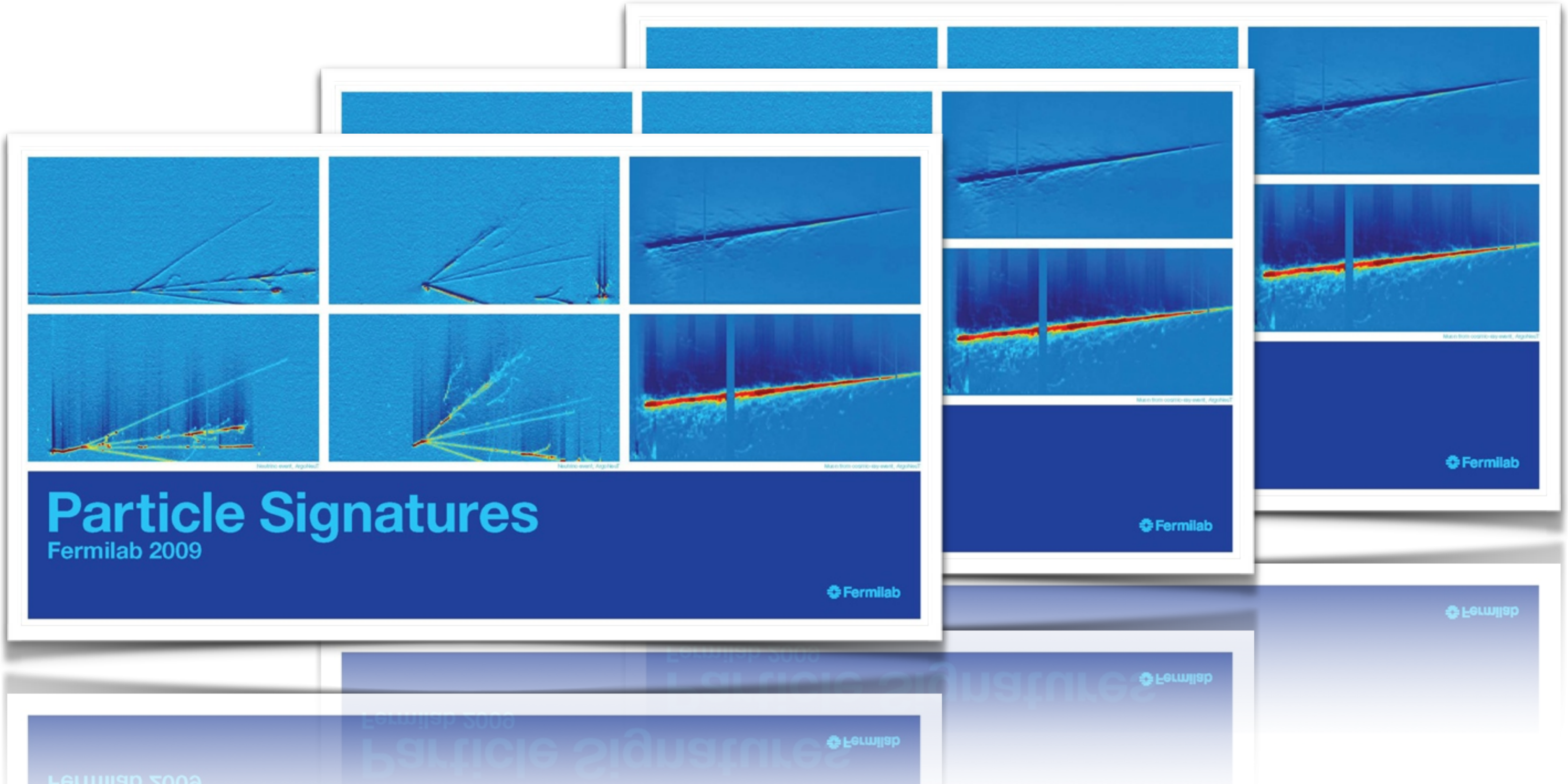

Neutrino energy reconstruction in presence of missing energy

ProtoDUNEs Science Workshop - Cern

June 28th, 2016

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Fermilab & Yale University*

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

Outline

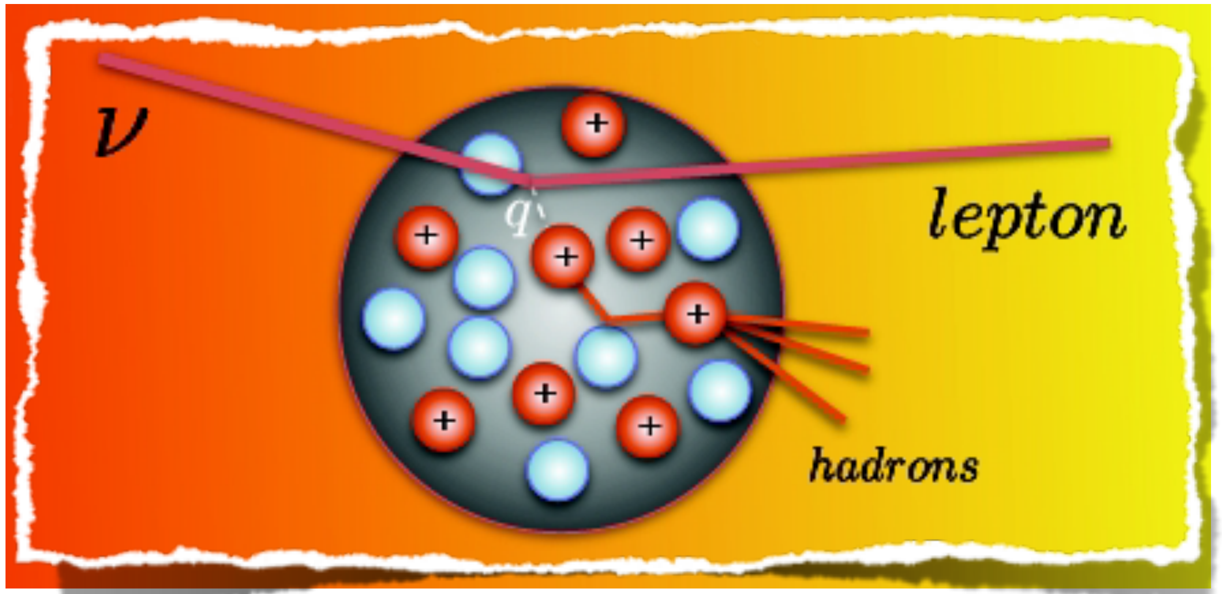
- LAr TPC enable the use different energy reconstruction methods
  - In particular, in LAr TPC we can infer E_ν from what we observe in the final state
- ArgoNeuT neutrino energy reconstruction method including estimates of missing/invisible energy
- Improved neutrino energy reconstruction including the measurement of neutrons

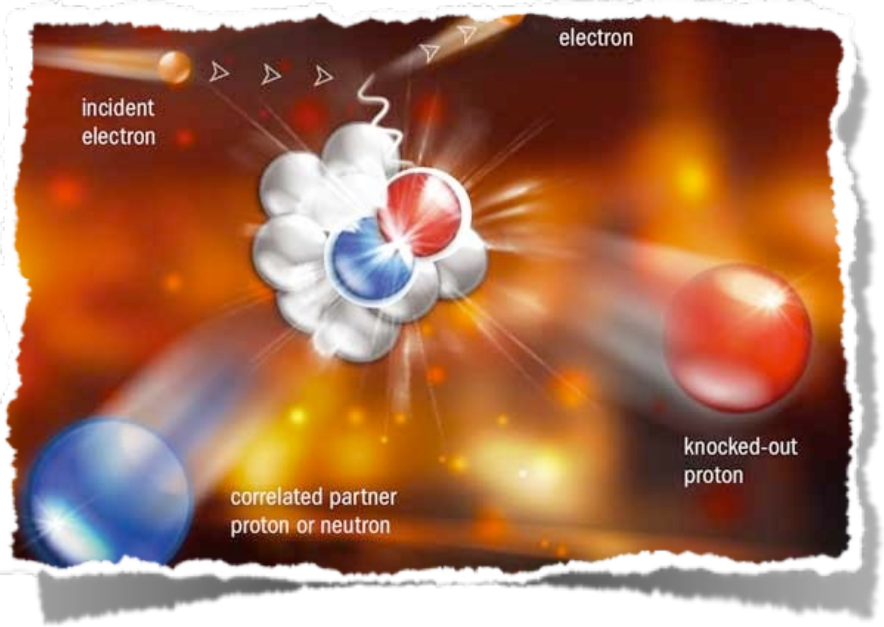
Neutrino Energy Reconstruction

- Accelerator Neutrino beams are not monochromatic but distributed on **broad band spectra**
- Precise and unbiased neutrino energy reconstruction is especially important for reducing systematics in precision neutrino oscillation experiments
  - Systematic which create a bias in neutrino energy definition could affect ability to measure oscillation parameters

ν scattering - Nuclear Effects

- ν experiments use complex nuclei as neutrino target → **Nuclear effects**

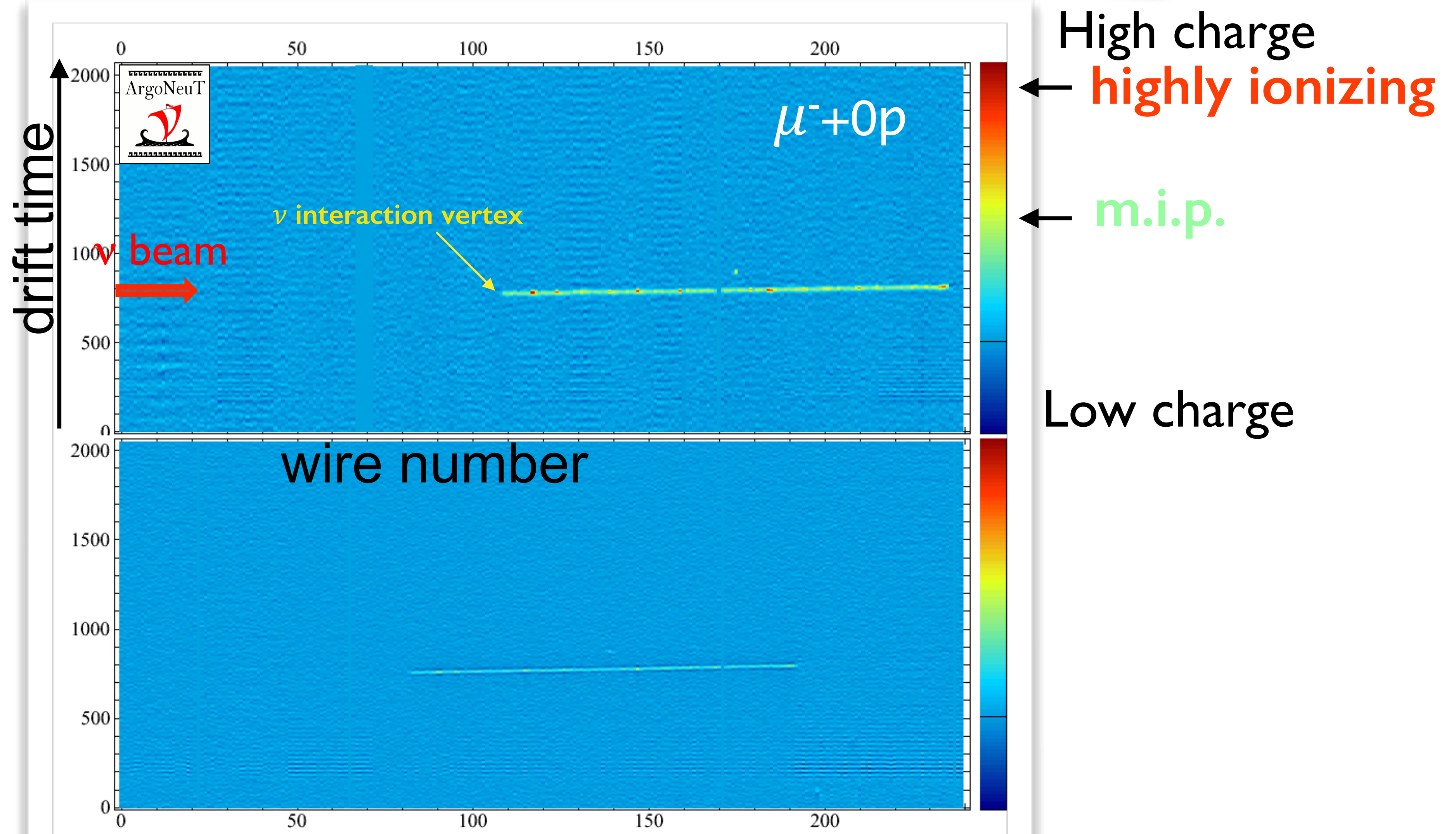




  - Significantly alter final state particle topology/kinematics.
  - Due to ***Intra-nuclear re-scattering*** *(FSI, processes like pion absorption, charge exchange…)* and effects of ***correlation between target nucleons***, even a genuine QE interaction can often be accompanied by the *ejection of additional nucleons*, emission of many *de-excitation γ's* and sometimes by *soft pions* in the Final State.

