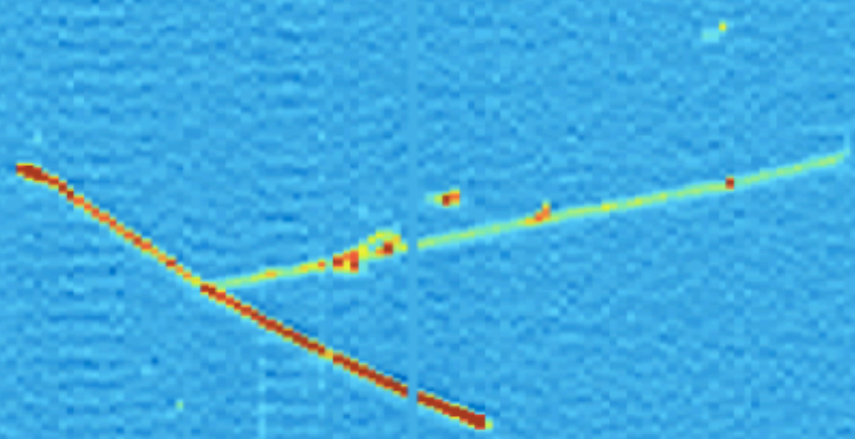
Recent results from ArgoNeuT



47th Annual Fermilab Users Meeting

June 12nd 2014

Ornella Palamara

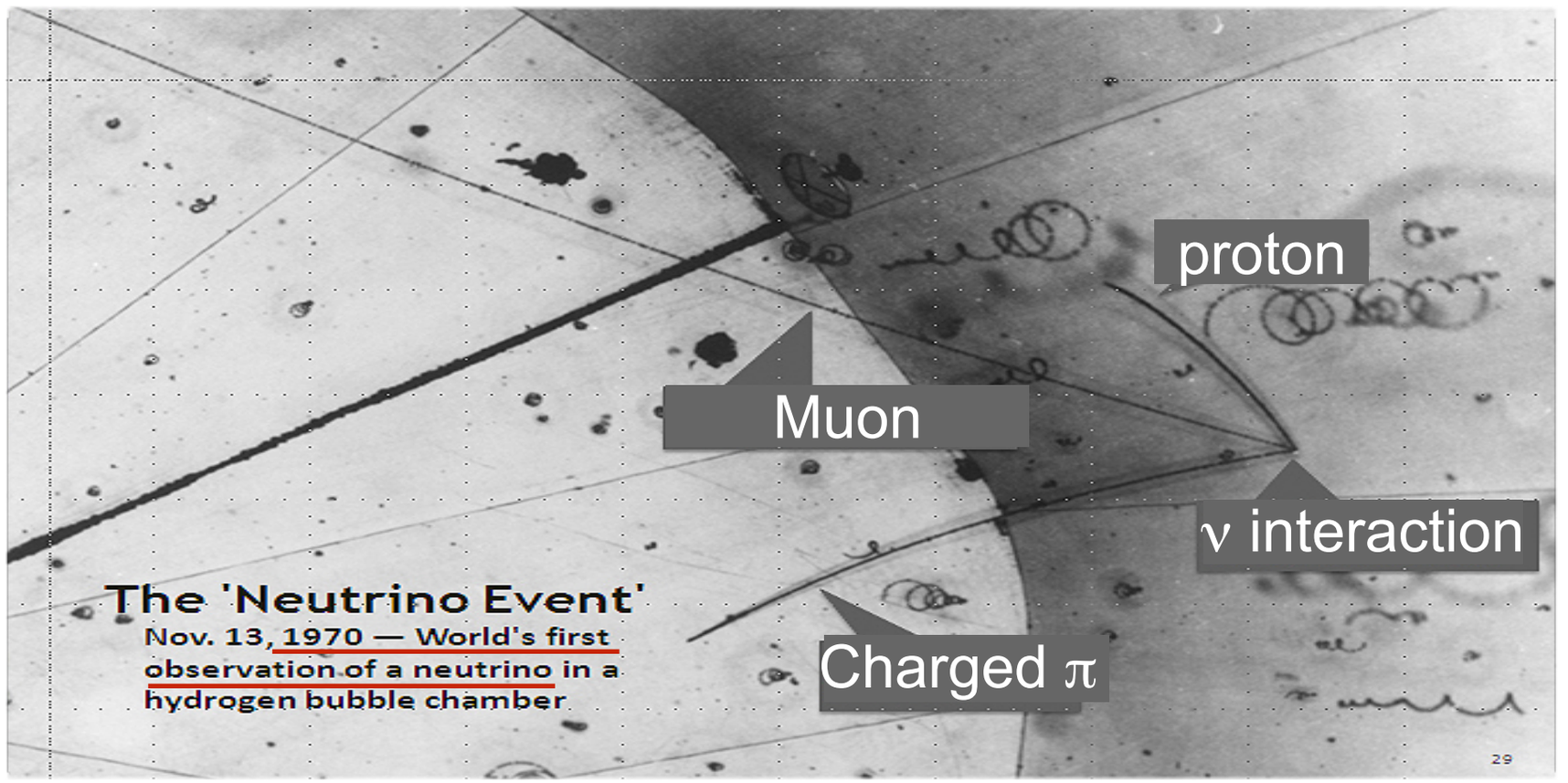
Yale University, USA*

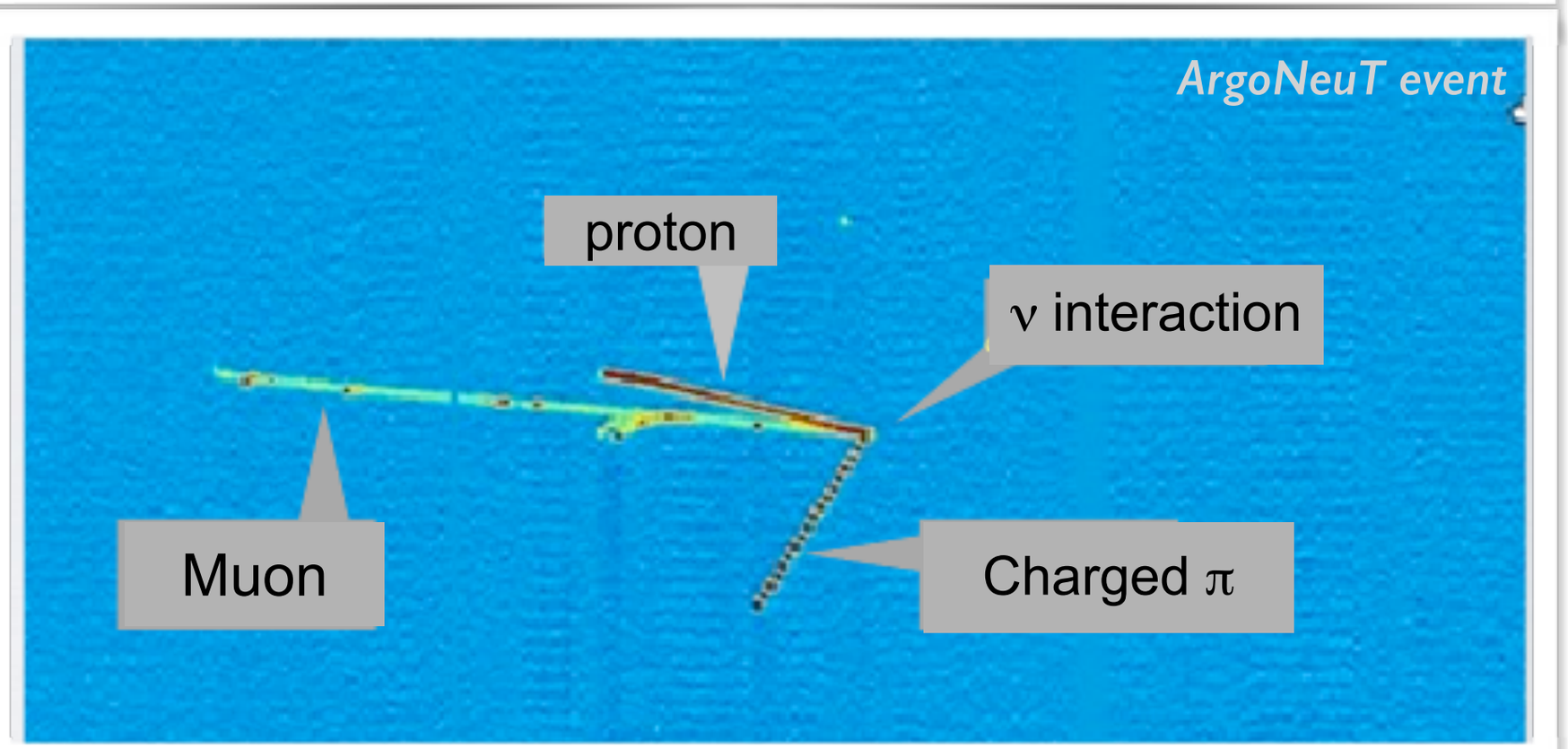
on behalf of the ArgoNeuT Collaboration

*on leave of absence from Laboratori Nazionali del Gran Sasso, Italy

Why Liquid Argon?

- Bubble chamber quality of data with added full calorimetry
- Can produce physics results with a "table-top" size experiment:
  - Benchmark - "standard candle" results
  - Physics enabled by LAr capabilities
  - Development towards future large detectors





US based LAr R&D program

This talk

Yale TPC

Location: Yale University
Active volume: 0.002 ton
operational: 2007

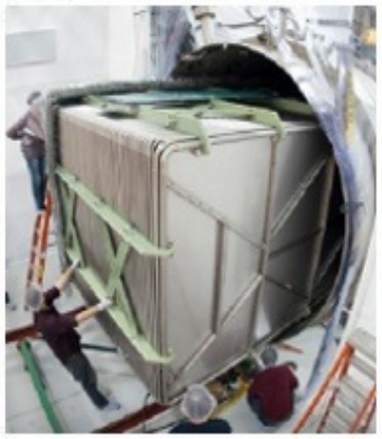
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

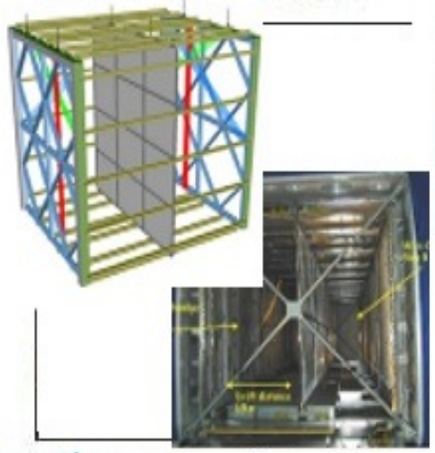
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



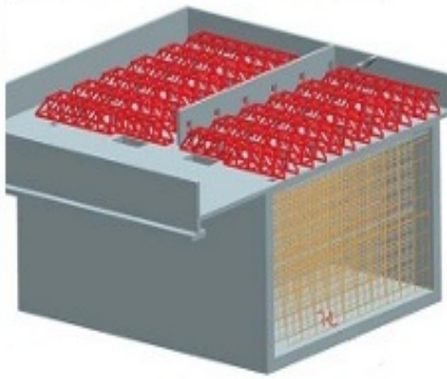
Location Fermilab
Active volume: 0.1 kton
Operational: 2014

SBN @ FNAL



Location: Fermilab
Active volume: 0.05 + 0.6 kton
Construction start: 2017

LBNE



Location: Homestake
Active volume: 35 kton
Construction start 202?

Luke

Location: Fermilab
Purpose: materials test st
Operational: since 2008

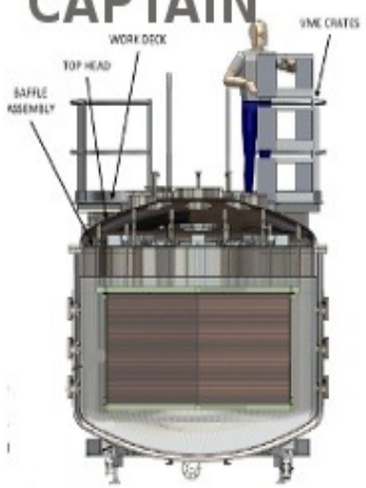
LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT

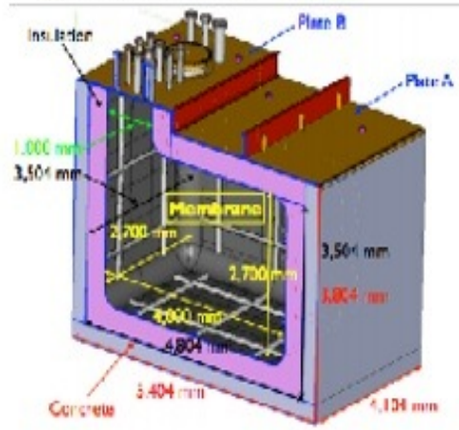
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN



Location: LANL
Purpose: LArTPC calibration
Operational: 2014

LBNE 35 Ton



Location: Fermilab
Purpose: purity demo
Operational: 2013

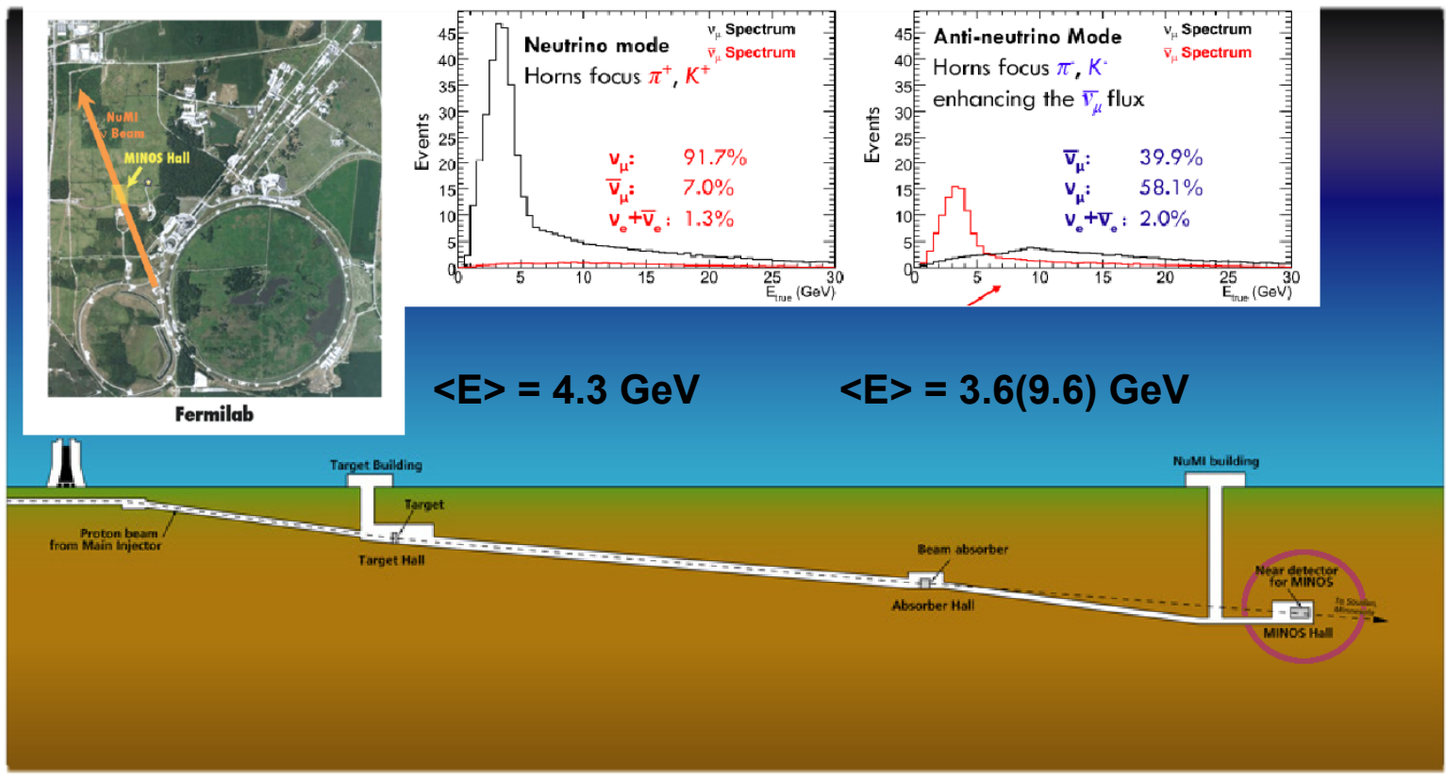
ArgoNeuT in the NuMI beam line

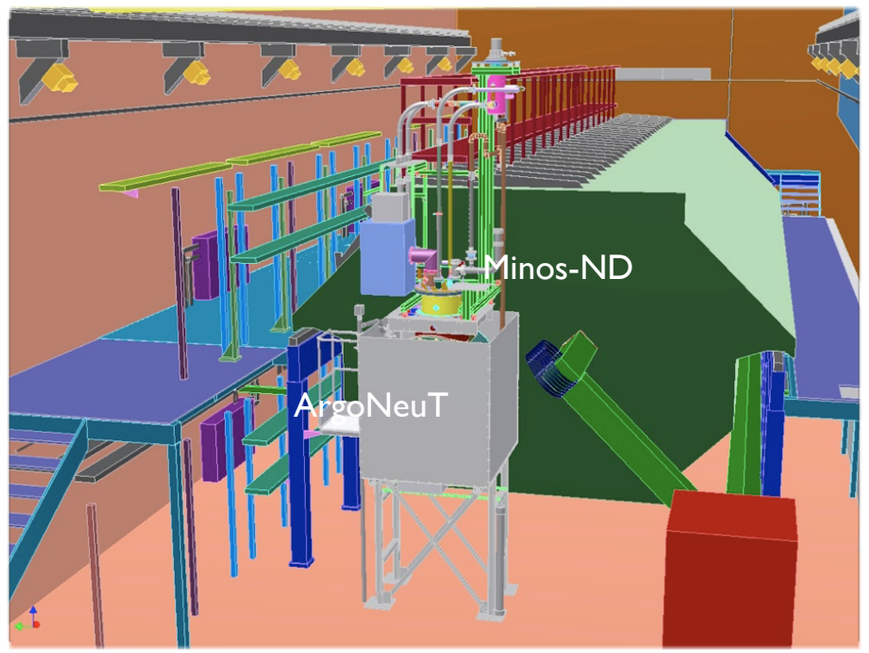
First LArTPC in a low (1-10 GeV) energy neutrino beam

Acquired 1.35 × 10^{20} POT, mainly in $\bar{\nu}_\mu$ mode

Designed as a test experiment.

But obtaining physics results!





ArgoNeuT in the NuMI beam line

240 Kg active volume

47×40×90 cm^3, wire spacing 4 mm

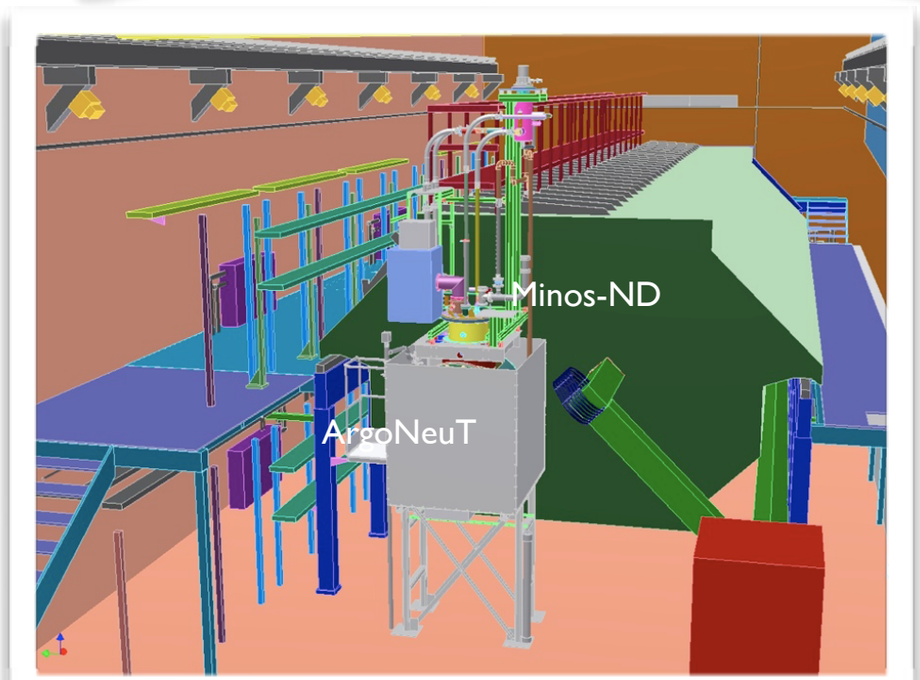
LAr TPC

~7000 CC events collected

Largest data sample of [low energy] neutrino interactions in LArTPC

ArgoNeuT tech-paper

C. Anderson et al., JINST 7 (2012) P10019



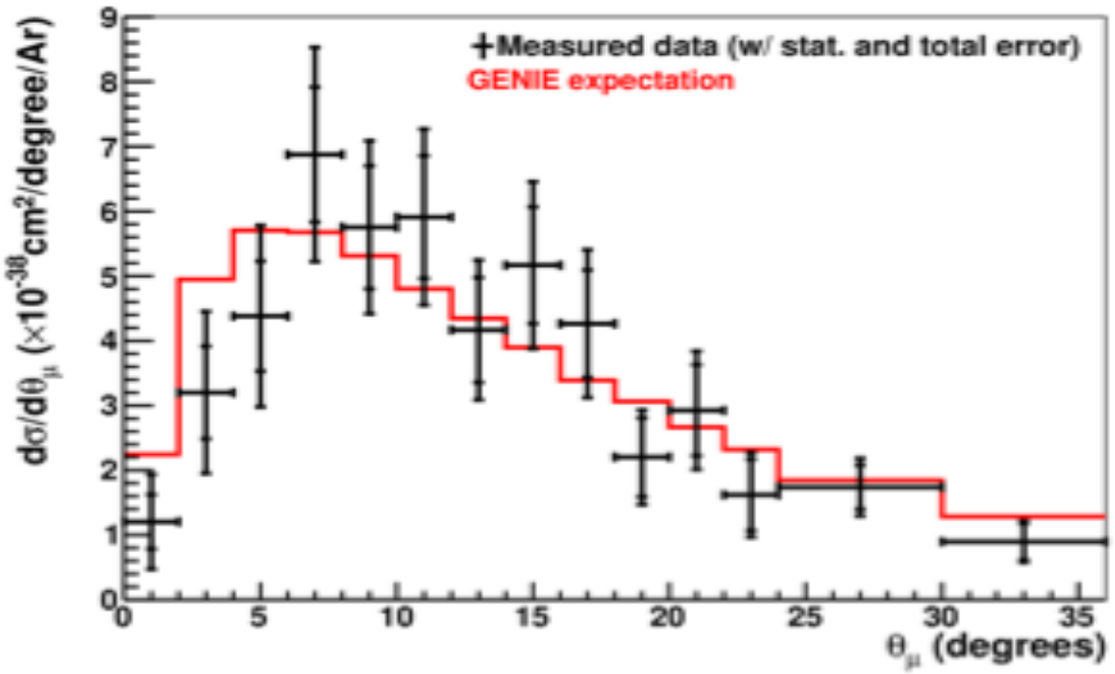
MINOS ND as muon spectrometer for ArgoNeuT events*

(momentum reconstruction and charge identification (q) of exiting muons)

**ArgoNeuT Coll. is grateful to MINOS Coll. for providing the muon reconstruction*

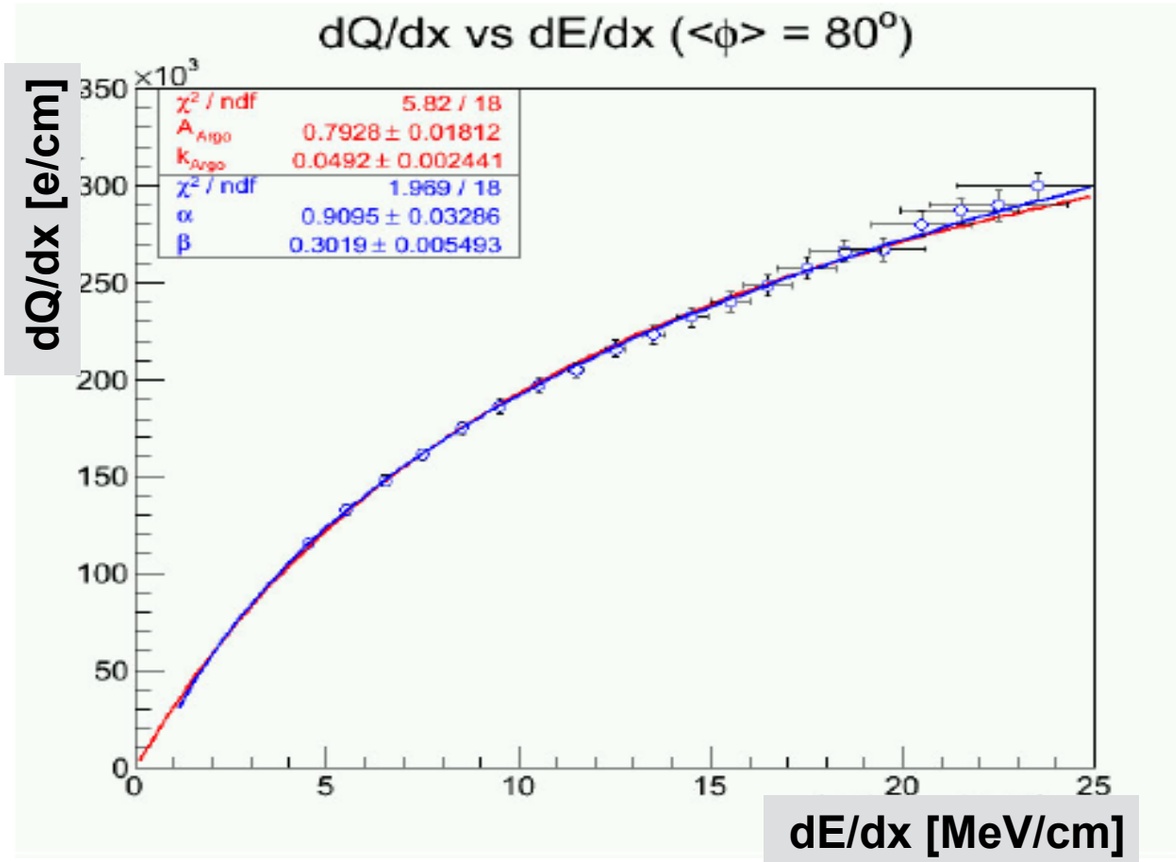
Previous ArgoNeuT results

Neutrino mode:
2 weeks of data taking



ν_μ CC-inclusive cross-section

C. Anderson et al., PRL 108, 2012



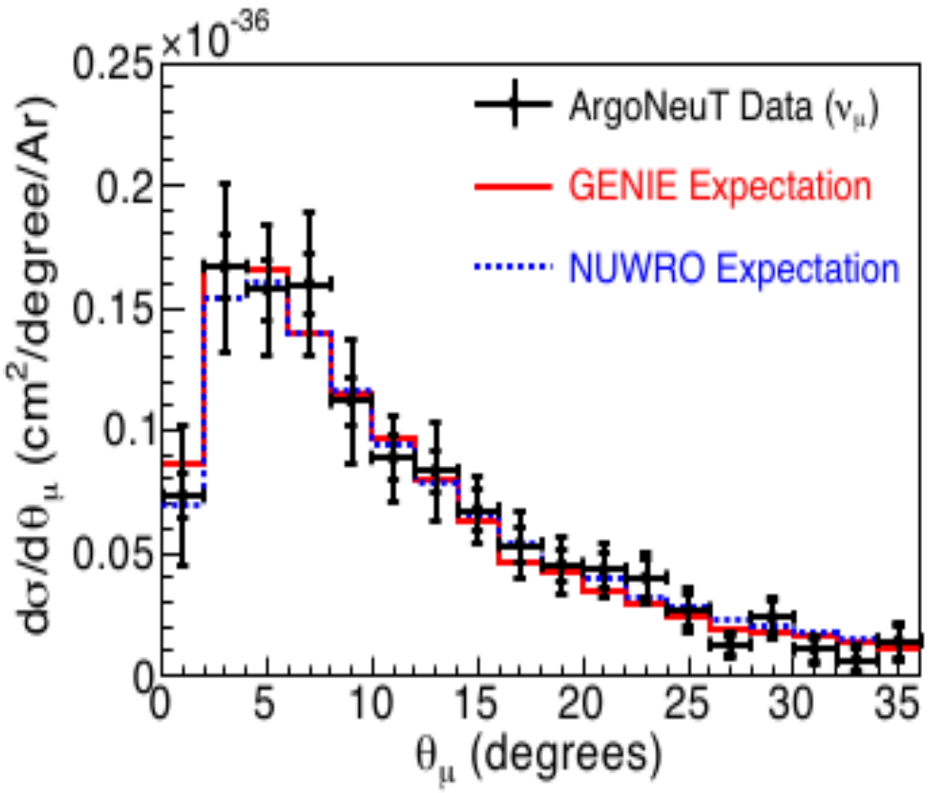
Charge recombination with stopping protons

