Observation of Anomalous Dimuon Events in the NuTeV Decay Detector

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- Introduction to NuTeV "Decay Channel" search and events
- Search criteria and "Conventional Physics" backgrounds
- Monte Carlo checks
- The Observed Events with an "Exotic Decay" and "Null" hypothesis
- Conclusions (Preliminary)

NuTeV Collaboration

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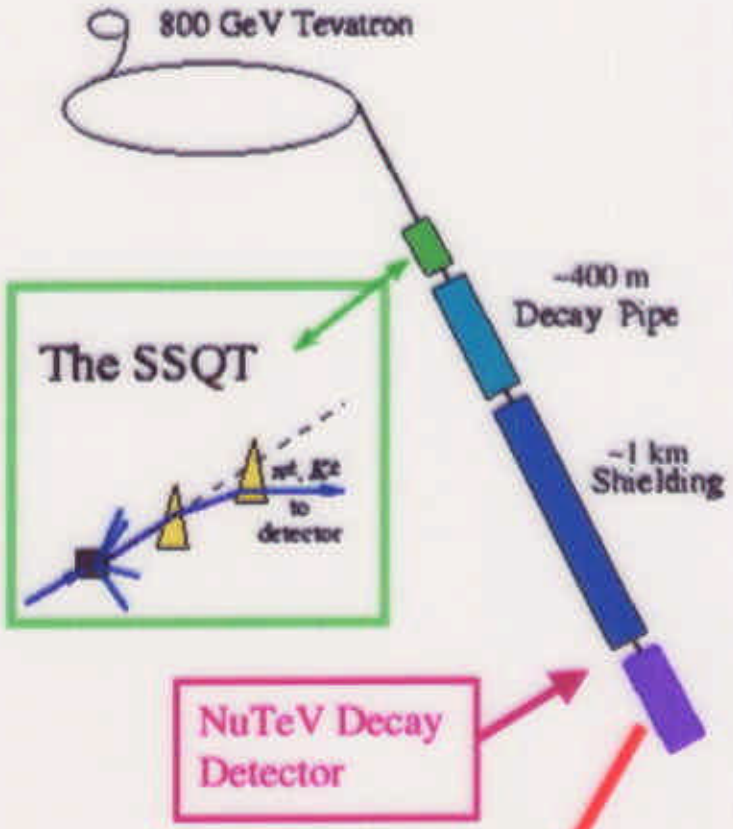
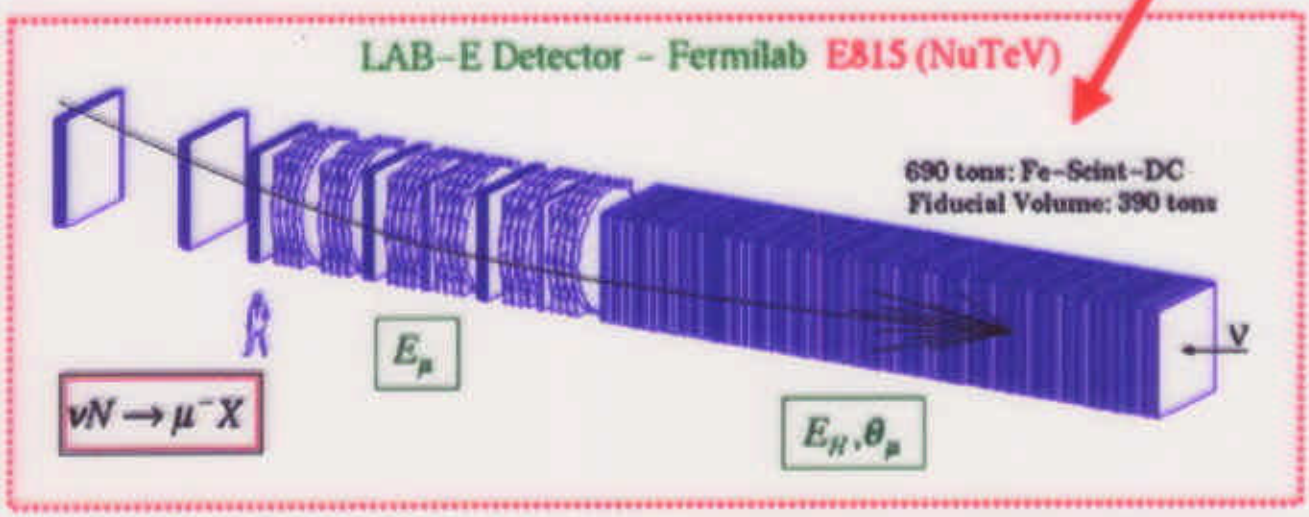
Key for the Decay Channel Analysis Group

- Graduate Students
- Members of the analysis group
- Members focusing mainly on this analysis

NuTeV Neutrino Experiment

- Tevatron 800 GeV primary proton → π and K meson (Sign-selected Quad Triplet *SSQT* beam) → ν_μ and $\bar{\nu}_\mu$
- 1996-97 Data Run
- ~4.5 million ν and $\bar{\nu}$ interactions (6:1 ratio)



