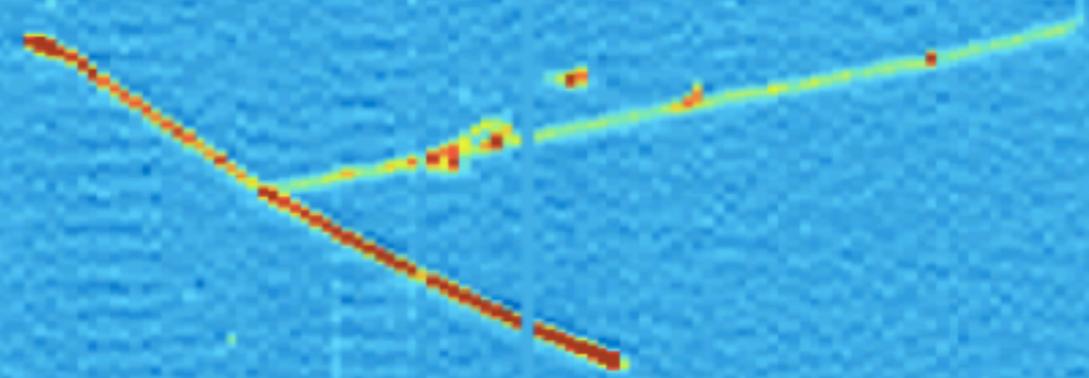


Correlations in neutrino-induced events.

"SRC mining
in neutrino land"



ArgoNeuT event

International workshop on Experimental and Theoretical topics in

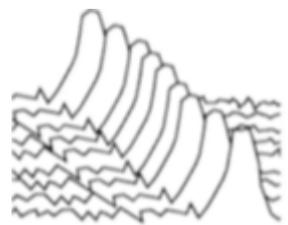
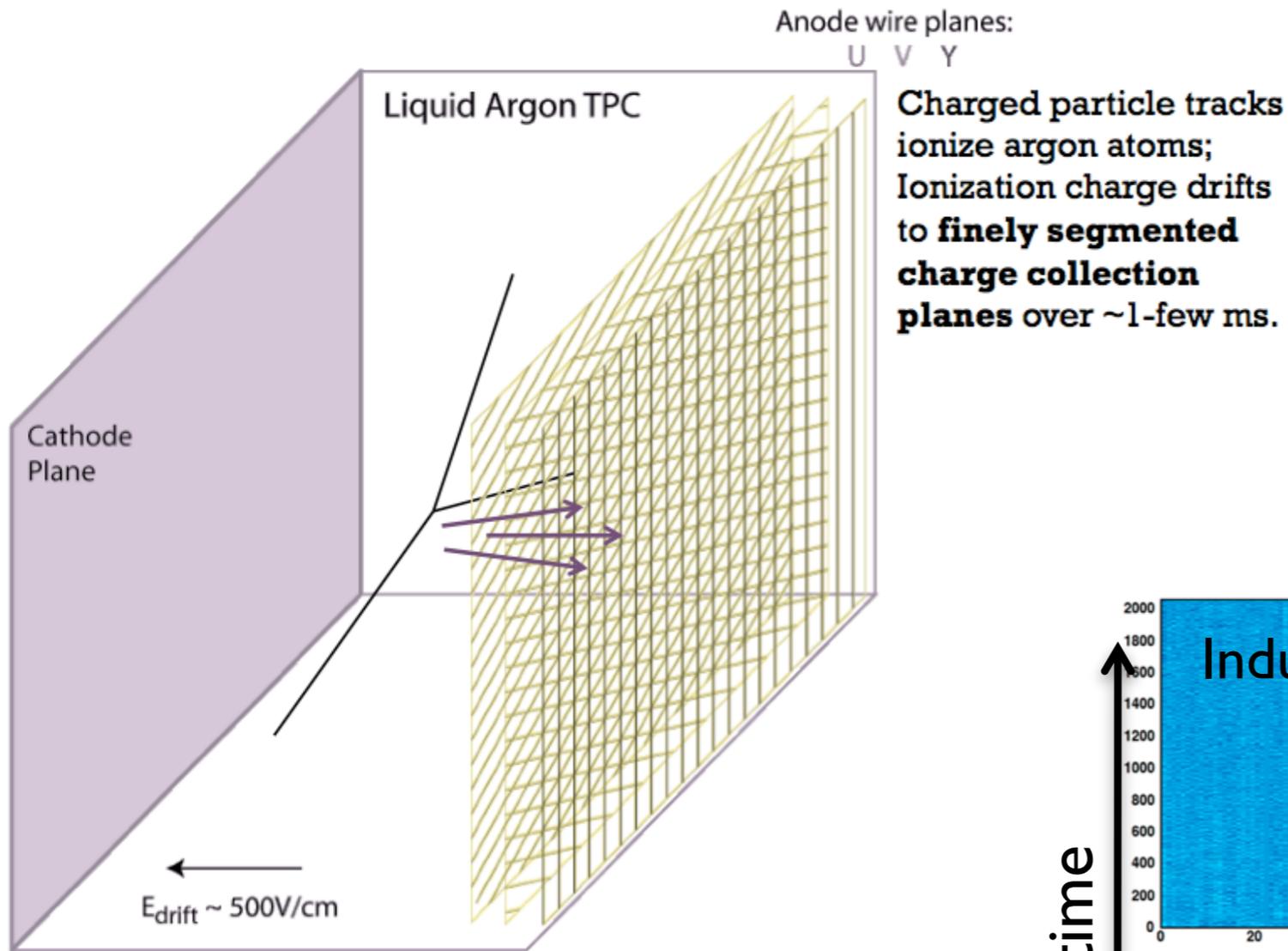
CLAS Data Mining

August 9th 2014

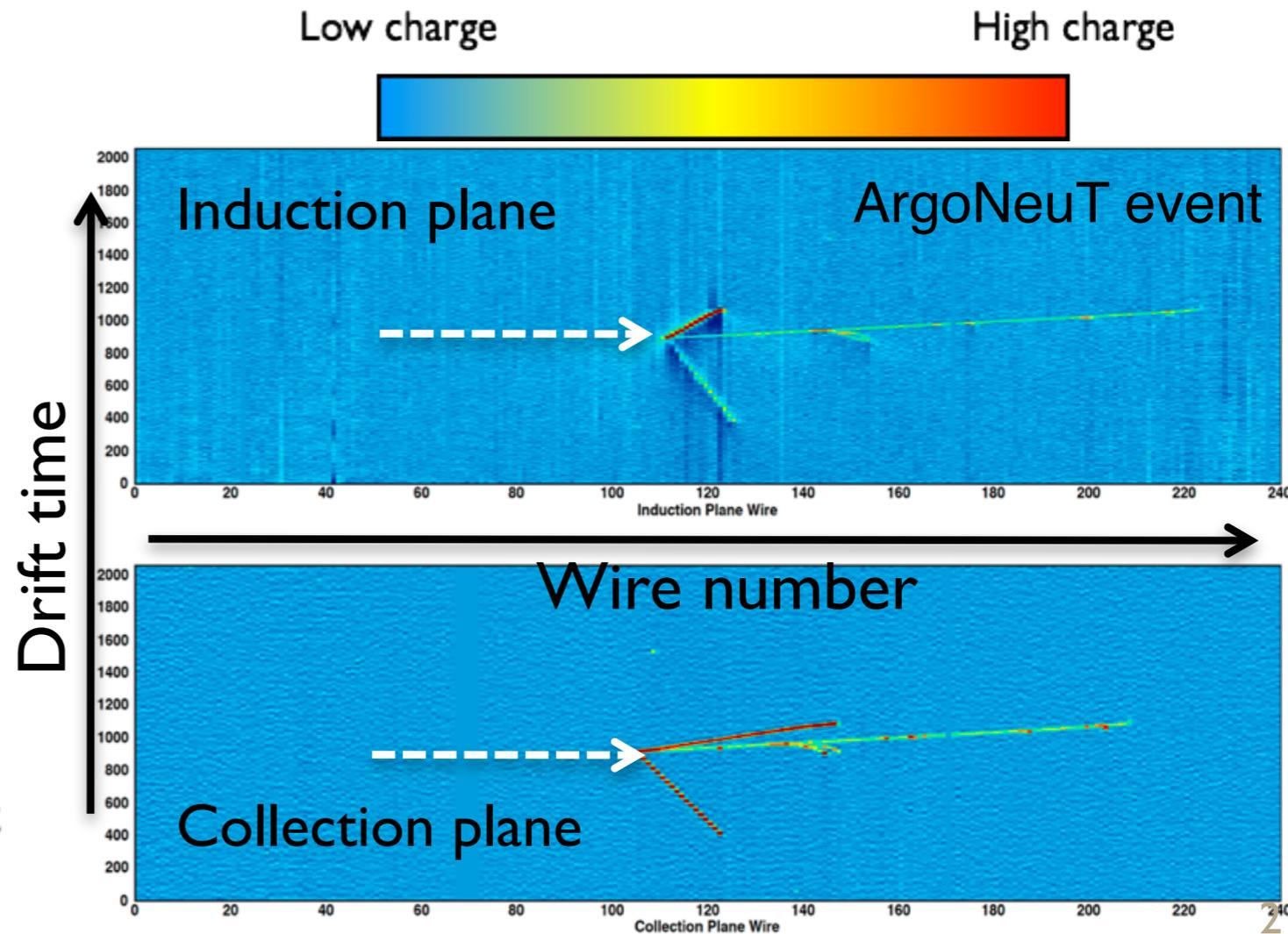
Ornella Palamara

Yale University, USA*

The Liquid Argon TPC concept



Wire pulses in time give the drift coordinate of the track

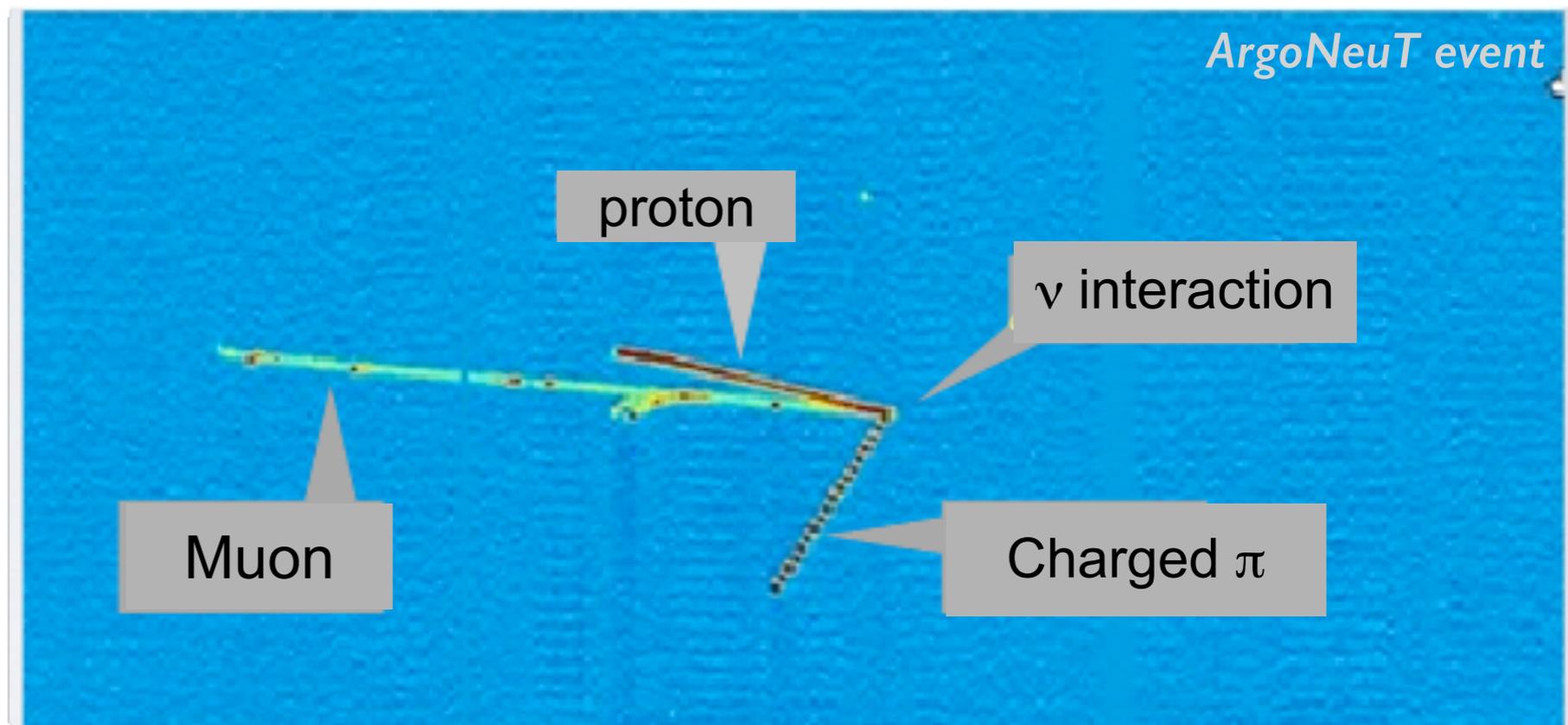
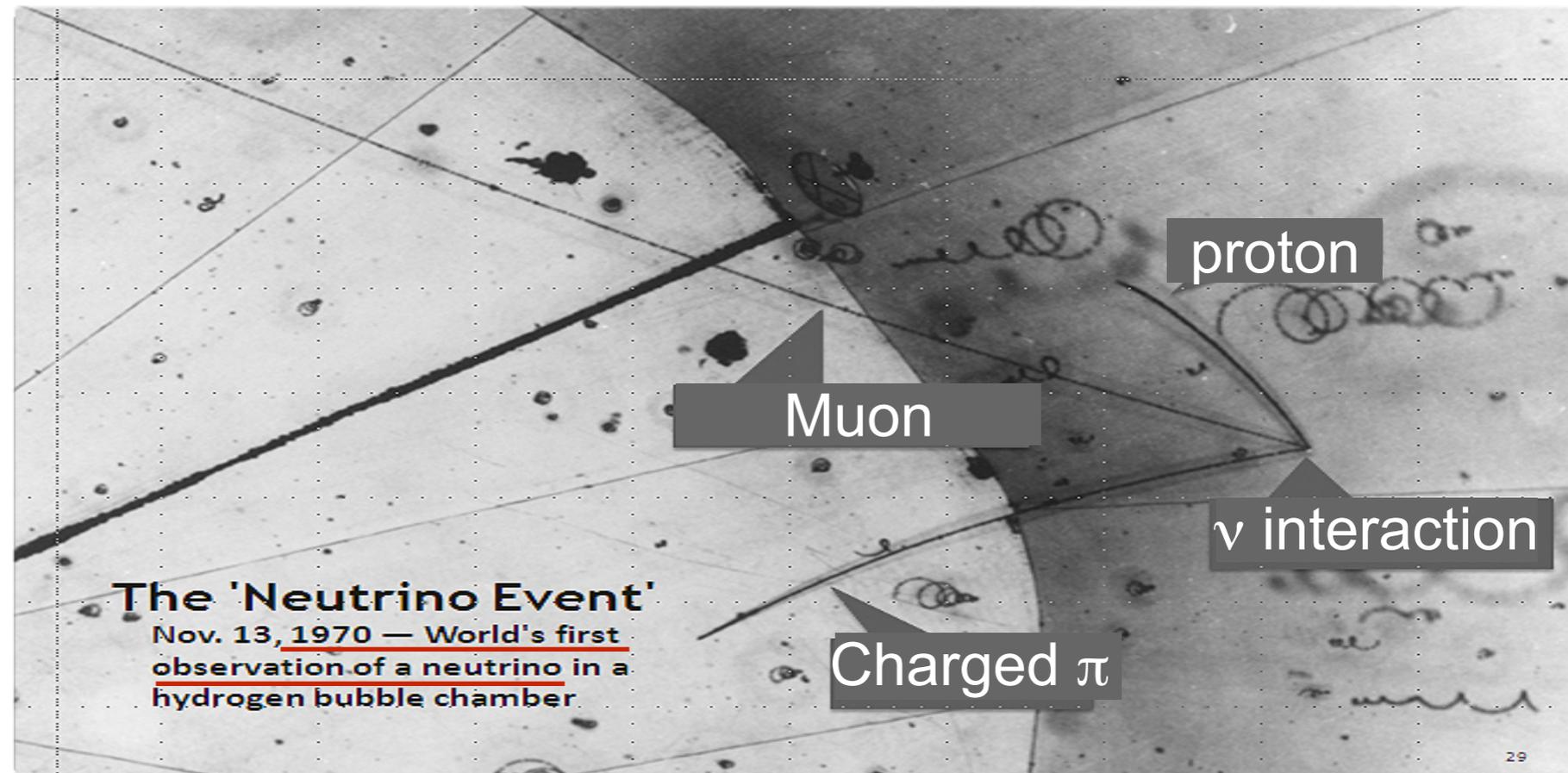


induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

Why Liquid Argon TPC?

Bubble chamber quality of data with added full calorimetry

Can produce physics results with a “table-top” size experiment



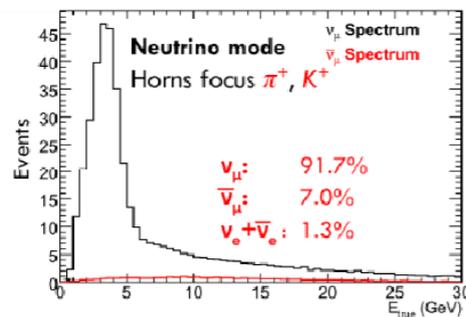
ArgoNeuT in the NuMI beam line

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

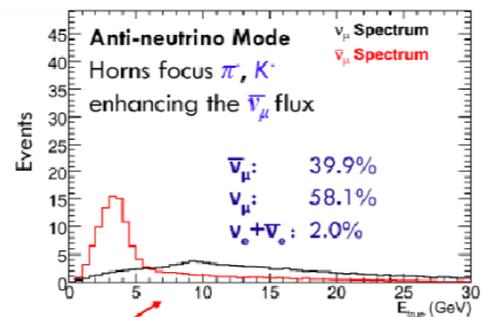
Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode

Designed as a test experiment.

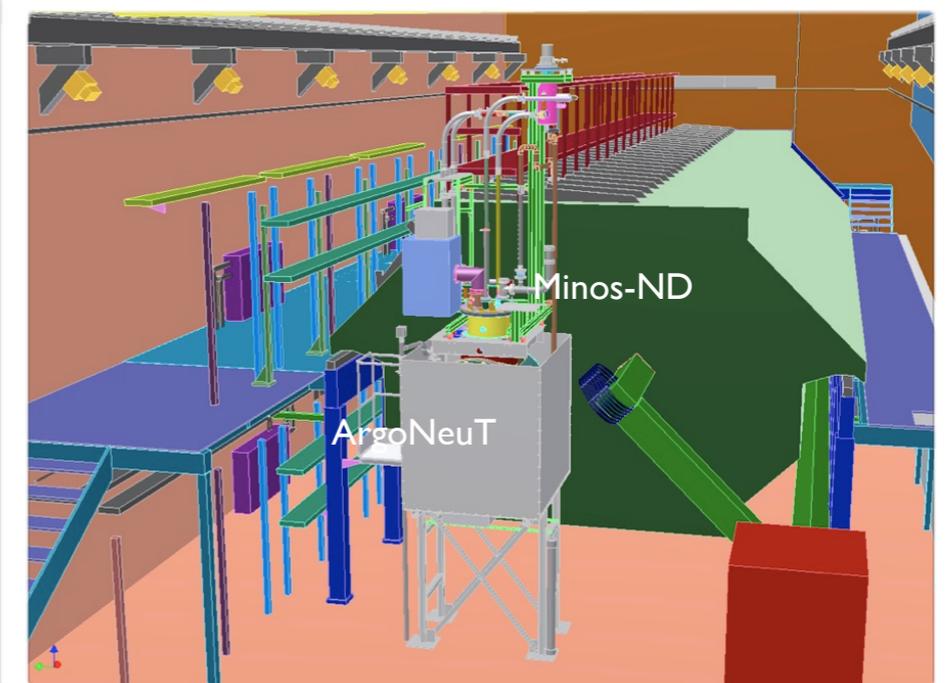
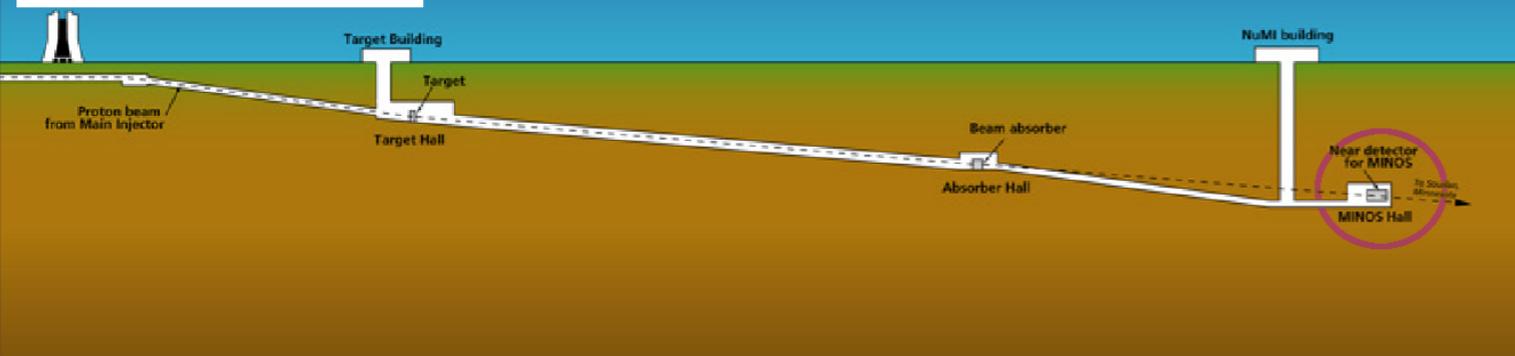
But obtaining physics results!



$\langle E \rangle = 4.3$ GeV



$\langle E \rangle = 3.6(9.6)$ GeV



ArgoNeuT in the NuMI beam line

240 Kg active volume
47×40×90 cm³, wire spacing 4 mm
LAr TPC

~7000 CC events
collected

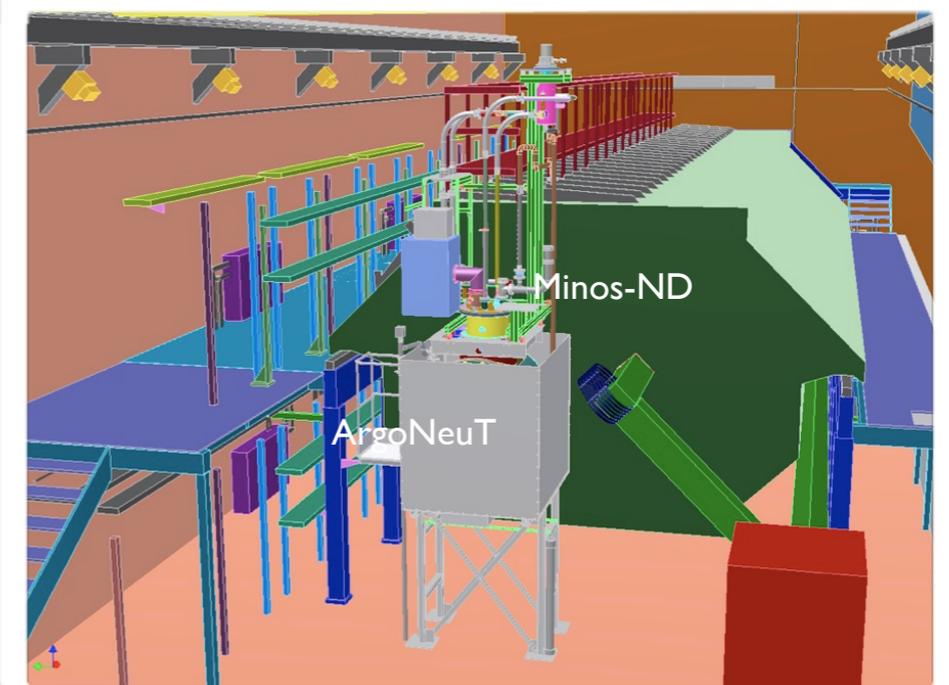
**Largest data sample of [low energy]
neutrino interactions in LArTPC**

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



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

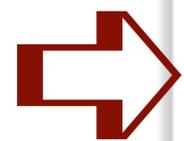
*ArgoNeuT Coll. is grateful to MINOS Coll. for providing the
muon reconstruction



The "new wave" in Neutrino Event Reconstruction

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 ($\mu + Np$, where $N=0, 1, 2, \dots$),
etc..

