Proton Reconstruction and Measurements in LArTPCs

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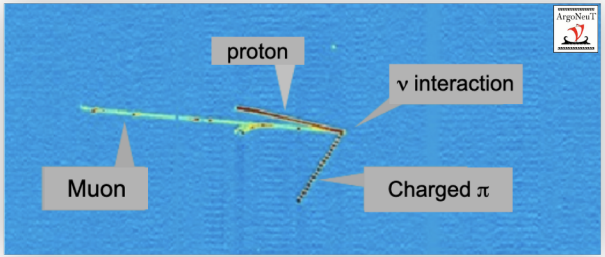
Outline

- How does a LArTPC identify/measure protons?
- The ArgoNeuT experience - pushing the limits
- The MicroBooNE experience - automation
- The Future: lowering thresholds for SBN

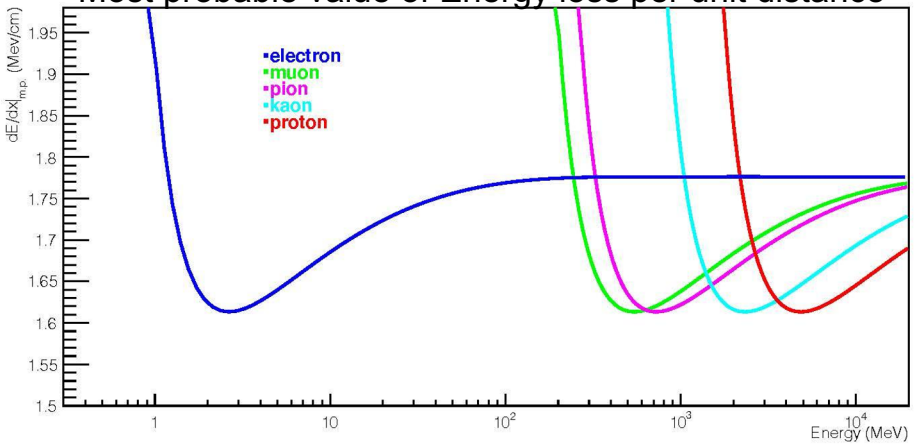
Particle Identification in LAr TPCs

Information left by the particles passing through the LAr TPC is used to perform Particle Identification

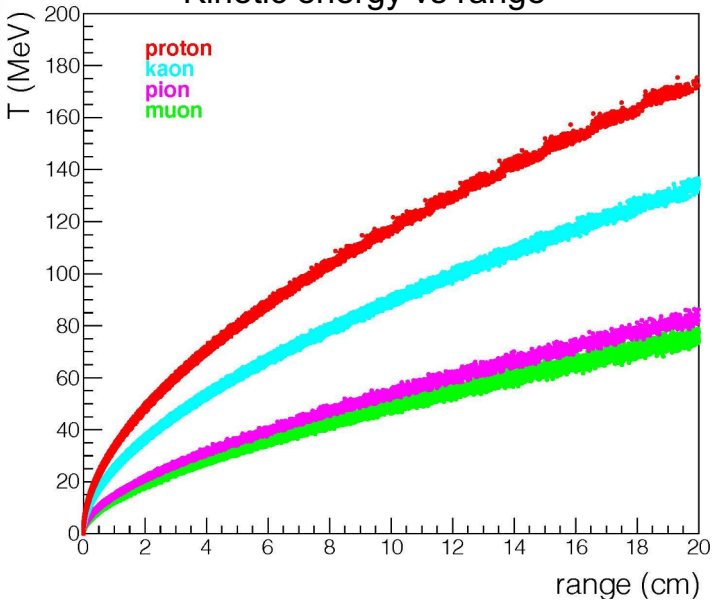
m.i.p.
highly ionizing



Most probable value of Energy loss per unit distance

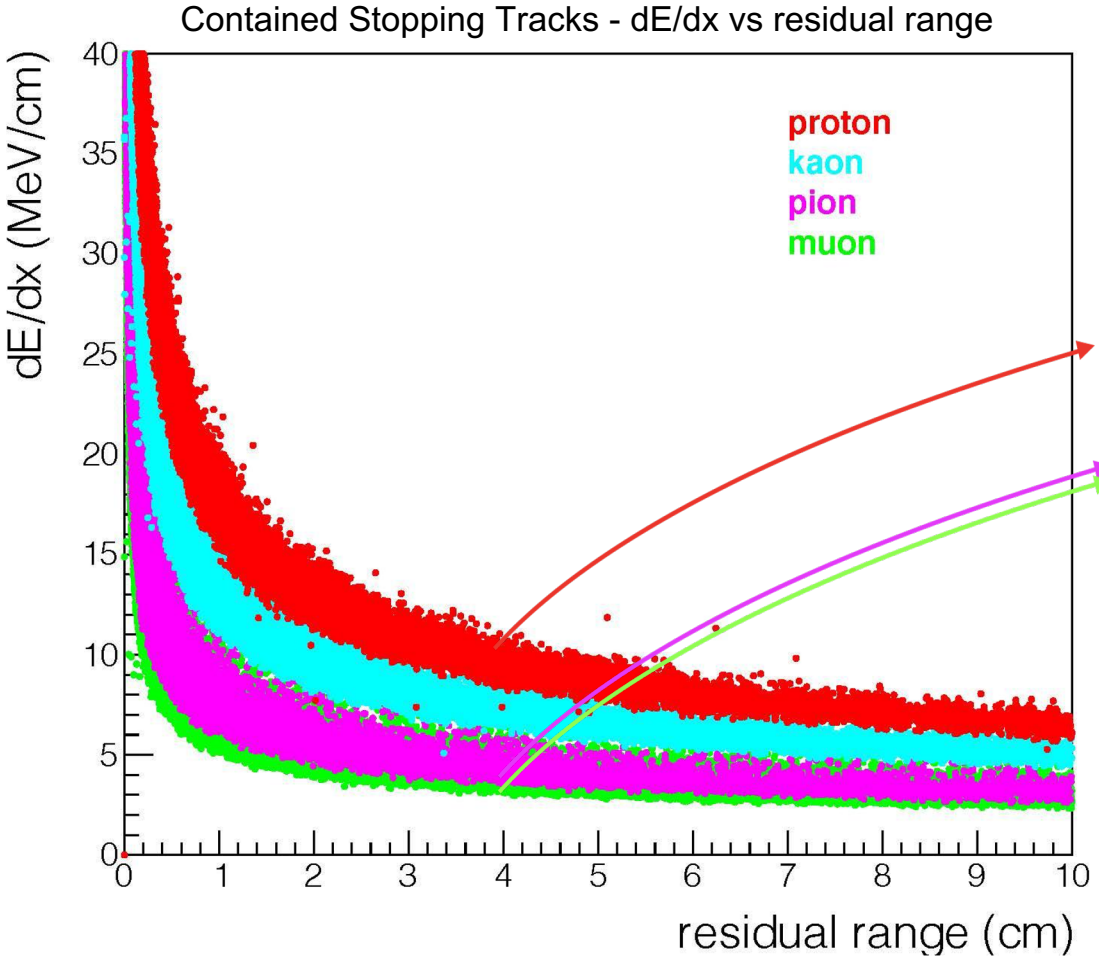


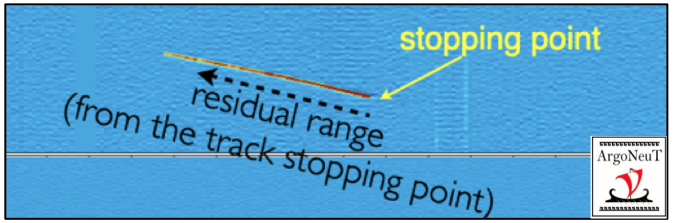
Kinetic energy vs range



Protons (highly ionizing) deposit a lot of energy in a few cm!

