The Current Landscape of LAr TPCs for Neutrino Physics

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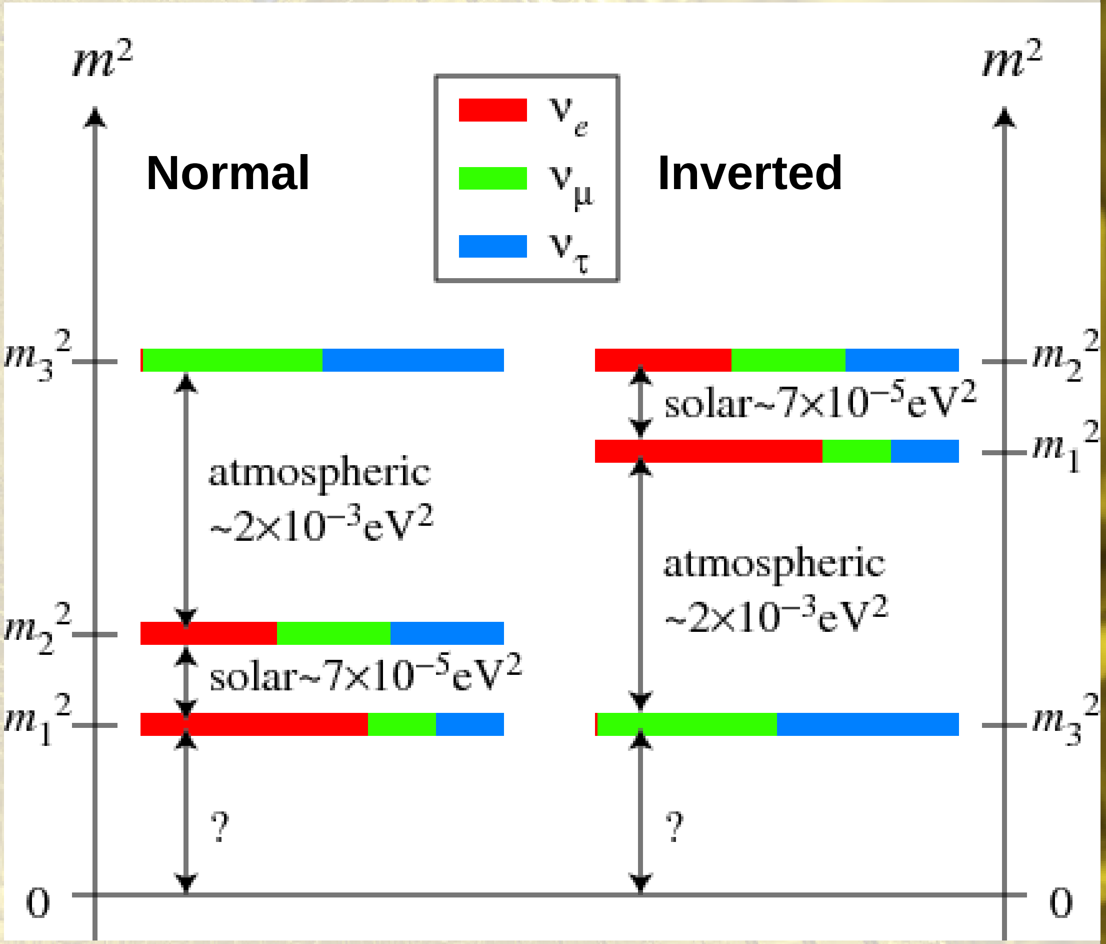
Colloquium Towards CP violation in neutrino Physics

Neutrinos The Big Questions Recap

- Do neutrinos violate CP? $\delta^{CP} \neq 0$.
- What is the neutrino mass hierarchy?
- Octant of θ_{23}?
- Are there other neutrinos yet to be discovered (Seesaw mechanism)?
- Are neutrinos Majorana or Dirac particles?
- Absolute Neutrino Mass?



solar — atm & reactor — atm

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

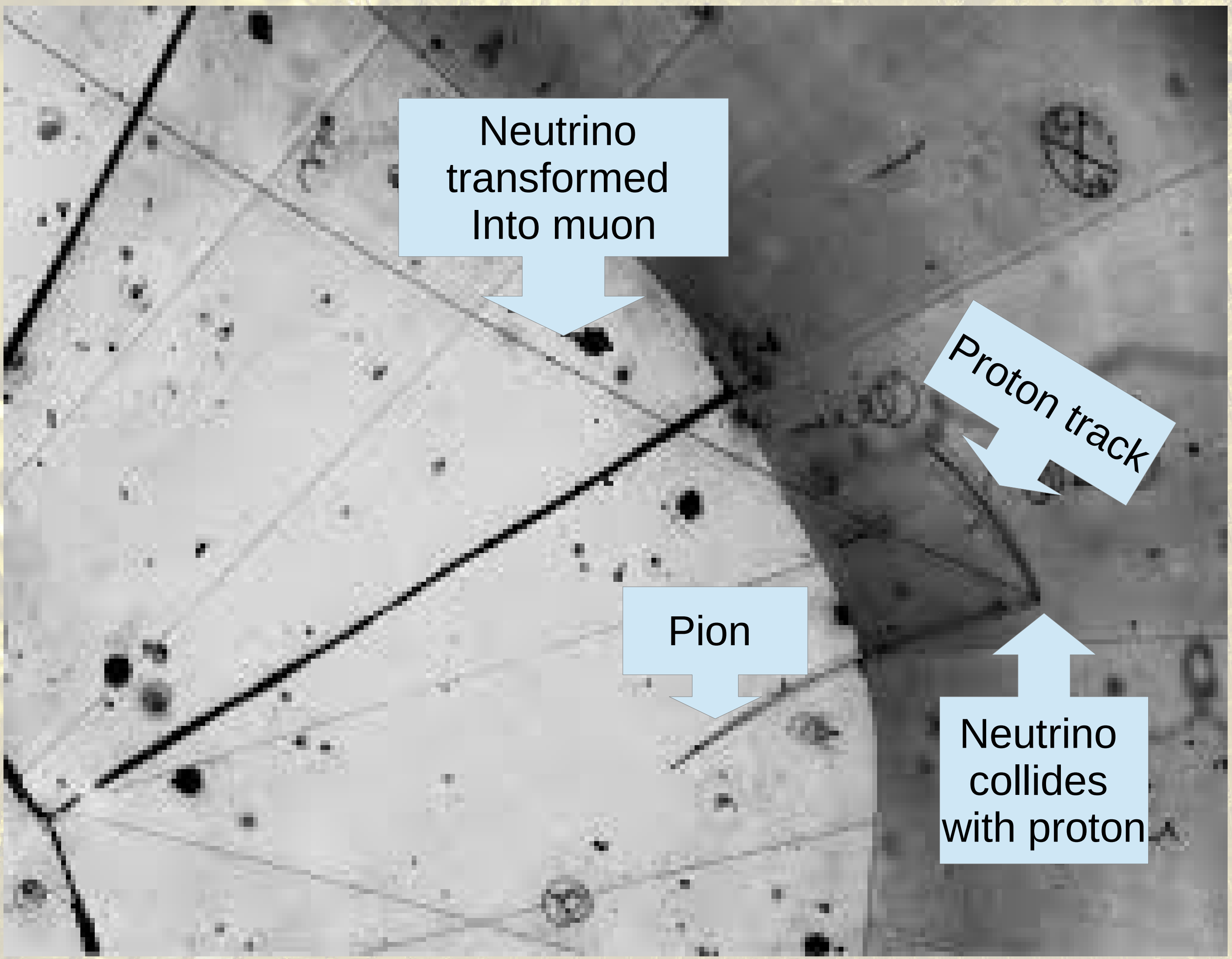
Where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$,

The Challenges...

- Reduce systematics to ~1%.
  - Understand nuclear effects
  - Cross sections.
- Understand neutrino scattering events.
  - Distinguish neutrino/neutron and neutrino/proton signals.
- Background reduction improvements.
- Event rate.
- Feedback into models... $\delta^{CP} \neq 0 \rightarrow$ Leptogenesis?

Lar TPCs: A History Lesson

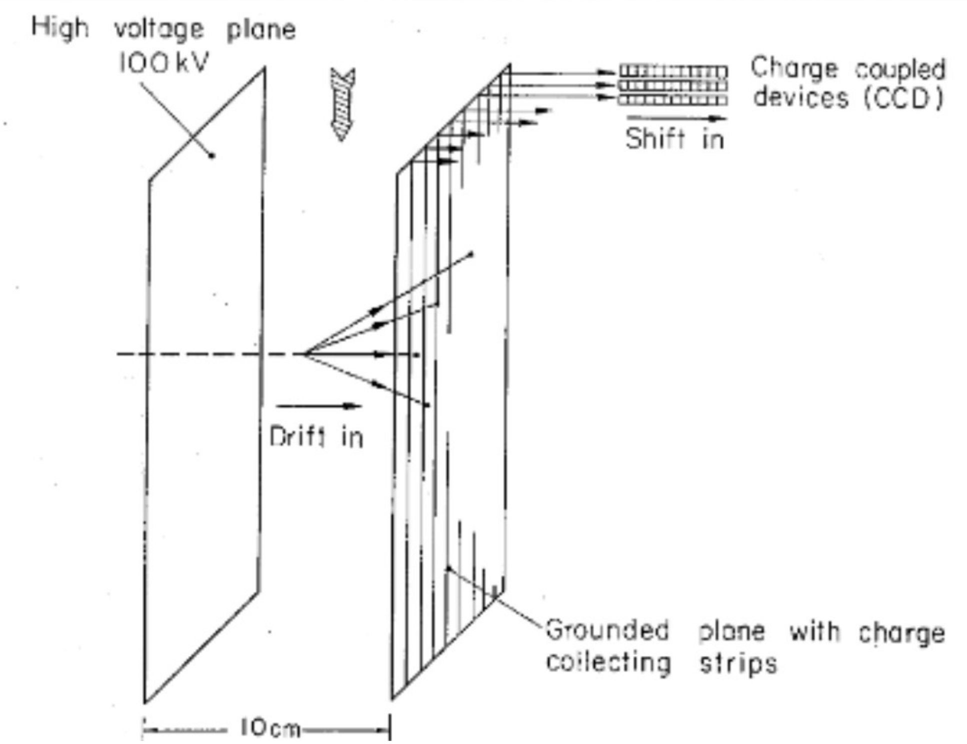
49 Years ago: November 13th 1970 — World's first observation of neutino in a hydrogen bubble chamber at Argonne.



How to keep topologyical information of the bubble chamber in a (high mass) neutrino detector?

