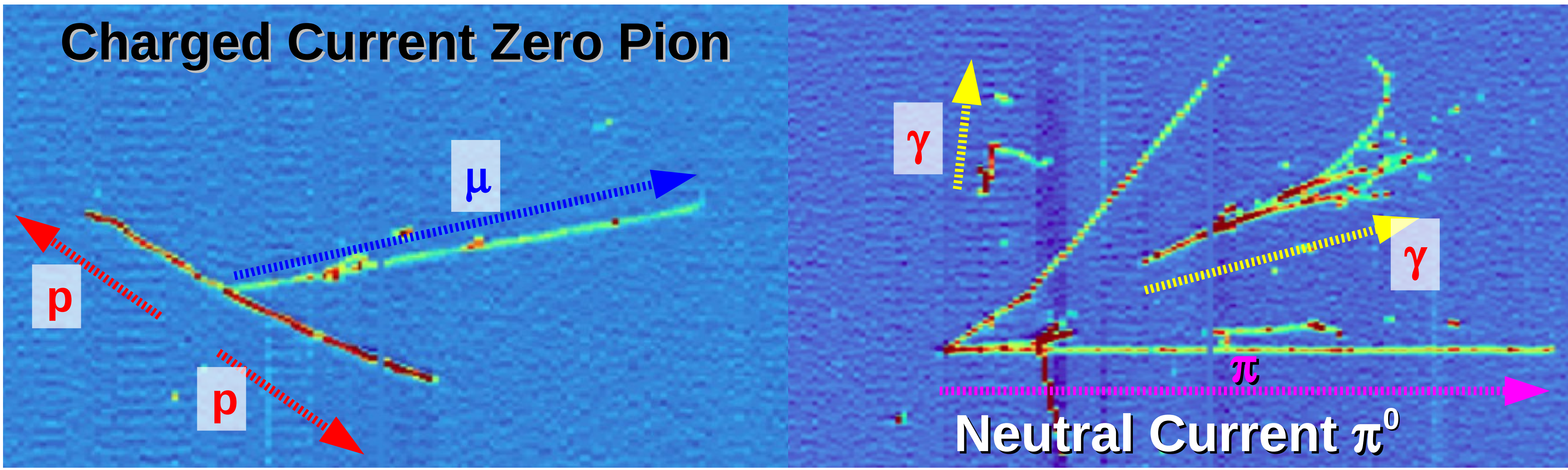
Detection of charged current zero π and neutral current π^0 final states in the ArgoNeuT experiment

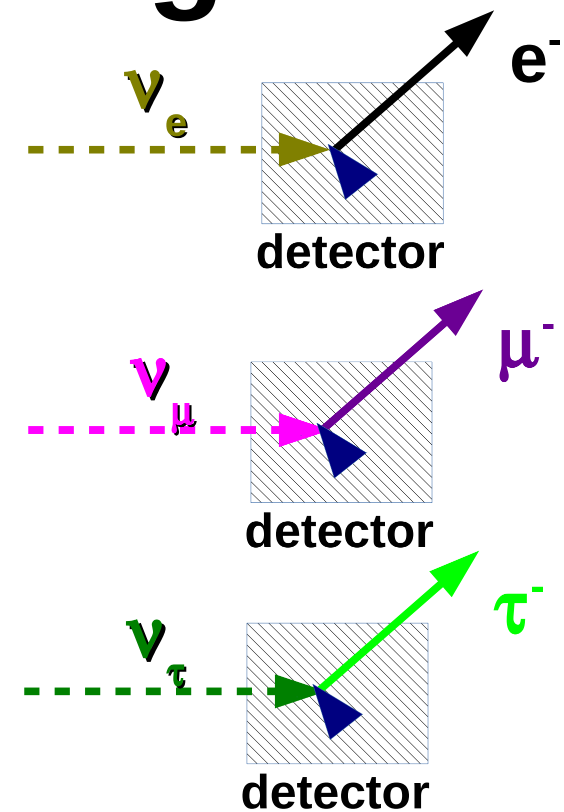


Jonathan Asaadi

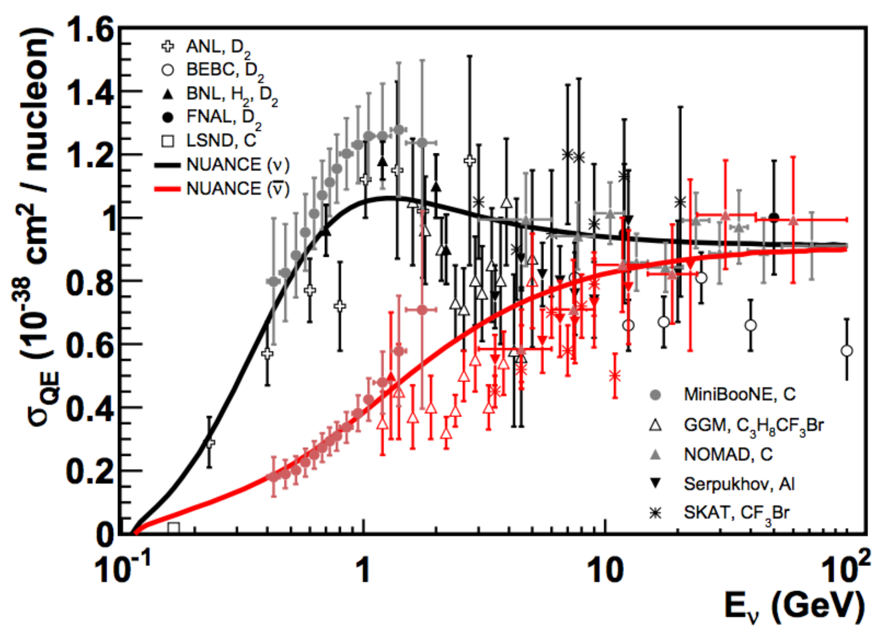
Syracuse University

ν-nucleus Scattering

- **In neutrino physics we are interested in extracting the physics and properties of the neutrinos interacting in our detector**

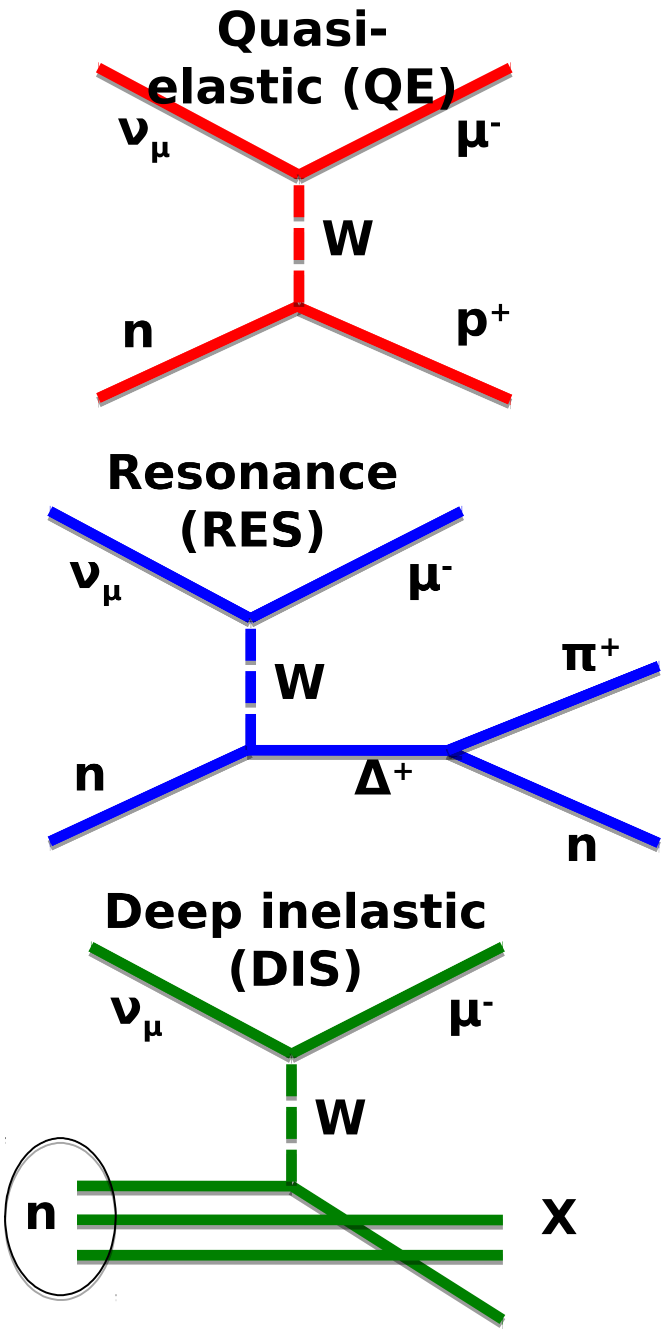


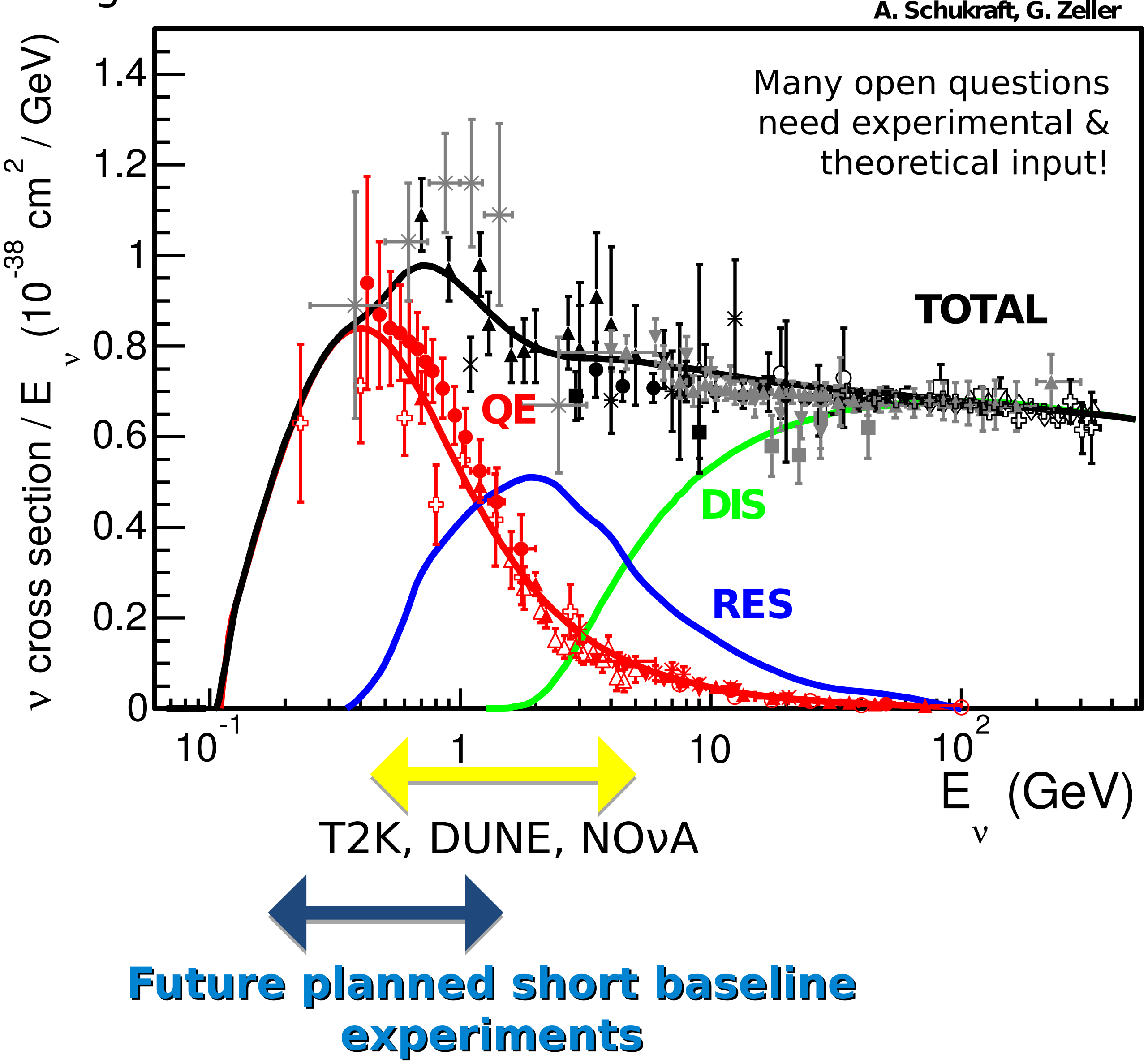
- **Often the physics we extract depends on the details of the neutrino nucleus interaction**
  - Ignoring the details often leads to discrepancies when multiple experiments attempt to measure the same thing



Neutrinos can interact with matter in many ways

Lots of interesting (nuclear) physics over all energy ranges.

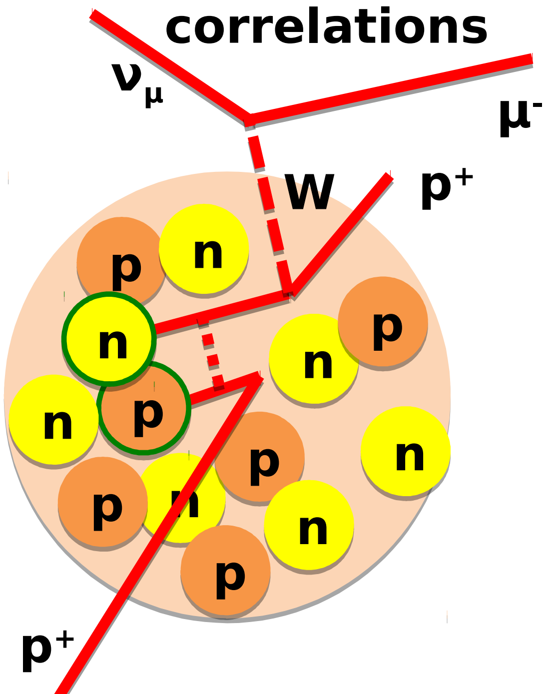




Of course this is an oversimplification

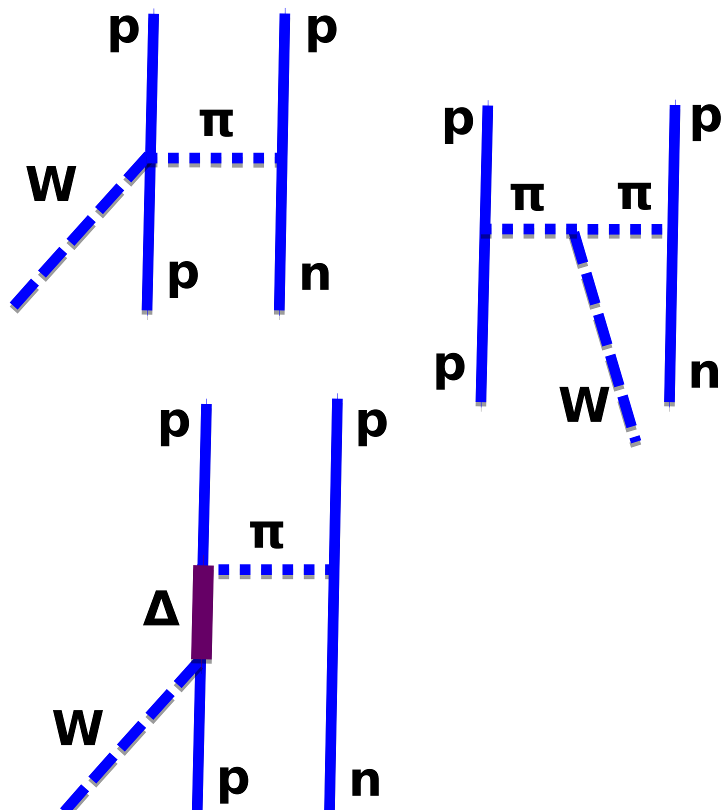
When scattering off nuclei instead of free nucleons the observed topology can be more complex:

