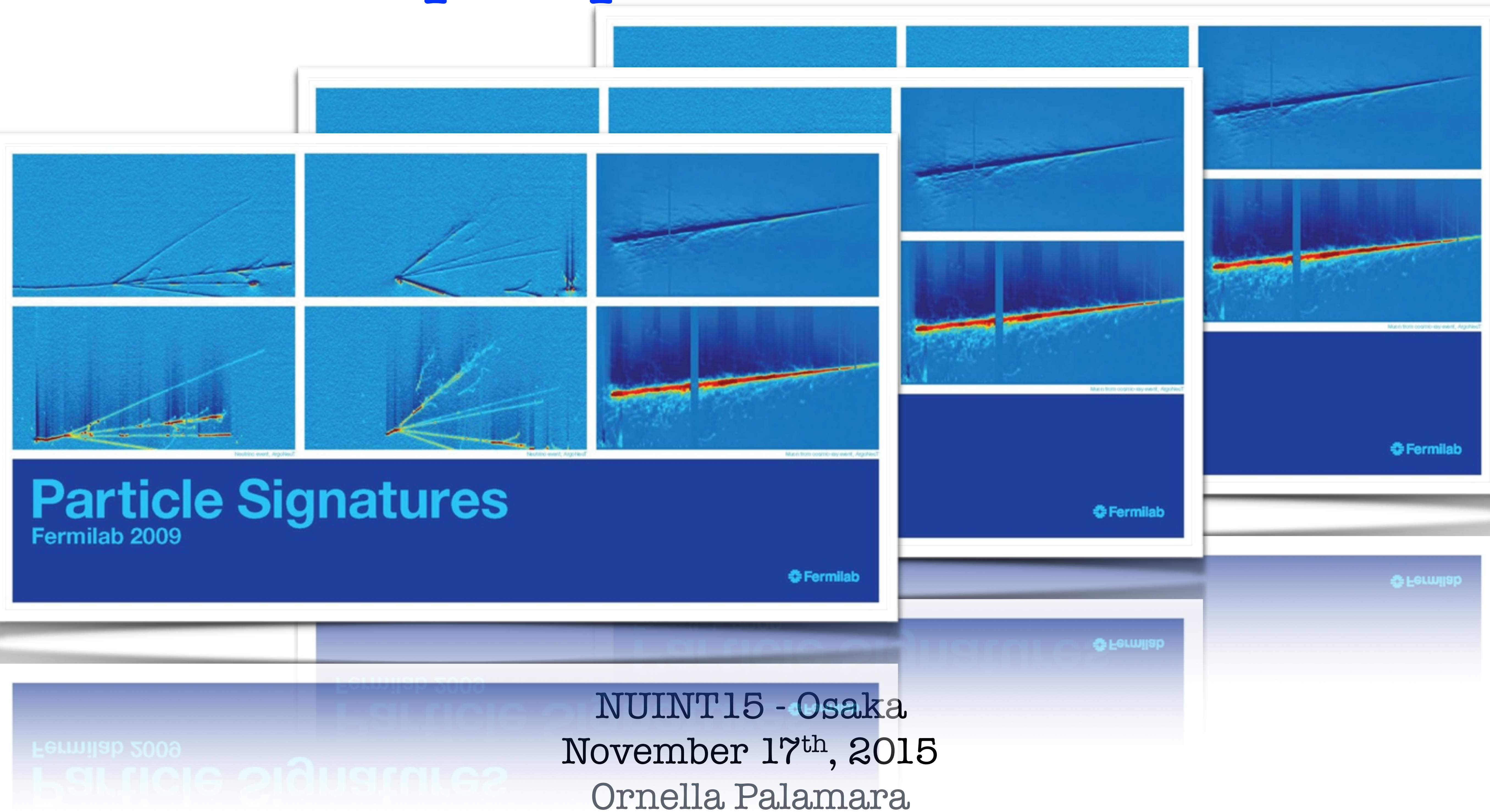
CC 0 pion: ArgoNeuT results & future prospects in LAr detectors



NUINT15 - Osaka

November 17th, 2015

Ornella Palamara

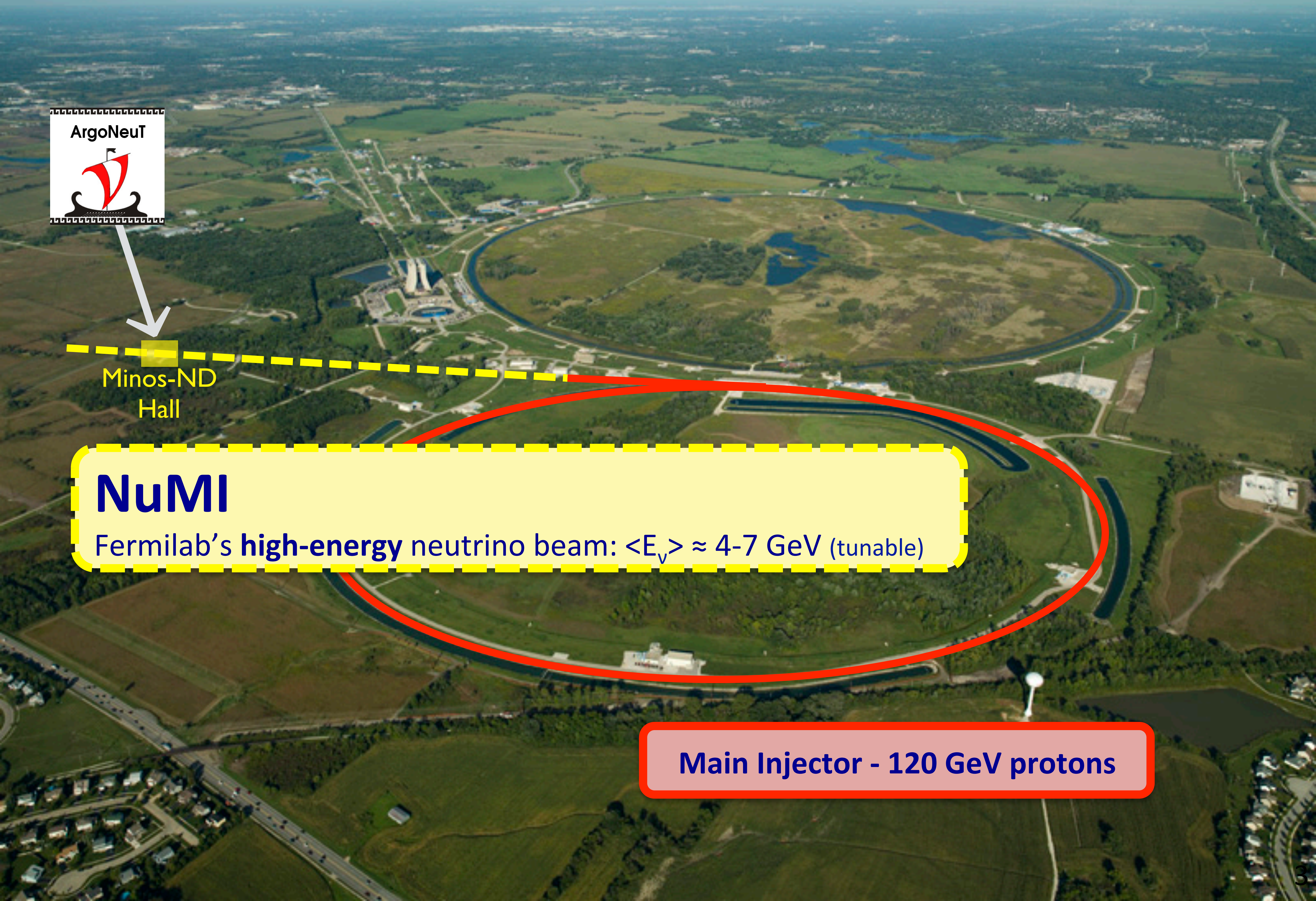
Fermilab & Yale University, USA *

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

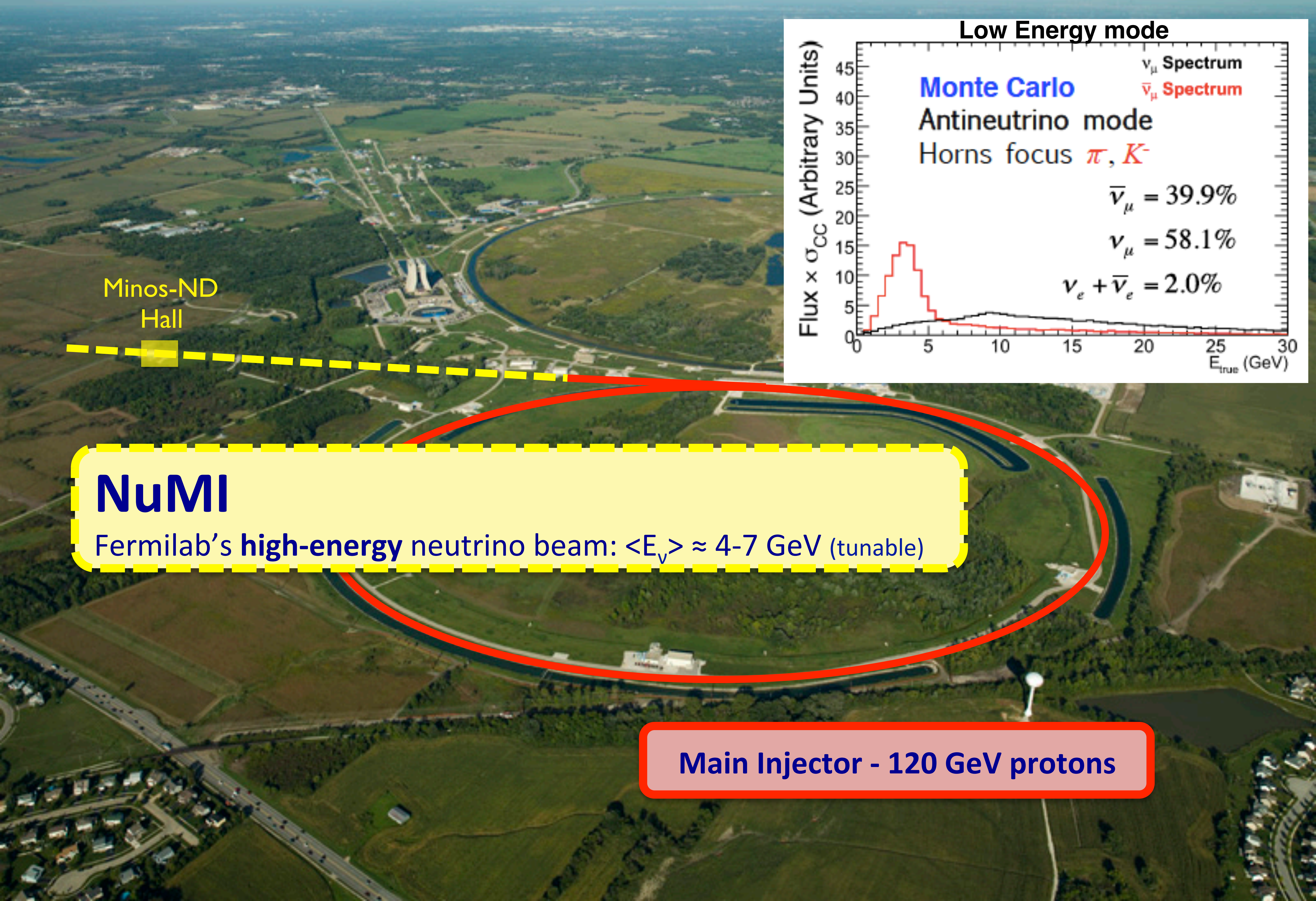
Outline

- **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



Fermilab – NuMI Neutrino beam



NuMI

Fermilab's **high-energy** neutrino beam: <E_ν> ≈ 4-7 GeV (tunable)

Main Injector - 120 GeV protons

ArgoNeuT experiment in the NUMI Beam

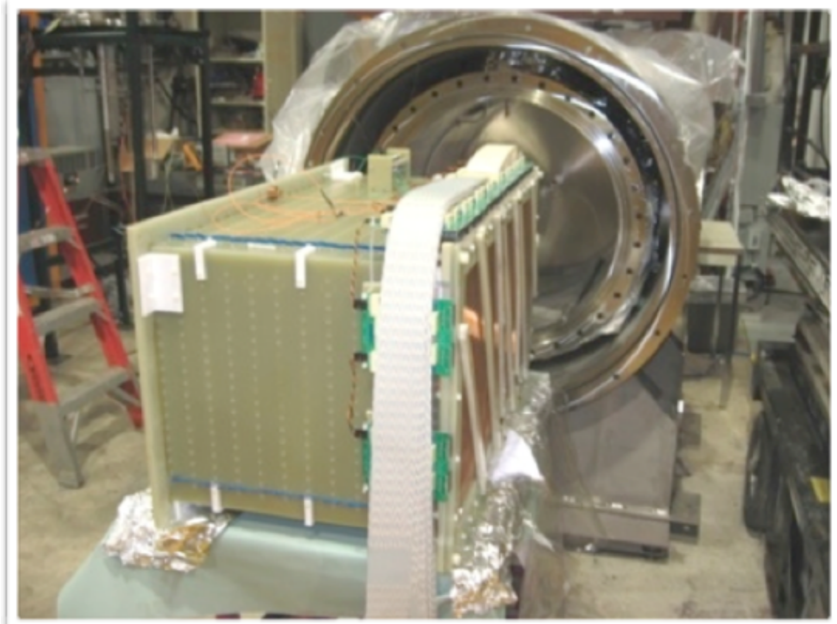
First LAr TPC in a neutrino beam in the US

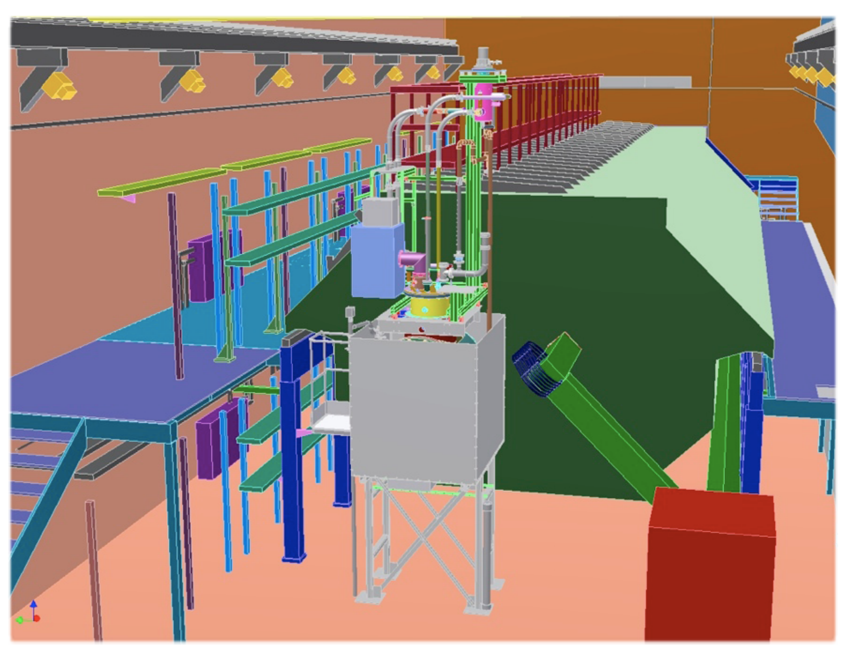
First LArTPC in a low (1-10 GeV) energy neutrino beam

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

240 Kg active volume
LAr TPC
$47 \times 40 \times 90$ cm^3, 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

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

ArgoNeuT experiment in the NUMI Beam

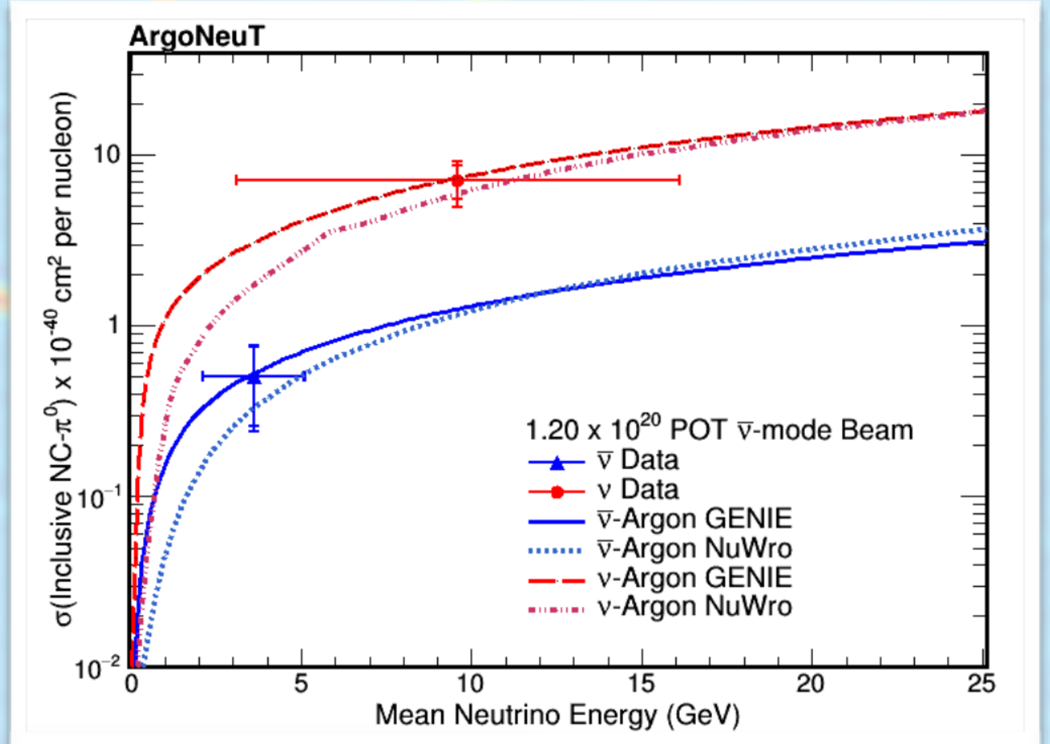
Designed as test experiment but obtaining physics results!

~7000 CC events collected

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

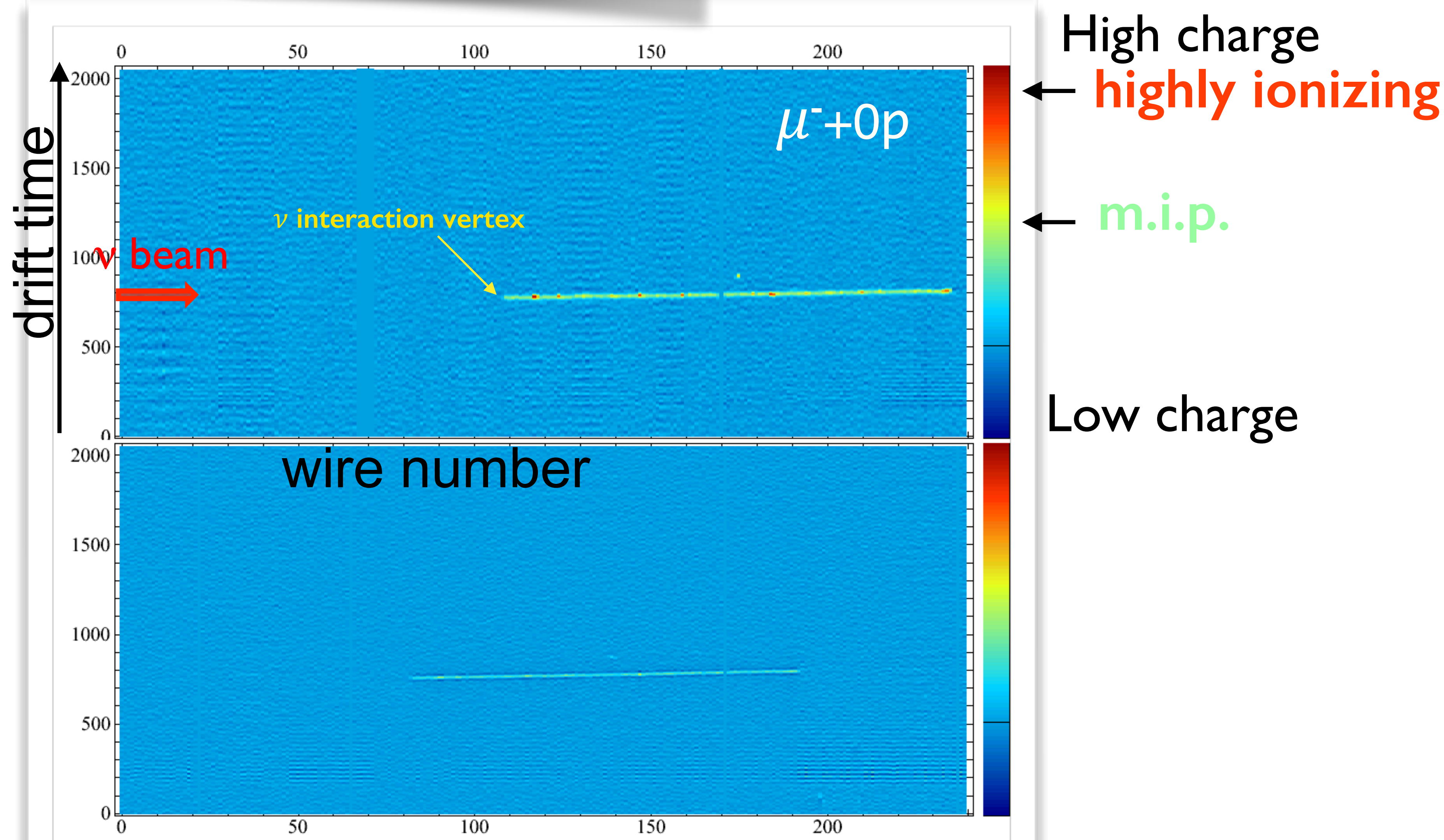
0 PION EVENT TOPOLOGY: leading muon accompanied by any number (N=0, 1, 2, 3, 4) of protons final state