Lar TPCs: A History Lesson

42 Years ago: in 1977 Carlo Rubbia proposes a TPC based on LAr to be both the neutrino target and detection medium. Many advantages:

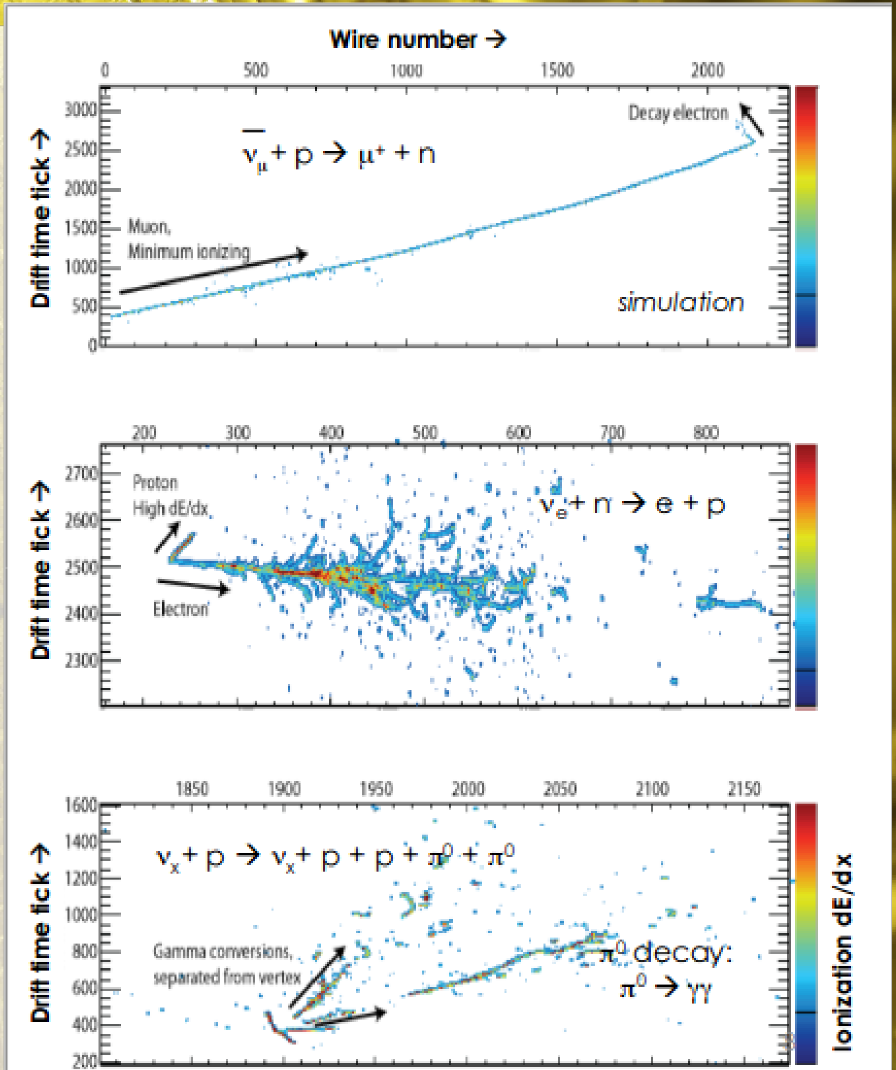


C. Rubbia,"The Liquid Argon Time Projection Chamber: A New Concept", 1977, CERN-EP-INT-77-08.

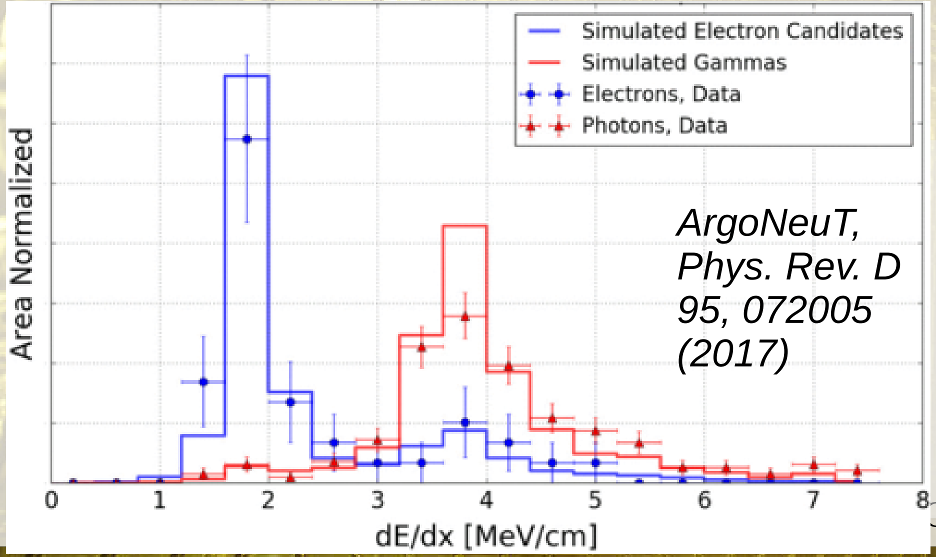
- High density
  - 1.395 g/cm^3.
- Long drift times for e/γ separation.
- High electron mobility (500 m^2/Vs).
- Argon cheaply/readily available
  - liquefaction from air,
  - can be liquefied by liquid nitrogen.
- Charge, scintillation light and Cherenkov light readout possible.

LAr TPC for νs

- Large, continuous, fully active volume.
- High density
  - high interaction probability,
  - higher statistics for same exposure.
- High ionization and scintillation yield and high transparency
  - low detection thresholds, higher detection efficiency.
- Relatively inexpensive
  - scalable to larger and larger sizes.



MicroBooNE Simulation



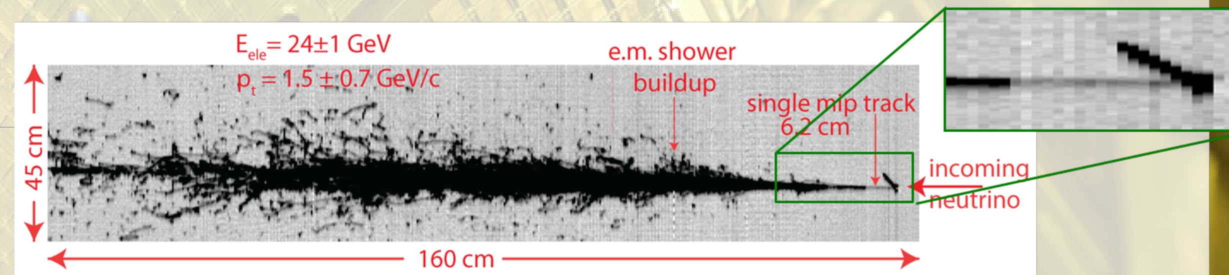
ArgoNeuT, Phys. Rev. D 95, 072005 (2017)

- High digitization rates, segmentation
  - high position and dE/dx resolution,
- Better particle identification
  - Single e indistinguishable from single γ in traditional, Cherenkov detectors.

The Birth of the LAr TPC Experimental ν Landscape

ICARUS

- Pioneered the use of LArTPCs for neutrino detection.
- 760 ton LArTPC detector.
- Long Baseline 730 km
  - CERN to Gran Sasso.
- Data taking 2010 – 2013.
- Moved to Fermilab in 2017 to join the short baseline programme and the hunt for sterile neutrinos.



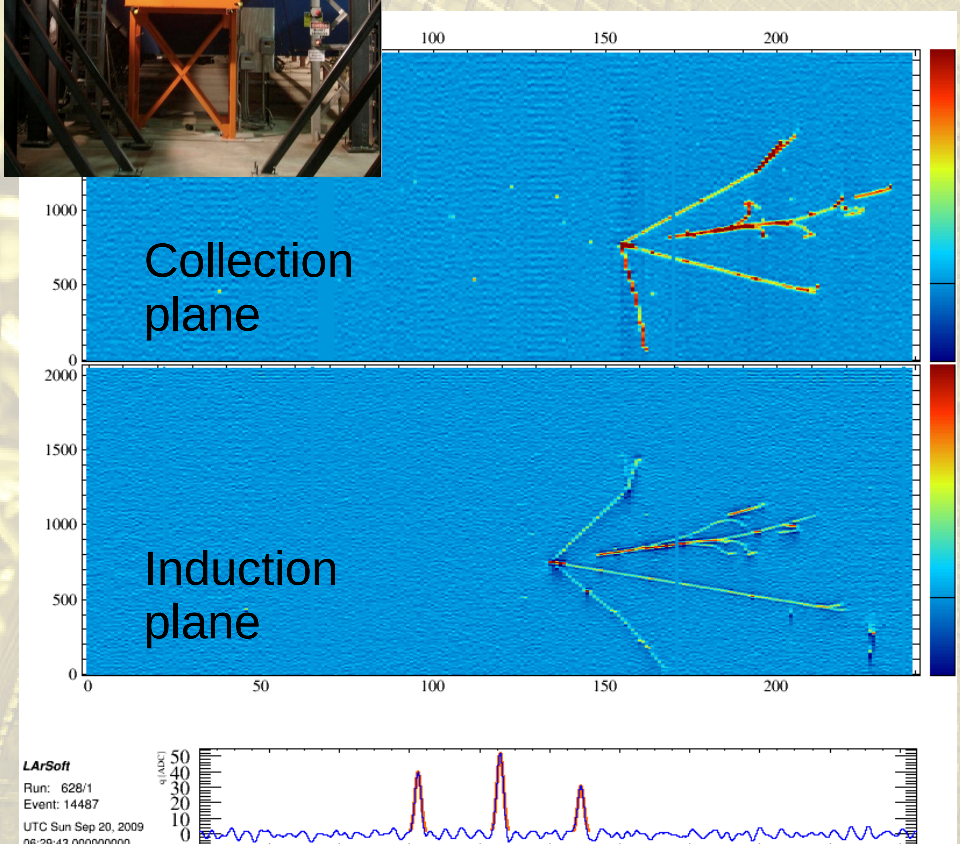
↑ CNGS ν_e CC event: high energy CC electron & highly ionizating proton, from the main ν vertex.

↓ Inside the ICARUS detector at CERN.

The Birth of the LAr TPC Experimental ν Landscape

← ArgoNeuT detector.

↓ ArgoNeuT event: Wire Num(x) Vs Time (y)



ArgoNeuT

- Small LArTPC experiment based at Fermilab.
- Data taking until 2010 and analysis ongoing.
- Energy resolution 0.1 to 10 GeV.
- First data for low energy neutrino interactions within a LArTPC.
- Essential testbed for large scale LArTPCs.

The LAr TPC Experimental Neutrino Landscape Today

Fermilab Short Baseline Programme:

- ICARUS T600.
- SBND (Short Baseline Near detector).
- MicroBooNE.

See Talk by C. Touramanis today at 15:00.

MicroBooNE

- 1st large LArTPC to acquire high stats sample of neutrino interactions.
- 170 ton LArTPC at 470m baseline.
- Taking data since 2015.

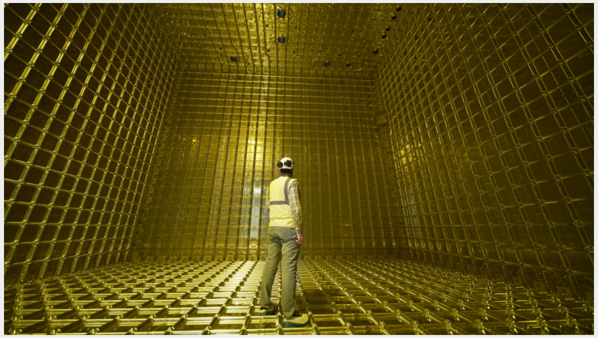
DUNE

- Long baseline 1300 km.
- 40,000 ton LAr far Detector.
- Under construction, data taking begins 2026.

See Talk by S. Soldner-Rembold tomorrow at 9:30.

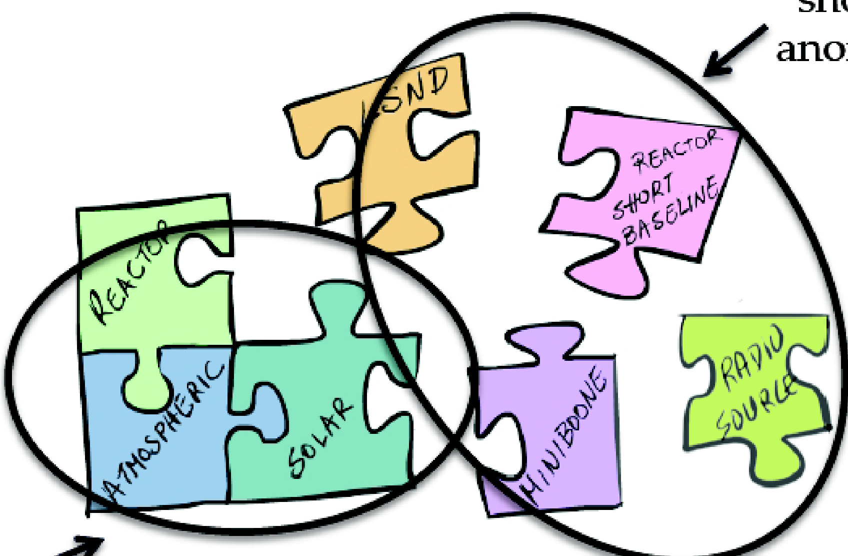
ProtoDUNE

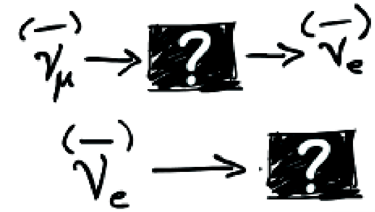
- DUNE R+D Experiment operating at CERN.



