QE or not QE, that is the question

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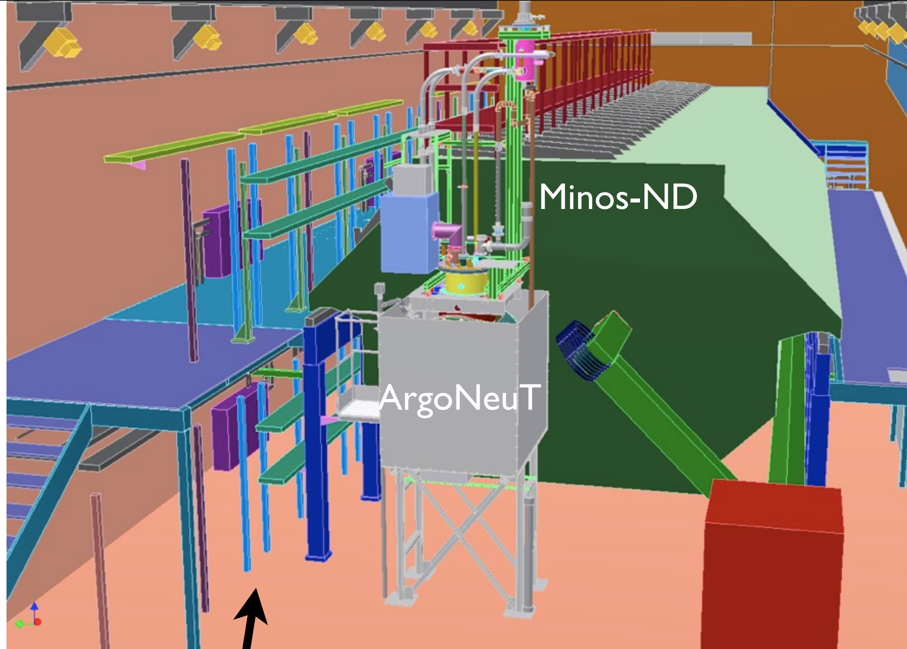
INT Workshop - Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments

Dec. 3rd 2013 - Seattle



ArgoNeuT

NuMI LE beam

ν−mode (2 weeks): 8.5×10^{18} POT

$\bar{\nu}$−mode (5 months): 1.20×10^{20} POT

"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

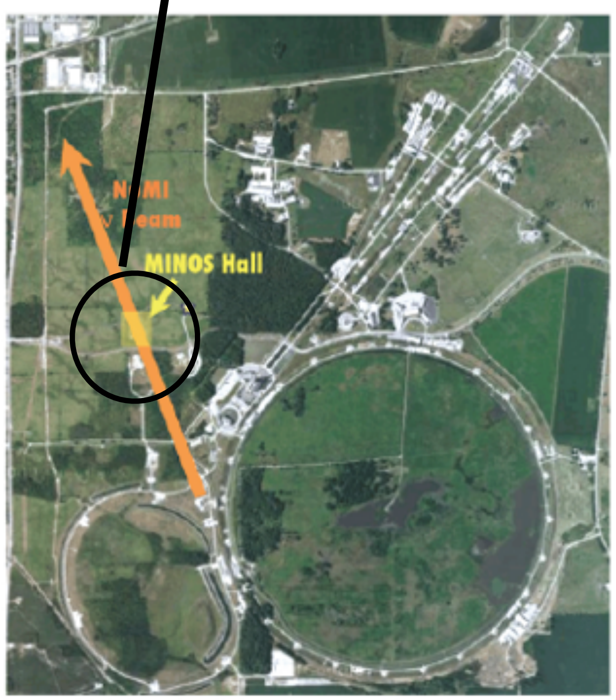
170 l active volume

$47\times40\times90$ cm^3, wire spacing 4 mm

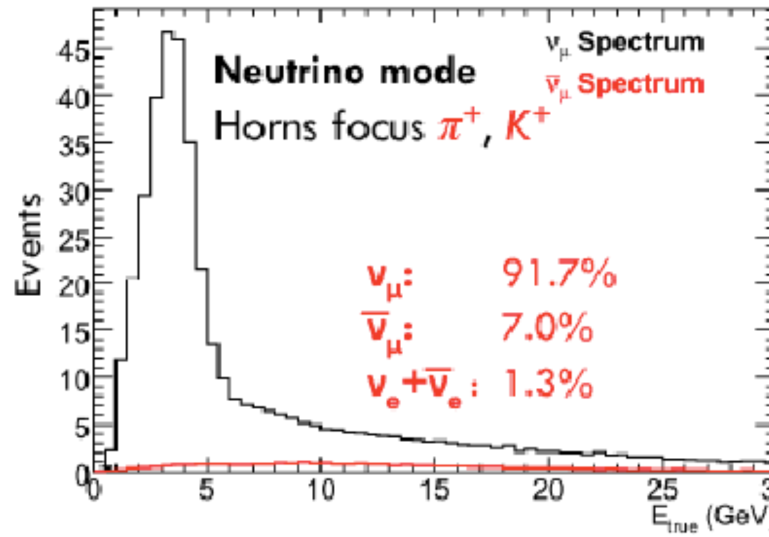
LAr TPC

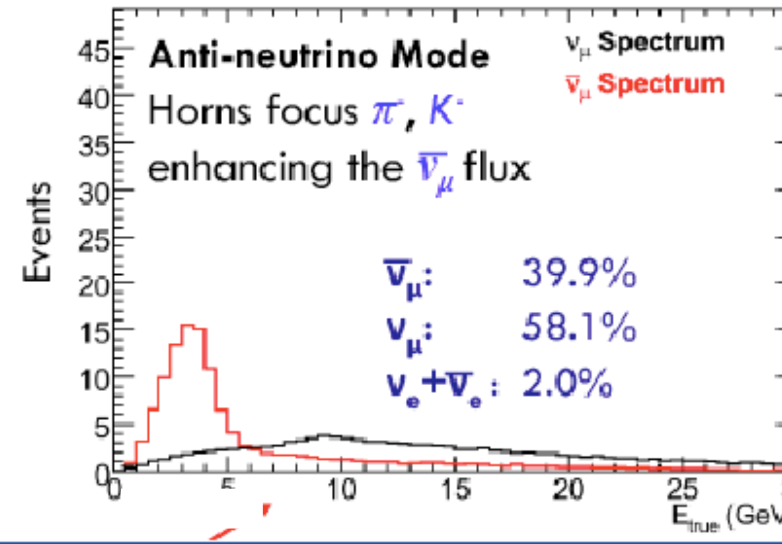
~7000 CC events collected

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

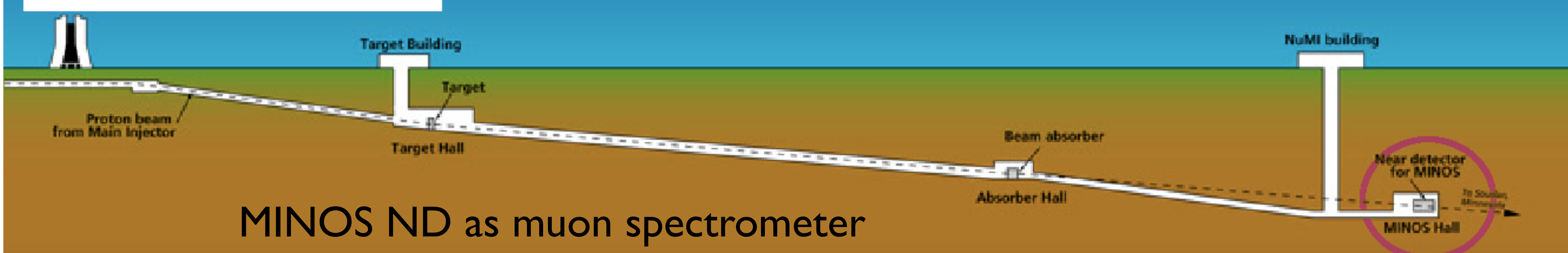


Fermilab





NuMI LE beam



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 providind the muon reconstruction*

(1)HOW DO YOU SELECT QE EVENTS, I.E., HOW DO YOU DEFINE A QE EVENT?

The "new wave" in Neutrino Event Reconstruction

LAr-TPC detectors, providing ***bubble-chamber-like quality images*** and ***excellent particle ID*** and ***background rejection***, allow for **MC independent measurements, nuclear effects exploration** and **Exclusive Topology** recognition with extraordinary sensitivity.

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…** , *1 pion* (μ+Np+1π) *events, etc..*

instead of QE events ⇨

Exclusive Topologies reconstruction in LAr-TPC experiments: a Novel Approach for precise Neutrino-Nucleus Cross-Sections Measurements

http://arxiv.org/abs/1309.7480

(2) HOW DO YOU DETERMINE YOUR NEUTRINO/ANTINEUTRINO FLUX?

- NuMI flux: see Nate Mayer talk

(3)

(3b) WHAT IS (ARE) YOUR PRIMARY QE MEASUREMENT(S)

AND

(3a) WHAT DO YOU FIND MOST IMPORTANT ABOUT YOUR DATA?

(3a) WHAT DO YOU FIND MOST IMPORTANT ABOUT YOUR DATA (I)?

ν_μ CC 0 pion analysis approach

Count (PId) and reconstruct protons at the neutrino interaction vertex* *(low proton energy threshold)*

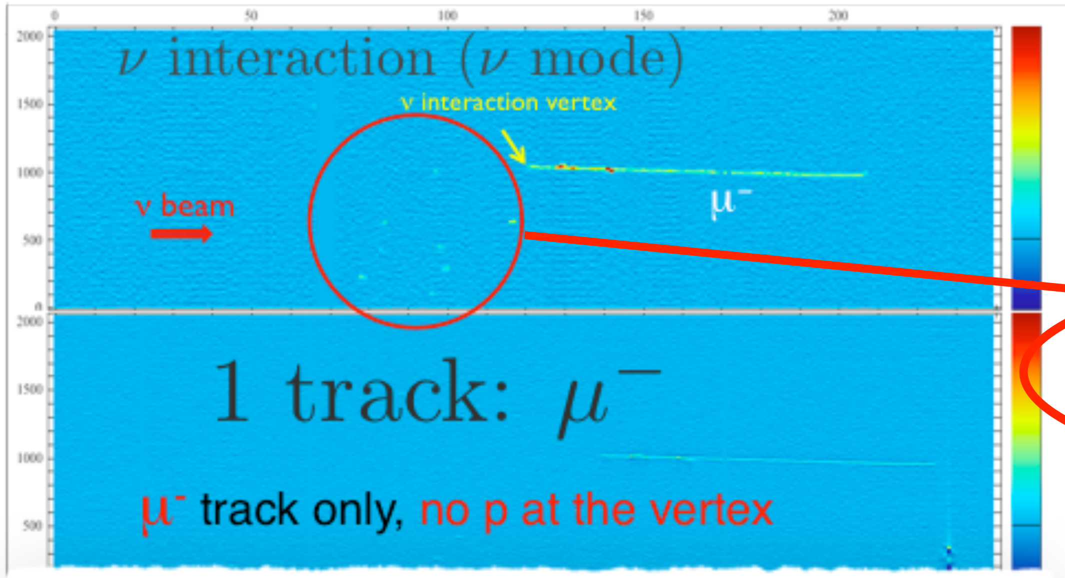
Analysis fully exploiting LArTPC's capabilities
(in other neutrino detectors all these classes of events are "CCQE like" events)

Event reconstruction in LArTPC

- 3D and calorimetric reconstruction for efficient Particle Identification
- Excellent resolution for final state
- Capability of "seeing" recoil proton(s)
- Good p / $\pi^{\pm}$ identification capability

*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.

(3a) WHAT DO YOU FIND MOST IMPORTANT ABOUT YOUR DATA (II)?



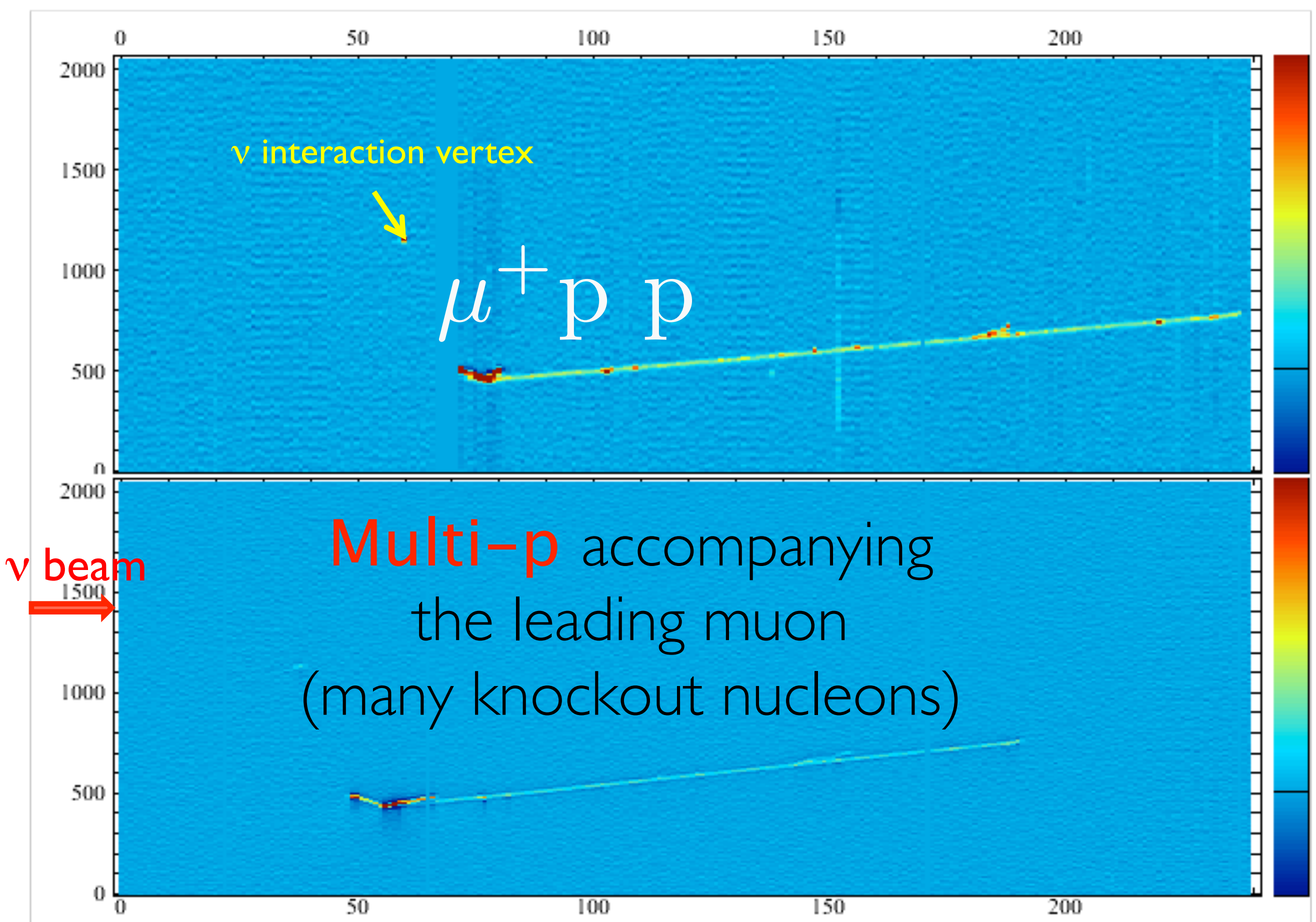
Evidence of Nuclear Effects

μ⁻ 0p

Hints for Nuclear Effects

Activity around the vertex
e's from nuclear de-excitation γ conversion

Note: *Due to bubble-chamber like quality of LArTPC, visual scanning presents a very powerful tool that allows to learn about features of neutrino interactions that have not been possible to explore with other technologies and existing experiments.*



ArgoNeuT events: Single μ- event (Left), Multi-proton event (Right)

(3b) WHAT IS (ARE) YOUR PRIMARY ~~QE~~ 0 PION MEASUREMENT(S)?

- ***Rates of different exclusive topologies*** (proton multiplicities) *with a proton threshold of 21 MeV Kinetic energy*

- ***Muon and proton kinematics*** in events with different proton multiplicity
- Most precise ***reconstruction of the incoming neutrino energy*** from ***lepton AND proton kinematics.***
- Features of neutrino interactions and associated ***Nuclear Effects*** [e.g. short range NN-correlations inside the nucleus] from identification/reconstruction of specific classes of neutrino events

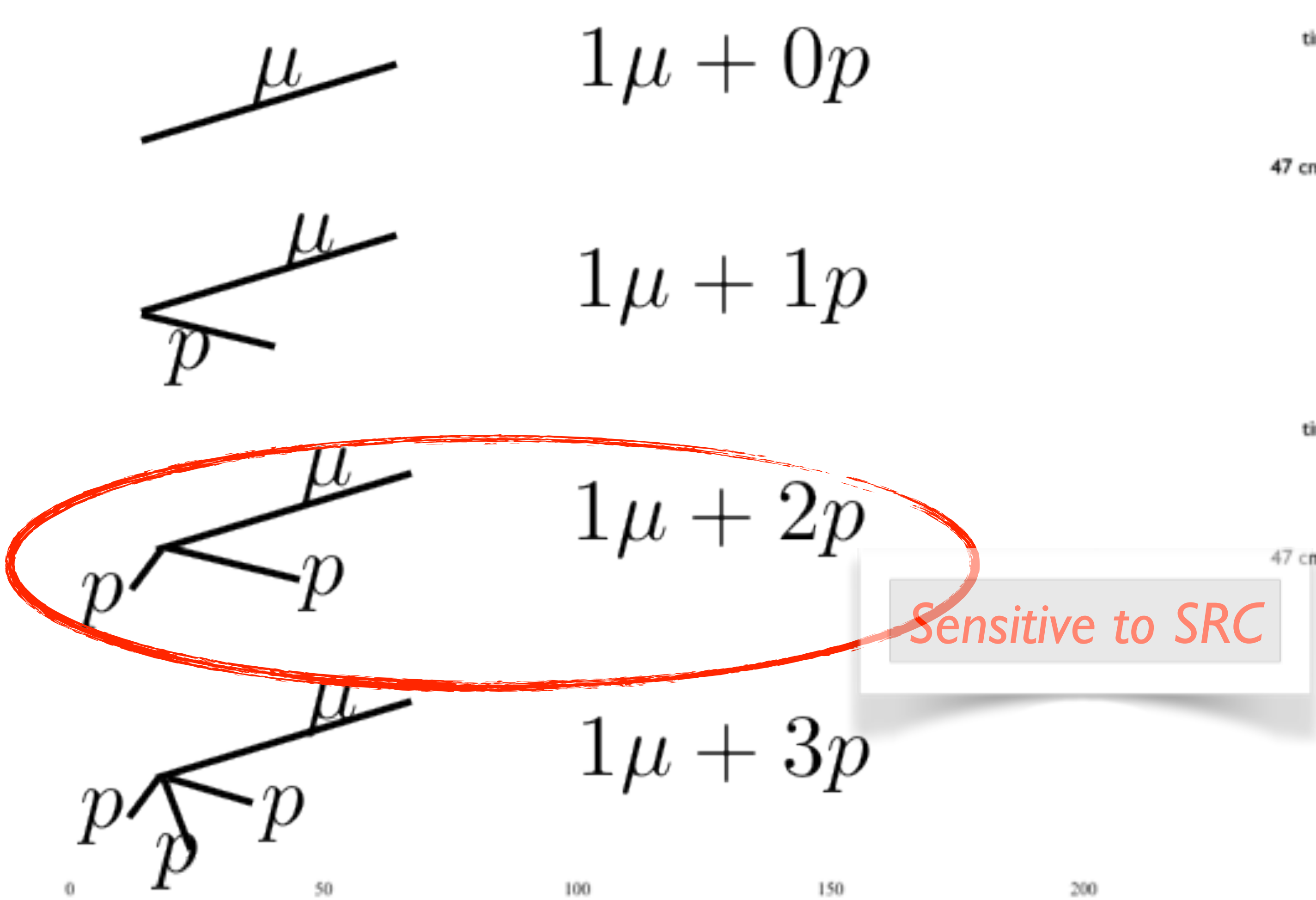
(4) WHAT ADDITIONAL QE MEASUREMENTS DO YOU HAVE PLANNED FOR THE FUTURE, IF ANY?

