

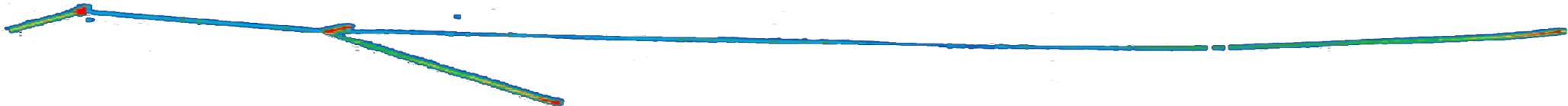
Neutrino Measurements in Liquid Argon and DUNE

Andrew Furmanski
LDMX eN meeting
9th March 2021



Introduction

- This is an attempt to explain:
 - How we make neutrino cross section measurements
 - What we're limited by
 - What measurements exist
 - What the future holds
- I may have included too much stuff...



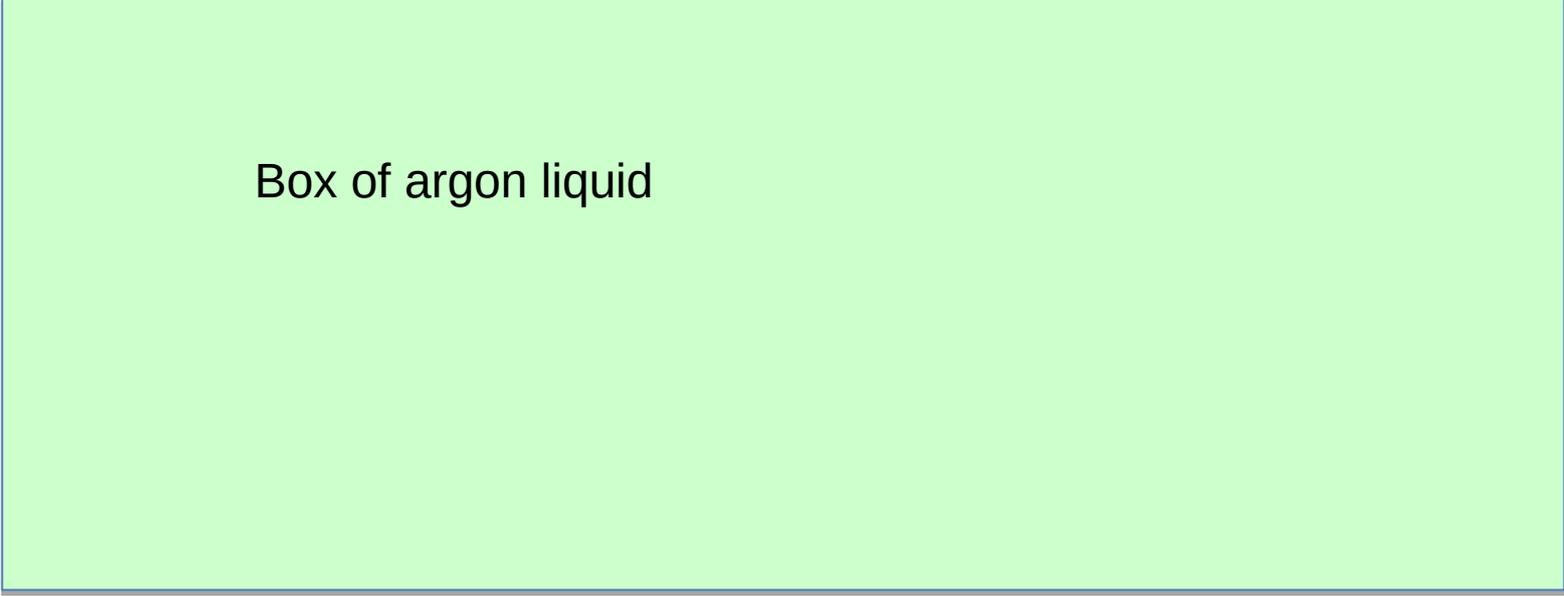
Outline

- Liquid argon detectors
- Neutrino beams and uncertainties
- Past & Recent measurements
- Prospects for DUNE

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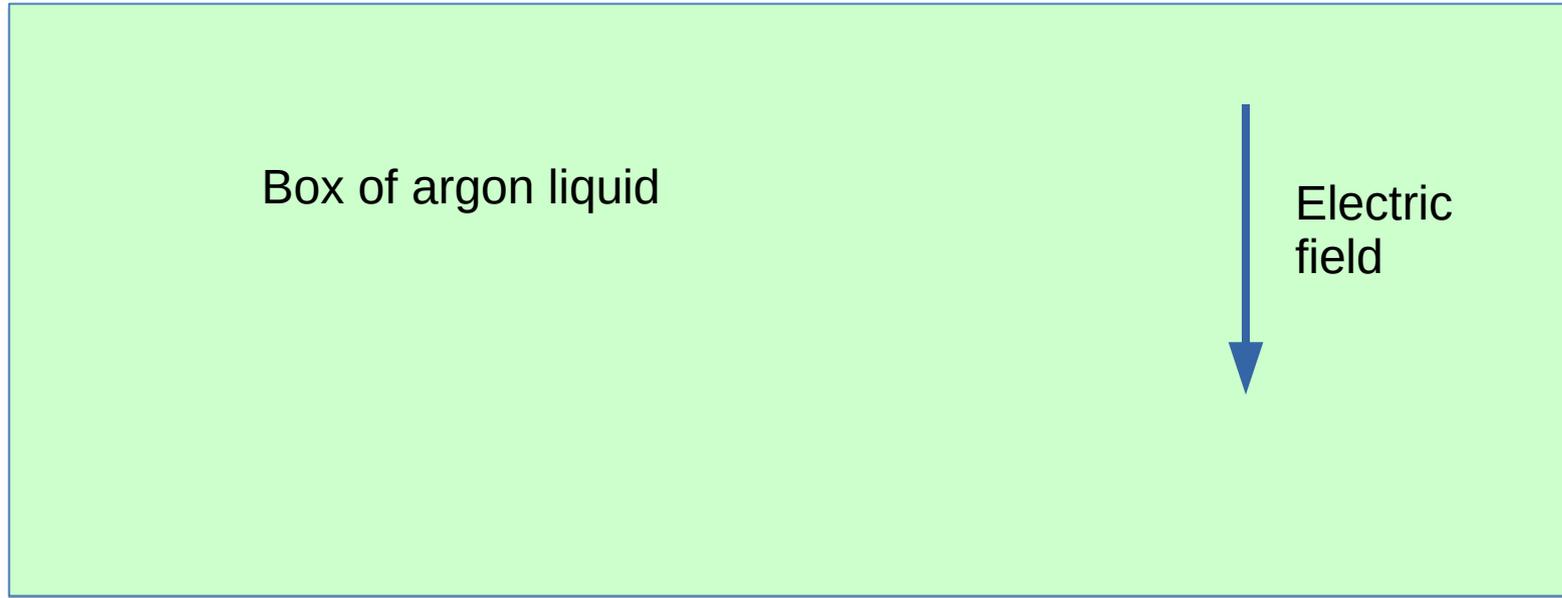
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Fundamental Principle

