Search for Neutral, Long-lived Particles at DØ

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HEP Seminar
Duke University
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• Why search?
• How?
• What did we find?
• What does it mean?
• Why search?
• How?
• What did we find?
• What does it mean?
“Who ordered that?”
- I.I. Rabi (1937)

Discovery of the muon

Prior to 1937
- electron
- proton
- neutron
- photon
- positron
- hypothesis of neutrino

1937
- Anderson and Neddermeyer
- Street and Stevenson

other examples: strange particles, $J/\Psi$, tau lepton
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.
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
A Search Experiment…

- only weakly interacting particles make it to the detector - neutrinos!
- anything else? (e.g. neutral heavy leptons)
- Goal:
  - look for decay of unstable particles traveling with neutrino beam
  - production is at proton target
  - add another decay region just in front of neutrino detector
Search Results...

• Neutral Heavy Leptons
  – $0.25 < M(\text{NHL}) < 2.2 \text{ GeV}$

• Karmen anomaly
  – $M(\text{ee}) = 33.9 \text{ MeV}$

• High mass $M > 2.2 \text{ GeV}$
Third search:
3 events found

Expected background:
0.07 ± 0.01 events
Interpretation

• Background
  – no known backgrounds are that large

• Signal
  – 3 events $\gg 0.07 \pm 0.01$
  – muon energies are asymmetric ($E_1 >> E_2$)
The conservative approach: set a limit
• Why search?
• **How?**
• What did we find?
• What does it mean?
What is DØ?

Fermilab Tevatron
proton-anti-proton collider

DØ is one of two collider experiments
2 Tesla solenoid

silicon detector

scintillating fiber tracker (CFT)
**Technique:**

1. identify events with two muons
   - fit to a common vertex
2. measure background
3. interpret results

\[ r = \sqrt{(x - x_{PV})^2 + (y - y_{PV})^2} \]
\( K_S^0 \rightarrow \pi^+ \pi^- \)

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

long lifetime = 9.0x10\(^{-11}\) s
natural source of neutral, long-lived particles

\[ M = 0.4983\pm 0.0001 \text{ GeV} \]
\[ \sigma = 0.0171\pm 0.0002 \text{ GeV} \]

\[ M = 0.4961\pm 0.0002 \text{ GeV} \]
\[ \sigma = 0.0235\pm 0.0005 \text{ GeV} \]
\[ K_S^0 \rightarrow \pi^+ \pi^- \]

expected lifetime

MC/Data is flat

\[ r = \sqrt{(x - x_{PV})^2 + (y - y_{PV})^2} \]
\[ K_{S}^{0} \rightarrow \pi^{+}\pi^{-} \]

efficiency is flat as a function of radius
A Possible Signal

R-parity violating unconstrained minimal supersymmetric model (MSSM)
- neutralino ($\chi_0^1$): lightest supersymmetric particle (LSP)
- lifetime depends of a parameter ($\lambda_{122}$)
- small $\lambda_{122} = $ long lifetime

\[
\begin{align*}
\tan\beta &= 10 \\
M_1 &= 3,5,8,10 \\
M_2 &= 200 \\
M_3 &= 400 \\
\lambda_{122} &< 0.01 \\
\mu &= -5000 \\
m_A &= 500 \\
M{\text{squark}} &= 300 \\
M{\text{other}} &= 1500
\end{align*}
\]
A Sample Event (simulation)

\[ q, g \rightarrow N^0 \]

\[ \bar{q}, g \rightarrow \bar{N}^0 \]

\[ \text{Decay vertex} \]

\[ \text{missing } E_T \]

\[ E_T \text{ scale } = 3 \text{ GeV} \]
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
383 ± 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

Data

Signal MC
Distance of Closest Approach

$DCA_{XY} > 0.01 \text{ cm}$
$DCA_{Z} > 0.1 \text{ cm}$
Event Selection

Muons
- segments in all 3 muon layers
- cosmic ray timing cut
- central track
  - $\chi^2<4$, $>13$ CFT hits
- isolation
  - $\Sigma E_{\text{cal}}(0.1<\Delta R<0.5) < 2.5$ GeV
  - $\Sigma E_{\text{trk}}(\Delta R<0.5) < 2.5$ GeV
- $p_T>10$ GeV
- $\text{DCA}_{XY}>0.01$ cm
- $\text{DCA}_Z>0.1$ 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
• Why search?
• How?
• What did we find?
• What does it mean?
How to estimate the background:

<table>
<thead>
<tr>
<th>Criterion #2</th>
<th>Fail</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fail</td>
<td>Sample 1A</td>
<td>Sample 1B</td>
</tr>
<tr>
<td>Pass</td>
<td>Sample 2A</td>
<td>Sample 2B</td>
</tr>
</tbody>
</table>

Sample 2A = \frac{\text{Sample 1A}}{\text{Sample 1B}}

final signal sample
### Estimated Background:

\[
\text{Sample 2B} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B} = \frac{3}{4} \times 1 = 0.75 \text{ events}
\]

### Vertex Radius

<table>
<thead>
<tr>
<th>0.3 &lt; r &lt; 5 cm</th>
<th>5 &lt; r &lt; 20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1A</td>
<td>Sample 1B</td>
</tr>
<tr>
<td>4 events</td>
<td>1 event</td>
</tr>
<tr>
<td>Sample 2A</td>
<td>Sample 2B</td>
</tr>
<tr>
<td>3 events</td>
<td>???</td>
</tr>
</tbody>
</table>

**DCA Criterion**

- 1 muon passes
- 1 muon fails
- Both muons pass
How good is this estimate?
use complementary samples

