Searches for Long-lived Particles in Hadron Colliders

Todd Adams
Florida State University
APS April Meeting
April, 2007

1) Reasons to Search
2) Search Techniques
3) Summary

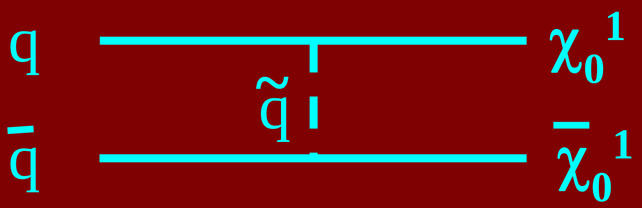
Why Look for Long-lived Particles at Colliders?

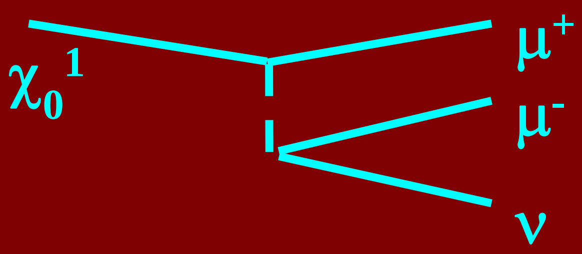
- Because we can…
- Because we might find something interesting…
  - "Who ordered that?" – I.I. Rabi
  - other examples: strange particles, J/Ψ, tau lepton
  - NuTeV result

- There are theoretical models which predict such particles…

Theoretical Models

- **R-parity violating supersymmetry (RPV SUSY)**
  - **neutralino (χ_0^1): lightest supersymmetric particle (LSP)**
  - **lifetime depends of a parameter (λ_{122})**





- **Hidden valleys**

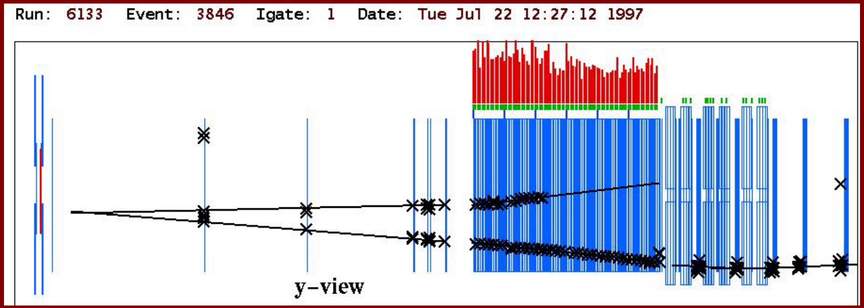
“Echoes of a Hidden Valley at Hadron Colliders”

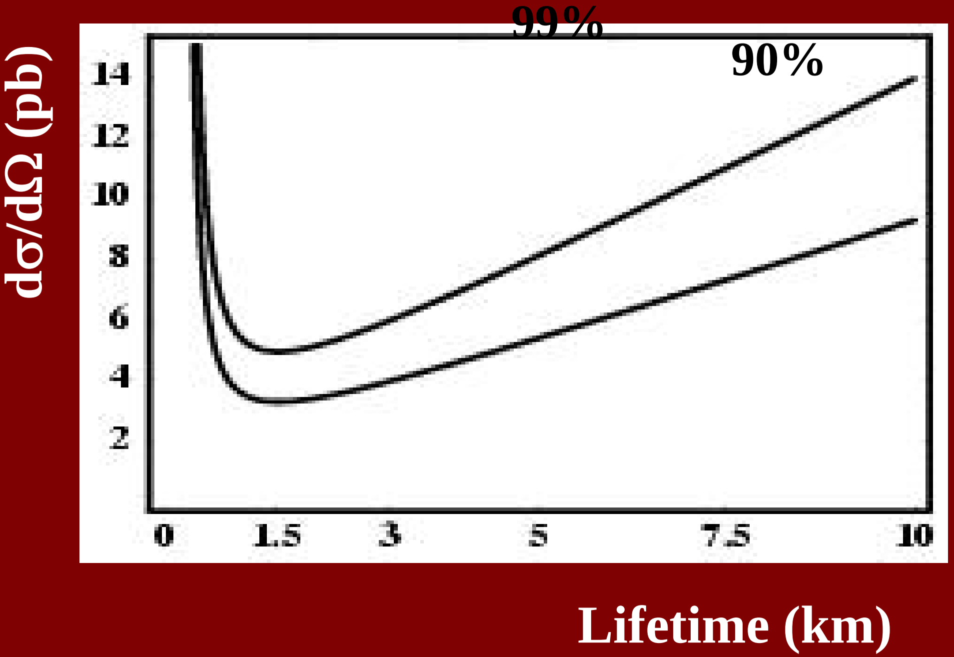
M. Strassler and K. Zurek hep-ph/0604261

  - **Predicts new class of “valley” particles**
    - **includes neutral, long-lived, low-mass particles**
    - **H→???**
  - **Recommends program to search at Tevatron and LHC**

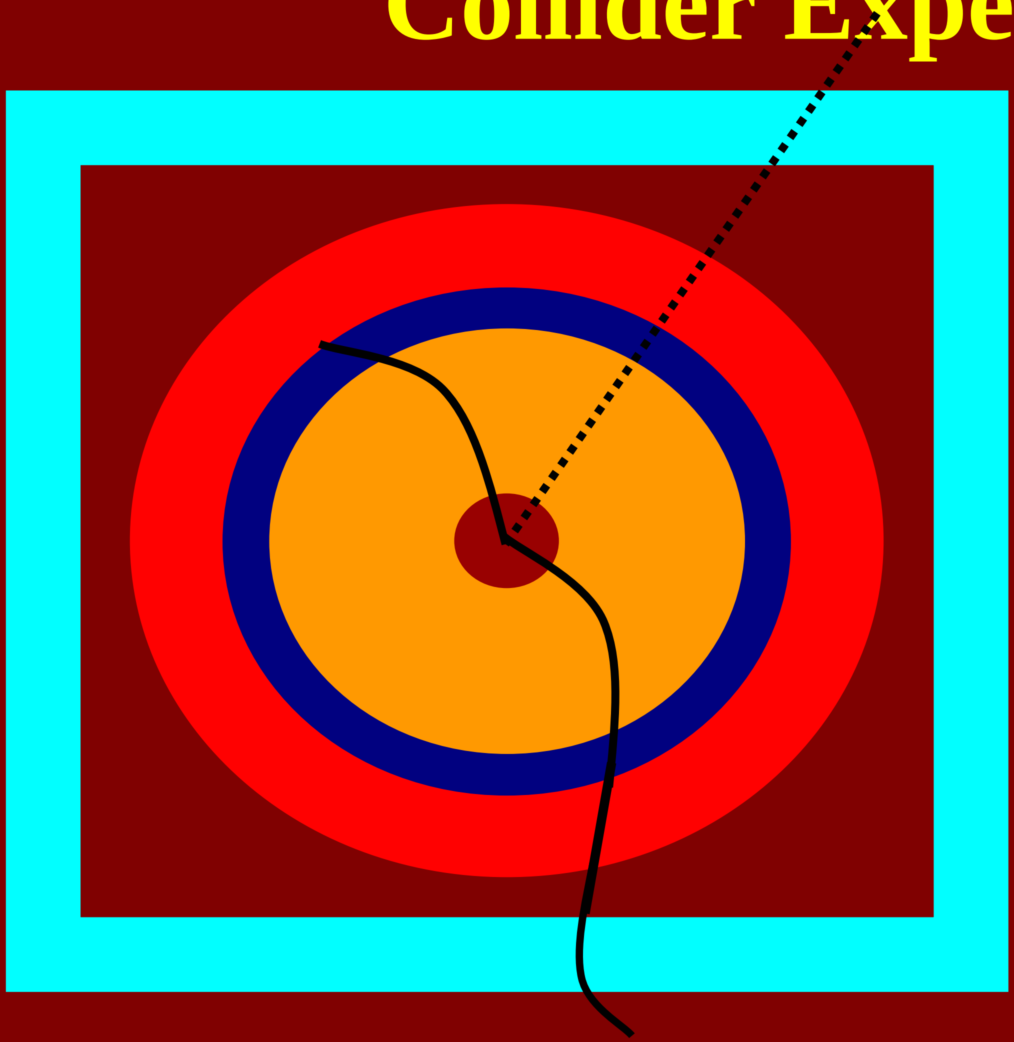
NuTeV Result

- NuTeV
  - neutrino deep-inelastic scattering experiment at Fermilab
- Searched for decays of particles along with neutrino beam
- 3rd search found
  - 3 events decaying to two muons
  - expectation of 0.07 ± 0.01
- No explanation to date