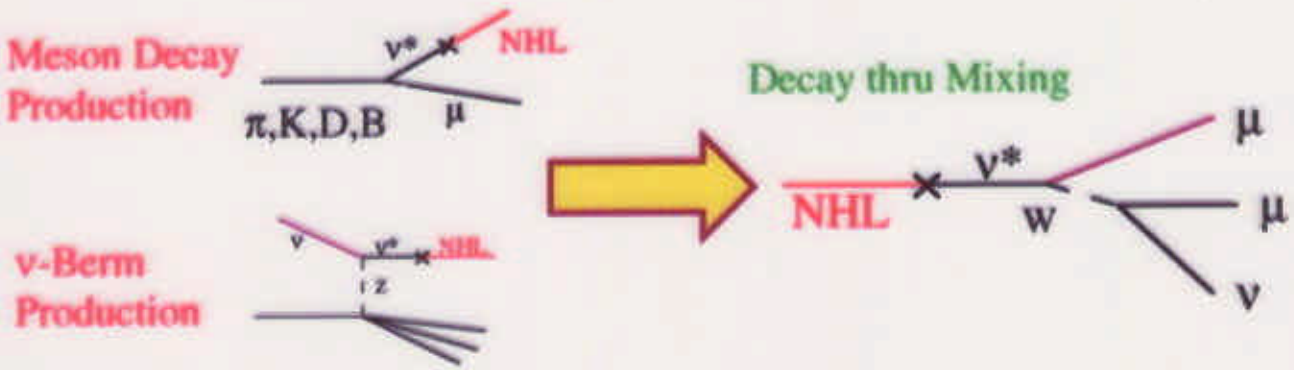


NuTeV Decay Detector Search for N^0's

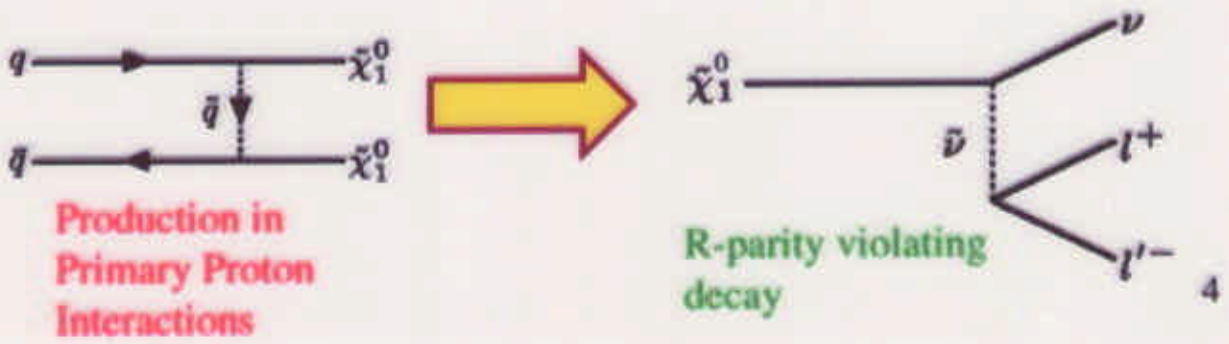
- Search for few-GeV, long-lived neutral particles (N^0's) that decay into two charged tracks ($\mu\mu\nu$, $\mu e\nu$, $\mu\pi$)

Examples:

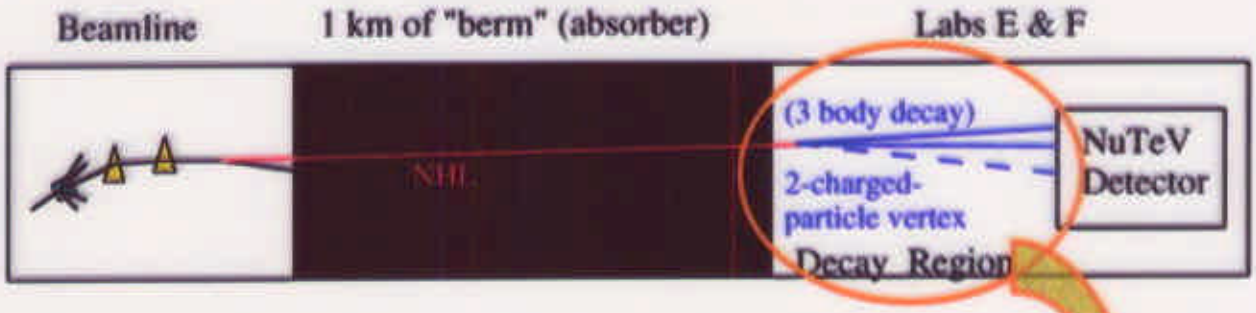
- Neutral Heavy Leptons (NHLs)
  - Isosinglet ("sterile") heavy neutrinos that are produced and decay through mixing



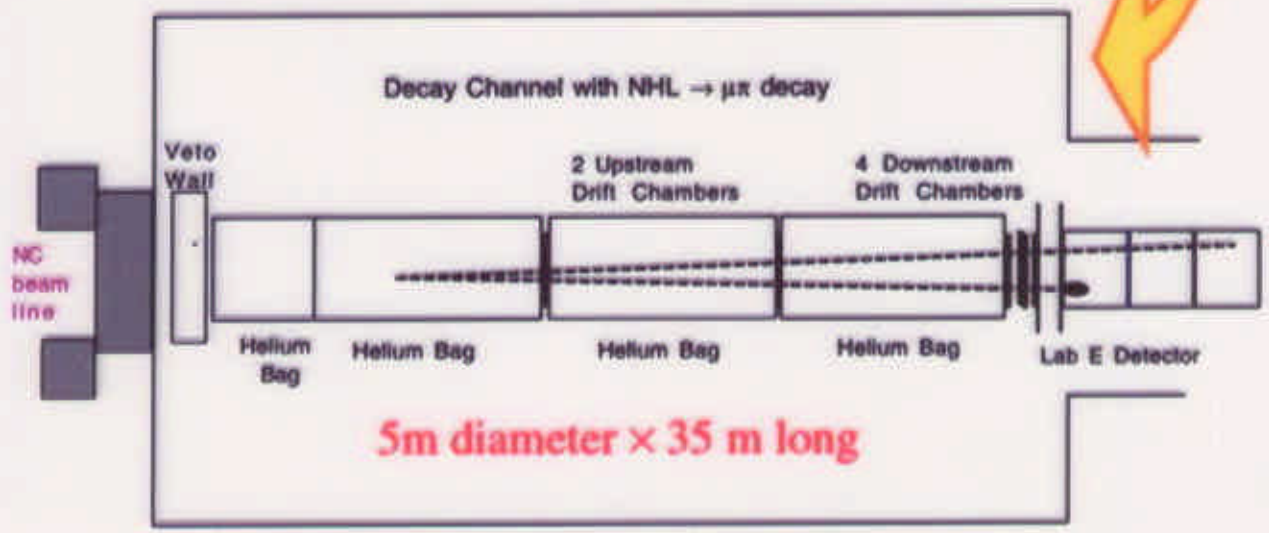
- Neutralinos
  - Long-lived neutralinos which decay through R-parity violation ($\gamma c\tau$ ~ 500 - 5000m)



