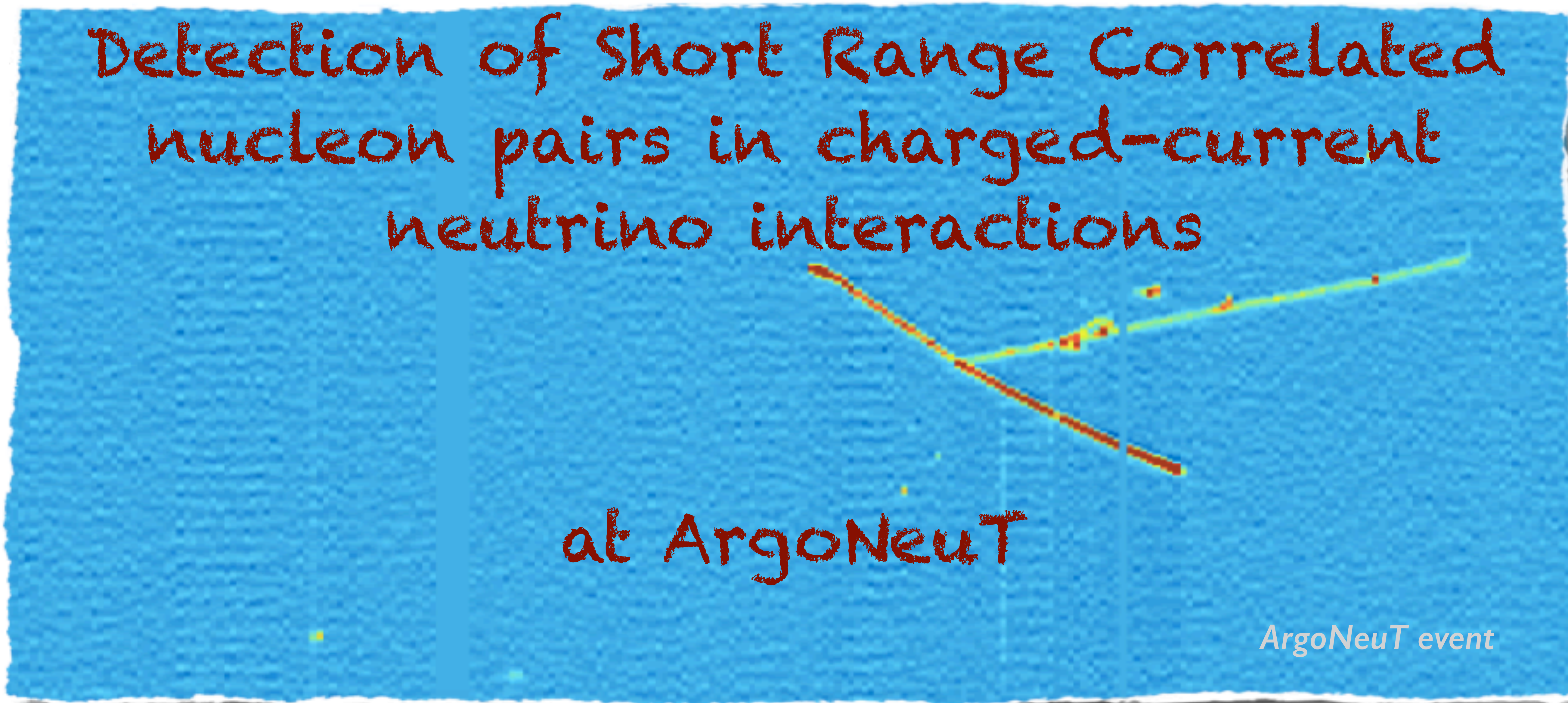
Detection of Short Range Correlated nucleon pairs in charged-current neutrino interactions

at ArgoNeuT



Wine and Cheese seminar

October 3rd 2014 - Fermilab

Ornella Palamara
Fermilab*

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

Outline

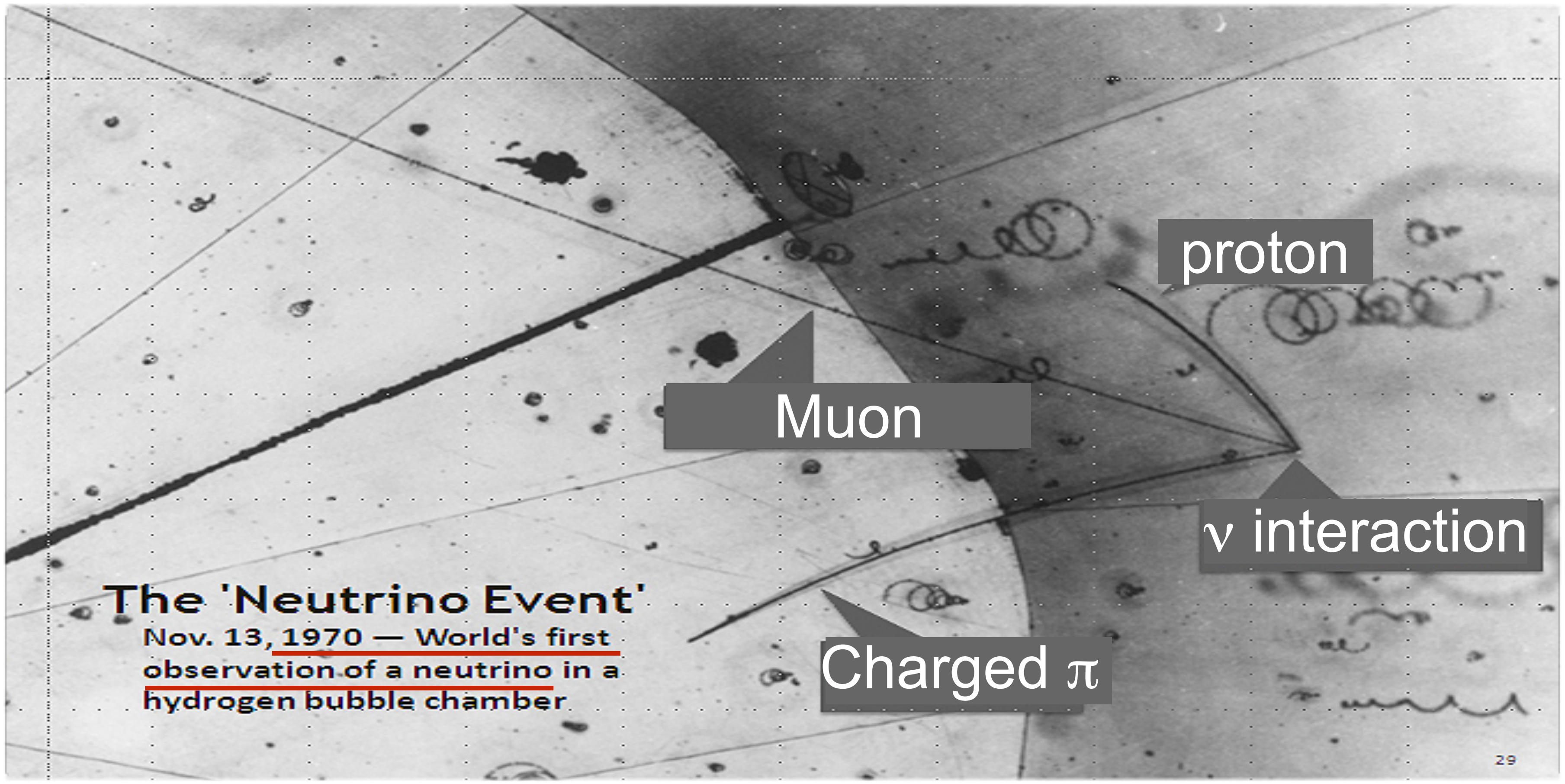
- Why LAr TPC?

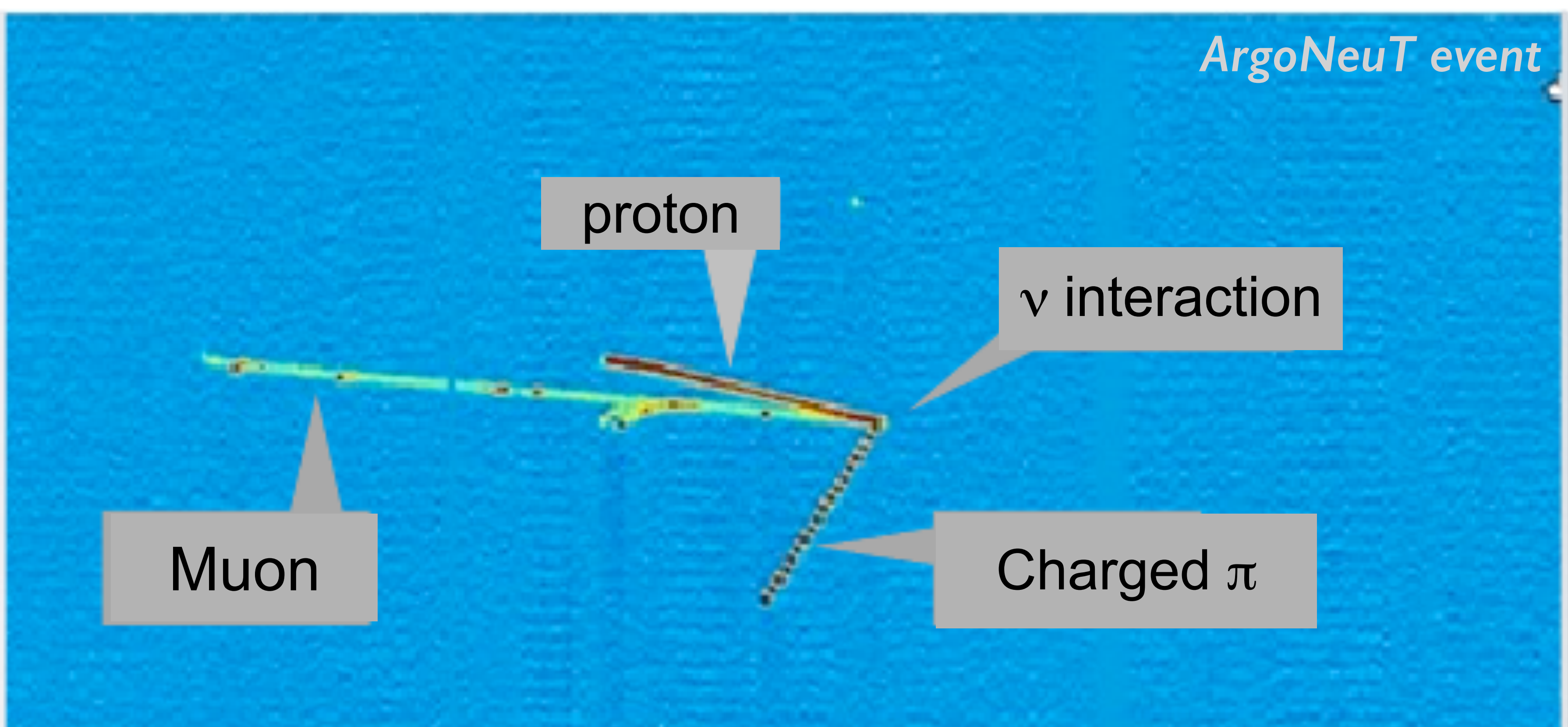
- The ArgoNeuT detector on the NuMI beam

- ν_μ CC 0 pion events - Topological analysis & nuclear effects

- Looking for ***Short Range Correlated nucleon pairs*** in ArgoNeuT data

Why Liquid Argon TPC?

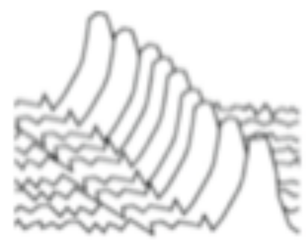




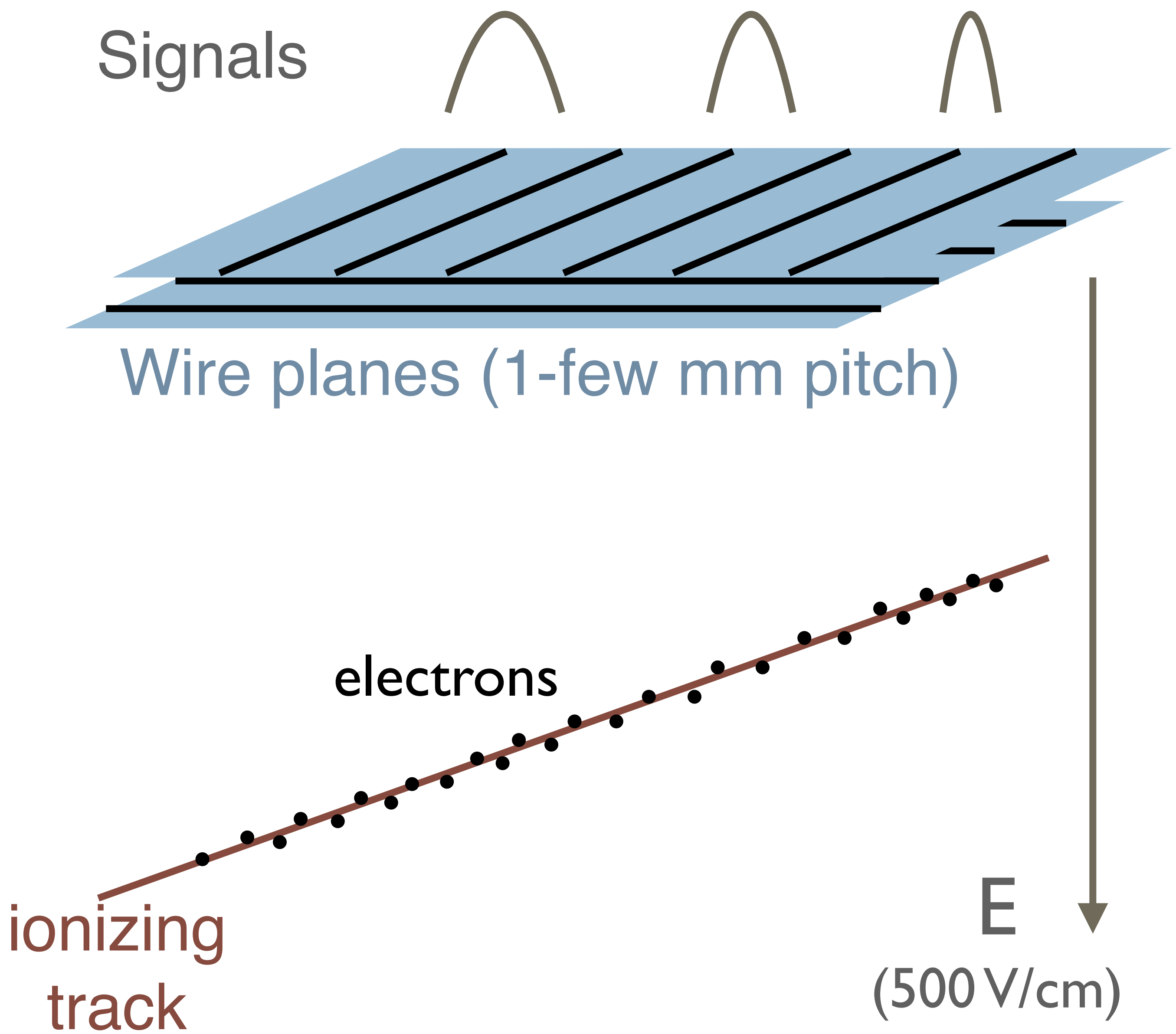
Bubble chamber quality of data with added full calorimetry

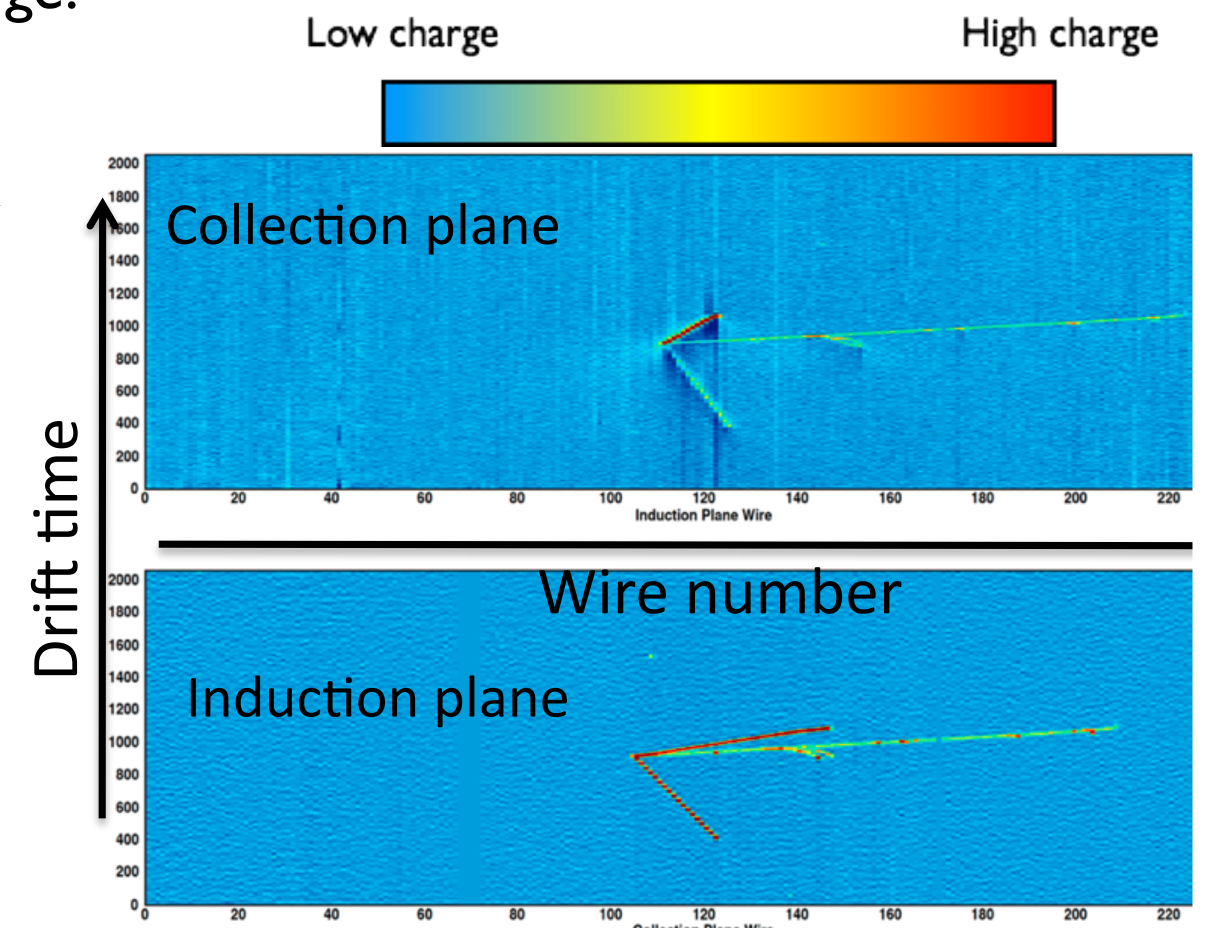
Can produce physics results with a "table-top" size experiment

The Liquid Argon TPC concept



Time of the wire pulses give the drift coordinate of the track. Amplitudes give the deposited charge.



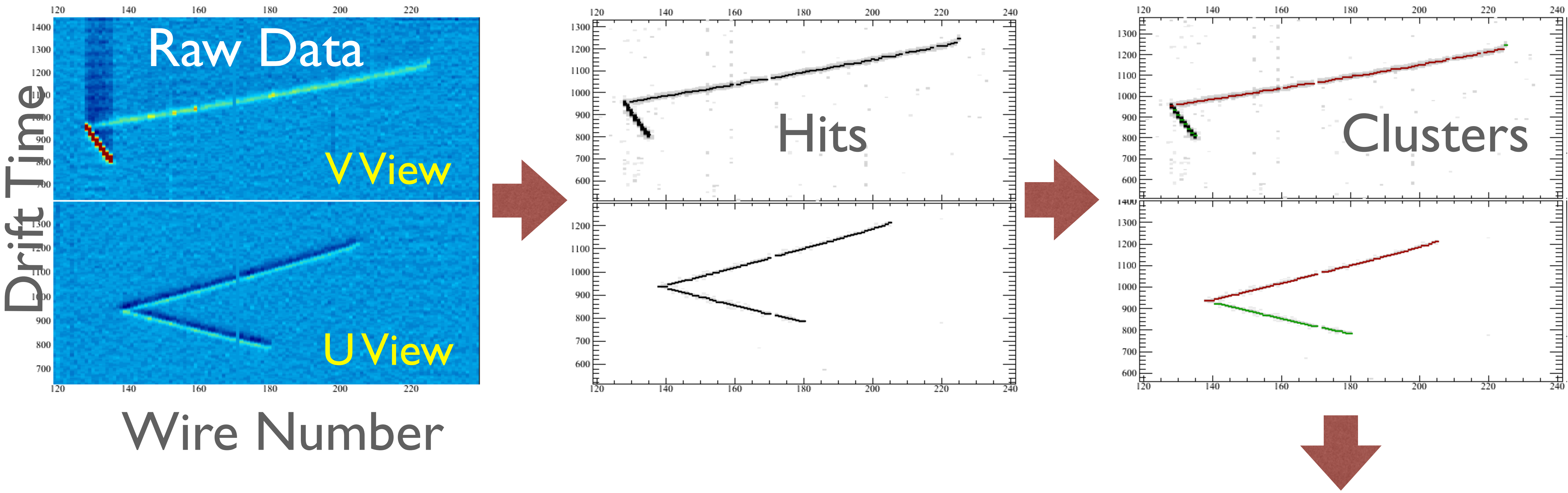


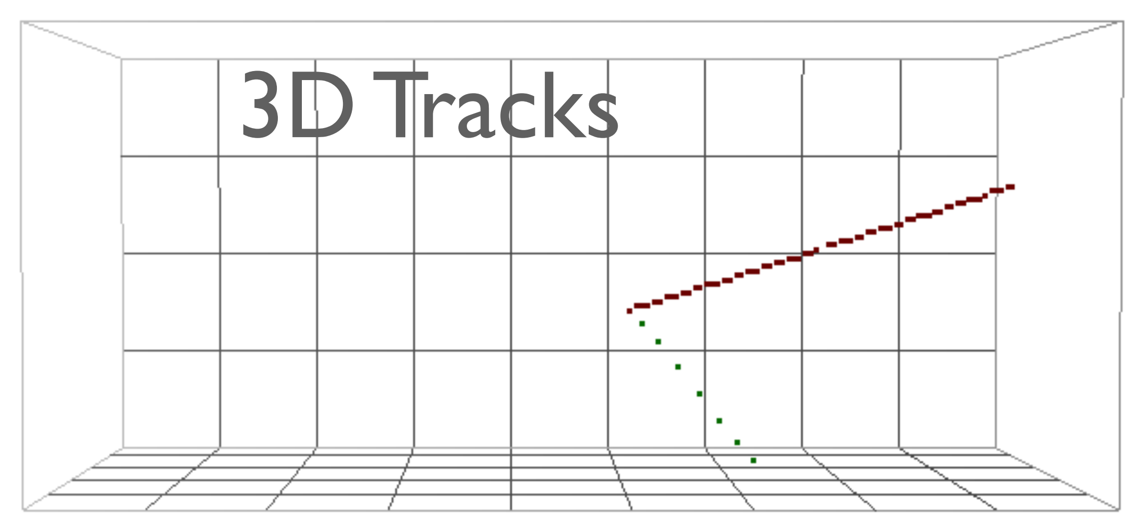
2D views from the two wire planes

mm-scale position resolution, three dimensional imaging, and calorimetry

induction plane + collection plane + time = 3D image of the event

Track Reconstruction





LArSoft

https://cdcvs.fnal.gov/redmine/projects/larsoft

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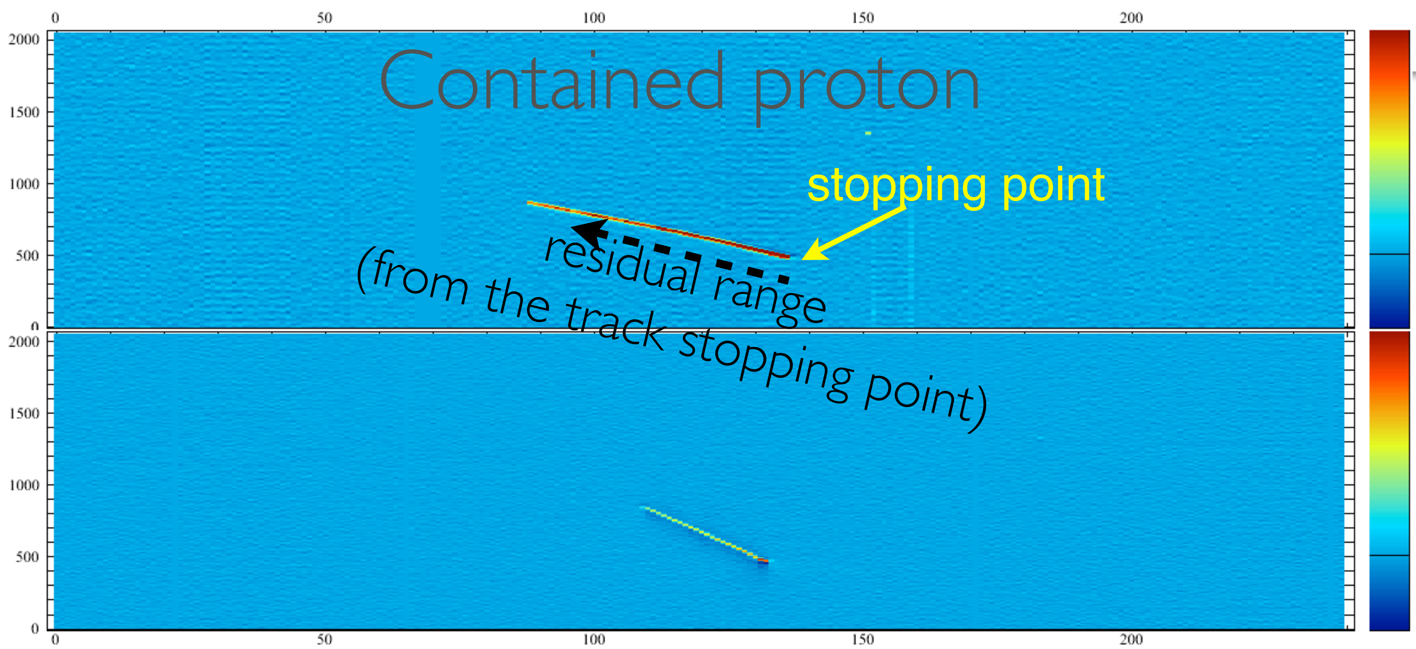
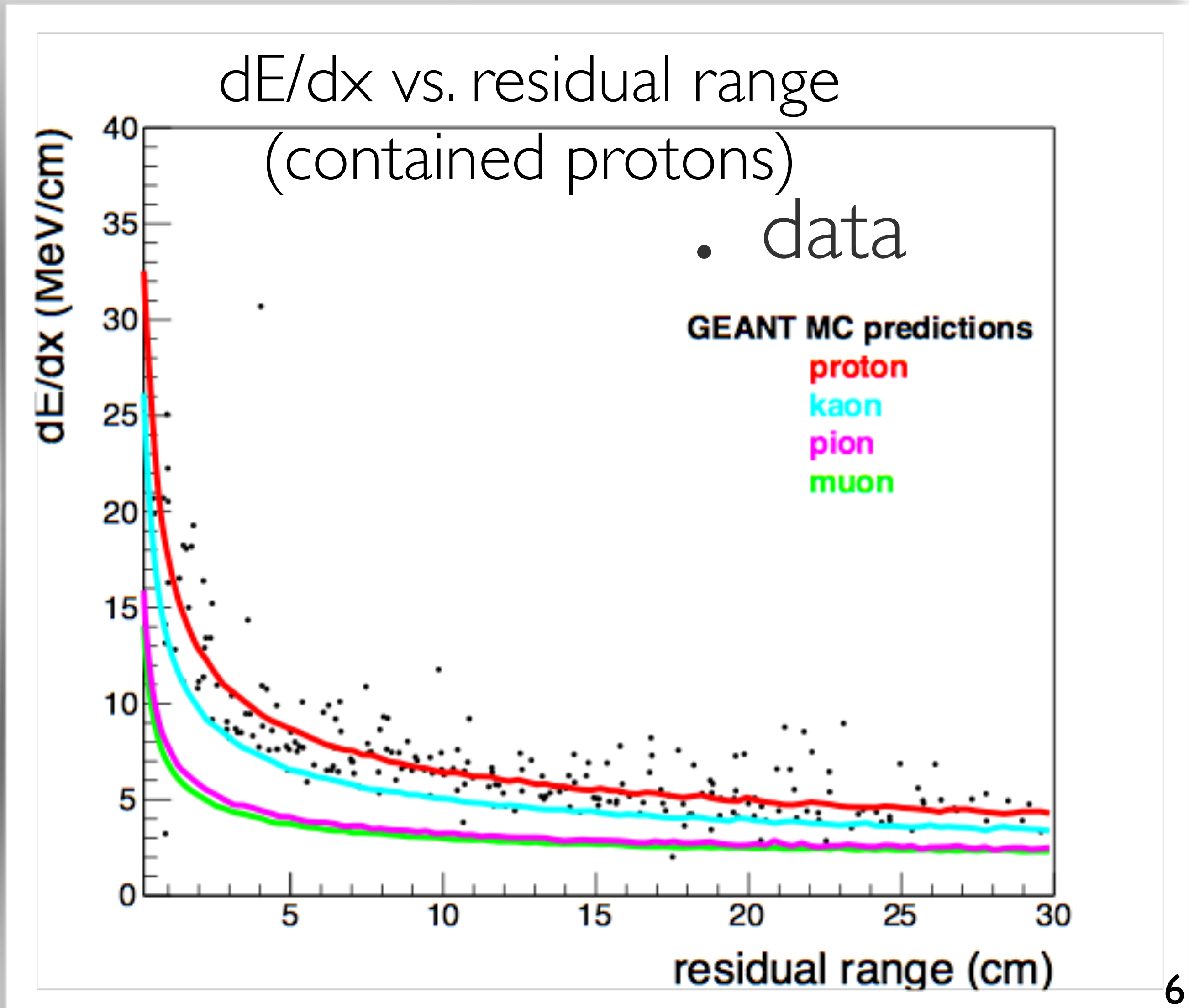
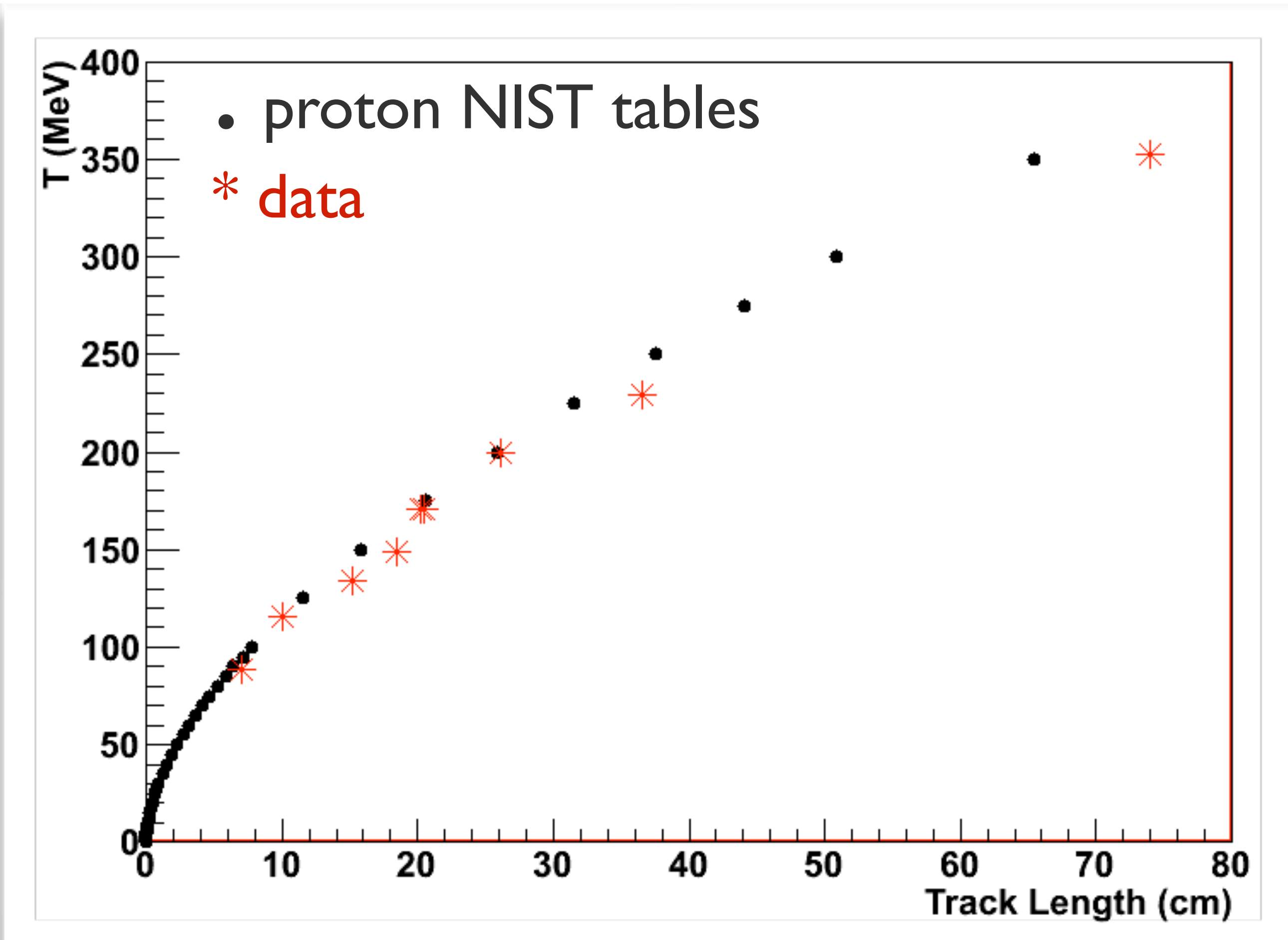
Stopping tracks - Calorimetric reconstruction and PID



The energy loss as a function of distance from the end of the track is used as a powerful (χ^2 based) method for particle identification.