Particle Identification in LAr TPCs

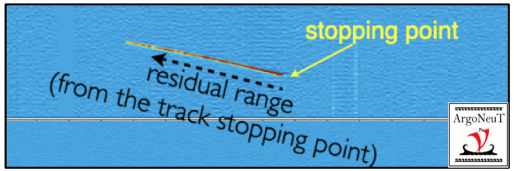


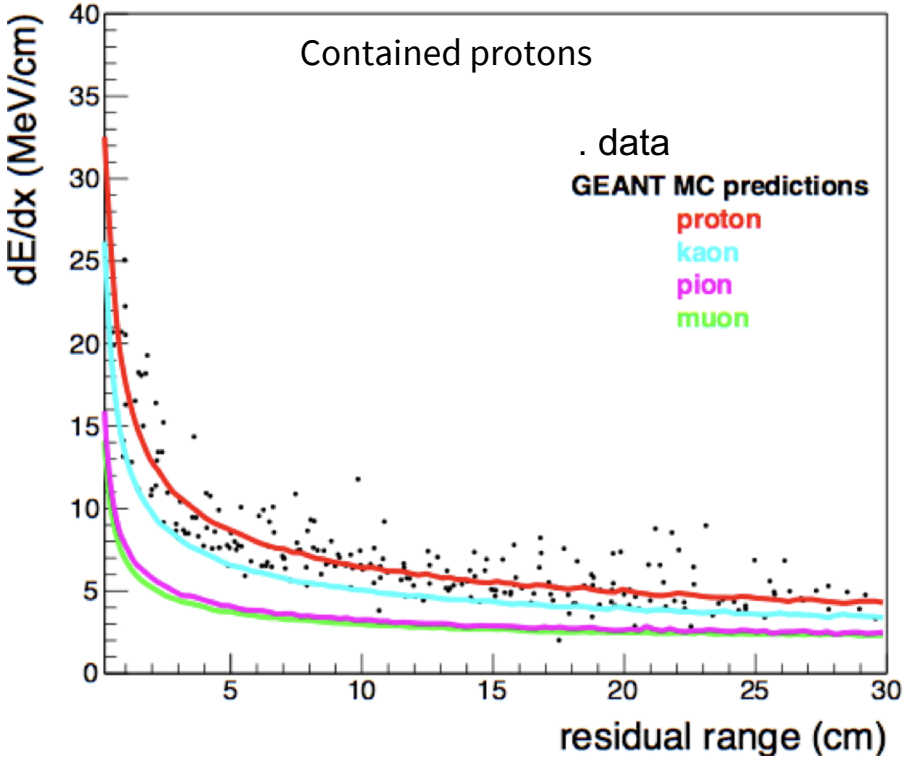


Large
proton
vs
pion/muon
separation

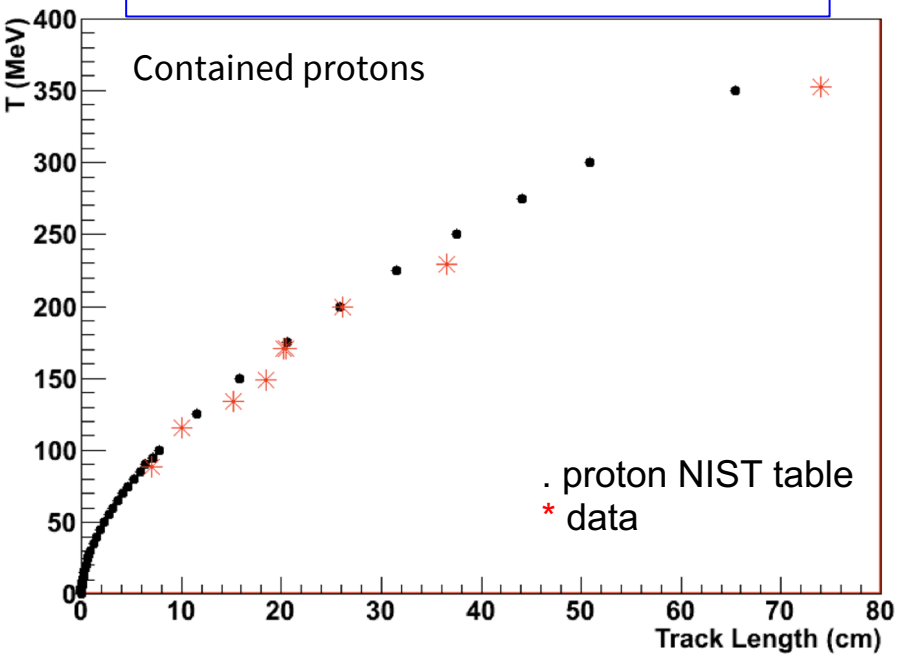
Proton Id and Calorimetric Reconstruction in LAr TPCs

"Traditional" method for PId:
Reconstructed dE/dx for each individual 3D hit
as a function of distance from the end of the track





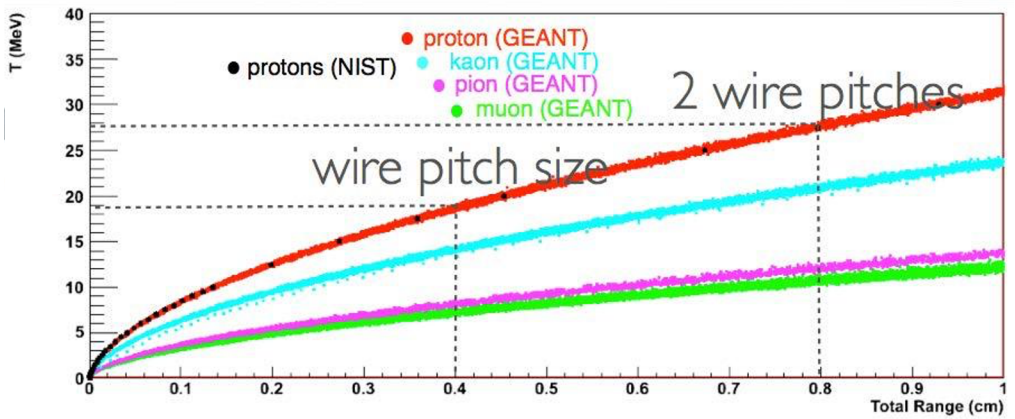
Total charge—>Deposited energy



Proton Id and Reconstruction - the ArgoNeuT Case

ArgoneuT LAr TPC

[0.24 t active volume - 5 months of data taking on NuMI, in front of the Minos-ND (spectrometer)]

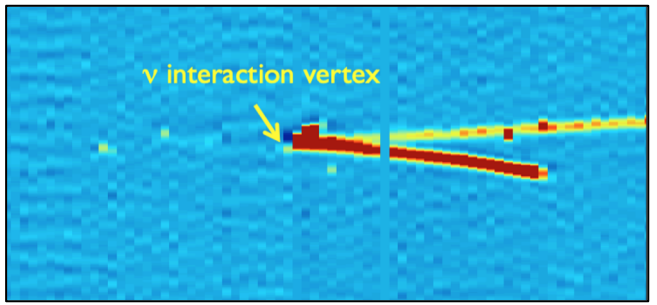


0.4 cm —> 18 MeV proton
8 MeV pion
0.8 cm —> 27 MeV proton
12 MeV pion

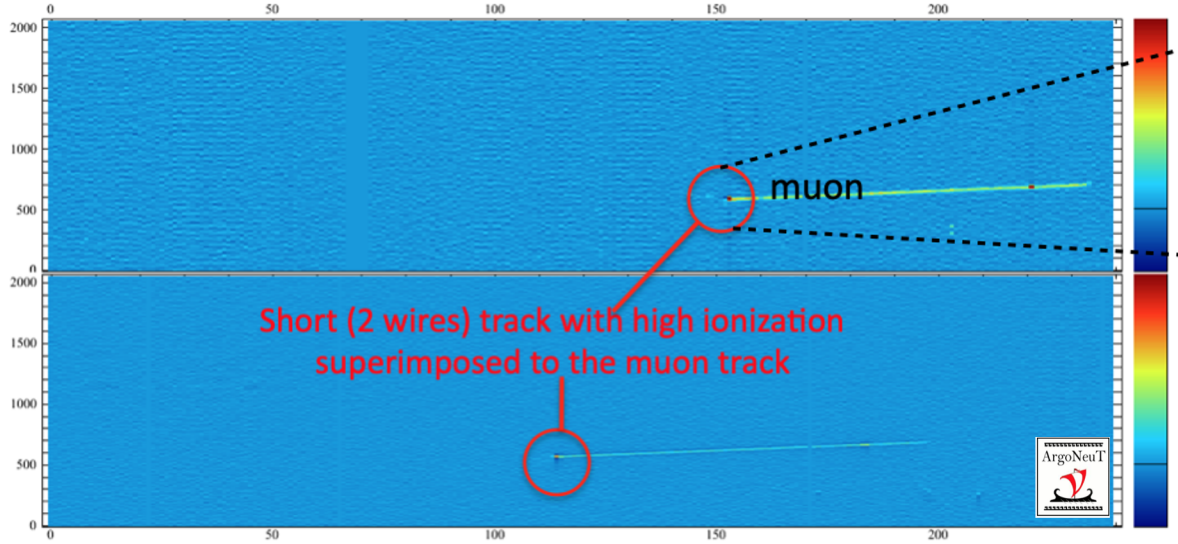
PId is the last step of event reconstruction. How well it works depends on the previous steps.

