Search for Narrow Dimuon Resonances at CDF

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Motivation

• Dilepton resonances have a strong track record for discovery
  - $J/\psi$, $Y$, $Z$

• Motivation continues at higher energy:
  - Unification of fermions/forces in the context of grand unified theories / String Theory typically based on extended gauge group, eg. $SO(10)$, $E_6$
  - Symmetry-breaking of larger gauge group to SM groups generates additional $U(1)$ gauge groups in intermediate stages, eg.
    - $E_6 \rightarrow SO(10) + U(1)_\psi \rightarrow SU(5) + U(1)_\psi + U(1)_\chi$
  - The breaking of these intermediate $U(1)$ gauge symmetries produces heavy $Z'$ bosons
  - Coupling of $\mathcal{O}(\alpha_{EW})$ implies small width/mass ratio
Motivation

- Gravity also enters the game
- Randall-Sundrum model of “gravity unification”
  - i.e. Ameliorating the problem of large hierarchy between electroweak symmetry breaking energy scale and Planck mass scale
  - a.k.a. “why is gravity so much weaker than electroweak force?”
- Suggested solution: its not really, but just appears to be so weak...

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Randall and Sundrum, PRL 83 (1999) 3370
Motivation

- Randall-Sundrum prescription
  - Construct Gravitational Lagrangian in bulk and on branes
  - Derive equation of motion for the metric, from principle of stationary action
  - Solve for metric $g_{\mu\nu}$:

\[ ds^2 = e^{-2kr_c|\phi|} \eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2 \]
Motivation

• Randall-Sundrum prediction:
  - Ground-state wave function of graviton small on our brane, ie gravity appears weak
  - But excited states of graviton wave function has big overlaps, ie. Massive Kaluza-Klein gravitons with electroweak-strength couplings to SM particles on our brane
Motivation

- Models of new physics also contains scalar particles
  - Higgs bosons with enhanced couplings to muons
  - Supersymmetric partner of neutrino in R-parity violating SUSY models: s-channel resonant production of sneutrino, decaying to dimuons

- We use sneutrinos, Z', and Gravitons as examples of new particles with spin 0, 1 and 2 respectively

- Particle spin affects the angular distribution of decay muons and the detector acceptance
Methodology

- Using the $Z'$ resonance as an example, we scan the dimuon mass spectrum using simulated templates generated as a function of $Z'$ mass.

- For each $Z'$ mass, we scale the expected dimuon mass distribution so as to vary its integrated number of $Z'$ events, $N(Z')$.

- The total expected distribution in dimuon mass is obtained by adding the (scaled) $Z'$ template distribution and the standard model and misidentification background distributions.

- The total expected distribution is normalized to the data in the $Z$ mass peak region.

- The binned poisson likelihood is computed between the total expected distribution and the data distribution in dimuon mass.
Methodology

- At each $Z'$ pole mass, we compute the total poisson likelihood over all data bins, as a function of $N(Z')$
  - Systematic uncertainties are correlated across the bins and are incorporated as nuisance parameters
  - Nuisance parameters are varied by expected uncertainty and averaged over
- We use the total poisson likelihood to compute the interval for $N(Z')$ at any specified confidence level
  - Feldman-Cousins prescription is used to construct the interval
  - The prescription automatically chooses 1-sided or 2-sided interval depending on whether $N(Z')=0$ is excluded
- We obtain the “maximum-likelihood” estimate of $N(Z')$ and its confidence interval at each value of the $Z'$ pole mass
Quadrant of Collider Detector at Fermilab (CDF)

Select events with two central \(| \eta | < 1\) muons

EM calorimeter provides precise electron energy measurement

COT provides precise lepton track momentum measurement

Calorimeters measure hadronic recoil particles
Collider Detector at Fermilab (CDF)

- Muon detector
- Central hadronic calorimeter
- Central outer tracker (COT)
Drift Chamber (COT) Alignment
Internal Alignment of COT

- Use a clean sample of \( \sim 200k \) cosmic rays for cell-by-cell internal alignment

- Fit COT hits on both sides simultaneously to a single helix (AK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'
Residuals of COT cells after alignment

CDFII preliminary

Before alignment

Cell number (φ)

Residual (microns)

after alignment

Final relative alignment of cells ~5 μm (initial alignment ~50 μm)
Signal Simulation and Fitting
Signal Simulation and Template Fitting

