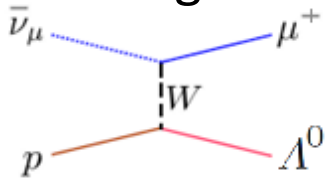
Strangeness Production in ArgoNeut via Anti-neutrino Scattering from Protons

Saima Farooq
Tim Bolton
Kansas State University
HEP Seminar Nov 17th, 2010

Motivation

- Λ Production is the Simplest $\bar{\nu}N$ Process after Quasi-Elastic Scattering process of Neutrino from the Nucleon



- Naively, Λ Production is Cabibbo Suppressed Process and is as an Order of Magnitude $\tan^2\theta_c\sigma_{QE} \sim 0.05\sigma_{QE}$ and thus, Possibly Important

- Existing Experimental Data on Λ (Strange Particle) Production is Sparse

- QE Λ Production will have Different Nuclear Response than QE $\bar{\nu}$ due to the absence of Pauli effects for the Λ

- LArTPC can SEE Λ. Other Coarser Grained Detectors Probably Cannot

- Much of the Argoneut Phase I Data is in $\bar{\nu}$ mode and all of Argoneut Phase II would be in ν mode

Strange Particle Production & Identification

Study Requires:

- **An Intense Neutrino Beam**
- **A Detector Capable of Identifying Strange Particles**

CC ν_l

$$\begin{aligned}
\bar{\nu}_l + p^+ &\rightarrow l^+ + \Lambda^0 \\
&\rightarrow l^+ + \Sigma^0 \\
&\rightarrow l^+ + \pi^0 + \Lambda^0 \\
&\rightarrow l^+ + \pi^0 + \Sigma^0 \\
&\rightarrow l^+ + K^- + p^+ \\
&\vdots \\
\bar{\nu}_l + n^0 &\rightarrow l^+ + \Sigma^- \\
&\rightarrow l^+ + \pi^- + \Lambda^0 \\
&\rightarrow l^+ + \pi^0 + \Sigma^- \\
&\rightarrow l^+ + K^- + \Lambda^0 \\
&\vdots
\end{aligned}$$

CC ν_l

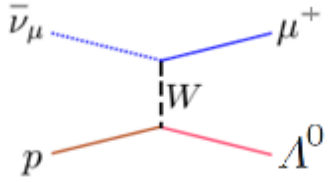
$$\begin{aligned}
\nu + p &\rightarrow \mu^- + p + K^+ \\
\nu + n &\rightarrow \mu^- + n + K^+ \\
\nu + n &\rightarrow \mu^- + p + K^0
\end{aligned}$$

$$\begin{aligned}
K_s^0 &\rightarrow \pi^+\pi^- \quad 69\% \\
K_L^0 &\rightarrow \pi^+\pi^-\pi^0 \quad 12.5\%
\end{aligned}$$

Strange Particle Production & Decay

- Secondary Detached Vertex

$$\overline{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$$



$$\Lambda^0 \rightarrow p\pi^- \quad 64\%$$
$$\rightarrow n\pi^0 \quad 36\%$$

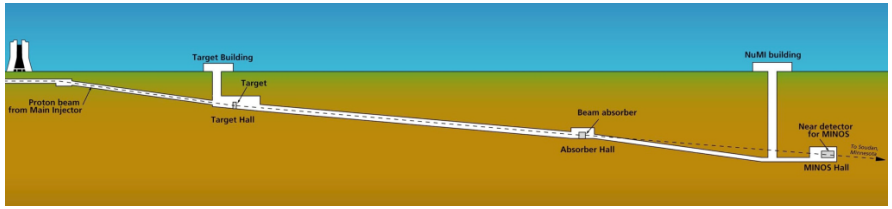
- QE Sigma Production may be Identifiable as we an Pick Up the Decay Photon in Principle
- Sigma Production Adds up to the Lambda Sample

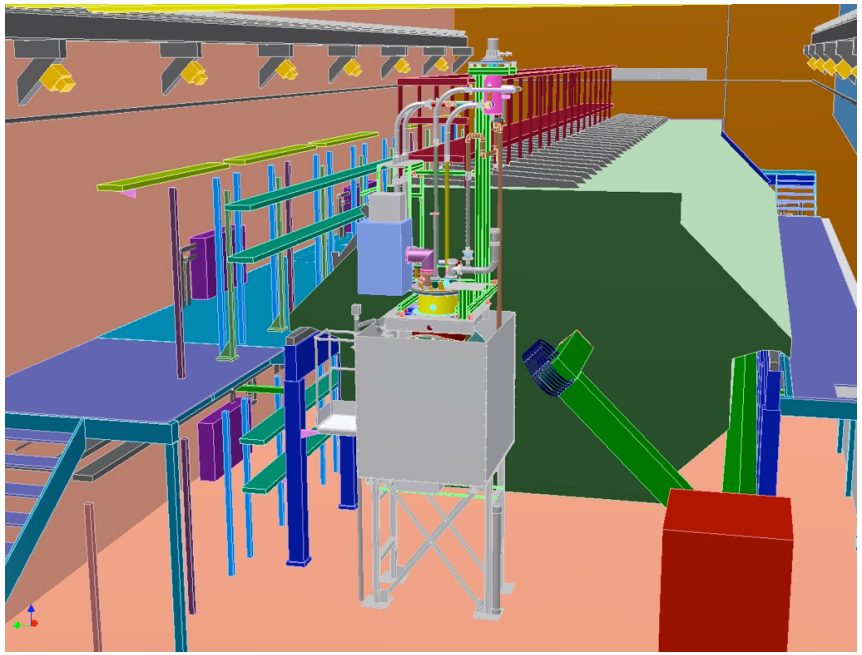
$$\overline{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$$
$$\Sigma^0 \rightarrow \gamma\Lambda^0$$
$$\Lambda^0 \rightarrow p\pi^-$$
$$\rightarrow n\pi^0$$

ArgoNeut

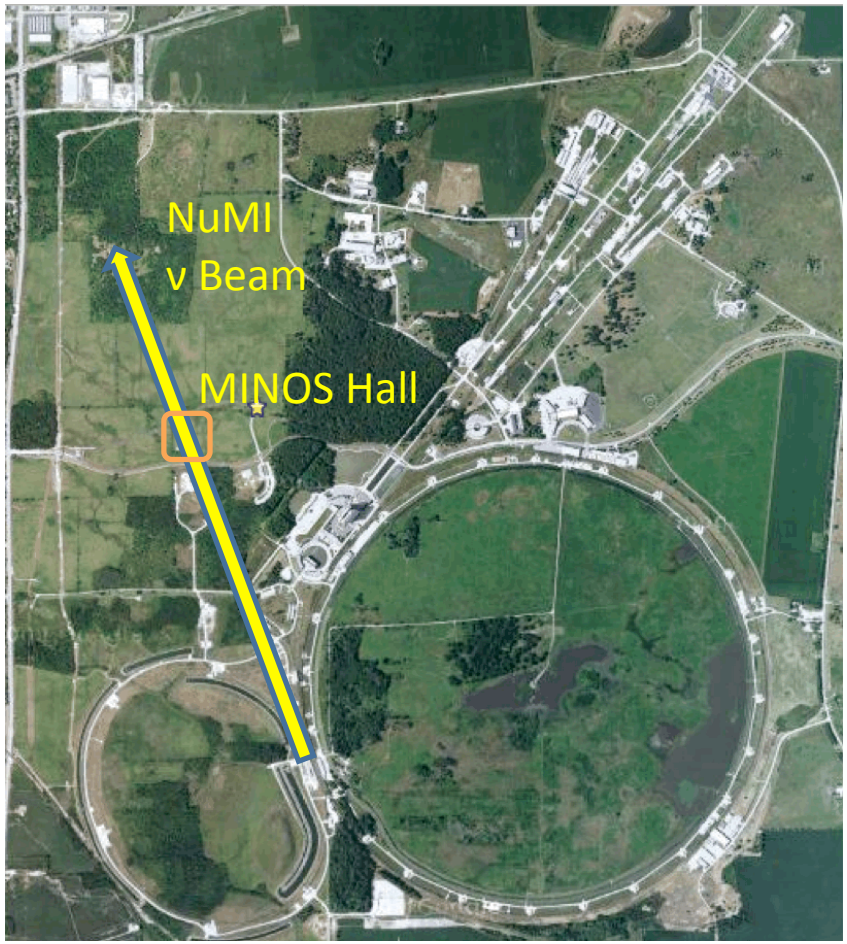
- ArgoNeuT is a joint NSF/DOE R&D test project at Fermilab to expose a small-scale “liquid argon time projection chamber” (LArTPC) to the NuMI neutrino beam
- ArgoNeuT is located at Fermilab upstream of the MINOS near detector, and is calibrated using muons that traverse the chamber and penetrate several layers into MINOS.
- ArgoNeut can see neutrino interactions (~150 events/day): 1st time in the U.S., 1st time ever in a low-Energy beam
- ArgoNeuT also serves as a stepping stone to larger detectors like MicroBooNE and LBNE, by providing experience in operating underground argon recirculation, trigger, and readout systems.

ArgoNeut Run-I Location at Fermilab





MINOS Hall at Fermilab, 1Km from Target
Argoneut in Downstream of MINOS



NuMI Beam at Fermilab
120GeV Protons -> Graphite Target -> Pions-> numu

ArgoNeut Goals

- **Low Energy Cross-Sections in Liquid Argon**

  techniques used can be applied to larger detectors to know more about neutrinos & their properties
- **Axial Mass** Measurement
- Liquid argon could also help measure **the strange content of nucleons.**
- **Increased Accuracy**: ArgoNeuT measures the value dE/dx. The measurement of a gamma's dE/dx is approximately twice that of an electron (~4.2 MeV/cm: ~2.1 MeV/cm).
- Demonstrating the Effectiveness of the

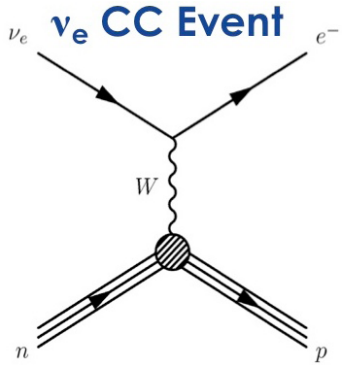
  Liquid Argon **Purification Techniques** for bigger

  and better detectors
- **Long Term Goals**: Continued measurements of

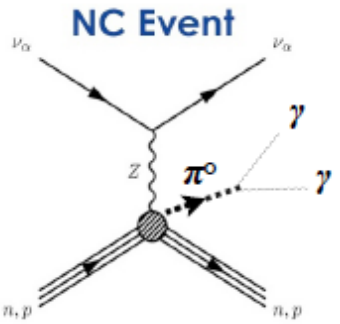
  neutrino oscillation parameters,

  testing for CP violation in the lepton sector,

  detecting dark matter directly, and searching for proton decay.



"appearance" signal



"appearance" background

ArgoNeut's Working

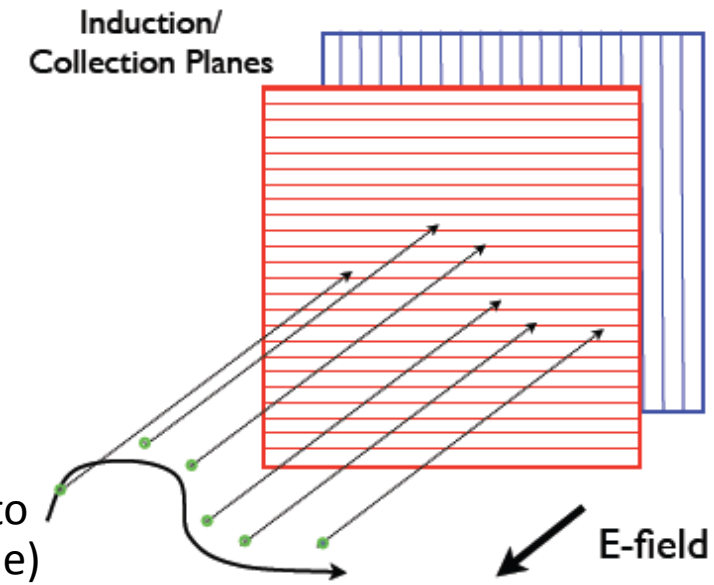
There are three main systems in ArgoNeuT:

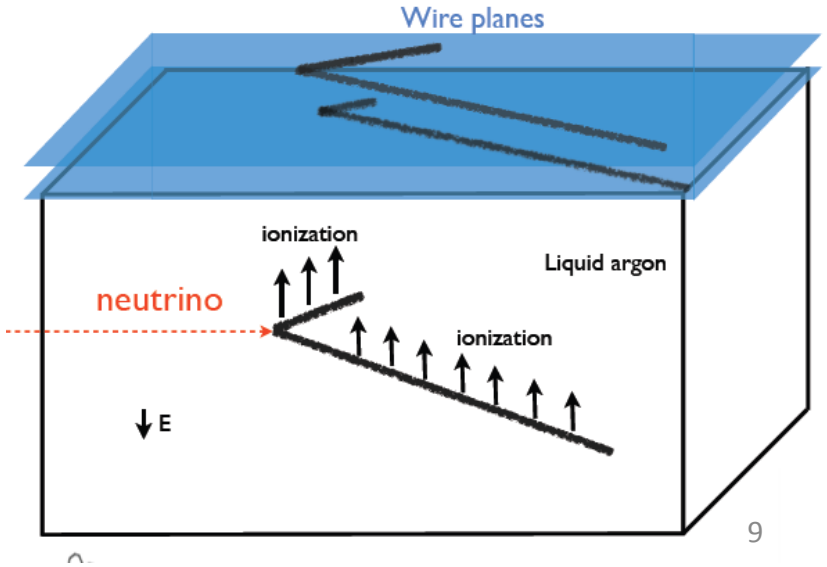
1. The Time Projection Chamber (TPC)
2. The Purity System
3. The Recirculation System

ArgoNeut's Working

1. The TPC:

- 0.5 x 0.5 x 1.0 m^3
- 175 L of liquid argon
- Two wire planes oriented at 60° relative to each other (induction and collection plane)
- Each plane has 240 wires spaced 4 mm apart (position and trajectory of particles in an event)
- Electric field of 500 V/cm
- The TPC records 2048 samples in 400 microseconds per NuMI beam spill, allowing for multiple snapshots of the same event.



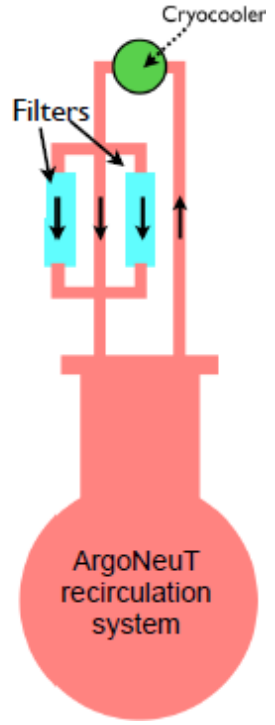


ArgoNeut's Working

2. **Purity System:**

- Filter contains copper granules, which are oxidized by the incoming oxygen impurities to form copper (II) oxide. (Oxygen is highly electronegative, could absorb ionized particles produced by an event and impact the energy registered by the system)

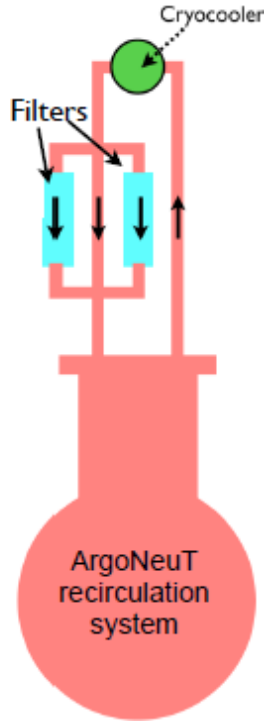
- Once the copper is saturated with oxygen, the filter is heated to around 250° C to regenerate and remove the oxygen from the copper granules, allowing the pellets to process more argon.



ArgoNeut's Working

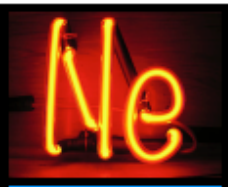
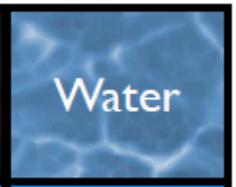
3. Recirculation System:

- Evaporated argon (B.P 87K) in the Cryostat travels up a system of pipes to a Cryocooler; a machine that extracts heat from an object to bring its temperature down to less than 150K. The newly liquefied argon flows back down another system of pipes to the TPC.



Why Nobel Gas a Target for Neutrinos?

- **Abundant ionization electrons** and scintillation light can both be used for detection.
- **Ionization can be drifted** over long distances, provided with the purity of liquid.
- **Excellent dielectric properties**, accommodates very large voltages.
- **Noble Liquids are dense**, so they make a good target for neutrinos.
- **Argon is relatively cheap** and easy to obtain (1% of atmosphere).

