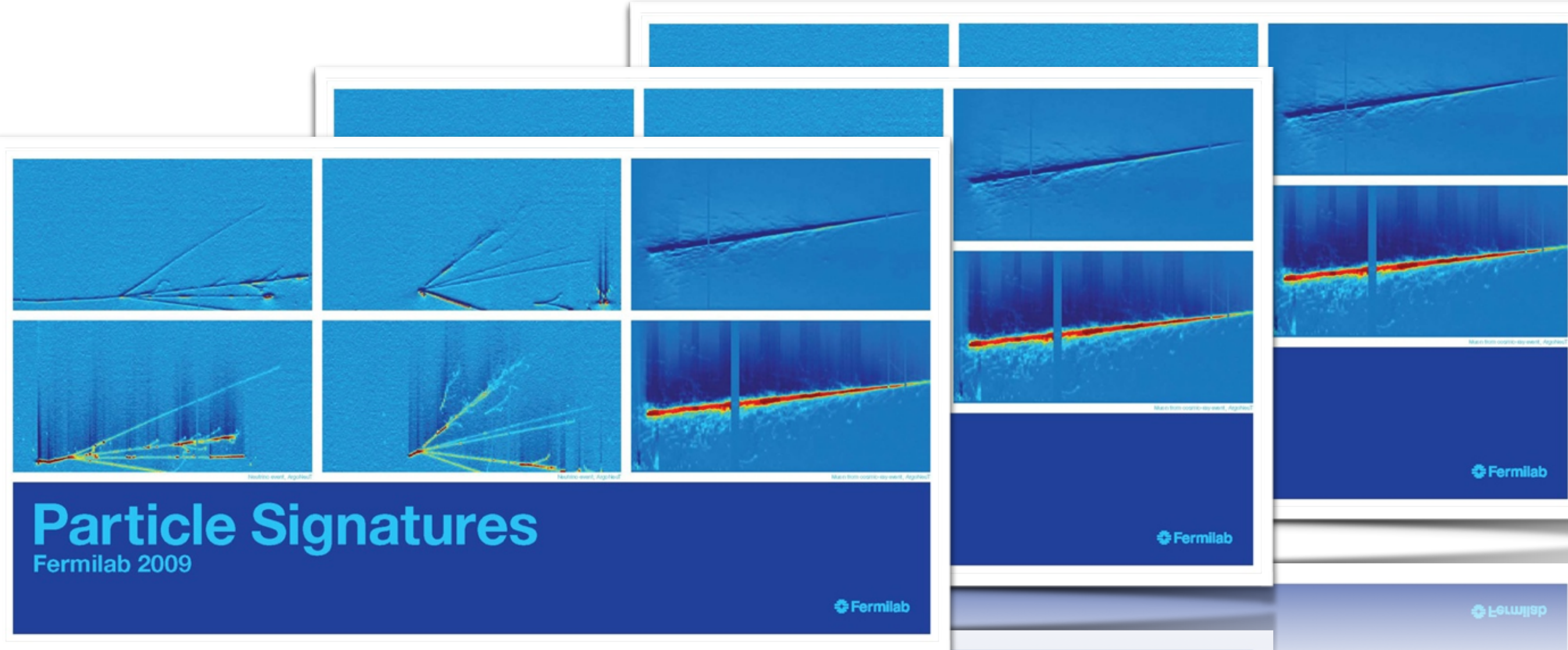


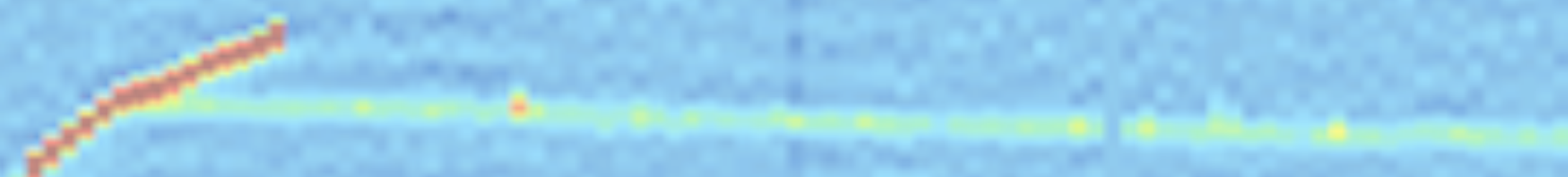
CC 0 pion: ArgoNeuT results & future prospects in LAr detectors



NUINT15 - Osaka
November 17th, 2015
Ornella Palamara
Fermilab & Yale University, USA *

Outline

- ◎ **ArgoNeuT ν_μ CC pion-less events (0 pion events)**
 - **Topological analysis**
 - **Inclusive and Exclusive cross sections**
- ◎ **Future prospects in LAr detectors (LArIAT, MicroBooNE and SBND experiments)**



Fermilab – NuMI Neutrino beam



Minos-ND
Hall

NuMI

Fermilab's **high-energy** neutrino beam: $\langle E_\nu \rangle \approx 4\text{-}7 \text{ GeV}$ (tunable)

Main Injector - 120 GeV protons

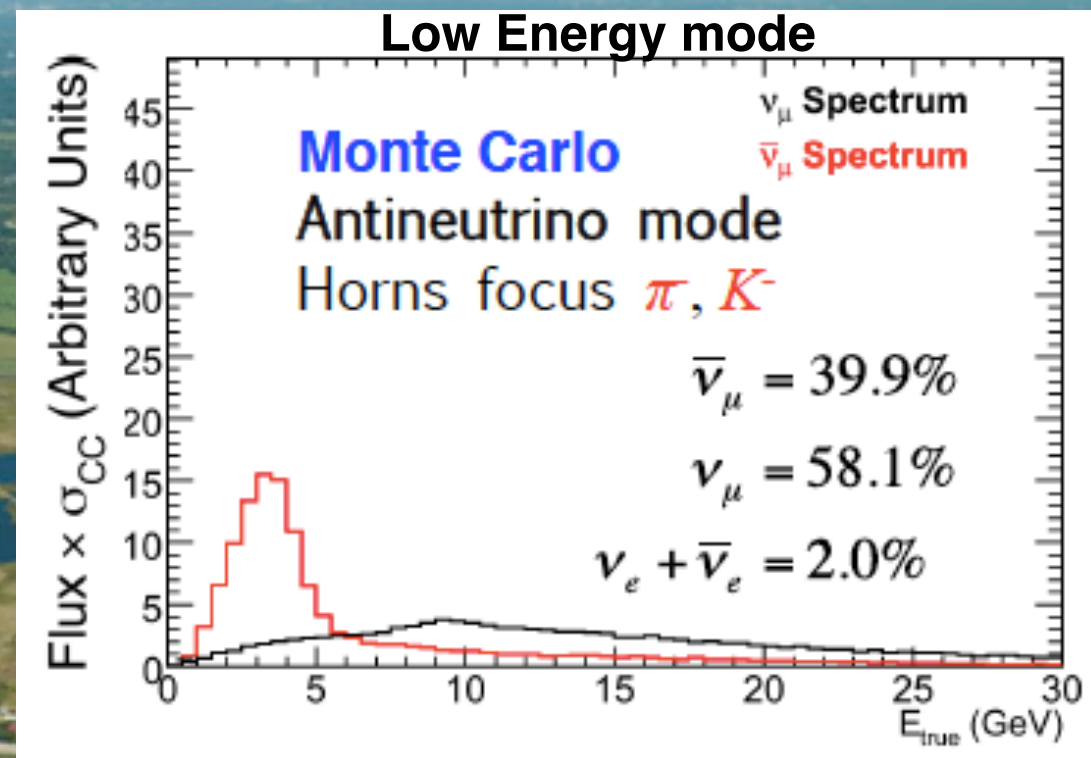
Fermilab – NuMI Neutrino beam

Minos-ND
Hall

NuMI

Fermilab's **high-energy** neutrino beam: $\langle E_\nu \rangle \approx 4\text{-}7\text{ GeV}$ (tunable)

Main Injector - 120 GeV protons



ArgoNeuT experiment in the NUMI Beam

First LAr TPC in a neutrino beam in the US

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

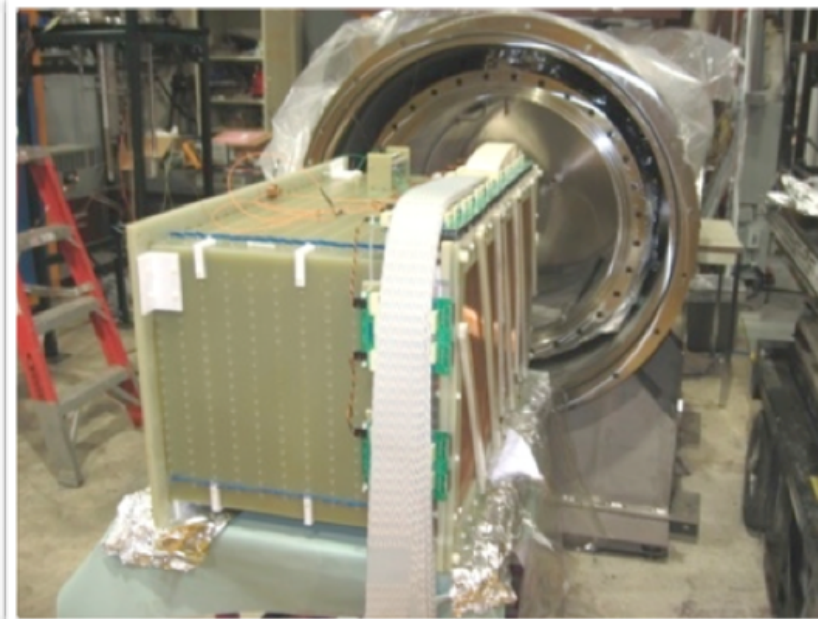
Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode

240 Kg active volume

LAr TPC

47×40×90 cm³, 2 readout planes,
480 wires, 4 mm spacing,
no light detection system

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*



ArgoNeuT experiment in the NUMI Beam

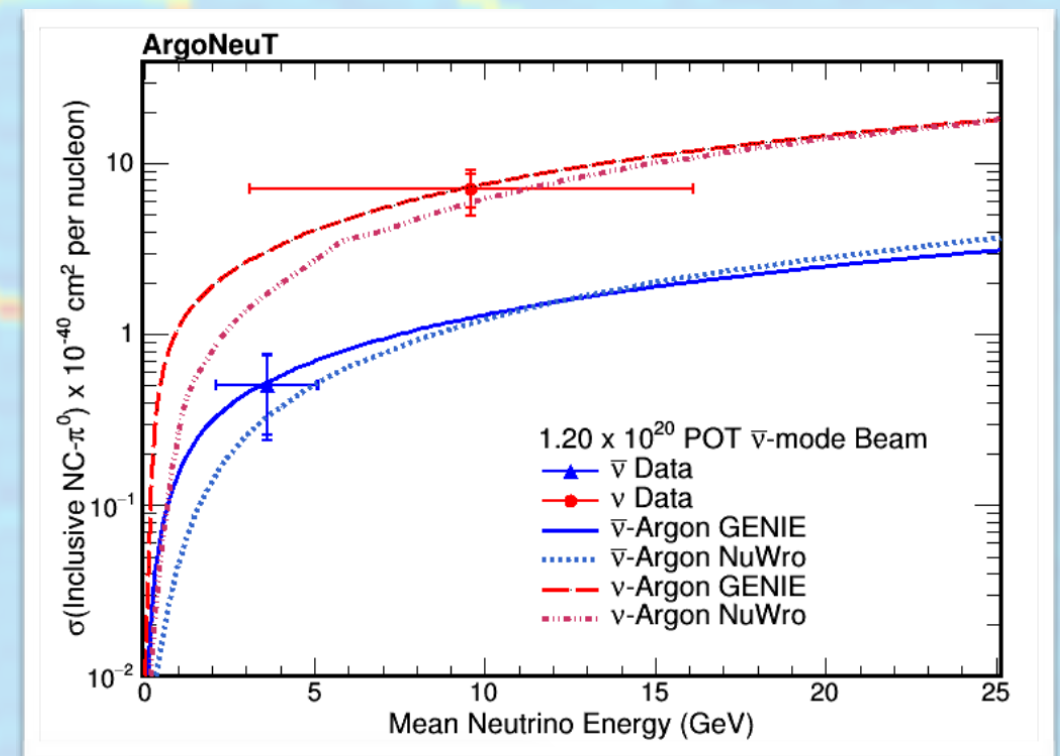


~7000 CC events
collected

Designed as test experiment
but obtaining physics results!

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

***New result:
Neutral Current π^0 cross sections***



<http://arxiv.org/abs/1511.00941>

Publications so far: ν -Ar cross
sections measurements, LAr TPC
calibration techniques and studies of
nuclear effects in ν -Ar interactions

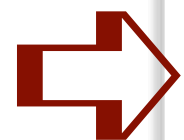
LAr TPC and Exclusive topologies

LAr TPC detectors

- provide *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* and
- allow for **Exclusive Topology recognition/reconstruction** and **Nuclear Effects exploration** from detailed studies of the **hadronic** part of the final states.

LAr TPC is an Ideal detector for Few-GeV ν scattering measurements

CC NEUTRINO EVENTS IN LAr CAN BE CLASSIFIED IN TERMS OF **FINAL STATE TOPOLOGY** BASED ON PARTICLE MULTIPLICITY:



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

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

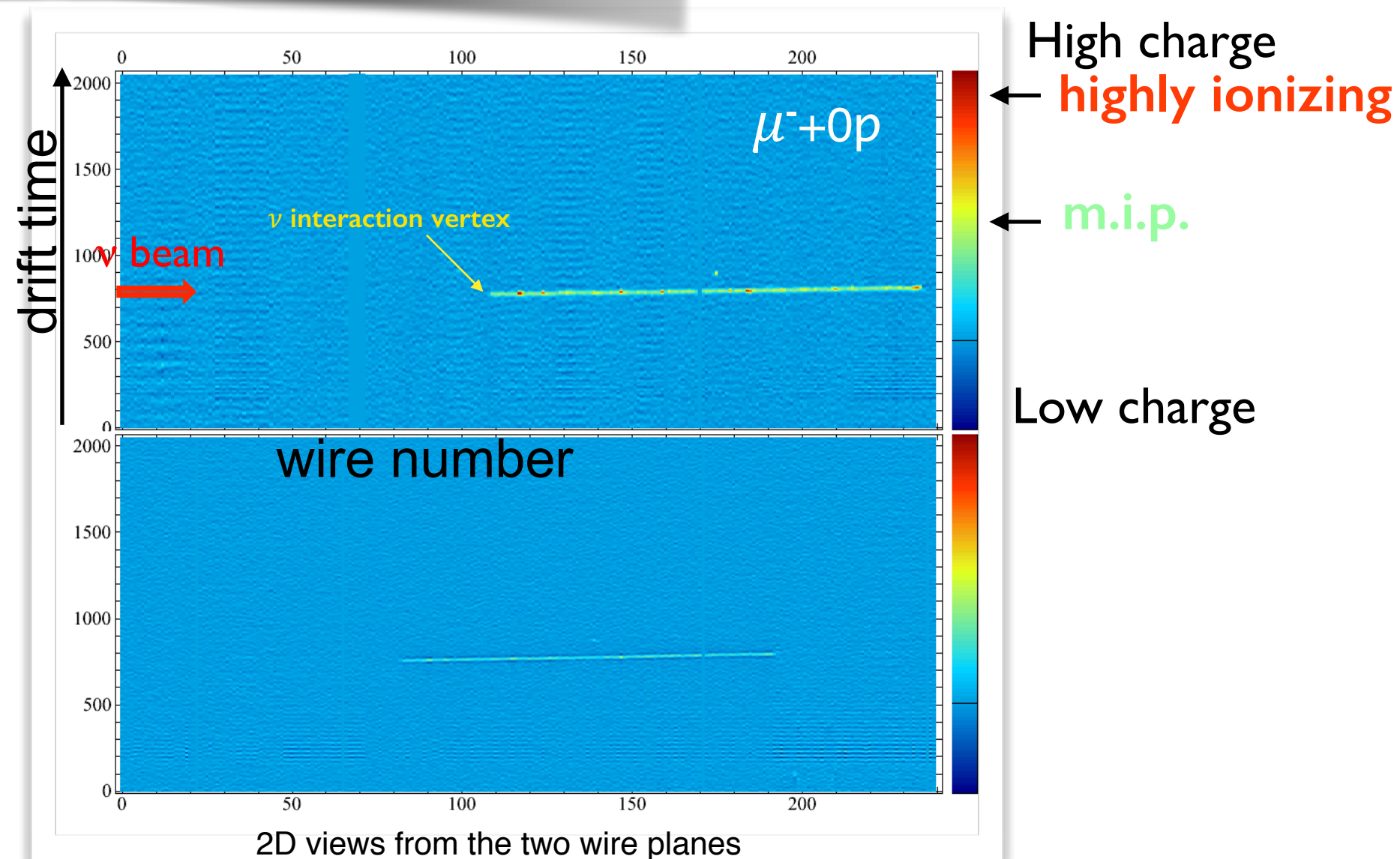
0 PION EVENT TOPOLOGY: leading muon accompanied by any number ($N=0, 1, 2, 3, 4$) of protons final state

Looking for pion-less final states

- Proton/pion separation through **energy deposition vs range** measurement
- Measurements of *proton multiplicity* at the neutrino interaction vertex and *reconstruction of proton(s) kinematics*

LAr TPC is an Ideal detector for Few-GeV ν scattering measurements

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

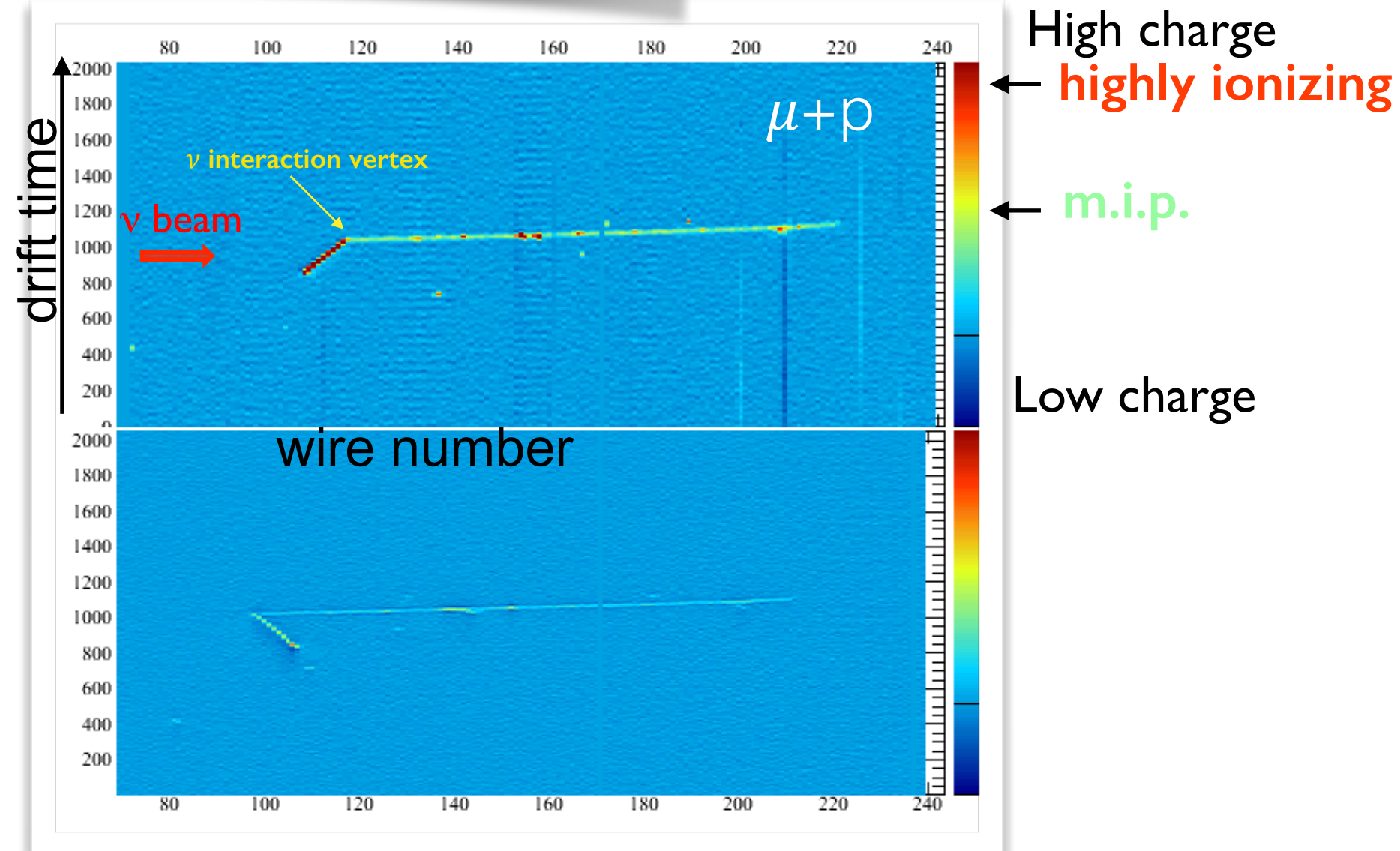


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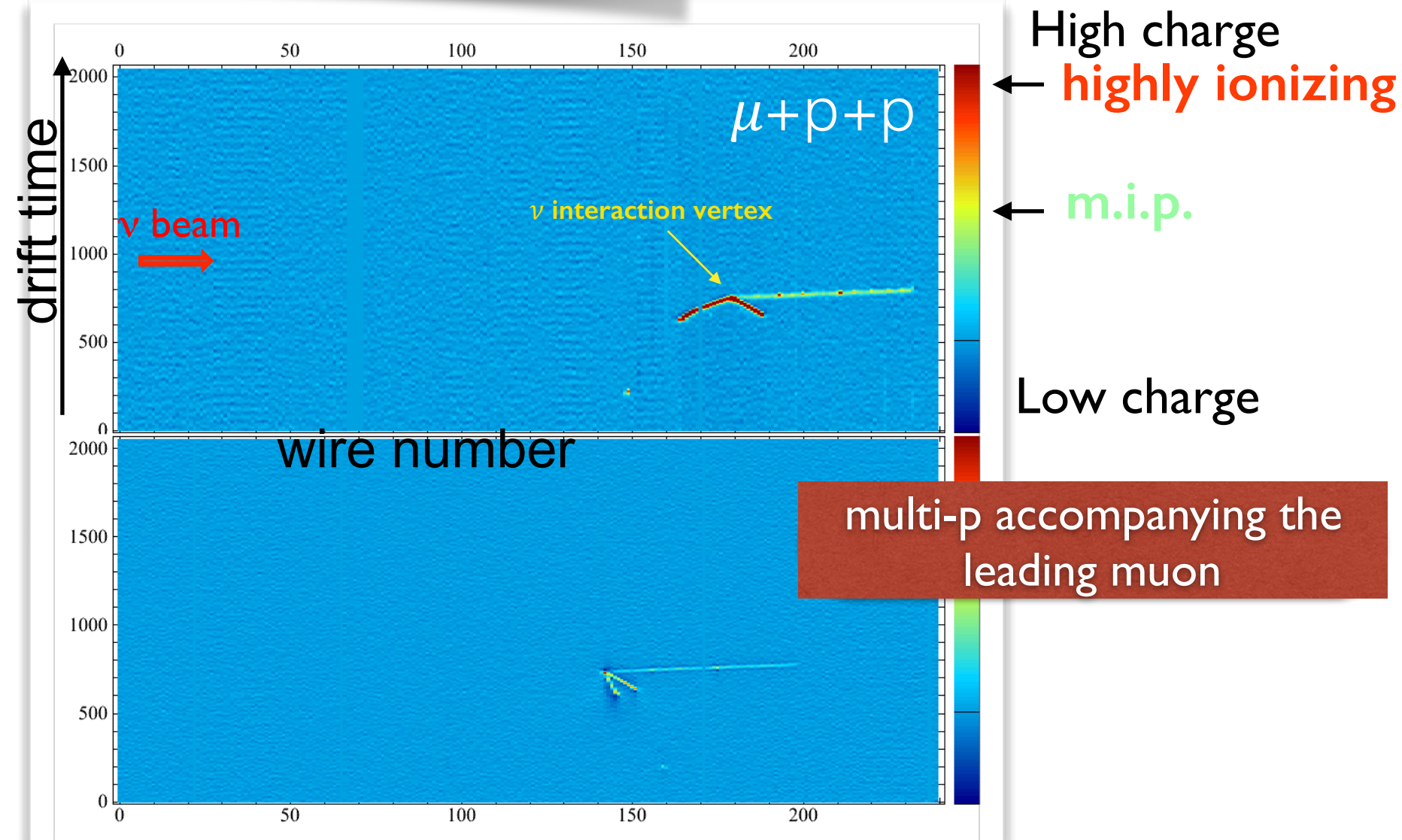


