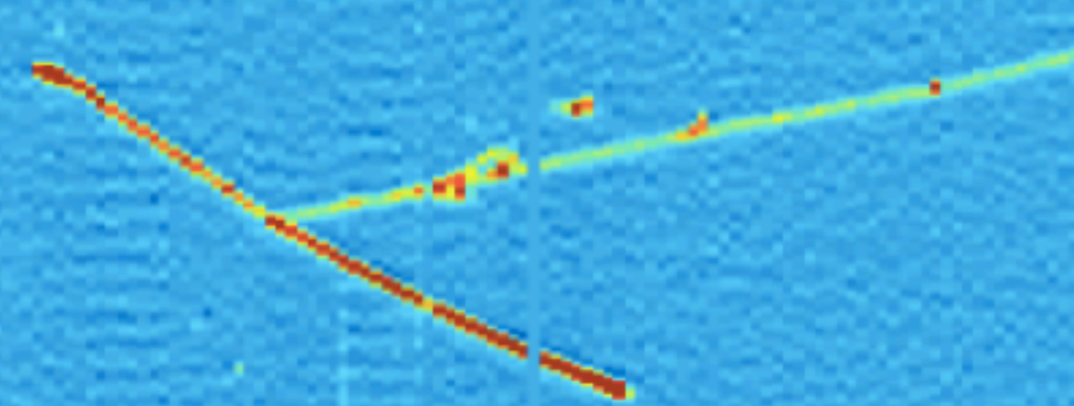
Detecting CC 0 pion events in LAr -

Cross sections and back-to-back proton events in ArgoNeuT



ArgoNeuT event

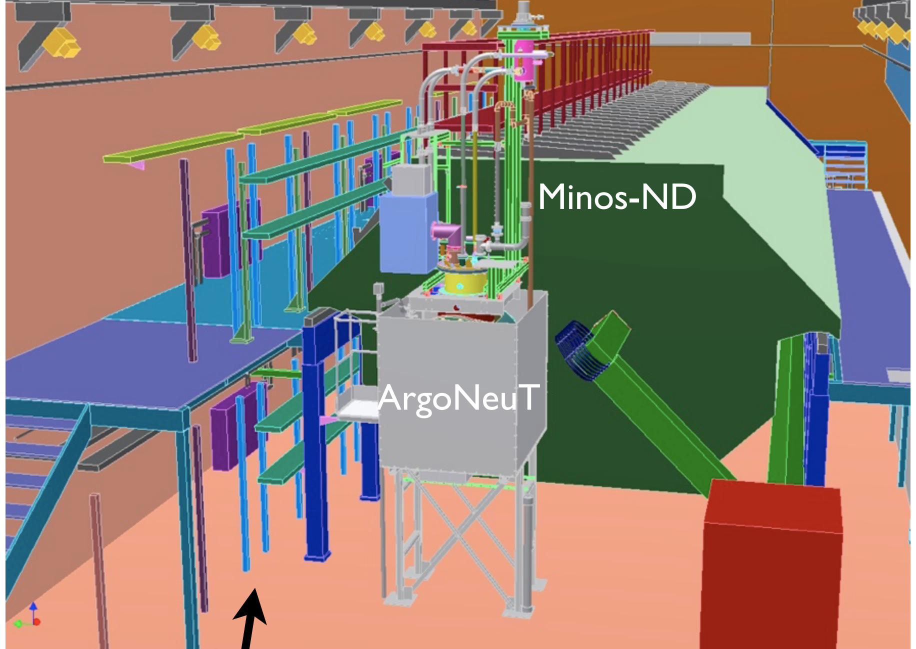
NUINT14

May 21st 2014 - Surrey UK

Ornella Palamara

Yale University, USA*

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



ArgoNeuT

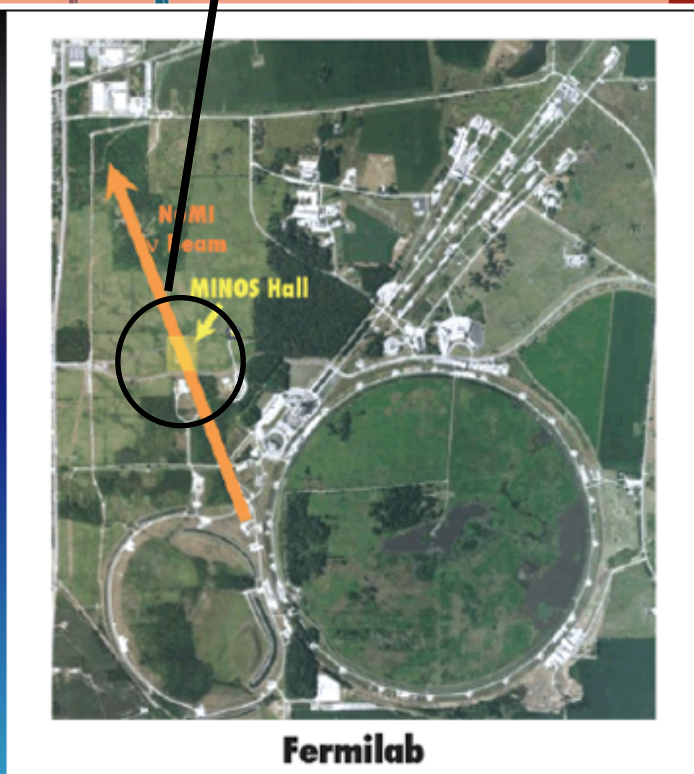
NuMI LE beam
ν−mode (2 weeks):
8.5×10^{18} POT
$\bar{\nu}$−mode (5 months):
1.20×10^{20} POT

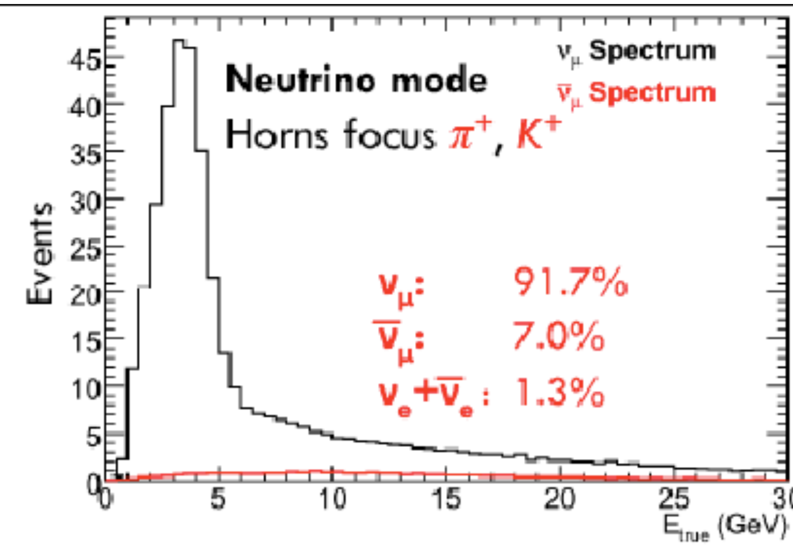
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

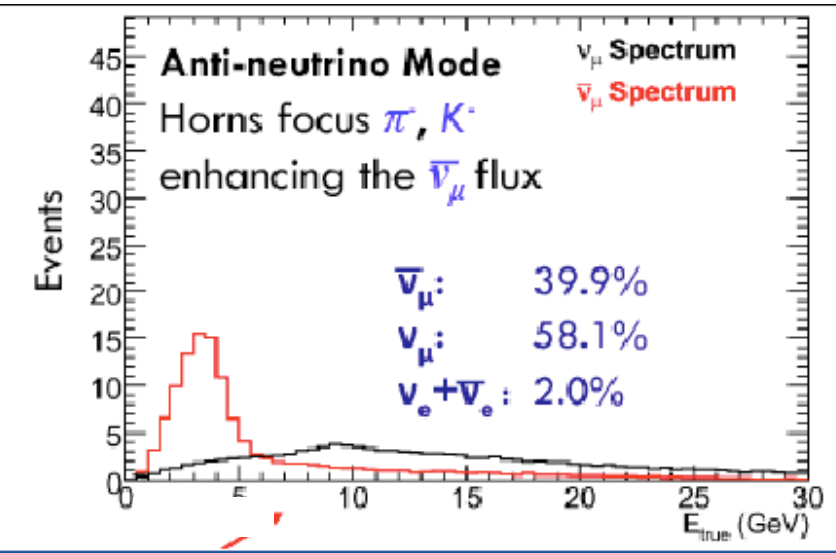
170 l active volume
$47 \times 40 \times 90$ cm^3, wire spacing 4 mm
LAr TPC

~7000 CC events collected

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

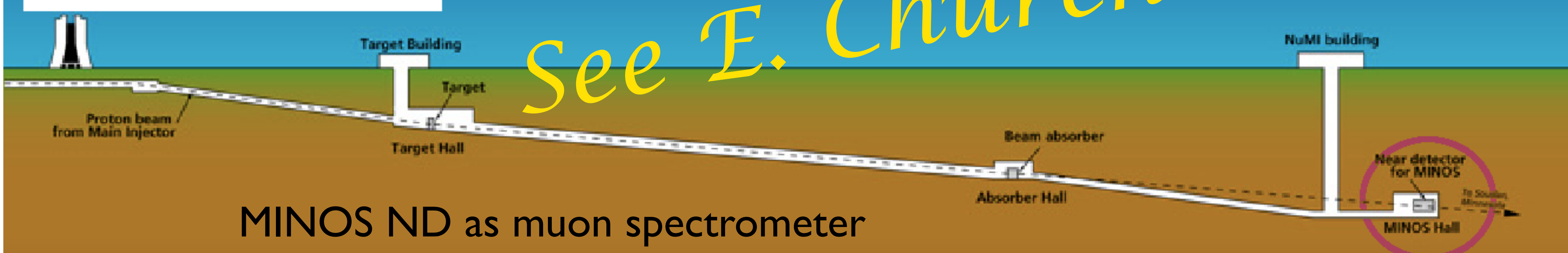






NuMI LE beam

See E. Church talk



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*

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

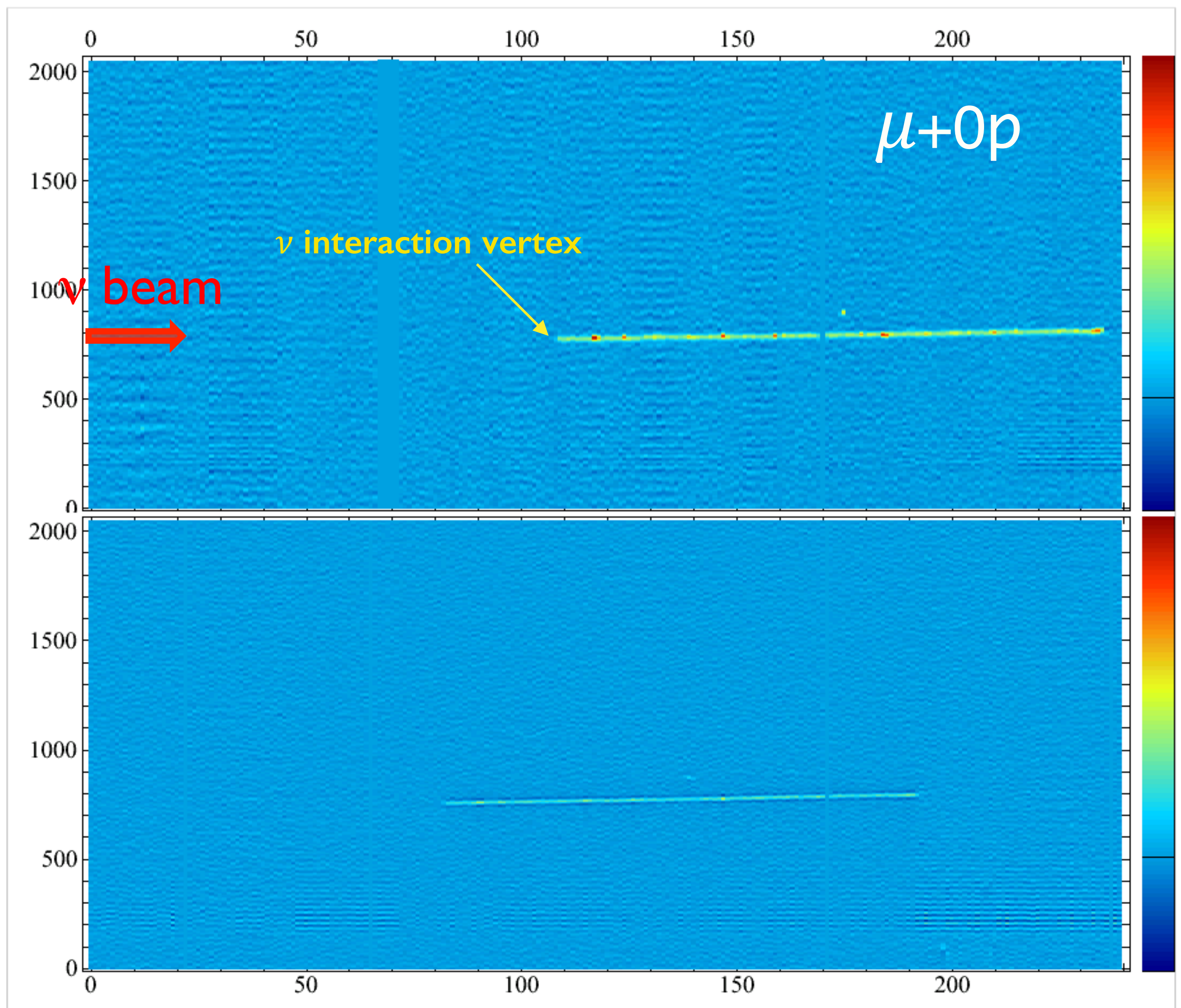
EVENT TOPOLOGY: leading muon accompanied by any number (N=0, 1, 2, 3, 4) of protons final state

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



2D views from the two wire planes

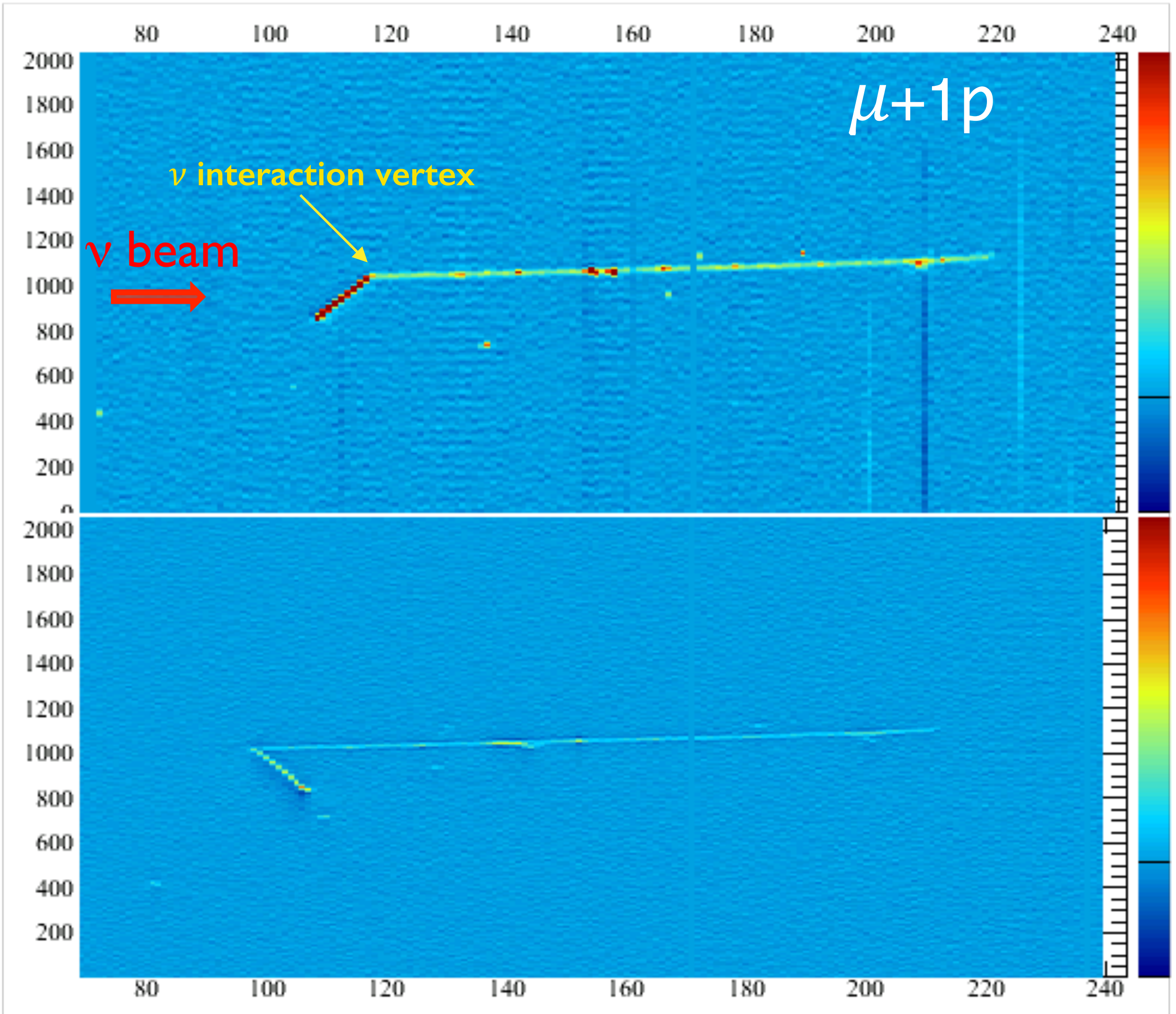
*The muon+Np sample can also contain neutrons. The presence of neutrons in the events cannot be measured, since ArgoNeuT volume is too small to have signicant chances for n to convert into protons in the LAr volume before escaping.

ArgoNeuT ν_μ CC 0 pion topological analysis

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

(low proton energy threshold)

Analysis fully exploiting LAr TPC's capabilities



2D views from the two wire planes

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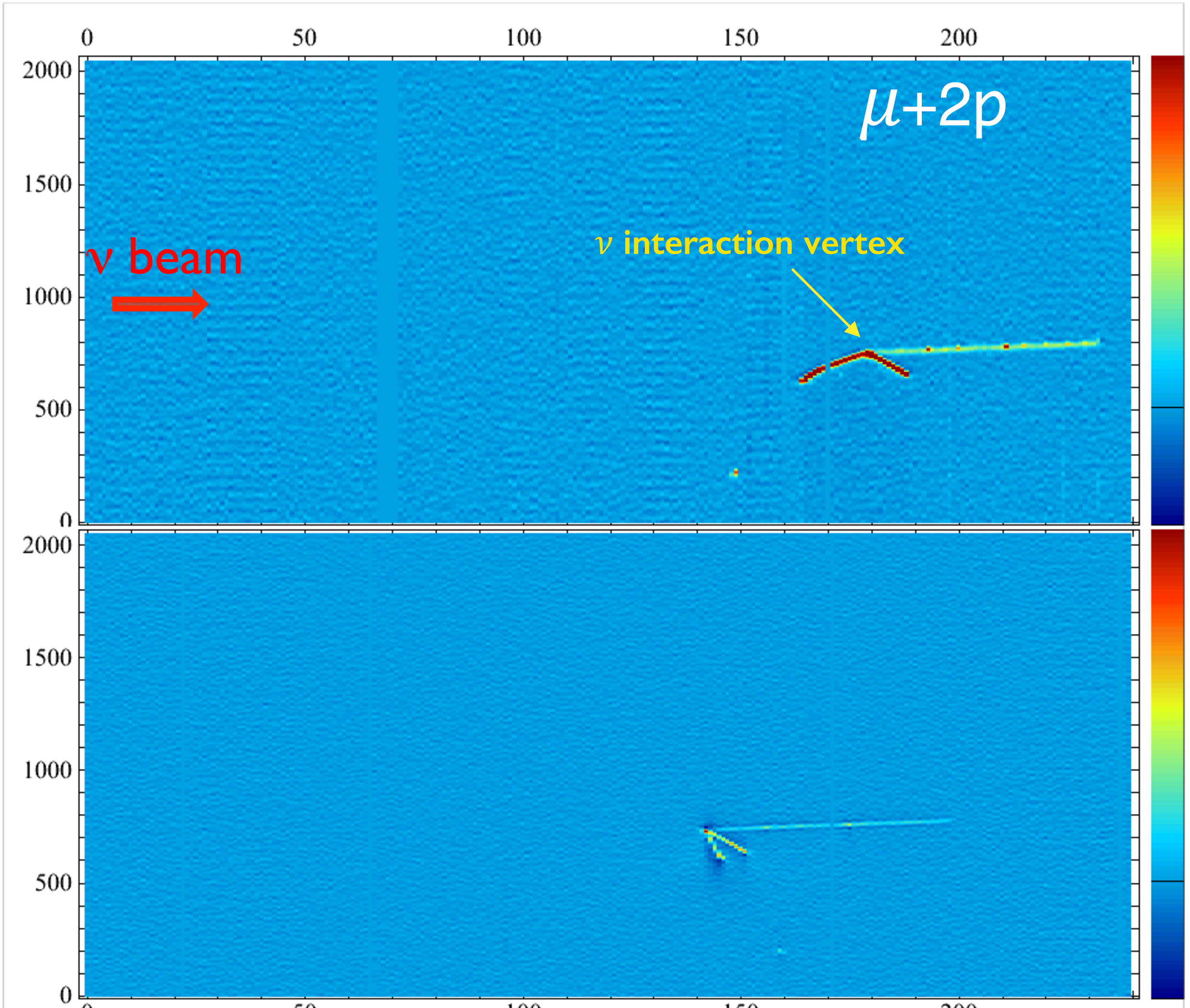


2D views from the two wire planes

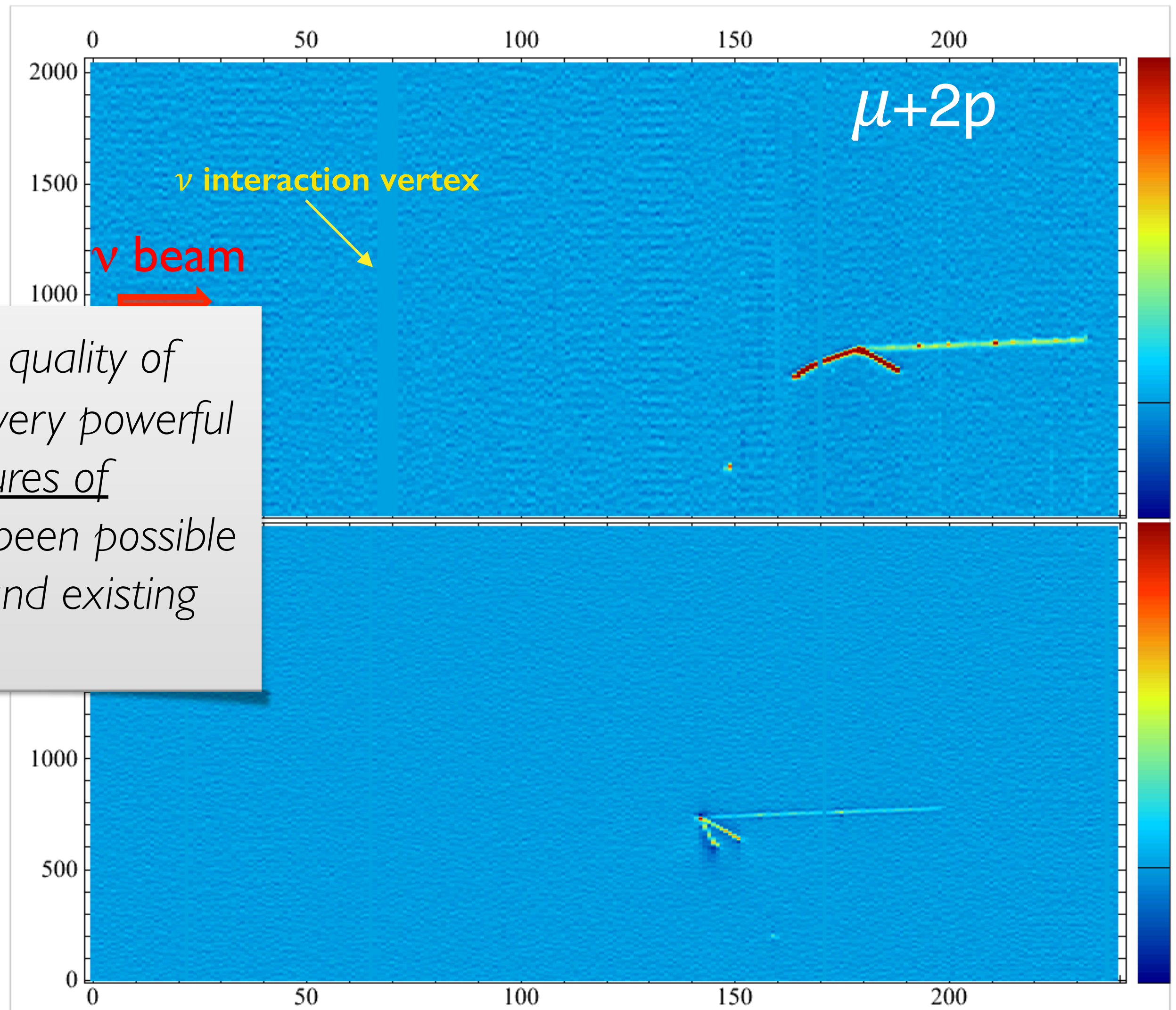
Multi-p accompanying the leading muon

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



2D views from the two wire planes

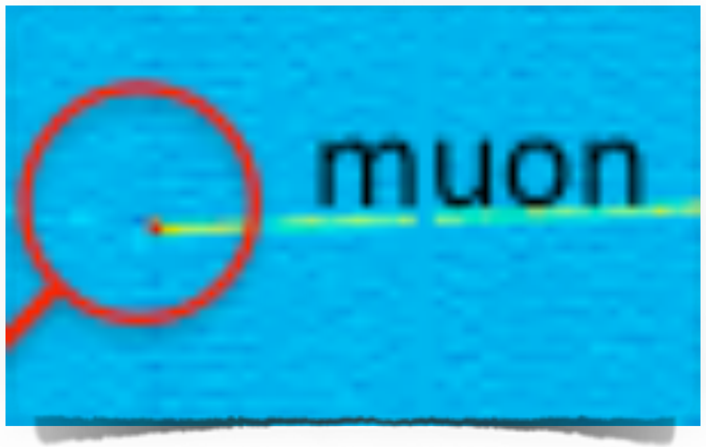
Note: *Due to bubble-chamber like quality of LArTPC, visual scanning presents a very powerful tool that allows to learn about features of neutrino interactions that have not been possible to explore with other technologies and existing experiments.*

(ν_μ +Np) events: Primary measurements

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

ν_μ events: ~50% N≠1

$\bar{\nu}_\mu$ events: ~32% N≠0



- ***Muon and proton kinematics*** in events with different proton multiplicity

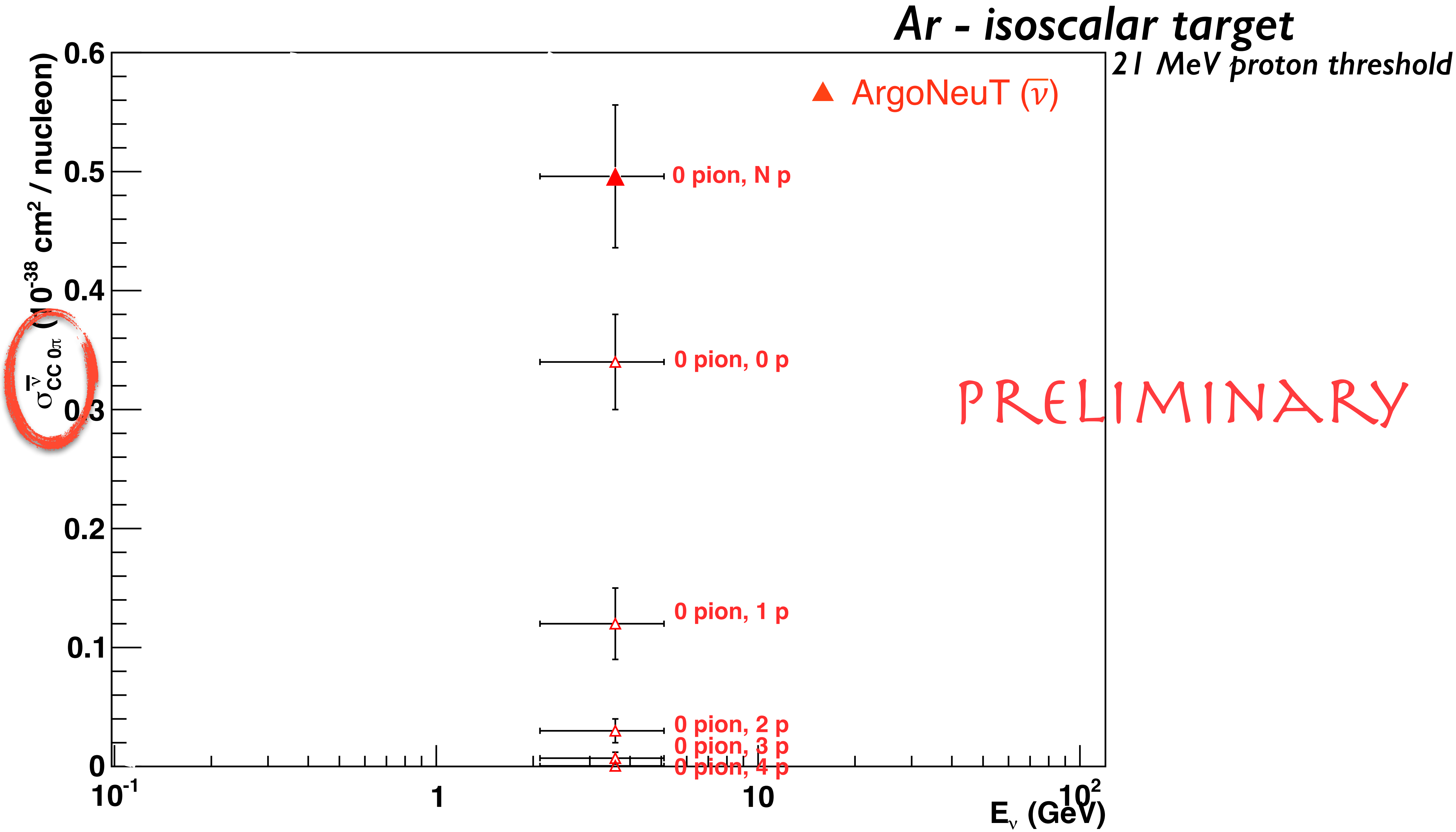
- Most precise ***reconstruction of the incoming neutrino energy*** from ***lepton AND proton reconstructed kinematics***

TODAY:

✓ Anti-neutrino ***CC 0 pion cross sections***

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

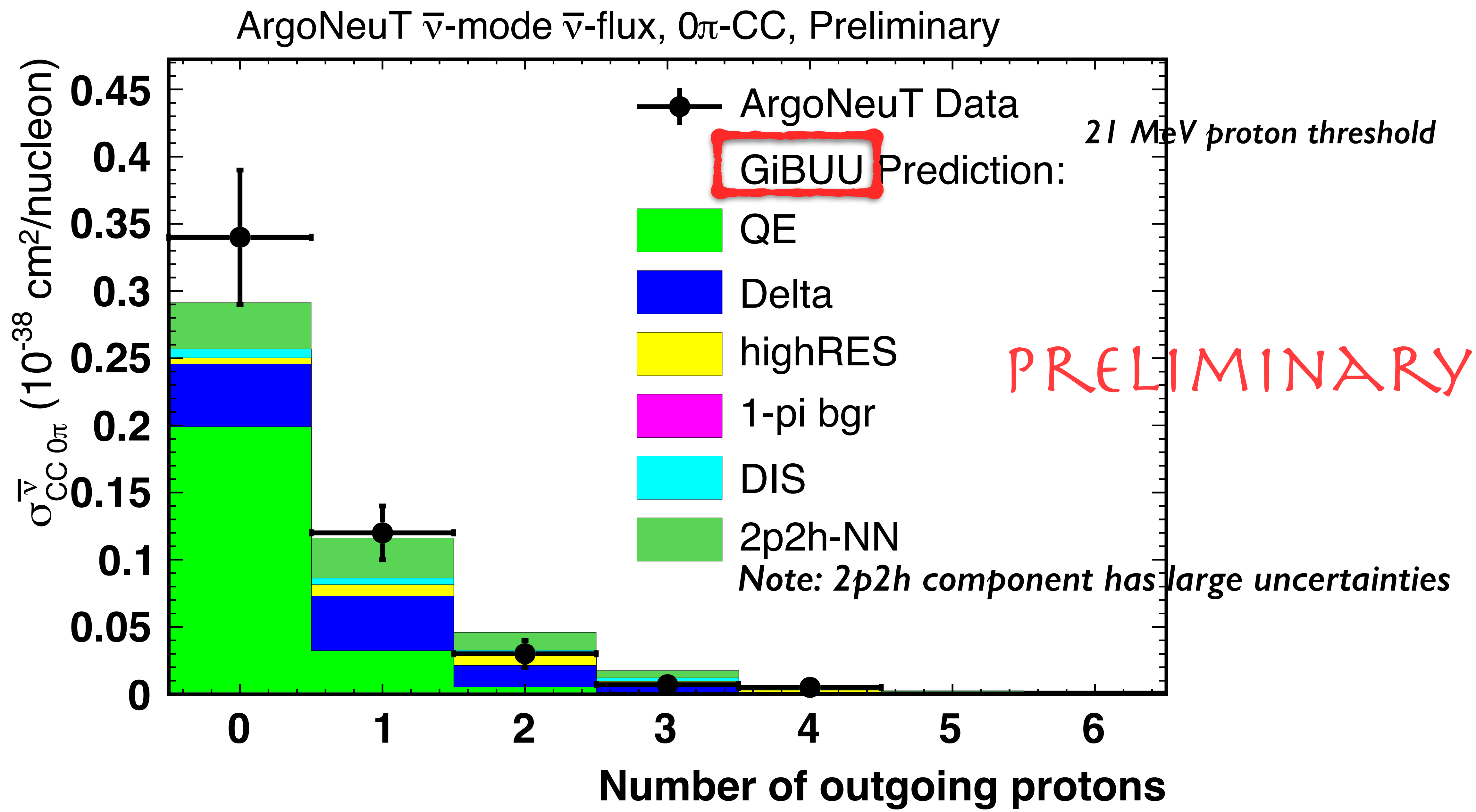
anti-ν_μ CC 0 pion cross section



$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.50 \pm 0.03(stat.) \pm 0.06(syst.)\ 10^{-38} cm^2$$

at <E_ν>=3.6± 1.5 GeV

anti-ν_μ CC 0 pion cross section - comparison with GiBUU MC*



$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.48\ 10^{-38} cm^2/nucleon$$