Because We Can…
Collider Experiments



multi-purpose detector

- tracking volume w/ magnetic field
- electromagnetic calorimeter
- hadronic calorimeter
- muon system w/ magnetic field

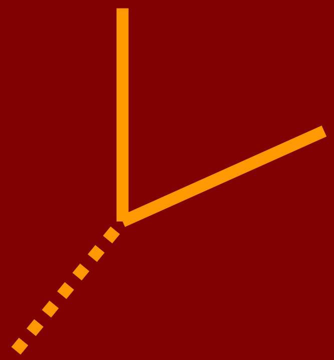
Possible Searches at Colliders

- **Short-lived (< 1 cm) decays** ☑
- **Very-long-lived (>>10 m) decays**
  - **missing transverse energy (neutral particles)** ☑
  - **slow moving, heavily ionizing (charged particles)** ☑
  - **stopped particles (stopped gluinos)** ☑
- **Long-lived decays (in between)**
  - **decays to stable particles (e.g. e, μ, γ, π, K)** ☑
  - **decays to unstable particles (e.g. τ, b)**

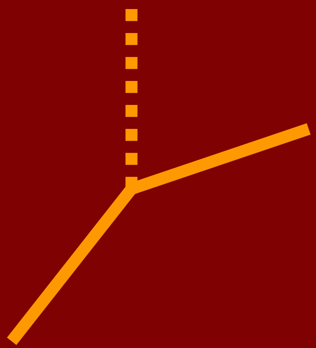
☑ **= already searched for at Tevatron**

Detached Vertices and Kinks

neutral → charged decay



charged → charged + neutral decay

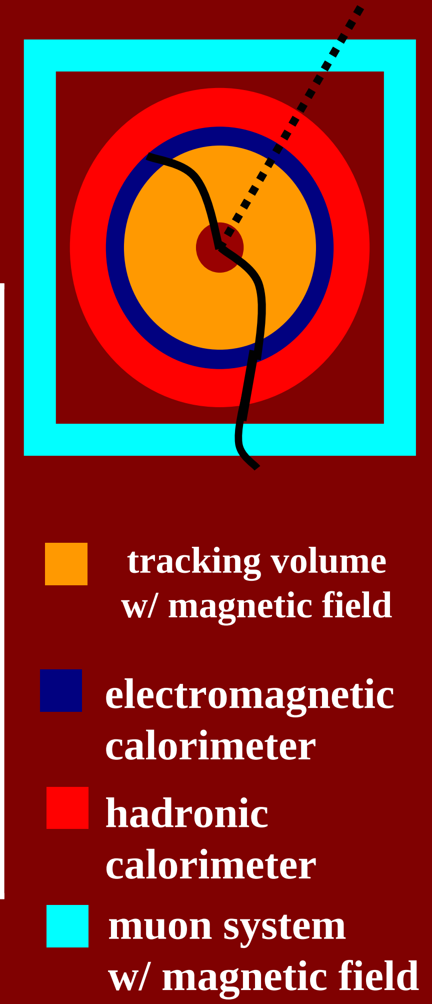


- **reconstruct highly-displaced vertices**
  - **well-beyond b-lifetime**
  - **can be multiple particles (e.g. decays to b-jets or taus)**

- **reconstruct tracks with a “kink”**
  - **find two “stubby” tracks which cross**
  - **need to separate from multiple scattering**

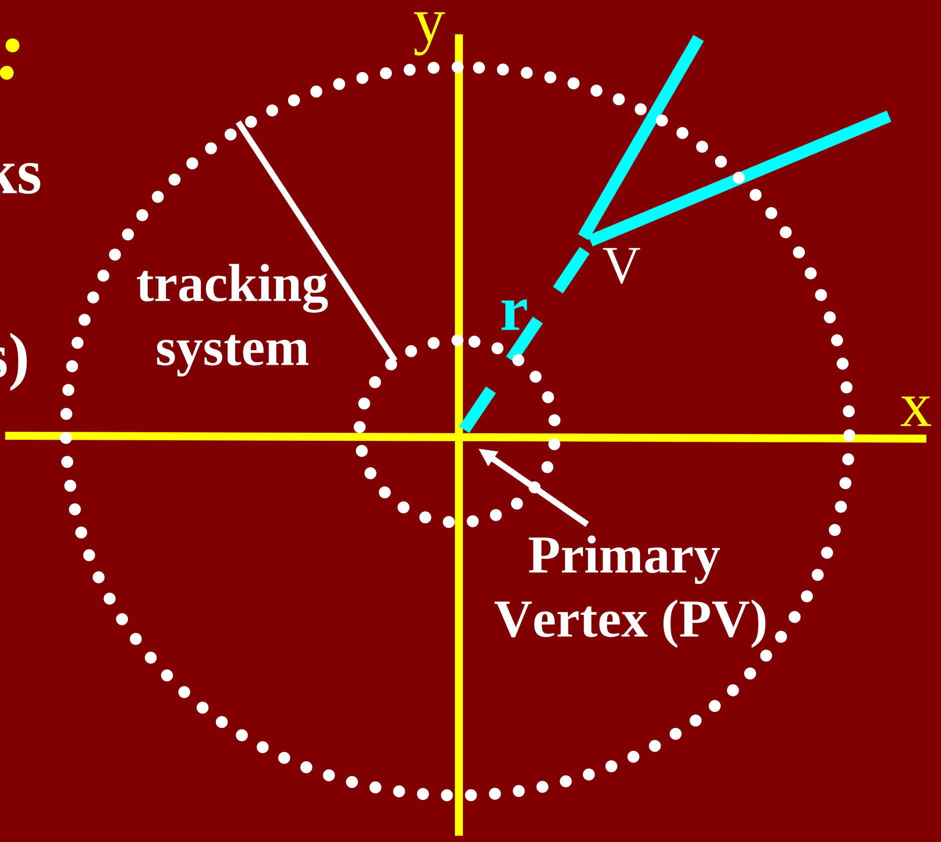
Hadron Collider Experiments

	CDF	D0	Atlas	CMS
√s (Tev)	1.96	1.96	14	14
Tracking	silicon & drift chamber	silicon & scint. fibers	pixels, silicon, & straw tubes	pixels & silicon
Inner /outer radius (cm)	1.3/132	1.5/50	5/115	4/108

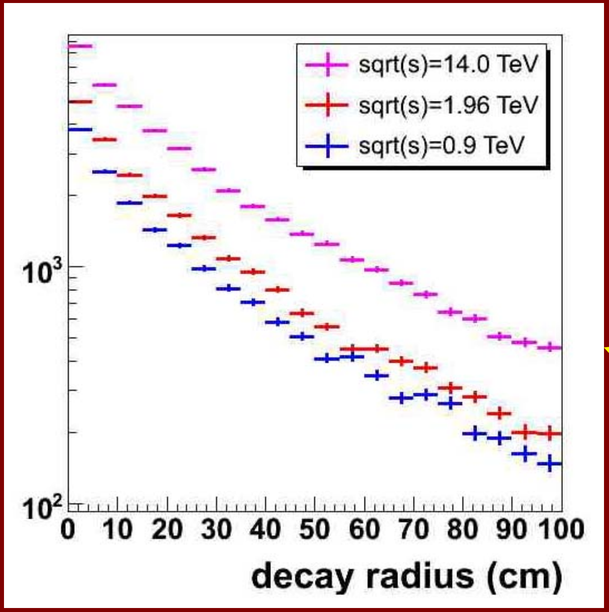


Two Track Technique:

1) identify events with two tracks
2) fit to a common vertex
3) measure decay length (radius)