Looking for pion-less final states

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LAr TPC is an Ideal detector for Few-GeV ν scattering measurements

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



$\nu_\mu/\bar{\nu}_\mu$ CC 0 pion event

Isolation cuts and reconstruction



Select events with:

- **1 muon** with the correct sign,
- **no pion** (10 MeV Kinetic energy threshold) and
- **any # of nucleons** [proton(s), fully contained in the Fiducial Volume (for PID) and above the energy threshold and any # of neutrons (undetected)]

- Selection cuts (fully **automated reconstruction**)
- **Automated reconstruction** of the **muon** (geometrical and calorimetry)
- **Semi-automated** reconstruction of the **proton(s)** at the interaction vertex: **Visual Scanning** (hit selection) and **automated reconstruction** (geometrical, calorimetry and PiD).
 - Efficiency of the automated reconstruction, detector acceptance, proton containment and backgrounds estimated from ν_μ CC 0 pion GENIE MC events.
 - Overall efficiency/acceptance for the (μ +Np) sample is estimated to be ~ 50% (neutrinos) and ~70%(antineutrinos), **dominated by** the requirement of proton containment in the FV.

ν_μ CC 0 pion events



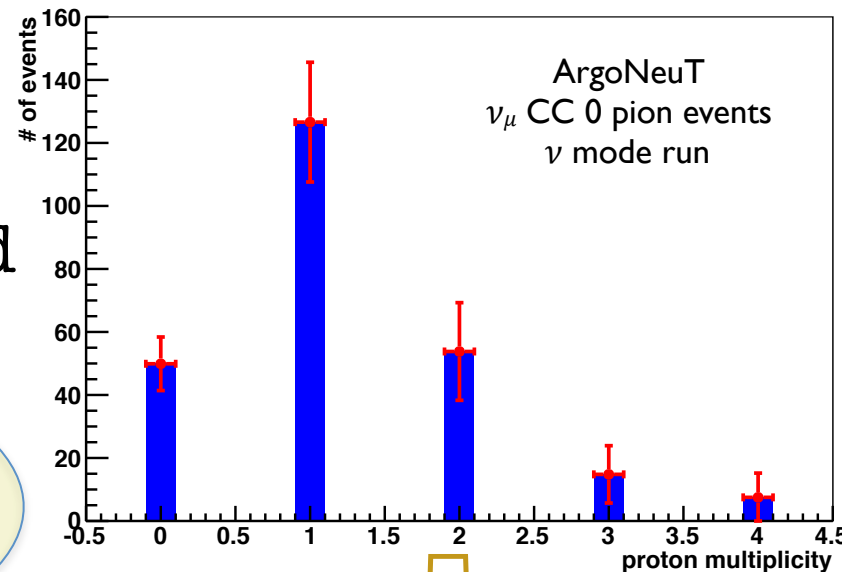
- ◉ Measure **model-independent exclusive final states**.
- ◉ Measure *muon and proton kinematics* in events with different proton multiplicity.
- ◉ Precisely *reconstruct the incoming neutrino energy from lepton AND proton reconstructed kinematics*.
- ◉ Measure features of neutrino interactions and associated *Nuclear Effects* from identification/reconstruction of specific classes of neutrino events (e.g. muon + 2 protons).
- ◉ Measure *inclusive and exclusive CC 0 pion cross sections*.


New results today

Inclusive and Exclusive ν_μ CC 0 pion cross sections

Rates at different multiplicities
(efficiency & acceptance corrected and background subtracted)

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



$N_{CC0\pi(Np)}$ = number of CC 0 π events (with N protons)-efficiency & acceptance corrected and background subtracted

N_{FID} = number of argon nuclei in the fiducial volume

$\Phi(E_\nu)$ = neutrino flux (at E_ν)

Inclusive
$$\sigma_{CC0\pi} = \frac{N_{CC0\pi}}{\phi \times Exp \times N_{FID}}$$

$$\sigma_{CC0\pi}(E_\nu) = \frac{N_{CC0\pi}(E_\nu)}{\phi(E_\nu) \times Exp \times N_{FID}}$$

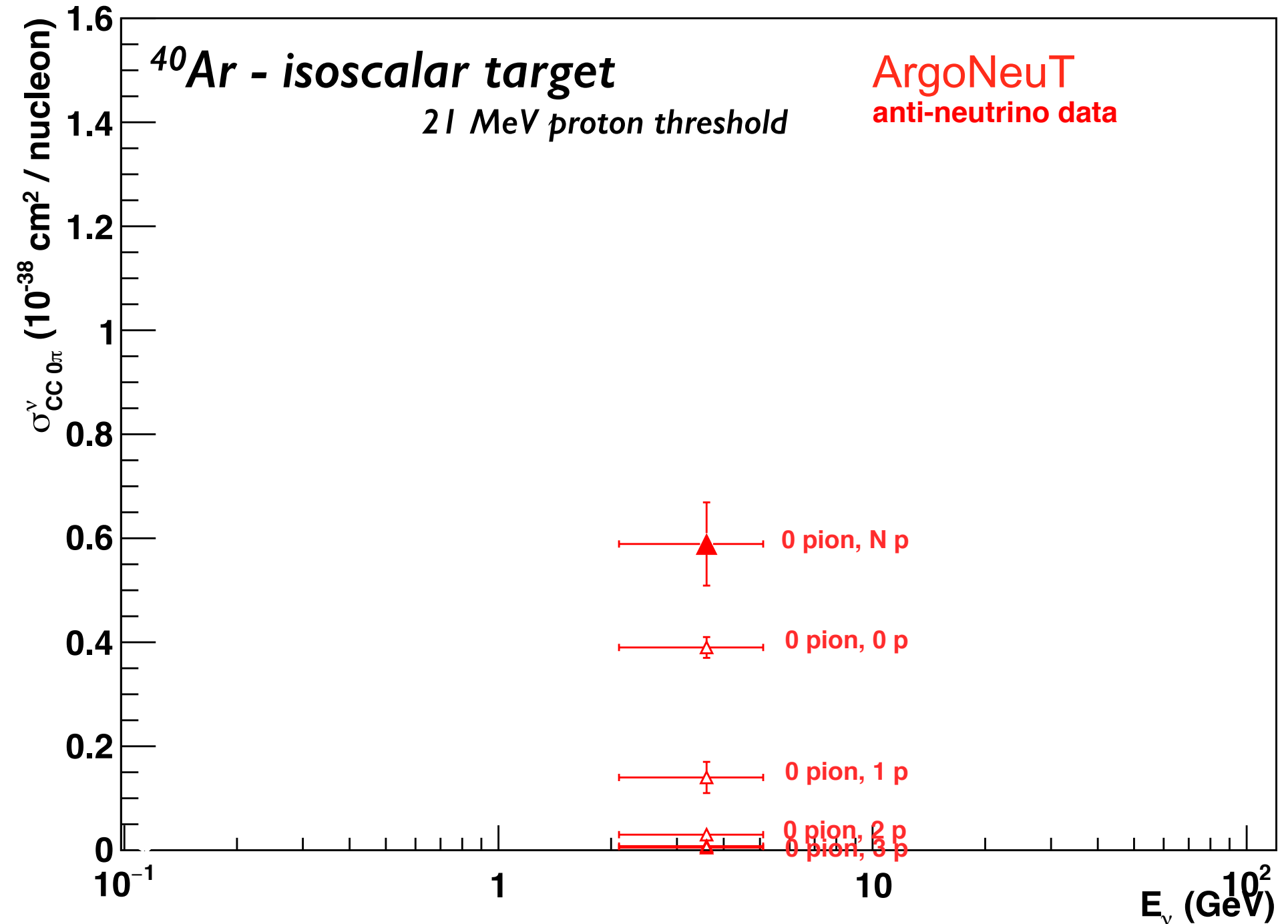
$$N_{CC0\pi} = \sum_N N_{CC0\pi, Np}$$

Exclusive
$$\sigma_{CC0\pi, Np} = \frac{N_{CC0\pi, Np}}{\phi \times Exp \times N_{FID}}$$

Systematic Uncertainties

	Uncertainty
FLUX (PRD 89, 112003)	11%
NC background	<1%
WS background	<1%
bckd from π^0 both γ not converting in LAr	2%
Muon momentum	5-10%
Proton Identification	97% efficiency
Proton angular resolution	1-1.5 ⁰ (depending on track length)
Proton Energy resolution	6-10% (depending on proton energy)
Neutrino Energy reconstruction	dominated by muon mom. resolution

Exclusive Antineutrino cross sections



Exclusive Antineutrino Cross Sections

$\langle E_\nu \rangle = 3.6 \pm 1.5 \text{ GeV}$

$$\sigma_{CC0\pi}^{\bar{\nu}} = 0.58 \pm 0.03(\text{stat.}) \pm 0.06(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,0p}^{\bar{\nu}} = 0.39 \pm 0.02(\text{stat.}) \pm 0.008(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

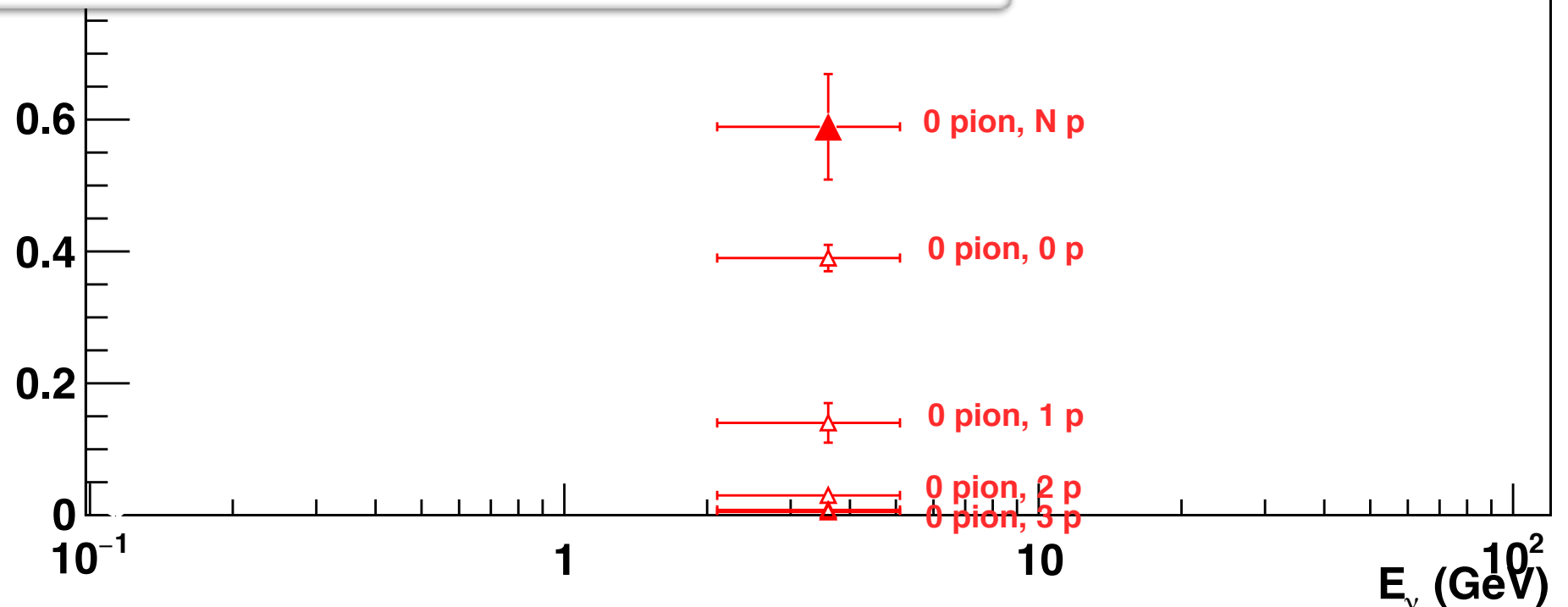
$$\sigma_{CC0\pi,1p}^{\bar{\nu}} = 0.14 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,2p}^{\bar{\nu}} = 0.035 \pm 0.007(\text{stat.}) \pm 0.002(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

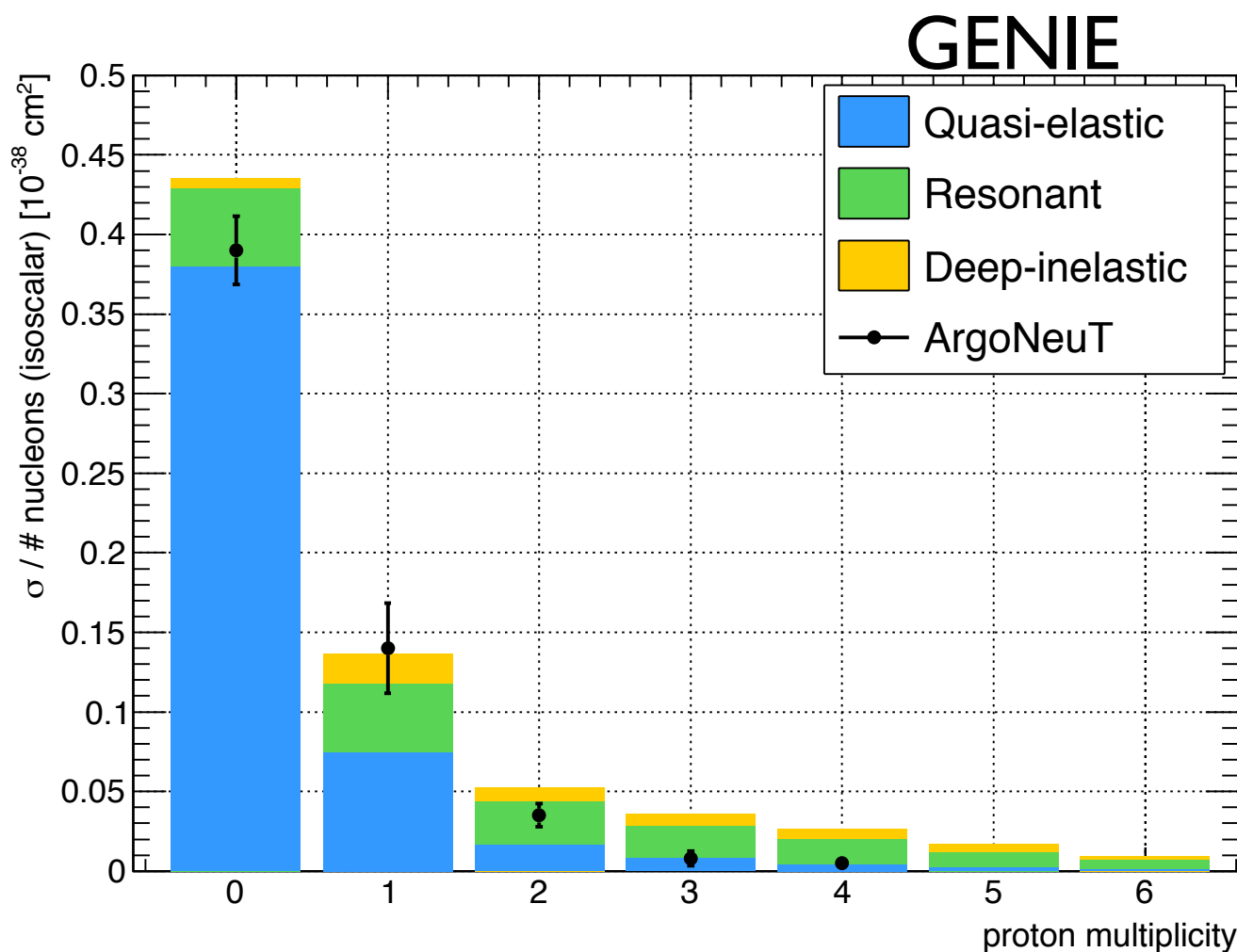
$$\sigma_{CC0\pi,3p}^{\bar{\nu}} = 0.008 \pm 0.004(\text{stat.}) \pm 0.002(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,4p}^{\bar{\nu}} = 0.005 \pm 0.004(\text{stat.}) \pm 0.001(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

ArgoNeuT
anti-neutrino data

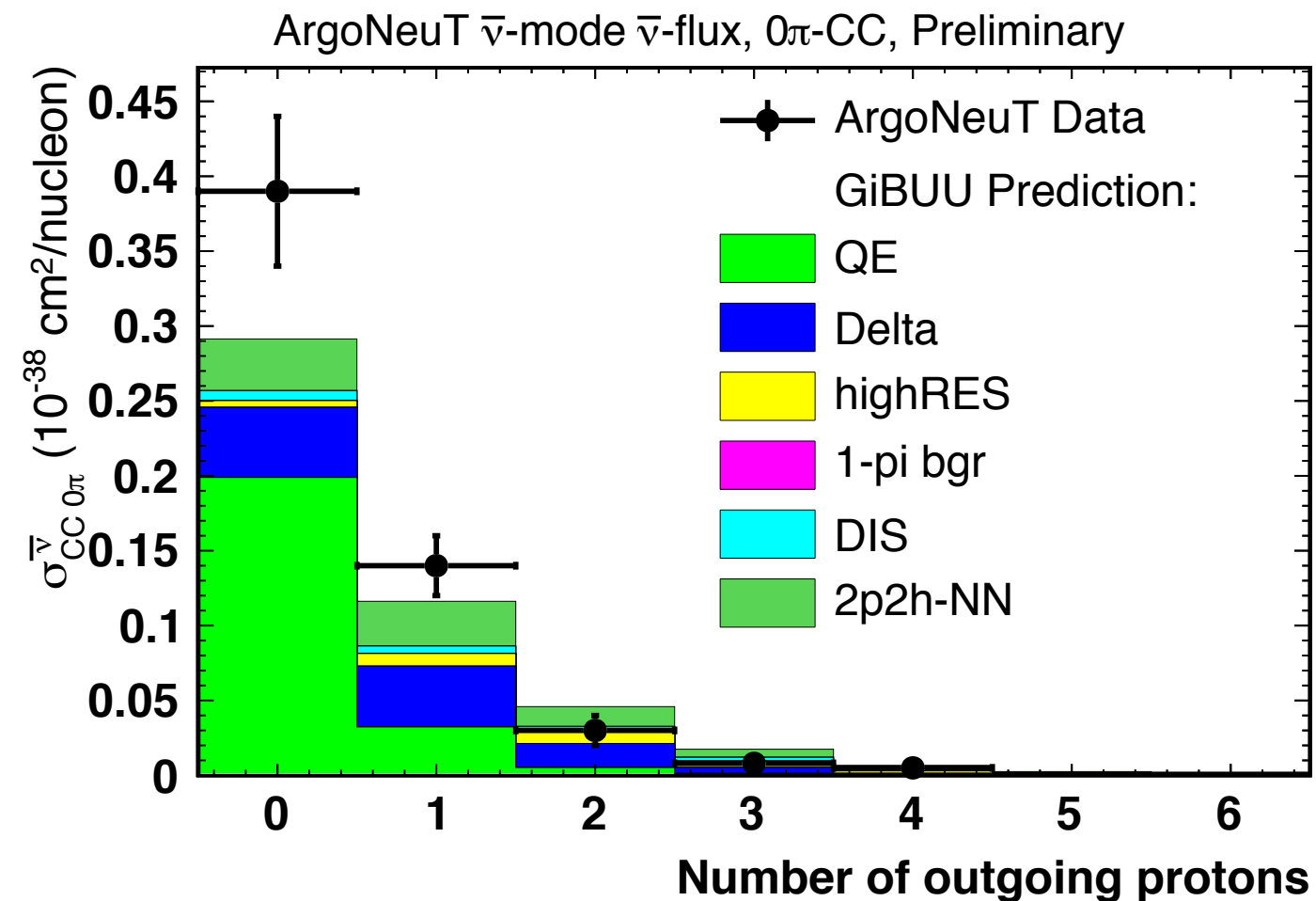


Exclusive Antineutrino Cross Sections Comparison with GENIE and GiBUU



$$\sigma_{CC0\pi} = 0.71 \text{ cm}^2/\text{nucleon}$$

GENIE MC



$$\sigma_{0\pi}^{\bar{\nu}} = 0.48 \text{ } 10^{-38} \text{ cm}^2/\text{nucleon}$$