- Loose
  - loosen several criteria
- 1 muon + 1 non-lepton track with isolation
- 1 muon + 1 non-lepton track without isolation
- 2 tracks
  - 0.6<M<0.9 GeV
    (exclude Kₜ)
- MC simulation b+b
  - use generated 4-vectors

<table>
<thead>
<tr>
<th>DCA Criteria</th>
<th>Vertex Radius</th>
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<tbody>
<tr>
<td>Sample 1A</td>
<td>Sample 1B</td>
</tr>
<tr>
<td>Sample 2A</td>
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</tbody>
</table>

Estimate 2B = \frac{Sample \ 2A}{Sample \ 1A} \times Sample \ 1B

compare estimate with measured value
**How good is this estimate?**
use complementary samples

evaluate

\[
\text{estimate} - \text{observed} \quad \text{estimate}
\]
(percentage difference)

assign systematic error of 150%

background estimate = 0.75 ± 1.1 (stat) ± 1.1 (sys)
Data/MC Corrections

• Use Z peak to measure data/MC corrections
  – use a fraction of the dataset

<table>
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<th>Value</th>
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<td>Track $\chi^2 &lt; 4$</td>
<td>0.94 ± 0.03</td>
</tr>
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<td>Ncft &gt; 13</td>
<td>0.91 ± 0.04</td>
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<td>Primary vertex</td>
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<tr>
<td>Cal iso &lt; 2.5 GeV</td>
<td>0.99 ± 0.04</td>
</tr>
<tr>
<td>Track pT iso &lt; 2.5 GeV</td>
<td>0.88 ± 0.04</td>
</tr>
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Test with full dataset
## Acceptance and Error Analysis

<table>
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<tr>
<th>Metric</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>luminosity</td>
<td>383 ± 25 pb(^{-1})</td>
</tr>
<tr>
<td>acceptance</td>
<td>0.129 ± 0.005</td>
</tr>
<tr>
<td>trigger effic. (approx)</td>
<td>0.88 ± 0.05</td>
</tr>
<tr>
<td>cal quality</td>
<td>0.97 ± 0.03</td>
</tr>
<tr>
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<tr>
<td>data/MC vertex eff.</td>
<td>0.92 ± 0.14</td>
</tr>
<tr>
<td>lumi * acceptance</td>
<td>28.7 ± 5.6</td>
</tr>
</tbody>
</table>

(Z/DY study)  
(K\(_s\) analysis)
• Why search?
• How?
• What did we find?
• What does it mean?
$N_{\text{DATA}} = 0 \quad N_{\text{BKGD}} = 0.75 \pm 1.1 \pm 1.1$
Conversion of NuTeV

- lifetime: assume average $p = 121$ GeV (Lorentz boost)
- differential cross-section: multiply by $4\pi$
- cross-section: use signal MC

\[ q,g \xrightarrow{\sim} Q \xrightarrow{\sim} N^0 \]

- $pp$ at $\sqrt{s} = 38$ GeV
- $p\bar{p}$ at $\sqrt{s} = 1960$ GeV

convert NuTeV $\rightarrow$ DØ
Summary

• We’ve used Run II data from DØ to search for neutral, long-lived particles
  – new technique
  – new search direction for collider physics

• No events observed
  – background estimate $0.75 \pm 1.1 \pm 1.1$ events

Put limits on interpretation of NuTeV excess of dimuon events
limit as a function of particle mass
Signal Monte Carlo

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

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

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

$M_1 = 3, 5, 8, 10$
$\tan\beta = 10$  $\mu = -5000$
$M_2 = 200$  $m_A = 500$
$M_3 = 400$  $M(\text{squark}) = 300$
$\lambda_{122} = 0.01$  $M(\text{other}) = 1500$

$\sigma = 0.022-0.025$ pb
Use data to estimate background

Two cuts:
- define 4 samples

For background:

\[
\frac{\text{Sample 1A}}{\text{Sample 2A}} = \frac{\text{Sample 1B}}{\text{Sample 2B}}
\]

\[
\frac{\text{Sample 1A}}{\text{Sample 1B}} = \frac{\text{Sample 2A}}{\text{Sample 2B}}
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Criteria #1

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Criteria #2

\[
\text{Sample 2B} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B}
\]

final signal sample
• DØ has just completed a 5 year data-taking period
  – upgrade underway
  – more data to come
• We’ve expanded our capabilities and addressed a significant outstanding experimental result
Third search:
3 events found
Expected background:
$0.07 \pm 0.01$ events

Decay to
two muons
• 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?
“Who ordered that?”
- I.I. Rabi (1937)

Discovery of the muon

Prior to 1937
- electron
- proton
- neutron
- photon
- positron
- hypothesis of neutrino

1937
- Anderson and Neddermeyer
- Street and Stevenson

other examples: strange particles,
- $J/\Psi$
- tau lepton
1947
New unstable particle
Called “vee” or strange particles
mass ½ of proton
November Revolution - 1974

J/Ψ
first charm meson
now: 4 leptons
and 4 quarks

Tau lepton
symmetry
destroyed

SPEAR

Mark I
Fermilab
Result of the Week

Fermilab Today

http://www.fnal.gov/pub/today/index.html
Observation of an Anomalous Number of Dimuon Events in a High Energy Neutrino Beam


Evidence for Anomalous Lepton Production in $e^+ - e^-$ Annihilation


Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \text{missing energy}$, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \geq 2 \text{ undetected particles}$$

of the detector, or particles very difficult to detect such as neutrons, $K_L^0$ mesons, or neutrinos. Most of these events are observed at center-of-