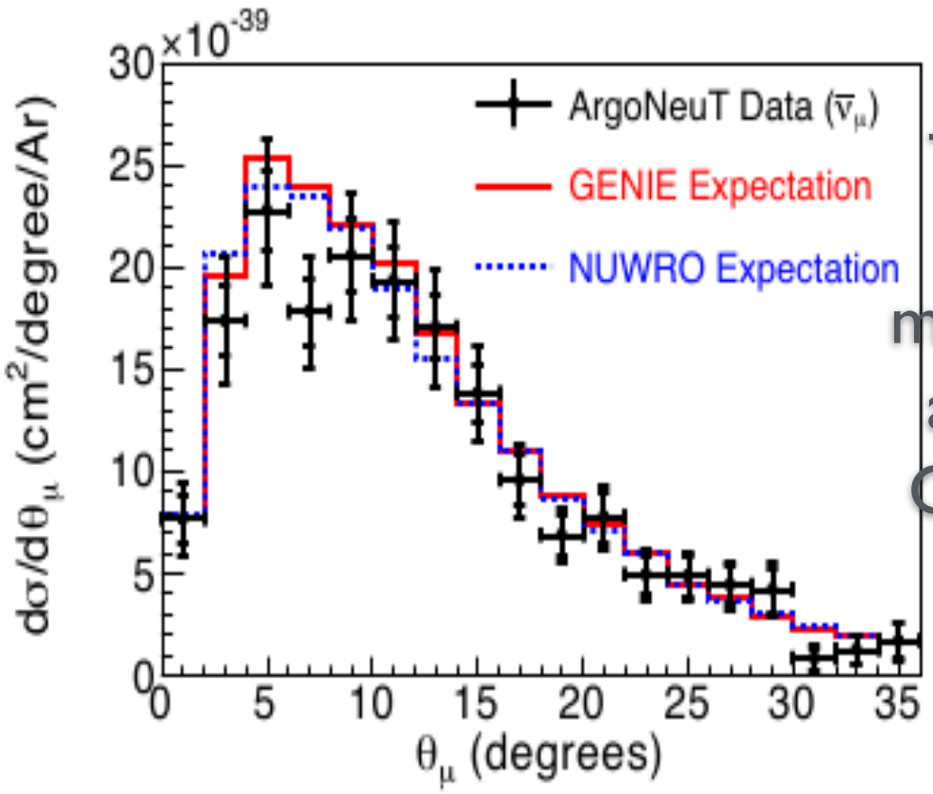
R. Acciarri et al. ,2013 JINST 8 P08005

Calorimetry with through-going muons

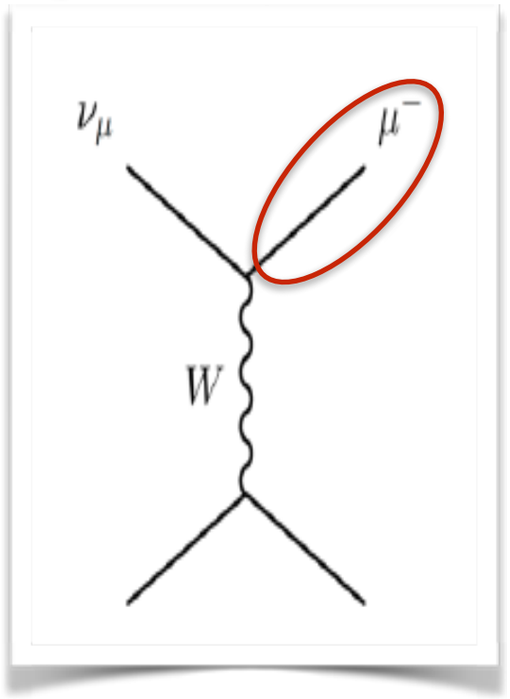
C.Anderson et al., 2012 JINST 7 P10020

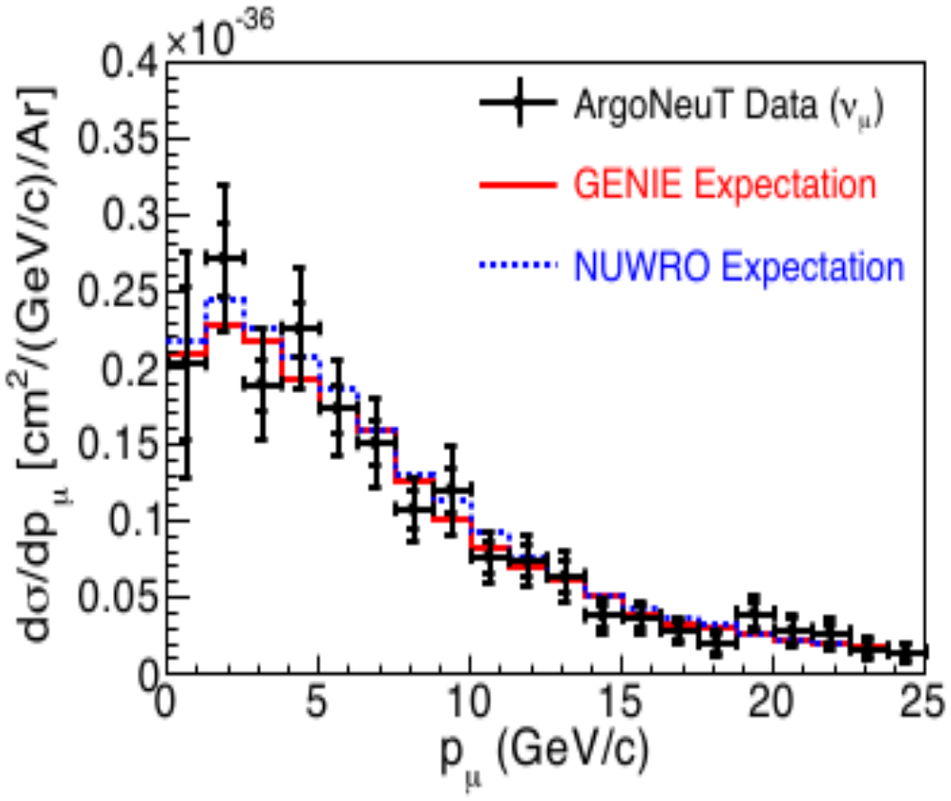
CC Inclusive cross-section in $\bar{\nu}_\mu$ mode

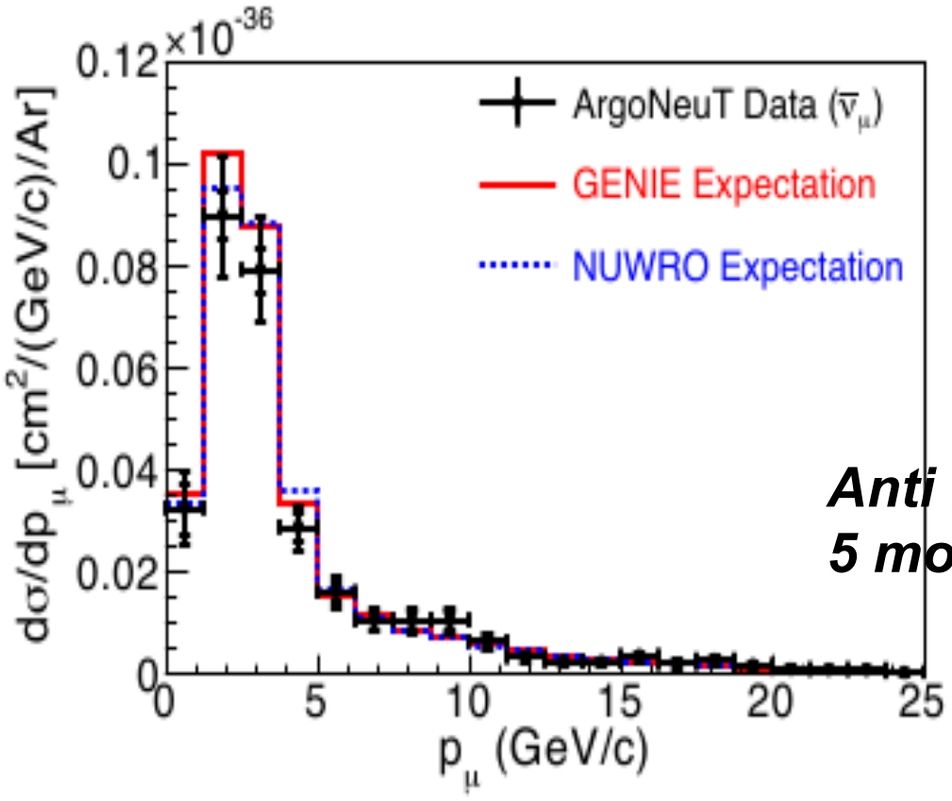




The composition of the beam allows measuring both the ν_μ and $\bar{\nu}_\mu$ components. Charge from MINOS





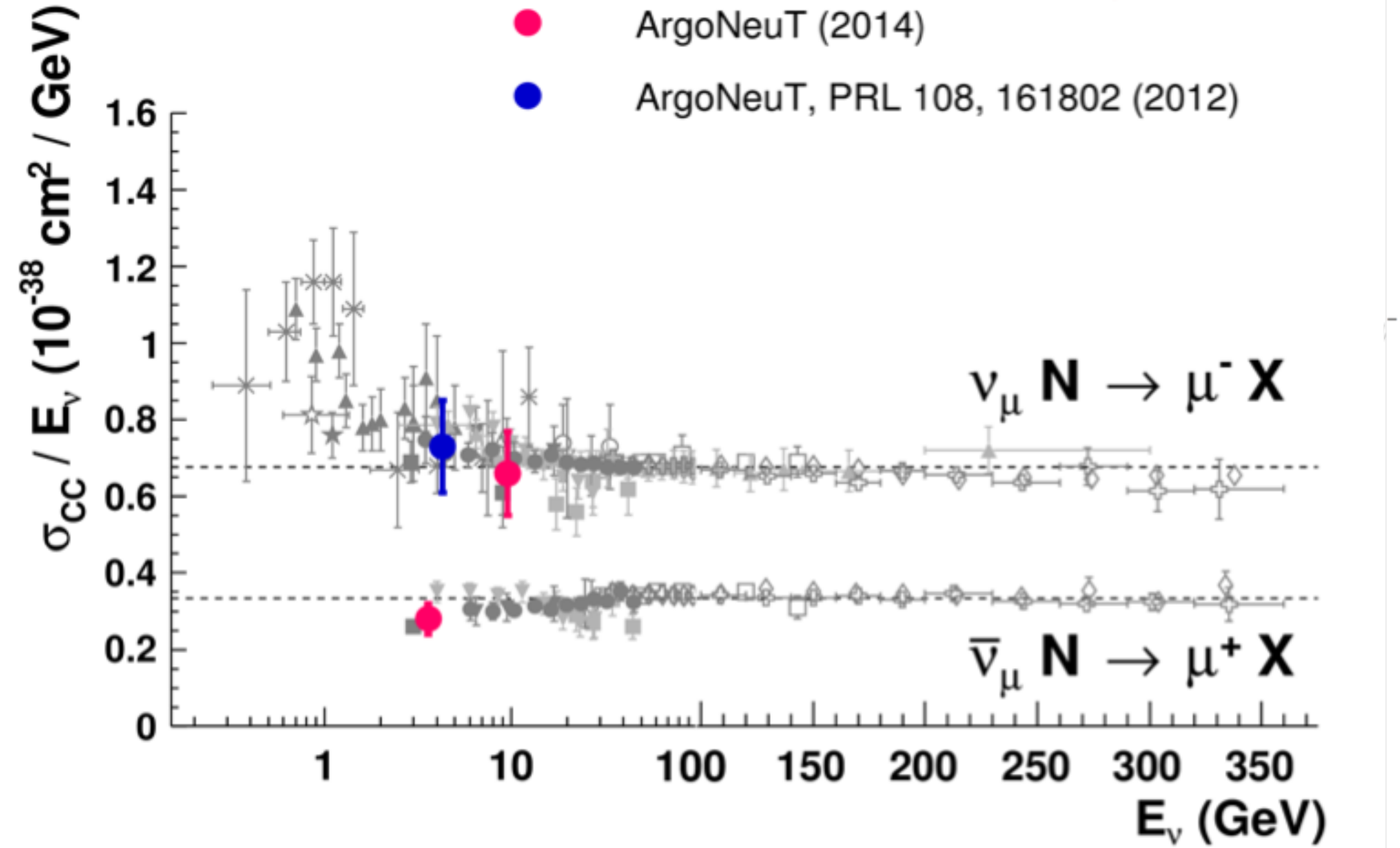


Anti Neutrino mode:
5 months of data taking

R. Acciarri et al. ,Phys. Rev. D 89, 112003

CC Inclusive cross-section in $\bar{\nu}_\mu$ mode

R. Acciarri et al. ,Phys. Rev. D 89, 112003



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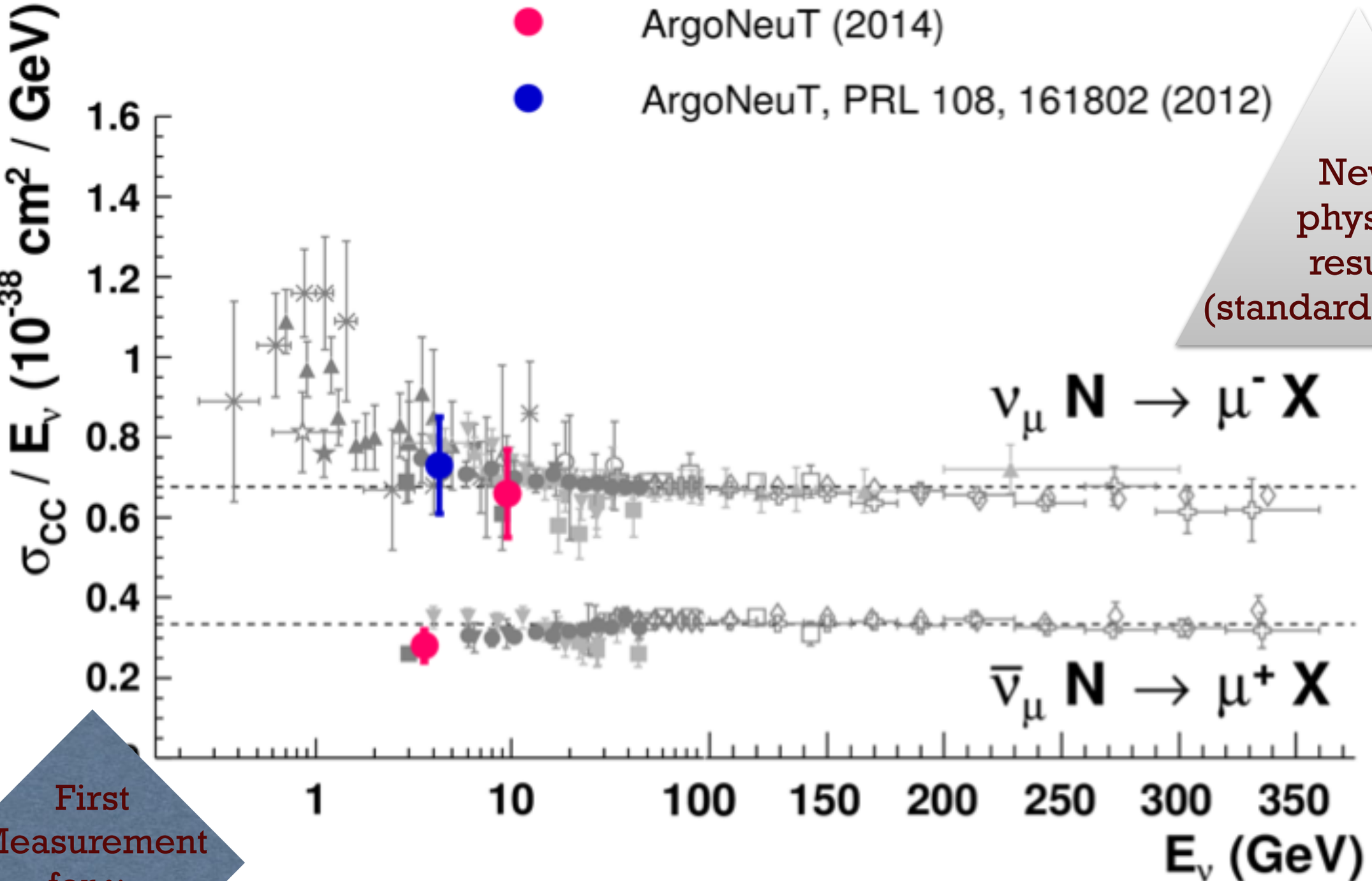
R. Acciarri et al. ,Phys. Rev. D 89, 112003



New physics result (standard candle)

First Measurement for ν_μ in argon!

Coherent charged Pion Production

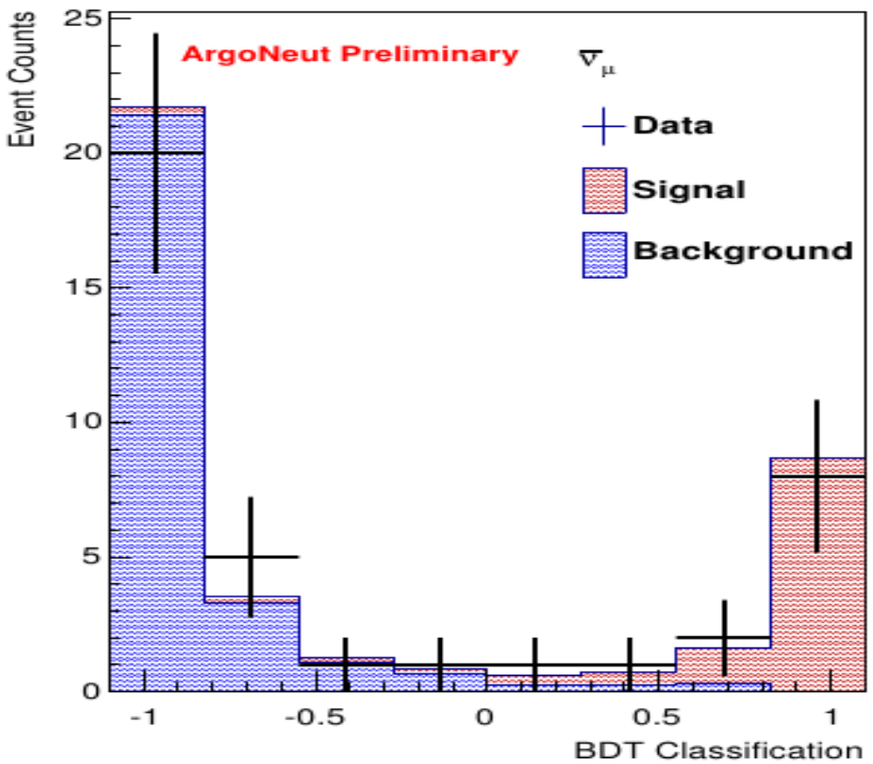
$$\nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.}$$

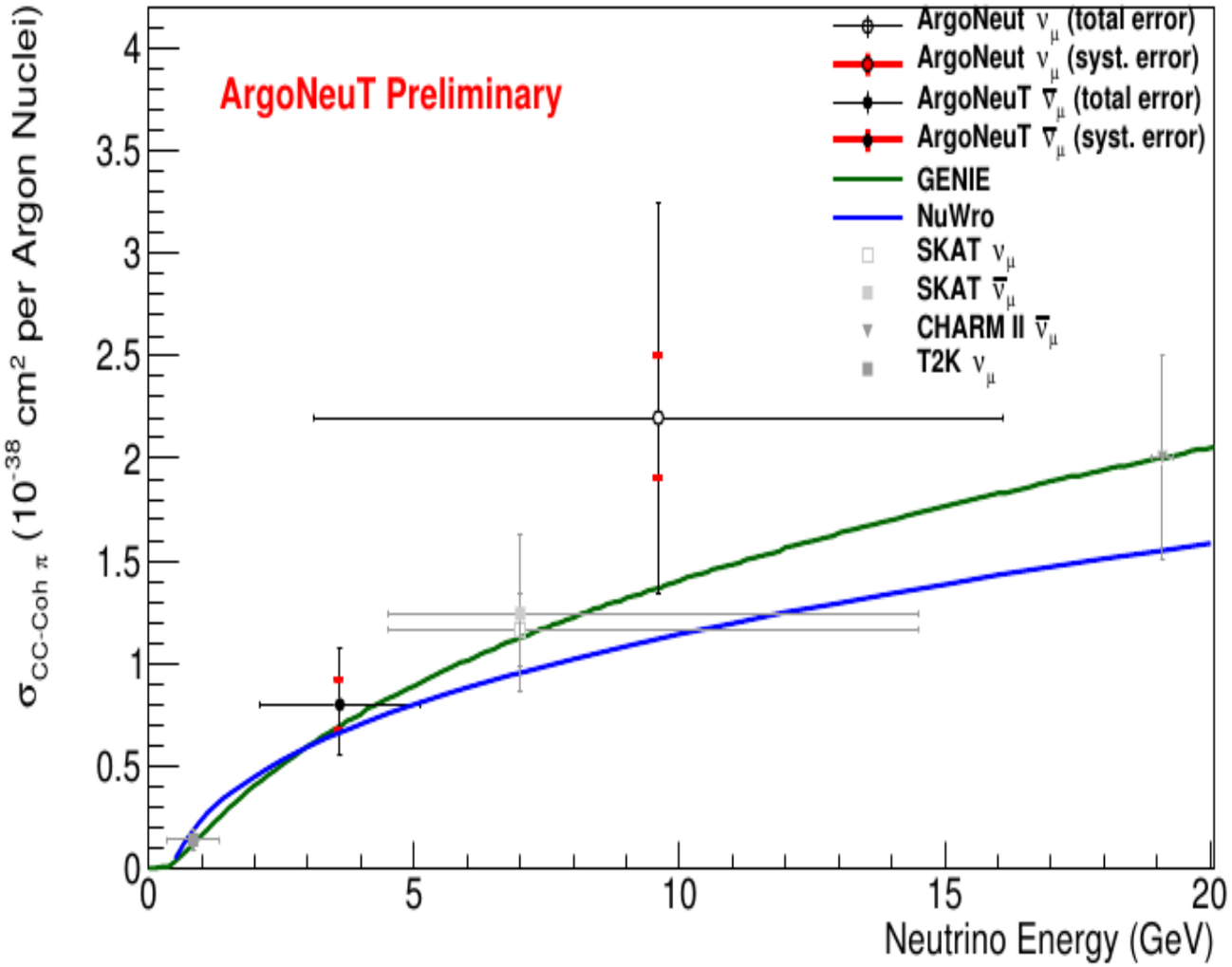
$$\bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.}$$

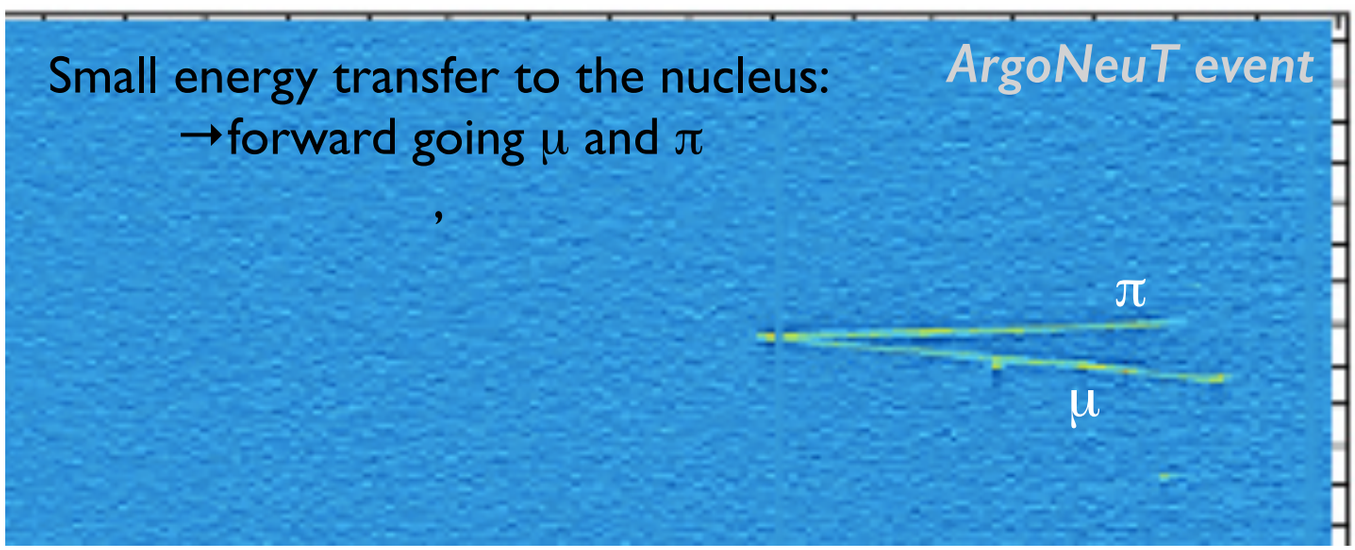
Most pions are not contained, so it is not possible to use Q^2 or t as discrimination.

MC used to build a binned background and signal expectation for a BDT response (based on kinematic variables).

This is then fit to the data.