Kinetic Energy vs. track length

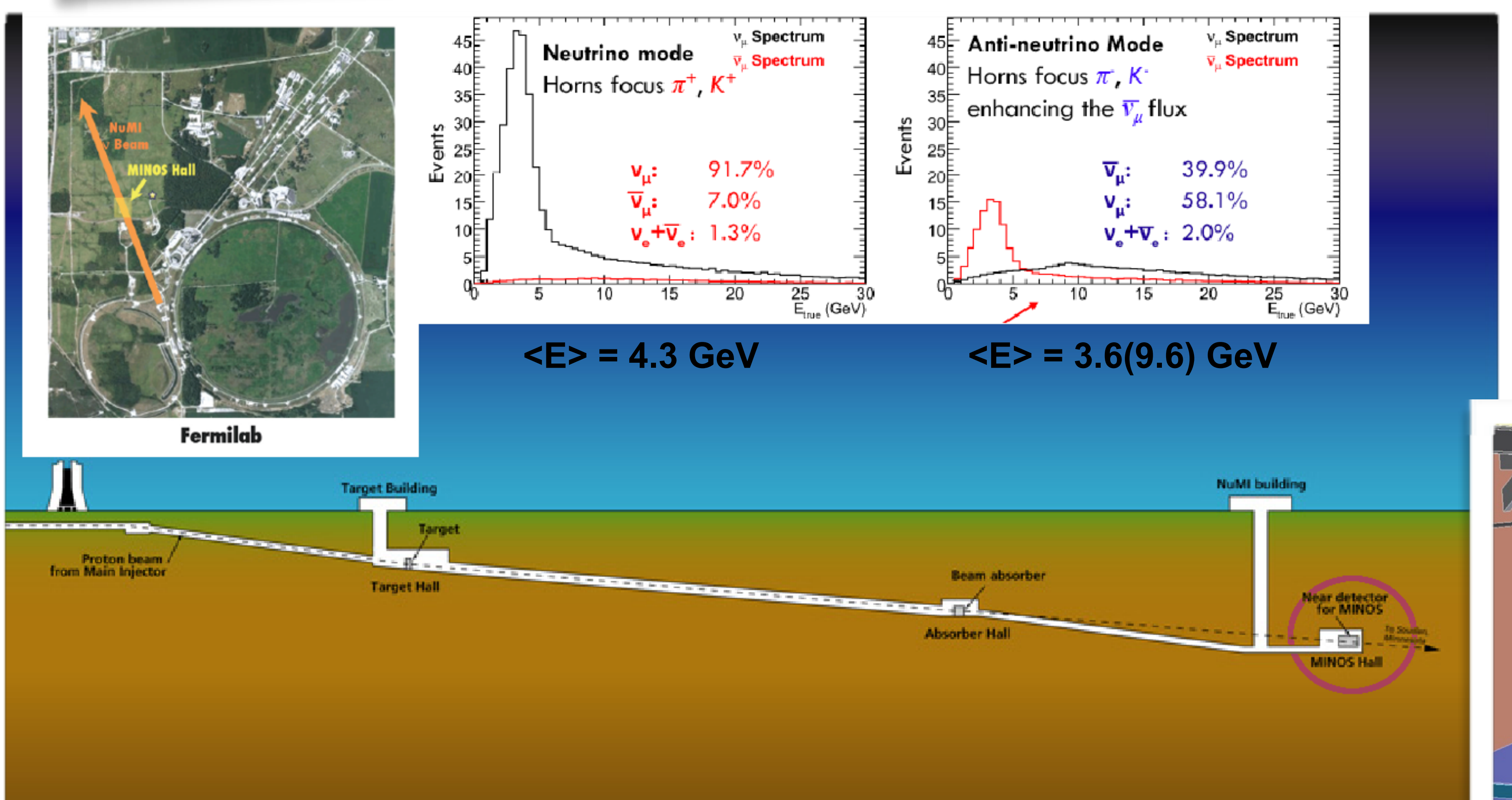


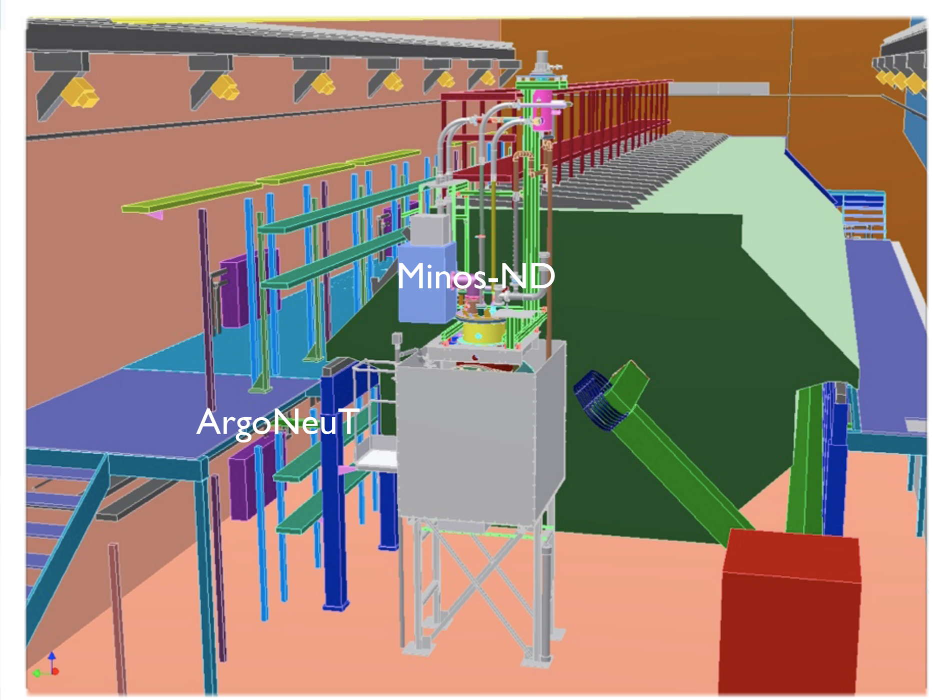
ArgoNeuT in the NuMI LE beam

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

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

Designed as a test experiment, but obtaining physics results!





ArgoNeuT in the NuMI LE beam

240 Kg active volume

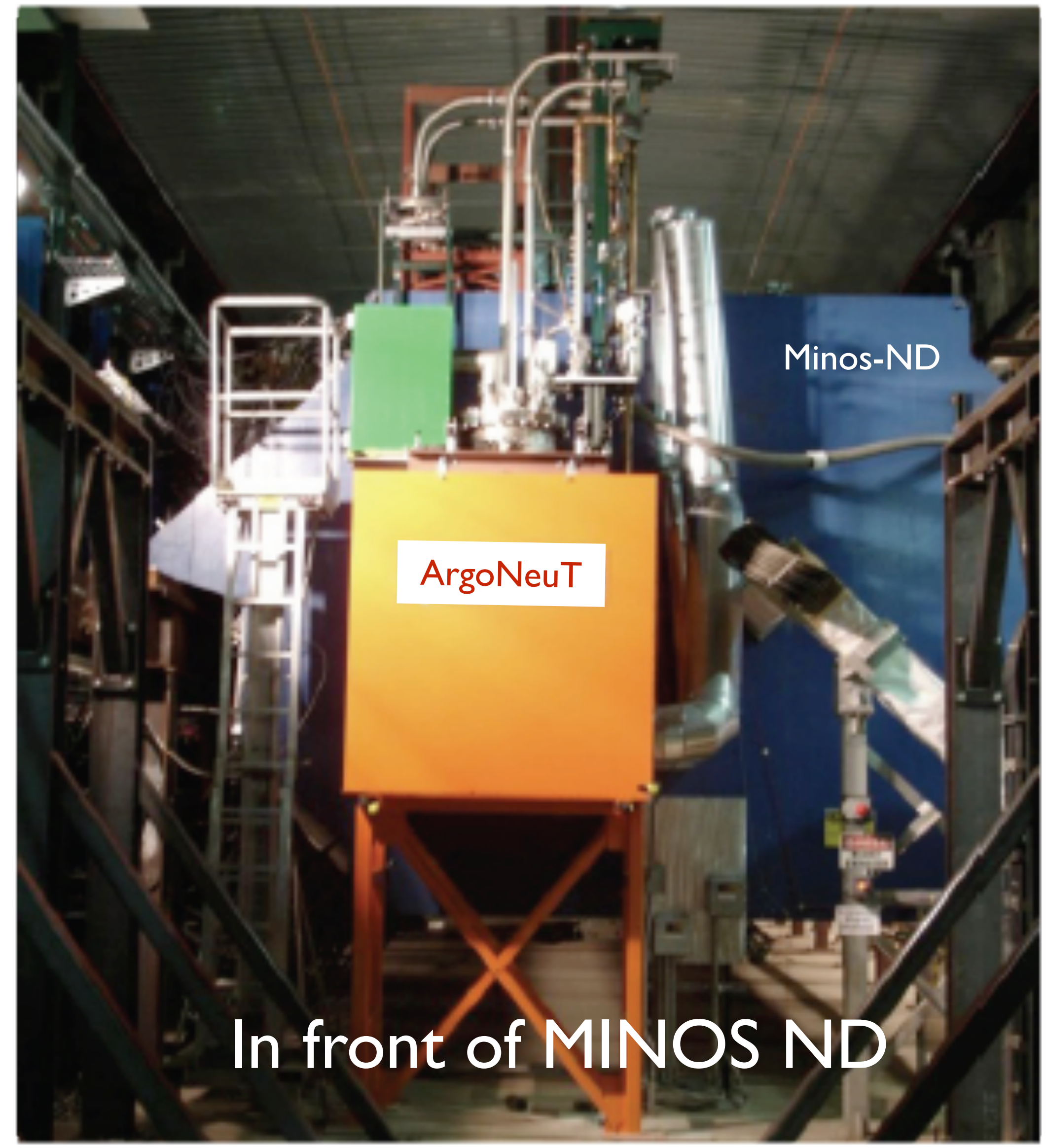
47×40×90 cm^3, wire spacing 4 mm

LAr TPC

~7000 CC events collected

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

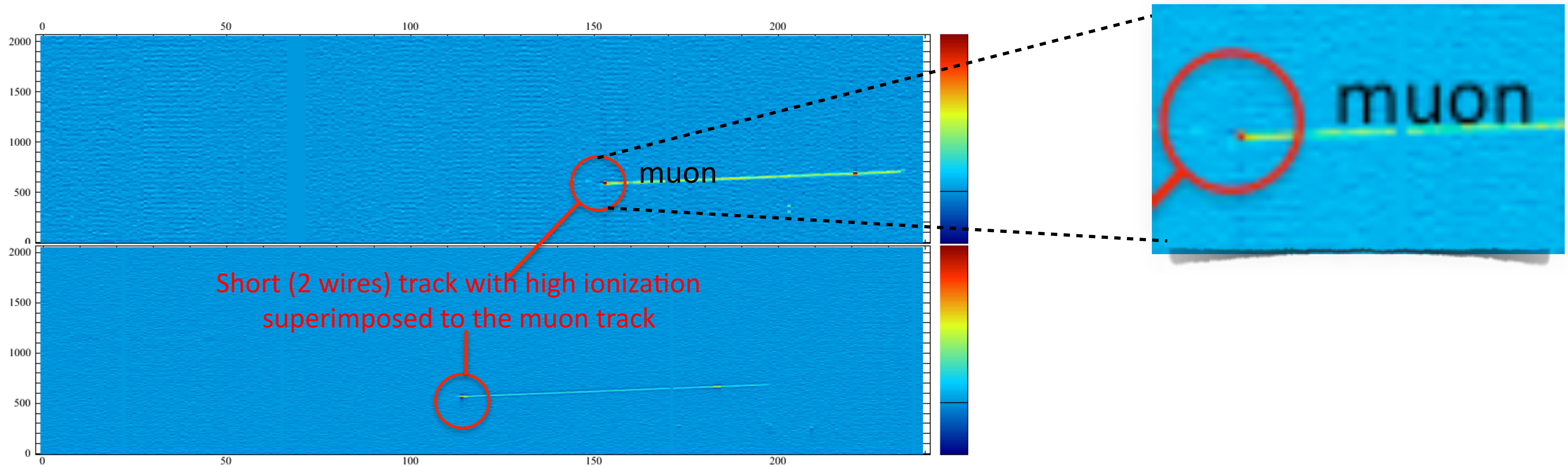
C. Anderson et al., JINST 7 (2012) P10019



MINOS ND as muon spectrometer for ArgoNeuT events*

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

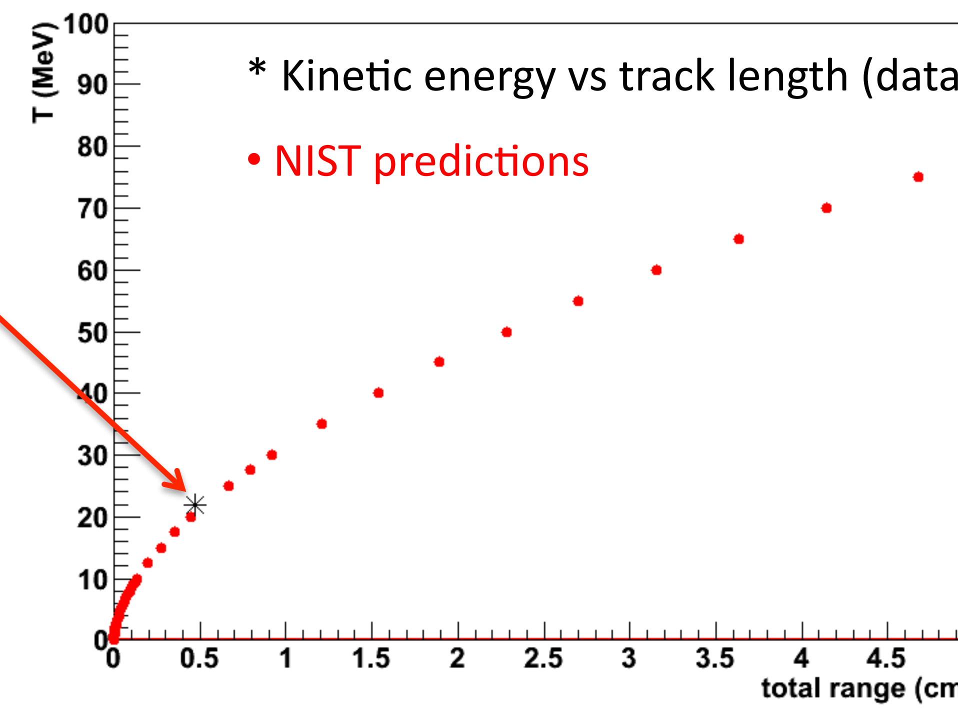
Low energy proton reconstruction



The short track behaves like proton

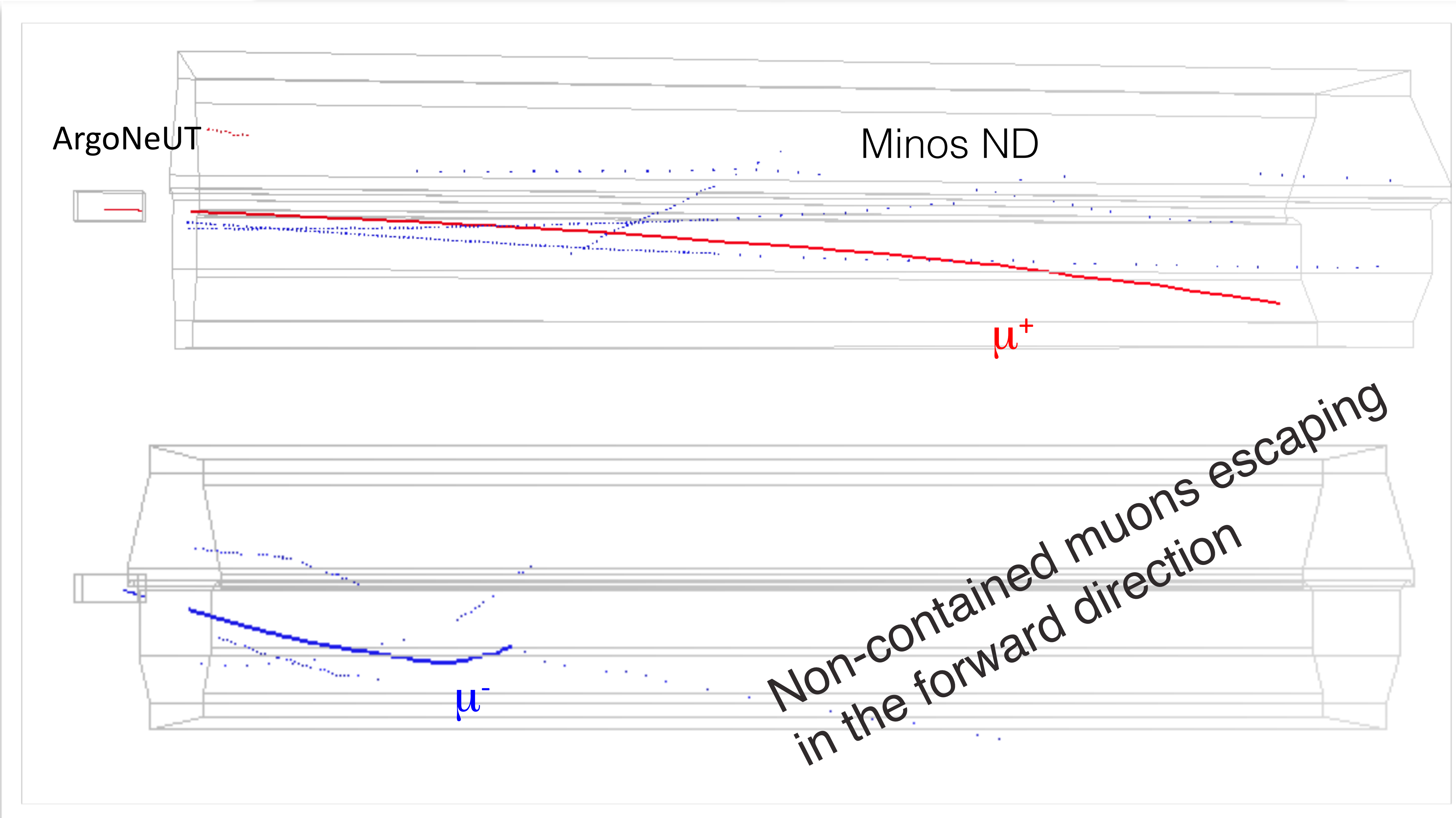
Length=0.5 cm

T_p=22±3 MeV



ArgoNeuT proton threshold: 21 MeV Kinetic Energy

Muon Reconstruction



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

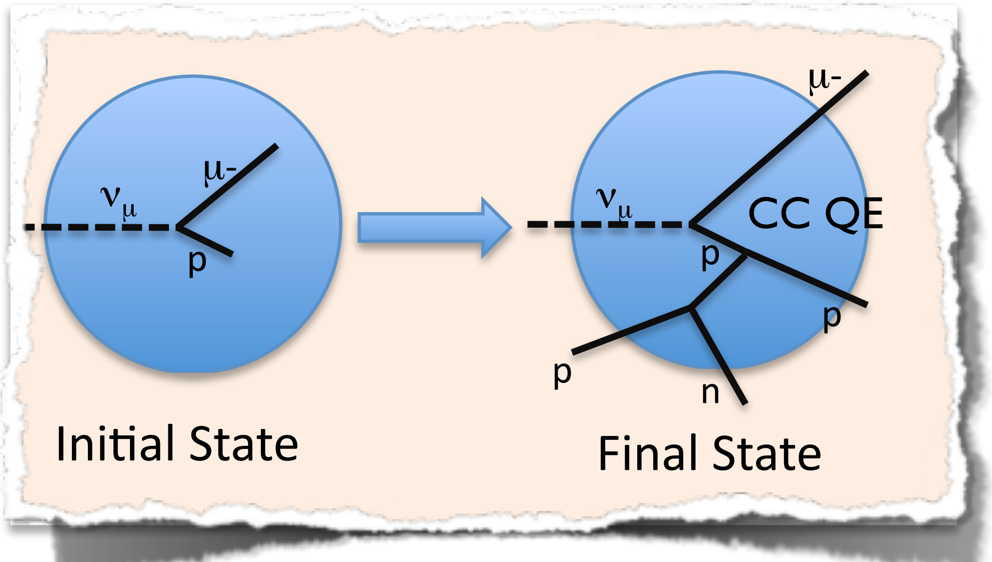
Muon kinematic reconstruction:
ArgoNeuT +MINOS ND measurement (momentum and sign)
Muon momentum resolution: 5-10%

Neutrino-nucleus interactions & nuclear effects

- 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 (heavy) 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.

Final State interactions



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

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

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..*

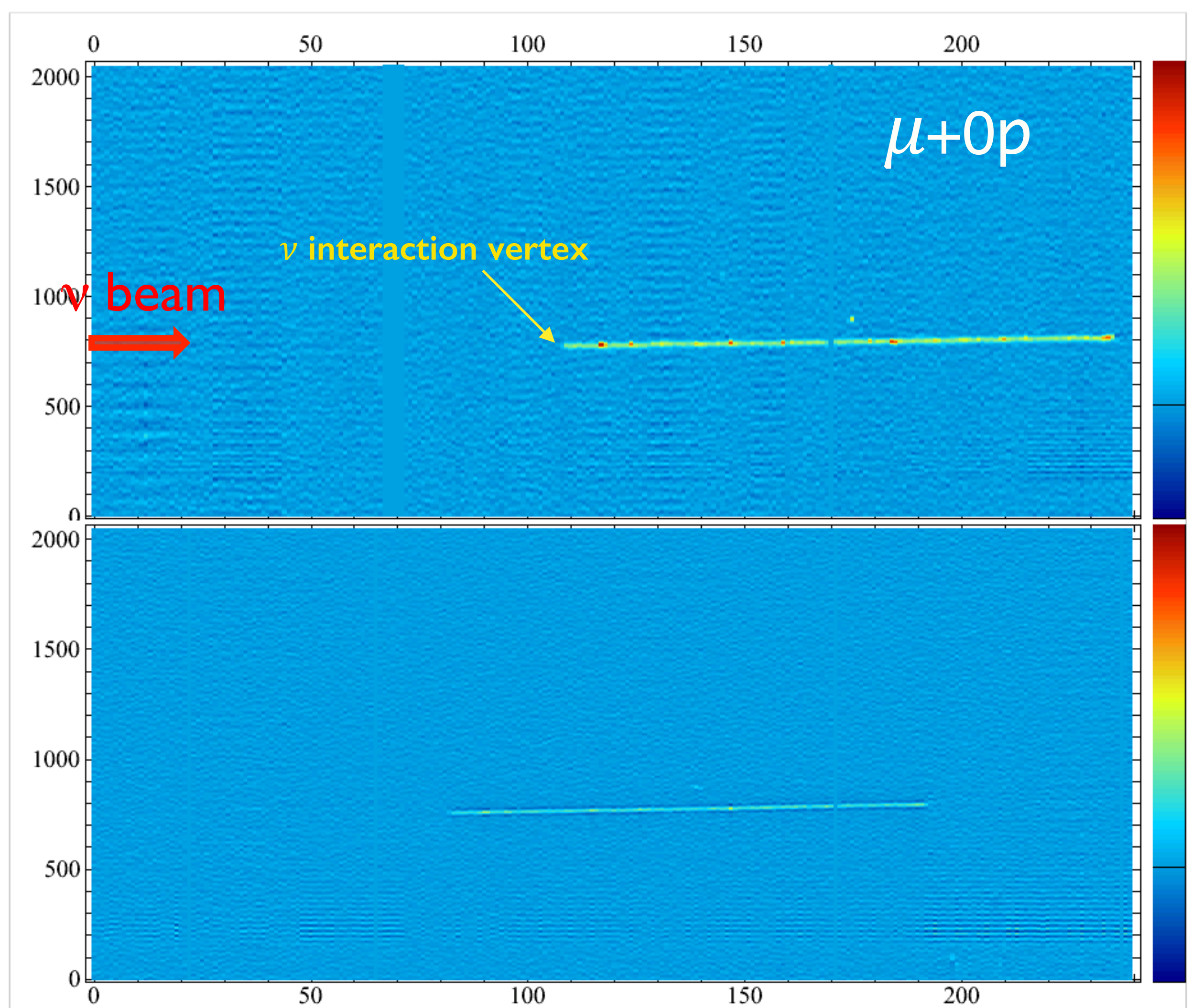
0 PION CC EVENT TOPOLOGY: **leading muon accompanied by any number (N=0, 1, 2, 3, 4) of protons final state**

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.

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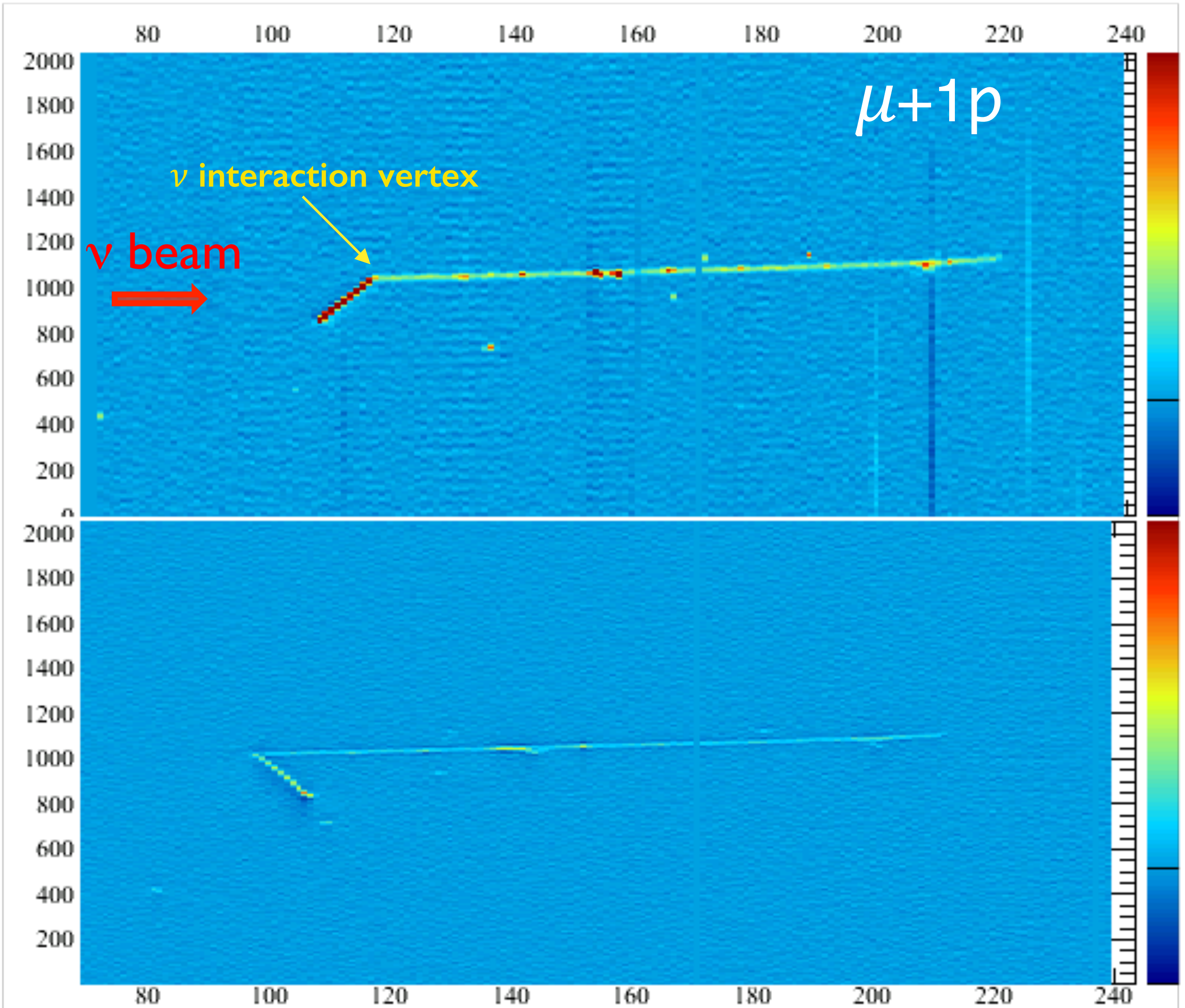

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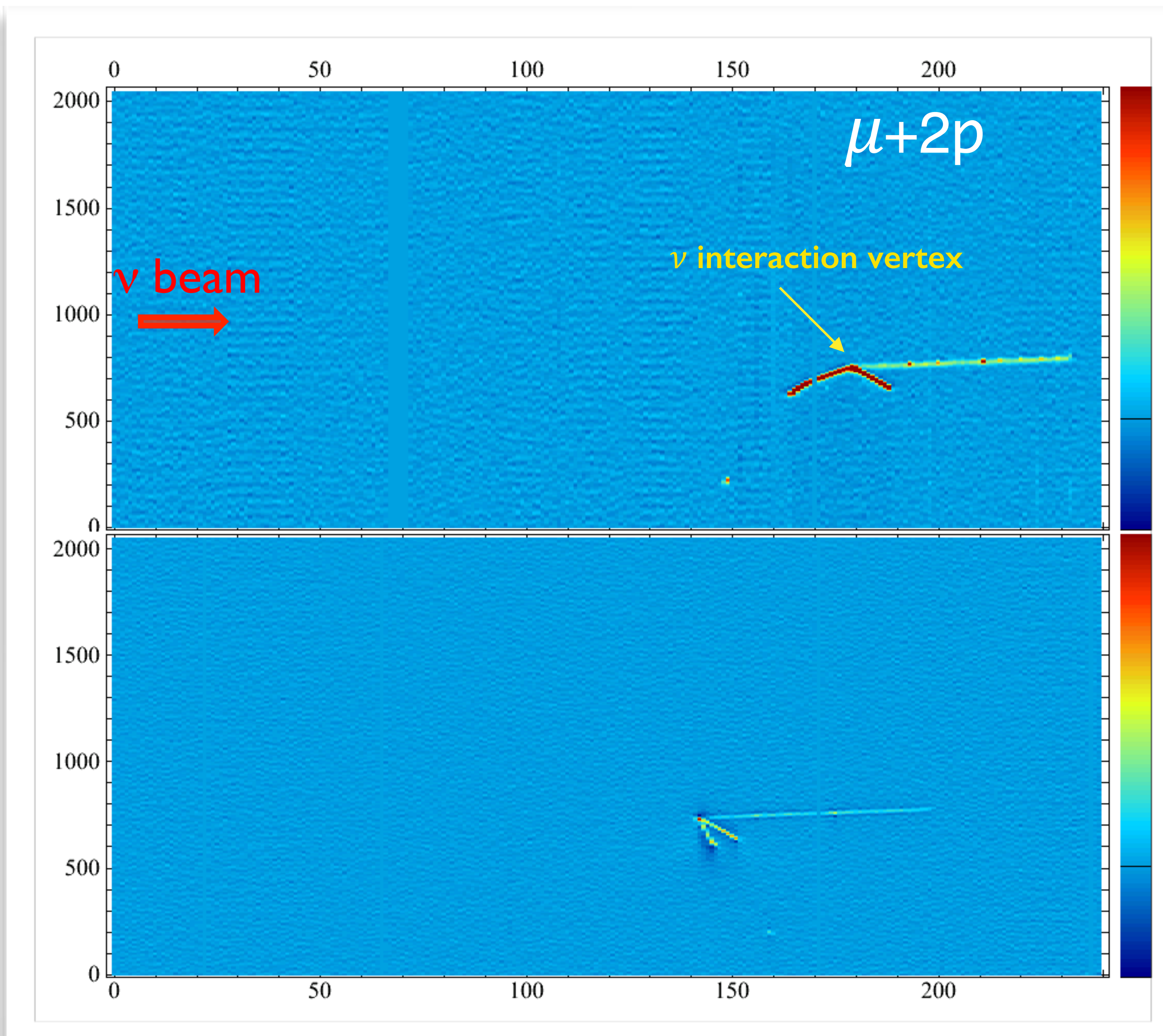

Multi-p accompanying the leading muon

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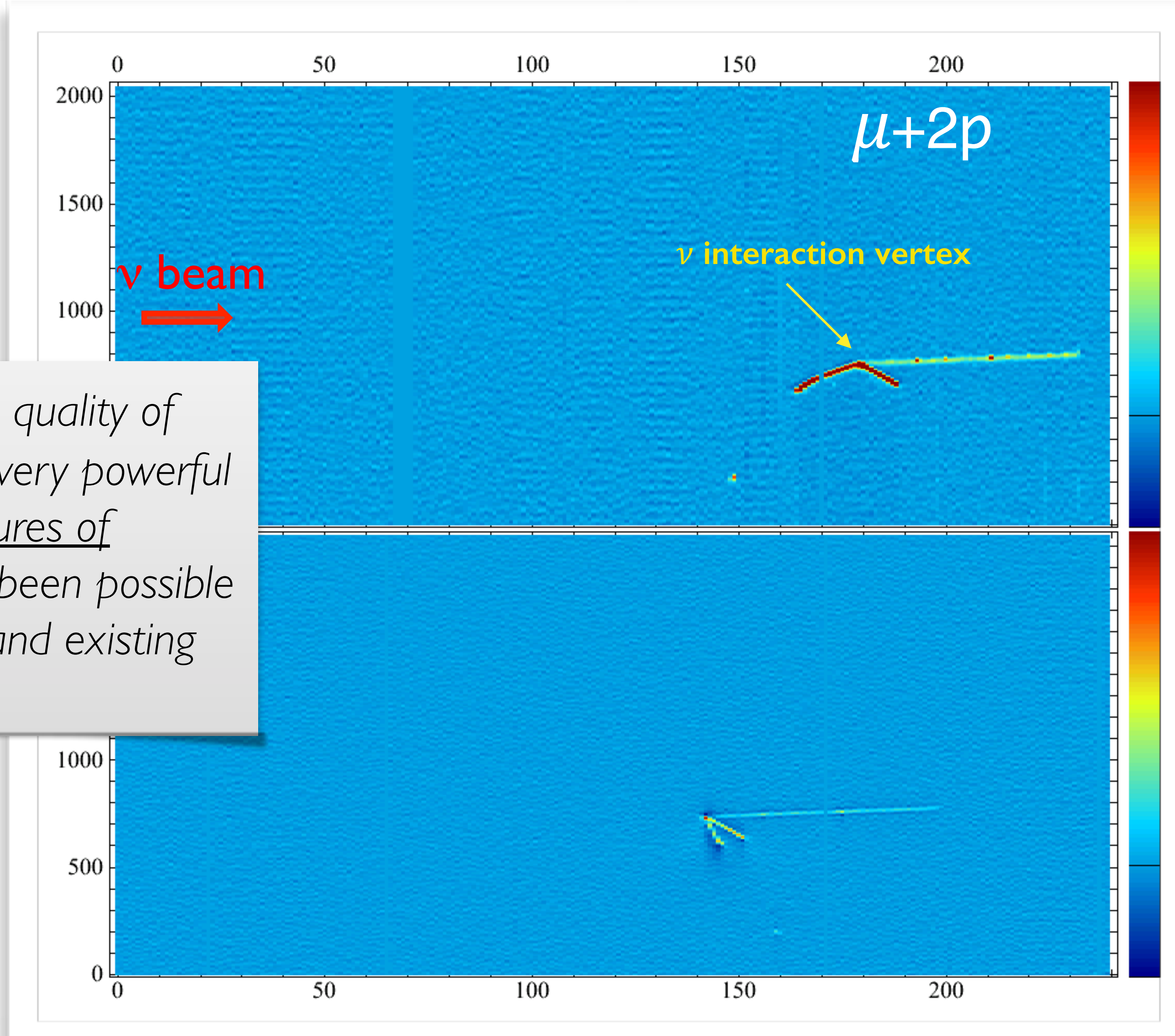
Analysis fully exploiting LAr TPC's capabilities



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.*

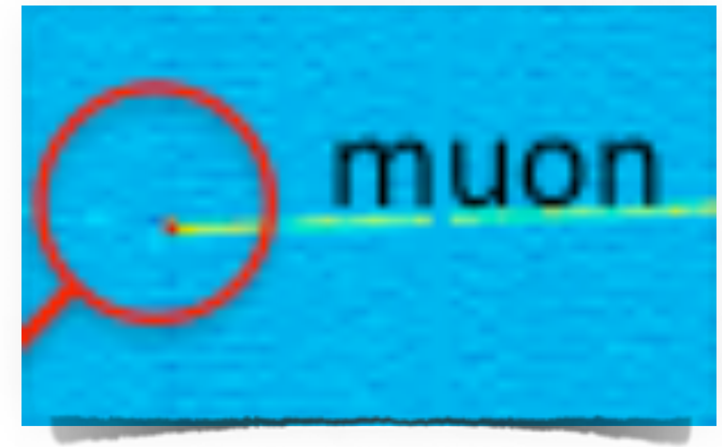
Multi-p accompanying the leading muon

(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***
- ***CC 0 pion cross sections***

