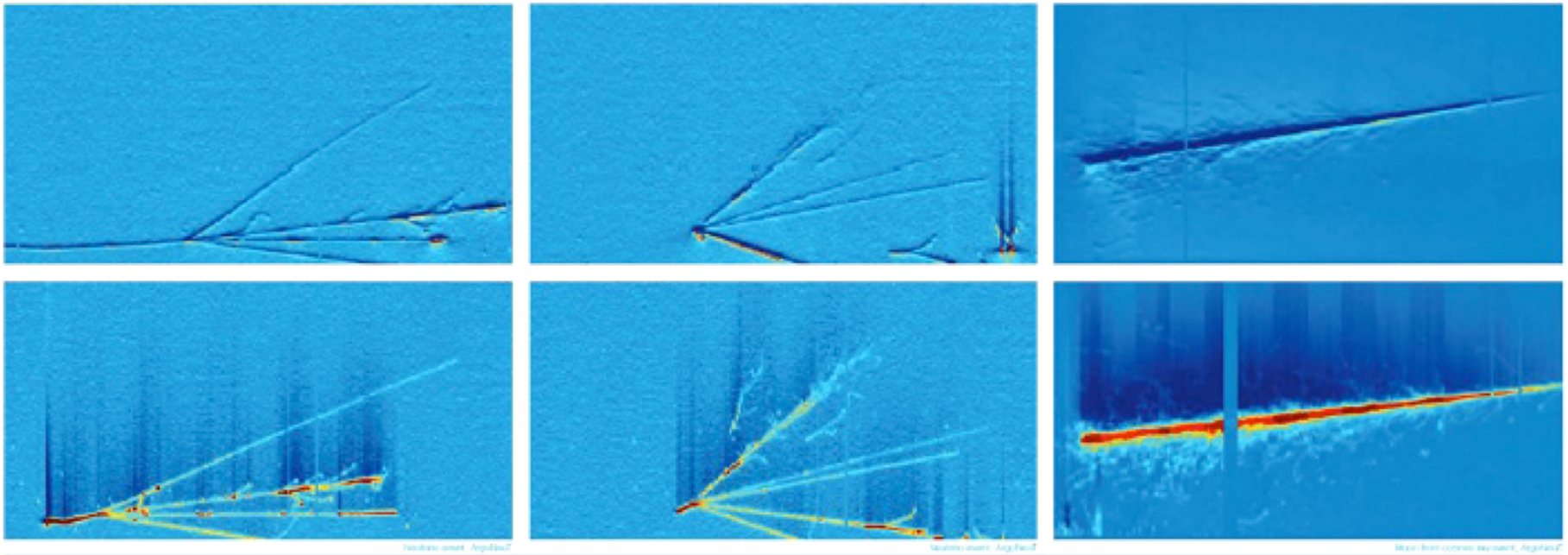
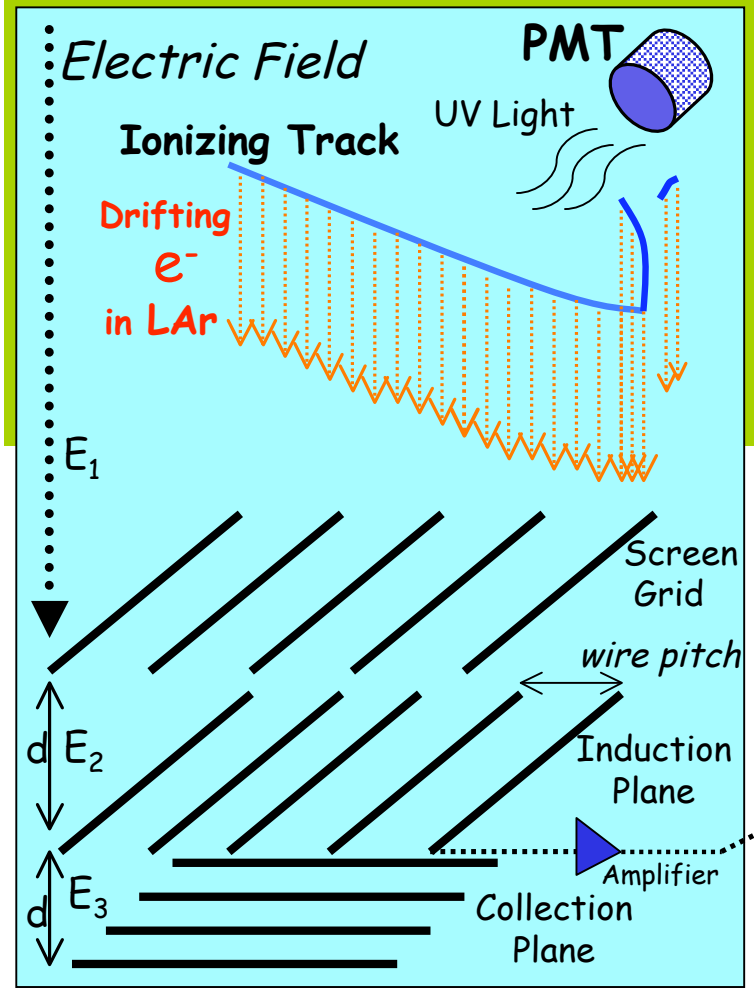


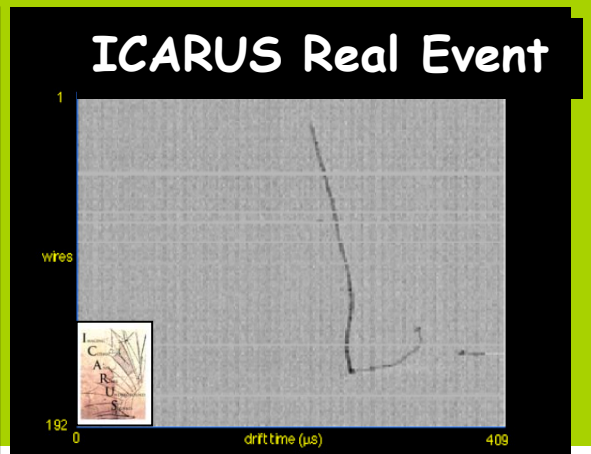
The ArgoNeuT Experiment at FNAL

Oxford U. (Dec. 1st, 2009)

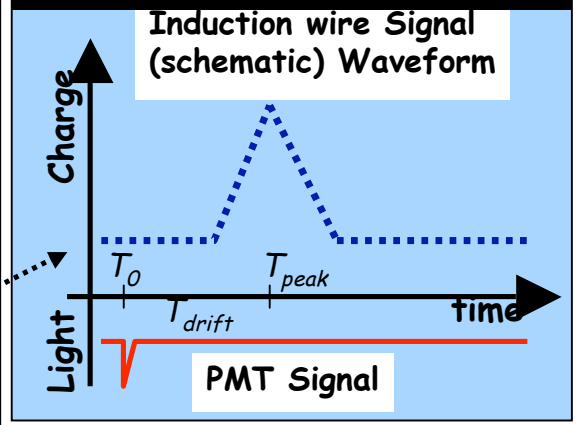
Rutherford Appleton Lab (Dec. 2nd, 2009)

Flavio Cavanna
L'Aquila University (Italy)





Stopping μ and decay (3t prototype)



LArTPC* Liquid Argon Time Projection Chamber

(developed by the Icarus Collab. since the '80)

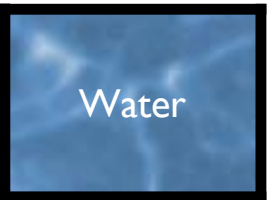
- (Neutrino) interactions inside the LAr-TPC produce charged particles ⇒ Ionization Tracks
- Ionization electrons drift along electric field lines towards anode planes of wires, which are connected to low-noise charge amplifiers and fast ADCs.

- Location of wires within a plane provide position measurements. Multiple (≥ 2) non-destructive wireplanes can be utilized providing (x,y) coordinates.
- Timing of pulse information (T_0 of event provided by PMTs sensitive to LAr scintillation light, and knowledge of drift speed v_d) determine drift coordinate (z) ⇒ Full 3D Image reconstruction.
- Collection of the ionization charge on last plane wires measures deposited energy ⇒ calorimetric informatic
- Scintillation light collected by Photomultiplier Tubes used in triggering.

Refs:
*.) *The Liquid-argon time projection chamber: a new concept for Neutrino Detector*, C. Rubbia, CERN-EP/77-08 (1977)

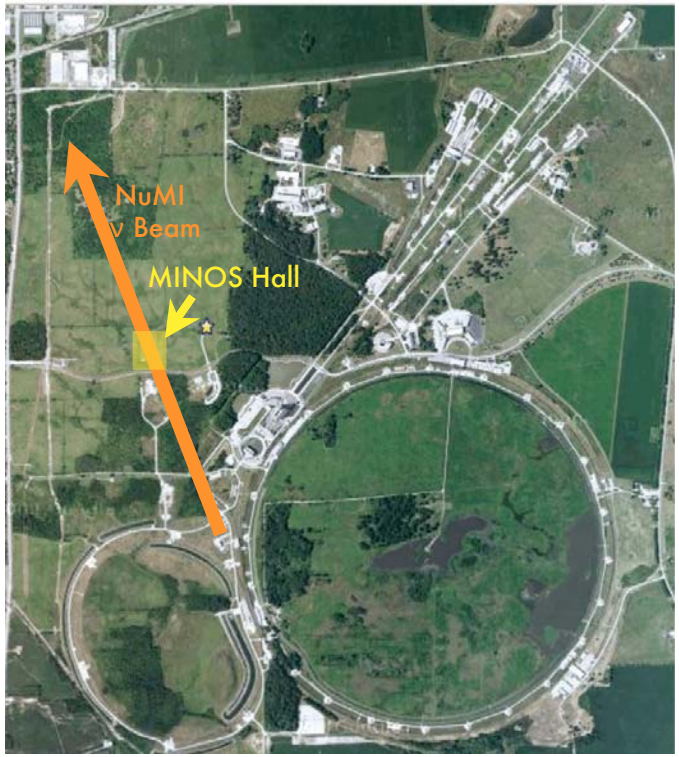
Noble Liquid Properties

- Abundant ionization and scintillation light can be used for detection.
- If highly purified (< 0.1 ppb), ionization electrons drift over long distances in these liquids.
- Excellent dielectric properties allow these liquids to accommodate very high-voltages.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).

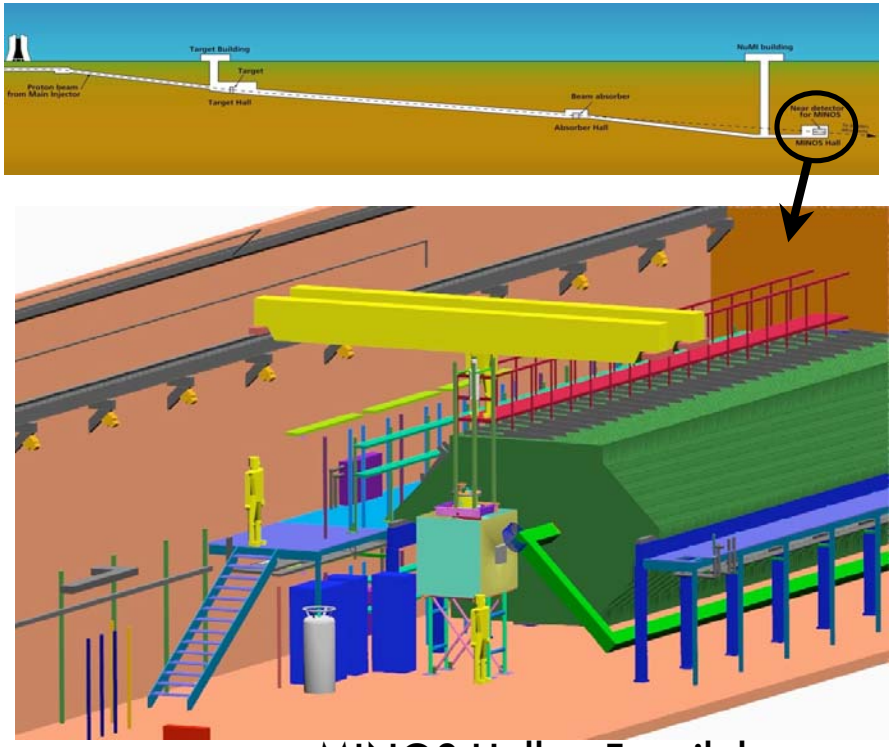
						
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation [nm]	80	78	128	150	175	

ArgoNeuT Introduction

- 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.
- … and then (early 2009) moved underground in the *NuMI* beam at Fermilab, in front of *MINOS Near Detector* to collect neutrino/antineutrino event in the "few GeV" range (*LE beam option*)



Fermilab



MINOS Hall at Fermilab

ArgoNeuT Collaboration

F. Cavanna, V. Caracciolo
L'Aquila University

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

M. Antonello, R. Dimaggio, O. Palamara
Gran Sasso National Laboratory

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

S. Kopp, K. Lang
The University of Texas at Austin

C. Anderson, B. Fleming*, S. Linden, M. Soderberg, J. Spitz, T. Wongjirad
Yale University

ArgoNeuT Physics Goals

- Measure charged-current cross-section in the "few GeV" (1-10 GeV) range:
  - CC Quasi-Elastic (QE) channel
  - CC Resonant (RES: $\Delta \rightarrow \pi$ N) channel

  with unprecedented sensitivity to products of FSI

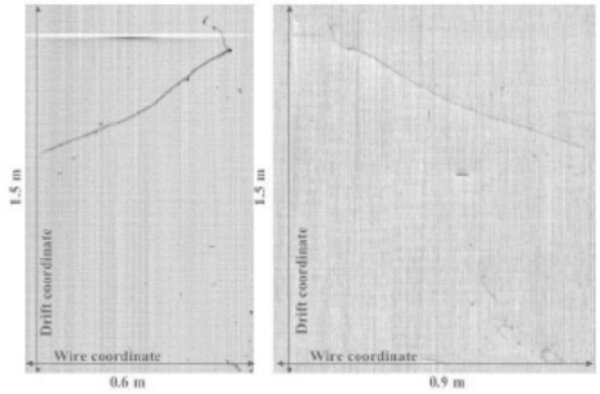
- *e*/γ separation study and optimization ⇒ superior background rejection
  - Particle identification comes from energy deposition (dE/dx) measured along track.
  - Important for ν_e appearance: Excellent signal (CC ν_e) efficiency and background (NC π^0) rejection
  - Topological cuts will also improve signal/background separation

- Develop reconstruction techniques useful for all future LArTPCs:
  - full 3D reconstruction of the event topology
  - precise calorimetric reconstruction of deposited energy

Where we start from…

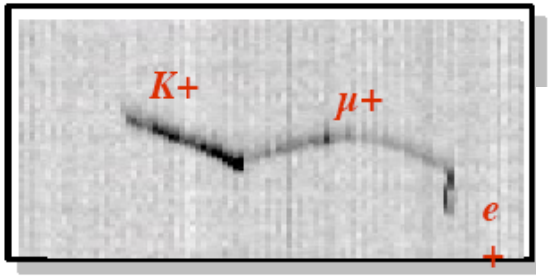
… the ICARUS experience

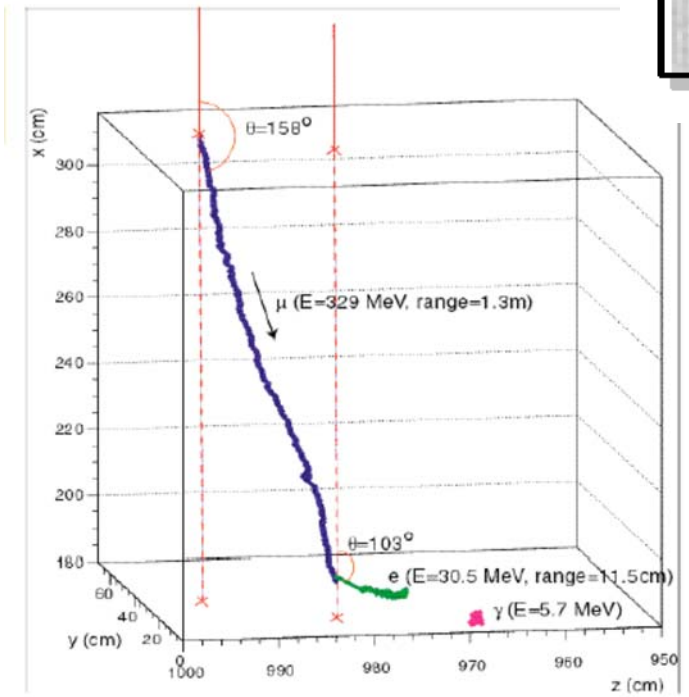
Development/optimization of reconstruction techniques with LArTPC