Short-range nucleon-nucleon correlations



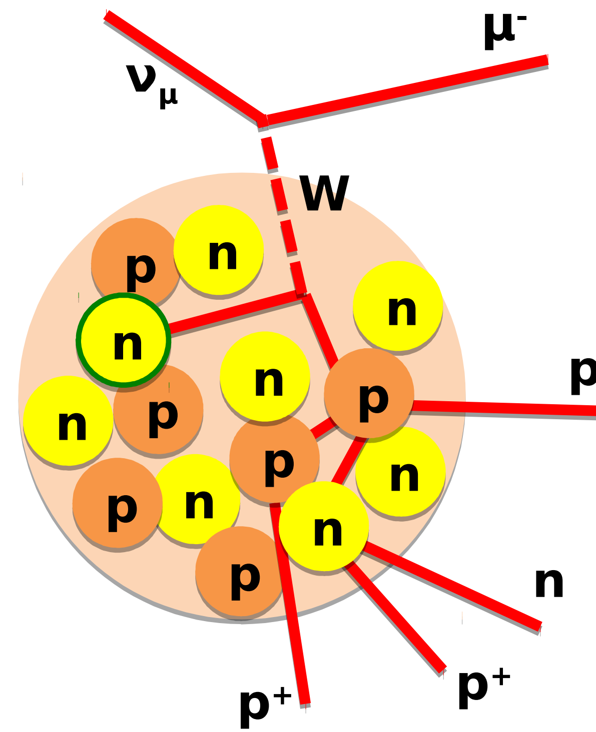
Two nucleons in correlation
Means for the experimentalist:
Multi-nucleon knockout!
The pair has:
large relative momentum,
small total momentum

Meson exchange currents



The observed state looks like QE but it was not!

Final state interactions



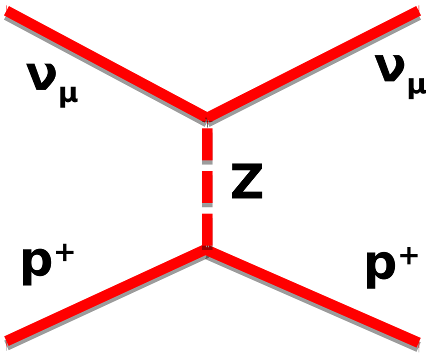
Multi-nucleon knockout through re-interaction of the outgoing nucleon

Credit: A. Schukraft for images

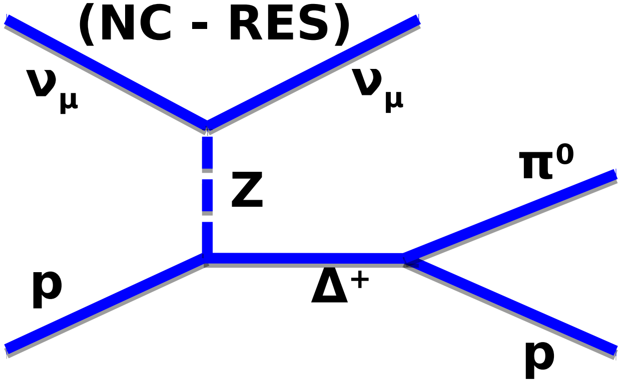
Veritable treasure trove of physics wrapped into ν-nucleus interactions

Neutrinos can interact with matter in many ways

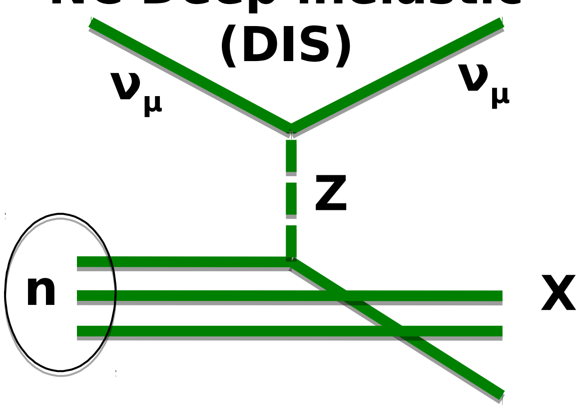
NC-elastic



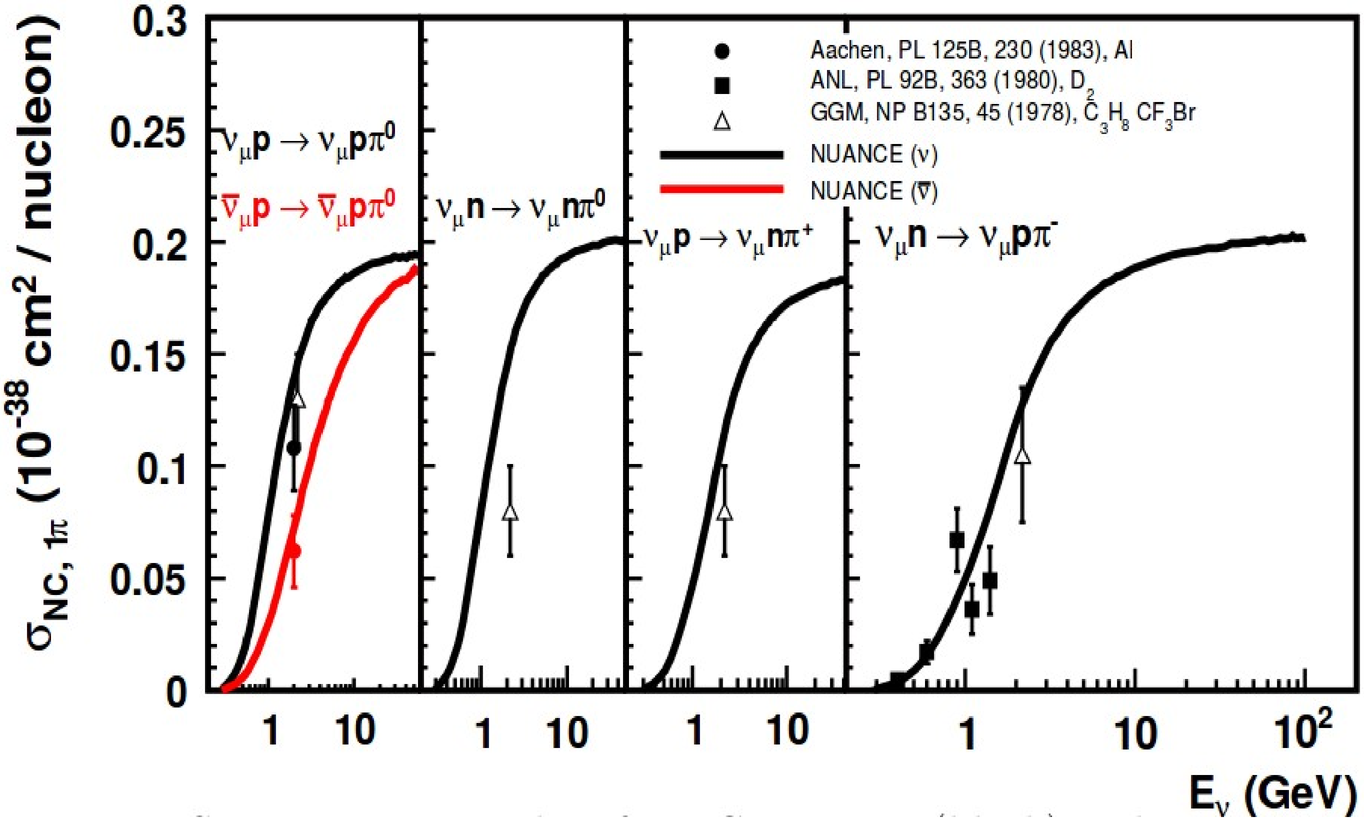
NC Resonance (NC - RES)



NC Deep inelastic (DIS)



Neutral current interactions are particularly interesting and little data exists



Having a powerful detector capable of disentangling the final states aids in our understanding of neutrino-nucleus interactions

LArTPC's

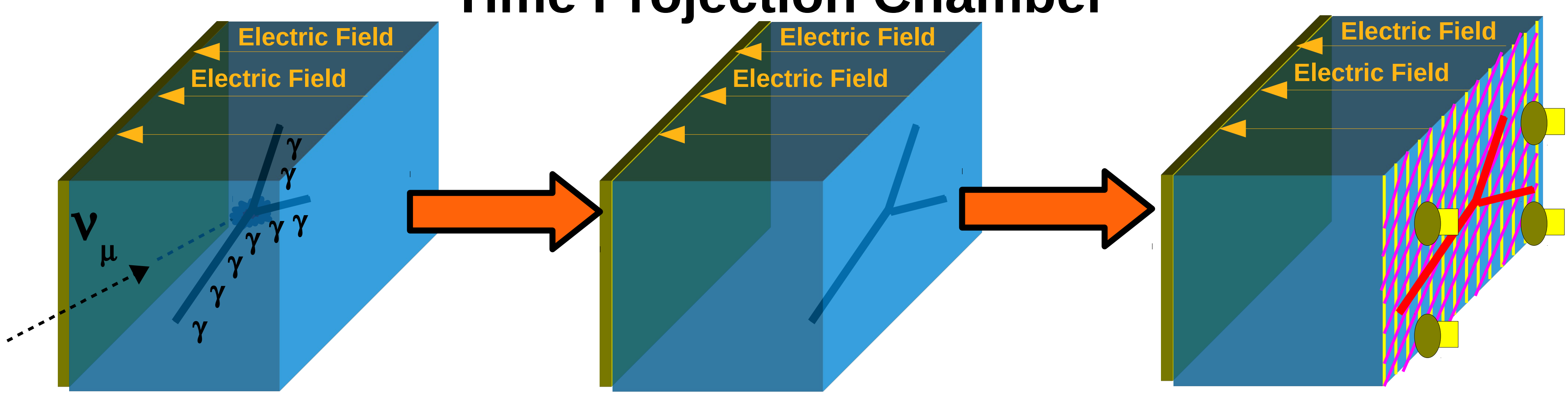
Liquid Argon is an excellent choice for neutrino detectors:

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

- **→ Dense**
  40% more dense than water
- **→ Abundant**
  1% of the atmosphere
- **→ Ionizes easily**
  55,000 electrons / cm
- **→ High electron lifetime**
  Greek name means "lazy"
- **→ Produces copious scintillation light**
  Transparent to light produced

Time Projection Chamber



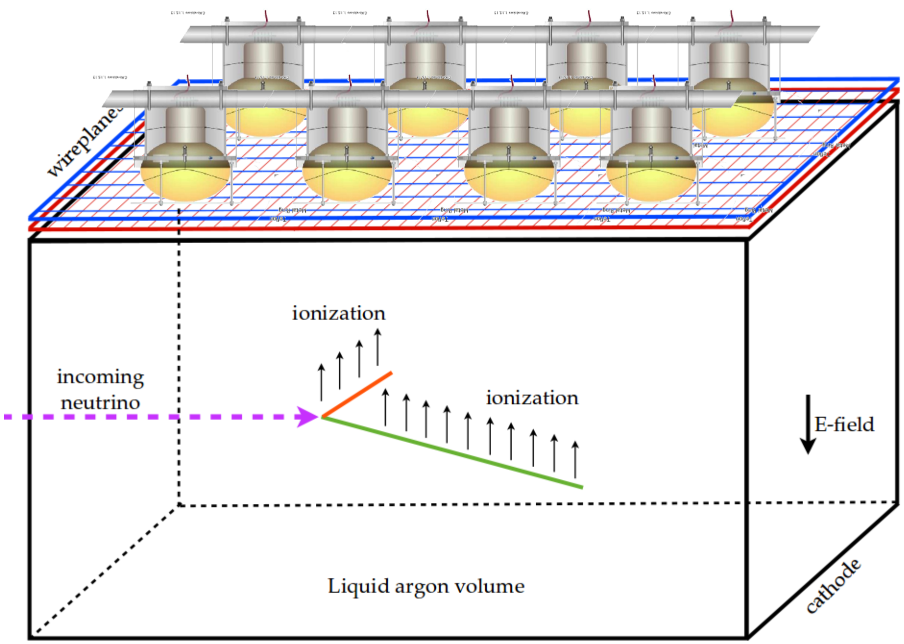
Neutrino interaction in LAr produces ionization and scintillation light

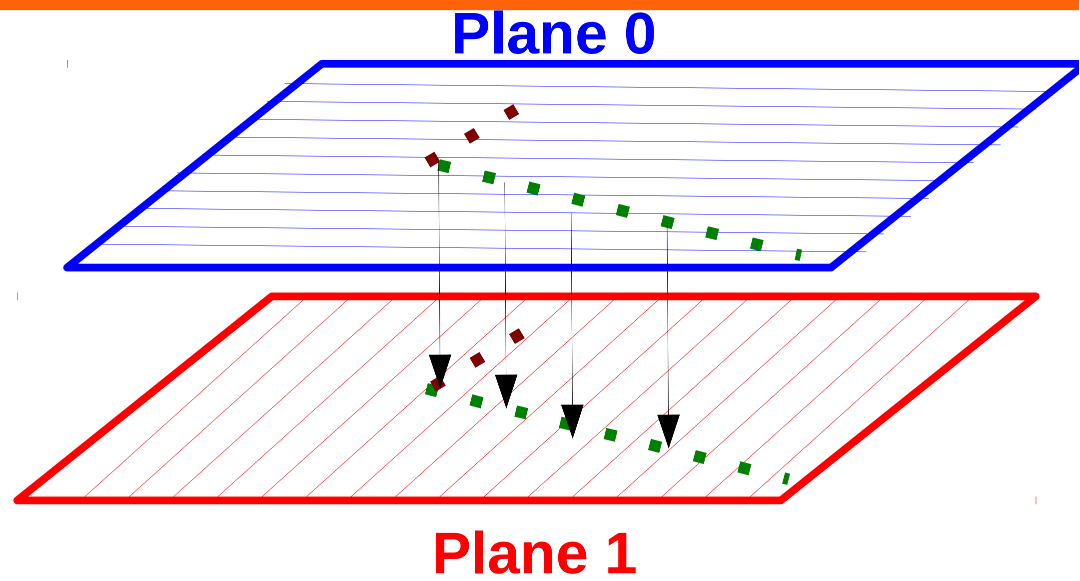
Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