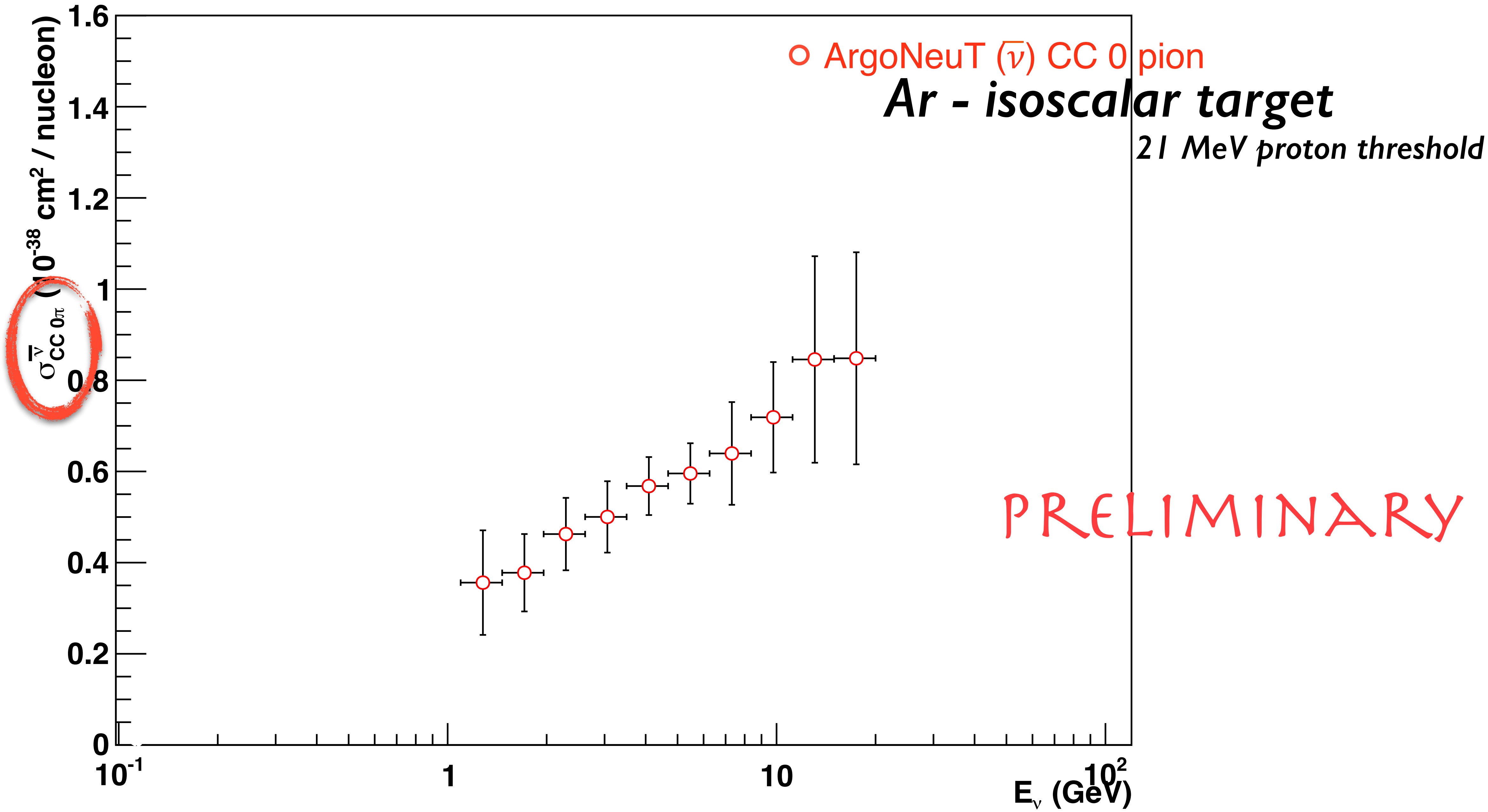
GiBUU MC

$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.50 \pm 0.03(stat.) \pm 0.06(syst.)\ 10^{-38} cm^2$$

ArgoNeuT data

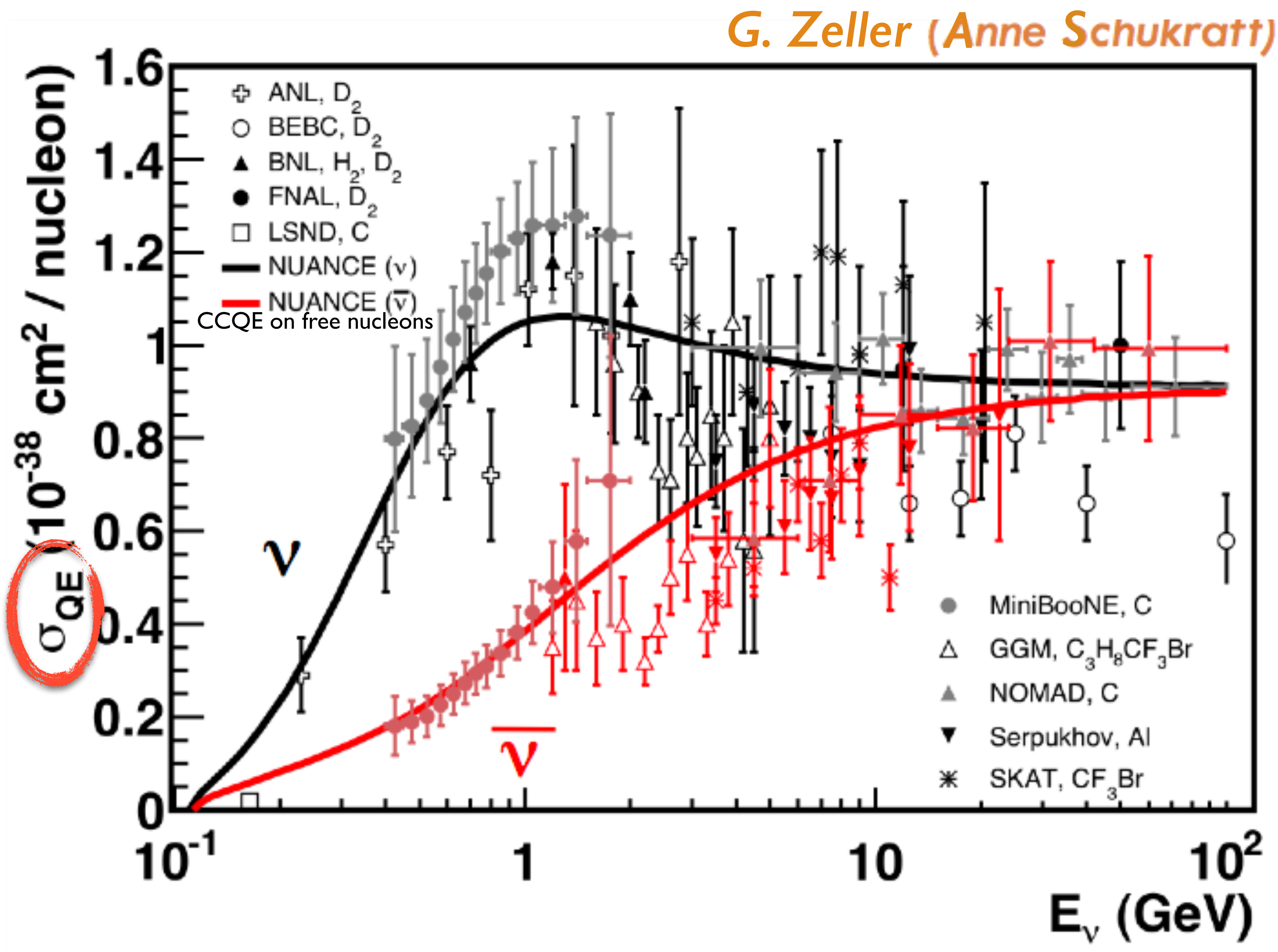
*ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

anti-ν_μ CC 0 pion cross section as a function of the **reconstructed*** neutrino energy



from ***lepton AND proton reconstructed kinematics:*** $E_\nu = (E_\mu + \sum T_{pi} + T_X + E_{miss})$

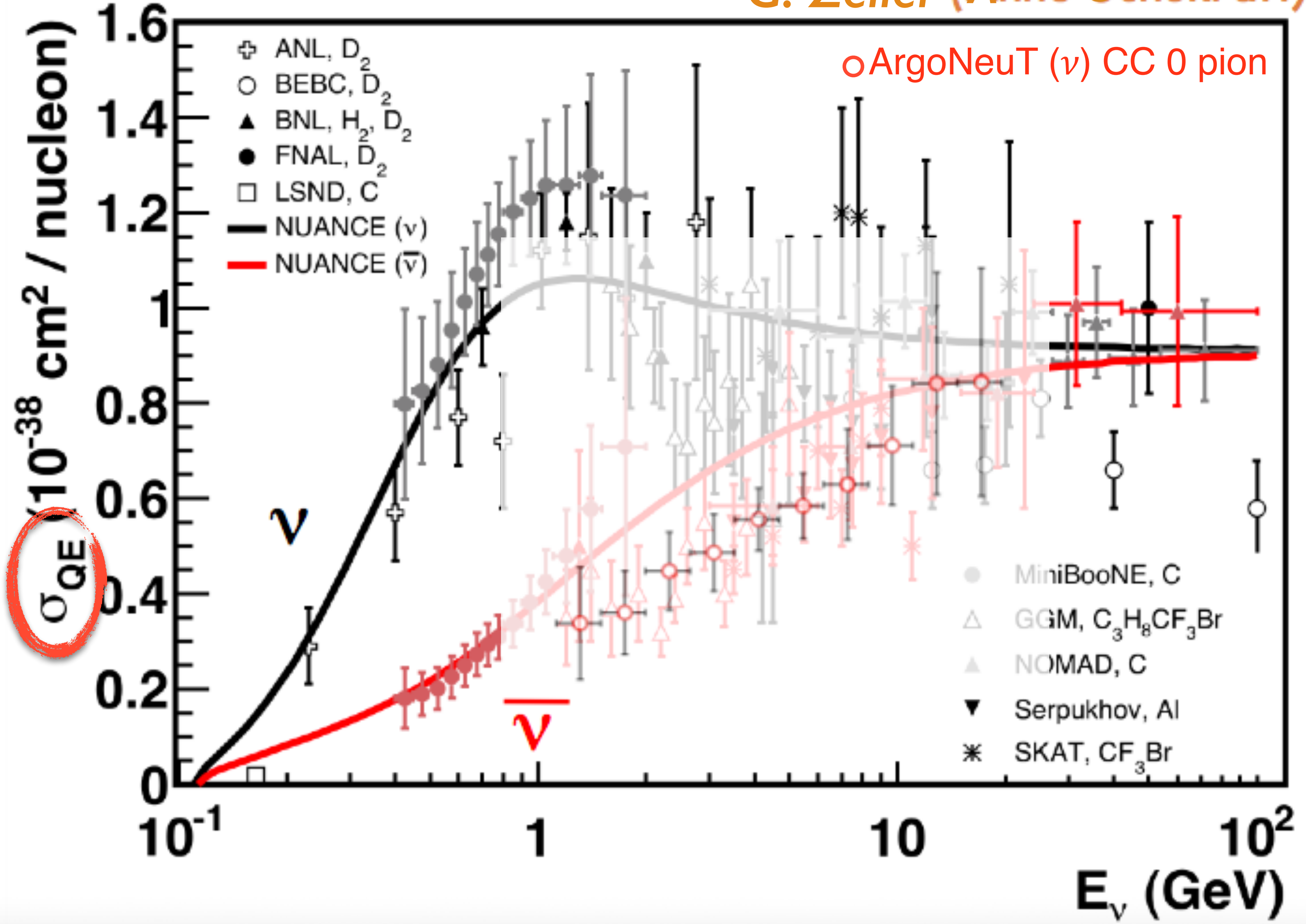
T_X=recoil energy of the residual nuclear system [estimated from missing transverse momentum],
E_{miss}=missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value)]



G. Zeller (Anne Schukratt)
ANL, D2
BEBC, D2
BNL, H2, D2
FNAL, D2
LSND, C
NUANCE (ν)
NUANCE (ν̄)
CCQE on free nucleons
MiniBooNE, C
GGM, C3H8CF3Br
NOMAD, C
Serpukhov, Al
SKAT, CF3Br
ν
ν̄
σQE (10-38 cm2 / nucleon)
Eν (GeV)

anti-ν_μ CC 0 pion cross section as a function of the **reconstructed*** neutrino energy

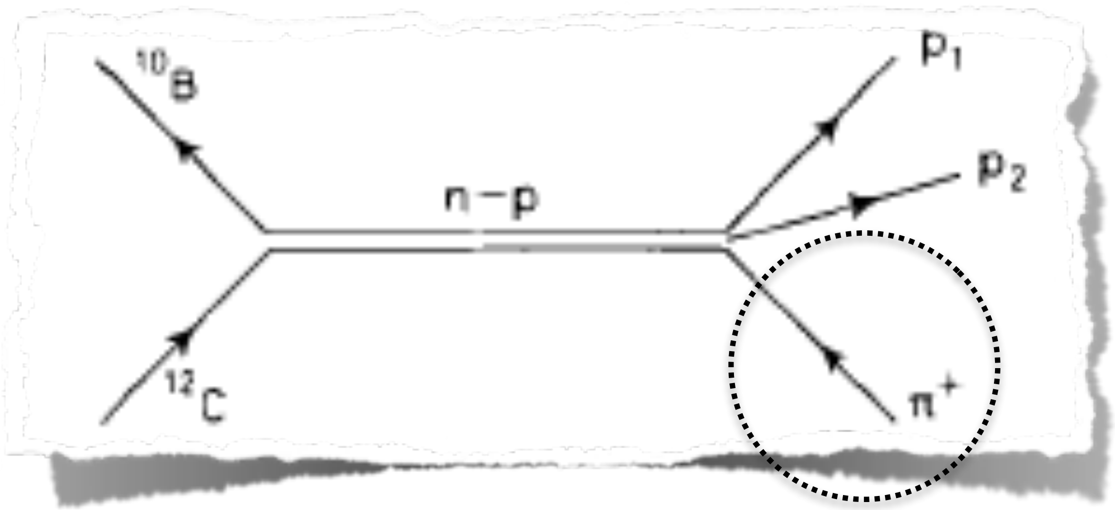
G. Zeller (Anne Schukraft)

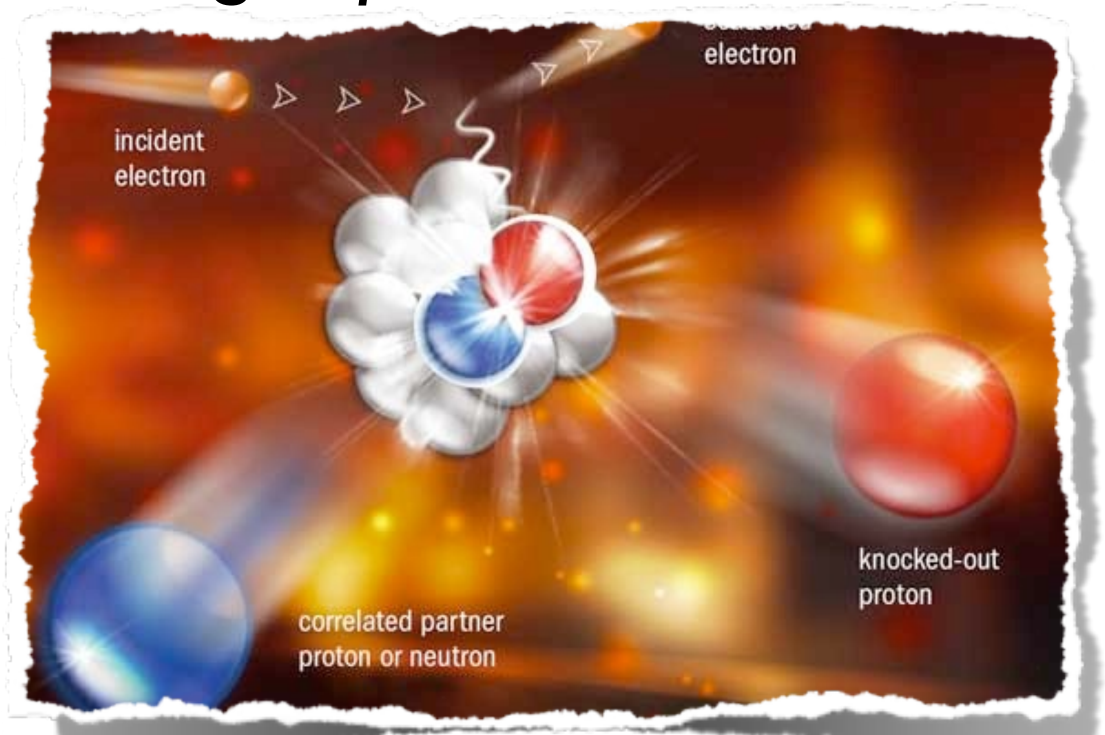


Note:
comparison of ArgoNeuT CC 0 pion data with CCQE experimental data and CCQE NUANCE predictions is reported just as guidance

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

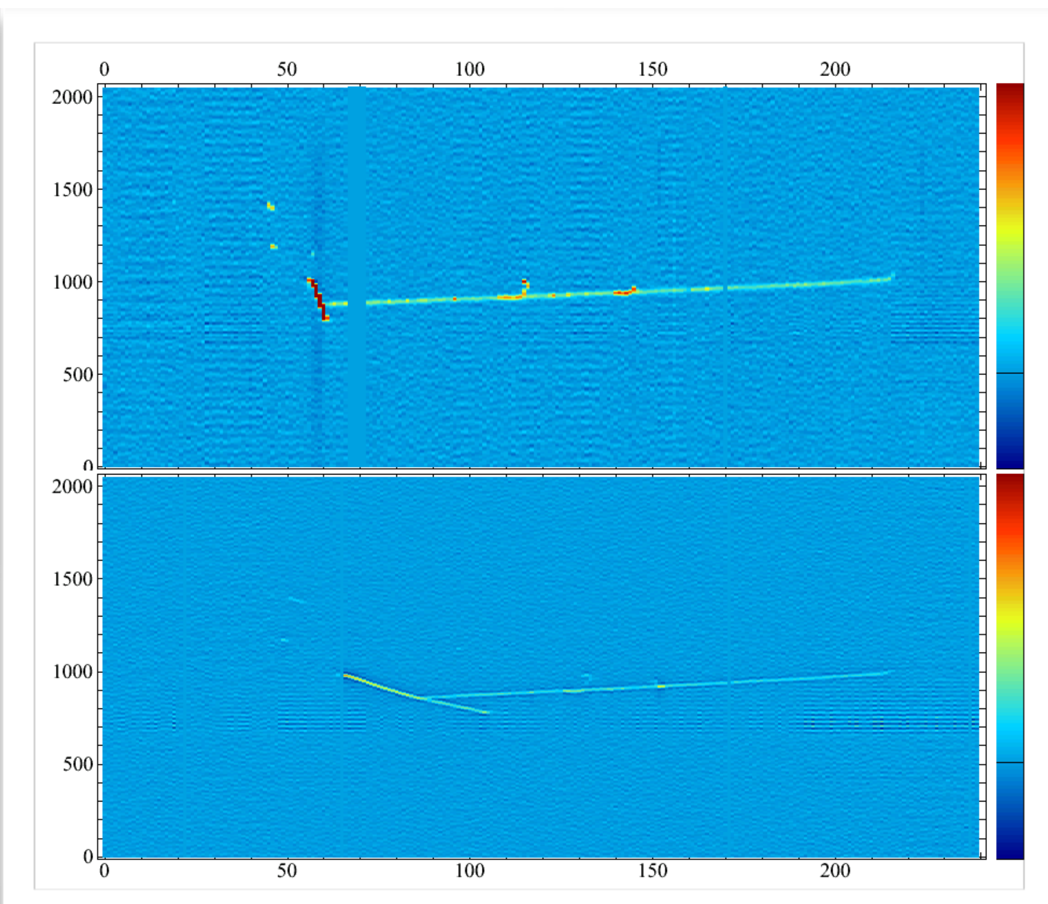
(μ^-+2p) data sample

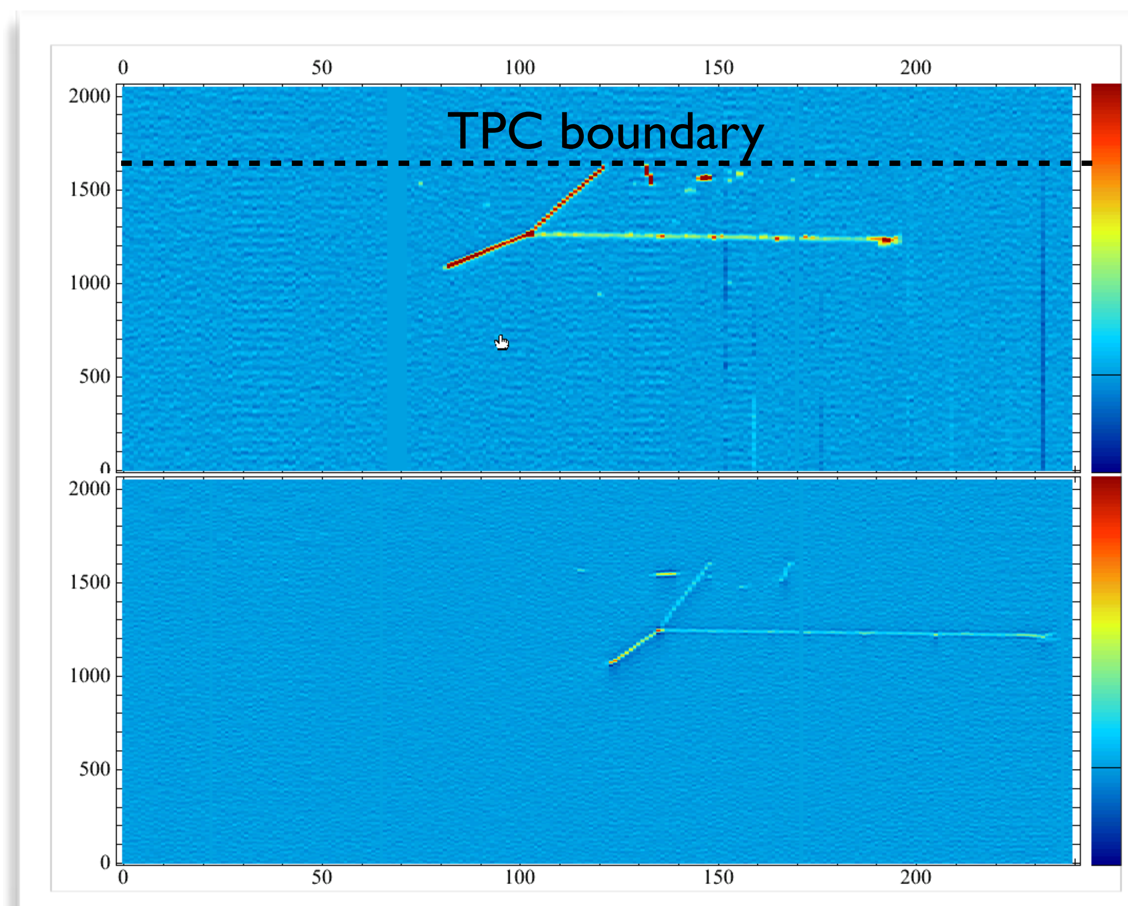
Data sample: N=2 protons in final state, i.e. (μ^-+2p) triple coincidence topology events

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).





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

- According to GENIE MC simulation: ~40% of (μ^-+2p) are due to CC QE interactions and about 40% to CC RES pionless interactions.

**muon momentum resolution 5-10% from MINOS-ND*
proton angular resolution: 1-1.5^0 , depending on track length
proton energy resolution: ~6% for protons above Fermi momentum

(μ^-+2p) data sample - **Hints for NN SRC**

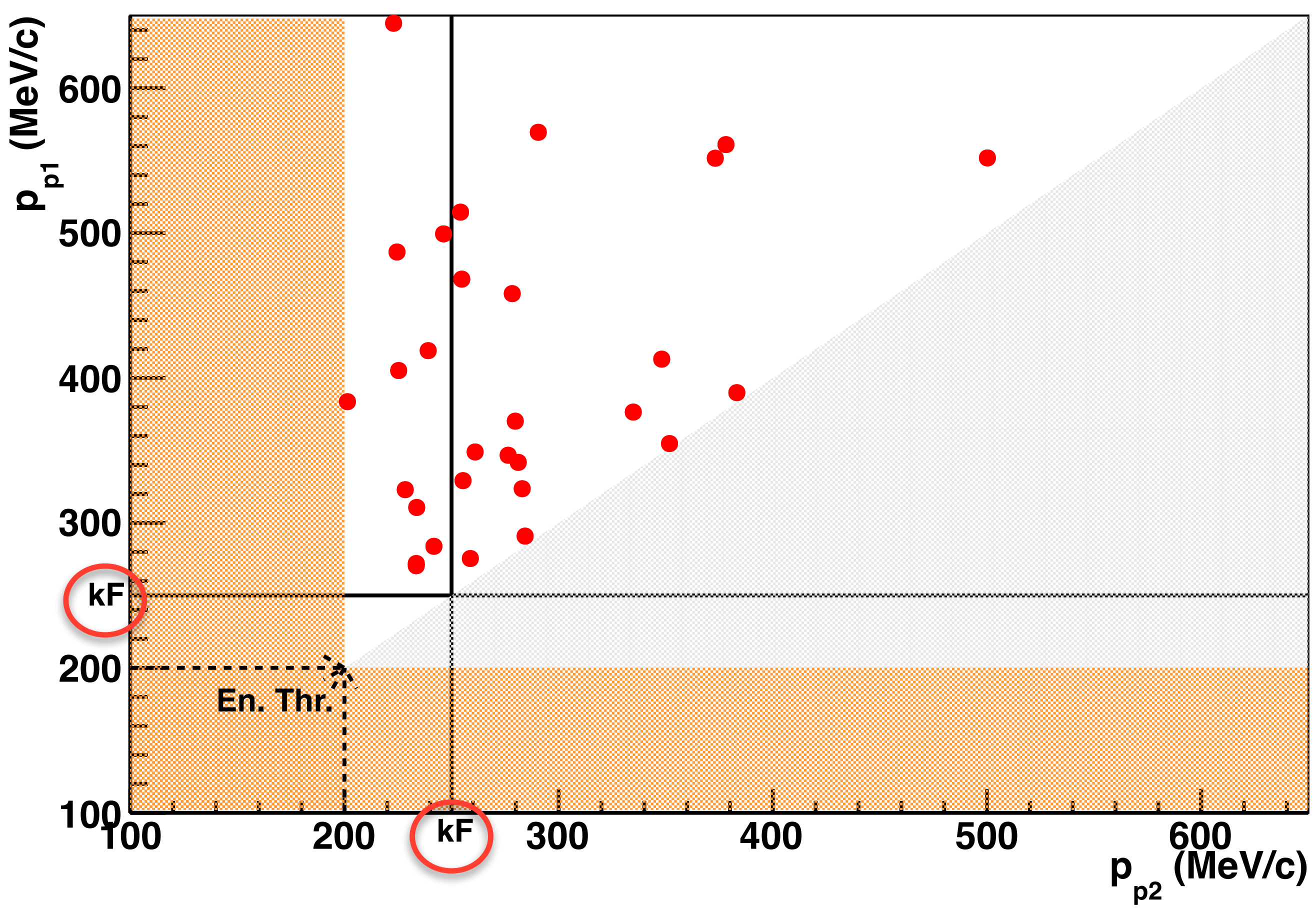
The specific final state topology which we have focused on is a pair of energetic protons at the interaction vertex accompanying the leading muon.

