ArgoNeuT

Coherent $\pi^{\pm}$ Production

Result

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on behalf of the ArgoNeuT Collaboration

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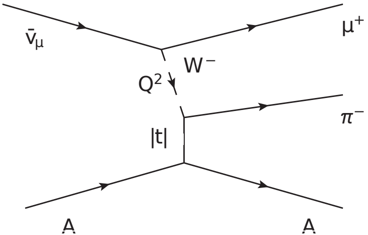
Introduction: CC Coherent π Production

Theoretical background

Small energy transfer to the nucleus:
$\rightarrow$ forward going μ and π,
$\rightarrow$ nucleus stays in the ground state.



PCAC Models (*Rein-Seghal, Berger-Sehgal, Schalla-Paschos*)

- relate $\sigma(\nu + A \rightarrow \mu + \pi + A)$ with the $\sigma(\pi + A \rightarrow \pi + A)$
- valid for high neutrino energies, used in all neutrino generator codes.

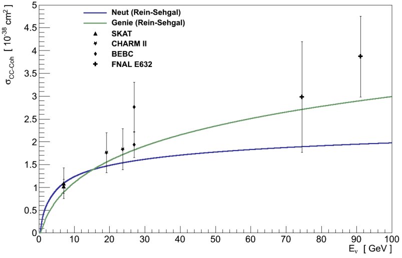
Microscopic Models (*Alvarez-Ruso, Hernandez, Nieves, Nakamura*)

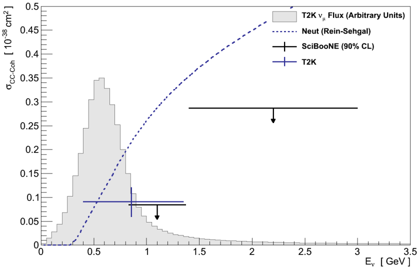
- excitation of the Δ resonance, full quantum mechanical treatment.

Introduction: CC Coherent π Production

Experimental background

Data is scaled assuming $A^{1/3}$ dependance.





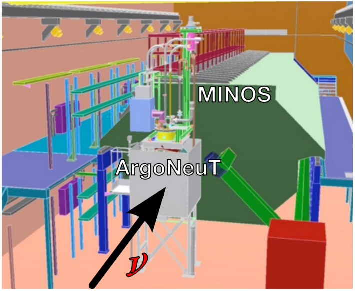
credit: http://danielscully.co.uk/thesis, Fig 4.4 and 6.38.

Introduction: The ArgoNeuT Detector

(see Eric's talk for more details)

The Argon Neutrino Test is a LArTPC at Fermilab

- 170 L TPC, 4 mm wire spacing;
- mm-scale resolution, 3-D imaging and calorimetry;
- MINOS ND used as a muon spectrometer (for μ charge & $\vec{p}$).



Introduction: The ArgoNeuT Detector

(see Eric's talk for more details)

At the NuMI beam, the antineutrino-enhanced run is rich in both $\bar{\nu}_\mu$ and ν_μ.

For the results shown today: 6-month run, total of 1.2e20 POT

	$\langle E \rangle$, GeV	Integrated Flux, cm^{-2}
$\bar{\nu}_\mu$	3.6 ± 1.5	2.94×10^{12}
ν_μ	9.3 ± 6.5	6.56×10^{11}

The Analysis

Event Selection

[Reconstruction Cuts]

↓

Event Classification

[Boosted Decision Tree]

↓

Signal Extraction & Cross Section

Event Selection

Recall the event topology:

$$\nu_\mu + A \rightarrow \mu^- + \pi^+ + A \quad (1)$$

$$\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A \quad (2)$$

where the μ and π are forward going.

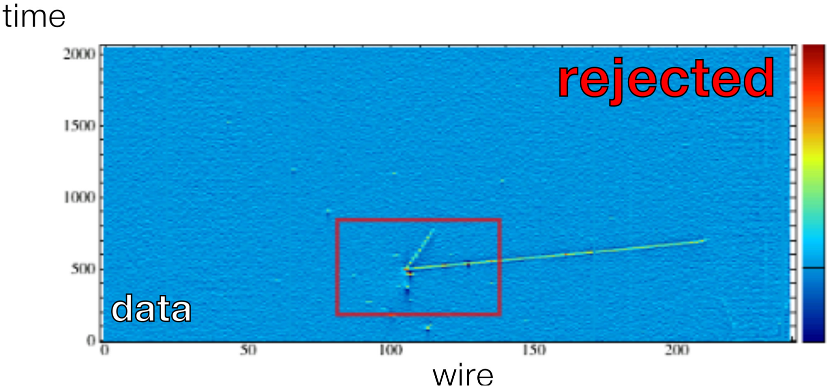
The neutrino interactions are reconstructed using the LArSoft software.

