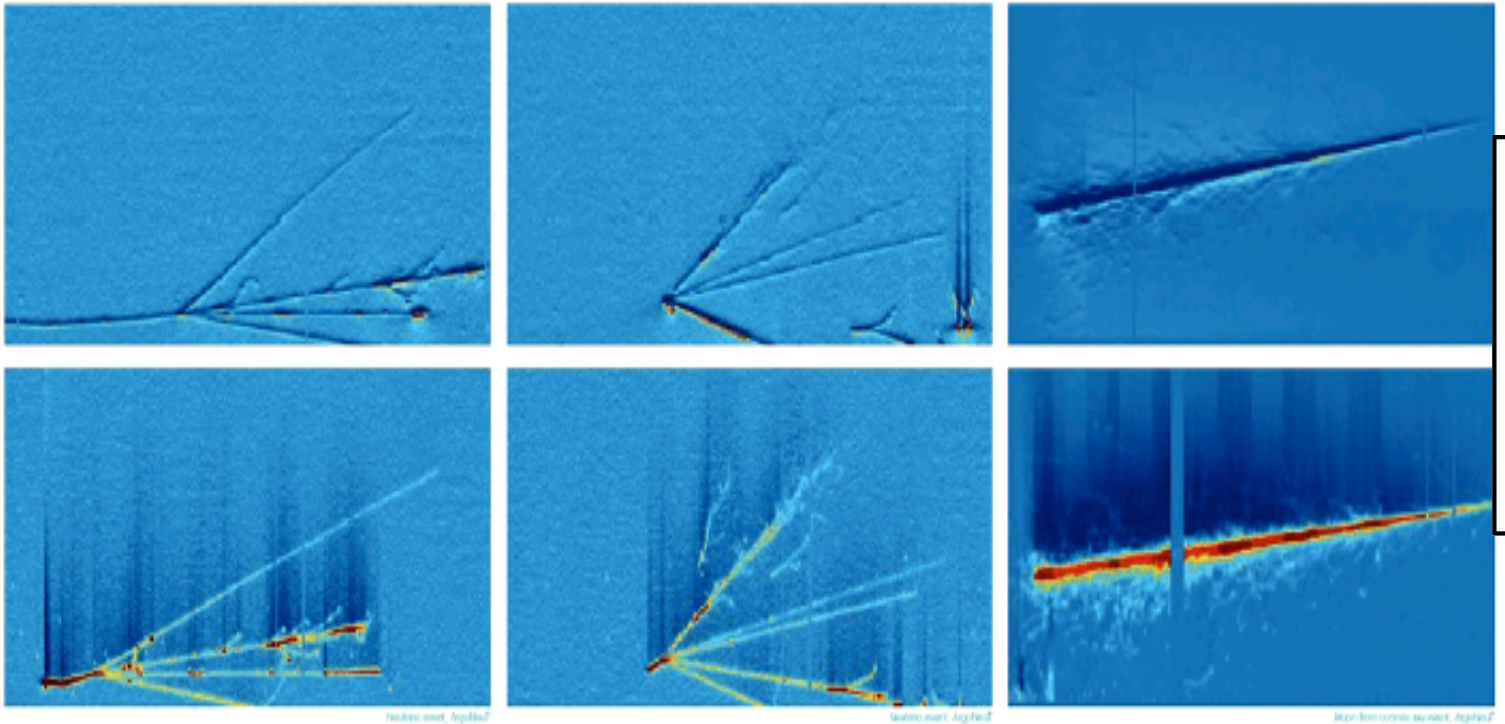


Neutrino detection in the ArgoNeuT LAr TPC

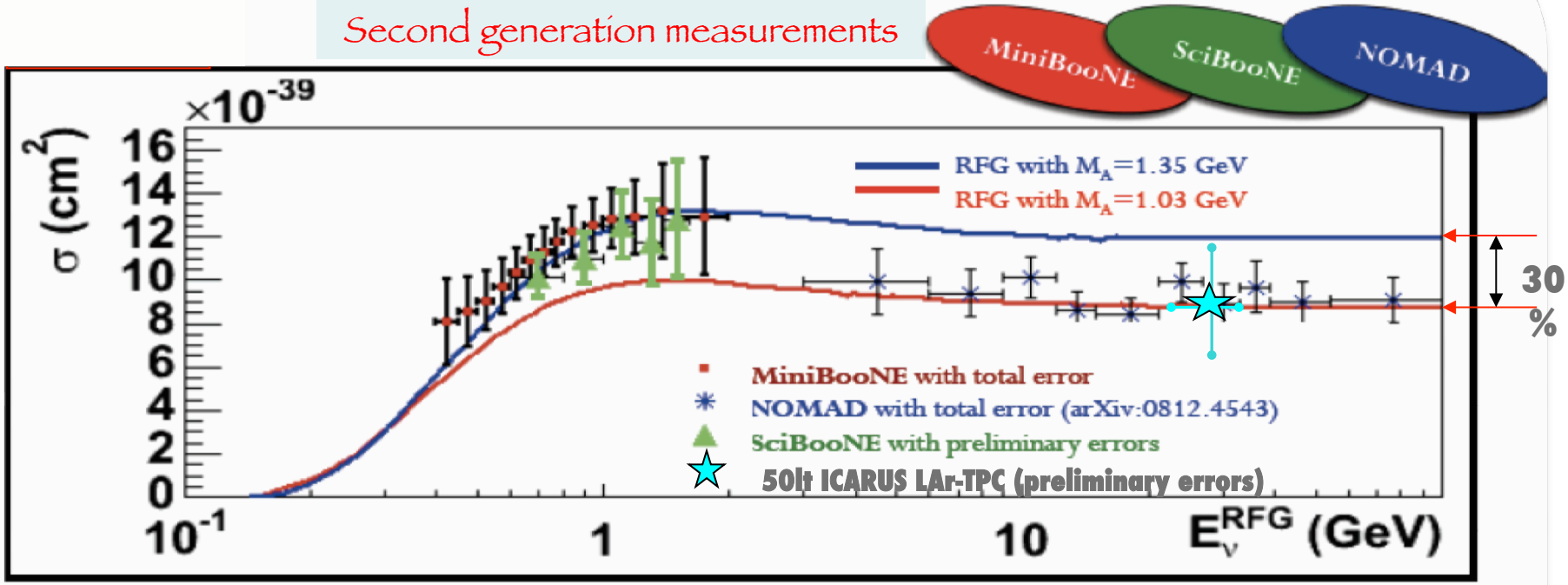
Ornella Palamara
INFN-LNGS (Italy)

Cern, August 5th 2011

One of the main uncertainties in the next generation long baseline oscillation experiments is given by the neutrino-nucleus interaction cross sections in the "few-GeV region".

- Charged-Current Quasi-Elastic Scattering

Second generation measurements

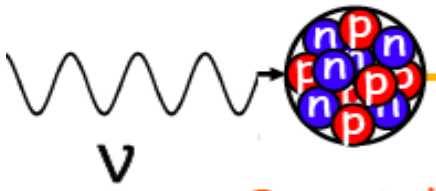


- MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon. This is not understood.

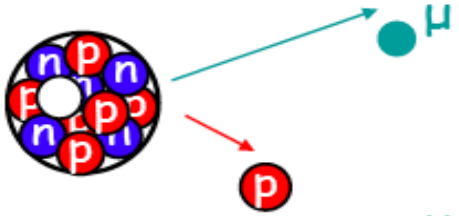
- Single point, first and so far unique measurement with **Ar target**, in agreement with NOMAD data (same, ***high energy*** ν beam - ***WANF***)

50lt ICARUS LAr-TPC

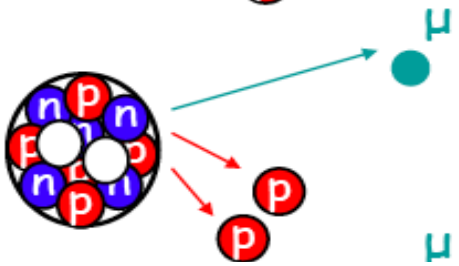
Neutrino - nucleus interaction @ $E_\nu \sim \mathcal{O}$ (1 GeV)

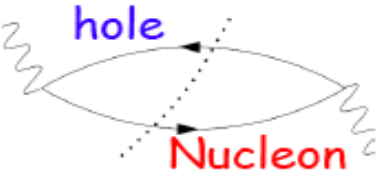


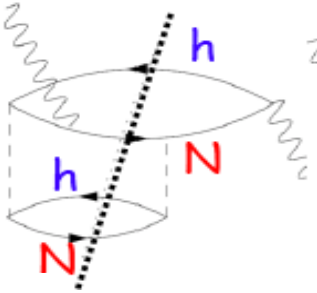
Quasielastic (QE)

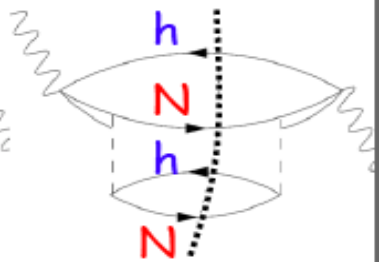


Two Nucleons knock-out (2p-2h)



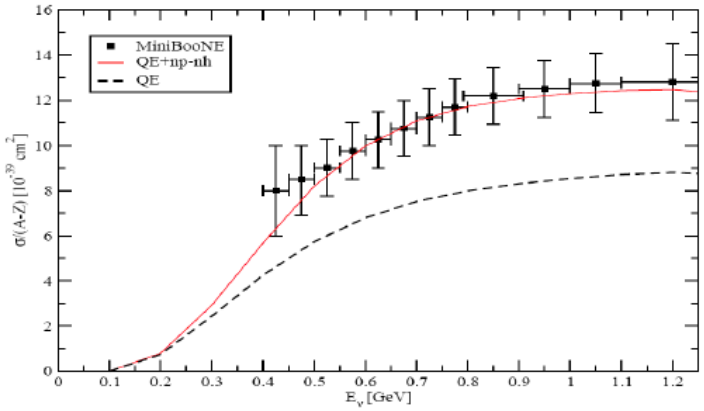


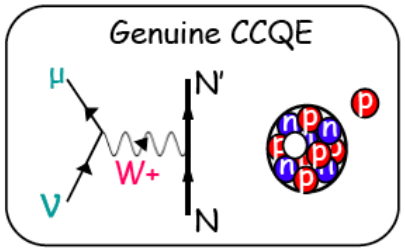


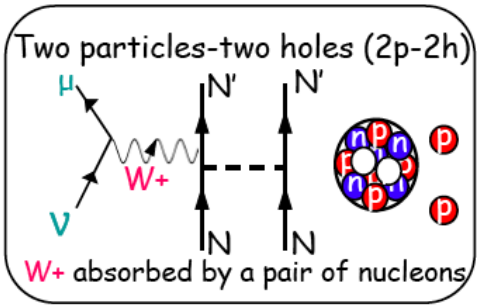


A possible explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







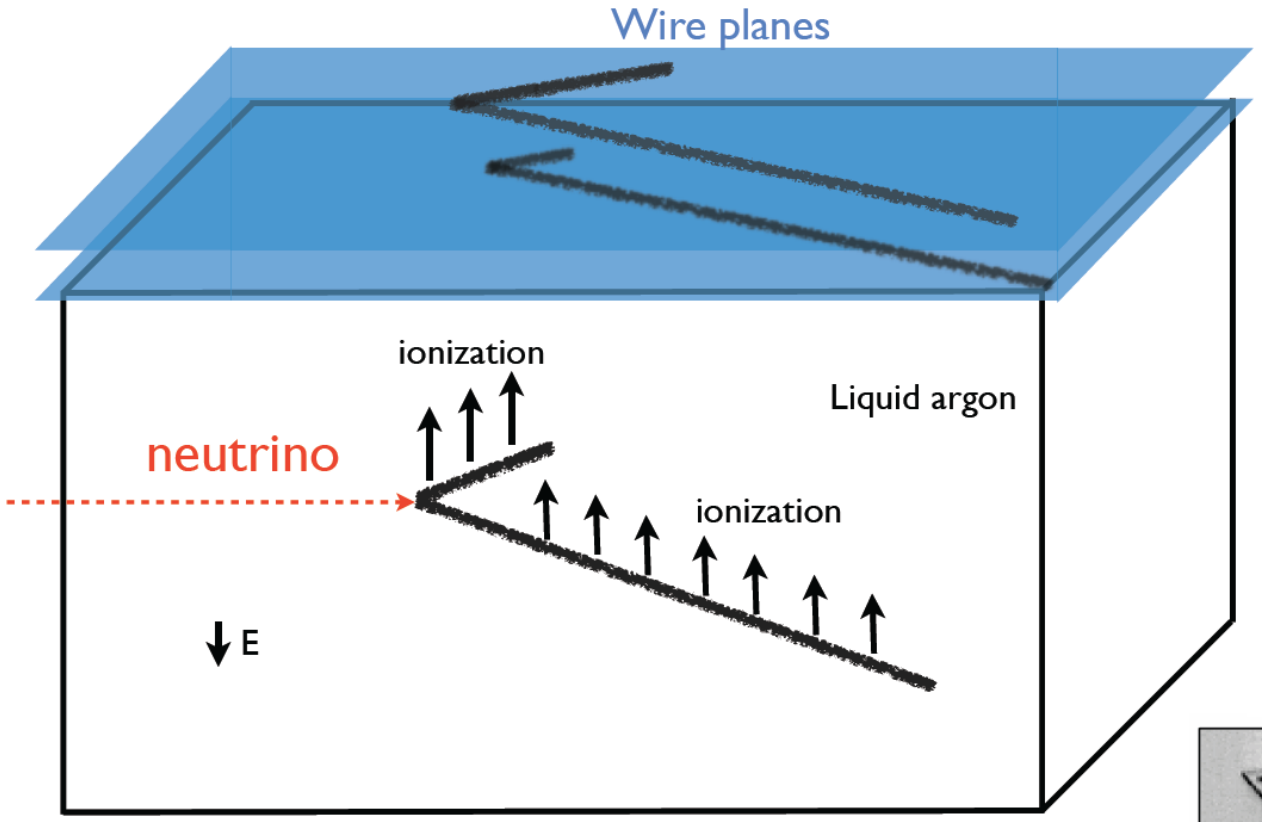
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

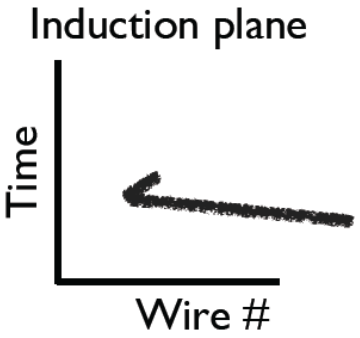
Agreement with MiniBooNE without increasing M_A

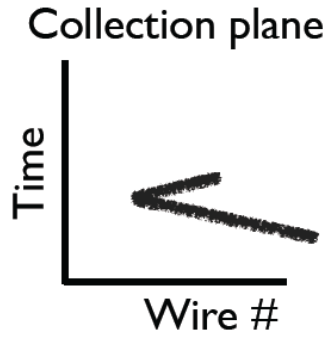
M. Martini presentation @ this conference

