Summer 2010 REU; Kansas State University

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Background

Neutrino Oscillations

- Experimental Evidence:
  - MINOS
  - KamLAND
  - Super-Kamiokande
  - SNO
  - K2K

- Neutrino sources:
  - Atmospheric, reactor, accelerator, solar, geo

Neutrino Oscillations (cont.):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(t=0)\rangle \; = \; |\nu_\mu\rangle \; = \; -\sin\theta\,|\nu_1\rangle \; + \; \cos\theta\,|\nu_2\rangle$$

Schrödinger's Equation!

$$|\nu_\mu(t)\rangle \; = \; -\sin\theta\,|\nu_1\rangle \; e^{-i\frac{E_1 t}{\hbar}} \; + \; \cos\theta\,|\nu_2\rangle \; e^{-i\frac{E_2 t}{\hbar}}$$

$$P\left(\nu_\mu \to \nu_e\right) \; = \; |\langle \nu_e|\nu_\mu(t)\rangle|^2$$

MATH!

$$P_{\nu_\mu \to \nu_e}(L, E) \; = \; \sin^2 2\theta \;\, \sin^2\left(1.27\,\Delta m^2 \frac{L}{E_\nu}\right)$$

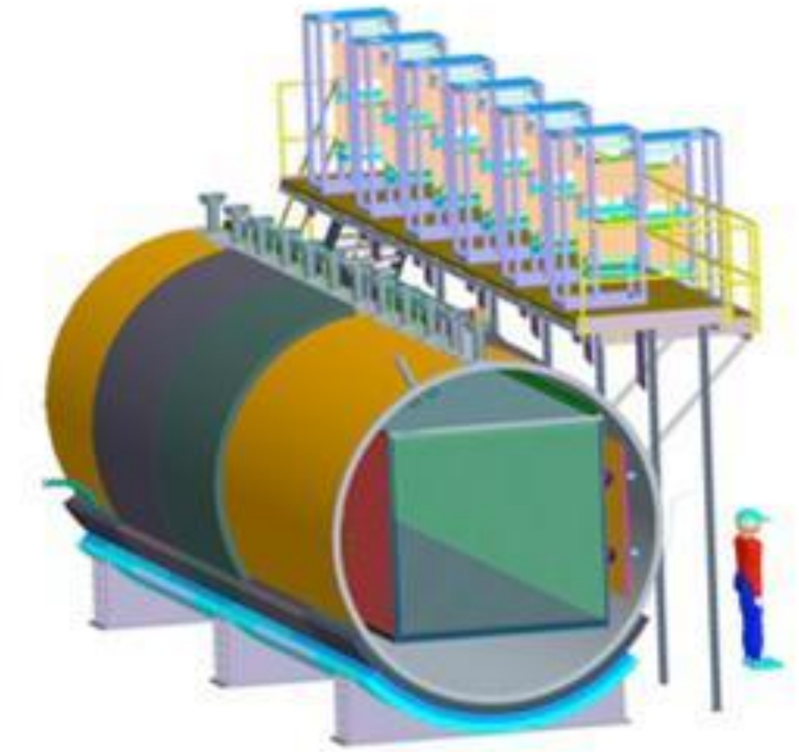
Neutrino Oscillation (cont.):

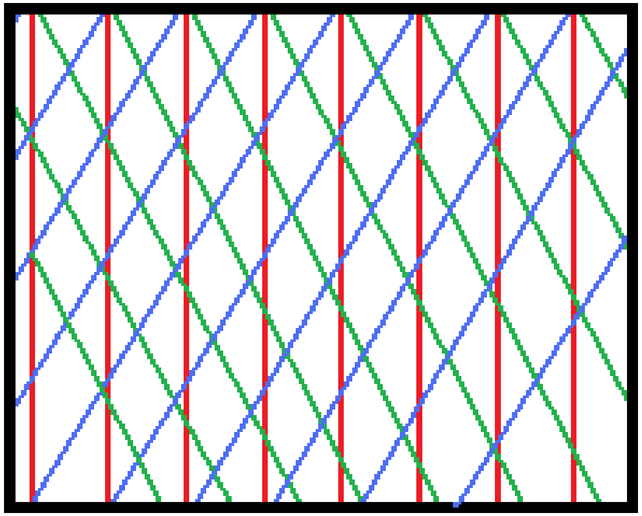
$$U = \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\times \, \mathrm{diag}(e^{i\alpha_1/2}, \; e^{i\alpha_2/2}, \; 1) \; .$$