TODAY:

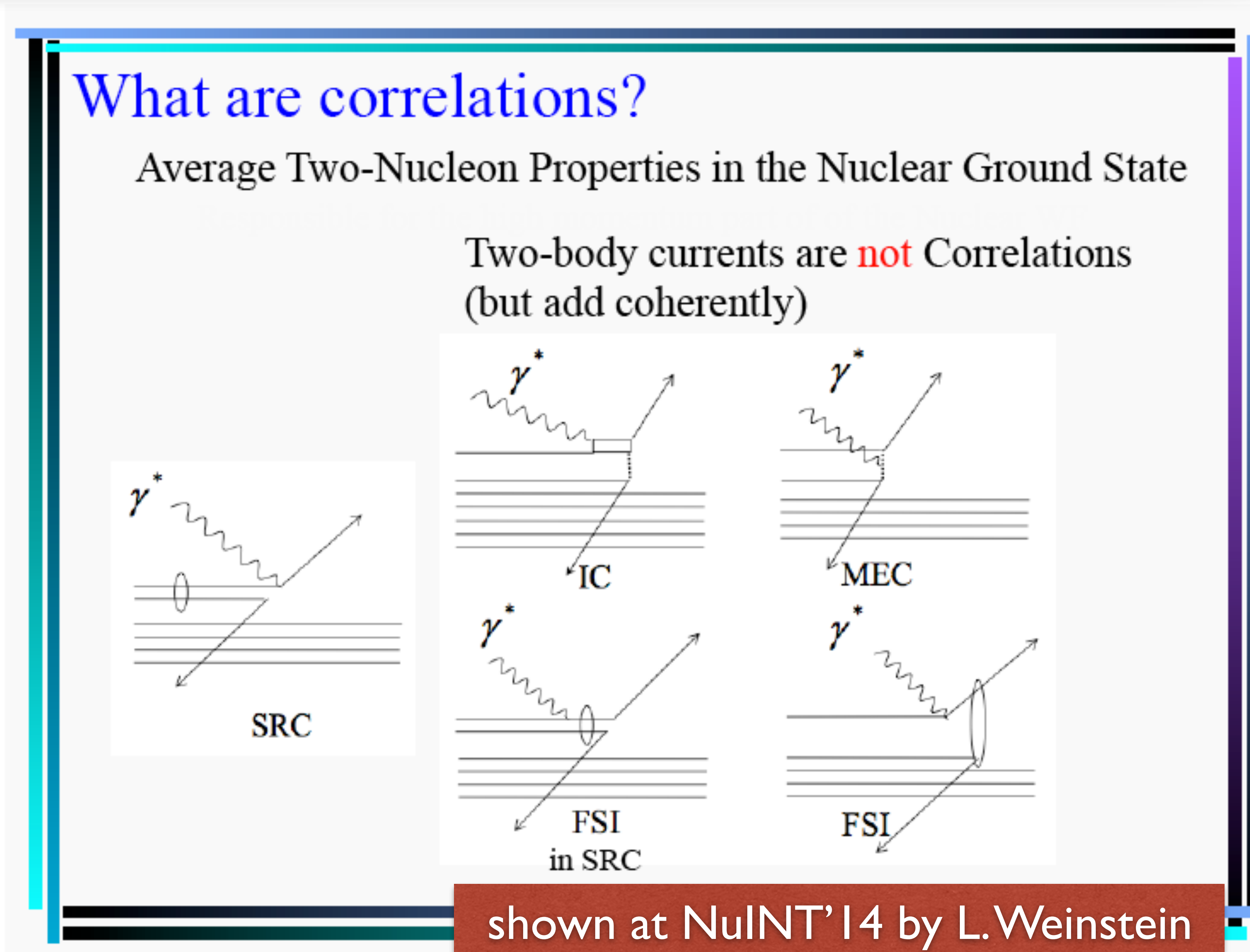
✓ Features of neutrino interactions and associated ***Nuclear Effects*** from identification/reconstruction of specific classes of neutrino events (muon + 2 protons)

learning from e-scattering experiments

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

Two nucleon ejection can be due to many different processes

- initial state short-range nucleon-nucleon correlations **(NN SRC)**,
- meson-exchange currents **(MEC and IC)** and
- final state interactions **(FSI)**
- *interference between the amplitudes of these mechanisms*



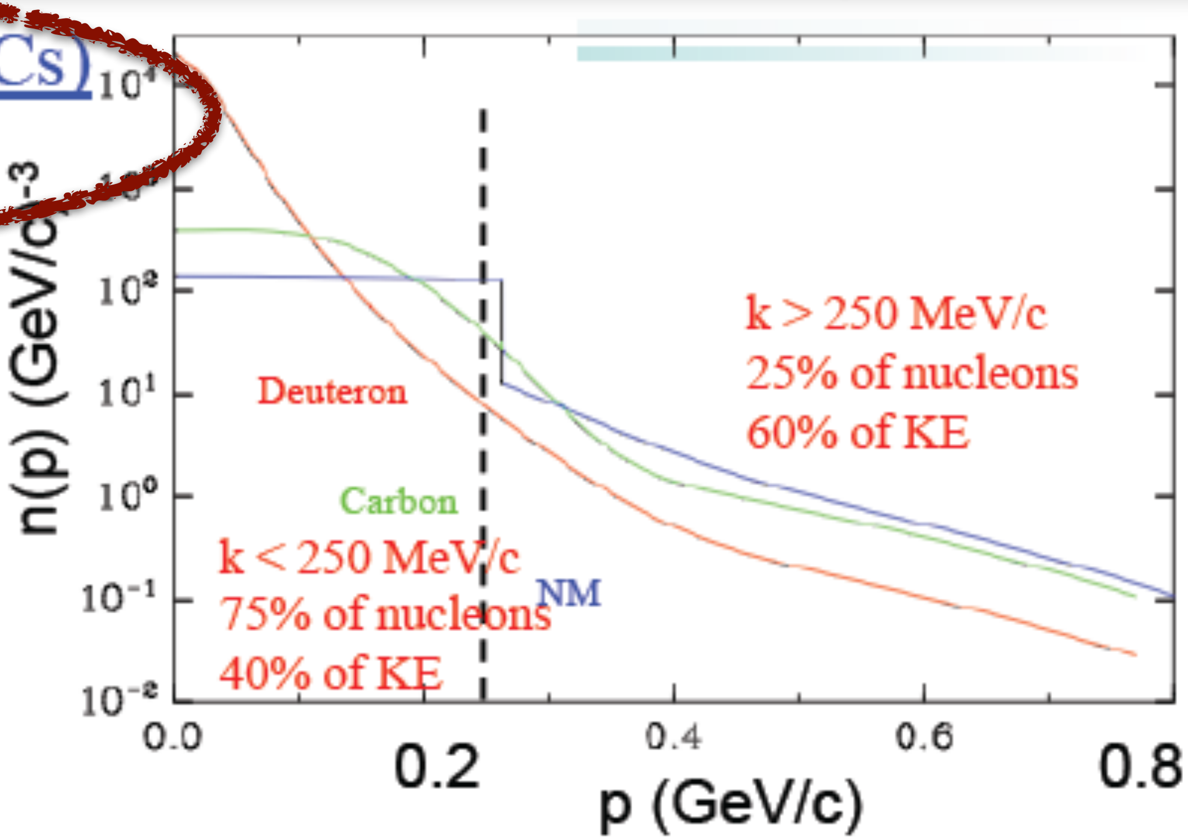
shown at NuINT'14 by L. Weinstein

NN SRC: learning from e-scattering experiments

Short Range Correlations (SRCs)

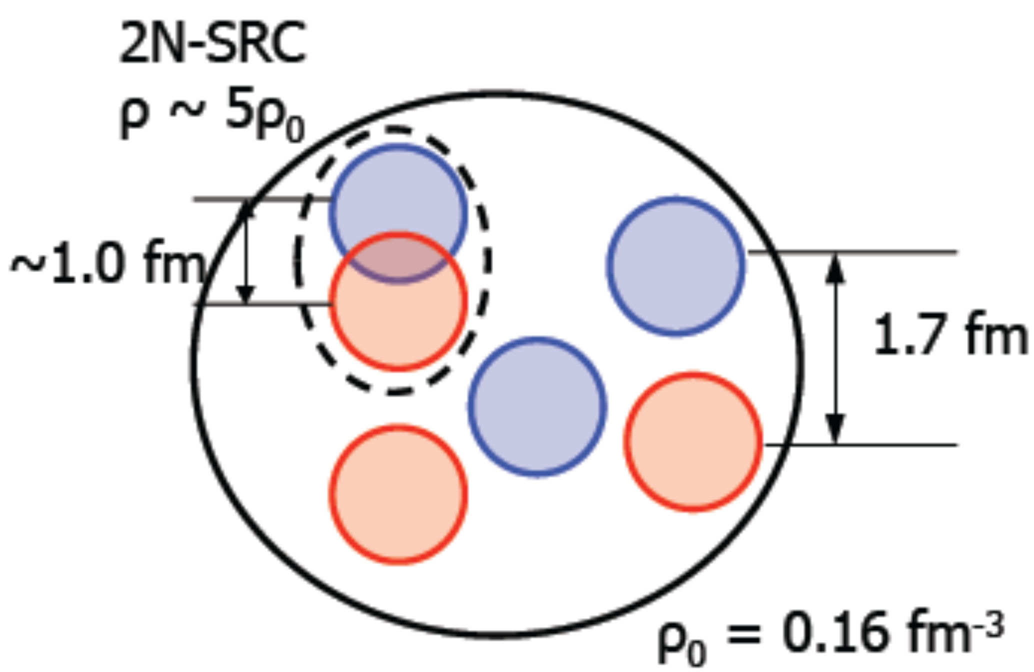
➔High momentum tails: $k > k_F$

Calculable for $A \leq 12$ nuclei and nuclear matter.
Not well constrained at $k >> k_f$



Effects:

- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - modification??
- Cold dense nuclear matter
- Neutron Stars



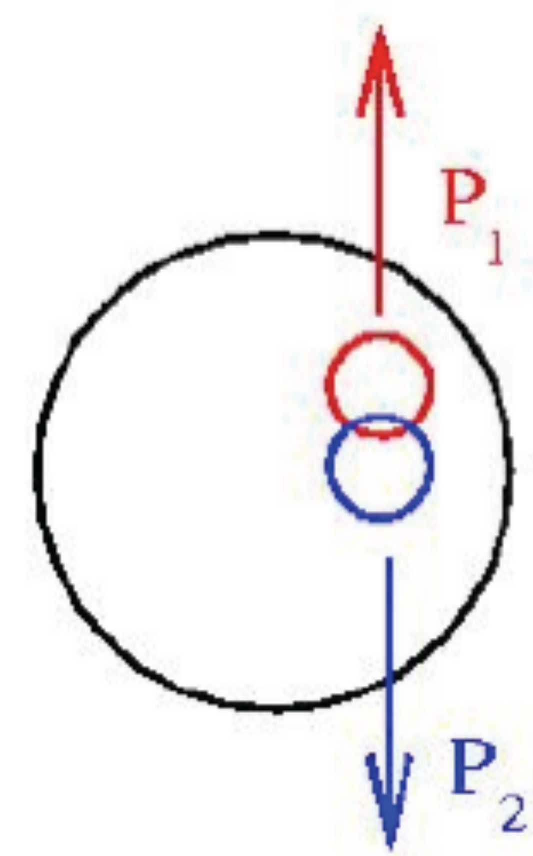
Nucleons are like people …

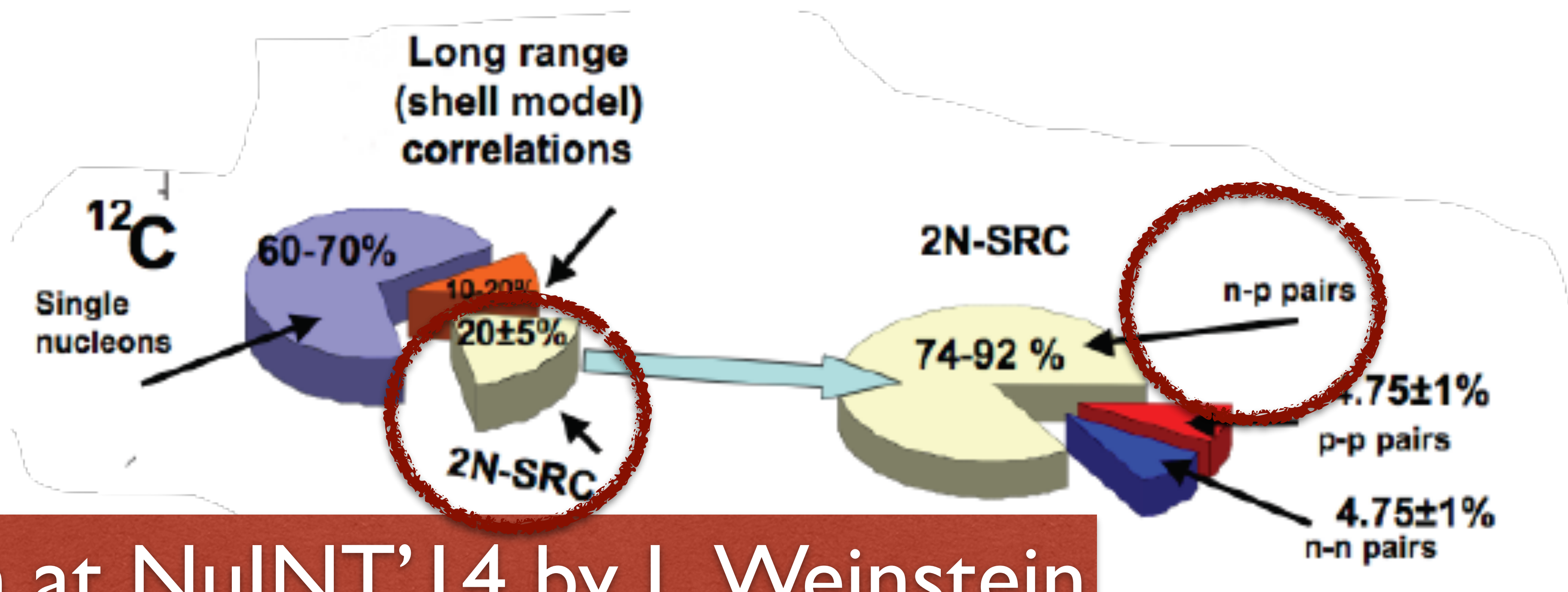
shown at NuINT'14 by L. Weinstein

Signatures for Correlations

An Experimentalist's Definition:

- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - NN Pair with
    - Large Relative Momentum
    - Small Total Momentum





shown at NuINT'14 by L. Weinstein

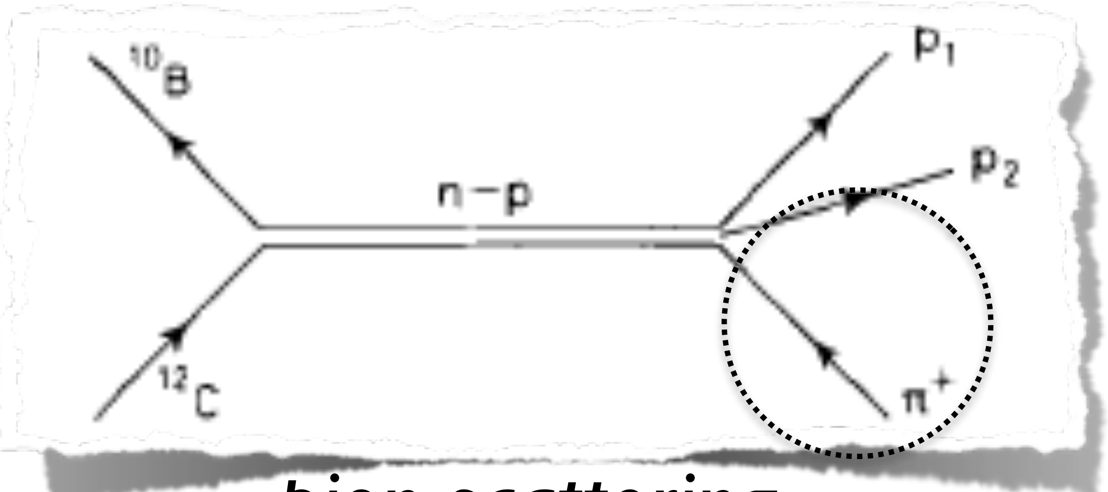
Effects of correlations on the analysis of neutrino scattering data

- 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 complicated*
- The realization of consistent models including all these nuclear effect 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.

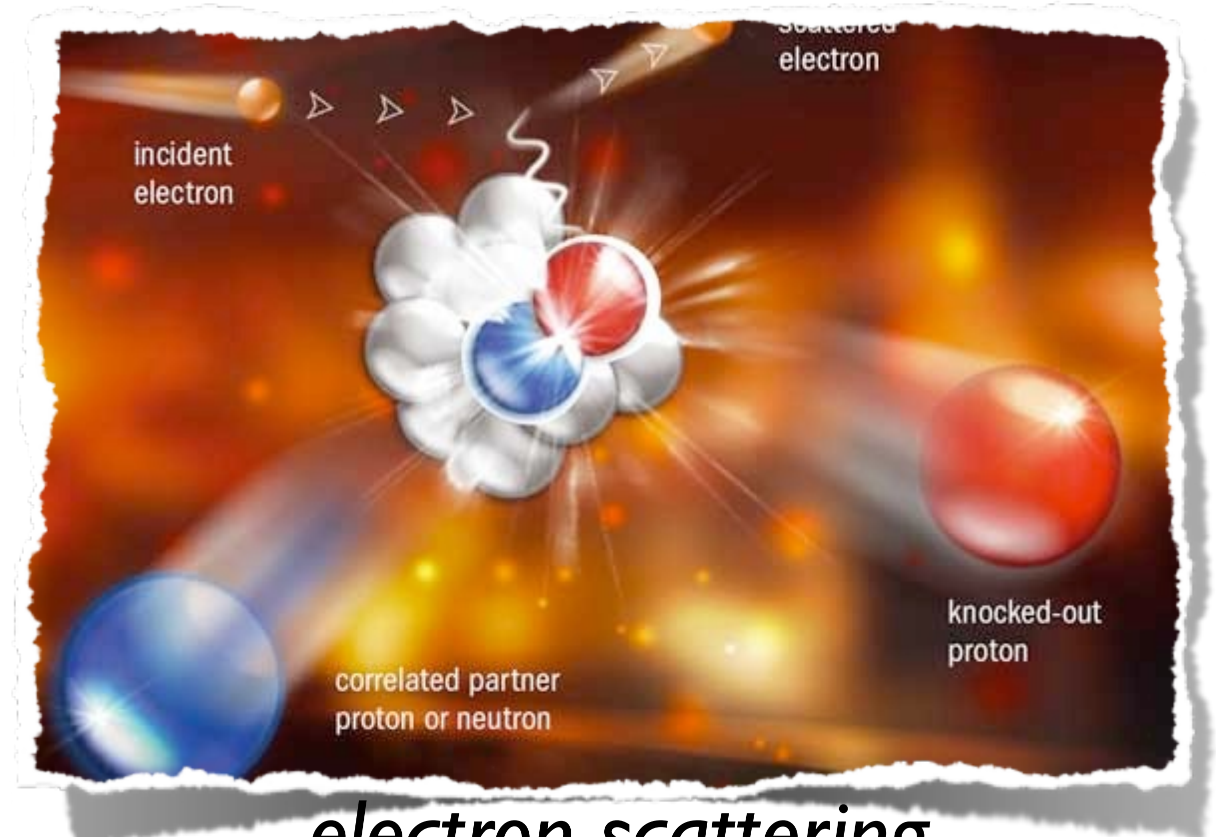
**In neutrino scattering experiments one main limitation comes from the intrinsic uncertainty on the 4-momentum transfer, due to the not fixed (broadly distributed in the beam spectrum) incident neutrino energy. An estimate can be inferred with satisfactory accuracy when all final state particles kinematics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

Two-nucleon knock-out events in ArgoNeuT

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



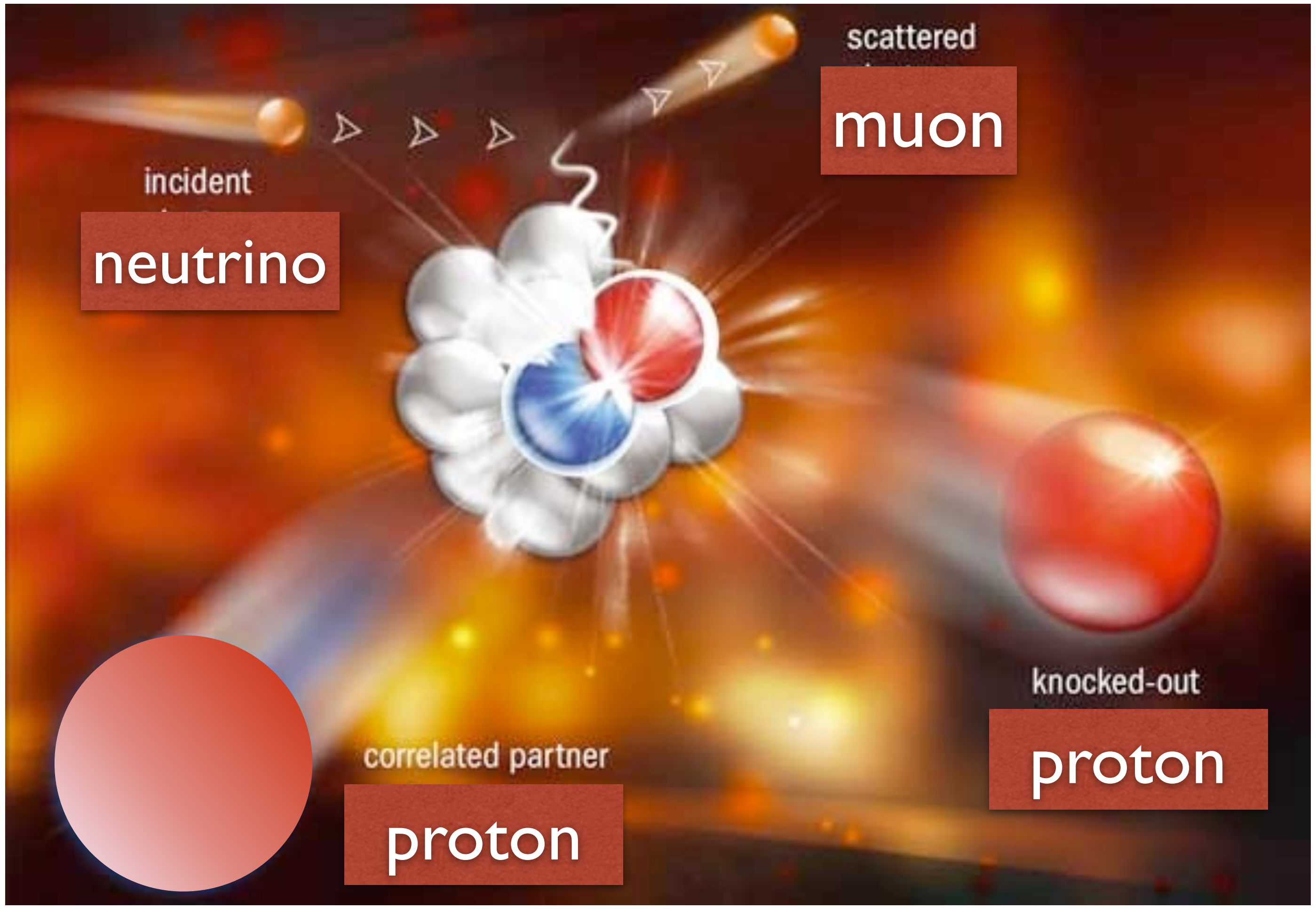
pion scattering



electron scattering

ArgoNeuT: Two-nucleon knock-out events from ***neutrino interactions***

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



Short Range Correlations

μ^- and 2 protons in the final state

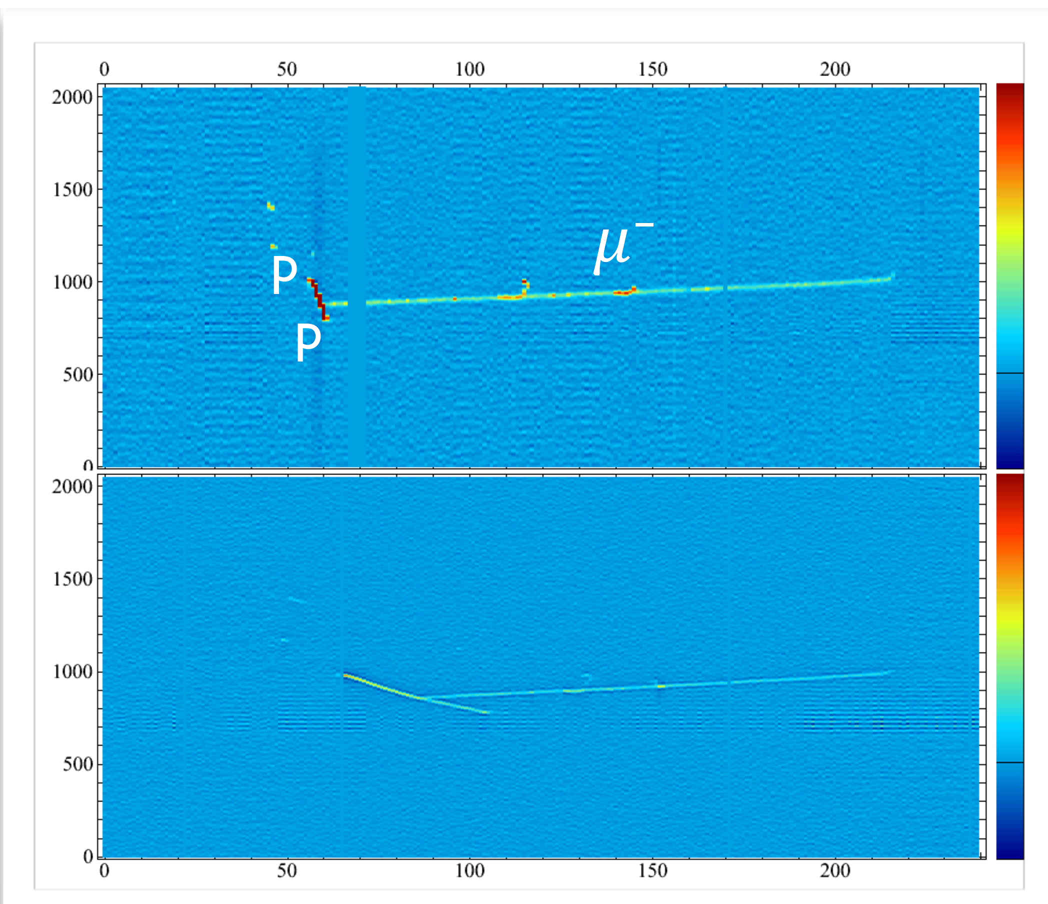
Neutrino scattering experiments, to our knowledge, have never attempted to directly explore SRC through detection of two nucleon knock-out

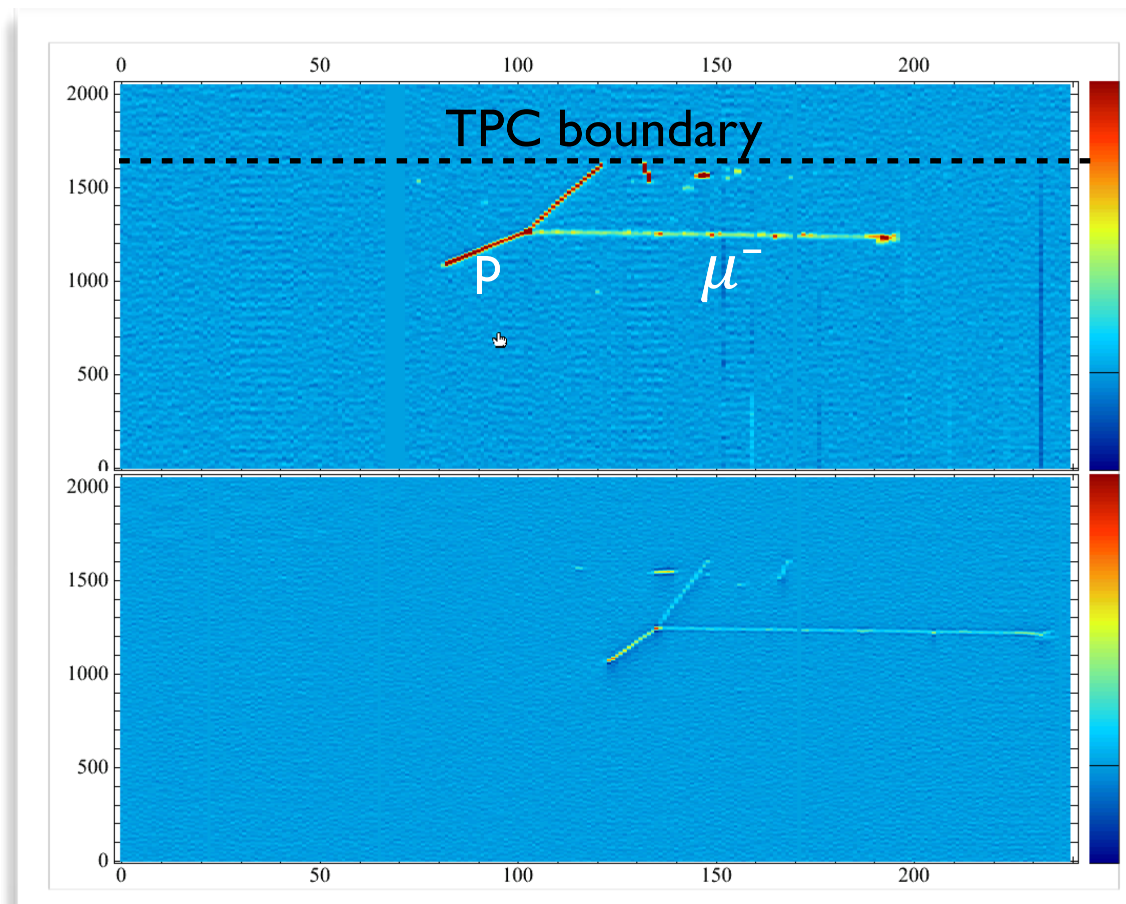
(μ^-+2p) data sample

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 ~35% (dominated by the containment requirement in FV).





(μ^-+2p) data sample

- Fully reconstructed events. Measured quantities*:
  the <u>3-momentum of the muon</u>, determined from the matched track in ArgoNeuT and MINOS-ND,
  the <u>sign of the muon</u> provided by MINOS-ND, and
  the <u>energy and direction of propagation</u> of the <u>two protons</u> 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

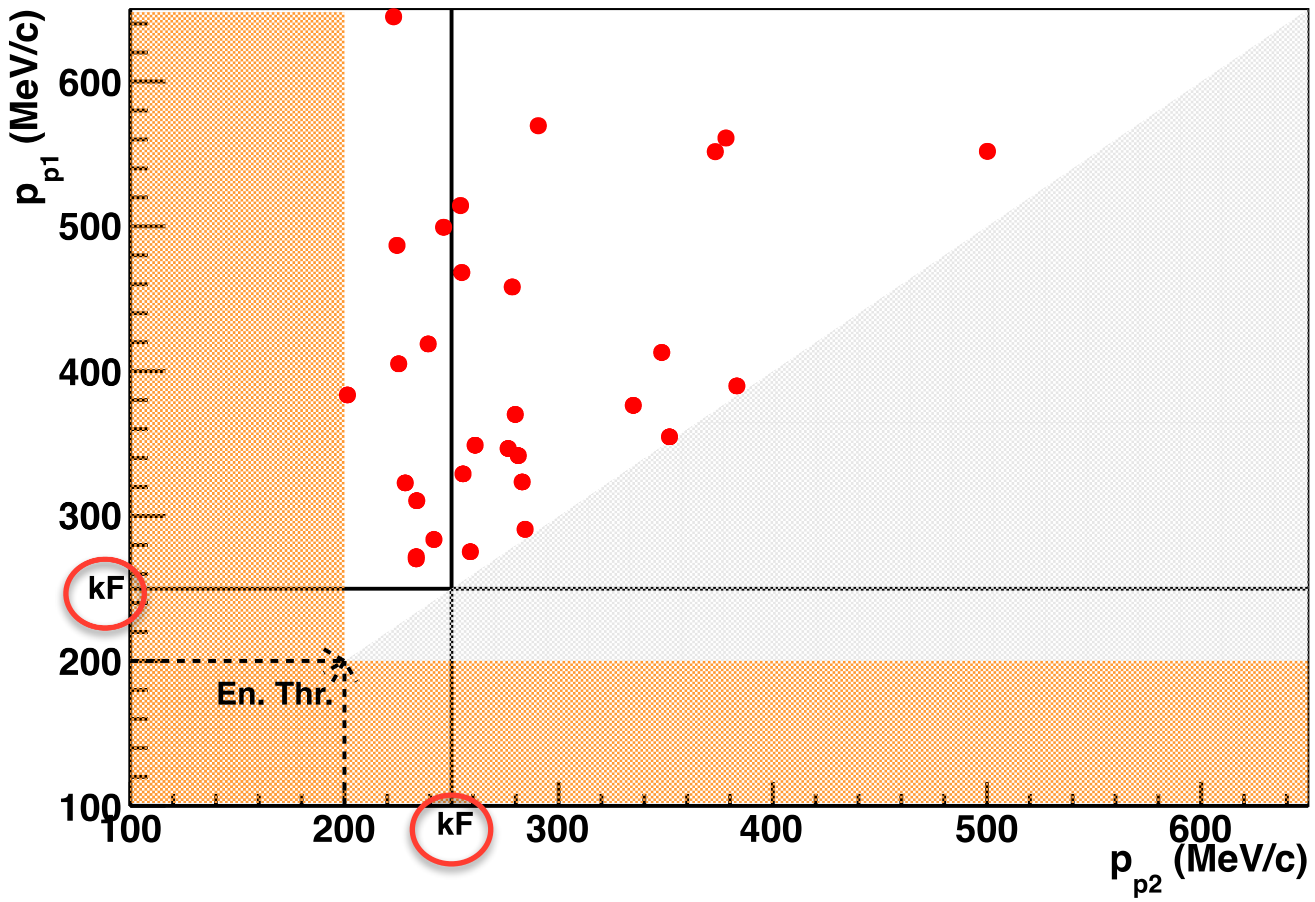
The specific final state topology which we have focused on is a pair of energetic protons at the interaction vertex accompanying the leading muon.