1 pion ($\mu + Np + 1\pi$) events,

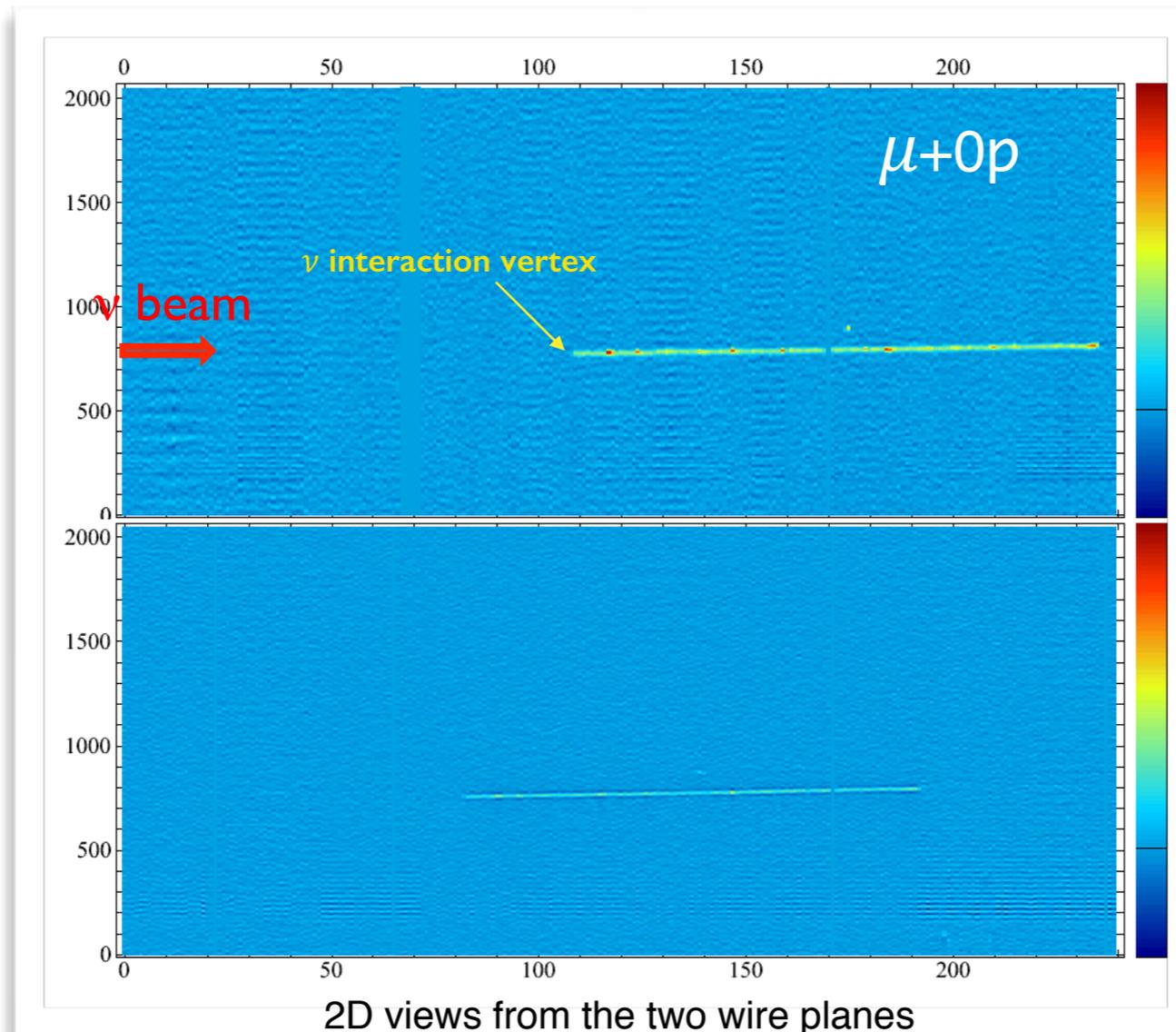
0 PION EVENT TOPOLOGY: leading muon accompanied by any number ($N=0, 1, 2, 3, 4$) of protons final state

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)

Analysis fully exploiting LAr TPC's capabilities



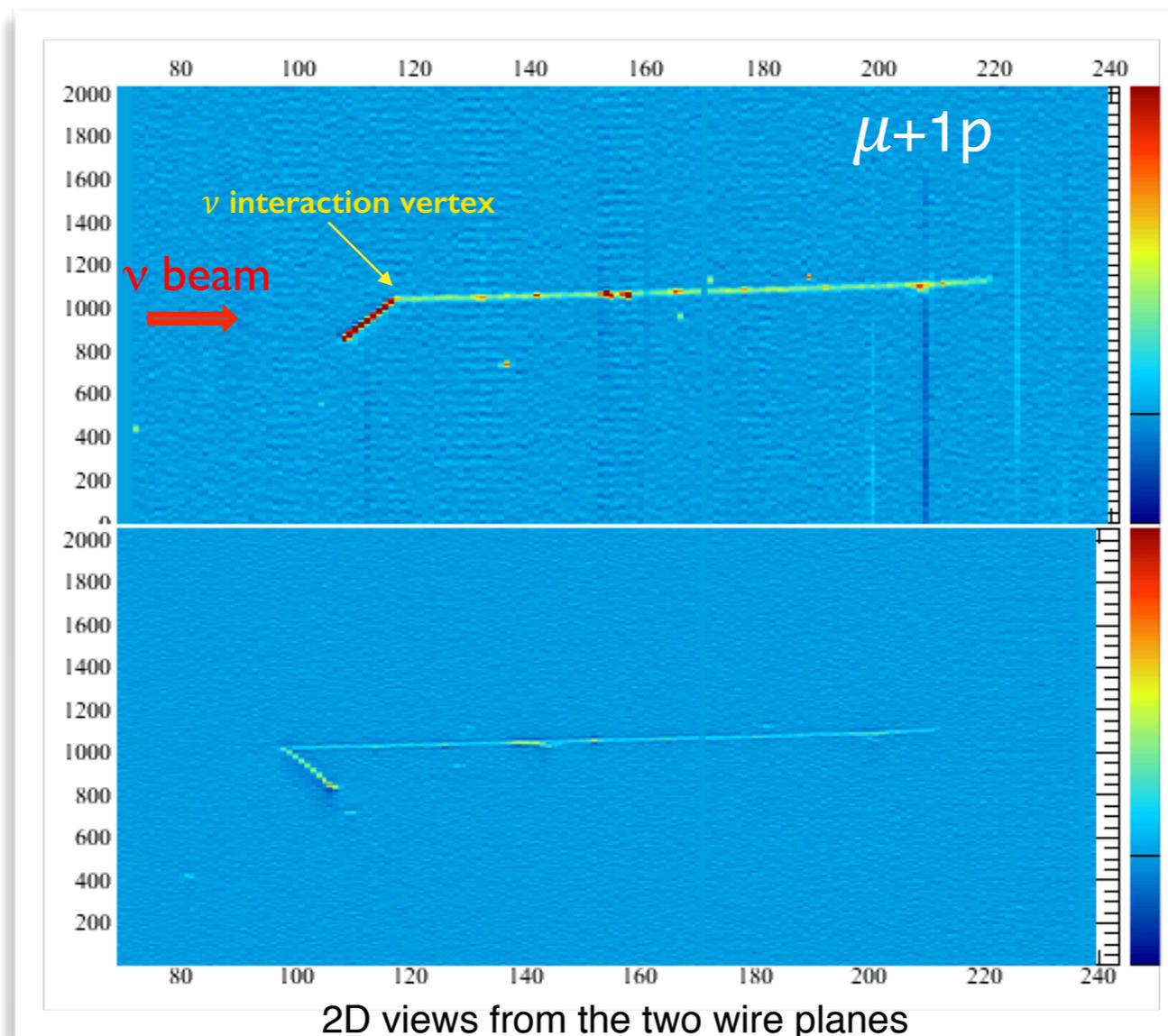
*The muon+Np sample can also contain neutrons. The presence of neutrons in the events cannot be measured, since ArgoNeuT volume is too small to have significant chances for n to convert into protons in the LAr volume before escaping.

ArgoNeuT ν_μ CC 0 pion topological analysis

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

(low proton energy threshold)

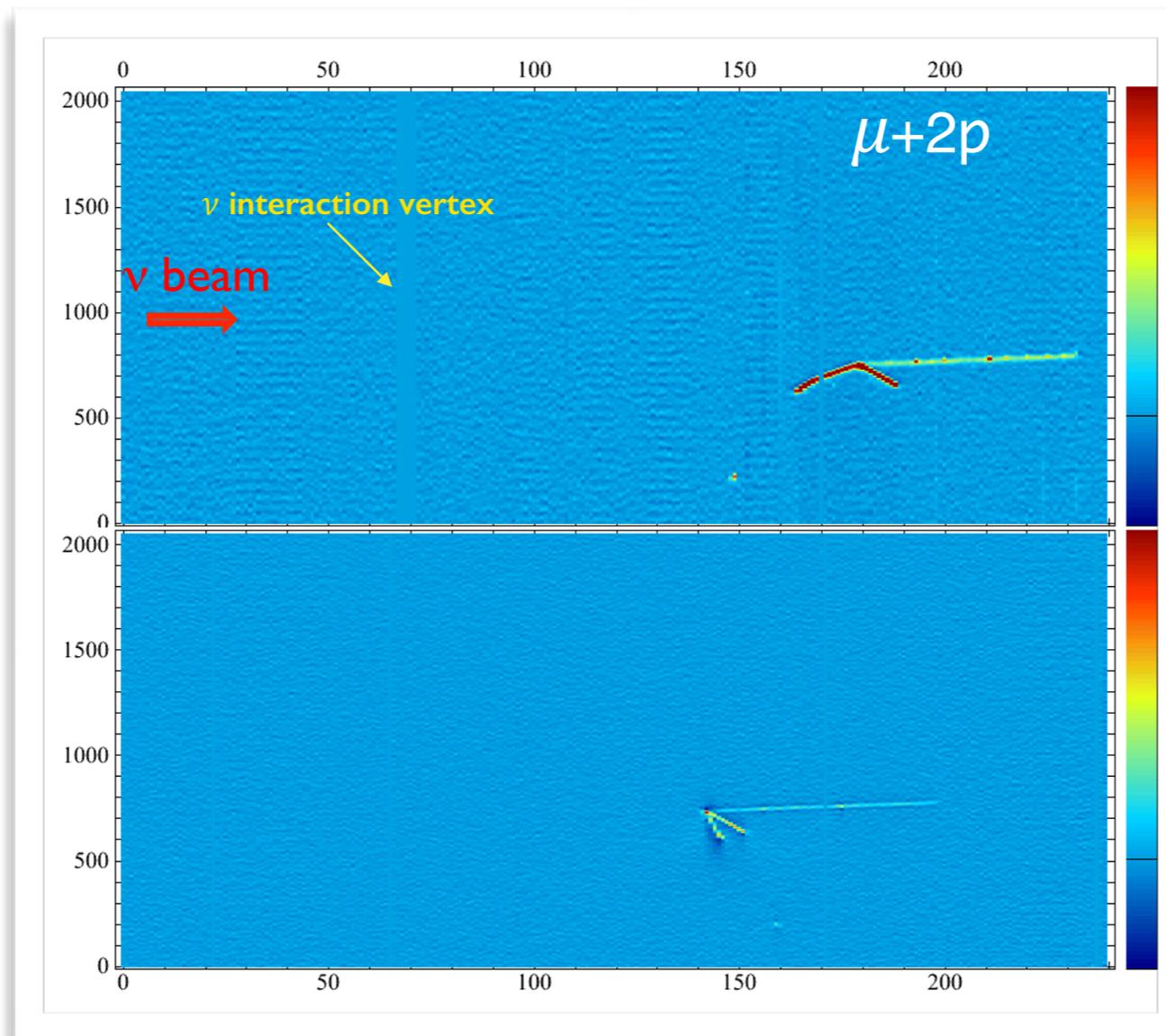
Analysis fully exploiting LAr TPC's capabilities



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*)

Analysis fully exploiting LAr TPC's capabilities

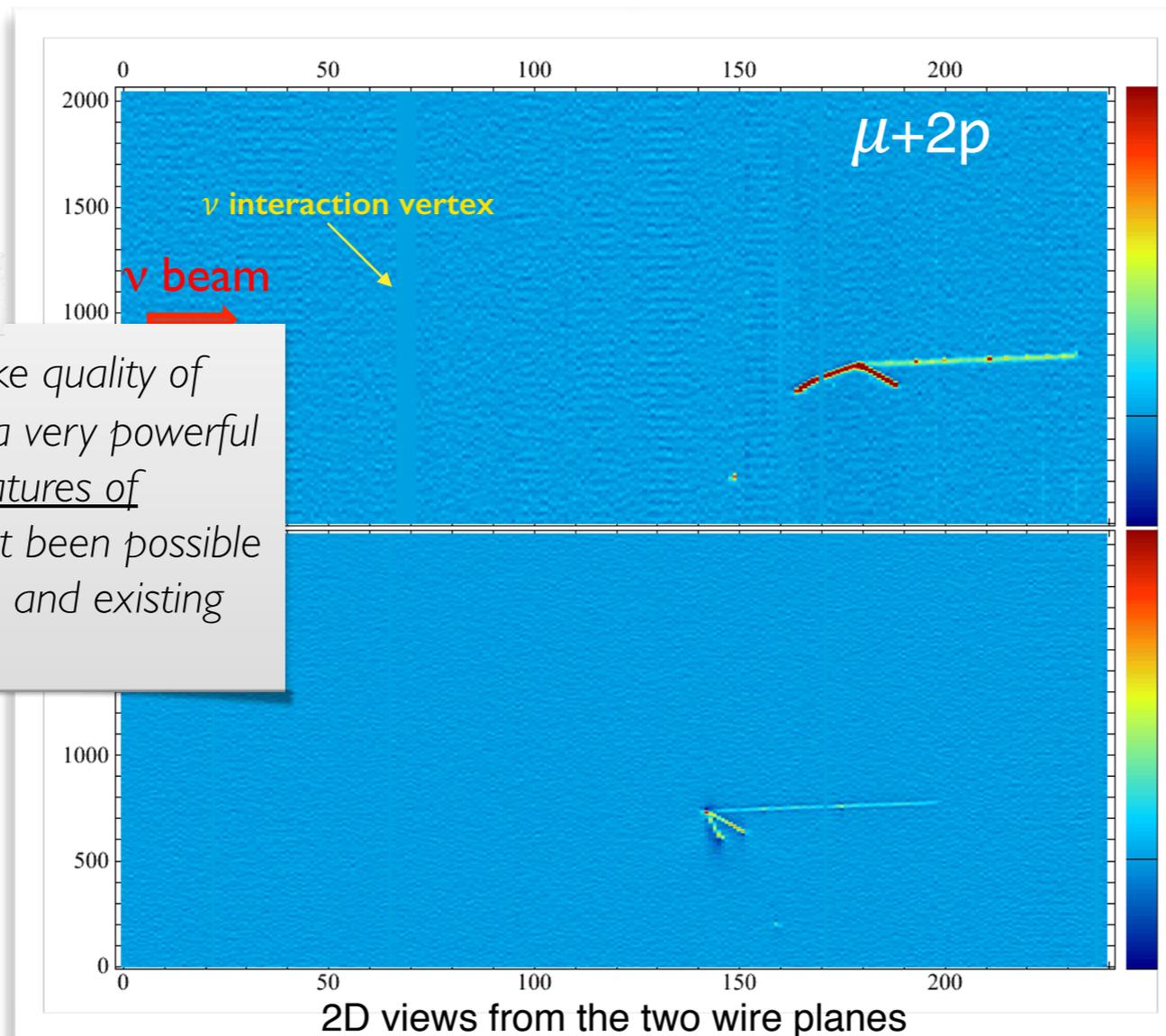


Multi-p accompanying the leading muon

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*)

Analysis fully exploiting LAr TPC's capabilities



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.

$(\nu_\mu + Np)$ events: Primary measurements

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

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



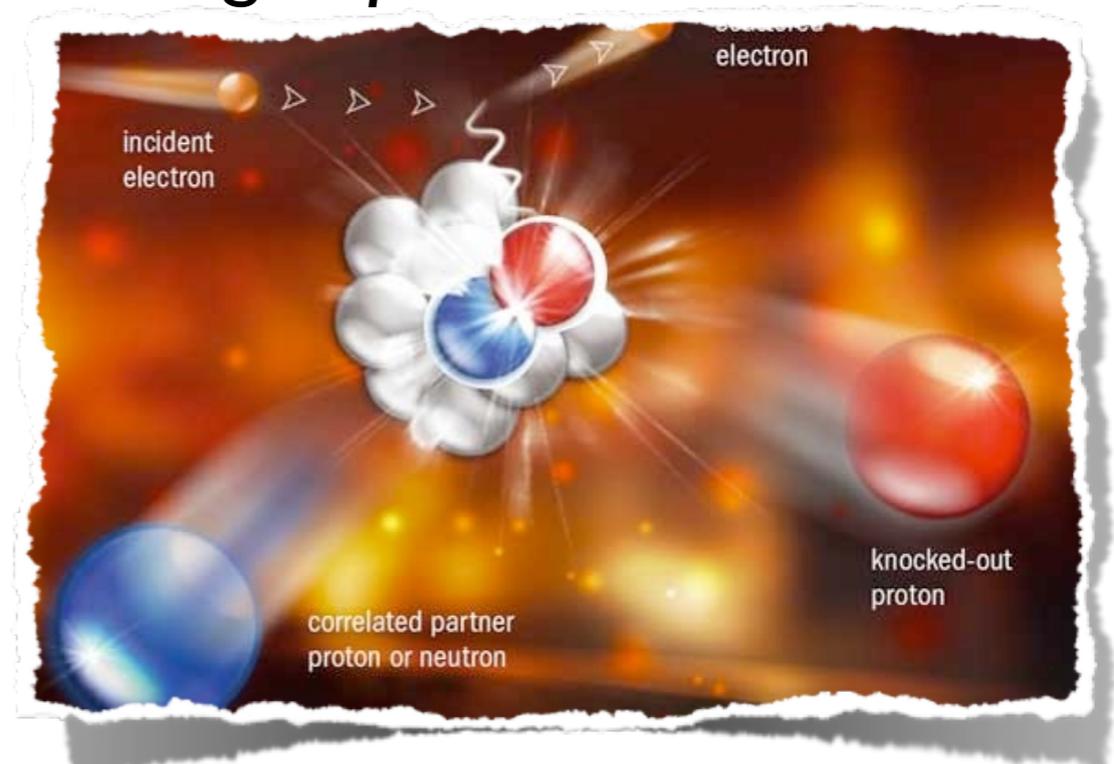
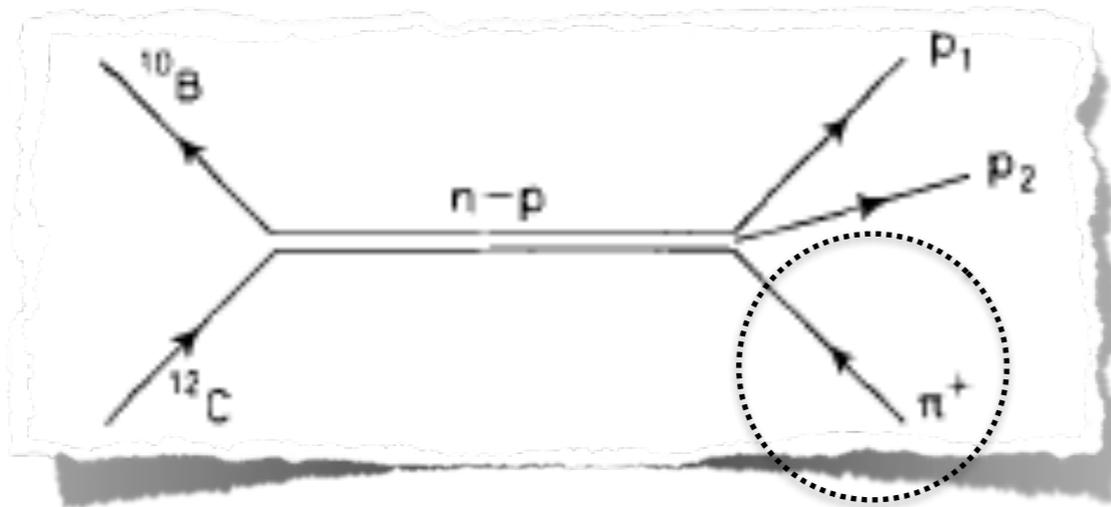
- ▶ **Muon and proton kinematics** in events with different proton multiplicity
- ▶ Most precise **reconstruction of the incoming neutrino energy** from **lepton AND proton reconstructed kinematics**

TODAY:

- ✓ Features of neutrino interactions and associated **Nuclear Effects** from identification/reconstruction of specific classes of neutrino events

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

(μ^-+2p) data sample

Data sample: N=2 protons in final state, i.e. (μ^-+2p) triple coincidence

topology events

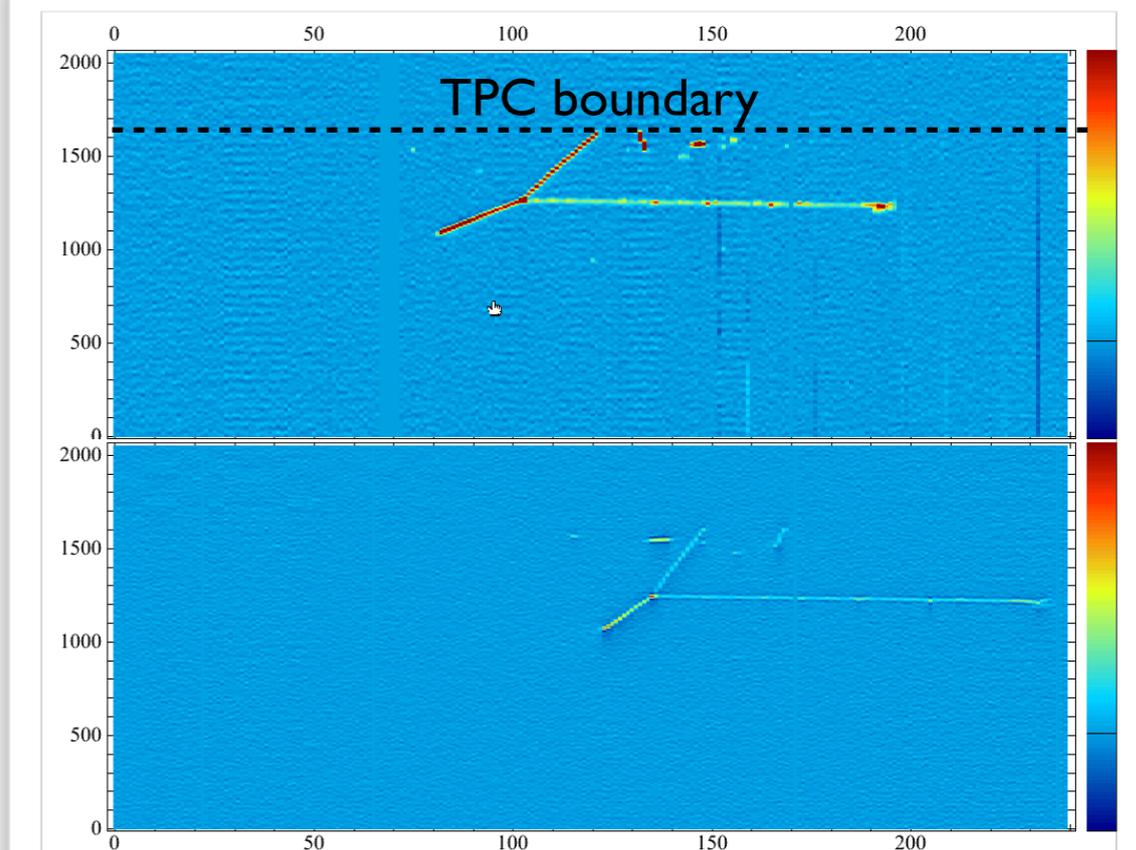
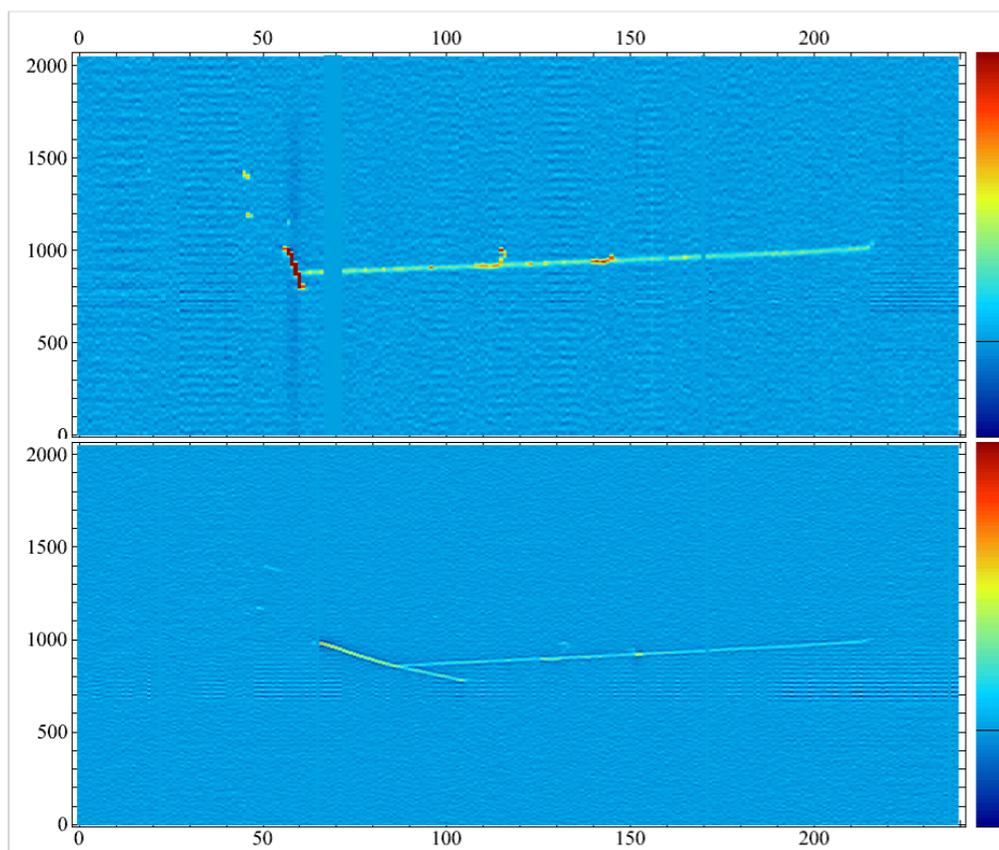
30 (19 collected in the anti-neutrino mode run and 11 in the neutrino mode run)

fully reconstructed events, where

the leading muon is accompanied by a pair of protons at the interaction vertex

Both proton tracks are required to be fully contained inside the fiducial volume (FV) of the TPC and above energy threshold.

From detector simulation, acceptance for the (μ^-+2p) sample is estimated to be around 35% (dominated by the containment requirement in FV).



$(\mu^- + 2p)$ data sample

- ▶ Fully reconstructed events. Measured quantities*:
 - ▶ the 3-momentum of the muon, determined from the matched track in ArgoNeuT and MINOS-ND,
 - ▶ the sign of the muon provided by MINOS-ND, and
 - ▶ the energy and direction of propagation of the two protons measured by ArgoNeuT.
- ▶ Event ratios:
 $(\mu^- + 2p)/(\mu^- + Np) = 21\%$ (26%) and
 $(\mu^- + 2p)/CC\text{-inclusive} \sim 2\%$ ($\sim 4\%$)
for the anti-neutrino-mode run (neutrino-mode) [efficiency corrected]
- ▶ According to GENIE MC simulation: $\sim 40\%$ of $(\mu^- + 2p)$ are due to CC QE interactions and about $\sim 40\%$ to CC RES pionless interactions.

* *muon momentum resolution 5-10% from MINOS-ND*
proton angular resolution: 1-1.5°, depending on track length
proton energy resolution: $\sim 6\%$ for protons above Fermi momentum

$(\mu^- + 2p)$ data sample - Hints for NN SRC

The specific final state topology which we have focused on is a pair of energetic protons at the interaction vertex accompanying the leading muon.

This topology may provide hints for NN SRC in the target nucleus **when the protons of the pair appear with high-momentum** (exceeding the Fermi momentum) and **in strong angular correlation**.