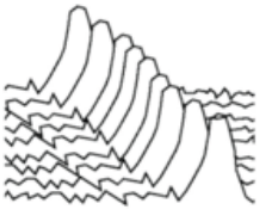
Need proof from sensitive exp.s

The LArTPC concept

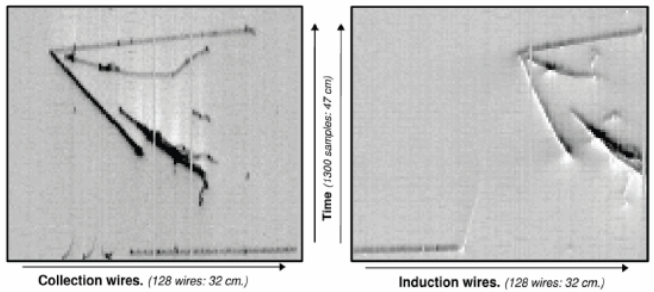








Wire pulses in time give the drift coordinate of the track

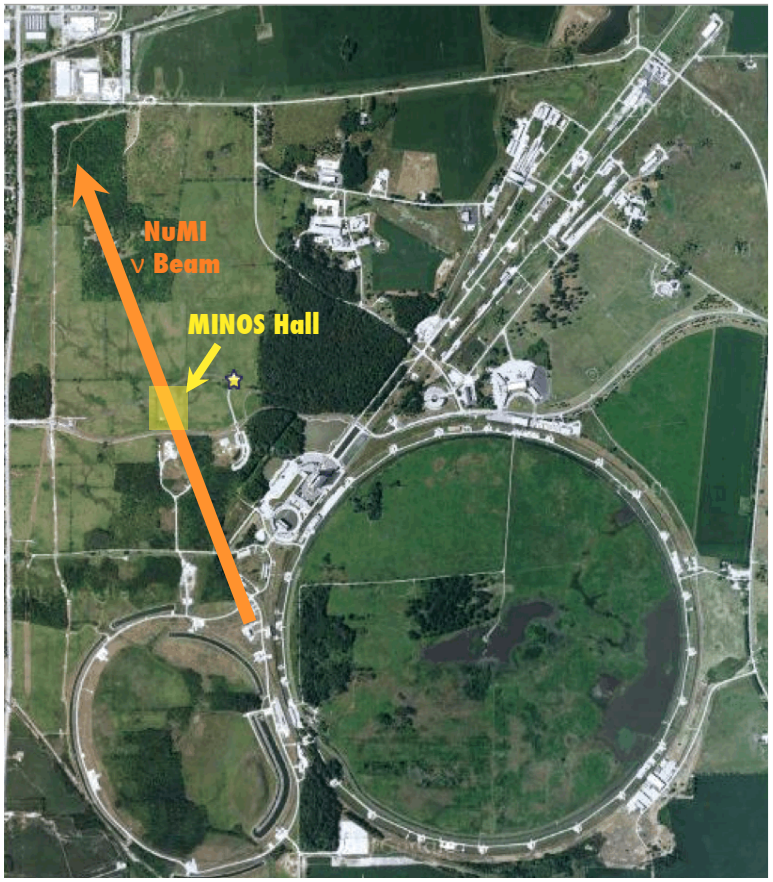


ICARUS 50 L in WANF neutrino beam

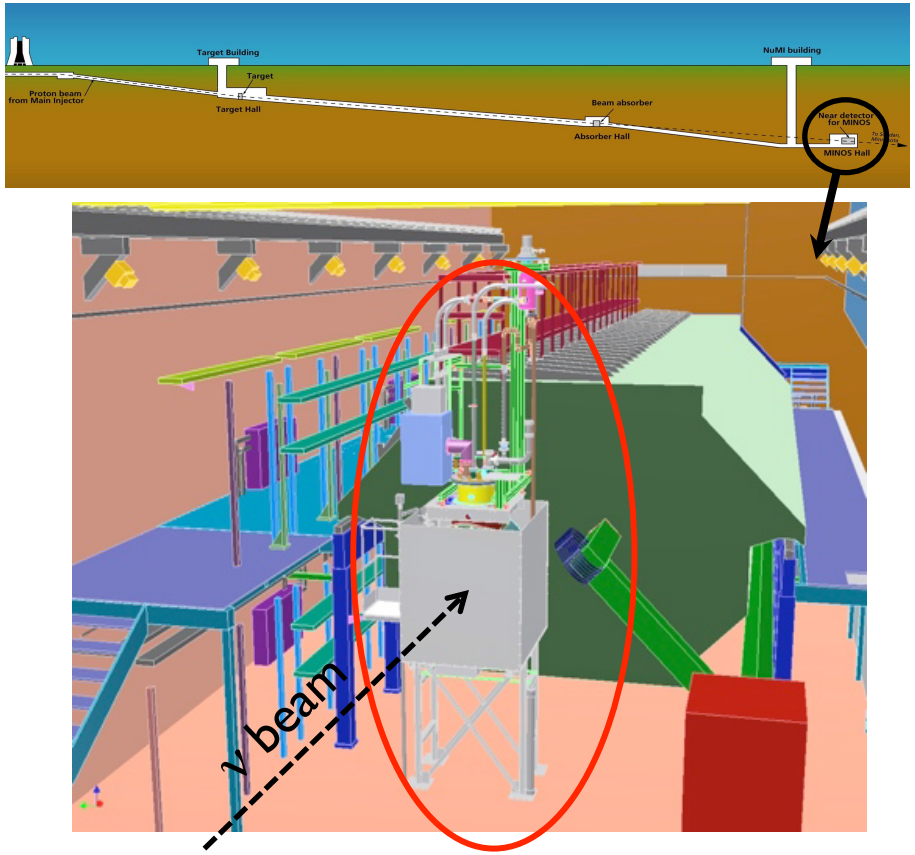
induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

ArgoNeuT

- ✓ ArgoNeuT is a 175 liter (active) Liquid Argon Time Projection Chamber (LArTPC) jointly funded by DOE/NSF
- ✓ Designed and assembled in 2007-08, first commissioned (on surface) at FNAL in Summer 2008
- ✓ Moved underground in the *NuMI* beam at FNAL, in front of *MINOS Near Detector*, early 2009
- ✓ Exposed to $\nu/\bar{\nu}$ beam (*LE beam option*): June'09 ⊕ Sept'09-Feb.'10

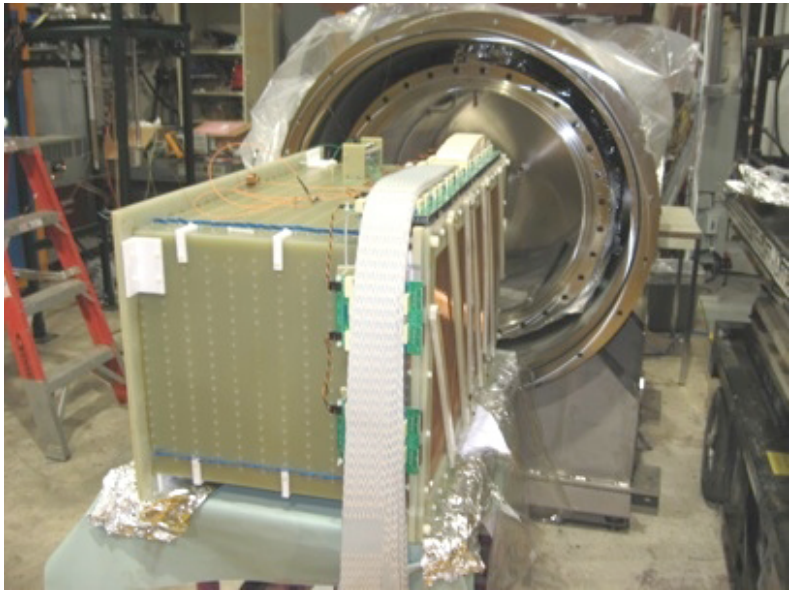


Fermilab, NuMI beam line

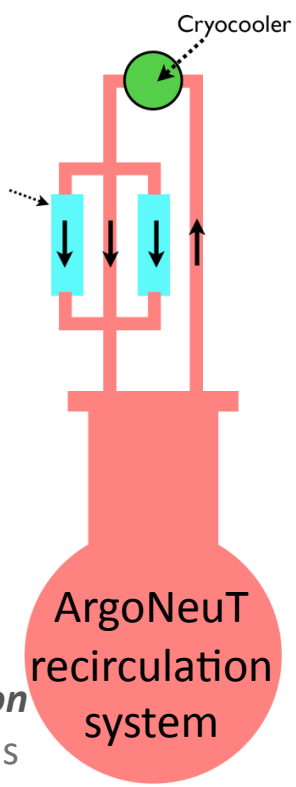


MINOS Hall: ArgoNeuT just upstream of the MINOS ND

ArgoNeuT Design



The TPC, about to enter the inner cryostat

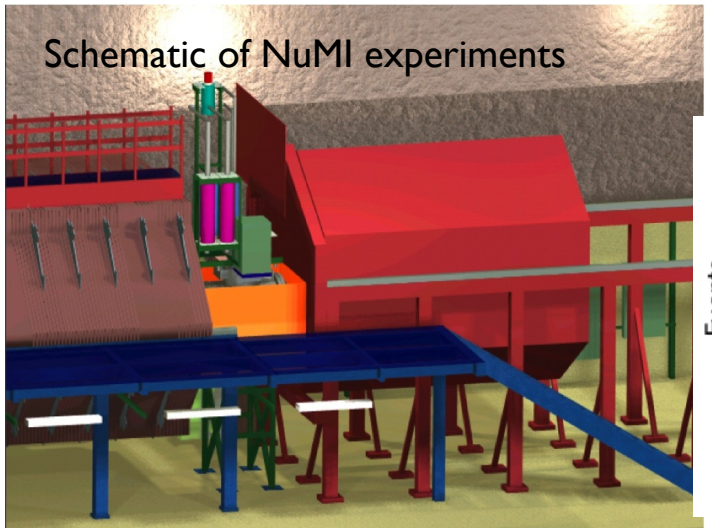


The fully-instrumented detector in the NuMI beamline

2 read-out planes: ***Induction and Collection***
each channel: 2048 samples in 400 microseconds

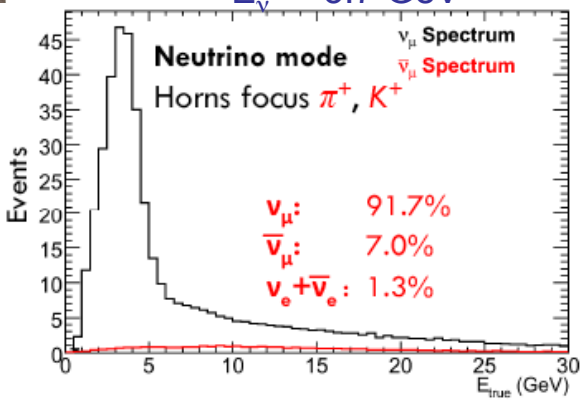
Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Electric field	500 V/cm

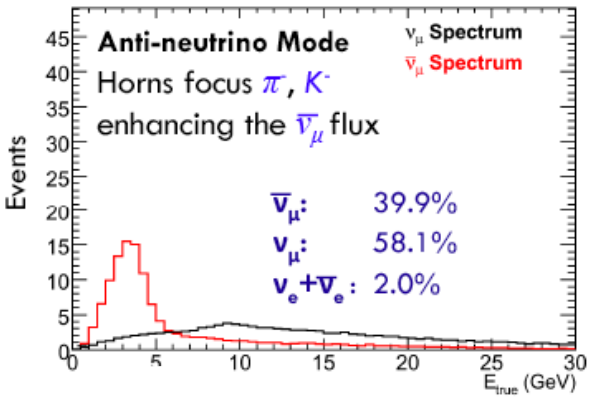
ArgoNeuT's physics run in the NuMI beam

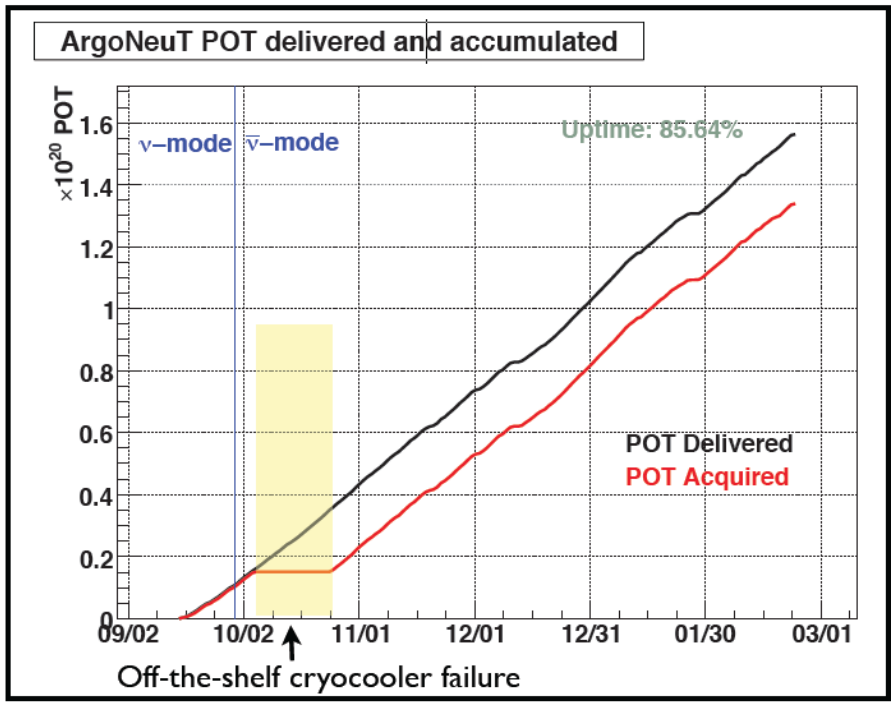


Composition of NuMI beam Fluxes - Low Energy (LE) mode

$\langle E_\nu \rangle$= 3.7 GeV





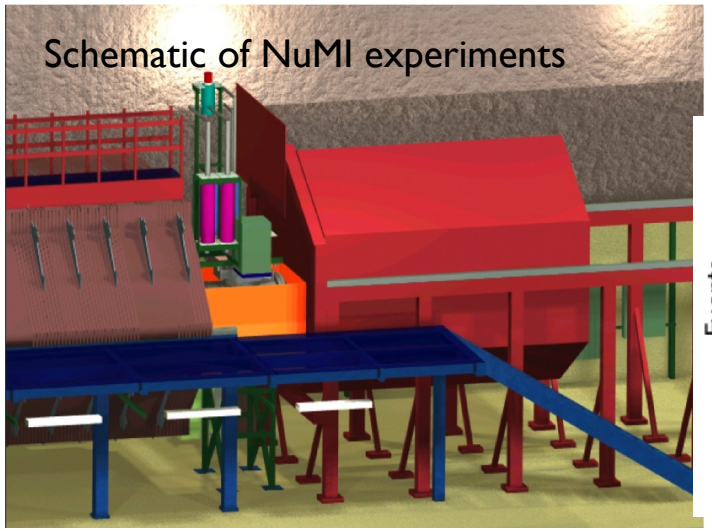


Reaction	#events in (~1.35E20 POT)
ν_μ CC	~6600
$\bar{\nu}_\mu$ CC	~4900
ν_μ CCQE	~600
ν_e CC	~130

✓Stable, shift-free operation for >5 months!

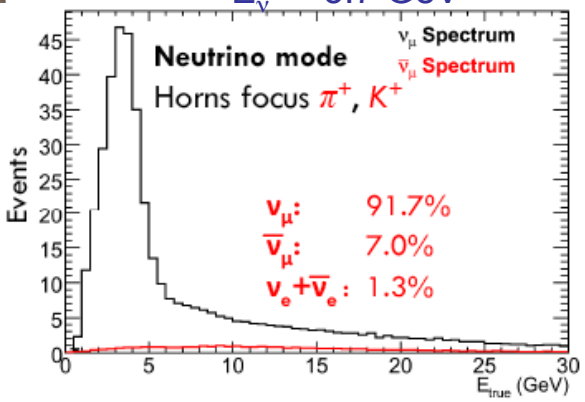
✓The first 1000s of (anti-)neutrino LArTPC events collected in a low-energy neutrino beam ever!