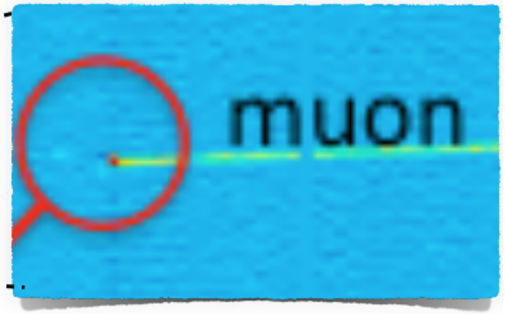
Accurate vertex reconstruction is crucial

Neutrino interaction vertex precisely identified via **"human assisted" vertex finding** for the analysis of ~ 700 muon (anti-)neutrino Charged Current 0-pion events



Proton Threshold - the ArgoNeuT Case





Length=0.5 cm

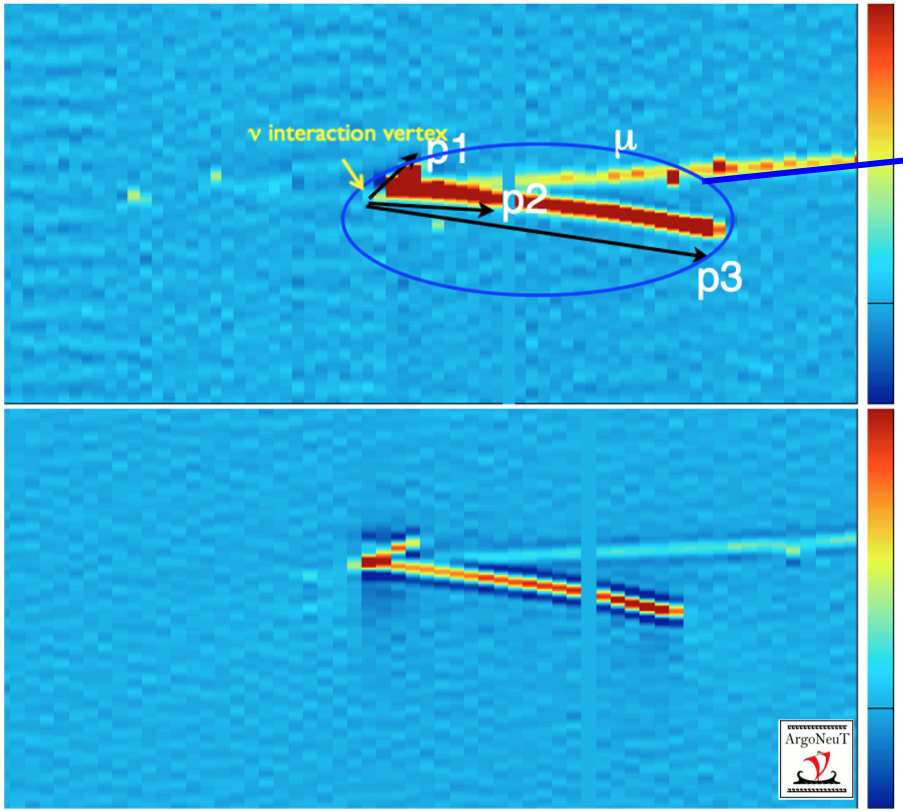
T_p=22±3 MeV

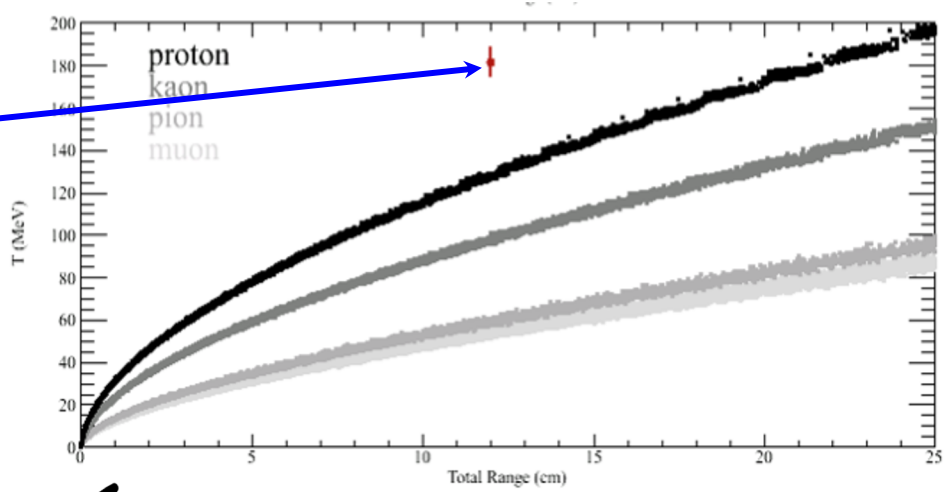
ArgoNeuT proton threshold: 21 MeV Kinetic Energy

Signal on 2 wires

ArgoNeuT - Proton Counting

muon + 2 or 3 protons?



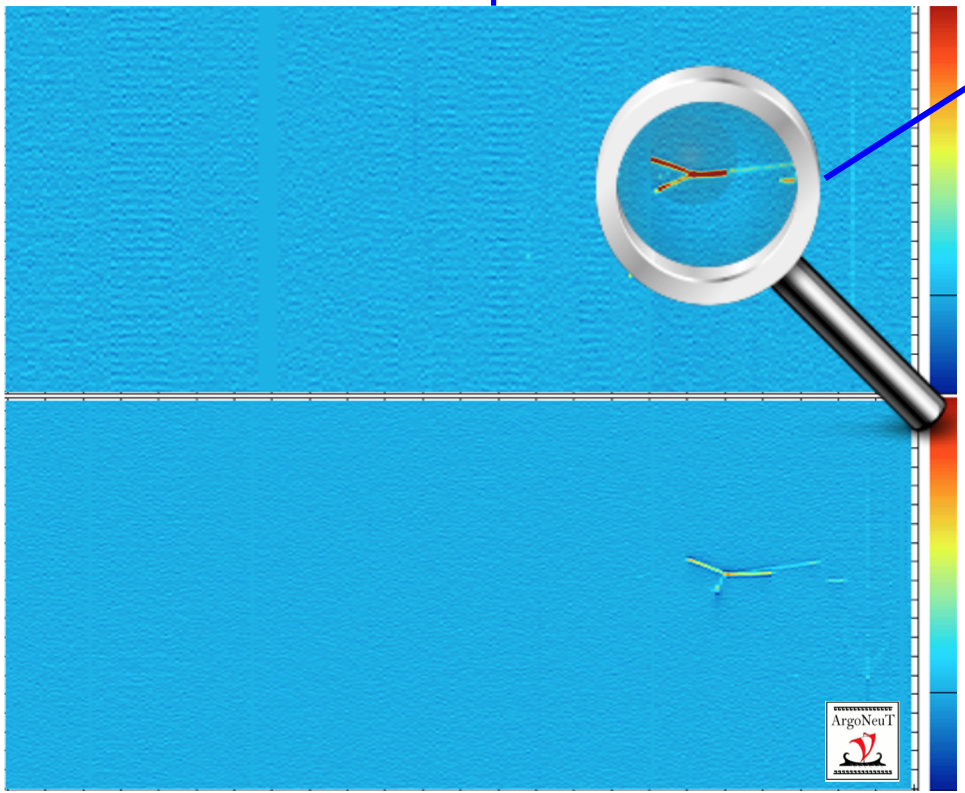


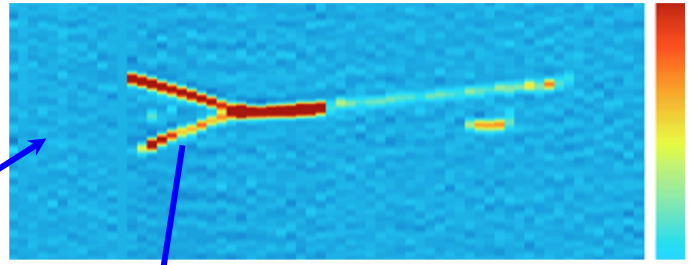
muon + 3 protons!

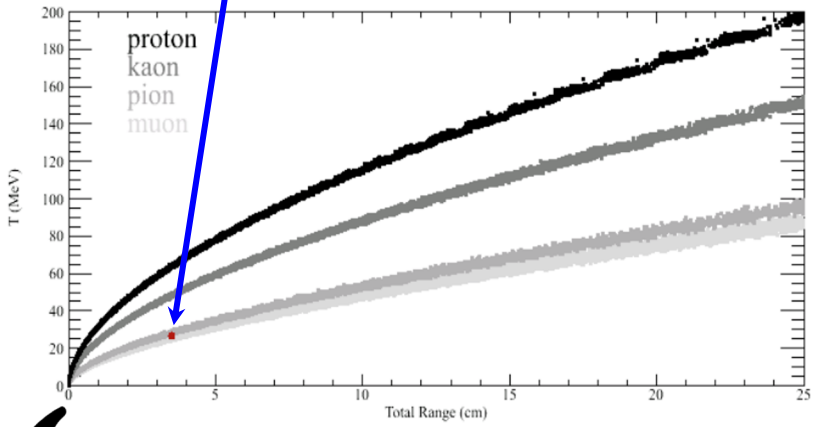
p1: 1.7 cm ----> T=42±4 MeV
p2: 3.6 cm ----> T=64±5 MeV
p3: 11.9 cm ----> T=126±7 MeV

ArgoNeuT - p/π± separation

muon + 3 protons?



