CDF note 7244

Search for Long-Lived Parents of the Z^0 Boson

The CDF Collaboration
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We present the results of a search for new particles with long lifetime that decay to a Z^0 boson. The possibility of a long-lived parent of the Z^0 is predicted by several models, such as a fourth generation quark and gauge mediated supersymmetry breaking scenarios in which the gravitino is the LSP. We vertex dimuons with invariant mass near the Z^0 peak and study the decay length distribution. No evidence of a long-lived component is found, and cross-section limits are presented using the fourth generation quark model.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

This note presents a search for a long-lived particle decaying to a Z^0 gauge boson created in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF detector [1] at the Fermilab Tevatron. We search for a non-prompt source of Z^0 bosons by vertexing the muons in $Z^0 \to \mu^+\mu^-$ and searching for an excess at large distances from the beam in the transverse plane, L_{xy}. These results extend the sensitivity obtained from previous searches [2].

There are several models that predict a long-lived particle decaying to a Z^0. For example, gauge-mediated SUSY models where the gravitino is the LSP [3] allow long lifetime due to the weak gravitino coupling, and the process in Figure 1 could produce displaced Z^0s. A 4$^{\text{th}}$ generation quark, b', is another example. If the b' has a mass less than the top quark mass, its dominant decay is $b' \to bZ^0$ through the loop diagram shown in Figure 1. We use the b' model to quantify our acceptance, but aim to maintain model independence in our selection.

Beyond these specific model dependent motivations, this is an experimentally appealing search mode with the background limited only by how well tracks can be reconstructed.

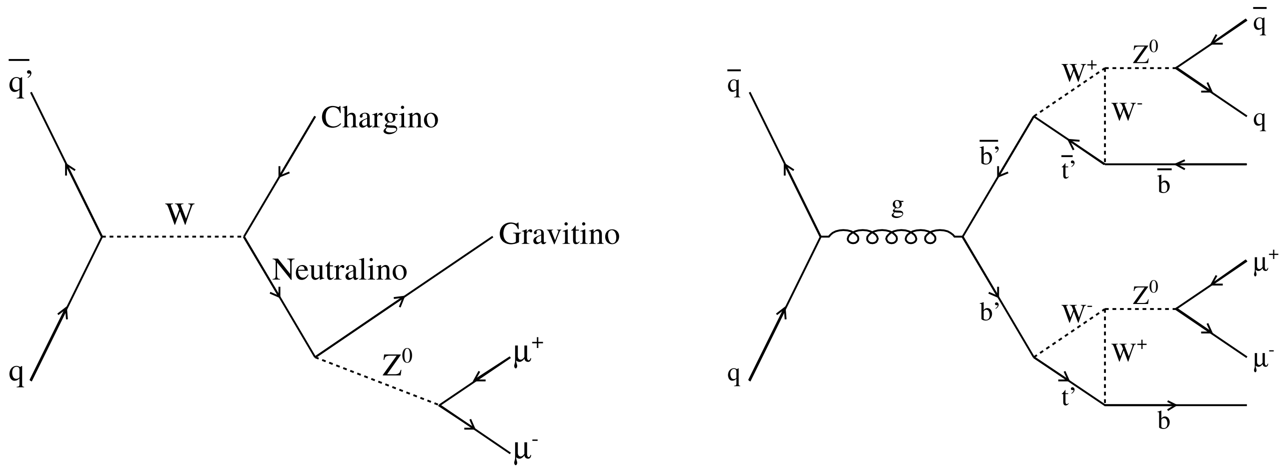

FIG. 1: Feynman diagrams for example models producing displaced Z^0s. Left: Chargino-Neutralino production and decay in a gauge-mediated SUSY breaking model. Right: b' production and decay in the 4$^{\text{th}}$ generation quark model with $m_{b'} < m_t$ and $m_{t'}$.