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,

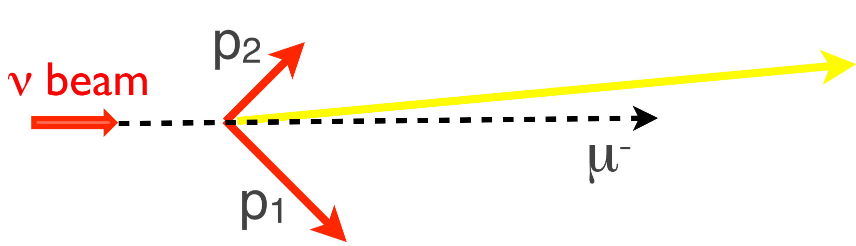
- a CCQE interaction on a neutron in a SRC pair is expected to produce back-to-back protons in the CM frame of the interaction,
- whereas a CC pionless RES reactions involving a SRC pair may produce back-to-back protons in the Lab frame

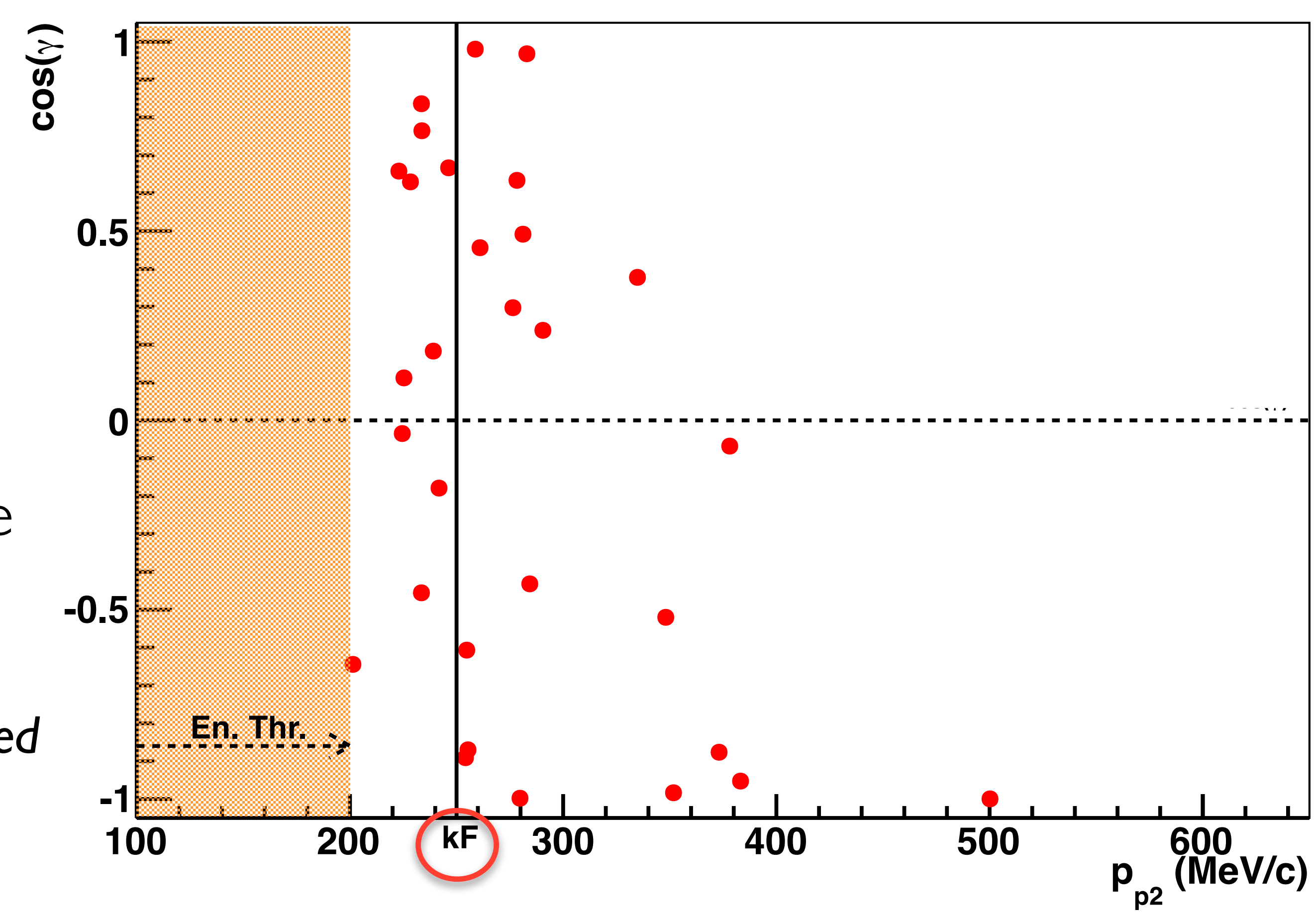
(μ^-+2p) data sample



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)



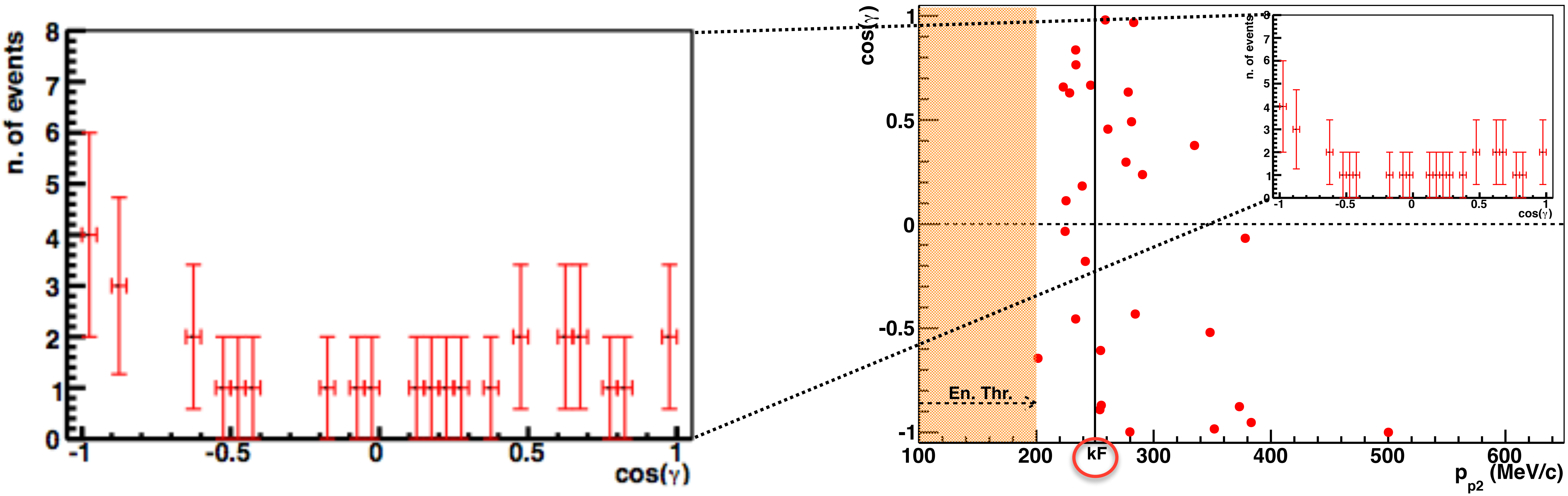


cos(γ) vs momentum of the least energetic proton p_{p2} in the pair for the 19 events with $p_{p1}, p_{p2} \geq k_F$

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

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

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



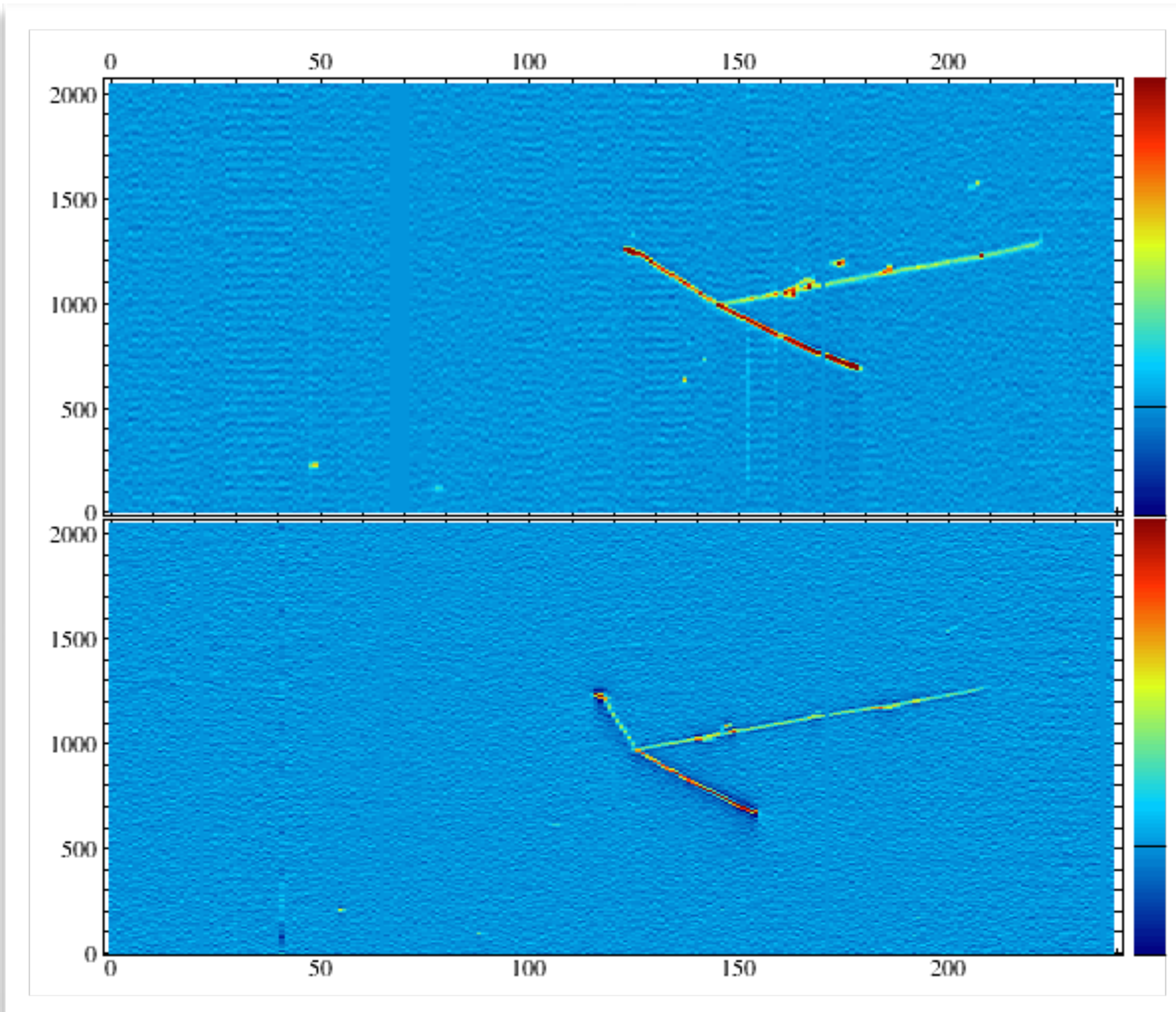
Four of the 19 2p-events are found with
the pair in a **back-to-back** configuration
in the Lab frame cos(γ)<-0.95

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

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

(μ^-+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(γ)<-0.95

(μ^-+2p) data sample - 4 ***"Hammer Events"***

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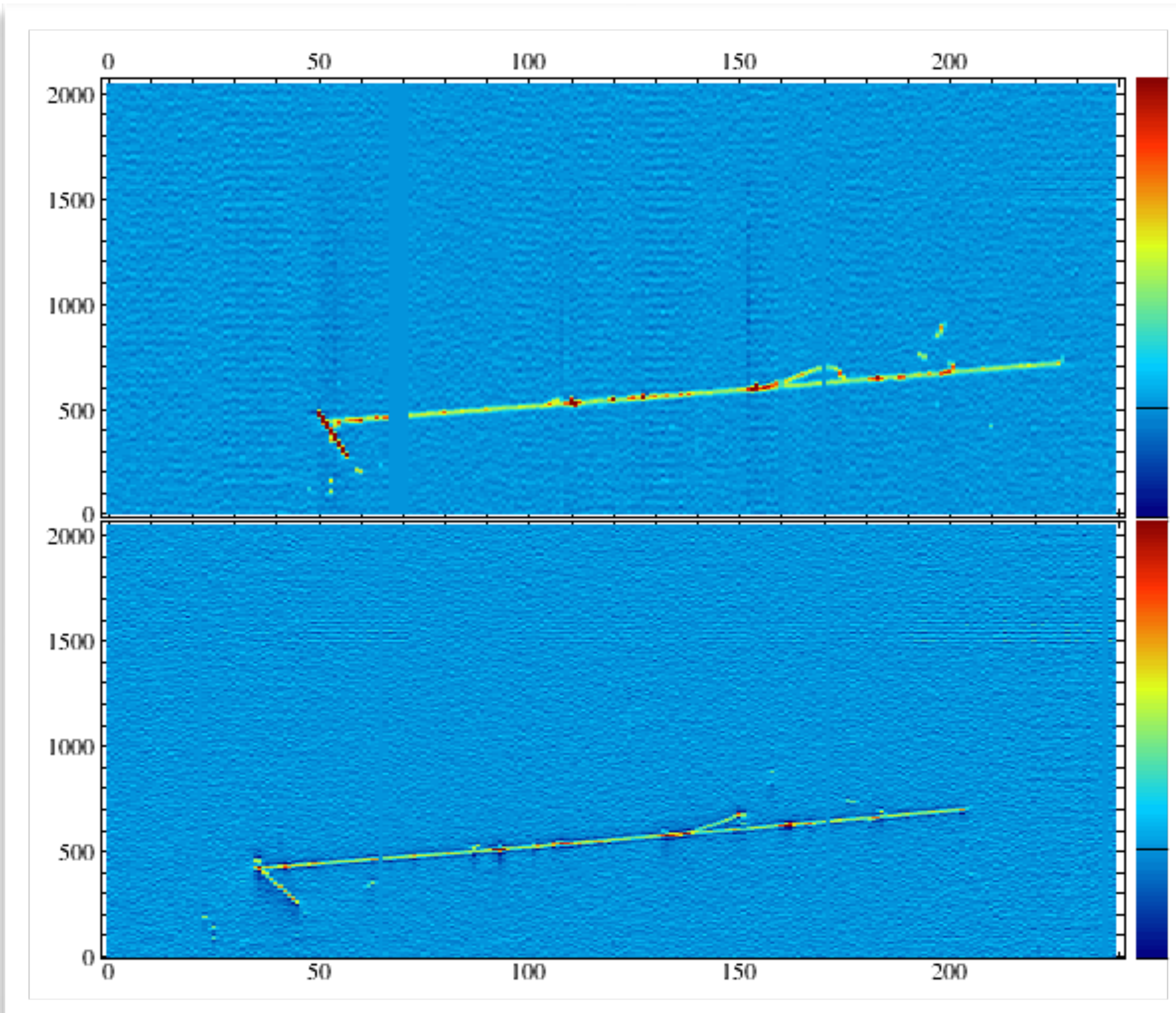

cos(γ)<-0.95

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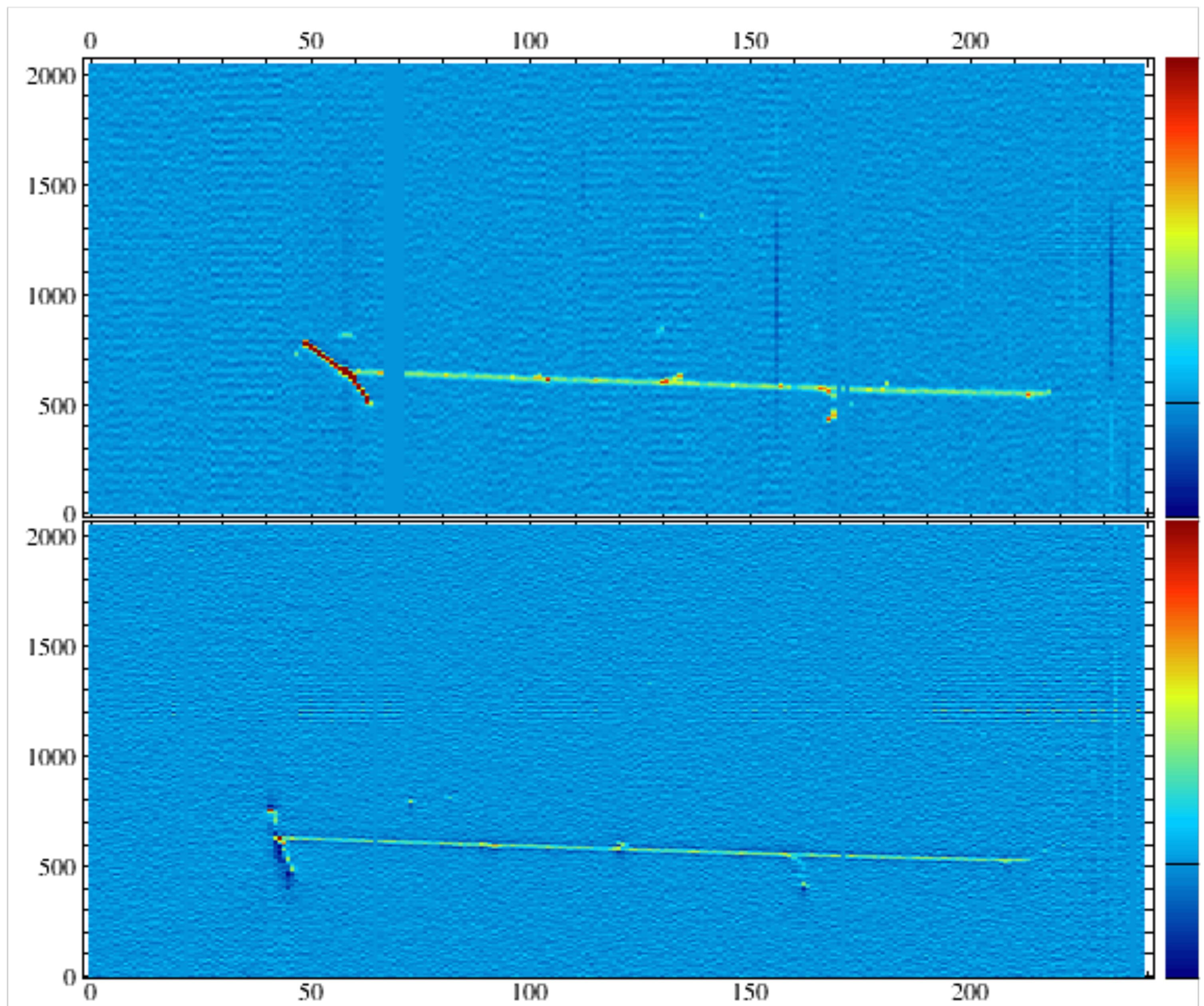

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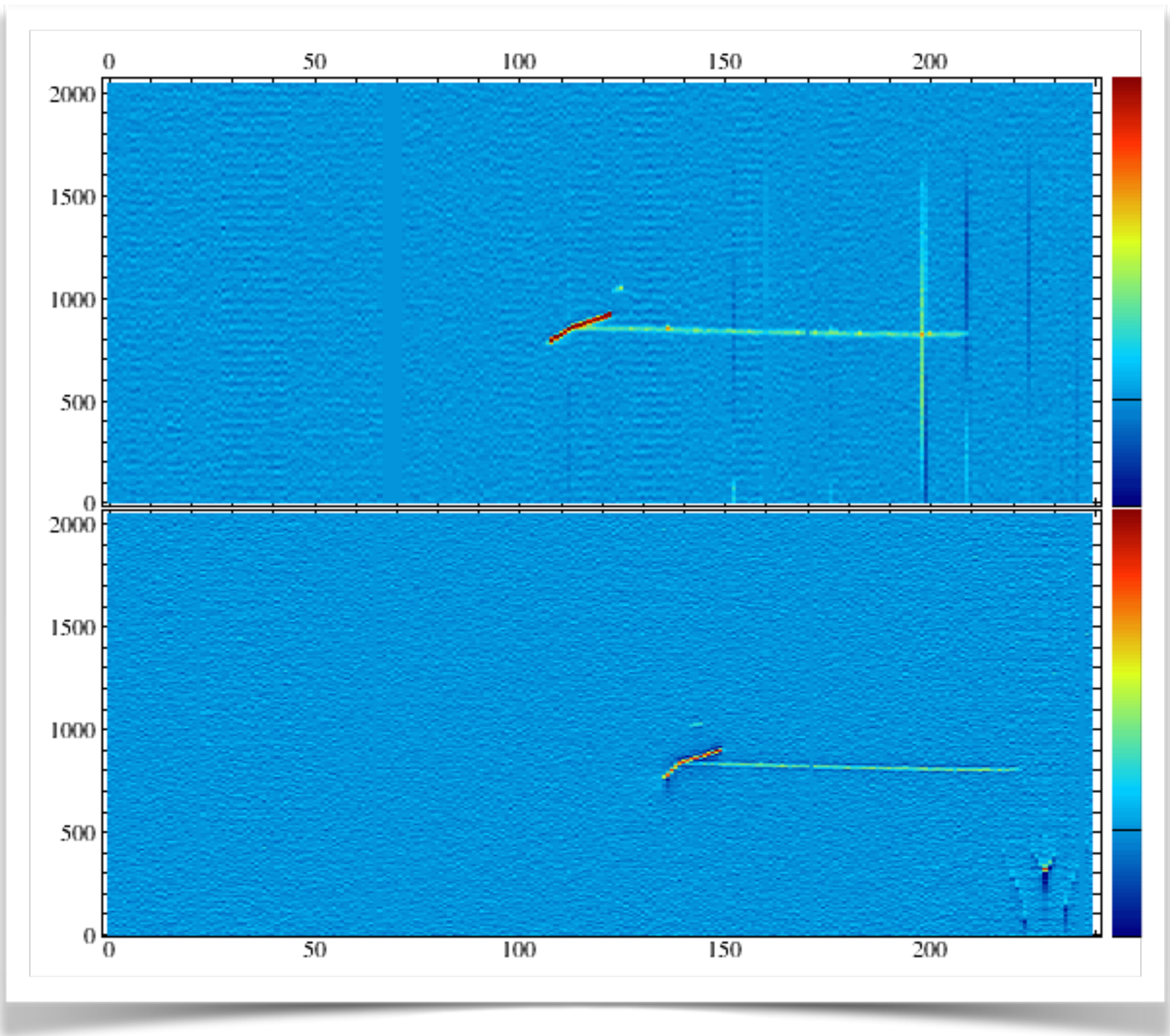


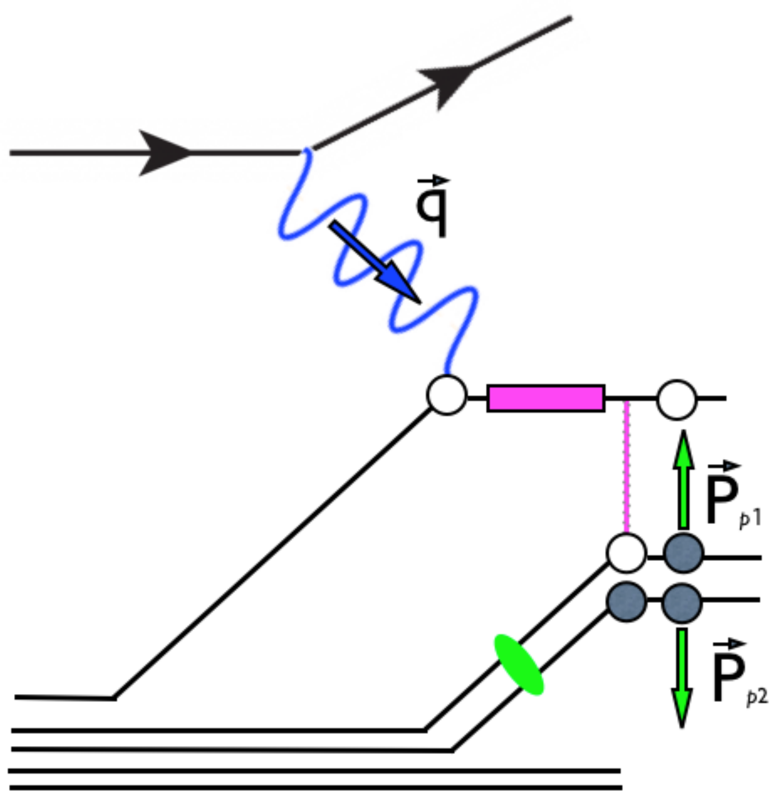
$\cos(\gamma)<-0.95$

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

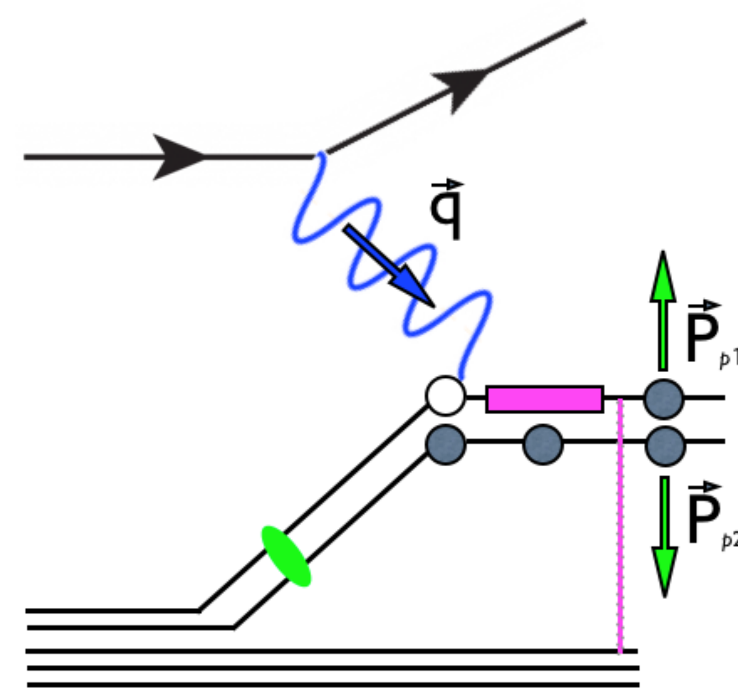
1) CC RES pionless mechanisms involving a pre-existing ***np*** pair in the nucleus.

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



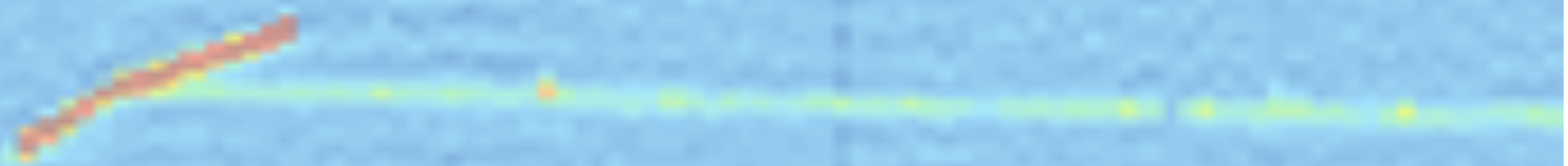
via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair



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,

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

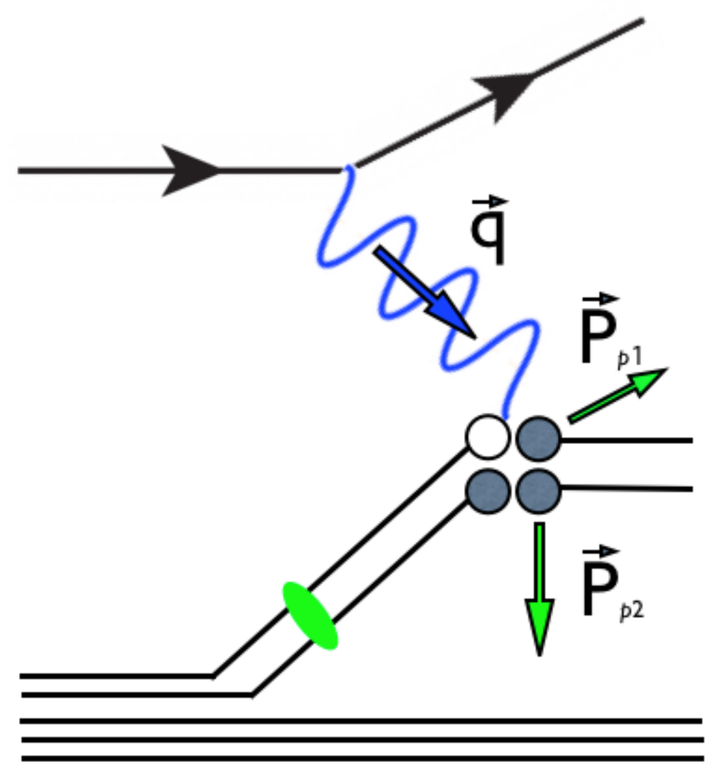
These features **look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC *np* pairs.**

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

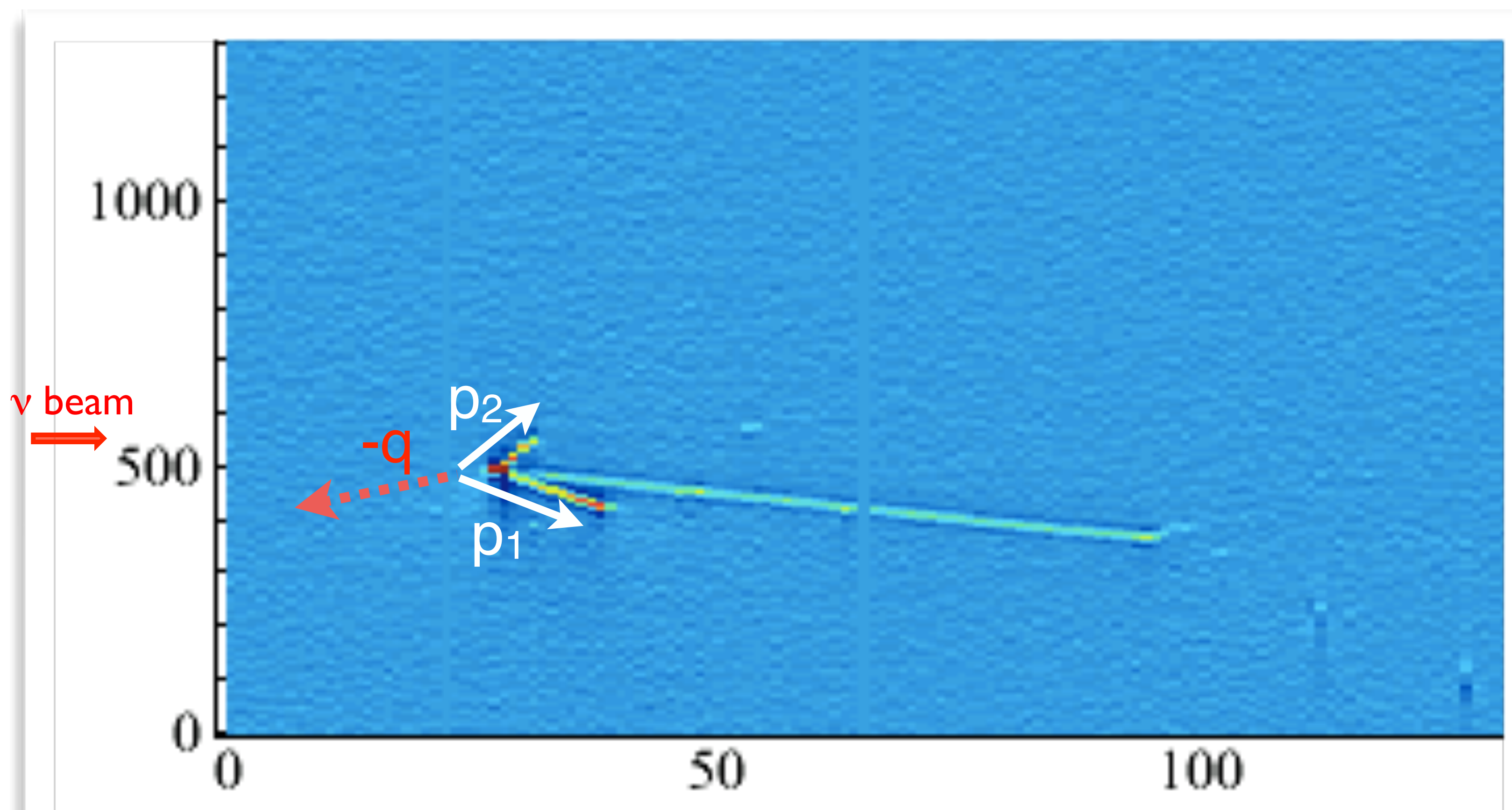
(μ^-+2p) - Initial momentum reconstruction

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 p2 identified as recoil spectator nucleon from within SRC]*

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

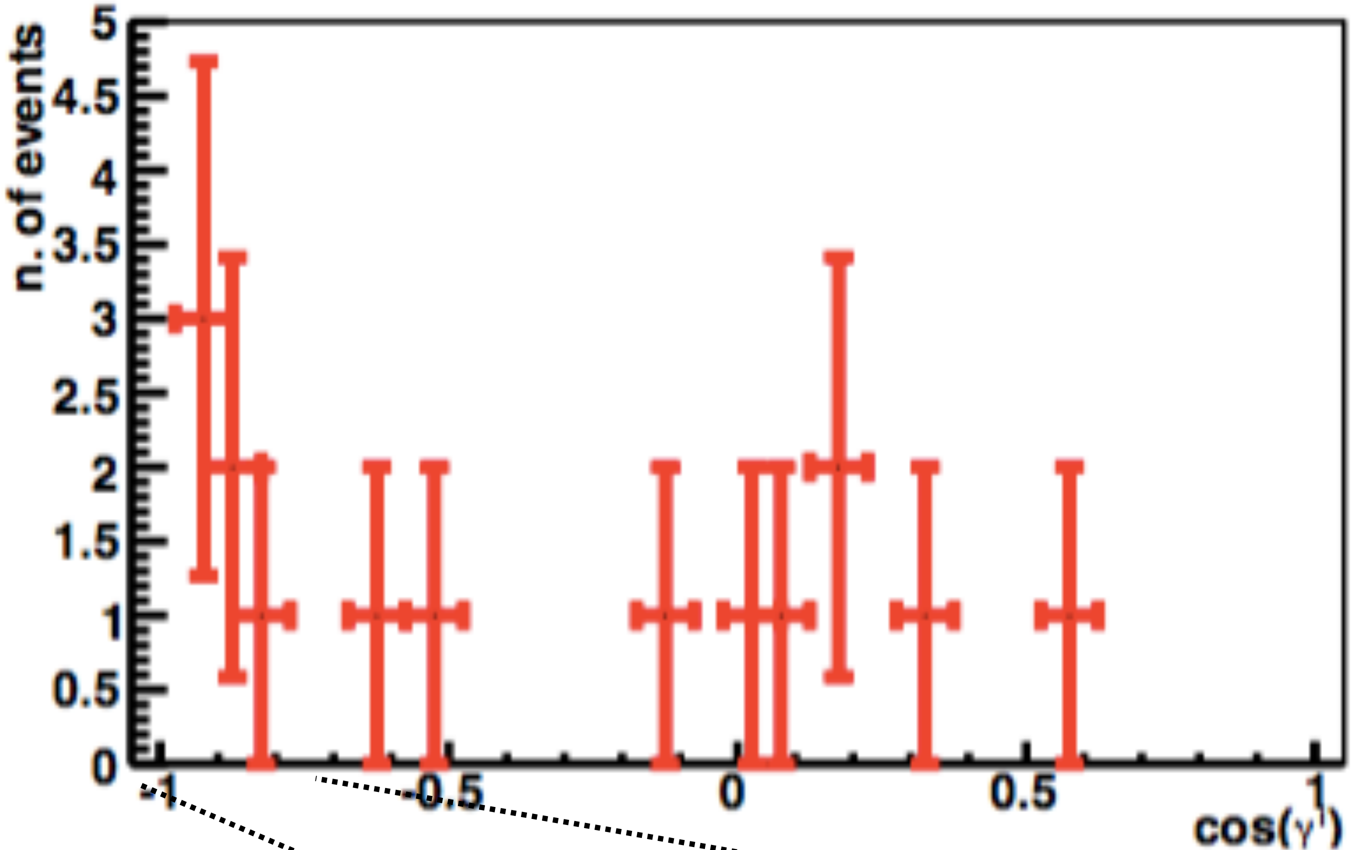
$\vec{q}$ is calculated from the reconstructed E_ν and the measured muon kinematics

