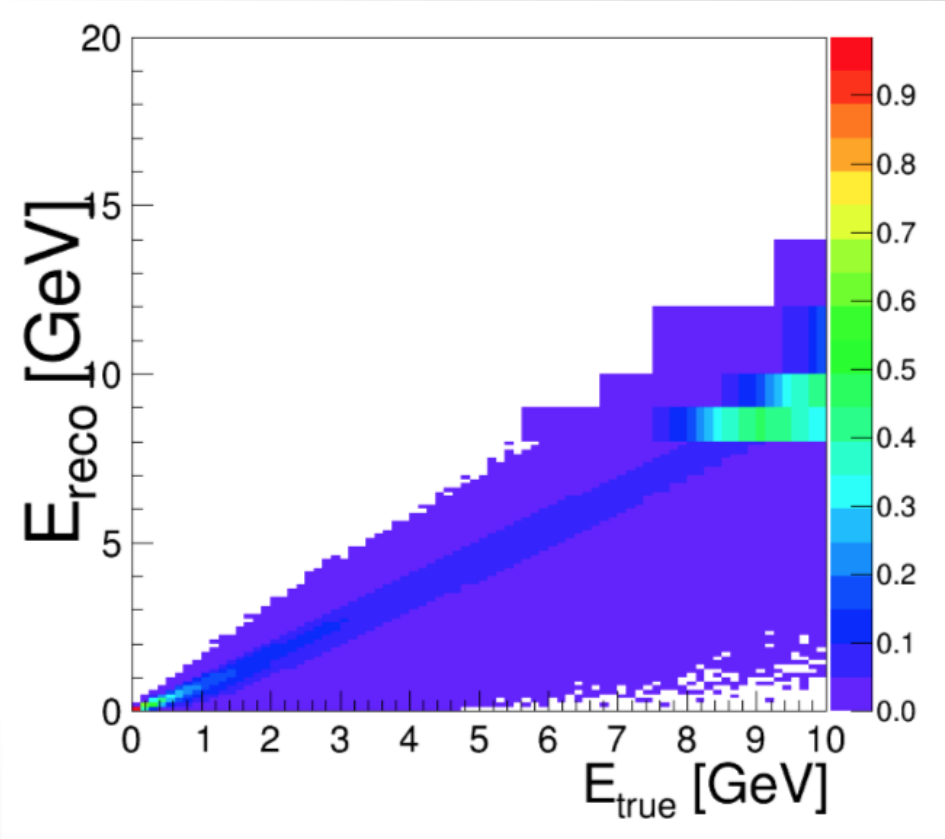
Our work

Neutrino
Energy outcome

Our goal

Migration Matrix



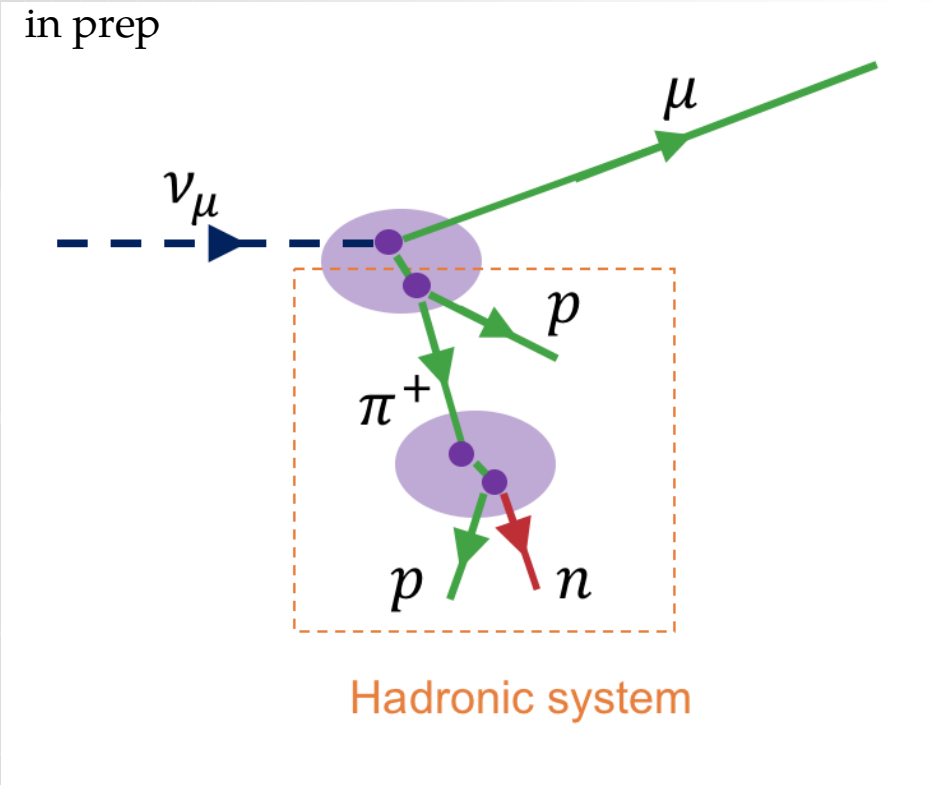


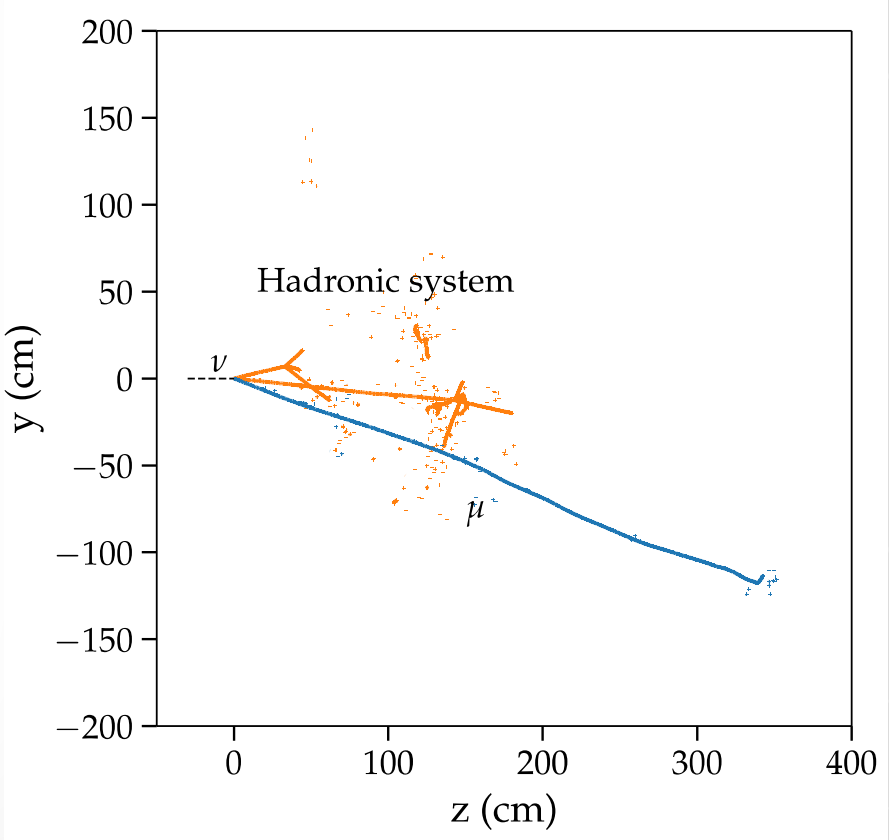
How do different effects contribute to these systematics?