NuTeV Decay Detector ("Decay Channel")



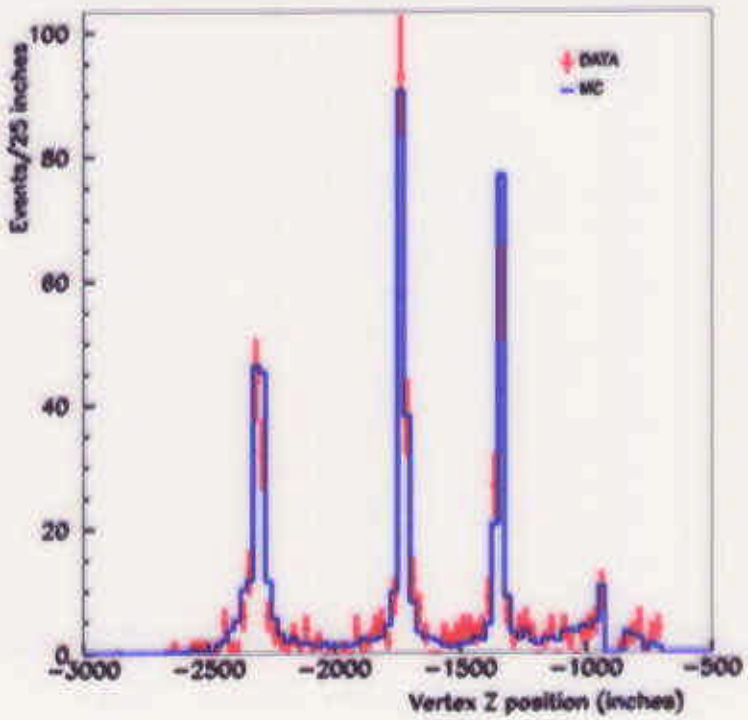
- Veto Wall to veto entering charged particles
- Helium bags reduce ν interactions relative to air
- Drift Chambers for tracking
- Lab E Neutrino Detector provides:
  - particle identification
  - energy measurements for e, π, K etc.
  - μ momentum measured in spectrometer



Neutrino Interactions in the Decay Channel

- Expect ~2500 ν interactions events in chambers and surrounding material and ~115 ν events in Helium
  - ν events in He with only two reconstructed tracks (others exit) is main background to search
- ν interaction Monte Carlo:
  - Includes quasi-elastic, resonance, and DIS
  - A-dependence included (Eskola *et al.*, Eur.Phys J. C9 (1999) 61)
  - Use Lepto/Jetset for quark fragmentation checked against EMC, BEBC, CCFR, and NuTeV data
  - Interface to hit-level GEANT Monte Carlo with chamber and counter noise added from data
    - Put through same full reconstruction as data
  - Normalized to data with ≥ 2 tracks with toroid μ

- Vertex Distribution for events with ≥ 2 tracks
  - Good agreement of data to MC (χ^2/DOF = 53.7/64)



N^0 Search Criteria (Cuts)

Criteria developed to isolate two track events with good reconstruction in Helium region

⇒ Use Background and signal Monte Carlo to develop cuts

A candidate data event was seen by the group early in the analysis but the details of the event were not used in developing the cuts.

Main requirements:

- Good Track and Vertex reconstruction
  ("χ^2_{track}"/dof < 10 , xy link, and "χ^2_{vertex}"/dof < 10)
- Require 2-track vertex and no veto
  (Only 2 tracks at vertex plus possible downstream δ–track)
- Energy Requirements and Good Particle Identification
  ($E_\mu > 2.2$ GeV , $E_{\pi \text{ or } e} > 10$ GeV , $\Sigma E_{tracks} > 12$ GeV)
- Isolate fiducial volume
  (Vertex with |x| < 50 in and |y| < 50 in)
  (z of vertex 40 inches or 3σ away from chambers)
- Isolate high mass region
  ($M_T = |p_T^{miss}| + (p_T^{miss\,2} + m_{inv}^2)^{1/2} > 2.2$ GeV)
  Previous limits for $M_T < 2.2$ GeV (A. Vaitaitis *et al.*, Phys. Rev. Lett. 83 (1999) 4943; J.A. Formaggio *et al.*, Phys. Rev. Lett. 84 (2000) 4043)
- Clean Cuts to remove DIS events with exiting tracks and neutrals
  (No extra neutral clusters in the calorimeter, ≤ 4 hits in each view downstream of vertex, ≤ 7 hits total in 2 chambers downstream in any one view)