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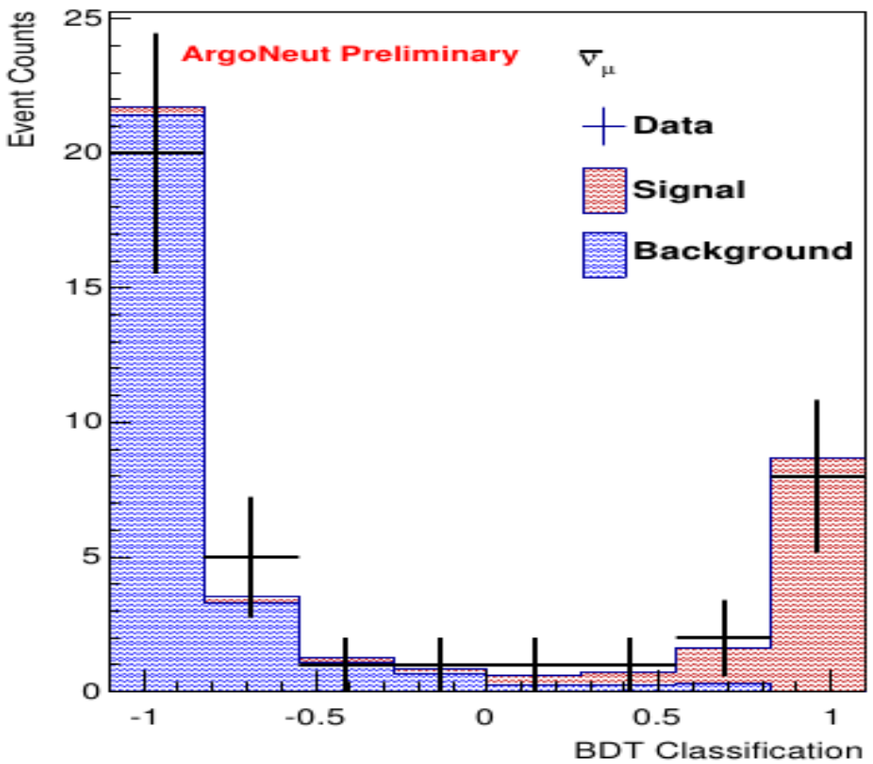
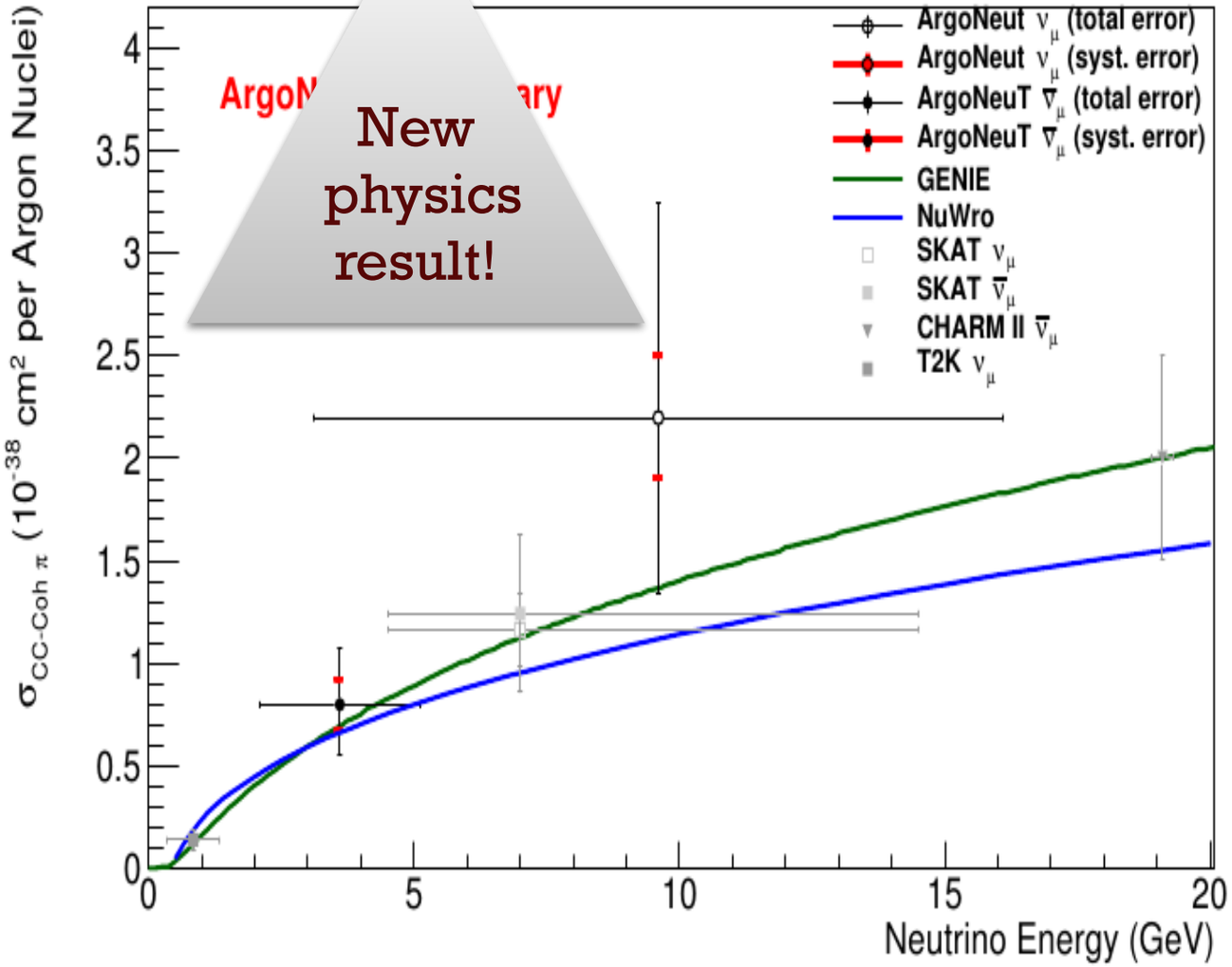
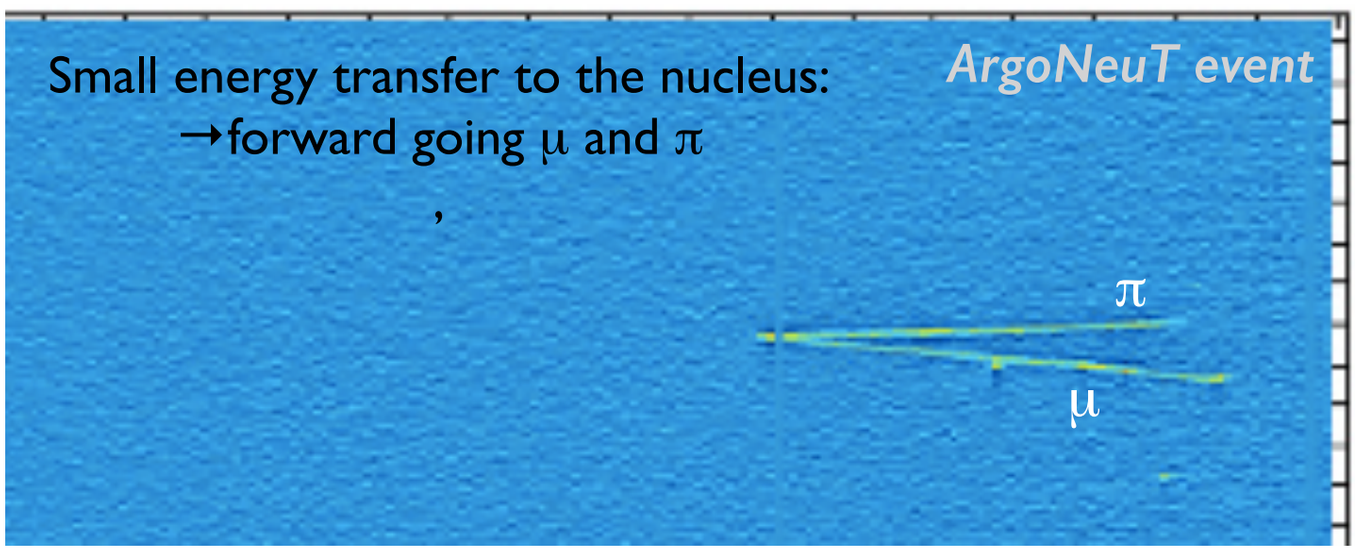






Observing proton multiplicity

LAr-TPC detectors, providing ***full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification*** allow for **MC independent measurements**, **Exclusive Topology** recognition and **Nuclear Effects exploration**

INSTEAD OF MC BASED CLASSIFICATION OF THE EVENTS IN THE INTERACTION CHANNELS *(QE, RES, DIS etc)*, *CC* NEUTRINO EVENTS IN *LAr* CAN BE CLASSIFIED IN TERMS OF **FINAL STATE TOPOLOGY** BASED ON PARTICLE MULTIPLICITY:

⇨ *0 pion* (**μ+Np,** *where* **N=0,1,2…**), *etc..*

1 pion **(μ+Np+1π)** *events,*

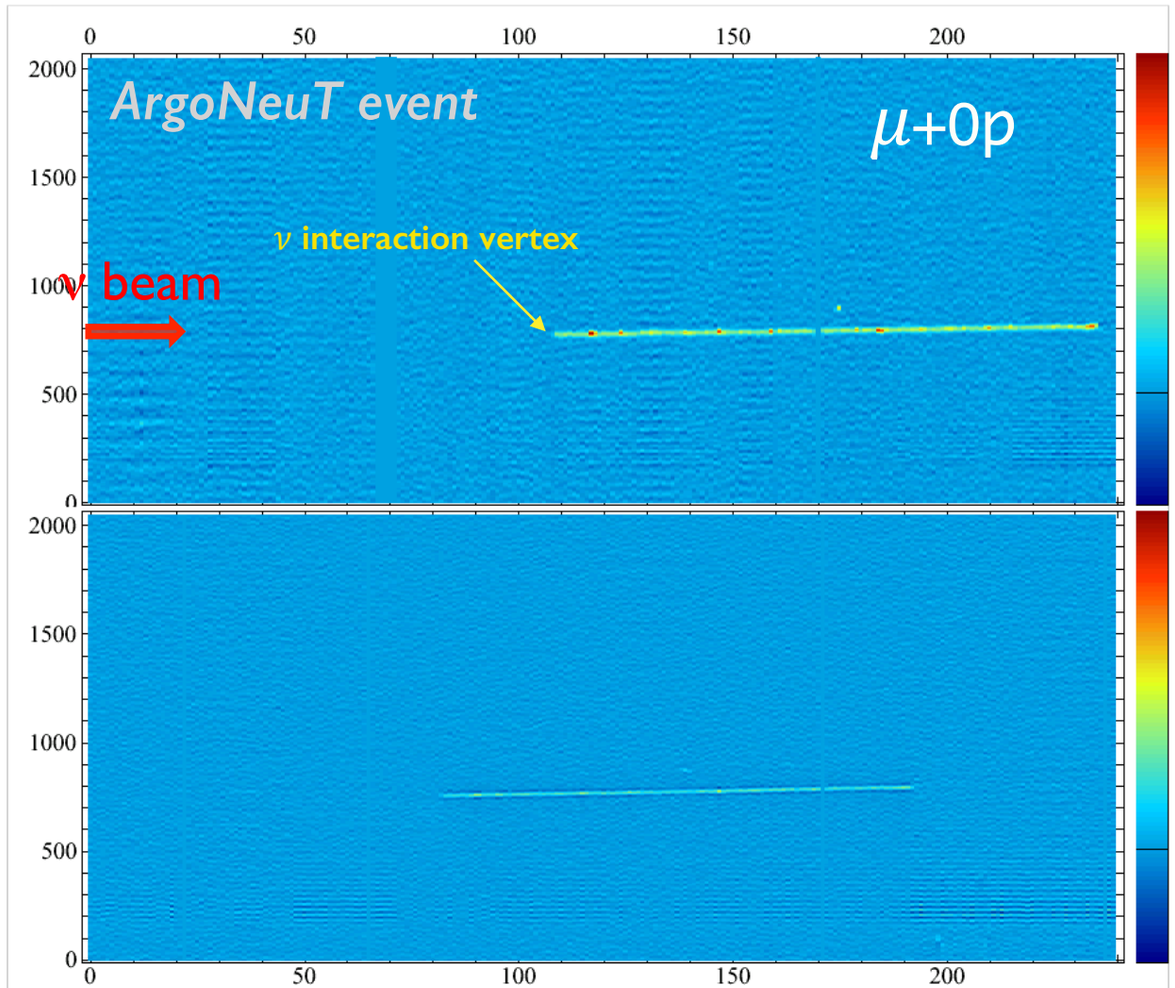
EVENT TOPOLOGY: leading muon accompanied by any number (N=0, 1, 2, 3, 4) of protons final state

ArgoNeuT ν_μ CC 0 pion topological analysis

Topological characterization of the events: Count (PId) and reconstruct protons at the neutrino interaction vertex*

(low proton energy threshold - 21 MeV Kin. En.)

Analysis fully exploiting LAr TPC's capabilities



2D views from the two wire planes

*The muon+Np sample can also contain neutrons. The presence of neutrons in the events cannot be measured, since ArgoNeuT volume is too small to have signicant chances for n to convert into protons in the LAr volume before escaping.

ArgoNeuT ν_μ CC 0 pion topological analysis

Topological characterization of the events: Count (PId) and reconstruct protons at the neutrino interaction vertex

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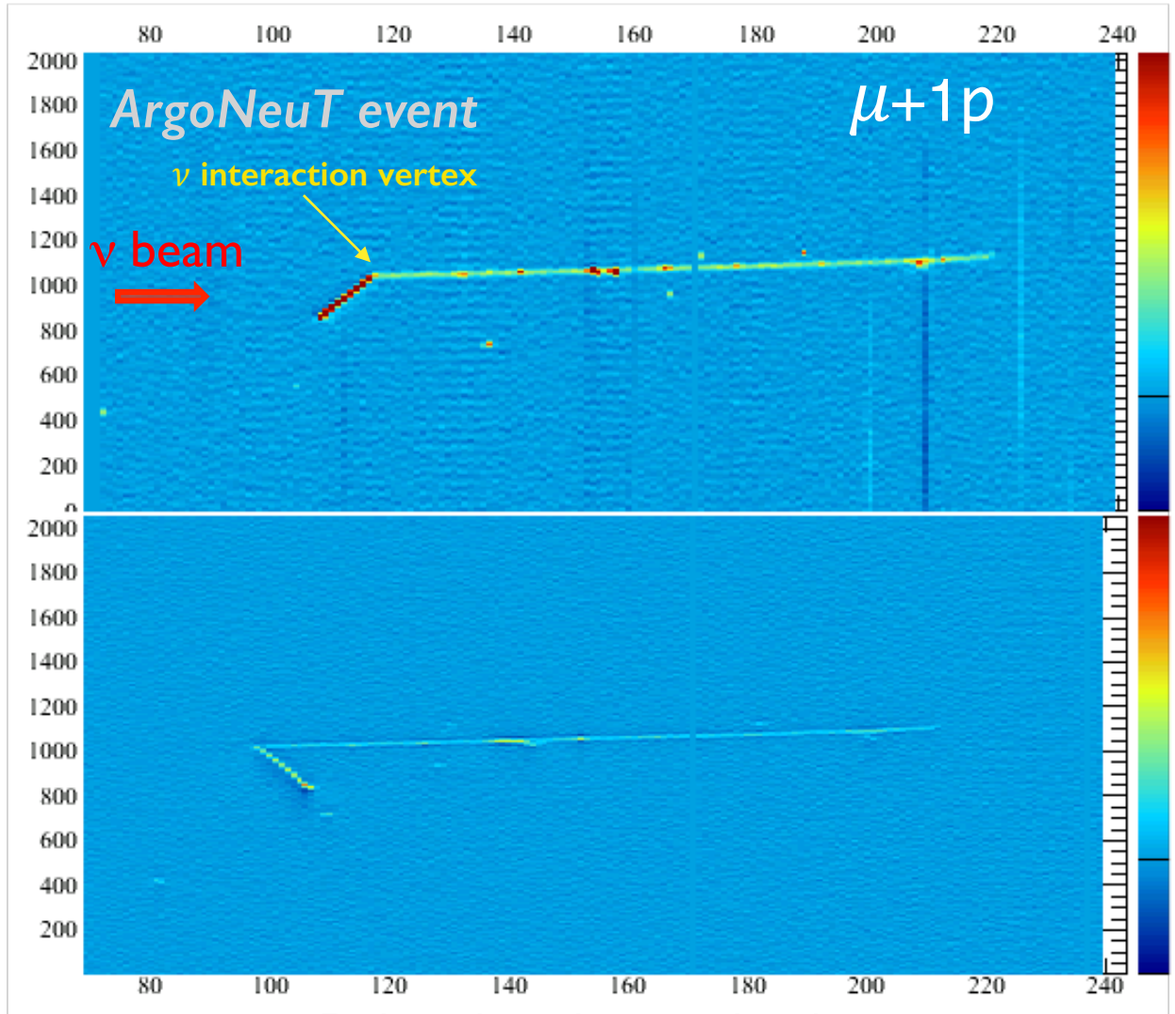

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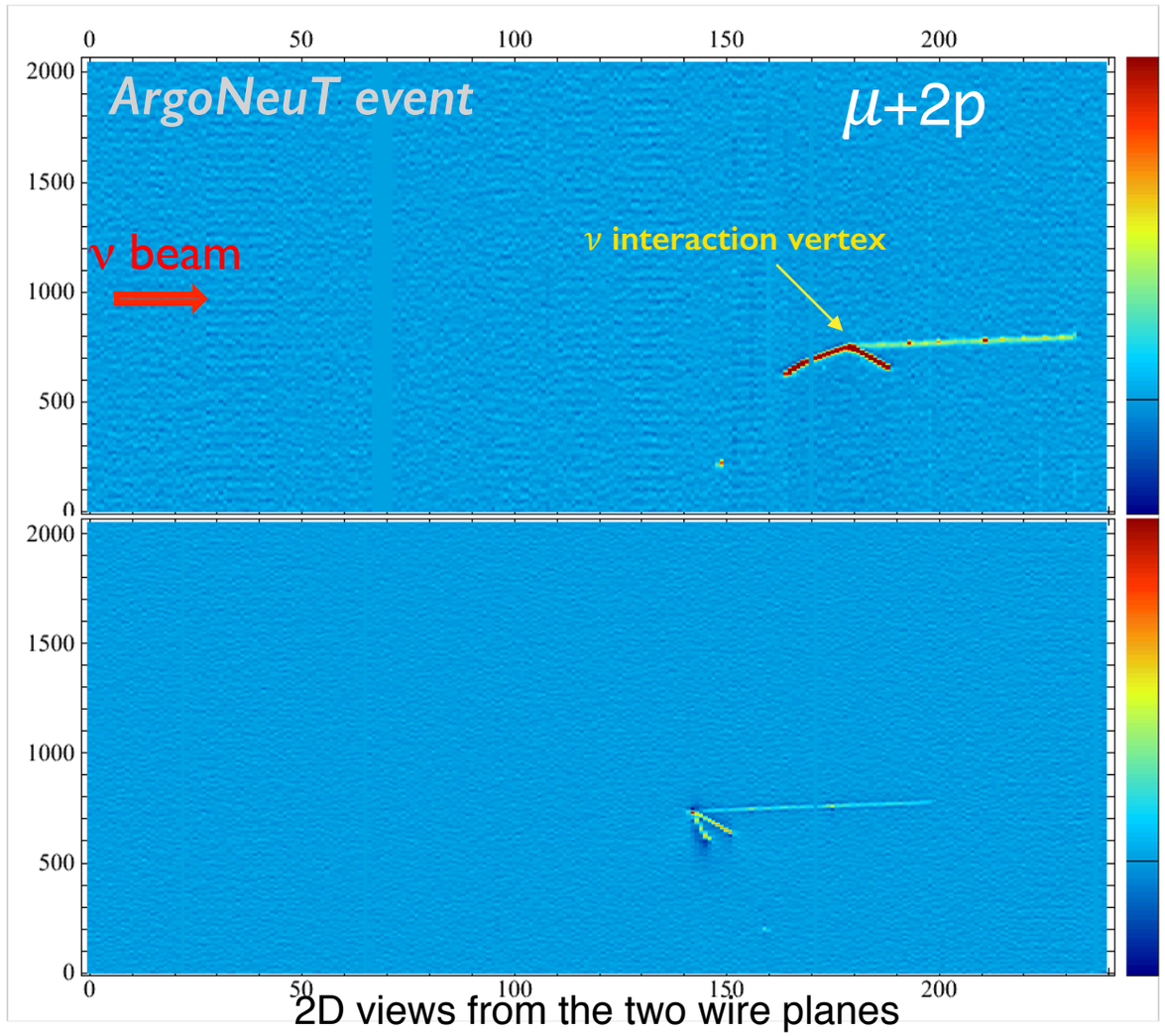
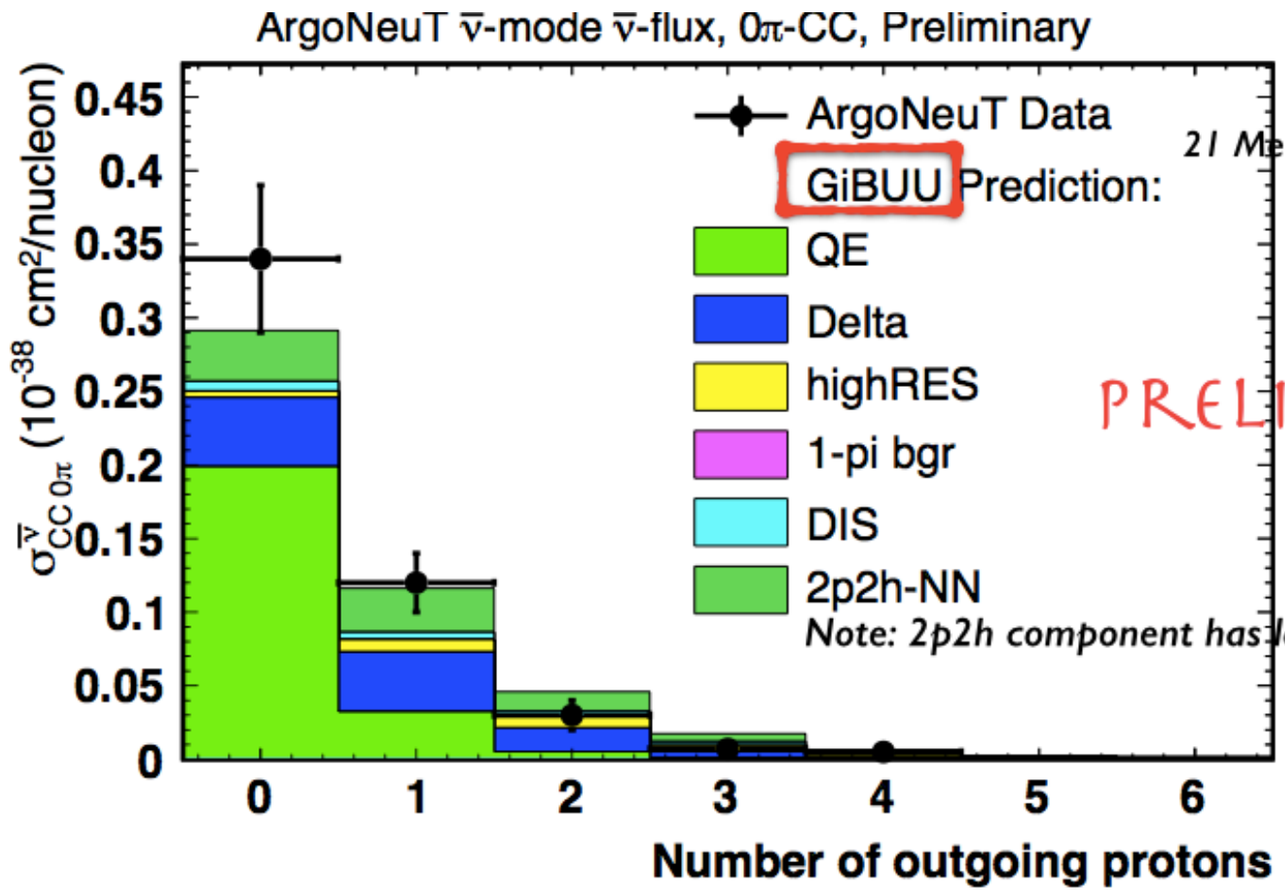
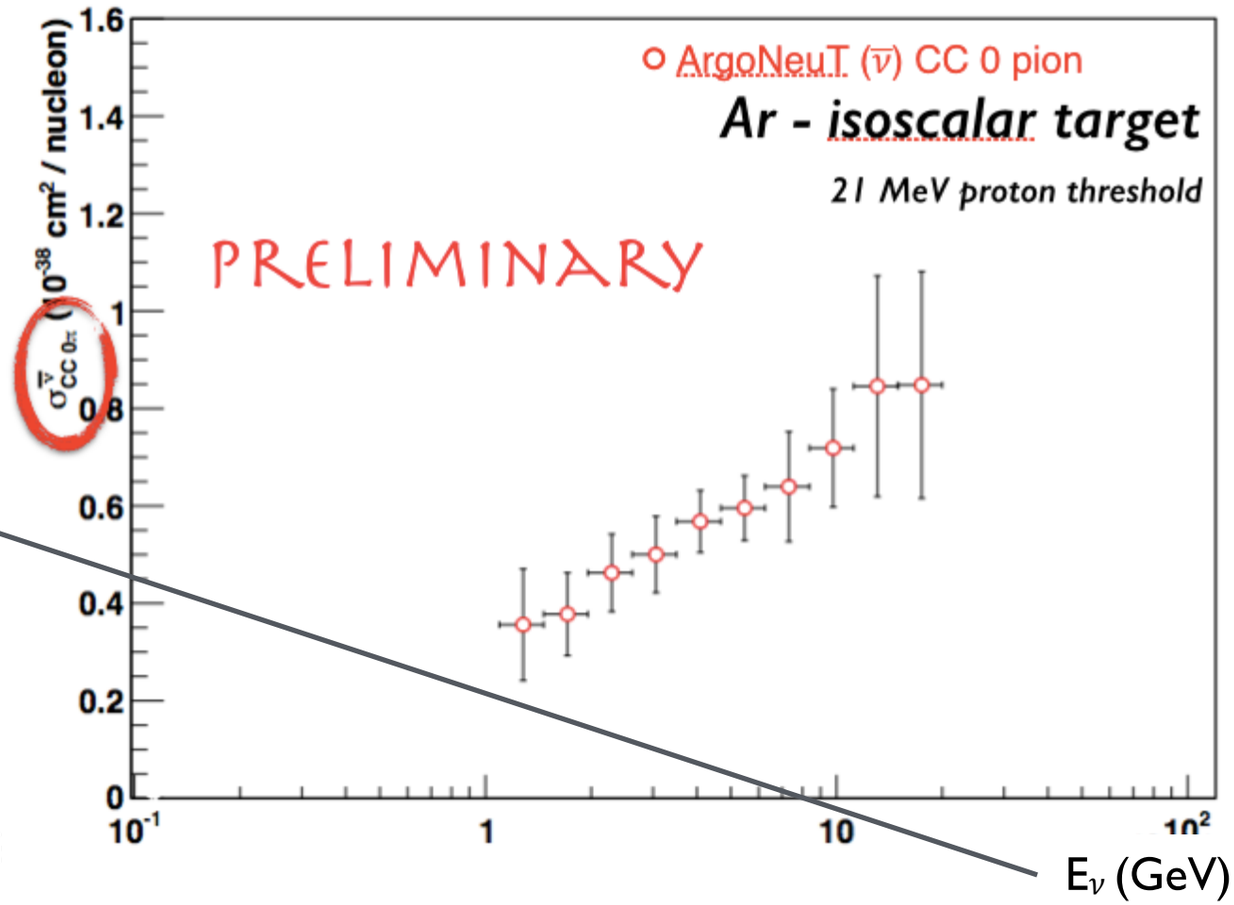


2D views from the two wire planes

Multi-p accompanying the leading muon

$\bar{\nu}_\mu$ CC 0 pion cross sections as a function of proton multiplicity



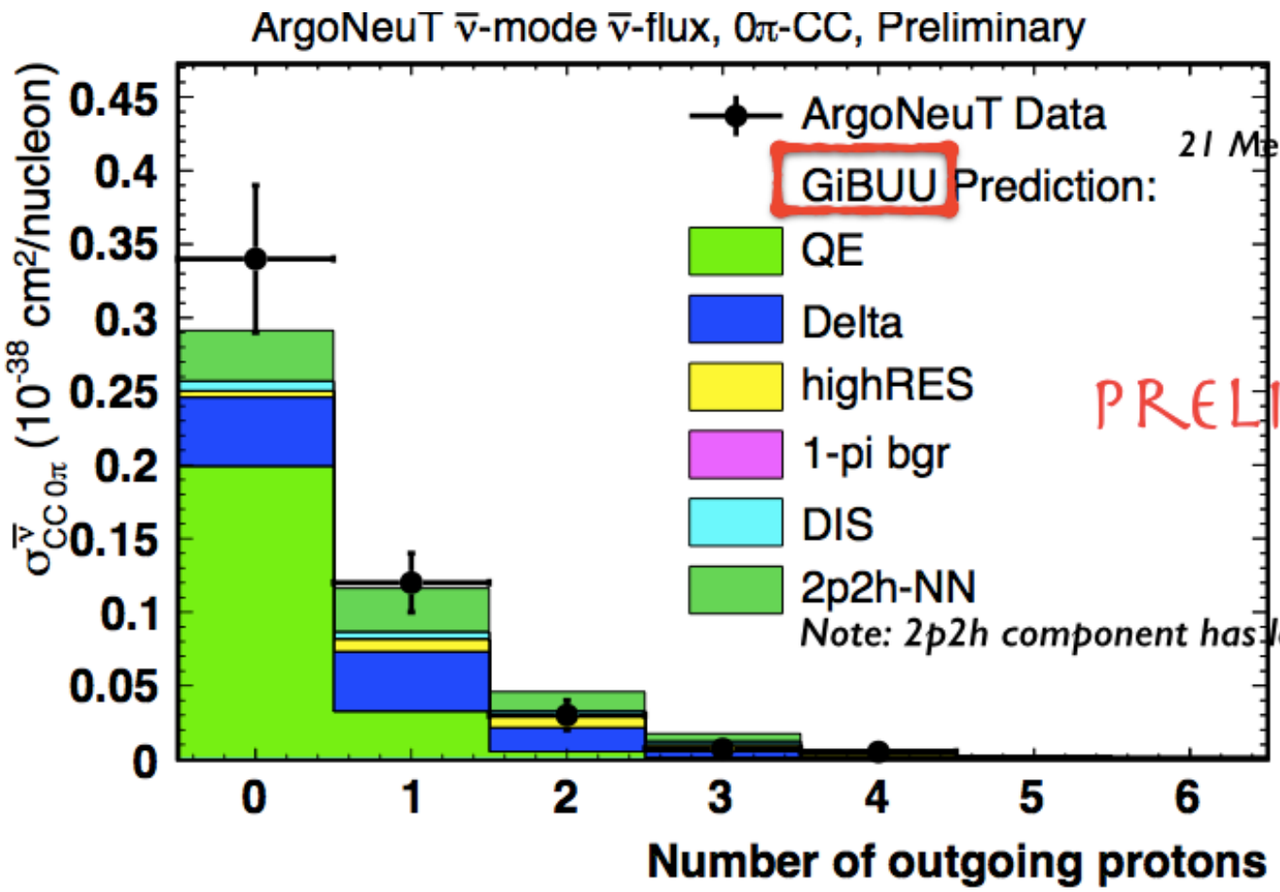


from *lepton AND proton reconstructed kinematics:*

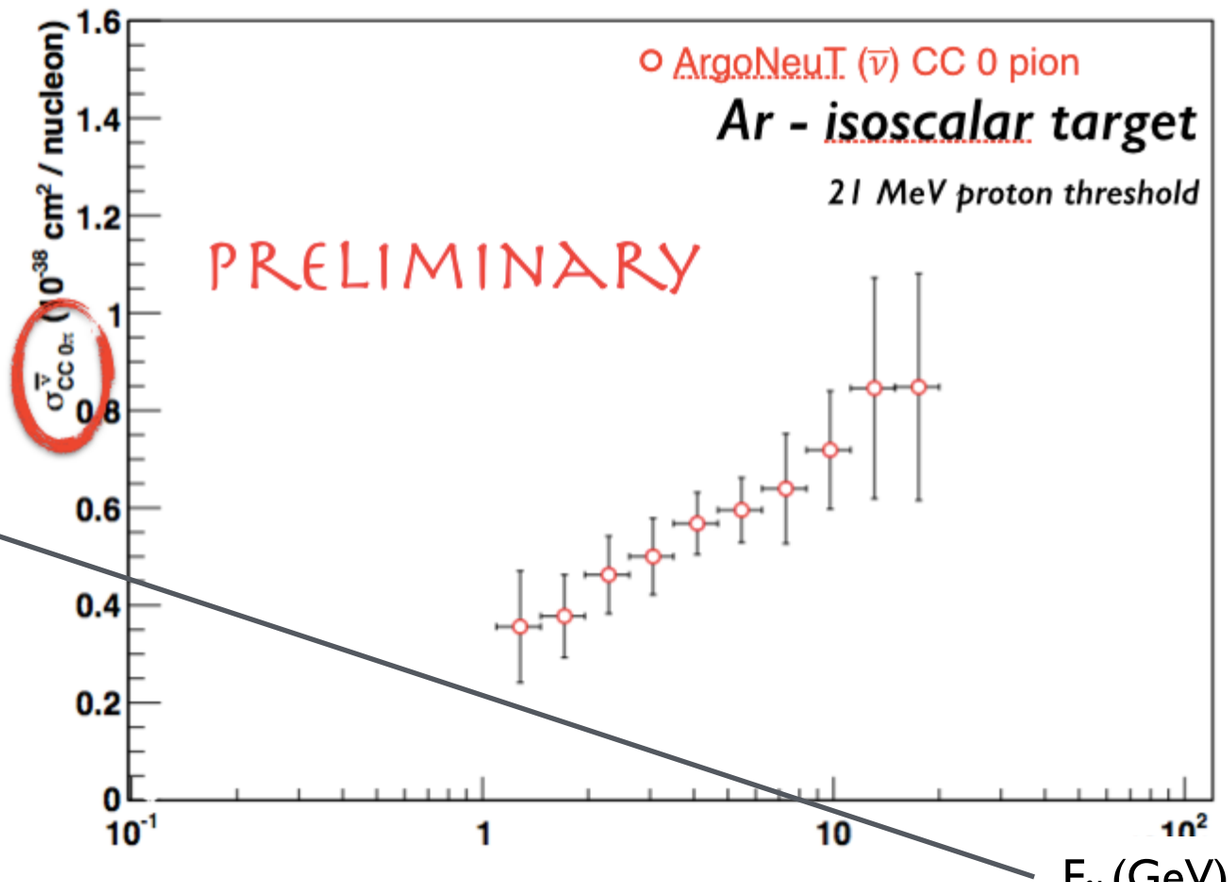
$$E_\nu = (E_\mu + \sum T_{pi} + T_X + E_{miss})$$

T_X=recoil energy of the residual nuclear system [estimated from missing transverse momentum],
E_{miss}=missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value)]

$\bar{\nu}_\mu$ CC 0 pion cross sections as a function of proton multiplicity



New, LArTPC enabled, physics result!