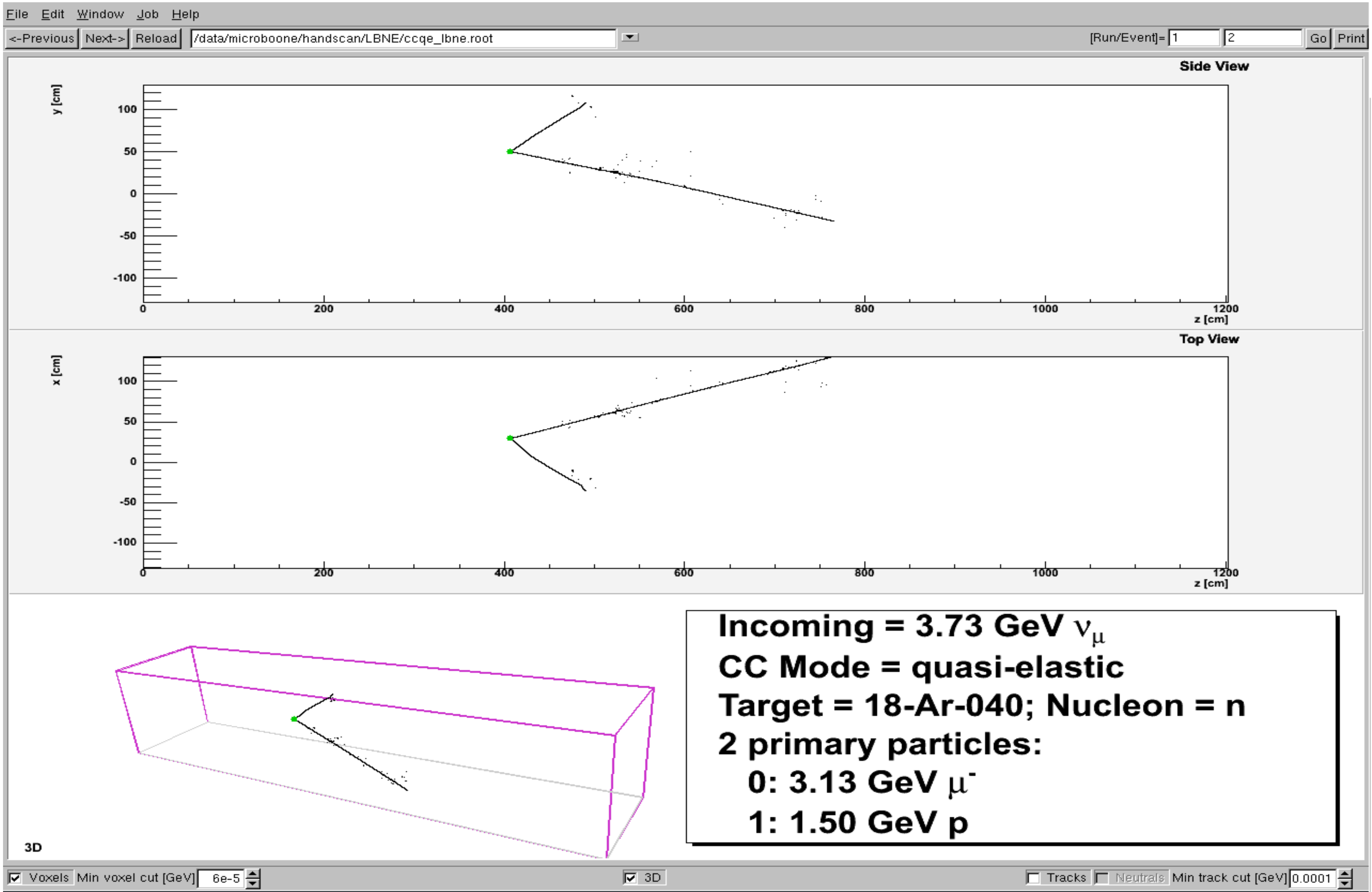
$$c_{ij} \equiv \cos\theta_{ij} \qquad\qquad s_{ij} \equiv \sin\theta_{ij}$$