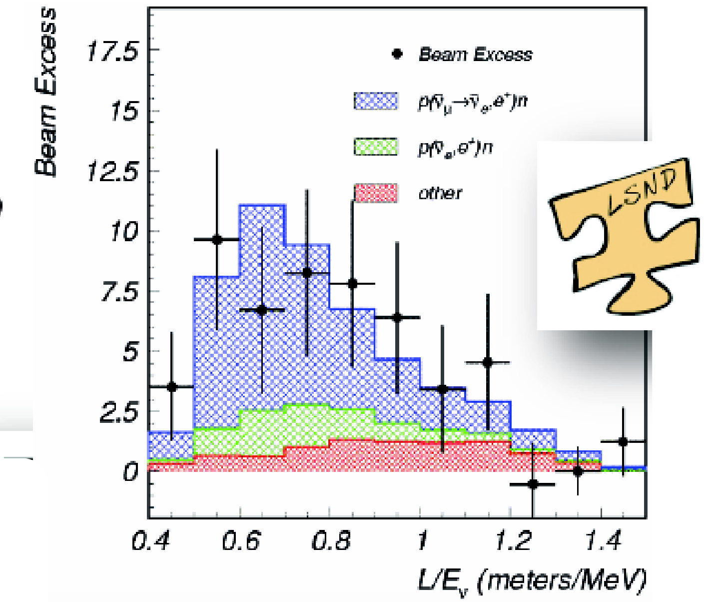
MicroBooNE: The Motivation

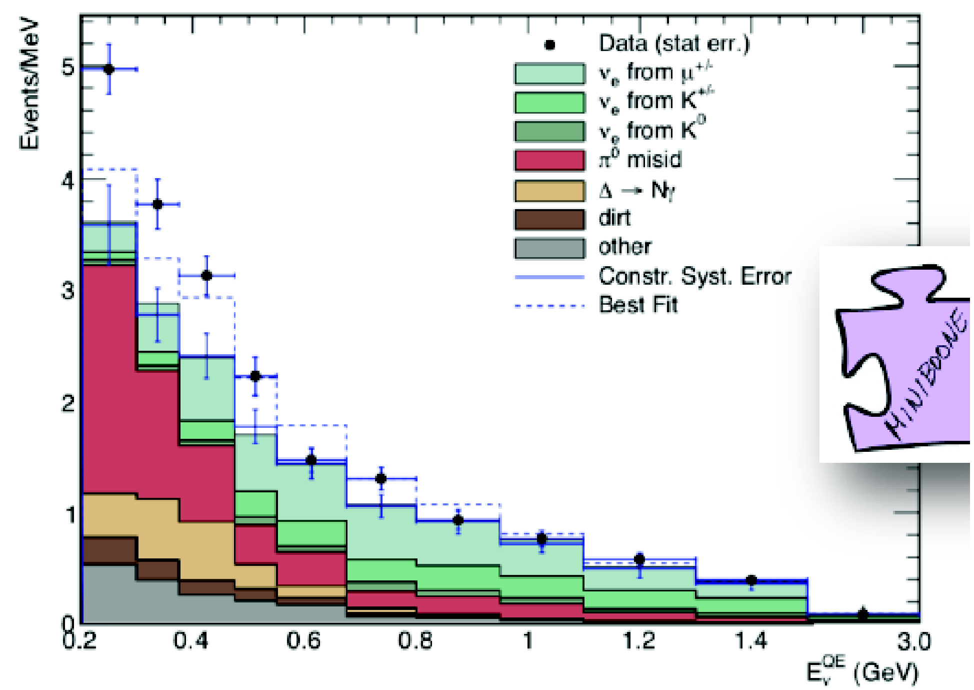
“short-baseline” anomalies





“long- and medium-baseline” data fit together

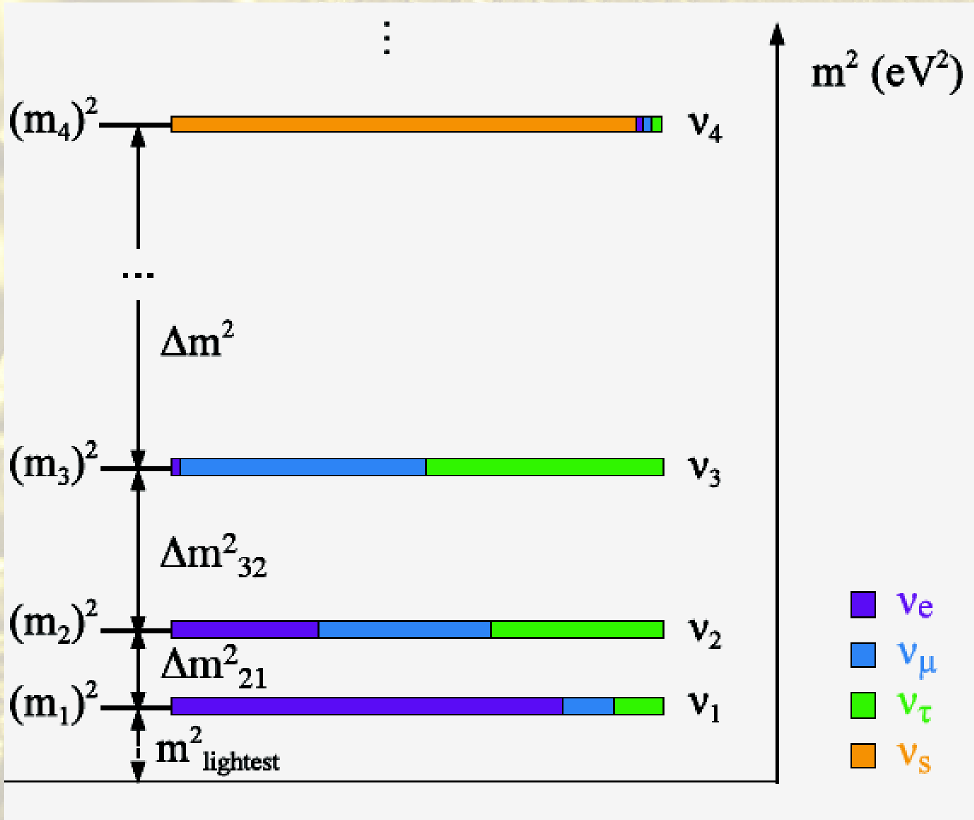




An excess of ν_e like events observed between 200 – 600 MeV

MicroBooNE: The Motivation

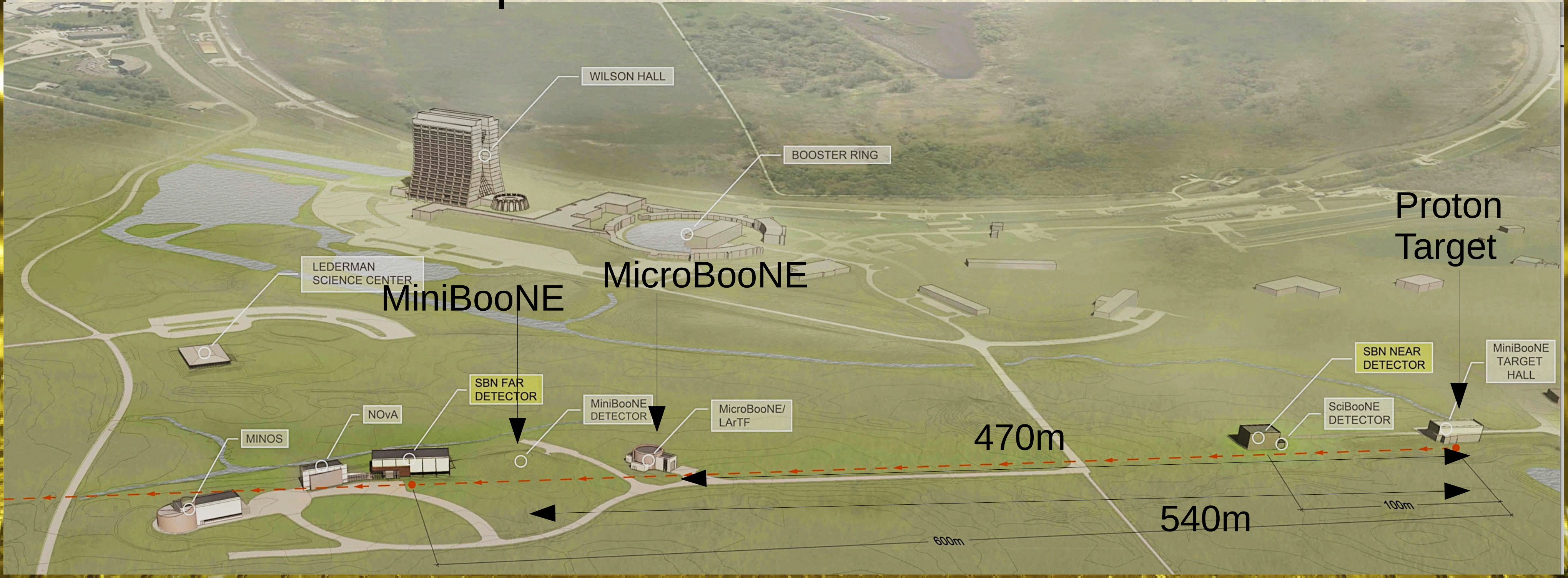
Low-energy excess = new “sterile” neutrino?



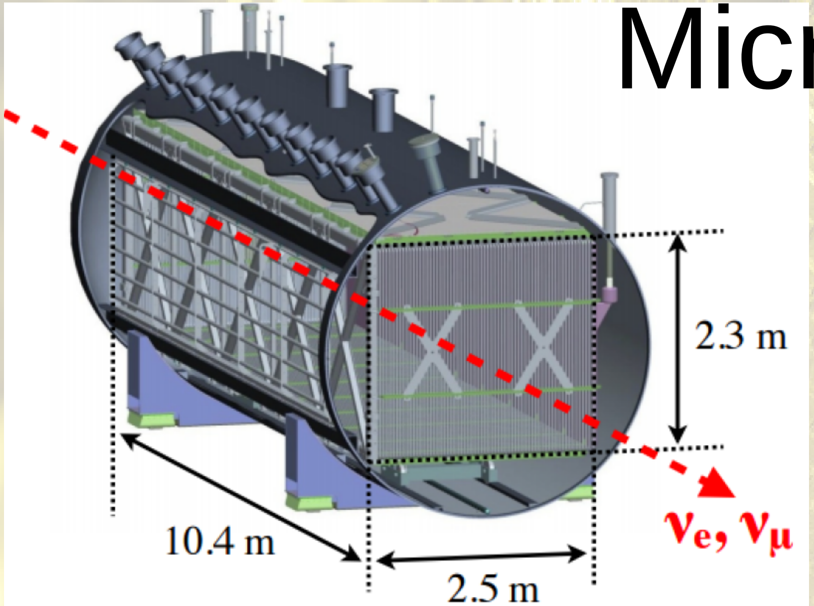
- Adding a sterile neutrino to the Standard Model is the simplest extension BSM.
- Theory remains anomaly free.
- Exciting:
  - Can give origin to neutrino masses and explain their smallness (at least in some cases).
  - Could explain matter assymetry.
  - Sterile neutrinos with KeV masses are a favorite Warm DM candidate.
- BUT MiniBooNE’s result is in tension with global 3+1 model fits.