- All signals simulated using a fast Monte Carlo
  - Generate finely-spaced templates as a function of the resonance pole mass
  - Perform binned maximum-likelihood fits to the data

- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation

- Generator-level input for W & Z simulation provided by PYTHIA

- Radiative photons generated according to energy vs angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackeroth, PRD59, 013002 (1998))
Fast Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
  - At each material interaction, calculate
    - Ionization energy loss according to complete Bethe-Bloch formula
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Deposit and smear hits on simulated COT wires, perform full helix fit including beam-constraint
Mass resolution vs mass

- Tracking resolution of muon momentum degrades rapidly as mass and $p_T$ increase, as $\Delta p_T \sim p_T^2$

- Rapidly varying resolution makes fixed binning sub-optimal at either low mass or high mass – ideally want variable mass binning such that $Z'$ propulates a fixed number of bins at any mass
Fractional mass resolution vs mass

Detector resolution dominates

Z boson intrinsic width of 2.8%
Mass\(^{-1}\) resolution vs mass

- Tracking resolution of muon momentum $\Delta(1/p_T) \sim \text{constant}$

- Instead of the dimuon mass distribution, we choose to work with the dimuon $(1/\text{mass})$ distribution, where resolution $\sim \text{constant}$

Resolution approximately independent of mass

Mass resolution is 16% at 1 TeV
Monte Carlo Pseudo-Experiment

- simulated Standard Model (Drell-Yan) background (RED) and Monte Carlo pseudo-experiment (BLUE) with SM + Z' (900 GeV)
- PYTHIA used as generator

$L \sim 2 / \text{fb}$
Monte Carlo Pseudo-Experiment

- Simulated SM (Drell-Yan) background (RED) and SM pseudo-experiment (BLUE)
Mass Peak Fitting

- Integral of $Z'$ template = number of $Z'$ events $N(Z')$
- Perform maximum likelihood fit to data for $N(Z')$, using sum of background and $Z'$ template shapes
  - Poisson probability per bin, product over bins

![Graph showing pseudo experiment and $Z'$ MC]
Technique

- We normalize all backgrounds to the data in the control region of the Z boson mass peak: $70 < m_{\mu\mu} < 100$ GeV
- We use the fast simulation to generate resonance templates
- Validate the acceptance and efficiency calculation of the fast simulation as a function of track momentum or dimuon mass, by comparing to data or detailed GEANT-based simulation
Muon Identification Efficiency

- Measure and correct the fast simulation for momentum-dependent identification efficiency measured from data
  - Use Z boson data, tagged with one well-identified muon and one loosely-identified track, use the latter for measuring efficiency

![Graph showing data/simulation calorimeter efficiency vs momentum (GeV)]
Backgrounds

- SM Drell-Yan dominant by far: generated from PYTHIA and simulated with fast simulation
- WW and ttbar from PYTHIA using GEANT simulation of detector
- Cosmic rays
- Jet fakes
- Decays-in-flight

fitted time of drift chamber track at beamline is called $t_0$ assuming outgoing direction

Normalization of cosmic ray bkg

Difference of $t_0$ between two candidate tracks
Jet Fakes and Decays-in-Flight Backgrounds

- Jet fakes = punch-throughs + combinatoric + heavy-flavor decays
  - “Muon” track momentum is correctly measured
  - Shape obtained from jet triggers
- Decay-in-flight component from “kinked” tracks when decay occurs in COT active volume
  - Kink causes large mismeasurement of track momentum

Same-sign data with loose cuts
COT Hit Pattern Cut for Decays-in-flight

A “transition” implies consecutive hits on opposite sides of the fitted track.
Jet Fakes and Decays-in-Flight Backgrounds

- Decay-in-flight component suppressed by COT-based cuts: track $\chi^2$, $\Delta z_0$, pattern of hit residuals

Same-sign data with tighter cuts

<table>
<thead>
<tr>
<th>$\chi^2 / \text{ndf}$</th>
<th>21.42 / 23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob</td>
<td>0.5552</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$1.827 \pm 0.496$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$0.04968 \pm 0.06089$</td>
</tr>
</tbody>
</table>
Systematic Uncertainties

- Uncertainties on luminosity and absolute acceptance and efficiency cancel, due to normalization of backgrounds to the Z boson control region

- **Mass-dependent uncertainties only..**
  - PDFs: increase linearly to 16% at 1 TeV
  - QCD k-factor: increase linearly to 9% at 1 TeV
  - Electroweak radiative corrections: increase linearly to 3% at 1 TeV
  - Total acceptance: increase linearly to 3% at 1 TeV
  - Momentum scale and resolution: tuned on Z boson peak, negligible uncertainty