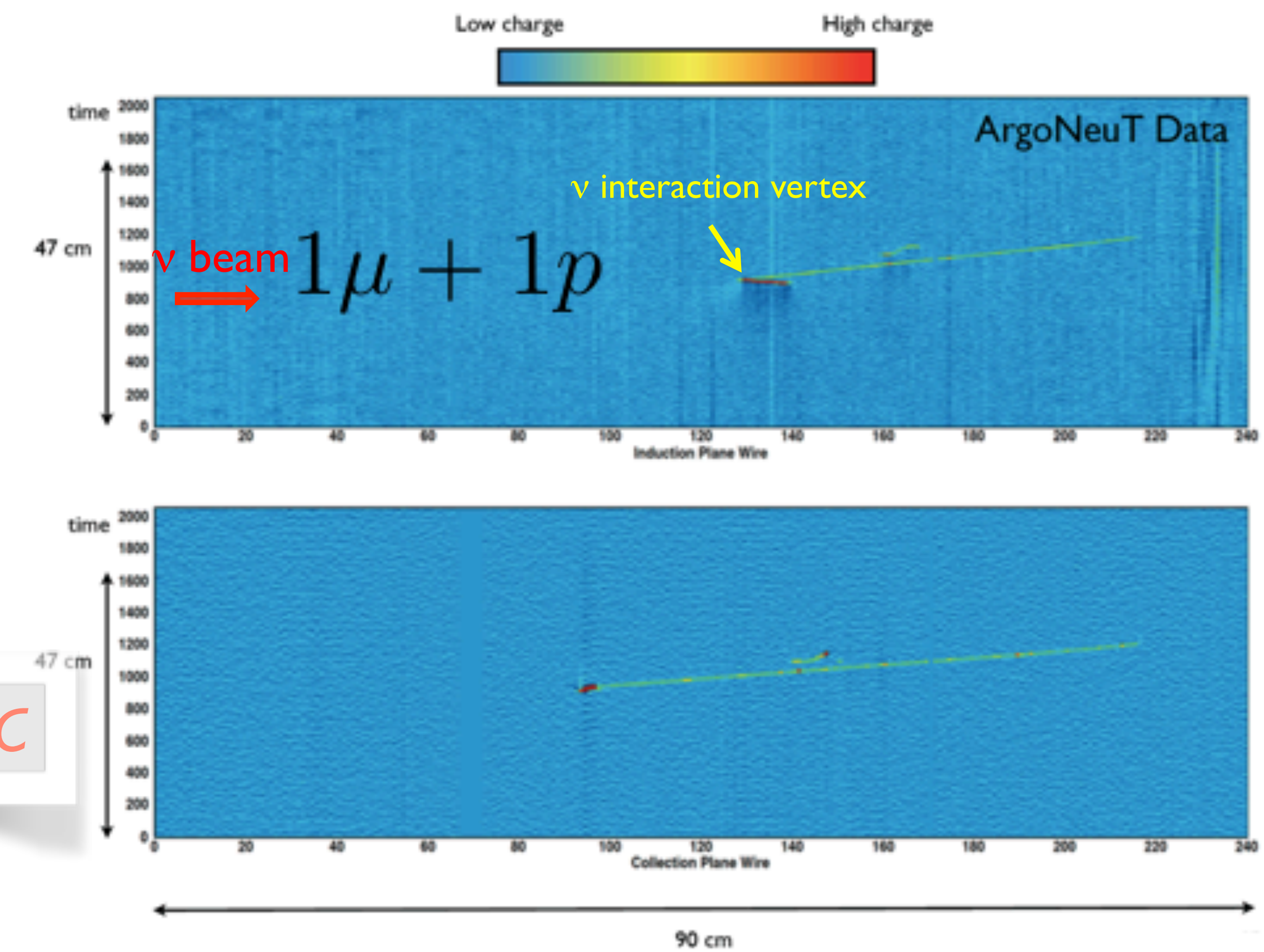
- Present results in terms of CC 0 pion cross section
- Extend the study of Nuclear Effects to anti-neutrino events
- Reconstruction of μ+Np+1π events to compare with other experiments
  - ArgoNeuT (CC 0 pion) vs. CC QE like results, applying equal threshold on pions.

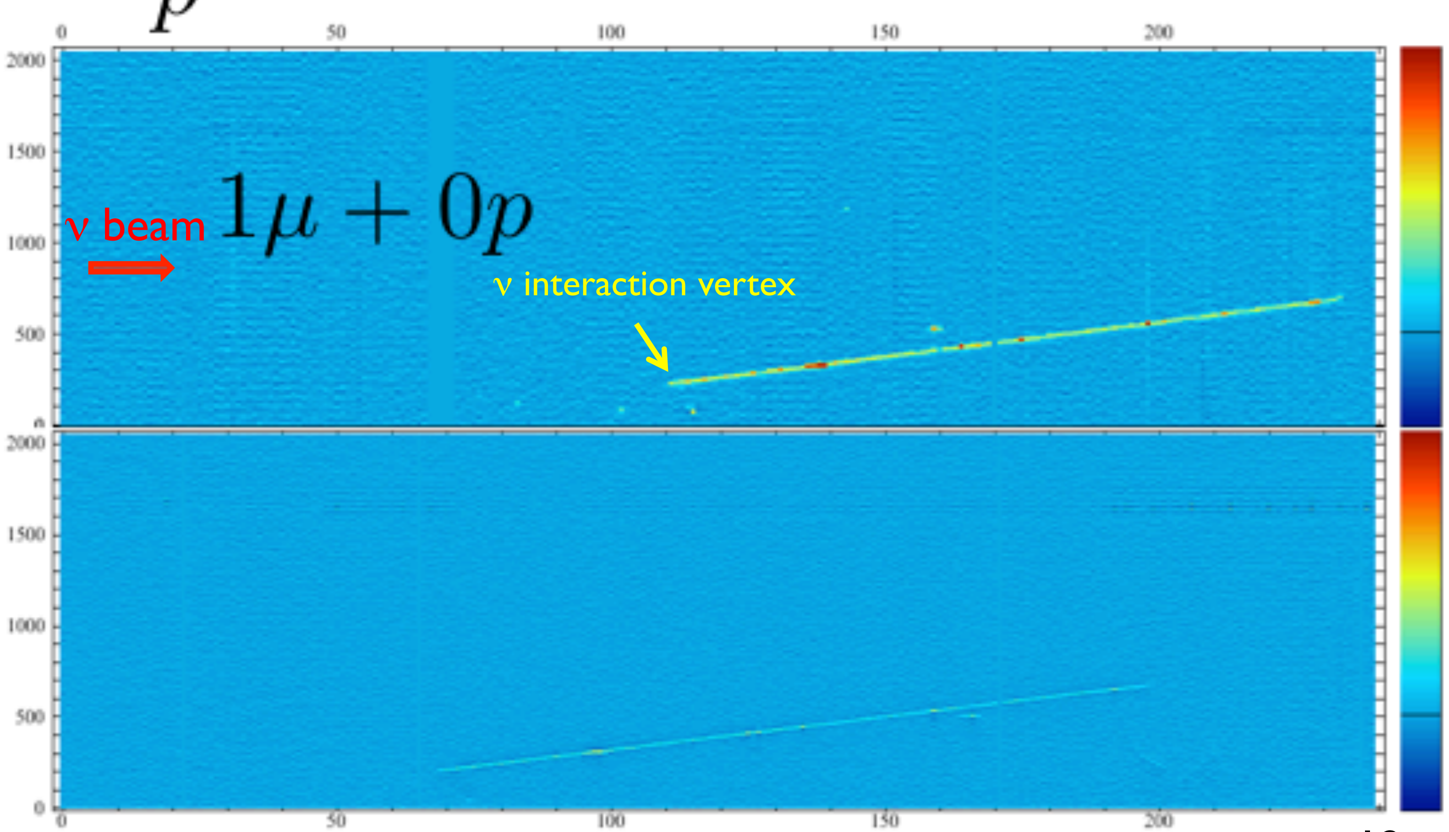
(5) SUMMARY TABLE: ArgoNeuT

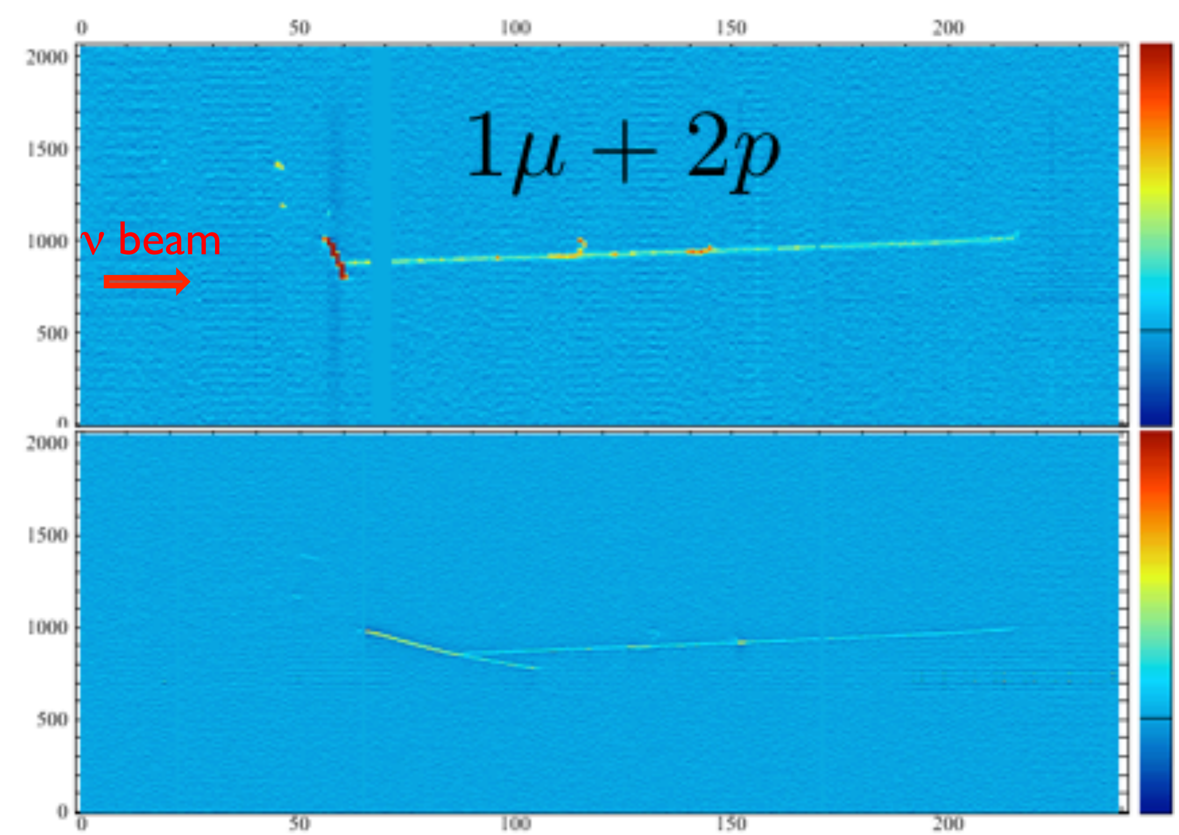
characteristics of selected ν_μ QE events	values
"QE event" selection	Neutrino events categorized in terms of final state topology based on particle multiplicity rather than in terms of interaction channel: "0-pion" (i.e. μ+Np, where N=0,1,2...) Neutrons can also be emitted in these events: ArgoNeuT has a very low efficiency to detect neutrons emerging from the interaction vertex since the LAr volume is too small to have significant chances for neutrons to convert into visible protons before escaping.
Nuclear target	$^{40}Ar_{18}$
Sign-selection	Muon sign selection from MINOS-ND
Muon energy range	Requiring muon sign determination from downstream MINOS-ND: T_μ>400 MeV
Muon angular range	About 2π forward w.r.t neutrino beam
Proton detection threshold	Proton reconstruction threshold: T_p> 21 MeV
How is E_ν determined?	From the lepton AND proton(s) reconstructed kinematics: $E_\nu = (E_\mu + \sum T_{pi} + T_X + E_{miss})$ *T_X=recoil energy of the residual nuclear system [from missing transverse momentum], E_{miss}=missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value)]*
How is Q^2 determined?	$Q^2 = -m_\mu^2 + 2E_\nu (E_\mu - p_\mu \cos\theta_\mu)$
Monte Carlo generator	GENIE 2.8.0 *(full simulation)*, GIBUU
QE measurements and associated publications	Rates of different exclusive topologies (proton multiplicities), muon and proton kinematics in events with different proton multiplicity, reconstructed neutrino energy, features of neutrino interactions and associated nuclear effects [e.g. short range NN-correlations inside the nucleus] from identification/ reconstruction of specific classes of events *NuInt 2012, Conf. Proc. in publication (AIP Conf.Proc.), arXiv:1309.7480v2 [physics.ins-det], "Observation of of back-to-back proton pairs in Charged-Current neutrino", in preparation*

EVENT TOPOLOGY

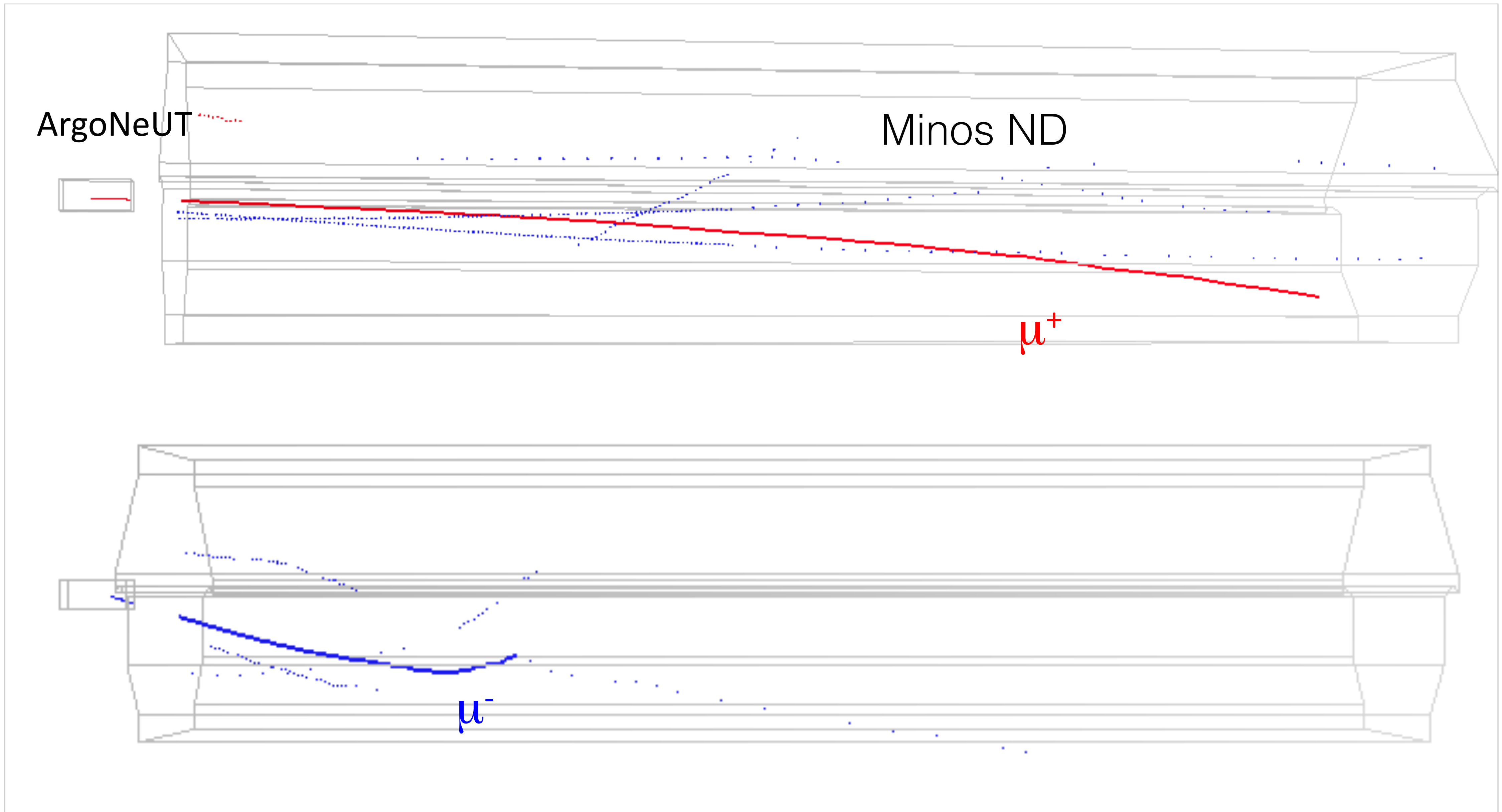








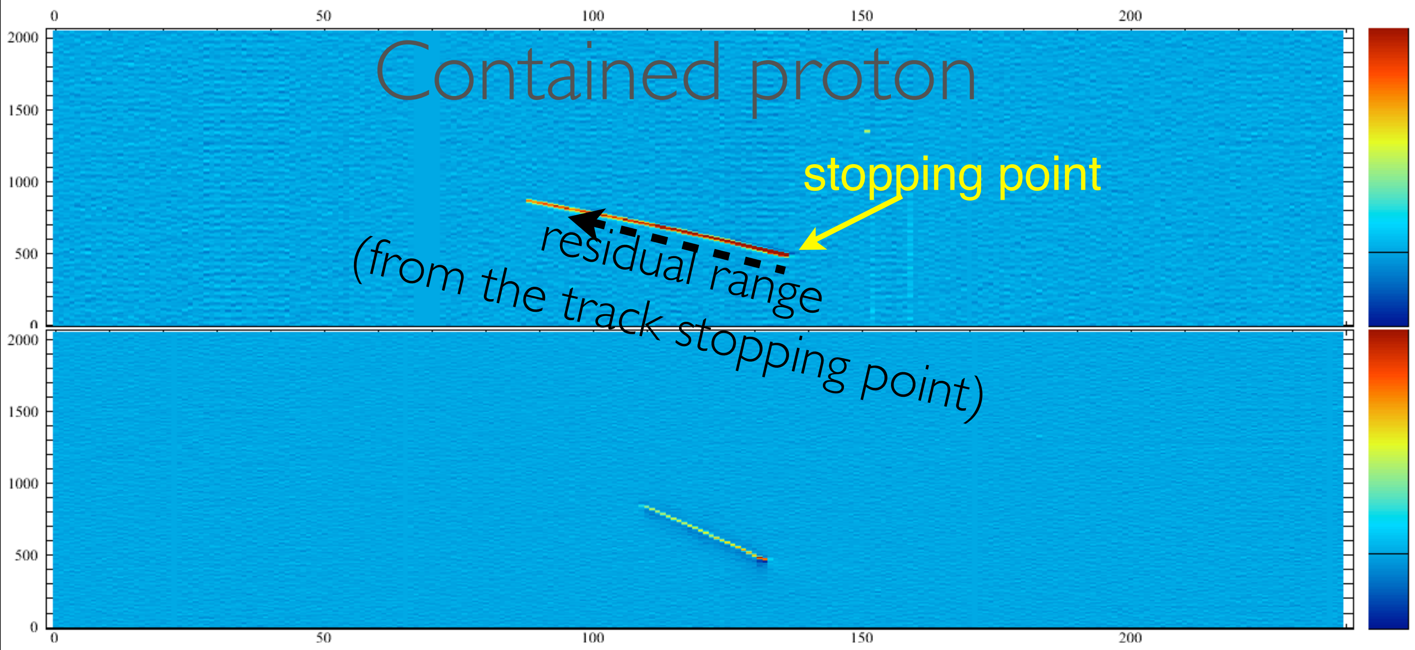
MUON reconstruction



"Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector"
JINST 7 P10020 (2012)

Muon kinematic reconstruction:
ArgoNeuT +MINOS ND measurement (momentum and sign)
Muon momentum resolution: 5-10%

STOPPING TRACKS - CALORIMETRIC RECONSTRUCTION and PID

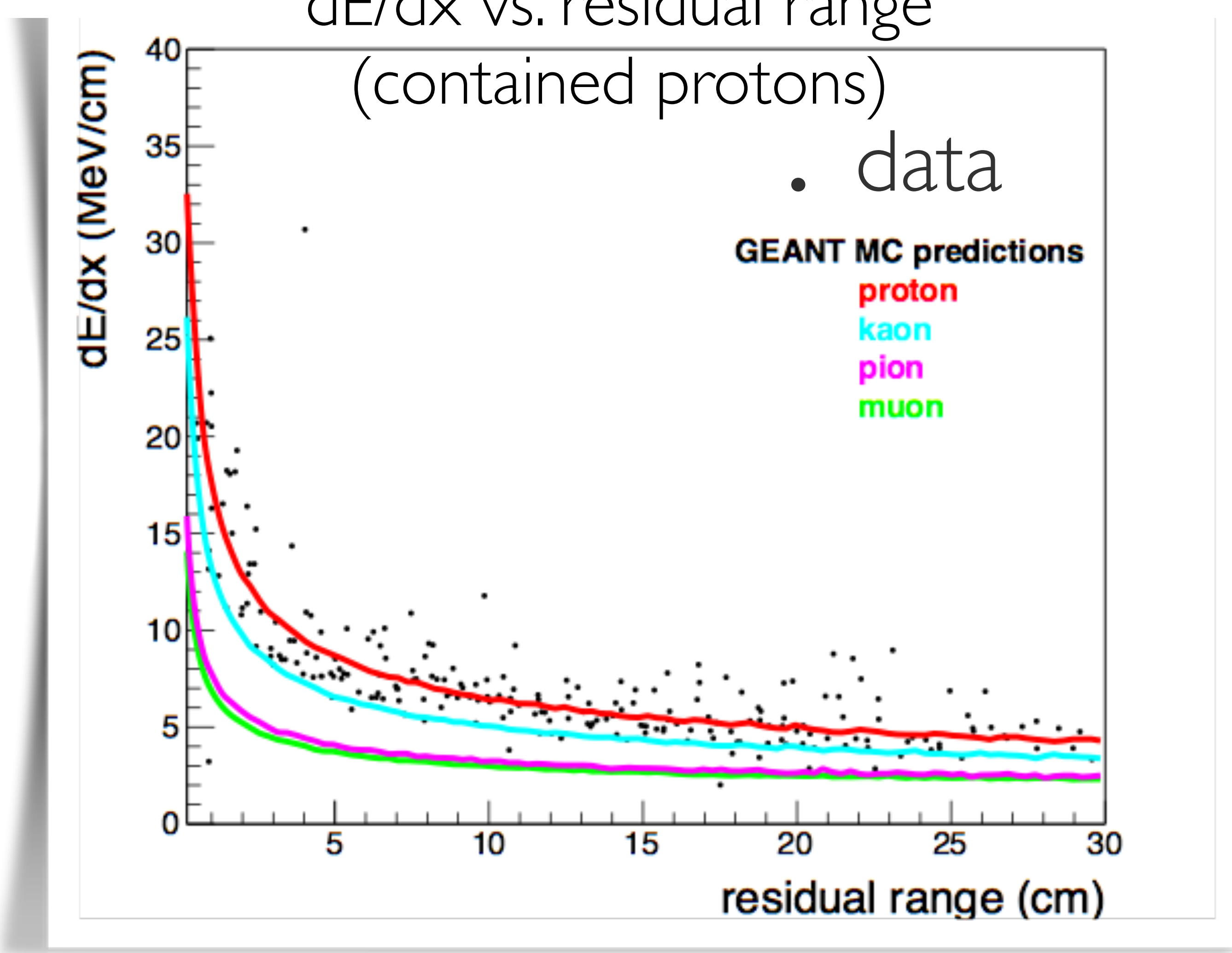


Measurement of:

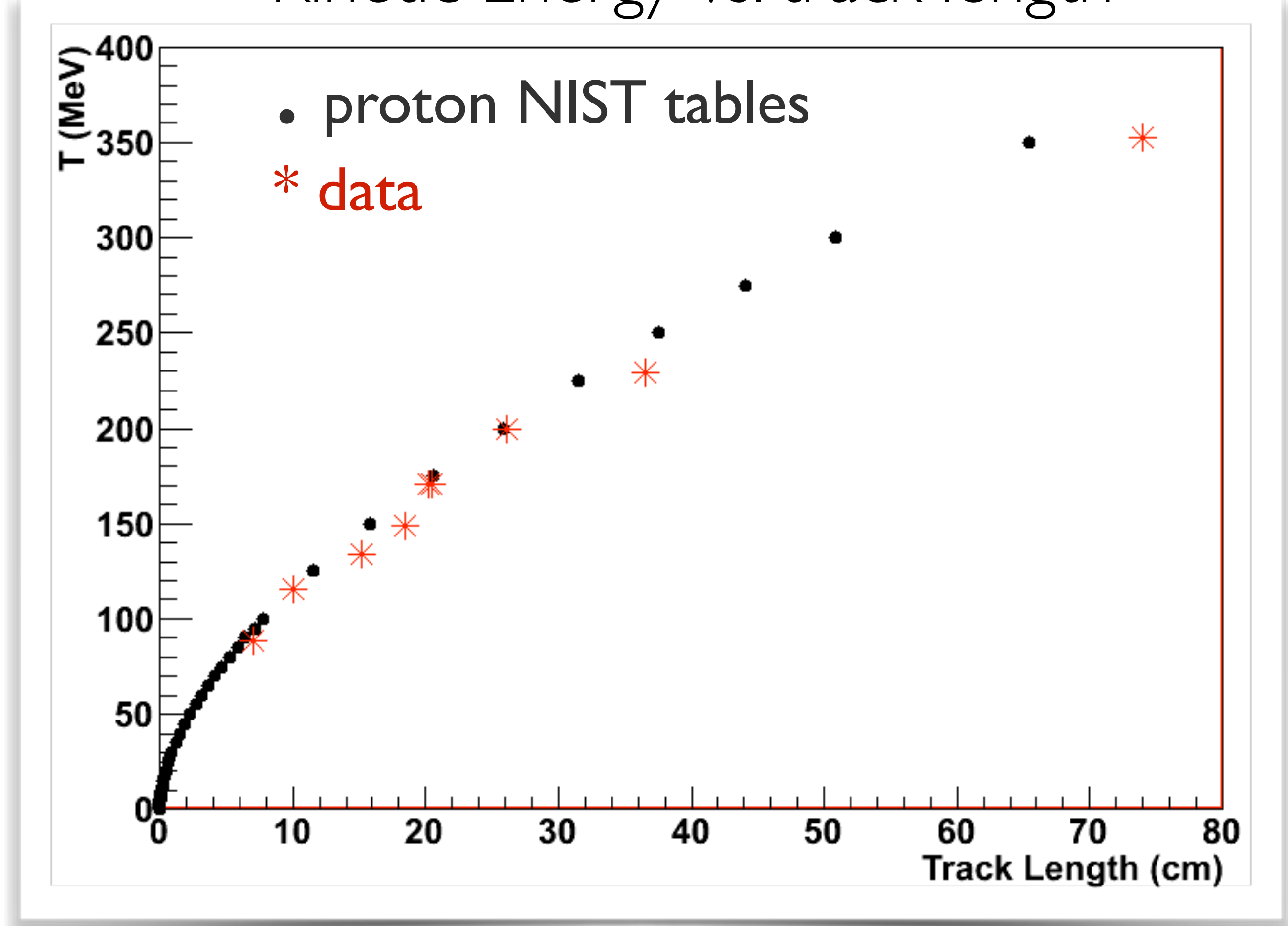
- dE/dx vs. residual range along the track
- kinetic energy vs. track length

χ^2 based method is used for PID

dE/dx vs. residual range (contained protons)

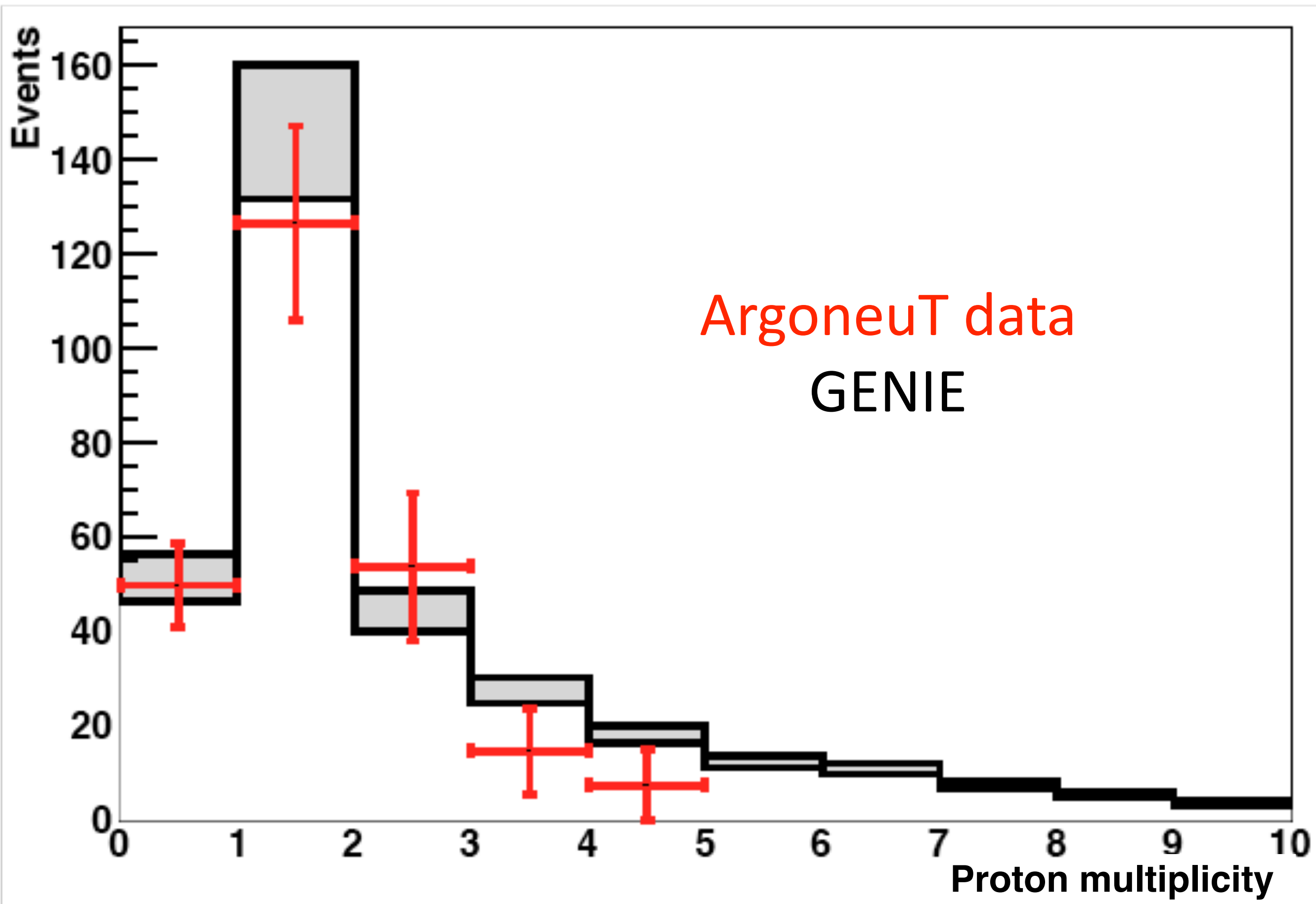


Kinetic Energy vs. track length

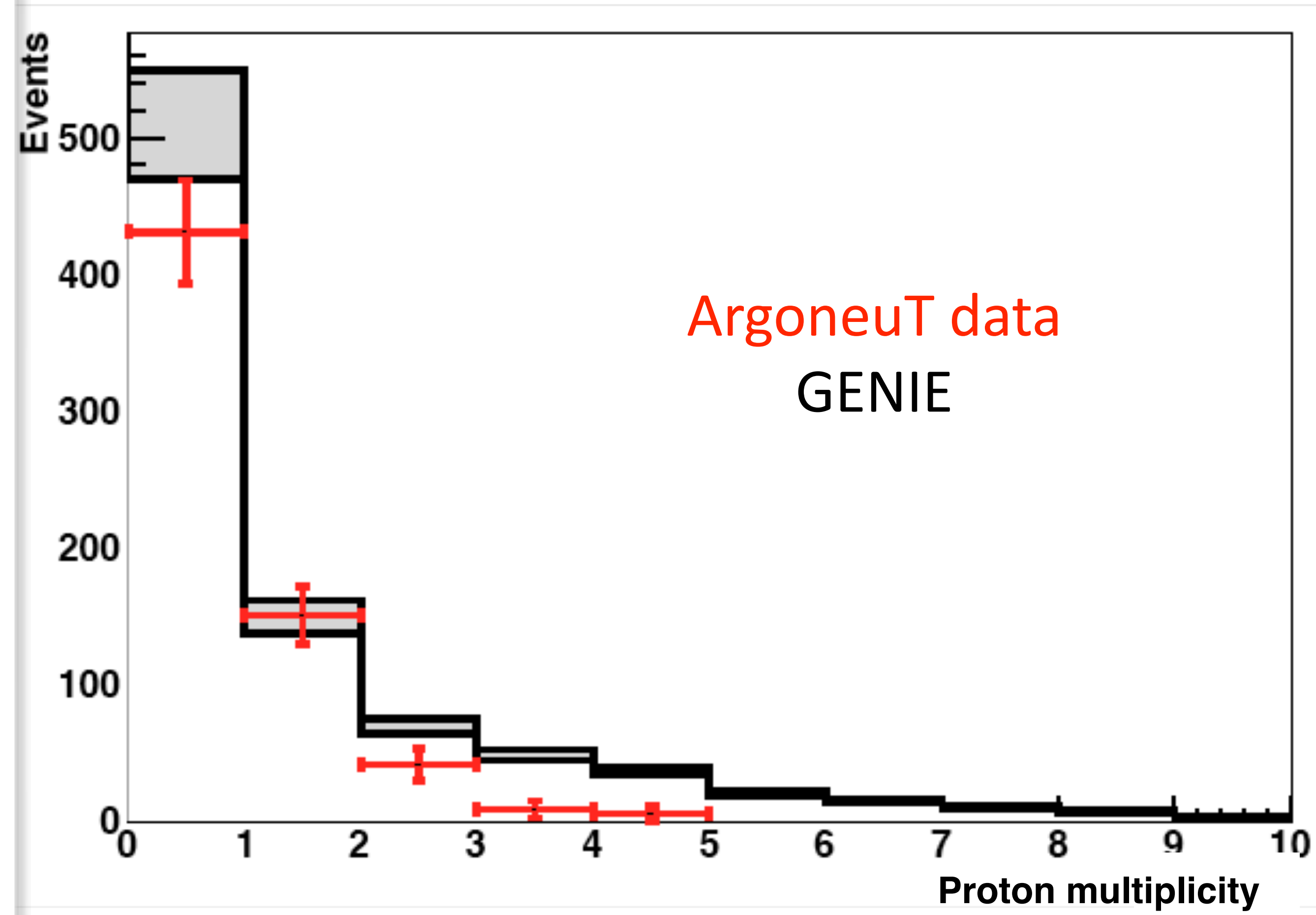


Proton Multiplicity (μ+Np events)

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 (see N. Mayer talk)

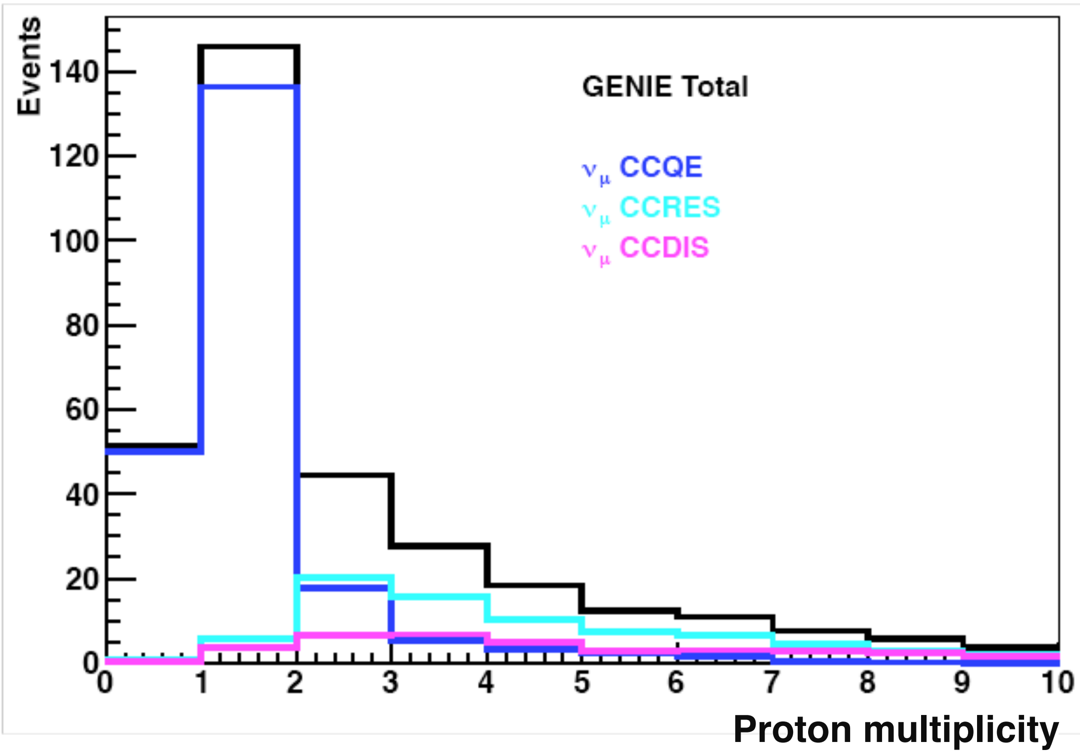
proton threshold:
T_p>21 MeV

ν_μ events: 50% N≠1
$\bar{\nu}_\mu$ events: 32% N≠0

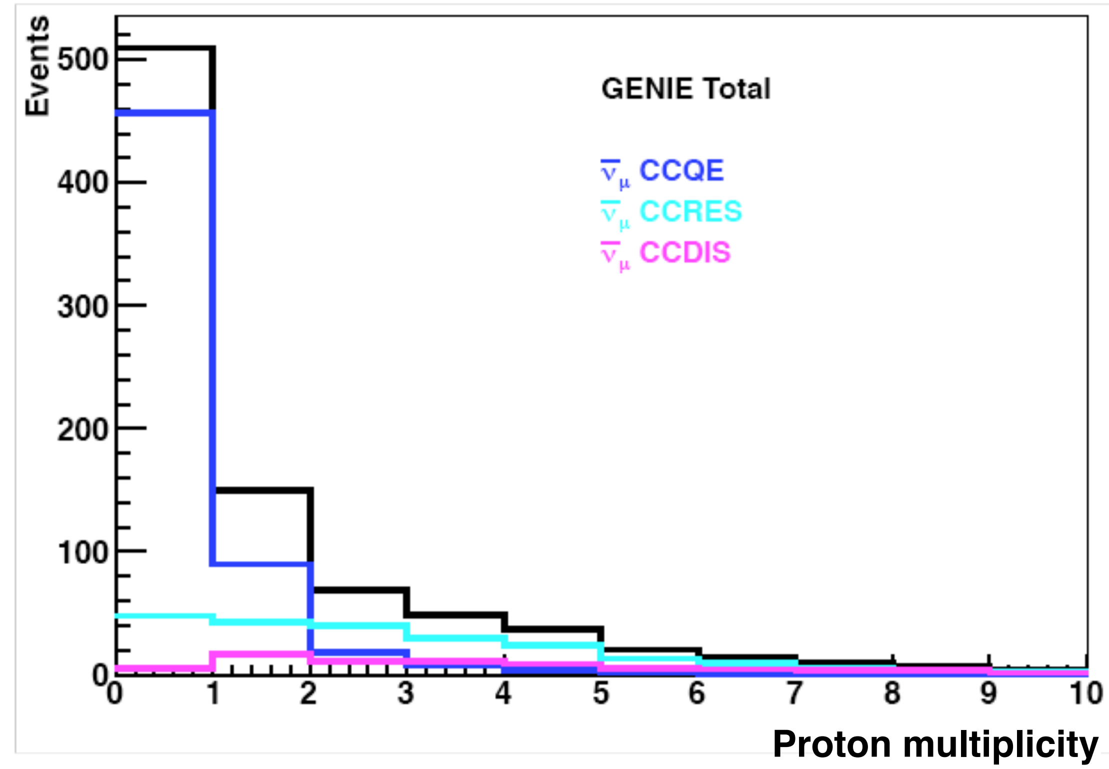
GENIE MC models more higher multiplicity events

MC PREDICTIONS by Physical Process

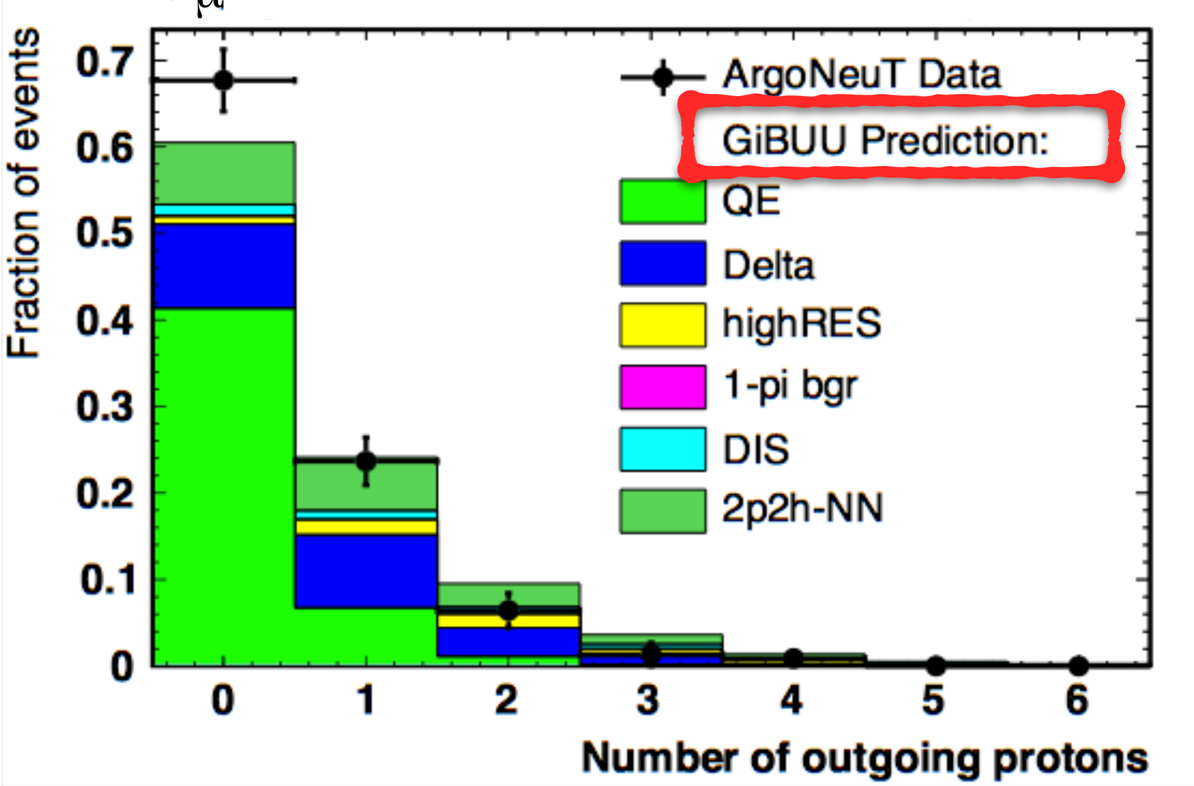
ν_μ - anti-neutrino mode run



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



ν_μ - anti-neutrino mode run



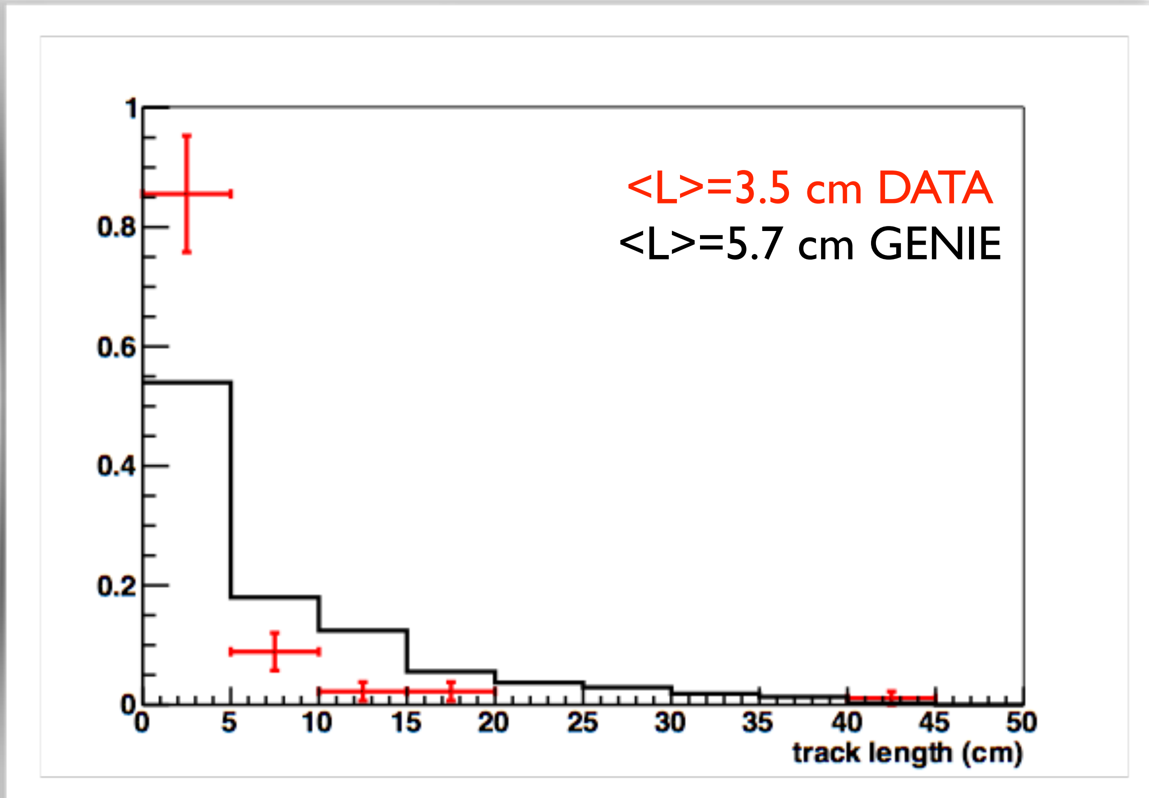
GENIE: ~30% contribution from non-CCQE events