MicroBooNE

- Why MicrobooNE:
  - Same beam, similar oscillation parameters as MiniBooNE but new detector technology.
  - Identification of e/γ is much improved.
- 85 ton active volume Liquid Argon Time Projection Chamber with 470m baseline. $\nu_\mu \rightarrow \nu_e$ appearance experiment.
- > 95% detector uptime.

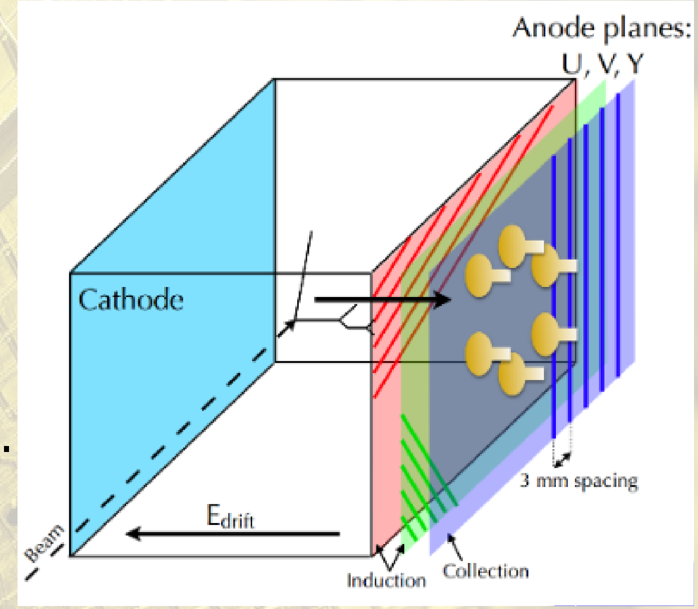


MicroBooNE



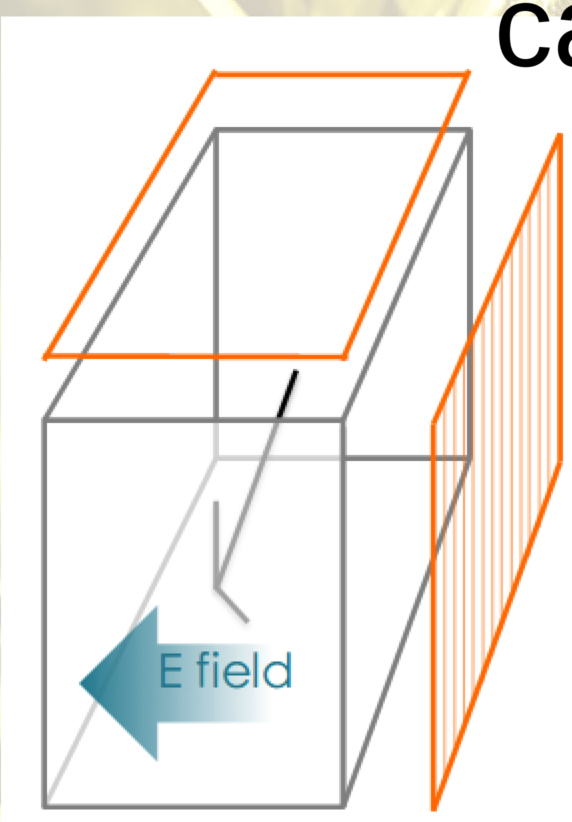
← Detector 170 tons (87 active).

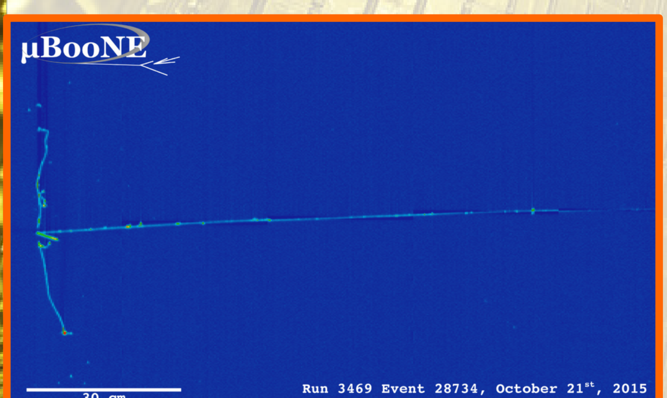
→ TPC drift volume.



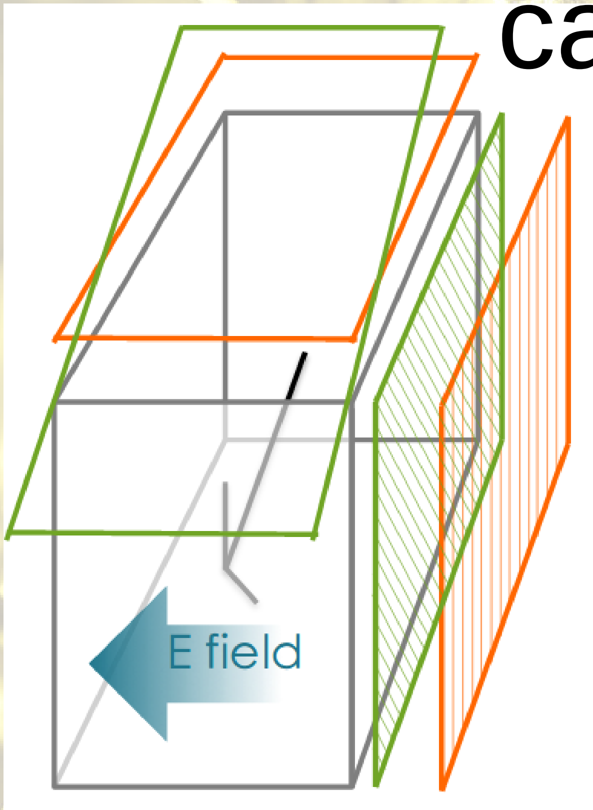
- 3 wire planes (8,256 wires):
  - 0°, ±60° from vertical, 3 mm wire separation.
- 2.5m drift length (~2 ms drift time with 70 kV on cathode).
- 32 PMT's, for t_0/drift coordinate determination,and triggering for empty neutrino beam spill rejection.
- Surrounded by cosmic veto.

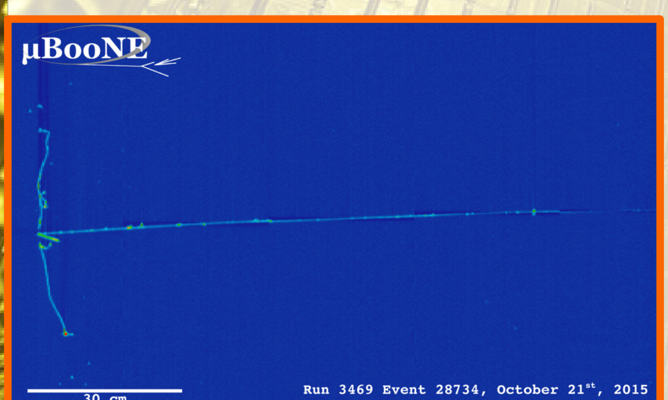
LArTPC: A high-resolution 3D camera for ionizing particles



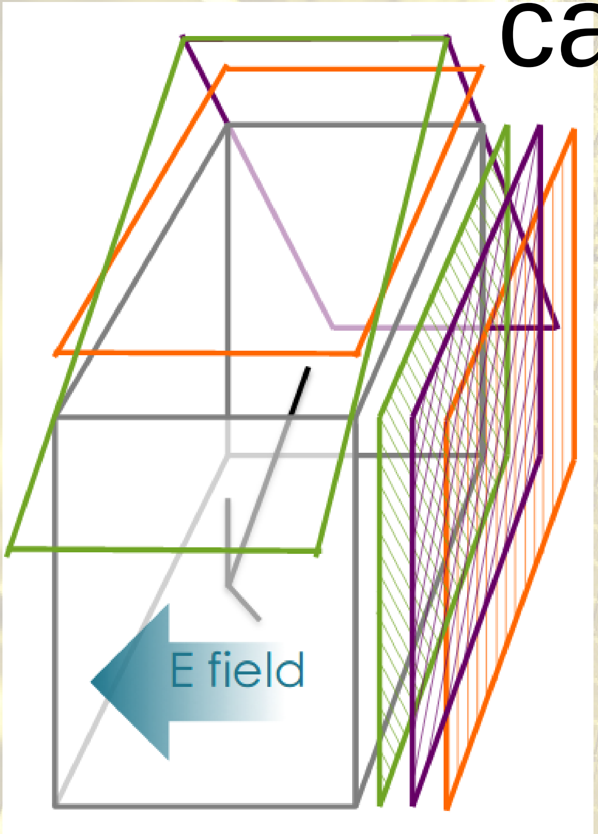


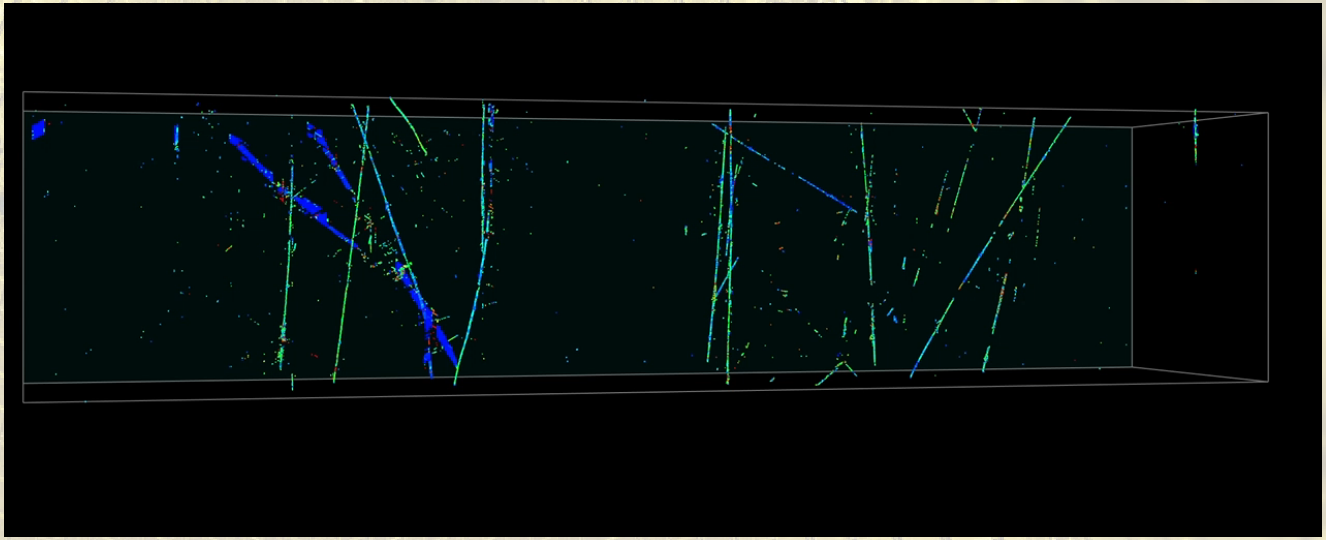
LArTPC: A high-resolution 3D camera for ionizing particles