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T_X=recoil energy of the residual nuclear system [estimated from missing transverse momentum],
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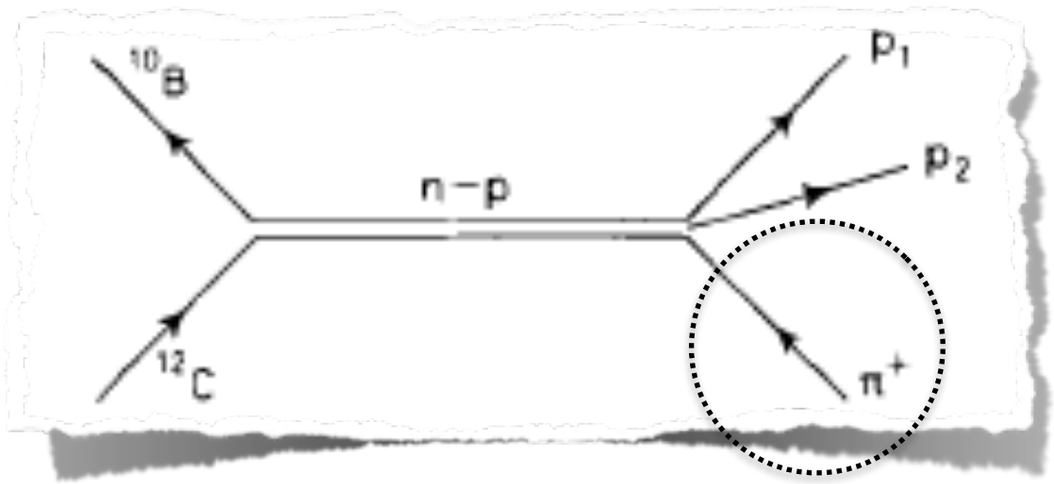
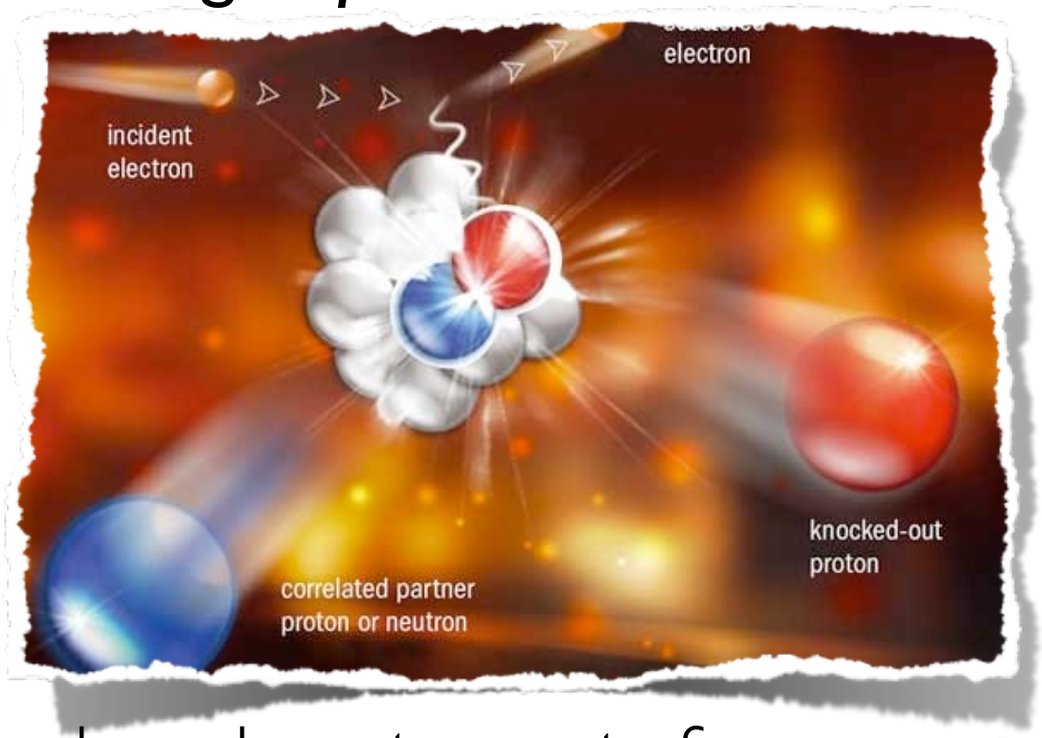
Two-nucleon knock-out events in ArgoNeuT

NN SRC have been extensively probed through two-nucleon knock-out reactions in both ***pion and electron scattering experiments***



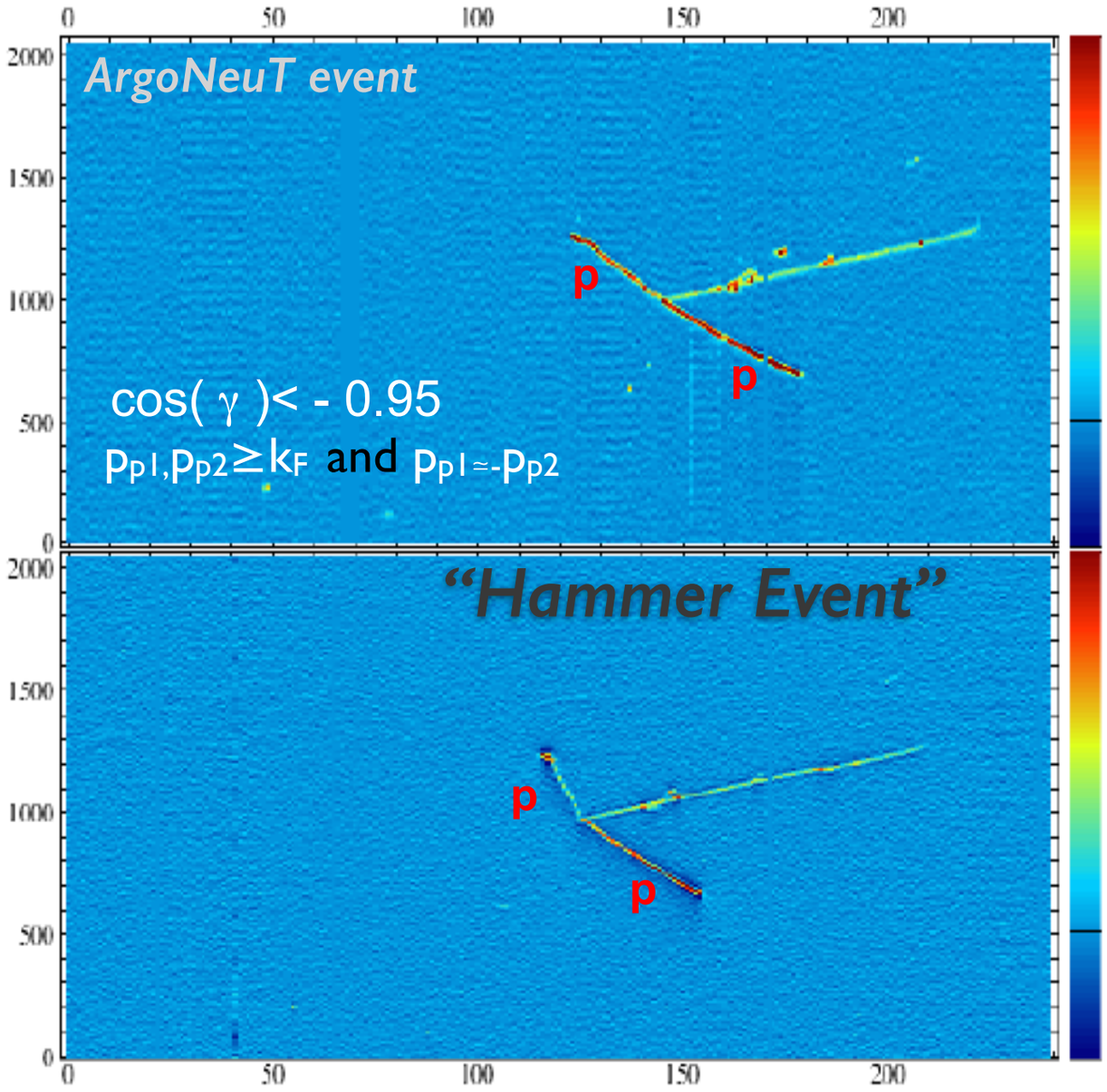


ArgoNeuT: detection of two-nucleon knock-out events from ***neutrino interactions***

Discuss topological features as possibly involving NN SRC content in the target argon nuclei

Neutrino scattering experiments, to our knowledge, have never attempted to directly explore SRC through detection of two nucleon knock-out

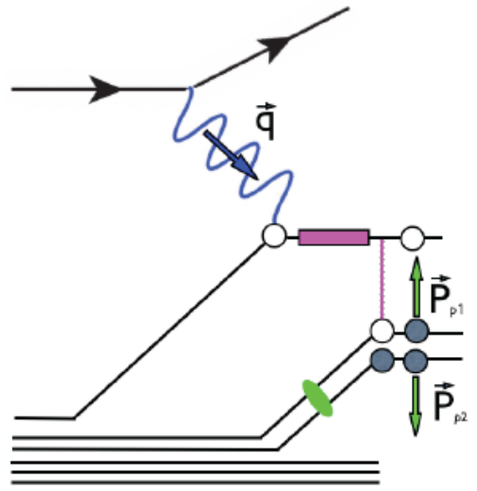
Detection of back-to-back proton pairs



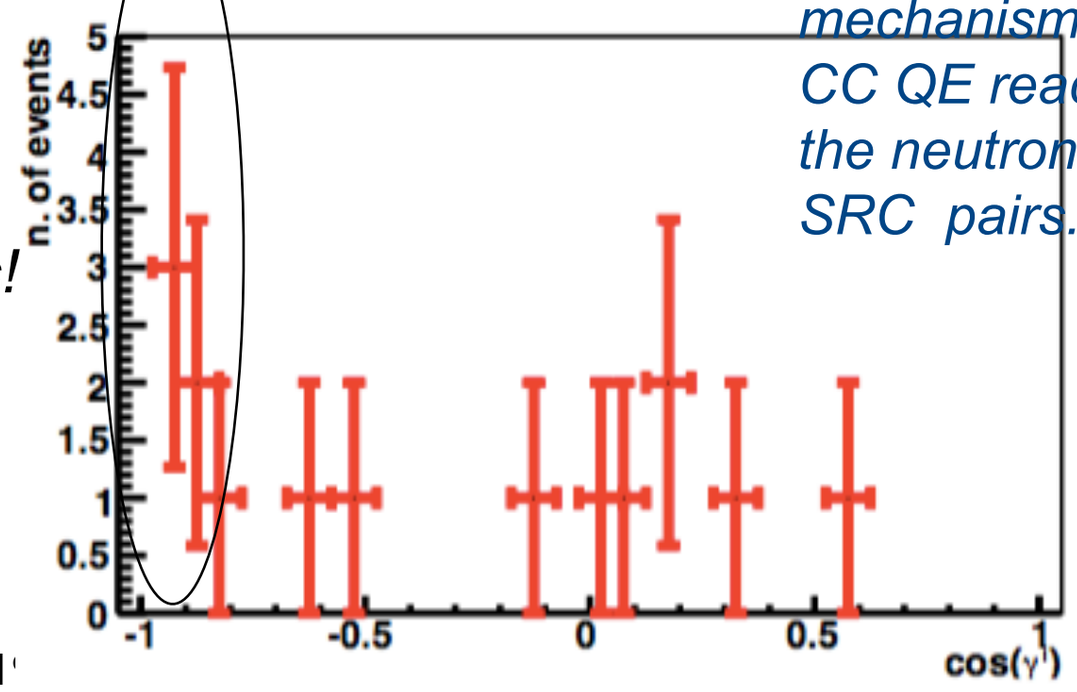
We can see nuclear effects!

4 back-to-back proton pairs events observed in Lab frame.

Possible mechanism is CC RES pionless reactions involving pre-existing SRC np pairs.

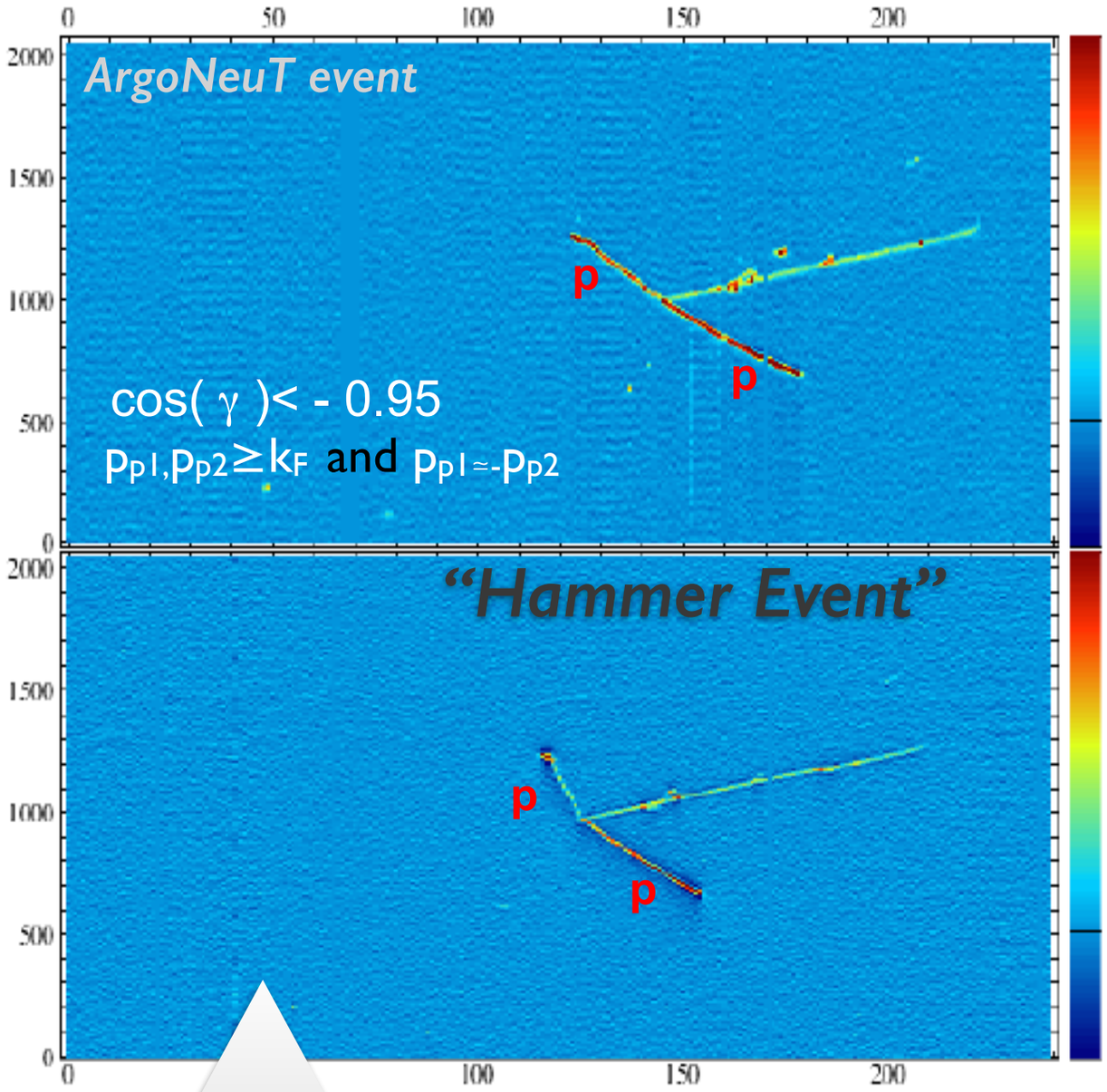


4 back-to-back protons in CM frame as well!



Possible mechanism is CC QE reaction on the neutron of a np SRC pairs.

Detection of back-to-back proton pairs



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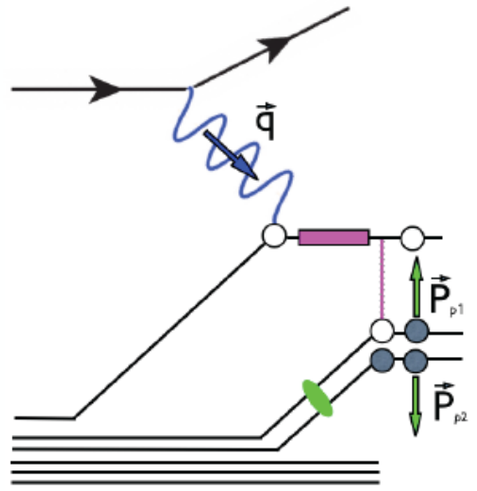
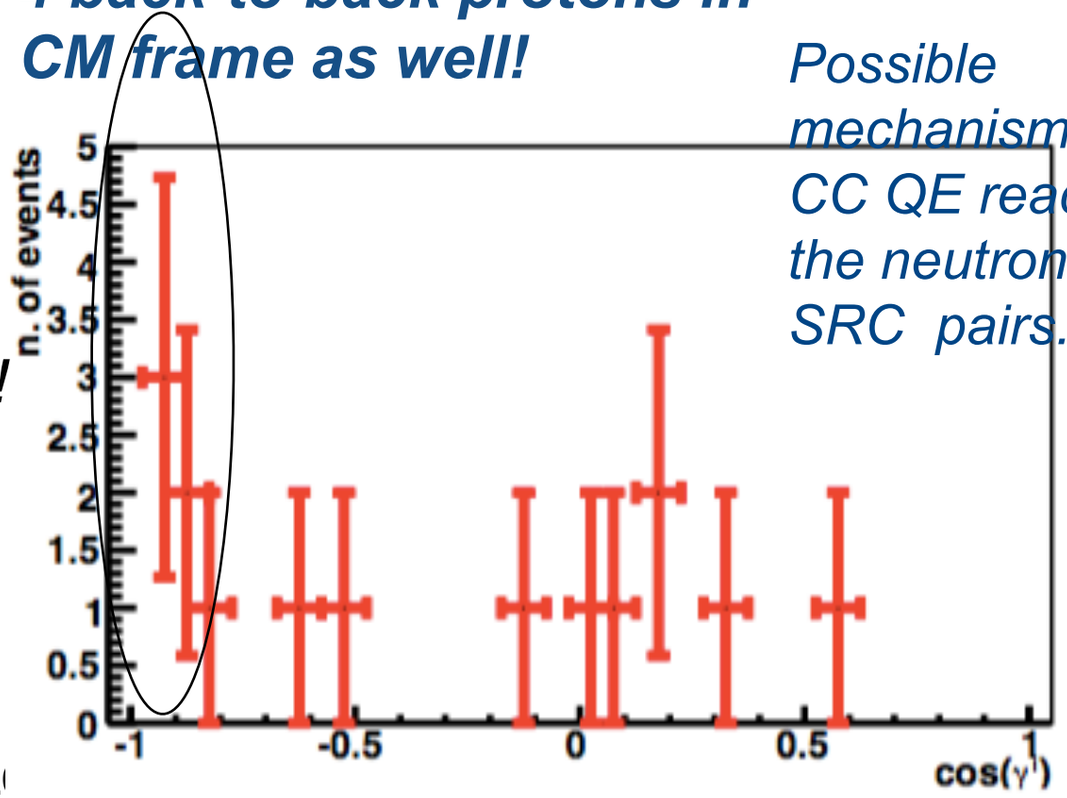


We can see nuclear effects!

New, LArTPC enabled, physics result!

R. Acciarri et al., ArXiv:1405.4261 Submitted to PRD

4 back-to-back protons in CM frame as well!

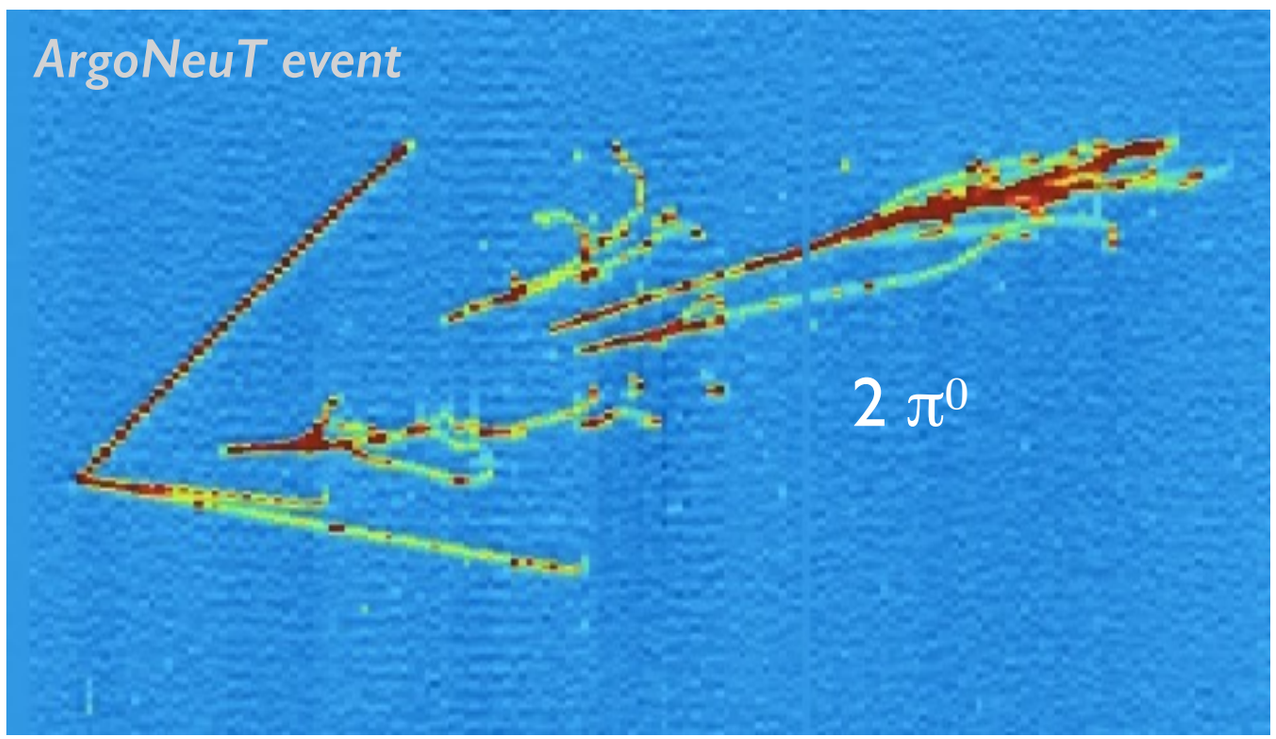


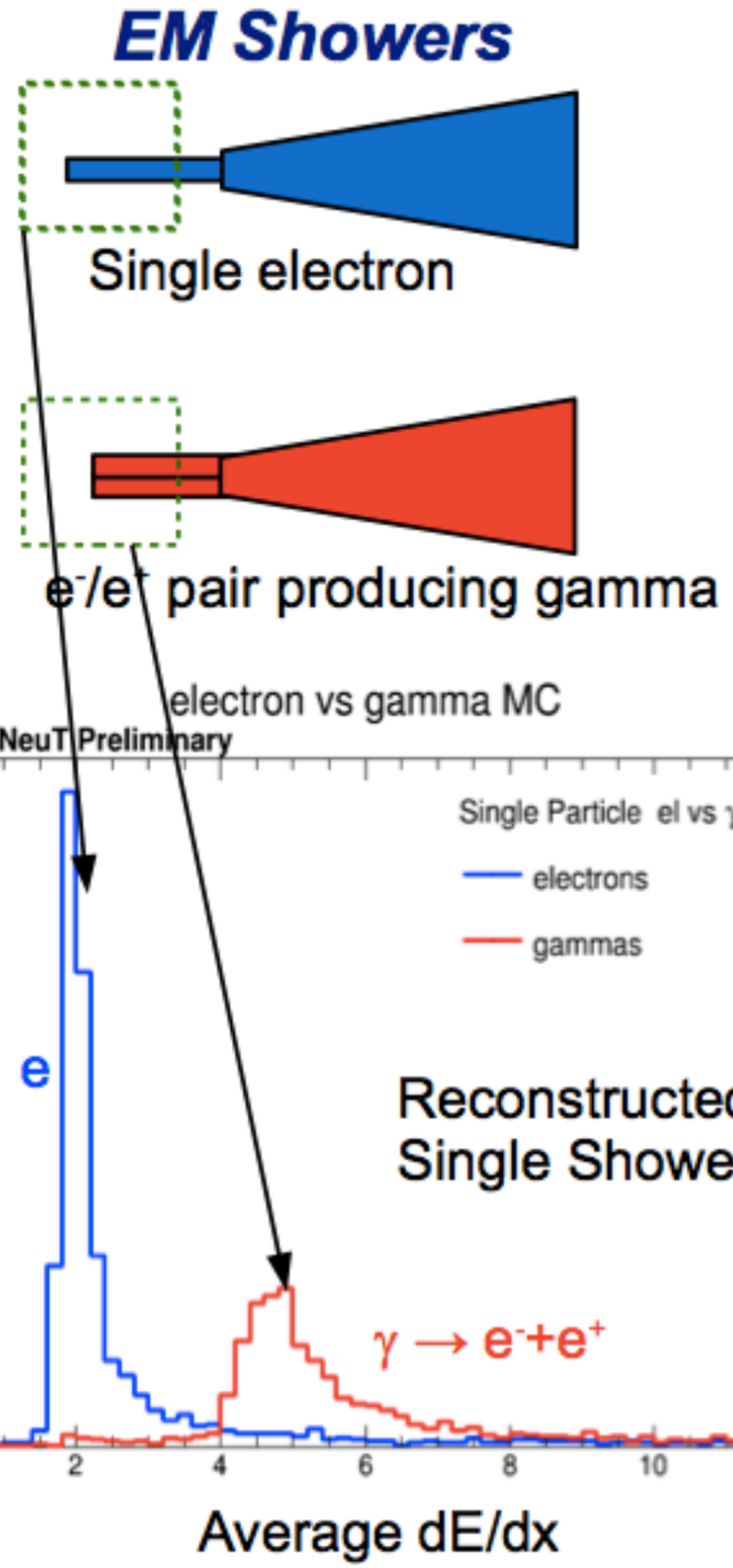
Possible mechanism is CC QE reaction on the neutron of a np SRC pairs.