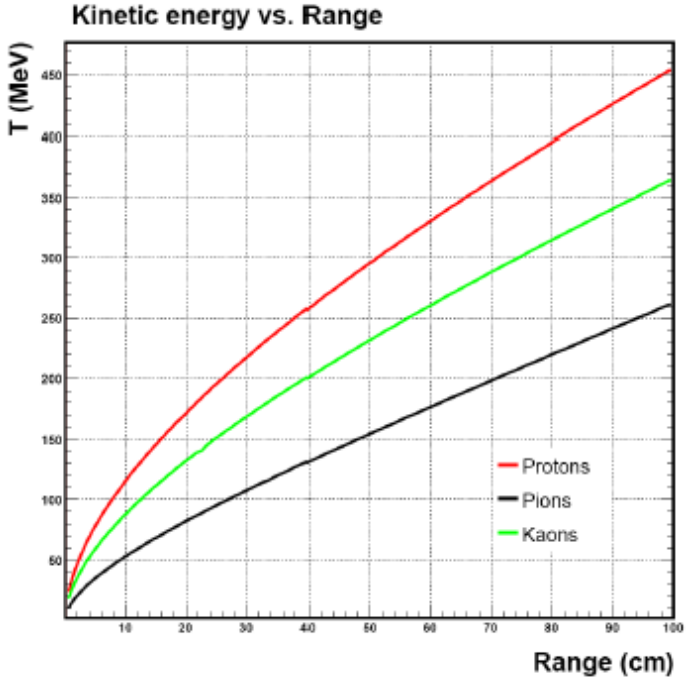
						
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

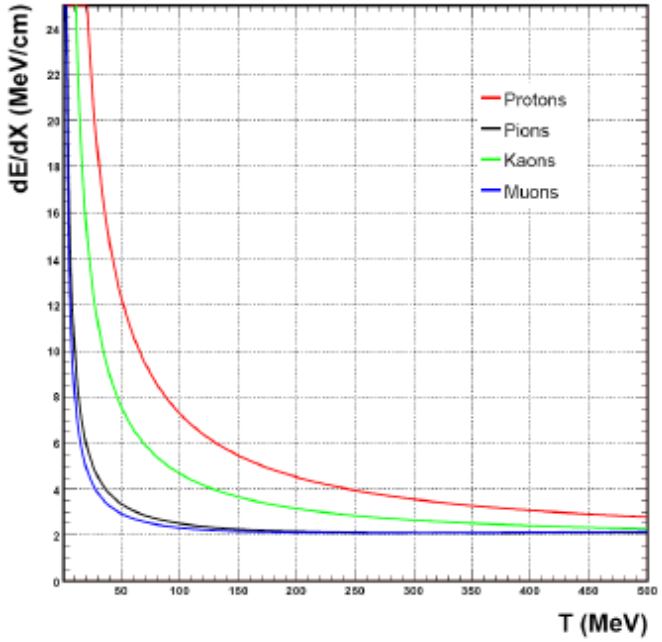
Reconstruction

Neutrino events in LArTPCs are reconstructed using the LArSoft.

- **Hit construction** and identification from the raw data signal information (HitFinder)
- **Hit clustering -** the grouping of proximal hits to form clusters (ClusterFinder)
- **2D line reconstruction -** to identify and fit line-like tracks (HoughLineFinder)
- **Vertex reconstruction -** End points of a hough line (VertexFinder)
- **3D track reconstruction -** from 2D line-like tracks on both wire planes (TrackFinder)
- **Track matching** with downstream MINOS near detector to fully reconstruct muons.

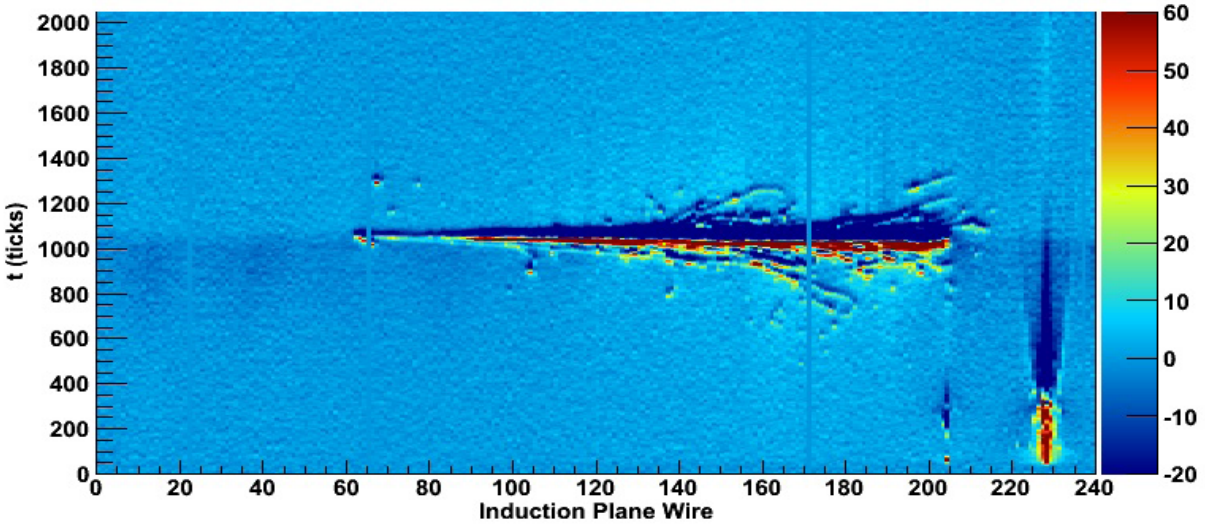
Particle Identification

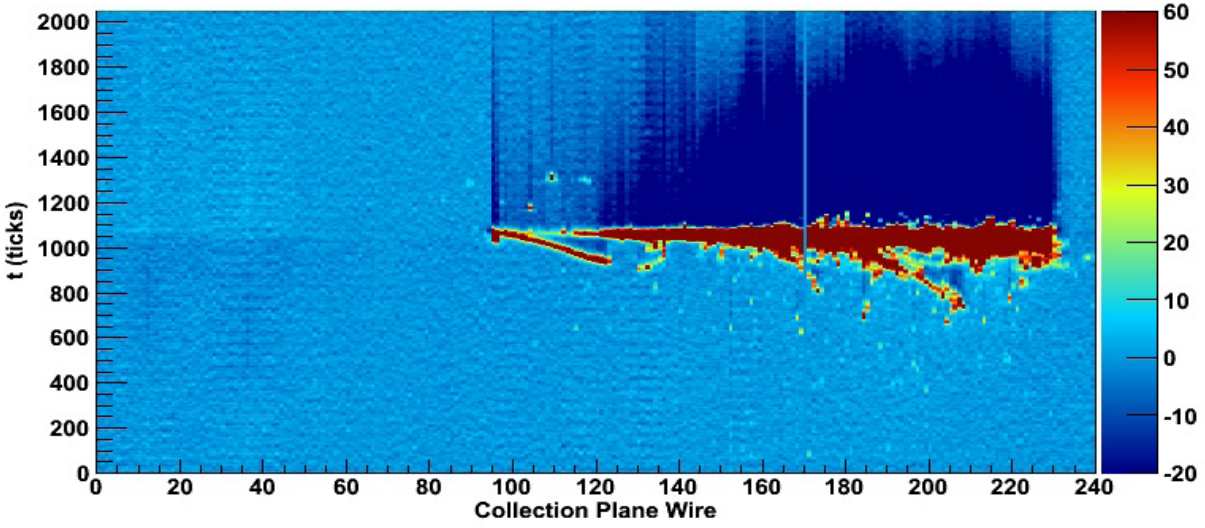


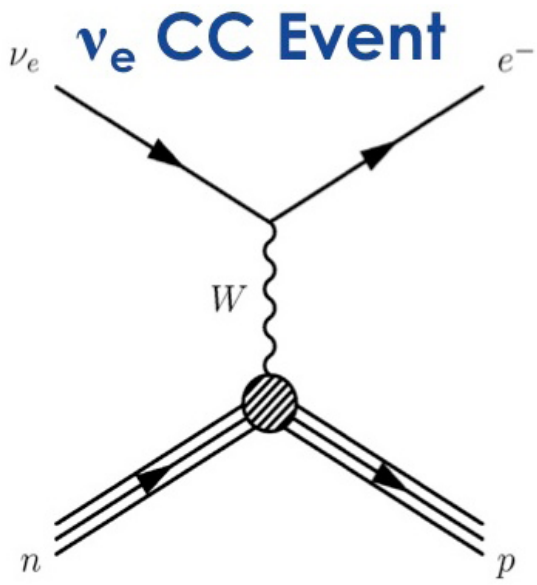


- Track Length tells the kinetic energy of the particle
- dE/dx (energy profile of a track) tells about the particle ID
- Pions and muons are hard to differentiate, muons are reconstructed by track matching with MINOS

Event Display

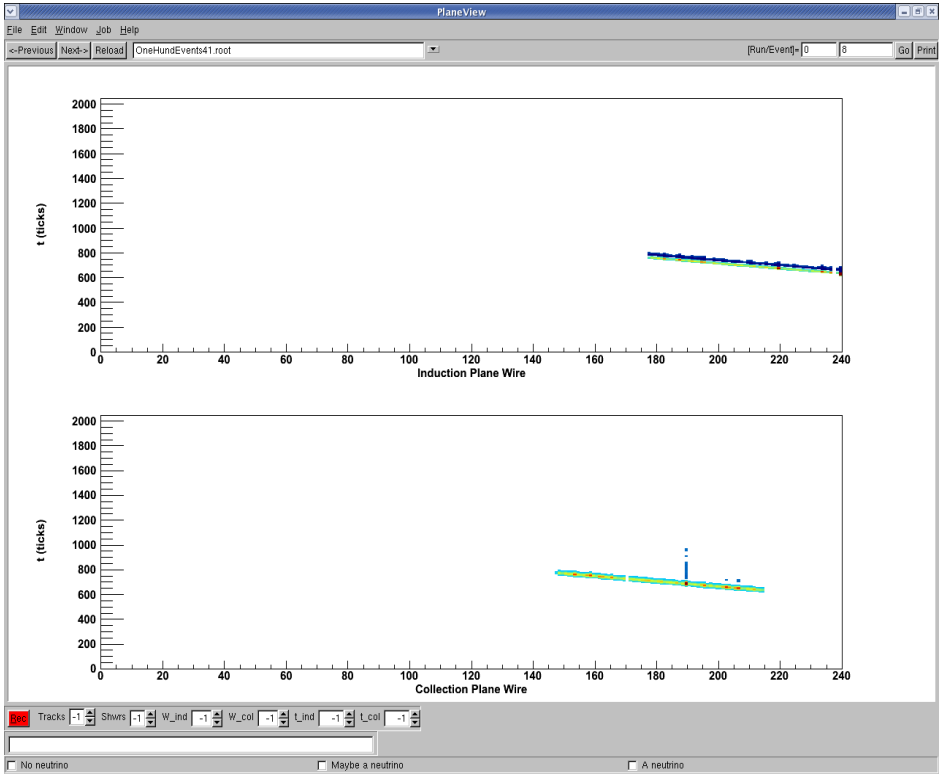


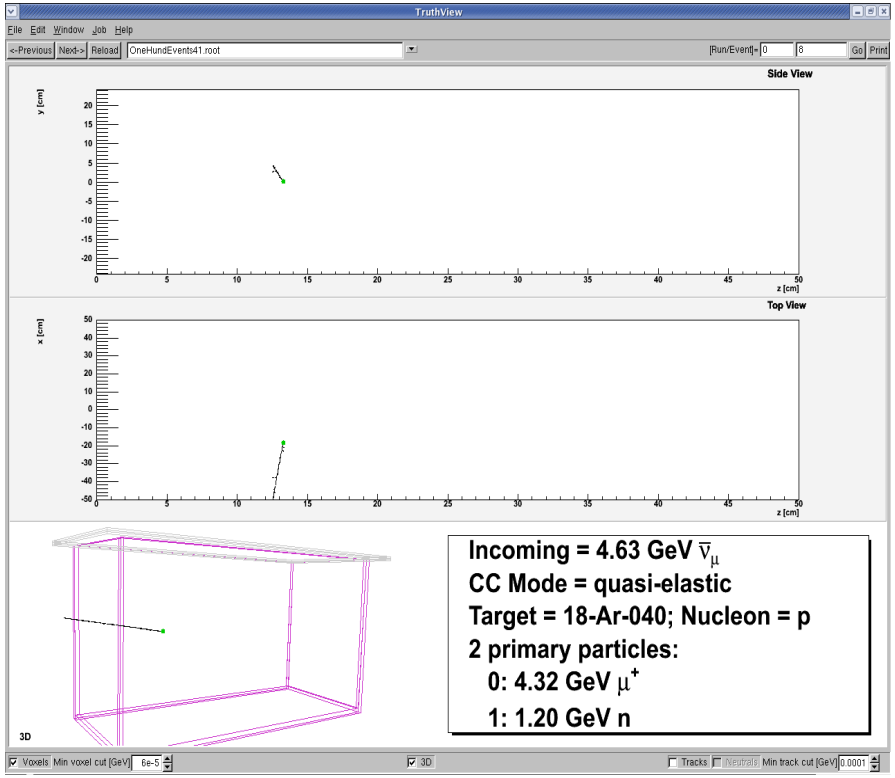




CCQE *ve* Candidate

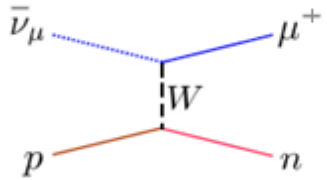
Event Display and HandScan





Plane View of the Simulated Event

CCQE Event



Truth View of the Event

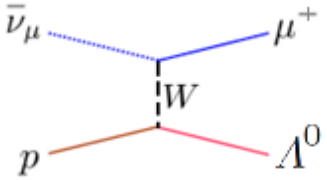
Lambda Production – Detached Vertex Visible

$$\bar{\nu}_\mu p \rightarrow \Lambda^0 \mu^+$$

$$\Lambda^0 \rightarrow p\pi^-$$

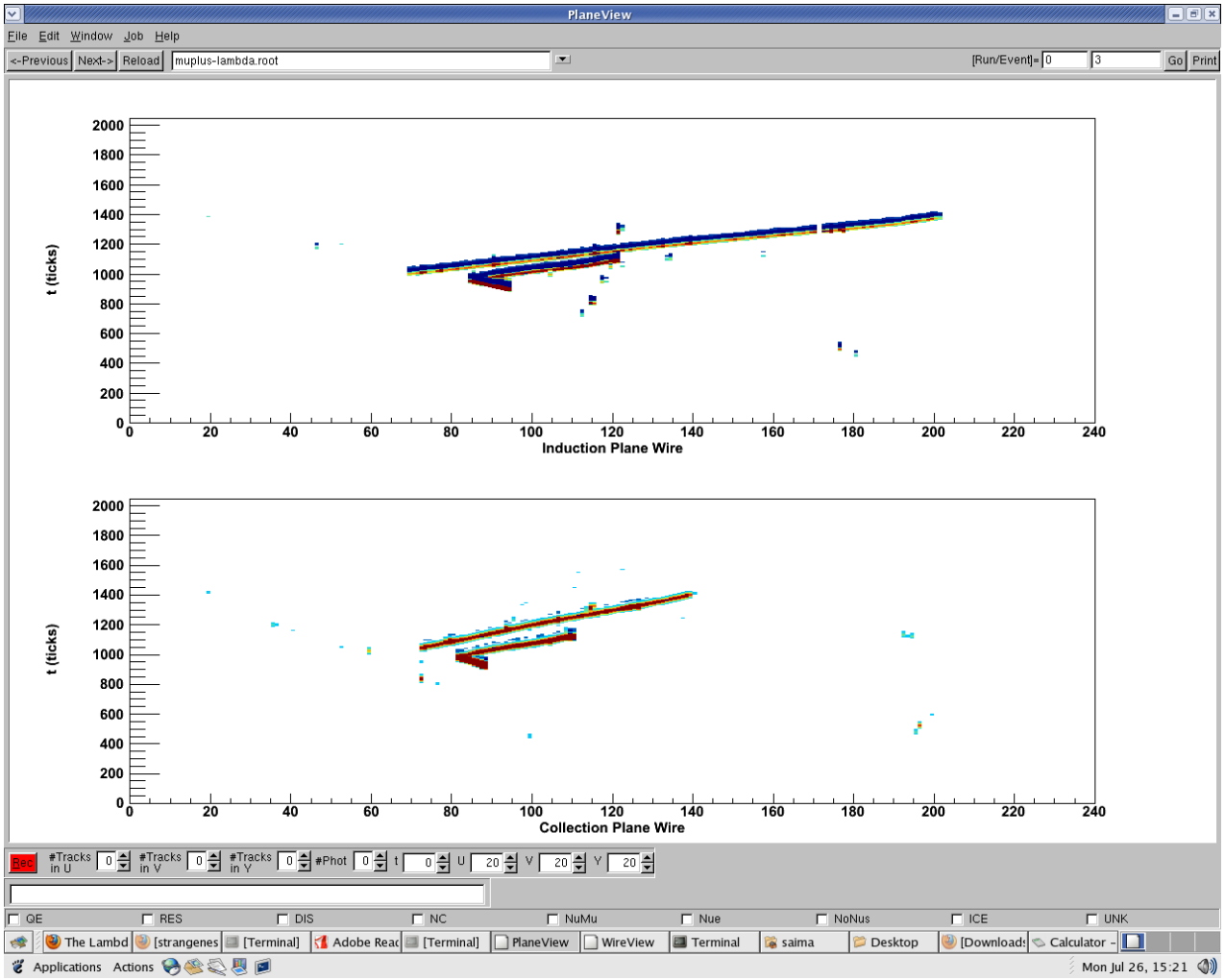
- Events Generated by Single Particle Generator

