LArTPC and the "new wave" in neutrino event reconstruction

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WHITEPAPERS COVERED IN THE TALK

- O. Palamara, K. Partyka, F. Cavanna, "***Neutrino-Nucleus Cross Sections: Development of Tools for Reconstruction of*** *Exclusive Topologies* ***in LAr TPC Experiments***"

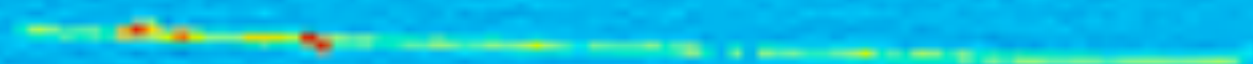
- C. Mauger et al., "***NuMI Running with the LANL LDRD Liquid Argon TPC***"

- C. Mauger et al., "***Neutron Running with a Liquid Argon TPC to Study Neutrino-Argon Final State Interactions and Cosmogenic Backgrounds Important for LBNE***"

- G. Sinnis et al., "***Measuring Neutrino Cross Sections on Argon for Supernova Neutrino Detection***"

OUTLINE

- ✓ LAr TPC TECHNIQUE
- ✓ LAR TPC ANALYSIS APPROACH
- ✓ IMPACT OF NUCLEAR EFFECTS



- ✓ HINTS FROM ARGONEUT DATA
- ✓ PERSPECTIVES FOR FUTURE EXPERIMENTS

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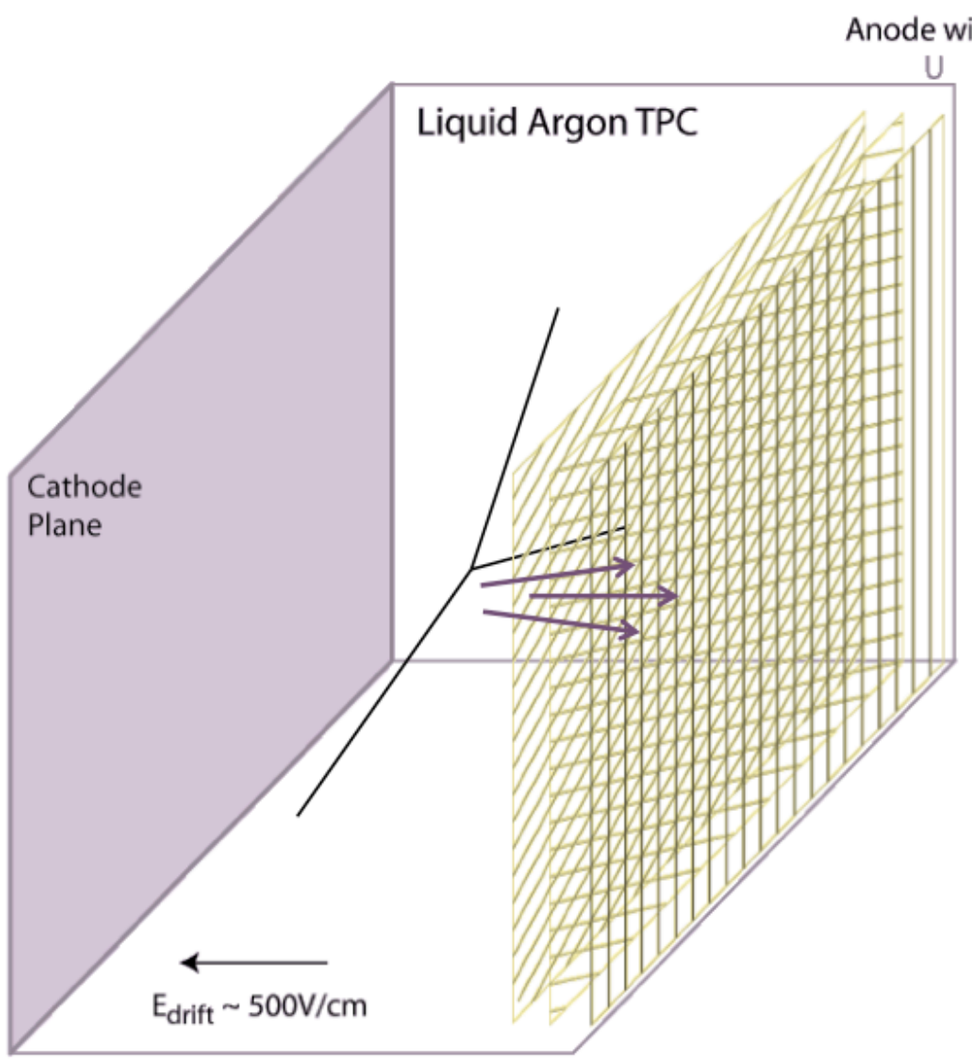
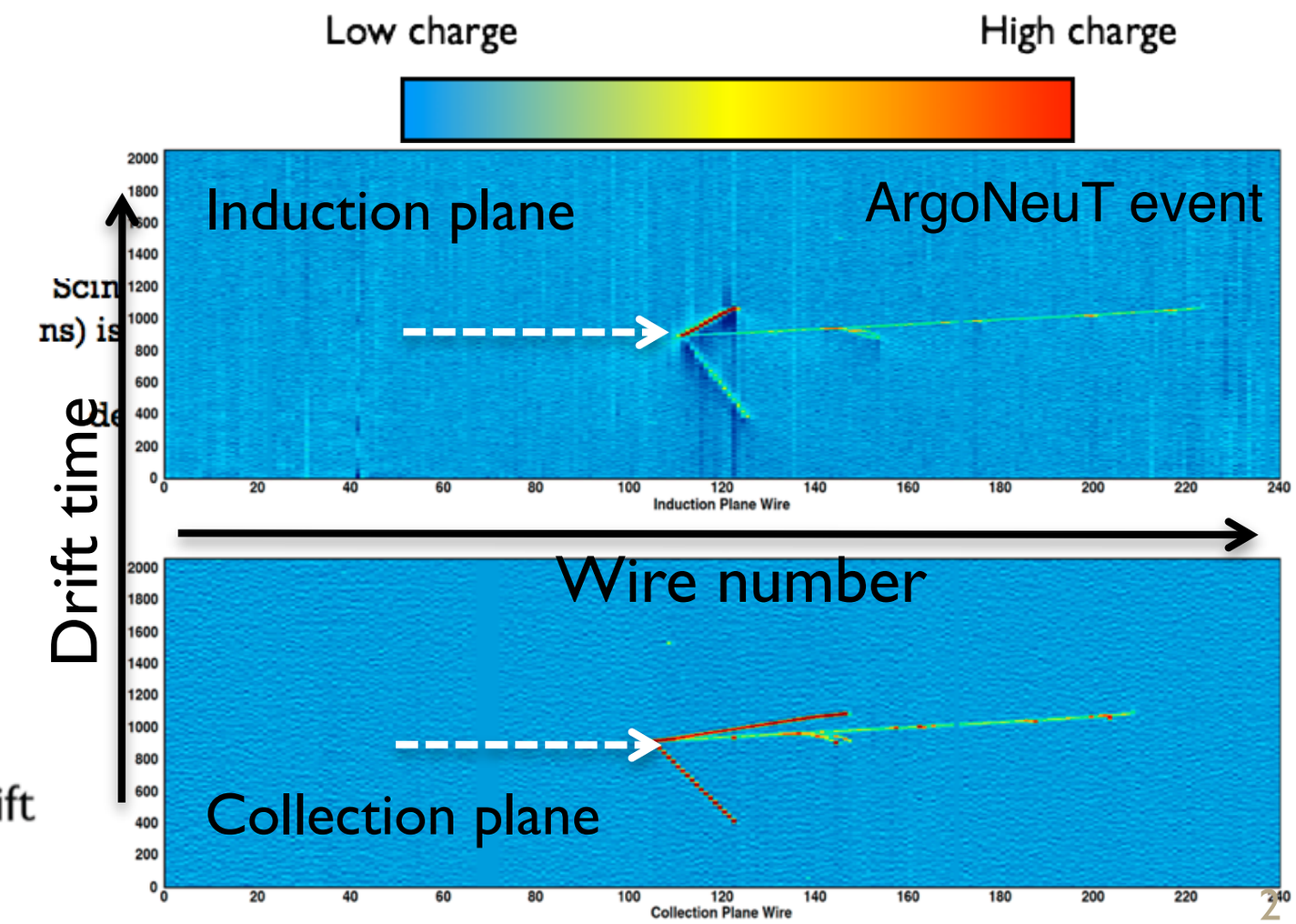
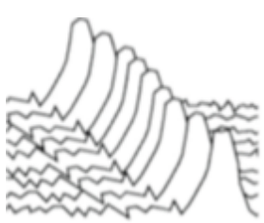
THE LAR TPC CONCEPT



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

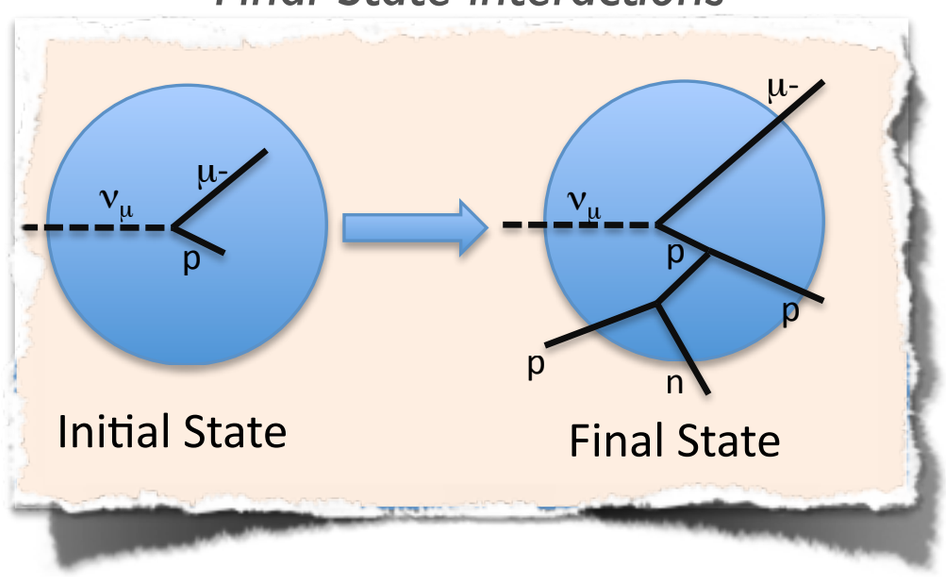
induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

Whitepaper: "*Neutrino-Nucleus Cross Sections: Development of Tools for Reconstruction of Exclusive Topologies in LAr TPC Experiments*"
O.Palamara, K. Partyka, F. Cavanna

- In the GeV energy range the most important neutrino-nucleus interaction channel is the CC quasi elastic ***(QE)*** scattering, historically referring to the emission of ***a charged lepton and a single nucleon***. For this reason, a lot of effort has been devoted to measurements of neutrino- and antineutrino-nucleus "QE like" cross-sections in a broad kinematical domain.

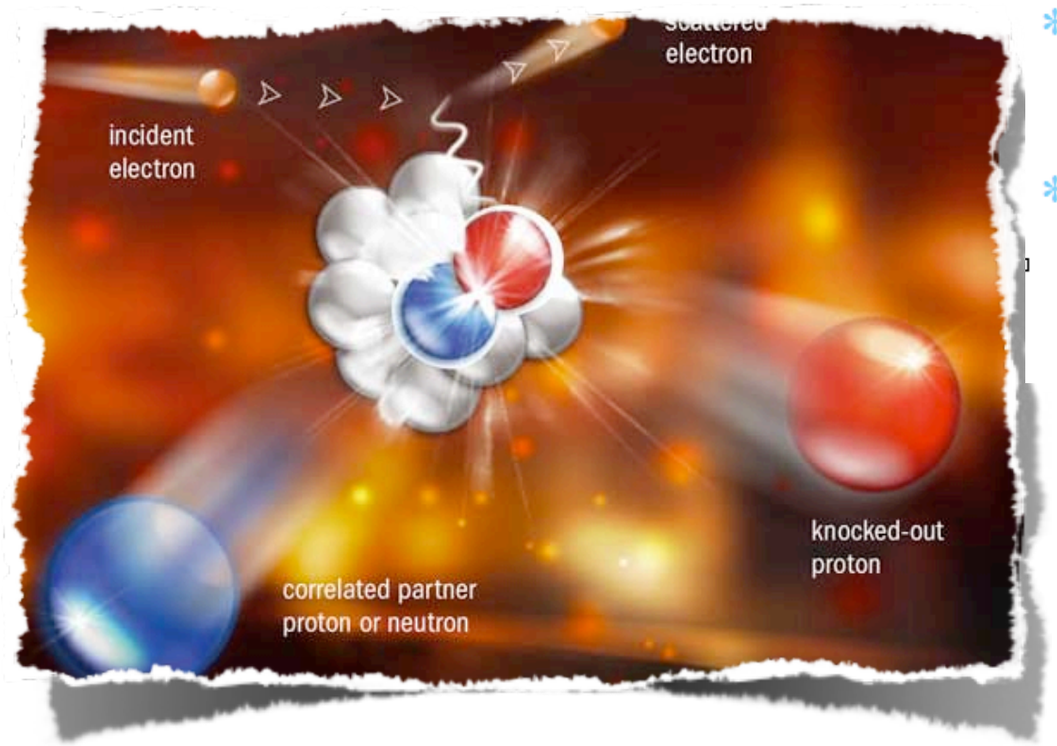
- ***Nuclear effects***, however, play a key role in neutrino-nucleus interactions in nuclear targets. Due to ***intra-nuclear re-scattering (FSI)***

Final State interactions

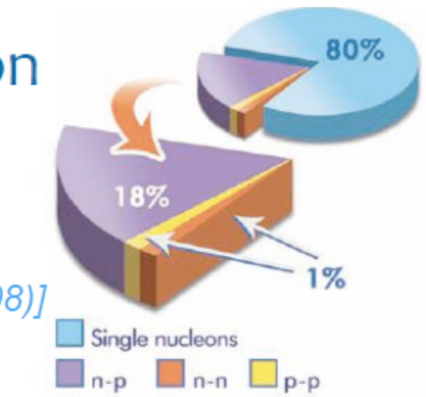


and possible effects of ***correlation between target nucleons***, a genuine QE interaction can often be accompanied by the ***ejection of additional nucleons***, emission of many ***de-excitation*** γ's and sometimes by soft pions in the Final State (after hadronization).

Multi-nucleon correlations

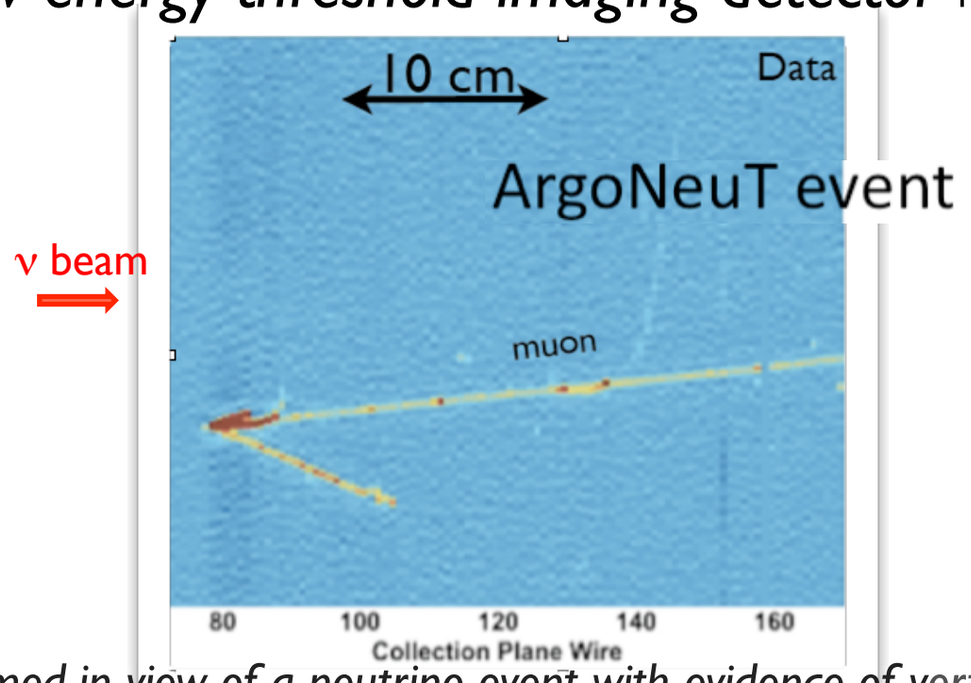


* Direct evidence for multi-nucleon correlations exists
* ^{12}C quasi-elastic scattering at Jlab final state studies see multiple nucleons ~20% of the time, mostly pn



*[R. Subedi et al., Science **320**, 1476 (2008)]*

- Neutrino interaction channel definitions 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.