Electron/gamma separation

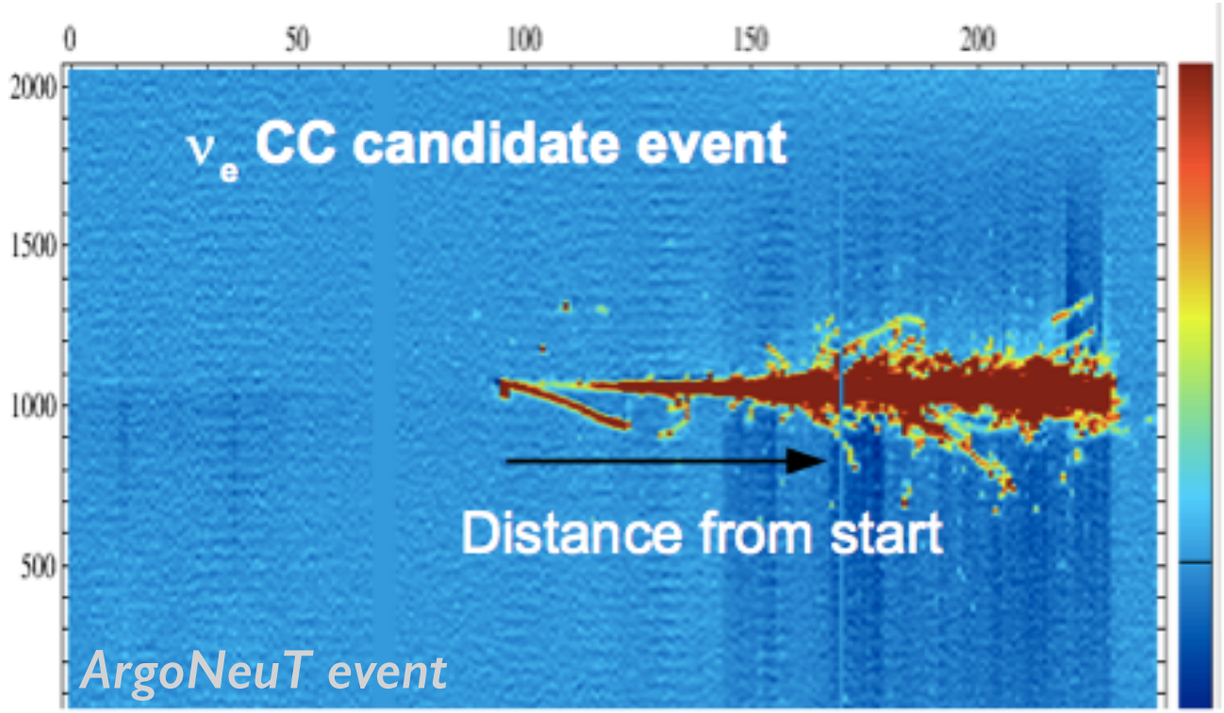
- An EM shower that starts after a gap from the vertex is always background (especially if one can see two of them).

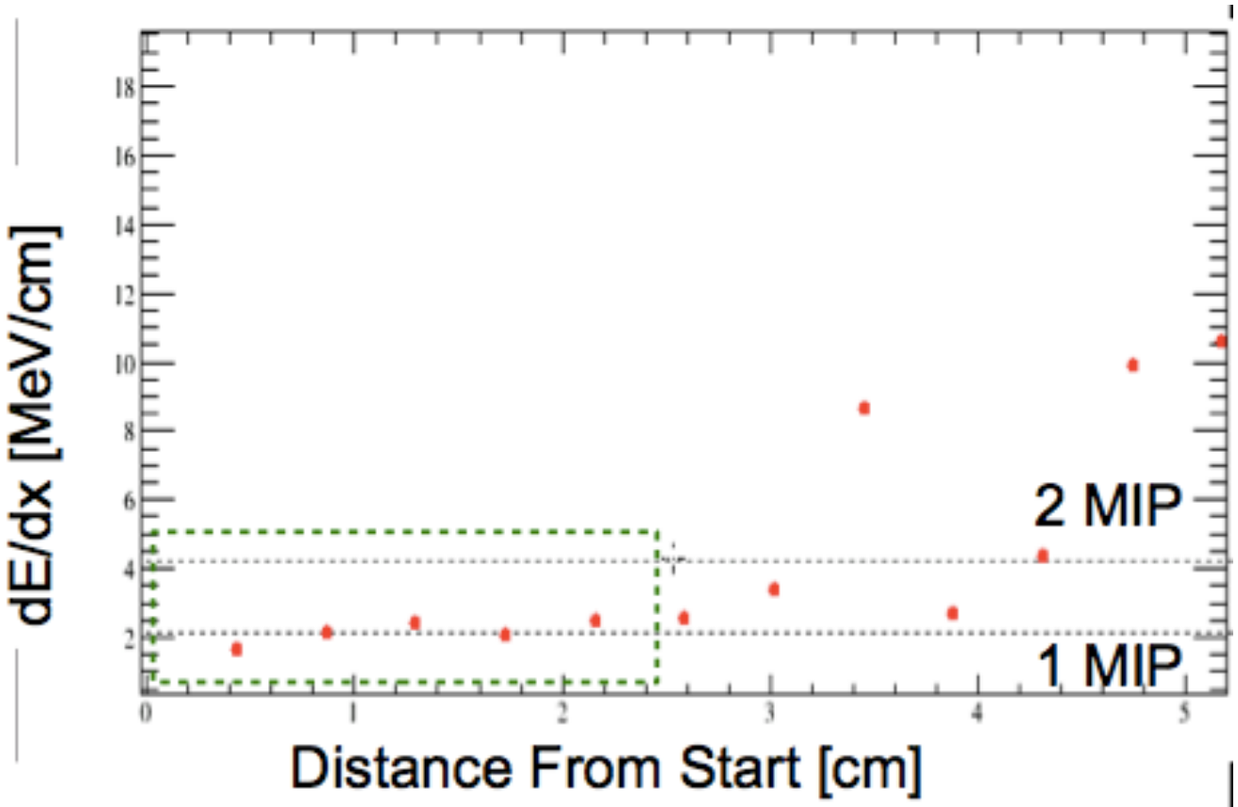
- Even if the gap is very small
  - in LAr can reconstruct the charge at the start of the shower - "dE/dx discrimination".

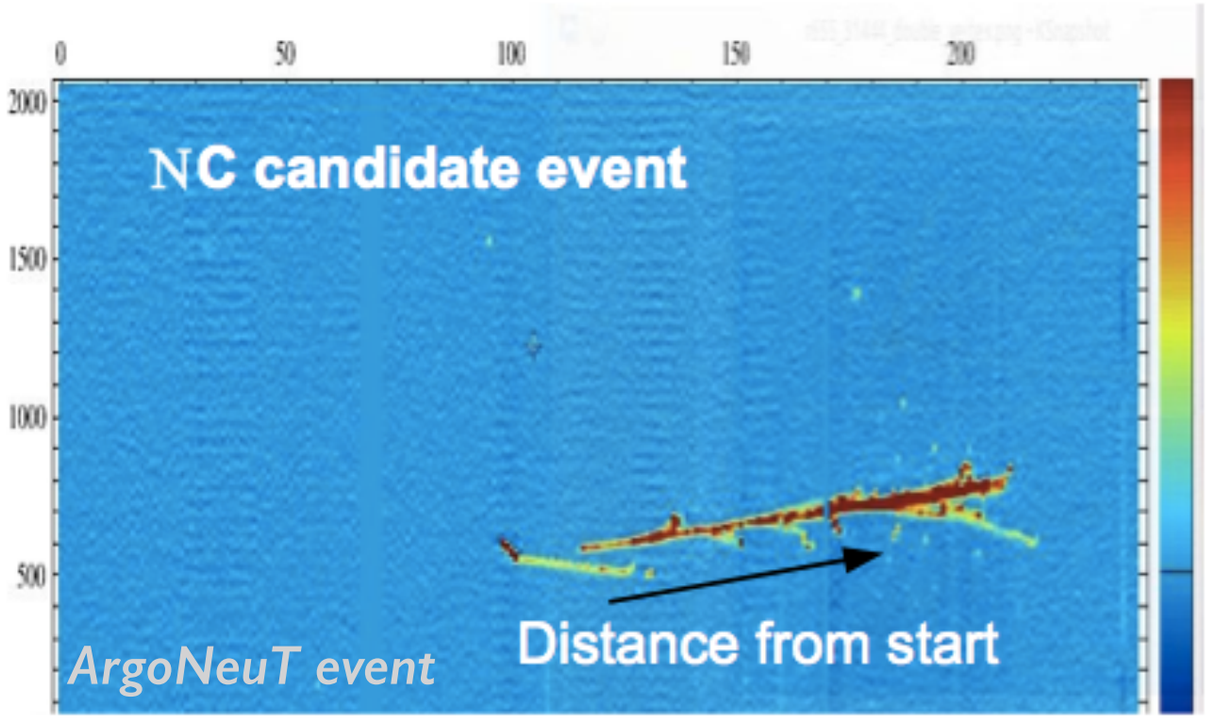


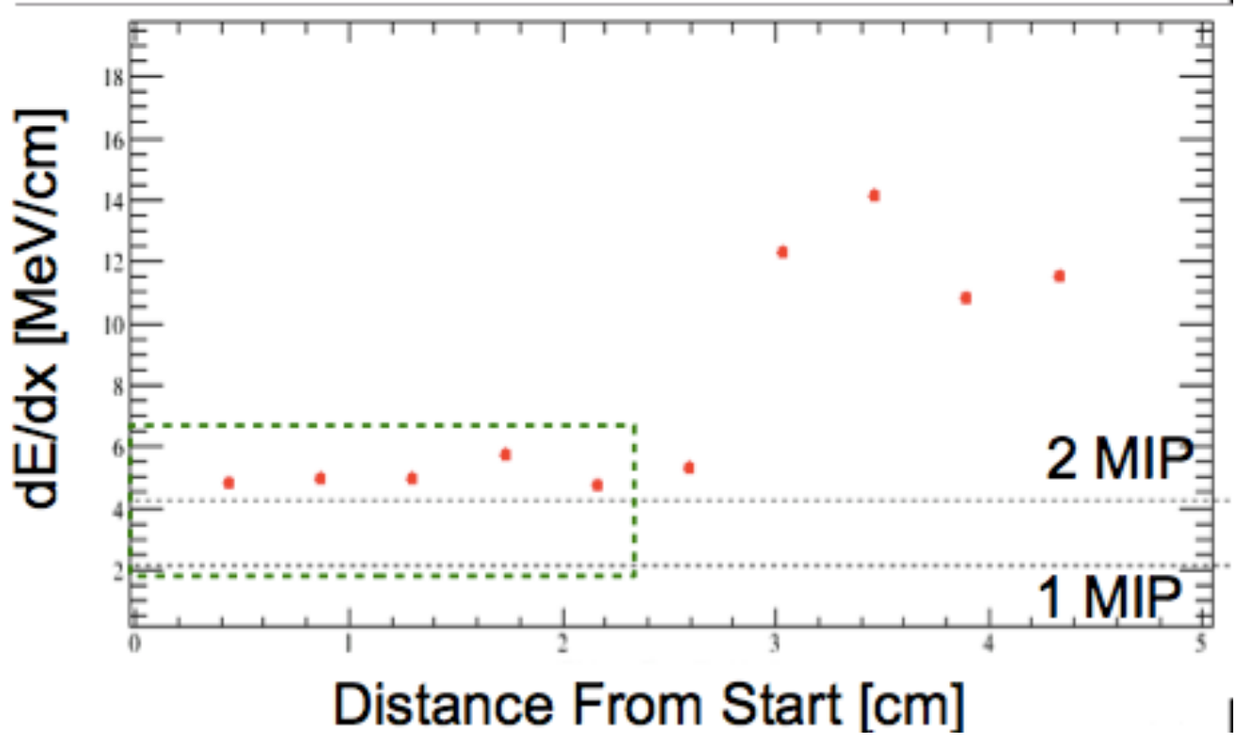


EM shower events





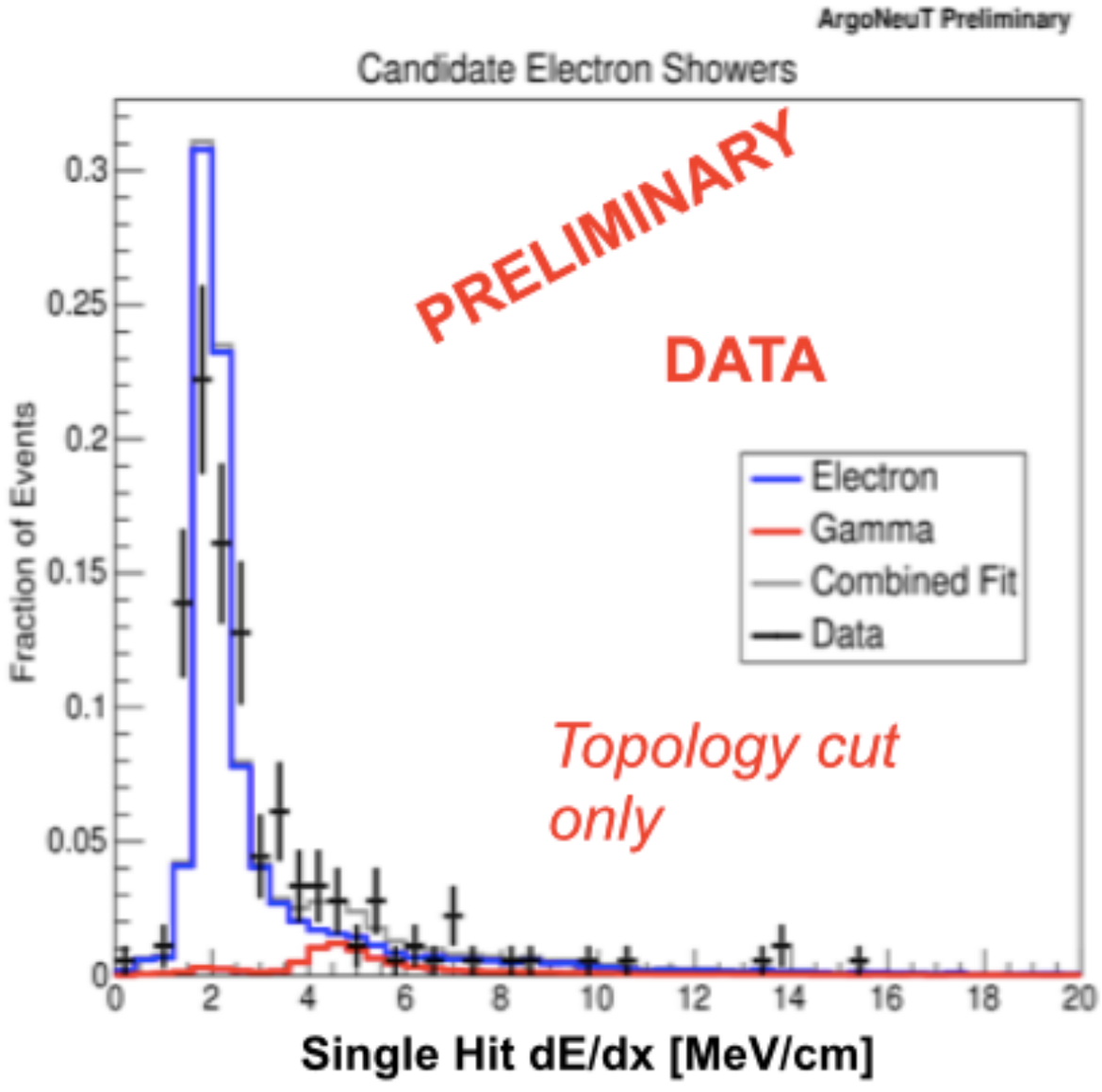




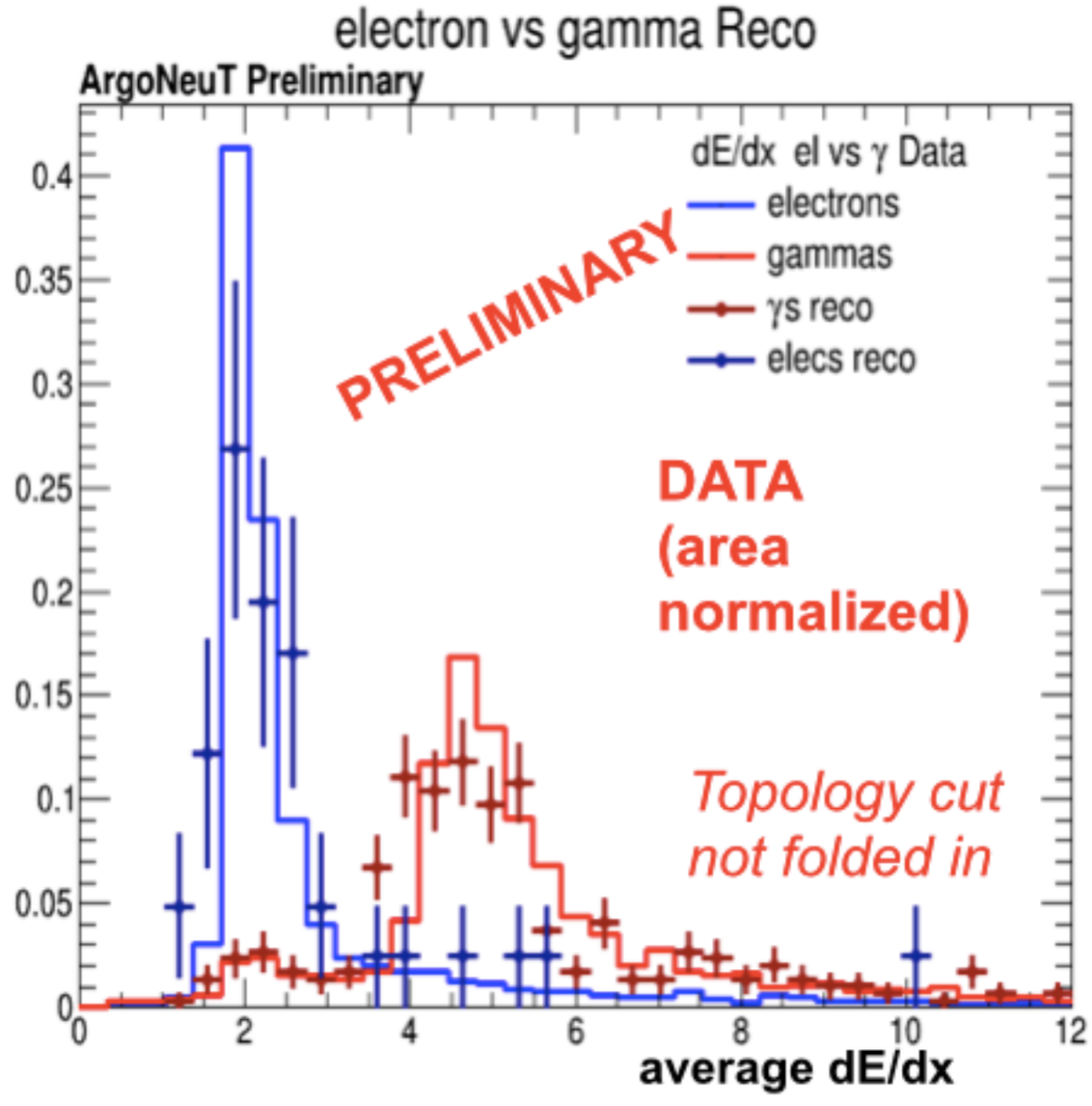
Data-based dE/dx plot

- Gammas defined as EM showers detached from visible vertex.
- Electrons defined as EM showers with visible vertex activity and no gap.
- Electron events require no track matched to MINOS muon.

Landau-like distribution of electron event.
Single hit charge depositions.



Electron/single gamma separation



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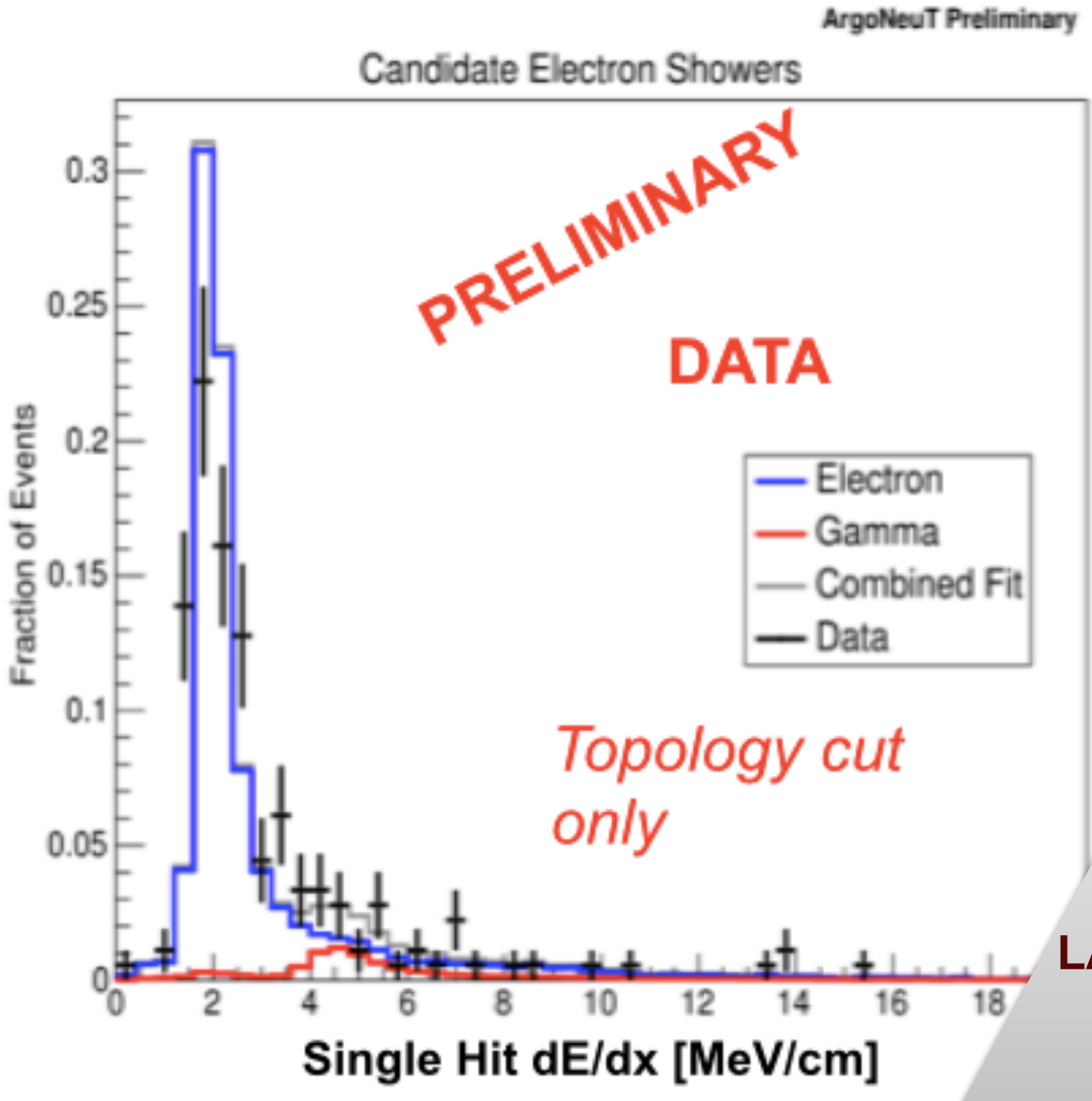