Background Sources

- ν events in the Helium
  - Low-multiplicity or many tracks that exit giving 2 tracks
- ν events in the chambers and other material
  - Mass is 20× helium
  - Mis-reconstructed vertex that appears to be in helium region and only 2 tracks
- Diffractive and Trident ν interactions in He/chambers
  - Measured by NuTeV - $D, D_s, \rho, \omega, \phi, \psi, \pi, K$ etc. See Adams *et al.*, PRD 61 (2000) 92001
- Wide angle K_L from interactions in berm, floor, etc.
  - Can give low m_{INV} (< 0.5 GeV) $\mu\pi$ decays
  - Reduced by $\Sigma E_{tracks} > 12$ GeV
- Other negligible types
  - Cosmic rays, berm photon conversions, berm μ punch-thru, two-event overlays, etc.
    ⇒ All constrained by data

Summary of the Sources of Background

Source	$\mu\mu$ Events
DIS Events, all sources	$(3.9 \pm 0.9) \times 10^{-2}$
Diffractive Charm	$(1.1 \pm 0.1) \times 10^{-3}$
Diffractive $\mu\pi$	$(1.7 \pm 0.1) \times 10^{-4}$
K_L decays from berm	$(3.9 \pm 3.9) \times 10^{-4}$
Diffractive μK	$(3.3 \pm 0.3) \times 10^{-7}$
Other Sources	$< 2.5 \times 10^{-4}$
Total $\mu\mu$ Background:	0.040 ± 0.009 events

Preliminary

Source	μe Events
DIS Events, all sources	$(1.4 \pm 0.2) \times 10^{-1}$
Diffractive Charm	$(1.5 \pm 0.1) \times 10^{-3}$
Diffractive $\mu\pi$	$(1.0 \pm 0.1) \times 10^{-4}$
K_L decays from berm	$(3.9 \pm 3.9) \times 10^{-4}$
Diffractive μK	$(2.5 \pm 0.2) \times 10^{-7}$
Other Sources	$< 1.6 \times 10^{-4}$
Total μe Background:	0.14 ± 0.02 events

Preliminary

Source	$\mu\pi$ Events
DIS Events, all sources	$(1.3 \pm 0.2) \times 10^{-1}$
Diffractive Charm	$(1.1 \pm 0.1) \times 10^{-3}$
Diffractive $\mu\pi$	$(3.5 \pm 0.3) \times 10^{-4}$
K_L decays from berm	$(3.9 \pm 3.9) \times 10^{-4}$
Diffractive μK	$(8.7 \pm 0.8) \times 10^{-7}$
Other Sources	$< 1.6 \times 10^{-4}$
Total $\mu\pi$ Background:	0.13 ± 0.02 events

Preliminary

Errors are Systematics ⊗ Monte Carlo Statistics.

"Other" Box Checks of Monte Carlo

- The "chamber antibox" (within ±6 in of chamber)

Type	Observed	MC
μμ	0	1.6
μe	1	1.8
μπ	2	2.7

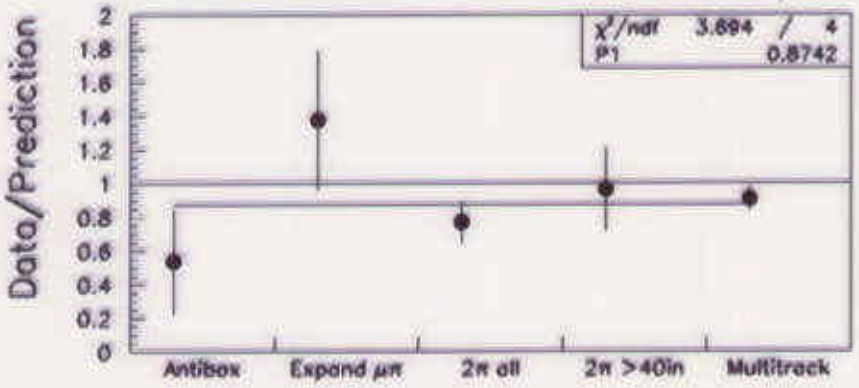
× 1/28 to He (mass/accept. ratio)

Predict He Interactions
<0.04
~0.04
~0.07

- Intermediate region (6 to 40 in from chambers)

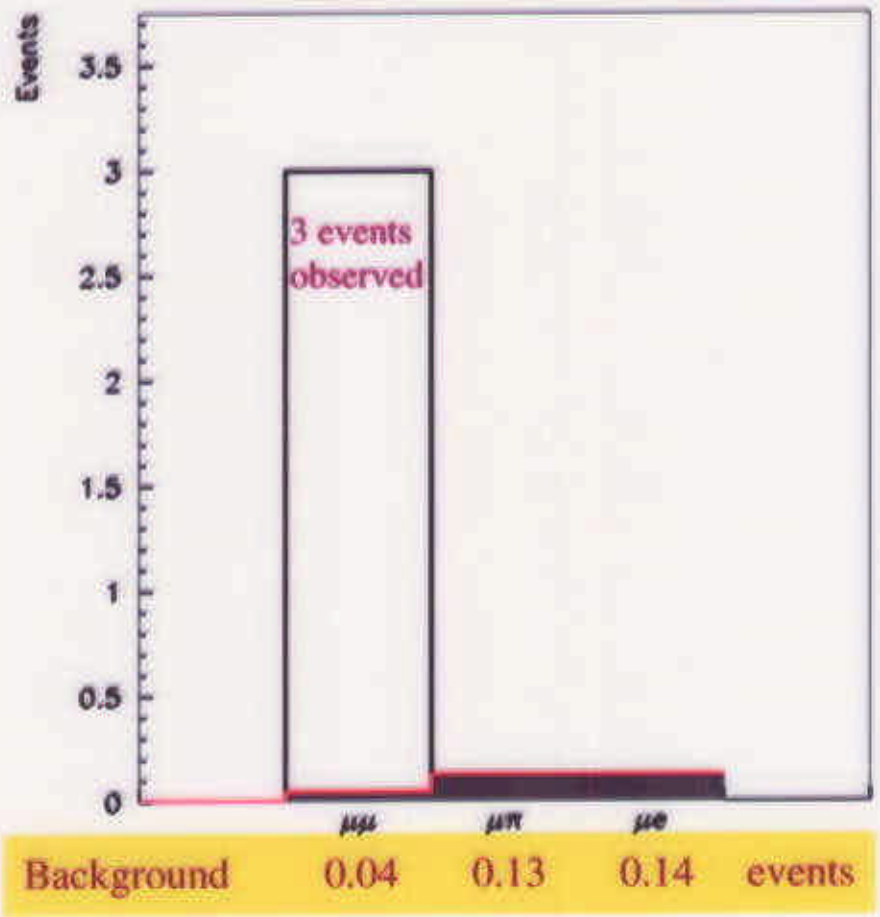
Type	Observed	MC
μμ	0	0.1 ± 0.05
μe	0	0.6 ± 0.1
μπ	0	0.7 ± 0.2