II. DATA SAMPLE & EVENT SELECTION

This search is performed using data collected with the CDFII detector between March 2002 and September 2003 corresponding to an integrated luminosity of 163 pb^{-1}. The data are collected with a trigger requiring at least one muon with $p_T > 18$ GeV/c. We then select Z^0 events offline with exactly two muons with $p_T > 20$ GeV/c and invariant mass near the Z^0 peak: $81 < M_{\mu\mu} < 101$ GeV. We use only muon tracks that are well-measured based on the number of hits used in the track fit and the uncertainty on the helix fit parameters as listed in Table I.

When the two tracks are nearly back-to-back, a small offset in the impact parameter of one track can lead to a large shift in L_{xy} as shown schematically in Figure 2. To reject such events, we require $\Delta\phi < 175°$ between the two muons. This rejects 99.8% of the large L_{xy} background but is very efficient for Z^0s produced with even a modest boost. Z^0s from the decay of a new particle would be boosted by the decay as well as any p_T of the parent.

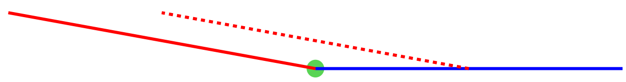

FIG. 2: Since dimuons from Z^0's produced at rest are close to back-to-back, a small offset on one of the tracks (shown by the red, dashed line) produces a large shift in the measured L_{xy}.

p_T of each dimuon track	> 20 GeV
# of muons with $p_T > 20$ GeV	$= 2$
Invariant mass of dimuons	$81 < M_{\mu\mu} < 101$ GeV
Tracking Quality cuts:	
# of drift chamber hits	≥ 60
# of $r\phi$ silicon hits	≥ 3
Silicon χ^2/dof	< 8
(Track d_0 error)^2	$< (28\ \mu\text{m})^2$
(Track ϕ_0 error)^2	$< (0.2\ \text{deg})^2$
(Track $curv$ error)^2	$< 8 \times 10^{-12}$ cm^{-2}
Δz of 2 muons at L_{xy} intersection	< 1.5 cm
$\Delta\phi_0$ of 2 muons	$2^\circ < \Delta\phi_0 < 175^\circ$
Δt_0 (for cosmic rejection)	< 3 ns
Muon ID Cuts, both legs:	
On both legs:	
E_{EM}	$< 2 + \max(0, 0.0115(p-100))$ GeV
E_{Had}	$< 6 + \max(0, 0.0280(p-100))$ GeV
Isolation Fraction	< 0.1
Muon Chamber Cuts, tight leg:	
CMU $\lvert\Delta$X$\rvert$	< 3.0 cm
CMP $\lvert\Delta$X$\rvert$	< 5.0 cm
CMX $\lvert\Delta$X$\rvert$	< 6.0 cm
Muon Chamber Cuts, loose leg:	No requirements
Signal Definition:	
With $p_T^Z > 30$ GeV cut	$L_{xy} > 0.03$ cm
Without a p_T^Z cut	$L_{xy} > 0.1$ cm

TABLE I: Signal Selection

High transverse momentum of the Z^0 boson is a generic feature for such decays, so we additionally require $p_T^Z > 30$ GeV. However, we do not heavily optimize this cut to avoid undue model dependence. Furthermore, we perform the search both with and without the p_T^Z cut. That broadens the model independence and adds sensitivity at long lifetimes where the background is already low.

It is common in b-quark tagging to require large impact parameters for the tracks and a large significance of the measured L_{xy}. We do not apply such cuts in order to retain the full L_{xy} distribution as a measure of the L_{xy} tails.

We define, *a priori*, a minimum L_{xy} for the signal region based on the expected background calculated from Standard Model Z^0 generated with `PYTHIA` and processed with a full detector simulation [4]. The requirement is $L_{xy} > 0.3$ mm which is tightened to $L_{xy} > 1.0$ mm in the case without a p_T^Z cut.

III. BACKGROUNDS

The dominant background is from Standard Model Z^0 bosons where mis-reconstruction of one of the muon tracks produces a large L_{xy}. We measure this background from Monte Carlo using the data in the anti-signal region to tune the Monte Carlo resolution modeling. Three tuning methods are used and the differences are taken as a systematic uncertainty on the background prediction. We find backgrounds of 1.1 ± 0.8 events in the $p_T^Z > 30$ GeV case and 0.72 ± 0.27 events for the case without a p_T^Z cut.

