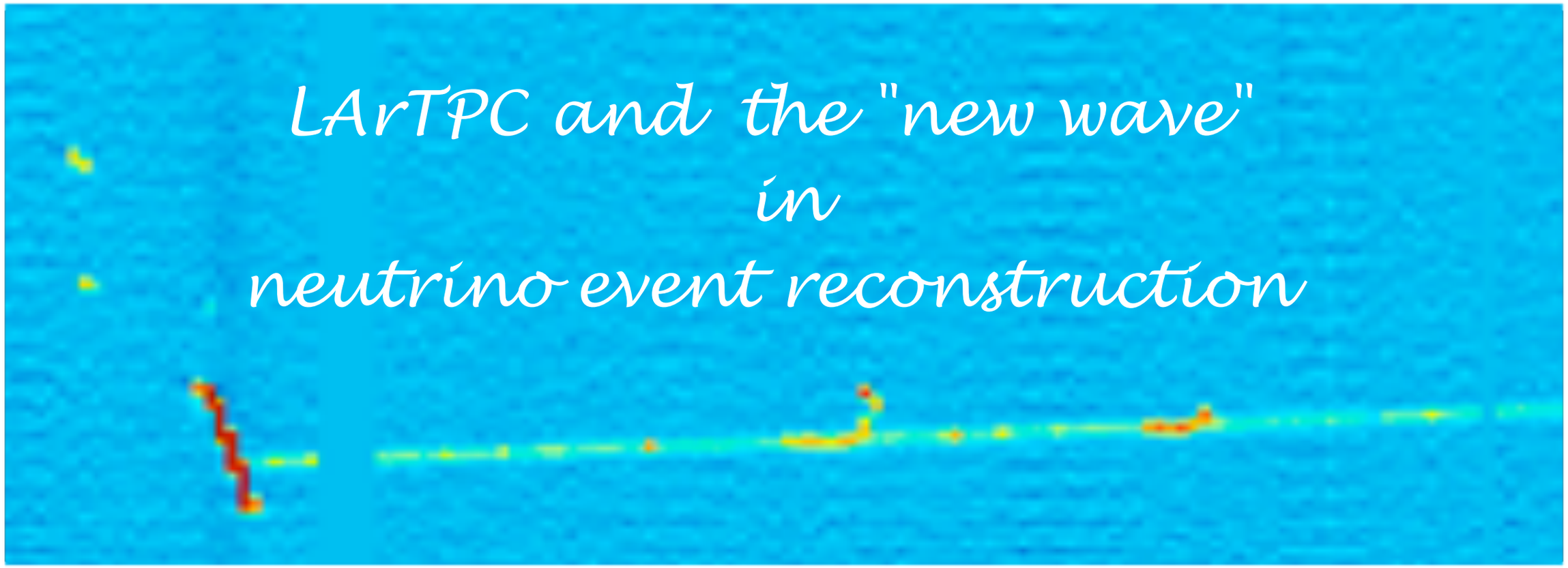


LArTPC R&D Workshop

20-21 March 2013 *Fermi National Accelerator Laboratory*

Flavio Cavanna
Yale University
& L'Aquila U. (IT)

The LArTPC ***SW-R&D*** at FNAL

Detector ("HW") R&D has been carried out by several groups worldwide over the past two decades (last ~decade in US).
All HW aspects have been studied, developed and optimized (cryogenics, LAr purification, ionization charge R/O, scintillation light R/O, low-noise Electronics, fast DAQ, ..)
Some HW aspects are already at their 2nd or even 3rd generation of development.

SW development for the full exploitation of the information provided by the LArTPC is instead still at a rather early stage: long term/high statistics data taking on neutrino beams only started in 2009/10 (with ArgoNeuT).

An "aggressive" ***SW-R&D program*** on both ***Off-Line event reconstruction and MC event simulation*** was initiated at FNAL in 2011 and is currently strongly pursued (this talk)

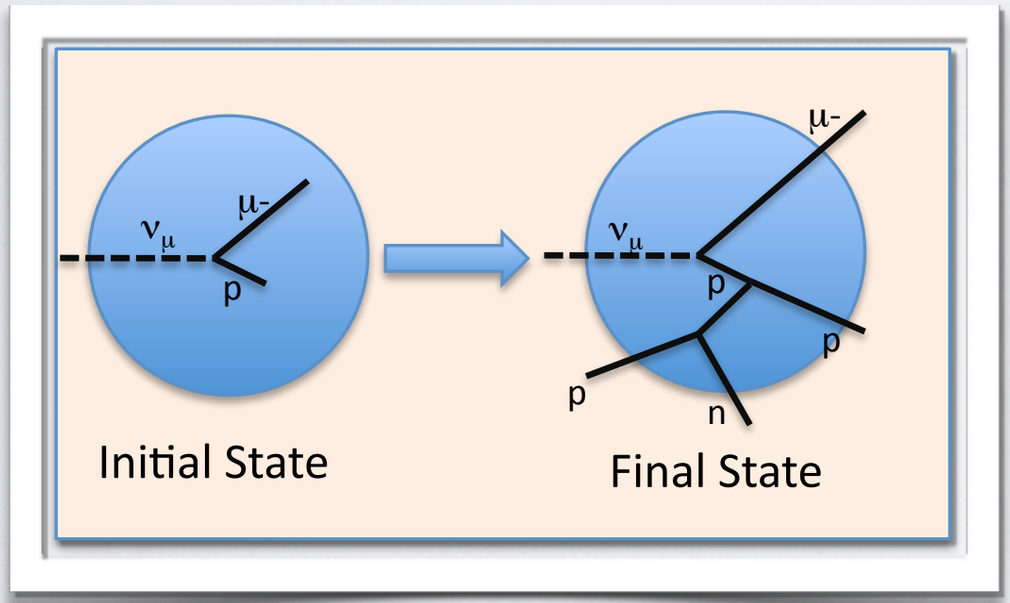
LArTPC: detection of Neutrino Interactions in the *O(1 GeV)* energy range

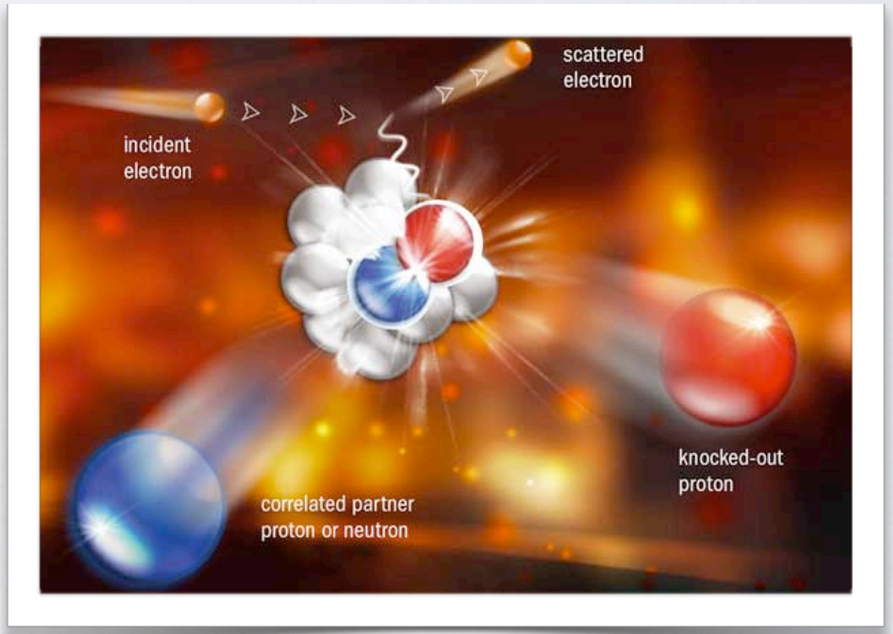
- In the GeV energy range the most important neutrino-nucleus interaction channel is the CC quasi elastic ***(QE)*** scattering, historically referring to the emission of

  a charged lepton and a single nucleon.

  For this reason, a lot of effort has been devoted to measurements of neutrino- and antineutrino-nucleus "QE like" cross-sections in a broad kinematical domain.

- ***Nuclear effects***, however, play a key role in neutrino-nucleus interactions in nuclear targets. Due to ***intra-nuclear re-scattering (FSI)***





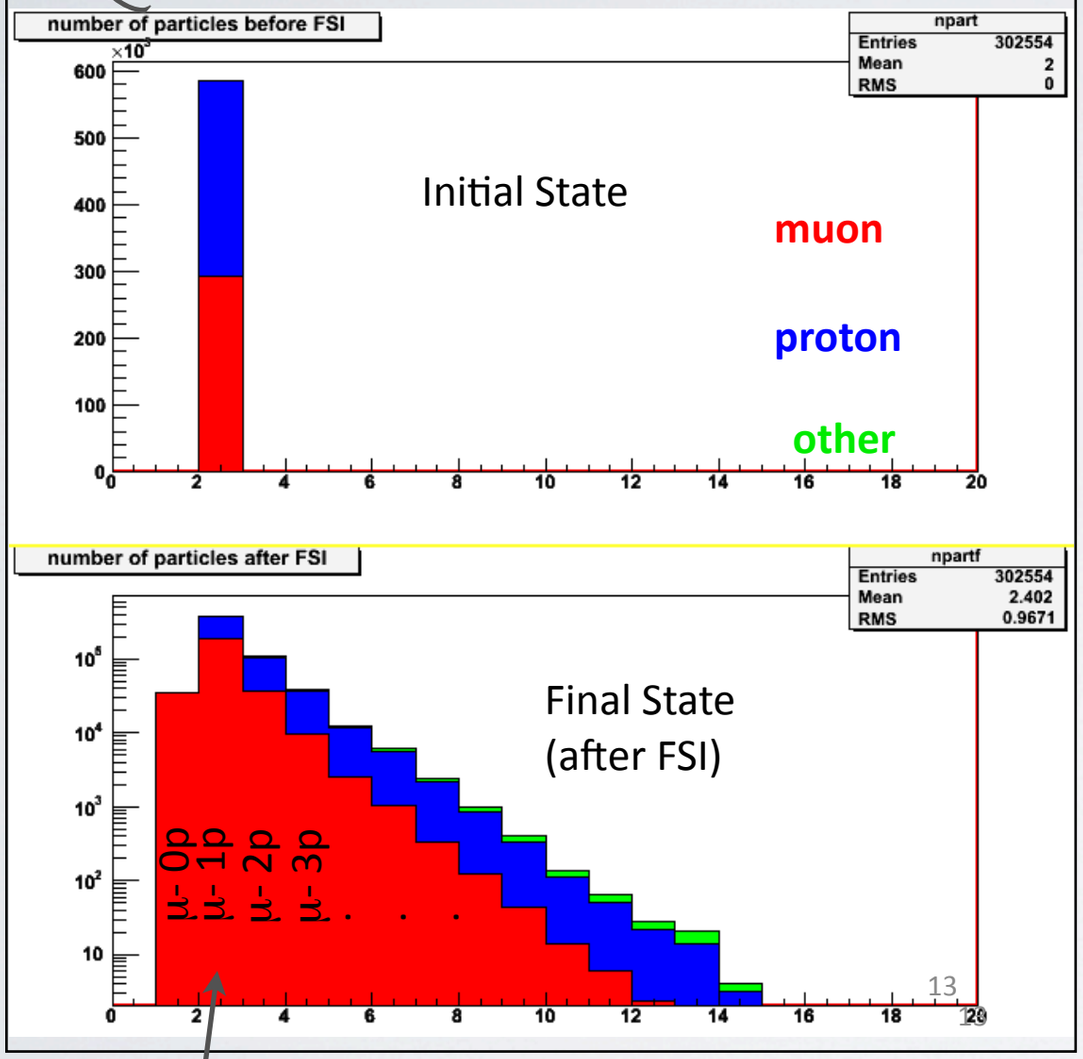
and possible effects of ***correlation between target nucleons***, a genuine QE interaction can often be accompanied by the ***ejection of additional nucleons***, emission of many ***de-excitation*** γ's and sometimes by ***soft pions*** in the Final State (after hadronization).

MC: EFFECTS OF FSI

an example: FLUKA simulation* – CCQE ν_μ events in LAr

NuMI beam LE spectrum - neutrino mode

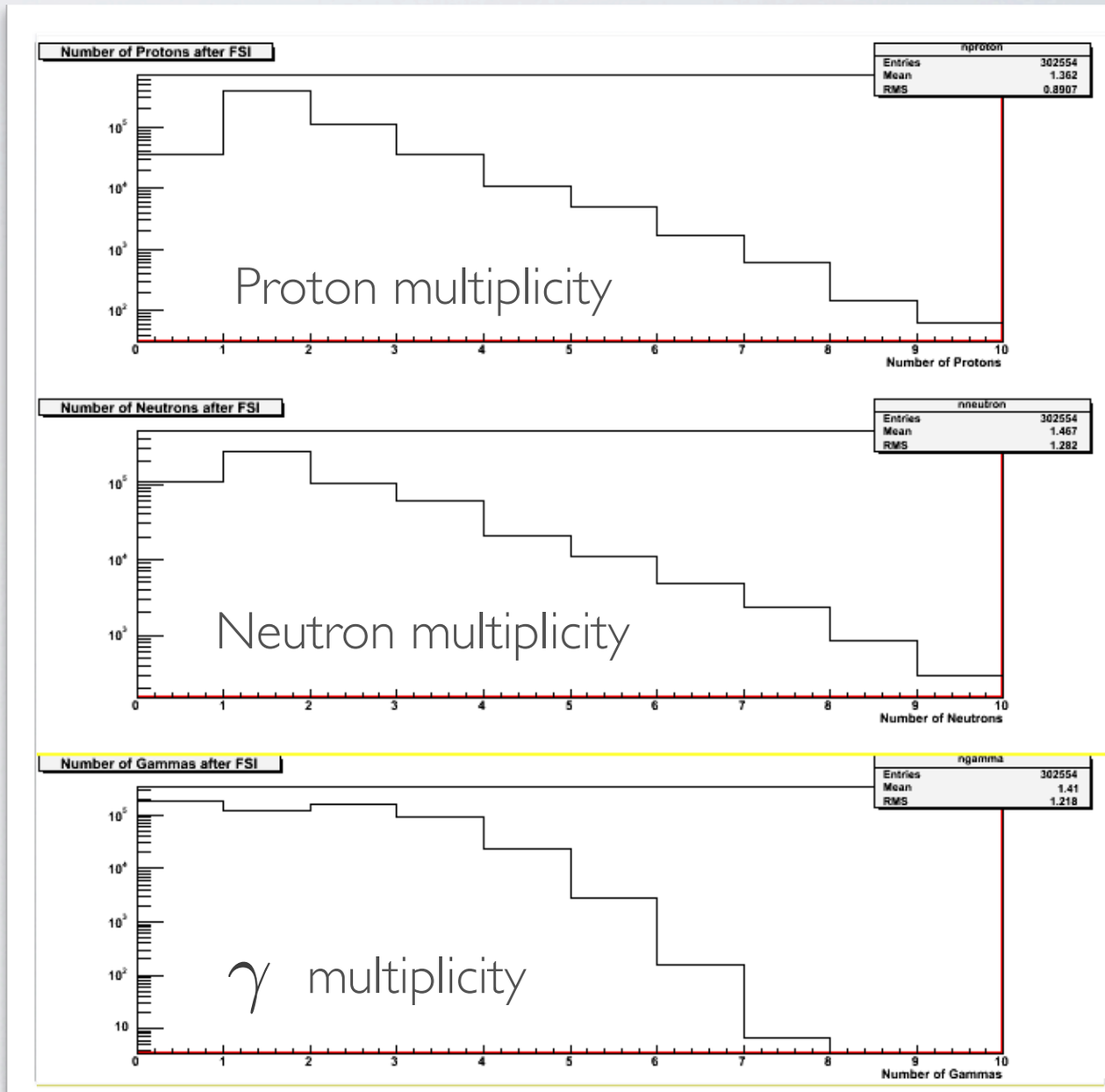
QE: Multiplicity of charged particles



$1\mu 1p$ events

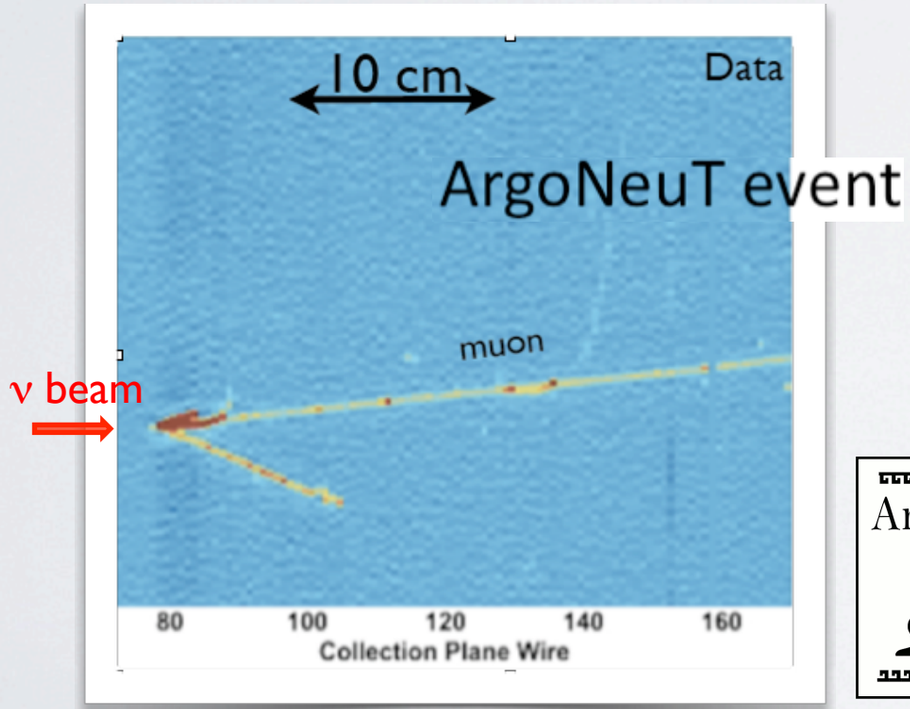
* offering a full simulation of nuclear effects but not multi-nucleon correlations

Vertex activity (multiple p at vtx., γ (→e) from nuclear de-excitation, neutrons)



➠ Neutrino interaction ***channel-definition***s are therefore largely ***ill-defined*** and ***the measurements of specific channels largely rely on MC simulation***.

In fact, these products are usually neglected
because not detectable,
unless a ***high quality, low energy threshold imaging detector*** is in use.



A zoomed-in view of a neutrino event with evidence of vertex activity

LAr-TPC detectors provide indeed

- ***HD-imaging*** (2D and 3D)
- ***excellent particle ID*** & *background rejection*.
- *precise calorimetry*

THE *"NEW WAVE"* IN NEUTRINO EVENT RECONSTRUCTION

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 (i.e.* μ+**N**p, *where* **N**=0,1,2...),

1 *pion* (i.e. μ+**N**p+**1**π),

etc..

same with $e \leftrightarrows \mu$

In imaging LAr-TPC detectors:

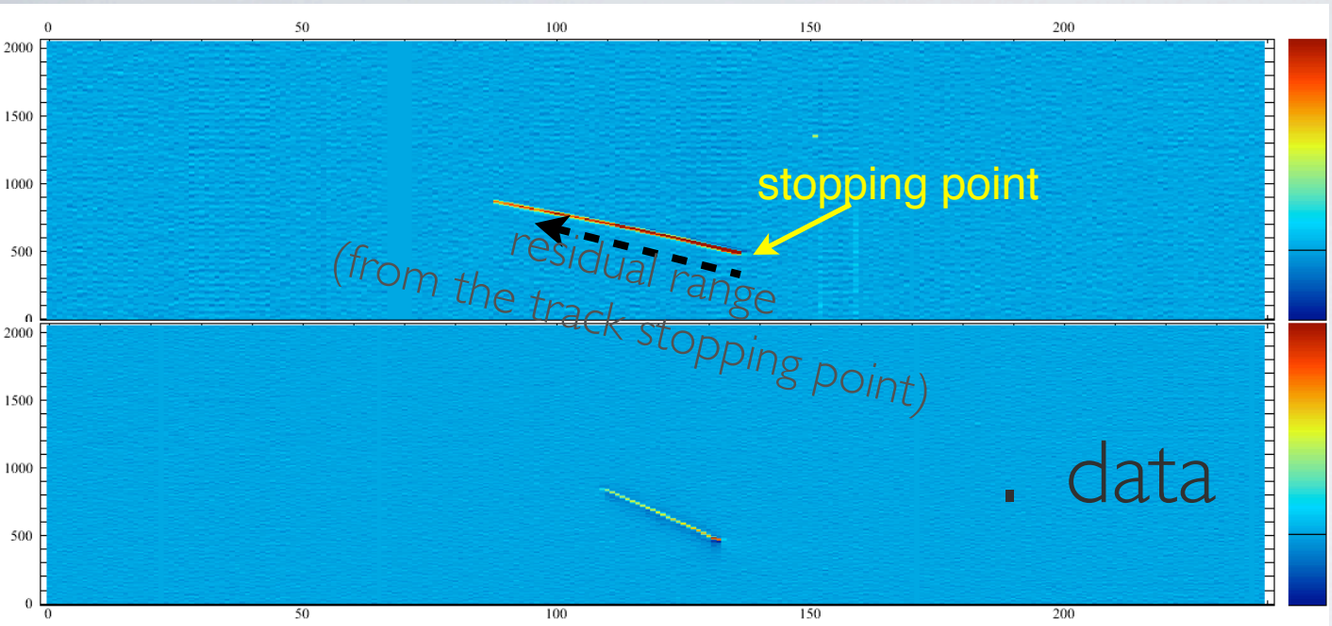
- ***exclusive topologie***s can be fully reconstructed (need high PID capability)

- determination of ***proton multiplicity*** at the neutrino interaction vertex can be performed (need ***ultra-low proton energy threshold***)

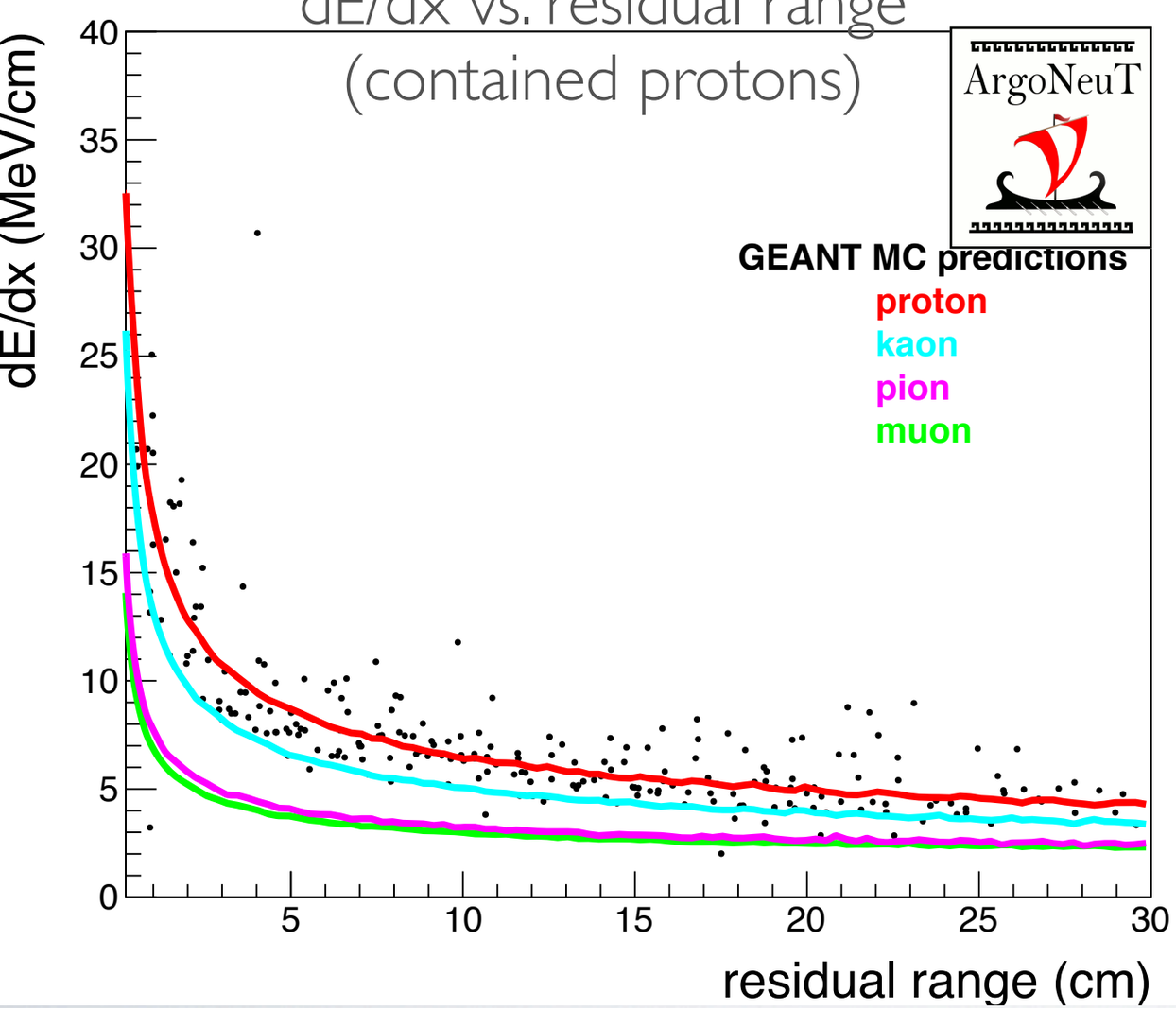
- ***reconstruction of proton(s) kinematics*** can ultimately allow for most precise ***reconstruction of the incoming neutrino energy*** (need ***excellent Energy and Spacial resolutions***).

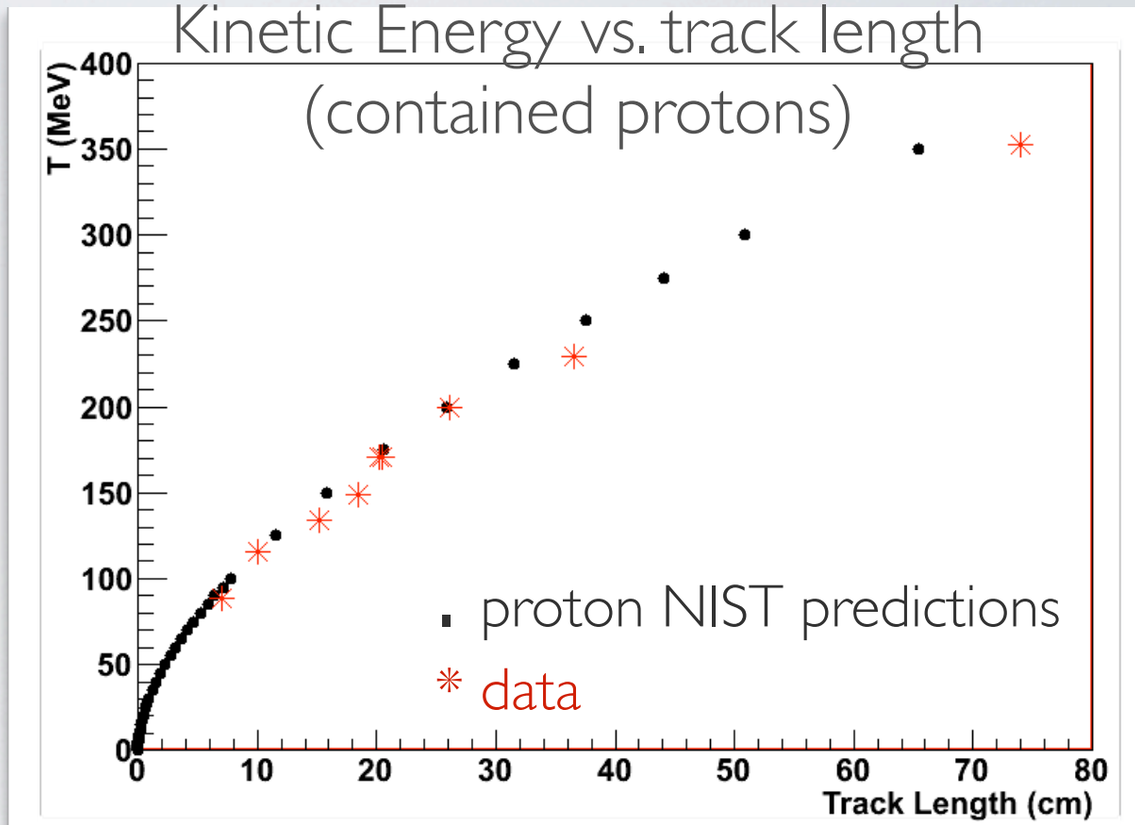
A dedicated effort is needed however on the development of ***Off-line SW*** and ***MC simulation*** to reach the (outstanding) levels of detector performance needed to accomplish with these goals.