We look for:

- Two-track events:
  - μ track matched to MINOS;
  - π candidate track might not be contained;
    - $< dE/dx >$ cut: must correspond to ~ 1 MIP;
    - If contained, calorimetry based PID is used.
- No activity around the vertex

Event Selection

- No activity around the vertex:
  - charge cut: a box surrounding the vertex is defined and the charge collected inside of it must be associated to the 2 tracks.



Event Selection

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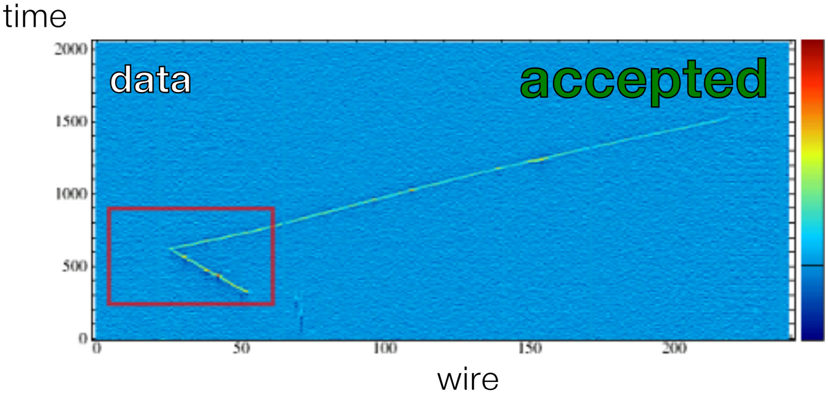
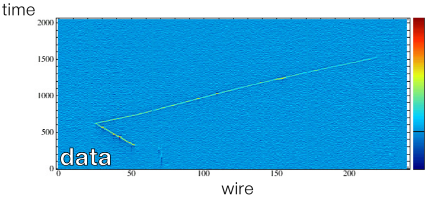
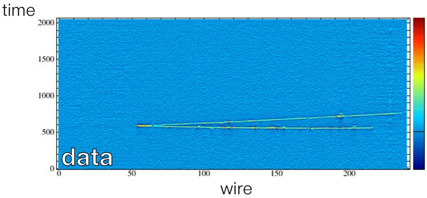


Event Selection

The Event Selection leaves us with a collection of neutrino/antineutrino events with clean 2 track topology.

Very exclusive selection: efficiency $\sim$ 20%.





The next step is to classify these events into Signal (CCCohPion) or Background (mainly CCRES and CCDIS)

Event Classification

Ideally, we would cut on Q^2 or $|t|$.

$$Q^2 = 2(E_\mu + E_\pi)(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2 \tag{3}$$
$$|t| = |(q - P_\pi)^2|$$

But the π's are frequently **not contained** in the TPC.

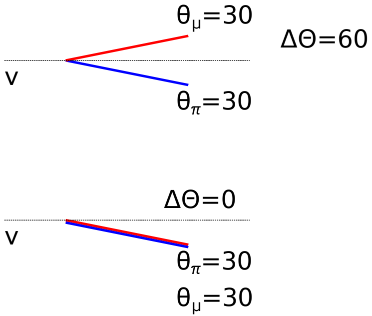
A multivariate analysis is set, using all kinematic observables, so that we can find the distinct kinematic features of CC Coh π production.

Event Classification

Multivariate method: Boosted Decision Tree[1] (BDT)

Inputs:

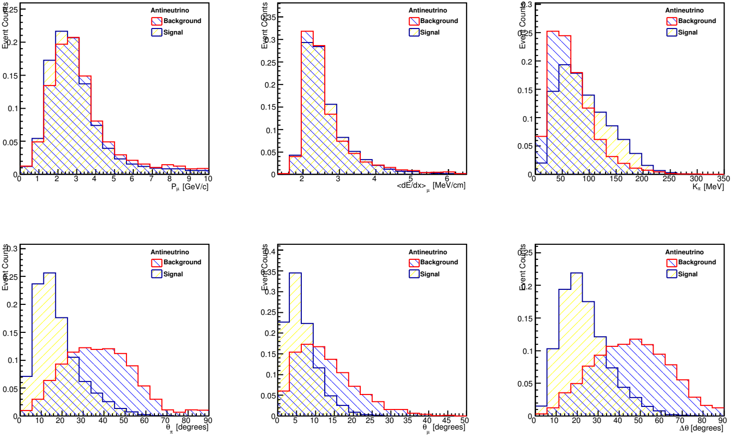
- θ_π: the angle of the π track.
- θ_μ: the angle of the μ track.
- $\Delta\theta$: the opening angle between the two tracks.
- K_π: the kinetic energy of the π based on calorimetry.
- P_μ: the μ momentum.
- $\left\langle \frac{dE}{dx} \right\rangle_\mu$: the average stopping power of the first third of the μ track.



