Searches for Long-lived Particles in Hadron Colliders

Todd Adams
Florida State University
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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, $\text{J}/\Psi$, tau lepton
  – NuTeV result
• There are theoretical models which predict such particles…
Theoretical Models

• R-parity violating supersymmetry (RPV SUSY)
  – neutralino ($\chi_0^1$): lightest supersymmetric particle (LSP)
  – lifetime depends of a parameter ($\lambda_{122}$)

• 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
    • $H \rightarrow ???$
  – 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

• 3\textsuperscript{rd} search found
  – 3 events decaying to two muons
  – expectation of $0.07 \pm 0.01$

• No explanation to date
Because We Can…
Collider Experiments

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

multi-purpose detector
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

- 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

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<thead>
<tr>
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<th>D0</th>
<th>Atlas</th>
<th>CMS</th>
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- **tracking volume w/ magnetic field**
- **electromagnetic calorimeter**
- **hadronic calorimeter**
- **muon system w/ magnetic field**
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 $\rightarrow \mu^+\mu^-$

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

  0 events observed
  $0.75 \pm 1.1 \pm 1.1$ expected

- Limits set on NLLP pair production cross-section $\times$ 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
  - incomplete

- 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

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- **Muon system w/ magnetic field**

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Searches for Long-lived Particles
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)
- $\sim 15 \times 10^9$ neutrinos per minute (in five 2ms pulses)
- 700 ton detector located 1.4 km from neutrino production
Search Results…

- Neutral Heavy Leptons
  - $0.25 < M(\text{NHL}) < 2.2$ GeV
- Karmen anomaly
  - $M(\text{ee}) = 33.9$ 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 $= 9.0 \times 10^{-11}$ s
natural source of neutral, long-lived particles

$M = 0.4983 \pm 0.0001$ GeV
$\sigma = 0.0171 \pm 0.0002$ GeV

$M = 0.4961 \pm 0.0002$ GeV
$\sigma = 0.0235 \pm 0.0005$ GeV
$\mathbf{K_S^0 \rightarrow \pi^+ \pi^-}$

**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
    • $\Sigma E_{\text{cal}}(0.1<\Delta R<0.5) < 2.5$ GeV
  – Tracking system
    • $\Sigma E_{\text{trk}}(\Delta R<0.5) < 2.5$ GeV
• $p_T>10$ GeV

Luminosity

$380 \pm 25$ 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

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  – $\Sigma E_{\text{trk}}(\Delta R<0.5) < 2.5$ GeV
• $p_T>10$ GeV
• $DCA_{XY}>0.01$ cm
• $DCA_Z>0.1$ cm

Events
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• >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
\tan\beta = 10 \quad \mu = -5000
M_2 = 200 \quad m_A = 500
M_3 = 400 \quad M(\text{squark}) = 300
\lambda_{122} = 0.01 \quad M(\text{other}) = 1500
\sigma = 0.022-0.025 \text{ pb}

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

\chi_0^1 \rightarrow \mu\mu\nu, \mu\nu\nu, e\nu\nu

p14.07.00 simulation
p14.06.01 recon
minbias = 0.4 events

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Searches for Long-lived Particles
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
  - $\chi_1^0$ 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?