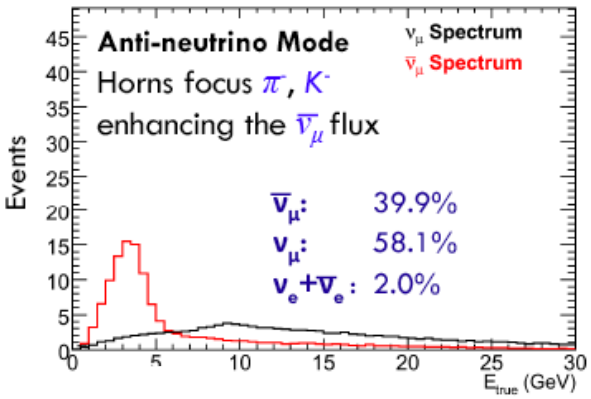
ArgoNeuT's physics run in the NuMI beam

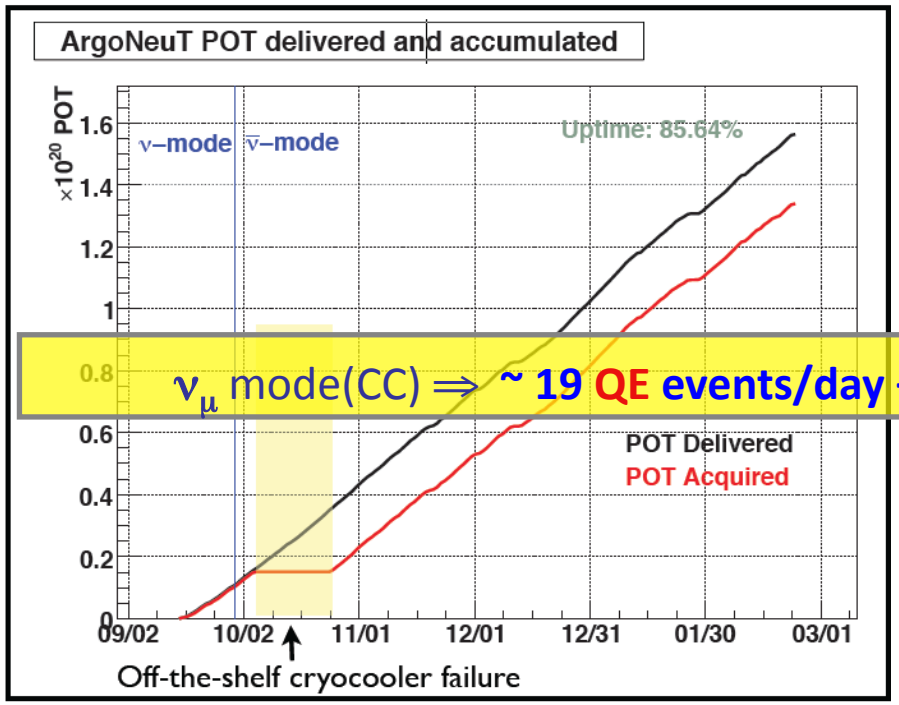


Composition of NuMI beam Fluxes - Low Energy (LE) mode

<E_ν>= 3.7 GeV





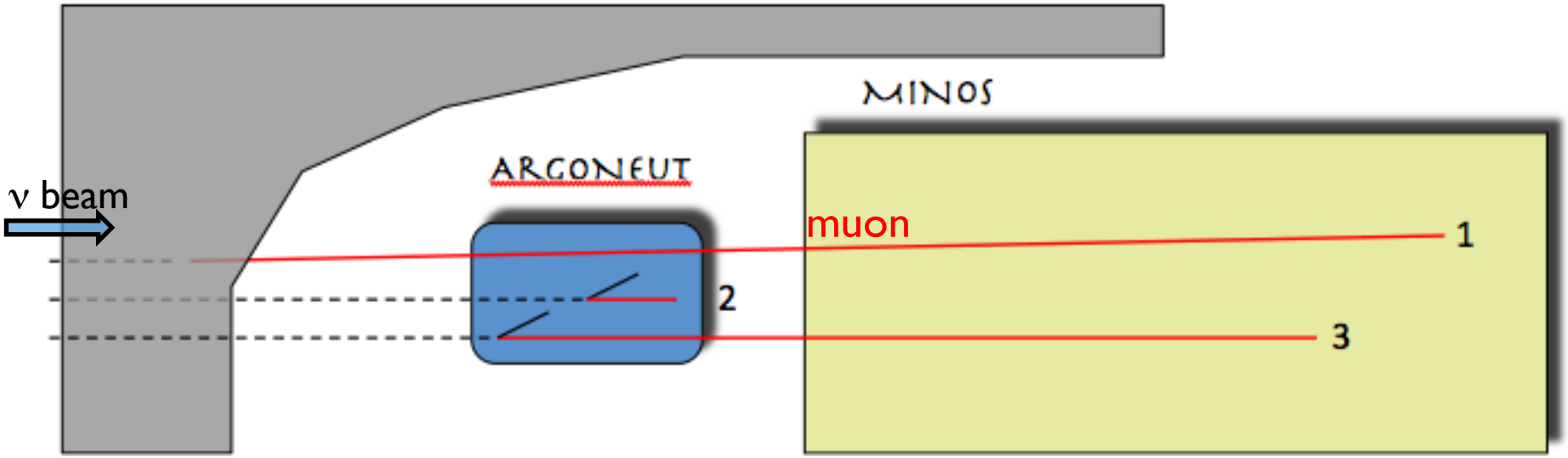


Reaction	#events in (~1.35E20 POT)
ν_μ CC	~6600
$\bar{\nu}_\mu$ CC	~4900
ν_μ CCQE	~600
ν_e CC	~130

ν_μ mode(CC) ⇒ ~ 19 QE events/day + ~ 15 RES events/day + ~ 83 DIS events/day

- ✓Stable, shift-free operation for >5 months!
- ✓The first 1000s of (anti-)neutrino LArTPC events collected in a low-energy neutrino beam ever!

ν event's topologies



1. Through-going μ from ν-int. in the rock upstream ArgoNeuT (large sample)
2. ν interaction fully contained in LAr (few events)
3. ν interaction not fully contained in LAr [track(s) escaping ArgoNeuT]

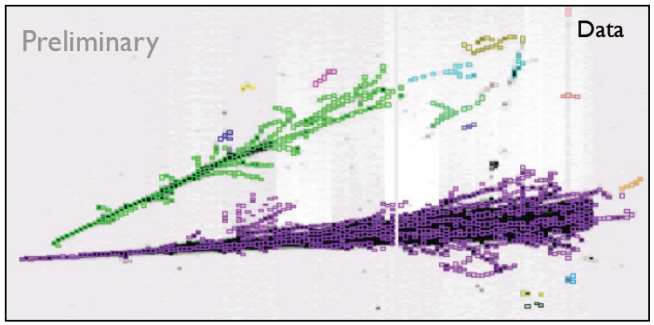
2. And 3.: good neutrino events to be selected

ArgoNeuT is a modest size LAr-TPC: MINOS ND spectrometer used for complete ν event reconstruction

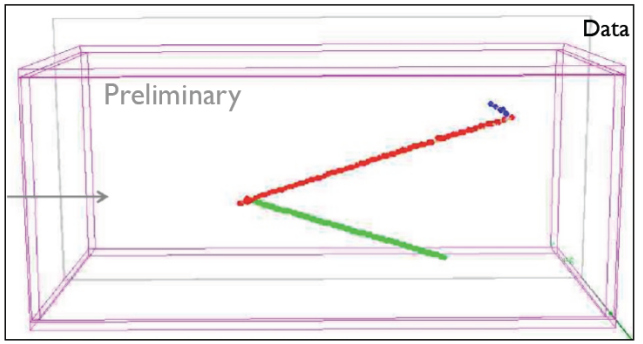
ν event Reconstruction

Offline reconstruction procedure:

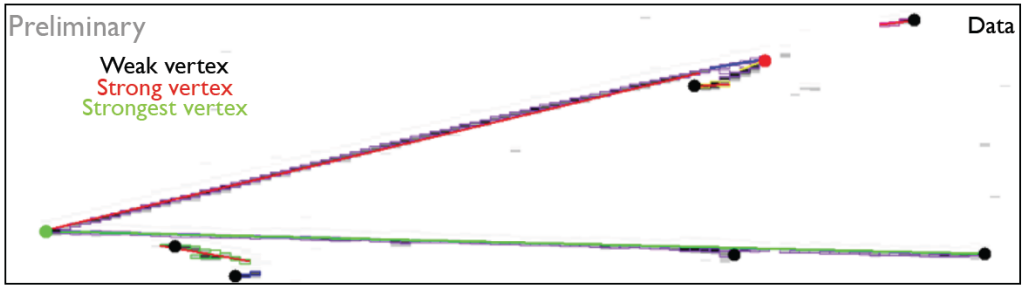
1. *Hit identification*
2. *Hit reconstruction*
3. *Cluster/Vertex reconstruction*
4. *3D track reconstruction*



Hit finding + density-based clustering.



3D reconstruction



5. *Calorimetric reconstruction*
6. *Particle Identification* (dE/dx along the track)

7. *Full energy reconstruction and sign determination of muons escaping ArgoNeuT by the MINOS ND*

LArSoft: SW tool for LAr experiments

ν Data Analysis

ν-mode: 0.1×10^{20} PoT (14 days),
$\bar{\nu}$-mode: 1.25×10^{20} PoT (185 days)

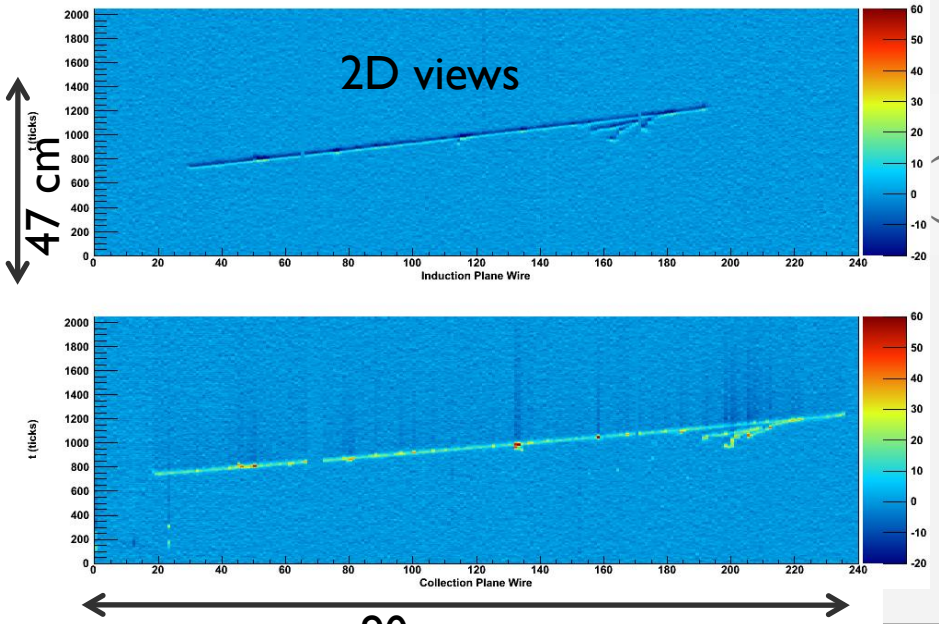
- Vertex in LAr volume → ν event
- ν event classified according to track multiplicity (including e.m. showers) by combination of software and human based event scanning

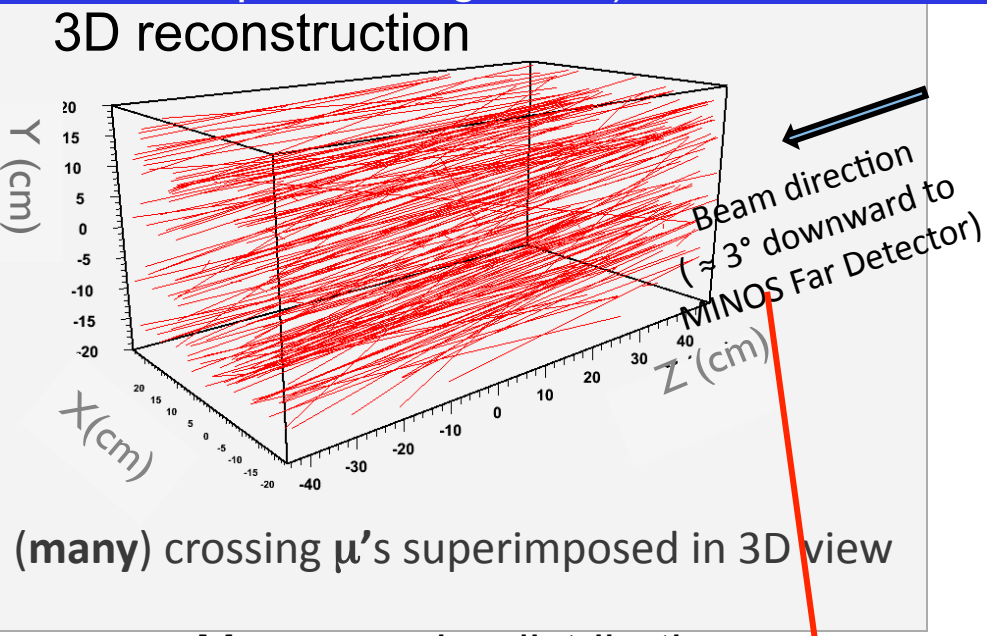
✓ Reconstruction of neutrino-induced through-going muons
✓ Investigate nuclear FSI in Ar ["Single μ" events from ν CC interactions]
✓ Measurement of CC inclusive cross section
- Measurement of CCQE cross section (and investigate nuclear FSI)
- Measurement of π^0 production and backgrounds to electron neutrino interactions
- Measurement of electron-neutrino content of the NuMI beam

- All of the above for *anti-neutrino interactions (w/~10 times greater statistics).*

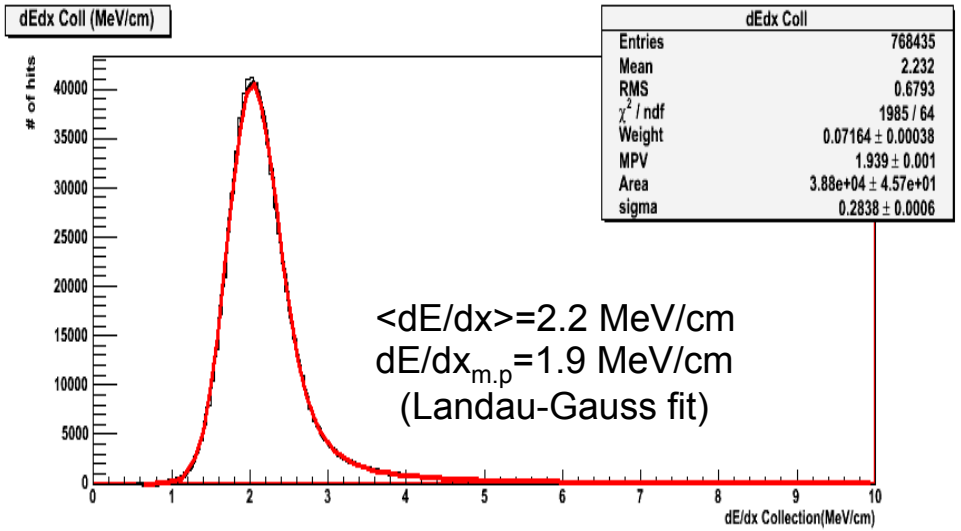
Reconstruction of through-going muons

(produced by ν interactions in the rock upstream ArgoNeuT)

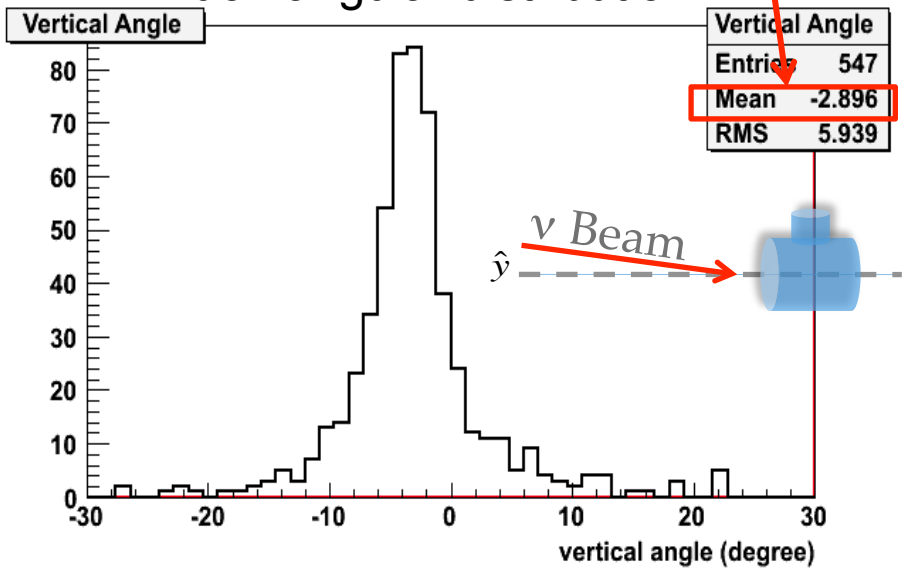




Muon calorimetric reconstruction

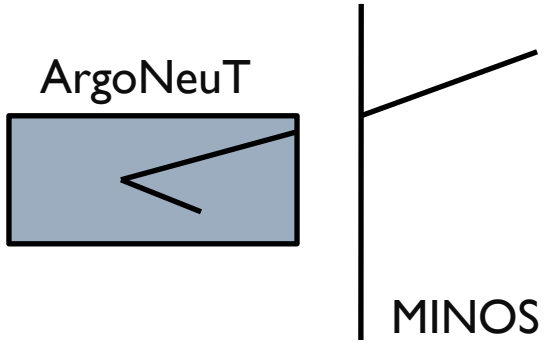


Muon angular distribution



Matching Muons from ArgoNeuT to MINOS

- ArgoNeuT employs the MINOS near detector in order to fully reconstruct escaping muons: ArgoNeuT reconstructed track needs to be matched with a reconstructed muon in MINOS.