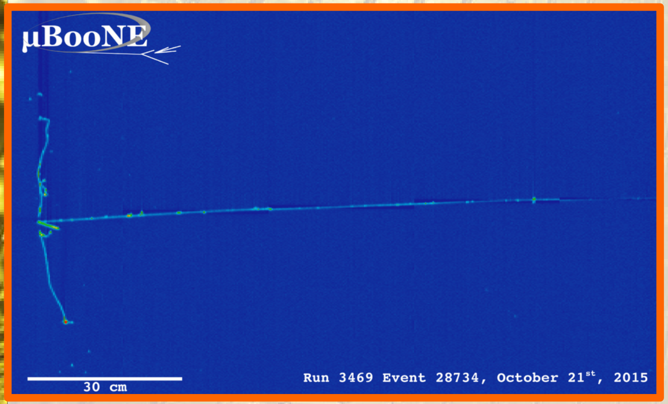


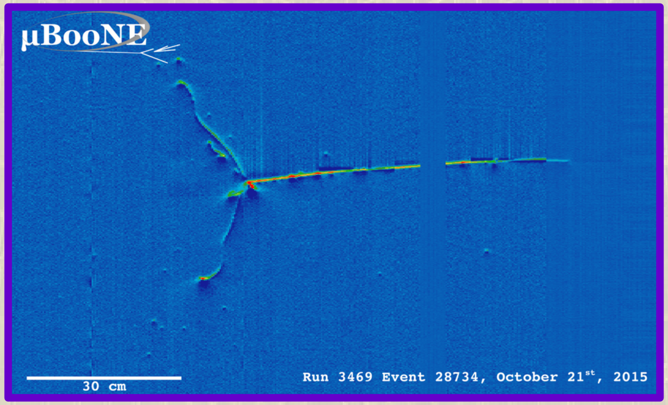
LArTPC: A high-resolution 3D camera for ionizing particles

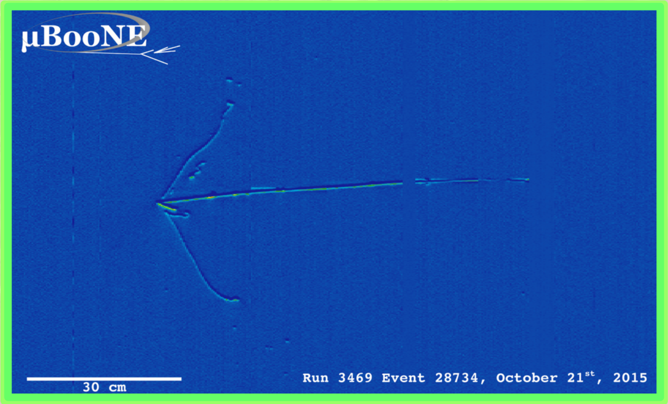




625 pics per plane per sec

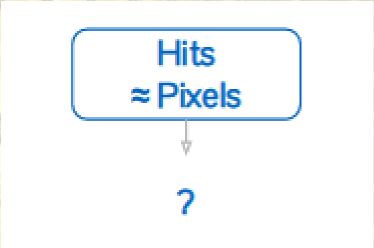


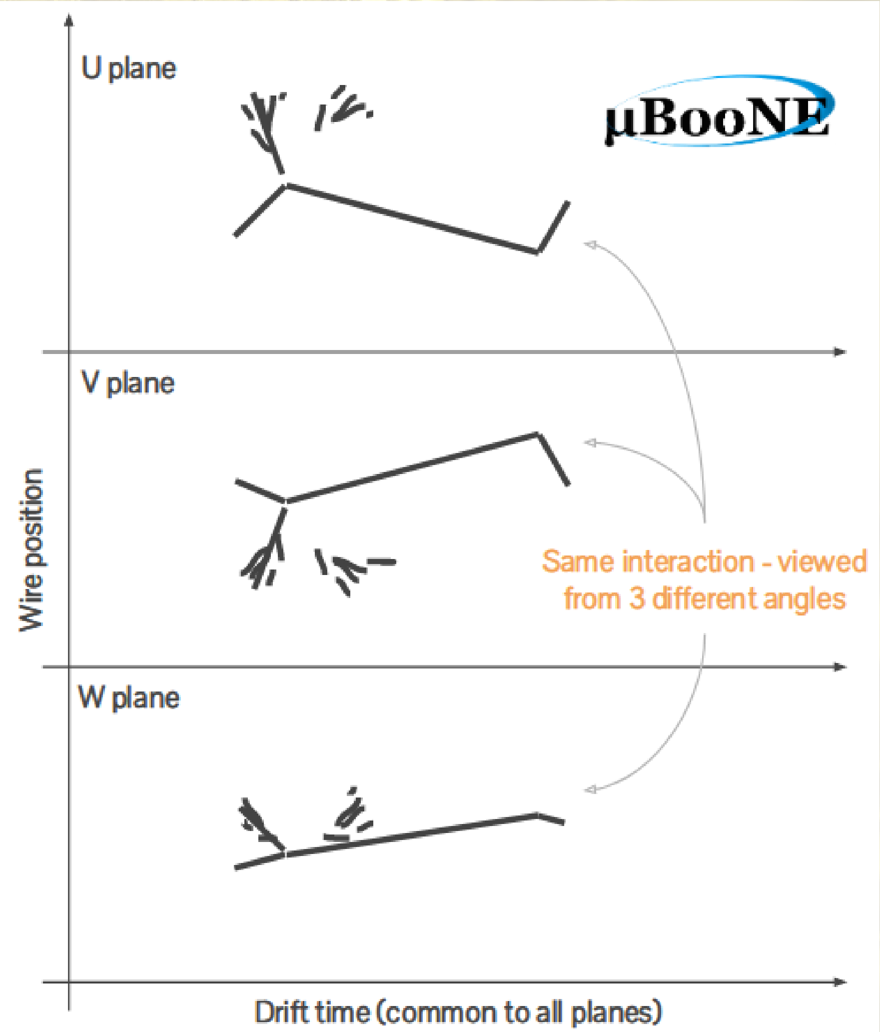




Pattern Recognition

- To fully exploit these rich images, we need to be able to identify the particles and their relationships
- Human brain excels at recognising patterns - but the development of an automated, algorithmic solution poses a significant challenge!





A cartoon LArTPC pattern recognition problem

Pandora: Pattern Recognition

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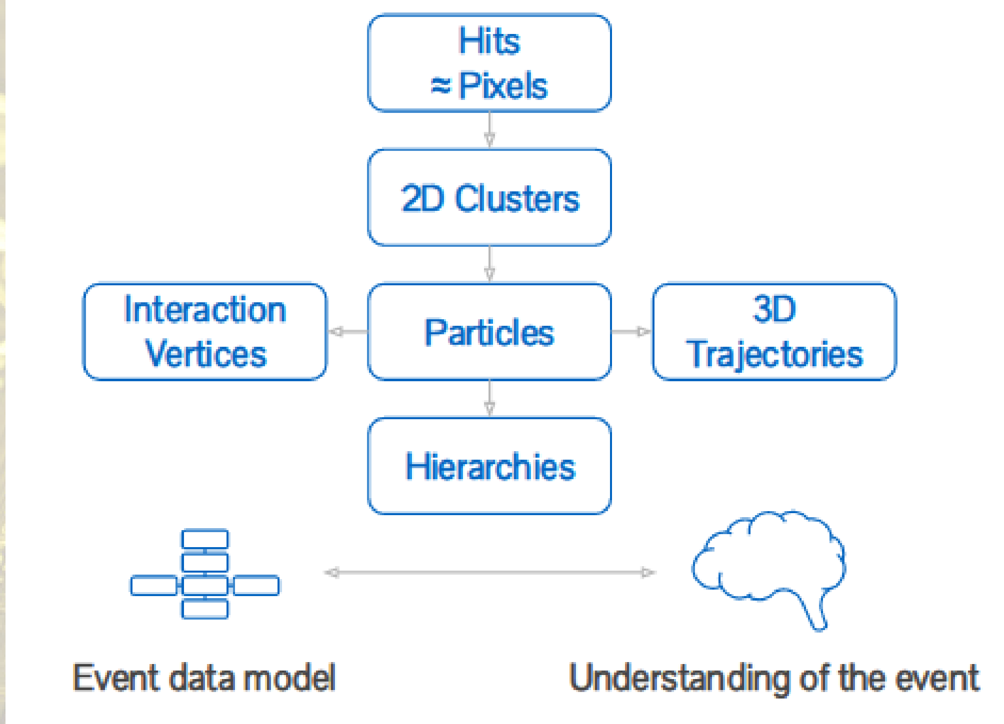
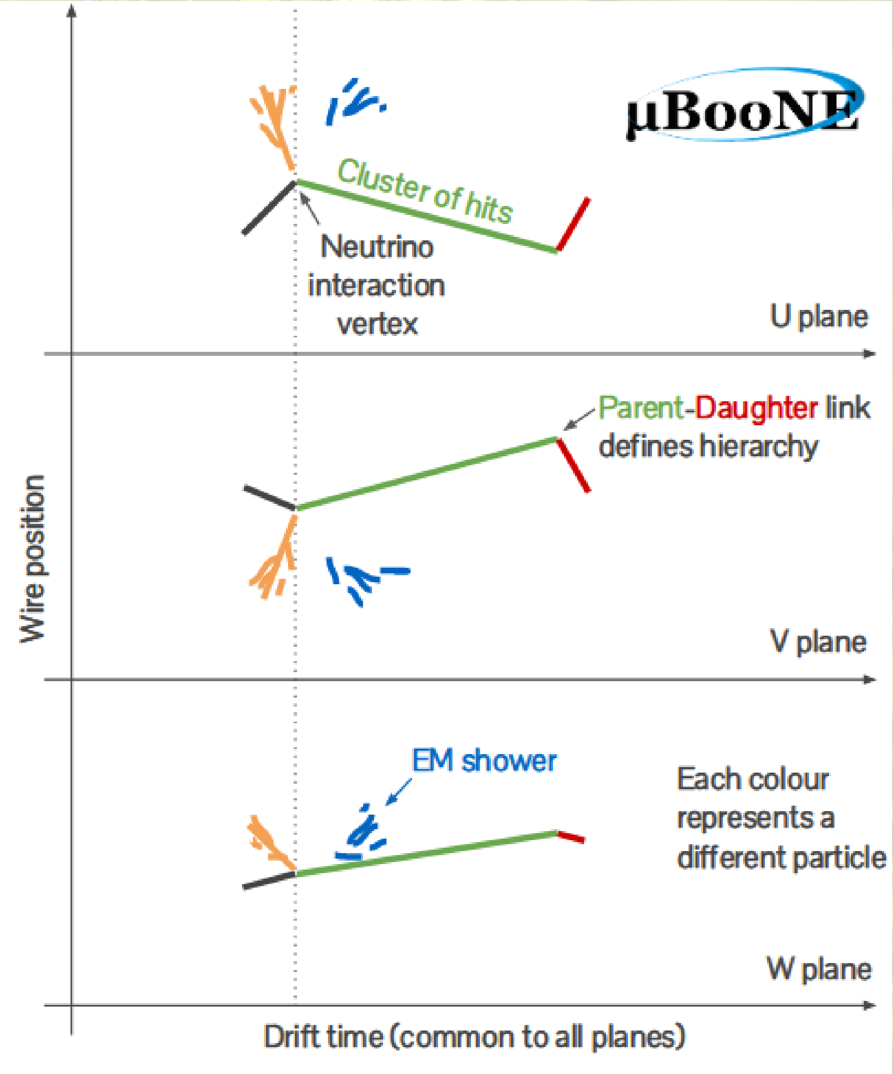




A cartoon LArTPC pattern recognition problem

Pandora

- General purpose open-source framework for pattern recognition
- Initially used for future linear collider experiments, now used primarily for LArTPC experiments!