A neutrino event

Signal: $\nu_\mu + A \to l + X$

Friedland, Li in prep





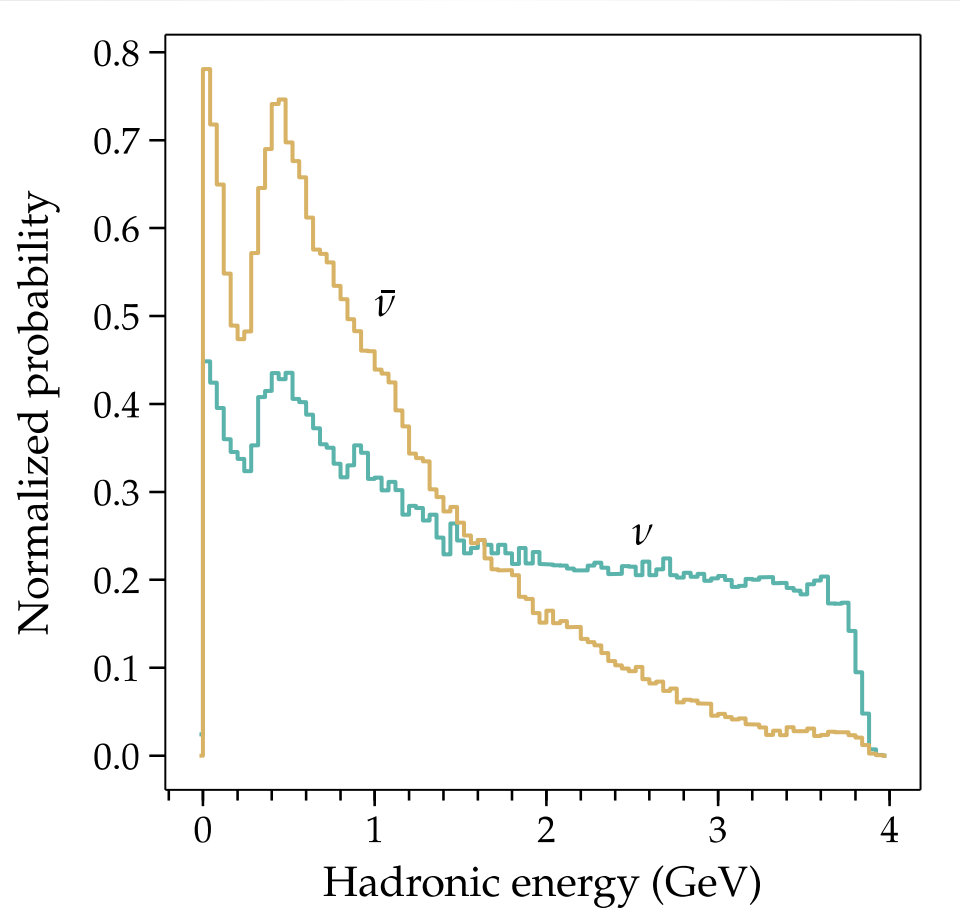
Hadronic system, not a single vertex

Hadronic energy

Prompt vertex: $\nu_l + A \to l + X$

Friedland, Li
in prep

GENIE
default model



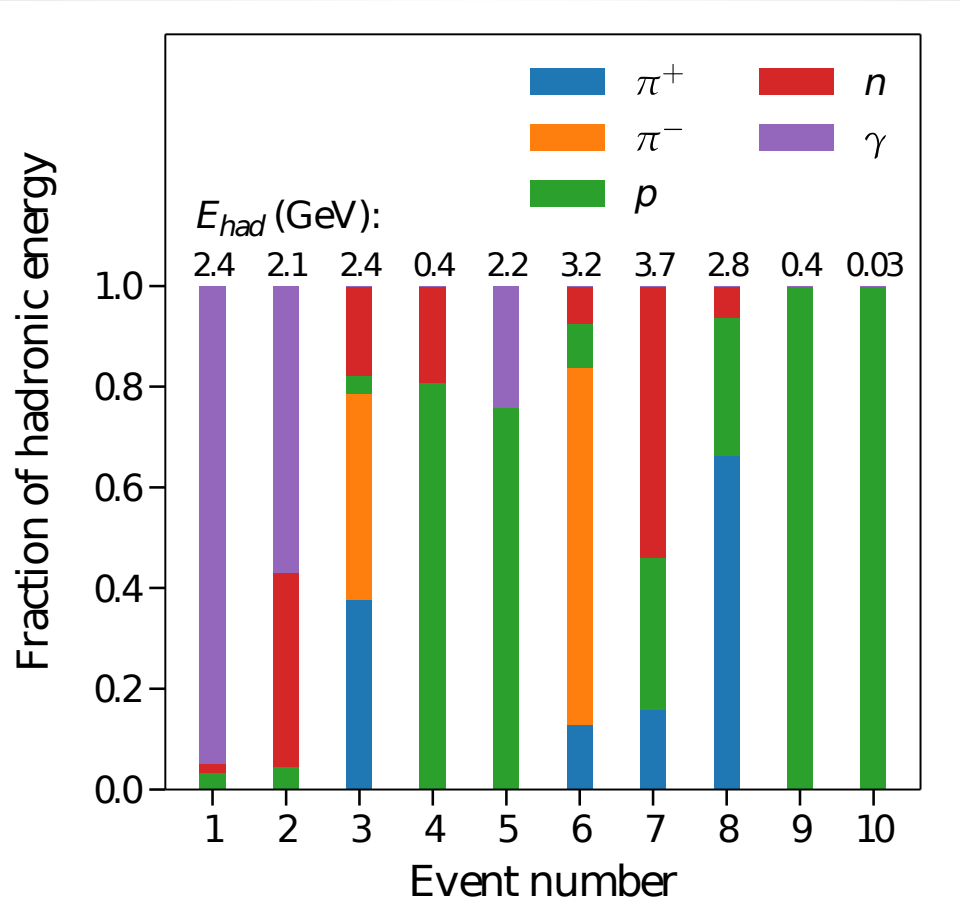
30 – 40% of neutrino energy, large fluctuations

Hadronic composition

Prompt vertex: $\nu_l + A \to l + X$

Friedland, Li
in prep

GENIE
default model



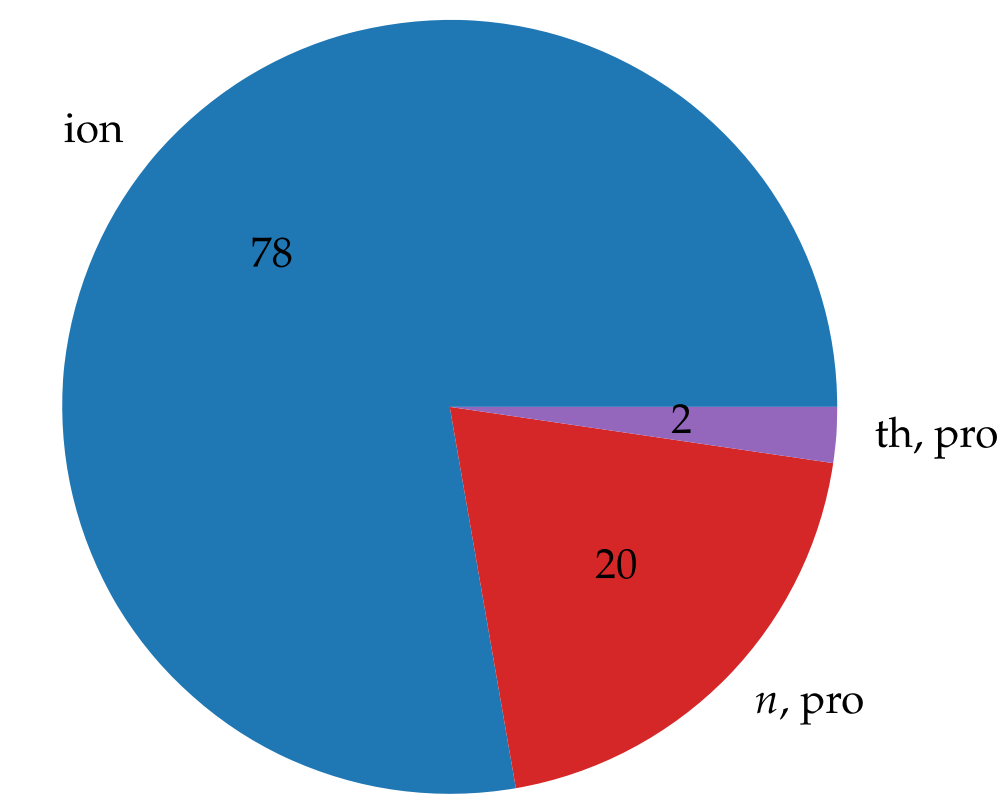
Multiple species contribute, large fluctuations