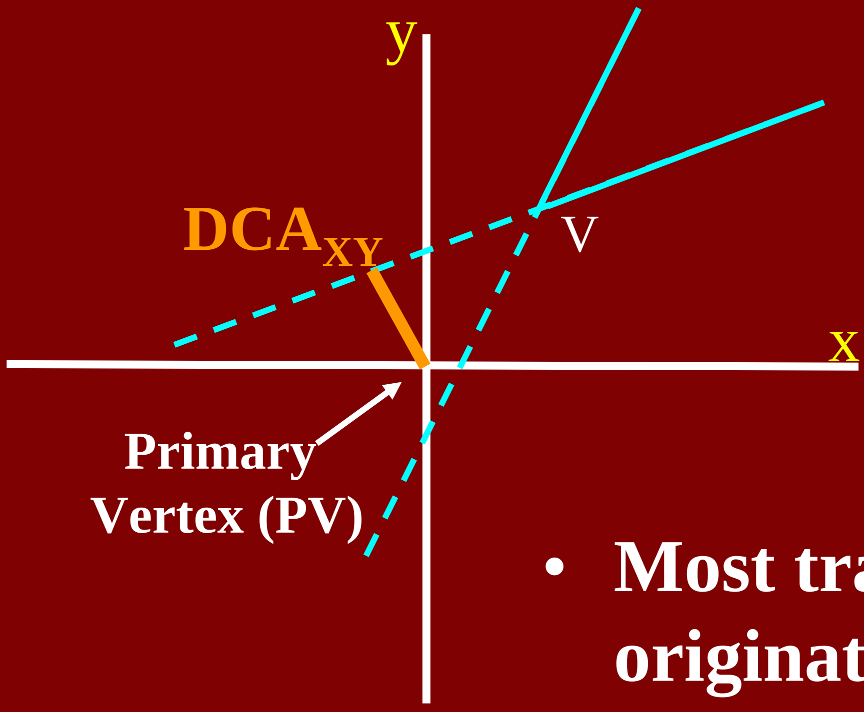


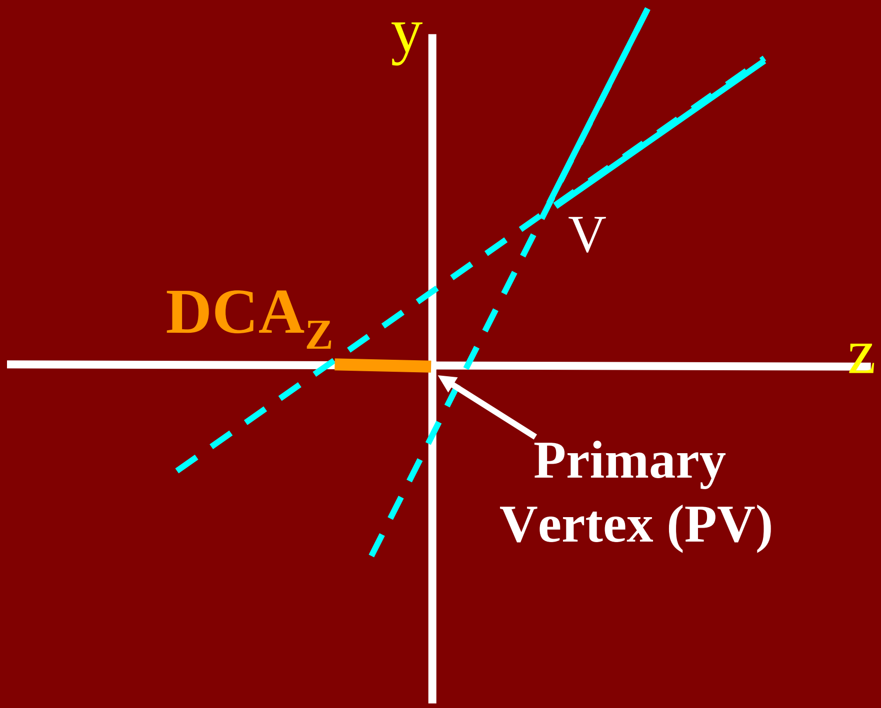
$$r = \sqrt{(x - x_{PV})^2 + (y - y_{PV})^2}$$



- Use $K_S^0 \rightarrow \pi^+\pi^-$ as control sample
- K_S^0 in QCD production at $\sqrt{s}$=0.9, 1.96, and 14 TeV
- Can study detached vertices beyond r=100 cm

Distance of Closest Approach

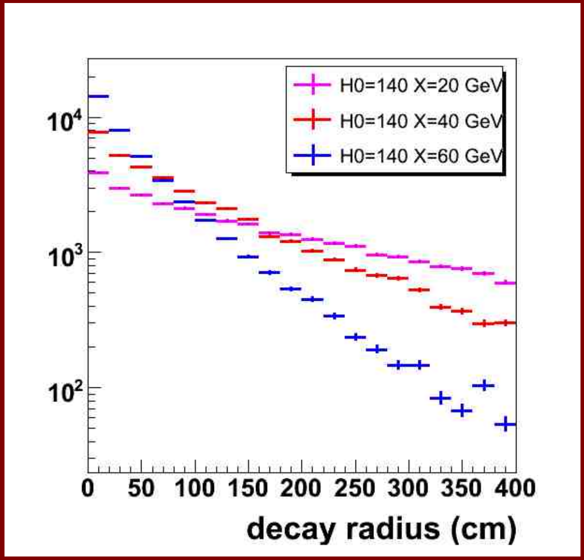


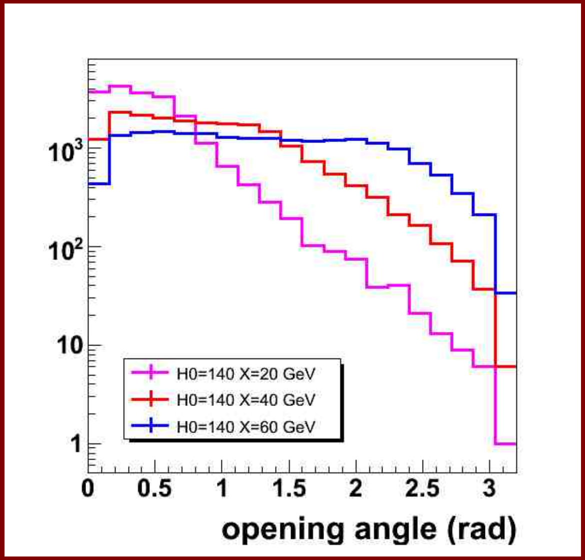


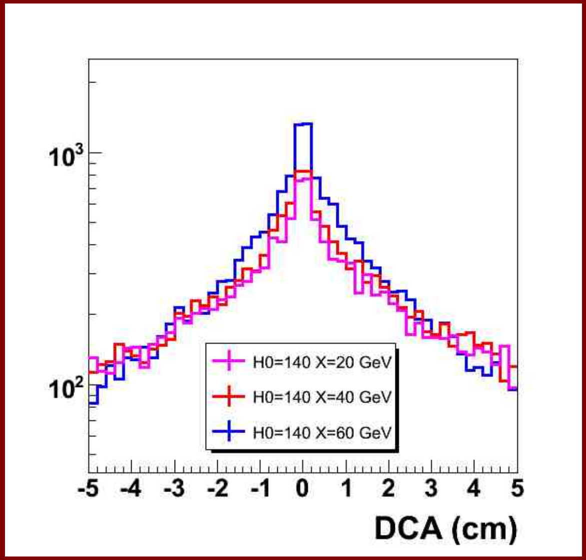
- **Most tracking code assumes track originates near center of detector**
- **Ability to reconstruct tracks from detached vertices related to DCA**

Sample "Hidden Valley" Model

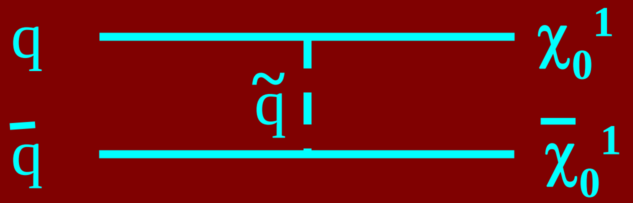
- $H \rightarrow X^0 X^0$, $X^0 \rightarrow \mu\mu$
  - $M(H)=140$ GeV, $M(X^0)=20, 40, 60$ GeV
  - $c\tau(X^0)=100$ mm