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)



2D views from the two wire planes

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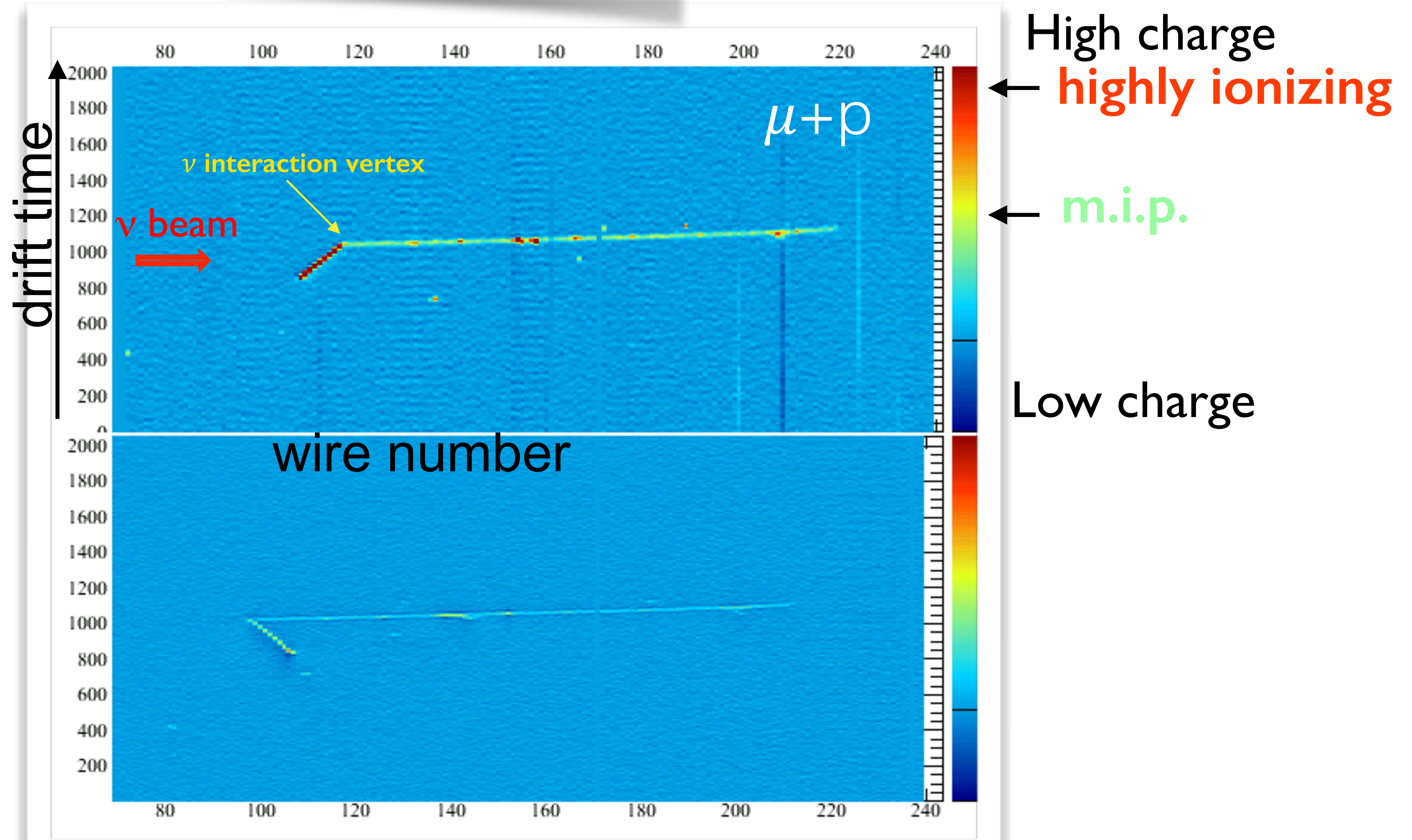

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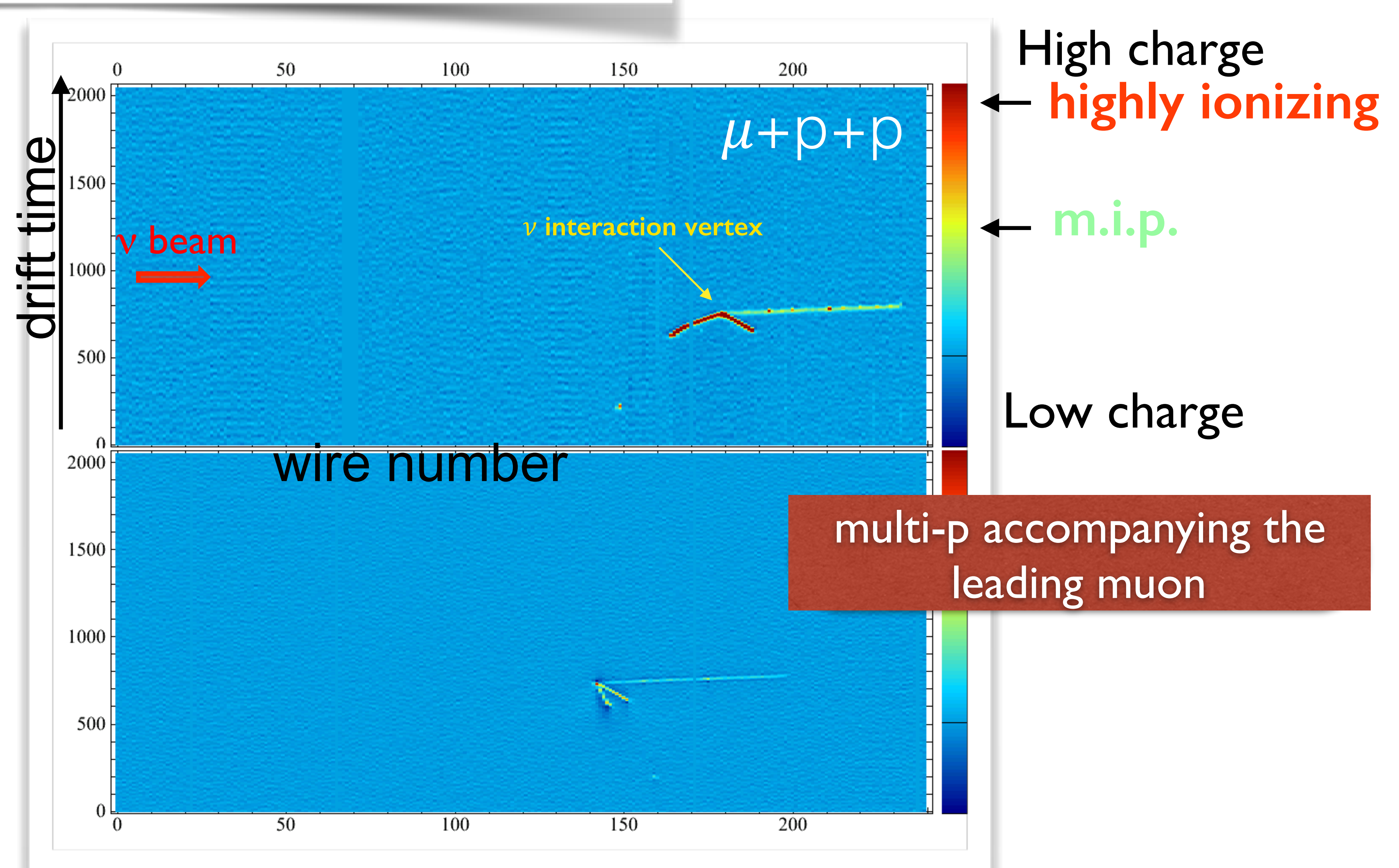


$\nu_\mu/\overline{\nu}_\mu$CC 0 pion event
Isolation cuts and reconstruction

ArgoNeuT

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_μCC 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

ArgoNeuT

- 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 i*nclusive* and *exclusive CC 0 pion cross sections*.

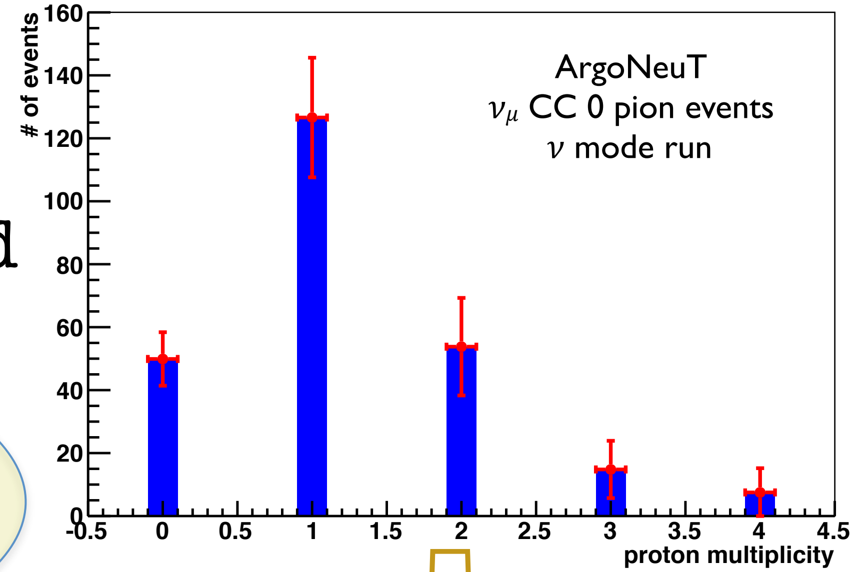
New results today

Inclusive and Exclusive ν_μ CC 0 pion cross sections

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

ν_μ events: ~50% N≠1

$\bar{\nu}_\mu$ events: ~32% N≠0



$N_{CC0\pi(,Np)}$=number of CC 0π 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

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

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

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

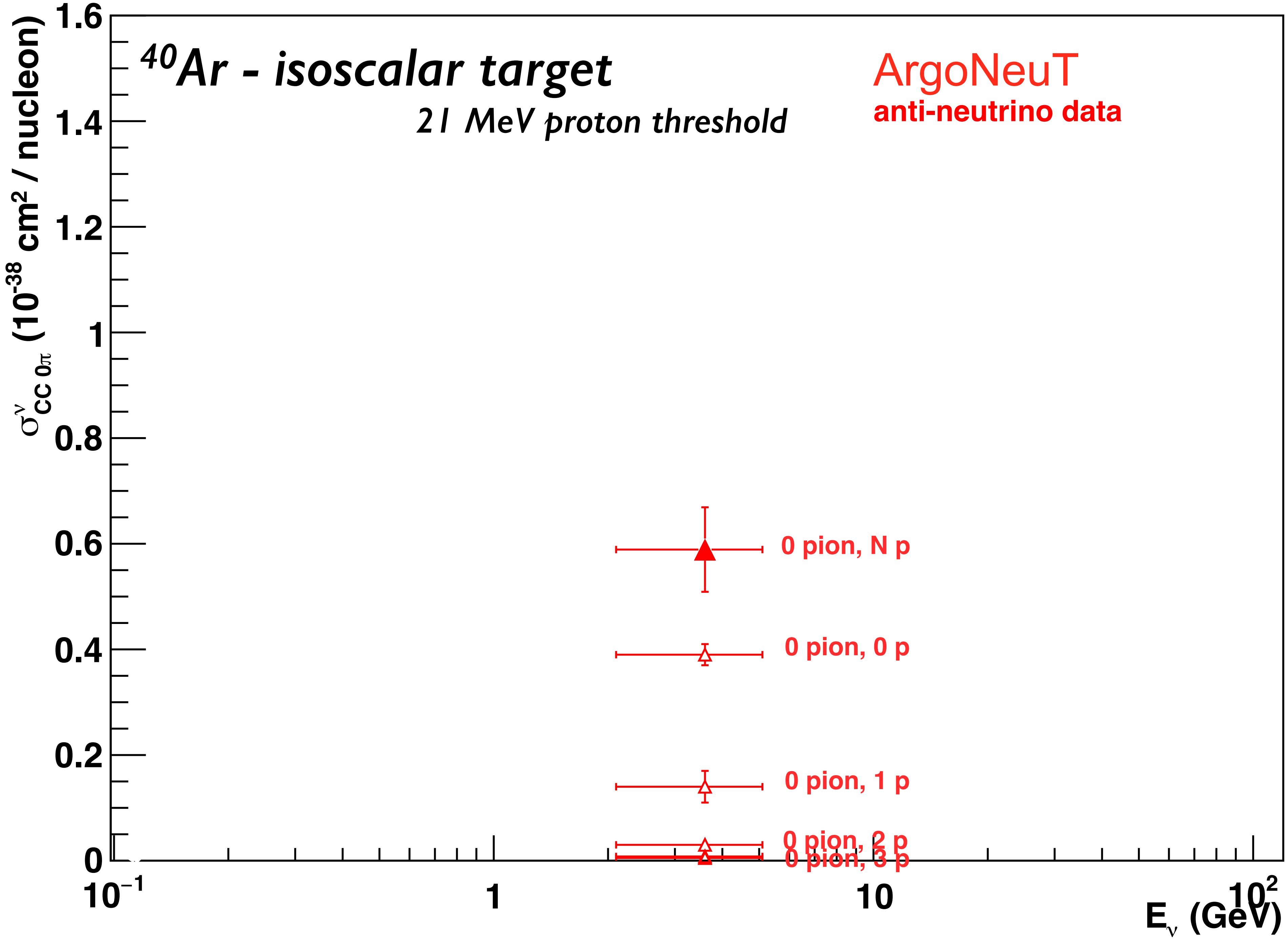
Exclusive

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

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 Idenfication	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

<Ev>=3.6±1.5 GeV

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

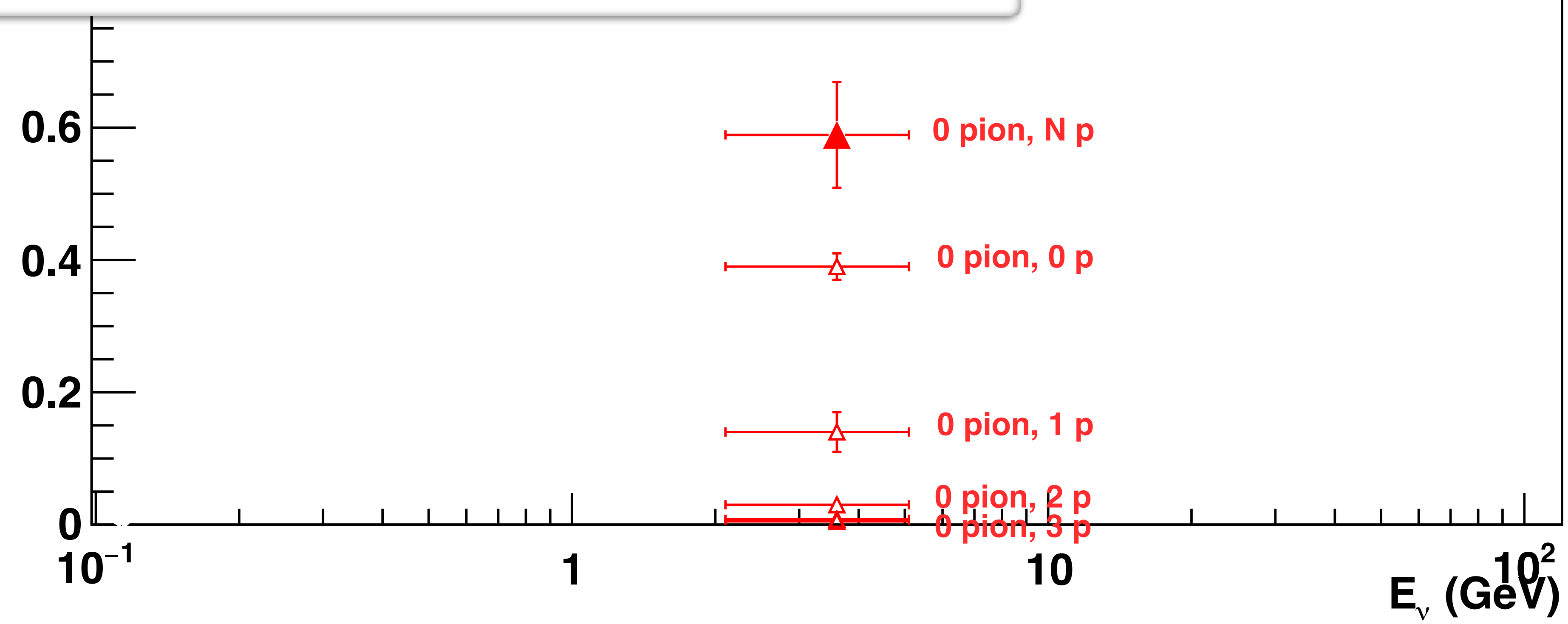
$$\sigma^{\bar{\nu}}_{CC0\pi,0p} = 0.39 \pm 0.02(stat.) \pm 0.008(syst.) 10^{-38} cm^2/nucleon$$

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

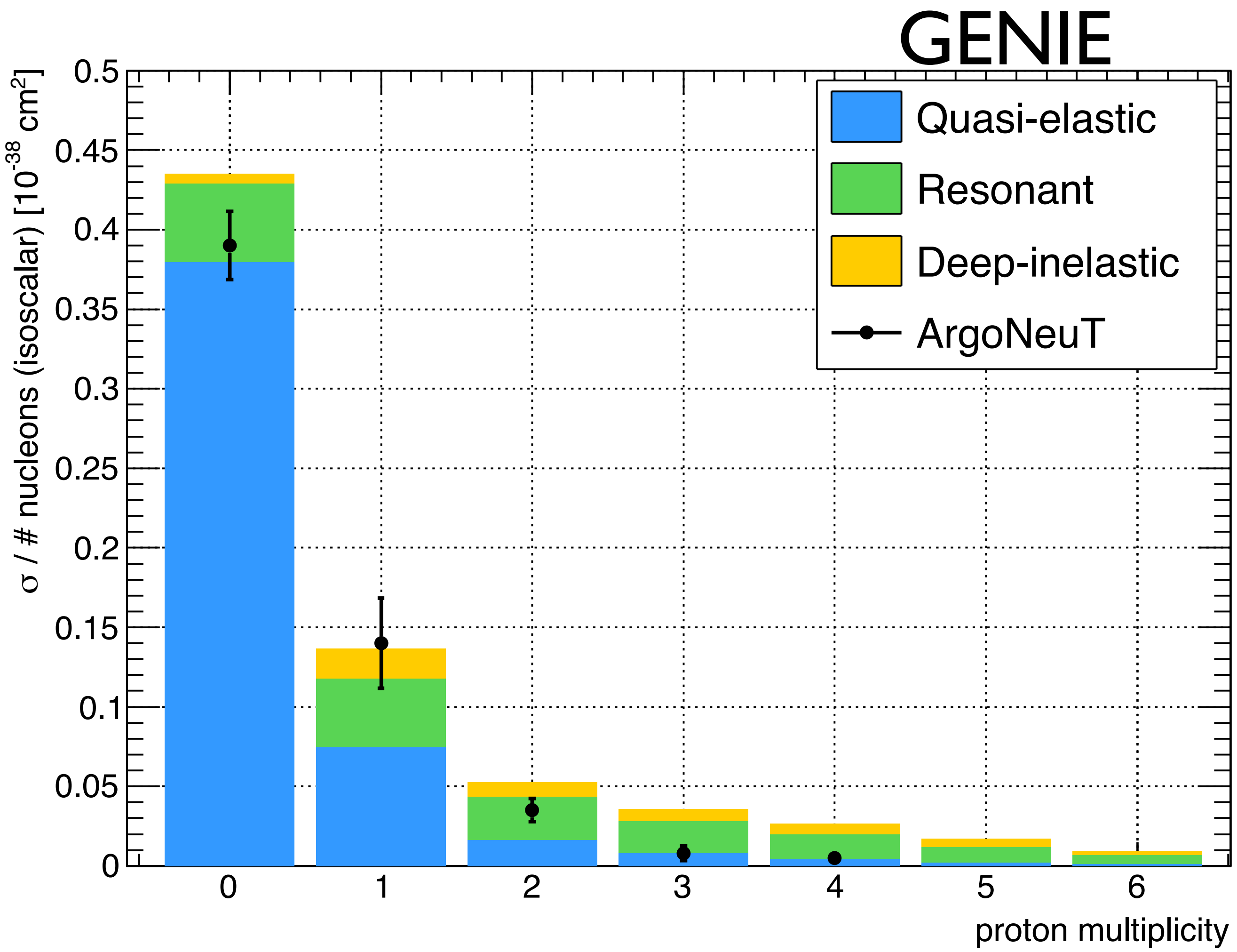
$$\sigma^{\bar{\nu}}_{CC0\pi,2p} = 0.035 \pm 0.007(stat.) \pm 0.002(syst.) 10^{-38} cm^2/nucleon$$