LArTPC's

Using the charge for 3-d reconstruction

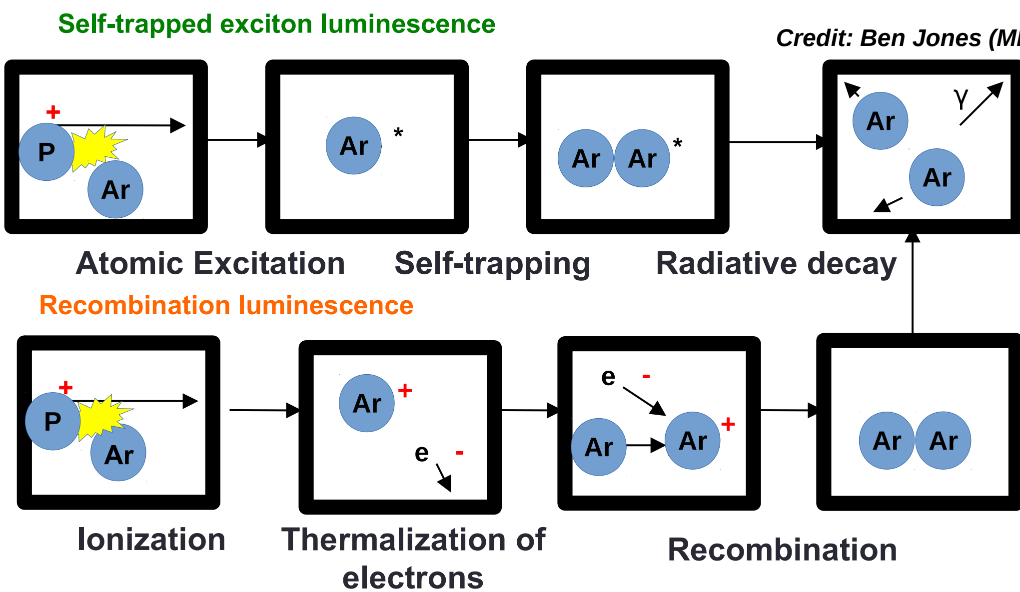


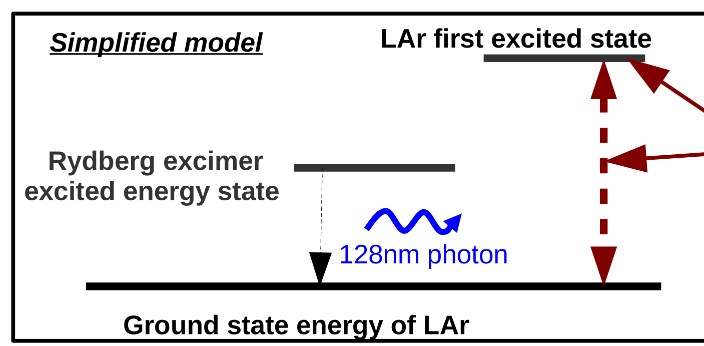


Matching charge locations across different angled wire planes allows for 3d reconstruction

Using the scintillation light to get the t-0

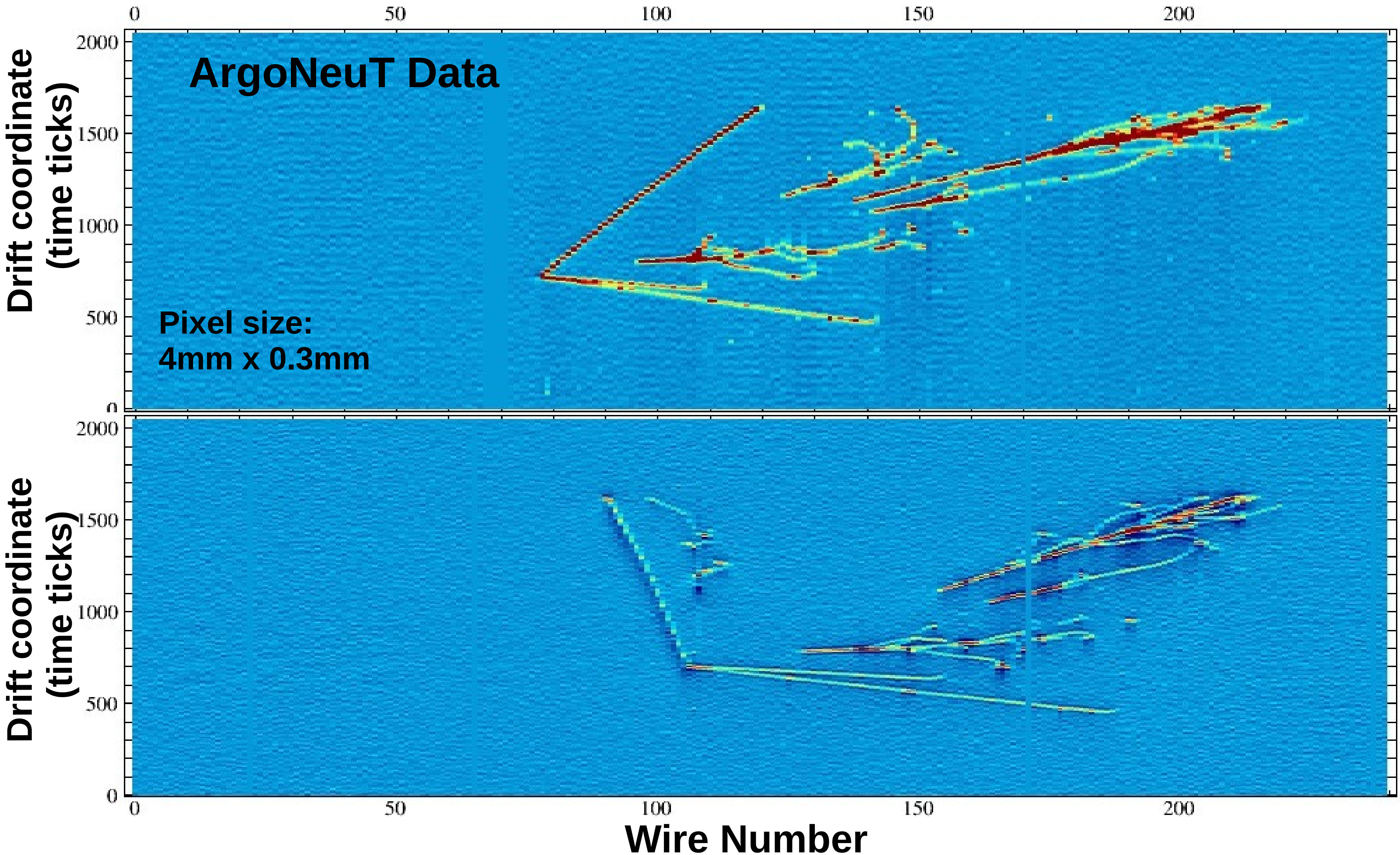
Credit: Ben Jones (MIT) for image



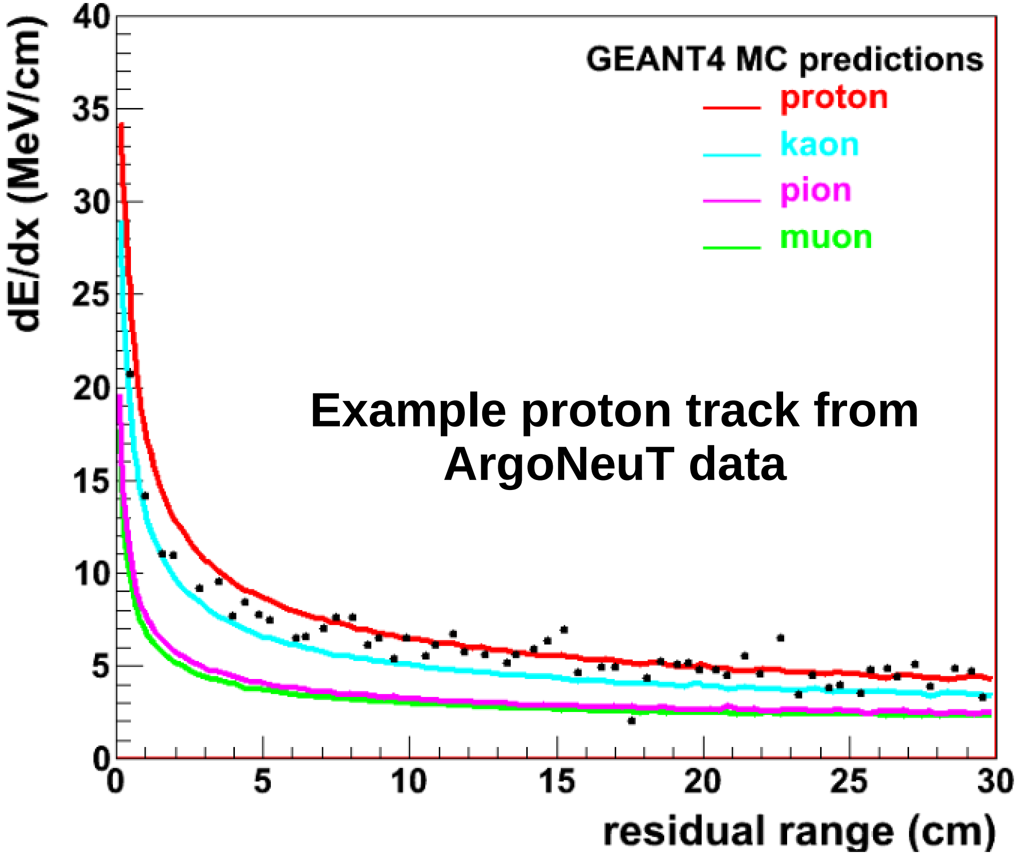


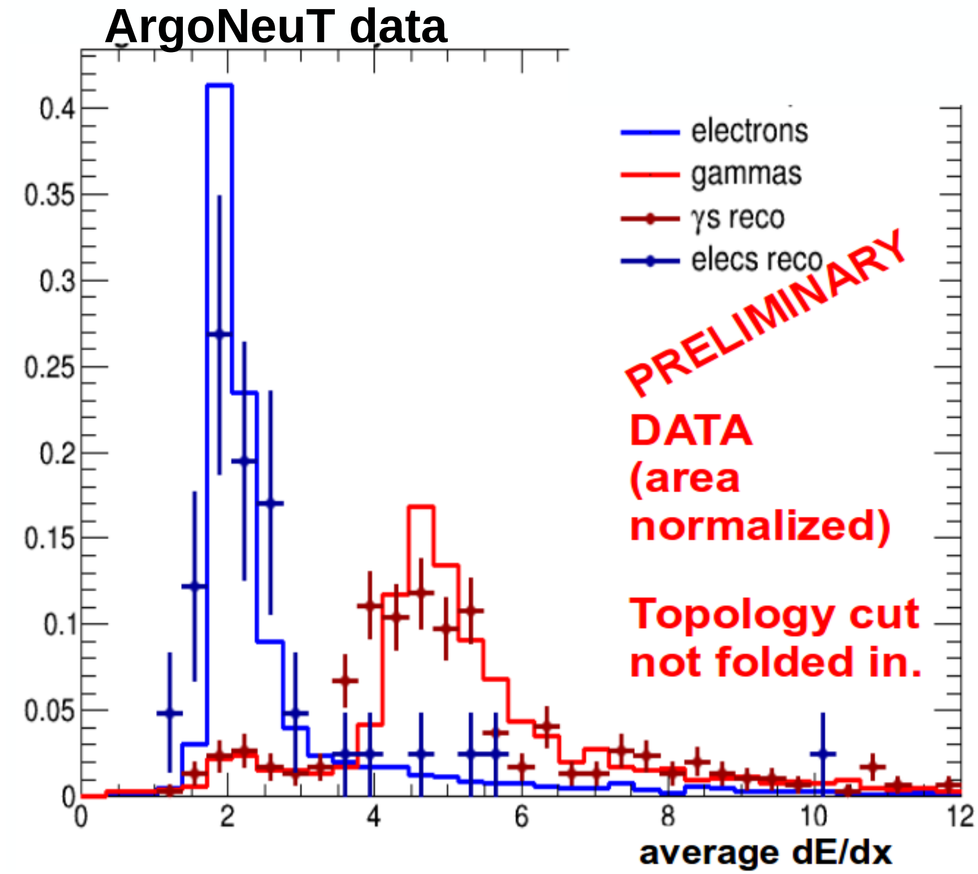
This difference between the energy levels is why LAr is transparent to the scintillation light it produces

Liquid Argon Time Projection Chamber



Liquid Argon Time Projection Chamber

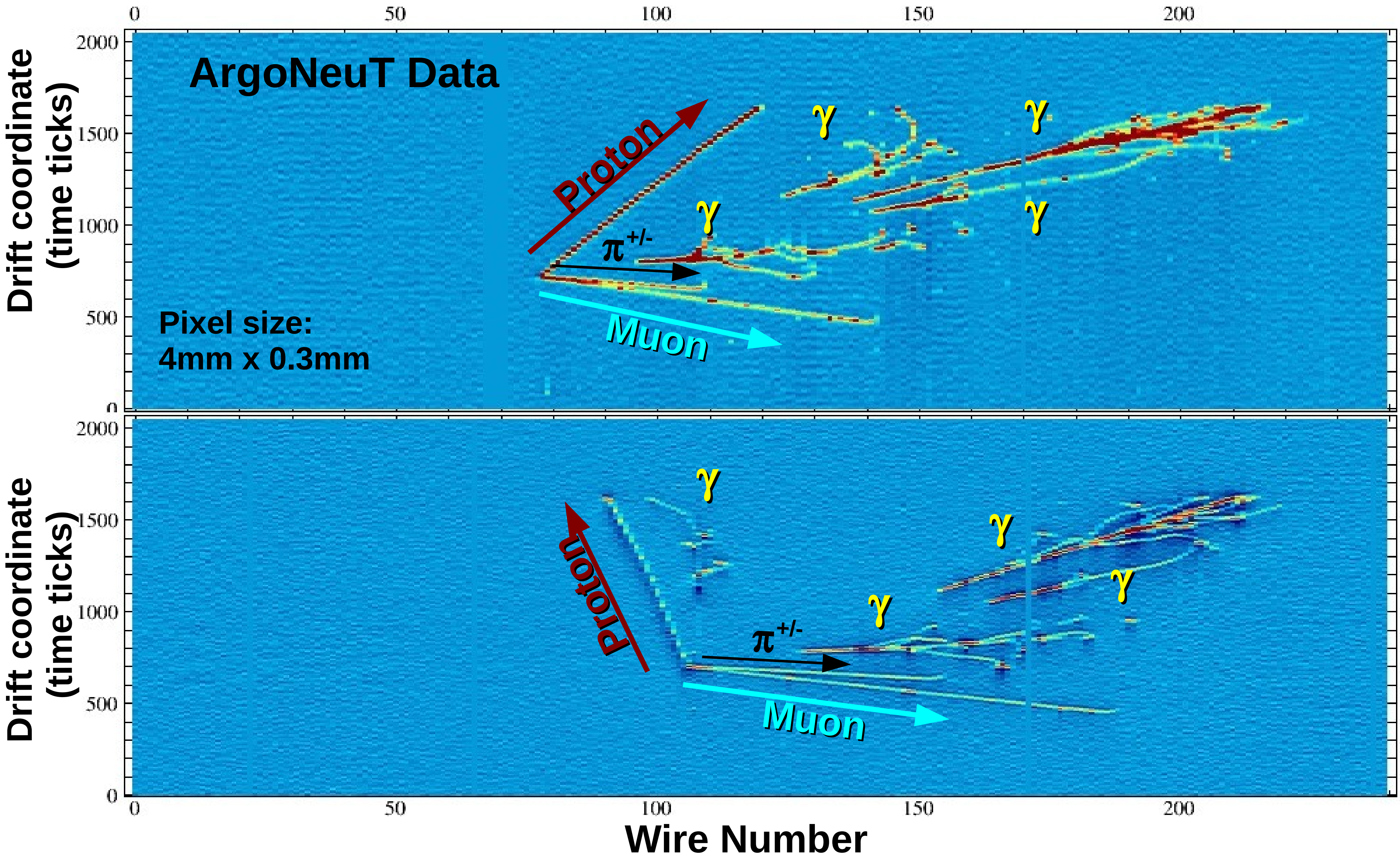




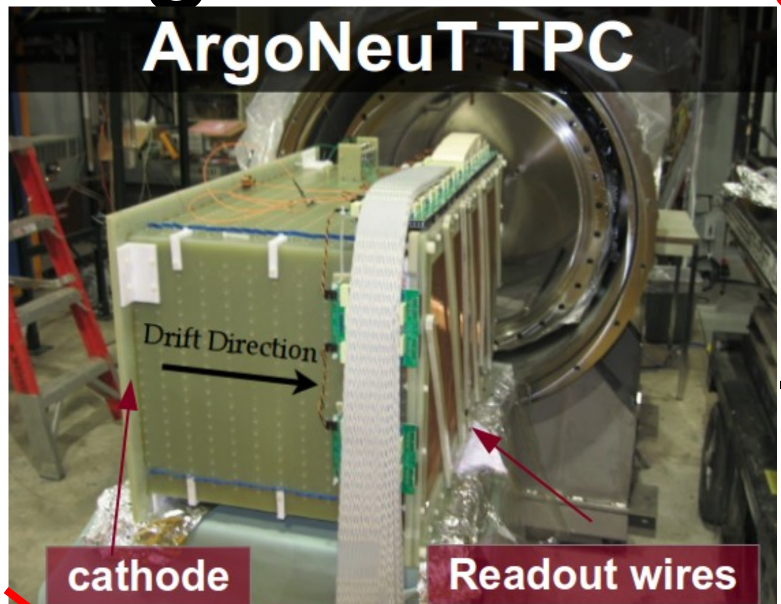
By analyzing the energy deposited along the track (dE/dX) as a function of distance along the track (range) you can perform particle identification (PID)