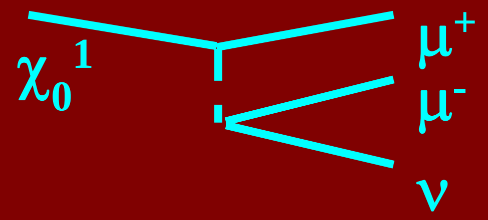


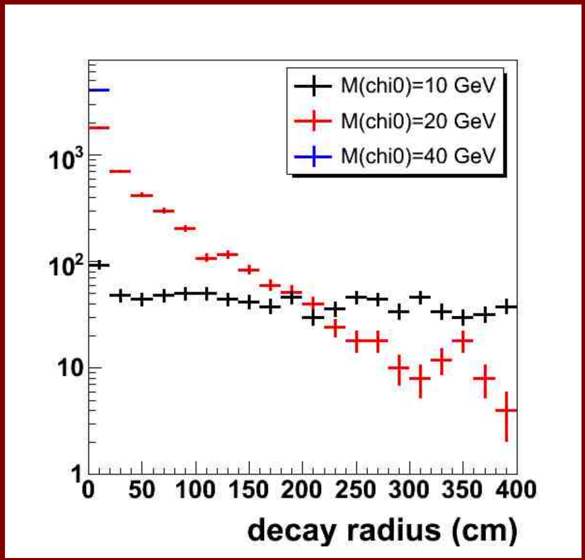


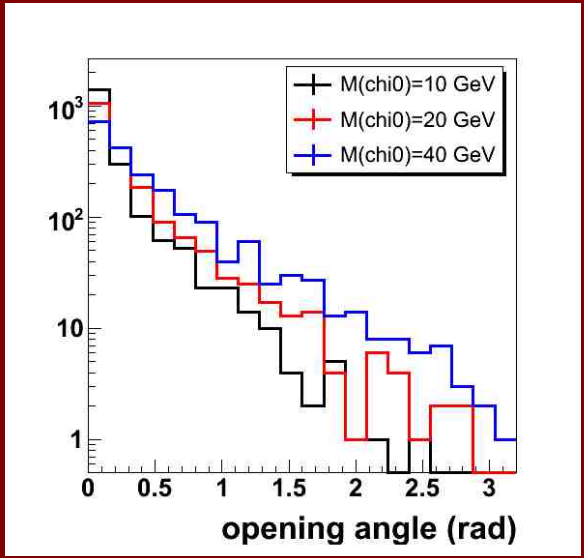
Sample SUSY Model

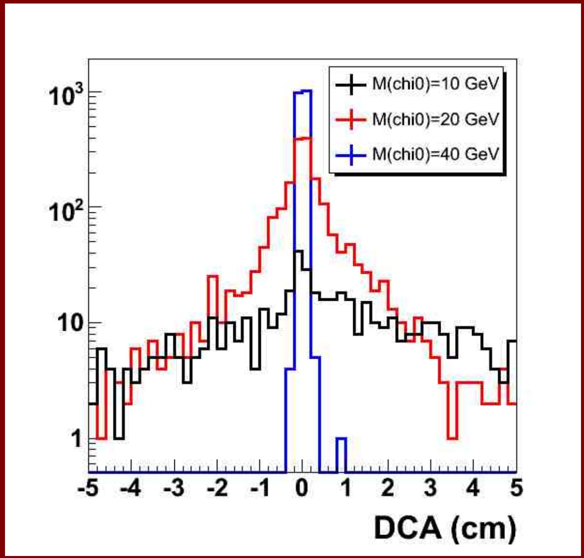


- **RPV unconstrained MSSM**
  - $M(\chi_0^1)$ = 10, 20, 40 GeV
  - $\lambda_{122} = 0.001$









Summary

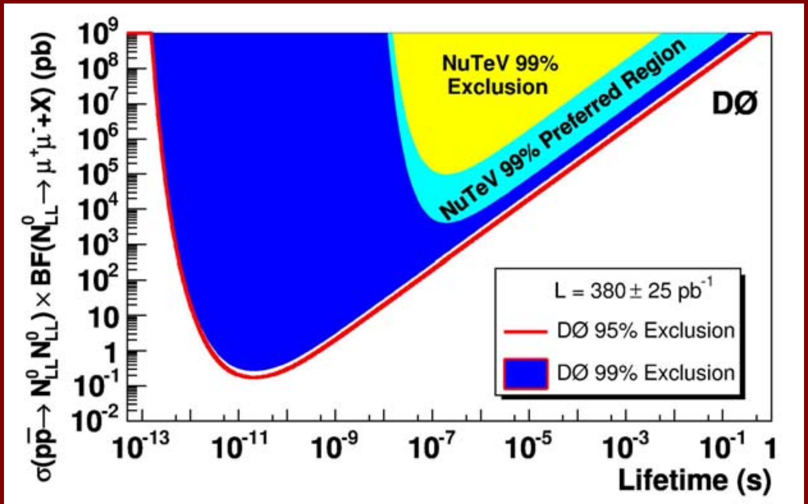
- **Collider experiments have the ability to study long-lived particles**
  - wide range of topics/techniques
- **Decays within the detector require extra effort**
  - reconstruct detached vertices
  - finding the tracks has issues such as lifetime, pT, opening angle and DCA
    - to determine sensitivity we need to take these into account
  - effort should be made to make experiments as sensitive as possible

Search for NLLP → $\mu^+\mu^-$

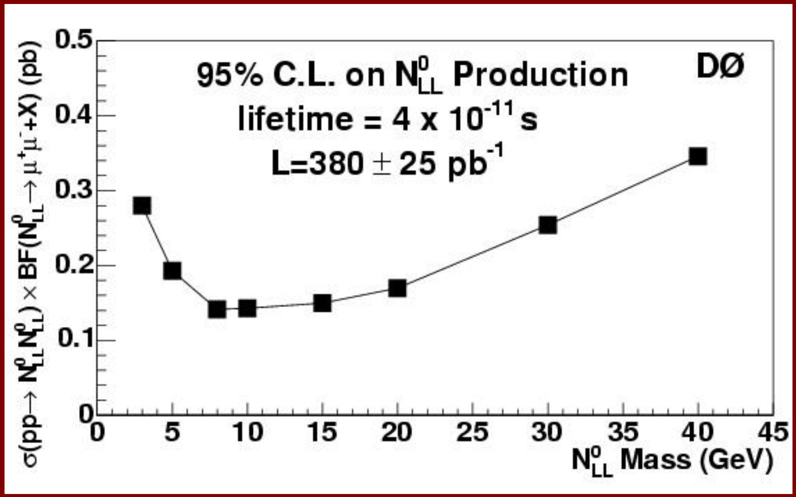
Phys. Rev. Lett. 97 161802 (2006)

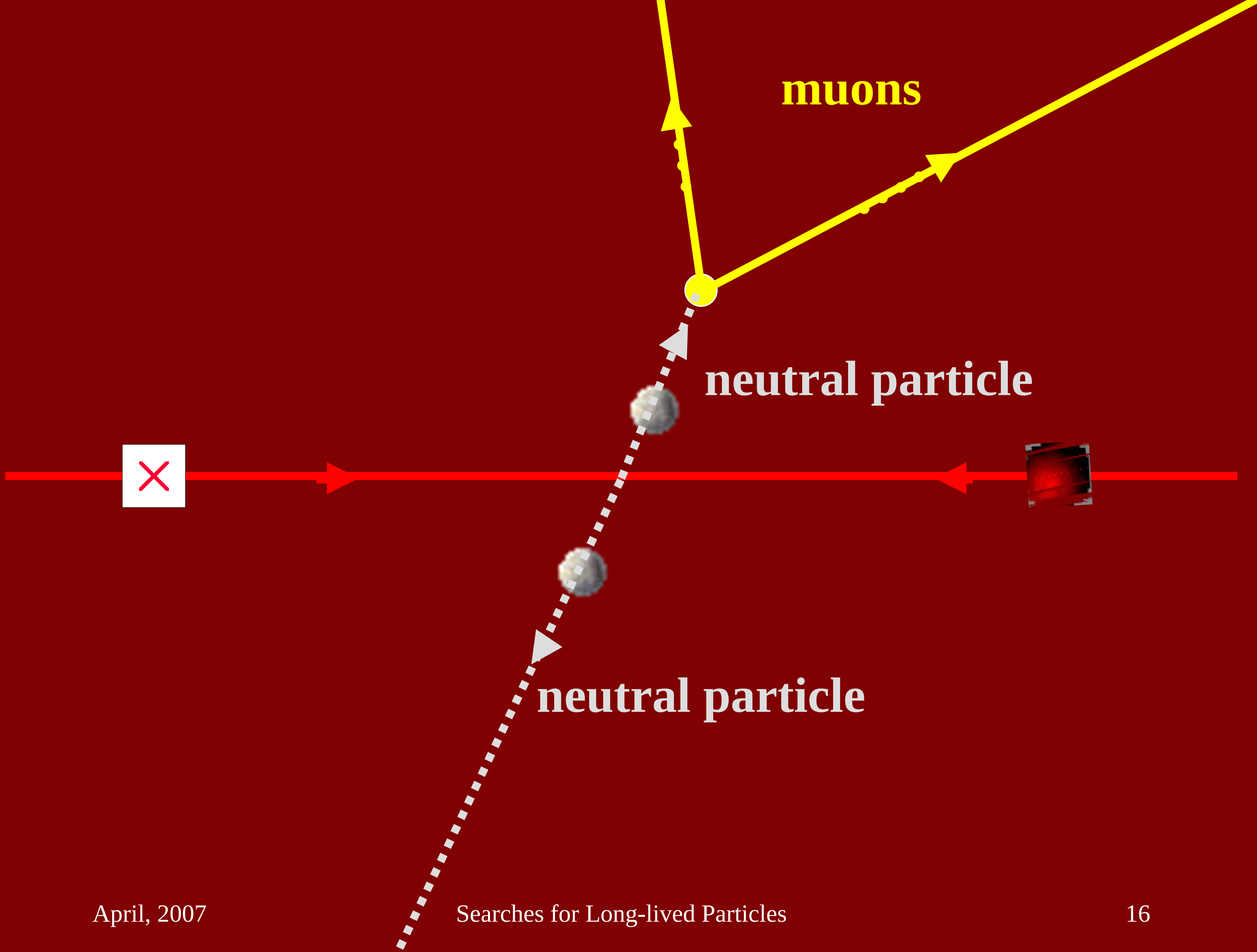
- Search for events with two muons from highly displaced vertex
  - p_T>10 GeV
  - 5 < r < 20 cm