Prompt missing energy study

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

Friedland, Li
in prep

GENIE
default model



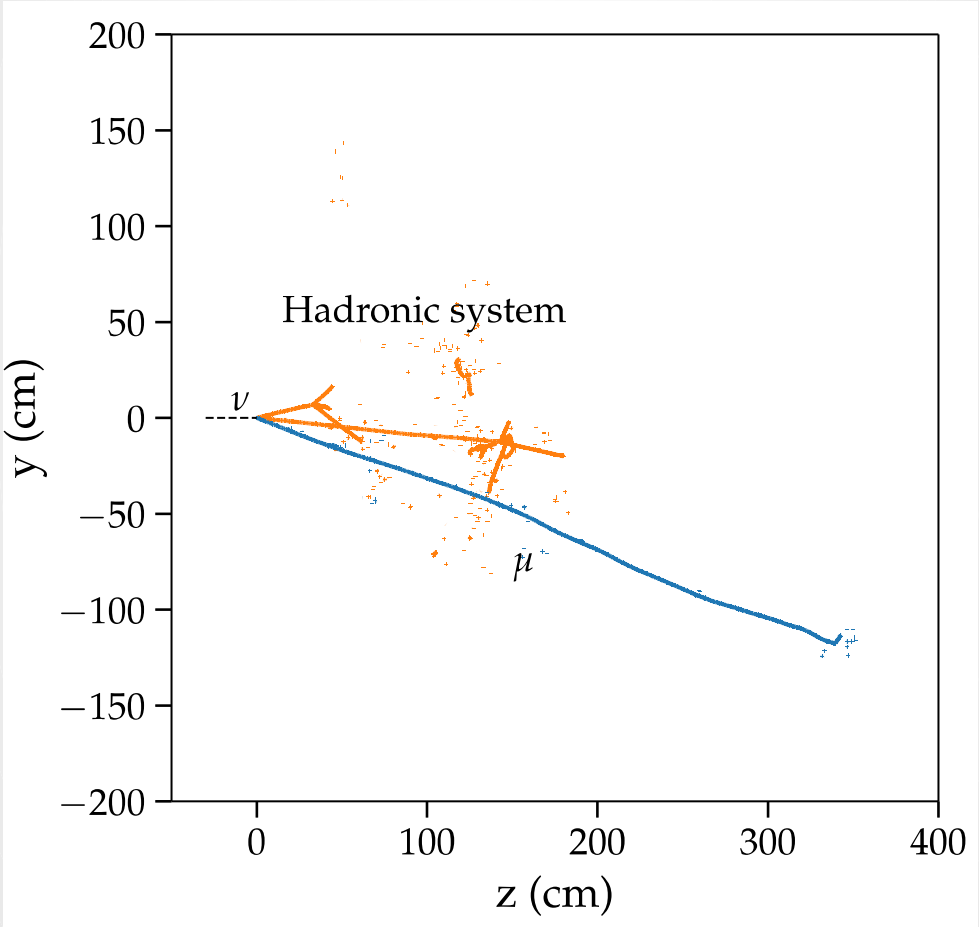
Prompt neutrons are the biggest issue

Prompt missing energy study

Prompt vertex: $\nu_\mu + A \to l + X$

Friedland, Li
in prep

GENIE
default model



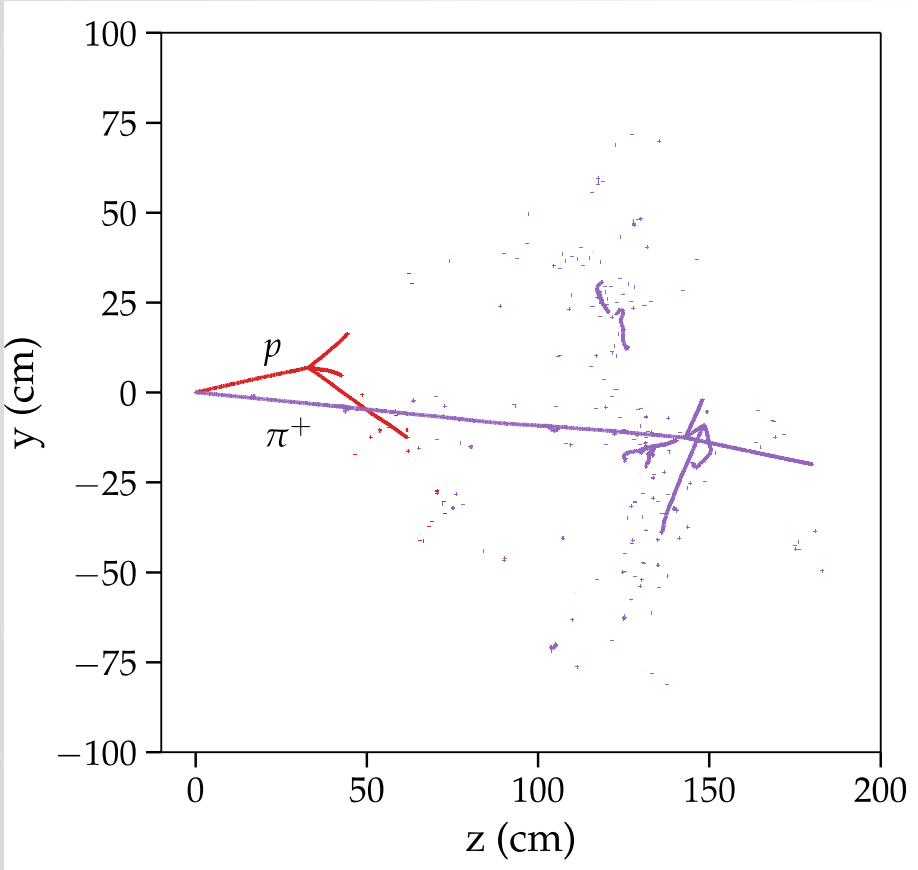