Analyzing the dE/dX for the start of an electromagnetic shower you can identify and separate photons from electrons

Liquid Argon Time Projection Chamber



ArgoNeuT: Argon Neutrino Teststand



ArgoNeuT was the first Liquid Argon TPC in a neutrino beam in the U.S.

Cliffnotes

Located in the NuMI Beam

- 0.40 m tall x 0.47 m wide x 0.90 m long

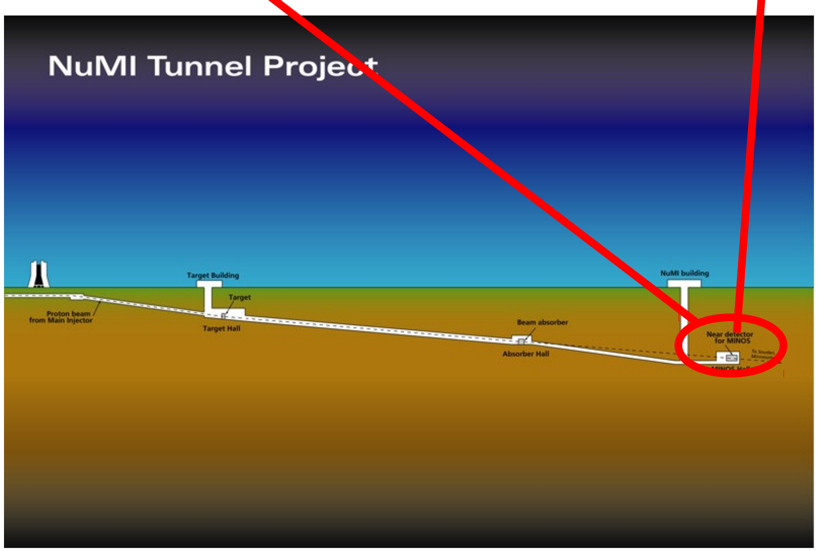
0.26 Tons (active mass)

- 480 wires (4mm pitch)

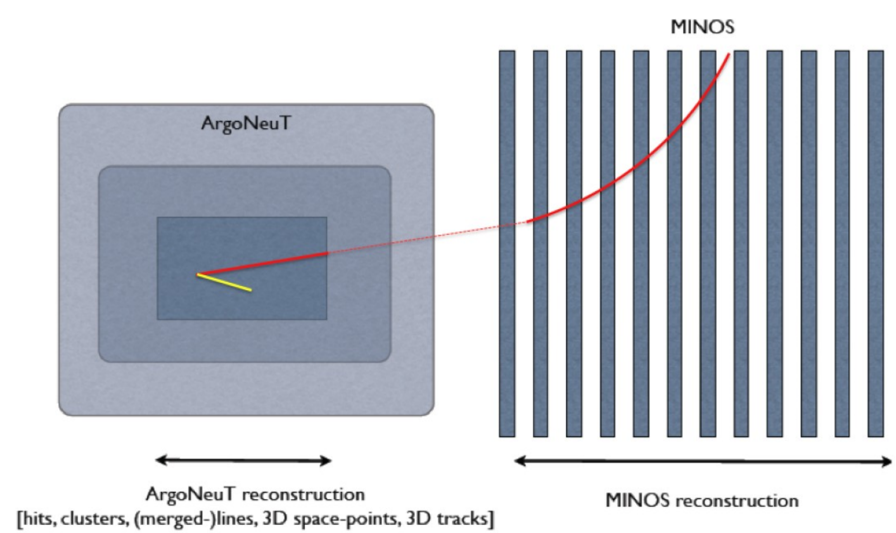
(Oriented +/- 30^o w.r.t vertical)

- No light detection system

- Utilized MINOS-ND as a muon spectrometer ***(sign and momentum)***



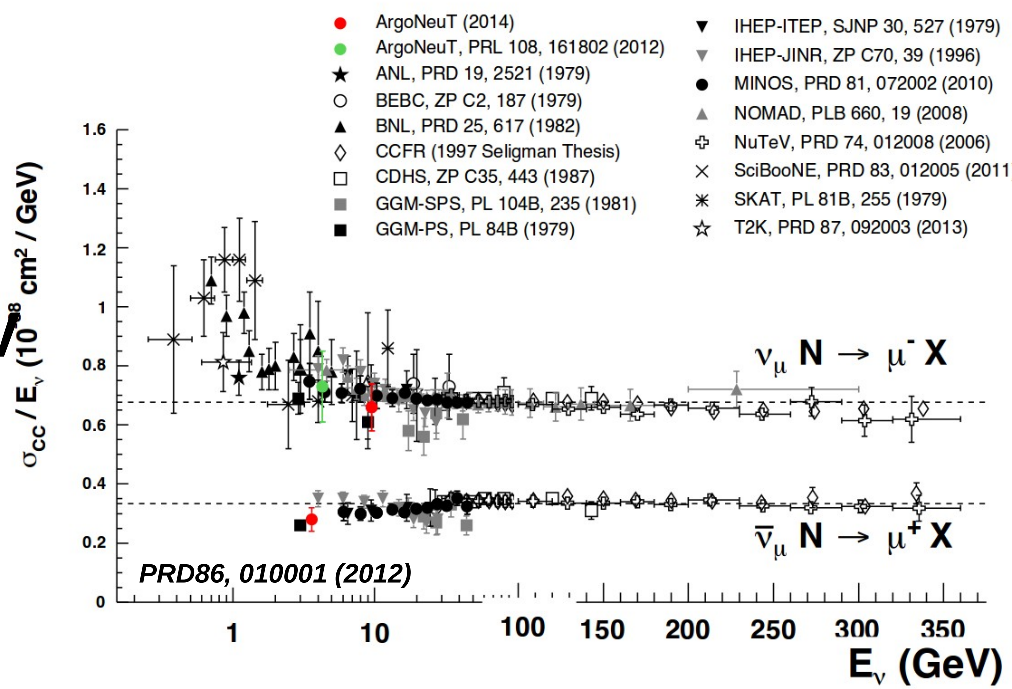
ArgoNeuT TDR: JINST 7 P10019 (2012)



ArgoNeuT

- **ArgoNeuT took data from 09/2009 – 02/2010**
  - 2 weeks in Neutrino mode (0.085×10^{20} POT)
  - 4 months in Antineutrino mode (1.2×10^{20} POT)
- **Collected high quality neutrino data in the range of 0.1 → 20 GeV**
- **7 publications so far!!**
  - Three ν-Ar cross-sections measurements
  - Calibration techniques with LAr detectors
  - Studies of neutrino nuclear effects
  - ***More publications on the way***

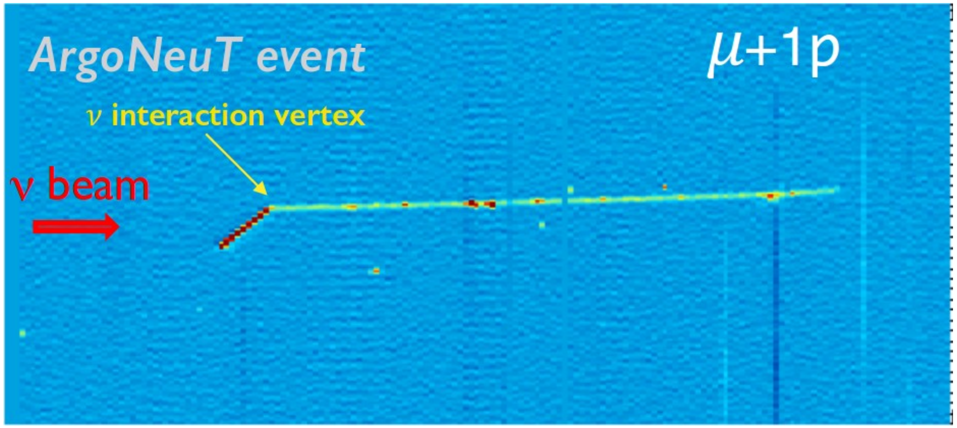
Taken from the Particle Data Group Booklet

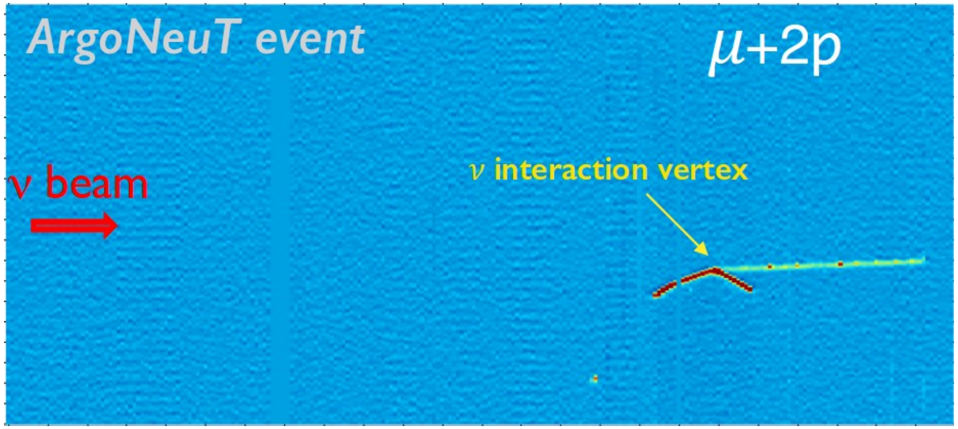


ArgoNeuT's contribution shown in colored data points

CC-Zero Pion

- Utilizing the 3-d imaging capabilities of LArTPC's as well as the calorimetric and particle ID allows for MC-independent measurements of both **exclusive topologies** (ν_μ-CC0π) as well as **exploring nuclear effects** (ν-nucleus scattering)

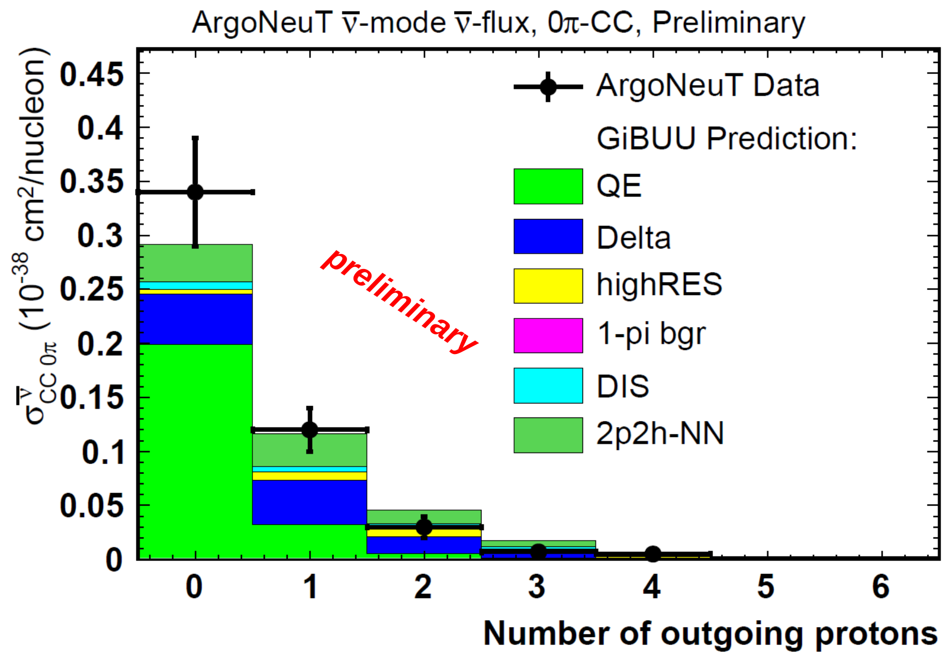


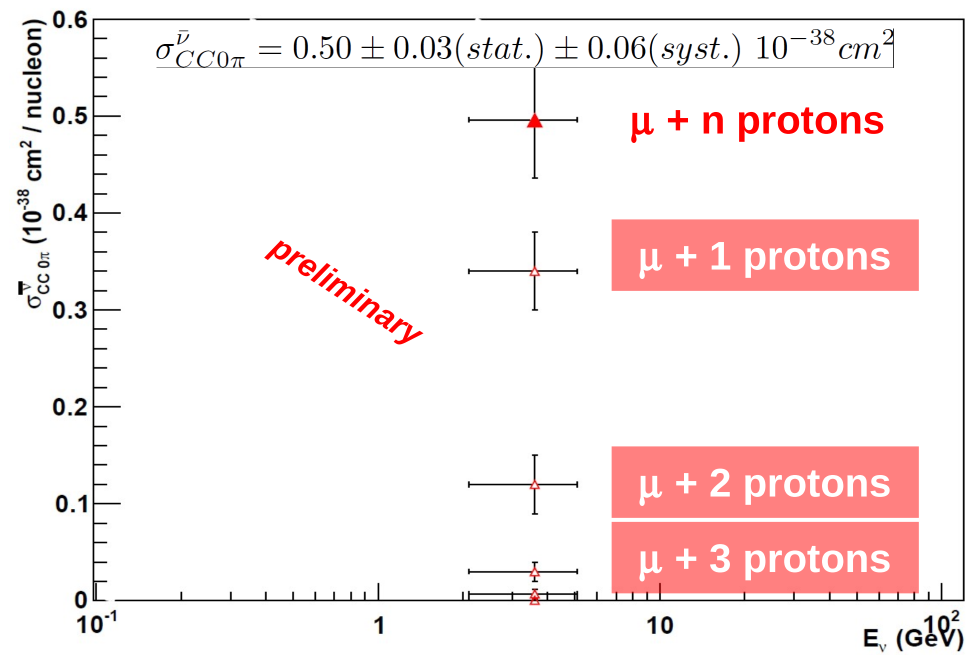


- **Event Topology:**
  - **Leading μ + N Protons**
    (neutrons present as well but not detected due to ArgoNeuT's small volume)
- **Proton Energy Threshold:**
  - **~21 MeV Kinetic Energy**