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,

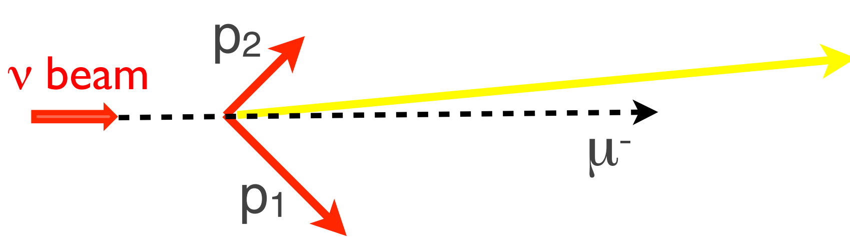
- a CCQE interaction on a neutron in a SRC pair is expected to produce back-to-back protons in the CM frame of the interaction,
- whereas a CC pionless RES reactions involving a SRC pair may produce back-to-back protons in the Lab frame

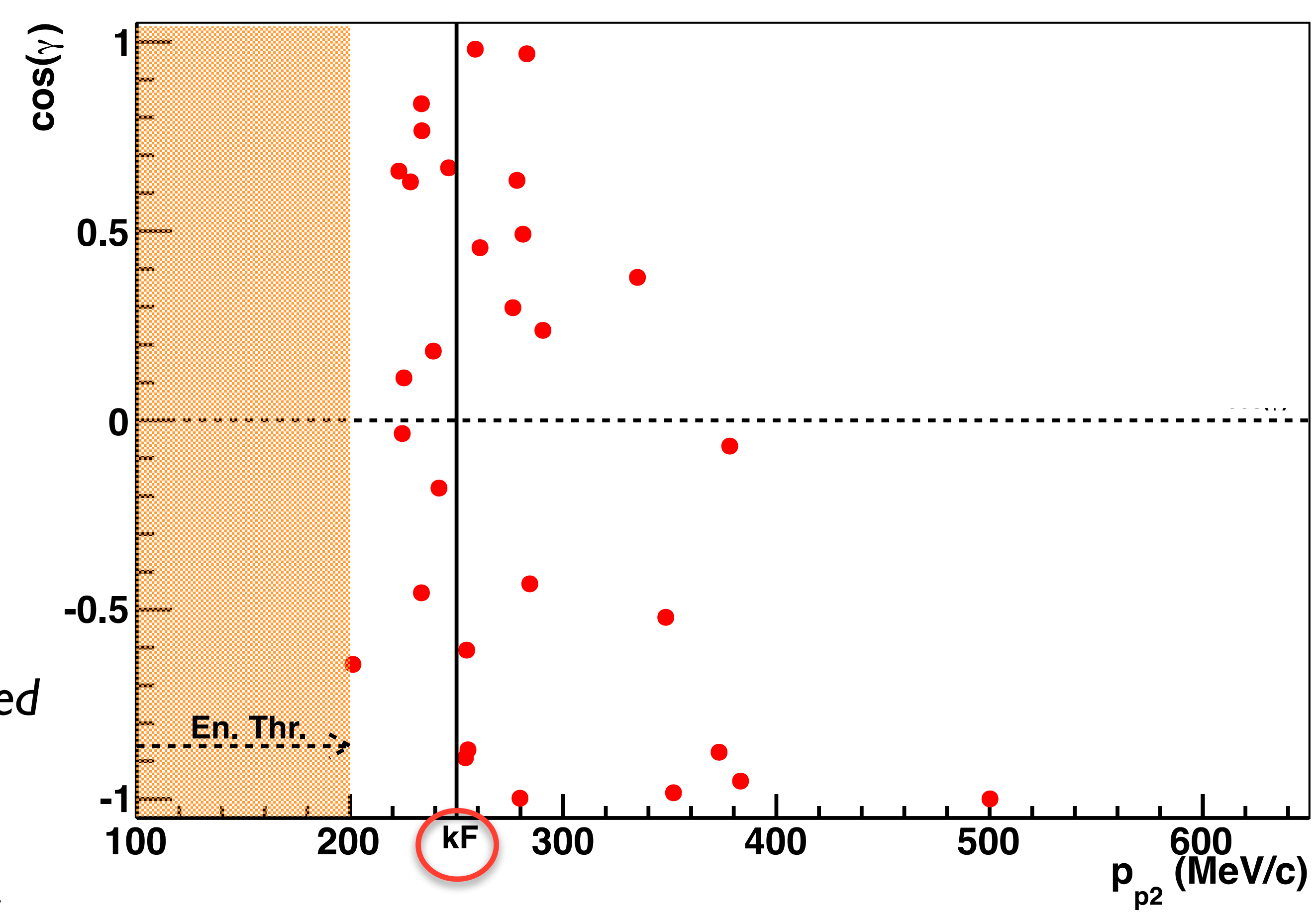
(μ⁻+2p) data sample



Momentum of the more energetic proton $\mathbf{p_{p1}}$ 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 ($k_F \simeq 250$ MeV/c)

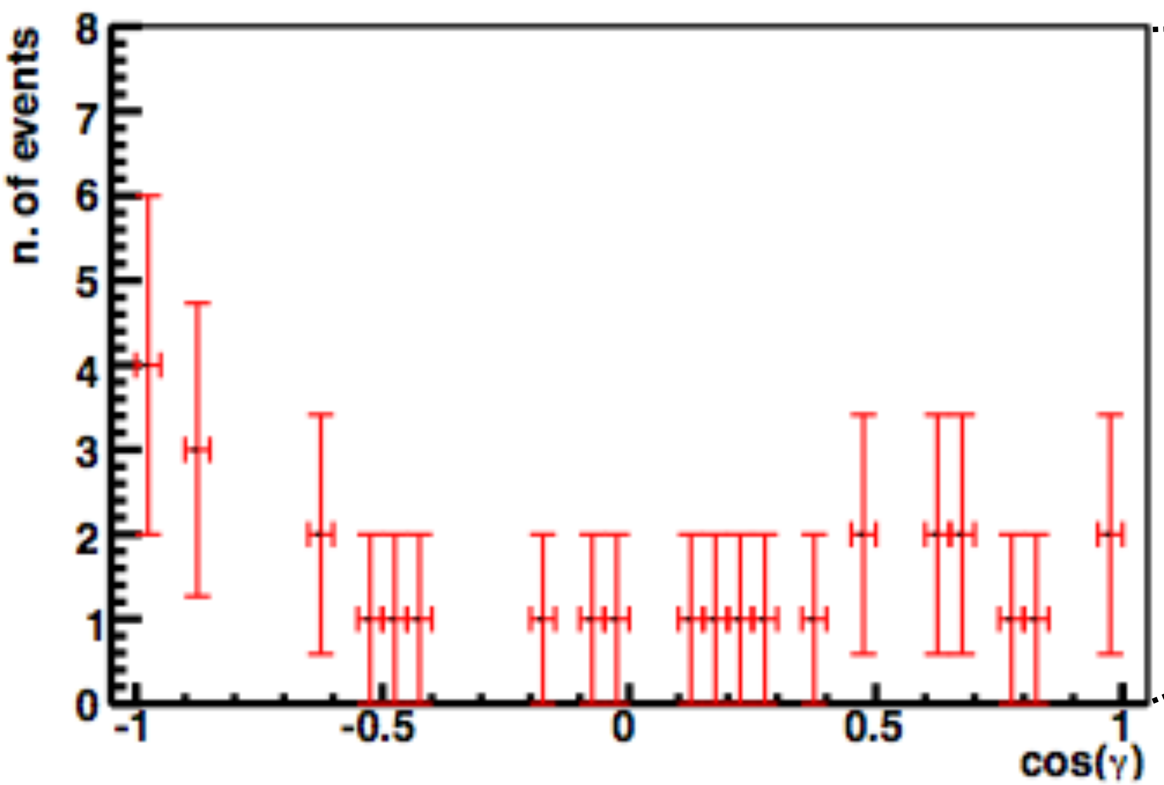




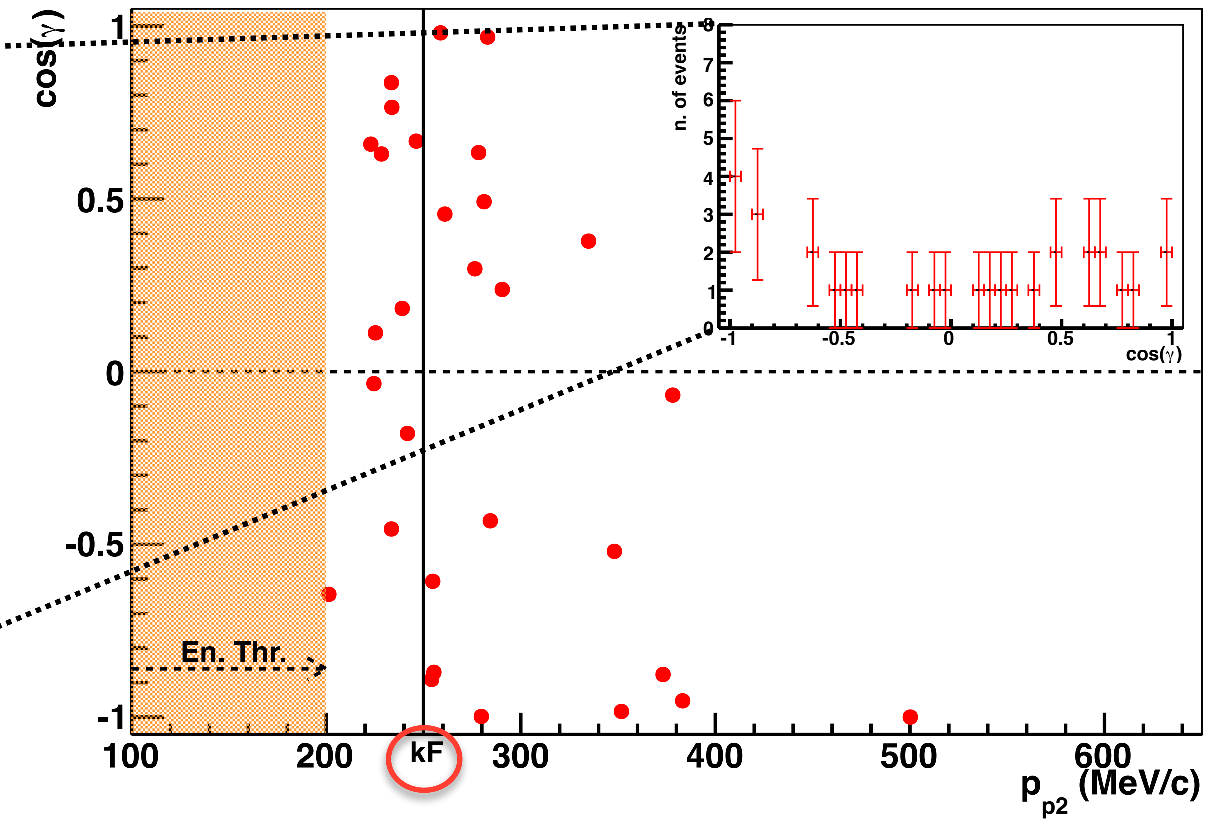
cos(γ) vs momentum of the least energetic proton $\mathbf{p_{p2}}$ in the pair

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

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



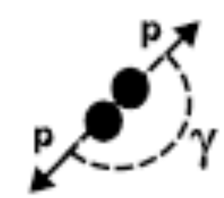
cos(γ) vs momentum of the least energetic proton p_{p2} in the pair



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

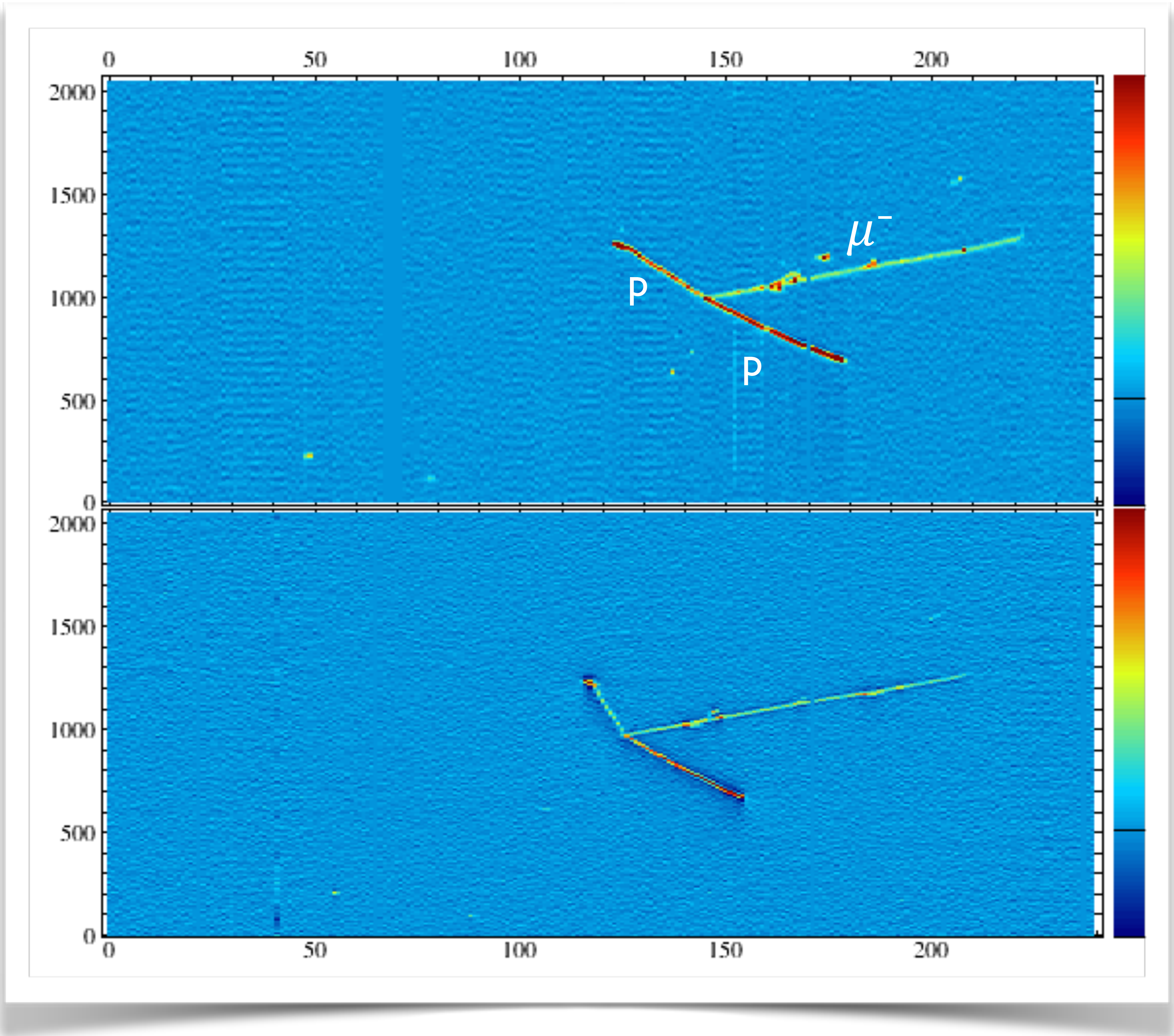
In all four events one proton is almost exactly balanced by the other

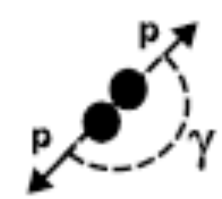
$p_{p1}, p_{p2} \geq k_F$ and $\vec{p}_{p1} \simeq -\vec{p}_{p2}$



(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.





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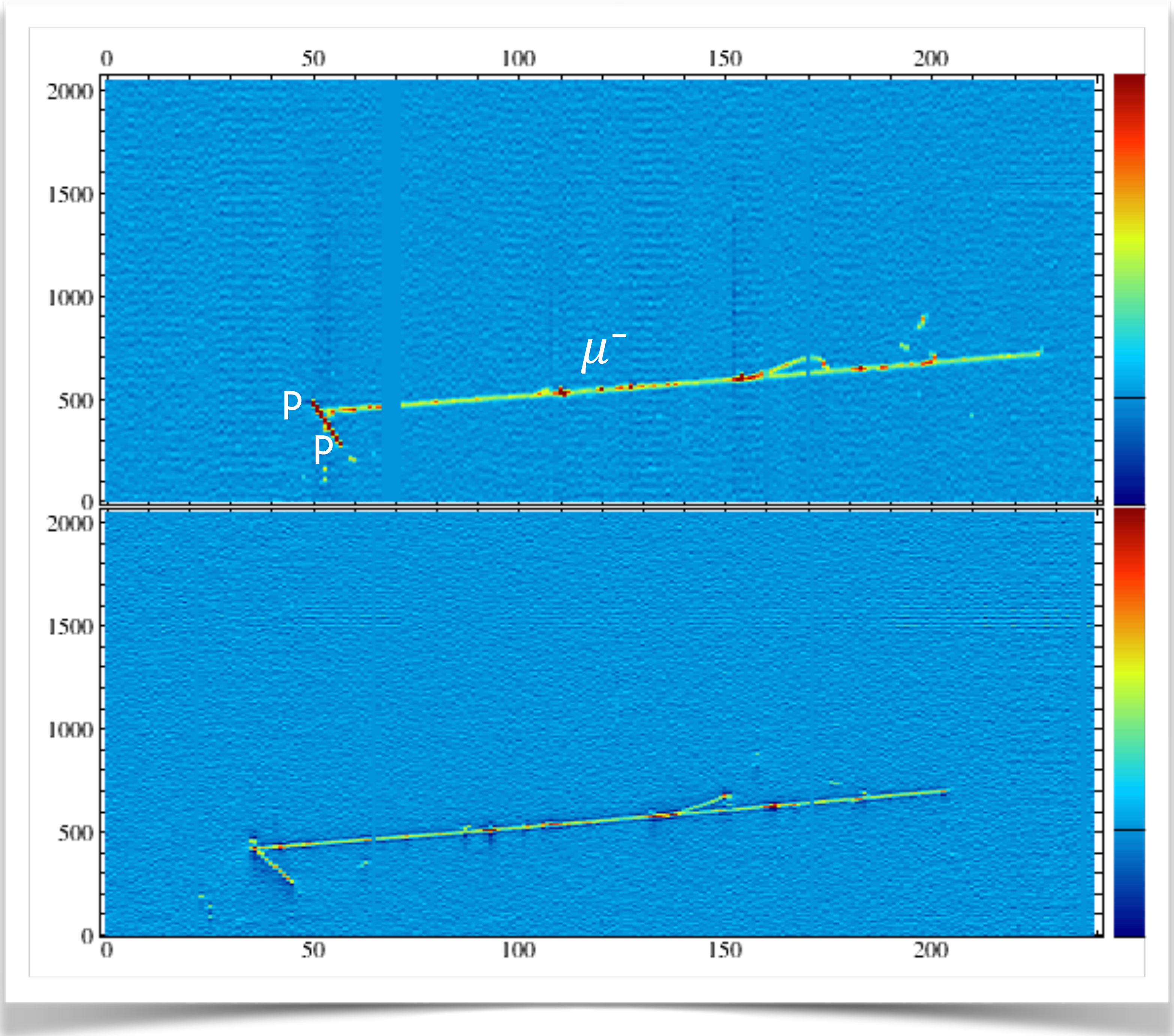

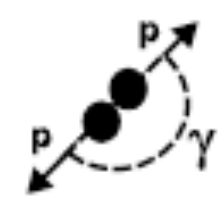

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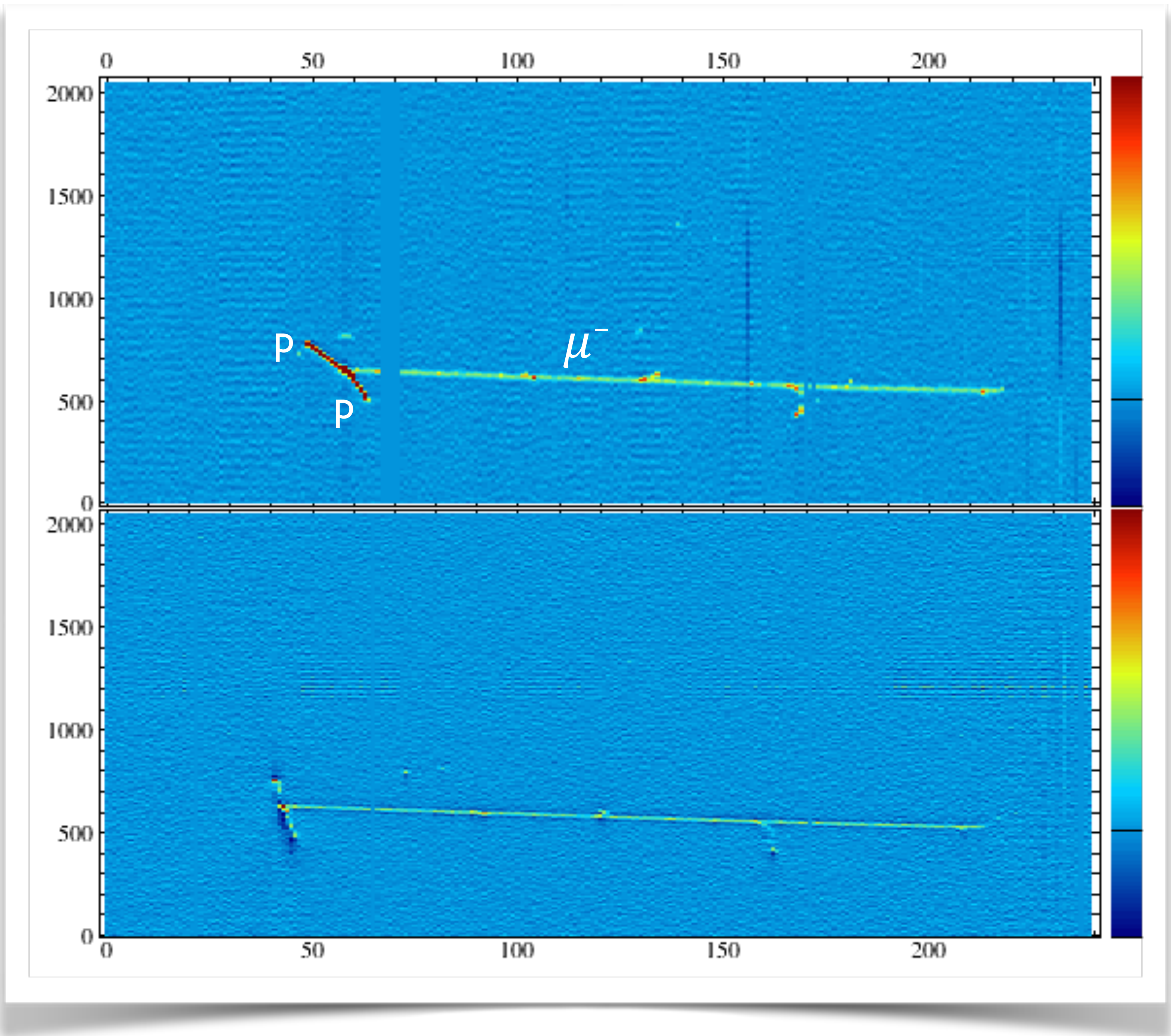

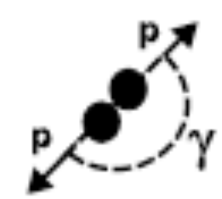

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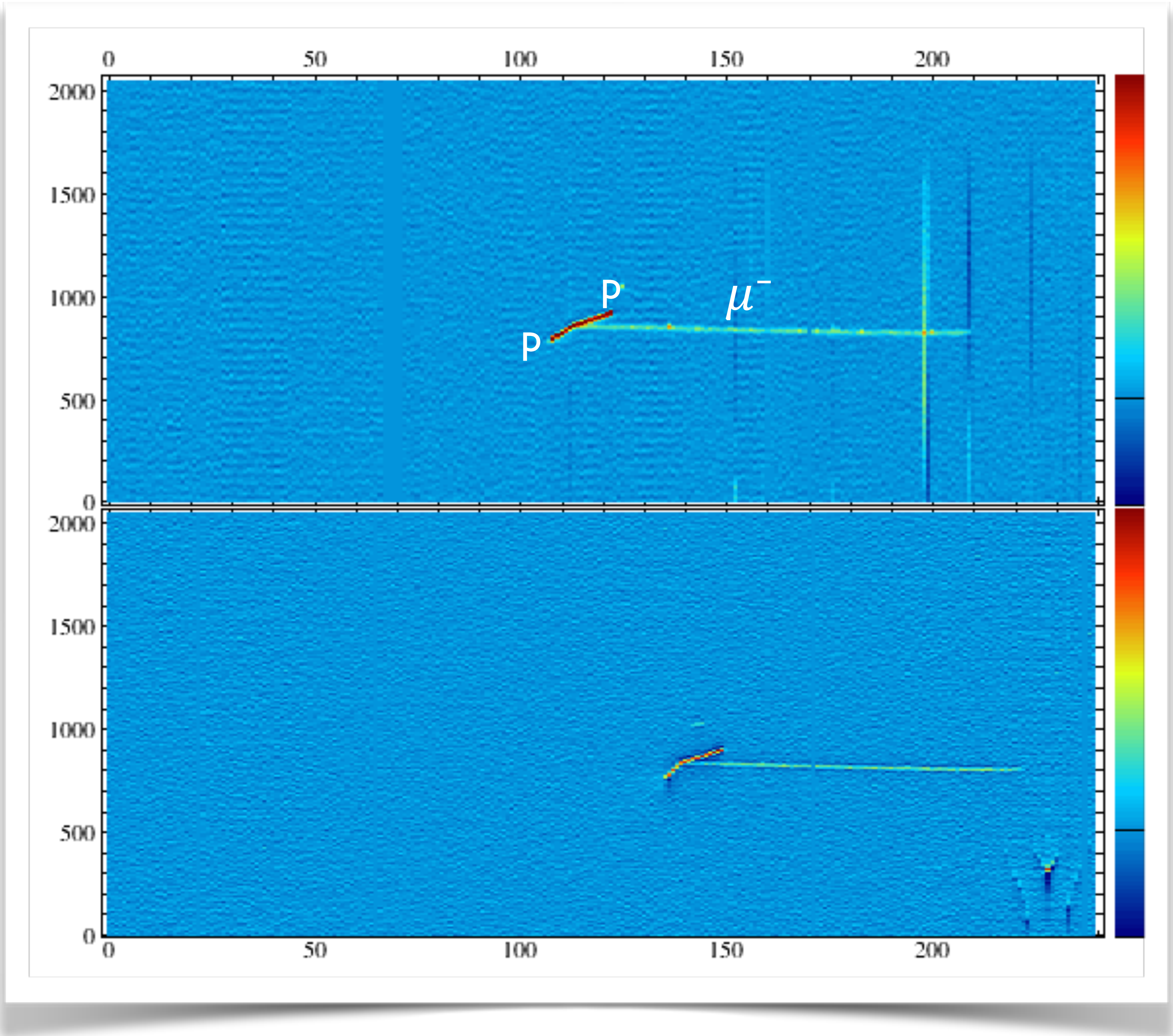
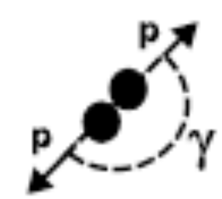
Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.



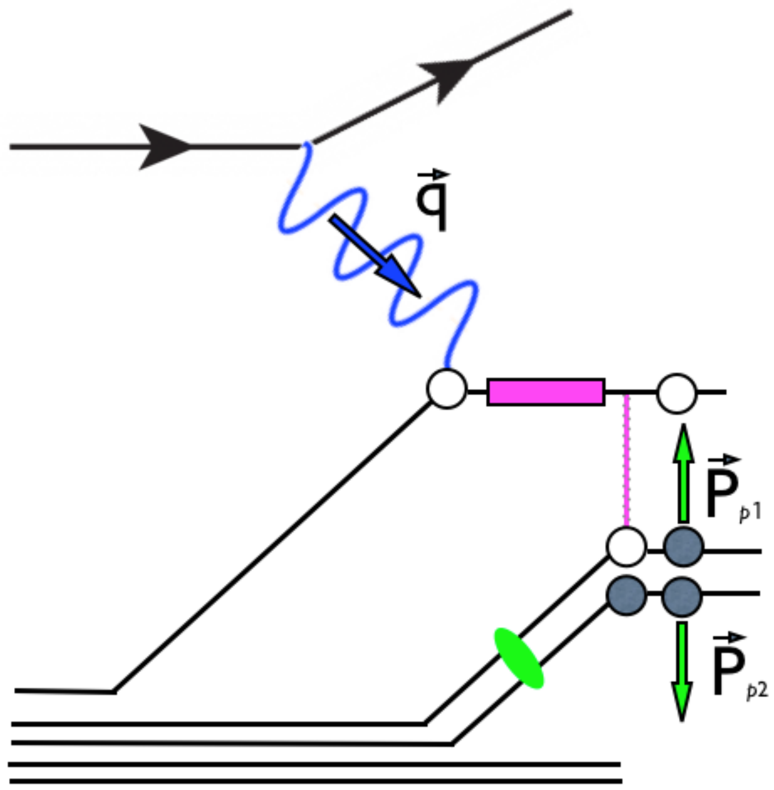


cos(γ)<-0.95

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

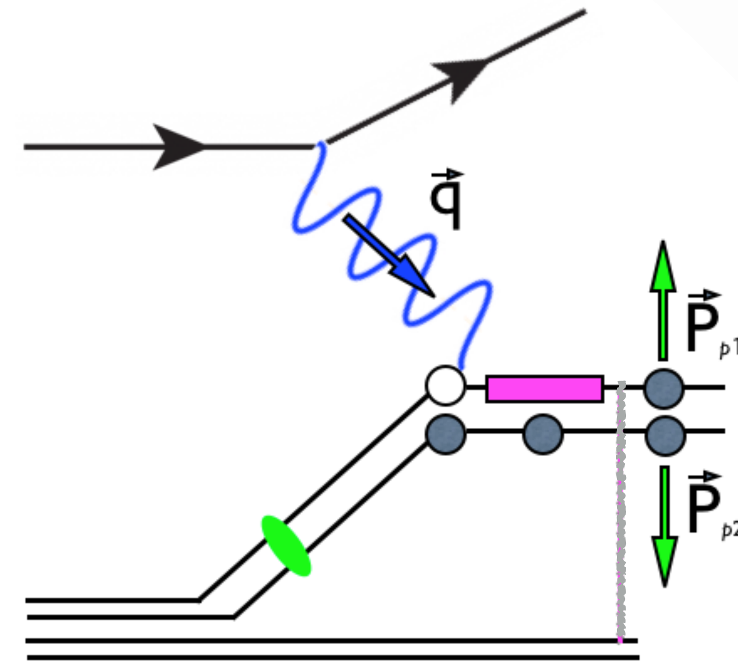
Pictorial diagrams of examples of two-proton knock-out CC reactions involving *np* SRC pairs

- 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

n carries away most of the transfer momentum

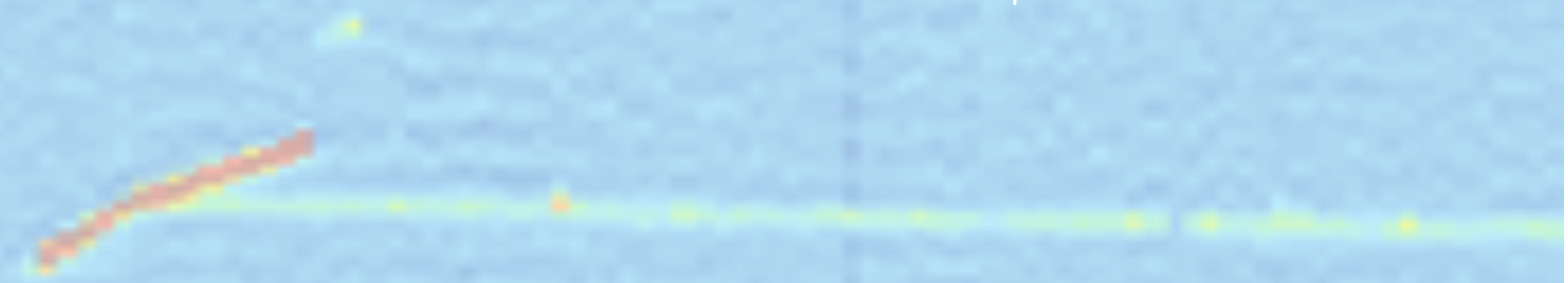


from RES formation inside a SRC pair (hit nucleon in the pair) and de-excitation through multi-body collision within the A-2 nuclear system

recoil nucleus carries away most of the transfer momentum

Back-to-back proton pairs in the Lab

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,

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

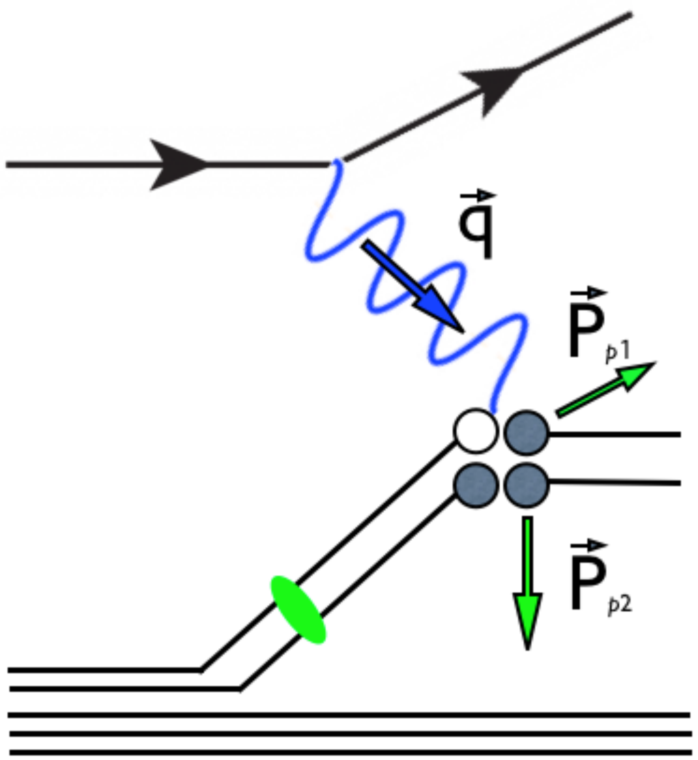
These features **look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC *np* pairs.**

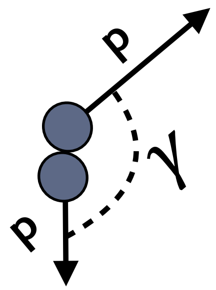
2-p knock-out CC reactions involving SRC pairs(II)

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





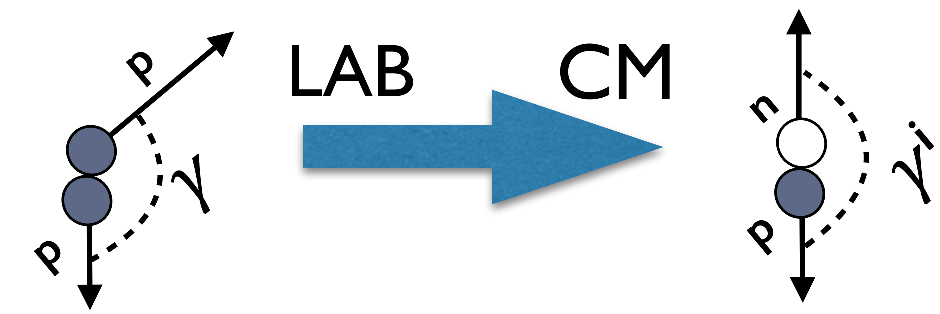
The high relative momentum will cause the correlated proton to recoil and be ejected. Within impulse approximation,

- the <u>struck nucleon</u> p1 being the higher in momentum and
- the lower p2 identified as the <u>recoil spectator nucleon</u> from within the SRC

(μ⁻+2p) - Initial momentum reconstruction

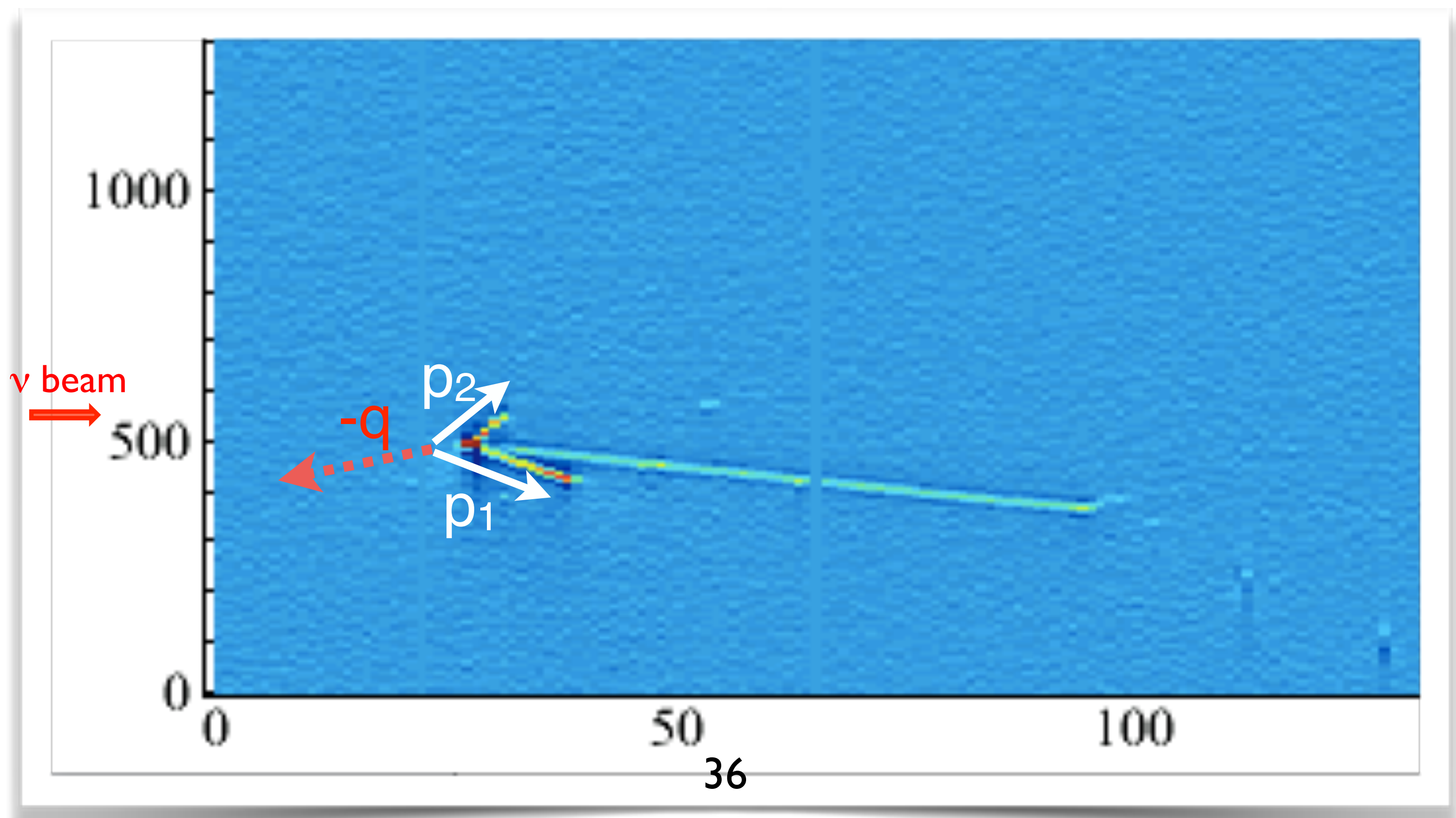
With an approach similar to the electron scattering triple coincidence analysis, the initial momentum of the struck neutron $\vec{p}_n^{\,i}$ is determined by transfer momentum vector subtraction to the higher proton momentum *[lower momentum p2 identified as recoil spectator nucleon from within SRC]*

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



$\vec{q}$ 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.