CALORIMETRIC RECONSTRUCTION & PID



"Off-Line SW R&D"





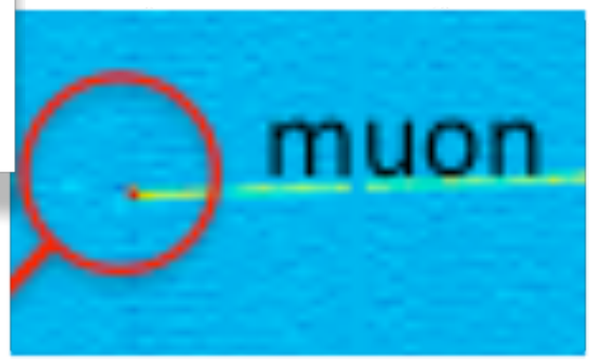
Measurement of:

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

Low energy proton reconstruction

"Off-Line SW R&D"

proton threshold is 21 MeV of Kinetic Energy (ArgoNeuT)

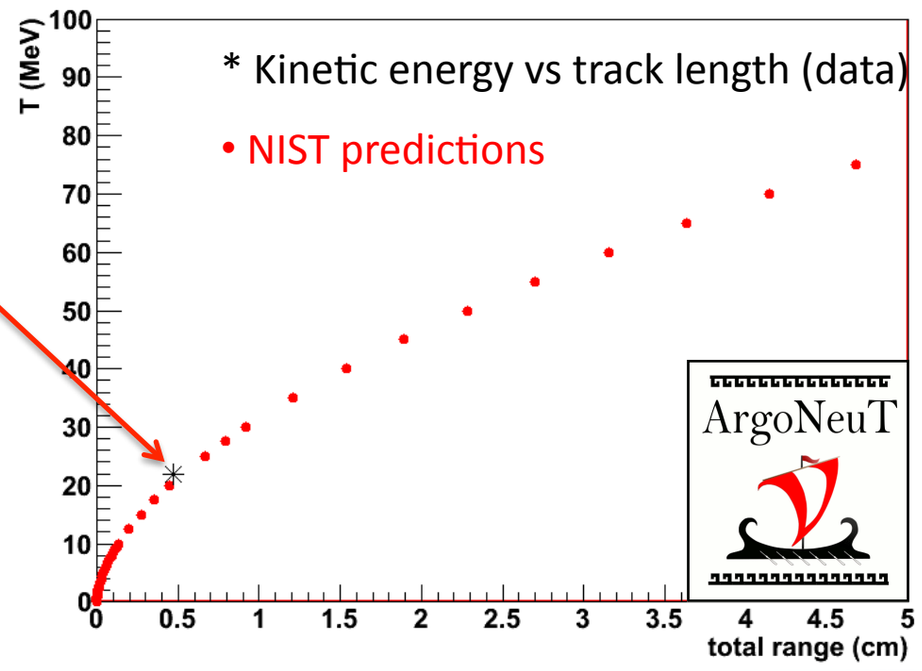


The short track behaves like proton

The event is (CCQE) 1p – 1 μ−

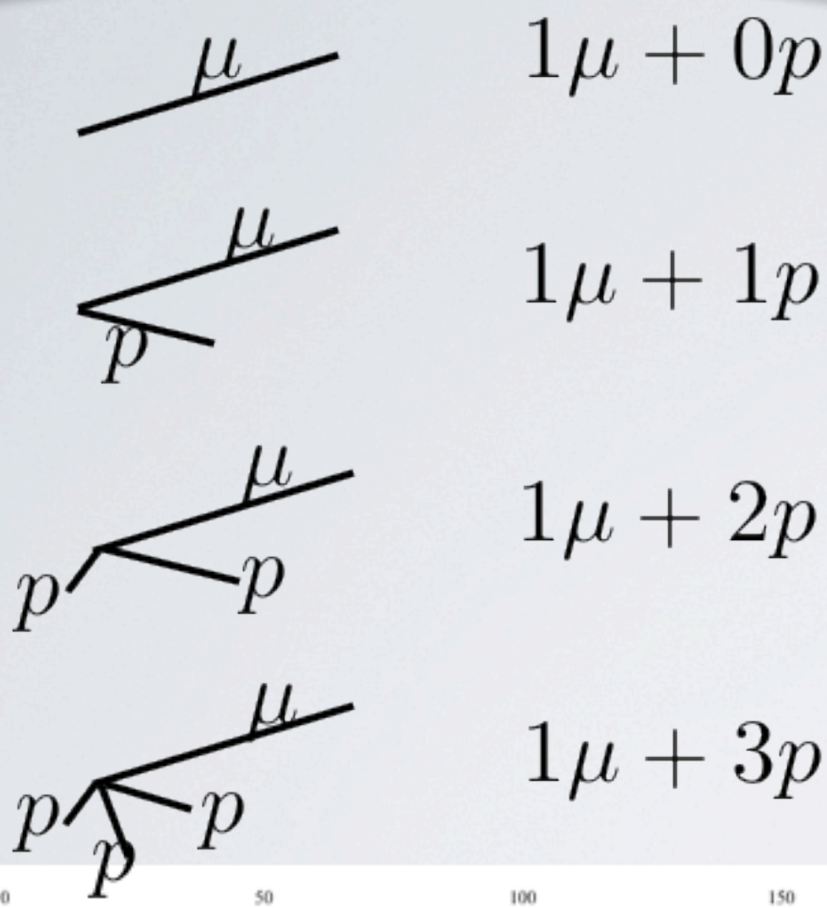
KE=22±3 MeV

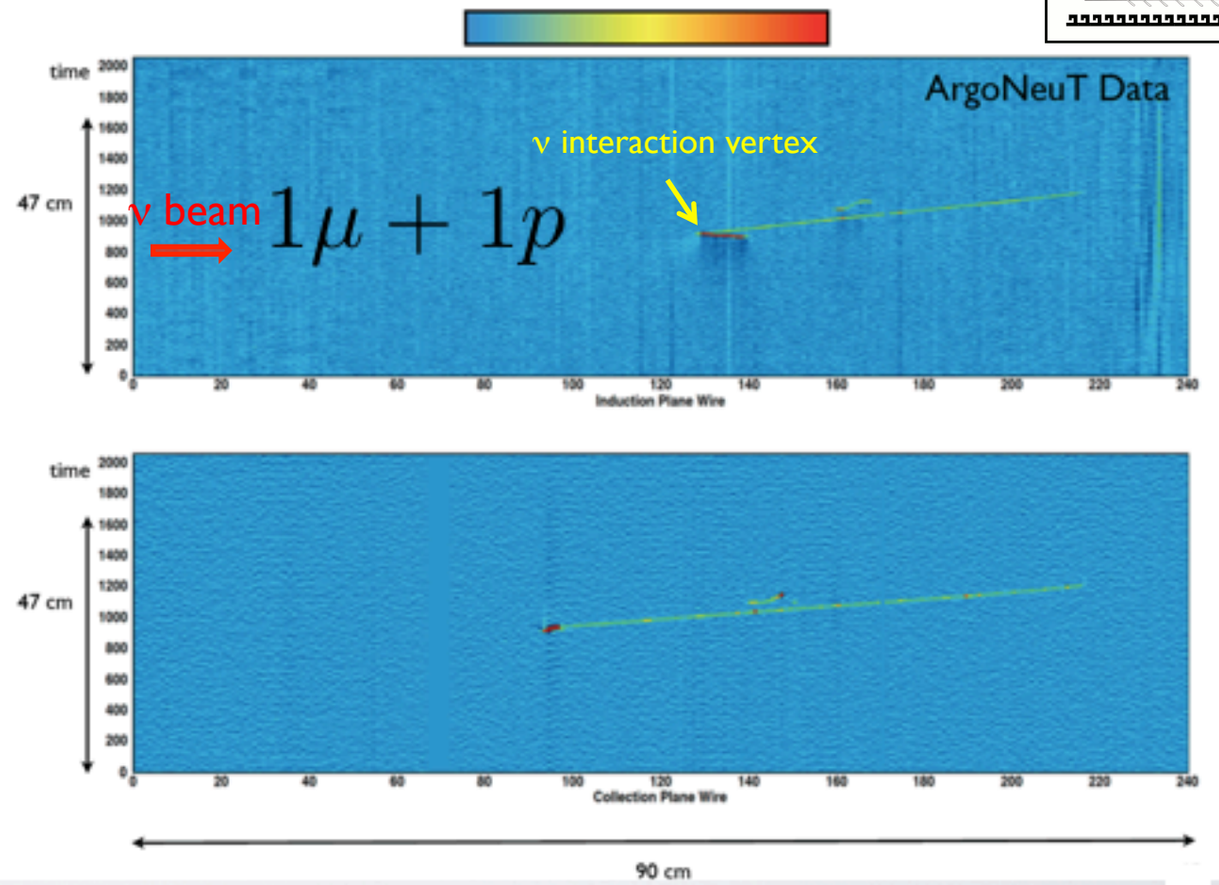
Length=0.5 cm

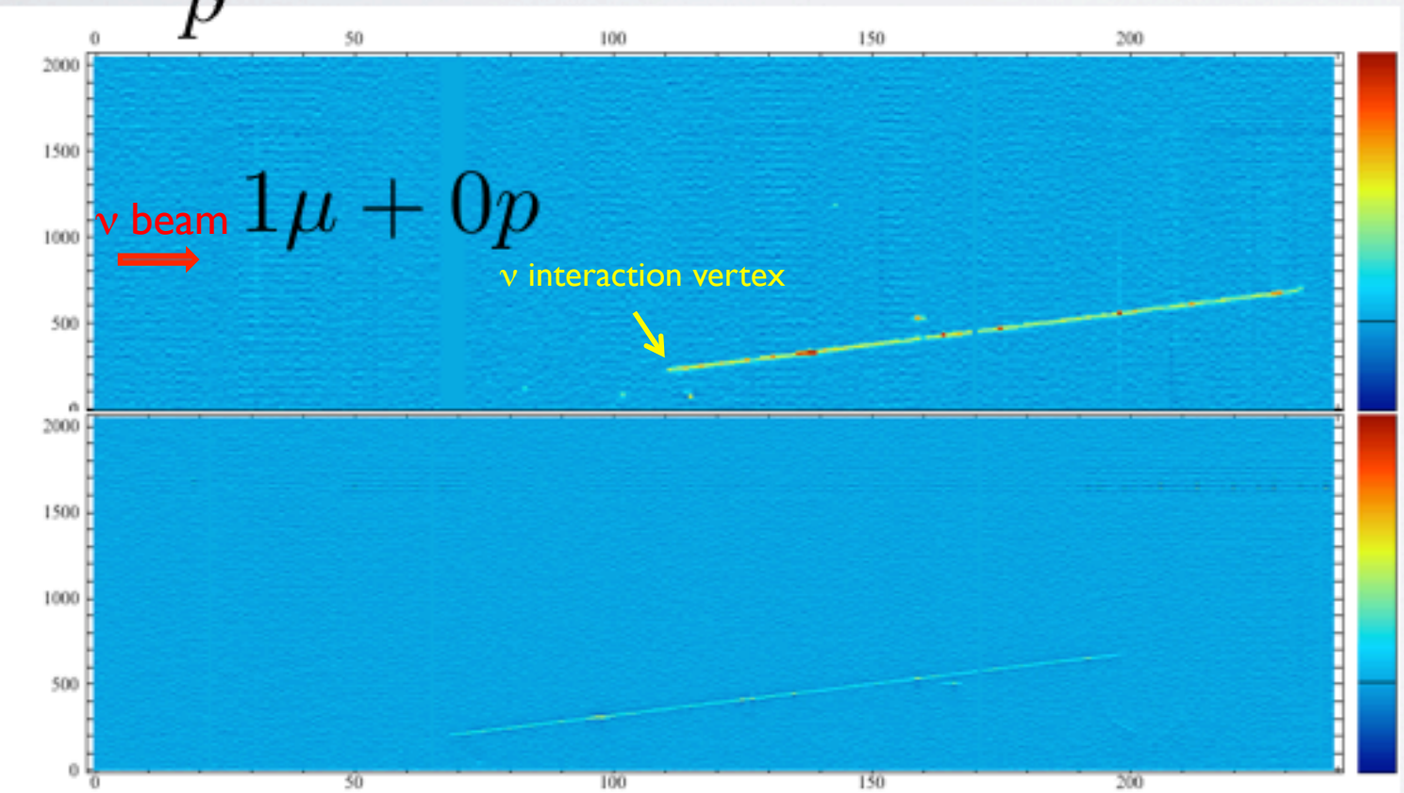


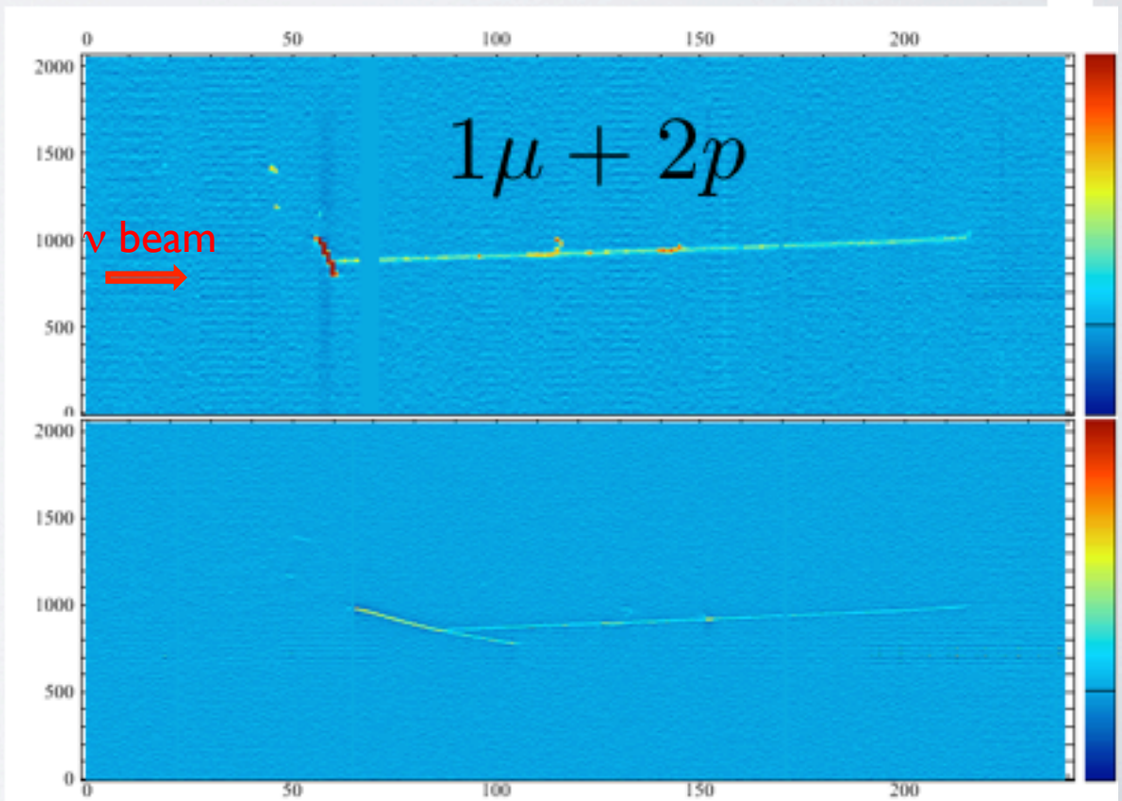
"Off-Line SW R&D"

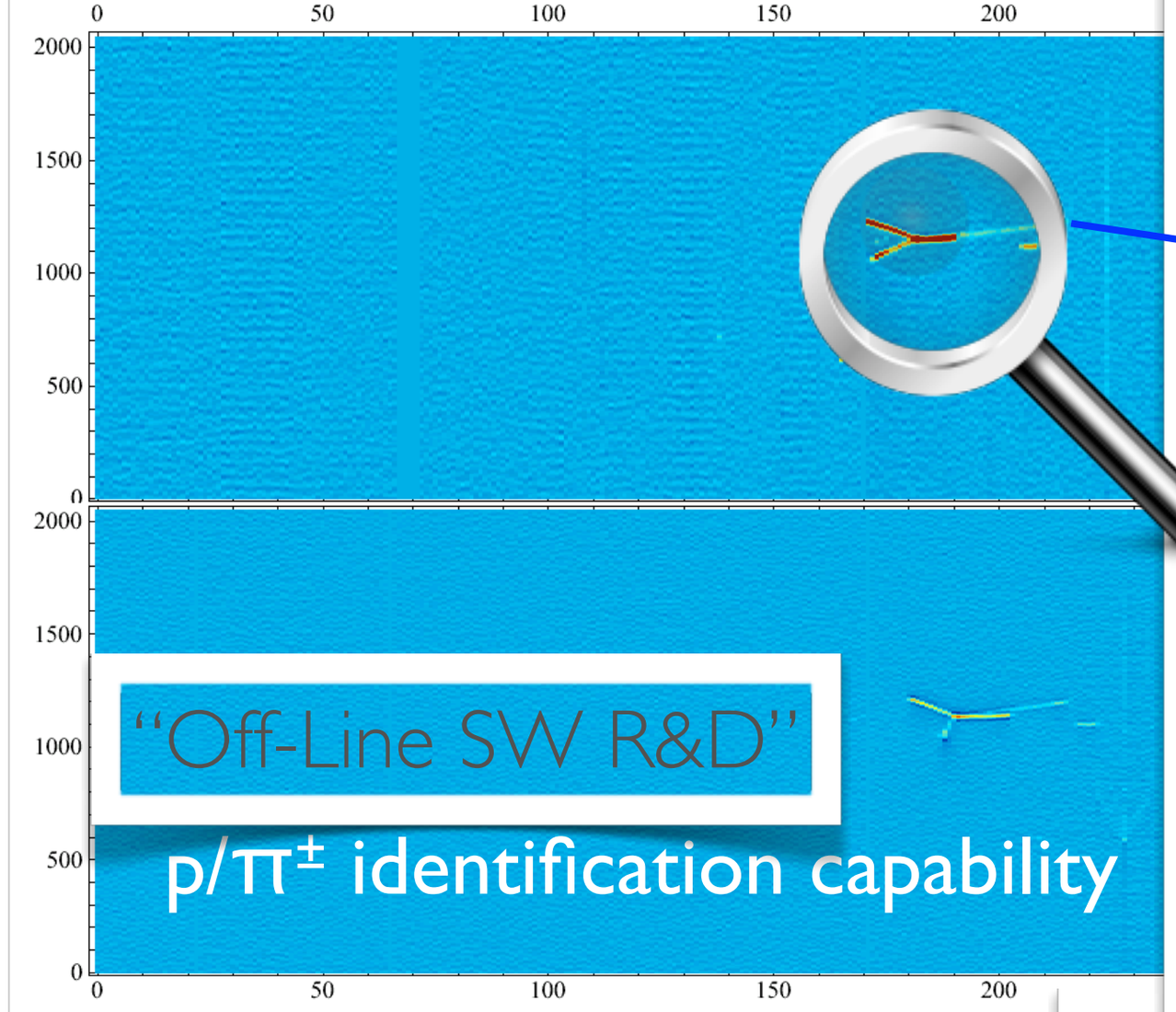
EXCLUSIVE EVENT TOPOLOGY





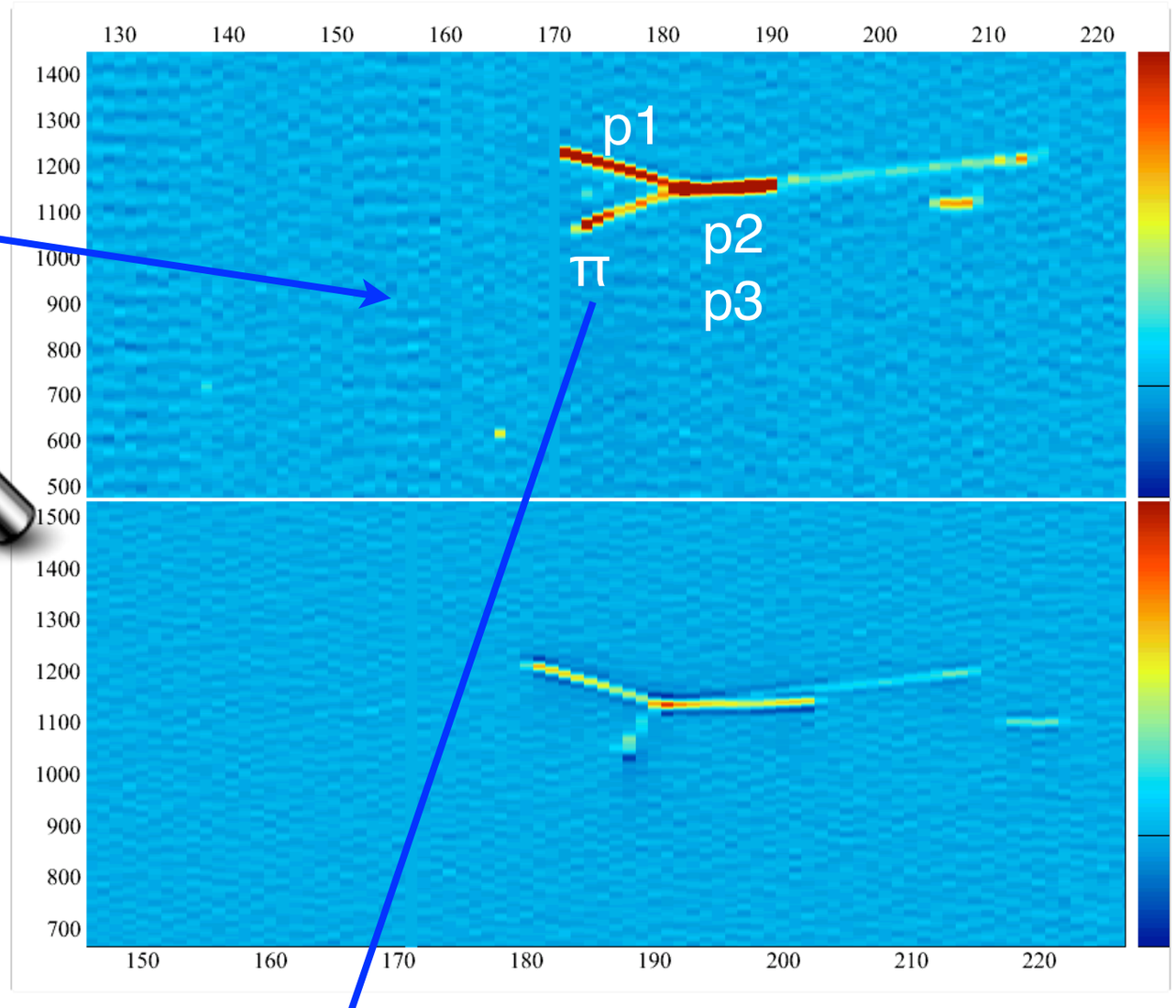


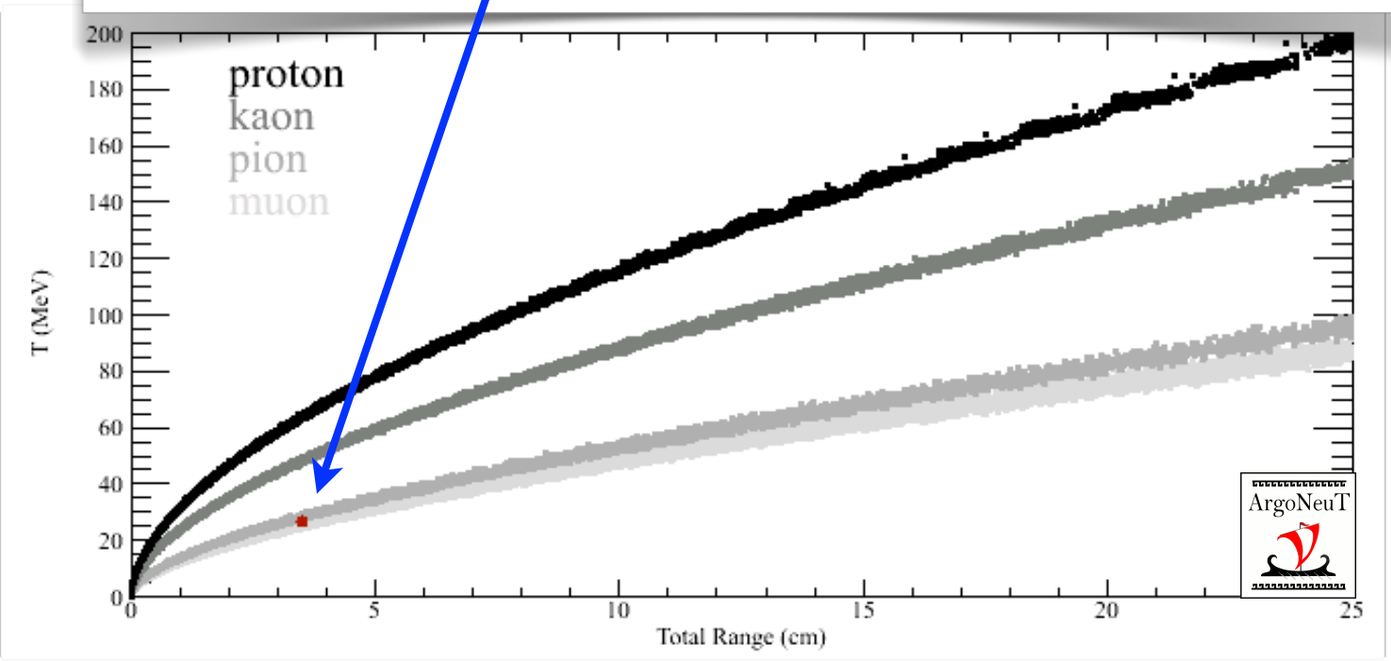




"Off-Line SW R&D"

p/π± identification capability





- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- π: 3.5 cm ----> T=26±3 MeV

1μ 3p 1π

⇒ Event not in the muon+Np sample

- **Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data, in particular** for nuclear effects understanding

All modern experiments contain nuclei as targets

1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

↓

Nuclear Physics based generators needed

U. Mosel

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

"MC R&D": DATA-MC COMPARISON

- GENIE- Generates Events for Neutrino Interaction Experiments*

  FSI: IntraNuclear Cascade model (INC)

  [Meson exchange (MEC) channel in the future]

- GIBUU – **The Giessen Boltzmann-Uehling-Uhlenbeck Project****

  FSI: Transport model
  2p2h-NN channel included
  2-particle-2-hole interaction with 2 nucleons produced

ArgoNeuT Coll. is grateful to GENIE authors, in particular S. Dytman and H.Gallagher, for many useful discussions