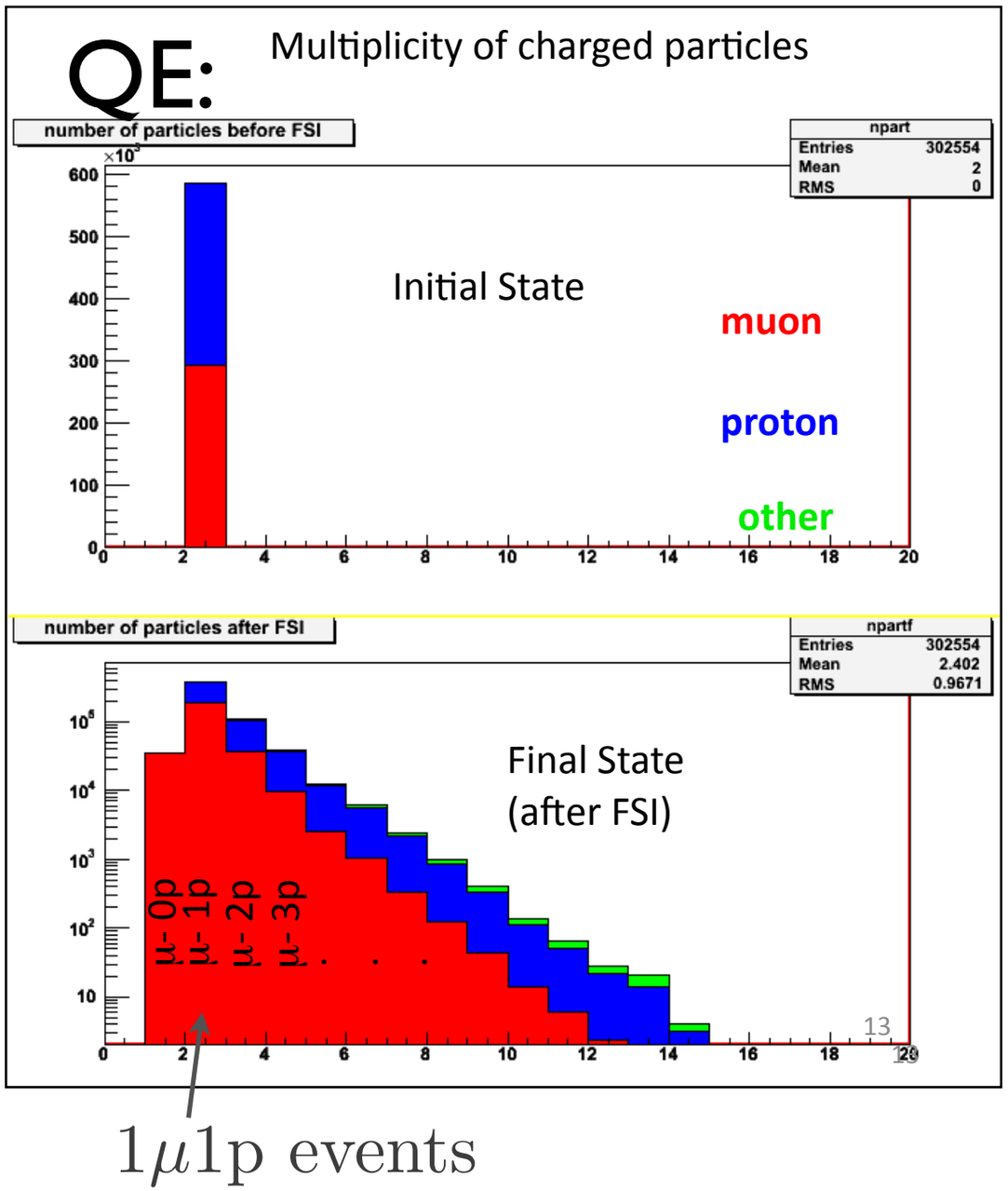
A zoomed-in view of a neutrino event with evidence of vertex activity

Additional difficulty is the separation of the effects of FSI from initial state correlations. Can we disentangle them?

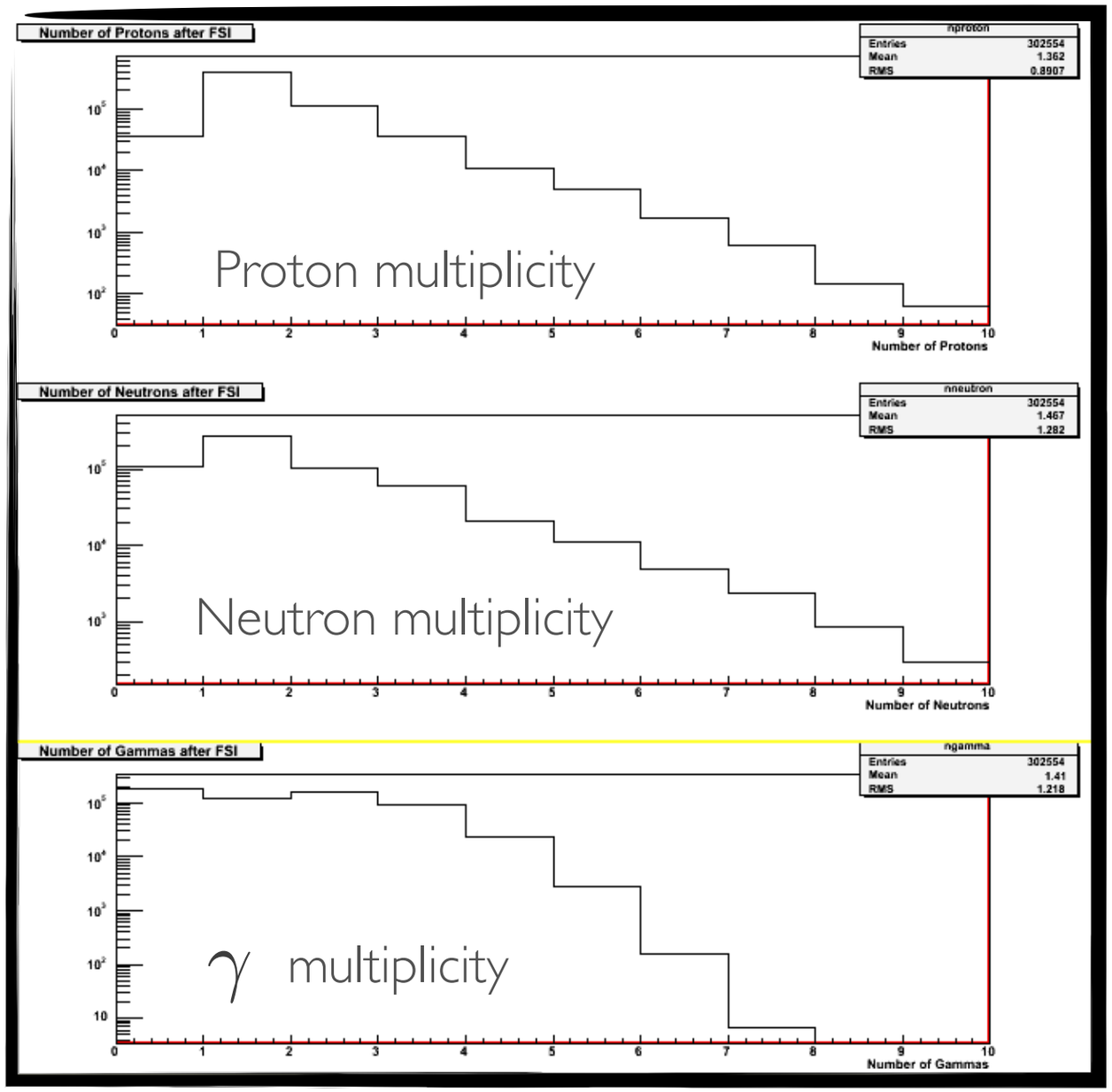
MC: EFFECTS OF FSI

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

NuMI beam LE spectrum - neutrino mode



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



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

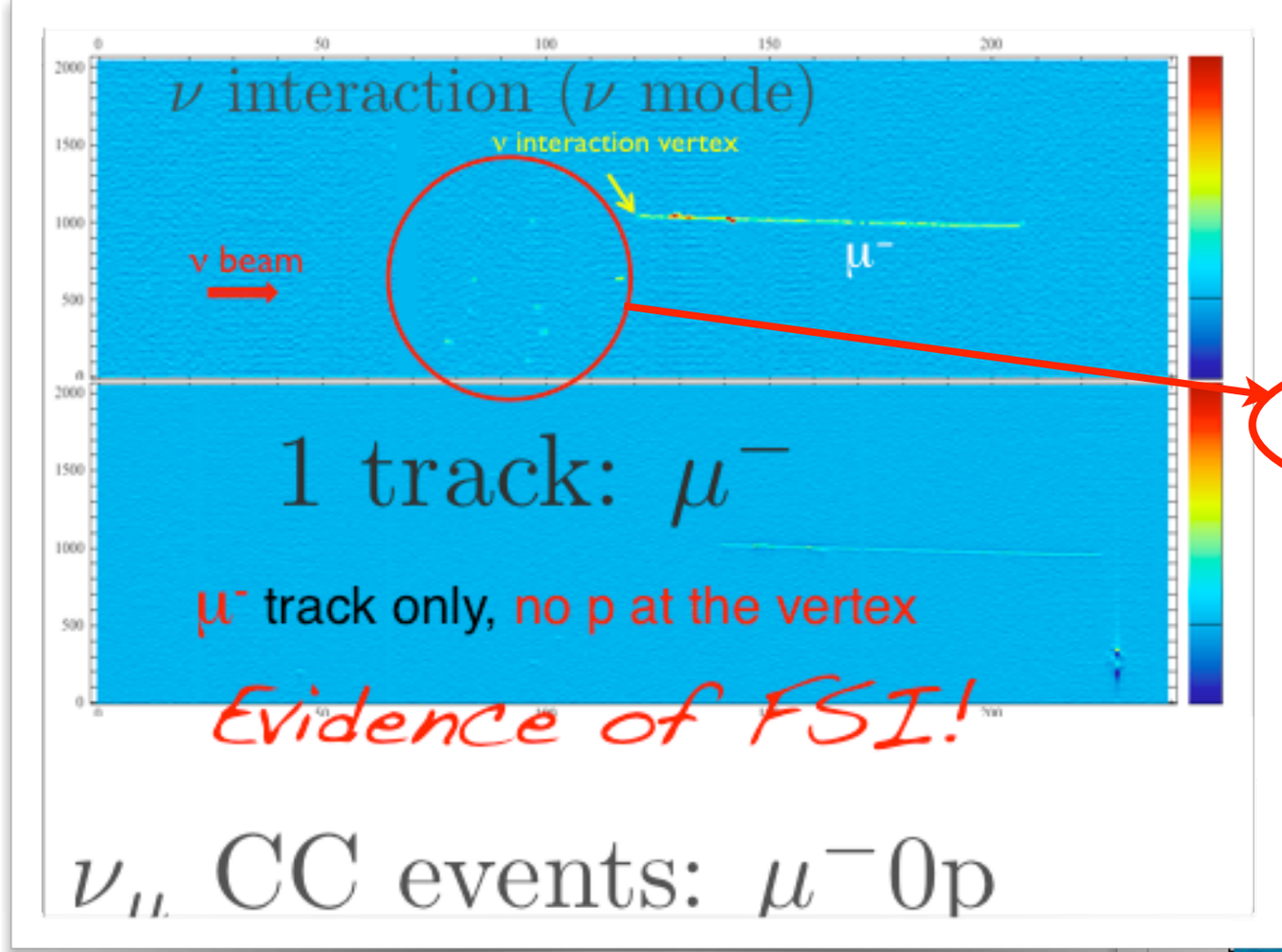
THE "NEW WAVE" IN NEUTRINO EVENT RECONSTRUCTION

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

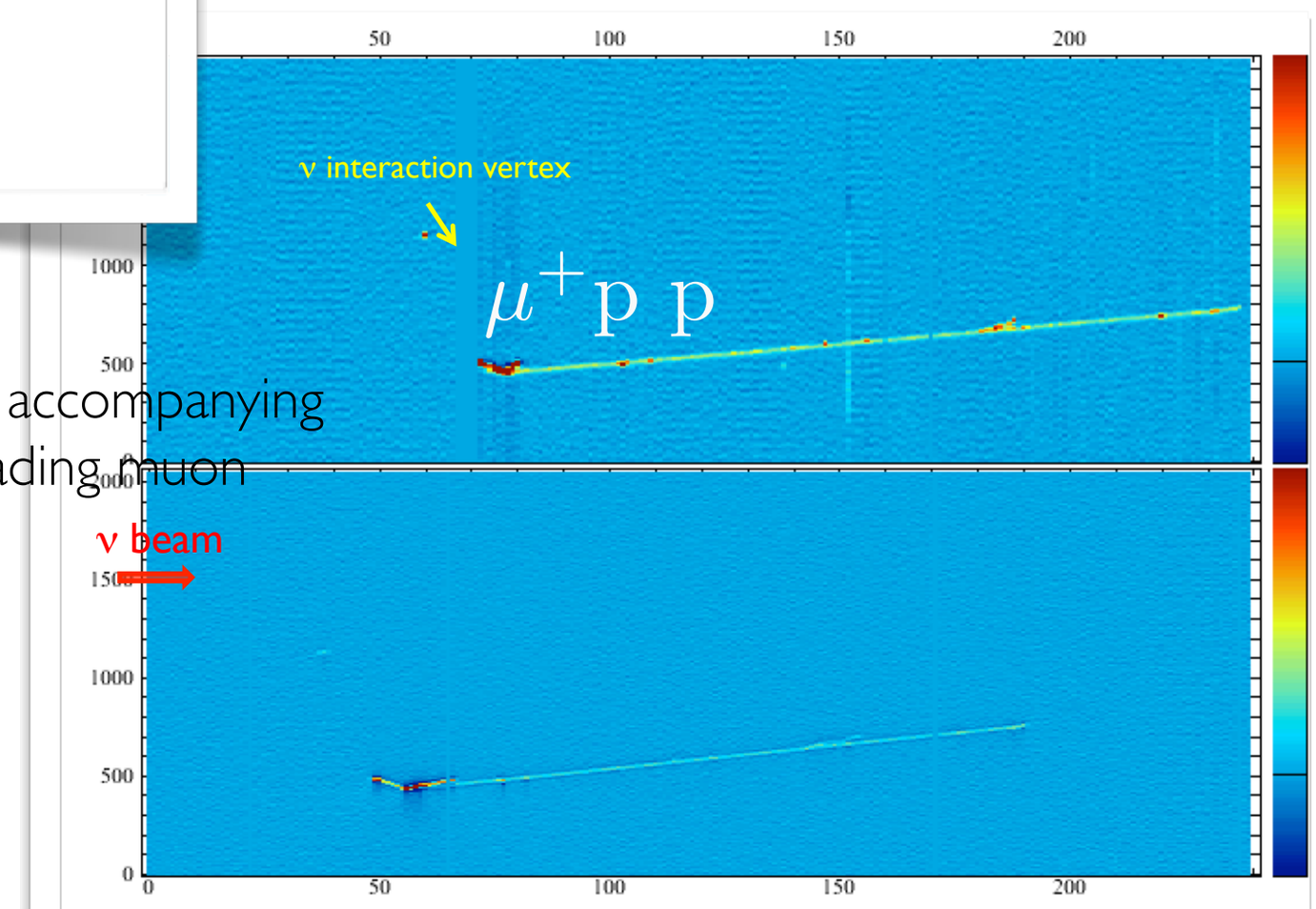
INSTEAD OF MC BASED CLASSIFICATION OF THE EVENTS IN THE INTERACTION CHANNELS *(QE, RES, DIS etc)*, *CC* NEUTRINO EVENTS IN *LAr* CAN BE CLASSIFIED IN TERMS OF **FINAL STATE TOPOLOGY** BASED ON PARTICLE MULTIPLICITY:

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

- In imaging LAr-TPC detectors these exclusive topologies can be fully reconstructed, measurements of ***proton multiplicity*** at the neutrino interaction vertex and ***reconstruction of proton kinematics*** in events with different proton multiplicity can be performed with very ***low proton energy threshold***, ultimately allowing for most precise ***reconstruction of the incoming neutrino energy*** from ***lepton AND proton kinematics.***



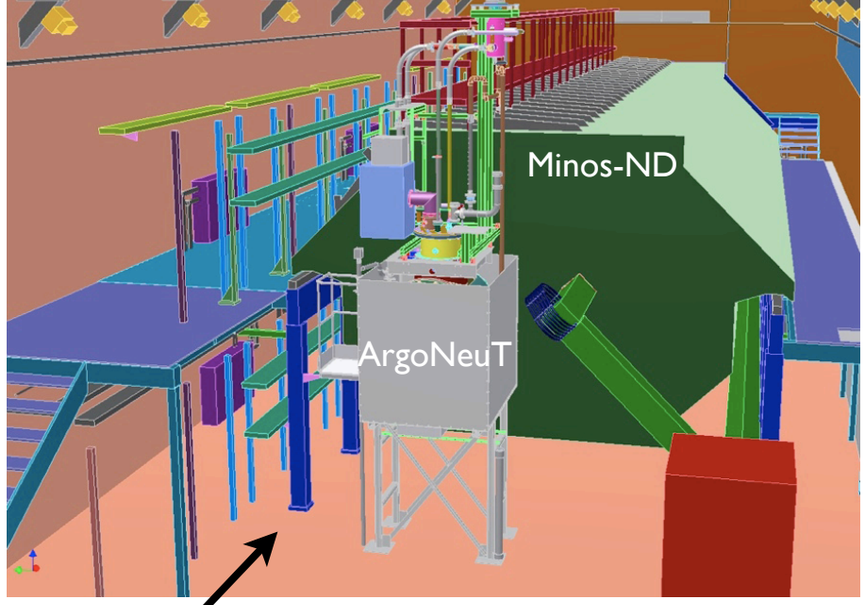
Activity around the vertex
e's from nuclear de-excitation γ conversion