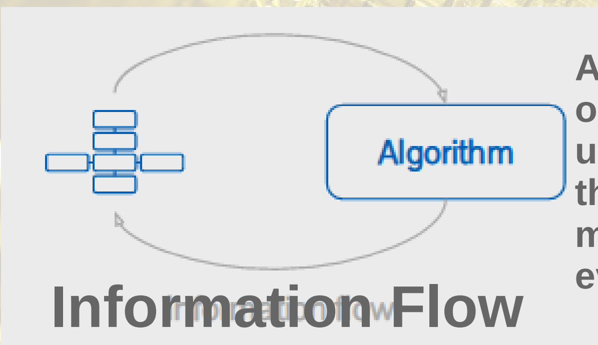
GitHub Repository
github.com/PandoraPFA

Software development kit
Eur.Phys.J. C75(2015) no.9, 439

μBooNE Algorithms
Eur.Phys.J. C78(2018) no.1, 82

The Pandora multi-algorithm Approach

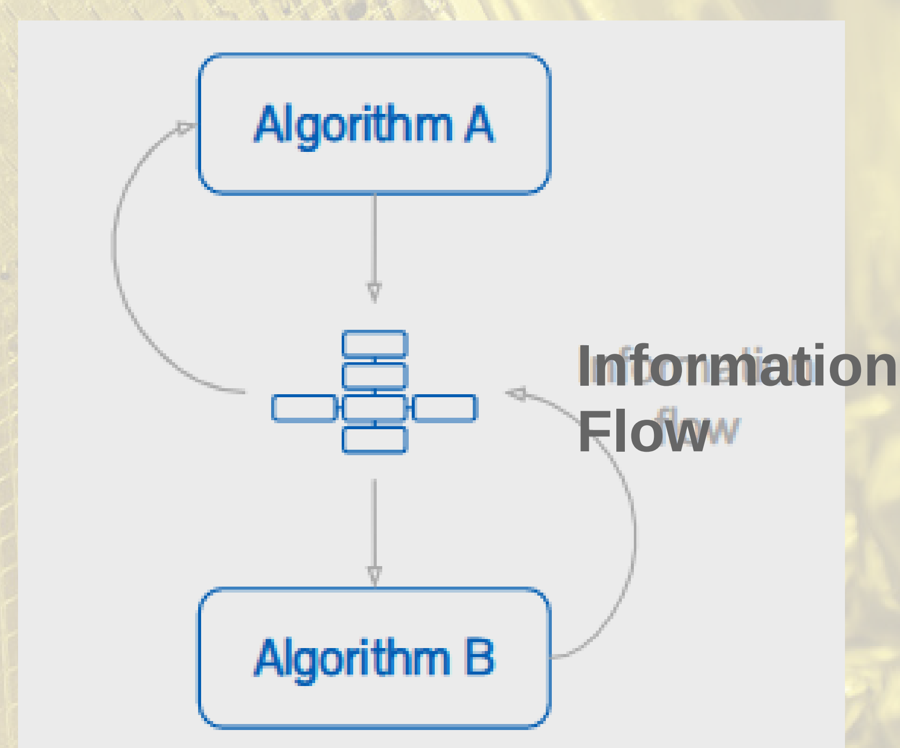
- Break the problem up into smaller well defined tasks and develop targeted algorithms for each task
  - E.g. Cluster together two hits if …



Algorithms update our current understanding of the event by modifying the event data

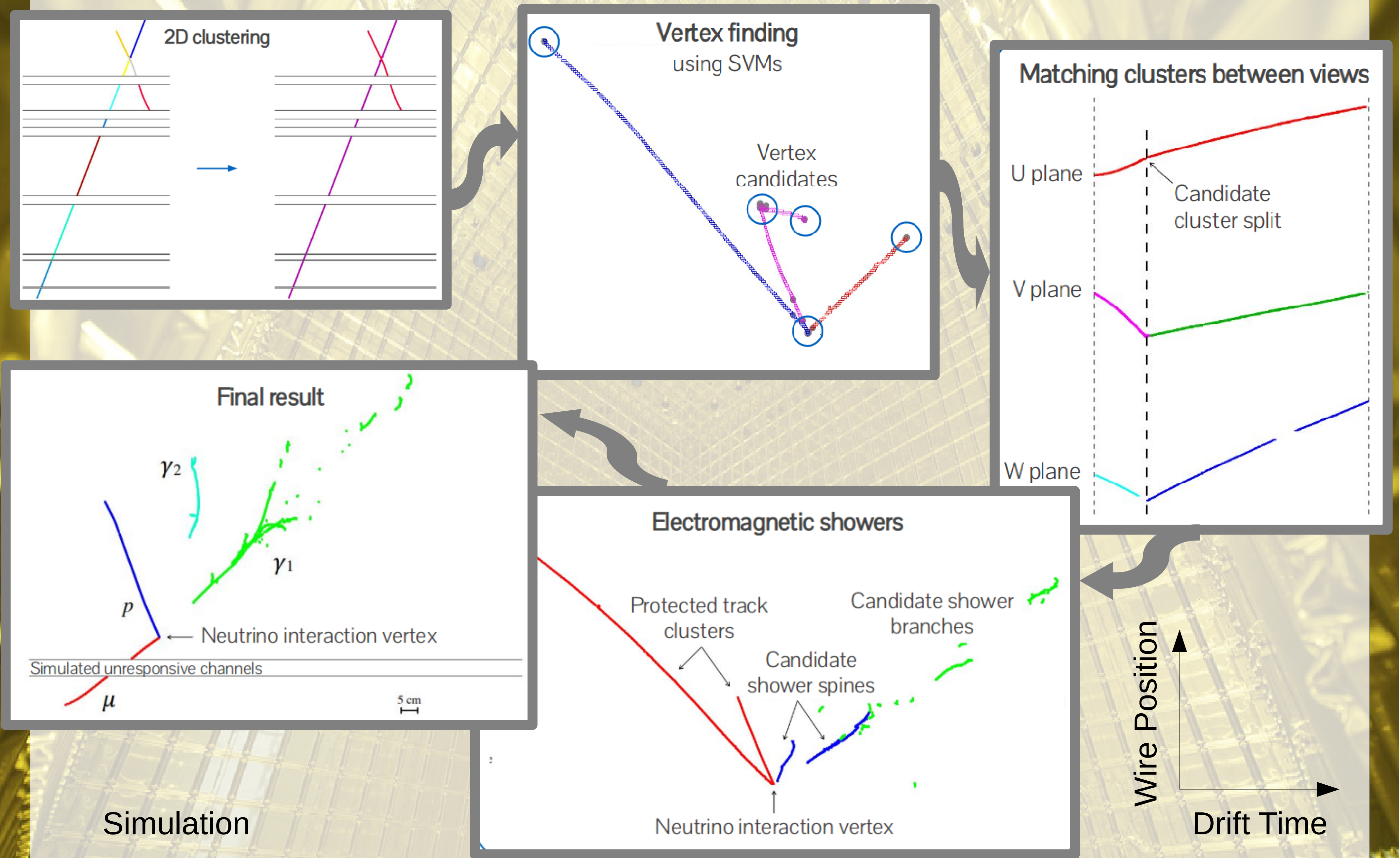
- Algorithm complexity varies from simple cuts up to more advanced machine learning techniques.
- The application runs many algorithms (for MicroBooNE ~100) to gradually build our understanding until a complete picture of the event develops.

- Iteration is used to allow 2-way information flow between algorithms

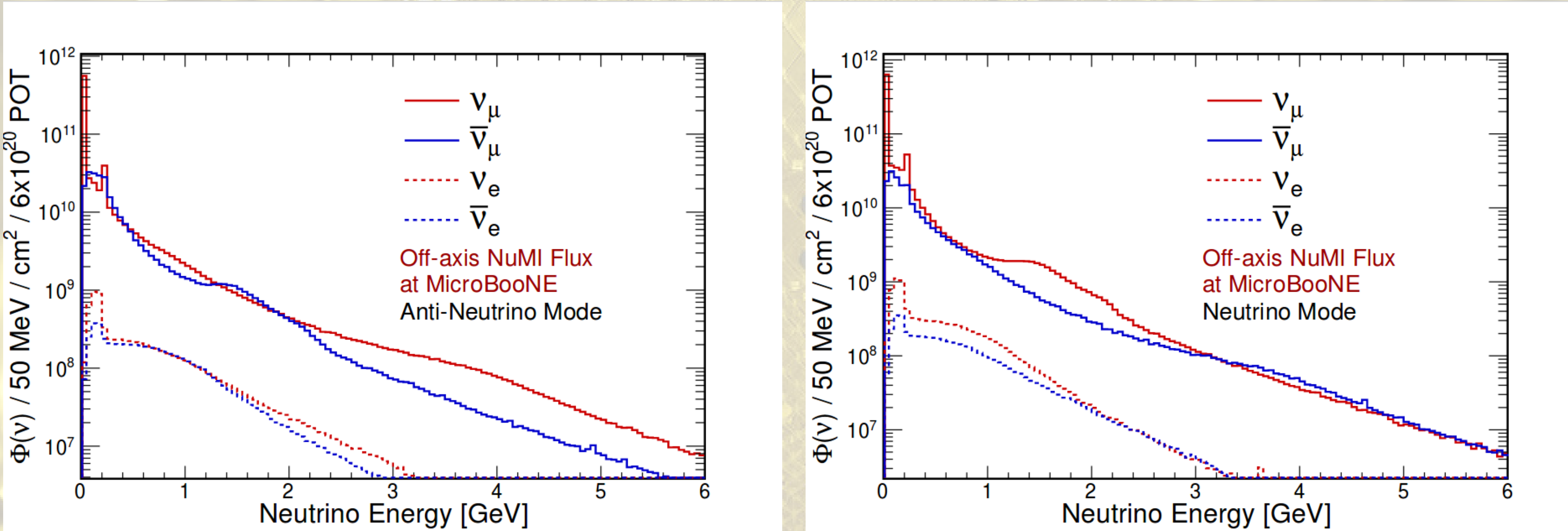


- Provides powerful feedback loops - a technique that Pandora frequently utilizes.

Pandora's algorithms for MicroBooNE



NuMi Flux at MicroBooNE



1.6e^{20} POT = current unblinded data.

MicroBooNE total expected on-beam data =

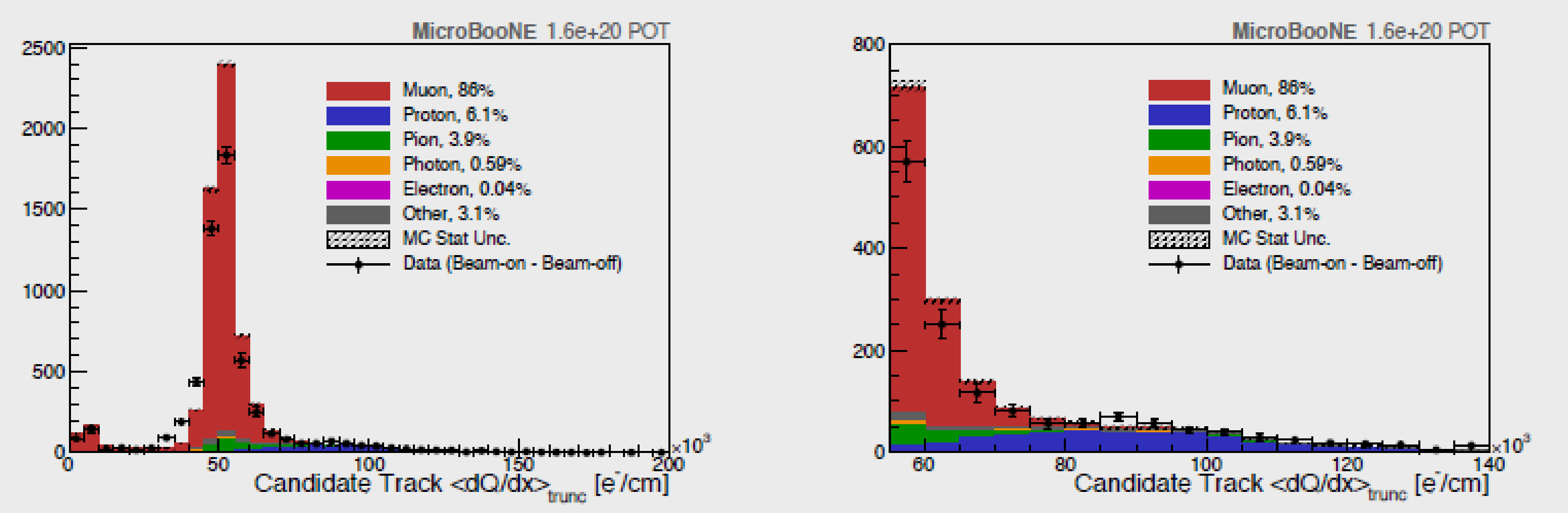
13.2e^{20} POT!

Data taking began 2015.