LArTPC

LAr TPC detectors providing *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* allow for **Exclusive Topology recognition** and **Nuclear Effects exploration** from detailed studies of the hadronic part of the final states



2D views from the two wire planes

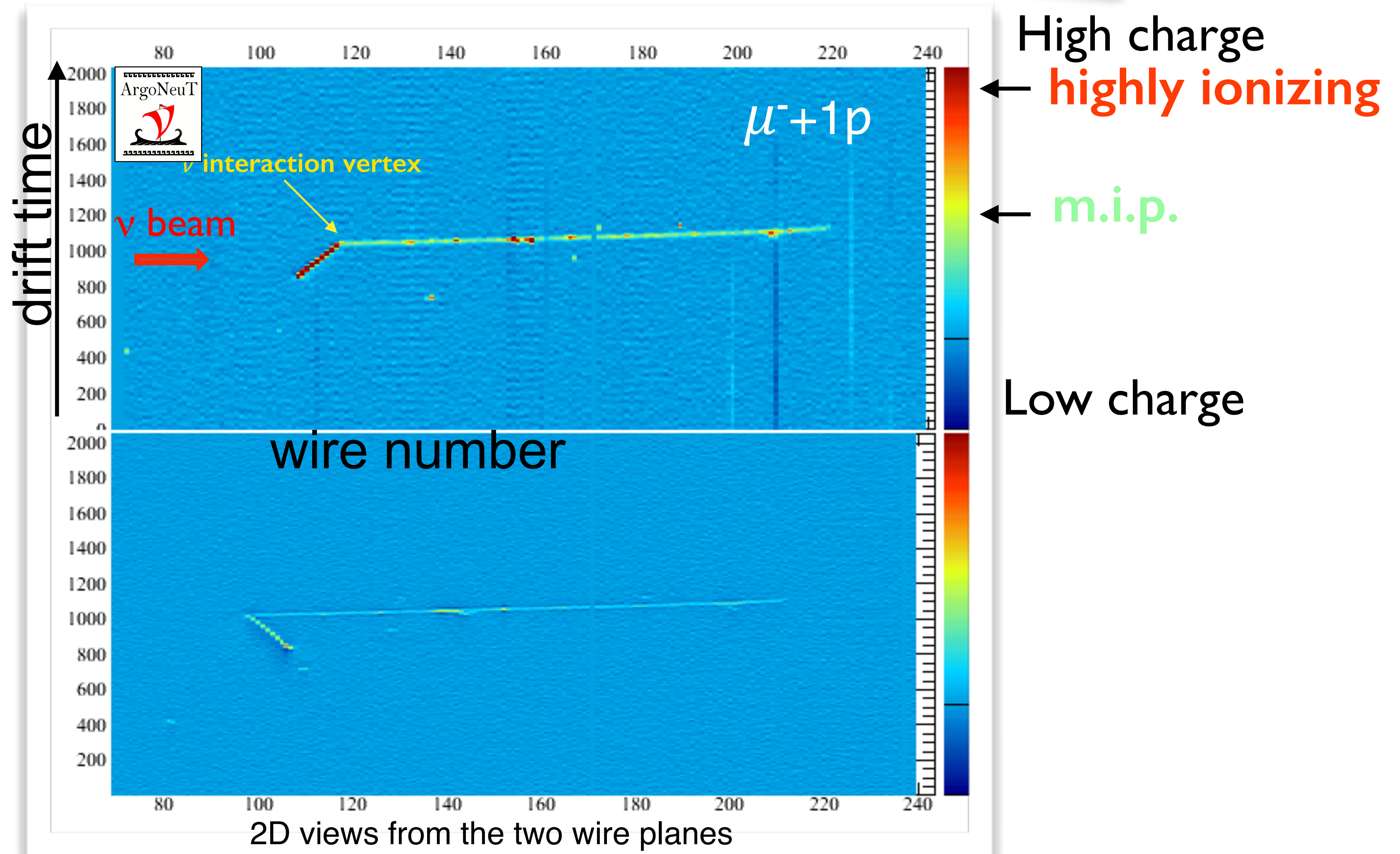
LArTPC

LAr TPC detectors providing *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* allow for **Exclusive Topology recognition** and **Nuclear Effects exploration** from detailed studies of the hadronic part of the final states

Low proton energy threshold
(21 MeV Kinetic energy - ArgoNeuT)

⇩

Neutrino energy reconstruction from all final state particles



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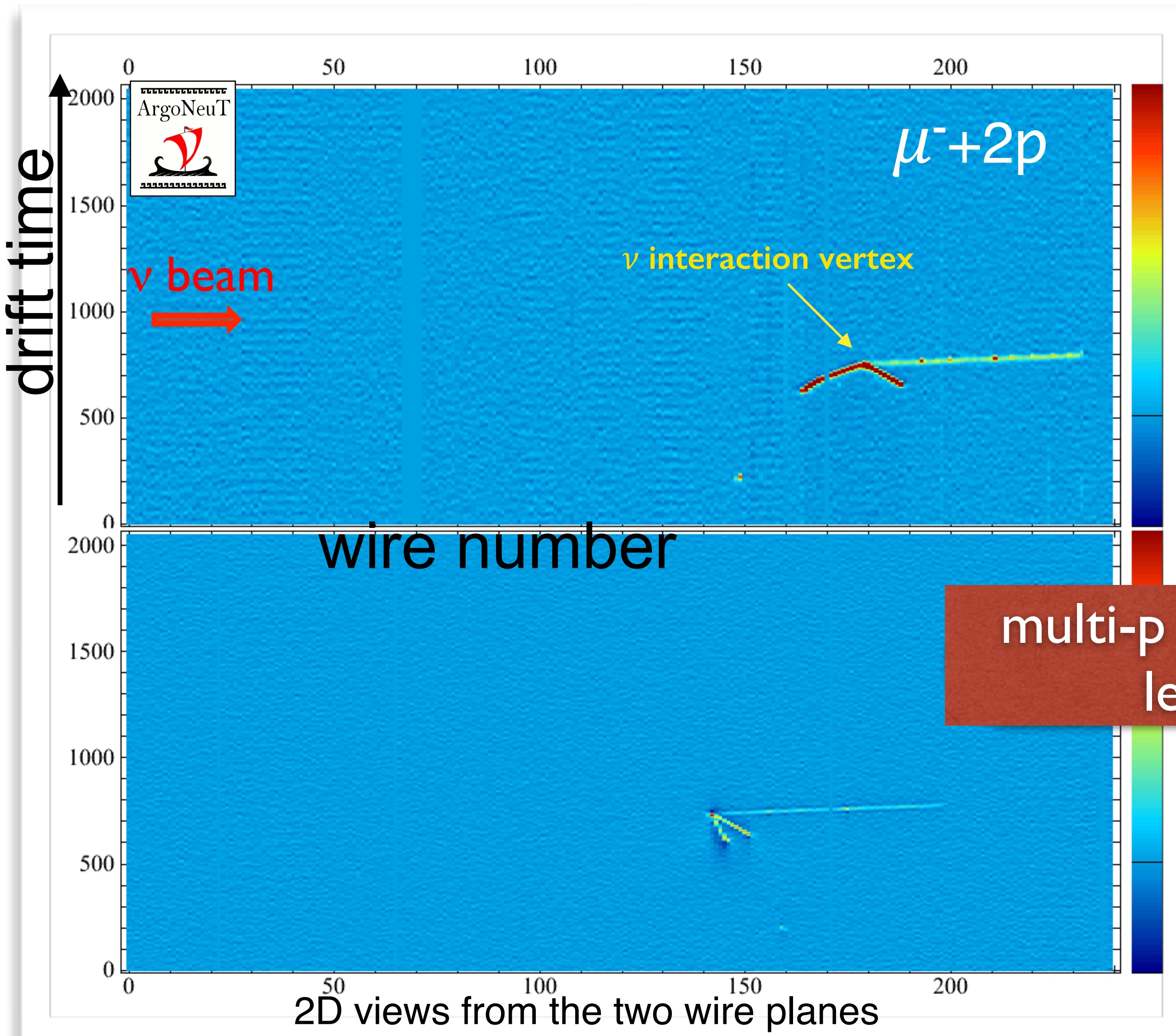


High charge

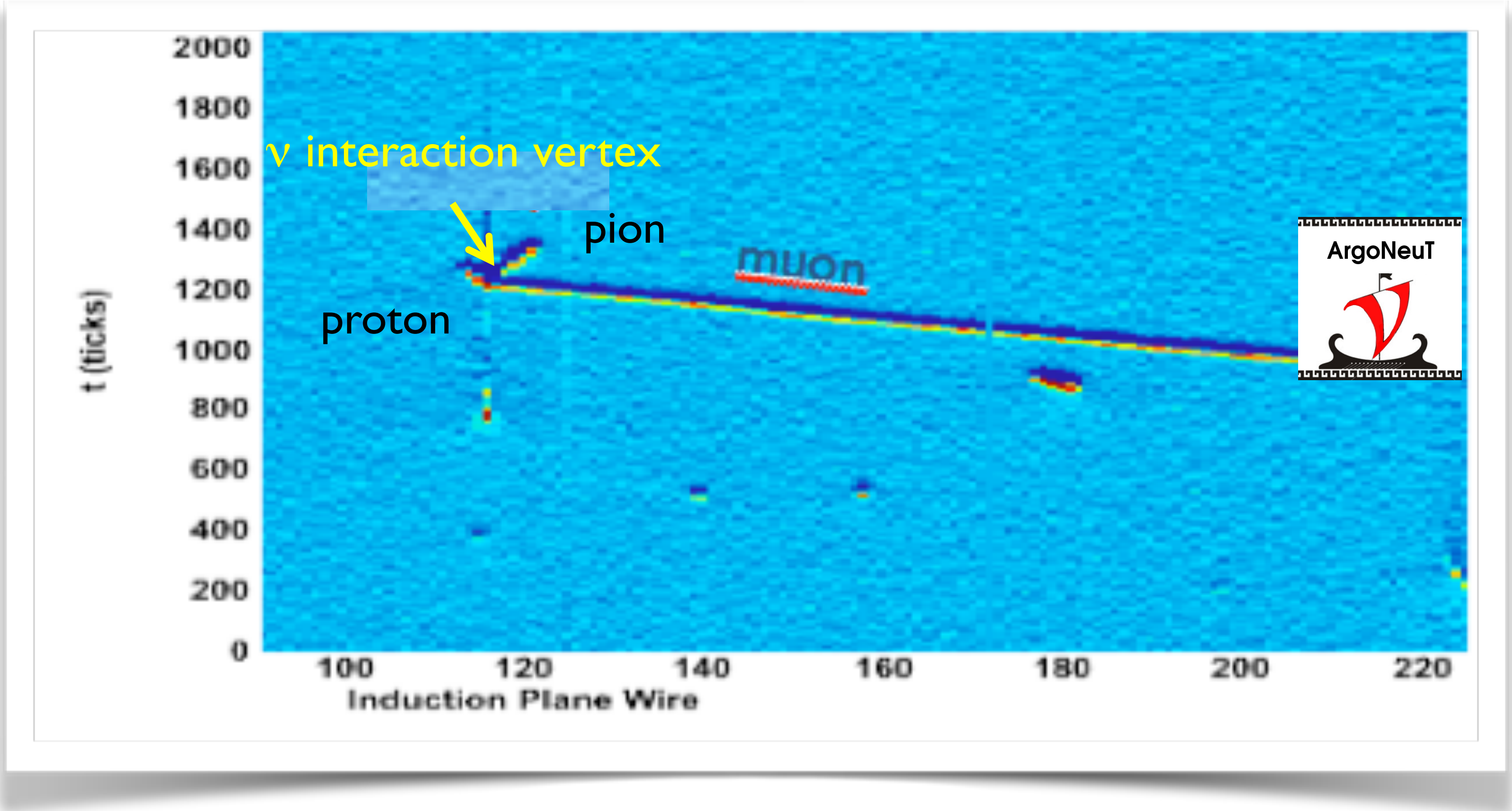
← **highly ionizing**

← m.i.p.

Low charge

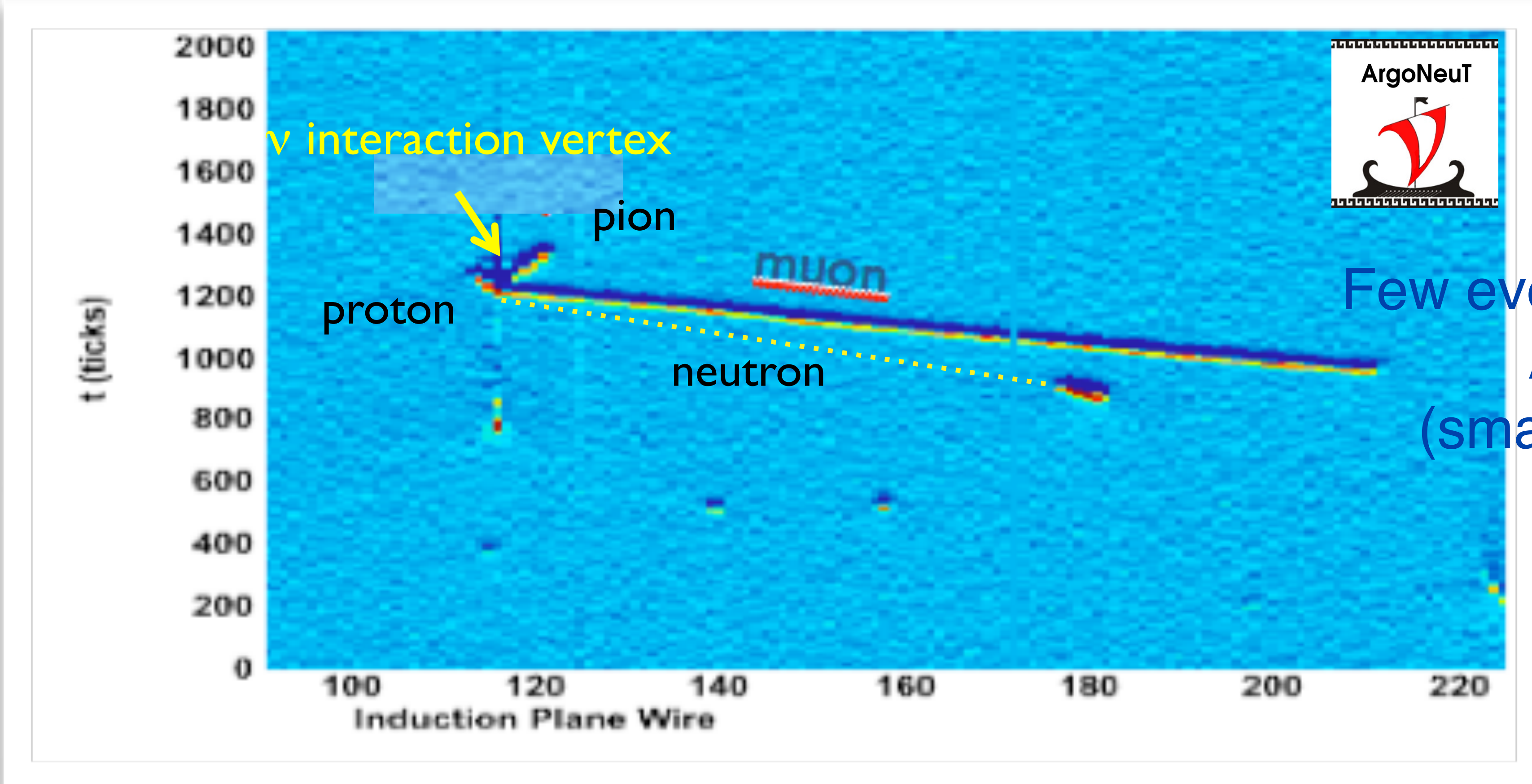
multi-p accompanying the leading muon

Reconstructing E_ν: Invisible Energy



- Reconstruct the energy of the incoming neutrino without knowing:
  - the initial state of the target (need model - particularly important at low energies)
  - if all final state particles are observable. Initial correlations and final state interaction affect the resolution
    - We know the neutrino direction, so we can determine the missing transverse momentum