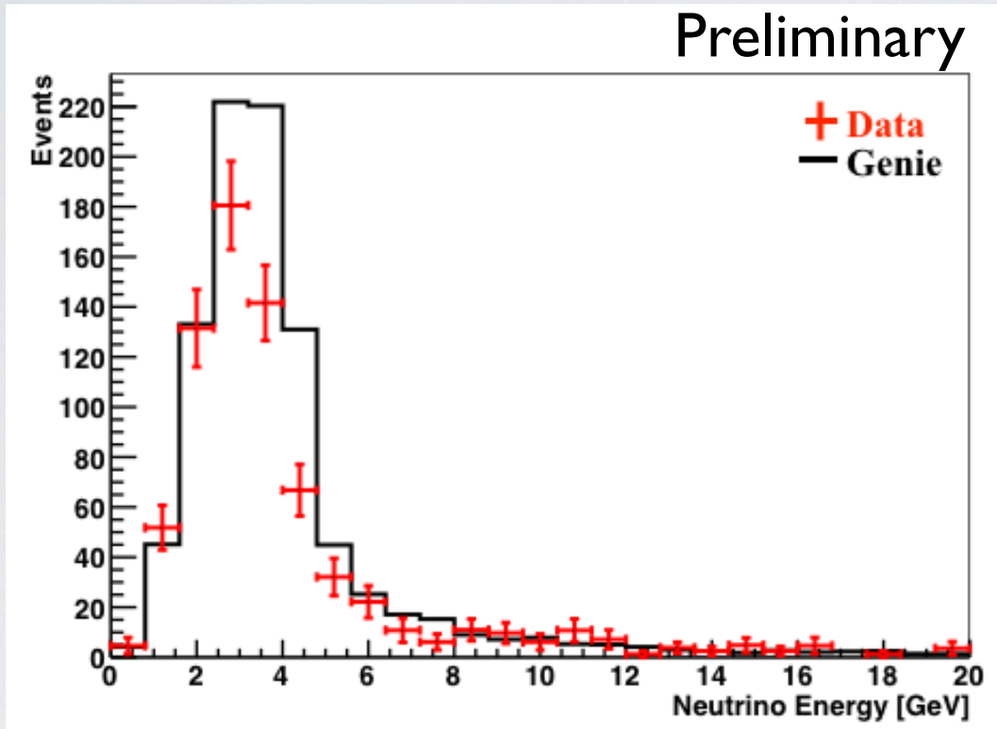
***ArgoNeuT Coll. is grateful to O. Lalakulich and U. Mosel for providing the GiBUU predictions and for many useful discussions*

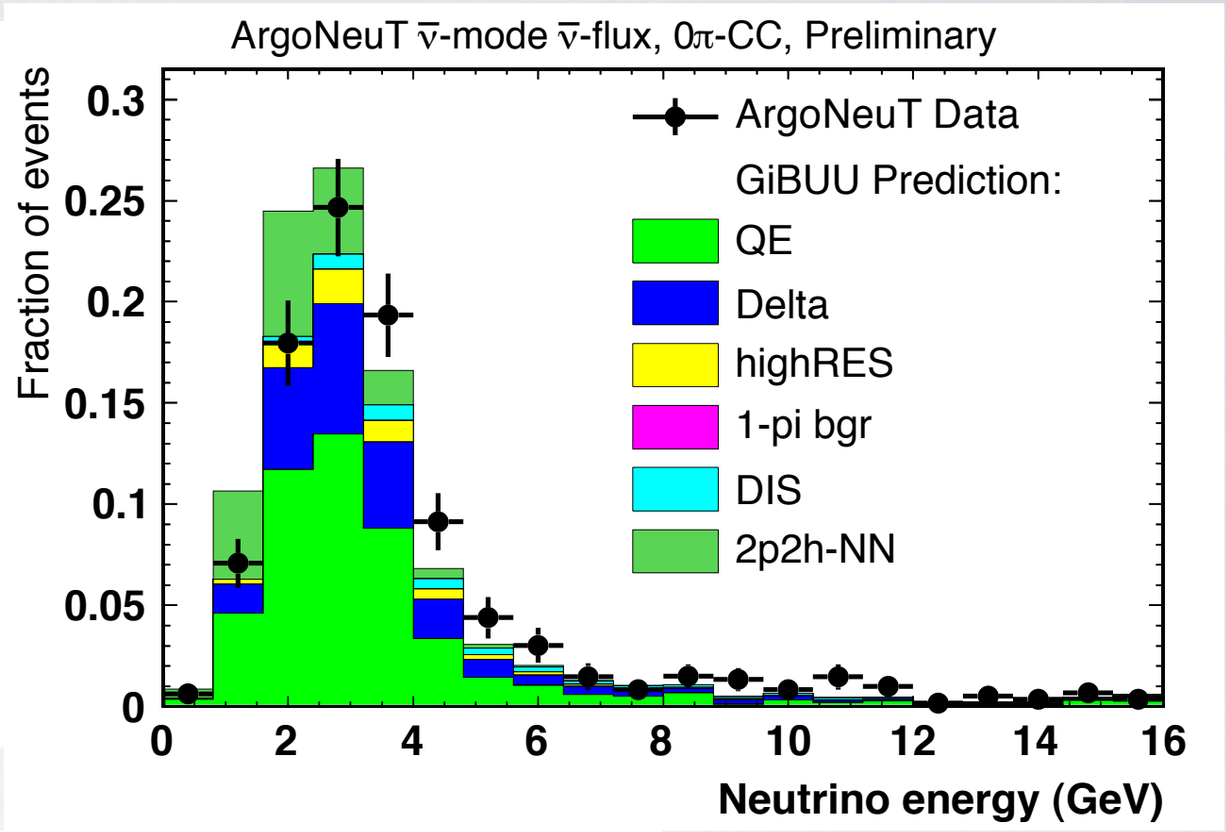
ArgoNeuT

First Physics Results

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

Neutrino energy (1μ+Np)



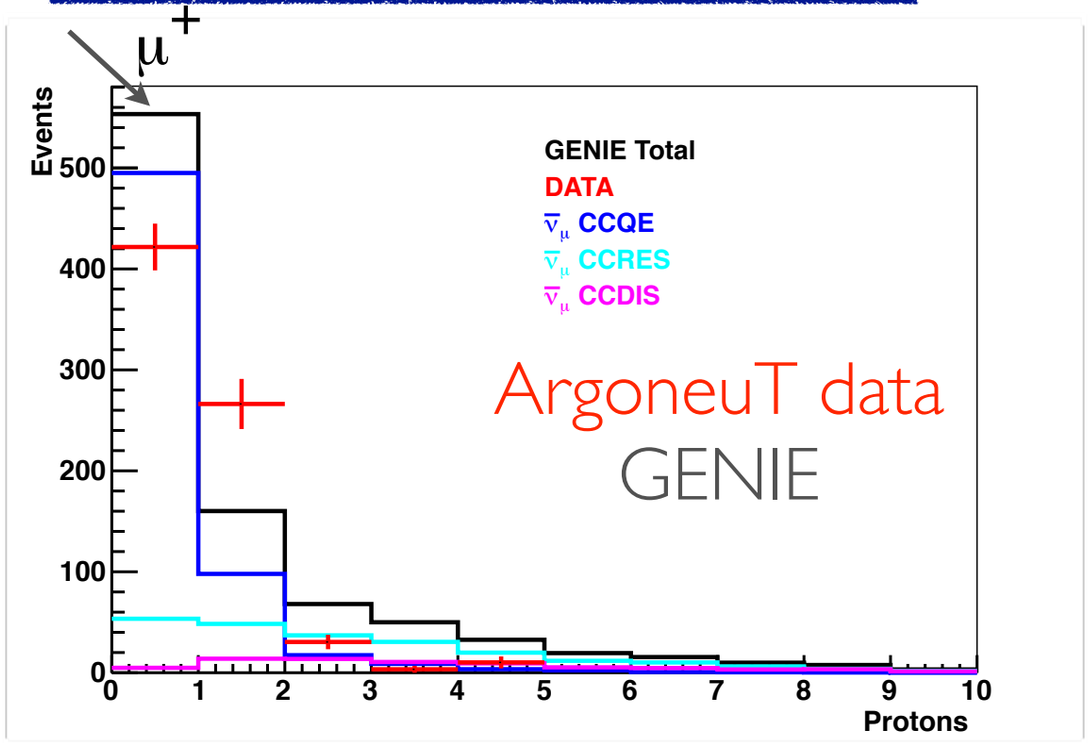


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

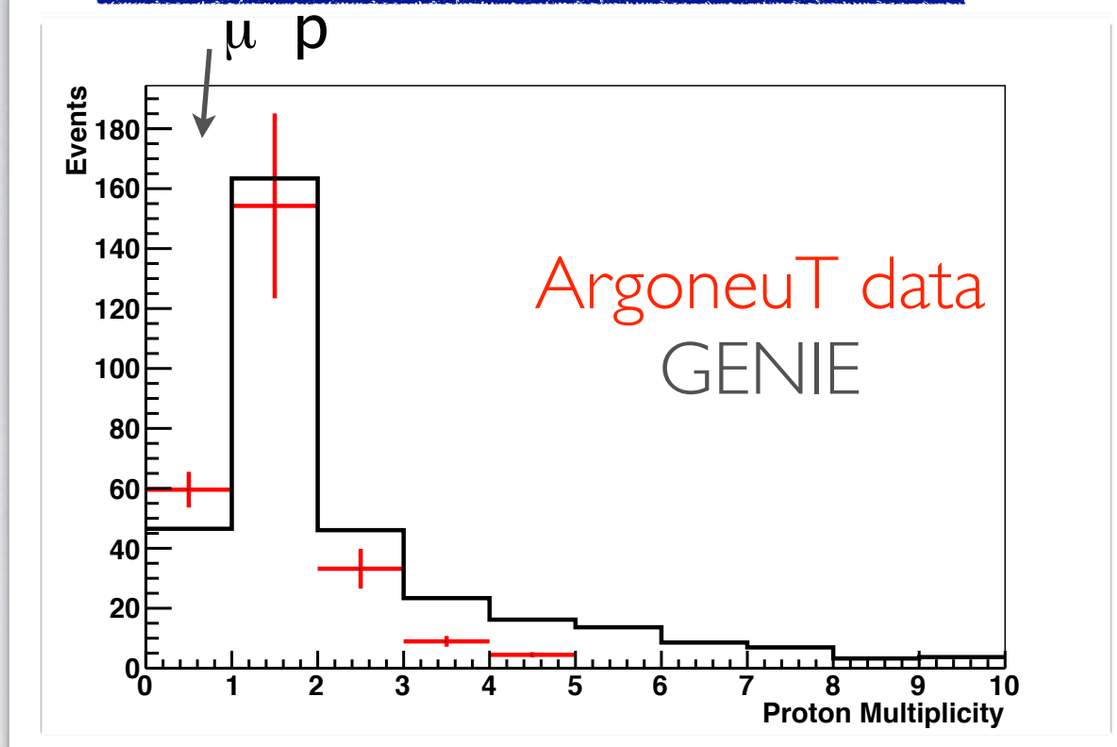
- Data energy reconstructed with the QE formula.
- Improved energy reconstruction including proton kinematics in progress.

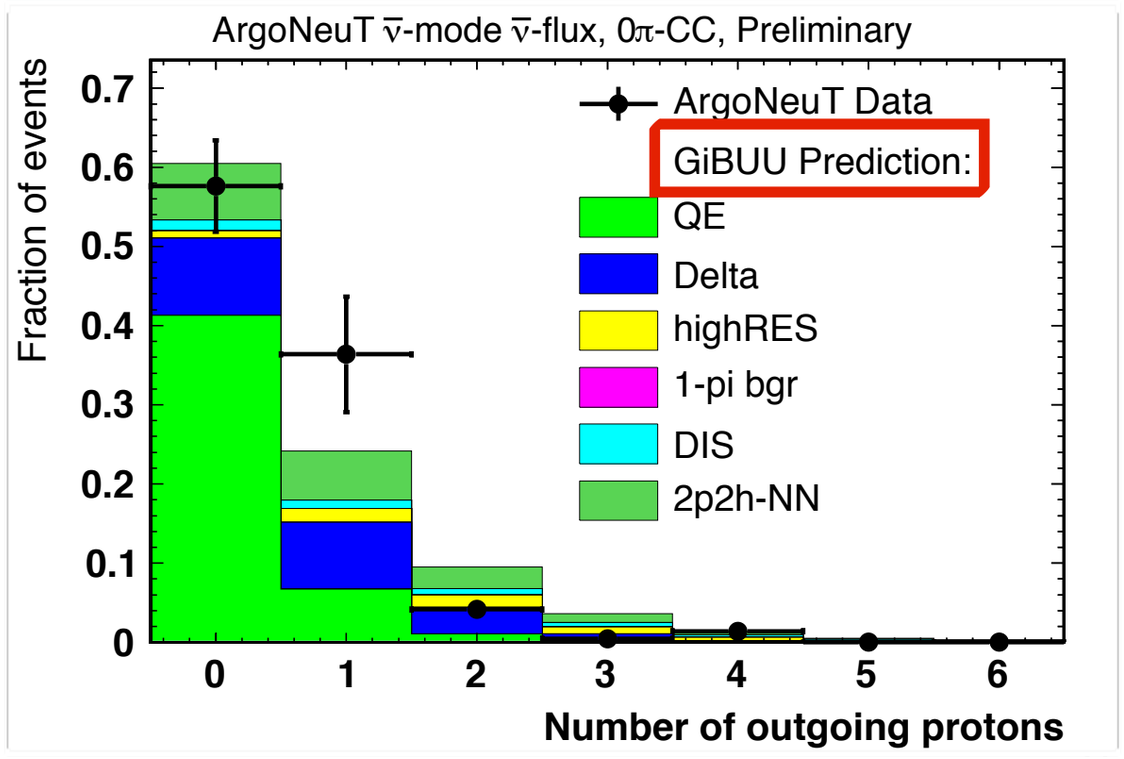
PROTON MULTIPLICITY

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



ν_μ - anti-neutrino mode run





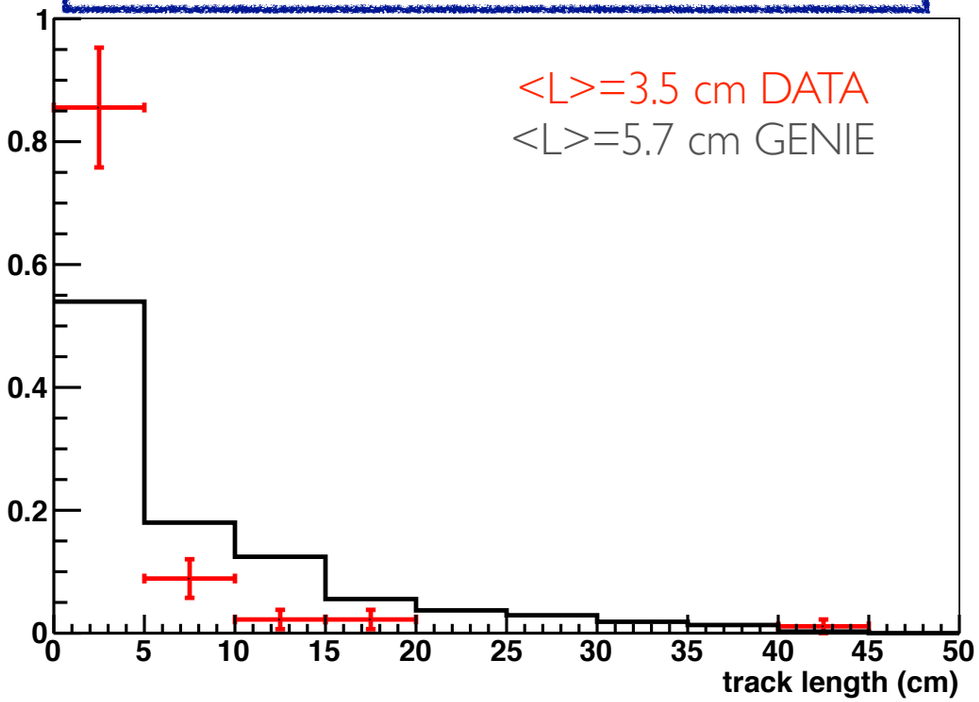
- Ratios among rates of different proton multiplicities in DATA don't agree with MC, in particular for $\overline{\nu}_\mu$
- ~30% contribution from not CCQE events (FSI)

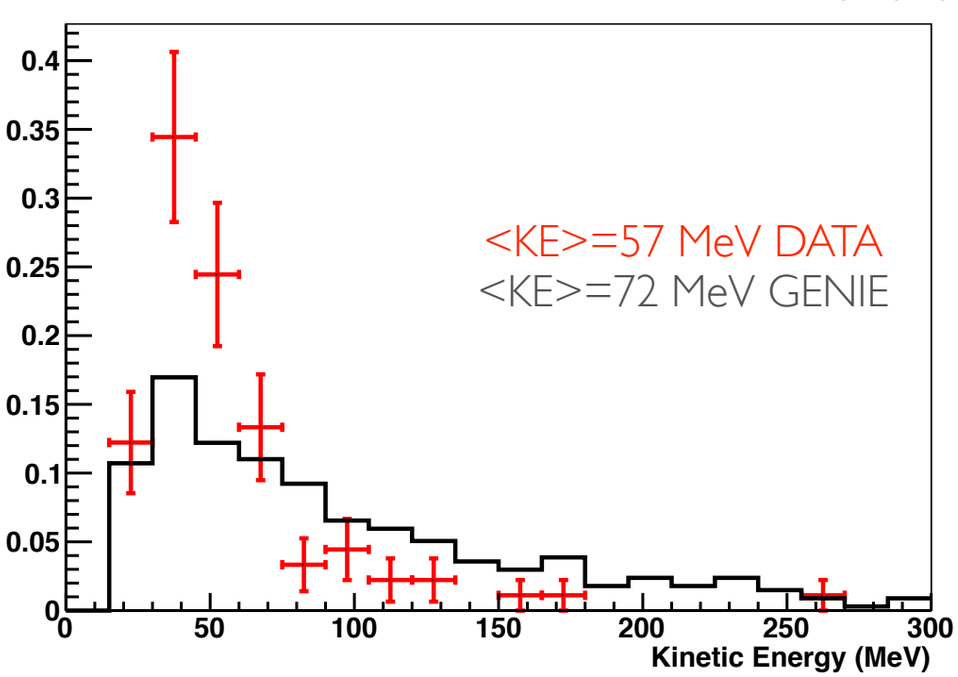
- *Uncertainties on the neutrino flux not yet included*
- *Efficiency for the selection of high multiplicity events not (yet) optimized*
- *Studies of background effects are ongoing and will be finalized soon*

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

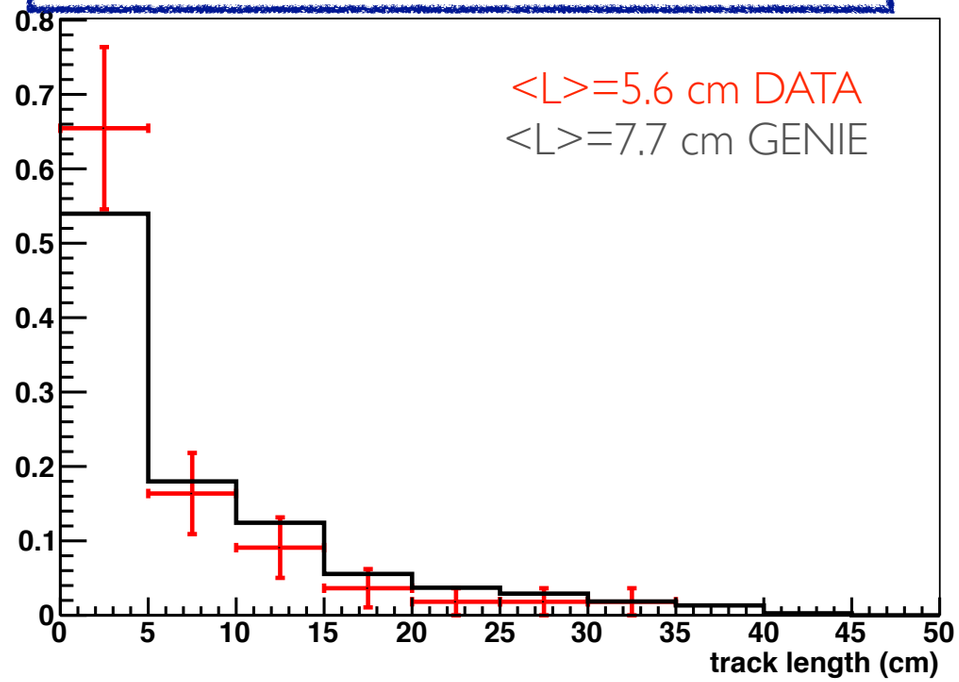
(Event-by event proton reconstruction)

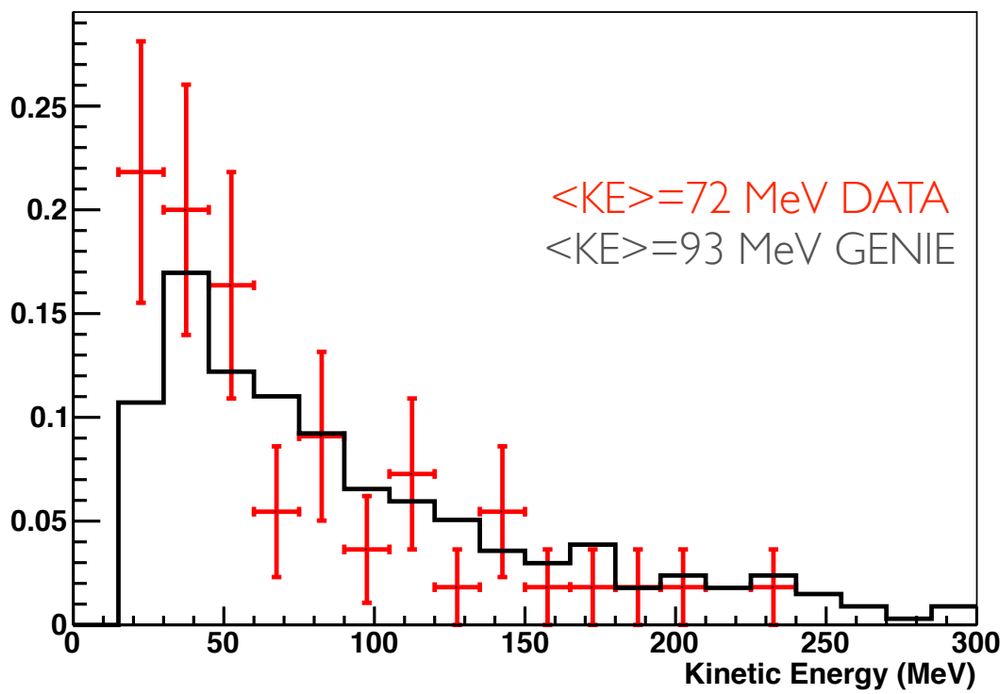
$\overline{\nu}_\mu$ - anti-neutrino mode run





ν_μ - anti-neutrino mode run





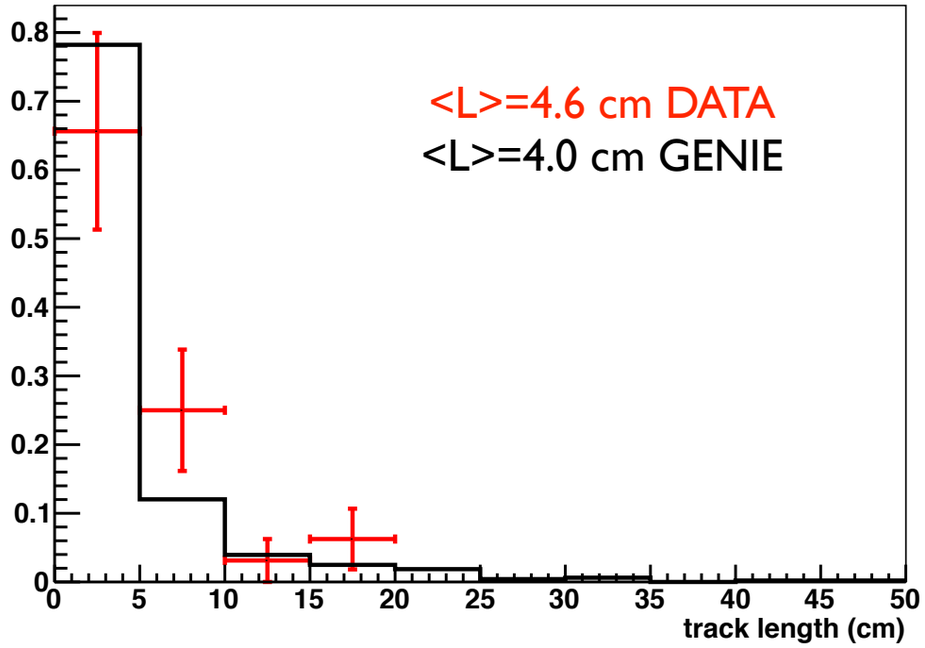
area normalized
comparison inside the detector

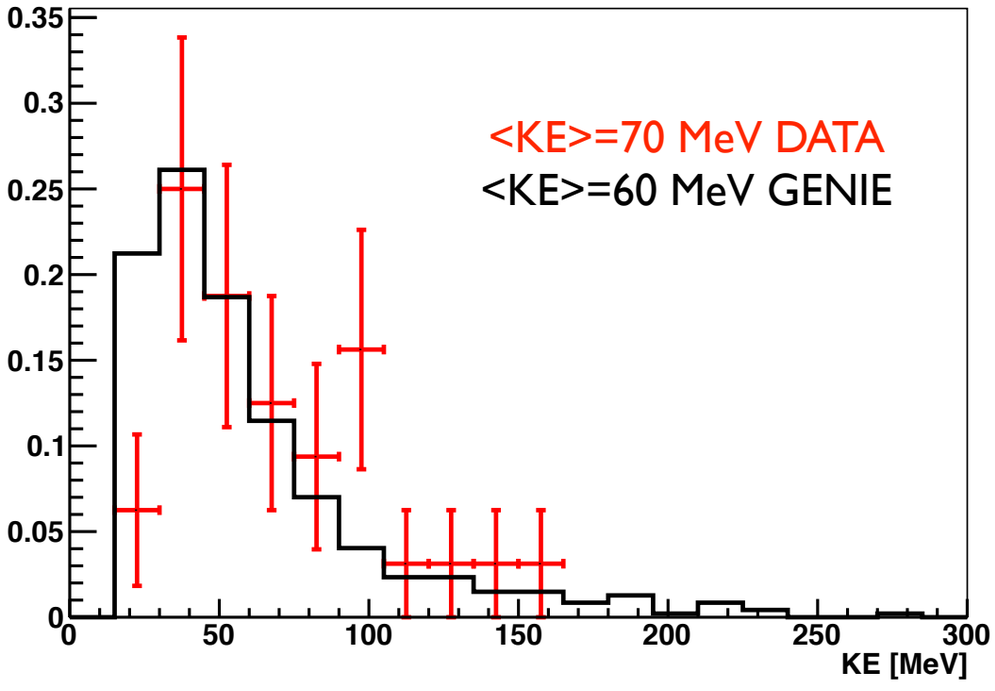
μ^+ 2p events

PROTON KINEMATICS
(Event-by event protons reconstruction)

ArgoNeuT

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



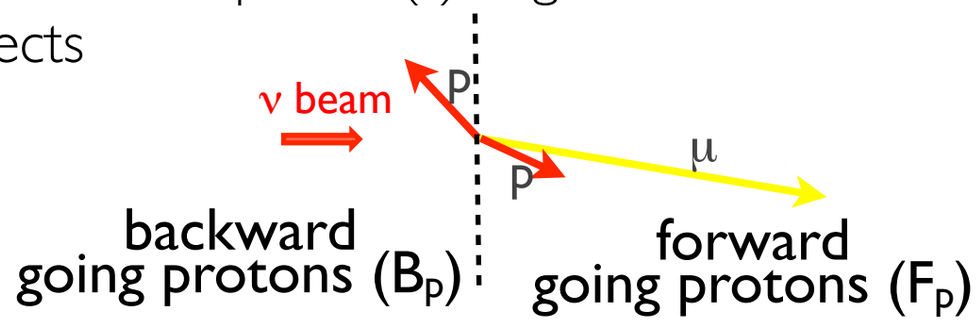


RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0-PION EVENTS IS IN PROGRESS

area normalized
comparison inside the detector

SW R&D: WHAT NEXT ? NUCLEAR EFFECTS

- The reconstruction of the proton(s) angle w.r.t. the neutrino direction provides important hints to study nuclear effects



- The production of ***Bp is kinematically forbidden*** in an interaction on a free and stationary nucleon. Their production in the high energy reactions off nuclei is a well established experimental fact and indicates the existence of nuclear effects in the scattering process

- Possible explanations are:

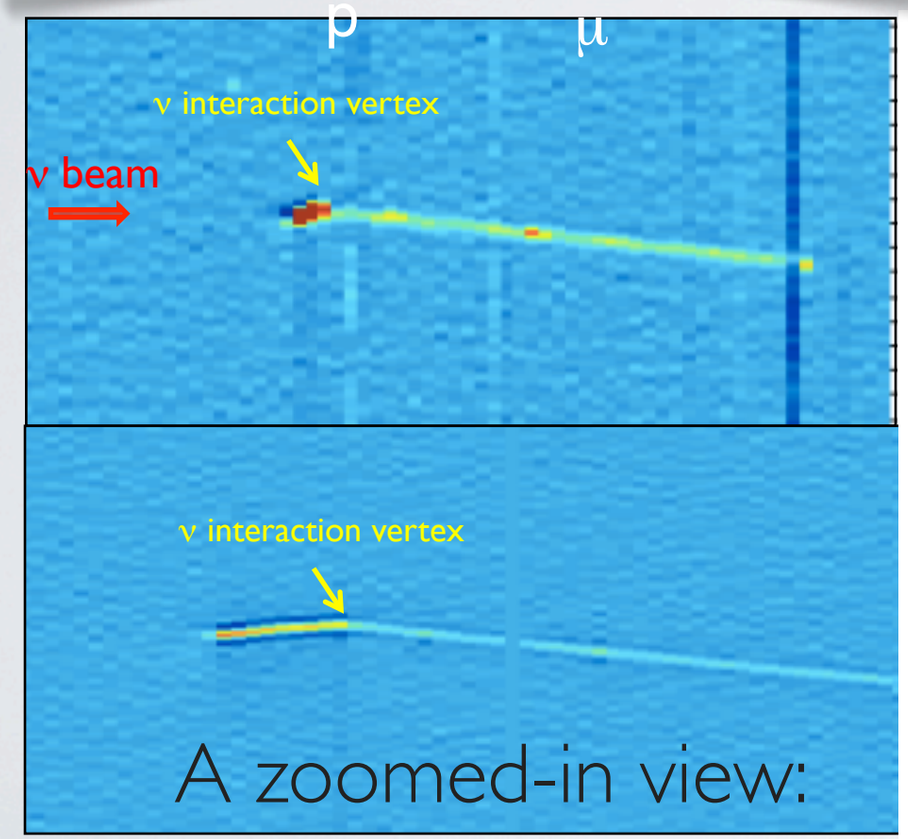
- Reinteractions (intranuclear cascade) inside the target nucleus
    - Bp can be produced in multiple scattering and interactions of slow hadrons, produced in the primary ν–nucleus collision, with the other nucleons during their propagation out of the nucleus.