GiBUU

$$\sigma_{CC0\pi}^{\bar{\nu}} = 0.58 \pm 0.03(\text{stat.}) \pm 0.06(\text{syst.}) 10^{-38} \text{ cm}^2/\text{nucleon}$$

ArgoNeuT data

GENIE: 22% higher than data, large difference at high multiplicity
GiBUU: 17% lower than data, large difference at 0p

Antineutrino

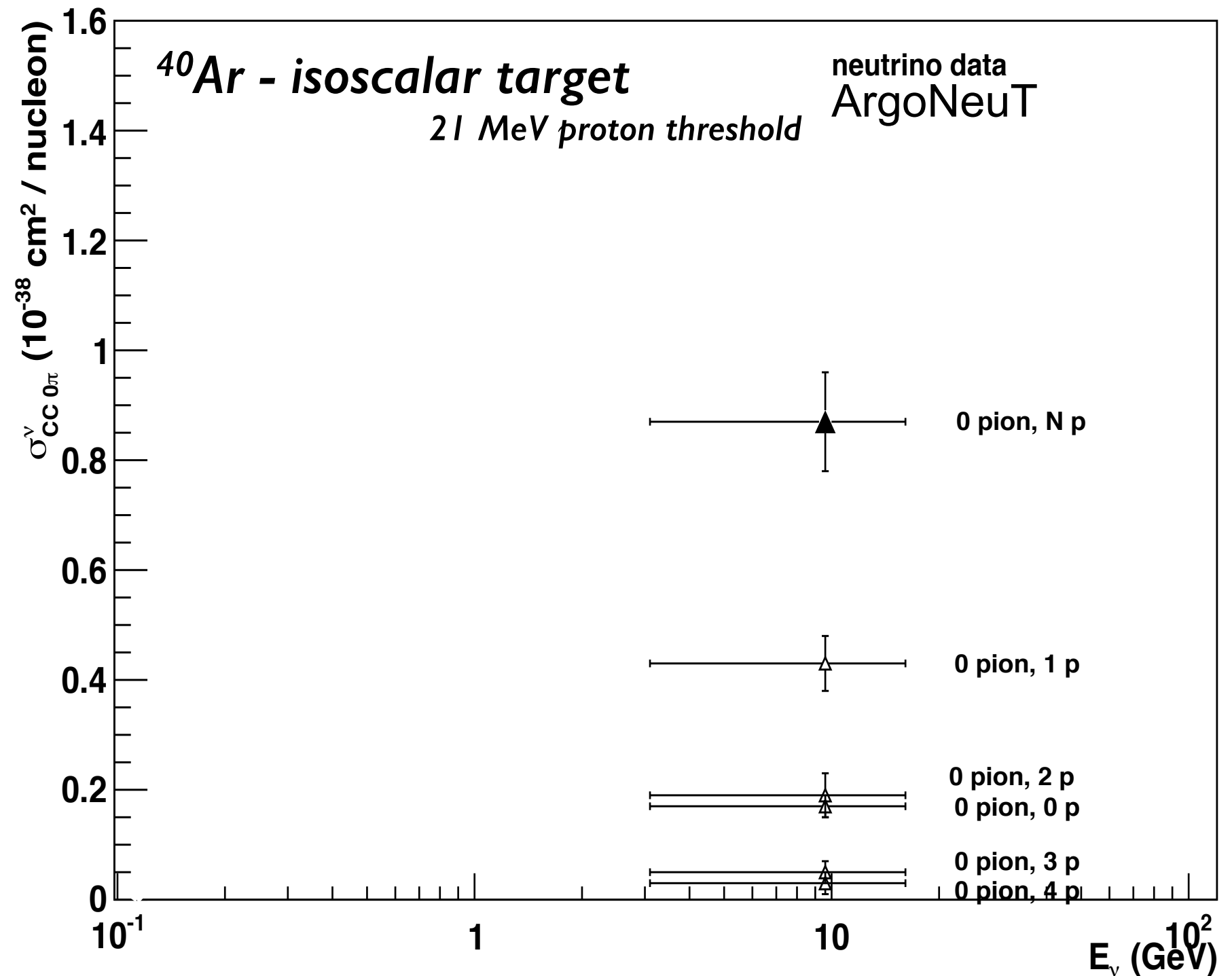
Comparison with different MC generators

J. Sobczyk
INT, Seattle
(2013)

# of protons	ArgoNeuT data (%)	GENIE (%)	GiBUU (%)	NUWRO (%)
0	67	61	61	65
1	24	18	24	23
2	6.0	7.3	9.5	8.0
3	1.3	4.9	3.5	2.8
≥ 4	0.8	12	1.8	1.6

The MC generators predict varying amounts of proton emission

Exclusive Neutrino Cross Sections



Exclusive Neutrino Cross Sections

$$\langle E_\nu \rangle = 9.6 \pm 6.5 \text{ GeV}$$

$$\sigma_{CC0\pi}^\nu = 0.87 \pm 0.08(\text{stat.}) \pm 0.004(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,0p}^\nu = 0.17 \pm 0.02(\text{stat.}) \pm 0.001(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,1p}^\nu = 0.43 \pm 0.05(\text{stat.}) \pm 0.005(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

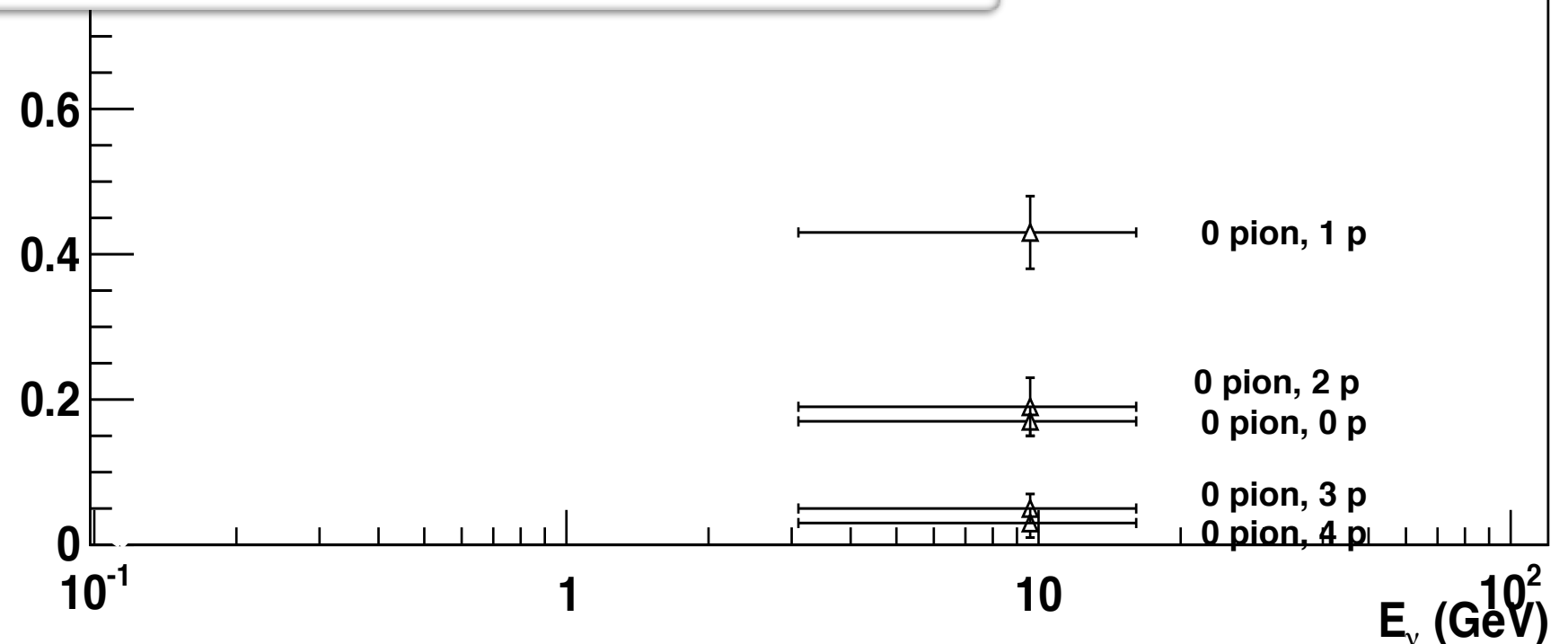
$$\sigma_{CC0\pi,2p}^\nu = 0.19 \pm 0.04(\text{stat.}) \pm 0.001(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,3p}^\nu = 0.05 \pm 0.02(\text{stat.}) \pm 0.003(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

$$\sigma_{CC0\pi,4p}^\nu = 0.03 \pm 0.02(\text{stat.}) \pm 0.003(\text{syst.}) 10^{-38} \text{ cm}^2 / \text{nucleon}$$

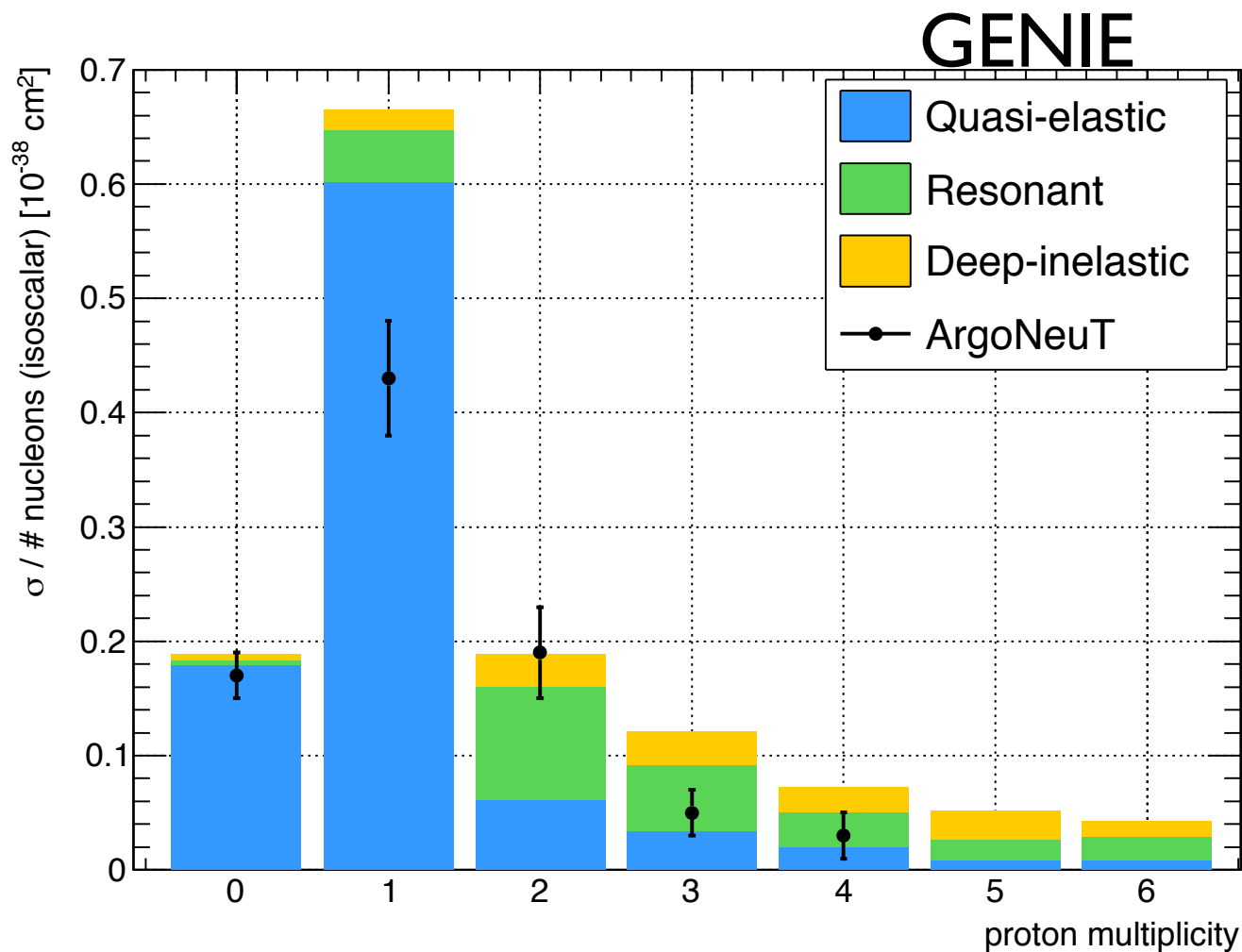
neutrino data
ArgoNeuT

0 pion, N p



Exclusive neutrino cross sections

Comparison with GENIE



Comparison with GiBBU and
NUWRO not yet available

$$\sigma_{CC0\pi} = 1.42 \text{ cm}^2/\text{nucleon}$$

GENIE MC

$$\sigma_{CC0\pi}^{\nu} = 0.87 \pm 0.08(\text{stat.}) \pm 0.004(\text{syst.}) 10^{-38} \text{ cm}^2/\text{nucleon}$$

ArgoNeuT data

GENIE: 64% higher than data, large difference at 1p and at high multiplicity

Neutrino Energy Reconstruction



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

Phys. Rev. D 90, 012008 (2014)

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

T_X =recoil energy of the residual nuclear system X [undetectable]. A lower bound is estimated from the measured missing transverse momentum:

$$T_X \approx \frac{(p_{miss}^T)^2}{2M_X}$$

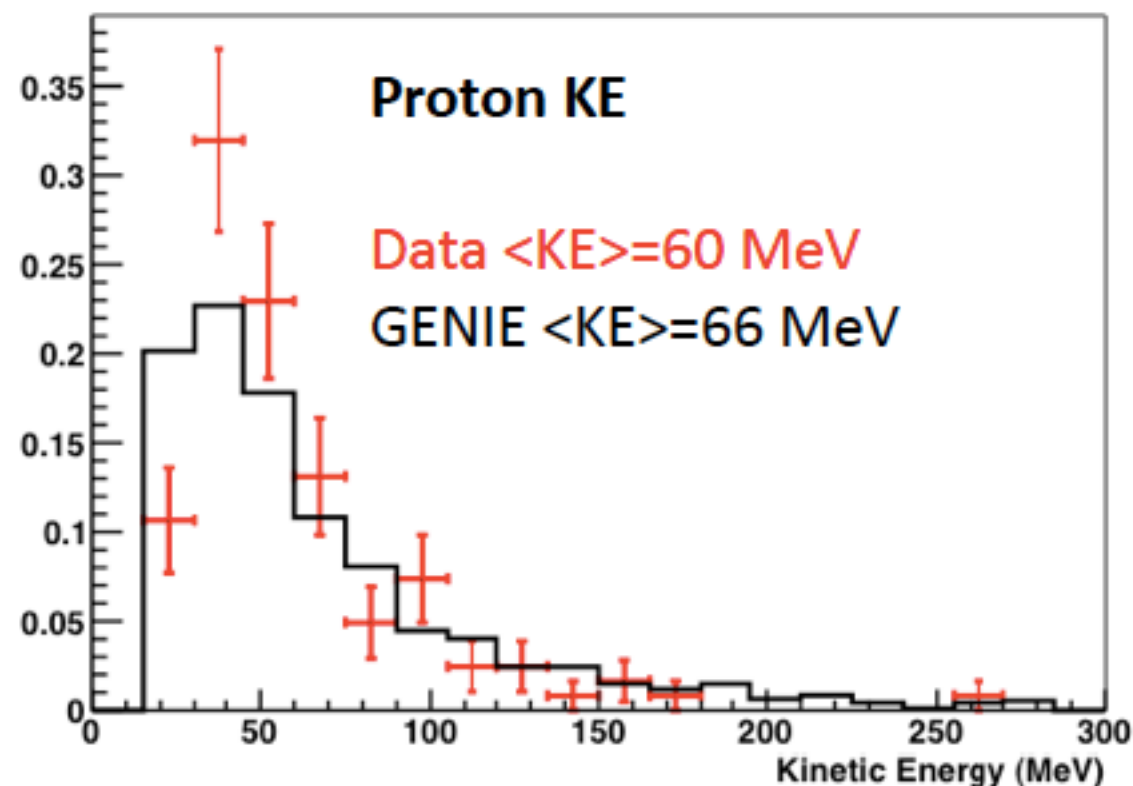
E_{miss} =missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value, e.g. $E_{miss}=30$ MeV for 2p events)]

(see J. Zennaro talk for a discussion about neutrino energy reconstruction)



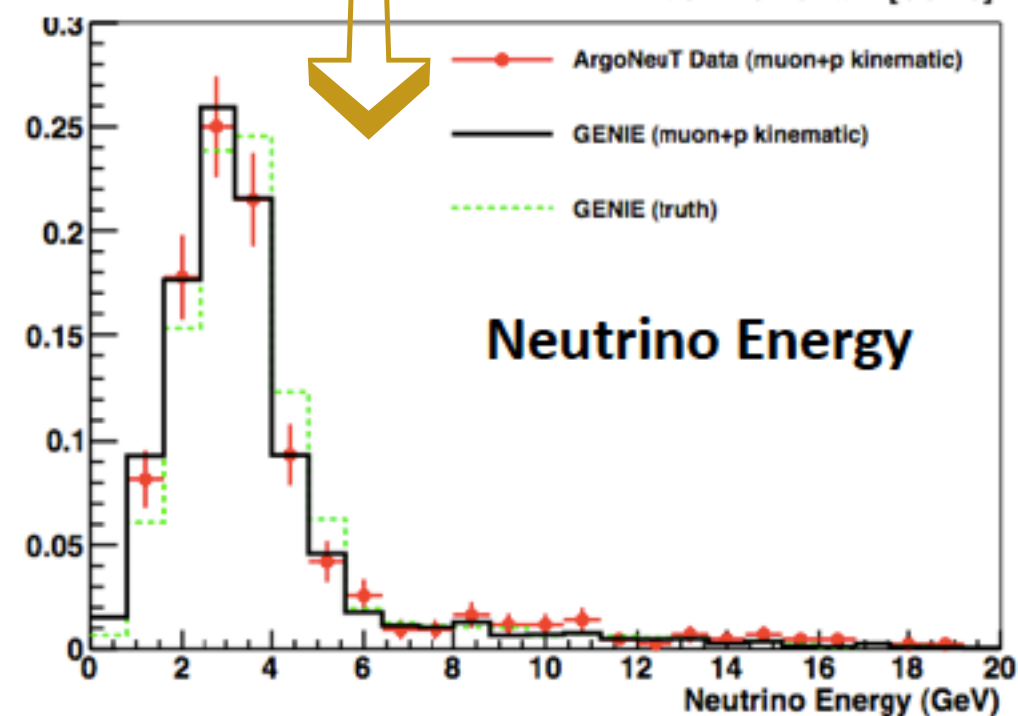
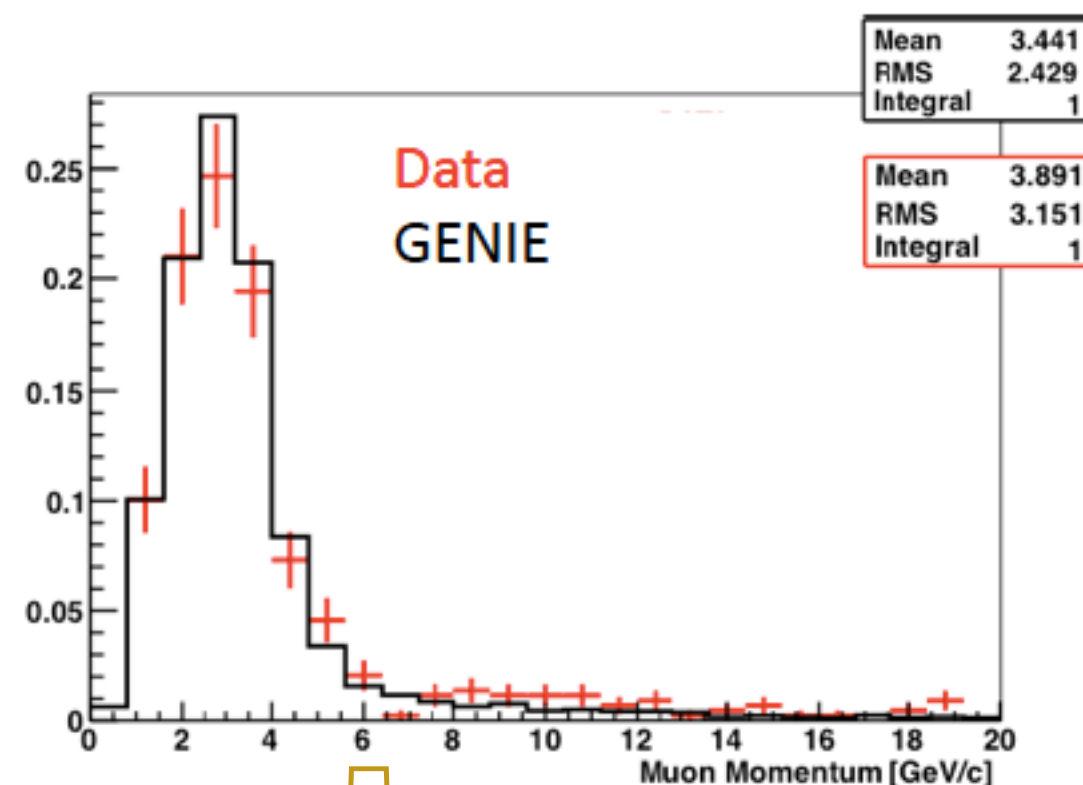
Neutrino Energy Reconstruction