Reconstructing E_ν: Invisible Energy



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

E_ν= deposited energy+invisible energy (from undetected particles, separation/excitation energy - for GeV neutrino events could ~10-20% of the total neutrino energy)

- We need to fully reconstruct the final state
  - If particles are missed, then the neutrino energy is incorrectly reconstructed
  - The missing hadronic energy is mostly responsible for the missing visible energy

Neutrino Energy Reconstruction in LArTPC

LArTPC enable the use of multiple neutrino energy reconstruction methods

Complication: Nuclear Effects

Sensitive to invisible energy

CCQE-Assumption

$$E_\nu^{QE} = \frac{m_N E_\mu - \frac{m_\mu^2}{2}}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Calorimetric Method

$$E_\nu^{calo} = E_\mu + \sum T_p$$

Calorimetric Method with Missing pT

Phys. Rev. D 90, 012008 (2014)

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

Includes estimate of (part of the) invisible energy

Neutrino Energy Reconstruction (CC 0 pion events)

ArgoNeuT

Phys. Rev. D 90, 012008 (2014)

Estimate of E_ν from the final state particle (muon AND protons) **measured** kinematics:

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

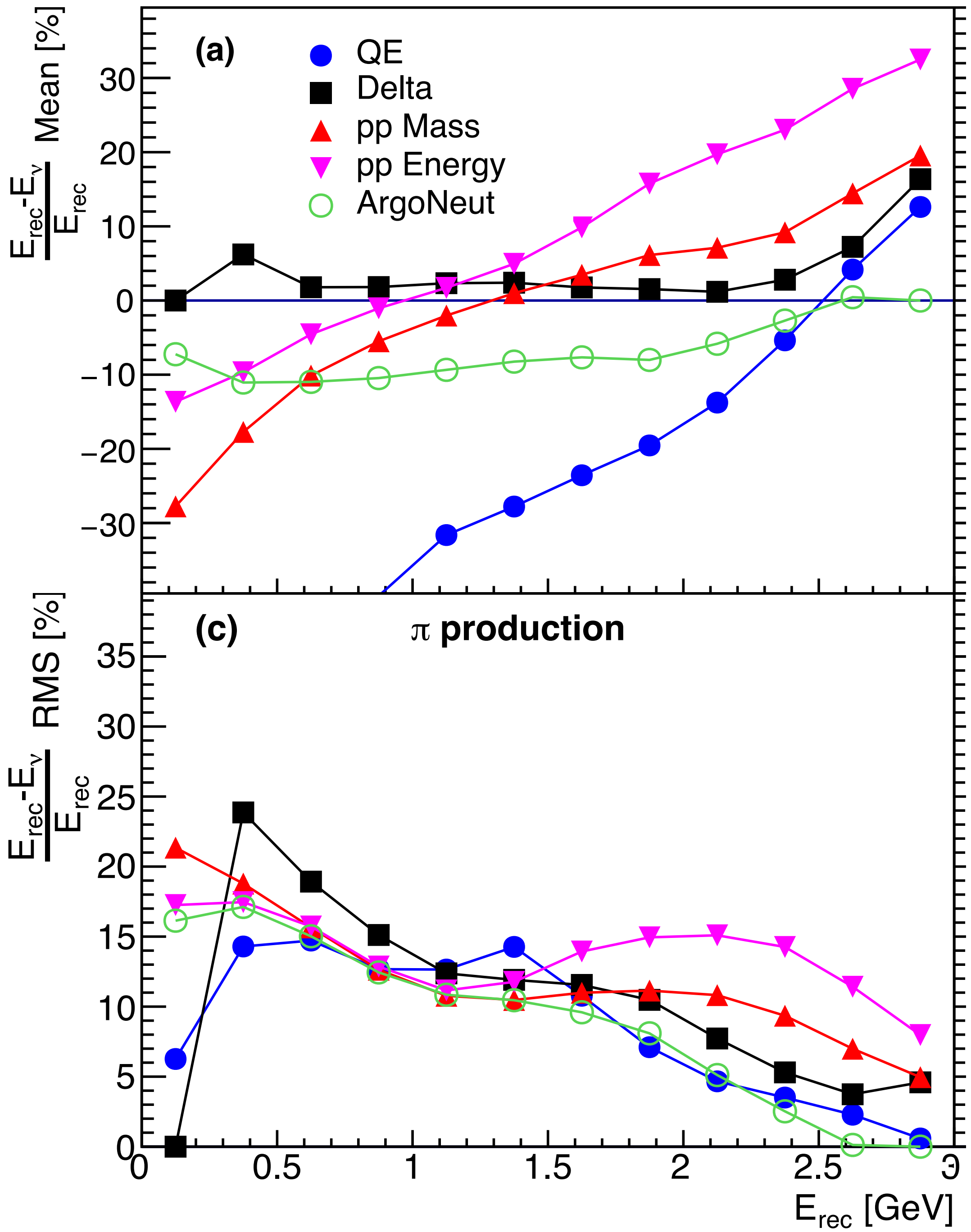
T_X=*recoil energy of the residual nuclear system* X *[undetectable]. A lower bound is estimated from the measured missing transverse momentum [we have no access to the longitudinal component of the missing momentum]:*

$$T_X \approx \frac{(p^T_{miss})^2}{2M_X}$$

E_{miss}=*missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value, e.g.* E_{miss}=30 MeV *for 2p events)*

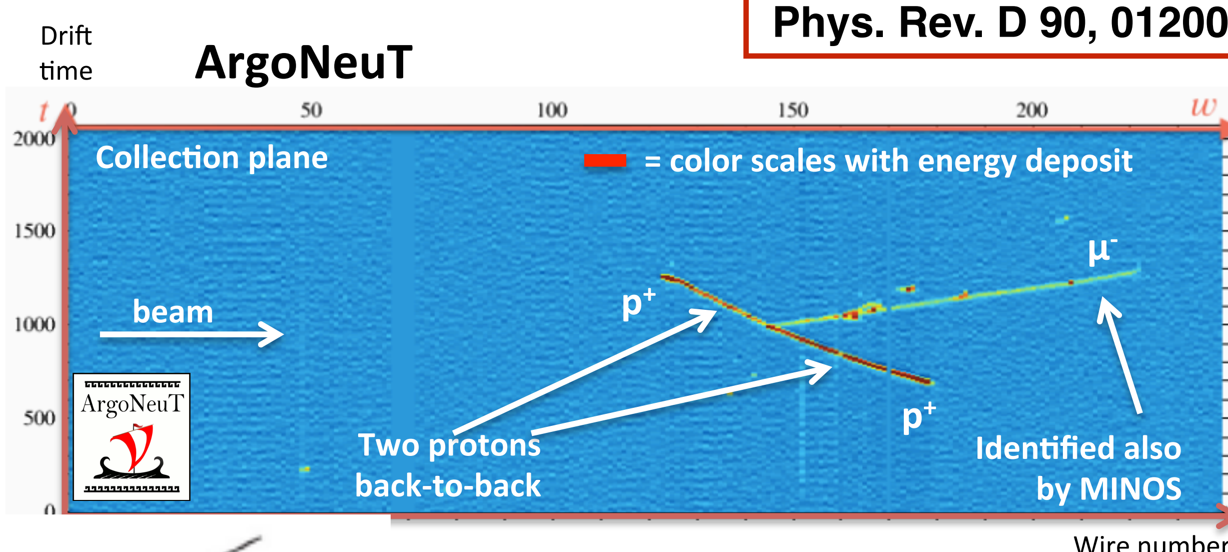
An example: "Hammer" Events

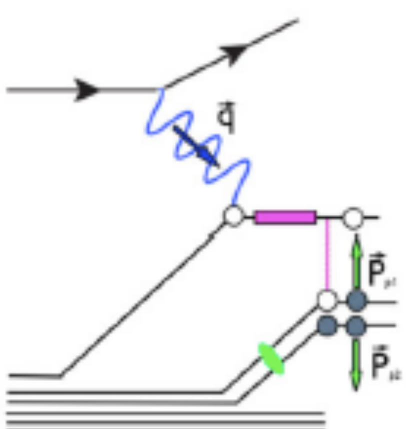
L.B. Weinstein, O. Hen, E. Piasetzky, "Hammer events, neutrino energies, and nucleon-nucleon correlations", arXiv:1604.02482



ArgoNeuT calorimetric & missing p_T energy reconstruction

Phys. Rev. D 90, 012008 (2014)



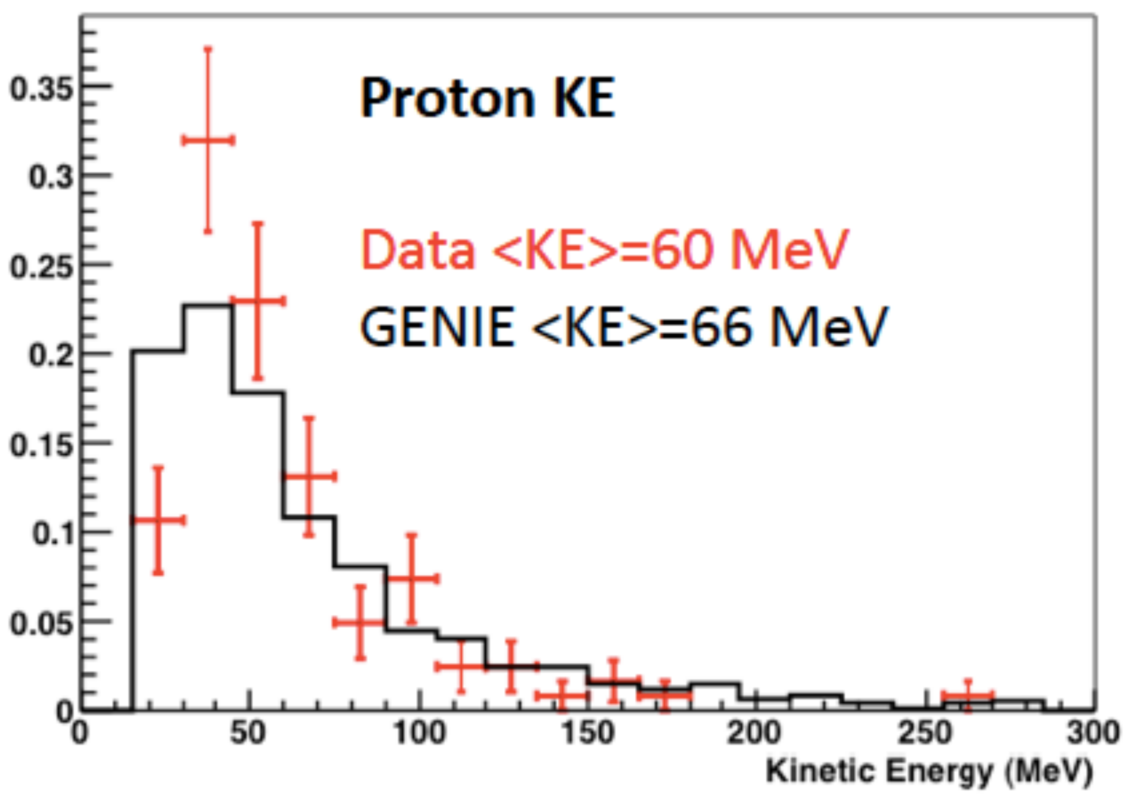


b-to-b proton events described by pion production and re-absorption model

Neutrino Energy Reconstruction (CC 0 pion events)