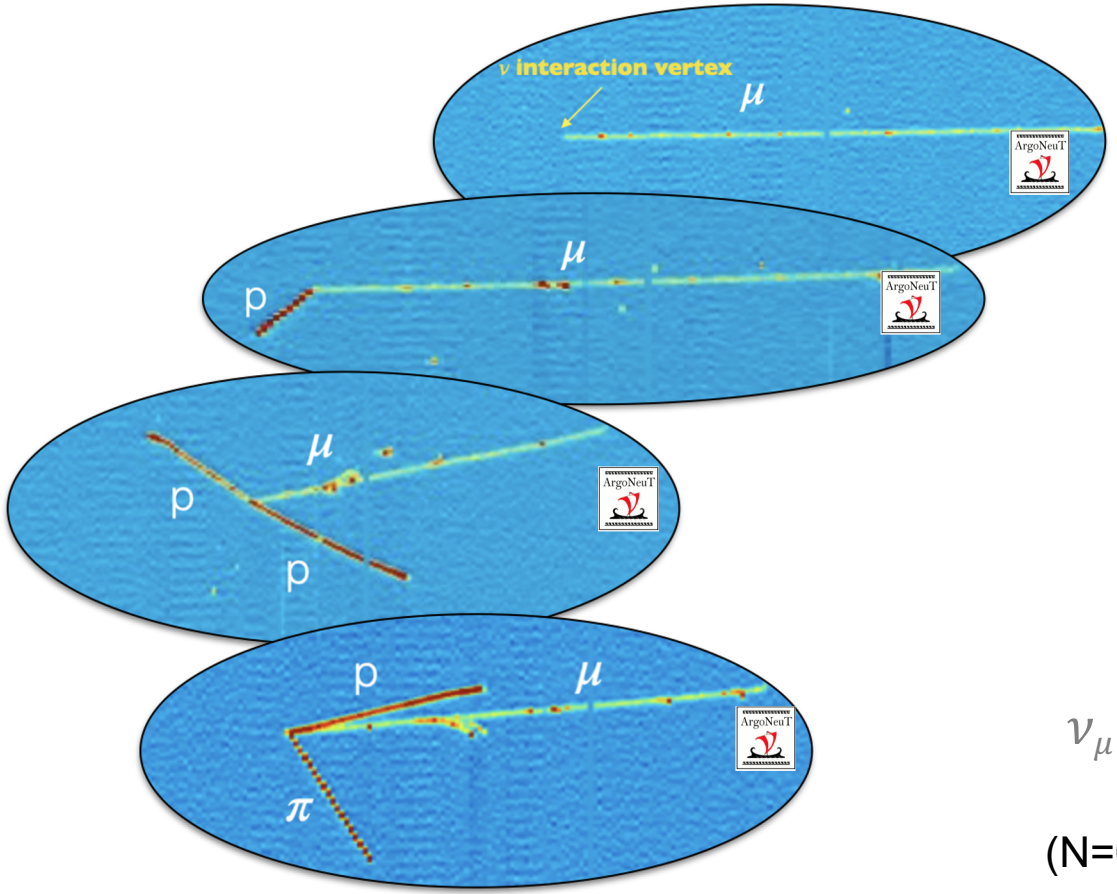




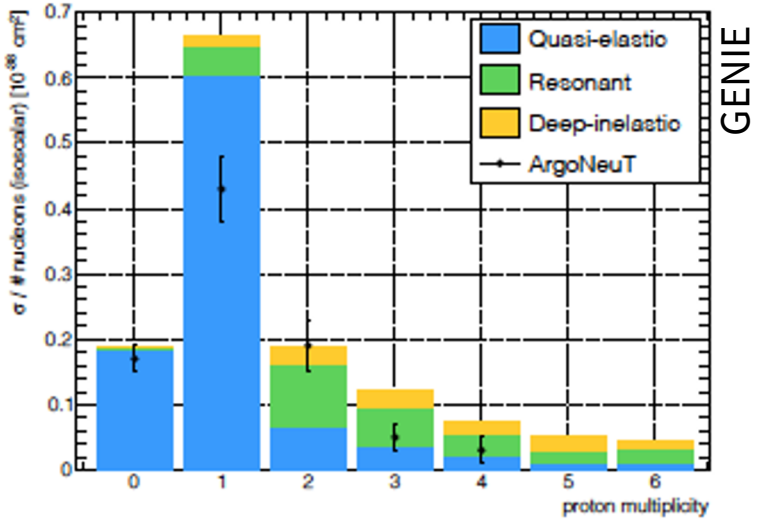
muon + 2 protons + 1 pion!

p1: 4.9 cm ----> T=83±5 MeV
p2: 5 cm ----> T=134±7 MeV
π: 3.5 cm ----> T=26±3 MeV

ArgoNeuT - Particle content and Kinematics



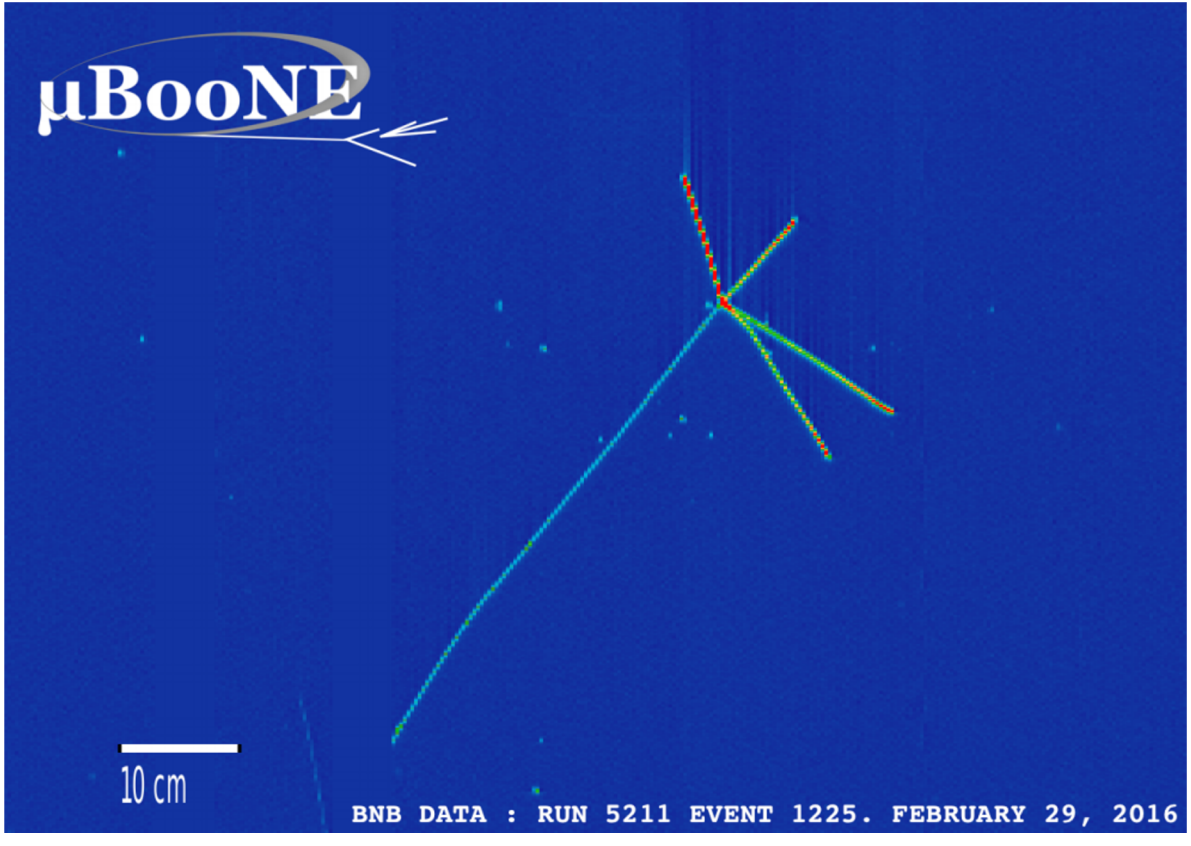
ArgoNeuT, JPS 12, 010017 (2016)



ν_μ Charged Current 0-pion events

Exclusive cross sections
(N=0,1, 2, 3, 4 protons, with 21 MeV kinetic energy threshold)

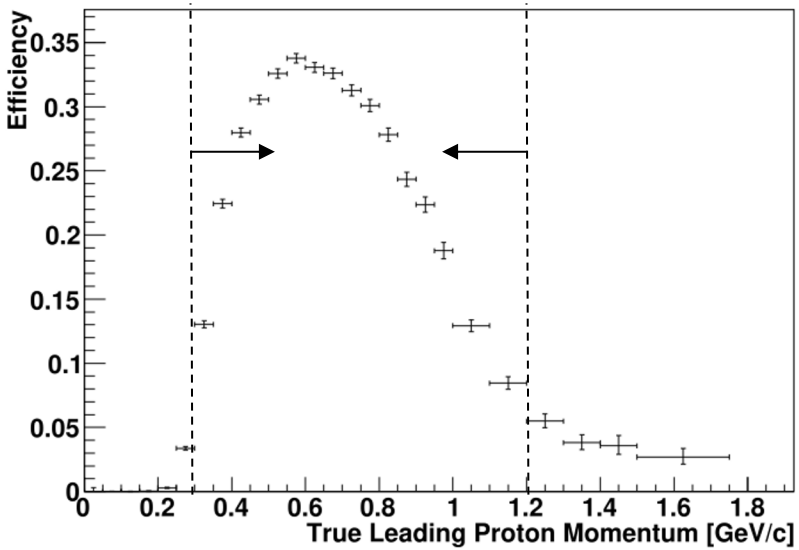
The MicroBooNE Experience - full automation