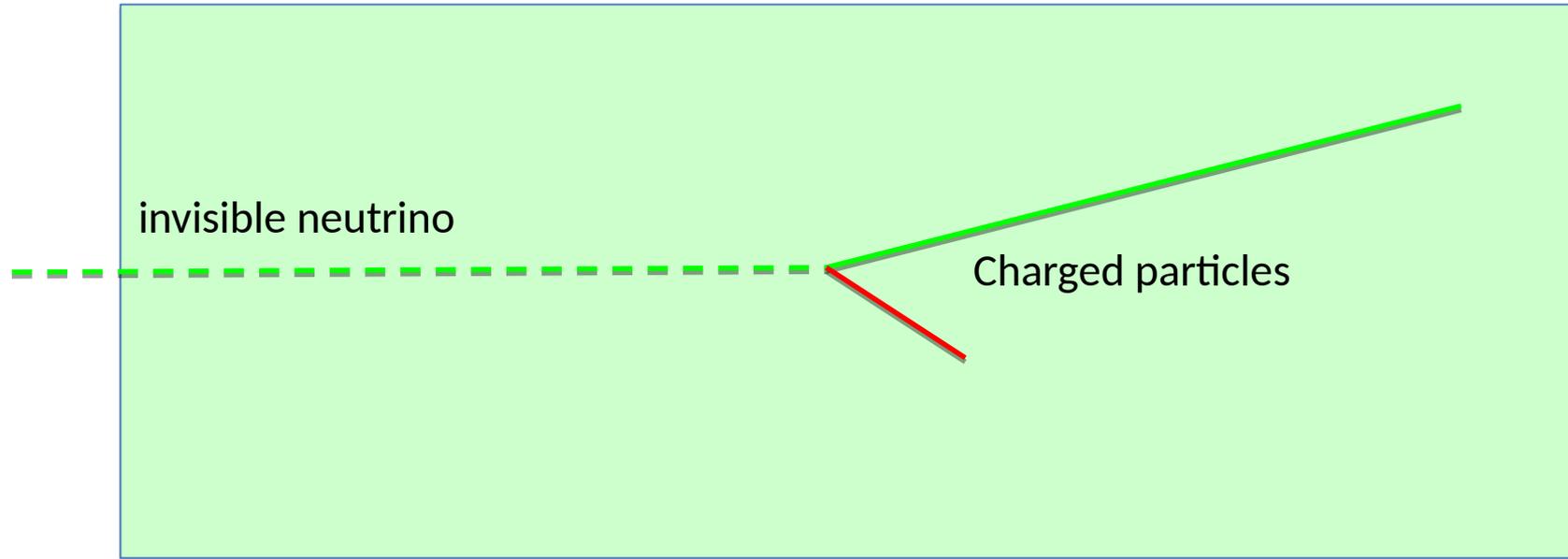


Box of argon liquid

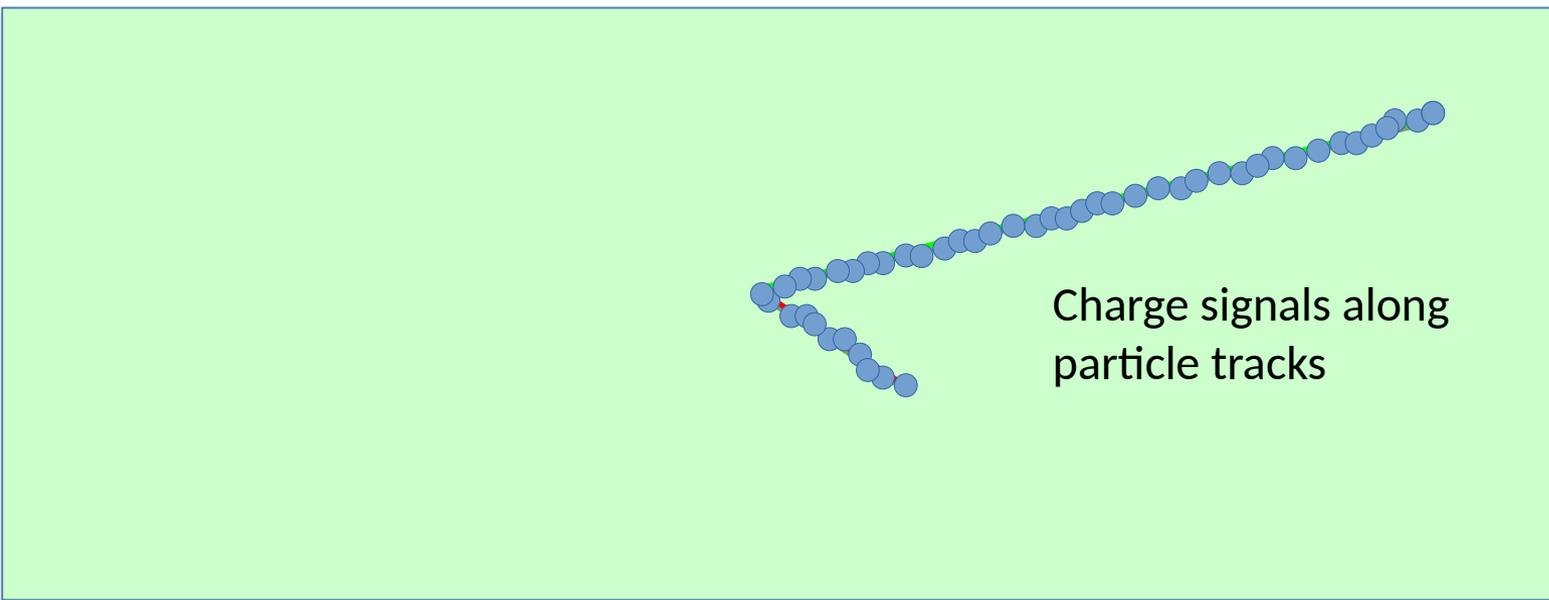
Fundamental Principle



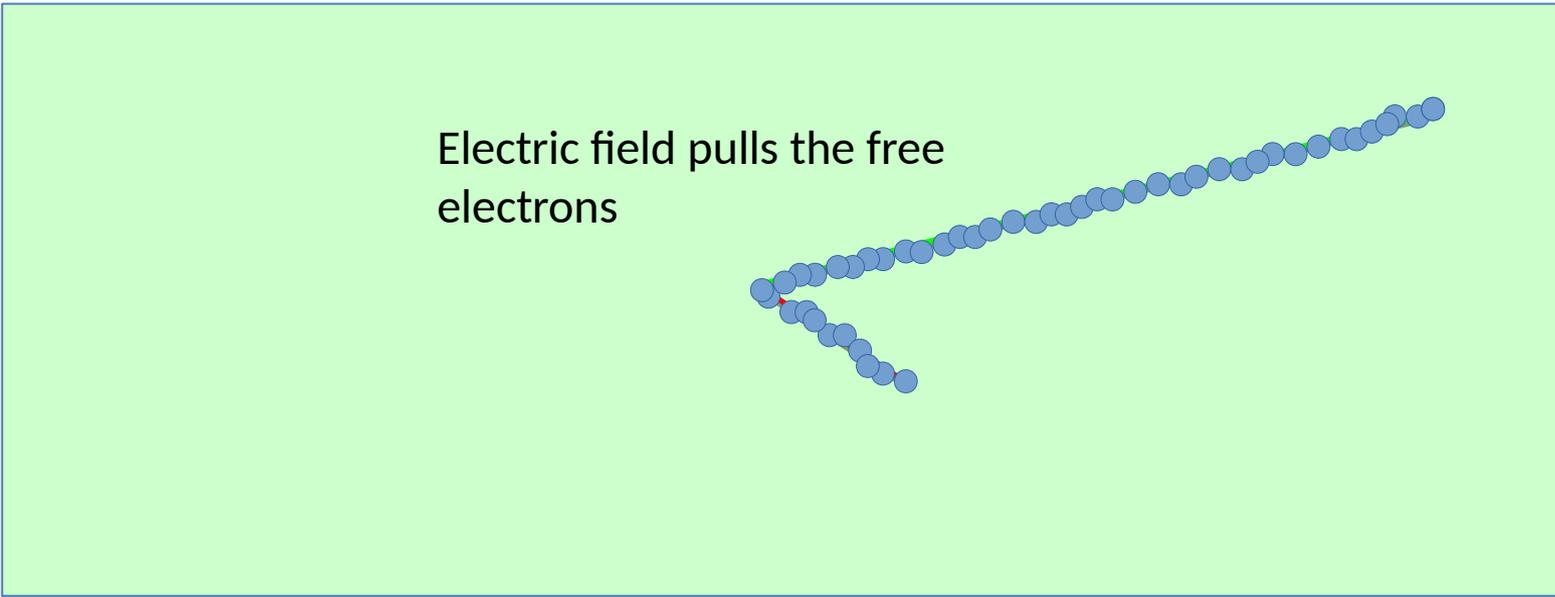
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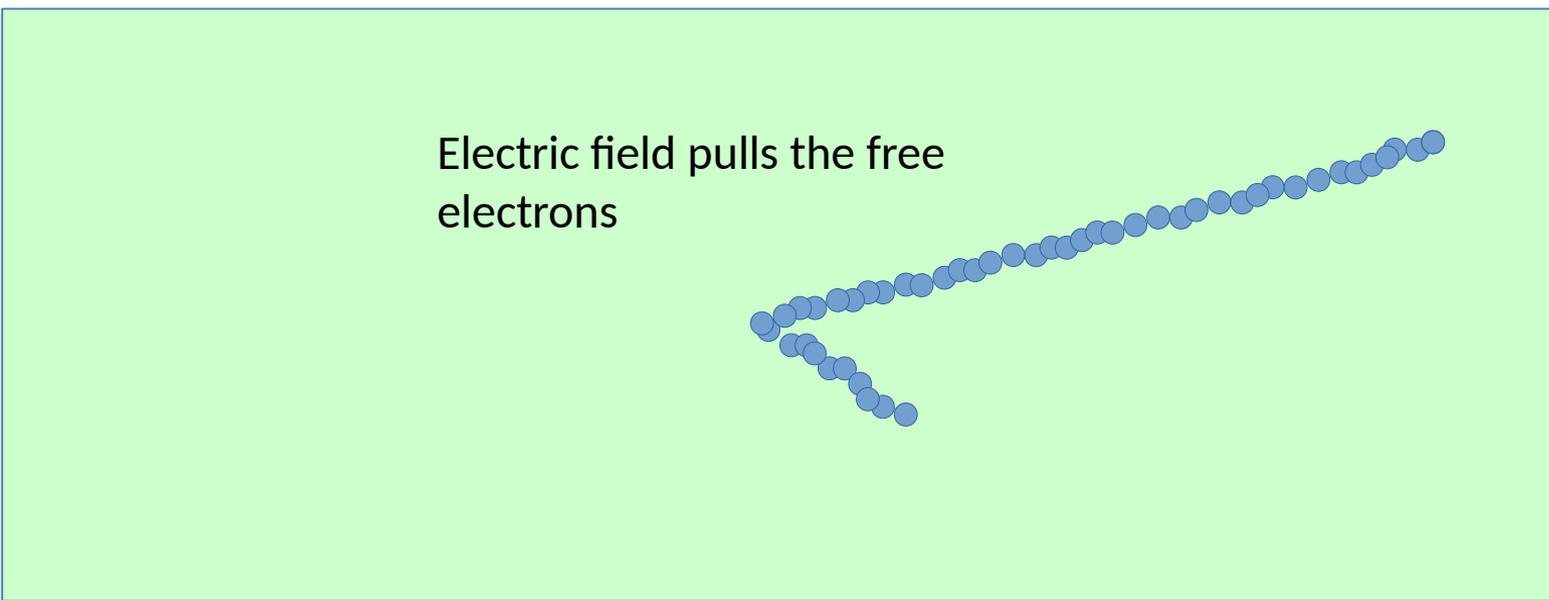
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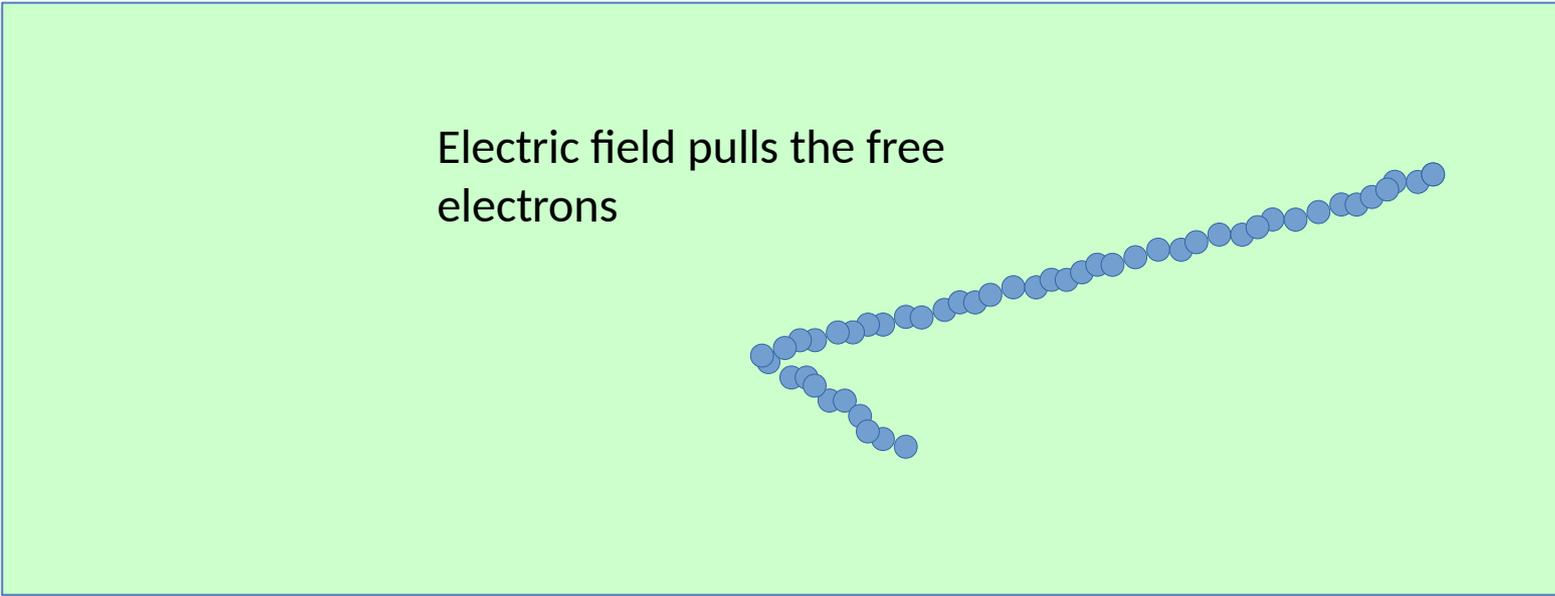
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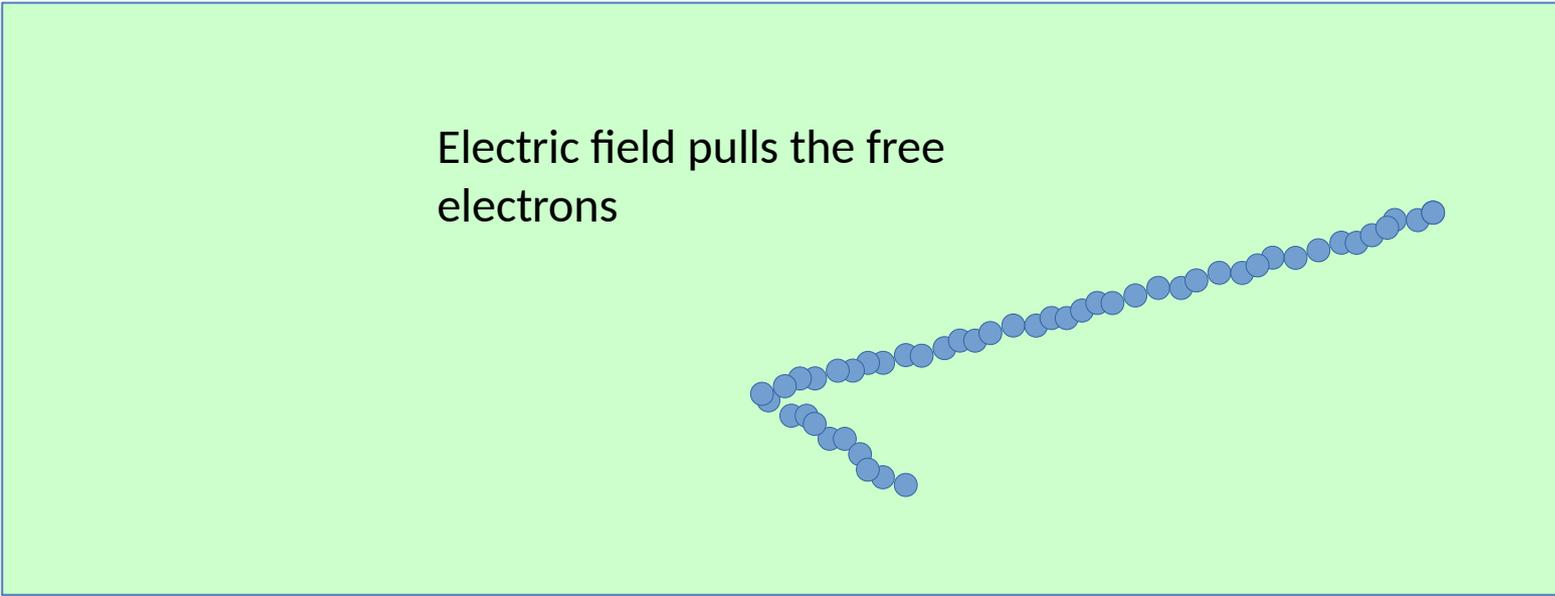
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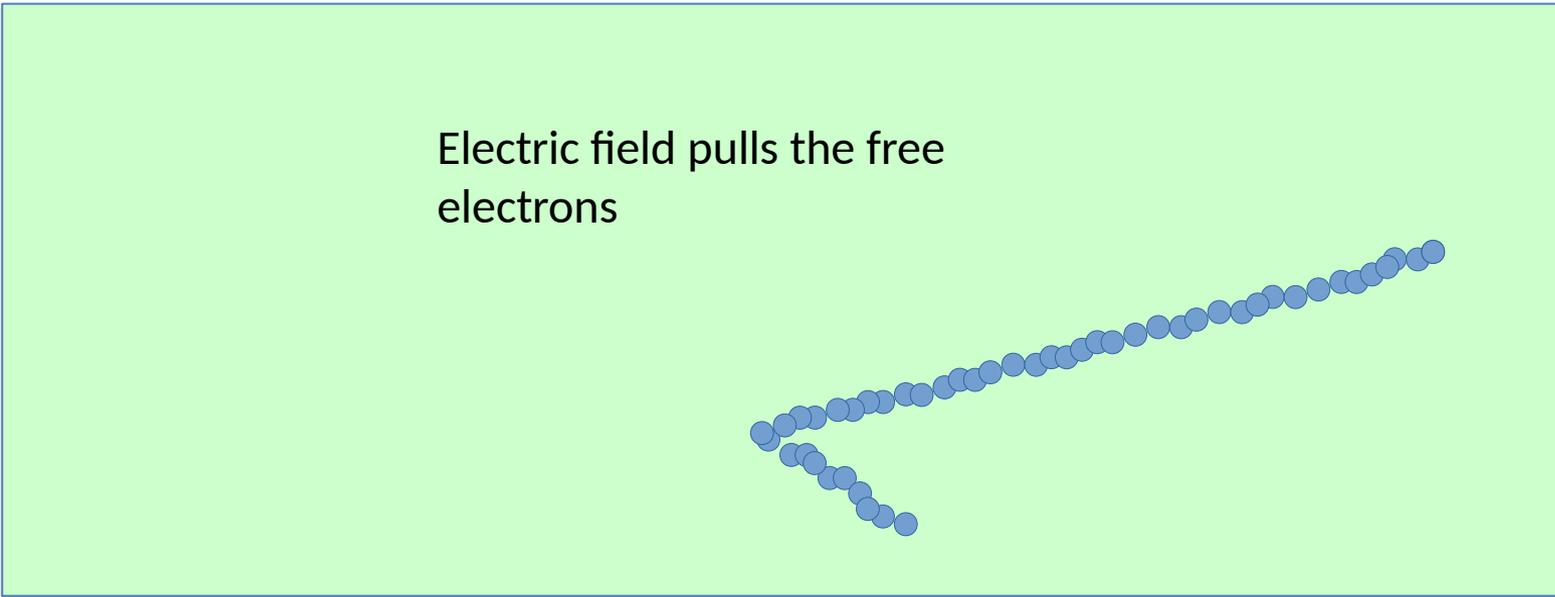
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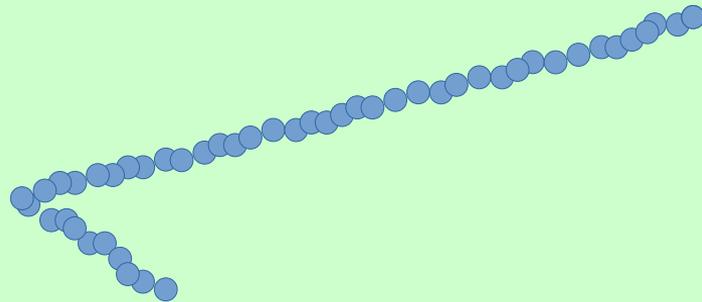