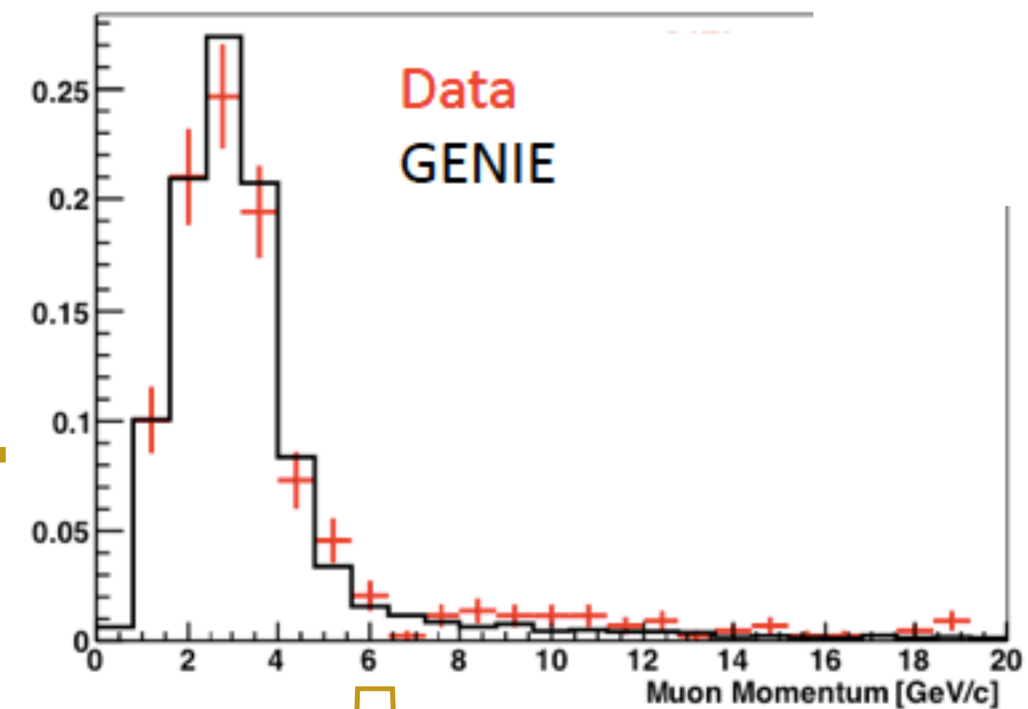
ArgoNeuT

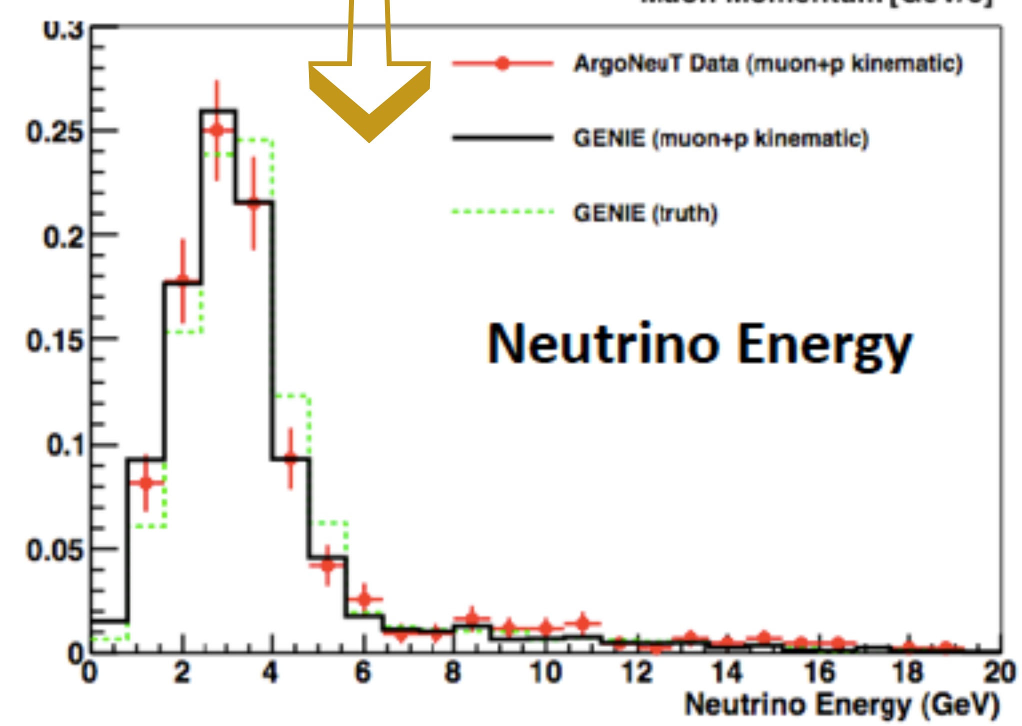
$\bar{\nu}_\mu$ – antineutrino mode run



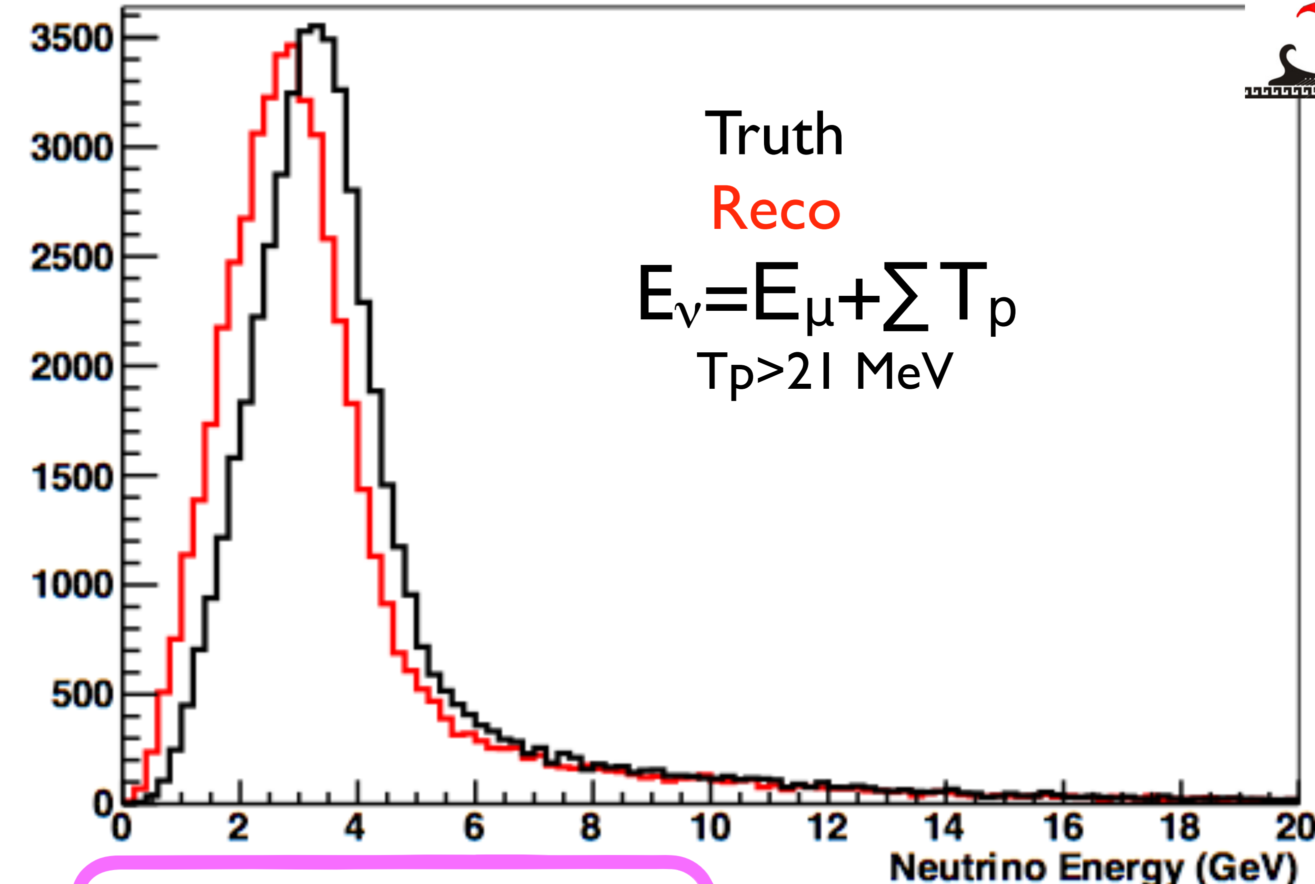
+

Muon Momentum





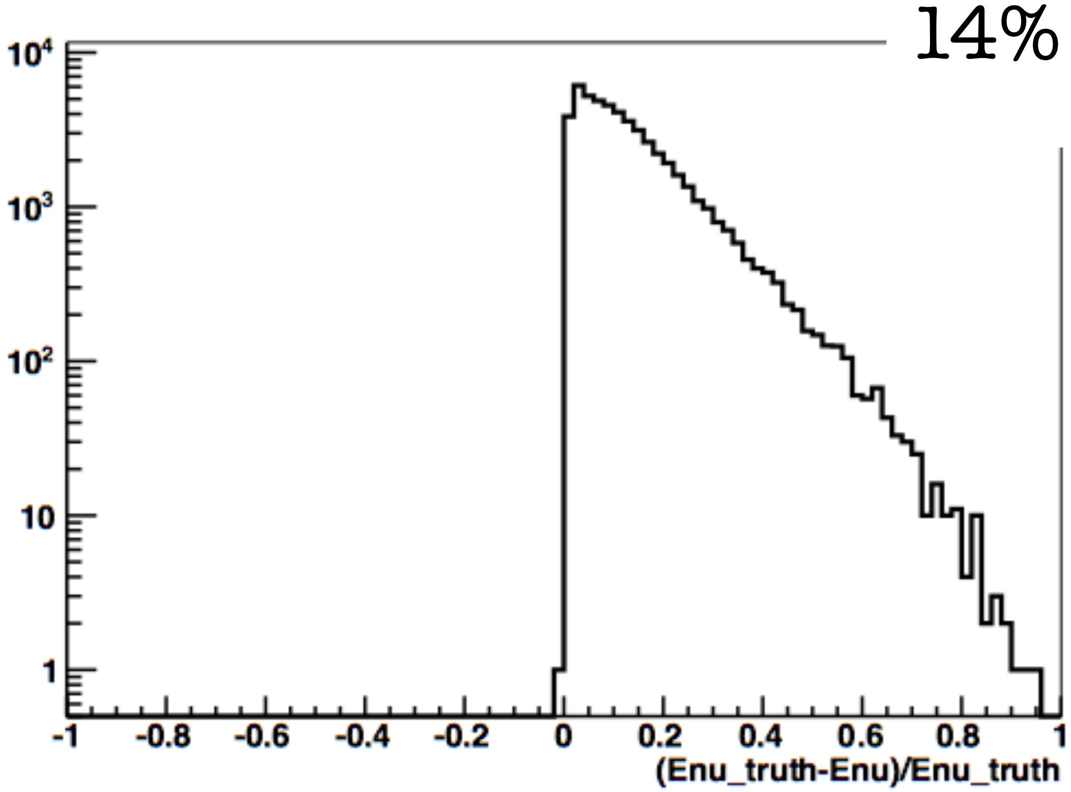
$\langle E_\nu \rangle = 3.6$ GeV



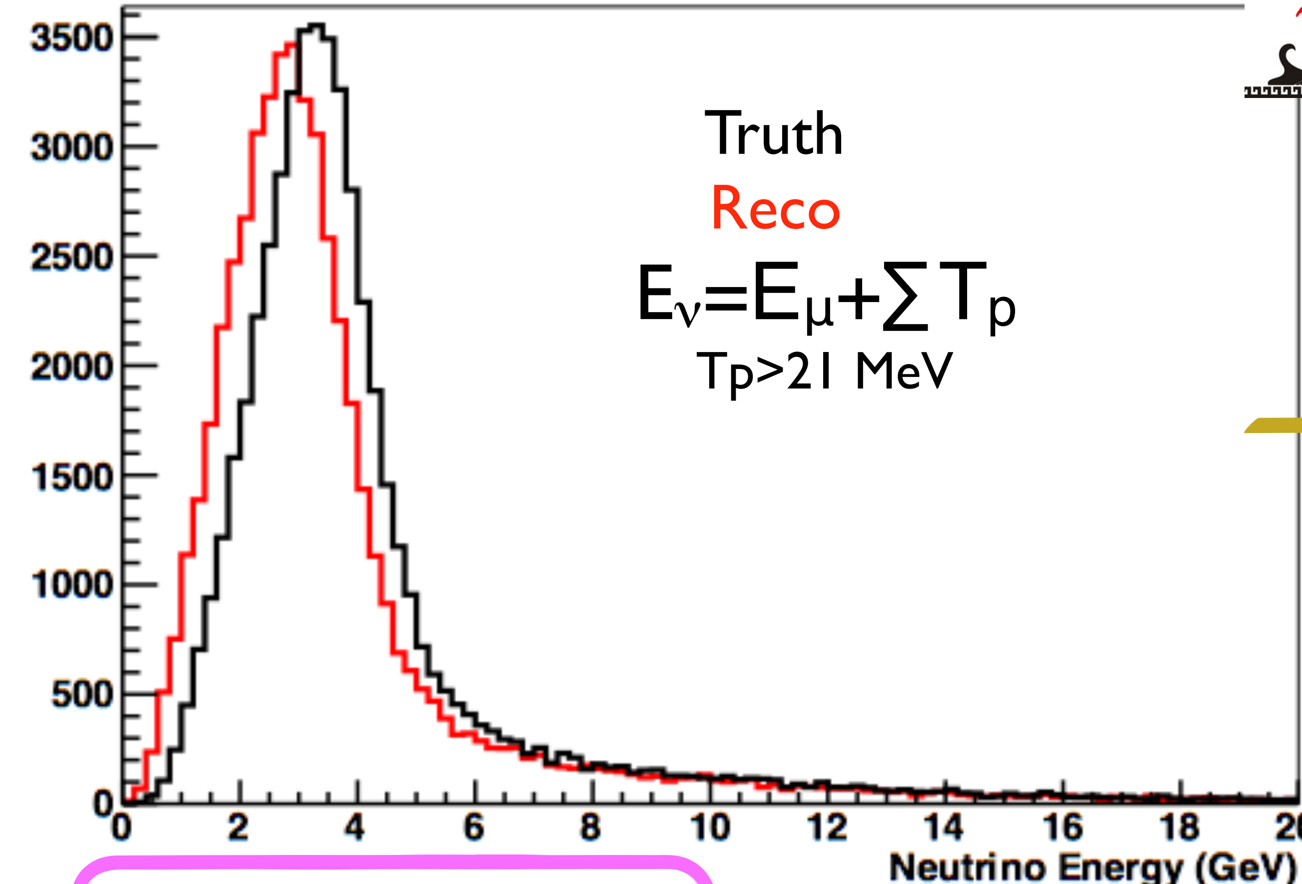
μ^+Np
final state events
anti-nu mode

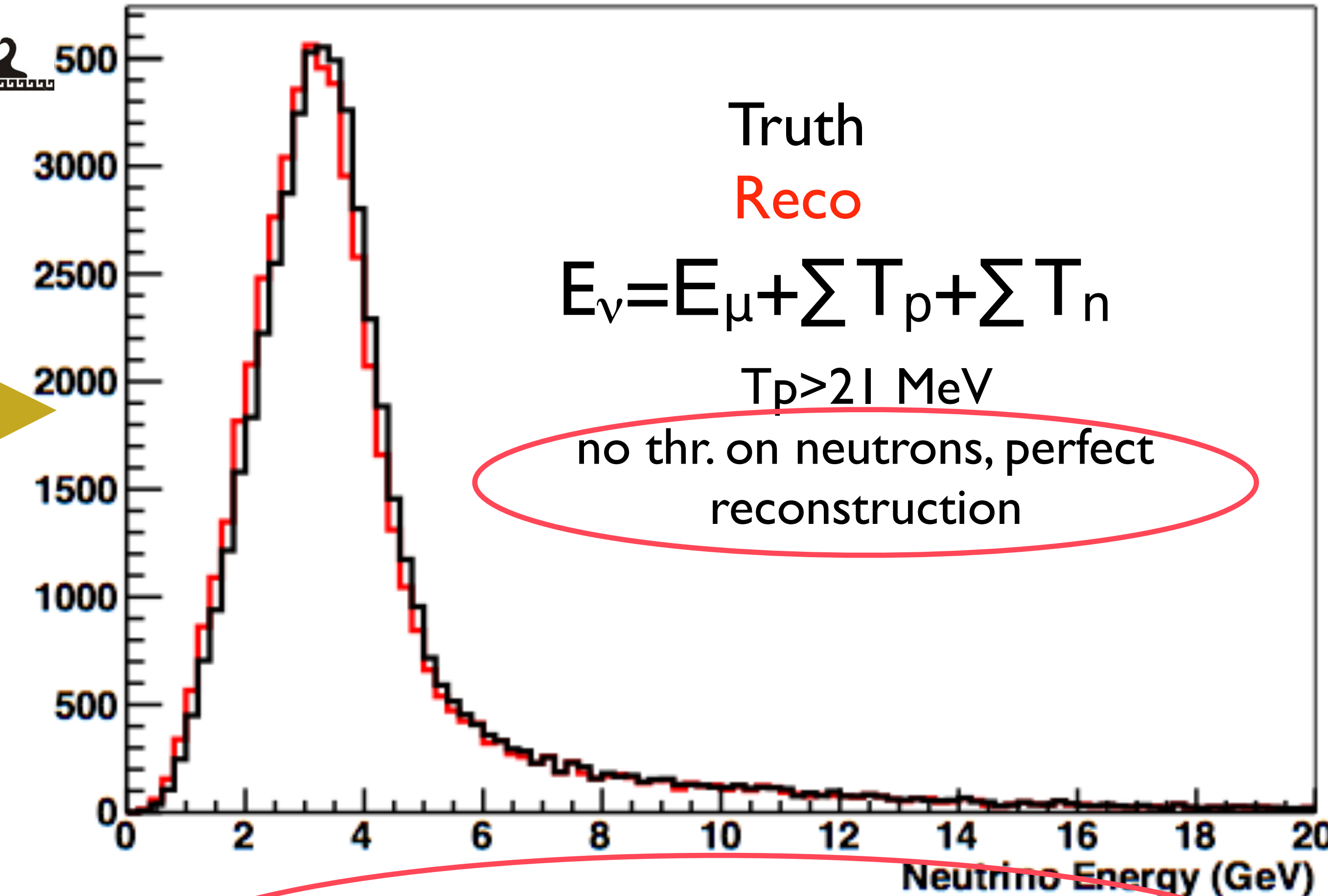
GENIE

14%



ArgoNeuT

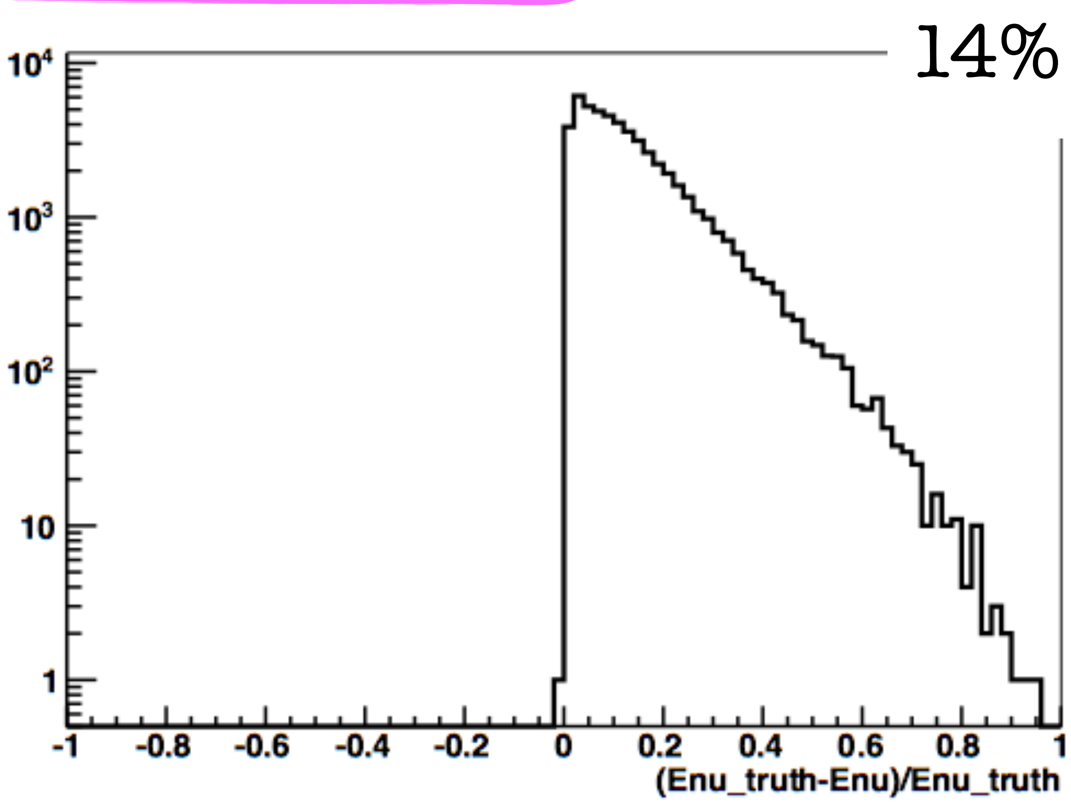


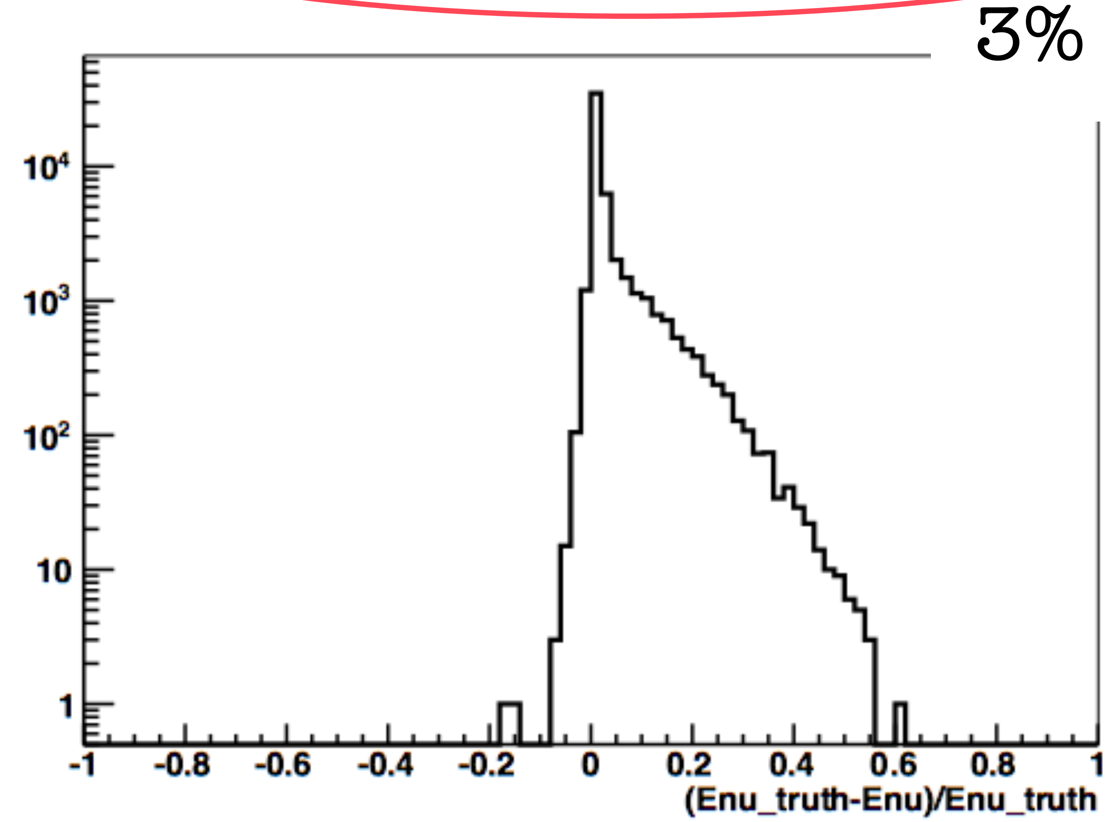


μ^+Np
final state events
anti–nu mode

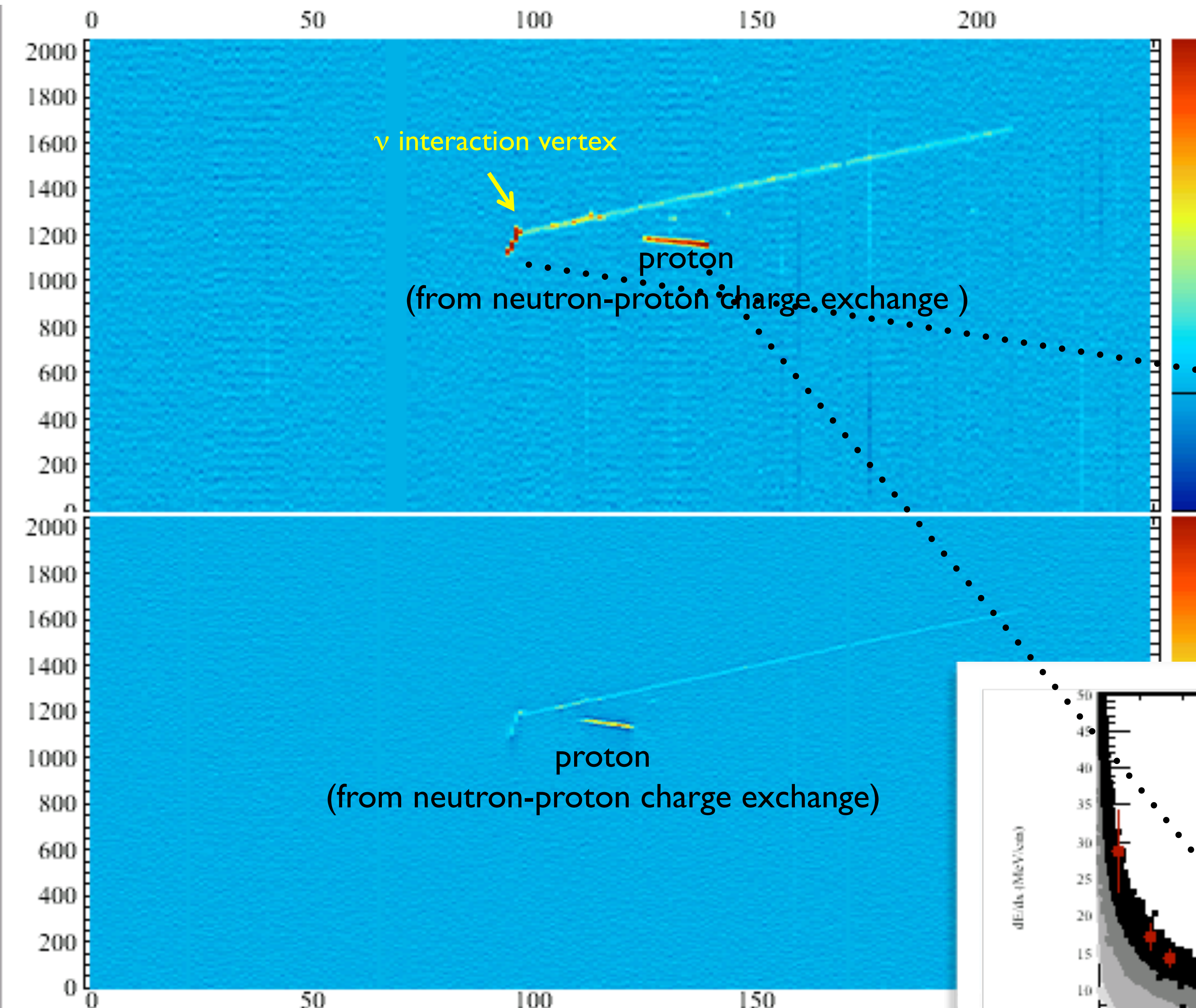