ICARUS T600 events

Particle IDentification

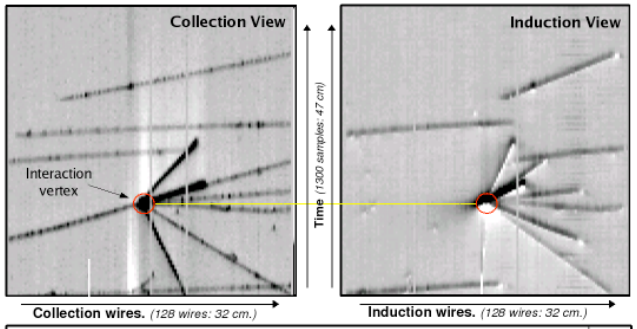


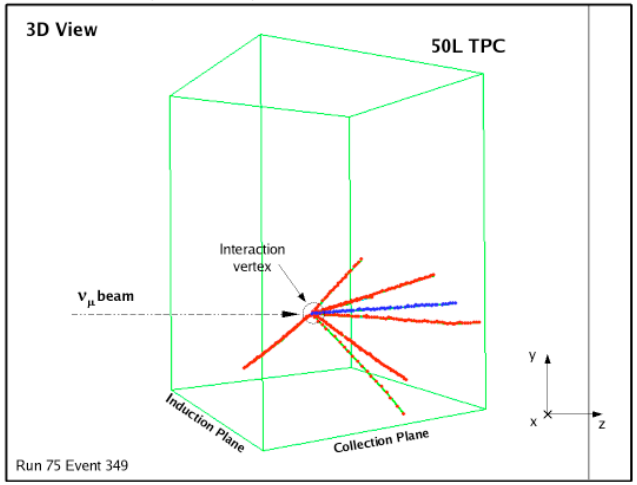


Fully reconstructed stopping muon event:
3D image and
Calorimetric information

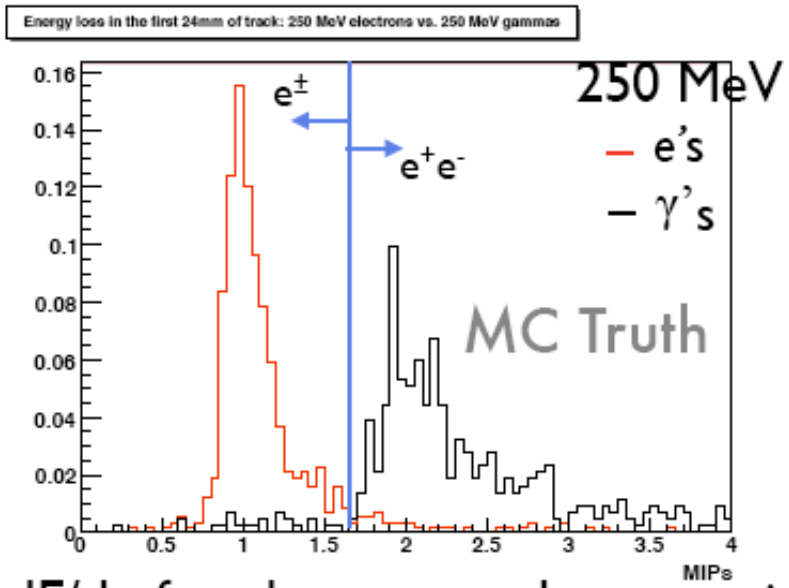
ICARUS 50 lt Detector

DIS nu-event:
3D image,
Calorimetric information
and PID of



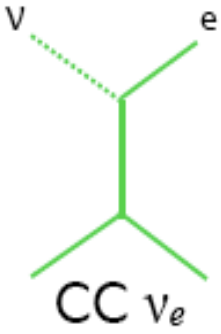


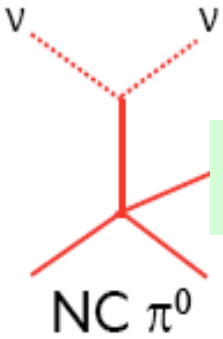
e/γ separation study and optimization



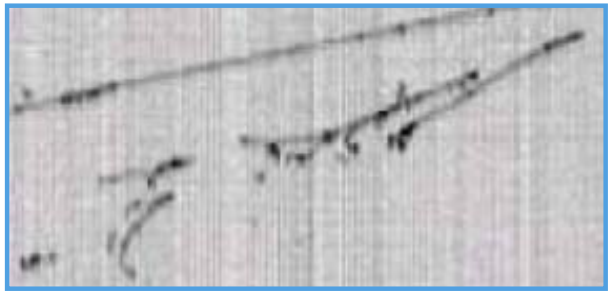
dE/dx for electrons and gammas in first 2.4 cm of track

For e^+e^- efficiency > 80%,
e contamination < 5%
(J. Spitz)



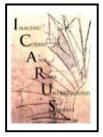


ICARUS T600 event



$\pi^0 \rightarrow \gamma\,\gamma \rightarrow (e^+e^-)\,(e^+e^-)$

CC-QE cross section in the "high Energy" range



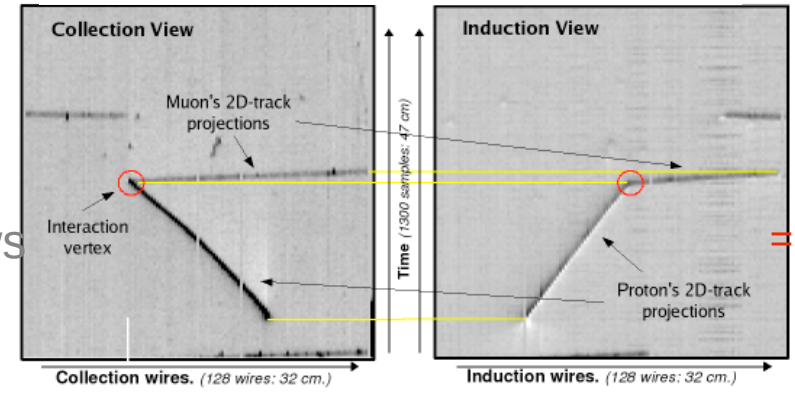
ICARUS 50 lt Detector

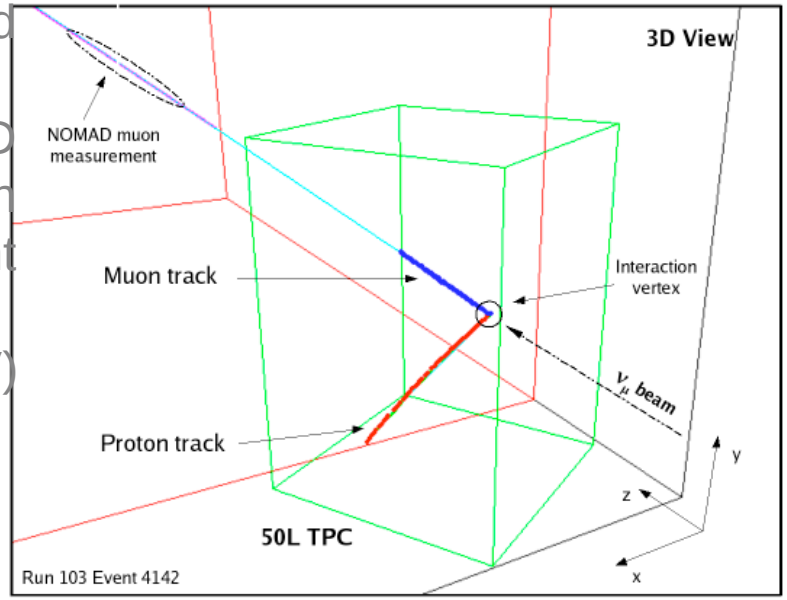
2D views

and

3D reconstruction of QE event

(T_p>40MeV)





QE Xsection:

$$\sigma_{QE} = \frac{N^{QE}}{\Phi \times E_{xp} \times N_{fid} \times T_{live} \times Acc^{QE} \times \mathcal{G}^{QE}}$$

$= [\ 0.90 \pm 0.10\ (stat) \pm 0.18\ (sys)] \times 10^{-38}\ cm^2$

measured ('98) at the CERN WANF High energy Neutrino beam (E_ν = 28 GeV)

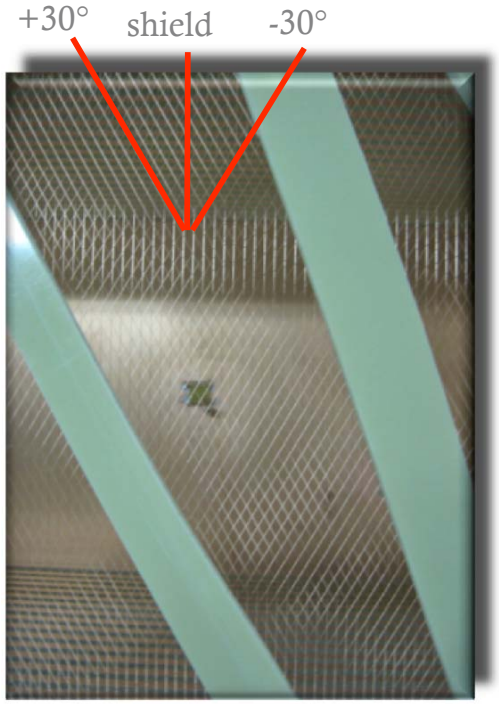
No QE (& RES) data on Ar target (yet) available in the "few GeV range, needed for next generation ν-osc. Experiments with LArTPC's

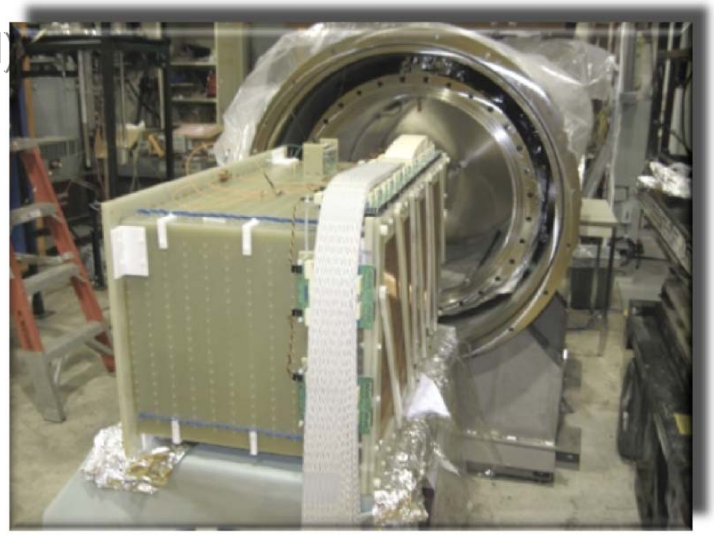
Where we are right now…

The ArgoNeuT detector: status and run

ArgoNeuT Design

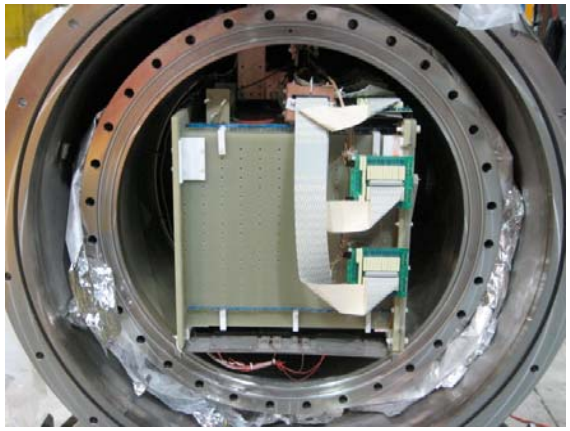
- 170 lt LAr active volume (47 x 40 x 90 cm^3 **~235 kg total**)
- 2 read-out planes: ***Induction and Collection***
- 240 wires per plane.
- Wires orientation: ± 30° with respect to vertical
- 4mm wire pitch, 4mm plane spacing
- 2048 samples over 400 microseconds (per spill)
- 500 V/cm electric field (v_d = 1.5 mm/μs)
- 47 cm maximum drift





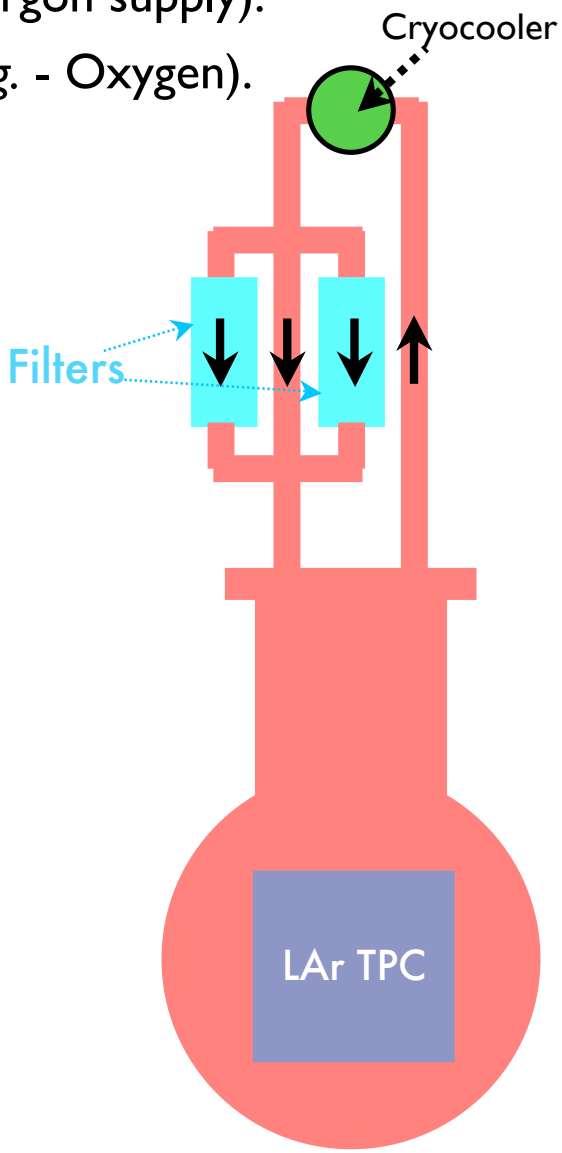
ArgoNeuT Cryogenics

- Self-contained cryogenic system (*i.e.* - maintain constant Argon supply).
- Recirculate argon through filters to remove impurities (*e.g.* - Oxygen).
- Cryocooler used to condense boil-off gas.
- Vacuum-jacketed cryostats/pipes for insulation.



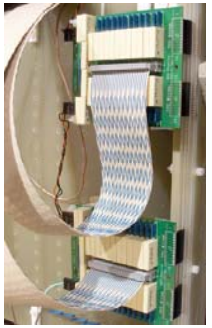
Vacuum-insulated vessel.

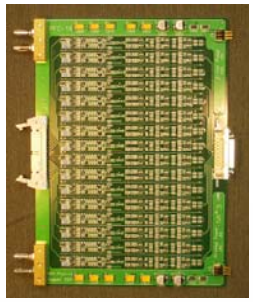
ArgoNeuT at PAB.

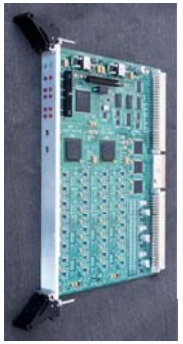


ArgoNeuT Electronics

- Bias voltage distribution & blocking capacitors on the TPC
- FET preamplifier similar to D0/ICARUS front-end
- Wide bandwidth filtering (10 - 159 kHz, now)
  - Full information on most hits/tracks
  - Employ DSP to extract hit/track parameters
- ADF2 card, sample at 5 MHz, 2048 samples/channel
- Minimize noise sources
  - Double shielding of feed-through and preamplifiers
  - Remote ducted cooling
  - Extensive DC power filtering

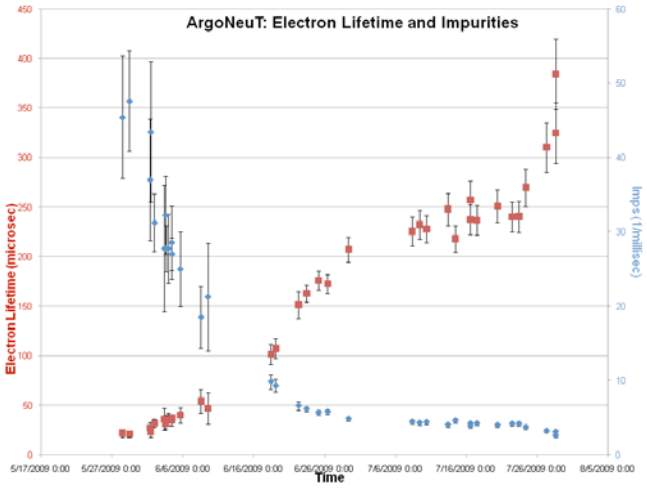






ArgoNeuT Detector: Status

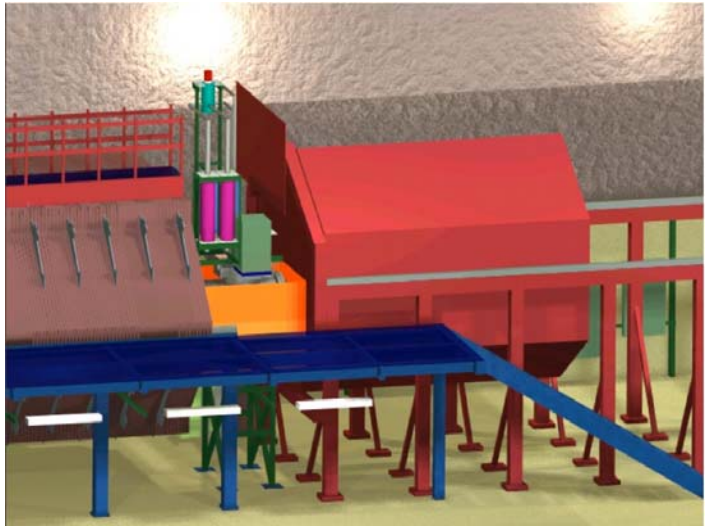
- Filled the cryostat underground (MINOS ND Hall) - May 8th, 2009
- Initial argon purity was low....recirculating has cleaned things up....
- Took neutrino data for ~1 month before summer shutdown (preliminary analysis under way).
- Took cosmic muons (dedicated ext. trigger) over summer (preliminary analysis under way).
- Neutrino/Antineutrino Beam operation restarted on Sept.09 ⇒ new ν-event collected



- *(Unexpected) Cryocooler failure on Oct. 8th.*
- After replacement, operation re-started !!! (Oct. 25th)
- Data taking (anti-neutrino mode) under way.