- Lambda/Sigma cross section model is required to get the final state kinematics right



$$E_{\mu^+} = 1.01\text{GeV}$$

$$E_{\Lambda^0} = 1.22\text{GeV}$$



Sigma Production in Neutrino-Nucleon Interaction

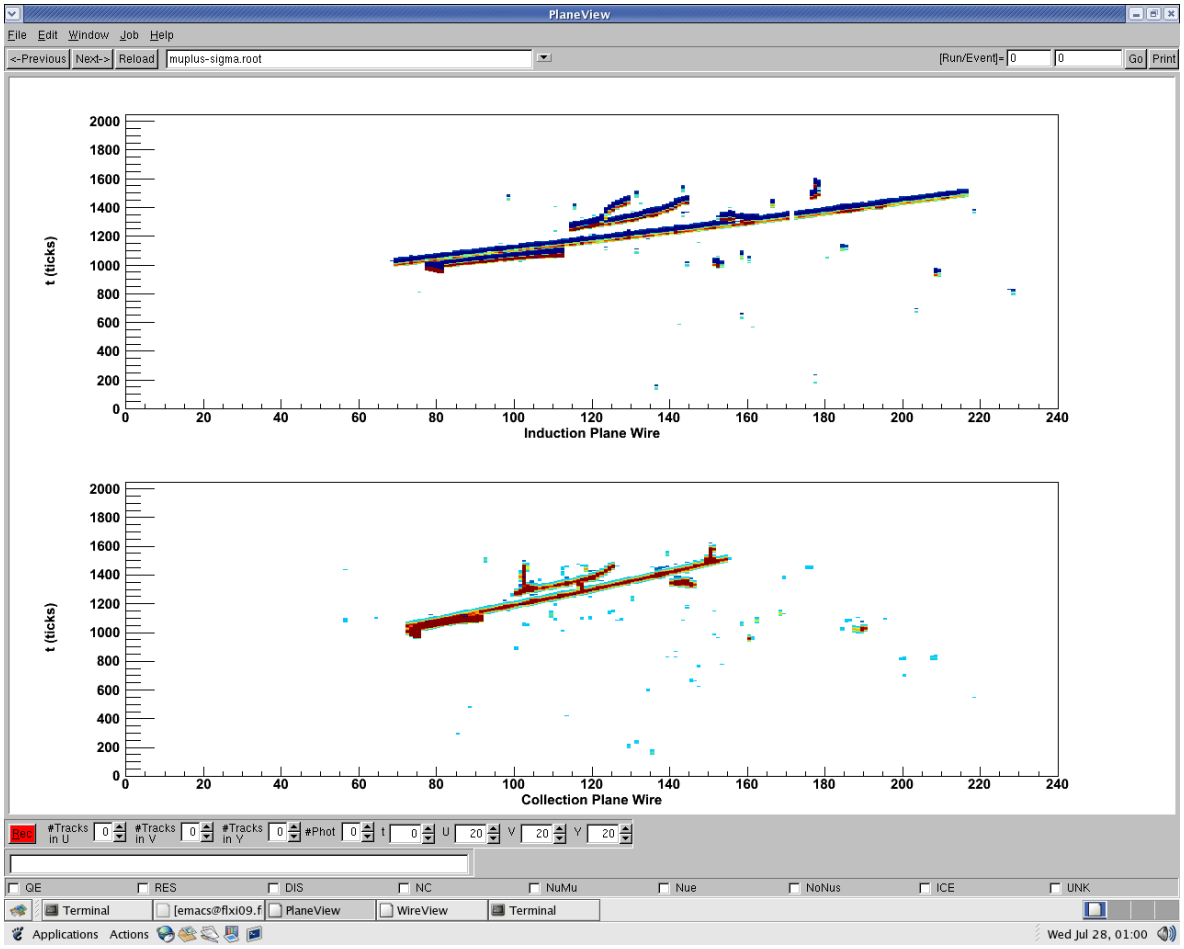
$$\overline{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$$
$$\Sigma^0 \rightarrow \gamma\Lambda^0$$
$$\Lambda^0 \rightarrow p\pi^-$$

- Events Generated by Single Particle Generator

- Lambda/Sigma cross section model is required to get the final state kinematics right

$$E_{\mu^+} = 1.01\text{GeV}$$

$$E_{\Sigma^0} = 1.29\text{GeV}$$



Total Cross section Measurement for Strangeness Changing CCQE Processes

$$\bar{\nu_L} + p \longrightarrow \Lambda + L^+ \text{ and } \bar{\nu_L} + p \longrightarrow \Sigma^0 + L^+$$

- The Cross Section Depends on Form Factors that are Similar to those of QE.

- The Form Factors Relate to those of QE by SU (3) Flavor Symmetry.

Lambda Production Cross-section

Lambda Production Cross section at 2GeV (NuMI) and at 1GeV (BNB)

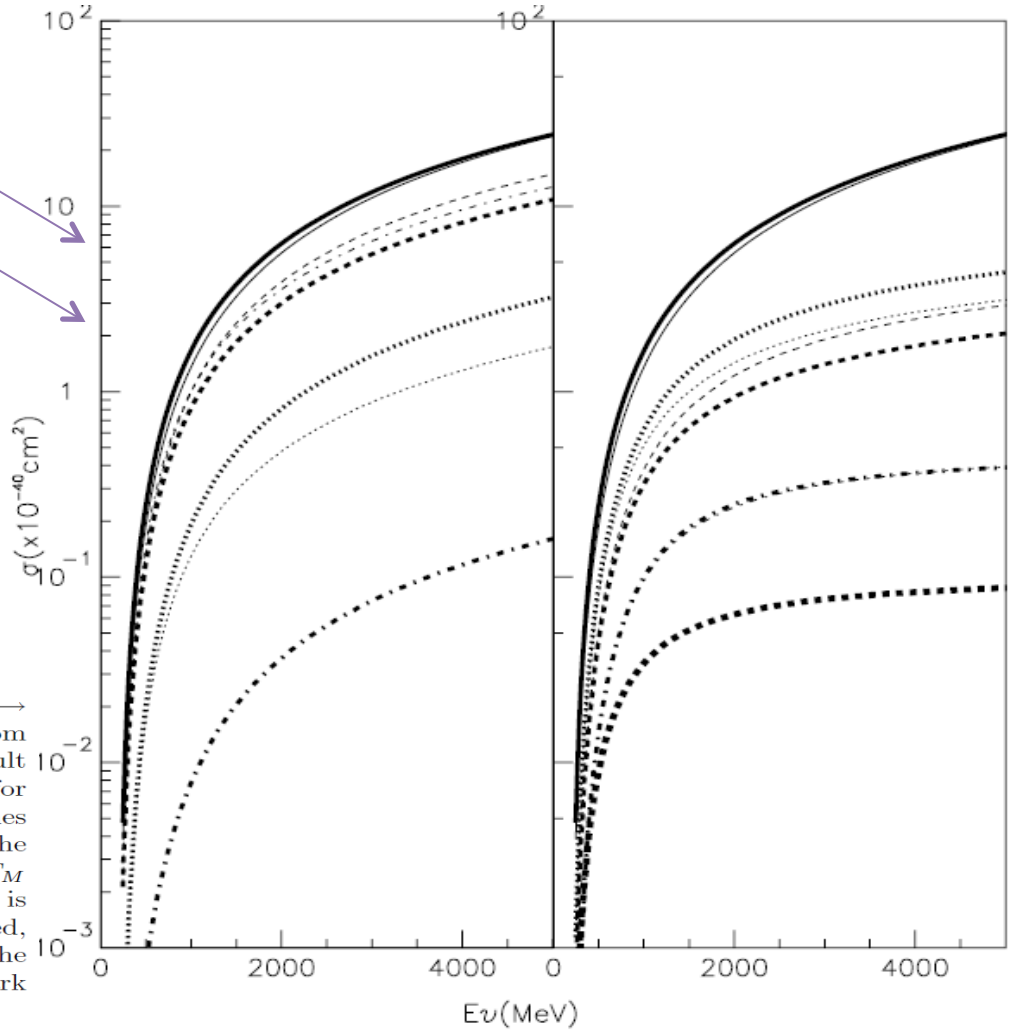


Fig. 2. Plot of the total cross-section for the reaction $\overline{\nu_e}+p \longrightarrow \Lambda + e^+$. In both panels the dark solid line is the result from polarization form factors and the light solid line is the result for the standard dipole form factor. The dark lines are for the polarization form factor contributions and the light lines are the dipole form factor contributions. In the left panel the dashed, dotted and light dash-dotted lines are the F_V, F_M and F_A squared contributions. The dark dot-dashed line is the contribution of F_E squared. In the right panel the dotted, dashed, and dot-dashed lines are the contributions from the $F_A F_M, F_V F_A$ and $F_V F_M$ interference terms. The lower dark dashed line is the $F_A F_E$ contribution.

S.L. Mintz and Lingling Wen, New Results for the Production of lambda and Sigma hyperons in antineutrino Scattering from Protons, Eur. Phys. J. A 33, 209-301 (2007)

Sigma Production Cross-section

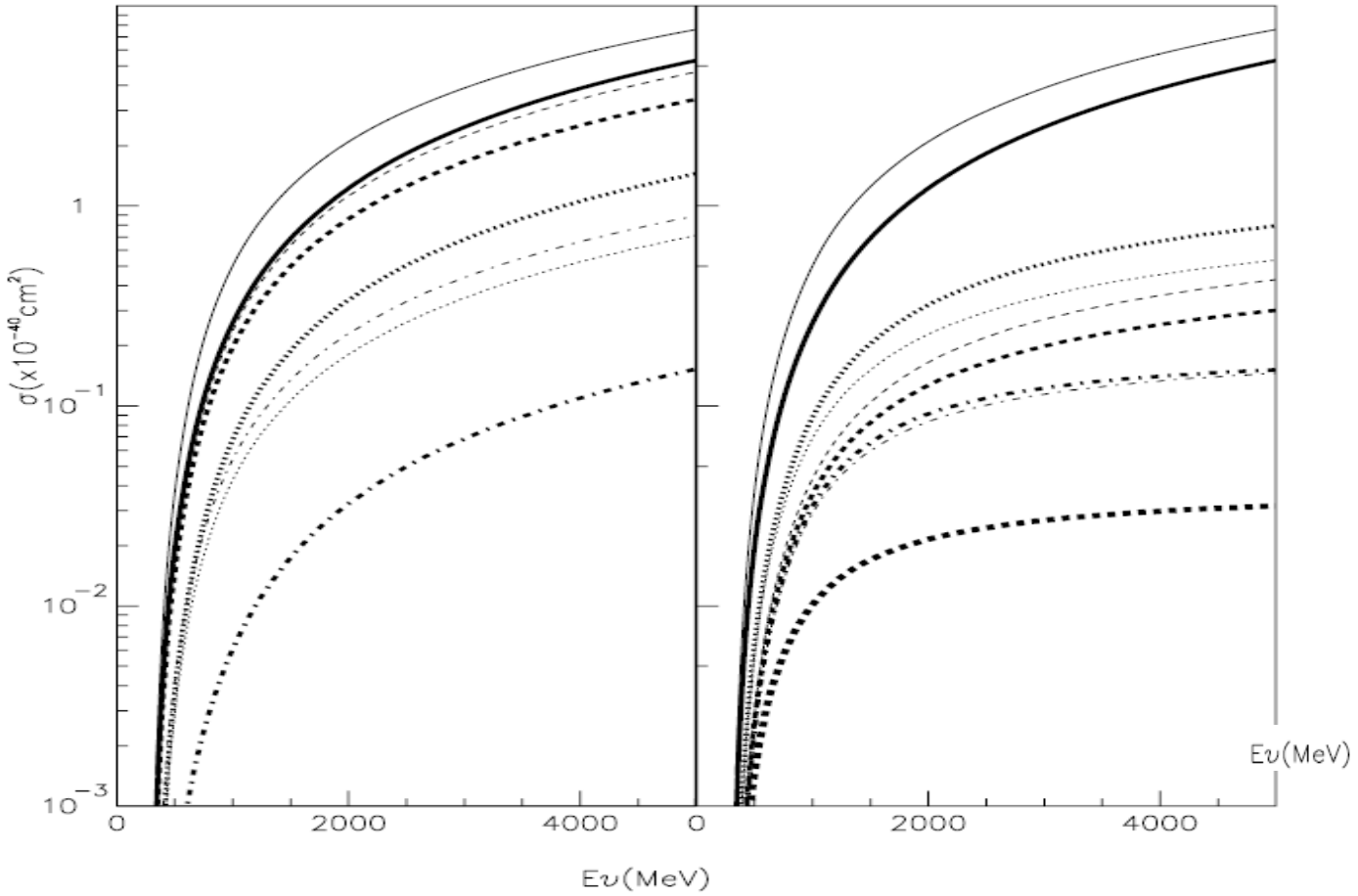


Fig. 3. Plot of the total cross-section for the reaction, $\overline{\nu_e} + p \longrightarrow \Sigma^0 + e^+$. The notation is the same as in fig. 2.

S.L. Mintz and Lingling Wen, New Results for the Production of lambda and Sigma hyperons in antineutrino Scattering from Protons, Eur. Phys. J. A 33, 209-301 (2007)

ArgoNeut Phase I

Antineutrino Mode (1.35x10^{20} POT)

Expected Lambda Yield

Preliminary

$$\sigma^{\bar{\nu}_\mu}_{QE}(2GeV) = 0.23x10^{-38}\,cm^2$$

$$\sigma_\Lambda(2GeV) = 6.75x10^{-40}\,cm^2\ *$$

$$\frac{\sigma_\Lambda(2GeV)}{\sigma^{\bar{\nu}_\mu}_{QE}(2GeV)} = 0.2935$$

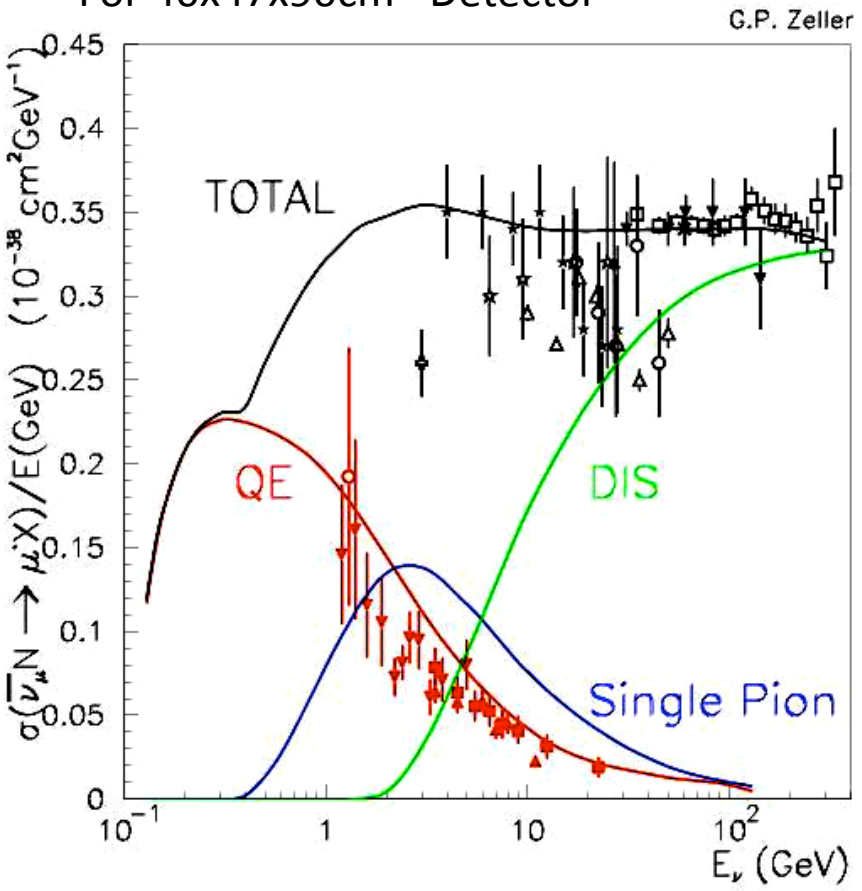
Too High?

$\Lambda \rightarrow p\pi^-$ Branching Fraction ~ 64%

No Detector or Energy Cuts for Event Rates

	# Events/180days
• CCQE (numu bar) • Lambda yield	• 1706 • 320

For 40x47x90cm^3 Detector



S.L. Mintz and Lingling Wen, New Results for the Production of lambda and Sigma hyperons in antineutrino Scattering from Protons, Eur. Phys. J. A 33, 209-301 (2007)

ArgoNeut Phase I

Antineutrino Mode (1.35x10^{20} POT)

Expected Sigma Yield

Preliminary

Sigma Production Rate is 30% Less than that of Lambda*

No Detector or Energy Cuts for Event Rates

	# Events/180days
• CCQE (numu bar)	• 1820
• Lambda Yield	• 320
• Sigma Yield	• 224

S.L. Mintz and Lingling Wen, New Results for the Production of lambda and Sigma hyperons in antineutrino Scattering from Protons, Eur. Phys. J. A 33, 209-301 (2007)

ArgoNeut Phase II

Antineutrino Mode (3.88x10^{20} POT)

Expected Lambda & Sigma Yield

Preliminary

$$\sigma^{\bar{\nu}_\mu}_{QE}(1GeV) = 0.195x10^{-38}\,cm^2$$

$$\sigma_\Lambda(1GeV) = 2x10^{-40}\,cm^2\ *$$

$$\frac{\sigma_\Lambda(1GeV)}{\sigma^{\bar{\nu}_\mu}_{QE}(1GeV)} = 0.1026$$

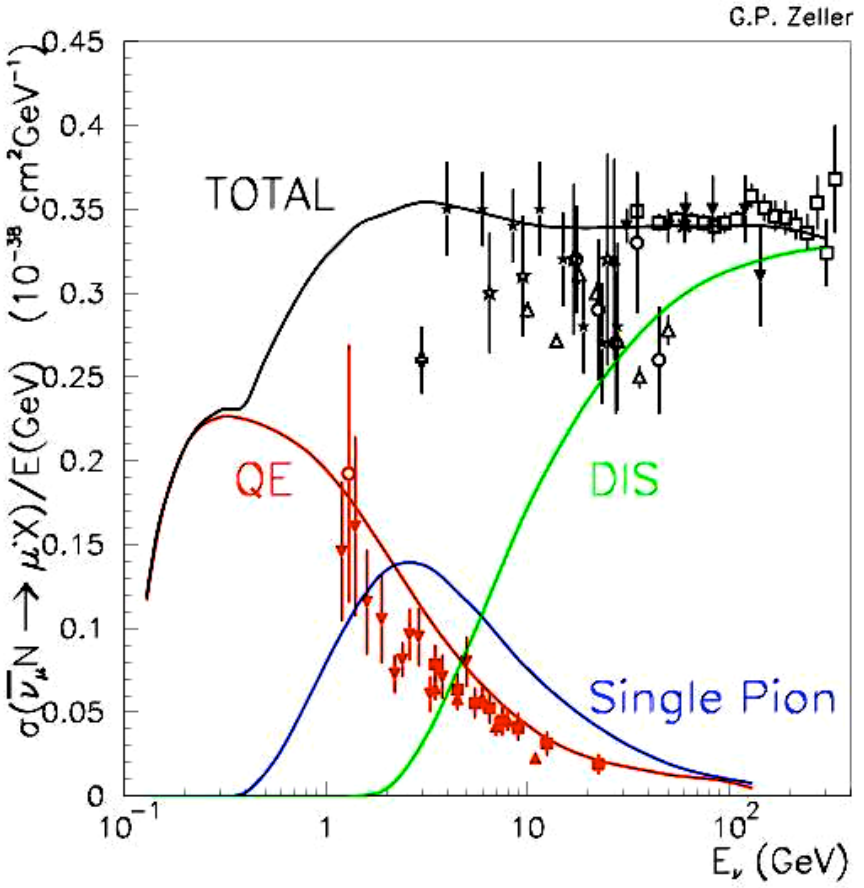
High?