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



(μ^-+2p) - Initial momentum reconstruction

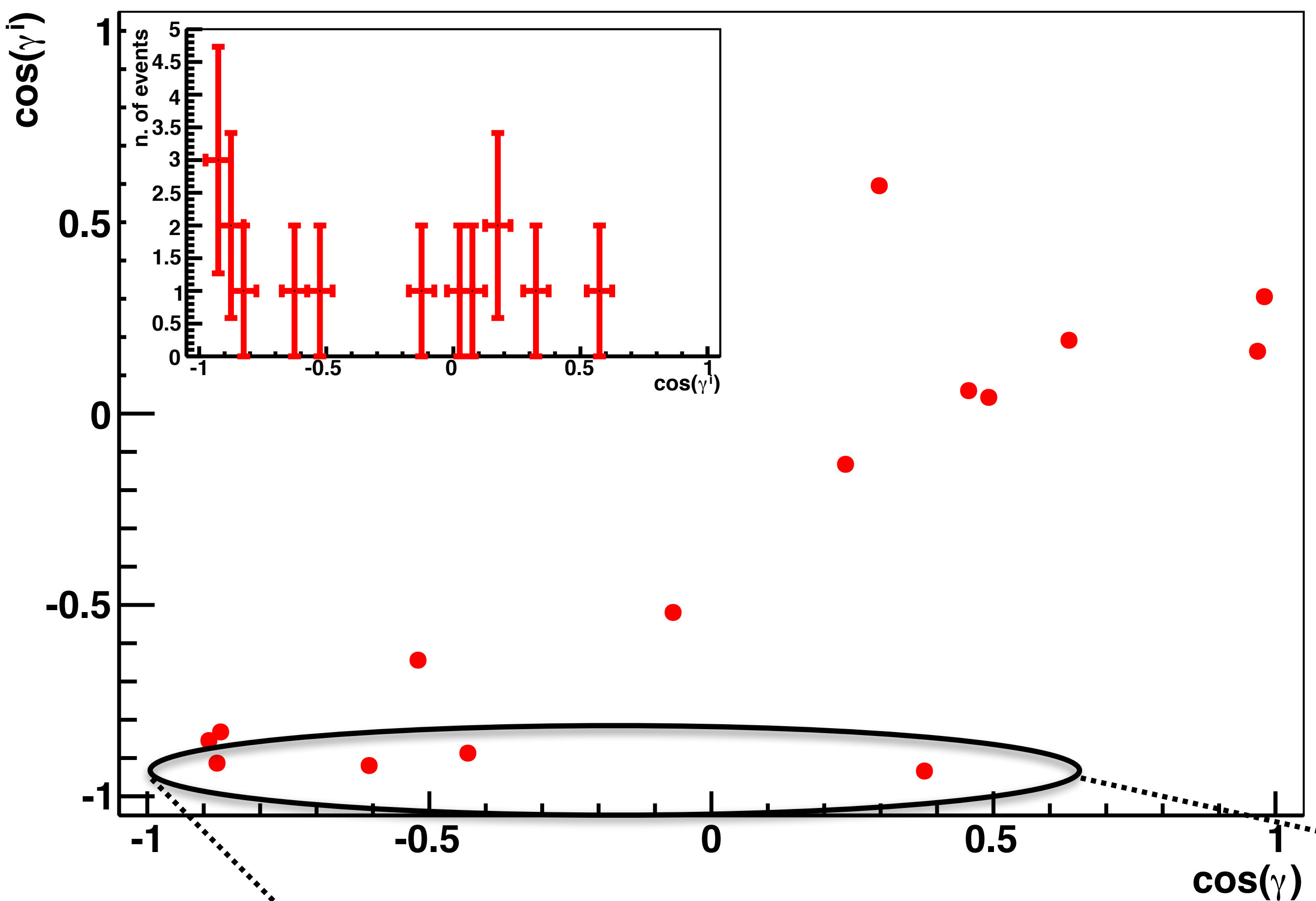
In most cases the reconstructed initial momentum is found opposite to the direction of the recoil proton ($\cos(\gamma_i) < 0$)



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(γ_i) vs cos(γ)

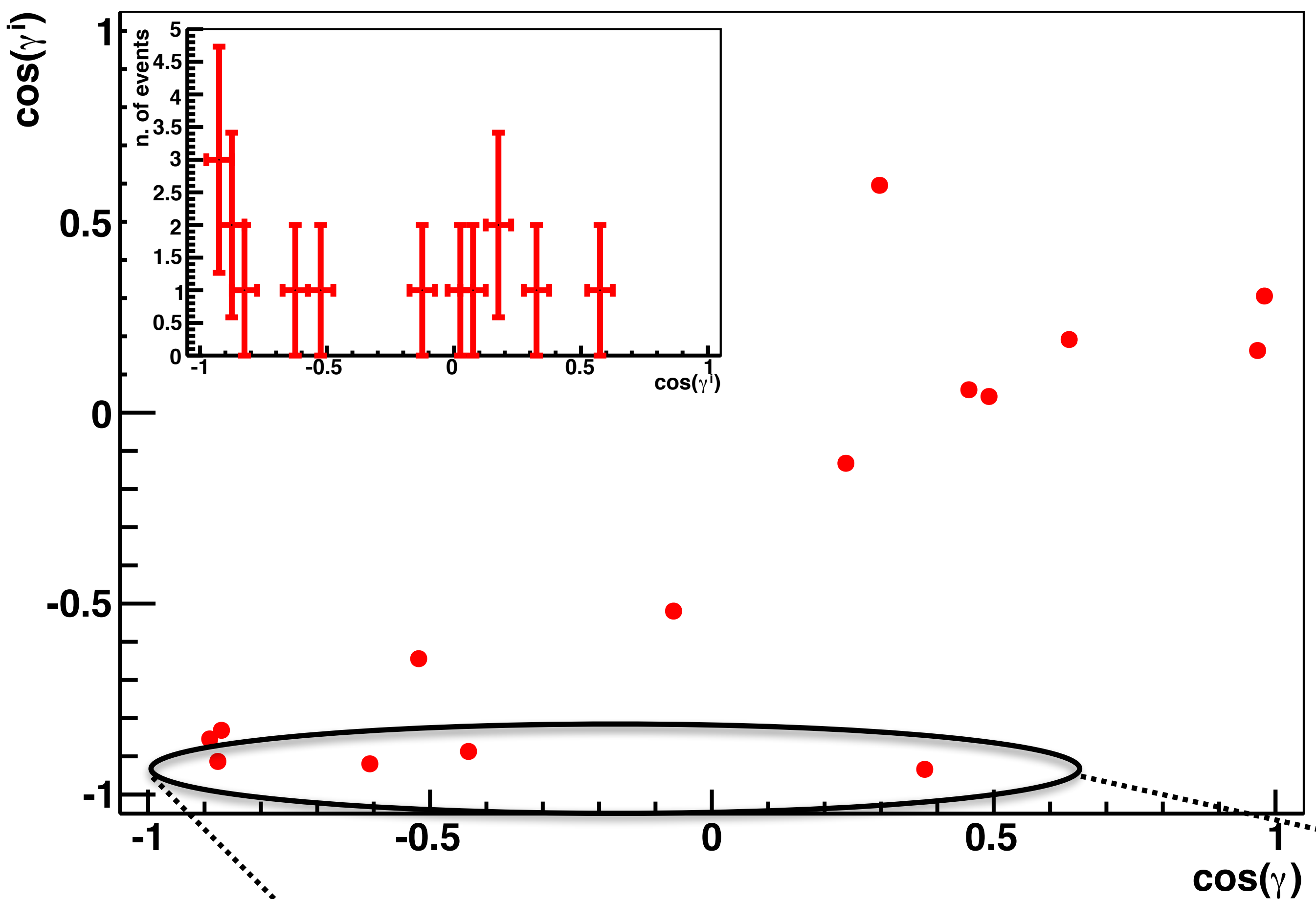
γ_i=opening angle between the reconstructed struck nucleon and the recoil proton in the np ***initial*** *pair*

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

Four events (those horizontally aligned in the lowest cos(γ_i) bin, rather separated from the others) are reconstructed with the pair in a **back-to-back** configuration in the CM frame, cos(γ_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(γ_i)

Back-to-back proton pairs in the initial state

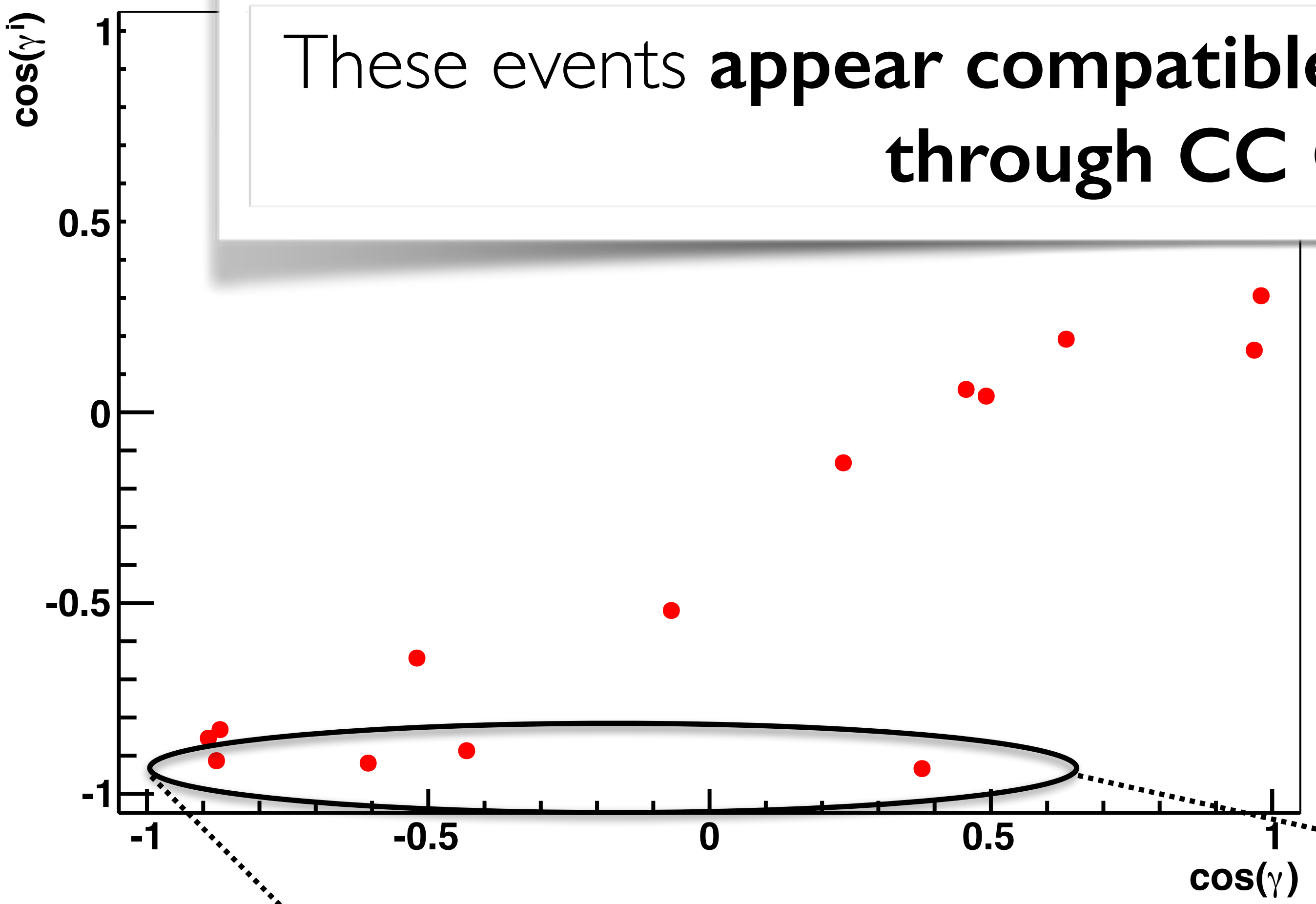


Four events (those horizontally aligned in the lowest $\cos(\gamma_i)$ bin, rather separated from the others) are reconstructed with the pair in a **back-to-back** configuration in the CM frame, $\cos(\gamma_i)<-0.9$ and have reconstructed initial momenta $>K_F$

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

Back-to-back proton pairs in the initial state

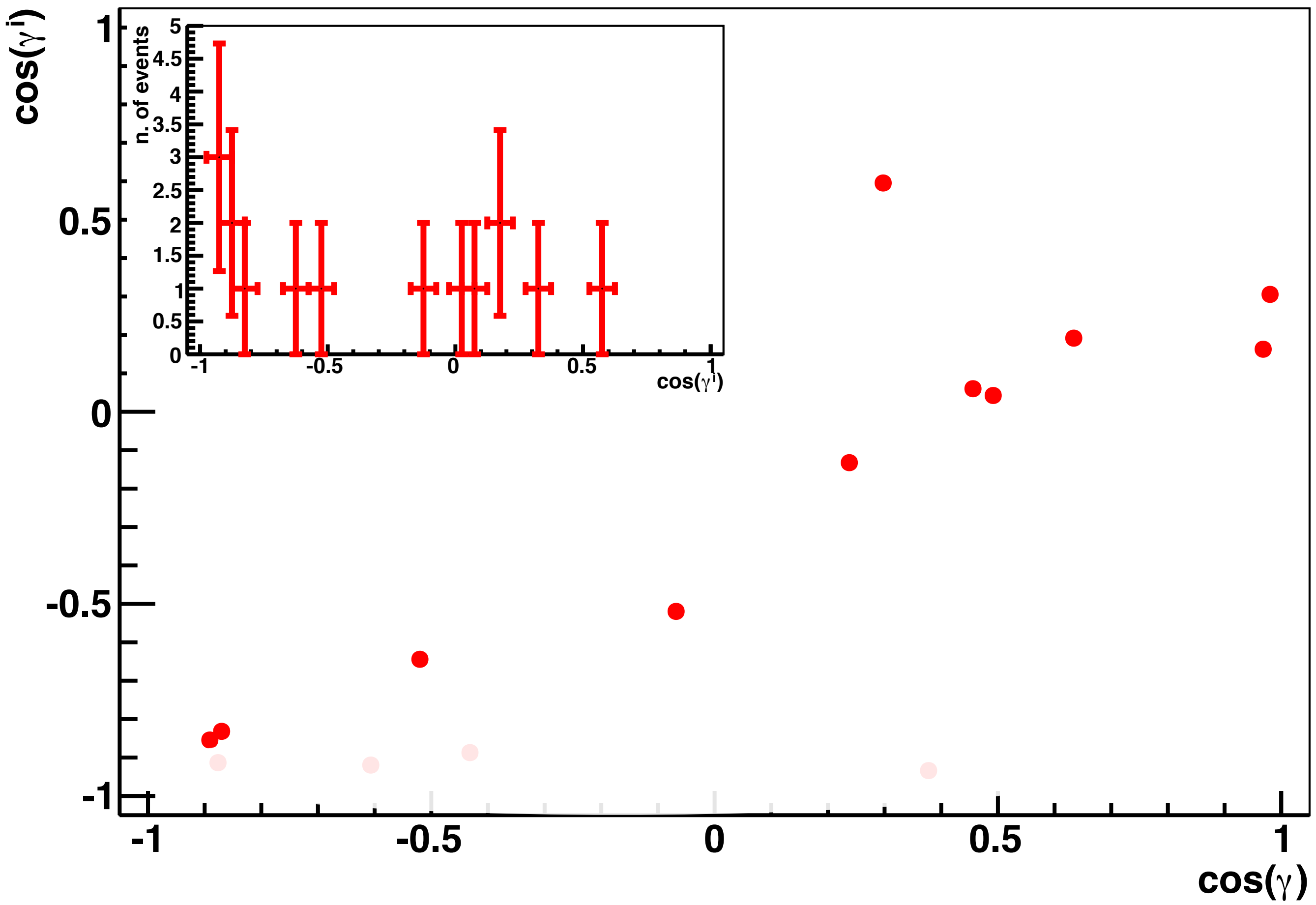
These events **appear compatible as originating from SRC pairs through CC QE reactions**



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 ($\lesssim$250 MeV/c).

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***

*O. Benhar et al., arXiv:1312.1210 [nucl-th] (2013)

Future LArTPC experiments: MicroBooNE, LAr1-ND…

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

MicroBooNE estimated events rates (GENIE)

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

See S. Gollapinni talk

LAr1-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

See R. Guenette talk

CONCLUSIONS

- Topological CC 0 pion sample analysis in ArgoNeuT:
  - First measurements on Ar nuclei ***anti-neutrino cross section.*** Neutrino cross sections are coming soon
  - Measurements are presented in terms of E_ν calculated from the observed ***final-state particle kinematics***

Model independent measurement

  - (μ^-+2p) analysis ➠ ***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.***

CONCLUSIONS

- Topological CC 0 pion sample analysis:
  - First measurements on Ar nuclei cross sections are coming soon
  - Measurements are presented in terms of the observed ***particle kinematics*** ***Model independent measurement***

The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line
http://arxiv.org/abs/1405.4261 (May 16 2014)

with the LAr TPC technology

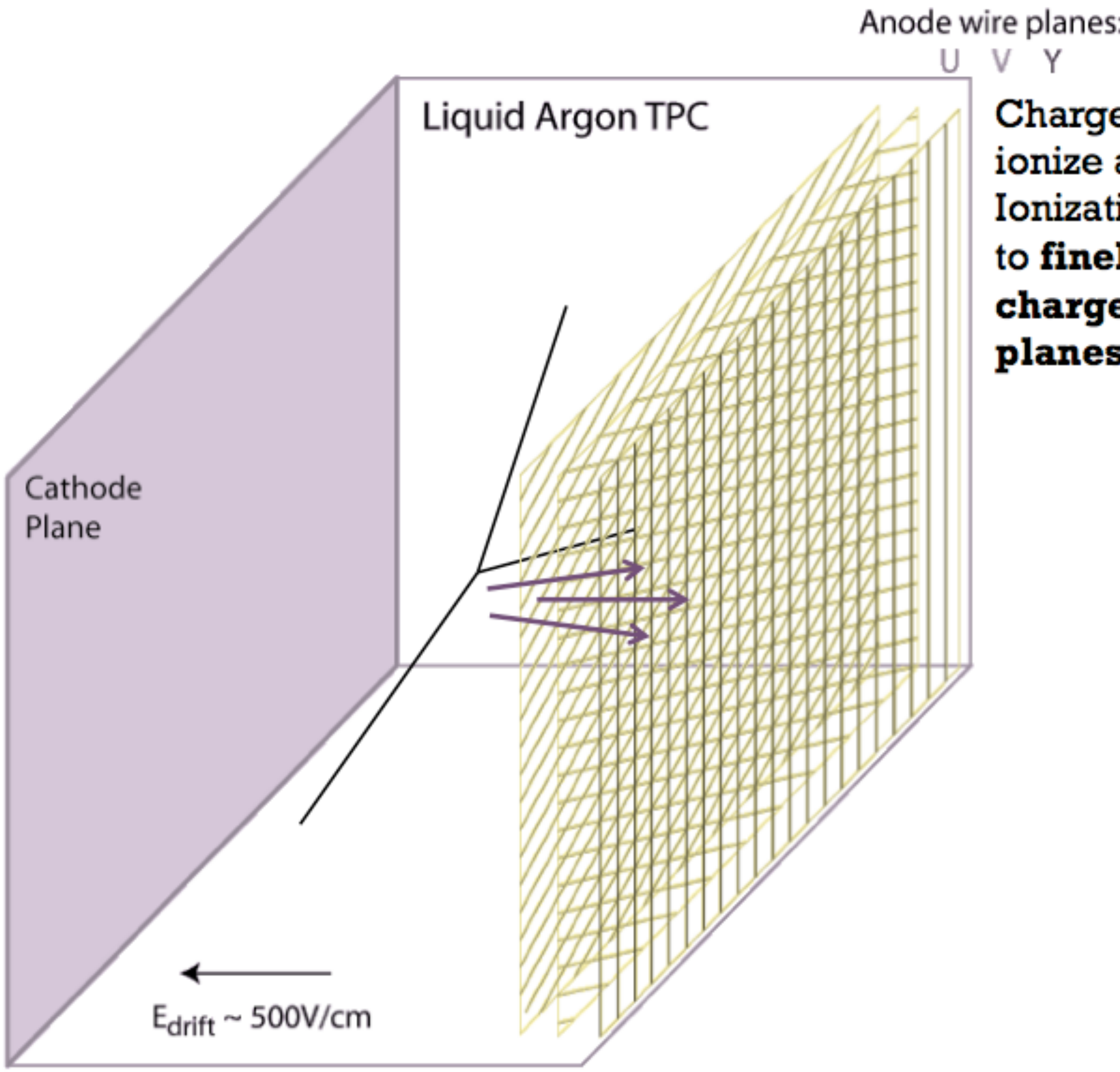
  - accurate and detailed MC neutrino generators are deemed necessary for comparisons with LAr data (with the inclusion of a realistic and exhaustive treatment of SRC in the one- and two-body component of the nuclear current
- We hope the ArgoNeuT data will encourage more studies in this area.

BACKUP

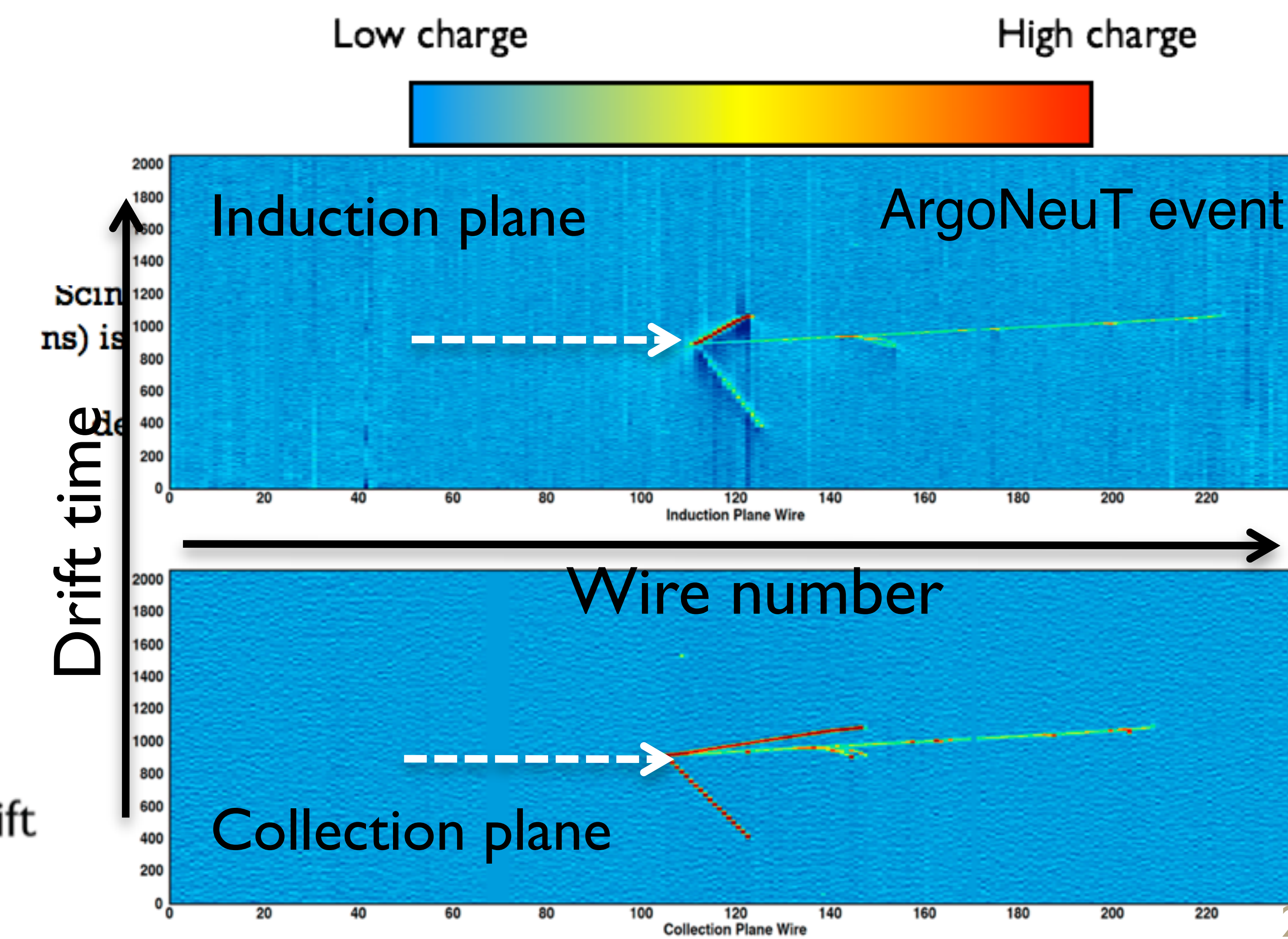
Nuclear effect in neutrino-nucleus Interactions

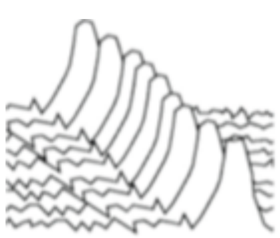
- Nuclear effects in heavy nuclear targets [initial state short-range nucleon-nucleon correlations (NN SRC), meson-exchange currents (MEC) and final state interactions (FSI)] play a big role in neutrino interactions
- The realization of consistent models including all these nuclear effect is now being actively pursued as well as their implementation in MonteCarlo generators (MC)
- 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 Liquid Argon Time Projection Chamber (LArTPC) technique opens new perspectives for detailed reconstruction of final state event topologies from neutrino-nucleus interactions.

THE LAR TPC CONCEPT



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



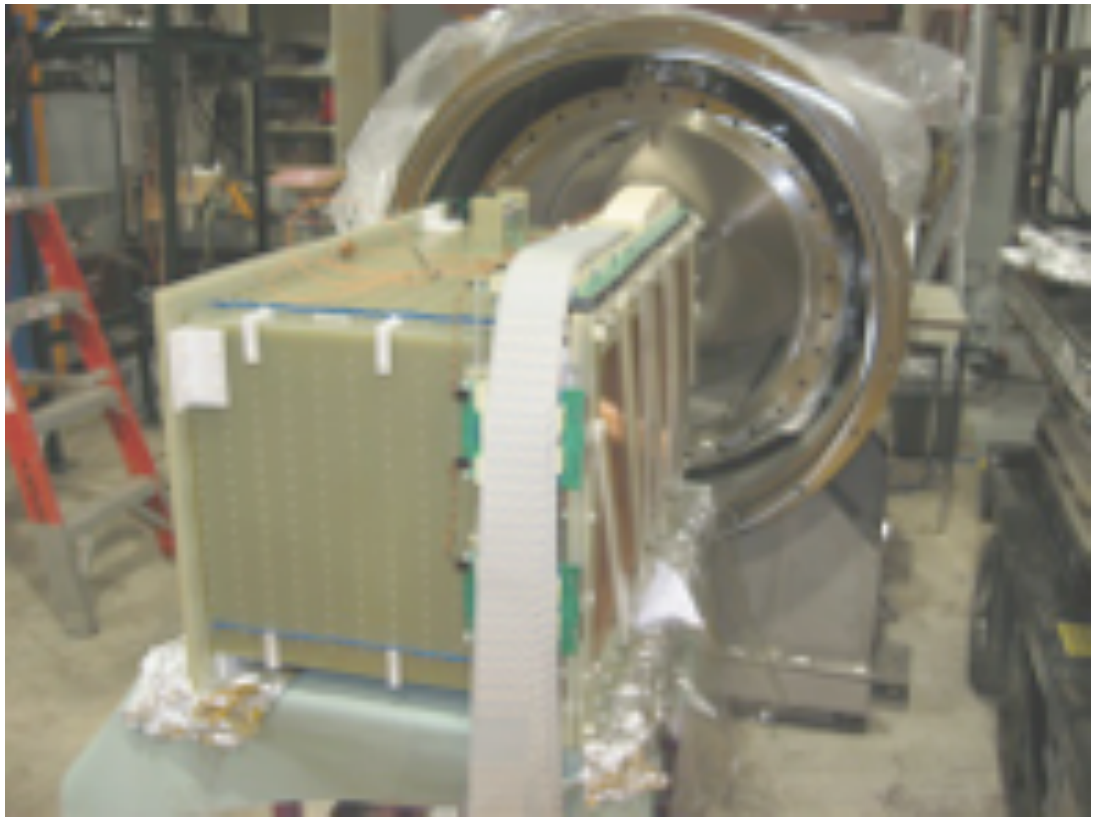


Wire pulses in time give the drift coordinate of the track

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

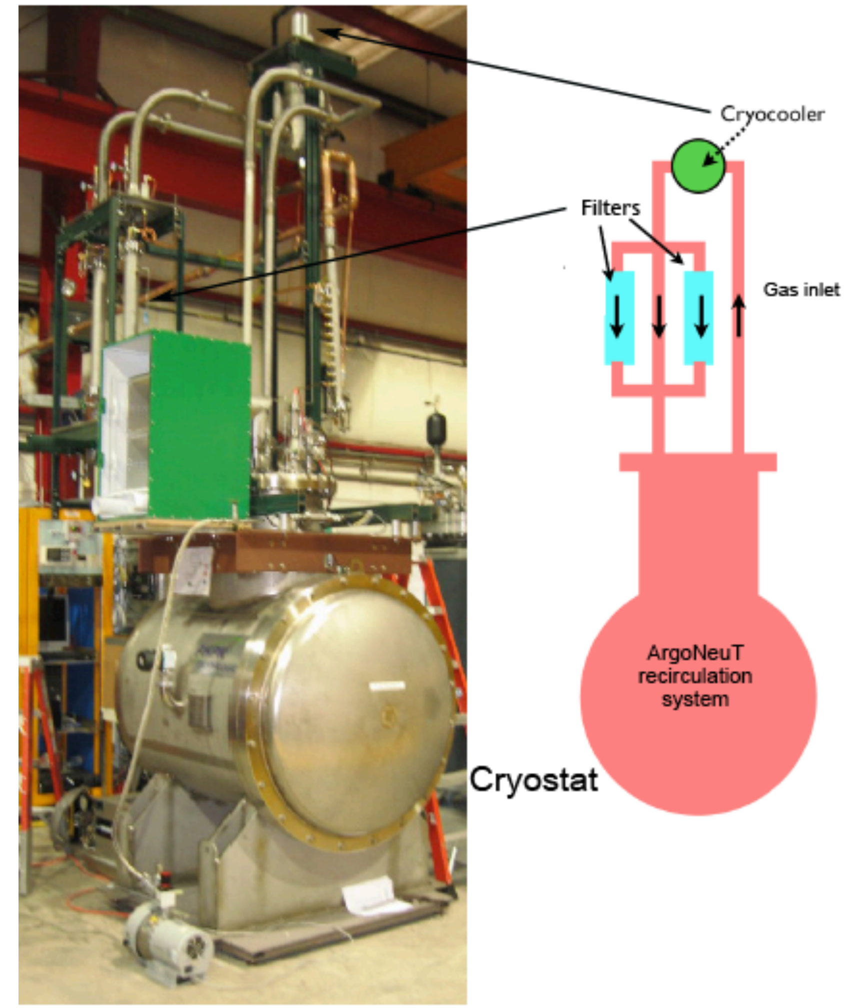
ArgoNeuT Detector

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



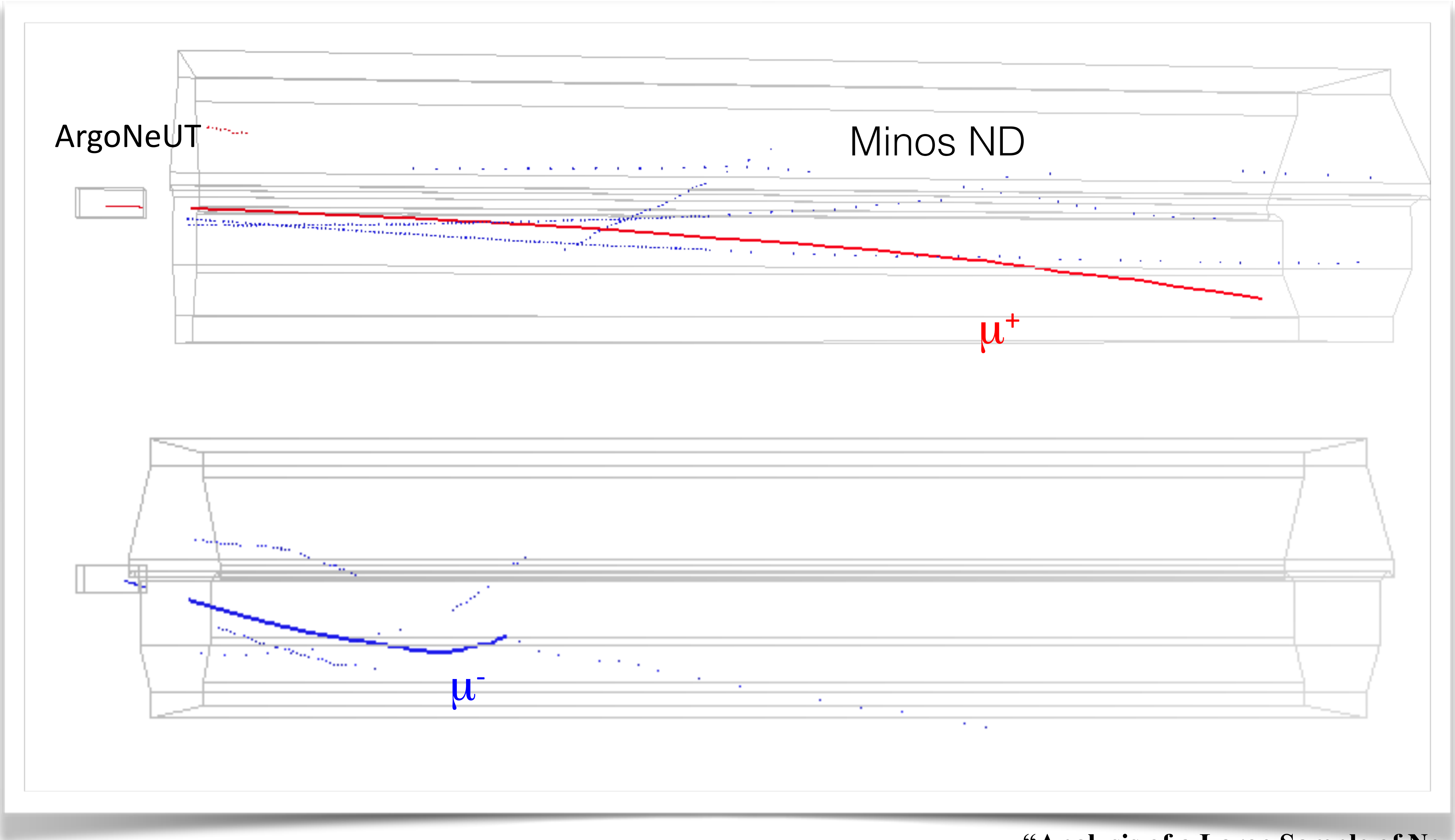
The TPC, about to enter the inner cryostat