Multi-p accompanying the leading muon

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

ArgoNeuT

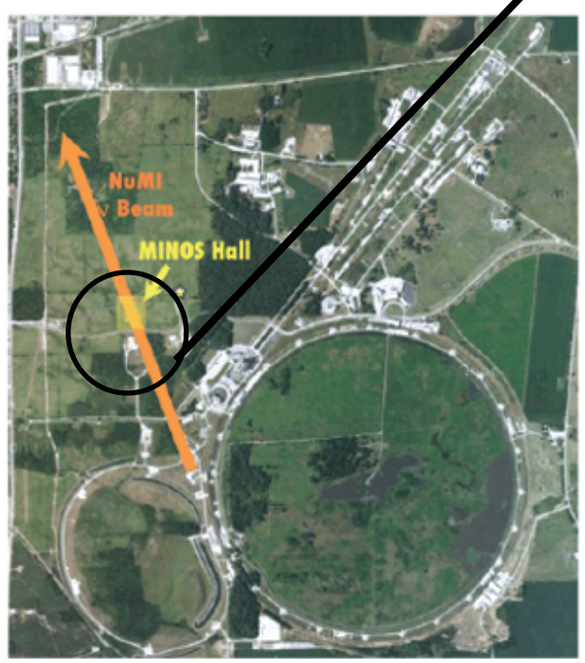


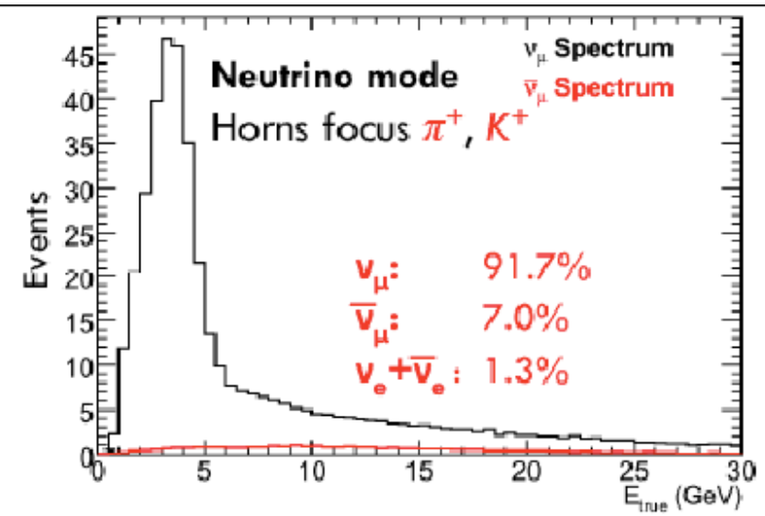
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

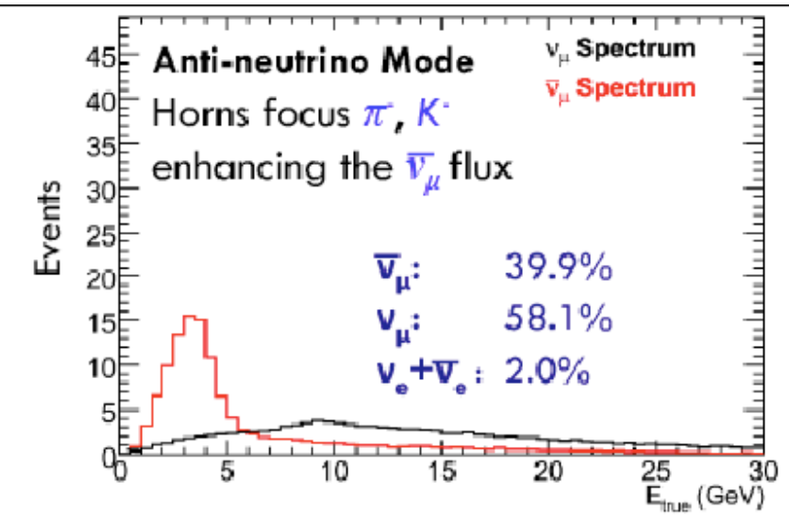
NuMI LE beam
ν–mode (2 weeks): 8.5×10^{18} POT
$\bar{\nu}$–mode (6 months): 1.20×10^{20} POT

175 l active volume

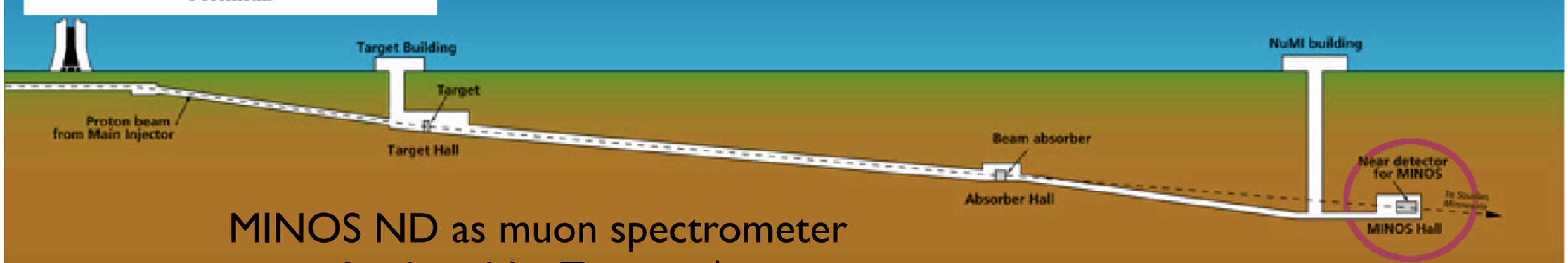
~10000 CC events collected







NuMI LE beam

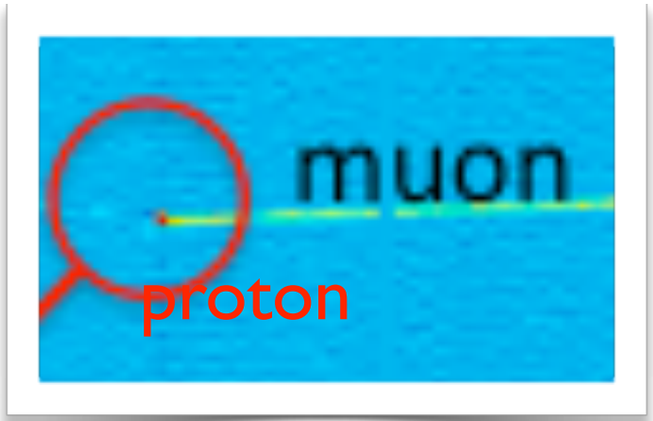


MINOS ND as muon spectrometer for ArgoNeuT events*
(energy reconstruction and charge identification (q) of exiting muons)

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

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

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



- Preliminary results from the analysis of 0 pion CC events few GeV energy region (both neutrino and anti-neutrino mode runs, DATA-GENIE MC comparisons), have been recently presented at the NUINT 2012 workshop [1], [2] and Aspen 2013 conference [3]:
  - Multi-p accompanying the leading muon and the presence of vertex activity are clearly visible (and measured) in the ArgoNeuT events.
  - Ratios among rates of different exclusive topologies provide indications of the size of nuclear effects.

New: hints on nuclear effects from reconstruction of proton kinematics

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

LAr TPC ANALYSIS APPROACH

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

Particle Identification with LArTPC

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

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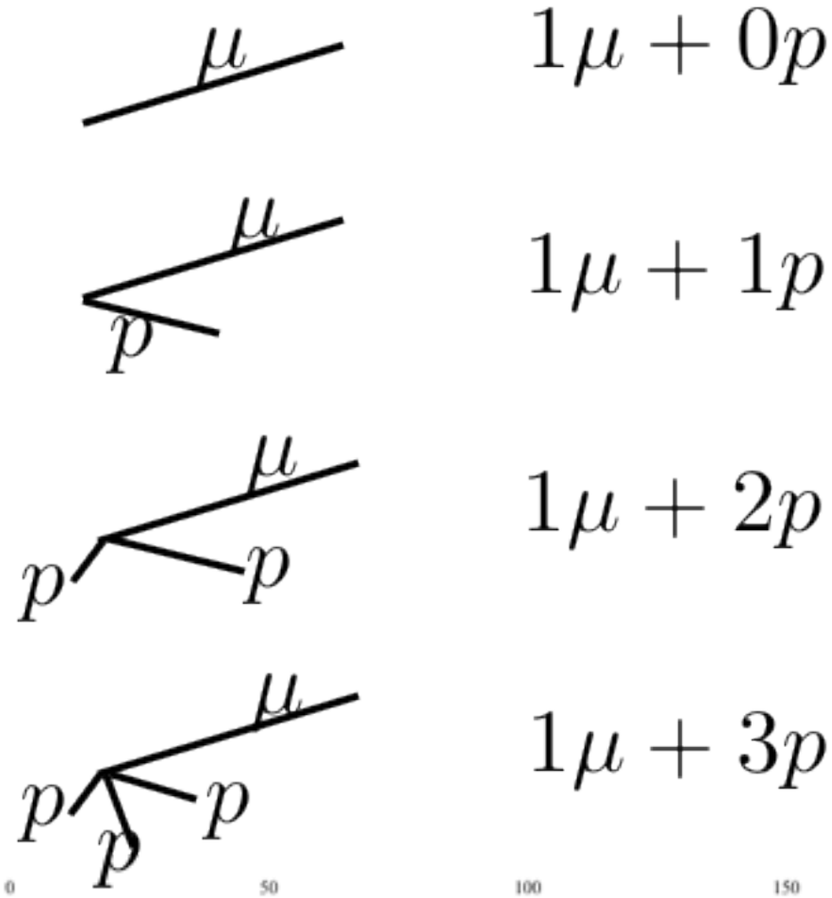
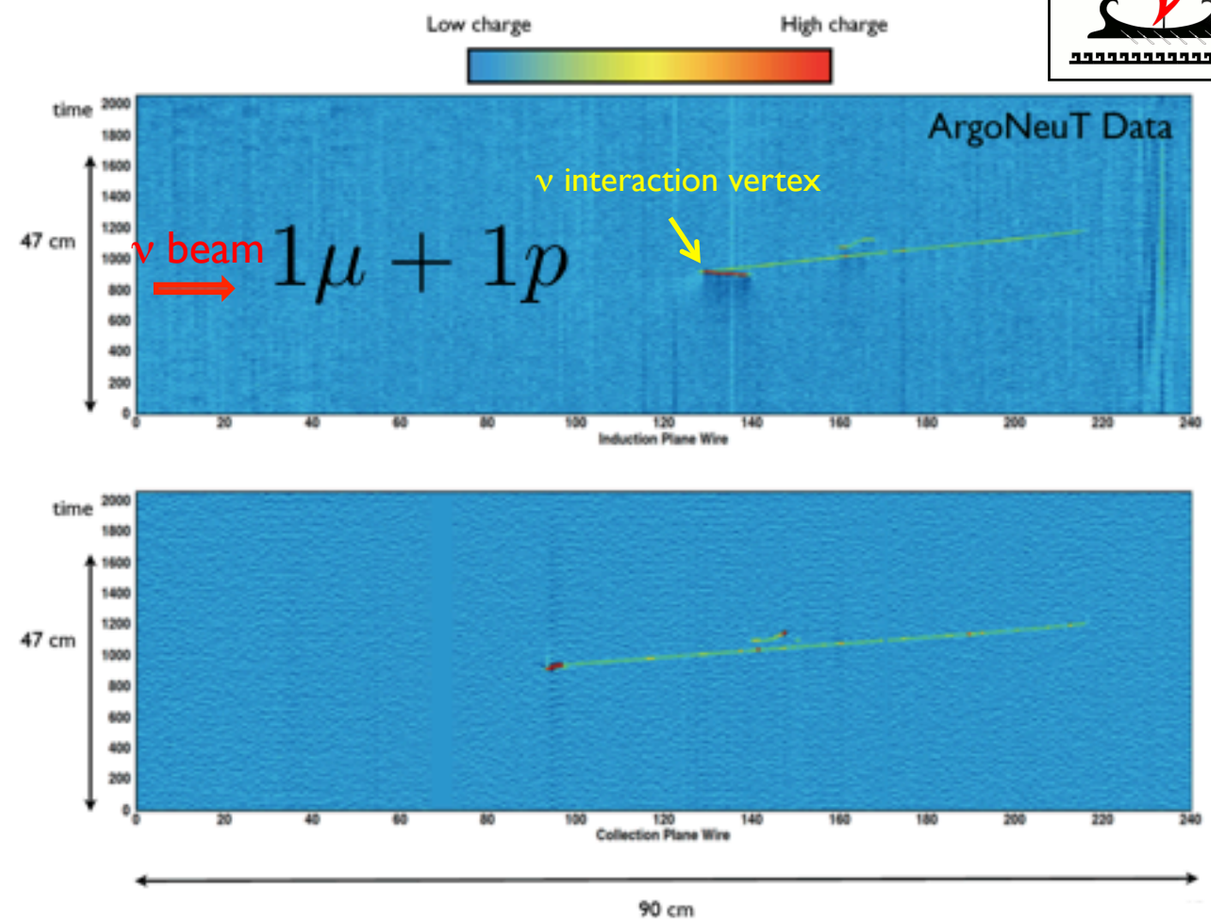
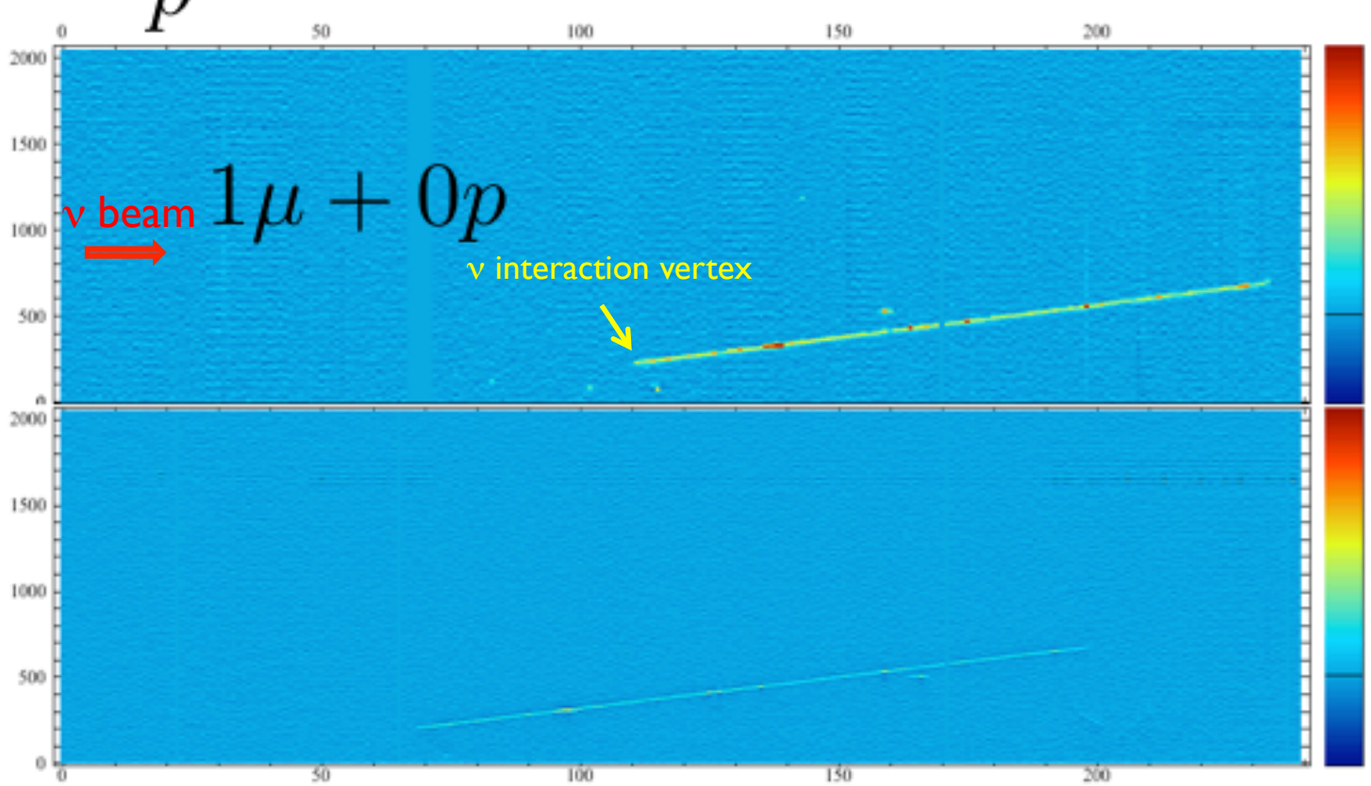
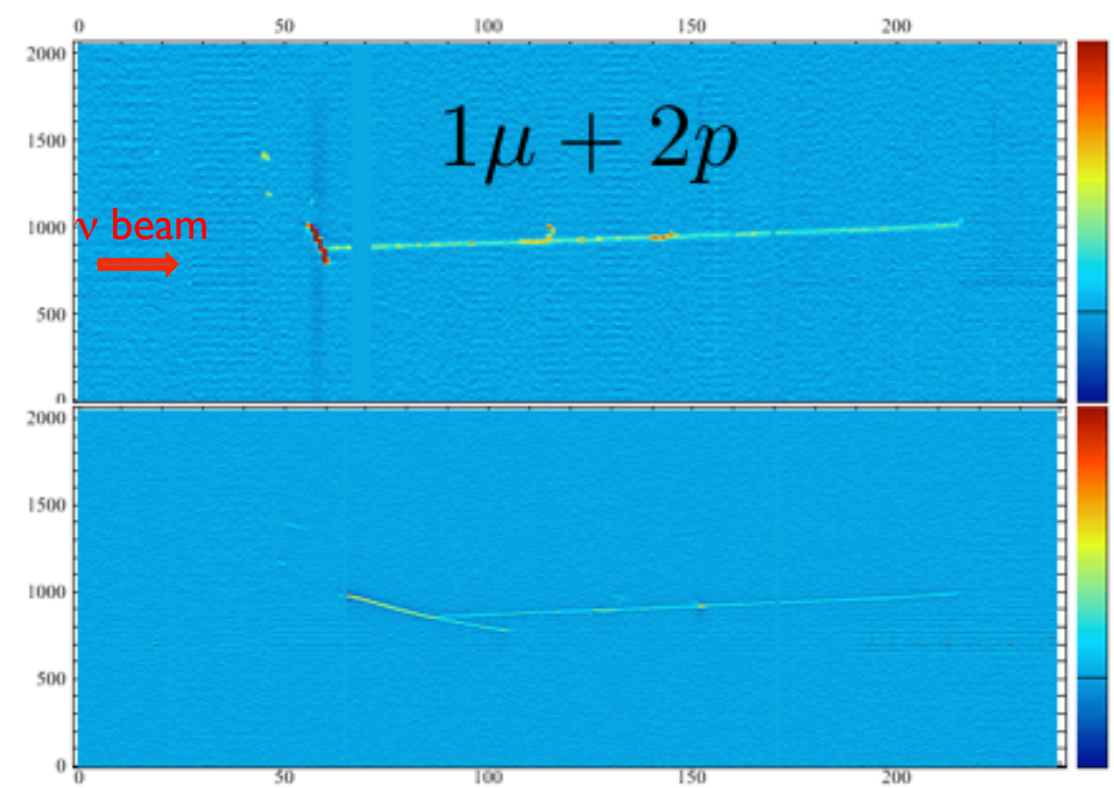
EVENT TOPOLOGY