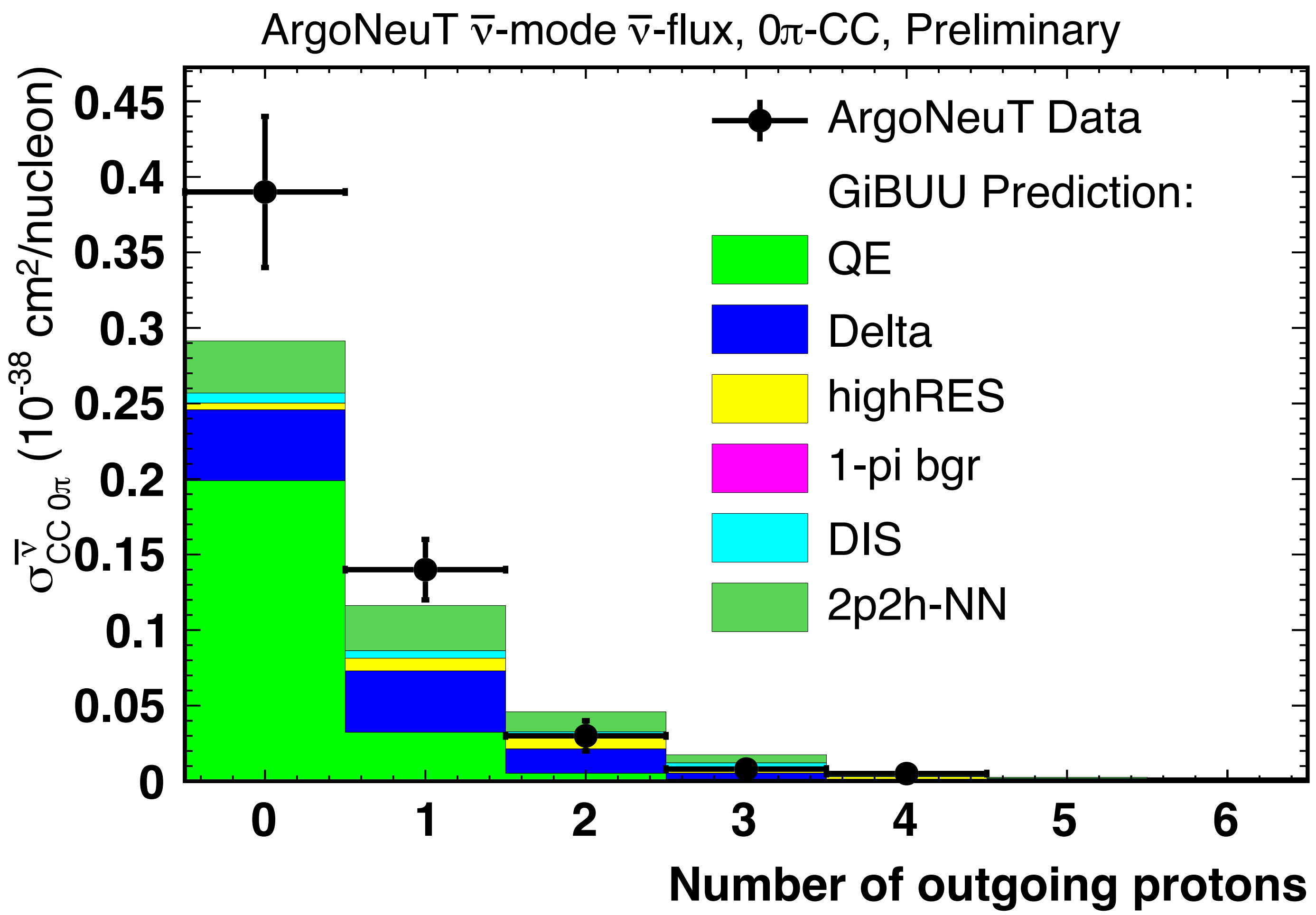
$$\sigma^{\bar{\nu}}_{CC0\pi,3p} = 0.008 \pm 0.004(stat.) \pm 0.002(syst.) 10^{-38} cm^2/nucleon$$

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



Exclusive Antineutrino Cross Sections Comparison with GENIE and GiBUU





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

$\sigma^{\bar{\nu}}_{0\pi} = 0.48\ 10^{-38}cm^2/nucleon$
GiBUU

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

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

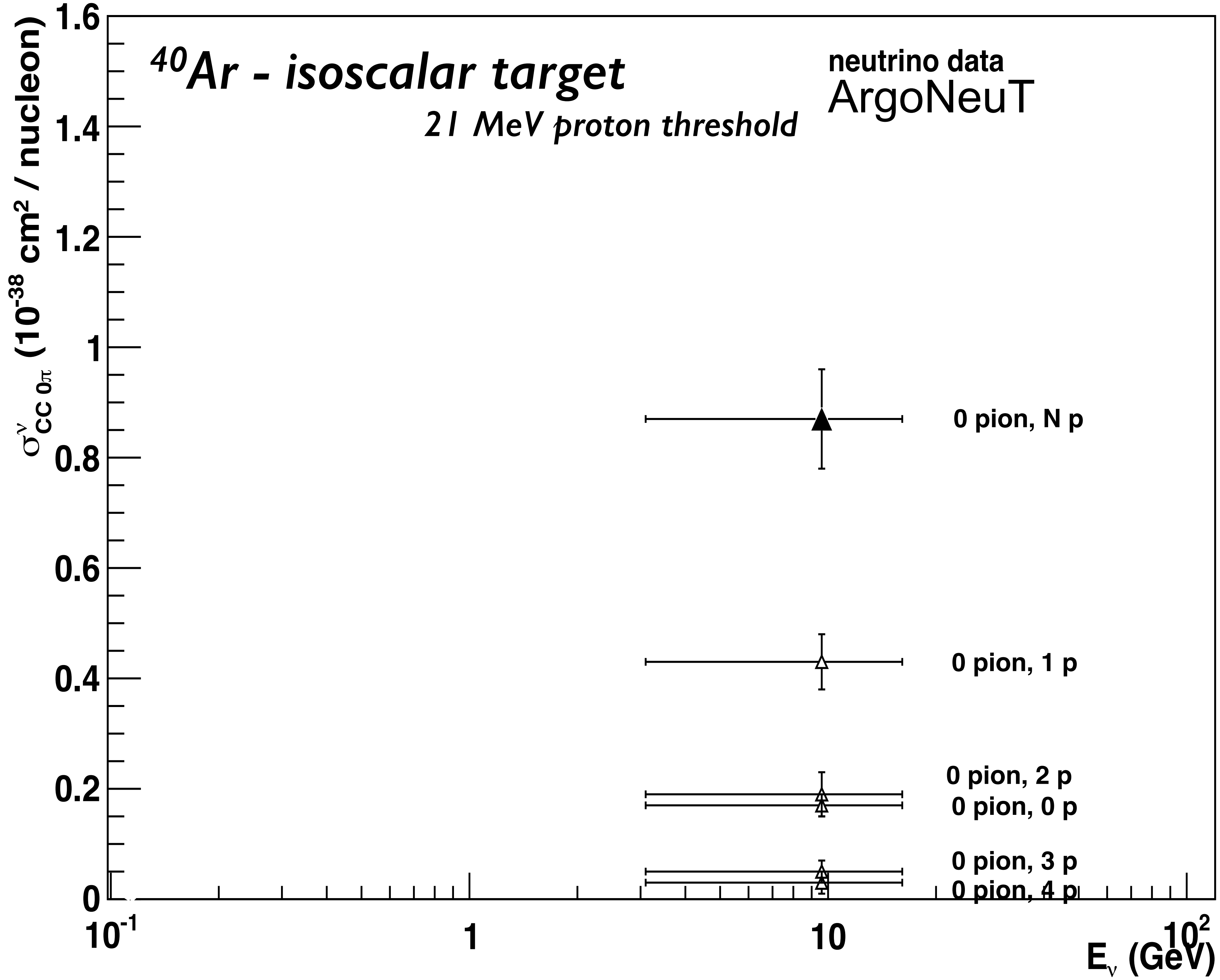
Antineutrino
Comparison with different MC generators

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

ArgoNeuT

<Ev>=9.6±6.5 GeV

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

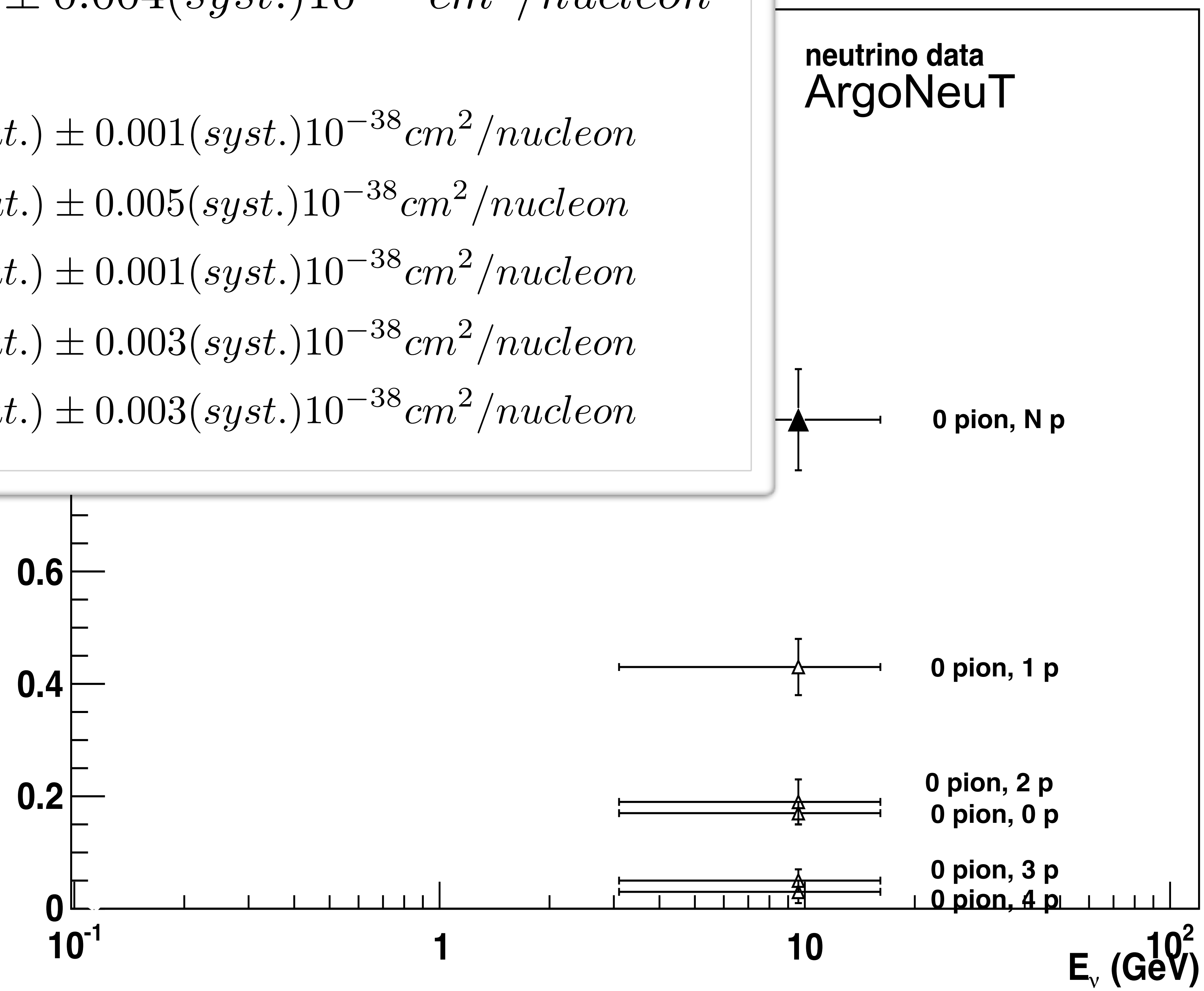
$$\sigma^{\nu}_{CC0\pi,0p} = 0.17 \pm 0.02(stat.) \pm 0.001(syst.)10^{-38} cm^2/nucleon$$

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

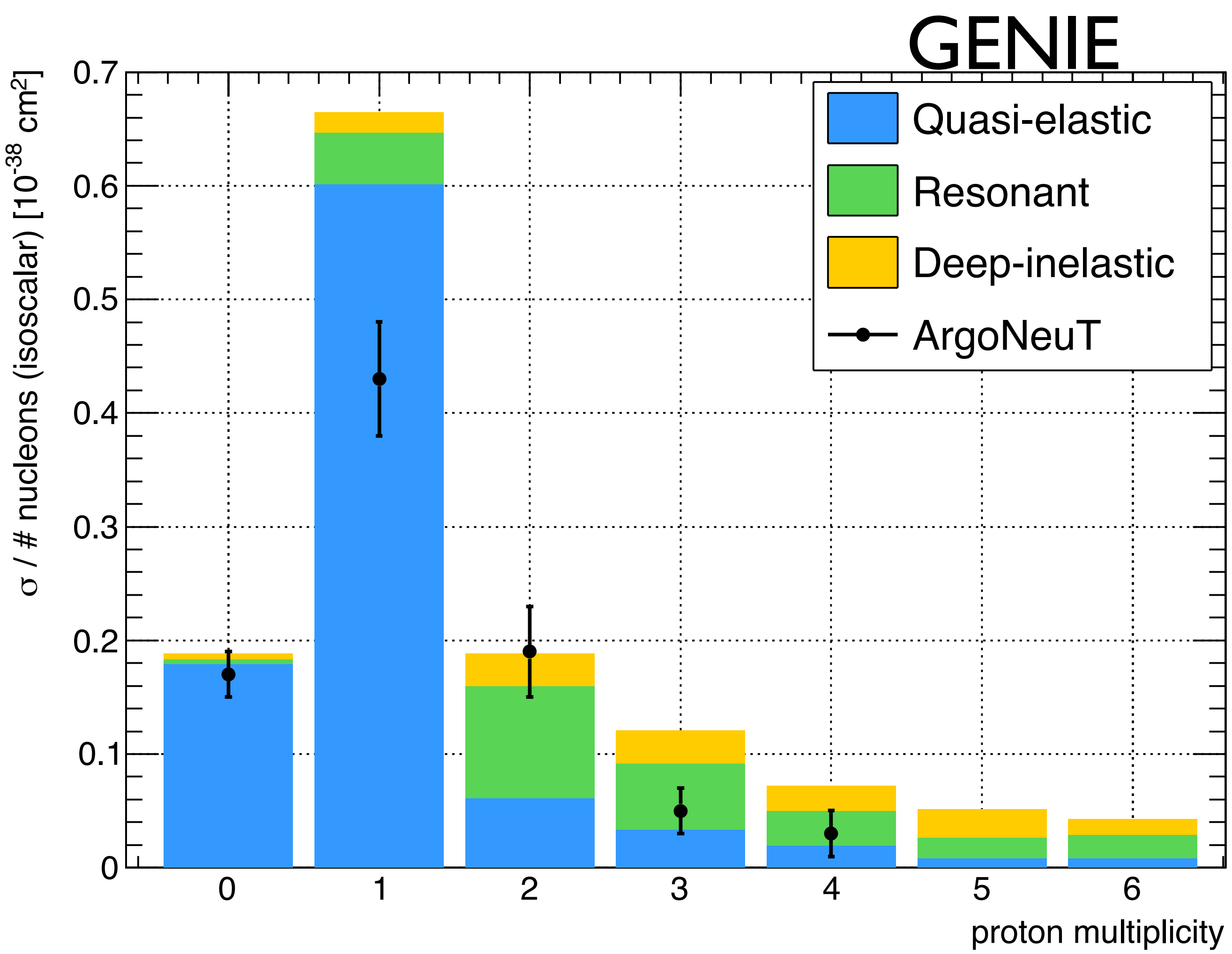
$$\sigma^{\nu}_{CC0\pi,2p} = 0.19 \pm 0.04(stat.) \pm 0.001(syst.)10^{-38} cm^2/nucleon$$

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

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



Exclusive neutrino cross sections
Comparison with GENIE



Comparison with GiBBU and NUWRO not yet available

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

GENIE MC

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

ArgoNeuT data

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

Neutrino Energy Reconstruction

ArgoNeuT

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

Phys. Rev. D 90, 012008 (2014)

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

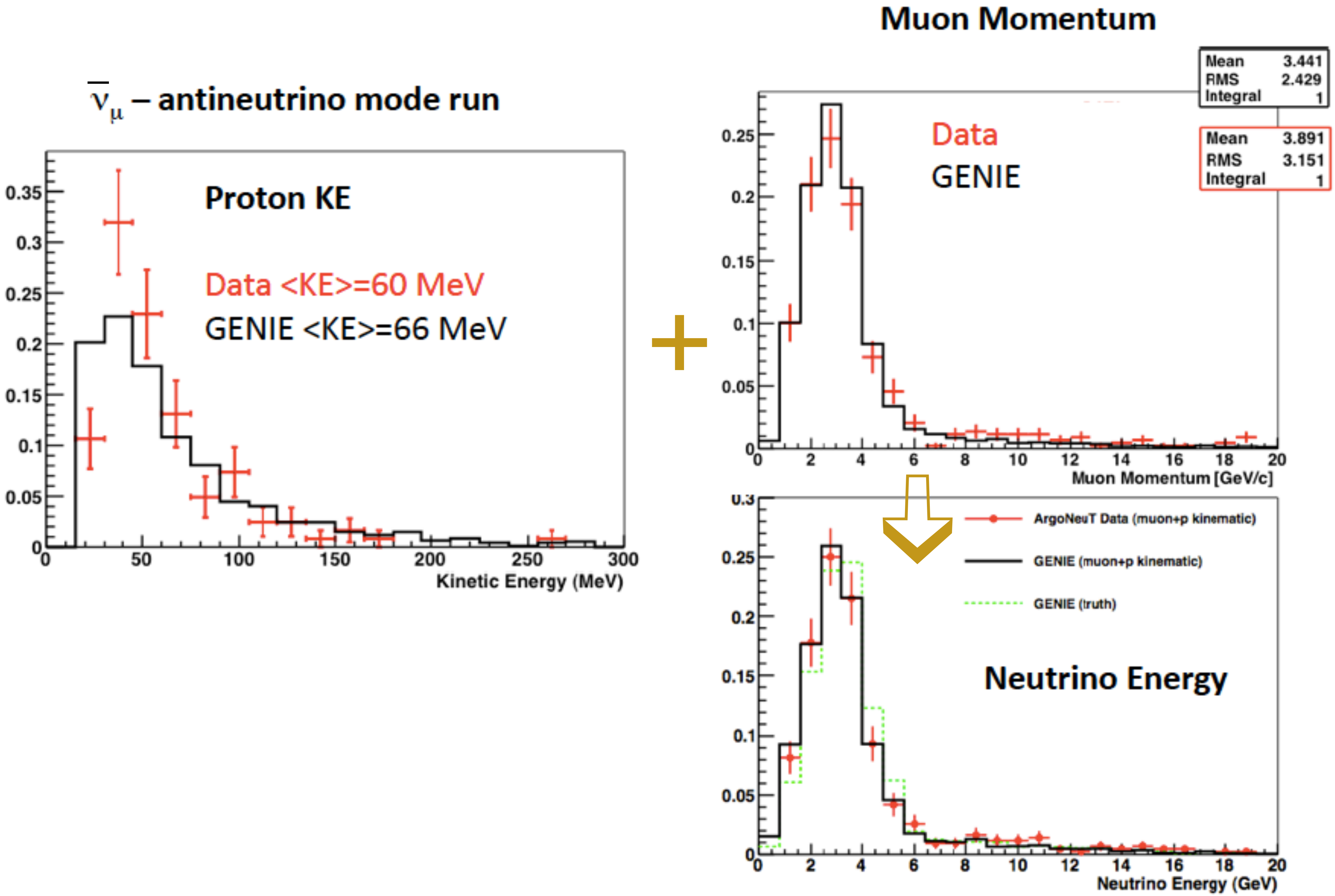
T_X=*recoil energy of the residual nuclear system* X *[undetectable]. A lower bound is estimated from the measured missing transverse momentum:*