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

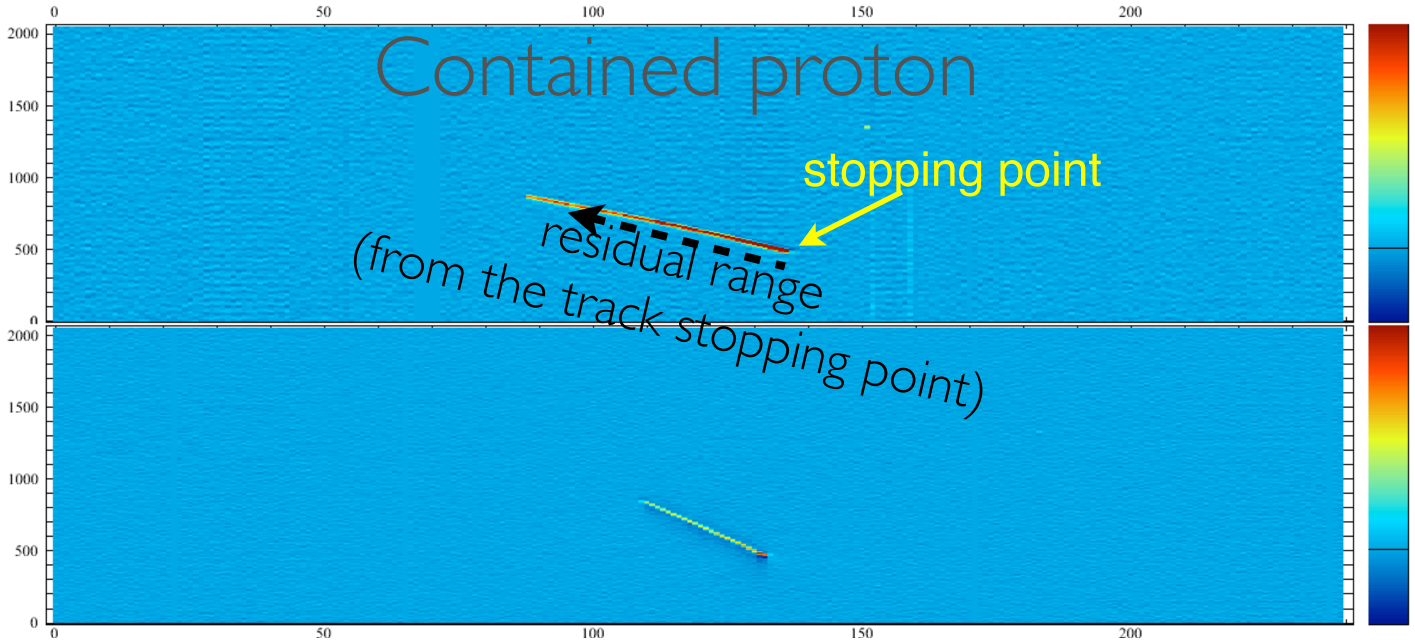
MUON reconstruction



"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%

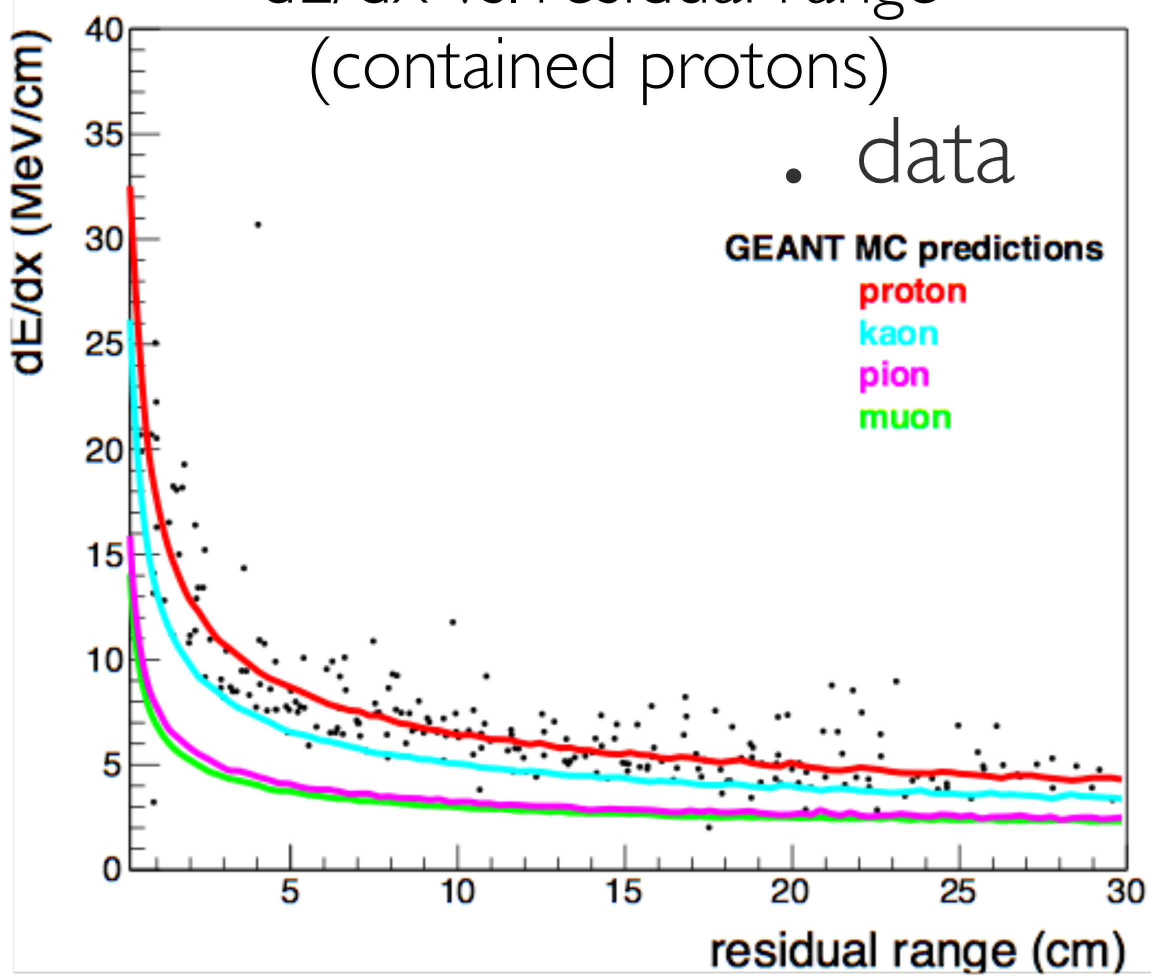
STOPPING TRACKS - CALORIMETRIC RECONSTRUCTION and PID

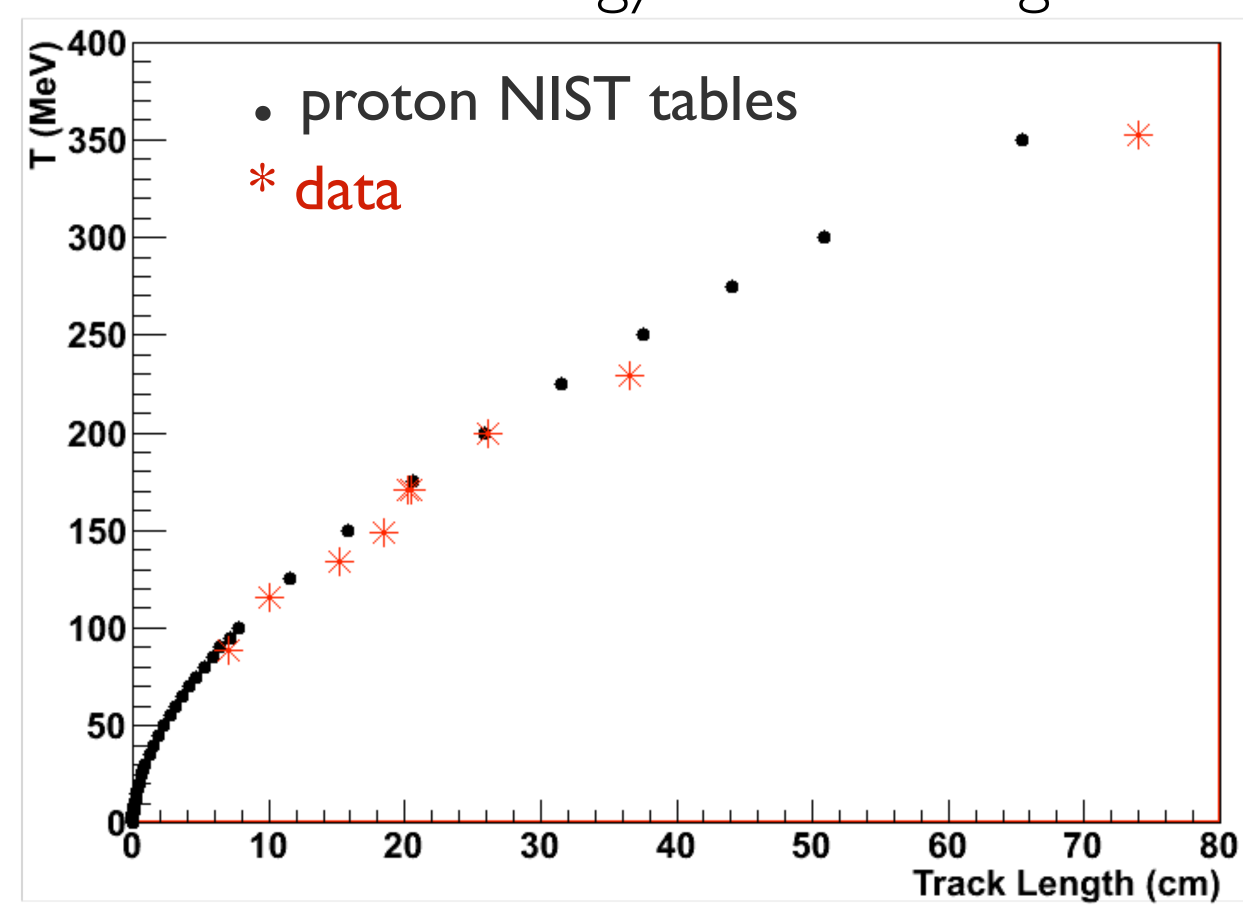


Measurement of:

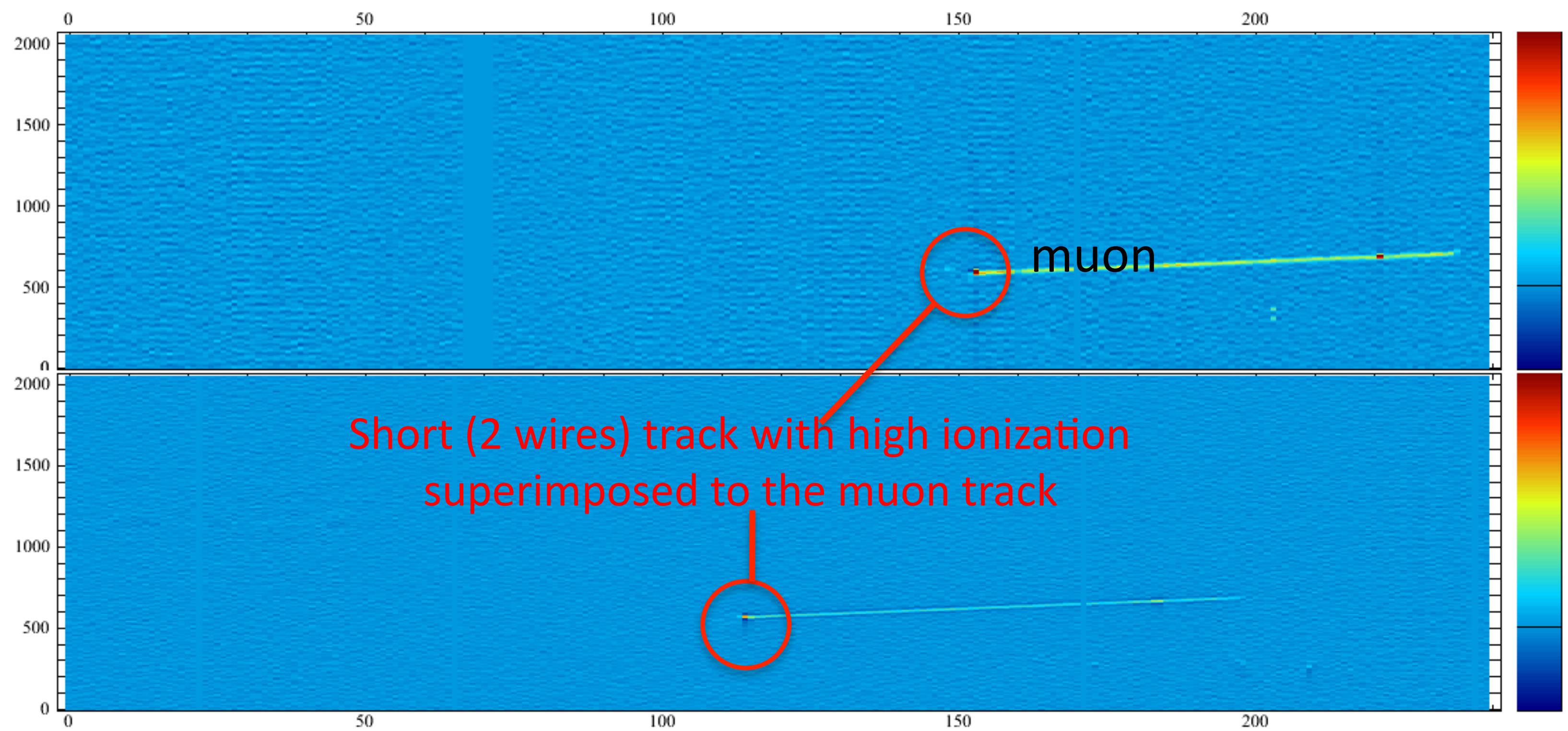
- dE/dx vs. residual range along the track
- kinetic energy vs. track length

χ^2 based method is used for PID





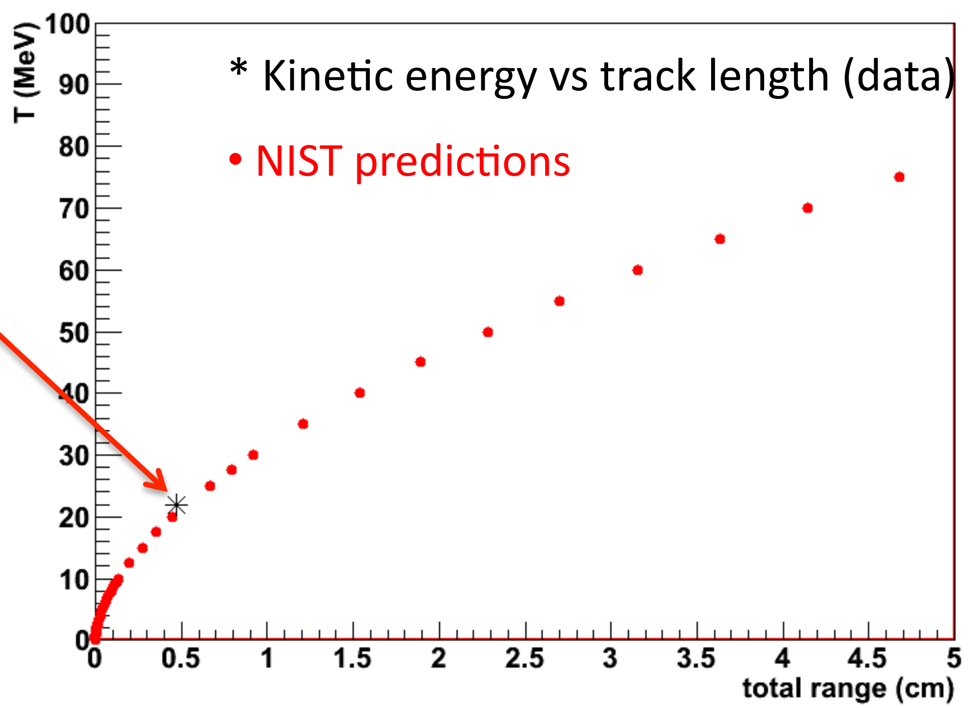
Example of Low energy proton reconstruction



The short track behaves like proton

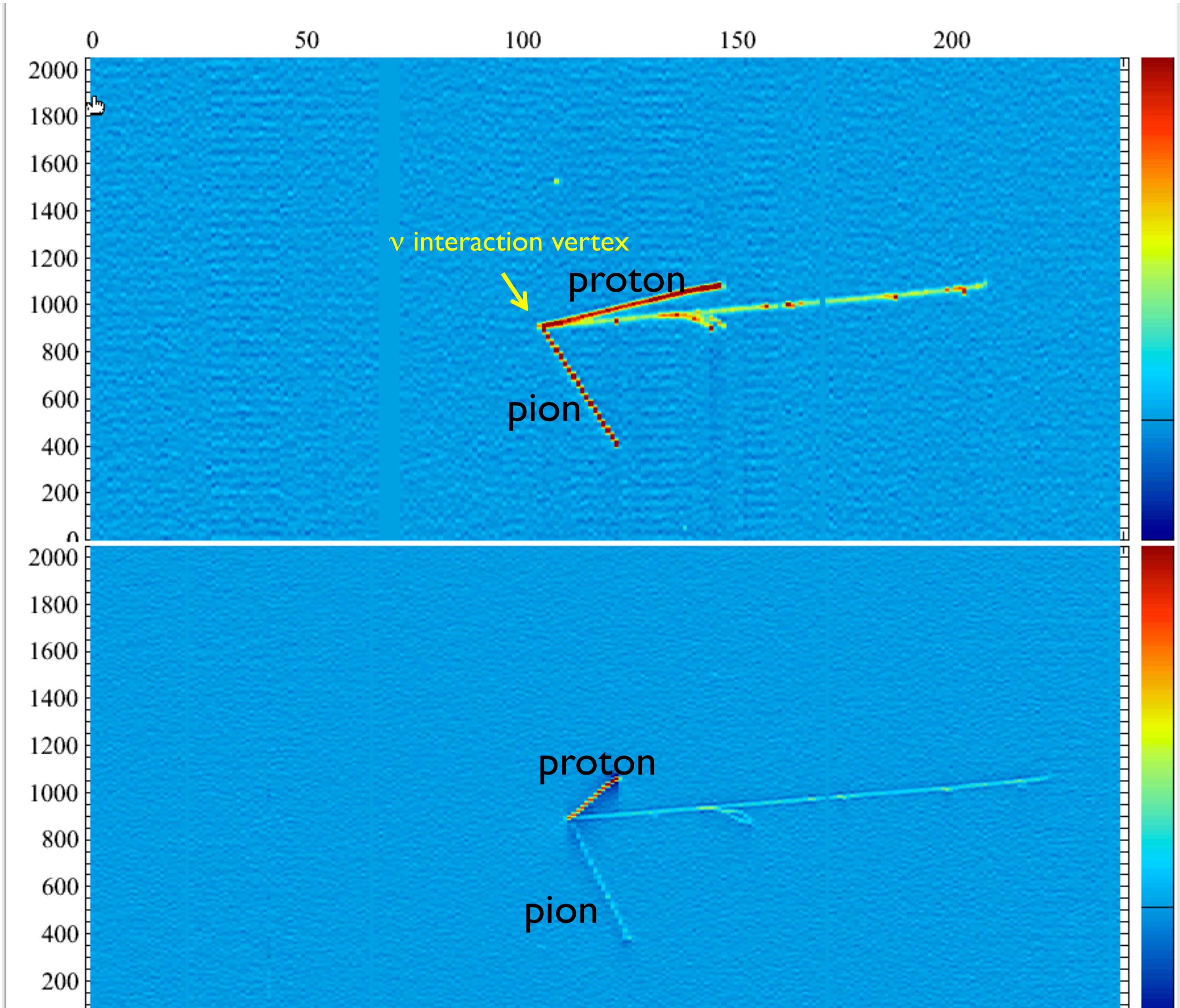
Length=0.5 cm

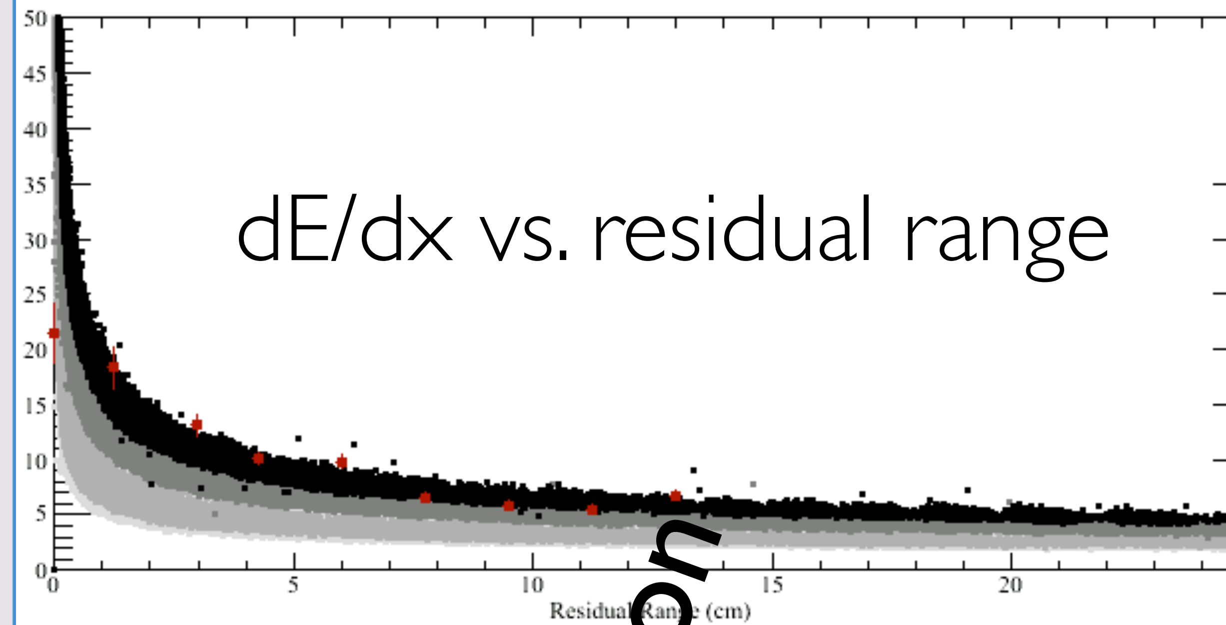
KE=22±3 MeV

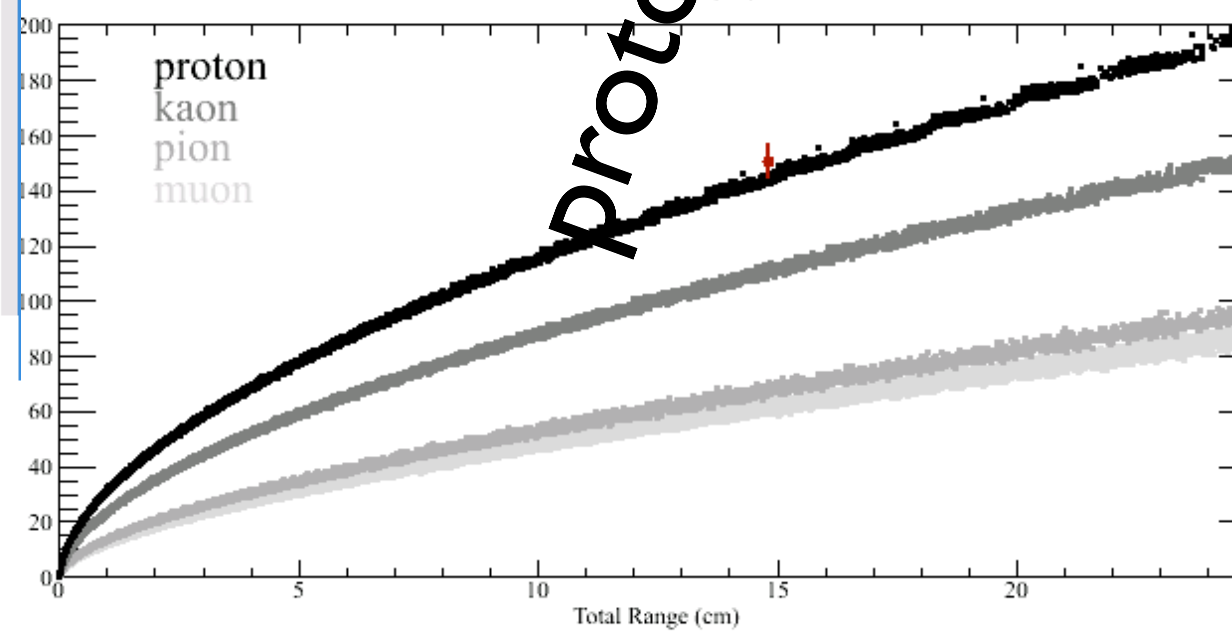


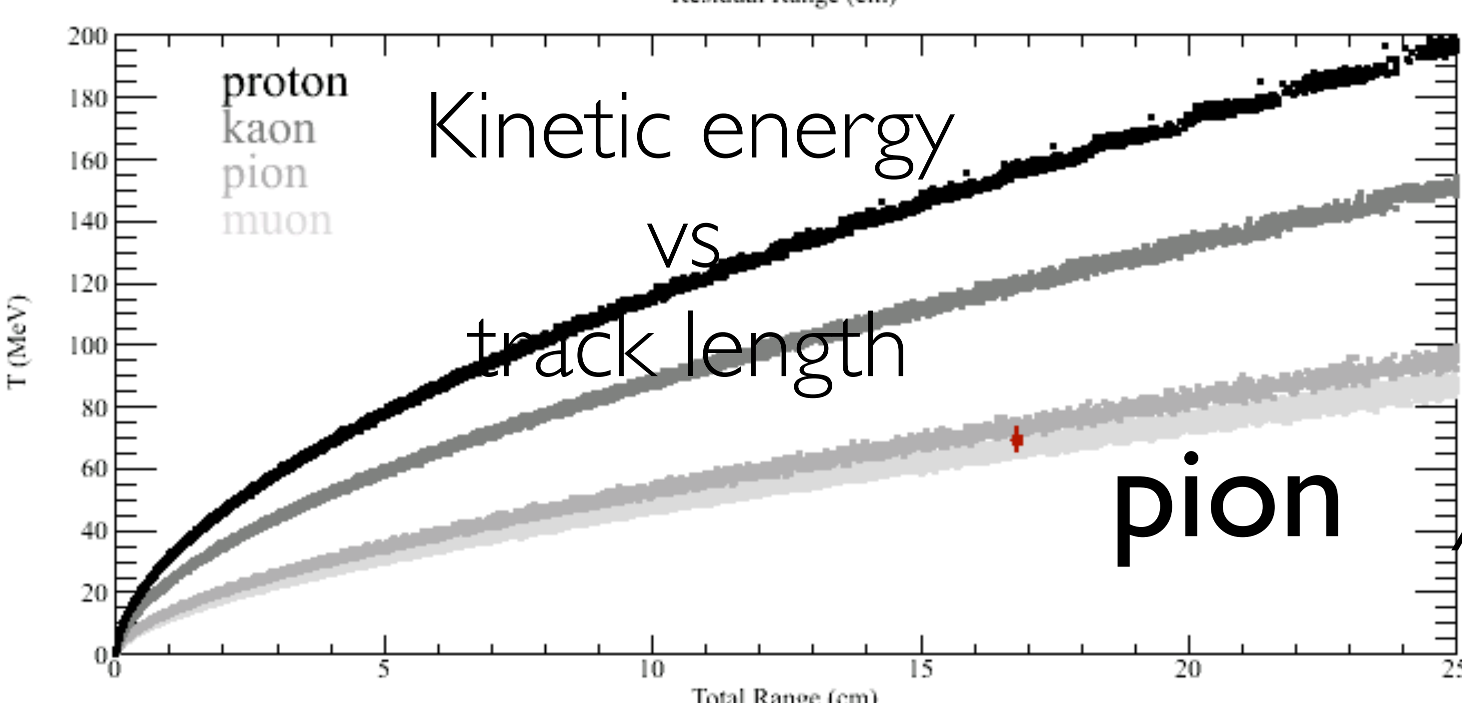
ArgoNeuT proton threshold: 21 MeV of Kinetic Energy