MicroBooNE:



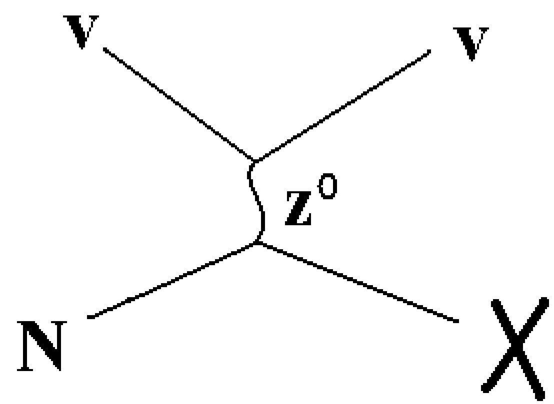


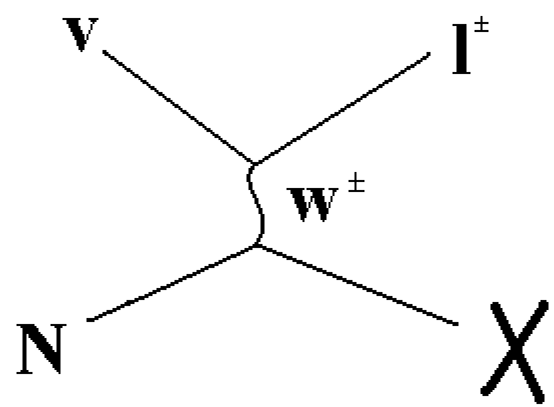
Hand-Scanning

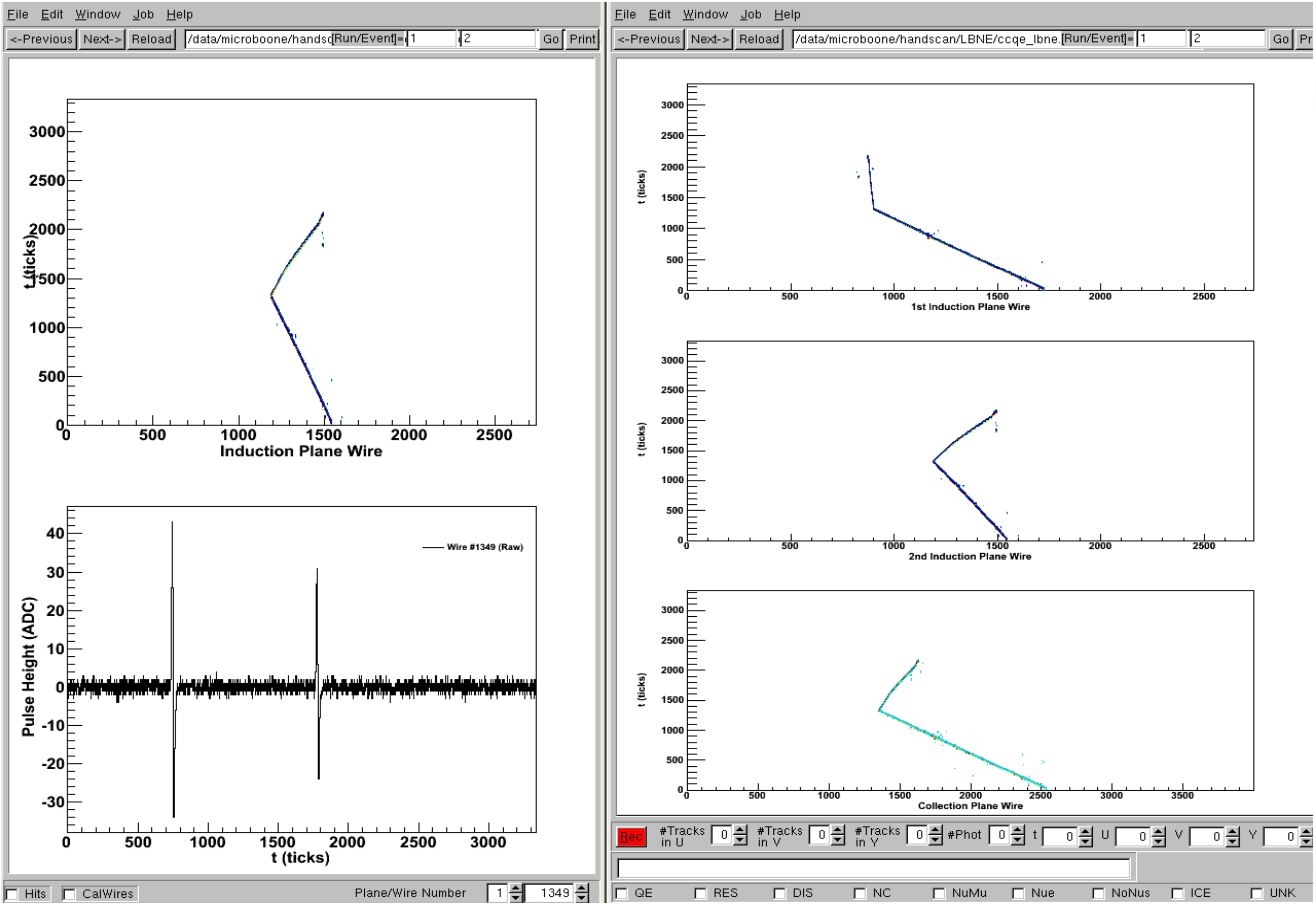

File Edit Window Job Help
<-Previous Next-> Reload /data/microboone/handscan/LBNE/ccqe_lbne.root
[Run/Event]= 1 2 Go Print
Side View
y [cm]
z [cm]
Top View
x [cm]
z [cm]
3D
Incoming = 3.73 GeV ν_μ
CC Mode = quasi-elastic
Target = 18-Ar-040; Nucleon = n
2 primary particles:
0: 3.13 GeV μ^-
1: 1.50 GeV p
Voxels Min voxel cut [GeV] 6e-5
3D
Tracks Neutrals Min track cut [GeV] 0.0001

Interactions:

- Neutral-Current (NC) vs. Charged Current (CC)
- Modes of Scattering:
  - Quasi-Elastic (QE)
  - Resonant (RES)
  - Deep-Inelastic Scattering (DIS)






File Edit Window Job Help
<-Previous Next-> Reload /data/microboone/handsc [Run/Event]= 1 2 Go Print
t (ticks)
Induction Plane Wire
Wire #1349 (Raw)
Pulse Height (ADC)
t (ticks)
Hits CalWires Plane/Wire Number 1 1349
<-Previous Next-> Reload /data/microboone/handscan/LBNE/ccqe_lbne. [Run/Event]= 1 2 Go
1st Induction Plane Wire
2nd Induction Plane Wire
Collection Plane Wire
Rec #Tracks in U #Tracks in V #Tracks in Y #Phot t U V Y
QE RES DIS NC NuMu Nue NoNus ICE UNK