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

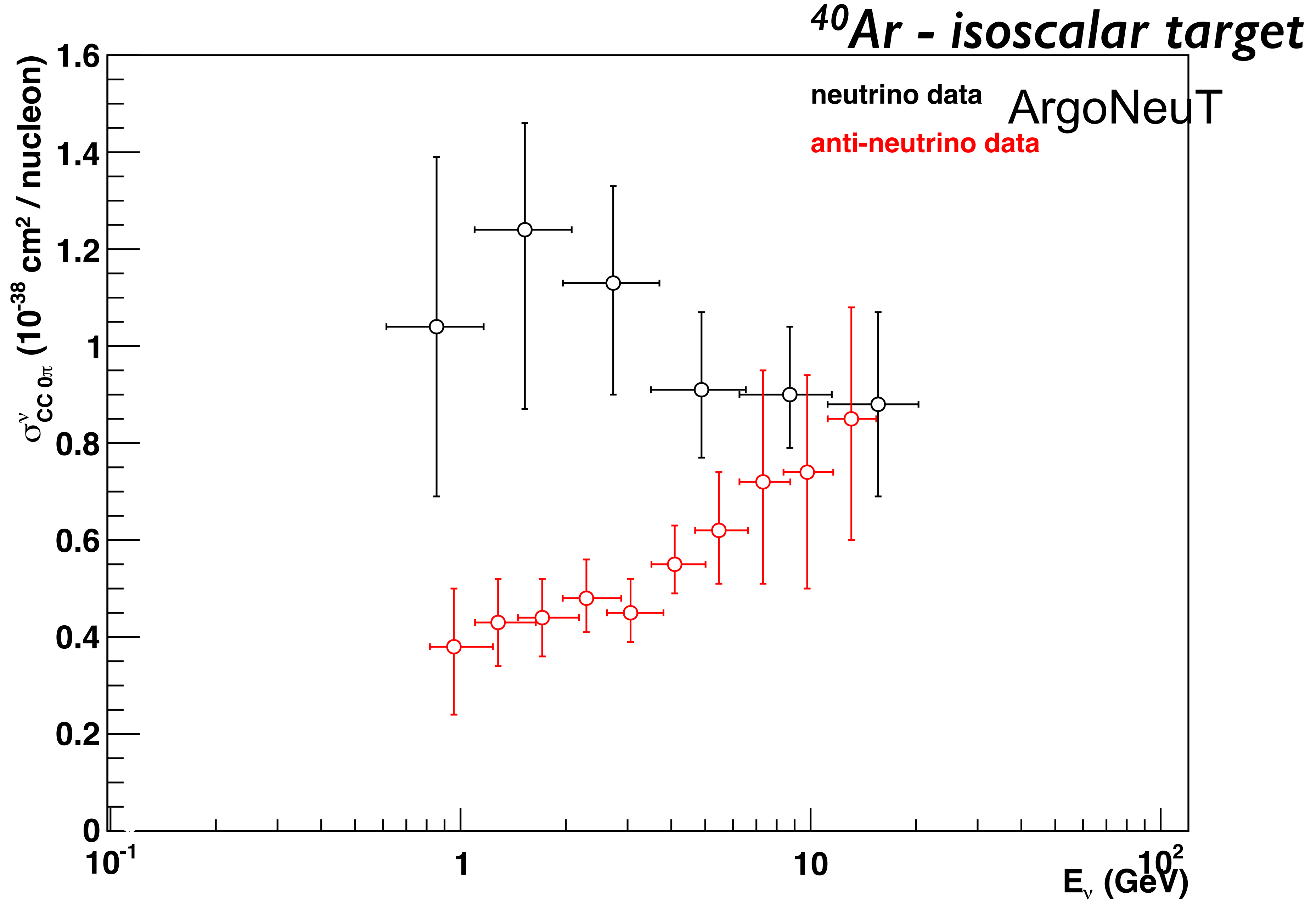
E_{miss}=*missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value, e.g.* E_{miss}=30 MeV *for 2p events)*

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

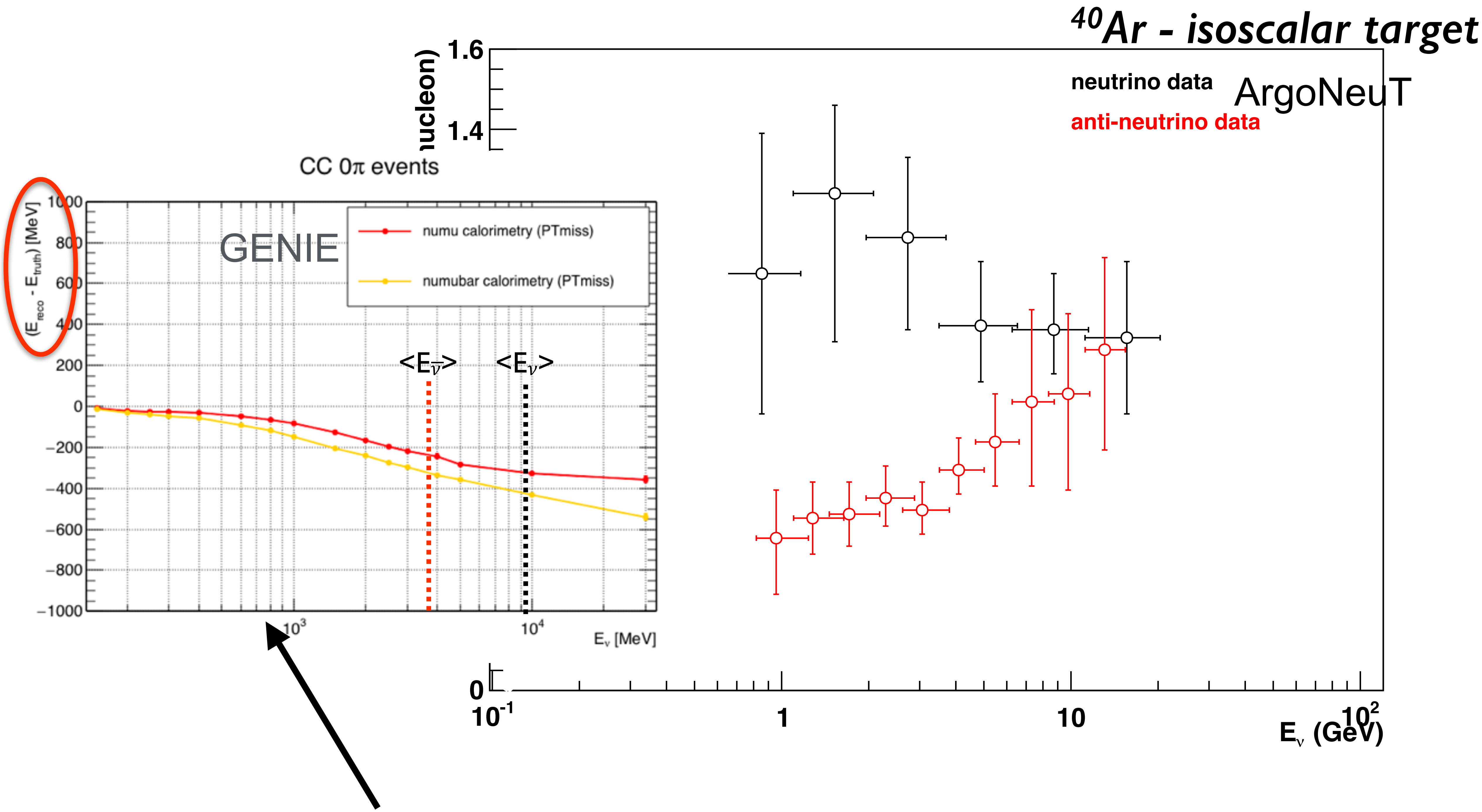
Neutrino Energy Reconstruction



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

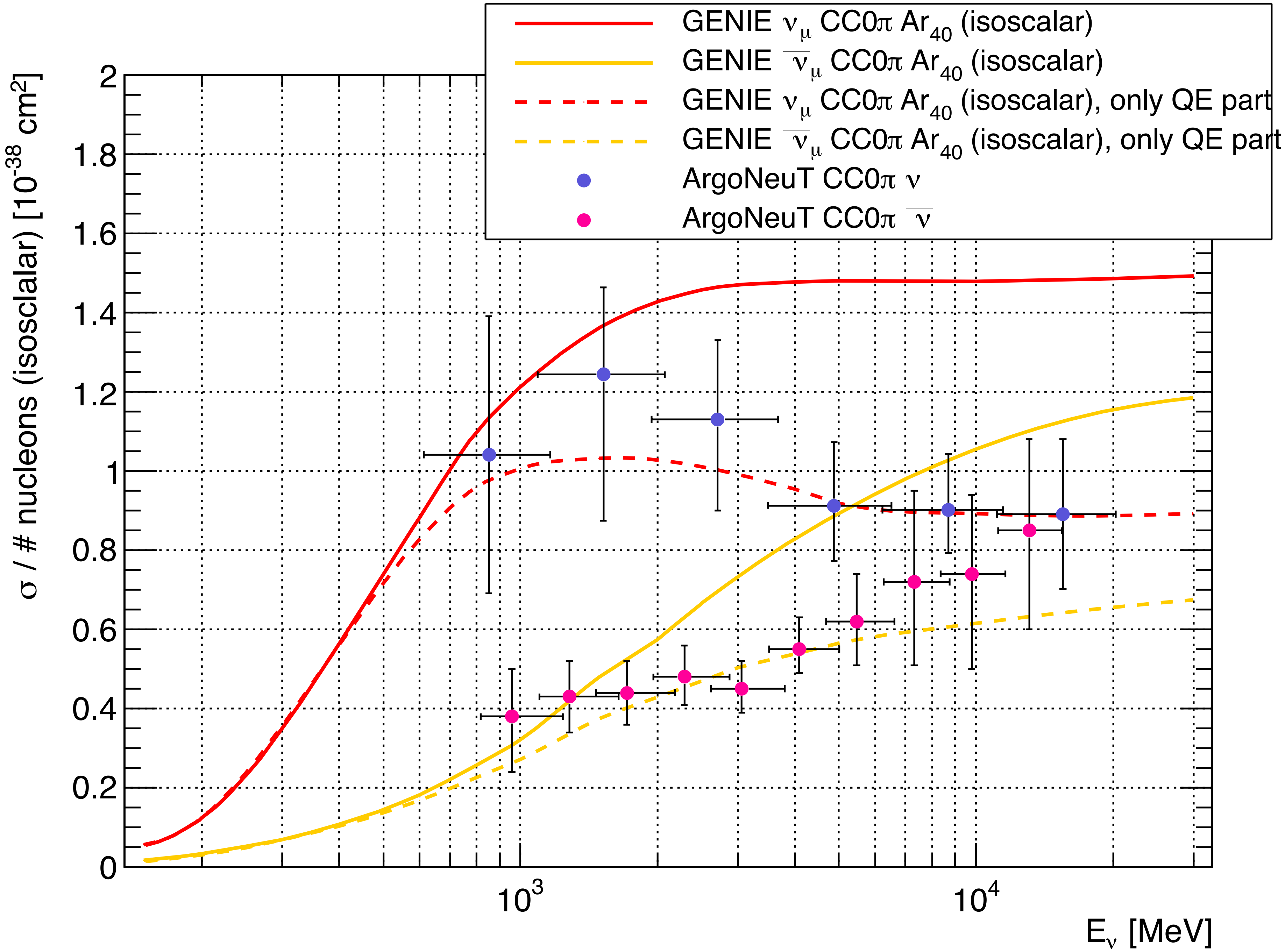


Neutrino/Antineutrino cross sections as a function of the neutrino energy

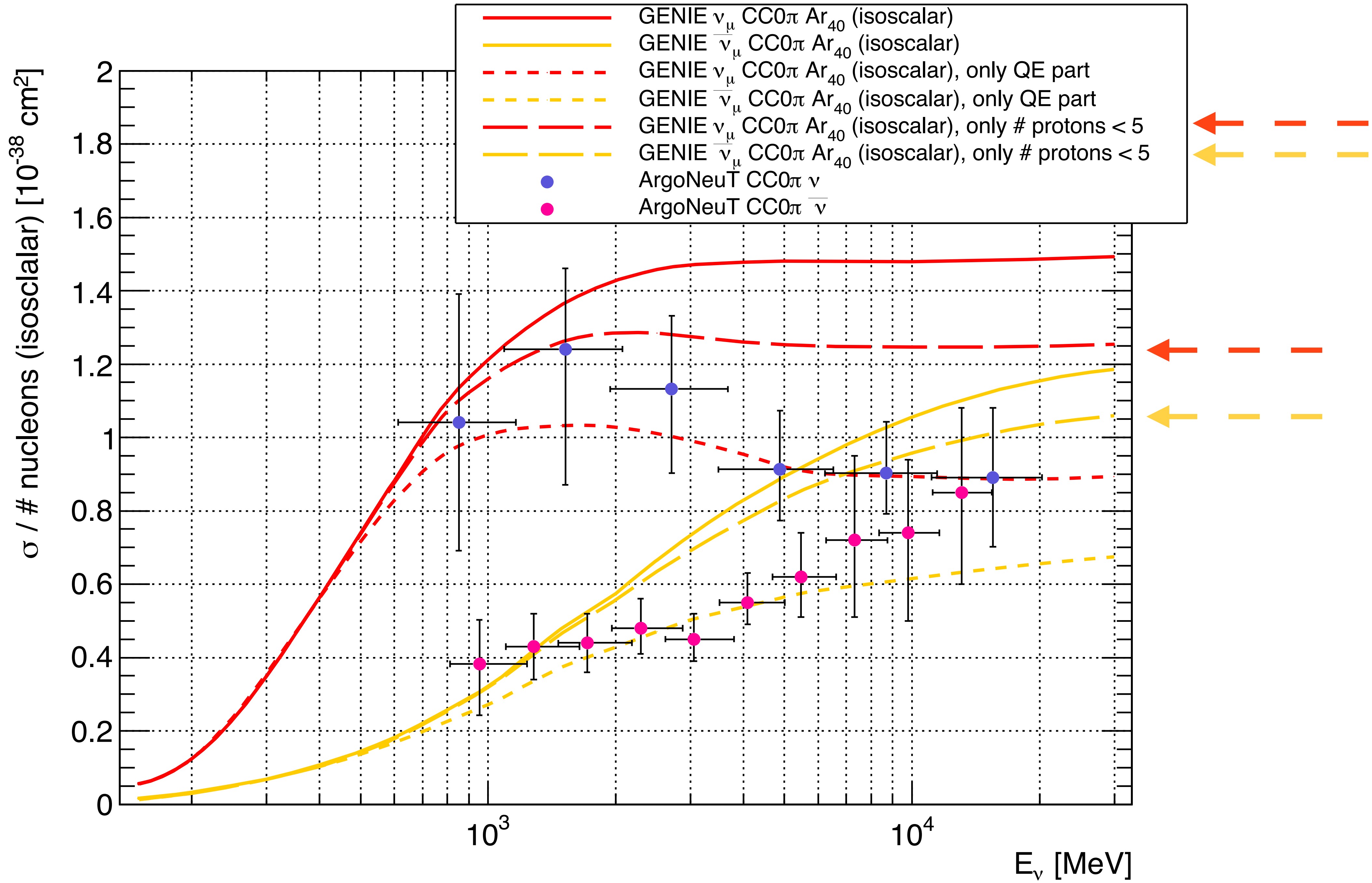


One-side errors added to account for systematic from neutrino energy reconstruction (GENIE - **underestimation** of E_ν, ~10% for $\bar{\nu}$ and ~4% for ν)