$\Lambda \rightarrow p\pi^-$ Branching Fraction ~64%

No Detector or Energy Cuts for Event Rates

	# Events/180days
• CCQE (numu bar)	• 671
• Lambda Yield	• 44
• Sigma Yield	• 31

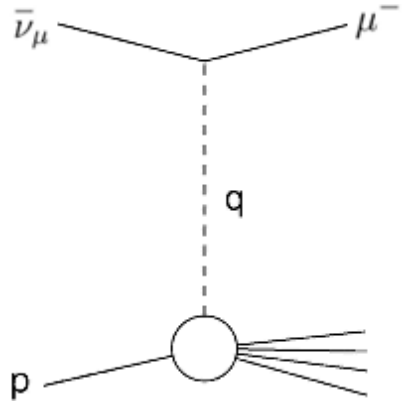
For 50x50x100cm^3 Detector



S.L. Mintz and Lingling Wen, New Results for the Production of lambda and Sigma hyperons in antineutrino Scattering from Protons, Eur. Phys. J. A 33, 209-301 (2007)

Lambda Production via CC-DIS from Protons

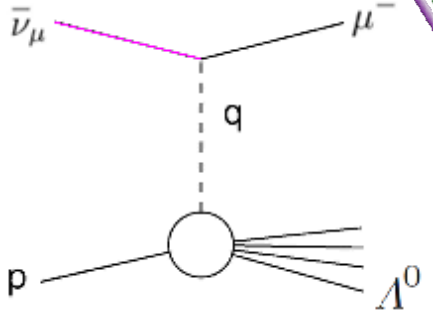
- CCQE (cabibbo suppressed) hyperon Production channel is NOT in the default list of event generation threads in GENIE (neutrino interaction model).

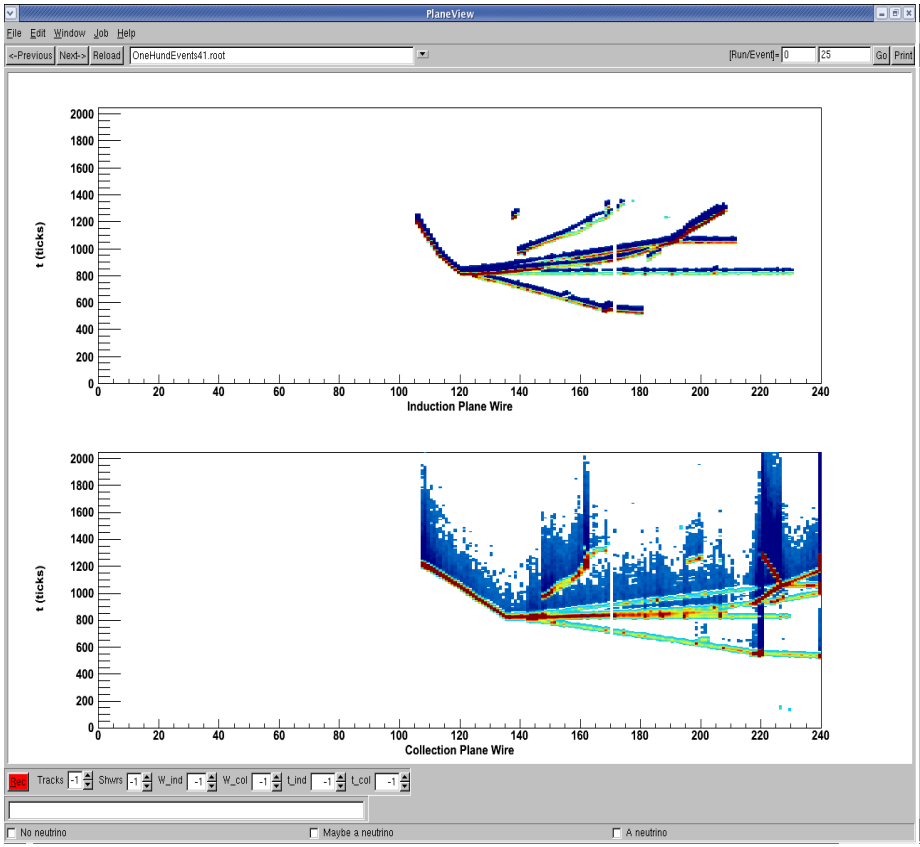


- It is hoped this channel be added in the near future.

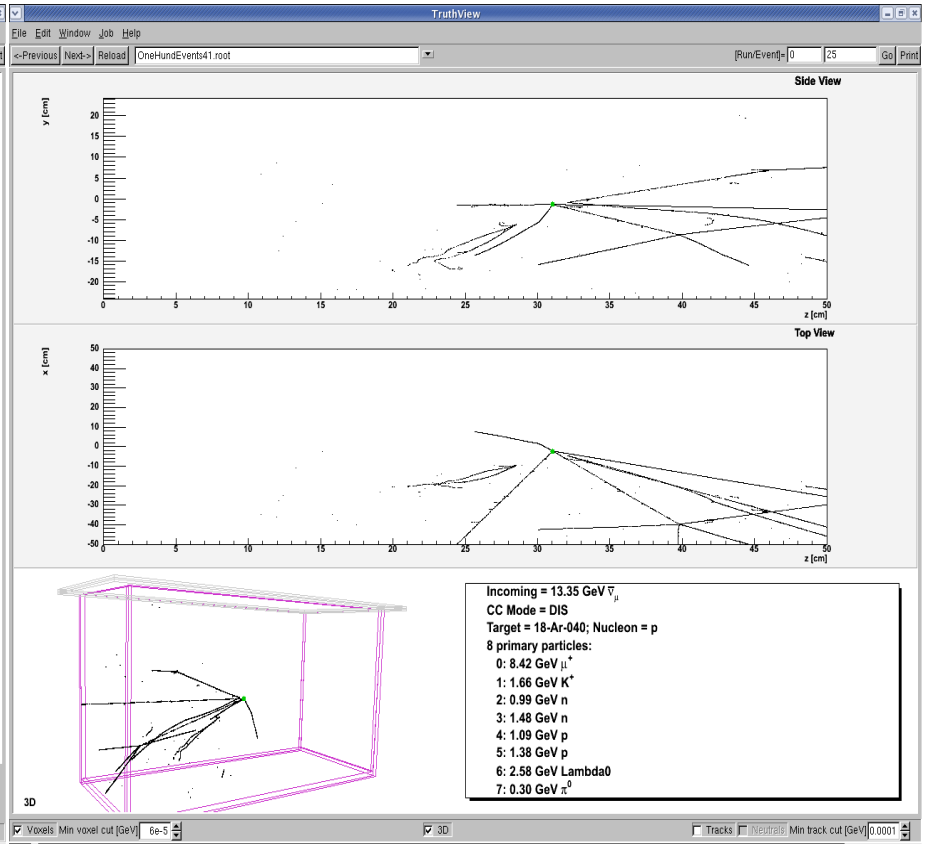
- An alternate analysis of lambda production is being carried out which is with CC-DIS lambda production events to be able to use or create the required tools.

CC-DIS Lambda Event in ArgoNeut



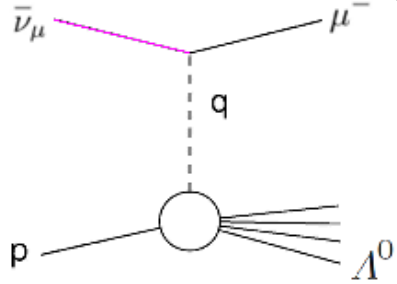


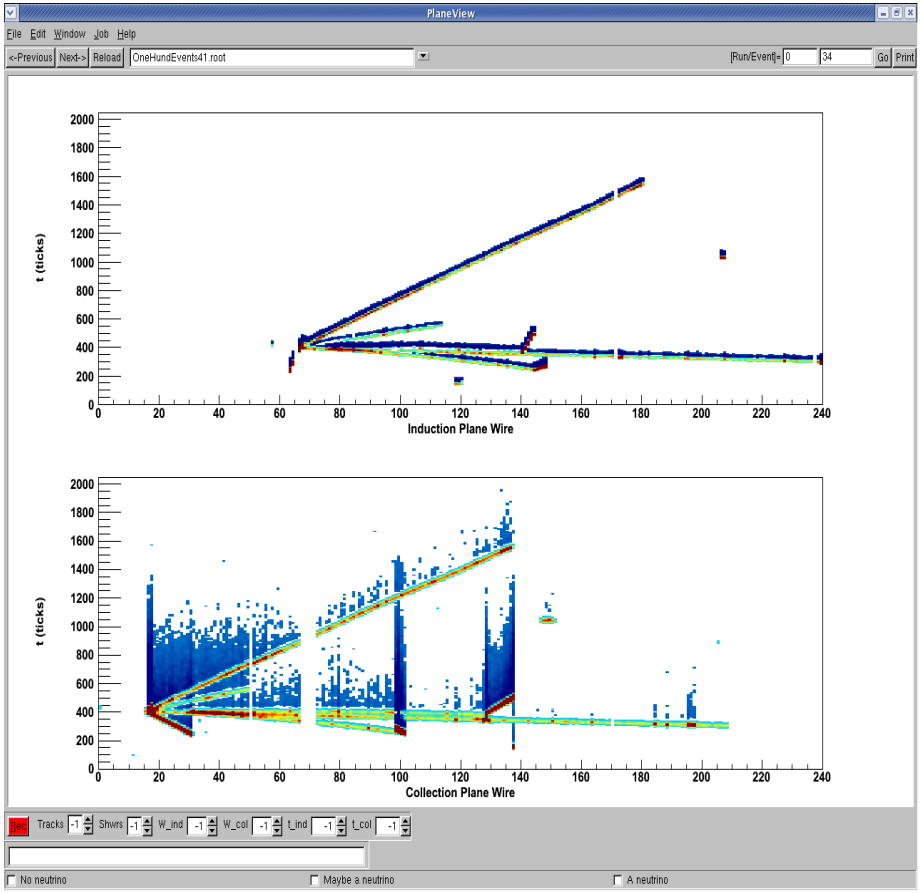
Collection and Induction Plane View



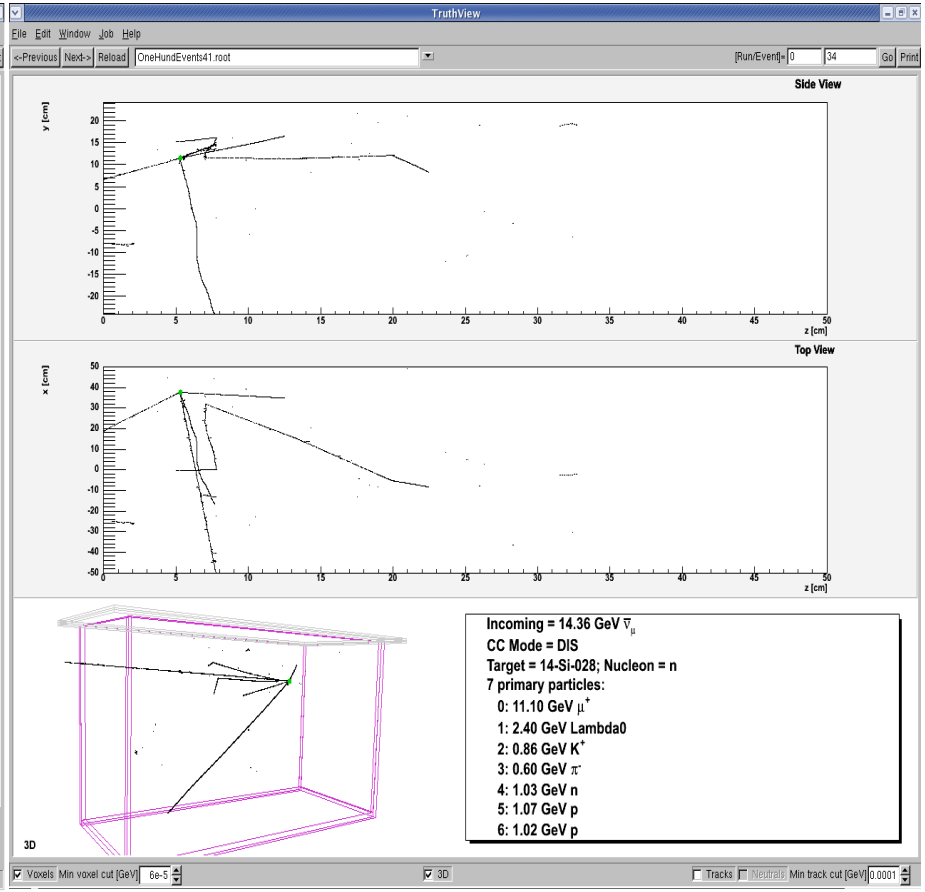
Truth view

CC-DIS Lambda Event in ArgoNeut



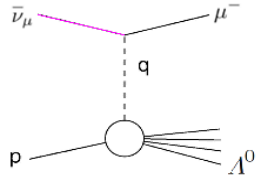


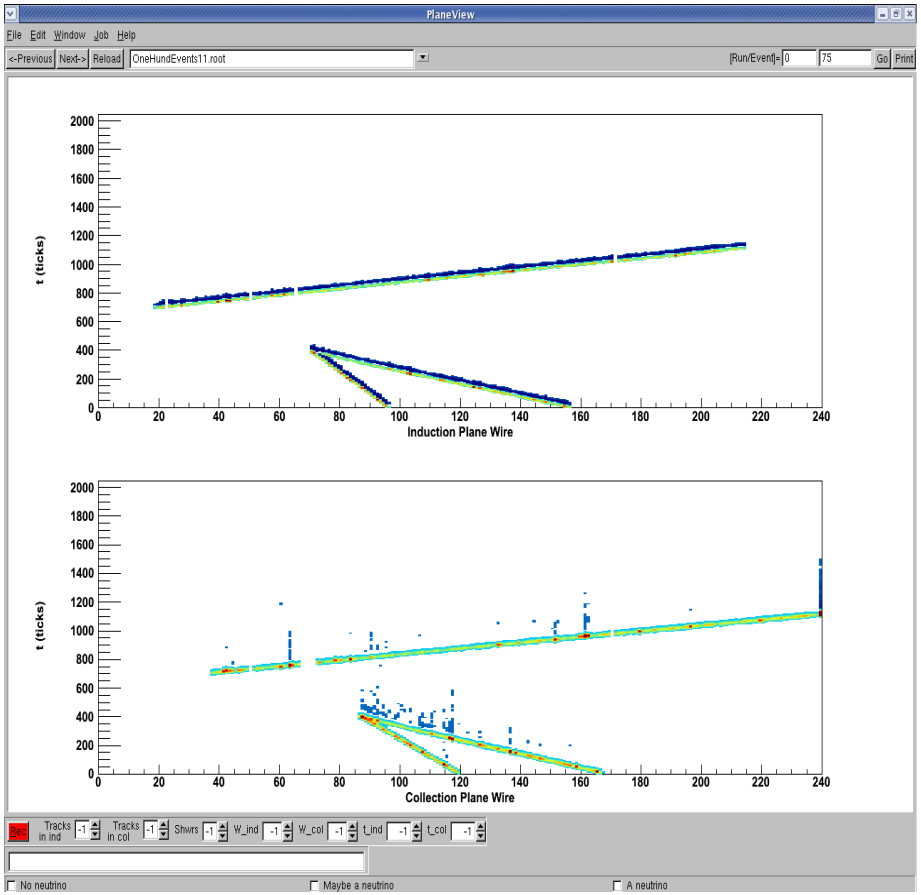
Collection and Induction Plane View



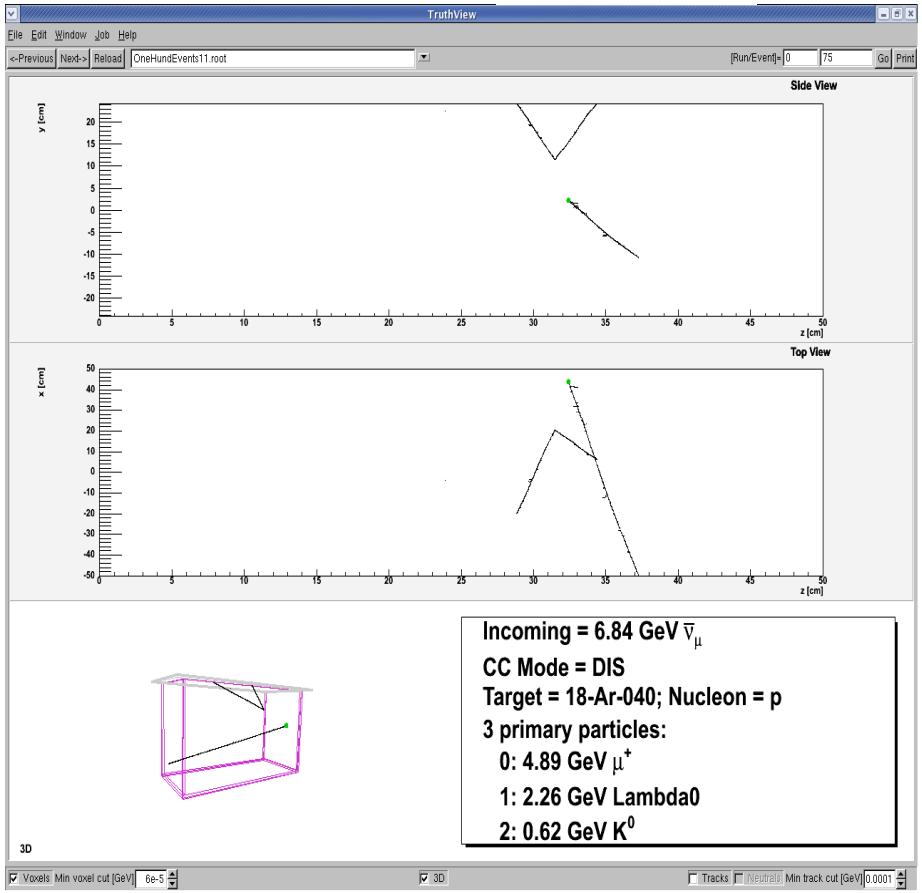
Truth view

CC-DIS Lambda Event (looks like CCQE Lambda)