$(\mu^{-}+2p)$ – ν energy reconstruction

From all final state particles kinematics

$$E_{\nu} = E_{\mu} + T_{p1} + T_{p2} + T_{A-2} + E_{miss}$$

We have no access to the longitudinal component of the missing momentum,

we may lower bound $T_{(A-2)} \leq (P^{T}_{miss})^{2}/2\, M_{A-2}$

$$E_{miss} = E_{sep} + \epsilon^{*}$$

$$E_{sep} = M_{(A-2)} + 2m_{p} - M_{A}$$

E_{miss}=energy expended to remove the nucleon pair from the nucleus.

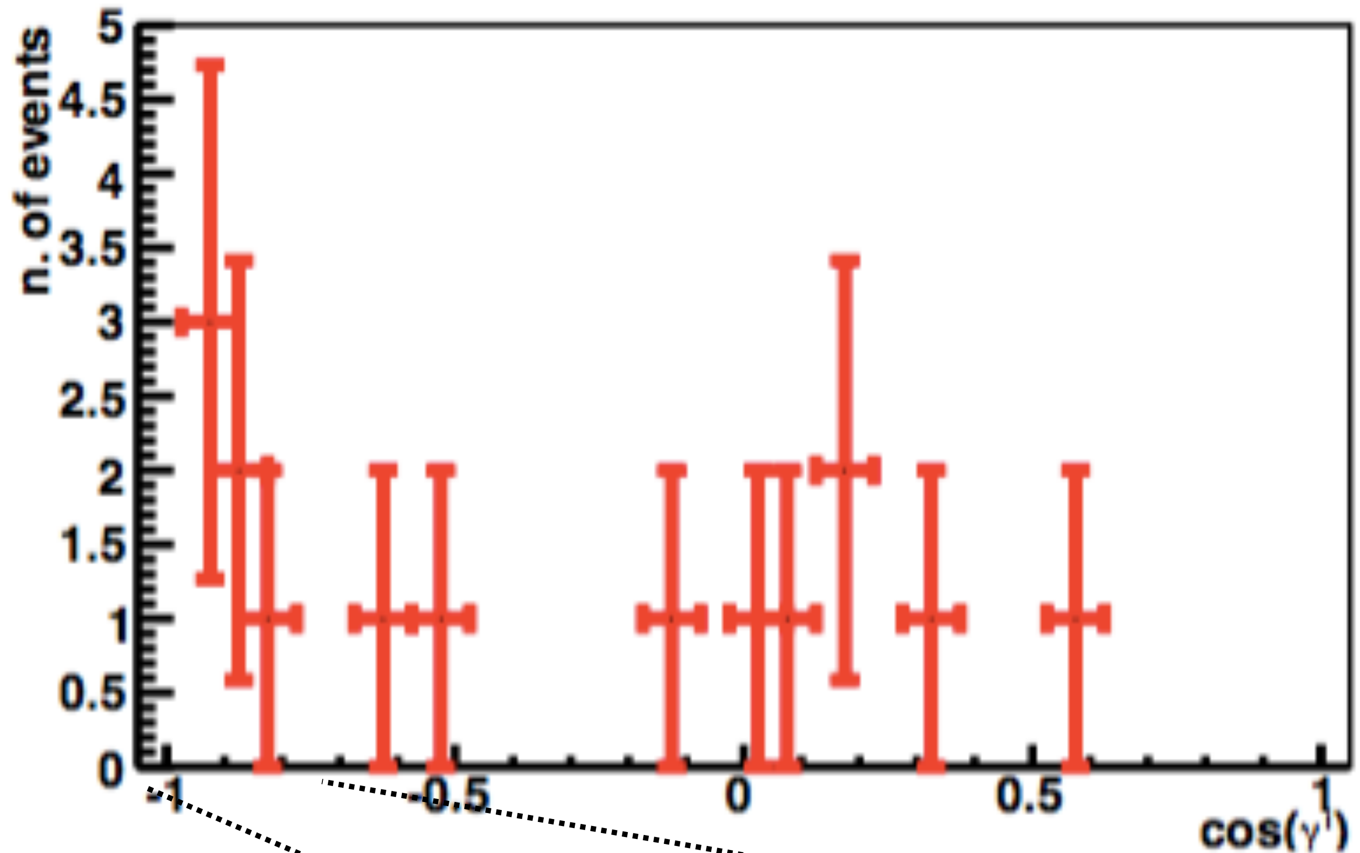
Esep=two-nucleon separation energy for argon

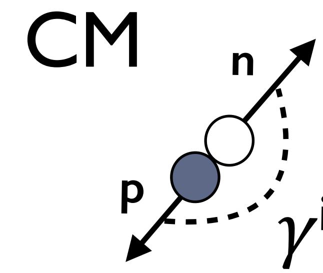
ϵ^{*}=actual excitation level of the residual nucleus

We set the total value to a constant E_{miss} =30 MeV. This is an approximation of the average energy to remove an np pair from an Ar nucleus extrapolated from single nucleon removal energy spectra for Ar nuclei.

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

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

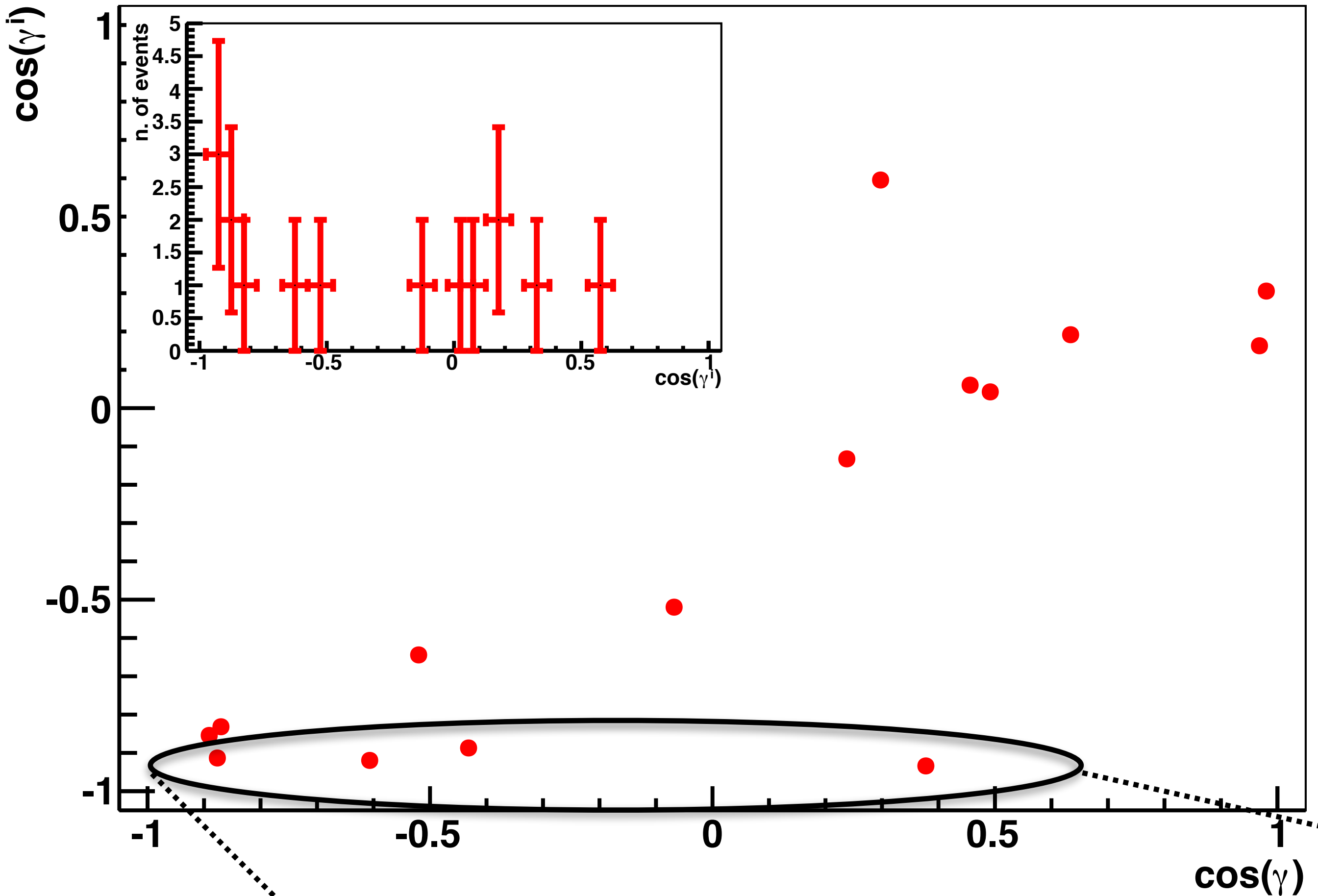




γ^i=opening angle between the reconstructed struck nucleon and the recoil proton in the np ***initial*** *pair*

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

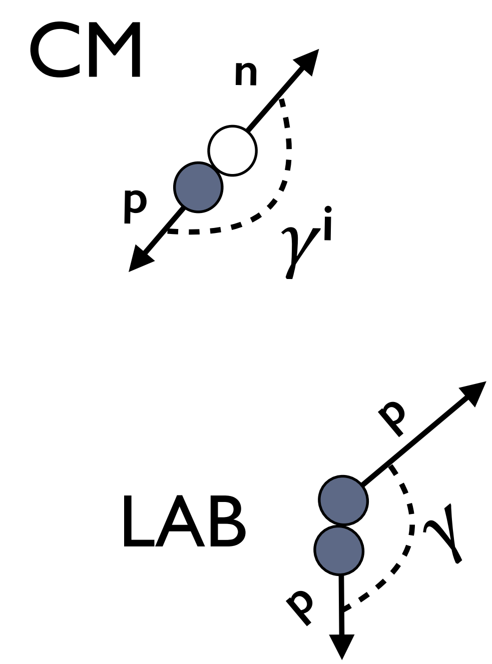
Back-to-back proton pairs in the initial state



cos(γ^i) vs cos(γ)

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

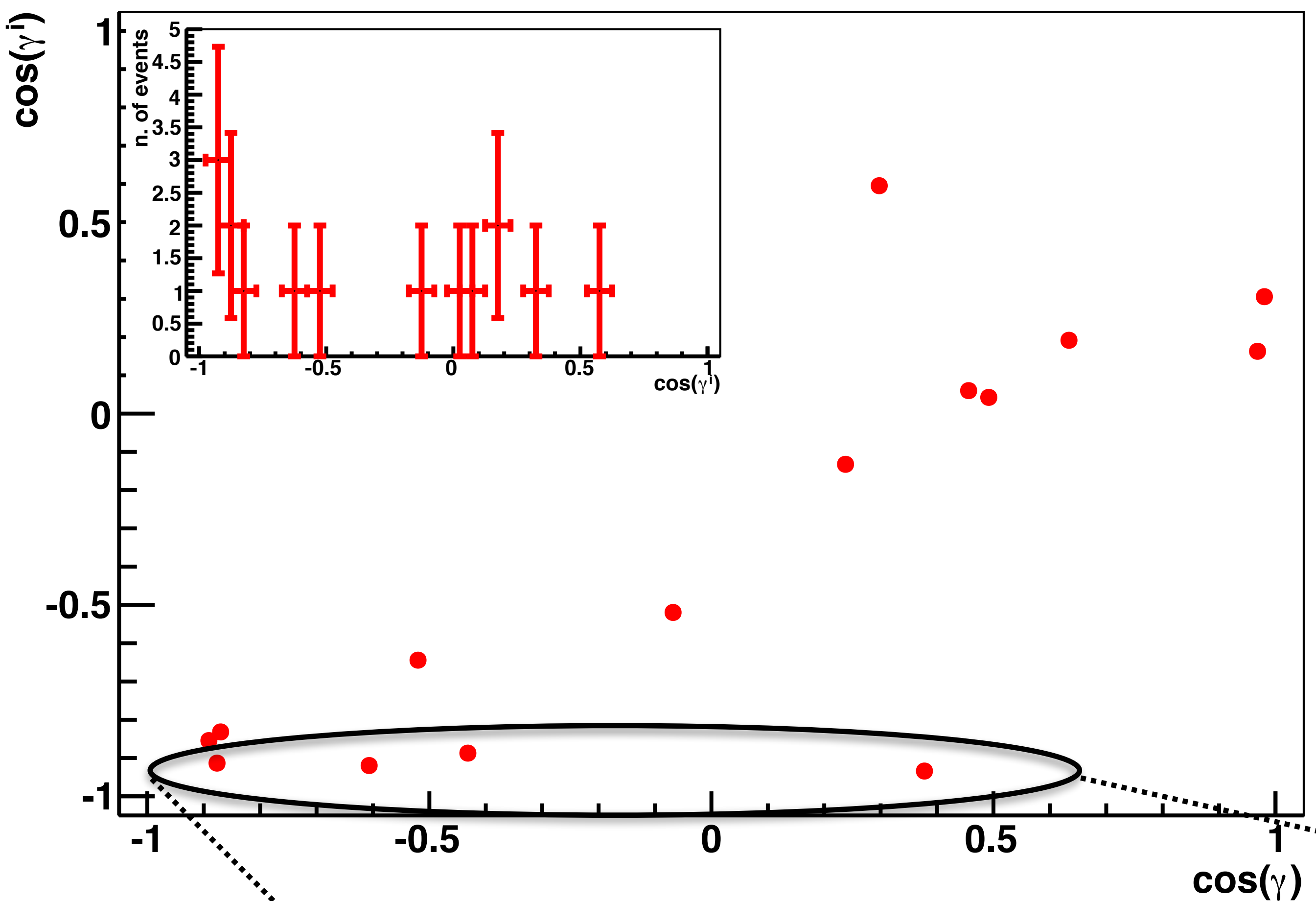
γ=angle in space between the two detected proton tracks in the ***Lab reference frame***



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

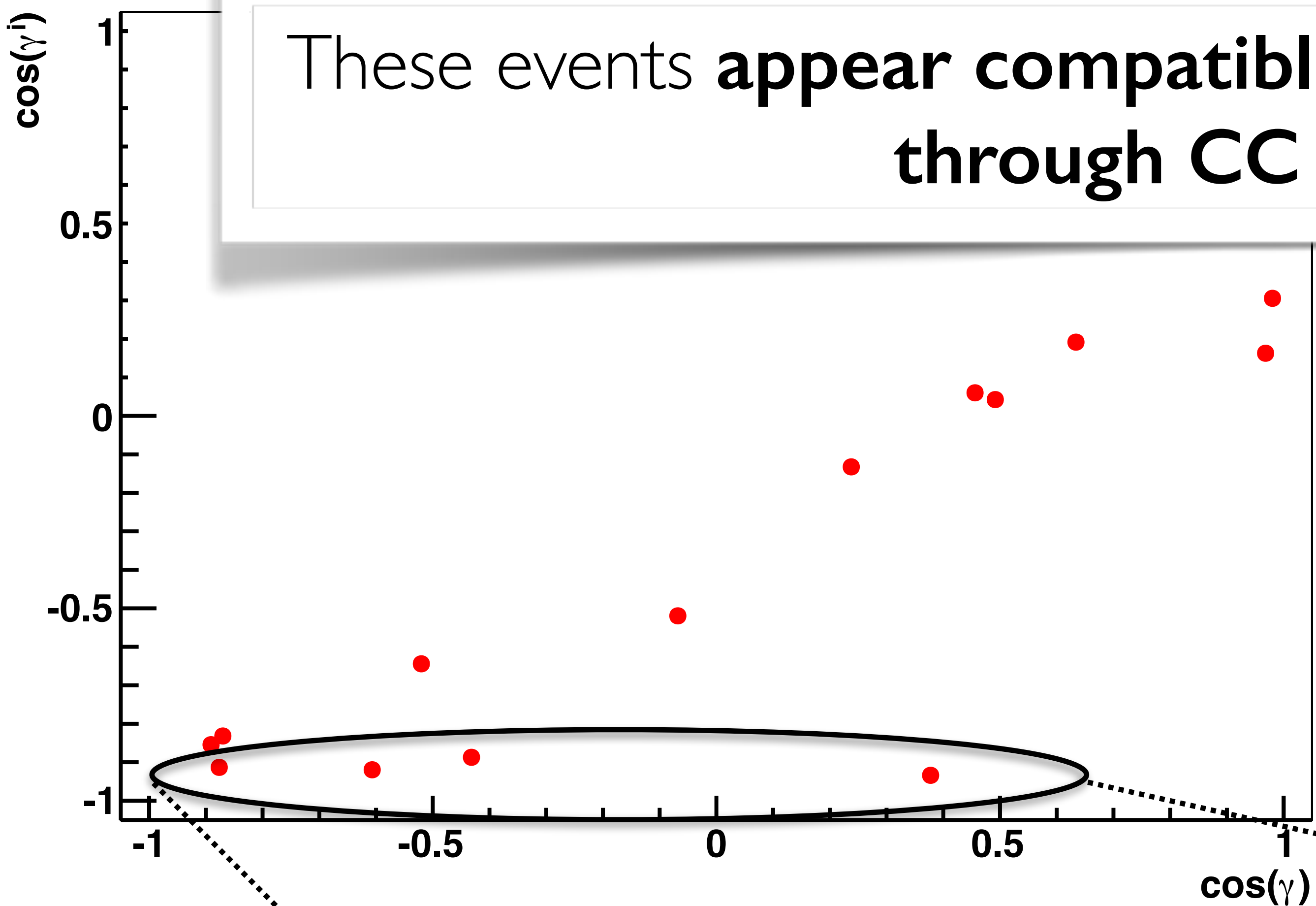


Four events (those horizontally aligned in the lowest $\cos(\gamma_i)$ bin, rather separated from the others) are reconstructed with the pair in a **back-to-back** configuration in the CM frame, $\cos(\gamma_i) < -0.9$ and have reconstructed initial momenta $> K_F$

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

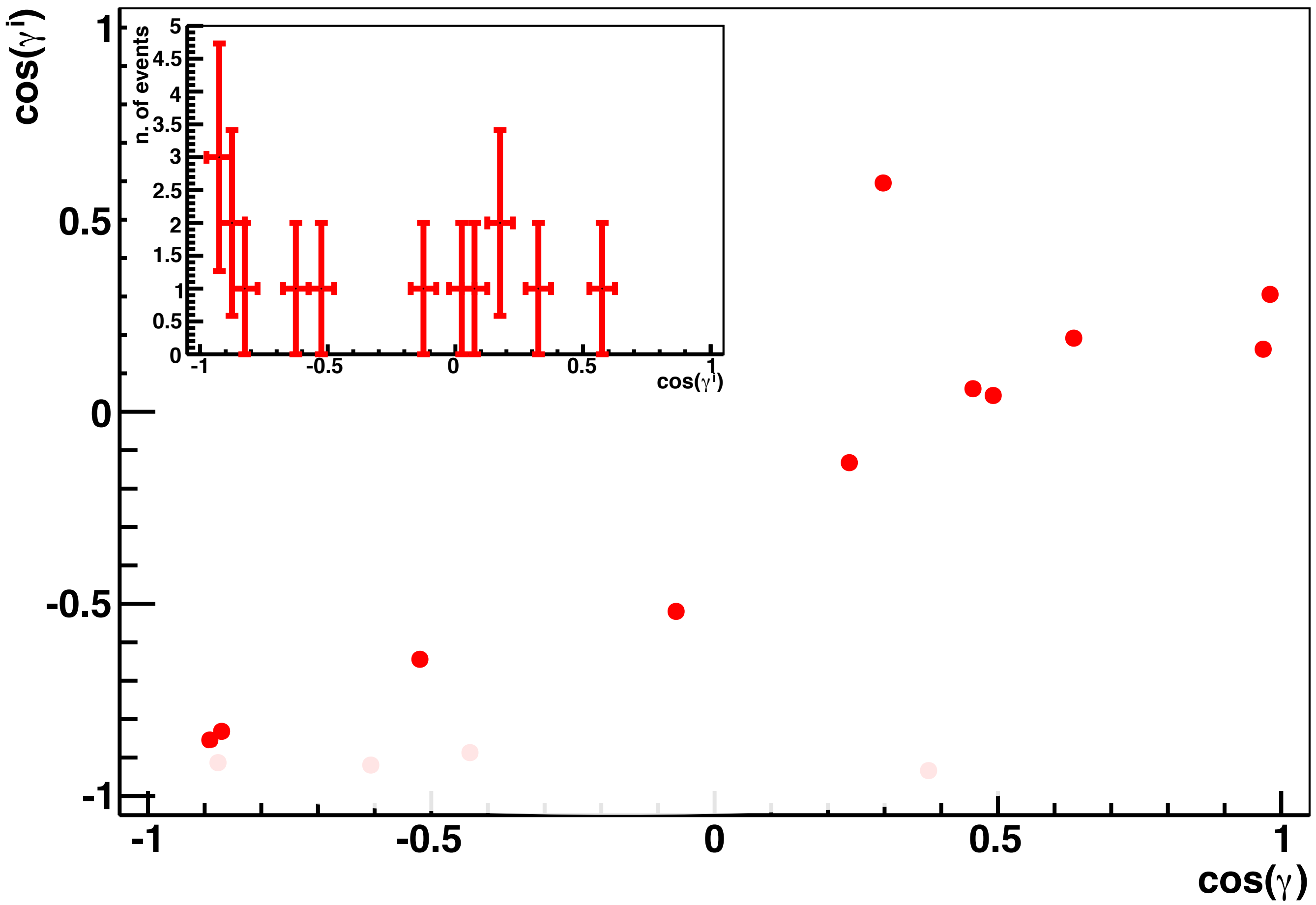
These events **appear compatible as originating from SRC pairs through CC QE reactions**



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 (≲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

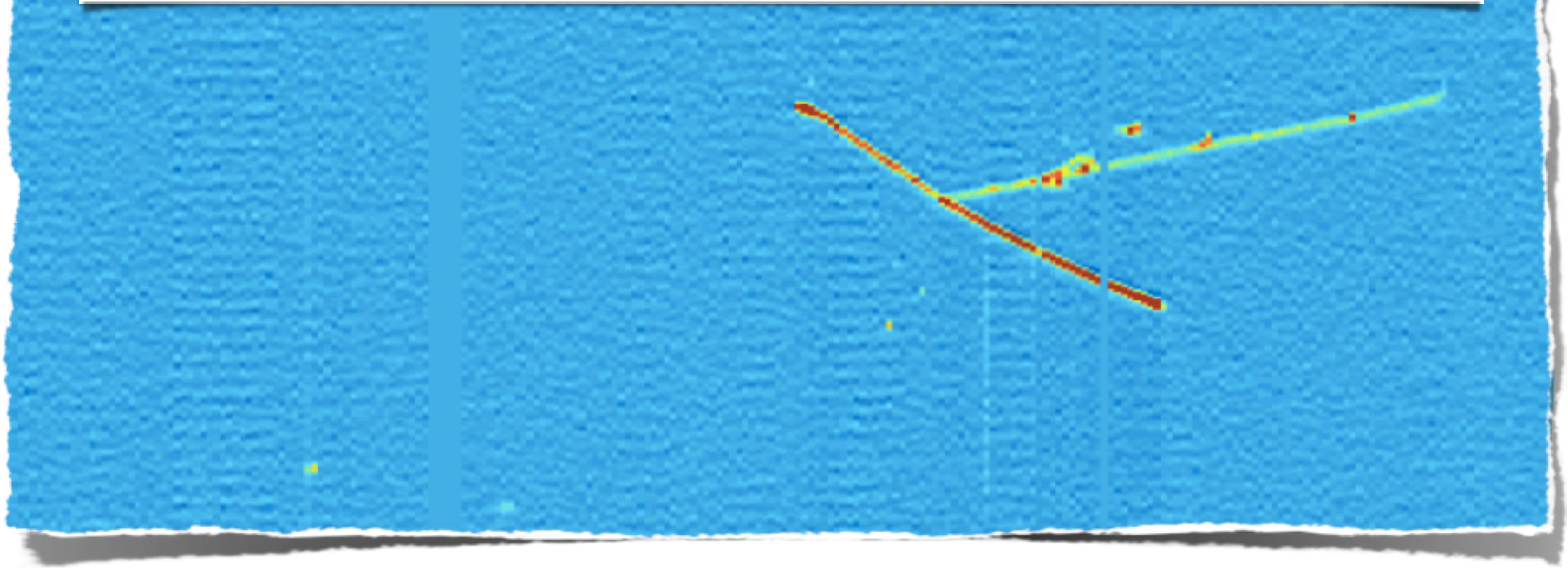
- Other mechanisms like interference between the amplitudes involving one-and two-nucleon currents, subject to current theoretical modeling*, can also potentially contribute
- ….

- 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***

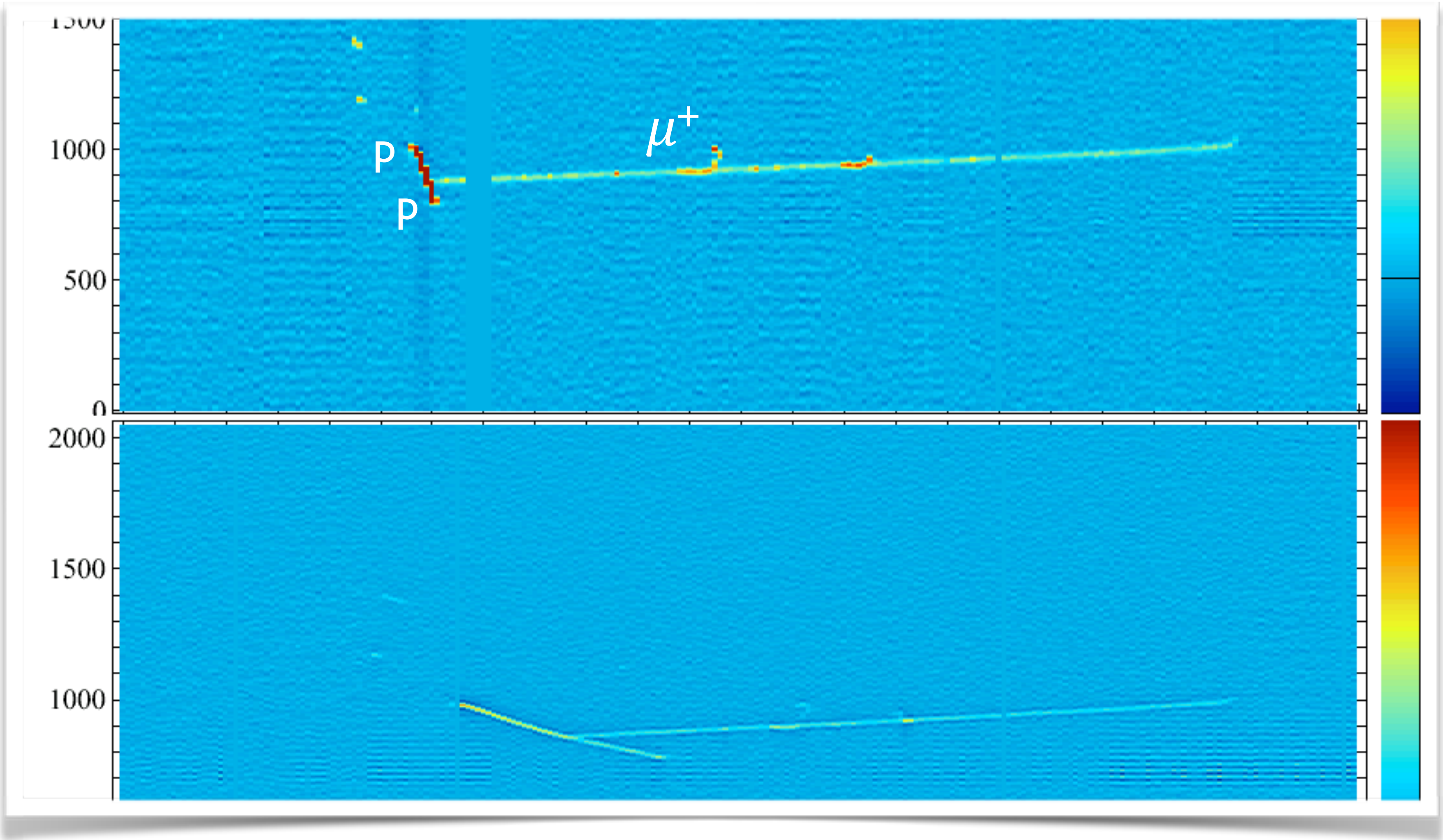
*O. Benhar et al., arXiv:1312.1210 [nucl-th] (2013)

"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)



Anything NEW ?!