- Short Range Correlations
    - Collisions off ***clusters composed of nucleons/quarks***. The clusters are formed under the action of the short range part of the nuclear force. **The nucleons in these structures can acquire high momenta and the fast backward going particles can be seen as a direct manifestation of the high momentum tail of the Fermi distribution**. The spectrum of the fast backward going particles reflects

Production in the backward hemisphere can have contributions from both mechanisms

BACKWARD GOING PROTONS (B_P)

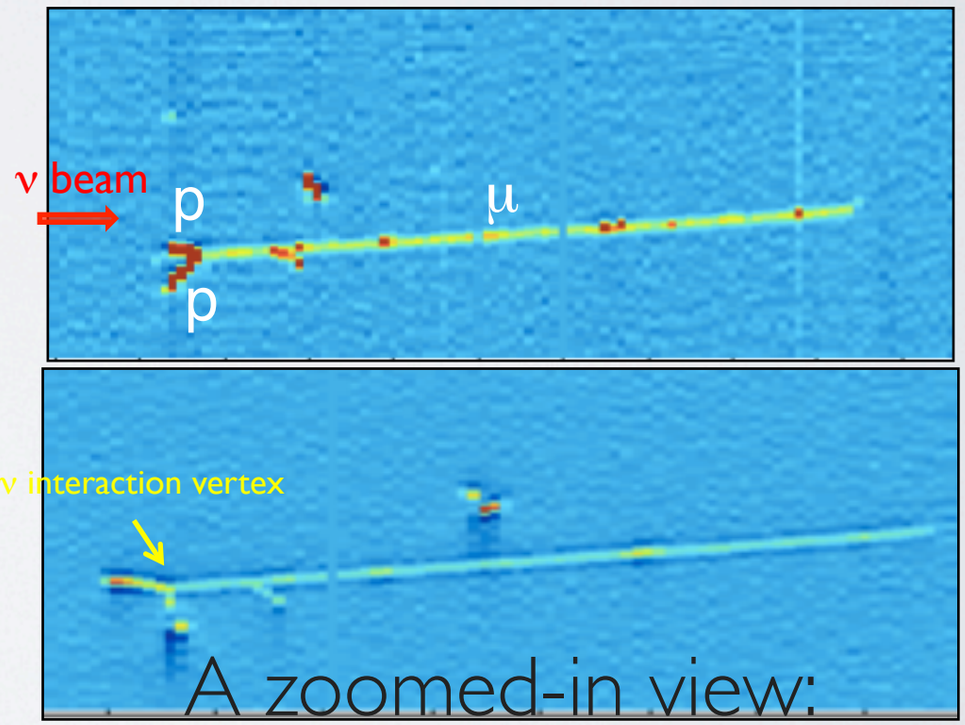
μ^+/μ^- 1p:
27 % of the events have a backward going proton



A zoomed-in view:

ν interaction with
a backward going p

μ^+ 2p:
16 % of the events have a backward going proton



A zoomed-in view:

ν interaction with
two backward going p's

NUCLEAR EFFECTS: BACK-TO-BACK PROTON PAIRS

If nucleon in a correlated pair is knocked out of a nucleus, the "paired" nucleon is also emitted. Detecting both nucleons can address many important questions.

Measurement of back-to-back pair emission: the "paired" nucleon is emitted in the opposite direction of the initial momentum of the knocked out nucleon:
"Fingerprints of nucleon-nucleon correlations"

L. Frankfurt, M. Sargsian, M. Strikman
arXiv:0806.4412v2 [nucl-th] 4 Sep 2008

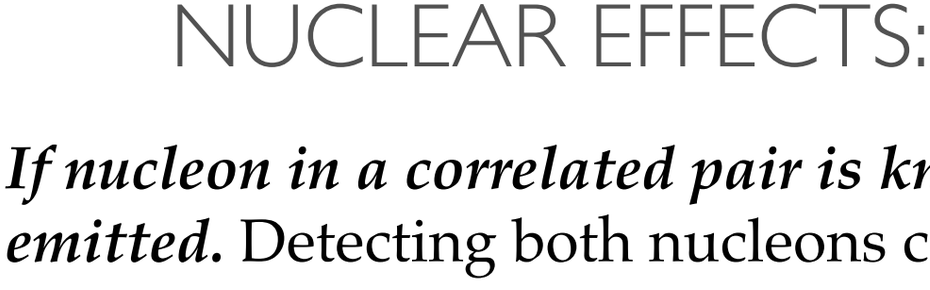
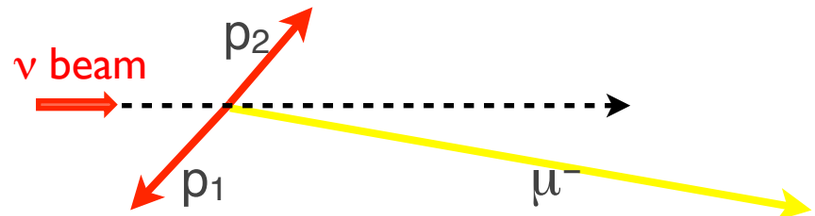


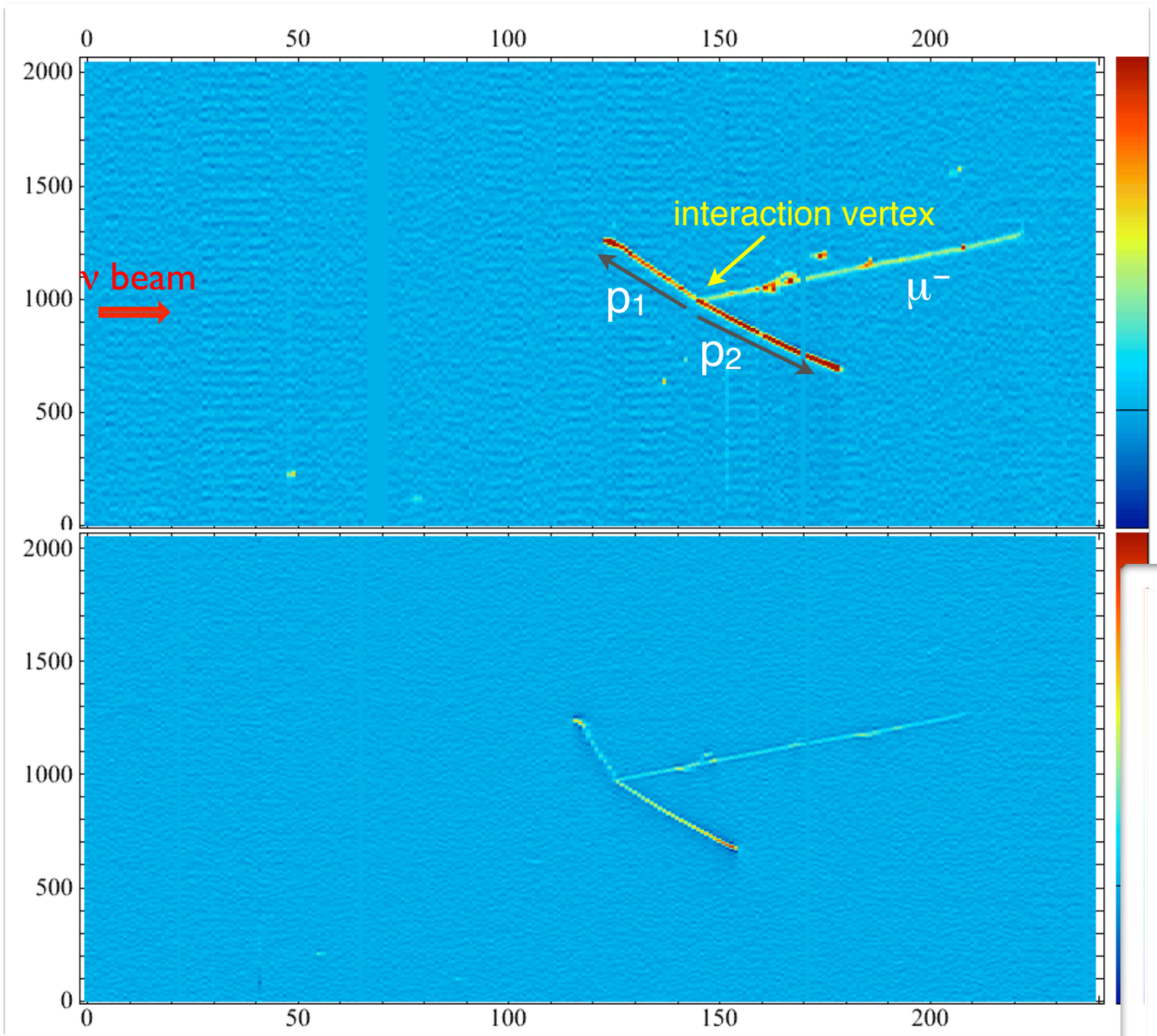
Figure 5: Interaction of virtual photon with three nucleon system in configurations in which two of the nucleons are in SRC.



back-to-back protons
(angle between 2 p ~ 180^0)

Search of back-back protons in the ArgoNeuT muon+2p event sample

BACK-TO-BACK PROTON PAIR (I)

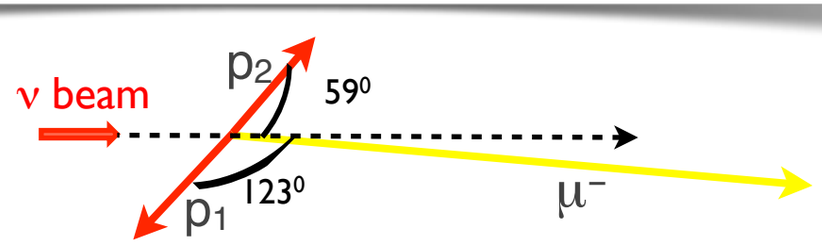


- p_1: $\theta_1=123^0$

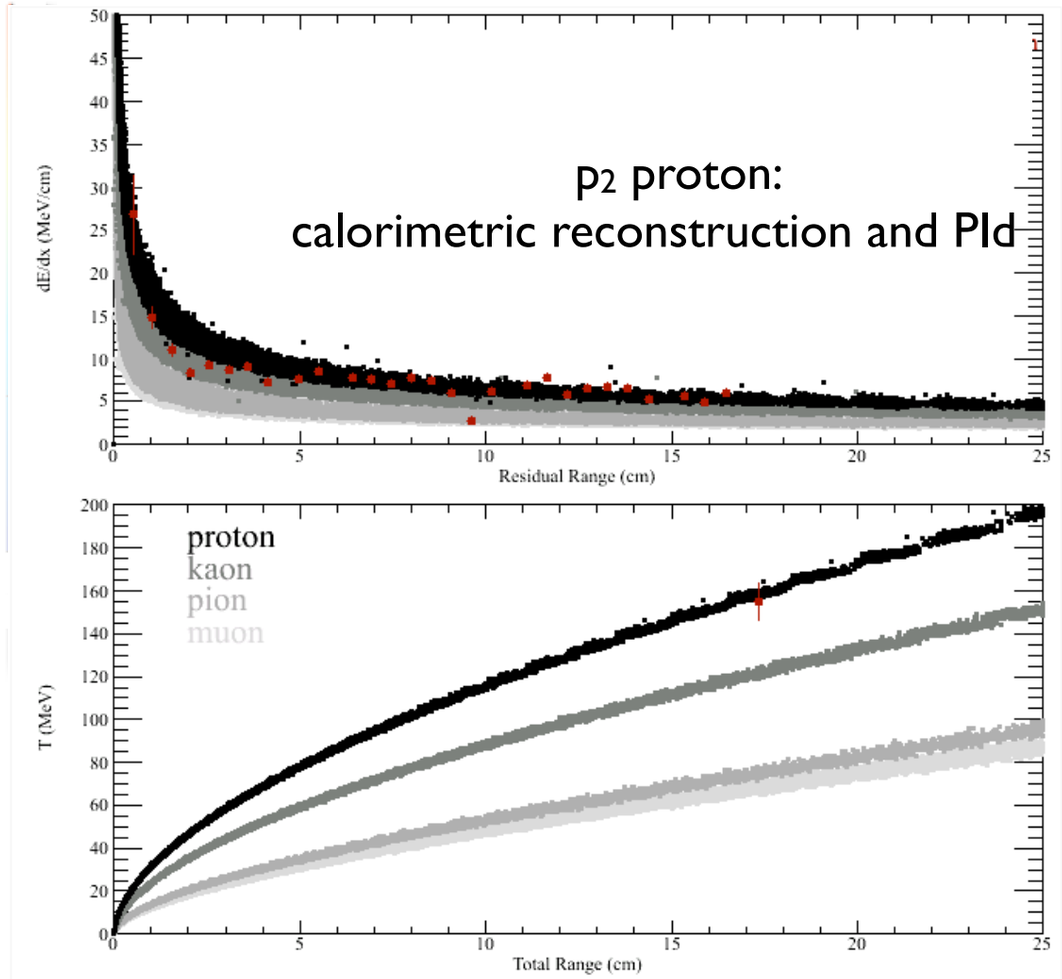
  L_1=12 cm ----> p_1=513±31 MeV/c
- p_2: $\theta_2=59^0$

  L_2=17 cm ----> p_2=566±34 MeV/c

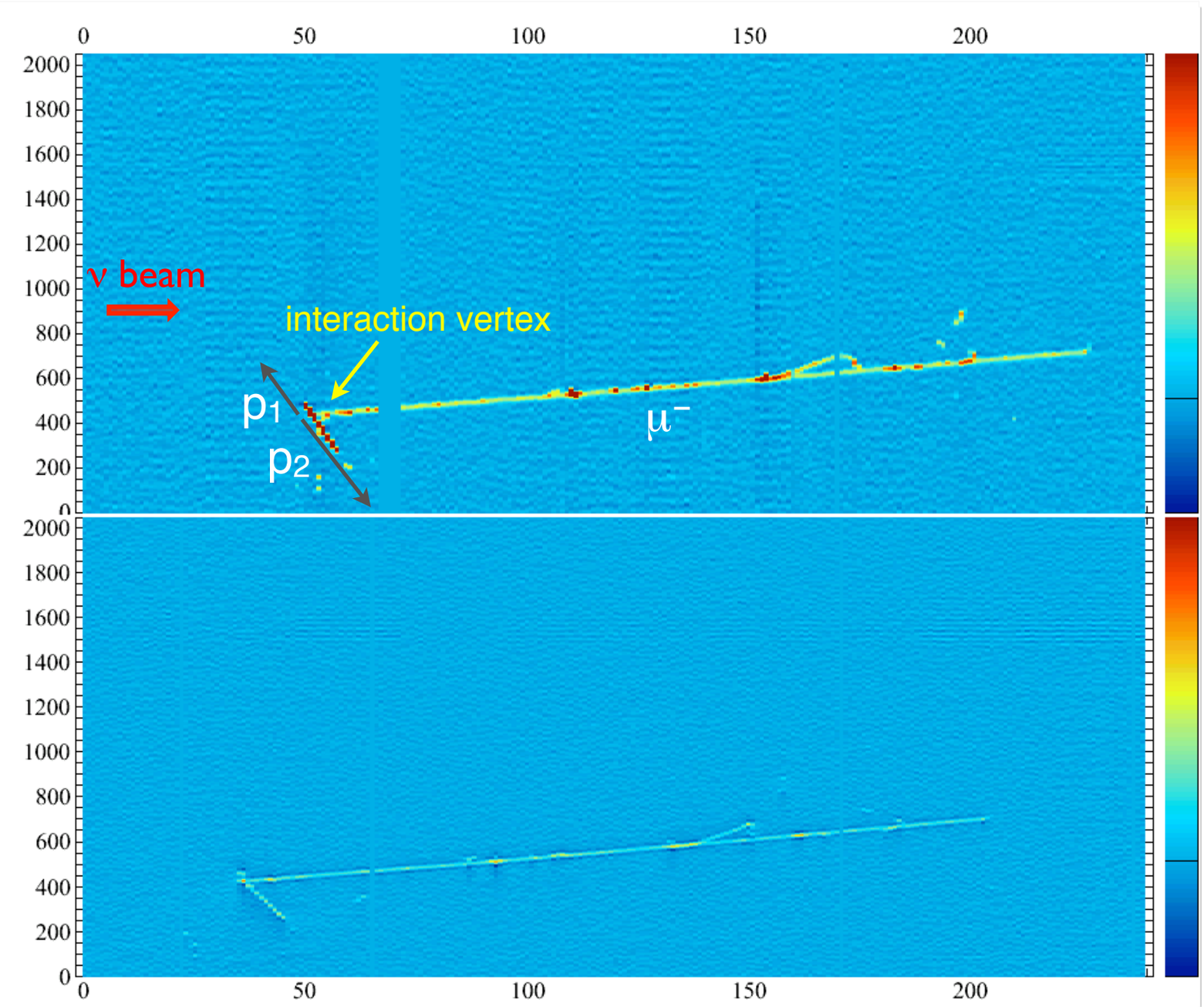
Angle between two protons $\gamma=183^0$



back-to-back protons



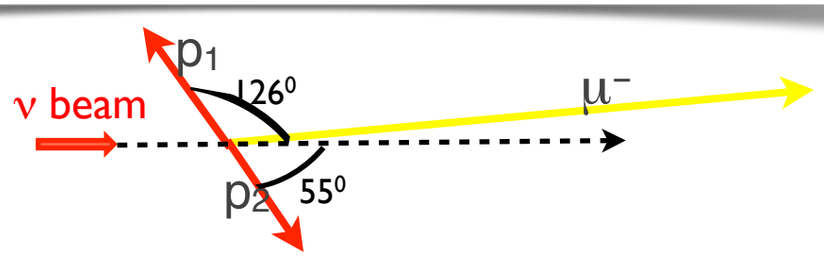
BACK-TO-BACK PROTON PAIR (II)



- p_1: $\theta_1=126^0$
  $L_1=1.8$ cm, $p_1=289\pm17$ MeV/c
- p_2: $\theta_2=55^0$
  $L_2=4.5$ cm, $p_2=381\pm23$ MeV/c

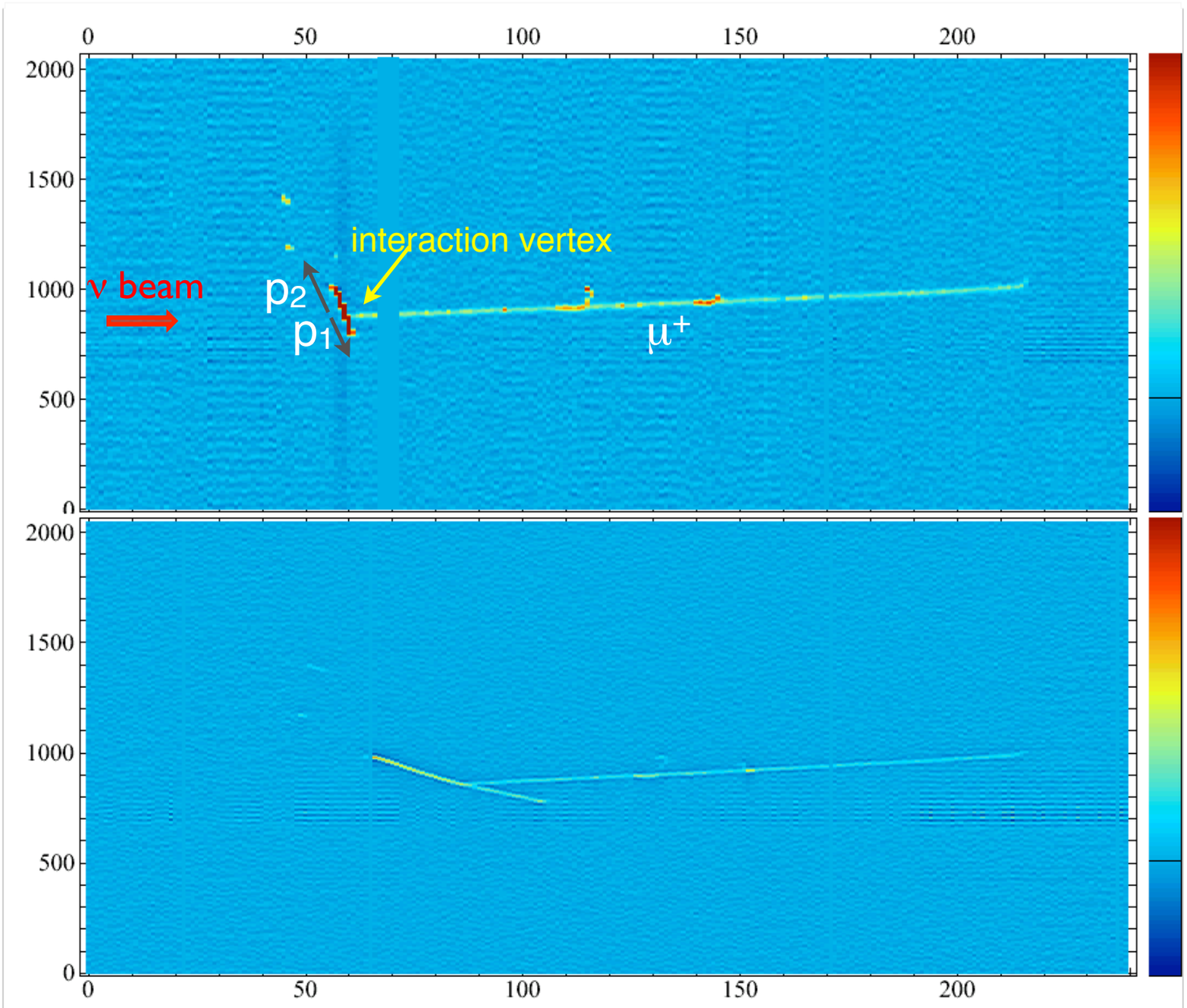
Angle between two protons $\gamma=181^0$

neutrino interaction producing a back-to-back proton pair



back-to-back protons

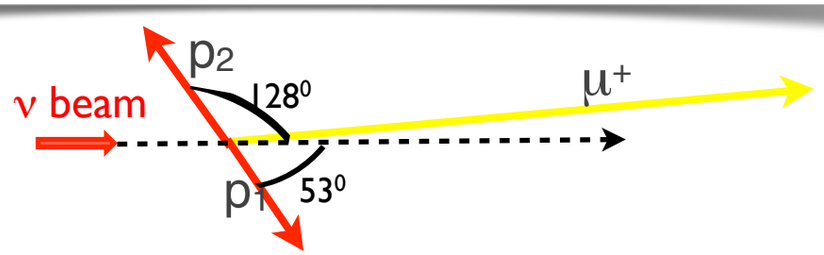
BACK-TO-BACK PROTON PAIR (III)



- p_1: $\theta_1=53^0$
  $L_1=7.5$ cm, $p_1=443\pm26$ MeV/c
- p_2: $\theta_2=128^0$
  $L_2=8.9$ cm, $p_2=466\pm28$ MeV/c

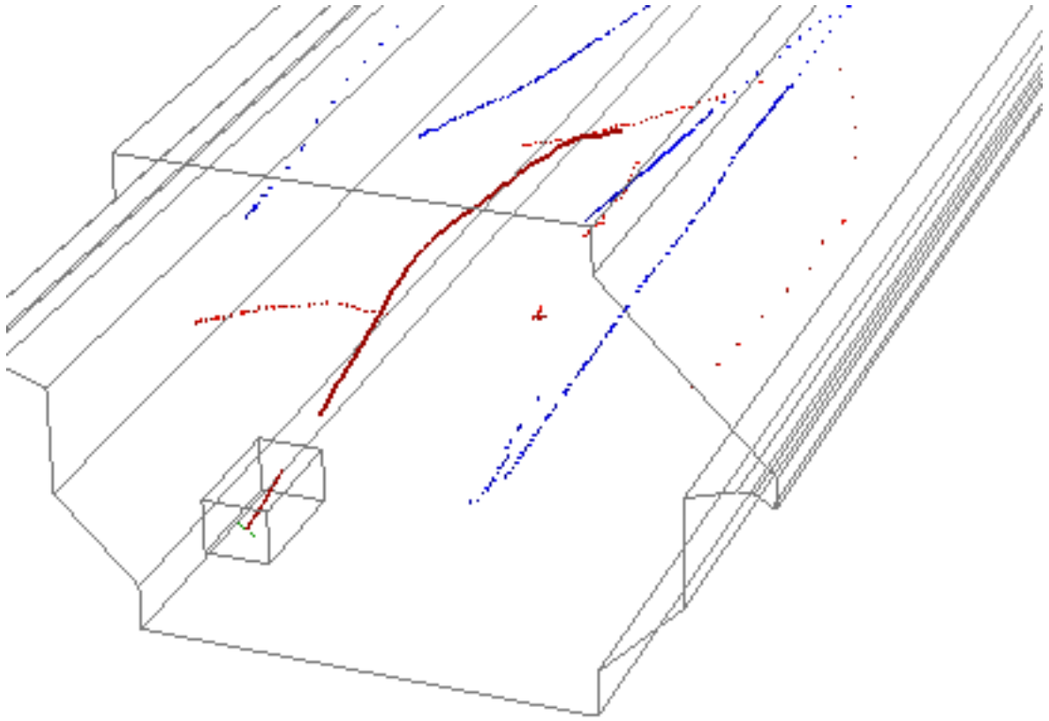
Angle between two protons $\gamma=181^0$

