Search for Long-Lived Particles Decaying to the $Z^0$ Boson

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Direct Searches For New Physics
Motivation

• What I want:
  • Same as what everyone wants
  • To find what physics lies beyond the Standard Model
• Alright, but how?
• Many possible theoretical and experimental signatures to choose from
  • Theoretical:
    • Higgs
    • SUSY
    • Extra dimensions
    • …
  • Experimental:
    • photons
    • leptons
    • neutrinos ($\bar{\nu}_e$)
    • quarks (jets)
    • gauge bosons: $Z^0$ and $W^\pm$
What We Do

- Our approach is to look at the gauge bosons for evidence of new physics
- We focus on new physics that couples to the $Z^0$
- $X \rightarrow Z^0$
  - Theoretically motivated
  - Might expect to see new physics to couple to heavy particles more strongly than the light ones
- Experimentally clean
  - Two leptons that reconstruct to the $Z^0$ mass has little background
  - The dominant background is from Standard Model $Z^0$’s
Standard Model $Z^0$

- To be sensitive to $X \rightarrow Z^0$, must distinguish the $Z^0$ from new physics with the Standard Model $Z^0$

- What do Standard Model $Z^0$ events look like?
  - $Z^0$ has low $p_T$
  - Events have little other activity in them (no jets, no $\not{E}_T$)
  - $Z^0$ has short lifetime
New Physics Couplings to $Z^0$

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- What would $Z^0$ new physics events look like?
  - $Z^0$ has *high* $p_T$
  - Events *a lot* of other activity *(many jets, large $\not{E}_T$)*
  - $Z^0$ parents (might) have *long* lifetime
Long-Lived Particle Decaying to $Z^0$

- Experimentally clean
  - Vertex dileptons from $Z^0$'s
  - Negligible background from actual displaced vertices
  - Dominant background is from tracking mistakes
- Theoretically motivated
  - Existing (and perhaps many non-existing) models predict a long-lived $Z^0$ parent
Let’s Do It!

- **Convention:**
  \[ L_{xy} = \text{distance in transverse plane from beam to dilepton intersection} \]
- Use transverse quantities because they are easier to measure

- **L_{xy} sign definition**
- **Motivation:**
  - Tracking mistakes are symmetric in \( L_{xy} \)
  - Signal has predominantly positive \( L_{xy} \)

- Search for excess above background at positive \( L_{xy} \)
- Negative \( L_{xy} \) gives a cross-check of the background
- Use \( Z^0 \rightarrow \mu\mu \) channel
- Plan to use \( Z^0 \rightarrow ee \) channel next
Selection Criteria

- **Selection Motivation:**
  - Clean sample of $Z^0$’s
  - Well-measured tracks
  - High efficiency for signal
  - Look for large $L_{xy}$
- Calibrated cuts and $L_{xy}$ calculation with $J/\psi \rightarrow \mu\mu$’s
  - Displaced vertices from B meson decay

- Two important cuts:
  - $\Delta\phi$ cut
  - $Z^0$ boson $p_T$ cut

<table>
<thead>
<tr>
<th>Two well-identified high $p_T$ muons</th>
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</thead>
<tbody>
<tr>
<td>Within $Z^0$ mass peak: $81 &lt; M_{\mu\mu} &lt; 101$ GeV</td>
</tr>
<tr>
<td>Tracking quality cuts to reduce mistakes</td>
</tr>
<tr>
<td>$L_{xy} &gt; 0.1$ cm</td>
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<th>Cosmic Rejection Cuts</th>
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<tr>
<td>$Z^0$ boson $p_T &gt; 30$ GeV</td>
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<tr>
<td>$L_{xy} &gt; 0.03$ cm</td>
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Due to the back-to-back nature of $Z^0$ events, even small mistakes in tracking can lead to large mistakes in $L_{xy}$