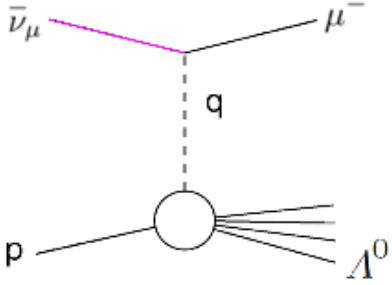


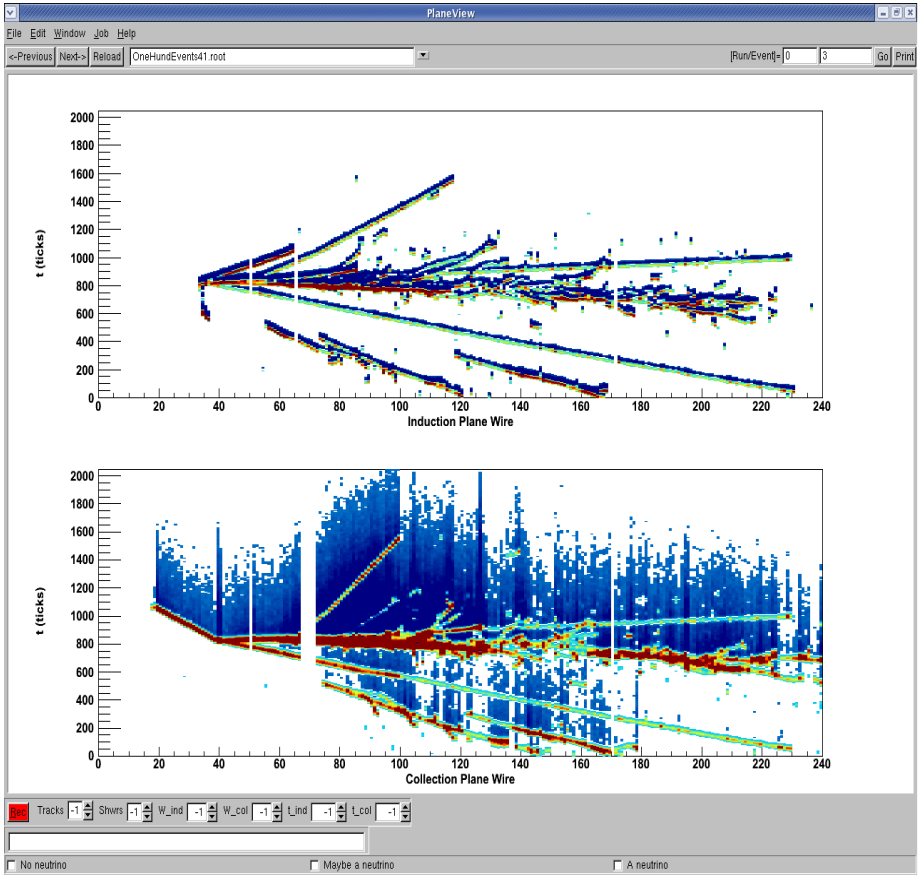
Collection and Induction Plane View



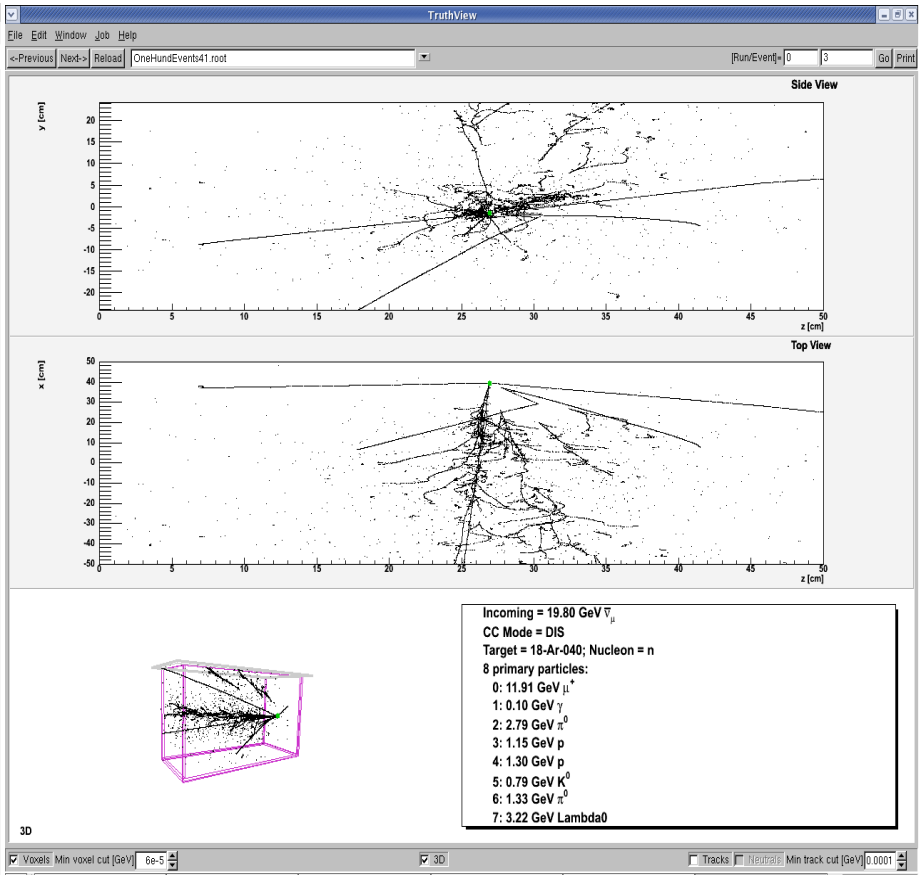
Truth view

CC-DIS Lambda Event in ArgoNeut





Collection and Induction Plane View

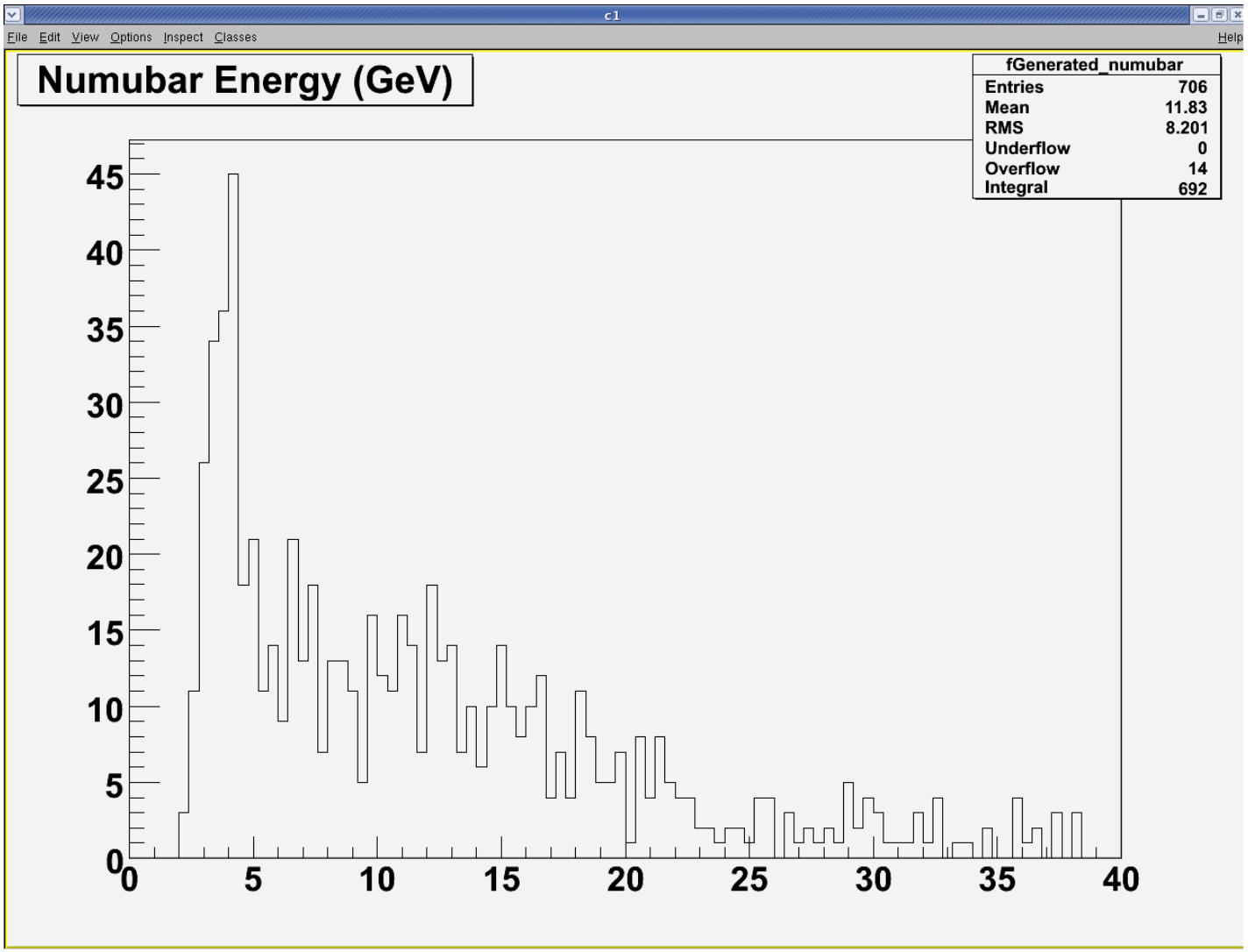


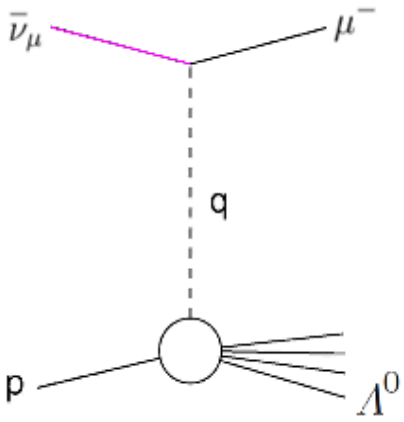
Truth view

Analysis of Λ Production via DIS from Protons

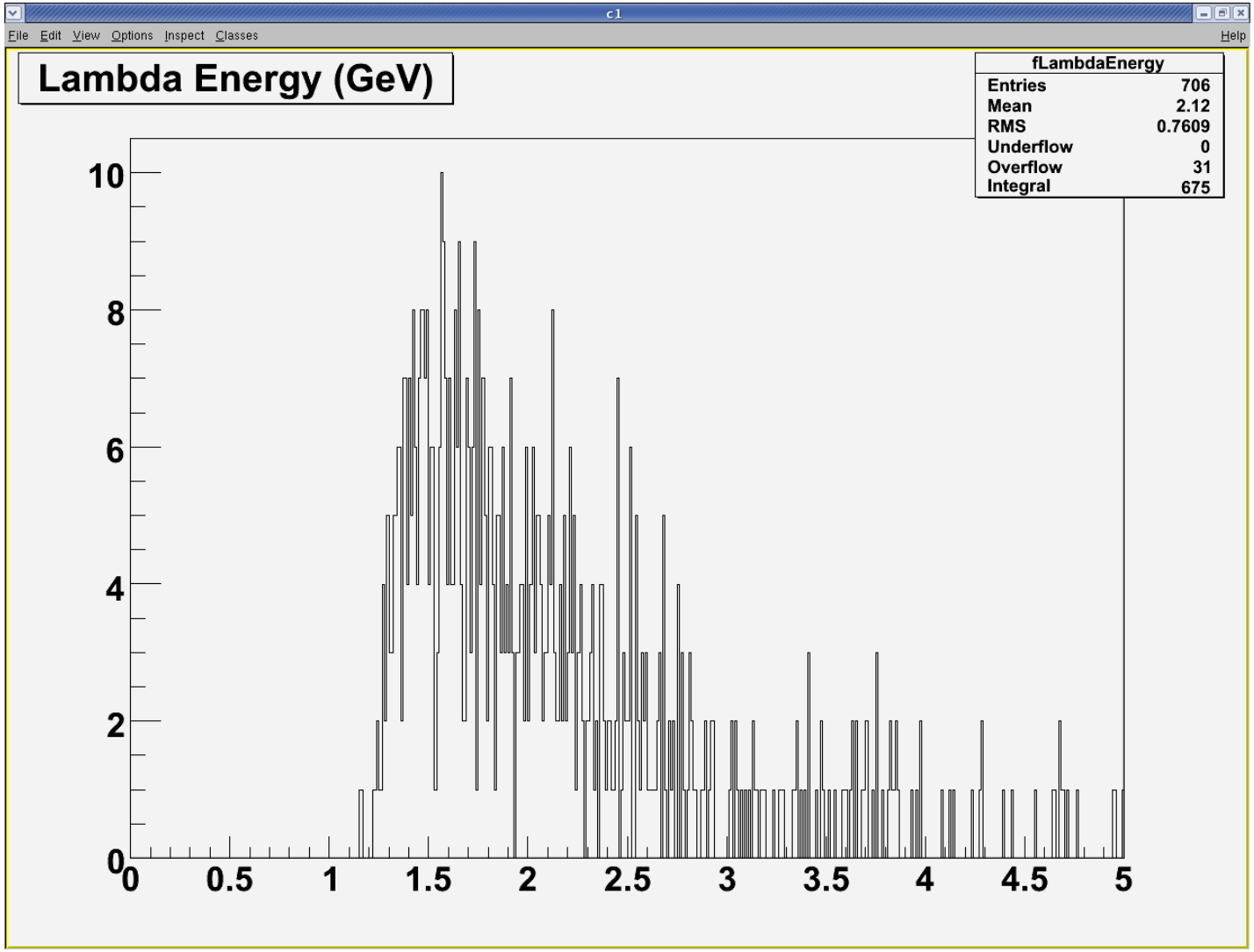
- Generator Level Analysis
- GENIE generates the Primary Neutrino Interaction (60 lambda events = ~24 Hours)
  - Anti-Neutrino Histogram **Flux of the NUMI** is used
  - Incident Neutrino is set to **Numu-Bar** Only
  - Interactions are set to **CC-DIS** Only
  - **'706/23,000'** are CC-DIS Lambda Events with **'628'** lambdas decaying, and the rest interacting further..
  - **'403/23,000'** decaying to Proton & Pi-