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

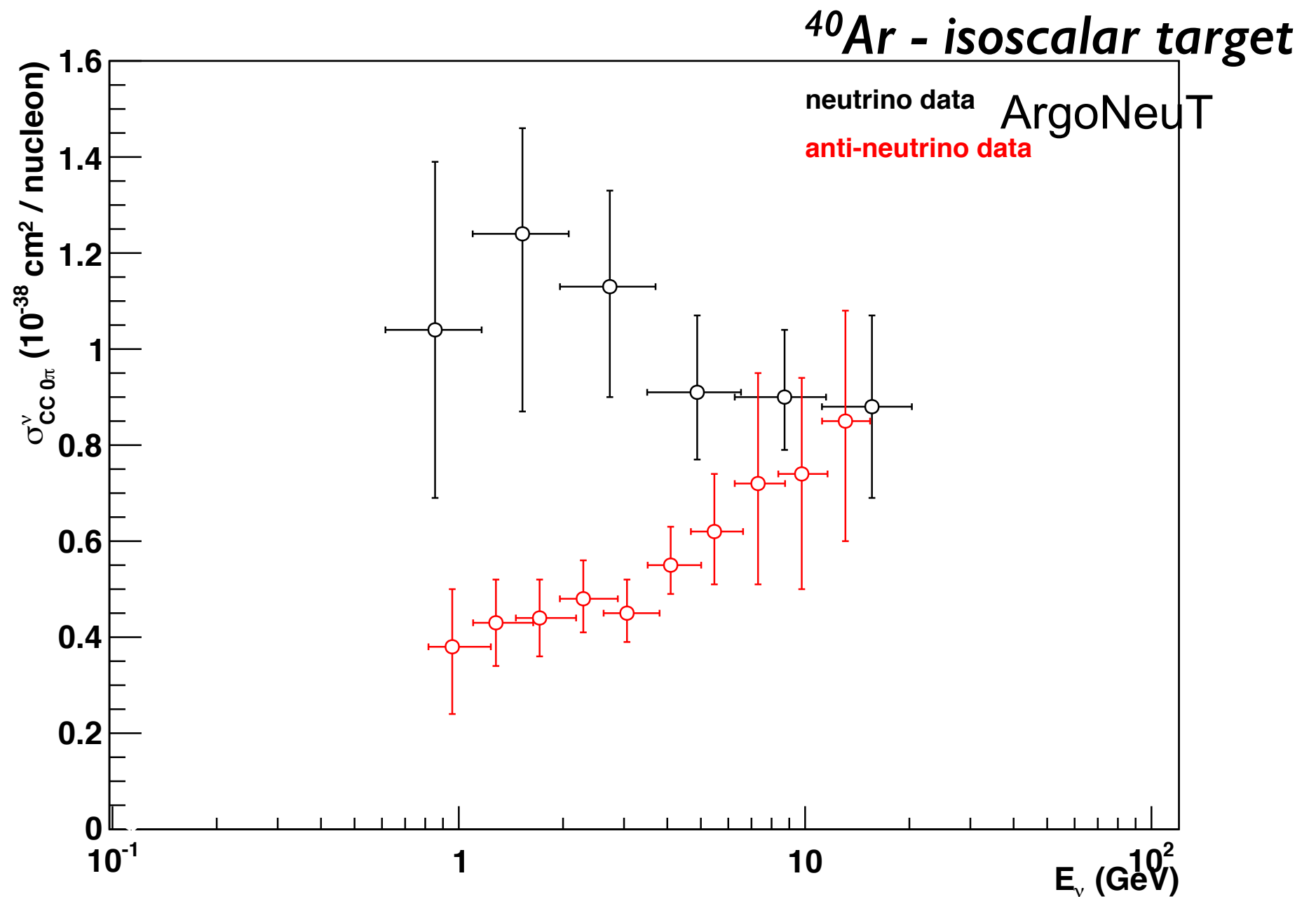


+

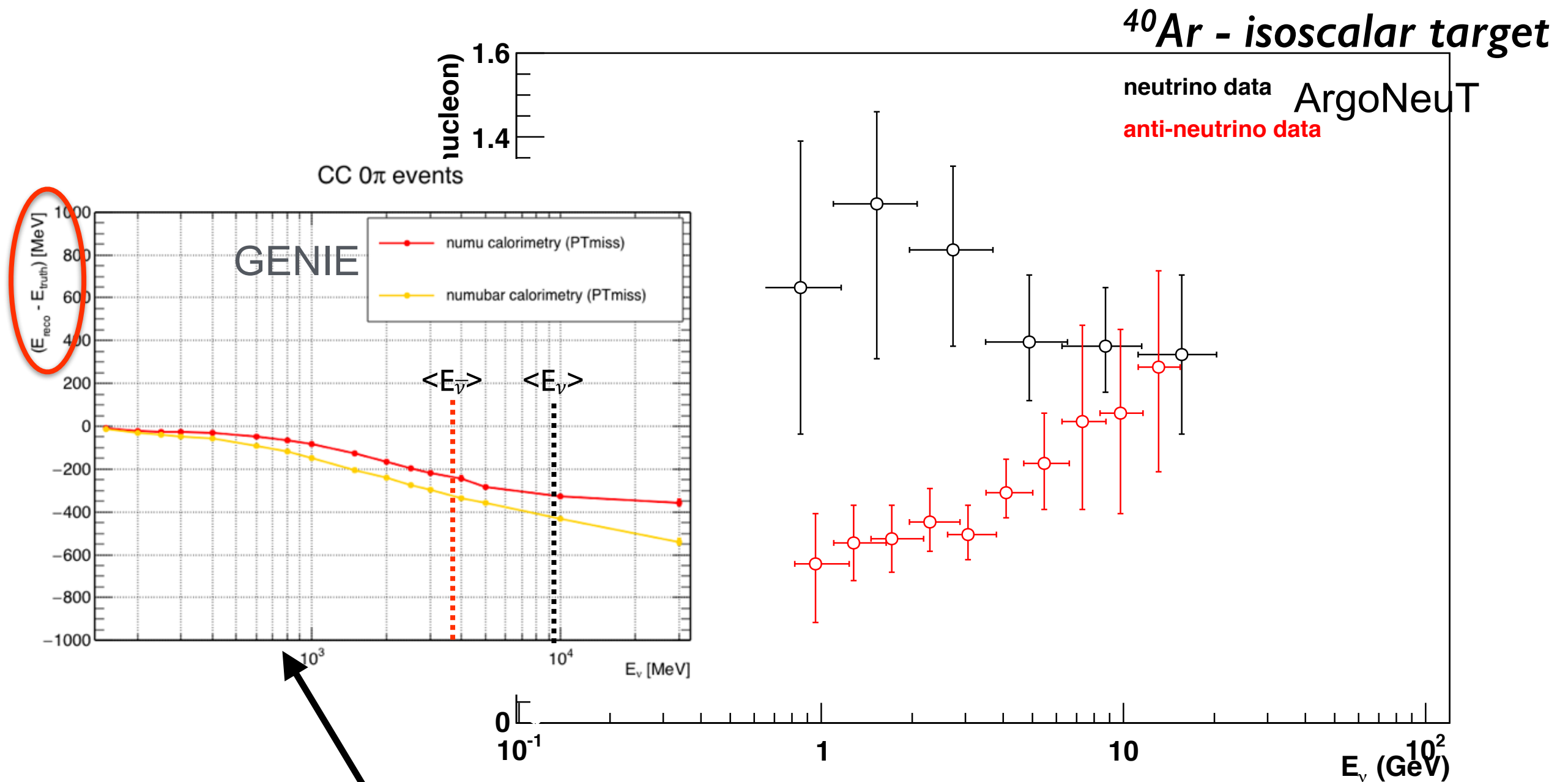
Muon Momentum



Neutrino/Antineutrino cross sections as a function of the neutrino energy

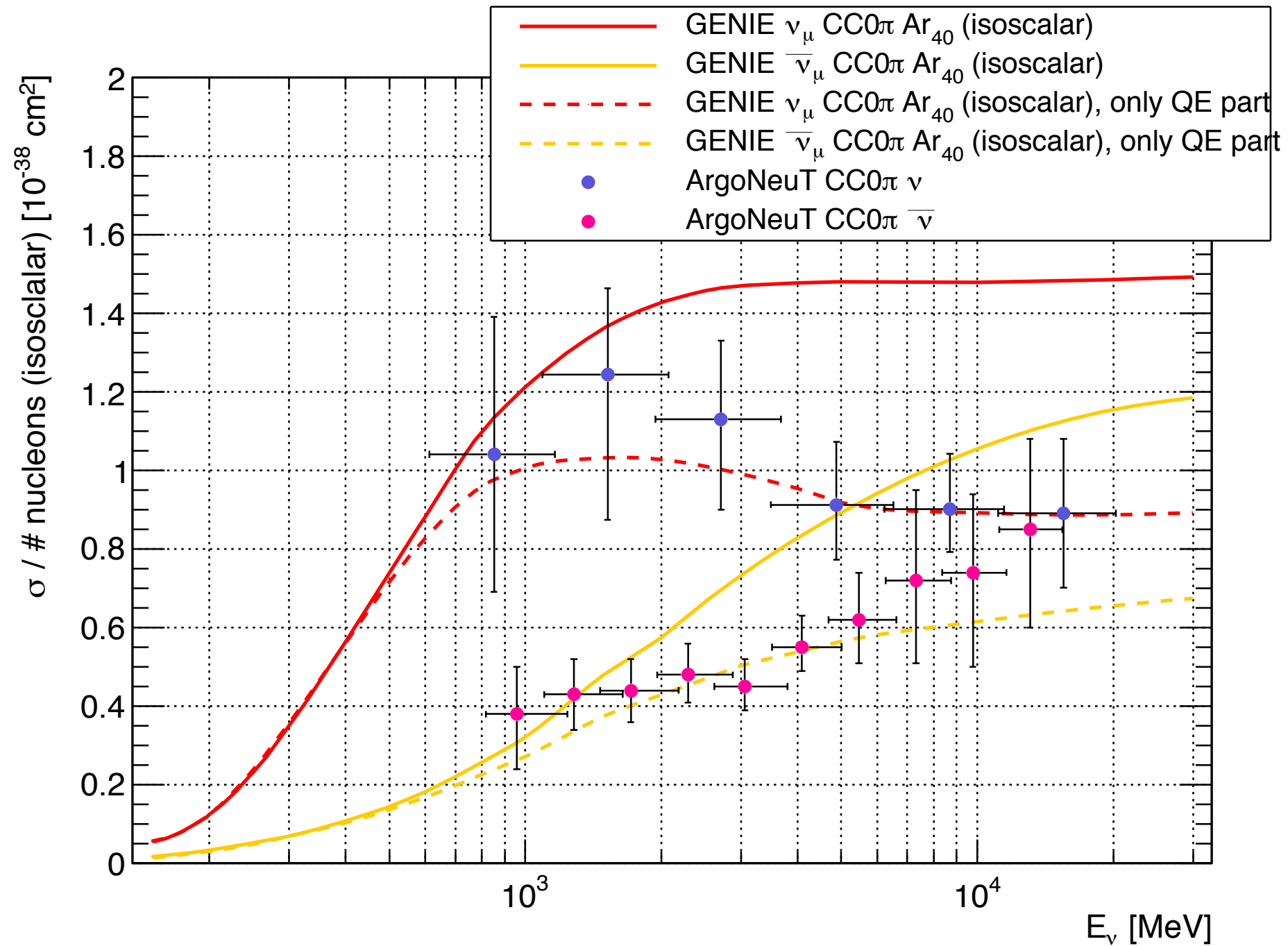


Neutrino/Antineutrino cross sections as a function of the neutrino energy

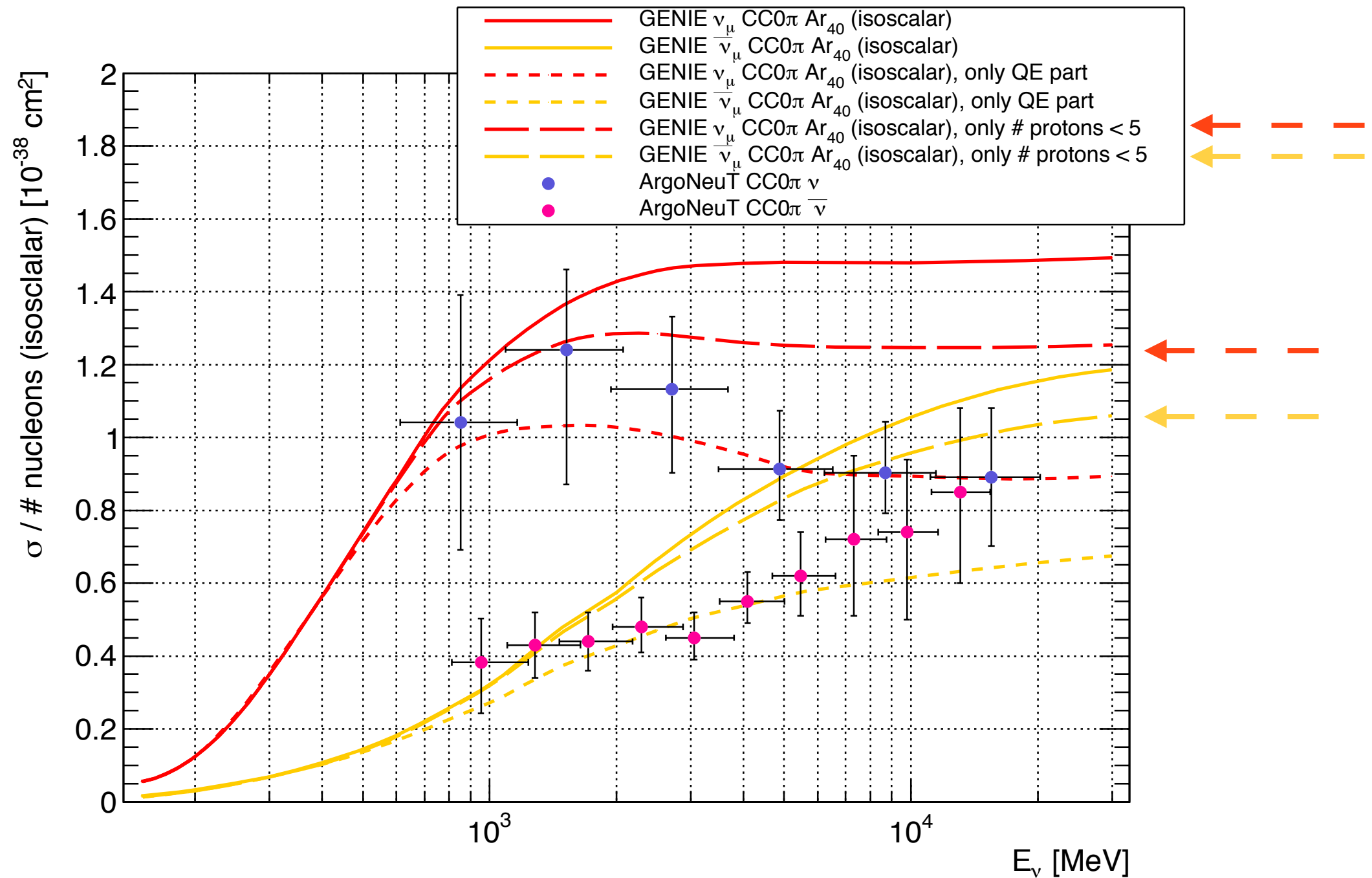


One-side errors added to account for systematic from neutrino energy reconstruction (GENIE - underestimation of E_{ν} , $\sim 10\%$ for $\bar{\nu}$ and $\sim 4\%$ for ν)

Neutrino/Antineutrino cross sections comparison with GENIE

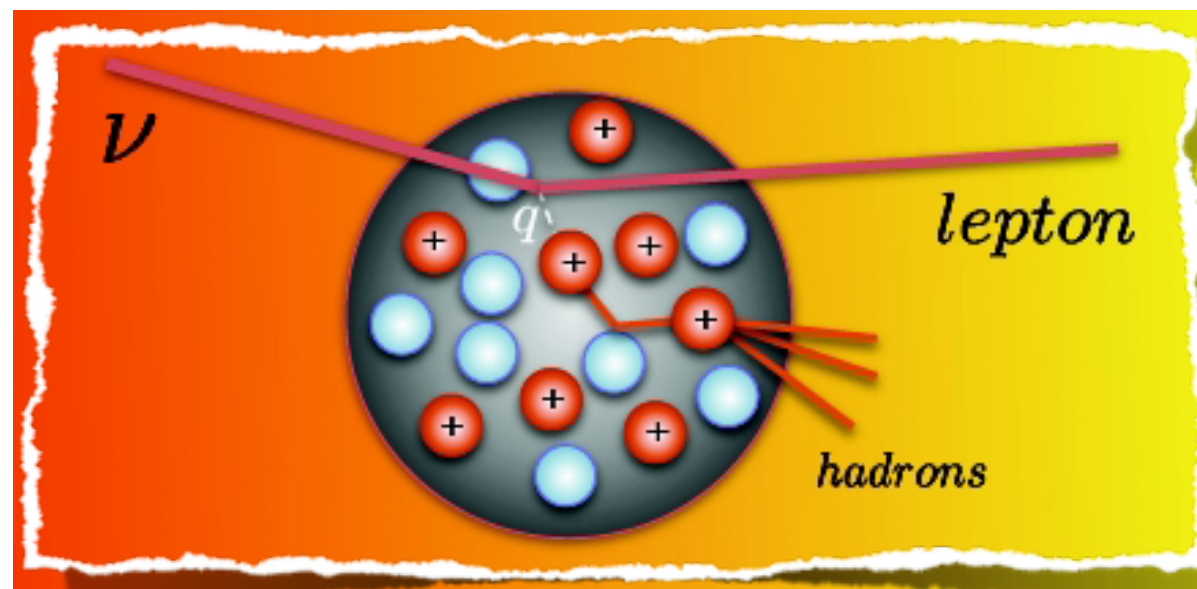


Neutrino/Antineutrino cross sections comparison with GENIE



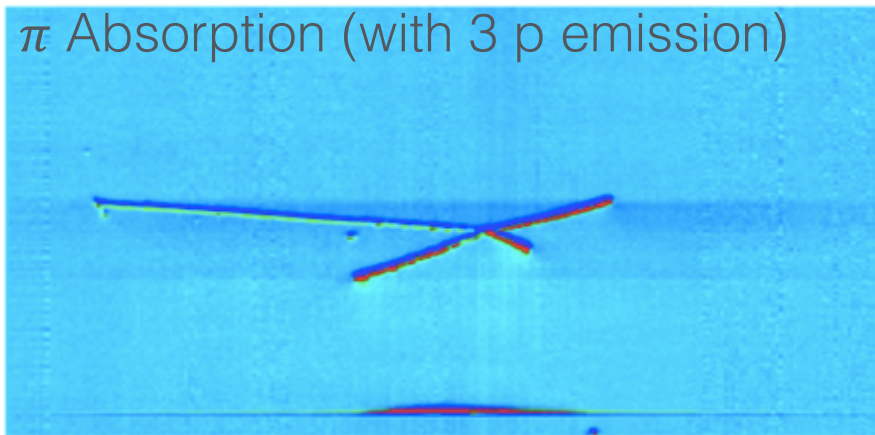
Nuclear Effects in LAr

- ◉ **Nuclear effects** significantly alter σ_ν 's and final state particle topology/kinematics.
- ◉ Main reason for disagreement between ArgoNeuT data and MC predictions is the treatment of nuclear effects in the MC generators.
- ◉ LAr data can provide an important discriminator among models.
- ◉ Pion absorption in the nucleus is a dominant effect for CC 0 pion events.

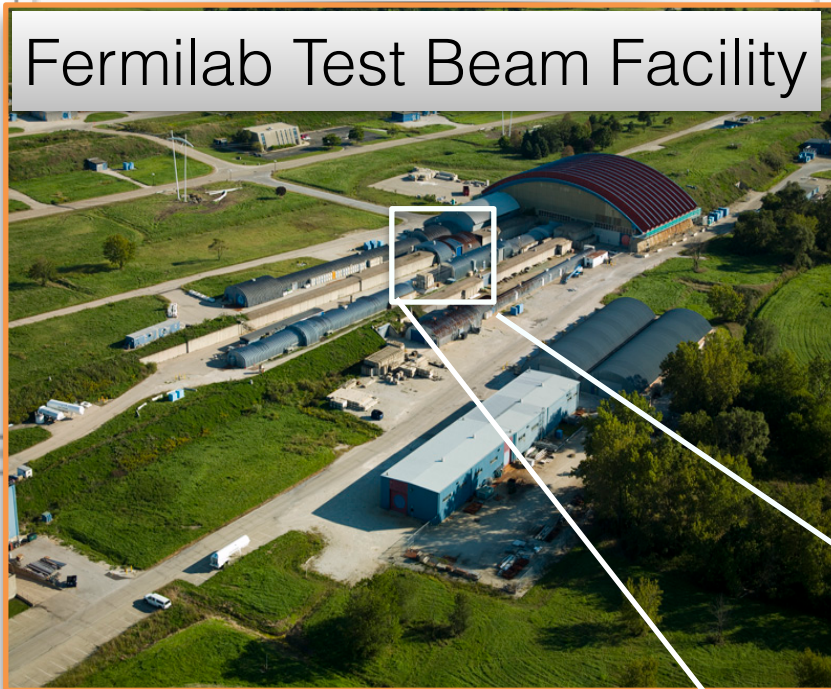


- ◉ **LArIAT** (**L**iquid **A**rgon TPC **I**n **A** Testbeam) **experiment** is measuring charged pion interaction cross section in LAr.