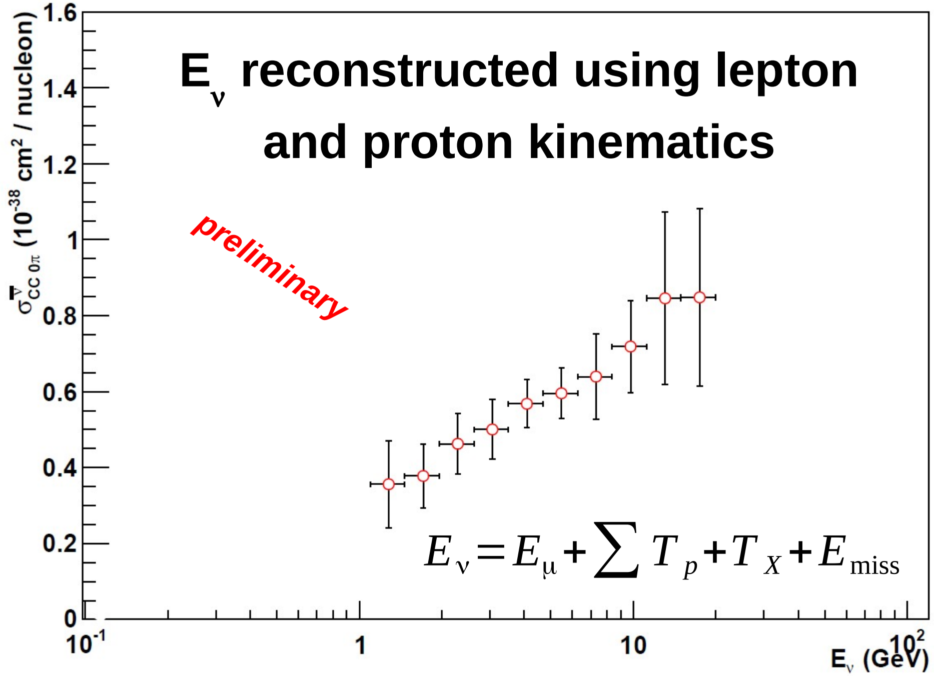
CC-Zero Pion

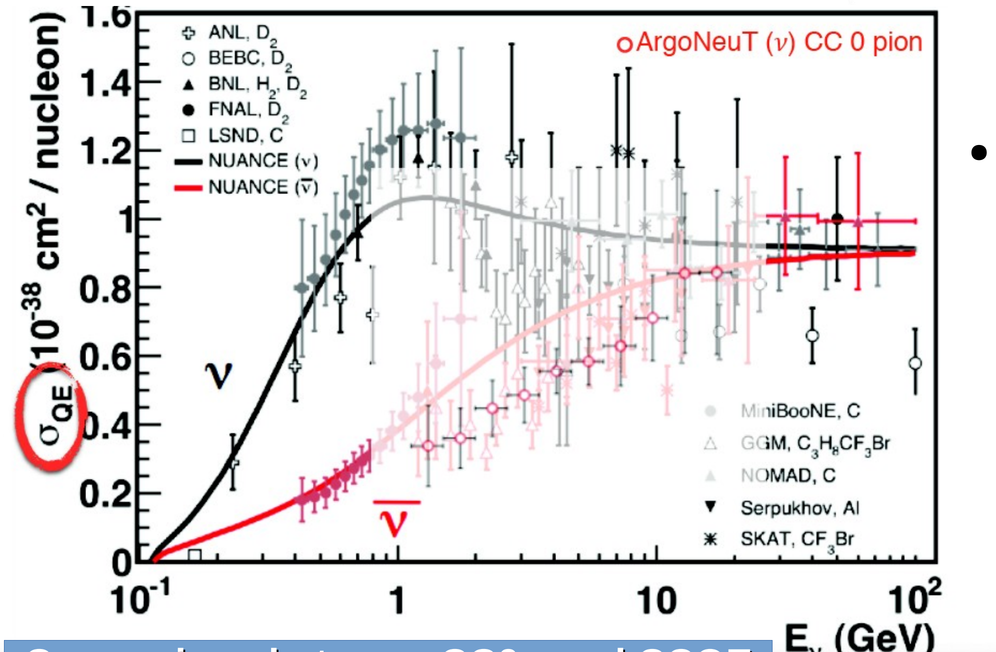
- LarTPC's enable you to examine the production cross-section as a function of the number of outgoing protons in the event
  - See good agreement between MC with final state interactions and data
- Inclusive cross-section for a <E_ν> = 3.6 GeV +/- 1.5 GeV
  - **0.5 ± 0.03** *(stat)* **± 0.06** *(sys)* **x 10^{-38} cm²**
  - Also shown as sum of its proton multiplicity components





CC-Zero Pion



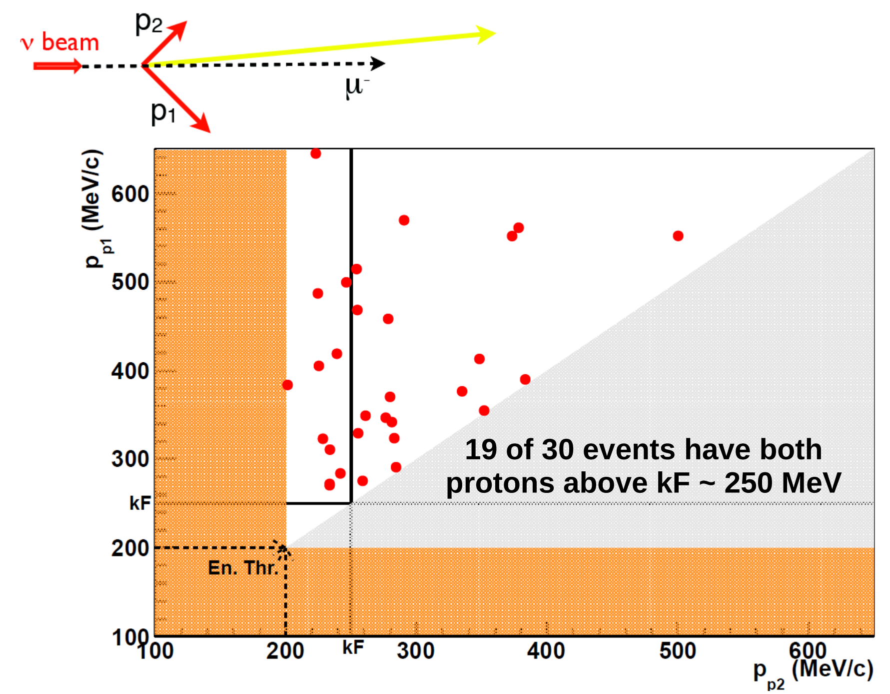


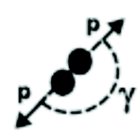
Comparison between CC0π and CCQE data and MC provided just "to guide the eye"

- **Interpret the data as a function of the reconstructed neutrino energy**
  - **T_p**: kinetic energy of the protons
  - **T_x**: Recoil energy of the residual nuclear system
    - Estimated from missing transverse momentum
  - **E_{miss}**: Missing energy
    - Nucleon separation energy from the nucleus + excitation energy of the residual nucleus
      - Estimated from a fixed average value
- **Plotting this compared to the world data for Quasi-elastic processes is expected to give some discrepancy**
  - We are not making a quasi-elastic assumption for our interaction
  - Detailed MC comparison currently underway

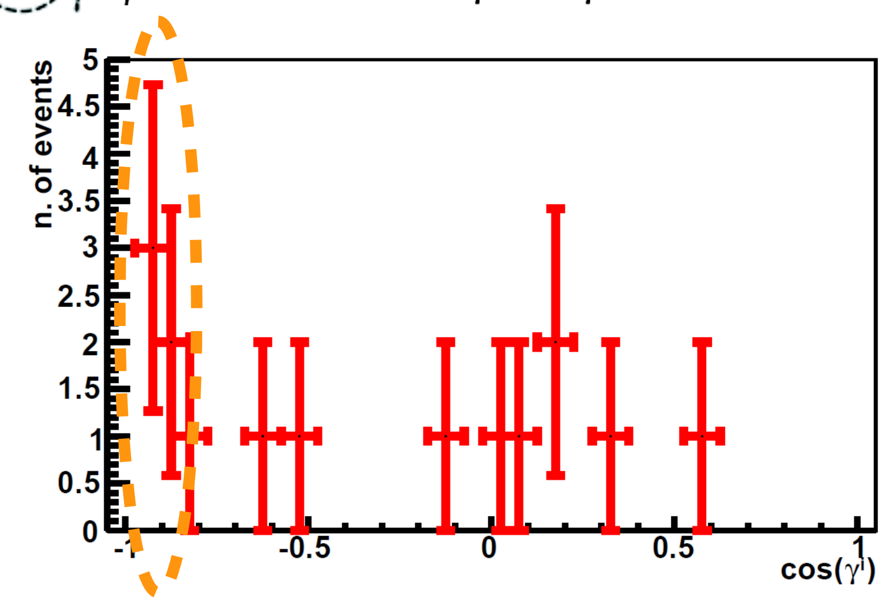
Studying Short Range Correlation

- Subsample from the CC0π sample is the μ+2p sample (30 events) which allows us to look for **hints for nucleon-nucleon short range correlation** (NN-SRC)
  - Look for pairs of protons with **high momentum** (above the Fermi momentum) and **strong angular correlation**
- Four events are found with two protons in a **back-to-back** configuration in the lab frame
  - cos(γ) < -0.95
  - All for have the momentum of the protons nearly perfectly balanced

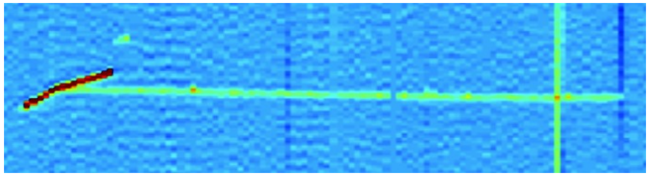


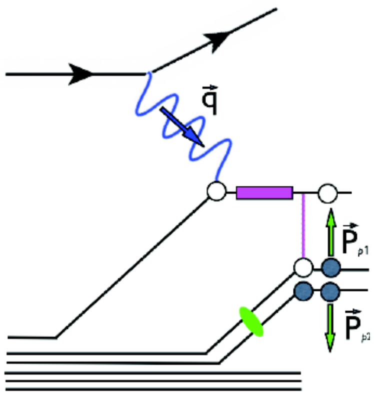


γ=angle in space between the two detected proton tracks in the Lab reference frame

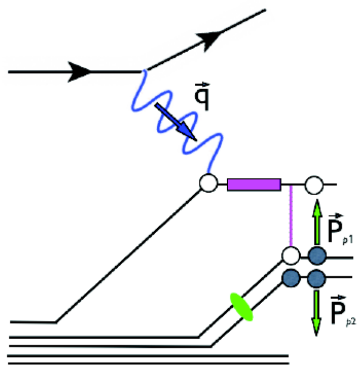


Studying Short Range Correlation

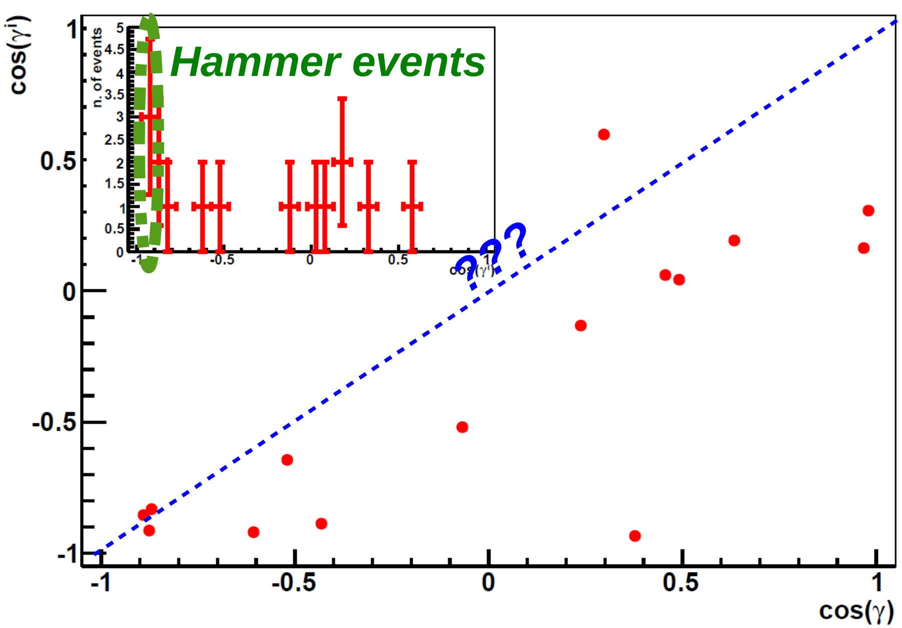




via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair

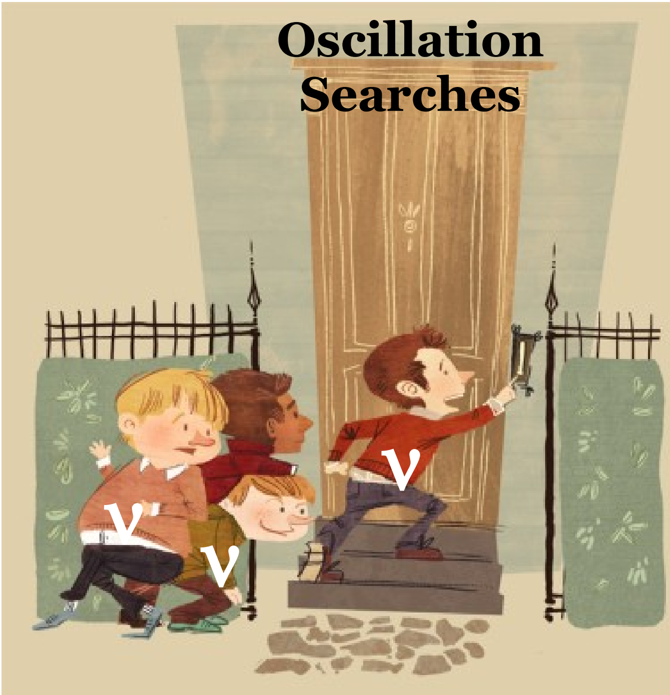


via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair



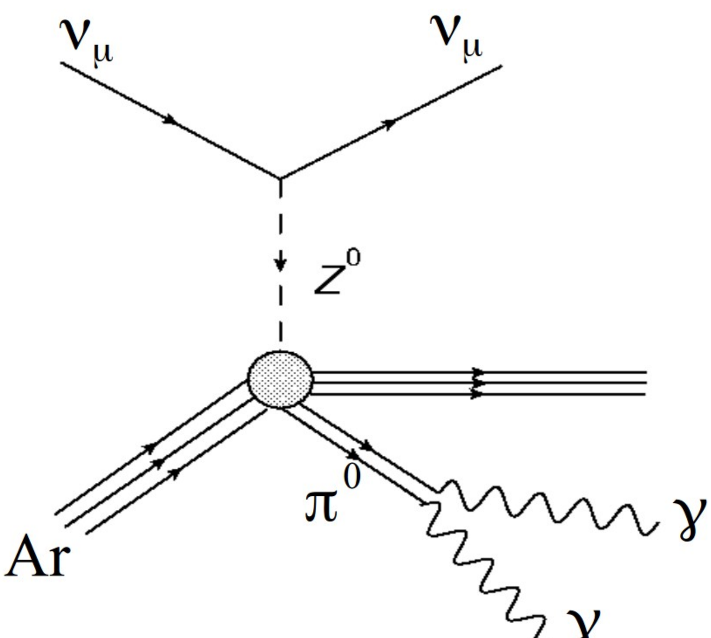
- The features of the four “hammer” events look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC np pairs
  - γi: opening angle between the struck nucleon and the recoil proton
  - γ: angle between the two proton tracks in the lab frame
- No immediate interpretation of the remaining events which seem to have an ***apparent correlation(?)***
  - Final State interactions appear disfavored because these events are energetic and angularly correlated
- **Future larger LArTPC experiments will study these effect with higher statistics in the near future**

Neutral Current π^0 in ArgoNeuT



"...sometimes, the neutrino opts to play ding-dong-ditch instead, depositing a fraction of its energy in the detector before speeding away. This is called a neutral current event, and, in many cases, it is the bane of the modern neutrino physicist's existence...."