Neutrino/Antineutrino cross sections comparison with GENIE

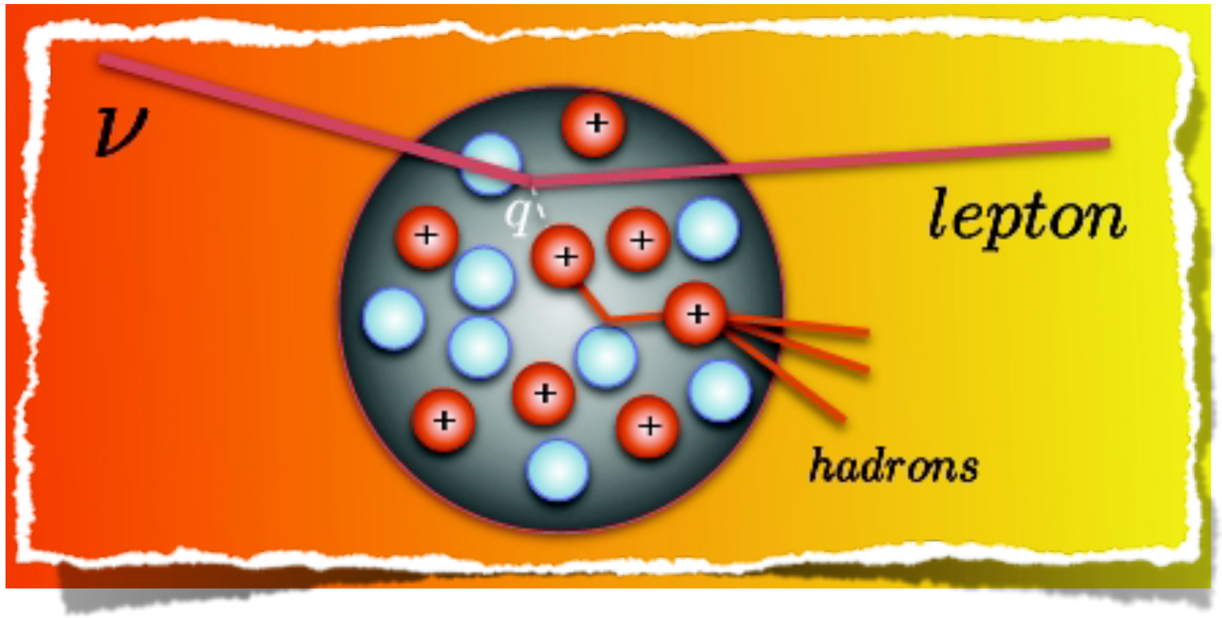


Neutrino/Antineutrino cross sections comparison with GENIE

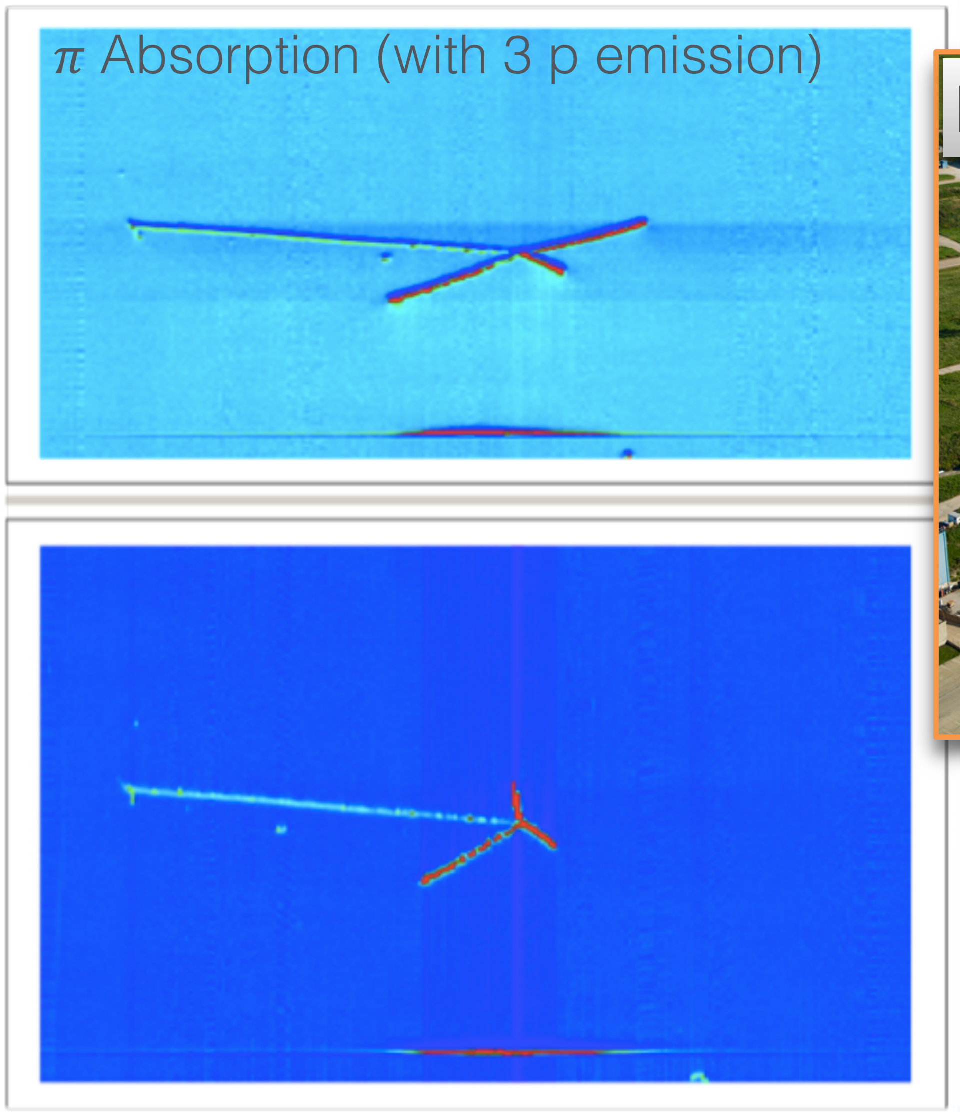


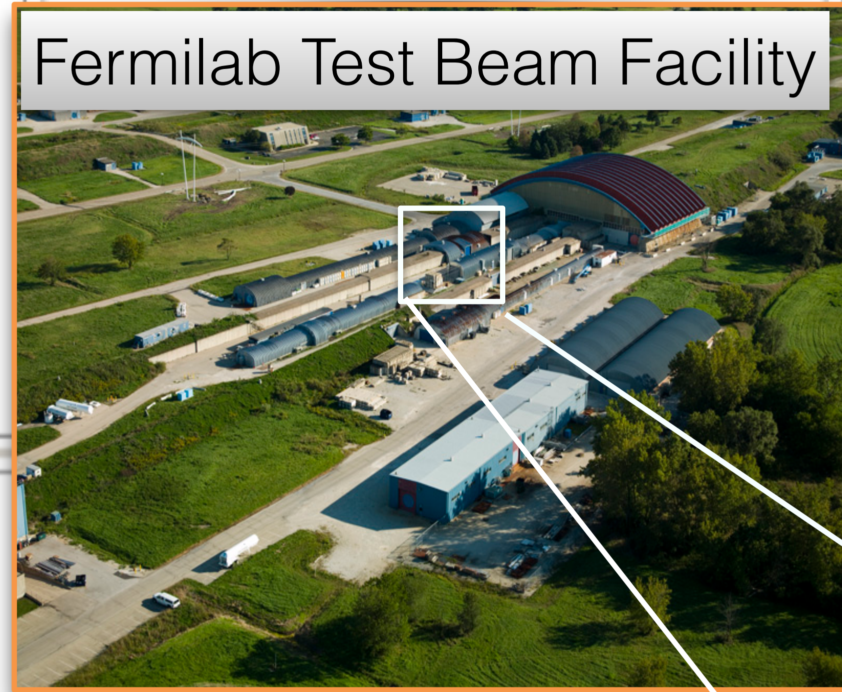
Nuclear Effects in LAr

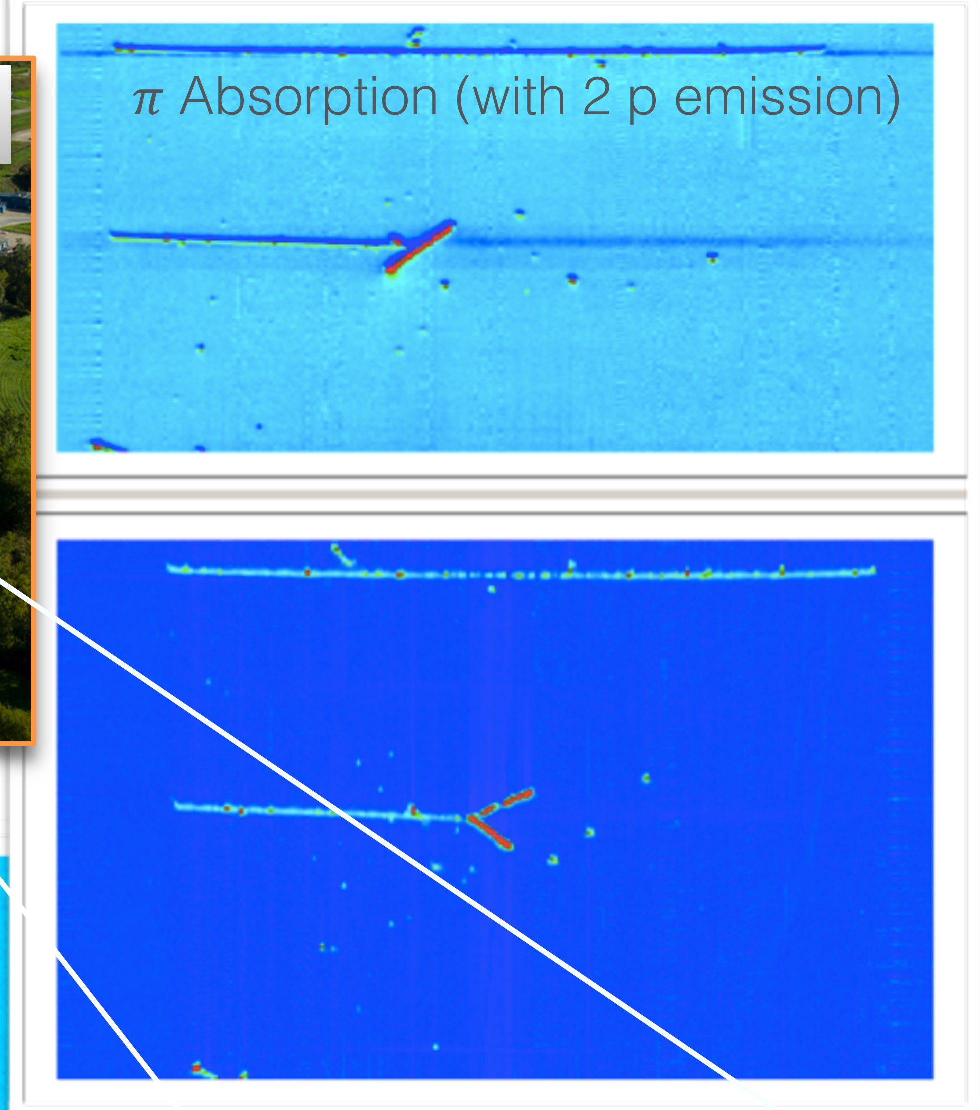
- **Nuclear effects** significantly alter σ_ν's and final state particle topology/kinematics.
- Main reason for disagreement between ArgoNeuT data and MC predictions is the treatment of nuclear effects in the MC generators.
  - LAr data can provide an important discriminator among models.
  - Pion absorption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

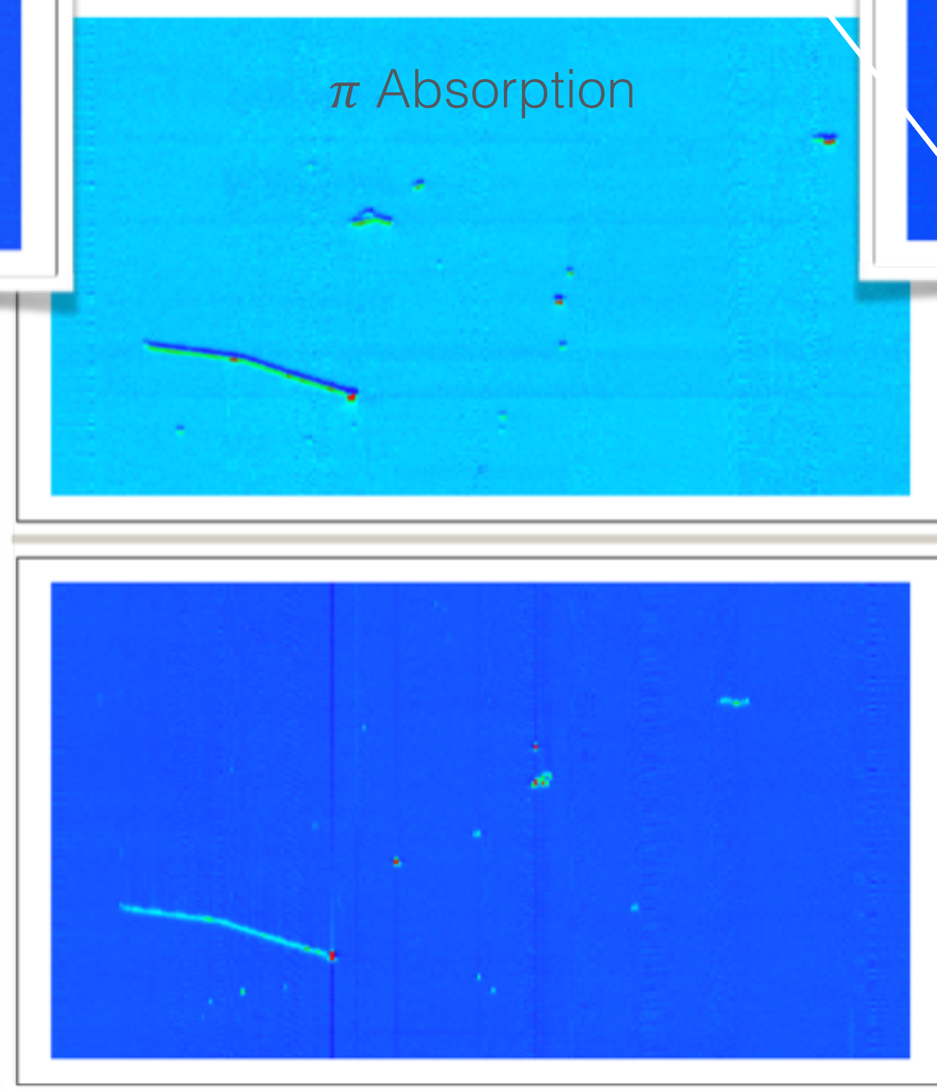


  - **LArIAT** (Liquid Argon TPC In A Testbeam) **experiment** is measuring charged pion interaction cross section in LAr.


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 (** <E_ν>=800 MeV**)**

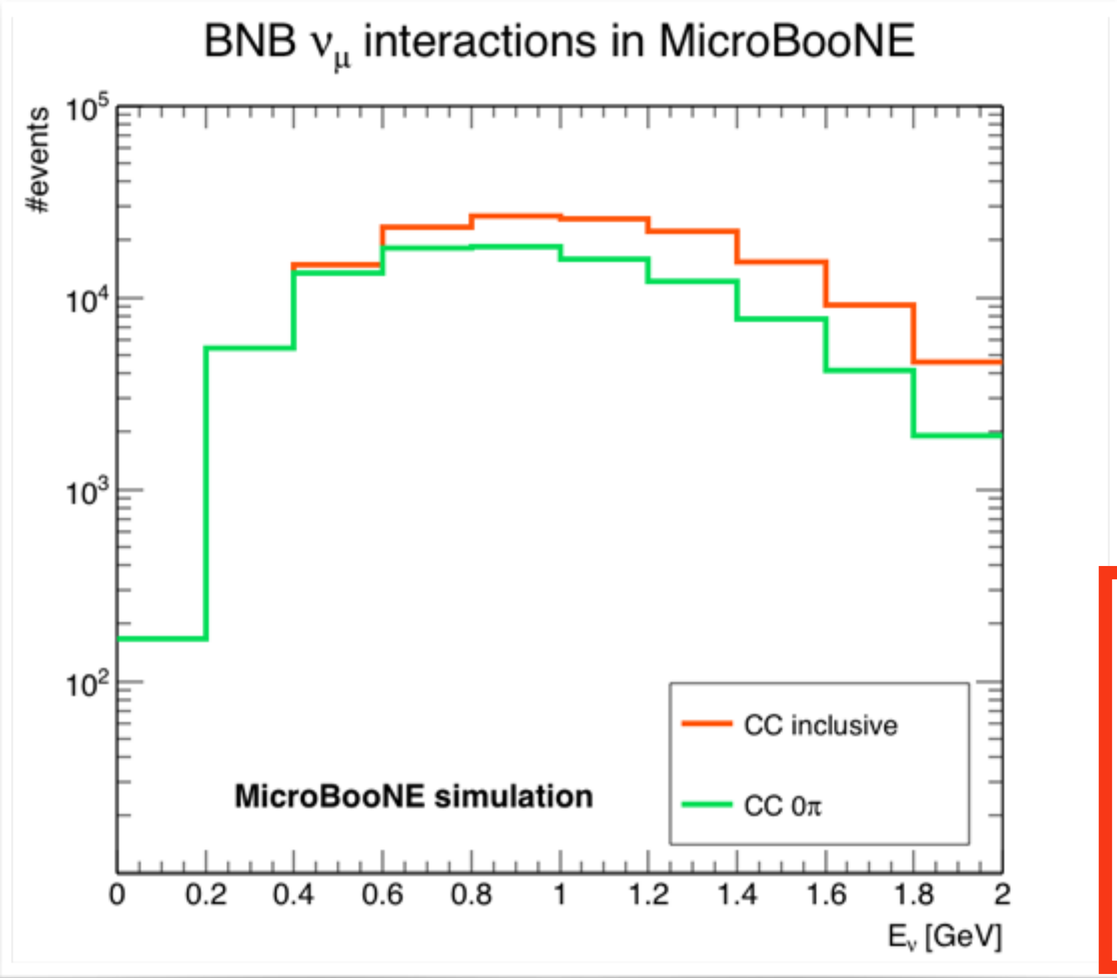
- Large samples in MicroBooNE (82 t AV) are coming! MicroBooNE will record ~ **50,000 ν_μ CC** per year (see A. Schukraft talk)
- SBND (112 t AV) will record **~1.5 million ν_μ CC** and **~12,000 ν_e CC interactions** per year (see C. Adams talk)

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

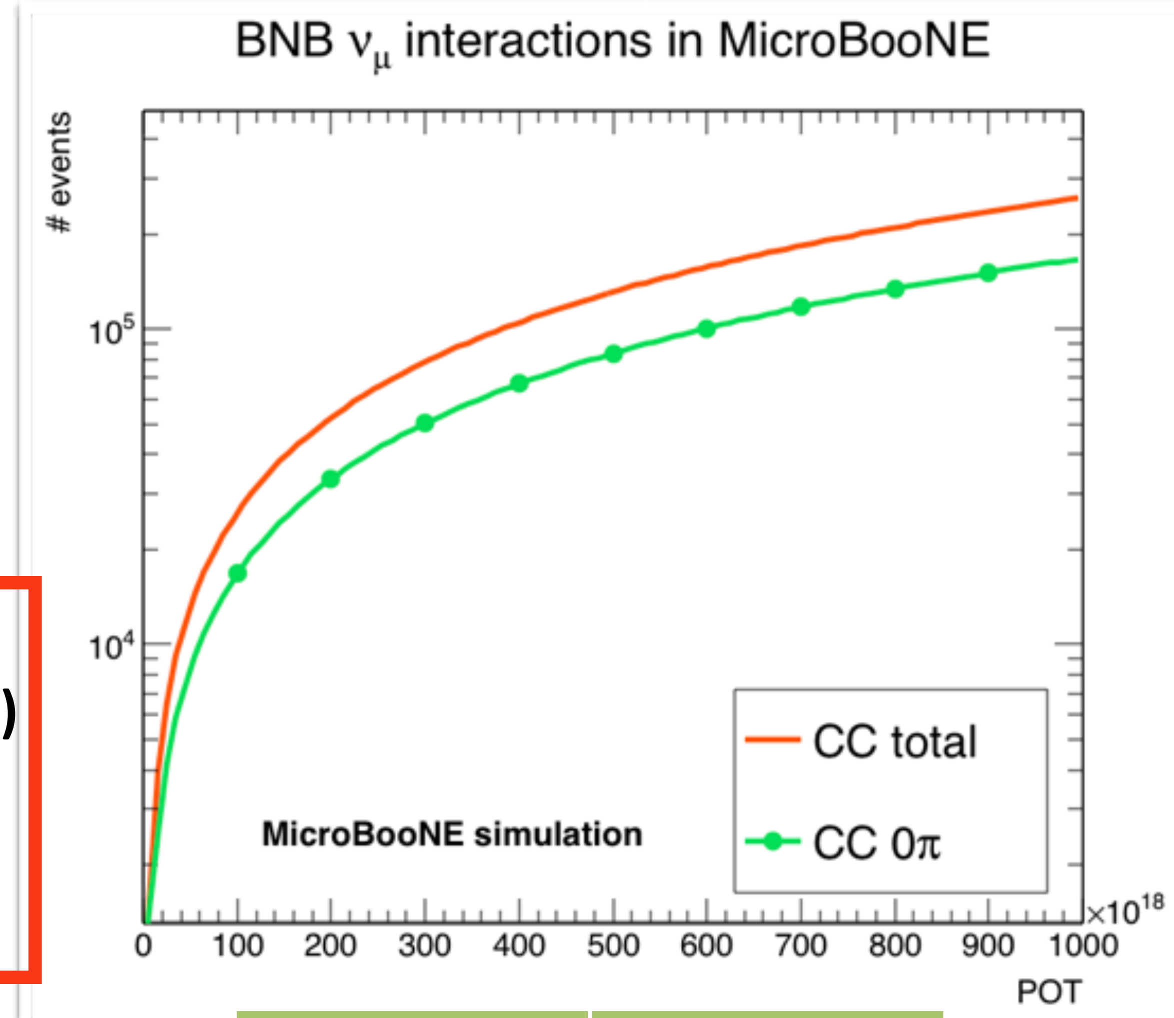
- High statistics measurement of ν_μ **and ν_e CC 0 pion events** will allow to **quantify** nuclear effects in neutrino-Ar scattering*

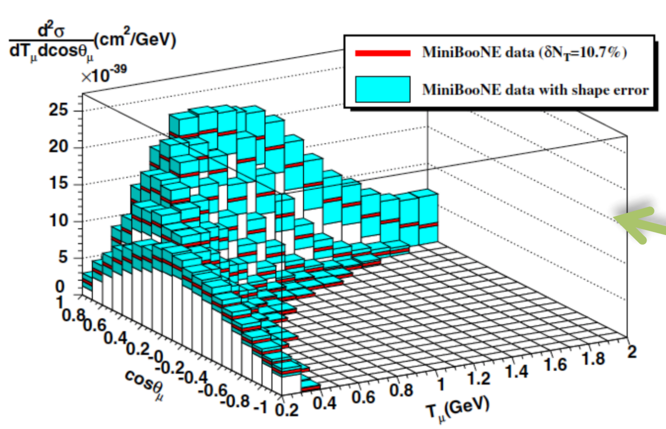
*only existing ν_μ **CC 0 pion** Ar scattering data are ~900 events from ArgoNeuT (NuMI beam, 3 GeV peak energy)

CC 0π events



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





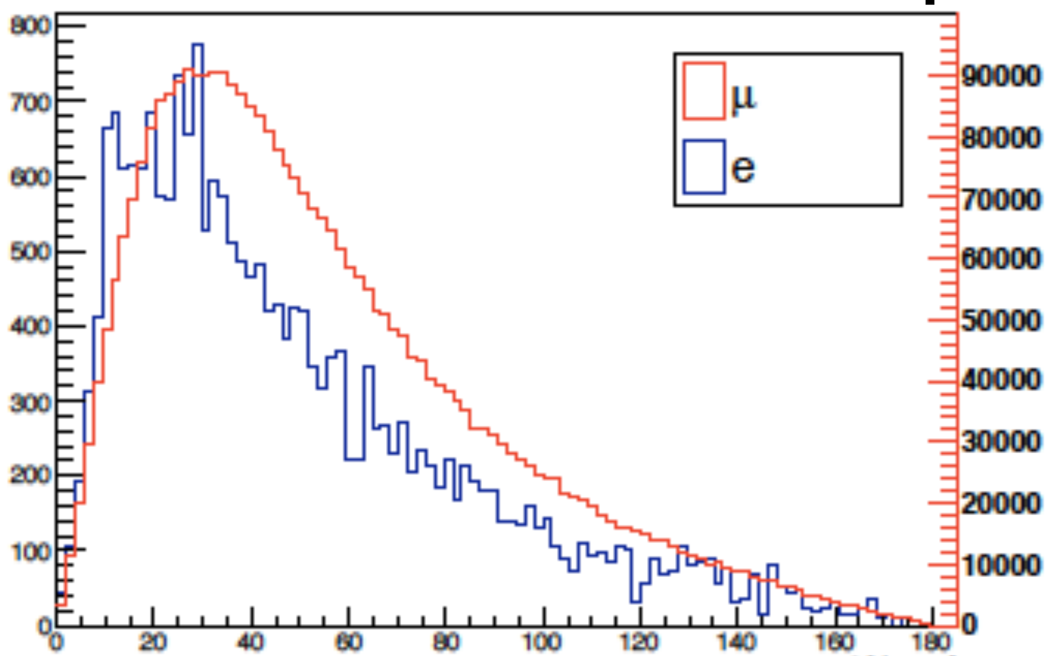
Phys. Rev. D81 092005 (2010);

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

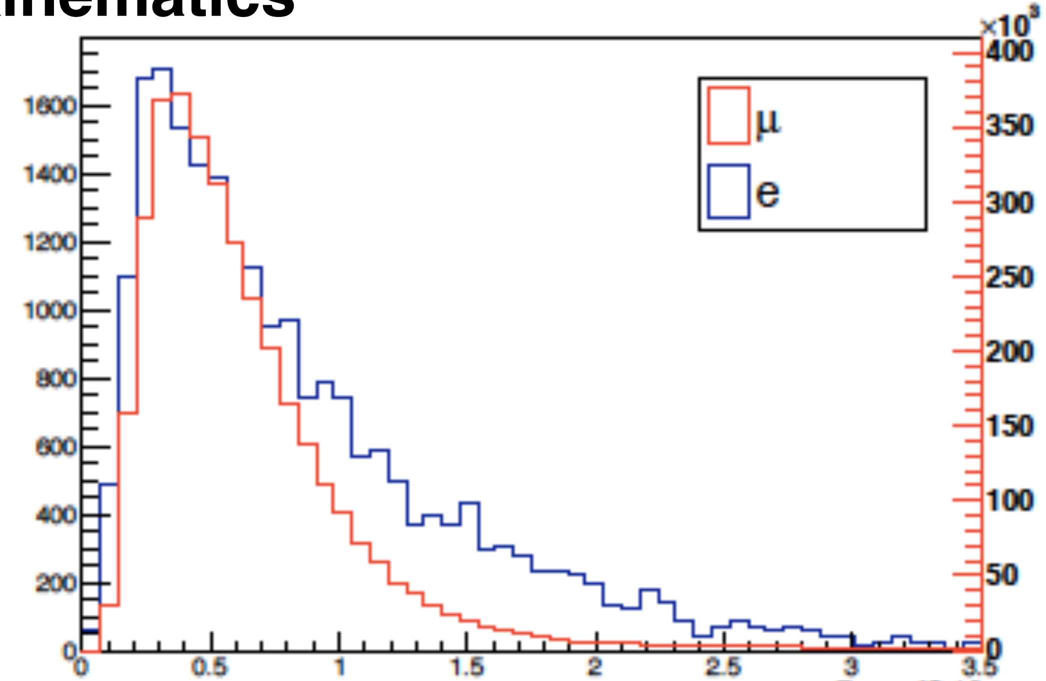
		CC 0 pion
~in 1 month	1.5×10^{19} POT	2550
~6 months	1×10^{20} POT	16997
	2×10^{20} POT	33994
~3 years	6.6×10^{20} POT	112180

CC 0π events

lepton kinematics



θ (deg)