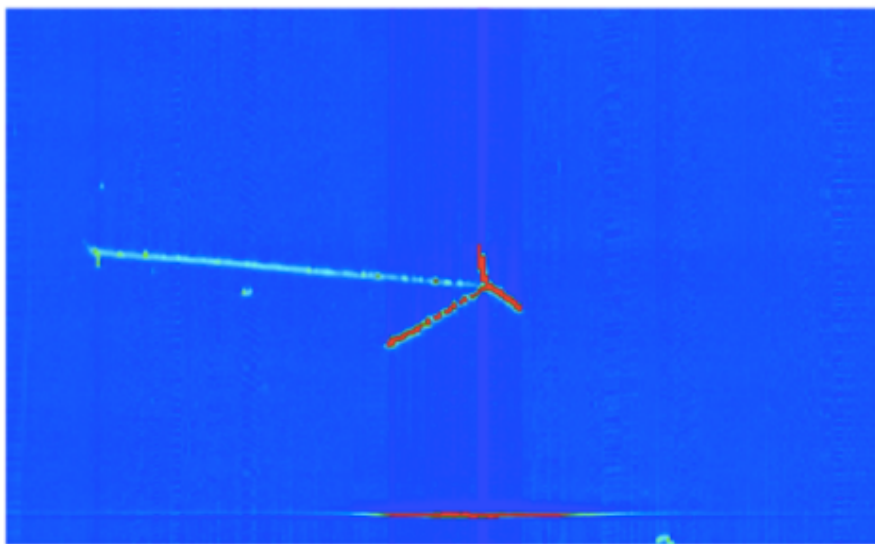
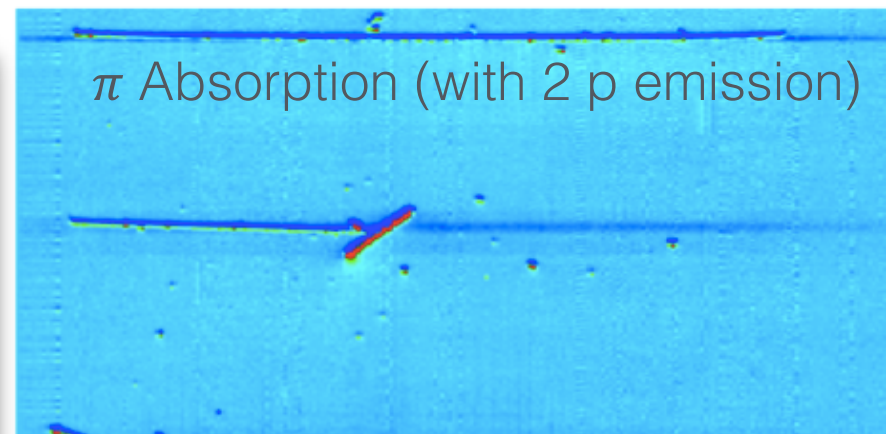
π Absorption (with 3 p emission)



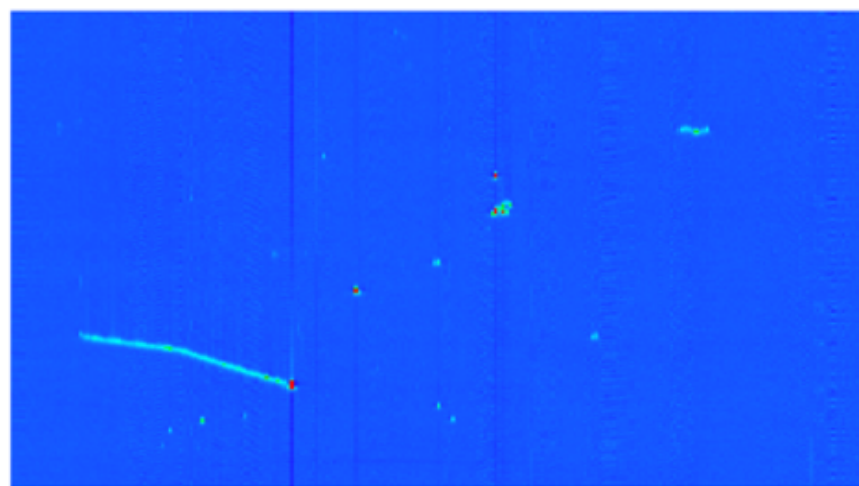
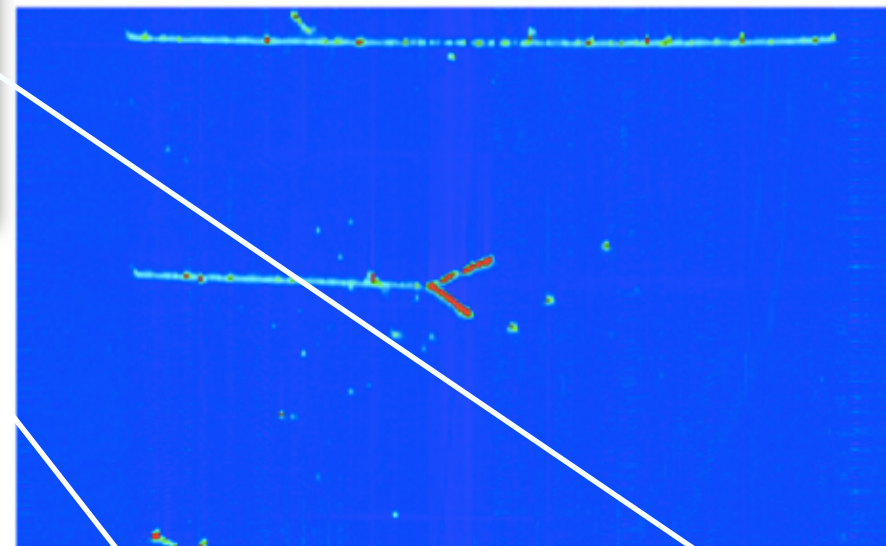
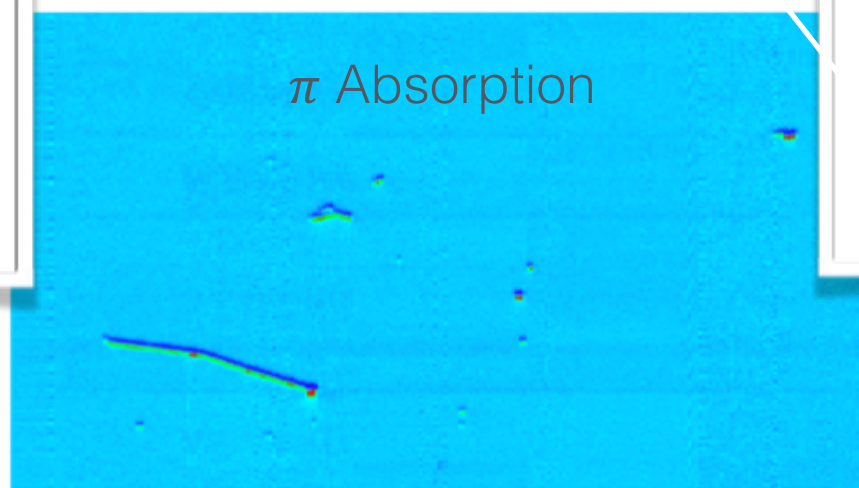
Fermilab Test Beam Facility



π Absorption (with 2 p emission)



π Absorption



MCenter Tertiary Beam
(looking upstream)

MicroBooNE and SBND experiments

Exclusive channels & Nuclear Effects

Short Baseline Neutrino program detectors will provide huge data sets of ν -Ar interactions from the **Booster Neutrino Beam** ($\langle E_\nu \rangle = 800$ MeV)

- Large samples in MicroBooNE (82 t AV) are coming! MicroBooNE will record $\sim 50,000$ ν_μ CC per year (see A. Schukraft talk)
- SBND (112 t AV) will record ~ 1.5 million ν_μ CC and $\sim 12,000$ ν_e CC interactions per year (see C. Adams talk)

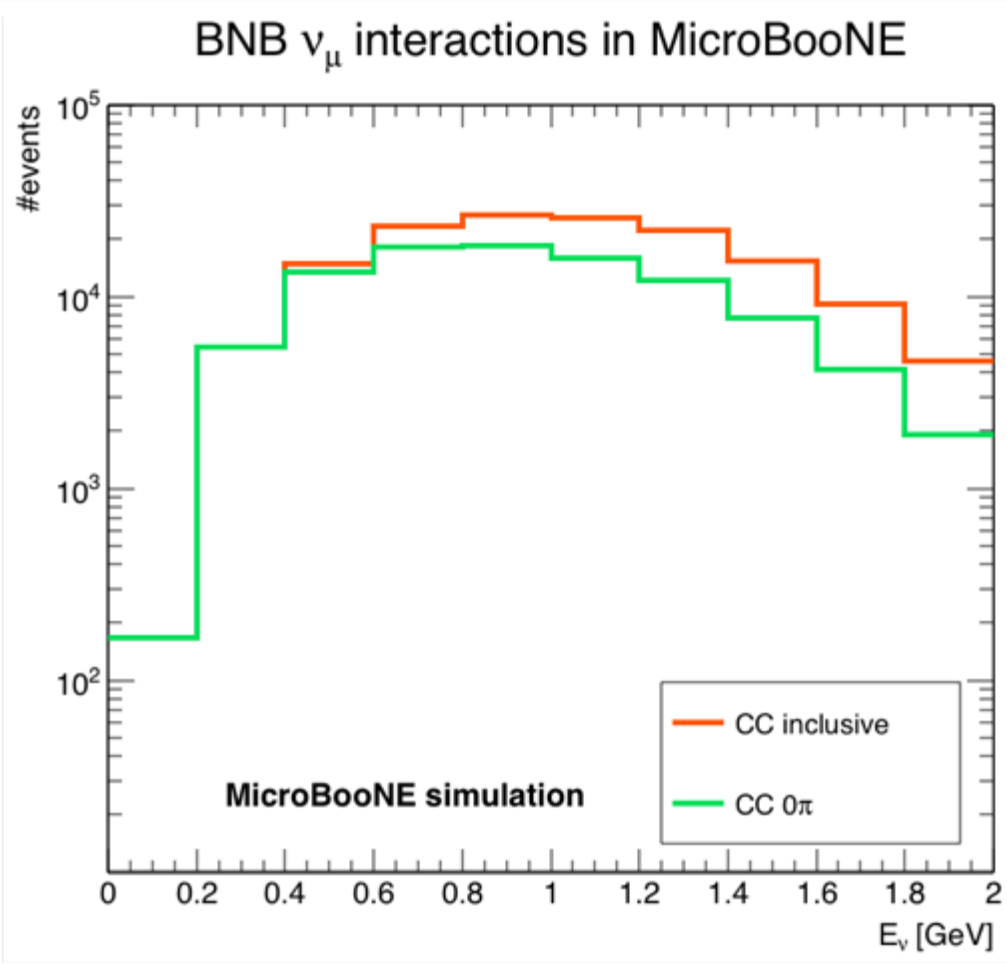
At the BNB CC 0 pion is the **dominant channel**

- High statistics measurement of ν_μ and ν_e CC 0 pion events will allow to **quantify** nuclear effects in neutrino-Ar scattering*

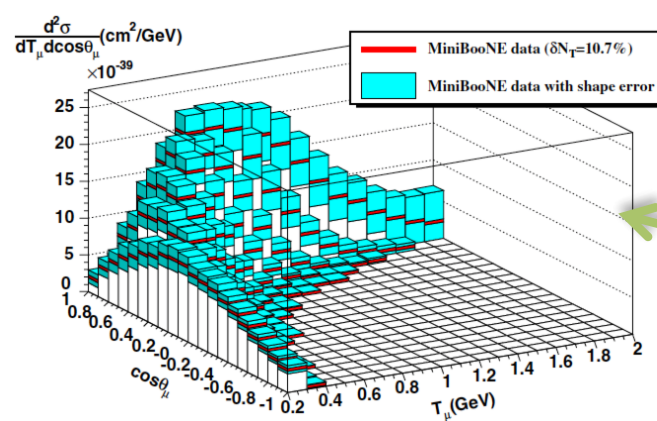
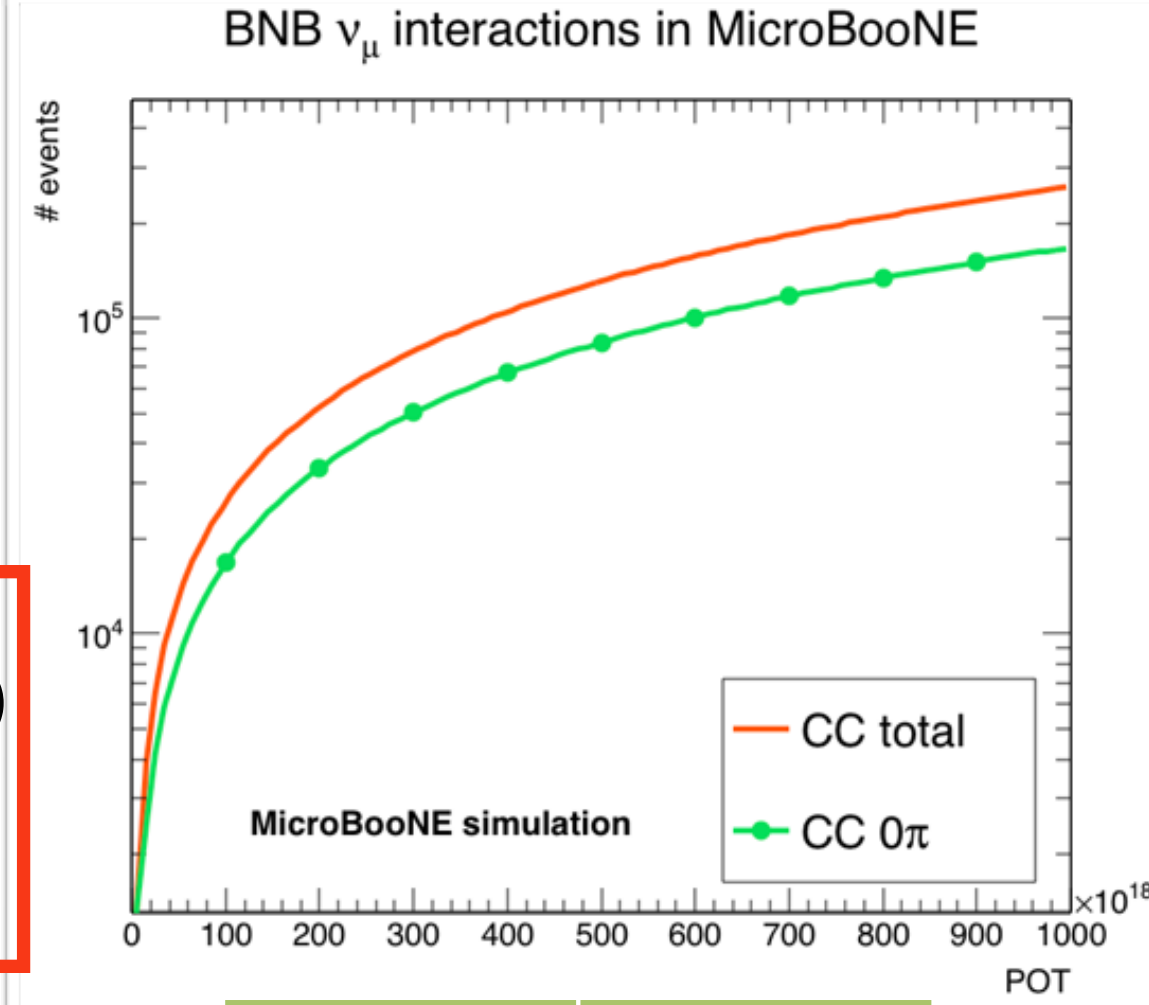


*only existing ν_μ CC 0 pion Ar scattering data are ~ 900 events from ArgoNeUT (NuMI beam, 3 GeV peak energy)

CC 0 π events



MicroBooNE will quickly (~15 days) reach ArgoNeuT statistics, at a lower energy



Will need the full 6.6e20 POT for double-differential measurements

~in 1 month

~6 months

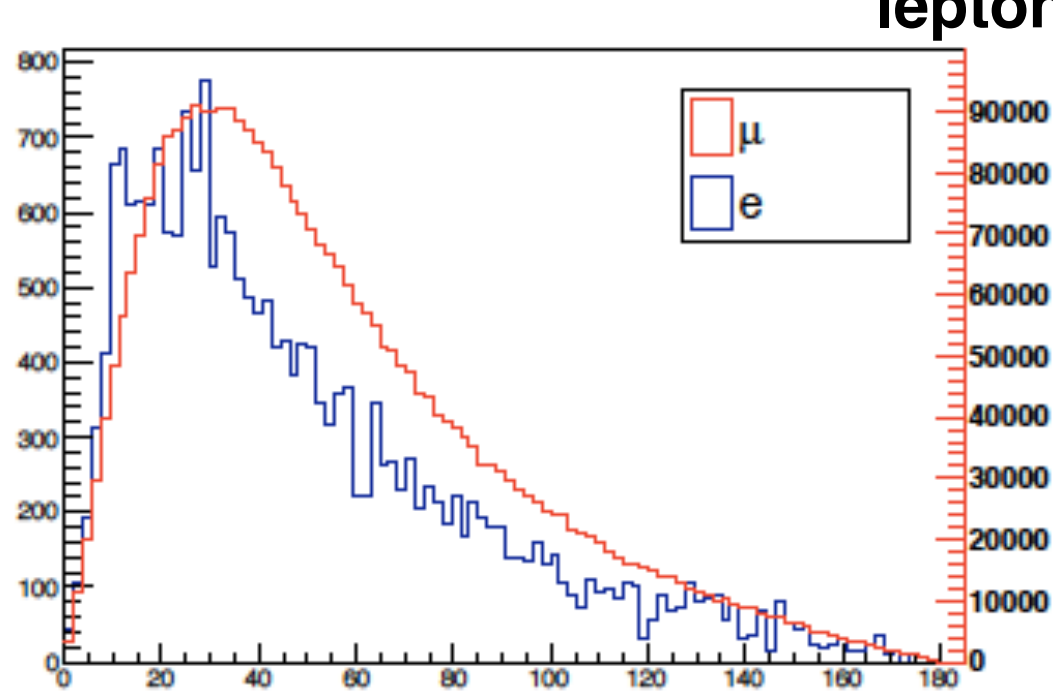
~3 years

	CC 0 pion
1.5x10 ¹⁹ POT	2550
1x10 ²⁰ POT	16997
2x10 ²⁰ POT	33994
6.6x10 ²⁰ POT	112180

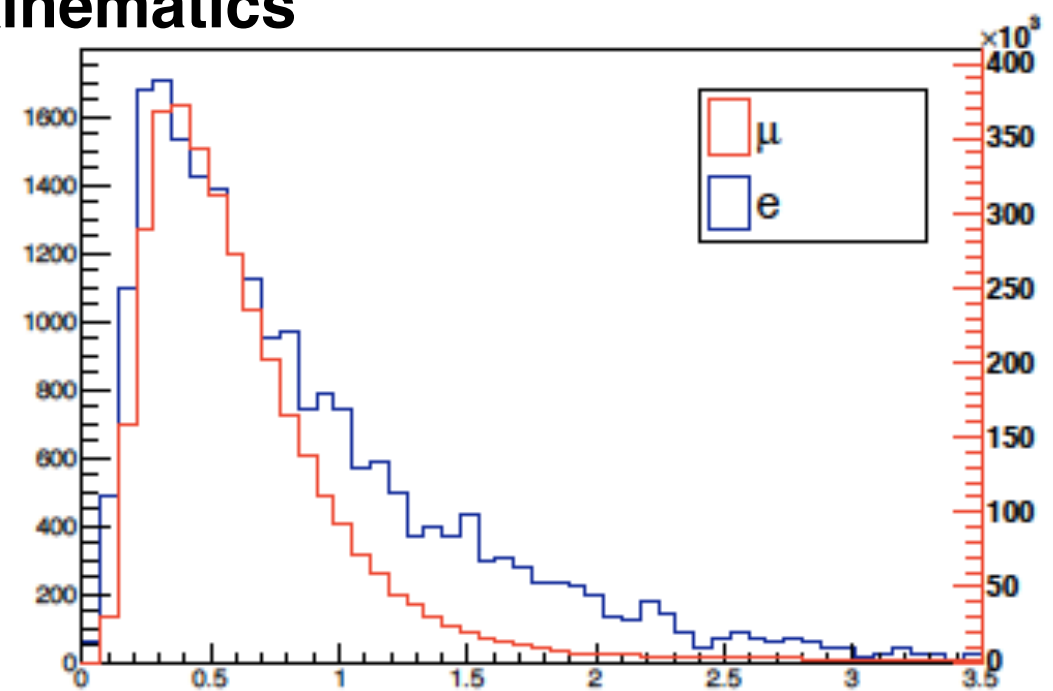
CC 0π events



lepton kinematics



θ (deg)