GENIE

Including neutrons

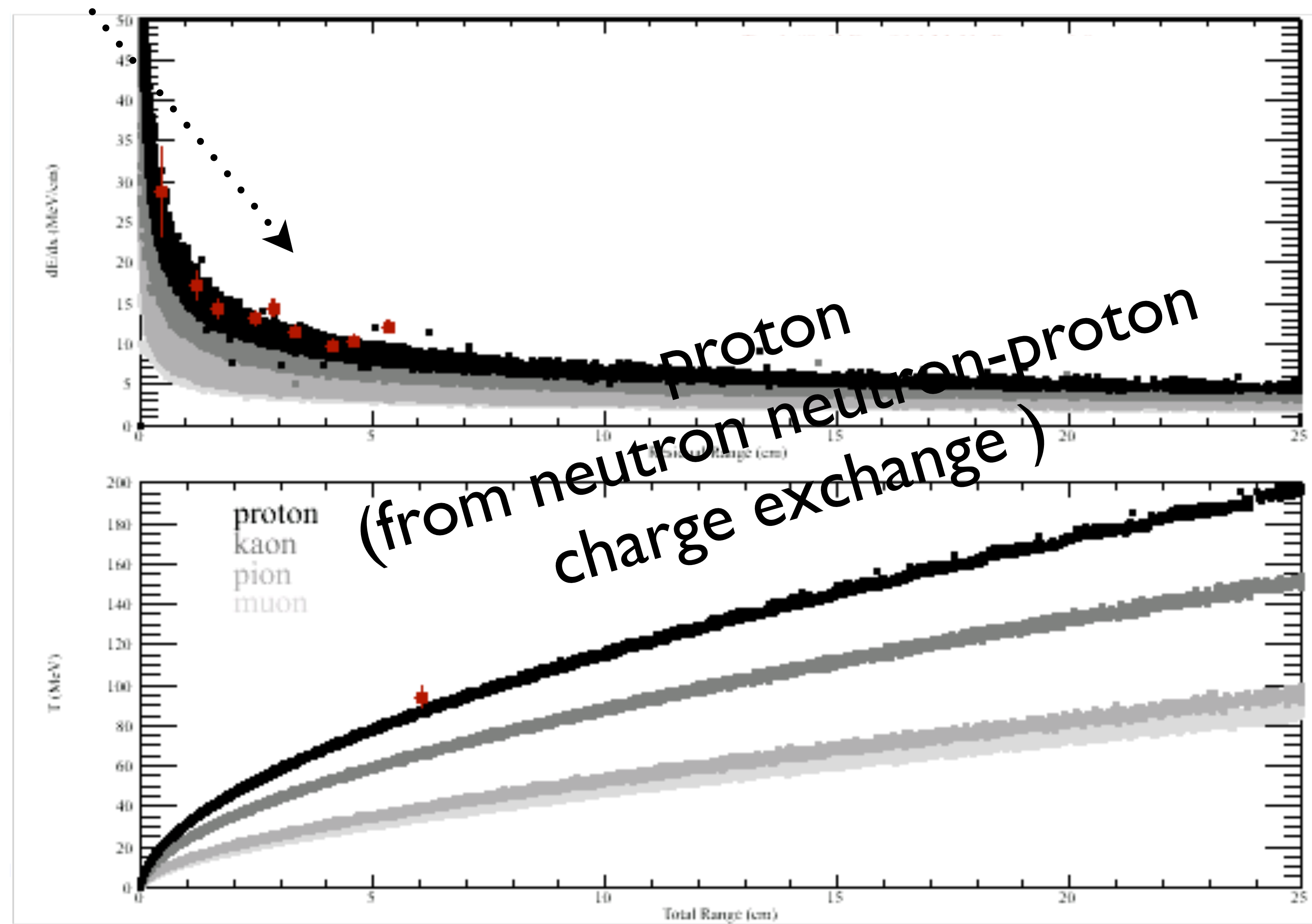




Reconstruction of neutrons in LAr (via proton from neutron-proton charge exchange scattering)



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

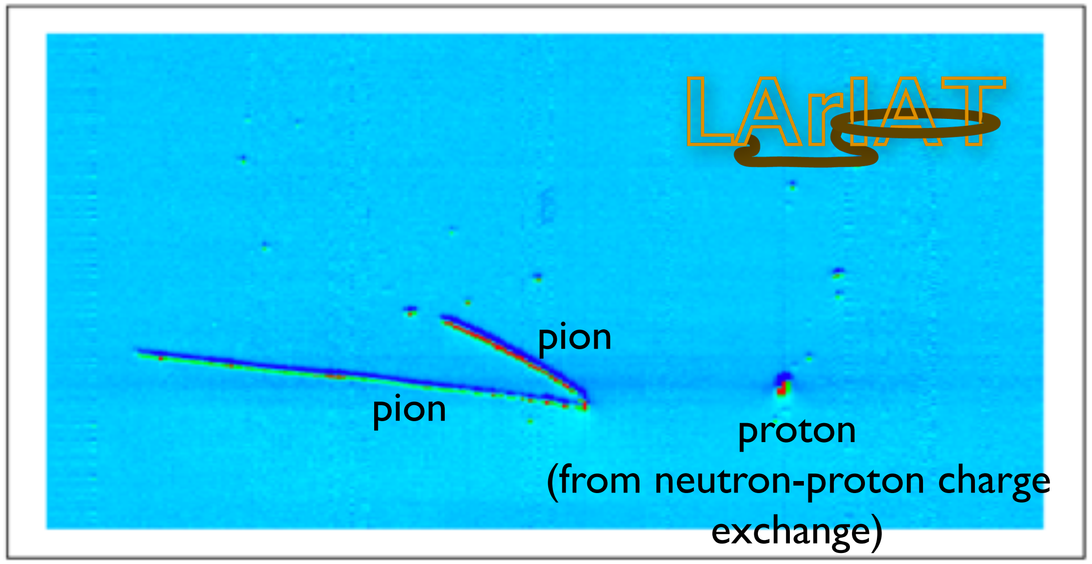


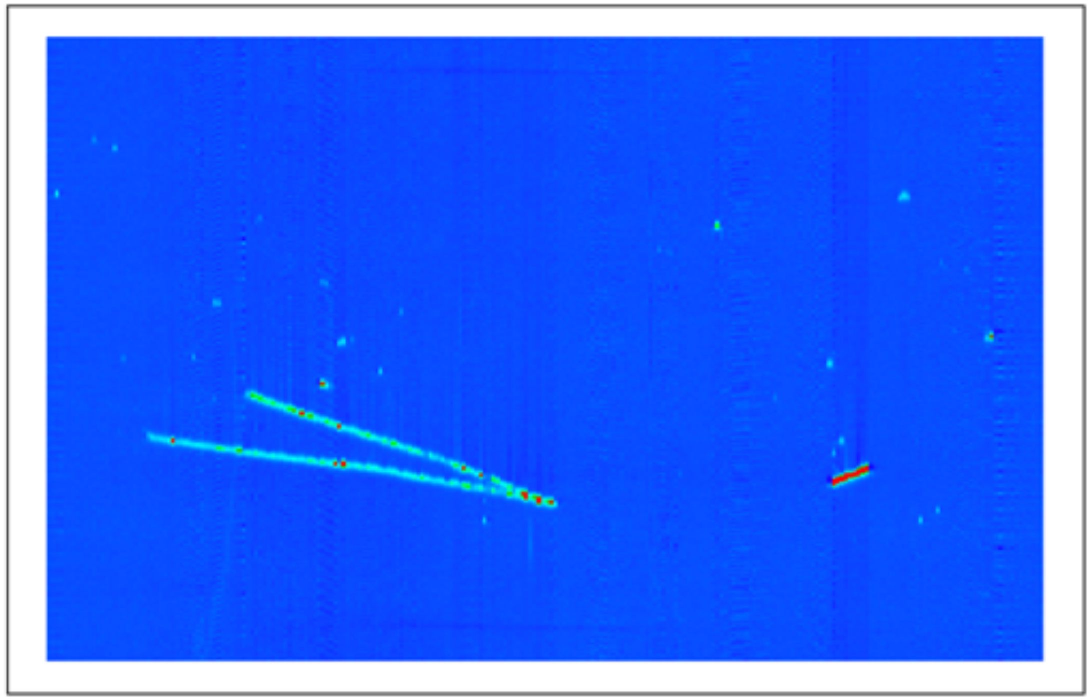
ArgoNeuT

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

Neutron energy reconstruction

- "Detection" of neutrons and estimate of neutron energy reconstruction in LAr
  - MC studies (neutron containment*, fraction of neutron-proton charge exchange scattering, proton energy vs neutron energy...)