Fundamental Principle

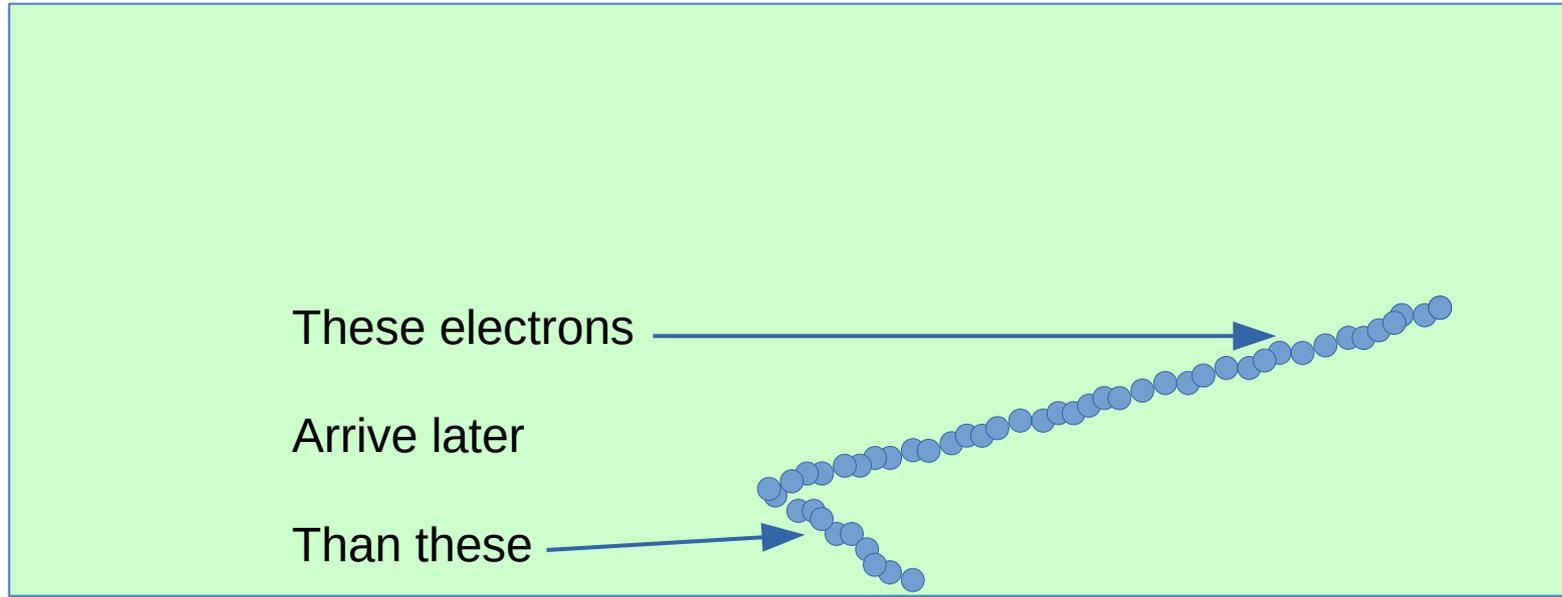


Fundamental Principle

Electric field pulls the free electrons

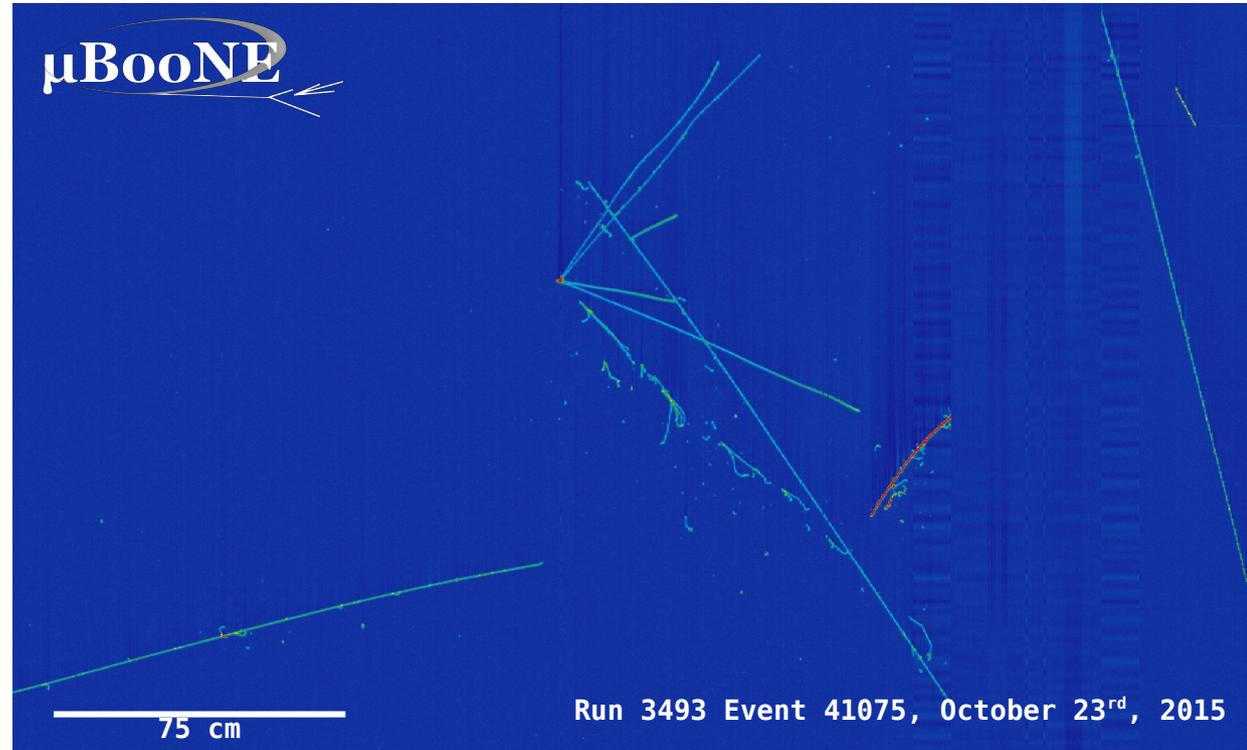


Fundamental Principle



Advantages of LArTPCs

- Highly granular fully active calorimeters
- Energy thresholds of ~ 20 MeV
- Scalable (just drift further)



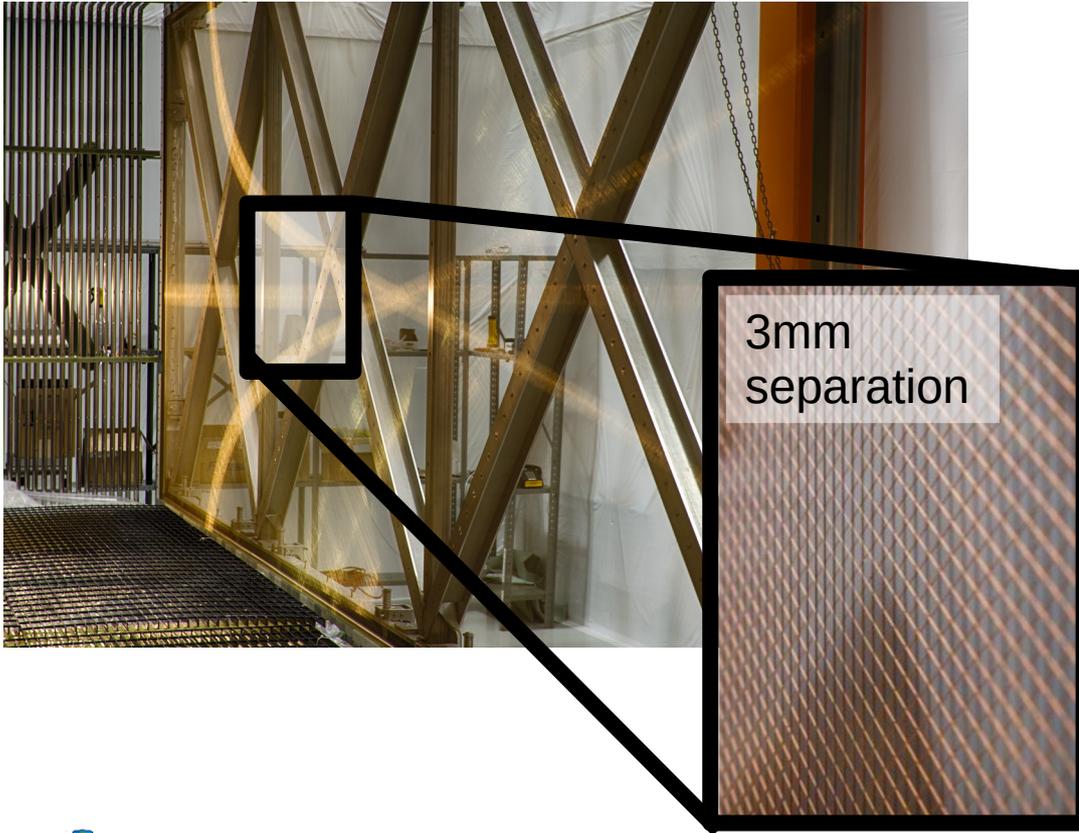
Limitations

- Slow readout:
 - No real time information: neutron TOF not possible
 - Surface detectors struggle from cosmics
 - High intensity (DUNE) struggle with pileup
- No magnetic field:
 - Momentum only available from range
 - Challenging when hadronic re-interactions occur
 - No sign identification

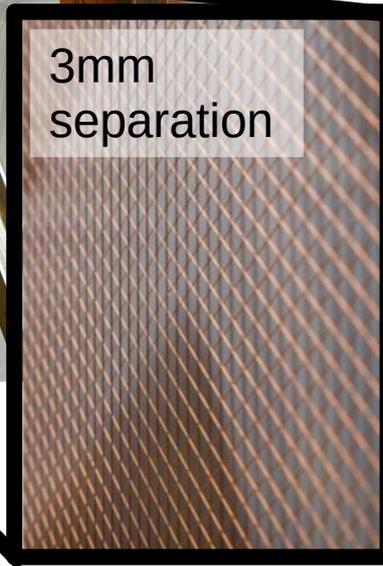
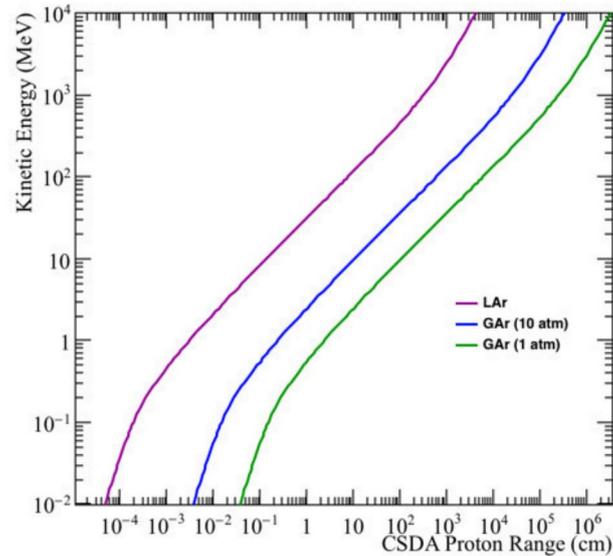
Energy Thresholds



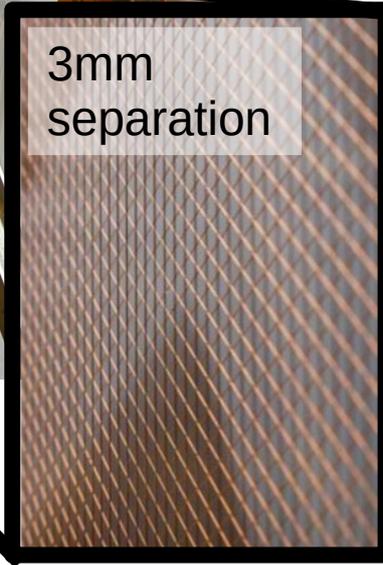
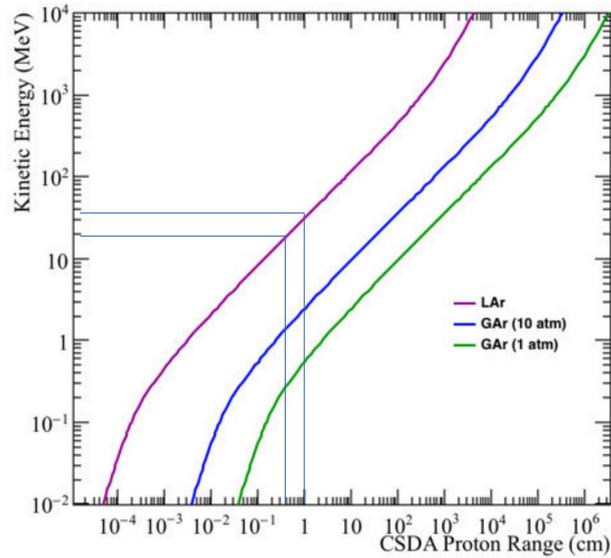
Energy Thresholds



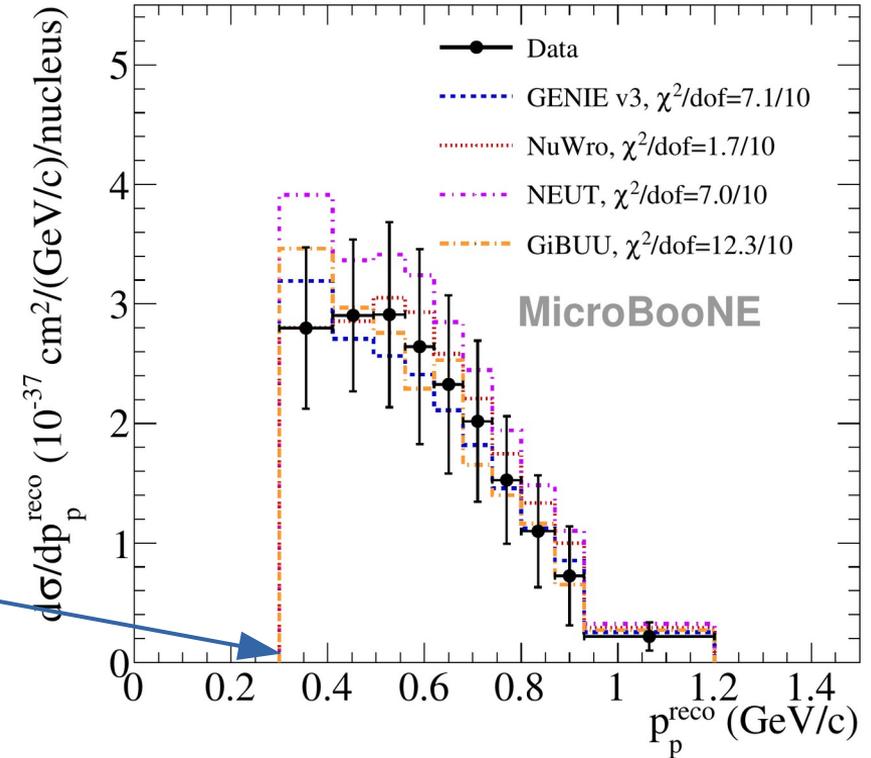
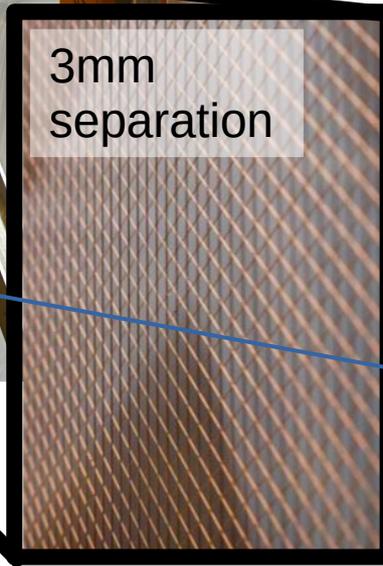
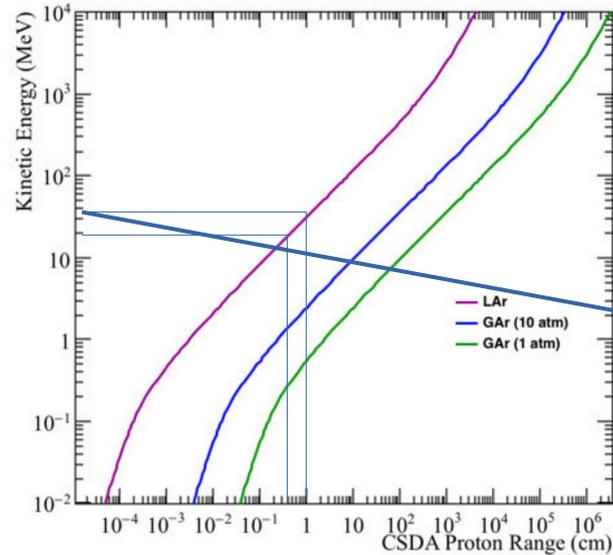
Energy Thresholds