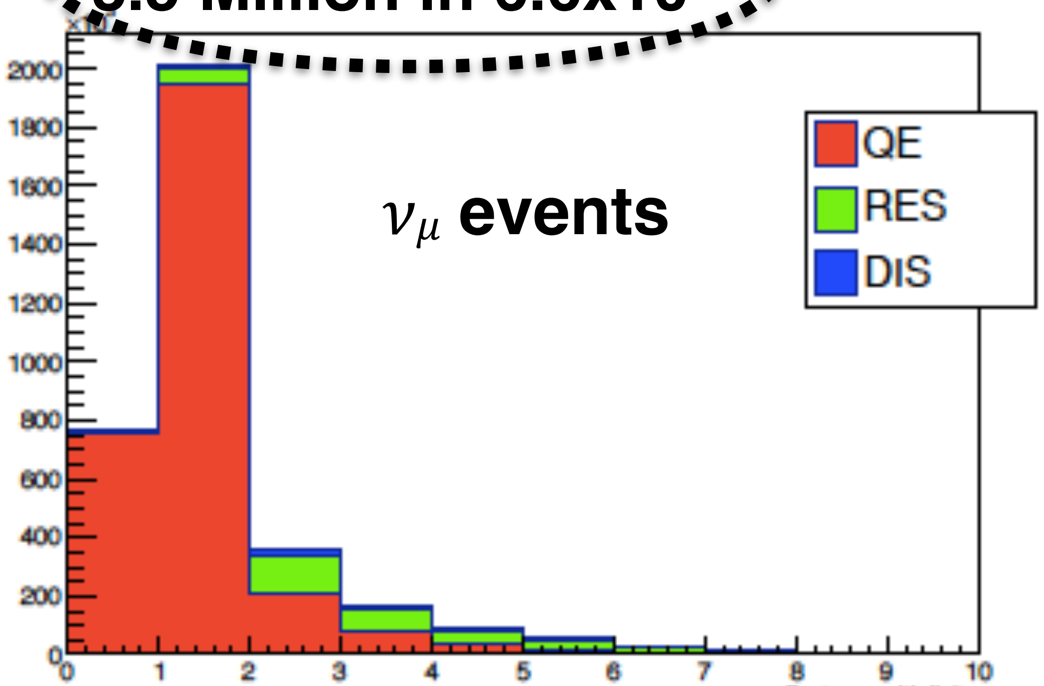


Energy (GeV)

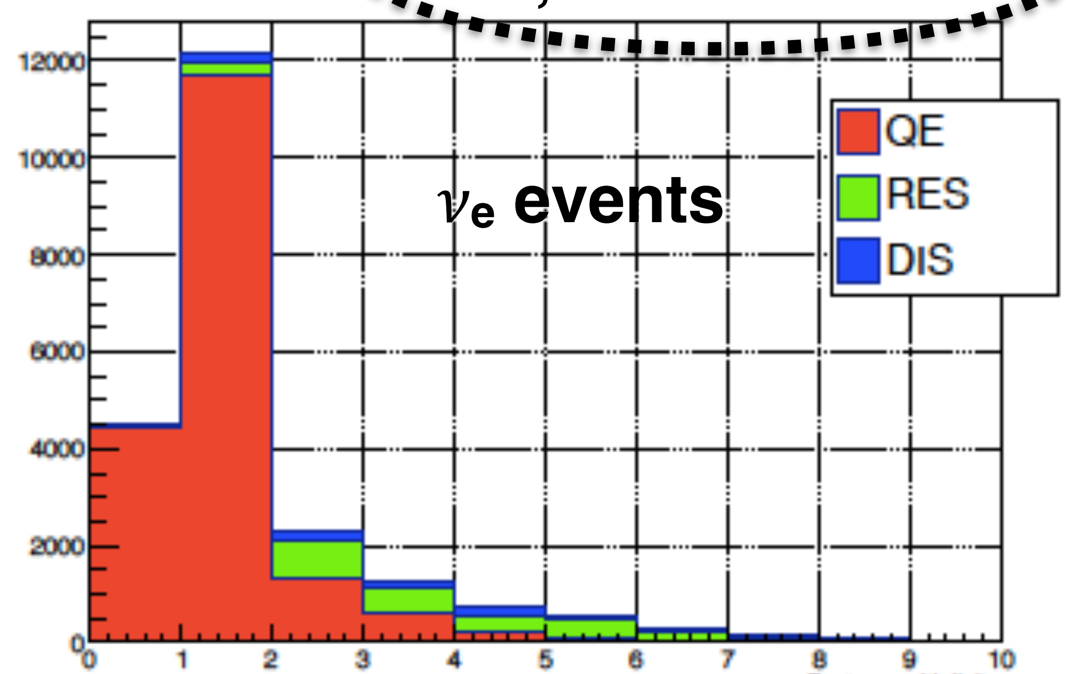
ν_μ events: 3.5 Million in 6.6x10^{20}

Proton multiplicity

ν_e events: 22,000 in 6.6x10^{20}

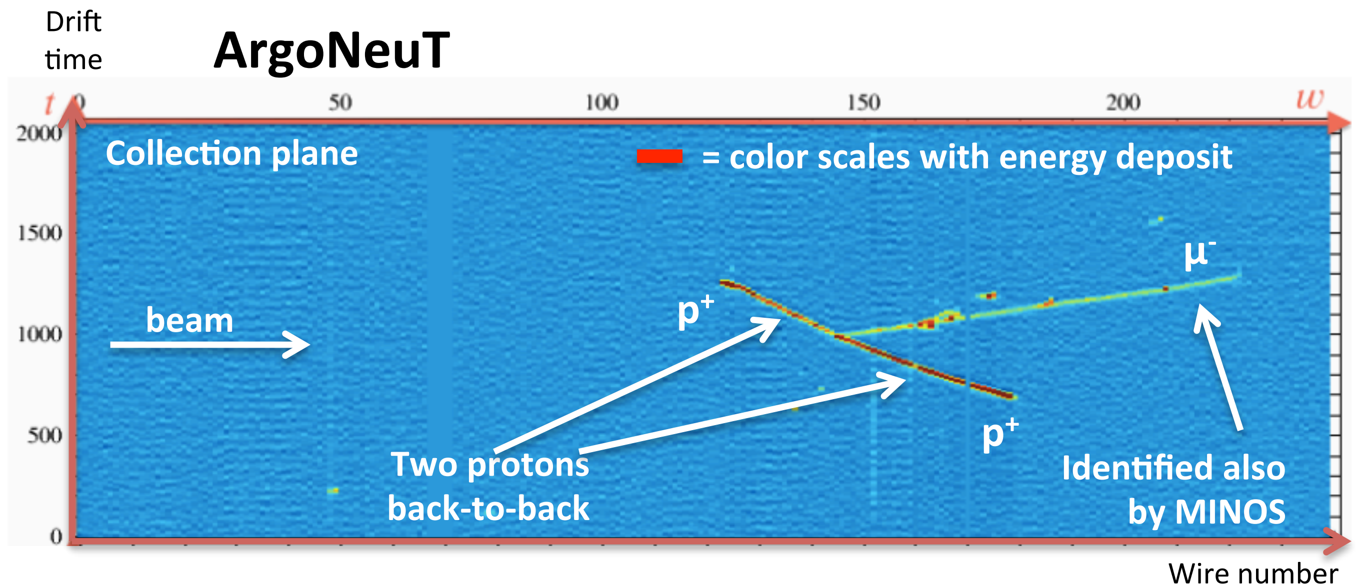


Proton Multiplicity

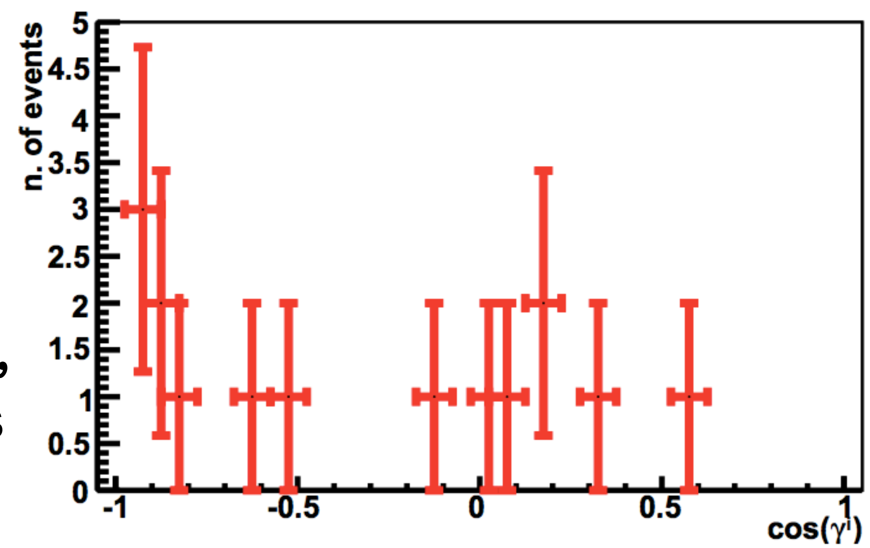


Proton Multiplicity

Looking for ***Short Range Correlated nucleon pairs***

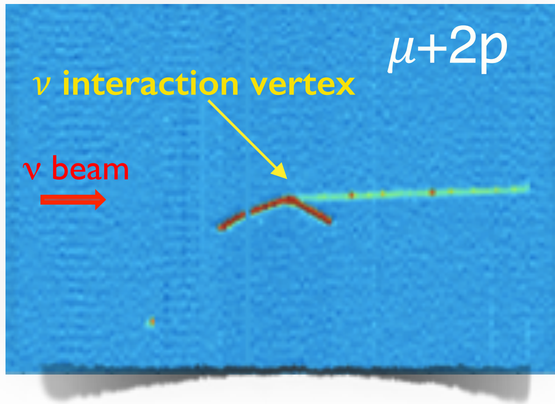


Phys. Rev. D 90, 012008 (2014)



Hints for SRC in **neutrino scattering,** analysis of 30 events

μ+2p events



MicroBooNE

	1μ⁻ + 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 μ+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)

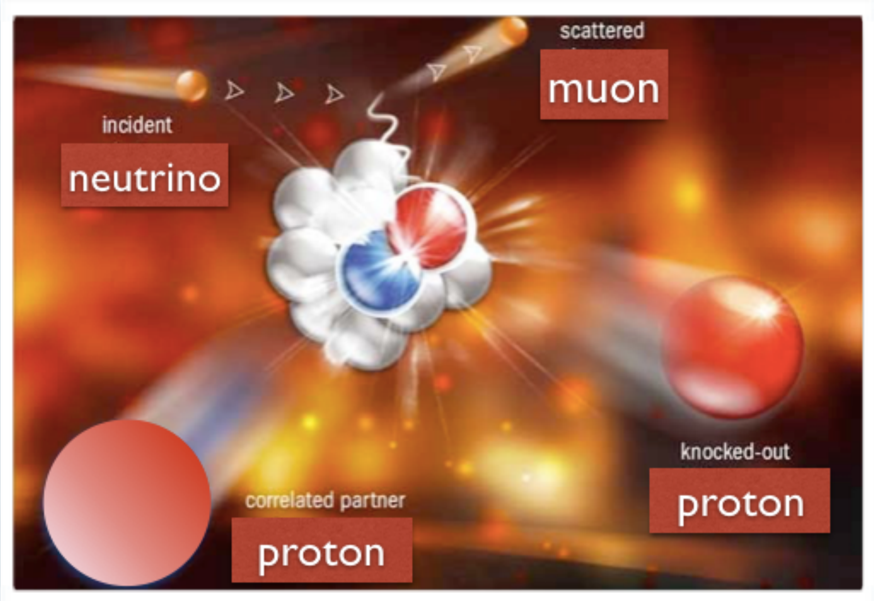
Conclusions

CC 0 pion events

- First topological analysis developed by the **ArgoNeuT** experiment.
  - 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.

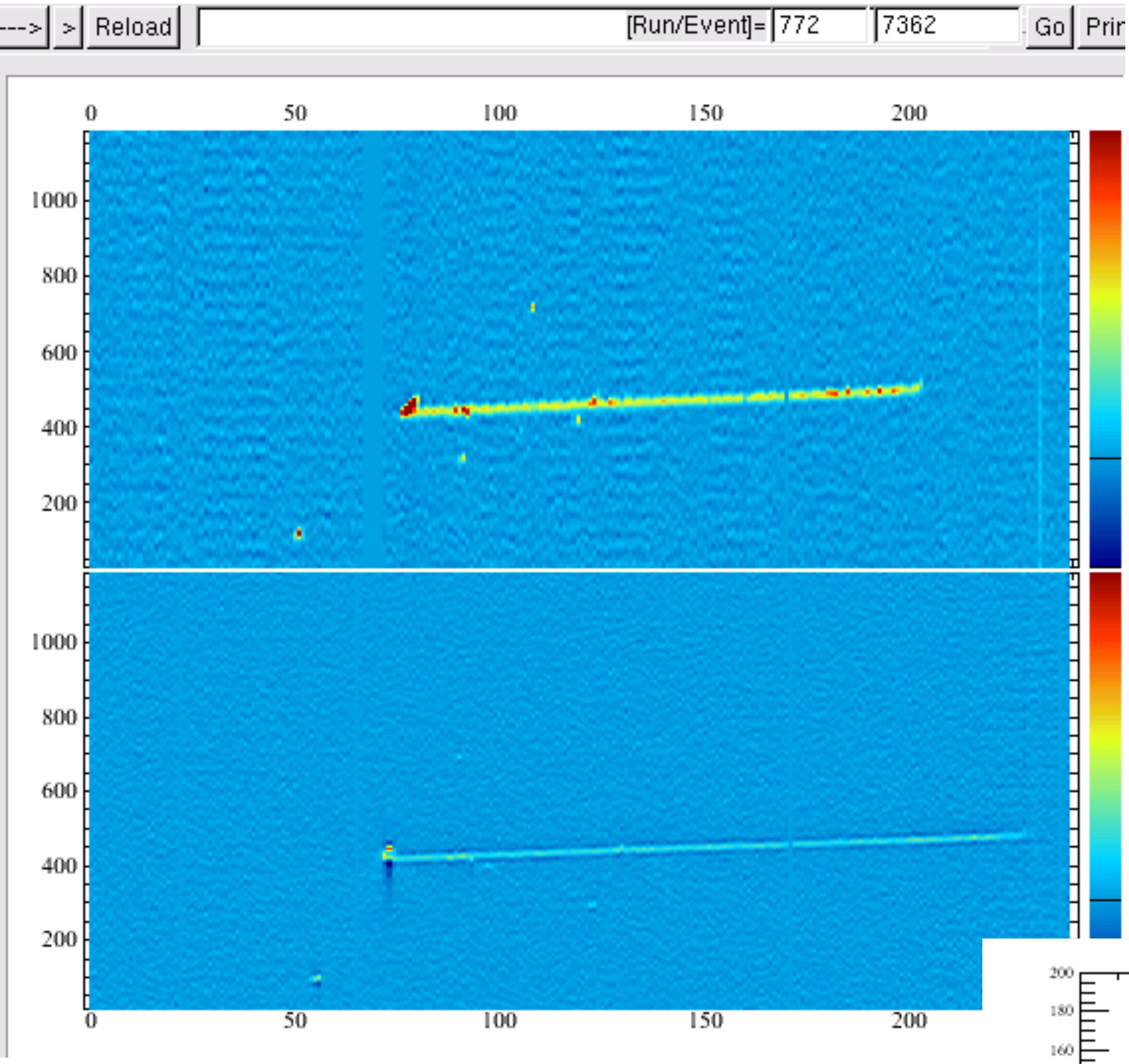
- Future **larger mass** and high statistics LAr-TPC detectors will allow to **quantify** nuclear effects in neutrino-Ar scattering.

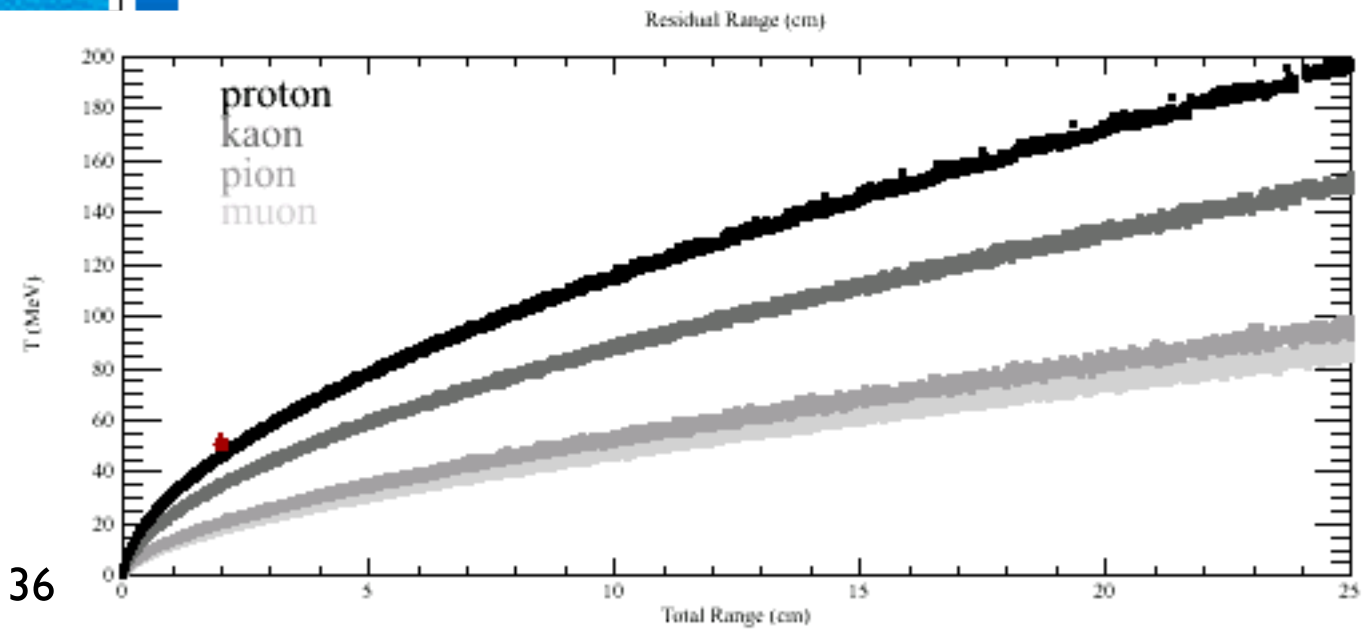
- Models including all nuclear effects as well as their implementation in ν MC generators are deemed necessary for comparisons with LAr data.



Overflow

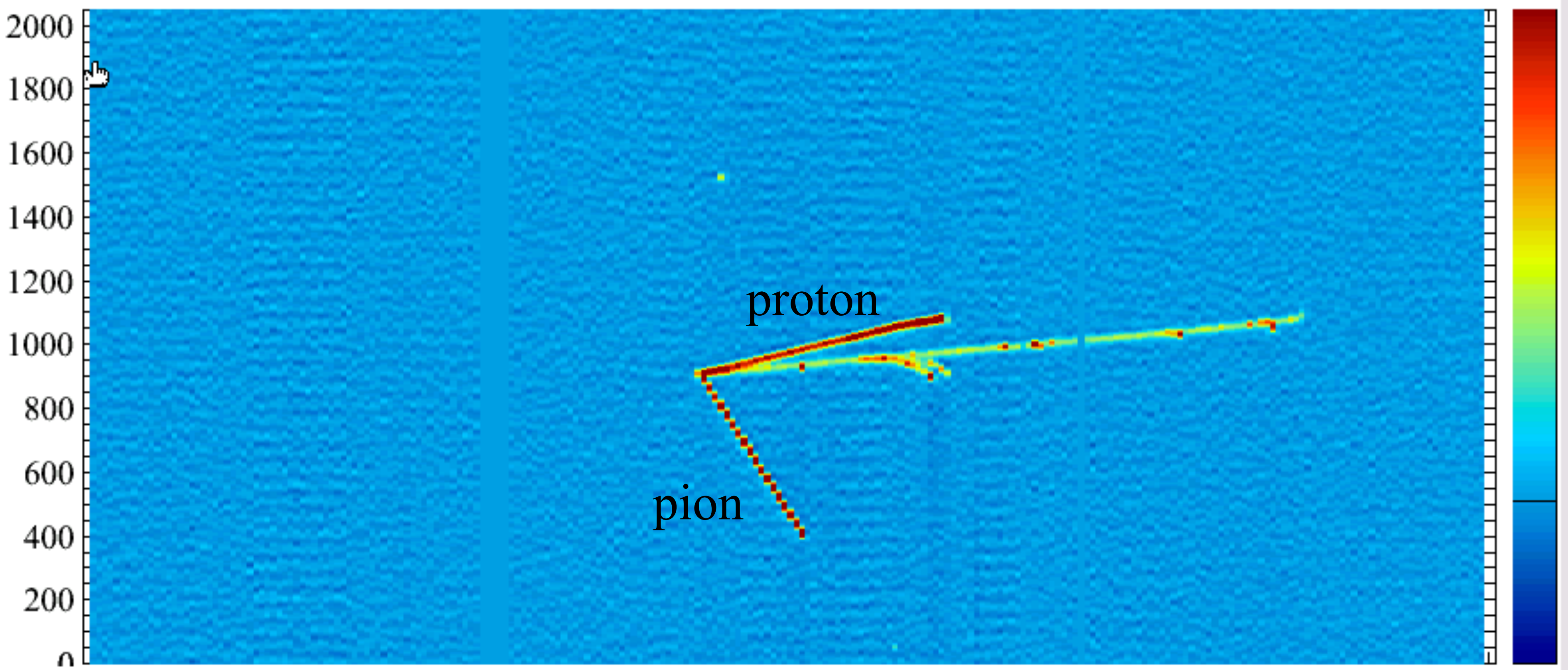
Example of Selected Event. Calorimetric reconstruction