  - Measurements in ProtoDUNE (via protons from neutron-proton charge exchange)





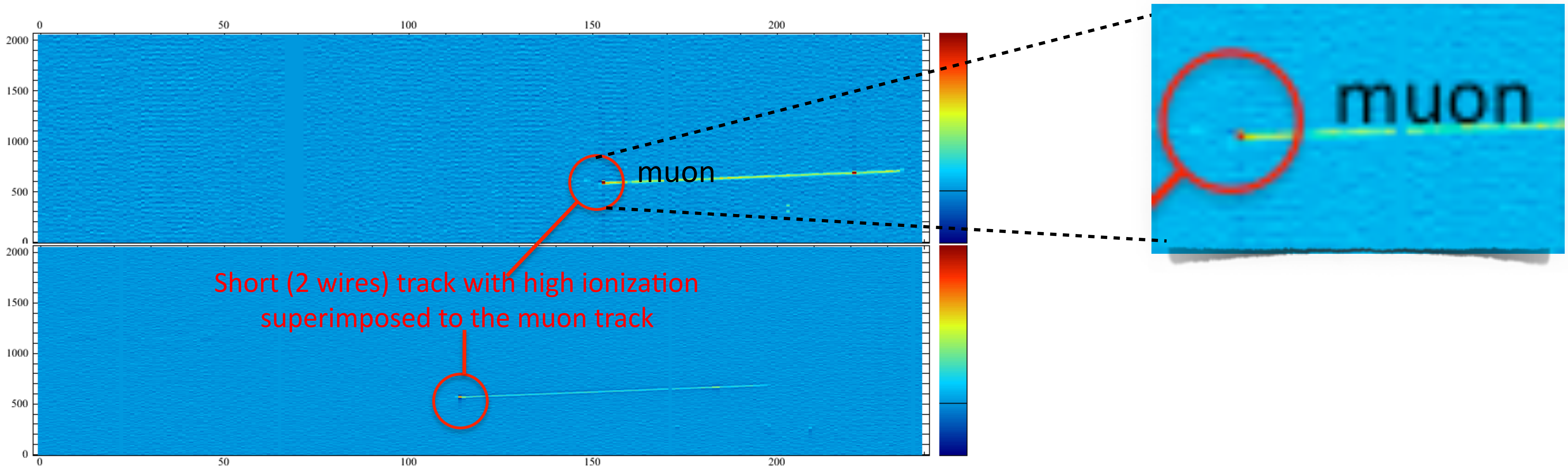
* see presentation on hadron containment by Pawel Guzowski

Summary

- Thanks to the LArTPC technology we can rely of different methods of neutrino energy reconstruction
- Missing transverse momentum can be used to improve the accuracy of energy reconstruction (ArgoNeuT)
- ProtoDUNE will tell us if the measurement of neutrons can further improve the neutrino energy reconstruction