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

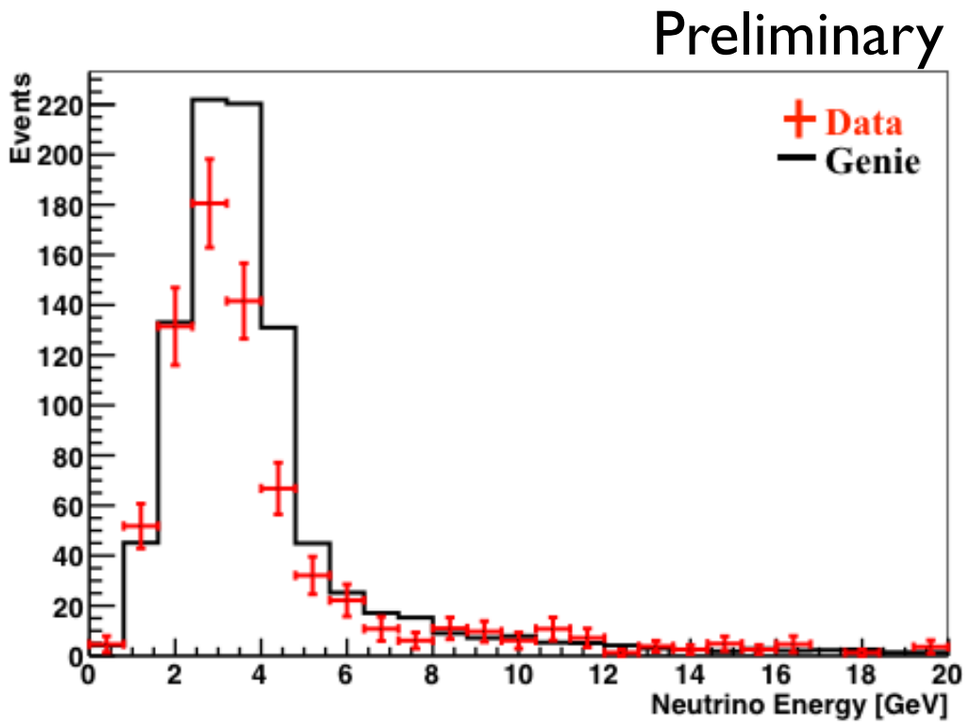
  2-particle-2-hole interaction with 2 nucleons produced

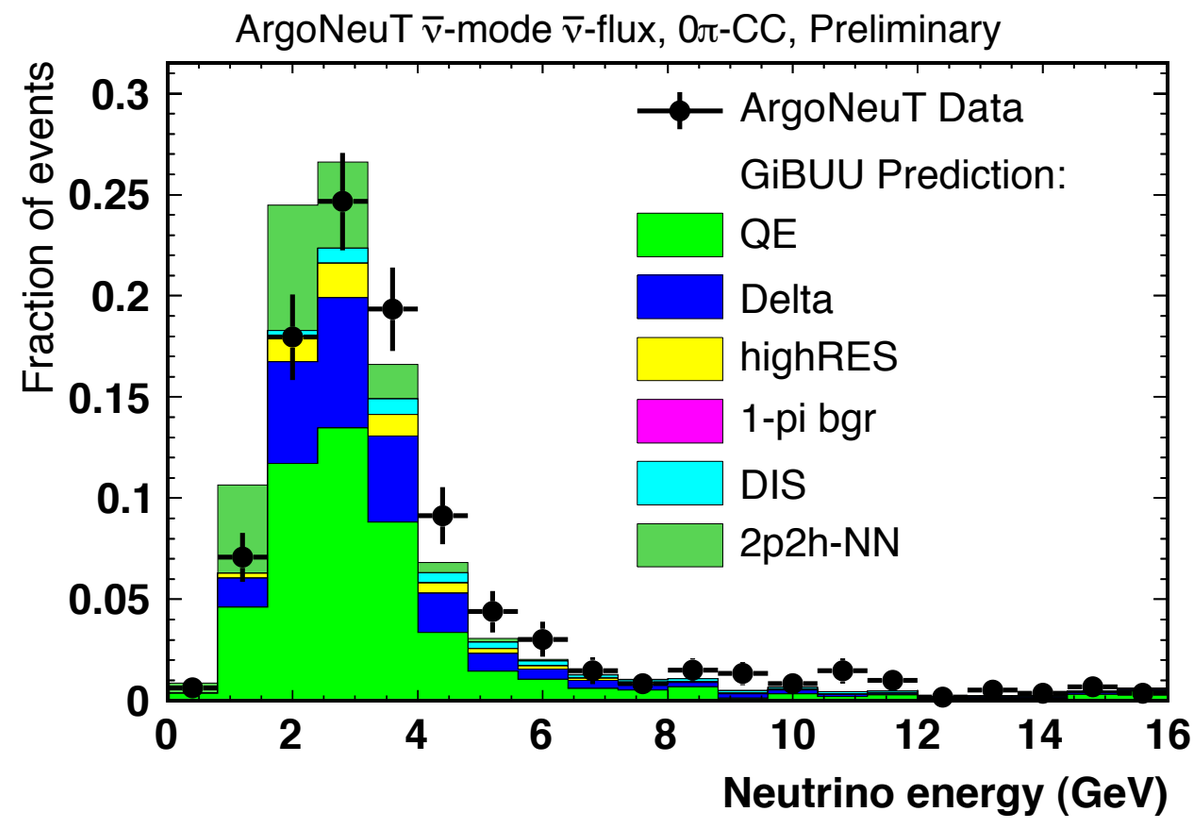
*ArgoNeuT Coll. is grateful to GENIE authors, in particular S. Dytman and H. Gallagher, for many useful discussions

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

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

Neutrino energy (1μ+Np)



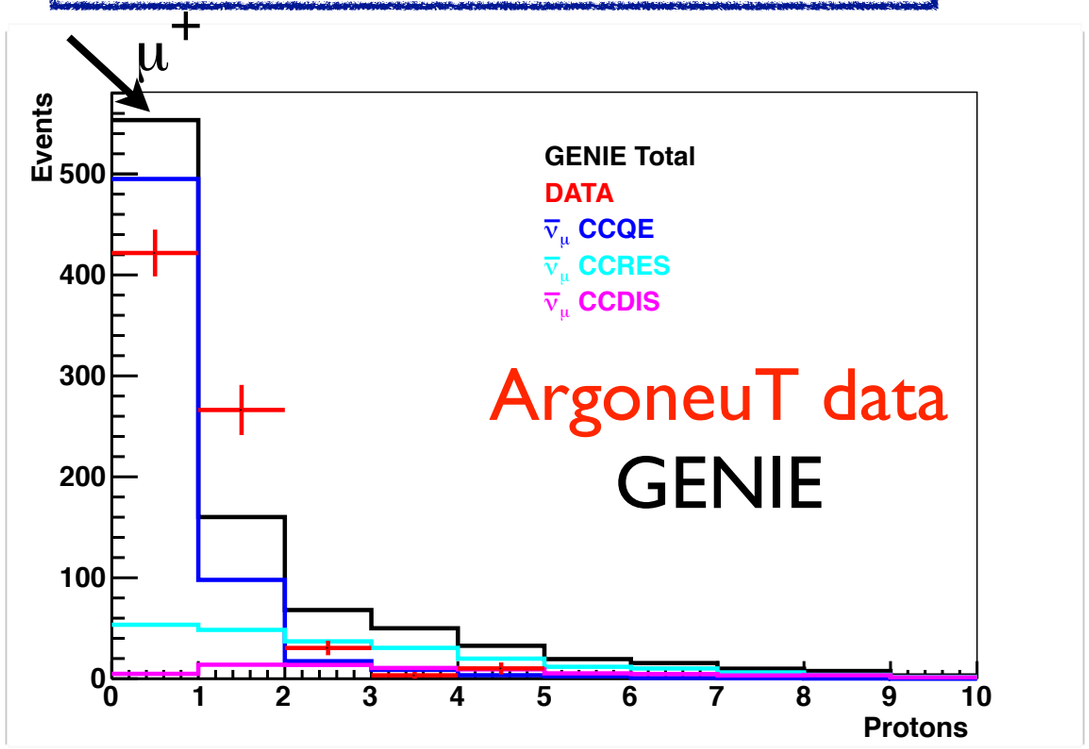


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

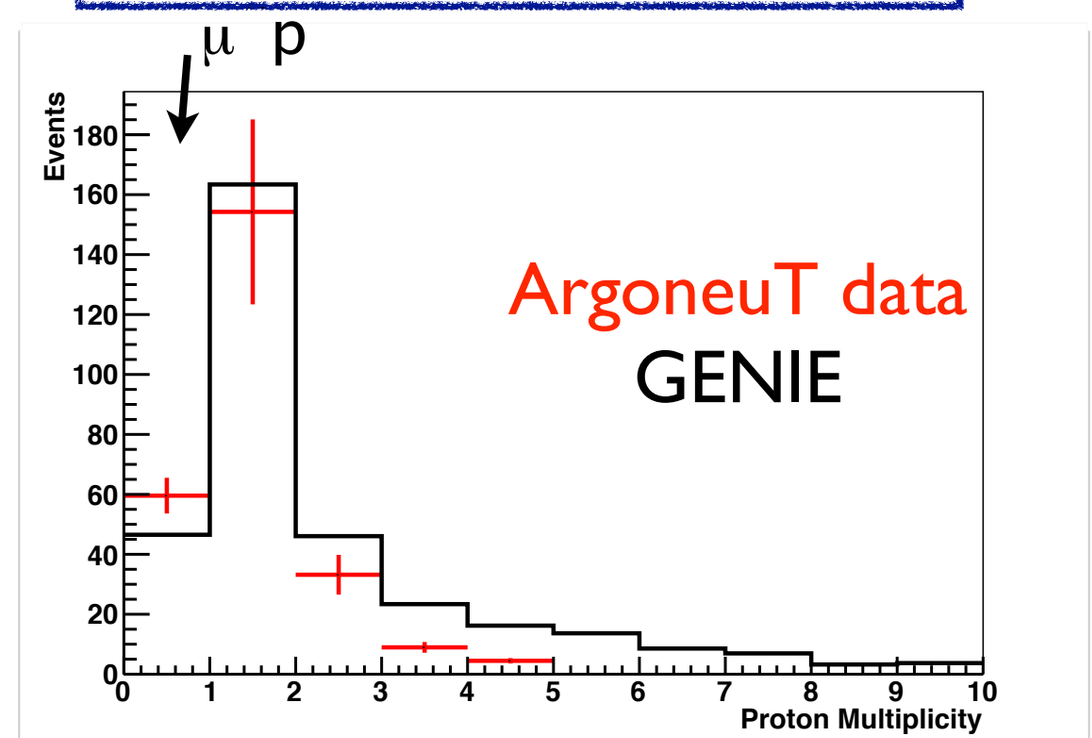
- Data energy reconstructed with the QE formula.
- Improved energy reconstruction including proton kinematics in progress.

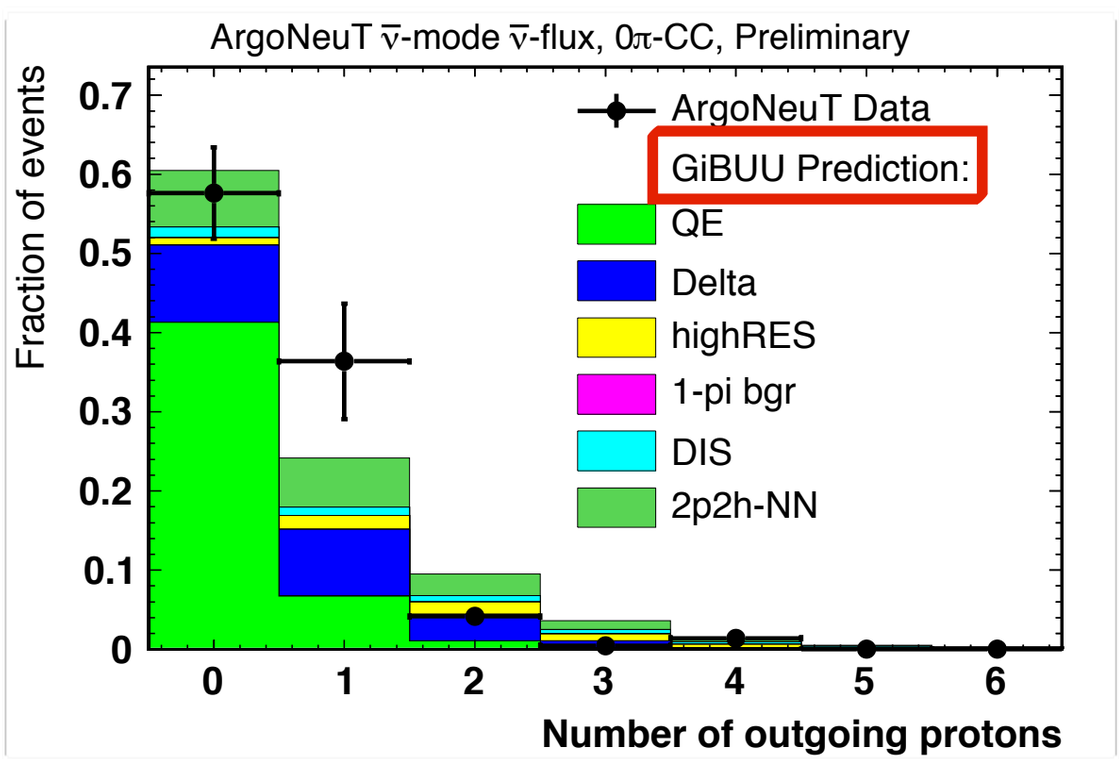
PROTON MULTIPLICITY

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



ν_μ - anti-neutrino mode run





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

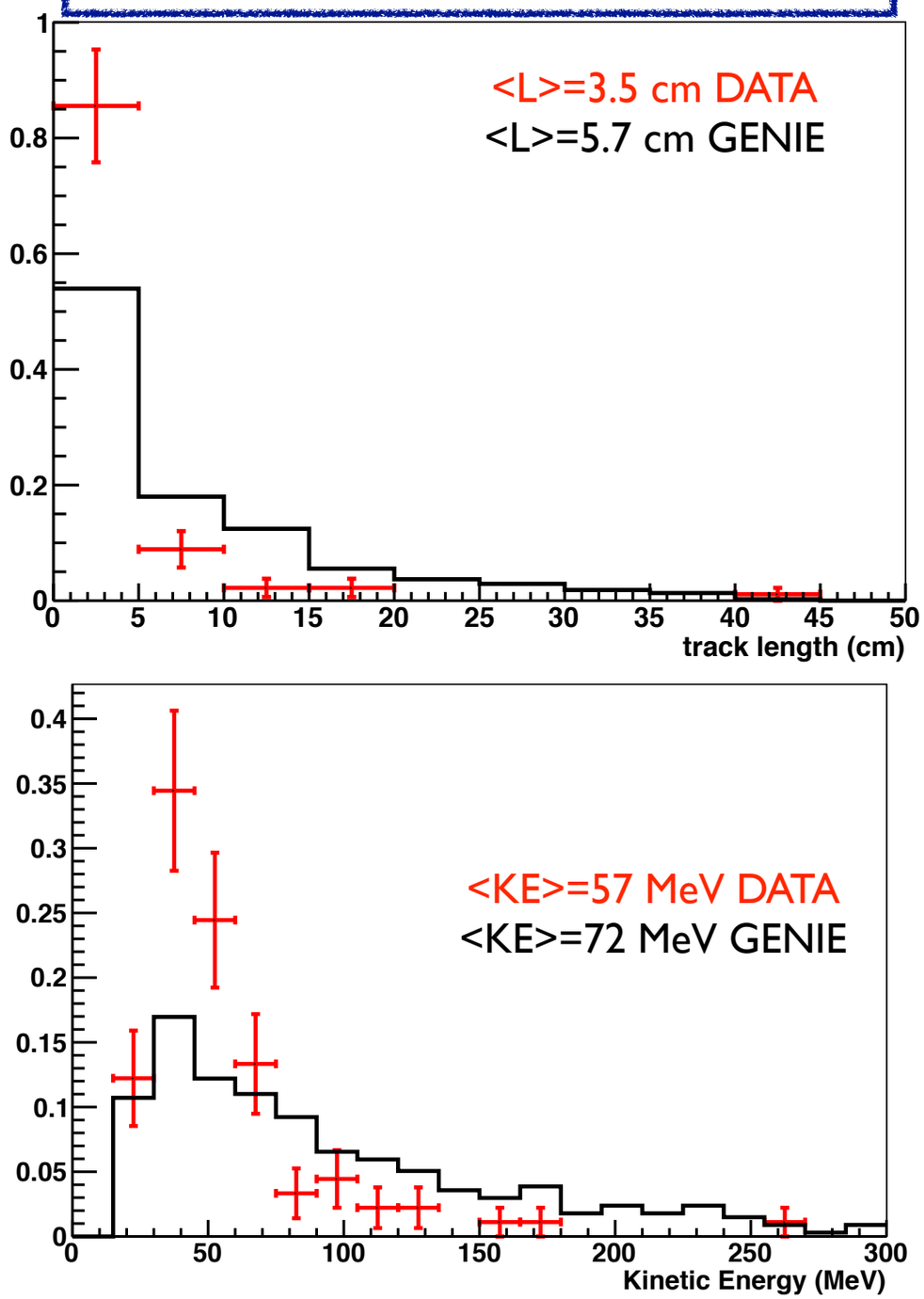
•Uncertainties on the neutrino flux not yet included
•Efficiency for the selection of high multiplicity events not (yet) optimized
•Studies of background effects are ongoing and will be finalized soon