– Symmetry Magazine, May 06th 2014

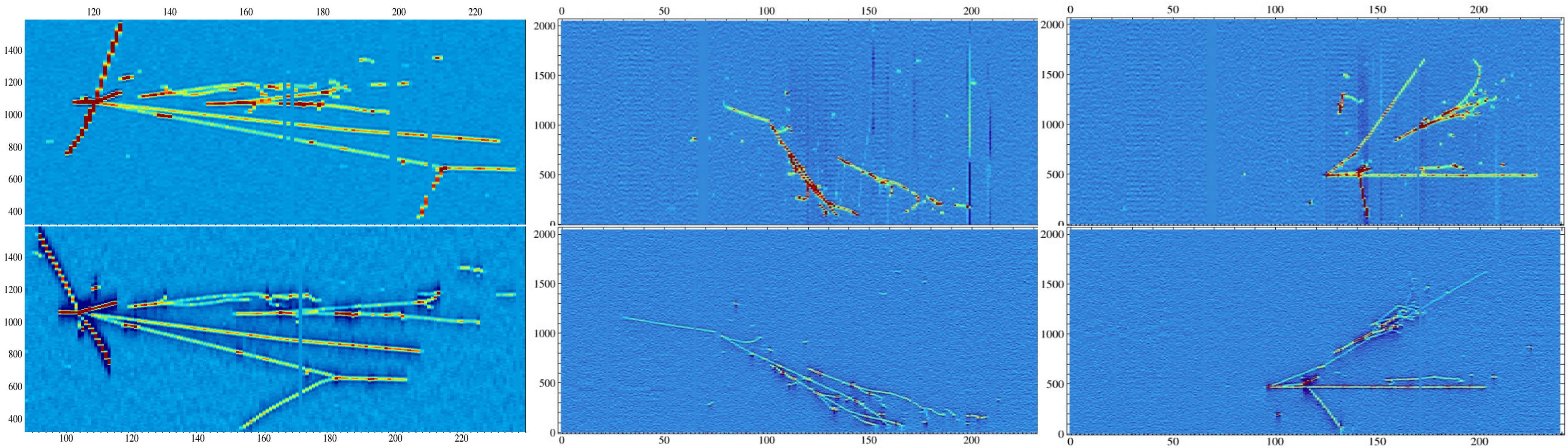


Important channel for oscillation searches and cross-section measurements.

→ Particularly insidious background for ν_e appearance searches

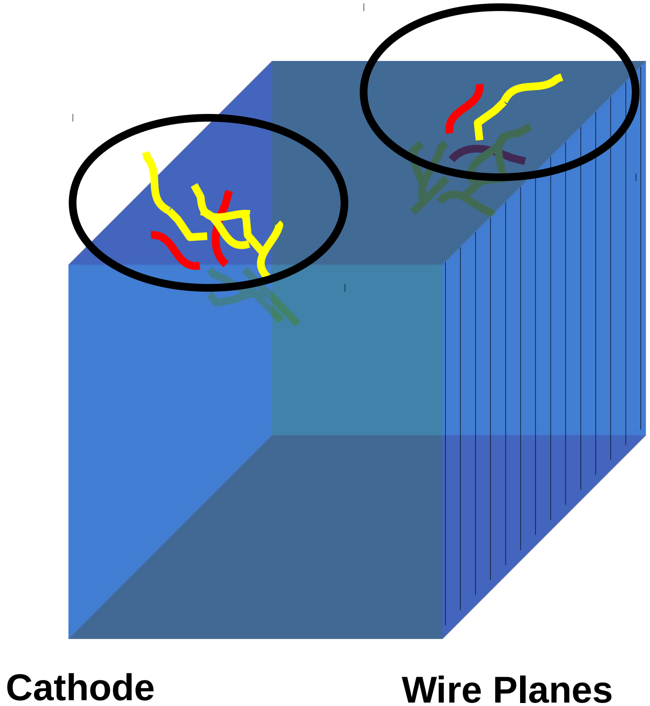
→ Despite the small volume and limited statistics in ArgoNeuT we want to begin to explore the capabilities of analyzing this channel in LAr

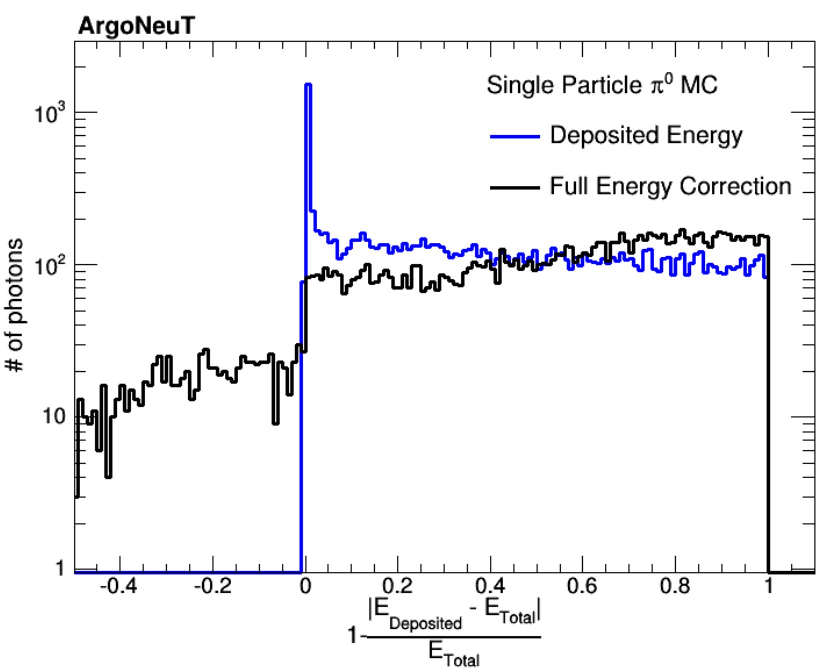
Neutral Current π^0



- **The process begins by selecting events that match the topology of having a $\pi^0 \rightarrow \gamma\gamma$ coming from a neutral current interaction**
  - ***No lepton (muon or electron)*** → **Neutral Current**
  - ***Two photons*** → $\pi^0 \rightarrow \gamma\gamma$
  - ***Reconstruct the photon showers*** → **Extract Physics!**

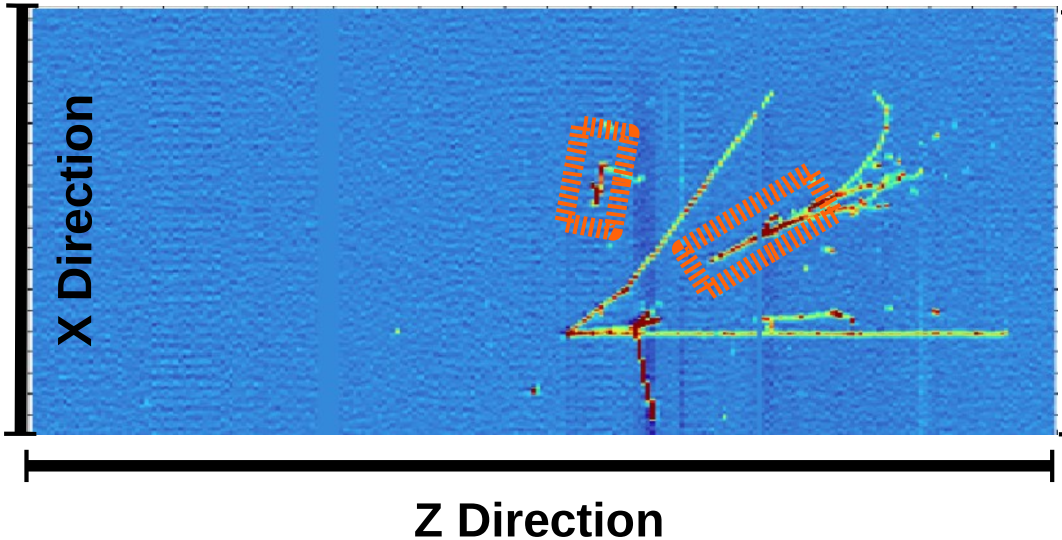
Neutral Current π^0

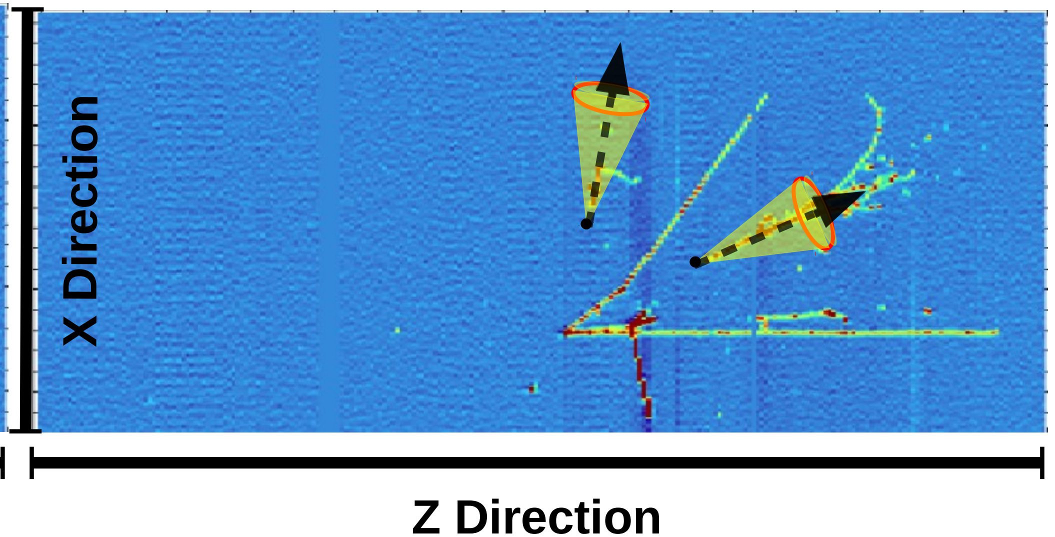




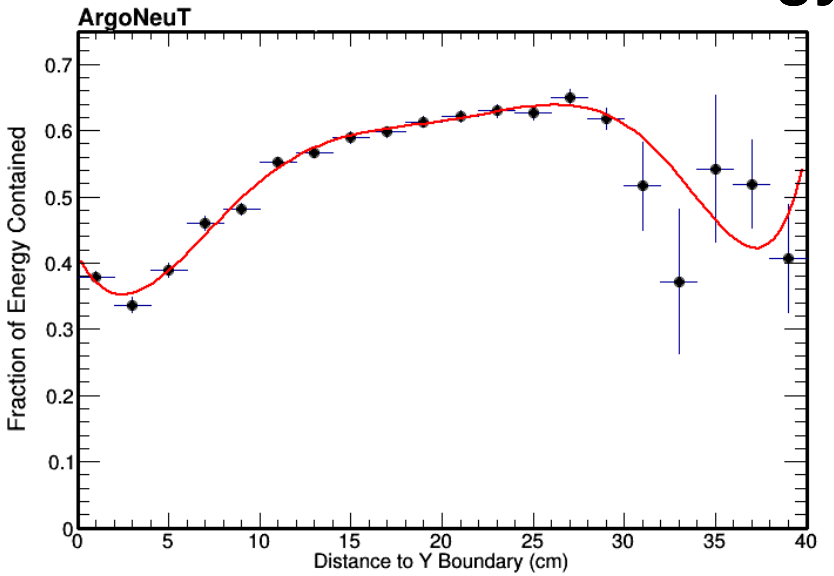
- Due to ArgoNeuT's small size the majority of the energy from the photons is not contained in the detector
- However, by utilizing the fine grain detection ability of LArTPC's we can correct back the missing energy from the photon showers