Overflow

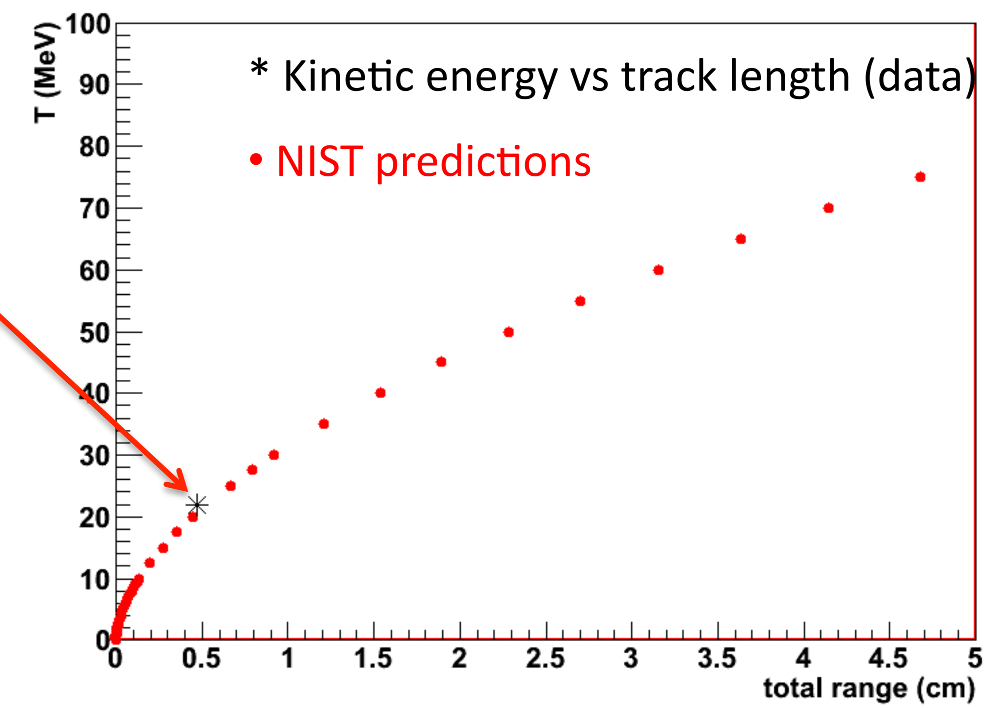
Low energy proton reconstruction



The short track behaves like proton

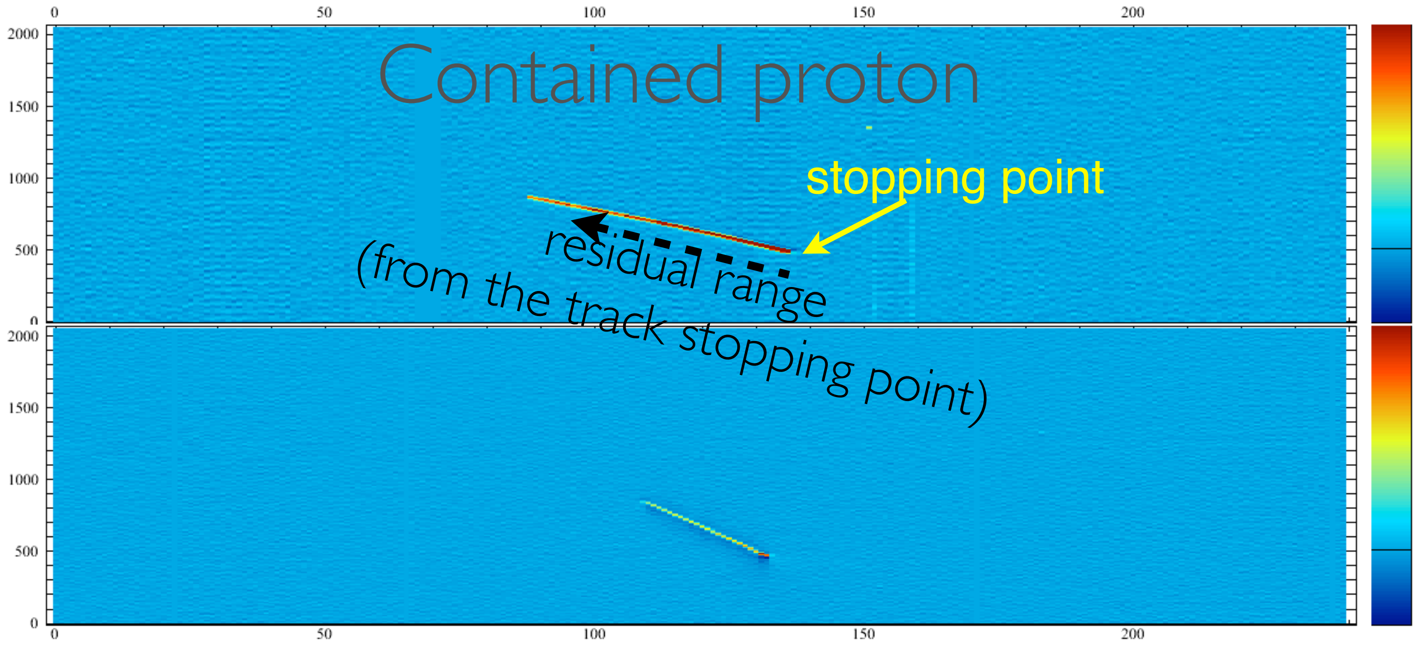
Length=0.5 cm

T_p=22±3 MeV

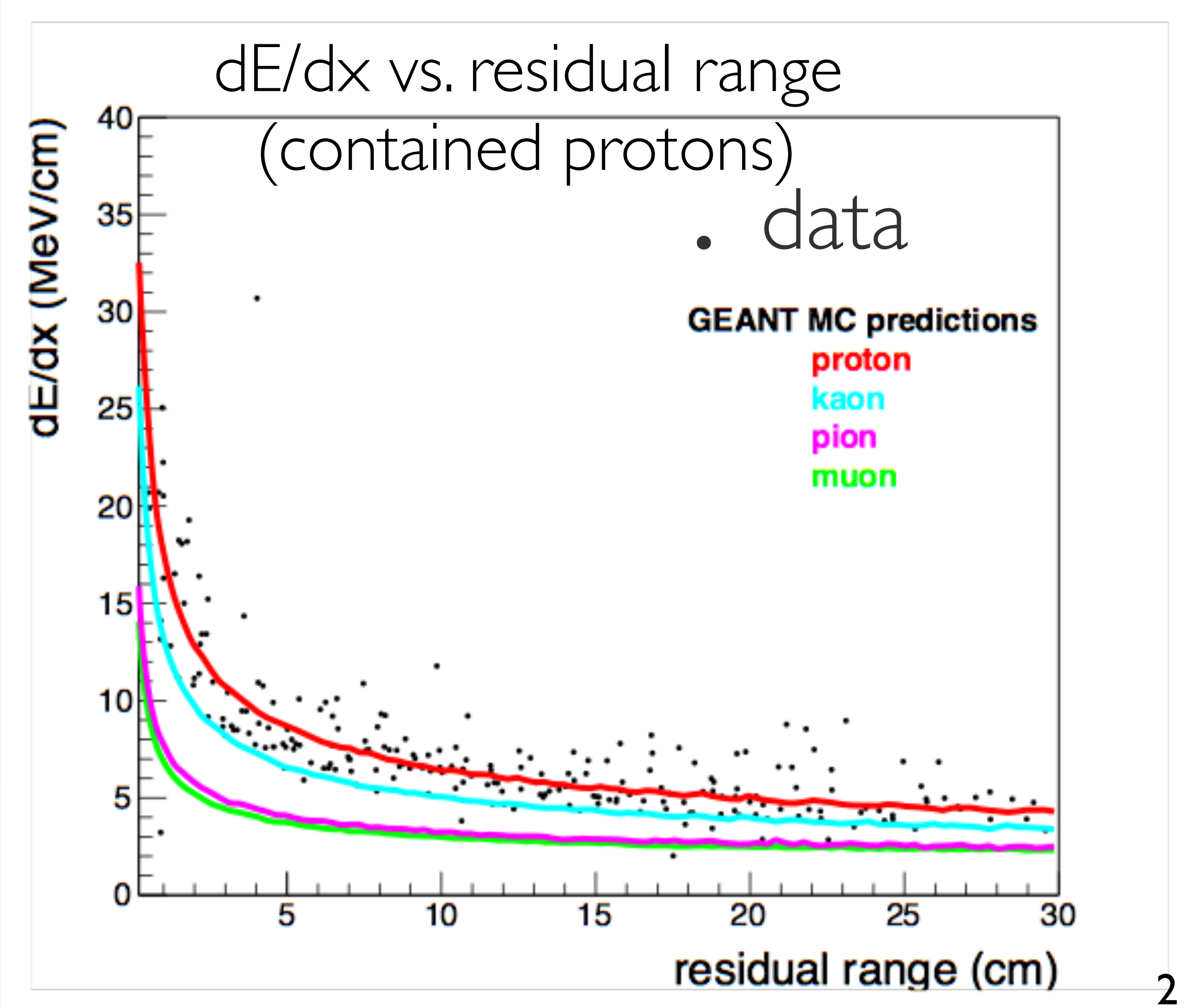


ArgoNeuT proton threshold: 21 MeV Kinetic Energy

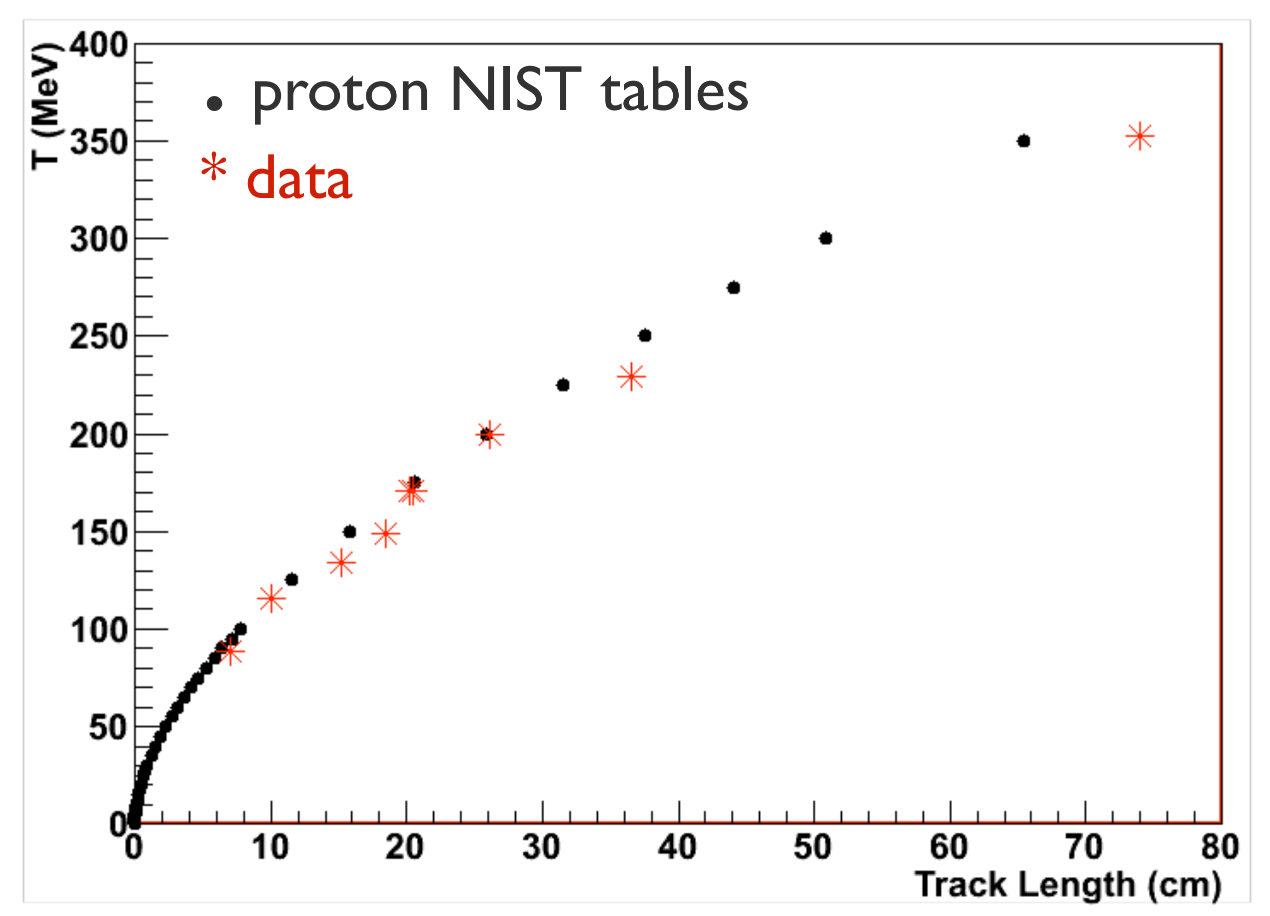
Stopping tracks - Calorimetric reconstruction and PID



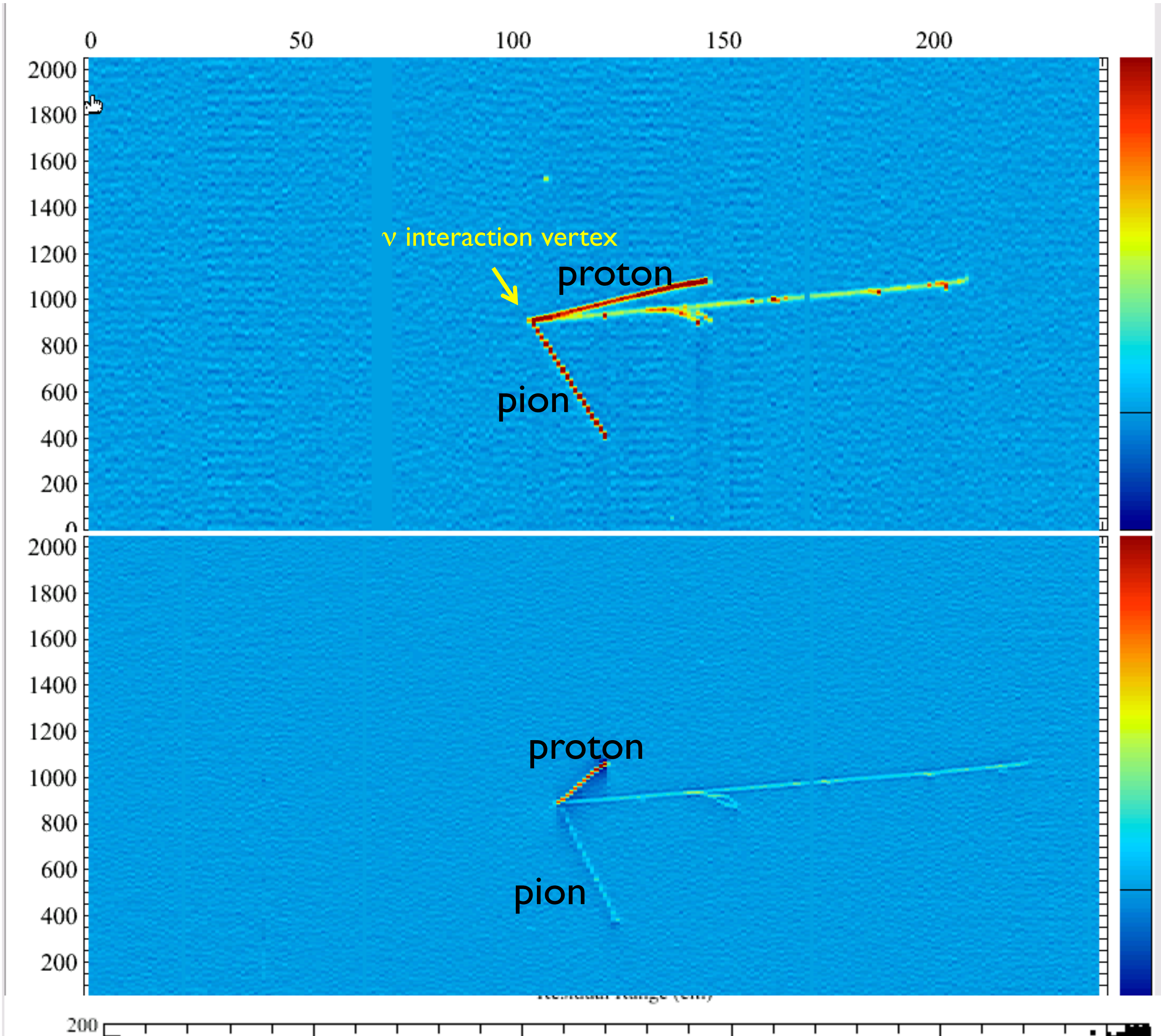
The energy loss as a function of distance from the end of the track is used as a powerful method for particle identification.