μ^+/μ^- p events

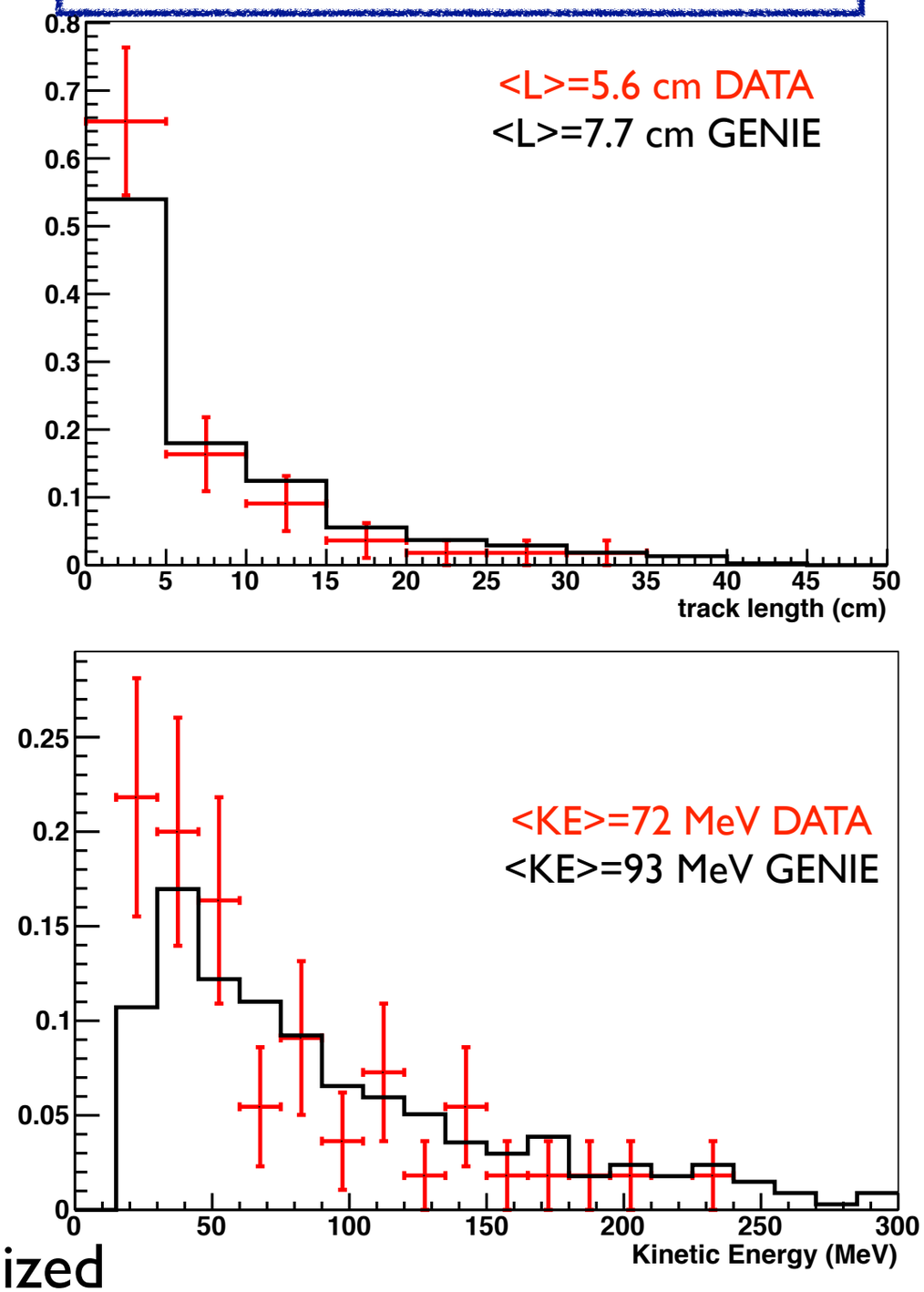
PROTON KINEMATICS

(Event-by event proton reconstruction)

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



ν_μ - anti-neutrino mode run



area normalized

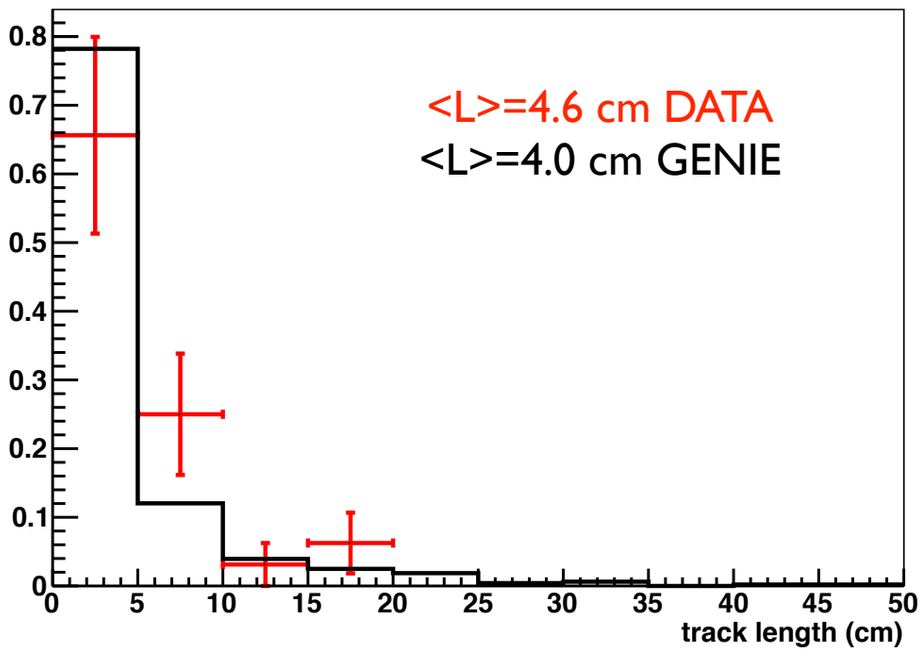
comparison inside the detector

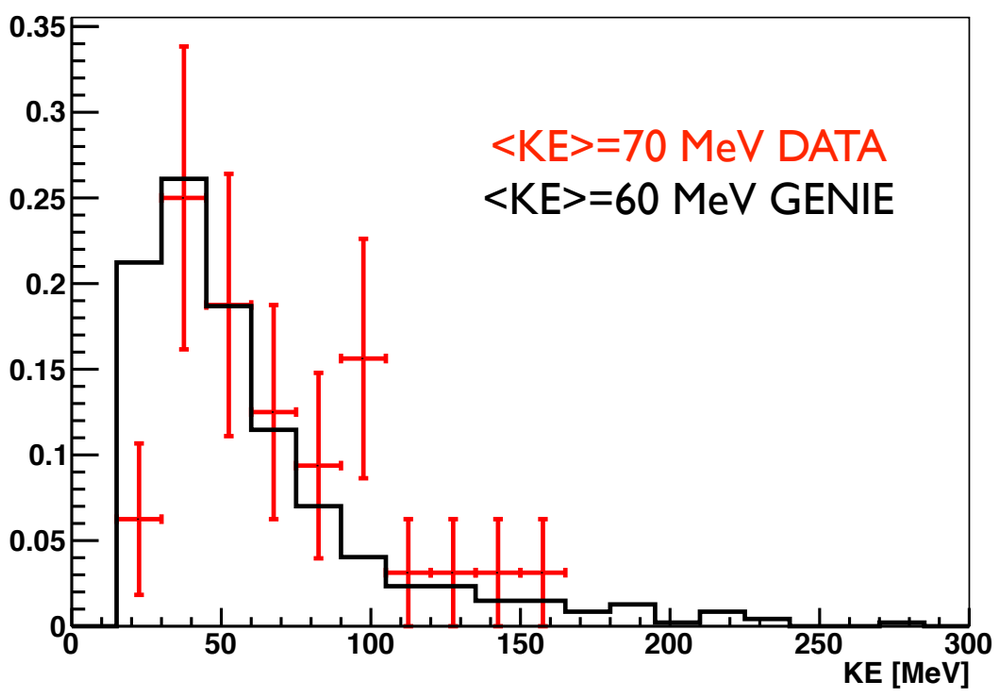
μ^+ 2p events

PROTON KINEMATICS
(Event-by event protons reconstruction)

ArgoNeuT

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



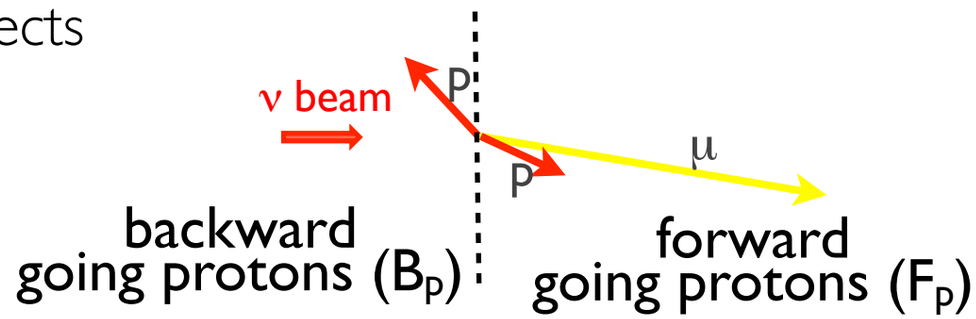


RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS IS IN PROGRESS

area normalized comparison inside the detector

PROTON KINEMATICS & NUCLEAR EFFECTS

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



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

- Possible explanations are:

  - Reinteractions (intranuclear cascade) inside the target nucleus

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

  - Short Range Correlations

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

Production in the backward hemisphere can have contributions from both mechanisms

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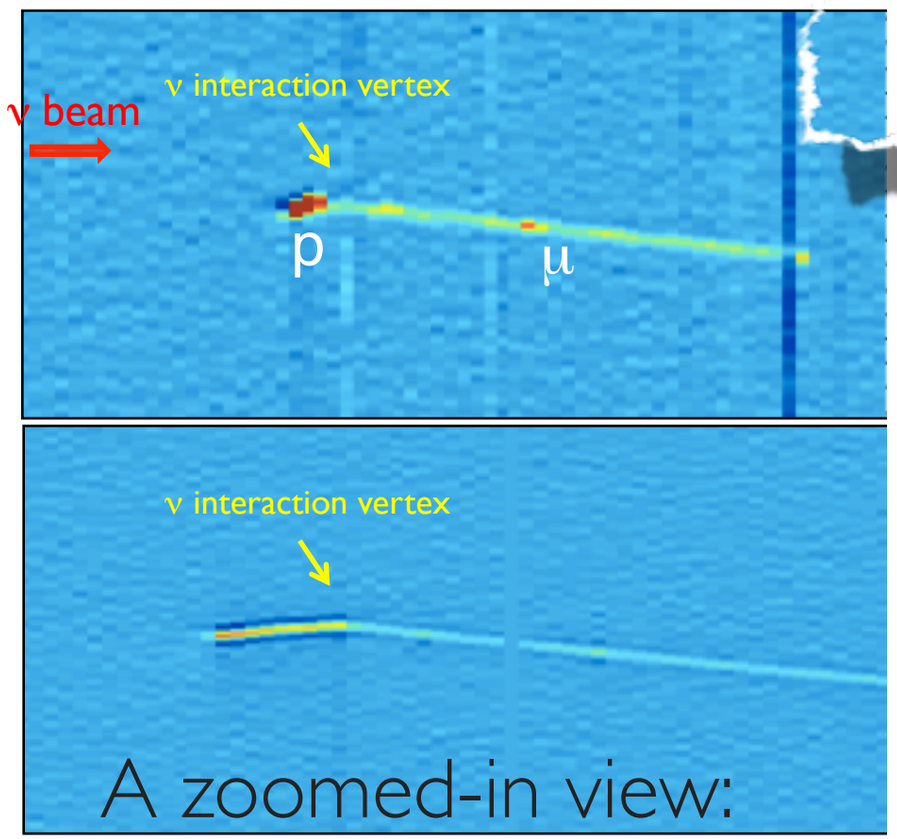
PROTON KINEMATICS: BACKWARD GOING PROTONS (B_P)

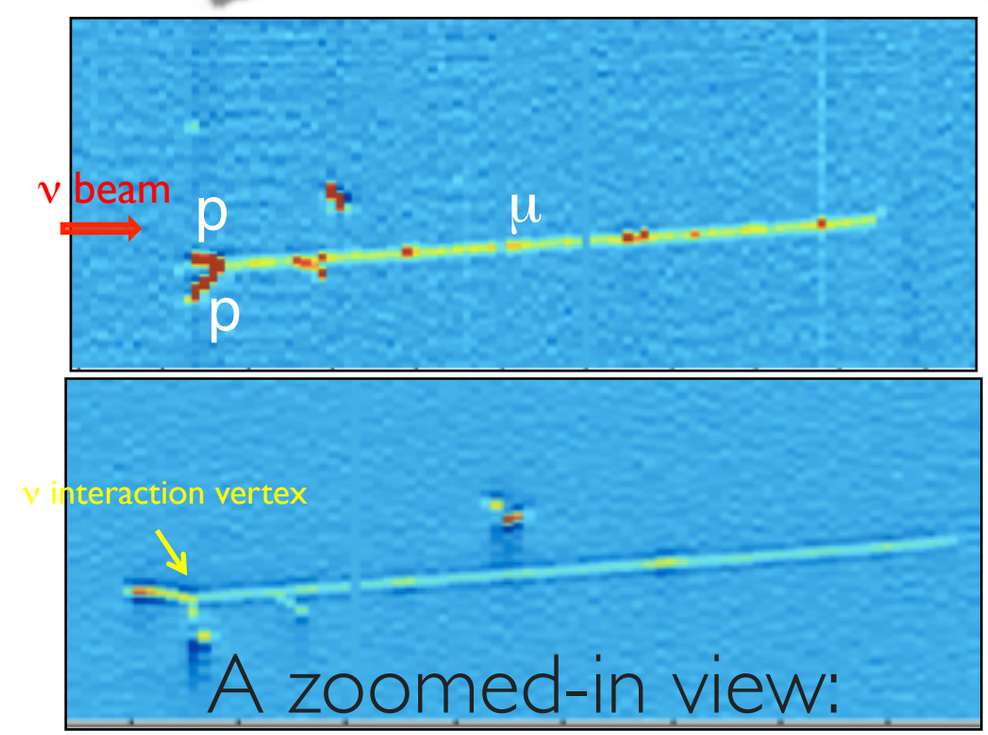
Backward going protons are detected and reconstructed in ArgoNeuT DATA.