p/π± identification









ArgoNeuT pion reconstruction threshold: ~8 MeV Kinetic energy

PID Efficiencies

Generated

Identified as

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

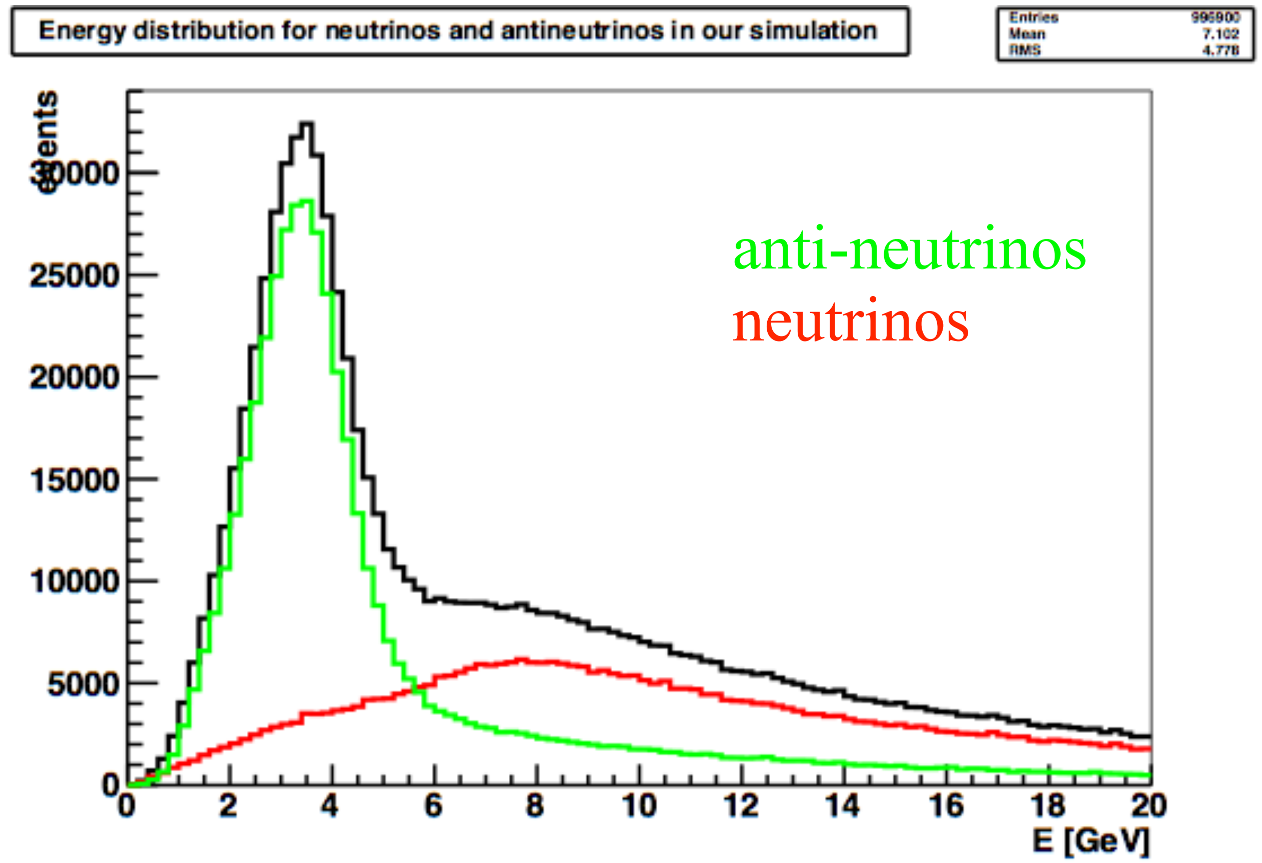
ArgoNeuT

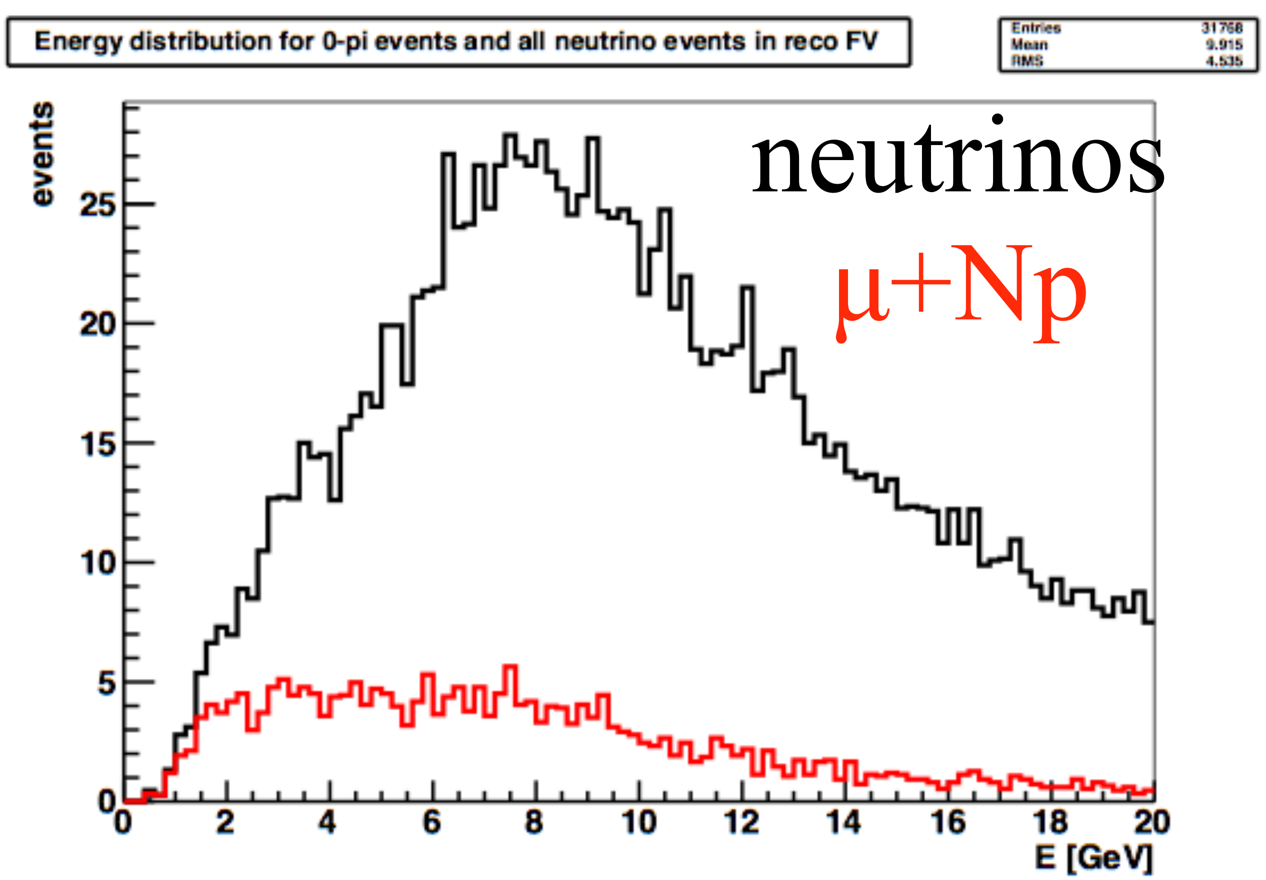
DATA-MC COMPARISON

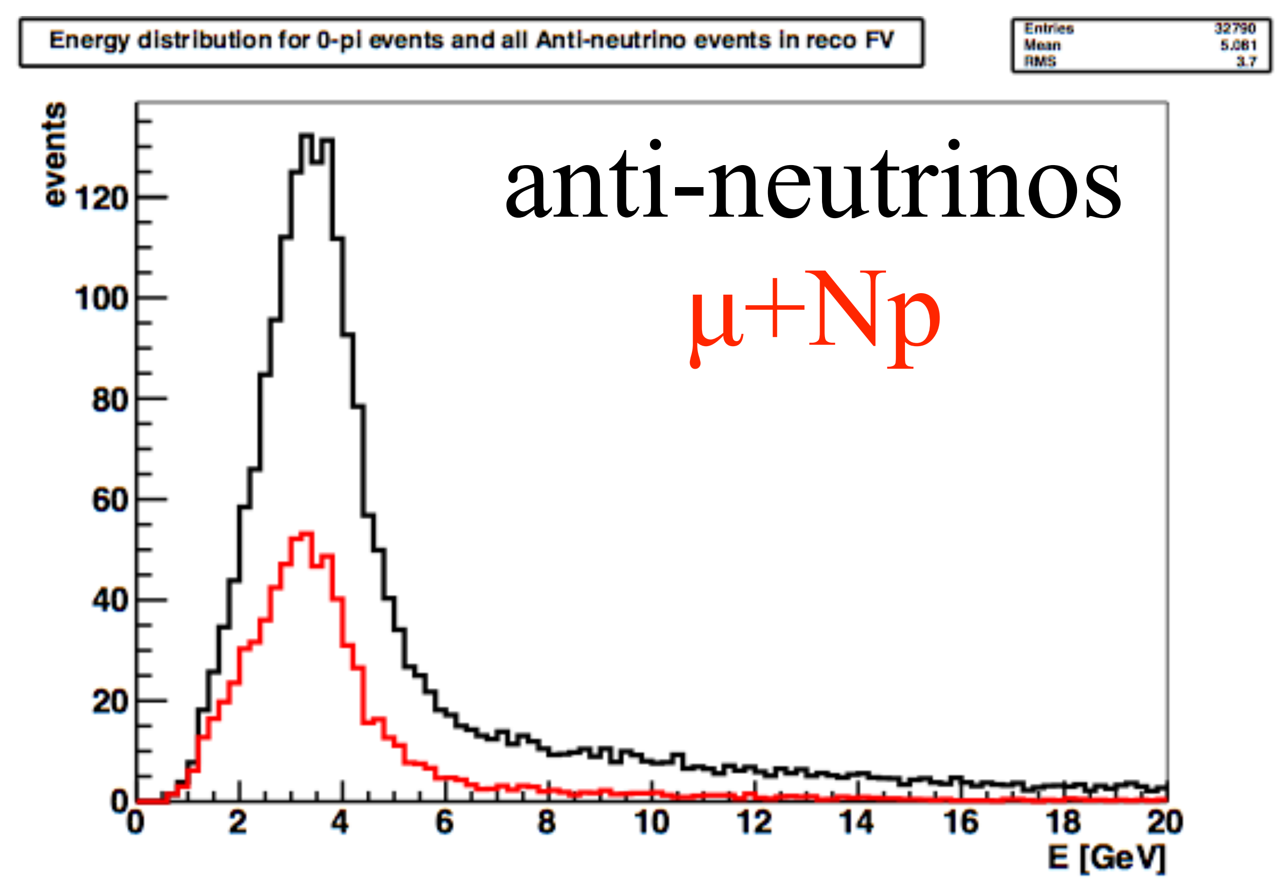
- GENIE- Generates Events for Neutrino Interaction Experiments*
  FSI: Intranuclear Cascade mode (INC)
  Meson exchange (MEC) channel in the future
- GIBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project**
  FSI: Transport model
  2p2h-NN channel included
    2-particle-2-hole interaction with 2 nucleons produced

*ArgoNeuT Coll. is grateful to GENIE authors, in particular S. Dytman and H. Gallagher, for many useful discussions
**ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

Energy spectrum in anti-neutrino mode







DATA ANALYSIS

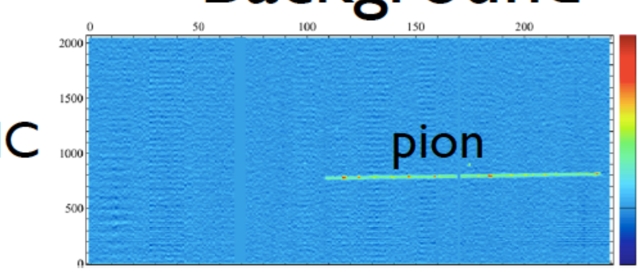
- Analysis steps:
  - ✓ automated reconstruction (muon angle and momentum)
  - ✓ visual scanning
  - ✓ calorimetric reconstruction

  } proton(s) angle and momentum reconstruction (applies to visual scanning and calorimetric reconstruction)
- Background estimate included
- GENIE MC:
  - ✓ estimate efficiency of the automated reconstruction, detector acceptance and proton containment (for PId)
  - ✓ estimate backgrounds

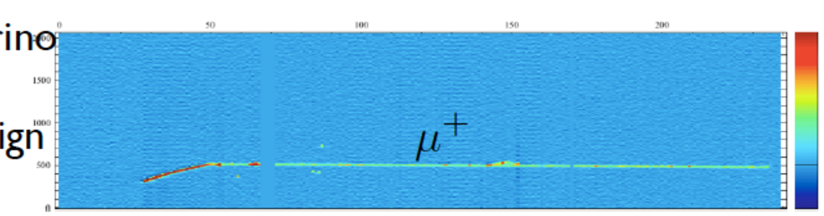
2-4% total {
- NC background
- WS background
- π^0 with both γ not converting

Background

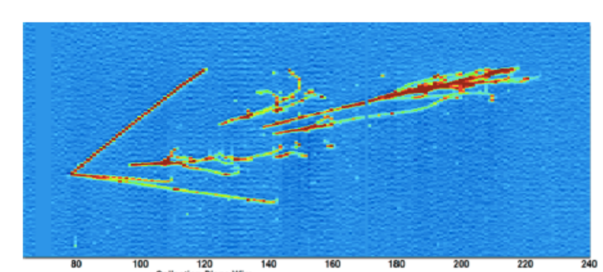
NC



WS in neutrino sample (opposite sign for antineutrinos)

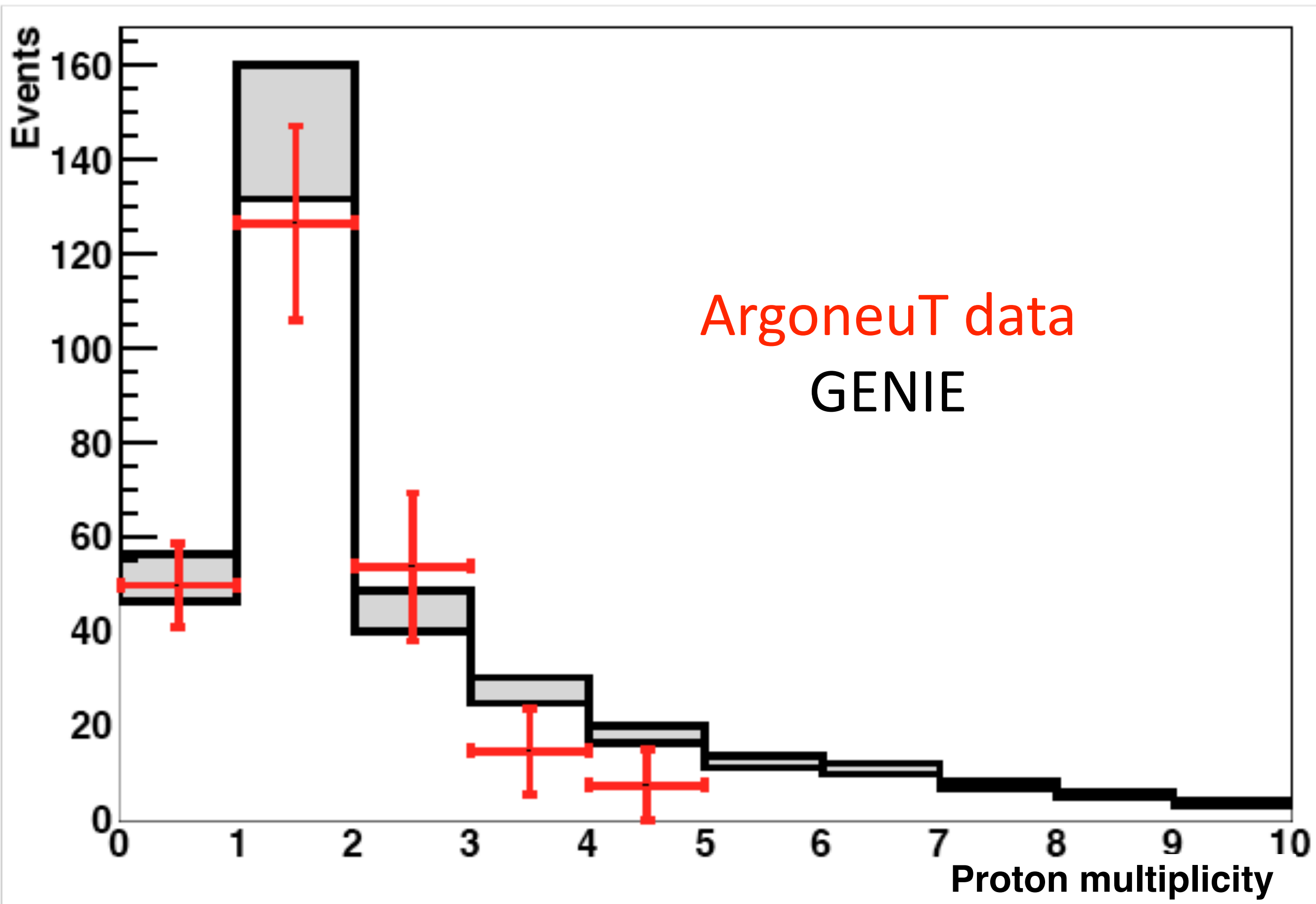


π^0

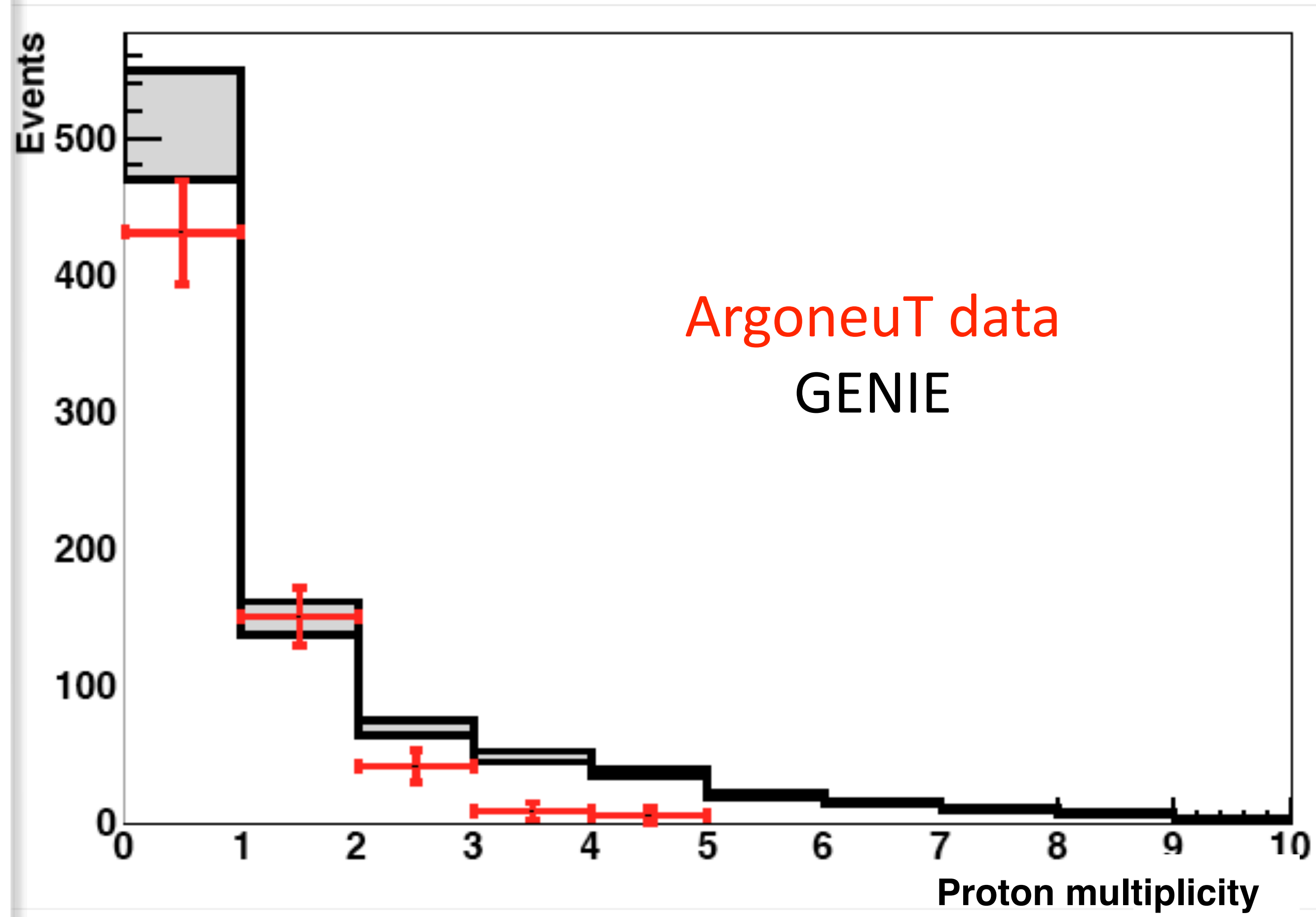


Proton Multiplicity (μ+Np events)

ν_μ - anti-neutrino mode run



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



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

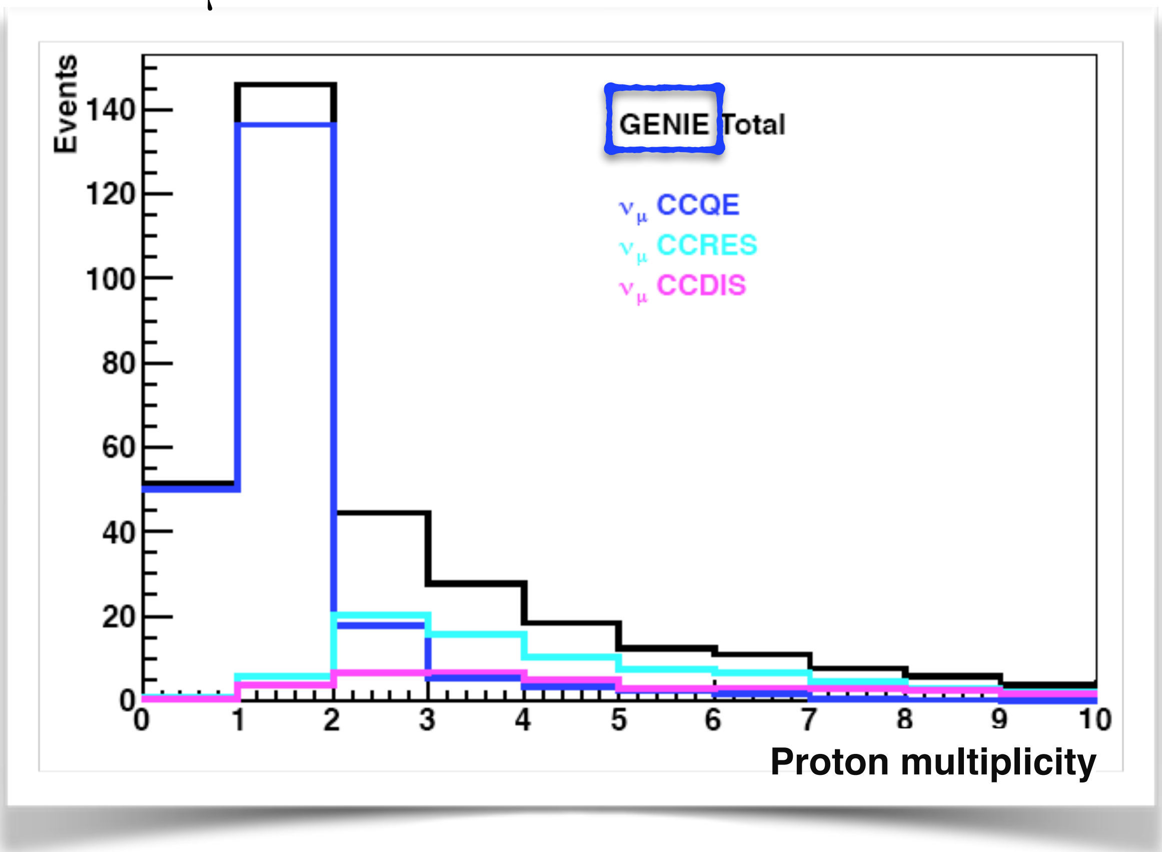
proton threshold:
T_p>21 MeV

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

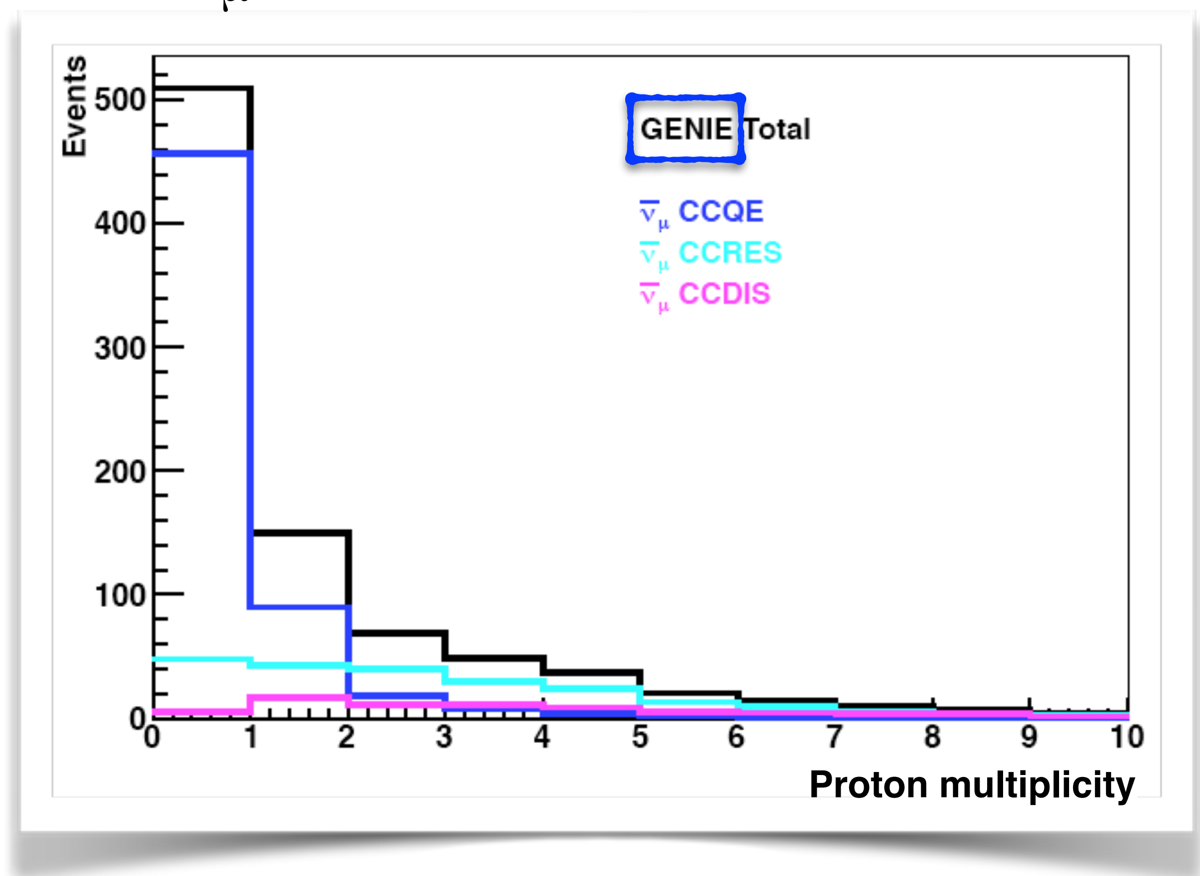
GENIE MC models more higher multiplicity events

CC 0 pion events: MC PREDICTIONS by Physical Process

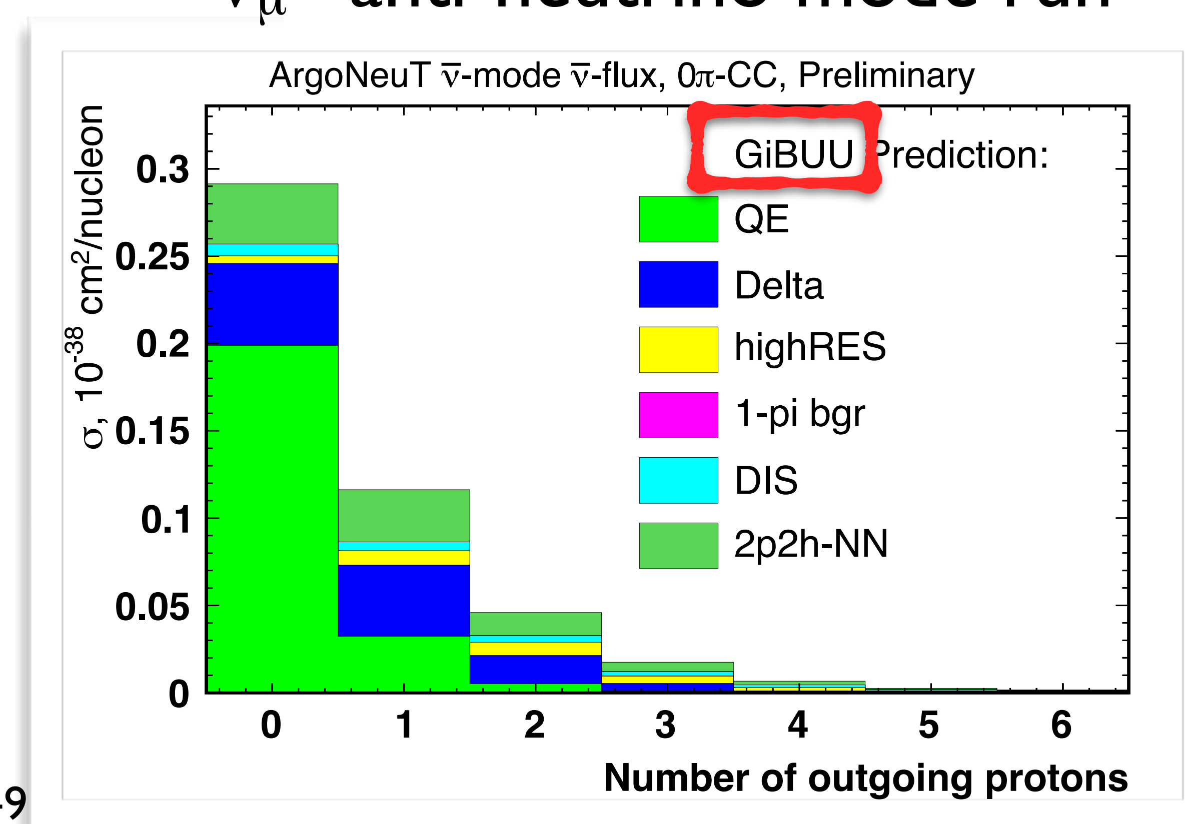
ν_μ - anti-neutrino mode run



$\bar{\nu}_\mu$ - 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.

anti-neutrino mode run

Multiplicity	% of non-CCQE GENIE ν events	% of non-CCQE GENIE $\bar{\nu}$ events
0p+μ	2.45	10.36
1p+μ	6.46	39.74
2p+μ	60.15	73.97
3p+μ	81.01	83.17
4p+μ	83.03	89.59
5p+μ	82.35	91.86
6p+μ	86.06	96.35
7p+μ	96.52	95.17
8p+μ	96.51	99.02
9p+μ	100	100
10p+μ	96.88	100

Anti-neutrino mode run

Proton Multiplicity - neutrinos

Multiplicity	Genie Expectation	Genie % of Total	DATA	DATA % of Total
0p+μ	51.4±1.8±5	15%	49.9±8.4±0.5	20%
1p+μ	145.8±3±14.2	43.5%	126.6±19±1.5	50%
2p+μ	44.5±1.7±4.3	13%	53.8±15.4±0.3	21%
3p+μ	27.6±1.4±2.7	8%	14.7±9.1±0.0	6%
4p+μ	18.4±1±1.8	5.5%	7.5±7.7±0.0	3%
Total (including >4p)	335.5±4.7±26.1	-%	252.5±27.2±1.6	-%

Proton Multiplicity - antineutrinos

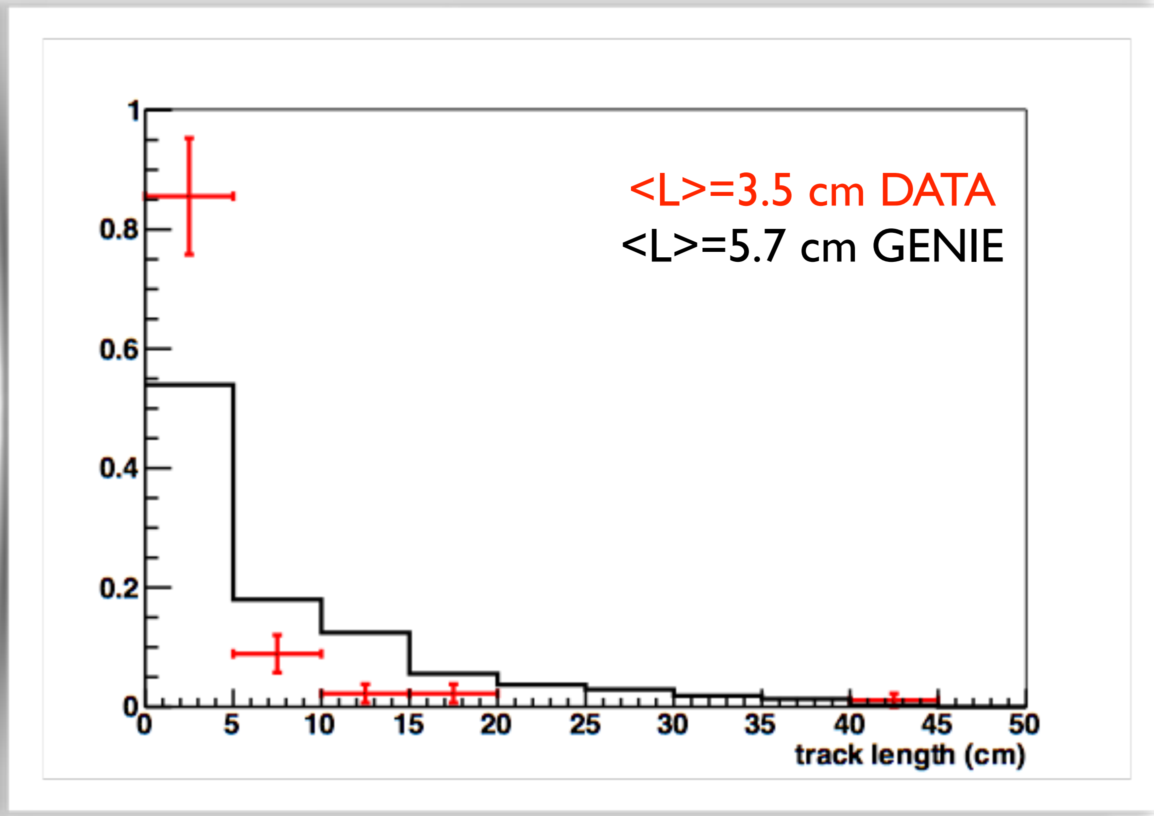
Multiplicity	Genie Expectation	Genie % of Total	DATA	DATA % of Total
0p+μ	510±5.8±40	58.4%	431±27.2±10.6	67.7%
1p+μ	149.4±3±11.8	17%	150.8±18.9±2.1	23.7%
2p+μ	69±2±5.5	8%	41.3±11.4±0.3	6.4%
3p+μ	48.5±1.8±3.9	5.5%	8.6±6.2±0.0	1.4%
4p+μ	37±1.5±3	4.2%	5.6±5.6±0.1	1%
Total (including >4p)	872.4±7.6±67	-%	637.3±36±10.8	-%