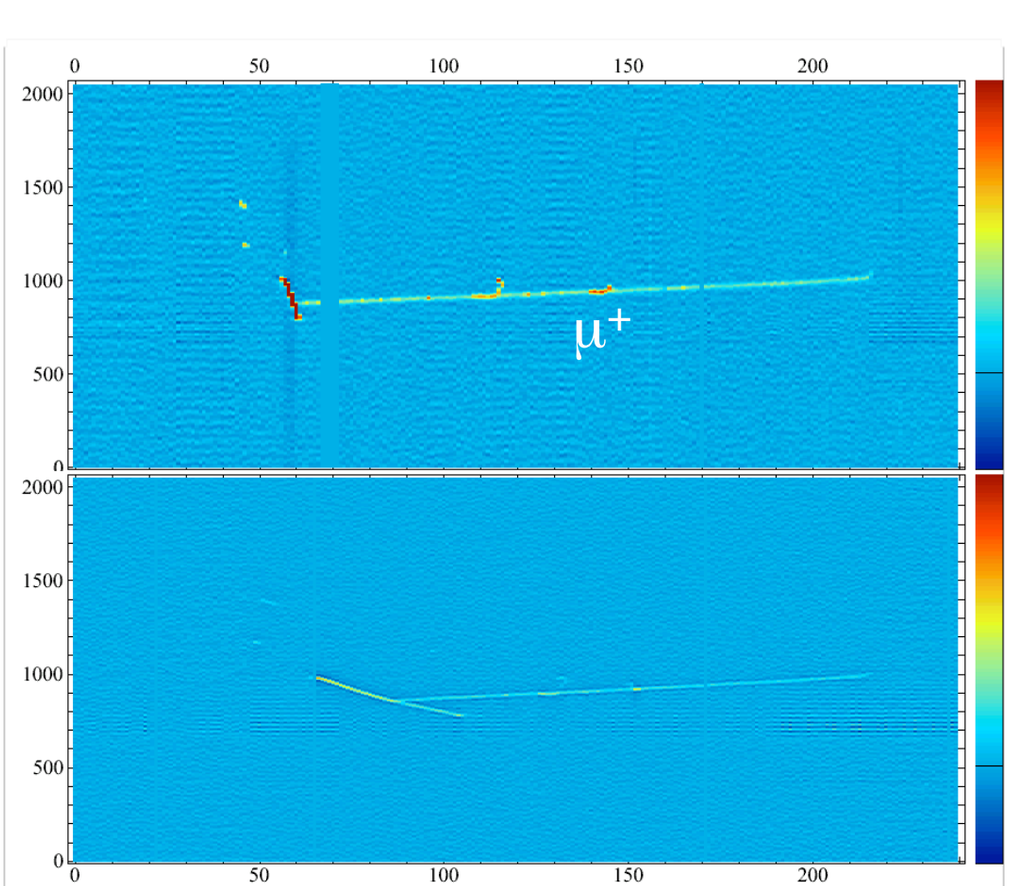
anti-Neutrino interaction producing a back-to-back proton pair



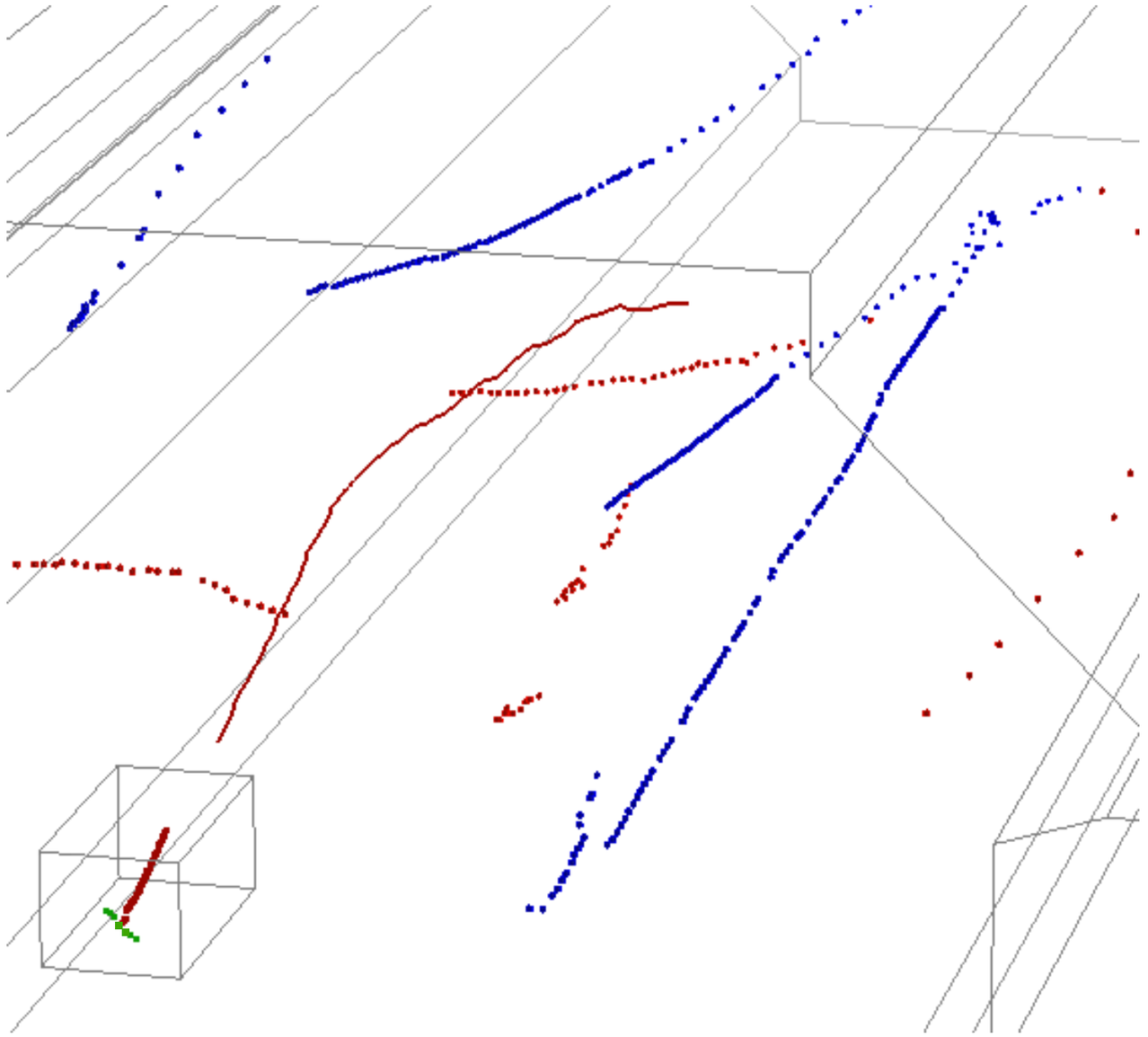
back-to-back protons

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





A DETAILED STUDY OF BACK-TO-BACK PROTONS IS IN PROGRESS



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

SUMMARY

LAr TPC have the capability to identify and reconstruct exclusive topologies with very low proton threshold

Lot of information from LAr TPC...
We are learning how to deal with each class of event/topology.

Off-Line SW R&D in progress

Proton multiplicity at the neutrino interaction vertex with presence of secondary particles in LArTPC events and reconstruction of the proton(s) kinematics provide indications about the presence and the size of nuclear effects in LAr.

The MC generators predict vastly varying amounts of proton emission.
LAr data can provide an important discriminator among models.

MC R&D in progress

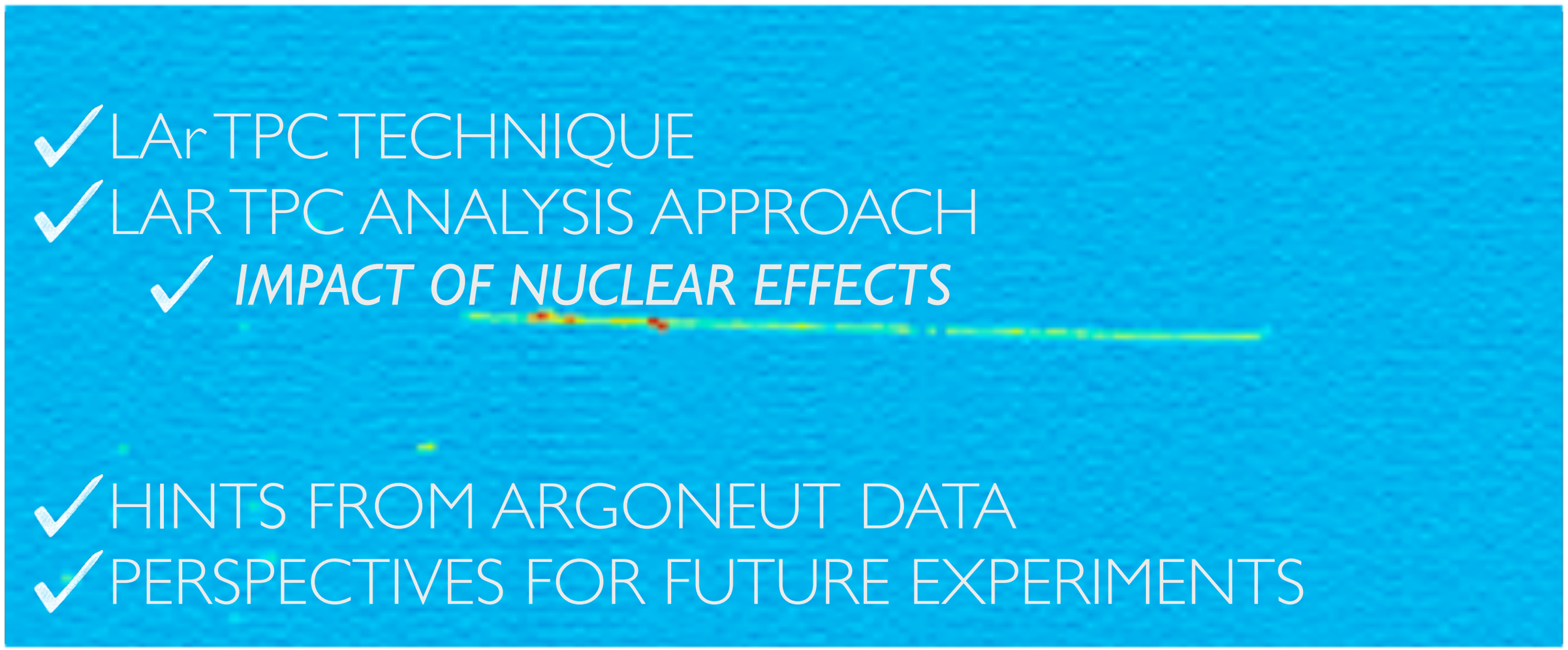
Progressing with the *development* of more and more accurate *reconstruction tools* for data analysis, in combination with *larger mass LAr-TPC detectors* is an important step for accurate topological analysis of neutrino events,

on the line pioneered by ArgoNeuT.

MAterial shown here based on (and thanks to):
[1] O. Palamara (for the ArgoNeuT Coll.), "Hints for nuclear effects from ArgoNeuT data"[NuInt12]
[2] *K. Partyka (for the ArgoNeuT Coll.), "Exclusive 0 pion topologies in ArgoNeuT" [NuInt12]*
[3] T.Yang (or the ArgoNeuT Coll.), "Neutrino Interactions on Liquid Argon – New Results from ArgoNeuT" [Aspen13]

Backup slides

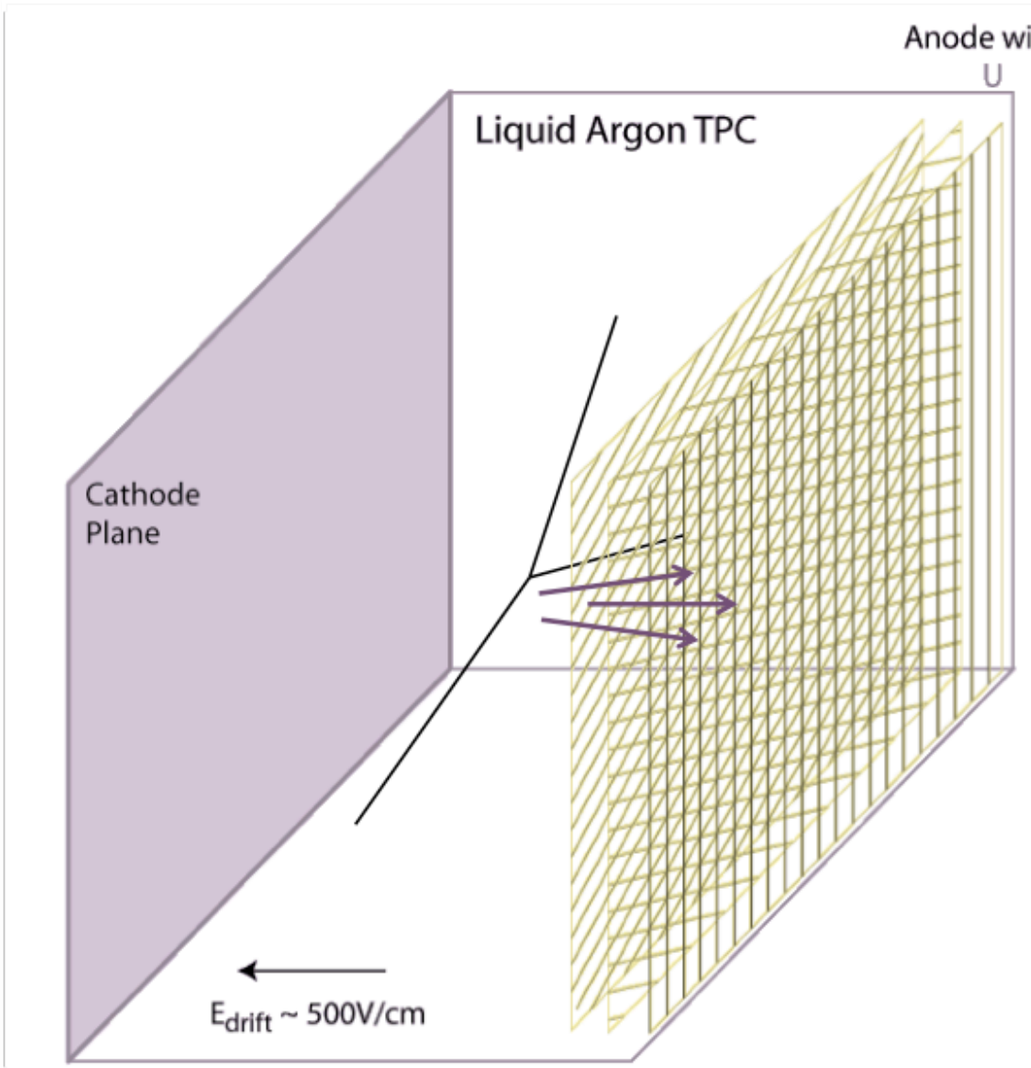
The LAr TPC ***SW-R&D*** at FNAL



- ✓ LAr TPC TECHNIQUE
- ✓ LAR TPC ANALYSIS APPROACH
  - ✓ *IMPACT OF NUCLEAR EFFECTS*
- ✓ HINTS FROM ARGONEUT DATA
- ✓ PERSPECTIVES FOR FUTURE EXPERIMENTS

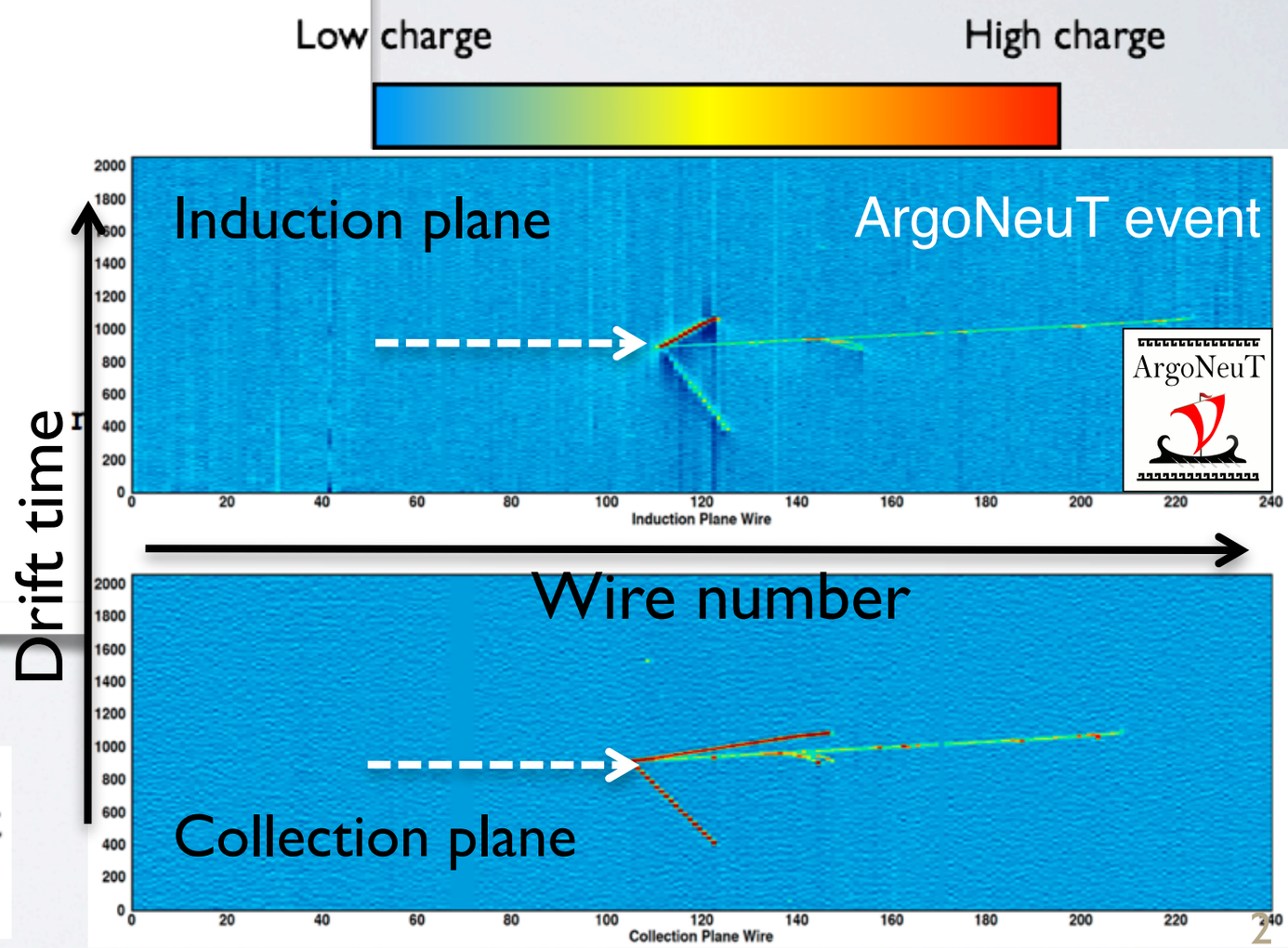
OUTLINE

THE LAR TPC CONCEPT



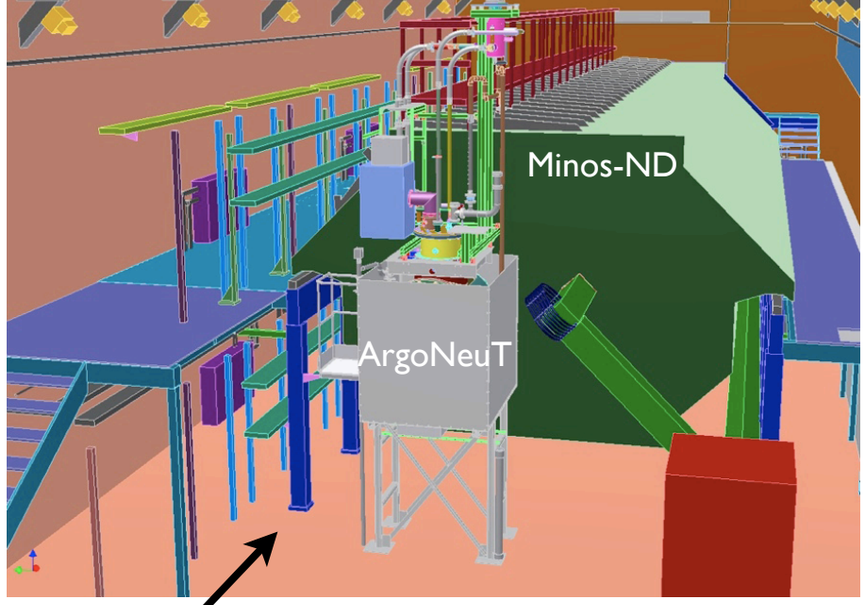
Charged particle tracks ionize argon atoms; Ionization charge drifts to finely segmented charge collection planes over ~1-few ms.

Wire pulses in time give the drift coordinate of the track



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

ArgoNeuT



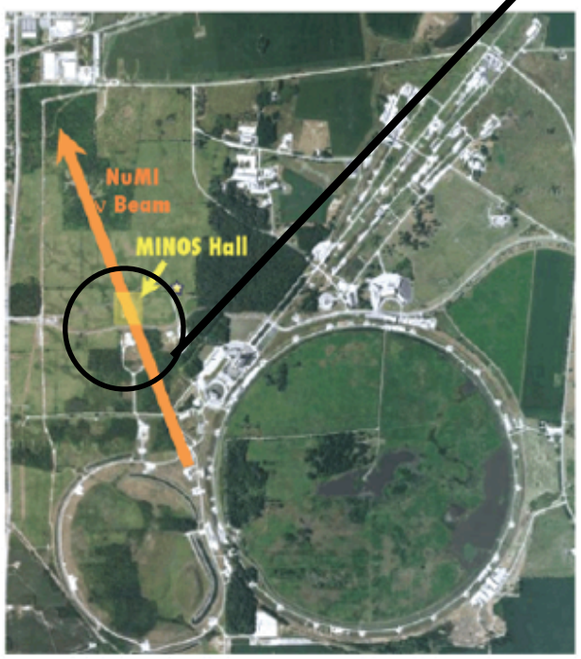
ArgoNeuT

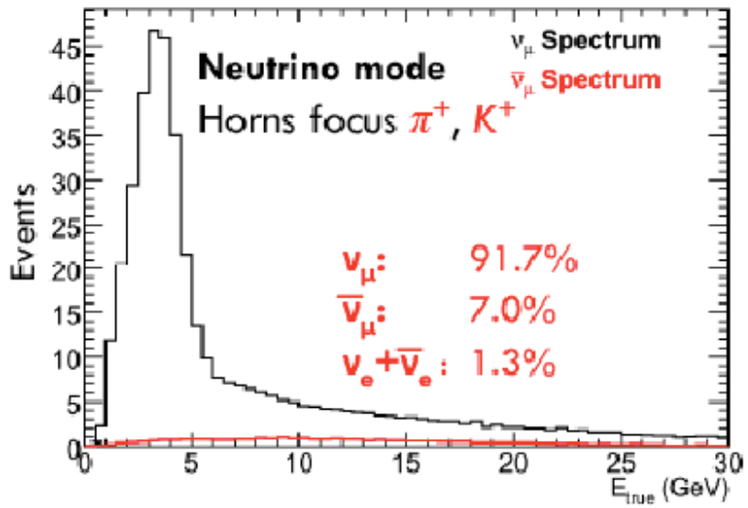
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

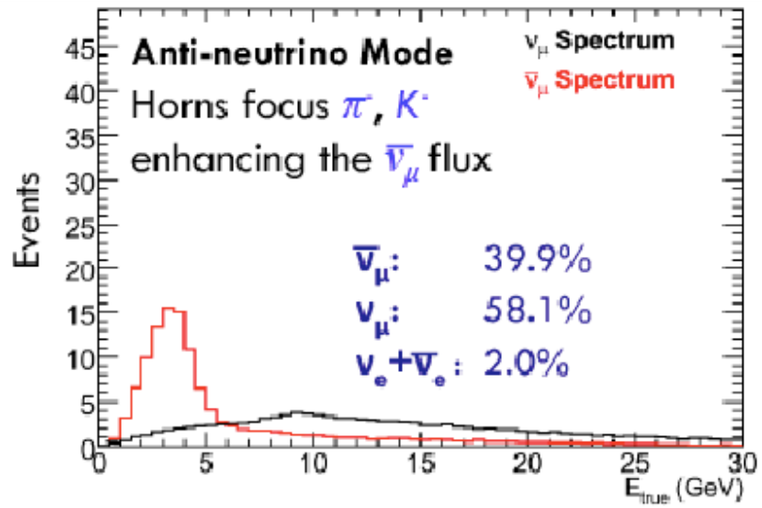
NuMI LE beam
ν–mode (2 weeks):
8.5×10^{18} POT
$\bar{\nu}$–mode (6 months):
1.20×10^{20} POT

175 l active volume

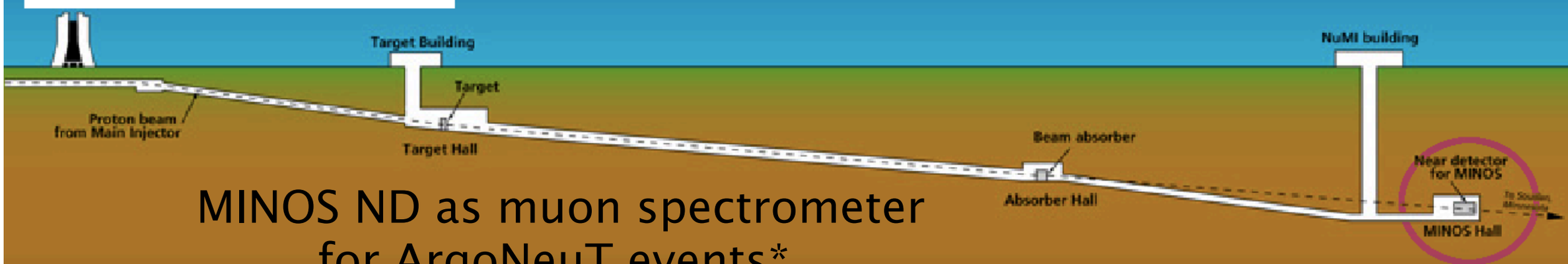
~10000 CC events collected







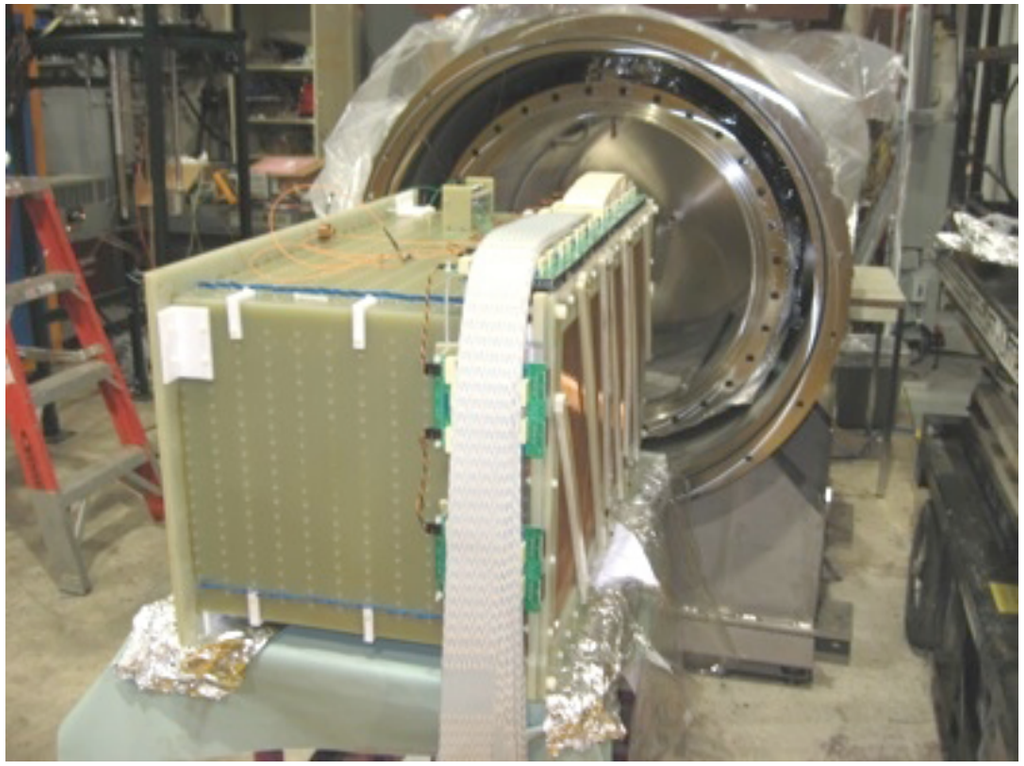
NuMI LE beam



MINOS ND as muon spectrometer for ArgoNeuT events*
(energy reconstruction and charge identification (q) of exiting muons)