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

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



ν interaction with
a backward going p



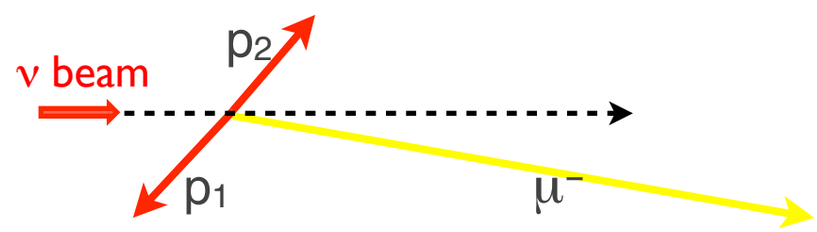
ν interaction with
two backward going p

A DETAILED STUDY OF B_P IS IN PROGRESS

PROTON KINEMATICS & NUCLEAR EFFECTS

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

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



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

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

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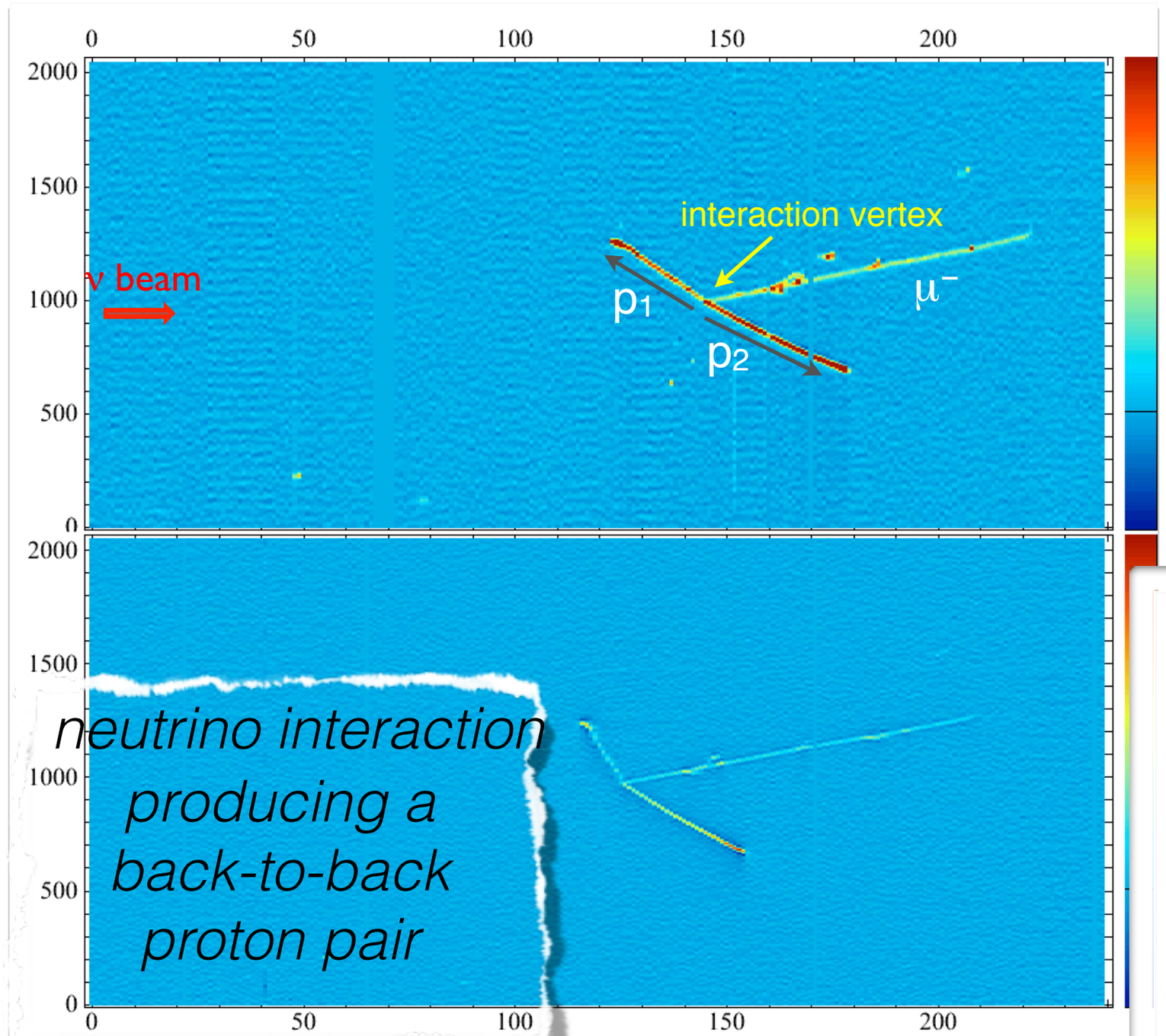
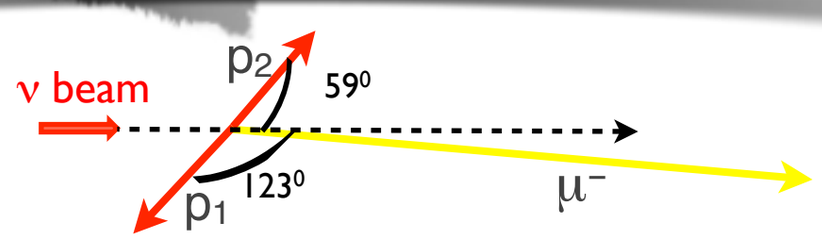
BACK-TO-BACK PROTON PAIR (I)

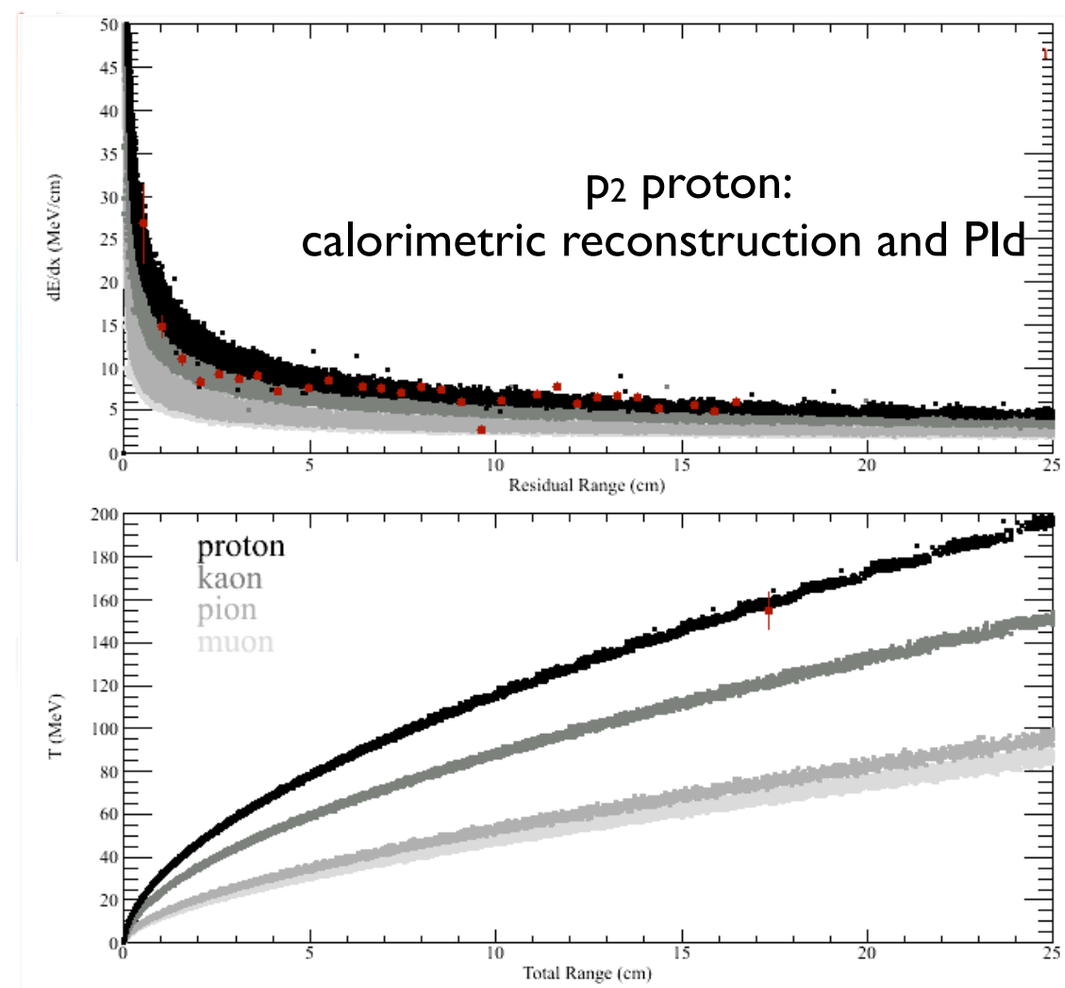


- p_1: θ_1=123^0
  L_1=12 cm ----> p_1=513±31 MeV/c
- p_2: θ_2=59^0
  L_2=17 cm ----> p_2=566±34 MeV/c

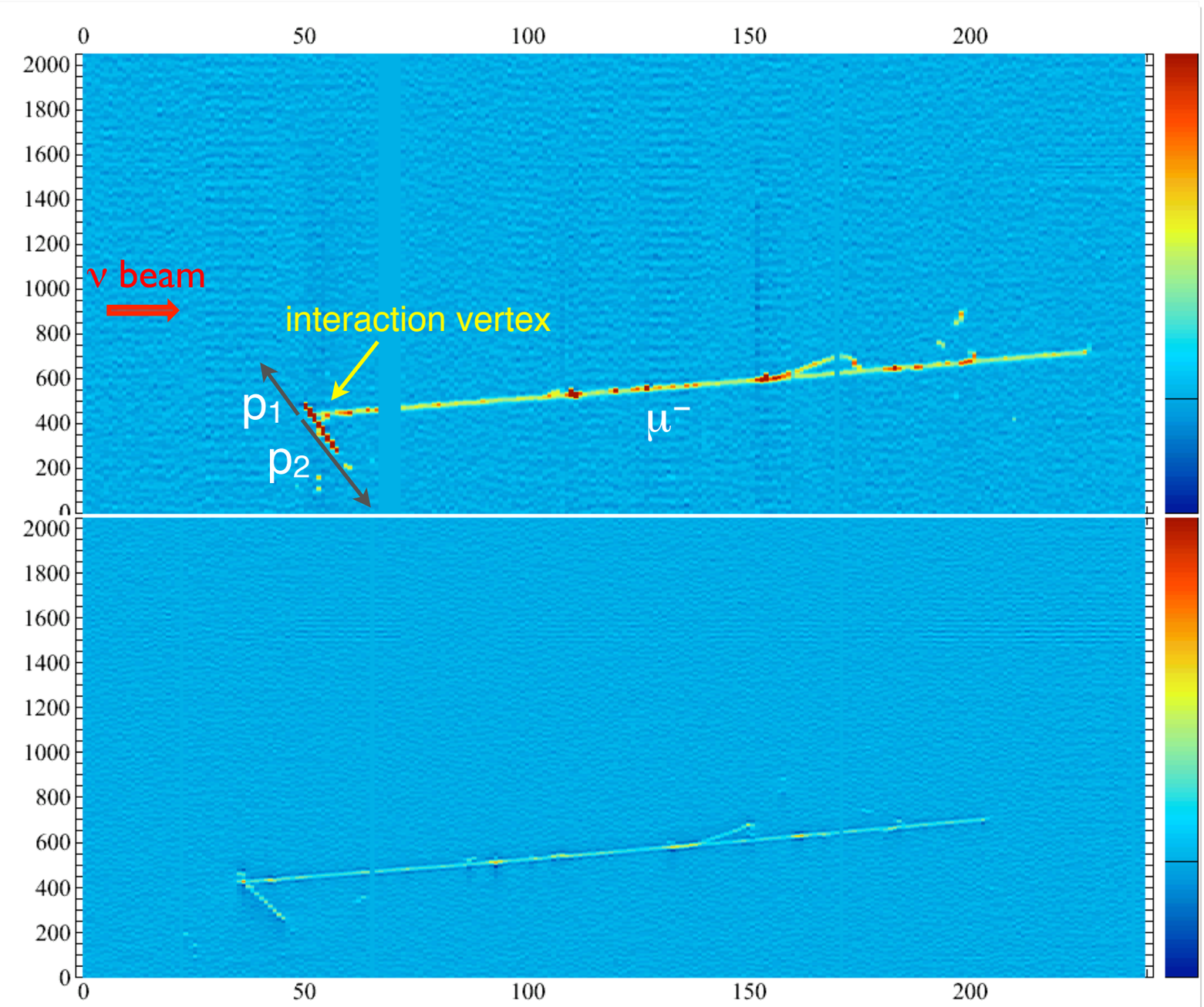
Angle between two protons γ=**183**^{0}



back-to-back protons



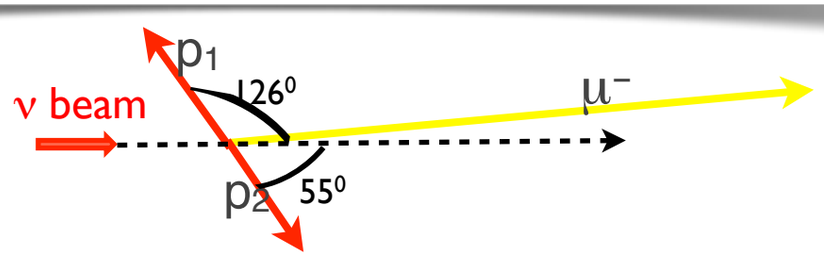
BACK-TO-BACK PROTON PAIR (II)



- p_1: θ_1=126^0
  L_1=1.8 cm, p_1=289±17 MeV/c
- p_2: θ_2=55^0
  L_2=4.5 cm, p_2=381±23 MeV/c

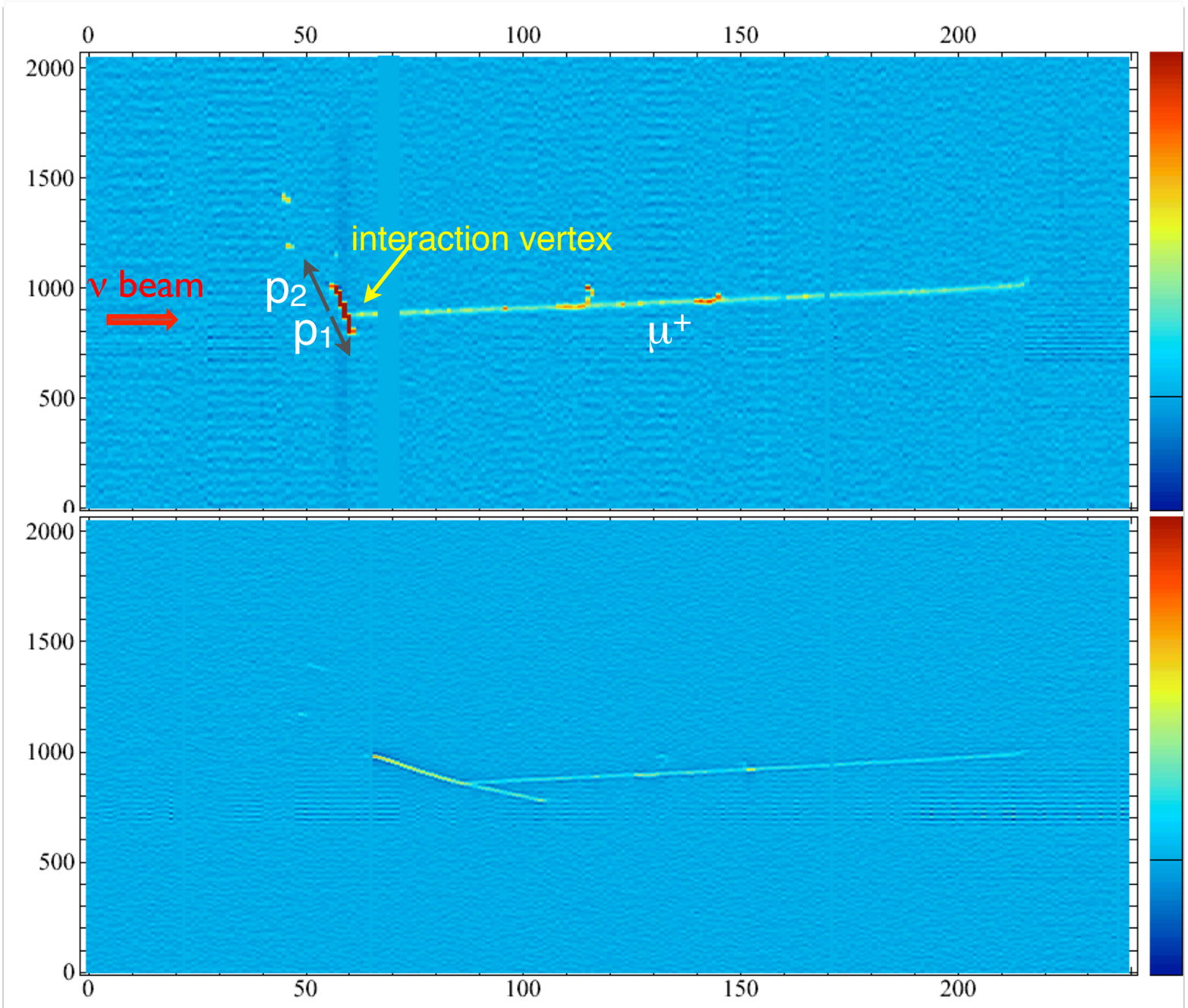
Angle between two protons γ=**181**^{0}

neutrino interaction producing a back-to-back proton pair



back-to-back protons

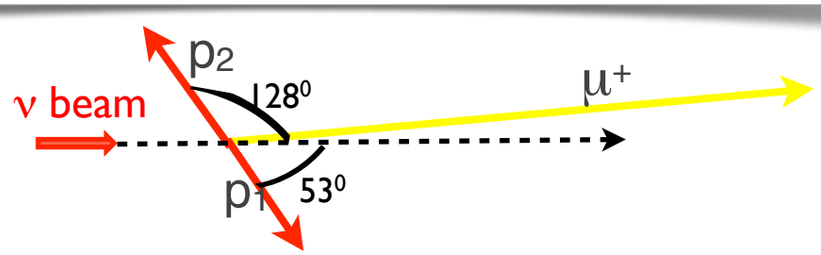
BACK-TO-BACK PROTON PAIR (III)



- p_1: θ_1=53^0
  L_1=7.5 cm, p_1=443±26 MeV/c
- p_2: θ_2=128^0
  L_2=8.9 cm, p_2=466±28 MeV/c