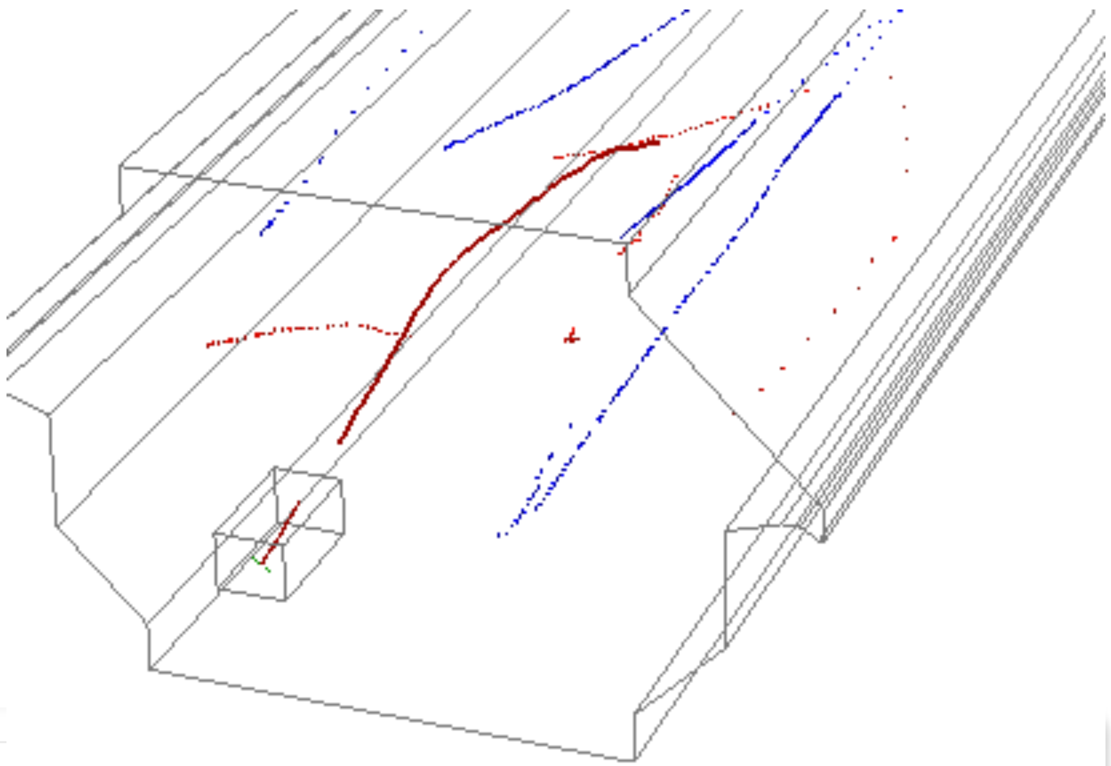


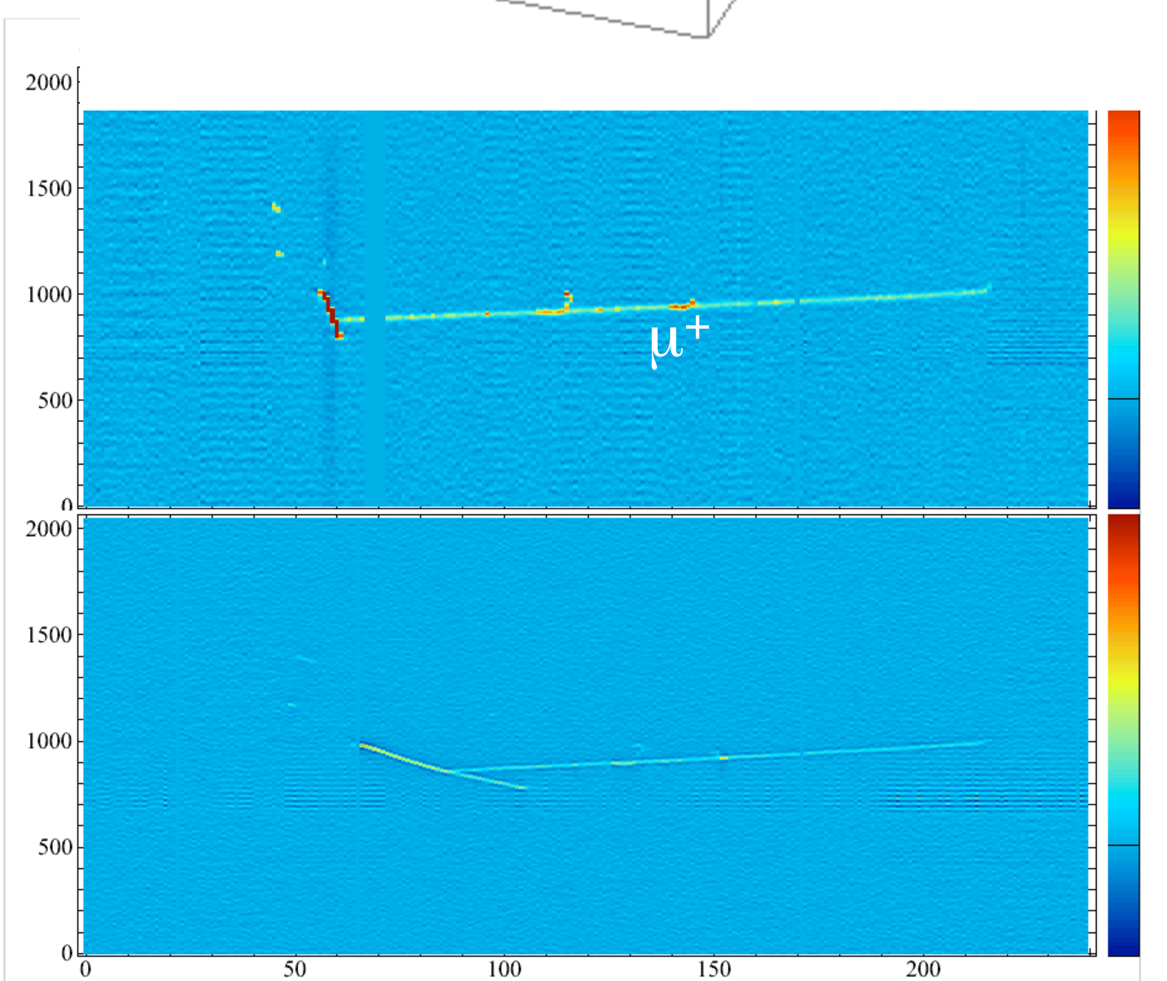
We have found another *puzzling* "Hammer event"…
in the AntiNeutrino event sample:

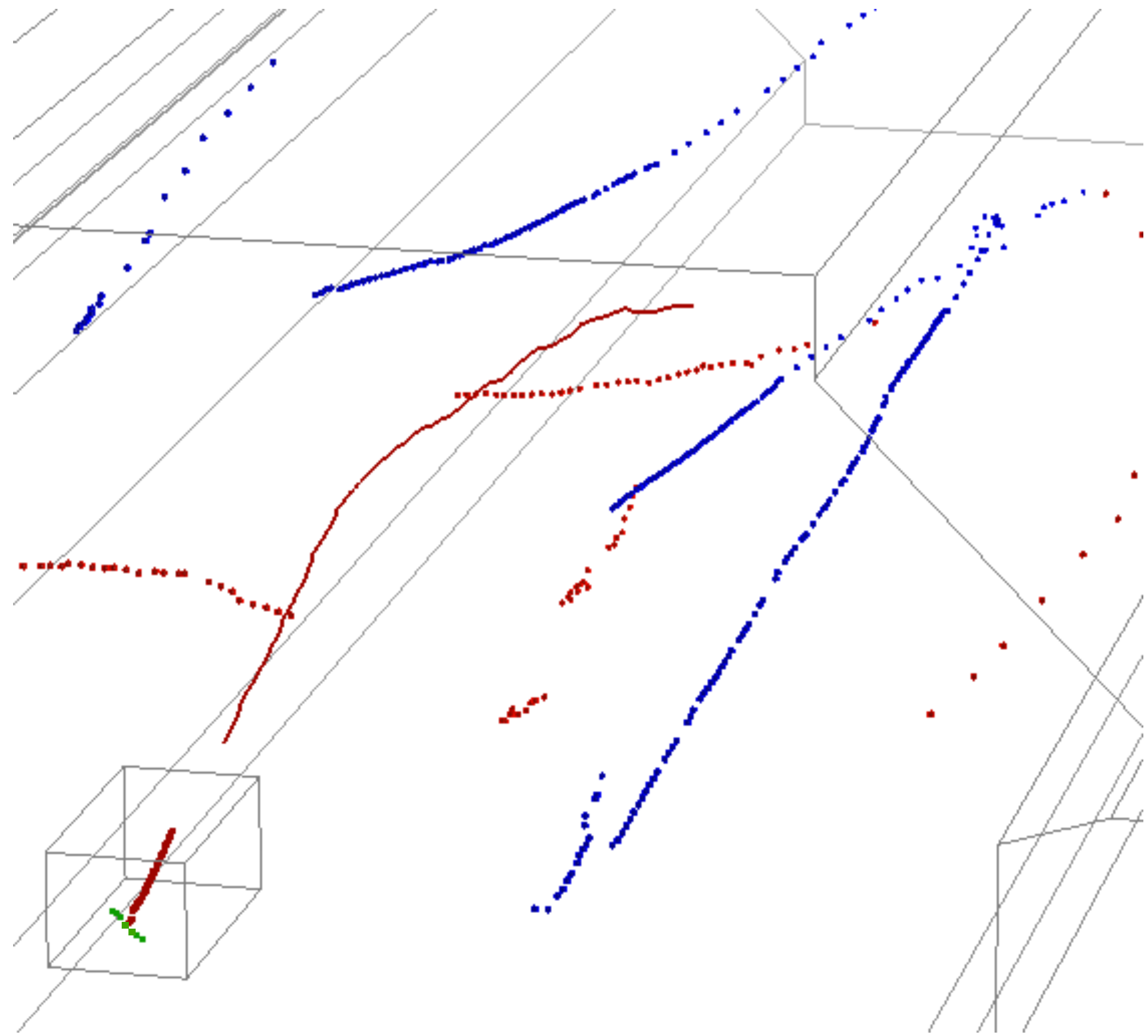
$$\bar{\nu} + Ar \rightarrow \mu^+ + 2p$$

(showing 3 positive charges in final state)

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



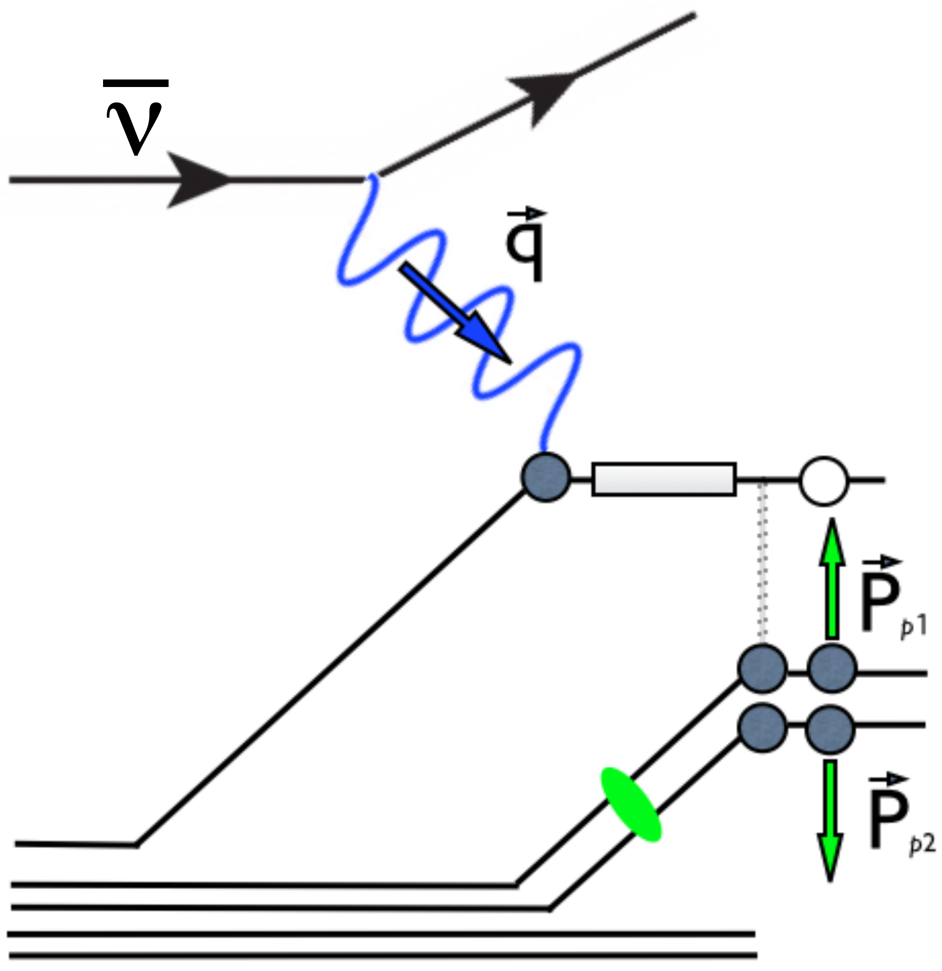


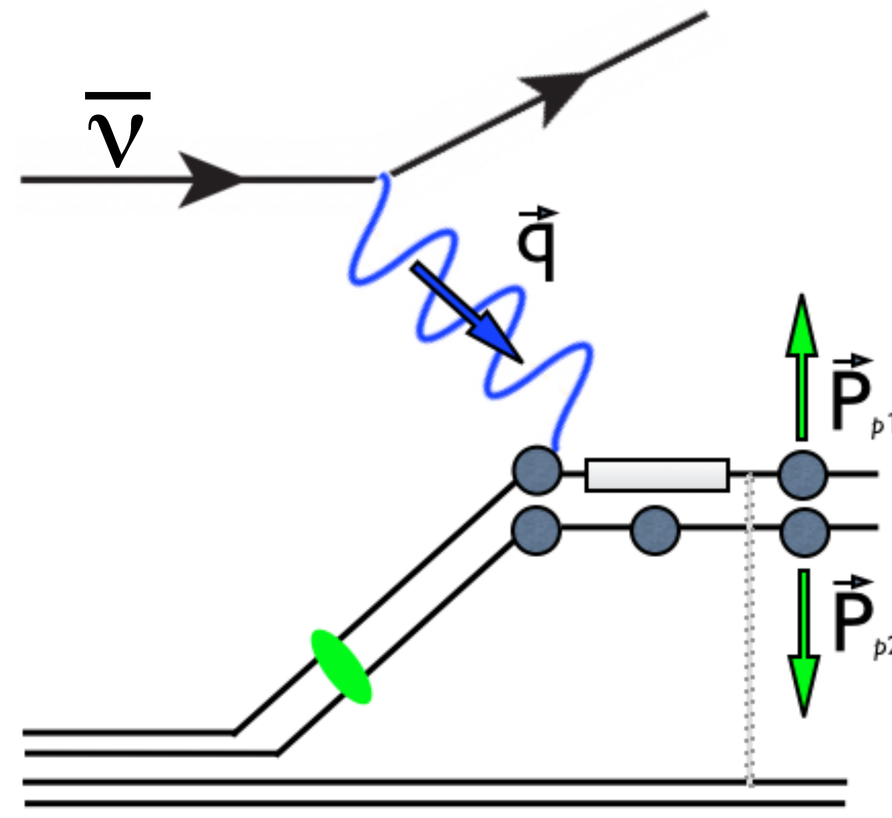


Red (blue): positive (negative) charge tracks determined by MINOS.

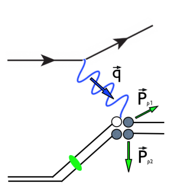
Exploring possible mechanisms in analogy with neutrino Hammer events

CC RES pionless mechanisms involving a pre-existing ***pp*** pair in the nucleus





Note: The QE mechanism(on single nucleon in a pair) is undetectable because (np) + W^{-} → (nn)



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

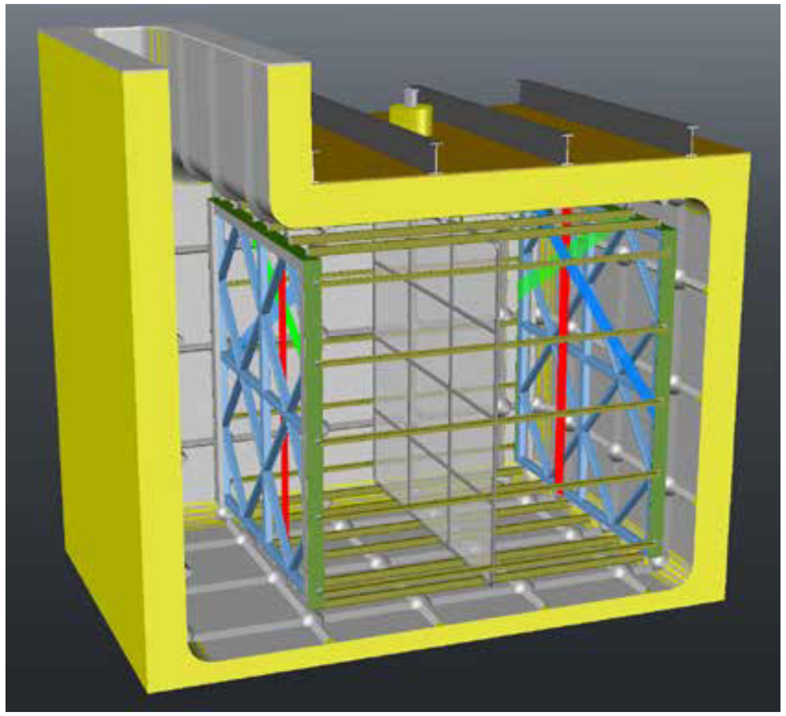
Future LArTPC experiments: MicroBooNE, LAr1-ND…

MicroBooNE estimated events rates (GENIE)

6.6 10^{20} POT exposure of MicroBooNE will provide an event sample of ~75000 CC 0-pion events

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



Summary

The LArTPC technique opens new perspectives for detailed reconstruction of final state event topologies from neutrino-nucleus interactions.

- Topological CC 0 pion sample analysis in ArgoNeuT:
  - (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.***

ArgoNeuT Collaboration

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*spokesperson

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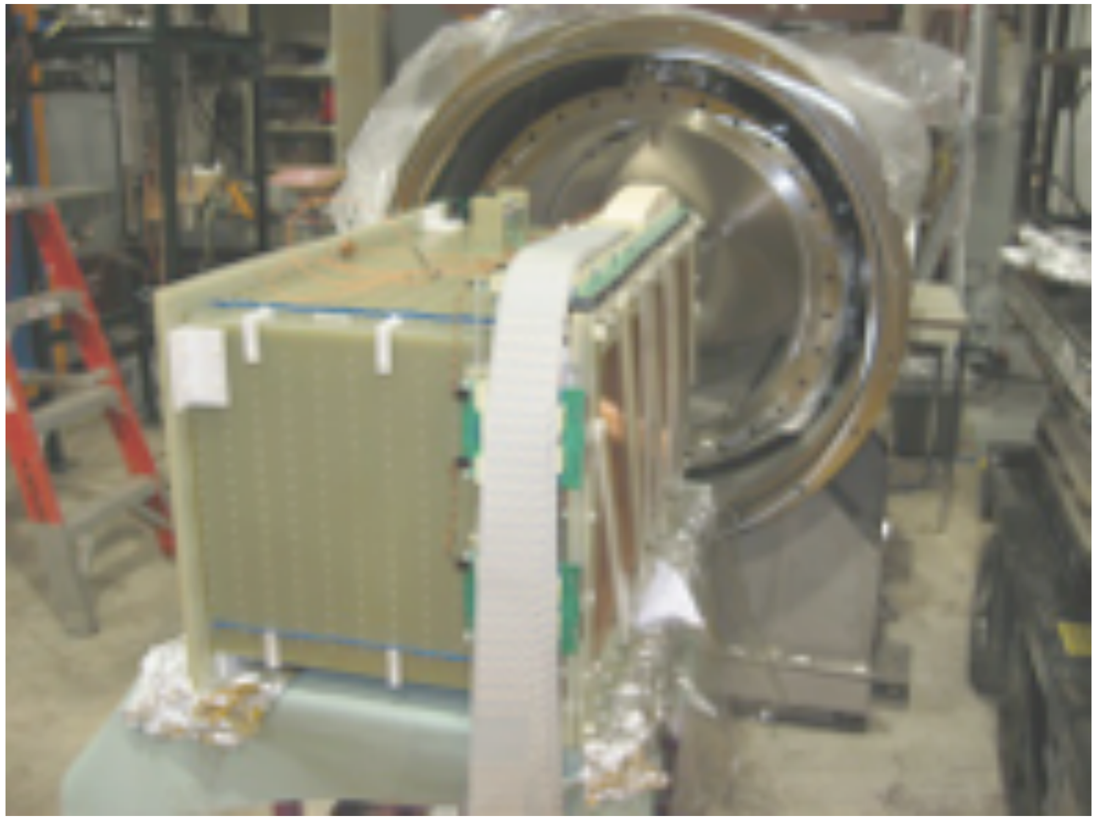
BACKUP

ArgoNeuT experiment

ArgoNeuT

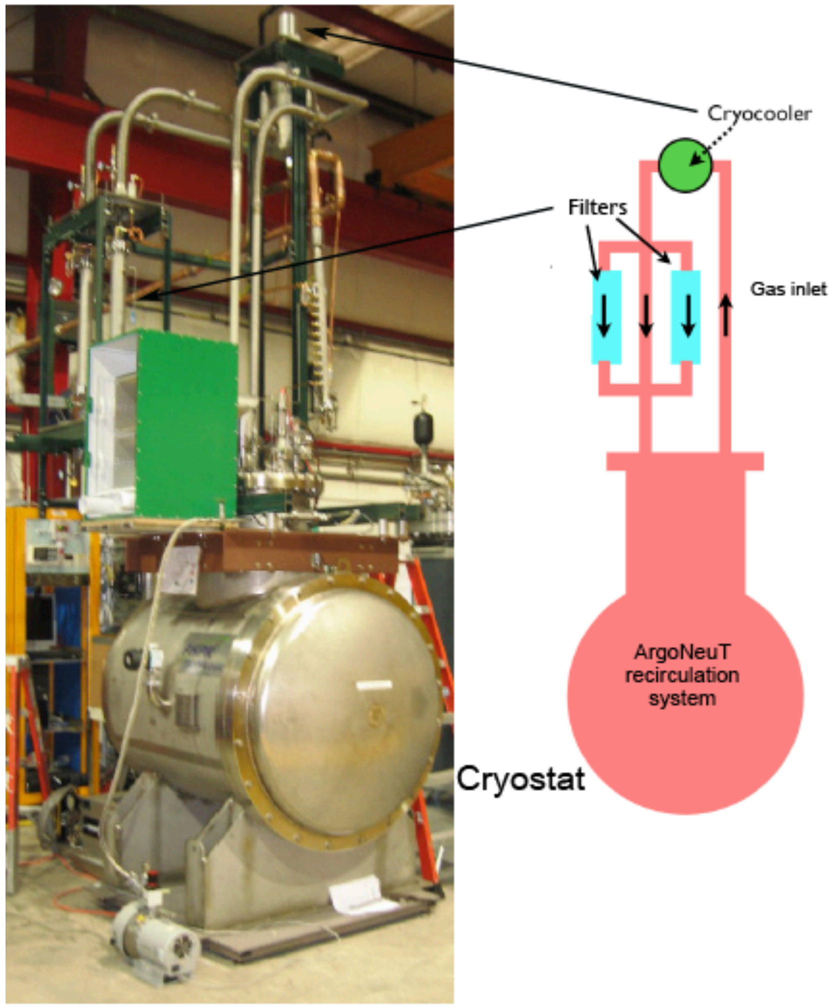
ArgoNeuT detector

"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

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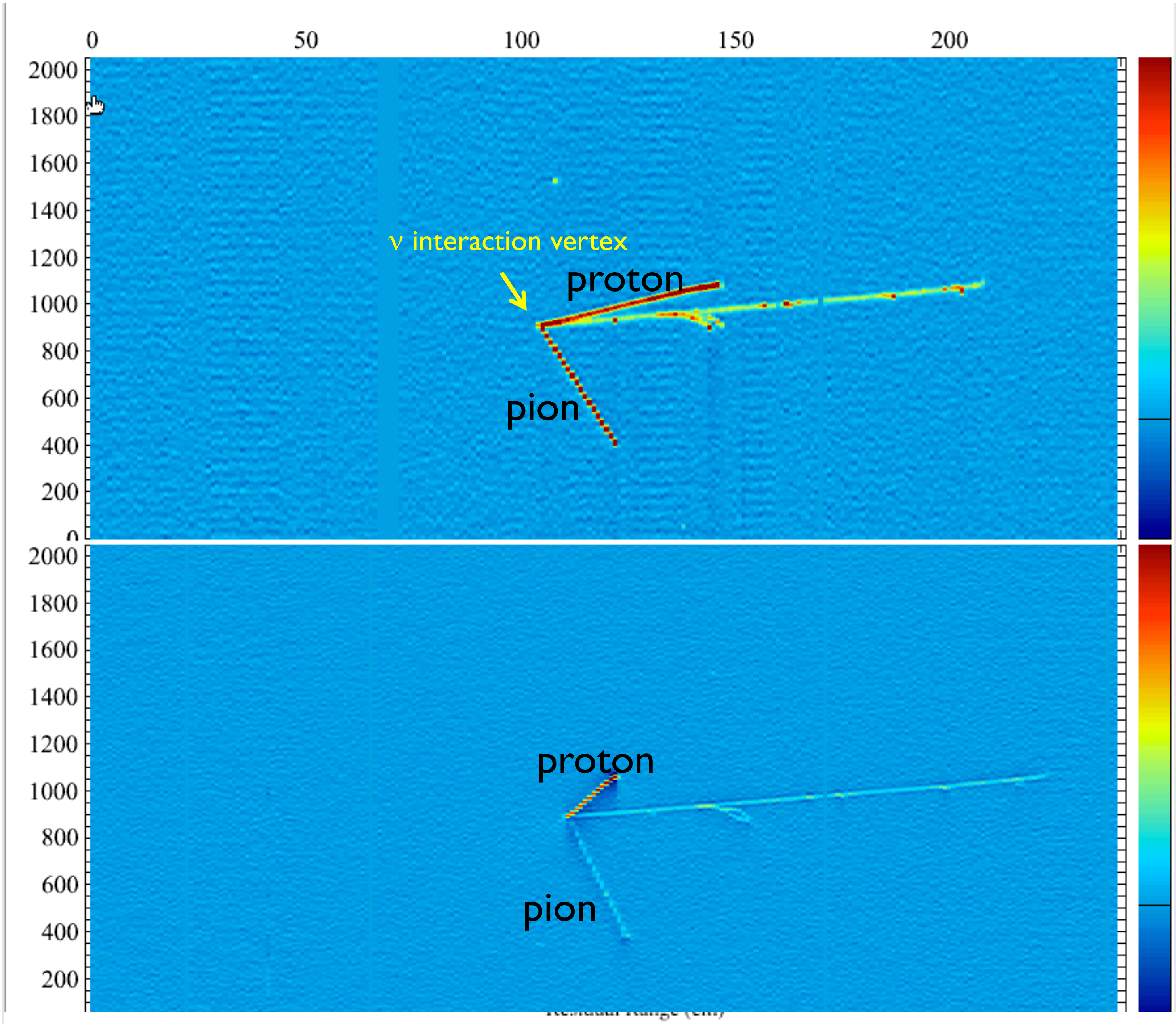
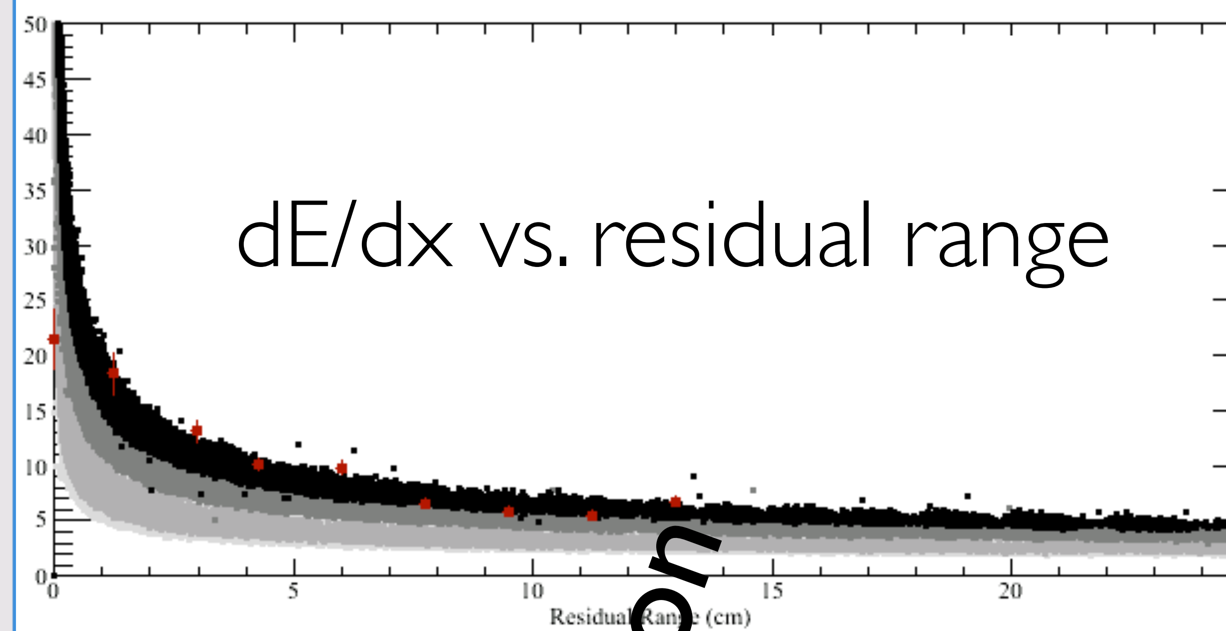
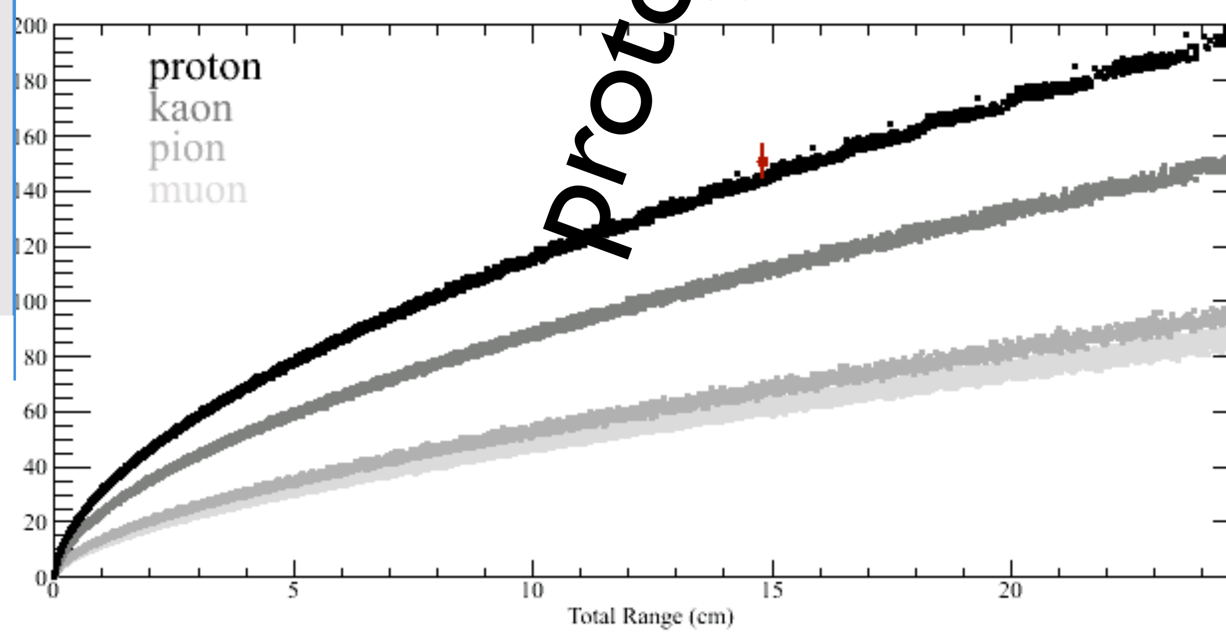
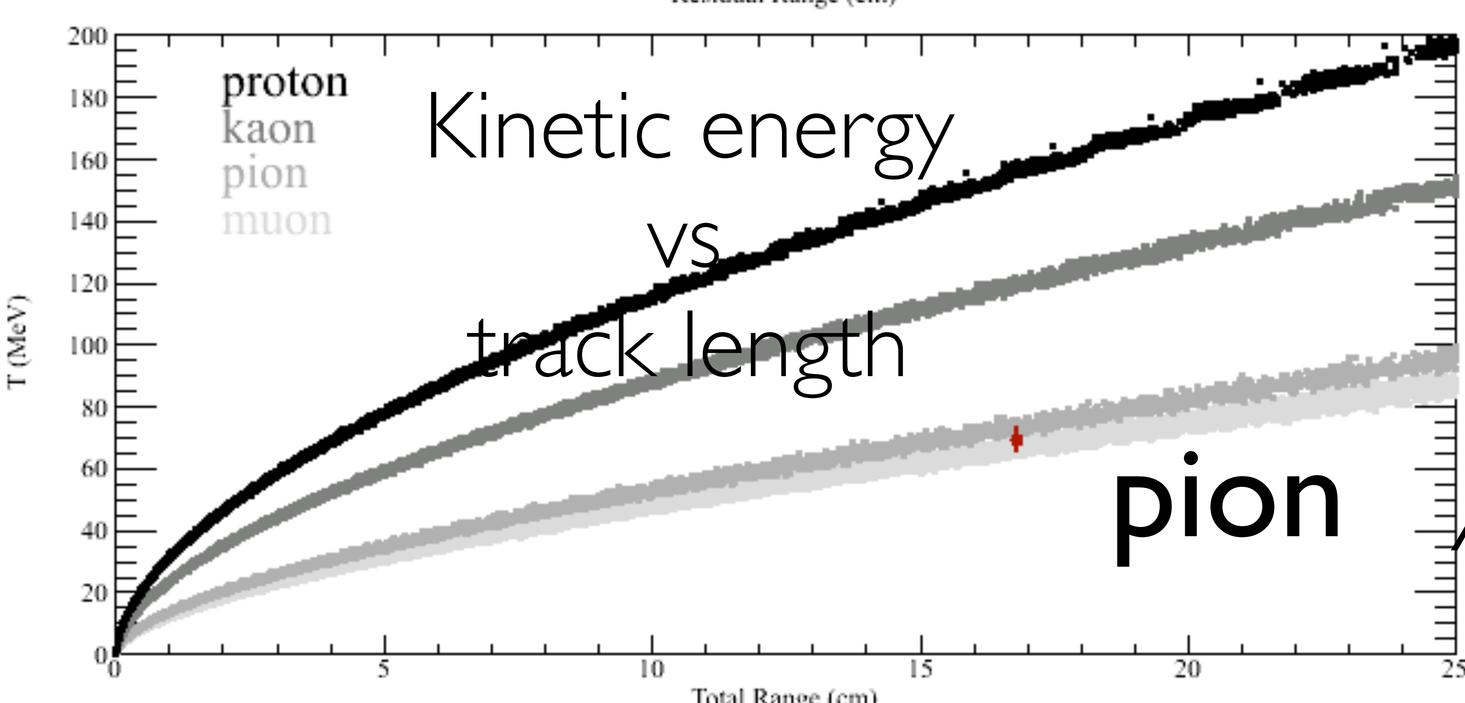
p/π± identification









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

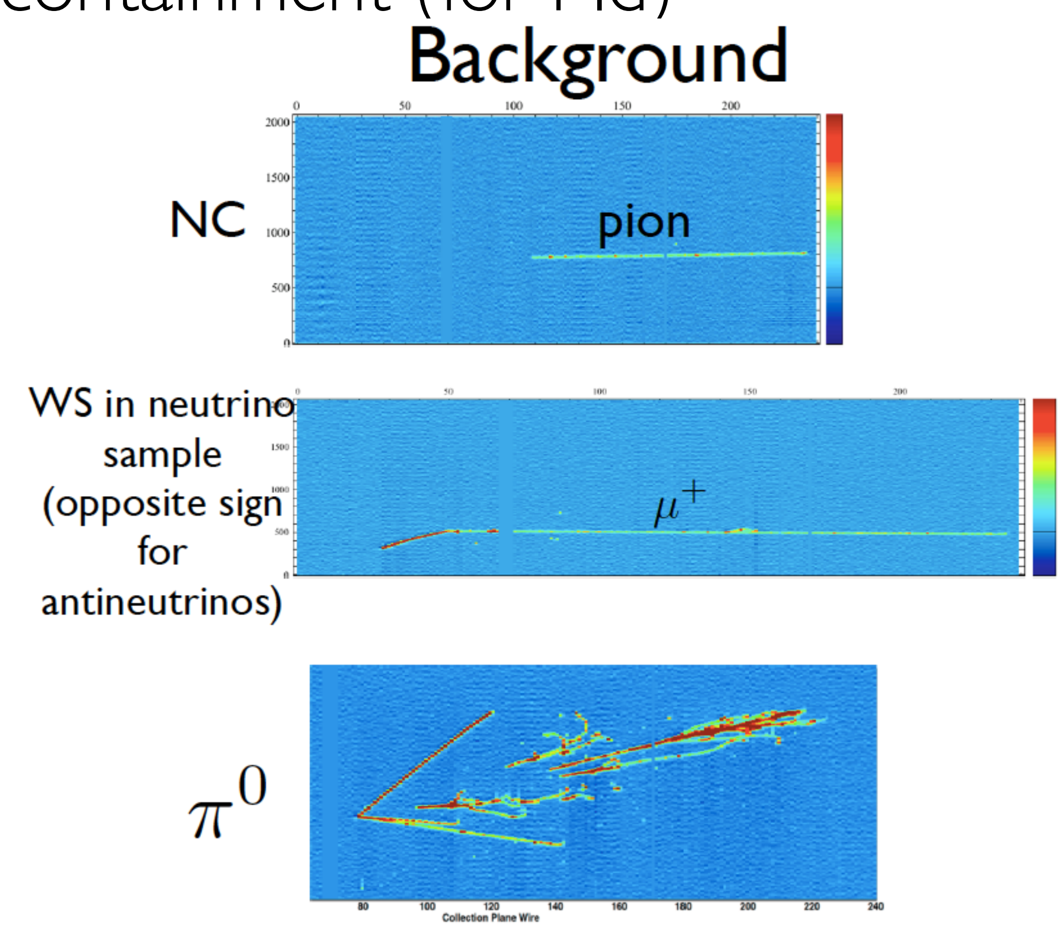
**ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