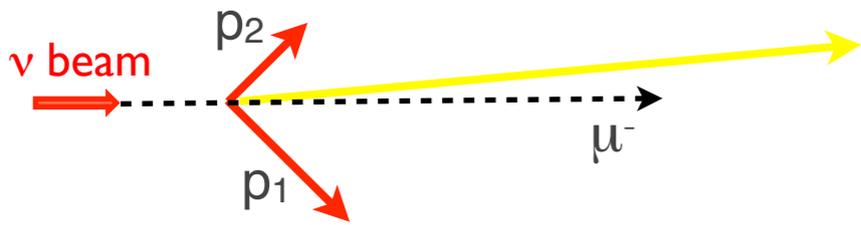
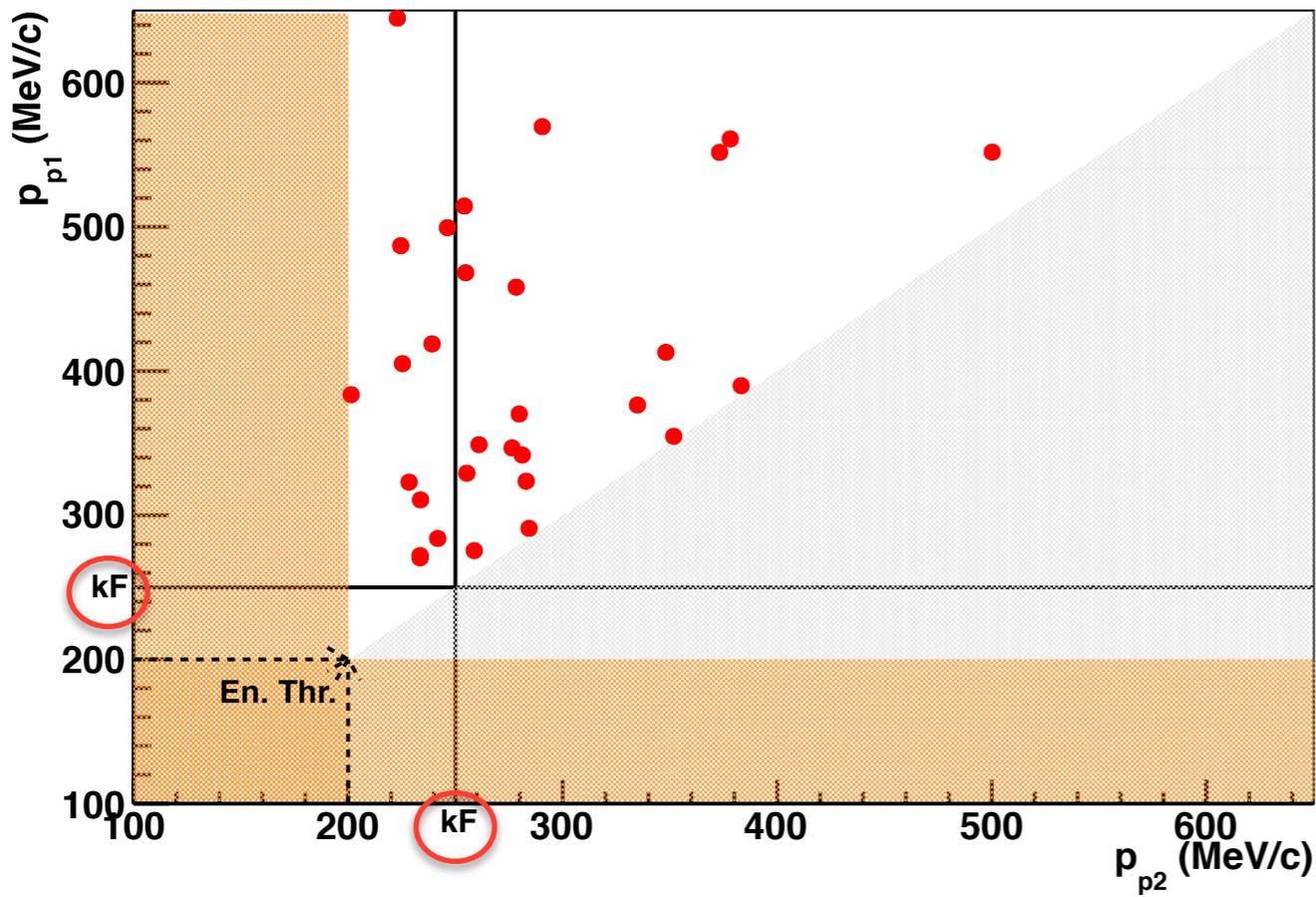
In particular, in analogy with findings from electron- and hadron-scattering experiments,

- a CCQE interaction on a neutron in a SRC pair is expected to produce back-to-back protons in the CM frame of the interaction,
- whereas a CC pionless RES reactions involving a SRC pair may produce back-to-back protons in the Lab frame

$(\mu^- + 2p)$ data sample

Momentum of the more energetic proton \mathbf{p}_{p1} in the pair vs. momentum of the other (less energetic) proton \mathbf{p}_{p2}

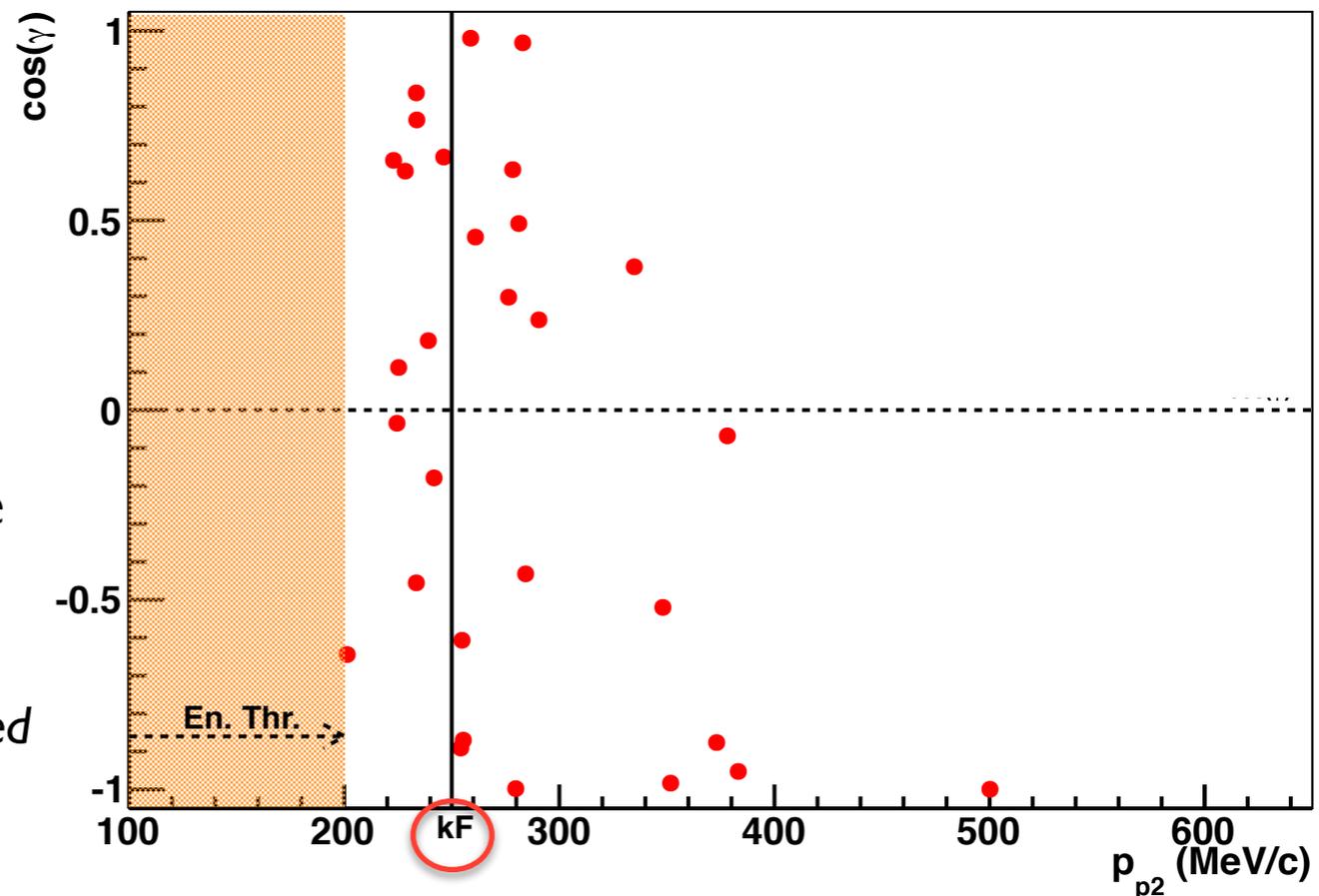
Most of the events (19 out of 30) have both protons above Fermi momentum of the Ar nucleus ($k_F \approx 250$ MeV)



$\cos(\gamma)$ vs momentum of the least energetic proton \mathbf{p}_{p2} in the pair for the 19 events with $\mathbf{p}_{p1}, \mathbf{p}_{p2} \geq k_F$

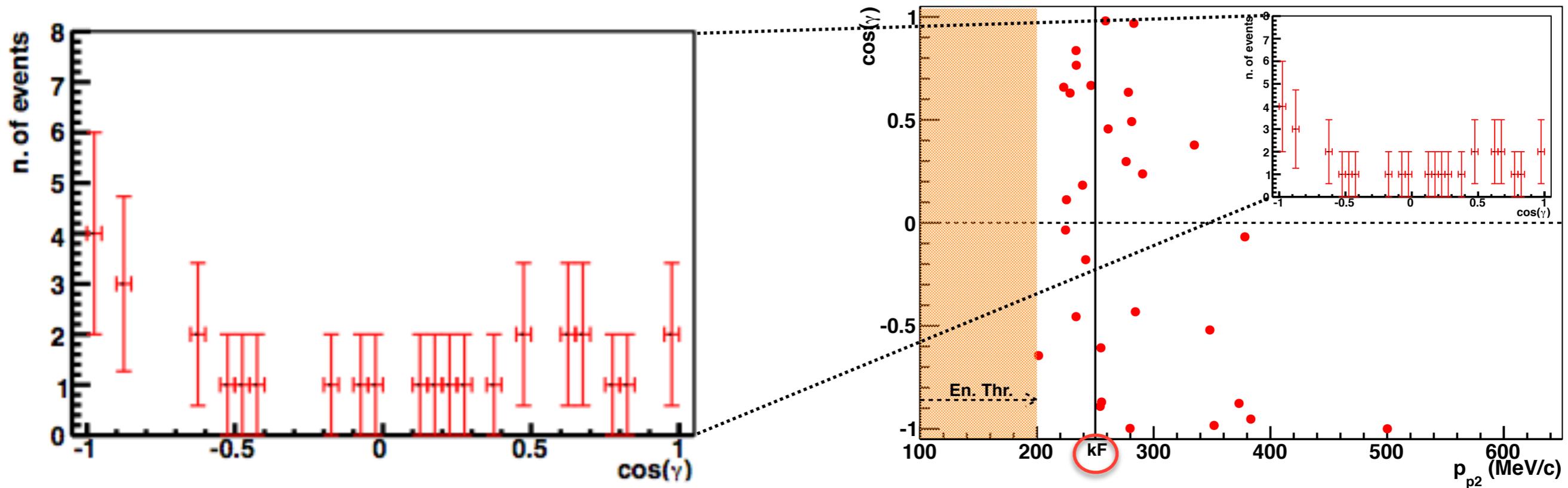


γ = angle in space between the two detected proton tracks in the Lab reference frame



$(\mu^- + 2p)$ data sample - back-to-back protons in the Lab

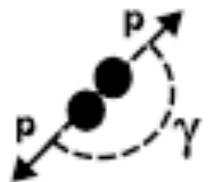
$\cos(\gamma)$ vs momentum of the least energetic proton p_{p2} in the pair



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

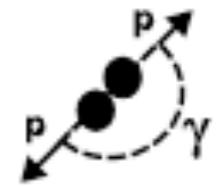
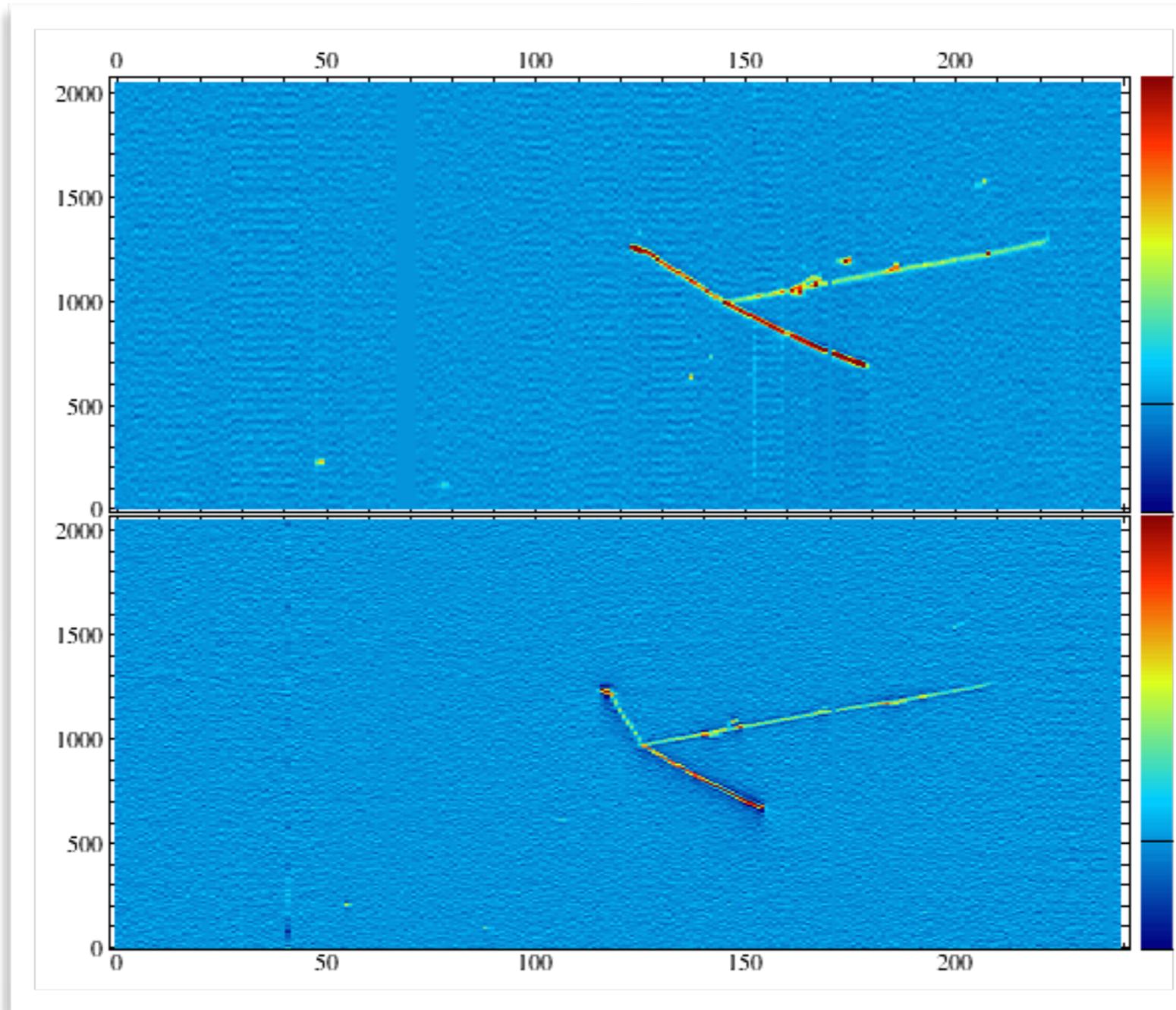
In all four events one proton is almost exactly balanced by the other

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



$(\mu^- + 2p)$ data sample - 4 “Hammer Events”

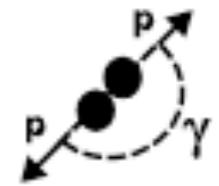
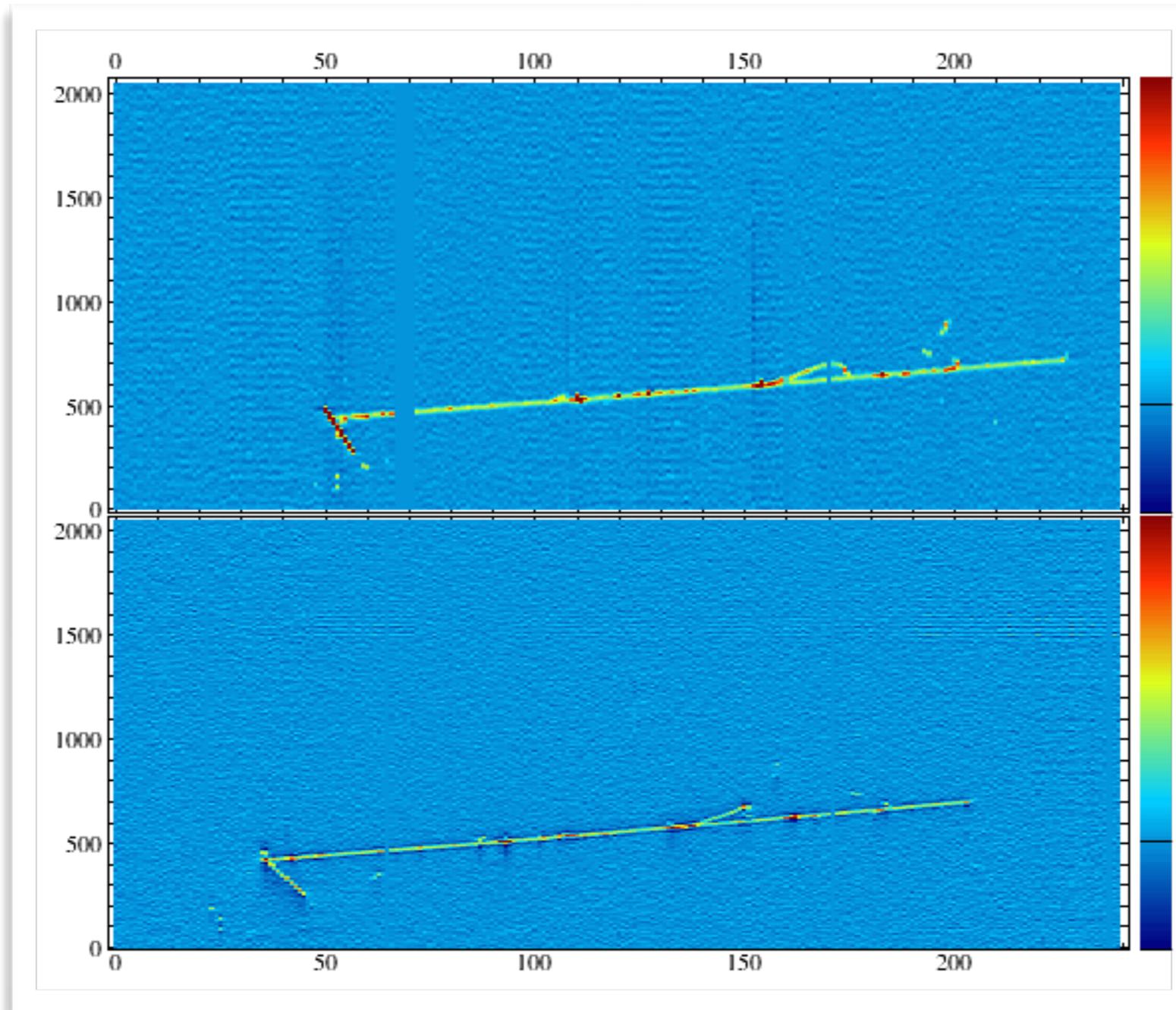
Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.



$$\cos(\gamma) < -0.95$$

$(\mu^- + 2p)$ data sample - 4 “Hammer Events”

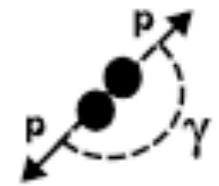
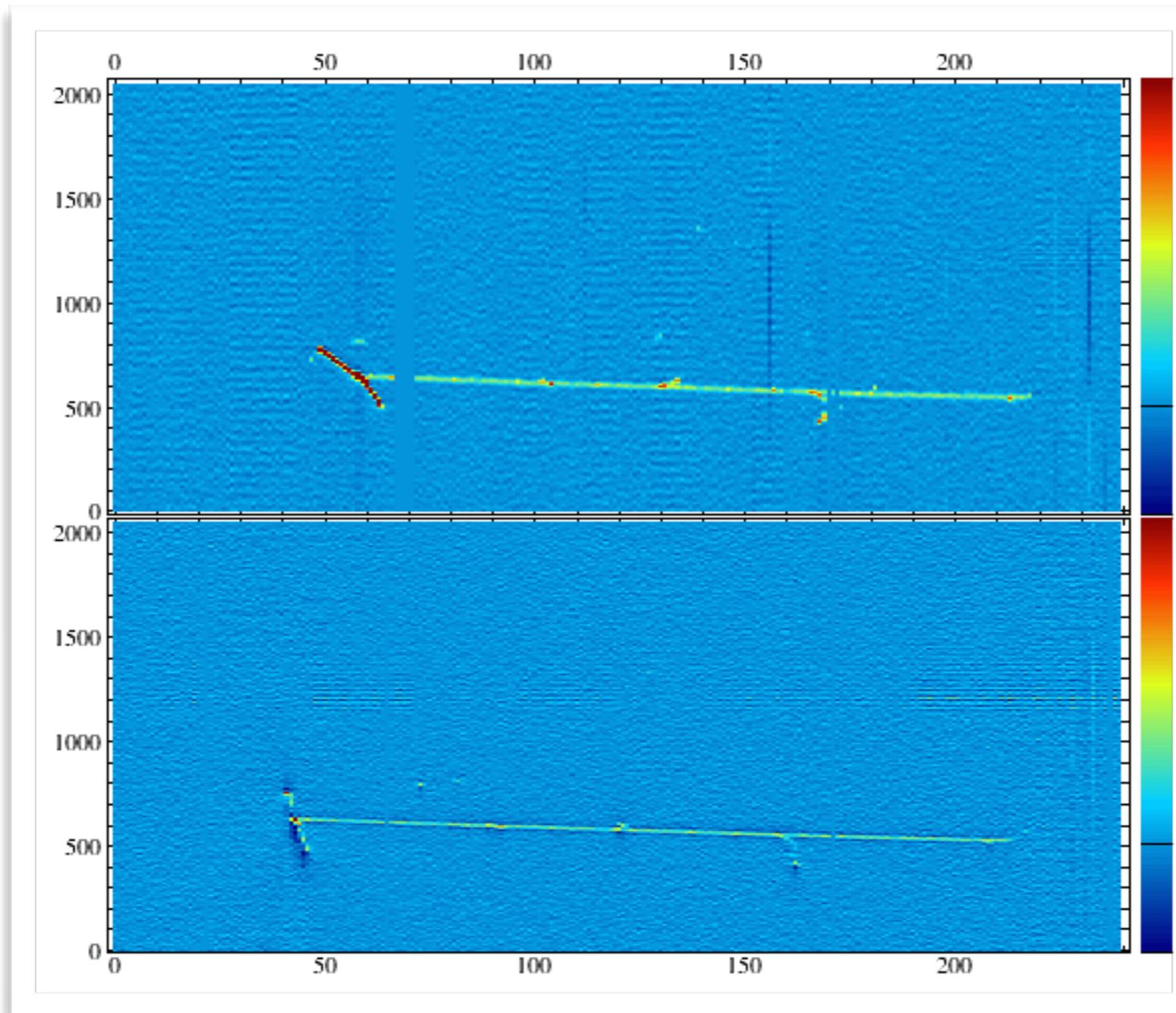
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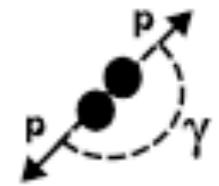
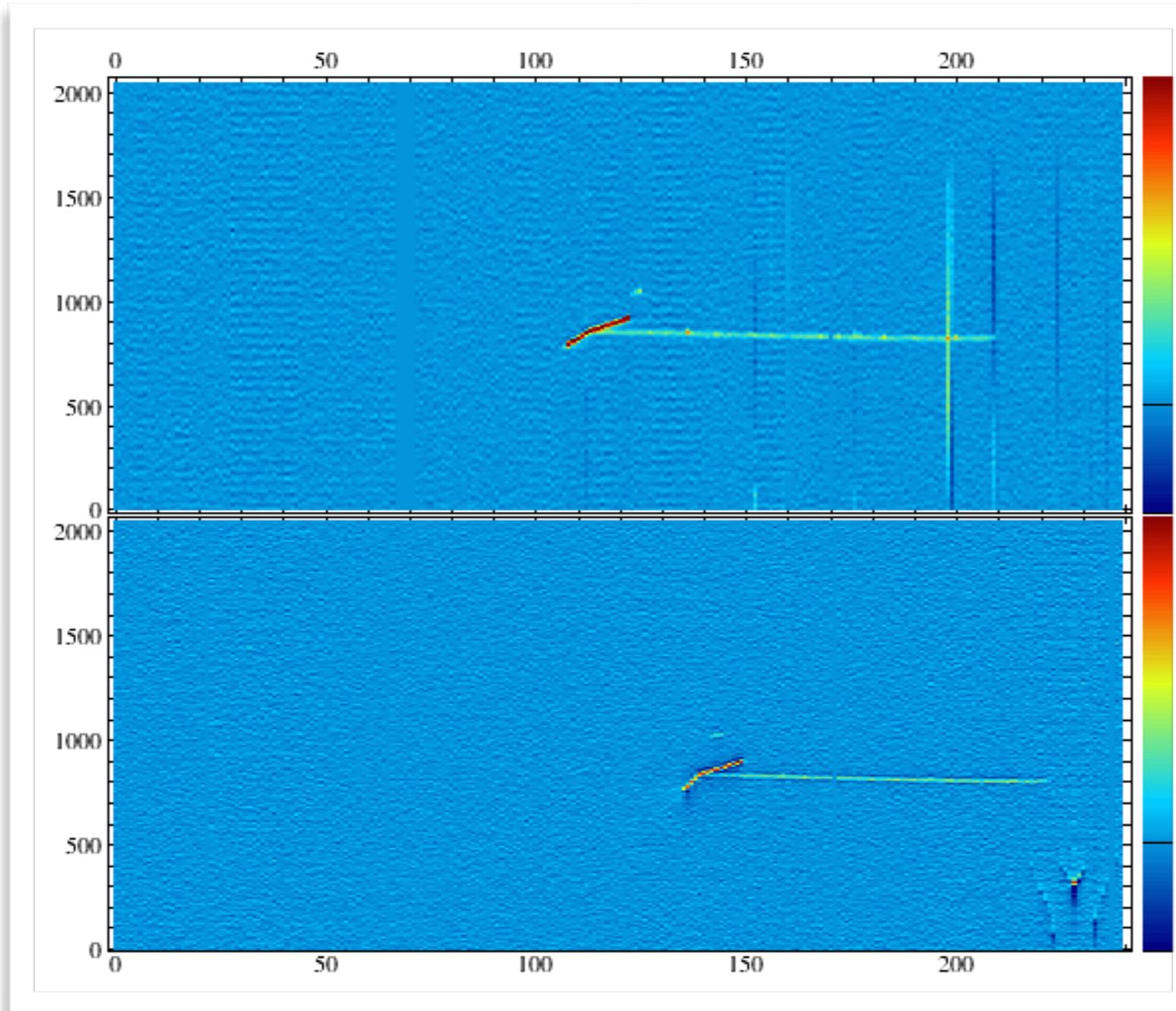
Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.



$$\cos(\gamma) < -0.95$$

$(\mu^- + 2p)$ data sample - 4 “Hammer Events”

Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.



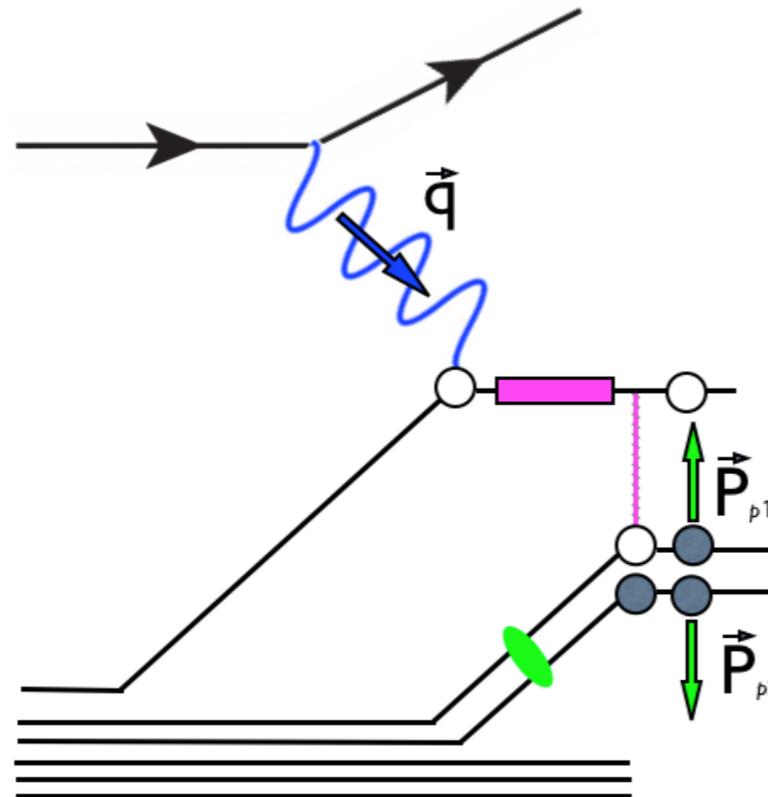
$$\cos(\gamma) < -0.95$$

2-p knock-out CC reactions involving SRC pairs(I)

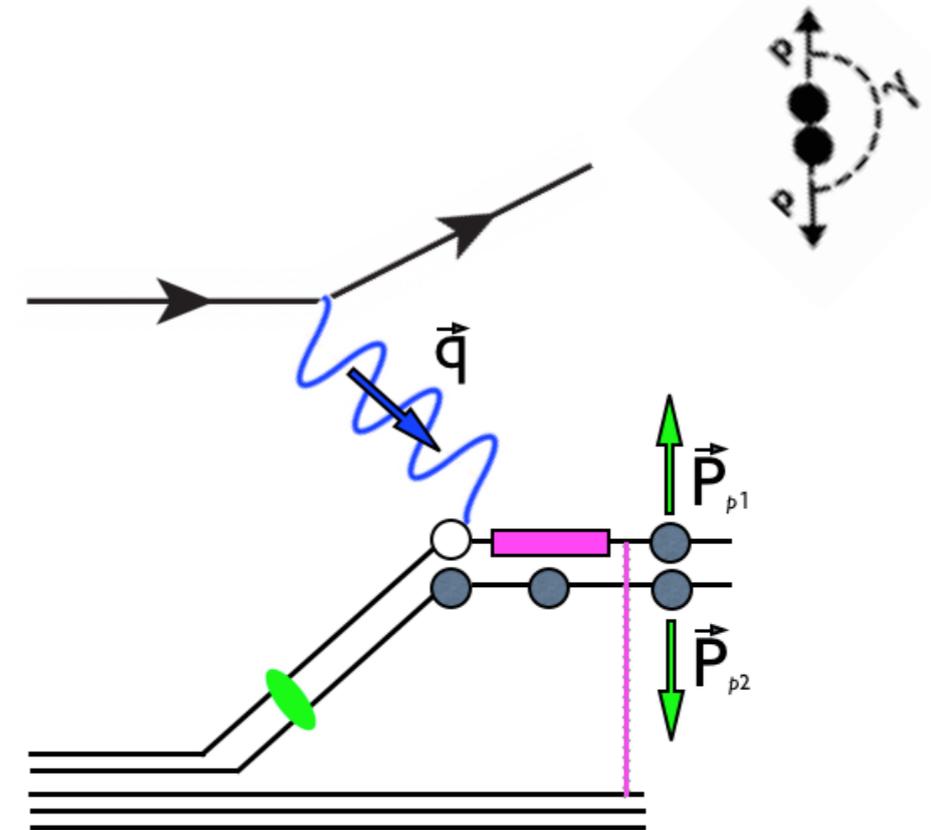
I) CC RES pionless mechanisms involving a pre-existing np pair in the nucleus.