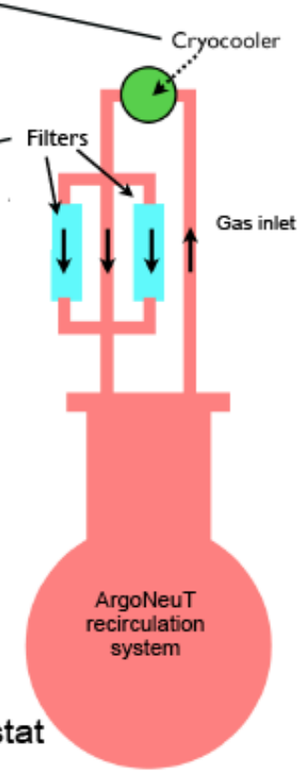
**ArgoNeuT Coll. is grateful to MINOS Coll. for providind the muon reconstruction*

ArgoNeuT Design



2 read-out planes: ***Induction and Collectio***
each channel: 2048 samples in 400 microsecond

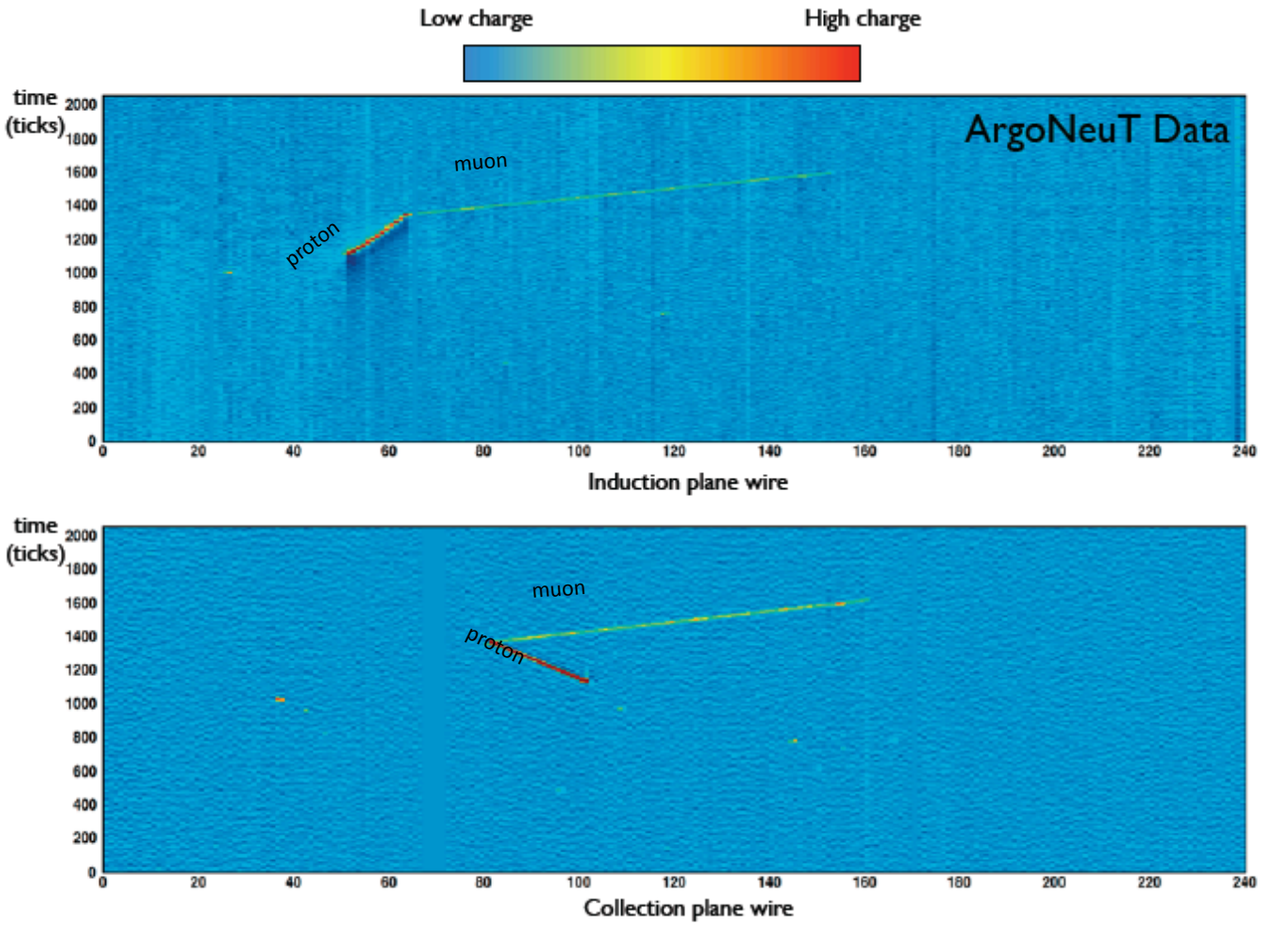
Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Electric field	500 V/cm



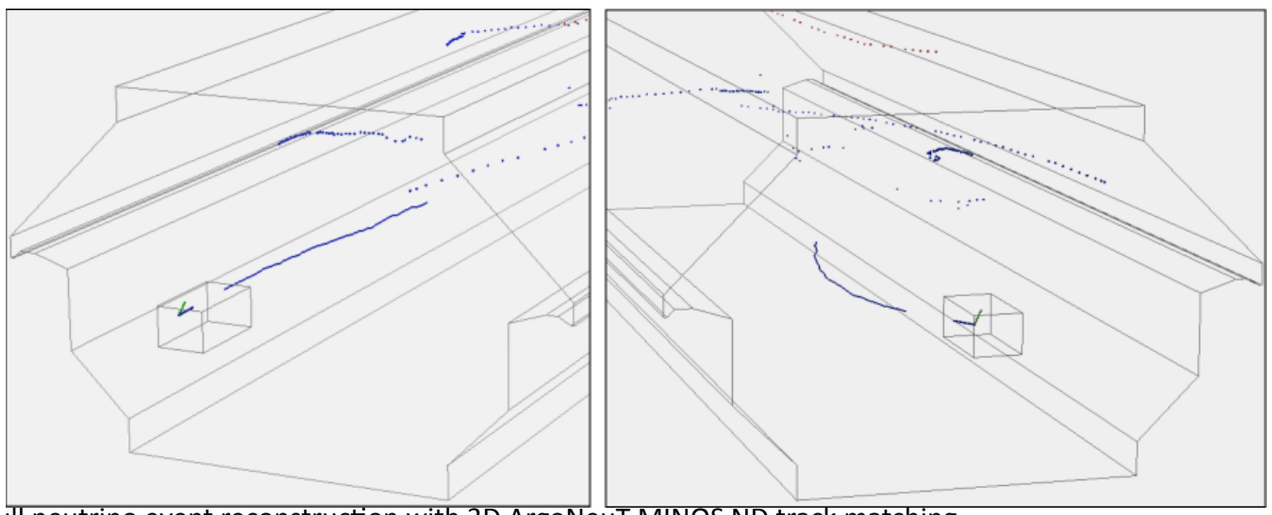
- Self contained system.
- Recirculate argon through a copper-based filter.
- Cryocooler used to recondense boil-off gas.

30

Reconstruction of $1\mu 1p$ events

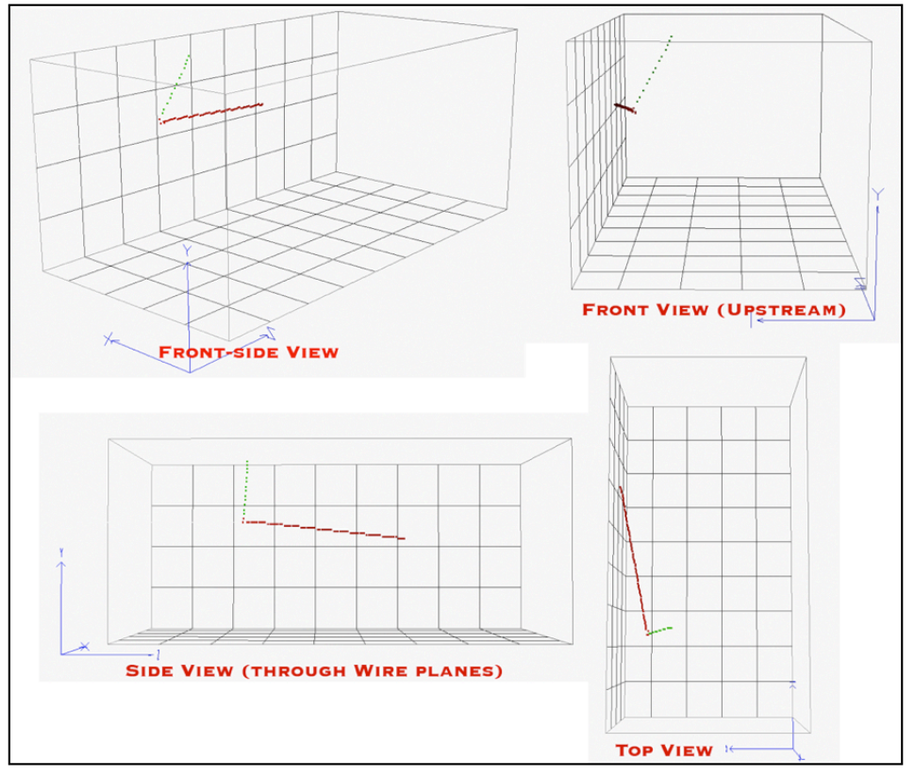


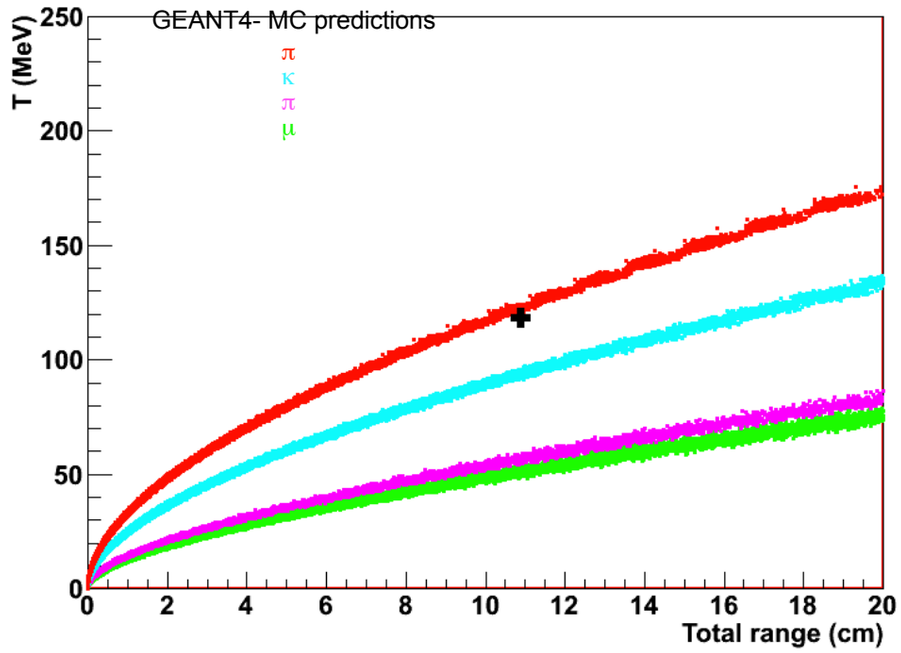
μ- escaping ArgoNeuT (and reaching MINOS-ND downstream)



Full neutrino event reconstruction with 3D ArgoNeuT-MINOS ND track matching

Neutrino event reconstructed in 3D space





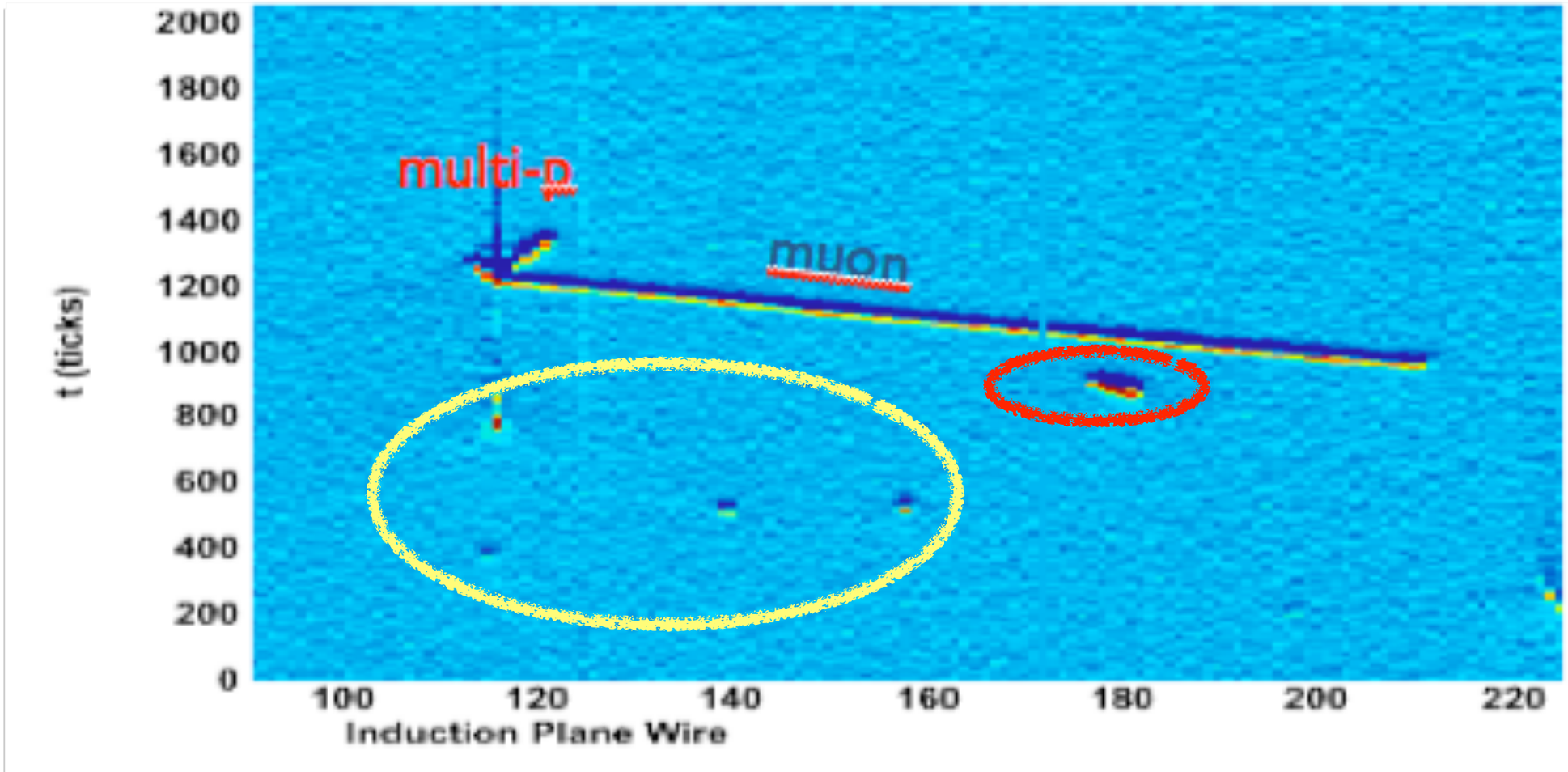
Proton (ArgoNeuT reconstruction): track length= 10.88 cm,
T=118 MeV, p=0.485 GeV/c

$\mu + p$ kinematics Reconstructed Neutrino Energy= 3.1 GeV

μ kinematics Reconstructed Neutrino Energy= 3.0 GeV

VERTEX ACTIVITY

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



LAr TPC ANALYSIS APPROACH

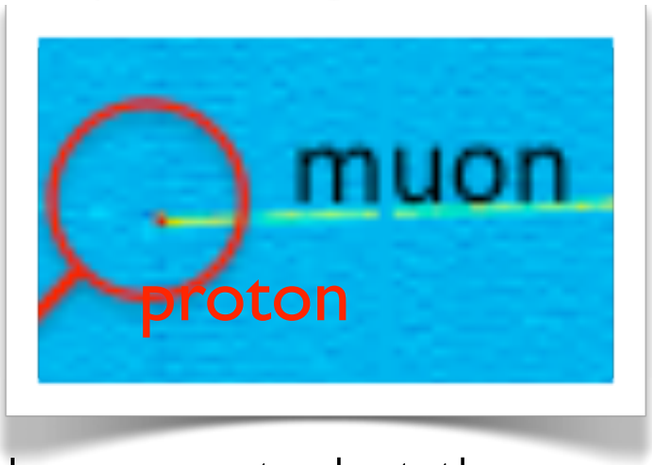
Count (PId) and reconstruct protons at the neutrino interaction vertex: analysis fully exploiting LAr TPC's capabilities (in Cherenkov detectors all these classes of events are 1 track "CCQE like" events)

Particle Identification with 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

0 PION ν_μ CC EVENTS: TOPOLOGICAL ANALYSIS AND HINTS FOR NUCLEAR EFFECTS

- A first Topological analysis is currently developed and exploited by the ArgoNeuT experiment *with a* ***proton threshold of 21 MeV Kinetic energy***.



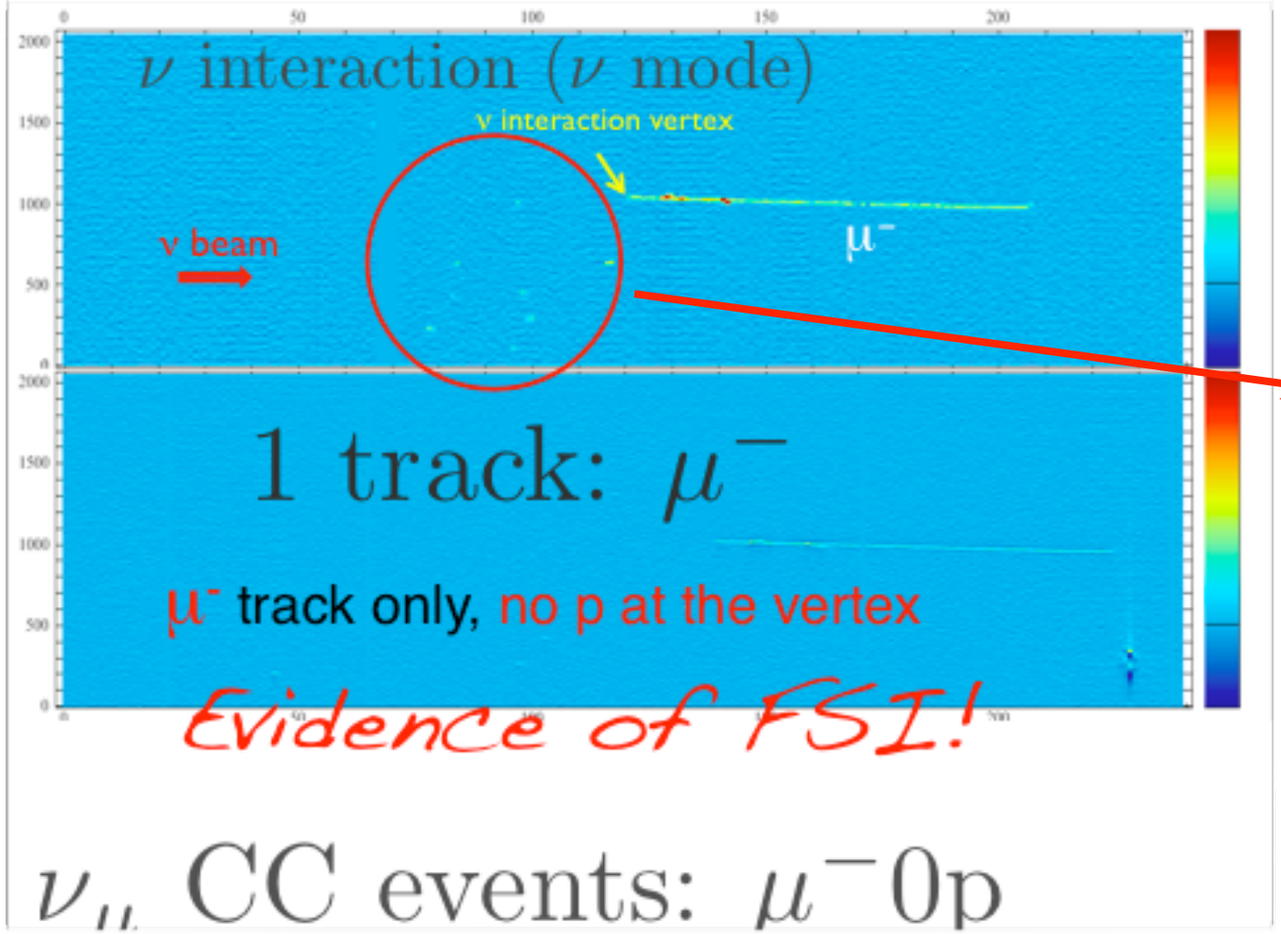
- Preliminary results from the analysis of 0 pion CC events few GeV energy region (both neutrino and anti-neutrino mode runs, DATA-GENIE MC comparisons), have been recently presented at the NUINT 2012 workshop [1], [2] and Aspen 2013 conference [3]:

  - Multi-p accompanying the leading muon and the presence of vertex activity are clearly visible (and measured) in the ArgoNeuT events.

  - Ratios among rates of different exclusive topologies provide indications of the size of nuclear effects.

New: hints on nuclear effects from reconstruction of proton kinematics

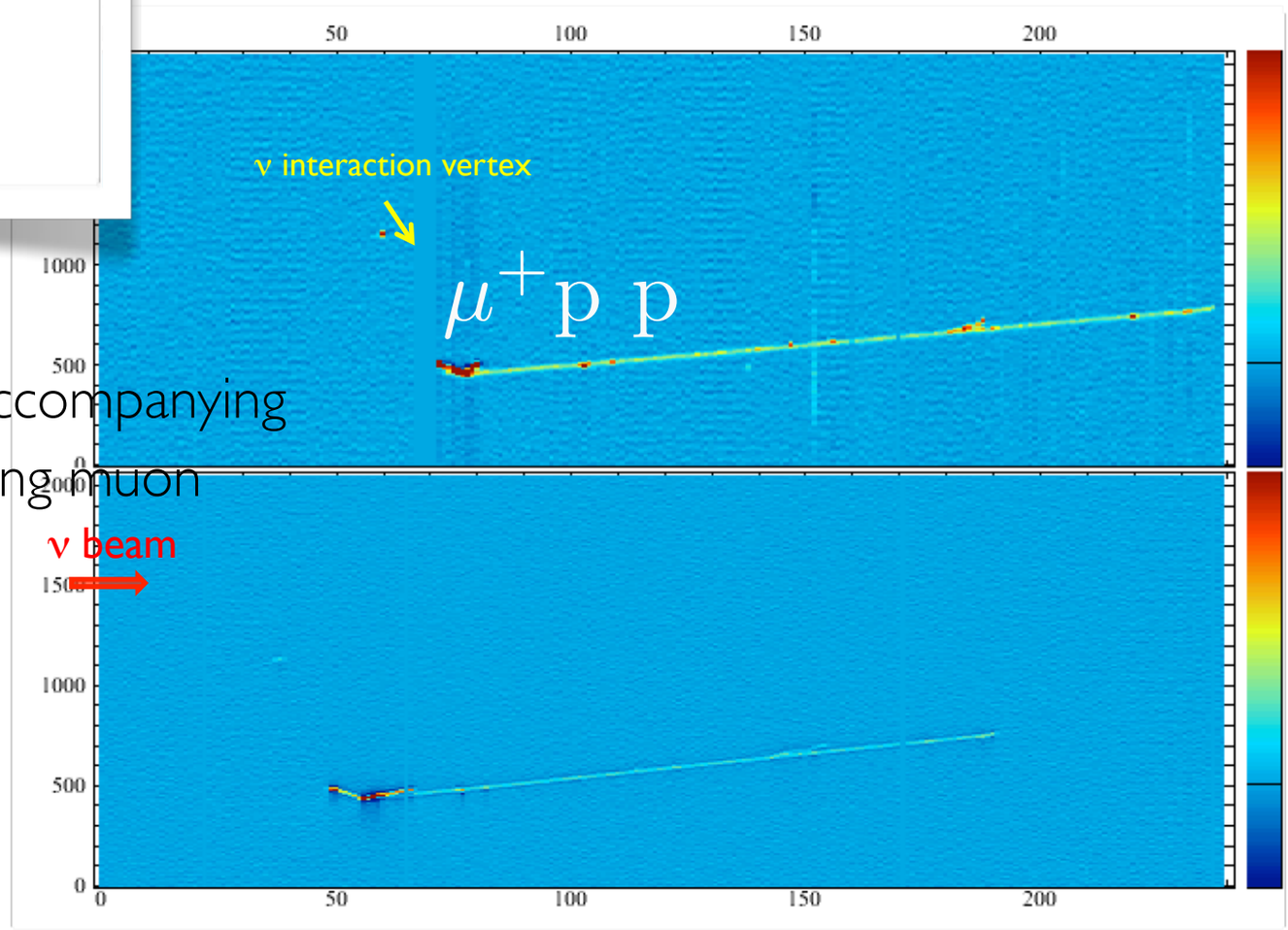
[1] K. Partyka (for the ArgoNeuT Coll.), "Exclusive 0 pion topologies in ArgoNeuT".
[2] O. Palamara (for the ArgoNeuT Coll.), "Hints for nuclear effects from ArgoNeuT data".
[3] T.Yang (or the ArgoNeuT Coll.), "Neutrino Interactions on Liquid Argon – New Results from ArgoNeuT" [Aspen 13]