  0 events observed
  0.75 ± 1.1 ± 1.1 expected



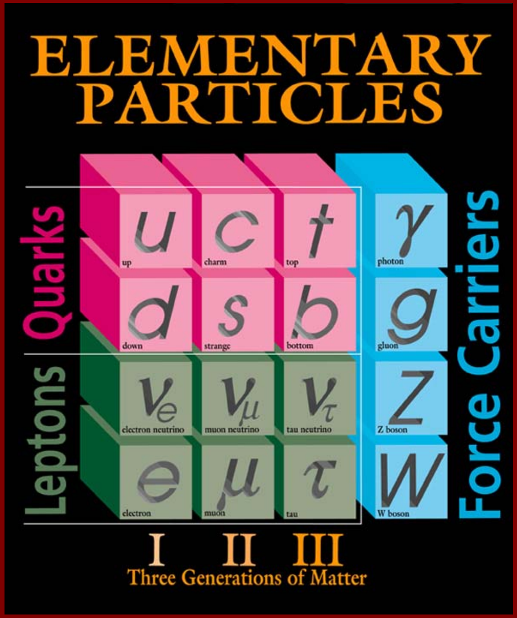
- Limits set on NLLP pair production cross-section x branching ratio
  - does not exclude example RPV SUSY point




muons
neutral particle
neutral particle

The Standard Model

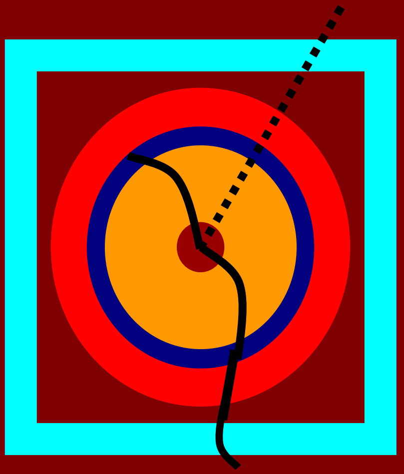
- well established
- more than 30 years of success
- <u>incomplete</u>



- E.g.
  - We have no deep understanding of the parameters and their values
  - We don't know the meaning of flavor and other quantum numbers.

Collider Experiments

	CDF	D0	Atlas	CMS
$\sqrt{s}$ (Tev)	1.96	1.96	14	14
Tracking	silicon & drift chamber	silicon & scint. fibers	pixels, silicon, & straw tubes	pixels & silicon
Inner /outer radius (cm)	1.3/132	1.5/50	5/115	4/108
Calorimeter		Liquid Ar-U	Liquid Ar & Steel/ Scintillator	Pb-Tungston & copper/ scintillator
Inner/Outer radius (cm)			115/420	