The next largest background is from $b\bar{b}$ events where B hadrons, which have real displaced vertices, decay semileptonically to muons. We estimate this background by using Monte Carlo normalized to the number of large L_{xy} events in the data in an independent mass window of $50 < M_{\mu\mu} < 70$ GeV. Using the data for normalization naturally incorporates other muon sources such as decay-in-flight or punch-through. We find a background of 0.06 ± 0.06 events.

Cosmic rays have inherently large L_{xy}. We estimate the background they contribute from the number of events we remove with the cosmic rejection cuts together with the efficiencies of these cuts measured using a clean sample of cosmics. We calculate a background of 0.0004 ± 0.0001 events.

IV. ACCEPTANCE × EFFICIENCY

We measure the acceptance×efficiency for signal as a function of mass and lifetime using a combination of data and Monte Carlo. In the absence of a general model, we use the b' model to quantify the acceptance. We measure efficiencies for the muon identification and track selection using independently selected Z^0 data and compare that to similar efficiencies measured from Z^0 Monte Carlo. The ratio of the data and Monte Carlo efficiencies is used to scale a signal Monte Carlo calculation of acceptance×efficiency. This models the dependence of the efficiency on mass and lifetime using the Monte Carlo but normalizes that to the data.

We measure and apply the trigger efficiency using Standard Model Z^0 candidates from data in which one leg is independently triggered. The tracking requirement in the trigger is not expected to be efficient for particles with very large impact parameter. We model this by removing events in which both muons have impact parameters outside the acceptance of the track trigger. The remaining lifetime dependence of the acceptance e.g., tracking pattern recognition dependence on impact parameter, is taken from the Monte Carlo.

The acceptance×efficiency is shown as a function of lifetime and mass in Figure 3.