Energy Thresholds

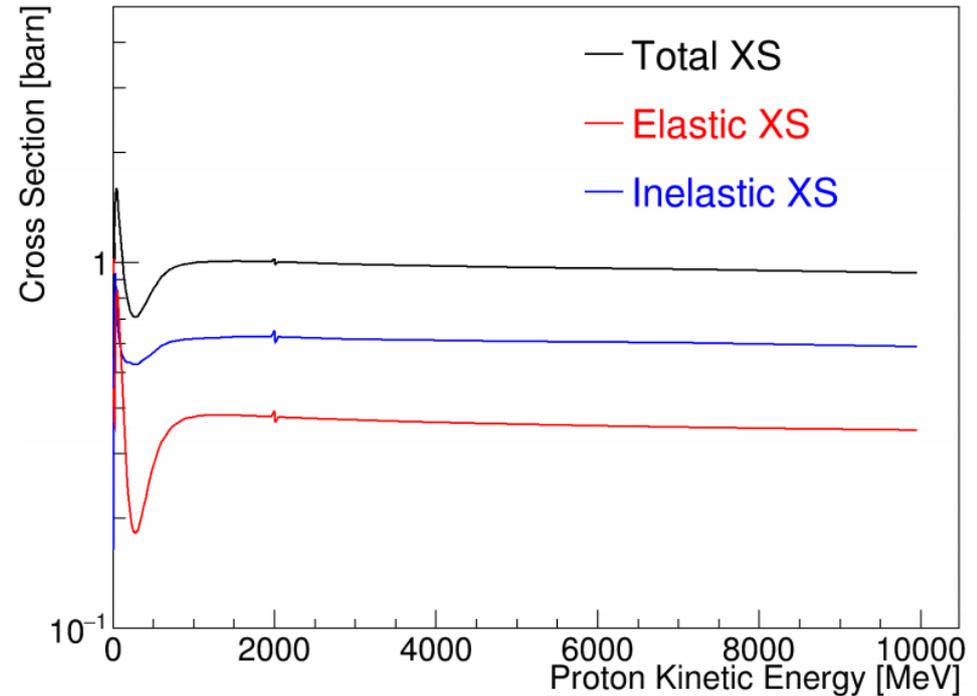


Energy Thresholds



Hadronic Interactions

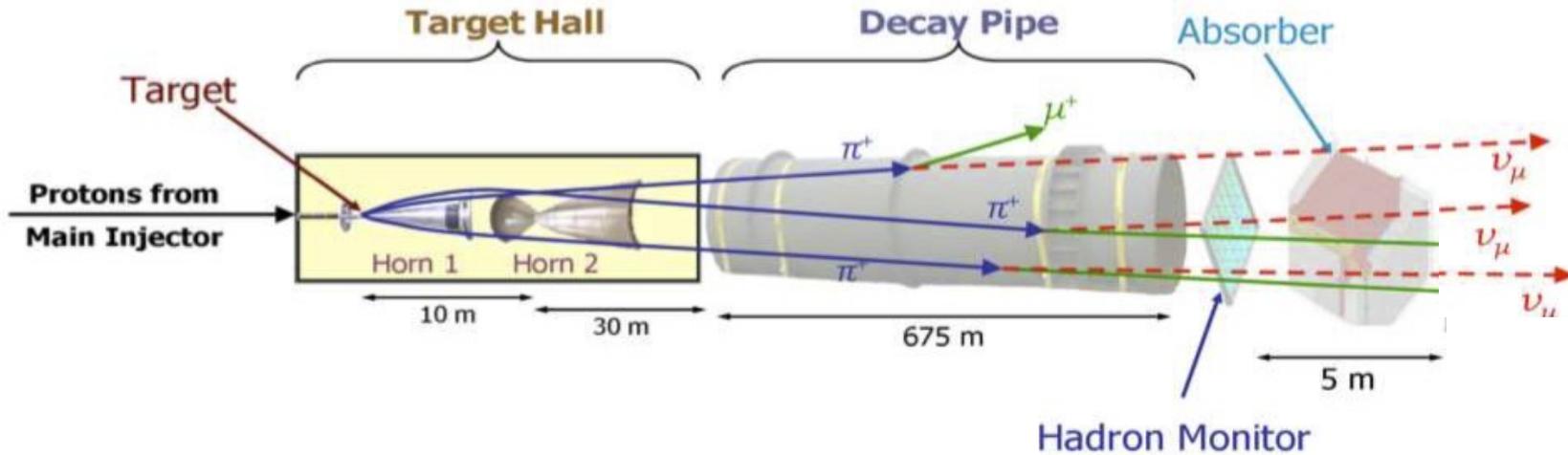
- No magnet – options for hadronic energy are:
 - Calorimetry
 - Track lengths
- Energy resolution different for pions and protons that shower
- Particle ID requires stopping particles
- Limits measurable energy range



Outline

- Liquid argon detectors
- Neutrino beams and uncertainties
- Past & Recent measurements
- Prospects for DUNE

How to make a neutrino beam



NuMI as an example

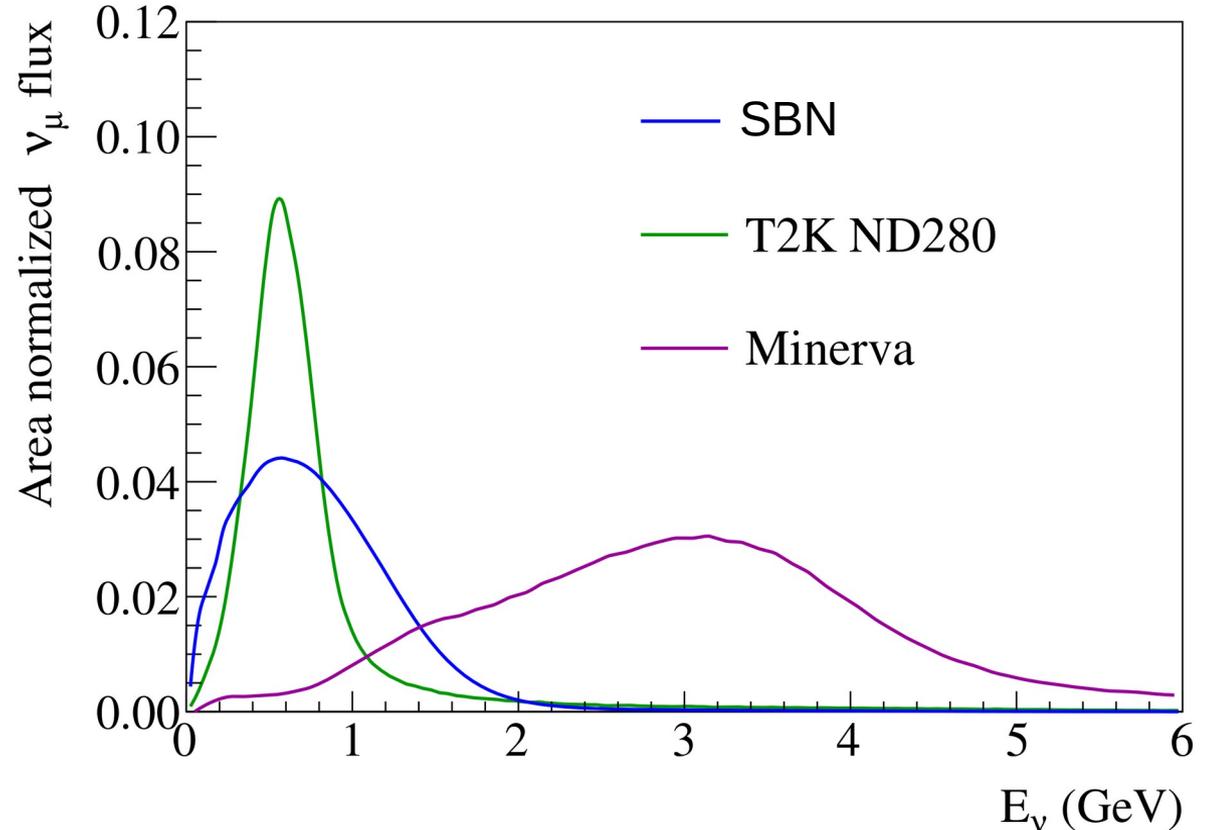
Neutrino “beams” are really neutrino showers

Wide spread in direction, wide spread in momentum



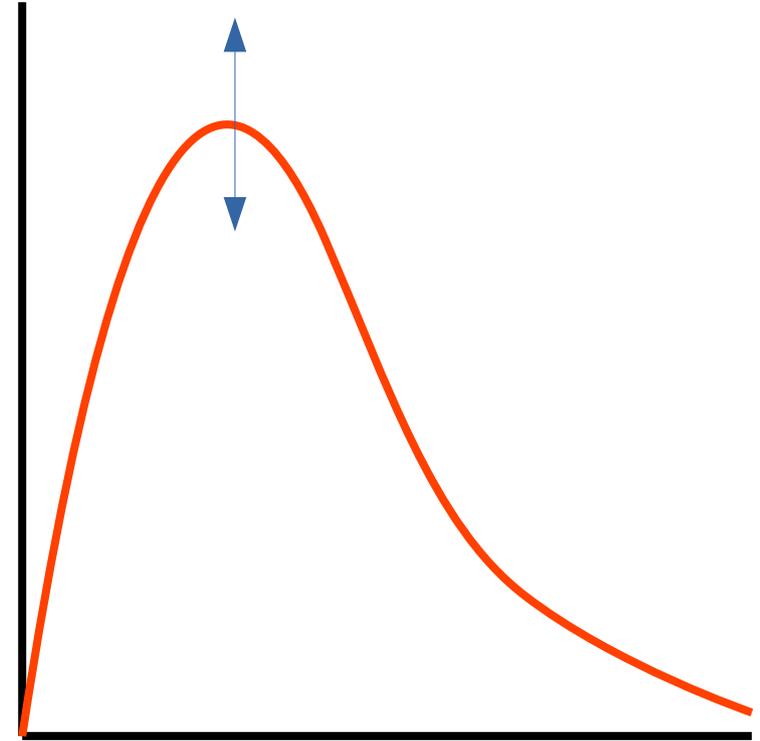
Neutrino Fluxes

- DUNE very similar to MINERvA
- All have a large spread of neutrino energies
- DUNE will be particularly wide (intentionally)



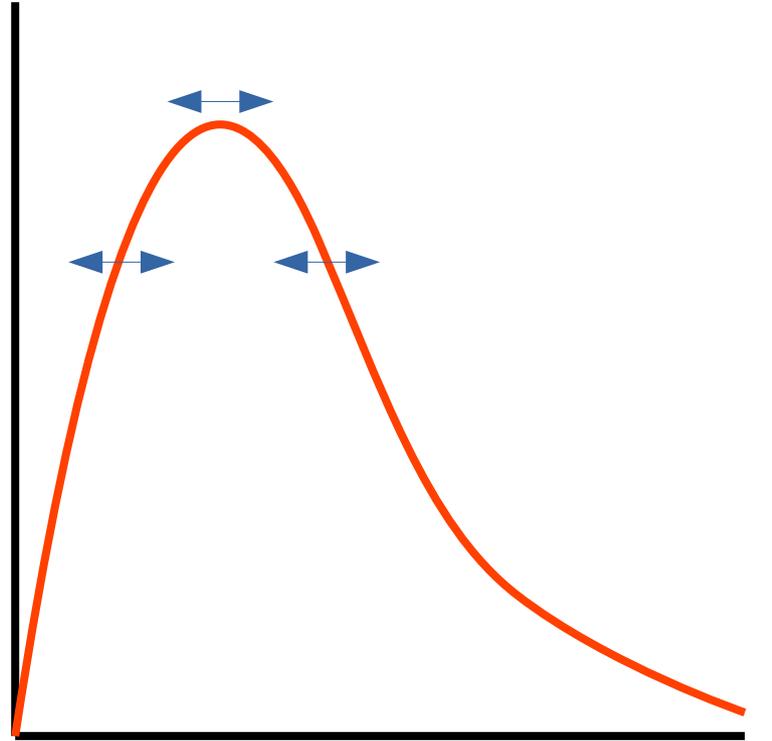
Flux uncertainties

- **Normalisation**
 - Uncertain pion production in the target
- **Focusing**
 - Focusing components alignment/currents
 - Generally small
- **High-energy tail**
 - Uncertain kaon production in the target