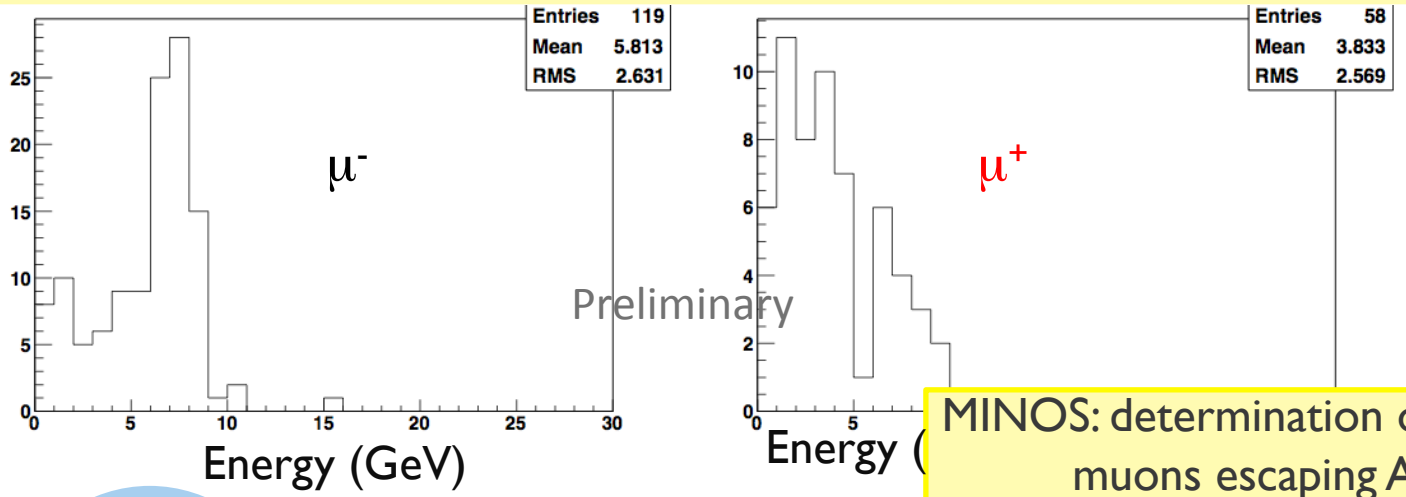


- All ArgoNeuT tracks that leave the TPC are projected onto MINOS and considered when attempting a match.
- MINOS tracks with a vertex in the upstream-most 20 cm of the detector are considered.
- The matching requirements are based on the angle between the ArgoNeuT track and the MINOS track (θ) and the difference between the projected-onto-MINOS ArgoNeuT track's radial position and the MINOS track (Δr).

- The definition of "best match" for events featuring multiple candidate matches is based on $\Delta r/\cos\theta$ between the projected ArgoNeuT track and the MINOS track/vertex.

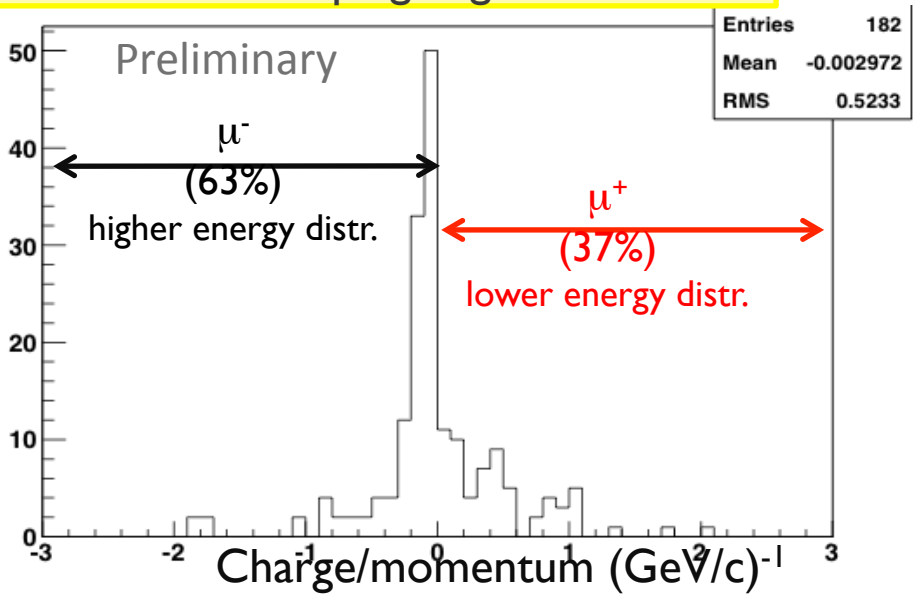
Matching Muons from ArgoNeuT to MINOS
(through-going muons data sample - anti-neutrino mode)

MINOS: measurement of the energy of the muons escaping ArgoNeuT



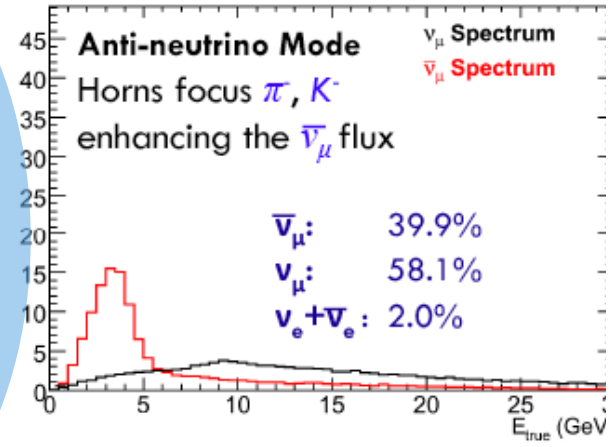
Muon momentum reconstruction from MINOS ND:
-by curvature in magn. field
- 12% resolution for a 10 GeV muon
- by range for stopping muons ~6% resolution)

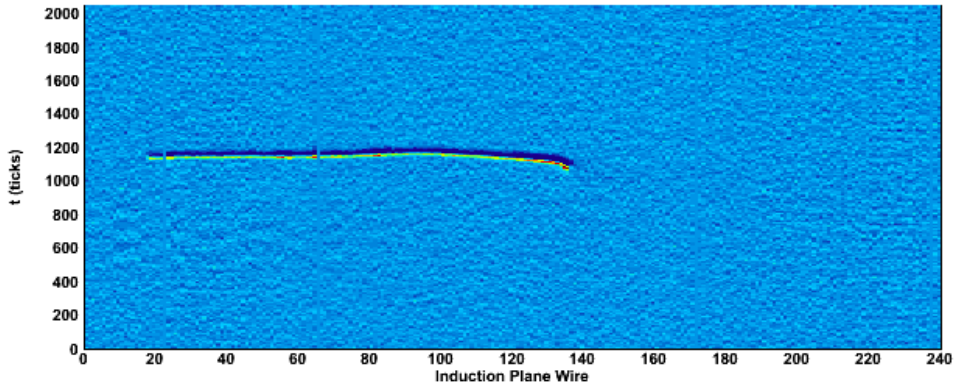
MINOS: determination of the sign of the muons escaping ArgoNeuT

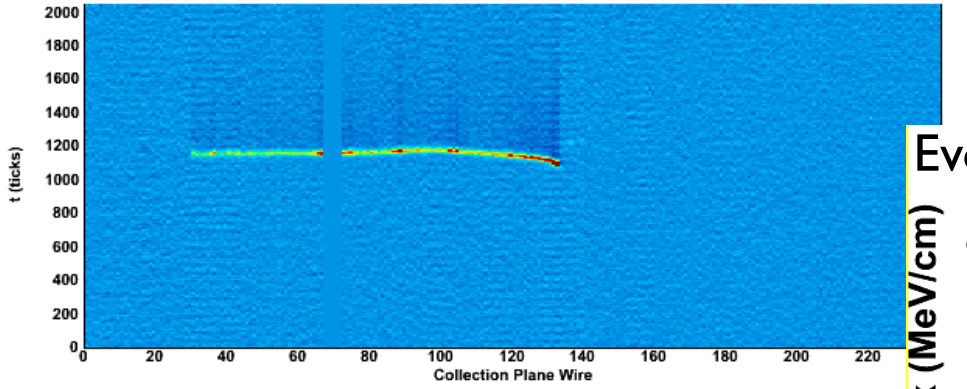


We gratefully acknowledge the cooperation of the MINOS Collaboration in providing their data for use in this analysis

NuMI





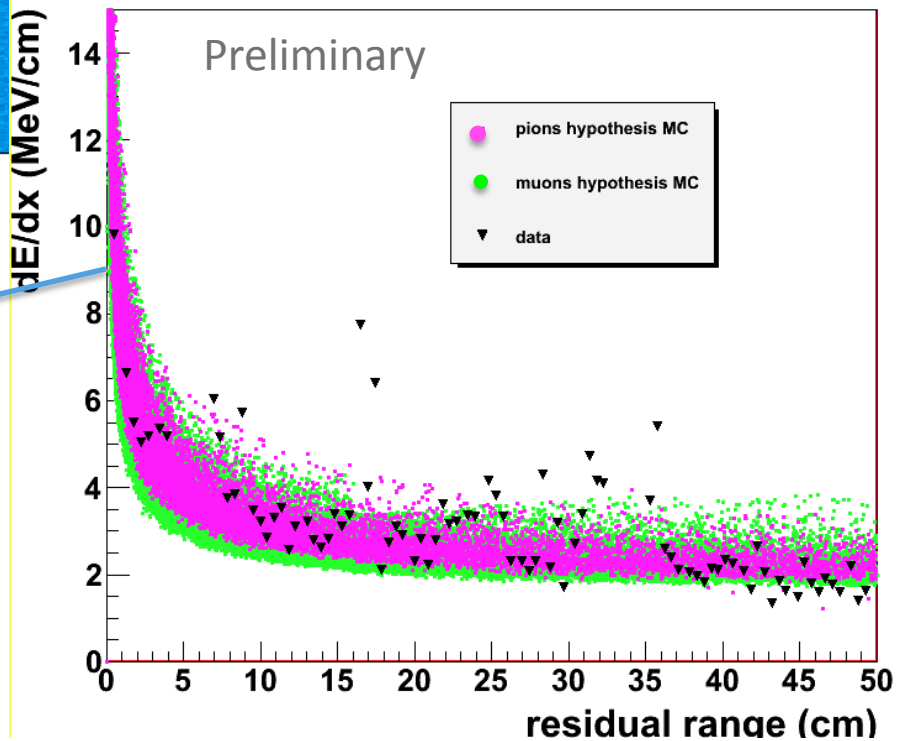


Energy reconstruction and particle ID of tracks stopping in LAr volume

ArgoNeuT

entering track
(produced by upstream ν interaction)
stopping in LAr

Evolution of the ionization along the track



Minimum ionizing ptcl:

muon or pion

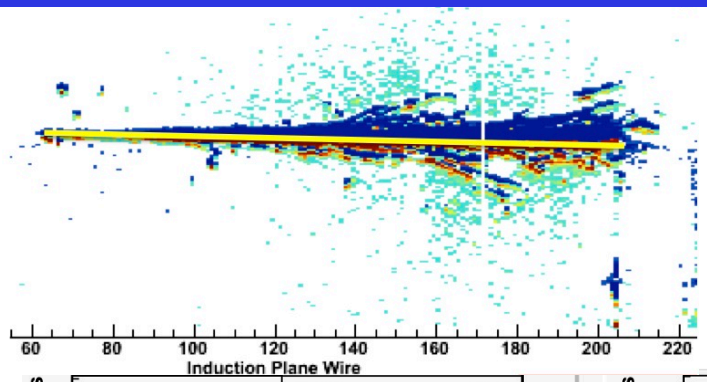
Track lenght= 52 cm
Kinetic Energy=160 MeV
(in agreement with expectations GEANT)

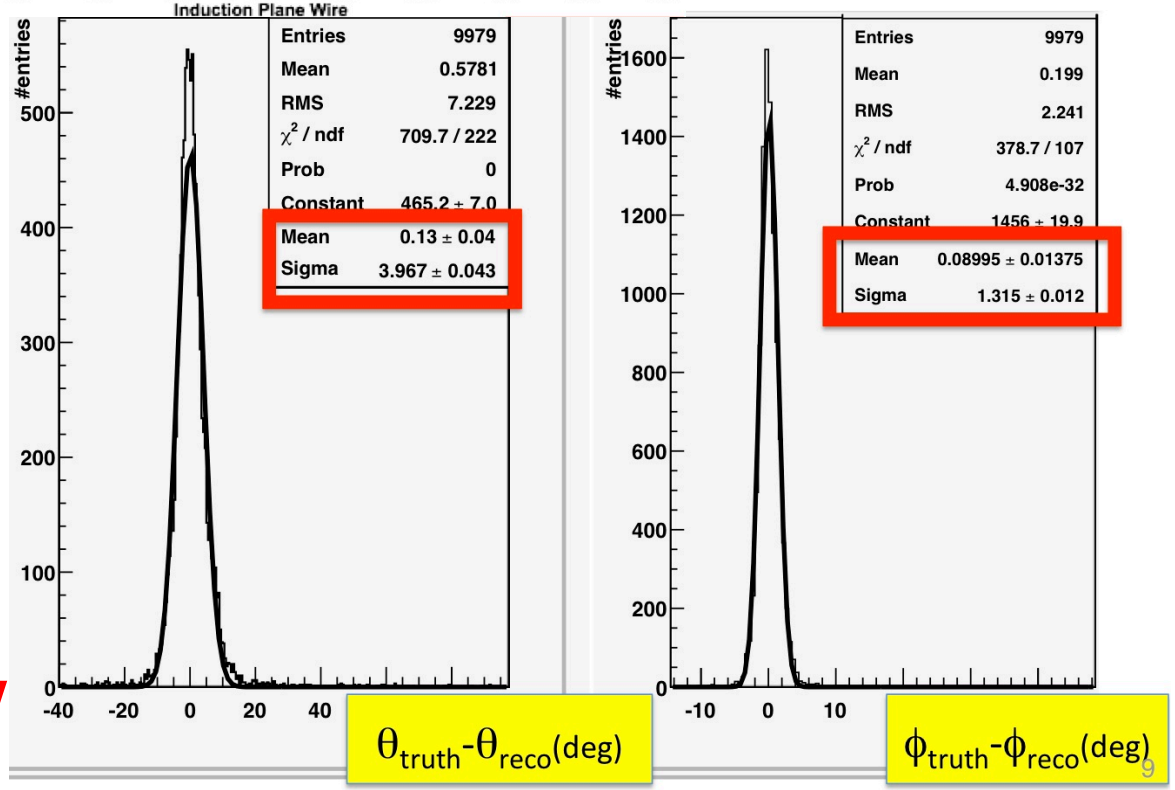
e.m. shower reconstruction

Tracking algorithm reconstructs direction of showers (electrons)

Compare to MC to determine angular resolution

Preliminary





MC Study of track direction reconstruction

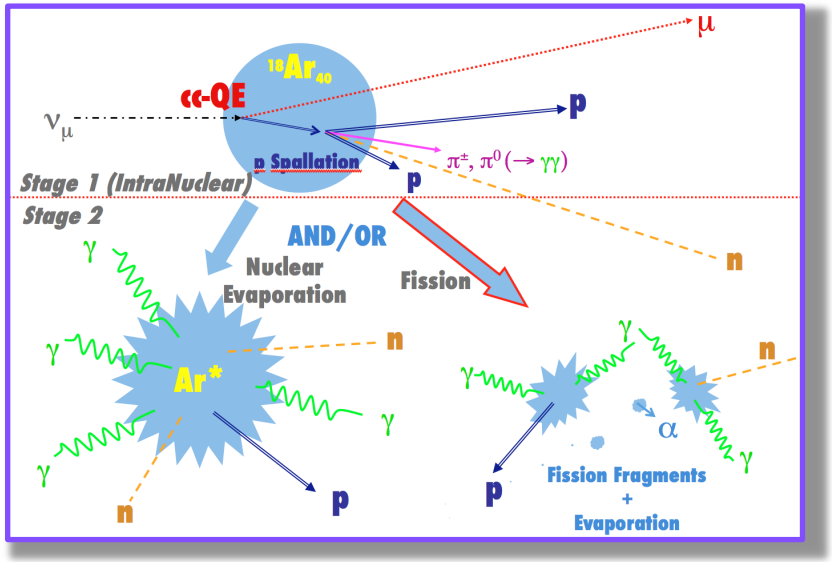
Understanding vertex activity (nuclear FSI)

"Final State (re)-Interactions"- *the main source of uncertainty*:

even the "easiest" topology (CC-QE) is not so simple

$\nu_\mu + n \rightarrow \mu^- + p$ (reaction on free nucleon)

$\nu_\mu + A(n) \rightarrow \mu^- + p + (A-1)^*$ (nucleon bound in the nuclear target)



FSI

- ***proton Spallation*** (intranuclear interactions with **p** and **n** emission ...but also $\pi^\pm$, π^0)
- ***Nuclear evaporation*** (lower kin.en. **p** and **n**)
- (and/or) ***Fission*** (nuclear fragments, α's,..)
- ***Nuclear de-excitation*** with **γ** emission

These products are usually neglected because not detectable, unless… …. a high quality imaging detector is in use !!