GIBUU: ~50% contribution from non-CCQE events

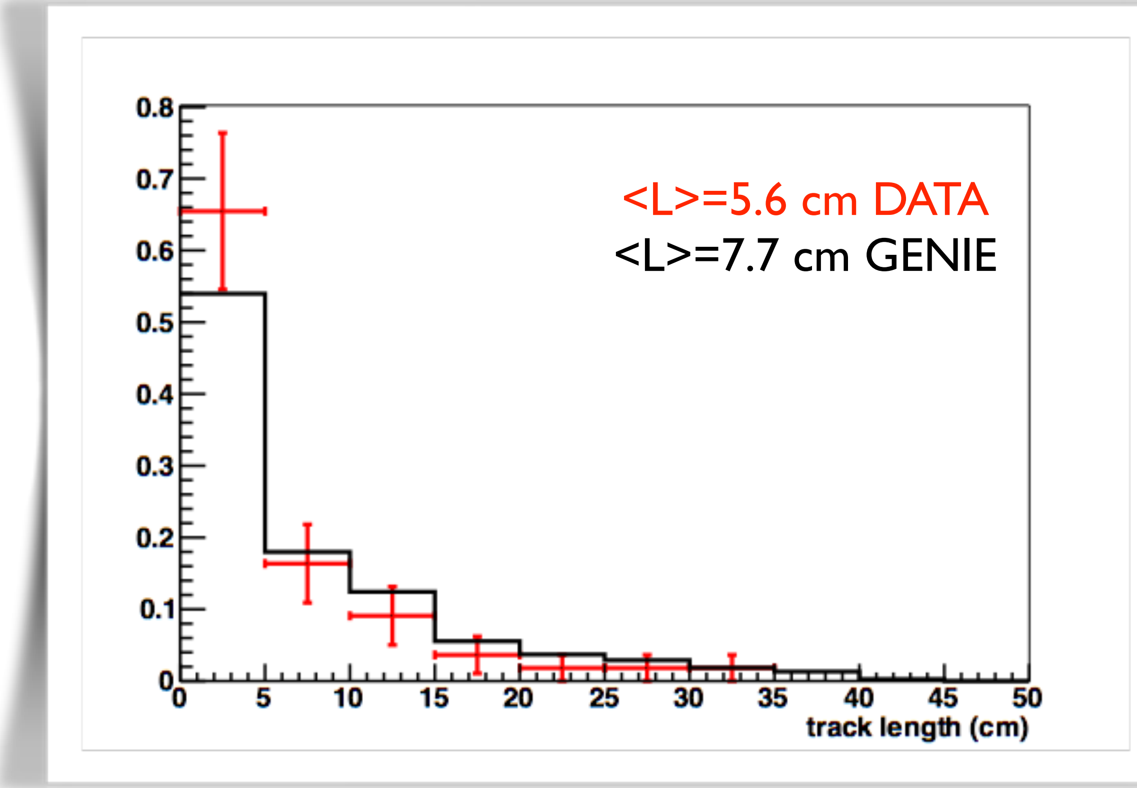
The MC generators predict varying amounts of proton emission.

μ^+ / μ^- 1 p events PROTON KINEMATICS

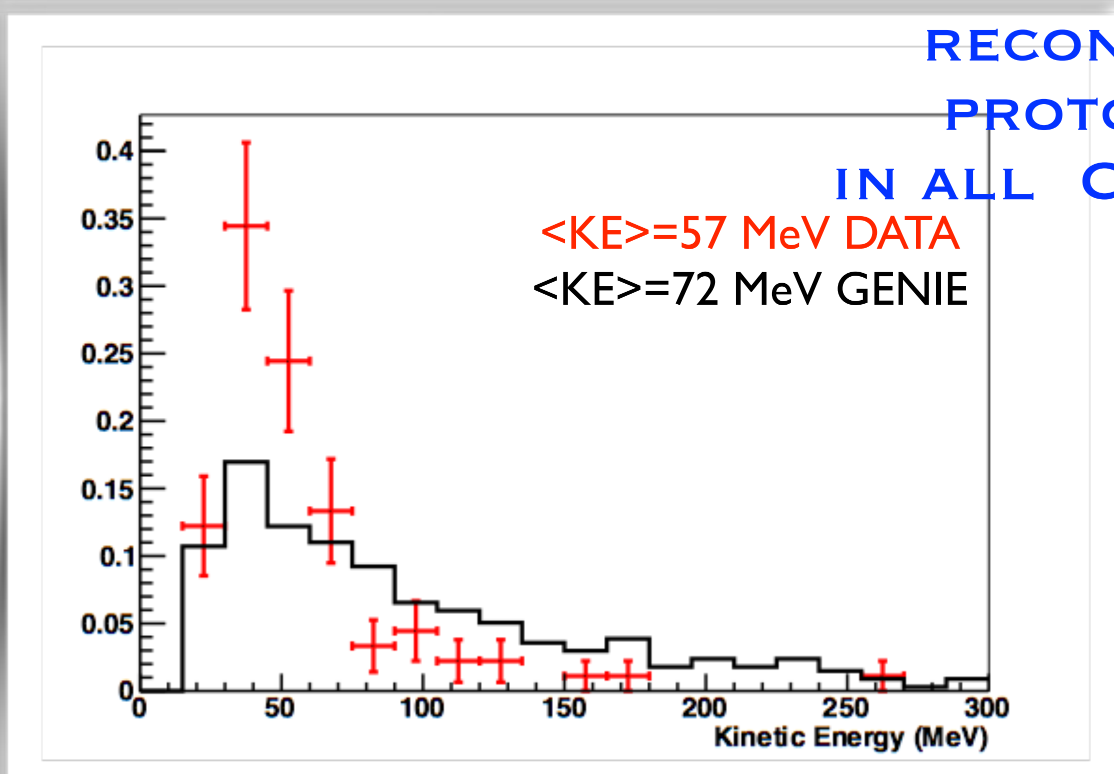
$\bar{\nu}_\mu$ - anti-neutrino mode run

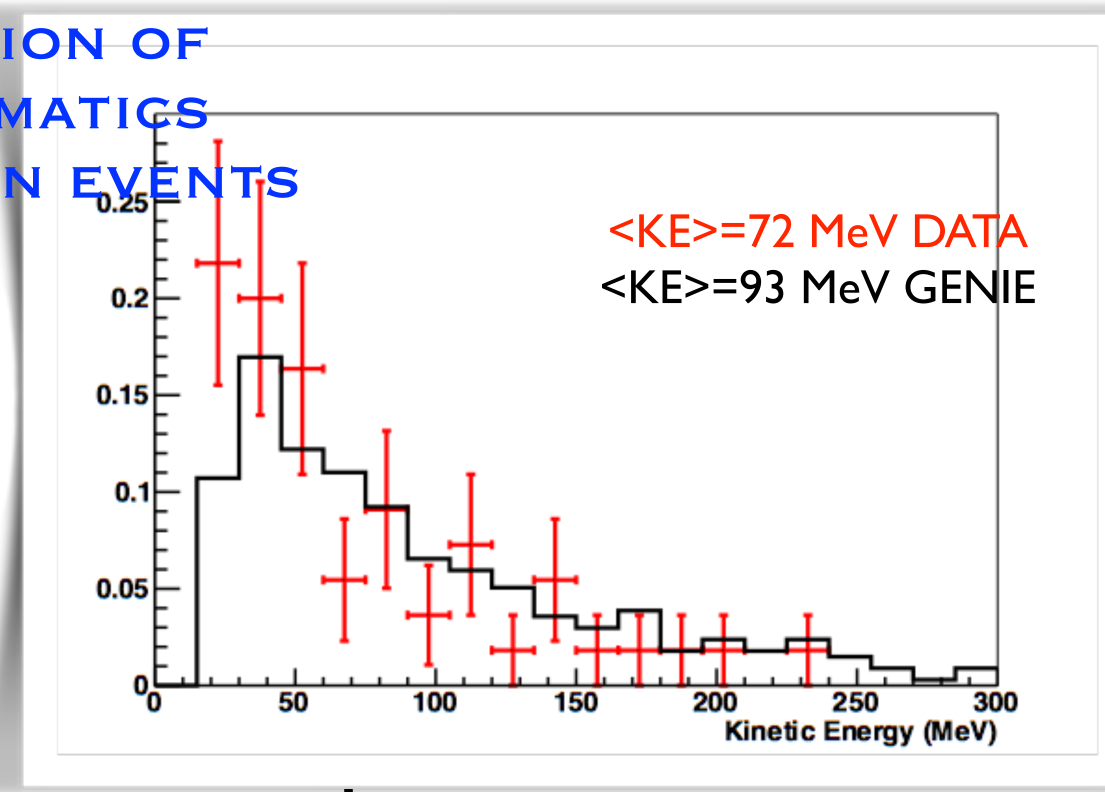


ν_μ - anti-neutrino mode run



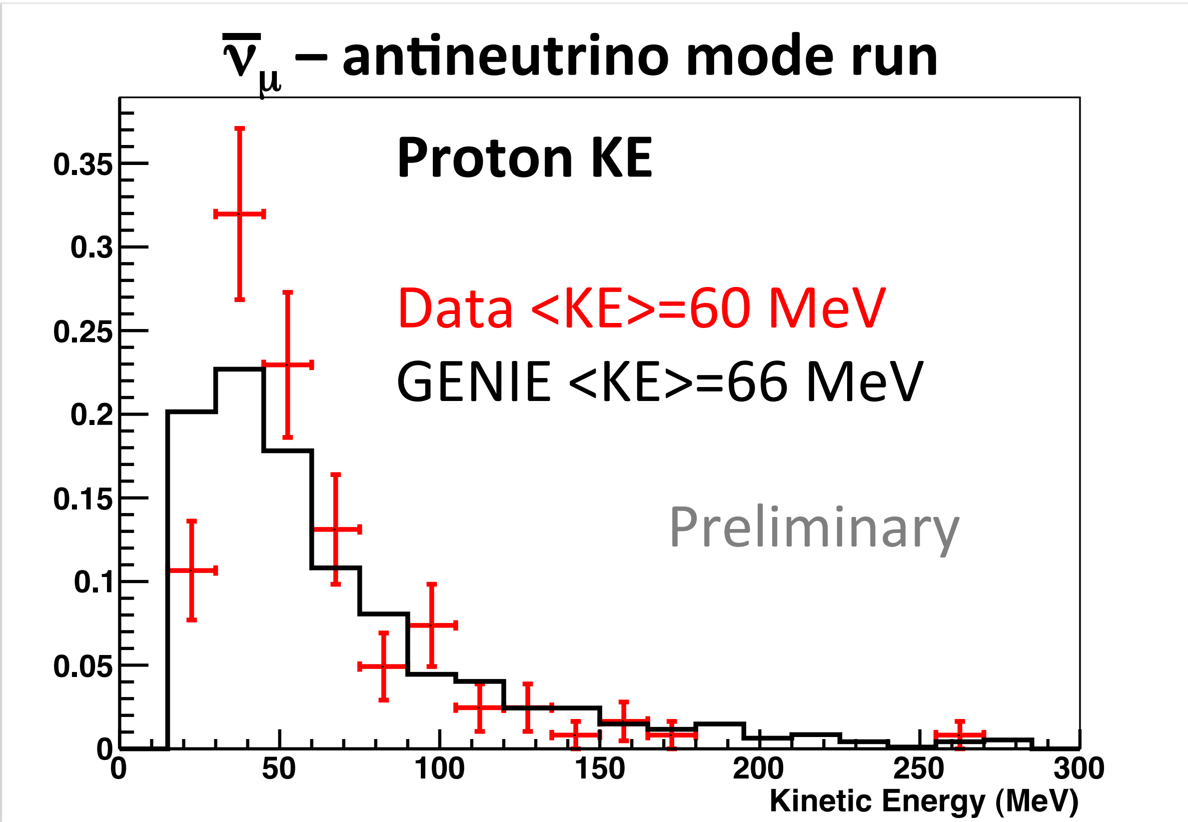
RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS





GENIE MC models more energetic protons

NEUTRINO ENERGY RECONSTRUCTION



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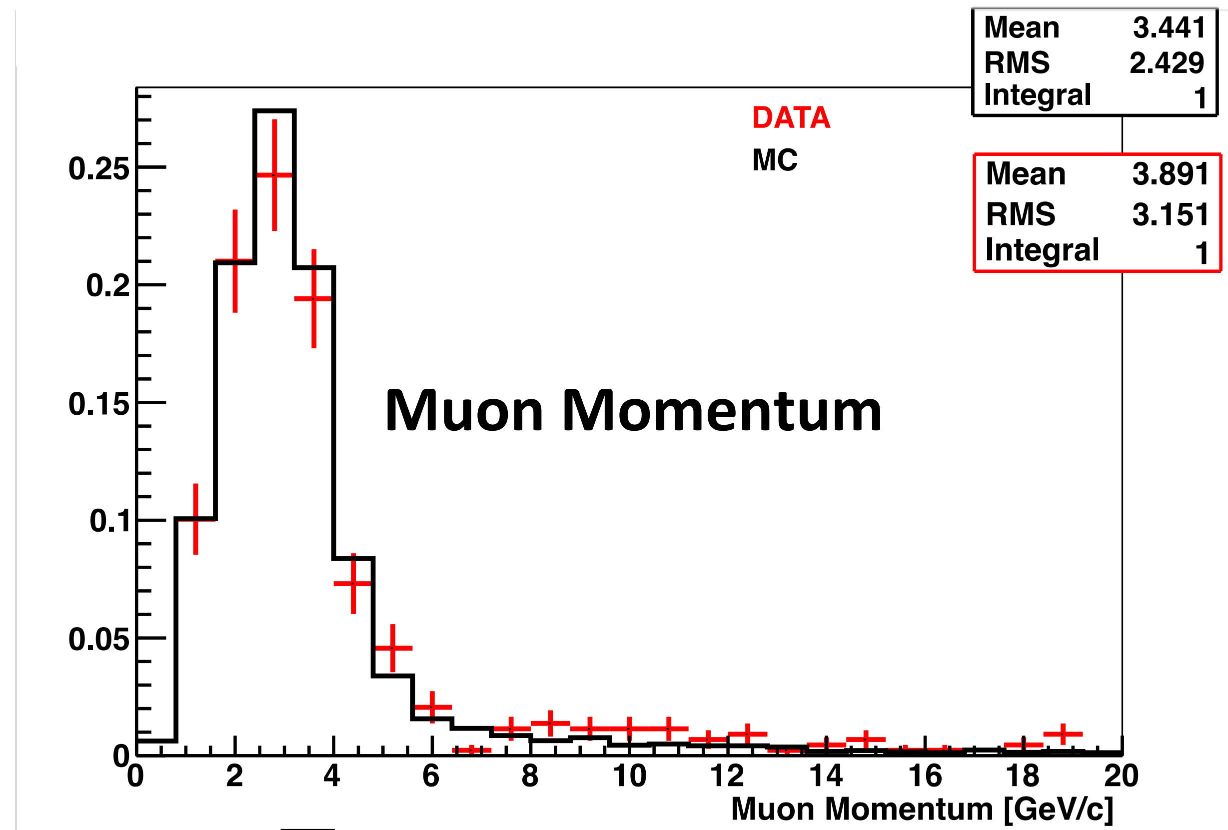
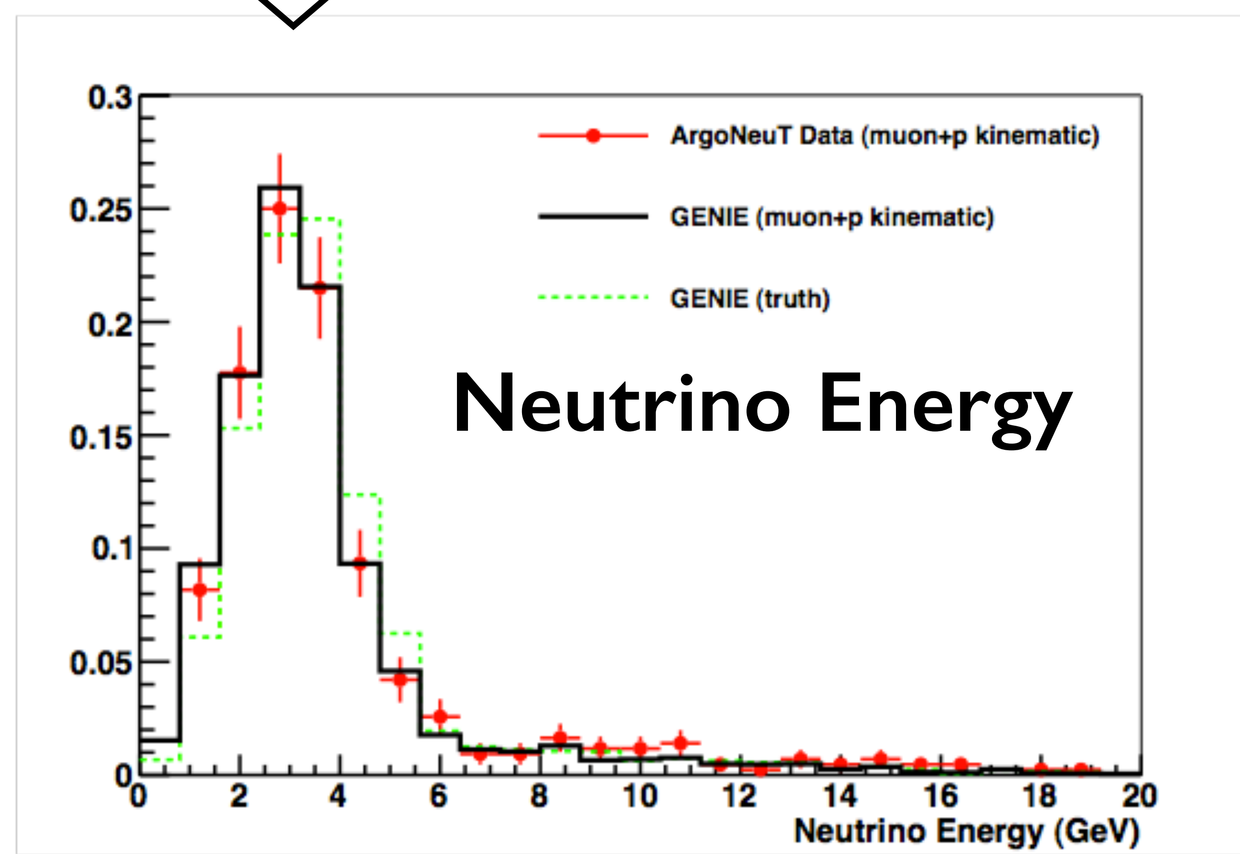




Neutrino Energy from muon+proton reconstructed kinematics:

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

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.)

NUCLEON-NUCLEON CORRELATIONS

Two-nucleon knockout from high energy scattering processes is the most appropriate venue to probe NN correlations in nuclei.

Two nucleons can be naturally ejected by:

- Two-body mechanisms:
  - MEC - two steps interactions probing two nucleons correlated by meson exchange currents, and
  - "Isobar Currents" (IC) - intermediate state Δ excitation of a nucleon in a pair with decay pion reabsorbed by the other nucleon.

  The NN-pairs in these two-body processes may or may not be SRC pairs.
- One-body interactions: two-nucleon ejection only if the struck nucleon is in a SRC pair, the high relative momentum in the pair would cause the correlated nucleon to recoil and be ejected as well.

NN pairs in two-body processes may or may not be SRC pairs.

- We know (now) that about 20% Nucleons in Nuclei are in SRC (np) pairs
- Long range correlations (MEC) are very relevant and may change significantly XSECT measurements
- Pion absorption (two-body) is relevant
- FSI's are always a big pain!
- All these effects are combined and interfere w/ each other - (e.g. MEC can involve SRC pairs !)