Moving underground

Looking through Minerva frame.

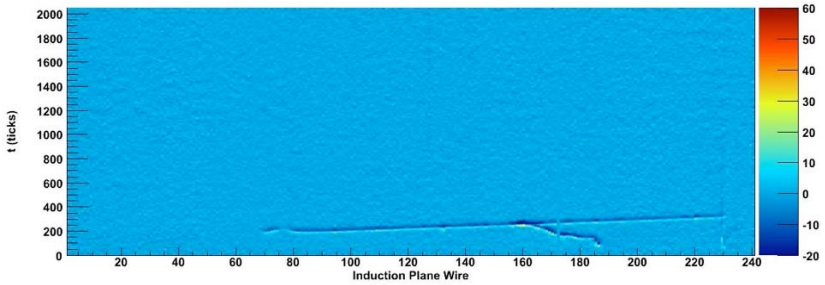


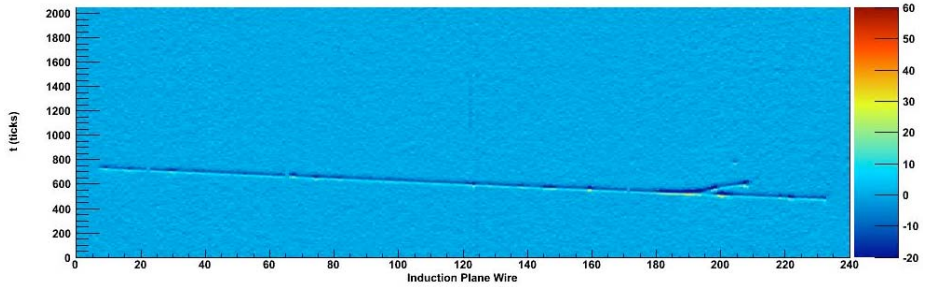
Schematic of NuMI experiments

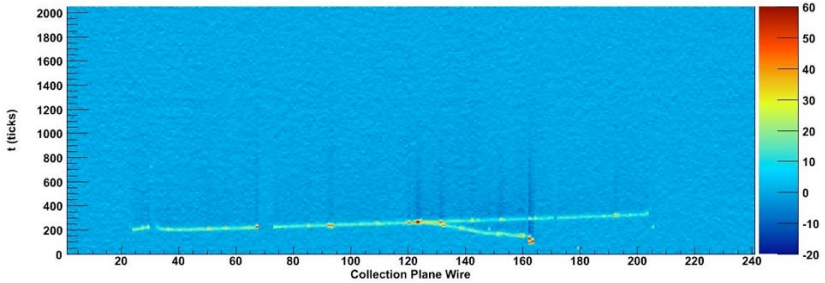
ArgoNeuT Events

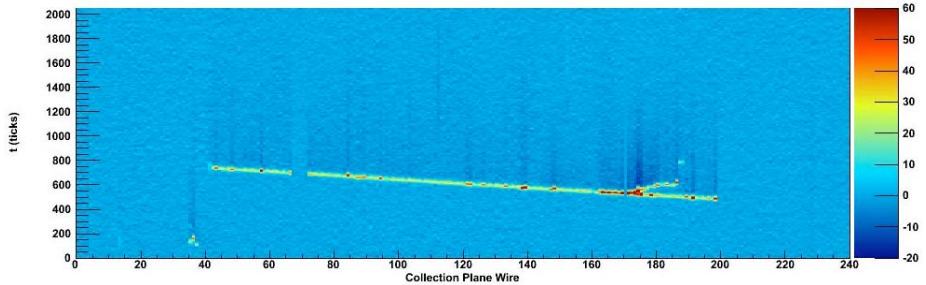
Event Displays,
Filtering and
Reconstruction
(all preliminary!)

Cosmic Muons with Deltas

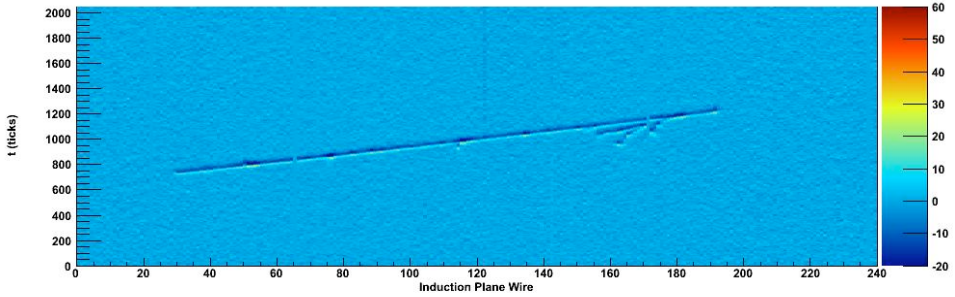


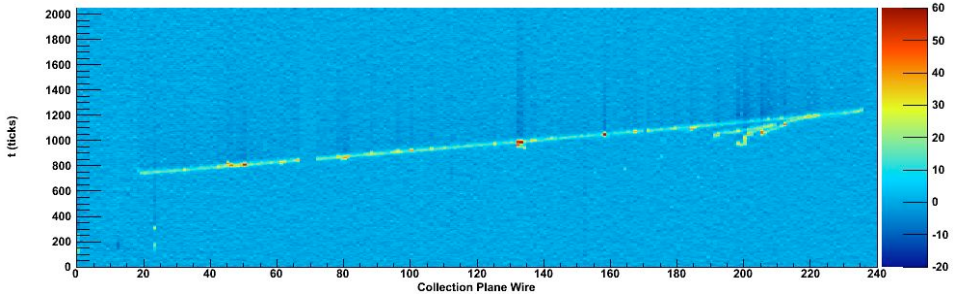






TPC provides two 2D-views of each event

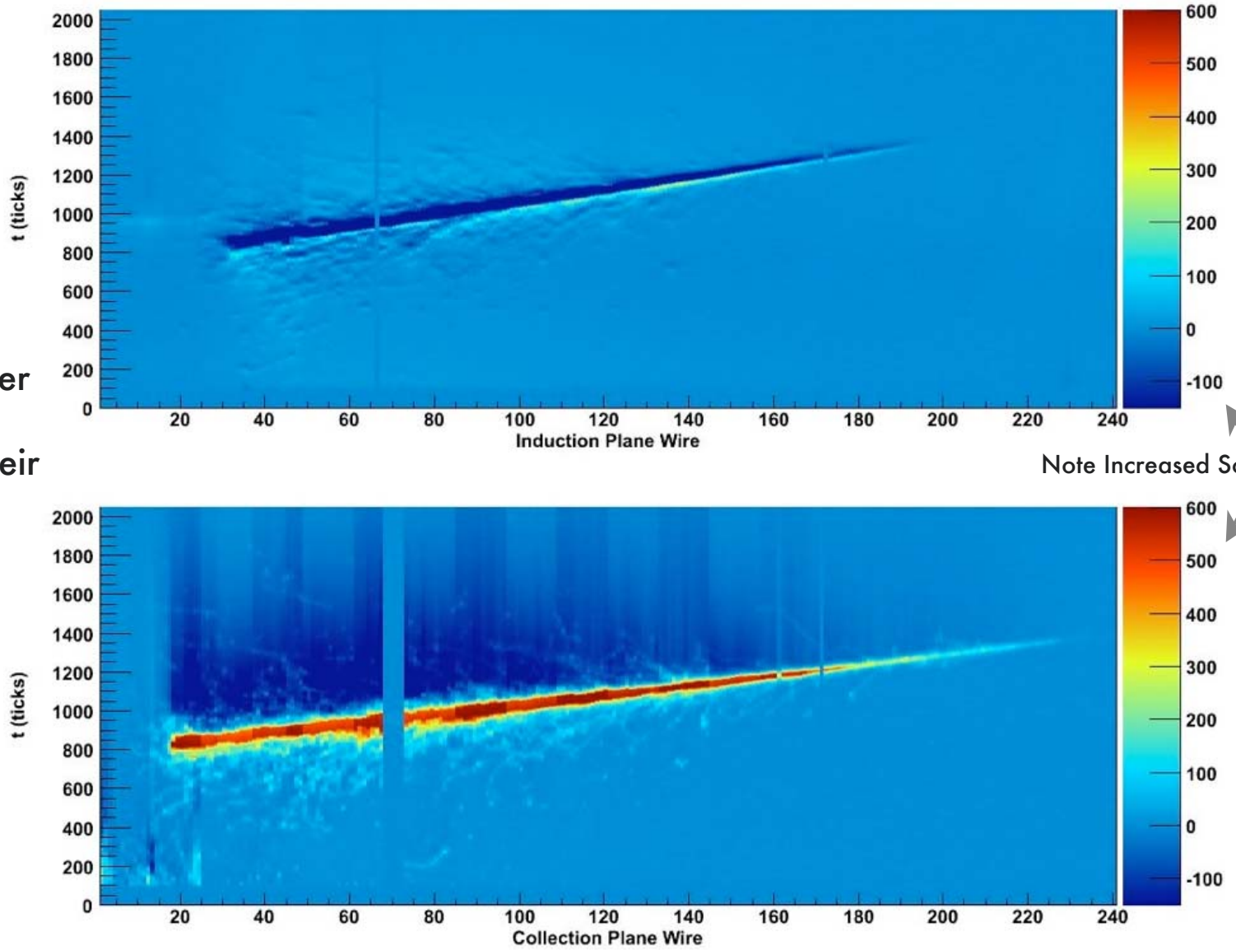




Color Index *(Collection plane)* proportional to amount of energy deposited

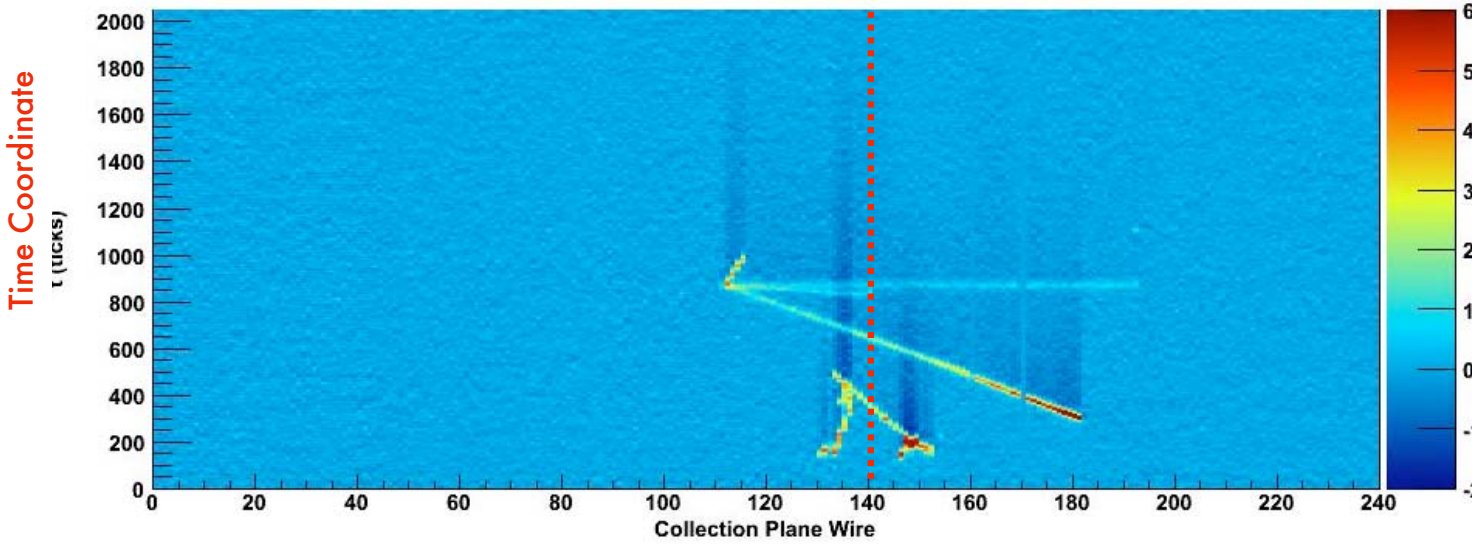
Cosmic Events

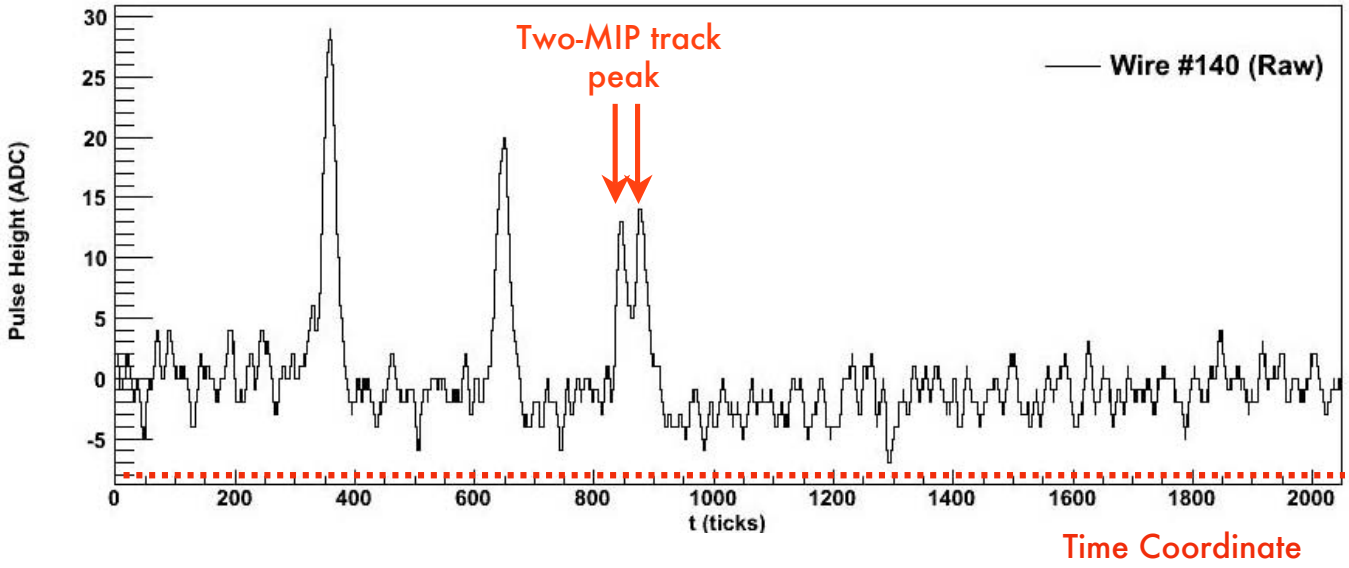
Very energetic cosmic-ray shower event…pushes many ADCs to their upper/lower threshold



Neutrino Events

- MIP yield: ~6000 e/mm
- Very fine pixel size (4mm x 0.3mm)
- ~12 ADC counts per 1fC of charge.
- Dark "shadow bands" are due to electronics returning to baseline...
- Fourier decomposition can be used to remove electronics response.
- Developing code to extract "hit" information from wire signals, perform tracking, Particle Id, deposited energy reconstruction, etc...