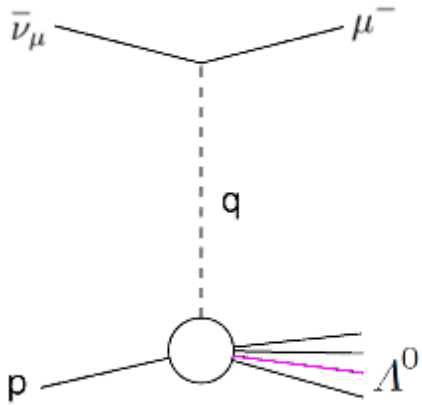
Neutrino Energy CC-DIS Lambda Events



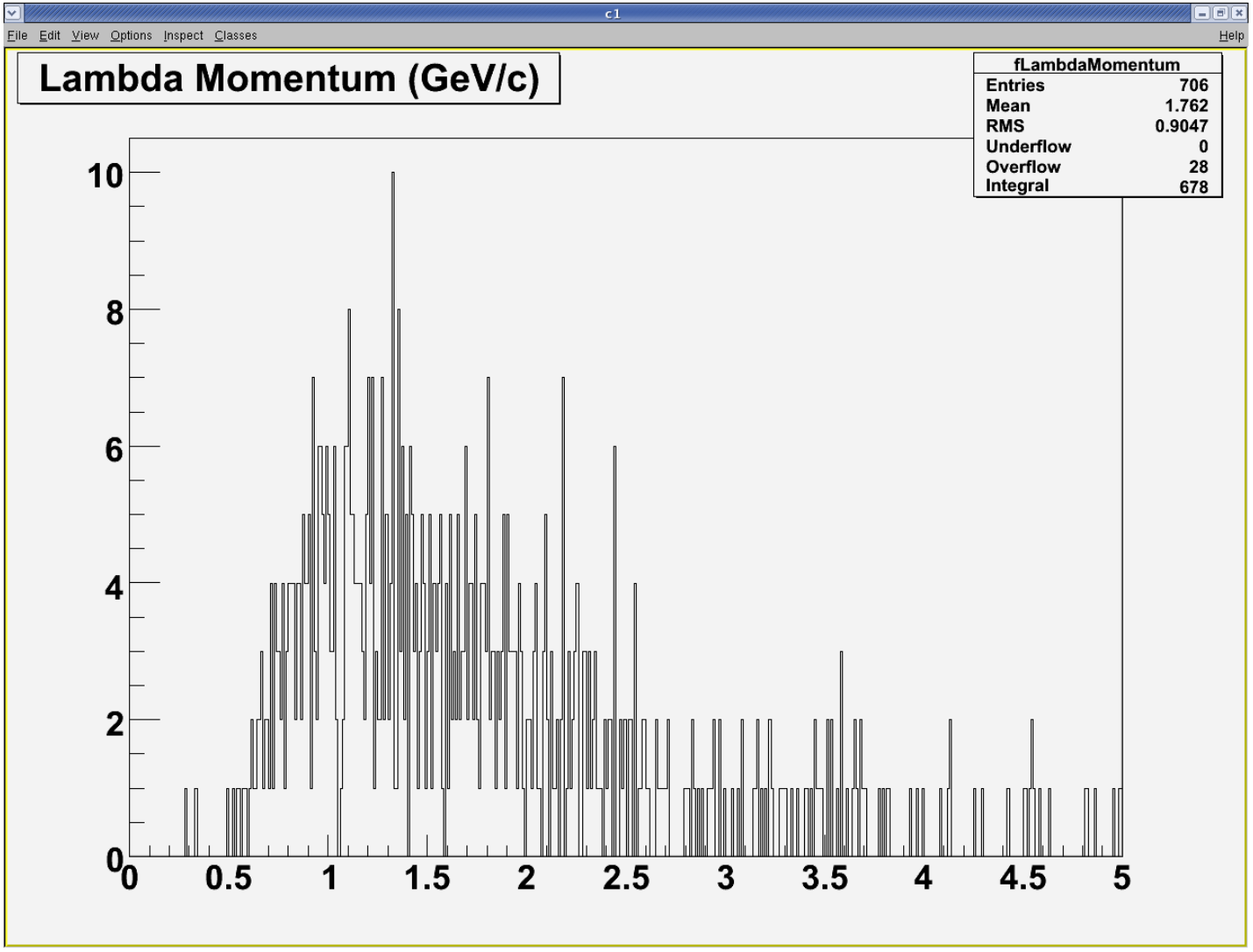


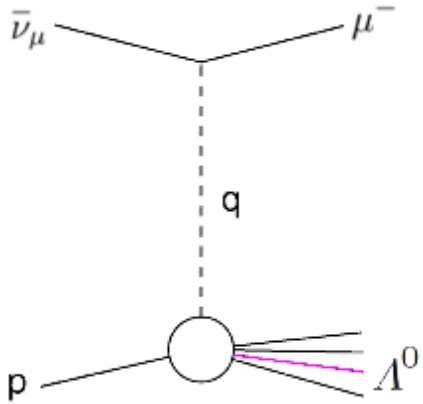
Energy of the Outgoing lambda CC-DIS Event



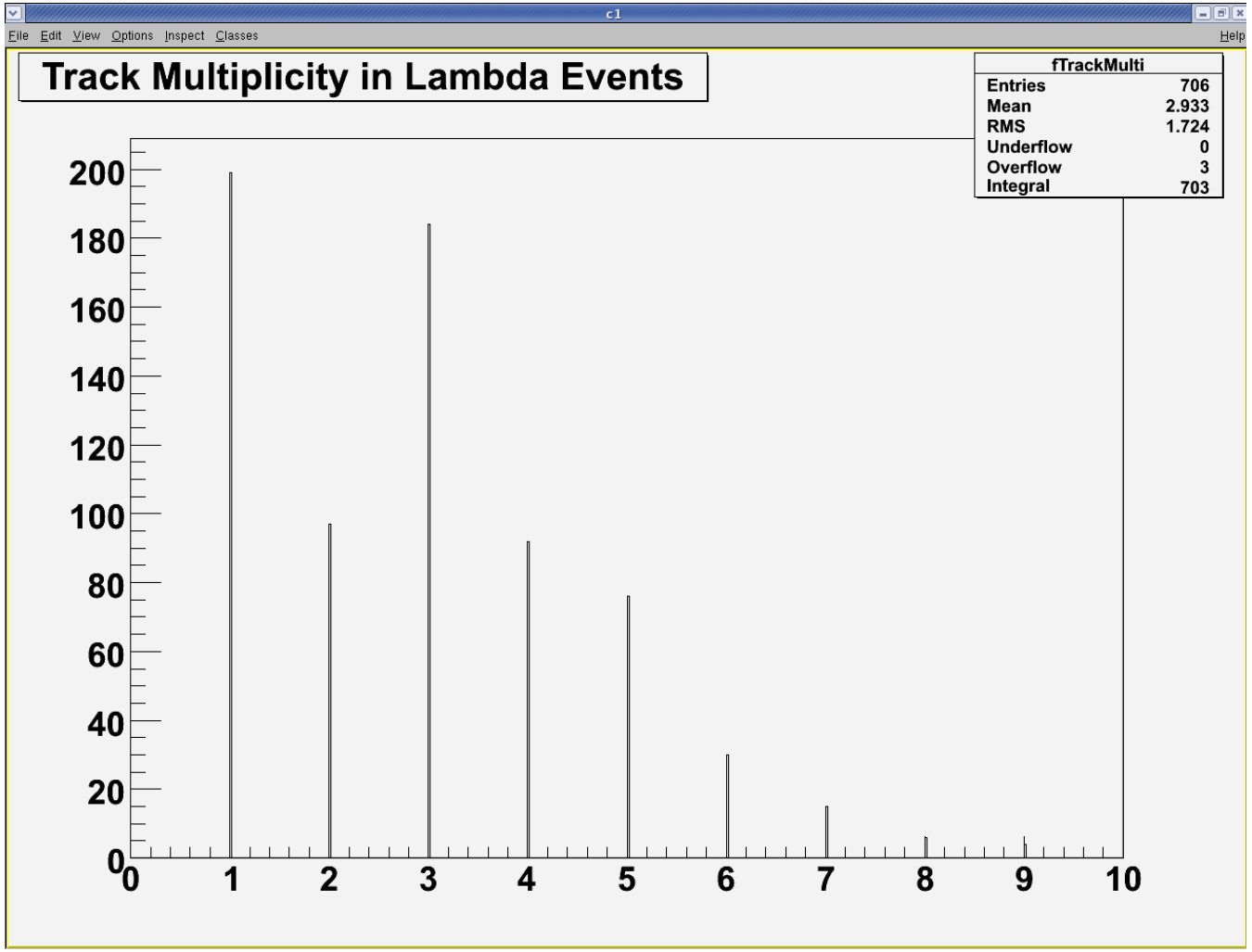


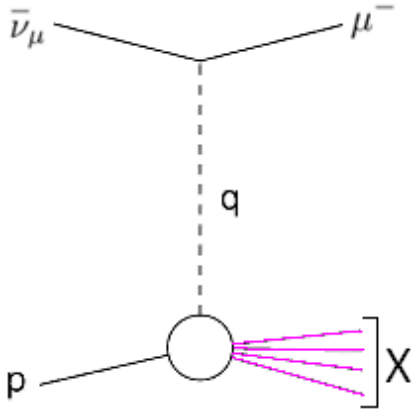
Momentum of the Outgoing Lambda in CC-DIS Event





Track Multiplicity of the CC-DIS Lambda Event





Neutral Particles:

- Lambda0
- Neutron
- Pi0
- K0
- Gamma
- KO-bar

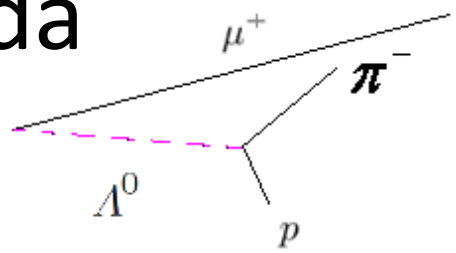
Contributing Particles

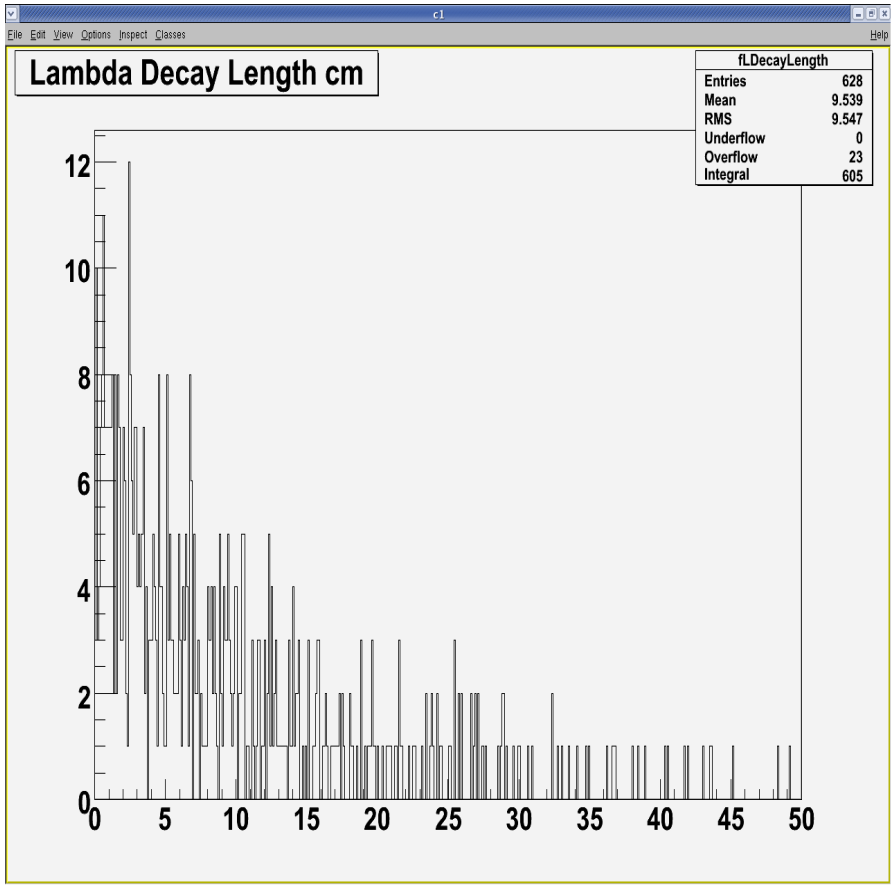
- mu+
- K+
- P
- Pi+
- Pi-

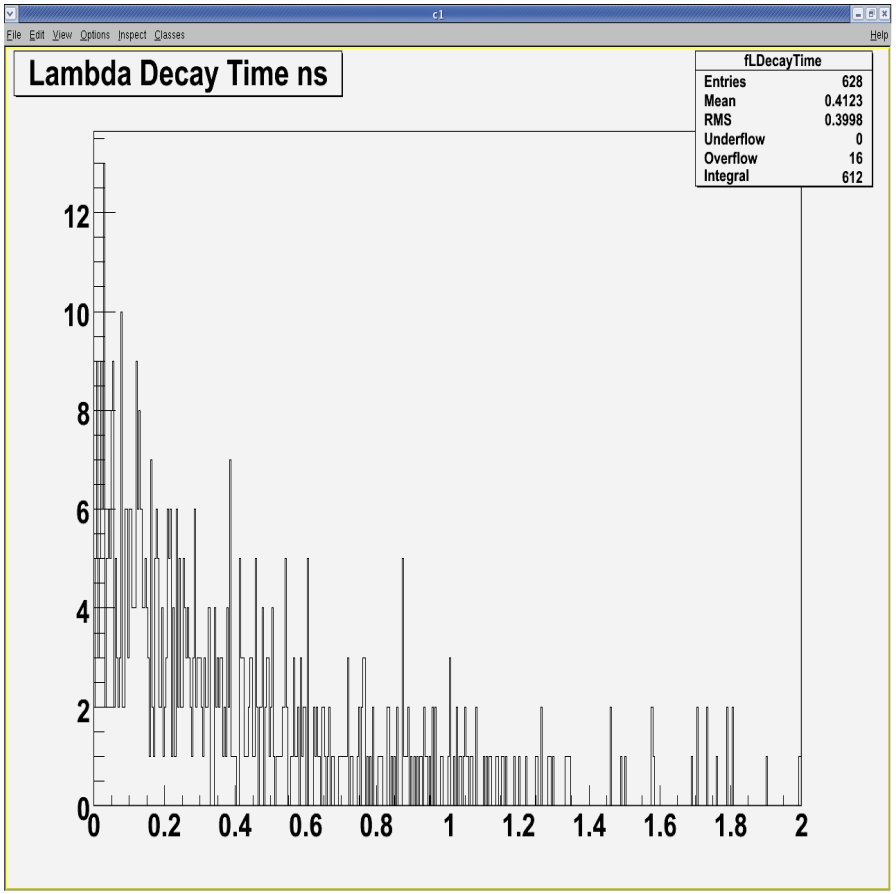
Lambda Decay

- GEANT 4 is used to find the 'decay length' and 'decay time' distributions of Lambda in Argon medium
- 628/706 lambdas decayed
- The events where Lambda re-interacted are discarded
- Direction Cosines are used to find the 'distribution of distance between the lambda Secondary Vertex and mu+ Track in XY-Plane'
- The distribution of the 'angle between mu+ and lambda track' is also plotted