ARGONEUT STUDY - (μ^-+2p) SAMPLE

- Search for possible hints of nucleon-nucleon correlations in the ArgoNeuT data, by specifically looking at the neutrino events with N=2 protons in final state, i.e. the (μ^-+2p) triple coincidence topology.

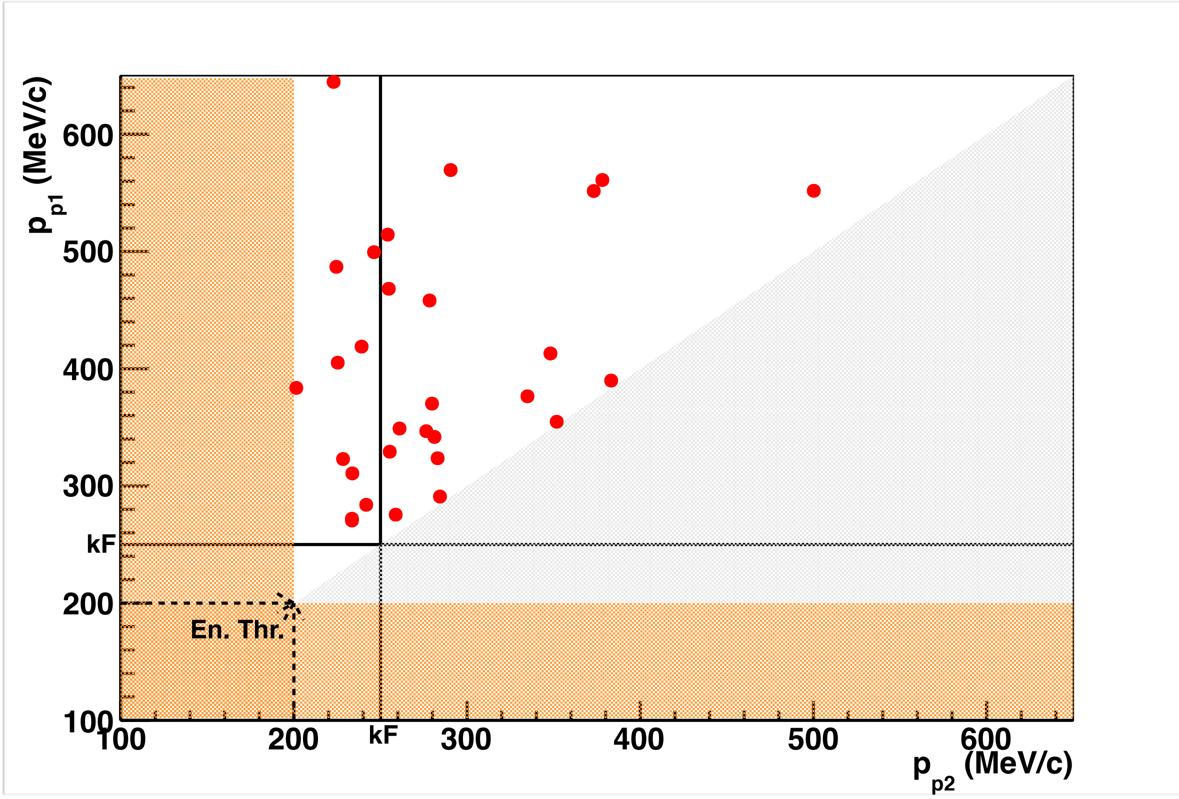
- Data sample: 30 events in total (19 collected in the anti-neutrino mode run and 11 in the neutrino mode run).

- Both proton tracks are required to be fully contained inside the fiducial volume (FV) of the TPC and above energy threshold. From detector simulation, the overall acceptance for the (μ^-+2p) sample is estimated to be around 35% (dominated by the containment requirement in FV).

- According to GENIE MC simulation: ~40% of these are due to CC QE interactions and about 40% to CC RES pionless interactions.

- (μ^-+2p)/(μ^-+Np)=21% (26%) and (μ^-+2p)/CC-inclusive~2% (~4%) for the anti-neutrino-mode run (neutrino-mode) [efficiency corrected]

(μ^-+2p) SAMPLE

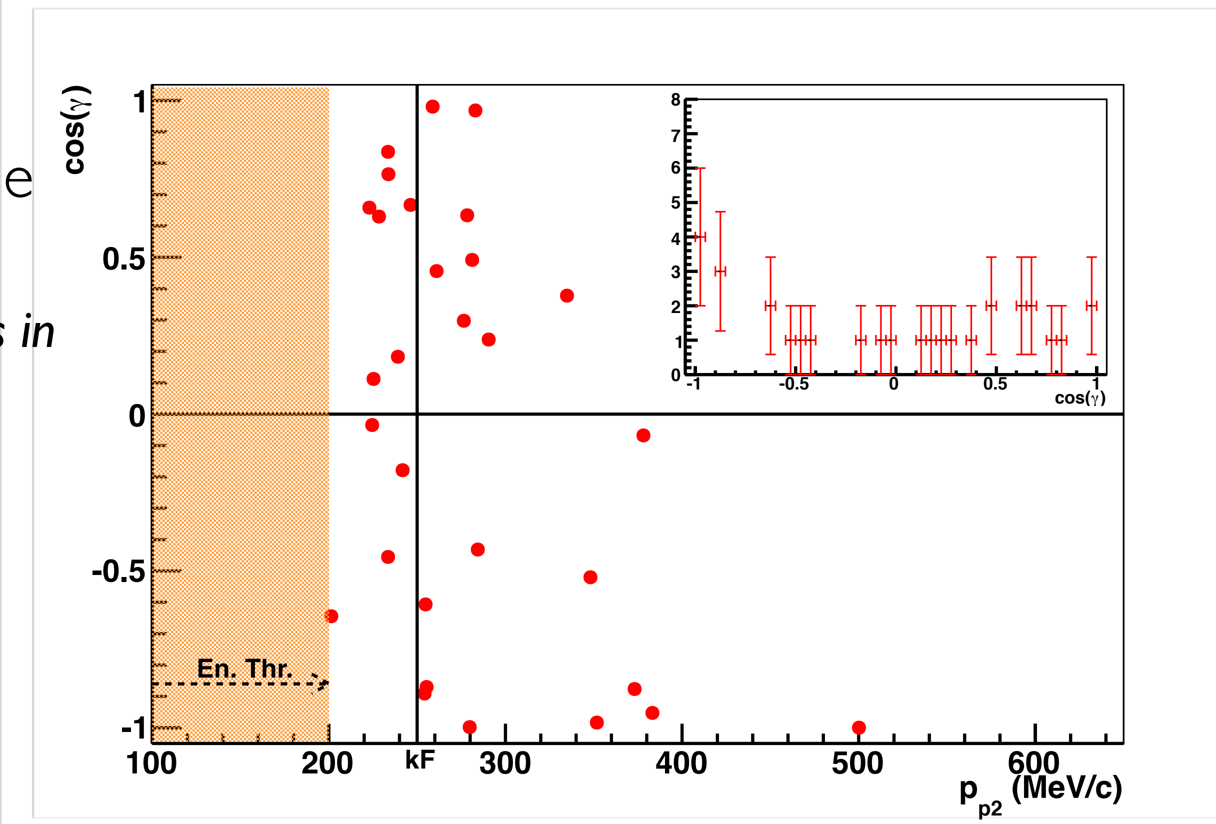


Momentum of the more energetic proton p_{p1} in the pair vs. momentum of the other (less energetic) proton p_{p2}

Most of the events (19 out of 30) have both protons above Fermi momentum of the Ar nucleus ($k_F \simeq$250 MeV)

cos(γ) vs the lower proton momentum in the pair and distribution of cos(γ) [insert]

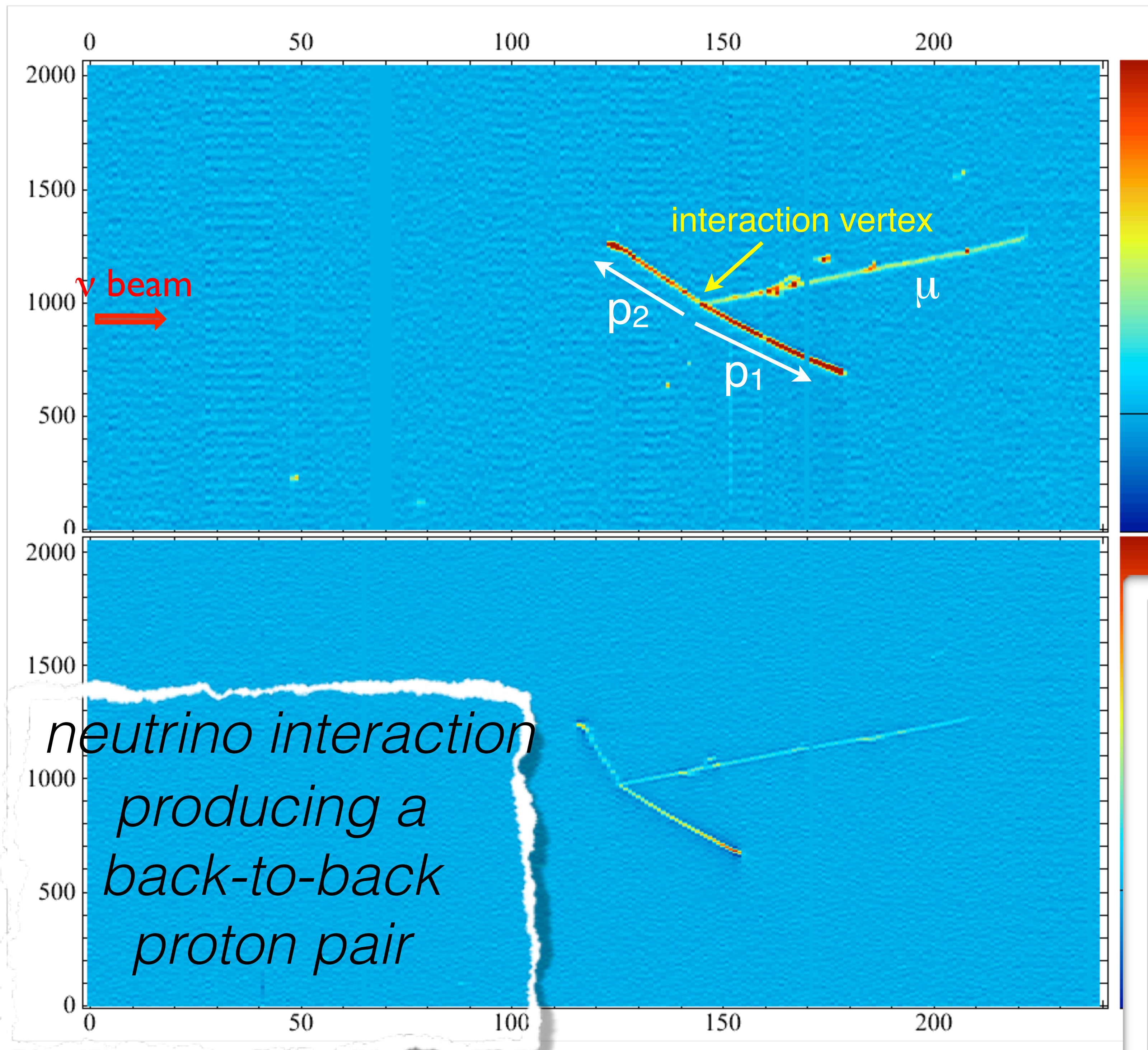
γ=angle in space between the two proton tracks in the Lab reference frame



proton angular resolution: 1-1.5^0
proton energy resolution: ~6% for protons above Fermi momentum

Four of the 19 2p-events are found with the pair in a back-to-back configuration [cos(γ)<-0.95, with one p almost exactly balanced by the other ($\vec{p}_{p1},\vec{p}_{p2} \geq k_F$ and $\vec{p}_{p1} \simeq -\vec{p}_{p2}$)]

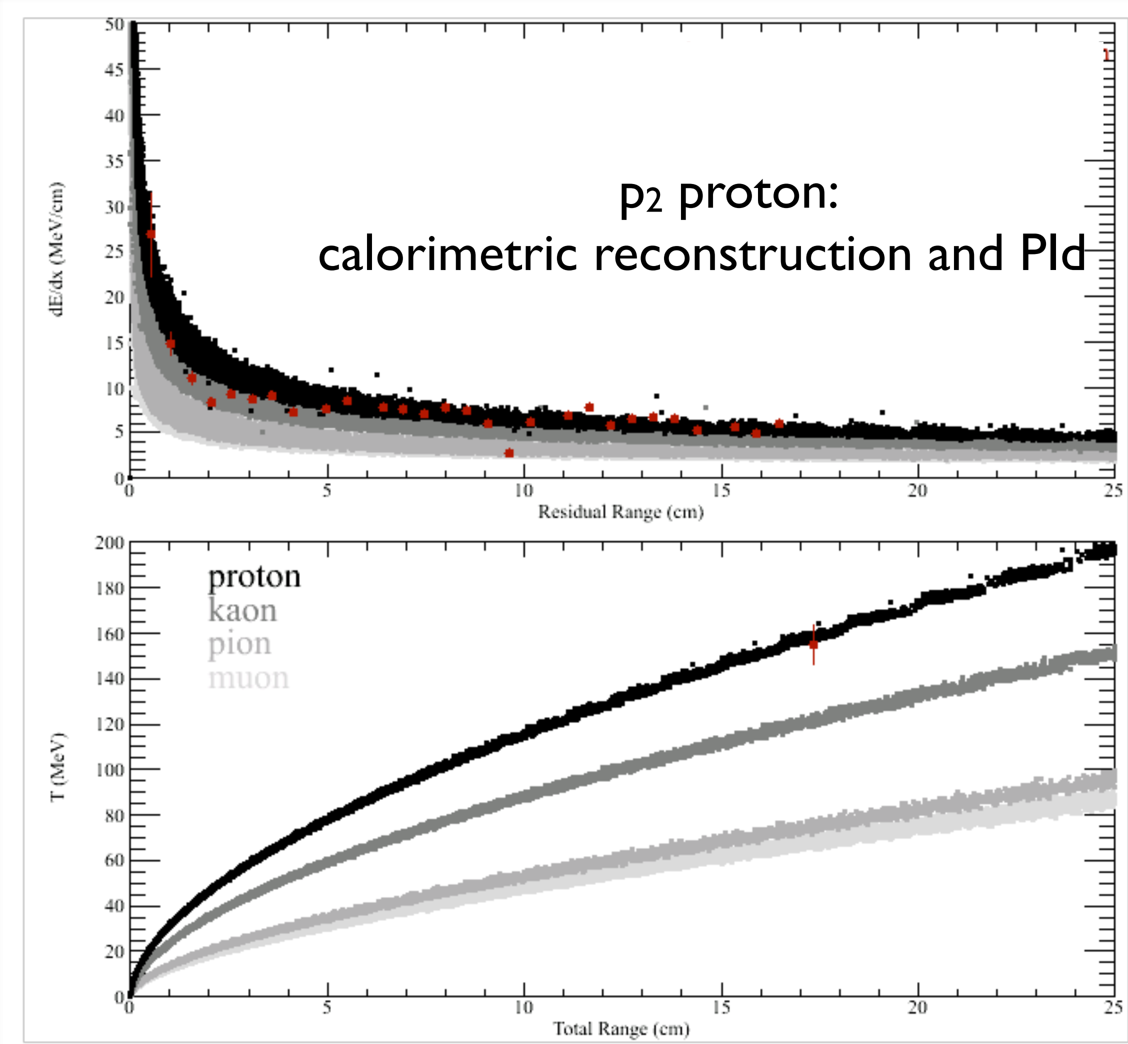
BACK-TO-BACK PROTON PAIR

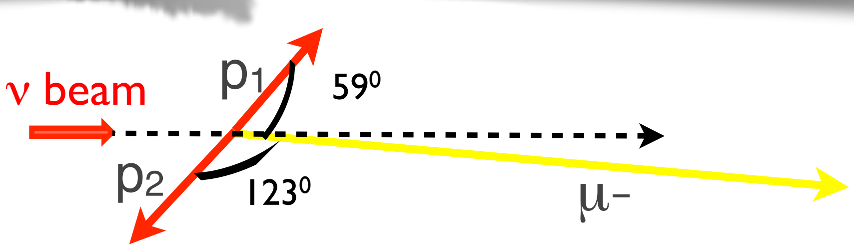


Visually appearing as <u>hammer</u>

(muon forming the handle and the back-to-back protons forming the head)

Angle between two protons γ=**178^0**





back-to-back protons

Pairs of energetic protons with 3-momentum $p_{p1}, p_{p2} \geq k_F$ detected at large opening angles directly in the Lab frame were observed in bubble-chamber by hadron scattering experiments (pion absorption on nuclei).
This was interpreted as **hints for SRC** *in the target nucleus.*

Electron scattering experiments extensively studied **SRCs**. Last generation experiments probe SRC by triple coincidence - A(e,e' np *or* pp)A-2 reaction - where both knock-out nucleons are detected at two fixed angles.

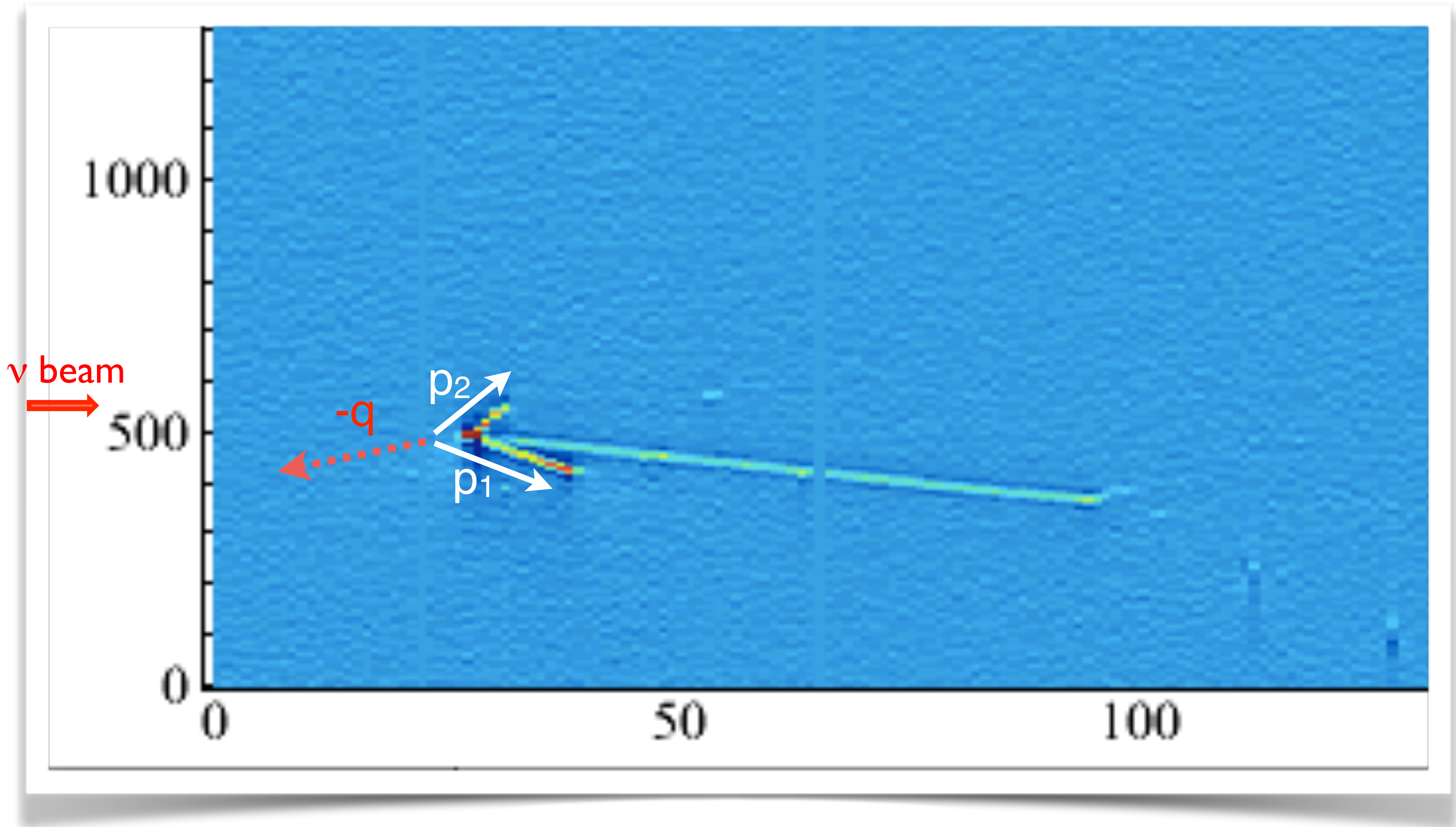
- The SRC pair is typically assumed to be at rest prior to the scattering and the kinematics reconstruction utilizes pre-defined 4-momentum transfer components determined from the fixed beam energy and the electron scattering angle and energy.
- The NN-SRCs are associated with finding a pair of high-momentum nucleons, whose *reconstructed* initial momenta are back-to-back and exceed k_F, while the residual nucleus is assumed to be left in a highly excited state after the interaction.

In neutrino scattering experiments one main limitation comes from the intrinsic uncertainty on the 4-momentum transfer, due to the not fixed (broadly distributed in the beam spectrum) incident neutrino energy. An estimate can be inferred with satisfactory accuracy when all final state particles kinematics is precisely measured.

(μ^-+2p) SAMPLE

With an approach similar to the electron scattering triple coincidence analysis, we applied transfer momentum vector subtraction to the higher proton momentum in our sub-sample of the remaining events with both protons above Fermi momentum.

Events consistent with pre-existing at rest SRCs would show $\vec{p}_{ni} \sim \vec{p}_{p2}$, i.e. back-to-back in the initial state.