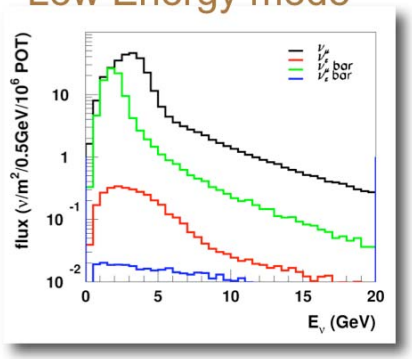




Neutrino Events

The NuMI Beam Flux

Low Energy mode



Beam Systematics

~ 5 % (possible)

~ 10 % (realistic)

ν_μ mean energy ≈ 3.7GeV

Intensity:

$\Phi_\nu = 3 \times 10^{-7}\ \nu$ /cm² /PoT

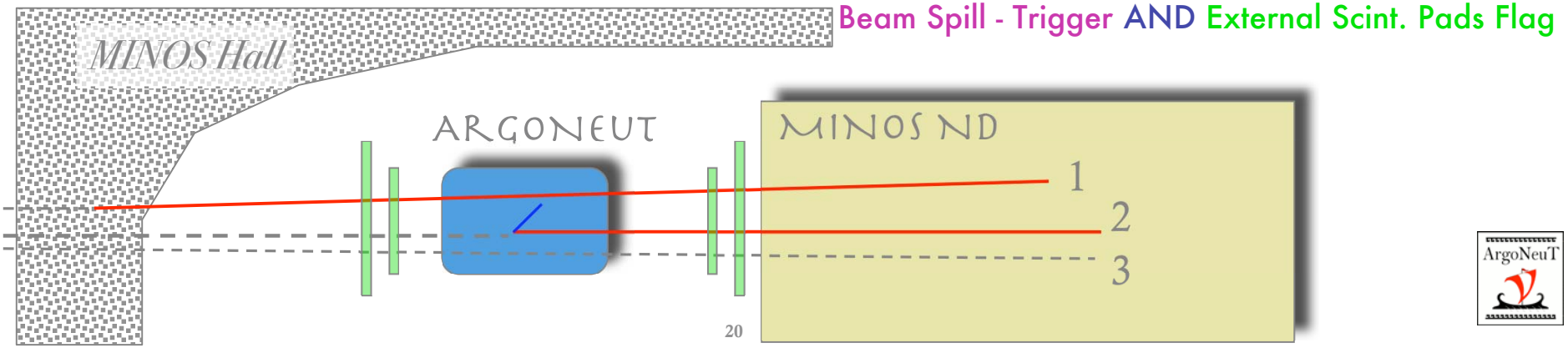
Exposure:

1.4×10^{20} PoT (in 6 months)

Event Type	# of events in 180 days (1.4×10^{20} POT) ν mode	# of events in 180 days (1.4×10^{20} POT) anti-ν mode
ν_μCC	19337	6109
anti-ν_μCC	1692	5490
ν_eCC	362	118
NC	6526	4015
Total	27917	15732

Standard ν CC-Xsect Decomposition: $\sigma_{tot} \approx \sigma_{QE} \oplus \sigma_{RES} \oplus \sigma_{DIS}$

ν_μ mode ⇒ **~ 19 QE events/day + ~ 15 RES events/day + ~ 83 DIS events/day**



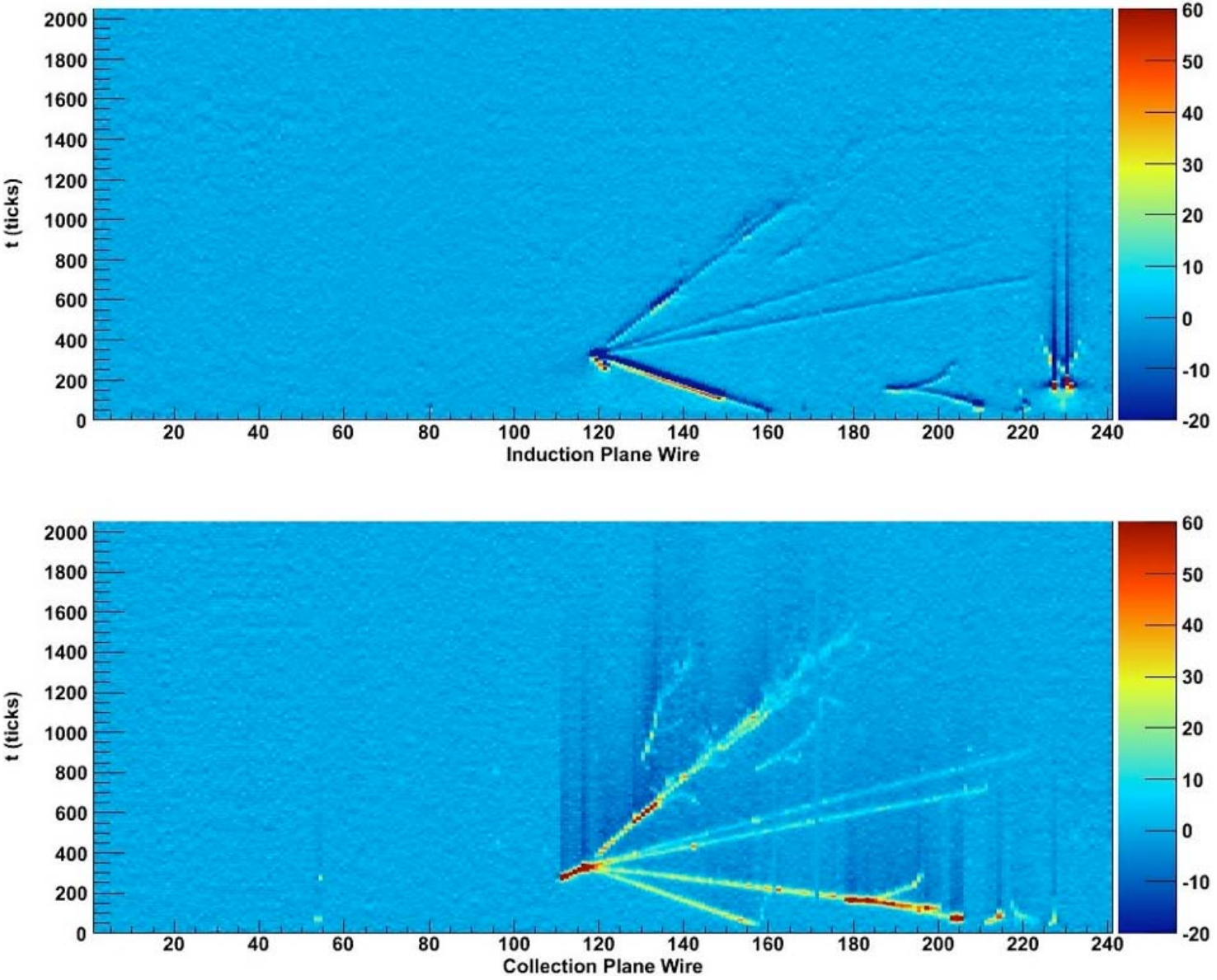
Beam Spill - Trigger AND External Scint. Pads Flag

ArgoNeuT

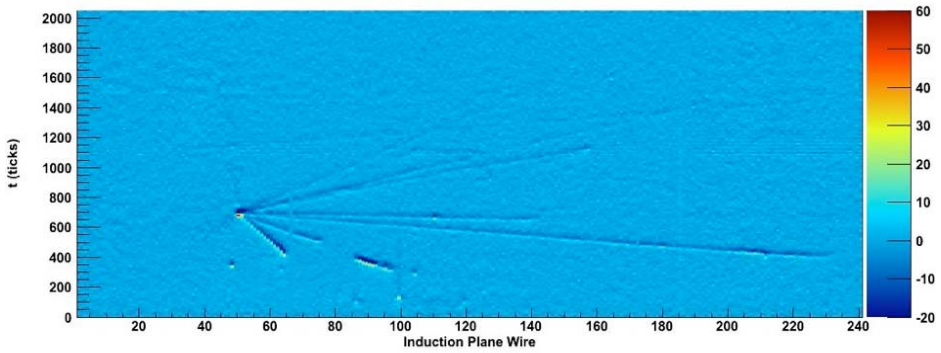
Neutrino Event: DIS Candidate

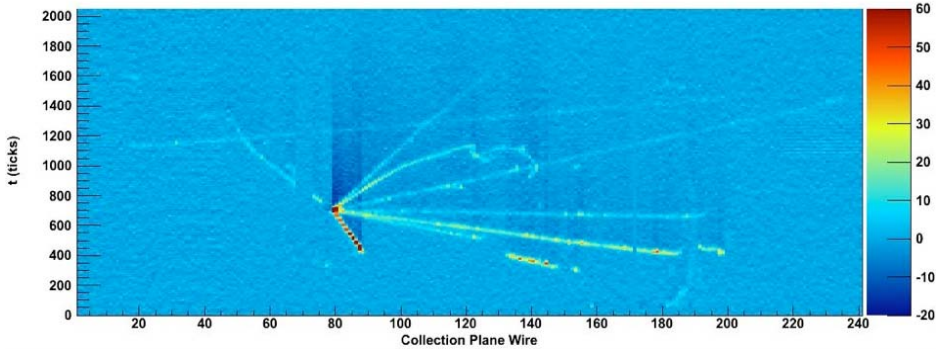
Multi-prong (DIS) event with
- μ (with δ-ray)
- π^0 ($\gamma\gamma$ into elm showers)
- Charged pions (uncontained)
- p (heavily ionizing short track)

NB: Ptcl. ID not really performed *(…just by visual attempt)*



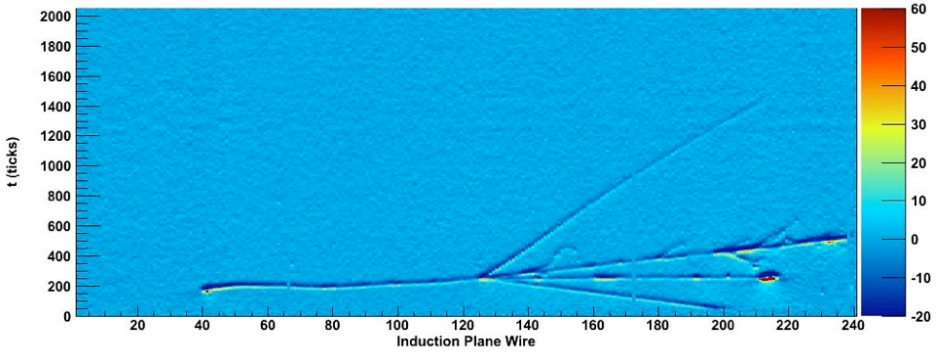
Neutrino Event: DIS Candidate

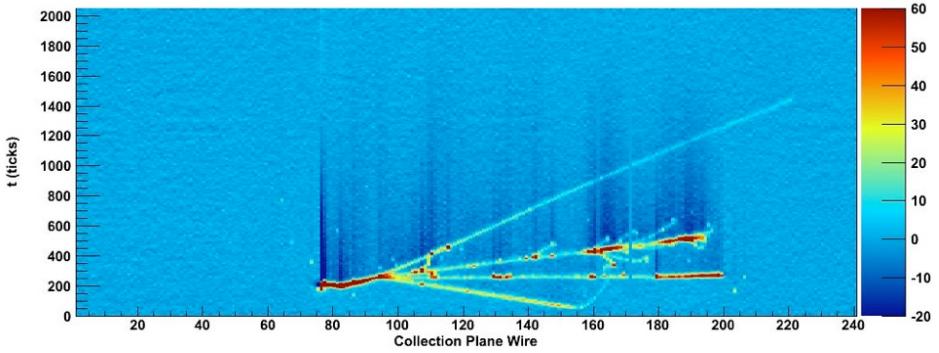




Recoil proton detectable
Down to 20-30 MeV kin.en

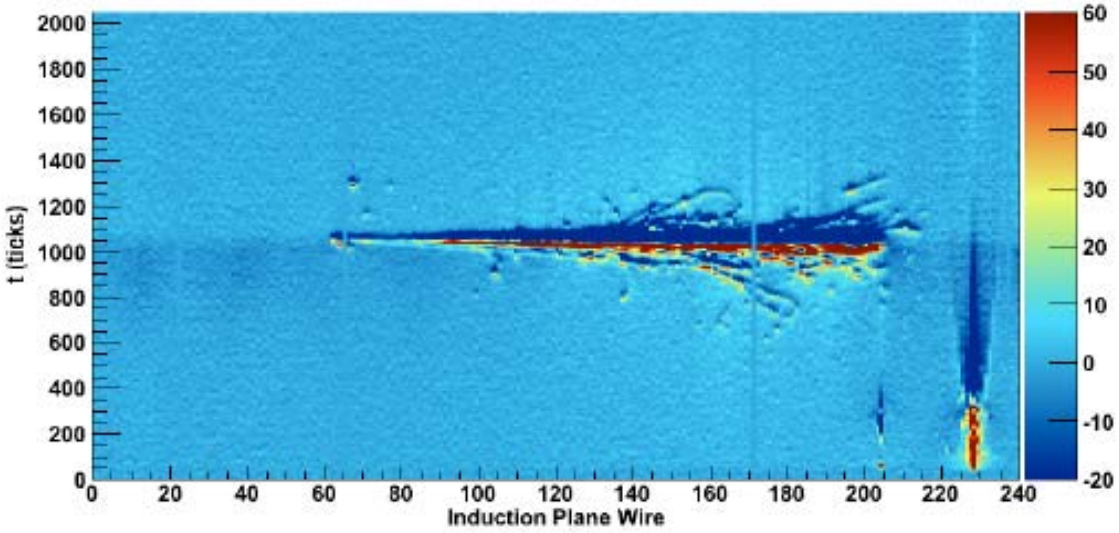
Two more DIS candidates.





Neutrino Event: ν_e- Candidate

ν_e- candidate



Induction View
(raw data)

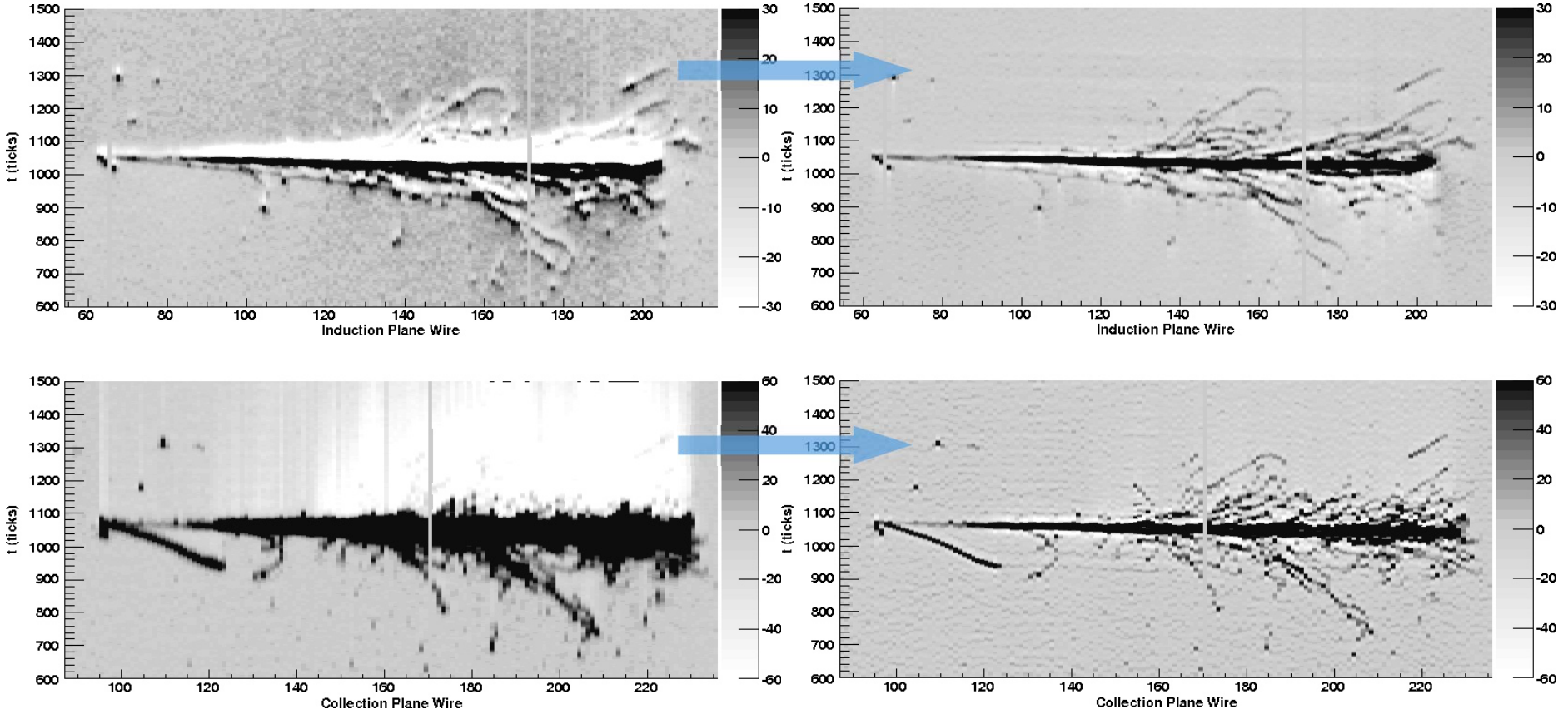
See next

El.M. shower (not fully contained) +
Short densely ionizing track at the vertex

Event Filtering

Much activity in developing reconstruction/full simulation software for ArgoNeuT (and future LArTPCs) [*LArSoft package: next slides*]