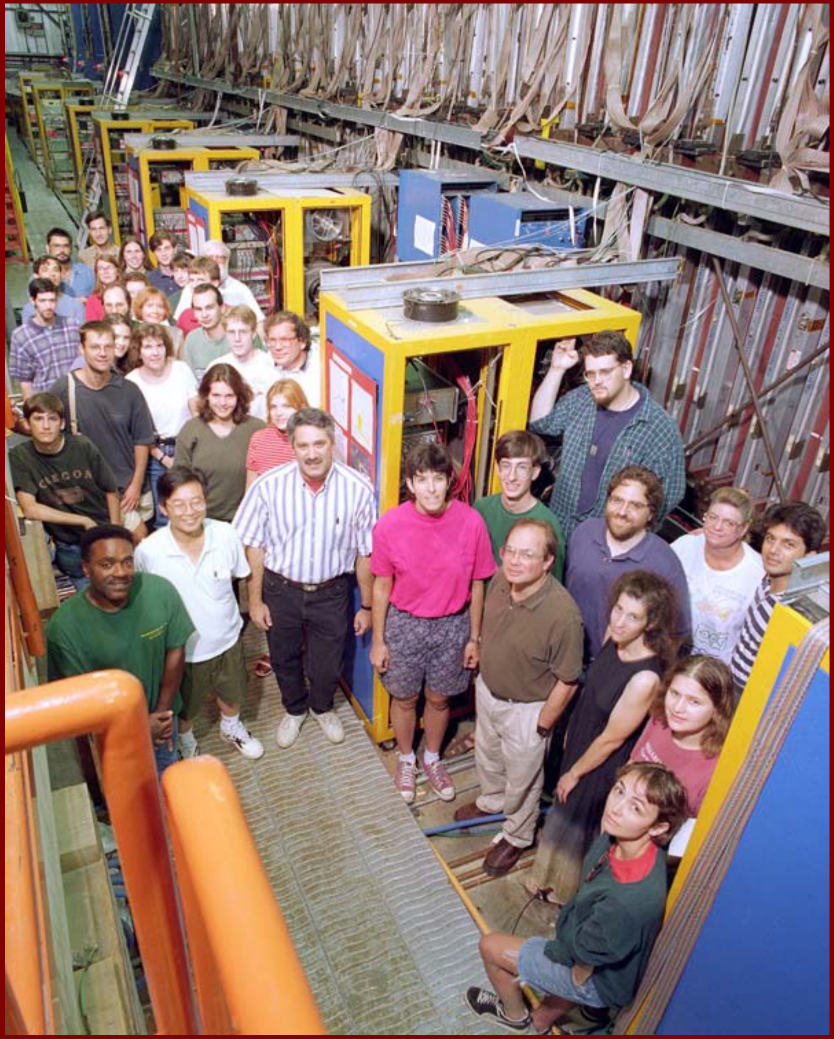


tracking volume w/ magnetic field

electromagnetic calorimeter

hadronic calorimeter

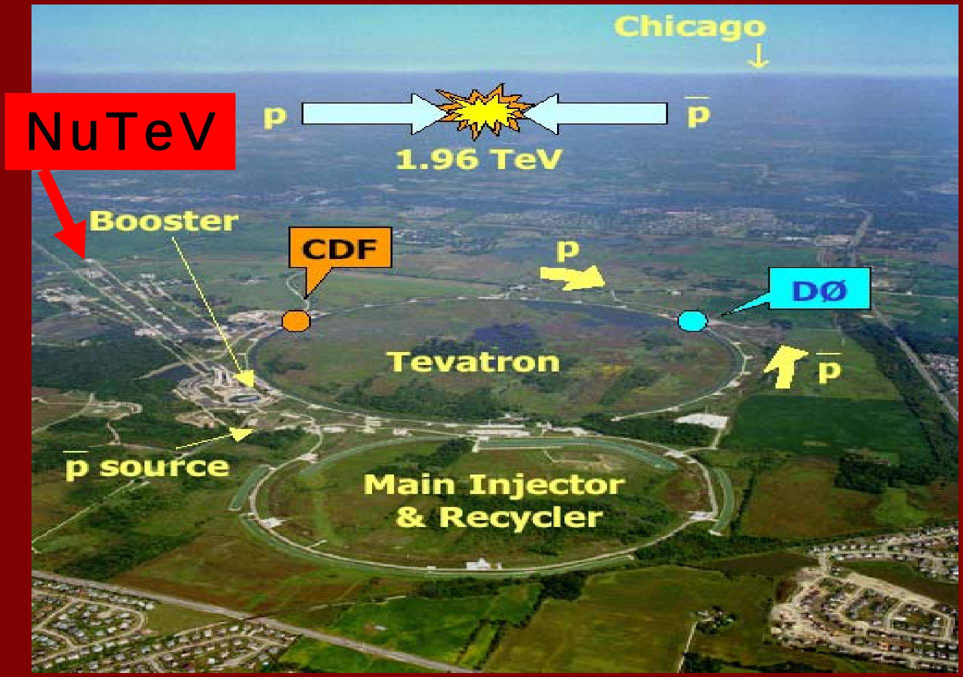
muon system w/ magnetic field



NuTeV

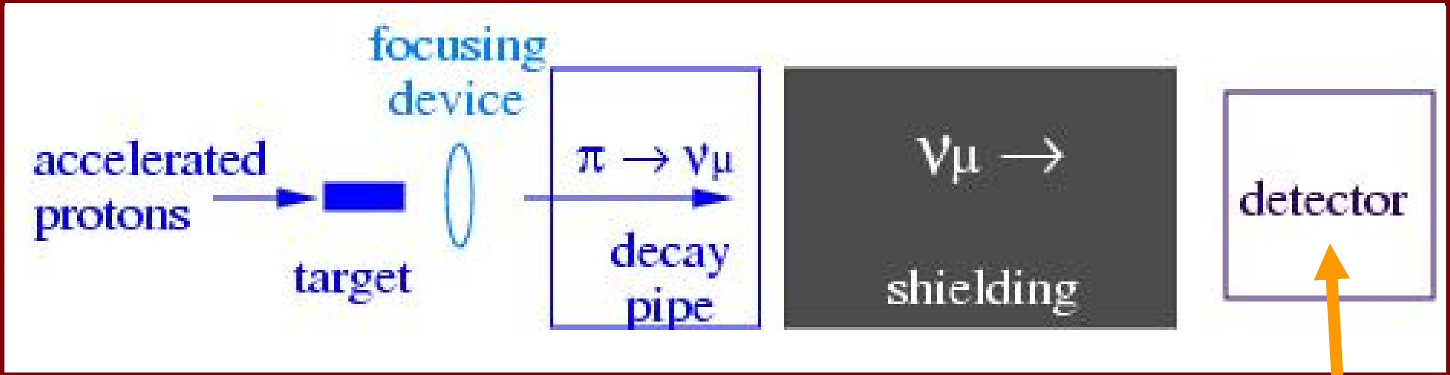
Neutrinos at the Tevatron

neutrino deep-inelastic scattering
$\sin^2\theta_w$
structure functions
charm production



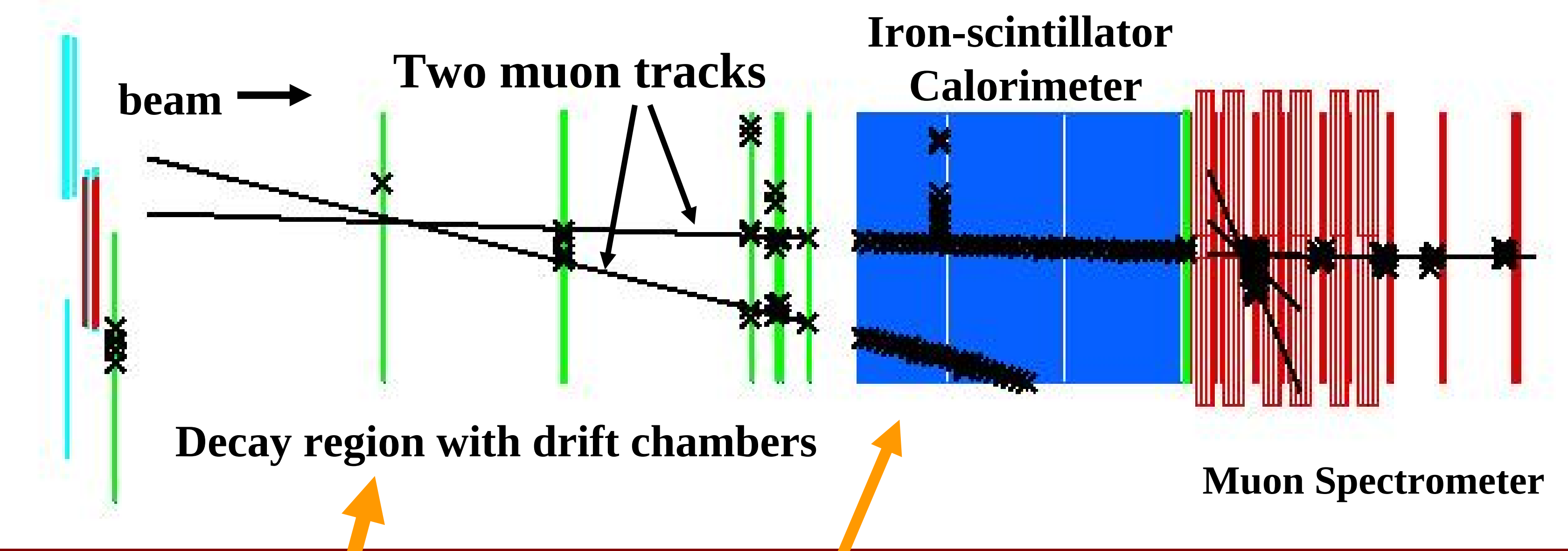
Fermilab E815
(1996-97)

A Neutrino Experiment…



NuTeV

- 10^{12} protons per minute (10^{7} Watts)
- ~15×10^{9} neutrinos per minute (in five 2ms pulses)
- 700 ton detector located 1.4 km from neutrino production



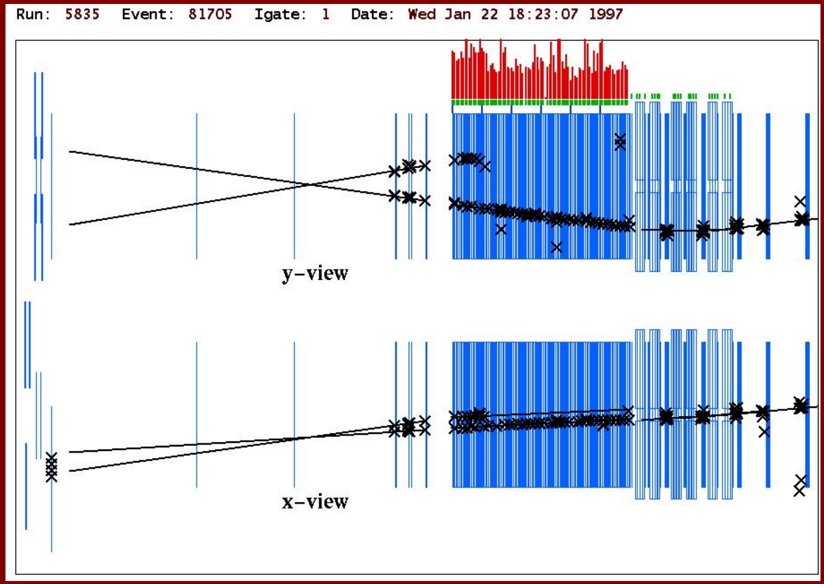
Search Results…

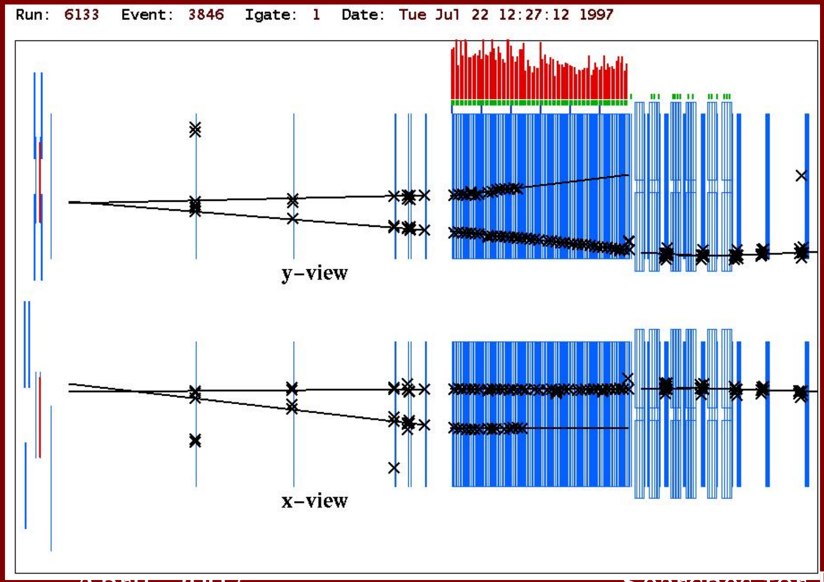
- **Neutral Heavy Leptons**
  - **0.25<M(NHL)<2.2 GeV**
- **Karmen anomaly**
  - **M(ee)=33.9 MeV**
- **High mass M>2.2 GeV**