Prompt neutrons are the biggest issue

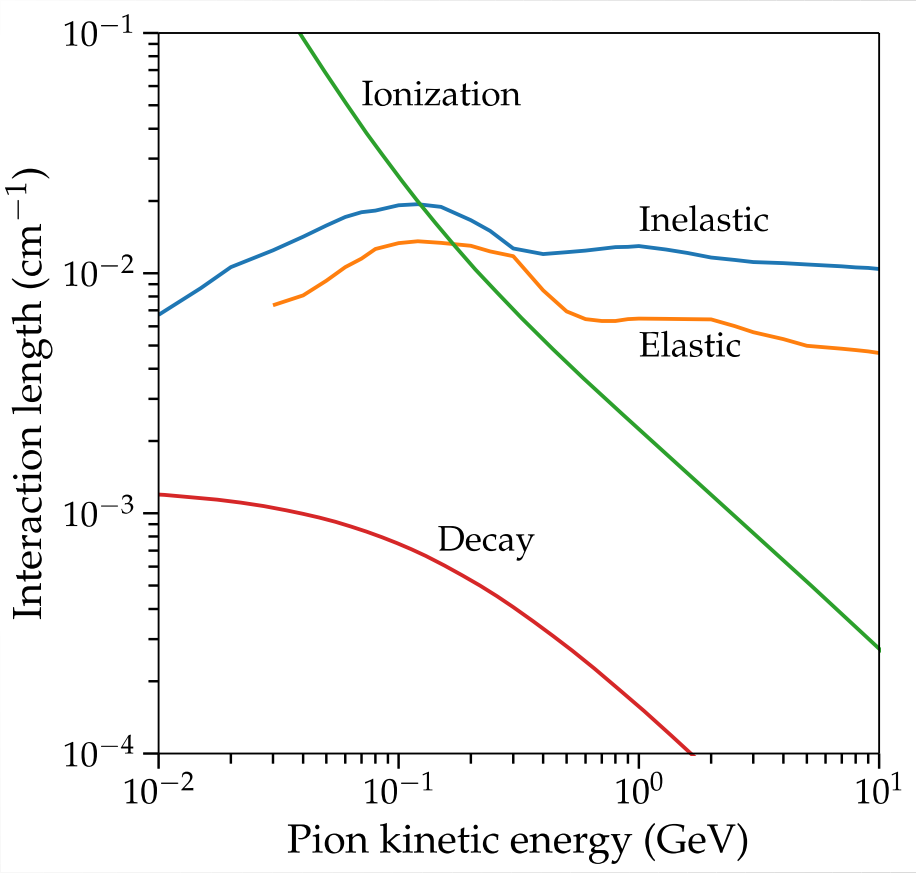
Secondary particle propagation

Charged particles

Friedland, Li
in prep

FLUKA





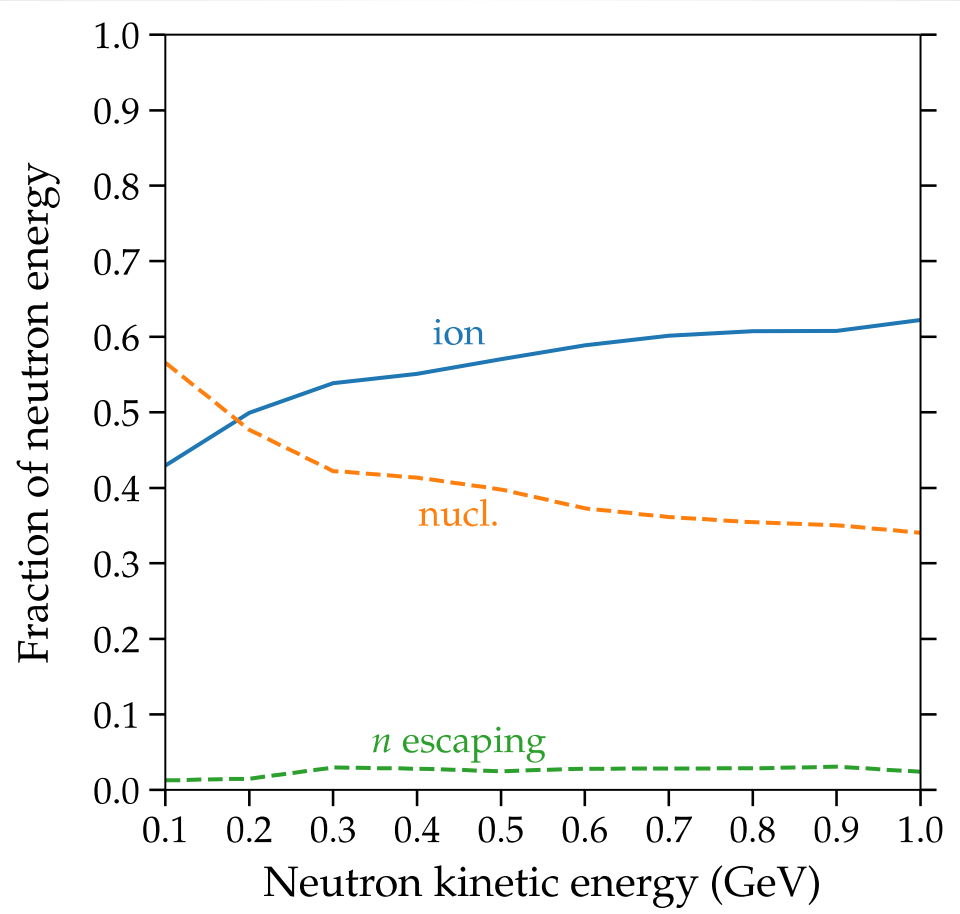
Many re-interactions

Secondary particle propagation

Friedland, Li
in prep

FLUKA

Neutrons



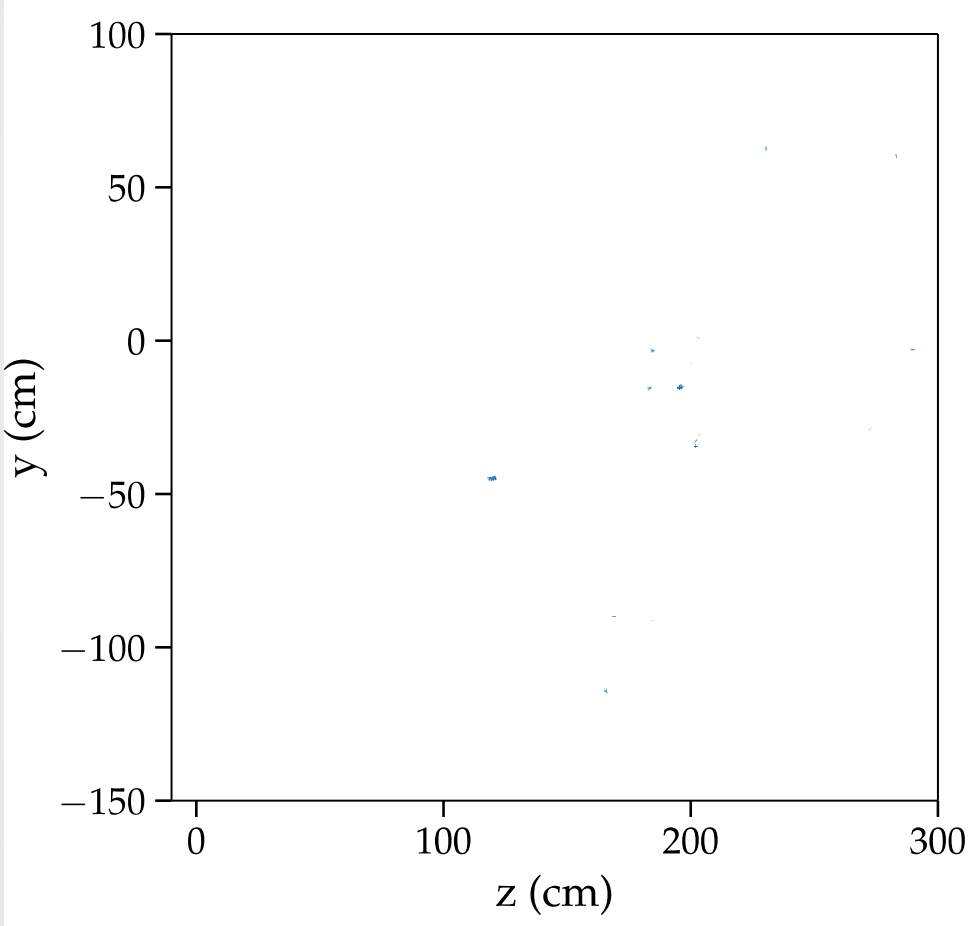
Neutron deposit ~ 50% of its energy in ionization