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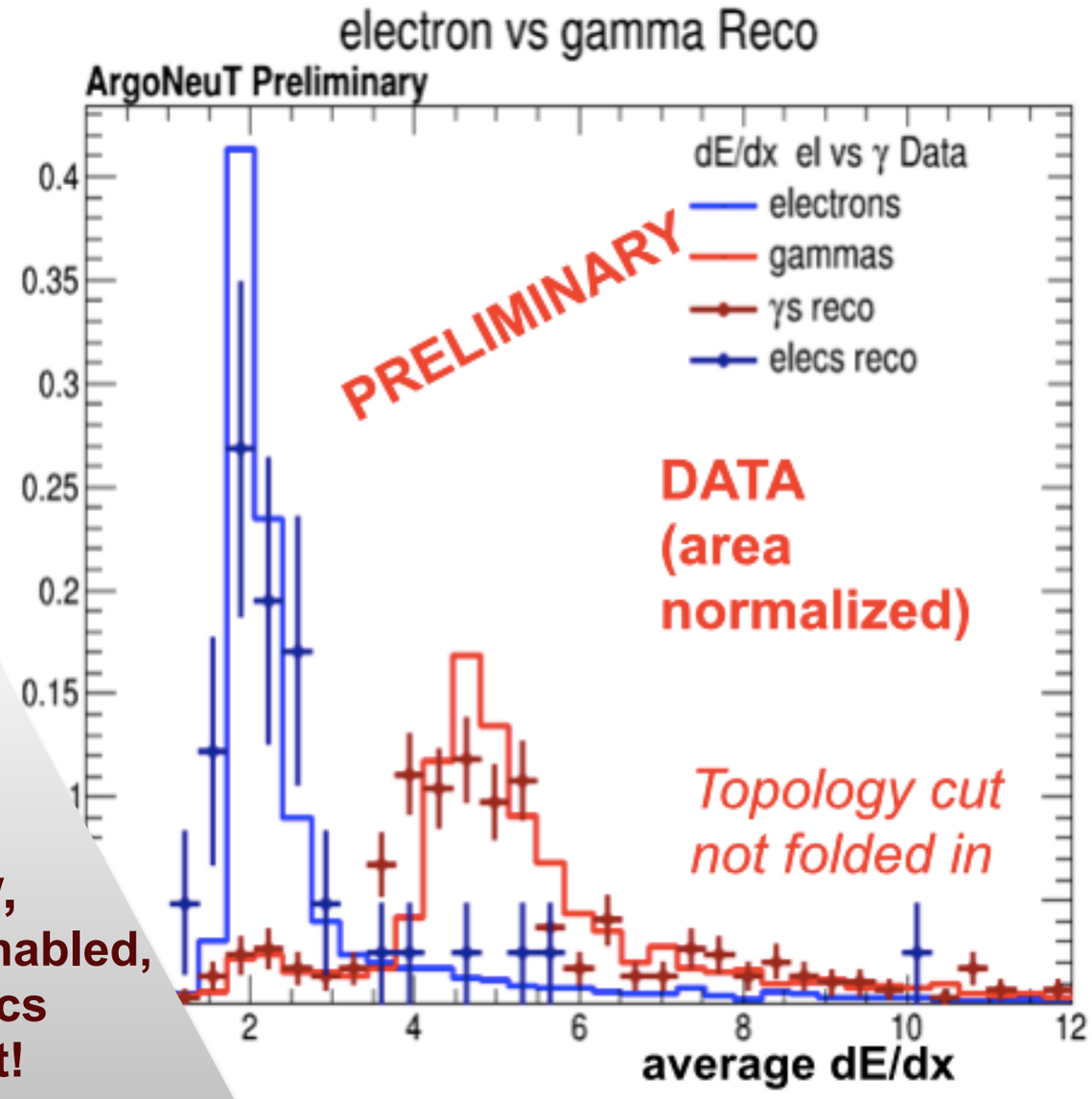
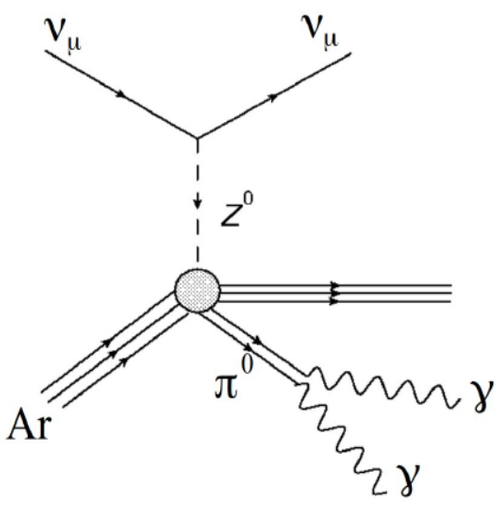
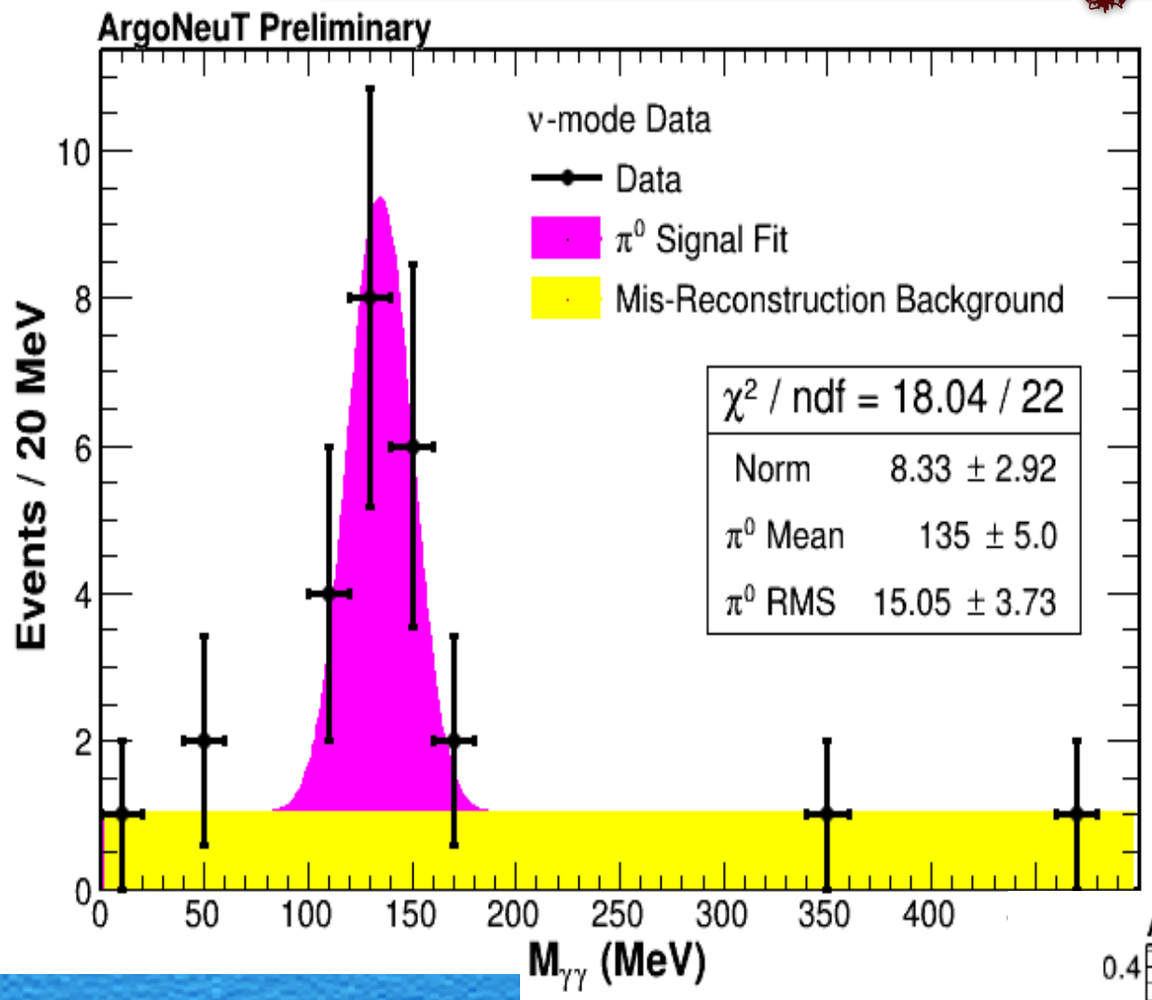


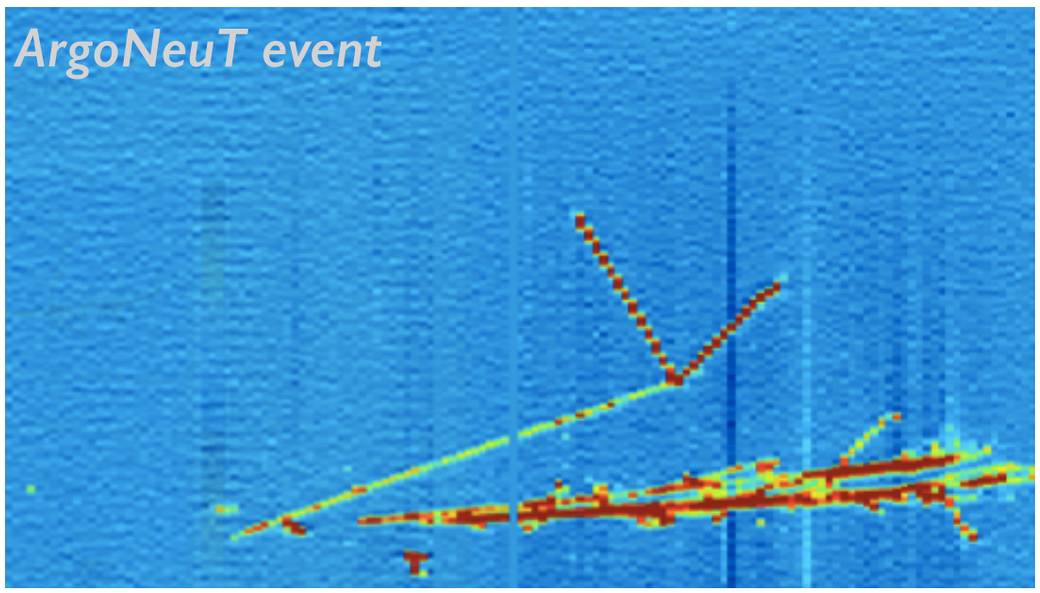
New, LArTPC enabled, physics result!

NC π^0 Study

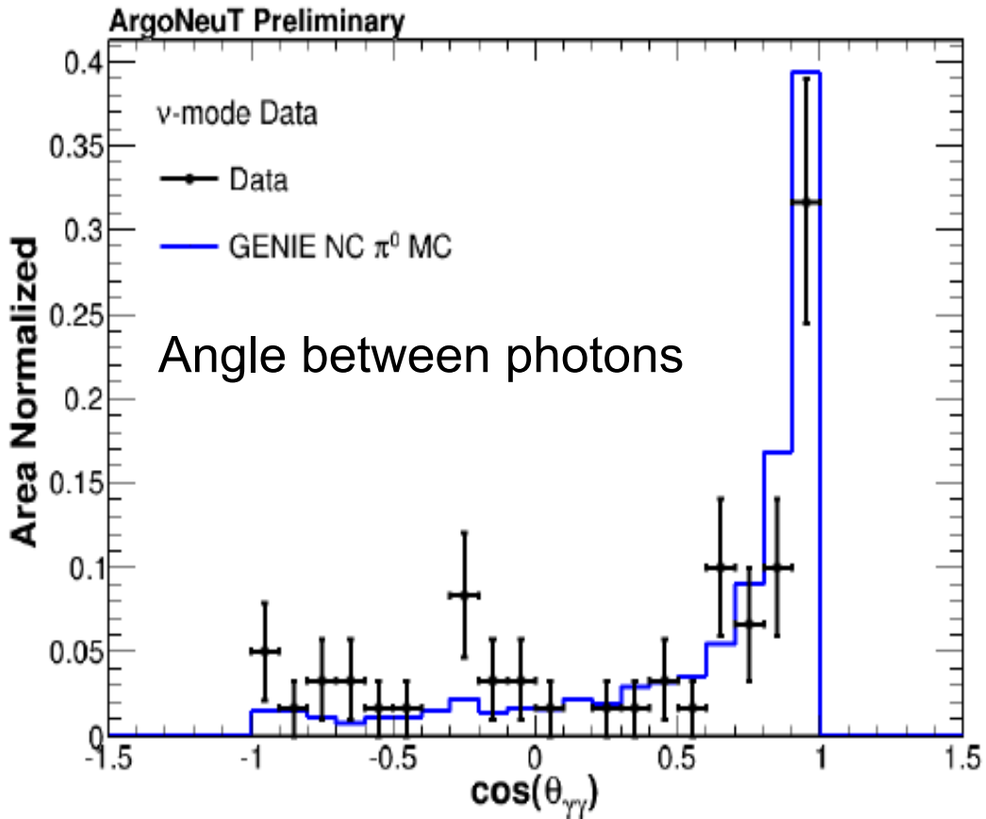




- ArgoNeuT is too small to contain the majority of photon showers from π0's.
- A MC based set of energy corrections based on event topology is needed.

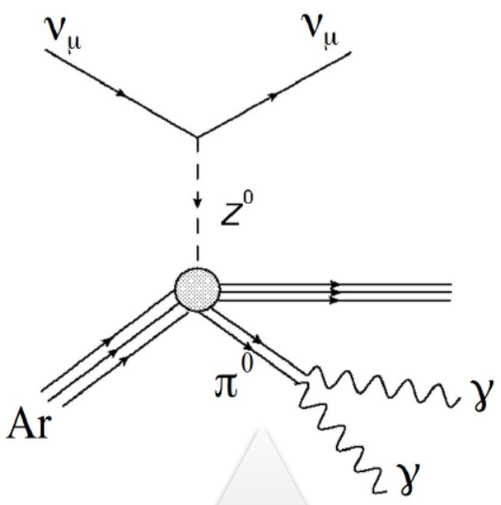


2 γ-initiazed showers

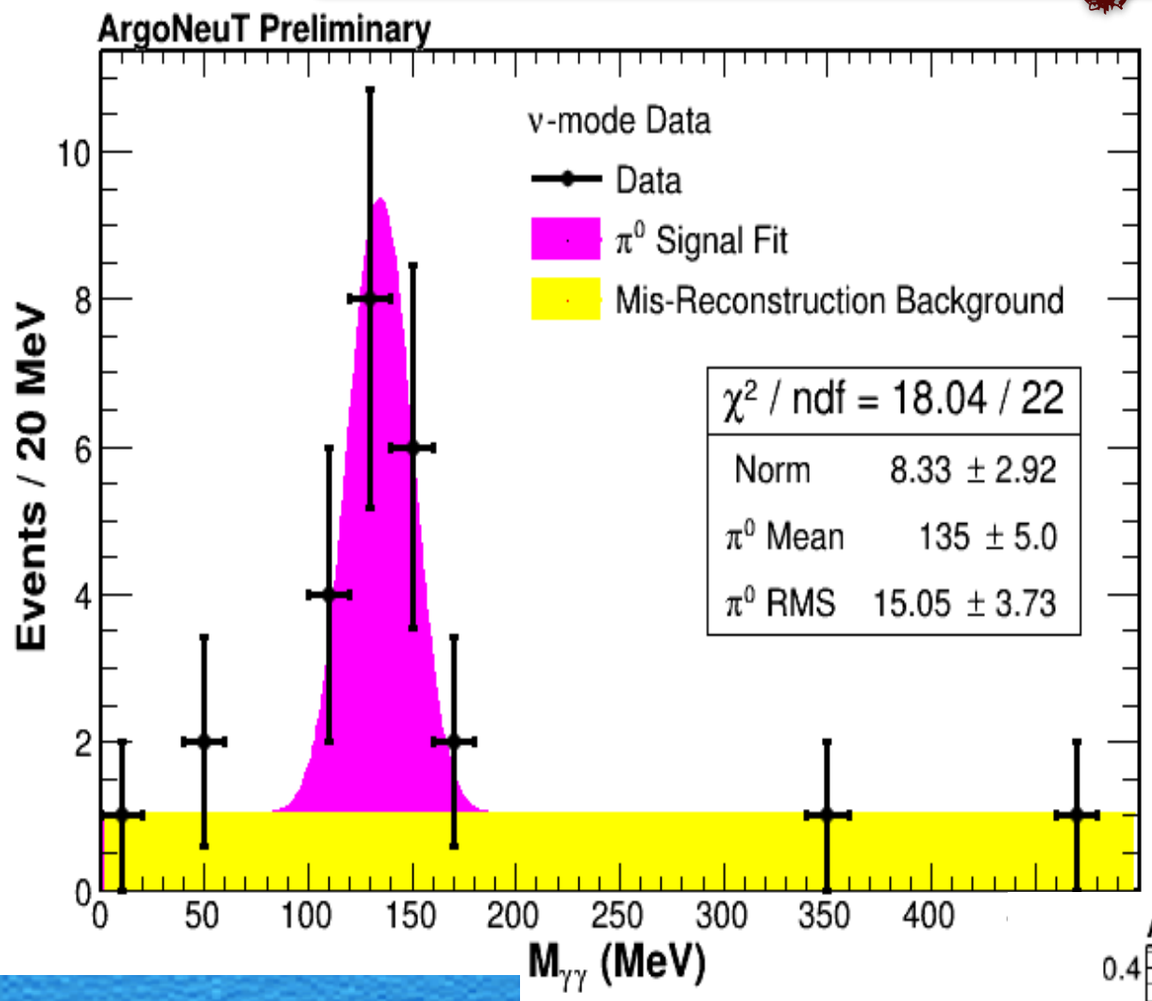


Work in progress to refine energy corrections and analyze the full data set

NC π^0 Study



New physics analysis



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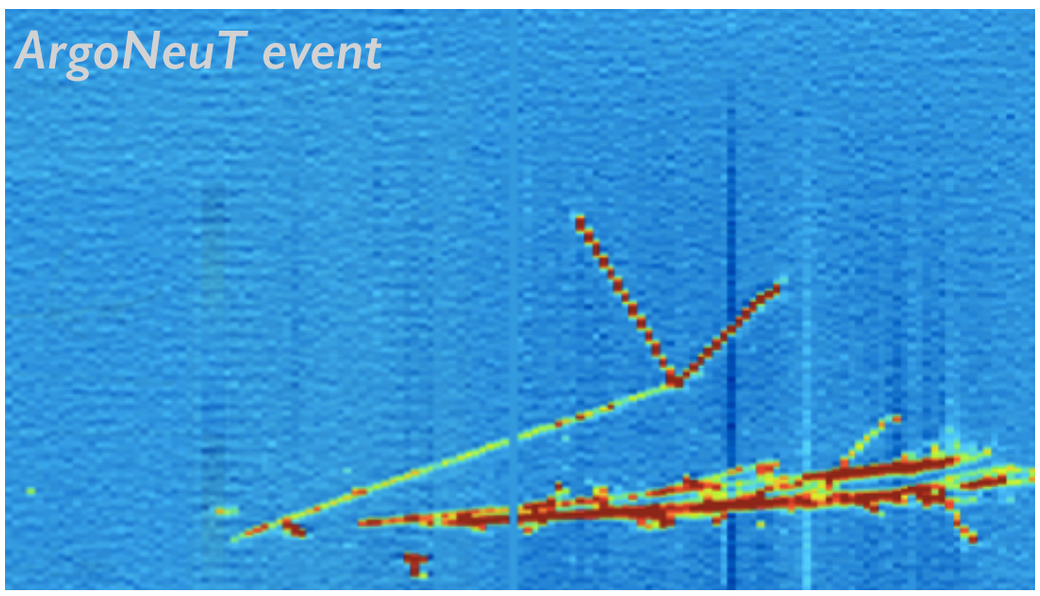

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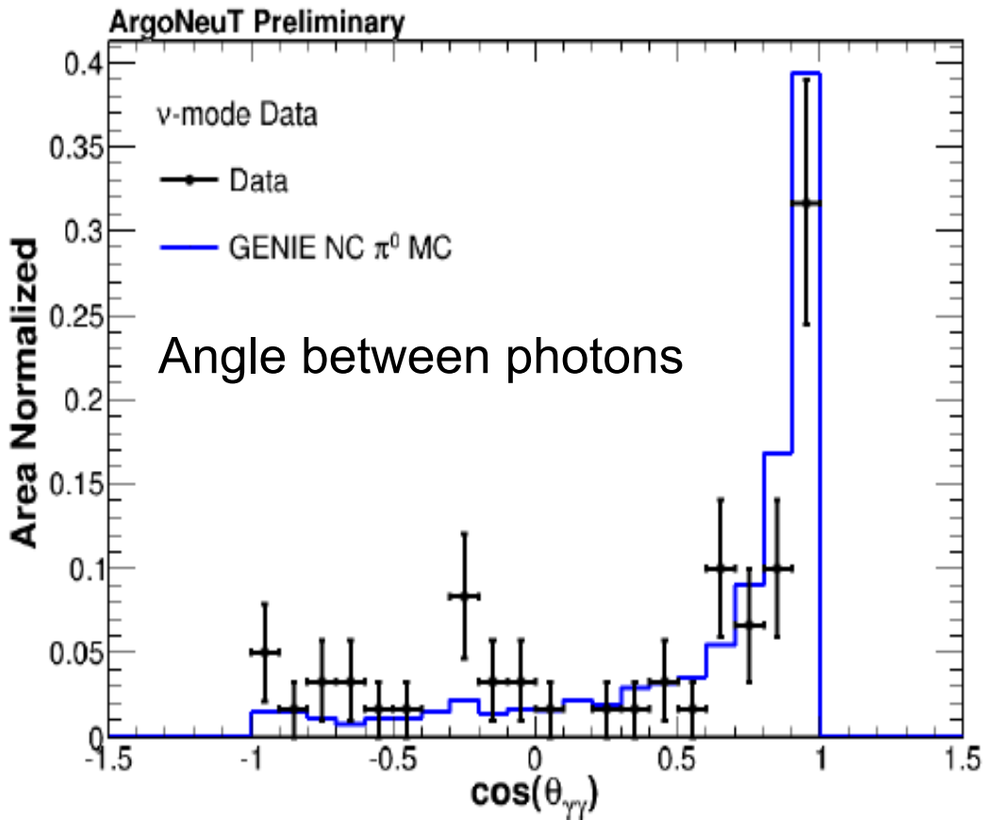
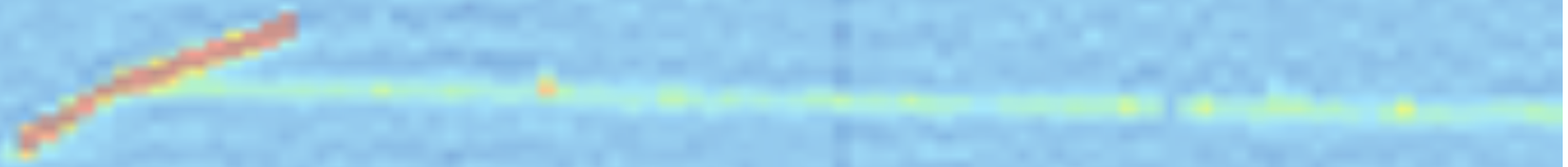


Work in progress to refine energy corrections and analyze the full data set

Summary

- Despite the ArgoNeuT modest active LAr mass (~1/4 T) and its short (~5 months) exposure to neutrino beams, the experience and the results obtained are highly relevant.

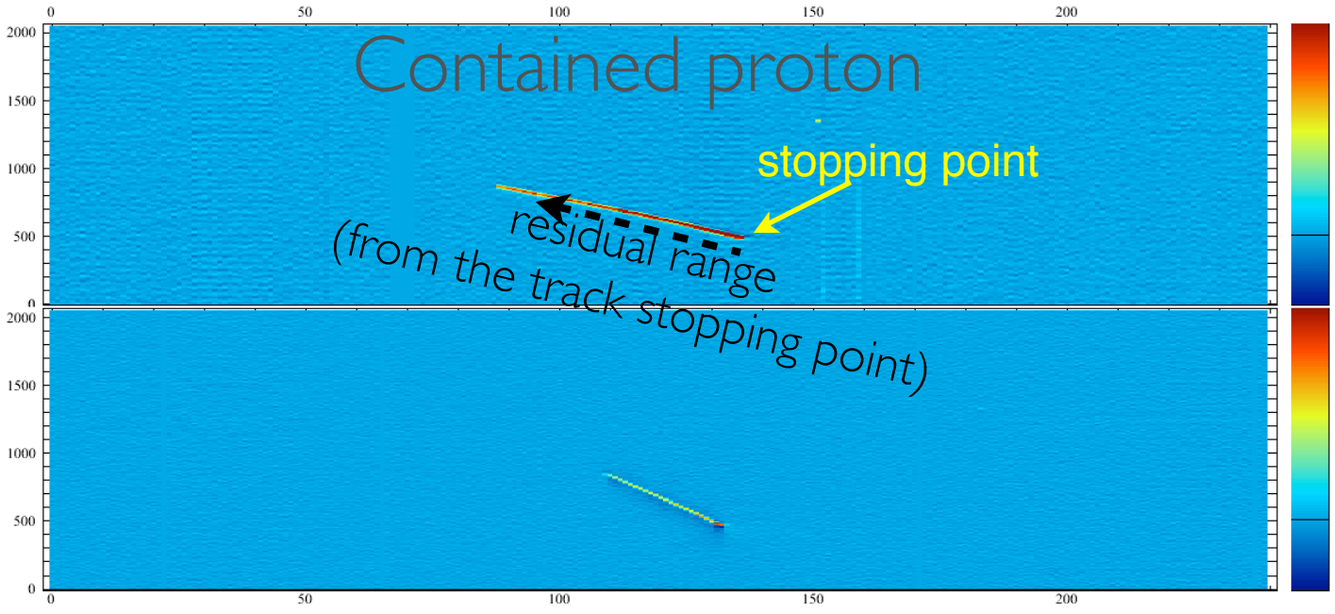
- ArgoNeuT was the first LArTPC operating in a low energy neutrino&antineutrino beam, the region of interest for current short-baseline and future long-baseline experiments.



- Its primary goal was to serve as technology demonstrator, but indeed made much more than that: ArgoNeuT has provided a wealth of physics results on neutrino interaction mechanisms yet not fully resolved, and is still yielding new intriguing outputs from the on-going studies.

Backup

STOPPING TRACKS - CALORIMETRIC RECONSTRUCTION and PID

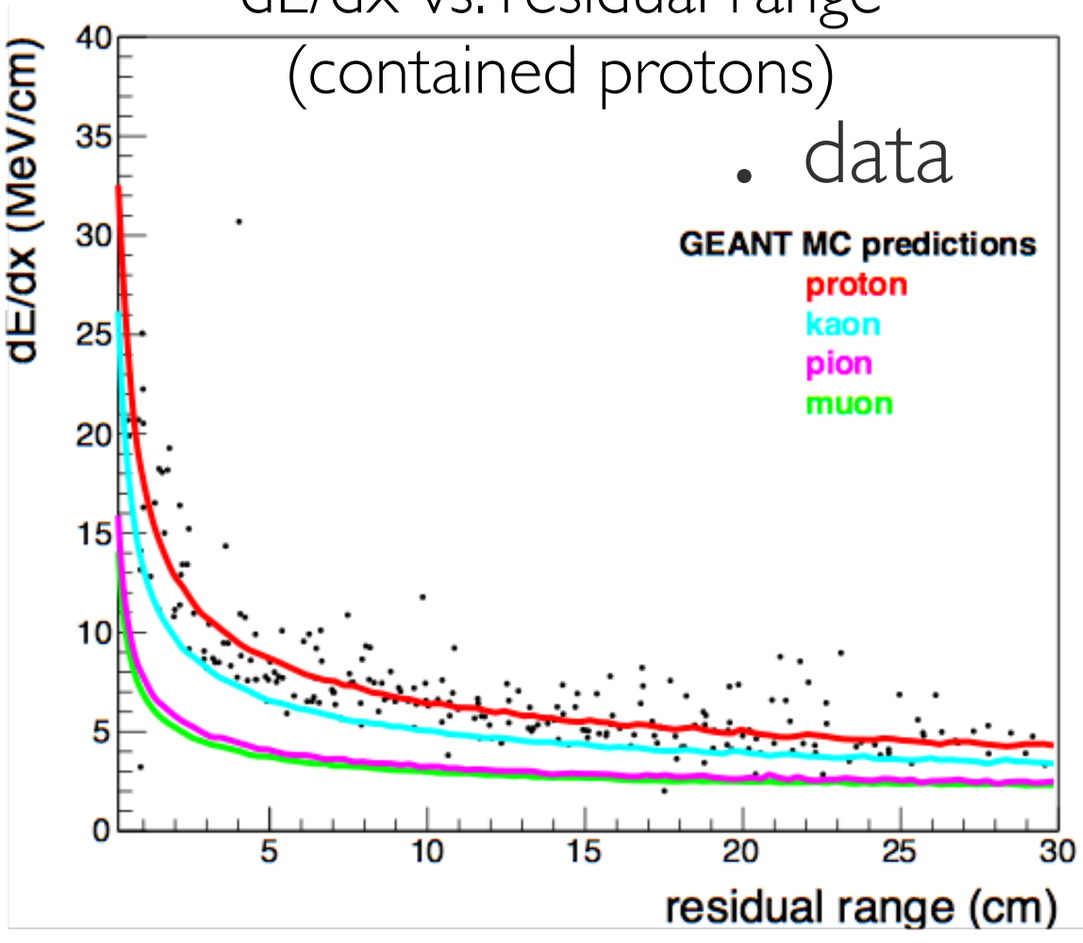


Measurement of:

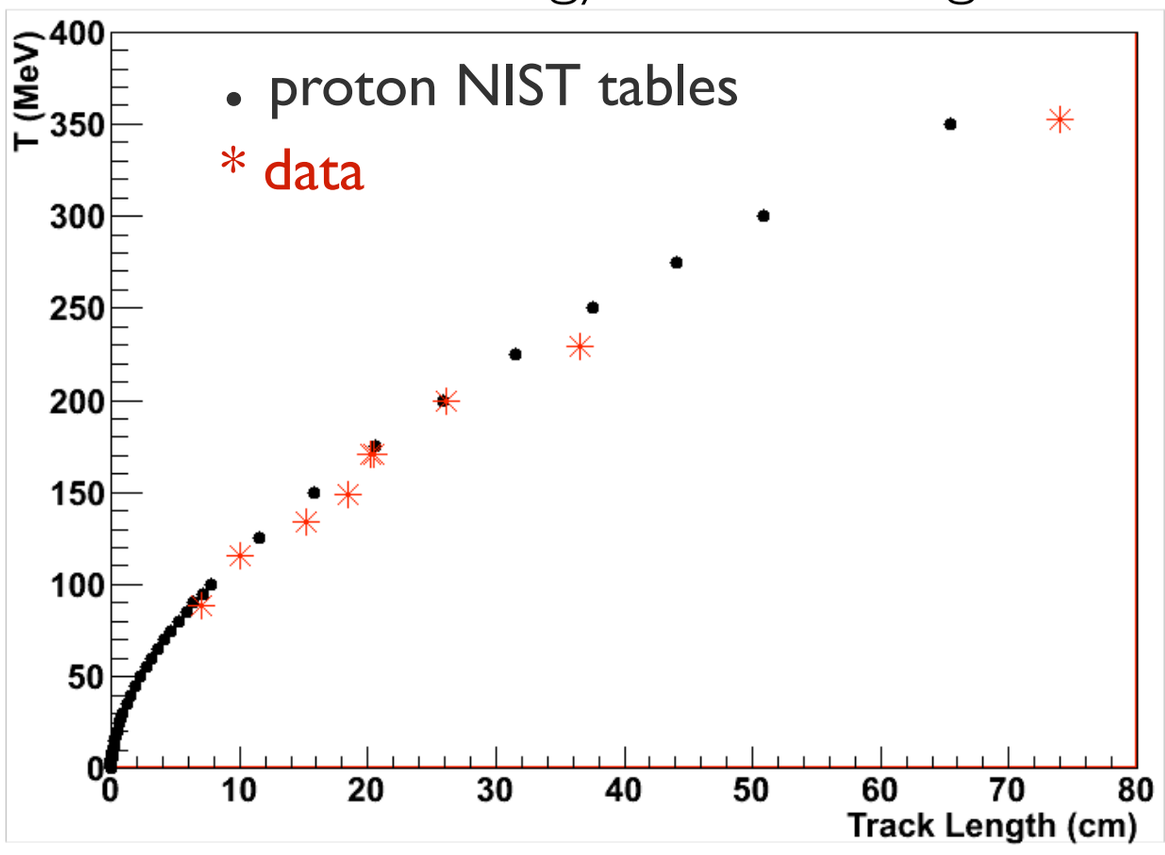
- dE/dx vs. residual range along the track
- kinetic energy vs. track length