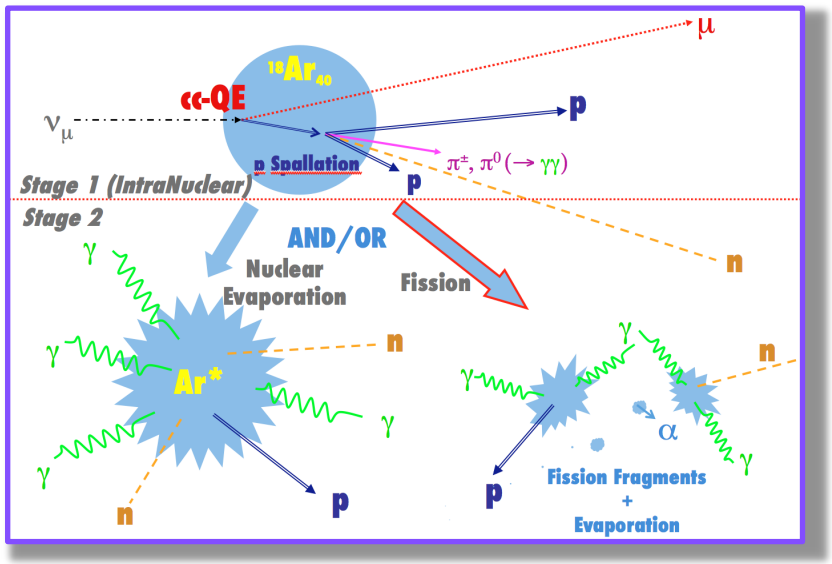
Understanding vertex activity (nuclear FSI)

"Final State (re)-Interactions"- *the main source of uncertainty*:

even the "easiest" topology (CC-QE) is not so simple

$\nu_\mu + n \rightarrow \mu^- + p$ (reaction on free nucleon)

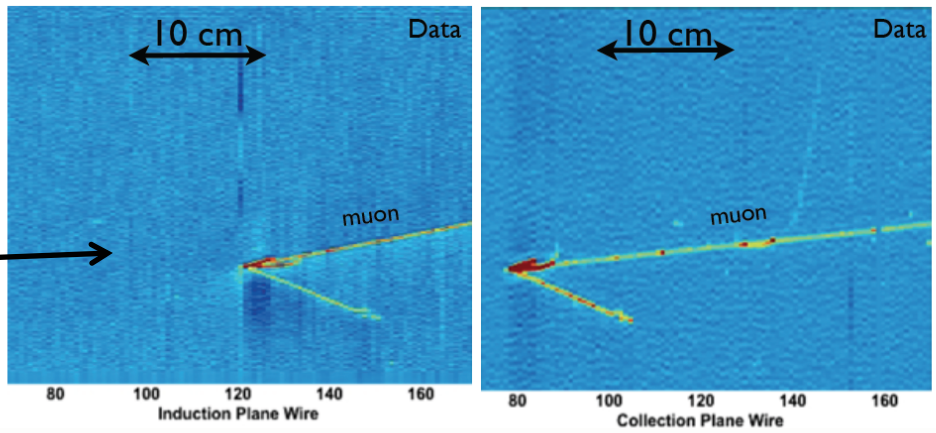
$\nu_\mu + A(n) \rightarrow \mu^- + p + (A-1)^*$ (nucleon bound in the nuclear target)



FSI

- ***proton Spallation*** (intranuclear interactions with **p** and **n** emission ...but also $\pi^\pm$, π^0)
- ***Nuclear evaporation*** (lower kin.en. **p** and **n**)
- (and/or) ***Fission*** (nuclear fragments, α's,..)
- ***Nuclear de-excitation*** with **γ** emission

These products are usually neglected because not detectable, unless... .... a high quality imaging detector is in use !!



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

ArgoNeuT MonteCarlo Simulation

Accurate and extremely detailed MonteCarlo generators are needed for the comparison with LArTPC data.

FSI in MC codes represent the most difficult present challenge in MC development.

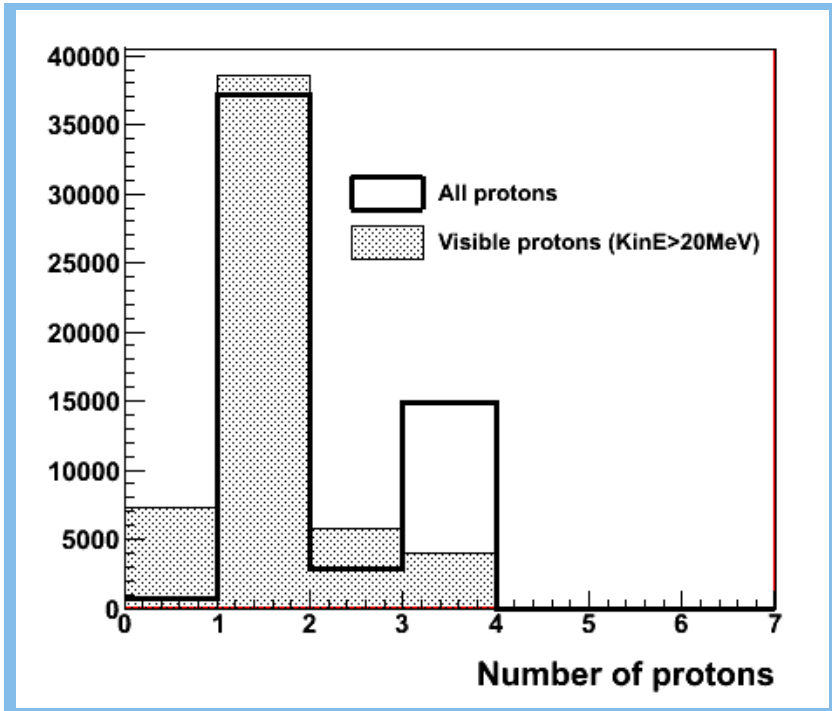
GENIE

FLUKA

collaboration with G. Battistoni

Data from LArTPC extremely useful for FSI understanding

MonteCarlo Simulation CC QE sample - LE ν_μ on ^{40}Ar



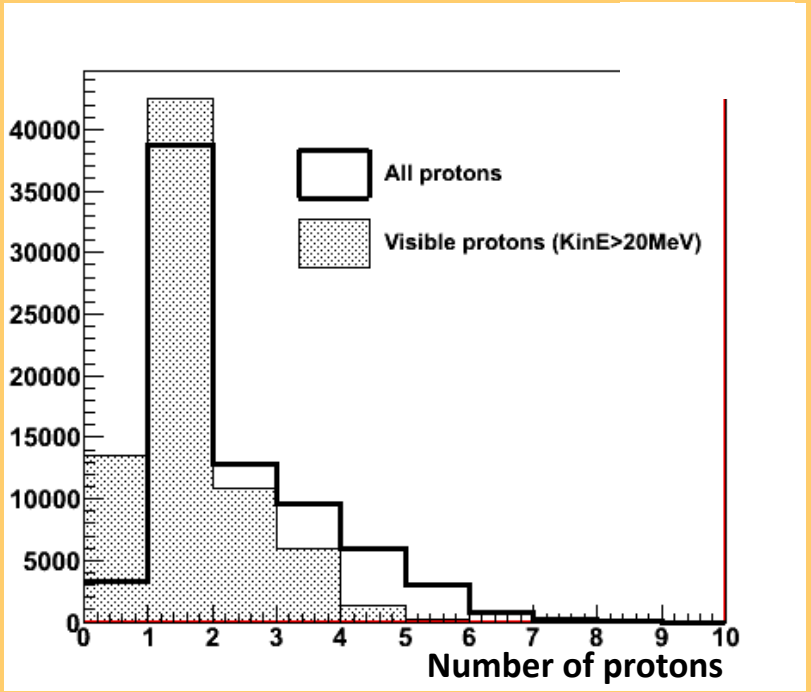
Visible proton: $T_p \geq 20$ MeV (87%)

0p	→	13%
1p	→	70%
2p	→	10%
3p	→	7%

Neutrons:

0 n	→	60%
1 n	→	10%
2 n	→	30%

GENIE



Visible proton: $T_p \geq 20$ MeV (82%)

0p	→	19%
1p	→	57%
2p	→	14%
3p	→	8%
4p	→	2%

Neutrons:

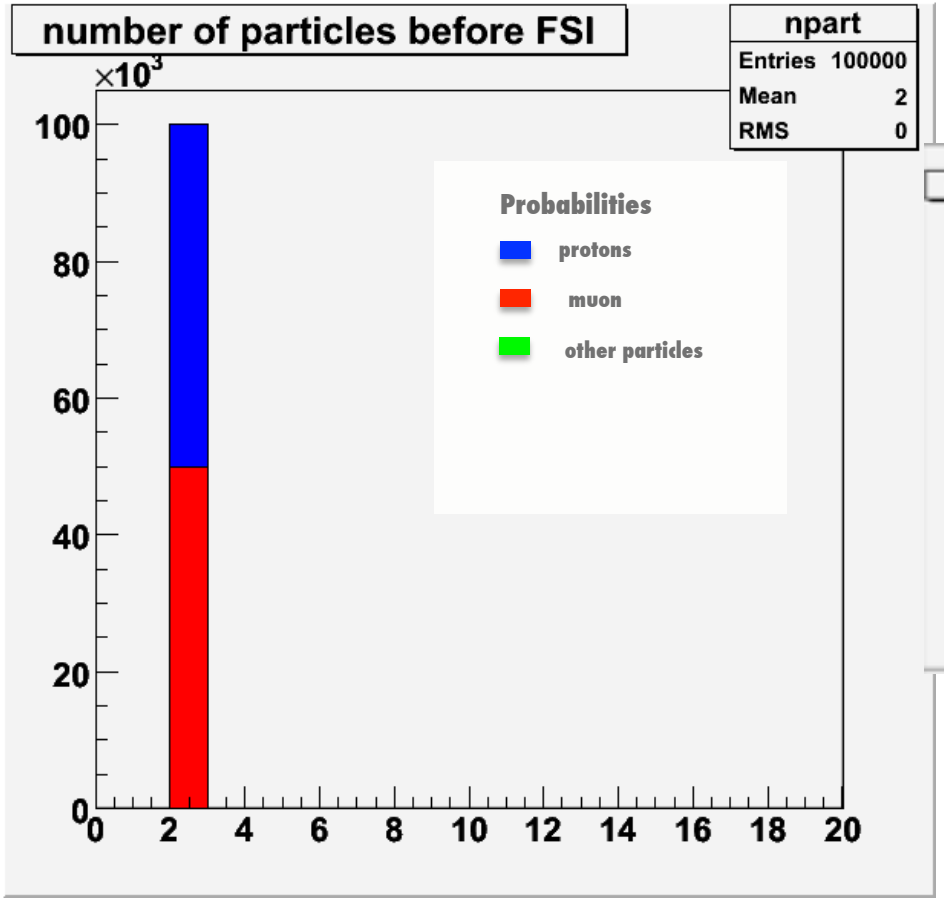
0 n	→	14%
1 n	→	37%
2 n	→	15%
3 n	→	13%
4 n	→	9%
5 n	→	8%
6 n	→	3%
7 n	→	1%

FLUKA

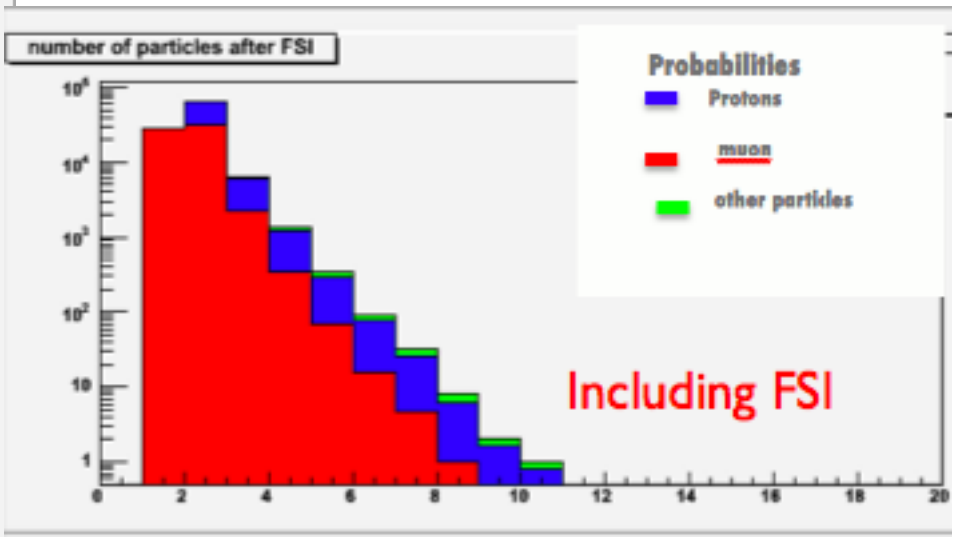
Also γ and α are frequently produced and give detectable signals