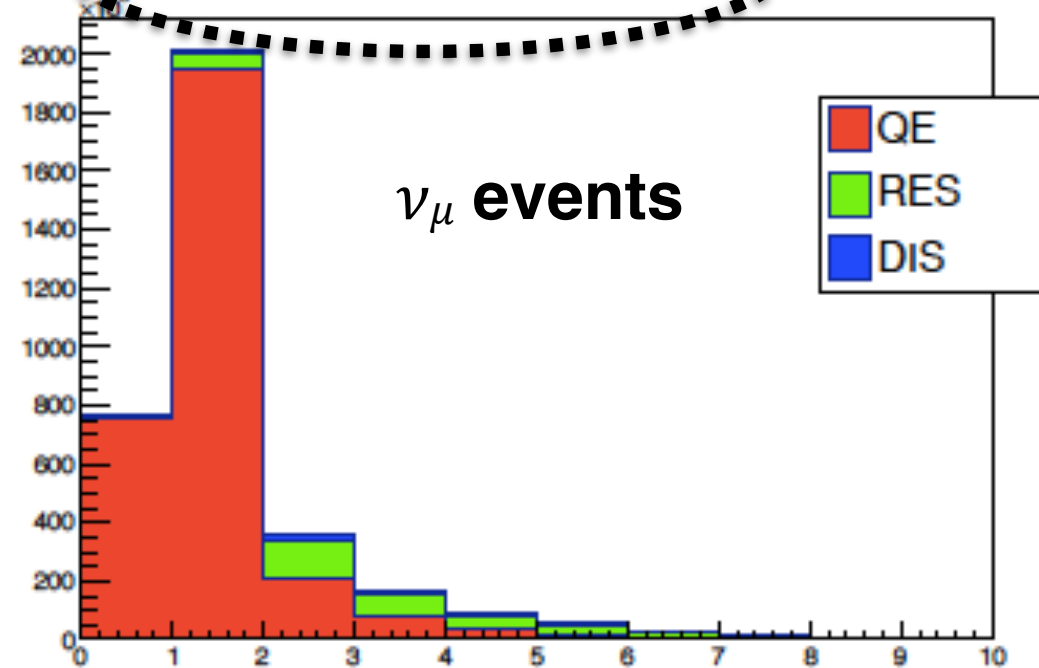


Energy (GeV)

ν_μ events:
3.5 Million in 6.6×10^{20}

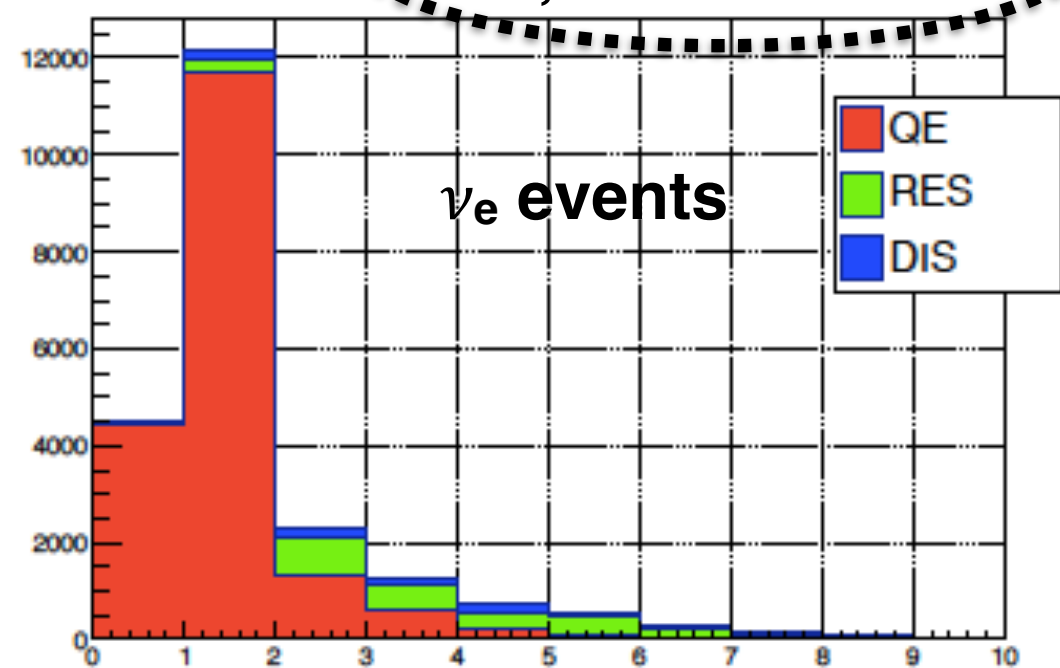
Proton multiplicity

ν_e events:
22,000 in 6.6×10^{20}



ν_μ events

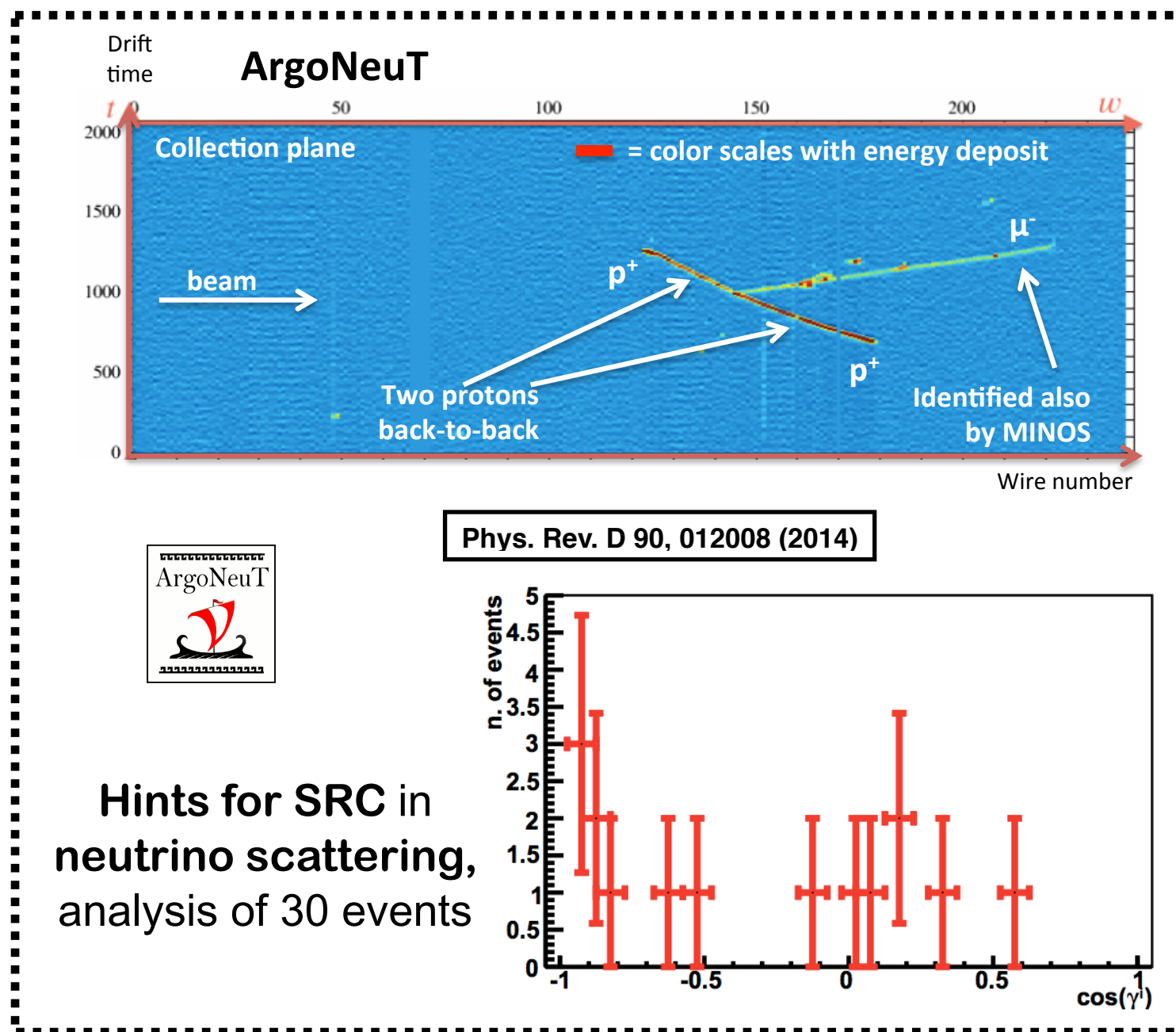
Proton Multiplicity



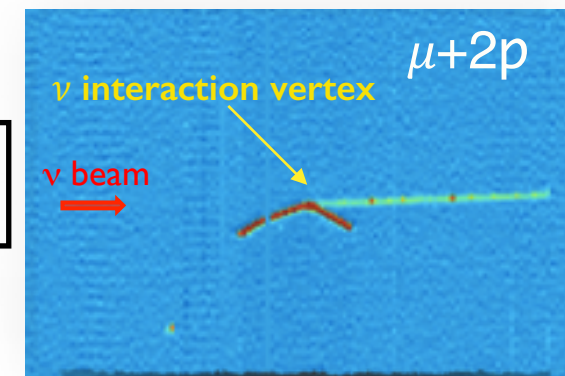
ν_e events

Proton Multiplicity

Looking for *Short Range Correlated nucleon pairs*



$\mu+2p$ events



MicroBooNE

	$1\mu^- + 2p$
1.5×10^{19} POT	269
5×10^{19} POT	896
1×10^{20} POT	1791
2×10^{20} POT	3582
6.6×10^{20} POT	11820

SBND in 1 year:
360,000 $\mu+2p$ events

Comparison with theory models with nucleon-nucleon correlation:

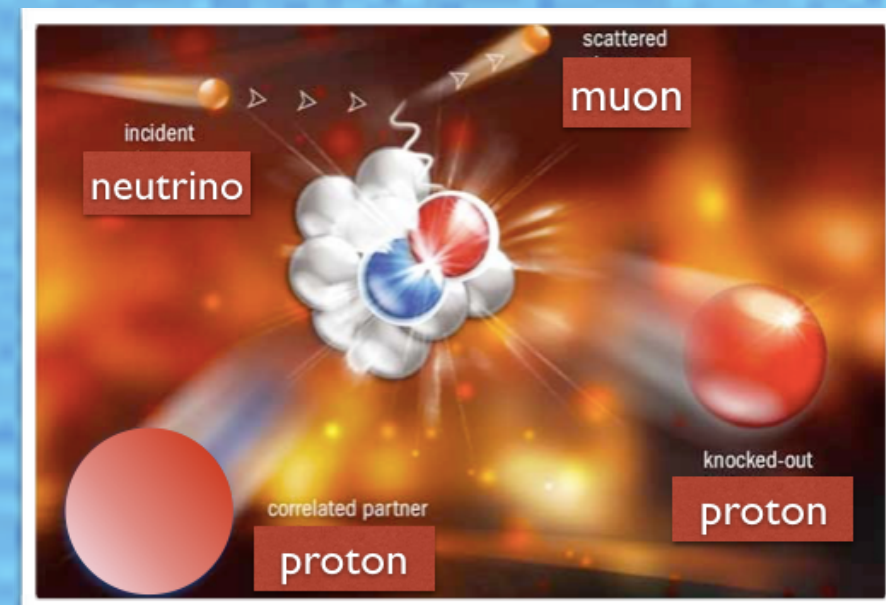
- ArgoNeuT data-NUWRO (K. Niewczas and J. Sobczyk arXiv:1511.02502v1)

(see J. Sobczyk talk)

Conclusions

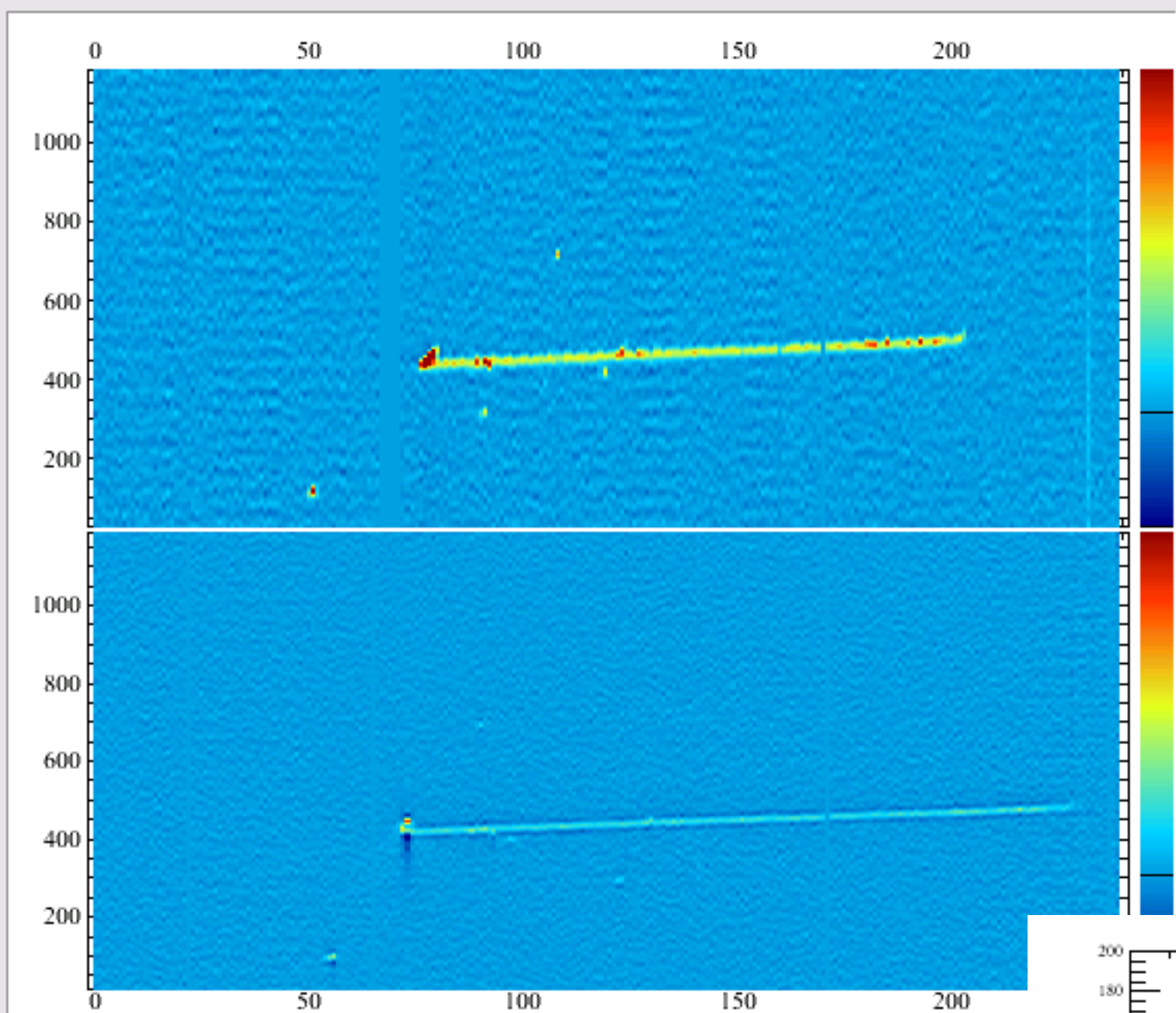
CC 0 pion events

- ◎ **First topological analysis** developed by the **ArgoNeuT** experiment.
 - ◎ **First measurement of exclusive channels cross sections.**
 - ◎ **First direct experimental investigations on nuclear effects and their impact on the predicted rates, final states, and kinematics of neutrino interactions.**
 - ◎ **Tension with current MC generators.**
 - ◎ **The statistics from ArgoNeuT events is very limited.**
- ◎ **Future **larger mass** and high statistics LAr-TPC detectors will allow to **quantify** nuclear effects in neutrino-Ar scattering.**
- ◎ **Models including all nuclear effects as well as their implementation in ν MC generators are deemed necessary for comparisons with LAr data.**