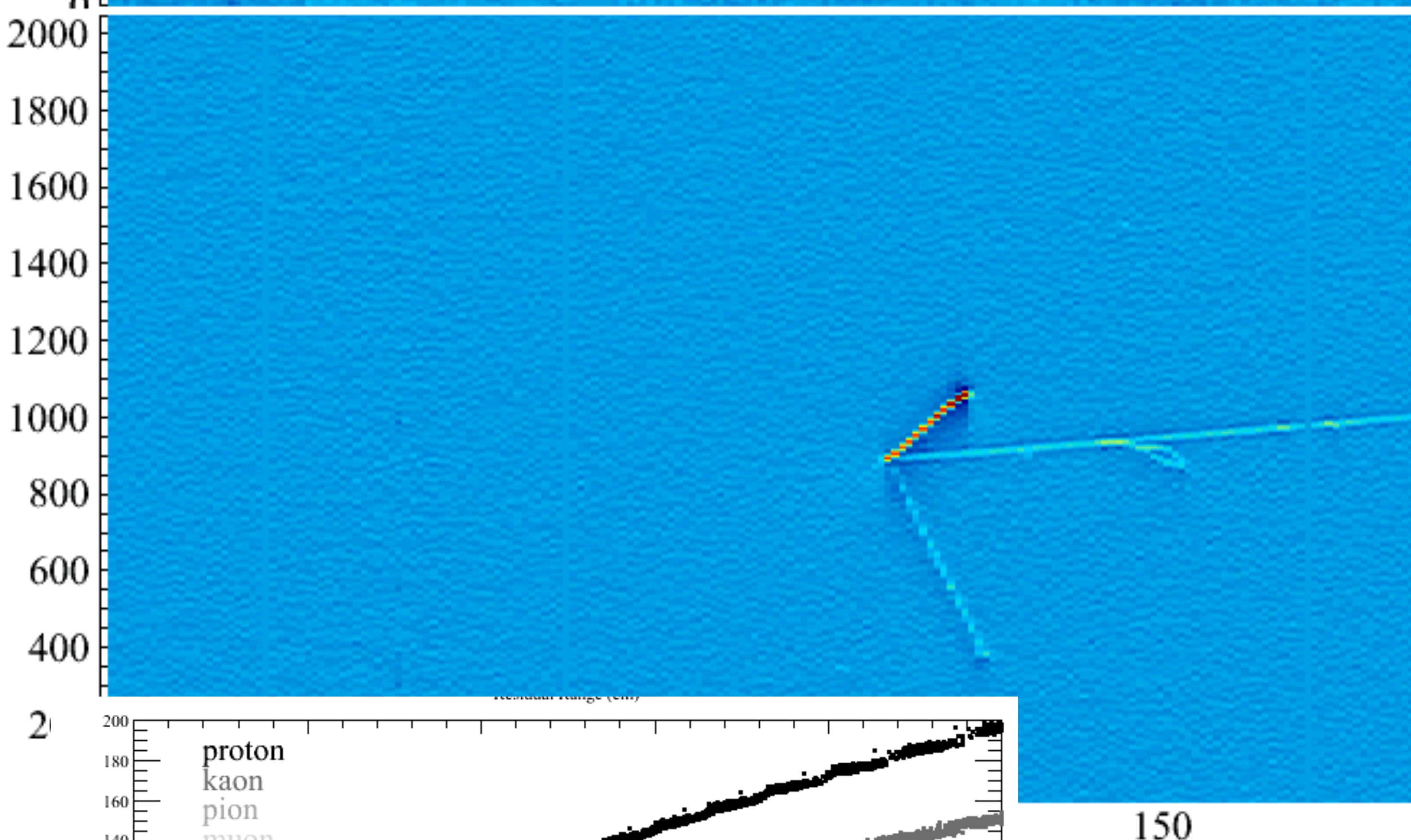


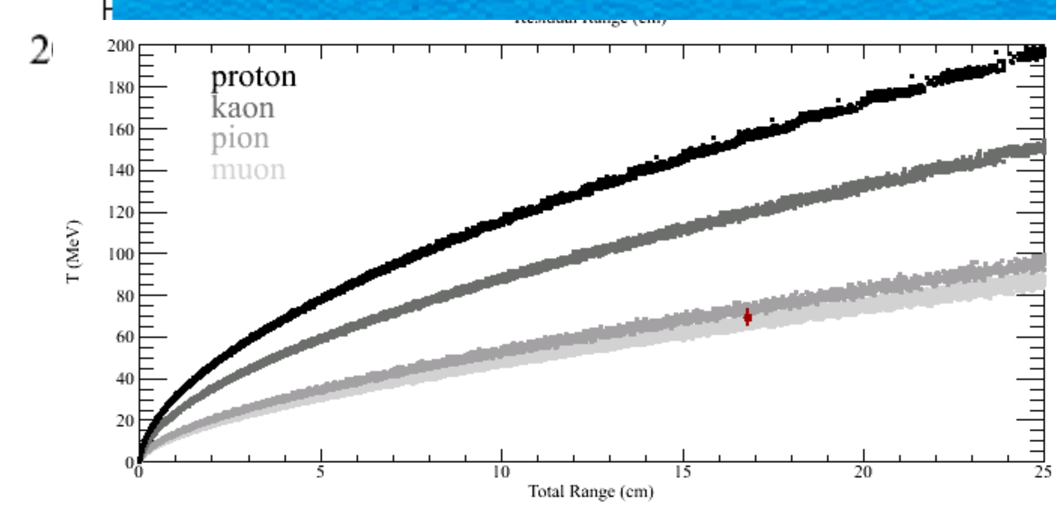


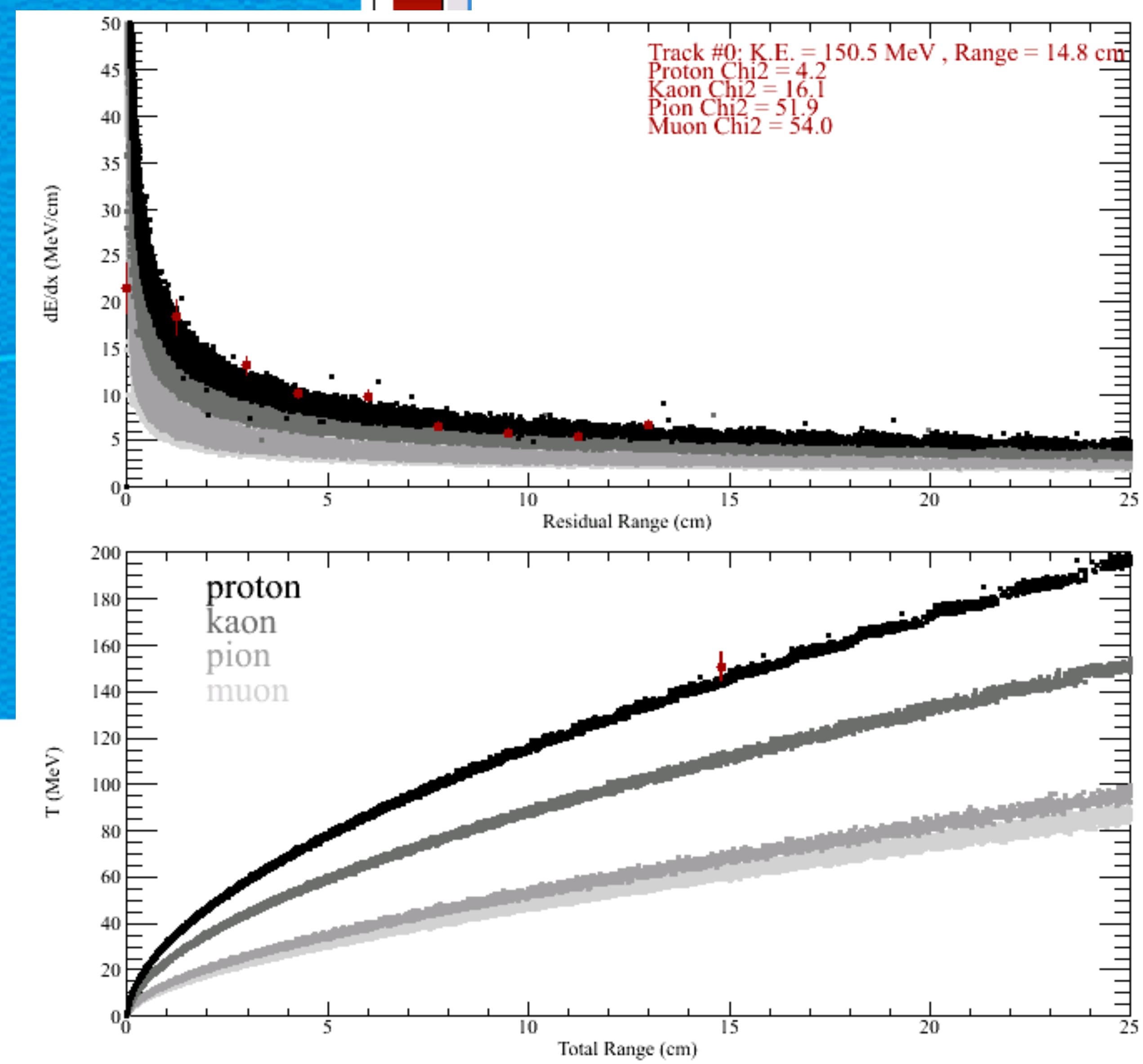
Example of Rejected Event

ArgoNeuT

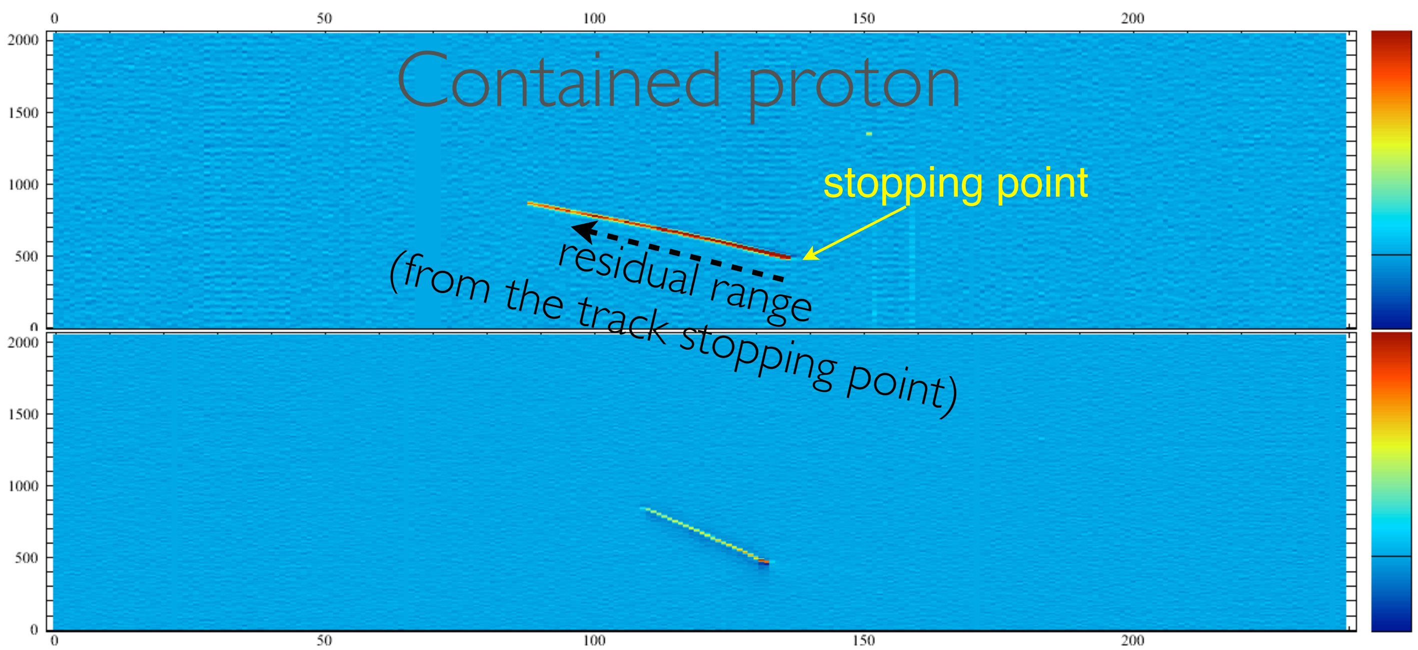




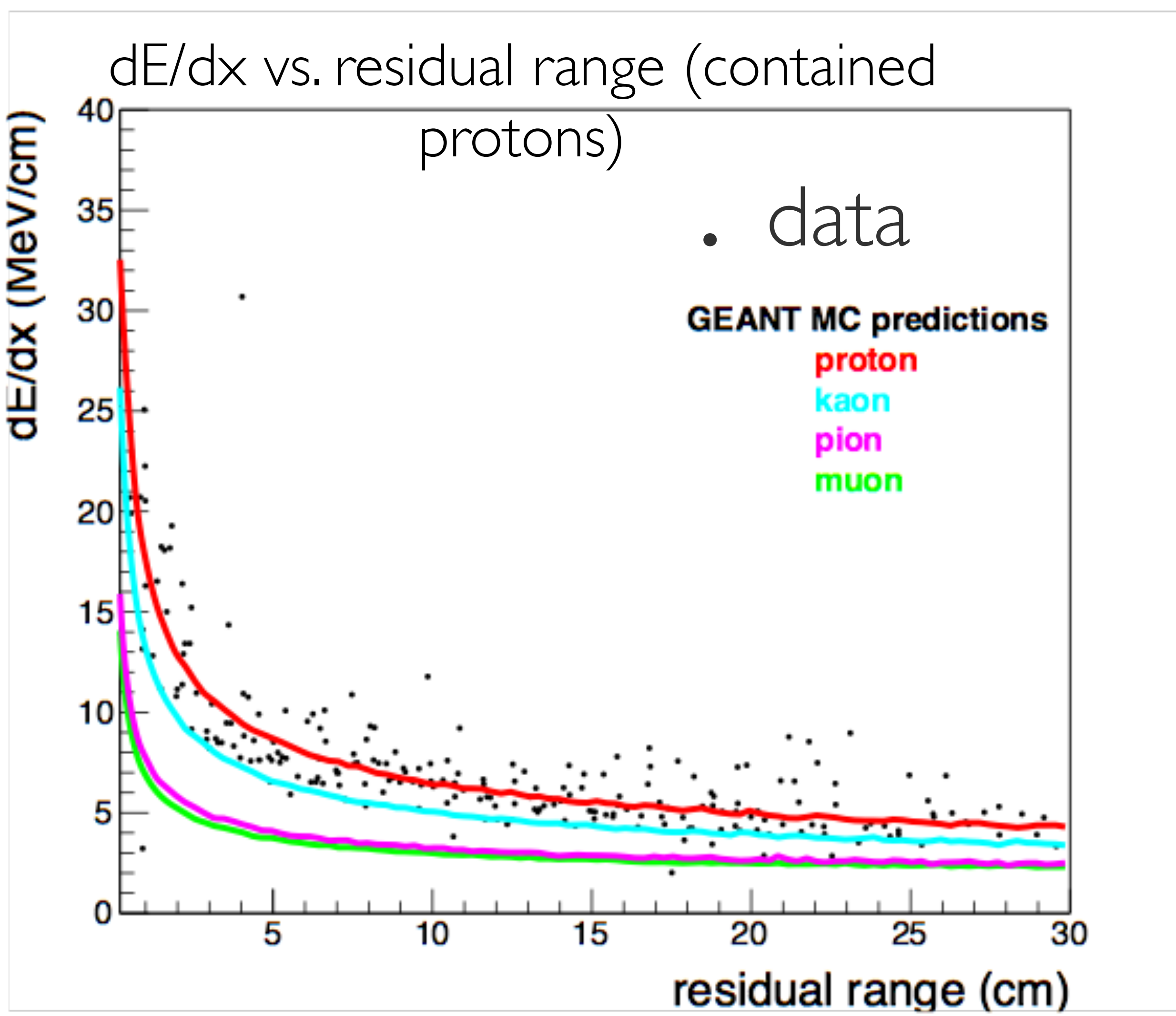




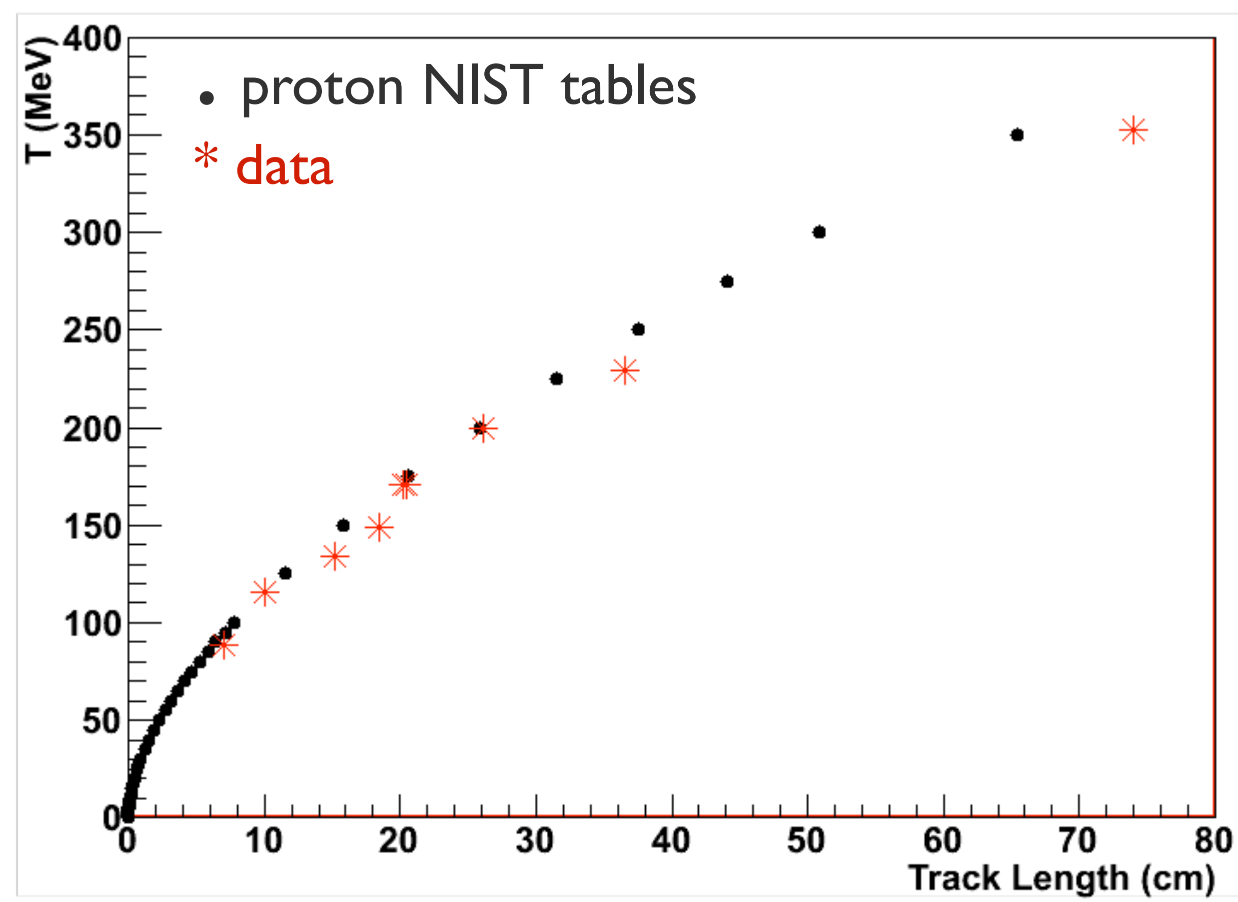
Stopping tracks - Calorimetric reconstruction and PID



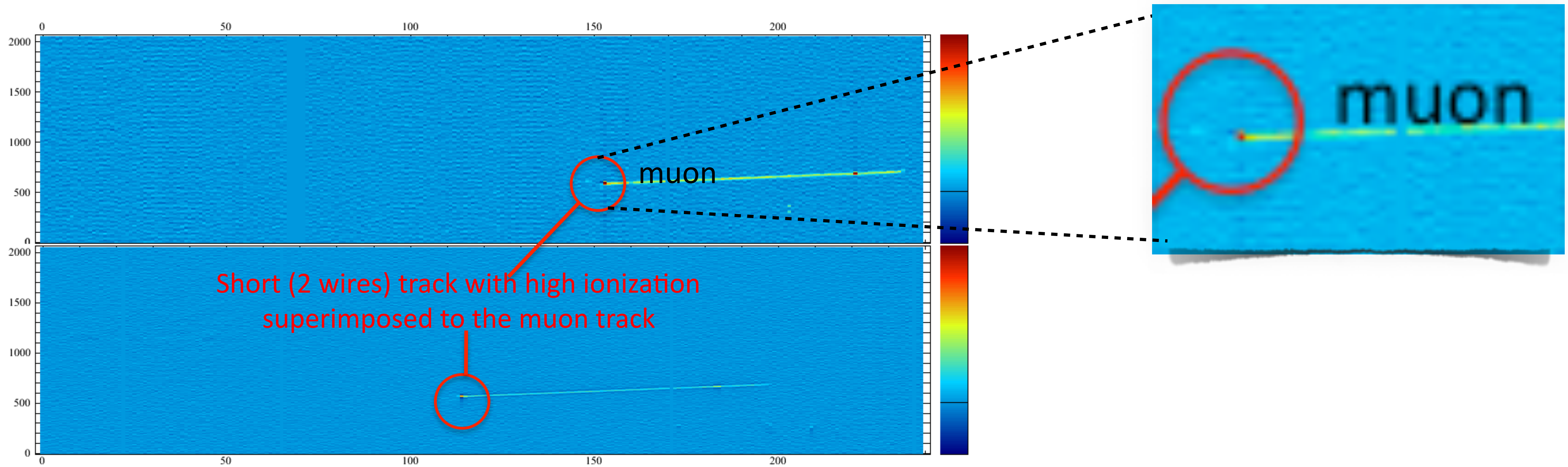
The energy loss as a function of distance from the end of the track is used as a powerful method for particle identification.