- Other studies:
  - Reduced cuts "chamber antibox" for μπ
  - ππ all and > 40in from chambers
  - Multitrack events with > 2 tracks at vertex



Agreement in all studies to ± 15%

Inside Signal Region ...



Background	0.04	0.13	0.14	events

Conclusions:

- We observe 3 μμ events, 0 μπ and 0 μe
- The three events are far above expectation (gray region)
- The MC background expectation has been checked several ways

Cut Reduction Studies

Start with full cuts and remove cuts sequentially

- Remove "Clean Cuts"

Event Type	Data Events	MC Predict
μμ	3 + 1	0.25
μe	0	0.25
μπ	0	0.13

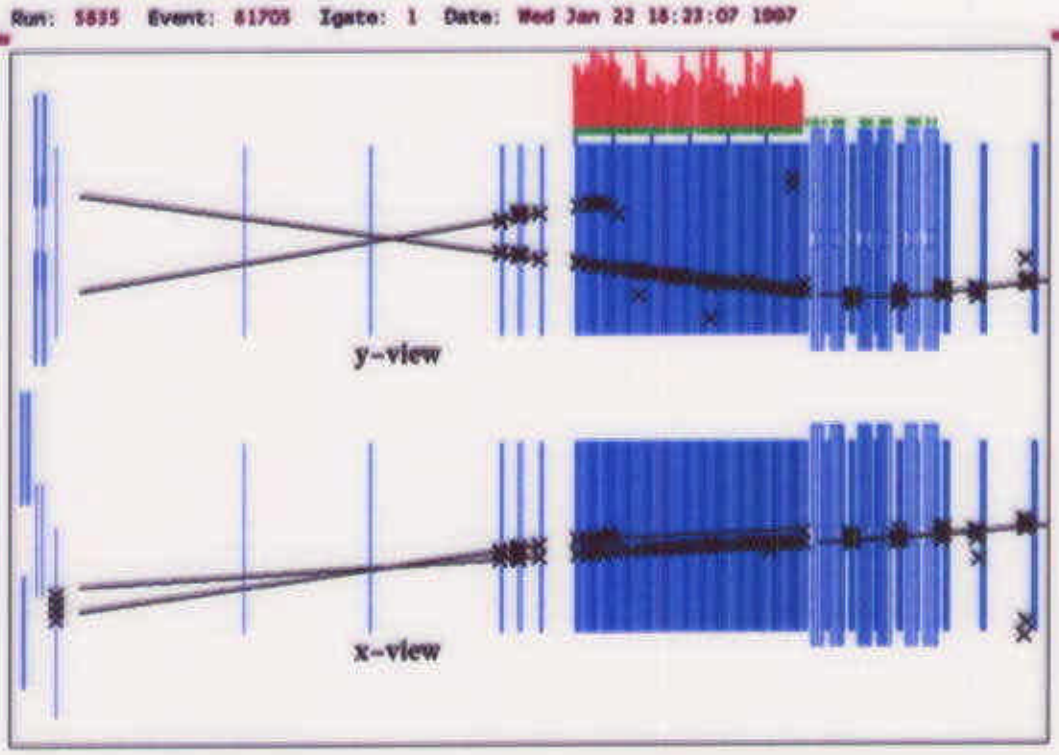
- Expand fiducial region to include chambers

Event Type	Data Events	MC Predict
μμ	3 + 2	1.4
μe	7	6.3
μπ	5	5.5

- Remove all energy and PID cuts

Event Type	Data Events	MC Predict
μμ	3 + 3	2.5
μe	10	13.8
μπ	10	13.8

Event 1



- Transverse Mass: 5.1 GeV
- Track information:

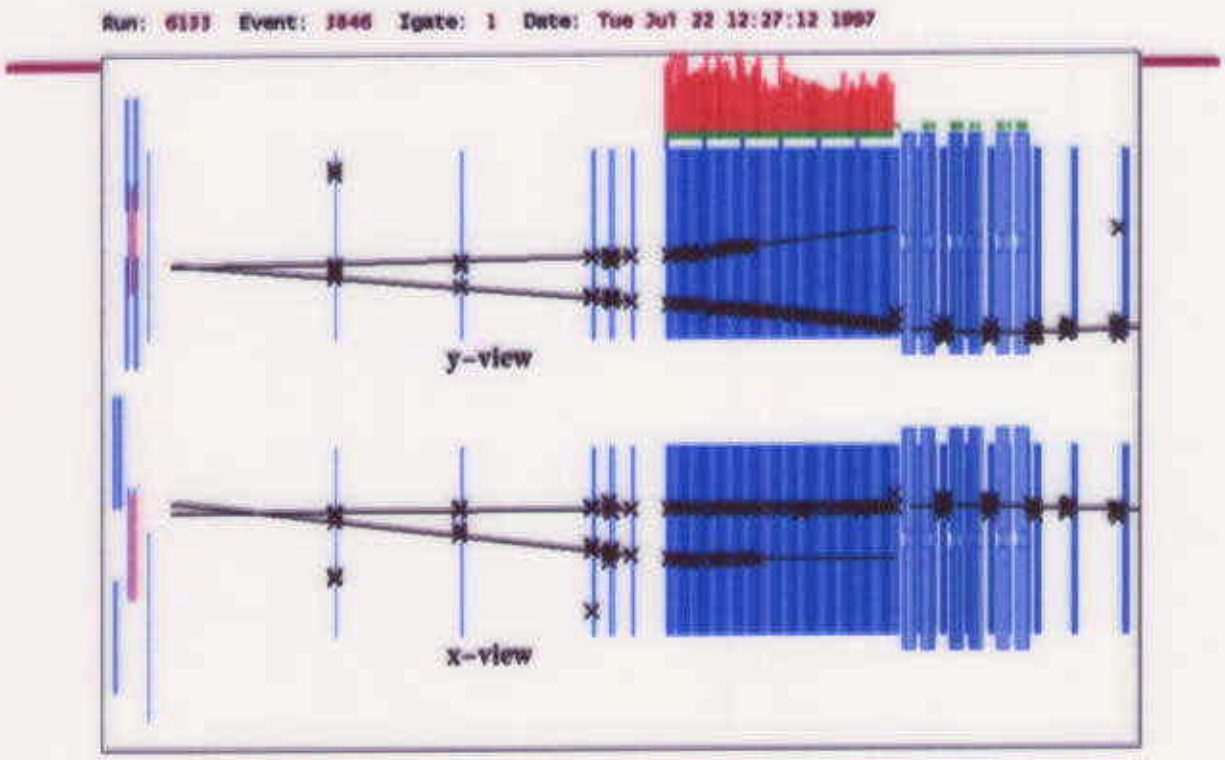
	Momentum	Pseudo-χ^2/DOF $(x;y)$	Charge
Track 1:	77.7 GeV	0.2/2; 2.4/2	negative
Track 2:	2.6 GeV	0.3/2; 3.1/2	unmeasured

- Vertex Information:

(x, y, z) in inches	$\Delta_z^{chamber}$	Pseudo-χ^2/DOF	error in z
$(-18.4, 1.4, -1265.9)$	77 inches (DK4)	6.3/9 (Prob=62%)	±9.5 inches

- Veto hit-time from trigger: +404, +536 ns

Event 2



- Transverse Mass: 3.1 GeV
- Track information:

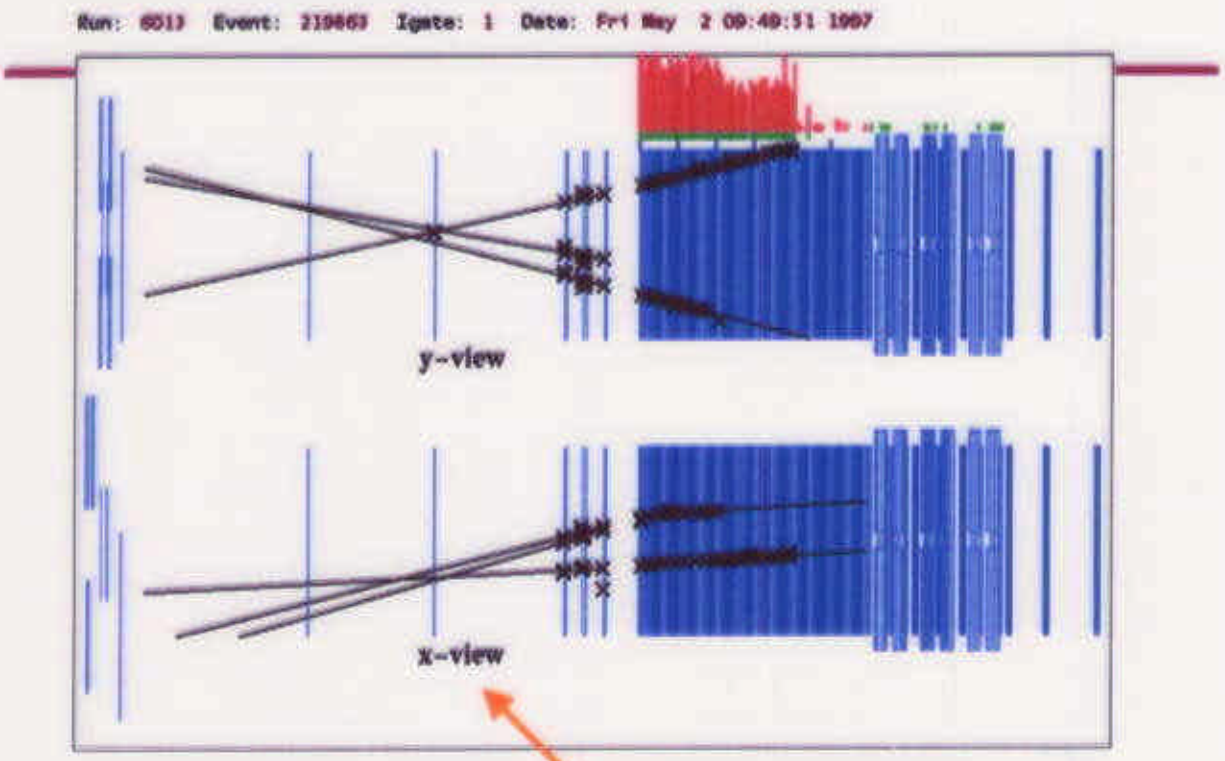
	Momentum	Pseudo-χ^2/DOF	Charge
Track 1:	92.0 GeV	1.8/4; 2.8/4	negative
Track 2:	5.8 GeV	5.1/4; 4.5/4	unmeasured