Phys. Rev. D102, 112013

MicroBooNE experience - automated reconstruction

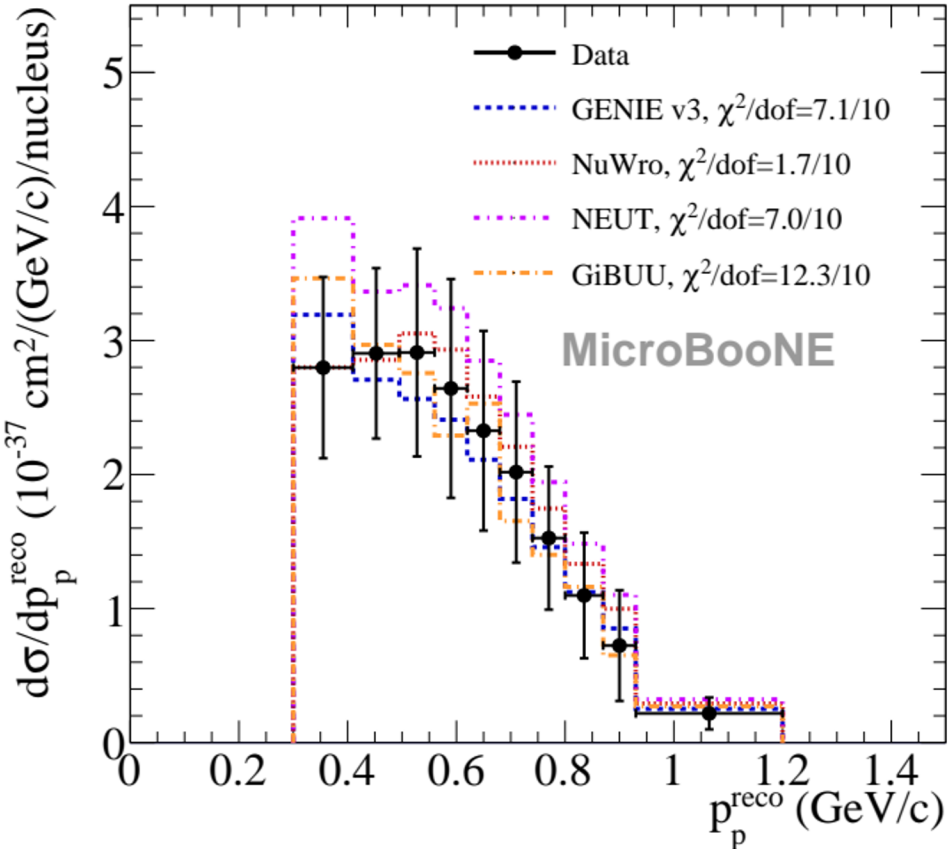
- Upper limit ~1.2 GeV/c momentum (~600 MeV KE)
  - Proton inelastic scatters start to dominate
- Lower limit 250-300 MeV/c momentum (approx. 35-50 MeV KE)
  - As threshold goes down, resolution gets worse
  - Angular dependencies (struggle with colinear tracks)



Phys. Rev. D102, 112013

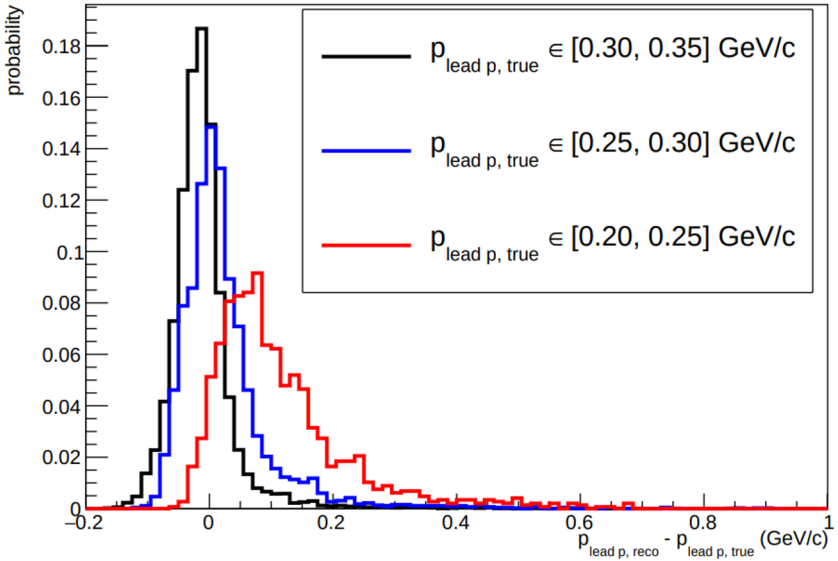
CC1p / CCNp with MicroBooNE

- Lower threshold opens new phase space not previously measurable
- First analysis had threshold of 300 MeV/c (~50 MeV KE)
- Limit: Needed **5 hits on one plane** (1.5 cm) for particle ID



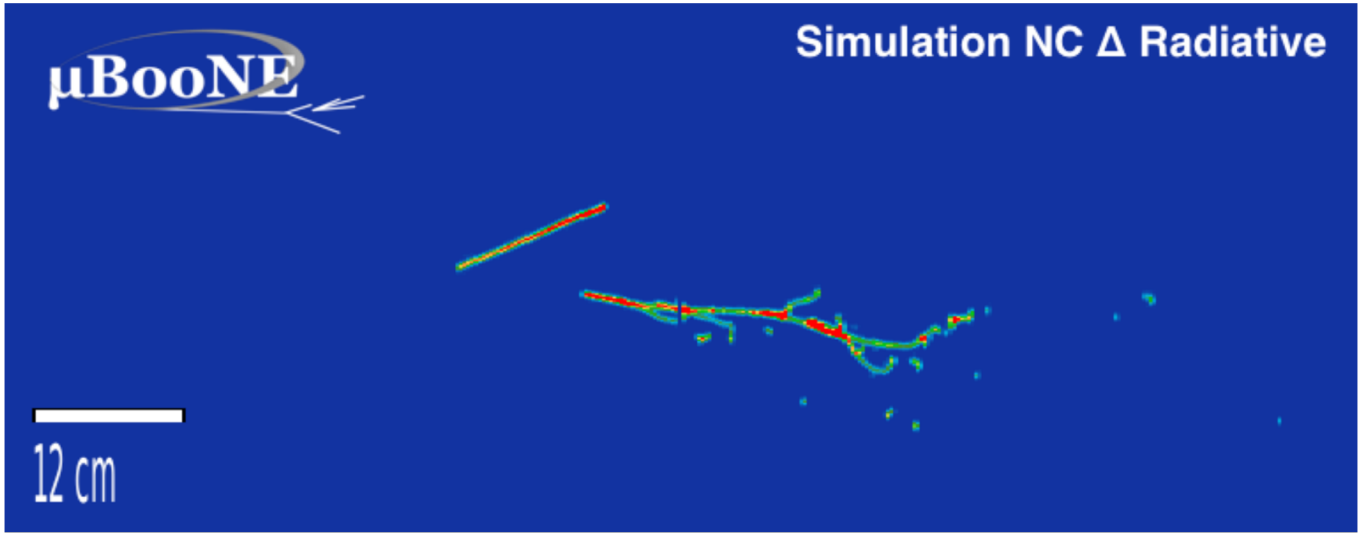
Pushing lower

- Using three planes for PID, threshold dropped
- Now limited by resolution
- 250 MeV/c momentum (35 MeV KE)
- Can tag protons down to 200 MeV/c (21 MeV), but momentum estimate highly biased
    - ArgoNeuT used human-assisted vertex finding to achieve the needed resolution



Separated protons

- Example: NC single photon analysis
  - Considers both with-proton and without-proton
  - Proton threshold ~50MeV (more challenging than CC as no vertex to tag)