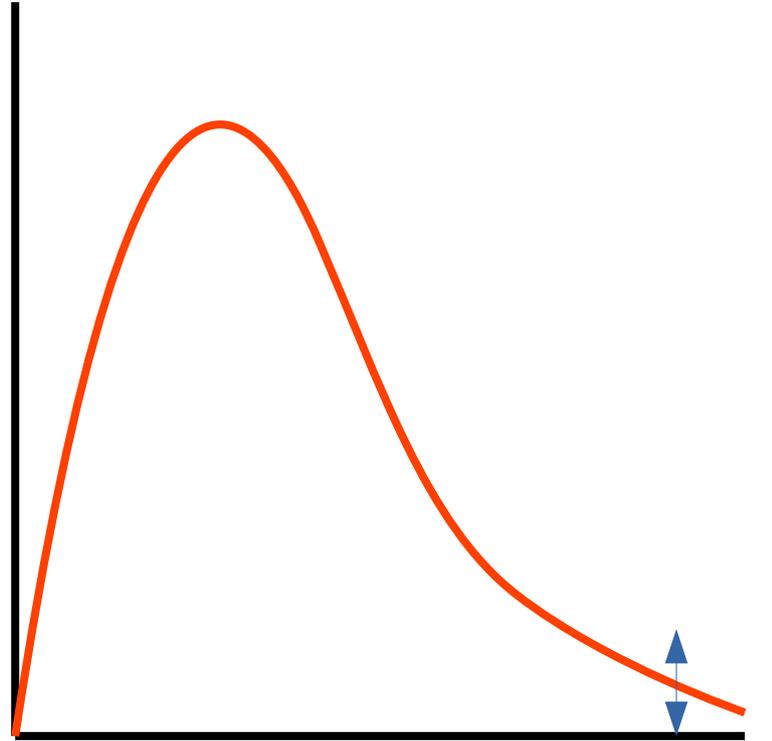
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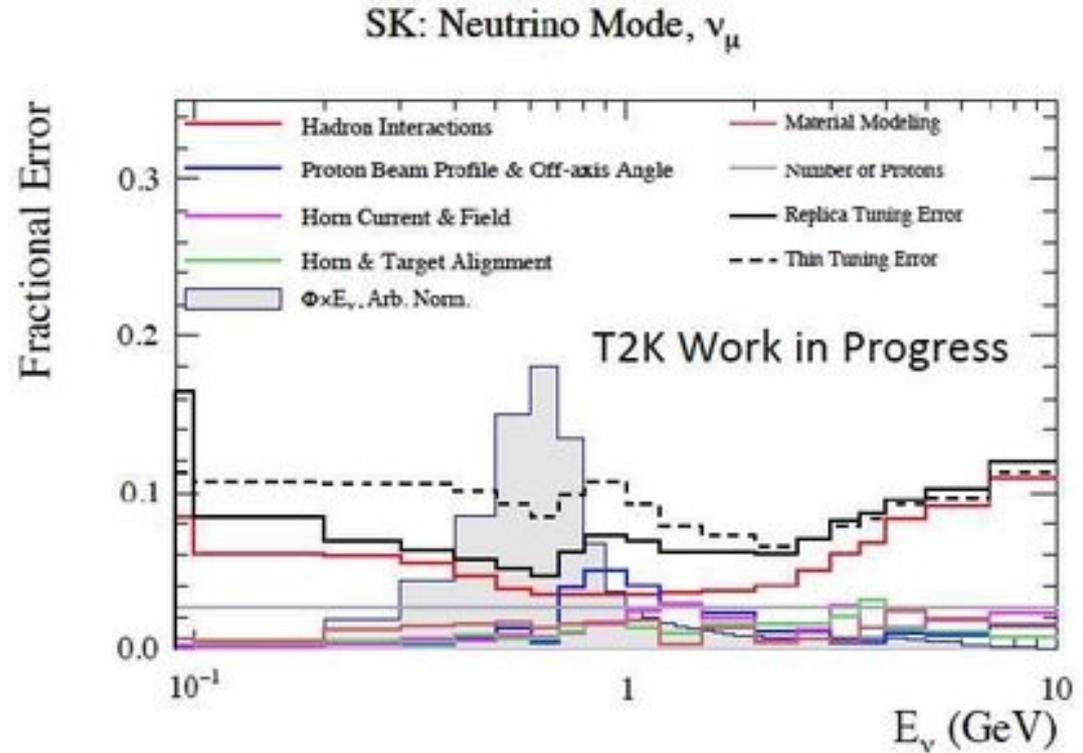
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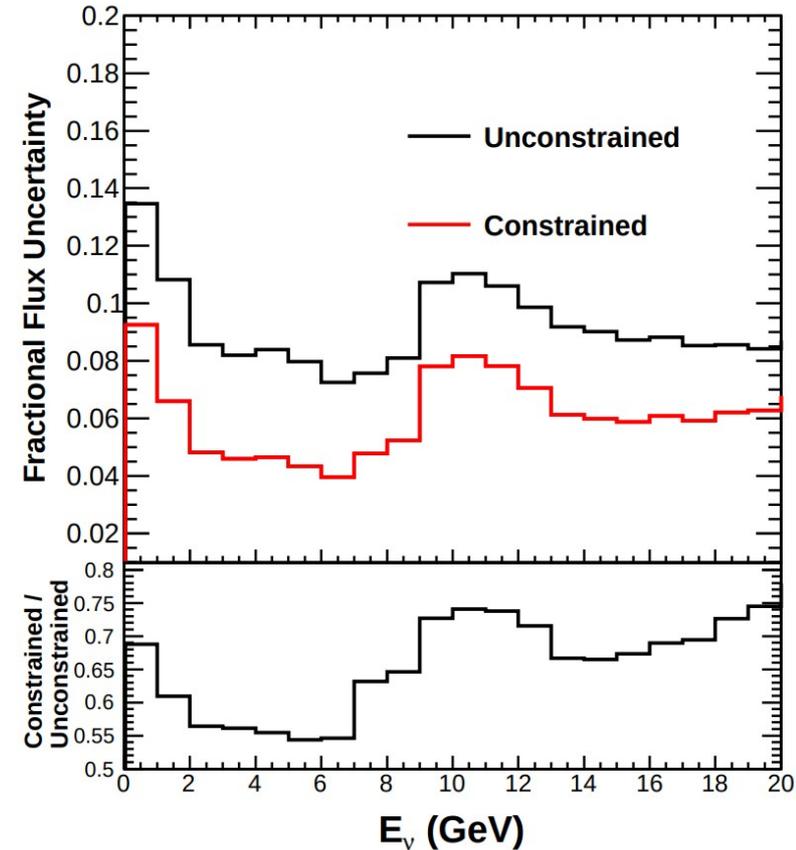
Example: T2K

- Focusing dominant on the high edge of the peak
- Everywhere else hadron production dominant
- Mainly a normalisation uncertainty



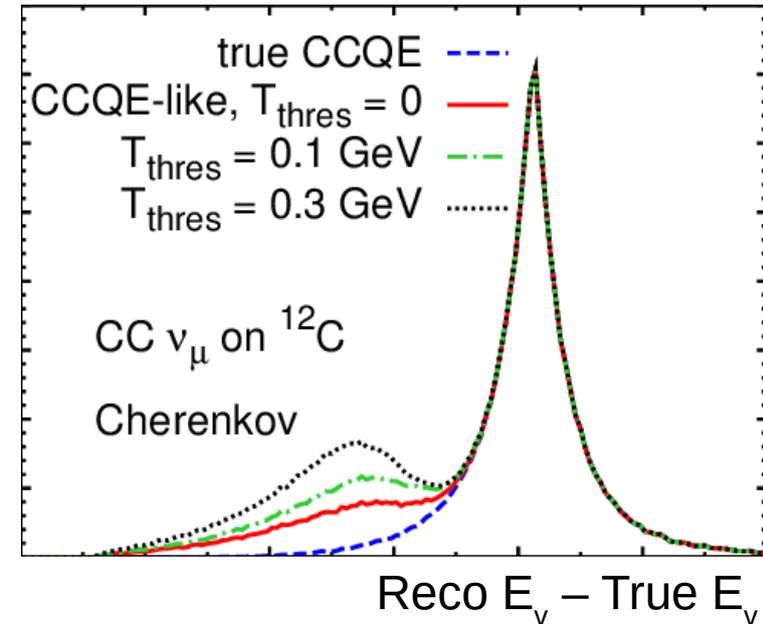
Neutrino-electron scattering

- Process with a perfectly known cross section
- Next-to-no shape information
- MINERvA reached $\sim 4\%$ uncertainty with this
- DUNE might get down to 1-2% or so



Neutrino Energy Measurement

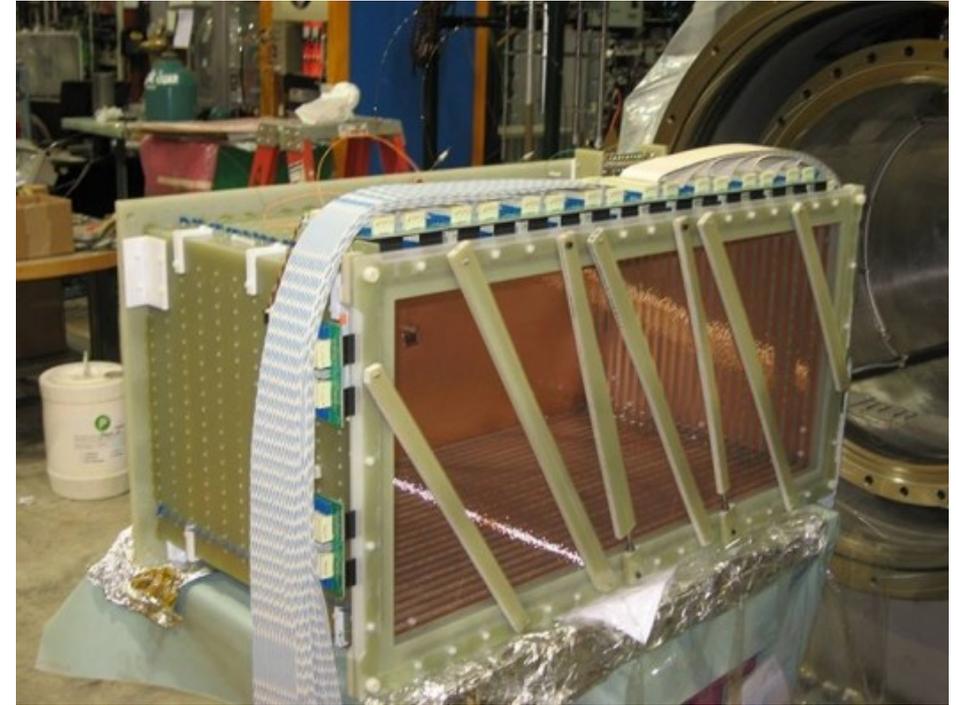
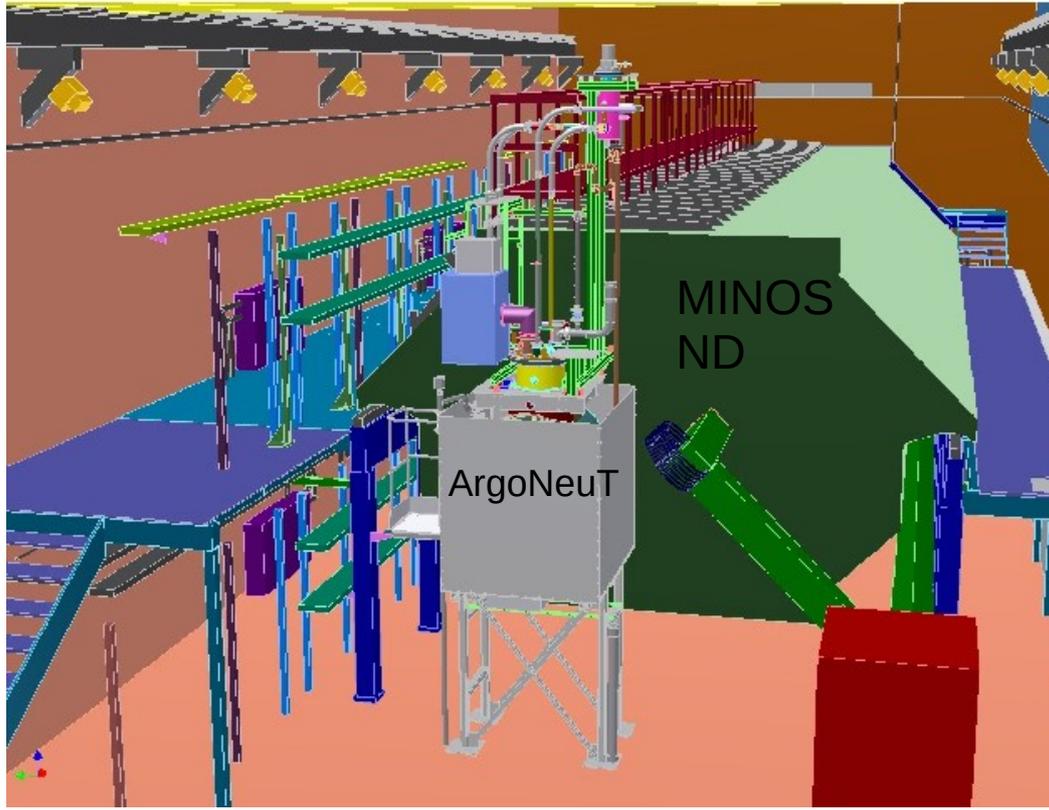
- Event-by-event no knowledge of the neutrino energy
 - Neutrino energy can be “reconstructed”
 - But always requires some nuclear corrections
 - Leads to large uncertainties in oscillation measurements
- “Modern” idea to constrain models:
 - Measure kinematics “integrated” over neutrino flux
 - Compare to an equivalent prediction
 - Rinse, repeat, use multiple experiments etc



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ArgoNeuT

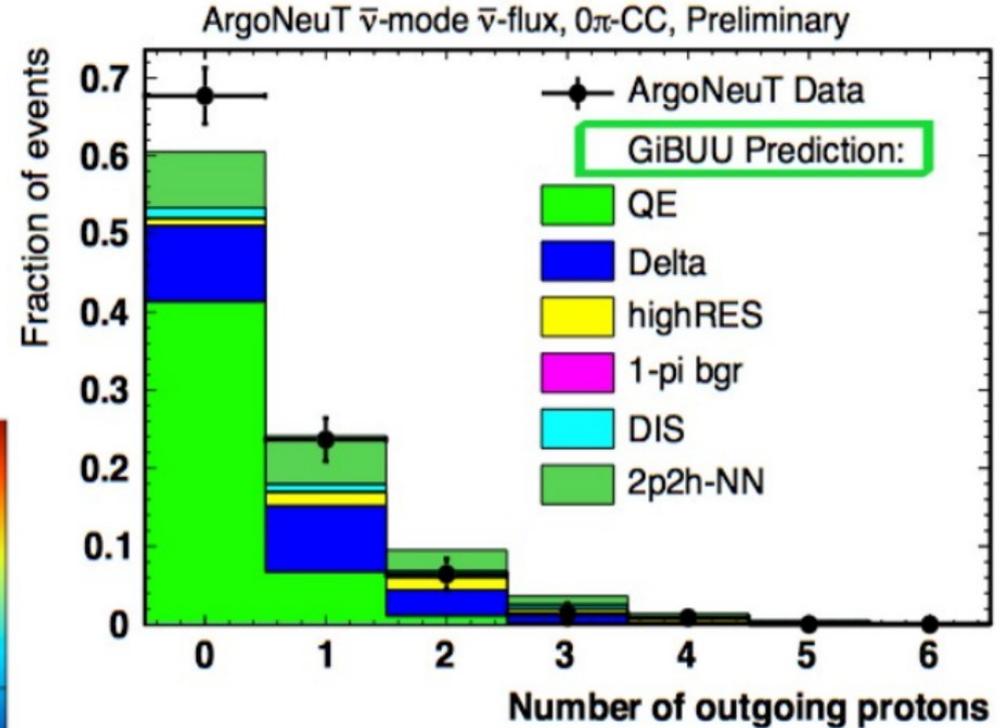
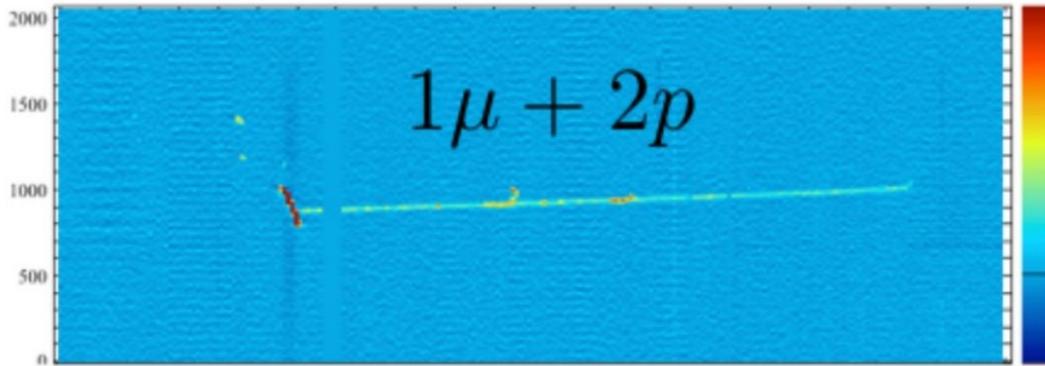