ArgoNeuT

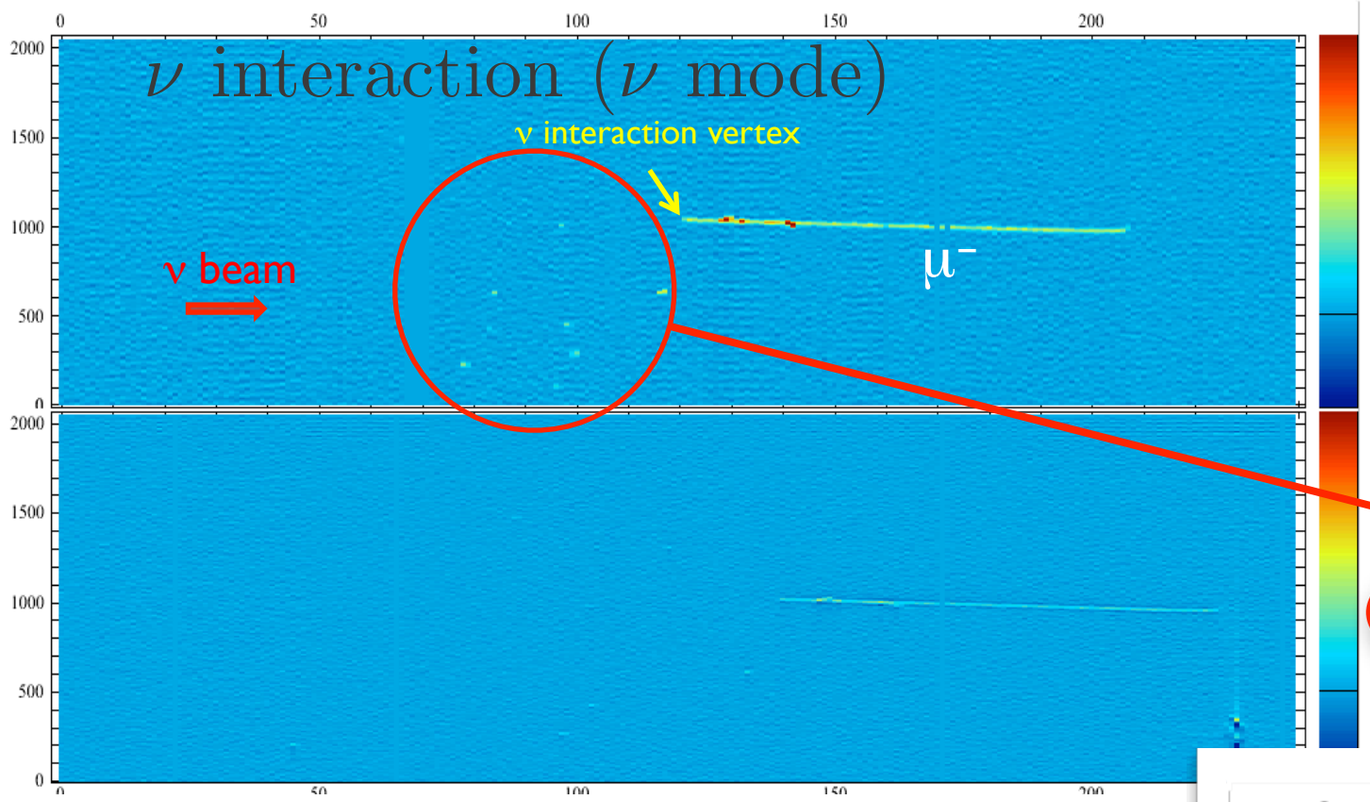
Activity around the vertex

e's from nuclear de-excitation γ conversion



Multi-p accompanying the leading muon

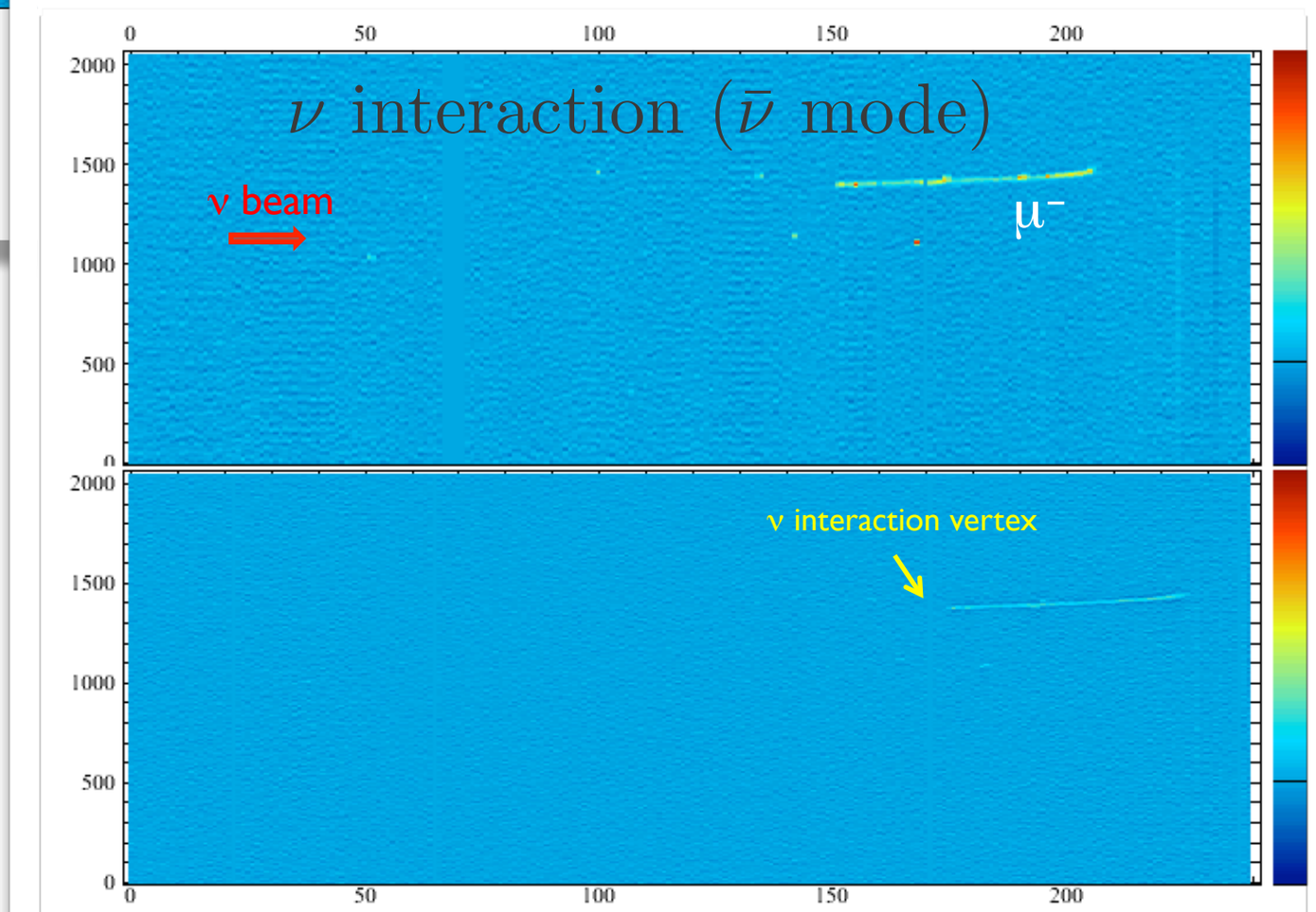
ArgoNeuT events: Single μ⁻ event (Left), Multi-proton event (Right)



DATA: EXCLUSIVE TOPOLOGIES

Activity around the vertex

e's from nuclear de-excitation γ conversion



1 track: μ^-

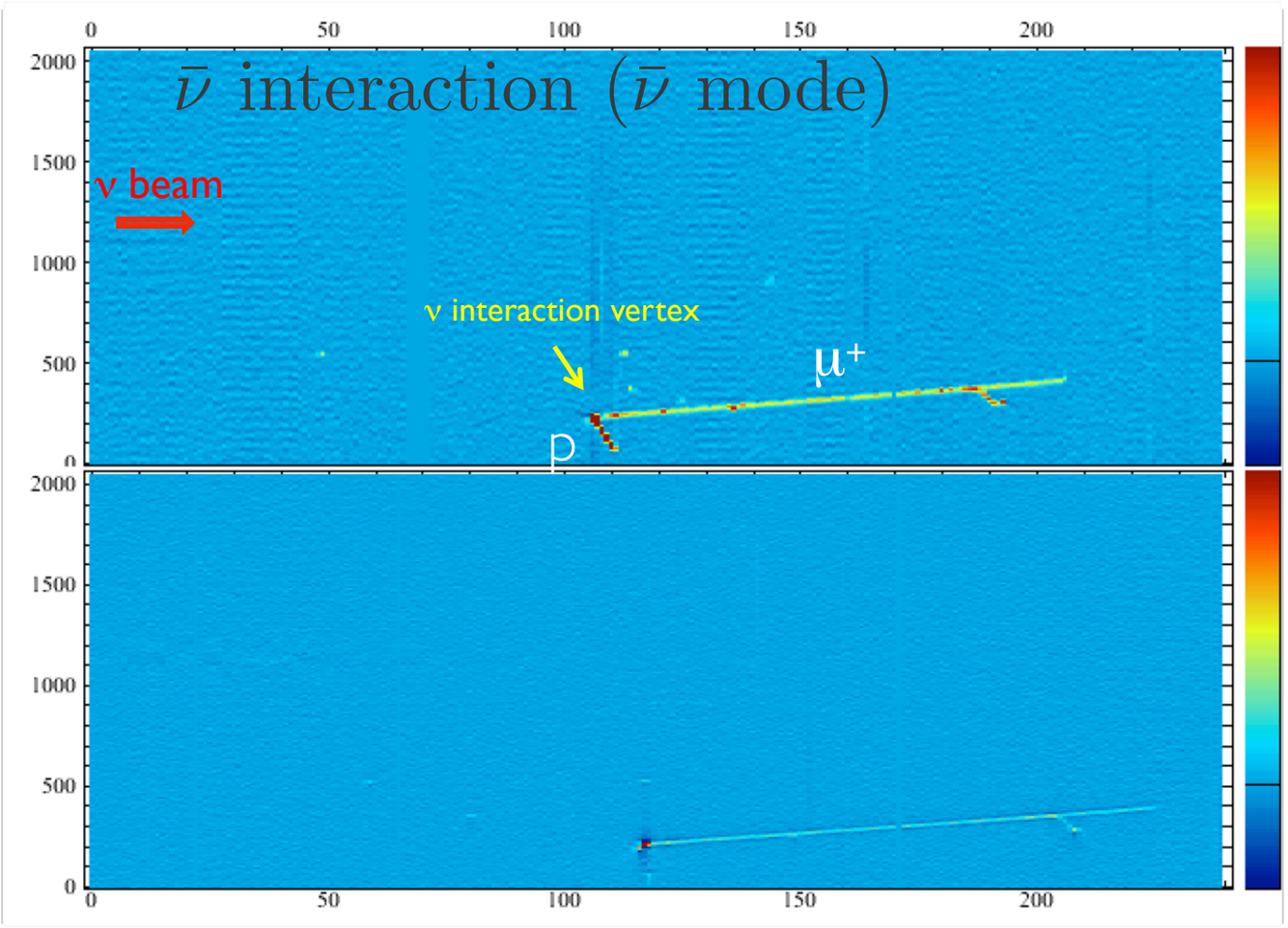
μ^- track only, no p at the vertex

Evidence of FSI!

ν_μ CC events: $\mu^- 0p$

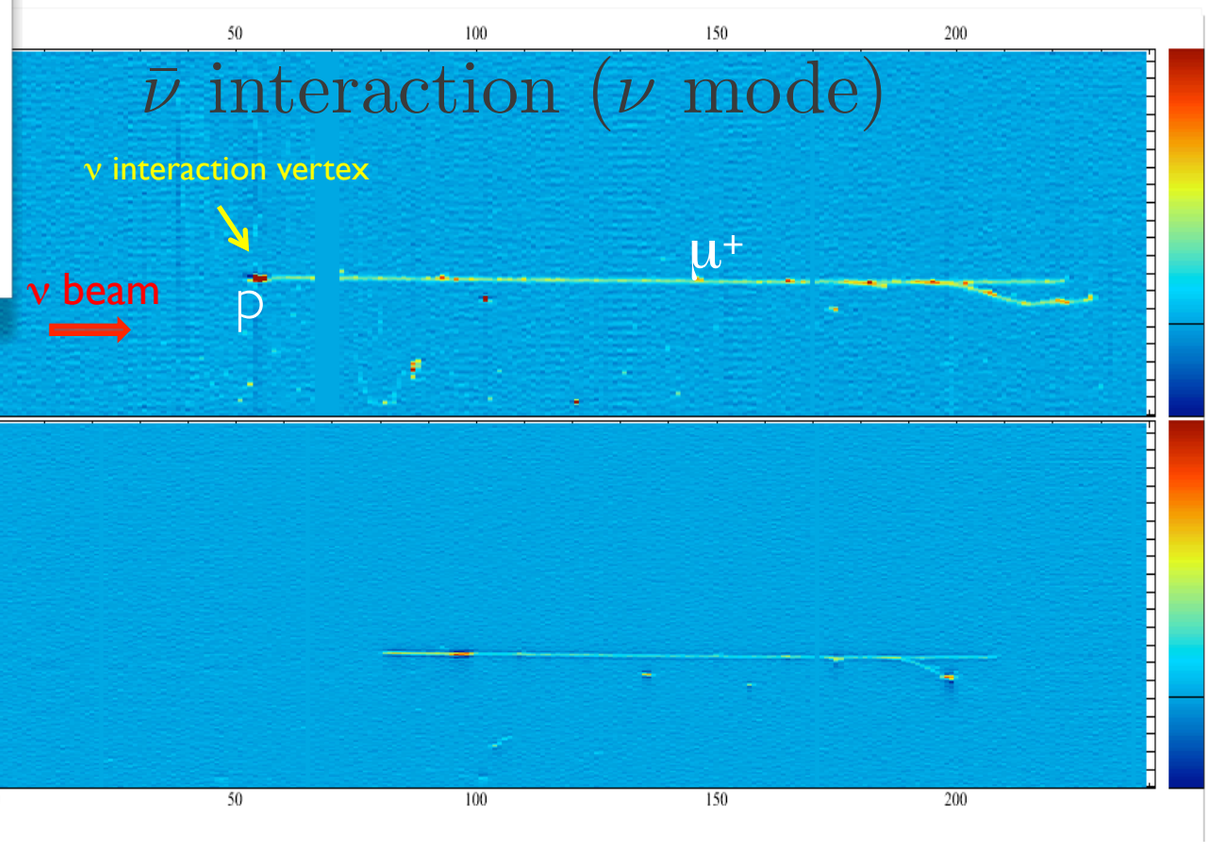
36

DATA: EXCLUSIVE TOPOLOGIES



Activity around the vertex

e's from nuclear de-excitation **γ** conversion



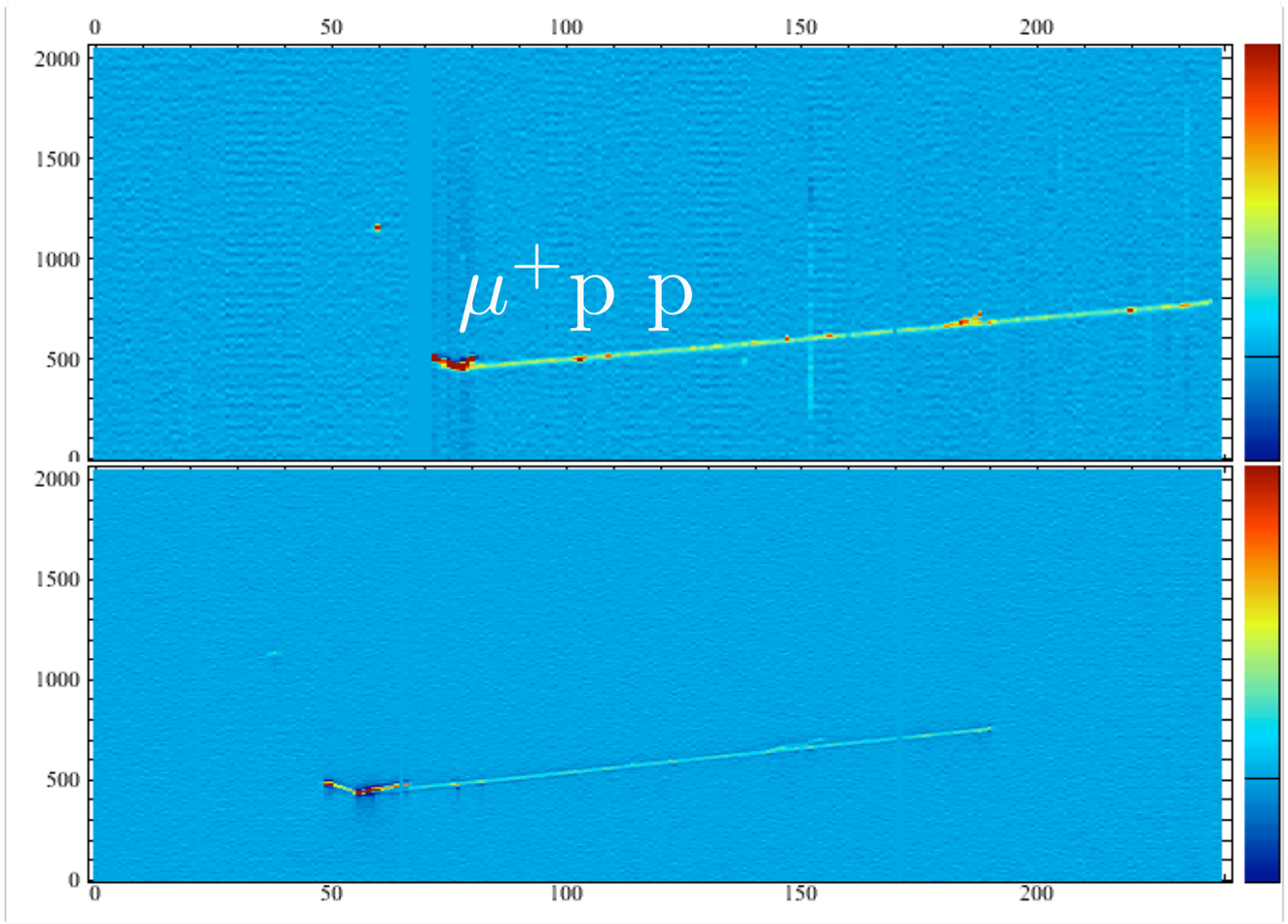
2 tracks: 1 μ^+ 1 p

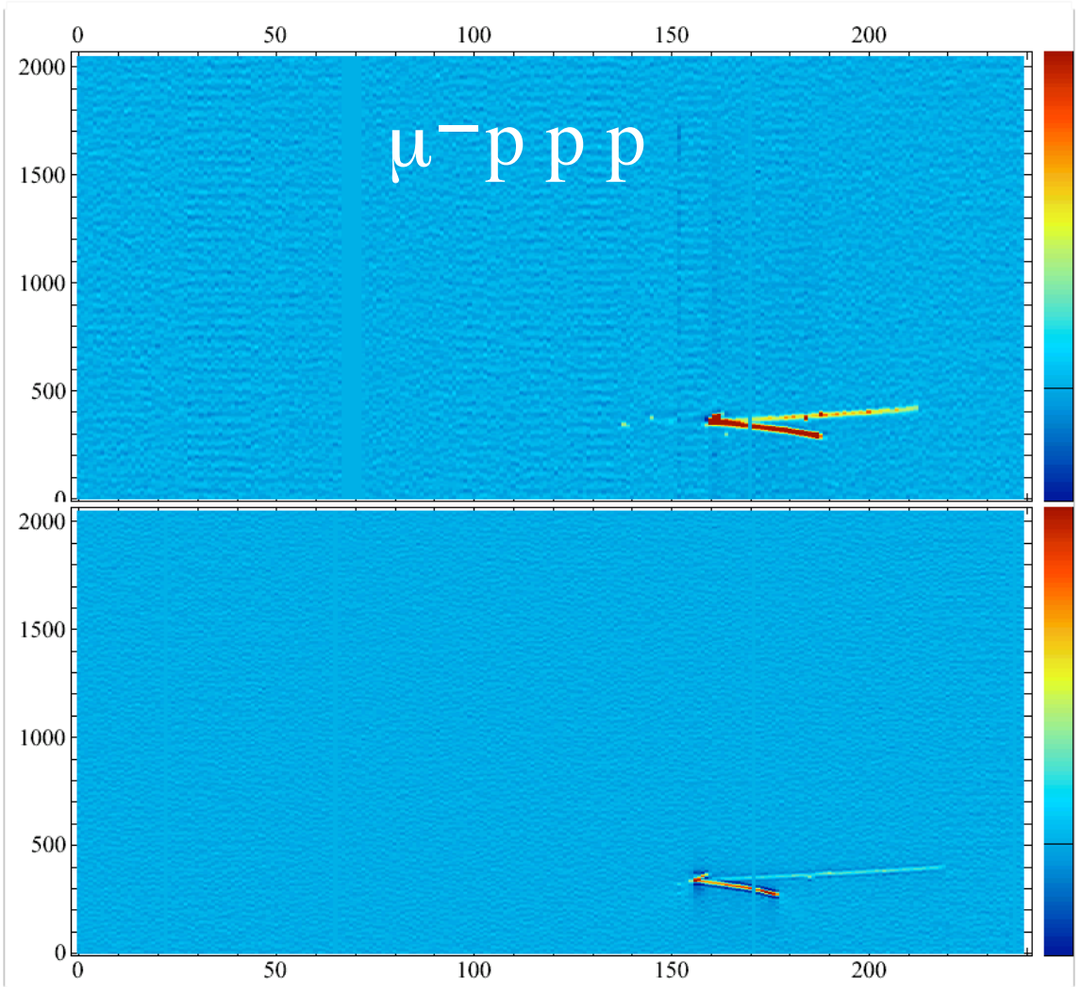
Evidence of FSI!

$\bar{\nu}_\mu$ CC events: μ^+p

DATA: EXCLUSIVE TOPOLOGIES

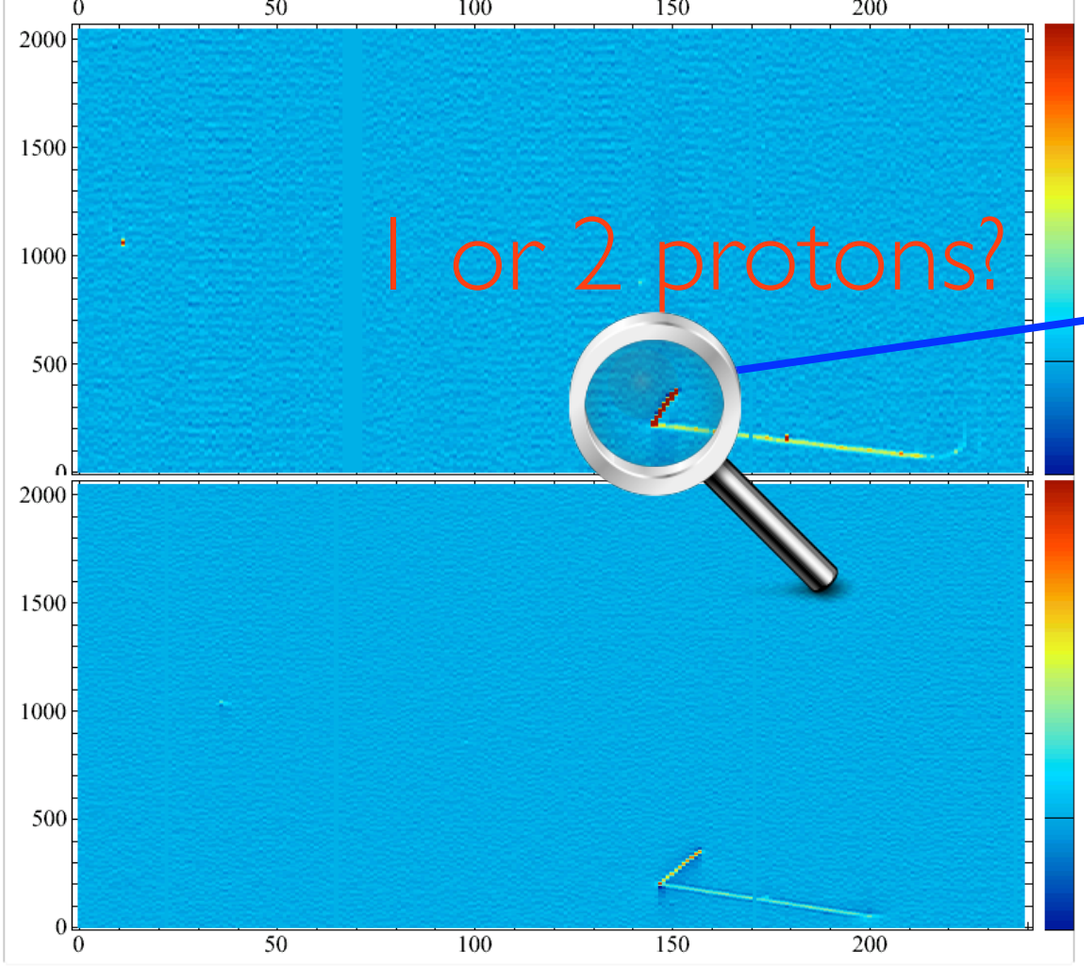
Multi-p accompanying
the leading muon
+ γ activity in the volume
around the vertex