- Vertex Information:

(x, y, z) in inches	$\Delta_z^{chamber}$	Pseudo-χ^2/DOF	error in z
(18.3, −15.2, −2041.2)	312 inches (DK5) 260 inches (TB)	166/17 (Prob=5%)	±7.2 inches

- Veto hit-time from trigger: +24 ns 6.3 σ out of time

Event 3



Missing hits in DK4

- Transverse Mass: 4.7 GeV
- Track information:

	Momentum	Pseudo-χ^2/DOF (x, y)	Charge
Track 1:	47.9 GeV	2.5/2; 0.8/2	unmeasured
Track 2:	4.3 GeV	13/2; 2.4/2	unmeasured
Downstream Track:	unmeasured ($< 2GeV$)	0.8/2; 1.2/2	unmeasured

Extra track

- Vertex Information:

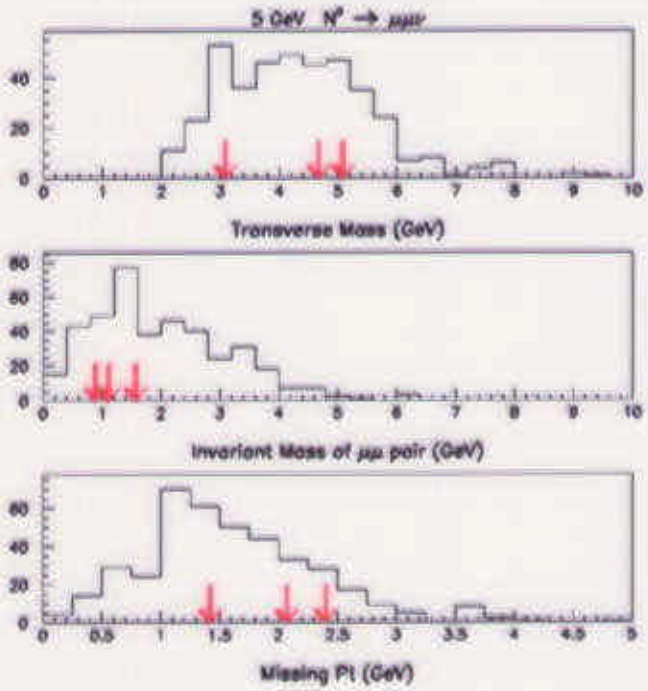
(x, y, z) in inches	$\Delta_z^{chamber}$	Pseudo-χ^2/DOF	error in z
$(-23.3, 5.8, -1416.7)$	73 inches (DK4)	23/10 (Prob=21%)	± 5.3 inches

- Veto hit-time from trigger: -256, $+320$, $+320$, $+1192$ ns

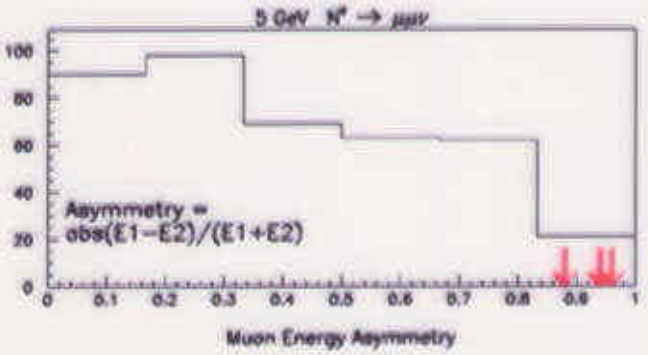
N^0 Hypothesis

N^0 Monte Carlo is a generic massive weak fermion decay (with mixing) based on NHL → μμν

- What's *right* about a N^0-decay explanation?
  - Events pass the analysis cuts ⇒ Background is 0.04 evts!
  - Events distributed in z and away from chambers ⇒ **Look like decays**
  - Reasonable values of M_T, M_{inv}, missing p_T for 5 GeV N^0



- What's *wrong* about a N^0-decay explanation?
  - All the events are highly asymmetric in muon energy
  - Probability for 3 events
    - N^0 ⇒ < 0.5 %
    - DIS ⇒ ~35 %



"Null Hypotheses"

Based on Neutrino Interactions in the Decay Channel

Why? E_μ asymmetry of two μ's, event kinematics, and leading muon charge consistent with neutrino scattering

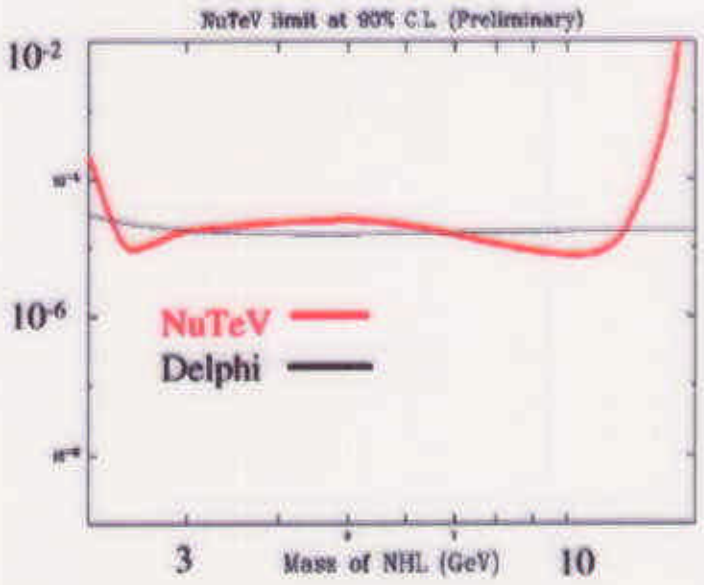
⇒ Challenge: Only see "clean" μμ events in the Helium (If interactions, then should be chamber events)

But all of these background hypotheses should already be included in Monte Carlo background estimate.