Event filtering: FFT tuning package running on LArSoft

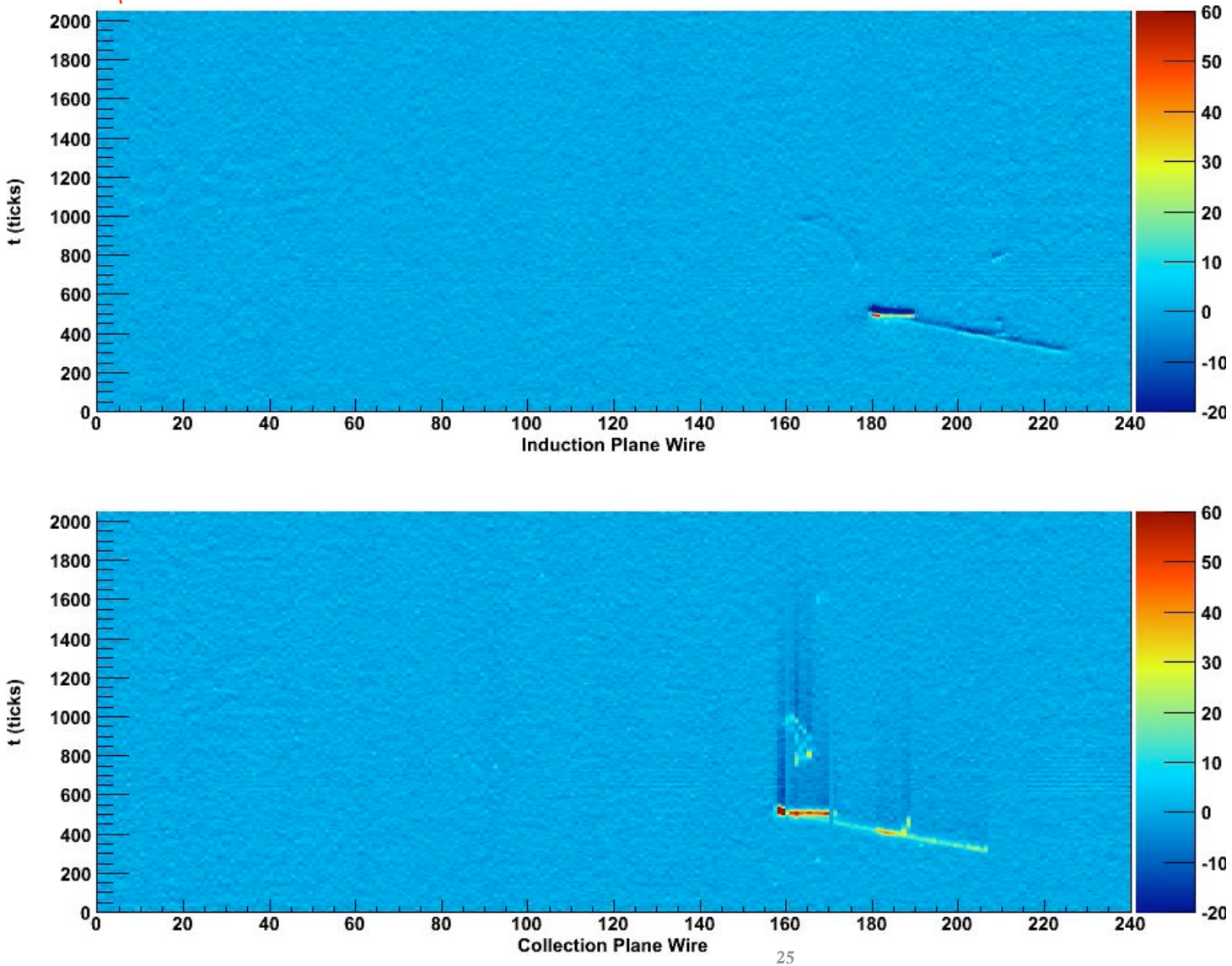


C. Bromberg/B. Page

ν_e CC Candidate Event

Neutrino Event: ν_μ- QE Candidate

ν_μ cc-QE Candidate (1)

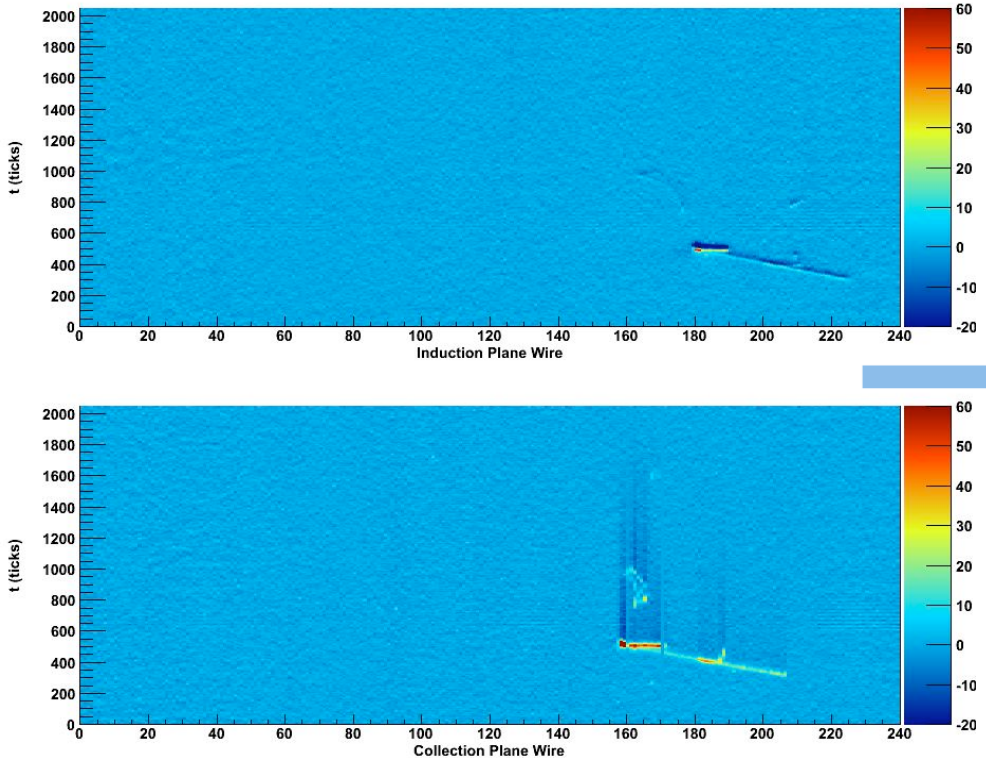


Muon track (uncontained)
+
Short densely ionizing track(s) at the vertex

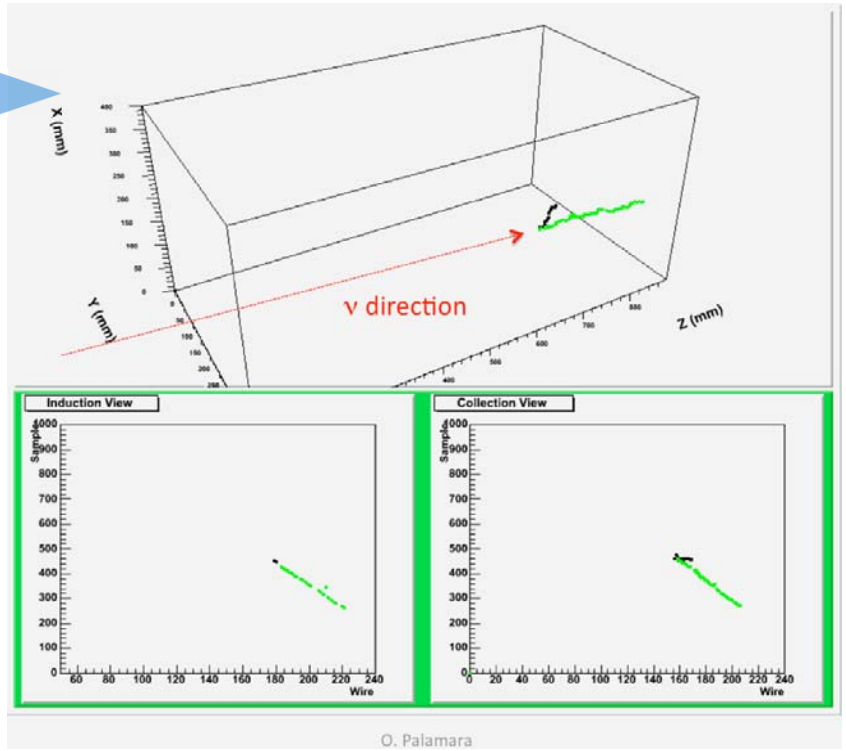
See next

3D Reconstruction

- Initial attempts at 3D event reconstruction *(and Analysis - next slides)*



Reconstructed "hits" and 3D view



ν_μ cc-QE Candidate (2)

Event Reconstruction (P.Id, E_{dep})

Reconstruction of neutrino CC interactions:
start with the "easiest" topology ⇒

cc-Quasi Elastic reaction

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

… when nucleon bound in the nuclear target nuclear effects must be taken into account:

$\nu_\mu + A(n) \rightarrow \mu^- + p + (A-1)^*$

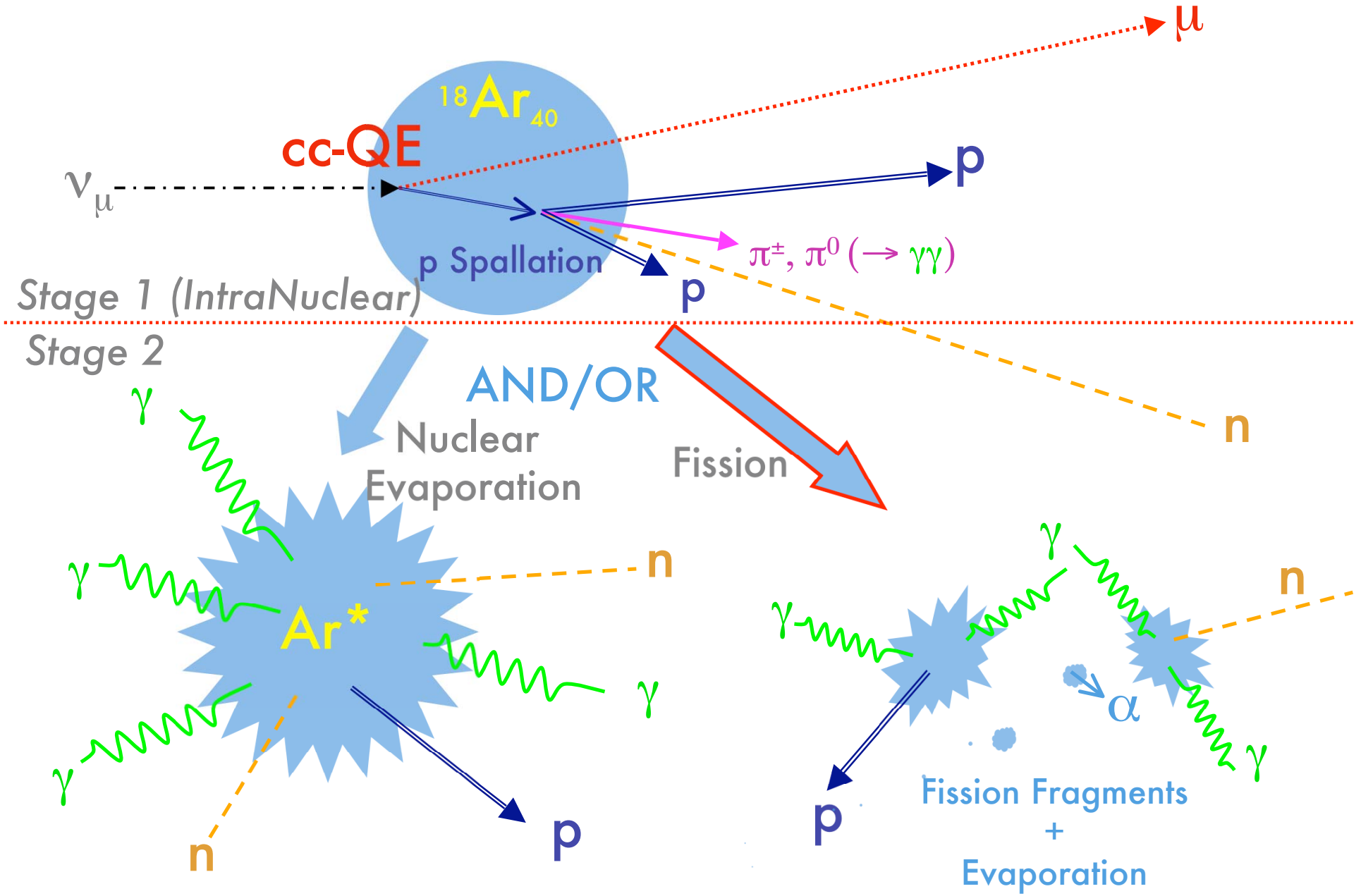
See next

FSI

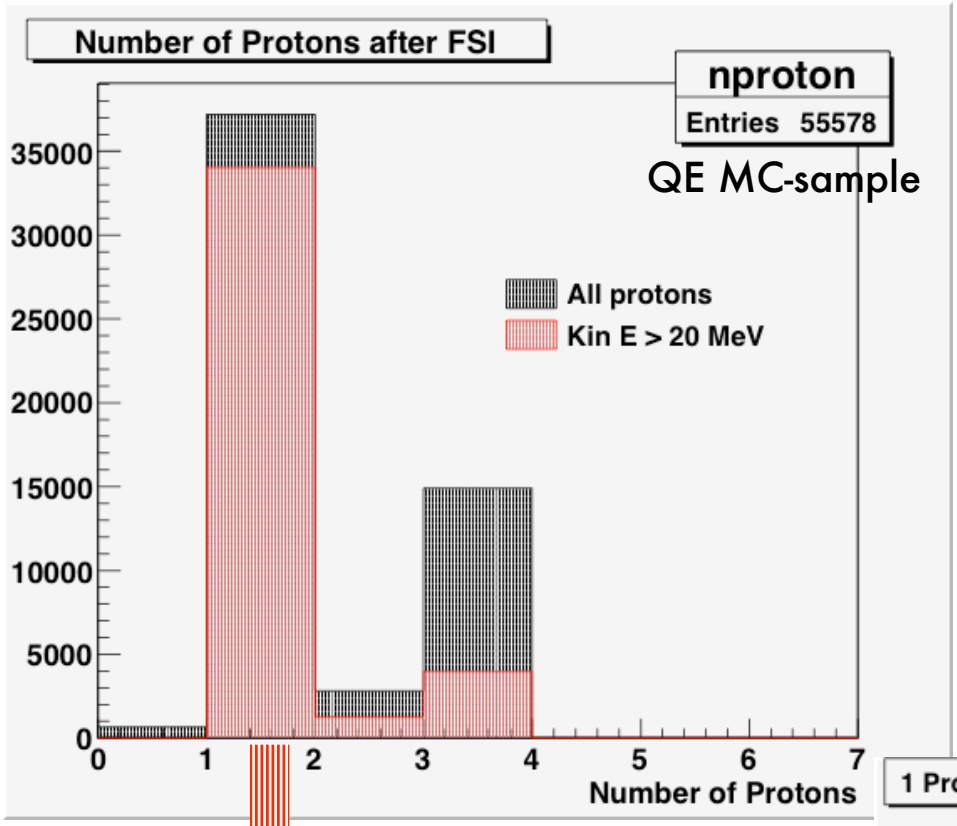
- ***proton Spallation*** (intranuclear interactions with p and n emission (..but also $\pi^{\pm}$, π^0)
- ***Nuclear evaporation*** (lower kin.en. p and n)
- (and/or) ***Fission*** (nuclear fragments, α's,..)
- ***Nuclear de-excitation*** with γ emission from

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

(possible) Underlying reactions (FSI)



MonteCarlo Information (GENIE)



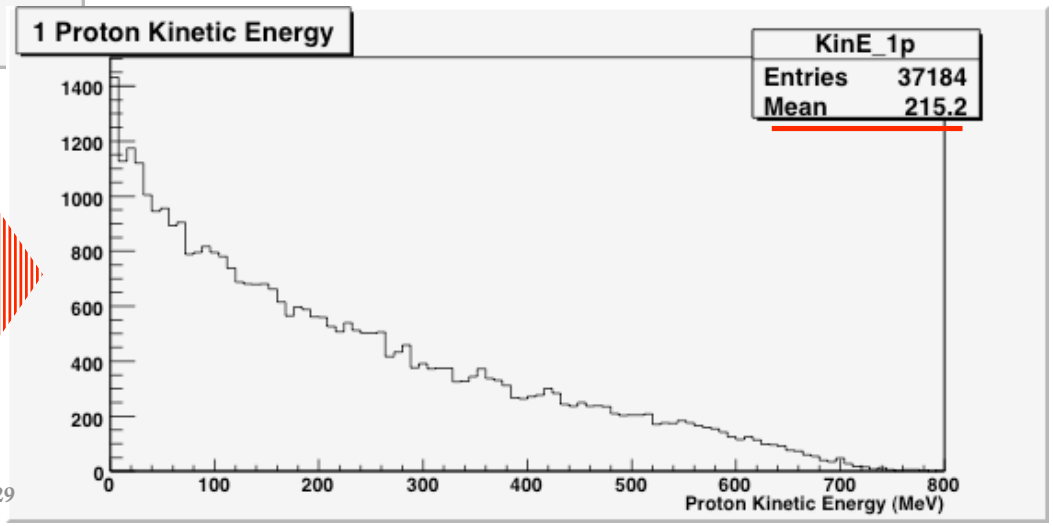
MC: 1GeV neutrino pilot beam

Events with 0 neutrons: 33838 (60%)
Events with 1 neutron: 5278 (10%)
Events with 2 neutrons: 16462 (30%)