- Systematic uncertainties incorporated as nuisance parameters and integrated out in likelihood calculation
Blind Analysis

Followed “Blind Analysis” procedure:

analysis method approved in CDF and frozen, prior to unblinding the data

ArXiv:0811.0053
Data-Background Agreement

Generally good agreement between data and backgrounds in the search region

\[ \left( \frac{\text{Data} - \text{background}}{\text{statistical error}} \right) \]

Momentum scale slightly off on Z peak

\[ \int L \, dt = 2.3 \, \text{fb}^{-1} \]

Search region

Normalization region

\[ m_{\mu\mu} \, (\text{TeV}^{-1}) \]
Best-Fit and Confidence Intervals on Potential Signal

At each value of $Z'$ pole mass, the point shows the best fit value of $Z'$ signal events.

Error bar shows the 95% C.L. Interval on $N(Z')$, built using Feldman-Cousins prescription.
Dielectron Search

An independent analysis at CDF of the dielectron mass spectrum

3.8σ excess at 240 GeV

2.5σ significance including “trials factor”

ArXiv:0810.2059
Z' Cross Section and Mass Limits

Convert N(Z') limit to Z' cross section limit, by incorporating mass-dependent acceptance and number of Z boson events observed.

p-value of most significant “excess” = 6.6%
Z' Cross Section and Mass Limits

Convert $N(Z')$ limit to $Z'$ cross section limit, by incorporating mass-dependent acceptance and number of $Z$ boson events observed.
Z' Mass Limits

Z' mass lower limits at 95% CL in specific models (eg. E\(_6\)-inspired models specifying left- and right-handed couplings to \(u\) and \(d\) quarks and leptons):

<table>
<thead>
<tr>
<th>Z'</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z'(_{SM})</td>
<td>1030 GeV</td>
</tr>
<tr>
<td>Z'(_{\psi})</td>
<td>878 GeV</td>
</tr>
<tr>
<td>Z'(_{\chi})</td>
<td>892 GeV</td>
</tr>
<tr>
<td>Z'(_{\eta})</td>
<td>904 GeV</td>
</tr>
<tr>
<td>Z'(_{I})</td>
<td>789 GeV</td>
</tr>
<tr>
<td>Z'(_{\text{sec}})</td>
<td>821 GeV</td>
</tr>
<tr>
<td>Z'(_{N})</td>
<td>861 GeV</td>
</tr>
</tbody>
</table>
Sneutrino & Graviton Acceptance

Incorporate spin-dependence of acceptance

include different graviton polarizations for $qq \rightarrow G$ and $gg \rightarrow G$
## Sneutrino & Graviton Mass Limits

### Lower mass limits at 95% CL

<table>
<thead>
<tr>
<th>RS graviton $k/M_{\text{Planck}}$</th>
<th>Graviton mass limit</th>
<th>$\tilde{\nu}$ BR $\lambda^2 \cdot BR$ mass limit</th>
<th>$\tilde{\nu}$ mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>293</td>
<td>0.00001</td>
<td>278</td>
</tr>
<tr>
<td>0.015</td>
<td>409</td>
<td>0.00002</td>
<td>397</td>
</tr>
<tr>
<td>0.025</td>
<td>493</td>
<td>0.00005</td>
<td>457</td>
</tr>
<tr>
<td>0.035</td>
<td>651</td>
<td>0.001</td>
<td>541</td>
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<tr>
<td>0.05</td>
<td>746</td>
<td>0.002</td>
<td>662</td>
</tr>
<tr>
<td>0.07</td>
<td>824</td>
<td>0.005</td>
<td>751</td>
</tr>
<tr>
<td>0.1</td>
<td>921</td>
<td>0.01</td>
<td>810</td>
</tr>
</tbody>
</table>

Spacetime curvature in the extra spatial dimension in the Randall-Sundrum model is given by $k^2$

BR denotes the sneutrino branching ratio to muons, $\lambda$ is the qq-sneutrino coupling
Summary

- search for narrow dimuon resonance in 2.3 fb\(^{-1}\) at CDF

- Data consistent with Drell-Yan expectation and other (small) backgrounds
  - Most significant "excess" occurs with p-value of 6.6%

- Most stringent limits on spin 0, 1 and 2 resonances at high mass