Pictorial diagrams of examples of two-proton knock-out CC reactions involving np SRC pairs

- SRC (green symbol)
- nucleons in the target nucleus are denoted by open-full dots (n-p)
- wide solid lines (purple) represent RES nucleonic states
- (purple) lines indicate pions



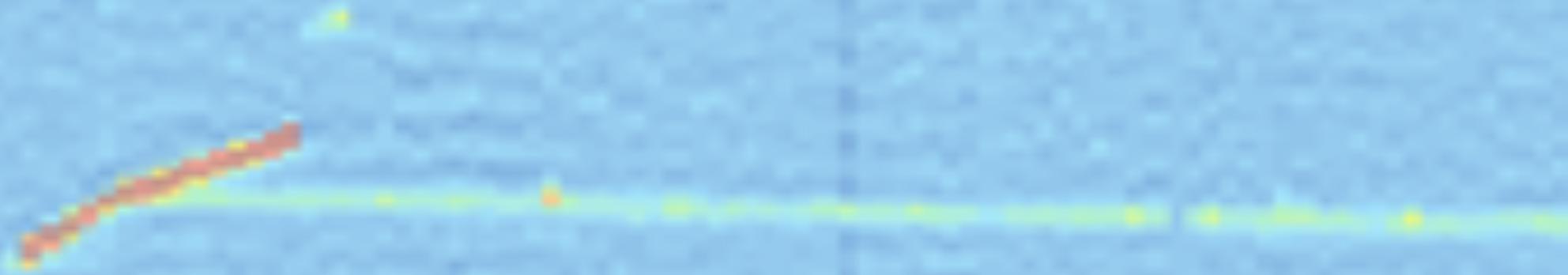
via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair



from RES formation inside a SRC pair (hit nucleon in the pair) and de-excitation through multi-body collision within the $A-2$ nuclear system

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,

$$p_{miss}^T \geq 300 \text{ MeV}/c$$

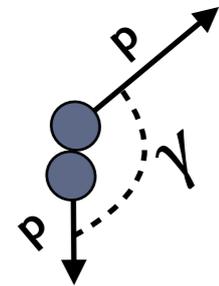
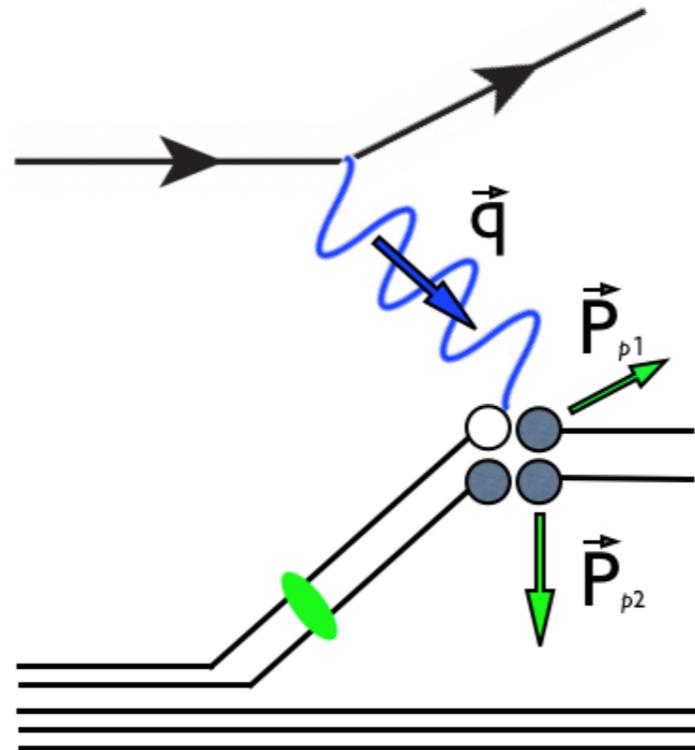
These features **look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC np pairs.**

2-p knock-out CC reactions involving SRC pairs(II)

- 2) CC QE one-body neutrino reactions, through virtual charged weak boson exchange on the neutron of a SRC np pair

Pictorial diagrams of examples of two-proton knock-out CC reactions involving np SRC pairs

- SRC (green symbol)
- nucleons in the target nucleus are denoted by open-full dots (n-p)
- wide solid lines (purple) represent RES nucleonic states
- (purple) lines indicate pions



The high relative momentum will cause the correlated proton to recoil and be ejected.

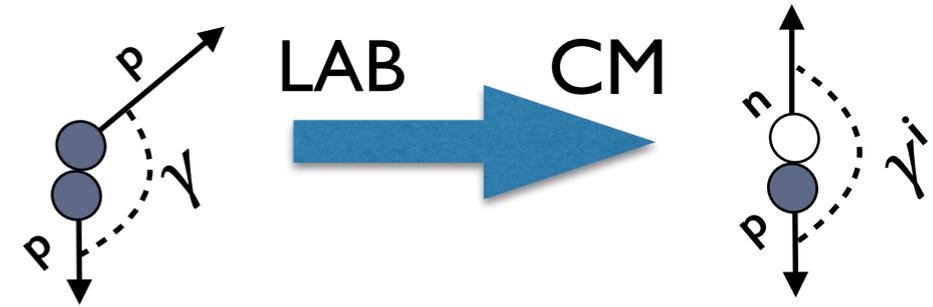
Within impulse approximation,

- the struck nucleon $p1$ being the higher in momentum and
- the lower $p2$ identified as the recoil spectator nucleon from within the SRC

$(\mu^- + 2p)$ - Initial momentum reconstruction

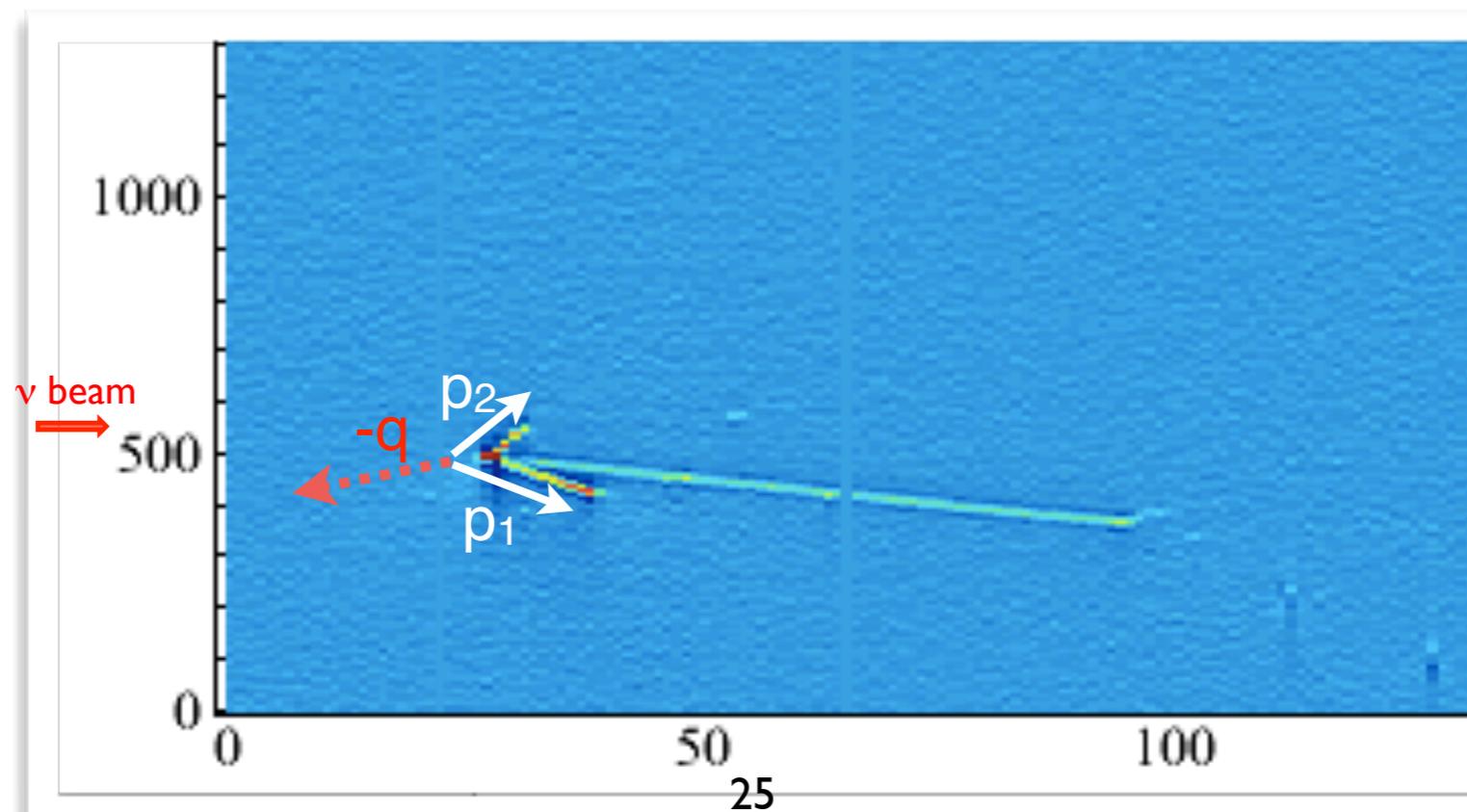
With an approach similar to the electron scattering triple coincidence analysis, the initial momentum of the struck neutron \vec{p}_n^i is determined by transfer momentum vector subtraction to the higher proton momentum [lower momentum p_2 identified as recoil spectator nucleon from within SRC]

$$\vec{p}_n^i = \vec{p}_{p1} - \vec{q}$$



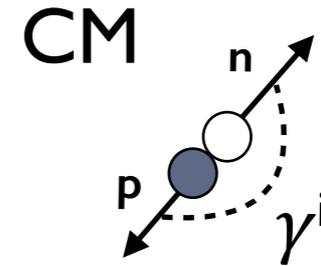
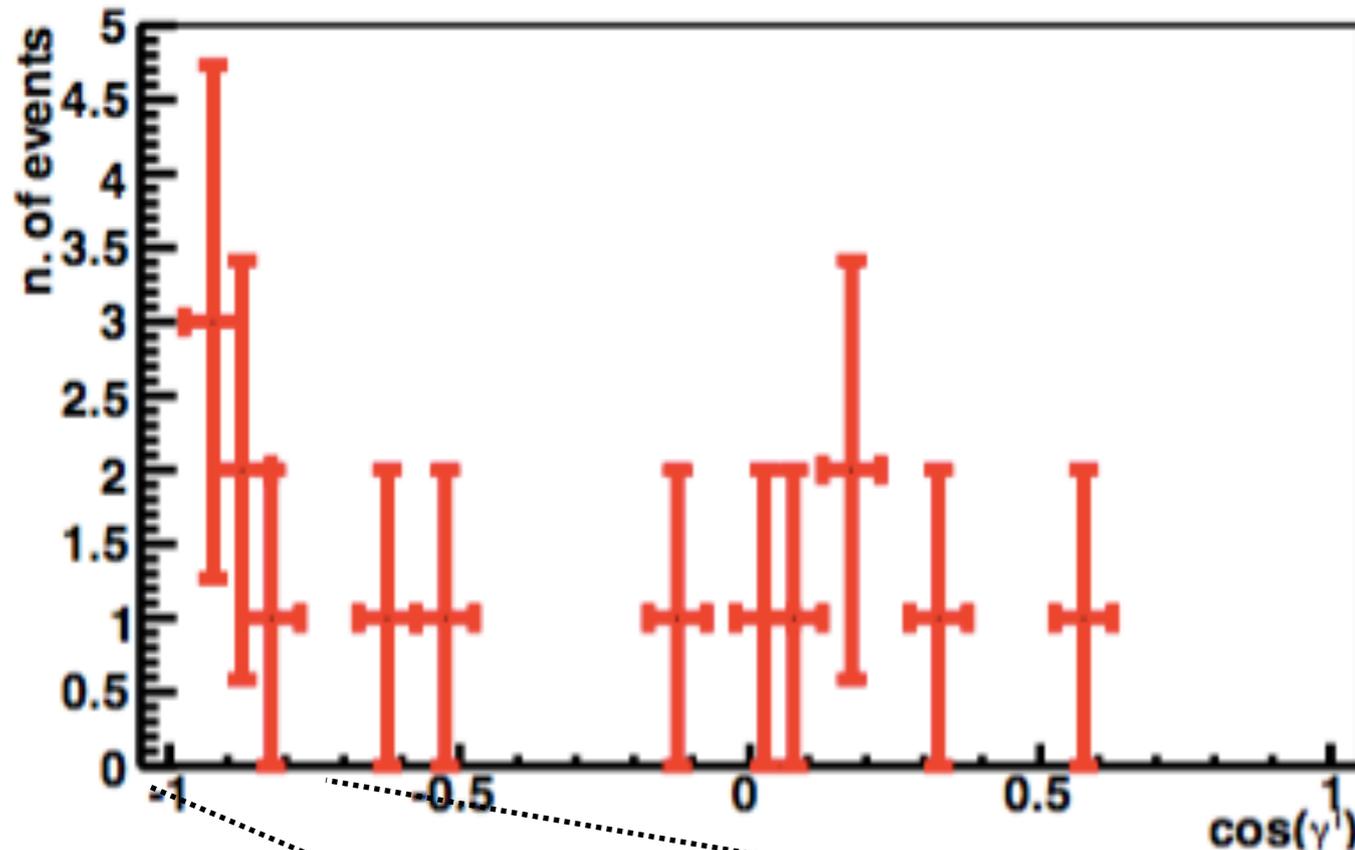
\vec{q} is calculated from the reconstructed E_ν and the measured muon kinematics

This procedure is applied to the remaining sub-sample of fifteen ArgoNeuT events $(\mu^- + 2p)$ with both protons above Fermi momentum, after excluding the four hammer events, already ascribed to other types of reactions.



$(\mu^- + 2p)$ - Initial momentum reconstruction

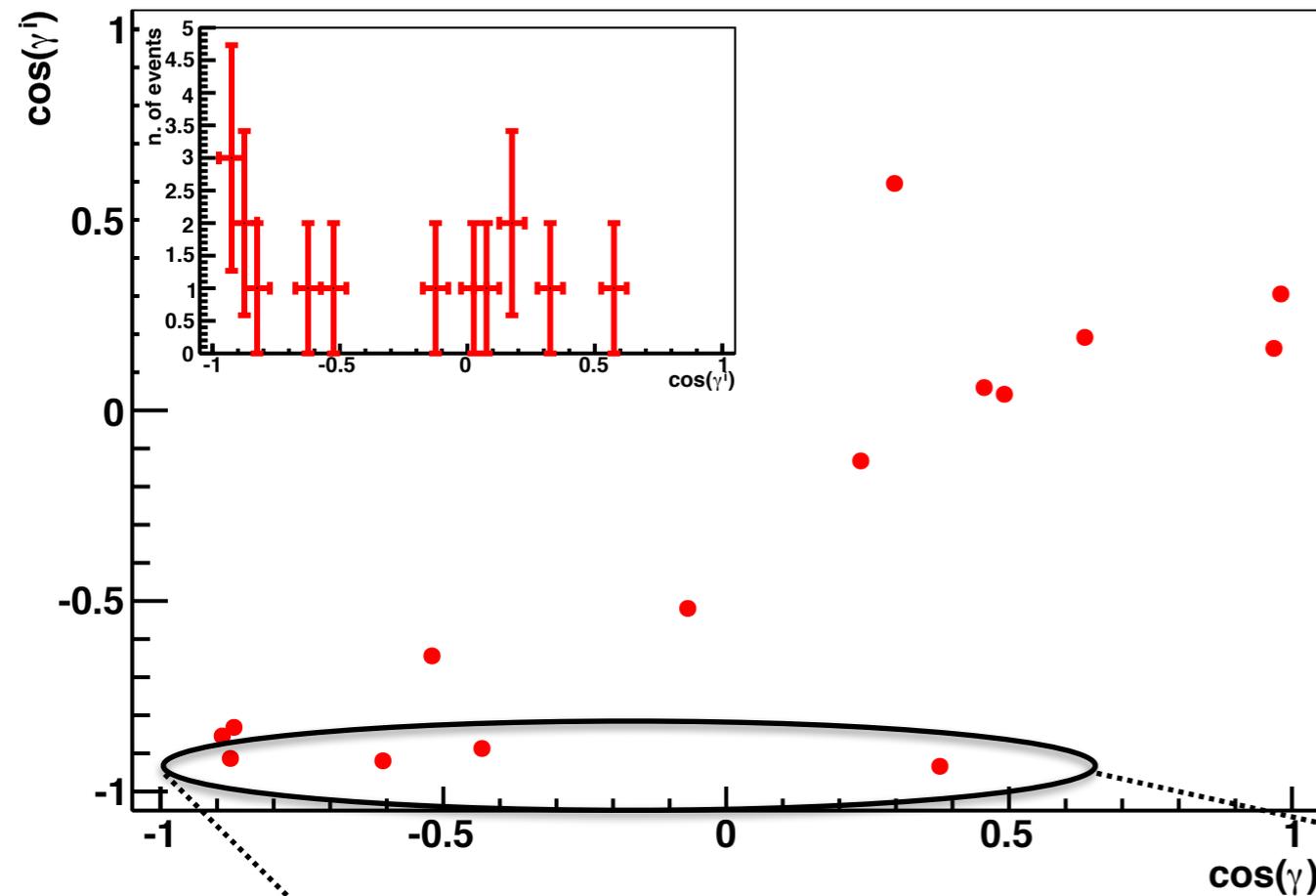
In most cases the reconstructed initial momentum is found opposite to the direction of the recoil proton ($\cos(\gamma_i) < 0$)



γ^i = opening angle between the reconstructed struck nucleon and the recoil proton in the np initial pair

A fraction of the events exhibit a strong angular correlation peaking at large, back-to-back initial momenta

Back-to-back proton pairs in the initial state



$\cos(\gamma^i)$ vs $\cos(\gamma)$

γ^i = opening angle between the reconstructed struck nucleon and the recoil proton in the np initial pair

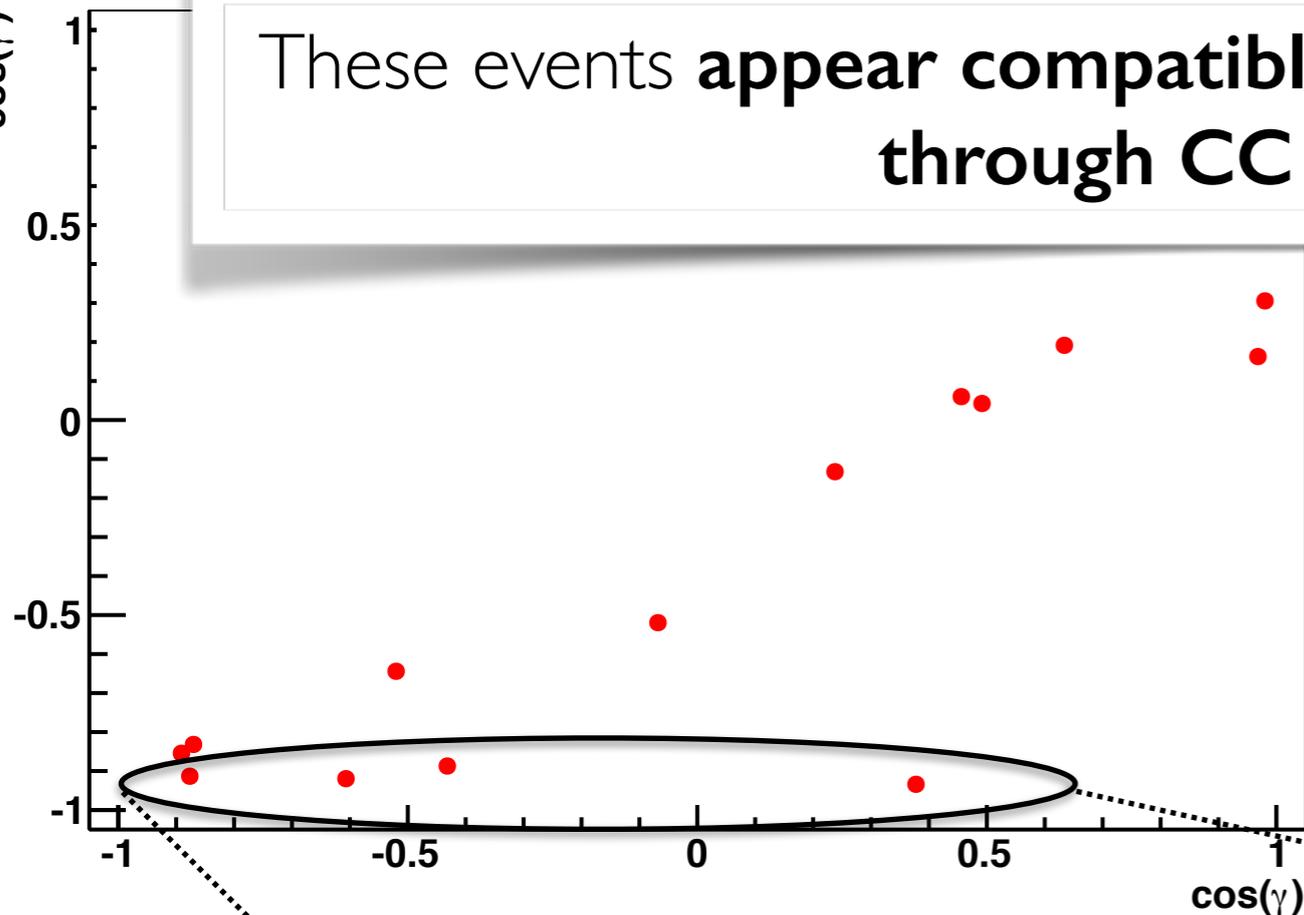
γ = angle in space between the two detected proton tracks in the Lab reference frame

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 $\cos(\gamma_i)$

Back-to-back proton pairs in the initial state

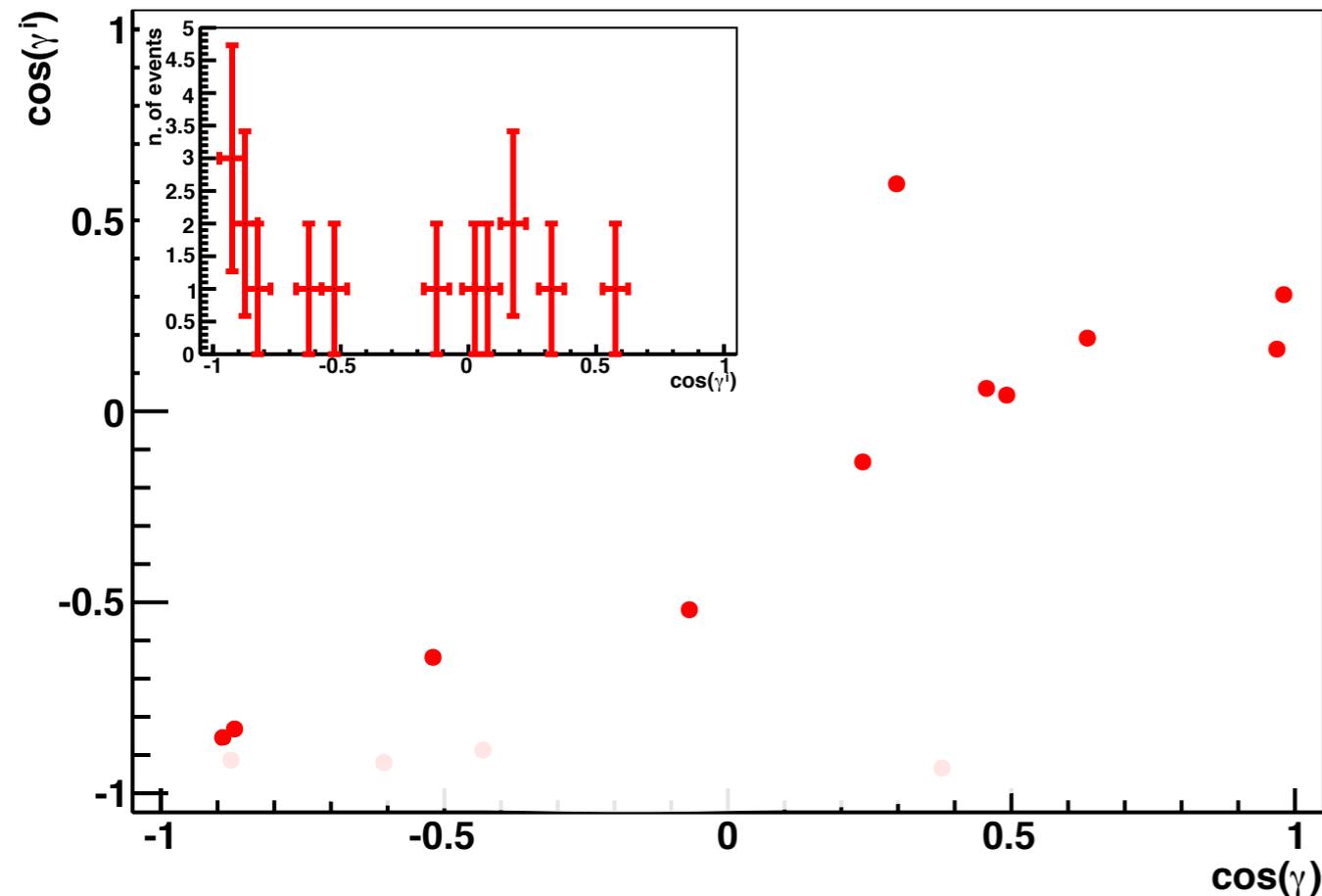
These events appear compatible as originating from SRC pairs through CC QE reactions



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

The measured transverse component of the missing momentum in these events is small (≈ 250 MeV/c).

What about the other (μ^-+2p) events?



There is no immediate interpretation for the *apparent correlation* of the remaining 11 events.

- ▶ Two-step process such as:
 - MEC** or
 - Isobar Currents (IC)** involving NN long-range correlated pair in the nucleus are obviously active in two-proton knock-out production

- ▶ Other mechanisms like interference between the amplitudes involving one- and two-nucleon currents, subject to current theoretical modeling*, can also potentially contribute

- ▶

- ▶ In all cases, protons can undergo **FSI** inside the residual nuclear system before emerging and propagating in the LAr active detector volume.

- ▶ *In general, however, the emission of energetic, angular correlated proton pairs from FSI appears disfavored*

The event statistics from ArgoNeuT is very limited
(~ 5 months run on the NuMI beam with a 240 Kg active volume LArTPC)

Future LArTPC experiments: MicroBooNE, LArI-ND...

MicroBooNE estimated
events rates (GENIE)

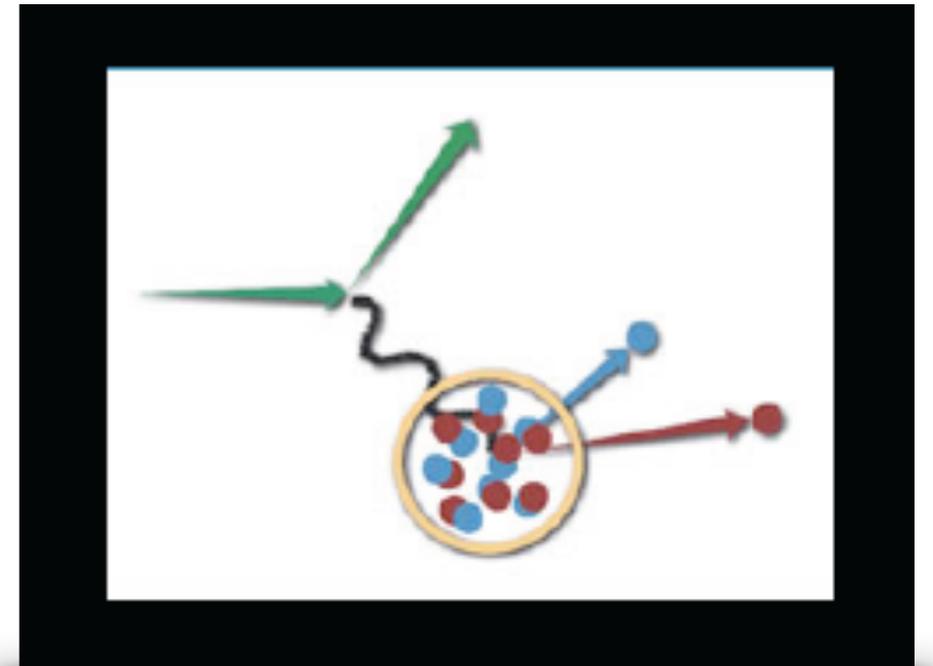
6.6 10^{20} POT exposure of MicroBooNE will
provide an event sample of
~57000 CC 0-pion events

LArI-ND estimated
events rates (GENIE)

2.2 10^{20} POT exposure of LAr1-ND will
provide an event sample 6-7x larger than
will be available in MicroBooNE

Effects of correlations on the analysis of neutrino scattering data (I)

- ▶ Nuclear effects in (heavy) nuclear targets [initial state short-range nucleon-nucleon correlations (**NN SRC**), meson-exchange currents (**MEC and IC**) and final state interactions (**FSI**) - *and interference between the amplitudes of these mechanisms*] play a big role in scattering processes



e-scattering experiments accumulated decades of in-depth experience and detailed knowledge: to be transmitted to the ν -scattering sector

Effects of correlations on the analysis of neutrino scattering data (II)

- ▶ Direct experimental investigations on the nature of nuclear effects and their impact on the predicted rates, final states, and kinematics of neutrino interactions are very compelling*
- ▶ The realization of consistent models including all these nuclear effects is now being actively pursued as well as their implementation in ν MonteCarlo generators
- ▶ The Time Projection Chamber (LArTPC) technique opens new perspectives for detailed reconstruction of final state event topologies from neutrino-nucleus interactions.