"single p" events (68%)

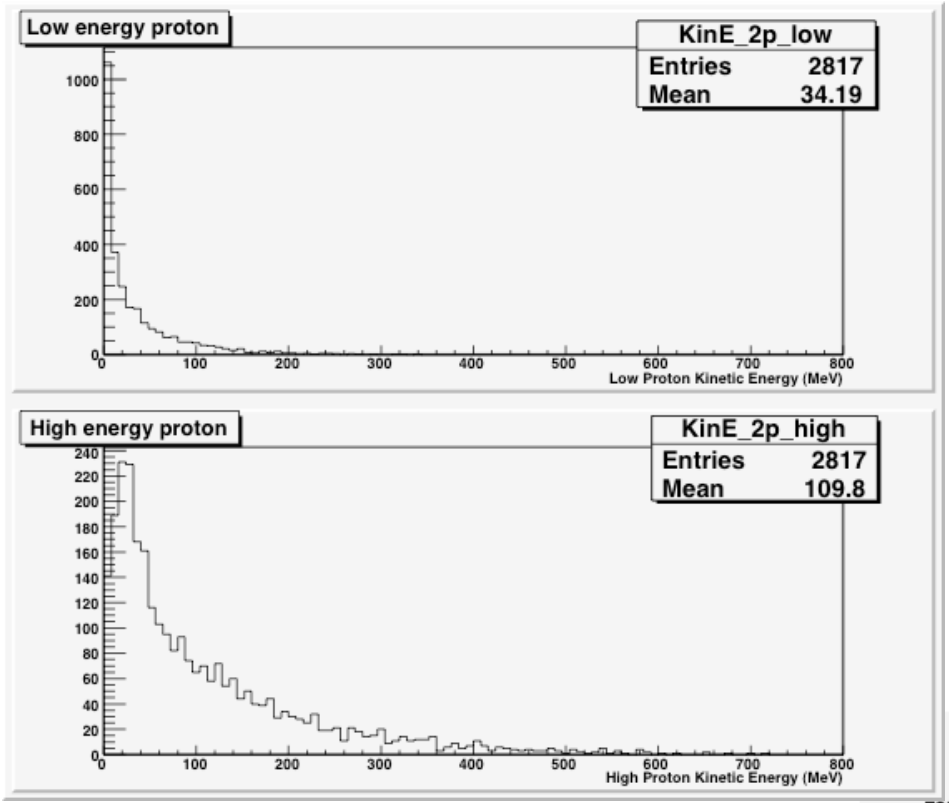
$T_p \geq$ 20-25 MeV
(ε=90%)

Single p energy distribution



M. Antonello, O. Palamara (LNGS)

MonteCarlo Information (GENIE)

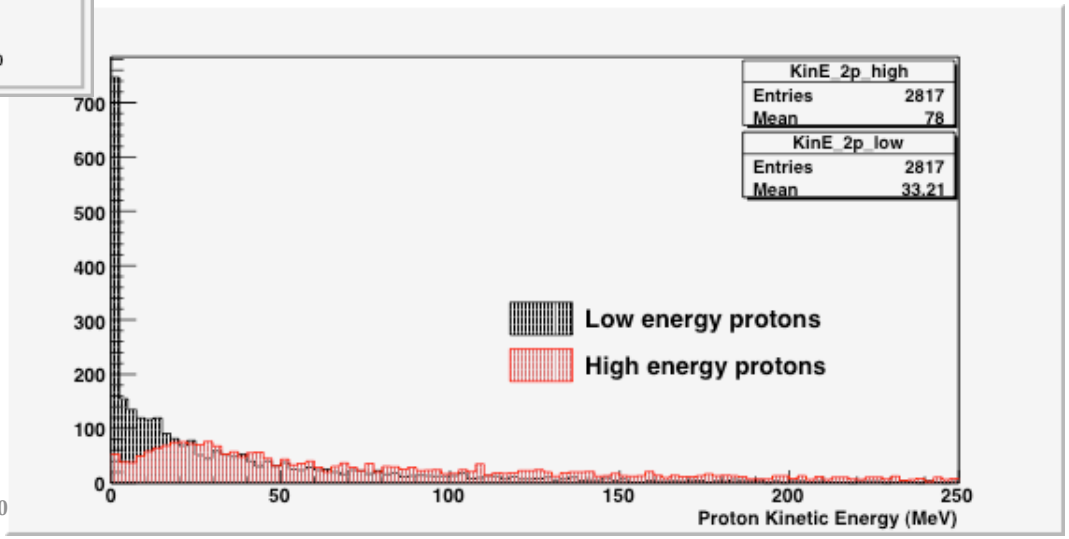


"Two p" energy distributions (p_1, p_2)

MC: 1GeV neutrino pilot beam

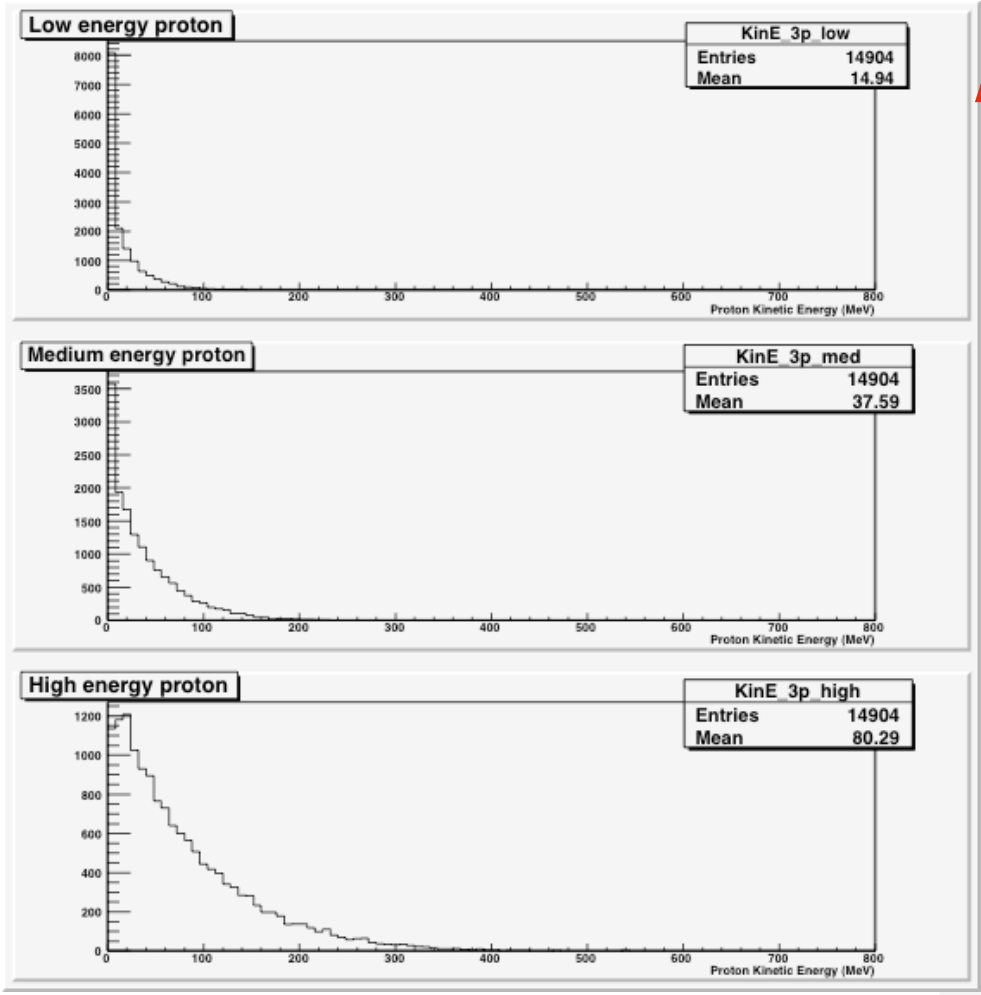
"Two p" events (5%)

$T_{p1}, T_{p2} \geq 20 - 25$ MeV
(ε=40%)



M. Antonello, O. Palamara (LNGS)

MonteCarlo Information (GENIE)

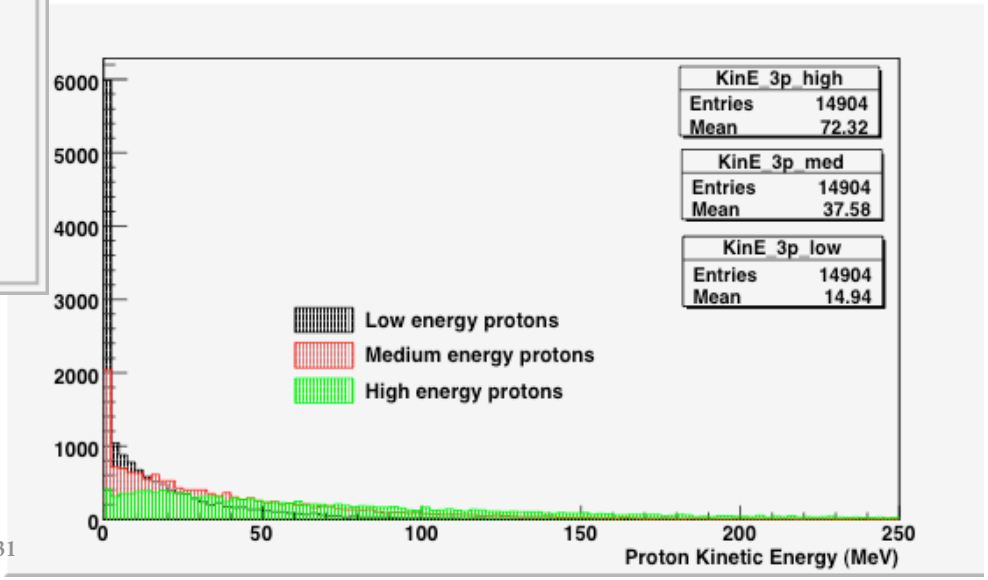


"Three p" energy distributions (p_1, p_2, p_3)

MC: 1GeV neutrino pilot beam

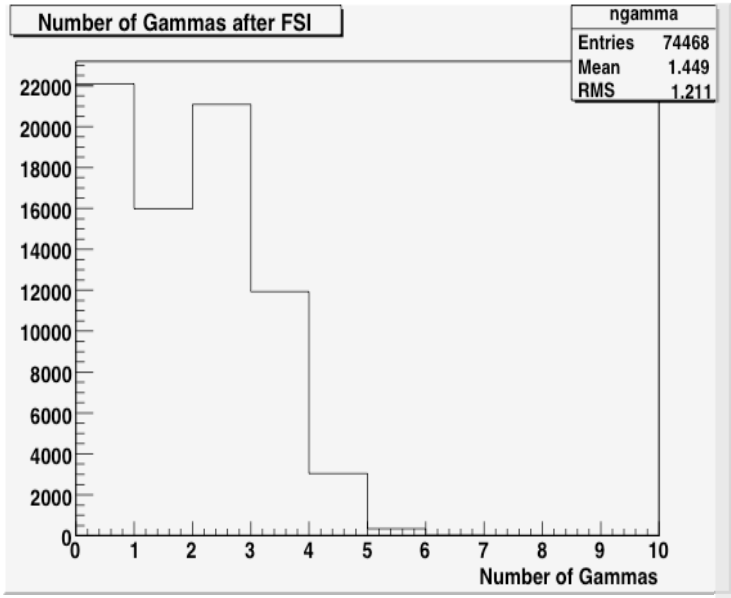
"Three p" events (27%)

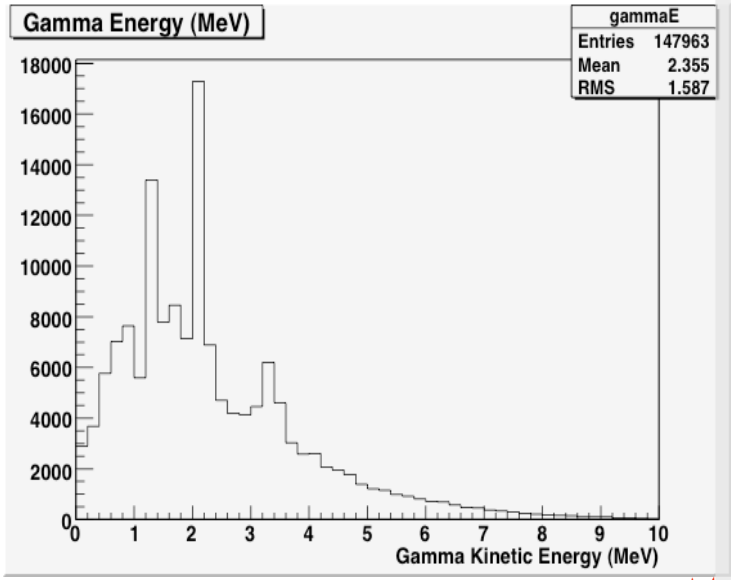
$T_{p1}, T_{p2}, T_{p3} \geq$ 20-25 MeV (ε=20%)



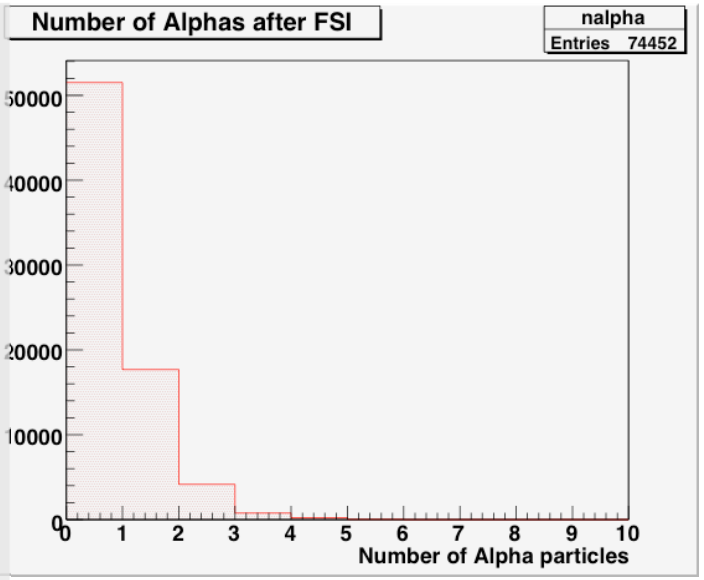
M. Antonello, O. Palamara (LNGS)

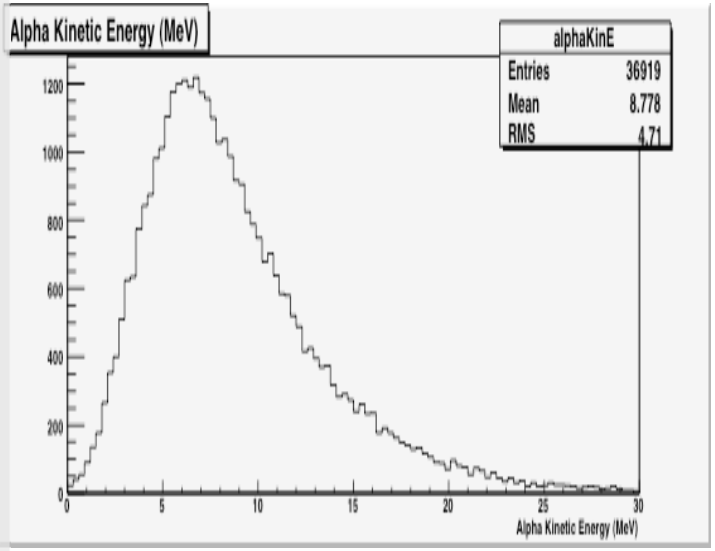
MonteCarlo Information (FLUKA)





Also γ and α to be carefully Simulated (not yet available in GENIE), since frequently produced and give detectable signals