χ^2 based method is used for PID

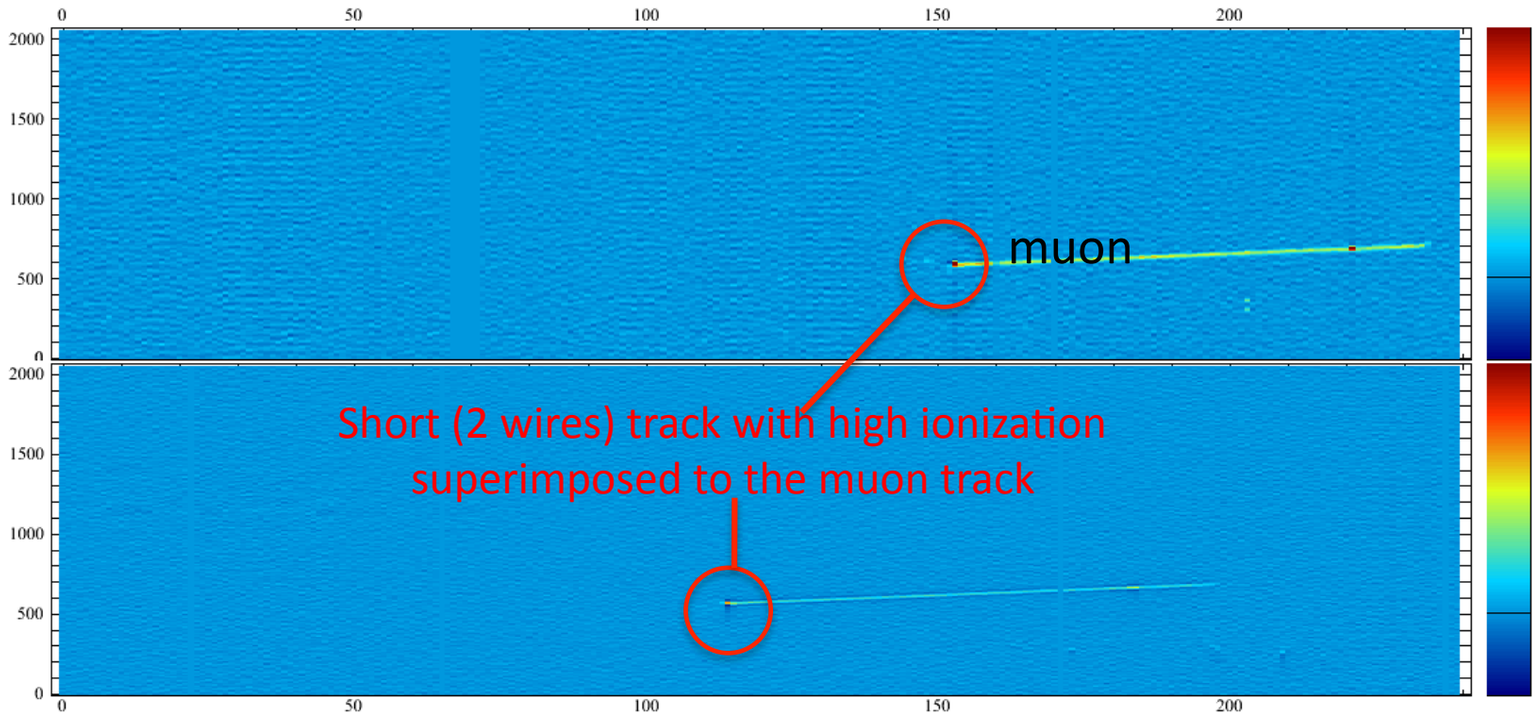
dE/dx vs. residual range (contained protons)



Kinetic Energy vs. track length



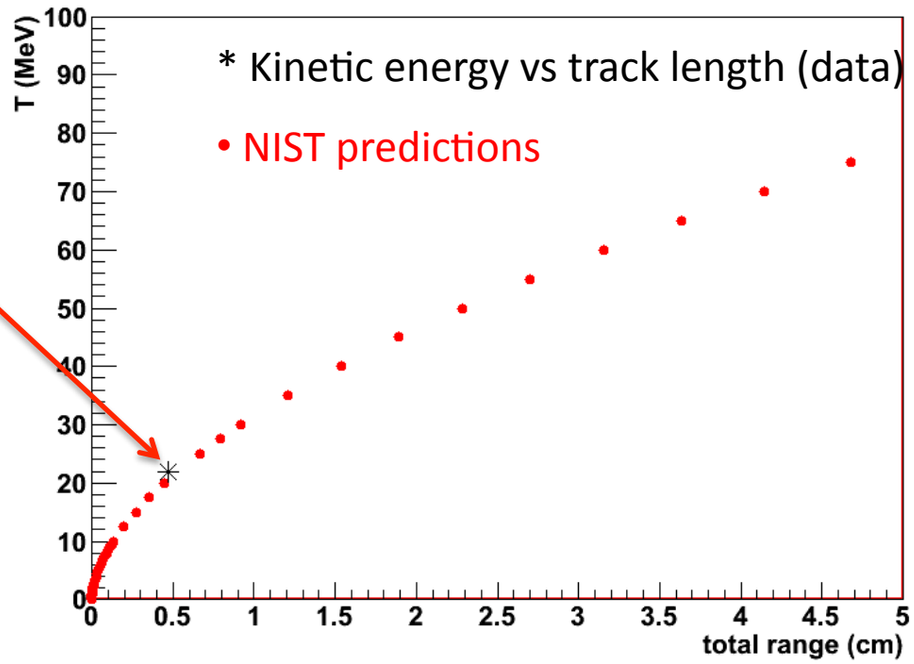
Example of Low energy proton reconstruction



The short track behaves like proton

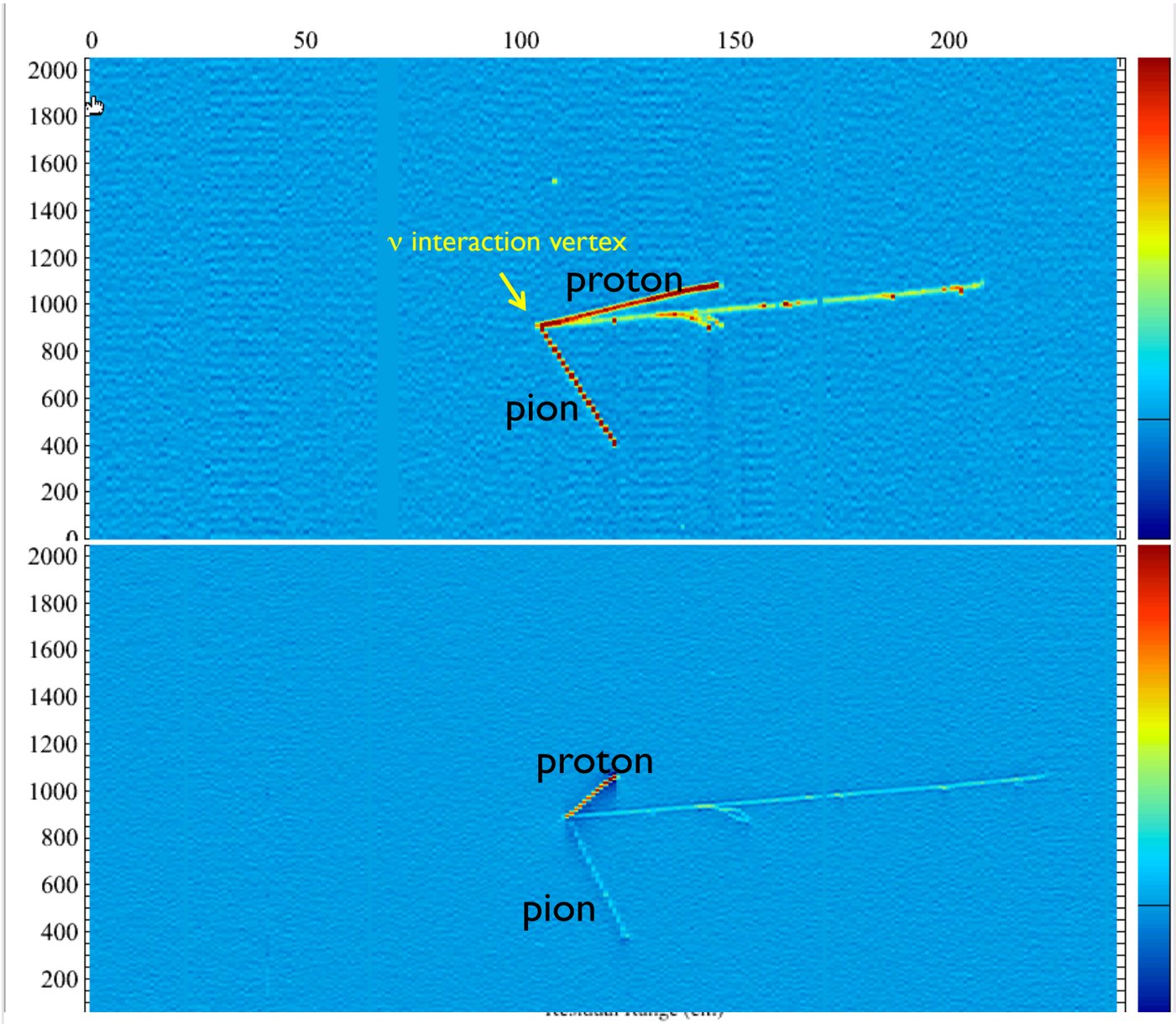
Length=0.5 cm

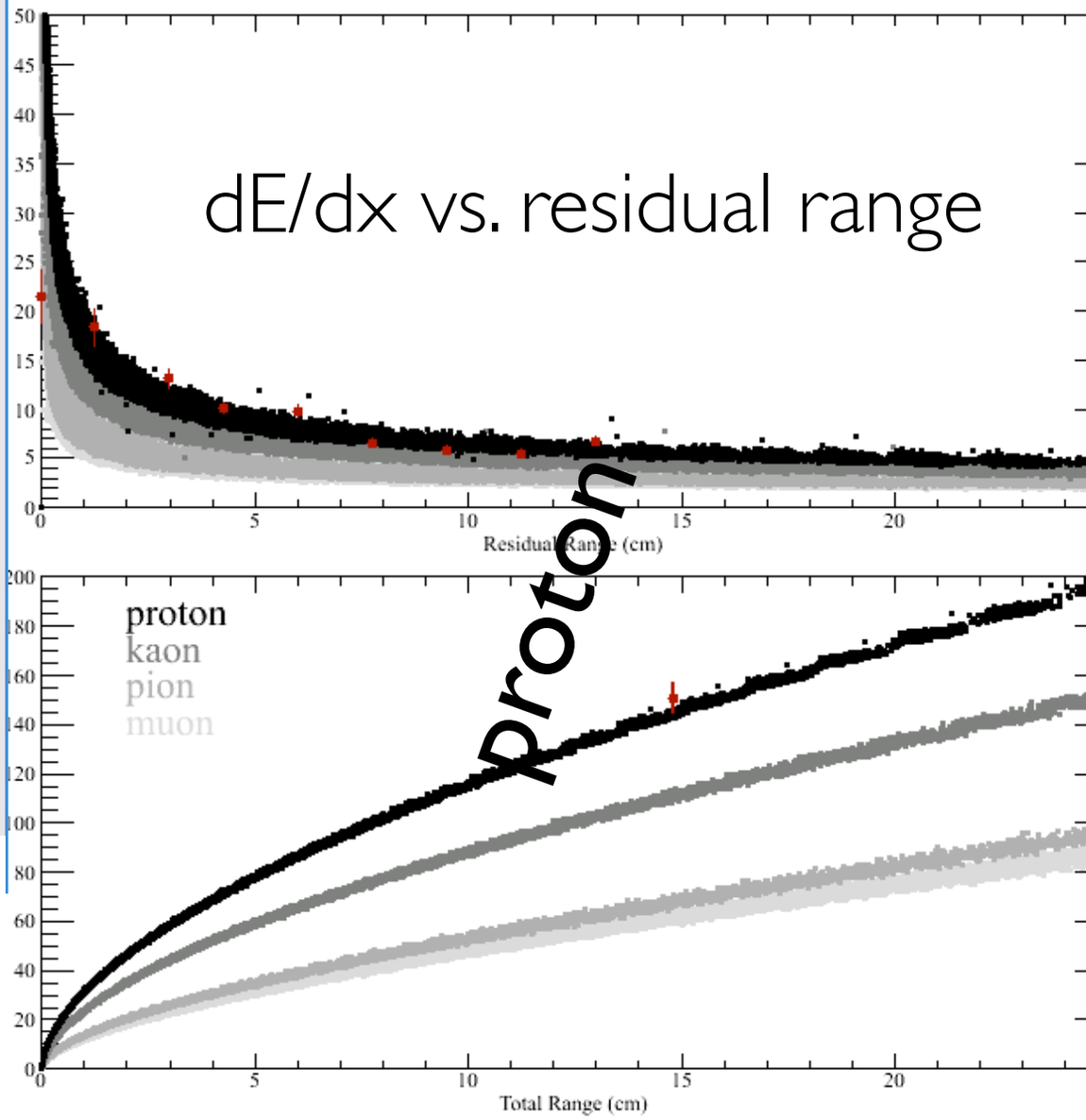
KE=22±3 MeV

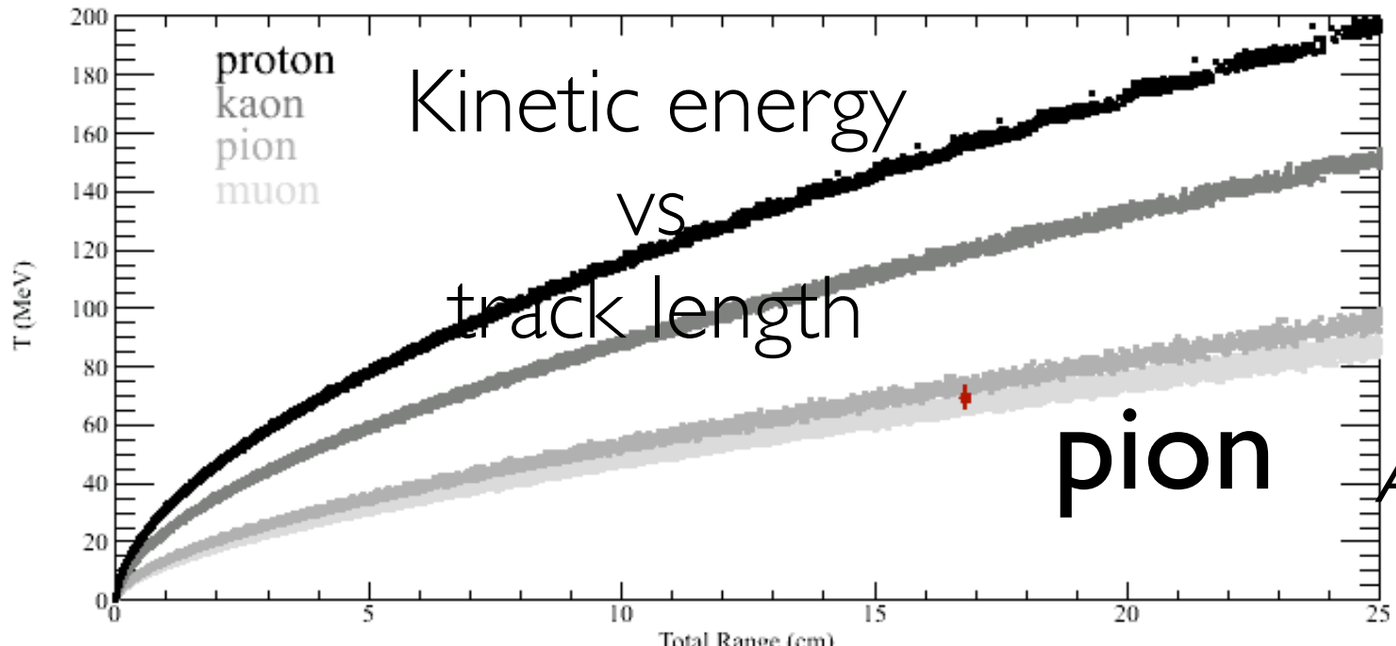


ArgoNeuT proton threshold: 21 MeV of Kinetic Energy

p/π± identification







ArgoNeuT pion reconstruction threshold:
~8 MeV Kinetic energy

PID Efficiencies

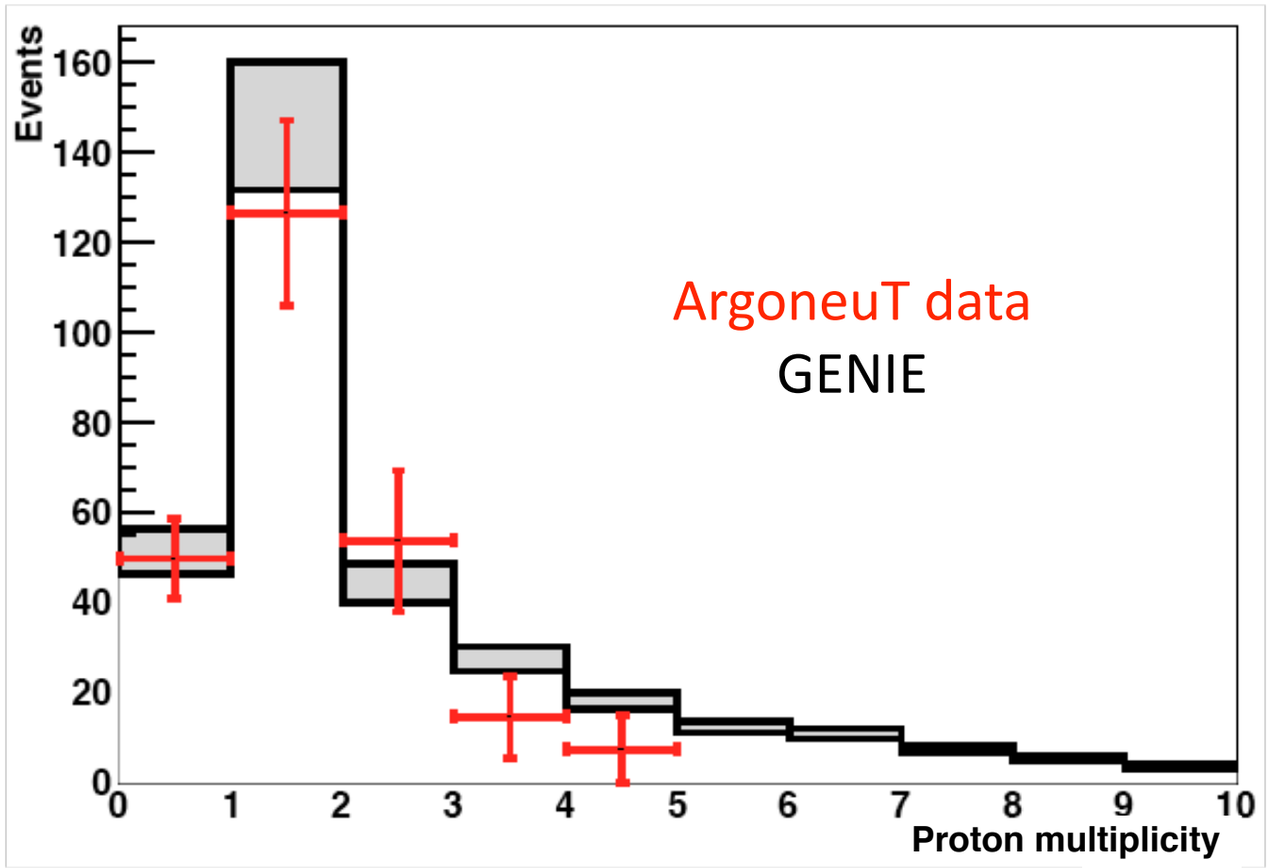
Generated

Identified as	Proton	Kaon	Pion	Muon
Proton	0.97	0.15	0.05	0
Kaon	0.03	0.60	0.09	0.01
Pion	0	0.06	0.25	0.28
Muon	0	0.20	0.61	0.71

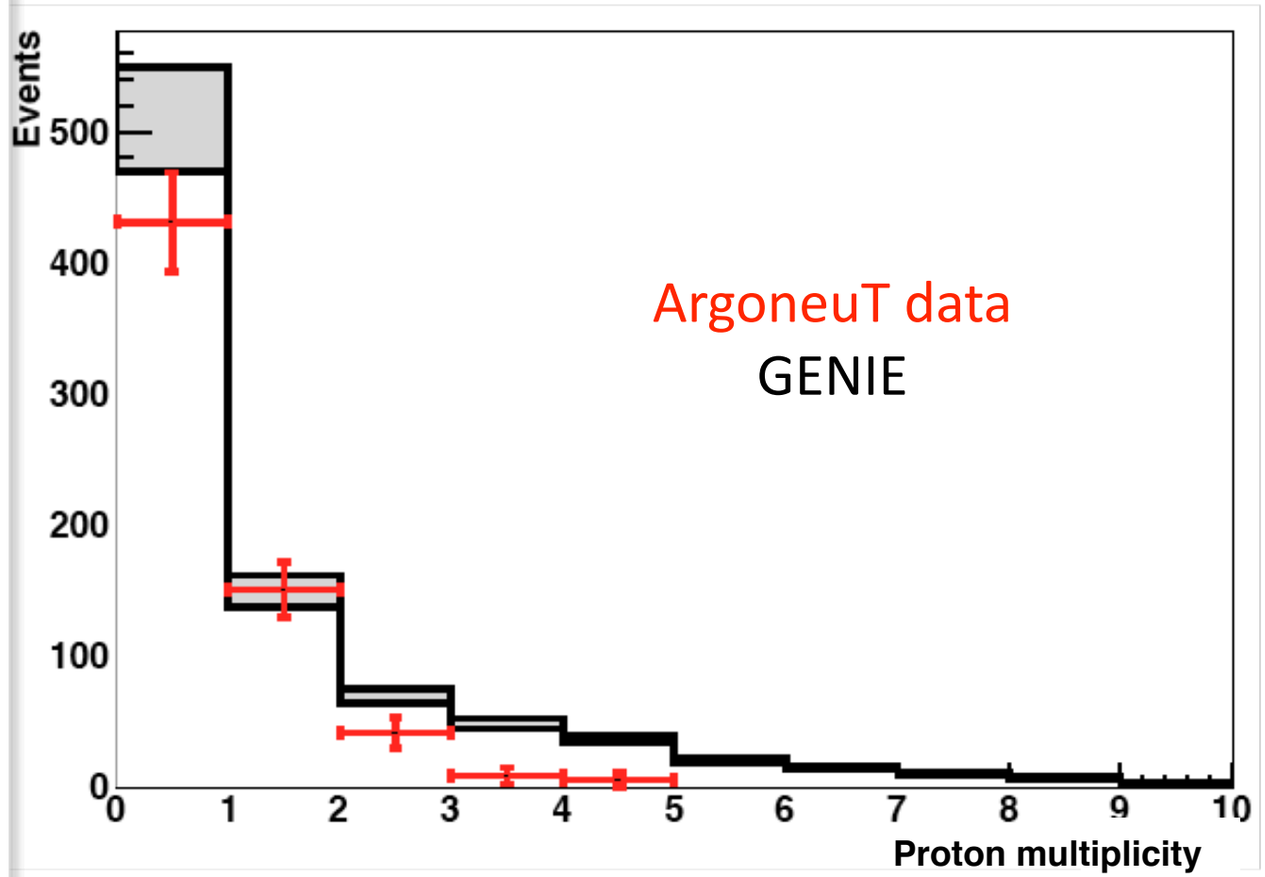
ArgoNeuT

Proton Multiplicity (μ+Np events)