ν_μ CC QE on ^{40}Ar *(NuMI LE-ν mode)* *[FLUKA]*

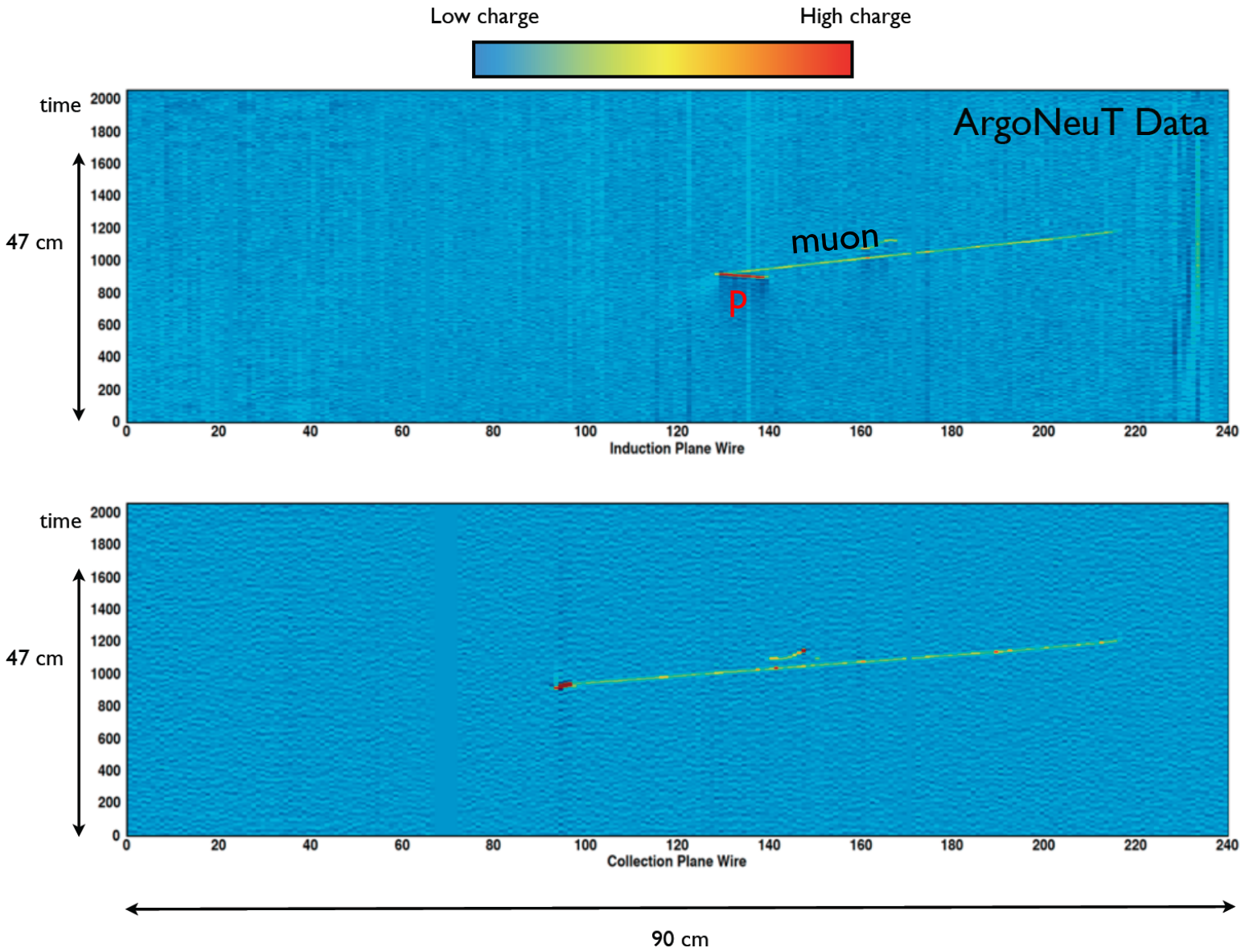
From the bare CC QE interaction



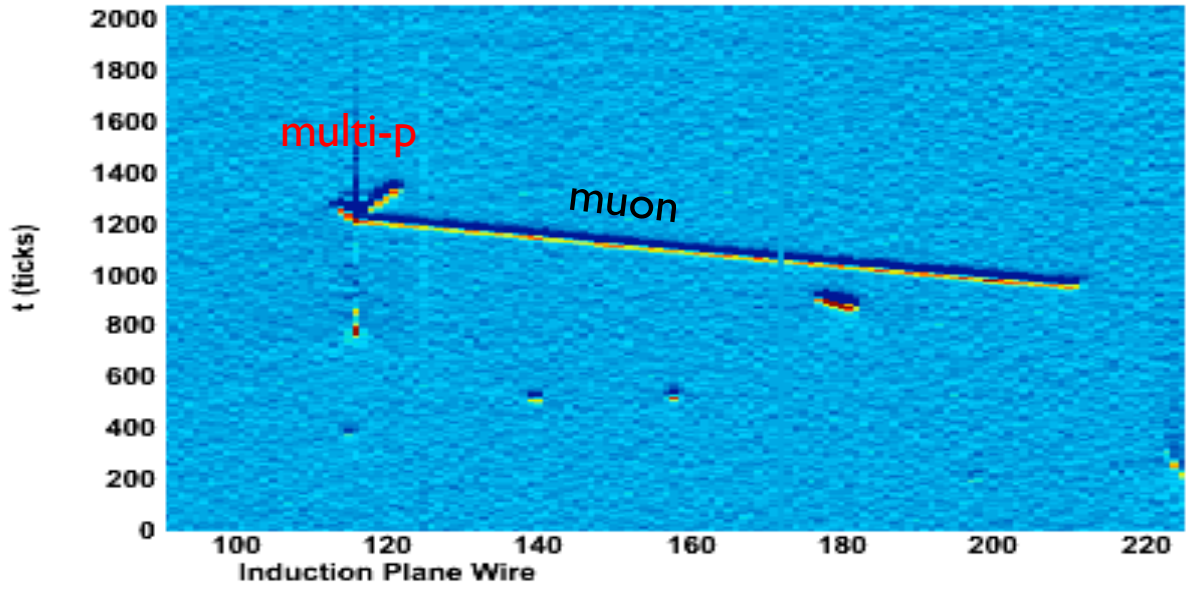
Visible tracks (kin. En. >20 MeV)

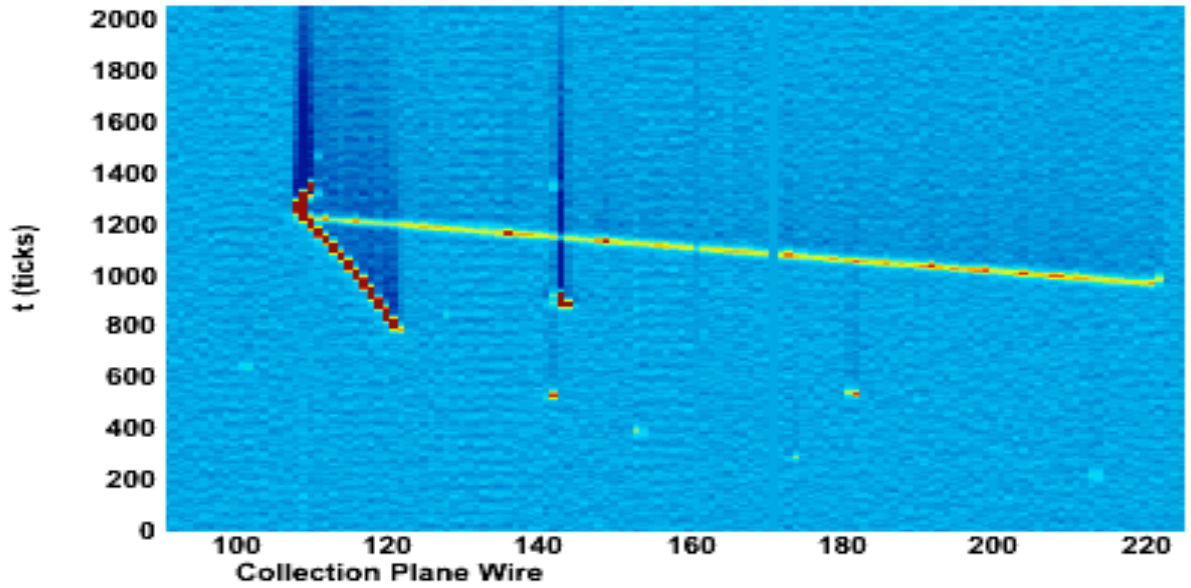


ν_μ CC QE candidate (2 tracks: 1 μ, 1 p)



multi-p ν_μ CC QE candidate





Example of event
with *multi-p*
accompanying
the leading muon
+
γ-Activity in the volume
around
the vertex

ν_μ CC differential cross sections

- CC ν_μ interaction ($\nu_\mu \rightarrow \mu^- X$) described in terms of the outgoing muon parameters (angle and momentum)

- The CC-inclusive analysis requires only a negatively charged outgoing muon, (and no exclusive final states*).

- Results based on *automatic LAr event reconstruction*, ν mode data sample.

- Measurement of the flux-integrated CC-inclusive ν_μ differential cross sections on Argon and isoscalar targets in terms of the outgoing muon momentum (p_μ) and angle with respect to the incoming neutrino direction (θ_μ)

$$\frac{d\sigma}{d\vartheta_\mu}; \frac{d\sigma}{dp_\mu}$$

*The present measurement does not utilize the full capabilities of a LArTPC to describe a neutrino event as it does not employ dE/dx for particle identification.

Why is this measurement interesting and relevant?

- The CC-inclusive set of channels provides a "standard candle" for determining the composition of a neutrino beam as it is minimally sensitive to the complicating effects of final state interactions (FSI) and exclusive channel definitions.

- Subsequent ArgoNeuT exclusive cross section measurements can also be compared to the inclusive one to perhaps disentangle the effects of FSI and nuclear modeling from the actual neutrino-nucleus interaction. [As an example, SciBooNE has measured the CC coherent pion production and neutral-current pion production cross sections using a normalization based on their CC-inclusive measurement]

Ideally, the double differential cross section $\frac{d\sigma}{d\vartheta_\mu dp_\mu}$ would be reported.

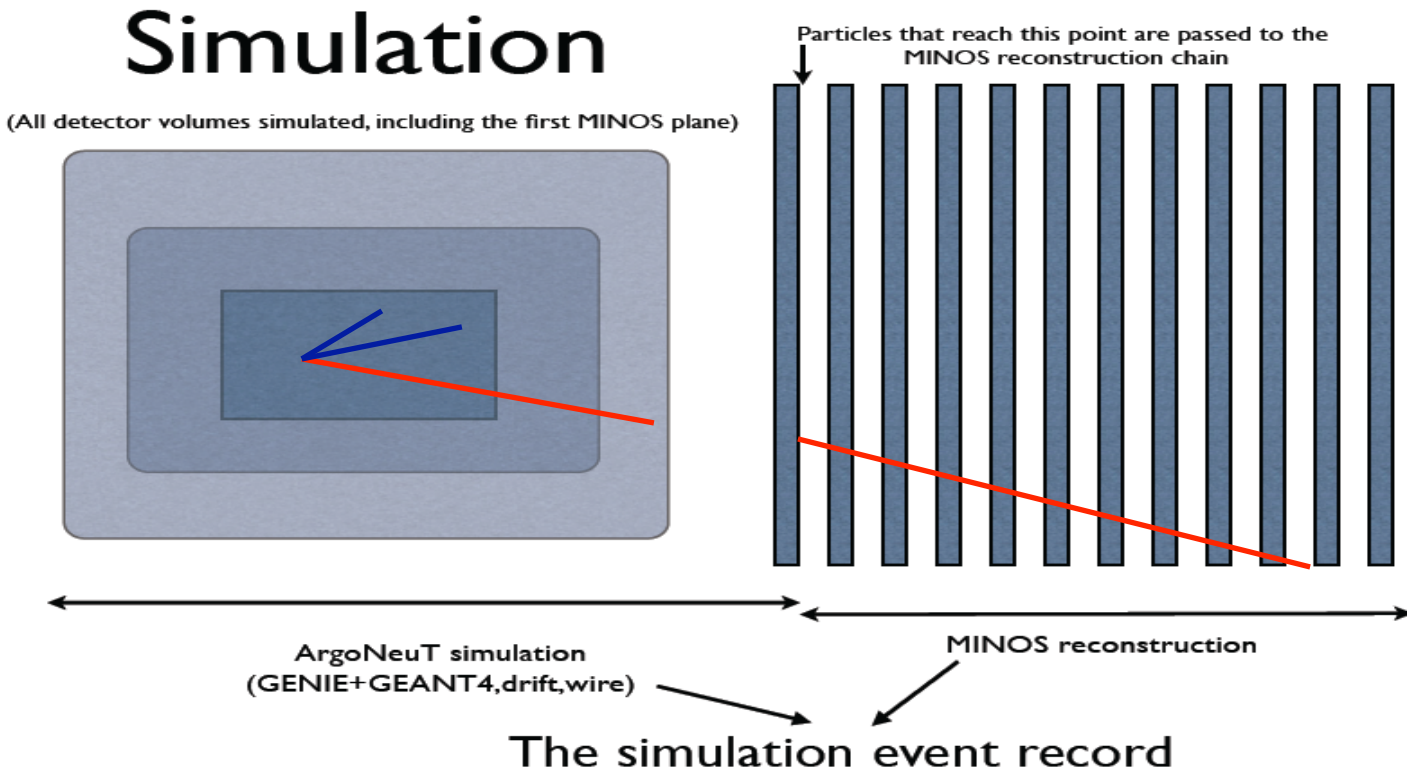
However, this requires very high statistics in order to populate the two dimensional bins in (θ,p) space (low statistics ν mode, to be done for the $\bar{\nu}$ mode run).

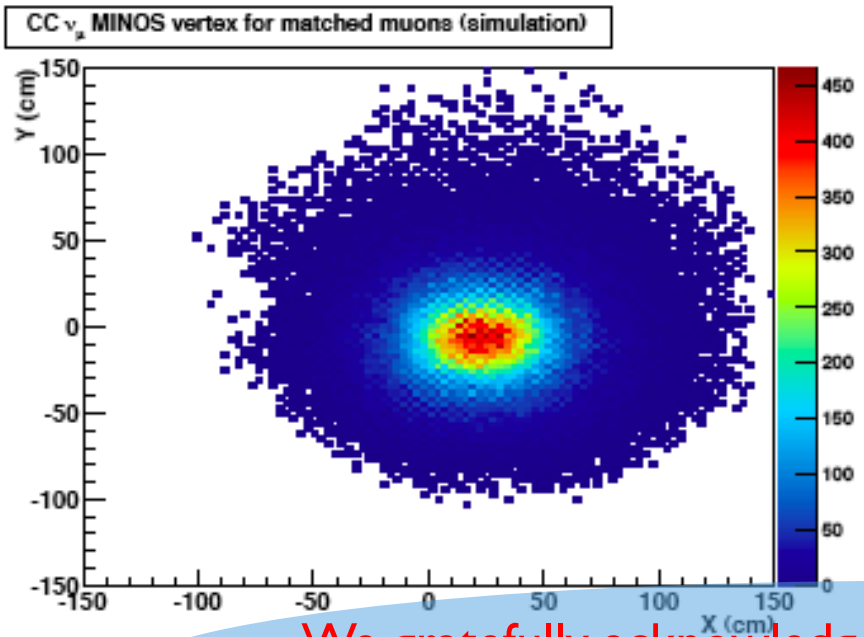
Matching Muons from ArgoNeuT to MINOS

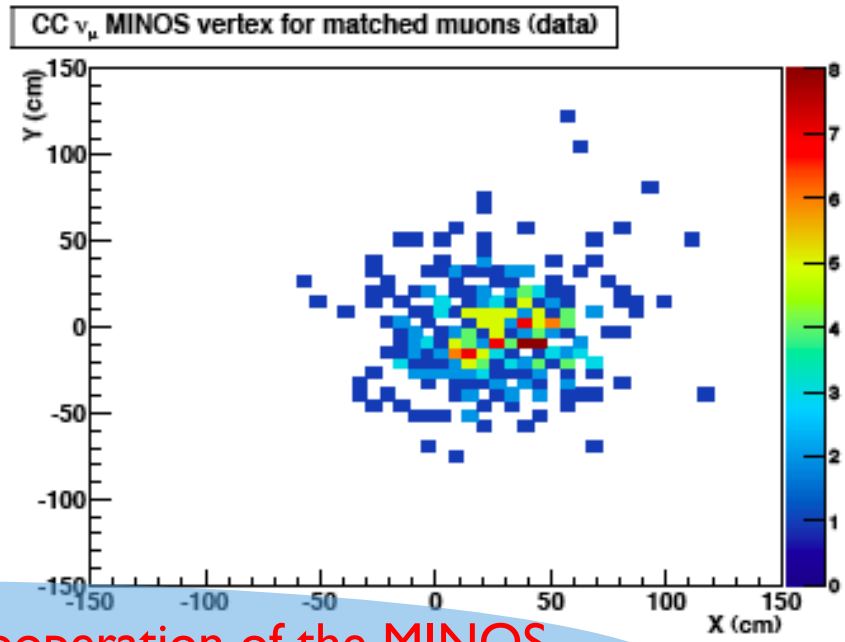
(Matching requirements)

- ArgoNeuT employs the MINOS near detector in order to fully reconstruct CC ν_μ-induced muons. For this to be accomplished succesfully, an ArgoNeuT reconstructed track needs to be matched with a reconstructed μ^- in MINOS.