Results in a paper in preparation, presently under internal review

CONCLUDING REMARKS

**NUCLEAR EFFECTS (IN HEAVY NUCLEAR TARGETS)
ARE IMPORTANT AND
FAR MORE COMPLEX AND OVERWHELMING
THAN USUALLY ASSUMED**

Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data, in particular for nuclear effects understanding (FSI+Nucleon-Nucleon correlations)

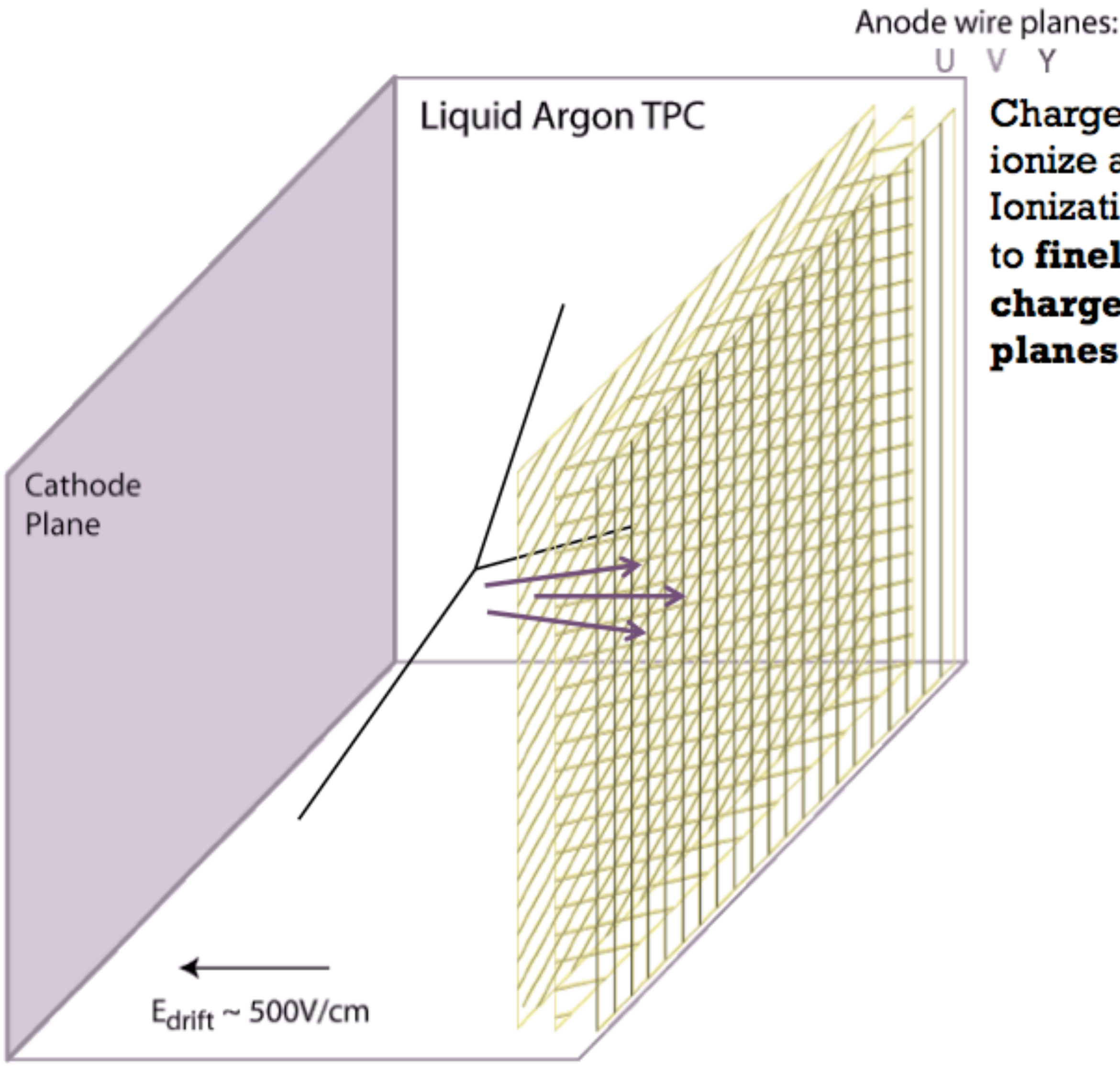
Data from LAr extremely helpful and
can provide important hints to tune MC generators
and discriminate among models

QE or not QE, that is the question

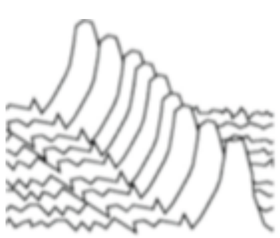
Future larger mass and high statistics LAr-TPC detectors have the opportunity to clarify the issue
[following the line pioneered with the (statistically limited) ArgoNeuT data sample]

BACKUP

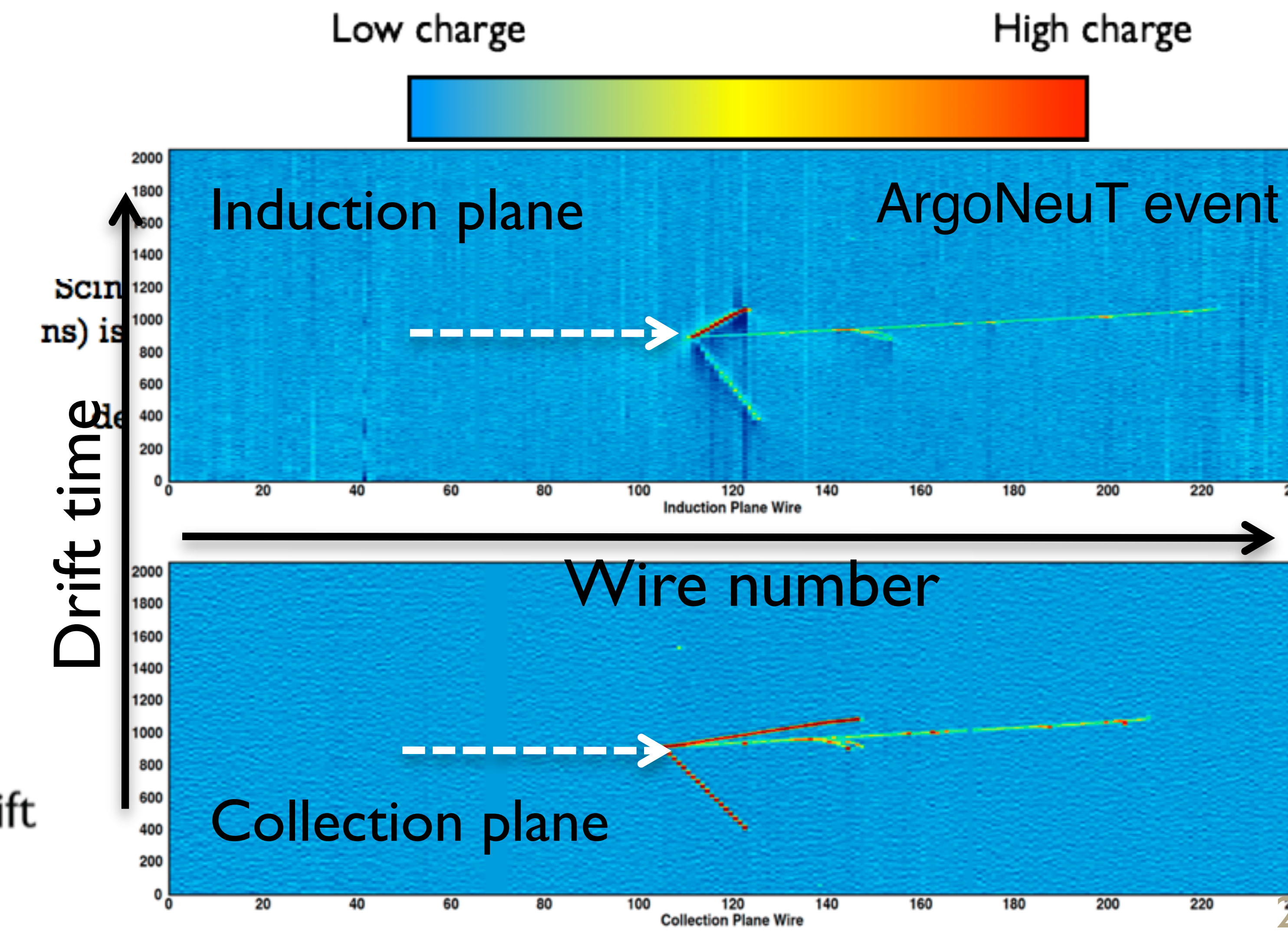
THE LAR TPC CONCEPT



Charged particle tracks ionize argon atoms; Ionization charge drifts to **finely segmented charge collection planes** over ~1-few ms.



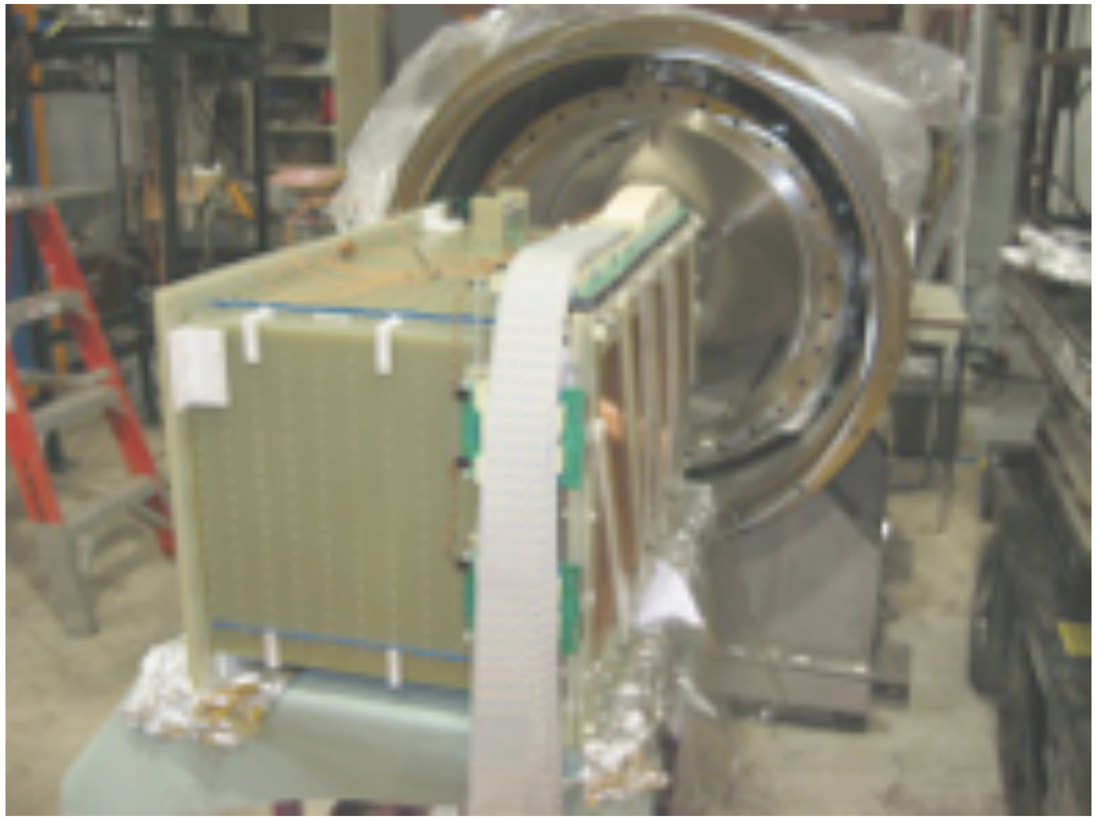
Wire pulses in time give the drift coordinate of the track



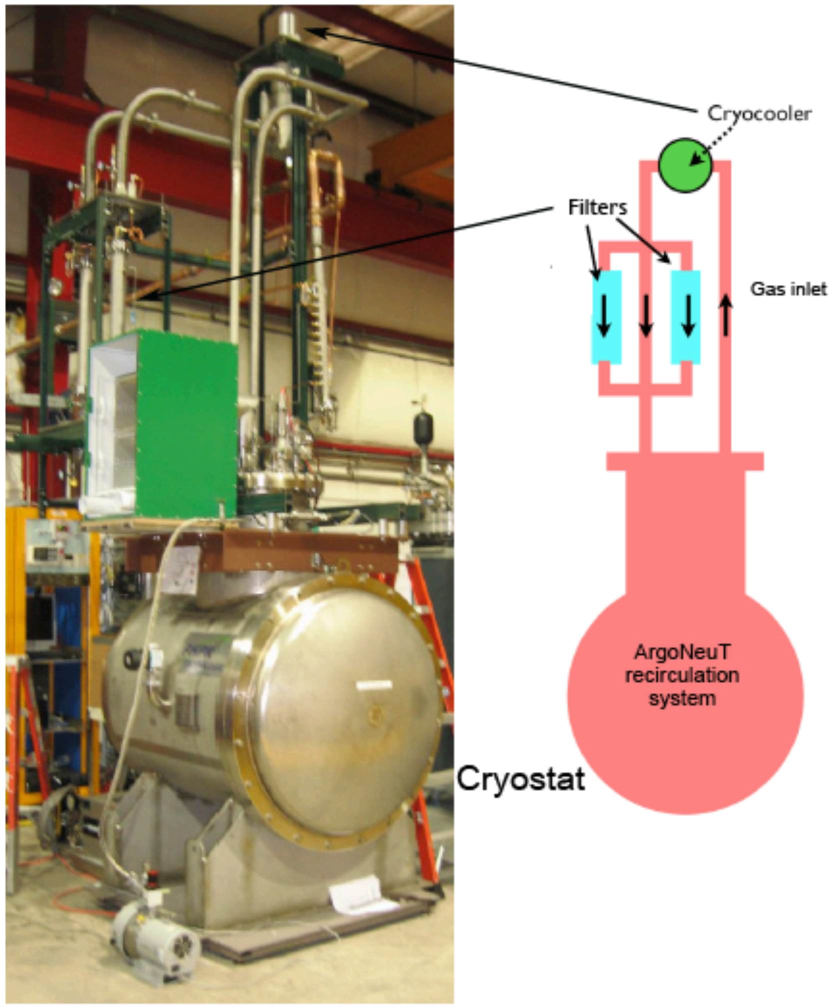
induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

ArgoNeuT Detector

"The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab" **JINST 7 (2012) P10019**



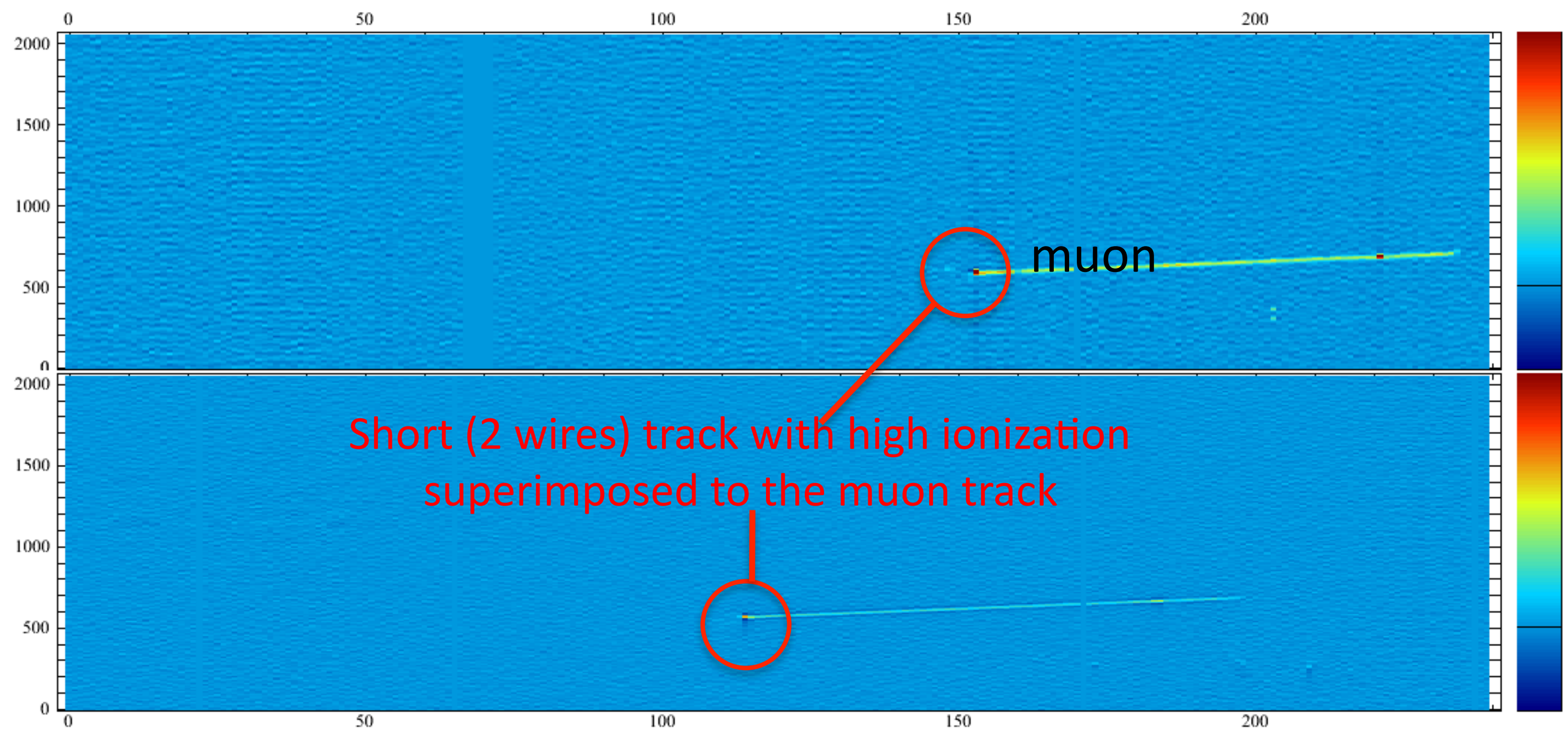
The TPC, about to enter the inner cryostat



Cryostat Volume	500 Liters
TPC Volume	170 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length	47 cm
Light Collection	None

- Self contained system
- Recirculate argon through a copper-based filter
- Cryocooler used to recondense boil-off gas

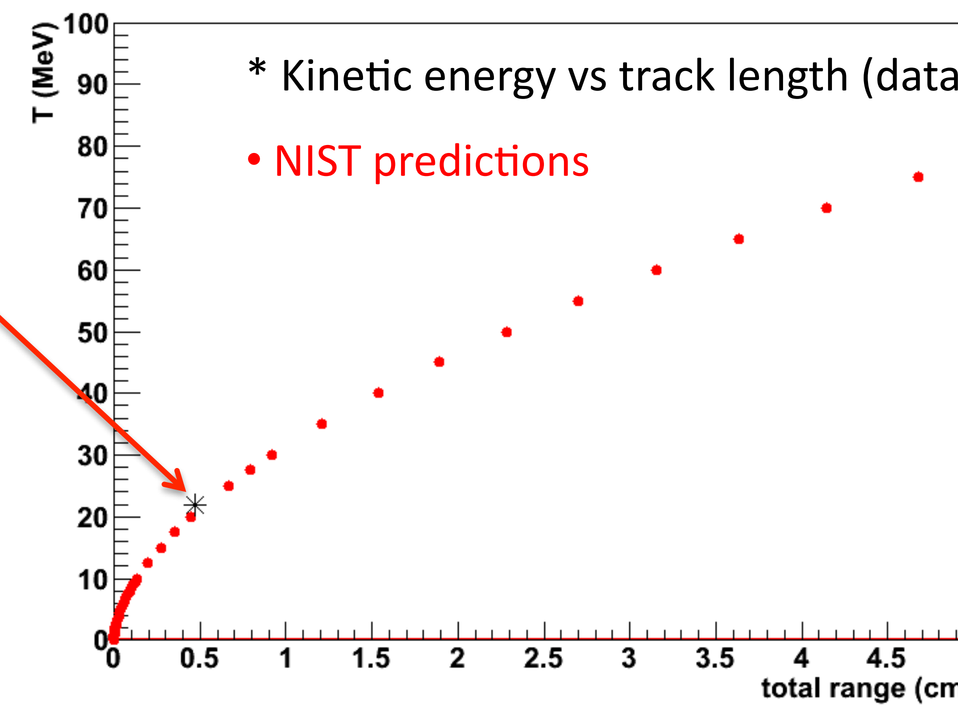
Example of Low energy proton reconstruction