The systematic error on the MC represent the NuMI flux uncertainty (see N. Mayer talk)

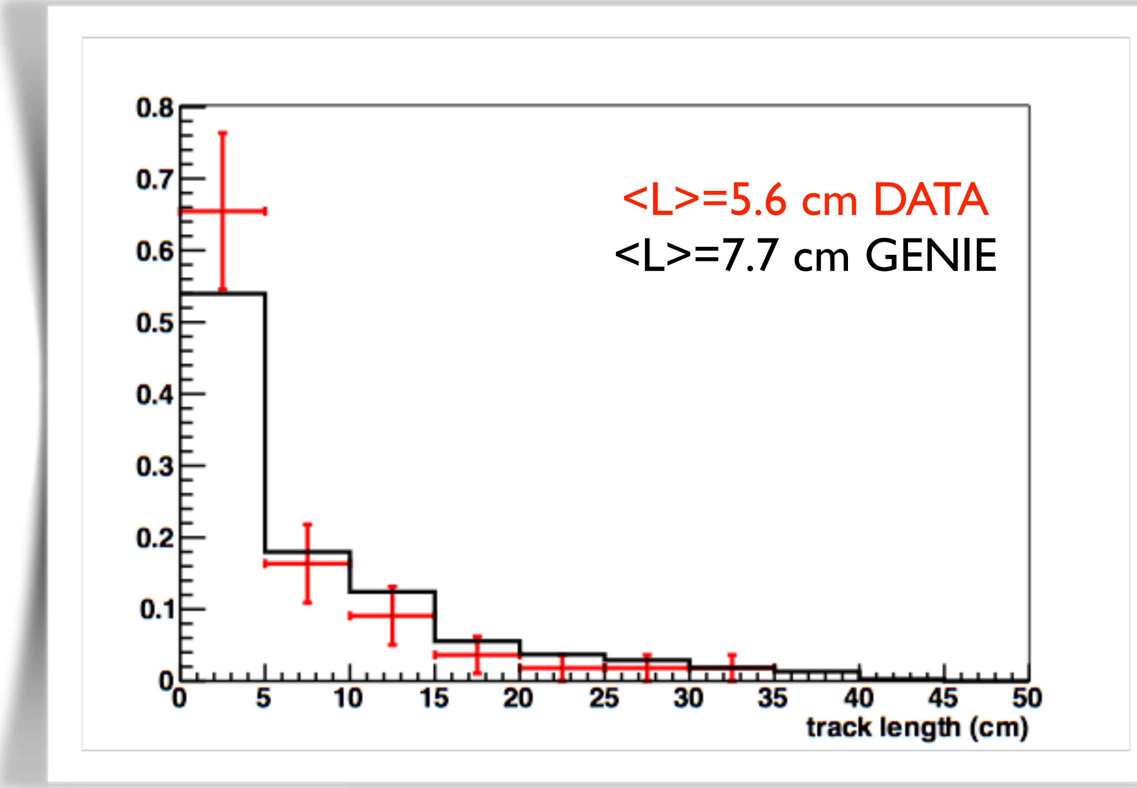
GENIE predictions are larger than data for both neutrinos and anti-neutrinos
(by 27% for anti-neutrinos and 25% for neutrinos)

μ^+/μ^- 1p events PROTON KINEMATICS

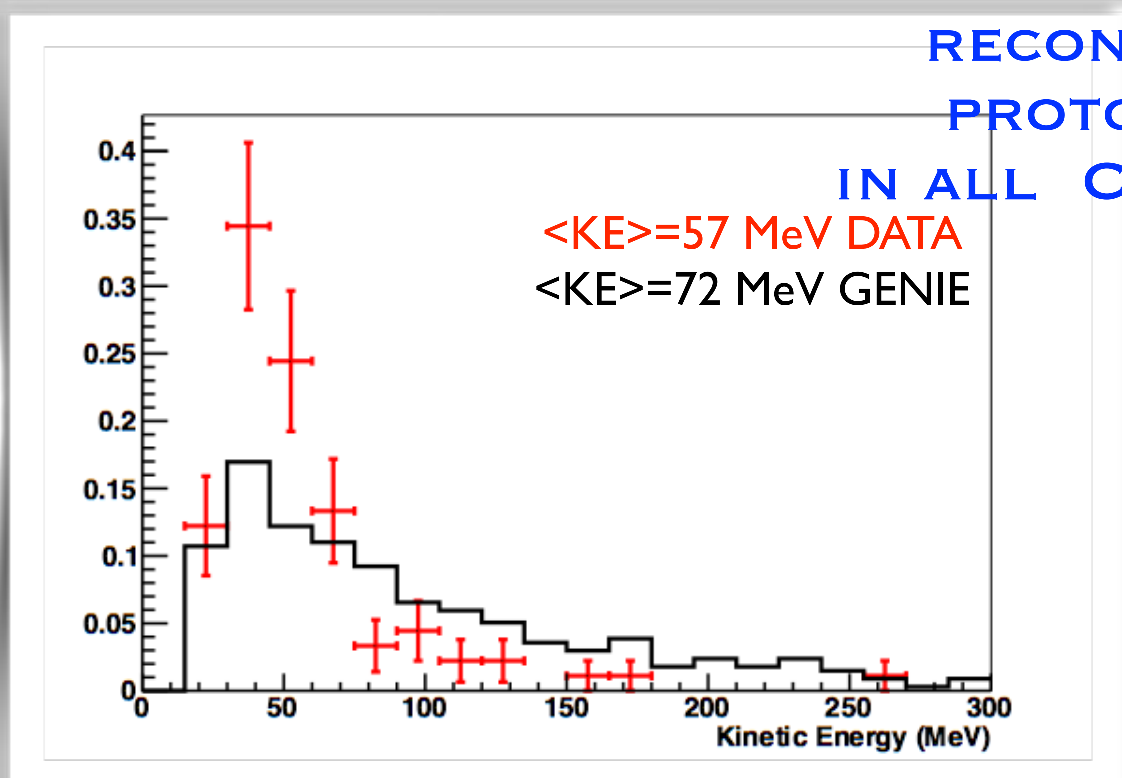
$\bar{\nu}_\mu$ - anti-neutrino mode run

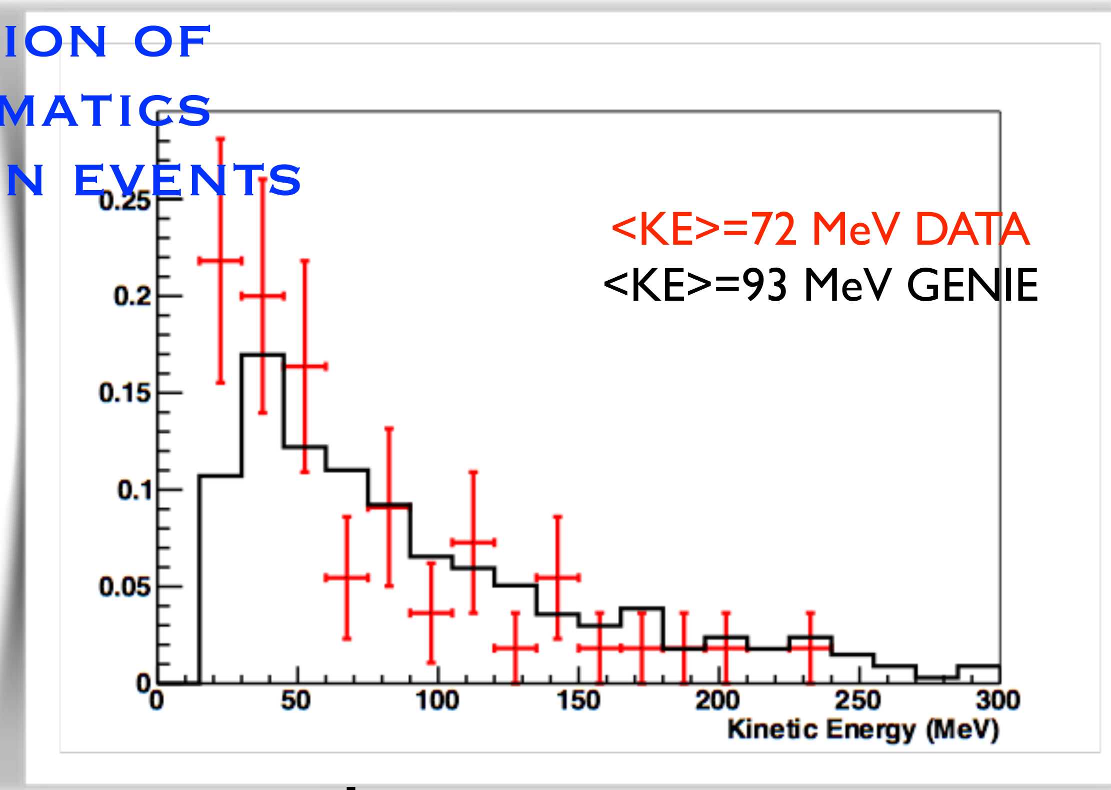


ν_μ - anti-neutrino mode run



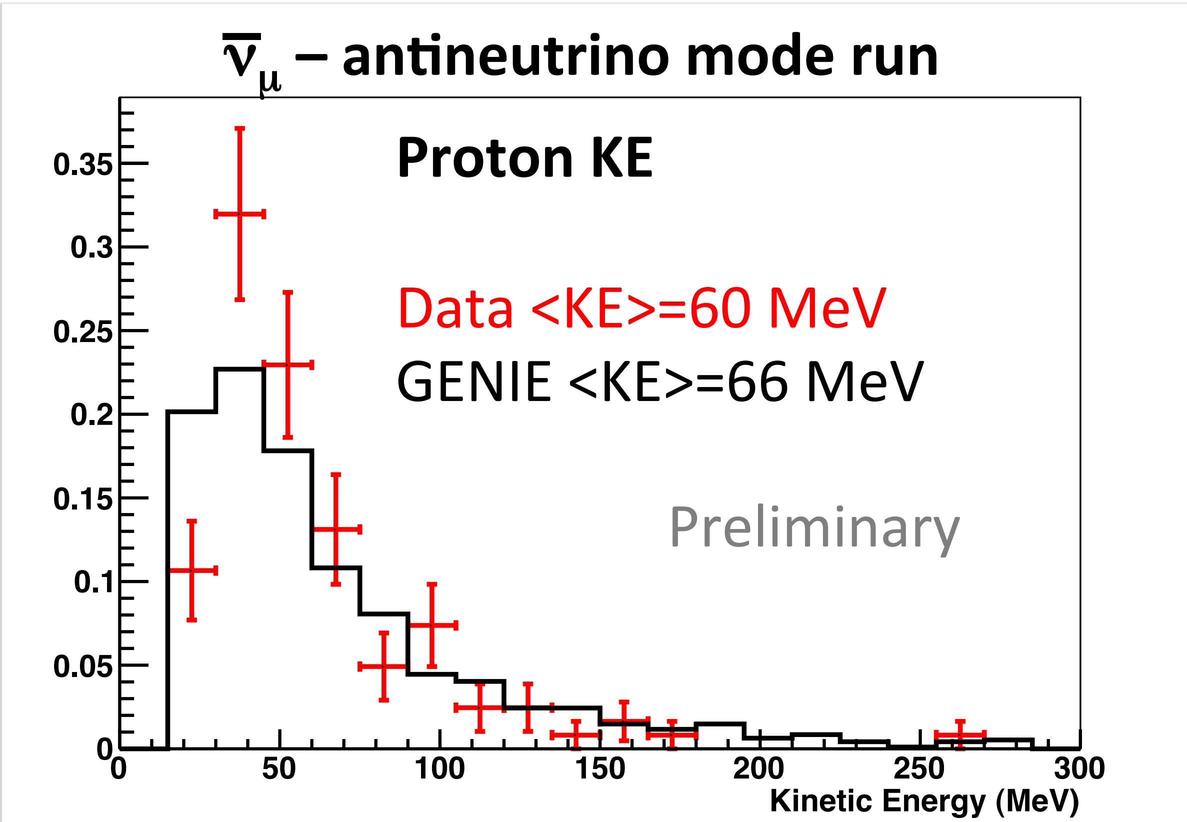
RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS





GENIE MC models more energetic protons

NEUTRINO ENERGY RECONSTRUCTION



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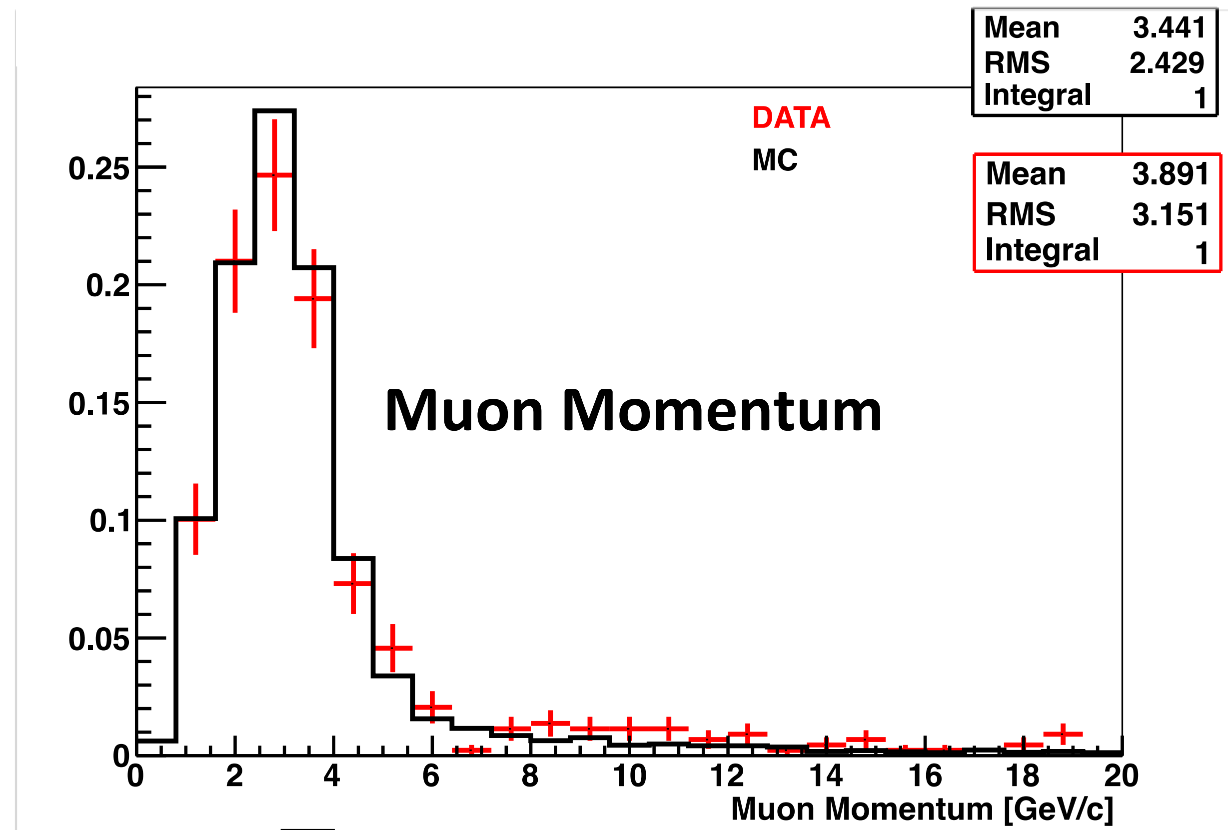
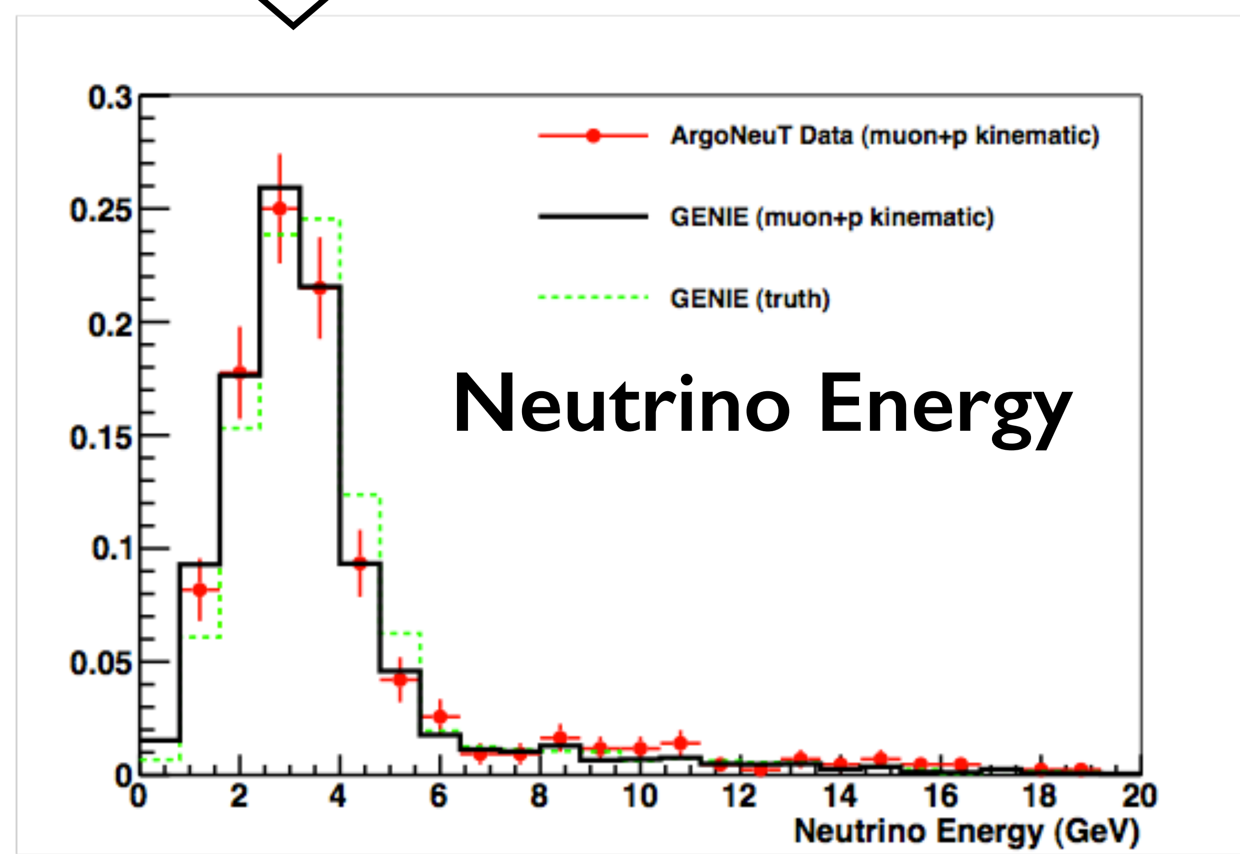




Neutrino Energy from muon+proton reconstructed kinematics:

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

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

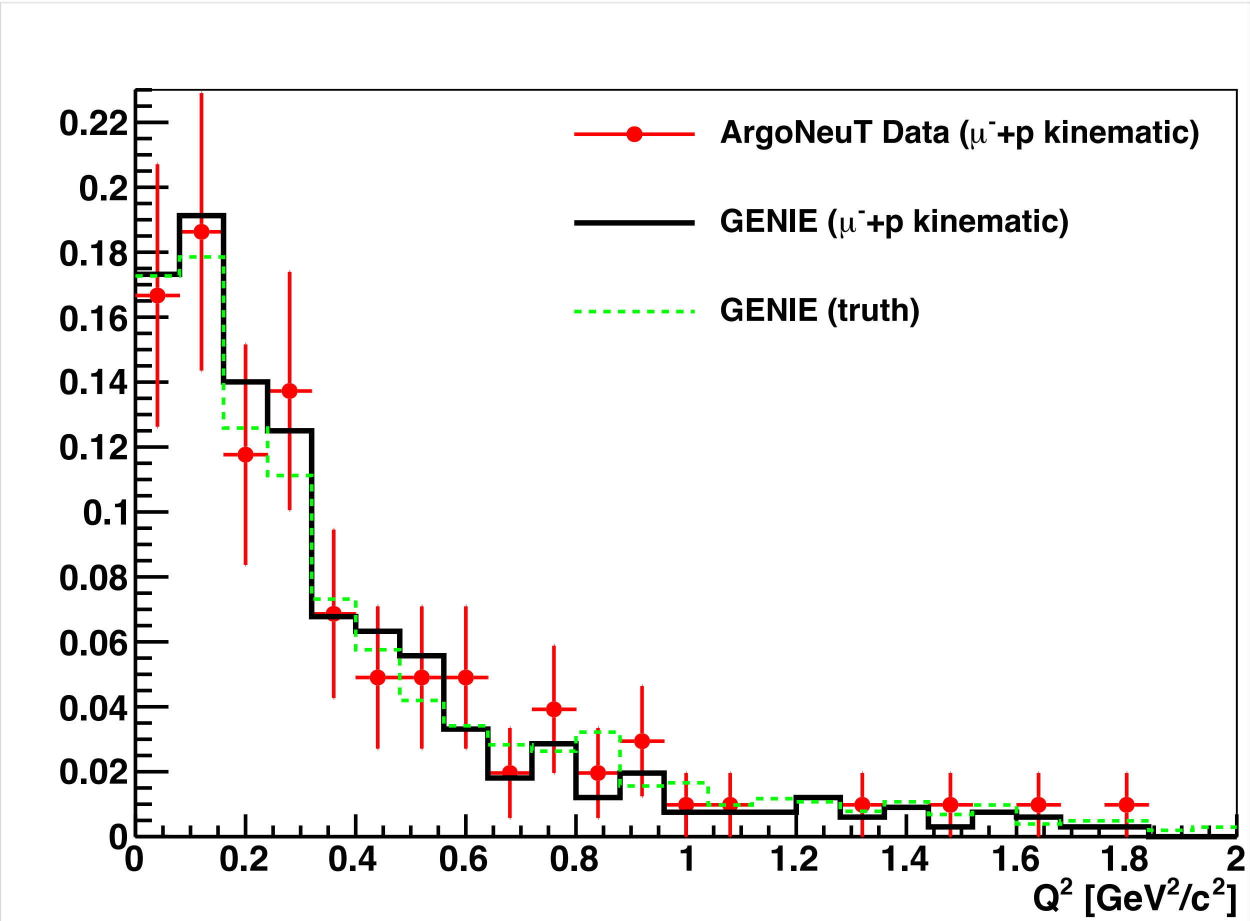
T_X=recoil energy of the residual nuclear system (estimated from missing transverse momentum)

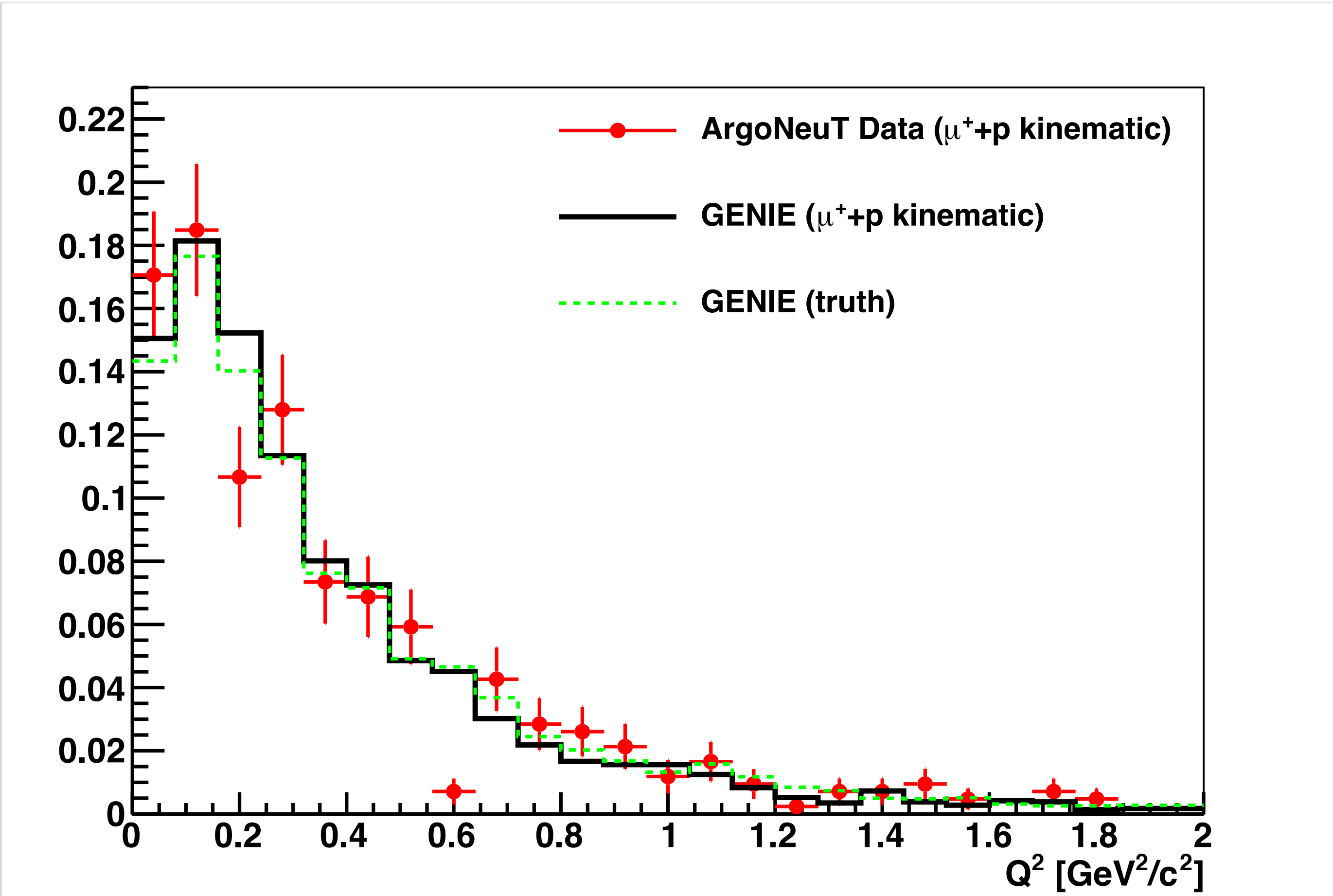
No just muon information

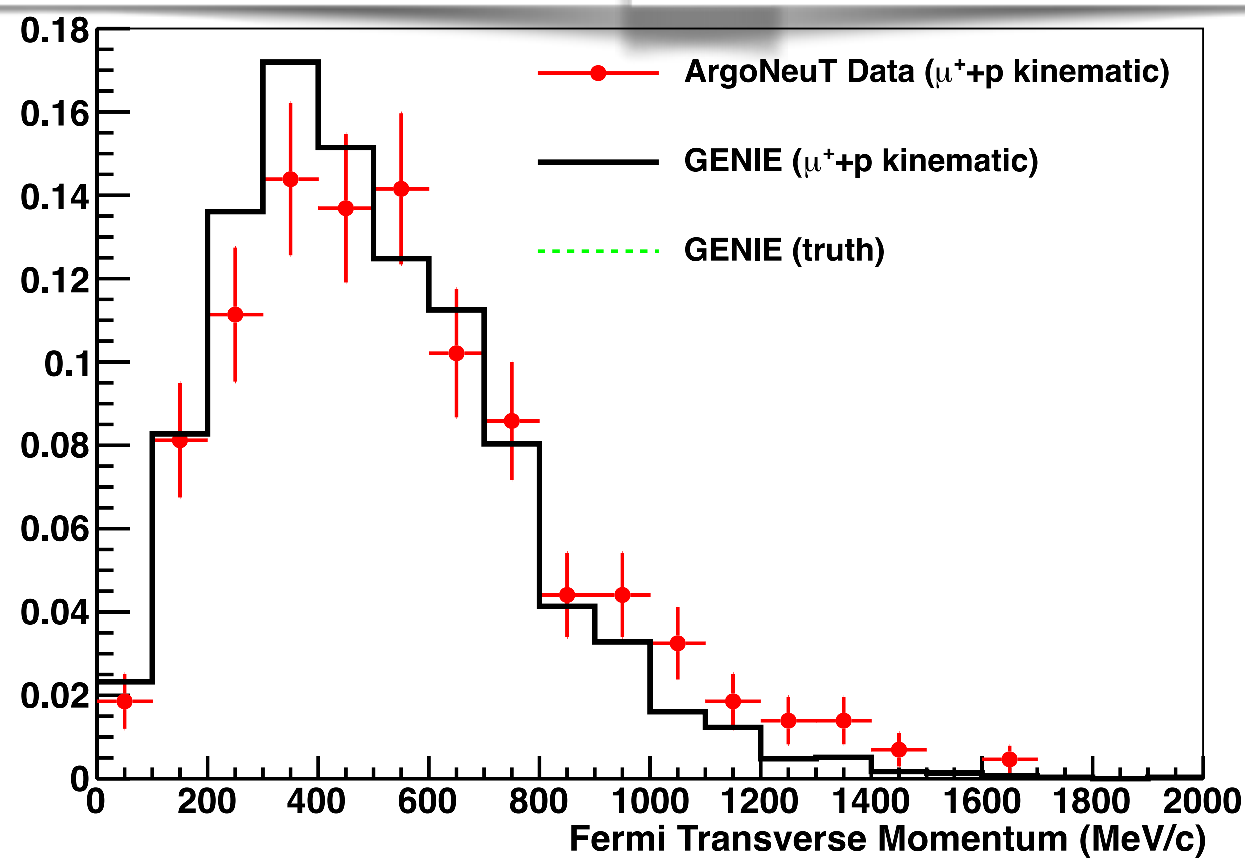
Reconstruction of other kinematic quantity (q, Q^2, p^T_{miss} etc.)