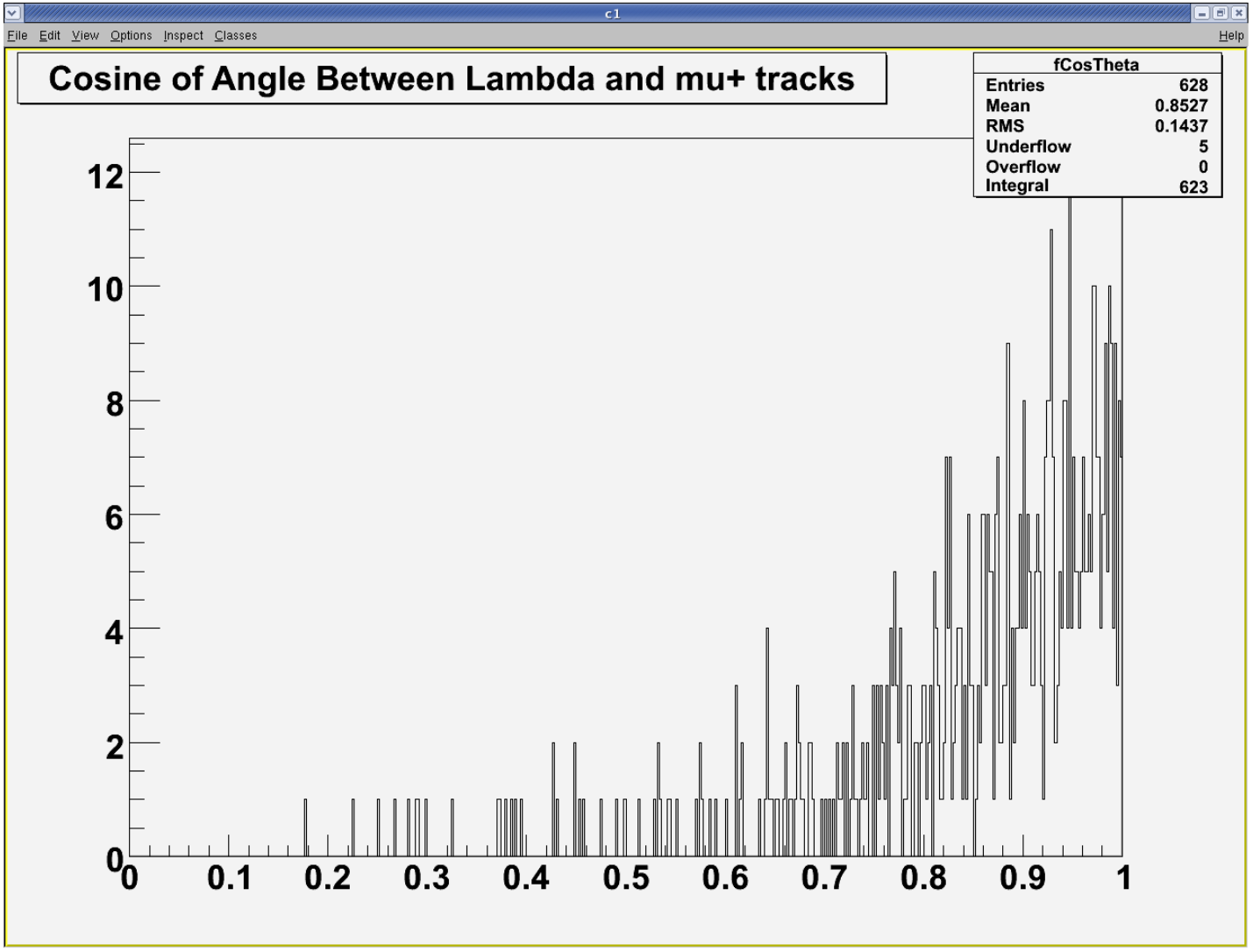
Decay Length and Life Time of Lambda

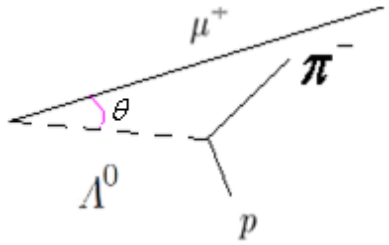




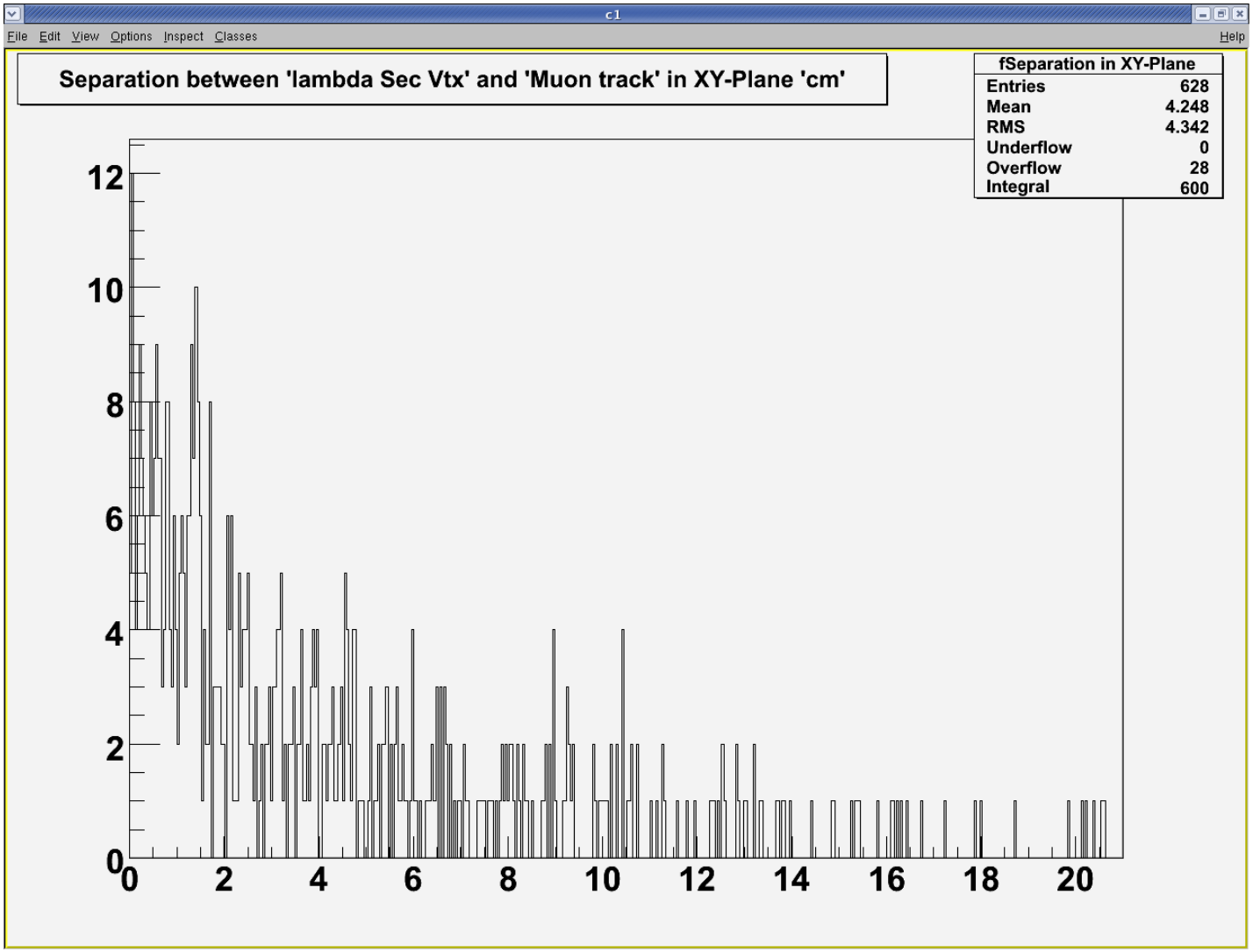


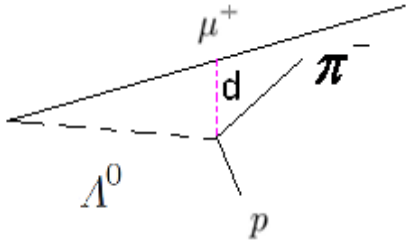
Cosine of the angle b/w mu+ and Lambda Track



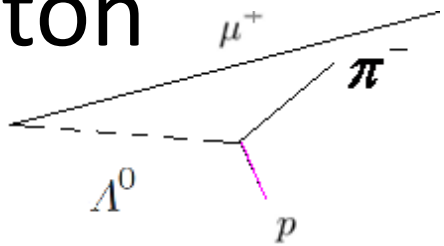


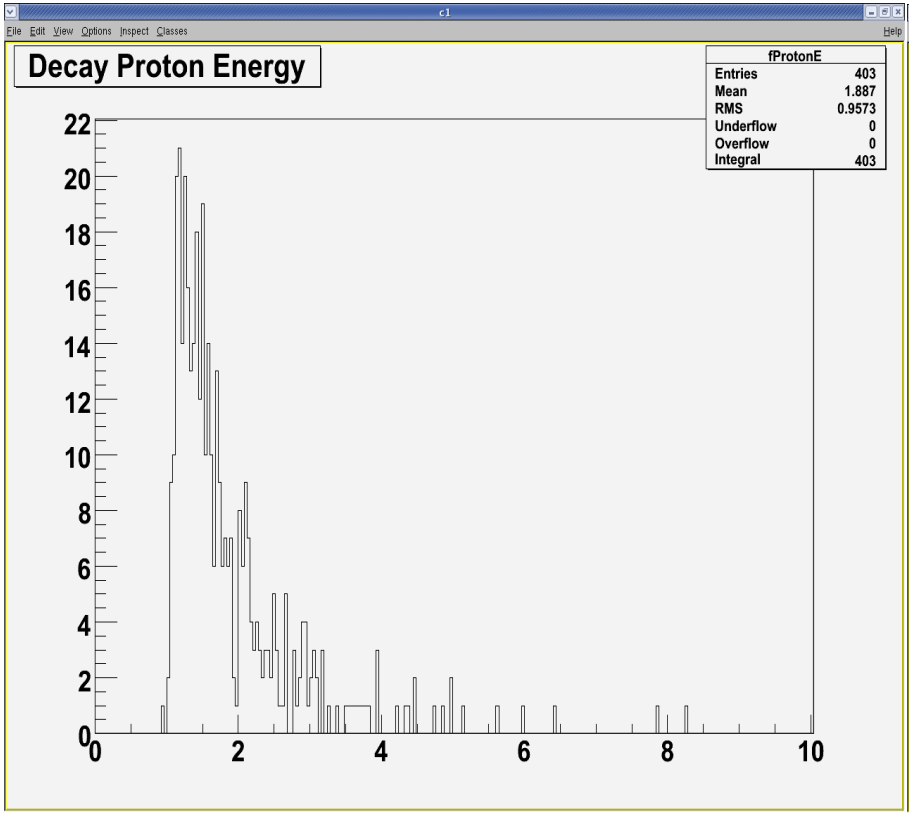
Lambda decay Vertex Distance from Muon Track in XY-Plane

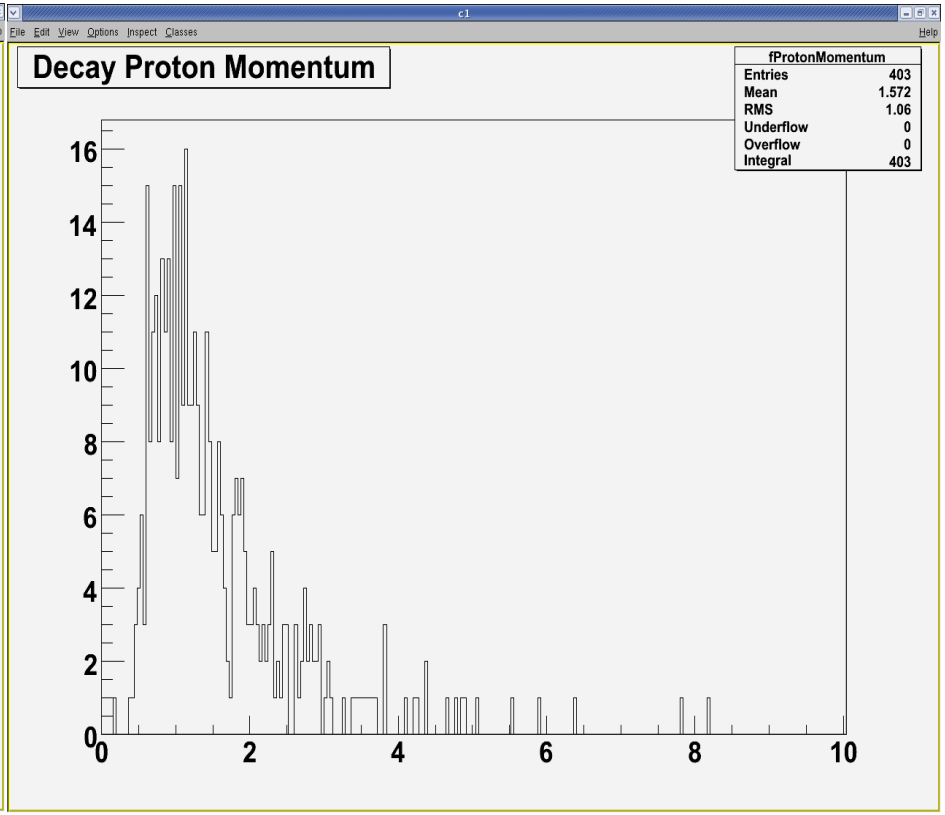




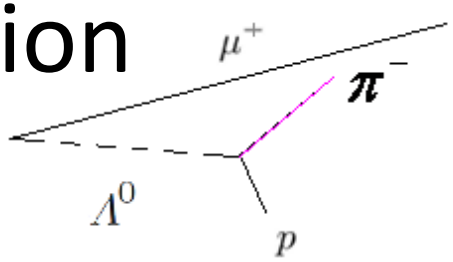
Energy & Momentum of Decay Proton

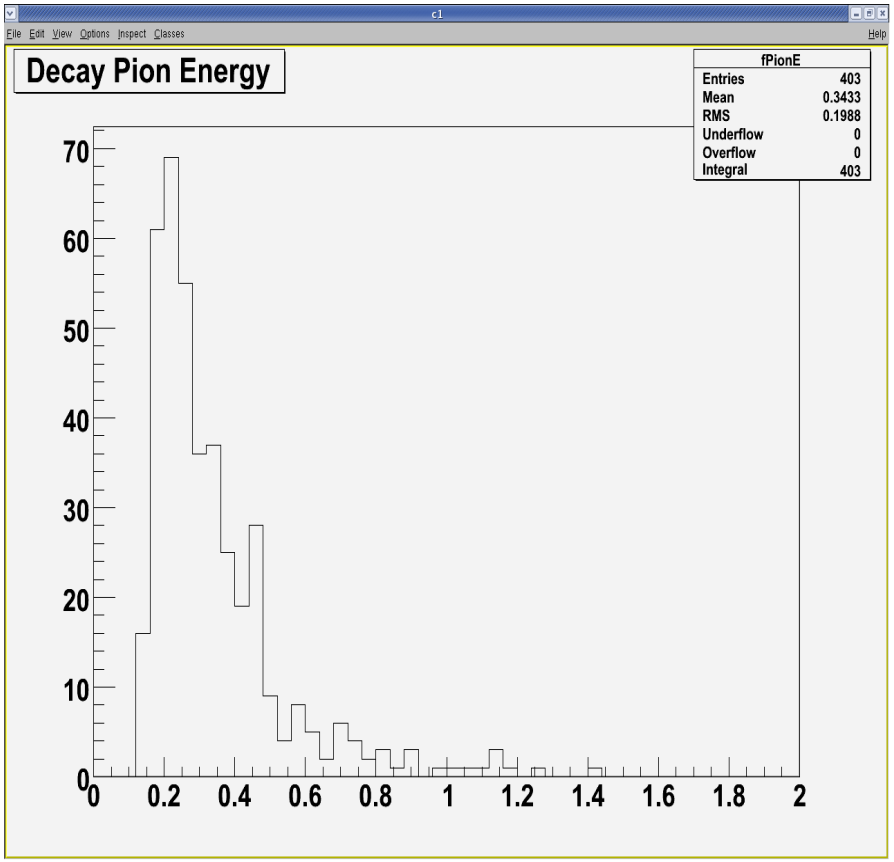


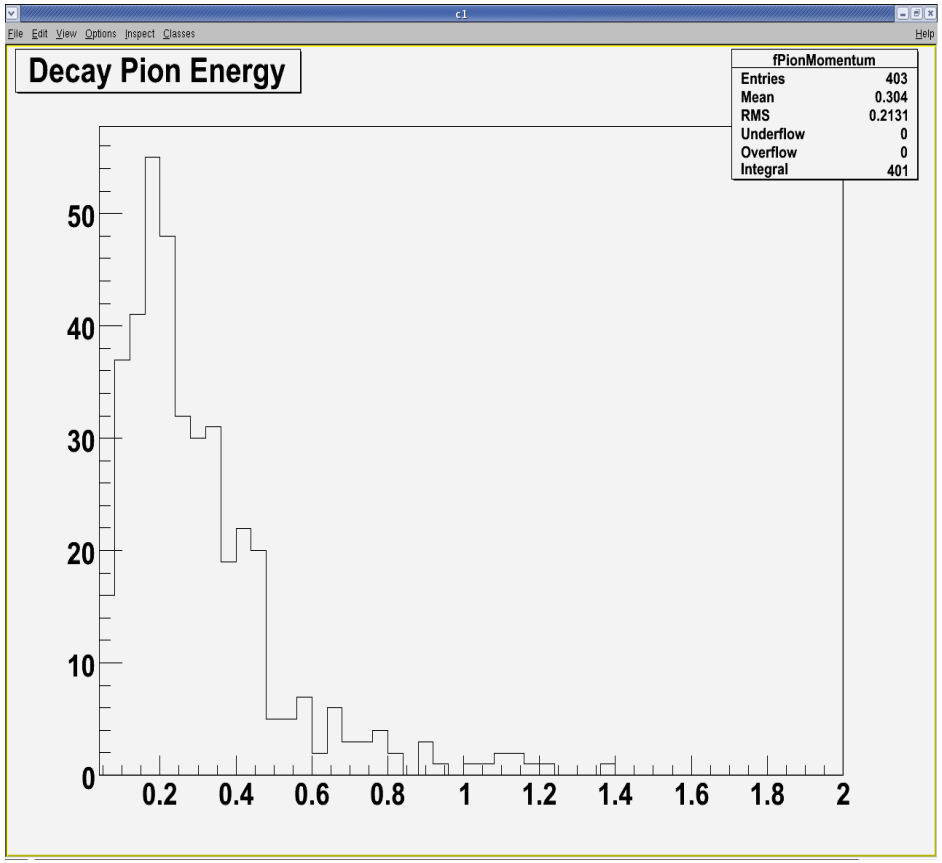




Energy & Momentum of Decay Pion







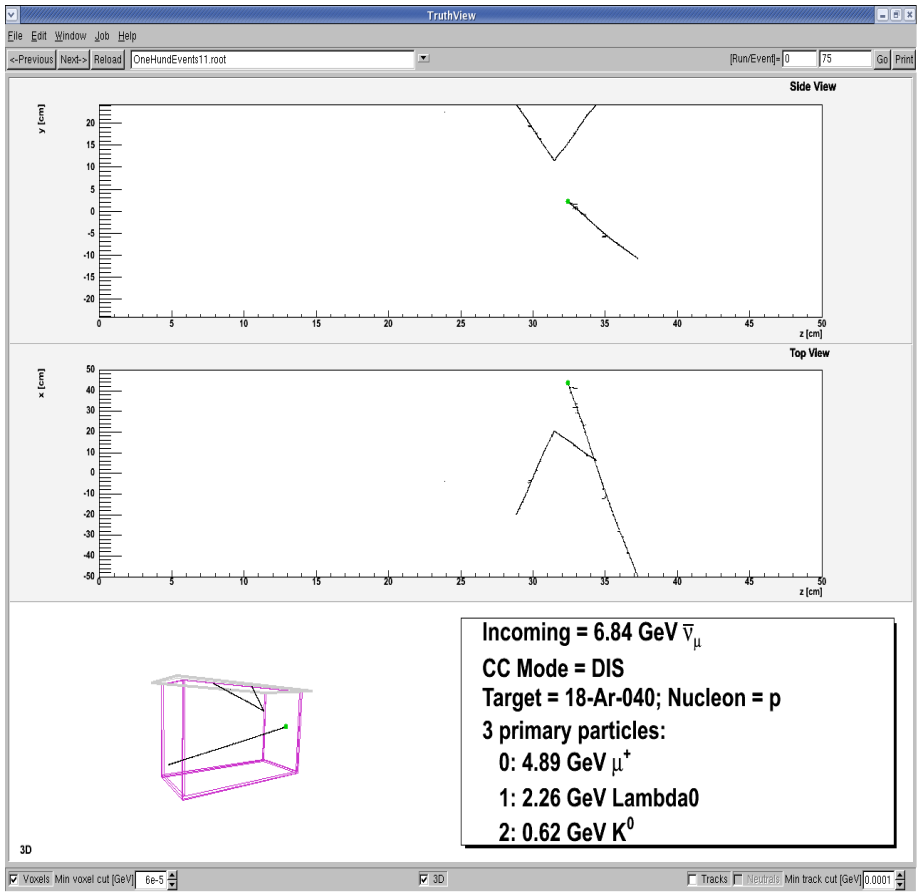
Goodness of Fit to Pick Out Lambda Events

Lambda event can be missed if one of the decay product of lambda is low energy!