DATA ANALYSIS

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

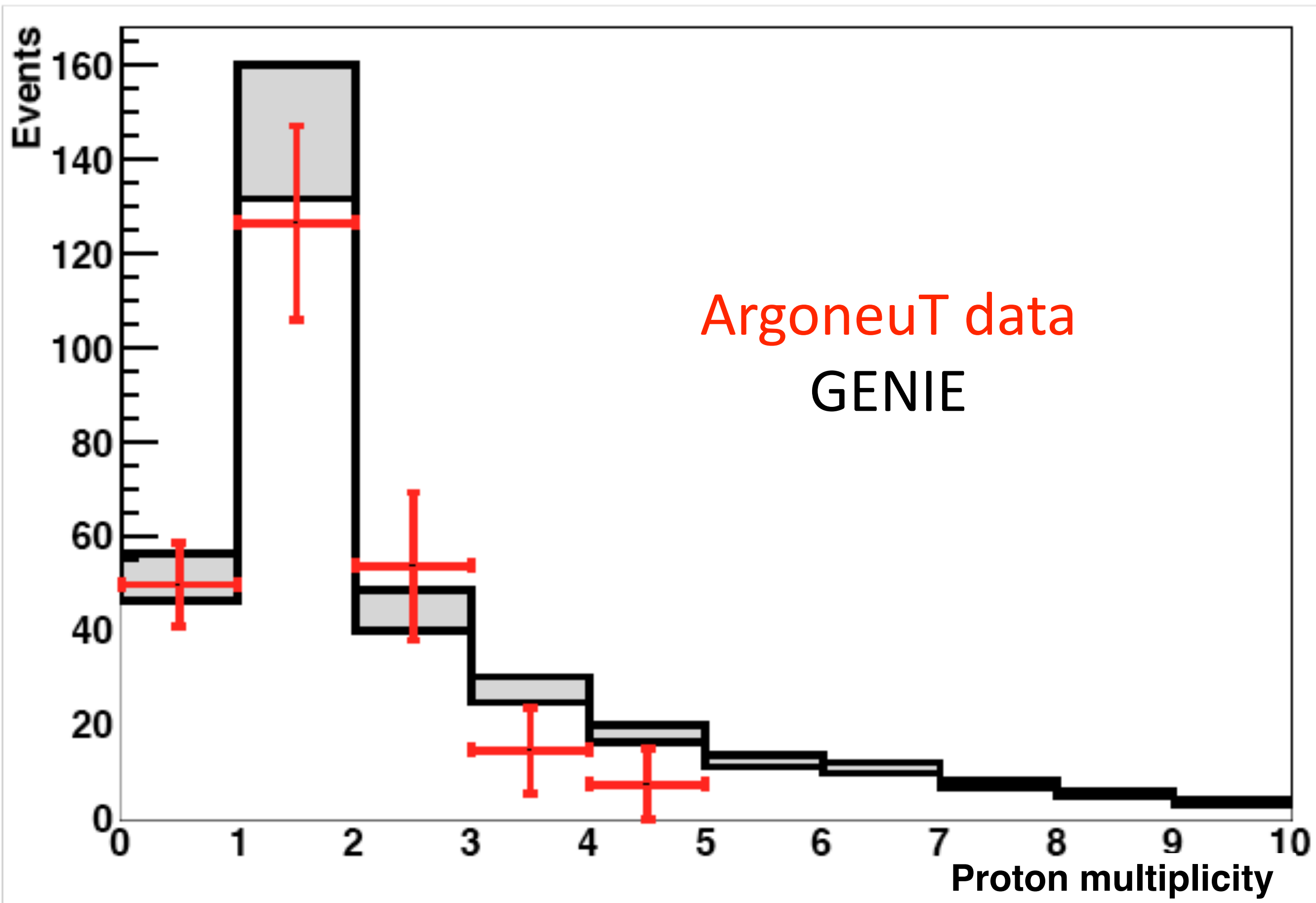
  } proton(s) angle and momentum reconstruction
- Background estimate included
- GENIE MC:
  - ✓ estimate efficiency of the automated reconstruction, detector acceptance and proton containment (for PId)
  - ✓ estimate backgrounds

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

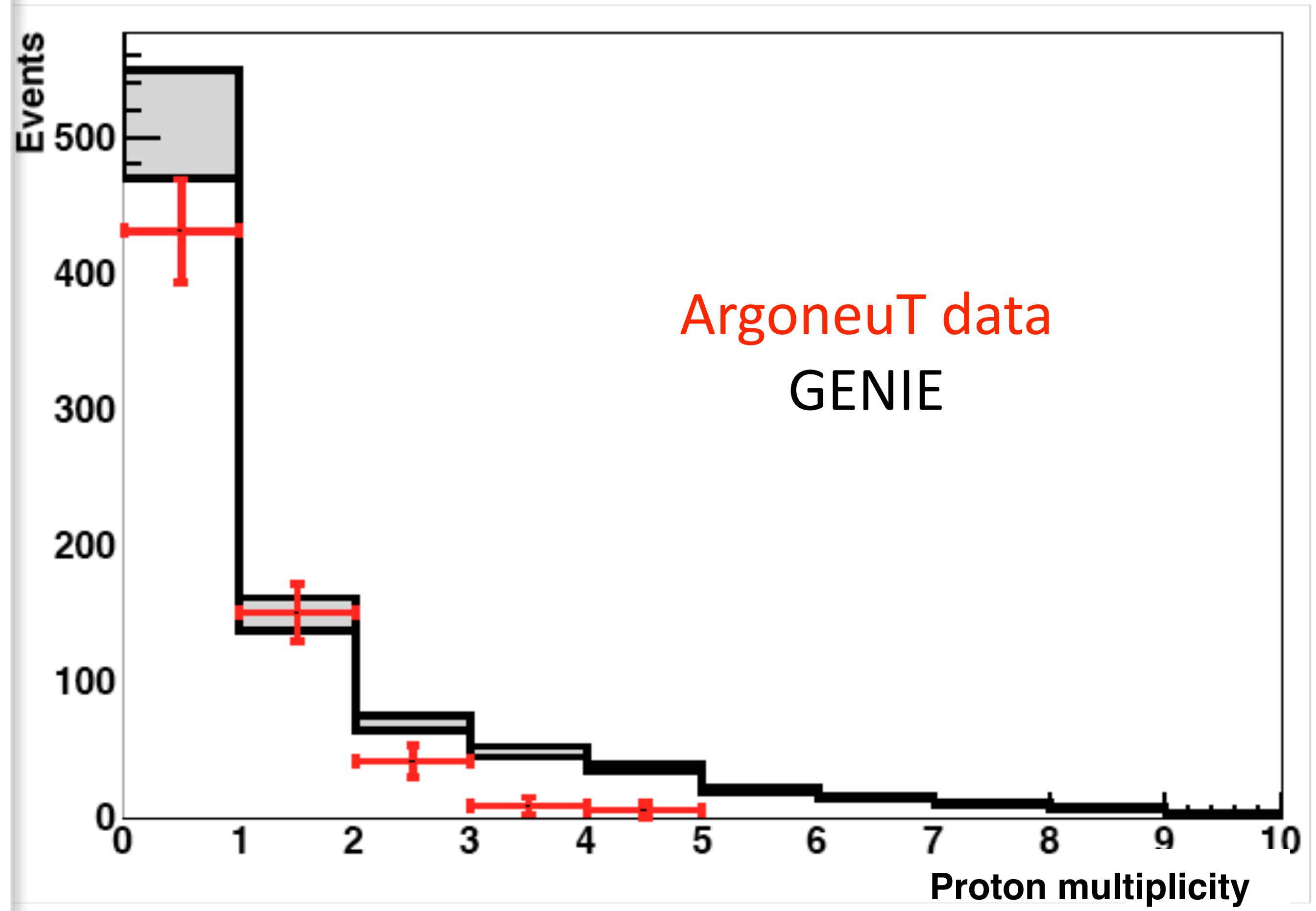


Proton Multiplicity (μ+Np events)

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

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

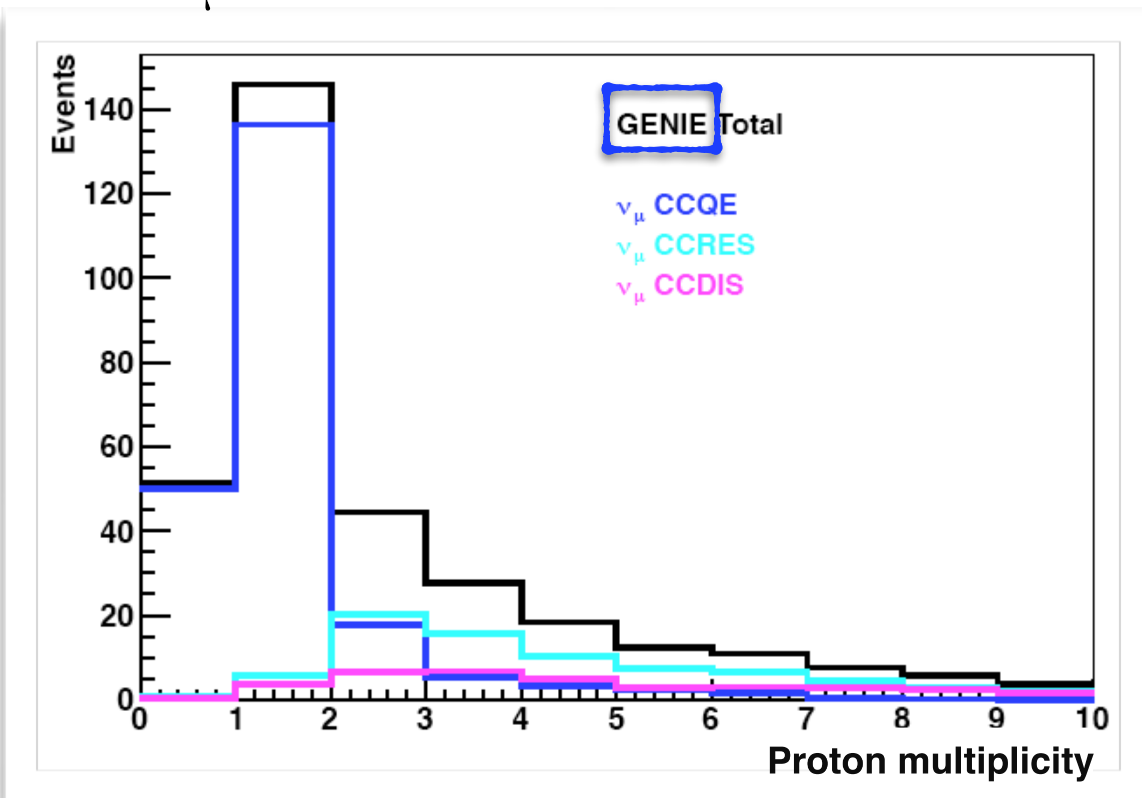
Multiplicity	Genie Expectation	Genie % of Total	DATA	DATA % of Total
0p+μ	510±5.8±40	58.4%	431±27.2±10.6	67.7%
1p+μ	149.4±3±11.8	17%	150.8±18.9±2.1	23.7%
2p+μ	69±2±5.5	8%	41.3±11.4±0.3	6.4%
3p+μ	48.5±1.8±3.9	5.5%	8.6±6.2±0.0	1.4%
4p+μ	37±1.5±3	4.2%	5.6±5.6±0.1	1%
Total (including >4p)	872.4±7.6±67	-%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

The systematic error on the MC represent the NuMI flux uncertainty

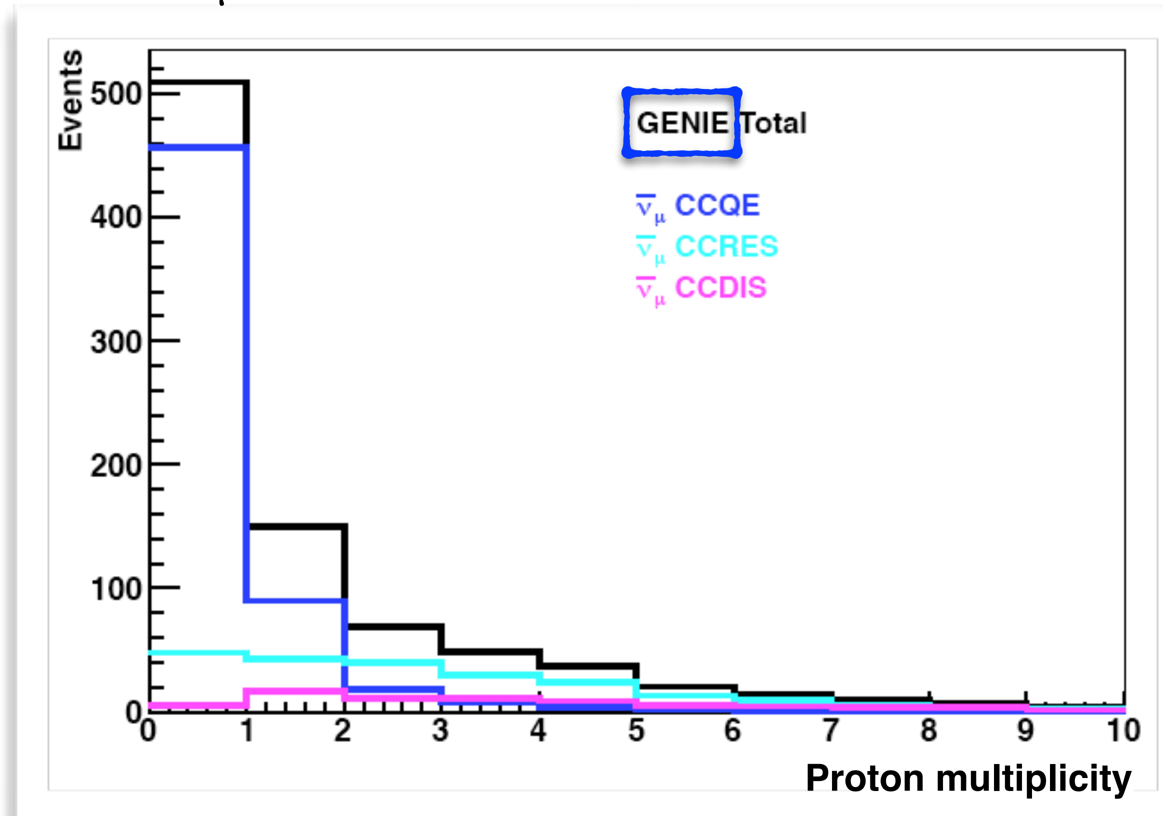
GENIE predictions are larger than data for both neutrinos and anti-neutrinos (by 27% for anti-neutrinos and 25% for neutrinos)

CC 0 pion events: MC PREDICTIONS by Physical Process

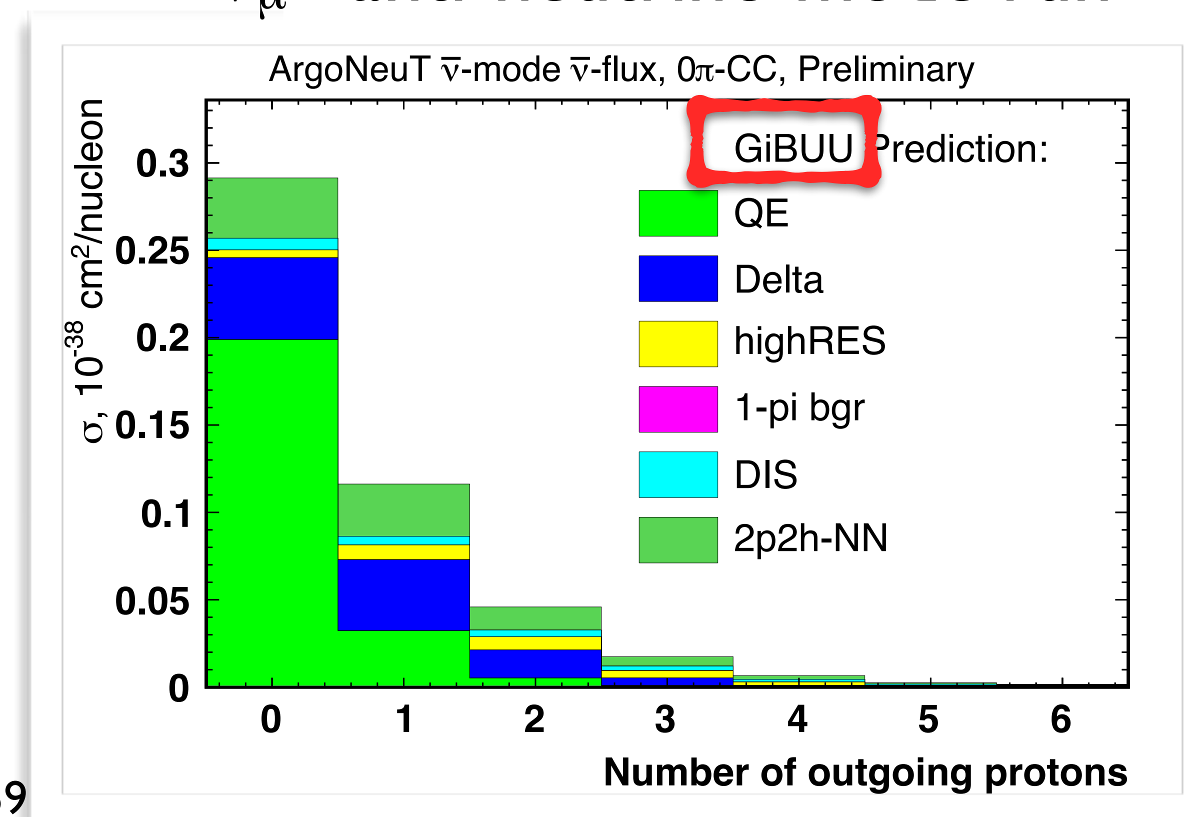
ν_μ - anti-neutrino mode run



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

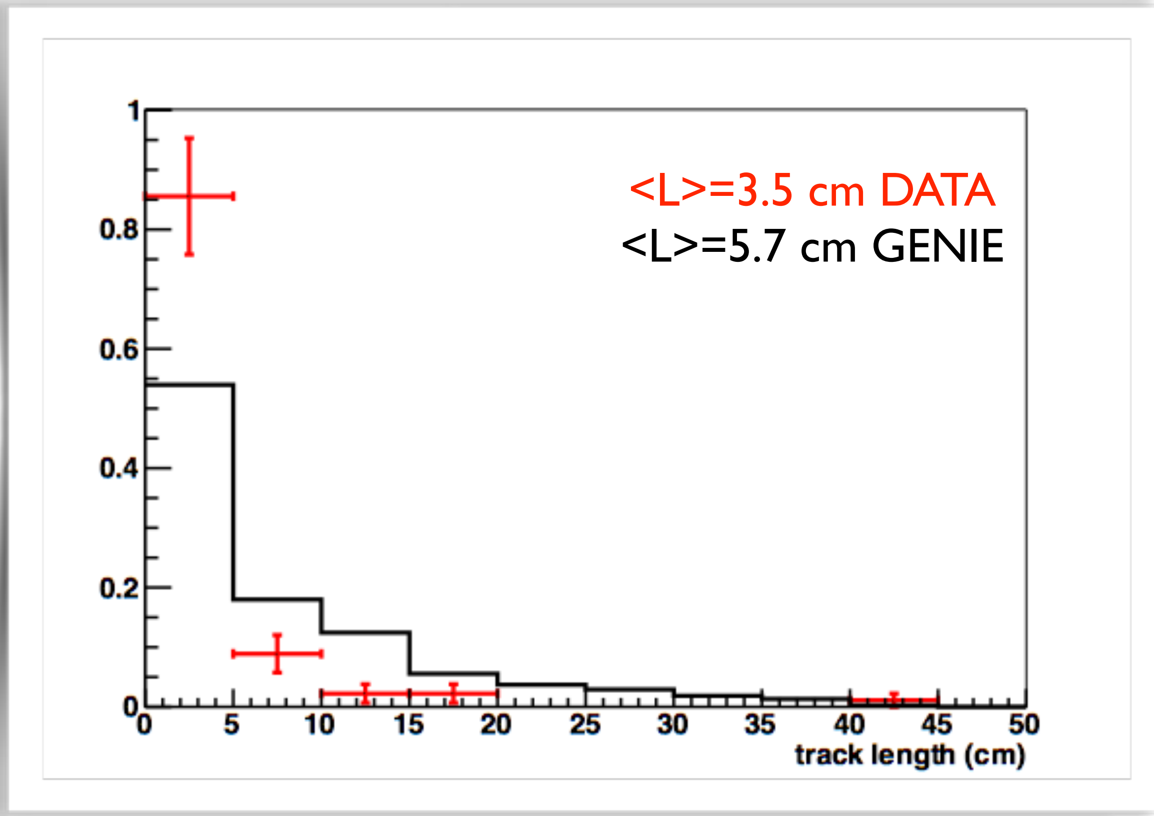
anti-neutrino mode run

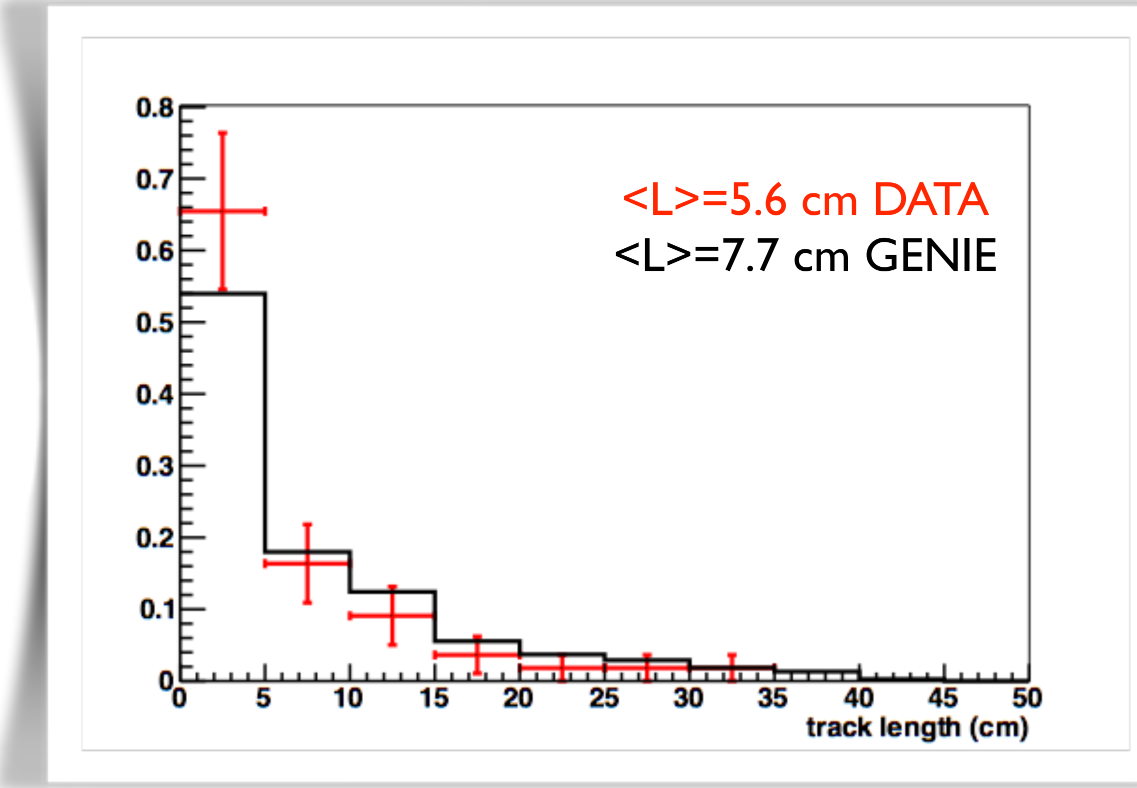
Multiplicity	% of non-CCQE GENIE ν events	% of non-CCQE GENIE $\bar{\nu}$ events
0p+μ	2.45	10.36
1p+μ	6.46	39.74
2p+μ	60.15	73.97
3p+μ	81.01	83.17
4p+μ	83.03	89.59
5p+μ	82.35	91.86
6p+μ	86.06	96.35
7p+μ	96.52	95.17
8p+μ	96.51	99.02
9p+μ	100	100
10p+μ	96.88	100

μ^+/μ^- 1p events PROTON KINEMATICS

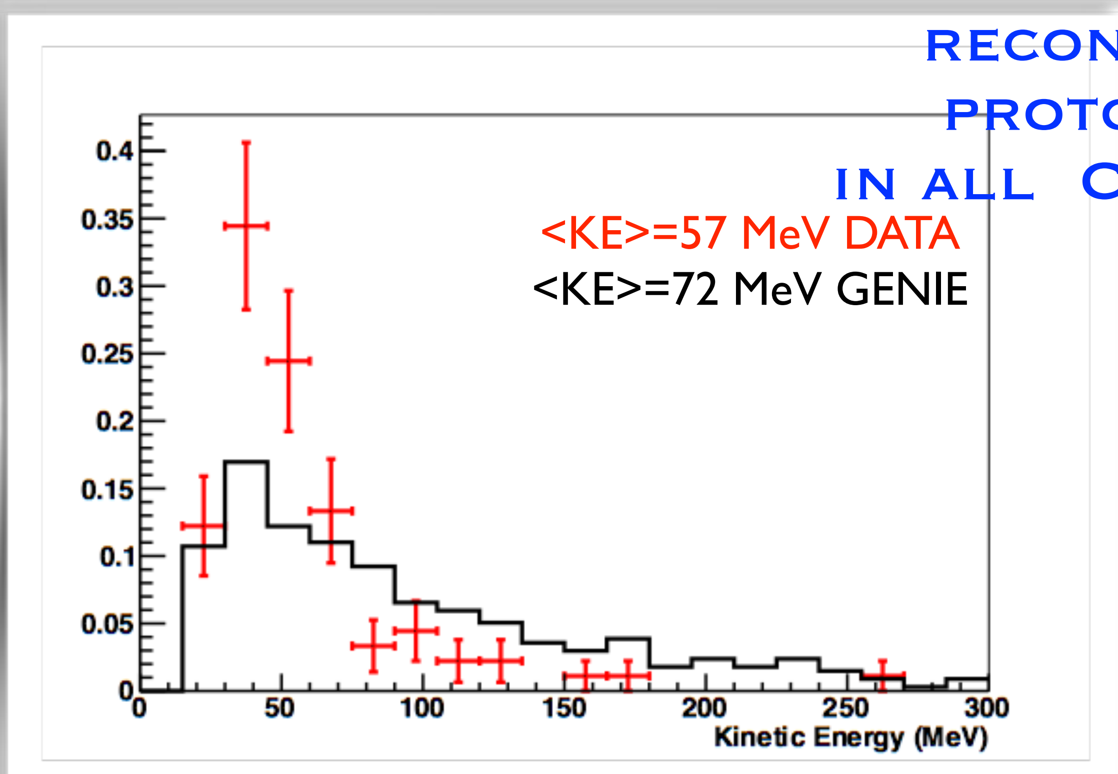
$\bar{\nu}_\mu$ - anti-neutrino mode run

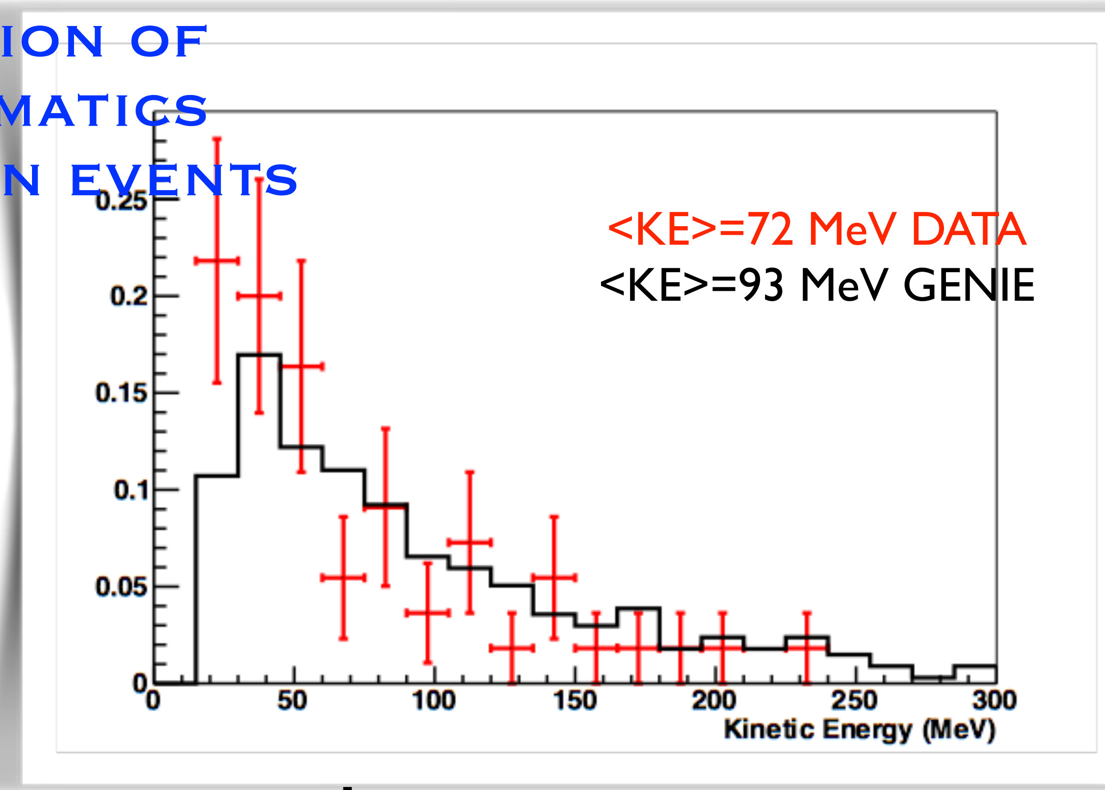
ν_μ - anti-neutrino mode run





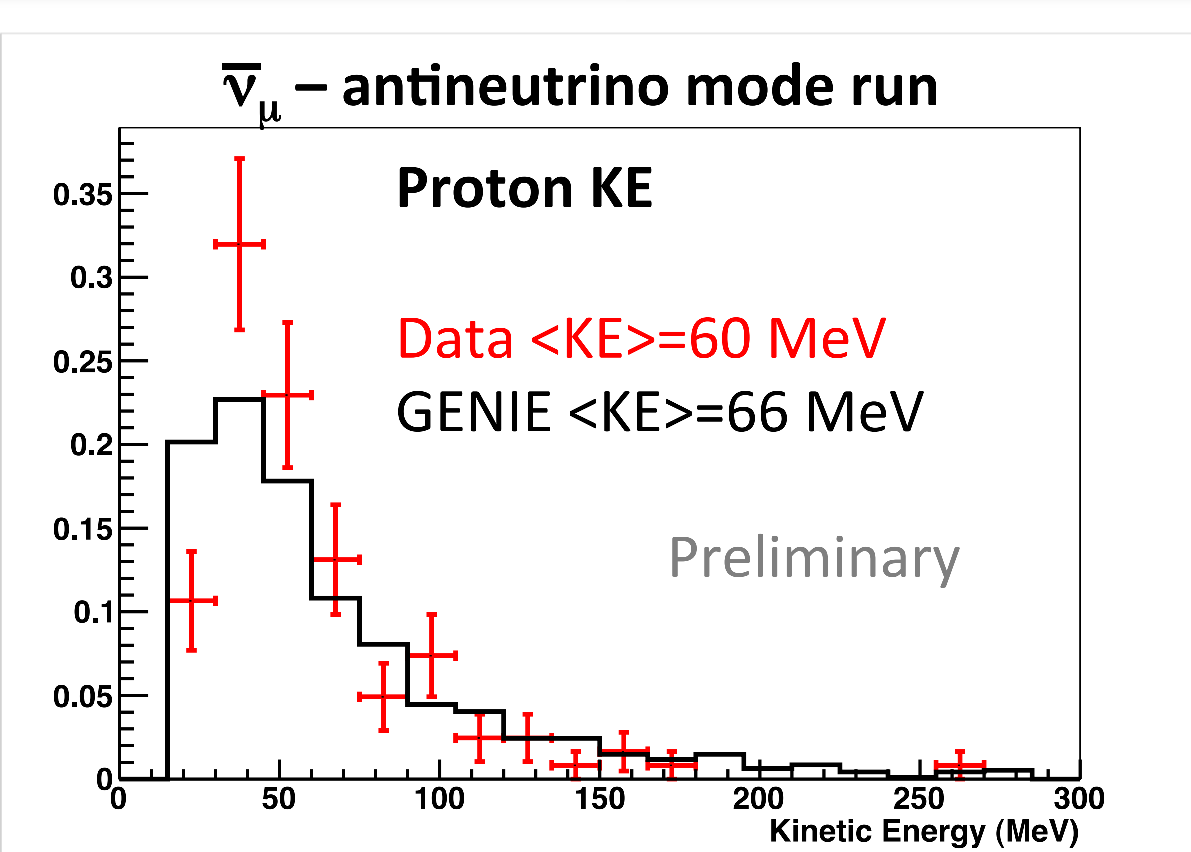
RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS

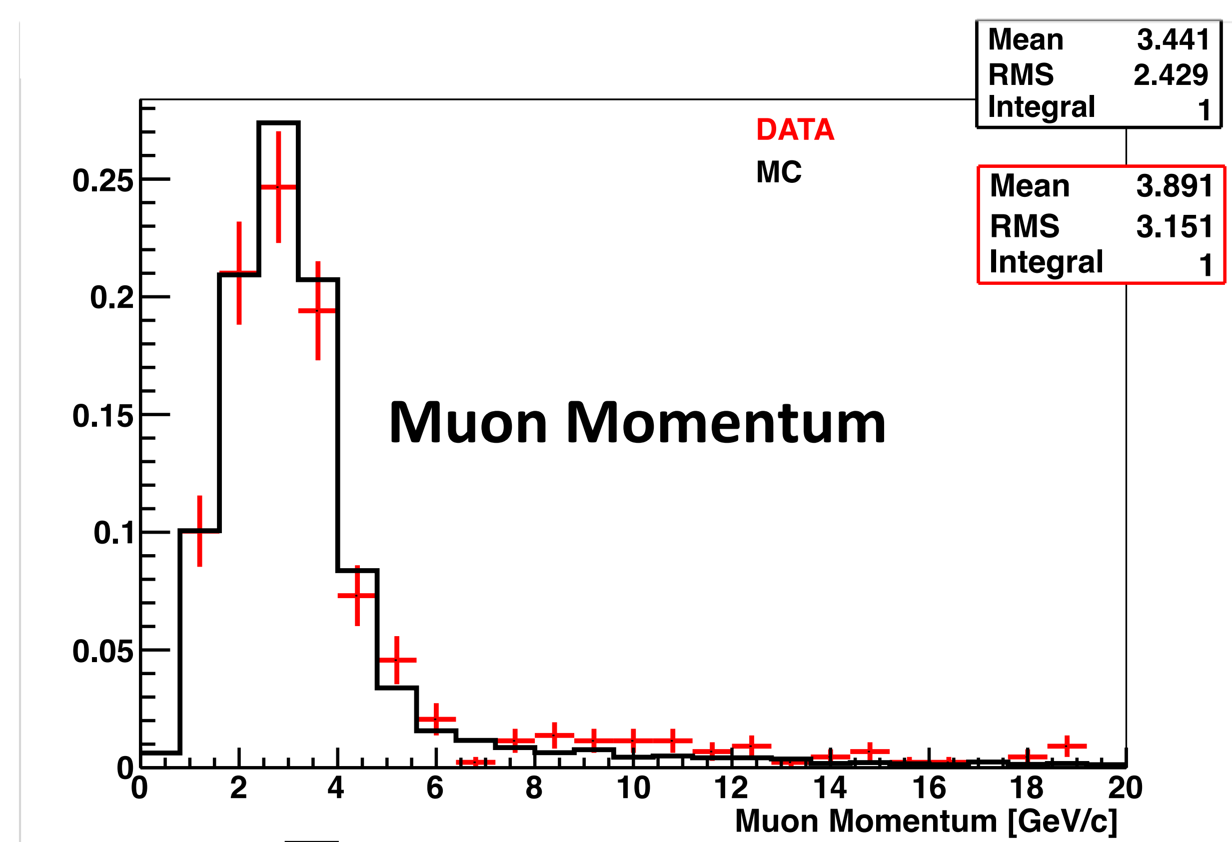


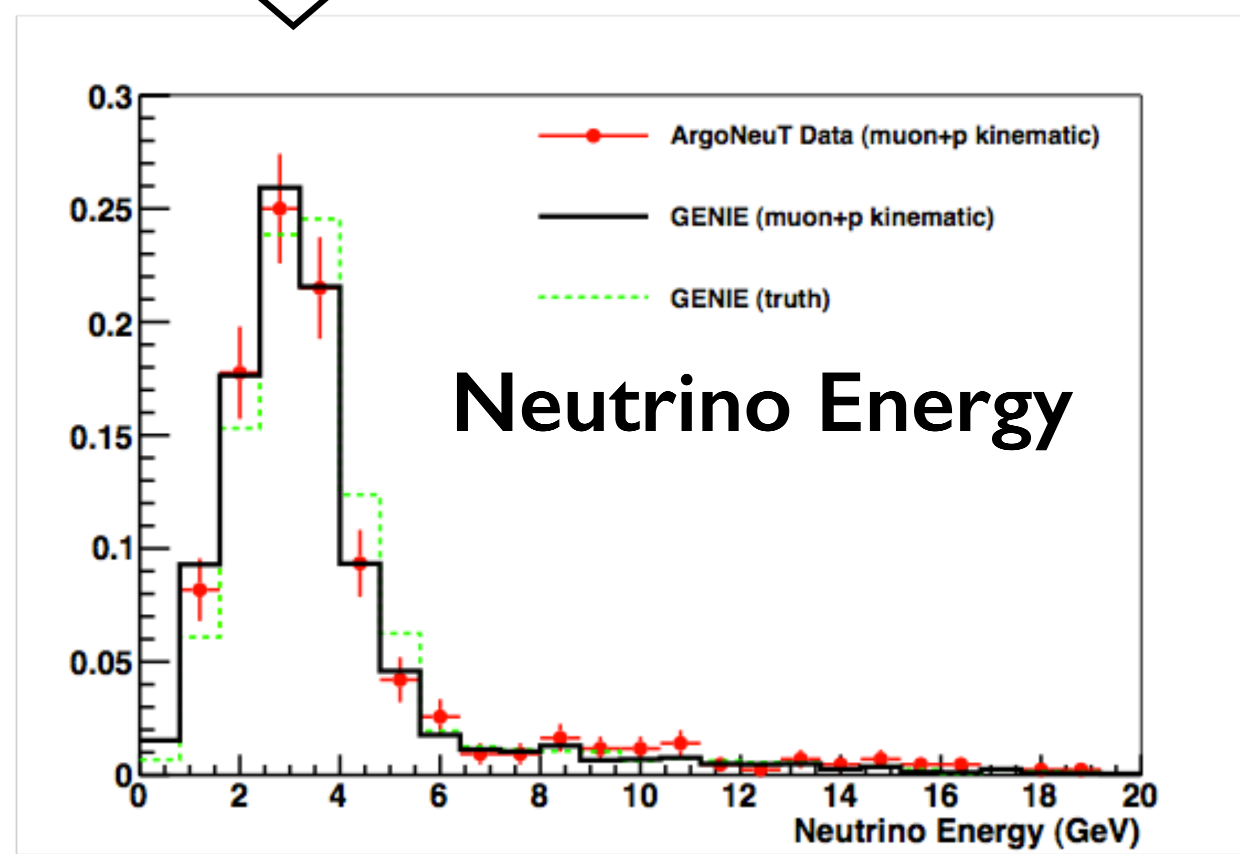


GENIE MC models more energetic protons

NEUTRINO ENERGY RECONSTRUCTION







Neutrino Energy from muon+proton reconstructed kinematics:

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

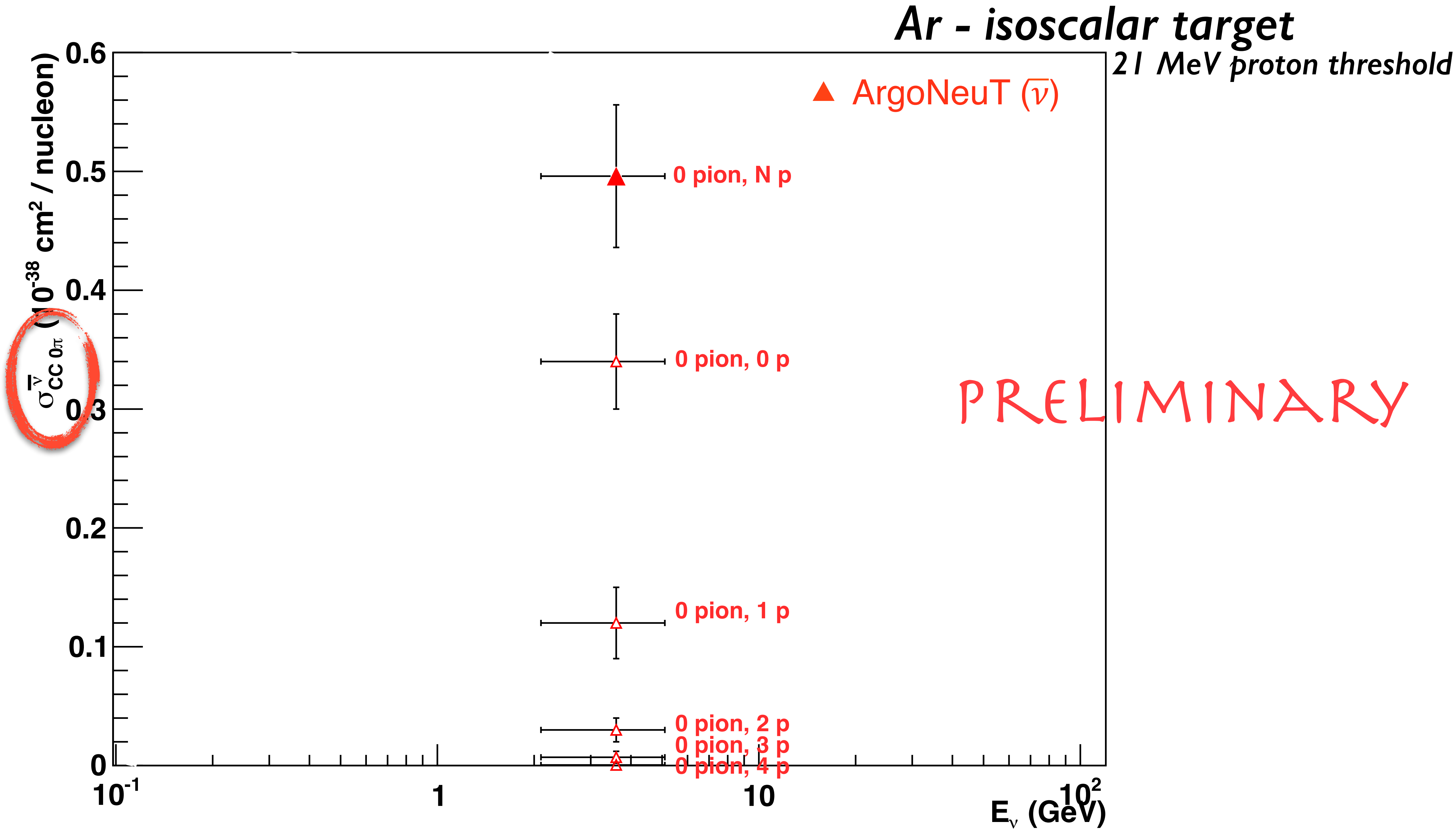
E_{miss}= energy expended to remove the nucleon(s) from the nucleus

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.)

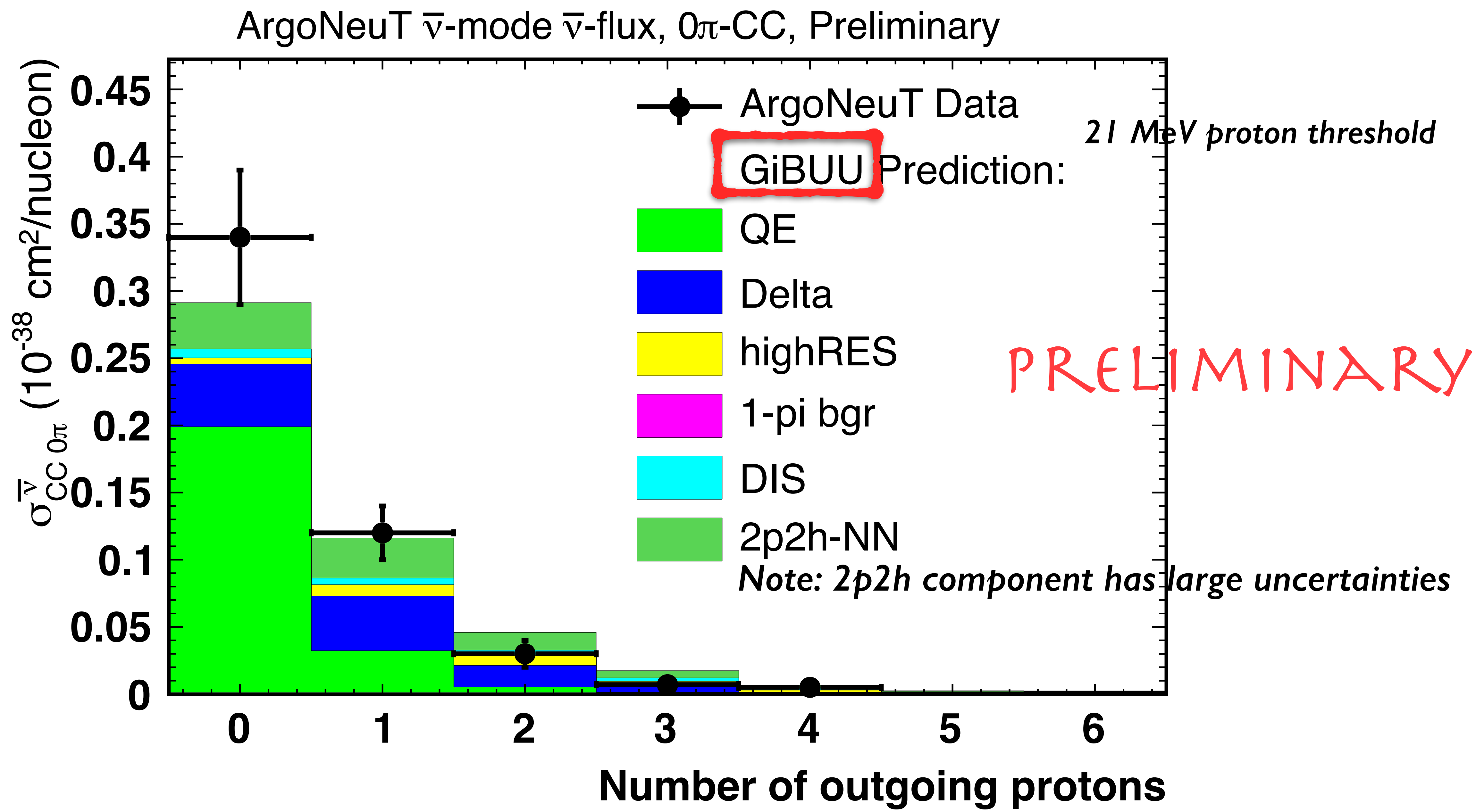
anti-ν_μ CC 0 pion cross section



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

at <E_ν>=3.6± 1.5 GeV

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



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

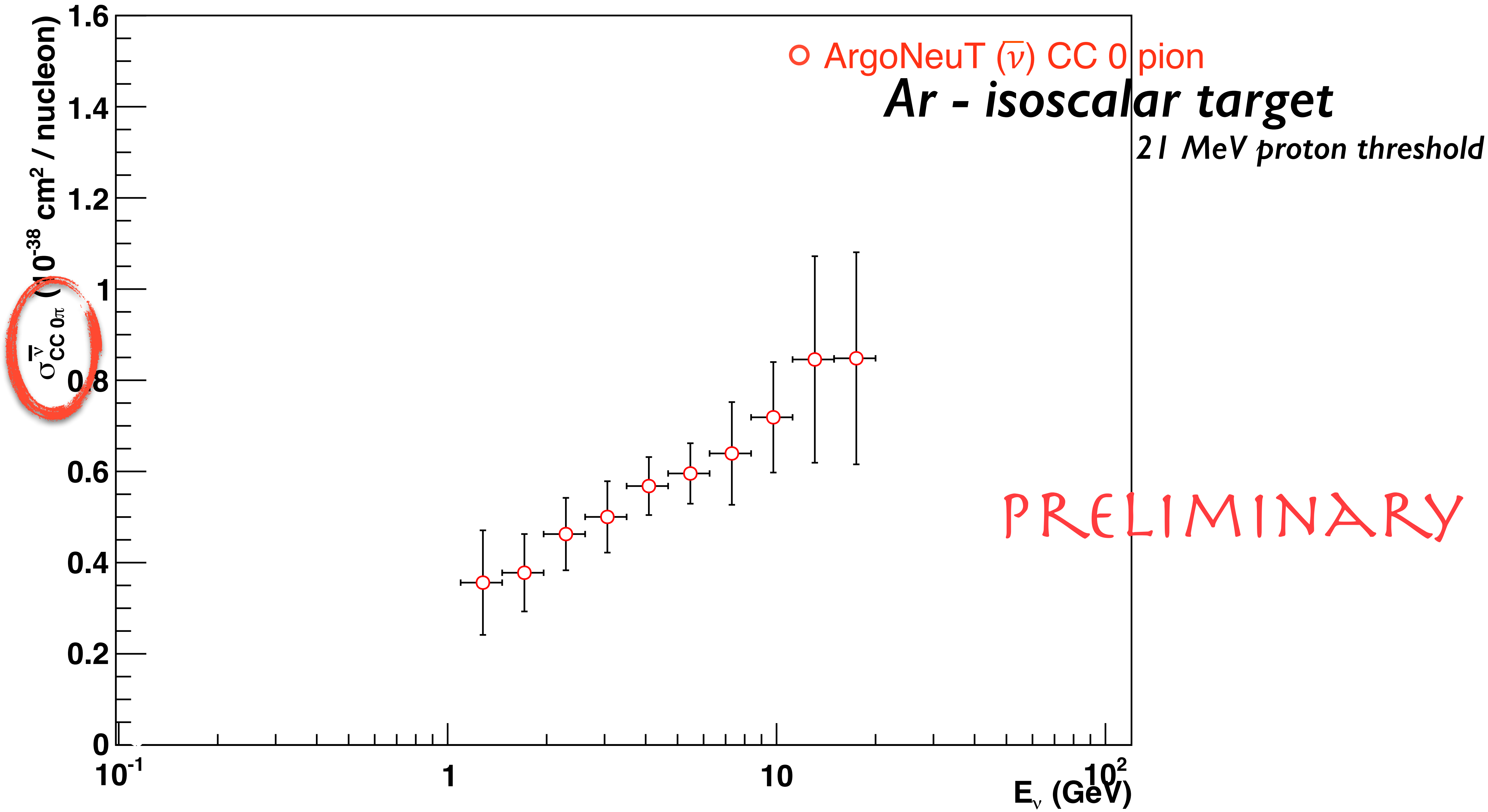
GiBUU MC

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

ArgoNeuT data

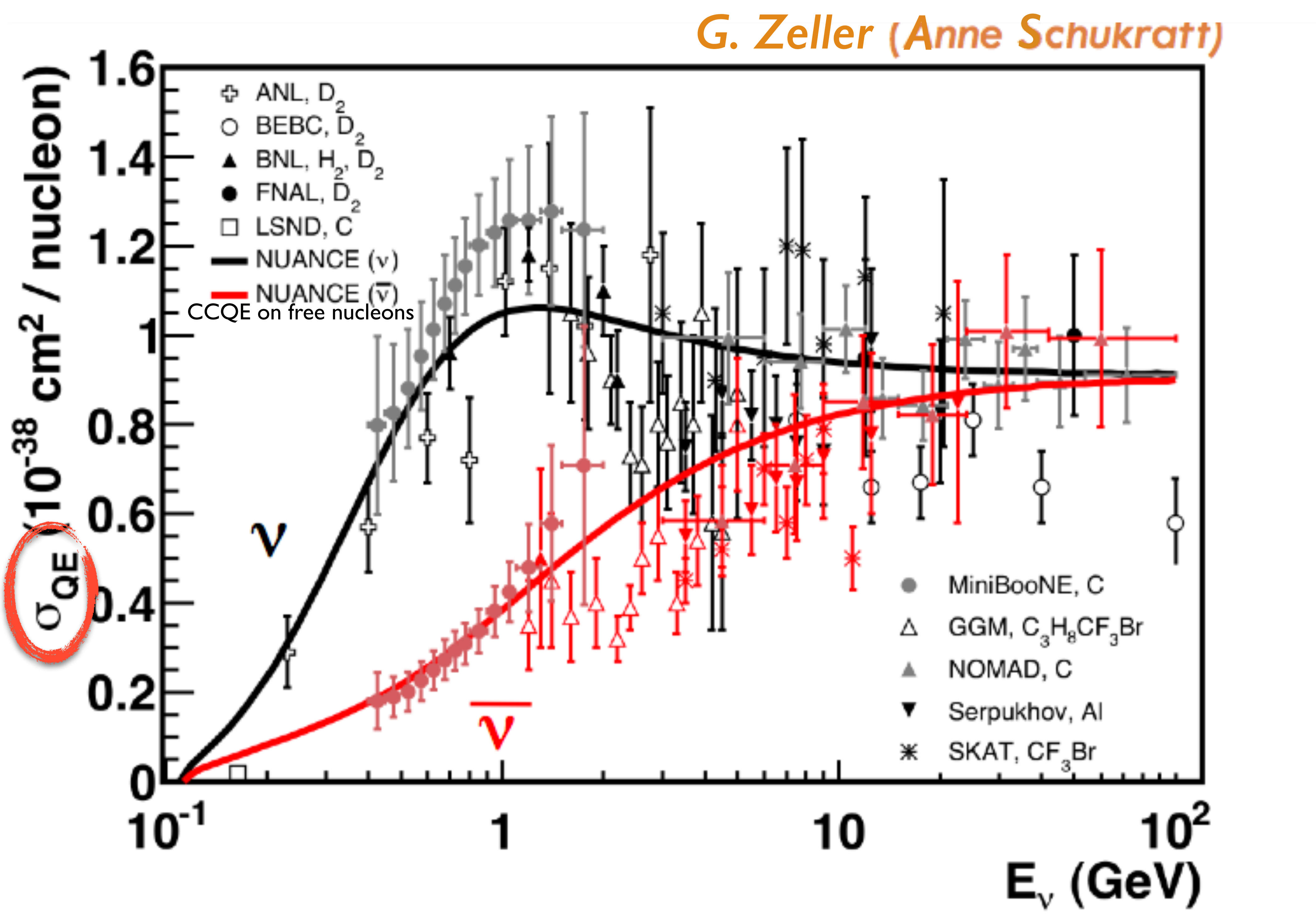
*ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

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



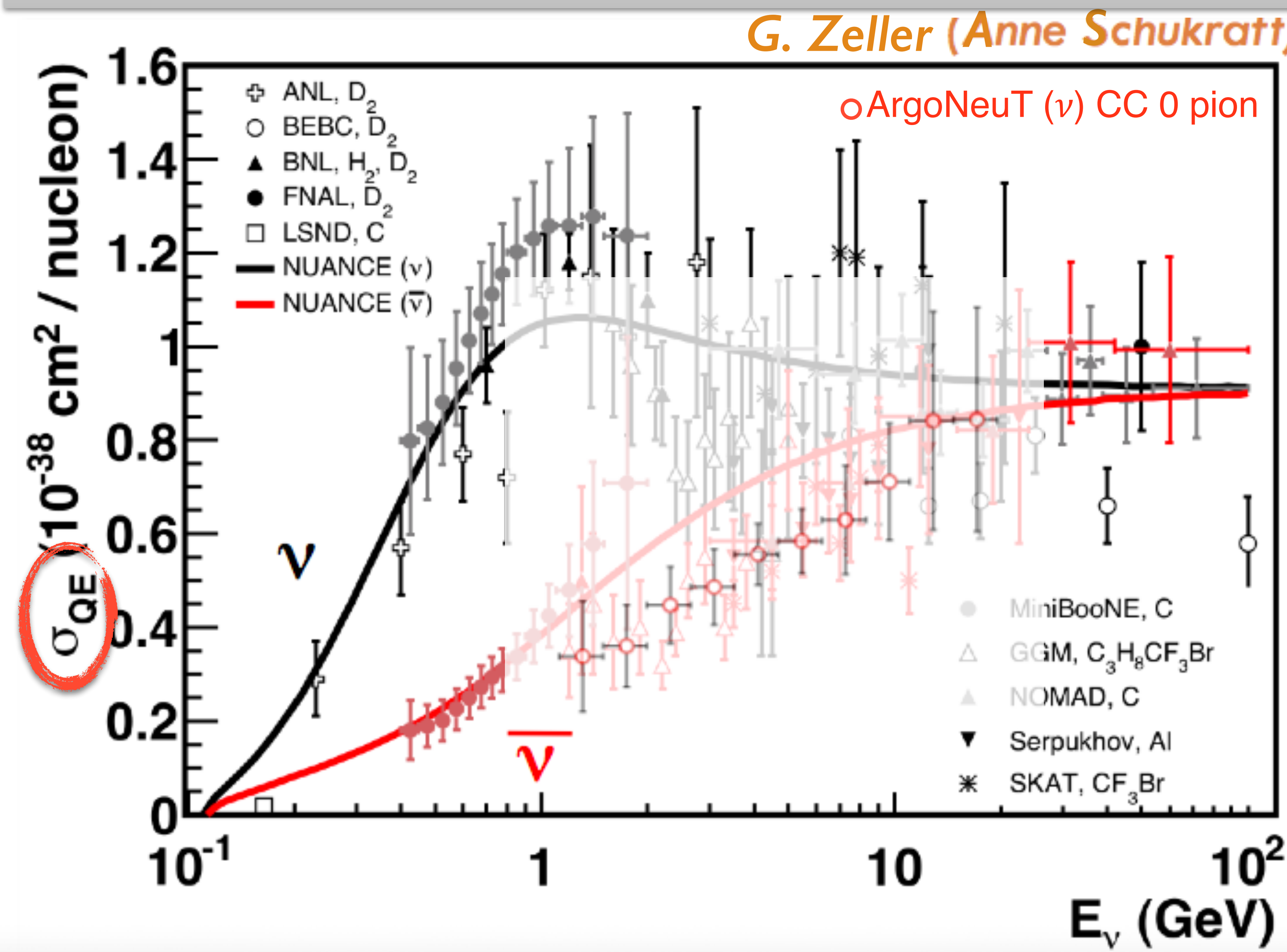
from *lepton AND proton reconstructed kinematics:* $E_\nu = (E_\mu + \sum T_{pi} + T_X + E_{miss})$

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)]



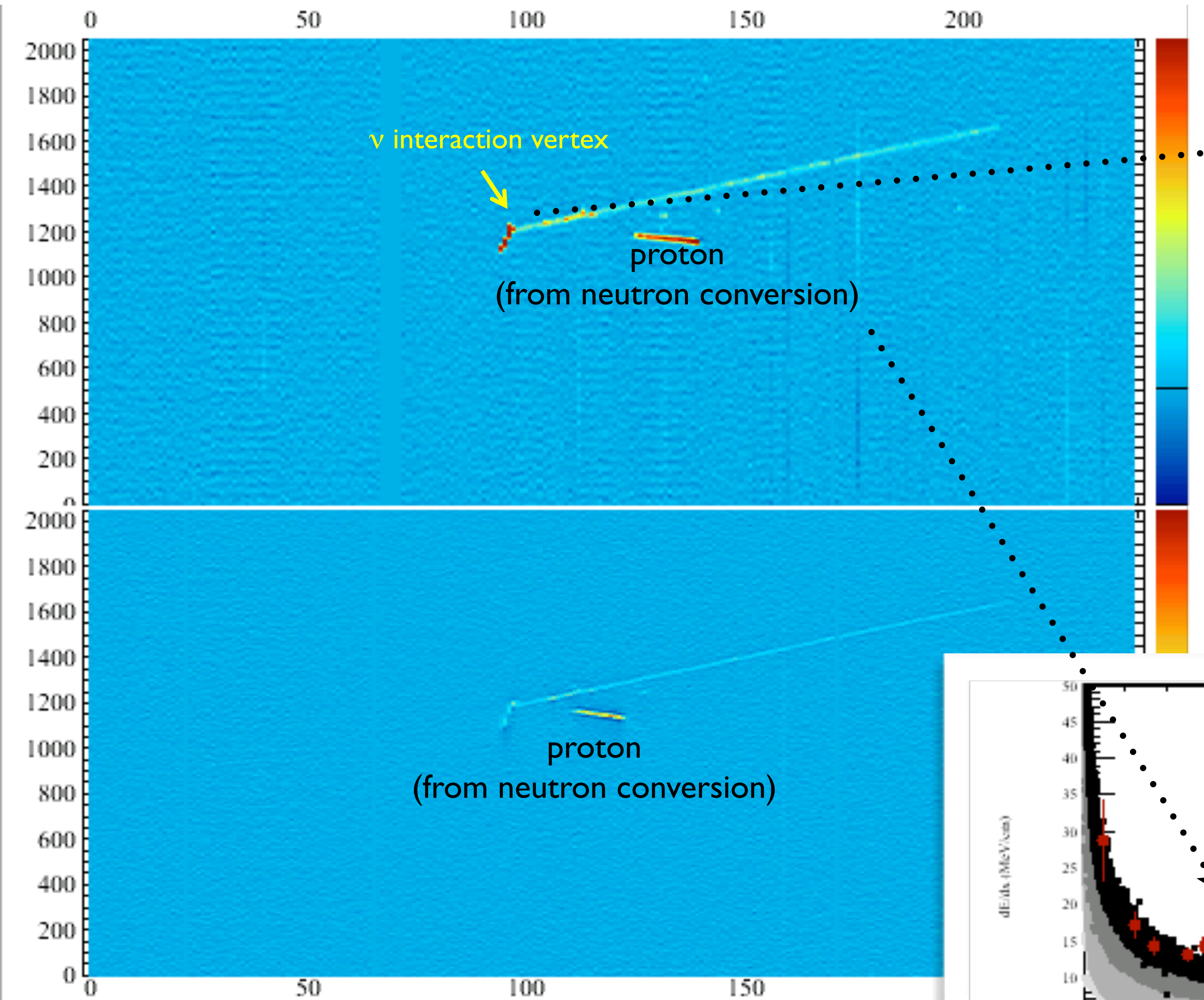
G. Zeller (Anne Schukratt)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
σ_QE (10^-38 cm² / nucleon)
ANL, D2
BEBC, D2
BNL, H2, D2
FNAL, D2
LSND, C
NUANCE (ν)
NUANCE (ν̄)
CCQE on free nucleons
ν
ν̄
MiniBooNE, C
GGM, C3H8CF3Br
NOMAD, C
Serpukhov, Al
SKAT, CF3Br
10^-1
1
10
10^2
Eν (GeV)

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

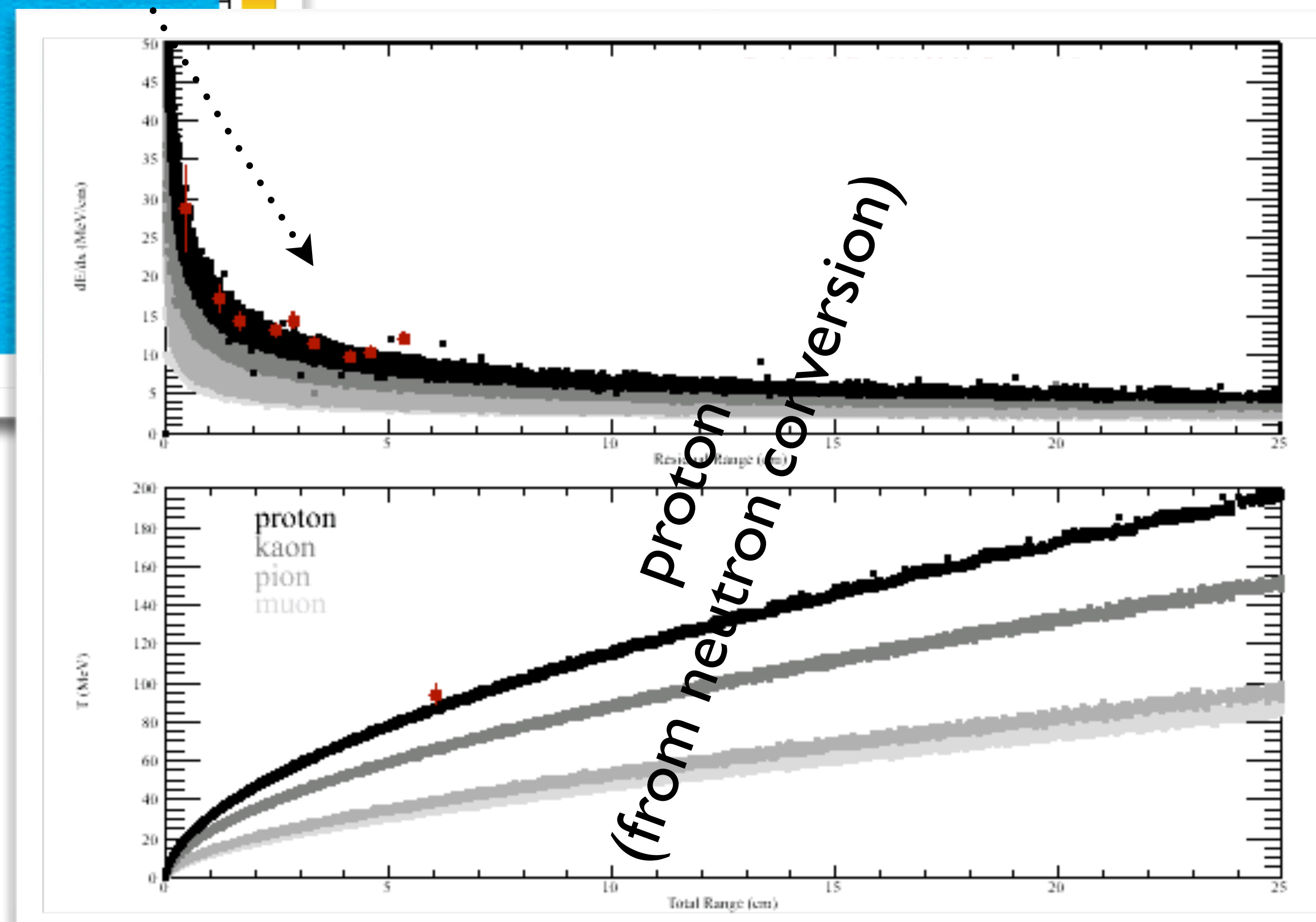


Note:
comparison of ArgoNeuT CC 0 pion data with CCQE experimental data and CCQE NUANCE predictions is reported just as guidance

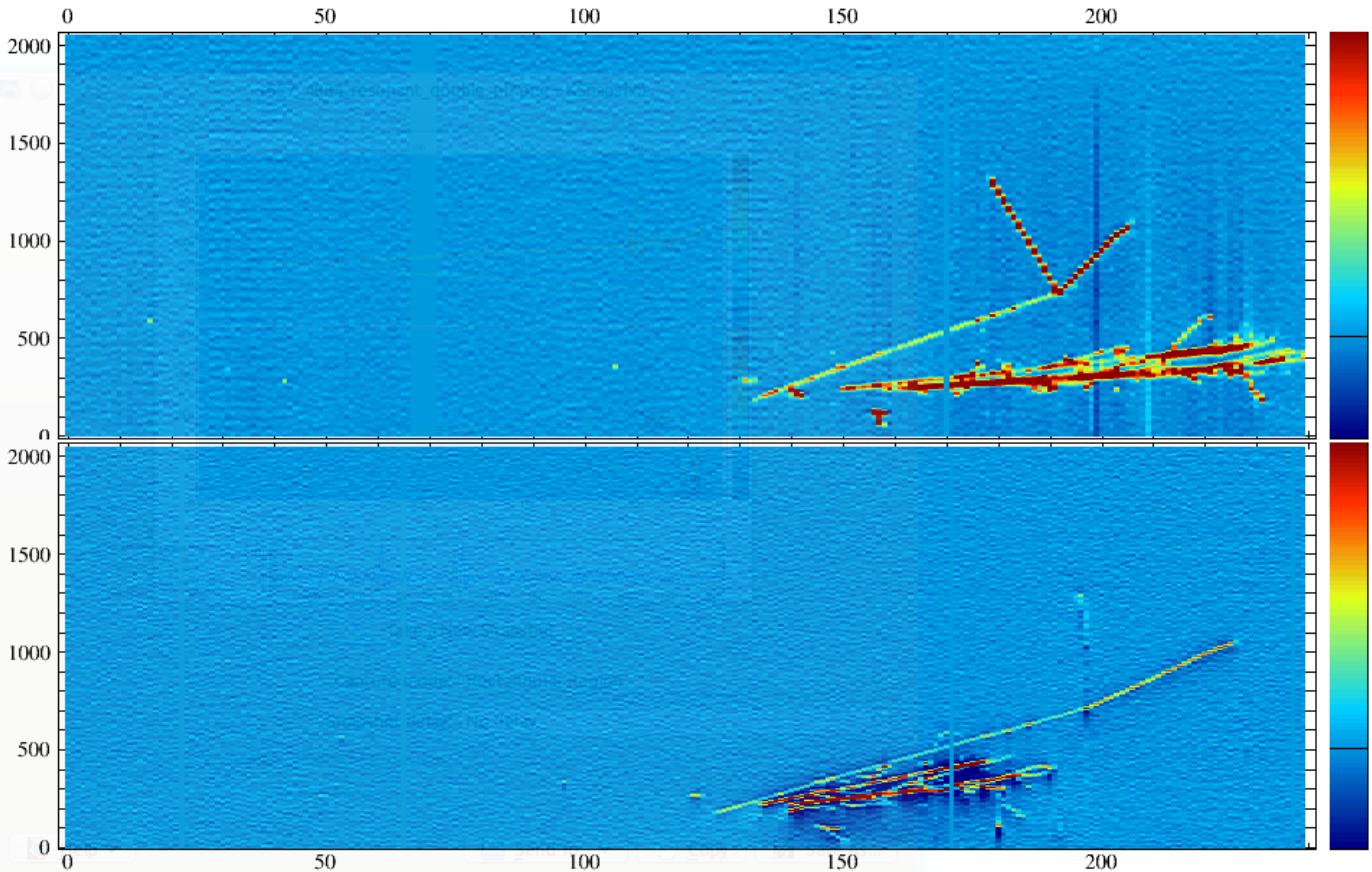
Reconstruction of proton from neutron conversion



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



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


0 50 100 150 200
2000 1500 1000 500 0
2000 1500 1000 500 0
0 50 100 150 200