*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.

Summary: SRC mining in LAr TPC neutrino data

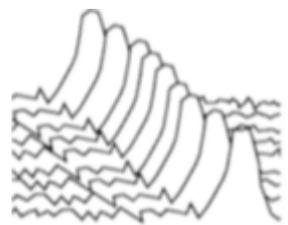
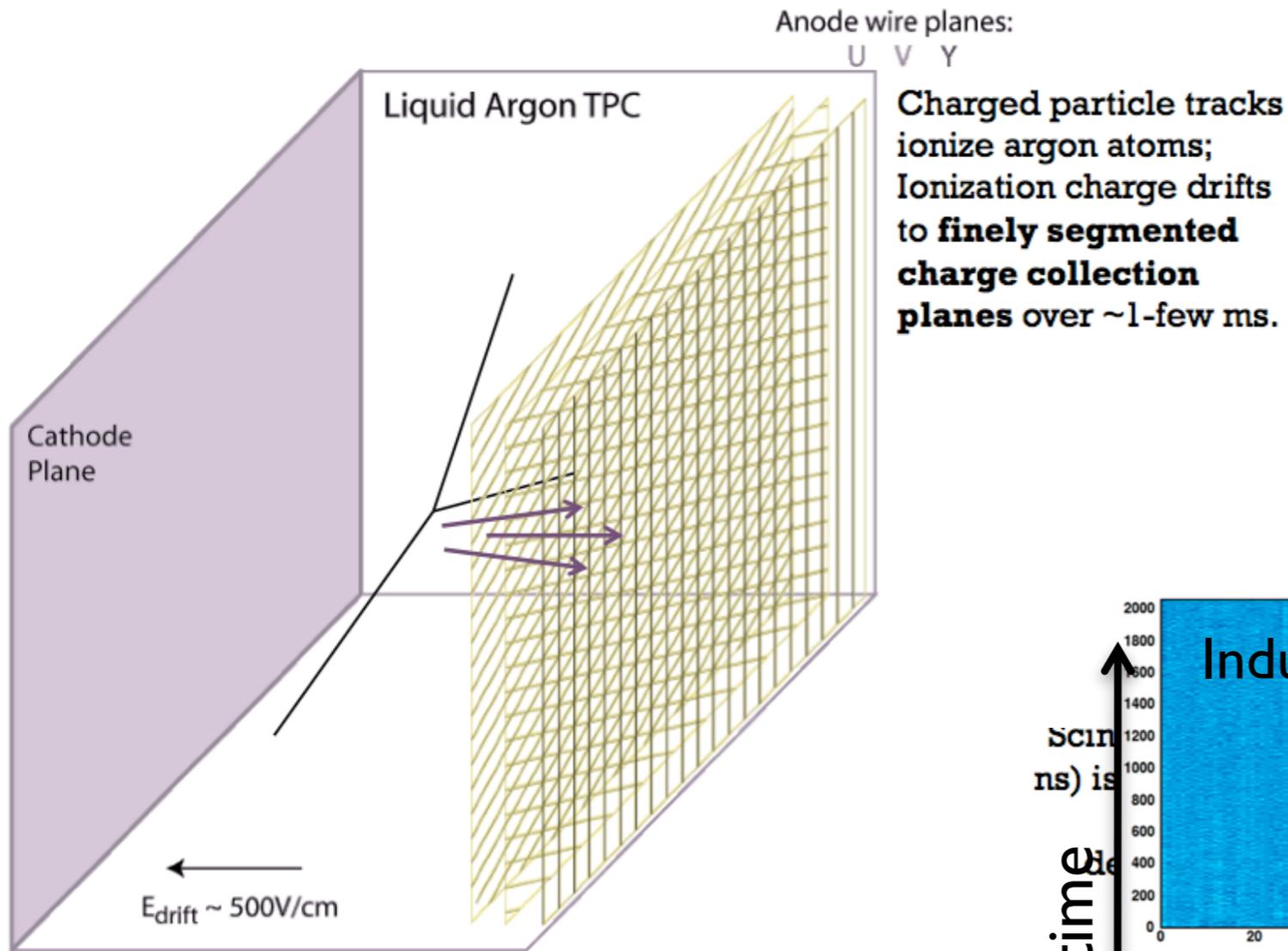
- ▶ Topological CC 0 pion sample analysis in ArgoNeuT:
 - ▶ $(\mu^- + 2p)$ analysis \Rightarrow **back-to-back proton events**:
 - ▶ suggests that mechanisms directly involving NN SRC pairs in the nucleus are active and can be efficiently explored in ν -argon interactions with the LAr TPC technology
 - ▶ accurate and detailed MC neutrino generators are deemed necessary for comparisons with LAr data (with the inclusion of a realistic and exhaustive treatment of SRC in the one- and two-body component of the nuclear current). **We hope the ArgoNeuT data will encourage more studies in this area.**

“Detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line”

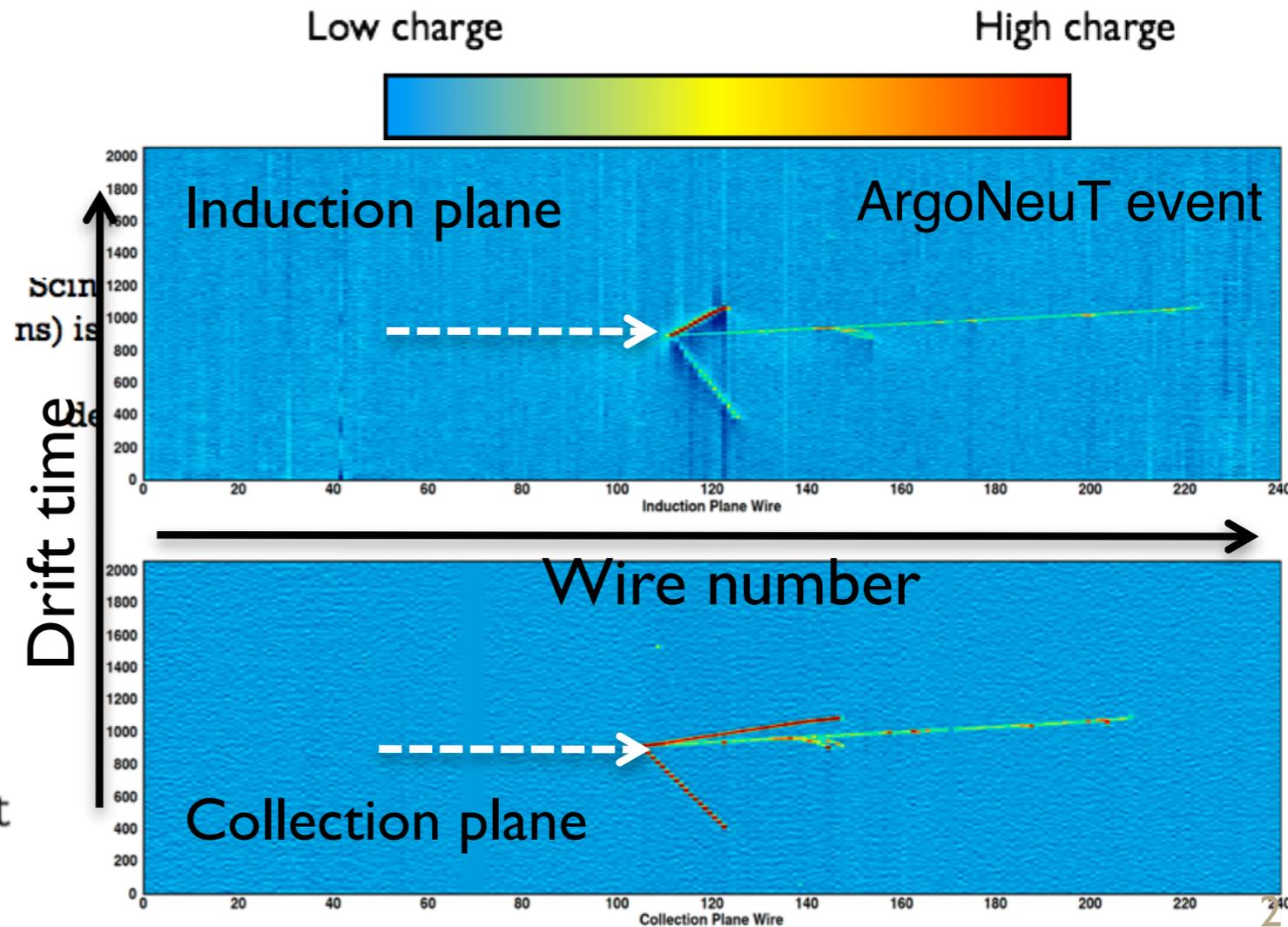
PHYSICAL REVIEW D 90, 012008 (2014)

BACKUP

THE LAR TPC CONCEPT



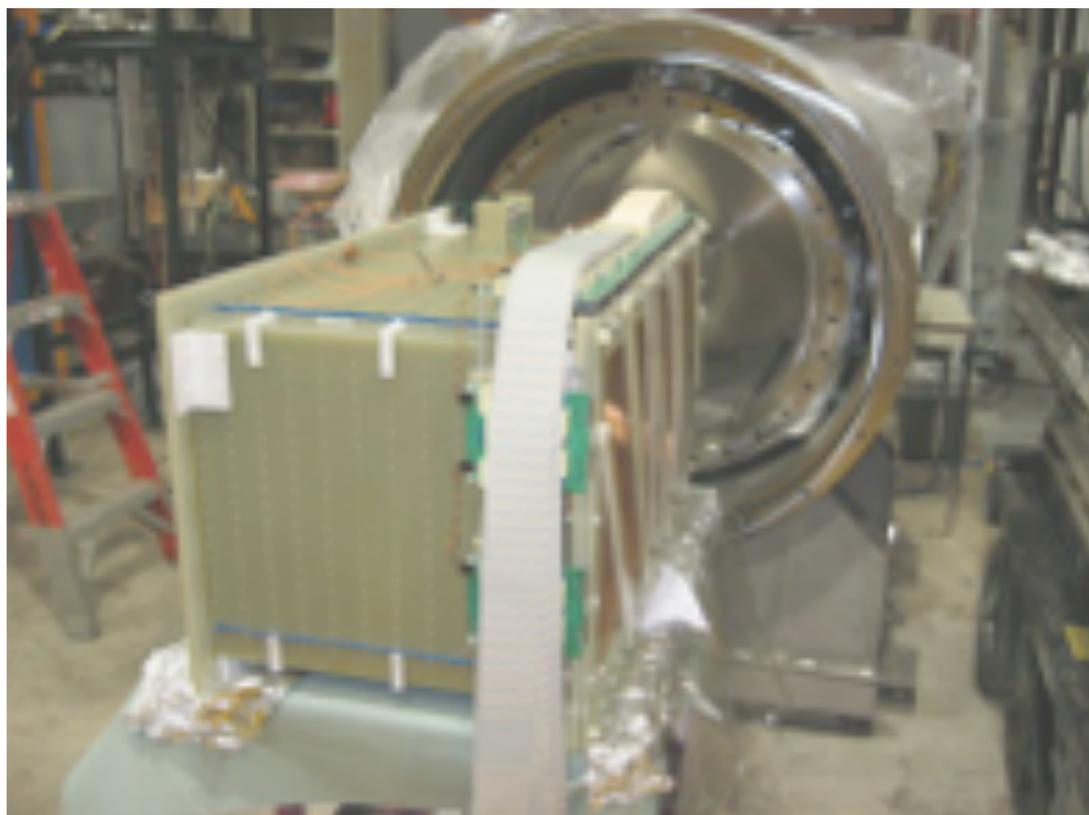
Wire pulses in time give the drift coordinate of the track



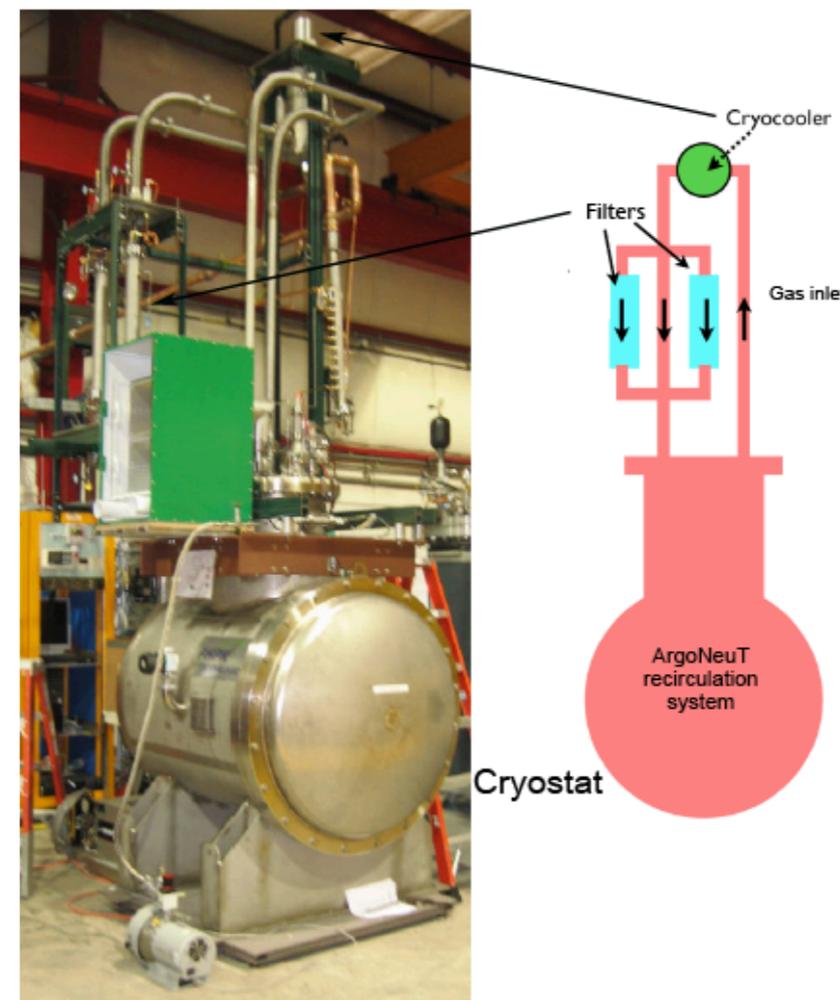
induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

ArgoNeuT Detector

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



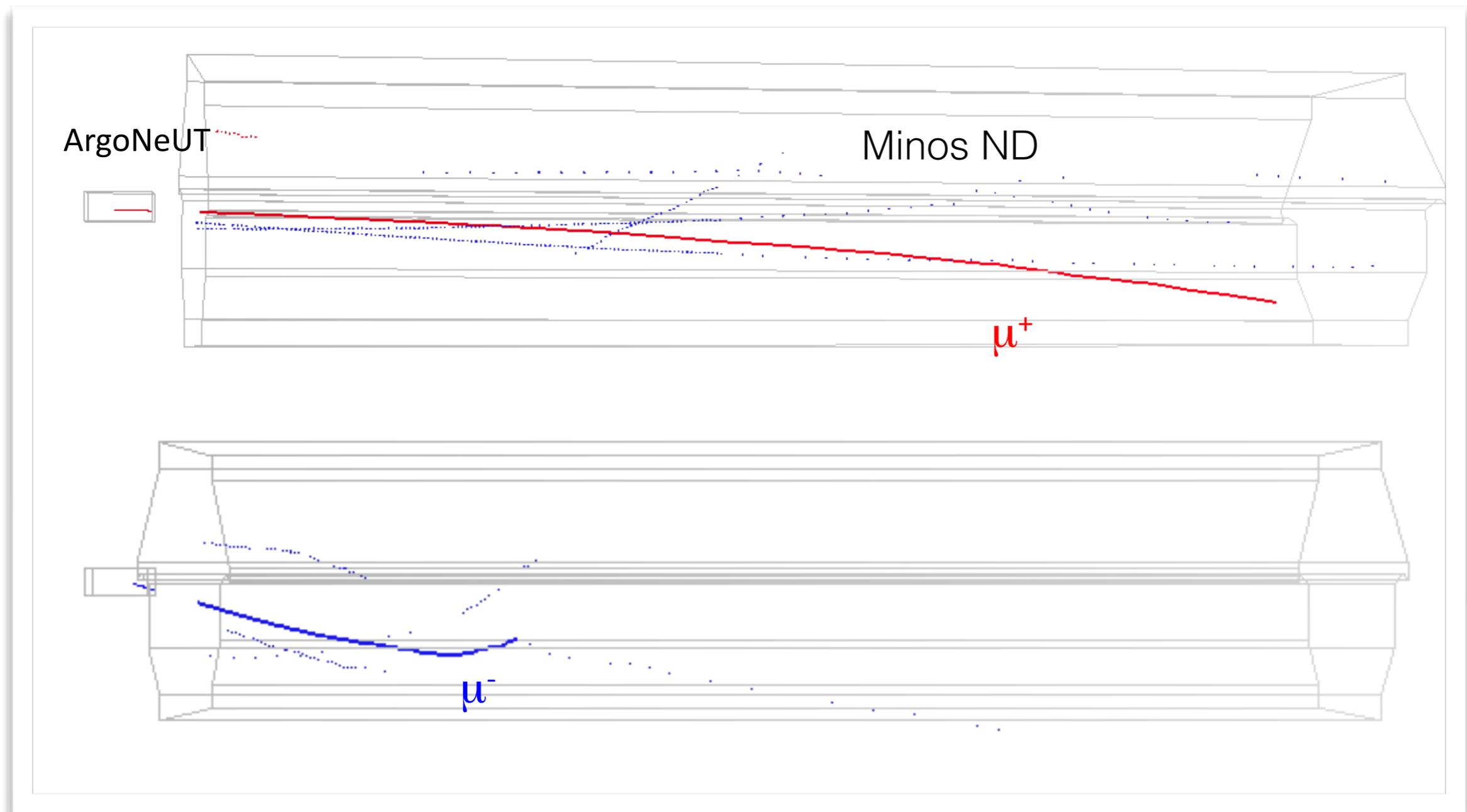
The TPC, about to enter the inner cryostat



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

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

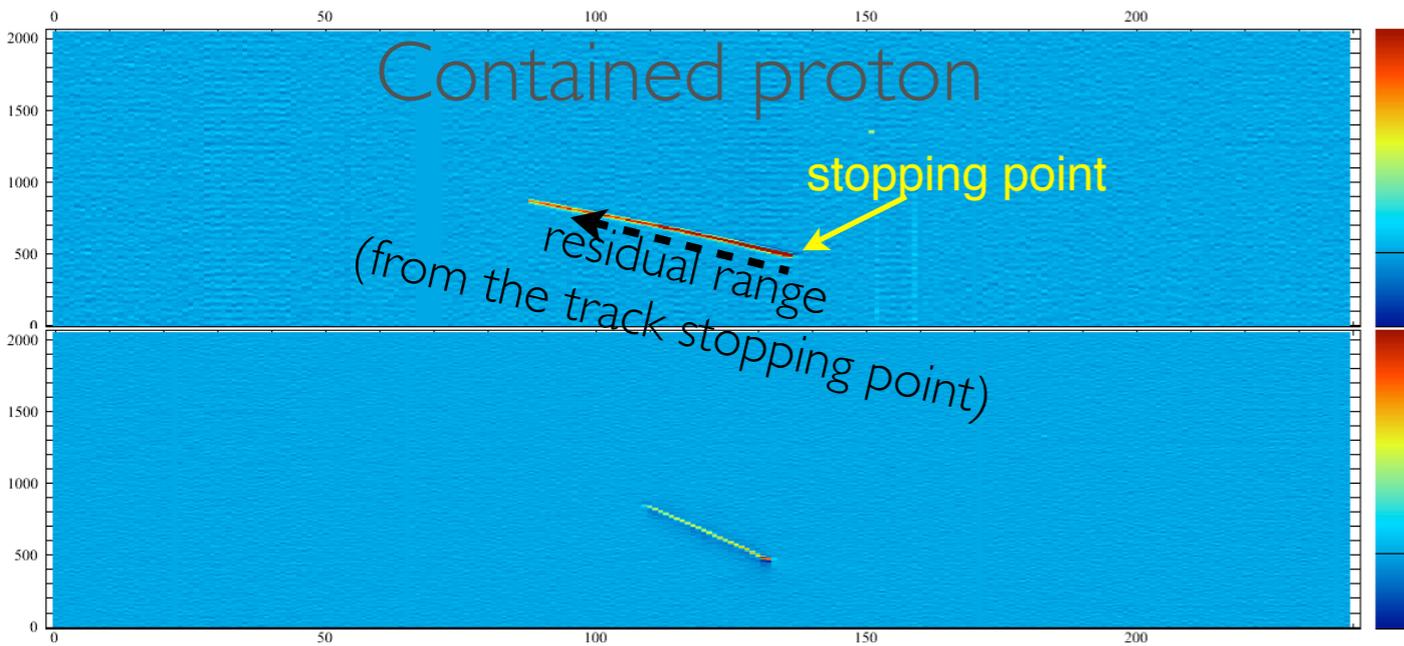
MUON reconstruction



“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

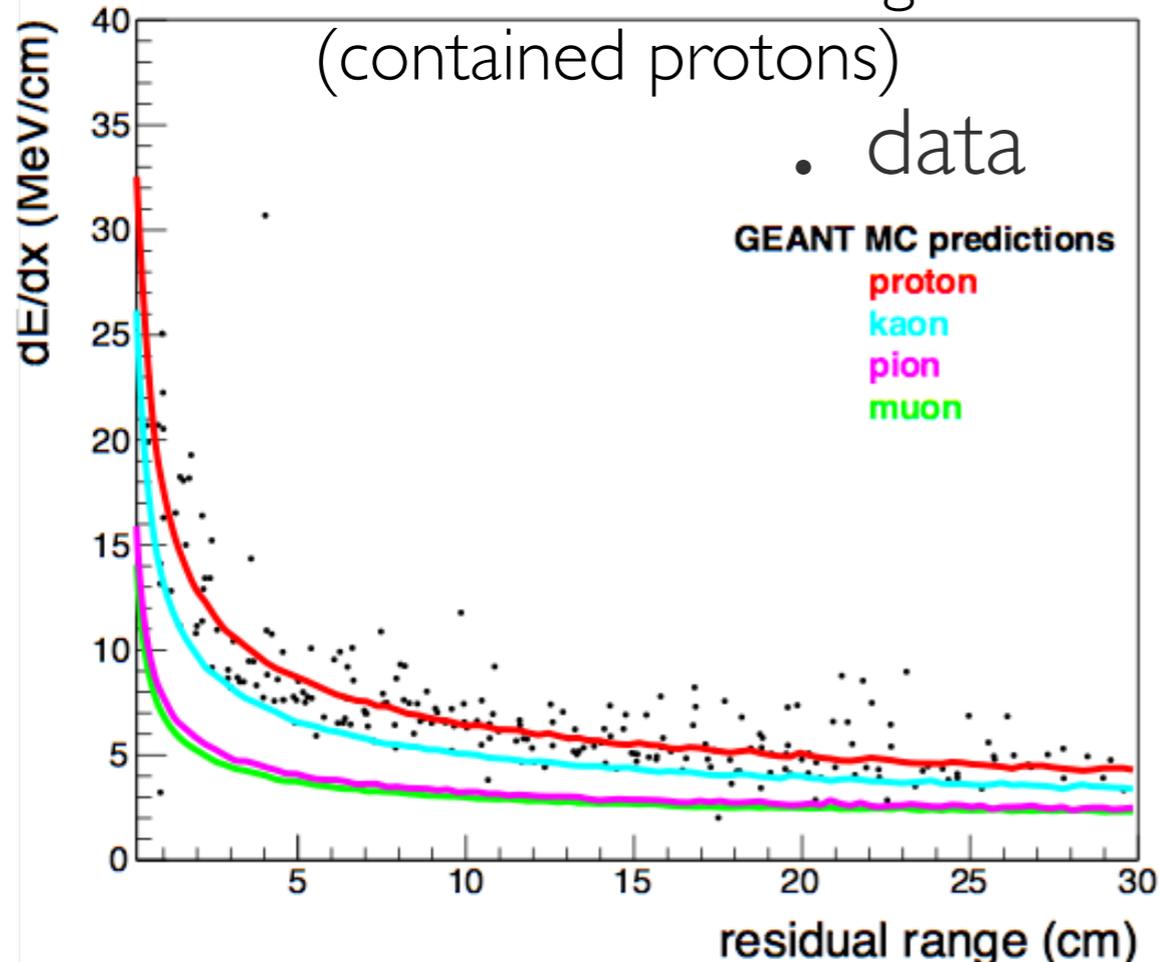


Measurement of:

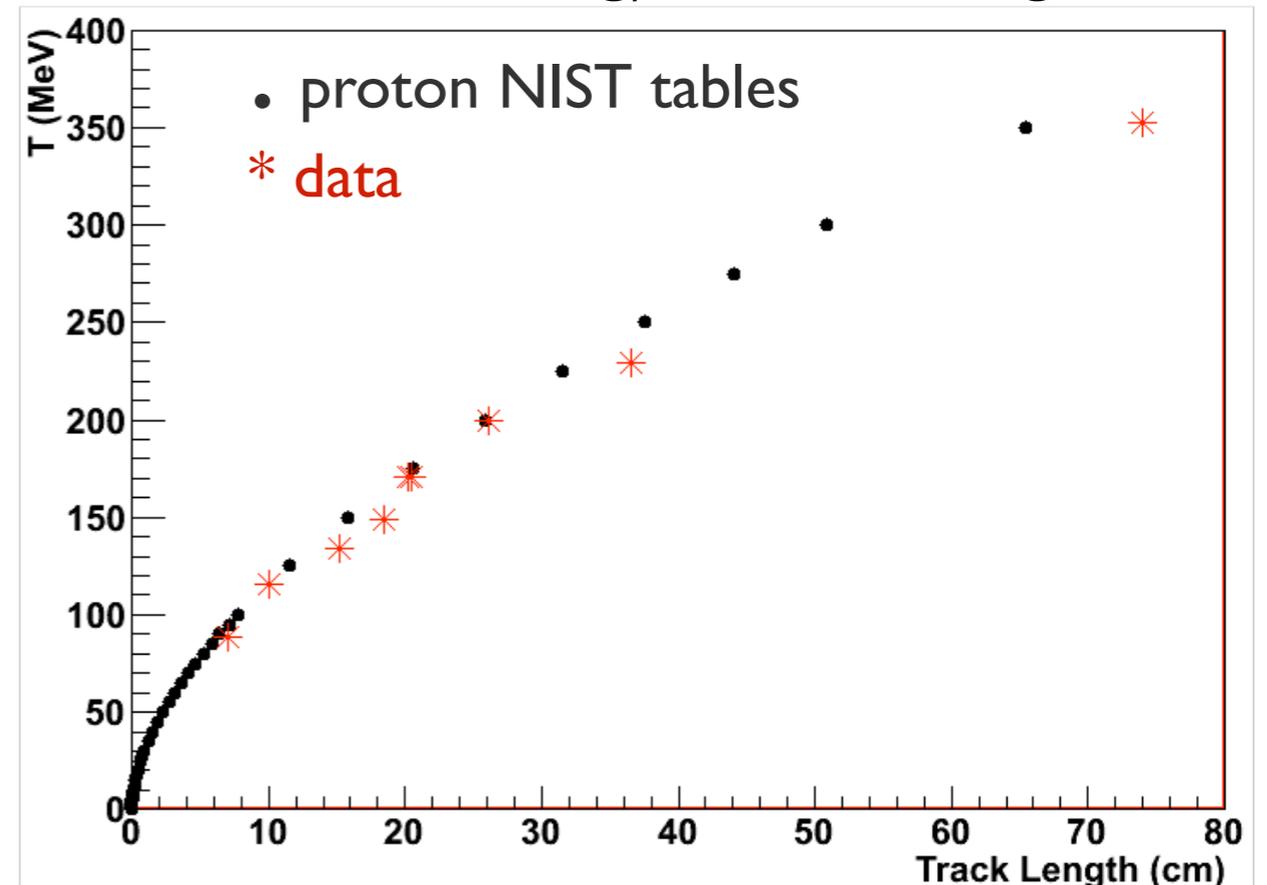
- dE/dx vs. residual range along the track
- kinetic energy vs. track length