Kinetic Energy vs. track length



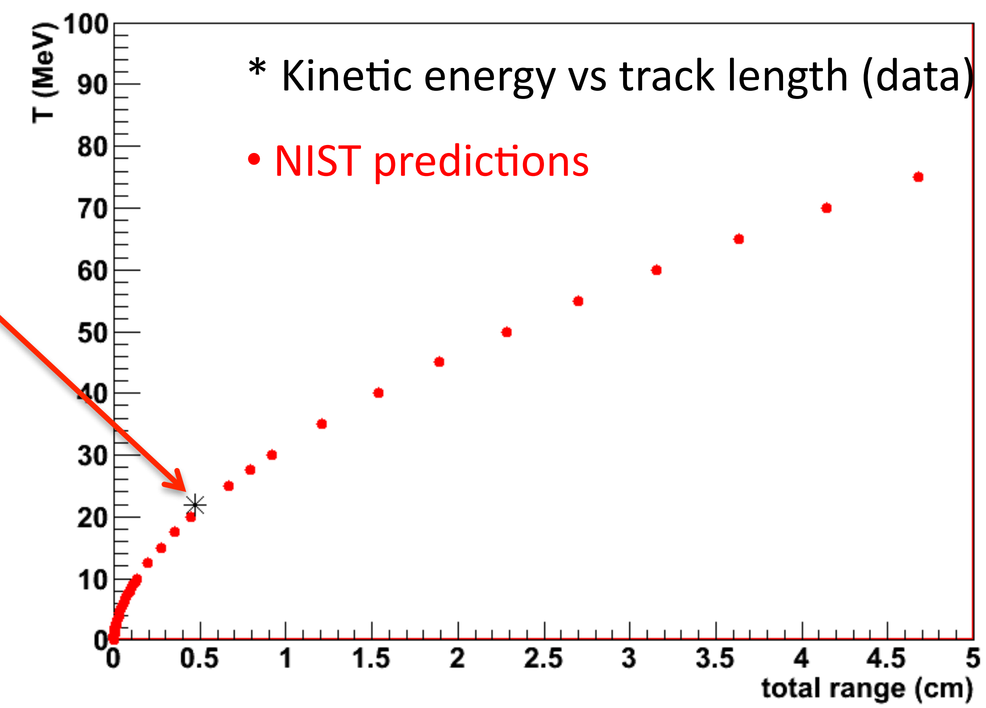
Low energy proton reconstruction



The short track behaves like proton

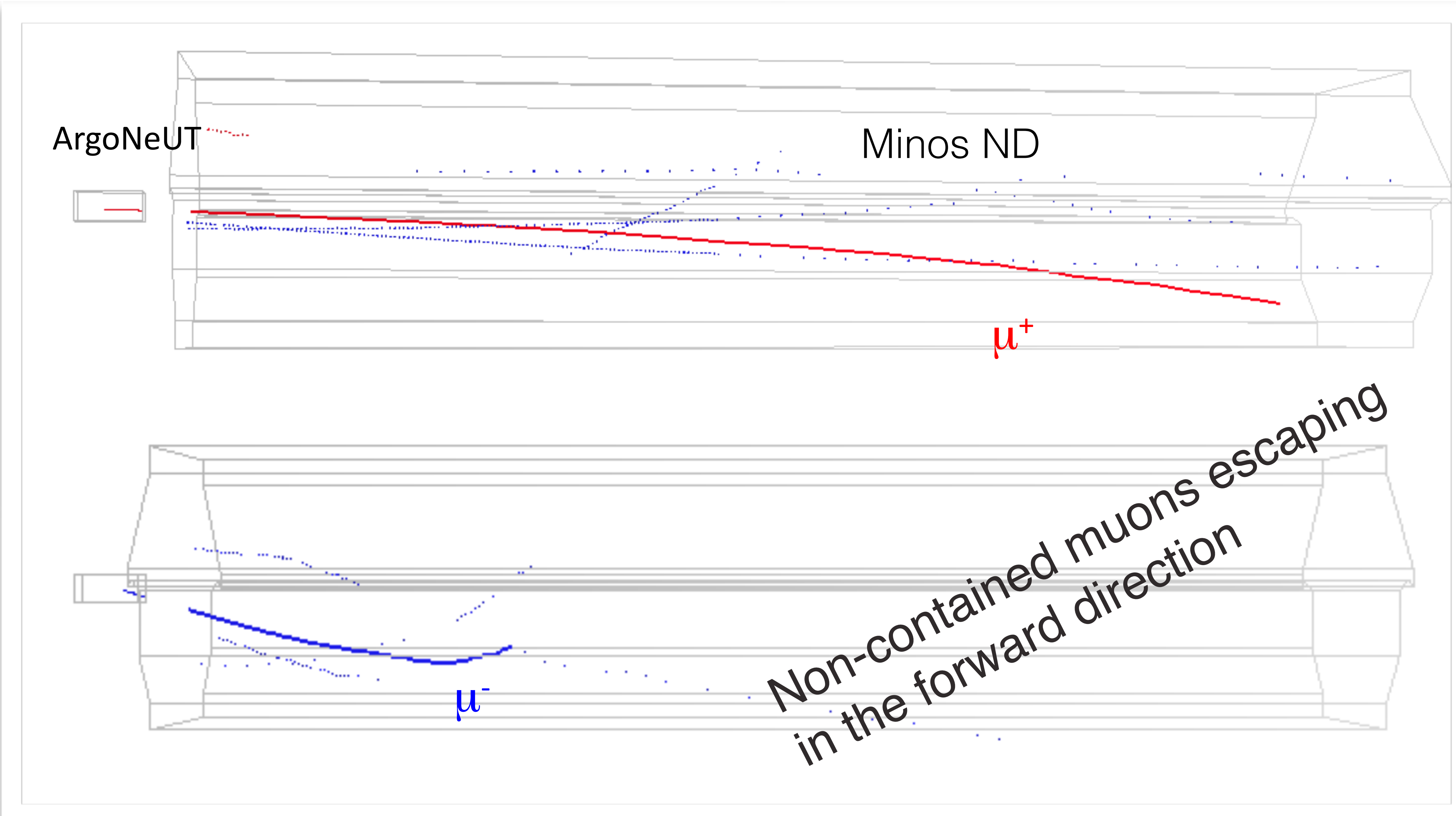
Length=0.5 cm

T_p=22±3 MeV



ArgoNeuT proton threshold: 21 MeV Kinetic Energy

Muon Reconstruction



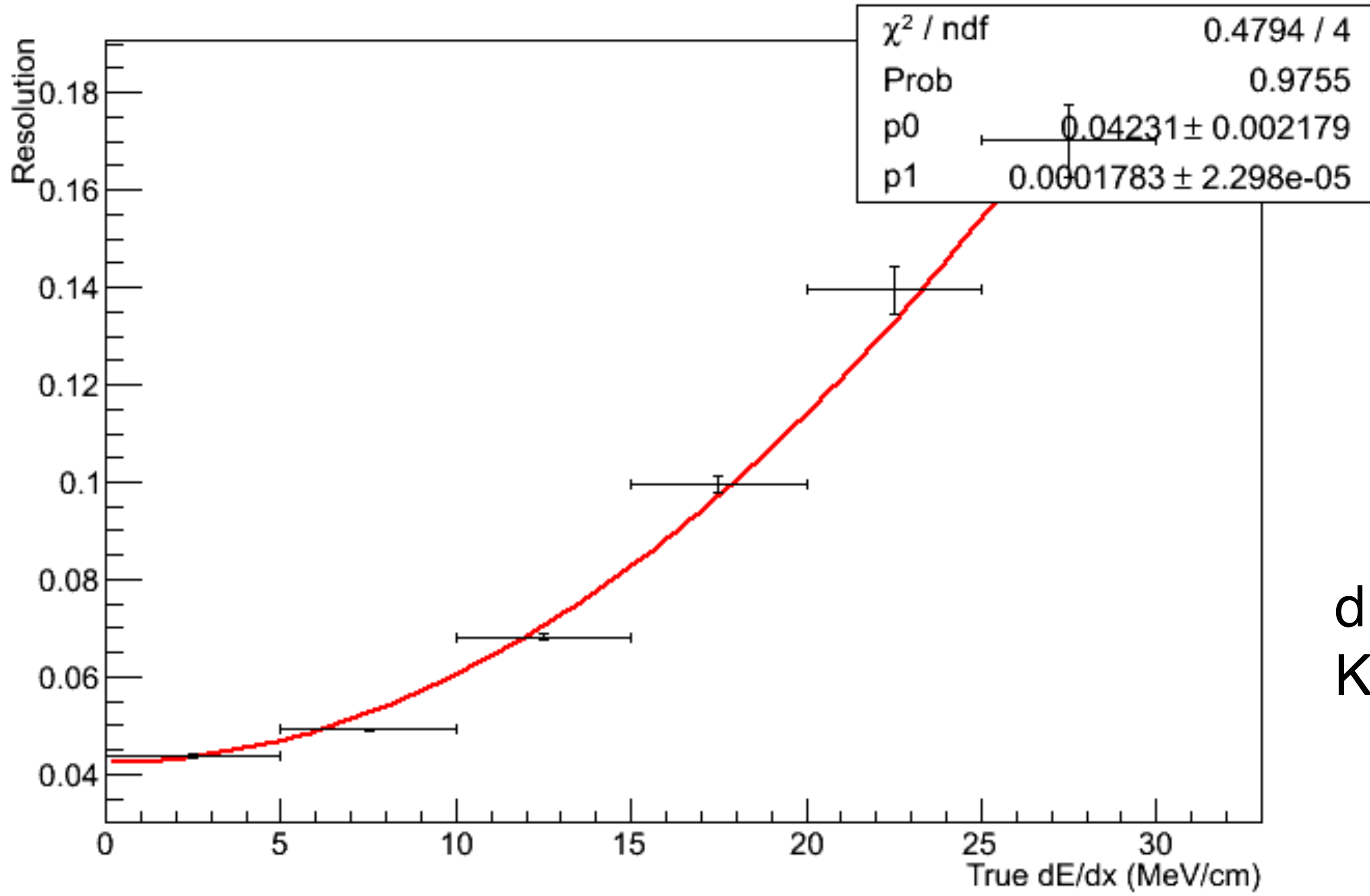
"Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector"
JINST 7 P10020 (2012)

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

Generated

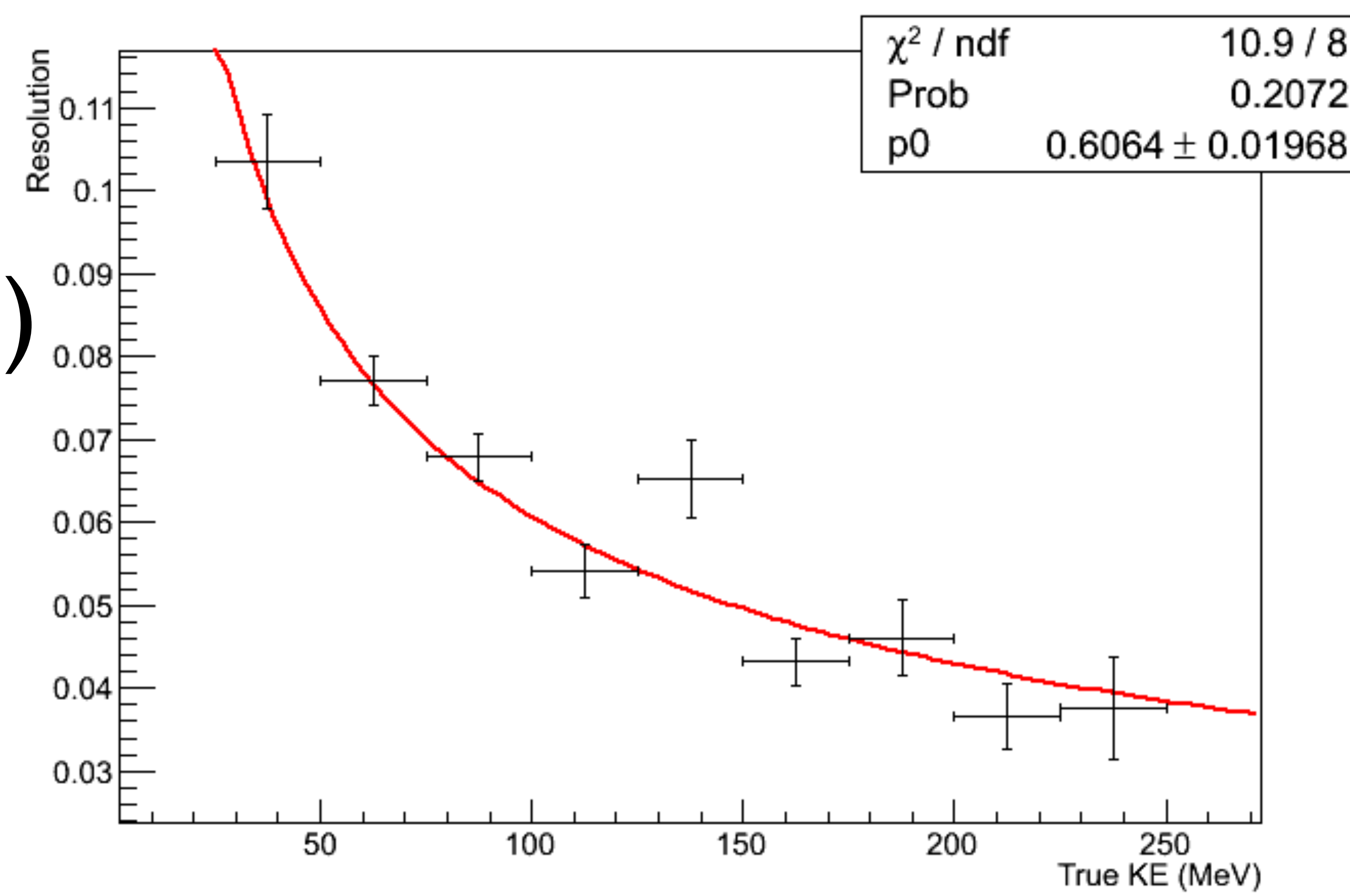
Identified as

	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

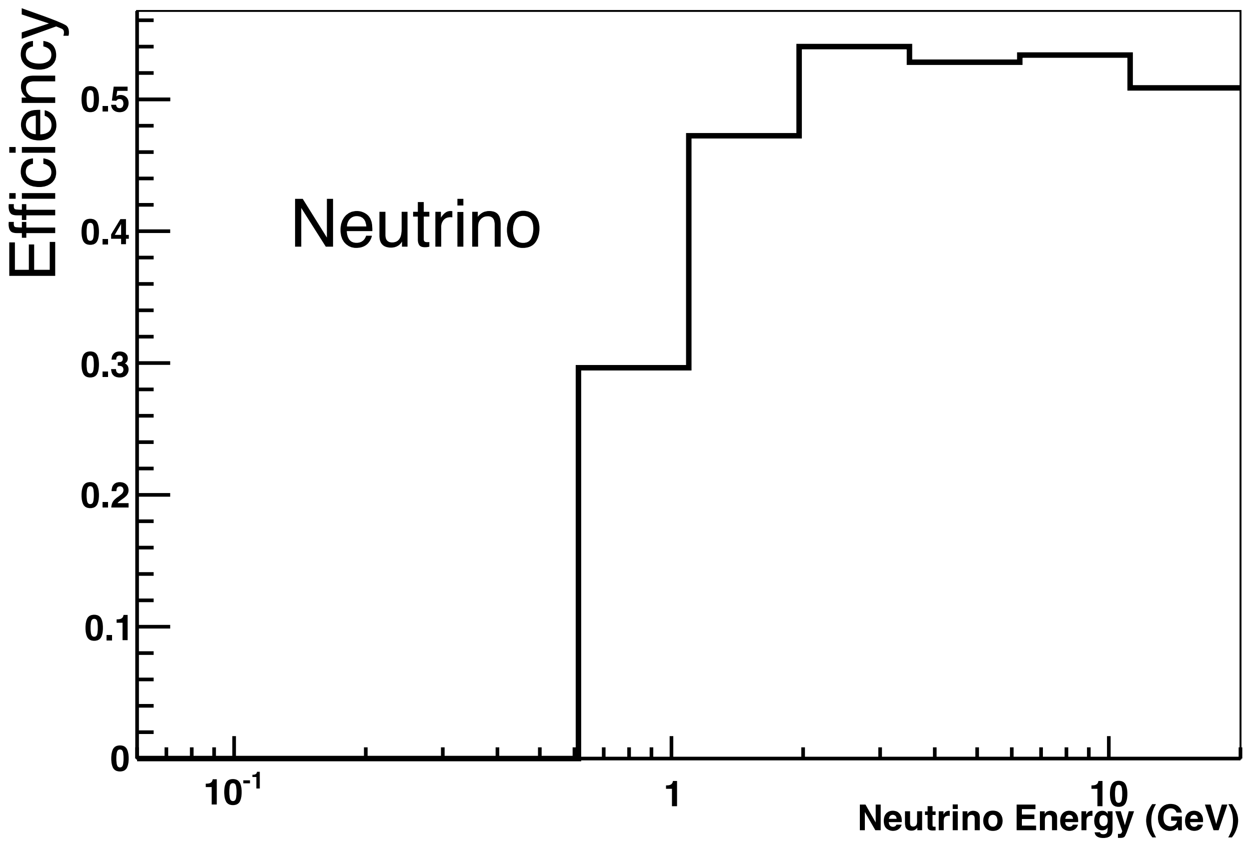


dEdx: 0.04231+0.0001783*(dEdx)^2
KE: 0.6064/sqrt(KE)

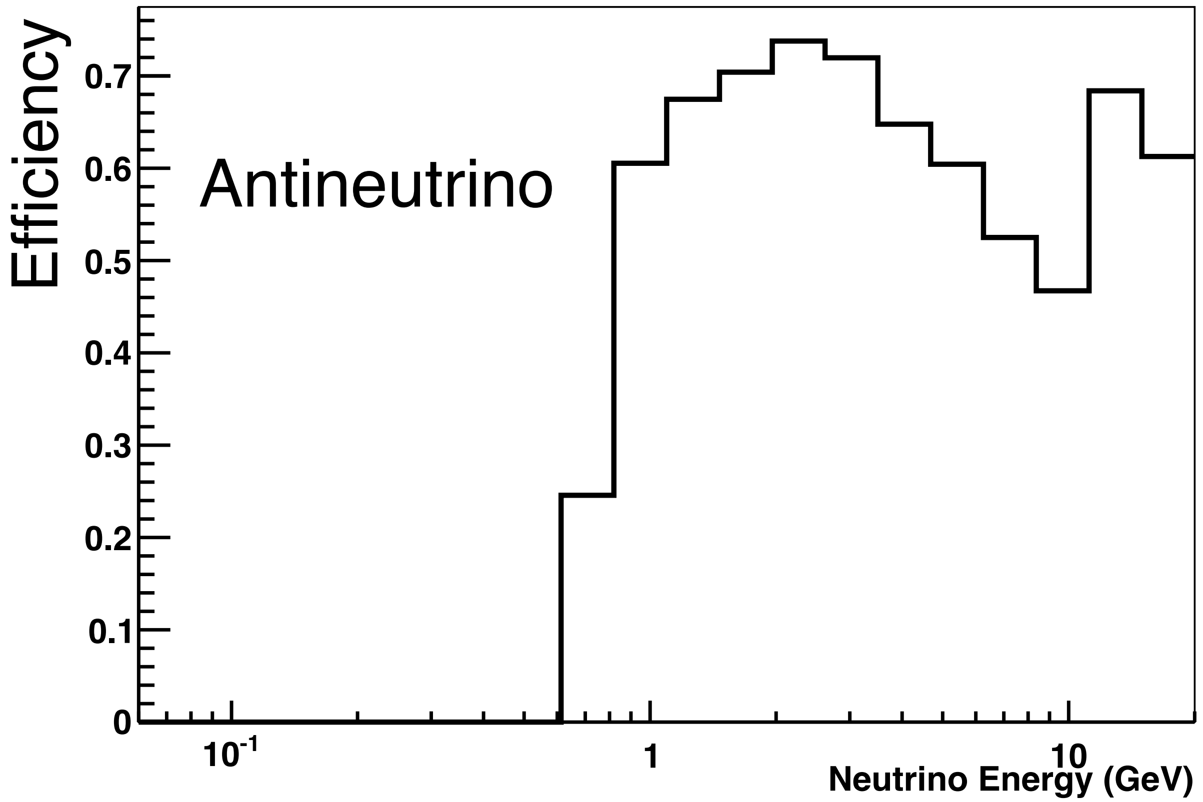
ArgoNeuT (4 mm wire pitch)
Resolution in dE/dx
and Kinetic Energy



Selection efficiency μ+Np events



Overall efficiency: 46%



Overall efficiency: 68%