Kindly from G. Battistoni

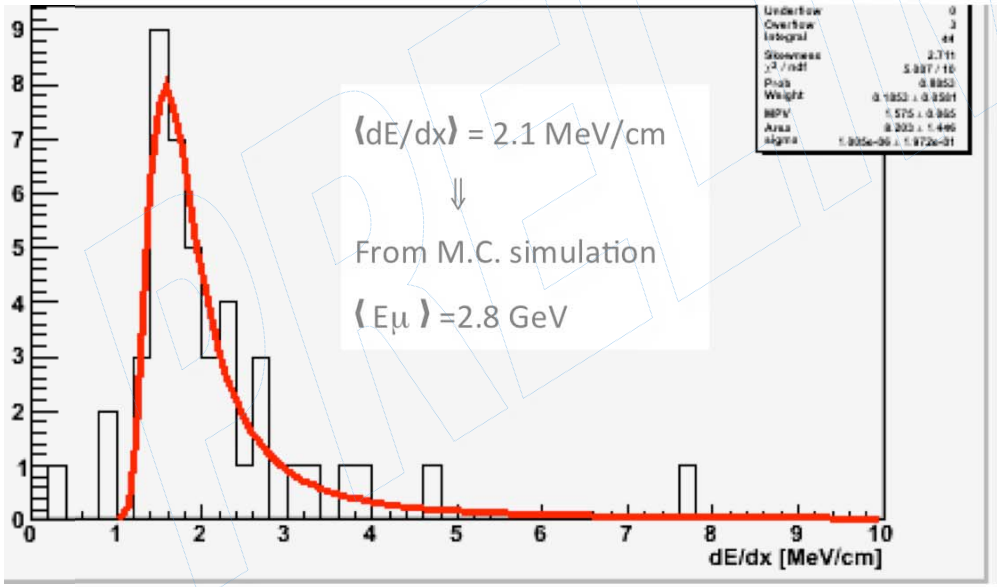
MC: 1GeV neutrino pilot beam

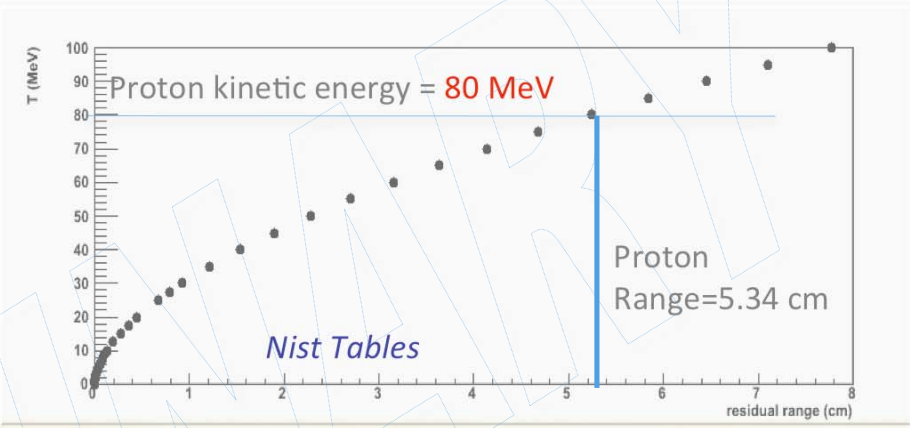
(back to) Real Event Reconstruction

A first (preliminary) attempt to

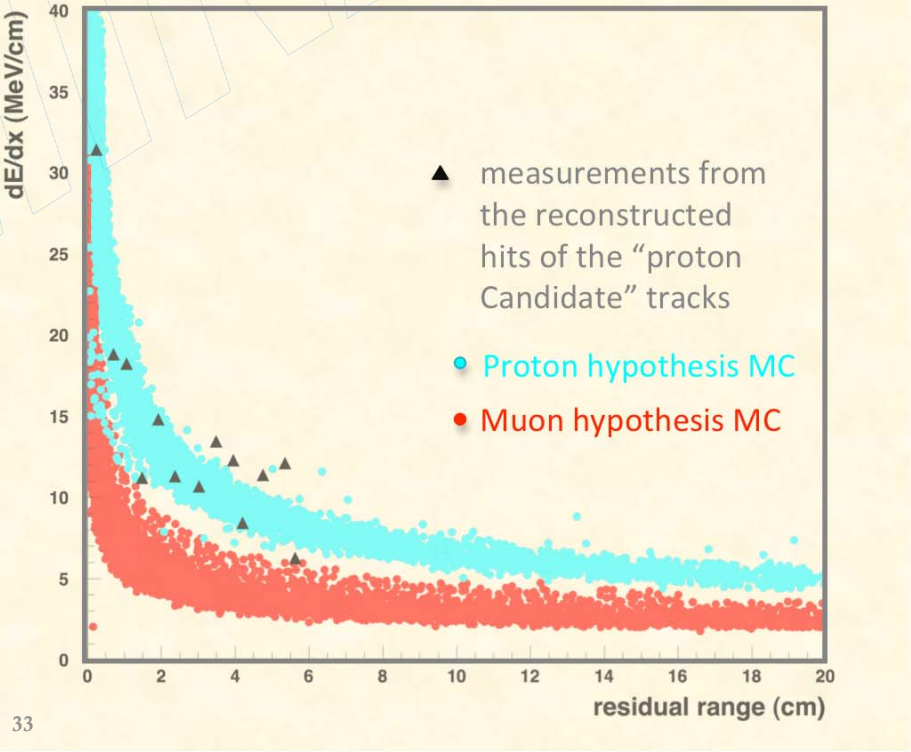
Final State
Muon and ***Proton***
reconstruction

Muon (TPC only)

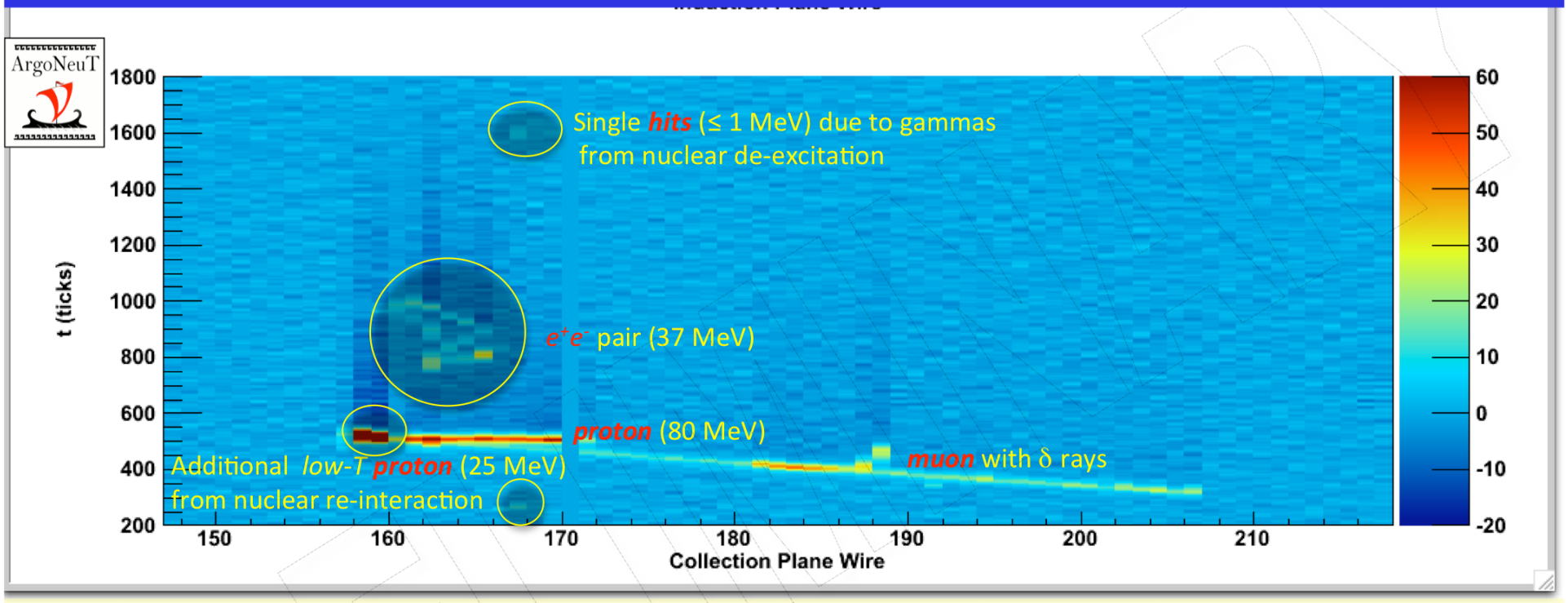




Particle ID: Proton track recognition



Real Event Reconstruction



1) **large activity near the vertex**

$\mu^- + p + X$ (X = additional "short track" [2 wires] associated with high energy density deposition)

X compatible with a second 25 MeV p track from nuclear evaporation (FSI in nucleus) or pion re-absorption

2) **an extra energy deposition** (37 MeV) possibly associated with the event (e^+e^- *pair*), induced by a neutral particle.

NB: This event reconstruction is preliminary.

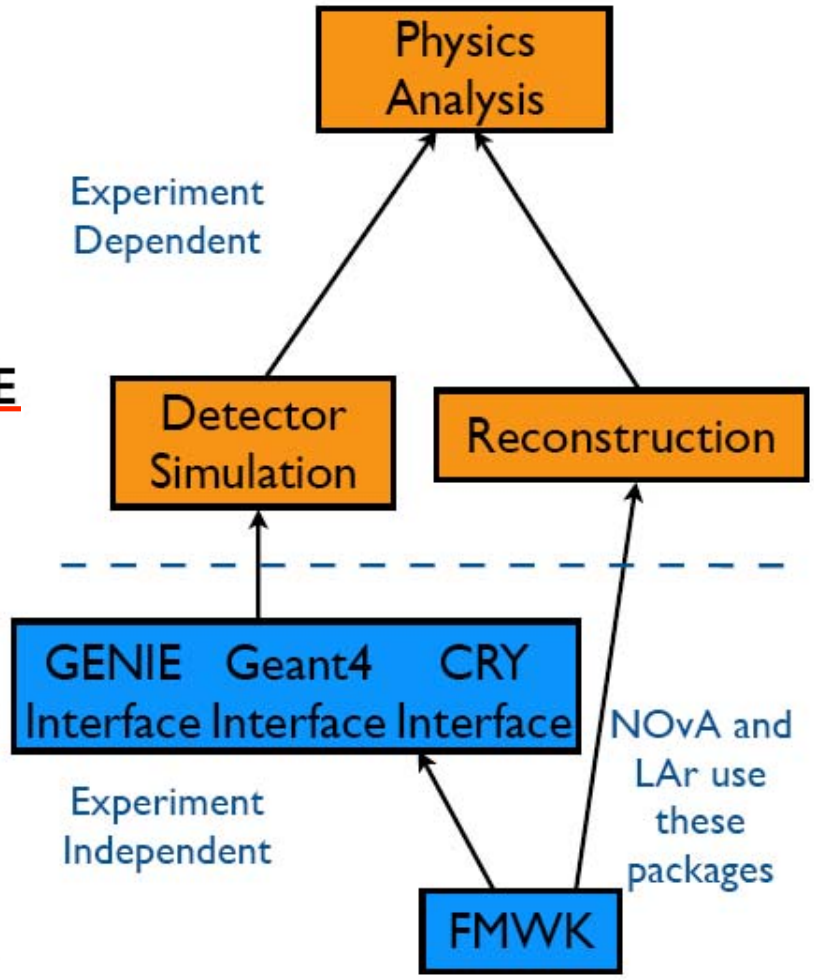
A full and detailed MC simulation including nuclear effects is required for validation.

A preliminary FLUKA & GENIE MC simulations support the possibility to detect such nuclear effects in LAr TPC.

Current SW development

Neutrino Software @ FNAL

- Recent effort made to get FNAL neutrino experiments on common framework, using common tools
- NOvA, ArgoNeuT, μBooNE using FMWK
- Use of common framework enables sharing of interfaces to flux files, GENIE (neutrino generator), Geant4, etc
- Water Cherenkov software can also easily be built on FMWK
- Enables direct comparisons between different detector technologies, people working on multiple experiments only learn one framework

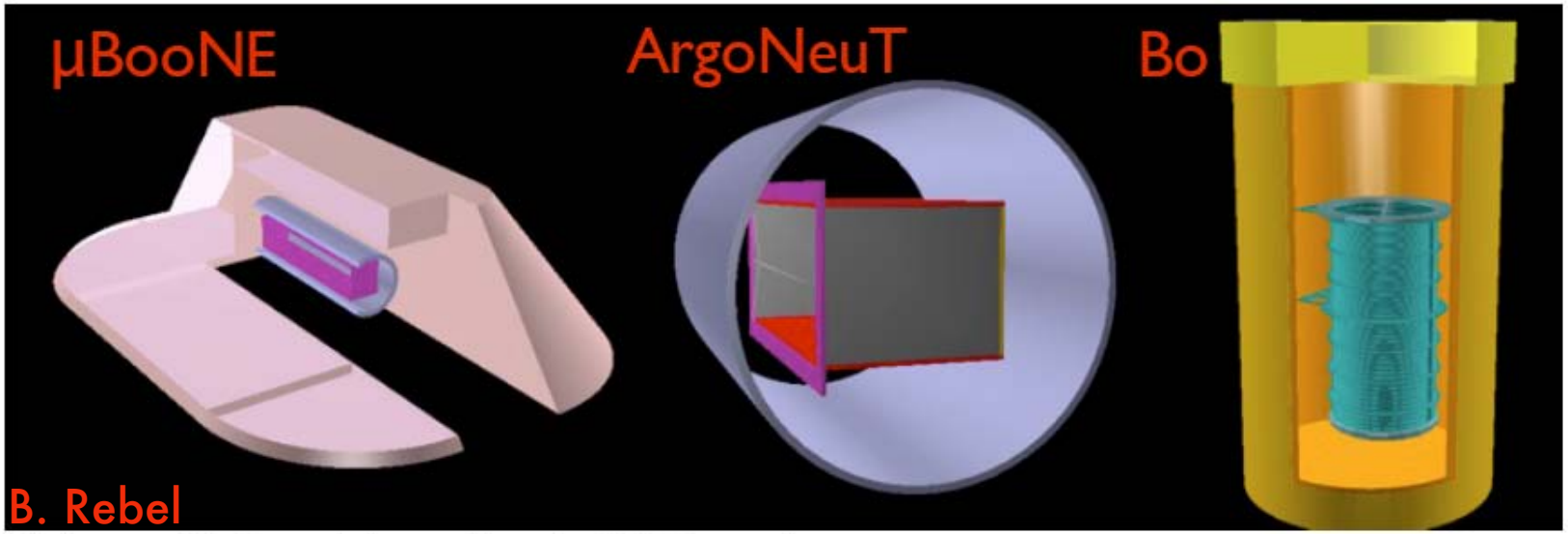


B. Rebel (FNAL)

Current SW development: LArSoft

LArSoft

- LArSoft is a distribution of code for the LAr experiments - MTS, ArgoNeuT, μBooNE, LBNE
- Each detector just needs to add a new geometry description
- Reconstruction knows how to access different geometries, but not dependent on any one



Current SW development: LArSoft

Computer Vision Reconstruction

- Computer vision is a branch of computer science that attempts to extract information from images
- Since LArTPC events are similar to pictures, seems like a good avenue to pursue
- Many different algorithms available in this field - distance transforms, skeletonization, center-line extraction
- This technique looks promising as each example shows ability to pick out central track and associated energy depositions

B. Kebel

Goal of Data Analysis: ν_μ cc-QE X-sect Measurement

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

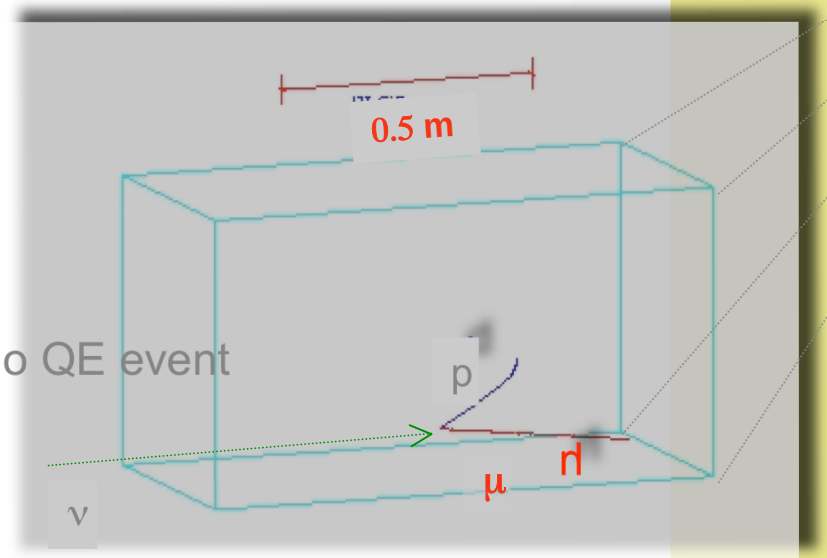
In this range the CC Quasi Elastic reaction is of primary interest.