- Cut at: $\Delta \phi < 175$ deg
  - Rejects 99% of large $L_{xy}$ tracking mistake background above 0.1 cm
  - 50% efficient on Standard Model $Z^0$’s
  - 90% efficient on signal sample

![Graph showing SM $Z^0$ Monte Carlo before and after $\Delta \phi$ cut](chart.png)
Z⁰ Boson p_T Cut

• Can use the Z⁰ transverse momentum to reject Standard Model background
• Increases sensitivity to smaller lifetimes

• Cut at:
  \( Z^0 \ p_T > 30 \ \text{GeV} \)
  \( L_{xy} > 0.03 \ \text{cm} \)

• Do not optimize heavily to retain model independence
• Use it as optional cut
  • Look at \( L_{xy} \) distribution with and without the cut
Acceptance $\times$ Efficiency

- Have calculated acceptance $\times$ efficiency of signal
- Used a $b'$ model
- Note: Assumes $\text{BR}(b' \rightarrow b Z^0) = 1$, and includes $\text{BR}(Z \rightarrow \mu\mu)$
Backgrounds

- Negligible backgrounds from:
  - Cosmics
  - QCD (semileptonic B decays to muons)
- Dominant background from:
  - Tracking mistakes from Standard Model $Z^0$ events
  - Difficult to measure
    - Use simulated Monte Carlo
    - Can cross-check the background measurement with the data in the negative $L_{xy}$ control region

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<thead>
<tr>
<th></th>
<th>No $Z^0$ $p_T$ cut</th>
<th>$Z^0$ $p_T &gt; 30$ GeV</th>
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<tr>
<td>Background:</td>
<td>0.72 ± 0.27 events</td>
<td>1.1 ± 0.8 events</td>
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</table>
The Data

- 2 events in signal region
- Background: 0.72 ± 0.27 events
- No events is negative $L_{xy}$ control region

- 3 events in signal region
- Background: 1.1 ± 0.8 events
- No events is negative $L_{xy}$ control region
Signal Events

• Have 2+3 events in signal regions
• Can look at events displays to find other information consistent with the signal or background hypothesis
• In the case of the signal:
  • Should have other activity in the event
  • Additional jets, etc.
  • In the case of the $b' \rightarrow b Z^0$ signal:
    • $b$ jets
    • Jets from other $Z^0$
Event Display Example

$L_{xy} > 0.1$ cm, without the $Z^0 \ p_T$ cut

CDF Run II Preliminary

run 155365

event 1953250
Event Display Example

$L_{xy} > 0.1 \text{ cm}, \text{without the } Z^0 p_T \text{ cut}$

CDF Run II Preliminary

run 155365
event 1953250

$Z^0$ boson $p_T = 14 \text{ GeV}$

$M_{\mu\mu} = 91 \text{ GeV}$
Event Display Example

$L_{xy} > 0.03 \text{ cm}, \text{ with the } Z^0 p_T > 30 \text{ GeV cut}$
Event Display Example

$L_{xy} > 0.03 \text{ cm}, \text{ with the } Z^0 p_T > 30 \text{ GeV cut}$
Limit

- No significant excess of signal above background
- Set a 95% confidence limit on the b’ model using Pythia at LO
Limit – Lifetime vs. Mass

- At $m_{b'} = 150$ GeV, exclude at 95% confidence:
  - $2.0 < c\tau < 70$ mm
  - $0.55 < c\tau < 52$ mm

- At $c\tau = 10$ mm, exclude at 95% confidence:
  - $m_{b'} < 174$ GeV

- Model only valid if $m_{b'} < m_t$

- More generally, we exclude a region in mass and lifetime parameter space
Conclusions

- We have completed a search and set a limit on long-lived particles decaying to $Z^0$’s at CDF in the dimuon channel
- Will now look at dielectrons
  - Will use experience gained from dimuon channel
  - Have greater acceptance for electrons
- Can do more searches using $Z^0$ bosons!
- And a lot more tools to use…

- What would $Z^0$ new physics events look like?
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