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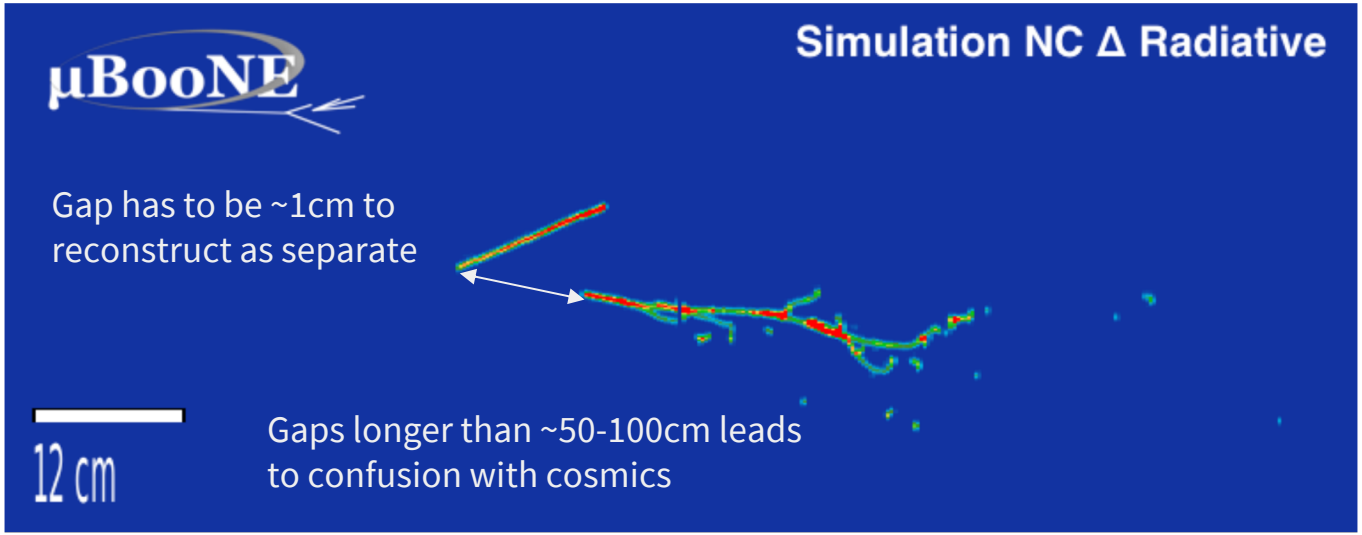
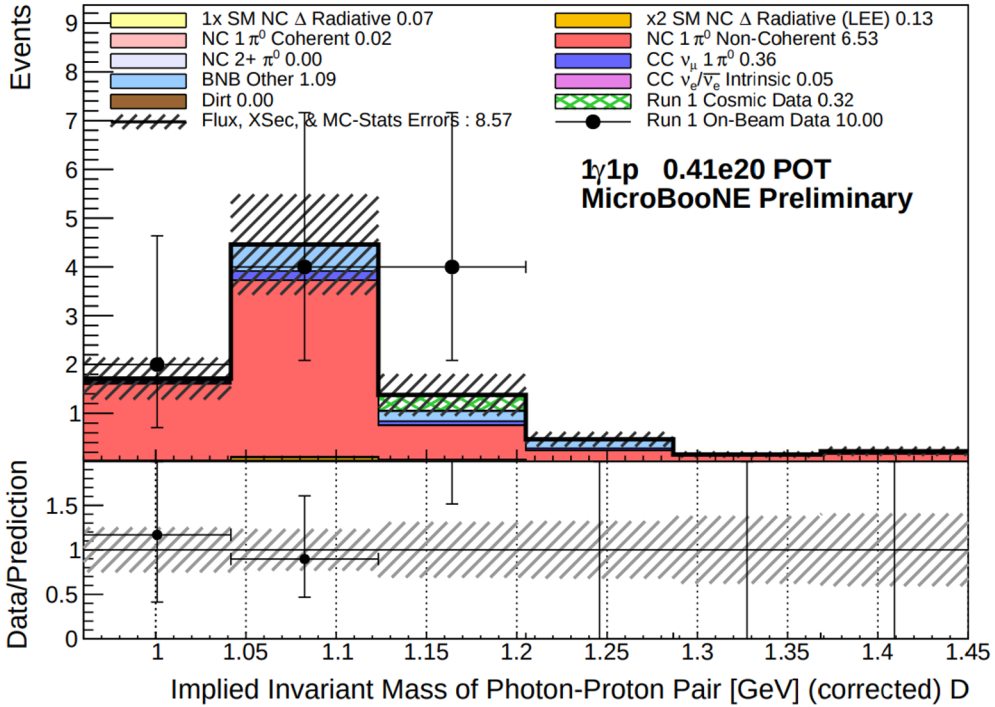
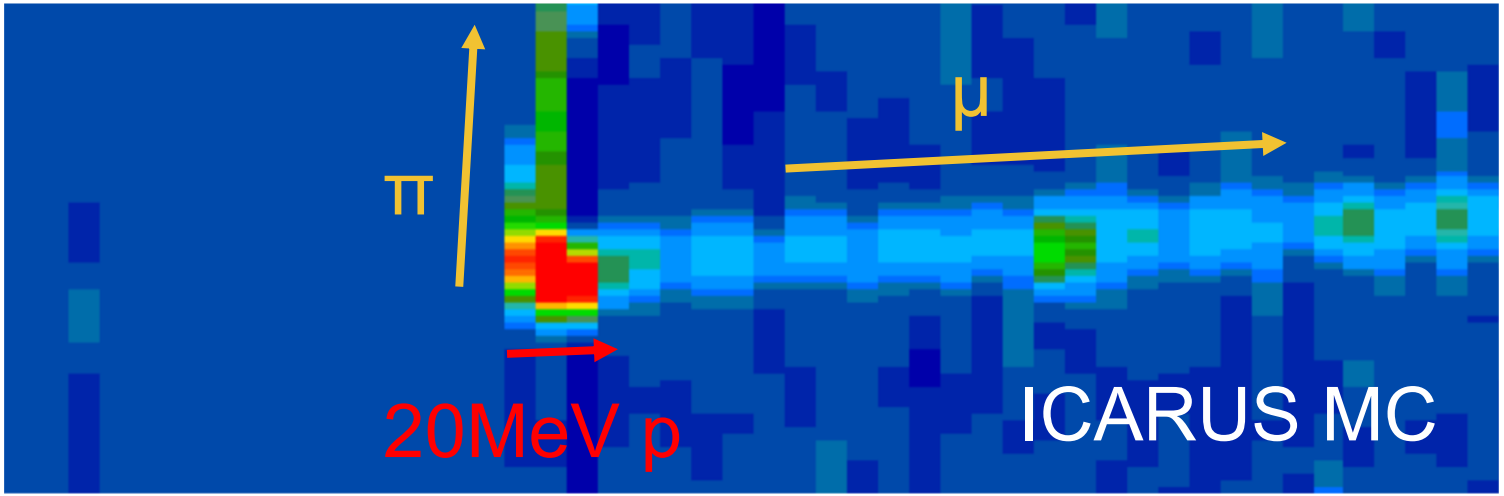


Measuring the proton

- Threshold given by need for proton to make a “track”
- I.e. must cross multiple wires
- 3D tracking gives energy and direction
- Can use to infer physics!
  - I.e. proton-photon invariant mass

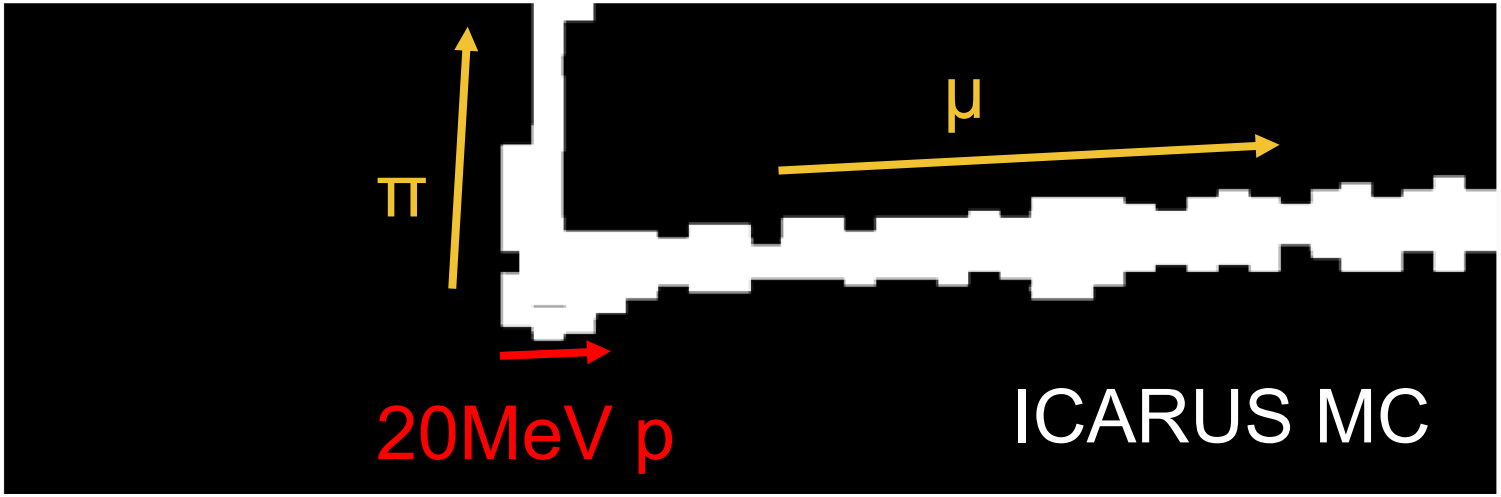


Improving Automated Reconstruction at Low Energy



A proton missed by existing reconstruction

Improving Automated Reconstruction at Low Energy



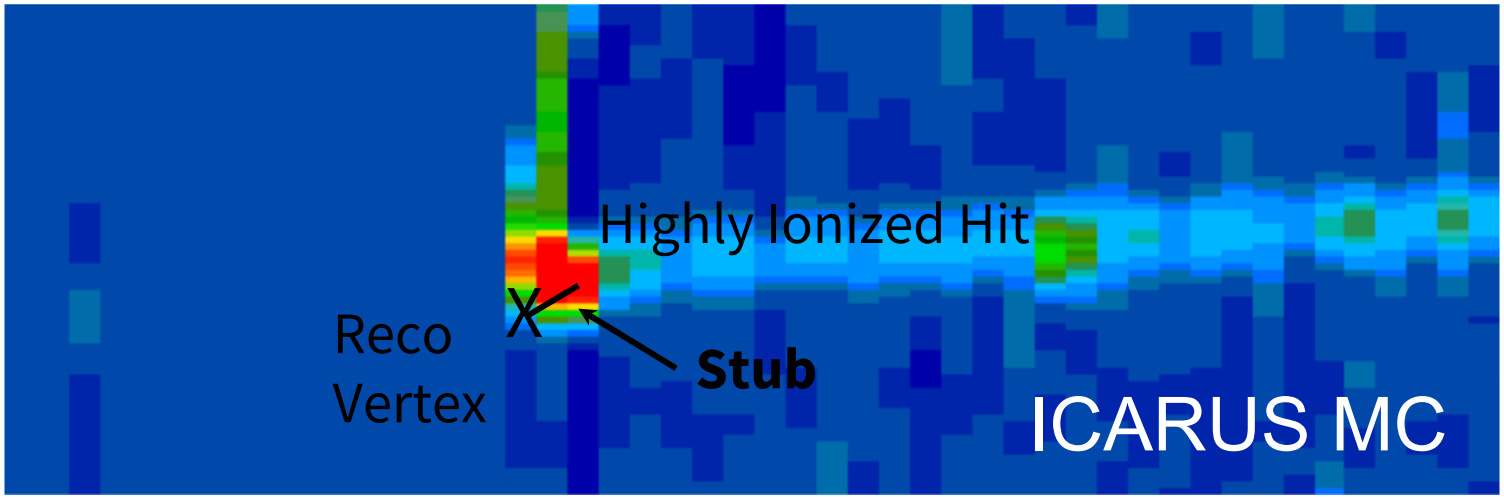
A proton missed by existing reconstruction,

which does not use charge information in reconstruction

Using Charge to Identify Protons: Stubs

Stubs are a new tool developed in SBN MC to identify low energy protons at a vertex