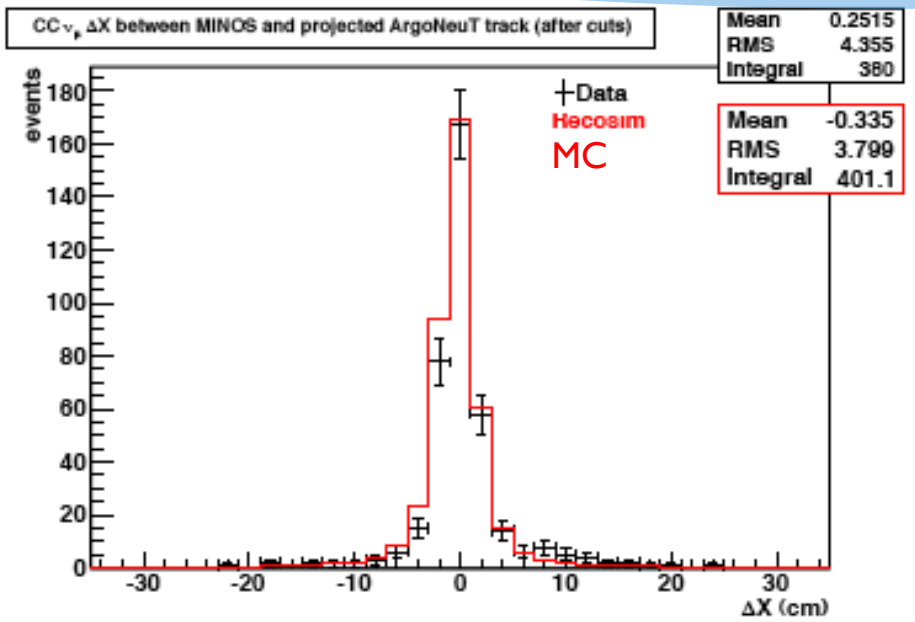
- The matching requirements have been set based on the Monte Carlo expectation for the radial/angular differences between the projected ArgoNeuT track and the candidate MINOS matched track.

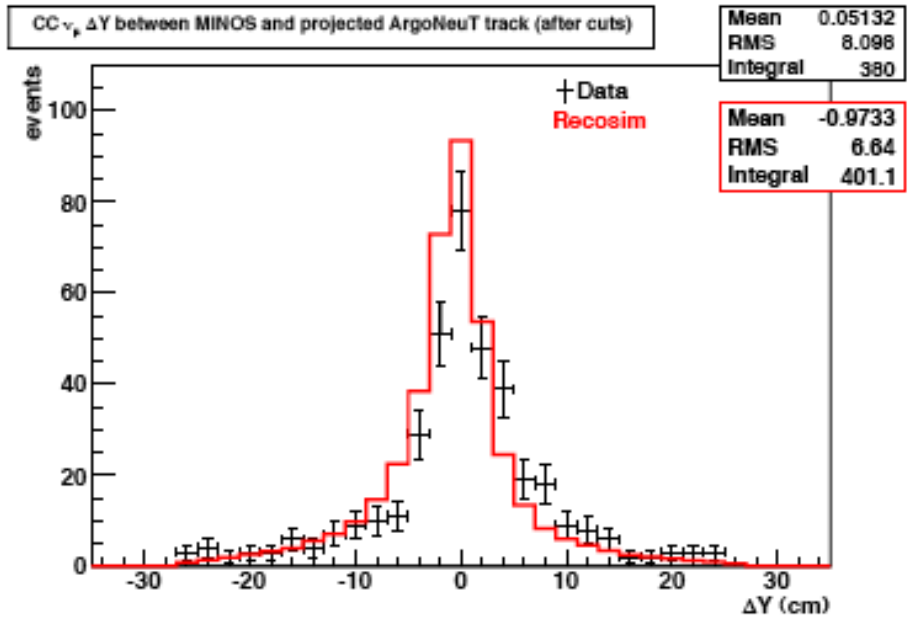






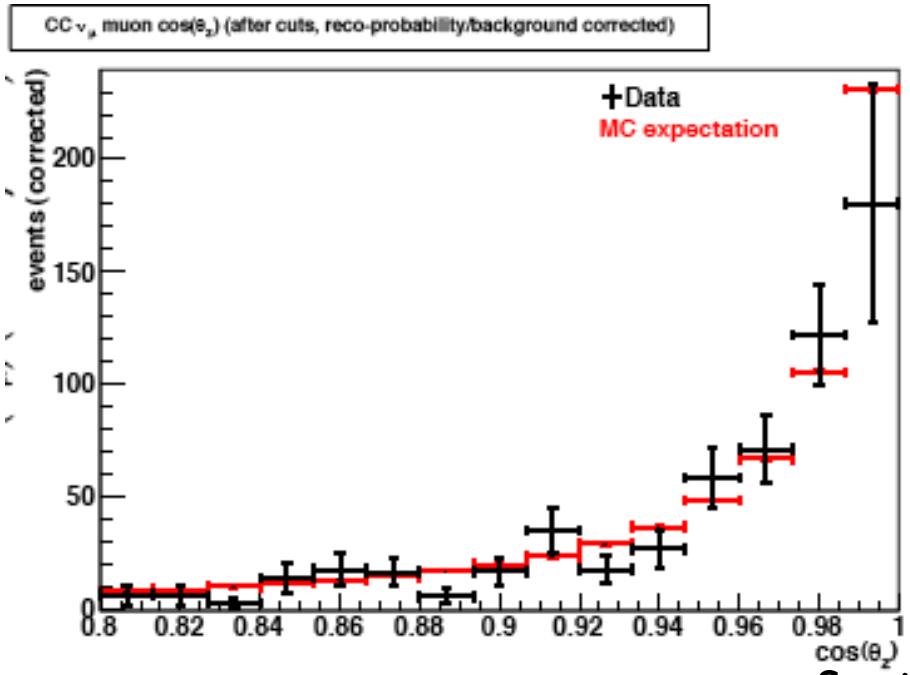
We gratefully acknowledge the cooperation of the MINOS Collaboration in providing their data for use in this analysis

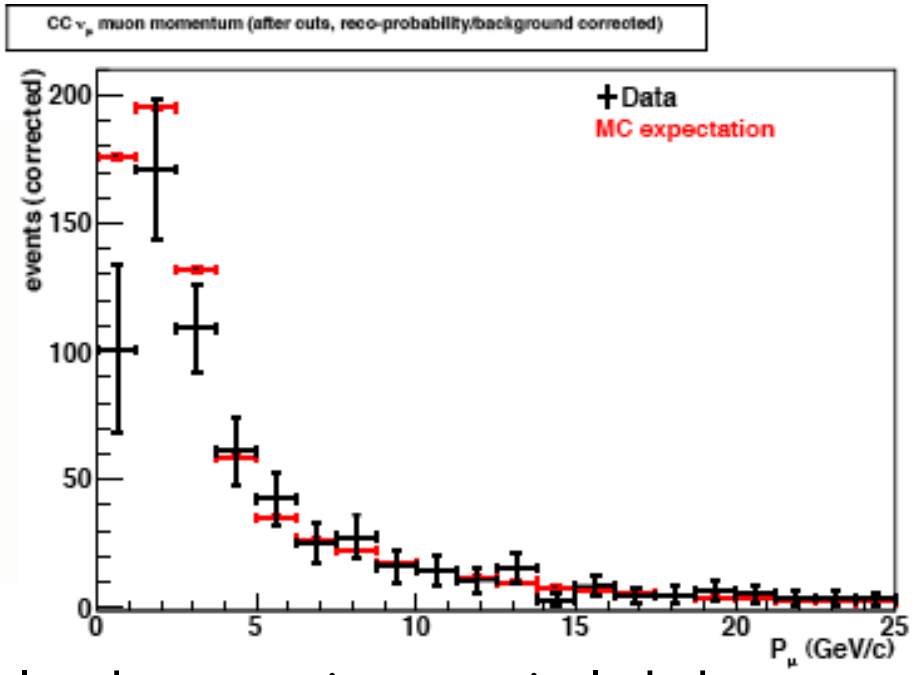




ν_μ CC-inclusive Rates vs θ_μ and p_μ

- After fiducial volume cuts, matching requirements, corrections for reconstruction efficiency (MINOS reconstruction ε, ArgoNeuT+matching reconstruction ε) and background subtraction (from through-going μ and NC events, few % contribution)





Statistical and systematic errors included

Using the integrated NuMI neutrino flux and proton on target exposure along with the number of target in the ArgoNeuT fiducial volume flux-integrated ν_μ CC differential cross sections $\frac{d\sigma}{d\vartheta_\mu}$ $\frac{d\sigma}{dp_\mu}$ are calculated (Josh Spitz PhD thesis – Yale University Aug. 4th 2011)

FSI studies: *"Single μ" events from ν CC interactions*

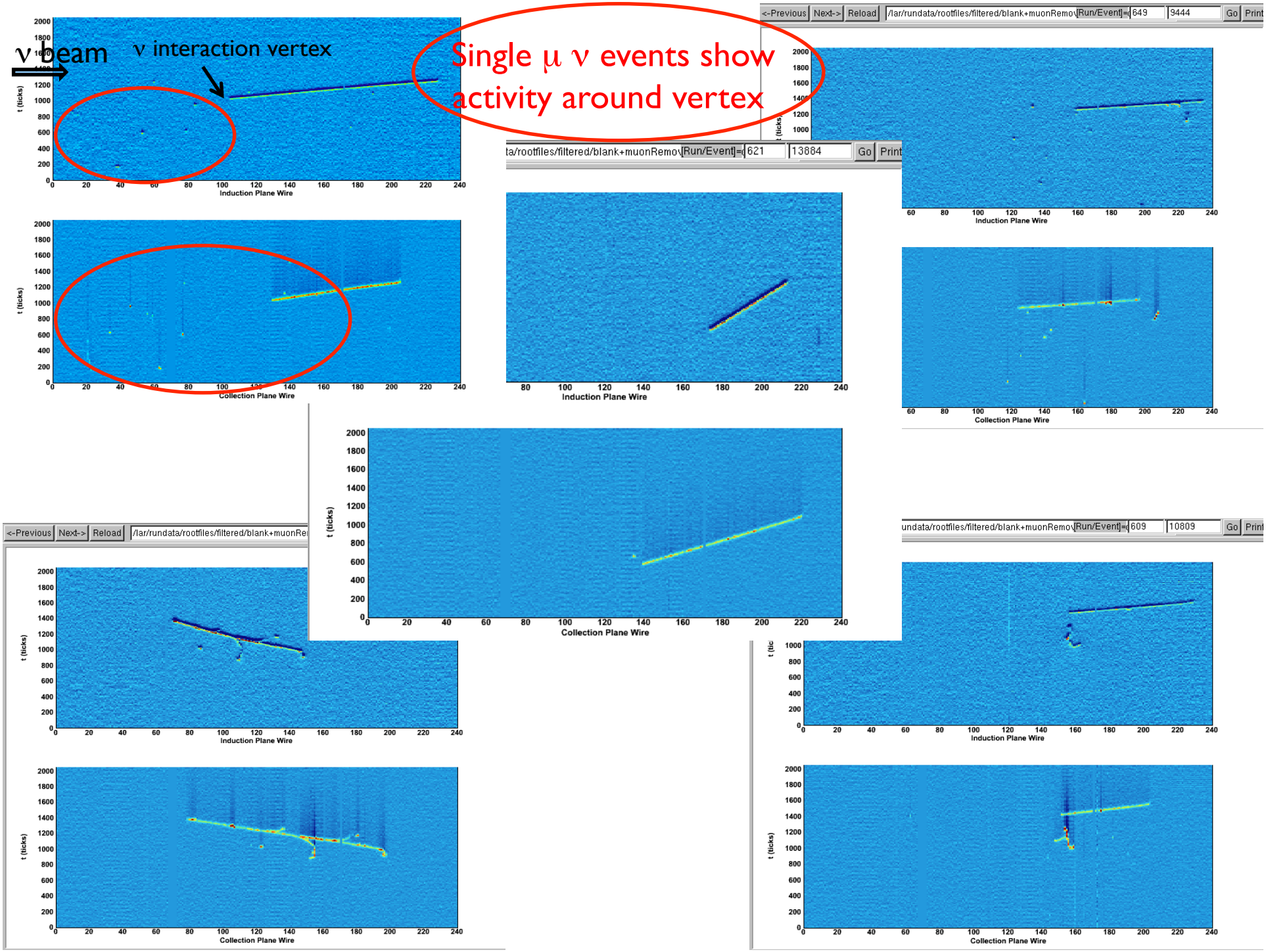
- Easiest topology (for complete reconstruction)
  - **1 track i.e.** "Single muon" (μ^+ or μ^-), originating in LAr from ν or

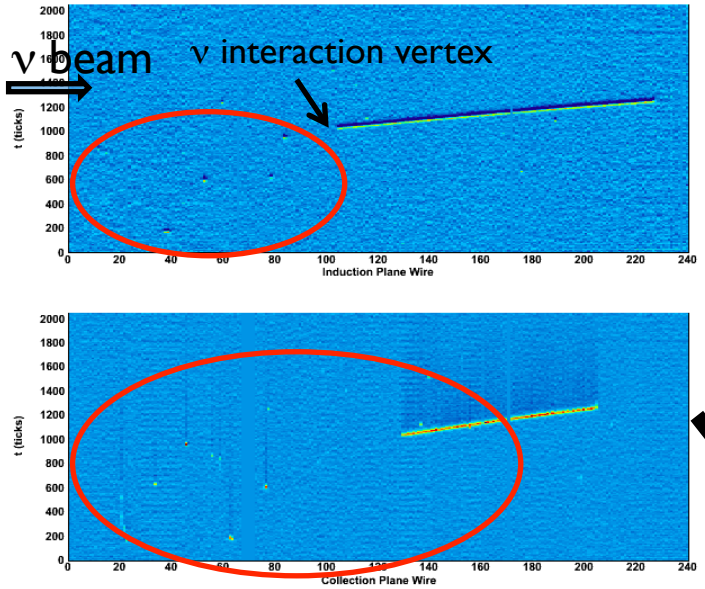
(μ^-) from ν_μ CC interaction
- CC QE [p absorbed (FSI) or not detected]
- CC RES [p, π absorbed (FSI) or not detected]

(μ^+) from $\bar{\nu}_\mu$ contamination (7%) in ν beam
- CC QE (n undetected)
- RES [π absorbed (FSI) or not detected]

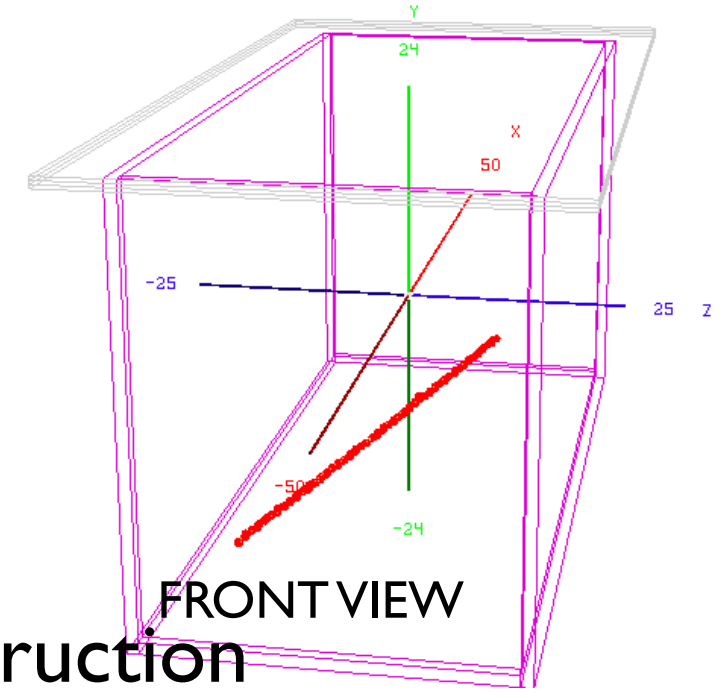
- ν-mode data Analysis:
  - 23 "single μ" candidates found

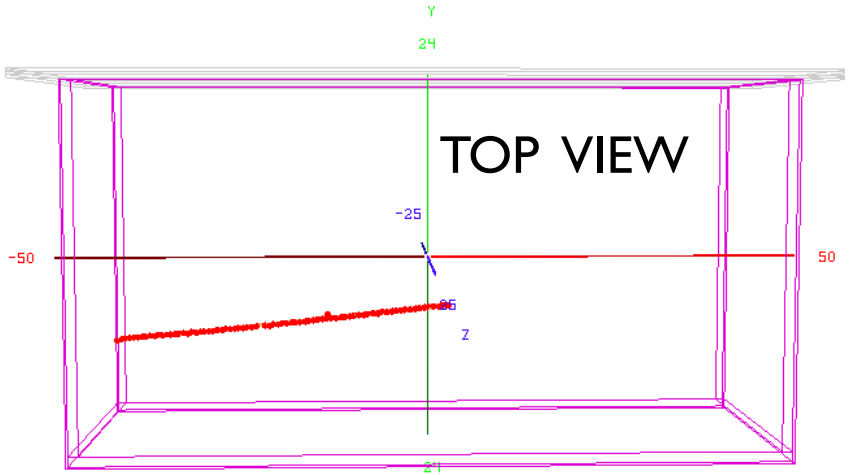
- Comparison with MC expectations [NUANCE + FLUKA(FSI)]