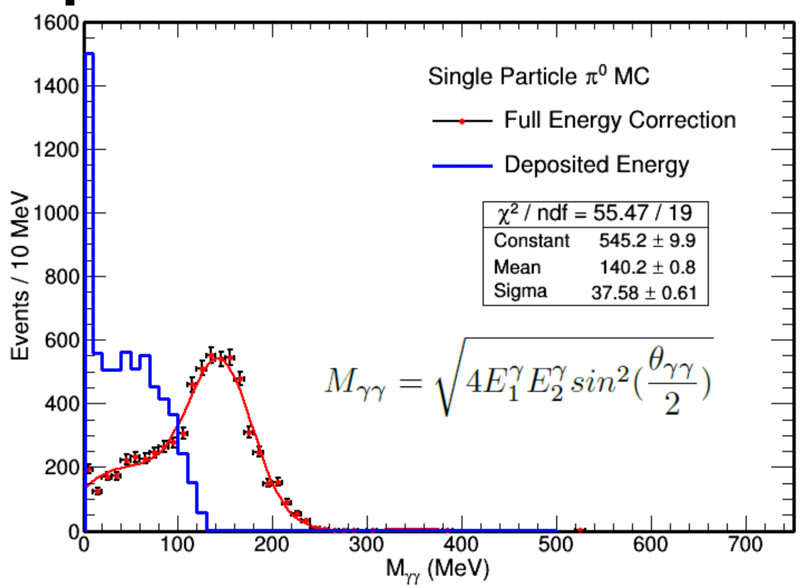
Neutral Current π^0



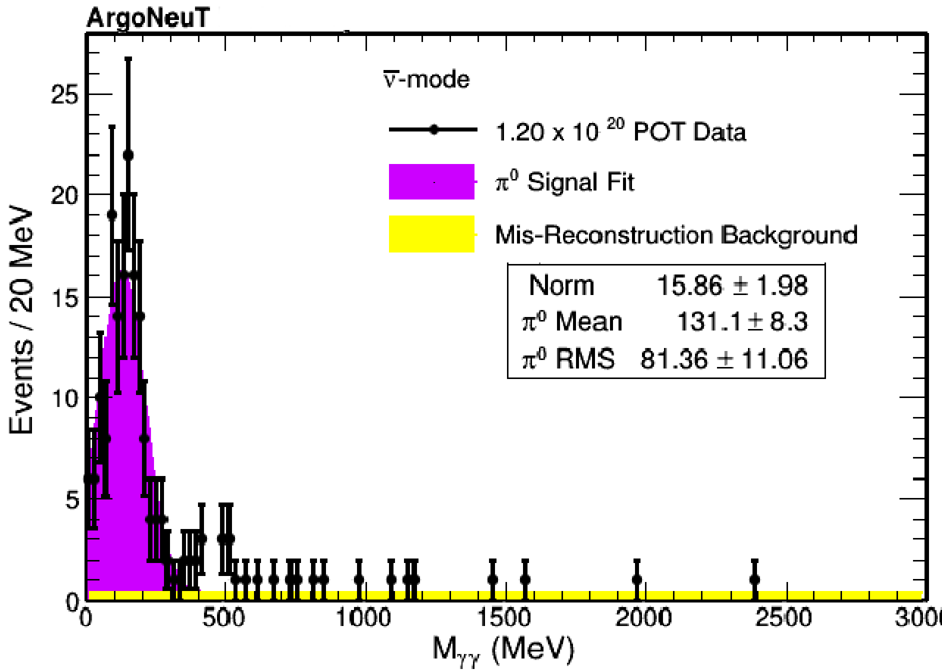


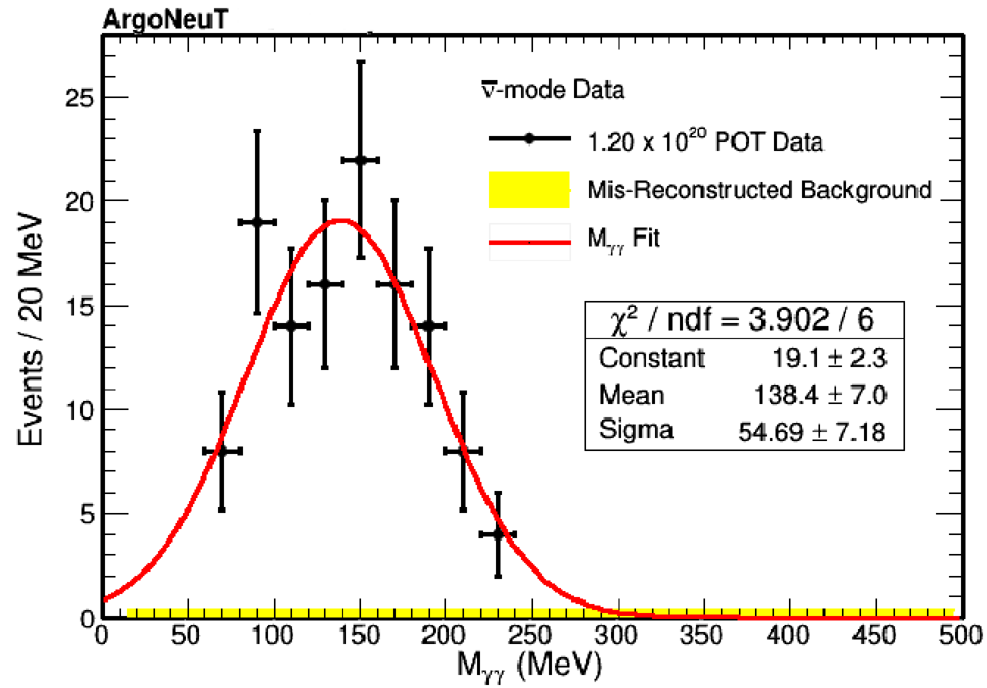
By finding the core of the shower and identifying the start point of the shower we can start to measure the 3-d shower parameters and apply template based energy corrections to correctly reconstruct the energy of the photon

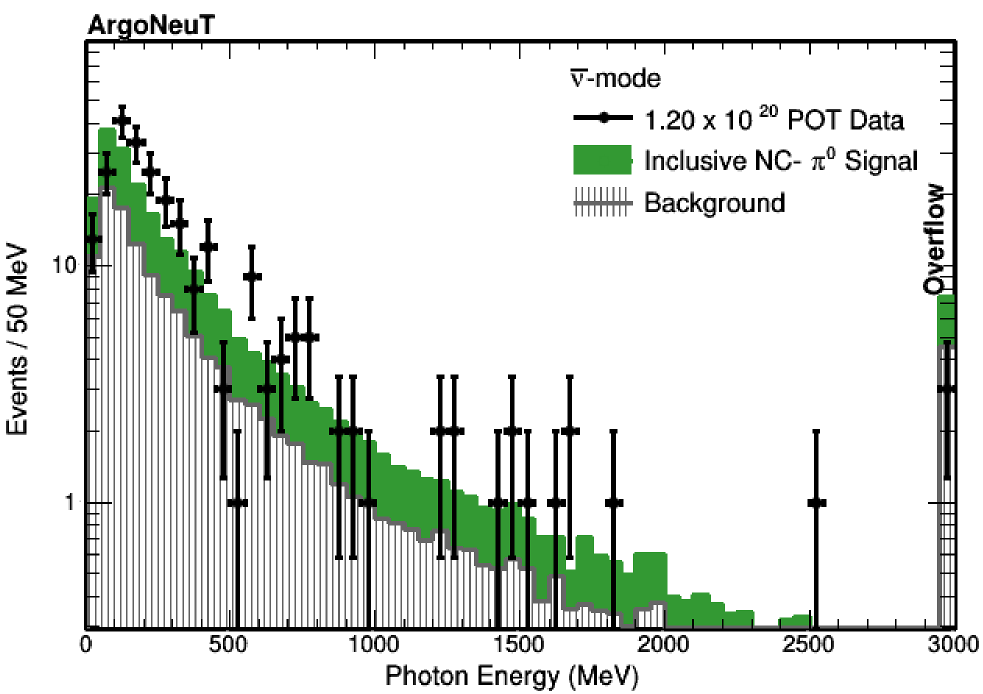


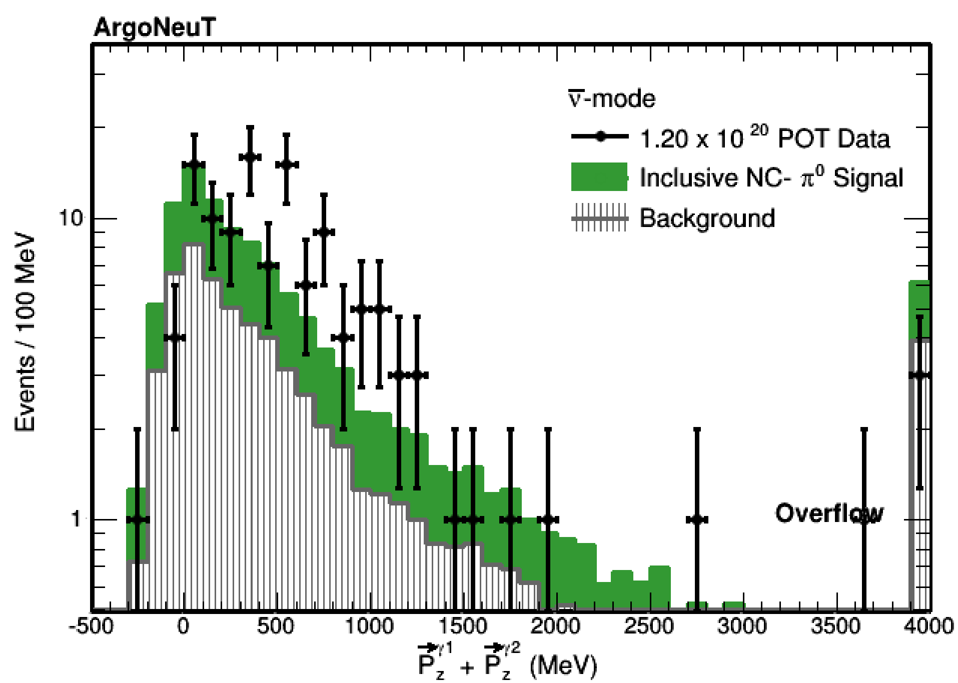


Measuring the photons from the π^0

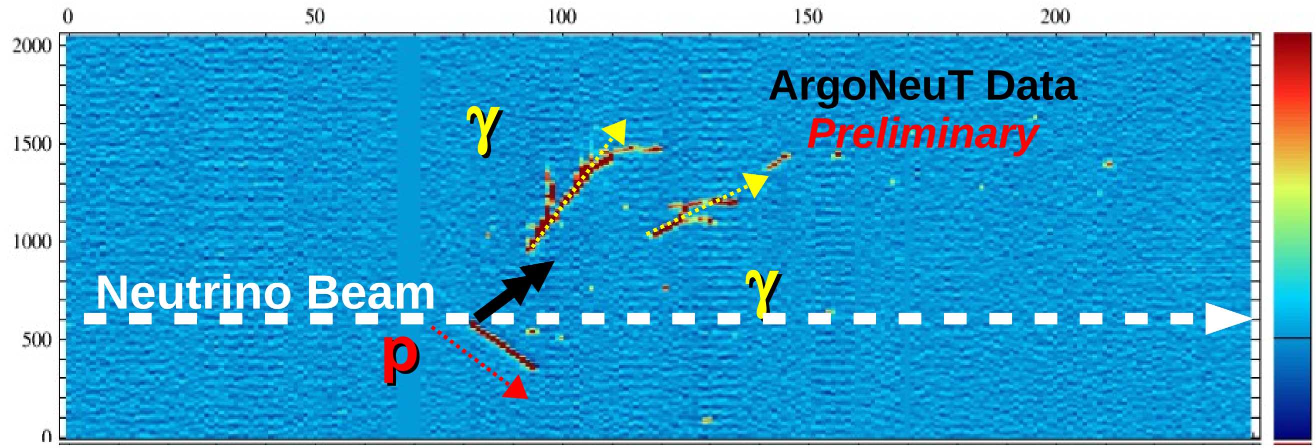




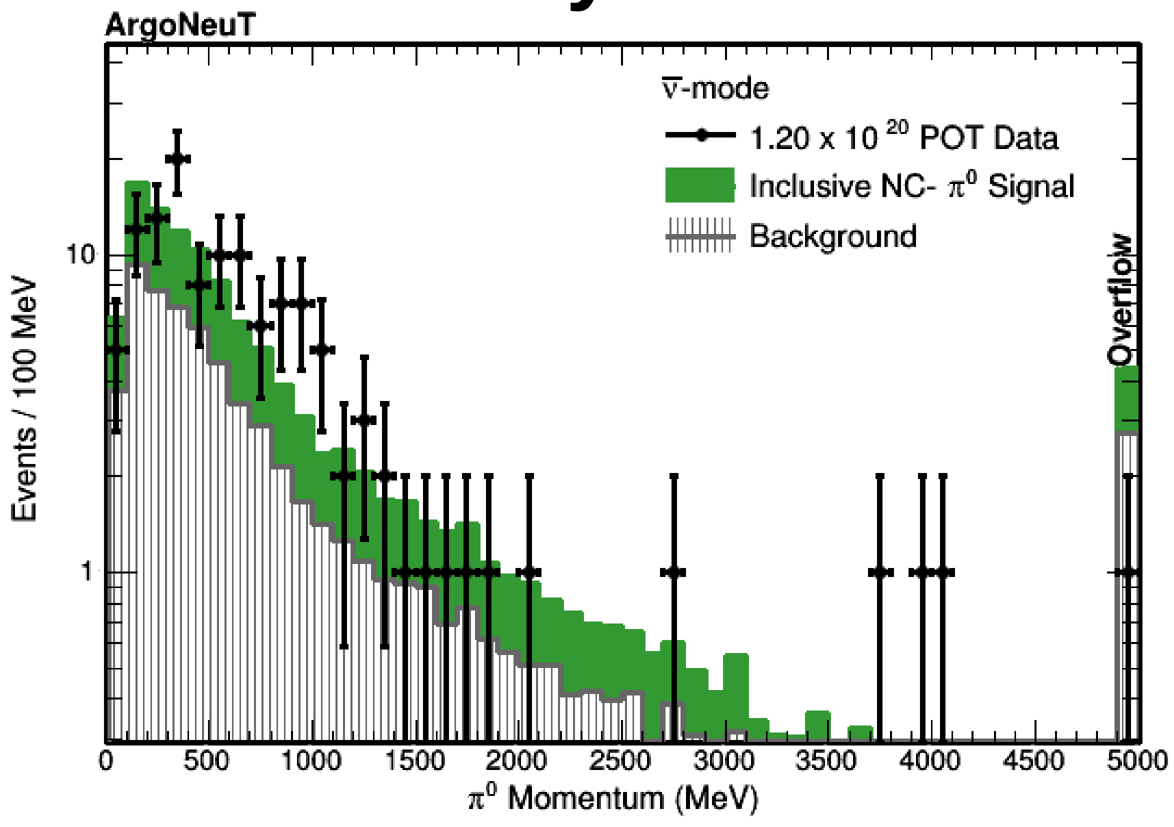




Neutral Current π^0

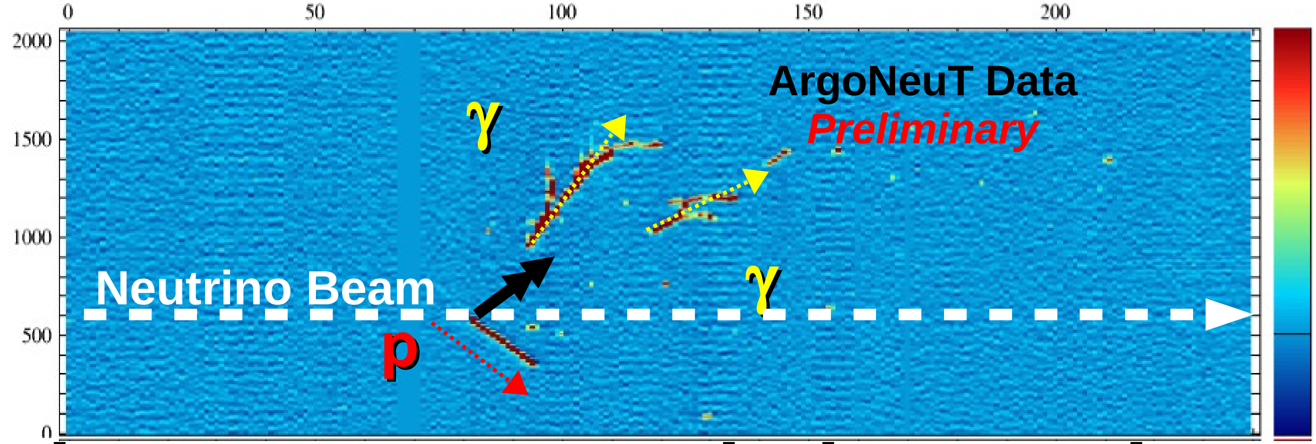


Utilizing the reconstructed photon showers you can now identify the momentum of the π^0