χ^2 based method is used for PID

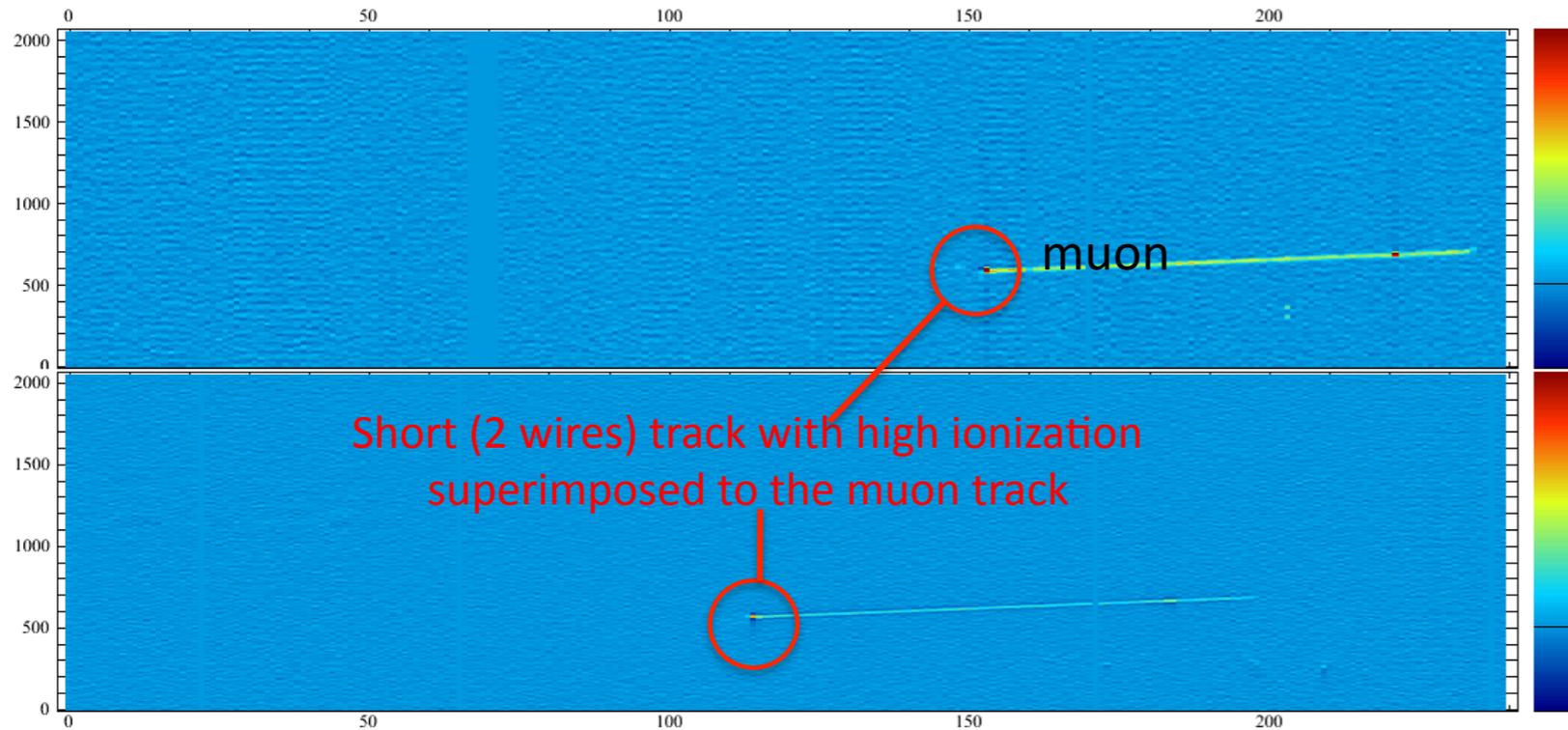
dE/dx vs. residual range
(contained protons)



Kinetic Energy vs. track length



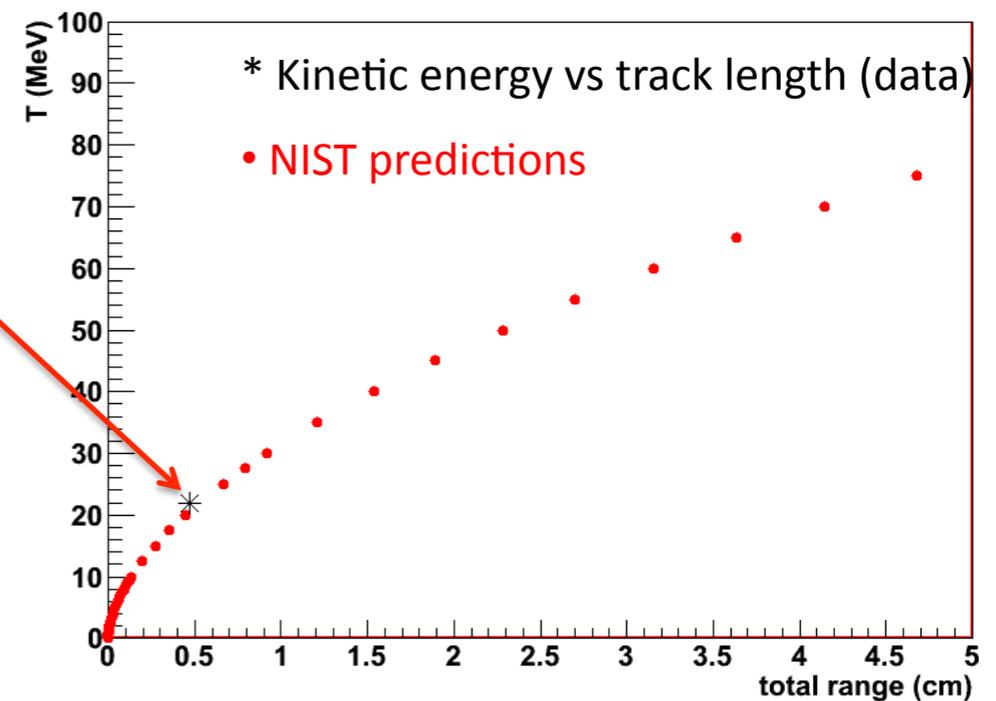
Example of Low energy proton reconstruction



The short track behaves like **proton**

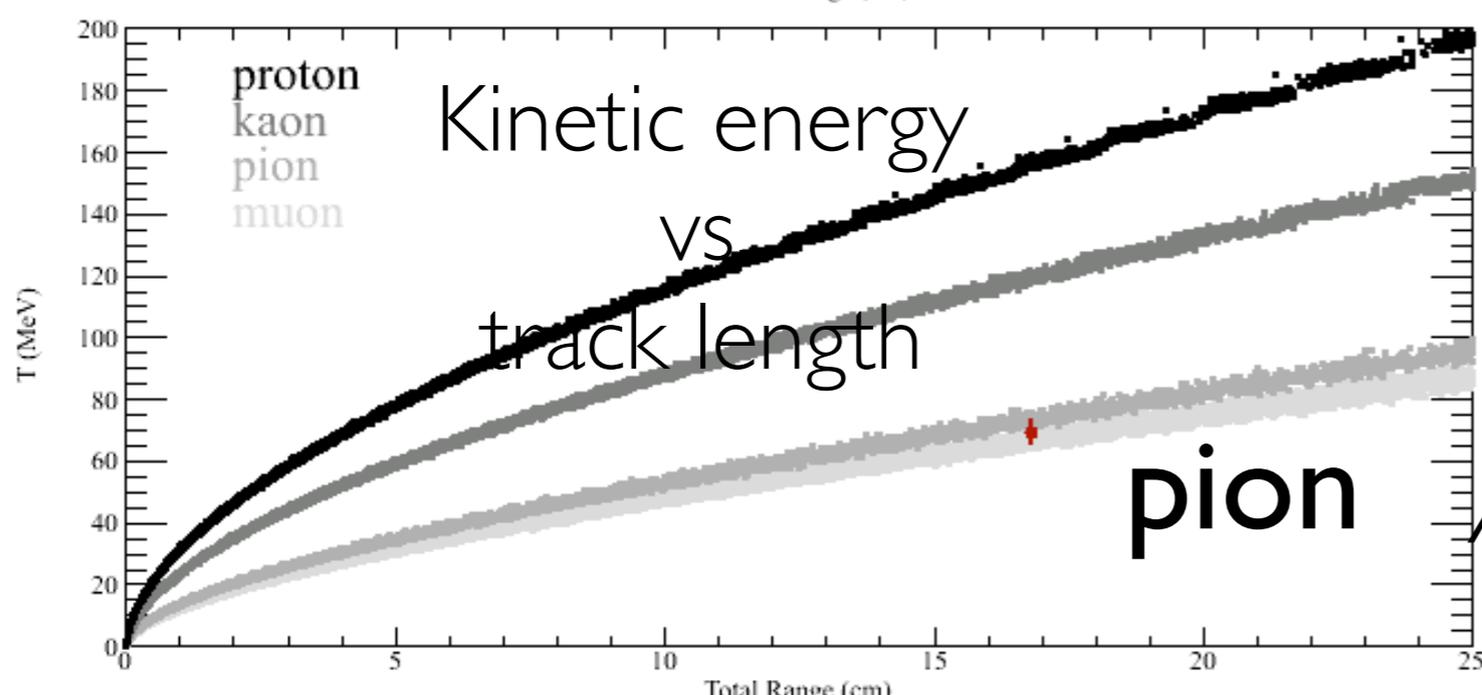
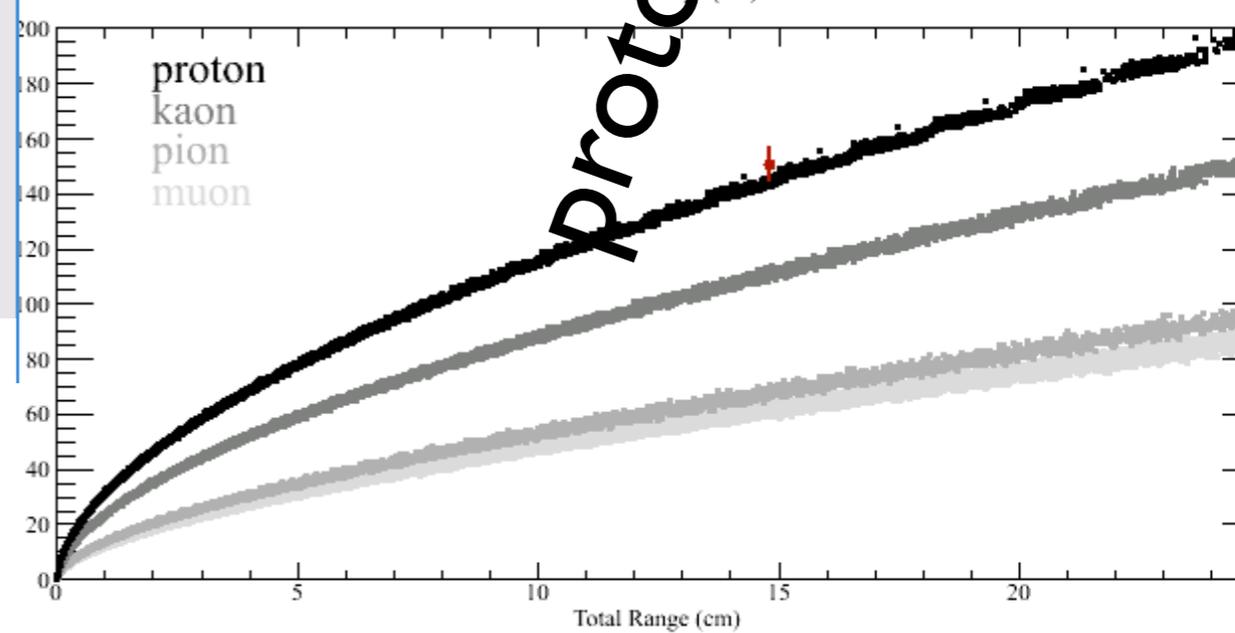
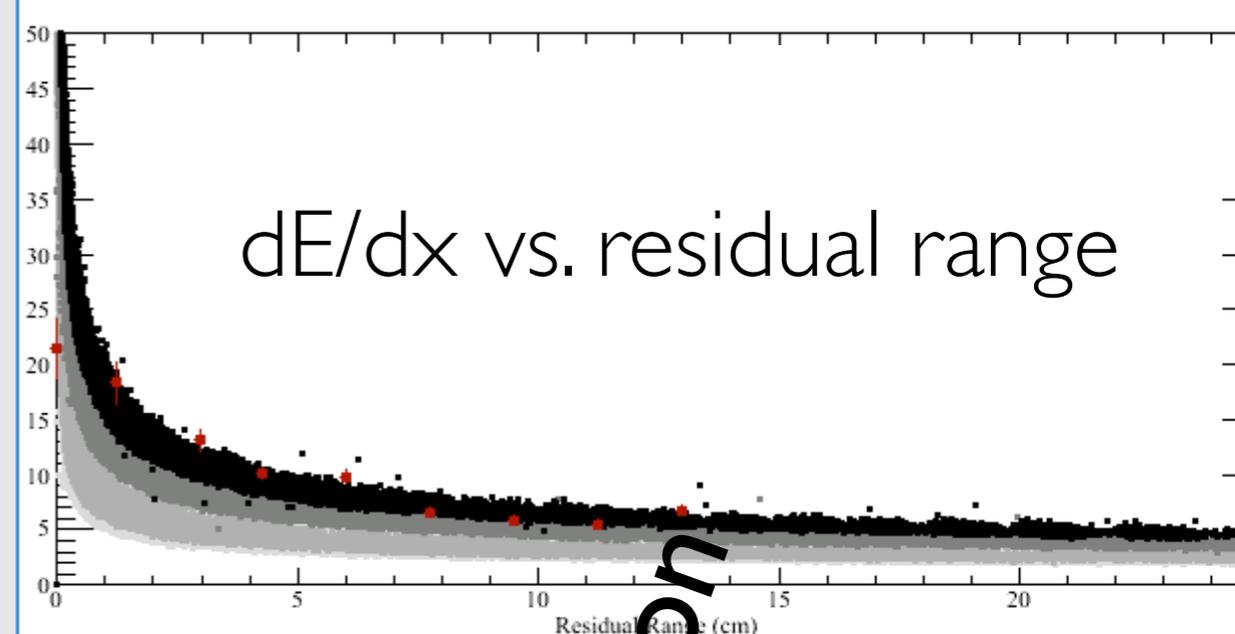
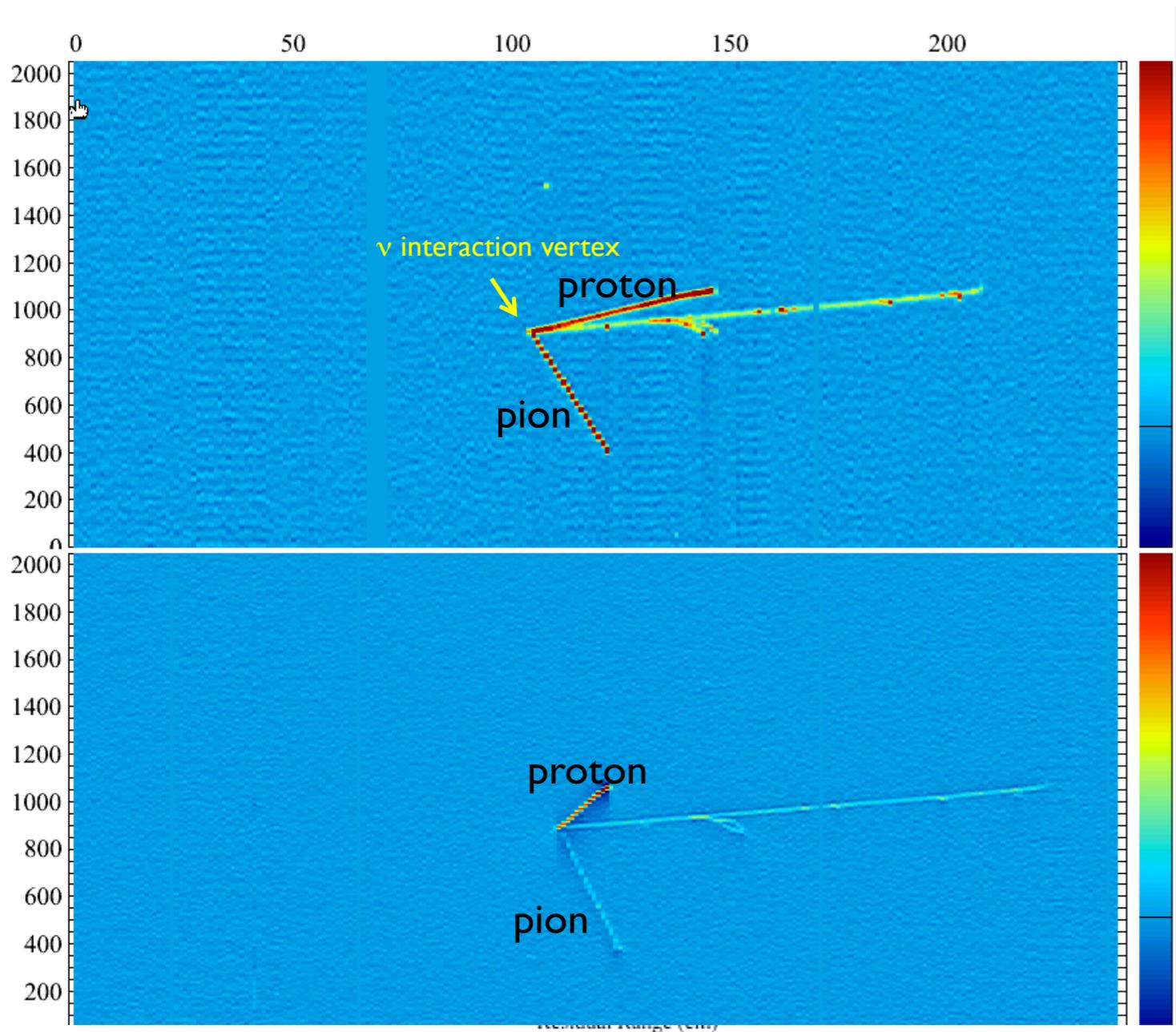
Length=0.5 cm

KE=22±3 MeV



ArgoNeuT proton threshold: 21 MeV of Kinetic Energy

ρ/π^\pm identification



ArgoNeuT pion reconstruction threshold:
~8 MeV Kinetic energy

PID Efficiencies

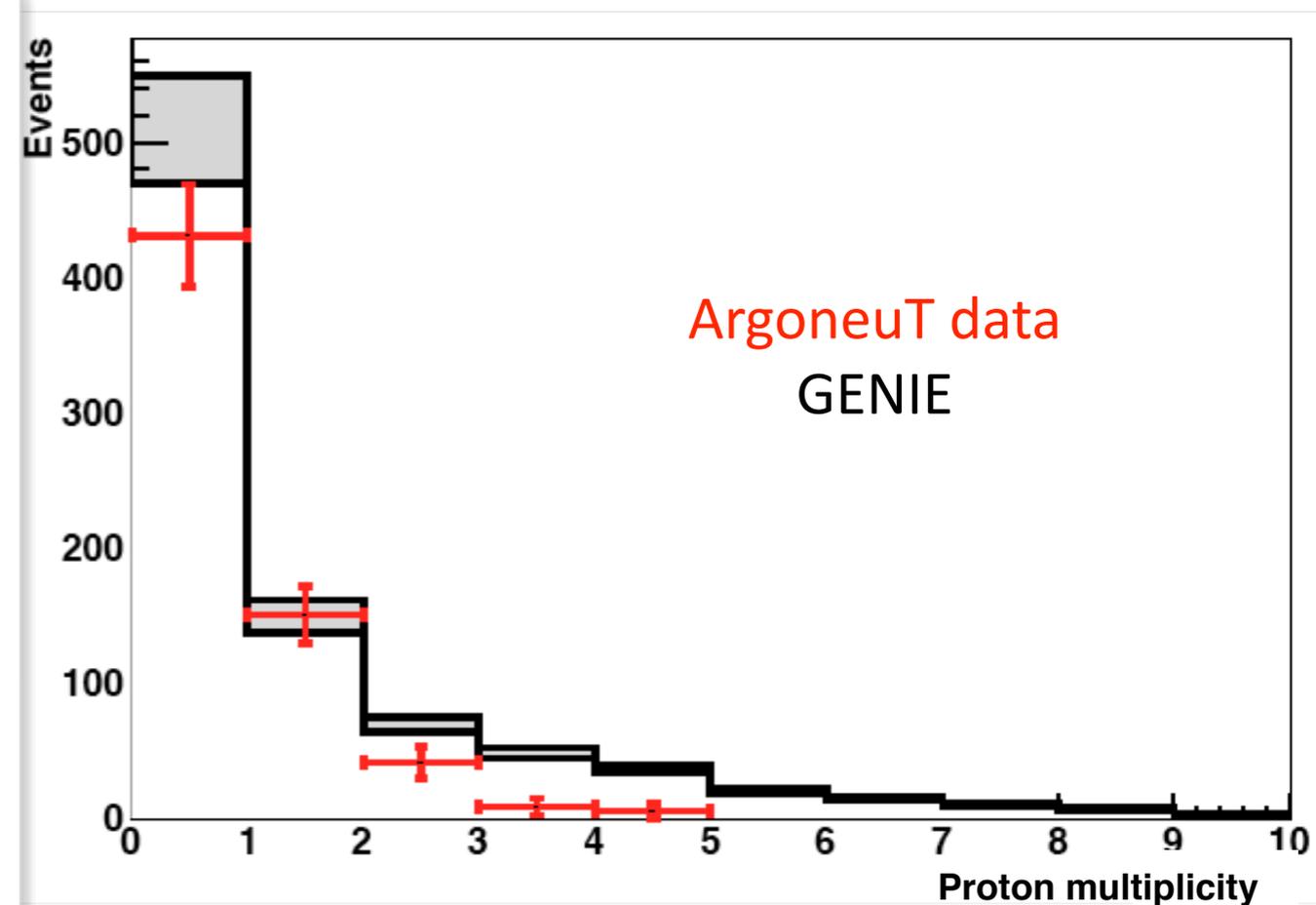
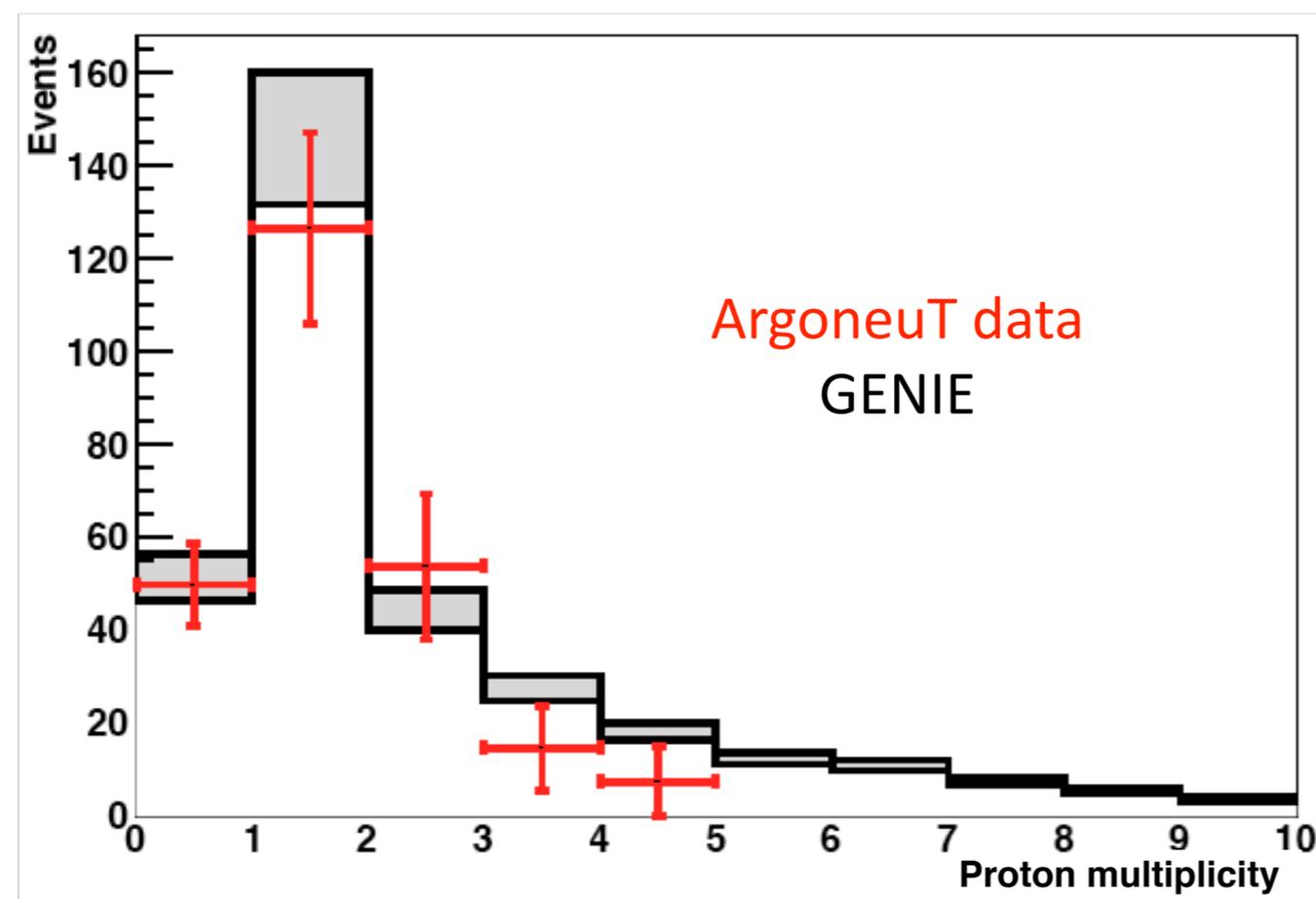
Generated

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

Proton Multiplicity ($\mu+N_p$ 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

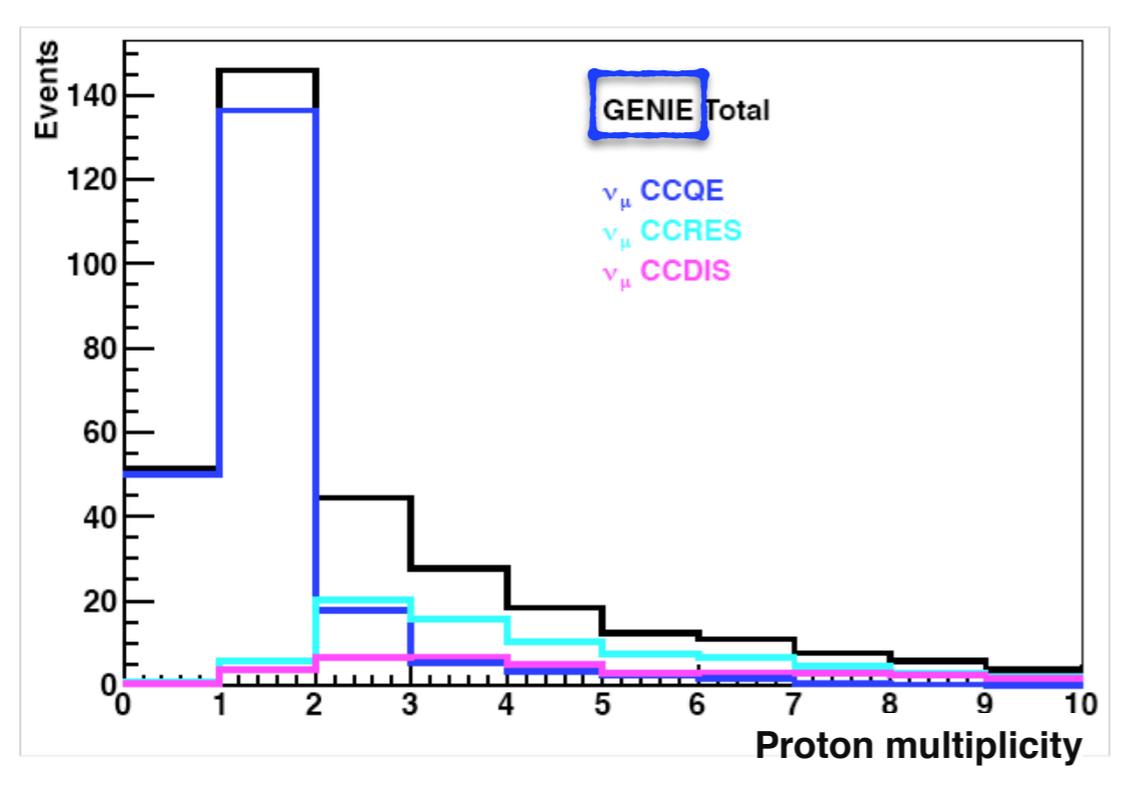
proton threshold:
 $T_p > 21 \text{ MeV}$