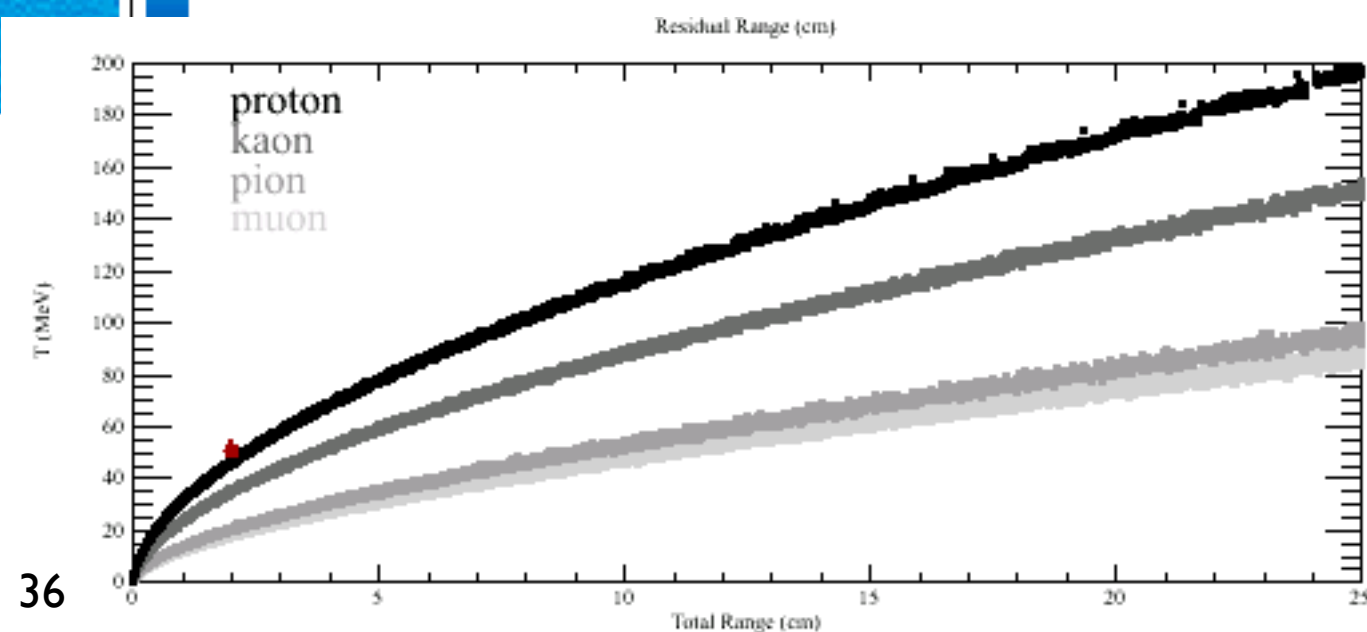


Overflow

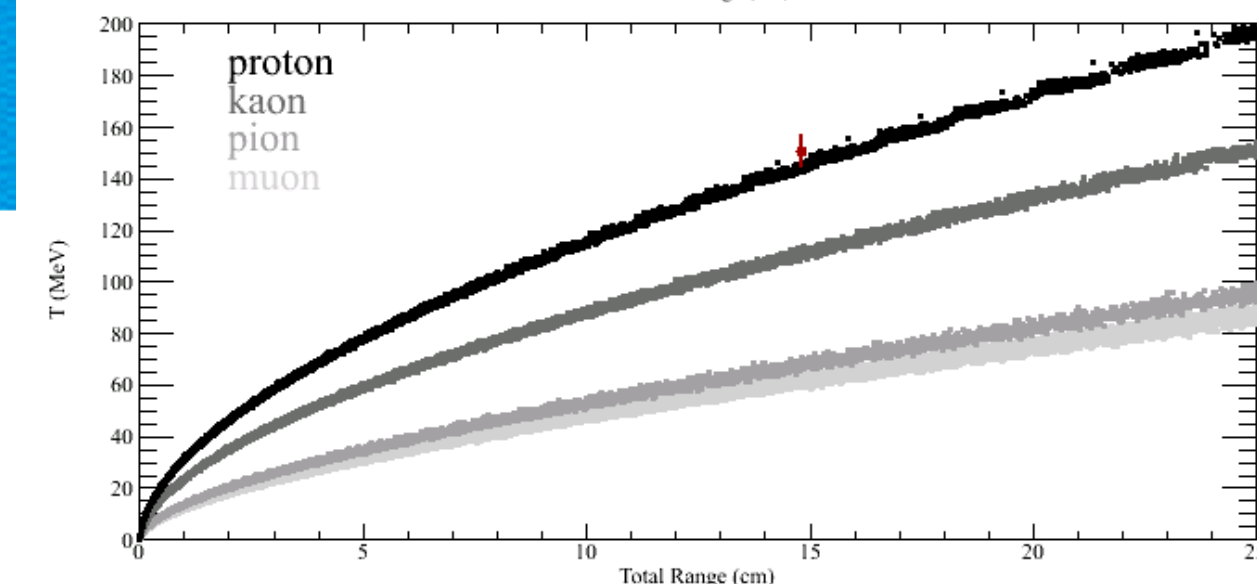
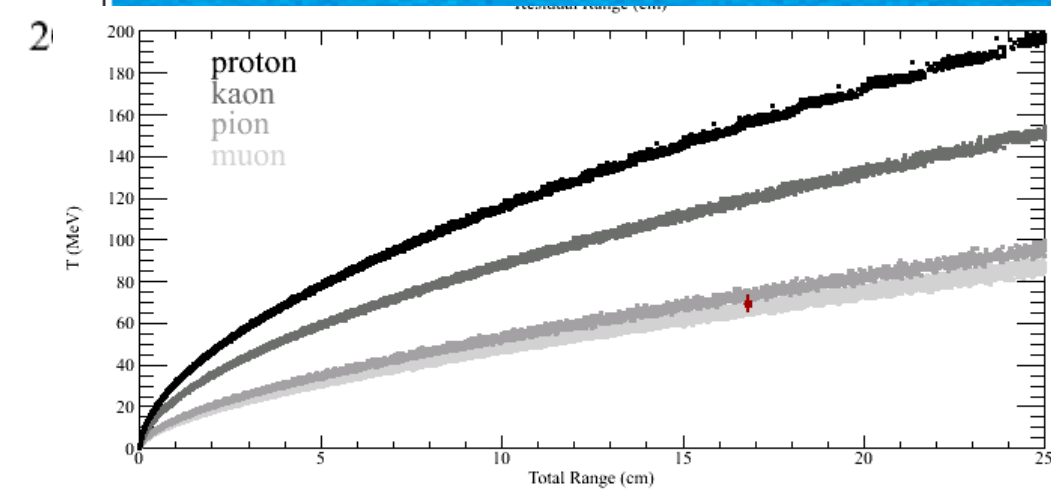
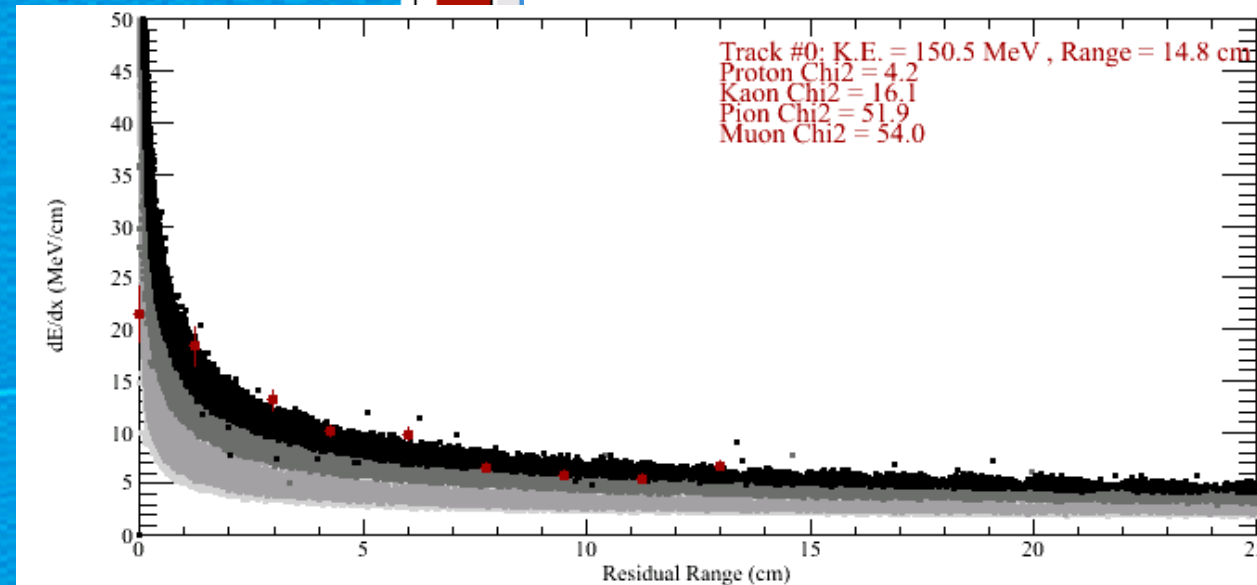
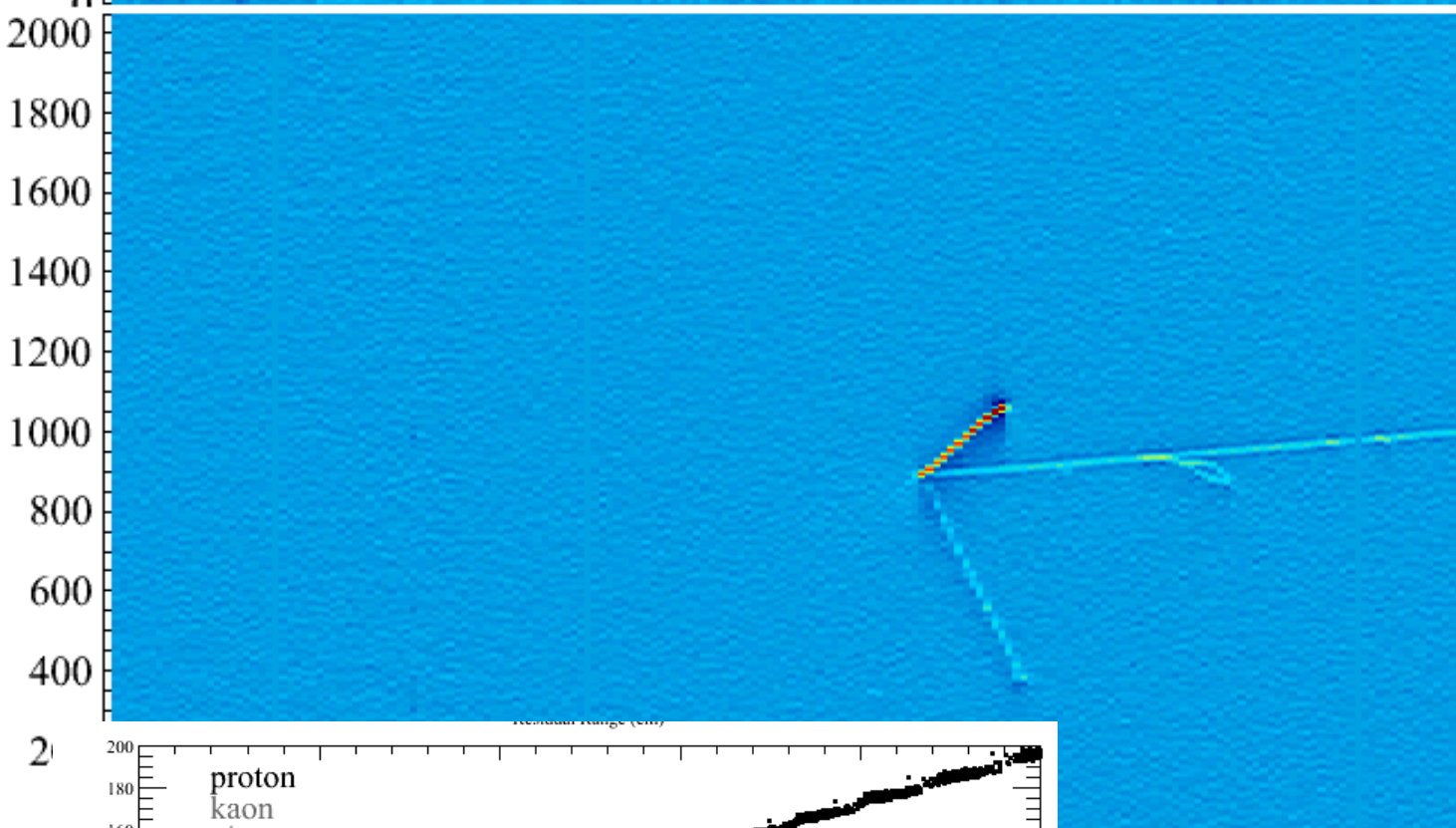
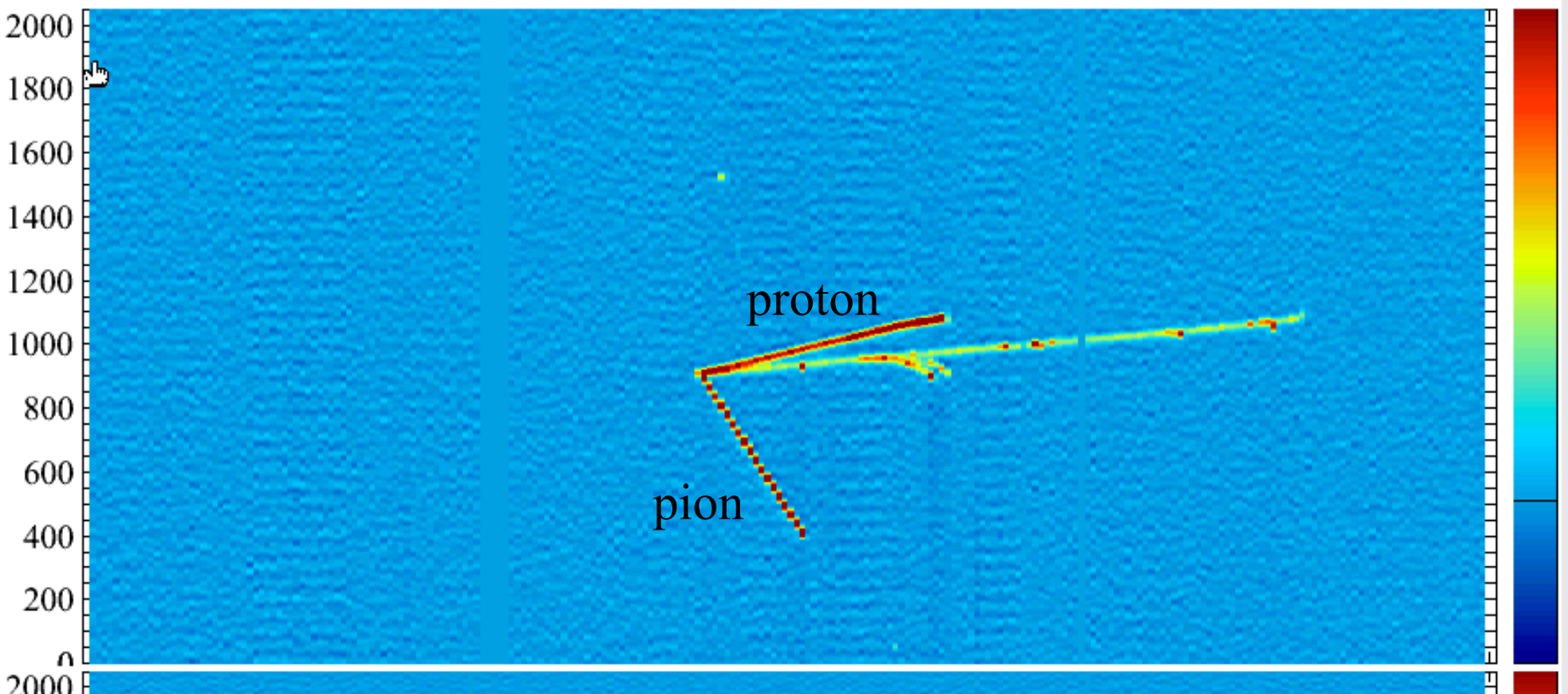
---> > Reload [Run/Event]= 772 7362 Go Pri



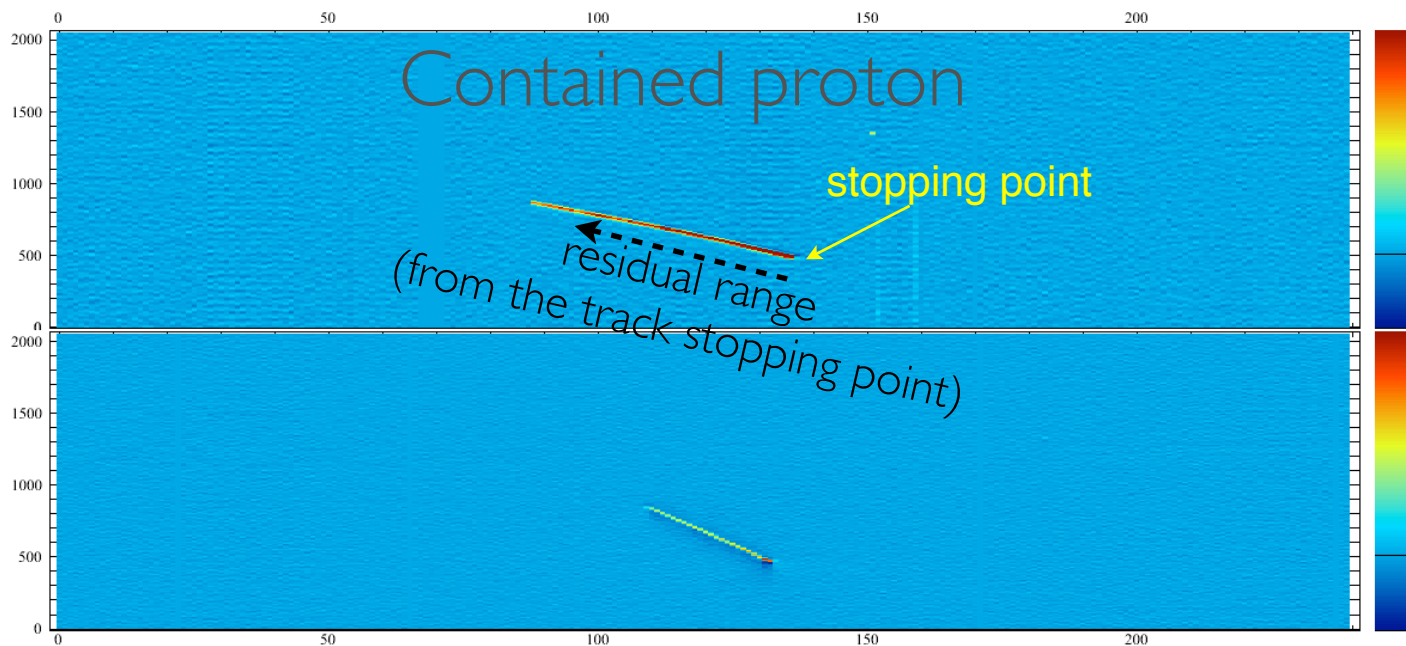
Example of Selected
Event.
Calorimetric
reconstruction



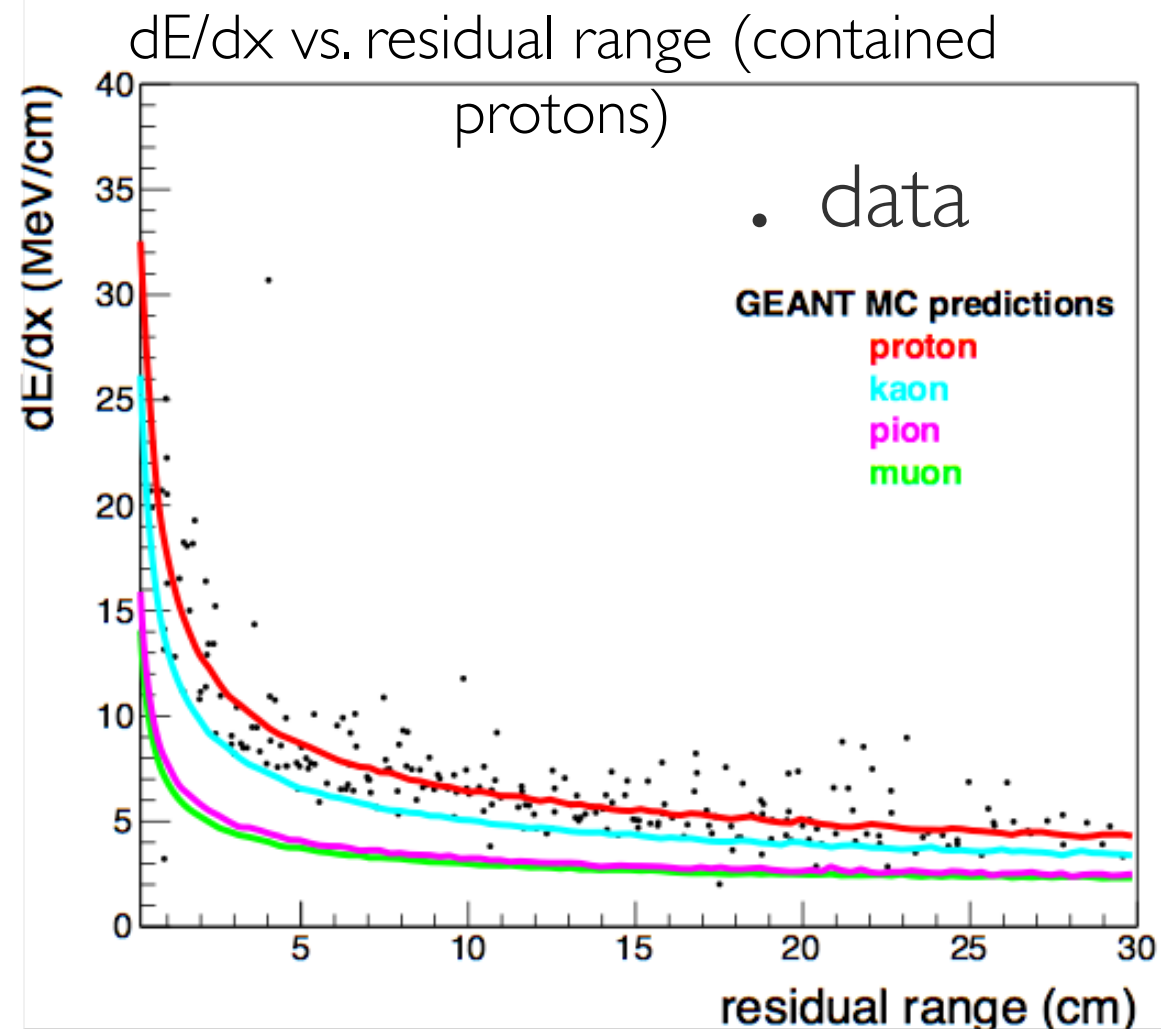
Example of Rejected Event



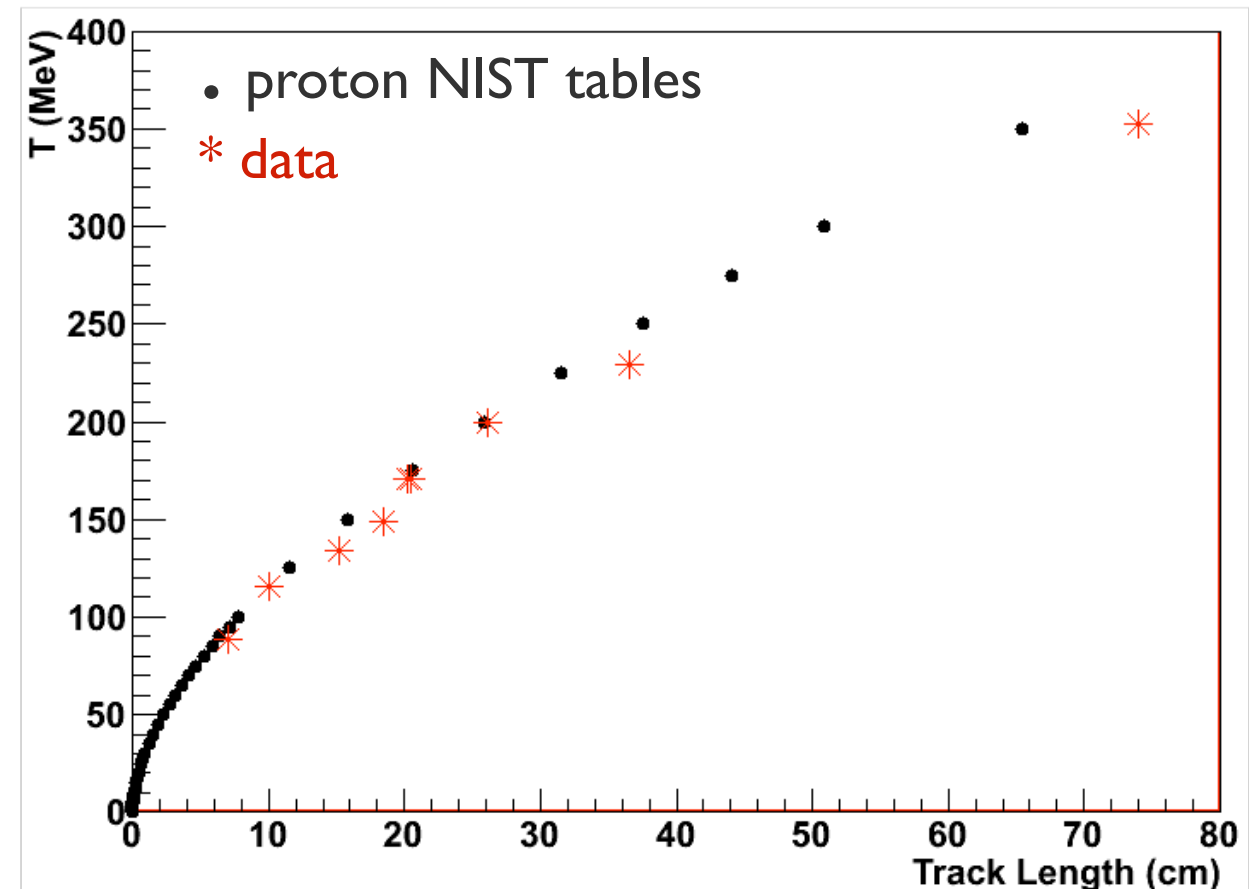
Stopping tracks - Calorimetric reconstruction and PID



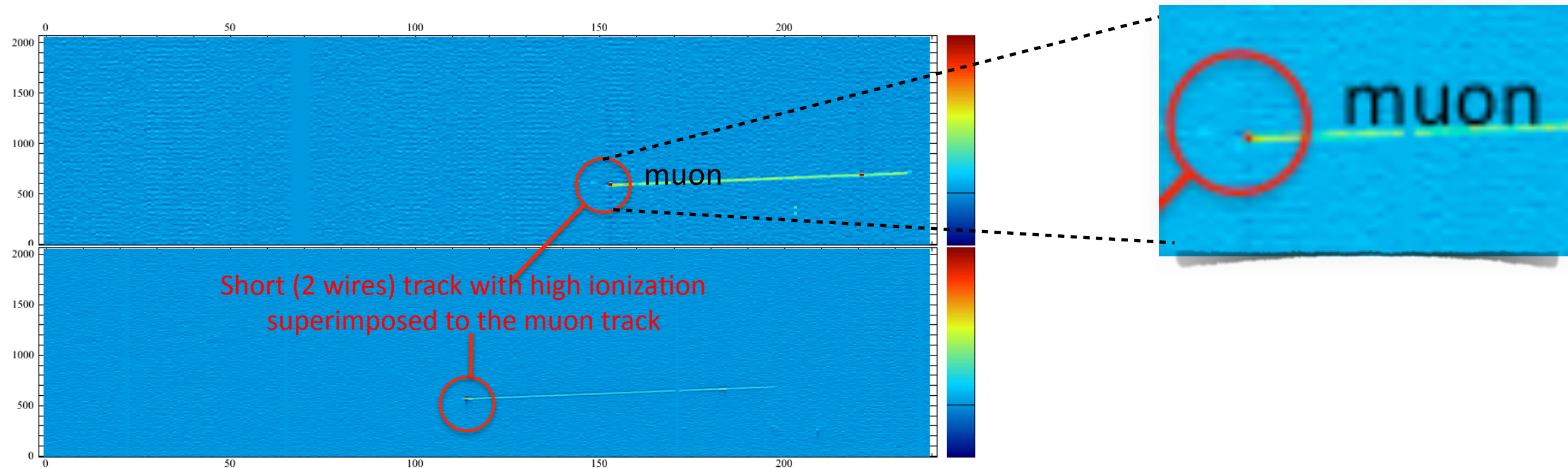
The energy loss as a function of distance from the end of the track is used as a powerful method for particle identification.