Need Full event reconstruction:

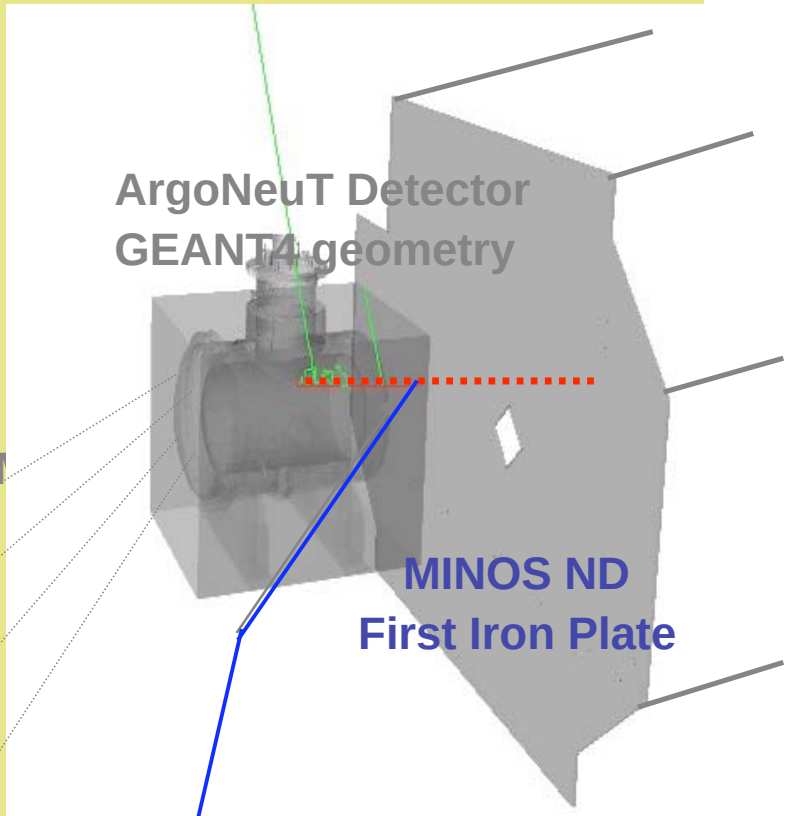
Vertex reconstruction in LArTPC

+

Muon momentum reconstruction from MINOS ND



Monte Carlo QE event



Muon escaping LAr and reaching MINOS

Goal of Data Analysis

The Abs.QE ν_μ X-sect: Experimental

$$\sigma_{QE} = \frac{N^{QE} \quad (= N - N^{nQE})}{\Phi \times E_{xp} \times N_{fid} \times T_{live} \times Acc^{QE} \times \mathcal{G}^{QE}}$$

μ p

Assuming Φ_ν precisely known

Acc^{QE} *(geometric)* ***Muon Acceptance*** *(MC: **86** % - ArgoNeuT +* ***MINOS_ND****)*

$\mathcal{G}^{QE}$ *Proton-rec "Acceptance-Efficiency" -*

- T_p threshold (30 MeV, possibly lower - LArTPC feature)
- Leading Proton containment (MC: 54%, ArgoNeuT feature)
- FSI !!! - need lot MC assumptions/development

N^{nQE} determined from RES-DIS Xsect. (need again MC info)

Goal of Data Analysis

The total number of QE ν_μ events and the relative energy distributions have been MC calculated (LE-NuMI: 8 x 10^{17} PoT/day) as a function of the incoming neutrino energy (bin size 0.5GeV).

The value of M_A adopted here is 1.03GeV/c^2 .

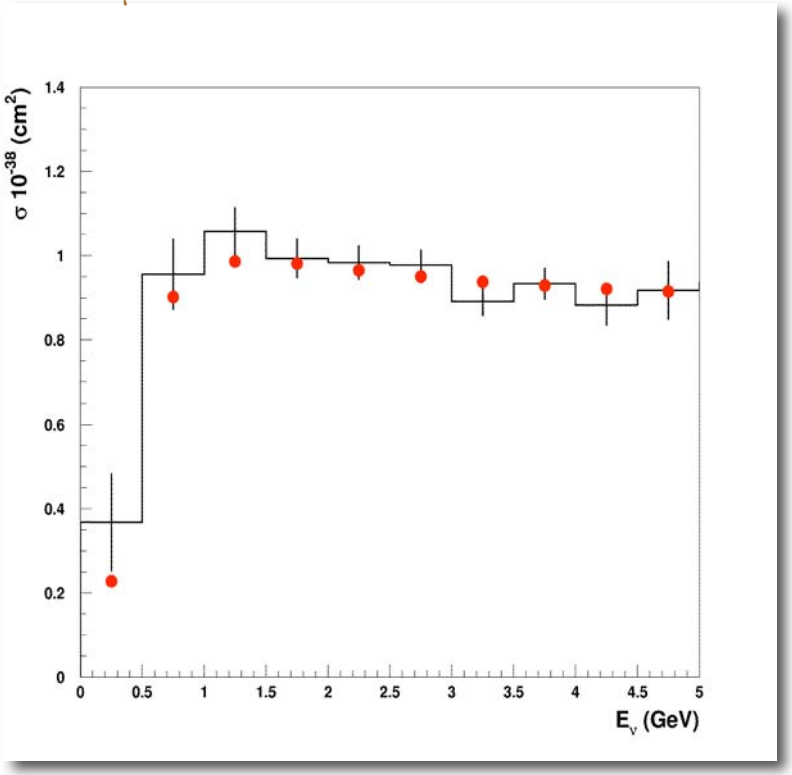
The experimental QE X-sect distribution (histogram) for ArgoNeuT has been MC reproduced as expected from a 180 days run of on-axis exposure on the NuMI Beam.

It was assumed that all the collected events are fully reconstructed (optimistic).

Statistical errors are reported.

The red dots indicate the theoretical X-sect (M_A= 1.03).

QE ν_μ Abs. X-sect Reconstruction



Goal of Data Analysis

Another (related) Topic: **the Axial Mass M_A measurement**

The total number of expected QE events (GENEVE MC) scales almost linearily with M_A.

Counting the QE interactions in ArgoNeuT may provide a way to determine M_A value in Argon (if the beam is sufficiently well known).

Several experiments extracted the M_A value from the fit of their data:

Experiments using D^2 and H^2 as mass target returned

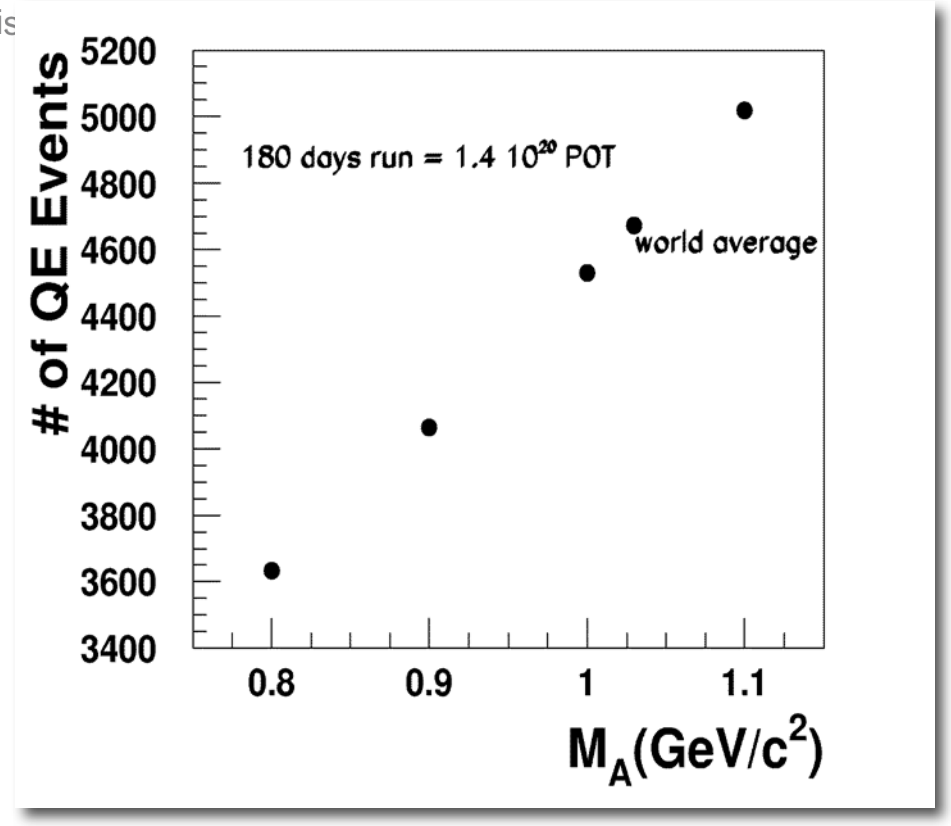
$M_A = 1.03$ GeV/c^2 (mean value)

Experiments employing havier nuclei reported
$M_A = 0.65 \div 1.0$ GeV/c^2

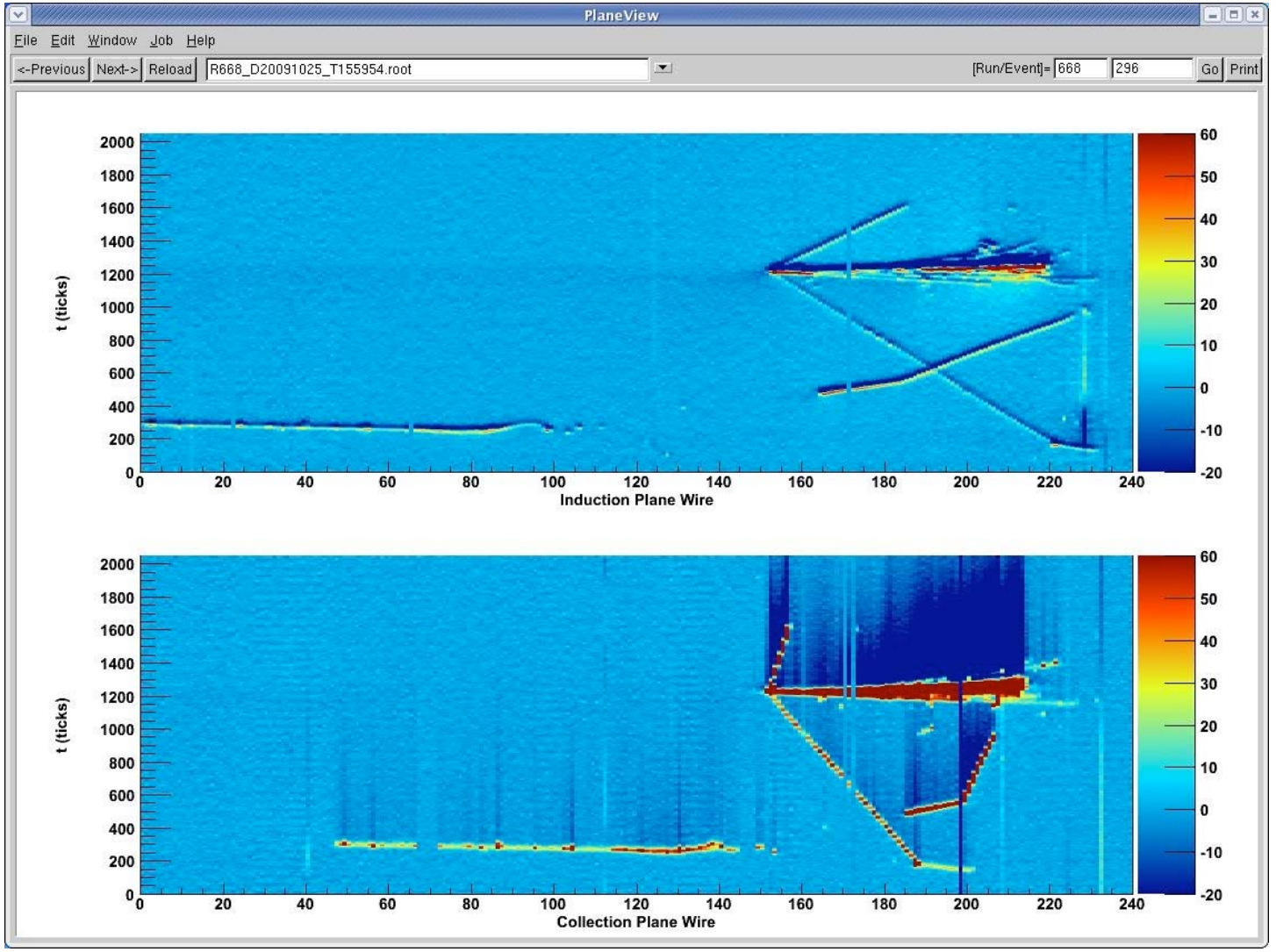
It is unclear if the difference depend on effective dependence on the target nuclear structure or to different systematics.

No M_A measurement have been ever performed in Liquid Argon !!

Early calculation referred to 350 kg



ArgoNeuT today…



This is the first anti-ν event collected after operation restart (Oct 25th) !

Data Taking currently under way in smooth conditions

Conclusion

Next-generation neutrino physics experiments require precision Particle IDentification and fine grained 3D imaging on very large scale. Liquid Argon TPC combines an ideal detection medium with a modern imaging and calorimetric readout technique, scalable to very large volume/mass.

ArgoNeuT is fully operational, providing (large) samples of neutrino/antineutrino events in a (small) LArTPC - for the 1st time in the U.S. and the 1st time ever in a low-Energy beam.

The present run will last untill March,'10.

After this, the extension to further run period is under evaluation

Extensive Real data/experience is invaluable in improving LArTPC technique.
Analysis software being developed is general purpose for future LArTPCs
Highly sophisticated/detailed MonteCarlo codes are needed

Acknowledgments
Many thanks to all ArgoNeut'rs!
In particular for the contributions from *B.Fleming, M.Soderberg, J.Spitz, C.Bromberg, D.Edmunds, B. Rebel, M.Antonello and O.Palamara*

Outlook

Liquid-Argon Time Projection Chambers

Outlook of R&D Program in the US

Active Volume

Yale TPC & Bo
Yale TPC: Dismantled
Bo: Operational

0.00002 kton

15x

2009/10/..

ArgoNeuT
Operational
Physics: Measure neutrino-argon cross sections

0.0003 kton

330x

Measure low energy neutrino Interactions:
•MiniBooNE low energy excess
•Suite of low energy cross section mmnts.

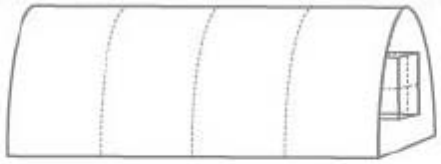
2013

MicroBooNE
Construction begins 2010
Physics: Investigate low-energy neutrino interactions

0.1 kton

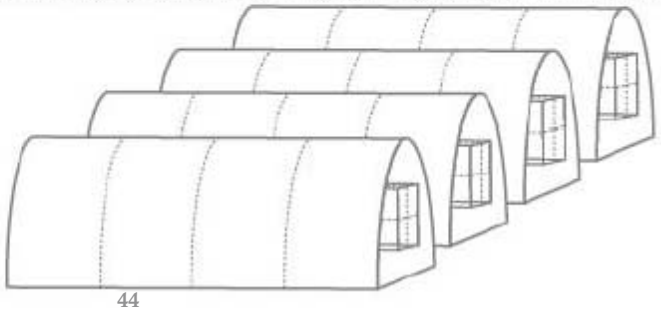
4x50x

LAr TPC for LBNE
R&D in progress
Physics: Measure neutrino oscillations at 1,000+ km



20 kton

Final goal
Replicate proven technology
Physics: Search for CP violation in neutrino sector



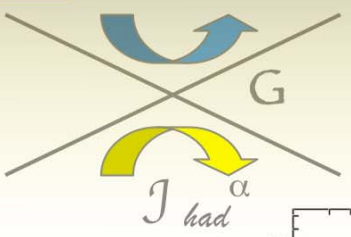
N x 20 kton

Back-up slides

[$\sigma_{Q\text{-}El}$] Quasi-Elastic Scattering on *free* N

(low Q^2, x=1, W=M_p):

$$\nu_\ell + n \rightarrow \ell^- + p$$

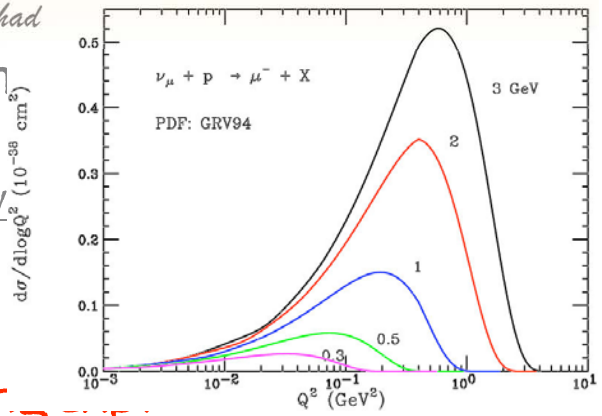


Dynamics described by Current-Current Lagrangian

$J^{had} \approx V - A$ defined through Nucleon Weak Form Factors:

Vector F.F. [$F_V^1(Q^2)$, $F_V^2(Q^2)$], related to El.M. F.F. (Hp. CVC)

Axial F.F. [$F_A(Q^2)$] and PseudoScalar F.F. [$F_{PS}(Q^2)$]



Note: Vector F.F. can be (are) determined from *e*-scatterir

Axial F.F. (assumed dipolar form) with M_A free parameter

$$F_A(Q^2) = g_A \left[1 + \frac{Q^2}{M_A^2}\right]^{-2}$$

This parameter cannot be derived theoretically because of the non conservation of axial weak current.

PseudoScalar F.F. term in Xsect is proportional to $(m_\ell/M_p)^2$

i.e. relevant only for $\nu_\ell = \nu_\tau$

Q-el scattering on N *bound* in A: the rise of Nuclear Effects (ISI,FSI)

(i.e. mainly non-perturbative effects of strong interactions inside the target)