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

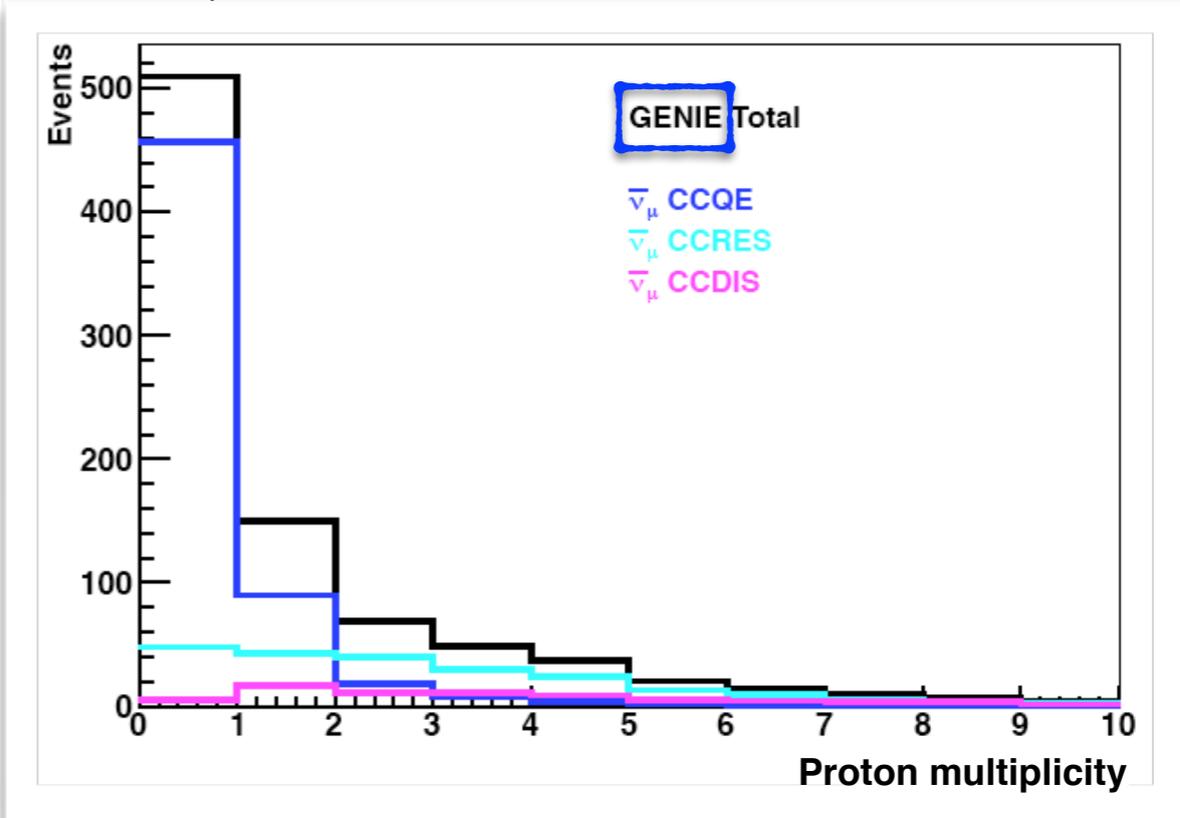
GENIE MC models more higher multiplicity events

CC 0 pion events: MC PREDICTIONS by Physical Process

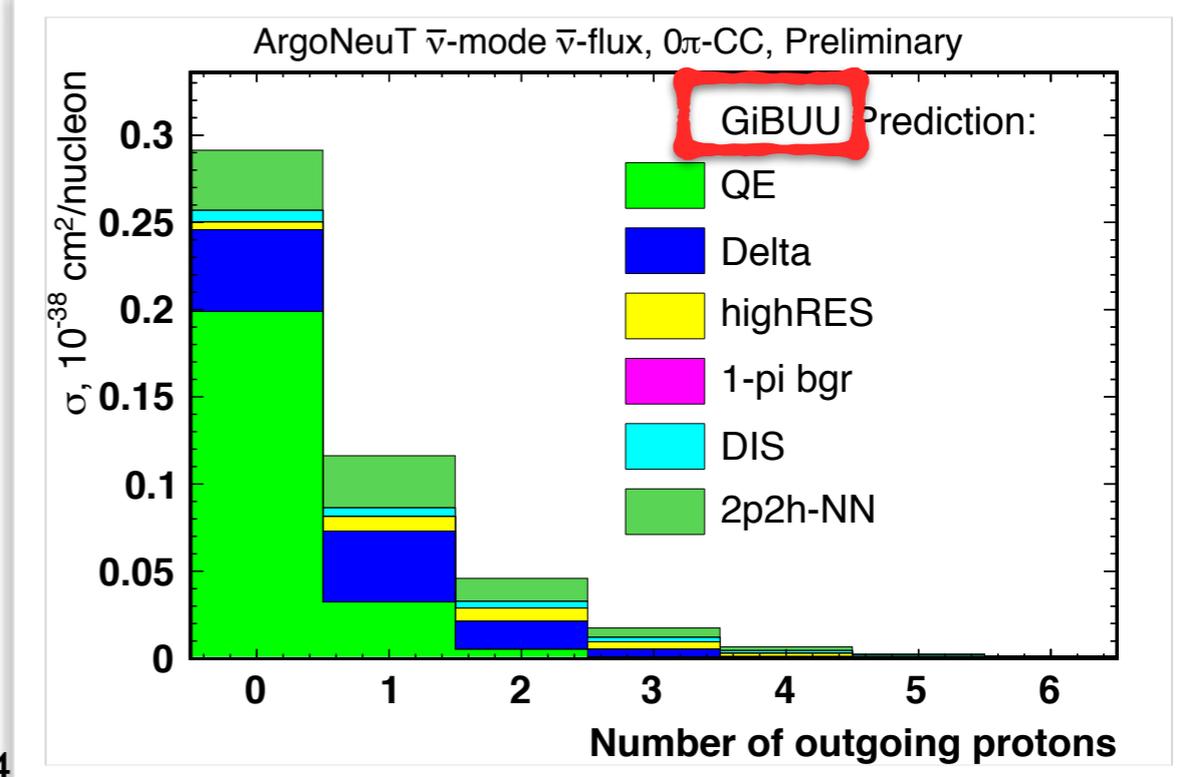
ν_μ - anti-neutrino mode run



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



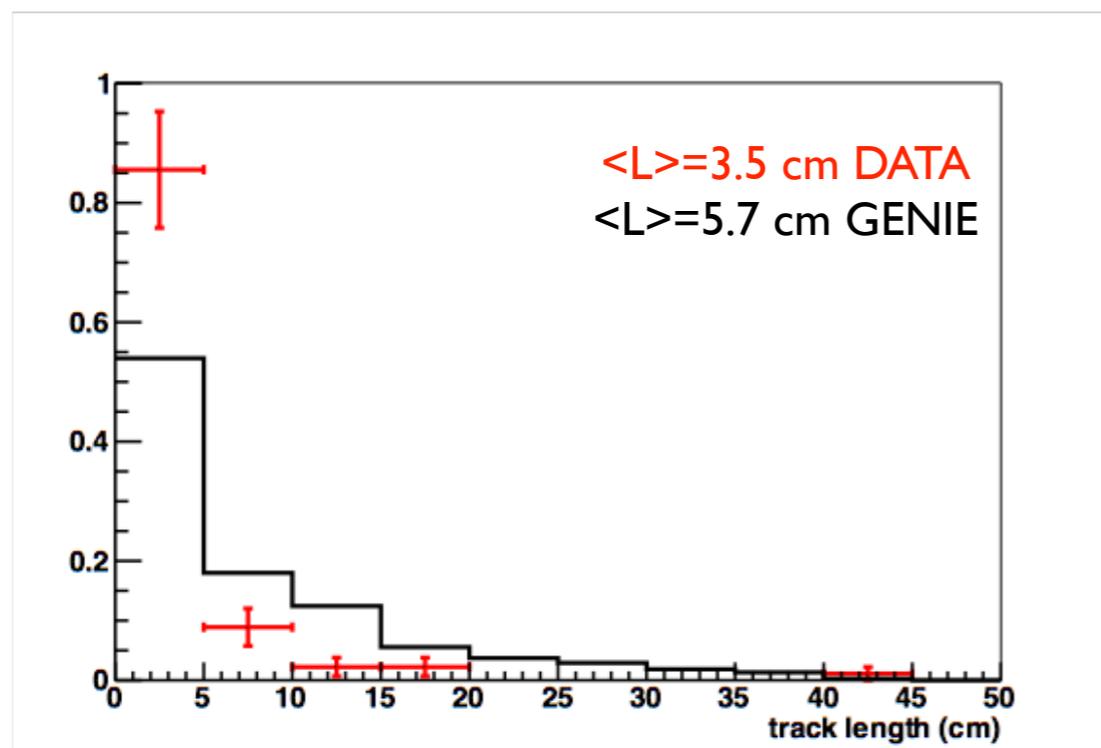
$\bar{\nu}_\mu$ - anti-neutrino mode run



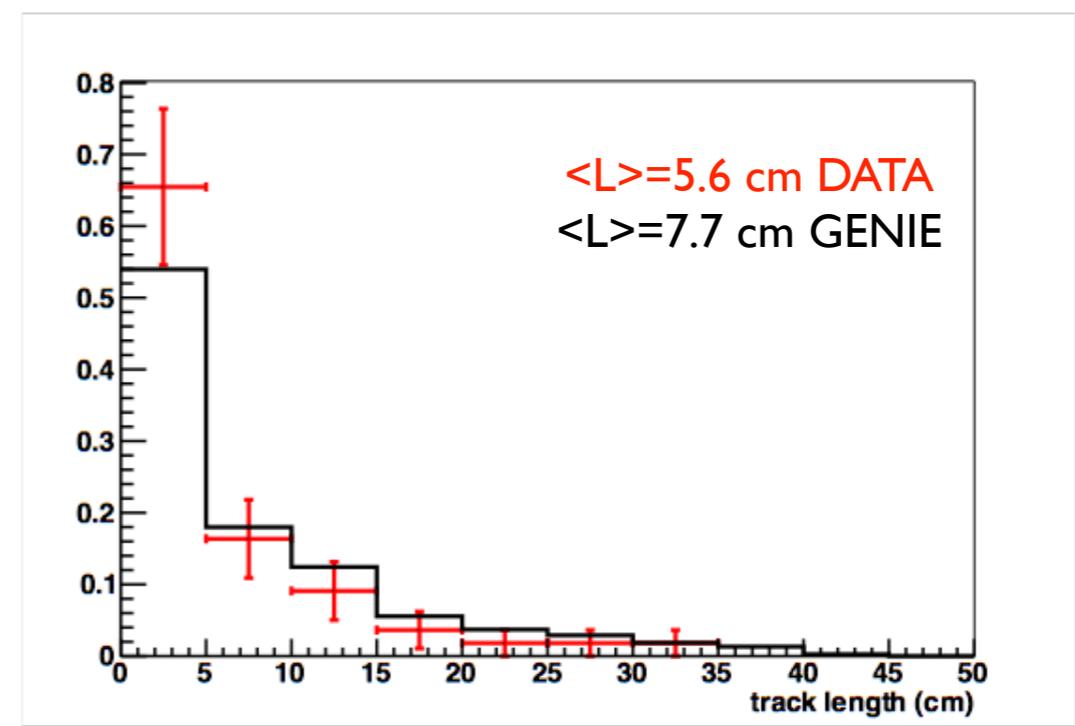
The MC generators predict varying amounts of proton emission and contributions from non-CCQE.

μ^+/μ^- **IP** events PROTON KINEMATICS

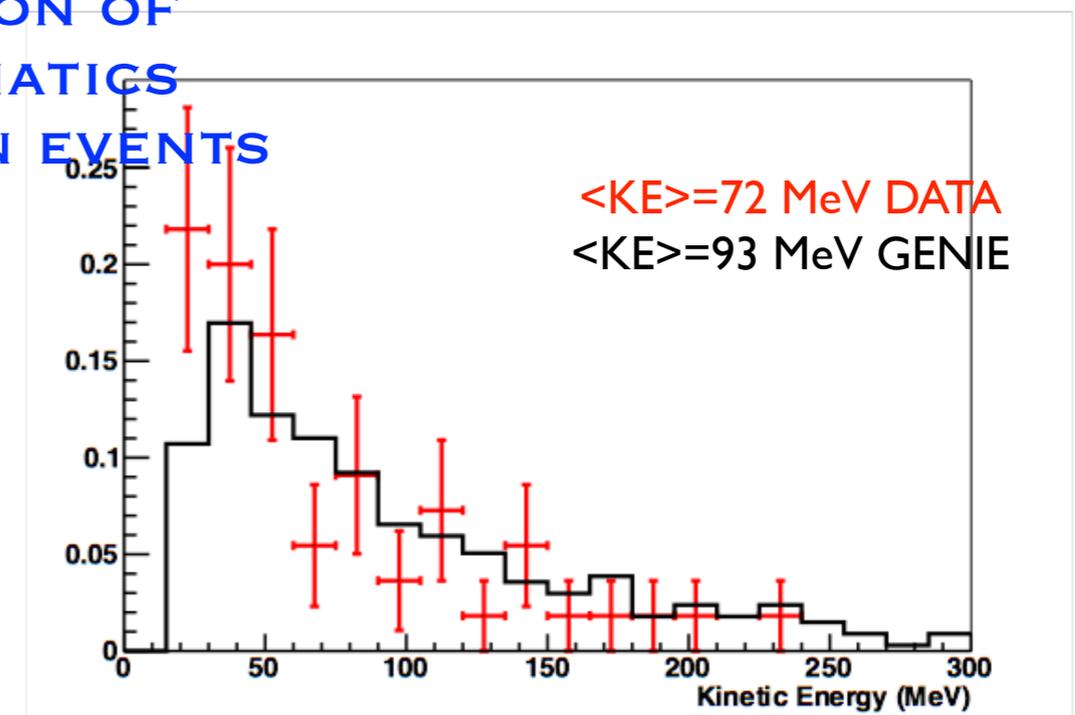
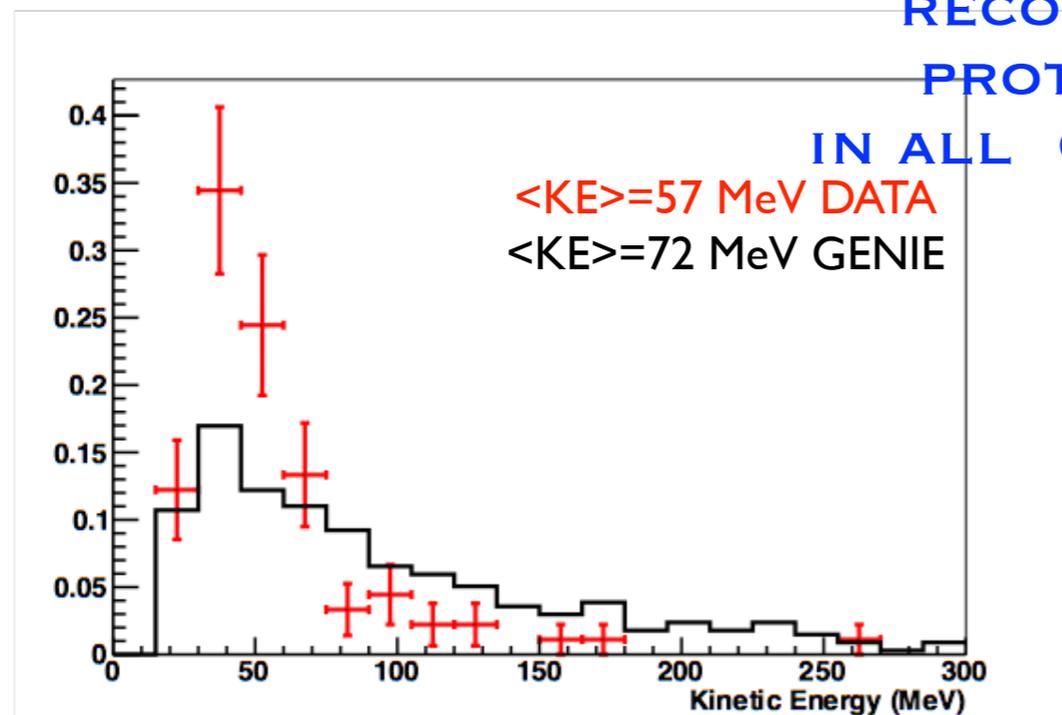
$\bar{\nu}_\mu$ - anti-neutrino mode run



ν_μ - anti-neutrino mode run

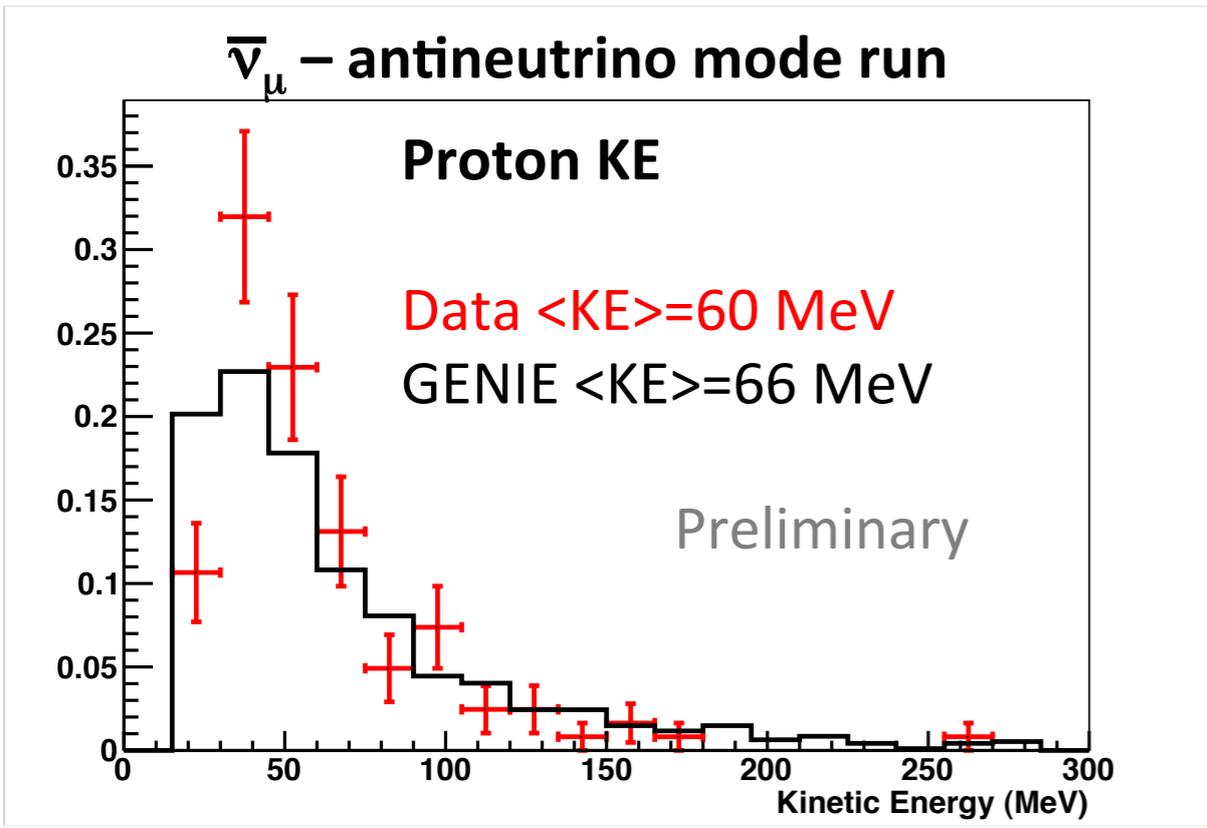


RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS

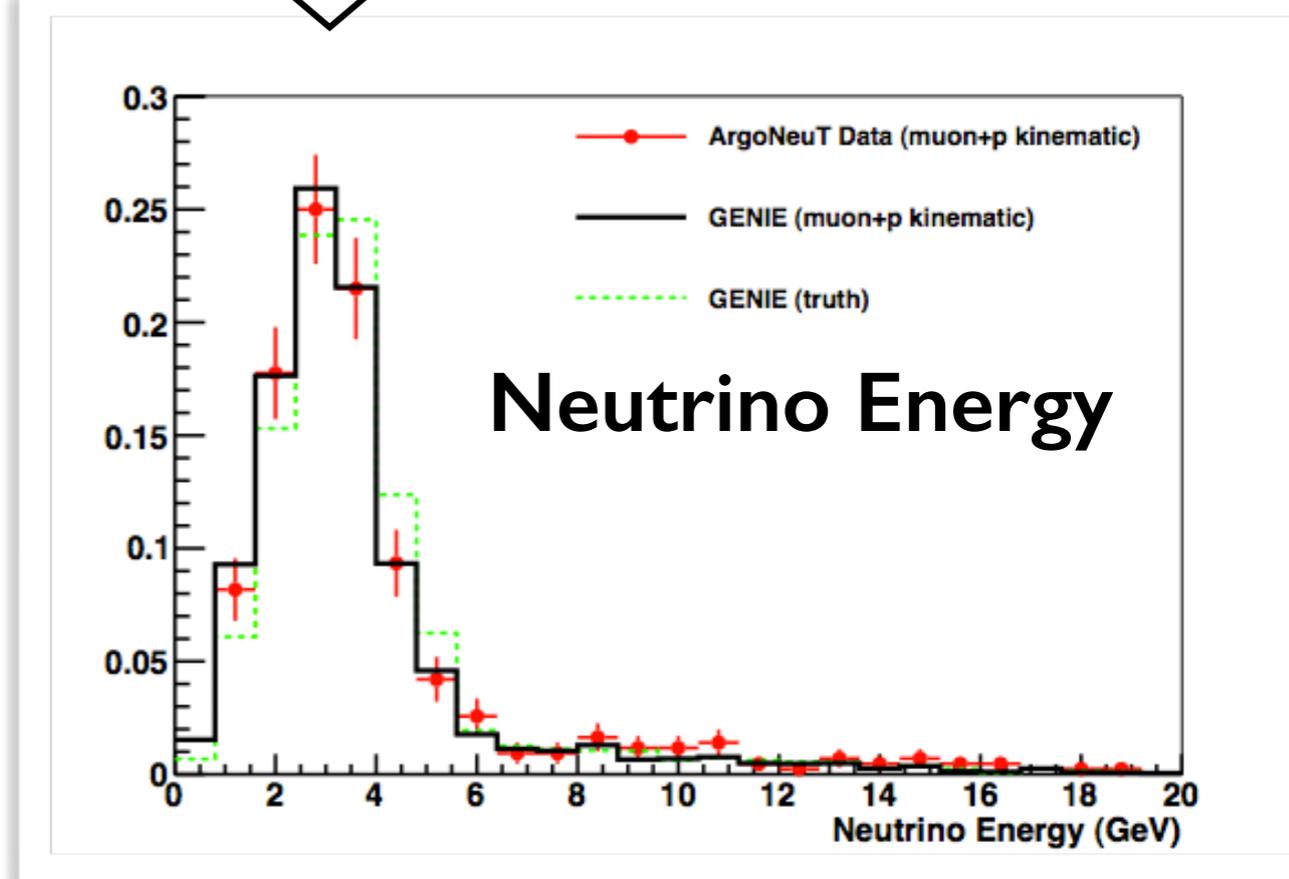
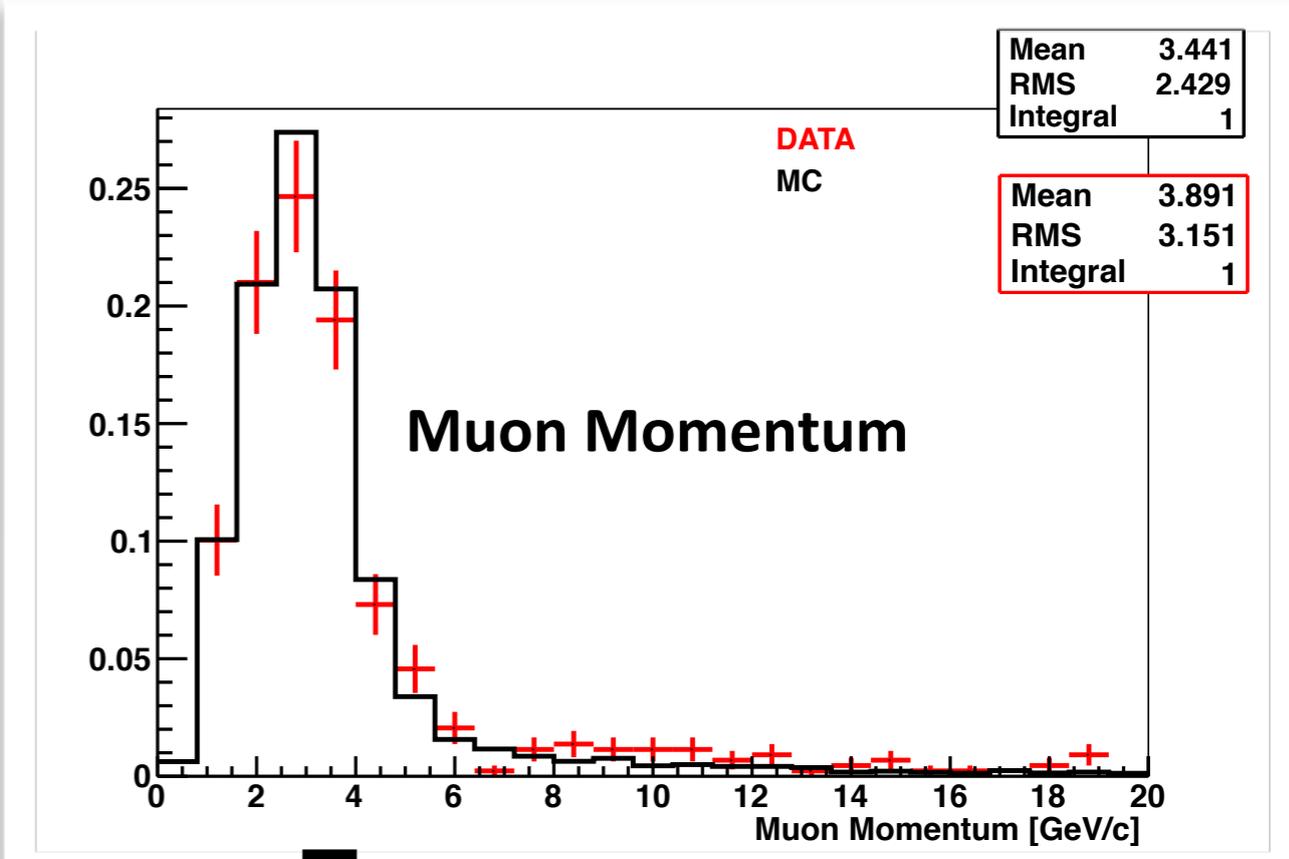


GENIE MC models more energetic protons

NEUTRINO ENERGY RECONSTRUCTION



+



Neutrino Energy from **muon+proton reconstructed kinematics**:

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

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

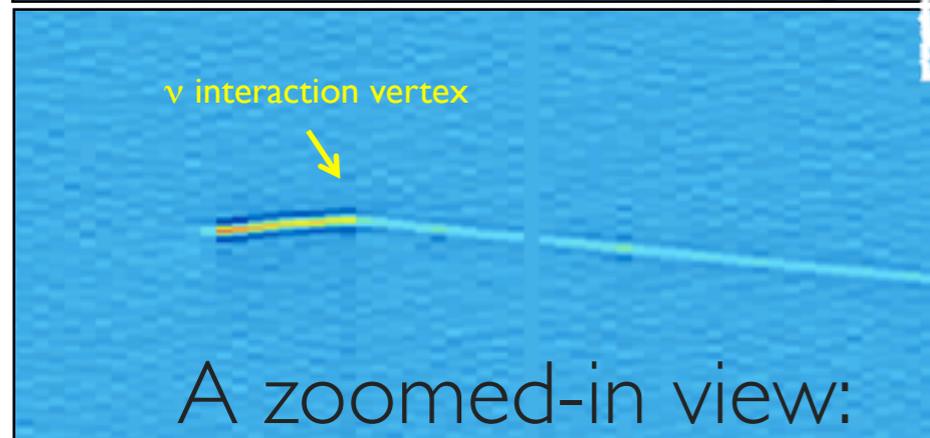
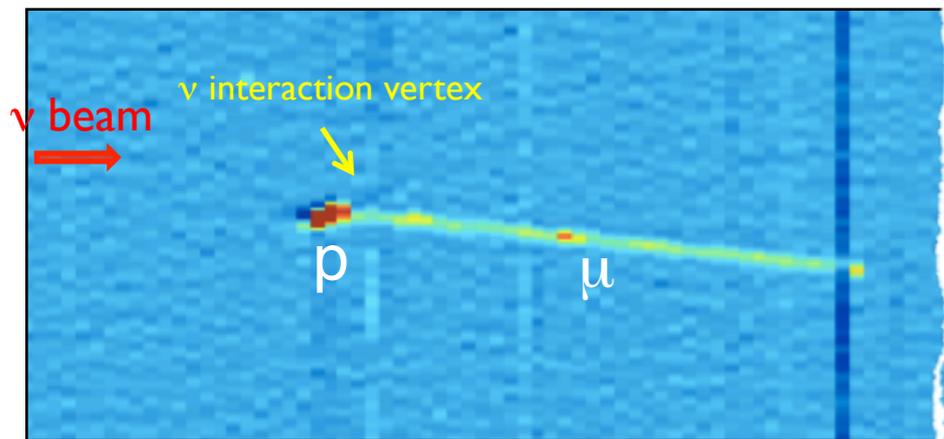
T_X = recoil energy of the residual nuclear system (estimated from missing transverse momentum)

No just muon information

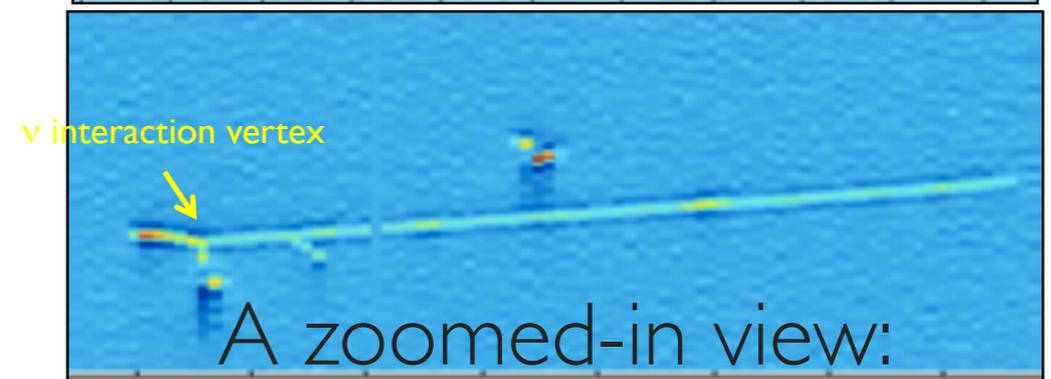
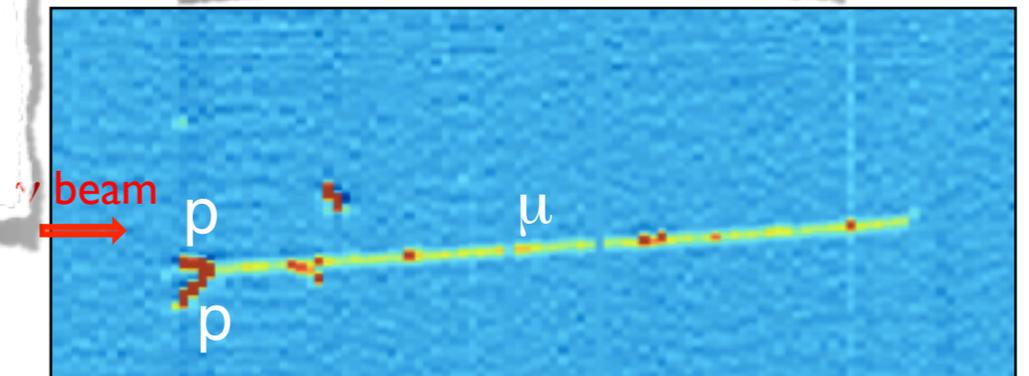
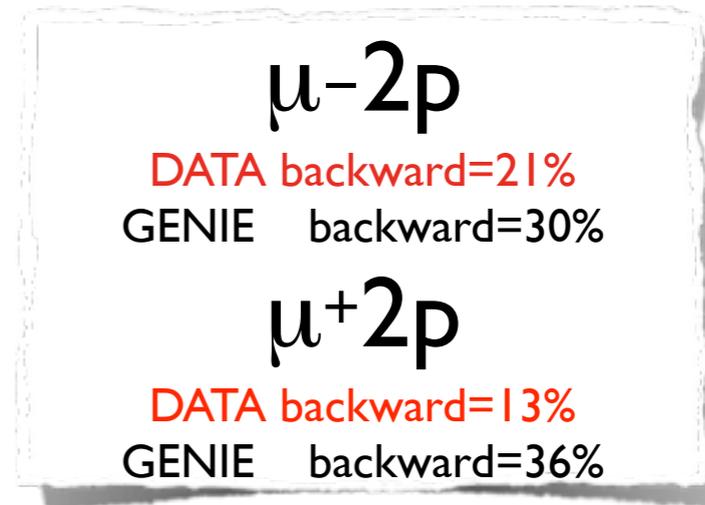
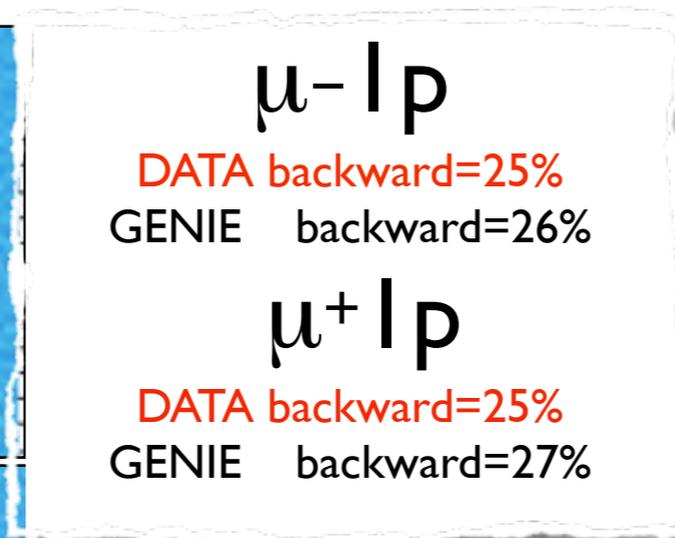
Reconstruction of other kinematic quantity (q, Q^2, p_{miss}^T etc.)

PROTON KINEMATICS: BACKWARD GOING PROTONS (B_P)

*Backward going protons are detected and reconstructed
in ArgoNeuT DATA*



A zoomed-in view:
 ν interaction with
one backward going p



A zoomed-in view:
 ν interaction with
two backward going p

**DETAILED STUDY OF B_P
IN PROGRESS**

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.

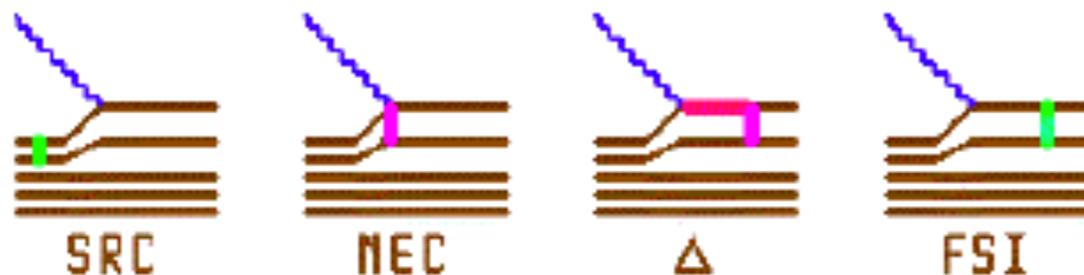
- We know (now) that about 20% Nucleons in Nuclei are in SRC (np) pairs

- Long range correlations (MEC) are very relevant and may change significantly XSECT measurements

- Pion absorption (two-body) is relevant

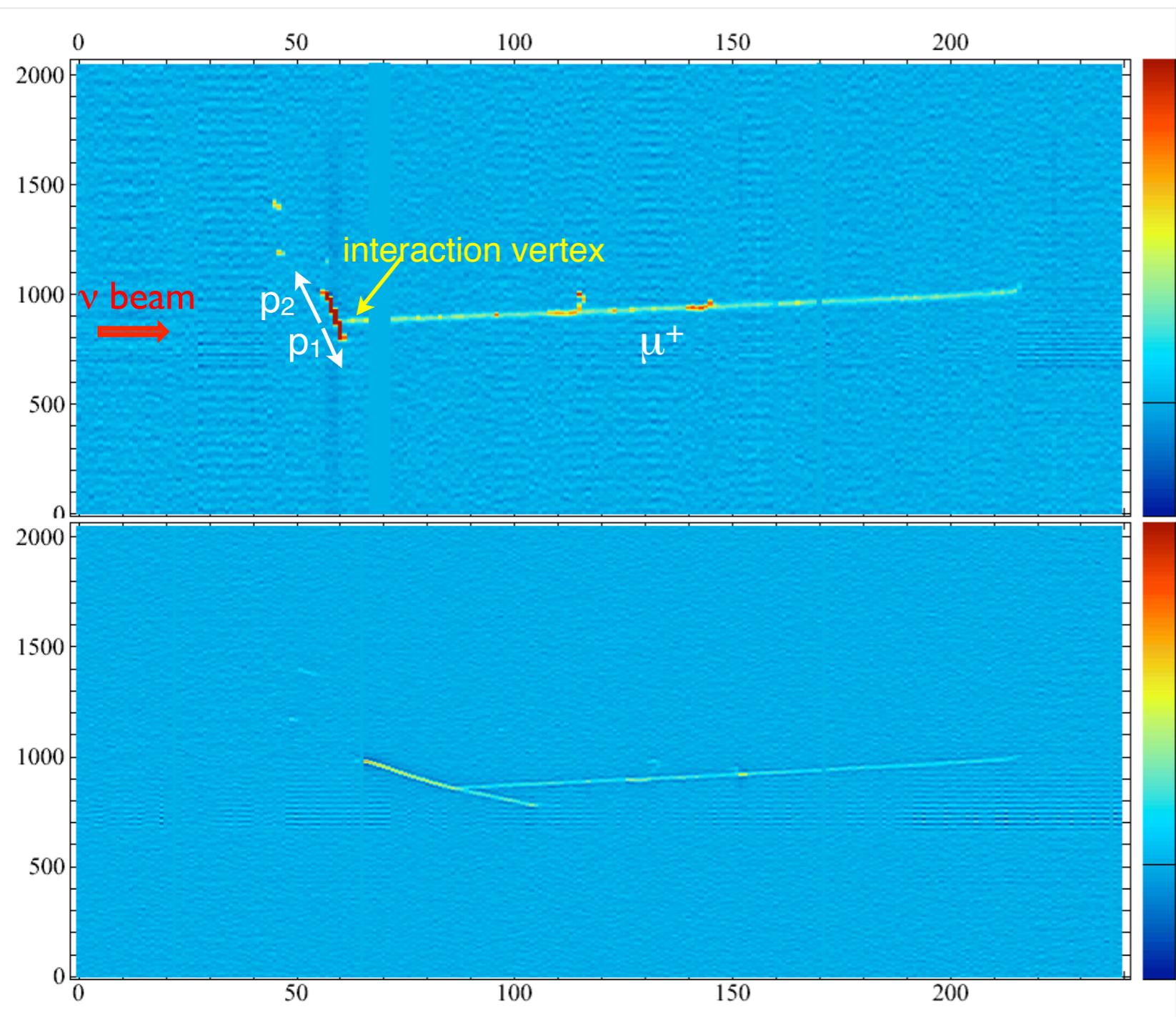
- FSI's are always a big pain!

- All these effects are combined and interfere w/ each other - (e.g. MEC can involve SRC pairs !)



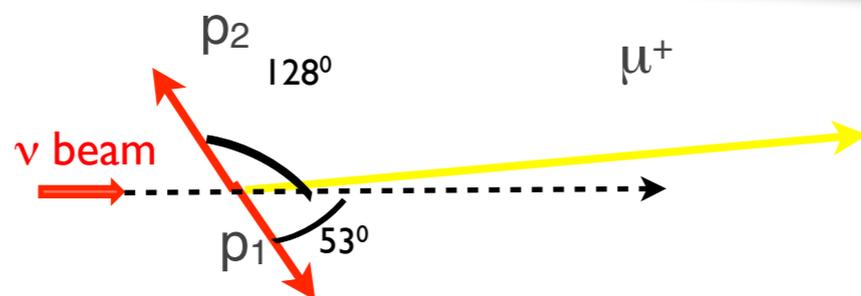
NN pairs in two-body processes may or may not be SRC pairs.

BACK-TO-BACK PROTON PAIR



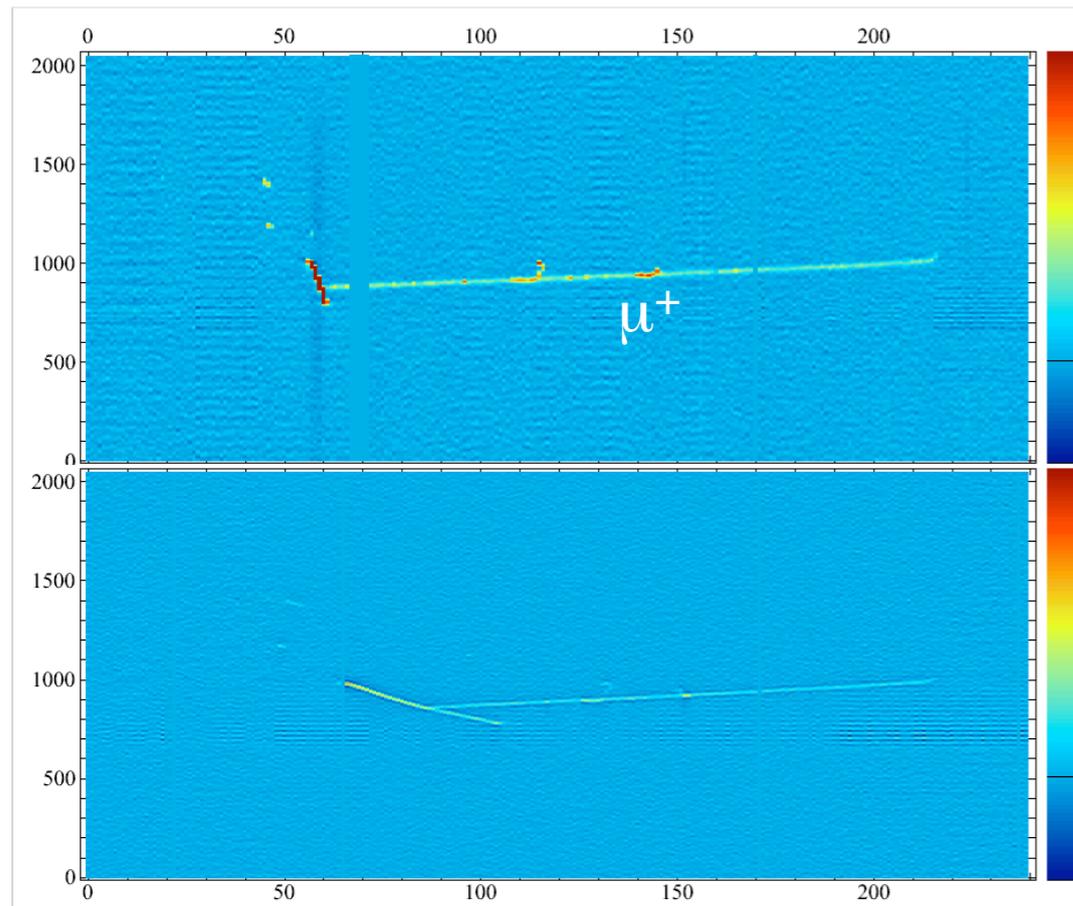
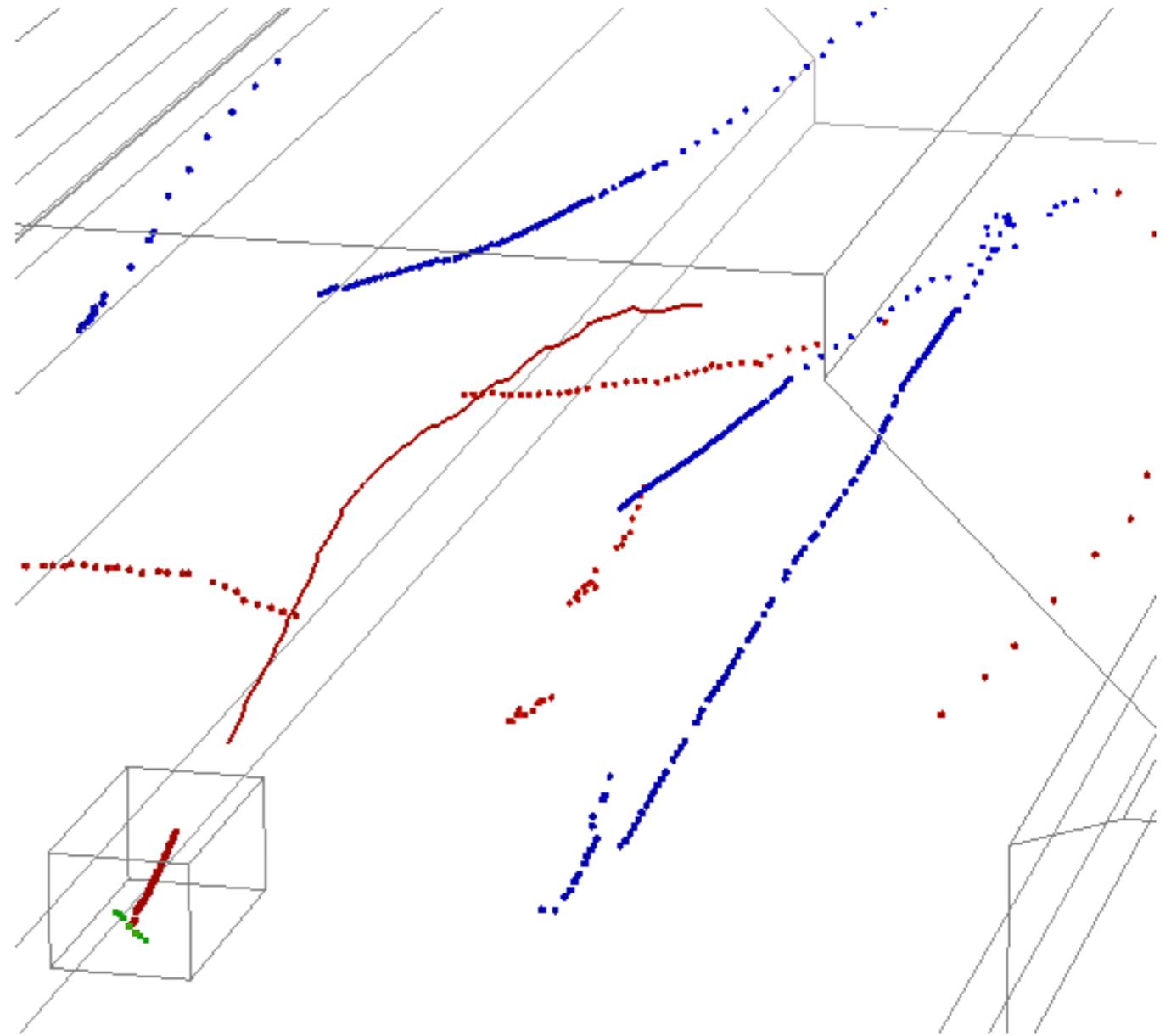
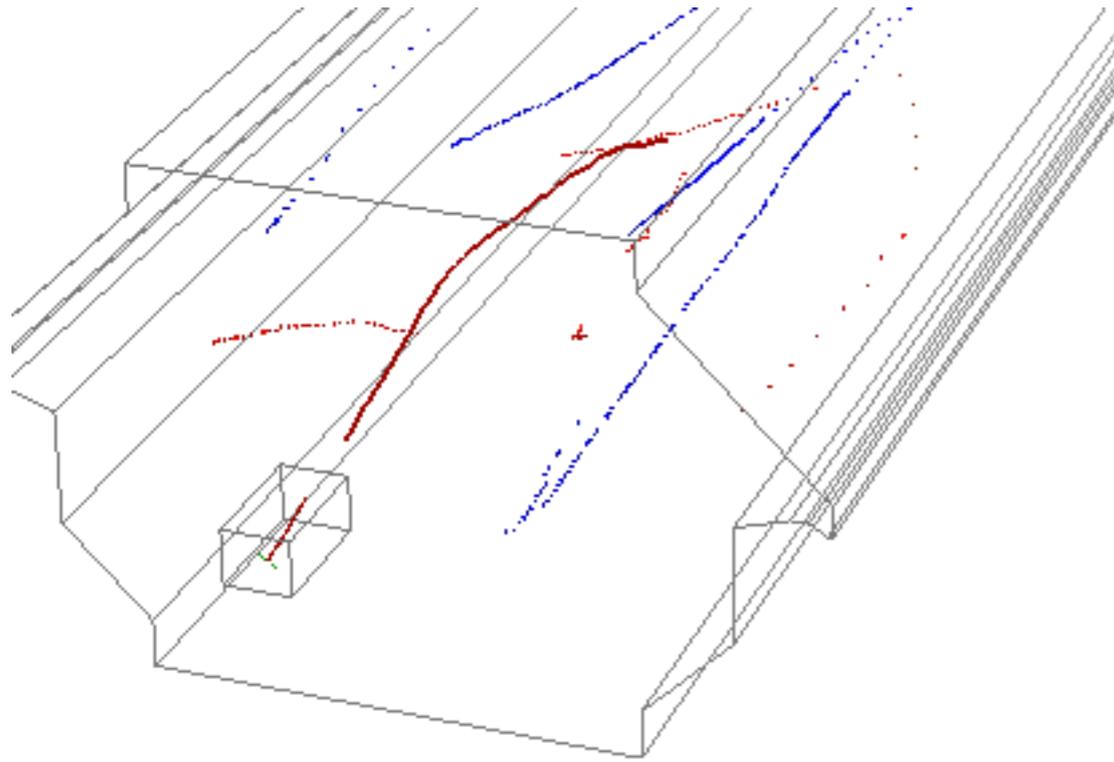
*Angle between two
protons $\gamma=177^\circ$*

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



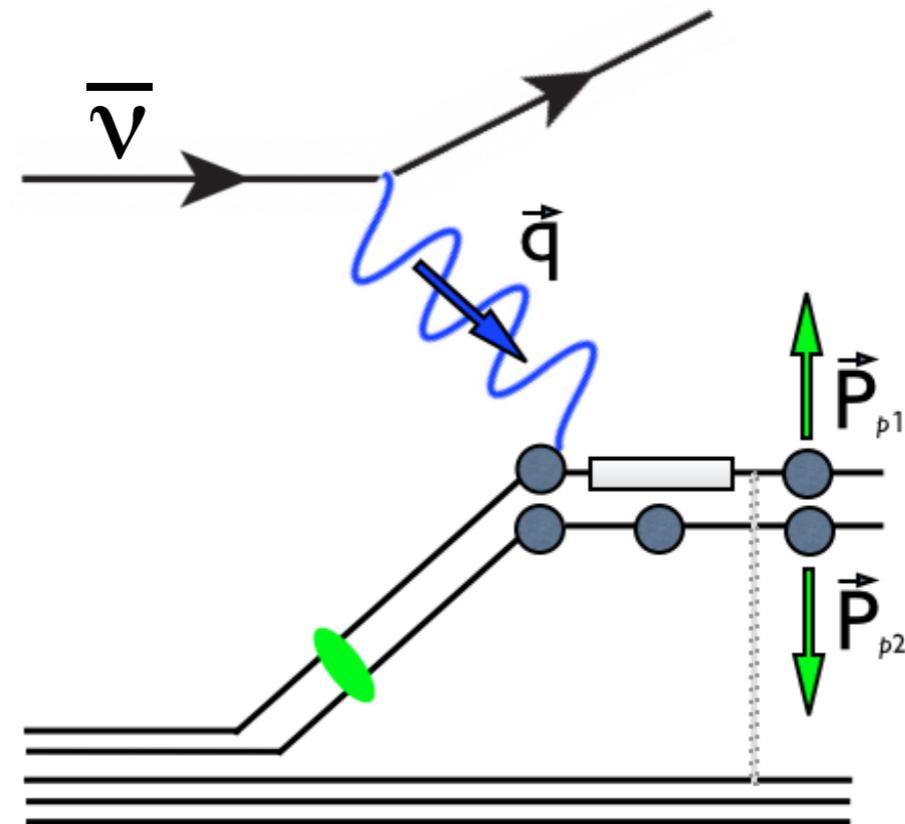
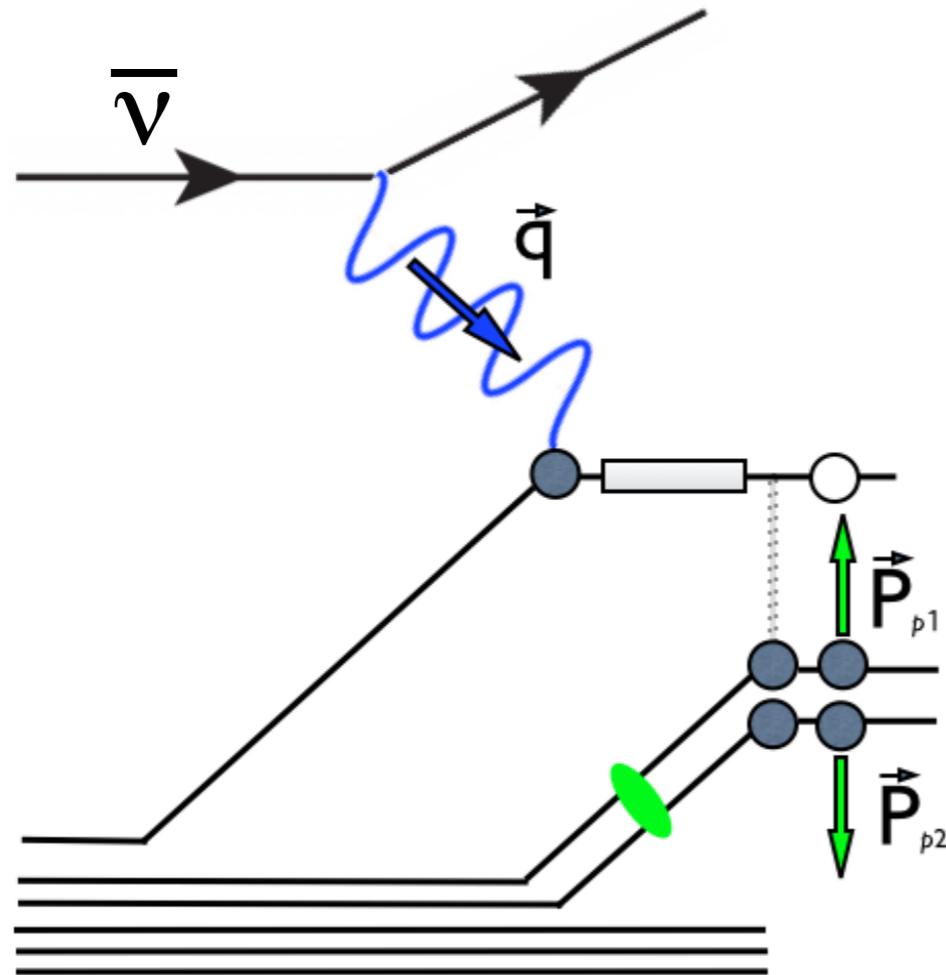
back-to-back protons

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



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

exploring possible mechanisms in analogy with neutrino Hammer events



Note: The QE mechanism (on single nucleon in a pair) is undetectable because $(np) + W^- \rightarrow (nn)$