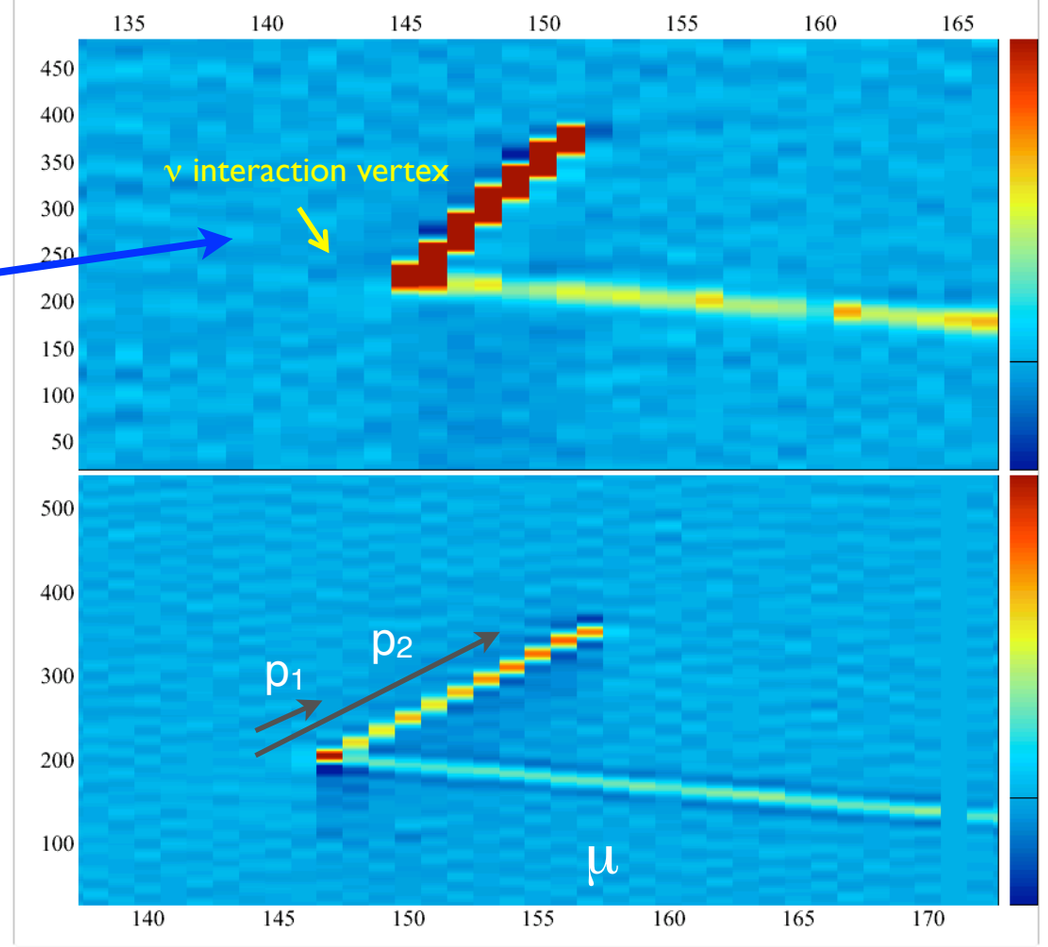


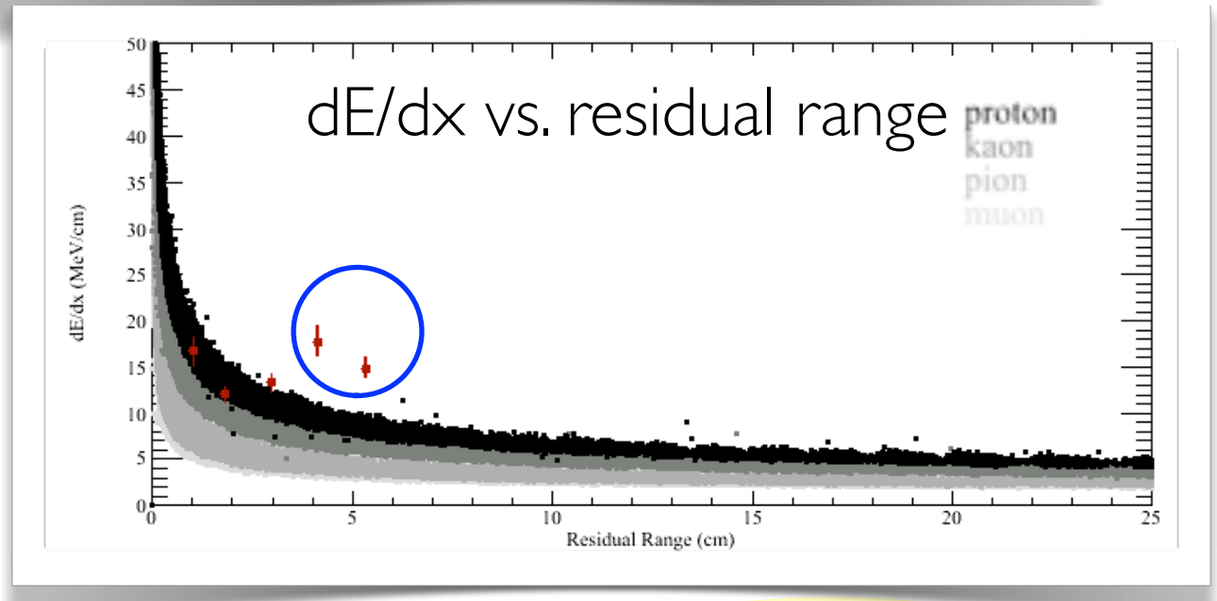


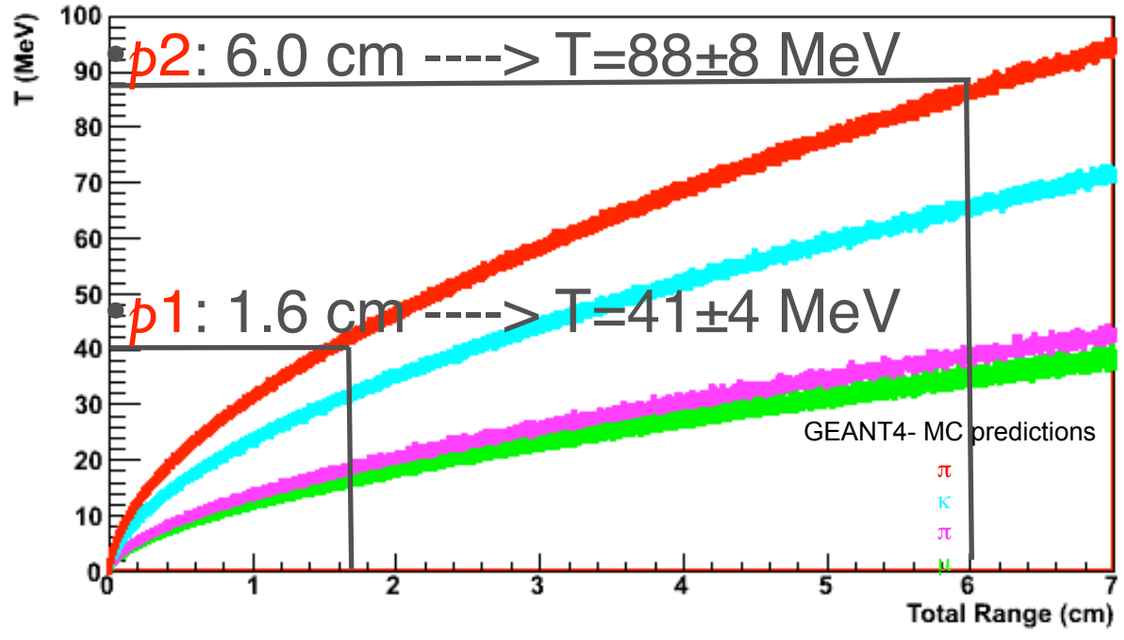
$\nu_\mu/\bar{\nu}_\mu$ CC events: $\mu^{-/+}$multi-proton

DATA: EXCLUSIVE TOPOLOGIES



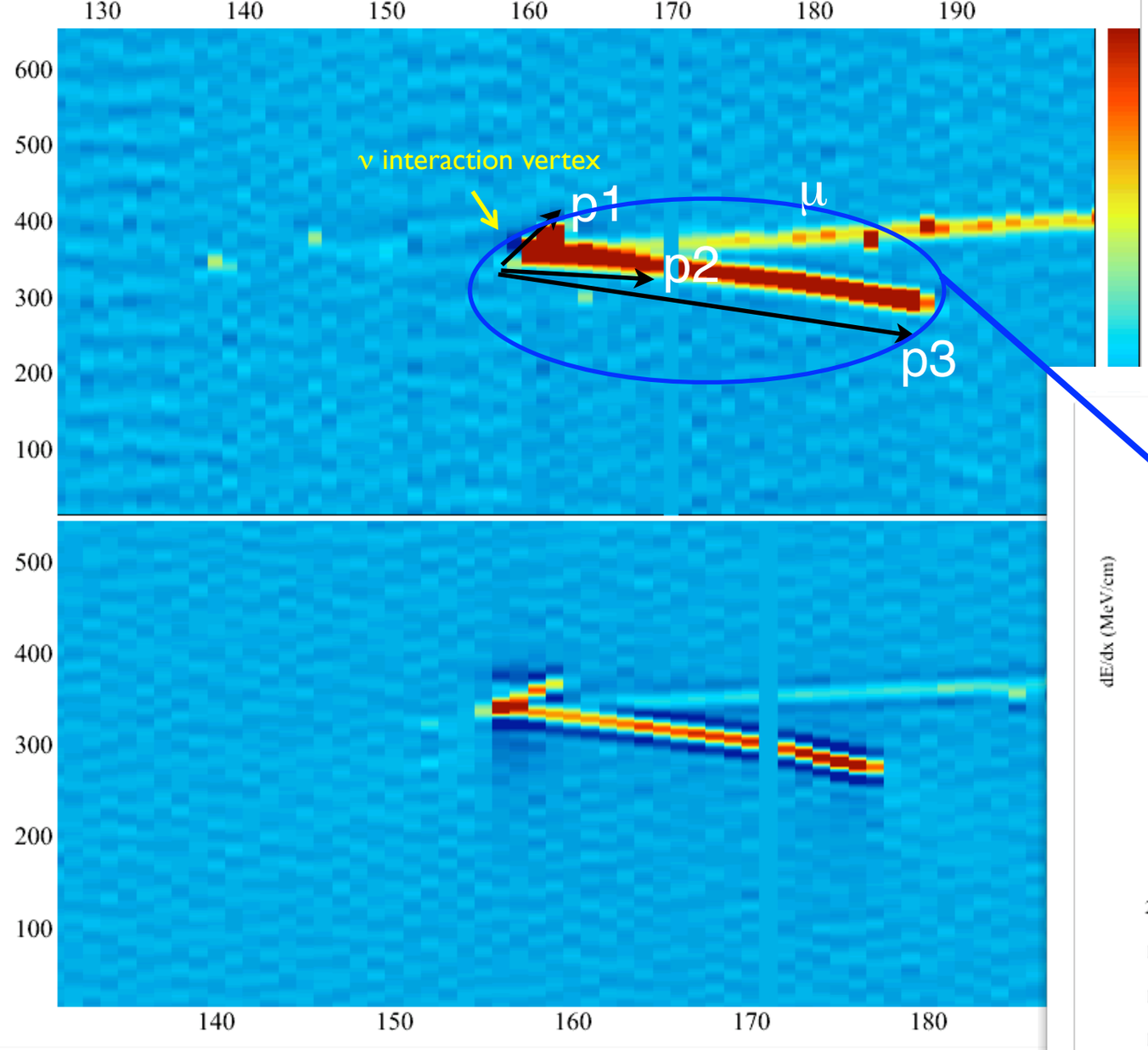


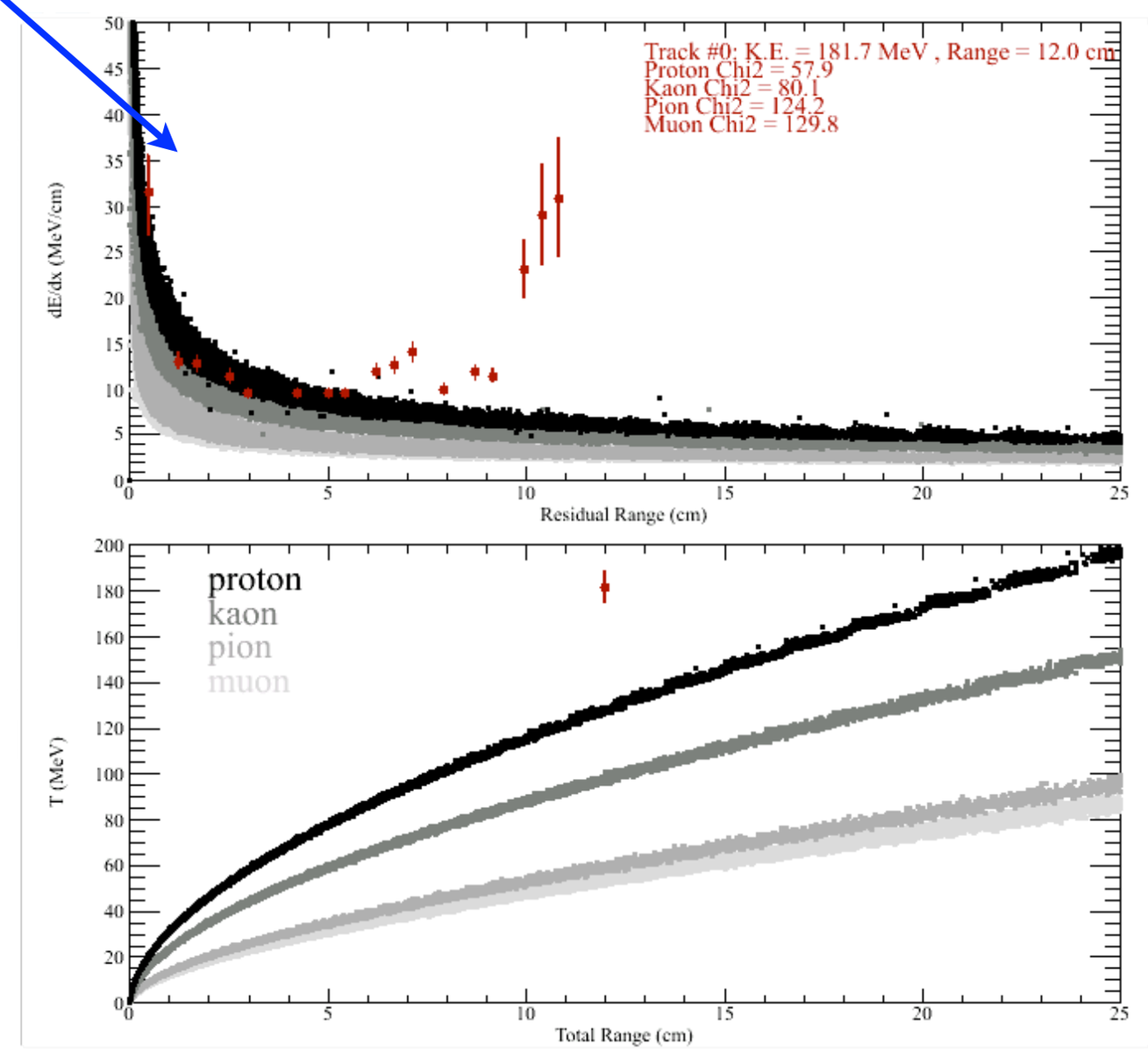




compatible with
1 μ 2p

DATA: EXCLUSIVE TOPOLOGIES





2 or 3 protons?

compatible with

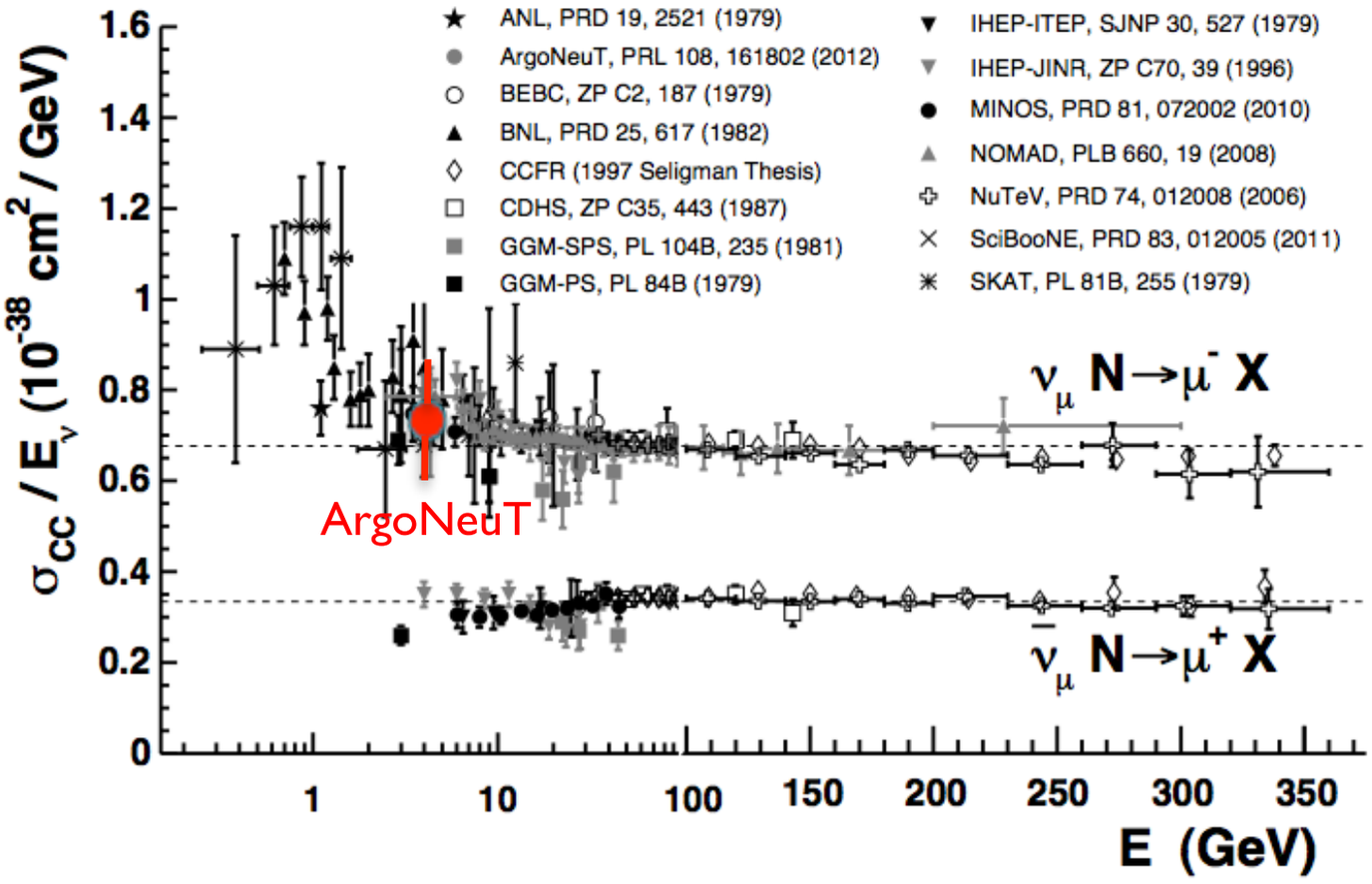
1 **μ** 3p

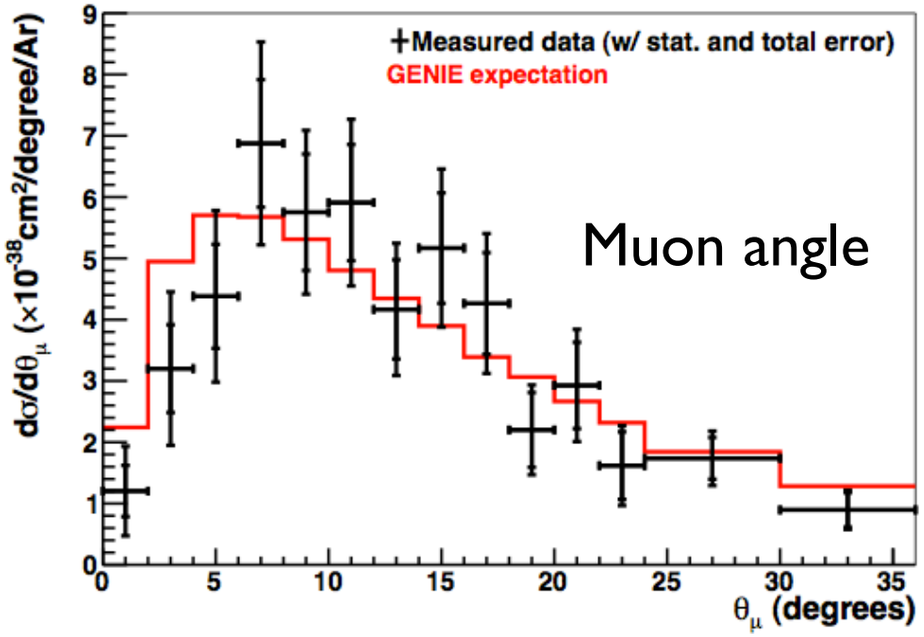
- *p1*: 1.7 cm ----> T=42±4 MeV
- *p2*: 3.6 cm ----> T=64±5 MeV
- *p3*: 11.9 cm ----> T=126±7 MeV

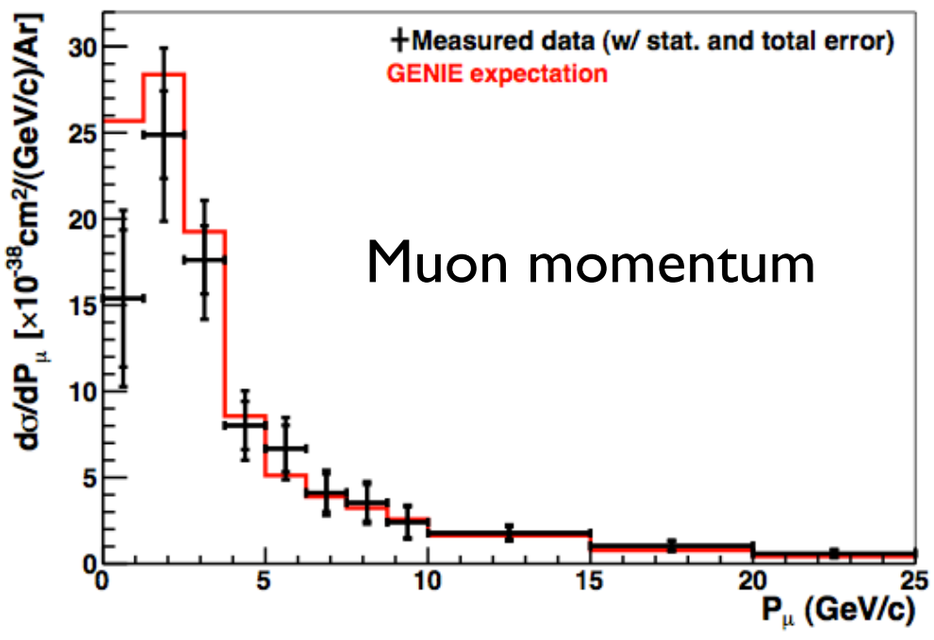
ArgoNeuT ν_μ CC inclusive

Previous results in ν mode (8.5e18 POT)

PRL 108 (2012) 161802







- Interaction vertex in fiducial volume.
- Track matched to muon in MINOS ND.
- Negatively charged muon in MINOS.

ARGONEUT DATA-MC COMPARISON

ν_μ - NuMI neutrino mode run

Lots of infos not yet processed, e. g.

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC ratio
0p+1mu	28±4	16%	15±3	14%	0.53
1p+1mu	80±7	47%	51±10	48%	0.63
2p+1mu	23±4	13.4%	28±6	26%	1.22
3p+1mu	14±3	8.3%	13±3	12%	0.93
4p+1mu	8±2	4.5%	0	0	
TOTAL (including >4p	172±10	-	107±12	-	0.62

$(0p/1p)_{DATA}=0.29$
$(0p/1p)_{GENIE\ MC}=0.35$
$(0p/1p)_{FLUKA}=0.32$

DATA-MC quite in agreement on % of total

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

$\bar{\nu}_\mu$ statistics is very low in neutrino-mode run

$(1p/0p)_{FLUKA}=0.35$

ARGONEUT DATA-MC COMPARISON (I)

$\overline{\nu}_\mu$ - anti-neutrino mode run (μ^+)

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	553±11	60%	422±42	58%	0.76
1p+1mu	160±6	17%	266±53	37%	1.66
2p+1mu	68±4	7%	30±6	4%	0.44
3p+1mu	50±3	5%	3±1	0.4%	0.06
4p+1mu	32±3	4%	3±1	0.4%	0.09
TOTAL (including >4p	925±15	-	727±68	-	0.79

Lots of infos not yet processed, e.g.

$\mu^-/\mu^+(DATA)=0.36$

$\mu^-/\mu^+(MC)=0.36$

$(1p/0p)_{DATA}=0.63$

$(1p/0p)_{MC}=0.29$

ν_μ - anti-neutrino mode run (μ^-)

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	46±3	14%	60±12	23%	1.3
1p+1mu	163±6	48%	154±31	59%	0.94
2p+1mu	46±3	13.6%	33±7	13%	0.71
3p+1mu	23±2	7%	9±2	3.5%	0.39
4p+1mu	16±2	5%	4±1	1.5%	0.25
TOTAL (including >4p	337±9	-	260±34	-	0.77

$(0p/1p)_{DATA}=0.39$

$(0p/1p)_{MC}=0.28$

0p events:

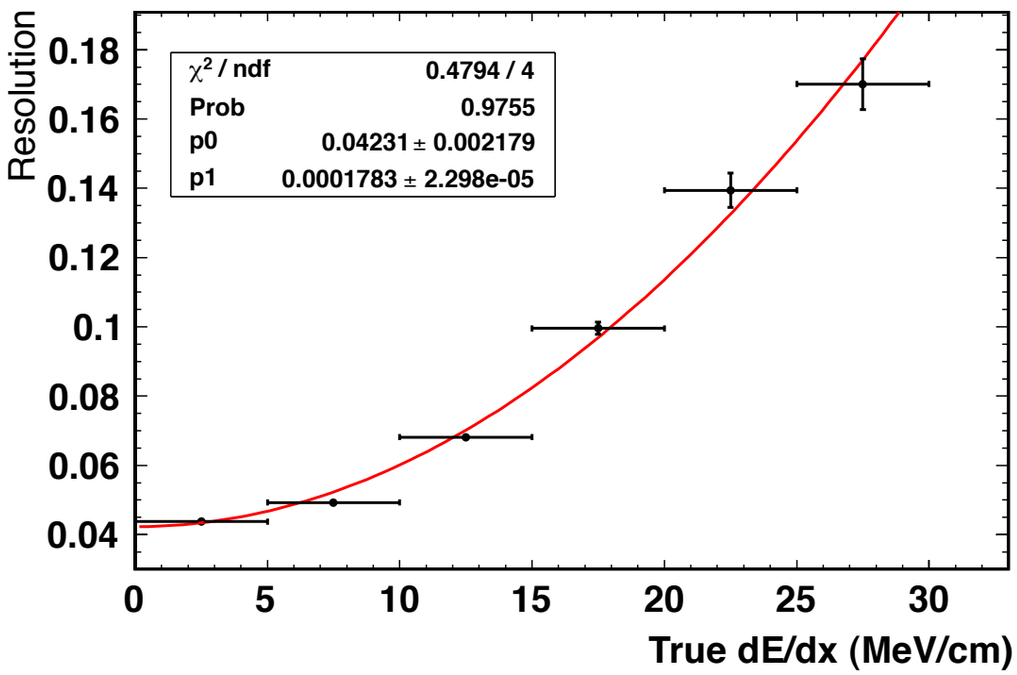
$(\mu^+/\mu^-)_{DATA}=7$

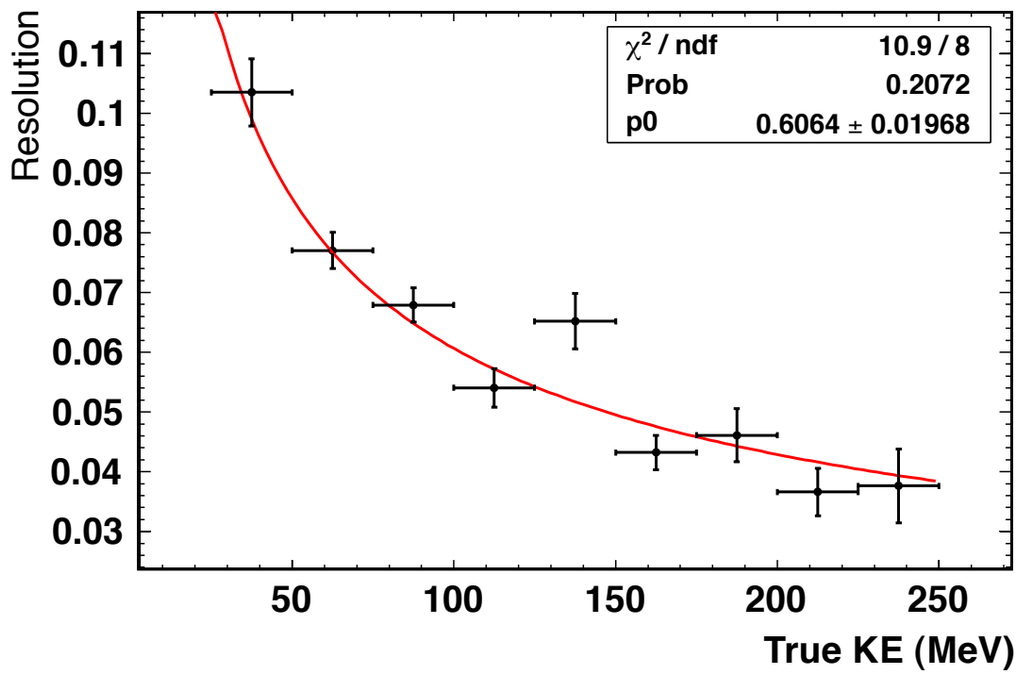
$(\mu^+/\mu^-)_{MC}=12$

- $\frac{N_{\mu^-}}{N_{\mu^+}}$ ratio

0p events

Useful for FSI studies: indication of nucleon charge exchange in Ar nuclei, less dependent (at 1st order) on multinucleon production





ArgoNeuT (4 mm wire pitch) Resolution in dE/dx and Kinetic Energy