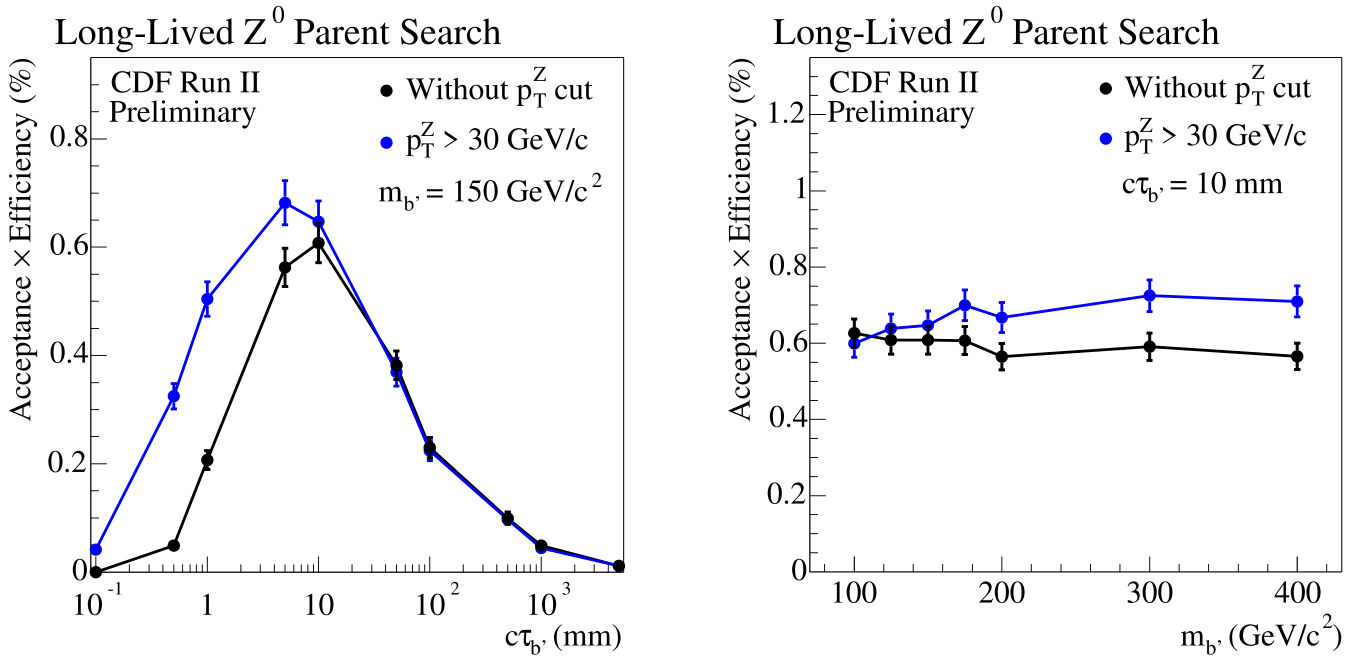

FIG. 3: Left: Acceptance×Efficiency versus b' lifetime for $m_{b'} = 150$ GeV. Right: Acceptance×Efficiency versus $m_{b'}$ for a lifetime of $c\tau_{b'} = 10$ mm.

Uncertainties on the efficiencies arise from the statistical precision with which they can be measured in the data and from systematic uncertainties in the Monte Carlo modeling. The modeling is found to be robust except for the silicon χ^2/dof which is sensitive to variations in the other cuts. We assign an additional systematic uncertainty for this equal to its variation of 7.3%. We also include a systematic uncertainty of 0.9% due to uncertainty on the L_{xy} resolution based on the variations found in the background estimate described above.

The systematic uncertainties on acceptance arise from incomplete knowledge of initial and final state radiation (ISR/FSR) and parton distribution functions (PDF). We estimate the ISR/FSR uncertainty by suppressing each separately in `PYTHIA`. We use uncertainties equal to half of the change in each case. This is done at a few extreme mass and lifetime points and the maximum uncertainty found, 11.2%, is then used for all mass and lifetime values. The PDF uncertainty is calculated by re-weighting Monte Carlo events according to variations in 20 independent sets of CTEQ PDF parameters [5]. The resulting change in acceptance×efficiency, 2.0%, is used as an uncertainty.

V. RESULTS

We plot the L_{xy} distribution of all selected events in Figure 4. We observe three events with $p_T^Z > 30$ GeV in the signal region of $L_{xy} > 0.03$ cm and two events in the signal region of $L_{xy} > 0.1$ cm without a p_T^Z requirement. In both cases, we see no events in the negative L_{xy} control regions.