[1] *credit to Root TMVA.*

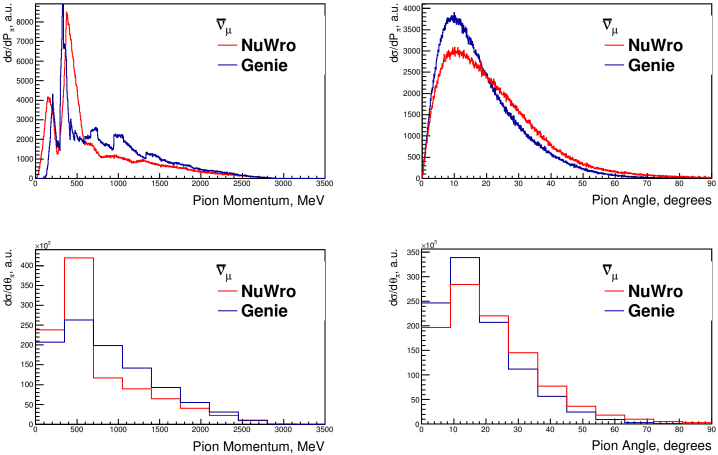
Event Classification

Signal/background discrimination.



Event Classification

Model dependance attenuated by coarse scanning of input parameters, when training the BDT.

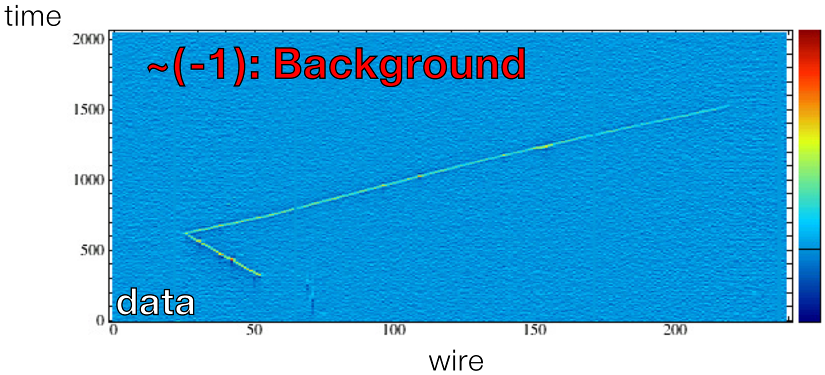


Event Classification

The BDT is trained using the MC Simulation:

- GENIE R-2.8.0[2] is the neutrino generator;

Each event is classified with a value $\in [-1, 1]$.



[2] *special thanks to the GENIE authors for their support!*

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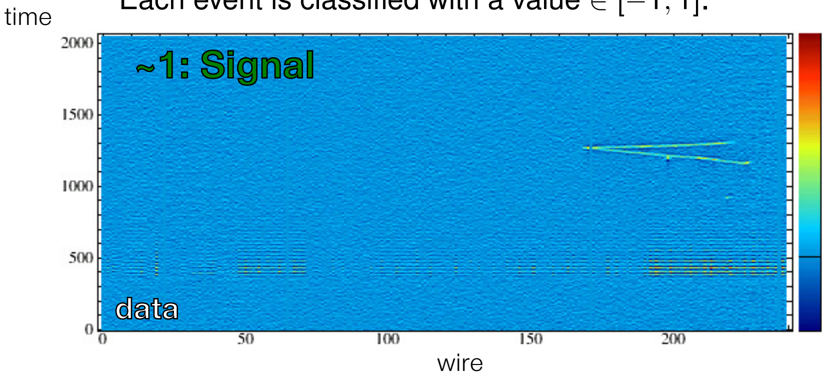
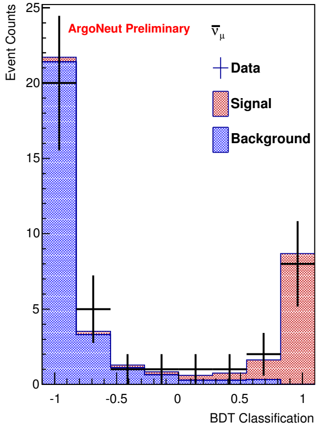