MicroBooNE First Cross-Section Measurement

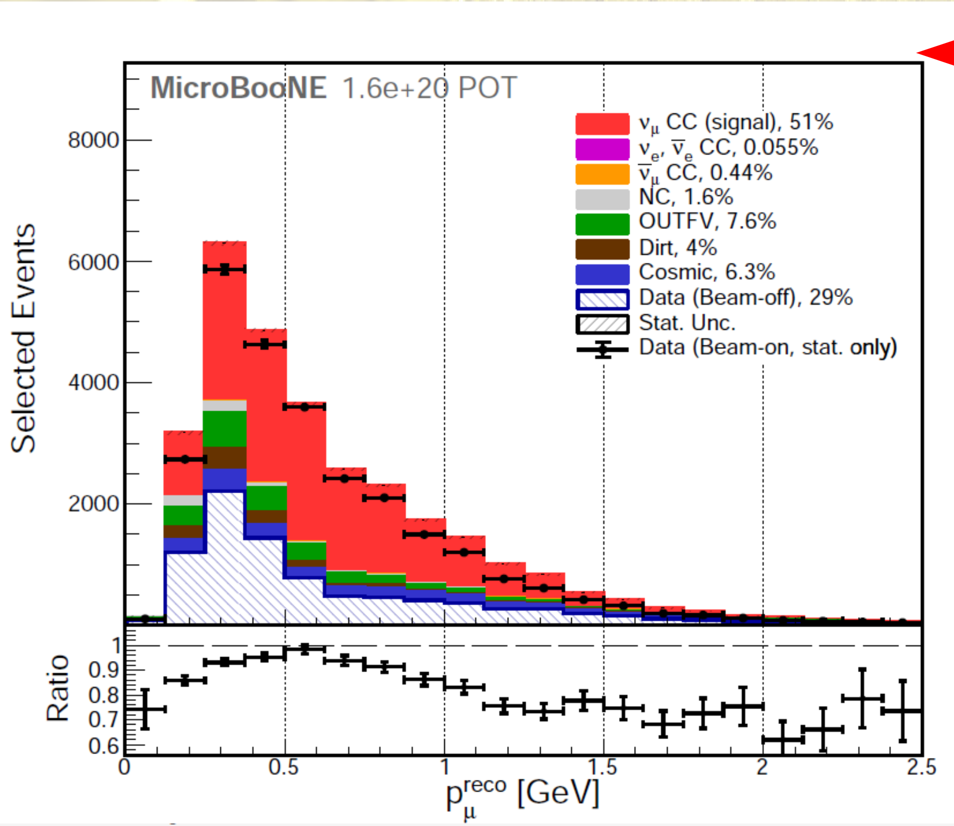
- First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at 0.8 GeV completed 2019!
- 1.6×10^{20} POT, after applying data quality cuts
  - ~4 months data Feb – July 2016
- On-beam (beam on) and off-beam (cosmics only) data used for analysis.
  - MicroBooNE is a ground level detector.
- Final event selection contains 27,200 events.

Charge-Current Muon Events



- Muon / proton separation to identify CC event topologies using truncated dQ/dx.
- Plots show the truncated average charge loss per unit length dQ/dx for the muon candidate track in the selection.
- Proton tracks populate regions of higher values of dQ/dx.

Backgrounds and Systematics



Final event distribution for the analysis event selection.

- Muon momentum.
- red histogram = signal events. Other colors = beam related and cosmic backgrounds.
- Blue shaded histogram shows pure cosmic event bckgrd (estimated from off-beam data).

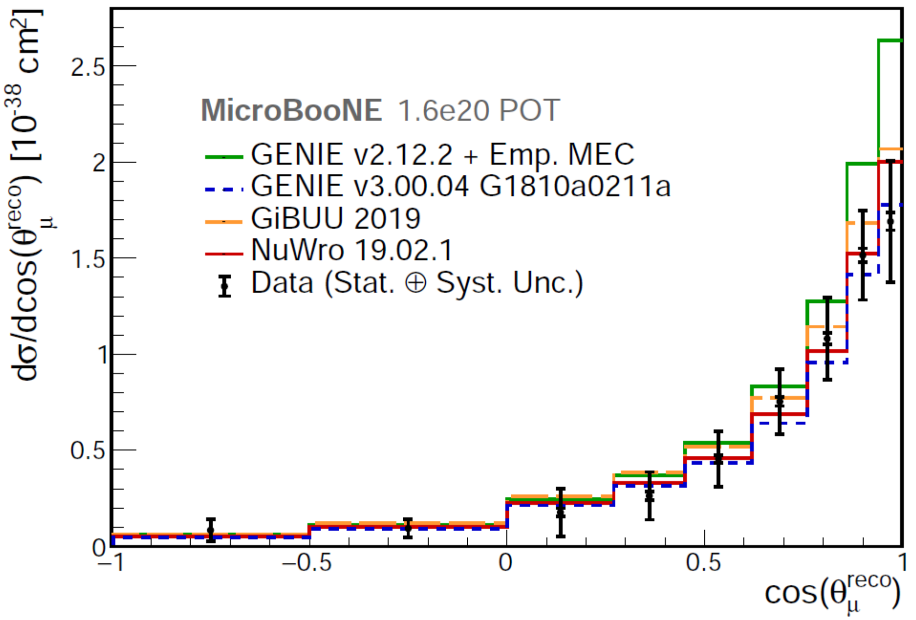
Ratio plot shows data/MC

Source of uncertainty	Relative uncertainty [%]
Beam flux	12.4
Cross section modeling	3.9
Detector response	16.2
Dirt background	10.9
Cosmic ray background	4.2
MC statistics	0.2
Statistics	1.4
Total	23.8

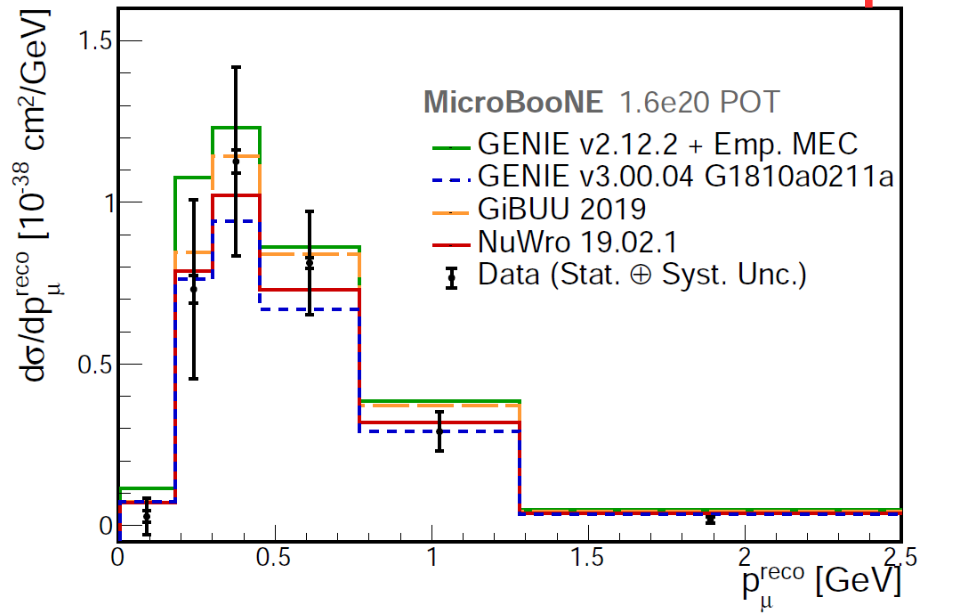
Contributions to the total cross section systematic uncertainty.