~200 kg Lar detector
MINOS ND used to measure muon energy



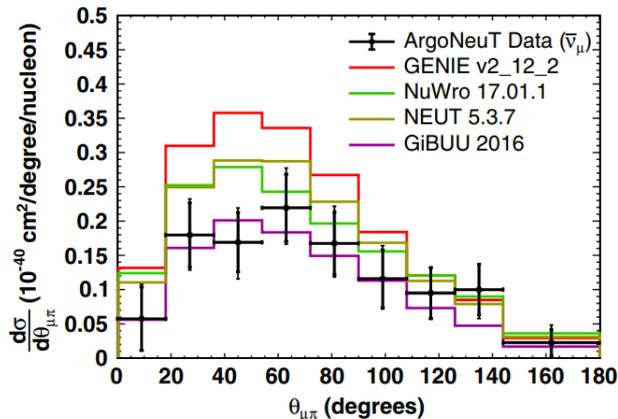
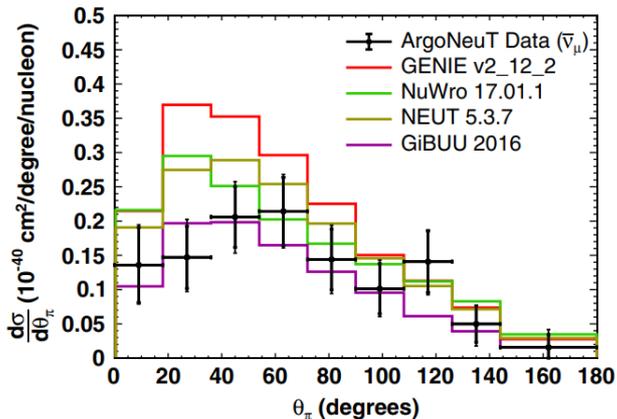
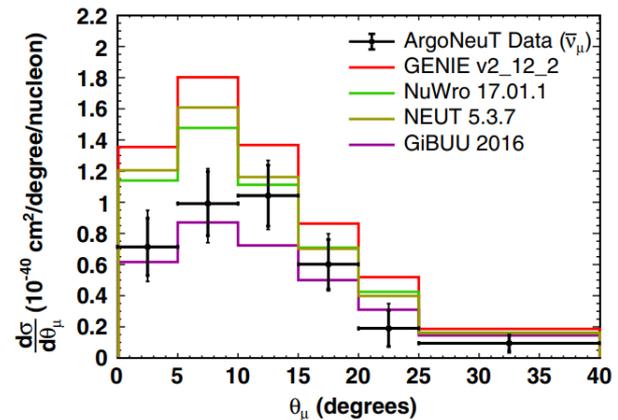
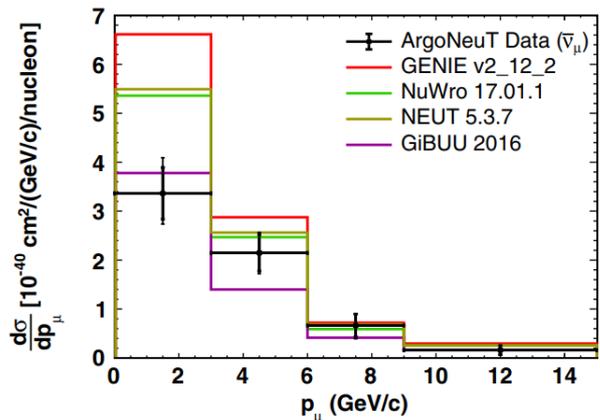
Zero-pion measurements

Primarily muon kinematics and proton multiplicity measured

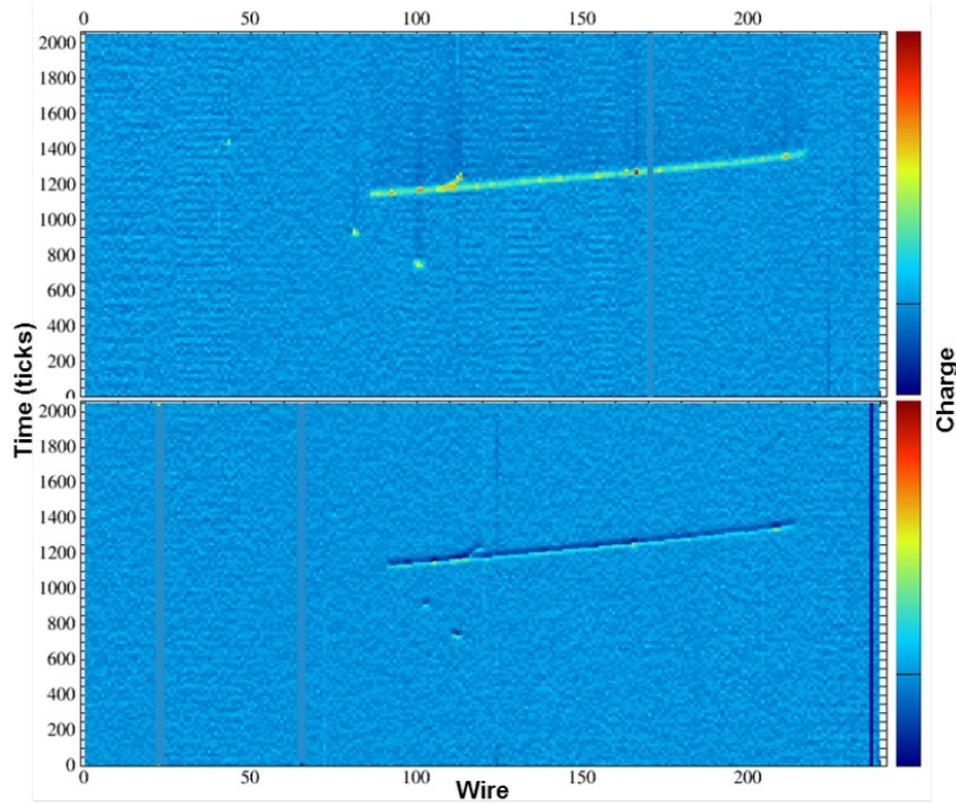


Pion measurements

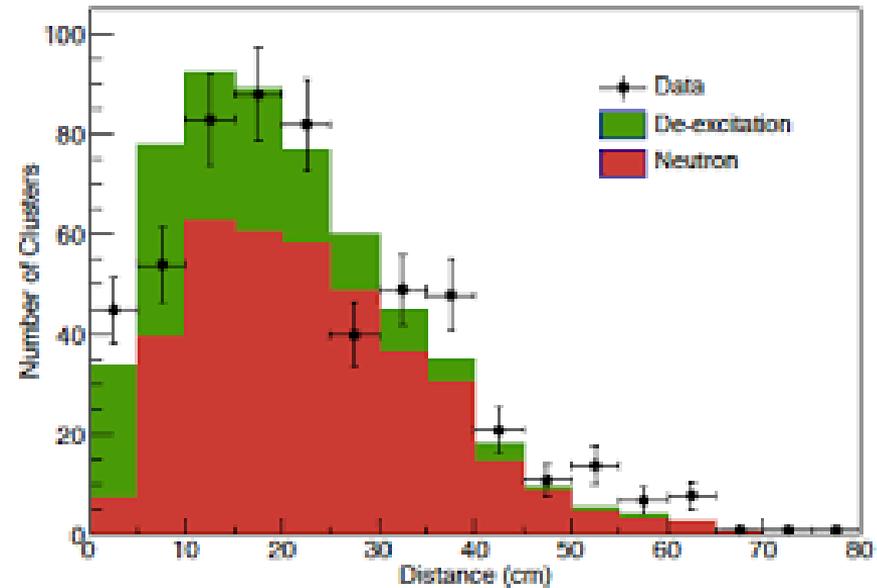
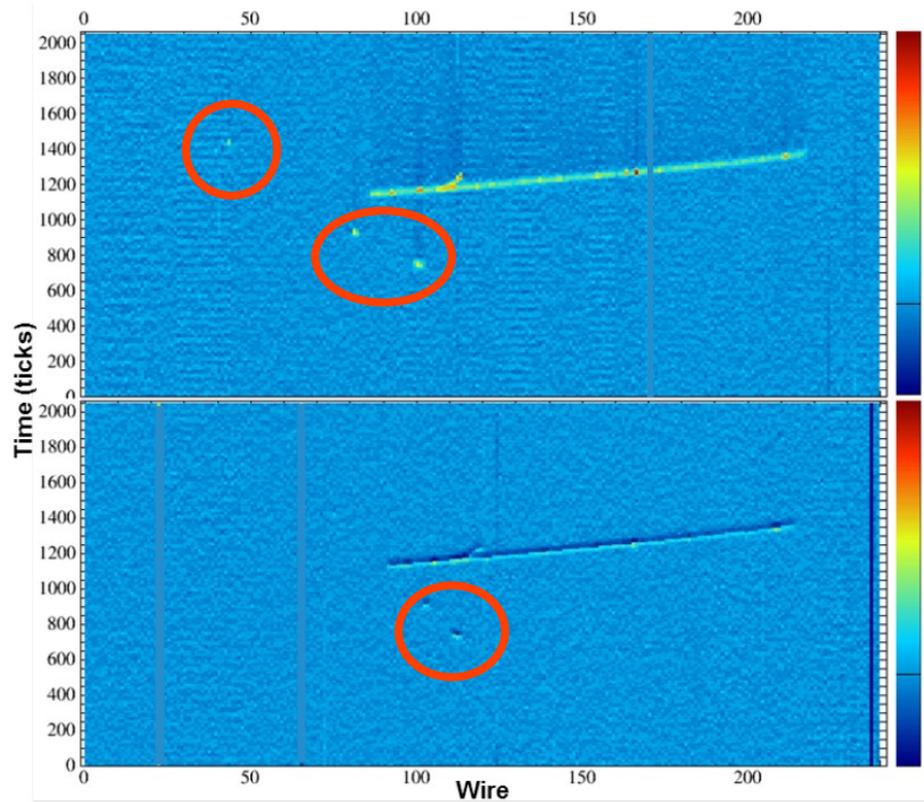
- No ability to measure charged pion energy
- Not particularly good agreement with predictions from generators...



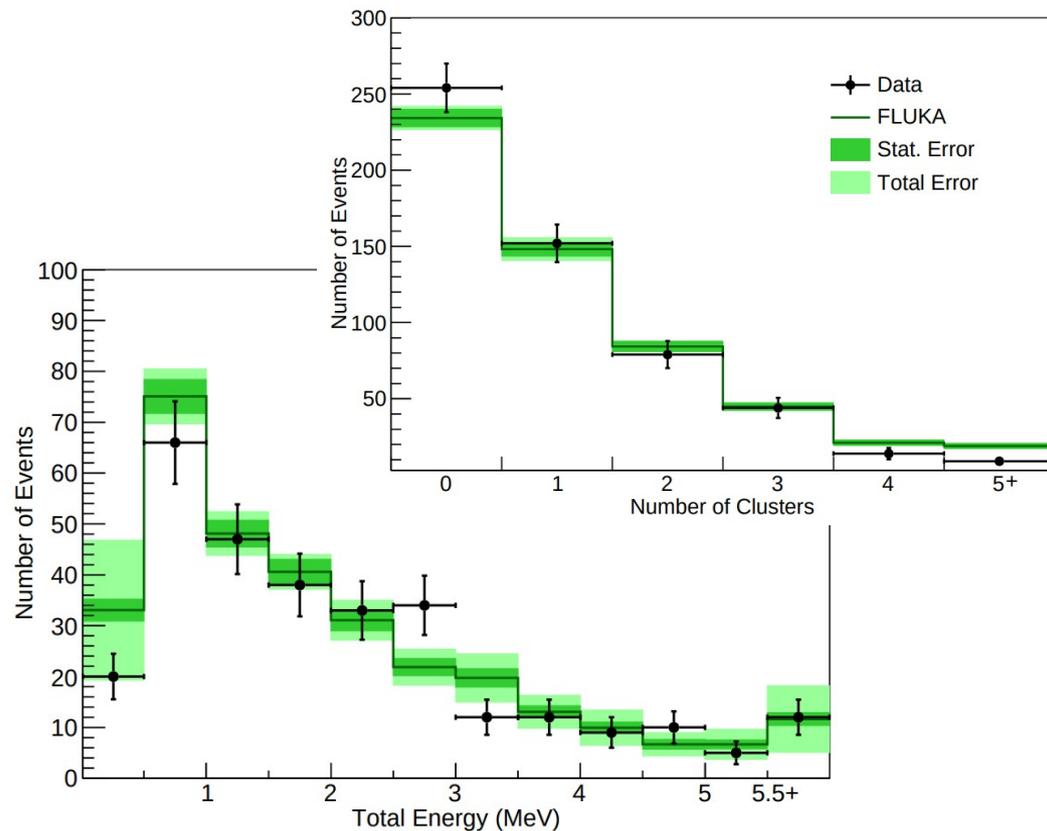
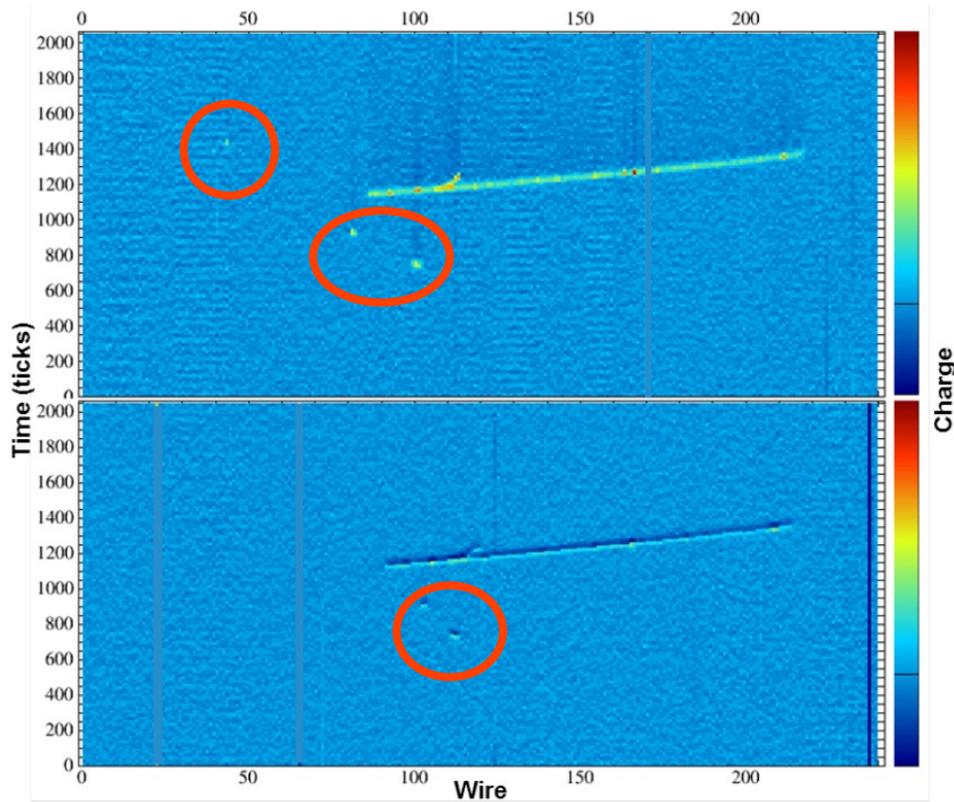
Low Energy Stuff