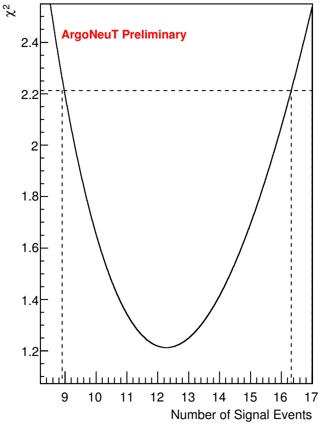
Signal Extraction

The MC is used to build a binned background and signal expectation for the BDT response.

This is then fit to the data.

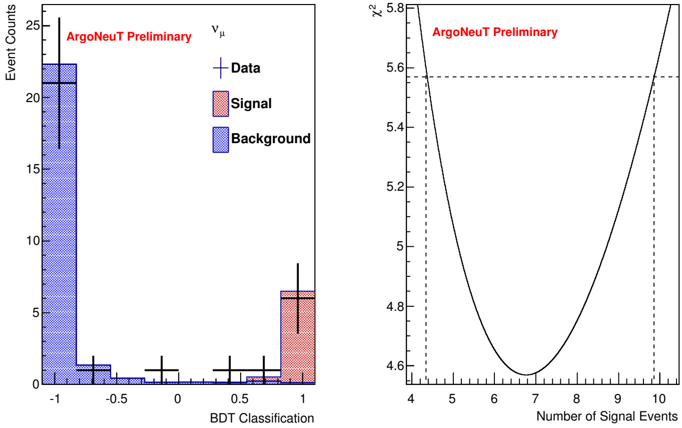
Signal Extraction - Antineutrino





Fitted signal: $12.3^{+4.0}_{-3.3}$ events.

Signal Extraction - Neutrino



Fitted signal: $6.8^{+3.1}_{-2.4}$ events.

Error Summary

Evaluating systematic errors:

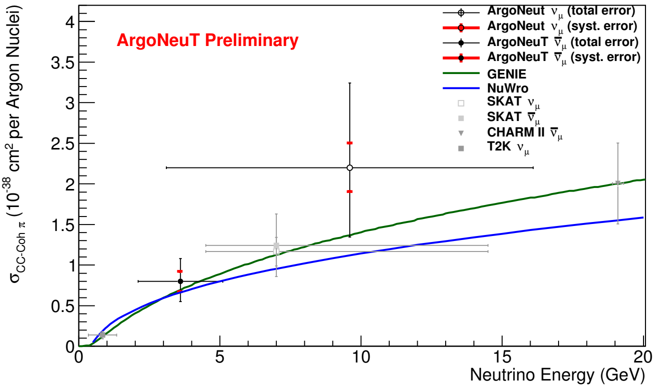
- Flux normalization (11%), POT (1%);
  - The leading systematic error.
- Reconstruction;
  - MINOS momentum res., ArgoNeuT angle res., energy scale;
  - The reconstructed parameters are varied by 1σ.
- Background Scale
  - We tweak the total cross section for background processes by $\pm 20\%$.
- Nuclear Effects
  - Background added by FSI. The model uncertainty is large, we vary this faction of events by $\pm 20\%$

Error Summary

		Frac. cross section uncertainty [%]	
Syst. Uncertainty		$\bar{\nu}_\mu$	ν_μ
Flux normalization (11%)		$^{+10}_{-12}$	$^{+10}_{-12}$
Recon.	MINOS momentum res. (4%)	±3.5	±2.5
	ArgoNeuT angle res. (1°)	±5.1	±5.2
	Energy scale (3.4%)	±8.0	±6.6
Bg. Scale	CC QE (20%)	±0.09	±0.32
	CC RES (20%)	$^{+2.3}_{-2.9}$	$^{+0.79}_{-0.87}$
	CC DIS (20%)	$^{+0.83}_{-0.91}$	$^{+1.5}_{-1.7}$
	NC (20%)	±0.13	±0.16
	Wrong-sign μ (20%)	±0.13	±0.7
Nuclear Effects (20%)		±1.3	$^{+0.9}_{-1.1}$
POT (1%)		$^{+1.0}_{-1.0}$	$^{+1.0}_{-1.0}$
Total systematics		$^{+14.5}_{-16.1}$	$^{+13.5}_{-15.1}$