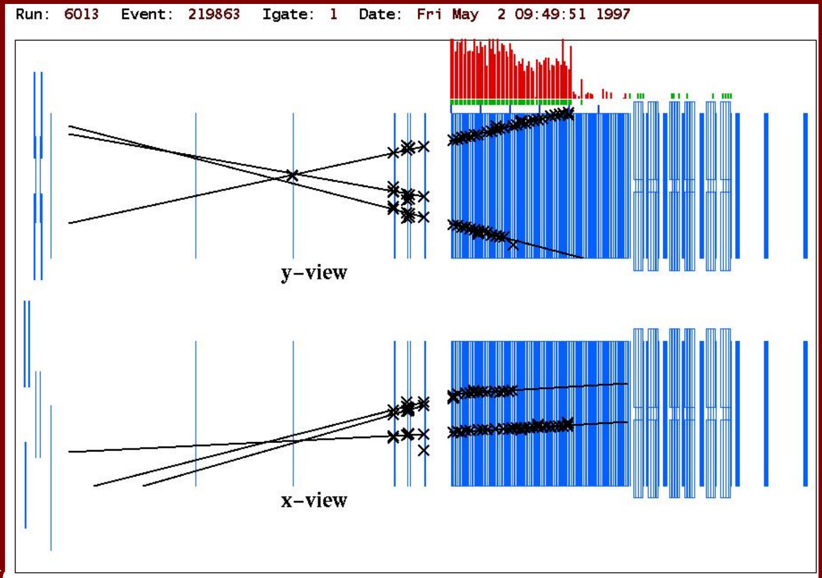
Third search:

3 events found

Expected background:
0.07 ± 0.01 events

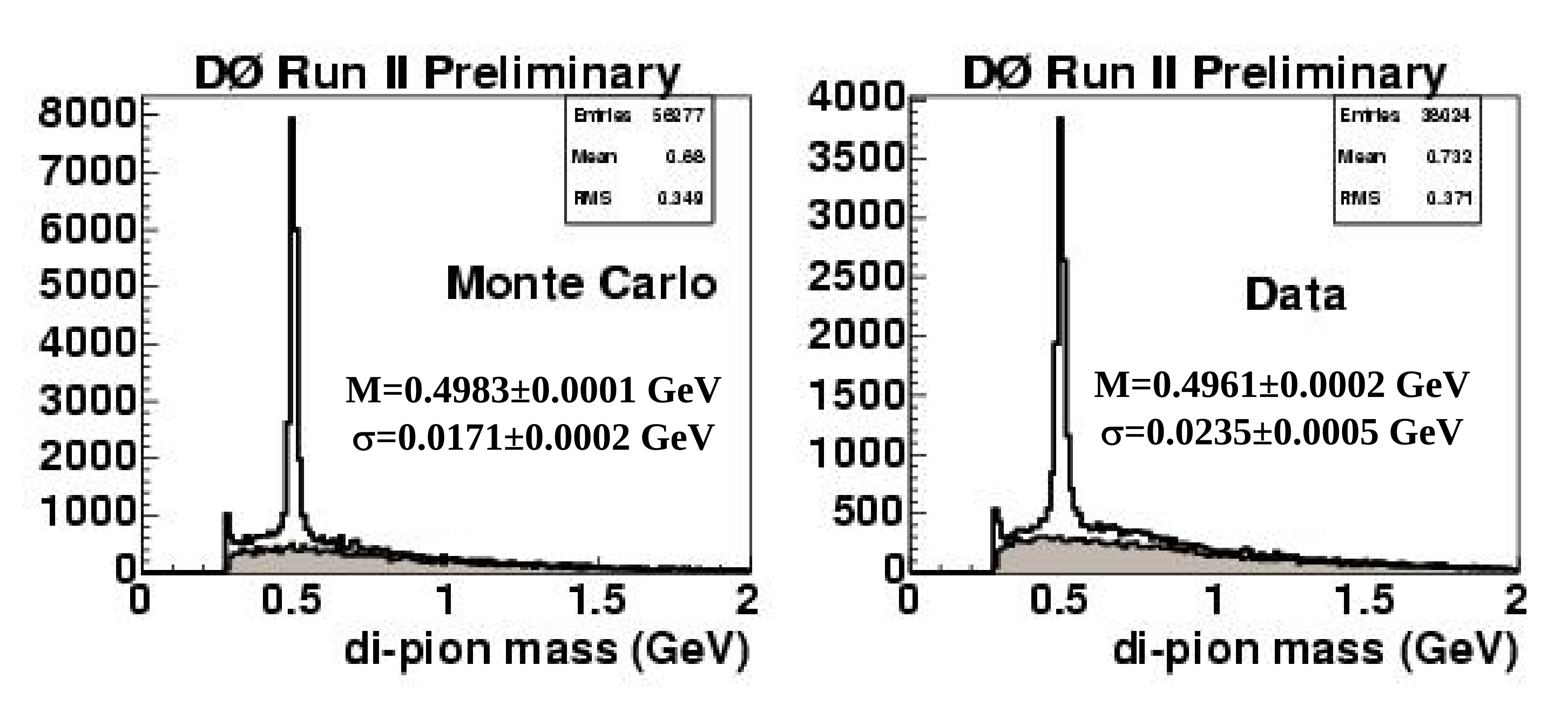






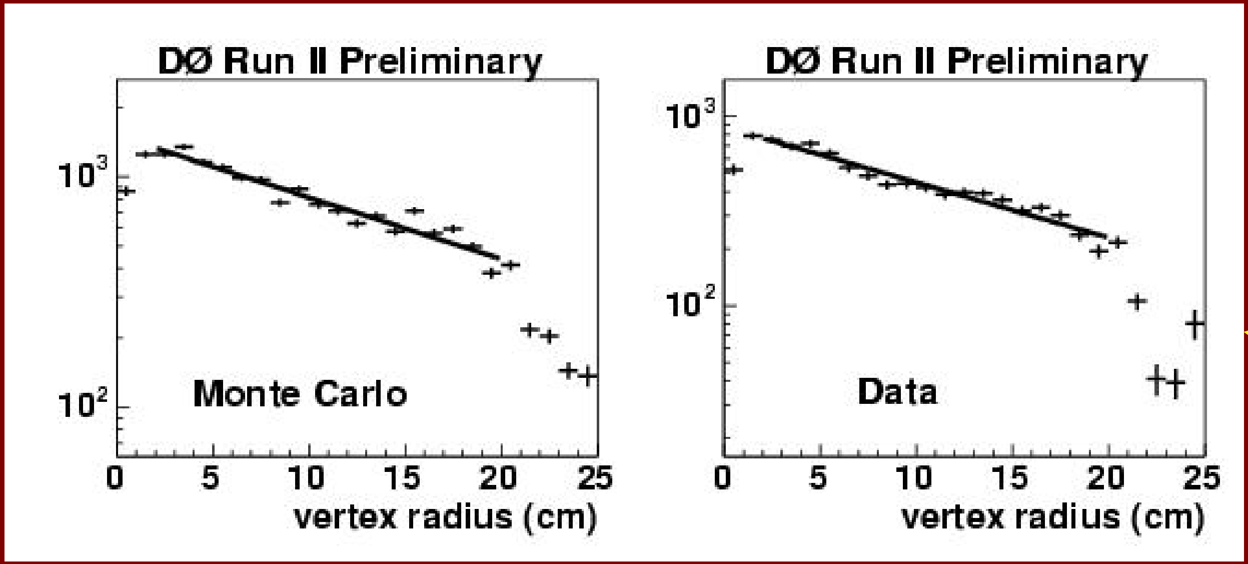
$K_S^0 \rightarrow \pi^+\pi^-$

fit pairs of tracks to common vertex
require r>0.5 cm



long lifetime = 9.0×10^{-11} s

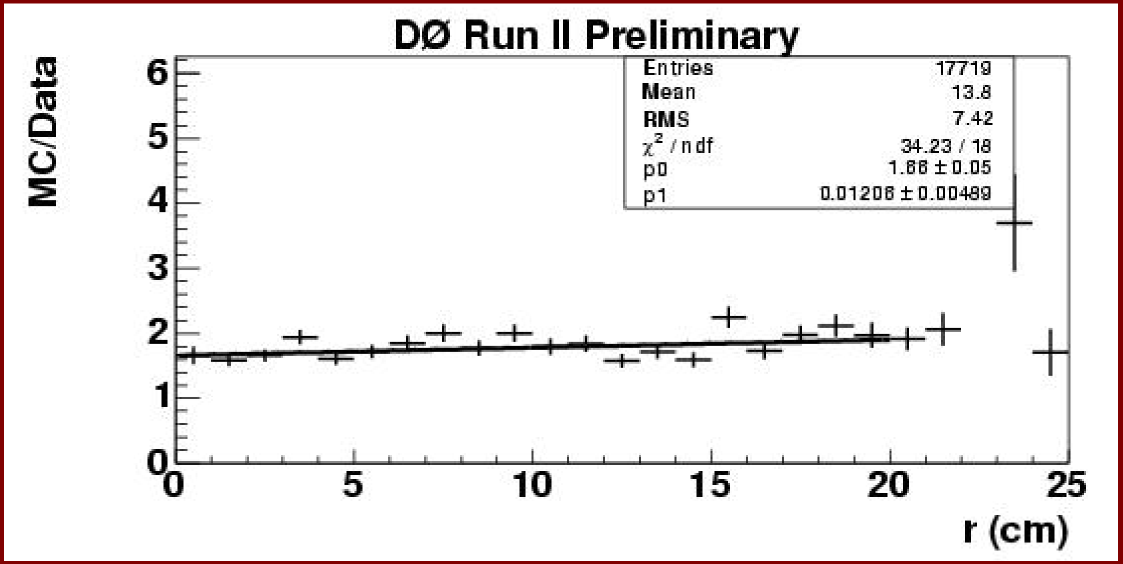
natural source of neutral, long-lived particles