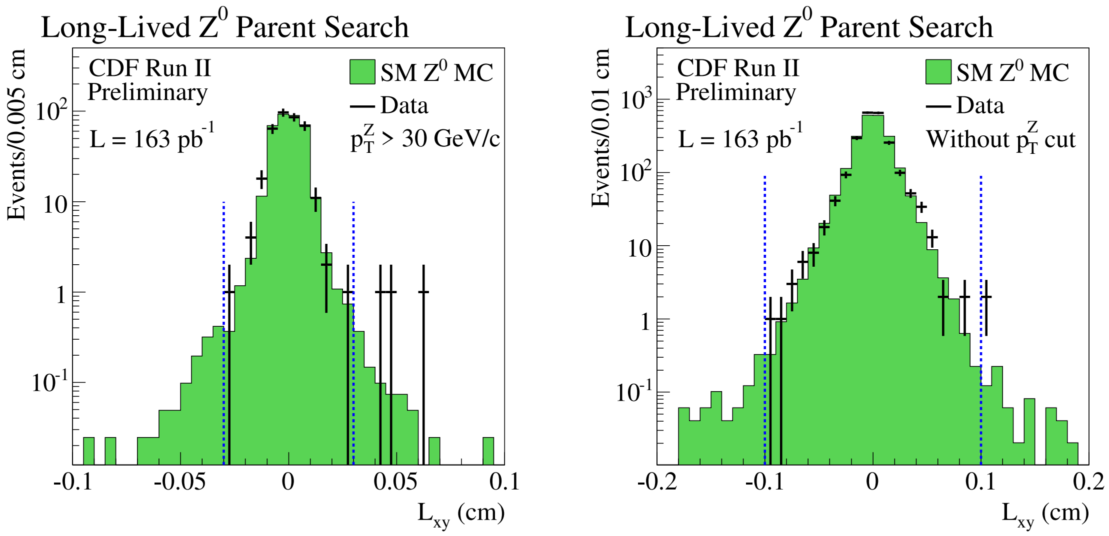

FIG. 4: L_{xy} distributions in data (points) and Monte Carlo (green). Left: With $p_T^Z > 30$ GeV. Right: Without. The dashed lines indicate the signal and control regions.

The observed events are consistent with the background expectation, and *a posteriori* inspection of the events shows them to be consistent with mis-reconstruction as expected for background. A sample event is shown in Figure 5.

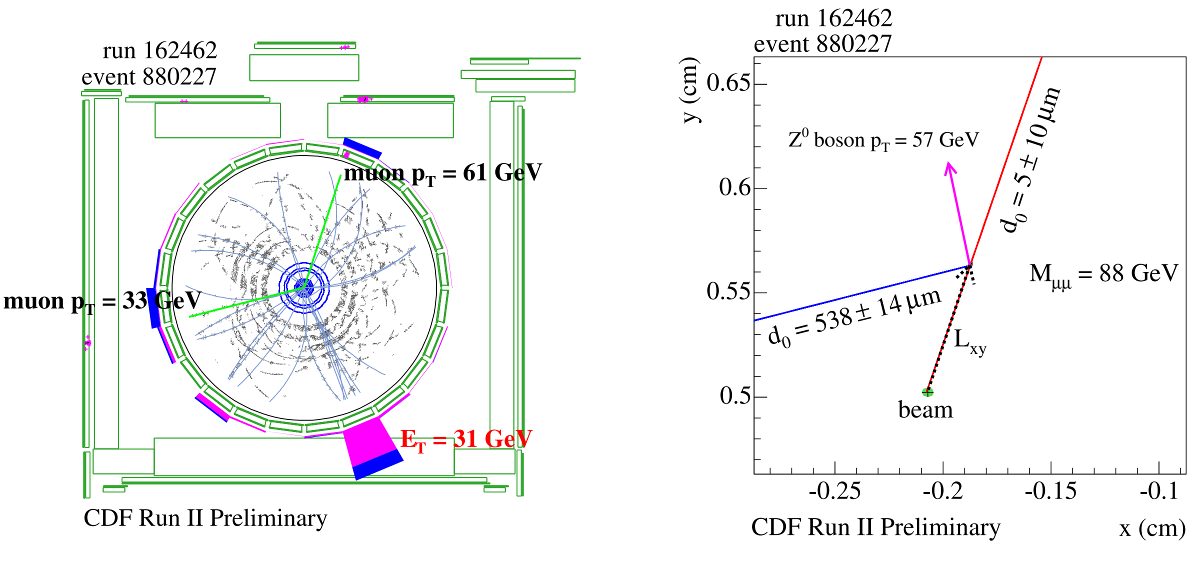

FIG. 5: Sample event display. Left: A full xy view of the event showing the $Z^0 \to \mu^+\mu^-$ recoiling against a jet with $E_T \approx 30$ GeV. Right: An enlarged view of the muon trajectories near the beam position. One of the tracks is consistent with the beam. The other is offset, most likely due to mis-reconstruction.

A. Limit

We calculate limits using the b' model for the acceptance$\times$efficiency. The cross section limits are plotted as a function of lifetime and mass in Figure 6 along with the LO theoretical cross section calculated using PYTHIA. The resulting range of mass and lifetime excluded by this result is plotted in Figure 7.