Cross Section Values

Preliminary: running final checks for very low energy protons.



$$\sigma_{\bar{\nu}_\mu} = \left(8.0^{+2.6}_{-2.1}(stat)^{+1.2}_{-1.3}(syst)\right) \times 10^{-39}\,\mathrm{cm}^2/\mathrm{nucl.}$$

$$\sigma_{\nu_\mu} = \left(2.2^{+1.0}_{-0.8}(stat) \pm 0.3(syst)\right) \times 10^{-38}\,\mathrm{cm}^2/\mathrm{nucl.}$$

Conclusion

We present the first measurement of CC Coherent π production on Argon.

Also the first time machine learning is applied to LAr data.

The LAr technique shows great potential for this measurement:

- great resolution at the vertex;
- precise calorimetry.

This measurement is affected by large statistical errors.

- future experiments (MicroBooNE/LAr1ND) will have much more precision (hundreds/thousands of events).

ArgoNeuT Collaboration

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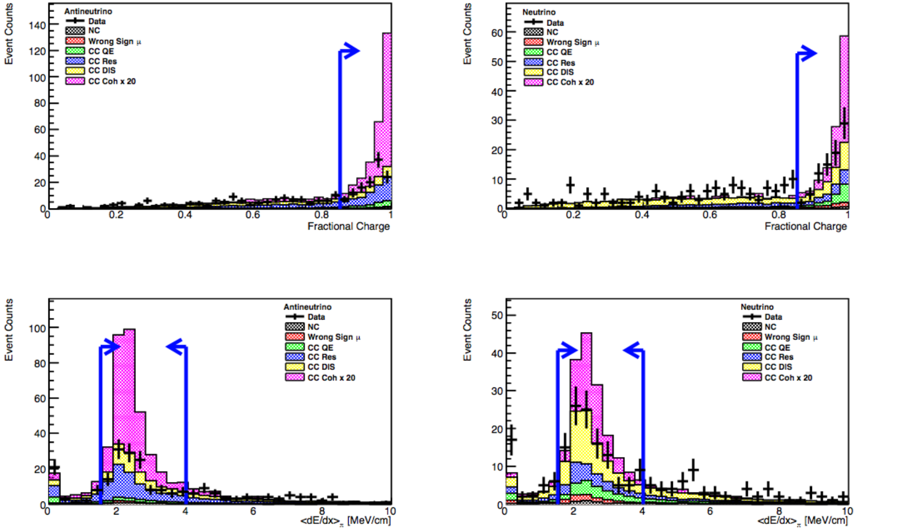
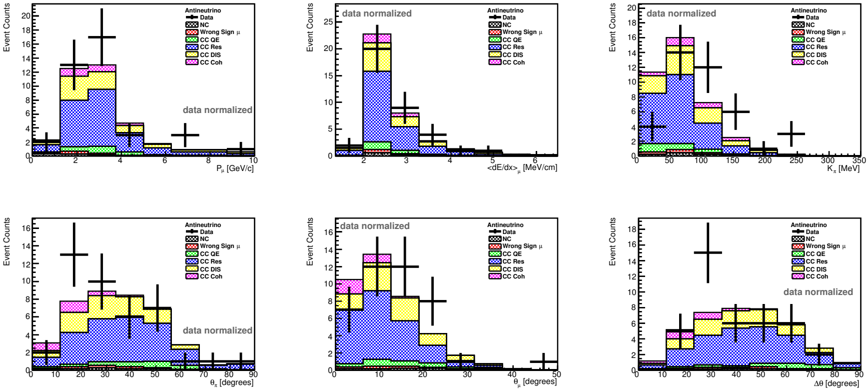
Backup

Event Selection



Event Classification



Signal Extraction

$$\chi^2 = 2\sum_{i=1}^{N}\left[\mu_i(n_s, \hat{n}_b) - n_{obs,i} + n_{obs,i}\ln\frac{n_{obs,i}}{\mu_i(n_s, \hat{n}_b)}\right]$$

$n_{obs,i}$ - number of data events observed in bin i;
$\mu_i(n_s, \hat{n}_b)$ - expectation value for bin i ($s_i + b_i$);
n_s - signal scale;
$\hat{n}_b$ - best estimate of background scale for a signal hypothesis.