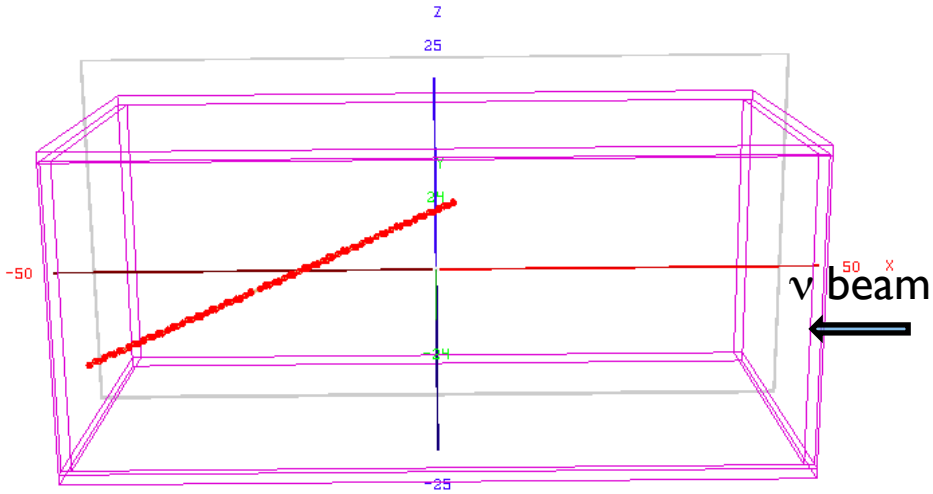

ν beam
ν interaction vertex
Single μ ν events show activity around vertex
t (ticks)
Induction Plane Wire
Collection Plane Wire
<-Previous
Next->
Reload
Go
Print



3D reconstruction

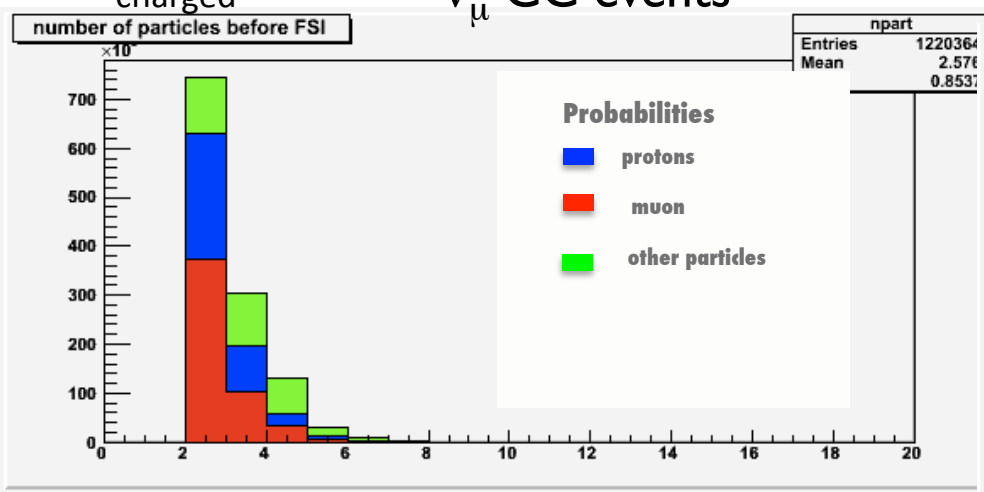


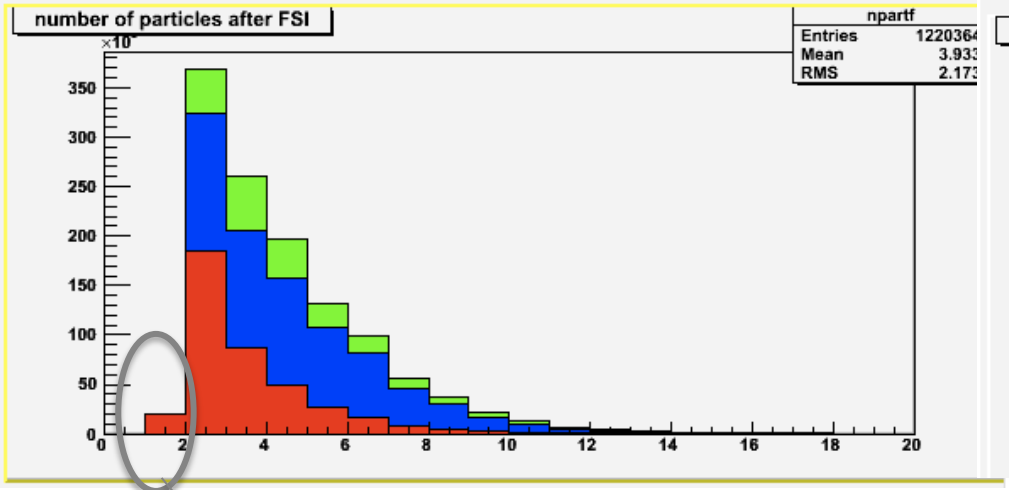




FLUKA MC: CC ^{40}Ar NuMI LE ν mode

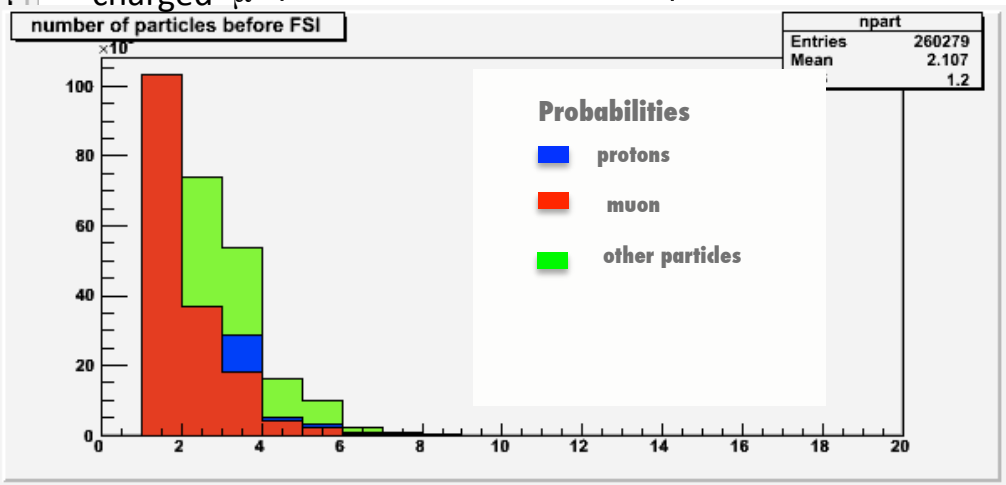
charged ν_μ CC events

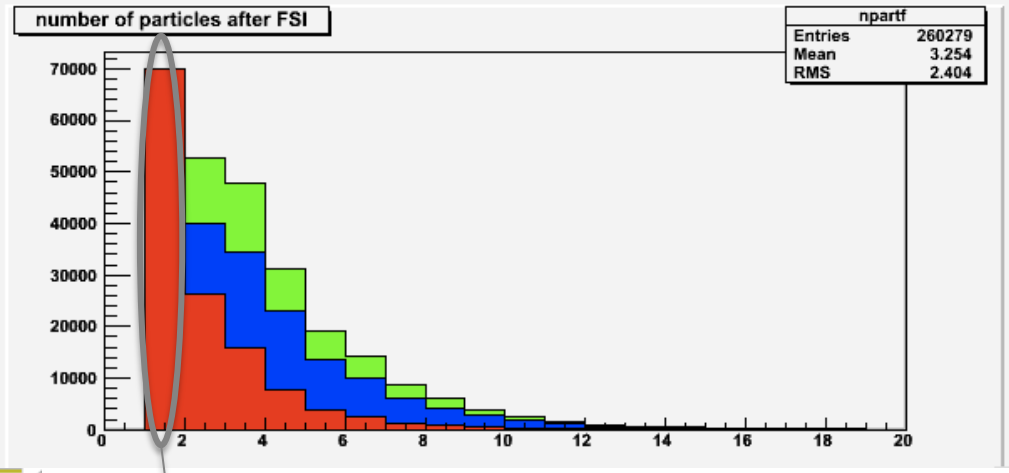




1.6% of the ν_μ CC are "single μ" events **after FSI**

charged $\overline{\nu}_\mu$ (7% contamination) CC events





26.8 % of the $\overline{\nu}_\mu$ CC are "single μ" events **after FSI**

"Single μ" events

Expected rates in the ν-mode run:

Nuance MC
662 ν_μ CC and
58 $\bar{\nu}_\mu$ CC expected

1.6 % (single μ) → 10.6 single μ^- events and
26.8 % (single μ) → 15.5 single μ^+ events expected
TOT = 26 "single μ" events expected

Number of identified "1-track" events:

- *very preliminary:* consistent with expectations
  (statistics is low in the short ν run, substantially larger in anti-ν run)

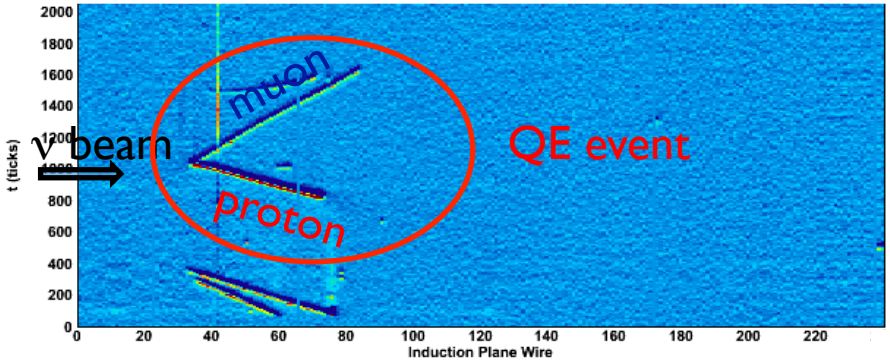
Interesting output (including muon sign reconstruction from MINOS - in progress)

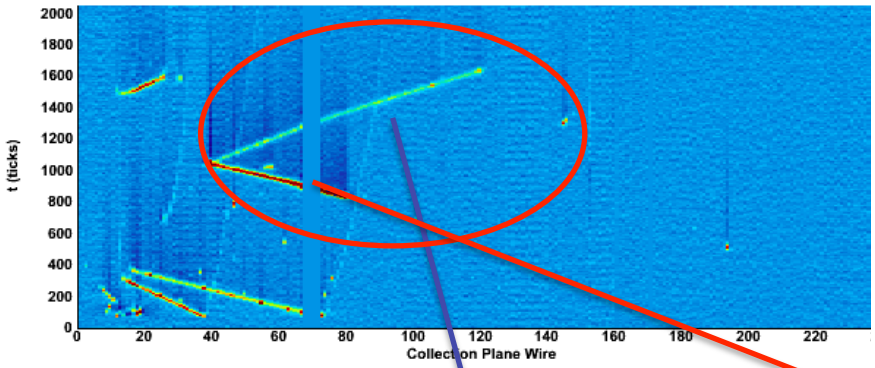
- $\frac{N_{\mu-}}{N_{\mu+}}$ ratio

Useful for FSI studies: indication of nucleon charge exchange in Ar nuclei

ν_μ CC QE event reconstruction

(waiting for finalization of automatic reconstruction procedure)





μ+p (ν_μ CC QE event)

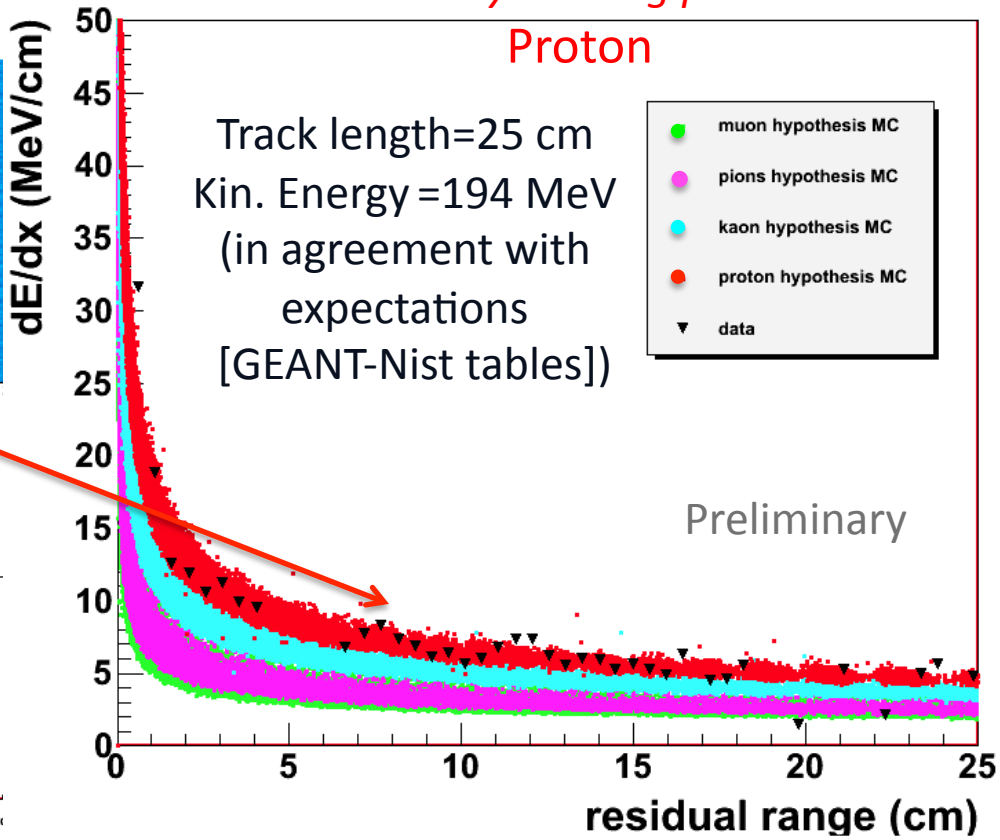
+

uncorrelated tracks from upstream neutrino interaction

Heavy ionizing ptcl.

Proton

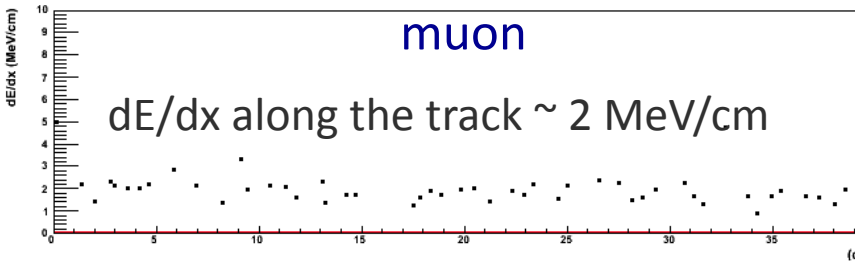
Track length=25 cm
Kin. Energy =194 MeV
(in agreement with expectations [GEANT-Nist tables])



m.i.p. particle

muon

dE/dx along the track ~ 2 MeV/cm



ArgoNeuT Collaboration

F. Cavanna
University of L'Aquila

A. Ereditato, S. Haug, B. Rossi, M. Weber
University of Bern

B. Baller, C. James, G. Rameika, B. Rebel, G. Zeller
Fermi National Accelerator Laboratory

M. Antonello, O. Palamara
Gran Sasso National Laboratory

T. Bolton, S. Farooq, G. Horton-Smith, D. McKee
Kansas State University

C. Bromberg, D. Edmunds, P. Laurens, B. Page
Michigan State University

M. Soderberg
Syracuse University

K. Lang, R. Mehdiyev
The University of Texas at Austin

E. Church, B. Fleming, R. Guenette, K. Partyka, J. Spitz
Yale University

Summary

ArgoNeuT is a fully operational LArTPC:
during the (first) ν-run, large samples of
neutrino/antineutrino events have been collected
for the 1st time ever in a low-Energy beam.

ArgoNeuT data analysis is in progress: first CC-inclusive analysis just completed.

Extensive "real data/experience" is invaluable in improving LArTPC technique.
Analysis software is being developed as general purpose tool for future LArTPCs.
Highly sophisticated/detailed MonteCarlo codes are needed,
and are currently under test/optimization.