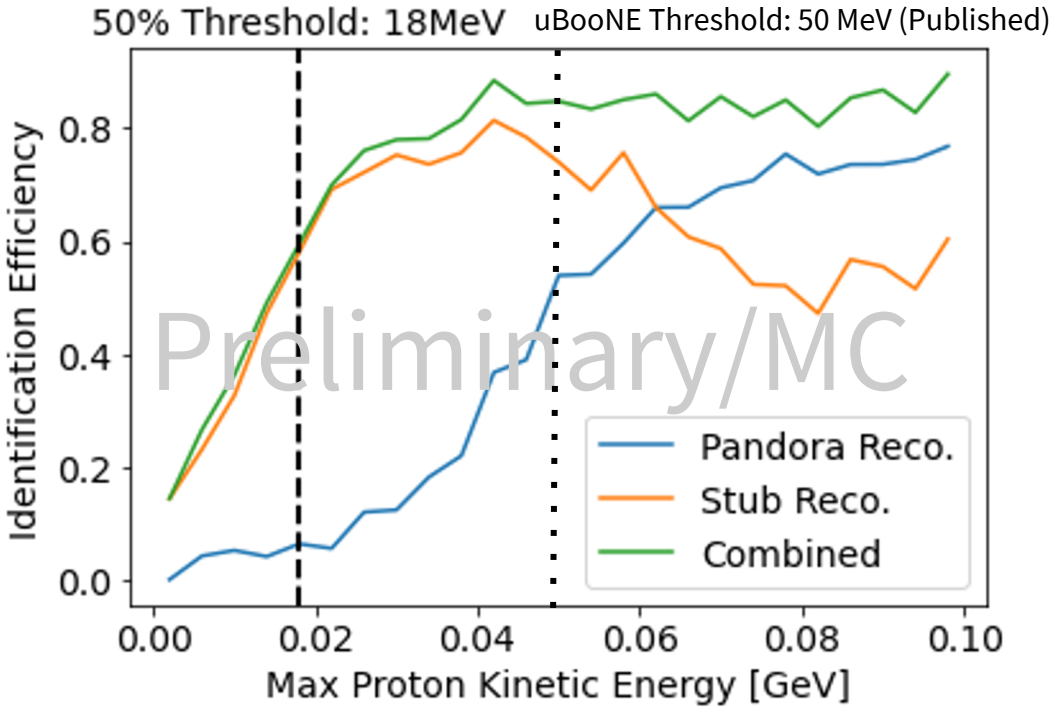
They are formed by identifying large depositions of charge near a vertex



Stub Reconstruction

Stubs allow identification of protons below the tracking energy threshold (Pandora)

NuMI @ ICARUS MC



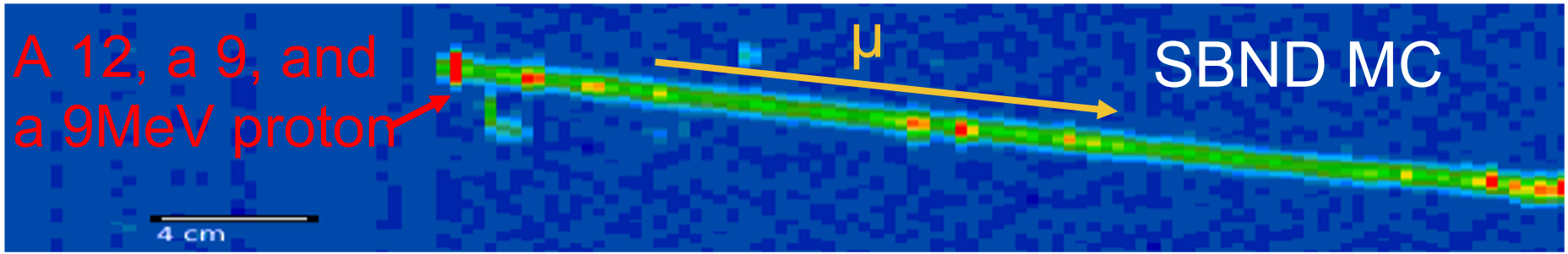
For fiducial νμ CC interactions with a reconstructed vertex within 5cm of the truth.

What can you Reconstruct at Low Energy?

Reconstructing properties of the proton become challenging at low energy

Orientation / length reconstruction is increasingly limited as you go down to one hit

Energy reconstruction is possible using charge, but there is a degeneracy between multiplicity and energy

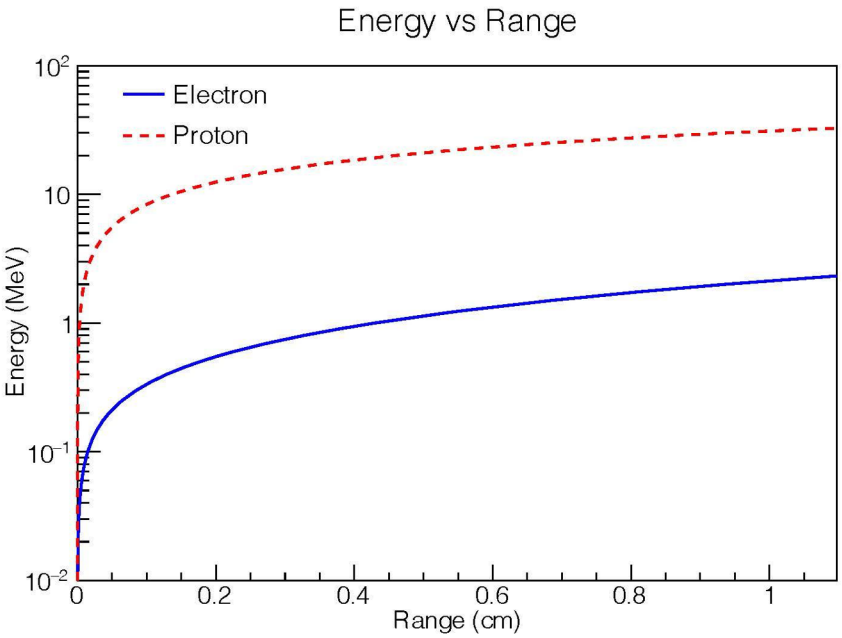


Identifying Low-Energy Protons Displaced from Vertices

What if the proton was displaced from the vertex? (like in 1γ1p, e.g.)

Then you would remove the background of energy depositions from other tracks at the vertex – potentially an even **lower energy threshold**

But… this is far from being implemented



One electron on a wire looks very different from one proton on a wire.

Summary: State of Proton Reconstruction

Algorithm	Automated Algorithm Exists?	Demonstrated on Data?	Identification Threshold (KE)	Physics Determining Threshold
Identify a Cluster of Hits	✓	✓	~50MeV	Proton long enough to be topologically distinct
Identify Charge at a Vertex	✓	✗	~15-20MeV	Significant deposition over μ/π/e Landau tail
Identify Charge Displaced from a Vertex	✗	✗	~single MeV (??)	Significant deposition over noise

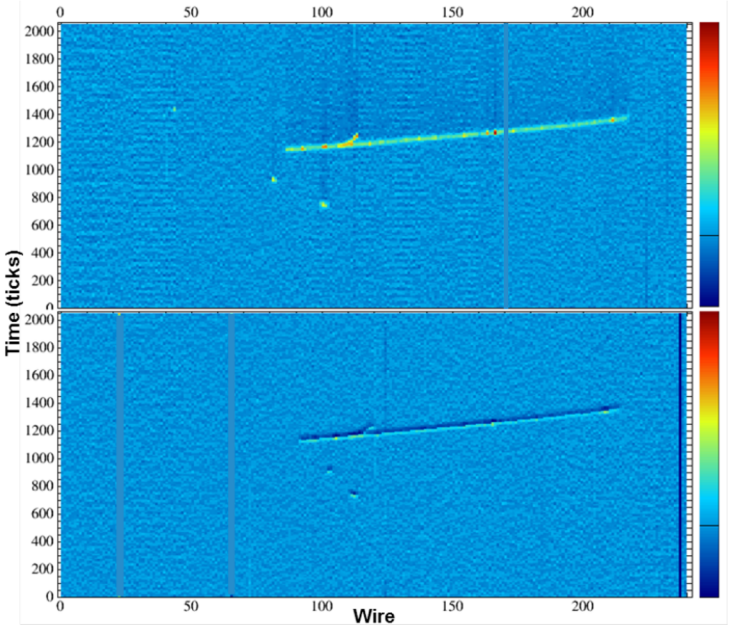
Identifying protons using charge would significantly reduce reconstruction thresholds from uBooNE

Thank you for listening!