Neutron efficiency

Friedland, Li
in prep

FLUKA

Neutron event #1

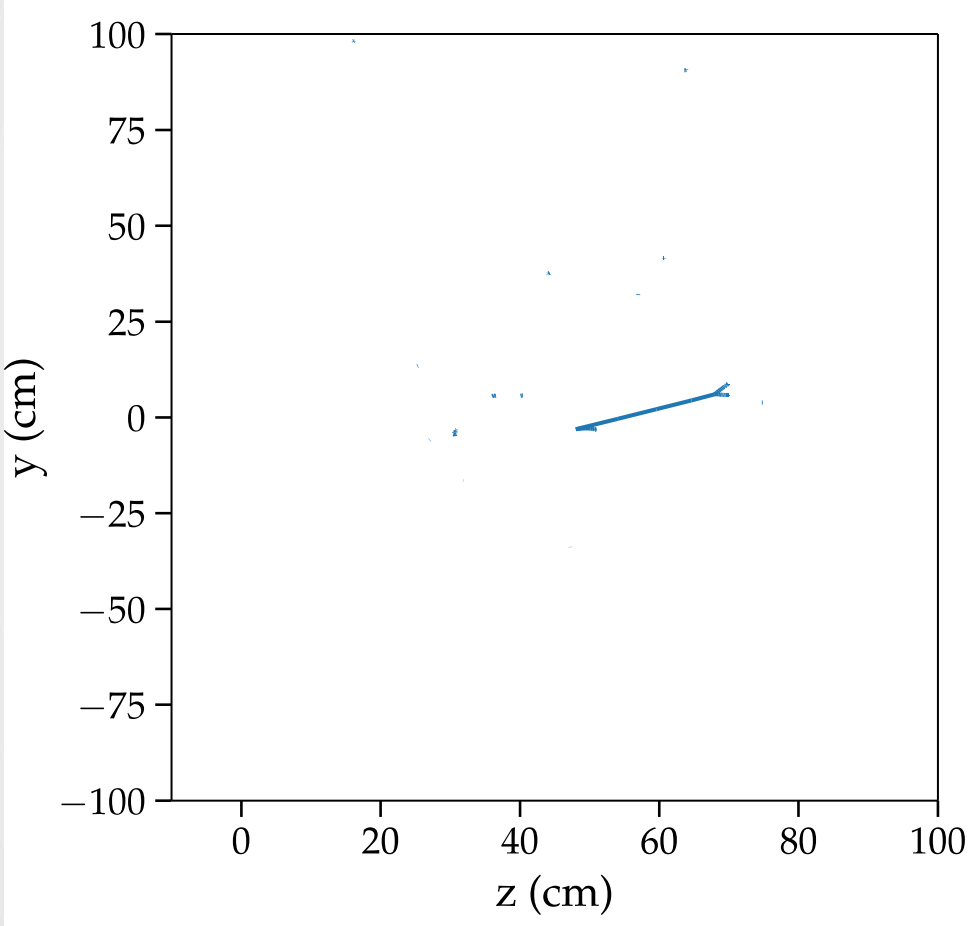


Neutron efficiency

Friedland, Li
in prep

FLUKA

Neutron event #2

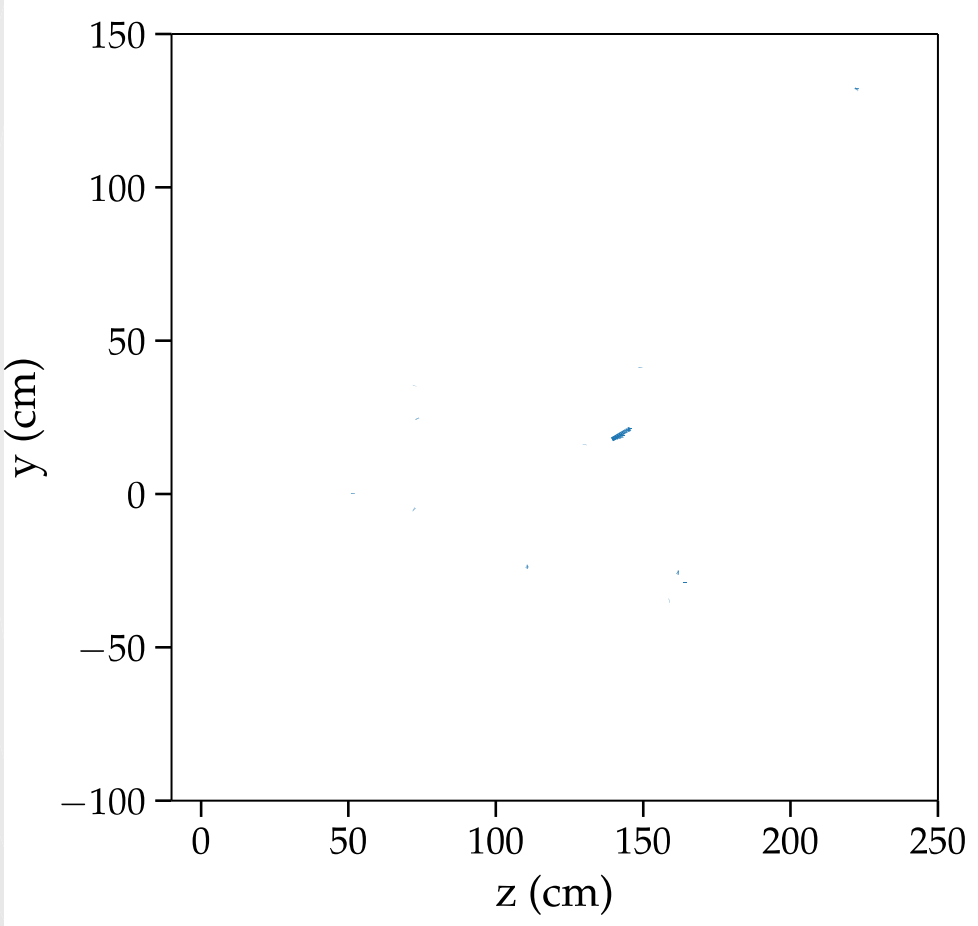


Neutron efficiency

Friedland, Li
in prep

FLUKA

Neutron event #3



Hard to estimate; need experimental calibration

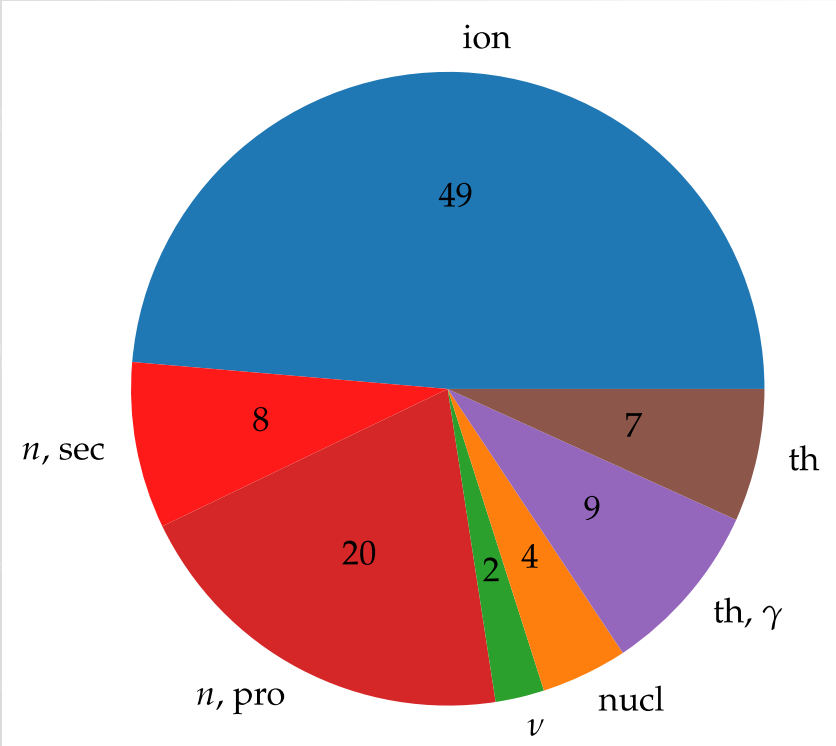