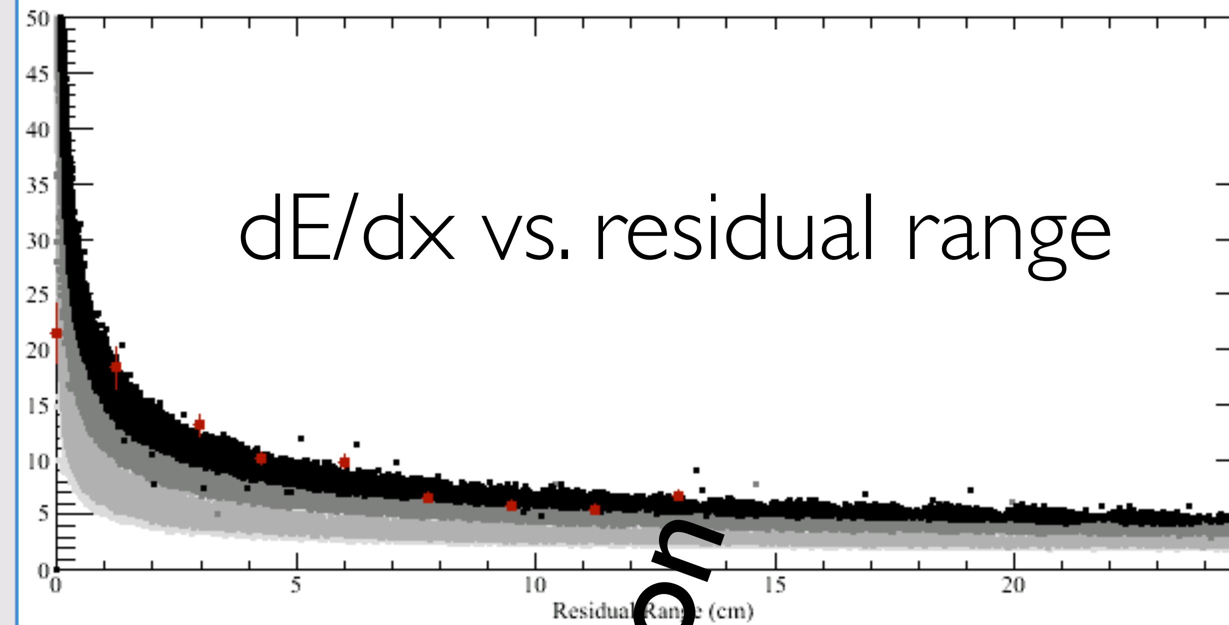


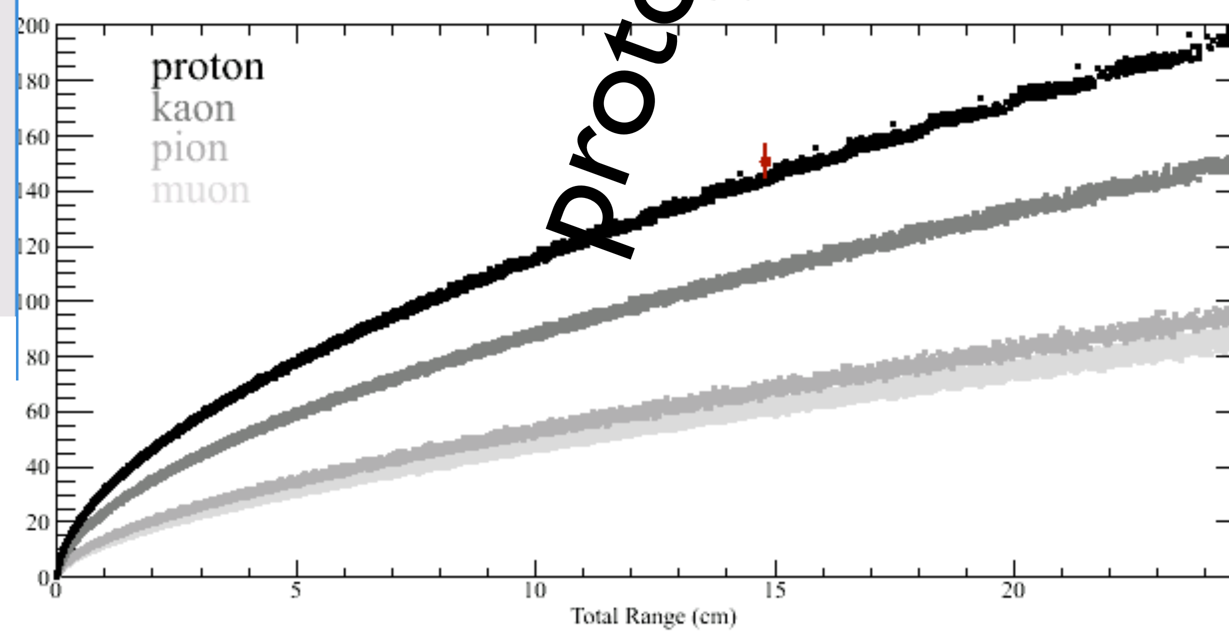
Kinetic Energy vs. track length

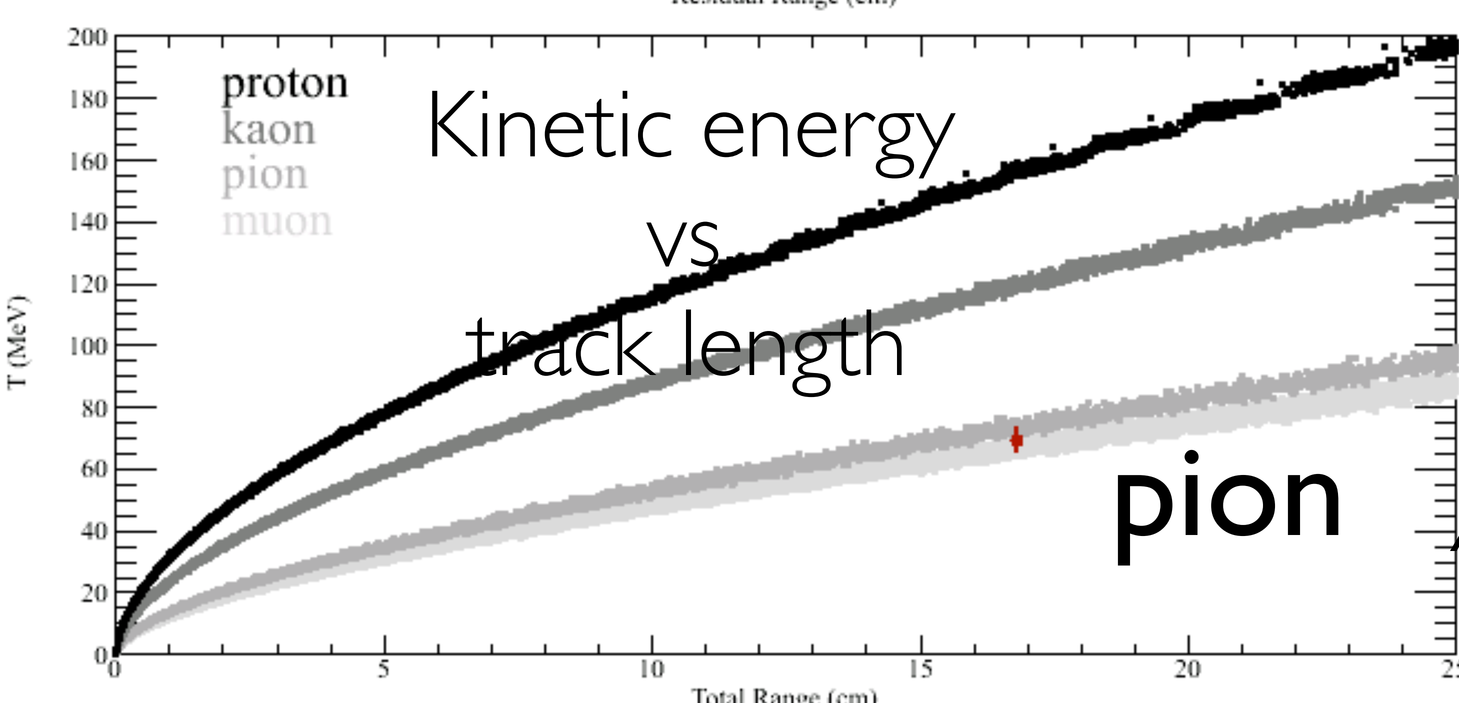


p/π± identification









ArgoNeuT pion reconstruction threshold: ~8 MeV Kinetic energy

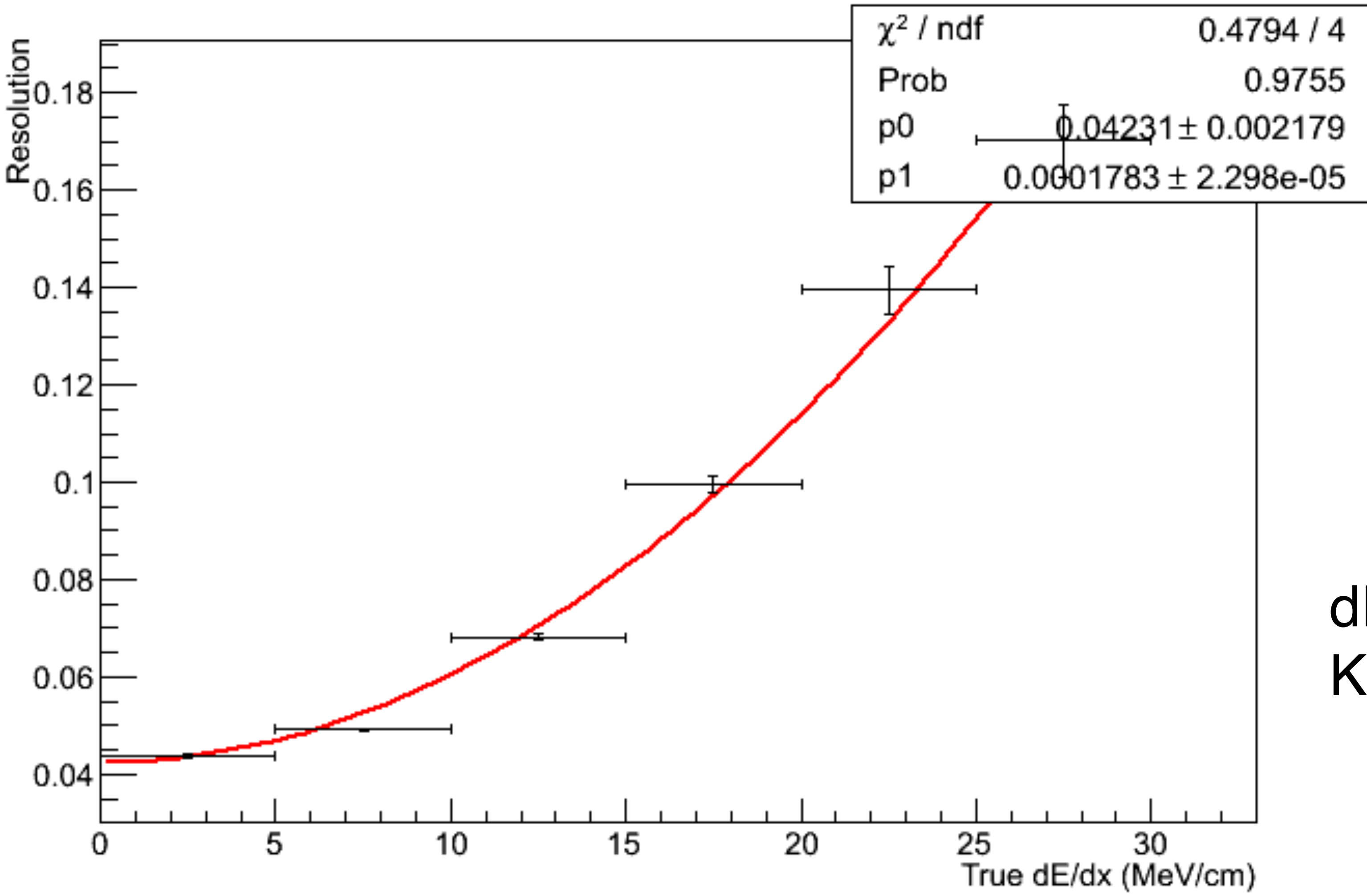
PID Efficiencies

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



dEdx: 0.04231+0.0001783*(dEdx)^2
KE: 0.6064/sqrt(KE)

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