$K_S^0 \to \pi^+\pi^-$

expected lifetime

MC/Data is flat



$$r = \sqrt{(x - x_{PV})^2 + (y - y_{PV})^2}$$

Event Selection

Muons

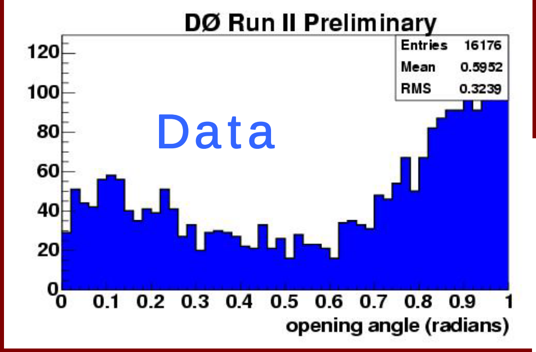
- hits in all 3 layers of muon system
- cosmic ray timing cut
- central track
  - $\chi^2<4$, >13 CFT hits
- isolation
  - Calorimeter
    - $\Sigma E_{cal}(0.1<\Delta R<0.5) < 2.5$ GeV
  - Tracking system
    - $\Sigma E_{trk}(\Delta R<0.5) < 2.5$ GeV
- $p_T>10$ GeV

Luminosity

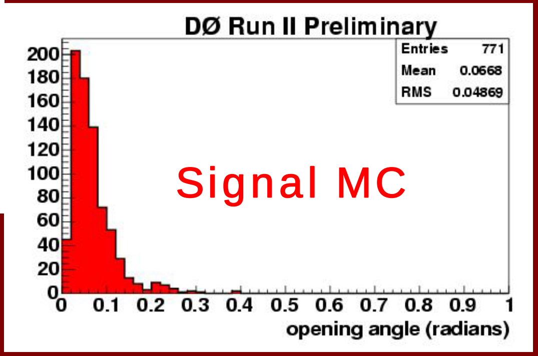
380 ± 25 pb^{-1}

Events

- dimuon trigger
- >1 muon
  - opposite signed
  - opening angle < 0.5 rad
- primary vertex
  - $|v_{x,y}|<0.3$ cm
  - $|v_z|<60$cm



opening angle



Event Selection

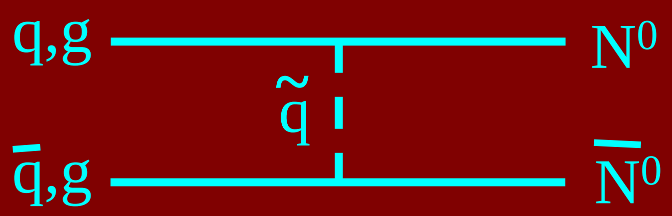
Muons

- segments in all 3 muon layers
- cosmic ray timing cut
- central track
  - $\chi^2<4$, >13 CFT hits
- isolation
  - $\Sigma E_{cal}(0.1<\Delta R<0.5)$ < 2.5 GeV
  - $\Sigma E_{trk}(\Delta R<0.5)$ < 2.5 GeV
- p_T>10 GeV
- DCA_{XY}>0.01 cm
  DCA_Z>0.1 cm

Events

- dimuon trigger
- >1 muon
  - opposite signed
  - opening angle < 0.5 rad
- primary vertex
  - $|v_{x,y}|<0.3$ cm
  - $|v_z|<60$cm
- dimuon vertex
  - $\chi^2 < 4$
  - $r > 6\sigma_r$
  - $5 < r < 20$ cm

Signal Monte Carlo



M_1 = 3,5,8,10

tanβ = 10	μ = -5000
M_2 = 200	m_A = 500
M_3 = 400	M(squark) = 300
λ_{122} = 0.01	M(other) = 1500

RPV unconstrained MSSM

- LSP: neutralino (3-10 GeV)
- small λ_{122} = long lifetime (m or km)
  - decay in region: radius = 0-25 cm

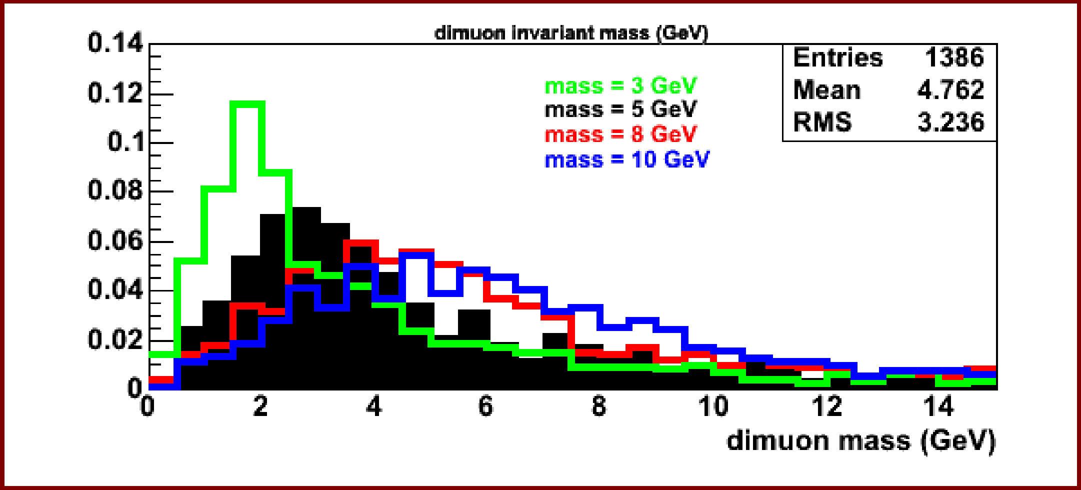
σ = 0.022-0.025 pb

$\chi_0^{\ 1} \rightarrow \mu\mu\nu,\ \mu e\nu,\ ee\nu$

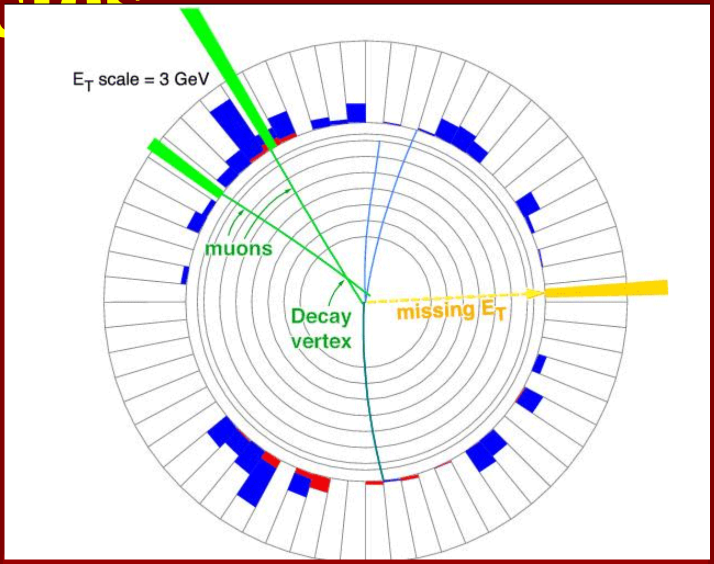
p14.07.00 simulation

p14.06.01 recon

minbias = 0.4 events



Search for Neutral, Long-lived Particles



- **Search for pair production of two neutral particles**
- **Look for decay well away from production point**
  - **two isolated muons p_T>10 GeV**
- **Sample signal**
  - **RPV SUSY**
  - **χ_1^0 pair production**

- **Why do searches?**
- **Why search for neutral, long-lived particles?**
- **How to search for neutral, long-lived particles at D0?**
- **What did we find?**
- **What does it mean?**

Beam pipe

Tracking detector

Magnet

EM calorimeter

Hadronic calorimeter

Muon detectors

Magnet