MicroBooNE Single Differential Cross Section

wrt the beam direction cos



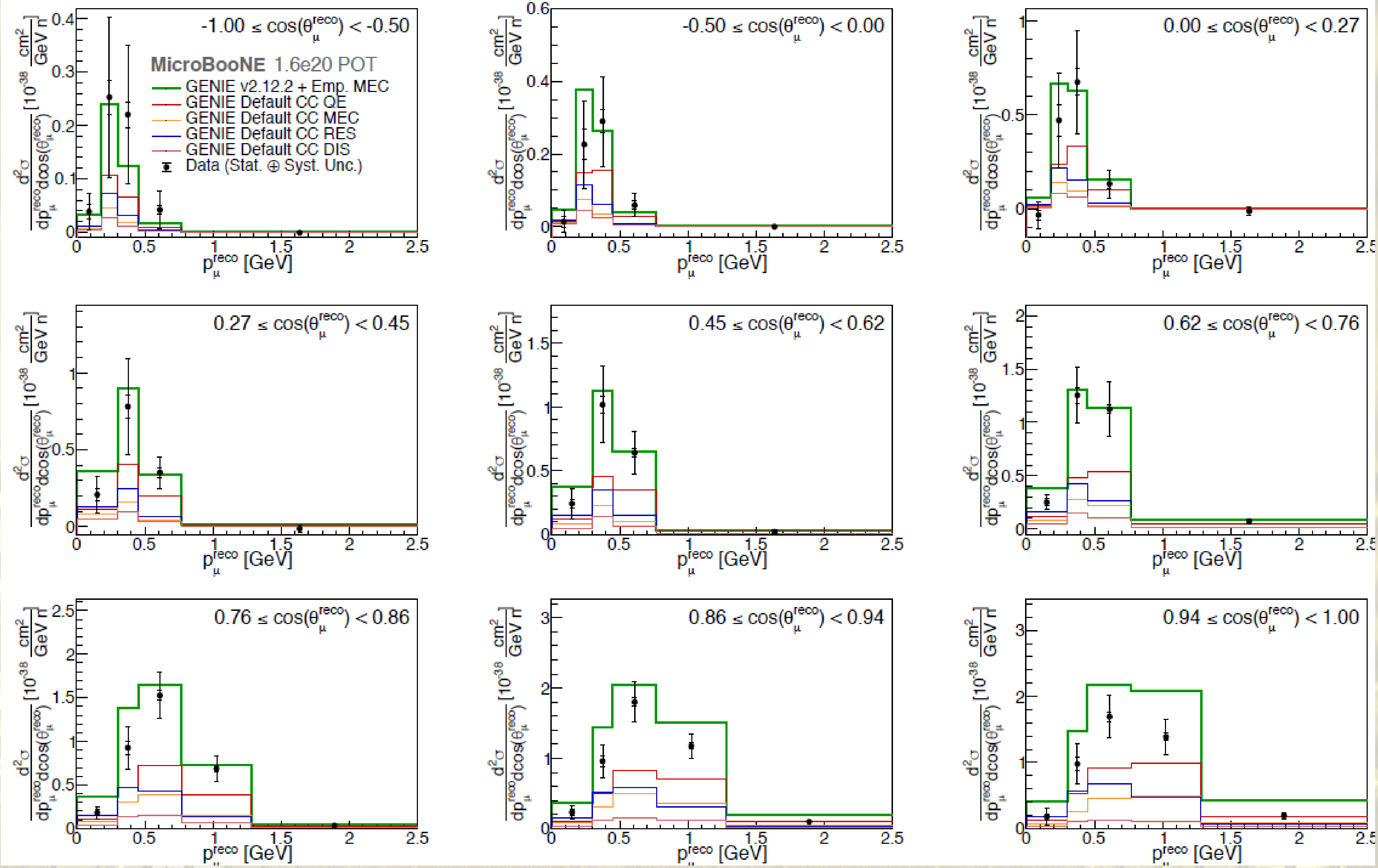
As func of muon momentum p



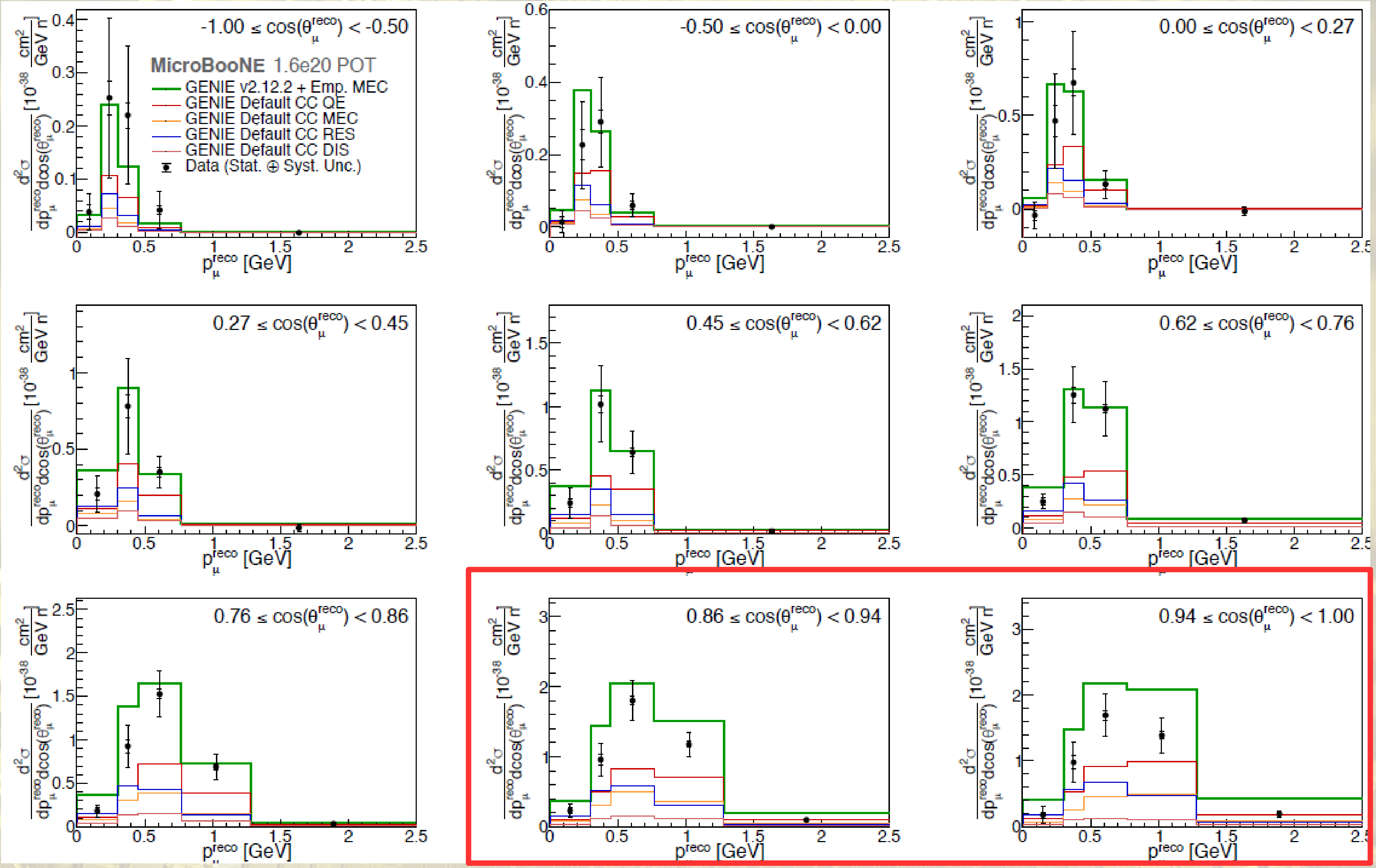
The black points show the MicroBooNE measurement with total uncertainty (outer error bar) and statistical uncertainty (inner error bar).

The result is compared to model predictions from GENIE v2.12.2 + Empirical MEC, GENIE v3.00.04 G1810a0211a, GiBUU 2019 and NuWro 19.02.1.

μBooNE double Differential Xsec Vs muon momentum p_μ



Panels show slices of measured muon angle wrt beam direction $\cos\theta_\mu$.
Compared to model predictions from GENIE v2.12.2 + Empirical MEC.



Largest disagreement in high-momentum, most forward-going muon angular bins of $0.94 \leq \cos\theta_\mu \leq 1$ & $0.86 \leq \cos\theta_\mu < 0.94$.

The total flux integrated cross section is measured by MicroBooNE to be $0.693 \pm 0.010\ (\text{stat}) \pm 0.165\ (\text{syst}) \times 10^{-38} \text{cm}^2$.

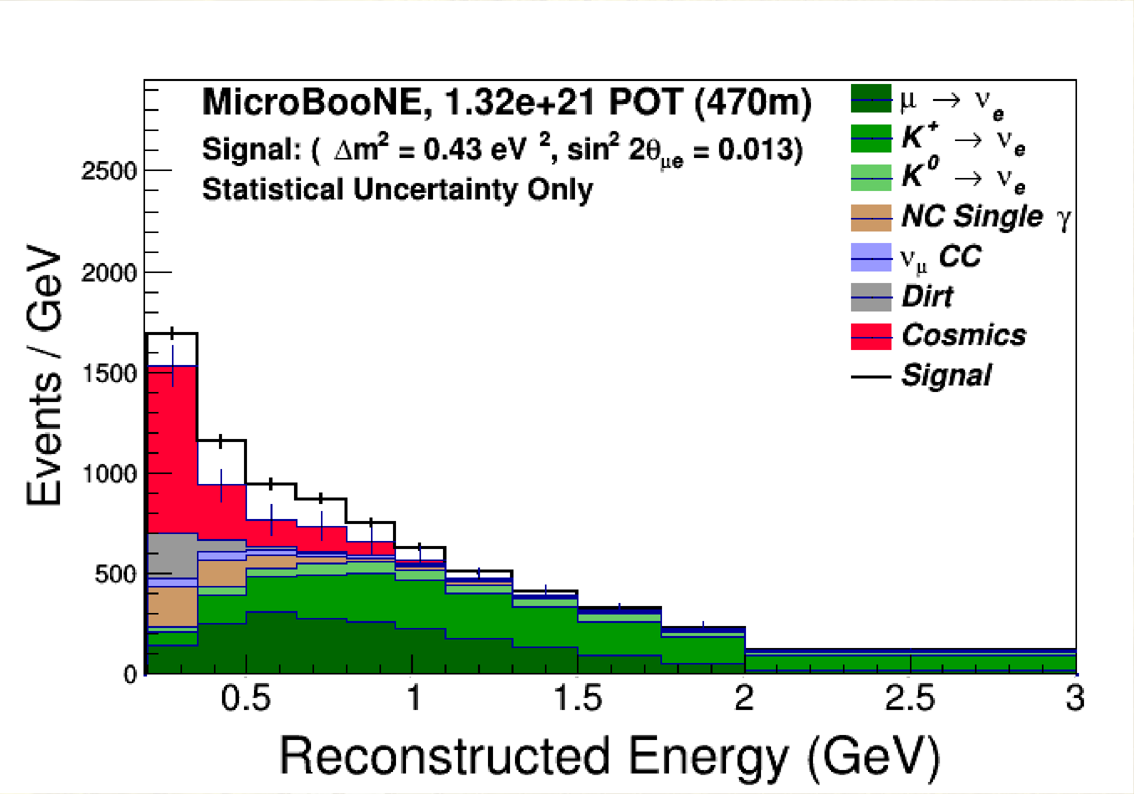
Better agreement with models containing more complete treatment of quasielastic scattering processes at low Q^2.

https://arxiv.org/pdf/1905.09694.pdf

Coming Soon!!

MicroBooNE LEE Analysis

Simulated ν_e distributions in MicroBooNE as a function of reconstructed neutrino energy.



All backgrounds shown, only muon proximity and dE/dx cuts used to reject cosmogenic backgrounds.

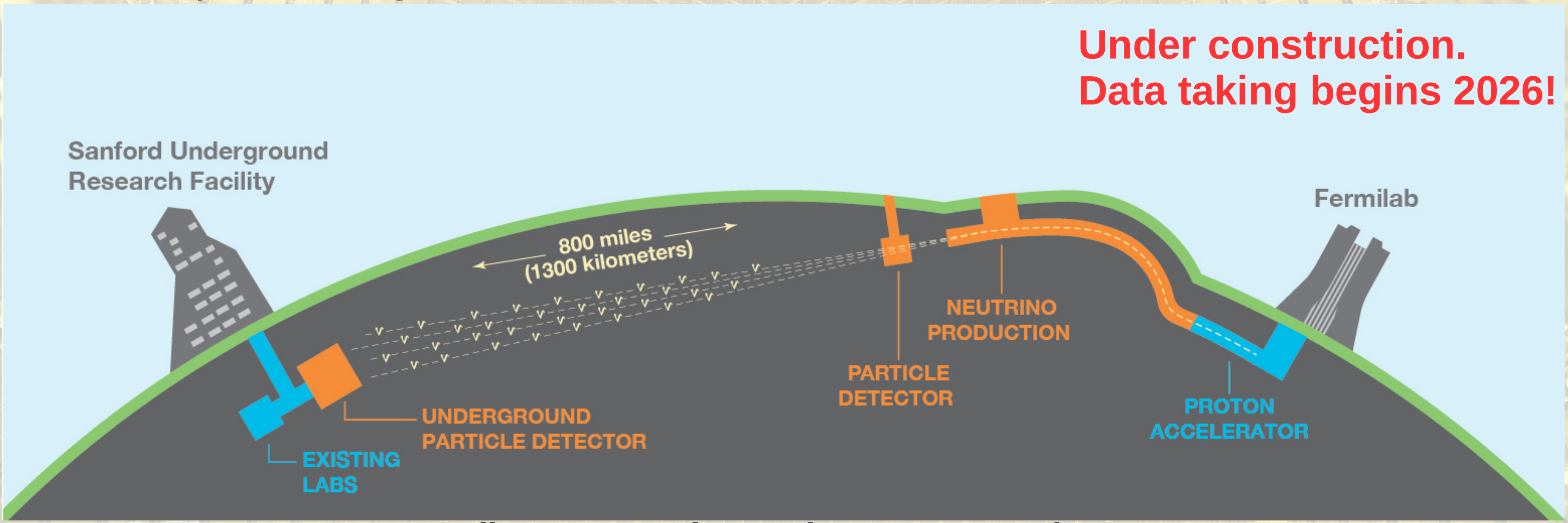
Oscillation signal events for the best-fit 3+1 oscillation parameters from Kopp et al. (arXiv:1303.3011) indicated by the white (top) histogram.

- Assumed ν_e recon efficiency of 80%, mis-id from photons of 6%, of events passing a topological cut.

DUNE

See Talk by S. Soldner-Rembold tomorrow at 9:30.

- Massive far detector: 4x10 kton Liquid Argon TPCs at Sanford South Dakota. Neutrino beam: 1.2-2.3MW at Fermilab.
- Very long baseline of 1300 km (increasing the matter effects).
- Measure δ^{CP} to 1-2% systematic error → Discover if neutrinos violate CP.
- Finally determine the neutrino mass hierarchy.
- Search for nucleon decay, e.g. $p^+ \rightarrow K^+ + \bar{\nu}$.
- Be ready to detect low-energy neutrinos from a core-collapse supernova.
- Search for Beyond Standard Model physics, e.g. sterile neutrinos, heavy neutral leptons, large extra dimensions, non-standard interactions.



Summary

- Significant challenges exist to answering the next big questions in neutrino physics including CP violation.
- LAr TPCs are an excellent way to meet these challenges. Higher density, charge and light collection, high position and dE/dx resolution etc.
- LarTPCs in use across neutrino physics.
- MicroBooNE aims to understand the low-energy excess of neutrinosobserved at LSND and MiniBooNE and make vital neutrino cross section measurements.
  - 170 (87) ton Lar TPC at FNAL in MiniBooNE beam.
  - First measurements of inclusive ν_μ CC differential cross Sections on Argon at 0.8 GeV this year.
  - Low-energy excess measurements coming.
  - Ideal testbed for future DUNE experiment.
- Pandora multi-algorithm machine learning software framework is used by most LArTPC experiments and growing daily.