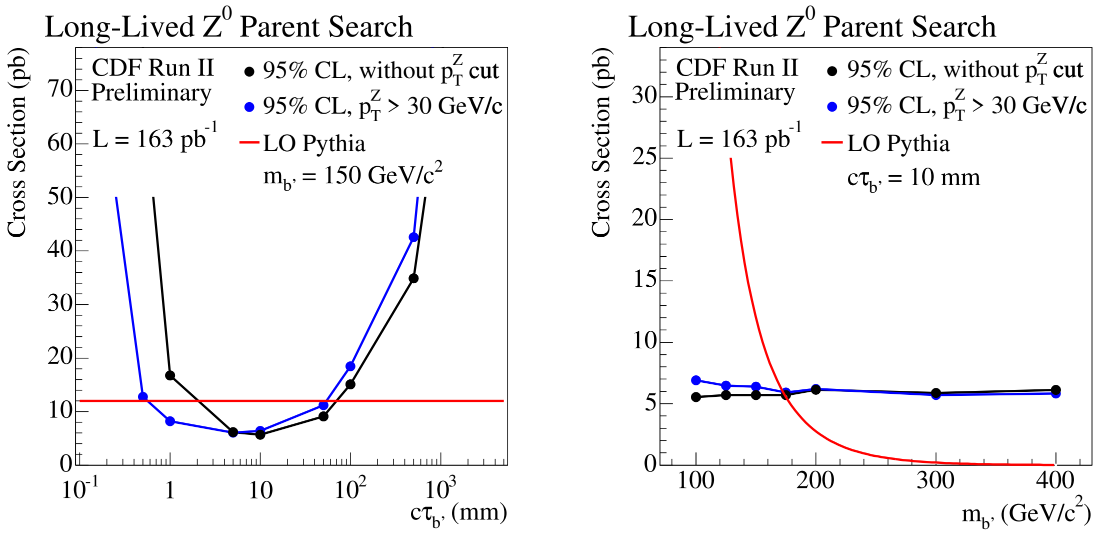

FIG. 6: Left: Cross section limits as a function of lifetime for $m_b' = 150$ GeV$/c^2$. Right: Cross section limits as a function of mass for a lifetime of $c\tau_b' = 10$ mm. The $b'\bar{b}'$ cross-section from PYTHIA is compared.

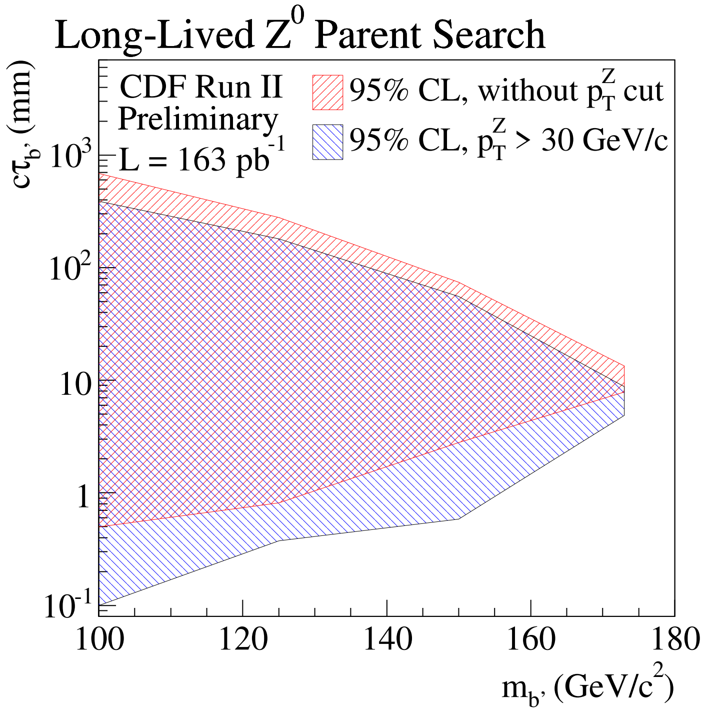

FIG. 7: Lifetime vs. mass exclusion region in the b' model.

Acknowledgments

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