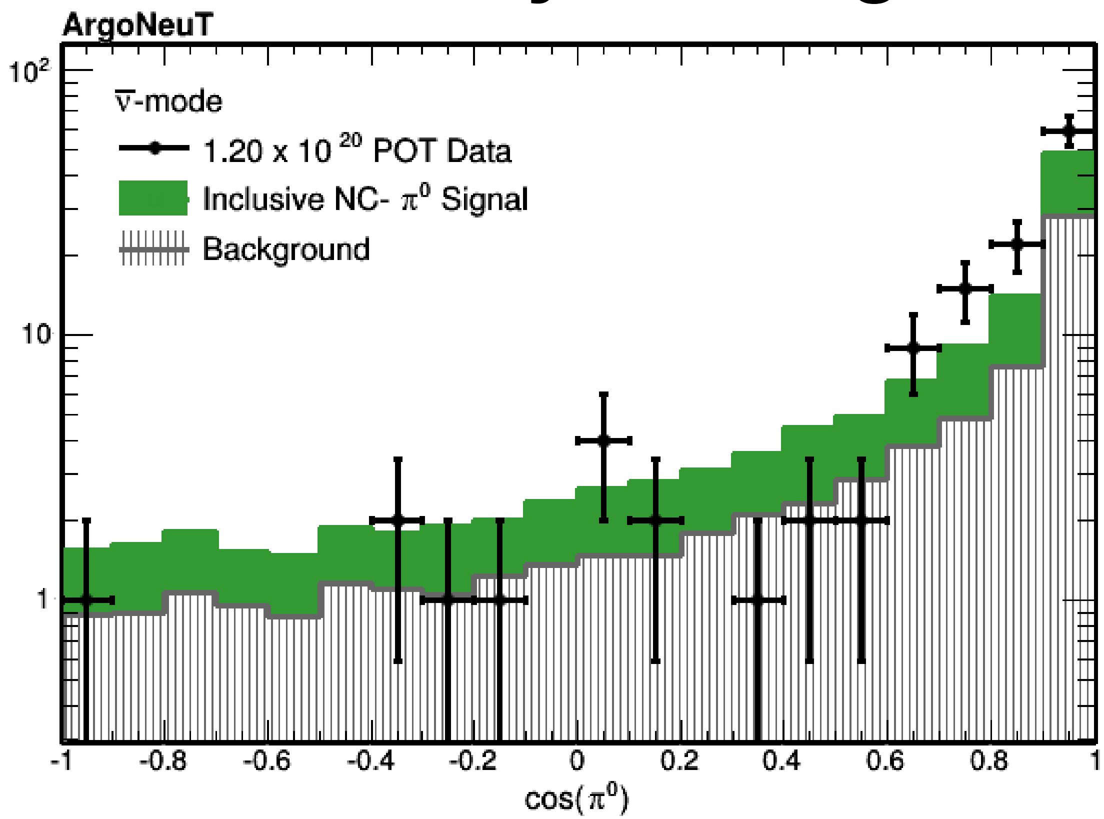


First time ever measured in ν–Ar interaction

Neutral Current π^0

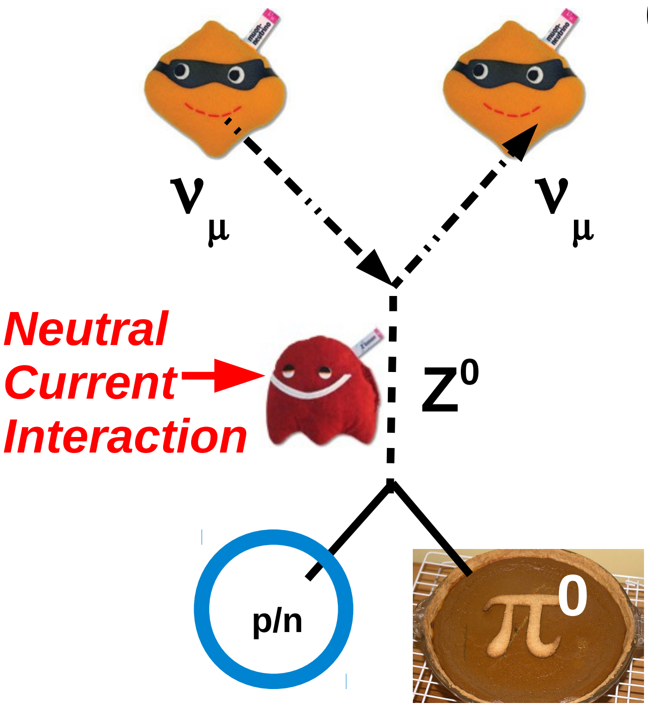


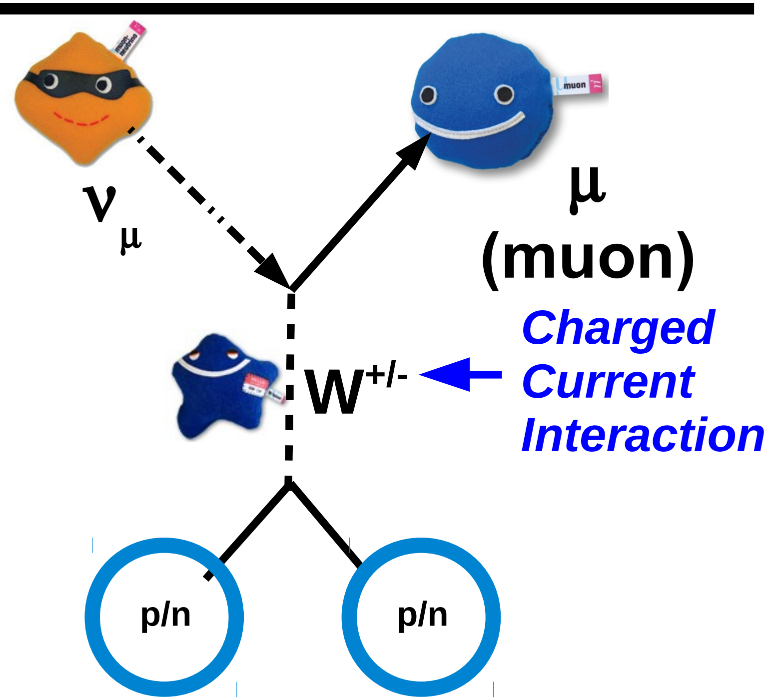
Utilizing the reconstructed photon showers you can now identify the angle of the π^0 w.r.t the beam

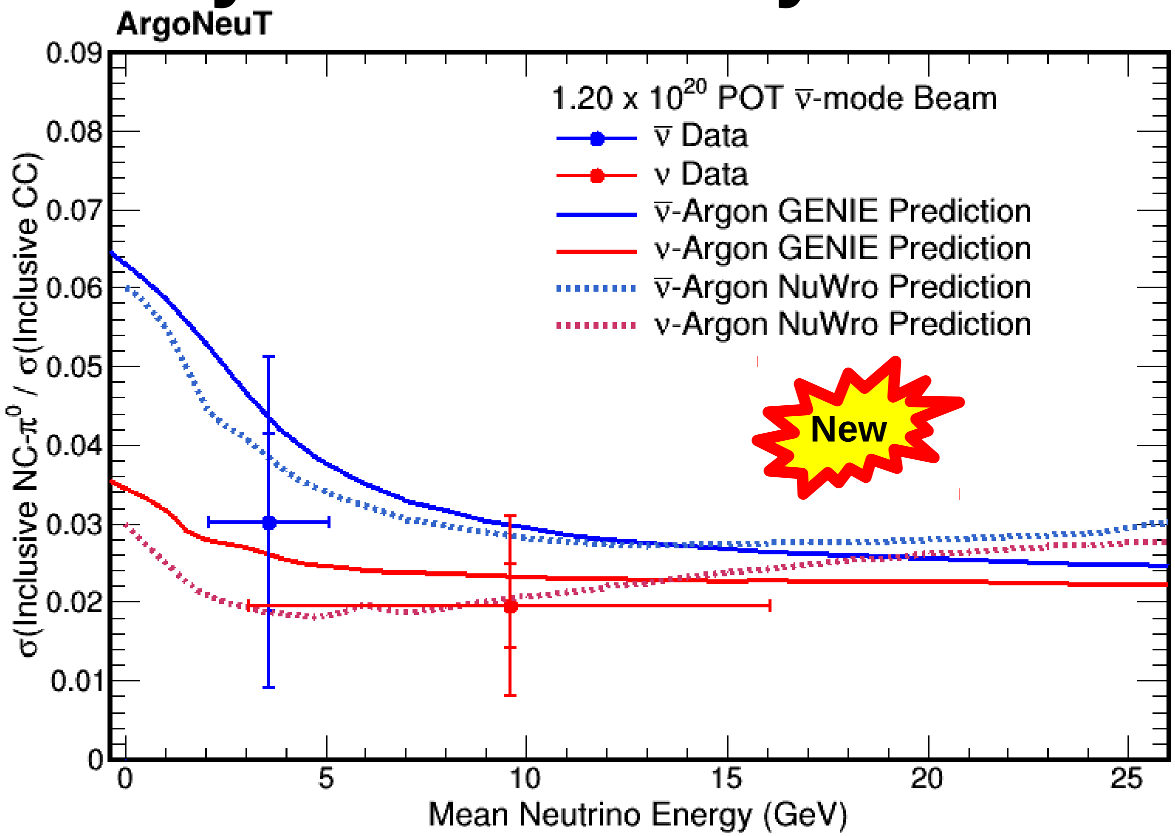


First time ever measured in ν–Ar interaction

Compare the production of neutral current π^0 to charged current as a way to test theory







Measurement of Inclusive Neutral Current π^0 Production in ArgoNeuT Detector

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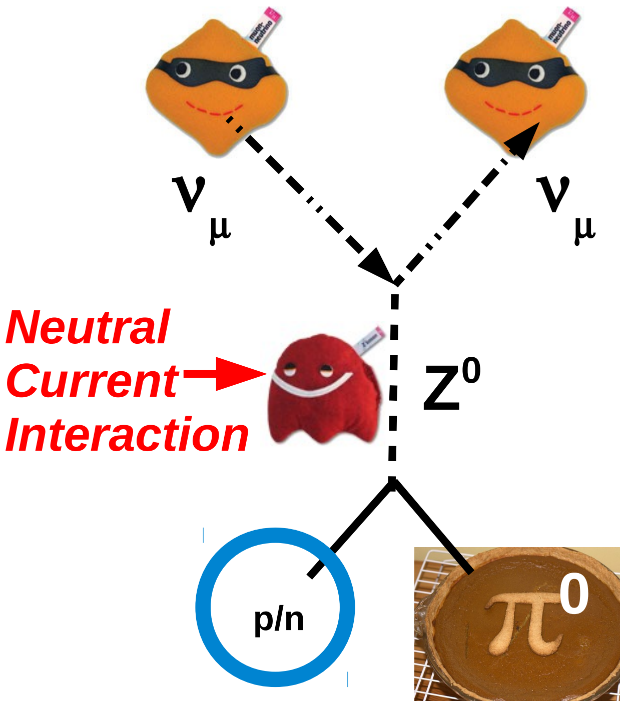
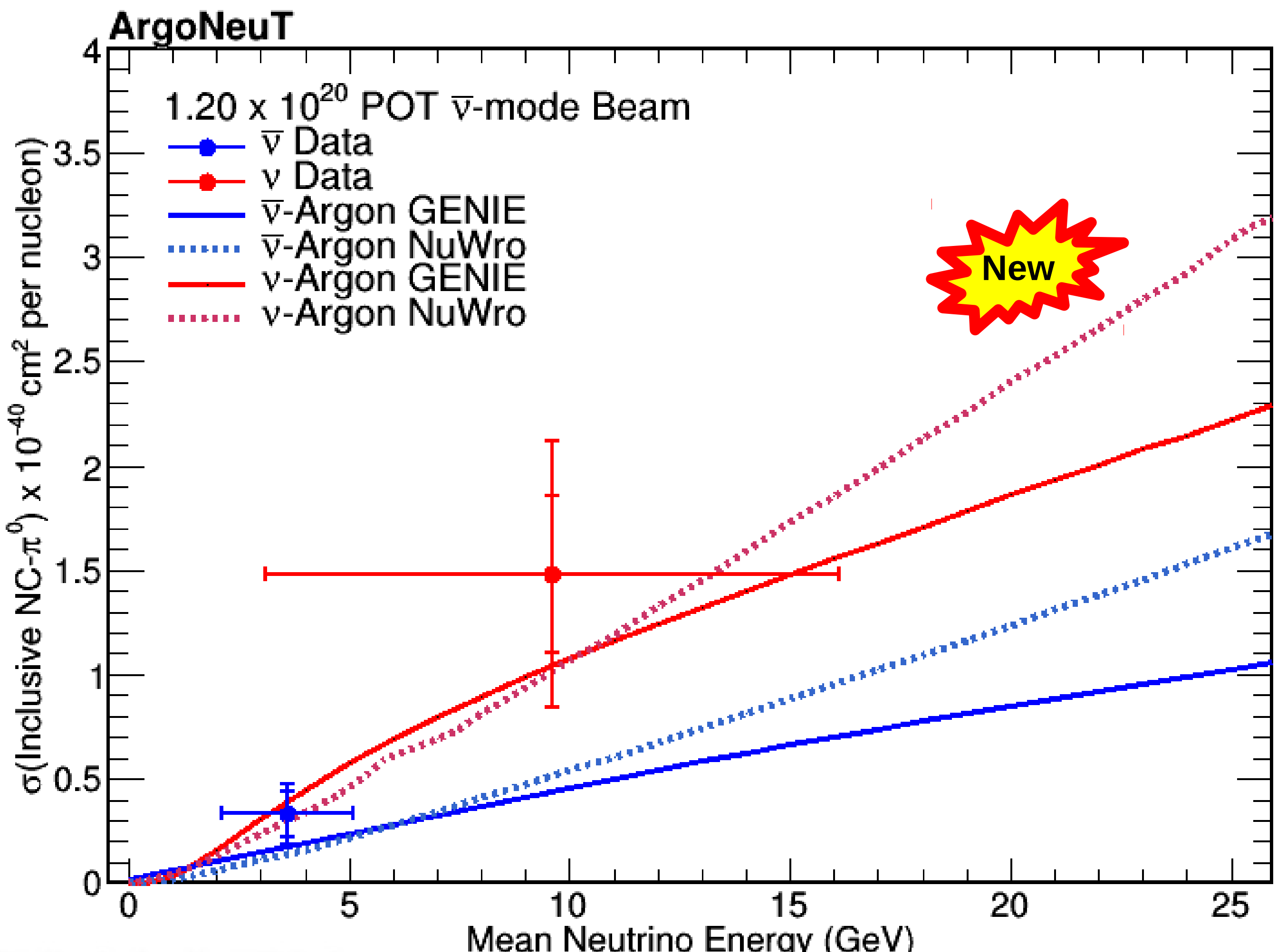
Paper under review

Compare the production cross-section of neutral current π^0 directly





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Conclusions

- **Understanding ν-nucleus scattering is important for both the extracting neutrino physics as well as understanding details of the nuclear scattering**
- **LArTPC's offer a powerful tool for extracting both!**
- **ArgoNeuT has pioneered a number of LArTPC results**
  - ν & $\bar{\nu}$ CCQE cross-sections
  - Coherent $\pi^{+/-}$ production cross-section
  - **CC0π cross-section**
  - **NC π^0 cross-section**
  - **Hints at short range correlation**

Spoke about today

- **Future LArTPC experiments (MicroBooNE, SBND, DUNE) will expand on these studies**

Thank you for your attention