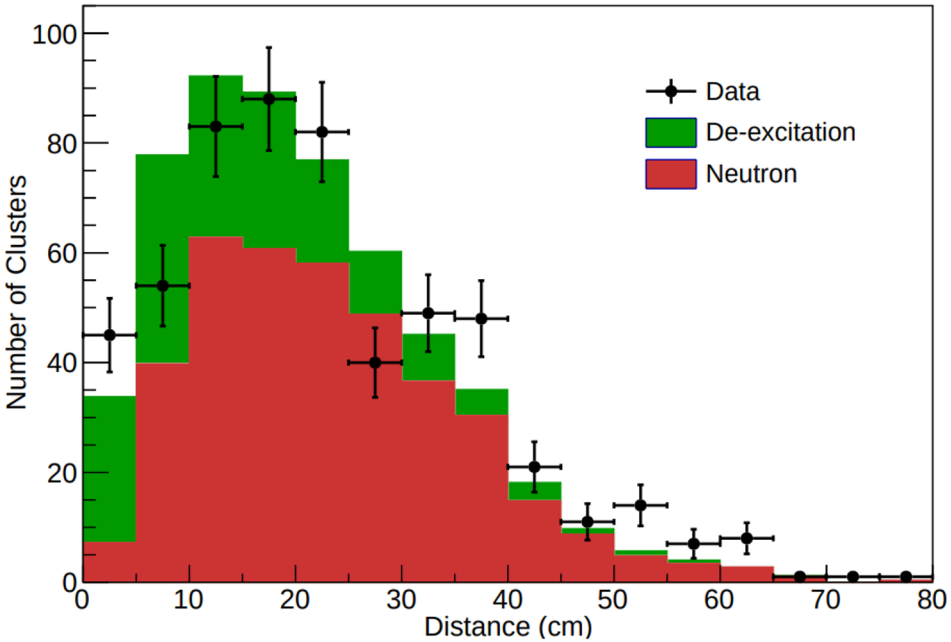
Neutron tagging through de-excitation

Neutrons capture on argon, releasing de-excitation photons

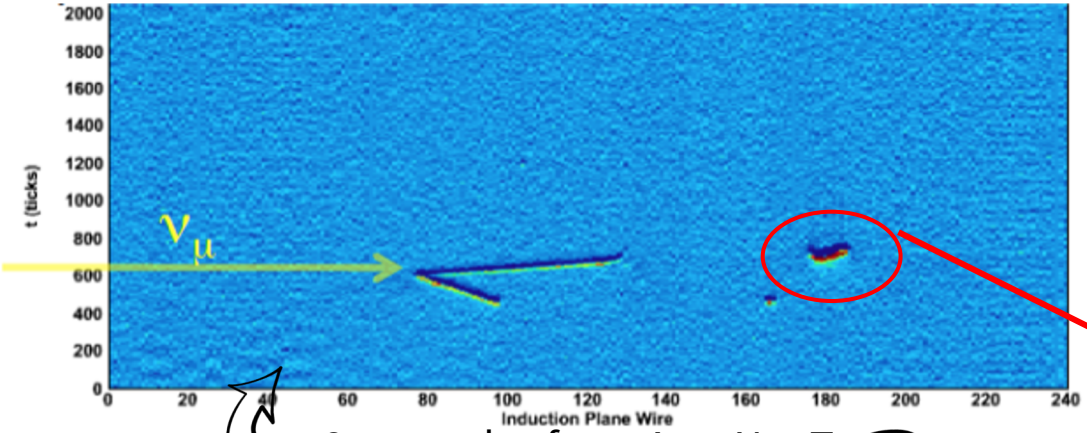
Hard (impossible?) to distinguish from de-excitation of of argon from initial neutrino interaction



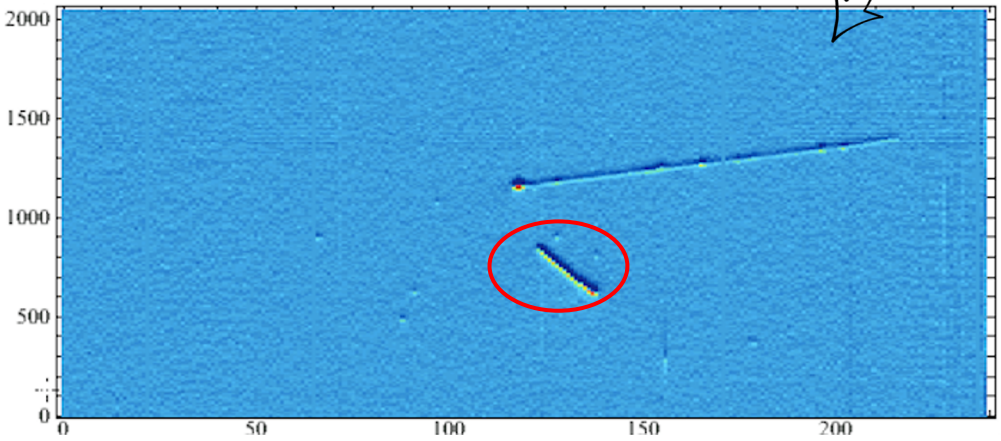
ArgoNeuT - Phys. Rev. D 99, 012002

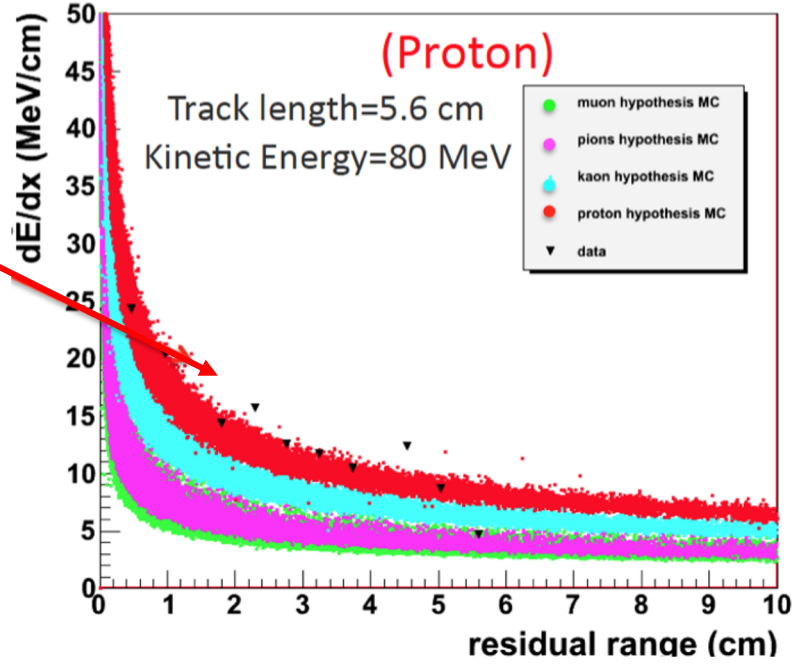


Neutron tagging through charge exchange



2 examples from ArgoNeuT





Limits to neutron tagging

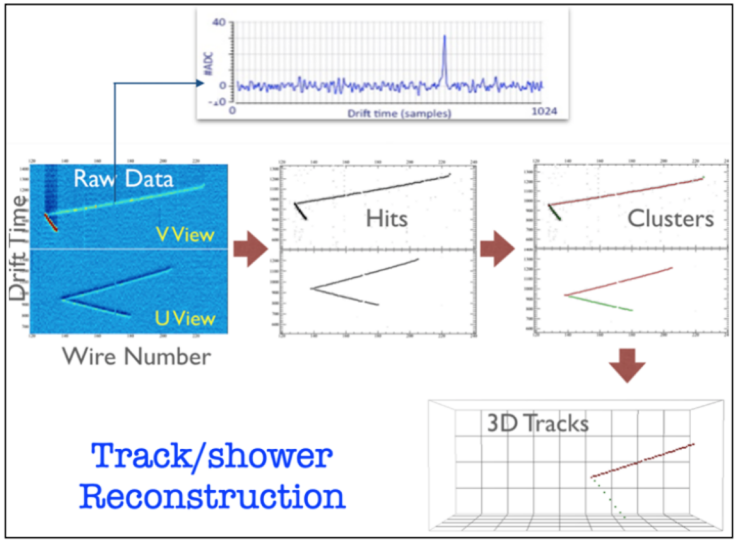
Likely low efficiency

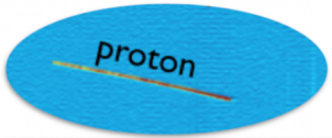
Very limited information - needs study

LAr TPC Event Reconstruction

Particle Identification is the last stage in event reconstruction

The reconstruction pipeline





Calorimetry & Particle Identification

- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

How well Pid it works depends on the performance of all the previous steps!