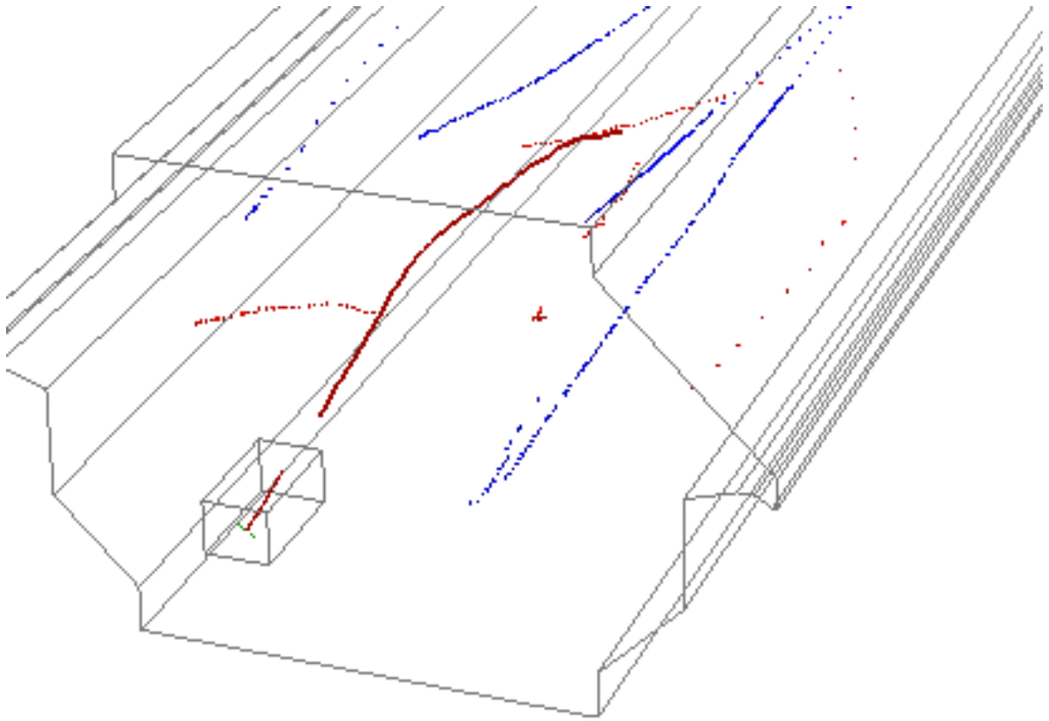
Angle between two protons γ=**181**^{0}

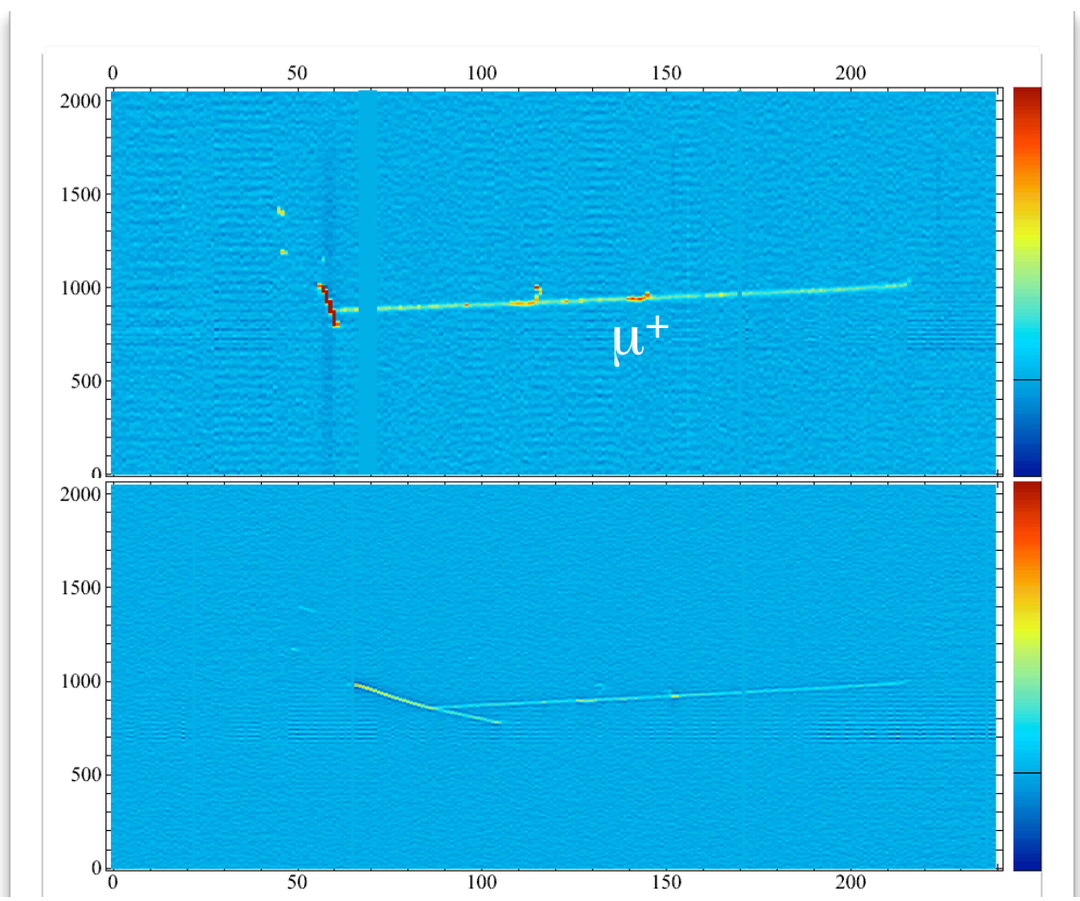
anti-Neutrino interaction producing a back-to-back proton pair



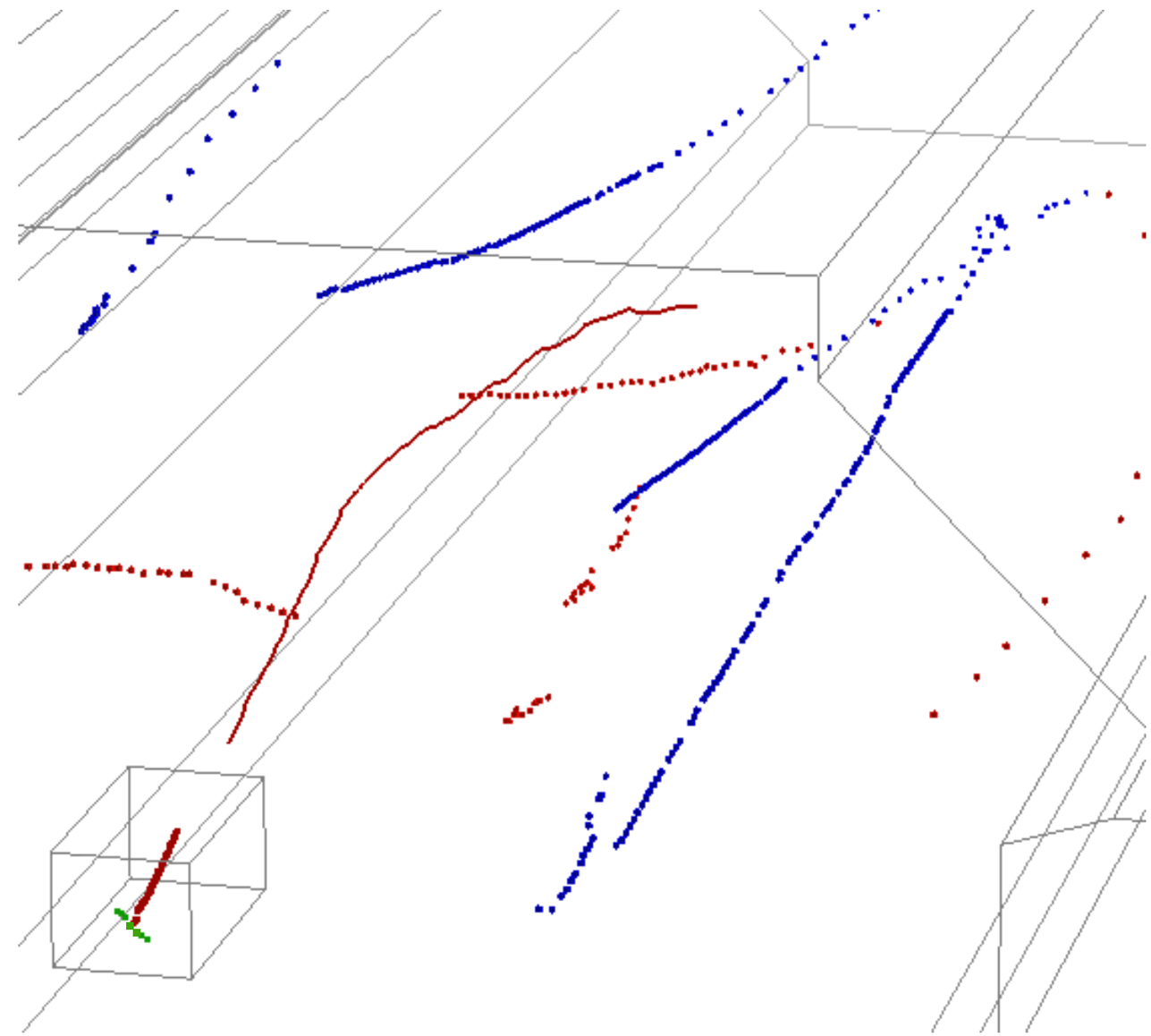
back-to-back protons

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





A detailed study of back-to-back protons is in progress



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

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

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

All modern experiments contain nuclei as targets

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

↓

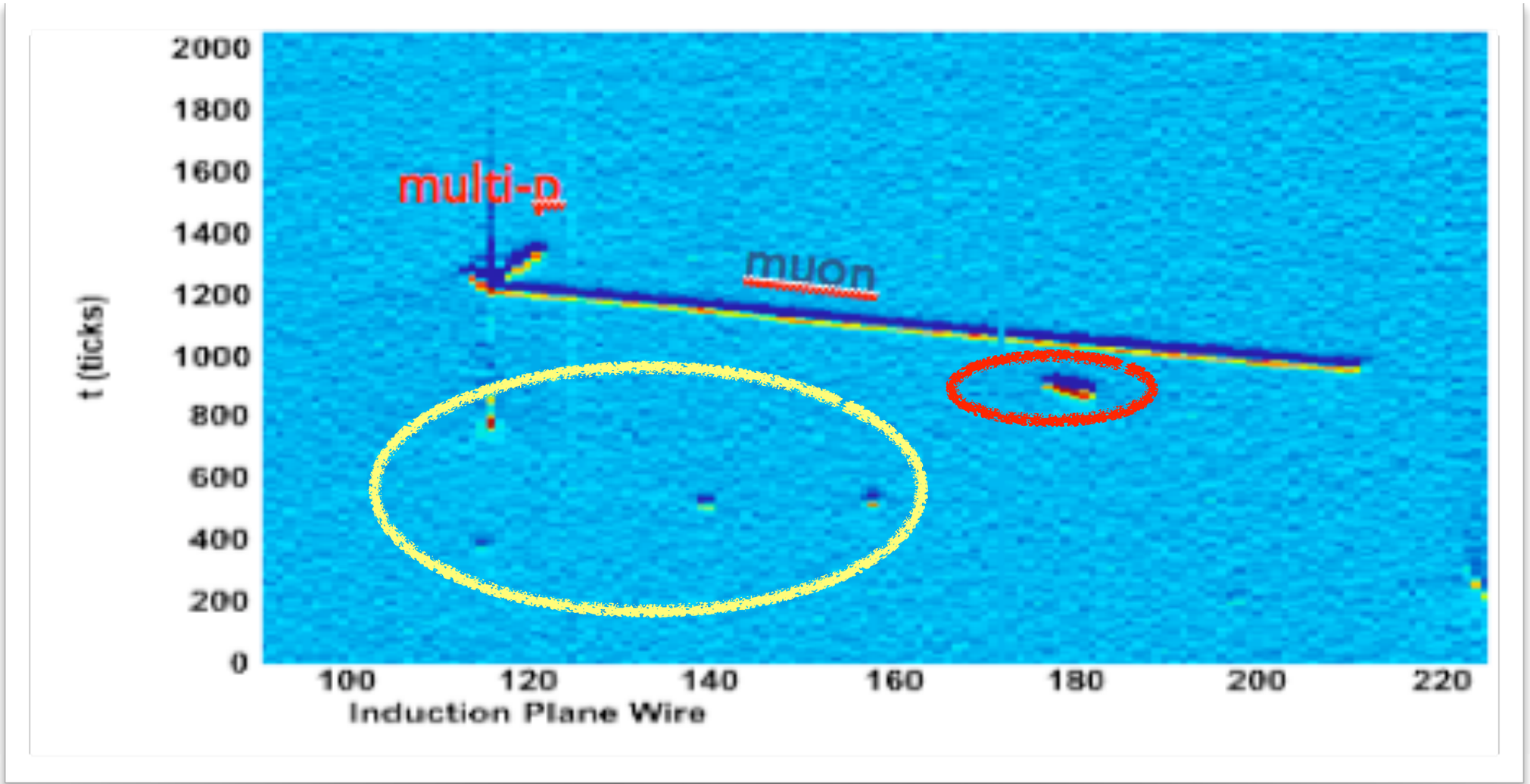
U. Mosel

Nuclear Physics based generators needed

- Progressing with the *development* of more and more accurate *reconstruction tools* for data analysis, in combination with *larger mass LAr-TPC detectors* (MicroBooNE and future LAr detectors) is an important step for accurate topological analysis of neutrino events, on the line pioneered by ArgoNeuT.

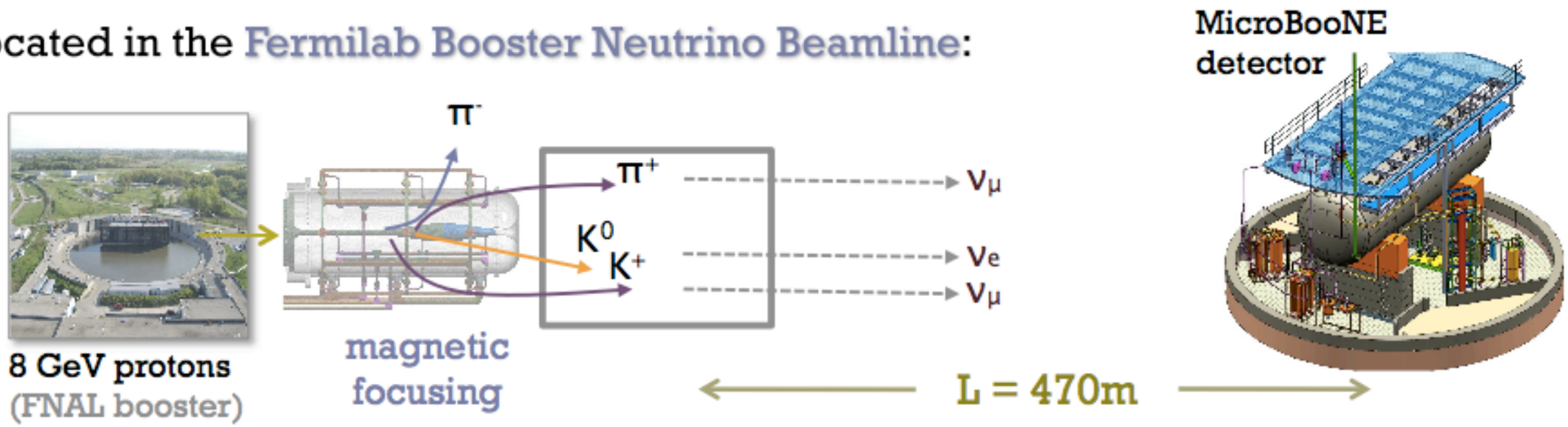
VERTEX ACTIVITY

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



MICROBOONE

Located in the Fermilab Booster Neutrino Beamline:



- Much larger statistics together with **3 wire planes** (vs 2 for ArgoNeuT)**, smaller wire pitch** (3 mm for MicroBooNE vs 4 mm for ArgoNeuT), **cold electronics** (much better S/N) will provide provides invaluable information!