Kinetic Energy vs. track length



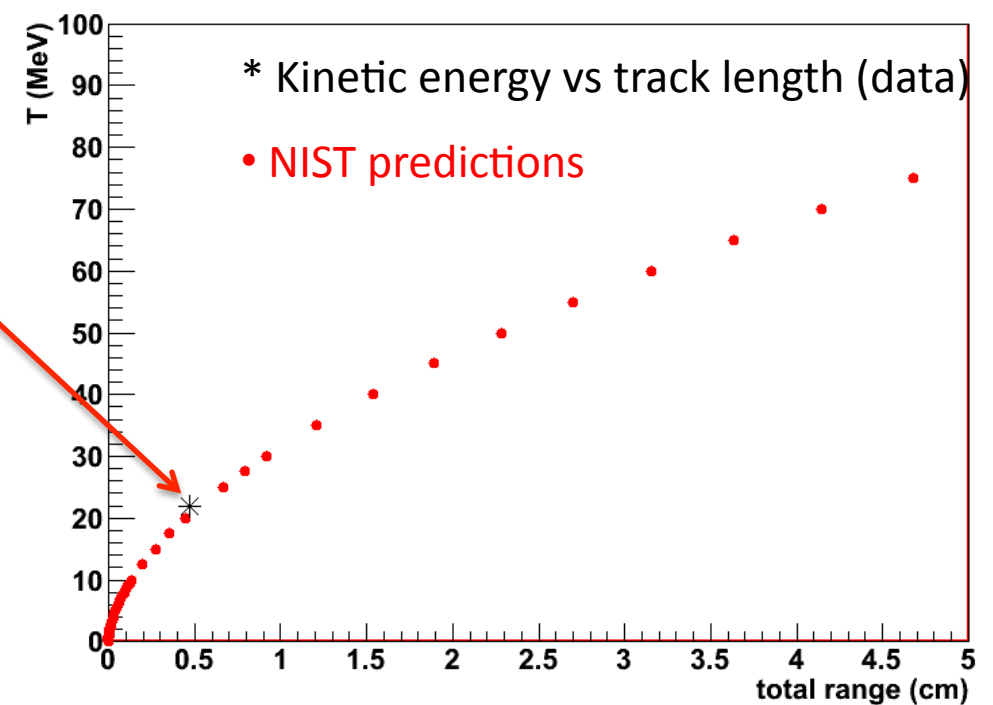
Low energy proton reconstruction



The short track behaves like **proton**

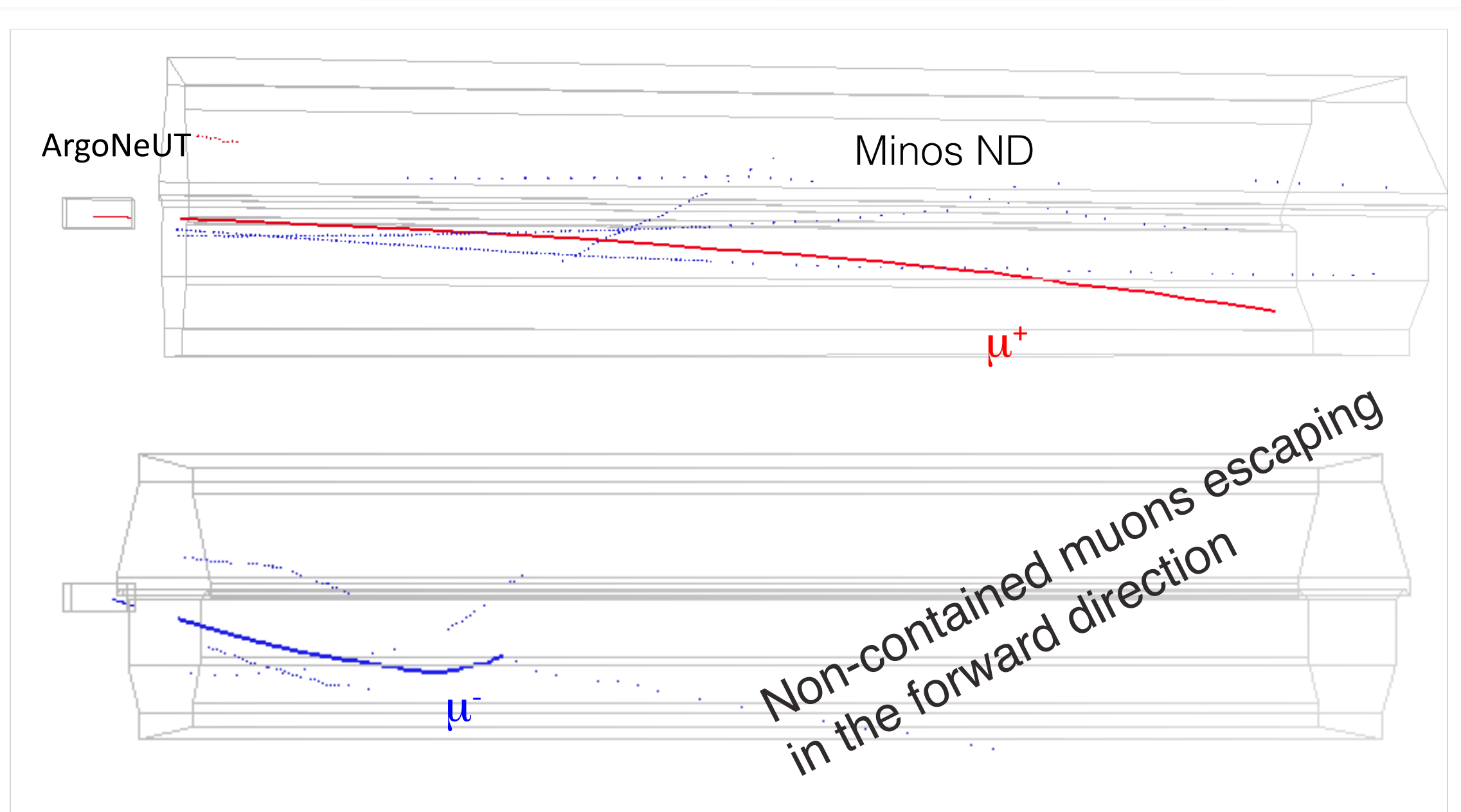
Length=0.5 cm

$$T_p = 22 \pm 3 \text{ MeV}$$



ArgoNeuT proton threshold: **21 MeV Kinetic Energy**

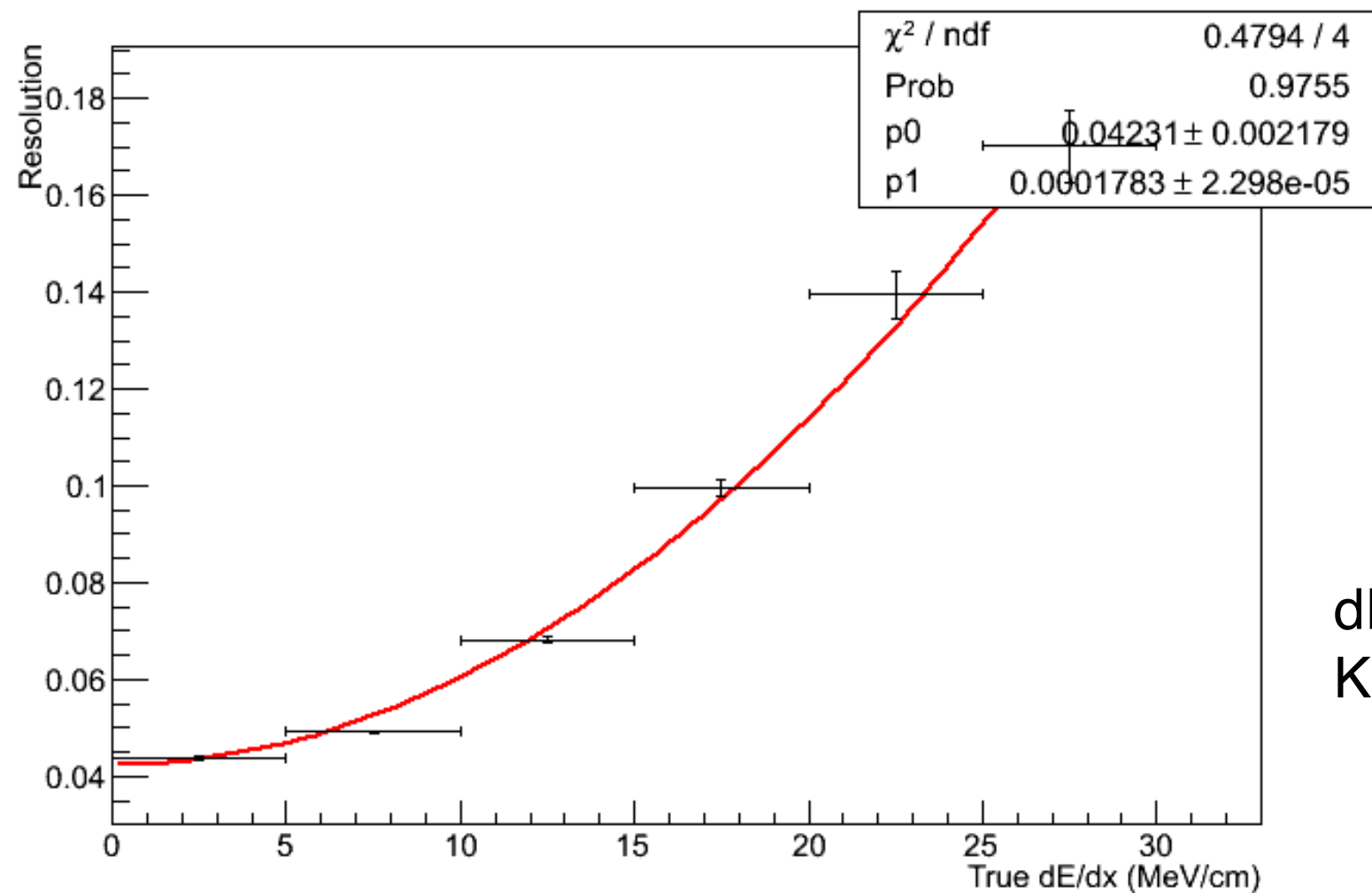
Muon Reconstruction



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

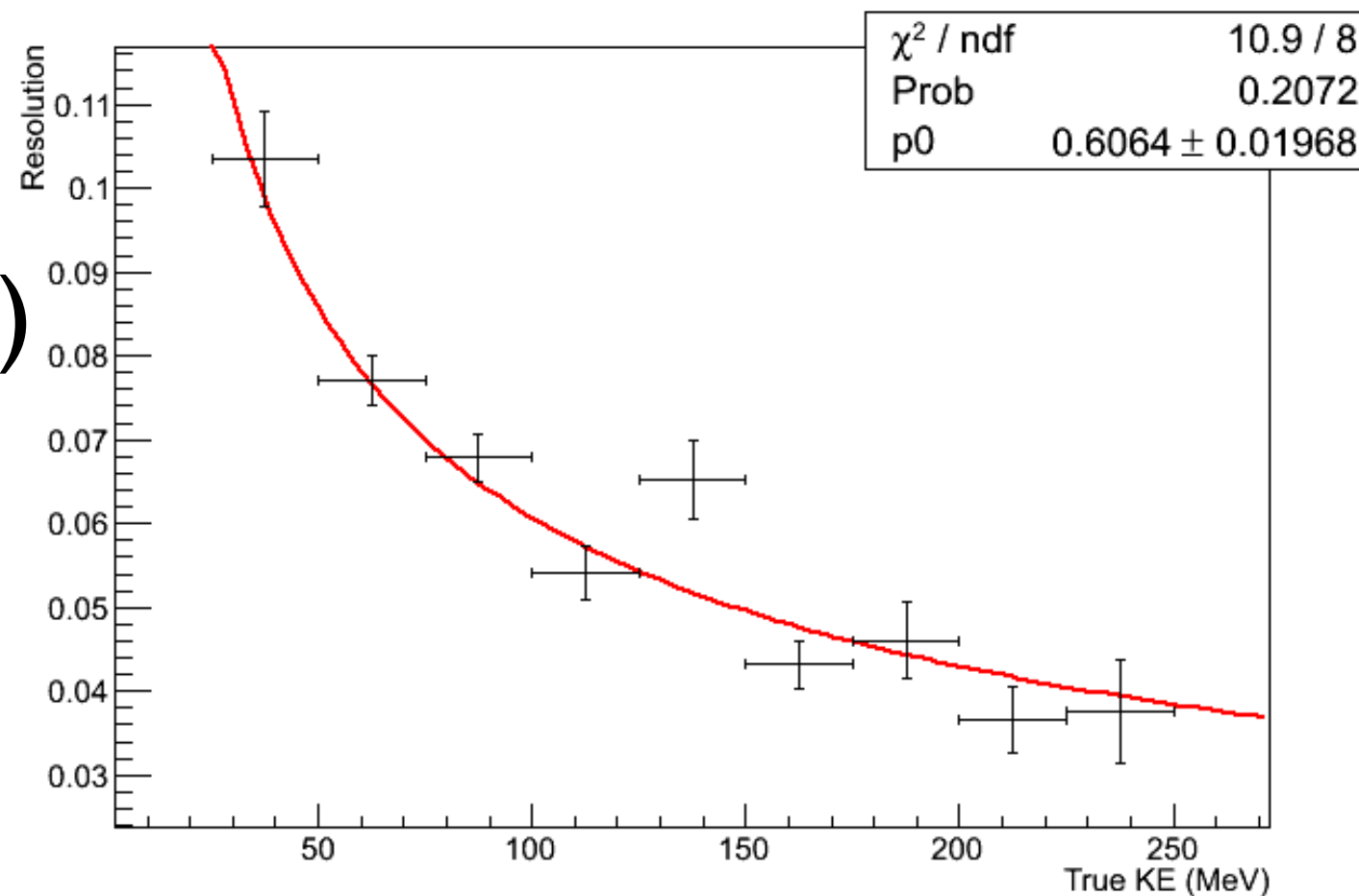
Muon kinematic reconstruction:
ArgoNeuT + MINOS ND measurement (momentum and sign)
Muon momentum resolution: 5-10%

		Generated			
		Proton	Kaon	Pion	Muon
Identified as	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

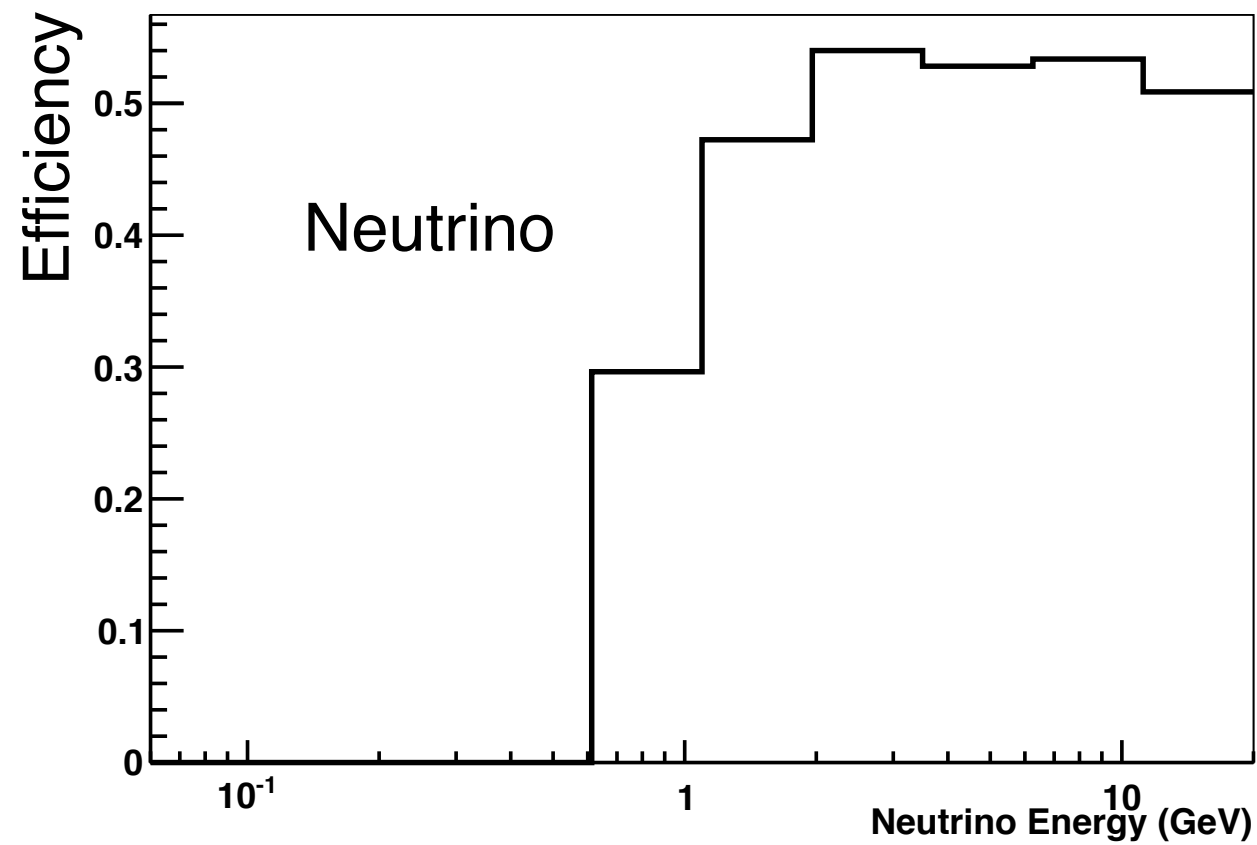


$dEdx: 0.04231 + 0.0001783 * (dEdx)^2$
 $KE: 0.6064 / \sqrt{KE}$

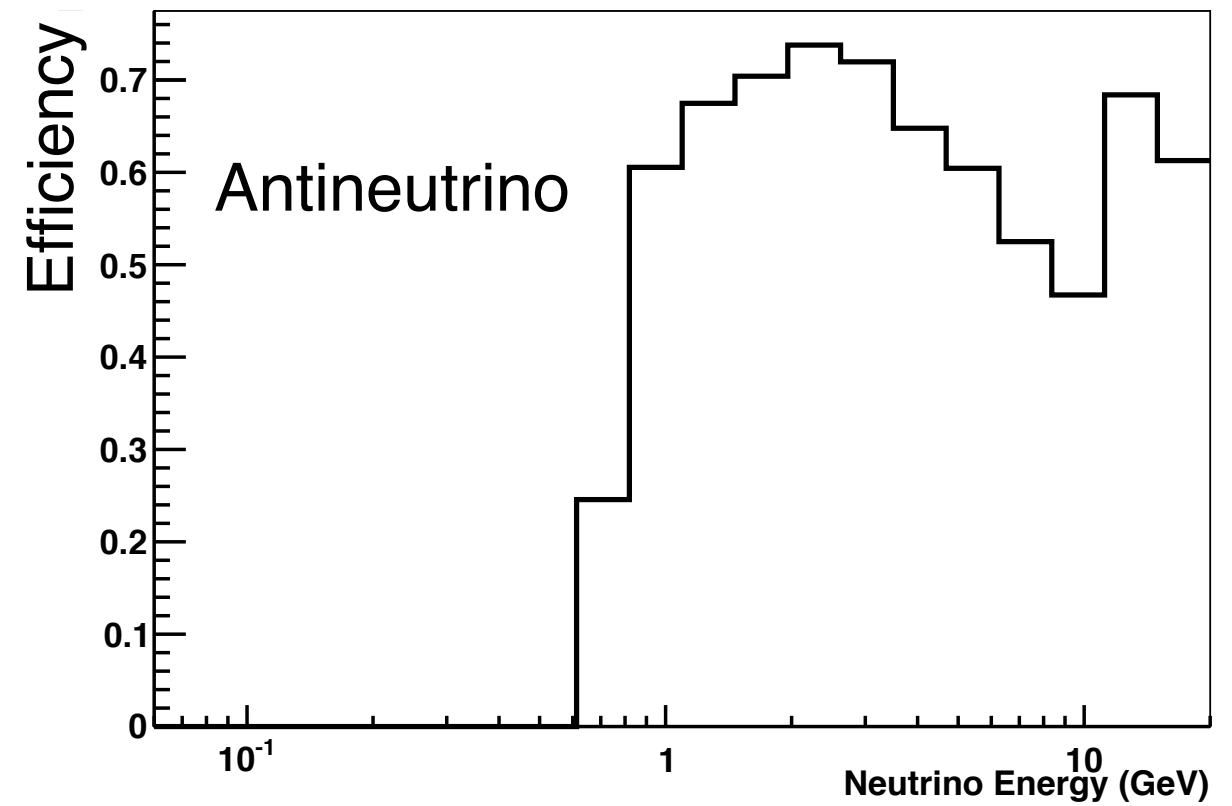
ArgoNeuT (4 mm wire pitch)
Resolution in dE/dx
and Kinetic Energy



Selection efficiency $\mu+Np$ events



Overall efficiency: 46%



Overall efficiency: 68%