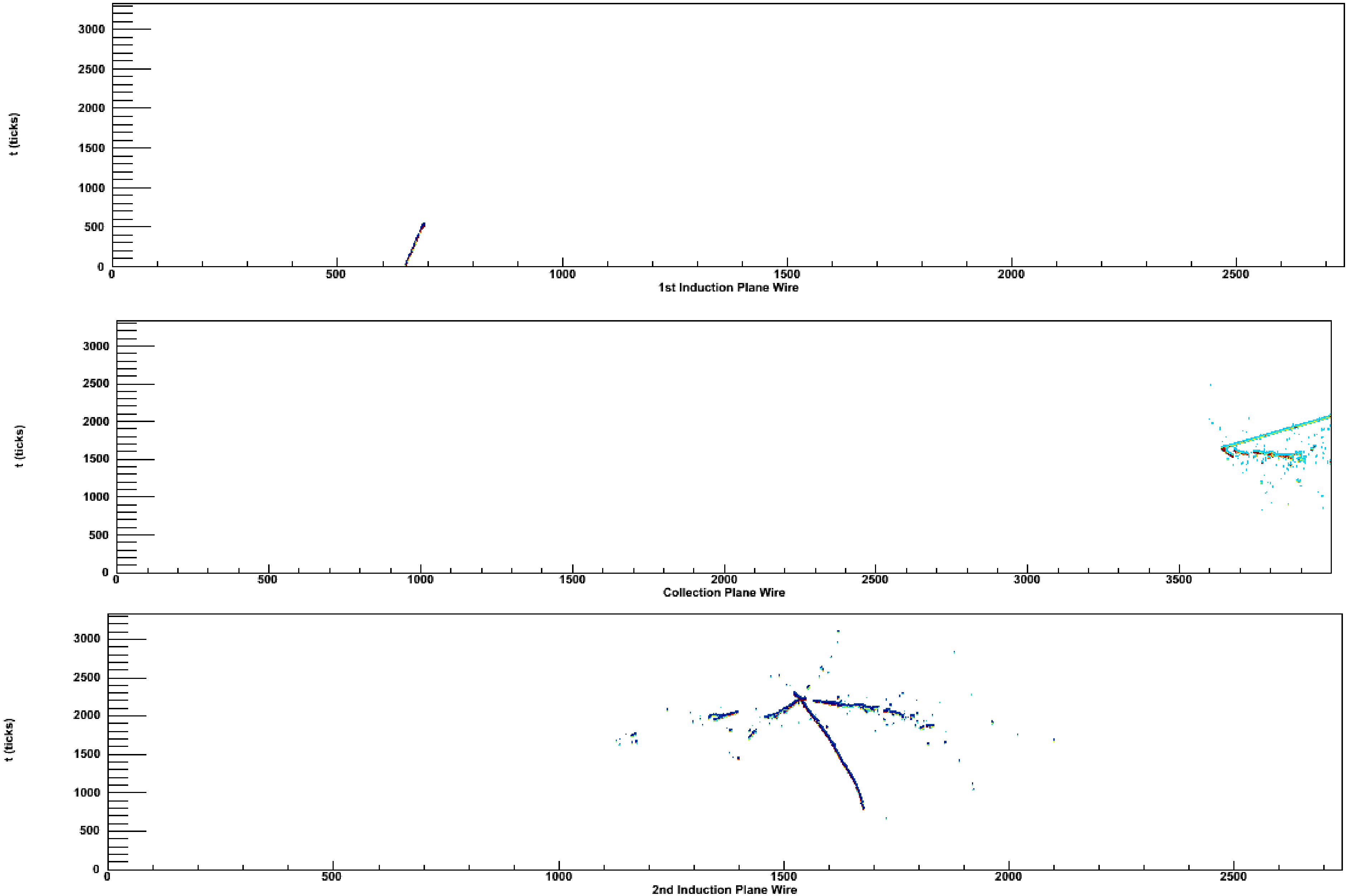
Algorithmic Procedure

- ν_e and ν_μ events expected
- Neutral-current (NC) interactions do not distinguish neutrino flavor
- Need to pick out small charged-current (CC) ν_e signal

	CC	NC
ν_e	✓	✗
ν_μ	✗	✗

Step 1, Neutrino Interaction Vertex Identification:

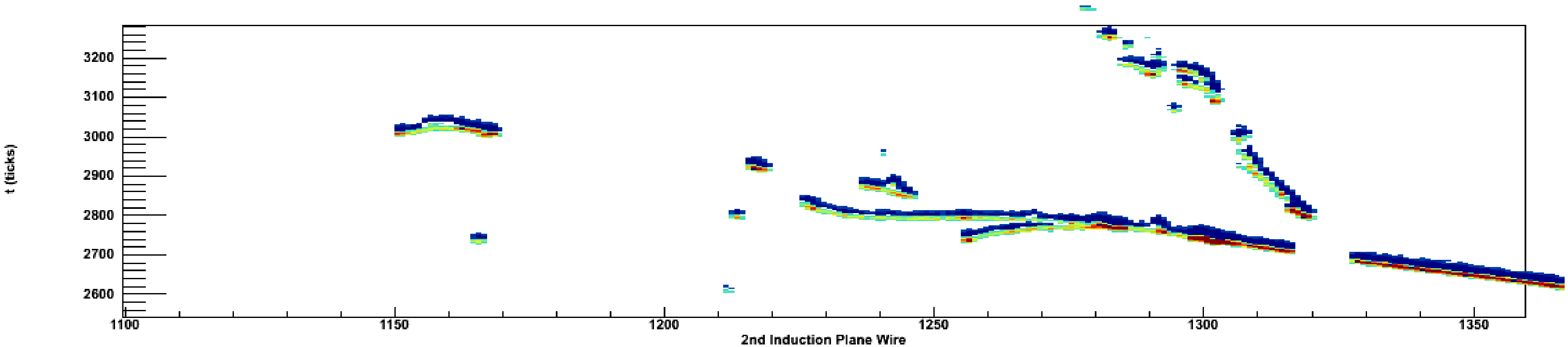
- Point from which all primary tracks originate
- The vertex should have the same time location in both induction planes and the collection plane
- Frequently there is a large energy deposition at the vertex
- Events without a well contained primary vertex are intractable and should be discarded

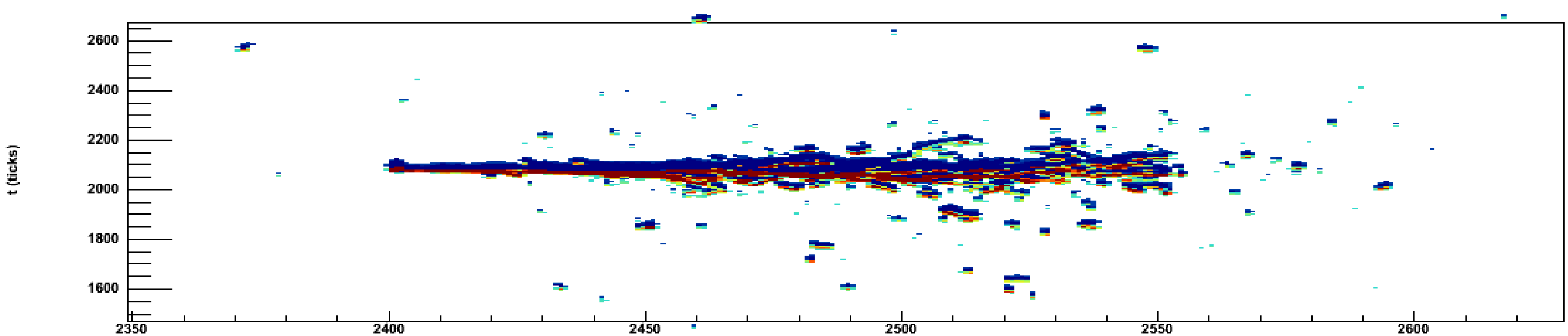

t (ticks)
1st Induction Plane Wire
t (ticks)
Collection Plane Wire
t (ticks)
2nd Induction Plane Wire

Step 2, Electromagnetic Shower Identification:

- Any identifiable v_e event will contain a shower, so if absent the event may be discarded
- Defined by a high concentration of isolated spots of energy deposition
- Often have “branching” or “forking”

Step 2 (cont.):


t (ticks)
3200
3100
3000
2900
2800
2700
2600
1100
1150
1200
1250
1300
1350
2nd Induction Plane Wire


t (ticks)
2600
2400
2200
2000
1800
1600
2350
2400
2450
2500
2550
2600

Step 3, μ Identification:

- Distinctive long, straight, minimum ionizing track
- Long: spanning over 700 wires
- Minimum ionizing: average pulse height 35 ADC
  - 50 a good upper limit
- If the event contains a μ, it can be discarded

Step 4, Determination of Shower Origin:

- Candidates: π^0, $\pi^\pm$, γ, e

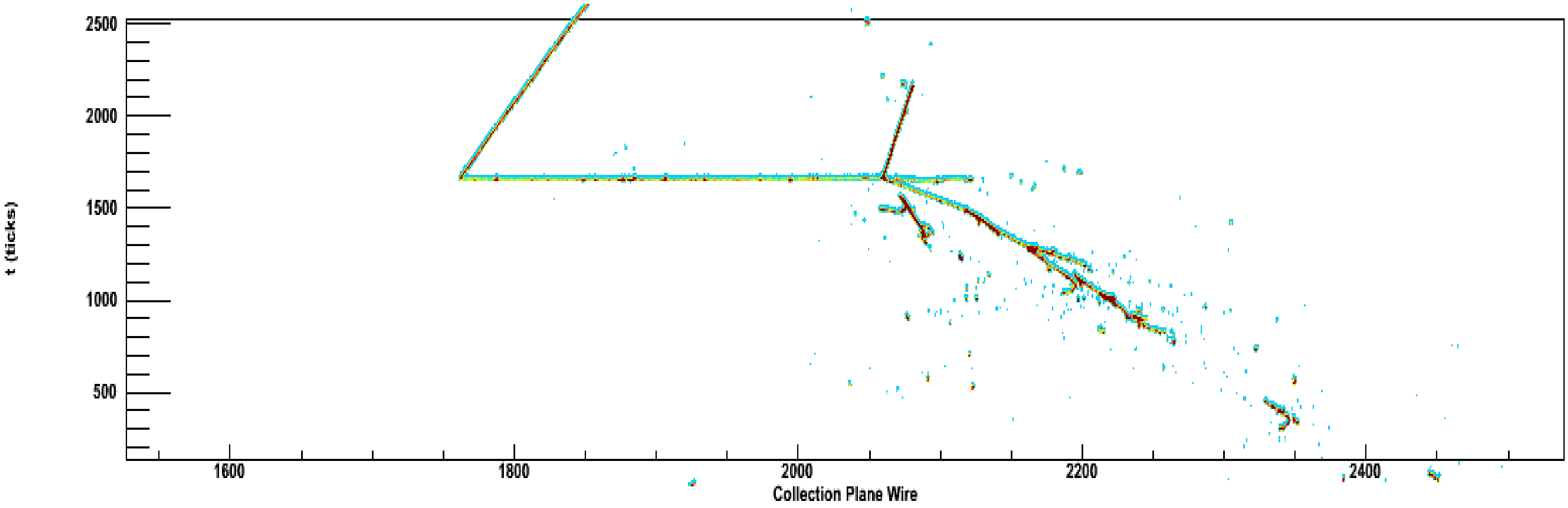
- γ :
  - Neutral particle
  - Gap spanning a couple wires
- π^0 :
  - $\pi^0 \rightarrow \gamma + \gamma$
  - Common origin
  - Typically lower energy

Step 4 (cont.):

- $\pi^{\pm}$:
  - Rarer event
  - Typically lower energy
  - Most often will contain a short tail before actual shower

- e :
  - Connected to primary interaction vertex in all planes
  - Usually dense showers

Step 4 (cont.):


2500
2000
1500
1000
500
t (ticks)
1600
1800
2000
2200
2400
Collection Plane Wire

Algorithm Summary:

- Remove all non-fiducial events
- Remove all non-showering events
  - NC QE, most ν_μ events
- Remove all μ-track containing events
- Remove NC showering events
  - NC RES, NC DIS