Low Energy Stuff

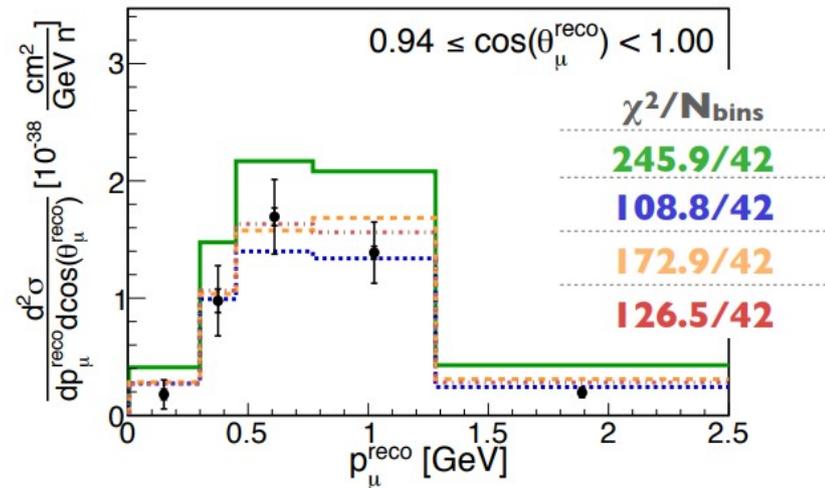
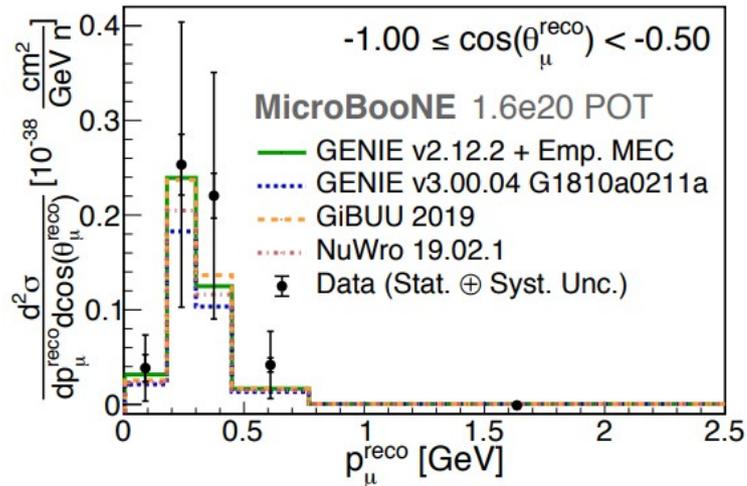


Low Energy Stuff



Inclusive measurements

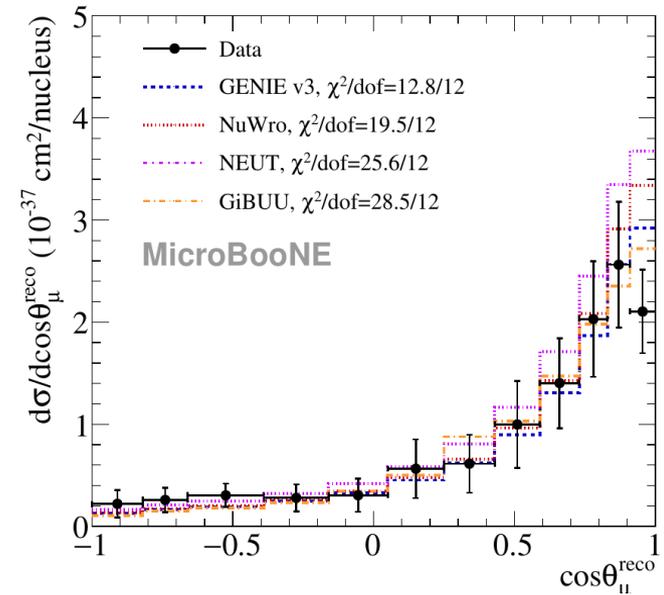
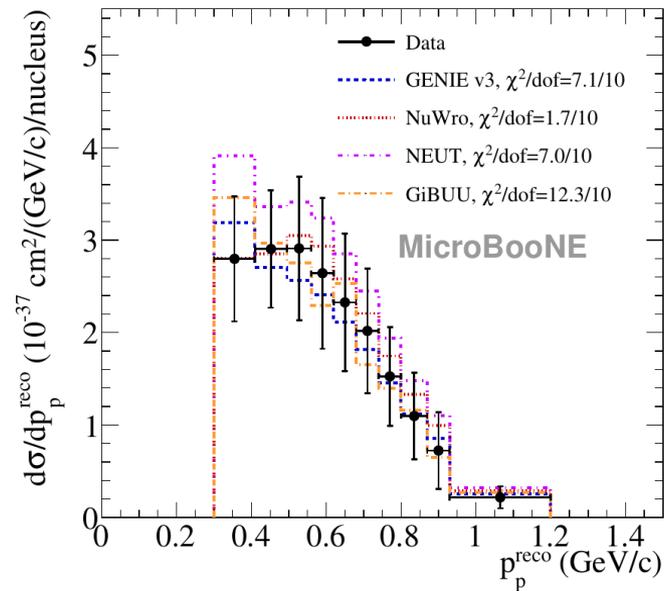
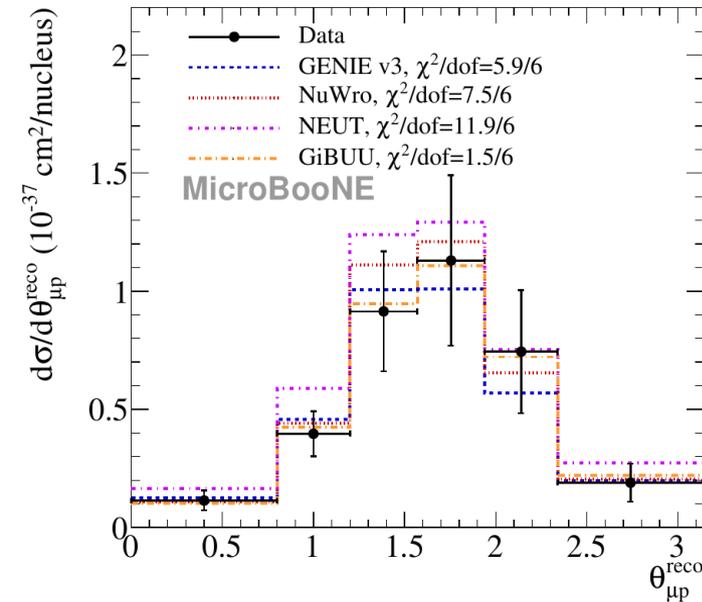
- Simultaneous muon momentum/angle measurement
- Generators unable to describe all bins
- Forward region most sensitive – “RPA” and MEC both impact interpretation



Zero-pion measurements

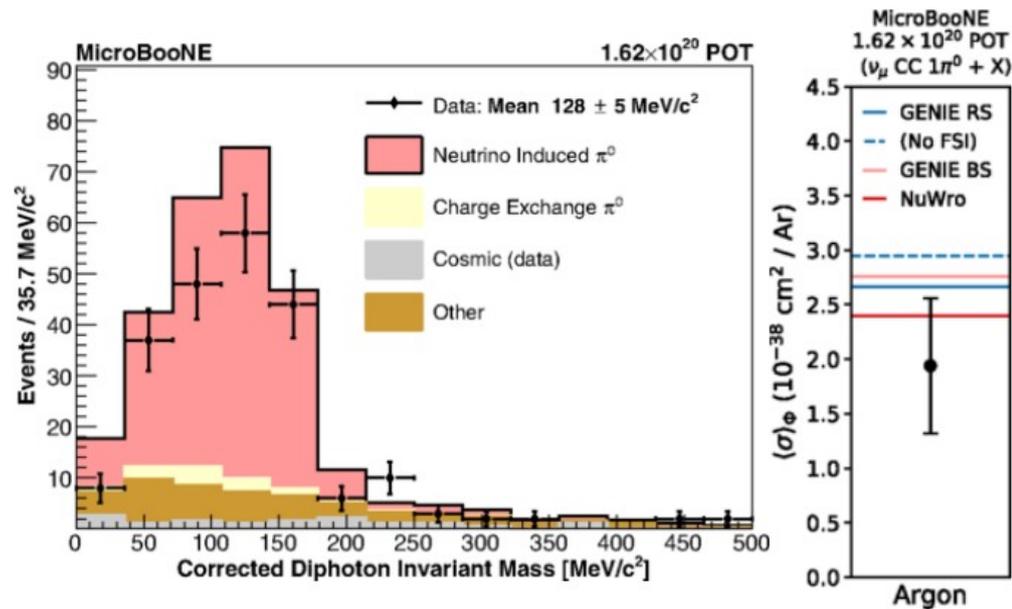
Only showing a snapshot, but the point is:

- Data suffer from large uncertainties (will improve)
- No generator does best in all variables



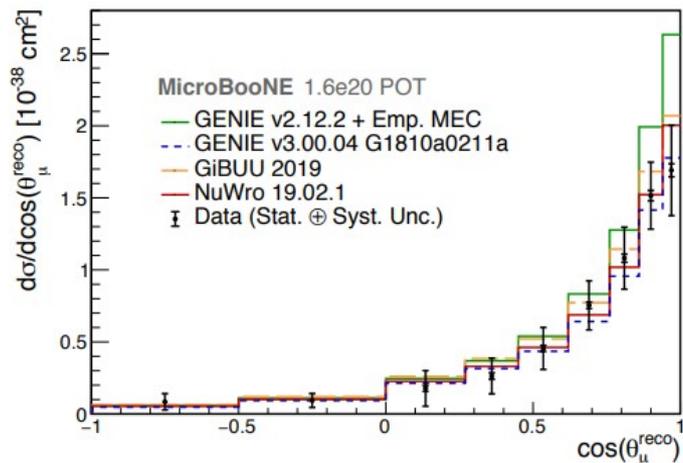
Pion measurements

- Neutral pion **total** cross section
- Working on differential measurements in pion kinematics
- Also working on charged-pion measurements (hard)



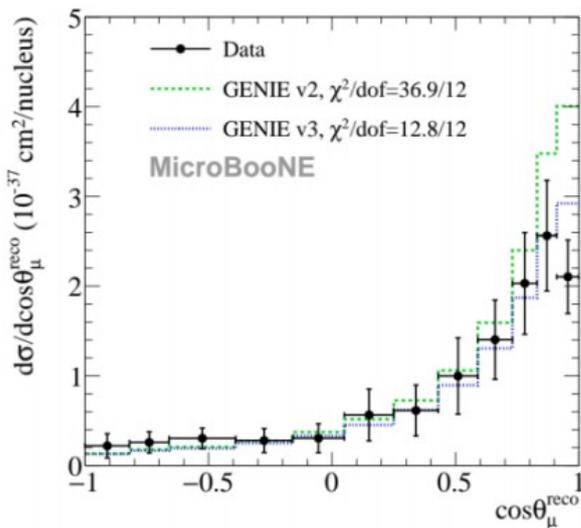
MicroBooNE Data Interpreting

GENIE v2 GENIE v3



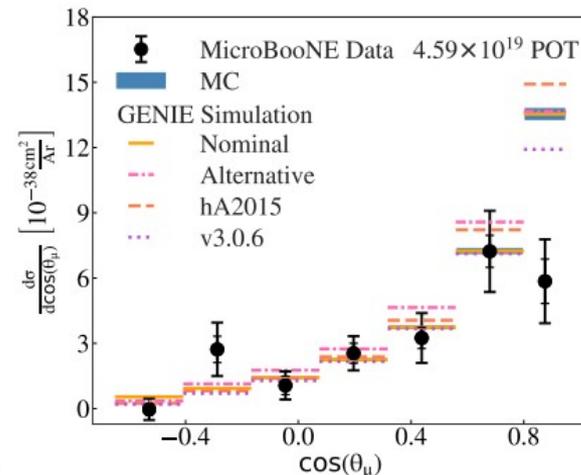
CC Inclusive
Inclusive
Some deficit

GENIE v2 GENIE v3



CC0πNp
More exclusive
Turnover in data

GENIE v2 GENIE v3



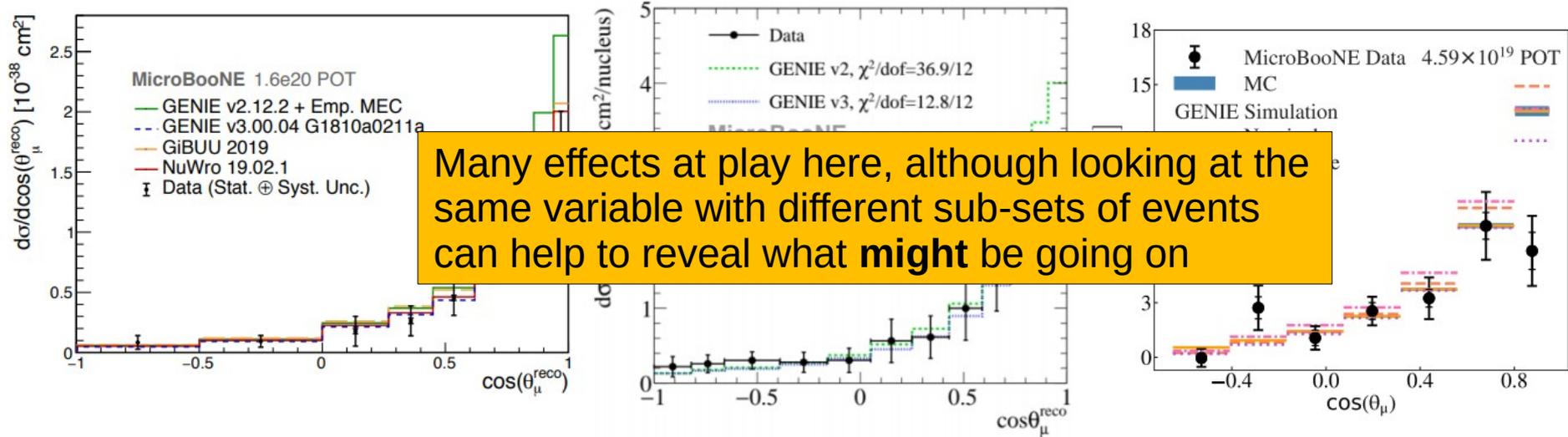
CCQE-like
Even more exclusive
Even more deficit

MicroBooNE Data Interpreting

GENIE v2 GENIE v3

GENIE v2 GENIE v3

GENIE v2 GENIE v3



Many effects at play here, although looking at the same variable with different sub-sets of events can help to reveal what **might** be going on