Taking 2 Tracks at a Time

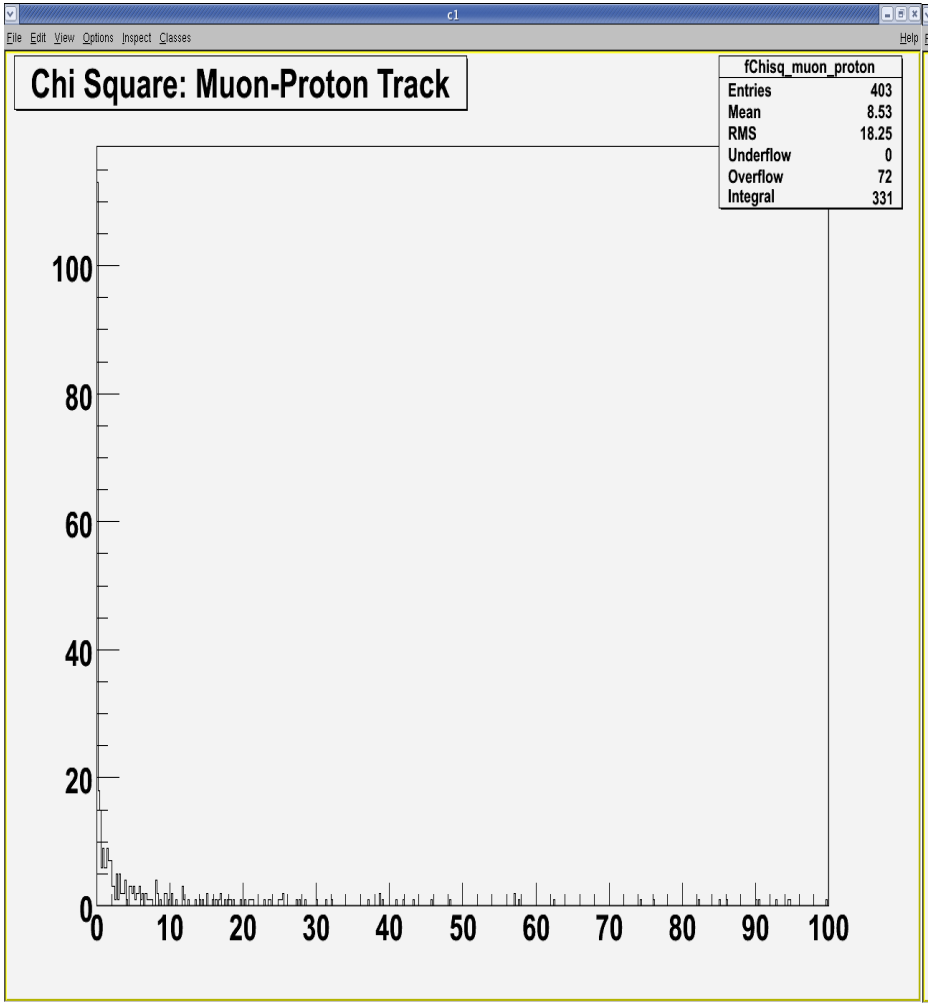
- mu+ & 1 decay particle track is extrapolated back to get **Intersection point**
  - Zx inTop View (XZ Plane)
  - Zy in Side View (YZ Plane)

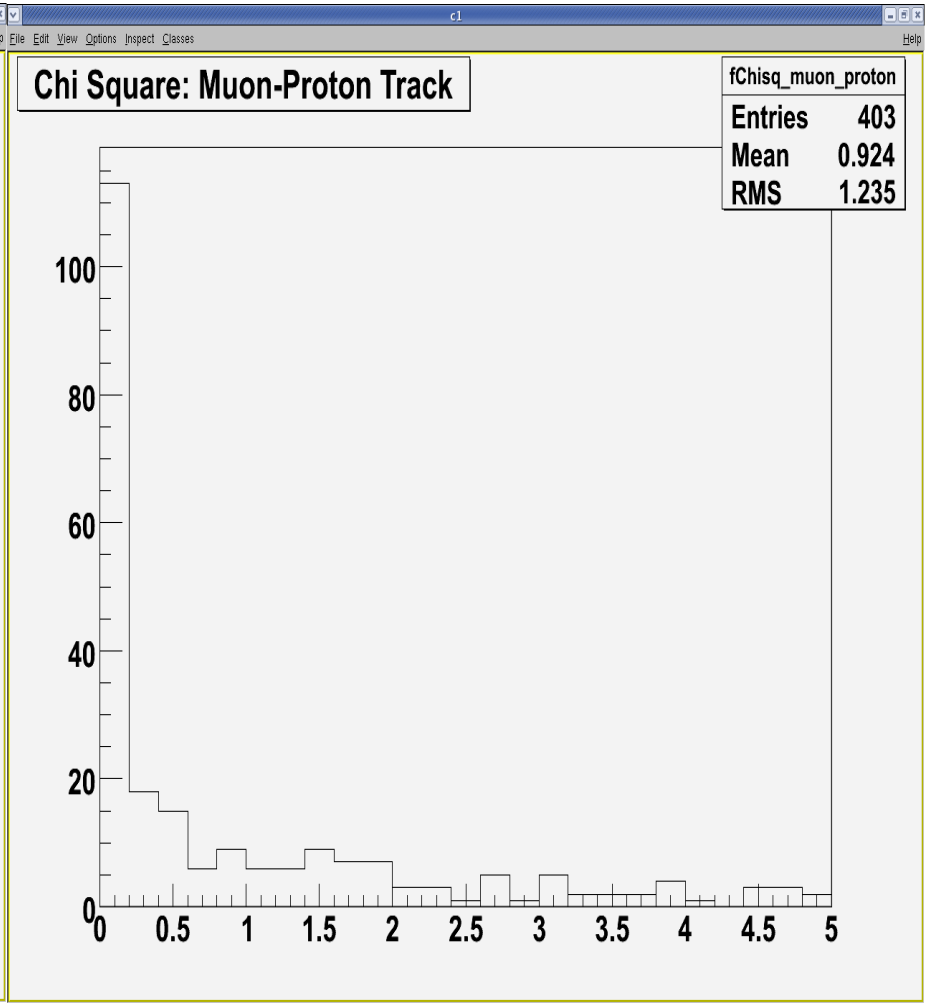
$$\chi^2 = \frac{(Zx - Zy)^2}{dZx^2 + dZy^2}$$



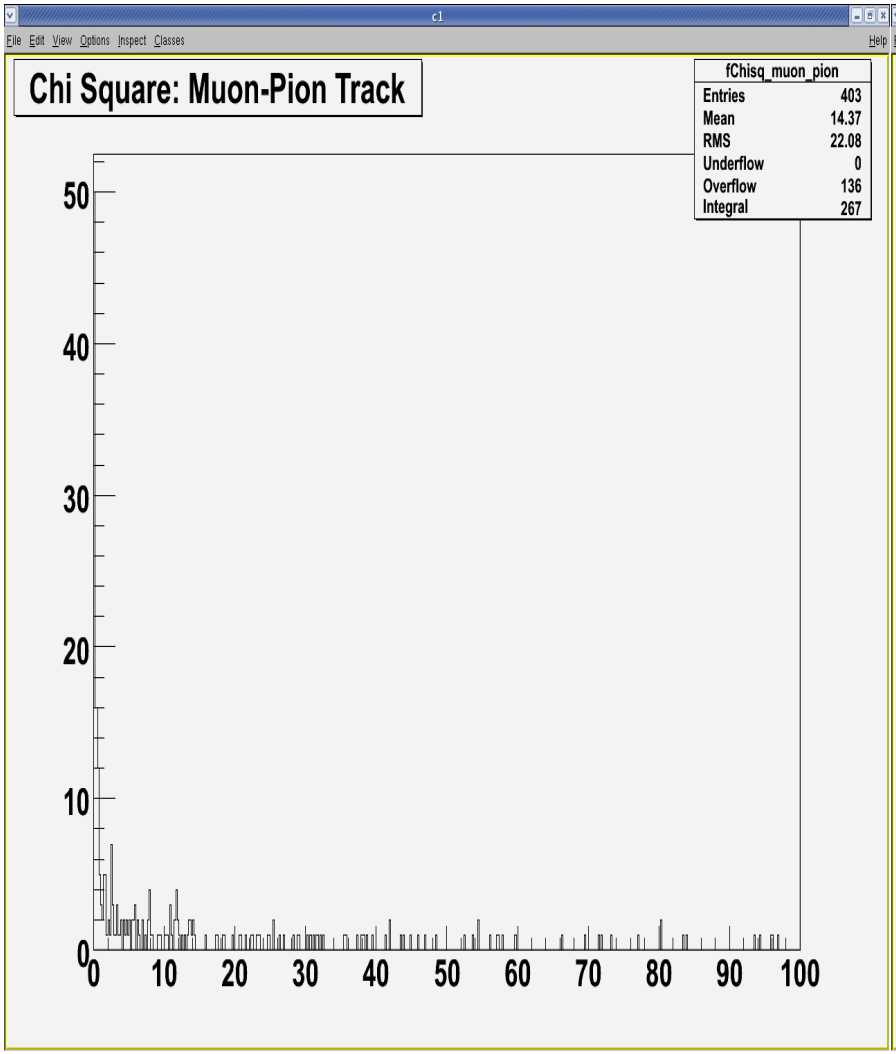
This value should be small for the tracks originating from the same vertex

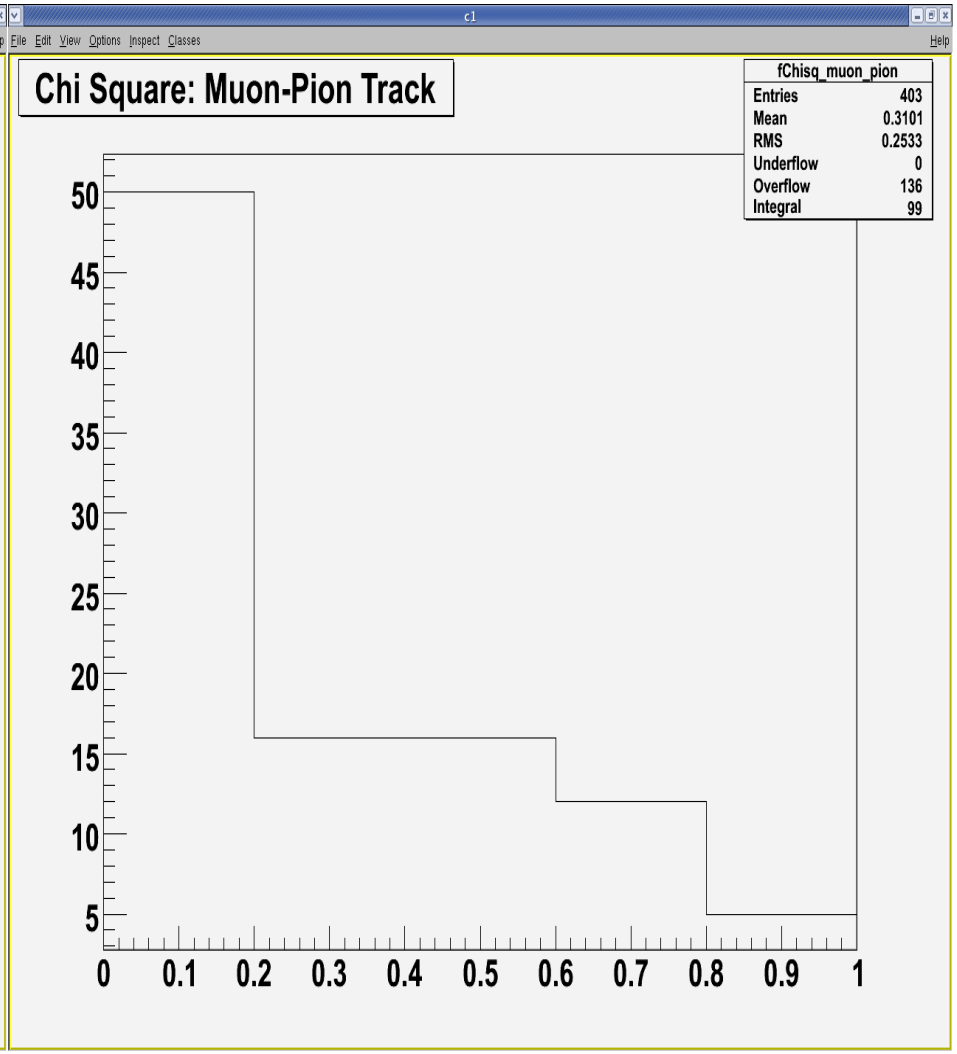
χ^2 Muon-Proton Track





χ^2 Muon-Pion Track





Background

Any Event with detached/displaced vertex can be a background to the lambda event

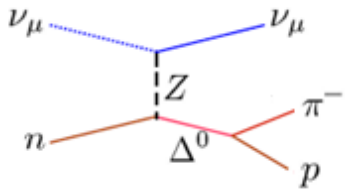
1. Secondary interaction of neutron with Argon nucleus $\overline{\nu}_\mu p \rightarrow \mu^- n$

   $\downarrow$

   $n + Ar \rightarrow \pi^- p$

2. Production of Kaon in CC-DIS $K_s^0 \rightarrow \pi^- + \pi^+$

3. Decay of Δ^0 (NC)



Cuts/Selection Criteria

- Lambda life time and/or decay length
- Lambda invariant mass
- Angular Distribution of decay products
- Need to work on how to not miss events with one decay particle track of lambda if any (Event Display is required which is in the process of port from FMWK to ART)

Polarization of Lambda Reweighting to get the Final State Kinematics Right (To Do!)

- In the rest frame of lambda0, the decay protons are distributed as

$$\frac{1}{N}\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}\cdot\mathbf{k})$$

  where

- N = number of lambdas
- Decay asymmetry parameter $\alpha_\Lambda = 0.642 \pm 0.013$
- **P** is lambda polarization vector
- **K** is the unit vector in the direction of proton

Dmitry V. Naumov, Measurement of lambda0 and lambda0-bar polarization in neutrino CC interactions in NOMAD, arXiv:*hep-ph/0206032v1* 4 Jun 2002

Reweighting the Monte Carlo

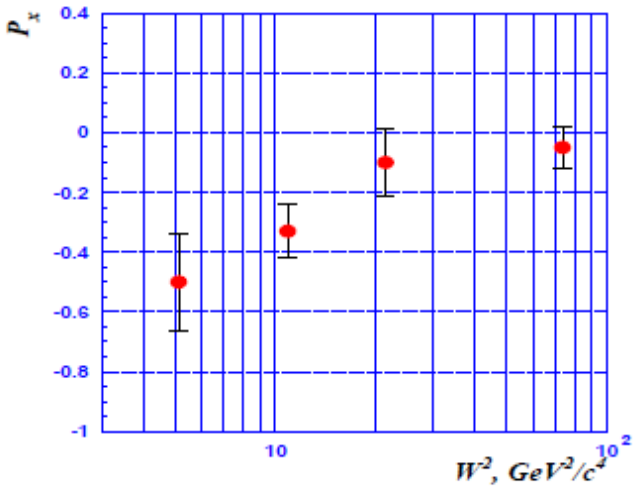


Fig. 1. Longitudinal polarization of Λ^0 as a function of W^2 for $x_F < 0$

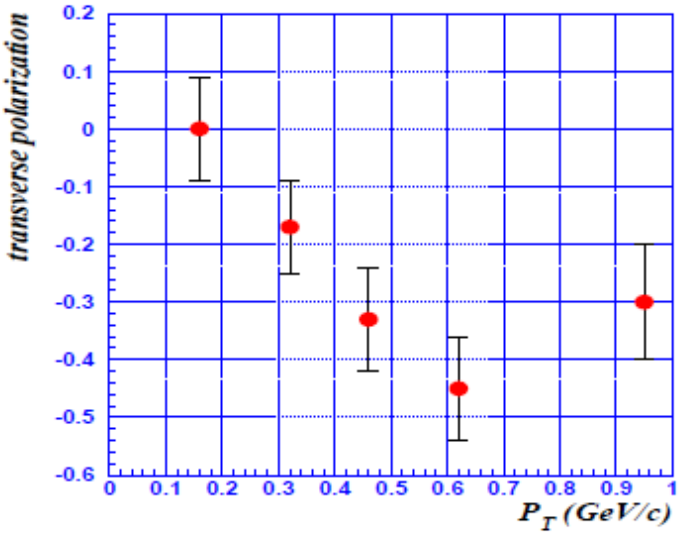


Fig. 2. Transverse polarization of Λ^0 as a function of P_T for $x_F < 0$

- Calculate the Longitudinal and transverse Polarization for each lambda on the basis of the fit to the above plots where W^2 and PT is calculated from the Truth information.
- Calculate **P.k** for each lambda event to weight it with the factor of $(1 + \alpha_\Lambda \mathbf{P} \cdot \mathbf{k})$

$$W^2 = M^2 + 2M\nu - Q^2$$

PT = transverse momentum of lambda with respect to neutrino

Dmitry V. Naumov, Measurement of lambda0 and lambda0-bar polarization in neutrino CC interactions in NOMAD, arXiv:*hep-ph/0206032v1* 4 Jun 2002

Once the Weighting Factor is Calculated..

- The Plots to be re-weighted
  - Energy and Momentum of decay Proton and Pion
  - Cosine of the angle b/w mu+ and Lambda Track
  - Separation of mu+ track and lambda secondary vertex in XY-Plane

Things To Do in Near Future

- Reweight the Histograms to get the Final State Kinematics Right
- Set up the Selection Criteria and Estimate the Overall Detector Efficiency
- Need to Study How Often Neutron Secondary Interaction Fake the Signal, $\overline{\nu}_{\mu} p \rightarrow \mu^{-} n$; $n + Ar \rightarrow \pi^{-} p$. Lambda Mass and Life Time are the Controls
- Need to Study How Often Can See a Clear 'V' Decay Topology of Lambda!
- Study if Lambda Identification can be Done Even if Only One Decay Particle 'a Pion' is Seen by Seeing Whether it Extrapolates Back to the Primary Vertex

ArgoNeut Future

- First ArgoNeuT results appearing in ~ Winter 2010.
- ArgoNeuT Phase II
  - An upgraded ArgoNeuT is being proposed to go in the Booster Neutrino Beam (BNB; SciBooNE hall) at Fermilab in Fall/Winter 2010.
- MicroBooNE
  - A 90 ton active volume LArTPC in the BNB at Fermilab, to explore the MiniBooNE low-energy excess, measure precise ~1 GeV cross sections, and perform R&D for kton-scale LArTPCs, starting in 2012/13.