Connecting GENIE + FLUKA …

Energy budget

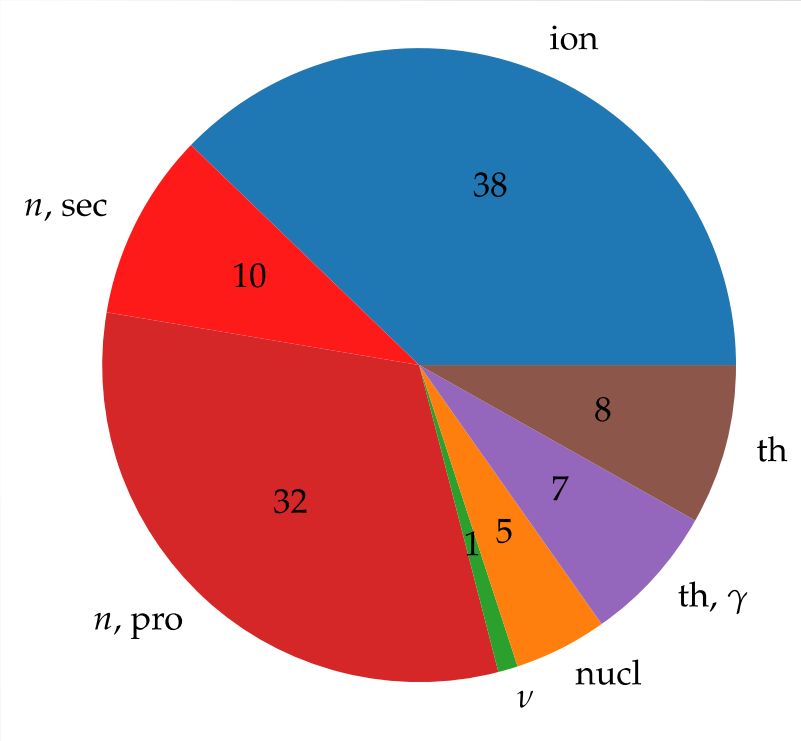
4 GeV neutrino in argon, average

Friedland, Li
in prep

ν



$\bar{\nu}$



Large missing energy from multiple sources

Connection to cross section

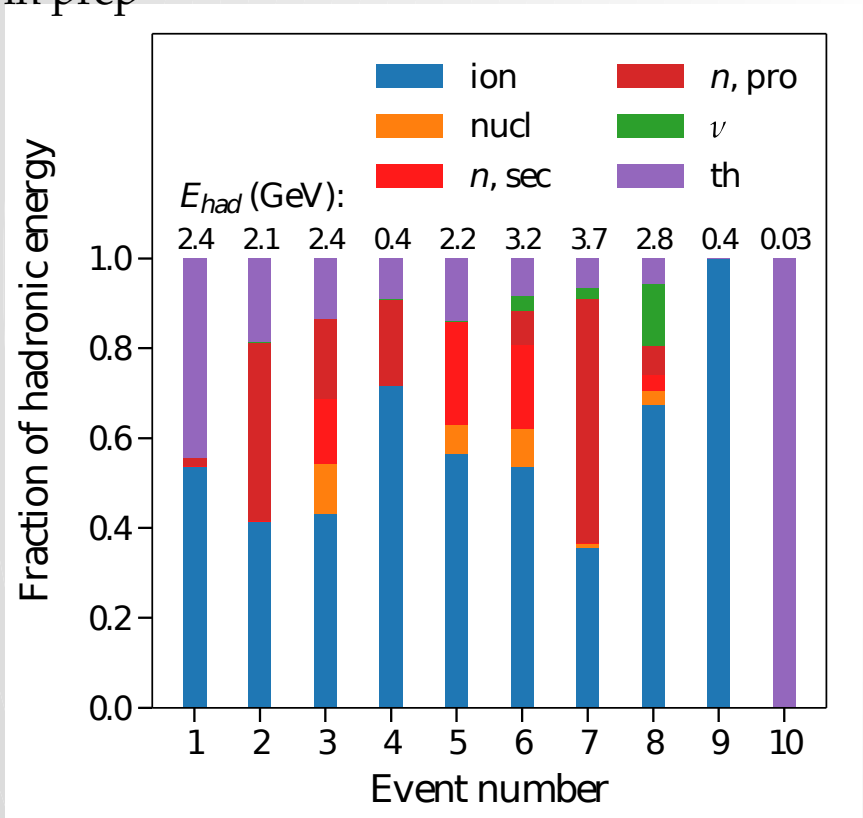
- Propagation is prerequisite for sensitivity studies
- Theory uncertainty and detector performance are closely intertwined