The short track behaves like proton

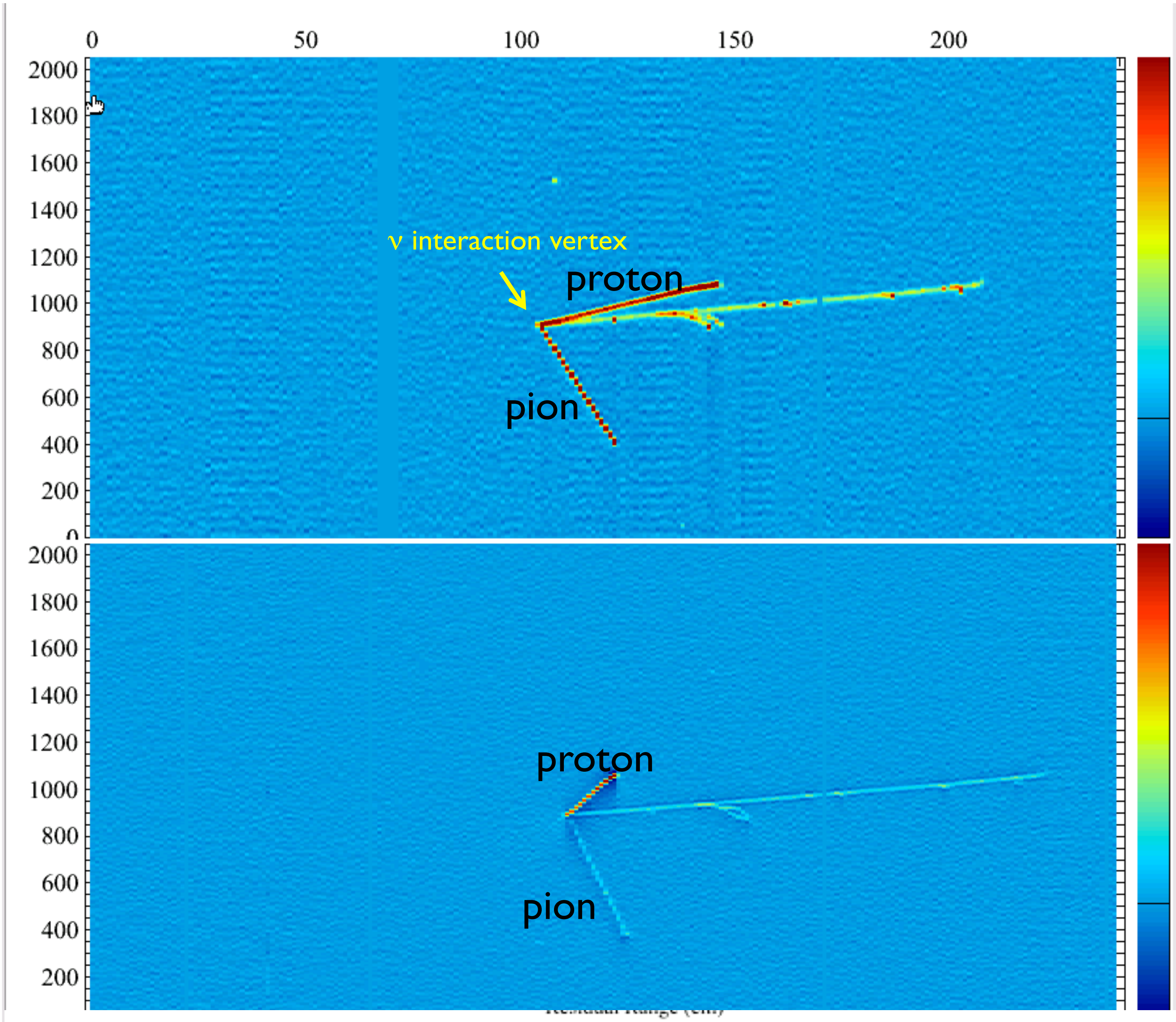
Length=0.5 cm

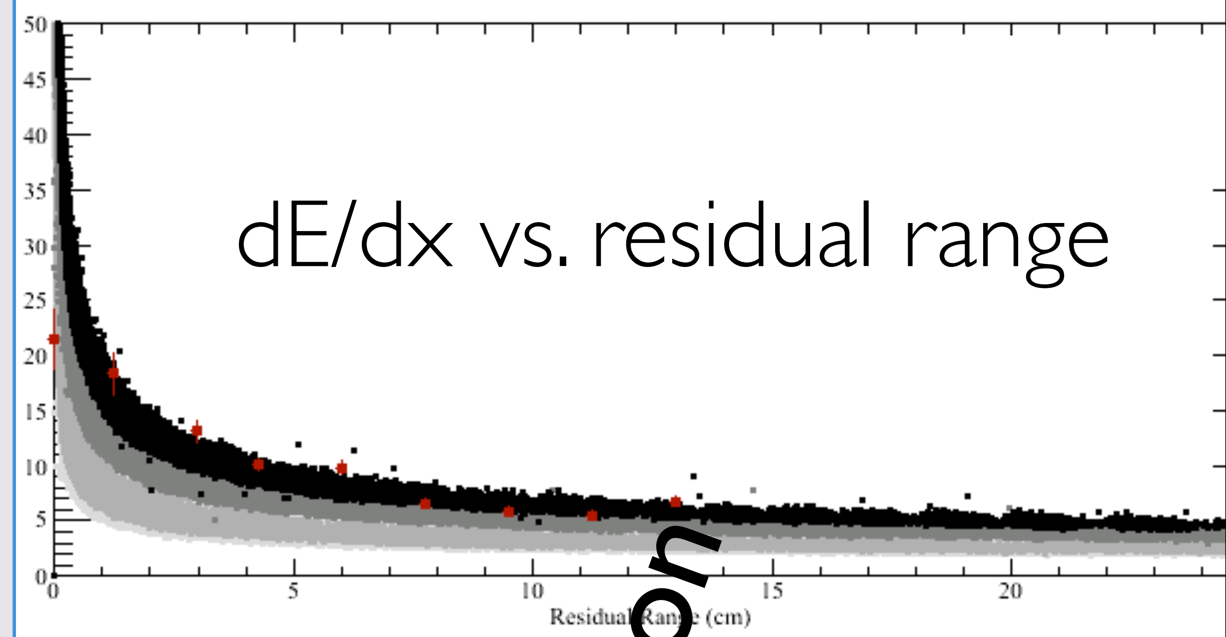
KE=22±3 MeV

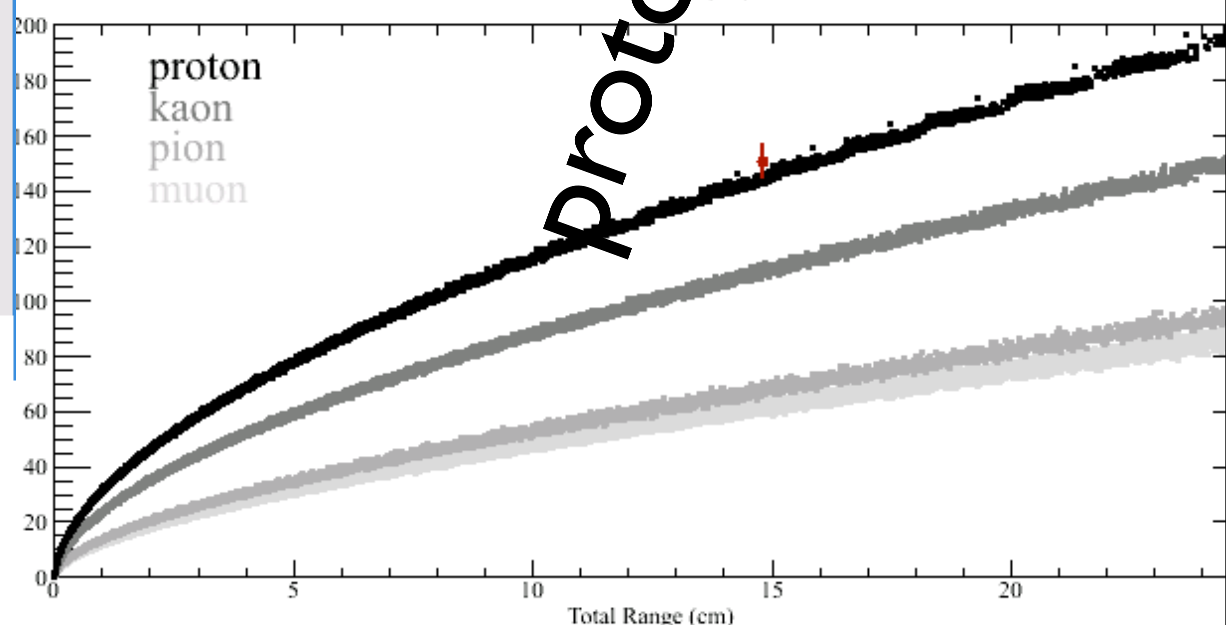


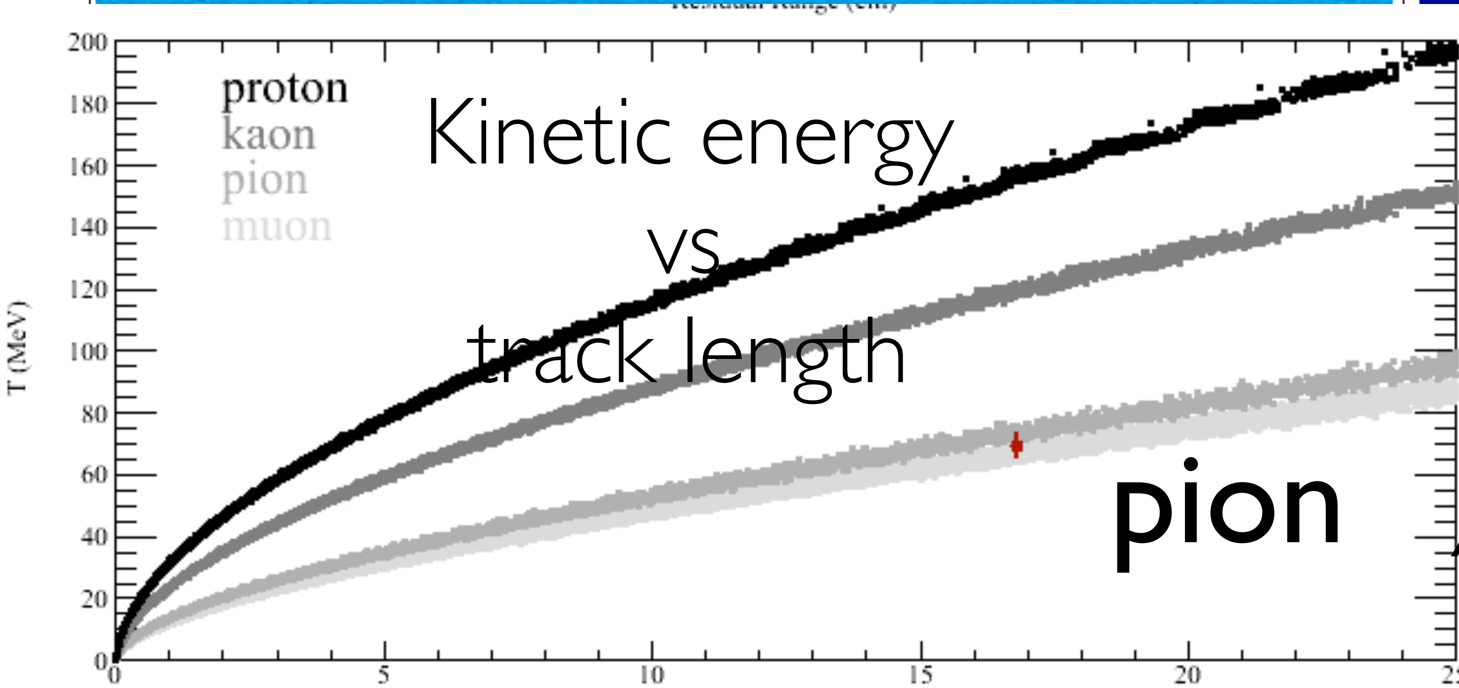
ArgoNeuT proton threshold: 21 MeV of Kinetic Energy

$p/\pi^{\pm}$ identification





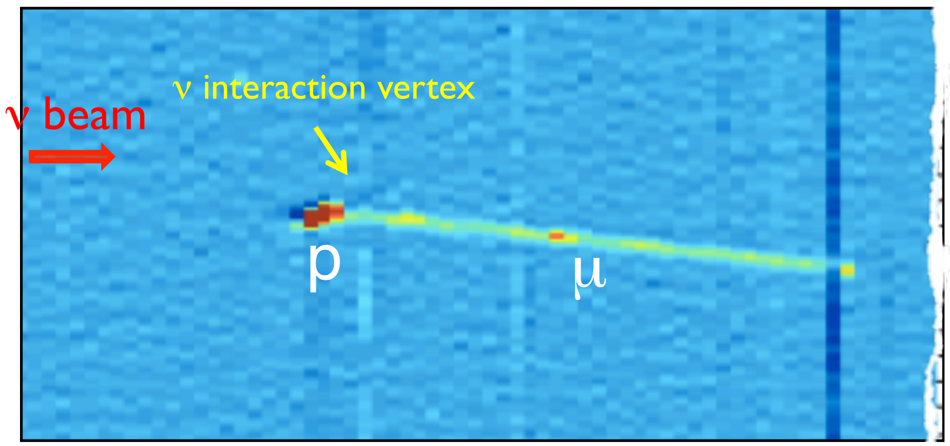


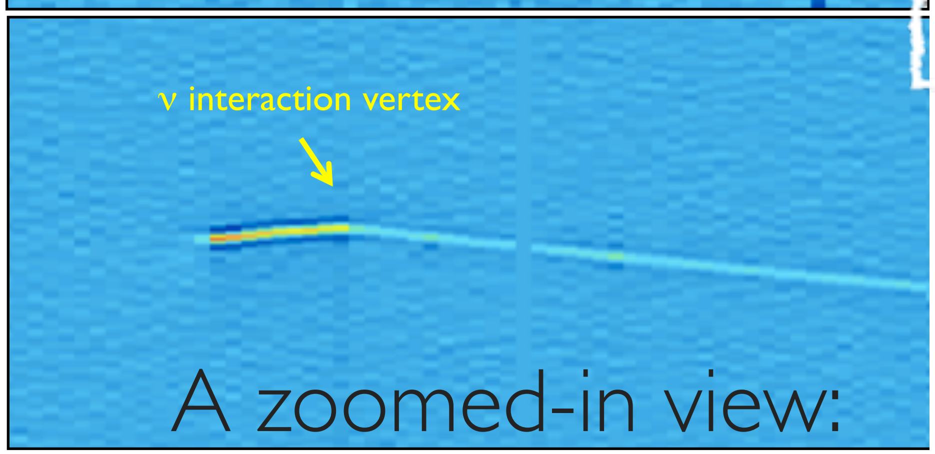


ArgoNeuT pion reconstruction threshold: ~8 MeV Kinetic energy

PROTON KINEMATICS: BACKWARD GOING PROTONS (BP)

Backward going protons are detected and reconstructed in ArgoNeuT DATA





A zoomed-in view:

ν interaction with

one backward going p

μ^-1p

DATA backward=25%

GENIE backward=26%

μ^+1p

DATA backward=25%

GENIE backward=27%

μ^-2p

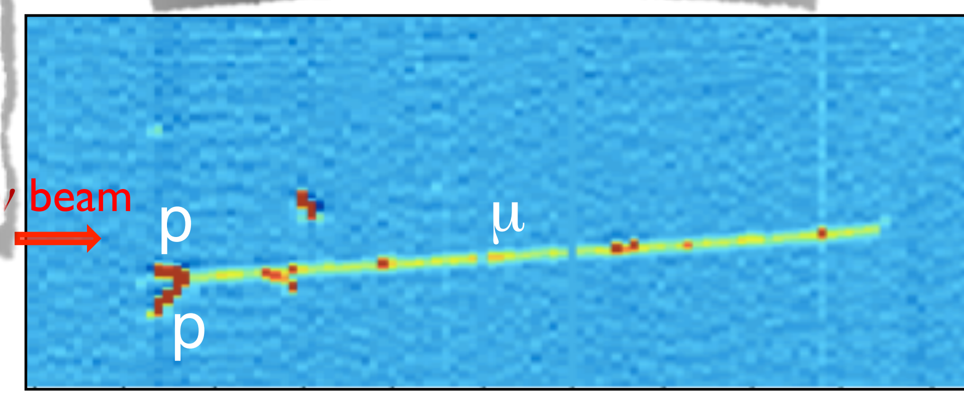
DATA backward=21%

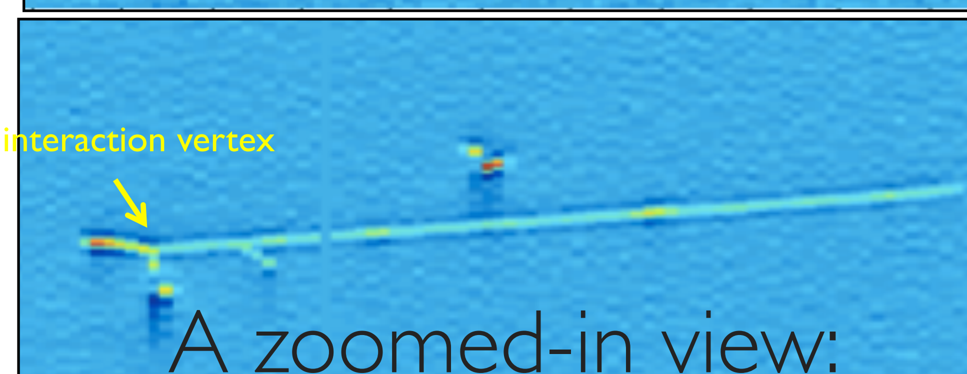
GENIE backward=30%

μ^+2p

DATA backward=13%

GENIE backward=36%





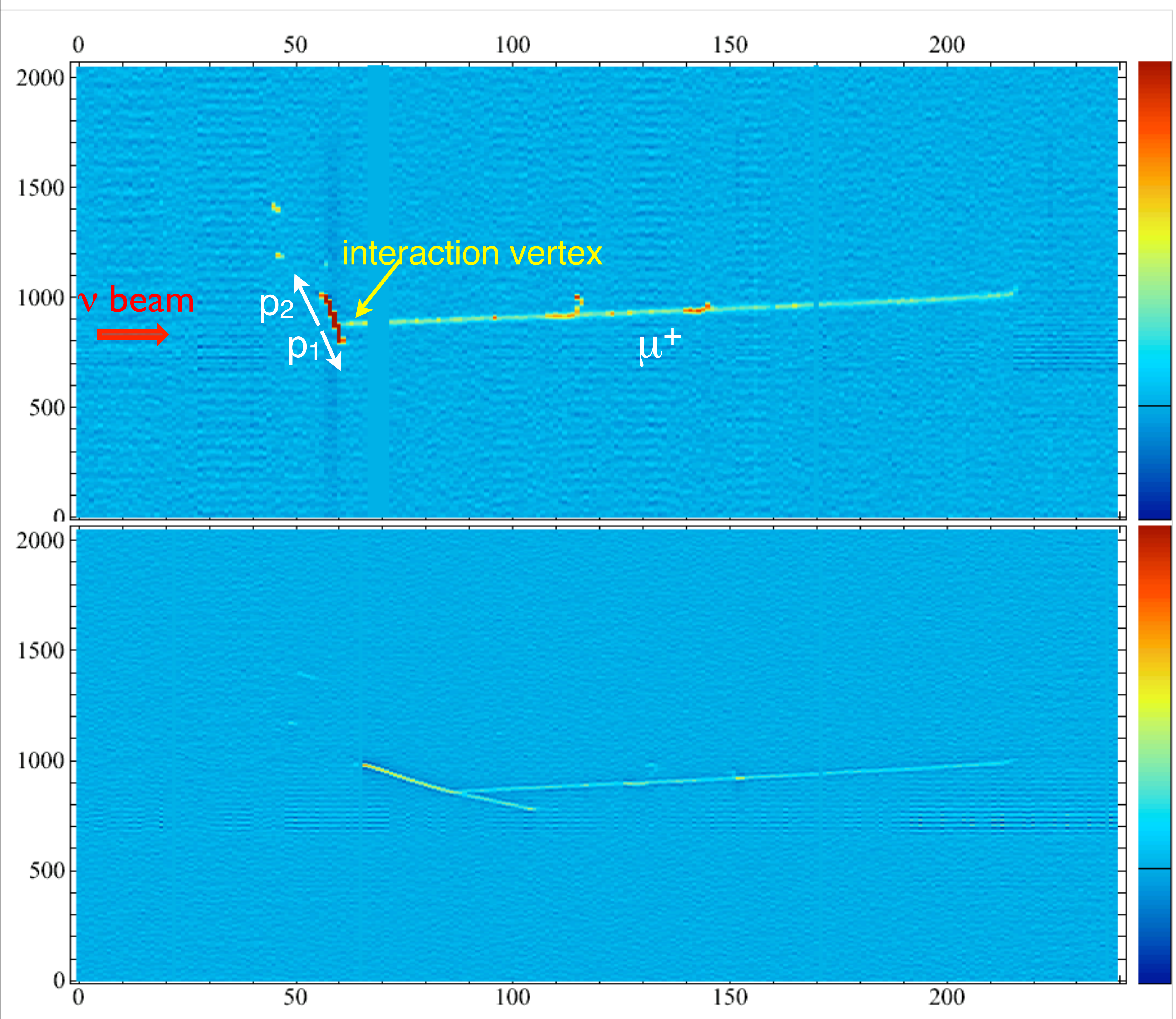
A zoomed-in view:

ν interaction with

two backward going p

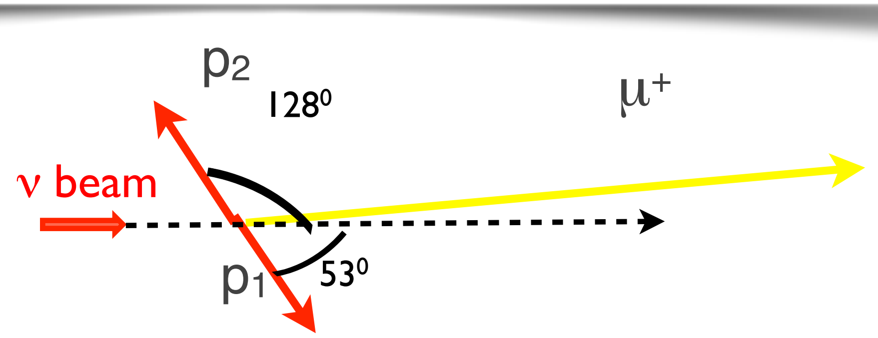
DETAILED STUDY OF BP IN PROGRESS

BACK-TO-BACK PROTON PAIR



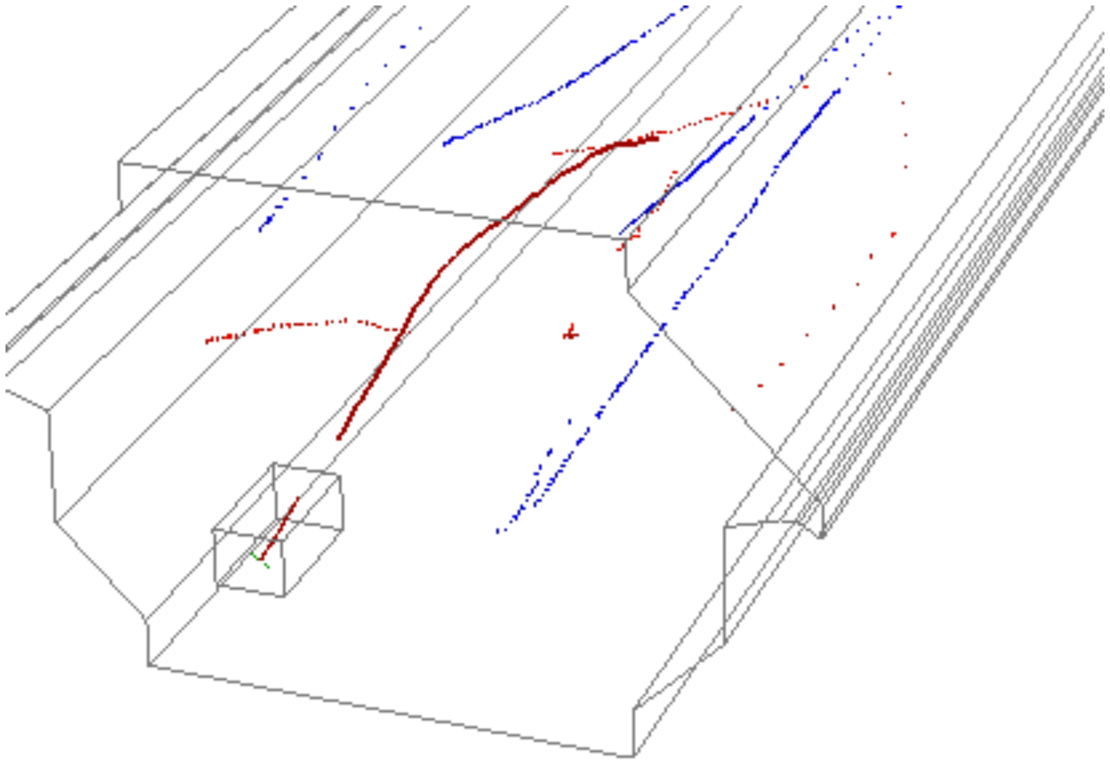
Angle between two protons γ=177⁰

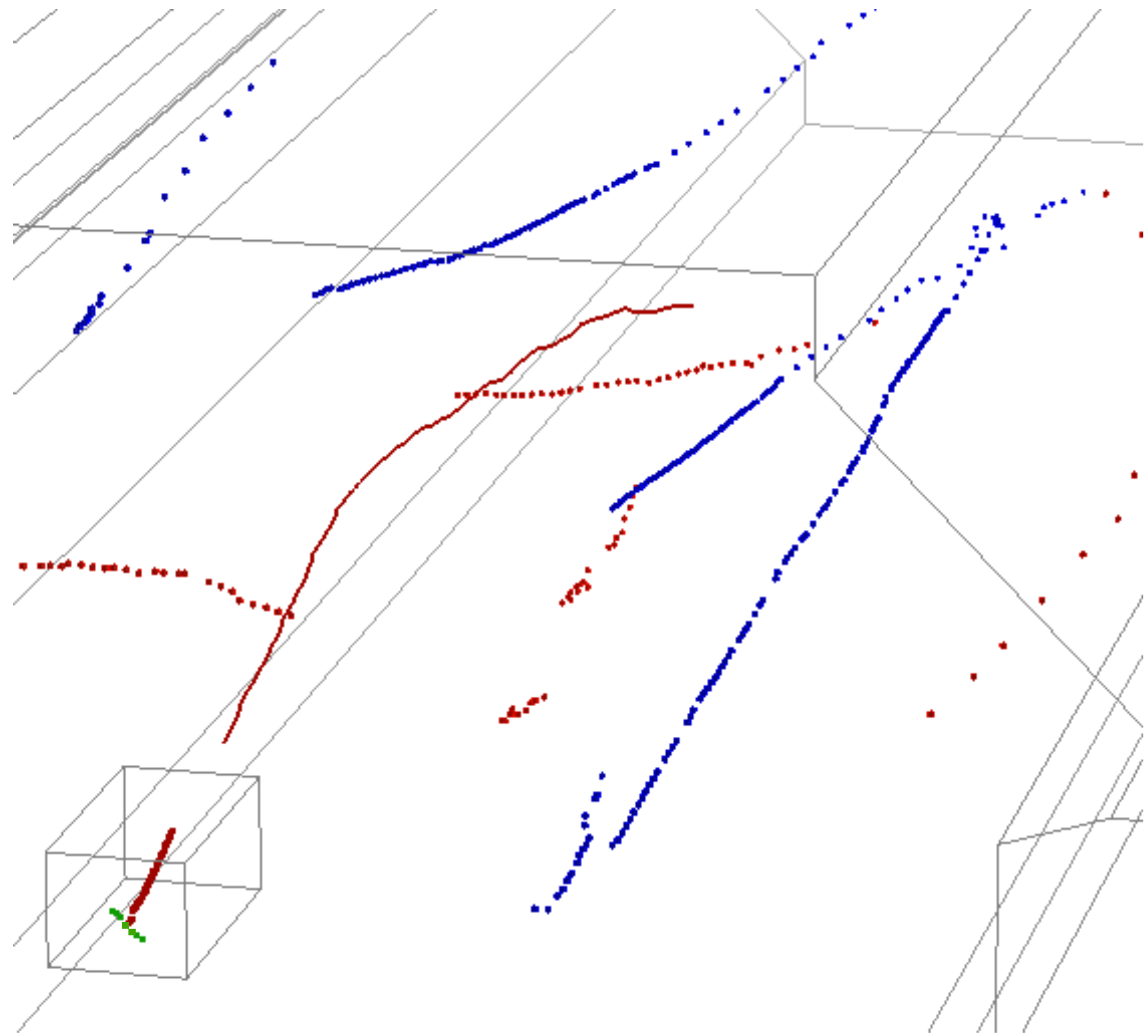
anti-Neutrino interaction producing a back-to-back proton pair

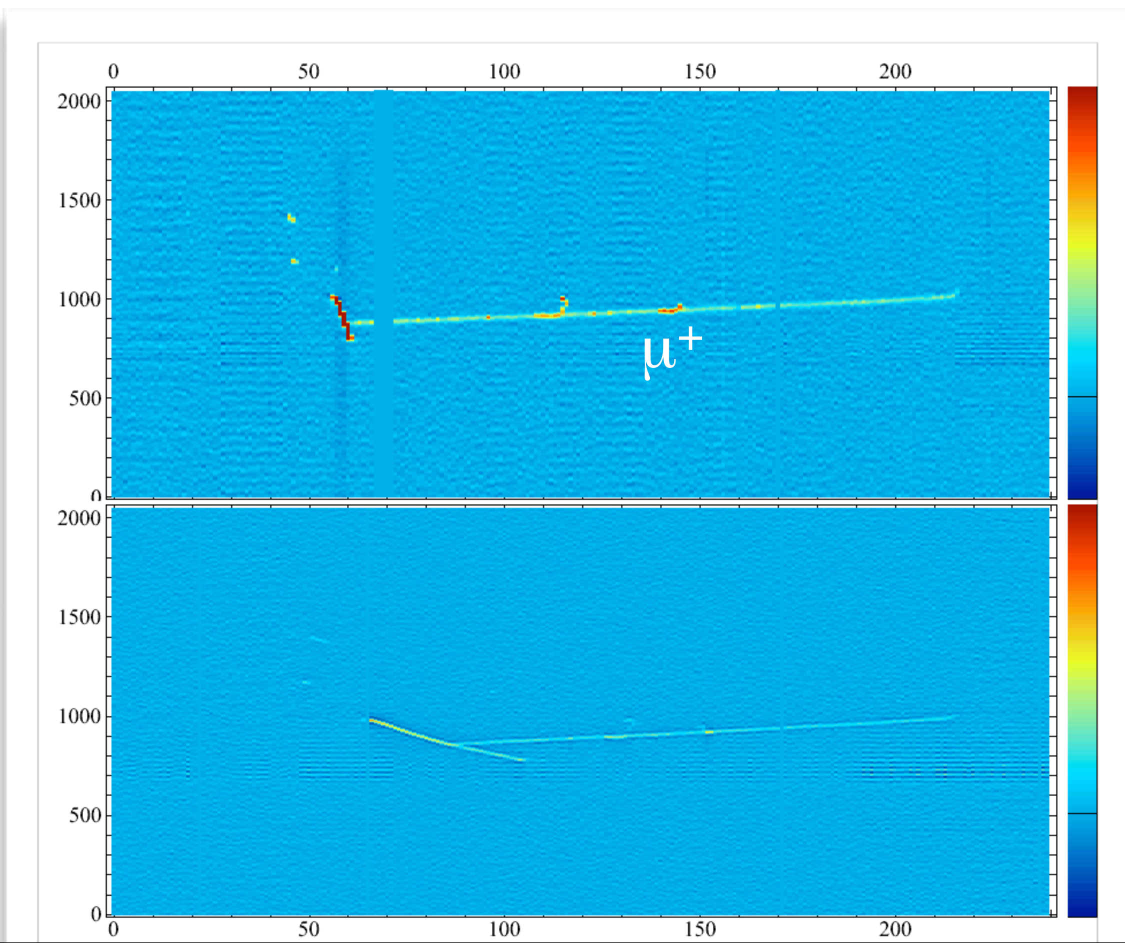


back-to-back protons

BACK-TO-BACK PROTON PAIR EVENT MUON TRACK MATCHING IN MINOS ND





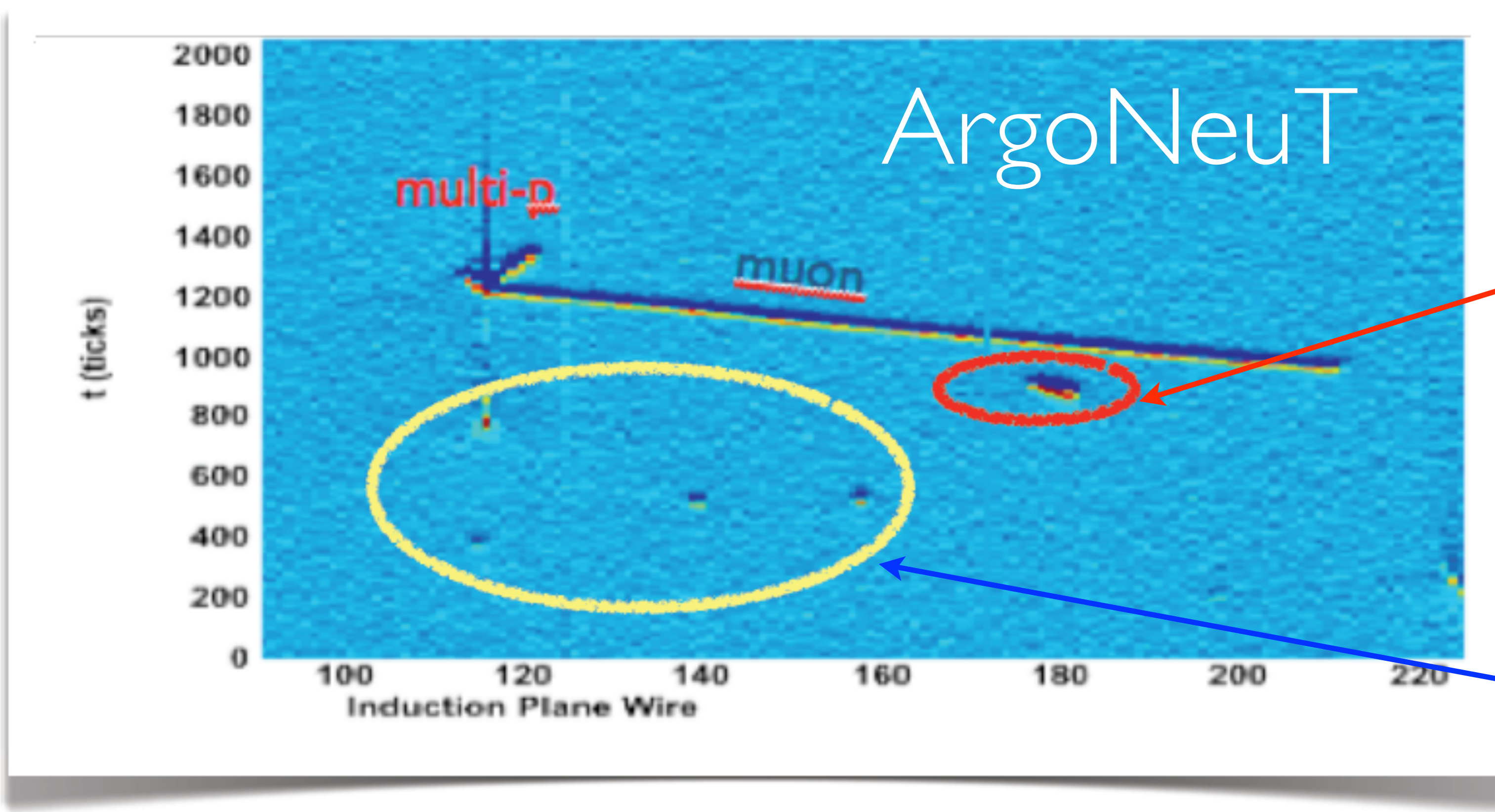


Red (blue): positive (negative) charge tracks determined by MINOS.

LArTPC: High-resolution detector

e.g VERTEX ACTIVITY

Measurement of γ activity around the vertex and neutron →proton can also help to tune MC generators



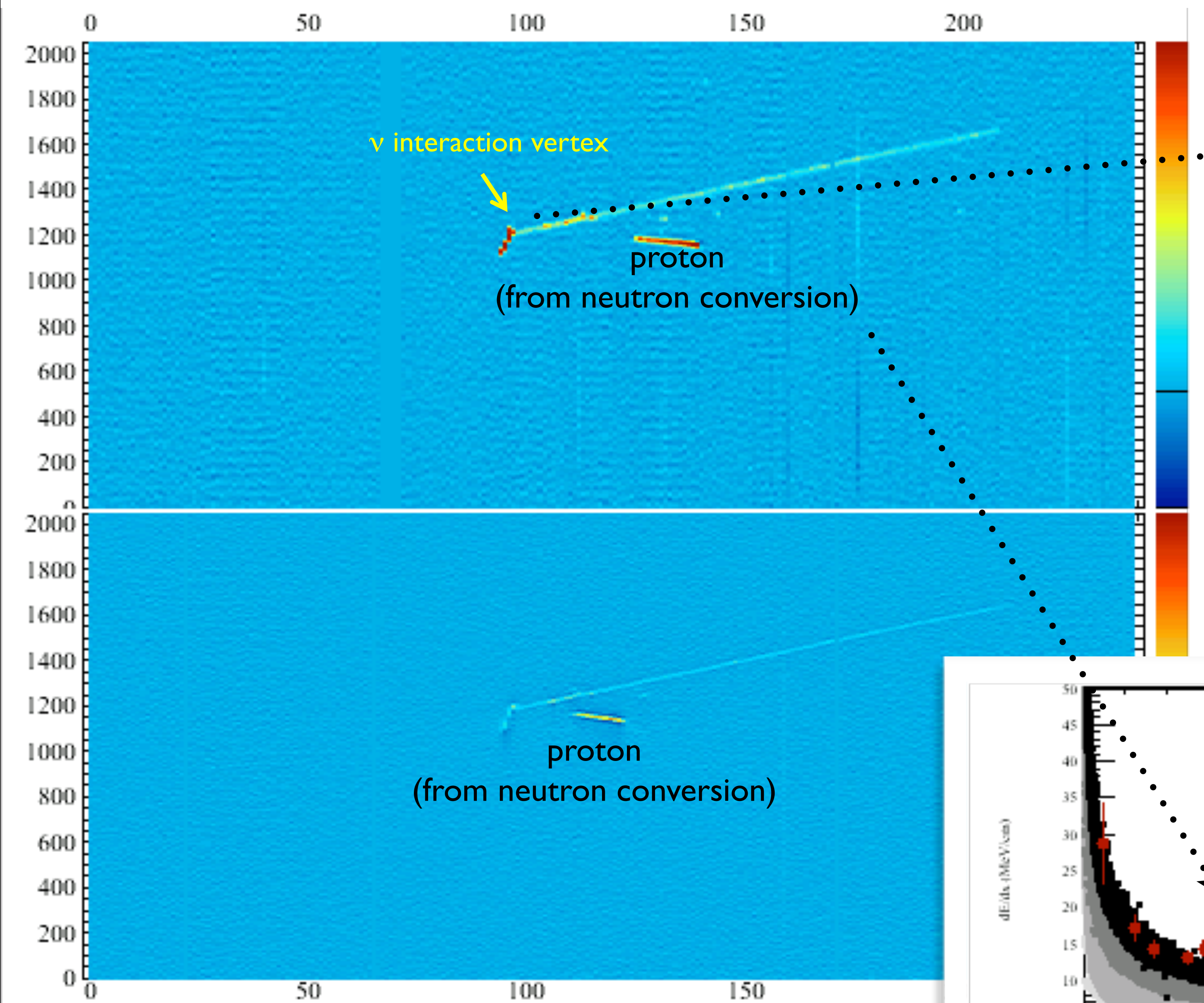
Direct access to nuclear effects requires:

- low threshold for proton detection (below Fermi level)
- neutron detection capability (p conversion via CEX)

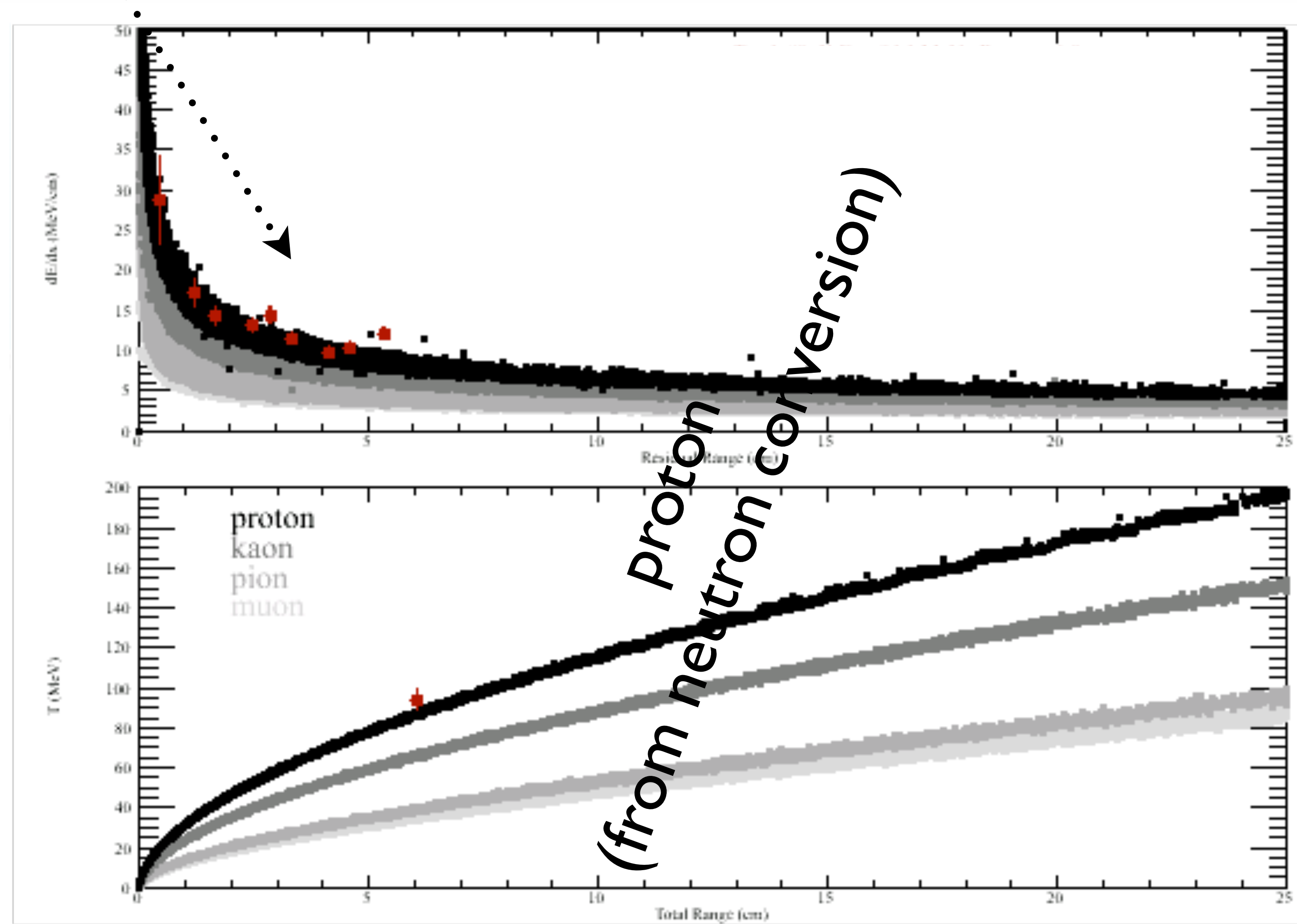
short heavily ionizing track detached from the vertex

- sensitivity to low energy de-excitation γ's (via Compton Sc.)

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)