CC Inclusive
Inclusive
Some deficit

CC0πNp
More exclusive
Turnover in data

CCQE-like
Even more exclusive
Even more deficit

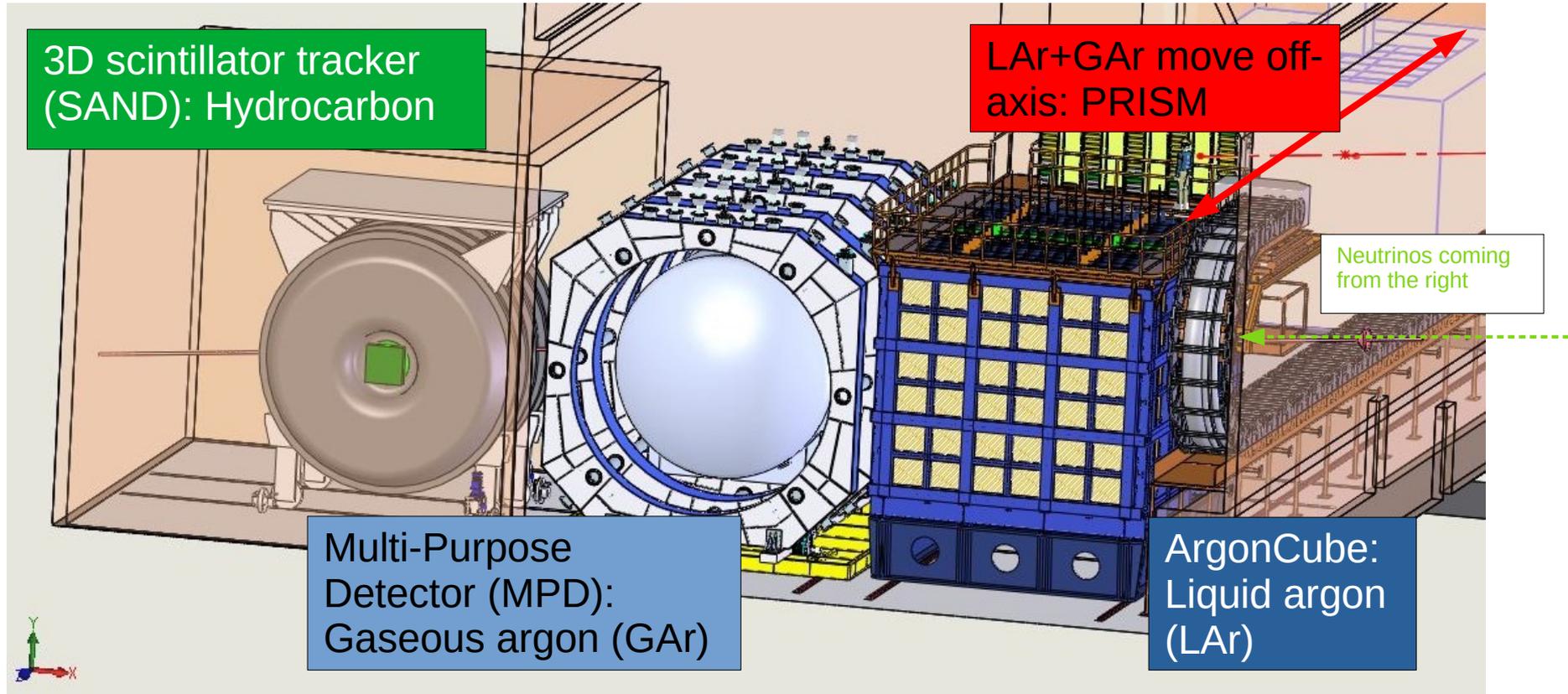
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- Past & Recent measurements
- **Prospects for DUNE**

DUNE Near Detector



DUNE Near Detector



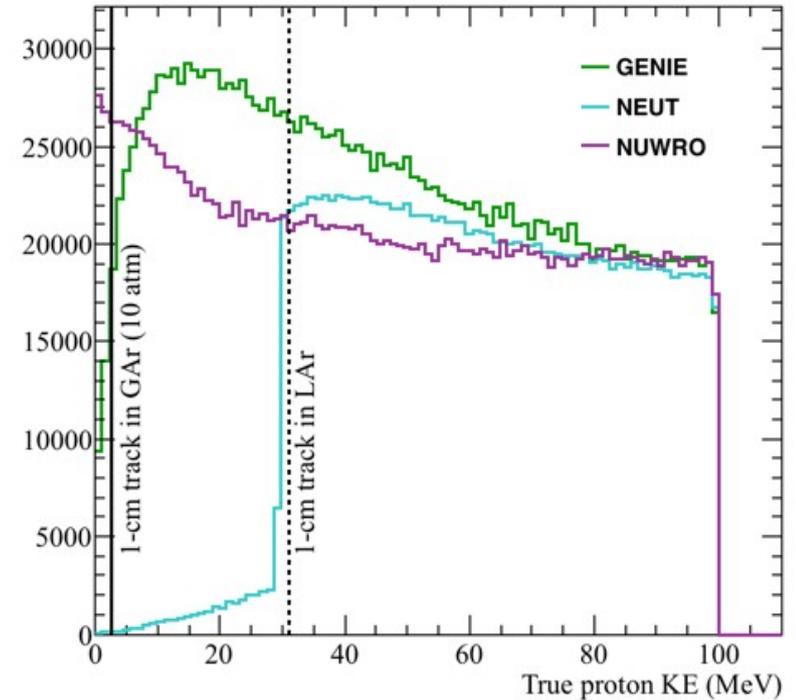
ND-LAr

- **Very** high event rate
 - Detector segmented into many small TPCs
 - Some dead space in between
- Many muons exit – caught by ND-Gar
- Flux normalisation uncertainties will be small (ν -e scattering)
- Large fraction of hadronic energy will shower
 - Therefore poor energy resolution



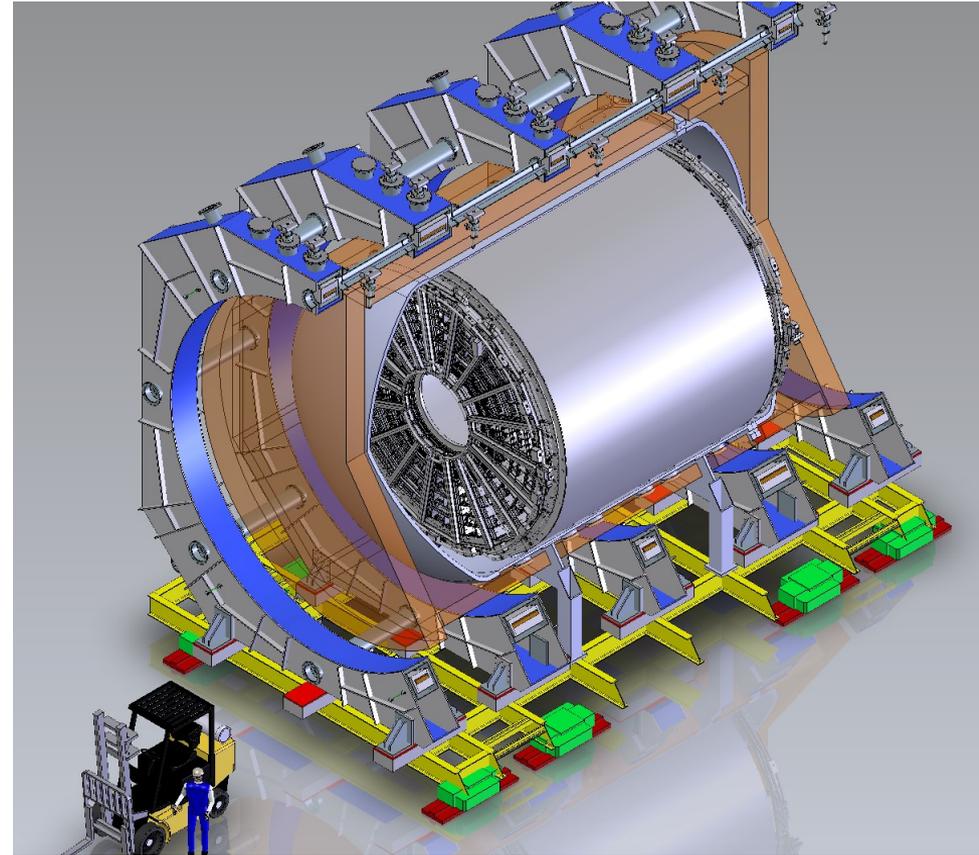
ND-GAr

- High-pressure gas
- Even lower thresholds than Lar
- Minimal showering
- Magnetic field (sign selection and good momentum measurements)
- But, lower event rate



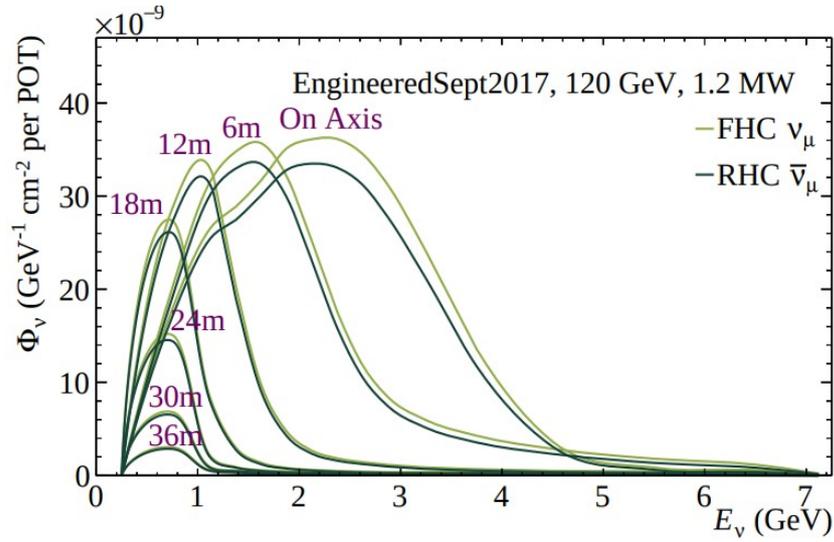
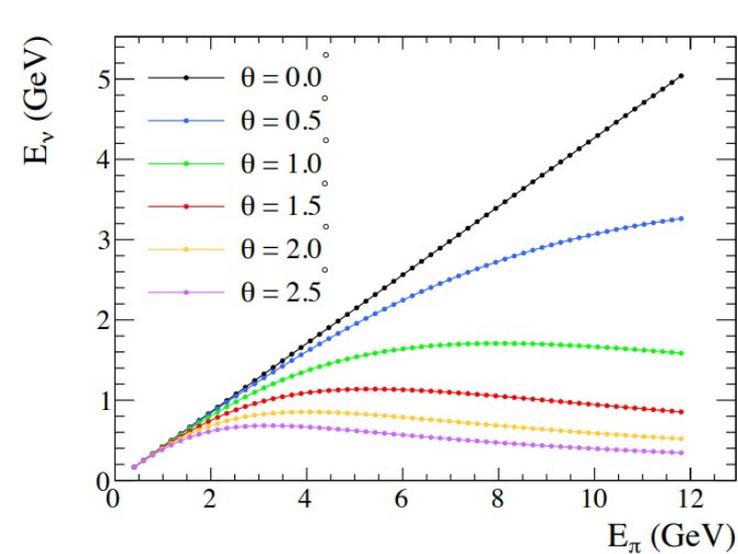
ND-Gar + ECAL?

- Image out of date...
- ECAL around gas allows measurements of:
 - Neutrons (+TOF for momentum)
 - Neutral pions (via photons)
- Also, improved PID, background rejection, etc



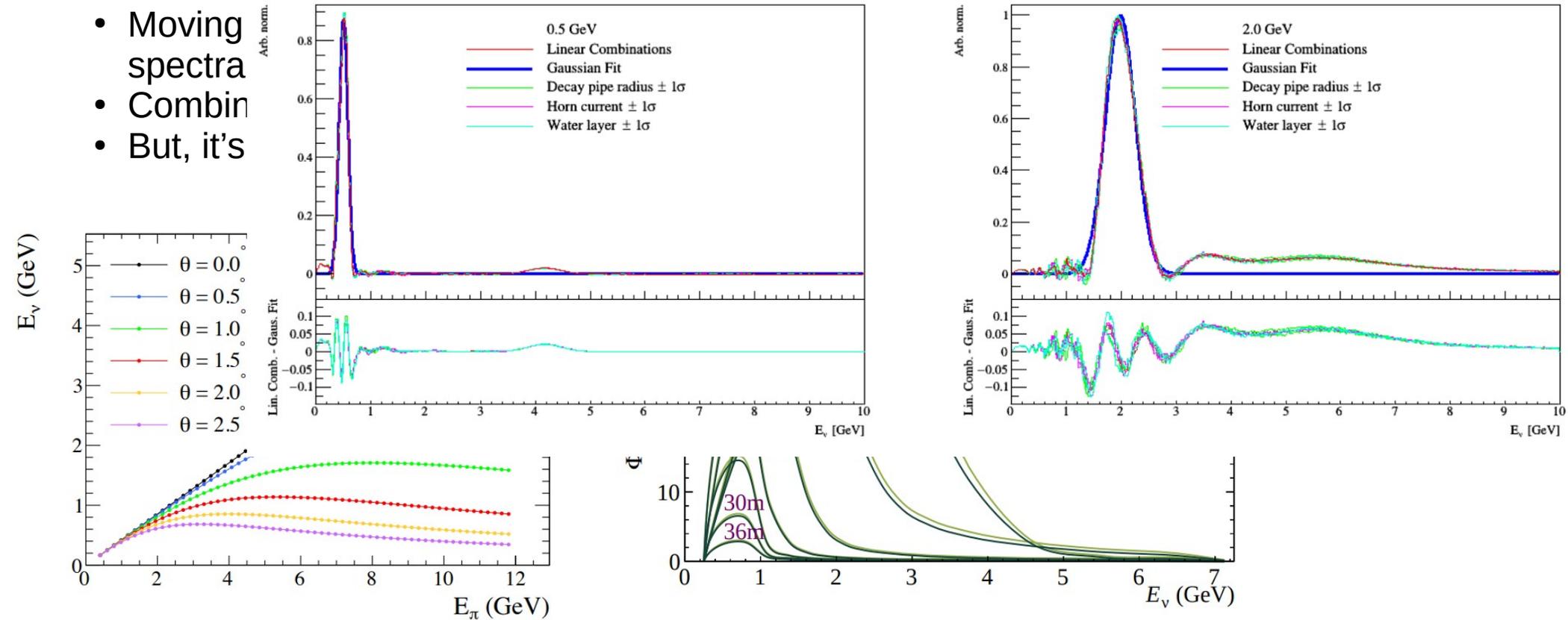
PRISM

- Moving detectors off-axis allows sampling of highly correlated but different energy spectra
- Combinations could make a quasi-monoenergetic beam
- But, it's not quite as monoenergetic as an electron beam...



PRISM

- Moving spectra
- Combin
- But, it's



Conclusion

- Neutrino measurements are very challenging
 - Wide energy spectra make interpretation hard
- DUNE will make significant improvements
 - But it's still limited by the neutrino beam
 - And won't start taking data until 2026 **at the earliest**
- LDMX can step in and measure:
 - Neutron production
 - Pion production
 - **Energy/momentum transfer** dependence