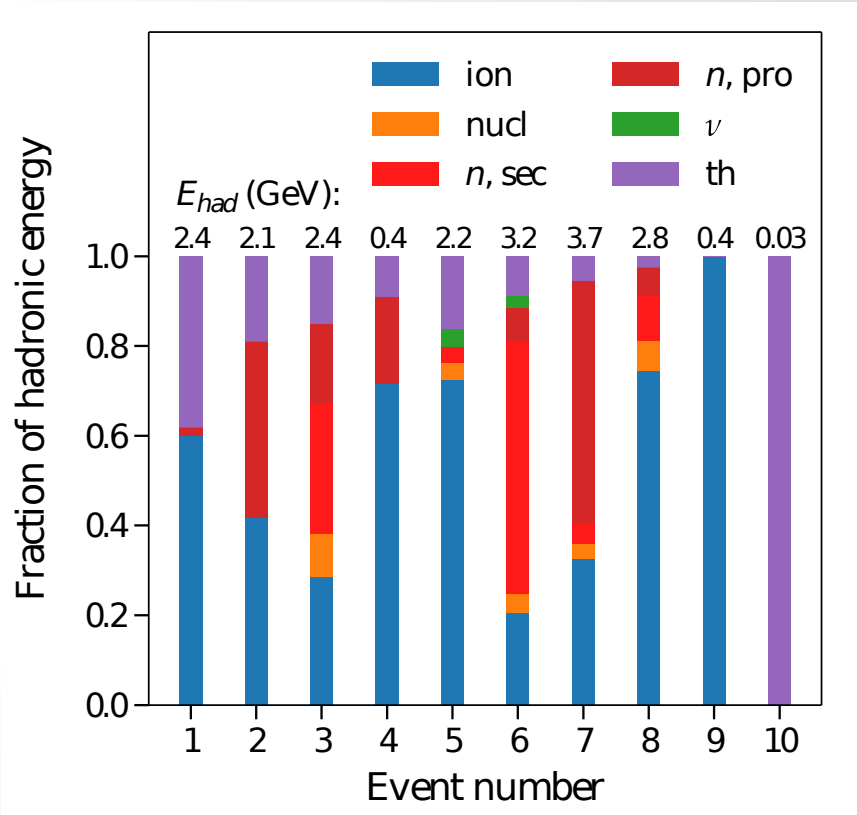
Energy budget

4 GeV neutrino in argon, examples

Friedland, Li
in prep

Two MC realizations





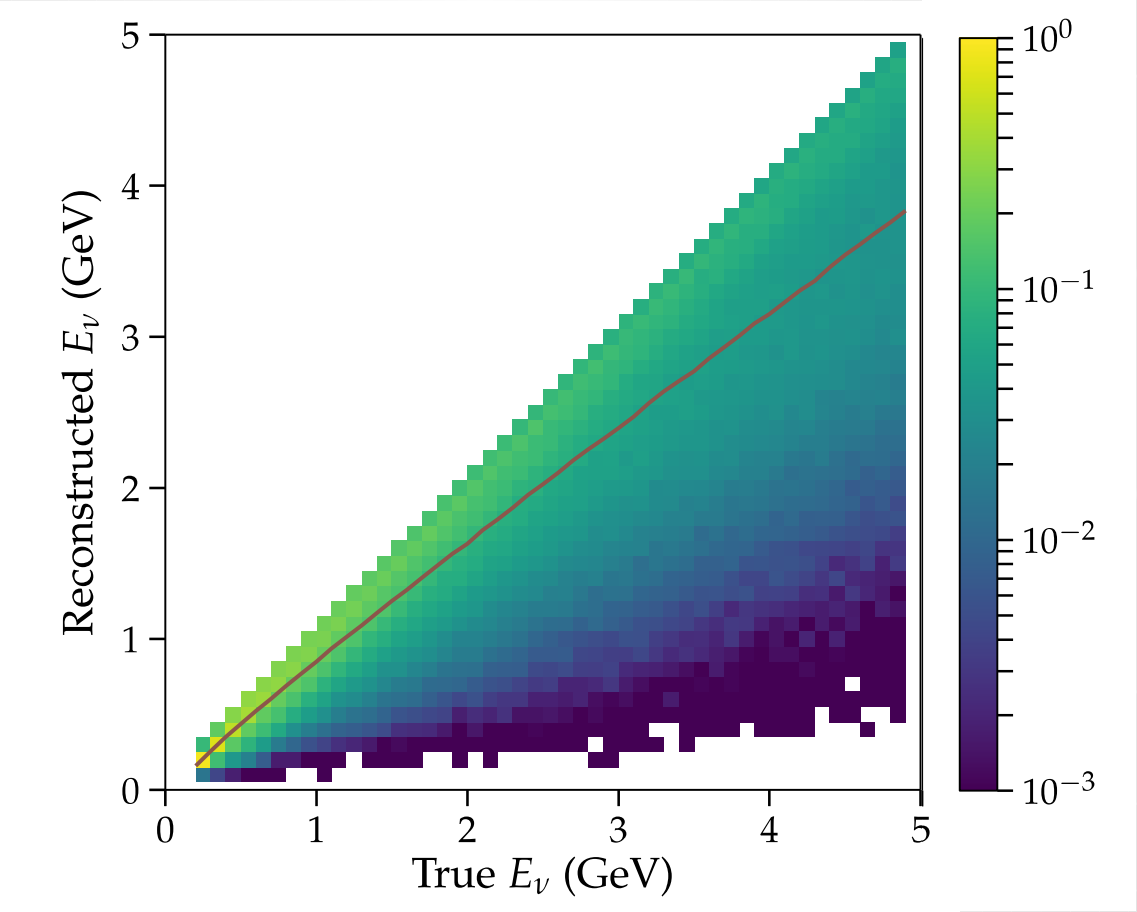
Large fluctuations

Migration Matrix

ν_μ with default assumptions

Friedland, Li
in prep

$$E_{\nu,\mathrm{rec}} = E_\mu + E_{\mathrm{had,rec}}$$

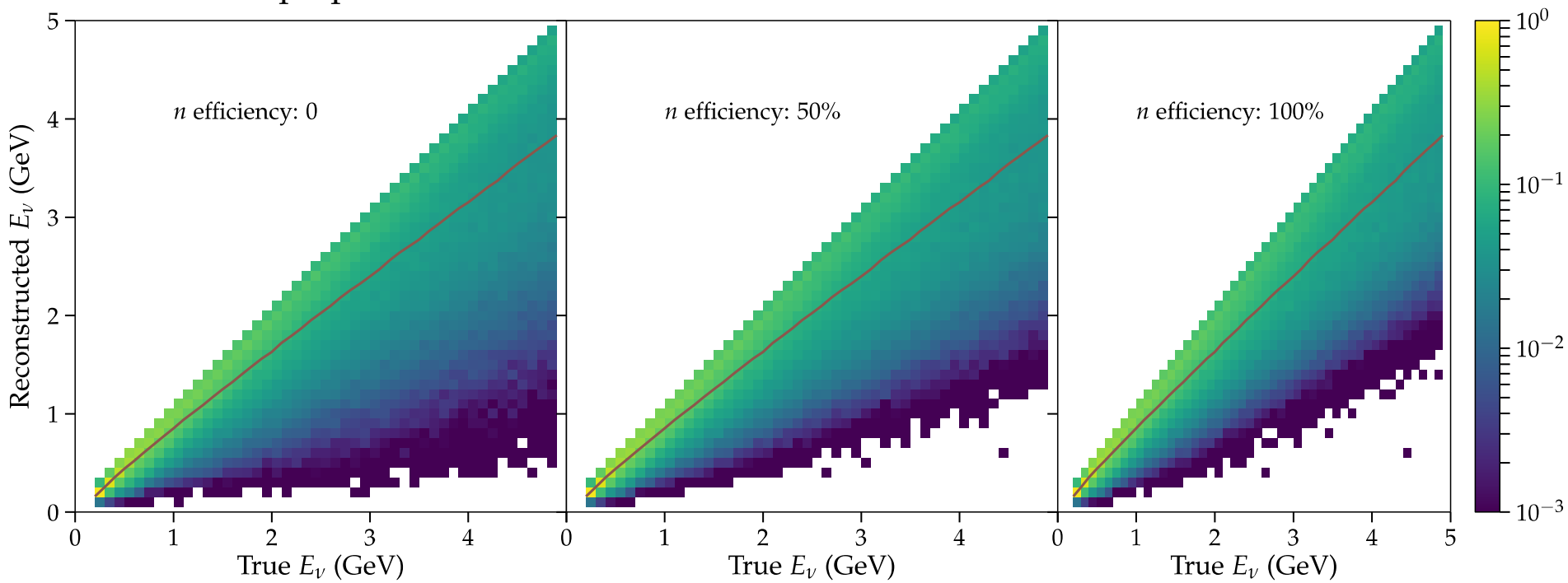


Highly non-Gaussian

Migration Matrix

How would it improve with better n detection?

Friedland, Li in prep

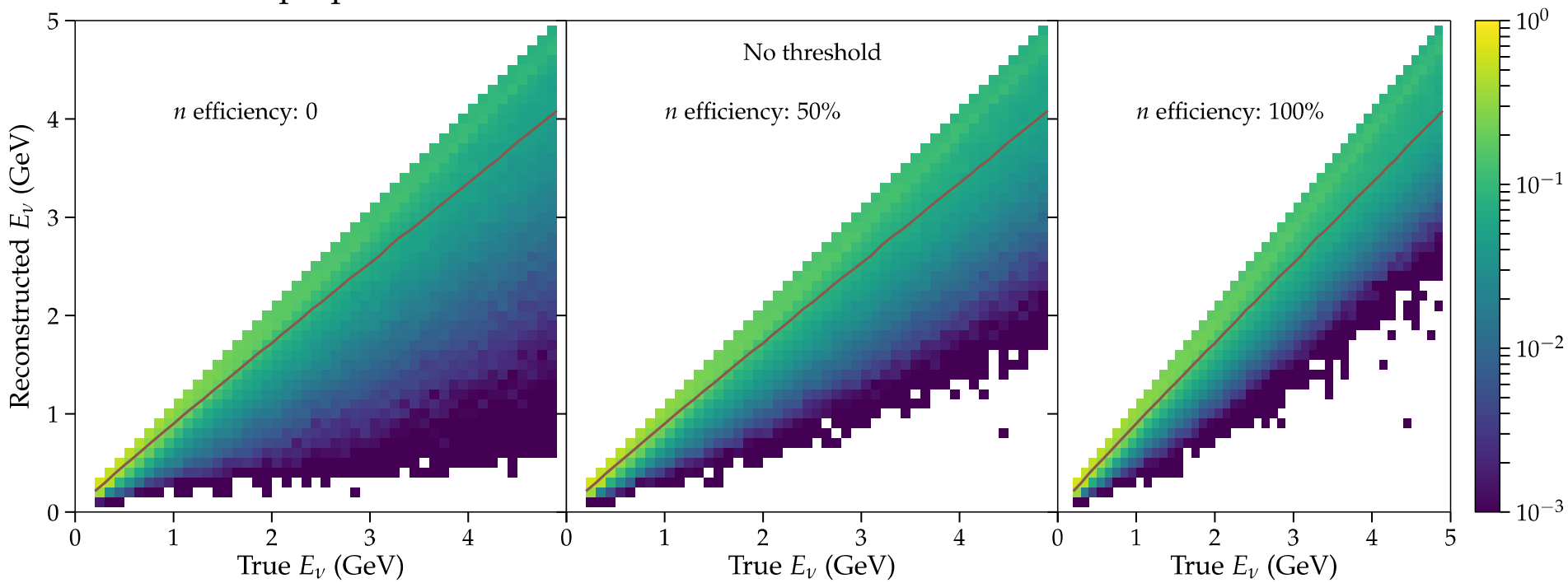


σ: 18% 16% 14%

Migration Matrix

How would it improve with lower thresholds?