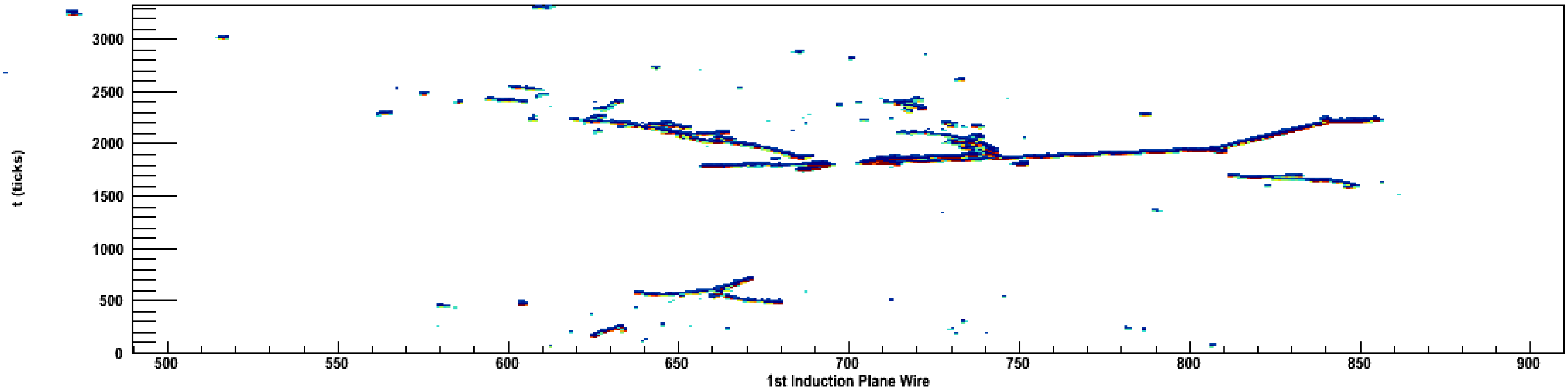
Conclusions

Results

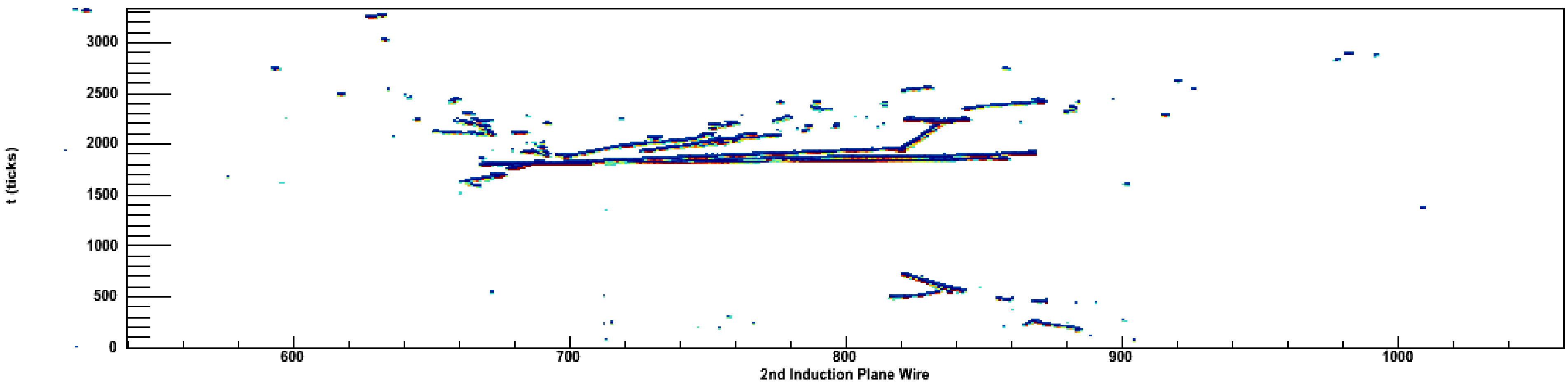
- Efficiency of background rejection:
  - 96%
- Efficiency of signal retention:
  - All identified
  - 6/1
  - 7%
- Breakdown of algorithm:
  - Efficiency of μ identification: 93%
  - Efficiency of $\pi^{\pm}$ shower identification: 70%
  - Efficiency of π^0 identification: 68%

Remaining Questions

- Looking quantitatively at particle energy and shower properties
  - Density of energy deposition
  - Could help differentiate π^0 and e
- Vertex gaps in electron events
  - Happens rarely
  - Loss of signal
- Look into higher mass particles
  - $K^{\pm}$, Σ^+, Λ^0



t (ticks)
0
500
1000
1500
2000
2500
3000
500
550
600
650
700
750
800
850
900
1st Induction Plane Wire



t (ticks)
0
500
1000
1500
2000
2500
3000
600
700
800
900
1000
2nd Induction Plane Wire

Acknowledgements:

- We'd like to thank the following for their help and guidance in this endeavor:
  - Tim Bolton
  - Glenn Horton-Smith
  - David McKee