Reconstruction of other kinematic quantities (Q^2, p^T_{miss})

From muon+proton reconstructed kinematics

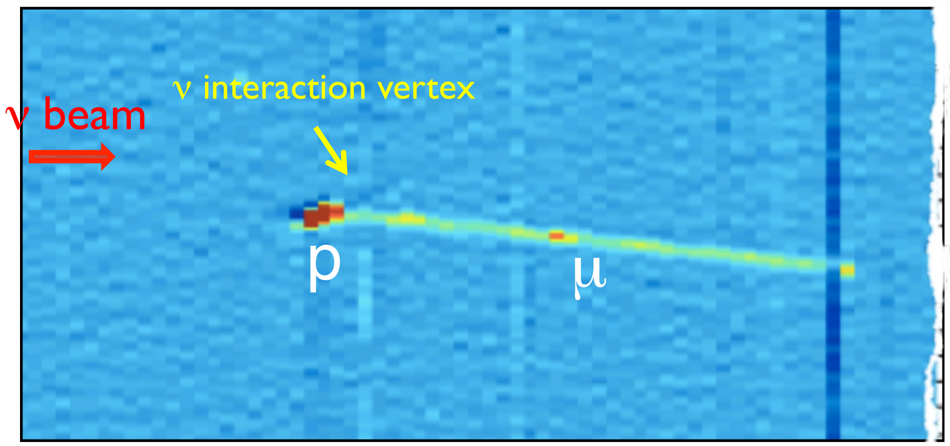


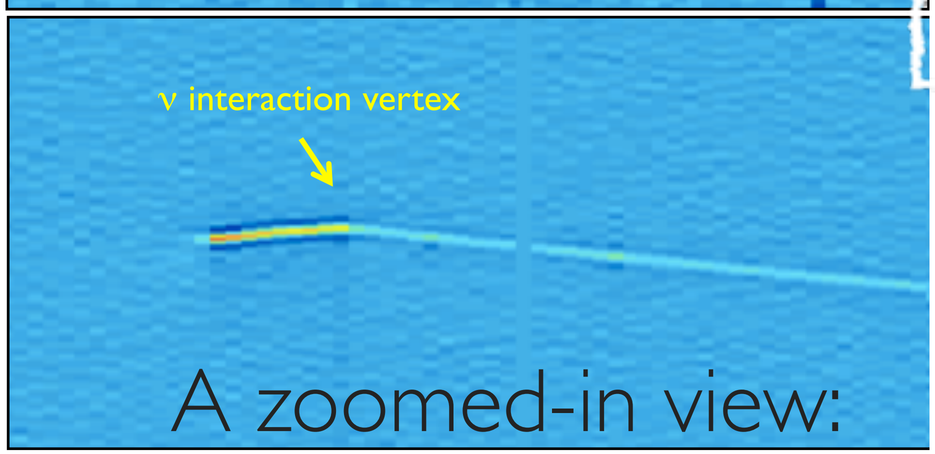




PROTON KINEMATICS: BACKWARD GOING PROTONS (BP)

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

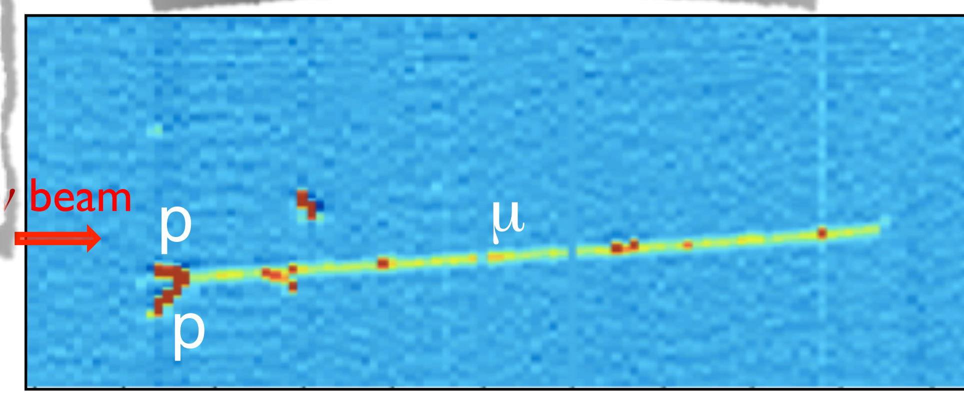
DATA backward=21%

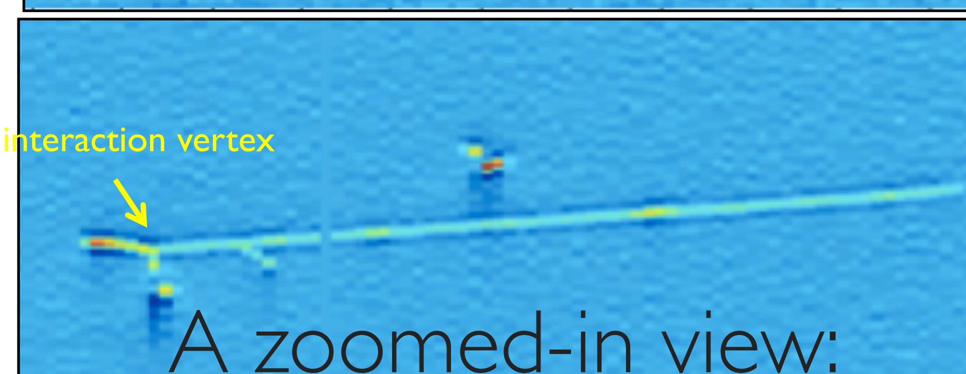
GENIE backward=30%

μ+2p

DATA backward=13%

GENIE backward=36%





A zoomed-in view:

ν interaction with

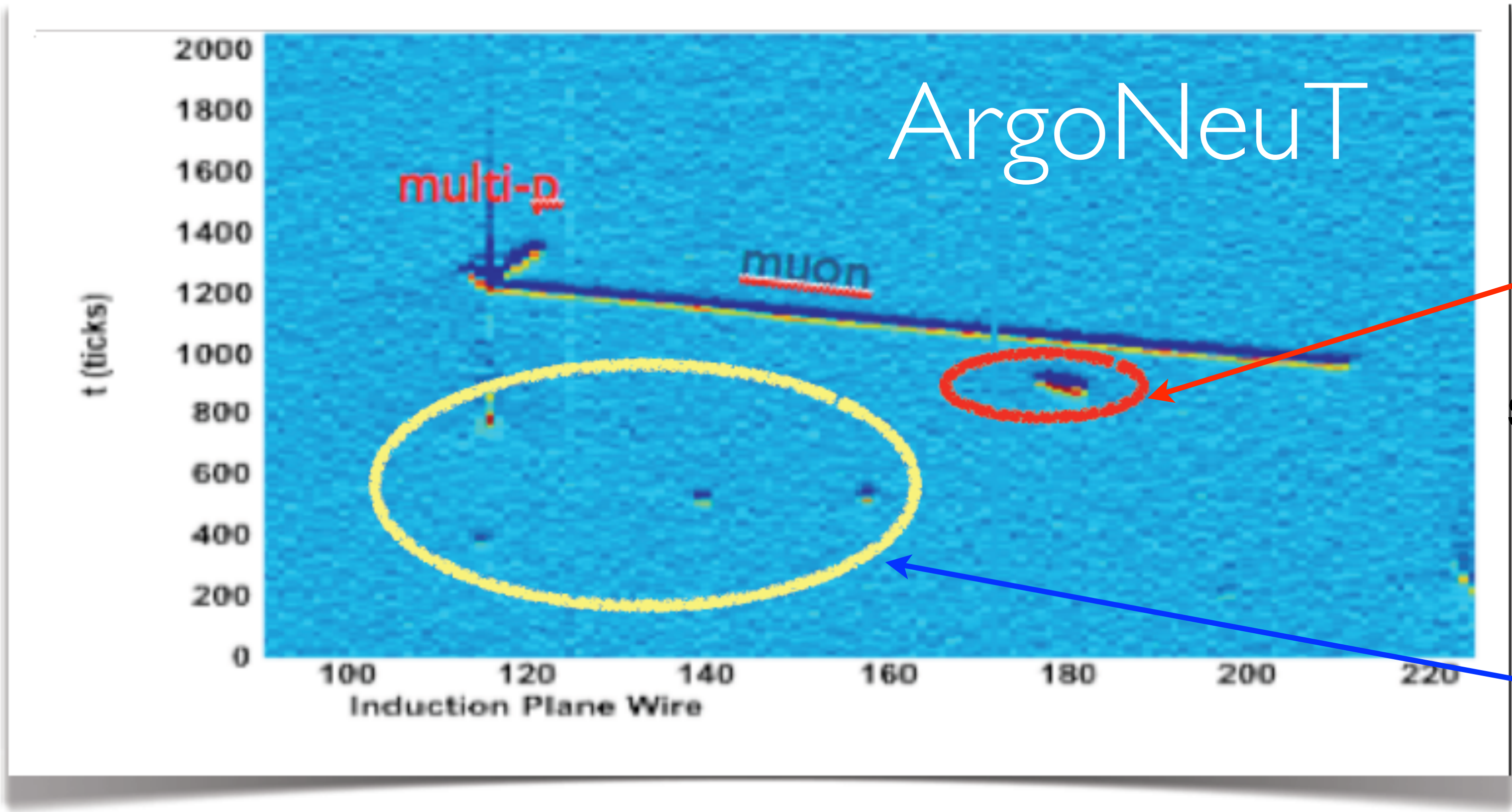
two backward going p

DETAILED STUDY OF BP IN PROGRESS

LArTPC: High-resolution detector

e.g VERTEX ACTIVITY

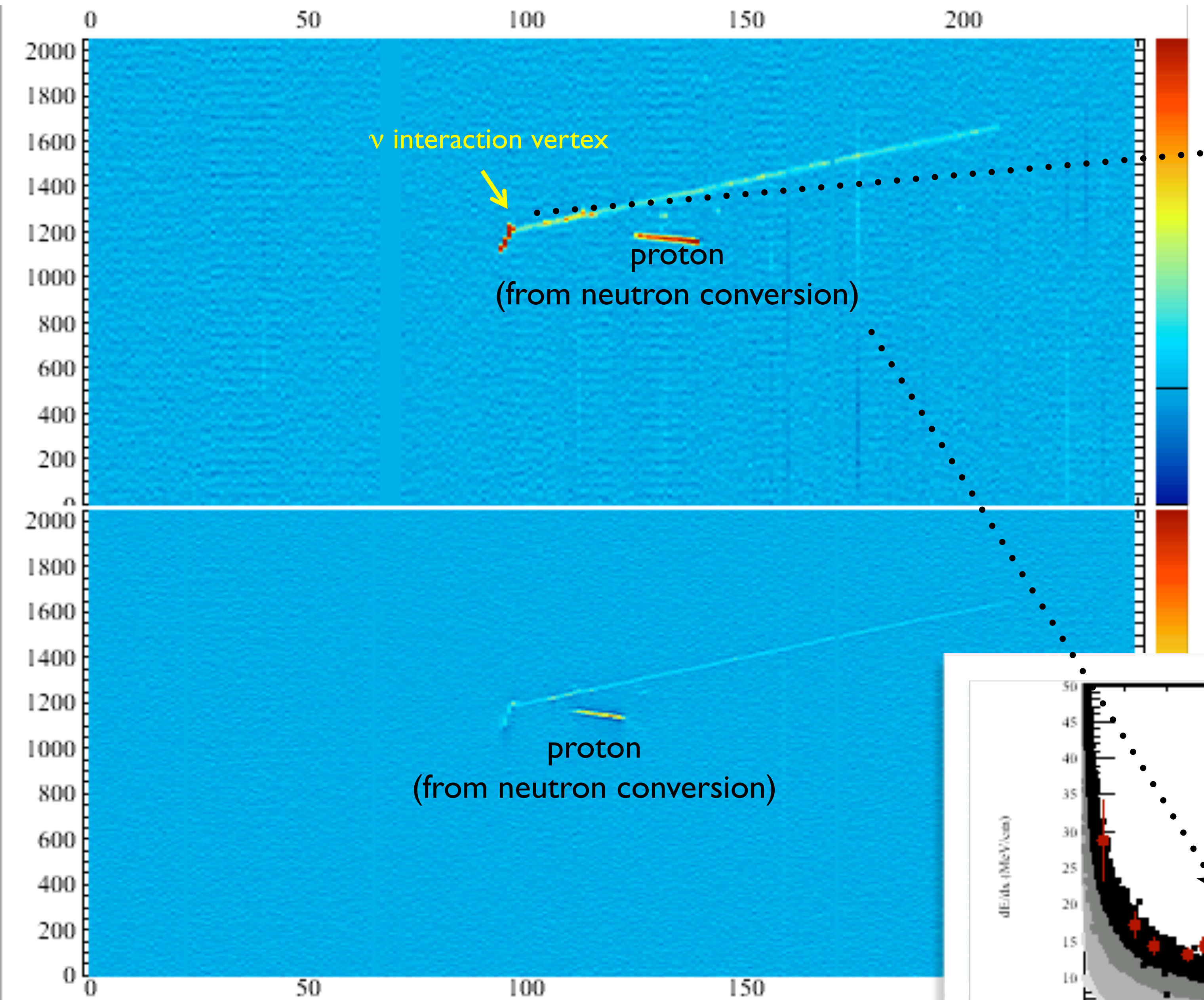
Measurement of γ activity around the vertex and neutron → proton can also help to tune MC generators



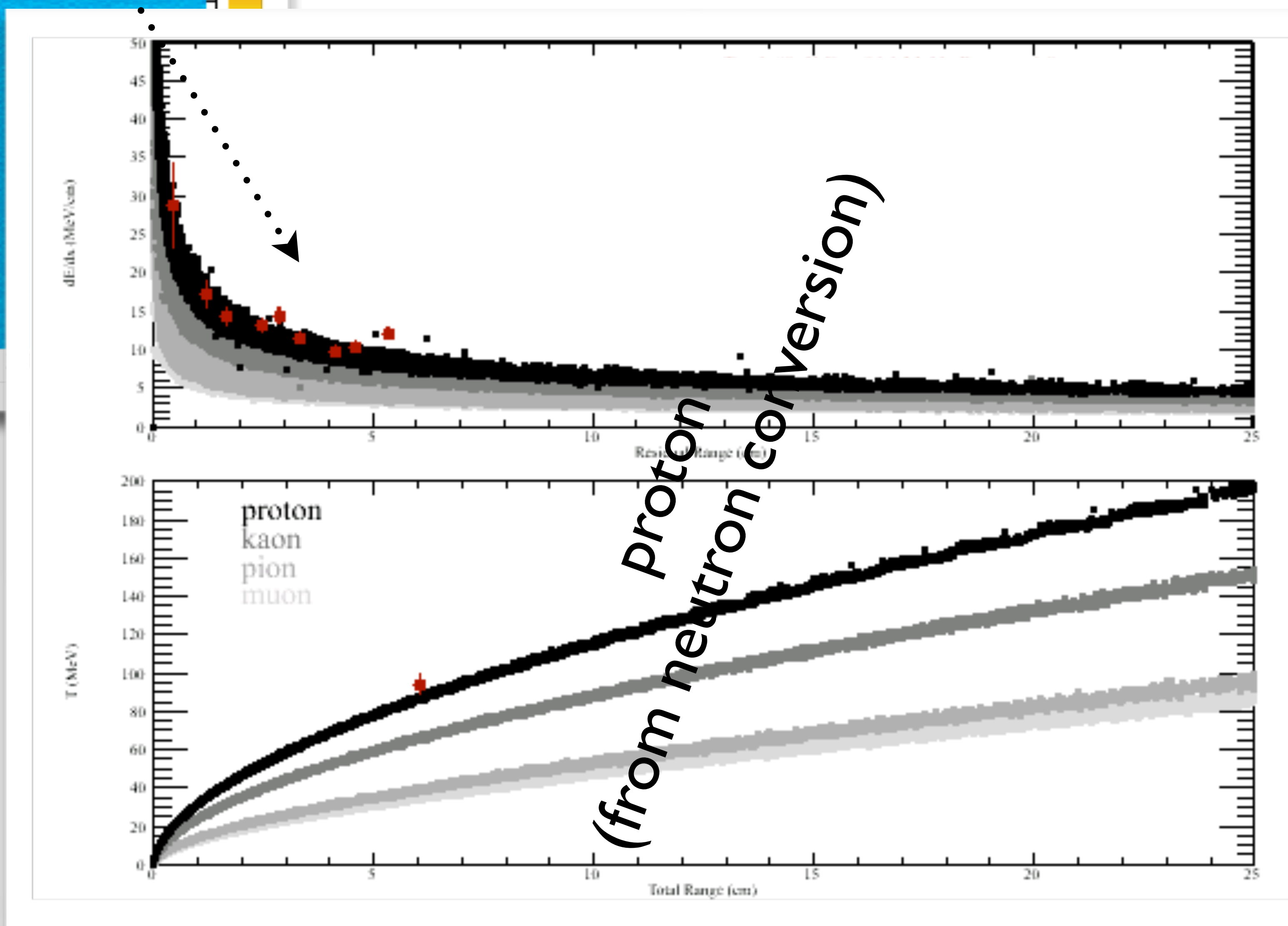
Direct access to nuclear effects requires:

- 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)

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 !)

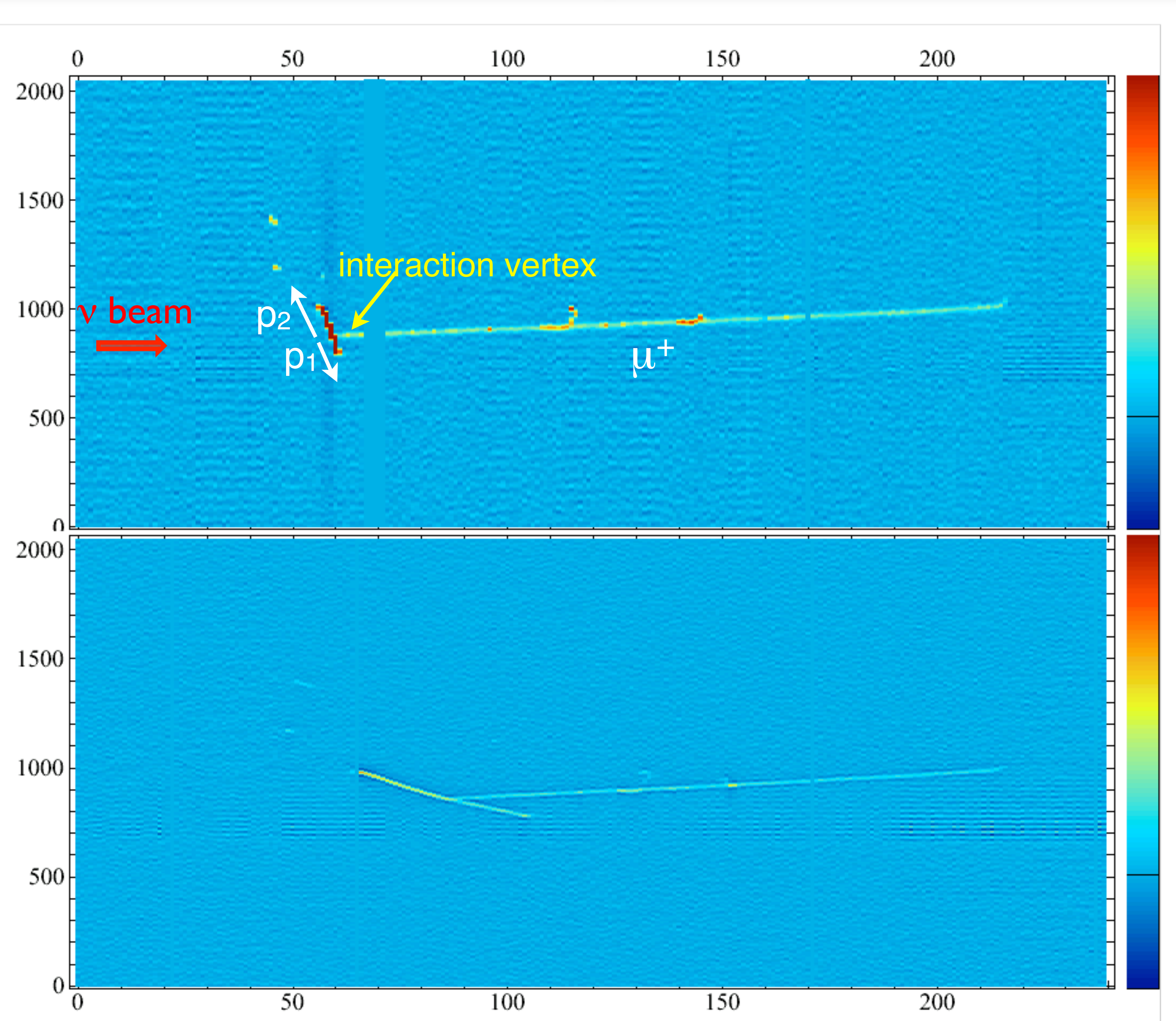
Pairs of energetic protons with 3-momentum $p_{p1}, p_{p2} \geq k_F$ detected at large opening angles directly in the Lab frame were observed in bubble-chamber by hadron scattering experiments (pion absorption on nuclei). This was interpreted as **hints for SRC** *in the target nucleus.*

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.

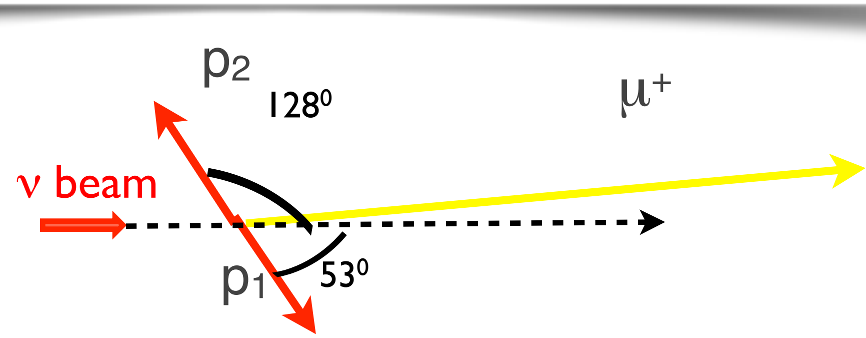
In neutrino scattering experiments one main limitation comes from the intrinsic uncertainty on the 4-momentum transfer, due to the not fixed (broadly distributed in the beam spectrum) incident neutrino energy. An estimate can be inferred with satisfactory accuracy when all final state particles kinematics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

BACK-TO-BACK PROTON PAIR



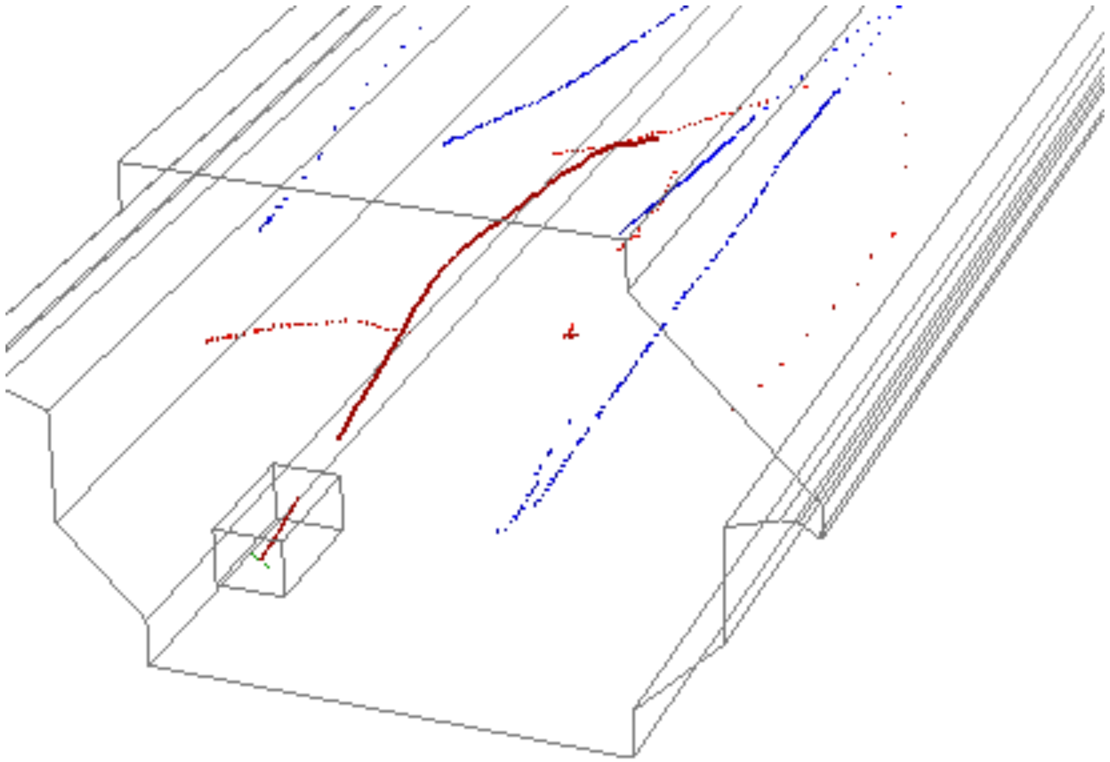
Angle between two protons $\gamma = 177^0$

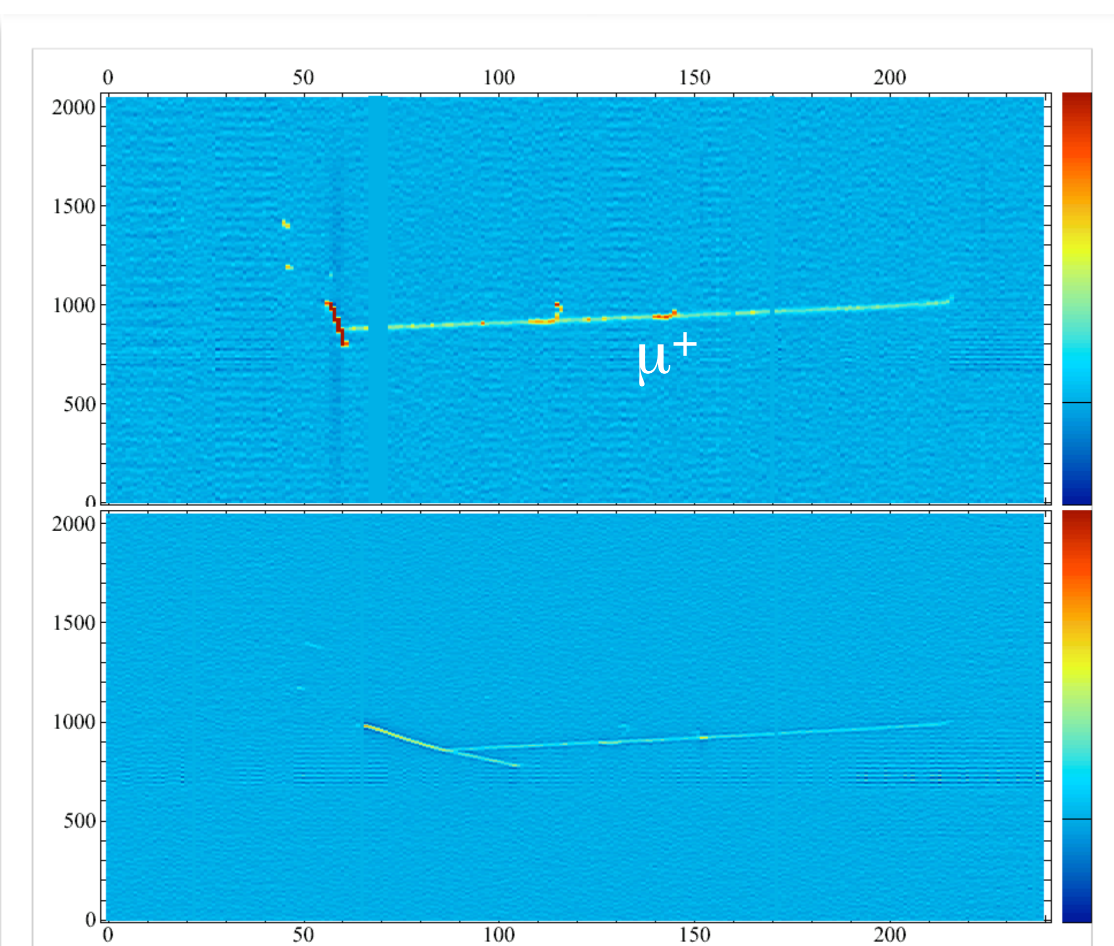
anti-Neutrino interaction producing a back-to-back proton pair

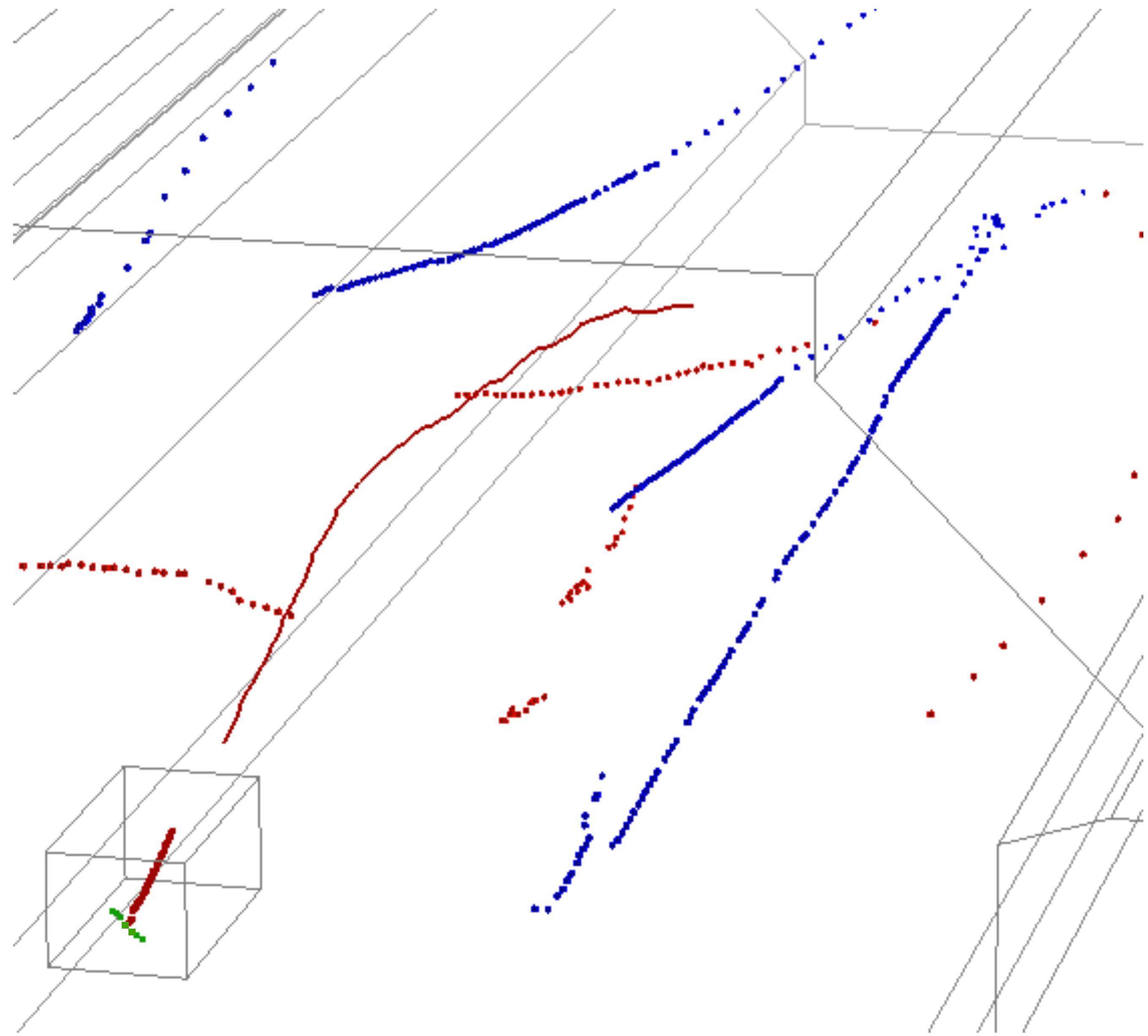


back-to-back protons

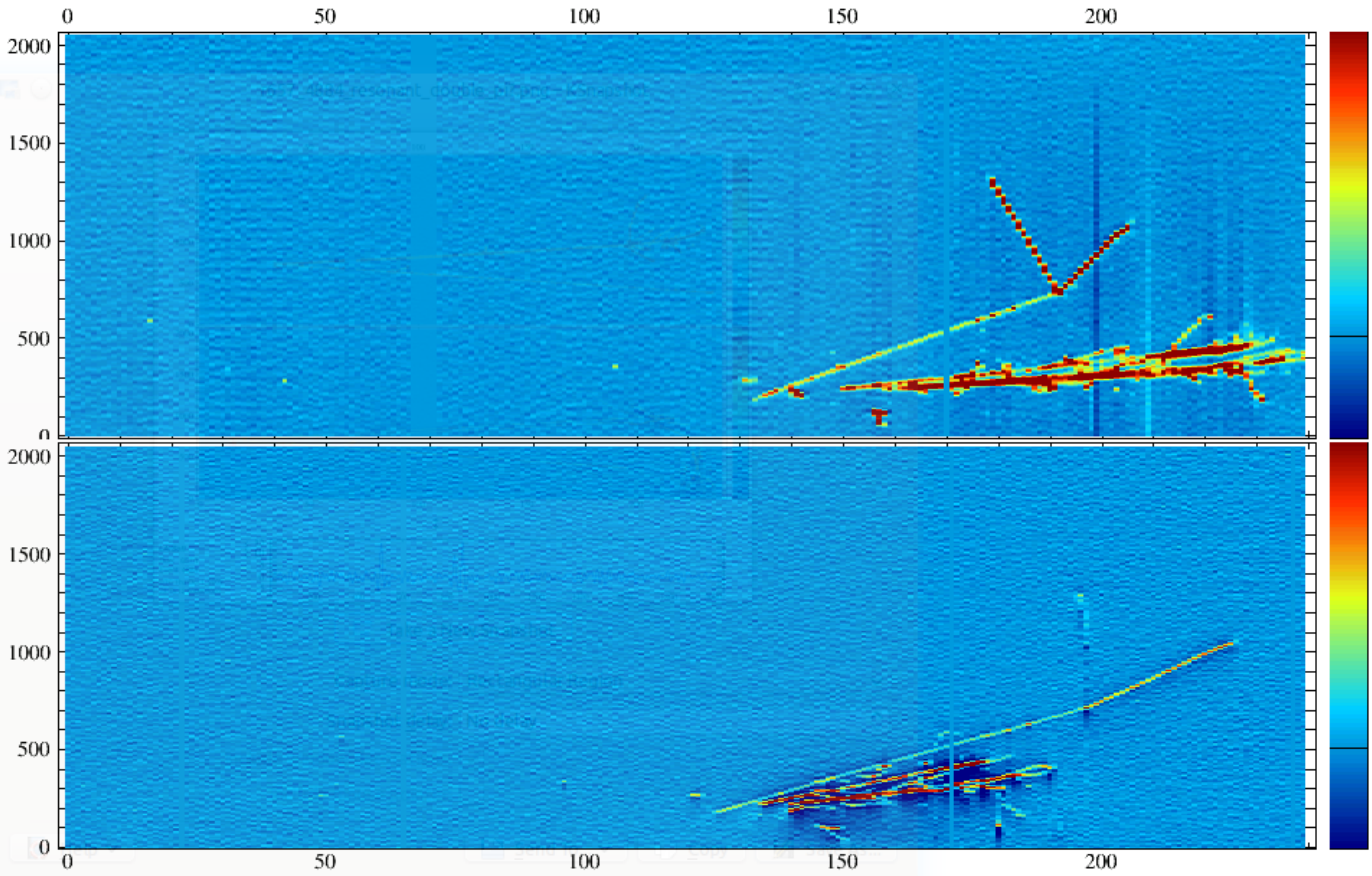
BACK-TO-BACK PROTON PAIR EVENT MUON TRACK MATCHING IN MINOS ND







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


0
50
100
150
200
2000
1500
1000
500
0