Friedland, Li in prep

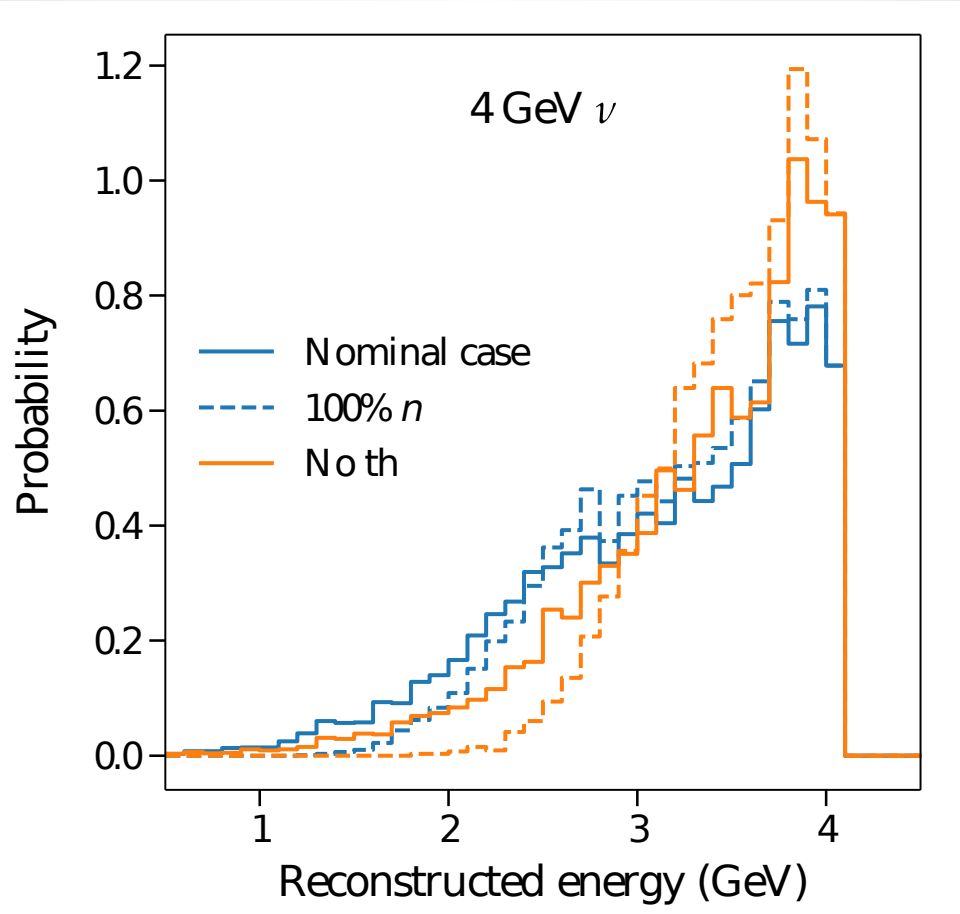


σ: 15% 15% 12% 12% 10% 10%

Migration Matrix

Friedland, Li
in prep

1-d projection

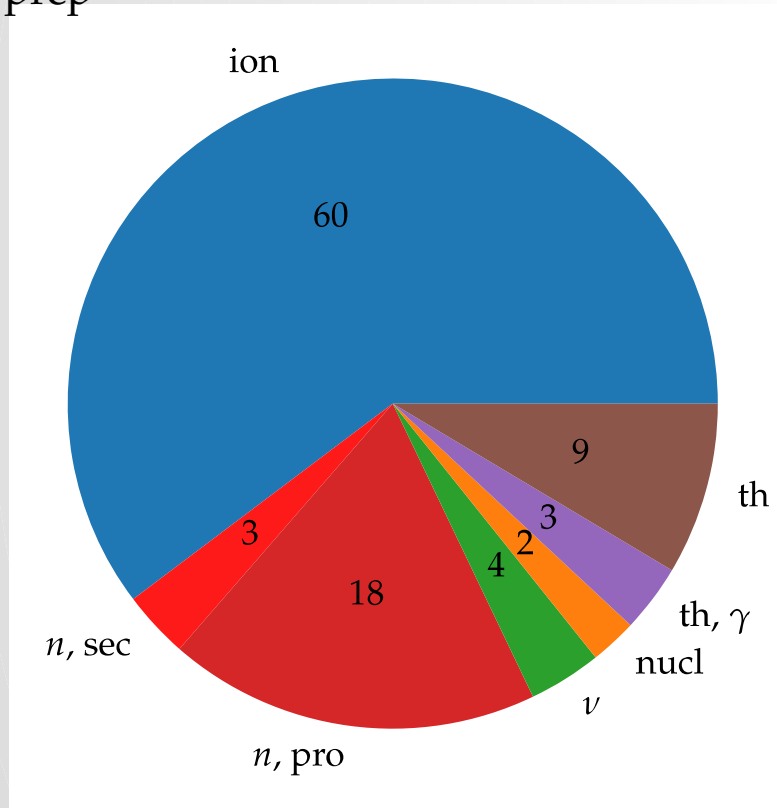


Both are important; calibration is crucial

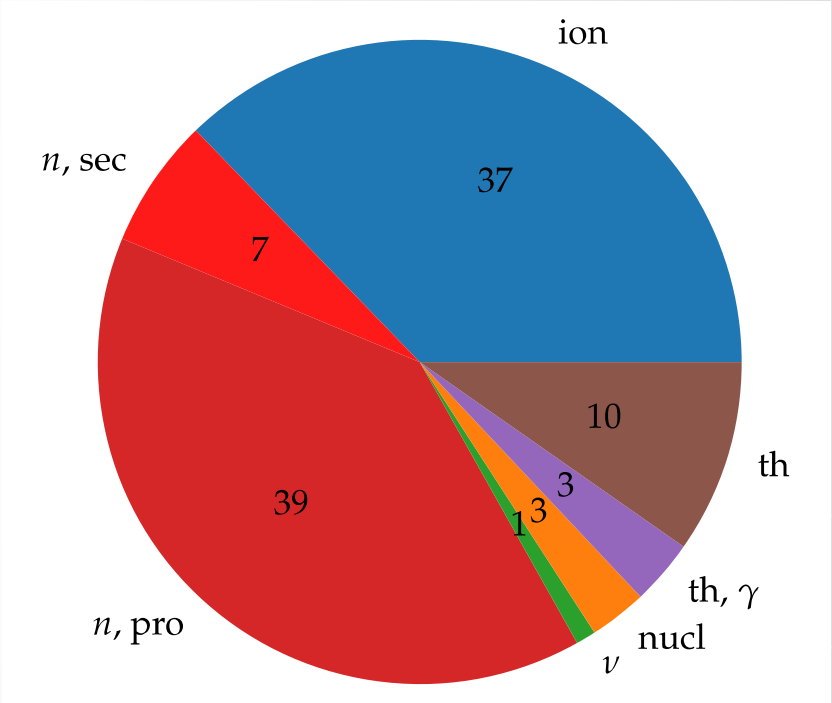
~ 2 GeV beam, scintillator (CH_2) detector

Friedland, Li
in prep

ν



$\bar{\nu}$



Qualitatively similar to DUNE

Conclusions

- Calorimetric energy reconstruction is important and not well understood
- We characterize the energy flow of neutrino events, build "theoretical MM"
- Secondary particle propagation is PREREQUISITE for any studies of cross section sensitivities
- Neutron efficiency and detector thresholds need calibration
- Other theoretical uncertainties in future study