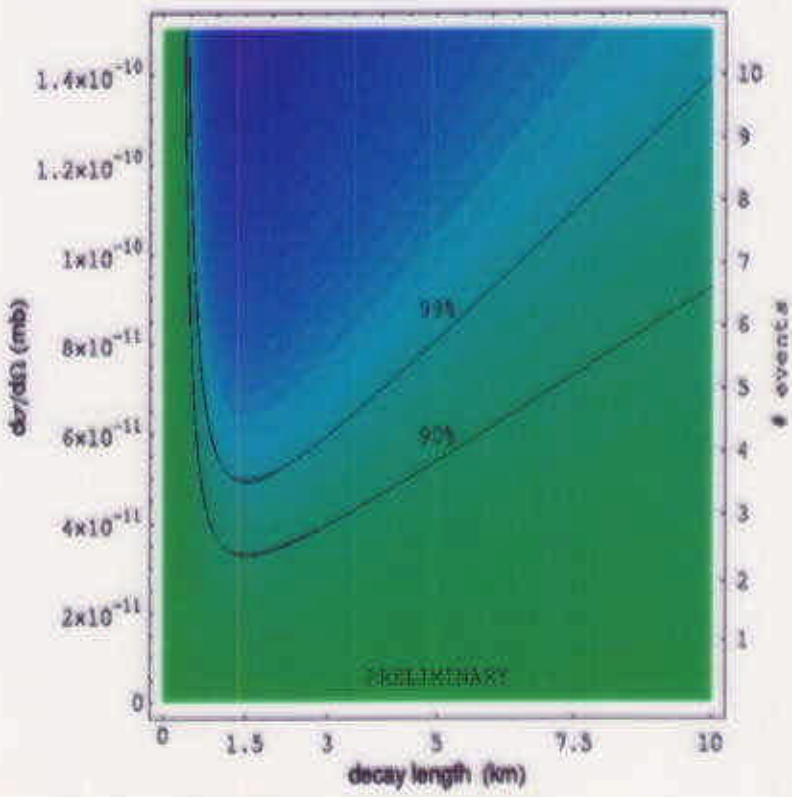
- Hypothesis 1: Misreconstructed chamber events
  - Constrained fits to chambers give much bigger χ^2/dof
  - Where are misreconstructed μπ and μe ?
- Hypothesis 2: Excess μπ → μμν events in chamber or He
  - Only 7% of pions decay so should see un-decayed μπ events
    ⇒ Predict 3 × (μπ/μμ) = 9.8 events but see 0 μπ
- Hypothesis 3: Excess μK → μμν events in chamber or He
  - p_T from K-decay can push chamber events into He
  - Only 22% of kaons decay and only 43% will form a downstream vertex so should see many μK events
    ⇒ Predict 38.5 μ "hadron"events but see 10

NHL and Neutralino Limits

- NHL Hypothesis:
  - For 5 GeV NHL $\mu\mu\nu:\mu e\nu:\mu\pi$ = 1 : 1.7 : 0.1 Then given 3 $\mu\mu$ events, expect 5 μe but 0 observed
  - Similar limit to Delphi 90% CL



- Neutralino Hypothesis:
  - N^0 could be a long-lived, R-parity violating χ^0
  - Can choose couplings to only give $\mu\mu\nu$ decays
  - First limit on long-lived χ^0 in this mass range



Conclusions (Preliminary)

- NuTeV has performed a search for the decay of an exotic N^0 particle with $M_T > 2.2$ GeV

Event Type	Data Events	Backgnd (Prelim.)
$\mu\mu$	3	0.040 ± 0.009
μe	0	0.14 ± 0.02
$\mu\pi$	0	0.13 ± 0.02

- Prob(≥ 3 $\mu\mu$ events) = 1.2×10^{-5}
  Prob(All modes with ≥ 3 events) = 4.1×10^{-3}
- Only see clean two-track events in He region not chambers which are 20 times more massive
  - Looks like a decay not an interaction
- Energy asymmetry is > 0.85 in all three cases
  - Probability is < 0.5% for an N^0 (~ 35% for DIS)
- Various DIS-inspired "Null-hypotheses" have been investigated but all have low probability for explaining these events.
- New limits set on NHLs and Neutralinos

Parameters for search: 2.54×10^{18} p.o.t. at 7.8 mr
Detector 1.4 km away with 2.5m × 2.5m × 35m fid. vol.
E * Neutrino flux into fid. vol. = 1.9×10^4 / p.o.t.

Summary of Energy and Mass Measurements for Events

Event	$E_{\mu\ 1}$ (GeV)	$E_{\mu\ 2}$ (GeV)	$P_{T\ miss}$ (GeV)	M_{inv} (GeV)	M_T (GeV)
5835/81705	77.7 ± 8.6	2.56 ± 0.31	2.42 ± 0.27	1.11 ± 0.07	5.08 ± 0.05
6113/3846	92.0 ± 10.12	5.84 ± 0.31	1.42 ± 0.17	0.89 ± 0.04	3.08 ± 0.34
6013/219863	48.0 ± 20.15	4.34 ± 0.31	2.07 ± 0.90	1.57 ± 0.30	4.67 ± 1.78

Summary of Vertex Measurements for Events

(position units are inches)

Event	x Vertex	y Vertex	z Vertex	Pseudo-χ^2/DOF	Prob
5835/81705	-18.44±0.18	1.41±0.28	-1265.9±9.5	6.3/9	62%
6133/3846	18.31±0.04	-15.25±0.12	-2041.2±7.2	166/17	5%
6013/219863	-23.25±0.18	5.83±0.24	-1416.7±5.3	23/10	21%