- 2.5 m x 2.3 m x 10.2 m TPC
- 170 (60) tons total (fiducial) mass
- 2.5 m drift length
- 3 wire planes, 0,±60° from vertical
- 3 mm wire pitch
- 8256 wires

Final State Tables for Genie Events

Experimental Signature	Event Rate (no energy cut)
1 μ + 0 p + 0 π	1,502
1 μ + 1 p + 0 π	42,192
1 μ + ≥2 p + 0 π	26,330
1 μ + 0 p + 1 π	4,865
1 μ + 1 p + 1 π	15,782
1 μ + ≥2 p + 1 π	13,079
1 μ + 0 p + ≥2 π	547
1 μ + 1 p + ≥2 π	1,769
other	44,025
total	150,090

any number of neutrons or de-excitation photons

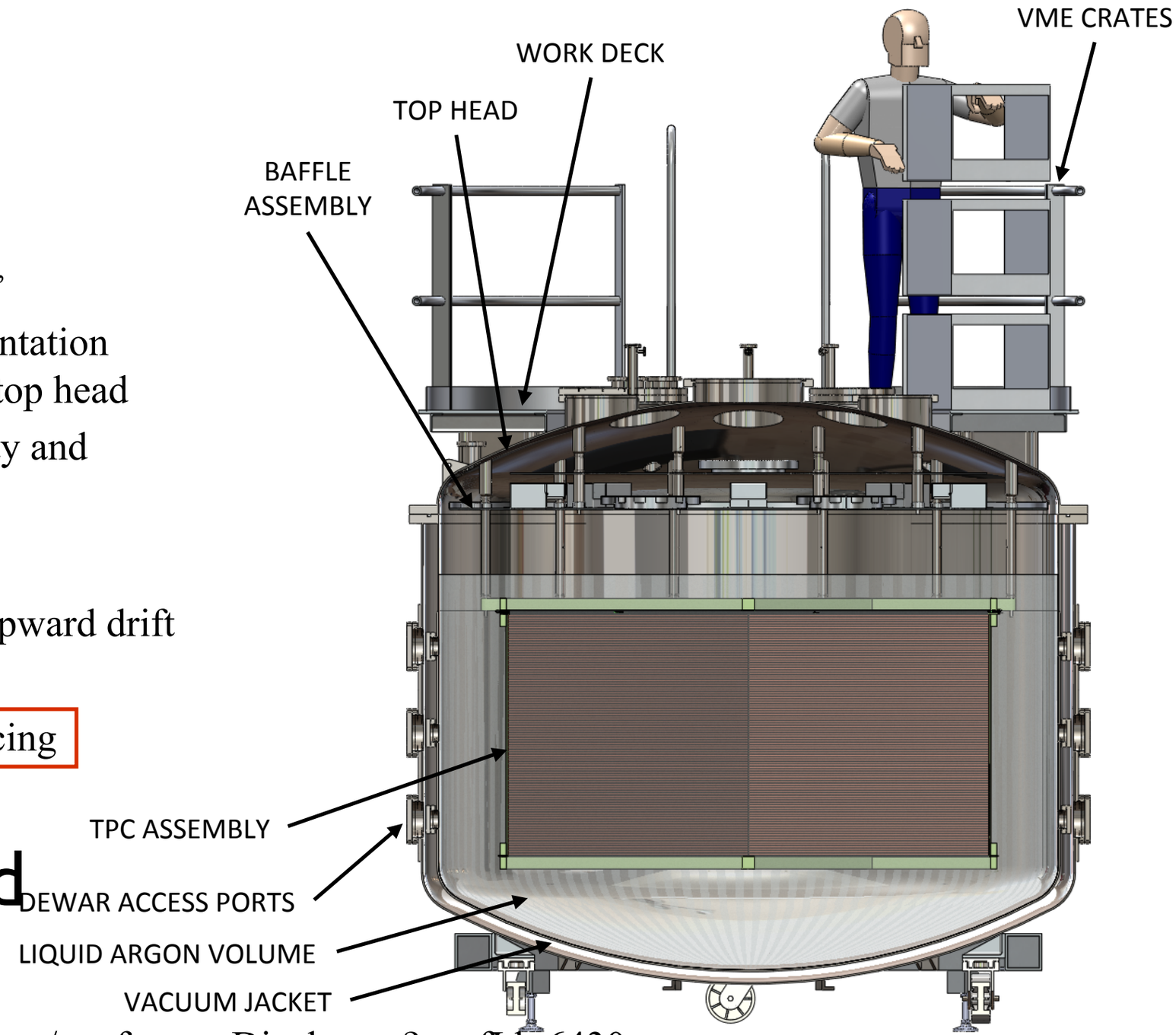
- Normalized to 6×10^{20} POT and 70 metric ton fiducial volume

Christopher Mauger
LANL

The CAPTAIN Detector

CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

- Cryostat
  - Capacity: ~7700 L
  - External dimensions
    - Flange diameter – 111”
    - Work deck height - ~101”
  - All cryogenic and instrumentation connections made through top head
  - Work deck for worker safety and convenience
- TPC
  - hexagonal prism, vertical upward drift
  - 5 instrumented tons
  - 2k channels with 3mm spacing
- Laser calibration system



MicroBooNE Cold electronics

More details: https://indico.fnal.gov/conferenceDisplay.py?confId=6430

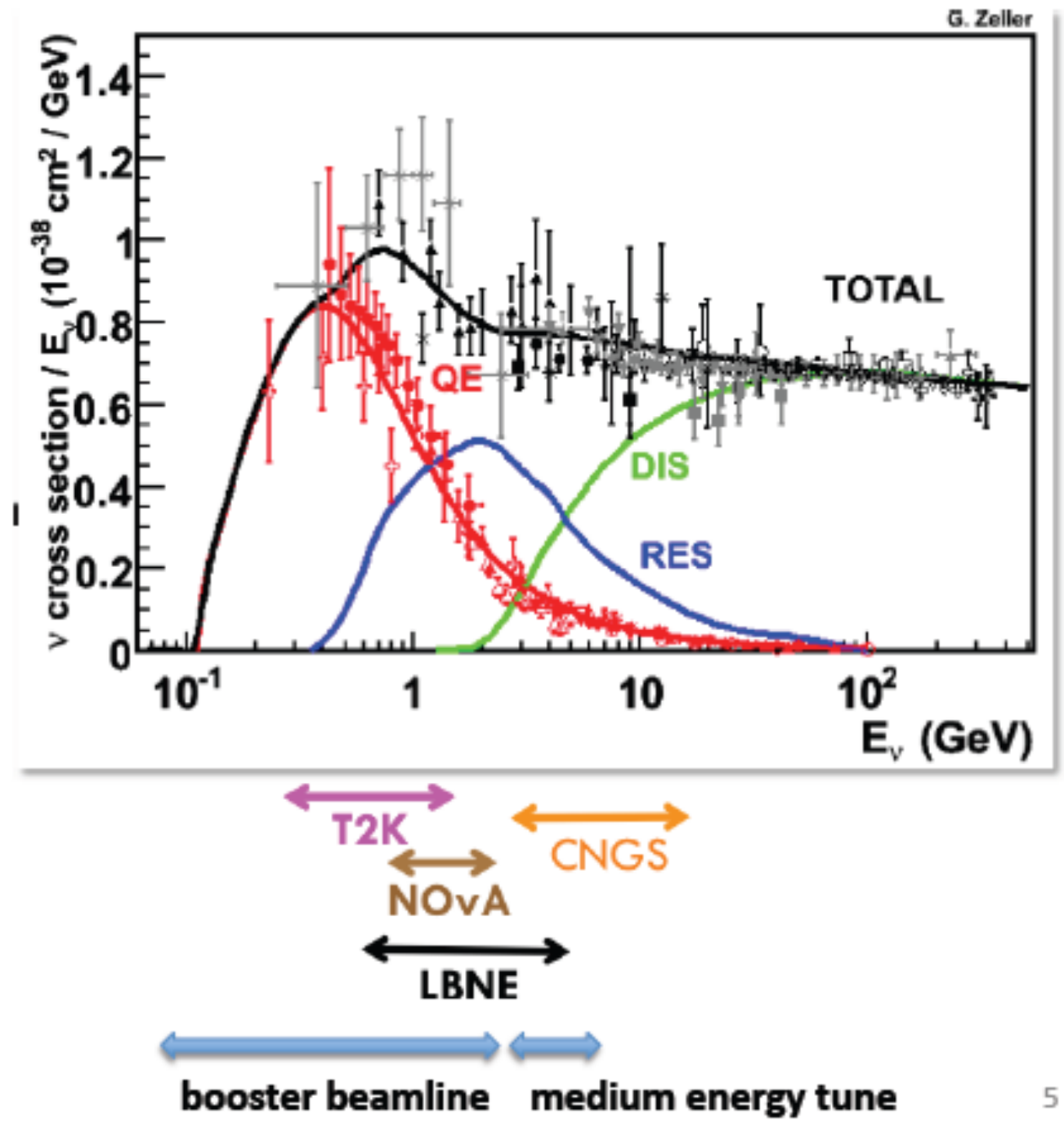
Whitepaper: NUMI Running with the LANL LDRD Liquid Argon TPC

Z. Djurcic[1], E. Guardincerri[2], C. Mauger[2], C. McGrew[3], C. Sinnis[2], M. Tzanov[4], A. Yarritu[2]
ANL(1), LANL(2), Stony Brook(3), LSU(4)

Christopher Mauger
LANL

Running at NUMI during Nova

- Run in on-axis position in NUMI
- Energy regime complementary to MicroBooNE – booster + on-axis NUMI running covers entire LBNE energy regime
- 10% containment of ``all but lepton'' for CC events – 400k contained events per year
- Exclusive and inclusive cross-sections – including the threshold region for pion production, extensive coverage in the resonance regime
- Reconstruction experience with higher energy neutrino interactions



Whitepaper: Neutron running with a liquid argon TPC to study ν-Ar final state interactions and cosmogenic backgrounds important for LBNE

D. Cline[1], Z. Djurcic[2], E. Guardincerri[3], K. Lee[1], C. Mauger[3], K. Rielage[3], C. Sinnis[3], B. Svoboda[4], H. Wang[1]
UCLA(1), ANL(2), LANL(3), UC Davis(4)

Christopher Mauger
LANL

Neutron Running

- Run in high energy neutron beam available at the Los Alamos Neutron Science Center – just down the mesa from the CAPTAIN commissioning laboratory
- Measure production of backgrounds to low energy neutrino events (e.g. burst supernova neutrinos)
- Benchmark spallation simulations with production as a function of neutron energy measured by time-of-flight
- Measure higher-energy processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$ that may be important for near-surface running of the LBNE far detector
- Measure a variety of interactions as a function of neutron energy to develop methodologies for constraining the number of neutrons emerging from the argon nucleus due to neutrino interactions in the GeV regime – important for determining or constraining the neutrino energy in these reactions

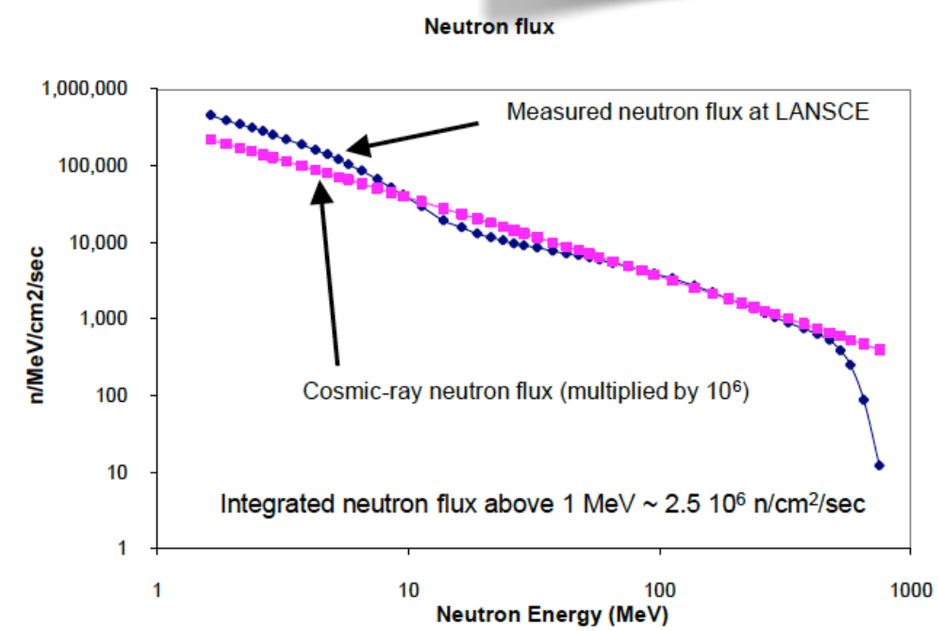
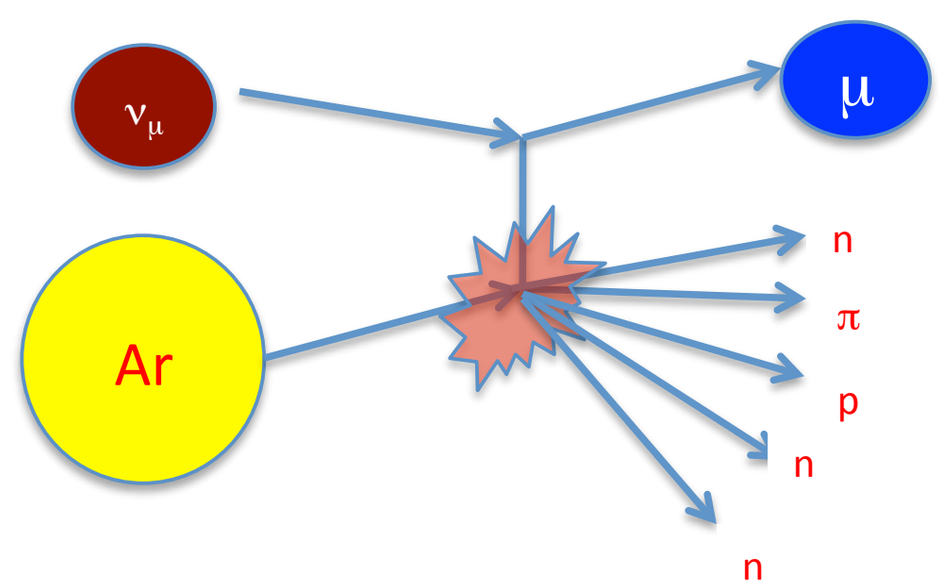


Figure. 1 The energy dependence of the cosmic-ray neutron flux and the measured neutron flux at LANSCE. The cosmic-ray neutron flux is multiplied by 1 x 10^6.



Whitepaper: **Measuring Neutrino Cross Sections on Argon for Supernova Neutrino Detection**

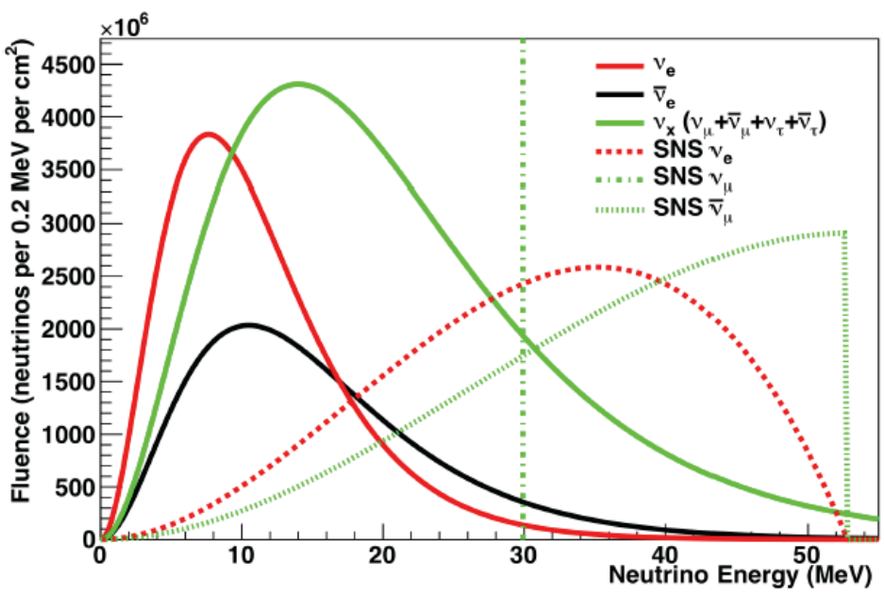
J. Carlson, D. Cline, Z. Djurcic, A. Friedland, G. Fuller, E. Guardincerri, W. Louis, C. Mauger, K. Scholberg, G. Sinnis

Christopher Mauger

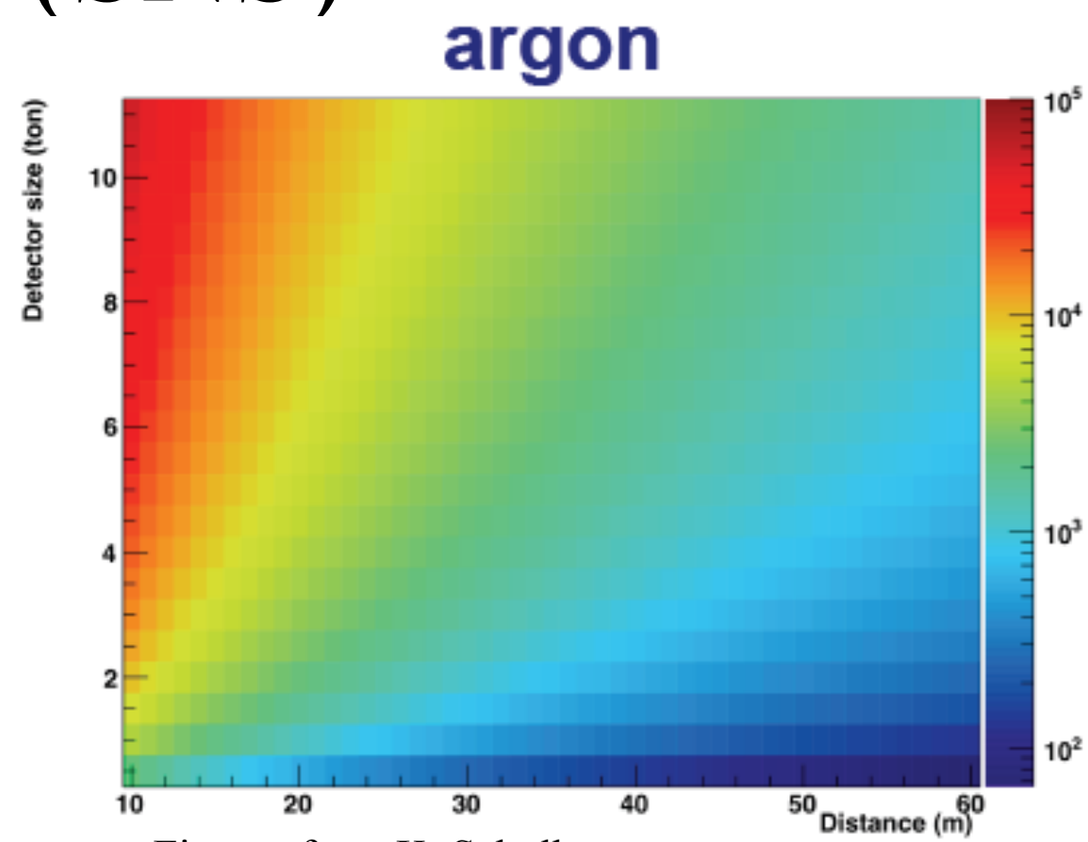
LANL

Running at a stopped pion neutrino source (SNS)

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



Study CC and NC interactions with various nuclei, in few to 10's of MeV range



Figures from K. Scholberg

- Measure CC and NC cross-sections with the well-characterized stopped pion source at SNS (or other location)
- Energies here are important for burst supernova detection
- The cross-sections have never been measured, so first measurement
- CC electon neutrino detection never demonstrated at supernova-relevant energies in a liquid argon TPC – important proof of principle for LBNE, demonstrate energy resolution

SUMMARY

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

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

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

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

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

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