ν_μ - anti-neutrino mode run



$\bar{\nu}_\mu$ - anti-neutrino mode run



The systematic error band on the MC represent the NuMI flux uncertainty

proton threshold:
T_p>21 MeV

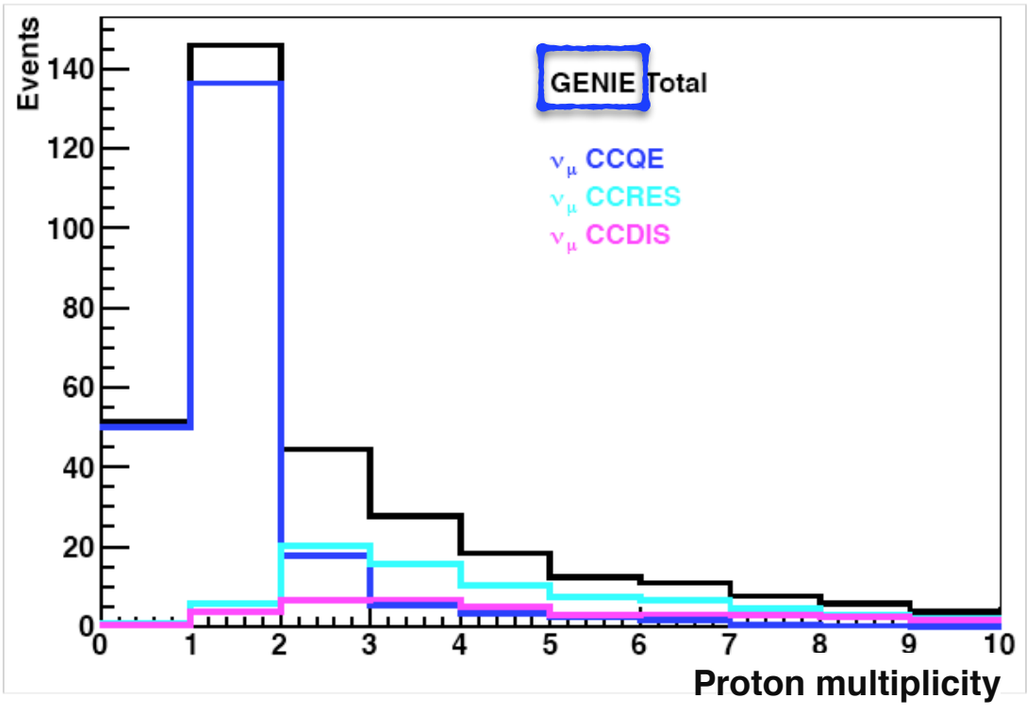
ν_μ events: 50% N≠1

$\bar{\nu}_\mu$ events: 32% N≠0

GENIE MC models more higher multiplicity events

CC 0 pion events: MC PREDICTIONS by Physical Process

ν_μ - anti-neutrino mode run



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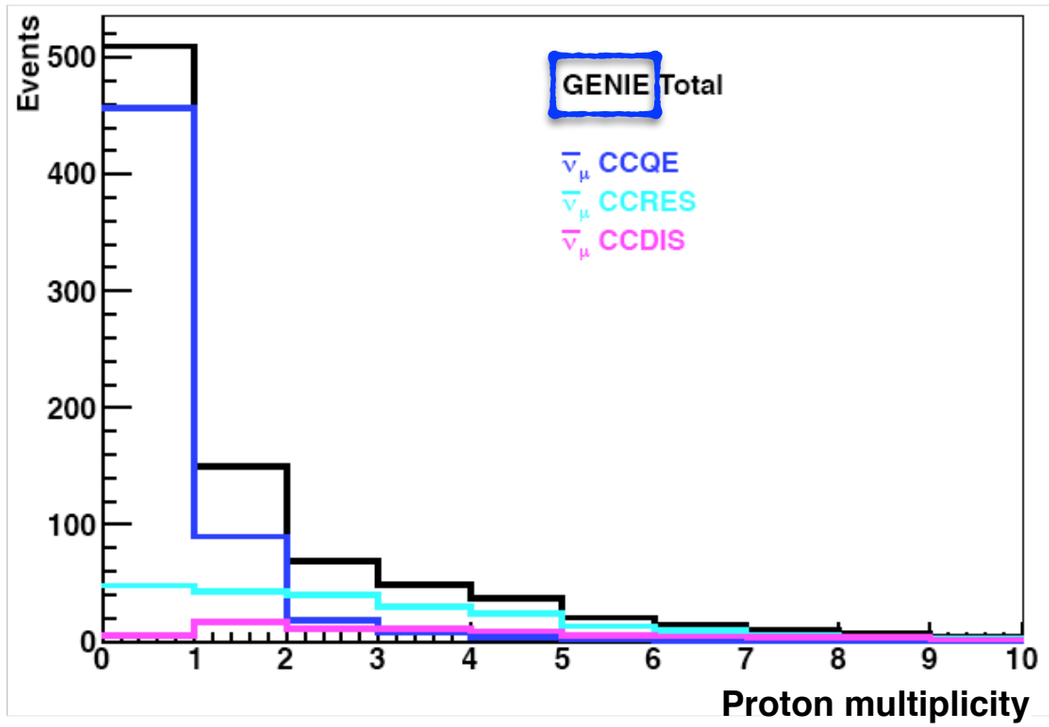
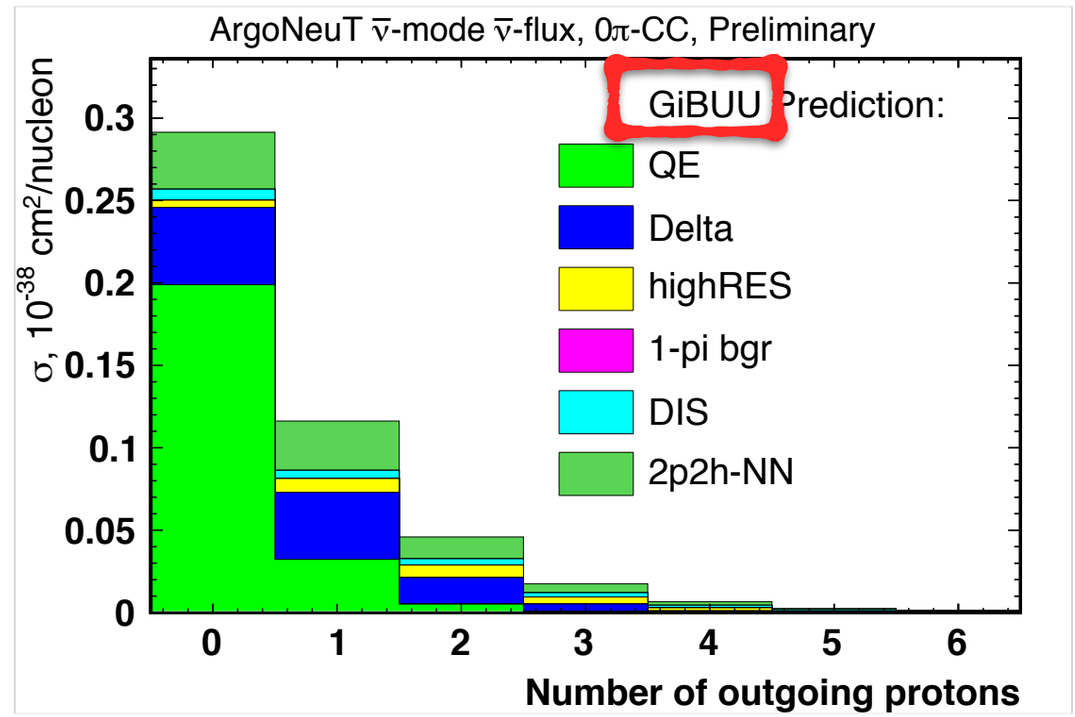
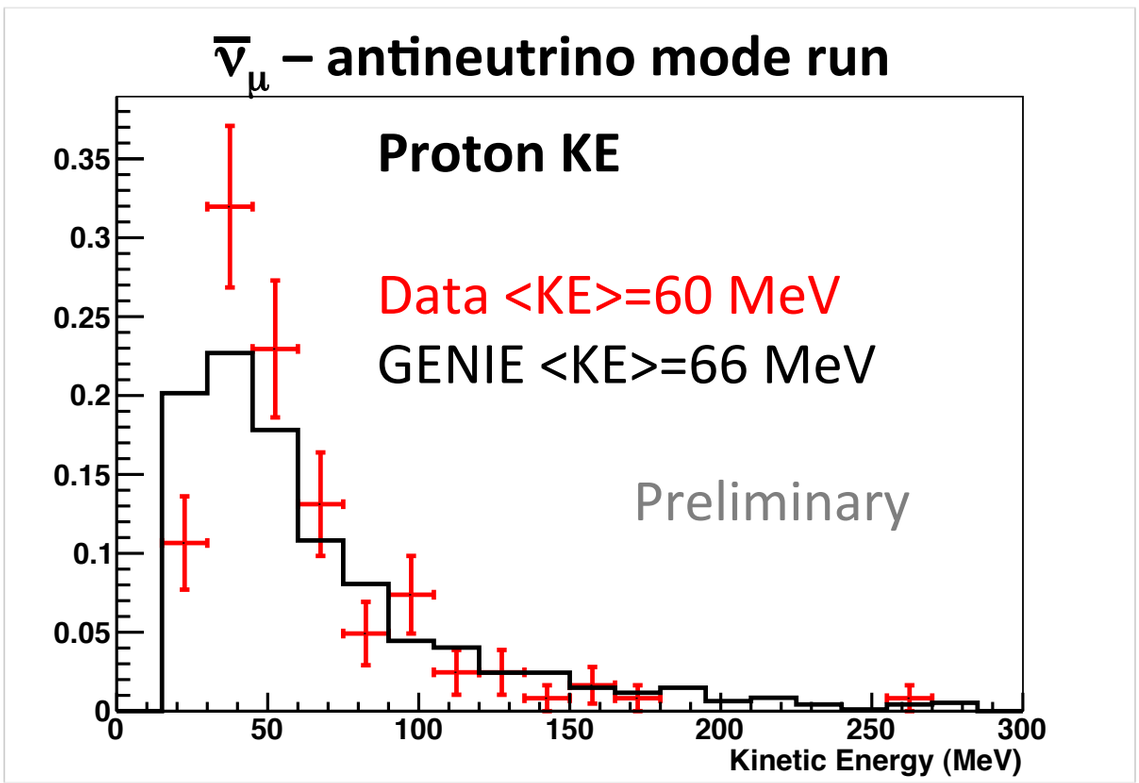


The MC generators predict varying amounts of proton emission and contributions from non-CCQE.

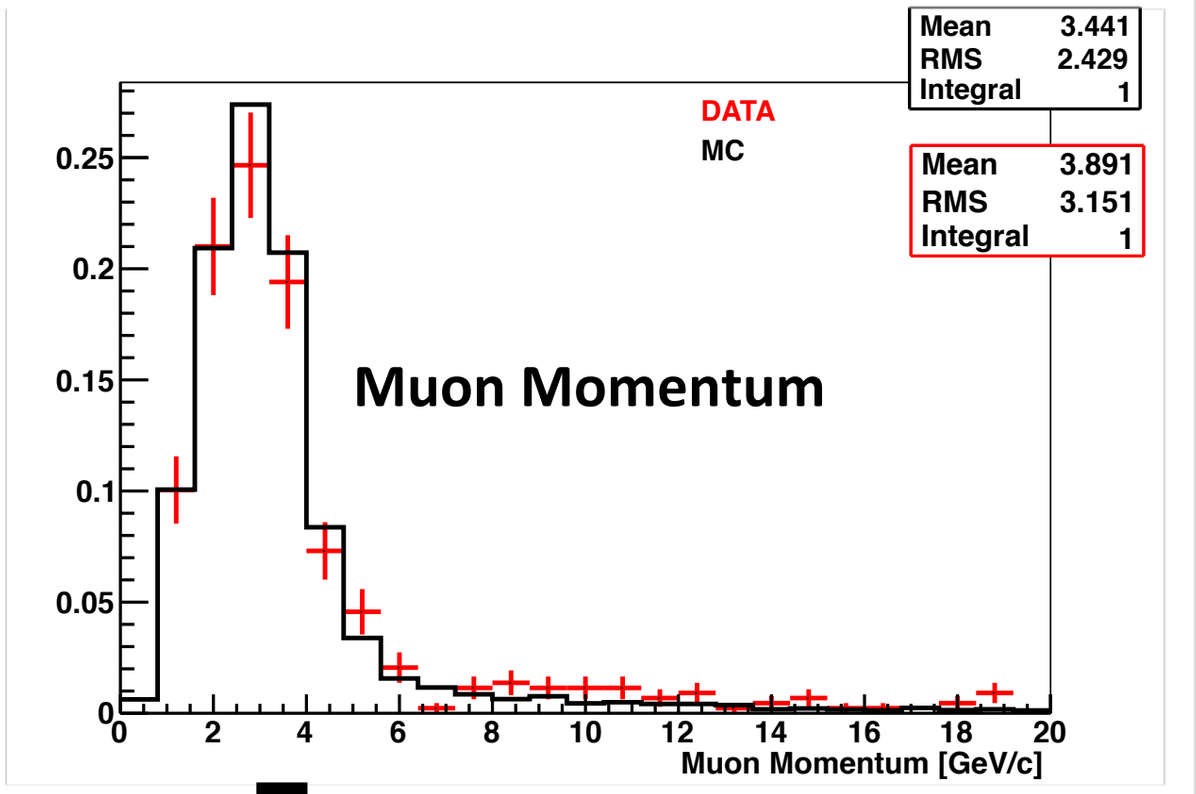
$\bar{\nu}_\mu$ - anti-neutrino mode run



NEUTRINO ENERGY RECONSTRUCTION



+



Neutrino Energy from muon+proton reconstructed kinematics:

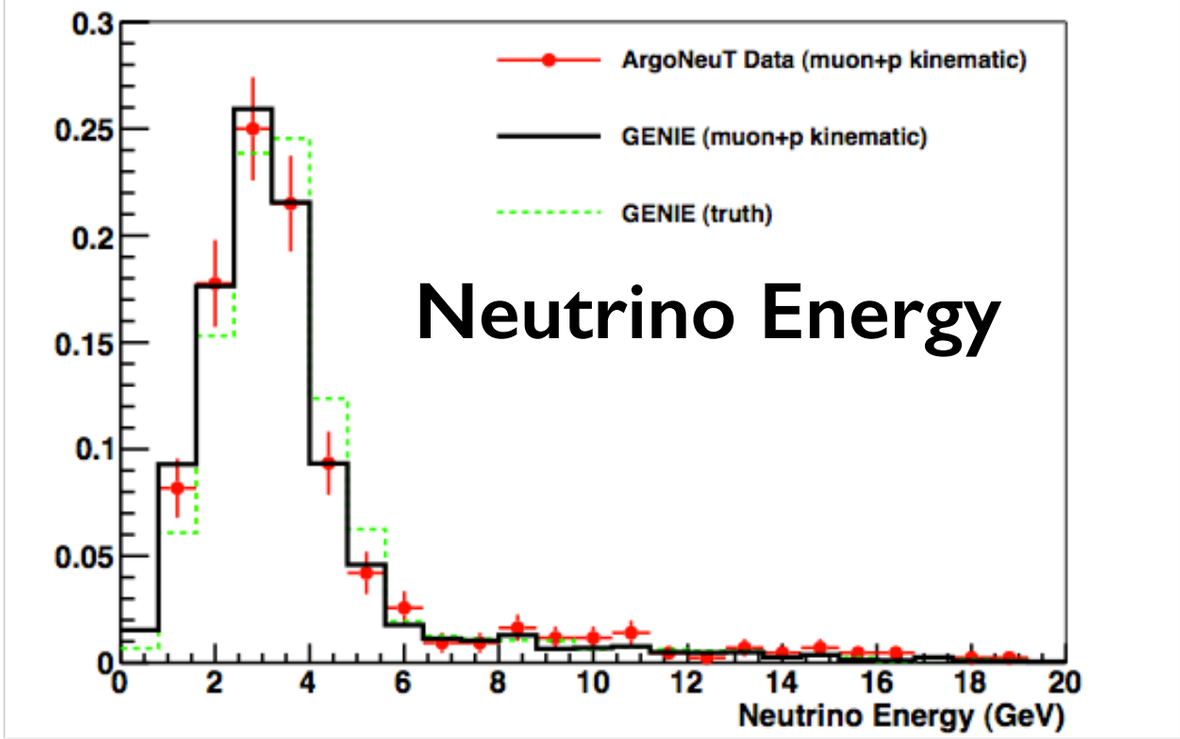
$$E_\nu = E_\mu + \Sigma T_{pi} + T_X + E_{miss}$$

E_{miss}= energy expended to remove the nucleon(s) from the nucleus

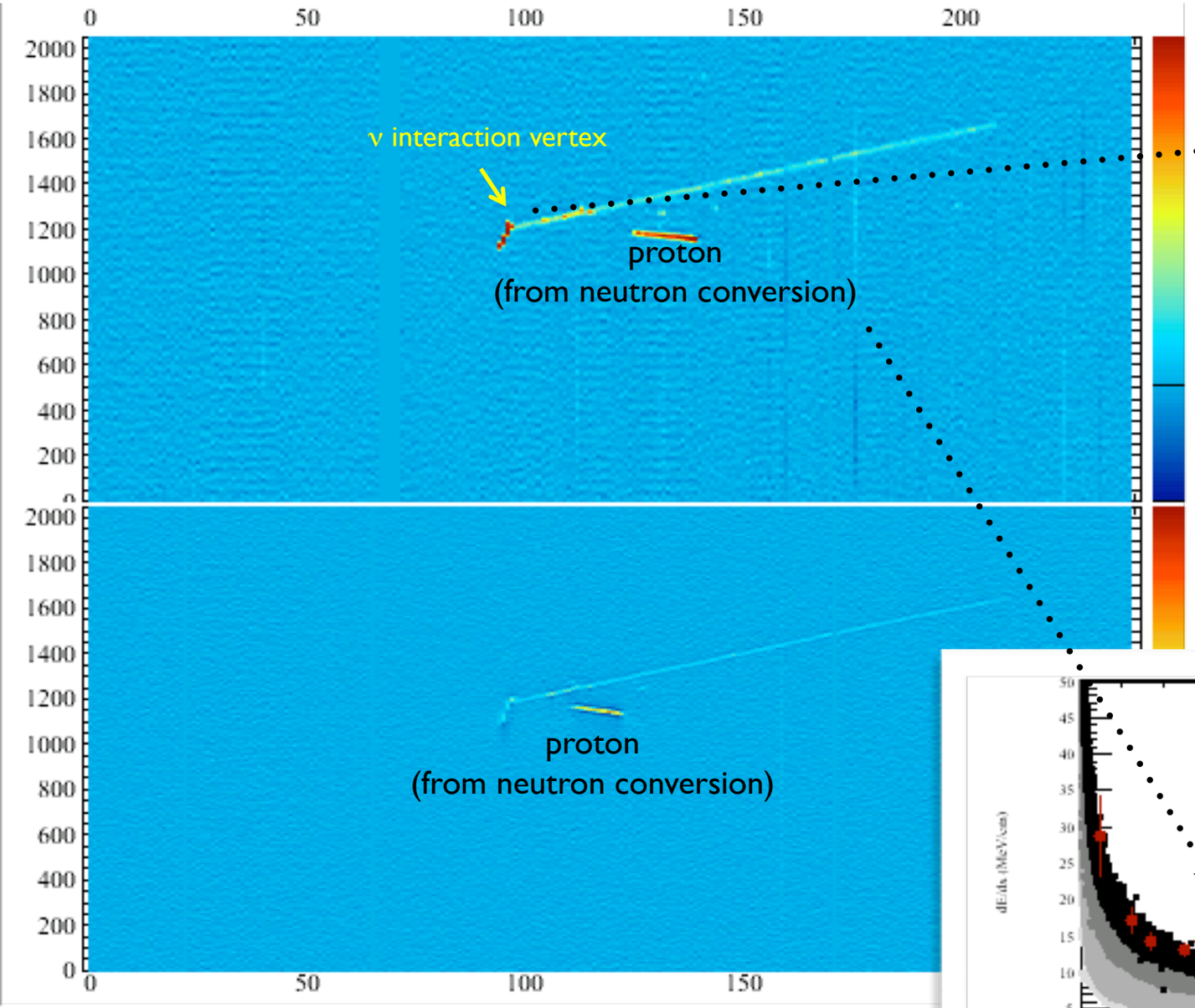
T_X=recoil energy of the residual nuclear system (estimated from missing transverse momentum)

No just muon information

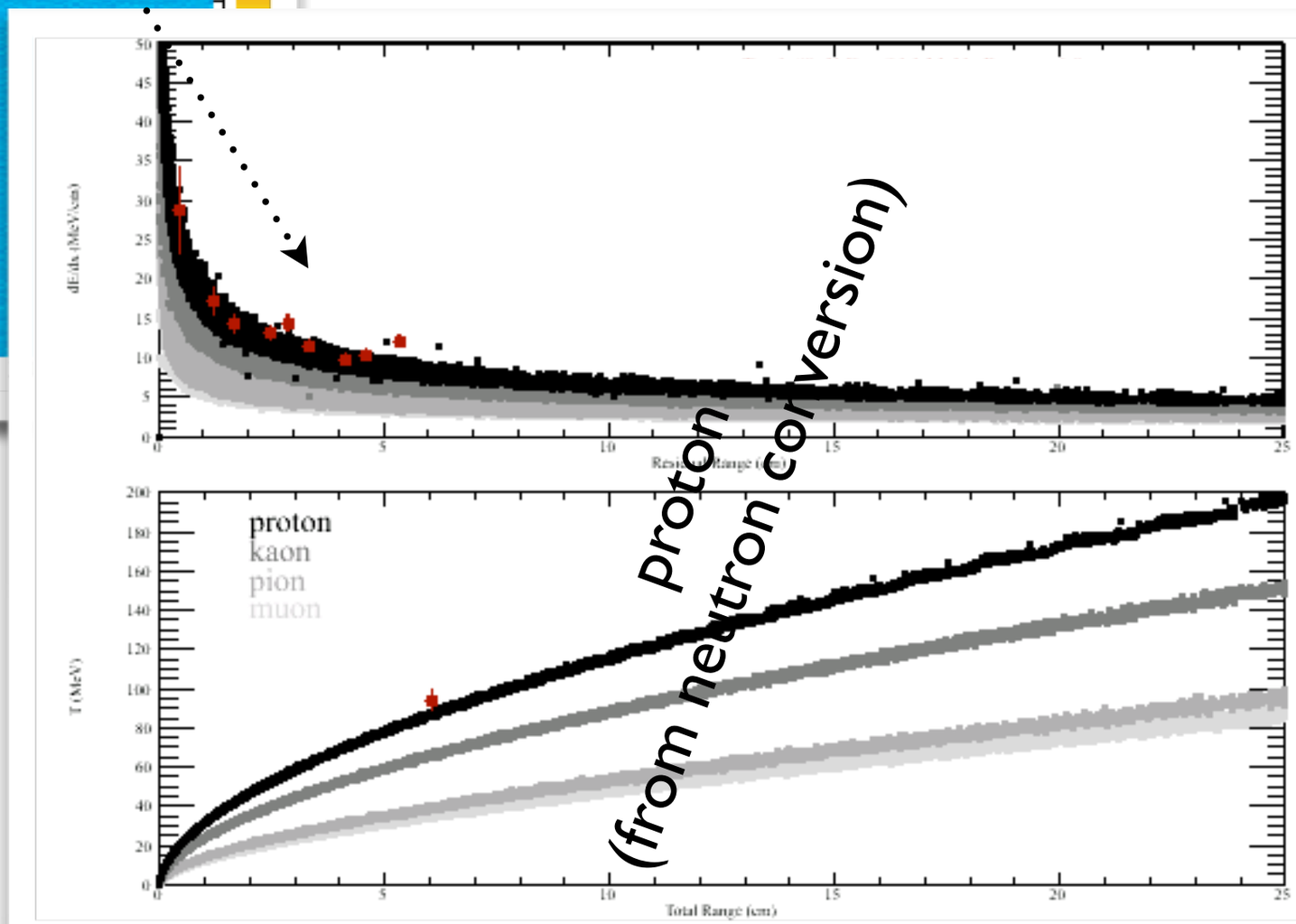
Reconstruction of other kinematic quantity (q, Q^2, p^T_{miss} etc.)



Reconstruction of proton from neutron conversion



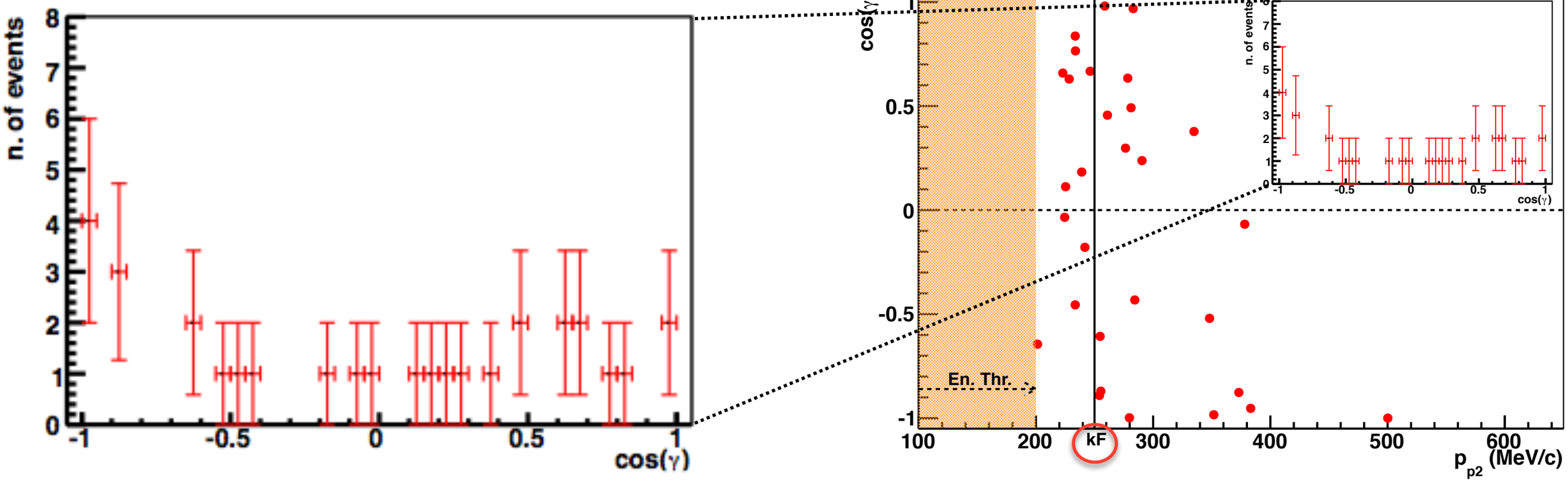
➤ proton at the vertex:
trk_length=2.91 cm, KE=39.5 MeV



Few events with n → p in ArgoNeuT
(small LAr volume)

(μ^-+2p) data sample - ***back-to-b protons in the Lab***

cos(γ) vs momentum of the least energetic proton p_{p2} in the pair



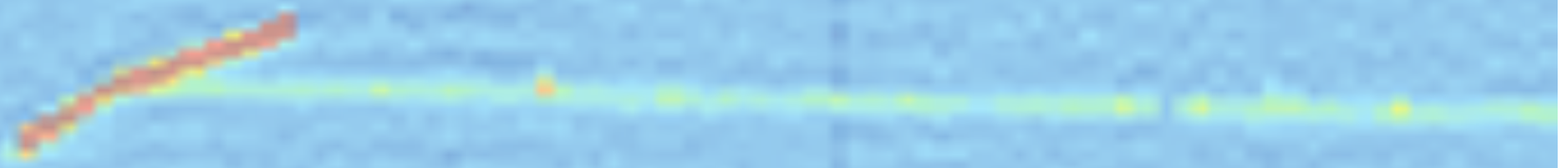
Four of the 19 2p-events are found with
the pair in a **back-to-back** configuration
in the Lab frame cos(γ)<-0.95

In all four events one proton is almost exactly balanced by the other

$p_{p1}, p_{p2} \geq k_F$ and $\vec{p}_{p1} \simeq -\vec{p}_{p2}$

Back-to-back proton pairs in the Lab frame

Back-to-back pp pairs in the Lab frame can be seen as "snapshots" of the initial pair configuration in the case of RES processes with no or low momentum transfer to the pair.



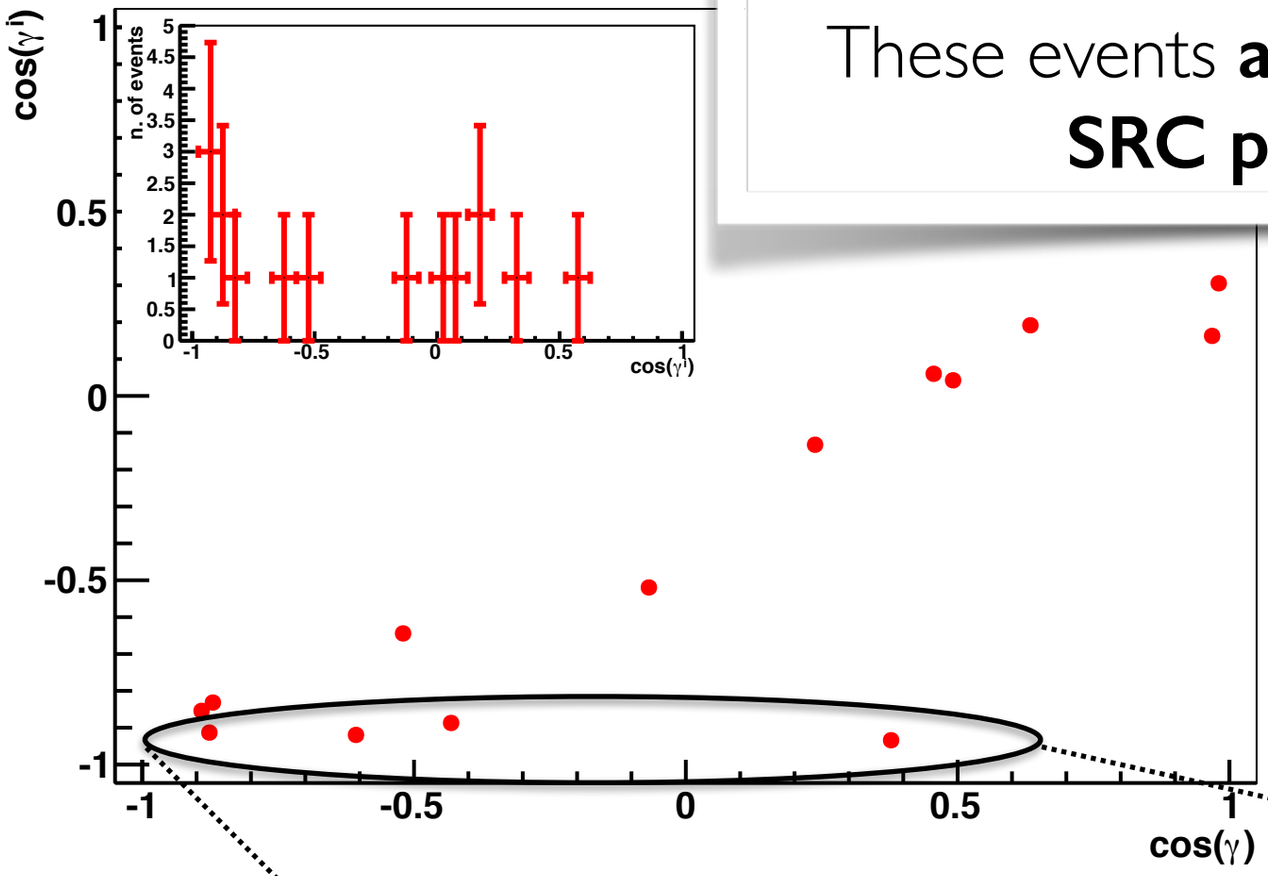
In all **four "Hammer" events**, both protons have:

- momentum significantly above the Fermi momentum,
- with one almost exactly balanced by the other
- all events show a rather large missing transverse momentum,

$$p^T_{miss} \geq 300\ MeV/c$$

These features **look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC *np* pairs.**

Back-to-back proton pairs in the initial state



These events **appear compatible as originating from SRC pairs through CC QE reactions**

$\cos(\gamma_i)$ vs $\cos(\gamma)$

*γ_i=opening angle between the reconstructed struck nucleon and the recoil proton in the np **initial** pair*

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

Four events (those horizontally aligned in the lowest $\cos(\gamma_i)$ bin, rather separated from the others) are reconstructed with the pair in a **back-to-back** configuration in the CM frame, $\cos(\gamma_i)<-0.9$ and have reconstructed initial momenta $>K_F$

The bin size includes the effect of the uncertainty in the transfer momentum reconstruction on the measurement of $\cos(\gamma_i)$